Highlights of SM and BSM Higgs Searches at the LHC

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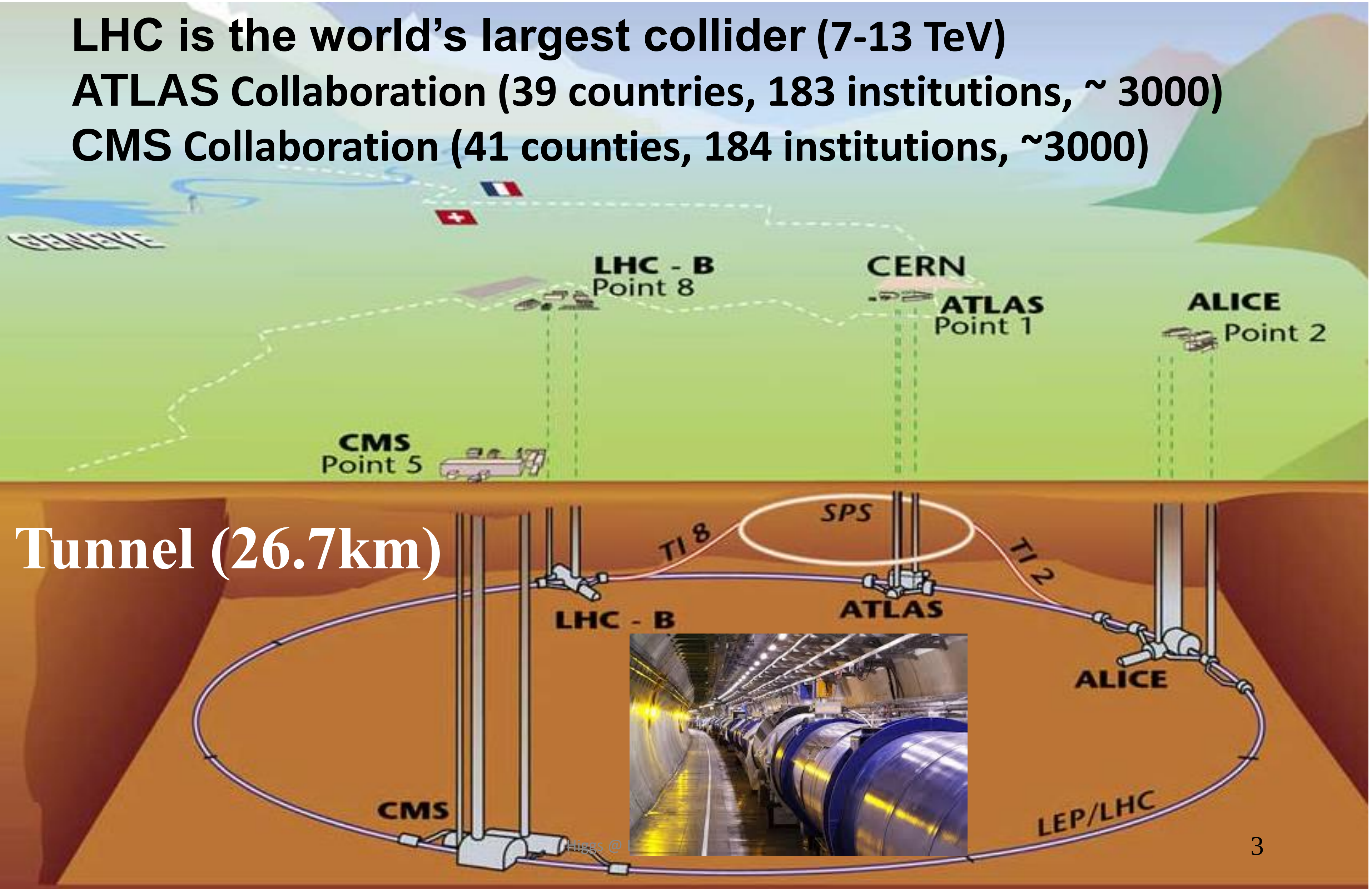
Center of High Energy Physics
Peking University, January 5, 2018

Outline

- About LHC, ATLAS and CMS
- Higgs @ LHC Run1
- Higgs @ LHC Run2
  - Re-discovery SM Higgs
  - Search for VBF, VH, ttH, tH Higgs production
  - Search for H→bb, ττ, μμ to study Yukawa couplings
  - Use Higgs boson as a tool to find new physics
    - Heavy Higgs
    - Charged Higgs
    - Double-Higgs production
    - Higgs BSM decays and couplings

Large Hadron Collider at CERN



LHC is the world’s largest collider (7-13 TeV)

ATLAS Collaboration (39 countries, 183 institutions, ~ 3000)

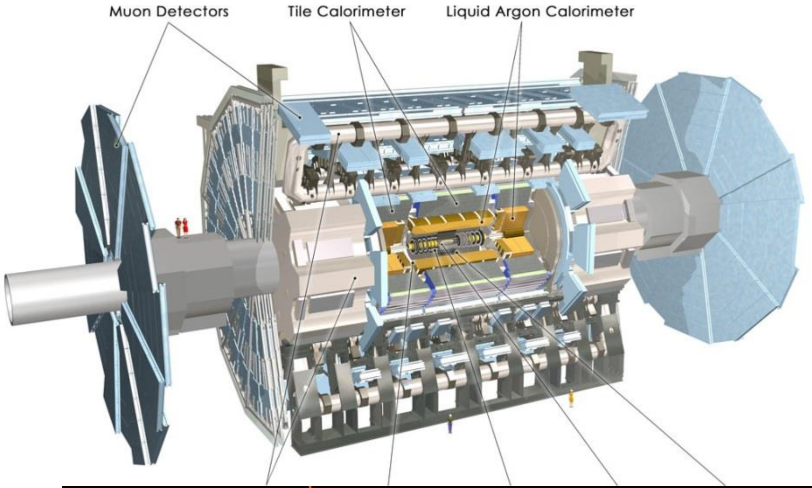
CMS Collaboration (41 counties, 184 institutions, ~3000)

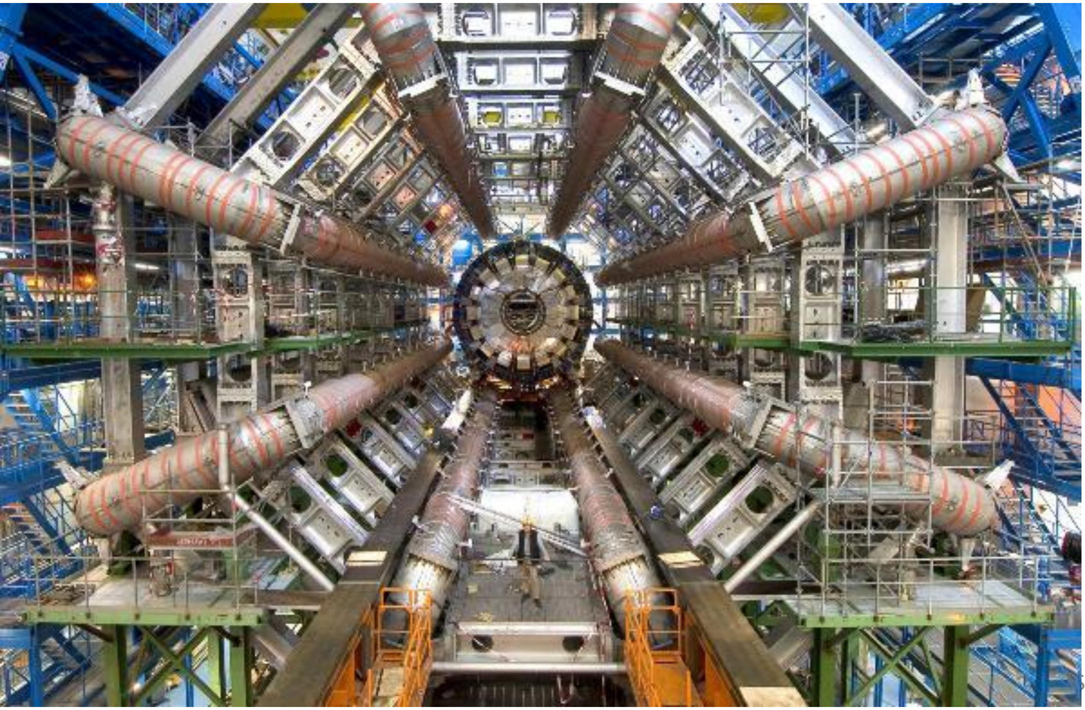
Tunnel (26.7km)

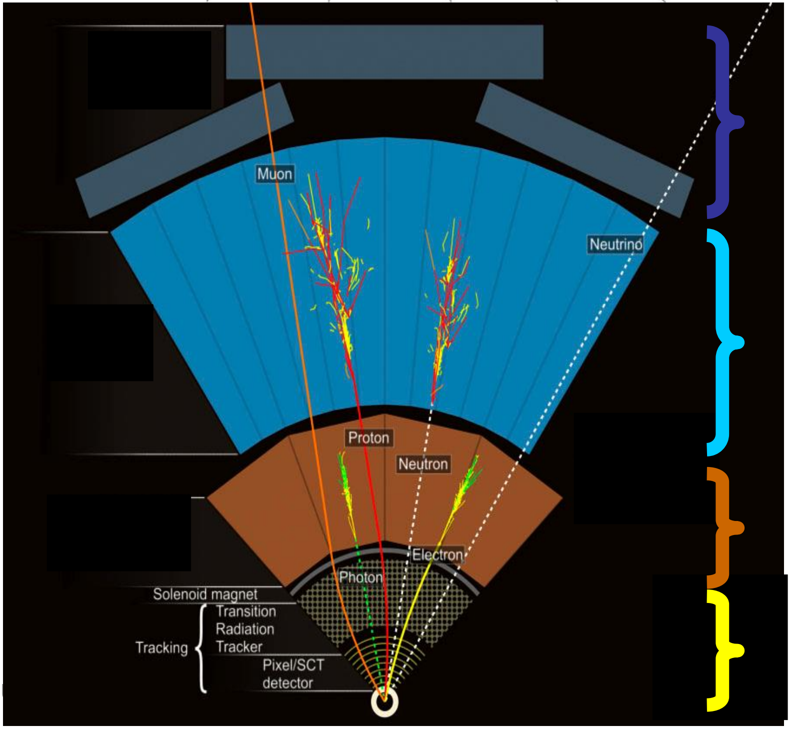
ATLAS Experiment

ATLAS-中国组(~120人)

- 高能所、南大、清华
- 科大、山大、交大
  李政道研究所

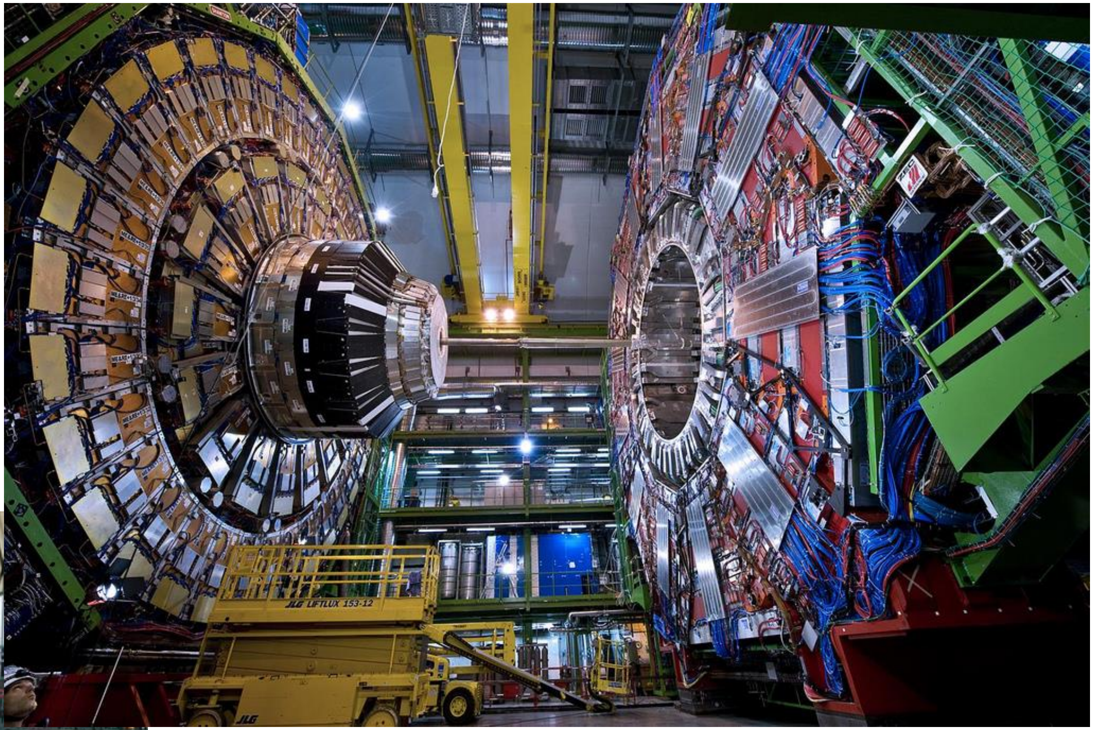


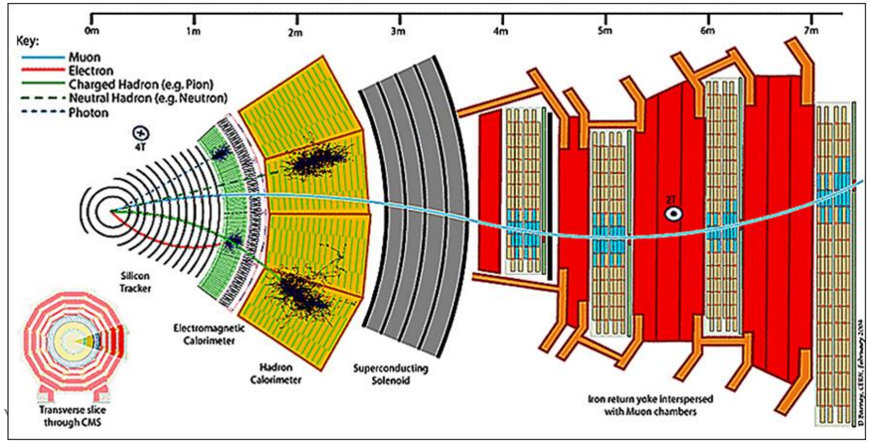




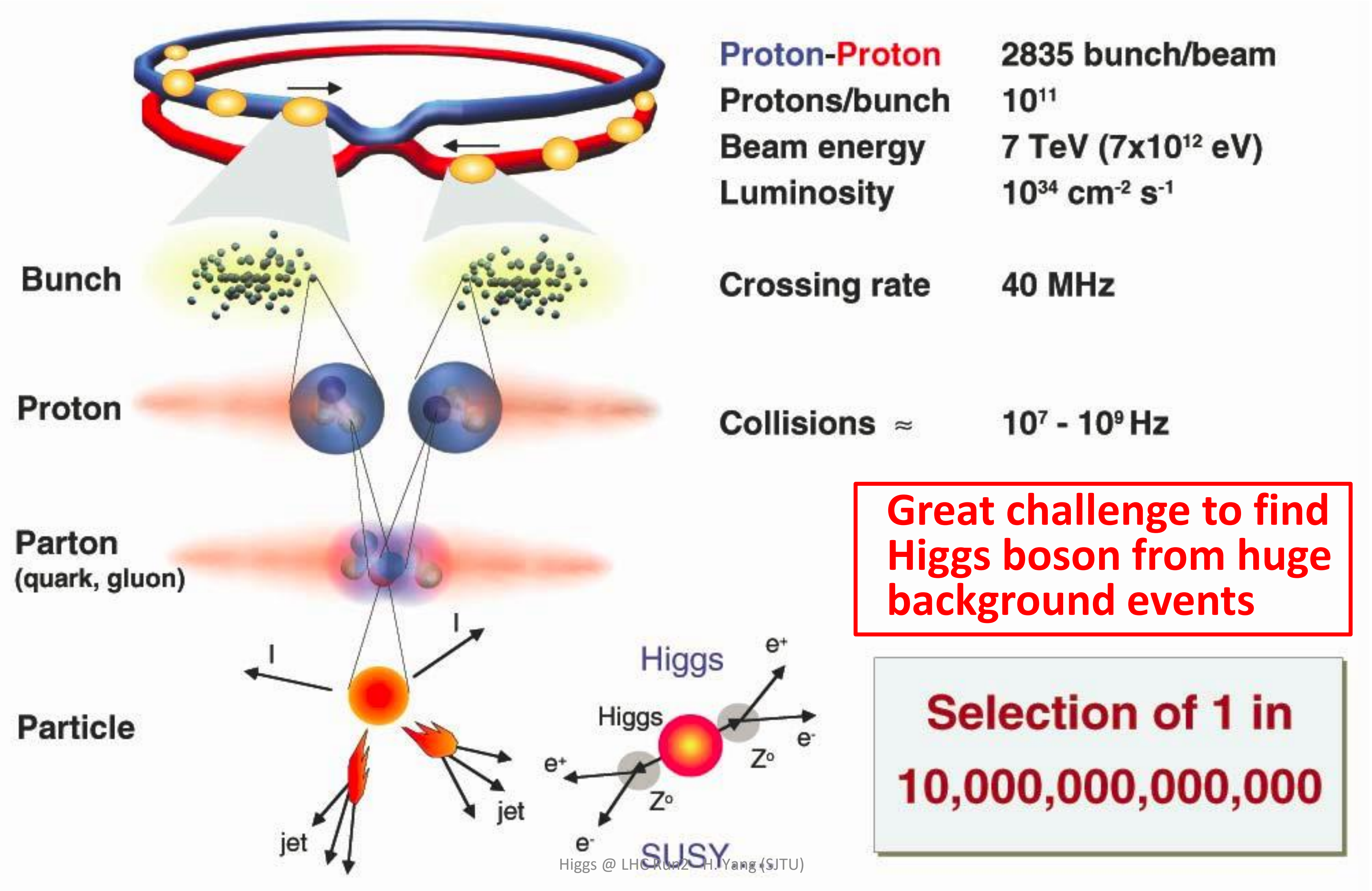
CMS Experiment

CMS-中国组(~80人)
- 高能所、北大
- 北航、清华
- 中山大学





Large Hadron Collider



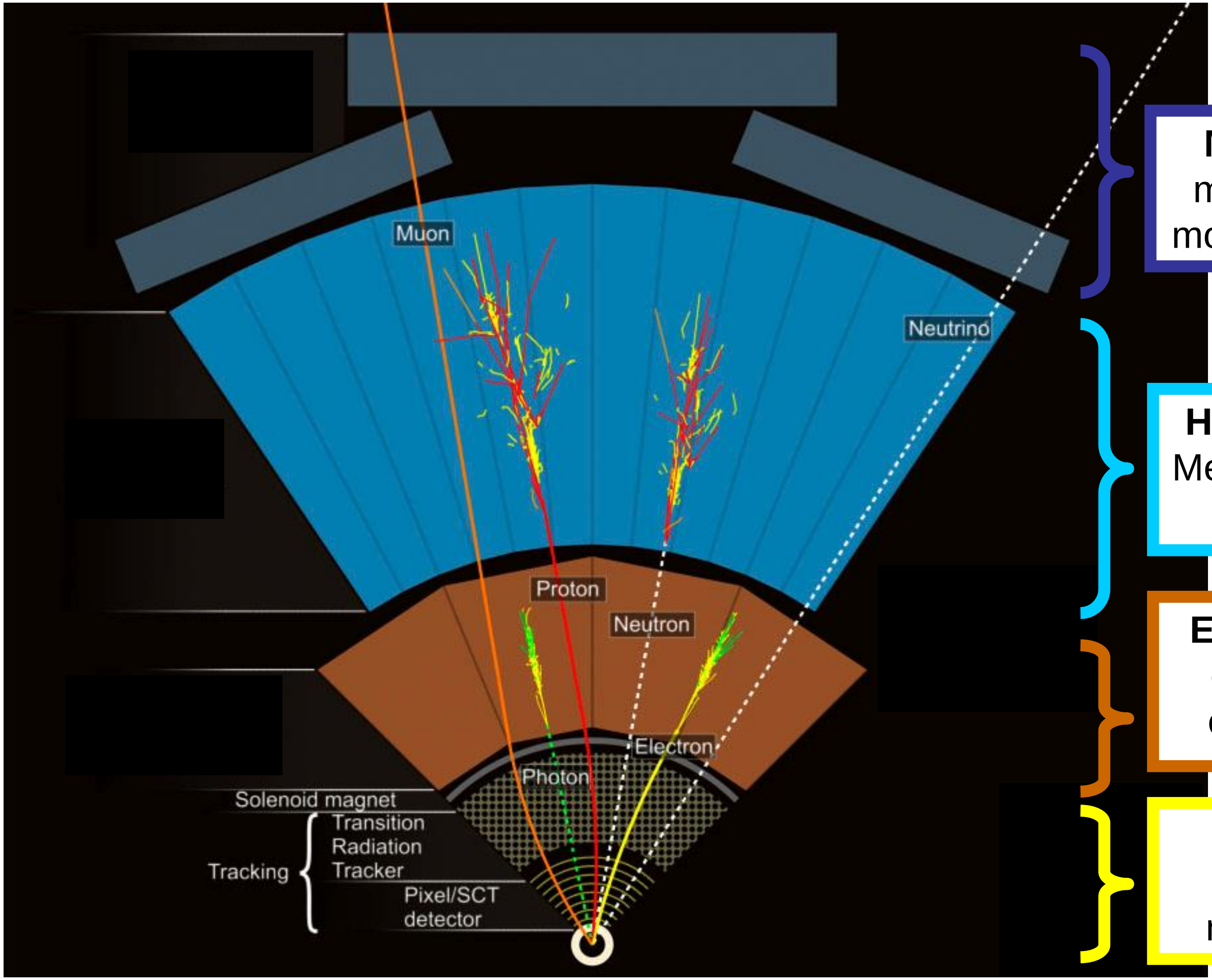
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Selection of 1 in

10,000,000,000,000

Great challenge to find Higgs boson from huge background events

Particle Identification



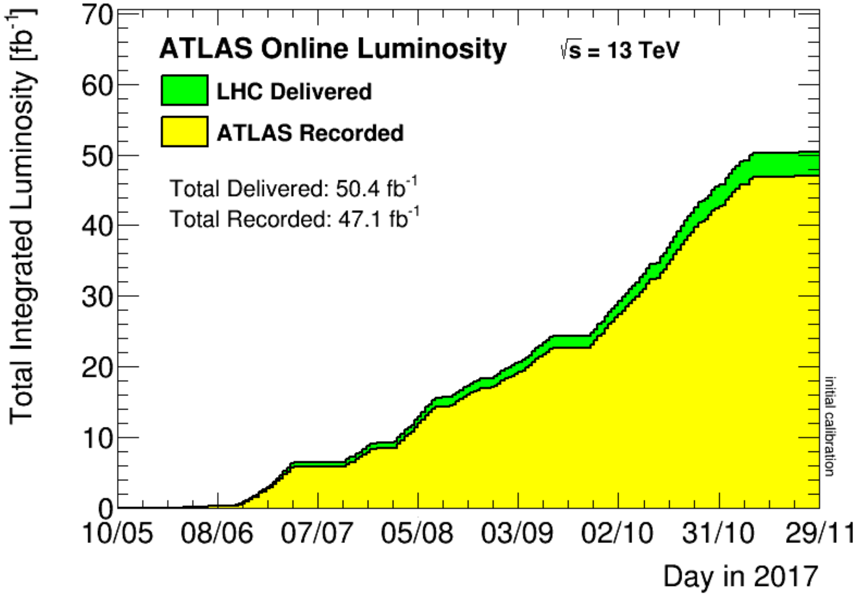
Muon Spectrometer:
muon identification and
momentum measurement

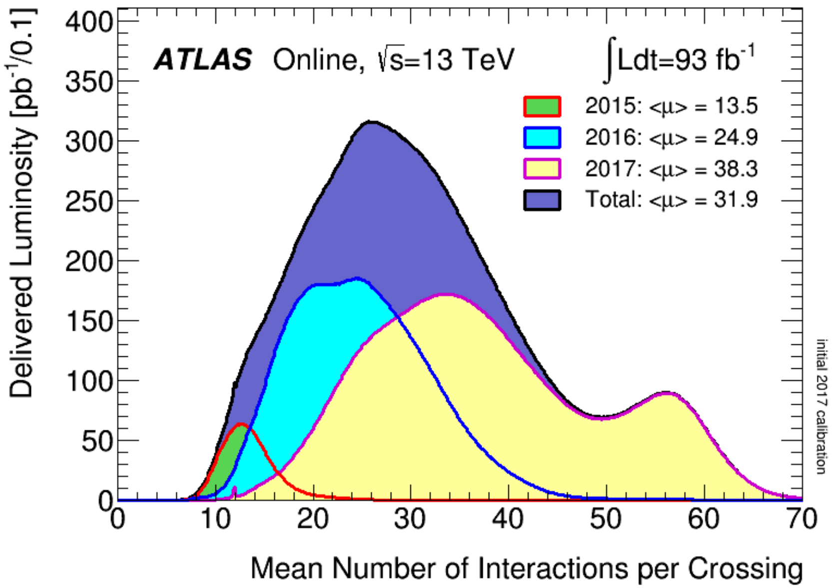
Hadronic calorimeter:
Measurement of jets and
missing energy

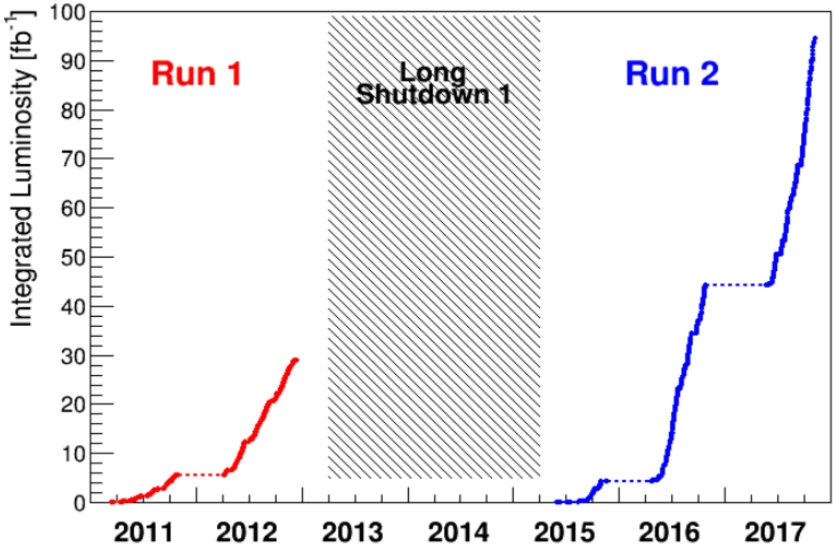
Electromagnetic calo:
e/γ identification and
energy measurement

Tracking system:
Charged particle
momentum, vertexing

LHC Online Luminosity



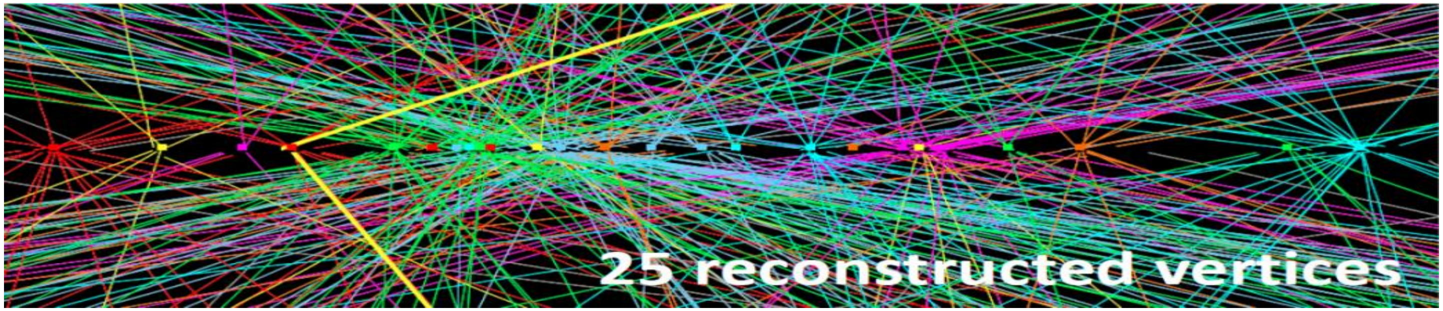


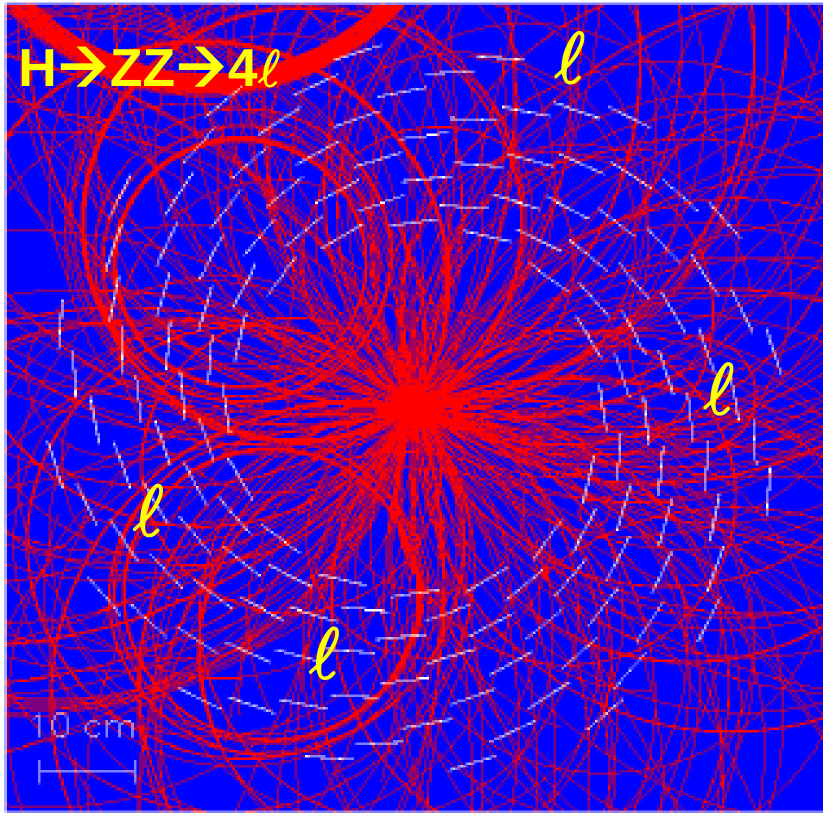


- ➢ **Challenge condition: Luminosity reached 2x10^{34} cm^{-2}s^{-1}**
- ➢ **Pileup μ reached up to 70, beyond ATLAS/CMS detector can handle μ ~ 60, need to improve High Level trigger and upgrade detector.**

Great Challenge

LHC Luminosity（2 x 10^{34} $cm^{-2}s^{-1}$ ）➔ Large Pileup Events





Great challenge for event reconstruction, identification and physics analyses.

BDT method developed by Haijun Yang etc. is widely used to improve Particle ID and event selection！

H. Yang et.al., NIMA543 (2005) 577-584
H. Yang et.al., NIMA555 (2005) 370-385

A Decision Tree

(sequential series of cuts based on MC study)

(N_{signal}/N_{bkgd})

40000/40000

bkgd-like

signal-like

9755/23695

30,245/16,305

bkgd-like

signal-like

signal-like

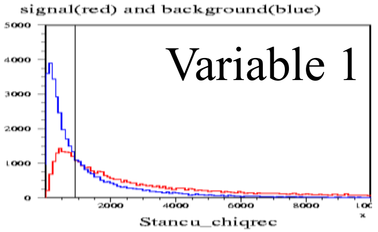
bkgd-like

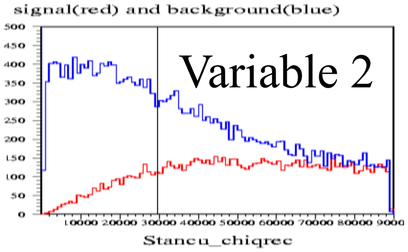
1906/16828

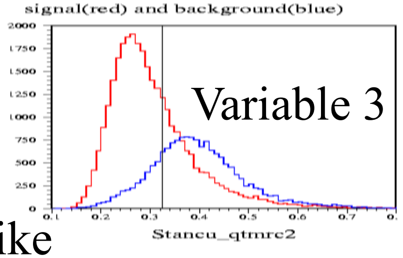
7849/6867

20455/3417

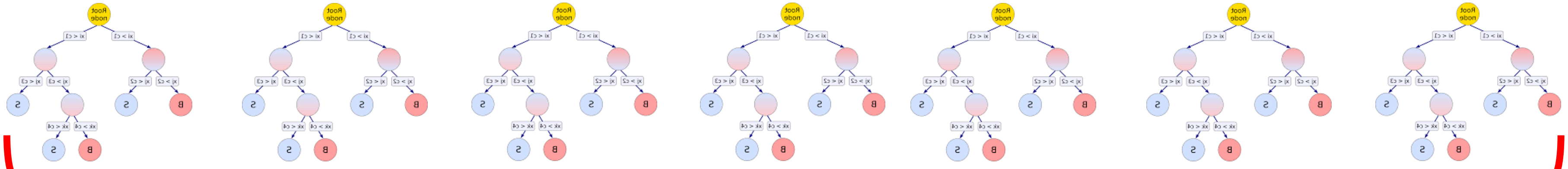
9790/12888

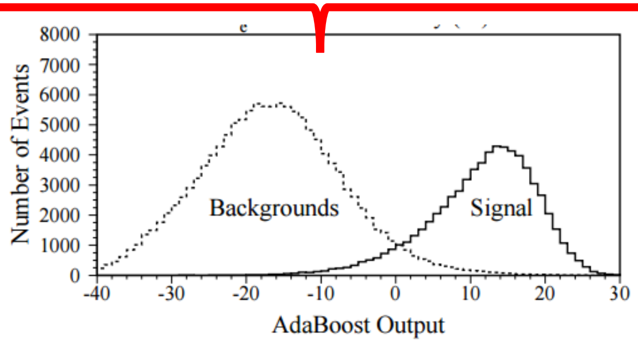






通过Boosting 算法不断提高误判事例的权重，产生一系列Decision Trees



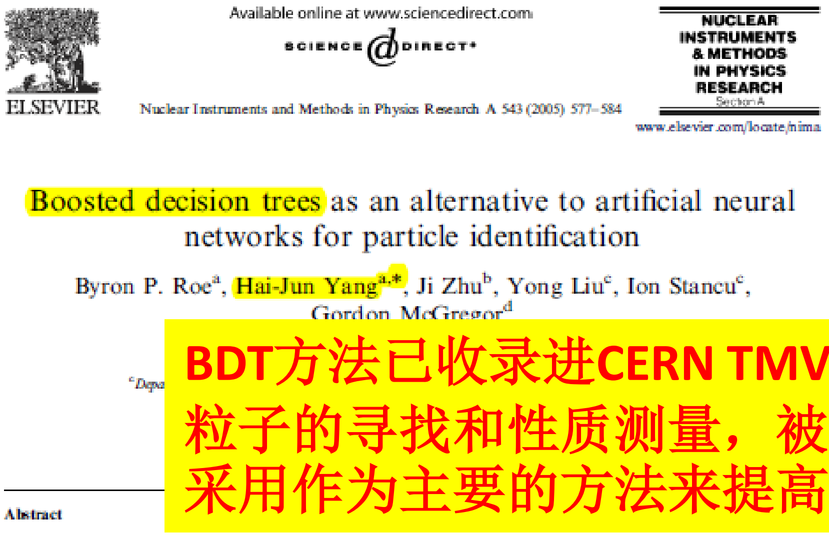


把每个事例在所有Decision Trees获得的积分累加，通过“Majority vote”方法提高性能和稳定性。

通过Boosting不断提高误判事例的权重，使得这些难以区分的事例在后续的Decision Trees获得的正确区分，提高效率。

Boosted Decision Trees (BDT)

CERN TMVA package , http://tmva.sourceforge.net/



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Nuclear Instruments and Methods in Physics Research A 543 (2005) 577–584

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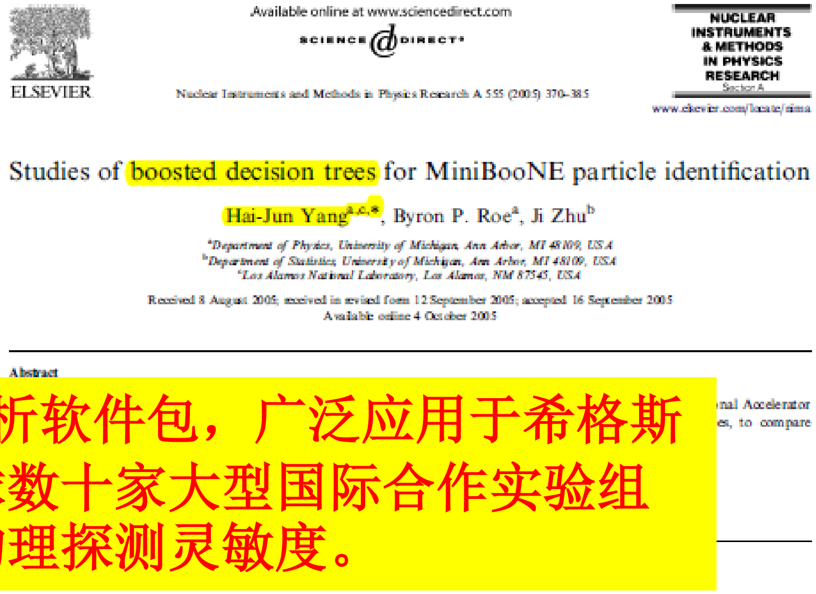
Boosted decision trees as an alternative to artificial neural networks for particle identification

Byron P. Roe[a], Hai-Jun Yang[a,*], Ji Zhu[b], Yong Liu[c], Ion Stancu[c], Gordon McGregor[d]

[a]Depa

Abstract



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Nuclear Instruments and Methods in Physics Research A 555 (2005) 370–385

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Studies of boosted decision trees for MiniBooNE particle identification

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[b]Department of Statistics, University of Michigan, Ann Arbor, MI 48109, USA
[c]Los Alamos National Laboratory, Los Alamos, NM 87545, USA

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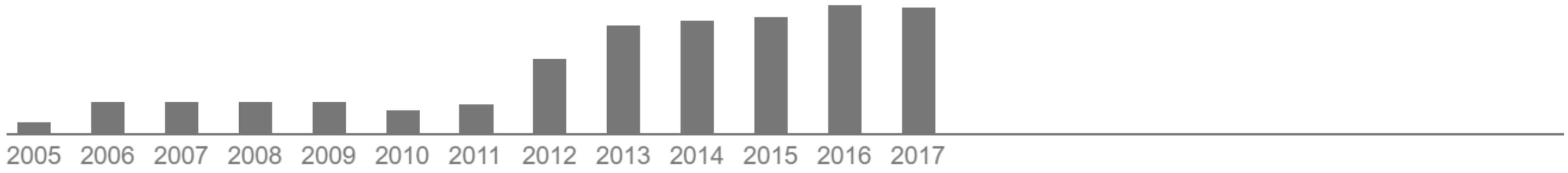
Available online 4 October 2005

Abstract

nal Accelerator
es, to compare

BDT方法已收录进CERN TMVA分析软件包，广泛应用于希格斯粒子的寻找和性质测量，被全球数十家大型国际合作实验组采用作为主要的方法来提高新物理探测灵敏度。

Total citations Cited by 505



Scholar articles Boosted decision trees as an alternative to artificial neural networks for particle identification
BP Roe, HJ Yang, J Zhu, Y Liu, I Stancu, G McGregor - Nuclear Instruments and Methods in Physics Research ..., 2005
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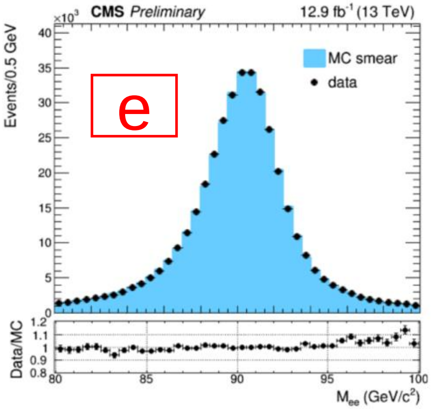
*Corresponding author.
E-mail address: yhj@umich.edu (Hai-Jun Yang).

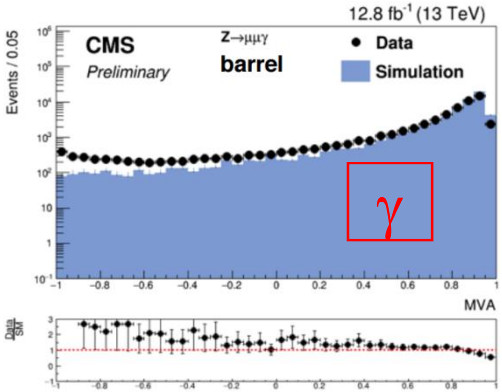
by the LSND experiment [2]. It is a crucial experiment which will imply new physics beyond

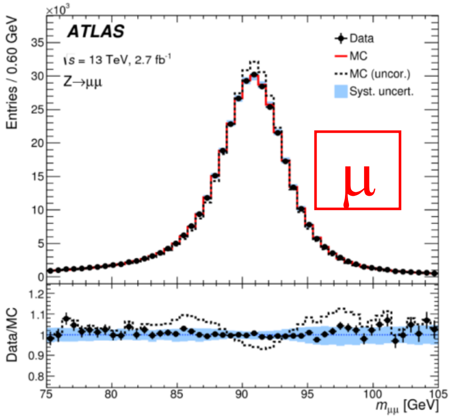
0168-9002/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2005.09.022

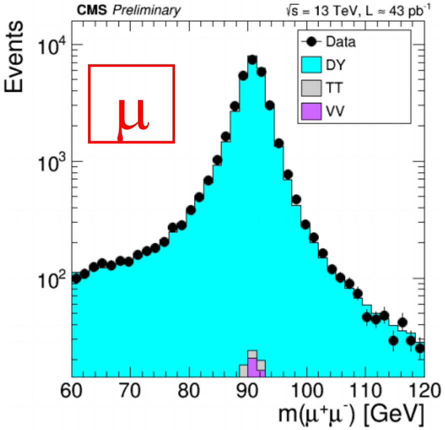
Particle Identification

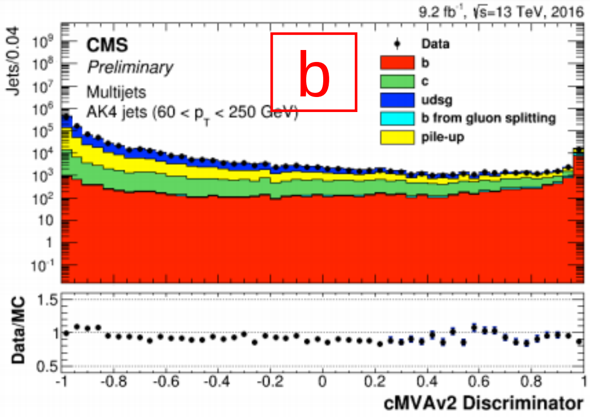
ATLAS-CONF-2015-041, ATL-PHYS-PUB-2016-015
Eur. Phys. J. C (2016) 76:292
CMS-DP-2015-015, CMS-DP-2016-015/042/049

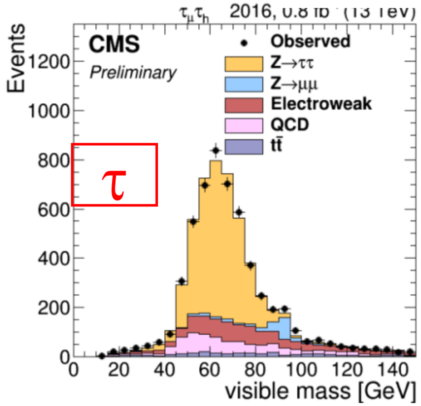




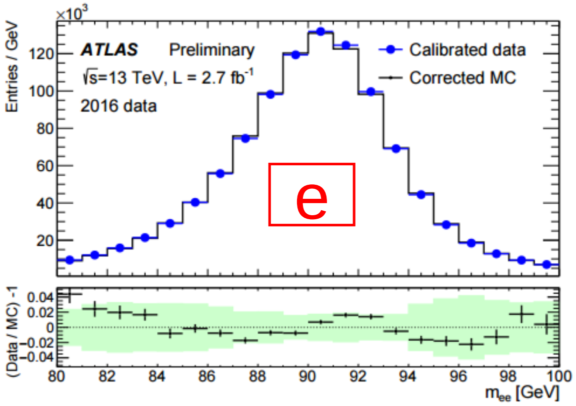


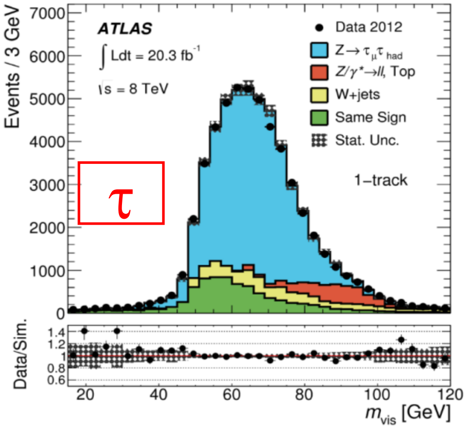


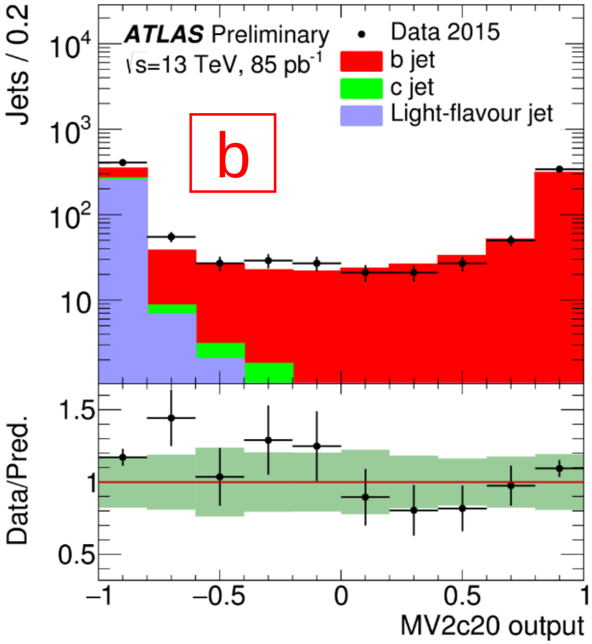


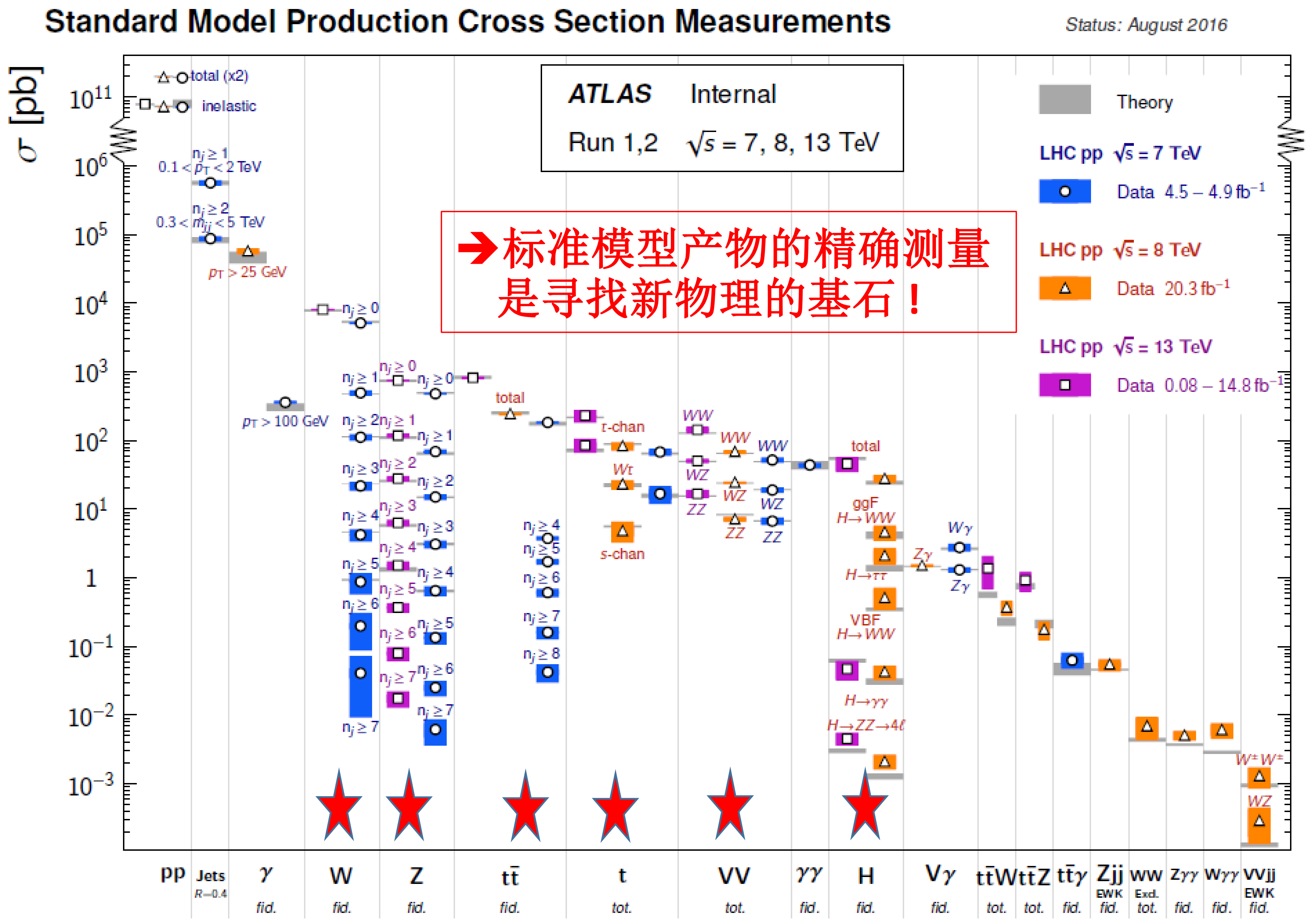


e, γ, τ, b identifications are based on BDT method





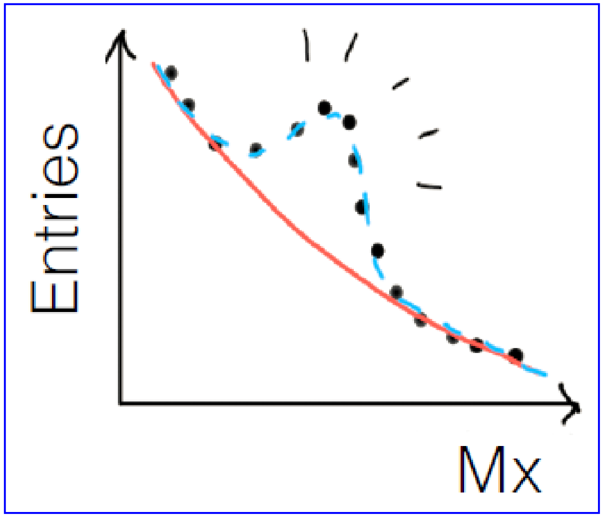




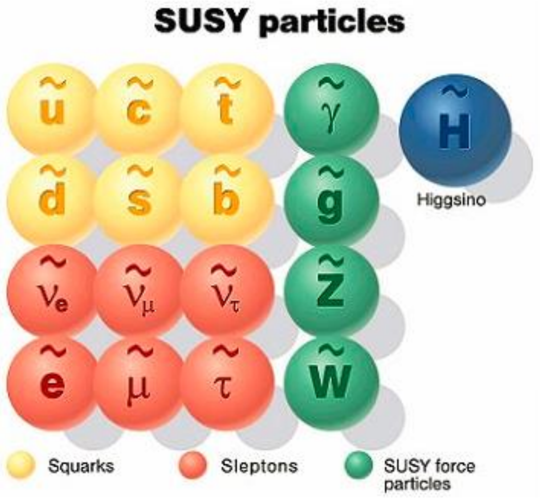
➔标准模型产物的精确测量是寻找新物理的基石！

Search for New Particles

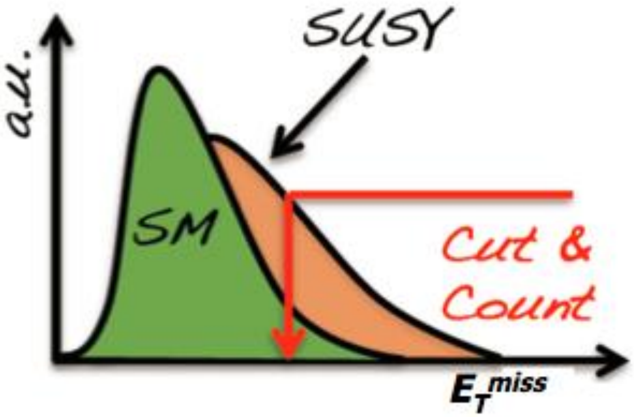
- ✓ X → di-boson
- ✓ X → di-lepton
- ✓ X → di-jets
- ✓ X → di-Higgs
- ✓ … …



Invariant Mass Distribution

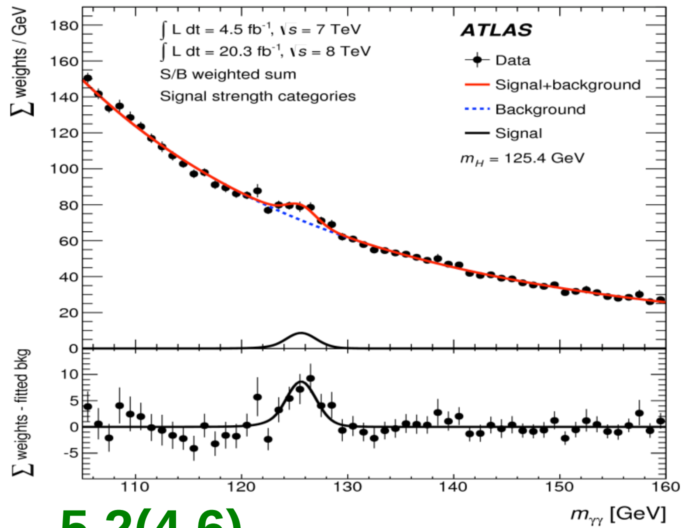


- ✓ SUSY
- ✓ Dark Matter
- ✓ Heavy Quark
- … …

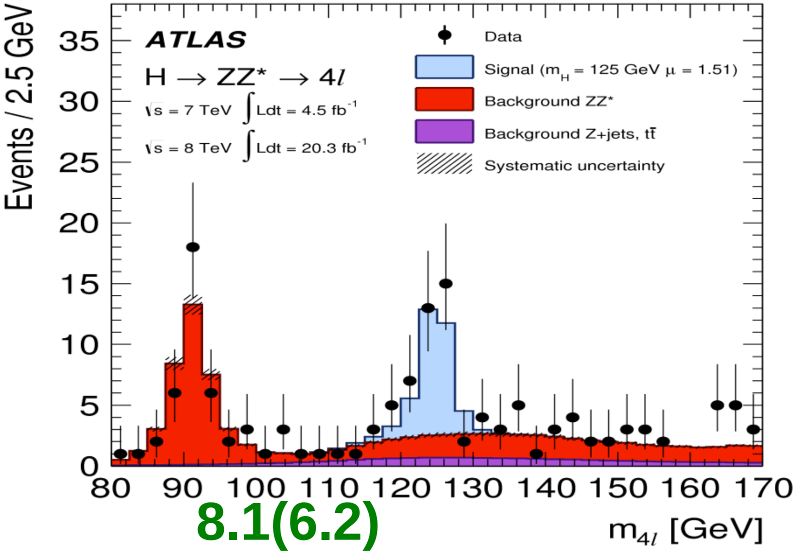


Discovery of the Higgs Boson

ATLAS



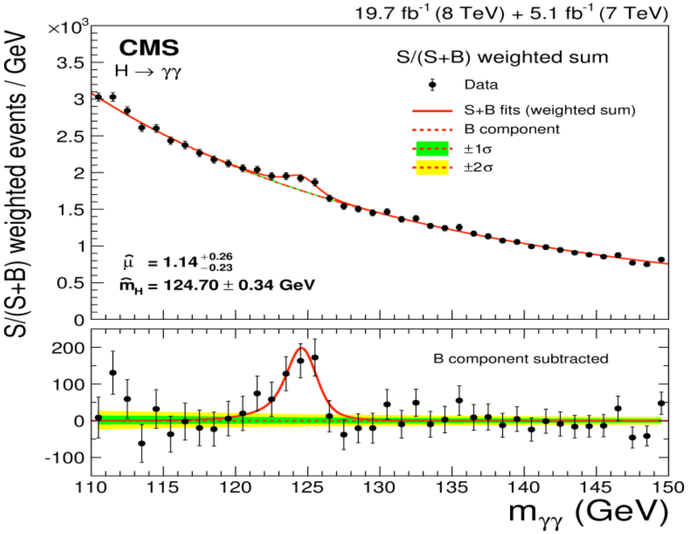
5.2(4.6)



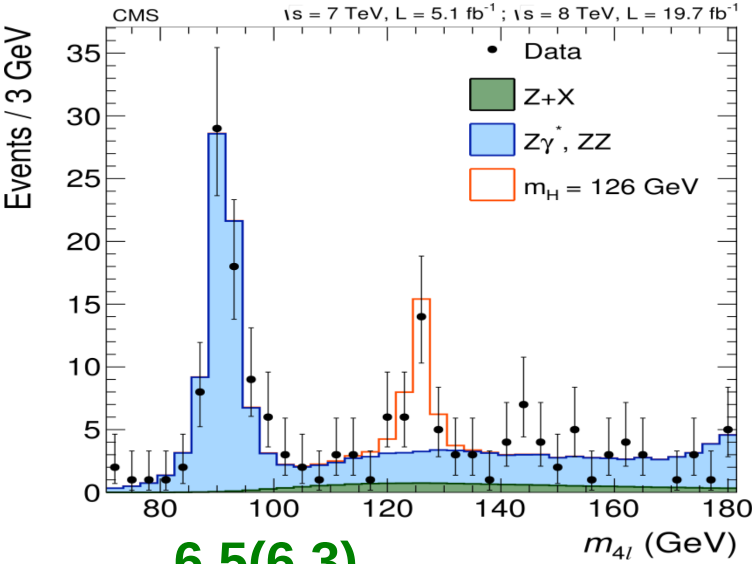
8.1(6.2)

obs(expected) significance

CMS

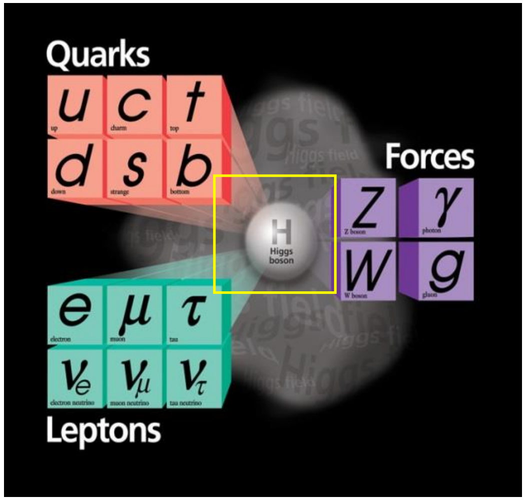


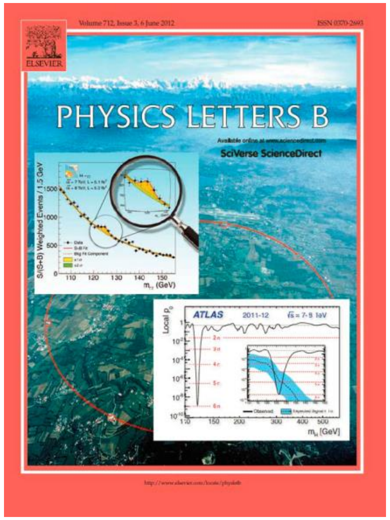
5.6(5.3)



6.5(6.3)

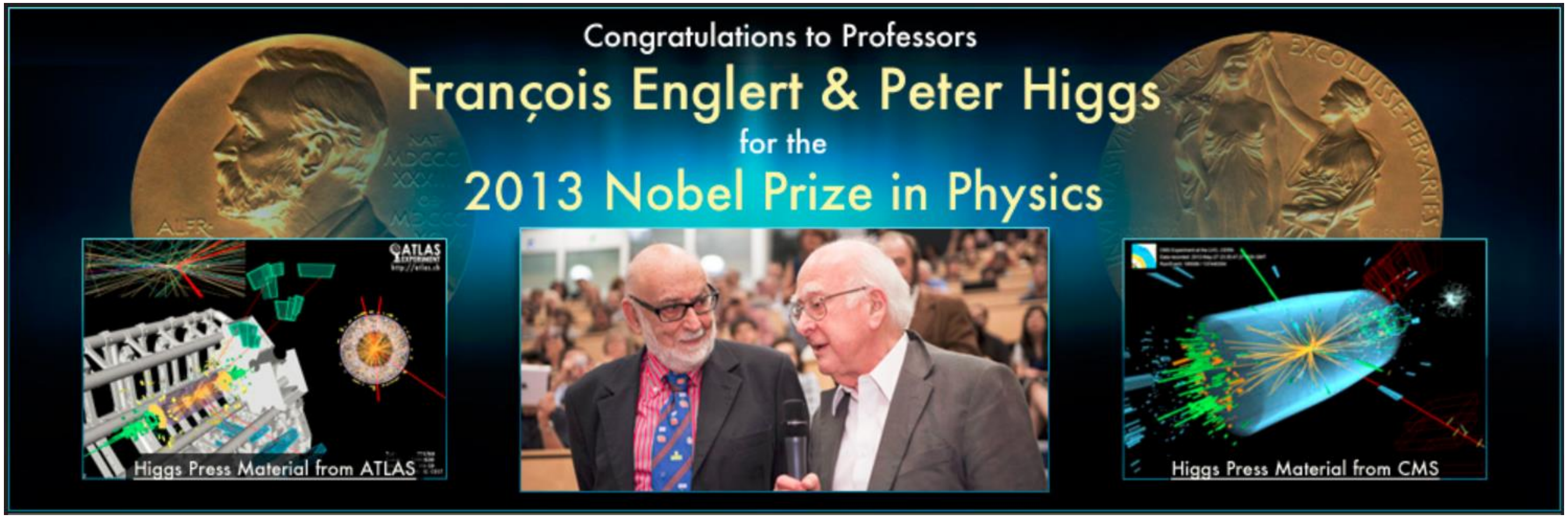
Discovery of the Higgs boson (2012)





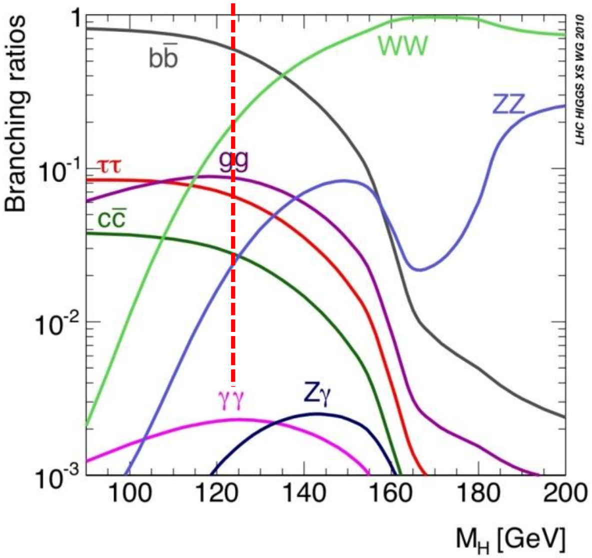
PLB 716 (2012) 1-29 (ATLAS)

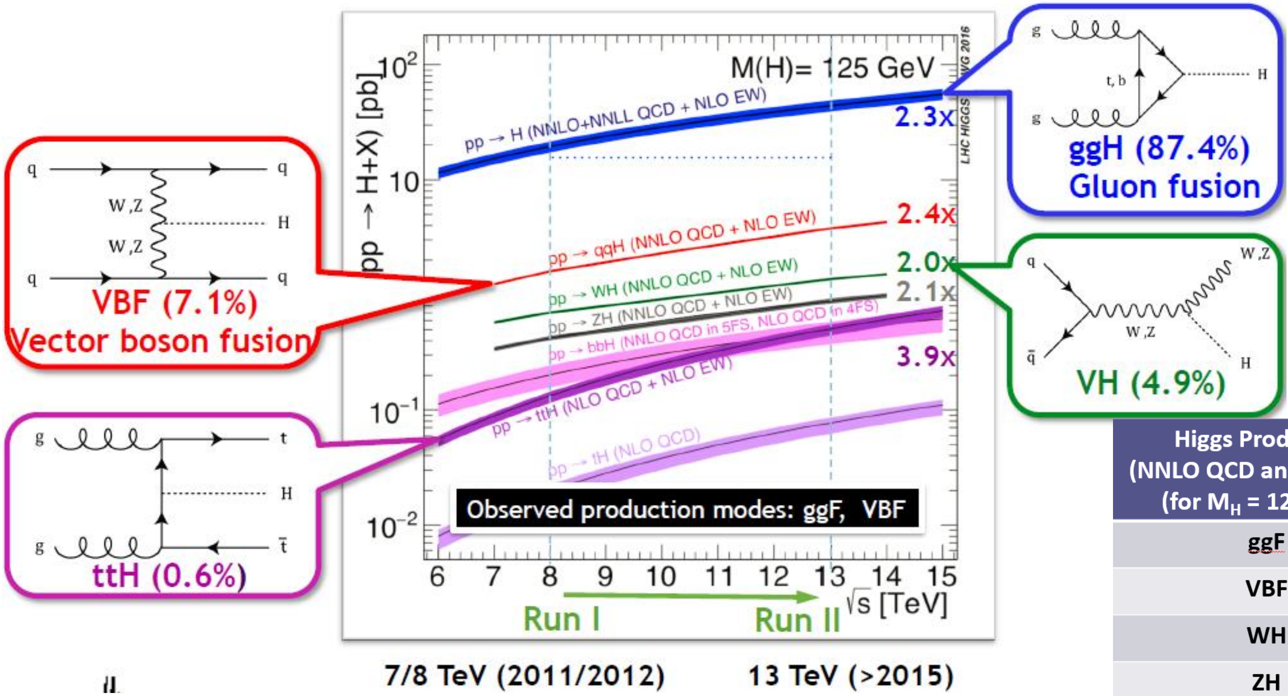
PLB 716 (2012) 30-61 (CMS)



Higgs Combined Results at Run1

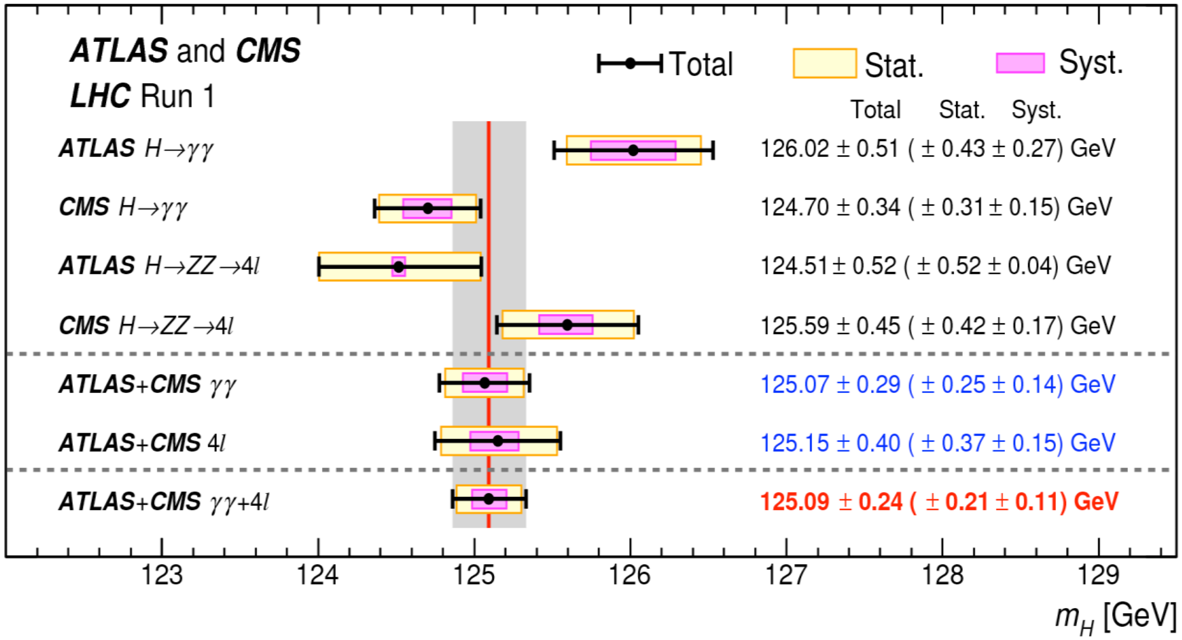
- **Combination of ATLAS and CMS results helps to improve statistics and reduce uncertainties.**
  - ATLAS: 4.5/fb at 7 TeV, 20.3/fb at 8 TeV
  - CMS: 5.1/fb at 7 TeV, 19.7/fb at 8 TeV





Higgs Production (NNLO QCD and NLO EW) (for M_H = 125 GeV)	Cross section (pb) √s = 8 TeV	Cross section (pb) √s = 13 TeV
ggF	19.27	48.5
VBF	1.58	3.78
WH	0.70	1.37
ZH	0.42	0.88
ttH	0.13	0.51
bbH	0.20	0.49
Total	22.30	55.53

Higgs Mass at Run1



PRL114 (2015) 191803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APS physics

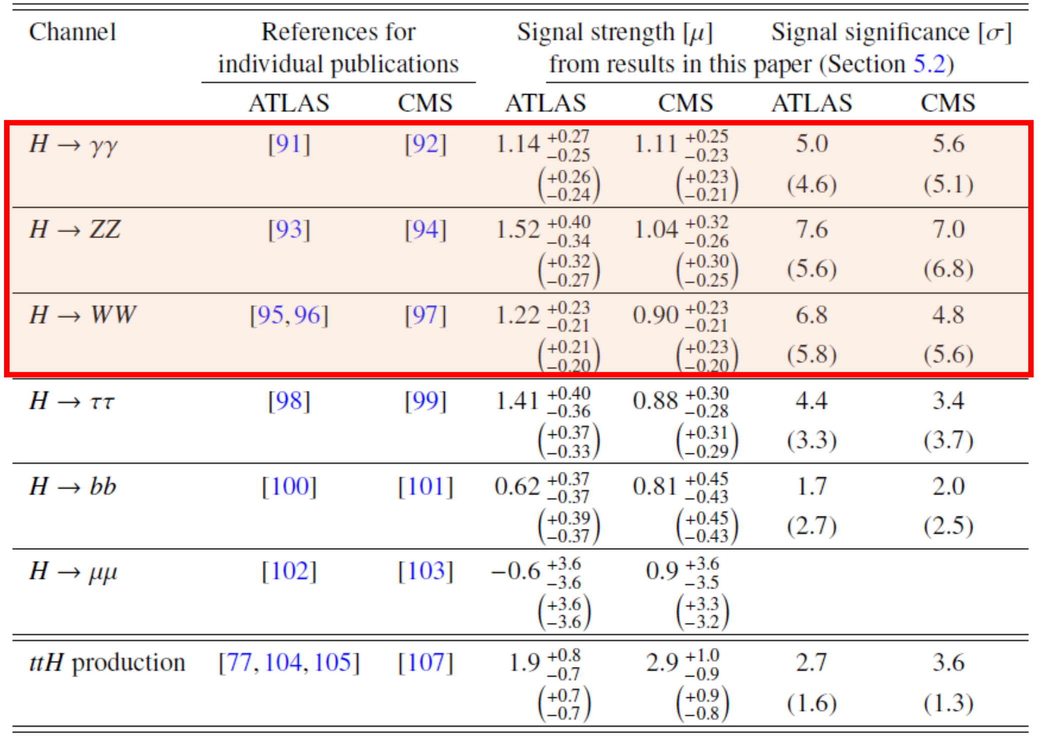
Volume 114, Number 19

- **Higgs mass precision at 0.2%**
- **Statistical error is dominant**
- **Editor’s suggestion, cover page**

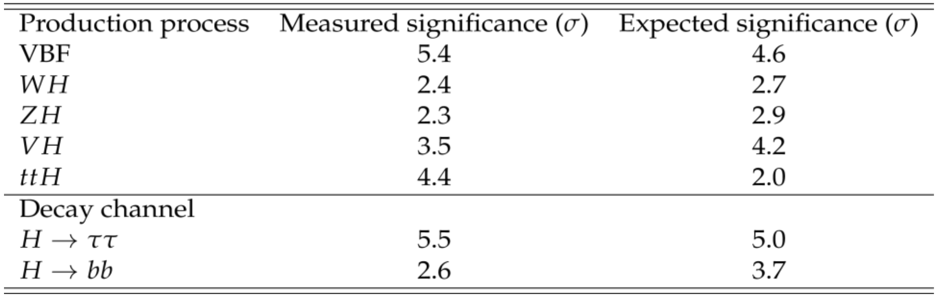
Higgs Combined Results

JHEP08(2016)045

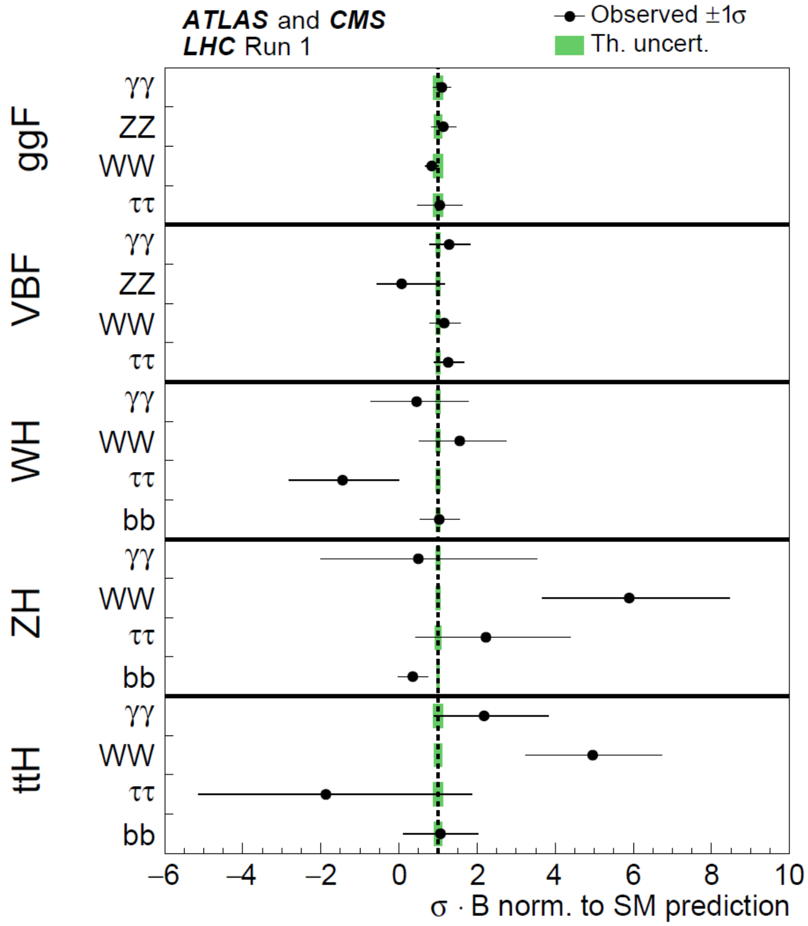
- ➔ H ➔ γγ, ZZ, WW, all diboson channels are discovered > 5σ ！
- ➔ H ➔ ττ has 5.5σ; VBF Higgs has 5.4σ ！



Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[91]	[92]	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[93]	[94]	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[95, 96]	[97]	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[98]	[99]	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[100]	[101]	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[102]	[103]	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[77, 104, 105]	[107]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)



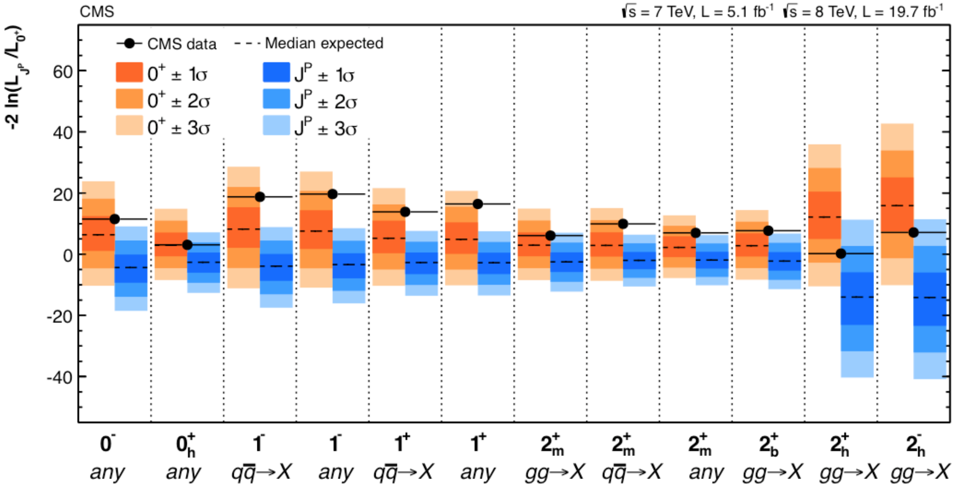
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

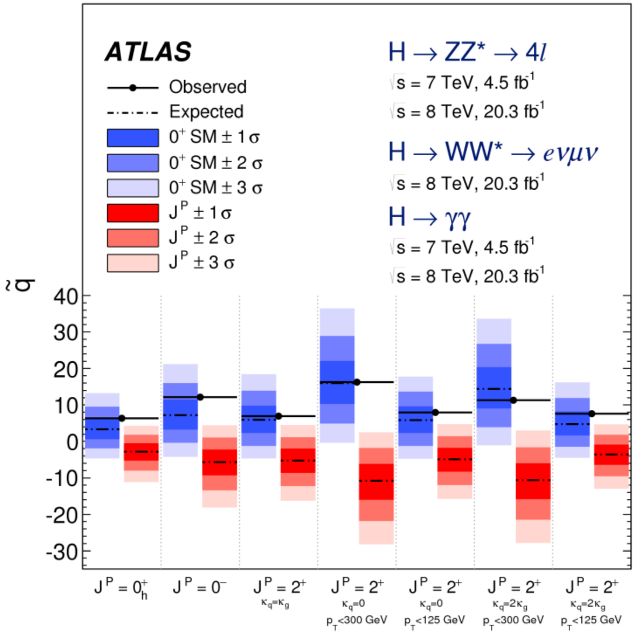


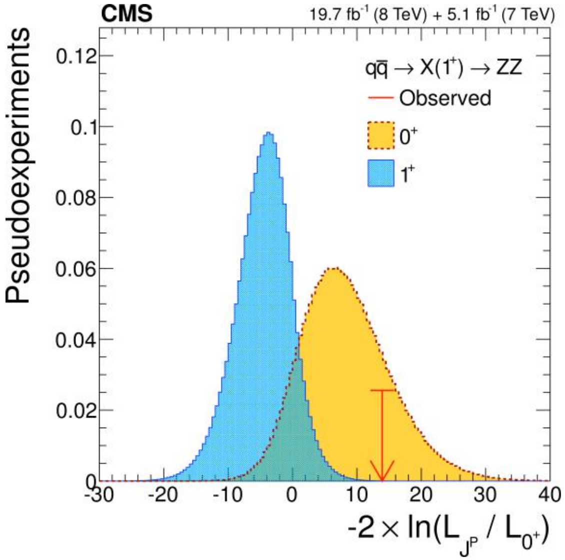
Higgs Spin and Parity

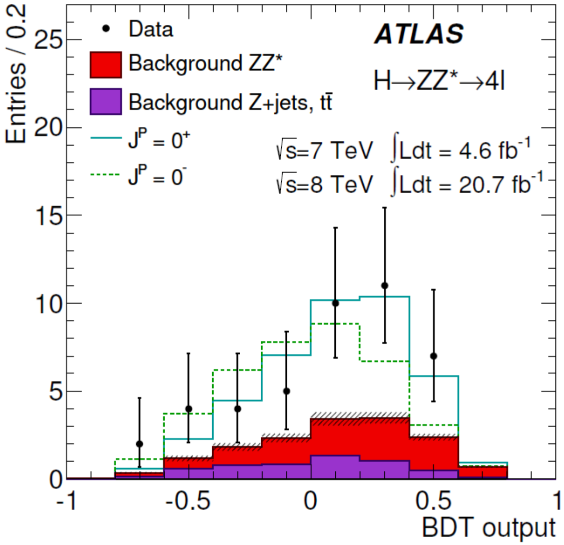
EPJC75, 476 (2015)
PRD89(2014)092007

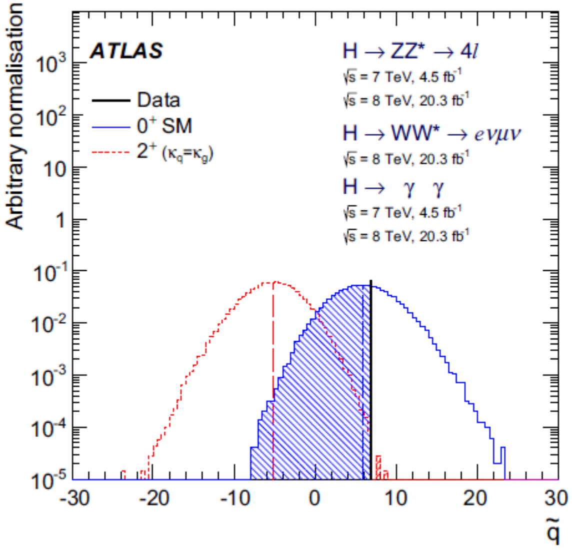
- ☐ Combined diboson final states, Higgs spin and parity agree well with SM predictions and exclude non-SM combinations with 99.9% CL.











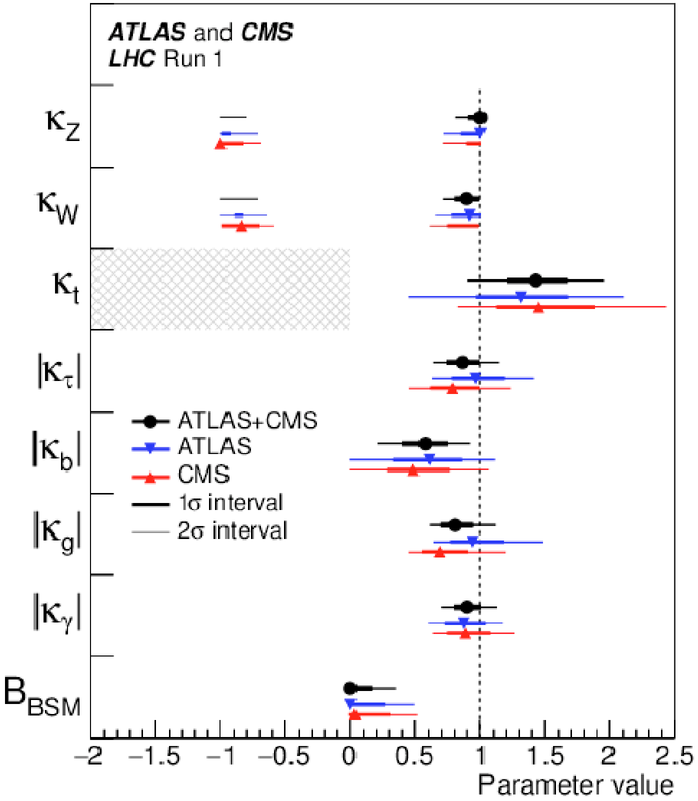
Higgs Couplings

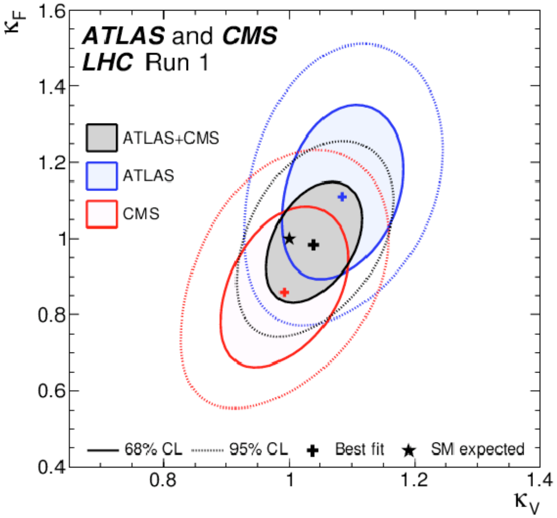
- ➢ **Higgs couplings measured from LHC data are consistent with SM.**

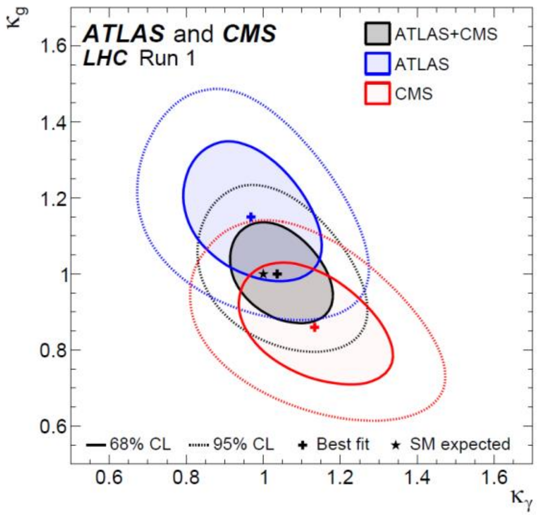
$$\frac{\sigma\cdot B\,(gg\to H\to\gamma\gamma)}{\sigma_{\rm SM}(gg\to H)\cdot B_{\rm SM}(H\to\gamma\gamma)}=\frac{\kappa_g^2\cdot\kappa_\gamma^2}{\kappa_H^2}$$

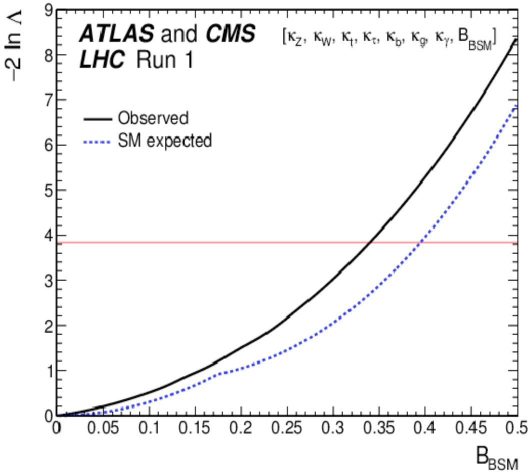
$$(\sigma\cdot \mathrm{BR})\,(gg\to H\to ZZ^*\to 4\ell)=$$

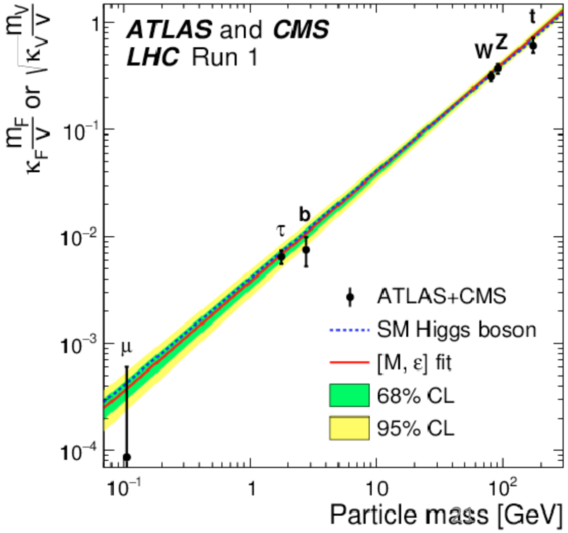
$$[\sigma(gg\to H)\cdot \mathrm{BR}(H\to ZZ^*\to 4\ell)]_{\rm SM}\;\times\;\frac{\kappa_g^2\cdot\kappa_Z^2}{\kappa_H^2}$$







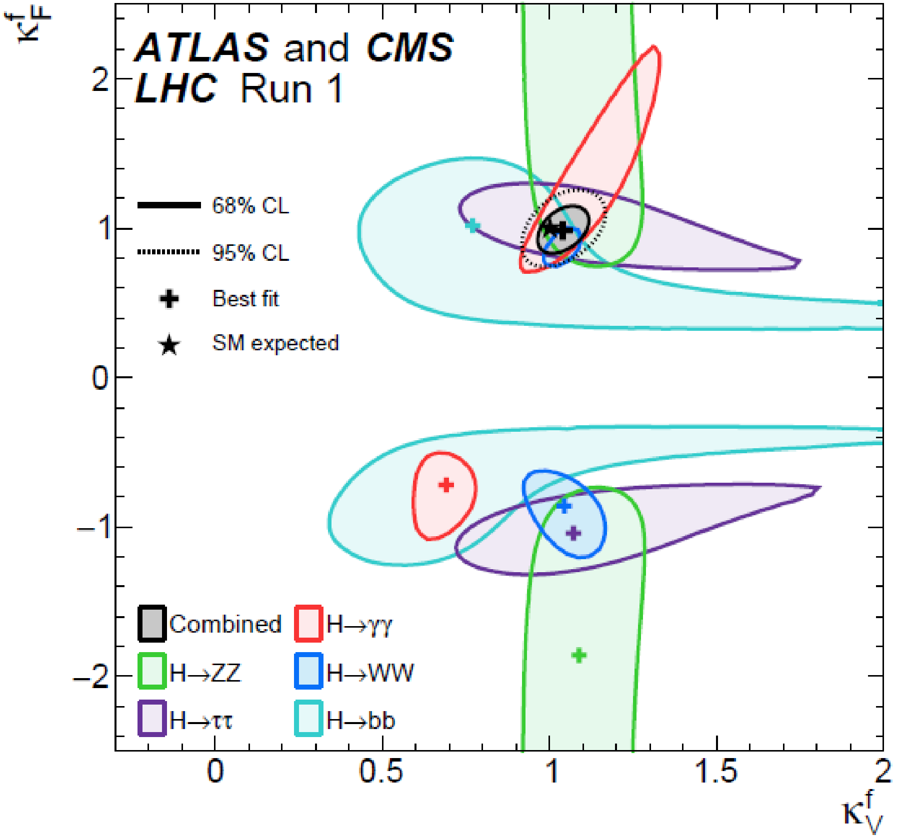




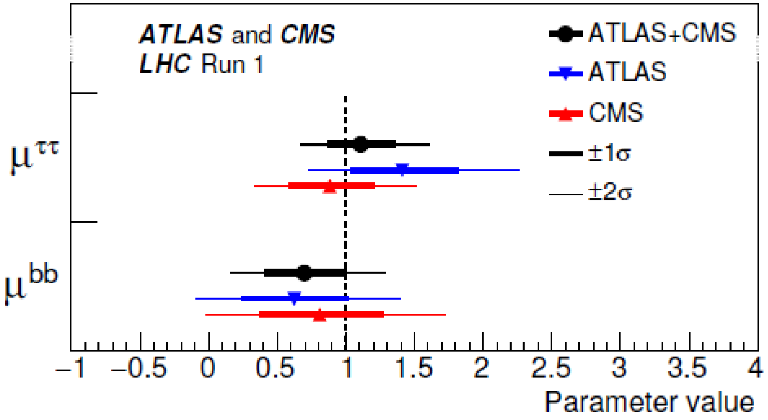
Higgs couplings to fermions

- Higgs couplings to fermions and bosons strongly constrained by LHC Run1 measurements

JHEP 08 (2016) 045



- In combination, search for $H \to \tau^+\tau^-$ exceeds 5σ.
- But, despite being the dominant decay mode, coupling to $b\bar{b}$ not yet observed.

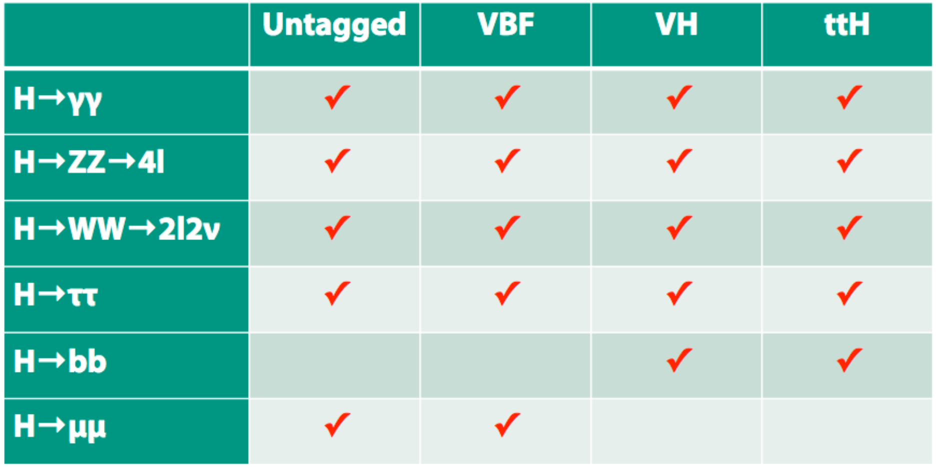


Higgs @ LHC Run2

LHC Run2 Priorities on Higgs:

- Re-discovery of SM Higgs
- Search for VBF, VH, ttH, tH Higgs production
- Search for H→bb, ττ to study Yukawa couplings
- Search for rare decays H→μμ
- Use Higgs as a tool to find new physics
    - Heavy Higgs, charged Higgs
    - Double-Higgs production
    - Higgs BSM decays and couplings

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001



	Untagged	VBF	VH	ttH
H→γγ	✓	✓	✓	✓
H→ZZ→4l	✓	✓	✓	✓
H→WW→2l2ν	✓	✓	✓	✓
H→ττ	✓	✓	✓	✓
H→bb			✓	✓
H→μμ	✓	✓		

Higgs Analysis Strategy

arXiv:1605.04692

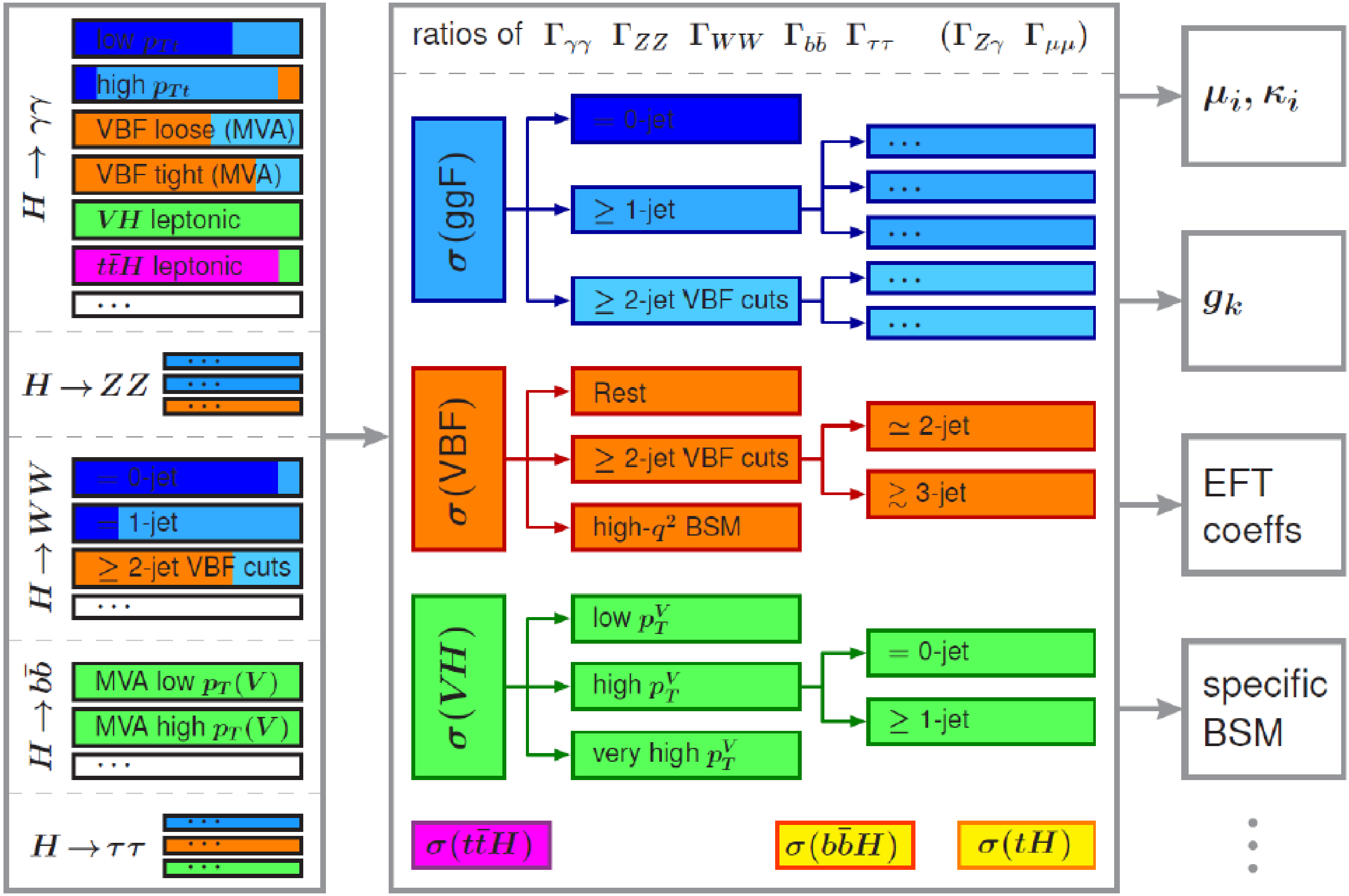
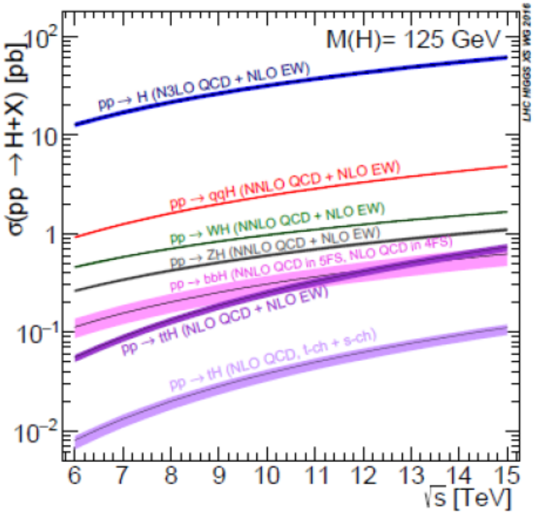
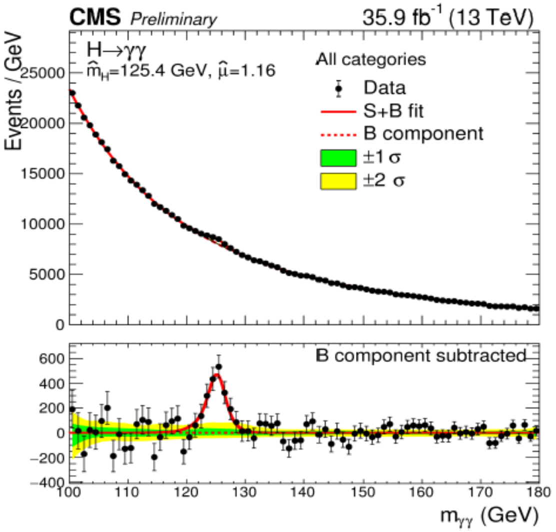
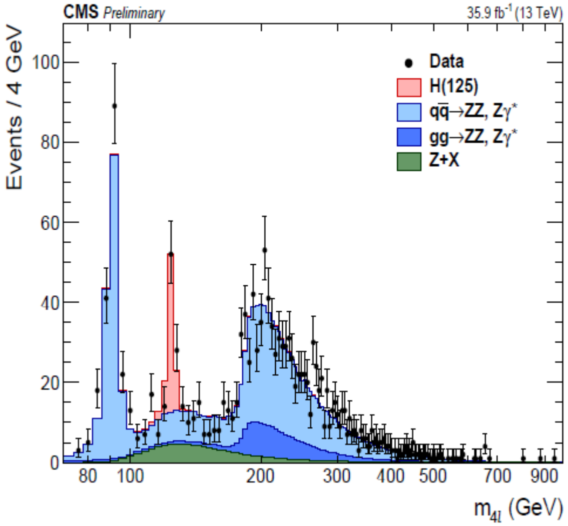


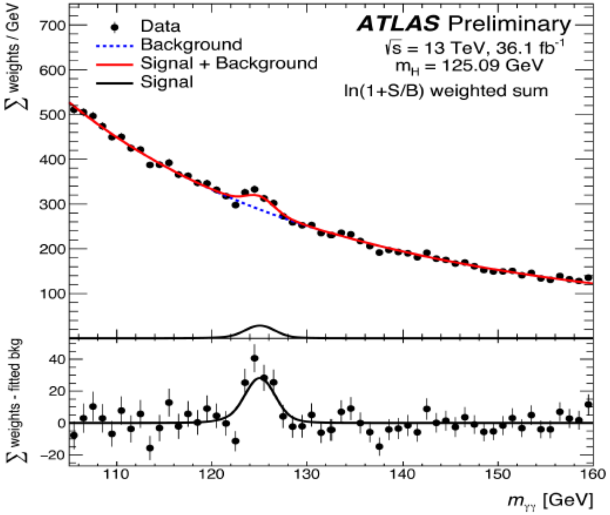
Fig. III.4: Schematic overview of the simplified template cross section framework.

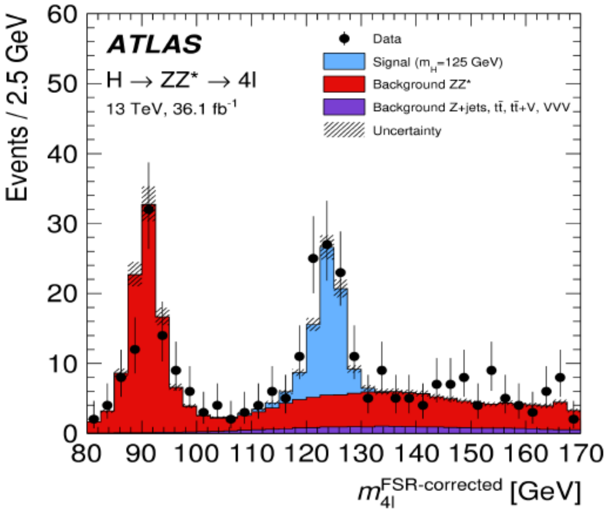
Re-discovery of SM Higgs Boson





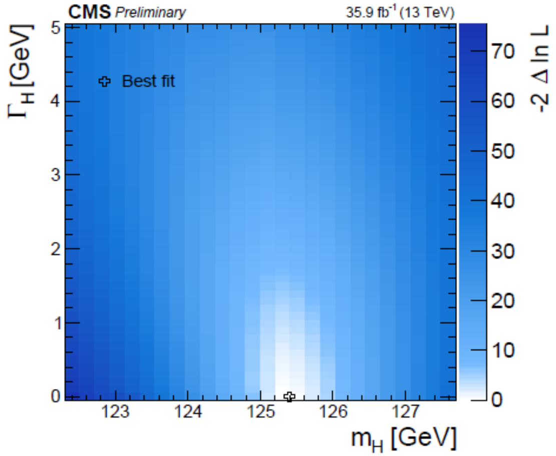


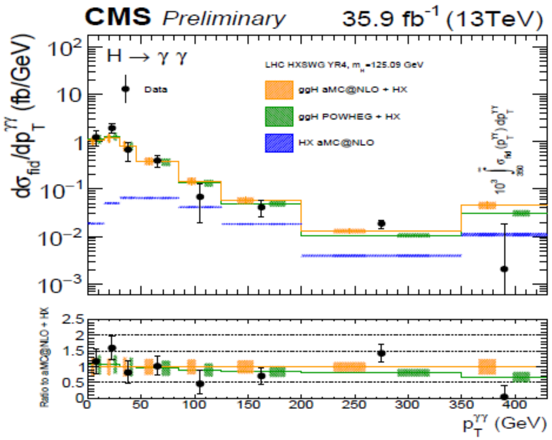


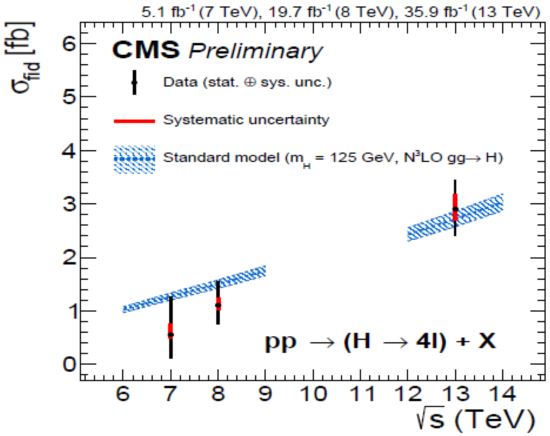


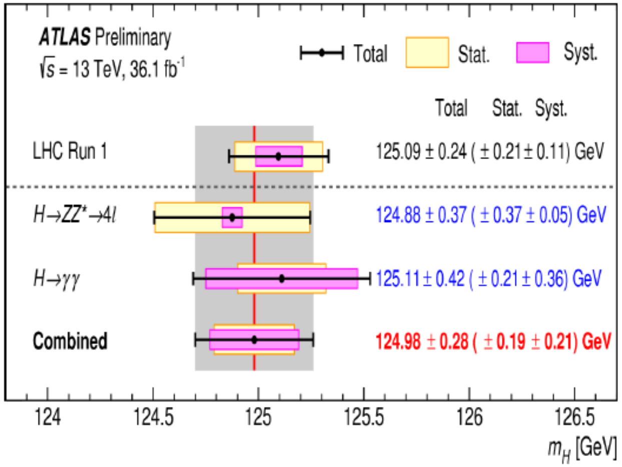
- CMS-PAS-HIG-16-040/041.
- ATLAS-CONF-2017-047/046/045.

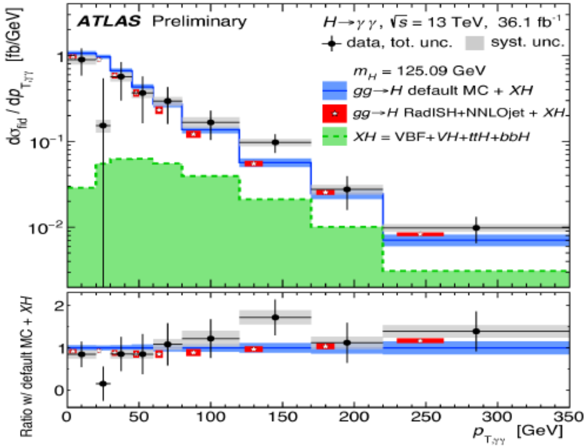
Precision Measurements of Higgs

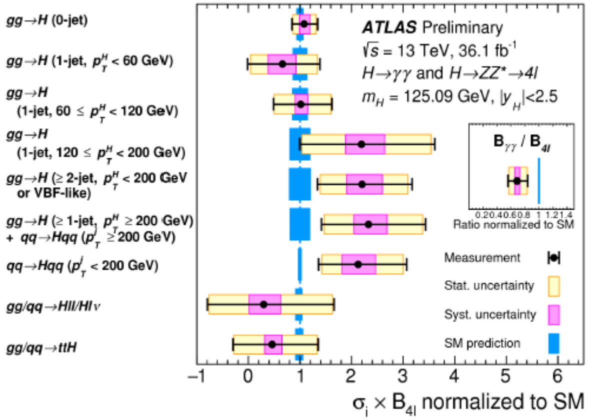








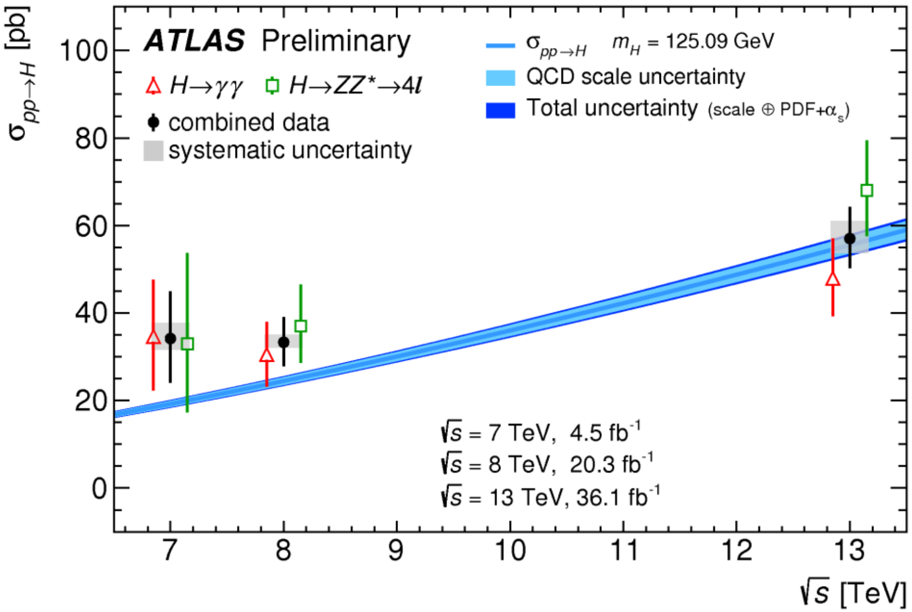




Mass, fiducial and simplified templete cross sections.

Larger dataset allows us to make more differential measurements ...

Total and Fiducial Cross Sections



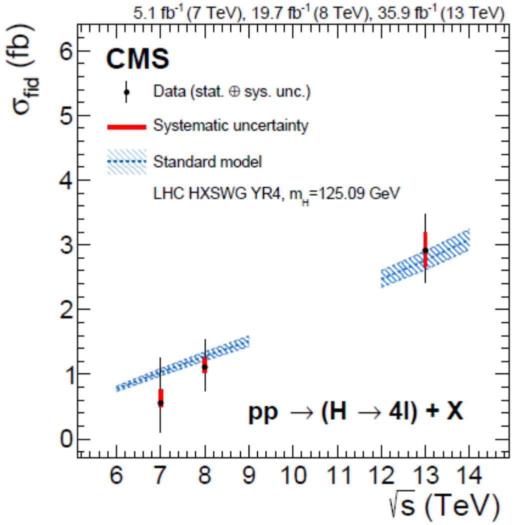
Total and fiducial cross section

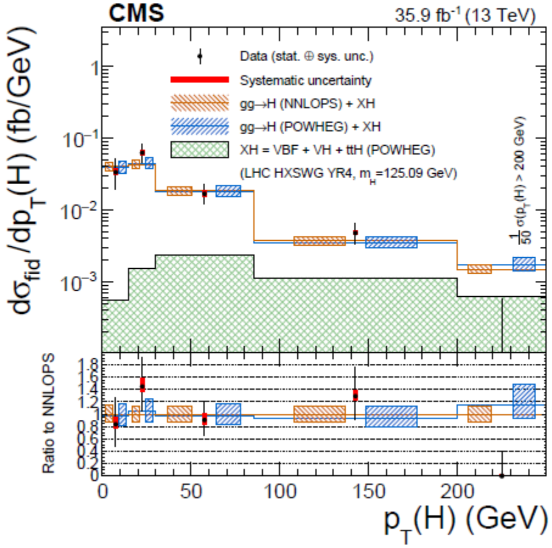
From H→ZZ*→4l and H→γγ

ATLAS-CONF-2017-047

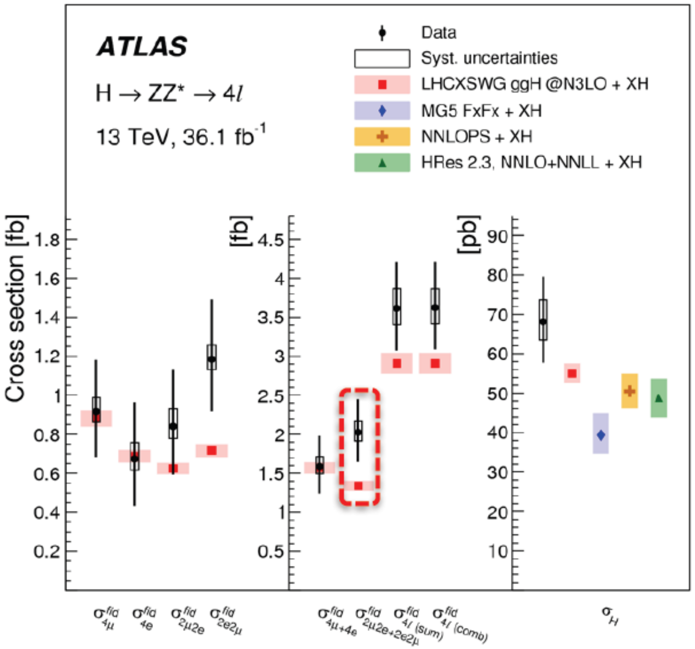
ATLAS: JHEP 10 (2017) 132

CMS: JHEP 11 (2017) 047





H→ZZ*→4l

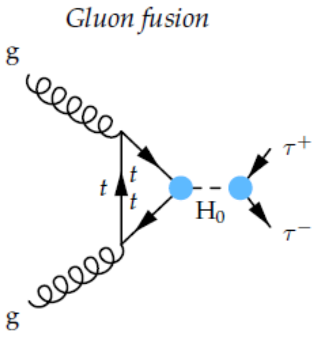


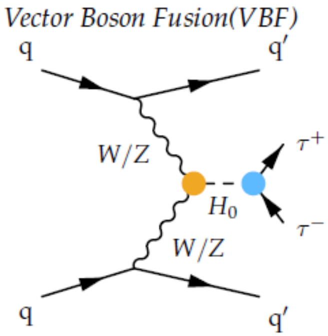
Search for Higgs → ττ

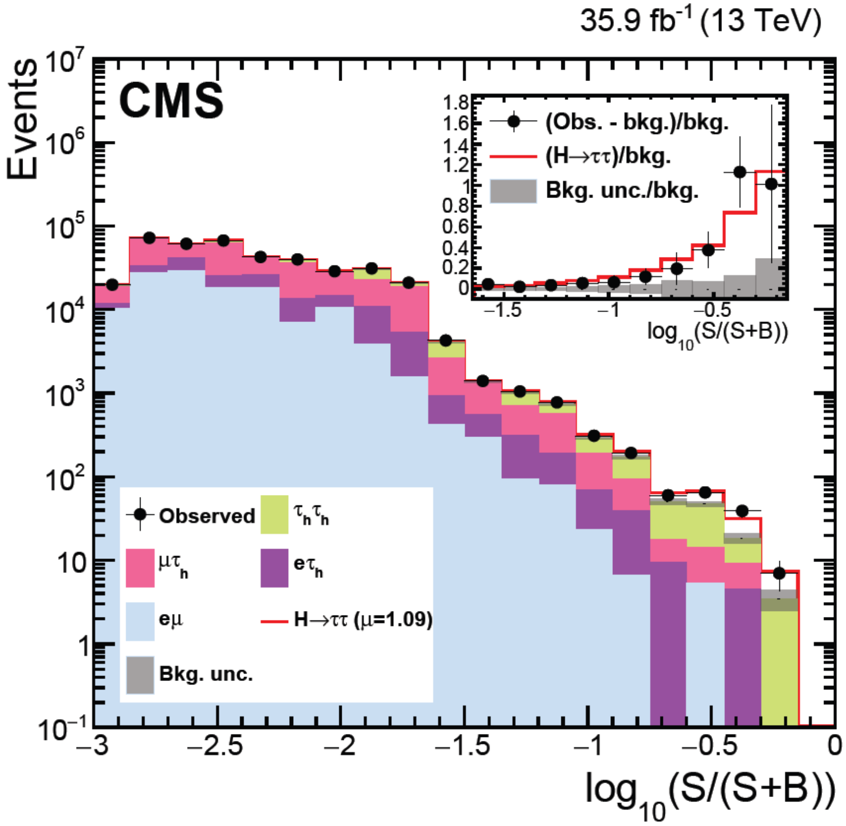
JHEP04 (2015) 117
arXiv:1708.00373, PLB

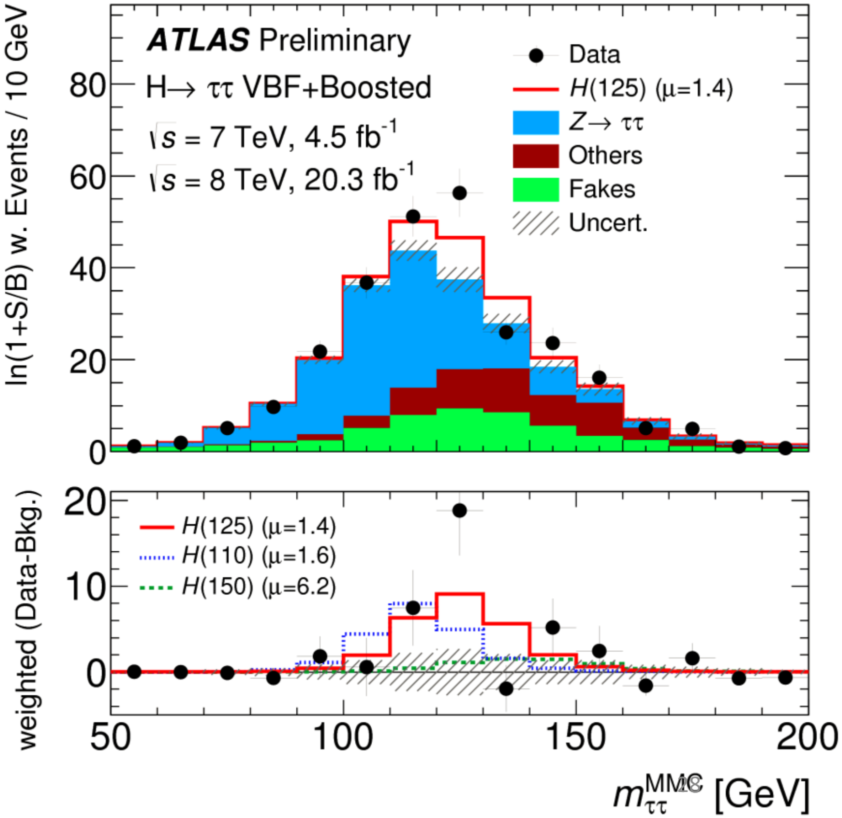
- H->ττ is an important channel to study Higgs Yukawa coupling.

H→ττ (Run1), ATLAS: 4.4σ , CMS: 3.4σ;
Combined result: 5.5σ (exp 5σ)
CMS Run1+Run2: 5.9σ (exp 5.9σ)









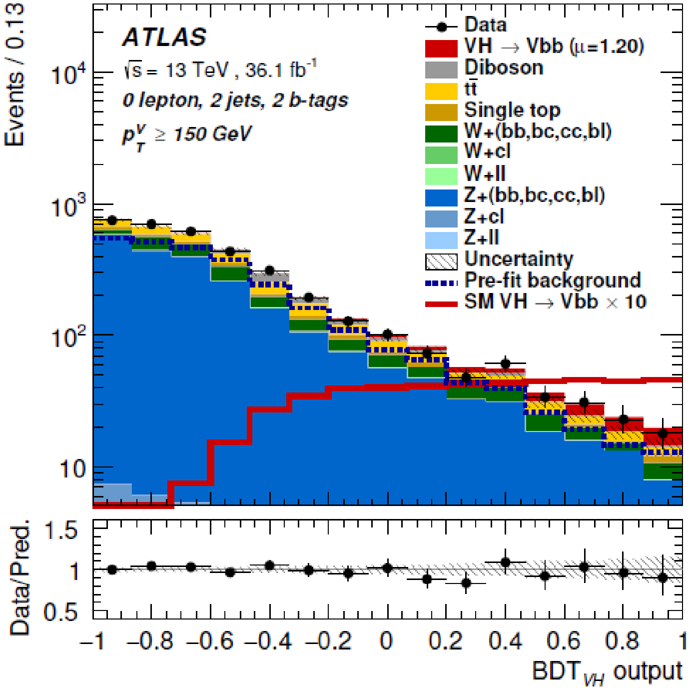
Search for Higgs → bb

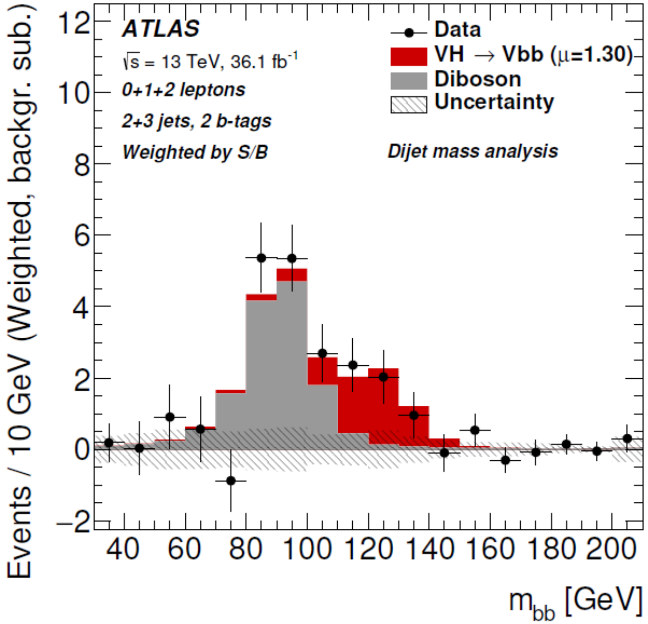
JHEP12 (2017) 024
CMS-HIG-16-044

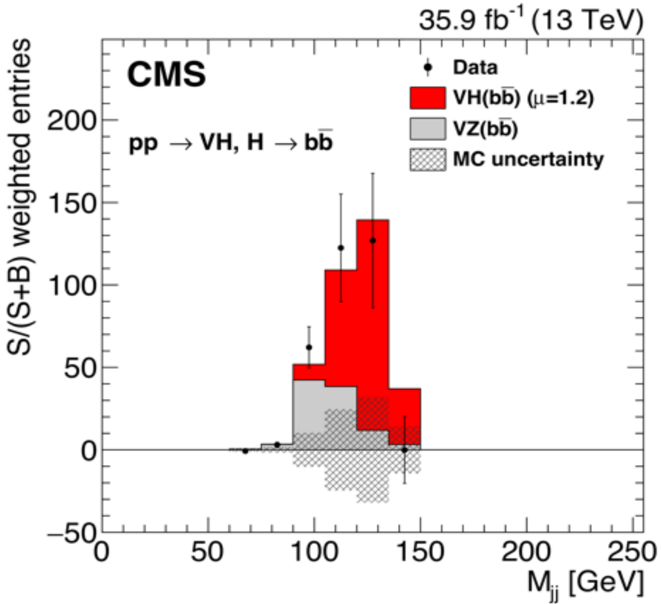
H→bb (58%) is an important channel to study Yukawa coupling, but with huge QCD bkgd.

Evidence of H→bb!

Significance	Obs.	Exp.
ATLAS	3.5	3.0
CMS	3.8	3.8





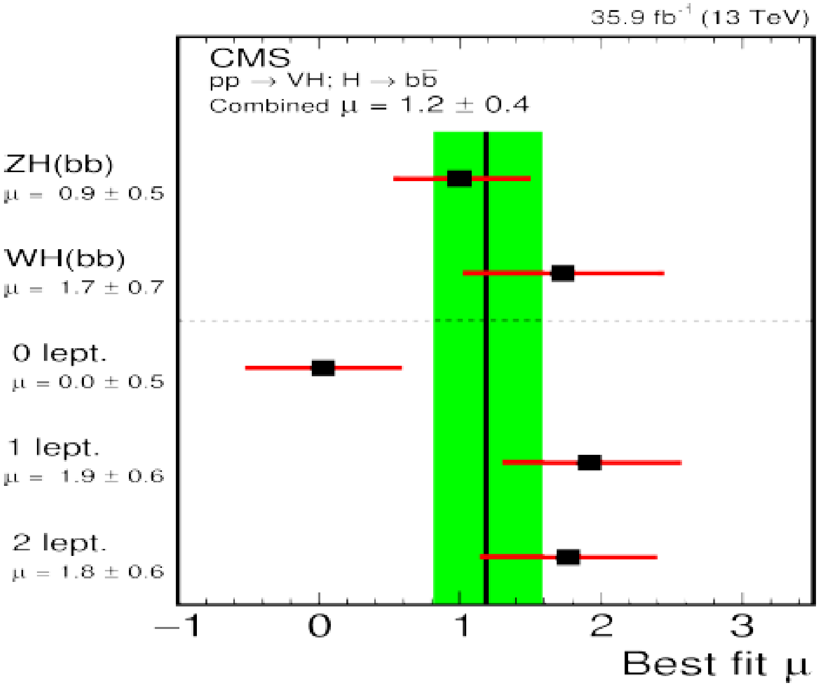


Search for Higgs → bb

JHEP12 (2017) 024
CMS-HIG-16-044

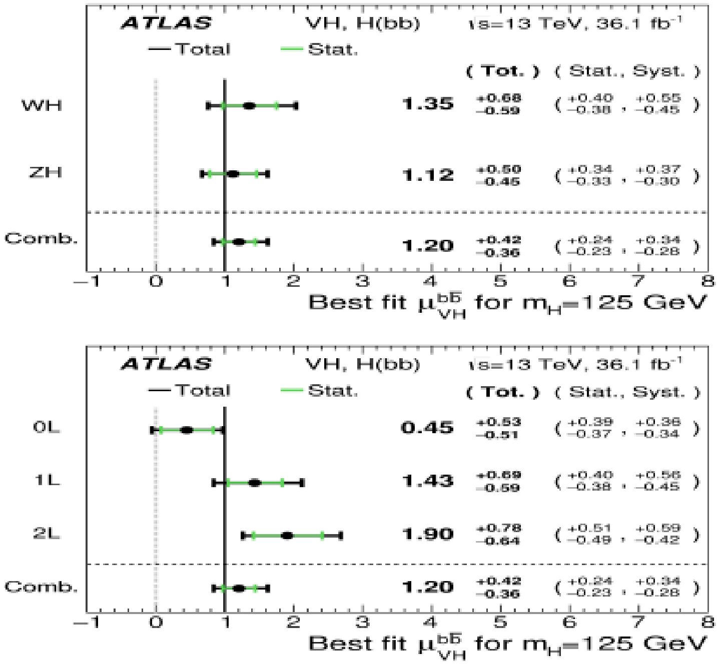
H→bb (58%) is an important channel to study Yukawa coupling

Submitted to PLB



- Best fit $\mu = 1.2 \pm 0.4$.
- Combined with Run 1 result, $\mu = 1.06^{+0.31}_{-0.29}$.

JHEP12(2017)024

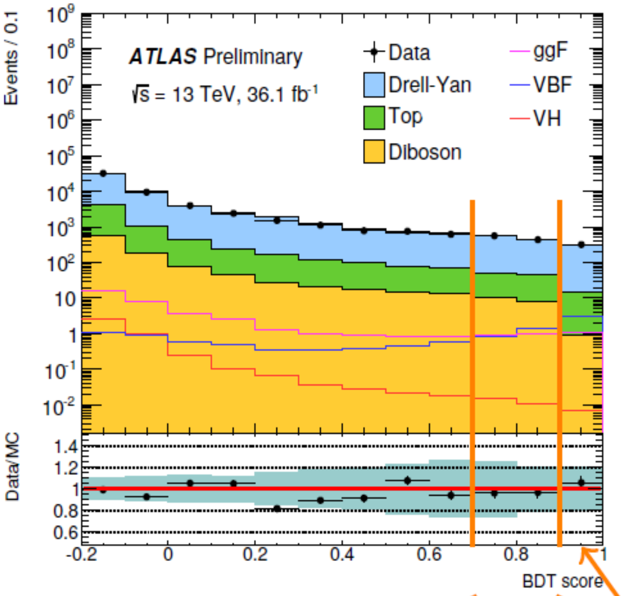


- $\mu = 1.2^{+0.24}_{-0.23}(stat.)^{+0.34}_{-0.28}(syst.)$
- Combined with Run 1 result, $\mu = 1.11^{+0.12}_{-0.11}(stat.)^{+0.22}_{-0.19}(syst.)$

Search for Higgs → μμ

PRL 119, 051802 (2017)
CMS-PAS-HIG-17-019

Higgs rare decay to muon pair, measure Yukawa coupling to the 2nd generation of fermion



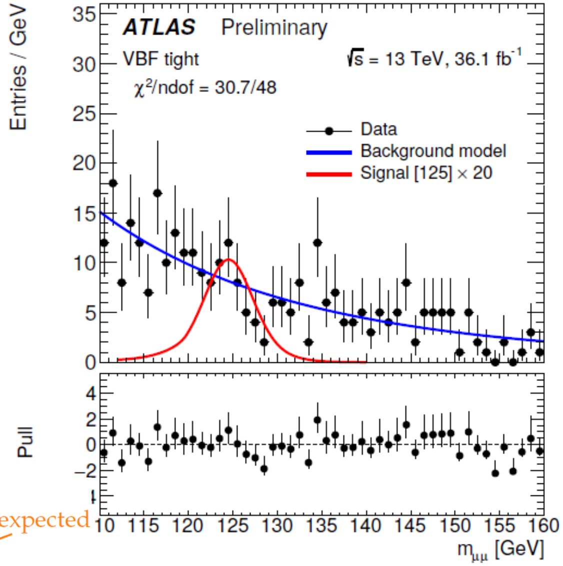
VBF loose

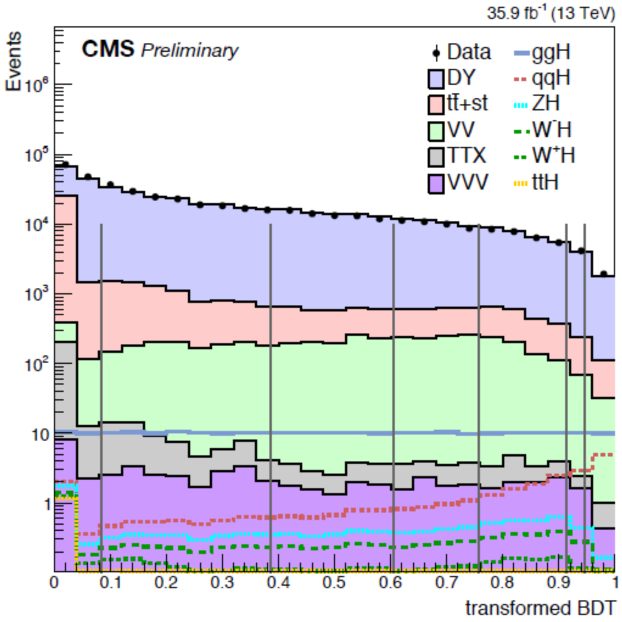
tight

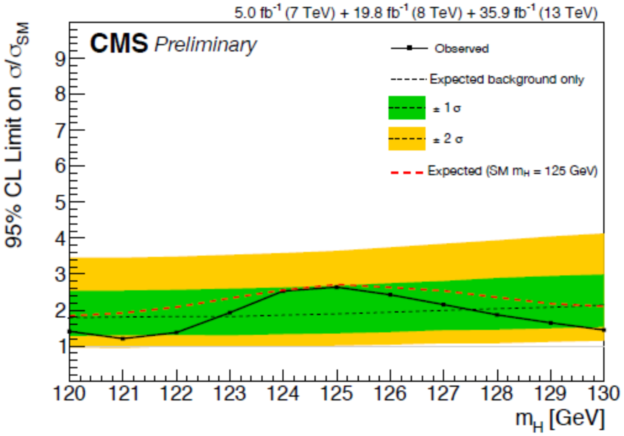
95% CL upper limit on $\sigma \times B(H \to \mu\mu)/SM$

95% CL	Obs.	Exp.
ATLAS	2.8	2.9
CMS	2.6	1.9

$m_{\mu\mu}$ in VBF tight category







prediction of the simulation

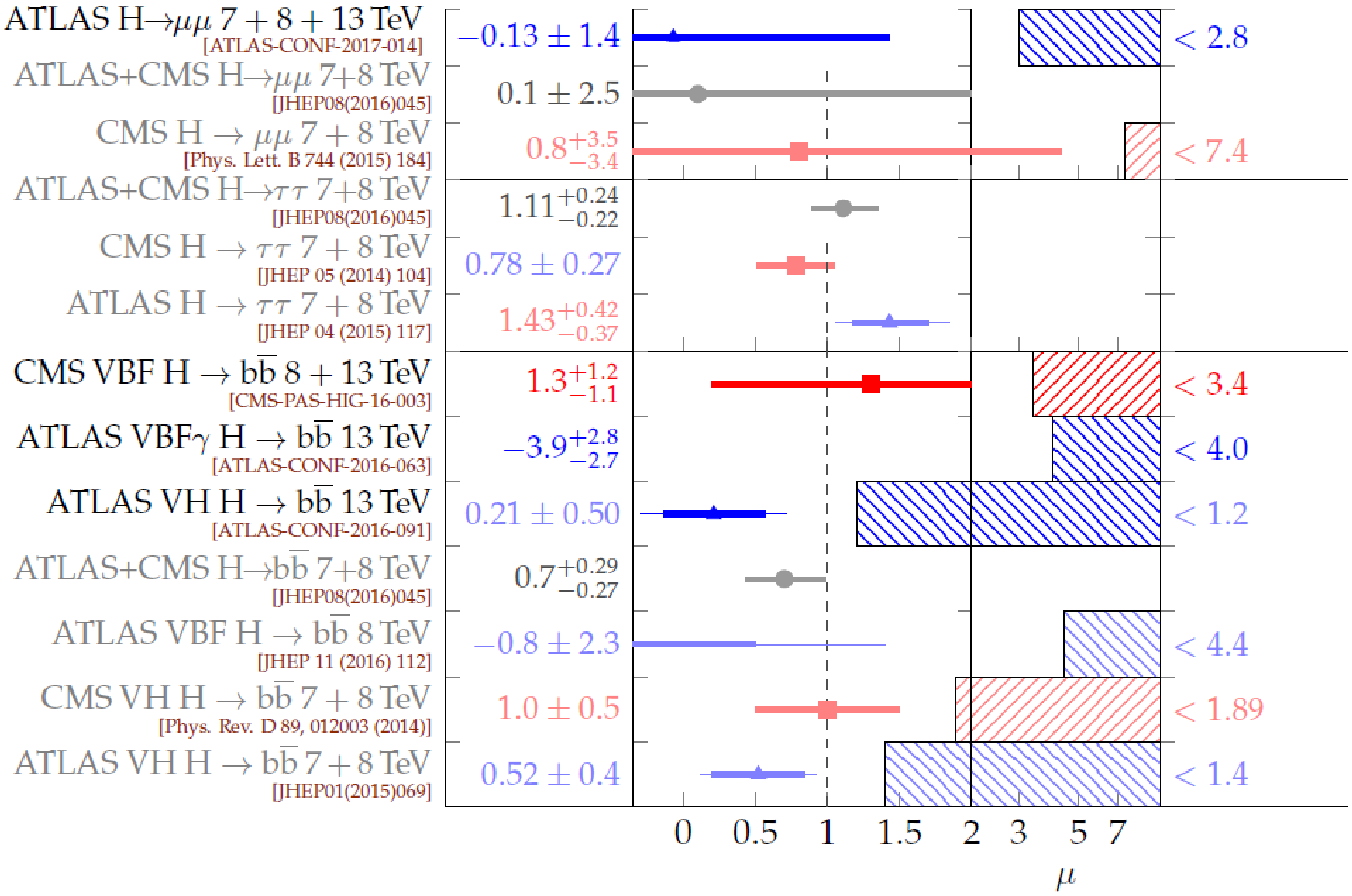
expected

	Signal Strength μ	Limit @ 95% CL
13 TeV:	$-0.07^{+1.5}_{-1.5}$	$< 3.0\ (3.1)$
7+8+13 TeV:	$-0.13^{+1.4}_{-1.4}$	$< 2.8\ (2.9)$

observed

Higgs couplings to 2nd and 3rd generation

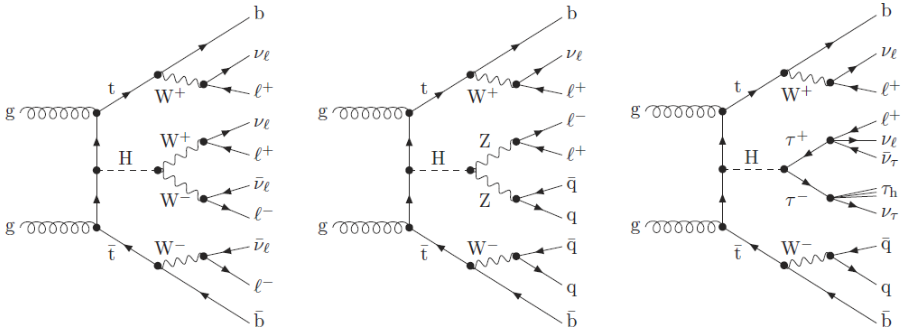
Measured signal strength μ and 95% CL limit on $\sigma \times \mathrm{Br}$ relative to the SM expectation for $m_H = 125\,\mathrm{GeV}$:

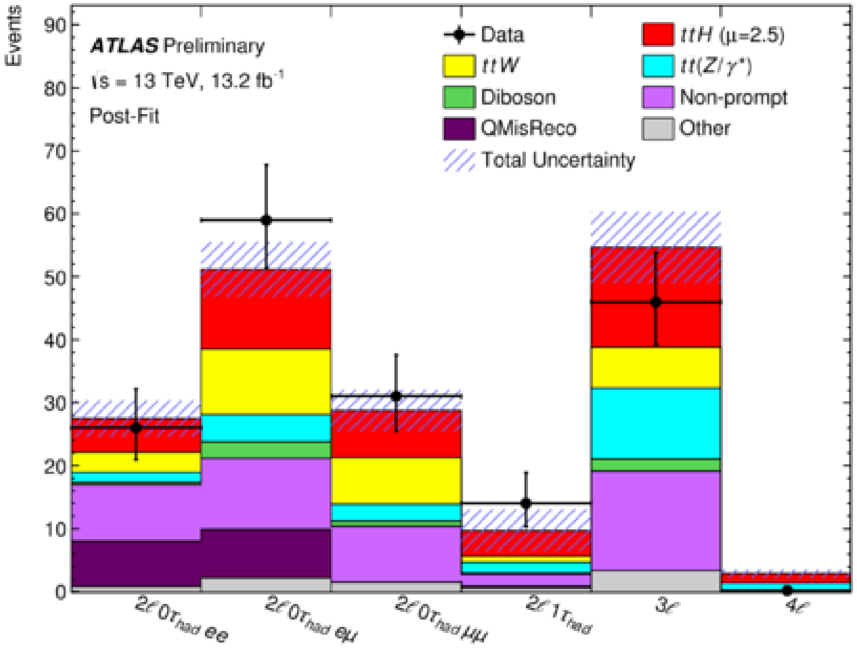


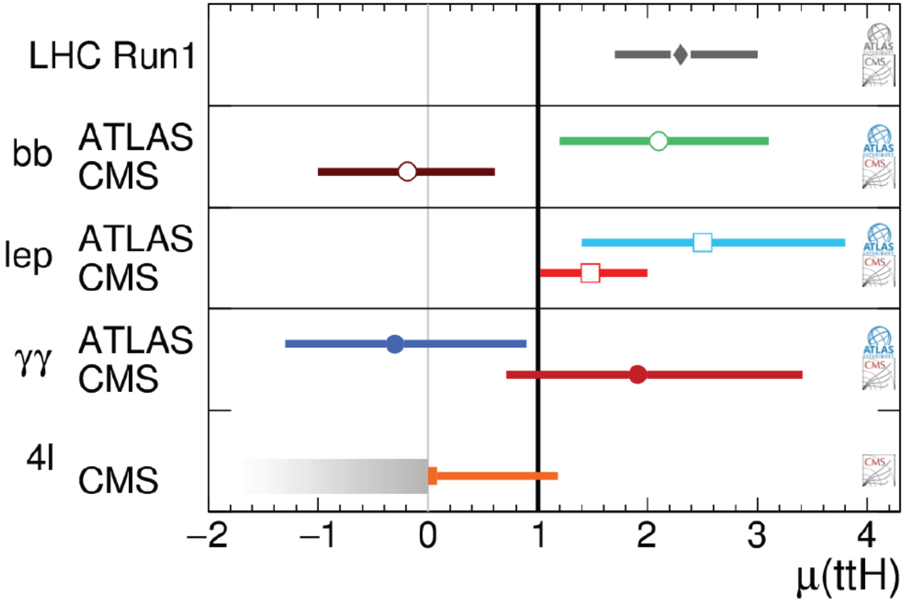
Search for ttH

ATLAS-CONF-2016-058
ATLAS-CONF-2016-068

➔ Combining ttH in γγ, multi-lepton (decay from H→WW, ZZ, ττ), bb states, obs (exp) significance of 4.2σ (3.8σ).

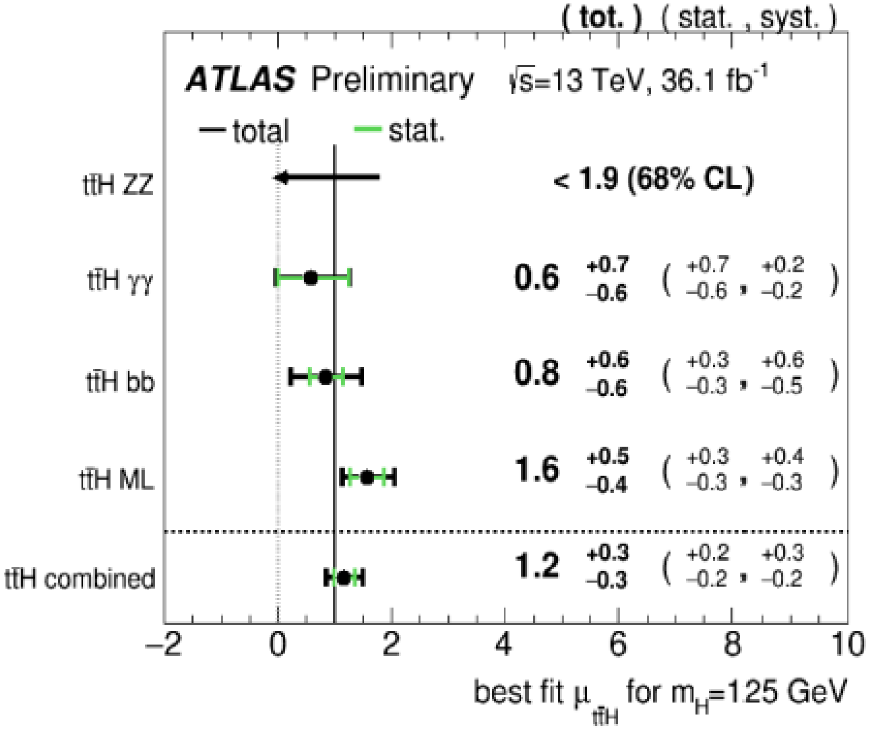




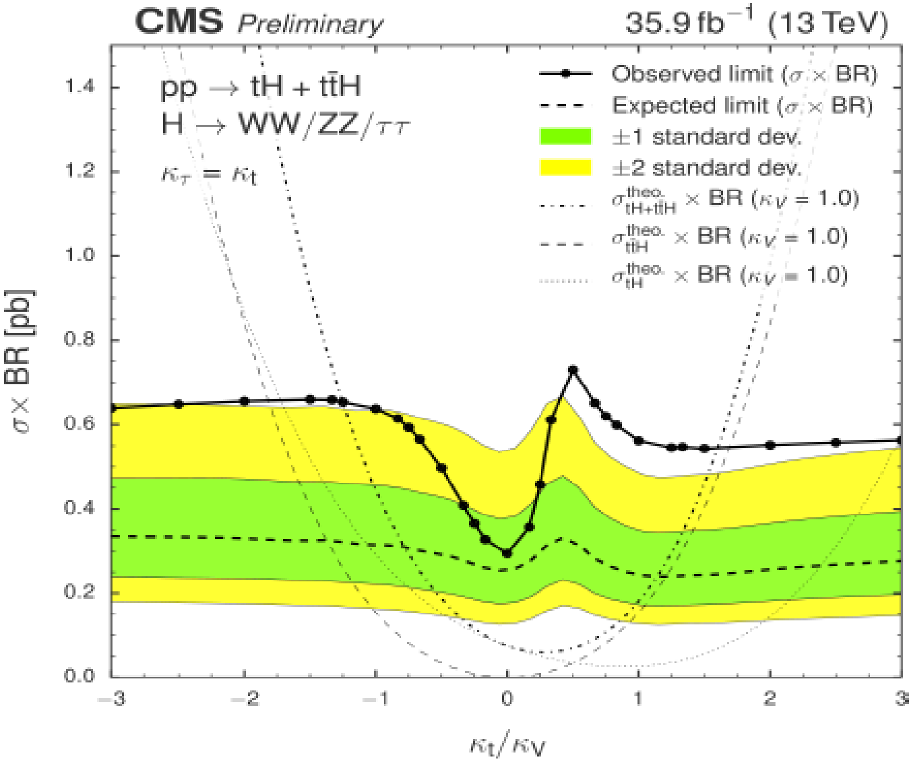


Search for ttH

ATLAS-CONF-2017-077



CMS-PAS-HIG-003/004/005

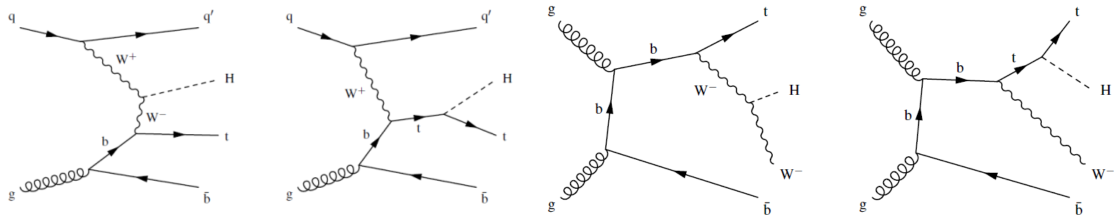


- Combined with $\gamma\gamma$, $b\bar{b}$ and ZZ reaches 4.2σ with 3.8σ expected.
- UL of combined cross section of tH+ttH times BR has been measured to 0.64 pb with 0.32 pb expected at 95% CL.

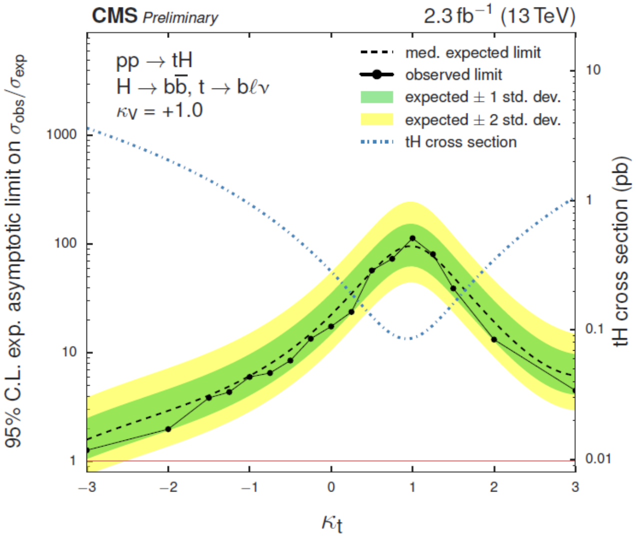
Search for tH, H→bb

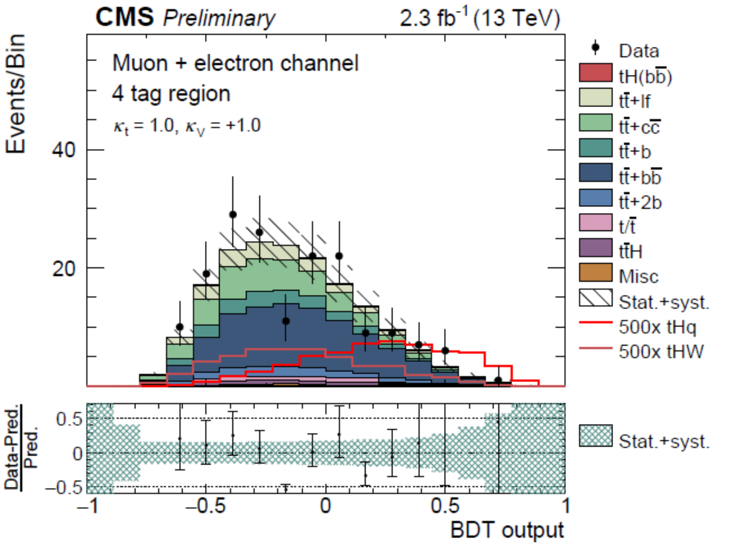
CMS-PAS-HIG-16-019

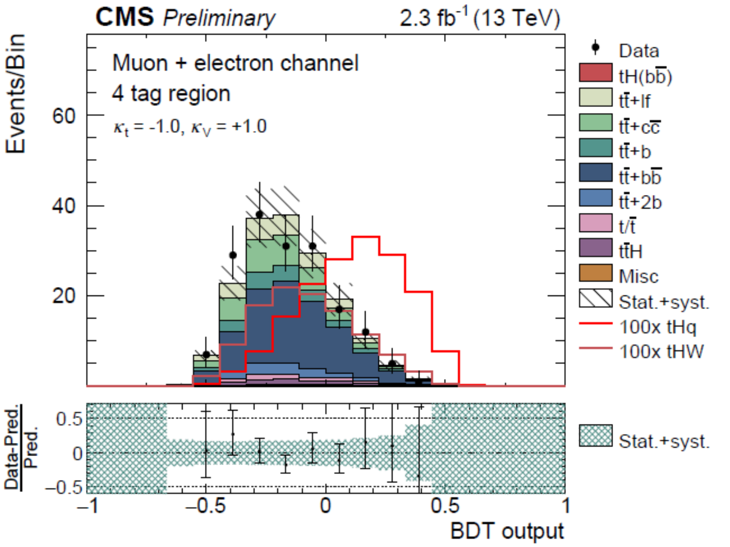
- ➔ tH production is sensitive to Yukawa coupling magnitude and sign of k_t, at 13 TeV,
- ➢ SM predict: tHq (71fb) and tHW (16fb)
- ➢ ITC predicts: tHq (739fb) and tHW (147fb)
- ➔ The obs (exp) 95% CL upper limit for ITC scenario is 6 (6.4) times predicted cross section.



	Region	Observed Limit	Median
SM scenario	3 tag	124.0	114.3
	4 tag	195.8	174.6
	Combination	**113.7**	**98.6**
ITC scenario	3 tag	7.4	7.4
	4 tag	9.2	10.0
	Combination	**6.0**	**6.4**

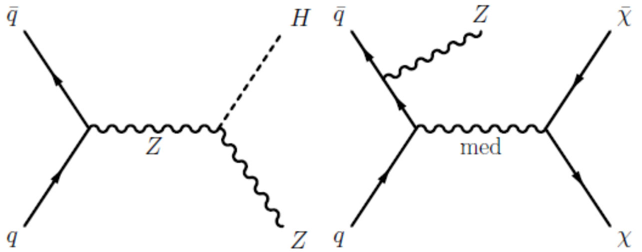




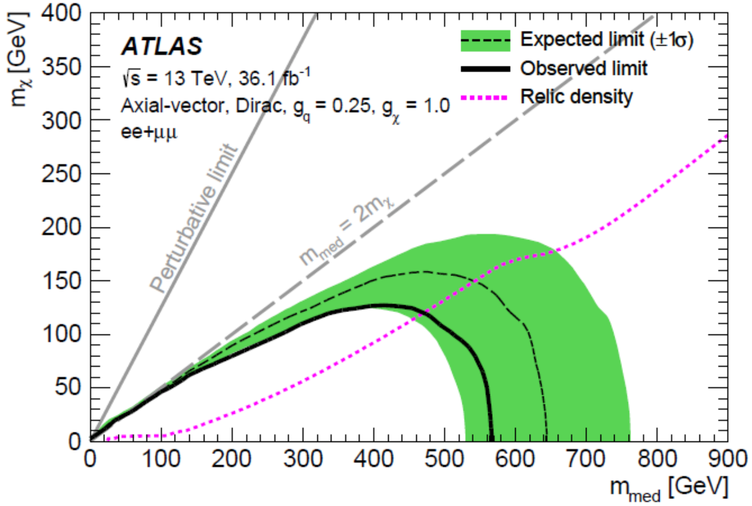


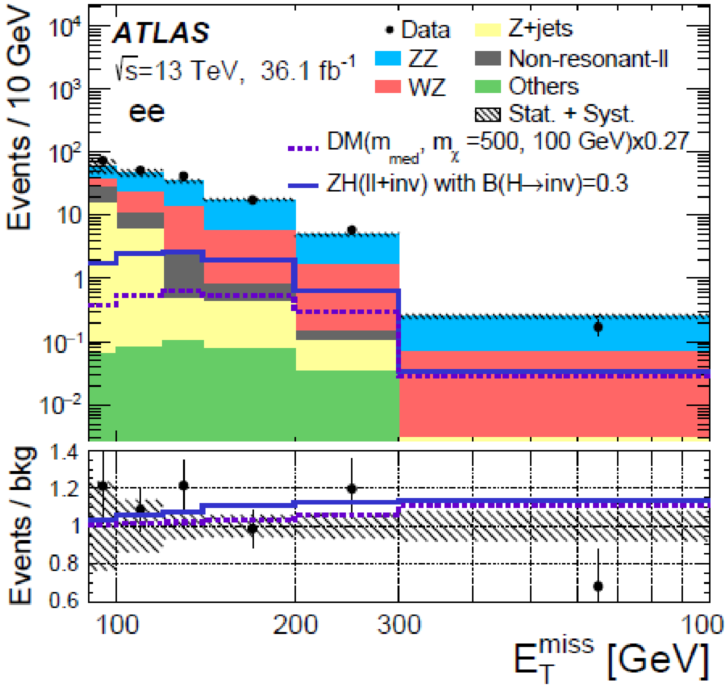
Search for ZH (H→inv)

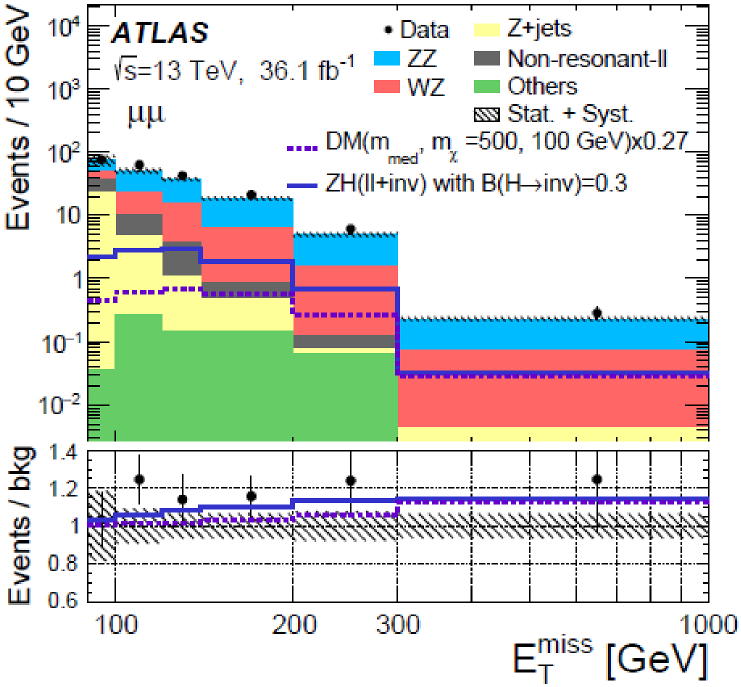
PLB 776 (2017) 318



	Obs. $B_{H\to\text{inv}}$ Limit	Exp. $B_{H\to\text{inv}}$ Limit $\pm1\sigma \pm 2\sigma$
ee	59%	$(51\,{}^{+21}_{-15}\,{}^{+49}_{-24})$ %
$\mu\mu$	97%	$(48\,{}^{+20}_{-14}\,{}^{+46}_{-22})$ %
$ee+\mu\mu$	67%	$(39\,{}^{+17}_{-11}\,{}^{+38}_{-18})$ %



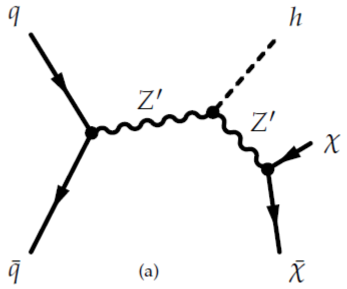




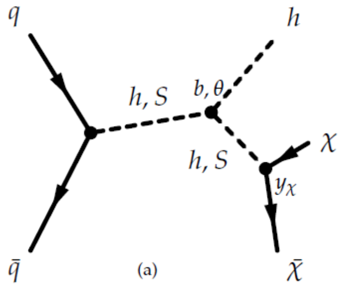
Search for Higgs + DM

ATLAS-CONF-2017-028

- ☐ To search for Dark Matter (MET) associated with a Higgs boson.

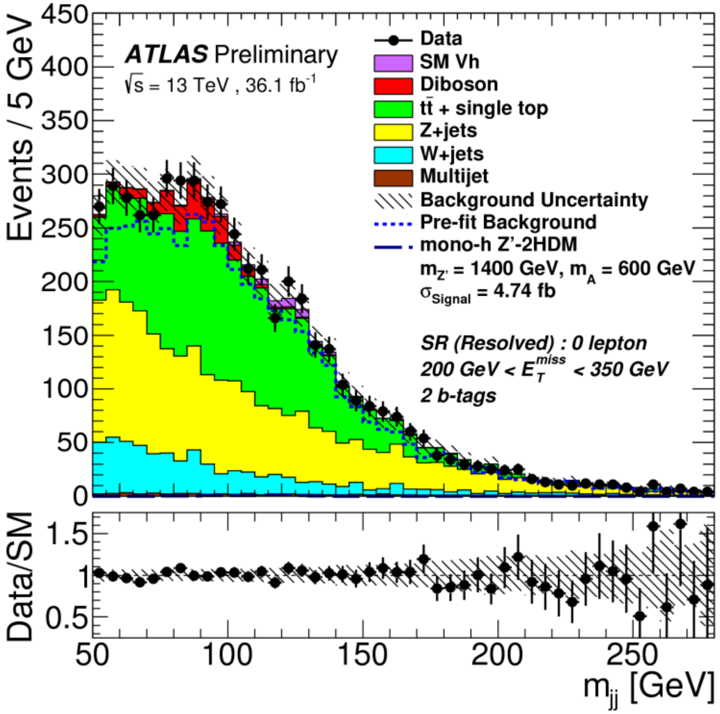


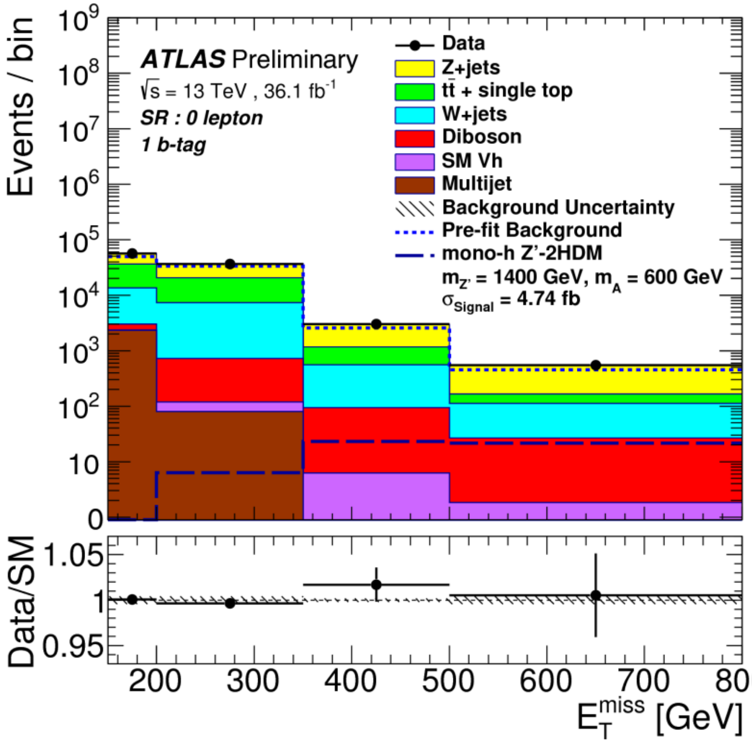
Vector mediator hZ’



Scalar mediator hS

No significant excess is found in search for Higgs (H→bb) with large MET.





Search for W'/Z'/A→VH

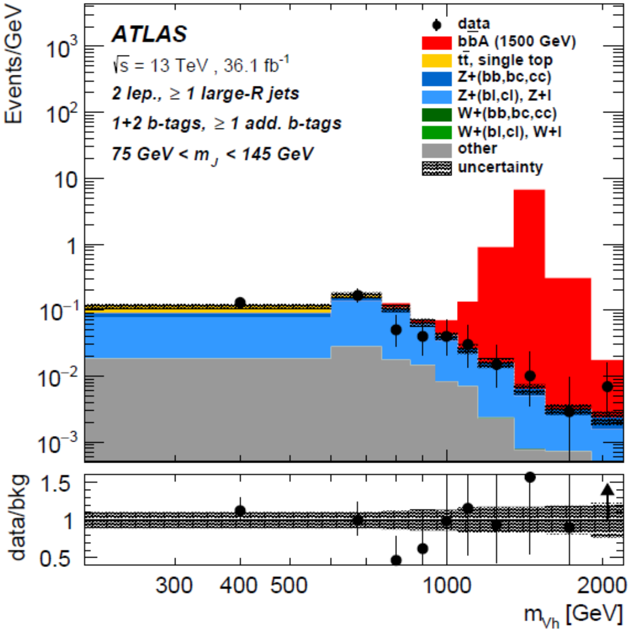
arXiv:1712.06518
arXiv:1707.06958

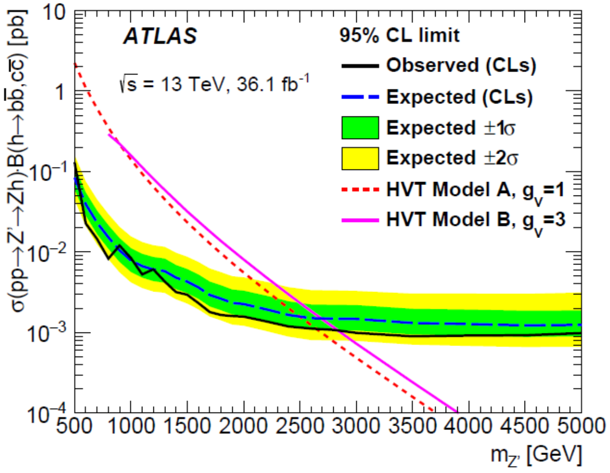
$$W' \rightarrow W^{\pm}h \rightarrow \ell^{\pm}\nu b\bar{b},\ Z'/A \rightarrow Zh \rightarrow \ell^{+}\ell^{-}b\bar{b},\ \text{and}\ Z'/A \rightarrow Zh \rightarrow \nu\bar{\nu}b\bar{b}$$

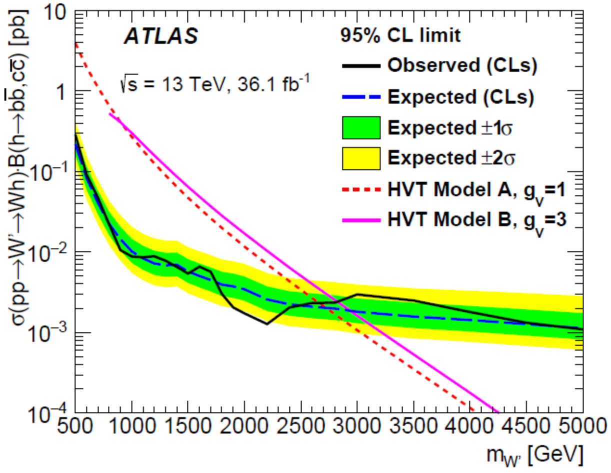
2HDM: Search for CP-odd Higgs boson A in semileptonic final states

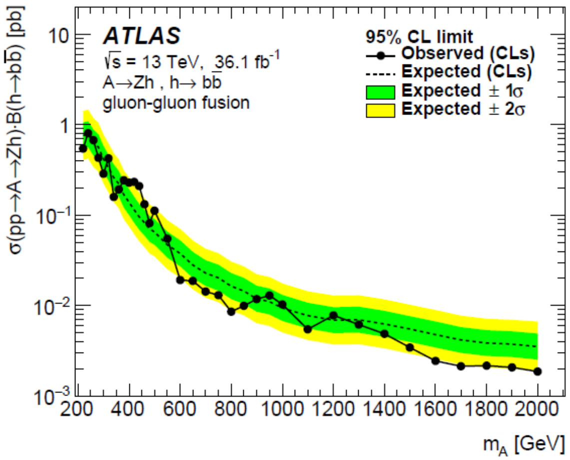
HVT (Heavy Vector Triplets, JHEP09 (2014)060): Search for W' and Z' heavy bosons

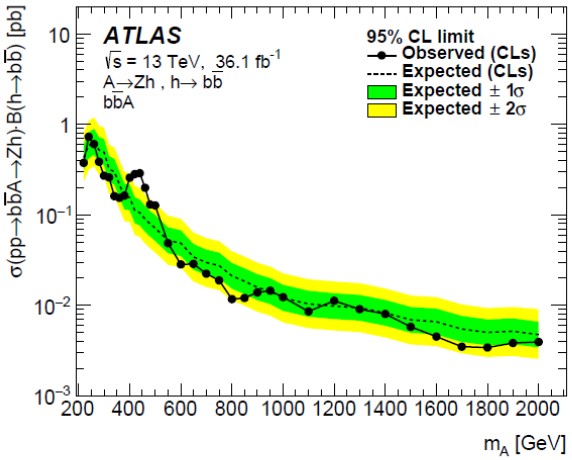
$M_{W'}$ < 2.67 TeV (2.82 TeV)
$M_{Z'}$ < 2.65 TeV (2.83 TeV)
For A boson, UL for ggF and associated b-quarks production are 5.5-240fb and 3.4-730fb respectively.









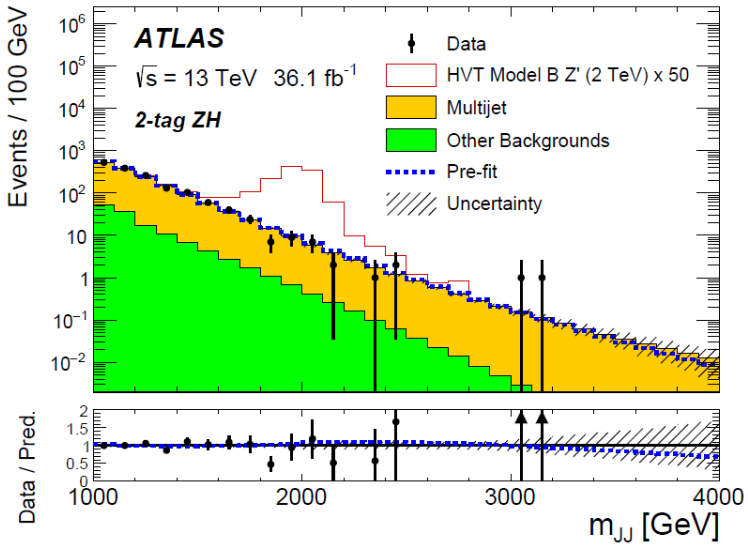


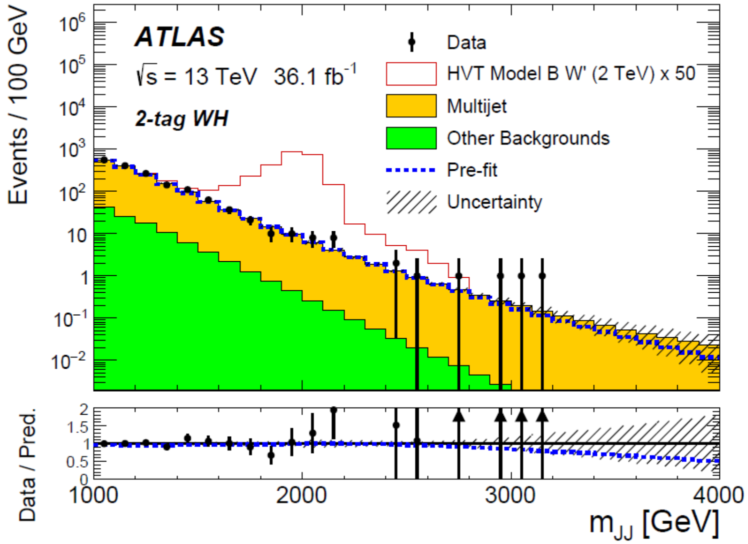
Search for W'/Z'→VH

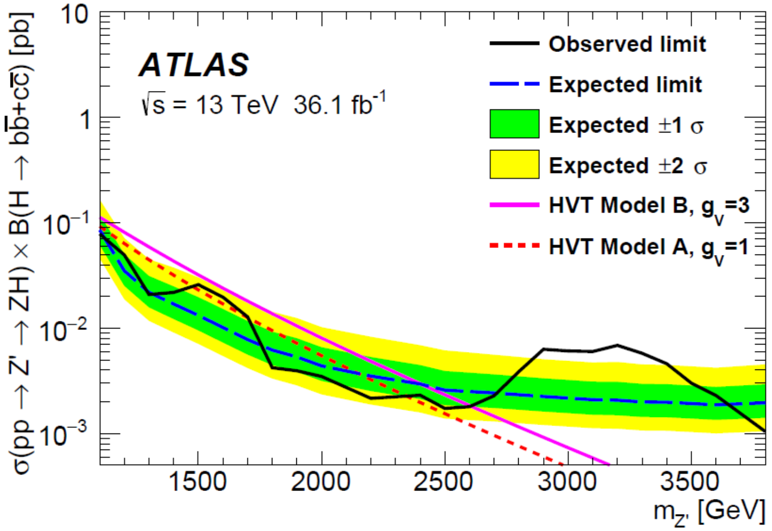
arXiv:1712.06518
arXiv:1707.06958
PLB 774 (2017) 494

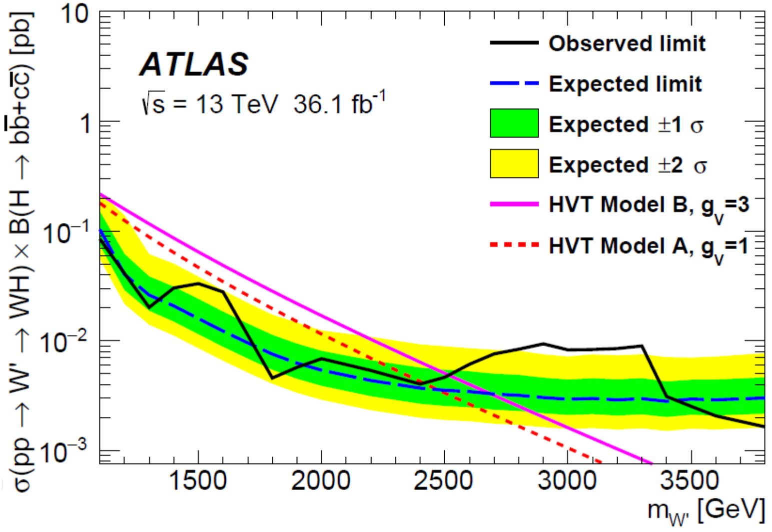
X → W/Z+H with H→bb and W/Z→qq'

→ Local (global) significance at 3 TeV VH signal region is 3σ (2.1σ)





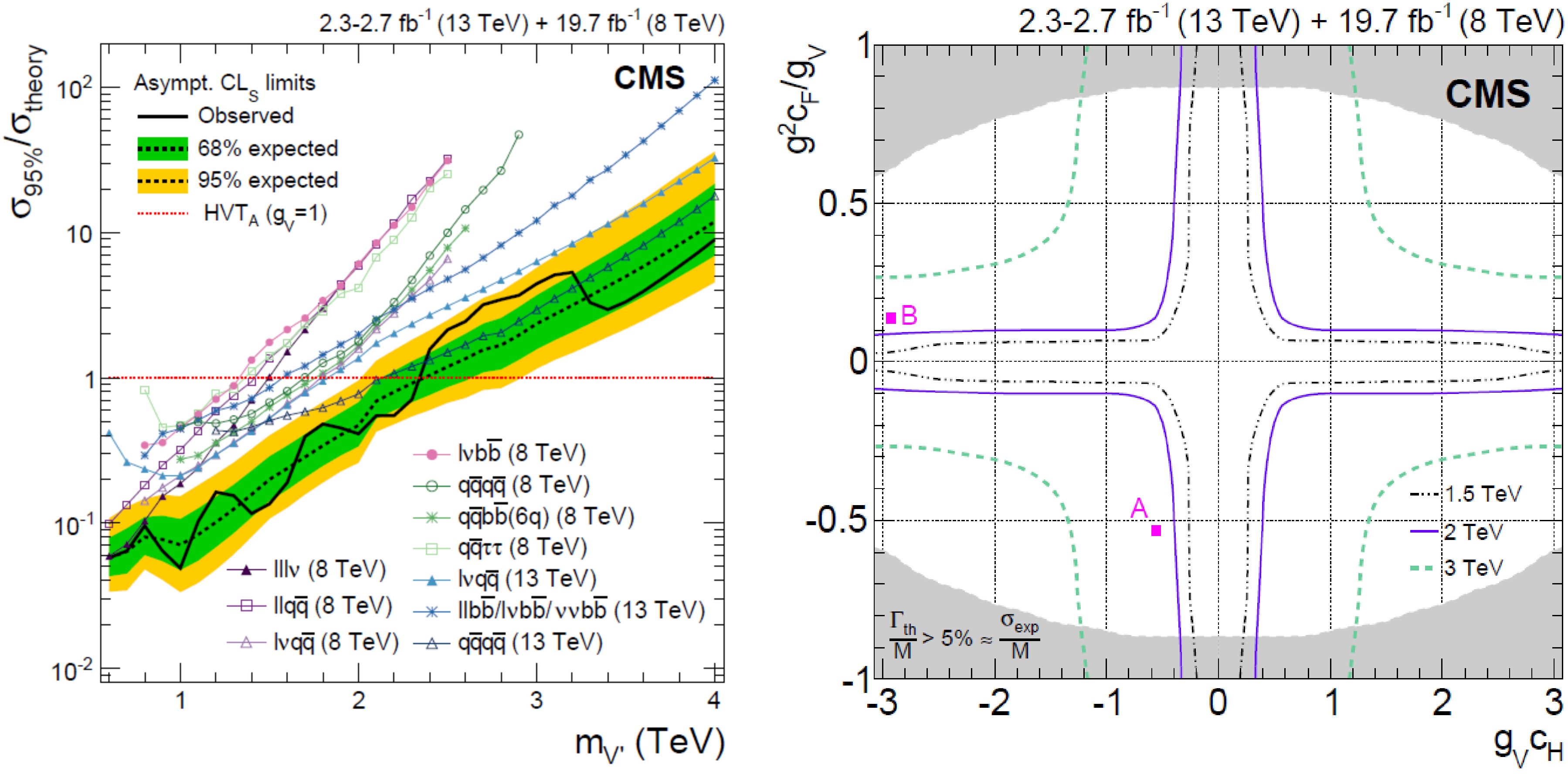




Search for X→WW/WZ/ZZ/VH

PLB 774 (2017) 533

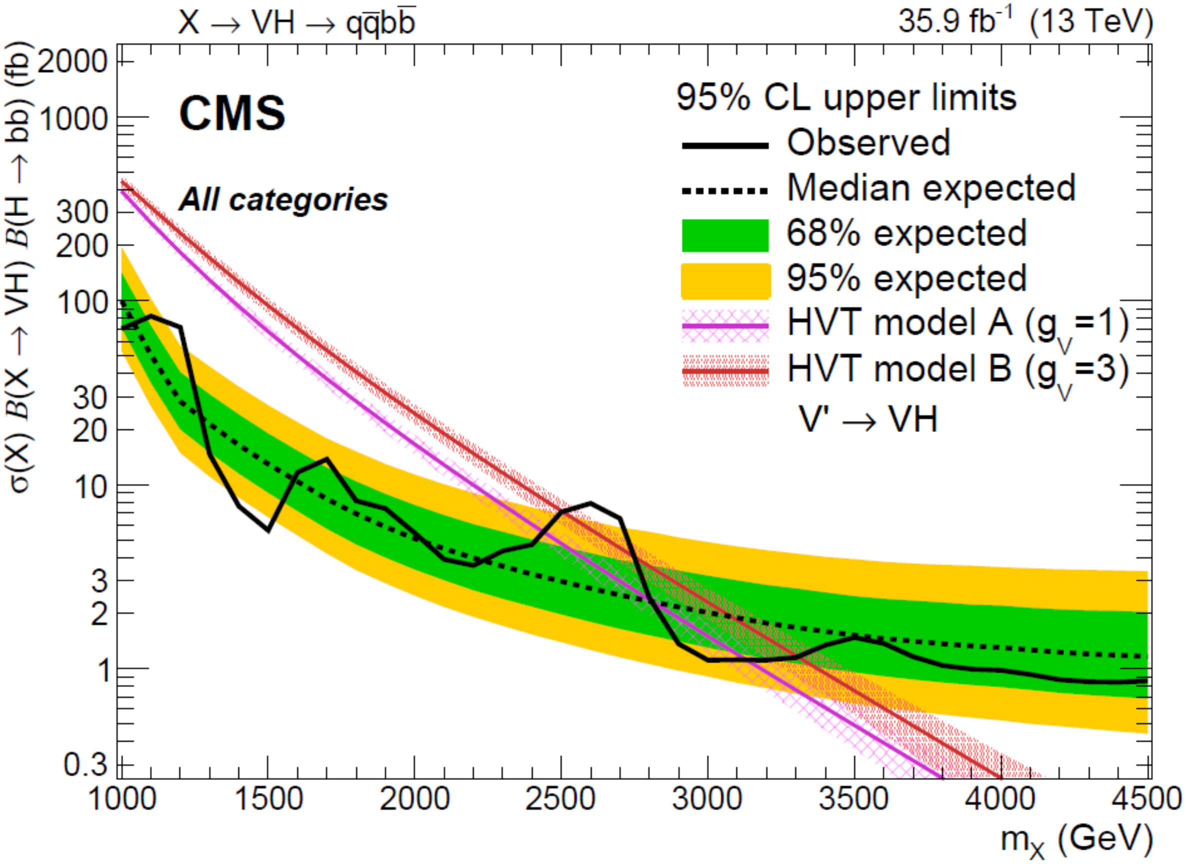
➔ The observed mass limit for W’ and Z’ is 2.4 TeV for HVT model based on the 8 TeV and 13 TeV data samples.



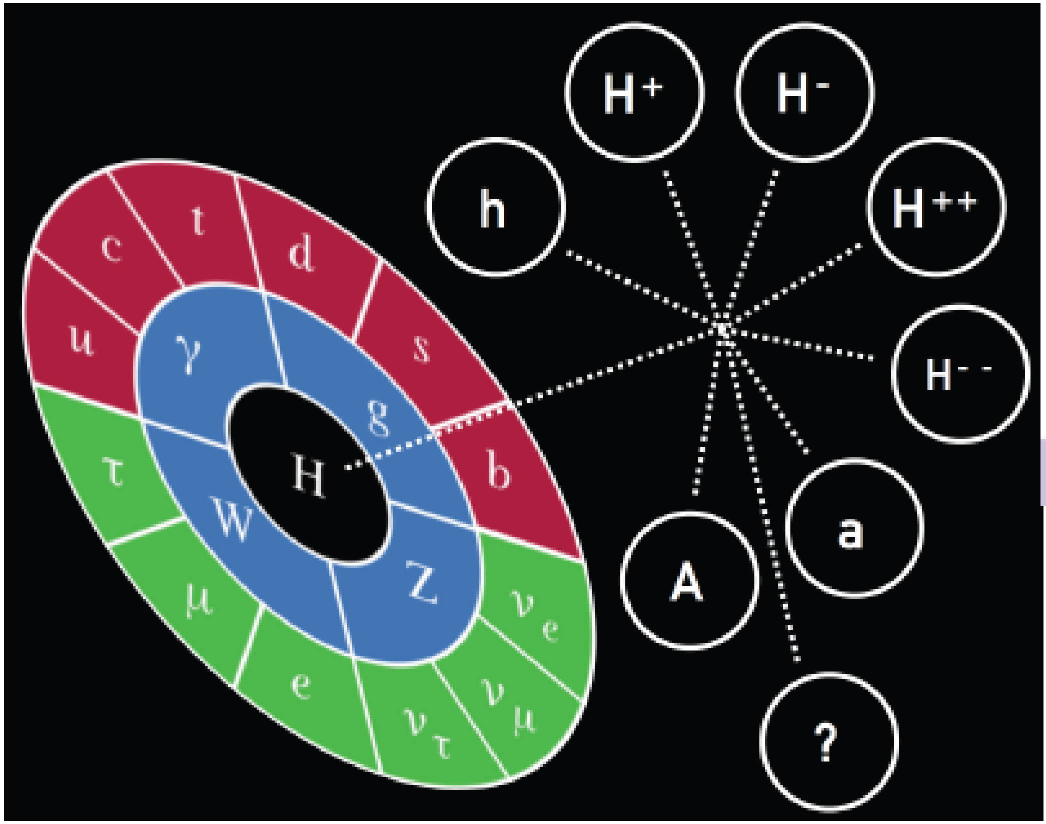
Search for X→WH and ZH

arXiv:1707.01303

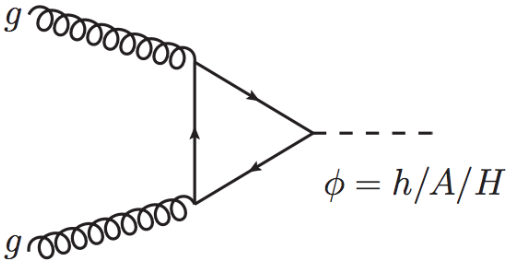
- ➔ With 35.9 fb^{-1} data, the observed mass limit for X→VH is 2.76 and 3.3 TeV for HVT models A and B, respectively.
- ➔ The largest local (global) significance is 2.6σ (0.9σ) at m_X=2.6 TeV.

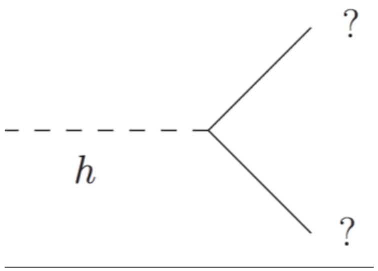


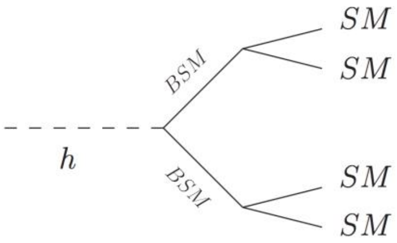
BSM Higgs Search

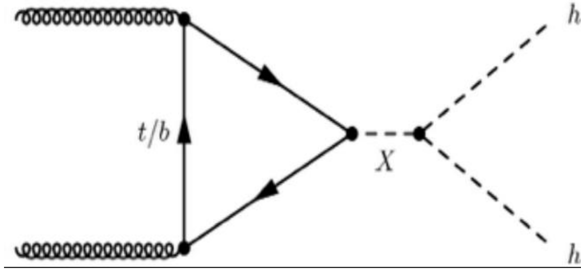


- Higgs Boson is not only responsible for the mass origin but also the bridging window to new BSM physics anomalies:
- Higgs-like h/A/H, (doubly-) charged higgs, Vh, resonant di-higgs, non-standard decayed higgs, …





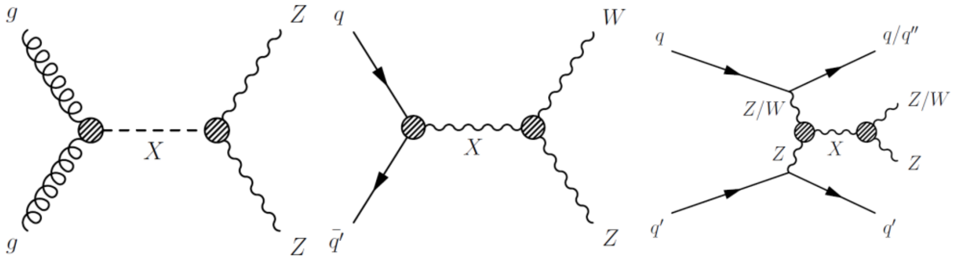


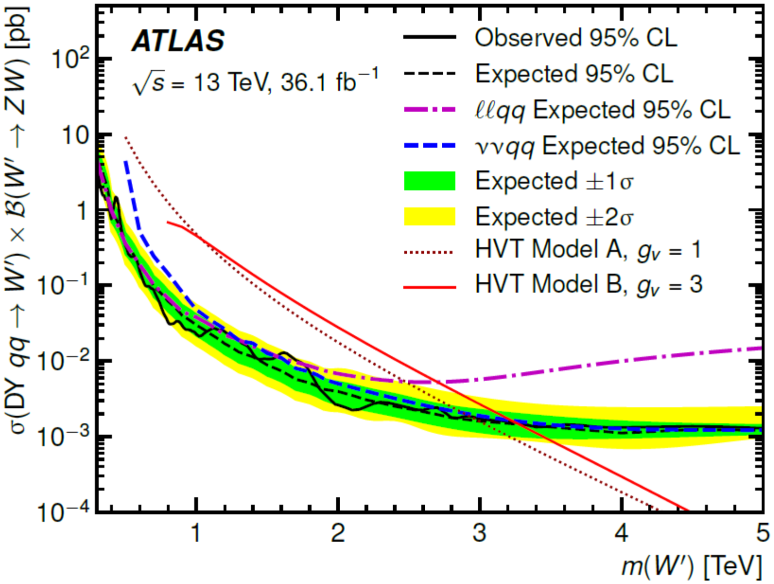


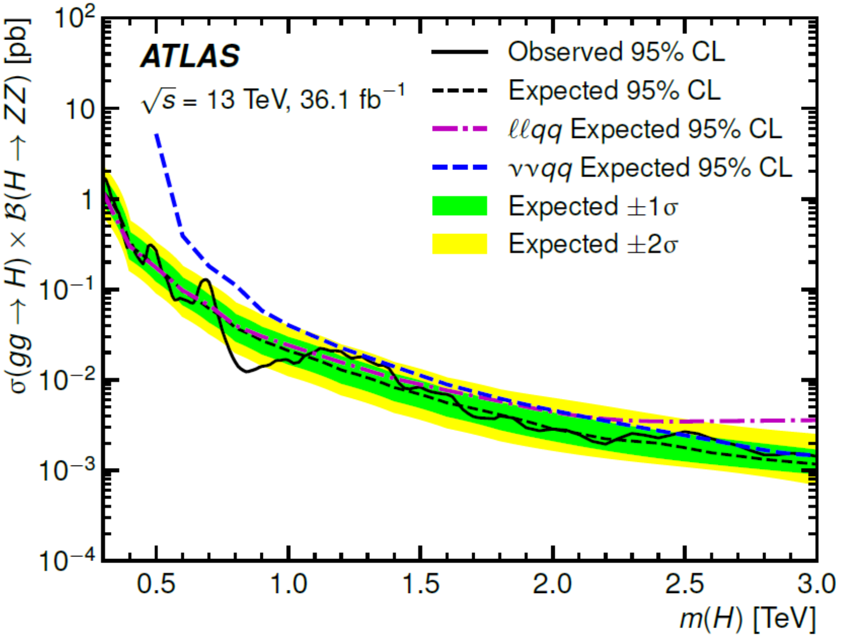
Search for X→ZZ/ZW (llqq, vvqq)

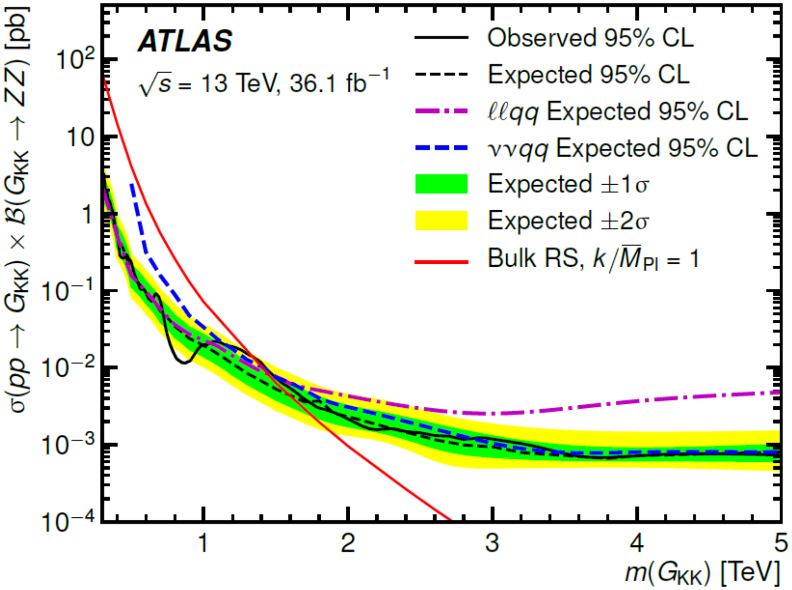
arXiv:1708.09638

ggF/VBF: HVT heavy H→ZZ
VBF/DY: HVT W'→ZW, $m_{W'}$> 2.9 (A) 3.2 (B) TeV
ggF: spin-2 KK excitations G_{KK} > 1.3 (observed) and 1.6 (expected) TeV at 95% CL.









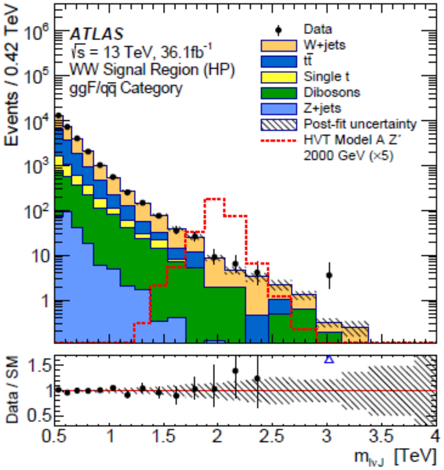
Search for X→WW/WZ (lvqq)

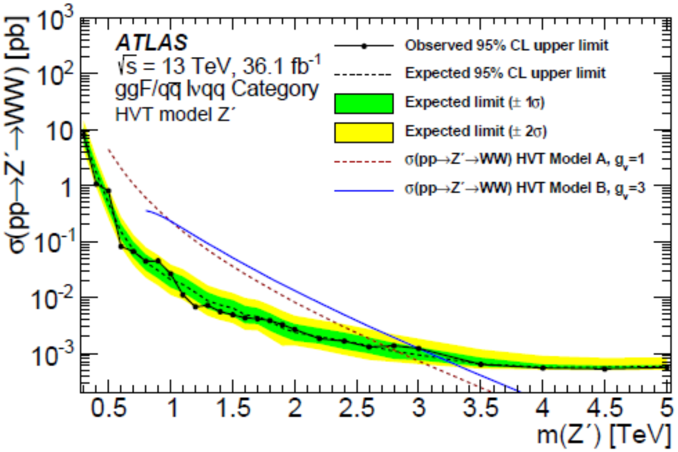
arXiv:1710.07235

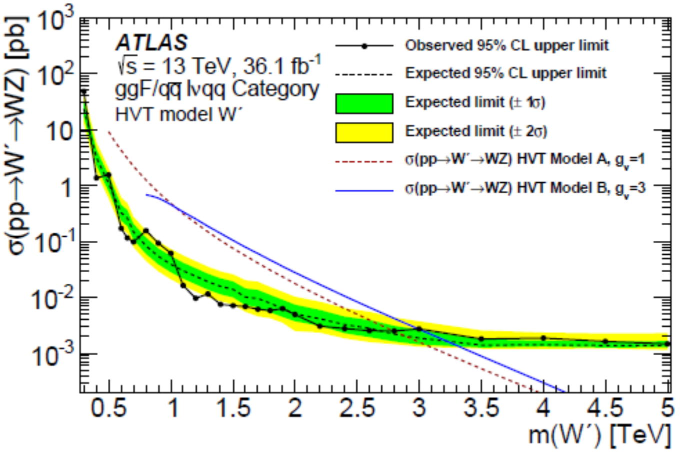
ggF/VBF: HVT $m_{W'}$> 2.8 (A) 3.0 (B) TeV

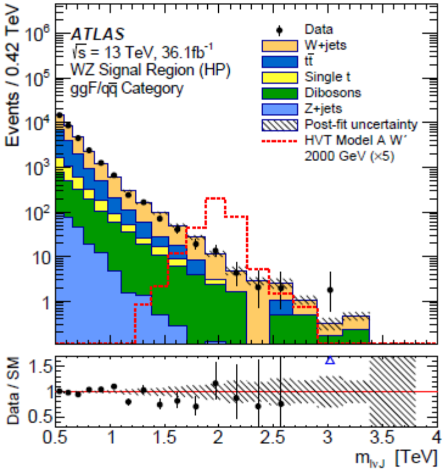
HVT $m_{Z'}$> 2.7 (A) 3.0 (B) TeV

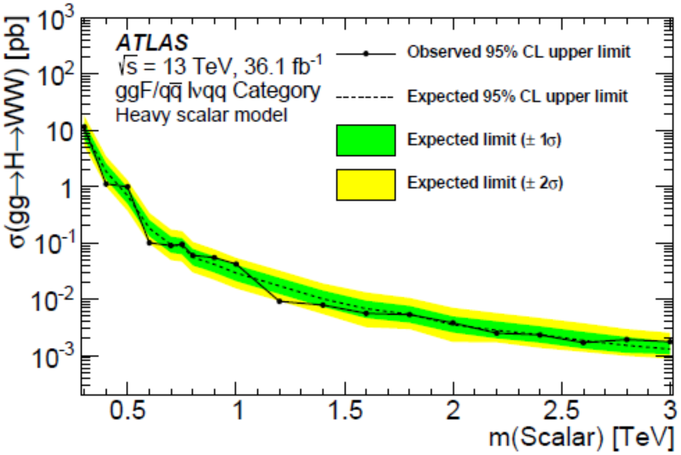
ggF/VBF: spin-2 KK excitations G_{KK} > 1.75TeV at 95% CL.

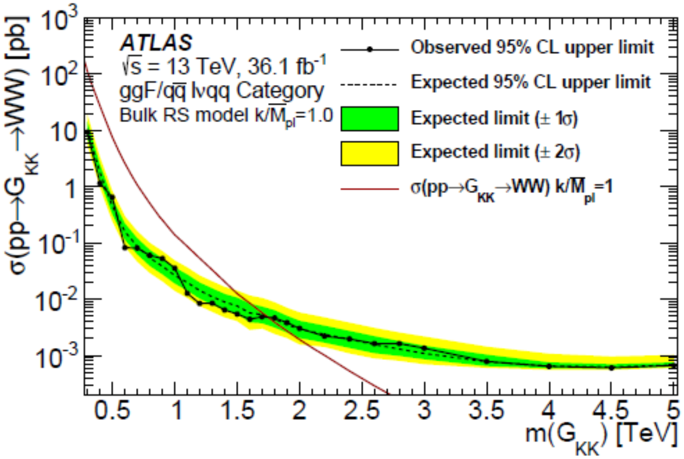






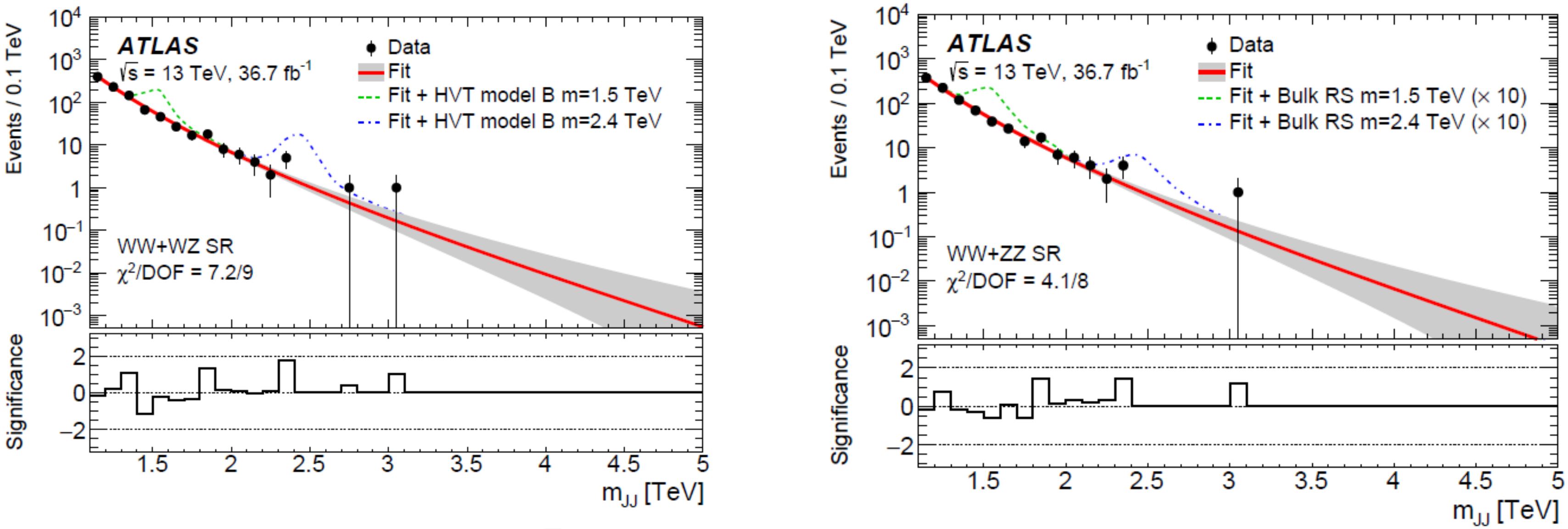


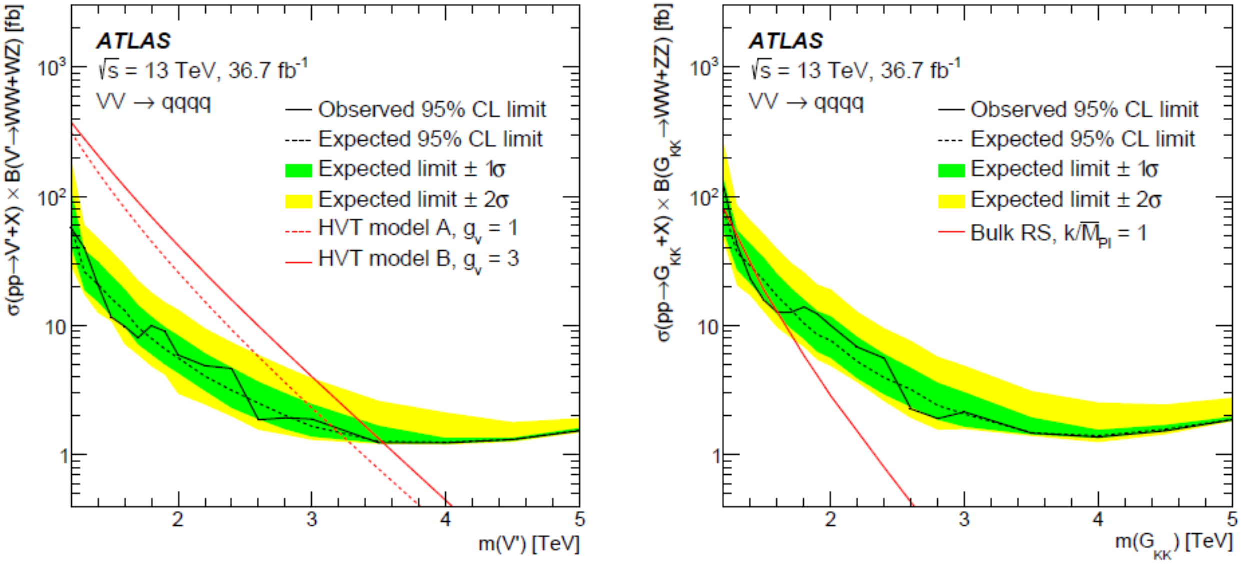




Search for X→VV (qqqq)

PLB777 (2017)91





(a) *WW* + *WZ* signal region for HVT model

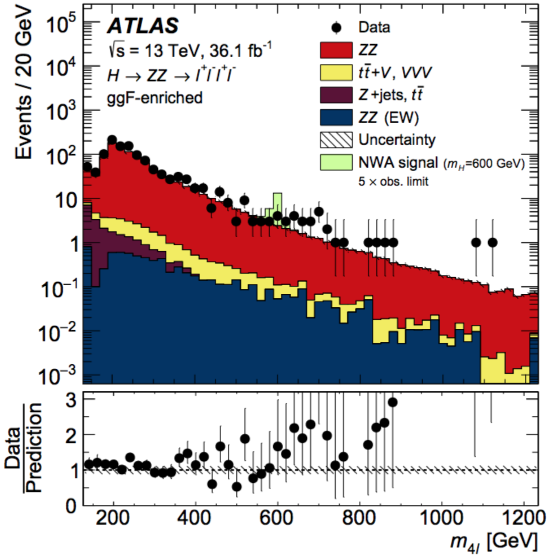
(b) *WW* + *ZZ* signal region for bulk RS model

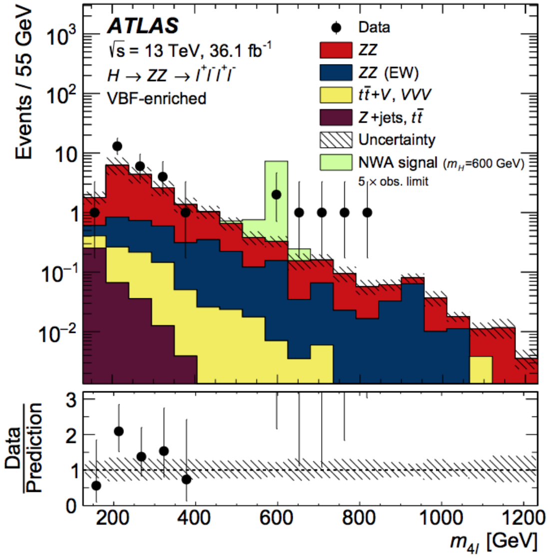
Model	Signal Region	Excluded mass range [TeV]
HVT model A, $g_V = 1$	*WW*	1.20 – 2.20
	WZ	1.20 – 3.00
	WW + *WZ*	1.20 – 3.10
HVT model B, $g_V = 3$	*WW*	1.20 – 2.80
	WZ	1.20 – 3.30
	WW + *WZ*	1.20 – 3.50
Bulk RS, $k/\overline{M}_{\rm Pl} = 1$	*WW*	1.30 – 1.45
	ZZ	none
	WW + *ZZ*	1.30 – 1.60

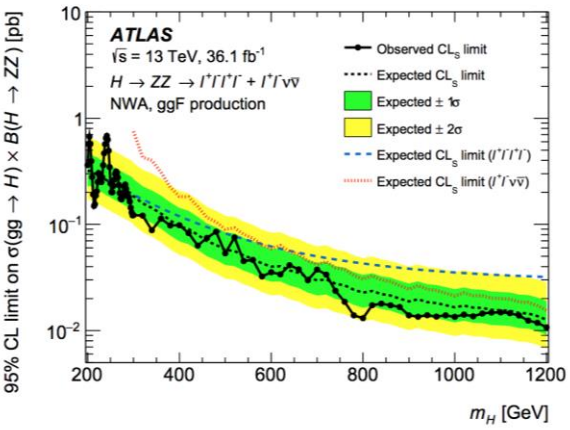
Search for Heavy H→ZZ→4l, 2l2v

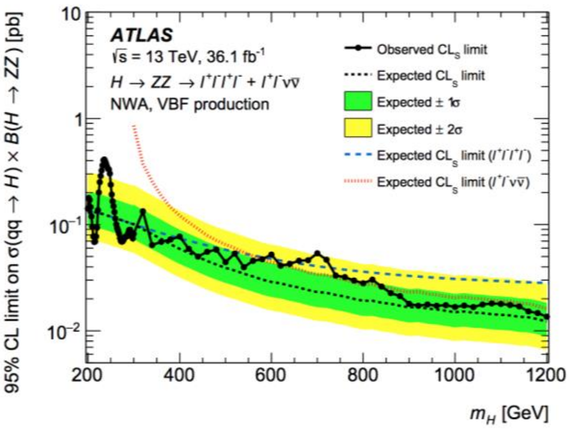
arXiv:1712.06386

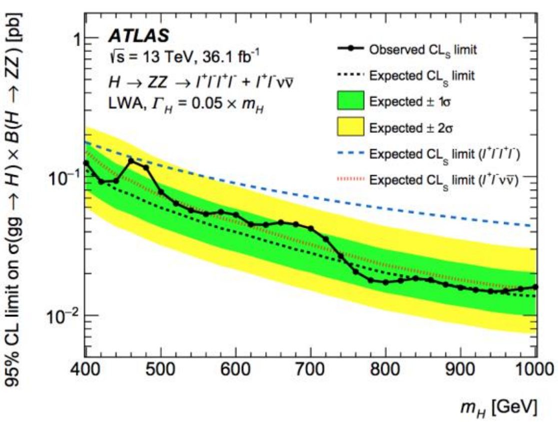
- ➢ **Combination of 4l and 2l2v**
- ➢ **Search for high mass heavy resonances in ggF and VBF modes, looking into LWA alongside NWA**
- ➢ **Interpretation in context of 2HDM, Higgs/scalar interpretations for DBL hadronic H→VV**







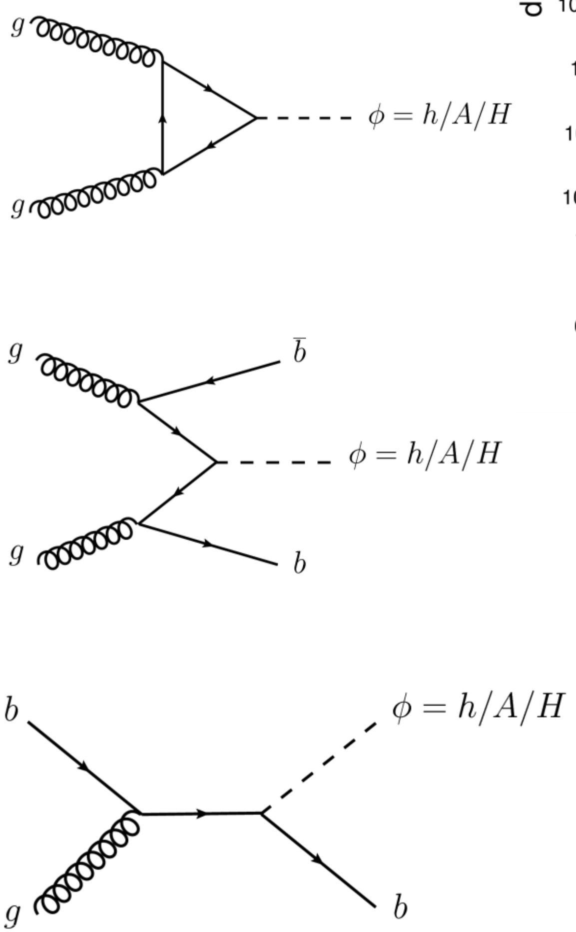


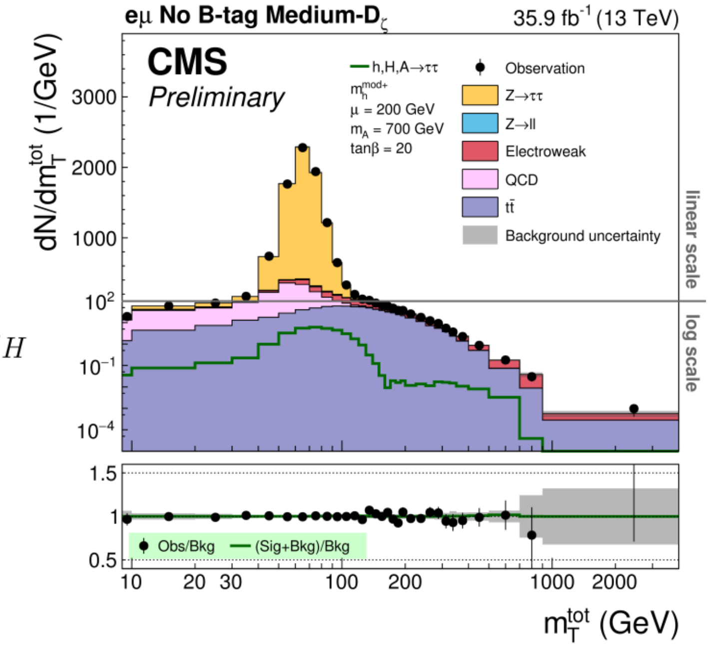


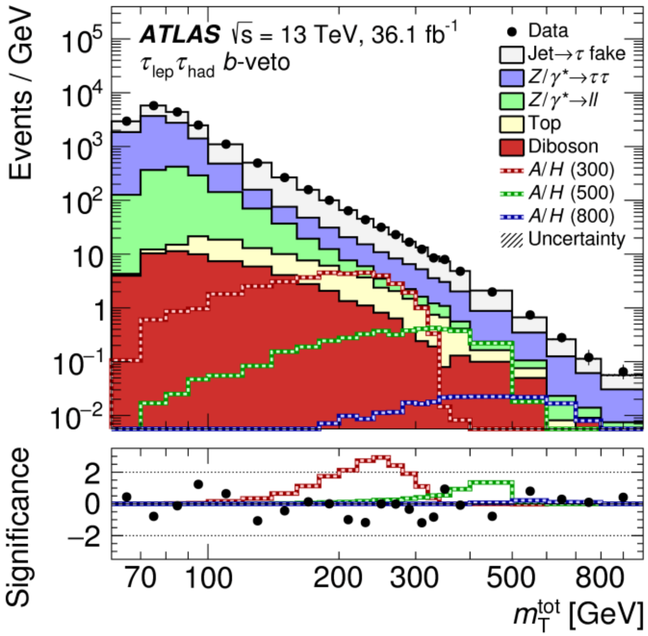
Neutral Higgs: $H/A/h \rightarrow \tau^+\tau^-$

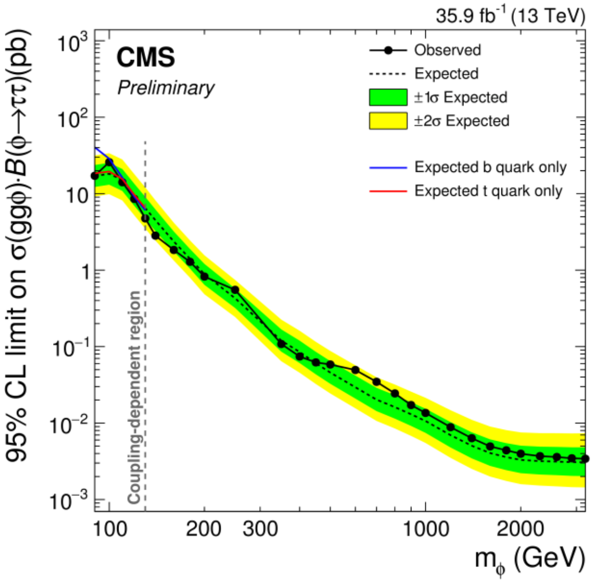
CMS-PAS-HIG-17-020
arXiv:1709.07242

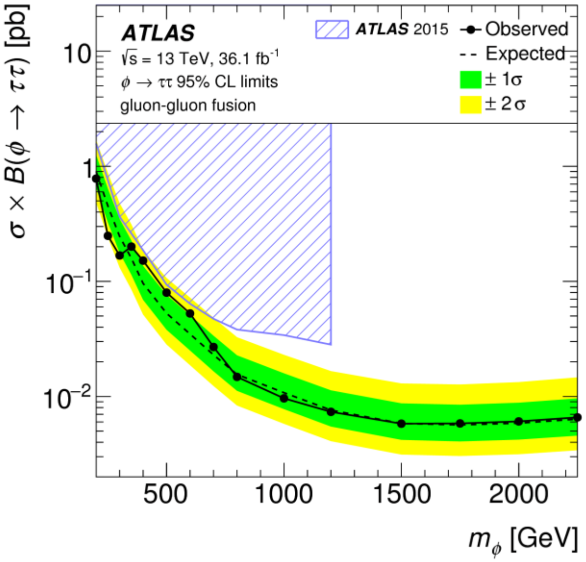
MSSM Higgs boson production modes







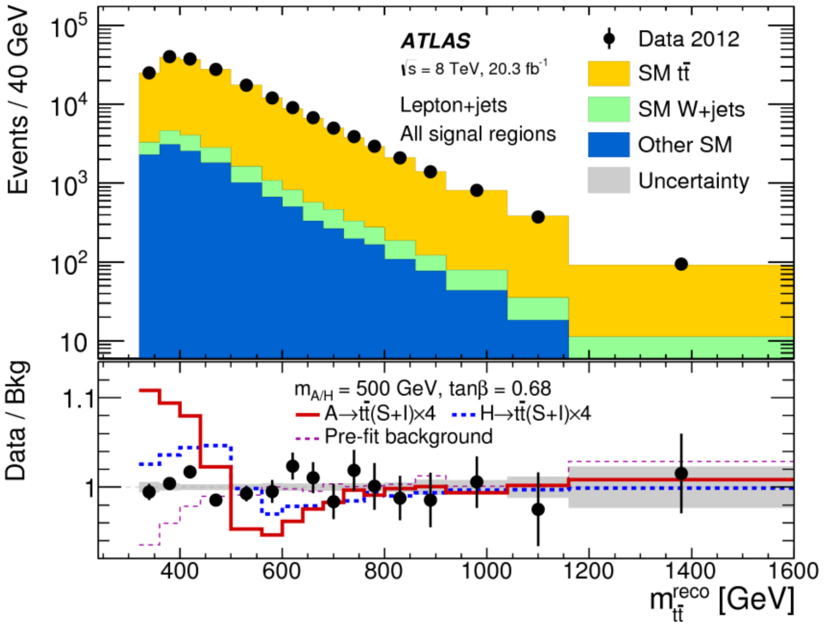


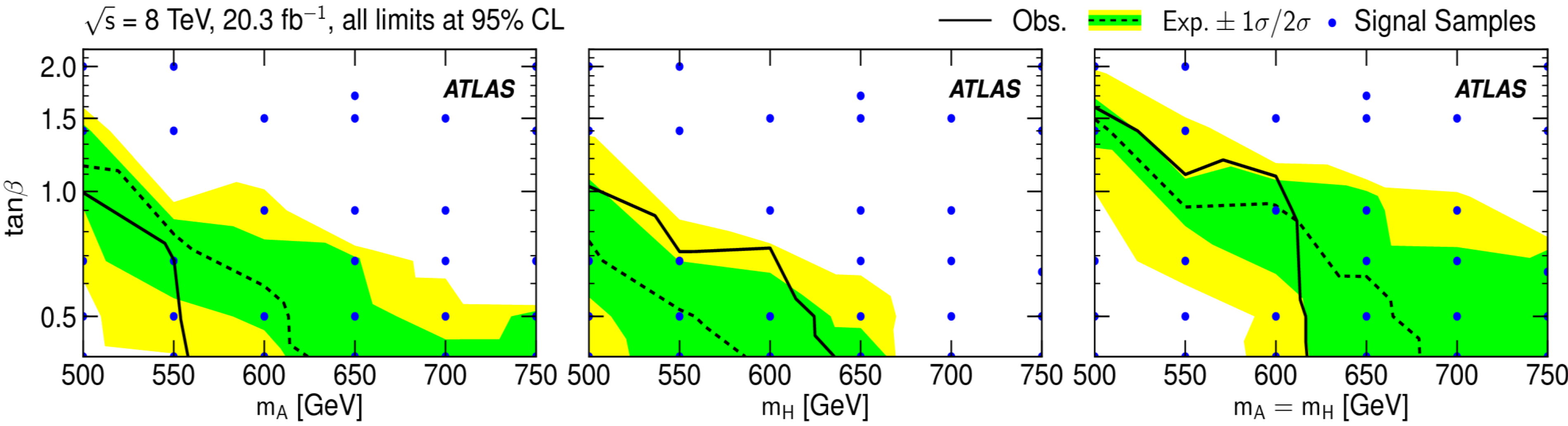


Neutral Higgs: H/A/h→ttbar

PRL 119 (2017) 191803

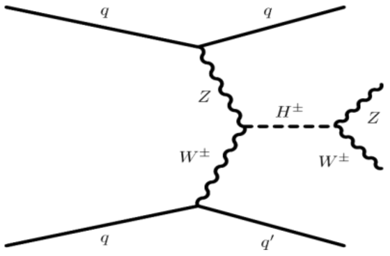
- Search for heavy (pseudo-)scalar higgs bosons in ttbar → lep+MET+jets final states
- Results interpreted within the context of a type-II two-Higgs-doublet model
- one of the main challenges: the large interference with ttbar bkg
- Exclusion limits on the signal strength at 95% CL in the $m_{A/H}$ versus tanβ plane



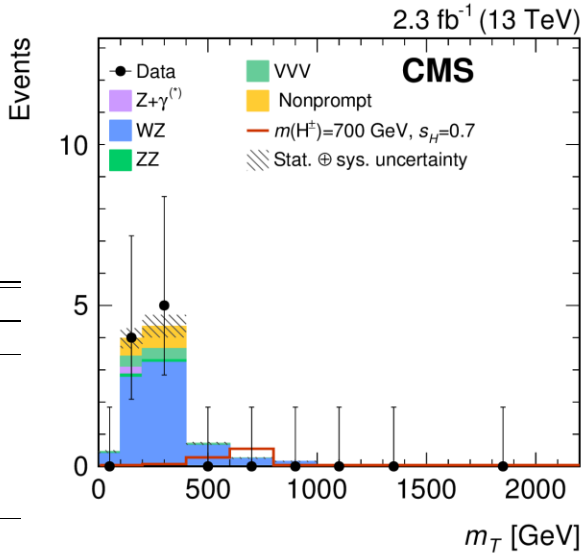


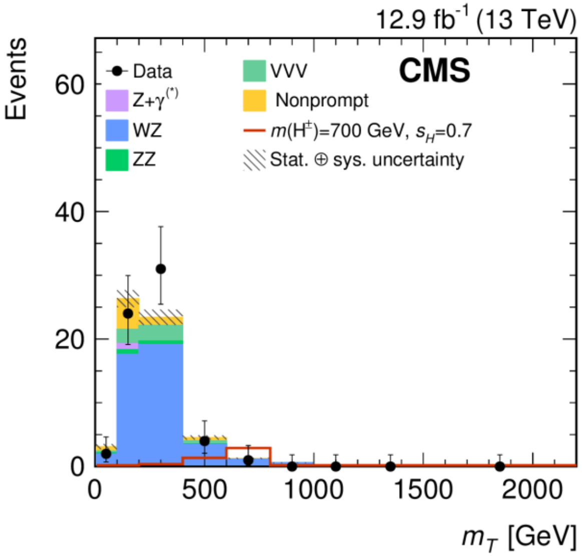
Search for Charged $H^\pm \rightarrow W^\pm Z$

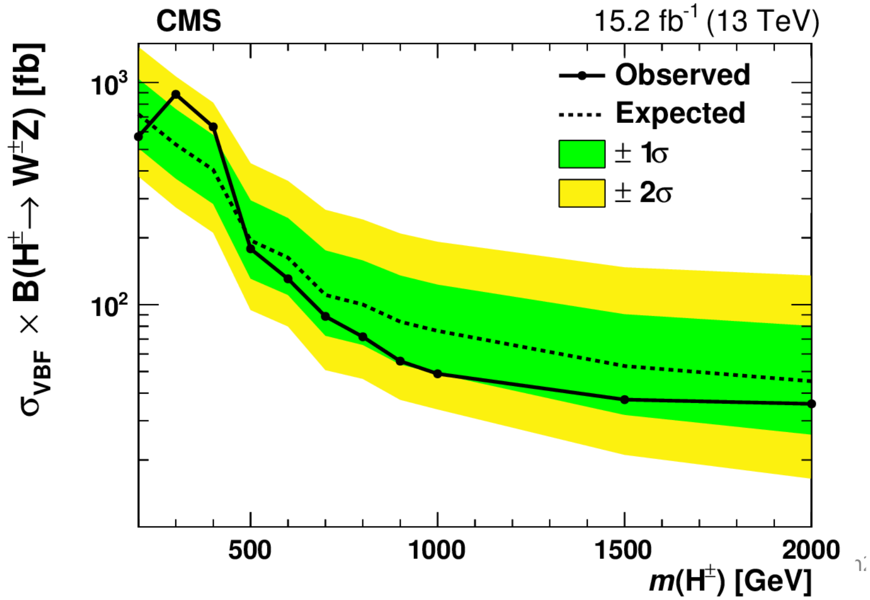
arXiv:1705.02942
PRL119 (2017)141802

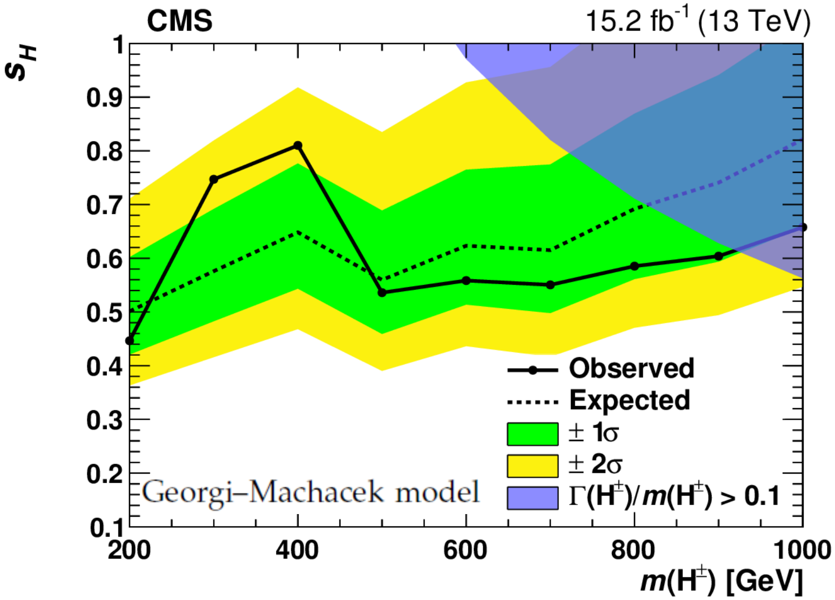


Data set	2015	2016
Data	9	62
WZ	7.5 ± 1.2	44.4 ± 5.7
ZZ	0.2 ± 0.1	1.6 ± 0.2
VVV	0.8 ± 0.2	5.5 ± 0.9
$Z\gamma$	0.2 ± 0.1	1.0 ± 0.6
Nonprompt	1.3 ± 1.0	7.4 ± 5.4
Total bkg.	10.0 ± 1.6	59.9 ± 8.0
Signal ($m(H^\pm) = 700\,\text{GeV}$)	0.9 ± 0.1	4.7 ± 0.5

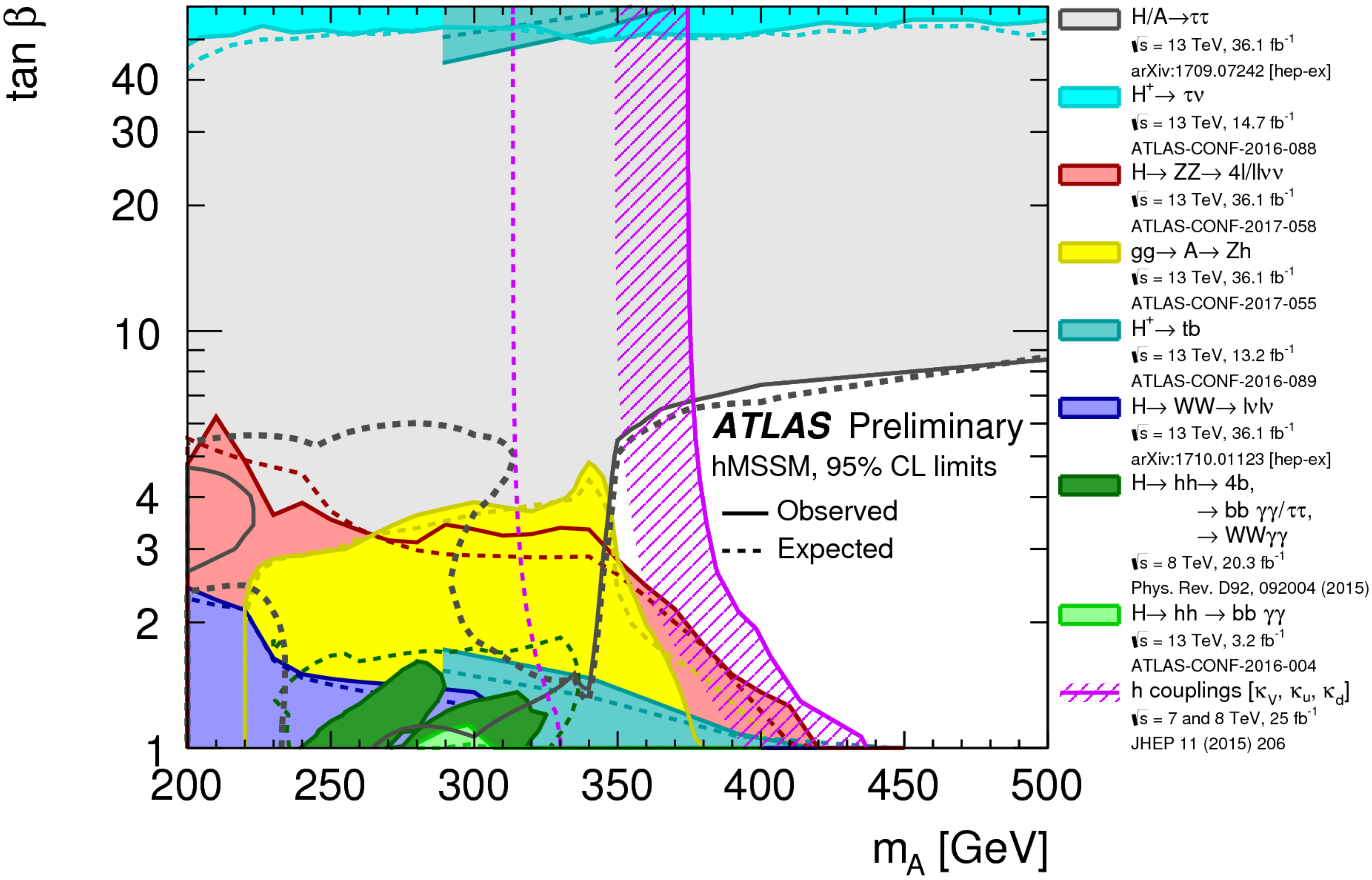








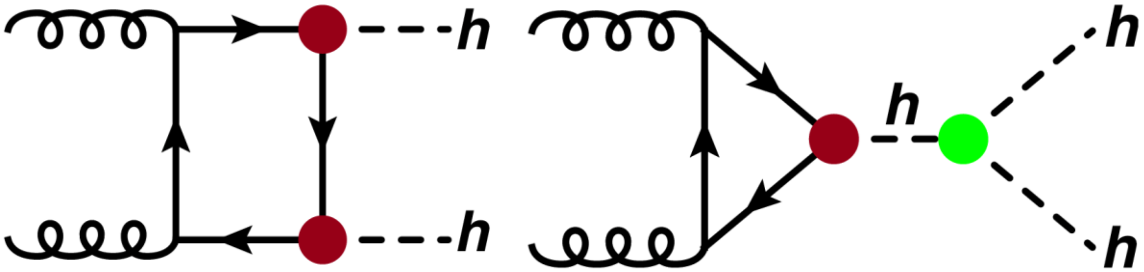
MSSM Higgs Searches



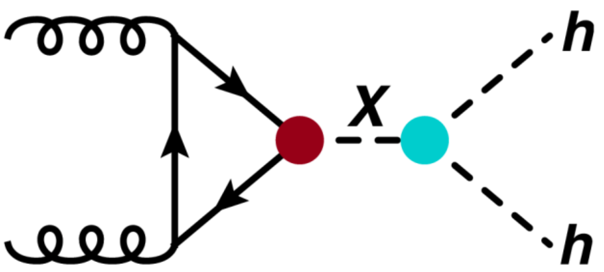
Search for Double-Higgs

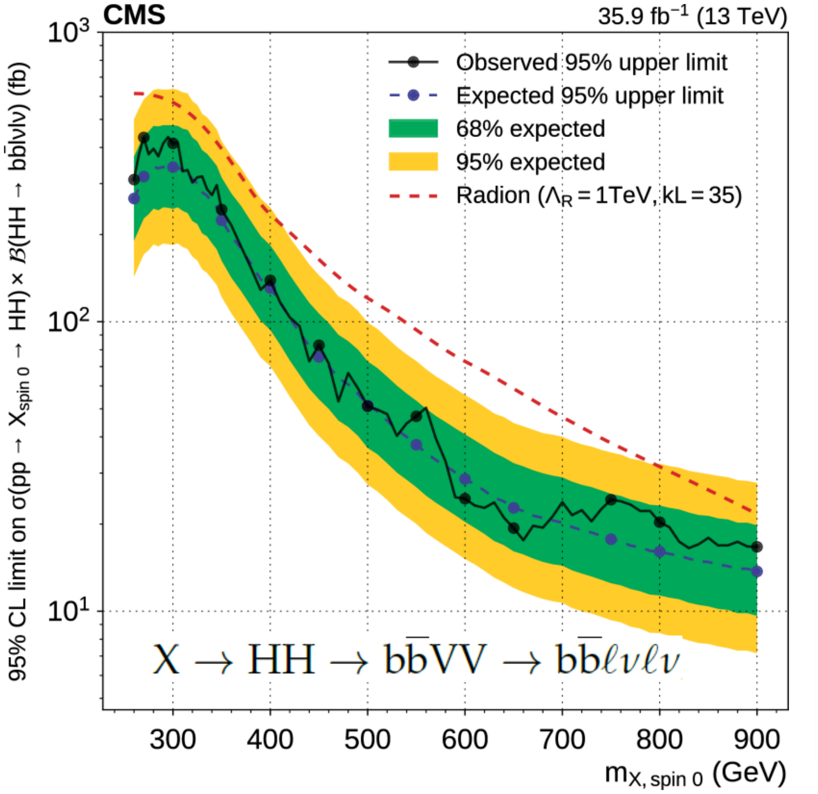
arXiv:1707.02909
arXiv:1708.04188

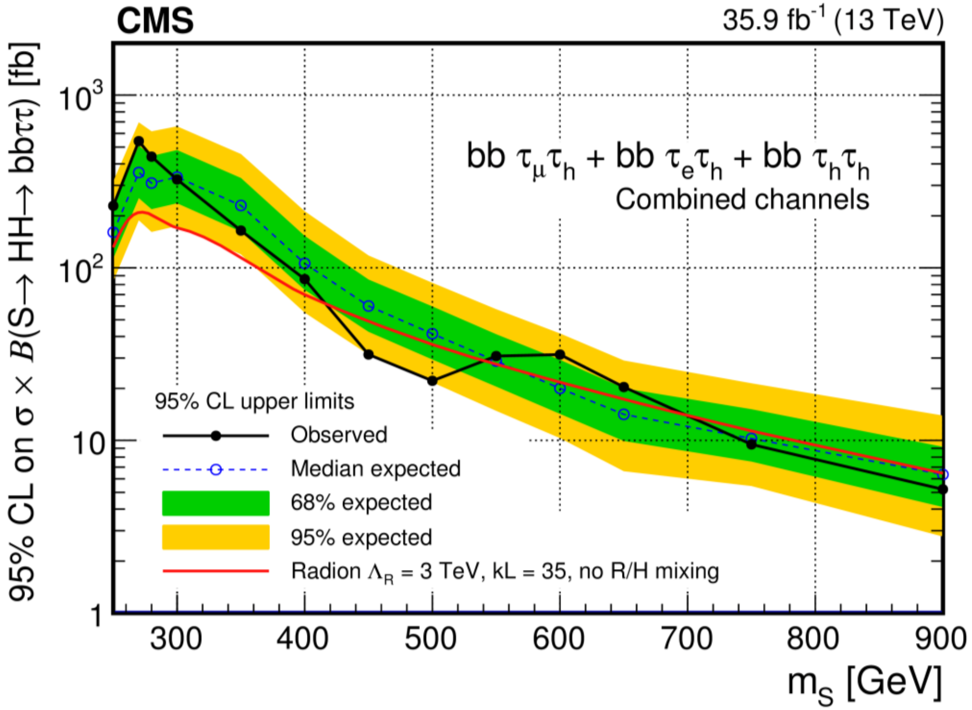
Non-resonant



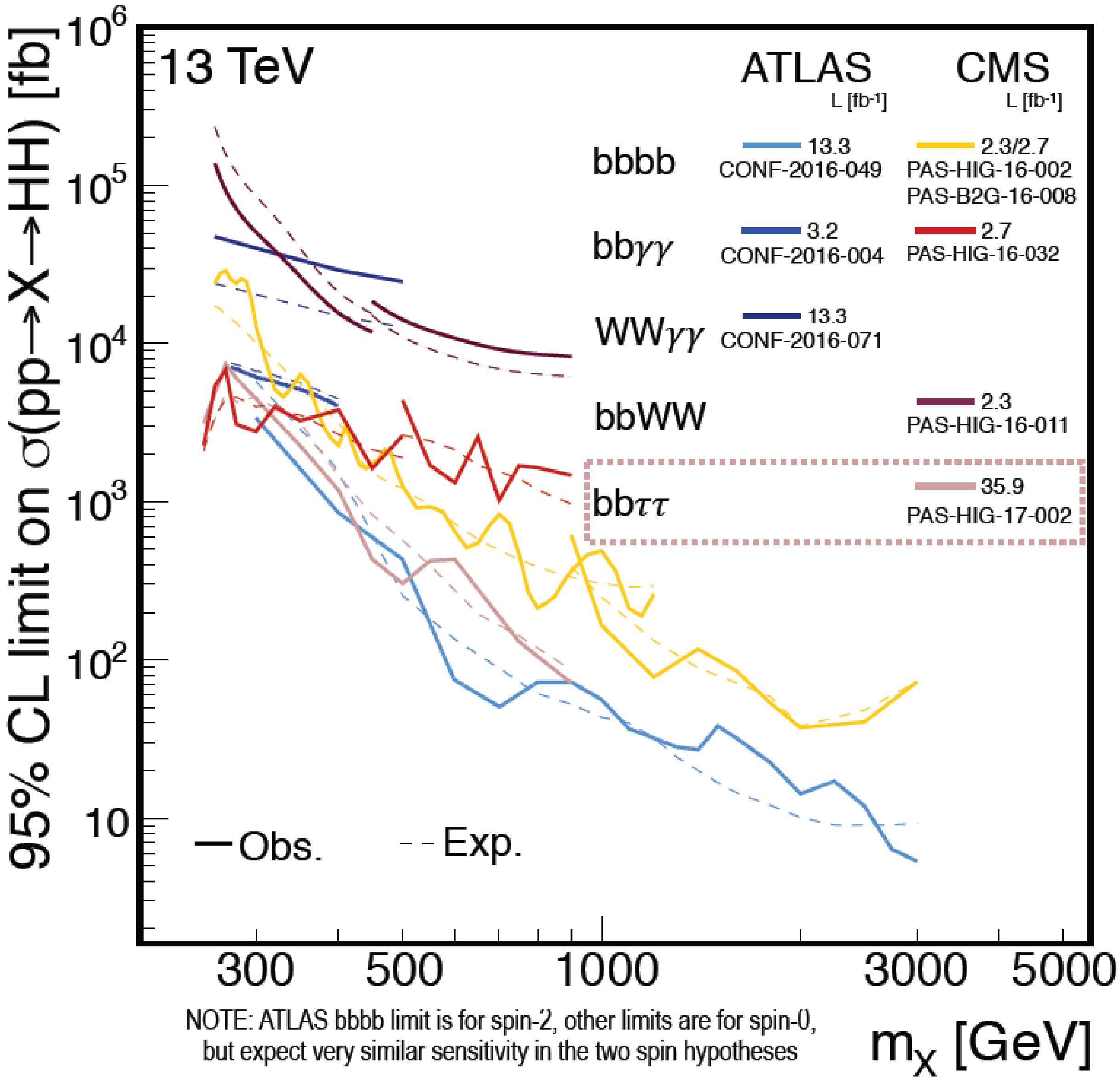
Resonant







Search for Double-Higgs



NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses

Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM}	
	ATLAS EXPERIMENT	CMS
bbbb	29 (38)	342 (308)
bbWW	-	410 (227) ▣
bbττ	-	28 (25) ▣
bbγγ	117 (161)	91 (90)
WWγγ	747 (386)	-

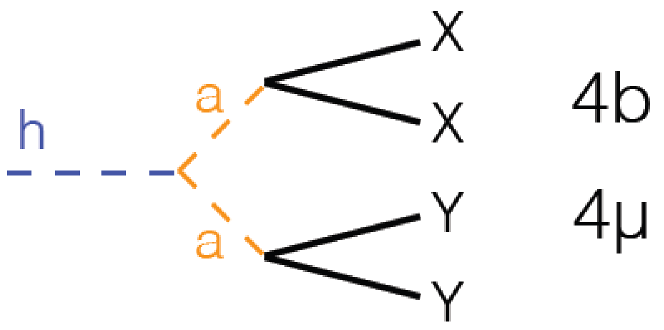
2.3-3.2 fb^{-1} 13.3 fb^{-1} 35.9 fb^{-1}

▣: Test of anomalous HH couplings

- Complementarity in different mass ranges
  - much to gain from a combination!

Higgs BSM Decays

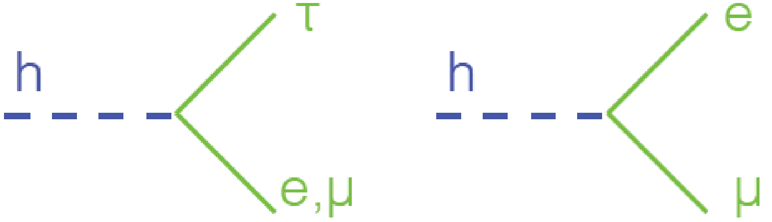
Higgs Decays to new particles



X and Y are SM particles

Flavor violating couplings

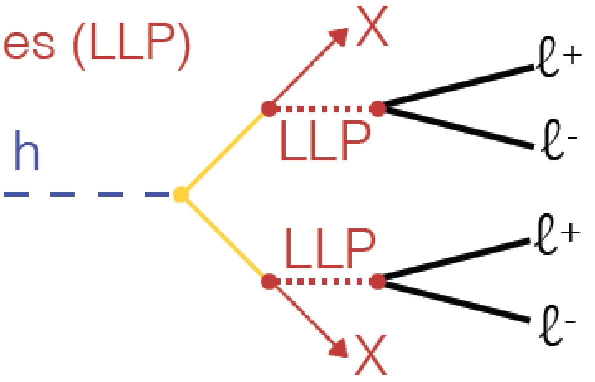
lepton decays



FV in quark sector also considered

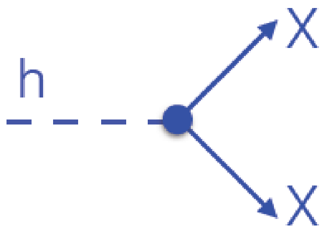
Long lived particles (LLP)

Many possible
signatures that
are sensitive to
a broad range
of lifetimes



2x2ℓ lepton jets
Nx2ℓ (4x2ℓ…) also possible

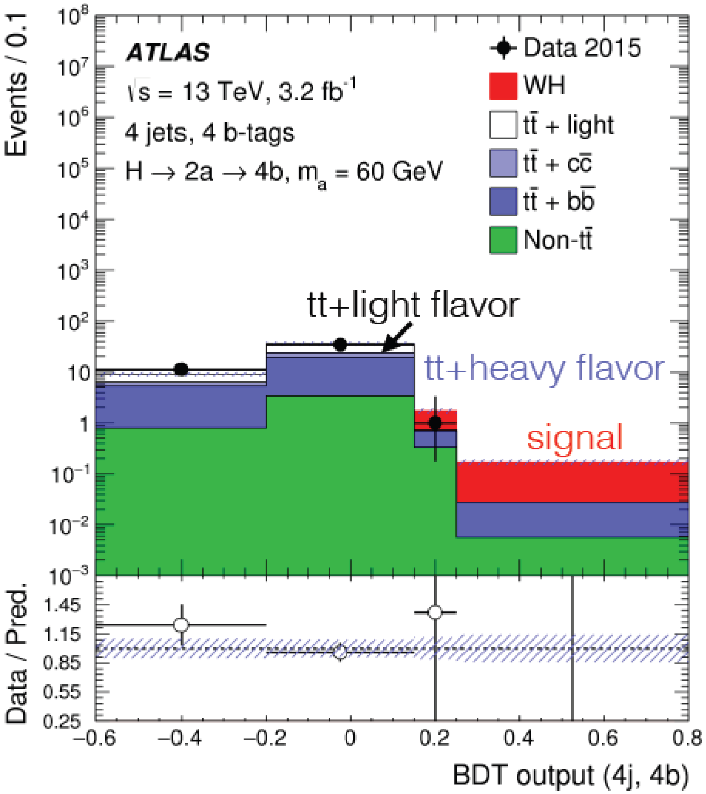
Invisible Decays



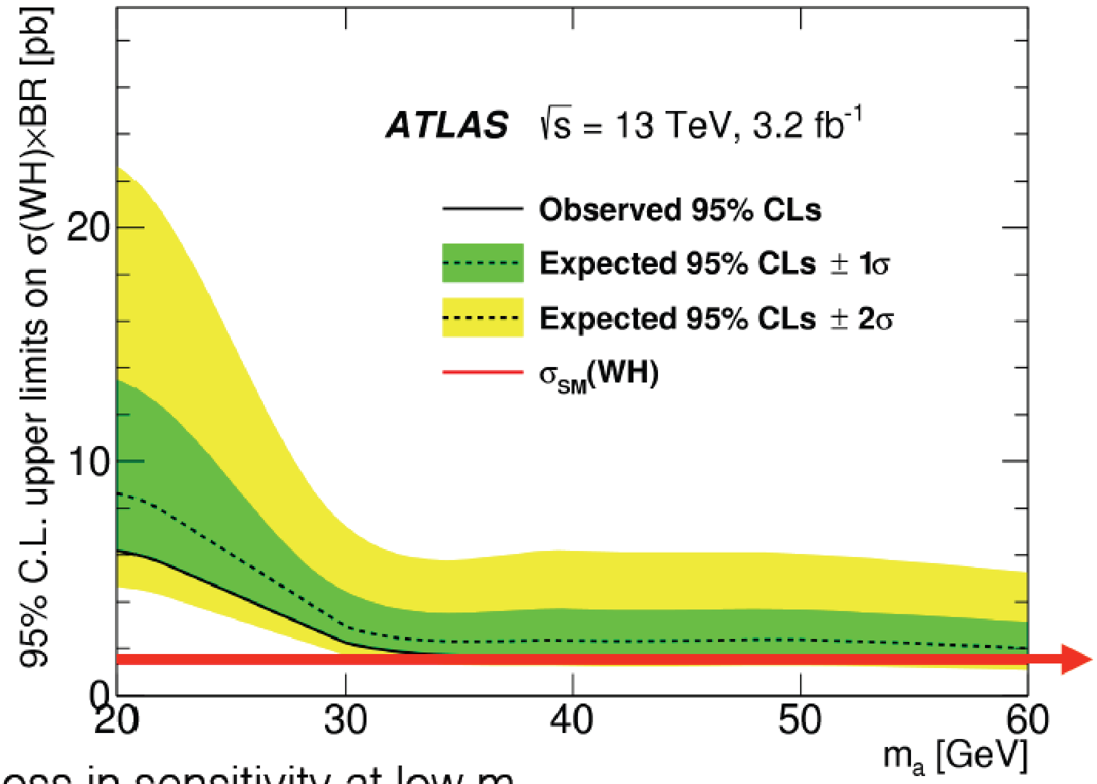
X gives E_T^{miss} signature

Search for H→2a→4b

EPJC 76 (2016) 605



variables included are m_{4b}, min. Δm_{bb}, av. ΔR_{bb}, H_T, m_{T2}

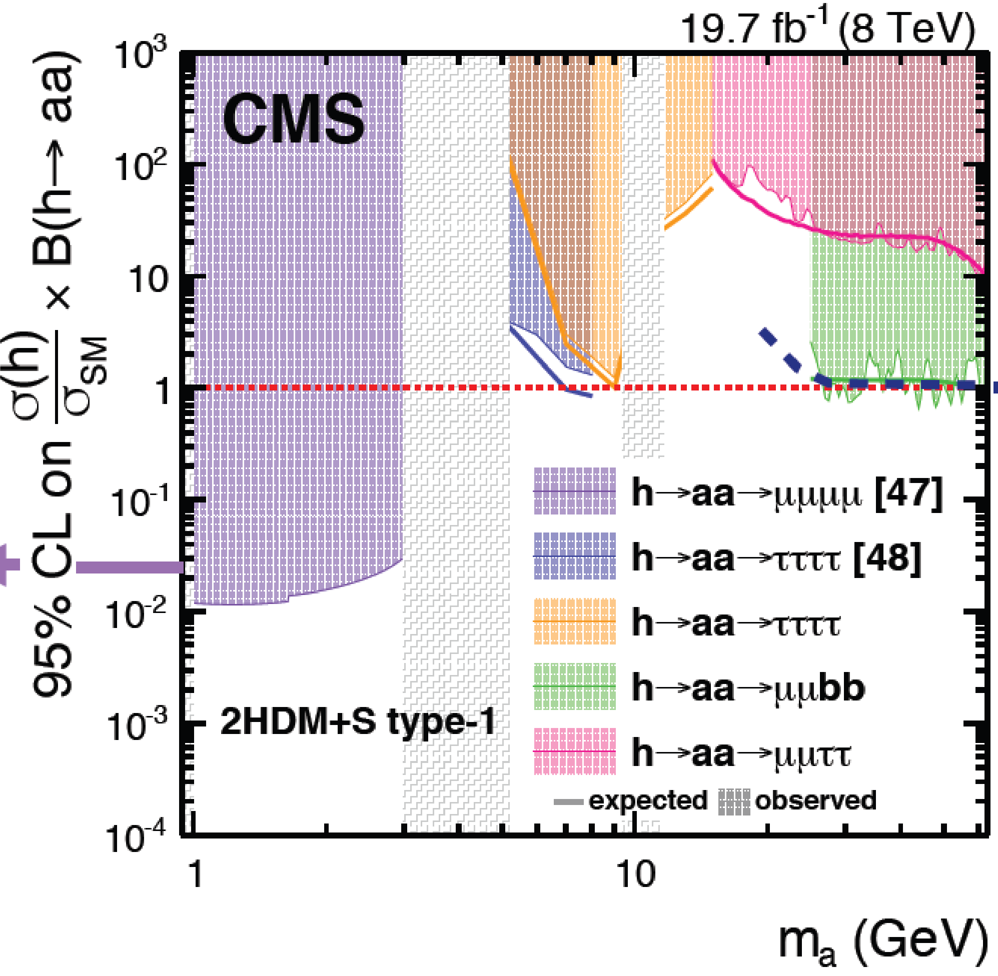


loss in sensitivity at low m_a
due to merged jets

$\sigma_{SM}(WH)$ = 1.37 pb
BR(h→4b)=1

expect great improvement in sensitivity with the full 13 TeV dataset

Searches for h→aa final states



results are model dependent
→ here Yukawa couplings

4b sensitivity with first 13 TeV analysis

Eur. Phys. J. C 76 (2016) 605
arXiv: 1606.08391

4μ extended to m_a<1 GeV in 13 TeV analysis

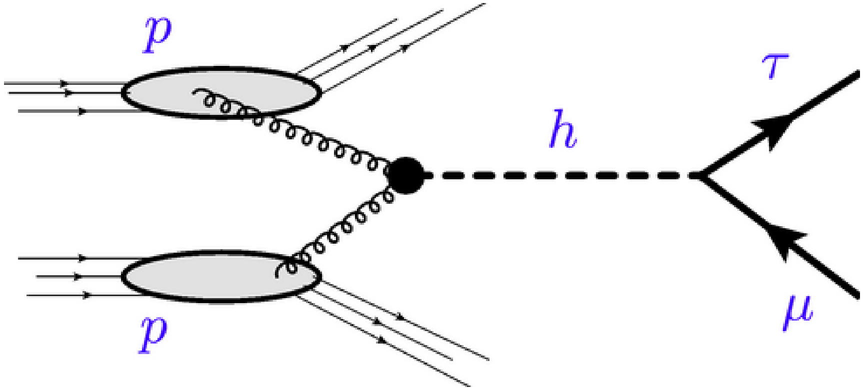
8 TeV result from ATLAS for 2τ2μ also available down to $m_{2\tau}$

Analyses starting to probe interesting region → stay tuned for 13 TeV updates

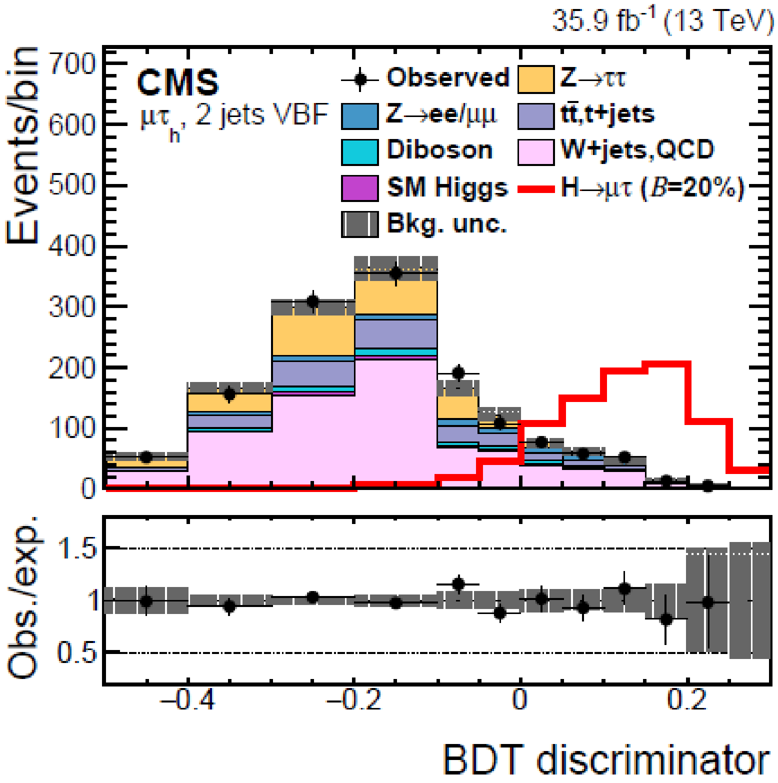
Hi ATLAS (8 TeV): Phys. Rev. D 92 (2015) 05002 , arXiv:1505.01609
CMS (8 TeV): submitted to JHEP, arXiv:1701.02032

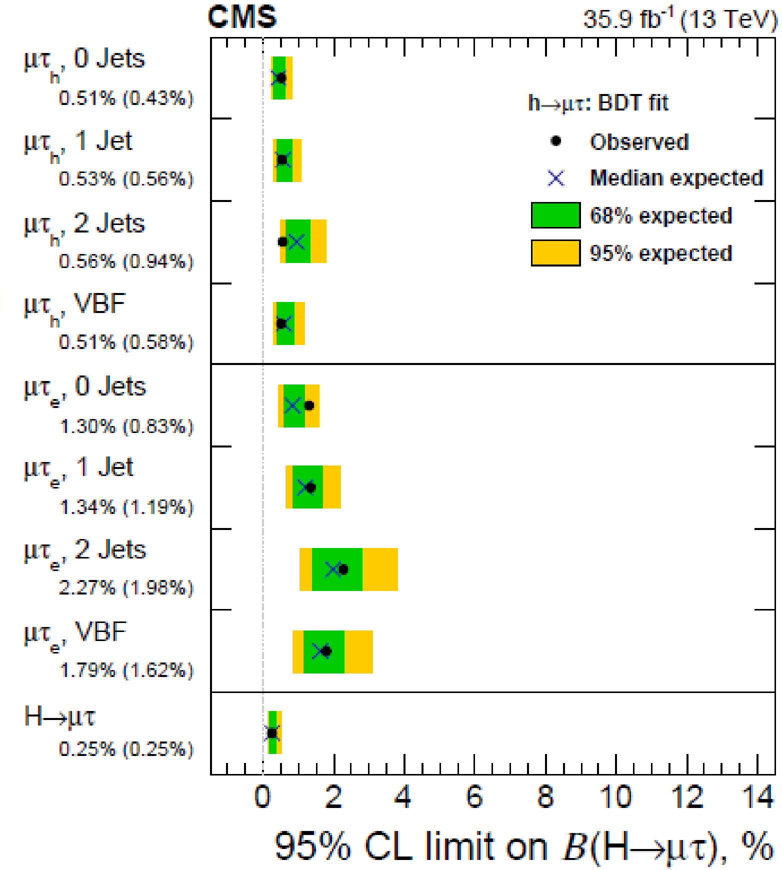
Higgs Flavor Violating Coupling

CMS-HIG-17-001
arXiv:1712.07173



	Observed (expected) limits (%)	
	BDT fit	M_{col} fit
$H \to \mu\tau$	<0.25 $(0.25)\%$	<0.51 (0.49) %
$H \to e\tau$	<0.61 (0.37) %	<0.72 (0.56) %

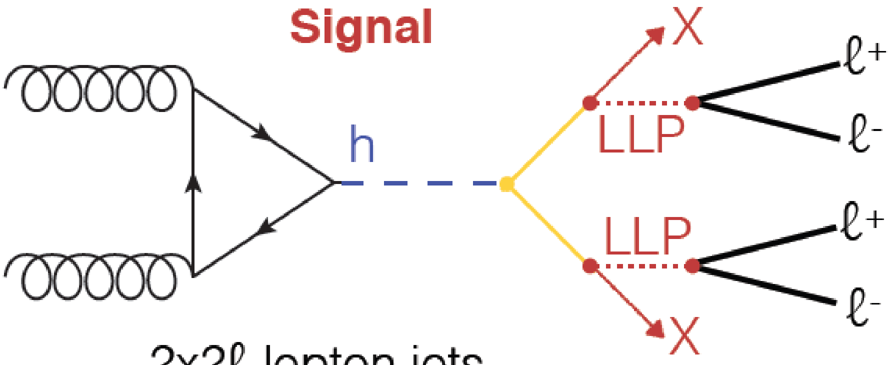




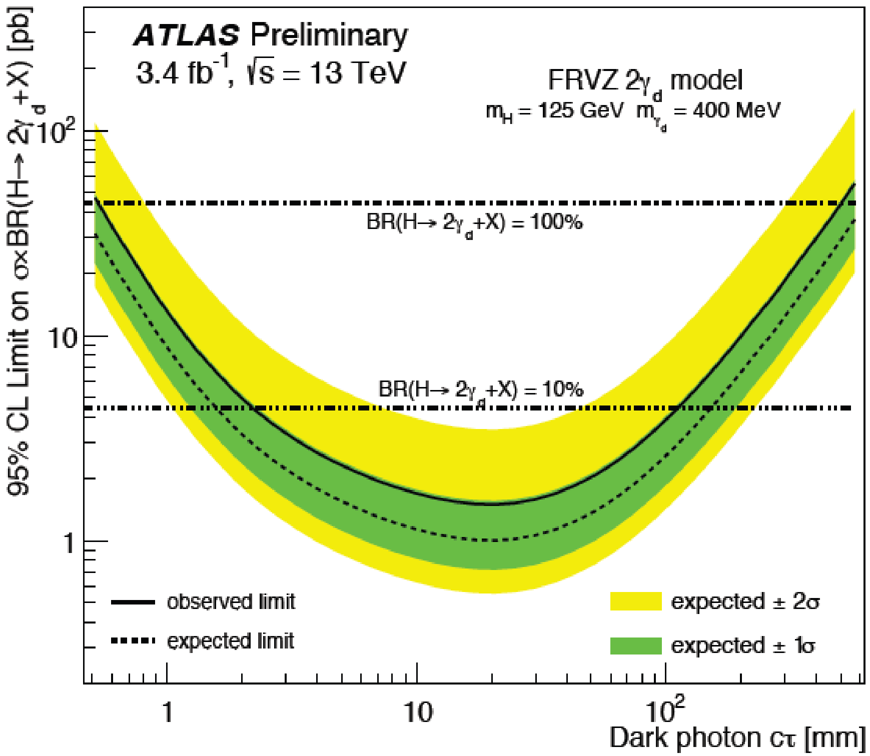
Searches for long-lived decay

ATLAS-CONF-2016-042

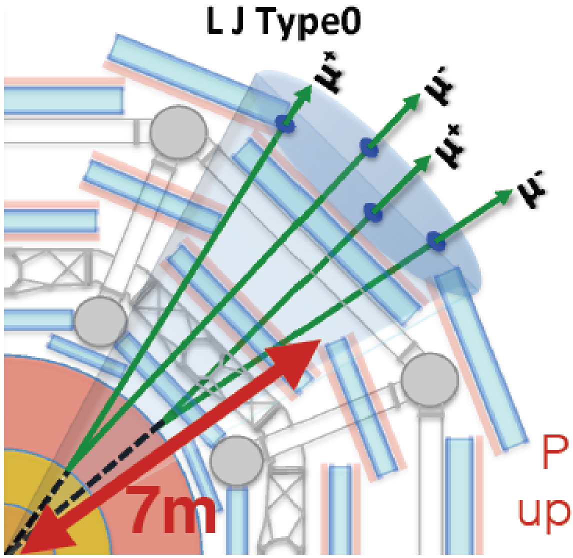
Many analyses targeting different signatures and lifetimes



2x2ℓ lepton jets
Nx2ℓ (4x2ℓ…) also possible



Sensitive to several models, for example dark photons: $h \rightarrow 2\gamma_d + X$ or $4\gamma_d + X$



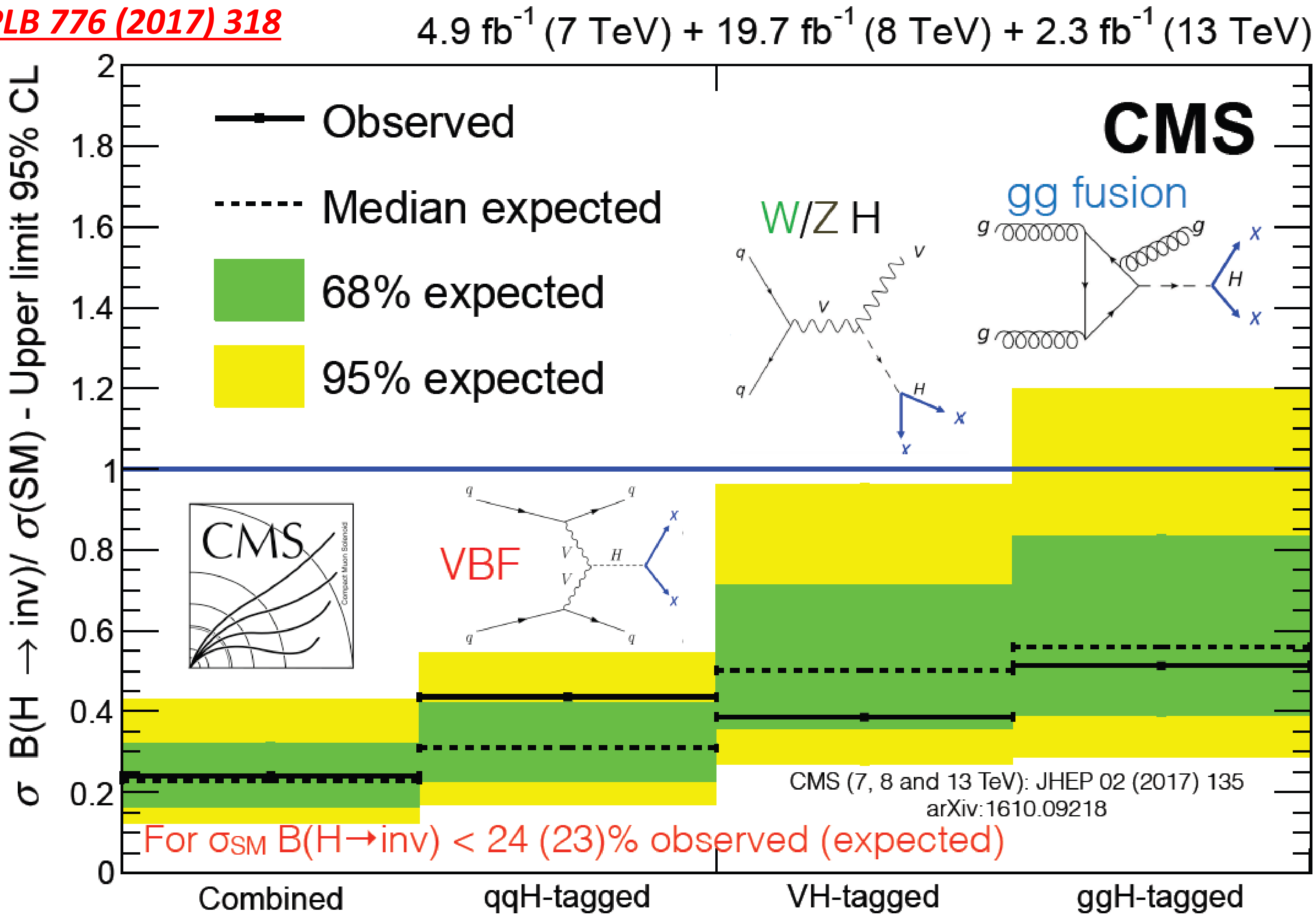
Probe displacements up to 7m away (muons)

Analyses at 8 TeV available for displaced decays in tracker, calorimeter and muon systems

Higgs Invisible Decays

similar results from ATLAS
JHEP 11 (2015) 206 arXiv:1509.00672

PLB 776 (2017) 318



CMS (7, 8 and 13 TeV): JHEP 02 (2017) 135
arXiv:1610.09218

For σ_{SM} B(H→inv) < 24 (23)% observed (expected)

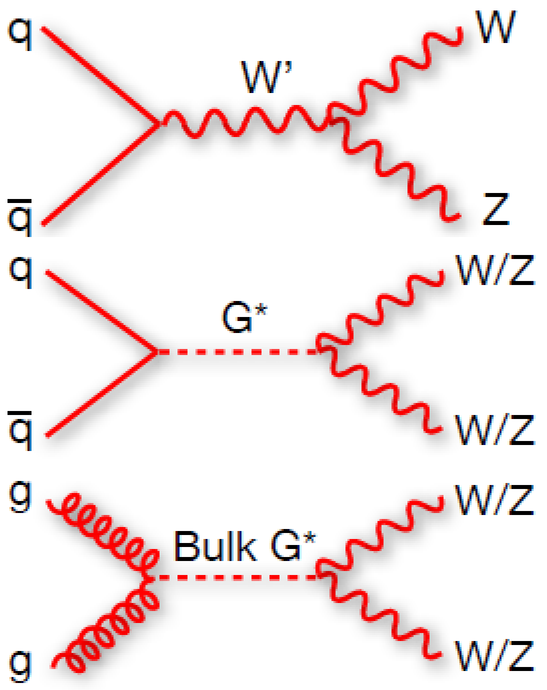
LHC runs extremely well
Results are consistent with SM
More results are coming
Please stay tuned

Thanks !

Backup Slides

A bit about the models...

Slide borrowed from V. Cavaliere...



Charged (WZ)

Sequential Standard Model (W', spin-1)

- Trilinear W'WZ coupling set by Extended Gauge Model: ~ $(M_W/M_{W'})^2$

Neutral (WW,ZZ,HH)

Randall-Sundrum graviton (RS G*, spin-2)

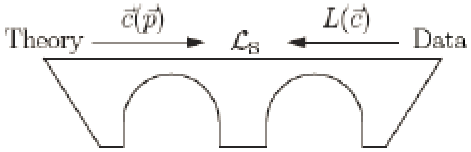
- Traditional benchmark model with extra dimensions

Bulk RS graviton (Bulk G*, spin-2)

- Graviton couples more with heavy particles (W, Z, t)
- Smaller σ, but larger branching ratio to WW, ZZ

Minimal Walking Technicolor (R_1,R_2, charged and neutral)

- Technicolor with minimal ingredients, can decay to ZH and WH



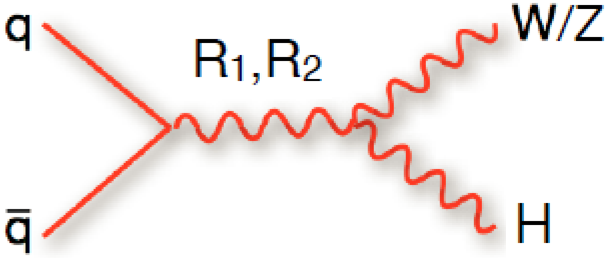
HVT (Simplified Lagrangian)

Model A

- weakly coupled vector resonances from extension of the gauge group

Model B

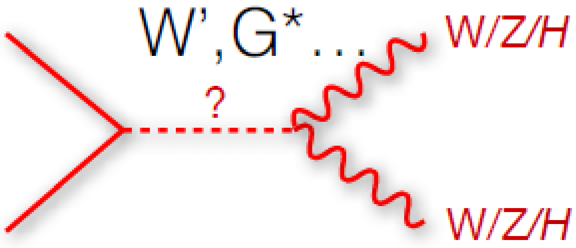
- produced in a strong scenario e.g. composite higgs model



Search for Diboson Resonance

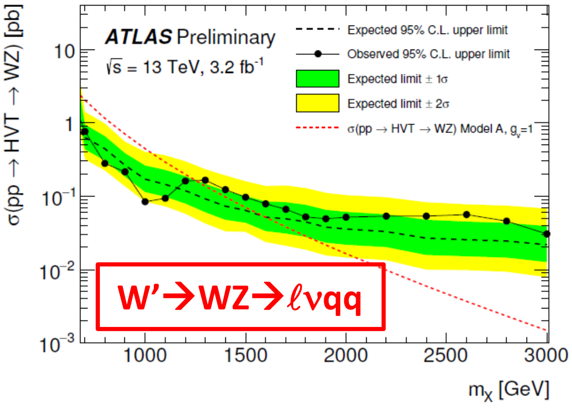
ATLAS-CONF-2015-071
ATLAS-CONF-2015-075

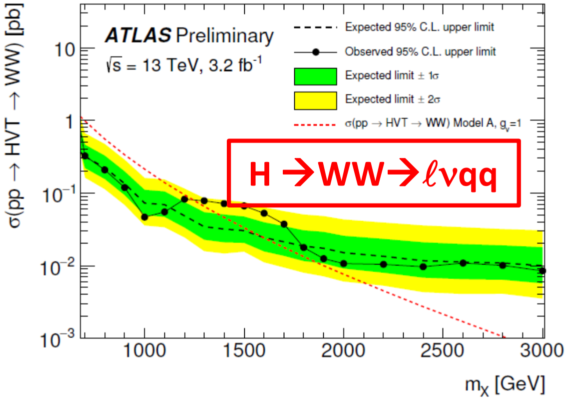
- ☐ **Search for heavy resonances in diboson final states (eg. ℓℓqq, ννqq, ℓνqq , qqqq), well-motivated extensions to the SM and has very rich phenomenology. LHC Run1 observed some excess which needs cross check using 13 TeV data at Run2**
  - ○ Heavy Vector Triplet (HVT) model A, BR(W’→ WZ) ~ 2%
  - ○ Kaluza-Klein (KK) modes in Randall-Sundrum(RS) graviton model, BR(G*→ZZ)~ 8-10%
  - ○ Generator: MadGraph5 2.2.2 (NNPDF23LO)

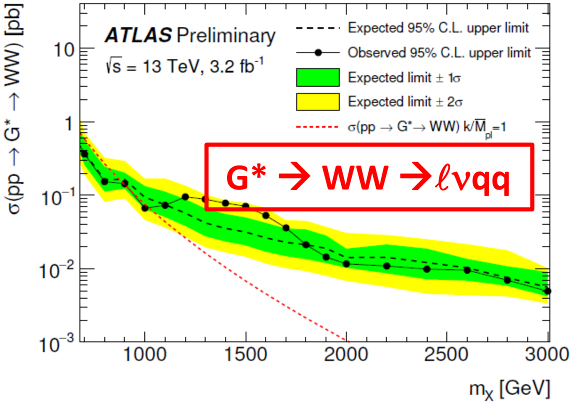


- ☐ **Two heavy Higgs-like boson hypotheses are tested (H→WW→ ℓνqq):**
  - ☐ Narrow Width Assumption (NWA, SM Higgs width of 4MeV) ,
  - ☐ Large Width Assumption (LWA, 5-15% of heavy Higgs mass)

- ☐ **No evidence is observed, masses below 1060 GeV and 1250 GeV are excluded at 95% CL for spin-2 RS G*→WW and H→WW. Upper limits on σ × BR(H→WW) with NWA/LWA ∊ [0.02, 0.3]pb**

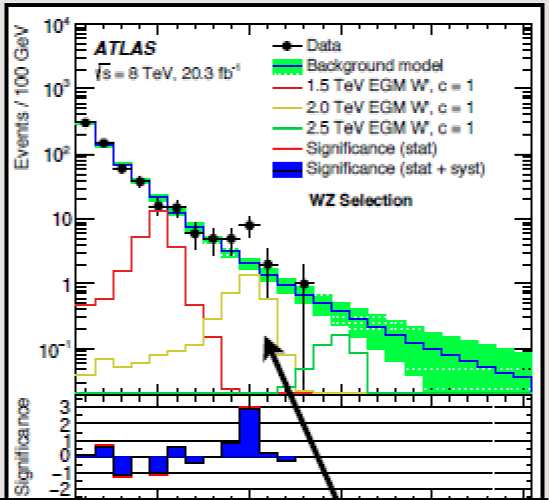




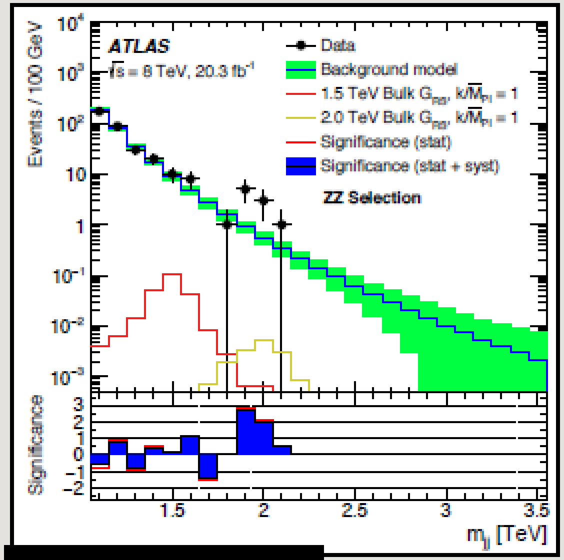


ZZ & WZ & WW → *qqqq*

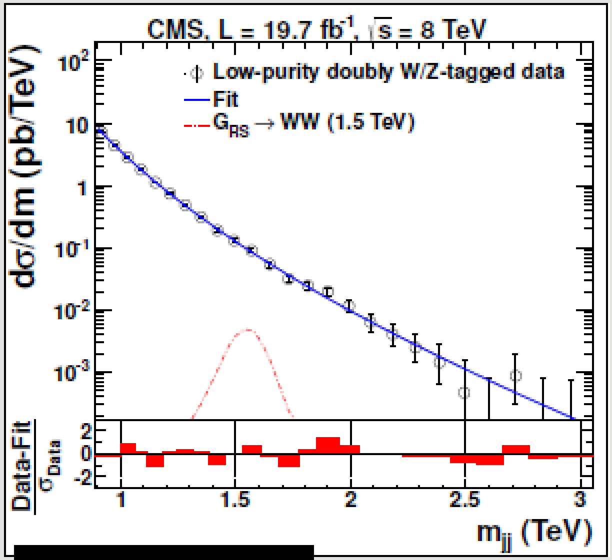
Dijet boosted final state:
Identification of di-boson state is
through the use of tagging techniques



3.4σ *local excess in WZ channel (2.5σ global)!*



arxiv.1506.00962



arxiv.1405.1994

ATLAS

CMS

Dedicated selection for all 3 channels based on W/Z jet mass requirements (26 GeV windows), implying **statistical overlap** between channels

2 large **CA** R=1.2 jets with n_{trk} < 30 are required in the events, satisfying boson tagging requirements (grooming & filtering). Extra topology requirements are used to reduce QCD backgrounds

Require 2 **CA** R=0.8 jets in the events along with topology requirements to reduce backgrounds

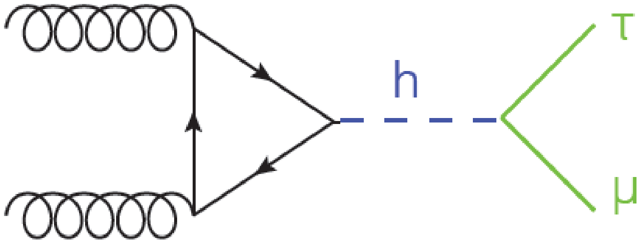
Jets are W/Z-tagged based on a combination of pruned mass and subjettiness requirements Separate events into 1/2 tag category, and use same **HP/LP** classification as in the *llqq* analysis

Searches for long-lived decay

CMS-EXO-2016-003
arXiv:1711.09120

Higgs Flavor Violating Coupling

Signal

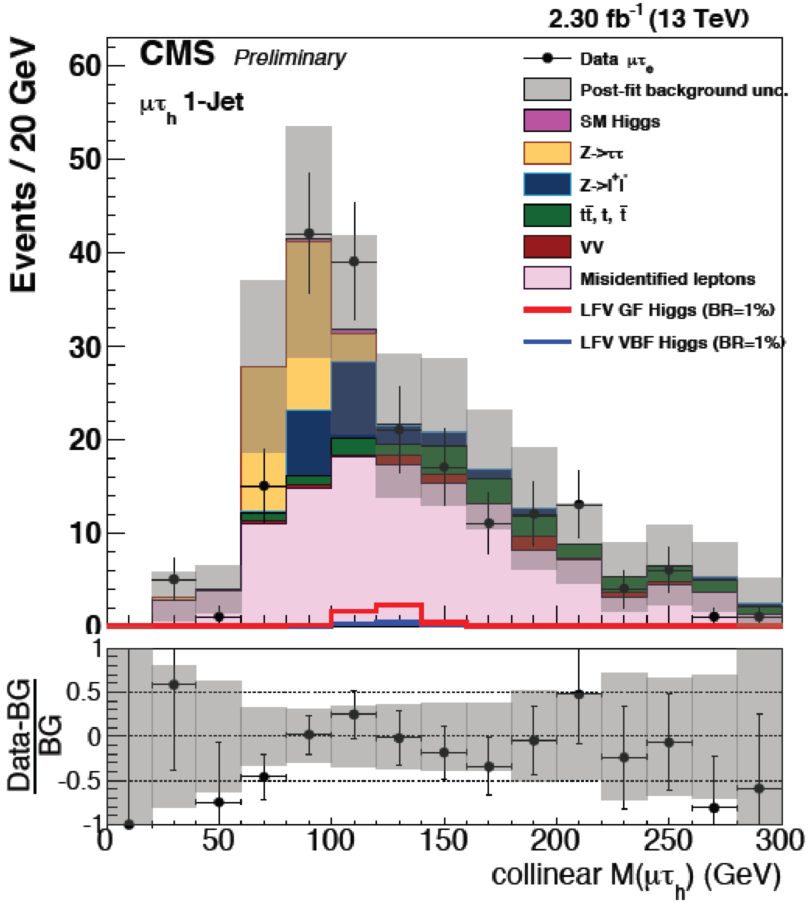


see JHEP 03 (2013) 26. arXiv: 1209.1397

2 channels ($\ell\tau_{\ell'}$, $\ell\tau_{had}$)
and 3 categories (0-1-2 Jets)

Large backgrounds
Template fits to the collinear mass distribution

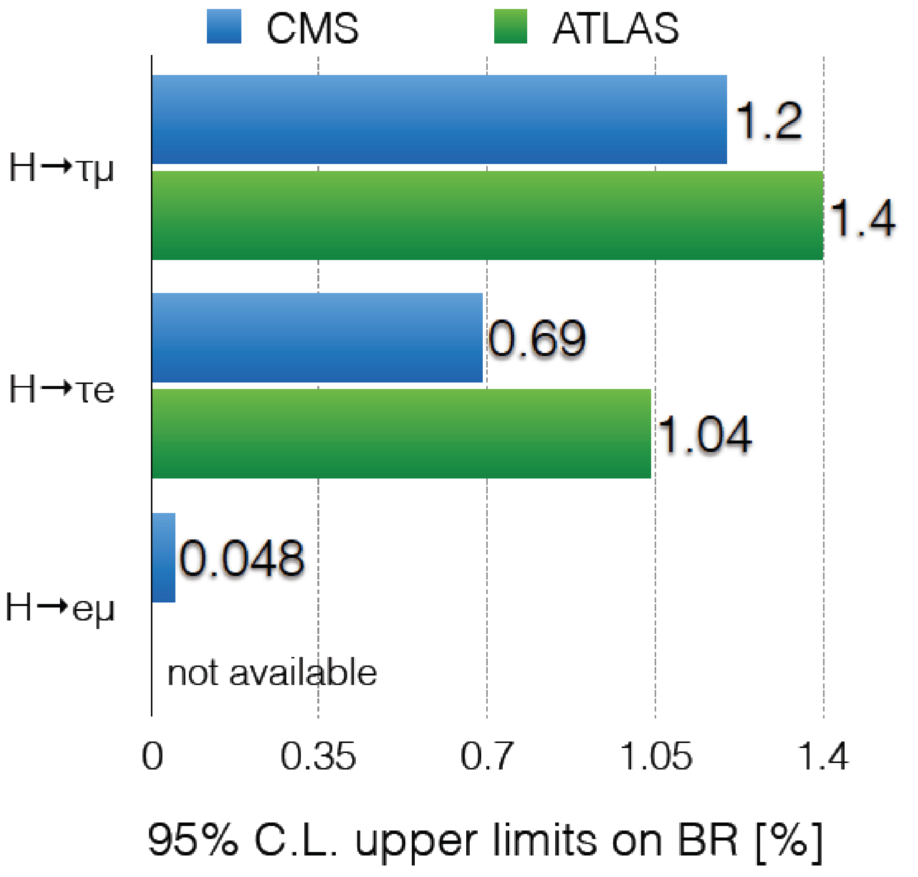
CMS (13 TeV): CMS-PAS-HIG-16-005
ATLAS (8 TeV): JHEP 11 (2015) 211 arXiv:1508.03372



13 TeV: Br(H→μτ)<1.20% (1.62% expected)

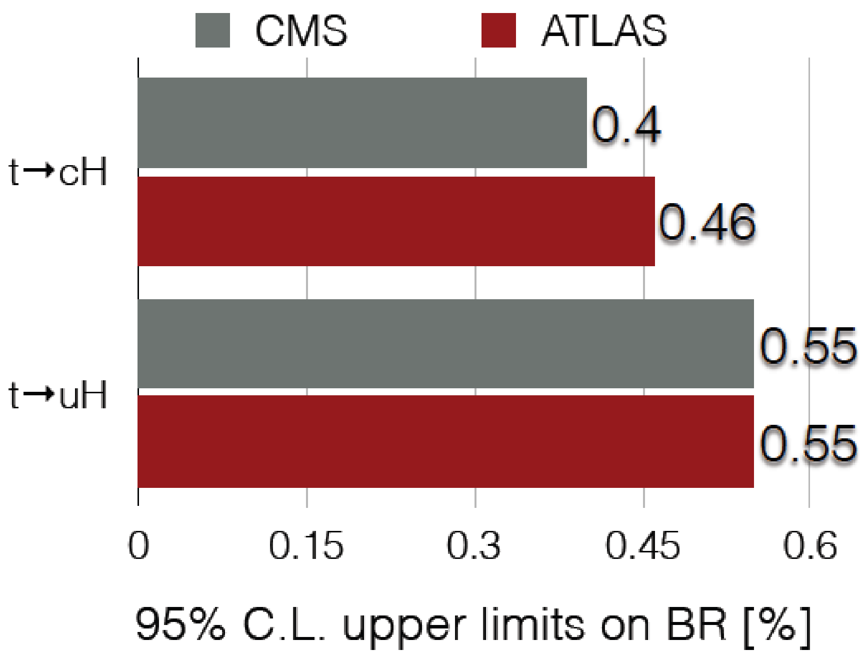
Higgs Flavor Violating Coupling

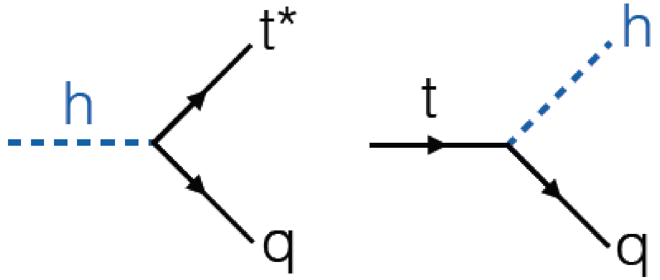
Lepton Couplings



CMS arXiv:1502.07400, arXiv:1607.03561, CMS-PAS-HIG-16-005
ATLAS arXiv:1508.03372, arXiv:1601.03567, arXiv:1604.07737
CMS arXiv:1410.2751, arXiv:1610.04857
ATLAS arXiv:1403.6293, arXiv:1509.06047

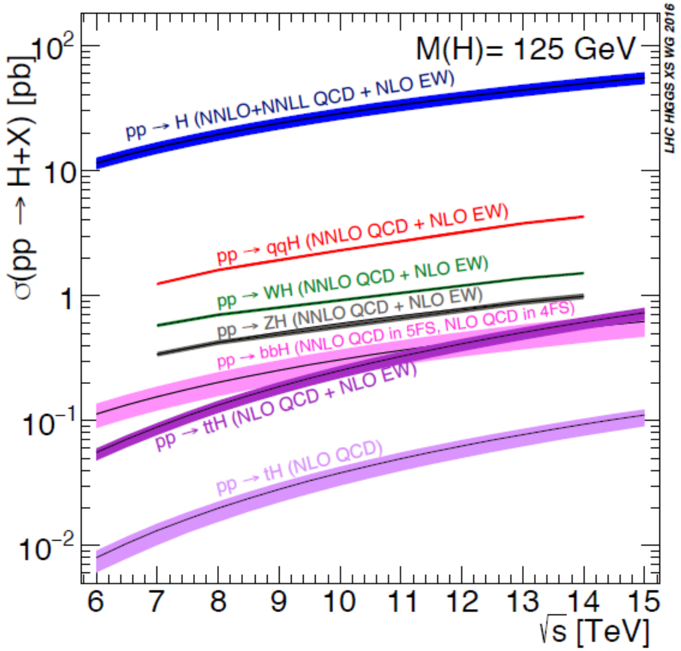
Quark Couplings

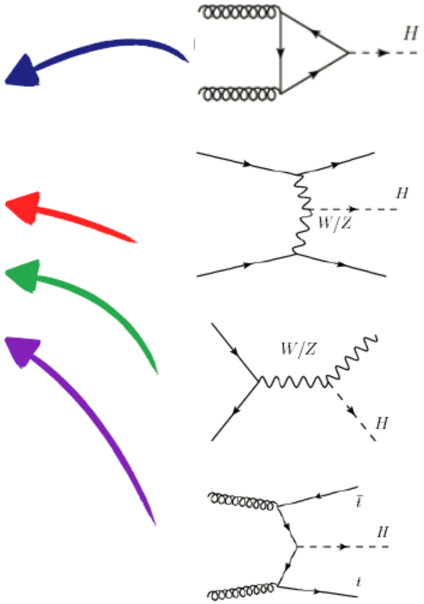




Both are sensitive to $|Y_{tq}|^2+|Y_{qt}|^2$

希格斯粒子的产生机制和衰变





@13TeV ggH 87%
m_H=125 GeV

(N3LO QCD + NLO EW)

@13TeV VBF 7%
m_H=125 GeV

@13TeV VH 4%
m_H=125 GeV

(NNLO QCD + NLO EW)

@13TeV ttH/bbH 2%
m_H=125 GeV

(NLO QCD + NLO EW)

- ➔ **ggH, ttH, bbH – Yukawa coupling**
- ➔ **VBF, VH – Gauge coupling**

Production cross section

@m_H=125 GeV

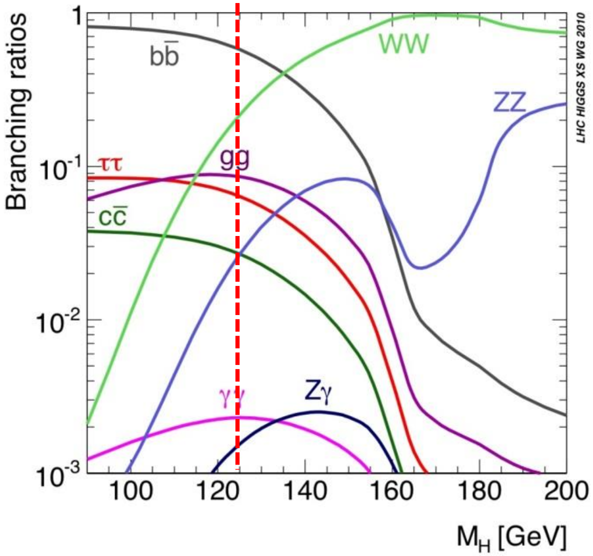
19.3 pb @7 TeV

24.5 pb @8 TeV

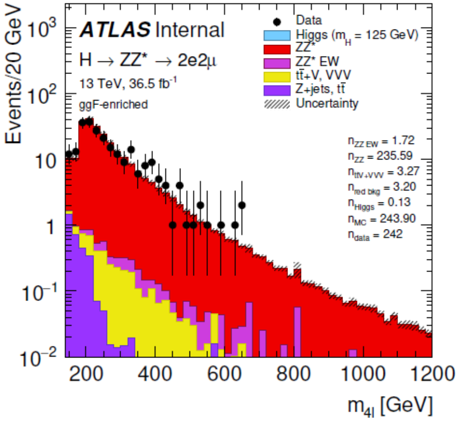
55.7 pb @13 TeV

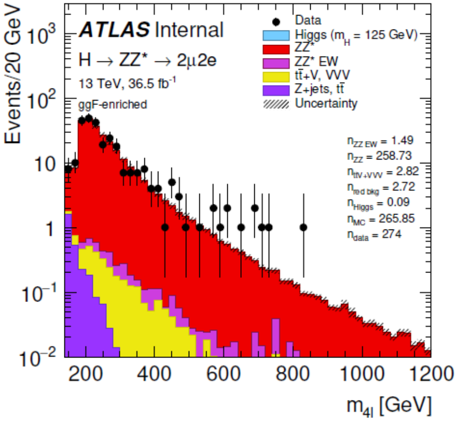
62.7 pb @14 TeV

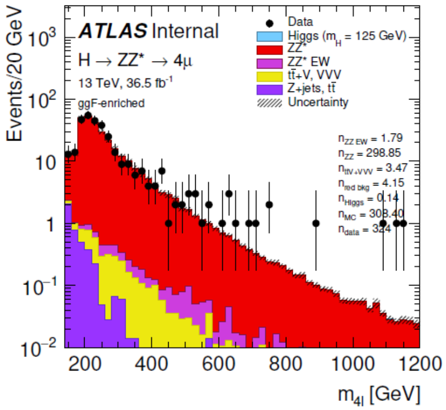
Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

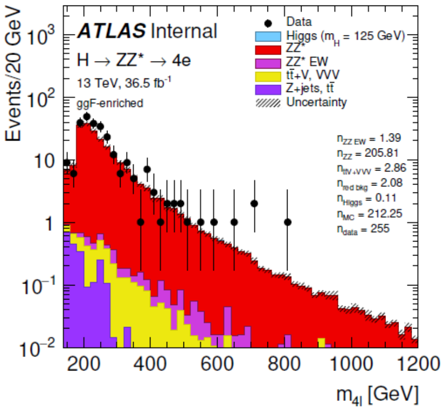


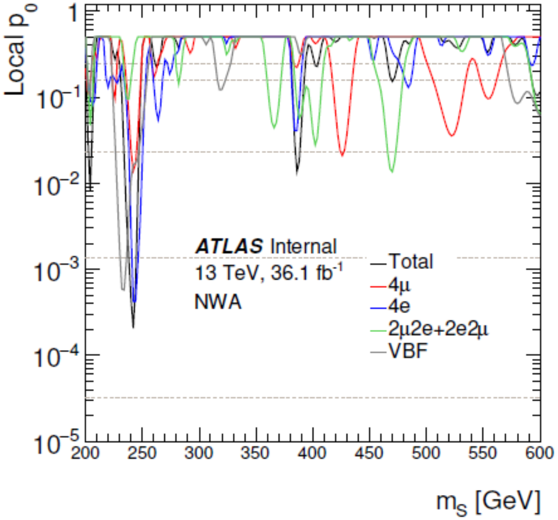
Search for heavy Higgs→ZZ*→4l

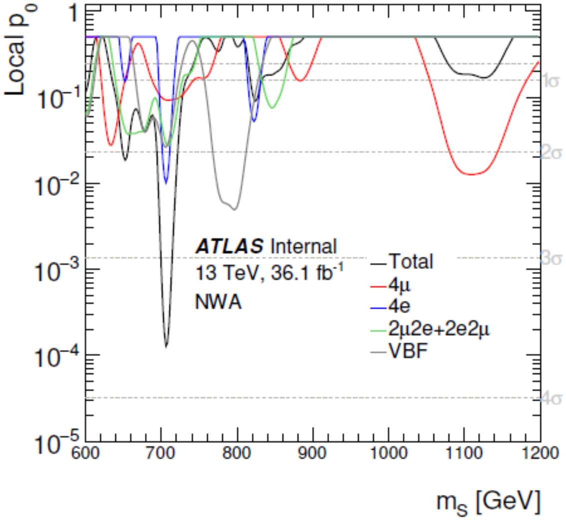


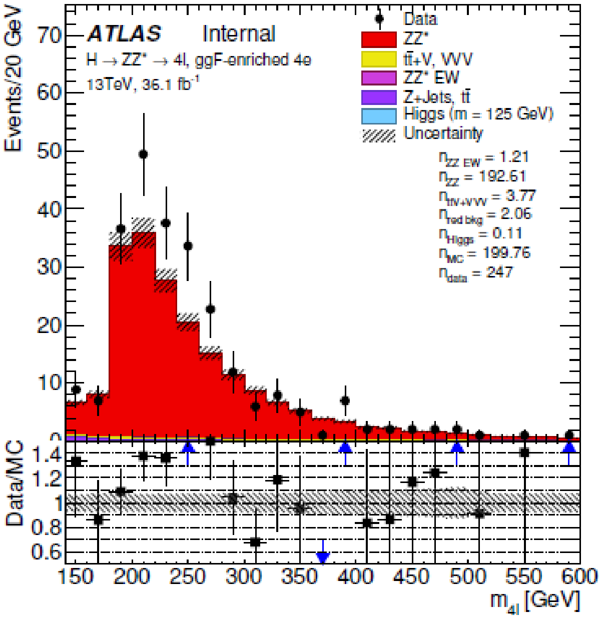








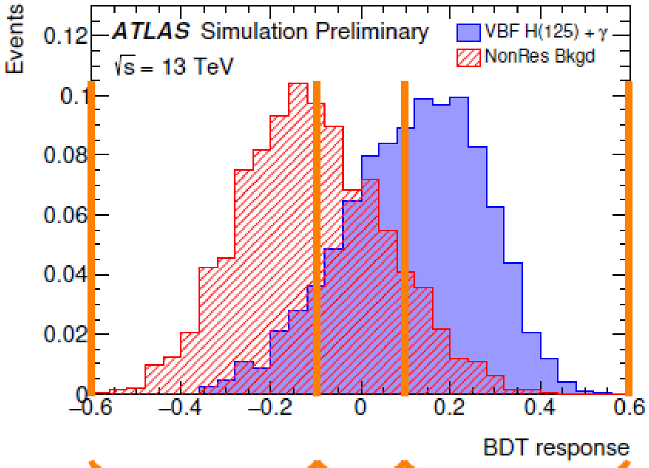




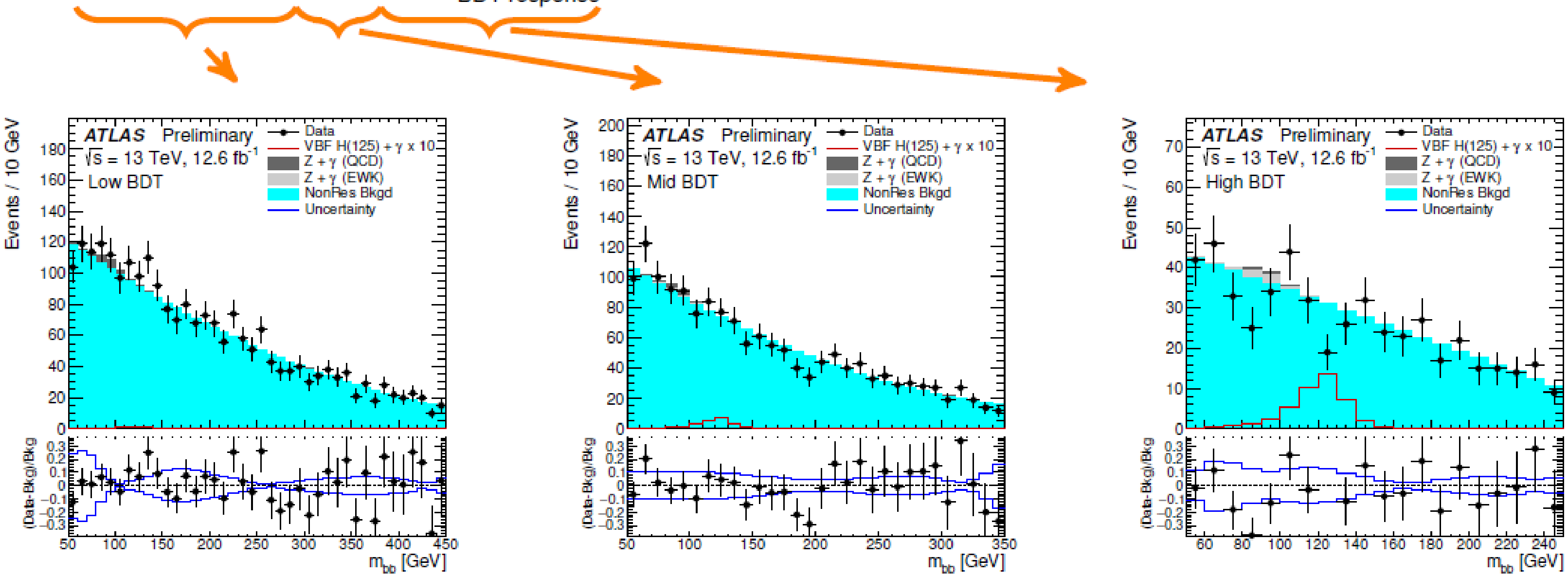
Excess at 242 GeV mainly driven by 4e category

mass	4μ	$4e$	$2\mu 2e$	VBF	Combined
242 Gev	2.20σ	$3.34\ \sigma$	0.63σ	2.13σ	3.53σ
706 Gev	1.33σ	$2.32\ \sigma$	1.93σ	1.94σ	3.66σ

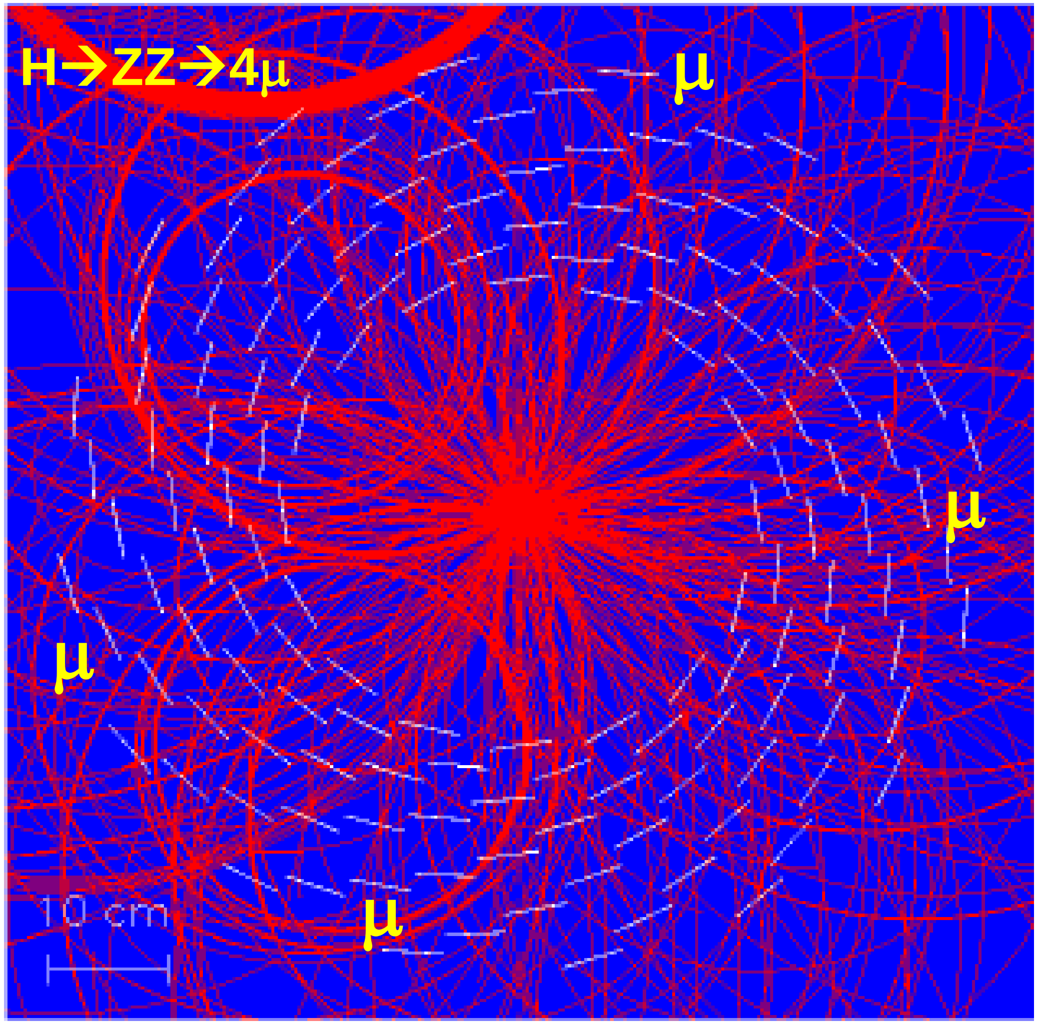
VBF H + γ



- BDT used to define categories.
- BDT inputs uncorrelated with $m_{b\bar{b}}$.
- Signal strength μ computed in unbinned likelihood fit as a function of $m_{b\bar{b}}$.



大量的事例堆积对探测器信号读出、粒子重建和鉴别造成巨大的挑战！



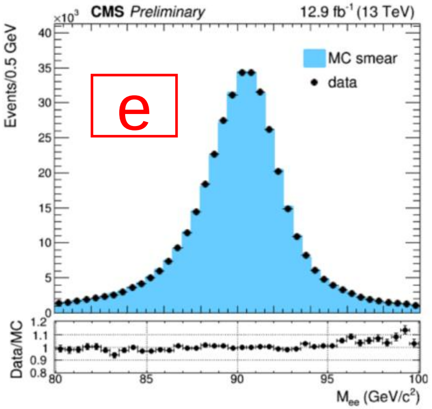
采用多变量

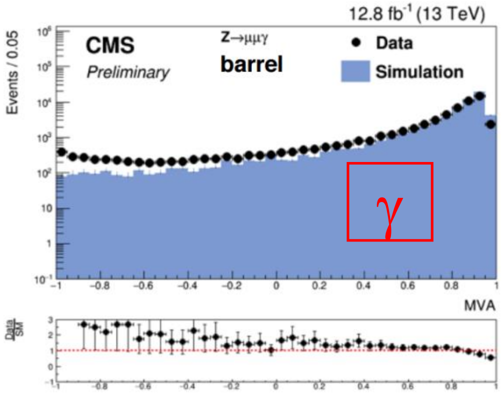
MVA-BDT

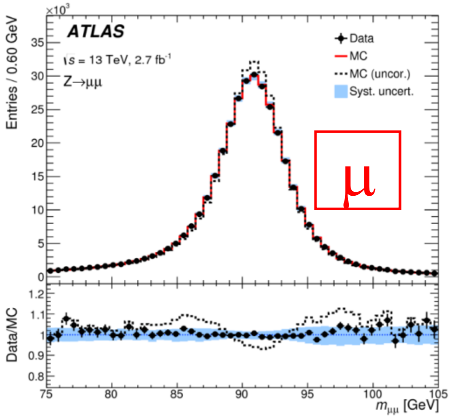
方法提高粒子鉴别效率和事例识别

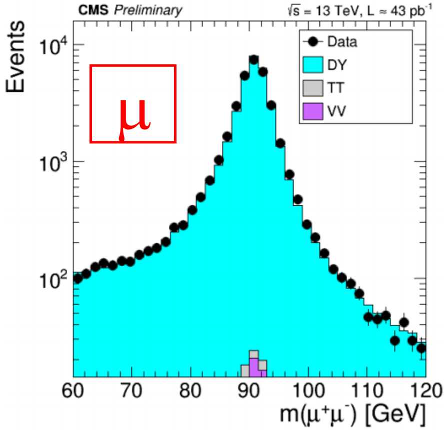
探测器性能-粒子鉴别

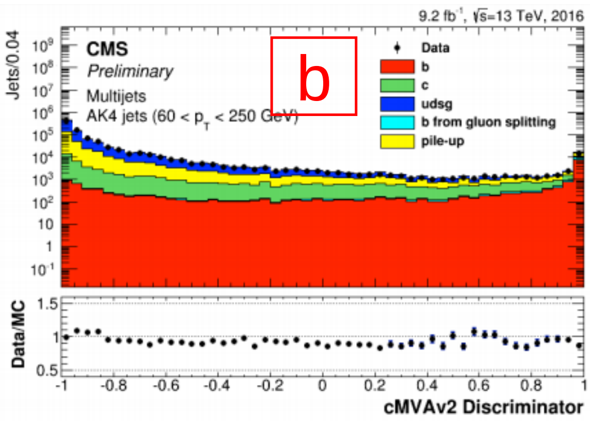
ATLAS-CONF-2015-041, ATL-PHYS-PUB-2016-015
Eur. Phys. J. C (2016) 76:292
CMS-DP-2015-015, CMS-DP-2016-015/042/049

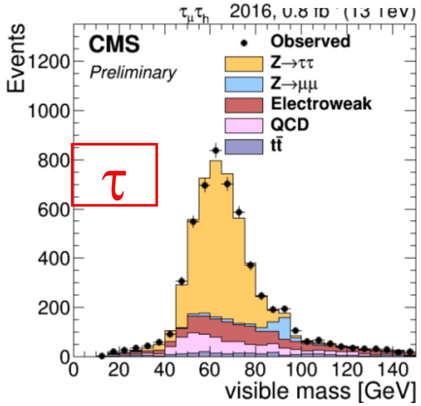




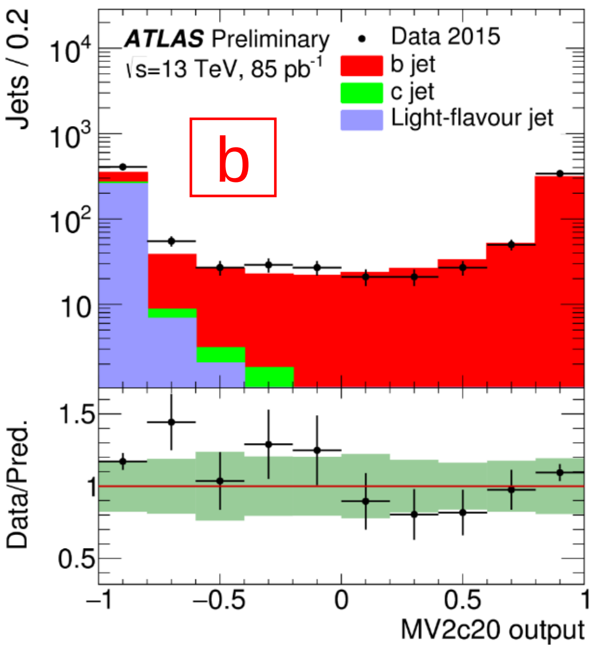


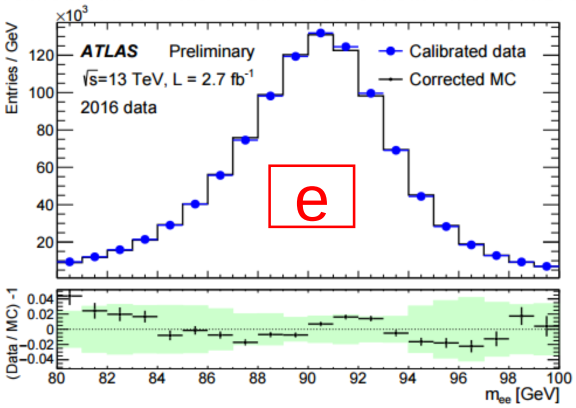


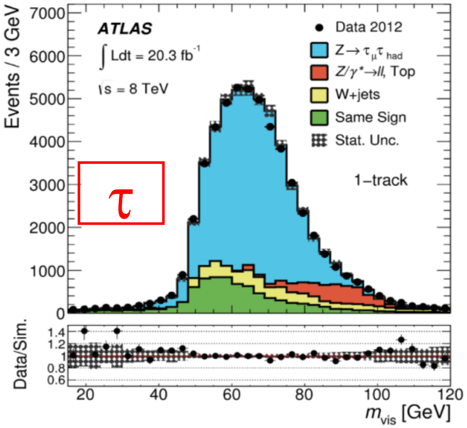




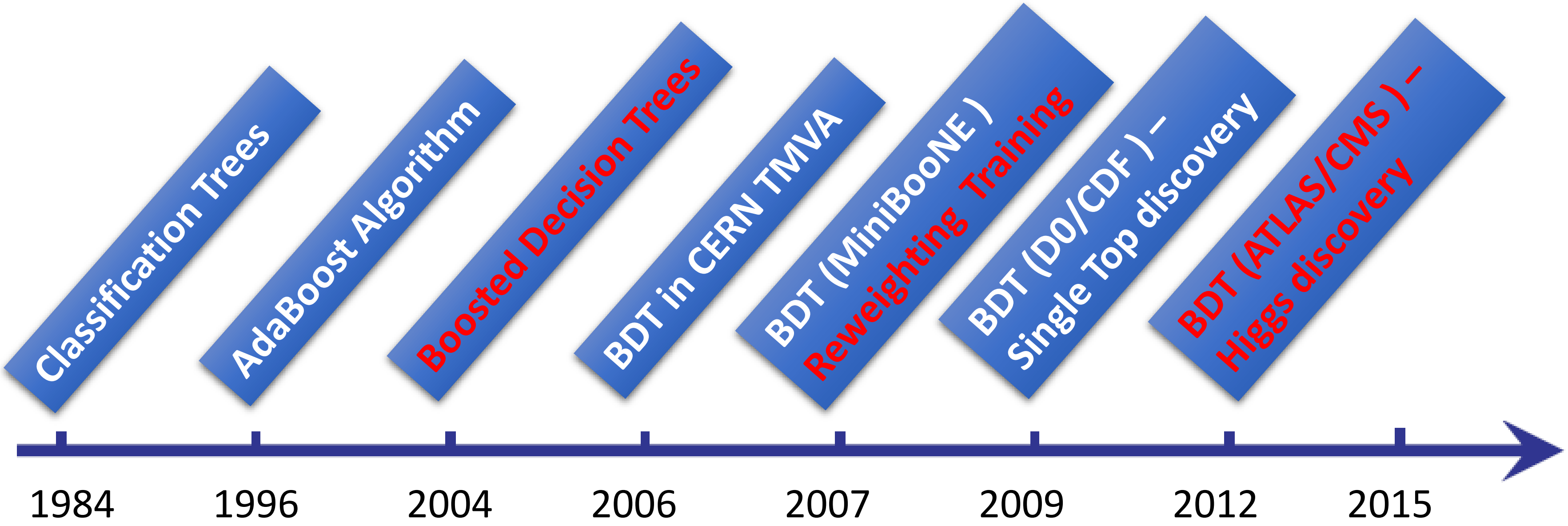
e, γ, τ, b粒子的鉴别采用多变量MVA-BDT方法。







Boosted Decision Trees (BDT)



➔1984. L. Breiman, J.H. Friedman, R.A. Olshen, C.J.Stone, “Classification and Regression Trees”, Wadsworth, 1984. **(首次提出 Classification Trees概念)**

➔ 1996. Ref: Y. Freund, R.E. Schapire, “Experiments with a new boosting algorithm”, Proceedings of COLT, ACM Press, New York, 1996, pp. 209-217. **(首次提出AdaBoost算法)**

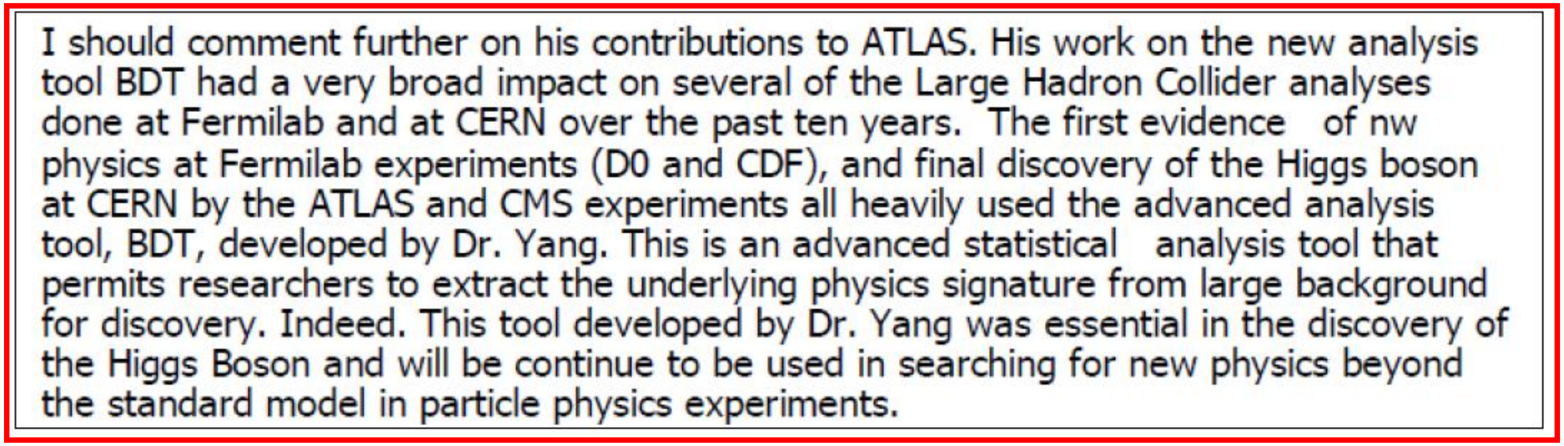
➔2004. 本人和Byron P. Roe, Ji Zhu首次把Boosting算法和Decision Trees结合，提出Boosted Decision Trees (BDT)，作为通讯作者发表4篇论文，为BDT应用于粒子物理实验数据分析做出了开创性的贡献。BDT广泛应用于希格斯粒子的发现和性质测量及新物理寻找等。

➔应用于ATLAS, CMS, LHCb, MiniBooNE, CDF, D0, BarBar, BESIII, AMS, IceCube, PandaX 等等.

Boosted Decision Trees (BDT)

- ➔ **2004/8/30, arXiv:physics/0408124, [Nucl.Instrum.Meth. A543 (2005) 577-584]**
  Byron P. Roe, **Hai-Jun Yang*,** Ji Zhu, Yong Liu, Ion Stancu, Gordon McGregor,
  "Boosted Decision Trees as an Alternative to Artificial Neural Networks for Particle Identification"
- ➔ **2005/8/8, arXiv:physics/0508045, [Nucl.Instrum.Meth. A555 (2005) 370-385]**
  Hai-Jun.Yang*, Byron P. Roe, Ji Zhu,
  "Studies of Boosted Decision Trees for MiniBooNE Particle Identification"
- ➔ **2006/10/31, arXiv:physics/0610276, [Nucl. Instrum. & Meth. A 574 (2007) 342-349]**
  Hai-Jun Yang*, Byron P. Roe, Ji Zhu,
  "Studies of Stability and Robustness for Artificial Neural Networks and Boosted Decision Trees"
- ➔ **2007/8/27, arXiv:0708.3635, [JINST3:P04004,2008]**
  Hai-Jun Yang*, Tiesheng Dai, Alan Wilson, Zhengguo Zhao, Bing Zhou,
  "A Multivariate Training Technique with Event Reweighting"

➔ **美国物理学会会长Homer A. Neal 教授对此高度评价**



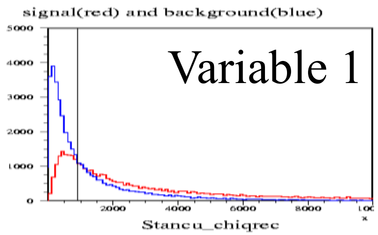
I should comment further on his contributions to ATLAS. His work on the new analysis tool BDT had a very broad impact on several of the Large Hadron Collider analyses done at Fermilab and at CERN over the past ten years. The first evidence of nw physics at Fermilab experiments (D0 and CDF), and final discovery of the Higgs boson at CERN by the ATLAS and CMS experiments all heavily used the advanced analysis tool, BDT, developed by Dr. Yang. This is an advanced statistical analysis tool that permits researchers to extract the underlying physics signature from large background for discovery. Indeed. This tool developed by Dr. Yang was essential in the discovery of the Higgs Boson and will be continue to be used in searching for new physics beyond the standard model in particle physics experiments.

A Decision Tree

(sequential series of cuts based on MC study)

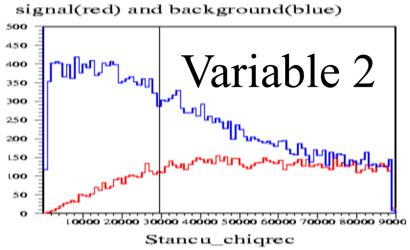
(N_{signal}/N_{bkgd})

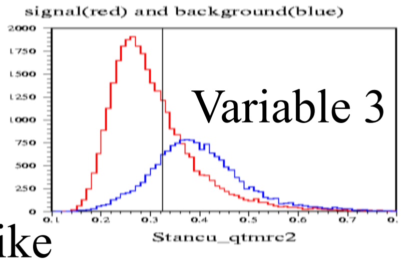
40000/40000



bkgd-like

signal-like





9755/23695

30,245/16,305

bkgd-like

signal-like

signal-like

bkgd-like

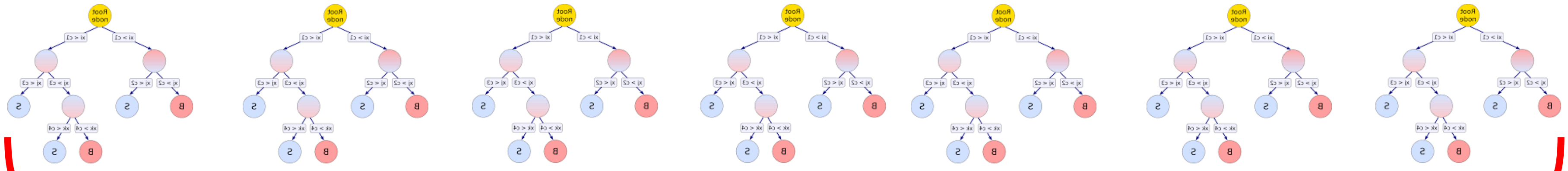
1906/16828

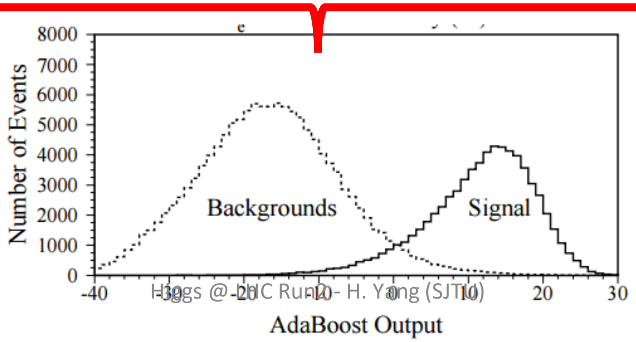
7849/6867

20455/3417

9790/12888

通过Boosting 算法不断提高误判事例的权重，产生一系列Decision Trees



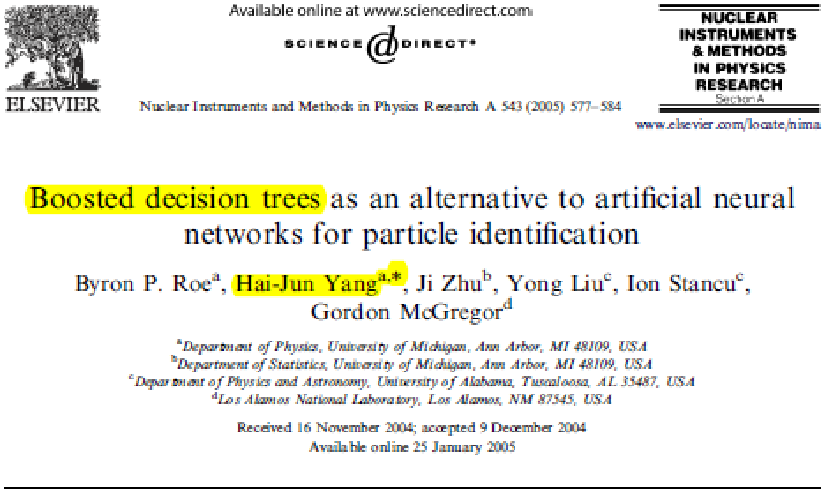


把每个事例在所有Decision Trees获得的积分累加，通过“Majority vote”方法提高性能和稳定性。

通过Boosting不断提高误判事例的权重，使得这些难以区分的事例在后续的Decision Trees获得的正确区分，提高效率。

Boosted Decision Trees (BDT)

CERN TMVA 软件包收入，http://tmva.sourceforge.net/



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Boosted decision trees as an alternative to artificial neural networks for particle identification

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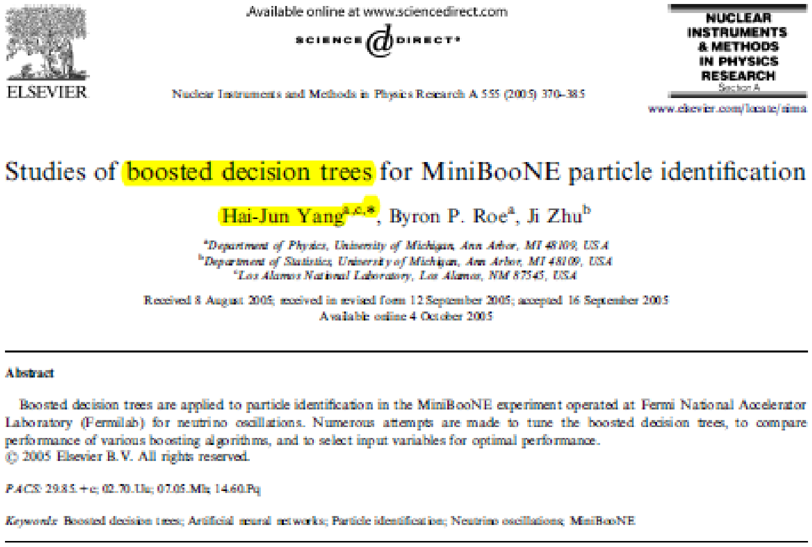

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Studies of boosted decision trees for MiniBooNE particle identification

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Abstract

Boosted decision trees are applied to particle identification in the MiniBooNE experiment operated at Fermi National Accelerator Laboratory (Fermilab) for neutrino oscillations. Numerous attempts are made to tune the boosted decision trees, to compare performance of various boosting algorithms, and to select input variables for optimal performance.
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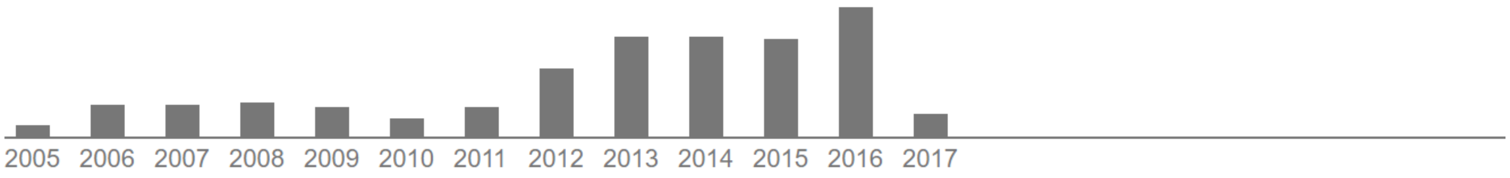
PACS: 29.85.+c; 02.70.Uu; 07.05.Mh; 14.60.Pq

Keywords: Boosted decision trees; Artificial neural networks; Particle identification; Neutrino oscillations; MiniBooNE

Total citations Cited by 422



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BP Roe, HJ Yang, J Zhu, Y Liu, I Stancu, G McGregor - Nuclear Instruments and Methods in Physics Research …, 2005
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experiment which will imply new physics beyond

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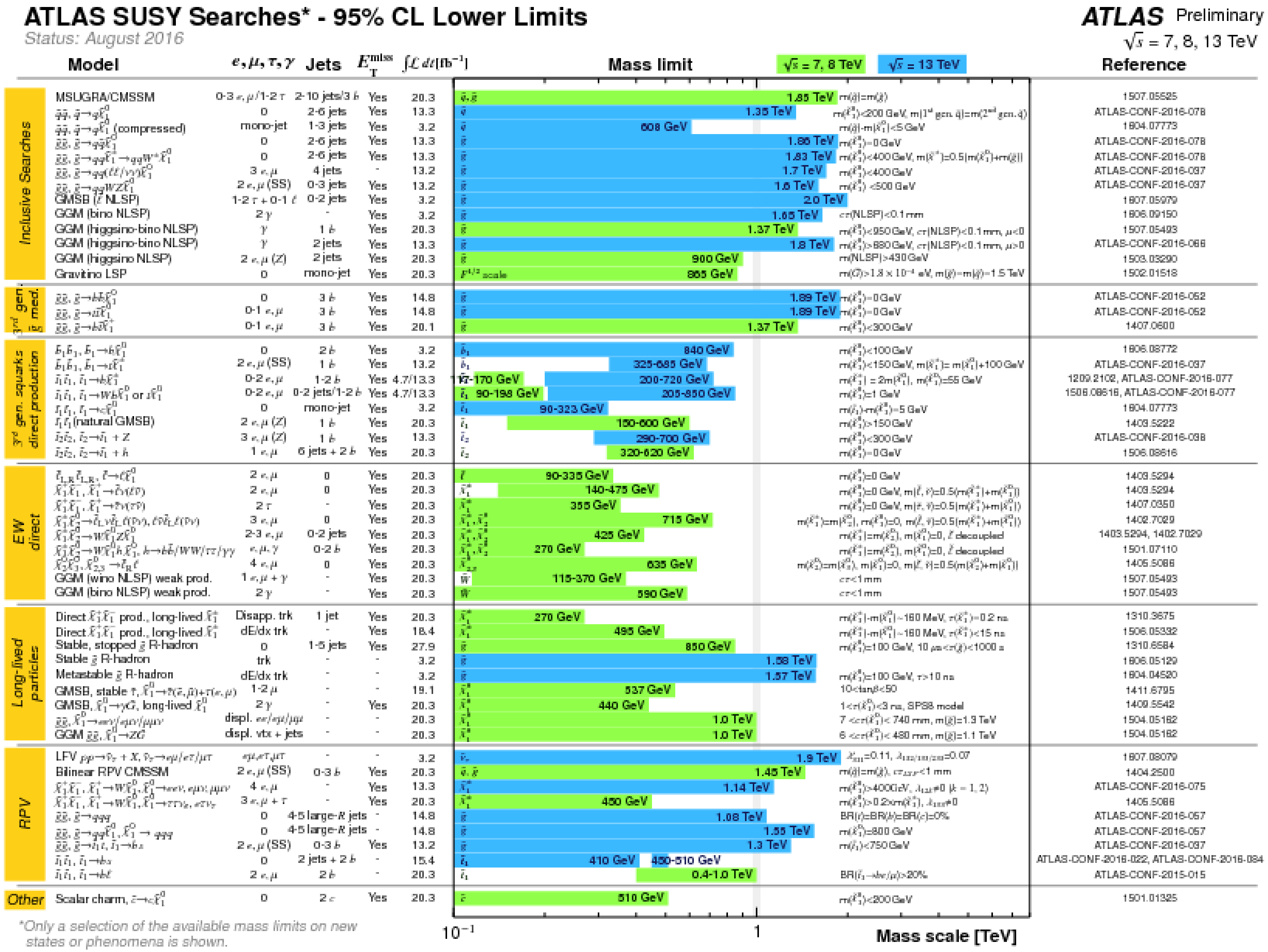
清华：王义

ATLAS SUSY Searches



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV
🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.85 TeV 🟩	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{q}$ 1.35 TeV 🟦	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV 🟦	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.86 TeV 🟦	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.83 TeV 🟦	$m(\tilde{\chi}_1^0)$<400 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV 🟦	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV 🟦	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV 🟦		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV 🟦	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV 🟩	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV 🟦	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV 🟩	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV 🟩	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV 🟦	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV 🟦	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV 🟩	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV 🟦	$m(\tilde{\chi}_1^0)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$ 325-685 GeV 🟦	$m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV 🟩 200-720 GeV 🟦	$m(\tilde{\chi}_1^{\pm})=2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 90-198 GeV 🟩 205-850 GeV 🟦	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 90-323 GeV 🟦	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV 🟩	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	13.3	$\tilde{t}_2$ 290-700 GeV 🟦	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$ 320-620 GeV 🟩	$m(\tilde{\chi}_1^0)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-335 GeV 🟩	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-475 GeV 🟩	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 355 GeV 🟩	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu),\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 715 GeV 🟩	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 425 GeV 🟩	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 270 GeV 🟩	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 635 GeV 🟩	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 115-370 GeV 🟩	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV 🟩	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV 🟩	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 495 GeV 🟩	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV 🟩	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV 🟦		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV 🟦	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV 🟩	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV 🟩	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV 🟩	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV 🟩	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV 🟦	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.45 TeV 🟩	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu,e\mu\nu,\mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$ 1.14 TeV 🟦	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e,e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV 🟩	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.08 TeV 🟦	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.55 TeV 🟦	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	13.2	$\tilde{g}$ 1.3 TeV 🟦	$m(\tilde{t}_1)$<750 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 410 GeV 🟦 450-510 GeV 🟦		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV 🟩	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV 🟩	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown.

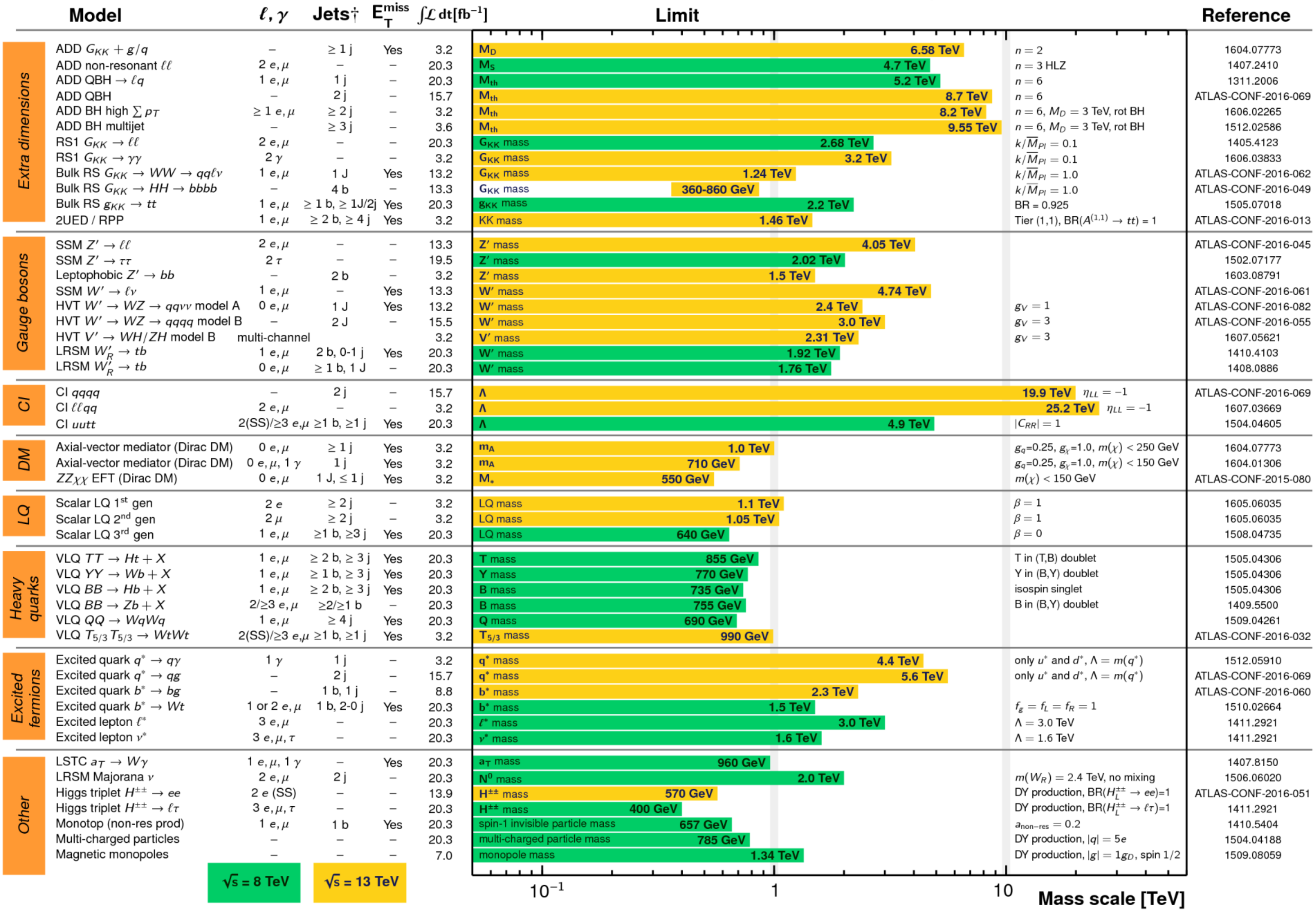
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	🟨 M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	3.2	🟨 G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	1 J	Yes	13.2	🟨 G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	4 b	–	13.3	🟨 G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, $\geq$ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	13.3	🟨 Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	🟩 Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	🟨 Z' mass 1.5 TeV		1603.08791
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	13.3	🟨 W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	🟨 W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	–	2 J	–	15.5	🟨 W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			3.2	🟨 V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \rightarrow tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	🟨 Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	🟨 Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	🟨 m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	🟨 m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
	VLQ $T_{5/3}T_{5/3} \rightarrow WtWt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	3.2	🟨 $T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	3.2	🟨 q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \rightarrow qg$	–	2 j	–	15.7	🟨 q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	8.8	🟨 b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	2 e (SS)	–	–	13.9	🟨 $H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

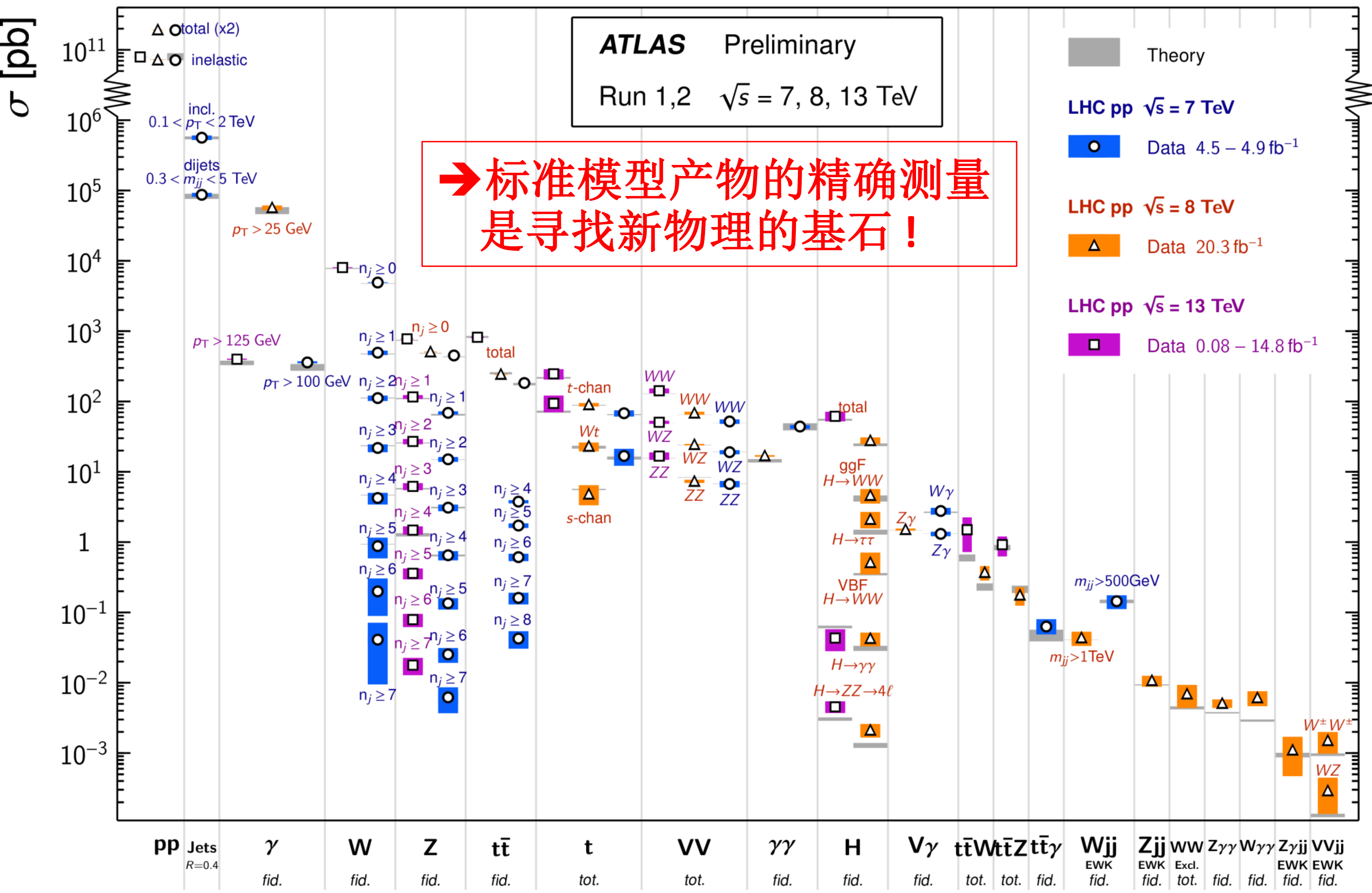
🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

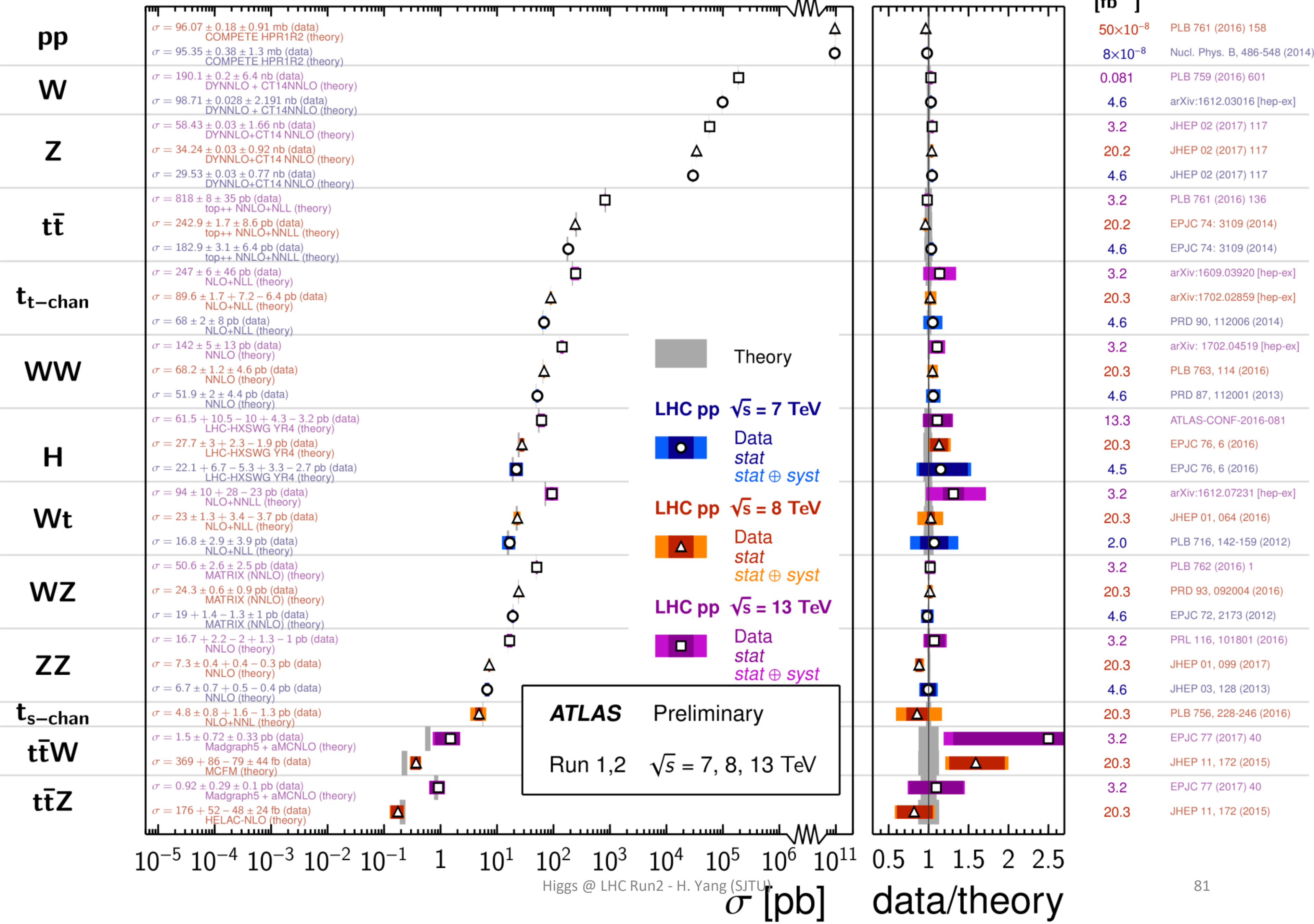
Standard Model Production Cross Section Measurements



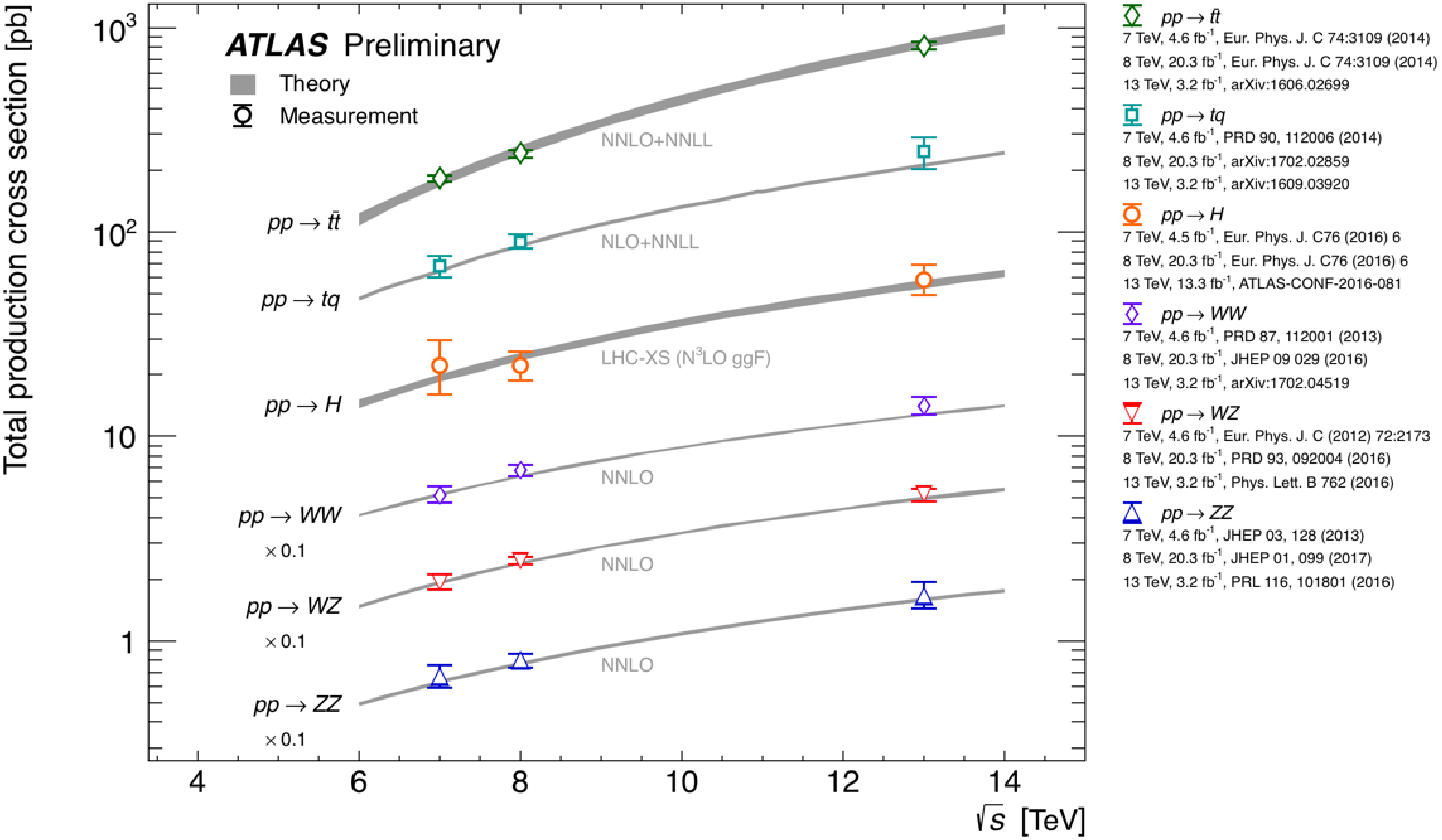
→标准模型产物的精确测量是寻找新物理的基石！

Standard Model Total Production Cross Section Measurements

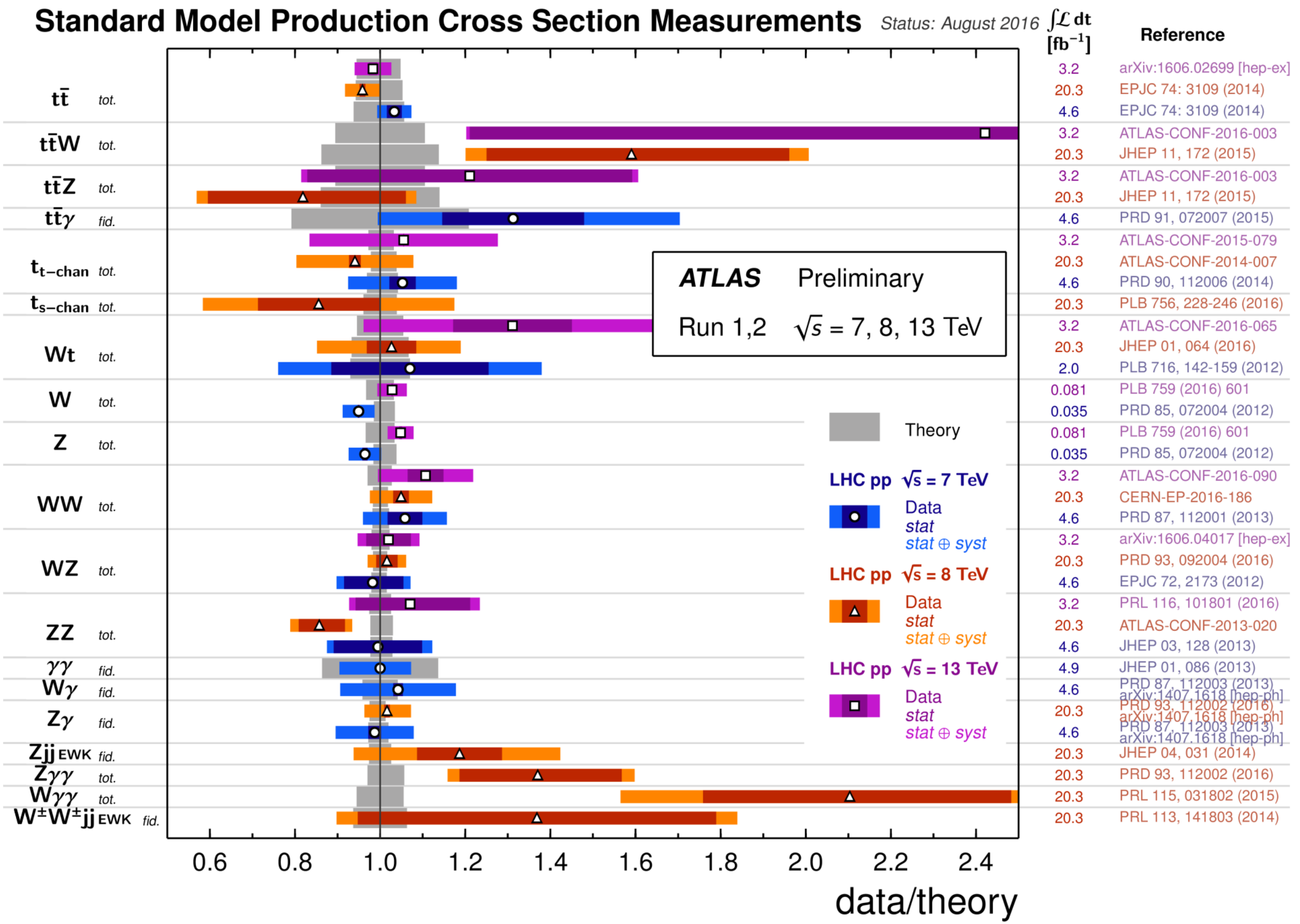
Status: March 2017



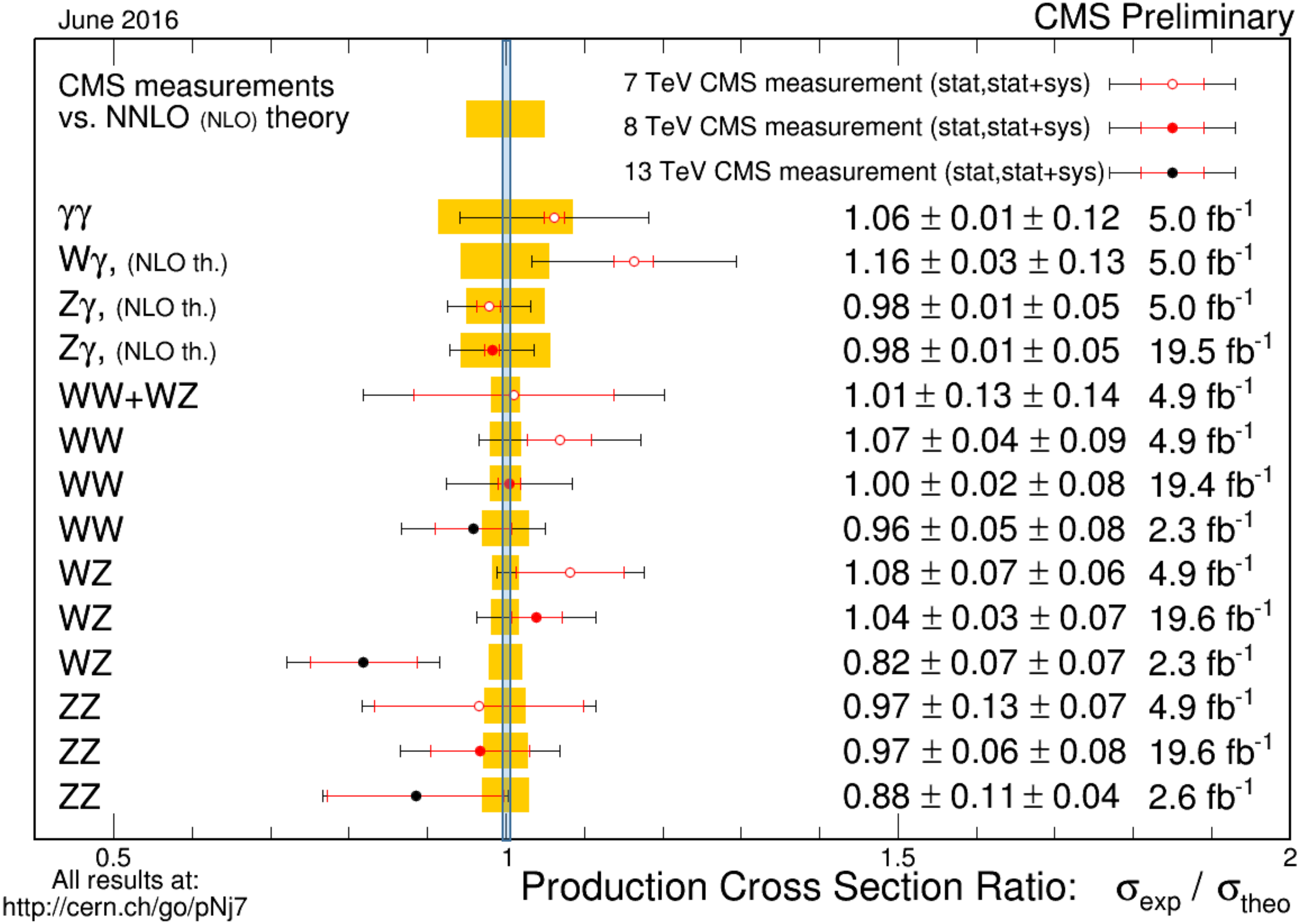
标准模型截面测量


ATLAS Preliminary
Theory
Measurement
Total production cross section [pb]
10^3
10^2
10
1
4
6
8
10
12
14
$\sqrt{s}$ [TeV]
$pp \to t\bar{t}$
$pp \to tq$
$pp \to H$
$pp \to WW$
$\times 0.1$
$pp \to WZ$
$\times 0.1$
$pp \to ZZ$
$\times 0.1$
NNLO+NNLL
NLO+NNLL
LHC-XS (N^3LO ggF)
NNLO
NNLO
NNLO
$pp \to t\bar{t}$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb^{-1}, arXiv:1606.02699
$pp \to tq$
7 TeV, 4.6 fb^{-1}, PRD 90, 112006 (2014)
8 TeV, 20.3 fb^{-1}, arXiv:1702.02859
13 TeV, 3.2 fb^{-1}, arXiv:1609.03920
$pp \to H$
7 TeV, 4.5 fb^{-1}, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C76 (2016) 6
13 TeV, 13.3 fb^{-1}, ATLAS-CONF-2016-081
$pp \to WW$
7 TeV, 4.6 fb^{-1}, PRD 87, 112001 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 09 029 (2016)
13 TeV, 3.2 fb^{-1}, arXiv:1702.04519
$pp \to WZ$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb^{-1}, PRD 93, 092004 (2016)
13 TeV, 3.2 fb^{-1}, Phys. Lett. B 762 (2016)
$pp \to ZZ$
7 TeV, 4.6 fb^{-1}, JHEP 03, 128 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 01, 099 (2017)
13 TeV, 3.2 fb^{-1}, PRL 116, 101801 (2016)

标准模型截面测量

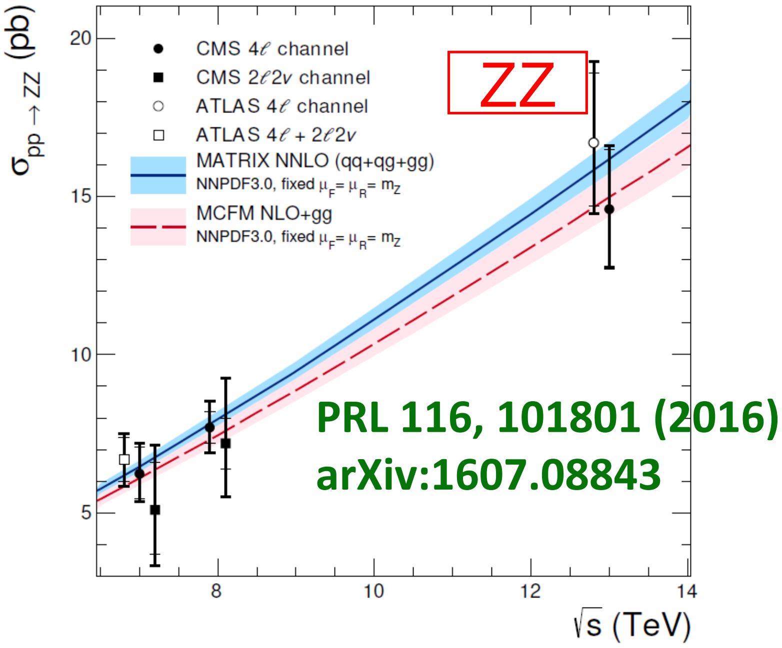

Standard Model Production Cross Section Measurements
Status: August 2016
∫ℒdt [fb⁻¹]
Reference
tt̄ tot.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
t t−chan tot.
t s−chan tot.
Wt tot.
W tot.
Z tot.
WW tot.
WZ tot.
ZZ tot.
γγ fid.
Wγ fid.
Zγ fid.
Zjj EWK fid.
Zγγ tot.
Wγγ tot.
W±W±jj EWK fid.
3.2 arXiv:1606.02699 [hep-ex]
20.3 EPJC 74: 3109 (2014)
4.6 EPJC 74: 3109 (2014)
3.2 ATLAS-CONF-2016-003
20.3 JHEP 11, 172 (2015)
3.2 ATLAS-CONF-2016-003
20.3 JHEP 11, 172 (2015)
4.6 PRD 91, 072007 (2015)
3.2 ATLAS-CONF-2015-079
20.3 ATLAS-CONF-2014-007
4.6 PRD 90, 112006 (2014)
20.3 PLB 756, 228-246 (2016)
3.2 ATLAS-CONF-2016-065
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
0.081 PLB 759 (2016) 601
0.035 PRD 85, 072004 (2012)
0.081 PLB 759 (2016) 601
0.035 PRD 85, 072004 (2012)
3.2 ATLAS-CONF-2016-090
20.3 CERN-EP-2016-186
4.6 PRD 87, 112001 (2013)
3.2 arXiv:1606.04017 [hep-ex]
20.3 PRD 93, 092004 (2016)
4.6 EPJC 72, 2173 (2012)
3.2 PRL 116, 101801 (2016)
20.3 ATLAS-CONF-2013-020
4.6 JHEP 03, 128 (2013)
4.9 JHEP 01, 086 (2013)
4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
20.3 PRD 93, 112002 (2016) arXiv:1407.1618 [hep-ph]
4.6 PRD 87, 112003 (2013) arXiv:1407.1618 [hep-ph]
20.3 JHEP 04, 031 (2014)
20.3 PRD 93, 112002 (2016)
20.3 PRL 115, 031802 (2015)
20.3 PRL 113, 141803 (2014)
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
data/theory

标准模型截面测量


June 2016
CMS Preliminary
CMS measurements
vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ
1.06 ± 0.01 ± 0.12 5.0 fb^{-1}
Wγ, (NLO th.)
1.16 ± 0.03 ± 0.13 5.0 fb^{-1}
Zγ, (NLO th.)
0.98 ± 0.01 ± 0.05 5.0 fb^{-1}
Zγ, (NLO th.)
0.98 ± 0.01 ± 0.05 19.5 fb^{-1}
WW+WZ
1.01 ± 0.13 ± 0.14 4.9 fb^{-1}
WW
1.07 ± 0.04 ± 0.09 4.9 fb^{-1}
WW
1.00 ± 0.02 ± 0.08 19.4 fb^{-1}
WW
0.96 ± 0.05 ± 0.08 2.3 fb^{-1}
WZ
1.08 ± 0.07 ± 0.06 4.9 fb^{-1}
WZ
1.04 ± 0.03 ± 0.07 19.6 fb^{-1}
WZ
0.82 ± 0.07 ± 0.07 2.3 fb^{-1}
ZZ
0.97 ± 0.13 ± 0.07 4.9 fb^{-1}
ZZ
0.97 ± 0.06 ± 0.08 19.6 fb^{-1}
ZZ
0.88 ± 0.11 ± 0.04 2.6 fb^{-1}
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σ_{exp} / σ_{theo}

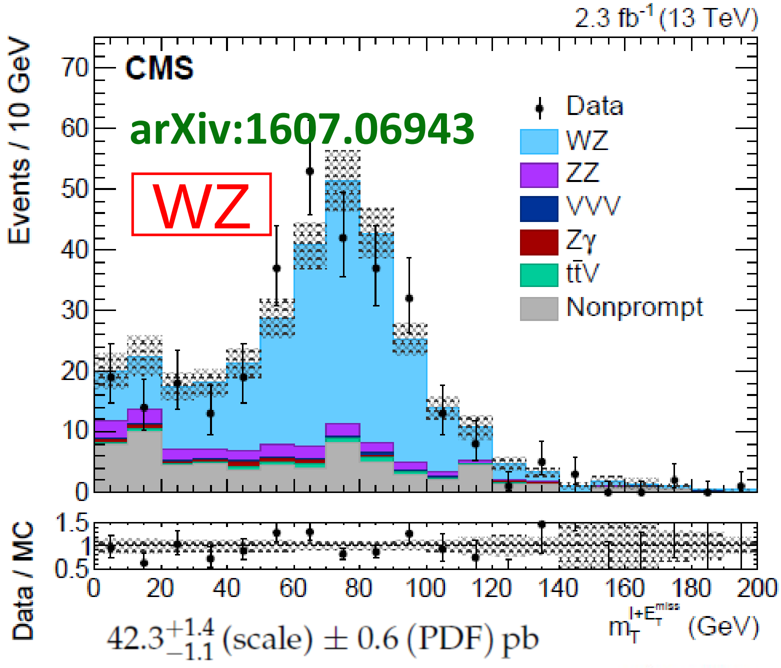
双玻色子截面

ATLAS-CONF-2016-043/090
arXiv:1607.06943
arXiv:1607.08843



ZZ

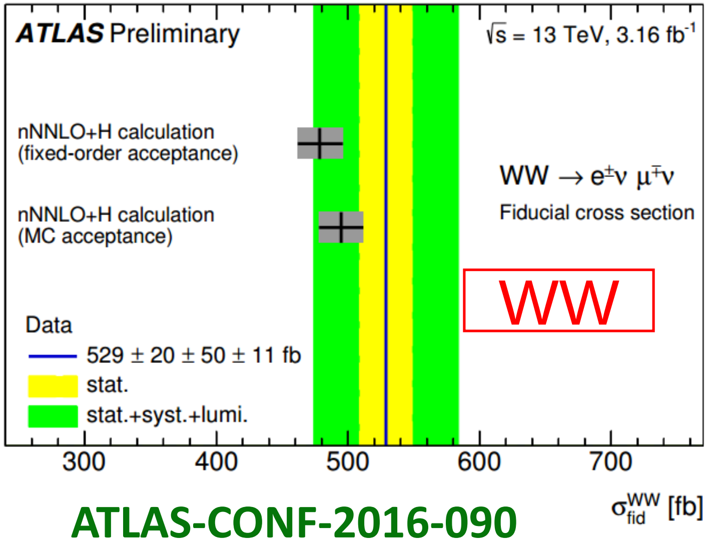
PRL 116, 101801 (2016)
arXiv:1607.08843



arXiv:1607.06943

WZ

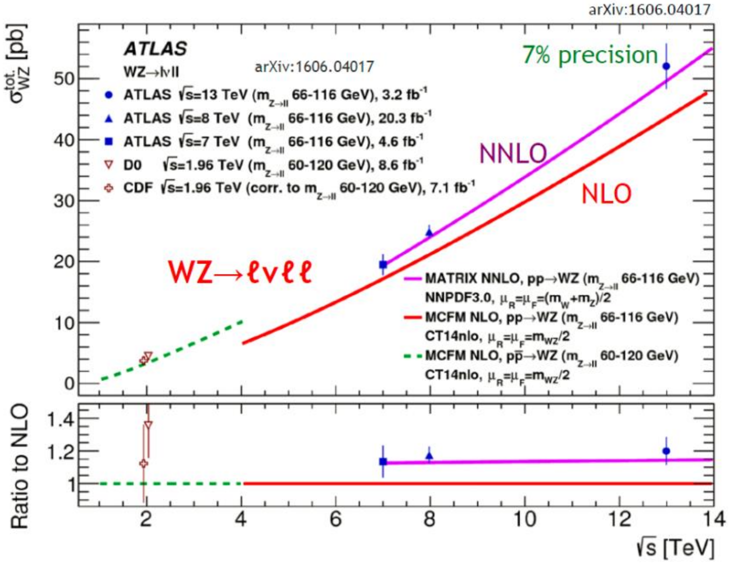
$42.3^{+1.4}_{-1.1}\,(\text{scale}) \pm 0.6\,(\text{PDF})$ pb



WW

ATLAS-CONF-2016-090

➔ WZ: ~20% correction for NNLO Which describes data better than NLO



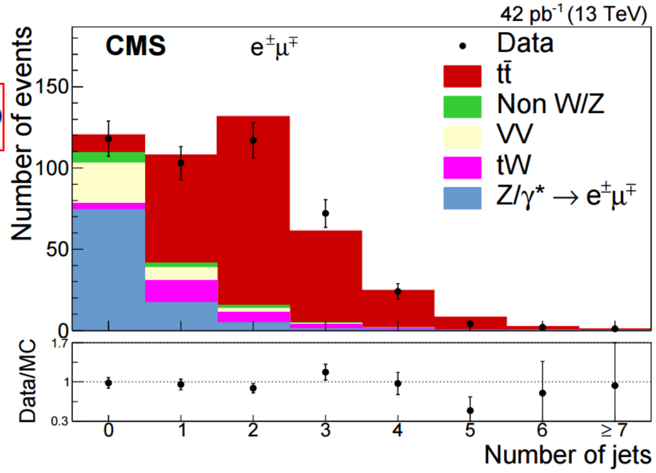
LHC: a Top quark factory

ATLAS-CONF-2016-005
PRL 116 (2016) 052002
CMS-PAS-TOP-16-006

➔ tt ➔ bbWW ➔ bb eμνν (OS-eμ)

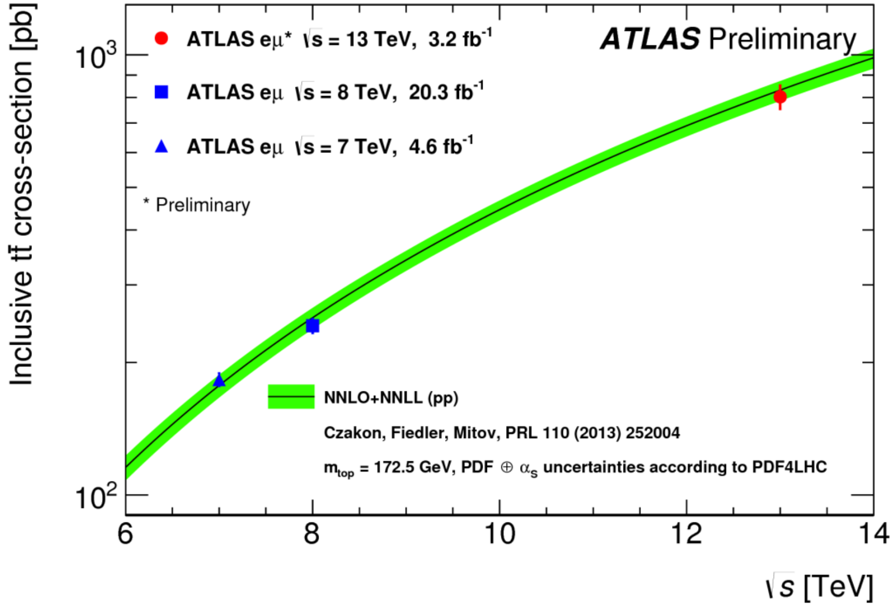
$$\sigma_{t\bar{t}} = 803 \pm 7\ (\text{stat}) \pm 27\ (\text{syst}) \pm 45\ (\text{lumi}) \pm 12\ (\text{beam})\ \text{pb}$$

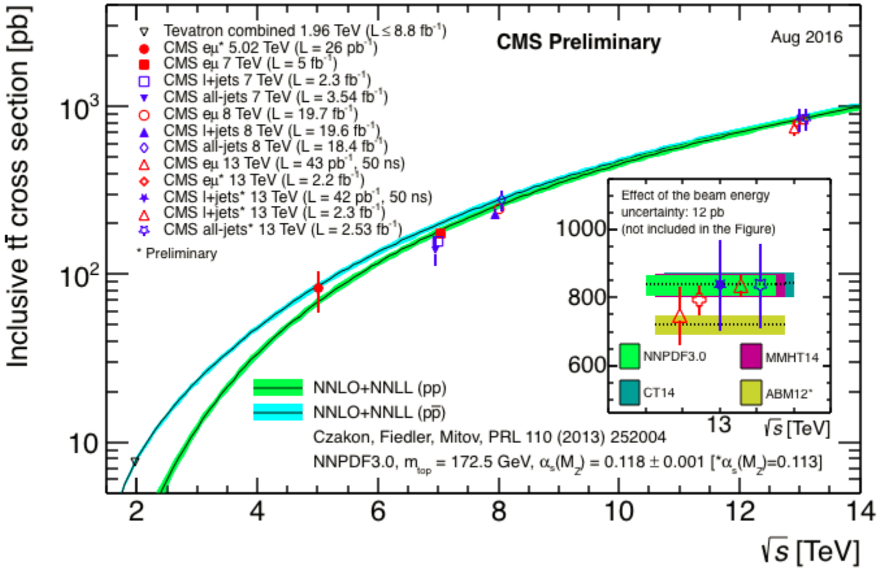
CMS: 746 ± 58(stat) ± 53(syst) ± 36 (lumi) pb



➔ Measured cross section agrees well with NNLO+NNLL theoretical prediction

$$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+40}_{-46}\ \text{pb}$$

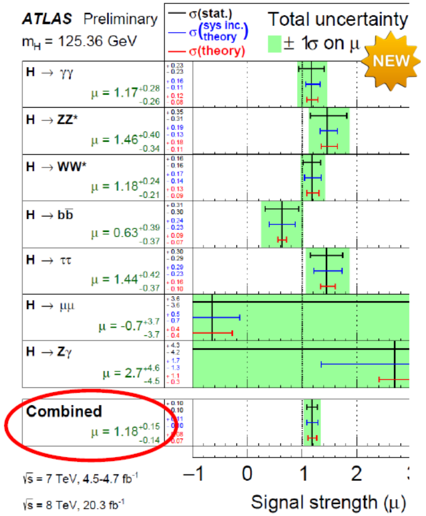


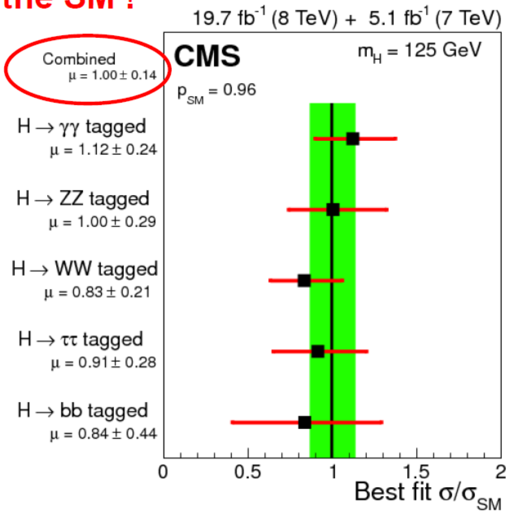


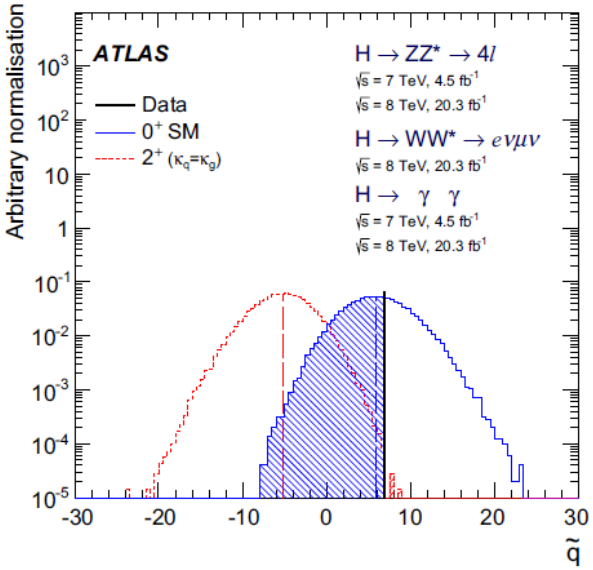
Higgs Properties at Run1

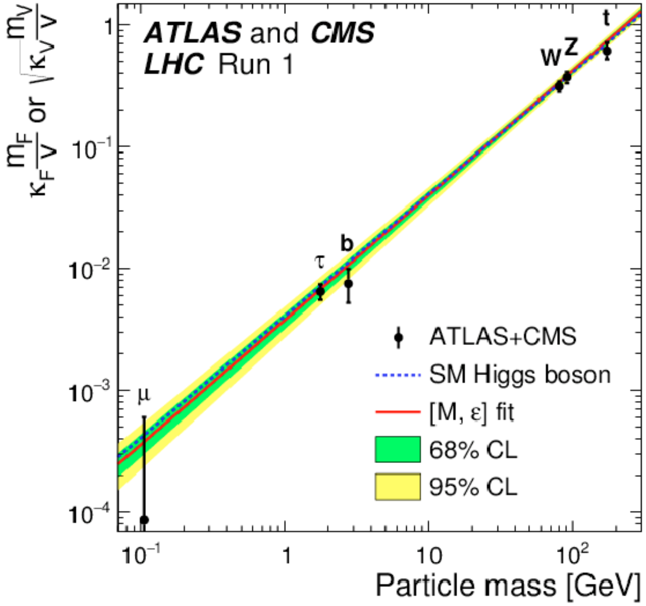
- **Higgs Strength μ = 1.09 ± 0.14**
- **Spin/Parity: 0⁺**
- **Couplings: agree with SM predictions**

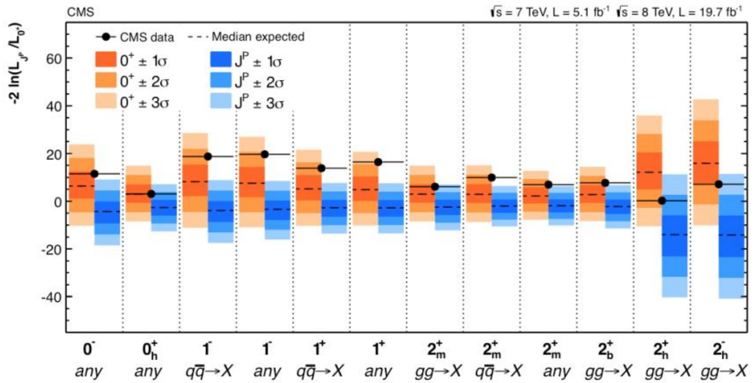
- **Results are consistent with the SM !**





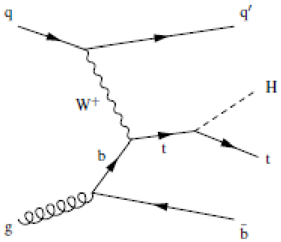






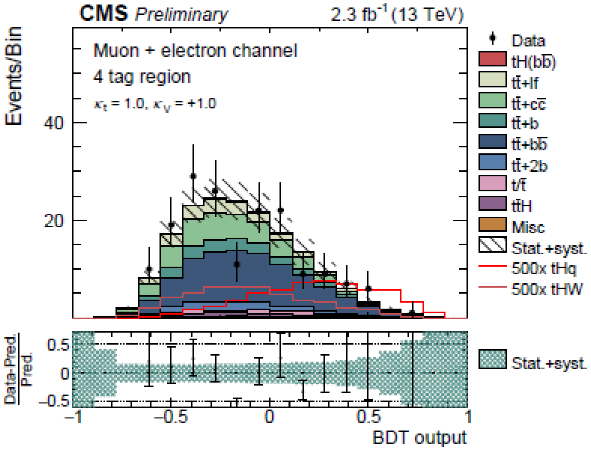
Search for tH (H→bb)

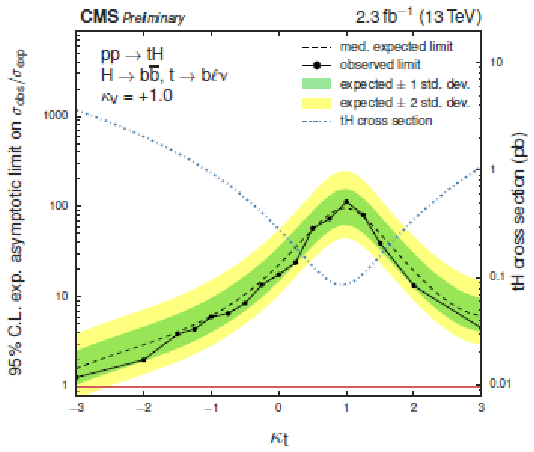
Search for $H \to b\bar{b}$ in association with a single top ($t \to b\, e\nu / b\, \mu\nu$)



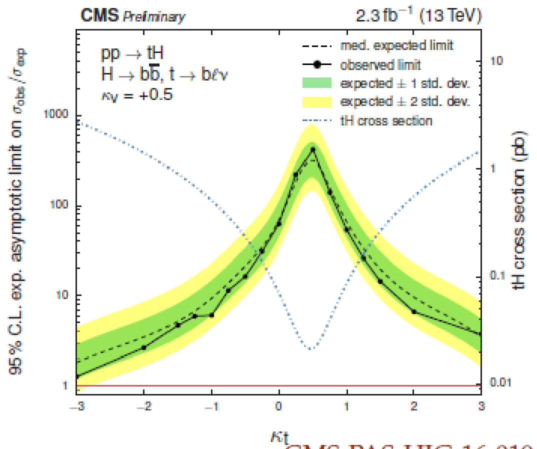
- final state e/μ + 3 or 4 b-tagged jets, one non b-tagged jet

1. MVA to find jet assignment for $t\bar{t}$ and tHq hypothesis
2. final discrimination MV classifier kinematics + kinematics interpreted in the two hypothesis.





SM coupling to W, Z

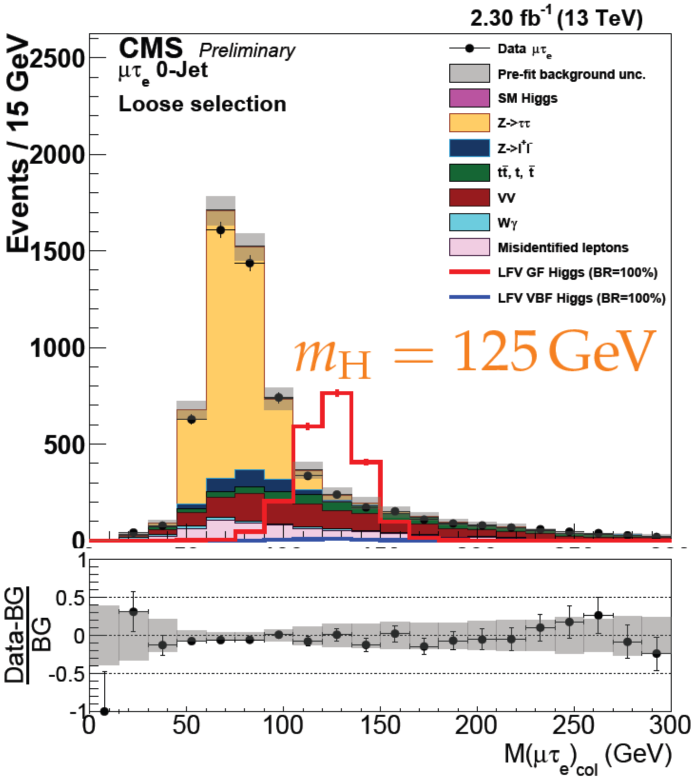


Reduced coupling to W, Z

CMS-PAS-HIG-16-019

Search for Higgs → $\mu\tau$

- A more complicated Higgs-sector could allow for lepton flavour violation.
- Search for $\mathrm{H} \rightarrow \mu\tau_{\mathrm{e}}/\tau_{\mathrm{had}}$, in categories of 0-2 extra jets.



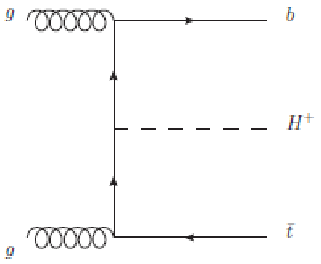
- Final discriminant visible mass corrected by estimated energy loss from ν_τ
- Limit on LFV Yukawa coupling ($m_{\mathrm{H}} = 125\,\mathrm{GeV}$):

$$\sqrt{|y_{\mu\tau}|^2 + |y_{\tau\mu}|^2} < 3.16\times10^{-3}$$

CMS-PAS-HIG-16-005

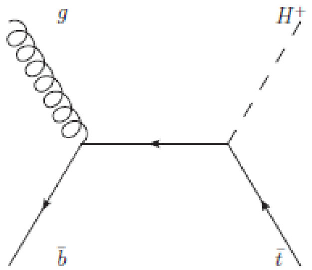
Charged Higgs →$\tau\nu$, tb

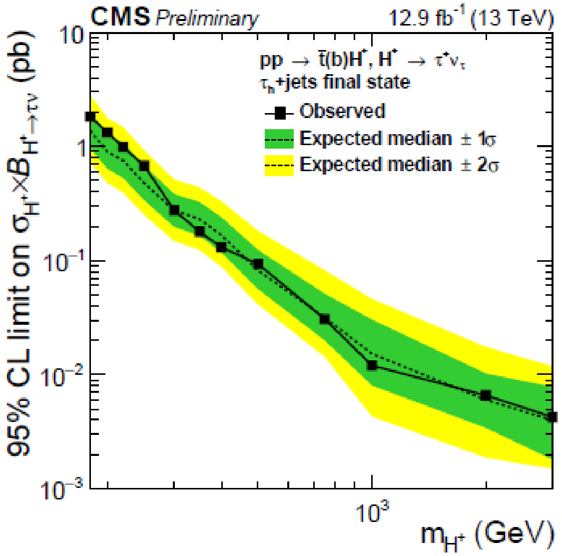
Couplings to fermions might be modified in case of an extended Higgs sector (MSSM, 2HDM, . . .). In such models a charged Higg is predicted.

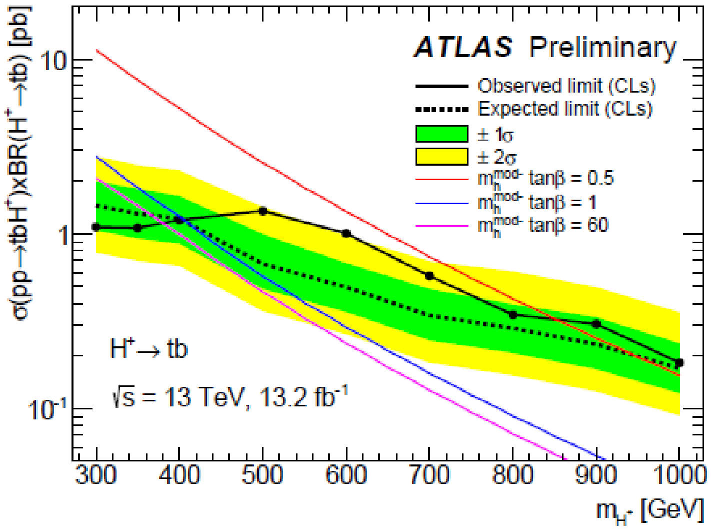


Search for $H^\pm \to \tau\nu$ in events with $\geq$ 3 jets, $\geq$ 1 b-tags ($pp \to tbH^\pm, H^\pm W^\mp b\bar{b}$).

Search for $H^\pm \to$ tb in events with $\geq$ 4 jets, $\geq$ 2 b-tags.







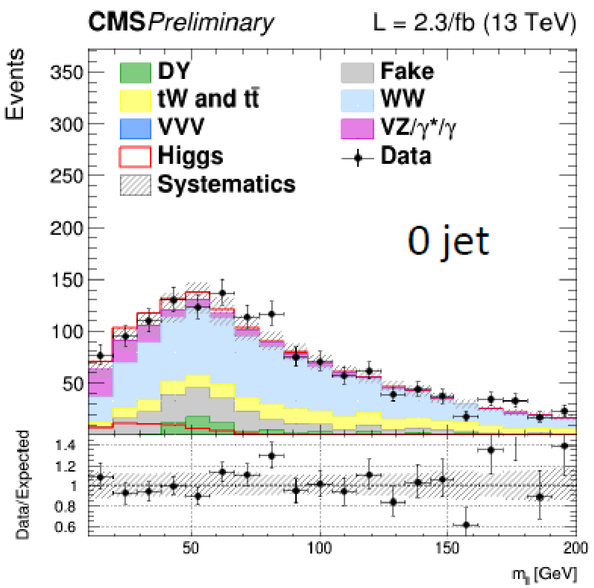
CMS-PAS-HIG-16-031

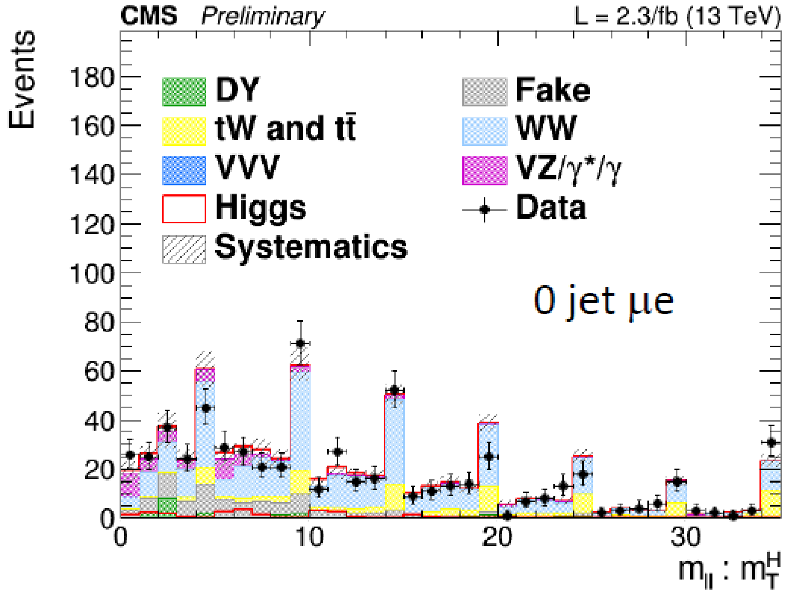
ATLAS-CONF-2016-089

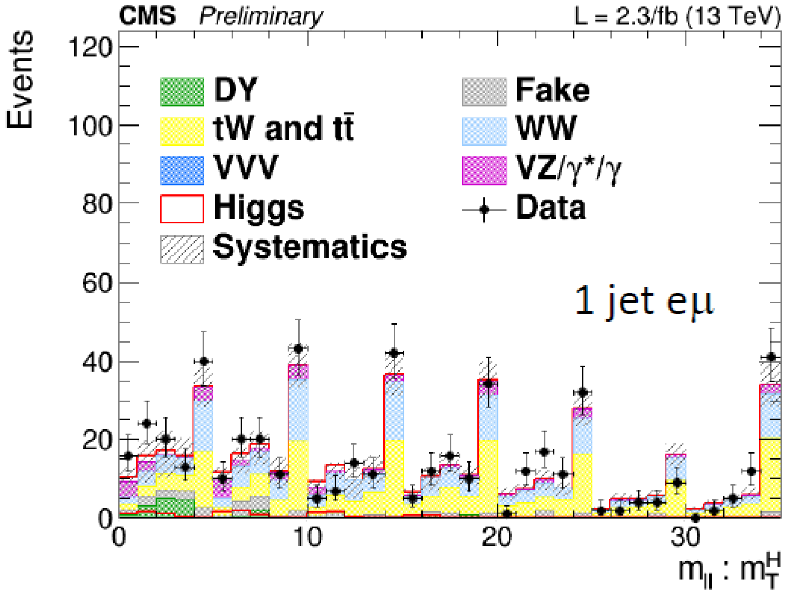
Higgs → WW*

CMS-PAS-HIG-15-003

- ggF production mode is the target.
- Event categorization is based on
  - 0 jet or 1 jet
  - eμ or μe (p_T ordered)
- Binned fit using template histograms of unrolled distributions of $m_{\ell\ell}$ and m_T^H
- $\mu = 0.3 \pm 0.5$







ATLAS-CONF-2016-068
CMS-PAS-HIG-16-020
CMS-PAS-HIG-16-041

Search for ttH, H→γγ, 4l

- **Small cross section, but top quarks provide good handles to trigger and event selection.**

- **Hadronic**
  H→bb, H→$\tau_h\tau_h$
- **Leptonic**
  H→WW, H→$\tau_\ell\tau_{any}$
- **Bosonic:**
  H→γγ, H→ZZ*→4ℓ

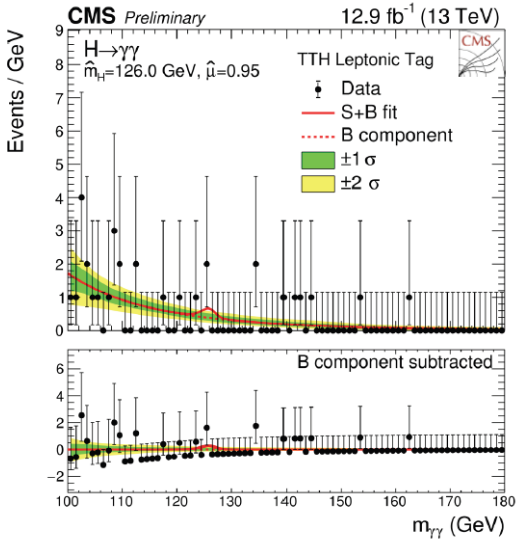
higher yield

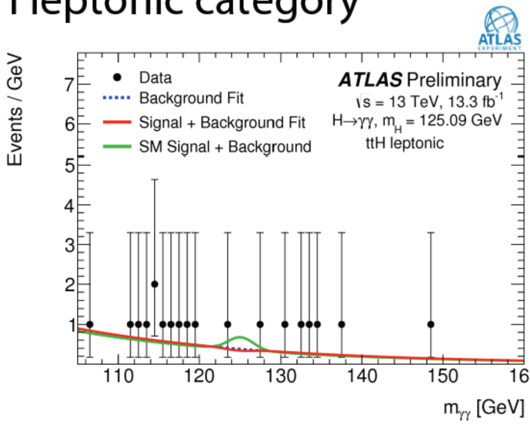
higher purity

– σ×BR: ~ 1 fb (γγ), ~ 0.14 fb (4ℓ)

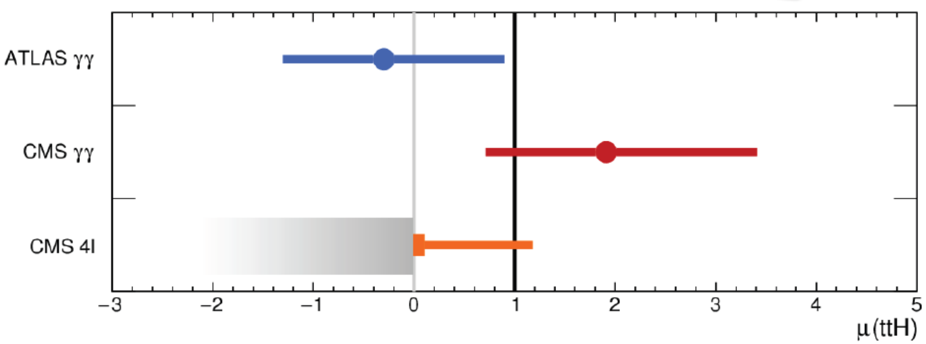
	μ	σ(all)
ATLAS γγ *CONF-2016-068, **13.3 fb⁻¹***	–0.3	+1.2 –1.0
CMS γγ *PAS HIG-16-020, **12.9 fb⁻¹***	1.9	+1.5 –1.2
CMS 4ℓ *PAS HIG-16-041, **35.9 fb⁻¹***	0.0*	+1.2* –0.0*

γγ data in the ttH leptonic category



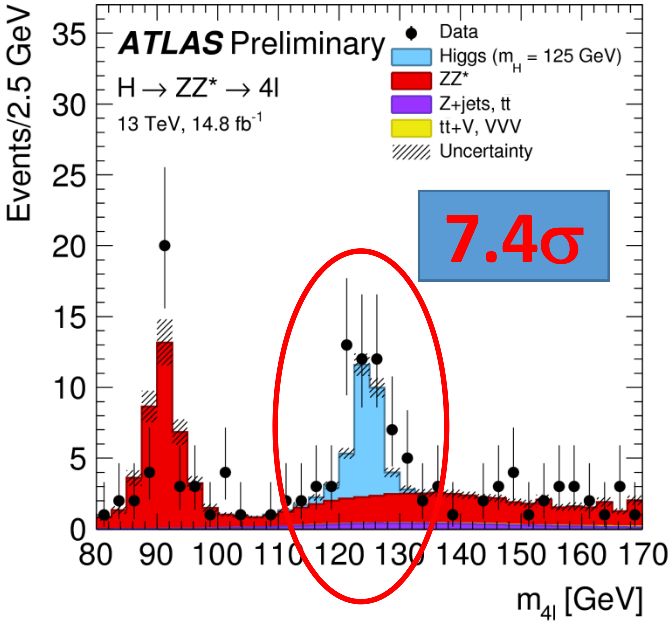


	S	B[±2σ$_{\gamma\gamma}$]
ATLAS	1.4	2.8(*)
CMS	1.1	2.7(*)



Re-discover Higgs → ZZ* →4l

ATLAS-CONF-2016-079

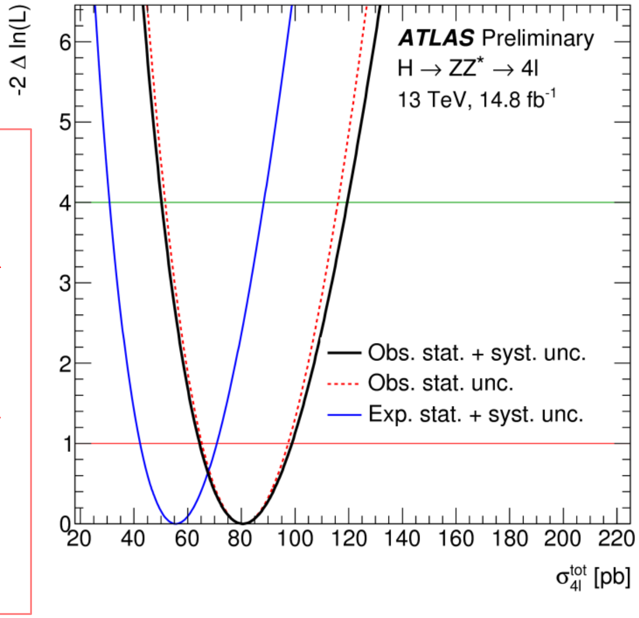


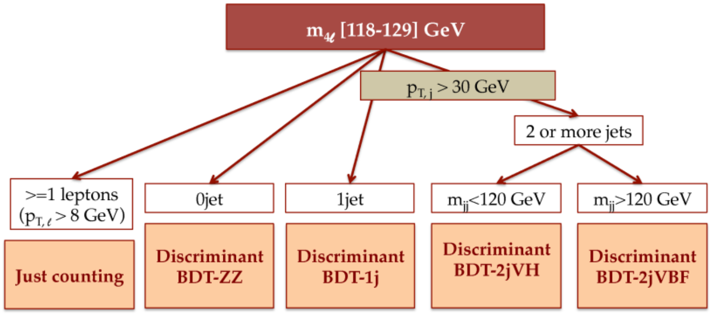
$$\sigma_{\mathrm{tot,SM}} = 55.5^{+3.8}_{-4.4}\ \mathrm{pb.}$$

$$\sigma_{\mathrm{tot}} = 81^{+18}_{-16}\ \mathrm{pb}$$

科大李冰、徐来林、赵政国，交大杨海军在 ATLAS Run1 参与H→ZZ*的分析，用BDT方法提高信噪比，测量自旋和宇称等，首次提出用Z→4l刻度希格斯质量，担任4篇Higgs论文的编辑之一。

Run2主要参与VBF 事例的选择优化，截面测量等。





$m_{4\ell}$ [118-129] GeV

$p_{T,j} > 30$ GeV

2 or more jets

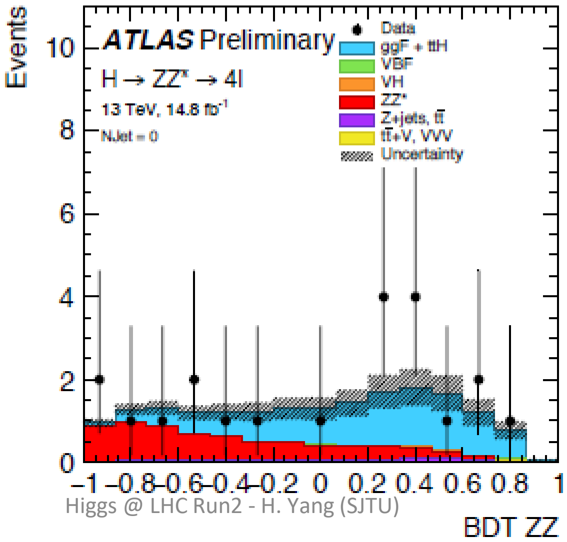
>=1 leptons ($p_{T,\ell} > 8$ GeV)	0jet	1jet	m_{jj}<120 GeV	m_{jj}>120 GeV
Just counting	**Discriminant BDT-ZZ**	**Discriminant BDT-1j**	**Discriminant BDT-2jVH**	**Discriminant BDT-2jVBF**

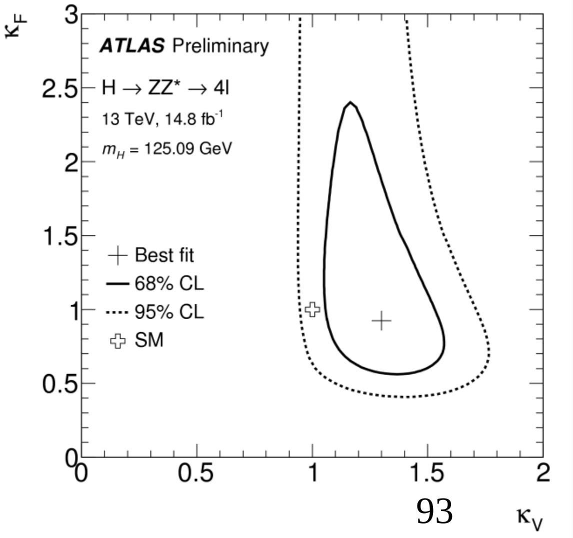
BDT_ZZ:
- $p_{T4\ell}$
- $\eta_{4\ell}$
- KD = $\log(ME_{HZZ}/ME_{ZZ})$

BDT_1jet:
- $p_{T,j}$
- η_j
- $\Delta R_{4\ell j}$

BDT_2jet_VH:
- $p_{T,j1}$
- $p_{T,j2}$
- η_{j1}
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell jj}$
- m_{jj}
- $\min(\Delta R_{Zj})$

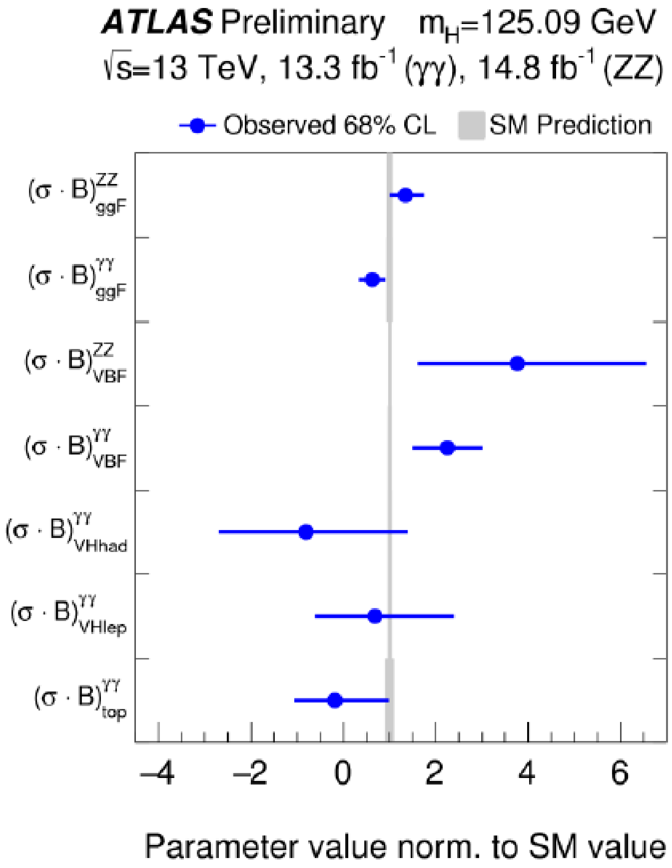
BDT_2jet_VBF:
- $p_{T,j1}$
- $p_{T,j2}$
- $p_{T,4\ell jj}$
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell jj}$
- m_{jj}
- $\min(\Delta R_{Zj})$

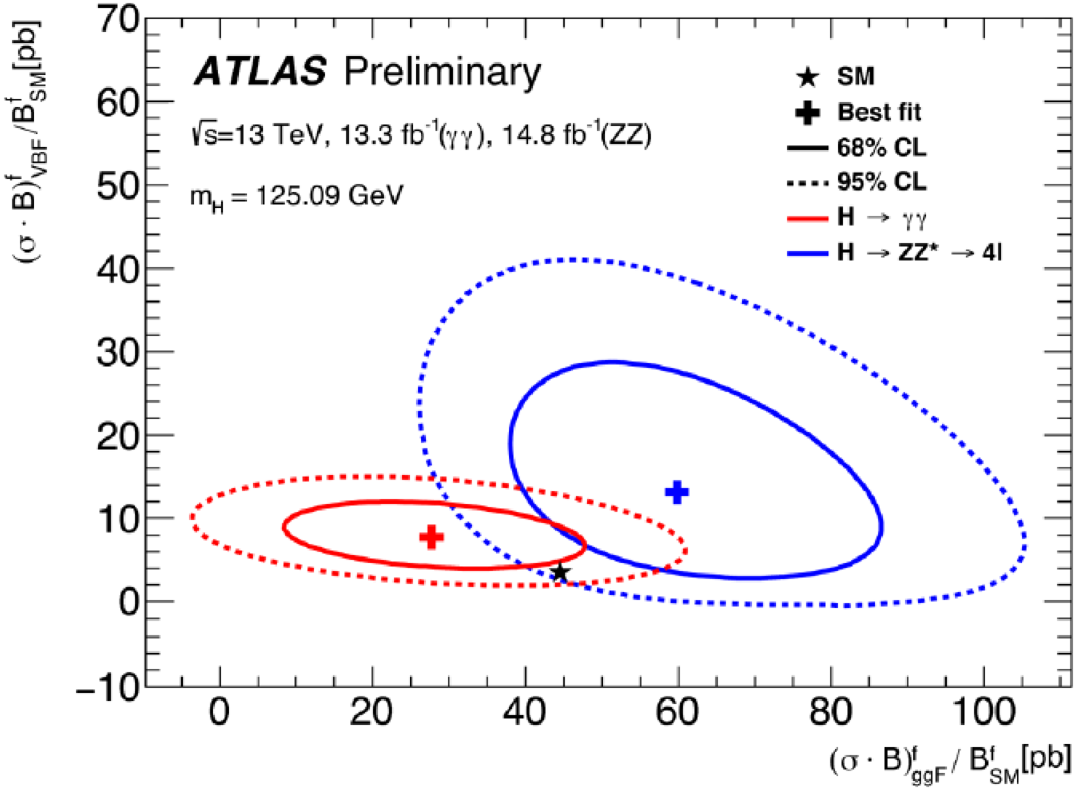




Re-discover Higgs → ZZ* →4l

- **Combined Run2 H→γγ and ZZ* results**
- **Inclusive signal strength:** $\mu = 1.13^{+0.18}_{-0.17}$

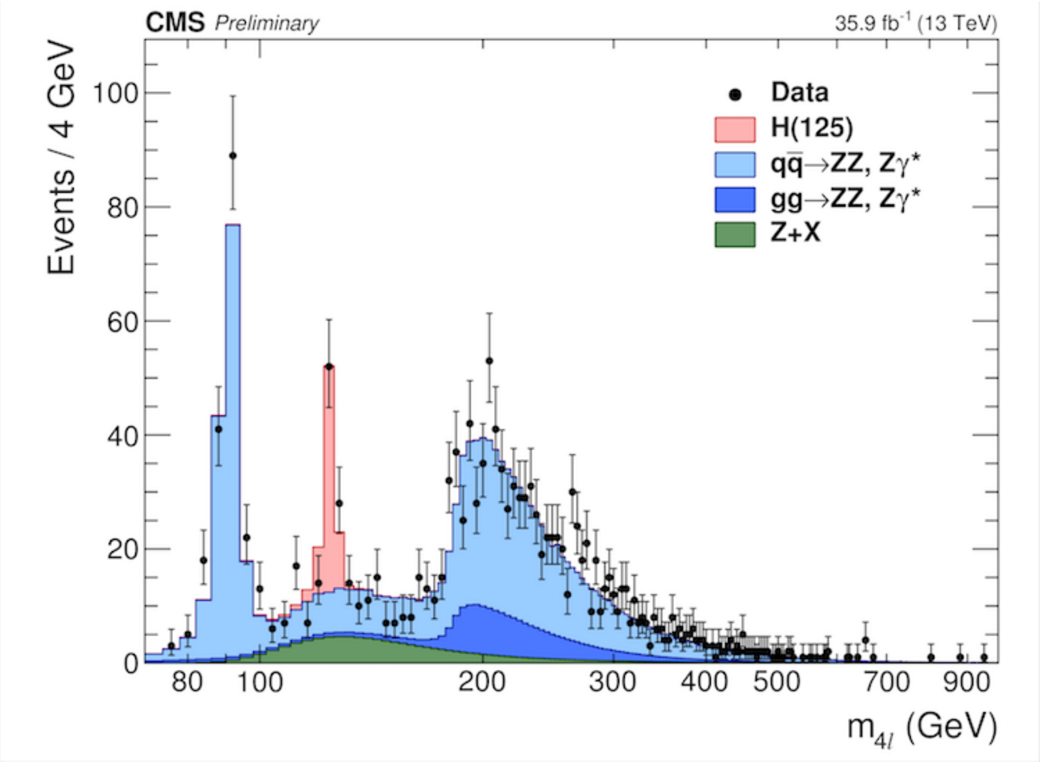


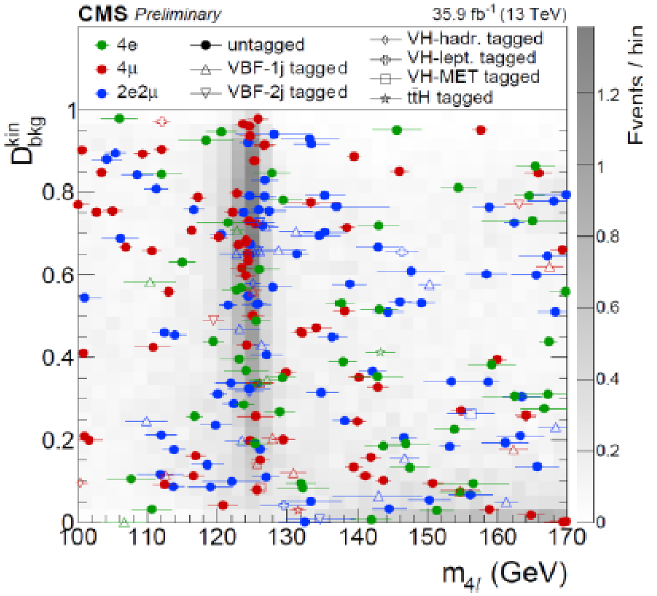


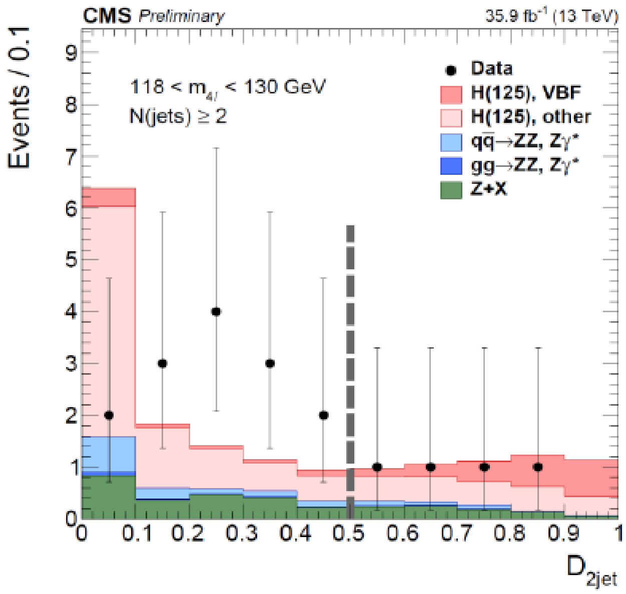
Re-discover Higgs → ZZ* →4l

CMS-PAS-HIG-16-033
CMS-PAS-HIG-16-041

- → **Probing 4 (ggH, VBF, VH, ttH) production modes with 7 event categories, make kinematic discriminants using matrix elements to reject background events.**
- →高能所陈明水、成瞳光、**Ahmad**、**Roko**参与希格斯质量、产生截面的测量。



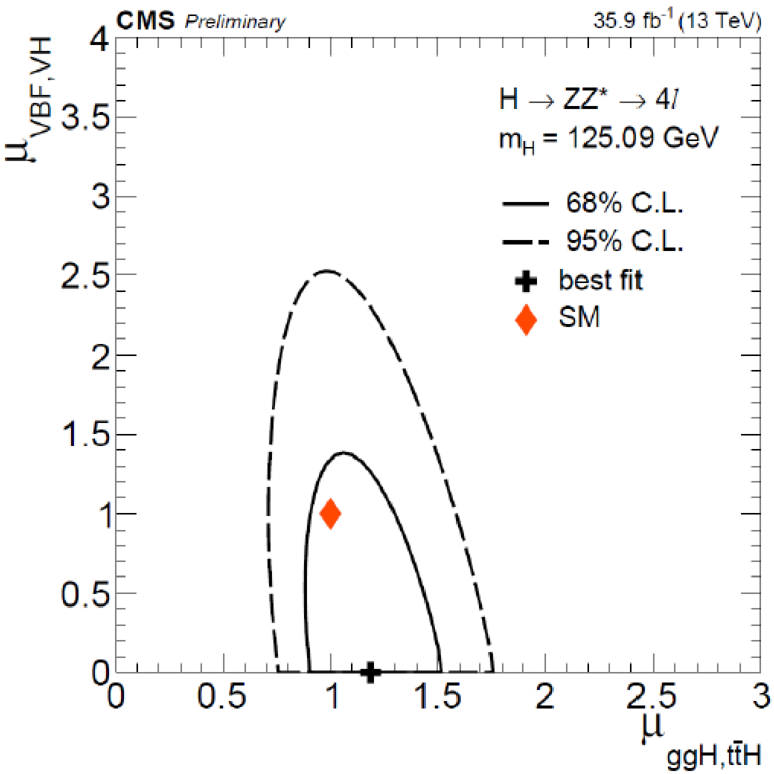


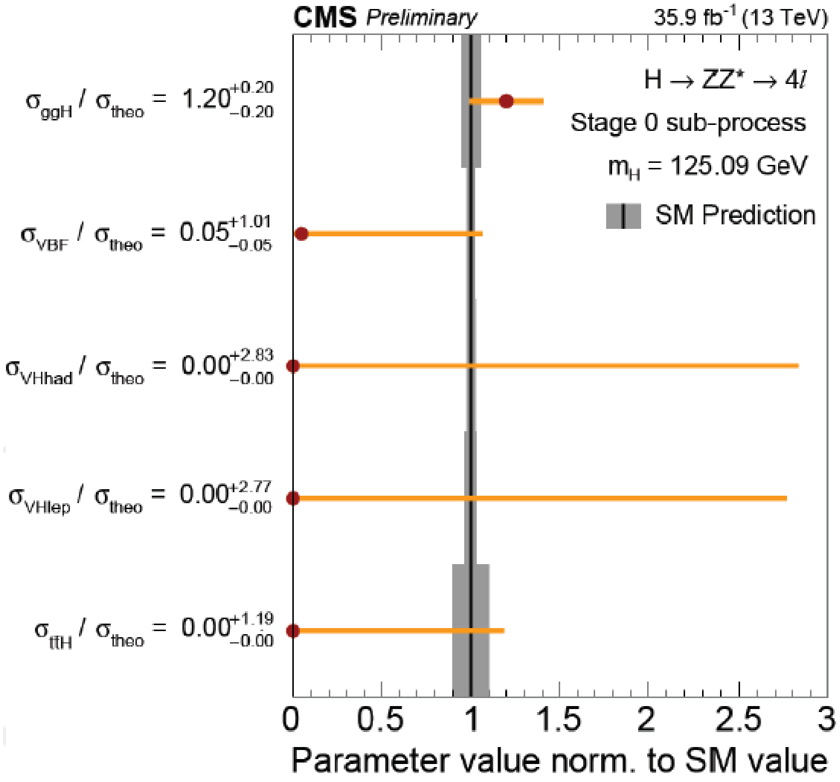


CMS-PAS-HIG-16-041

Re-discover Higgs → ZZ* →4l

- $\mu = 1.05^{+0.15}_{-0.14}(\text{stat.})^{+0.11}_{-0.09}(\text{syst.})$
  - Combined signal strength at m_H=125.09 GeV.
- Simplified template cross sections for $|y_H|$<2.5.

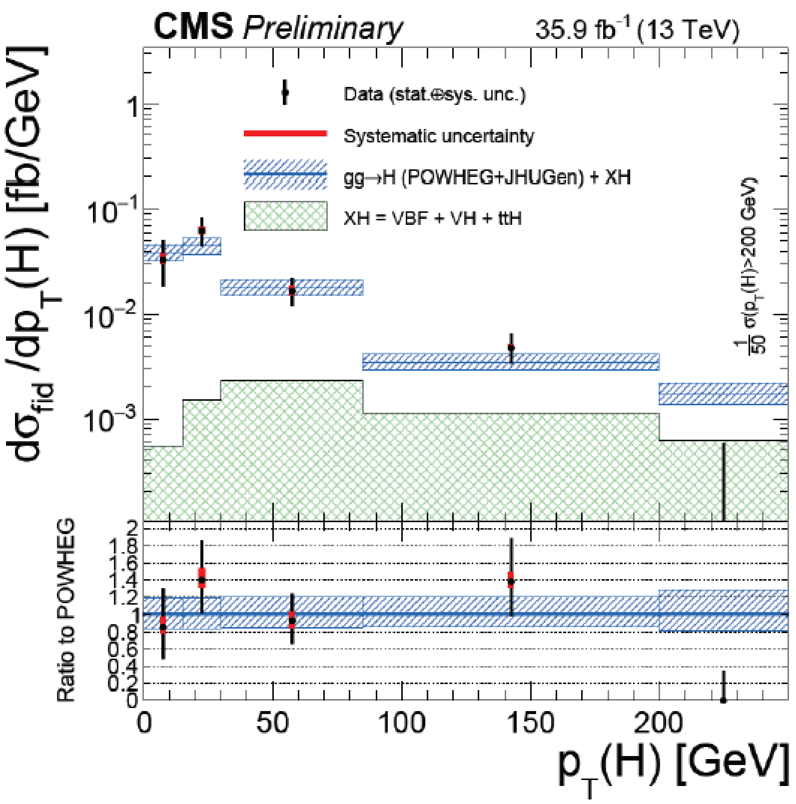


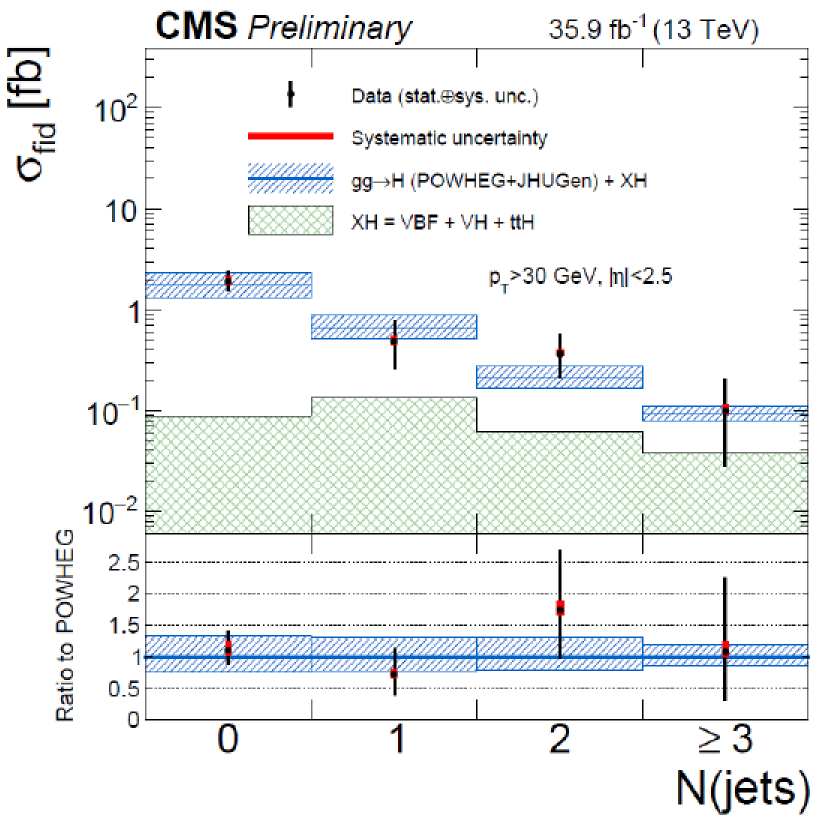


CMS-PAS-HIG-16-041

Re-discover Higgs → ZZ* →4l

- Differential cross-section with respect to $p_T(H)$ and the number of jets.
- Consistent with the SM expectations within uncertainty.





Higgs Mass

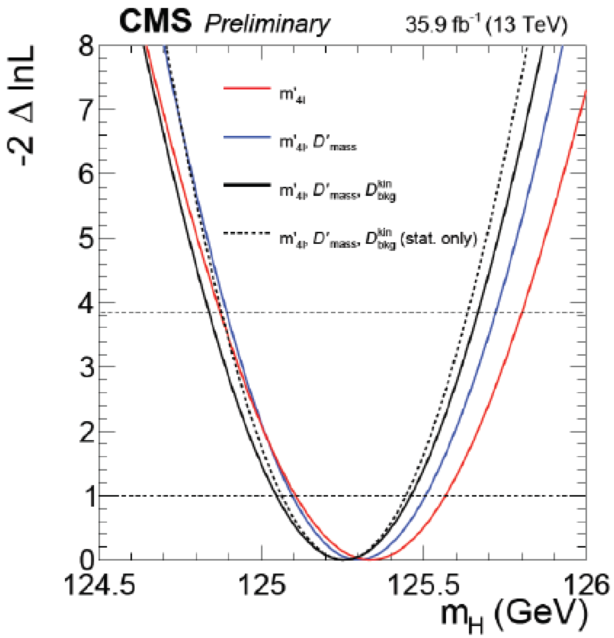
CMS-PAS-HIG-16-041

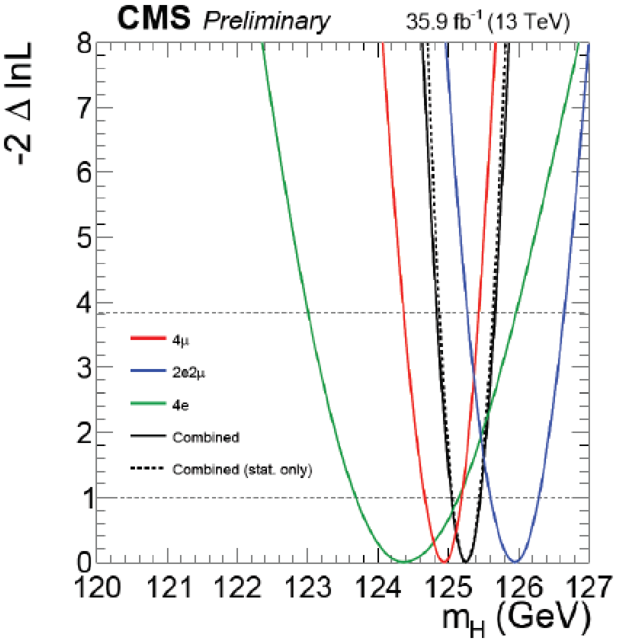
- Mass is determined by 3D measurement with m(Z1) constraint
  - Invariant mass of 4l and Mass error
  - Discriminant for qq/gg → 4l

- $m_H = 125.26 \pm 0.20\,(\text{stat.}) \pm 0.08\,(\text{syst.})$ GeV
  - Run 1 ATLAS and CMS combination

  $m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.10\,(\text{syst.})$ GeV

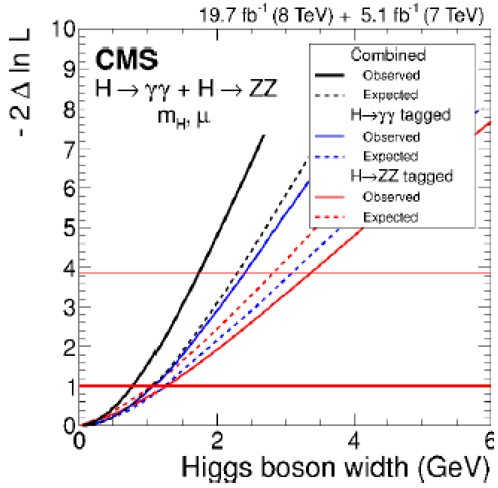
NEW



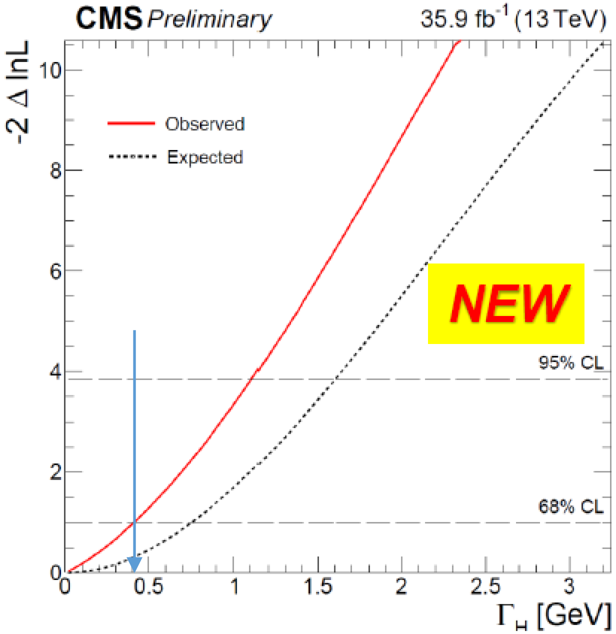


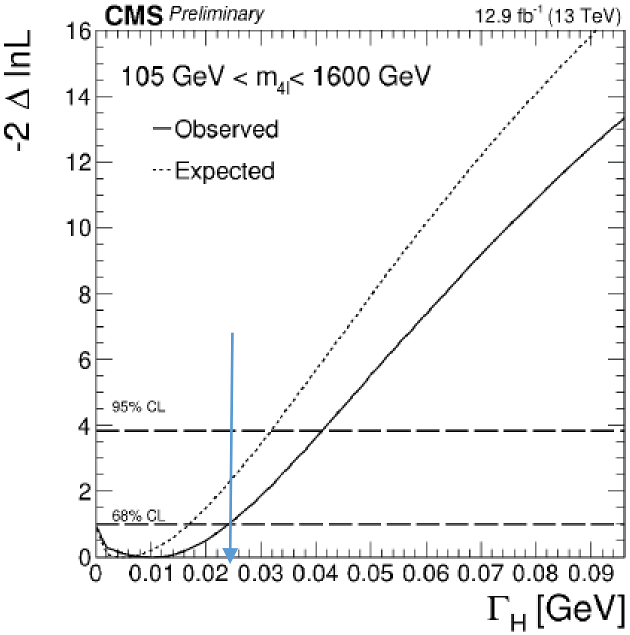
Higgs width

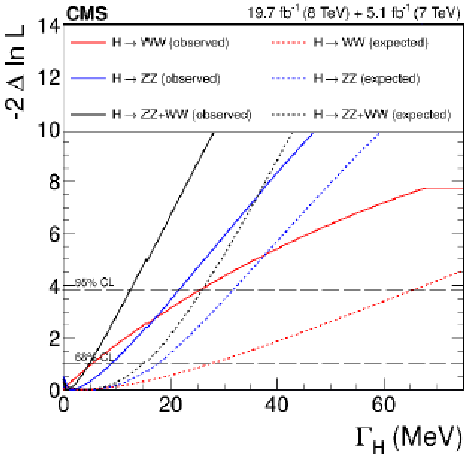
- Mass width is measured with two very different methods.
- $\Gamma_H = 0.00^{+0.41}_{-0.00}$ GeV with only on-shell
  - Tighter limit than Run 1
- $\Gamma_H = 10^{+14}_{-10}$ MeV with both on-shell and off-shell
  - With strong theory assumptions
  - With only 12.9 fb^{-1}



EPJC 75 (2015) 212





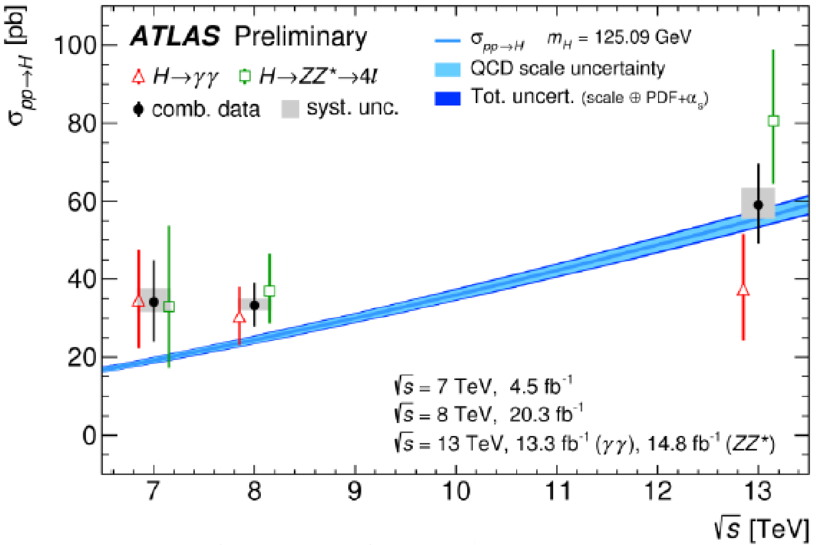


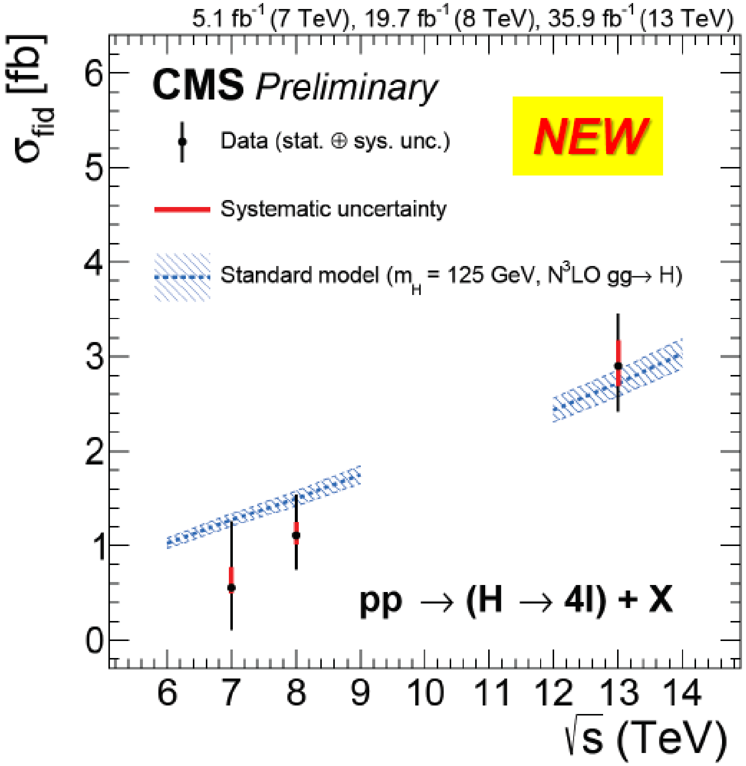
JHEP 09 (2016) 051

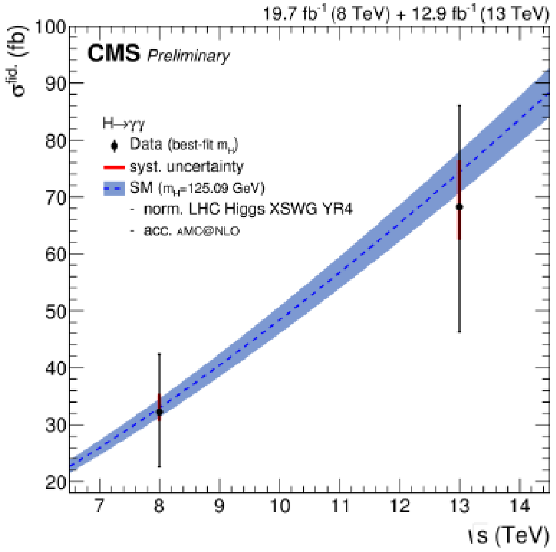
Total / fiducial Cross Section

ATLAS-CONF-2016-081
CMS-PAS-HIG-16-020
CMS-PAS-HIG-16-041

- Total (ATLAS) and fiducial (CMS) cross sections are consistent with N^3LO QCD calculation with NLO electroweak corrections.

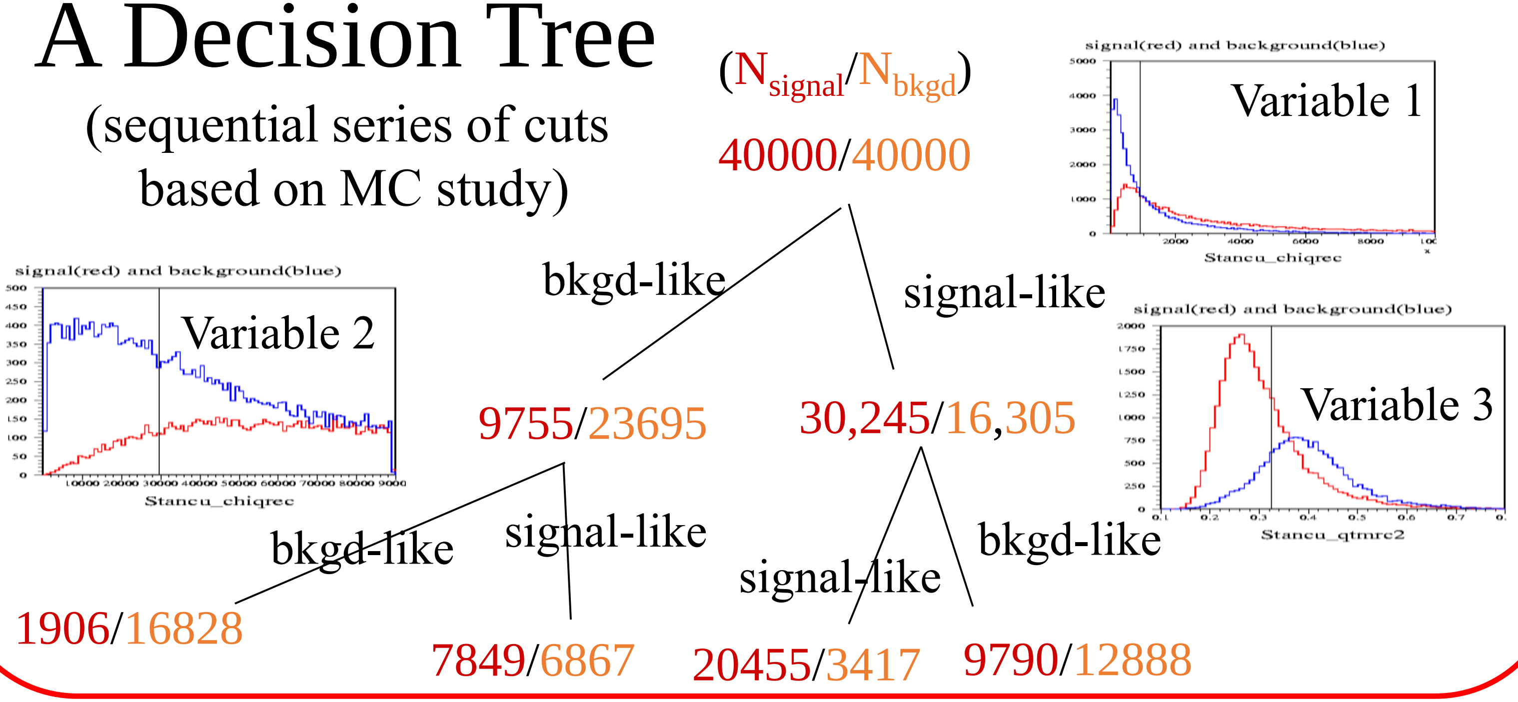






A Decision Tree

(sequential series of cuts based on MC study)



(N_{signal}/N_{bkgd})

40000/40000

bkgd-like

signal-like

9755/23695

30,245/16,305

bkgd-like

signal-like

signal-like

bkgd-like

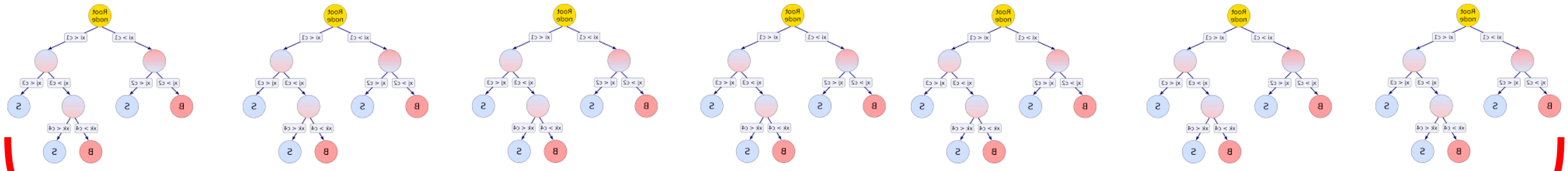
1906/16828

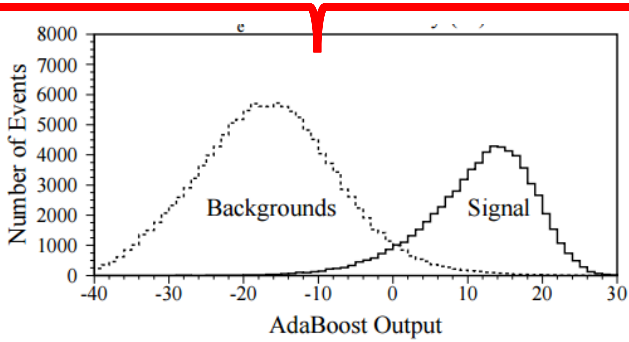
7849/6867

20455/3417

9790/12888

通过Boosting 算法不断提高误判事例的权重，产生一系列Decision Trees



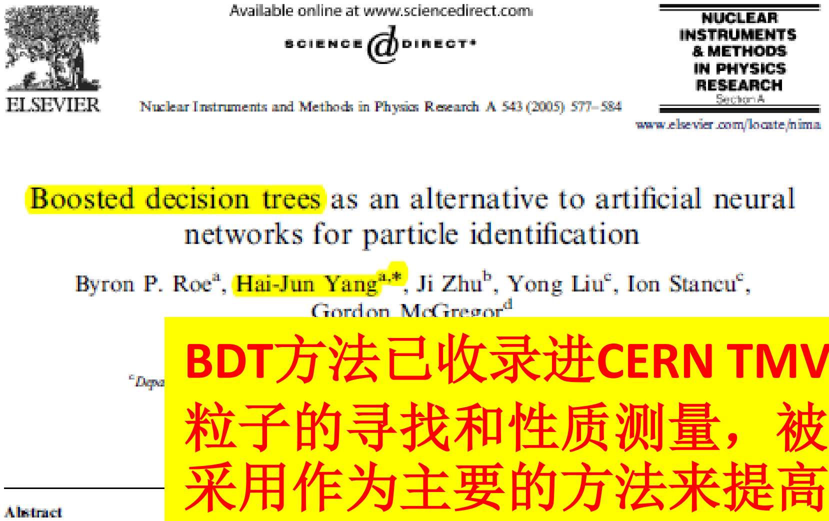


把每个事例在所有Decision Trees获得的积分累加，通过“Majority vote”方法提高性能和稳定性。

通过Boosting不断提高误判事例的权重，使得这些难以区分的事例在后续的Decision Trees获得的正确区分，提高效率。

Boosted Decision Trees (BDT)

CERN TMVA package , http://tmva.sourceforge.net/



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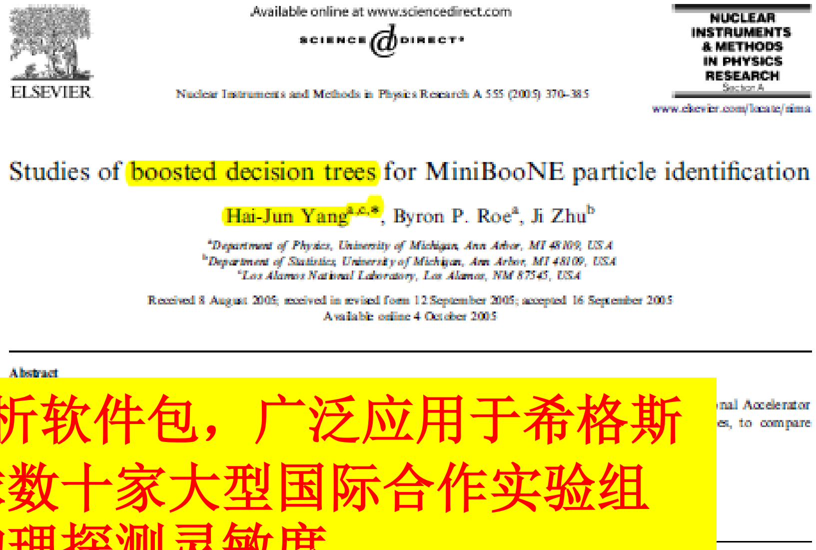
Boosted decision trees as an alternative to artificial neural networks for particle identification

Byron P. Roe[a], Hai-Jun Yang[a,*], Ji Zhu[b], Yong Liu[c], Ion Stancu[c], Gordon McGregor[d]

[c]Depa

Abstract



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Studies of boosted decision trees for MiniBooNE particle identification

Hai-Jun Yang[a,c,*], Byron P. Roe[a], Ji Zhu[b]

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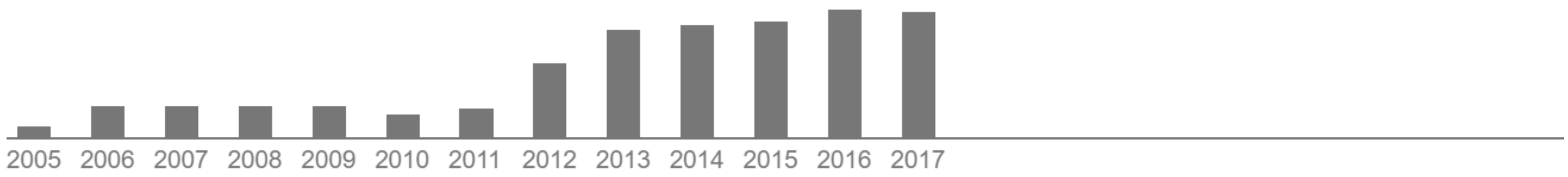
Received 8 August 2005; received in revised form 12 September 2005; accepted 16 September 2005
Available online 4 October 2005

Abstract

nal Accelerator
es, to compare

BDT方法已收录进CERN TMVA分析软件包，广泛应用于希格斯粒子的寻找和性质测量，被全球数十家大型国际合作实验组采用作为主要的方法来提高新物理探测灵敏度。

Total citations Cited by 505



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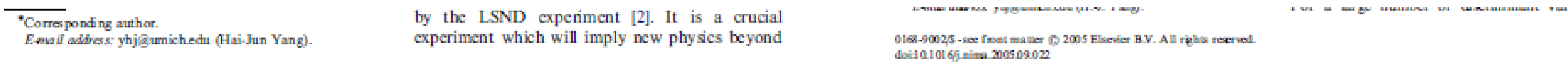

*Corresponding author.
E-mail address: yhj@umich.edu (Hai-Jun Yang).

by the LSND experiment [2]. It is a crucial experiment which will imply new physics beyond

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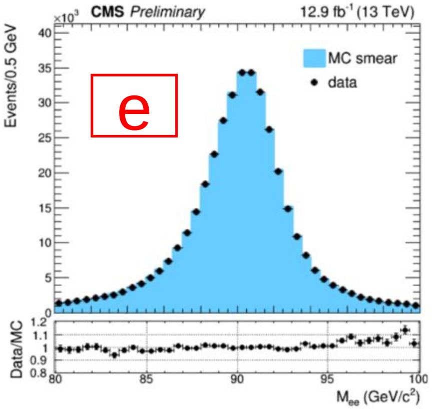
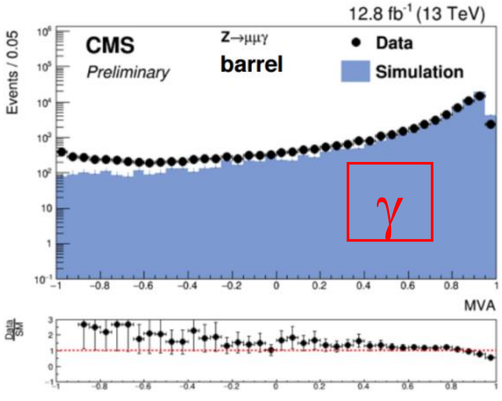
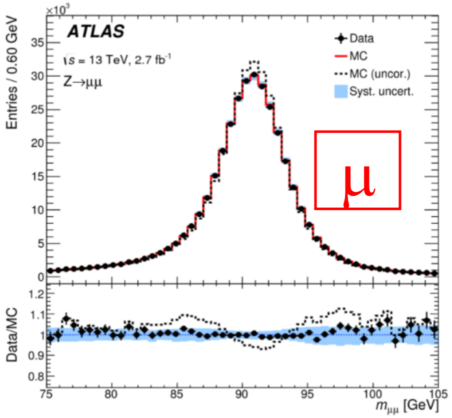
doi:10.1016/j.nima.2005.09.022

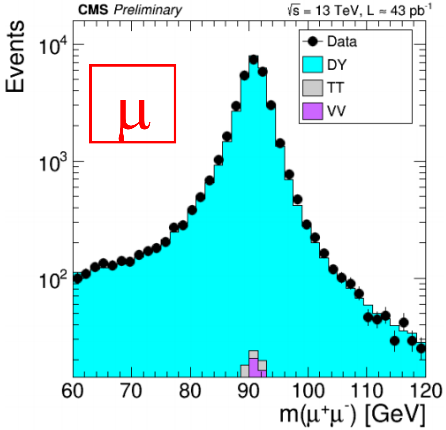
Particle Identification

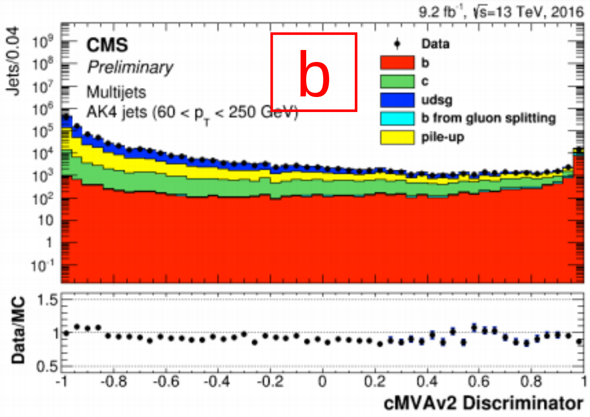
ATLAS-CONF-2015-041, ATL-PHYS-PUB-2016-015
Eur. Phys. J. C (2016) 76:292
CMS-DP-2015-015, CMS-DP-2016-015/042/049

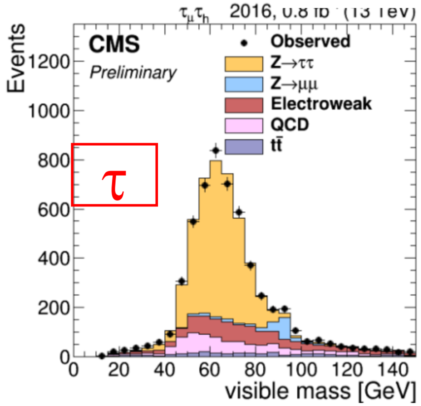




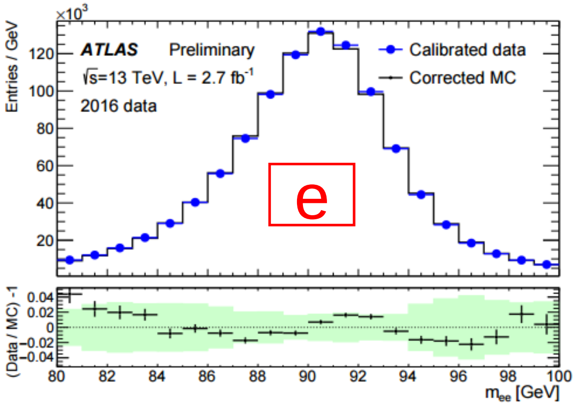


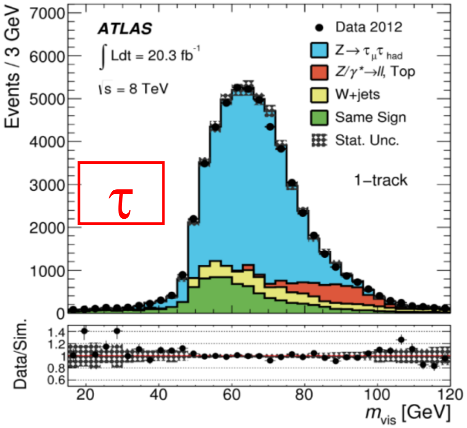


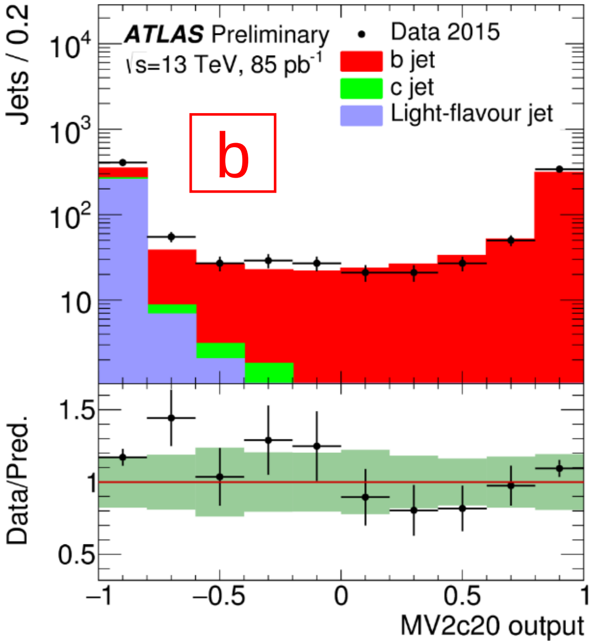


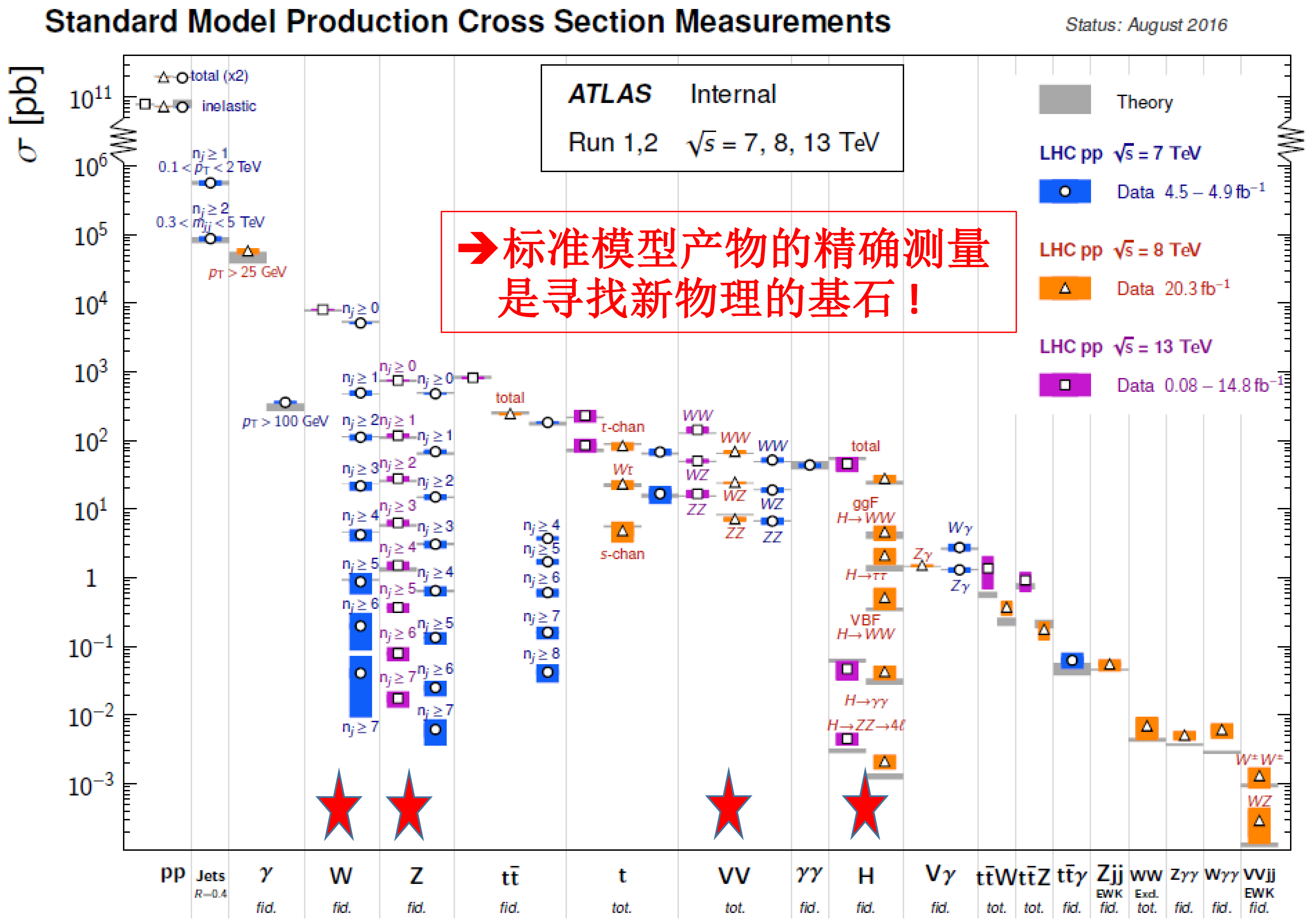


e, γ, τ, b identifications are based on BDT method





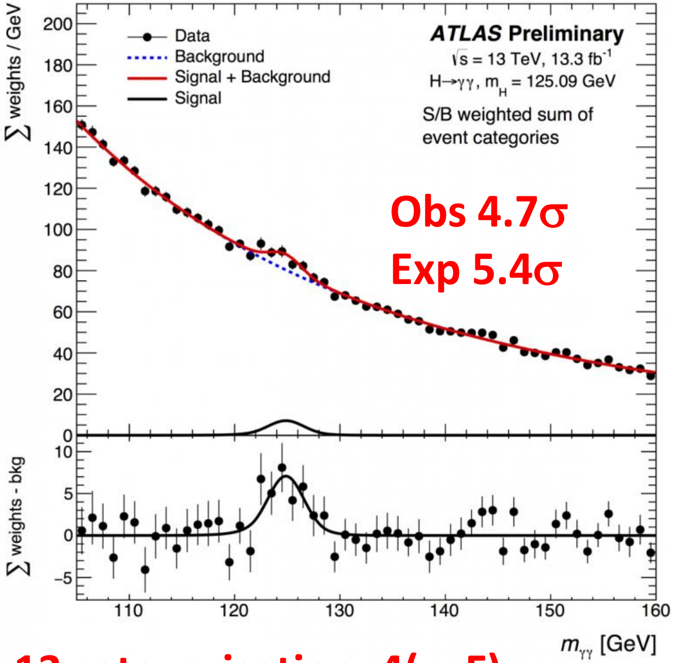




➔标准模型产物的精确测量是寻找新物理的基石！

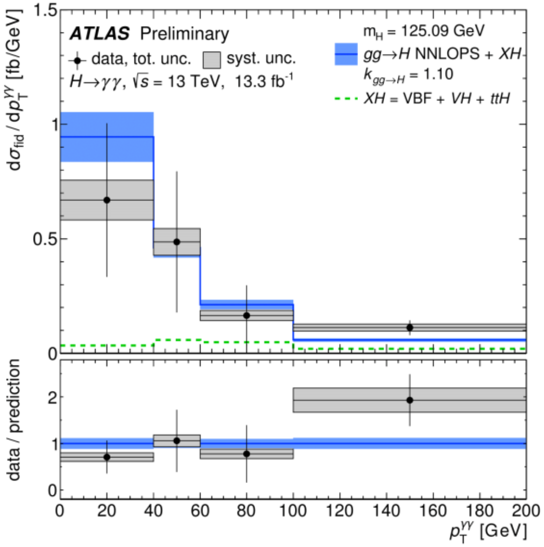
Re-discover Higgs → γγ

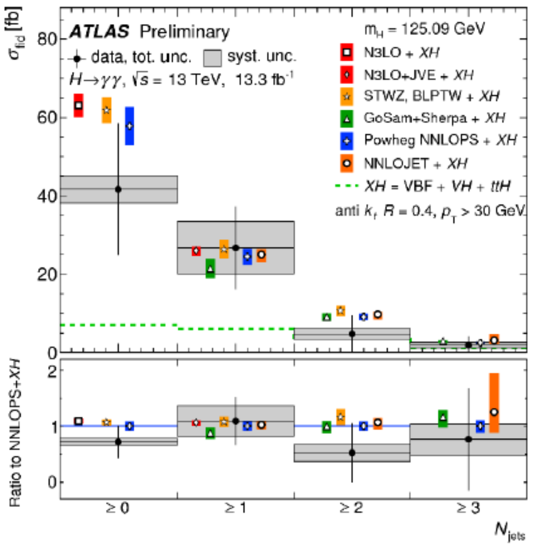
ATLAS-CONF-2016-067
ATLAS-CONF-2016-081
ATLAS-CONF-2016-068

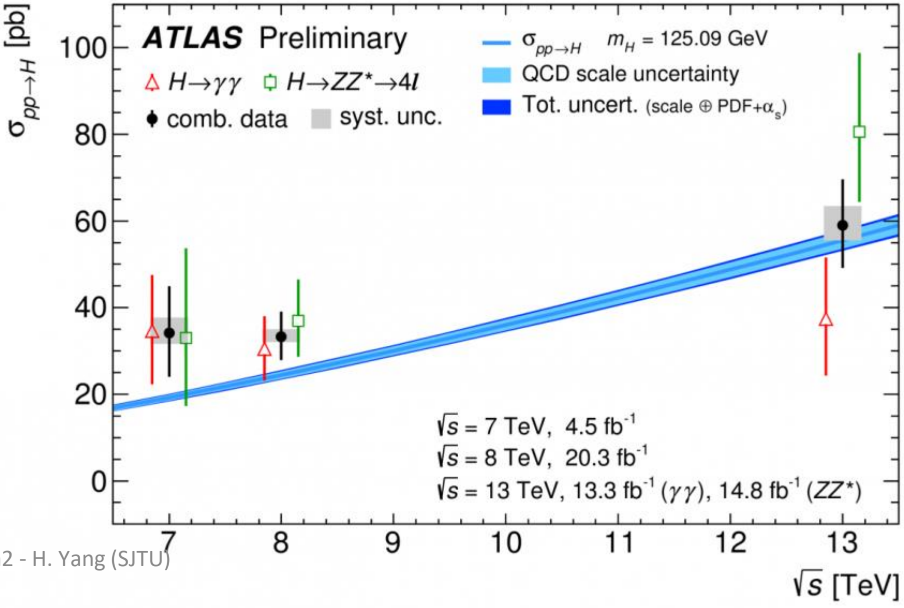


Obs 4.7σ
Exp 5.4σ

13 categorisation: 4(ggF) 2(VBF), 5(VH), 2(ttH)





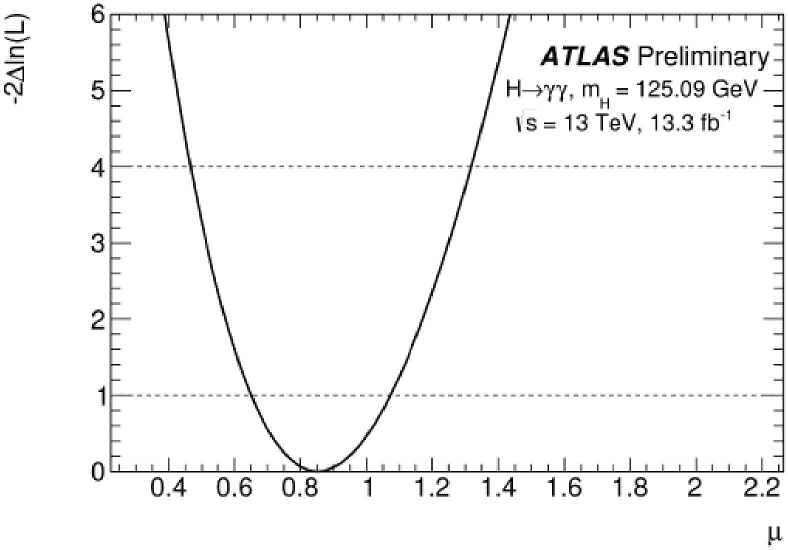


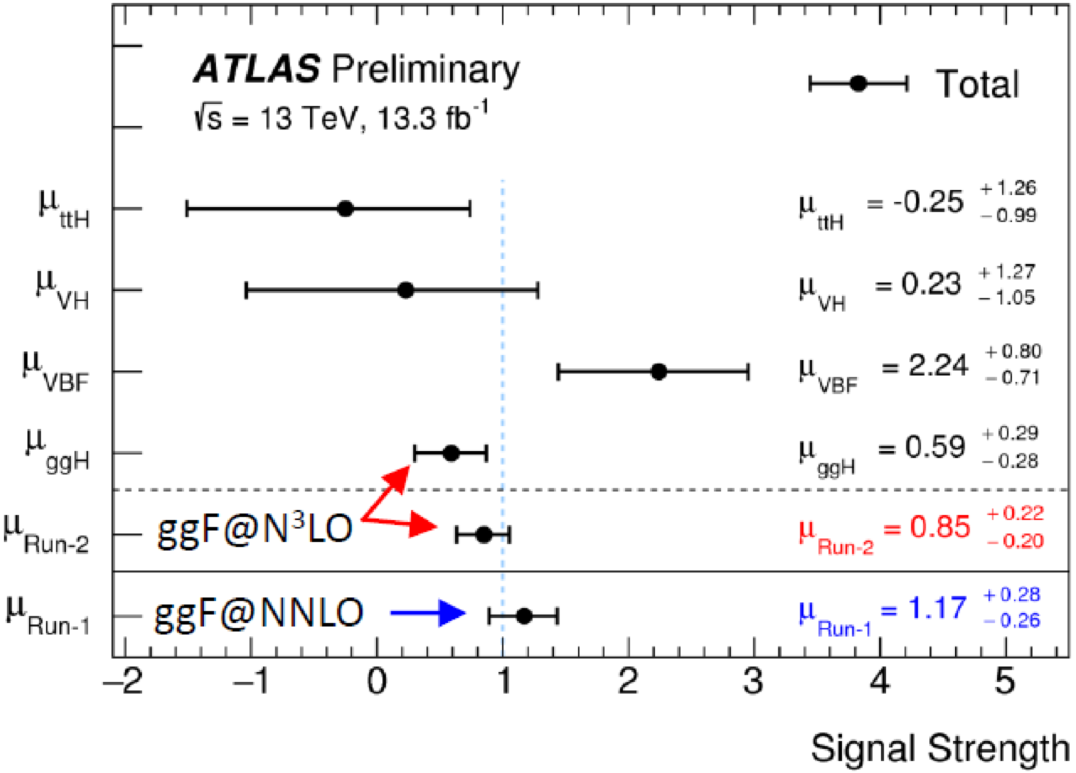
- ● 高能所金山、黄燕萍、彭聪在LHC实验率先开展H→γγ 截面测量研究，在该分析中发挥主导作用，担任Editor，发表多篇文章和 Conf-Note。
- □ 上海交大王子瑞、杨海军参与VH，(H→γγ)事例选择和优化，光子isolation。

ATLAS-CONF-2016-067

Re-discover Higgs → γγ

- Signal strength is obtained for each production mode
- No significant deviation from the SM expectations is observed
- Run1 and Run2 results use NNLO and N^{3}LO calculation for ggF
- N^{3}LO calculation results in ~10% increase of σ_{ggF}.





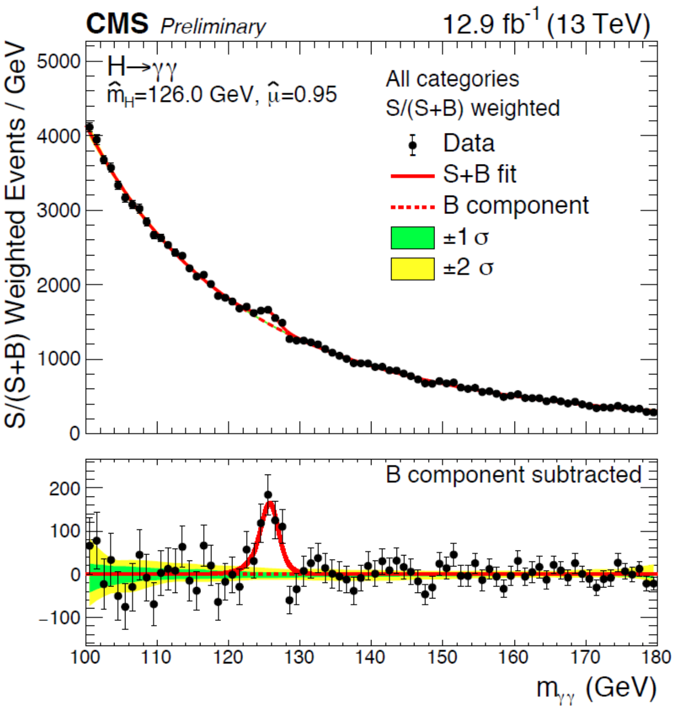
Re-discover Higgs → γγ

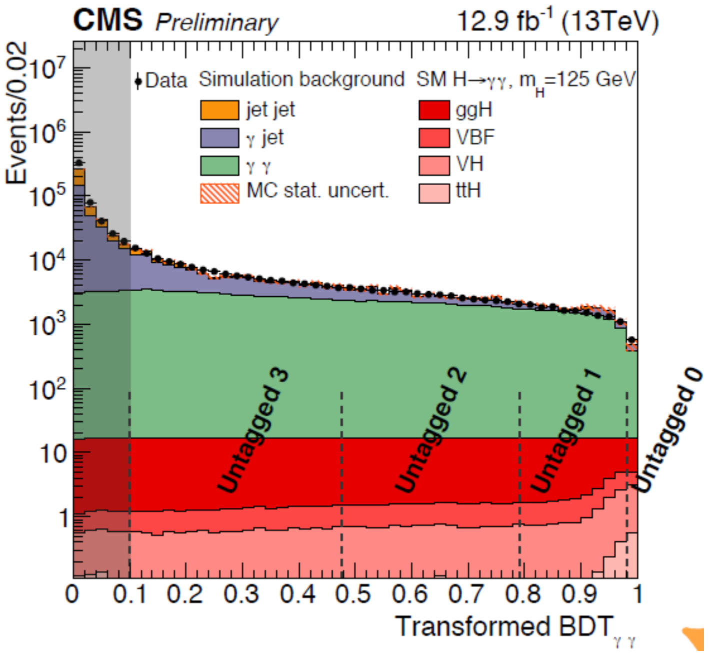
CMS-PAS-HIG-16-020

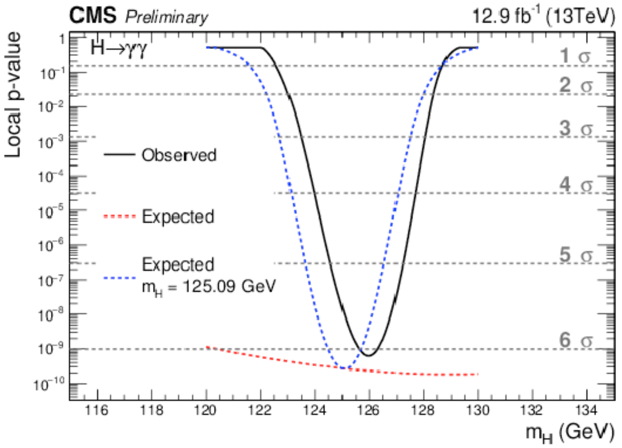
- ➔ H→双光子末态观察到6.1σ，信号强度和截面测量与标准模型吻合。
- ➔高能所陶军全等参与光子鉴别及Z→μμγ检验，担任论文编辑之一。

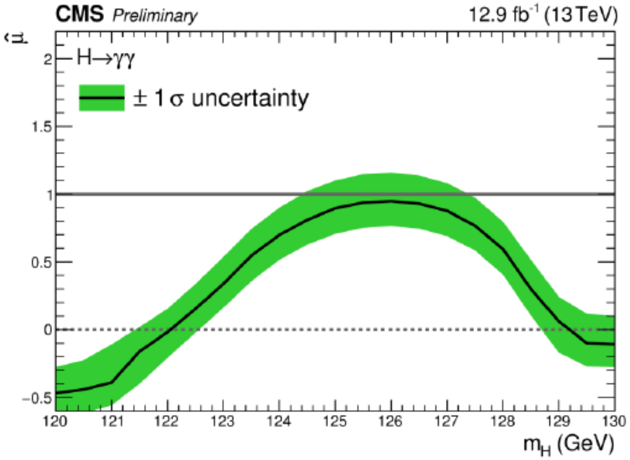
$$\mu = 0.95 \pm 0.20$$

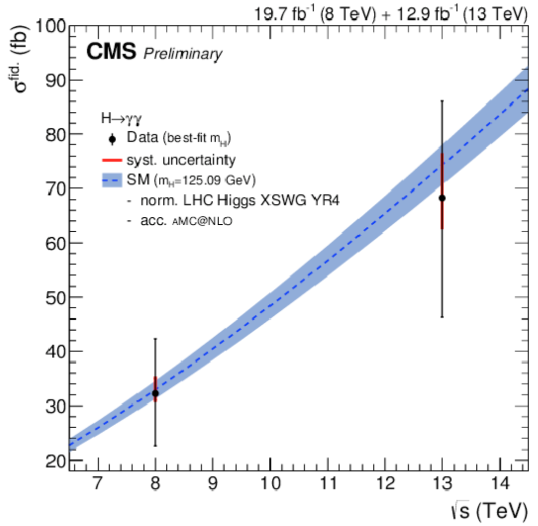
6.1σ at 126 GeV.







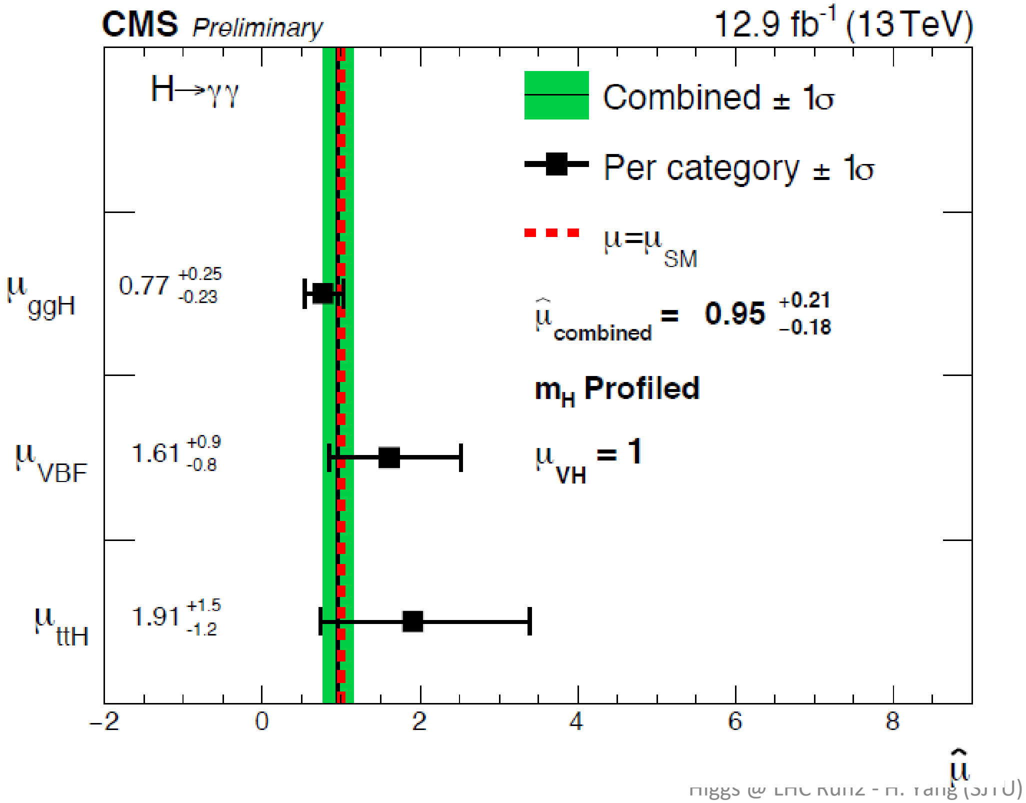


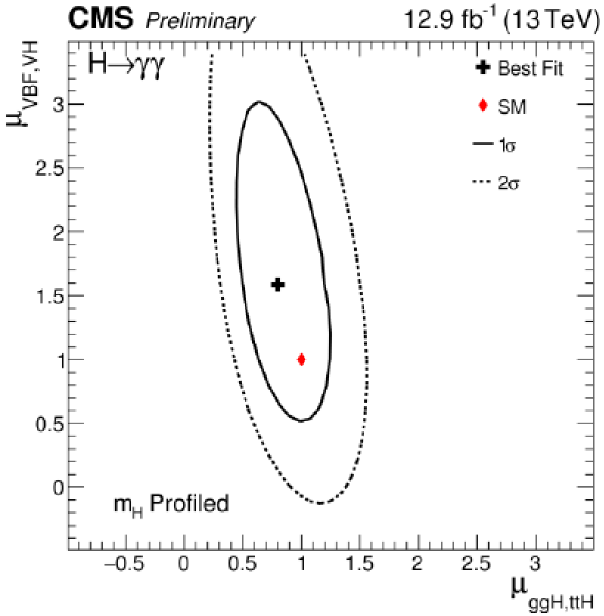


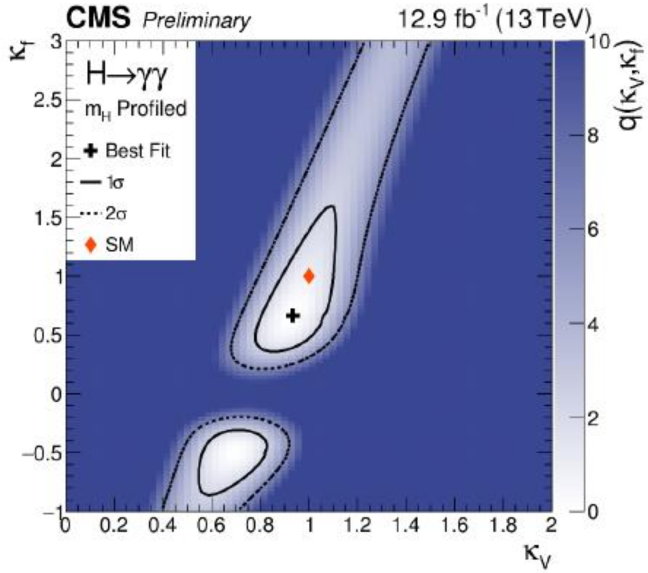
Re-discover Higgs → $\gamma\gamma$

CMS-PAS-HIG-16-020

- Signal strength agrees with SM
- Couplings K_V and K_F are consistent with the SM expectation.







CMS-PAS-HIG-17-011

Anomalous HVV interactions

- Scattering amplitude for a spin-0 boson and two spin-1 gauge bosons $VV\ (= ZZ^*, Z\gamma^*)$

$$\left[\underbrace{a_1^{VV}}_{\text{SM (CP+)}} + \underbrace{\frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{\kappa_3^{VV}(q_1+q_2)_1^2}{\left(\Lambda_Q^{VV}\right)^2}}_{\text{BSM (CP+)}}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \underbrace{a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{BSM (CP+)}} + \underbrace{a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{BSM (CP-)}}$$

Anomalous Coupling	Coupling Phase	Effective Fraction	Translation Constant
a_3	ϕ_{a3}	f_{a3}	$\sigma_1/\sigma_3 = 6.53$
a_2	ϕ_{a2}	f_{a2}	$\sigma_1/\sigma_2 = 2.77$
Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$	$\sigma_1/\tilde{\sigma}_{\Lambda 1} = 1.47 \times 10^4\ \text{TeV}^{-4}$
$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	$\sigma_1'/\tilde{\sigma}_{\Lambda 1}^{Z\gamma} = 5.80 \times 10^3\ \text{TeV}^{-4}$

Effective fractions

$$f_{aj} = \frac{|a_j|^2 \sigma_j}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\ \sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\ \sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \cdots}$$

Coupling phases

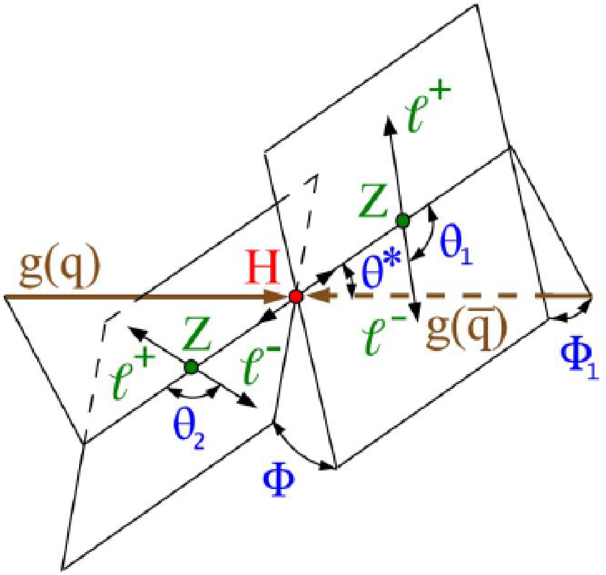
$$\phi_{aj} = \arg\left(\frac{a_j}{a_1}\right)$$

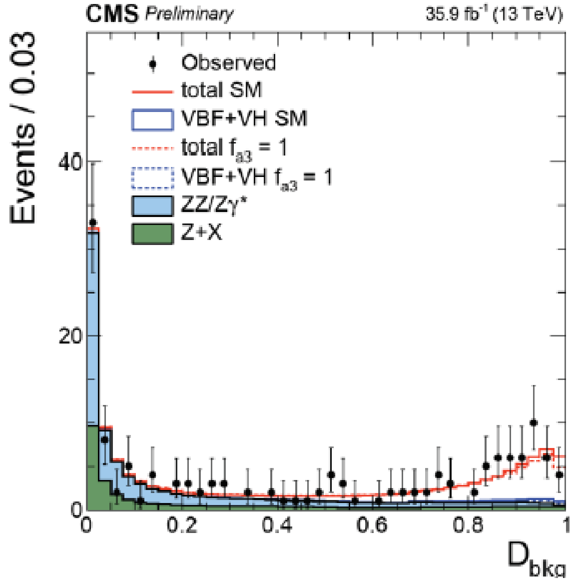
$$\phi_{\Lambda 1}$$

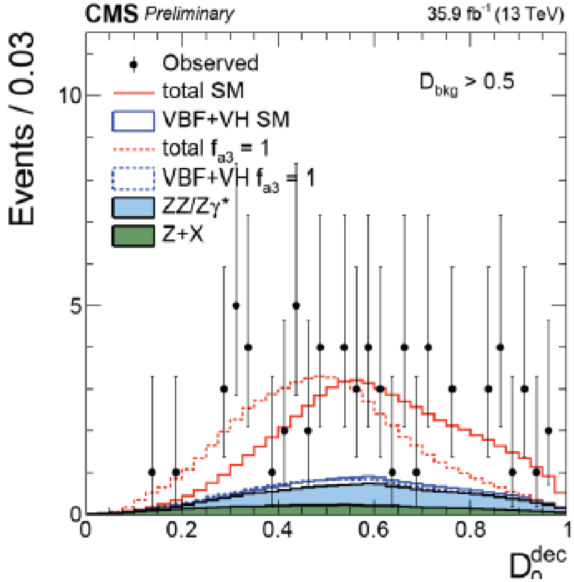
CMS-PAS-HIG-17-011

Anomalous HVV interactions

- The full kinematic information from each event using either the spin-0 boson **decay** or associated particles in its **production** is extracted using matrix element calculations.
  - Up to 13 observables
- Three types of discriminants are defined for either production or decay.
  - Separate signal and background
  - Separate SM and BSM contributions
  - Isolate SM-BSM interference contributions



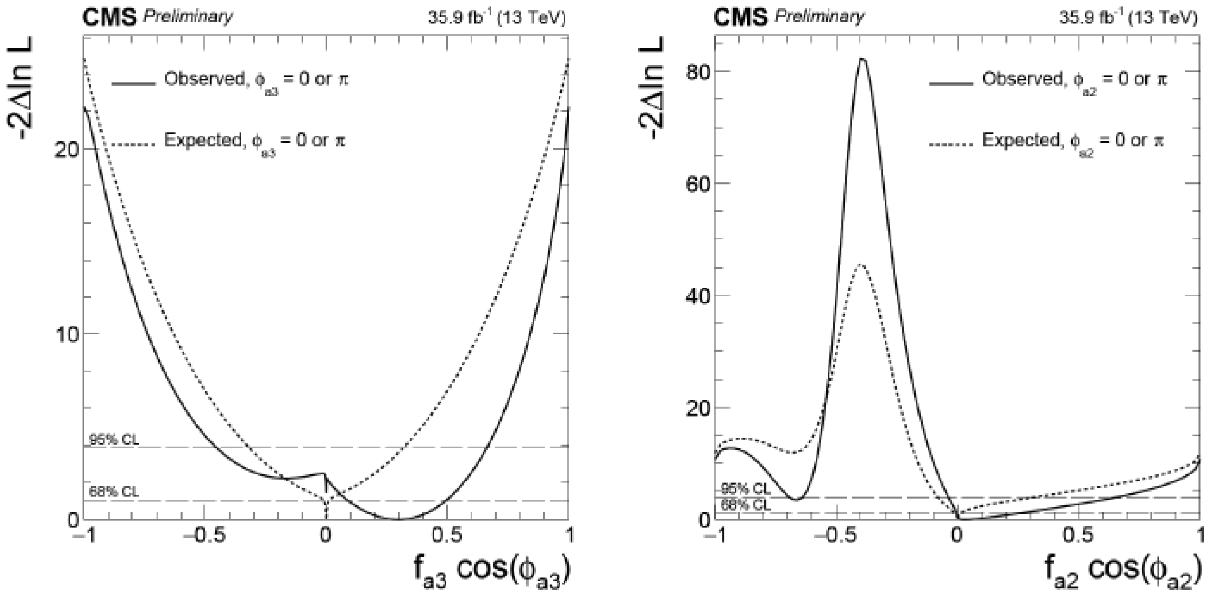




CMS-PAS-HIG-17-011

Anomalous HVV interactions

NEW



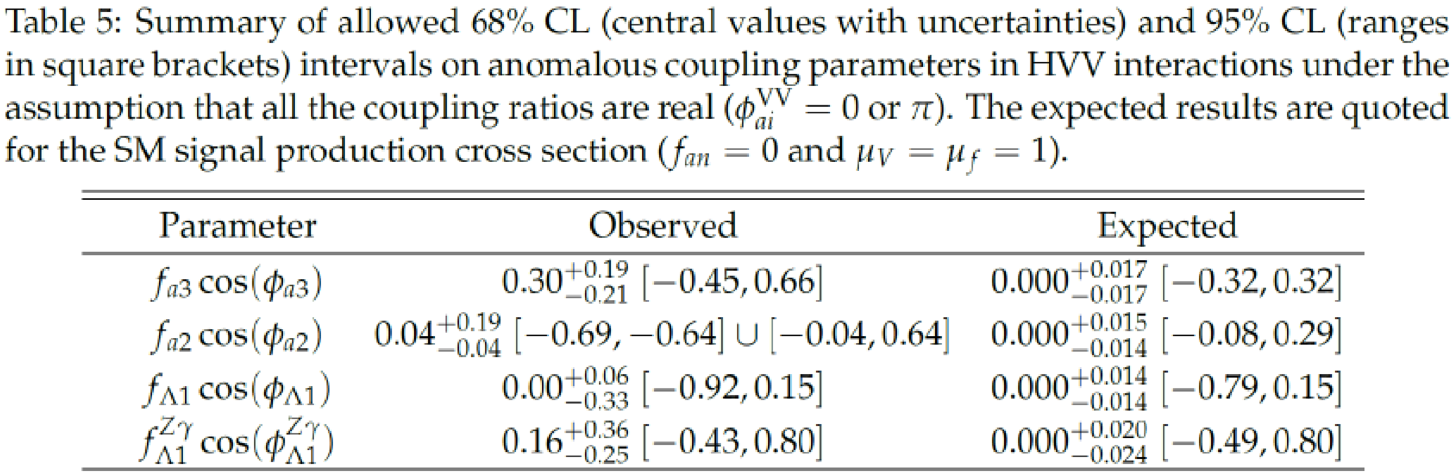


Table 5: Summary of allowed 68% CL (central values with uncertainties) and 95% CL (ranges in square brackets) intervals on anomalous coupling parameters in HVV interactions under the assumption that all the coupling ratios are real ($\phi_{ai}^{VV} = 0$ or π). The expected results are quoted for the SM signal production cross section ($f_{an} = 0$ and $\mu_V = \mu_f = 1$).

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$

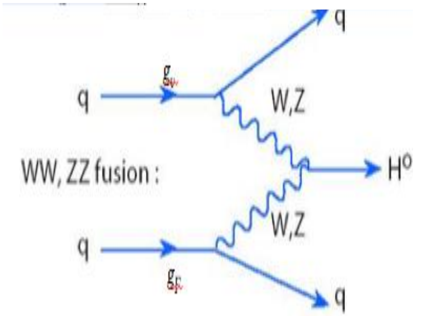
All observations are consistent with the SM expectations.

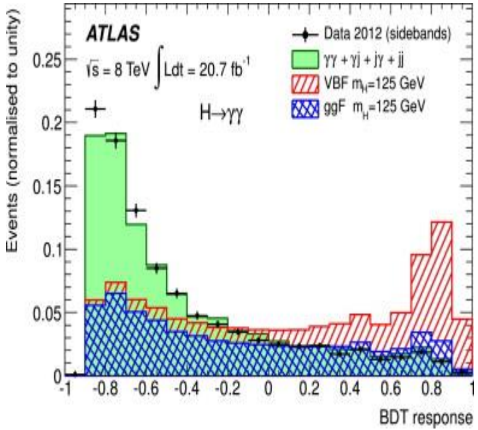
Search for VBF Higgs

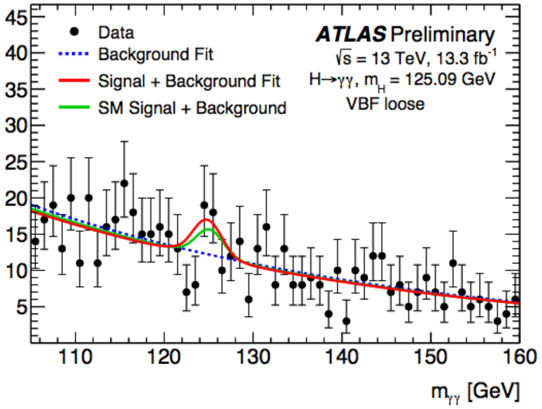
ATLAS-CONF-2016-068
ATLAS-CONF-2016-063

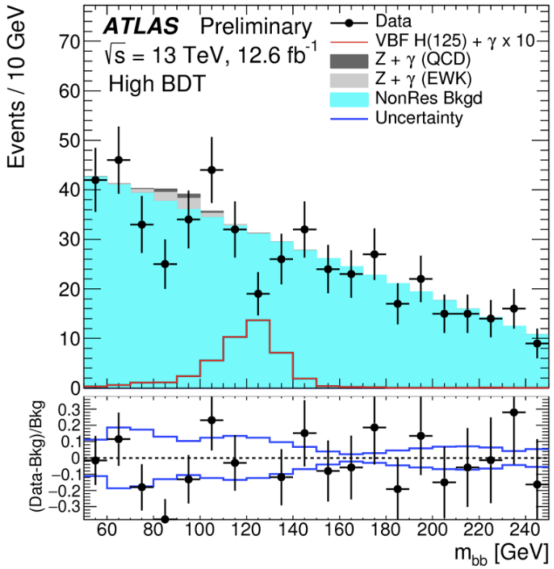
- VBF 是希格斯粒子产生的第二大机制，能否在实验上观测到VBF Higgs是希格斯发现后重要研究课题之一。
- 高能所方亚泉、章宇、娄辛丑率先提出多变量方法BDT分析VBF H→γγ。担任分析的Contact和文章editor，发挥主导作用，已发表多篇文章和Conf-Note。

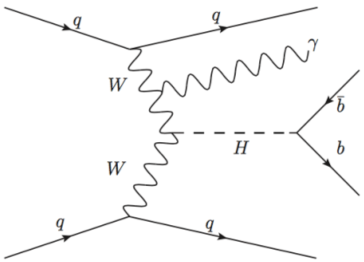
$$\mu_{\mathrm{VBF}} = 2.10\,^{+0.89}_{-0.79} = 2.10\,^{+0.84}_{-0.76}\,(\mathrm{stat.})\,^{+0.29}_{-0.22}\,(\mathrm{syst.})\,^{+0.08}_{-0.04}\,(\mathrm{theory})$$











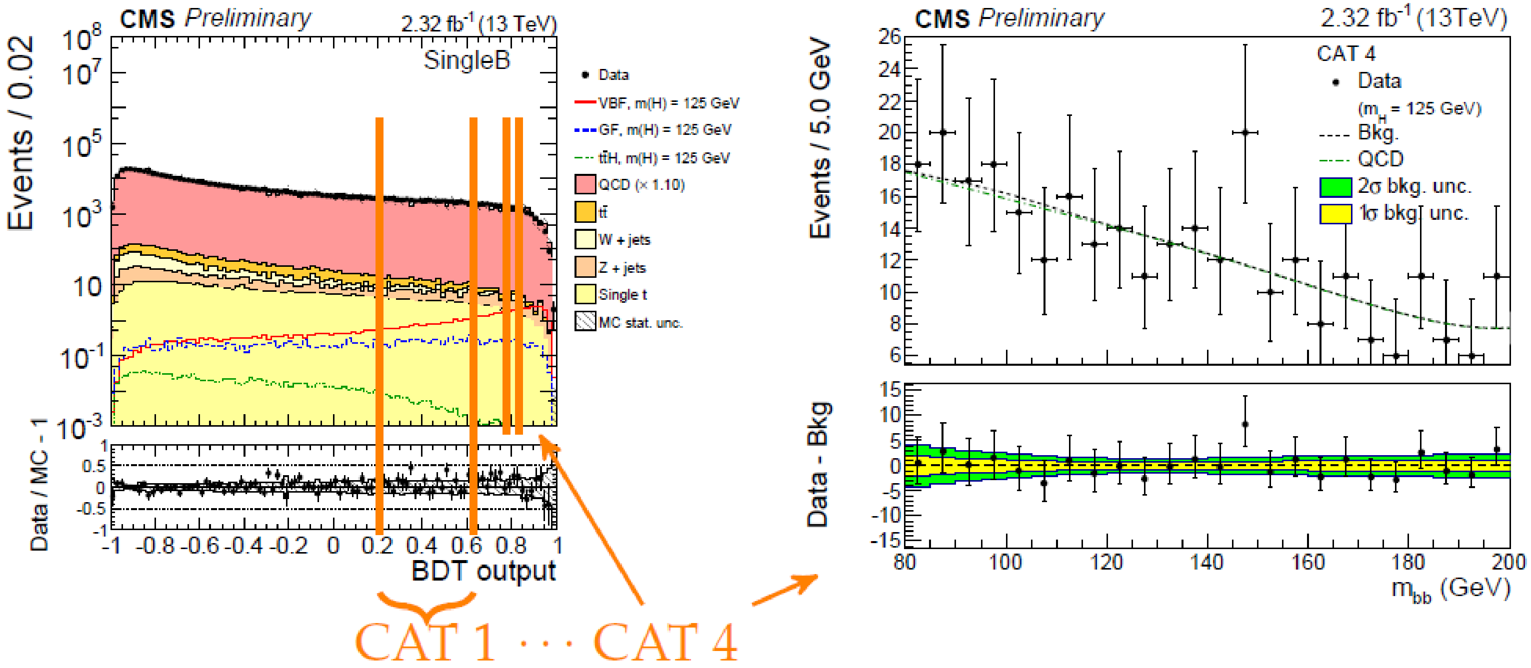
$$\mu = -3.9^{+2.8}_{-2.7}$$

- 目前唯一可以区分WWH 与ZZH的贡献的分析是H(→bb)γ，
- 高能所梁志均, Javier Llorente Merino 率先提出该分析，并担任分析的Contact，給Approval报告，发挥主导作用。

Search for VBF H→bb

CMS-PAS-HIG-16-003

Multivariate classifier to identify VBF like events for events with 1 and 2 b-tagged jets:



Signal extract in simultaneous fit to $m_{b\bar{b}}$ spectrum in all categories.

Result using 2.3 fb^{-1} @ $\sqrt{s} = 13$ TeV: $\mu = -3.7^{+2.4}_{-2.5}$

Combination with Run I (18 – 19 fb^{-1} @ 8 TeV): $\mu = 1.3^{+1.2}_{-1.1}$

Search for VH, H→bb

ATLAS-CONF-2016-091

- 测量H->bb衰变分支比和汤川耦合
- 按照末态轻子，喷注数和运动学划分信号区，采用BDT降低本底。

➔ 科大李昌樵、陈程、刘衍文 (b-tagging, CxAOD，BDT分析，统计分析)

➔ 山大马延辉、马连良 (WH→lνbb, b-tagging, top本底估计)

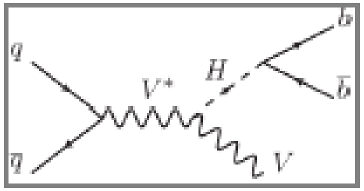
➔ 高能所单连友参与WH→WWW*分析

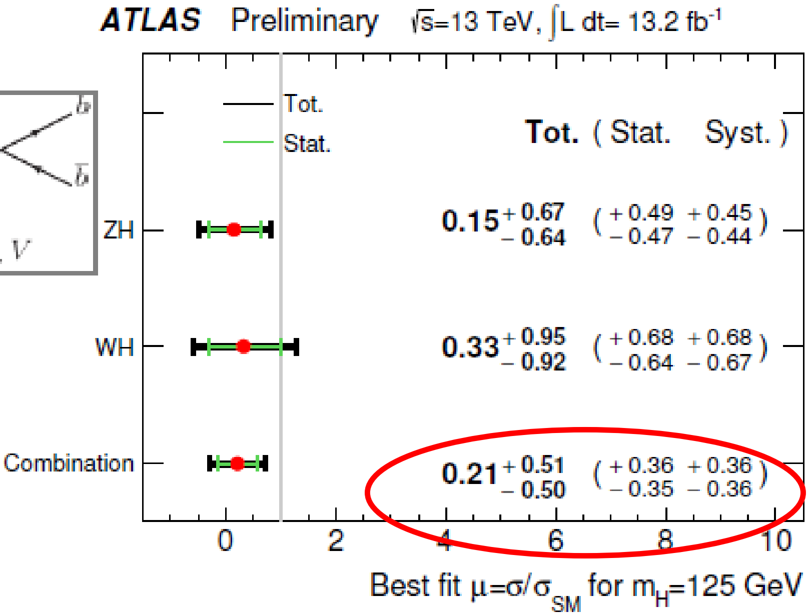
➔ 南大王超、陈申见 (A→ZH)

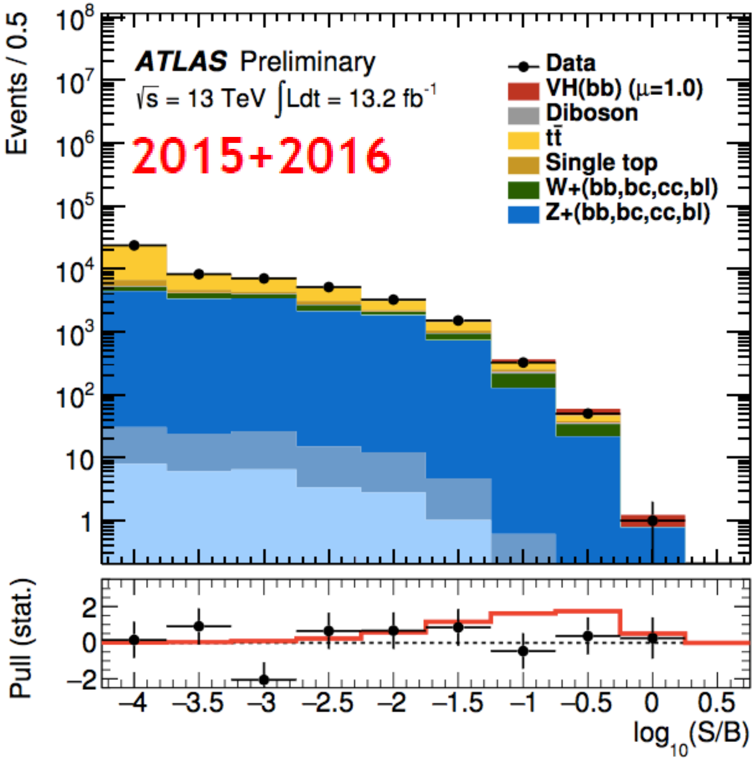
➔ 交大Nataliia、郭军、杨海军 (A→ZH→ννbb分析)

Run1: ATLAS+CMS combined
H→bb 2.6σ (exp. 3.7σ)

Run2: 13 TeV (2015+2016)
Z→ll, W→lν, Z→νν
ATLAS 0.4σ (exp. 1.9σ)



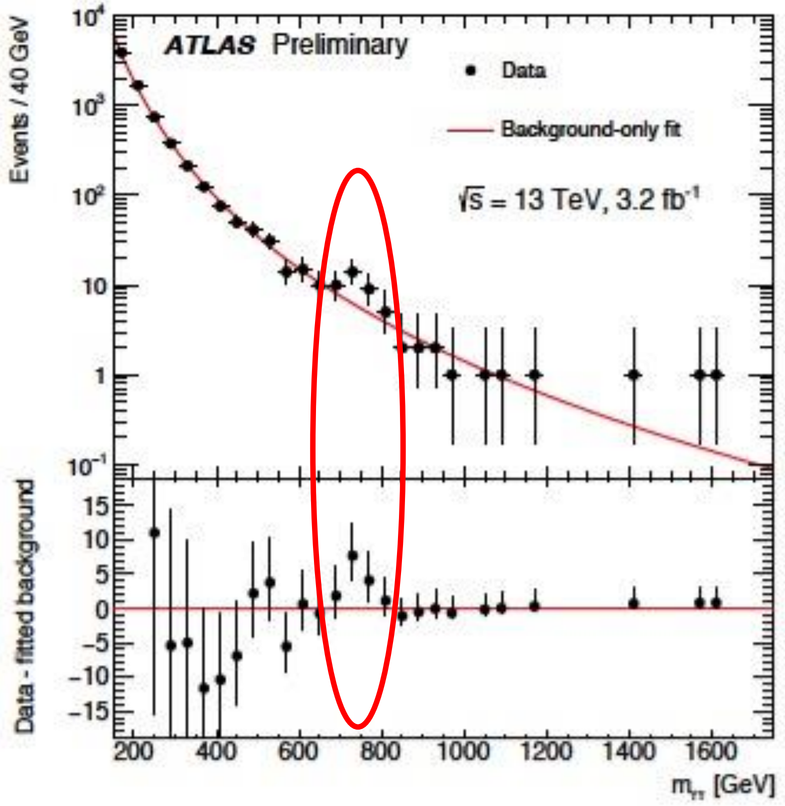


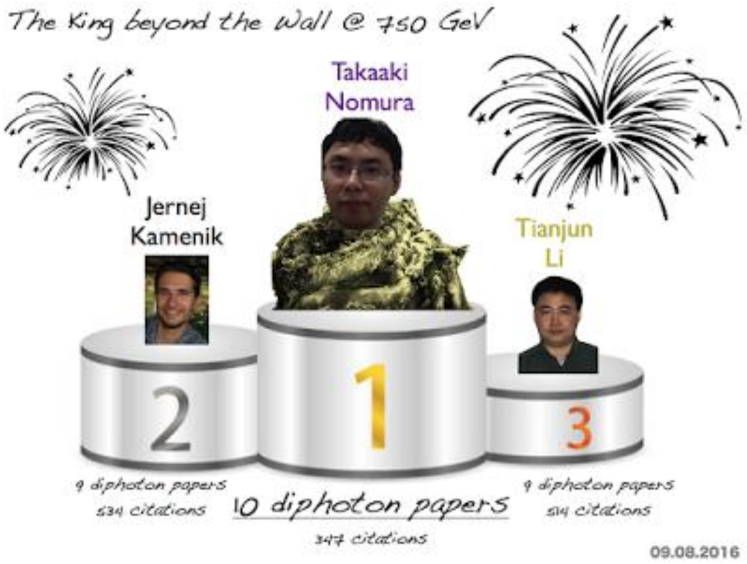


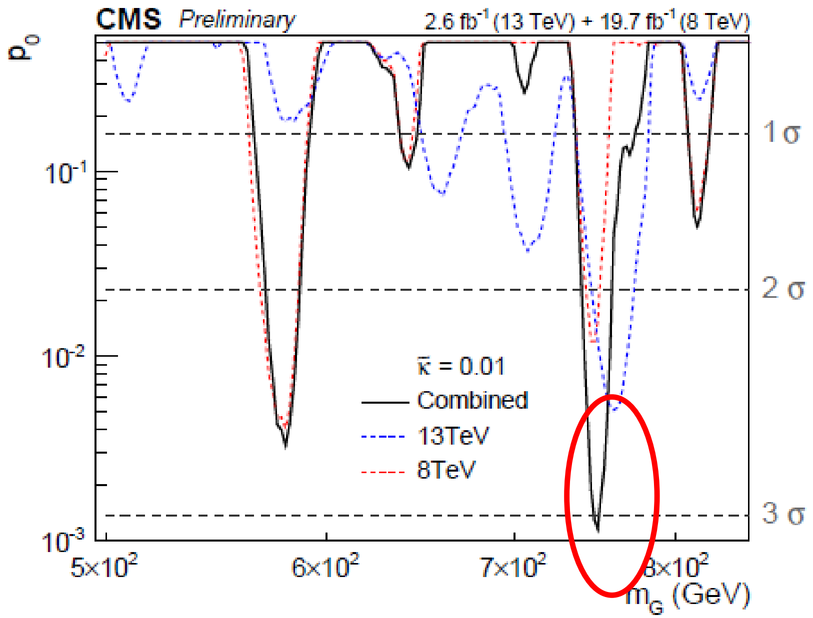
*Search for X → γγ

ATLAS-CONF-2016-018
arXiv:1606.03833
CMS-PAS-EXO-15-004

- 寻找高质量共振态粒子，2015年在LHC实验数据中ATLAS和CMS观测到750GeV附近分别约有3.4 σ和 3.0σ超出，引起了理论家的广泛兴趣！

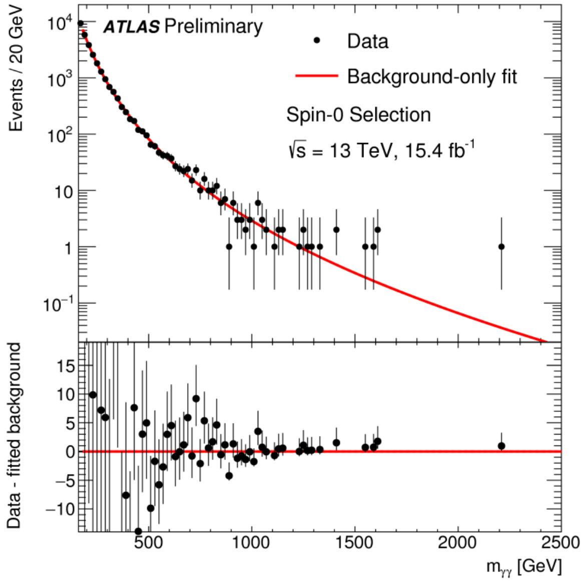


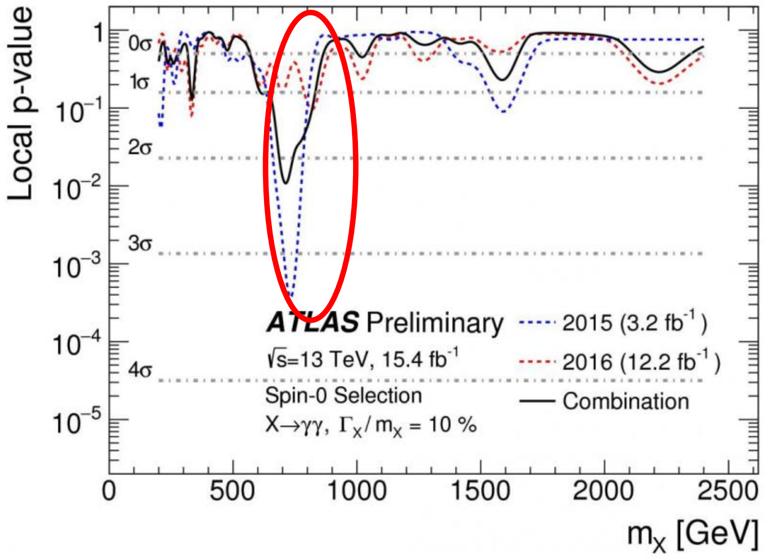


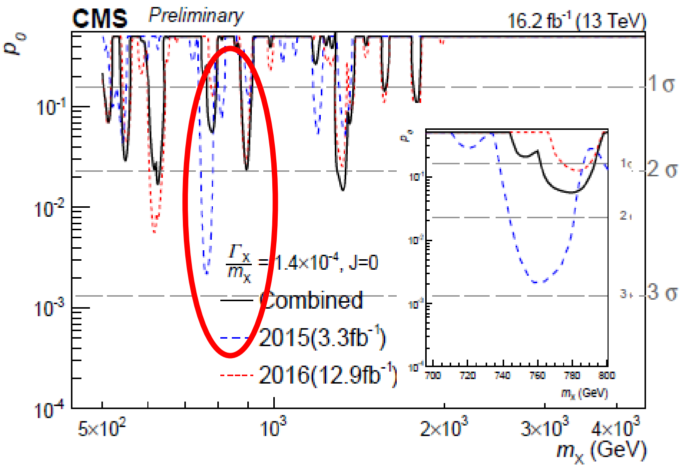


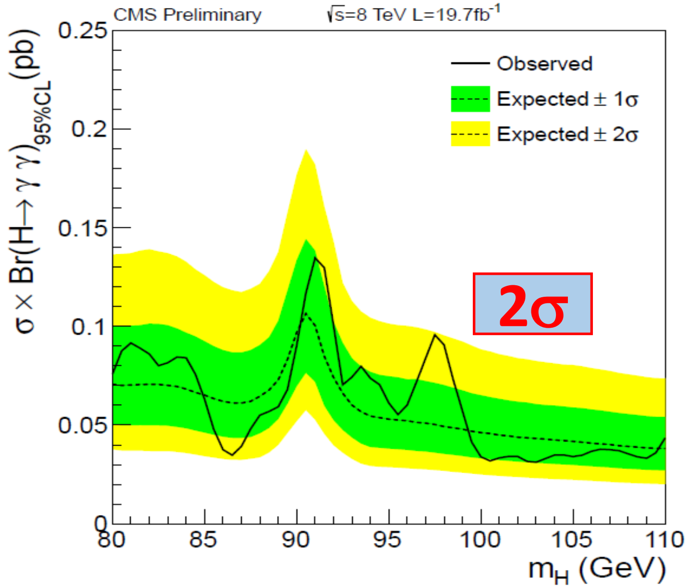
*Search for X → γγ

ATLAS-CONF-2016-018/059
JHEP 09 (2016) 1
CMS-PAS-EXO-16-027









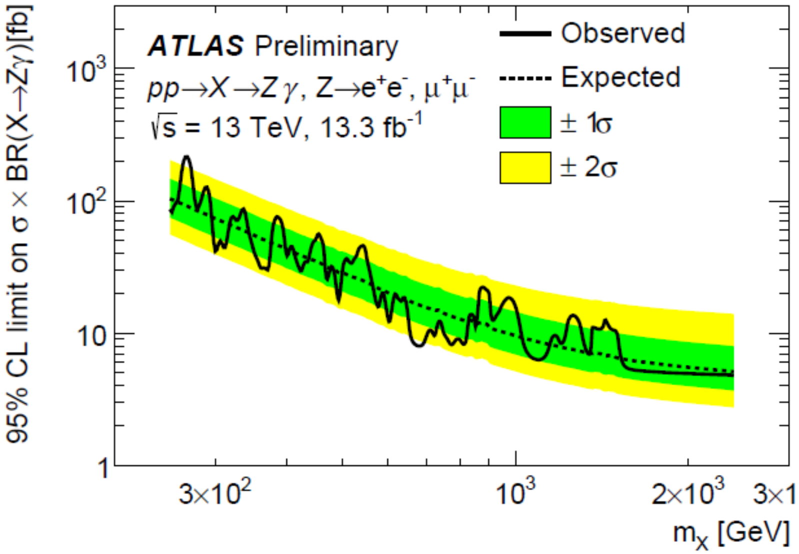
ATLAS和CMS最新的Run2数据中都没有观测到750GeV 附近有显著超出！

- ➢高能所金山、黄燕萍、彭聪、冉坤林、韩朔、方亚泉、章宇、娄辛丑等做出重要贡献，包括本底估计、多喷注分类、CR研究和统计分析等。
- ➢交大王子瑞、杨海军参与光子isolation研究
- ❖高能所CMS组主导低质量双光子分析，范嘉伟完成主要分析。

*Search for X → Zγ

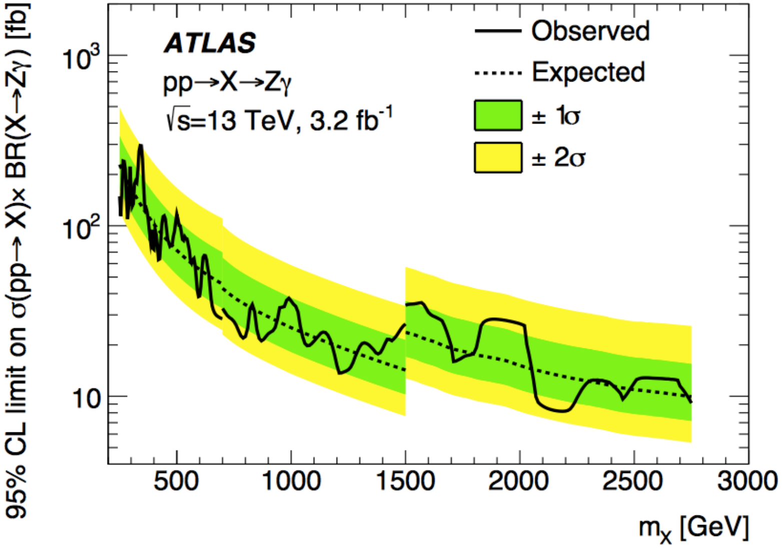
ATLAS-CONF-2016-044
arXiv:1607.06363

- Zγ末态有可能发现类似Higgs粒子的高质量的新粒子。
- 高能所金山、黄燕萍、韩朔主导完成了Z→ee,μμ分析的全过程，事例选择，信号显著性优化，信号建模，本底组成分析，系统误差、统计分析。
- 担任Contact editor 发挥主导作用，已投送1篇 (arXiv:1607.06363)



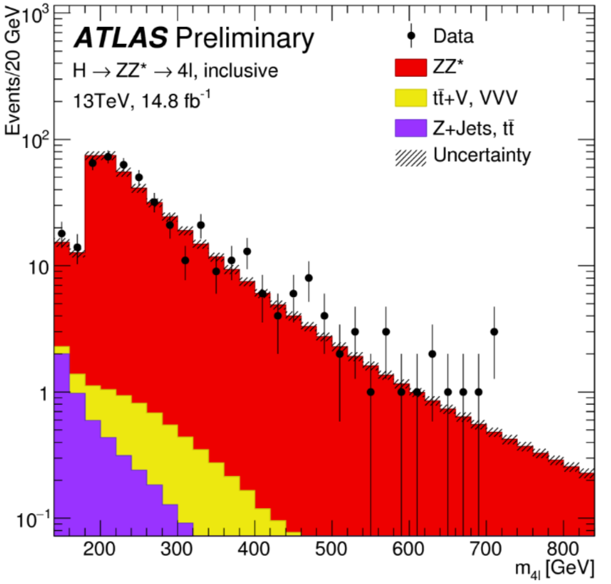
✓ 高能所梁志均、孙小虎、方亚泉分析Z→di-jet末态，主要贡献：估计本底；信号效率的误差估计；统计分析。

● 担任分析的Contact，文章editor，給 approval talk, 在该分析中发挥主导作用。已投送一篇 PLB (arXiv:1607.06363)

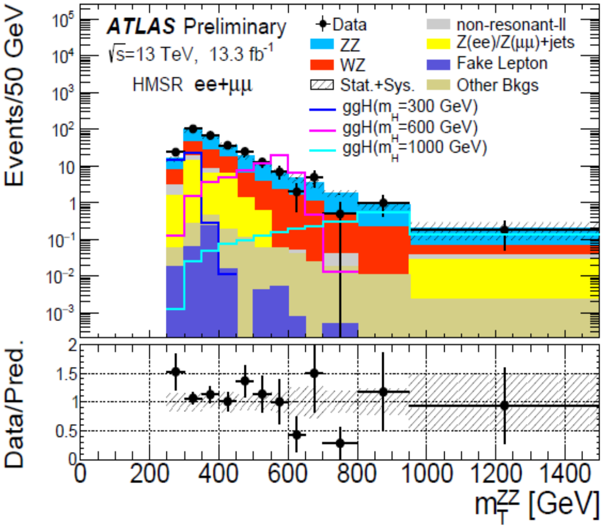


Search for Heavy H →ZZ

ATLAS-CONF-2016-079/056
EPJC76(2016)45
CMS-PAS-HIG-16-033



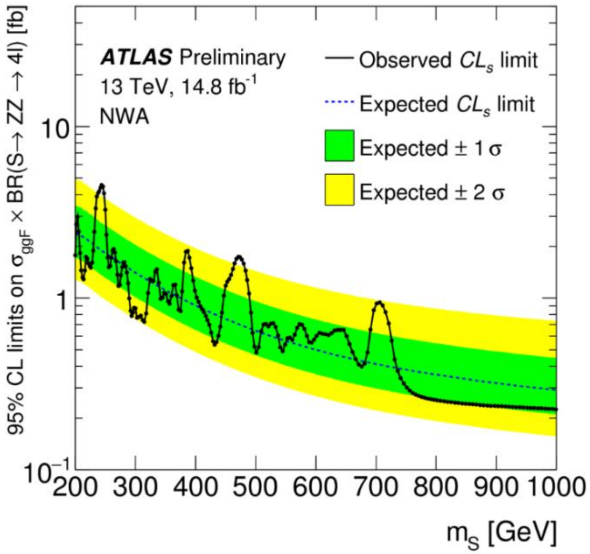
H→ZZ*→4l

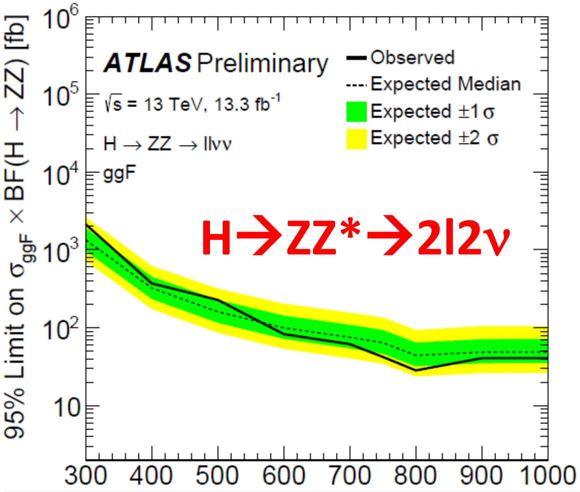


➔交大杨海军和Marc参与H➔ZZ*➔ 4l末态分析，山大刘波和冯存峰参与 2l2ν分析，作 Approval 报告。

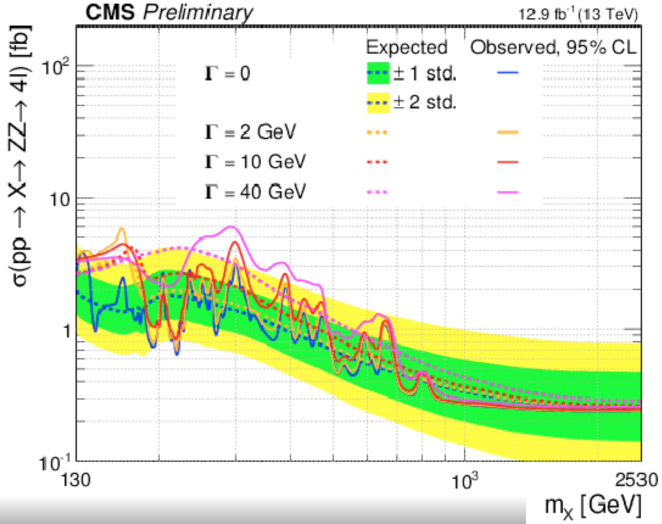
➔南京大学李依宸、王超、陈申见等参与高质量希格斯衰变WW/ZZ的寻找。

➔高能所陈明水、成瞳光参与CMS H➔ZZ高质量共振态分析。





H→ZZ*→2l2ν

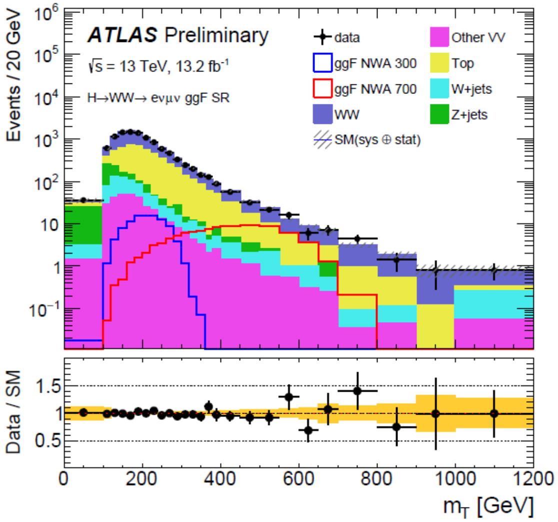


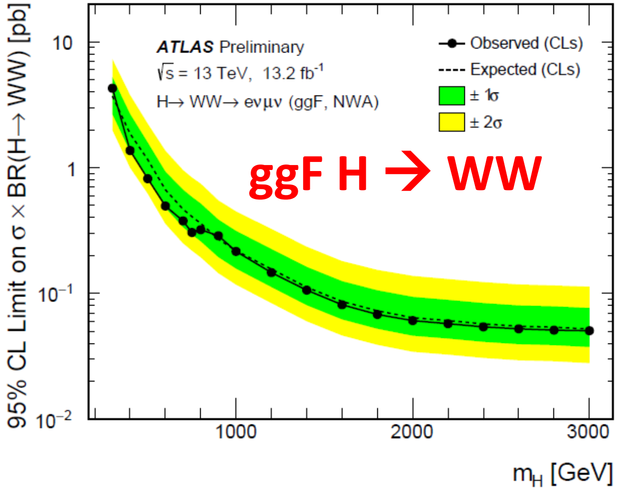
Search for H → WW

ATLAS-CONF-2016-085
ATLAS-CONF-2016-074
ATLAS-CONF-2016-021
ATLAS-CONF-2016-089

➔ 寻找超出标准模型的重希格斯粒子(末态lνlν)，检验NWA/LWA两种模型。
科大韩坤霖，胡启鹏，朱莹春参与系统误差研究，W+jet本底估计。
山大赵永柯、宋维民、马连良、张学尧主导H→WW→eνμν分析，负责事例优化，信号区间和本底控制区间定义，主要本底误差估计等。

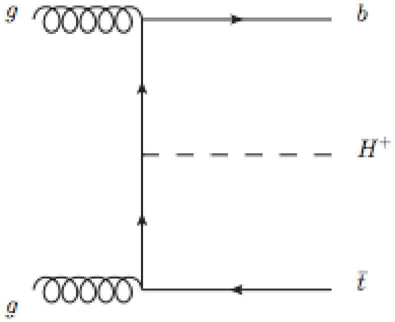
没有发现BSM超重希格斯粒子的迹象

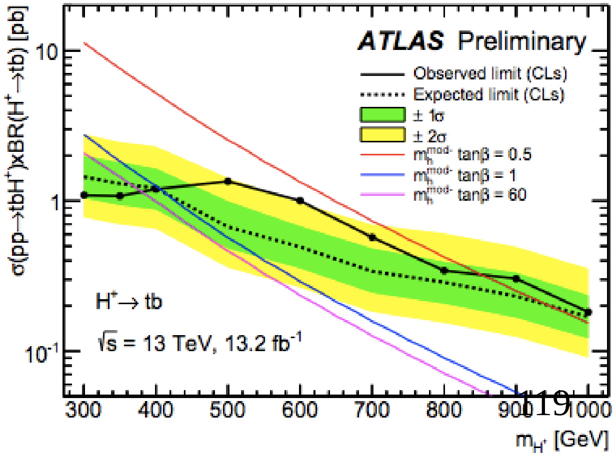




ggF H → WW

- ➔ H^+ → tb → e(mu) + jets
- ➔ Split signal regions by Njets
- CR: 4j2b, 4j>=3b, 5j2b, >=6j2b
- SR: 5j3b, 5j>=4b, >=6j3b, >=6j>=4b
- Use HT_had in CR, BDT in SR
- ➔ 山大杨轩、冯存峰参与分析

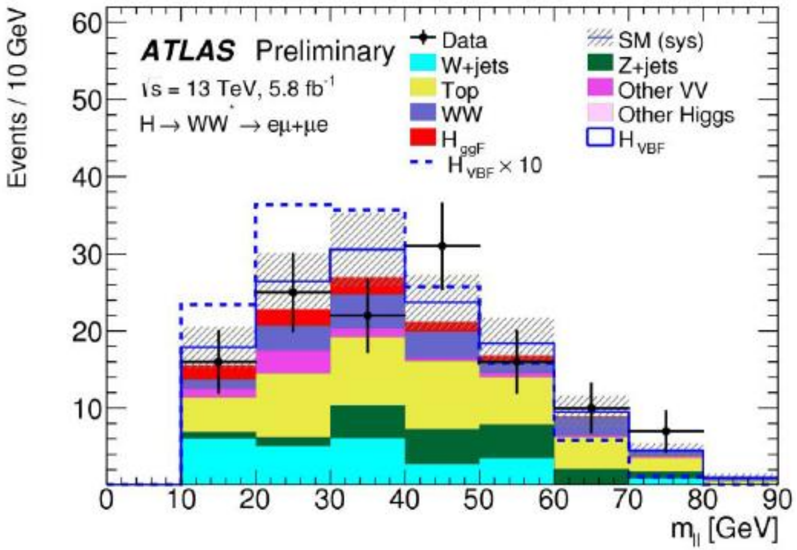


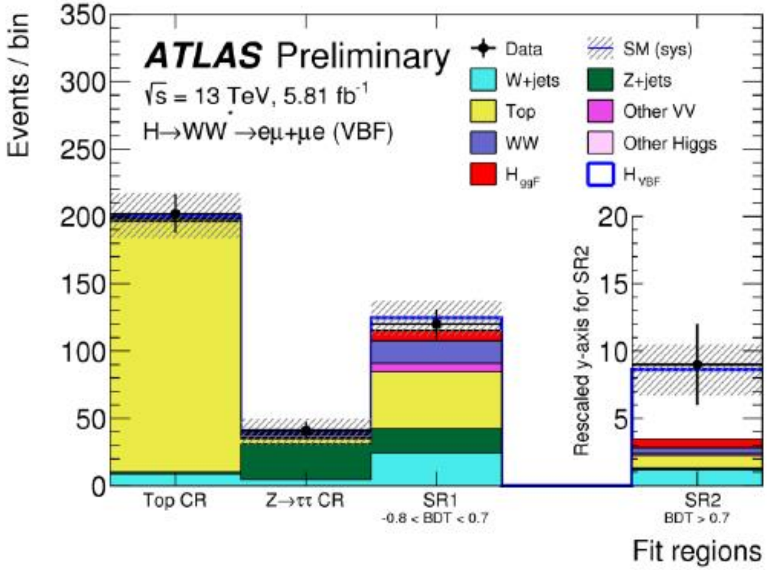


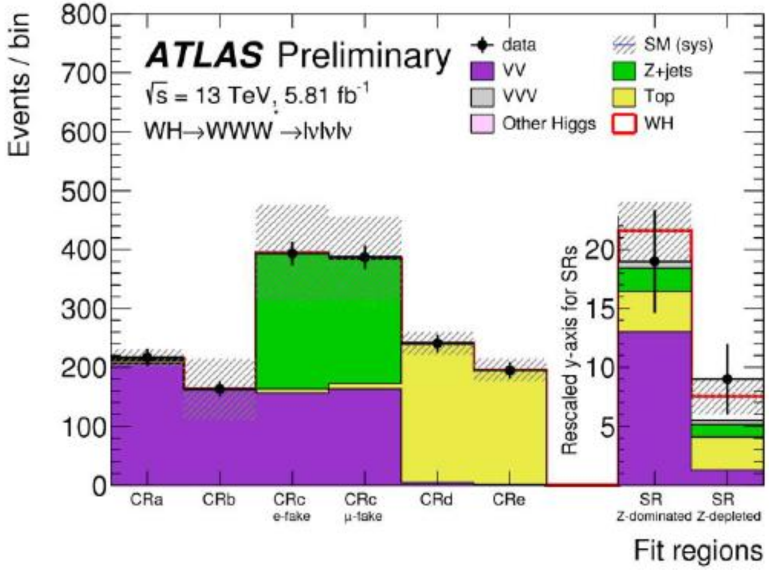
Higgs → WW*

ATLAS-CONF-2016-112

- VBF and WH production modes are studied.
- Events are categorized based on jet and lepton multiplicity.
- $\mu_{VBF} = 1.7^{+1.1}_{-0.9}$, $\mu_{WH} = 3.2^{+4.4}_{-4.2}$
  - Consistent with the SM

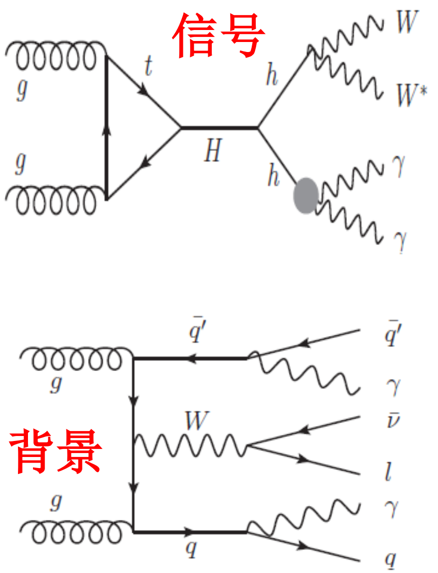


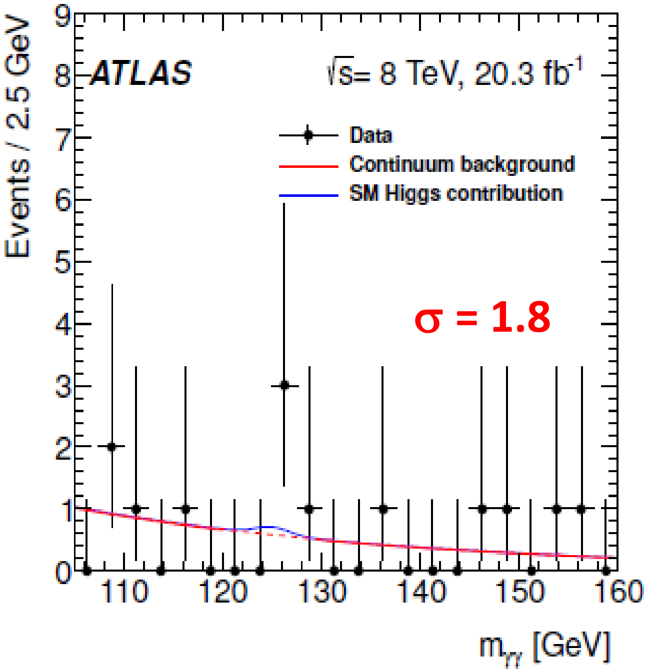


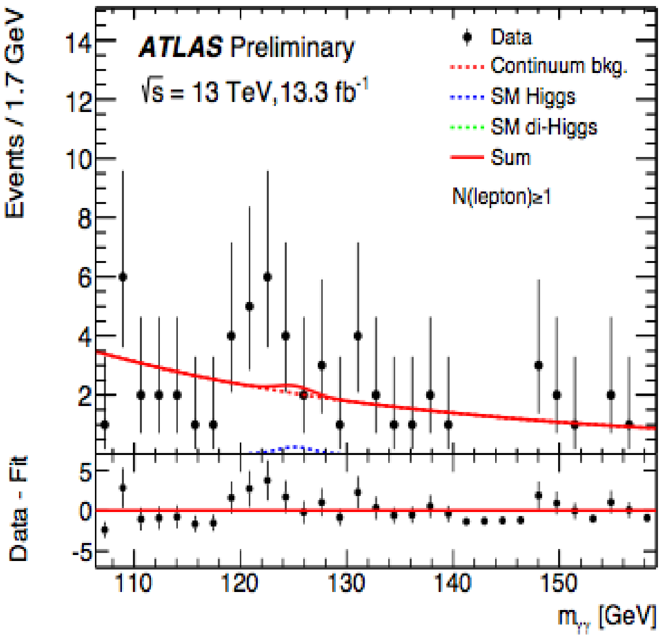


Search for H→hh→WWγγ

ATLAS-CONF-2016-071
PLB755 (2016) 509
PRD92, 092004 (2015)

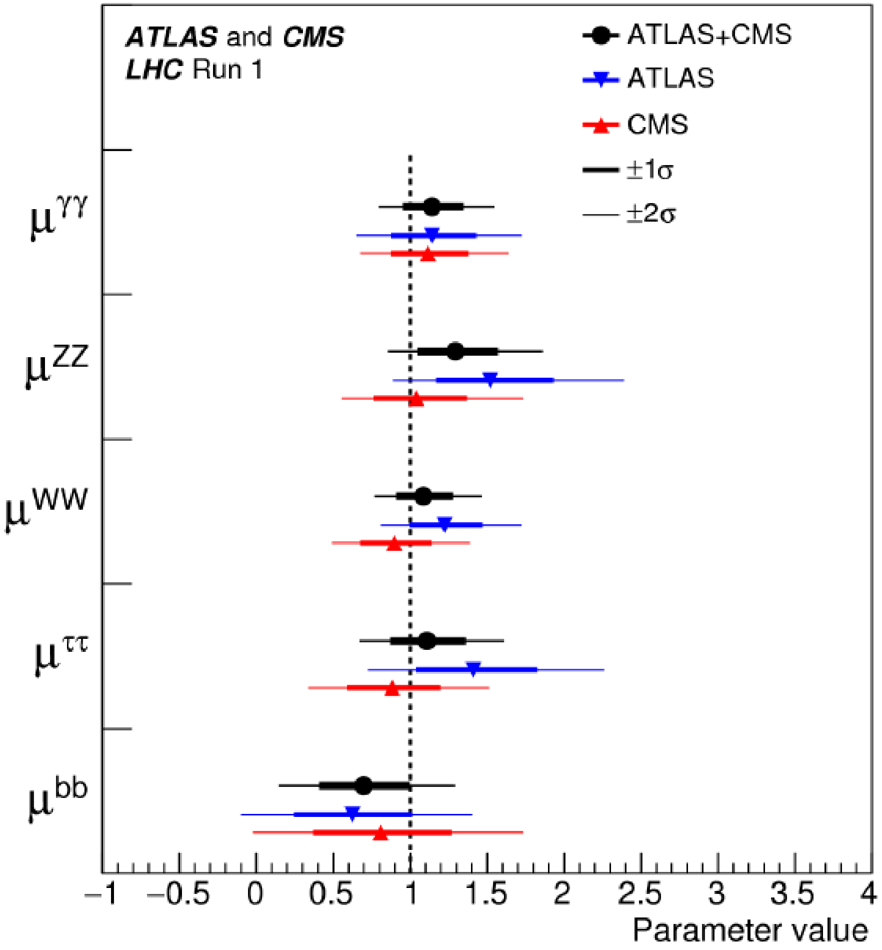


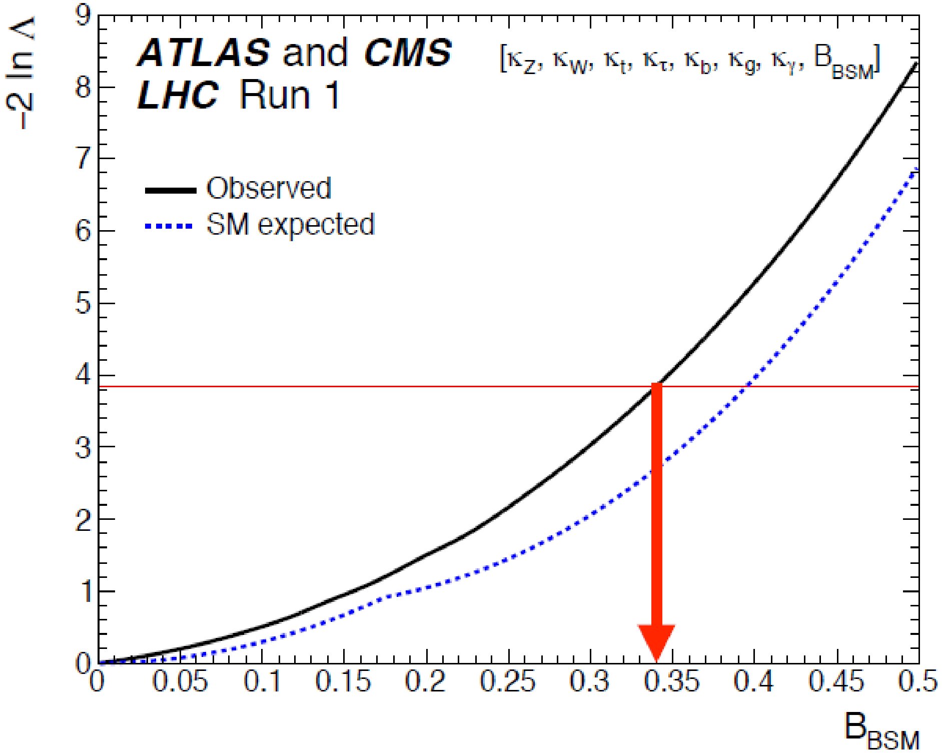




- 高能所方亚泉、孙小虎、娄辛丑、李奇、周茂森等提出寻找重希格斯衰变到两个希格斯粒子，并进一步衰变到双光子和两个W玻色子 (W全轻子或者半轻子衰变)。
- 在Run1分析中，高能所提出和主导该课题，并完成半轻子衰变道分析，观测到1.8σ，发表文章两篇。Run2继续分析。
- Run2，交大李亮和李兴国与高能所方亚泉等开展hh→WWWW分析。

Search for Higgs BSM Decays





JHEP 08 (2016) 045, arXiv:1606.02266

Available measurements are only able constrain BSM decays to < 34%