Discovery of Higgs boson at LHC

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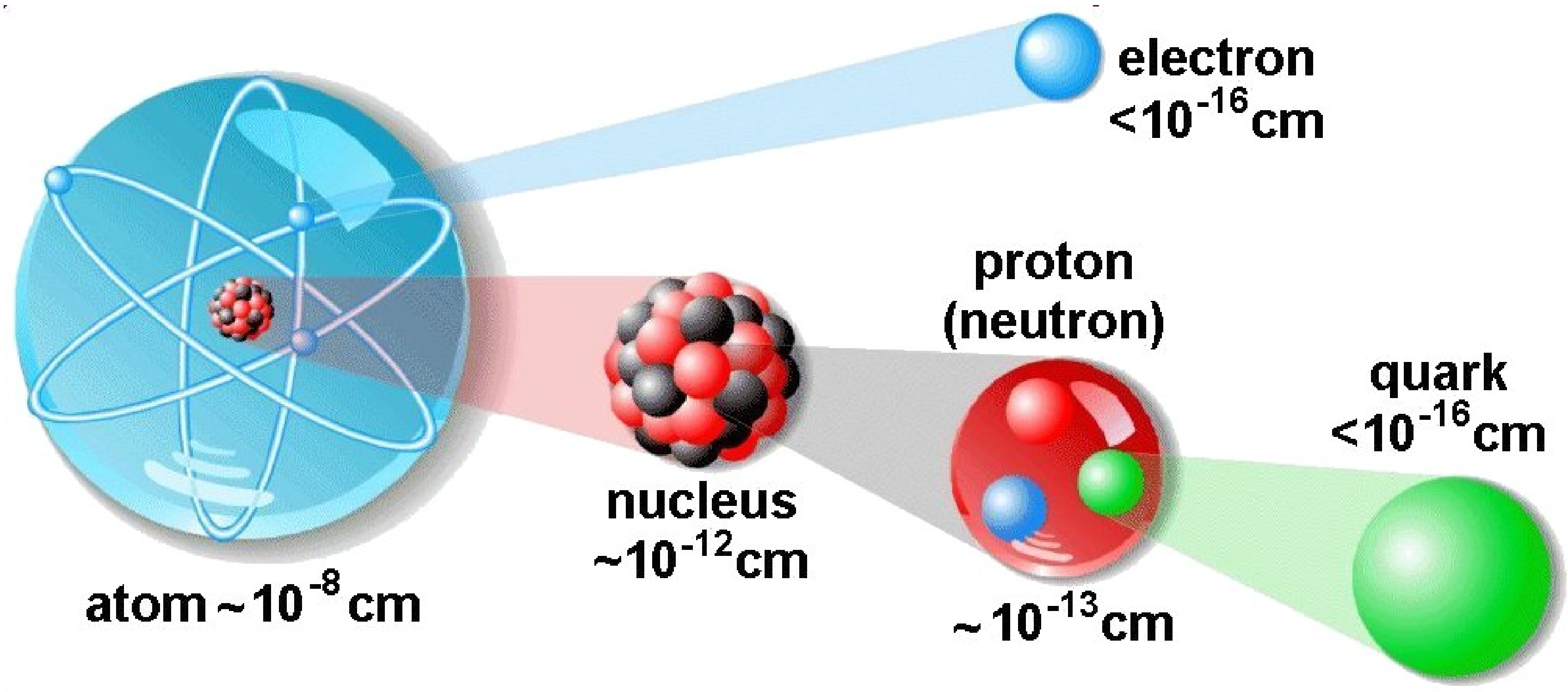
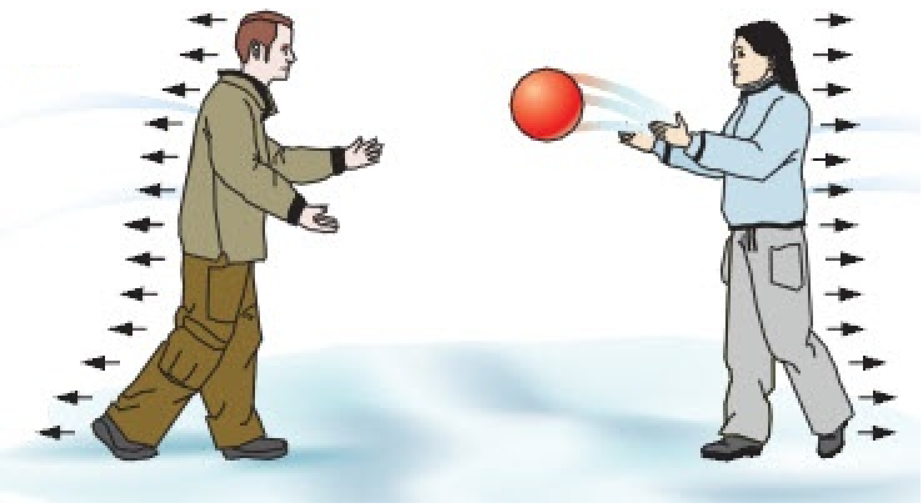
Colloquium at Department of Physics
Shanghai Jiao Tong University
September 12, 2012

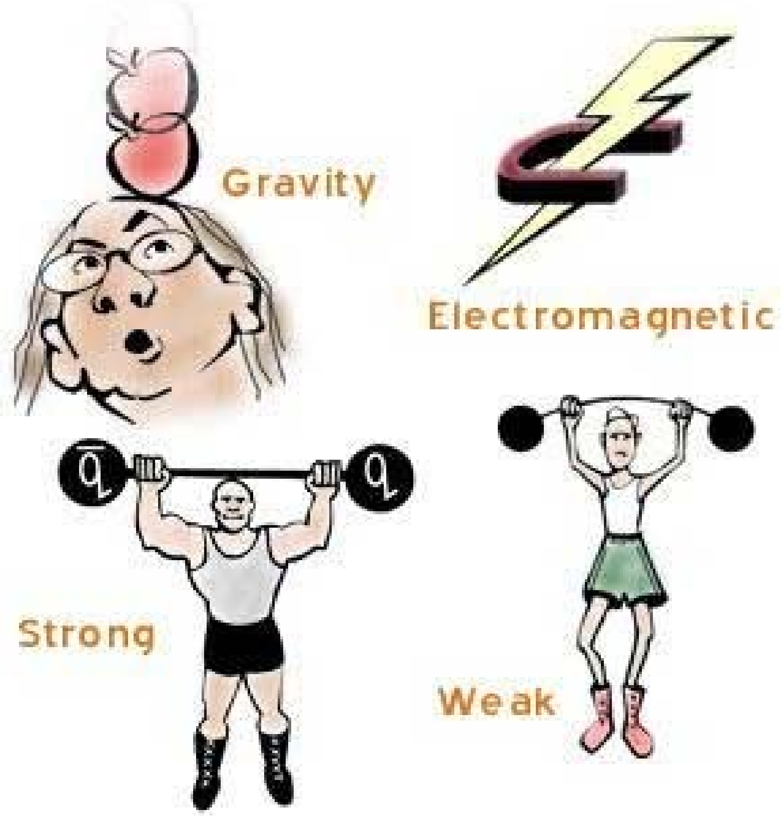


Particle Physics studies the properties of fundamental building block of matters and their interactions.

Interactions of Particles

- Force is explained by exchange of force carriers between particles (Gravitational, Electromagentic, Strong, Weak)
- Long-range force: light force carrier (γ, graviton)
- Short-range force: heavy force carrier ($W^{\pm}$, Z^{0})





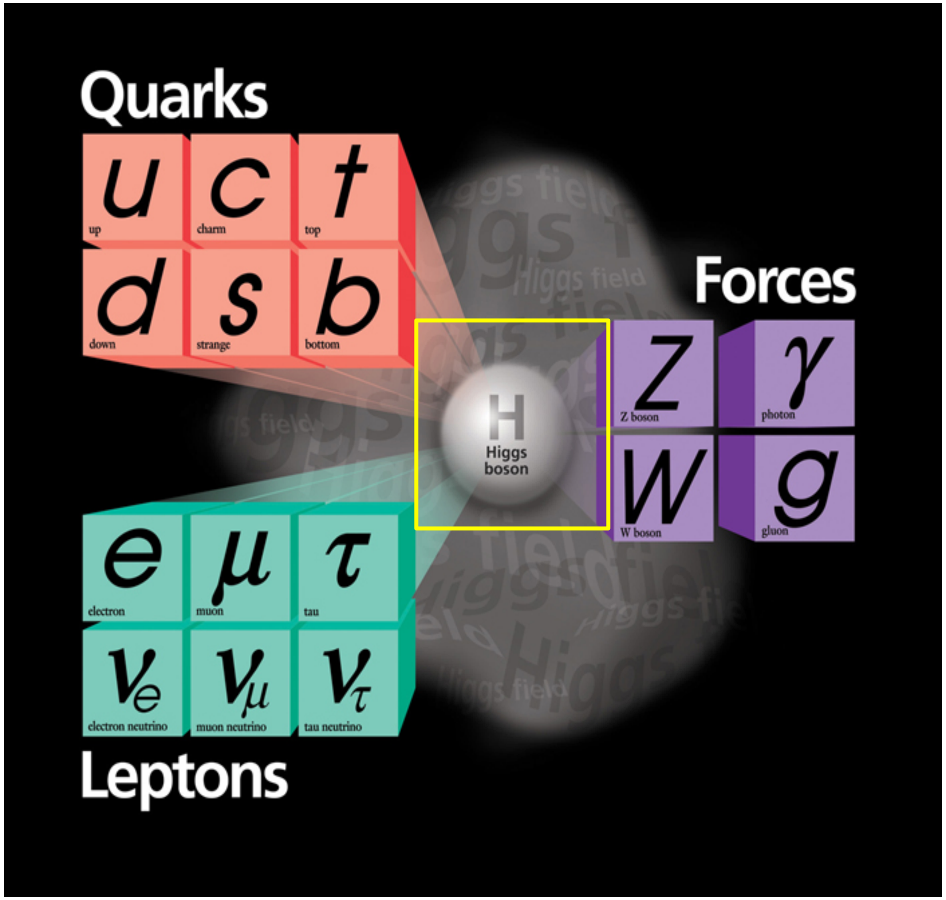
Standard Model of Elementary Particles

- **Elementary Particles**

  > 100 years' discoveries

- The SM is in excellent agreement with the numerous experimental measurements.

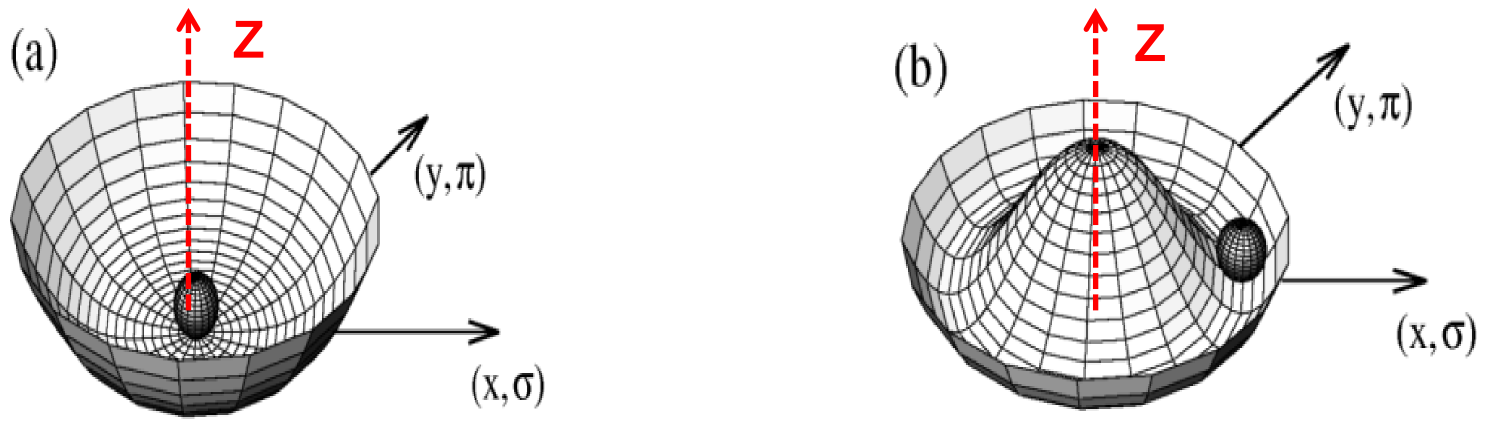
- The only missing SM particle is the Higgs boson which is proposed to responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.



→ Hunting for the Higgs boson is one of main goals in particle physics (LEP, Tevatron, LHC)

Higgs Mechanism

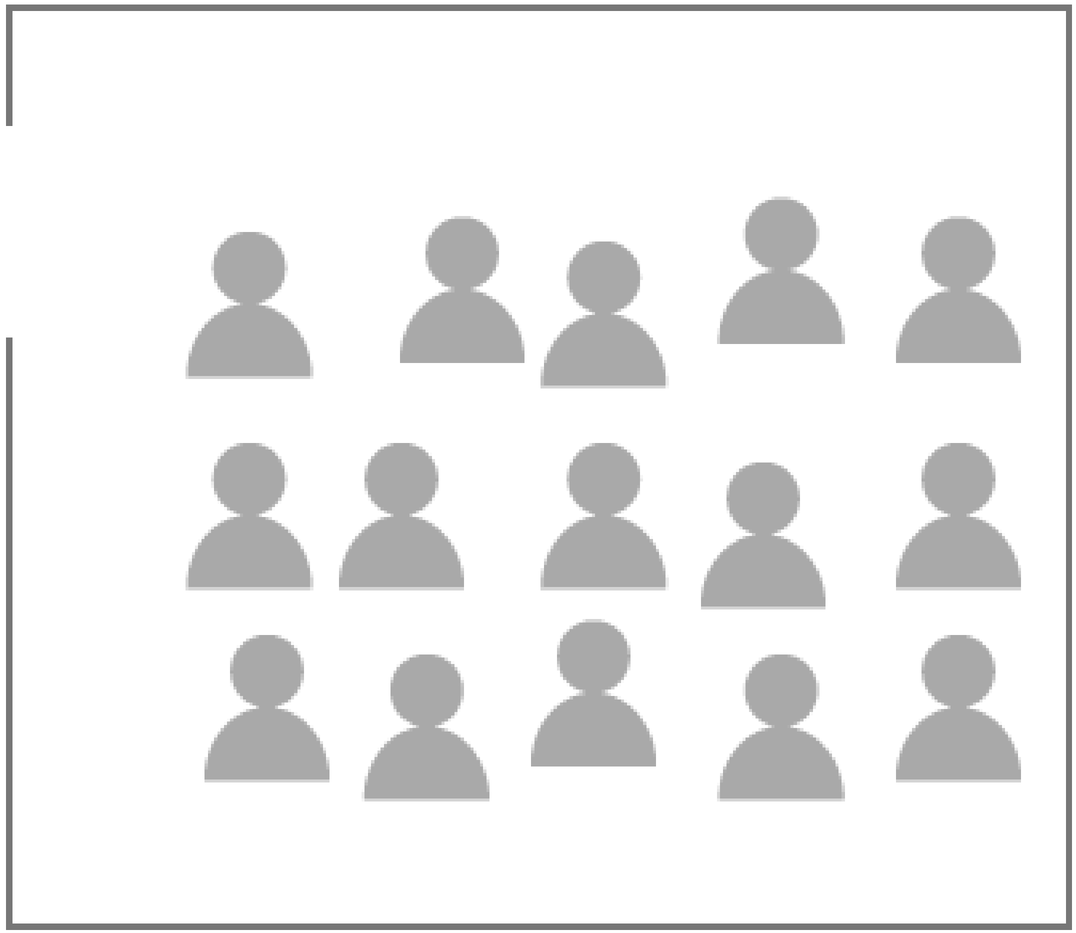
- The potential in (a) is symmetric
- The potential in (b) the potential is still symmetric,
  but the symmetry of the ground state is spontaneously broken.



- Spontaneously symmetry breaking ➔ Nambu-Goldstone bosons (no spin, mass)

- Peter Higgs showed that Goldstone bosons need not occur when a local symmetry is spontaneously broken in a relativistic theory. Instead, the Goldstone mode provides the third polarisation of a massive vector field. The other mode of the original scalar doublet remains as a massive spin-zero particle – the Higgs boson.

Cartoon Explanation of the Higgs Boson

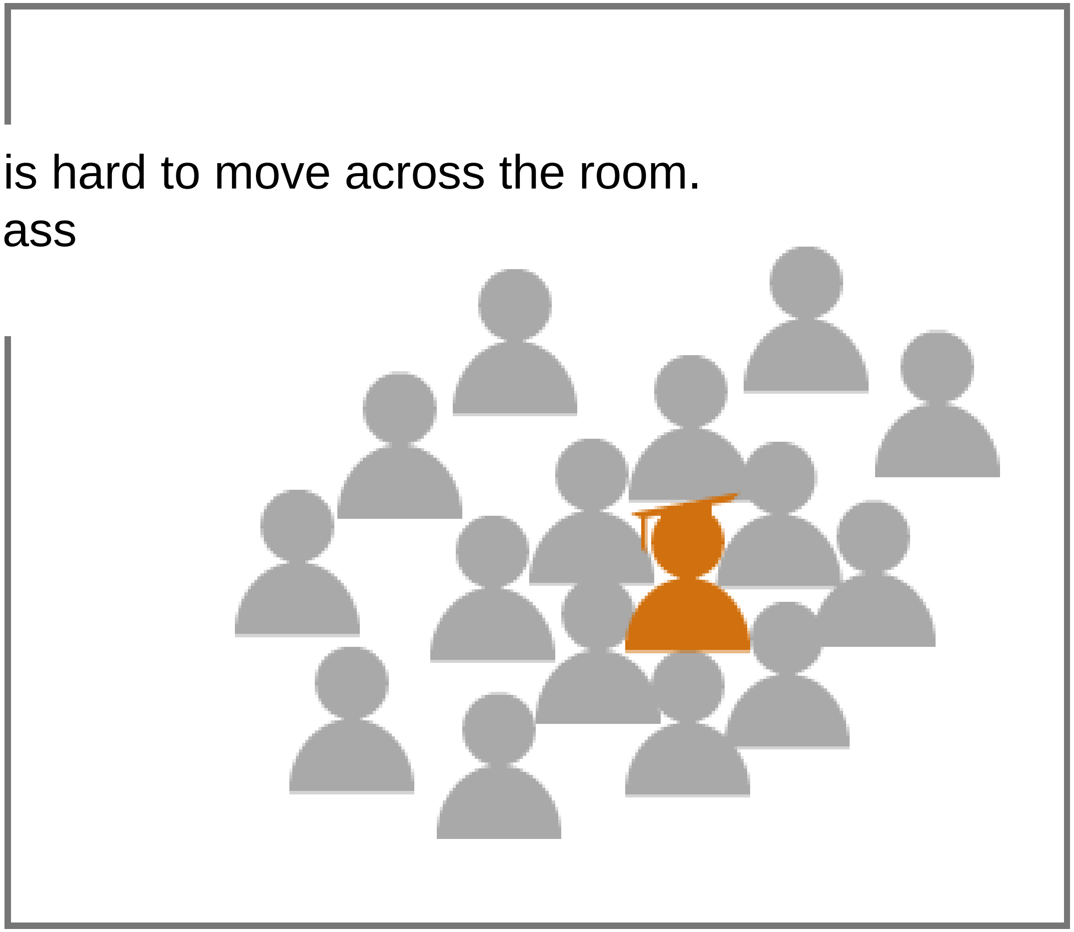


Physicists
"Higgs field"

Cartoon Explanation of the Higgs Boson

Cartoon Explanation of the Higgs Boson

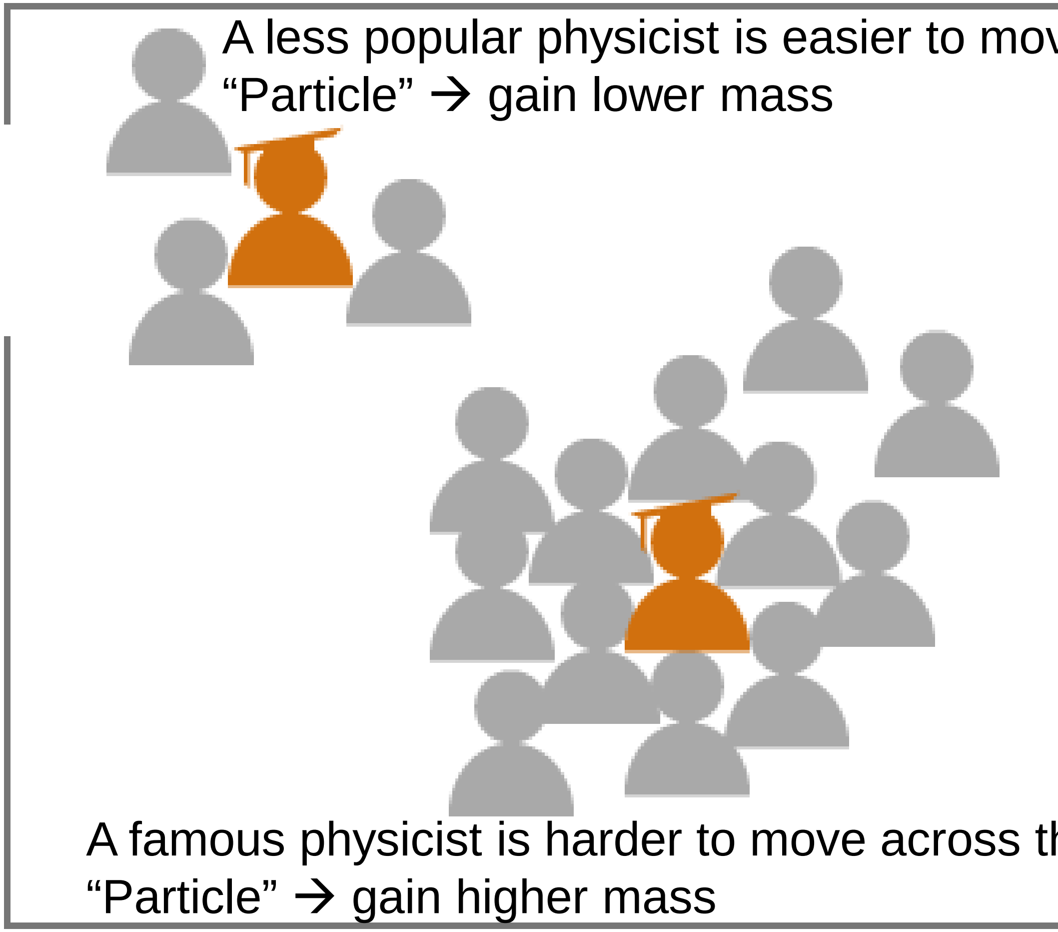
A famous physicist is hard to move across the room.
“Particle” → gain mass



Physicists
“Higgs field”

Cartoon Explanation of the Higgs Boson

A less popular physicist is easier to move across the room.
“Particle” → gain lower mass



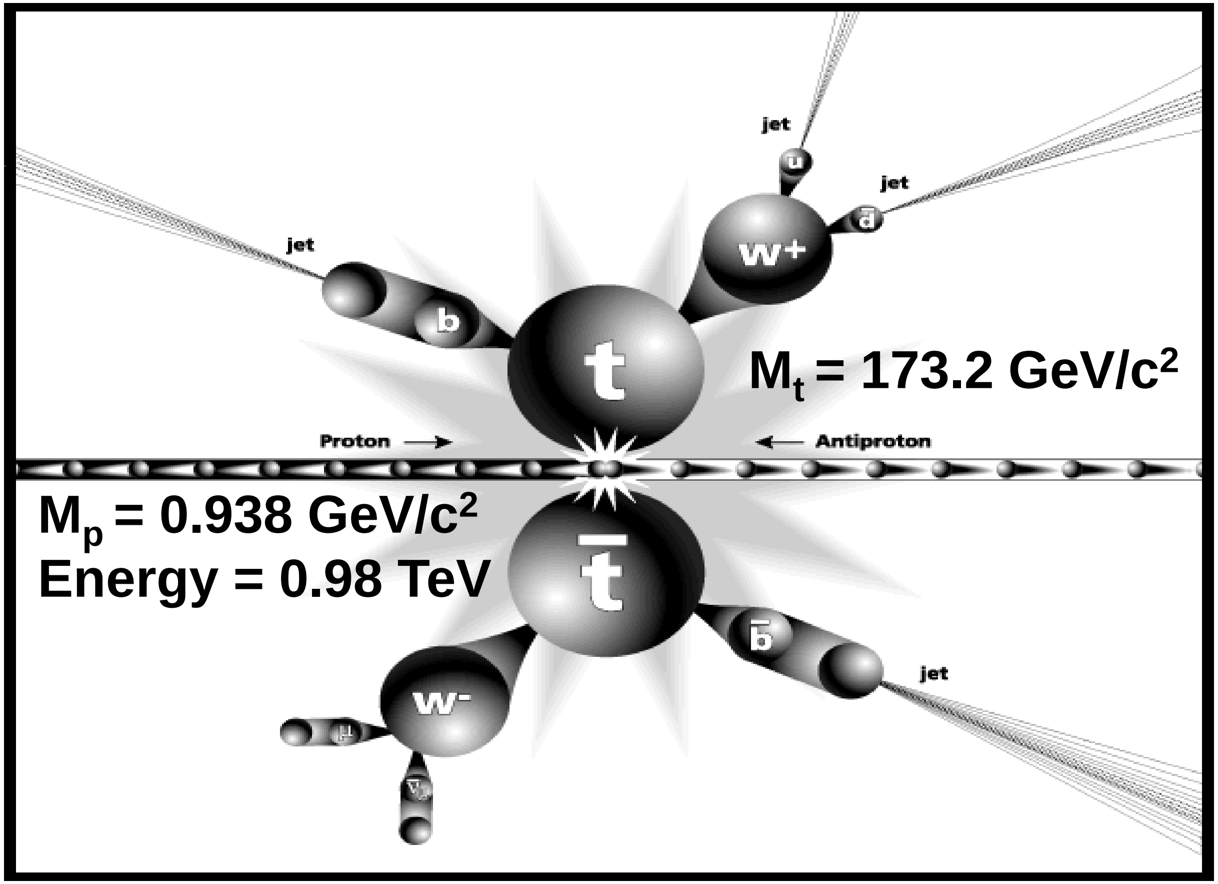
Physicists
“Higgs field”

A famous physicist is harder to move across the room.
“Particle” → gain higher mass

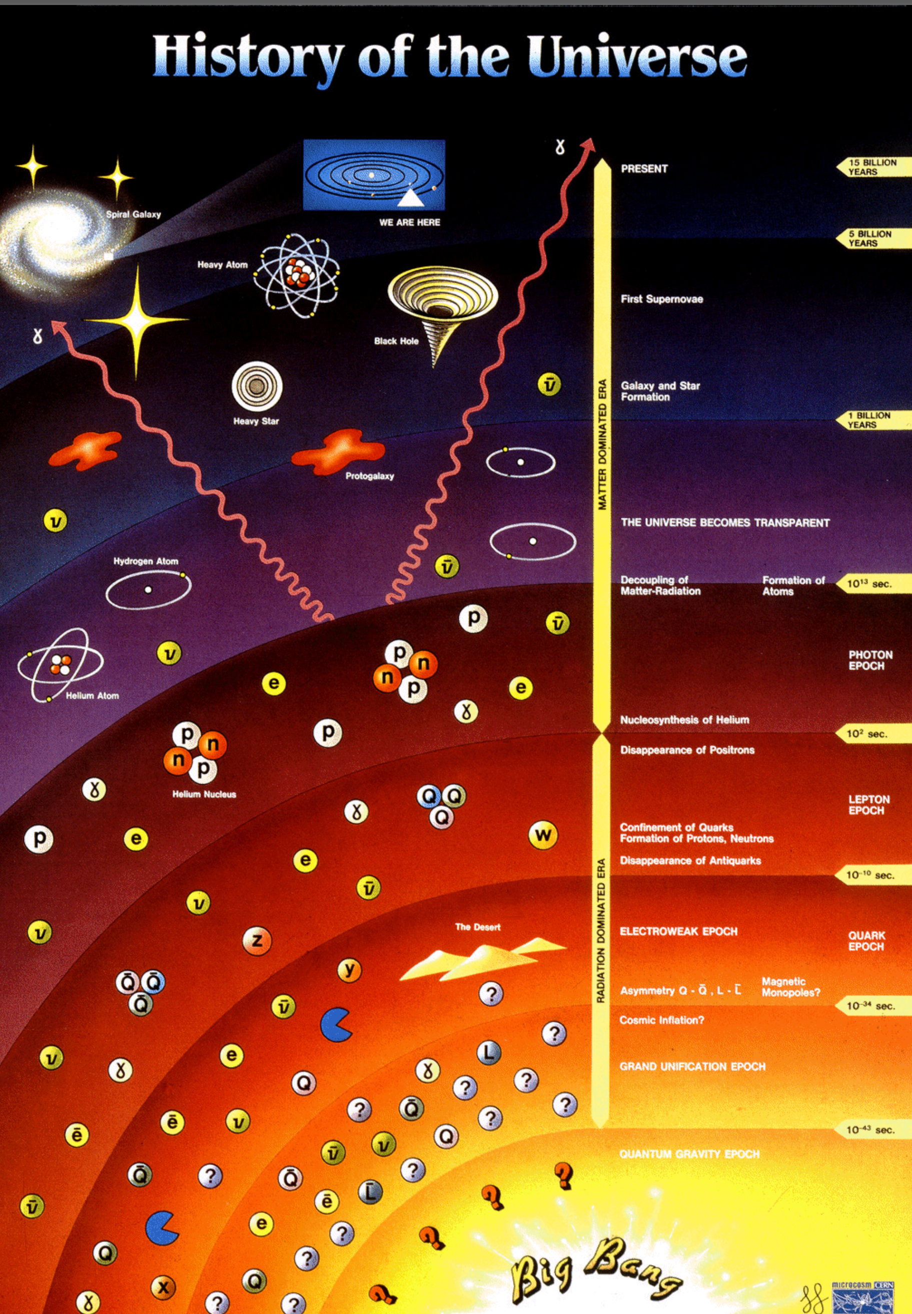
Source: Cern/UCL

Our Tool: High Energy Collider

- **Energy is the currency in particle physics !**
  - Shorter distance ↔ Higher energy ($\lambda=\hbar/p$)
  - Heavier matter particle ↔ Higher energy ($E = mc^2$)
- **High energy beam and big machine to study the smallest scale**



Our Tool: High Energy Collider



- Higher energy beam collisions ↔ higher temperature (E = κT)
- **Use high energy collider to recreate the conditions right after the Big Bang.**

Shortest scale in particle physics

↕

Largest scale in the Universe

← LHC, time ≈ 10^{-13} s, Temp ≈ 10^{17} K, Energy ≈ 8 TeV, distance ≈ 10^{-19} m

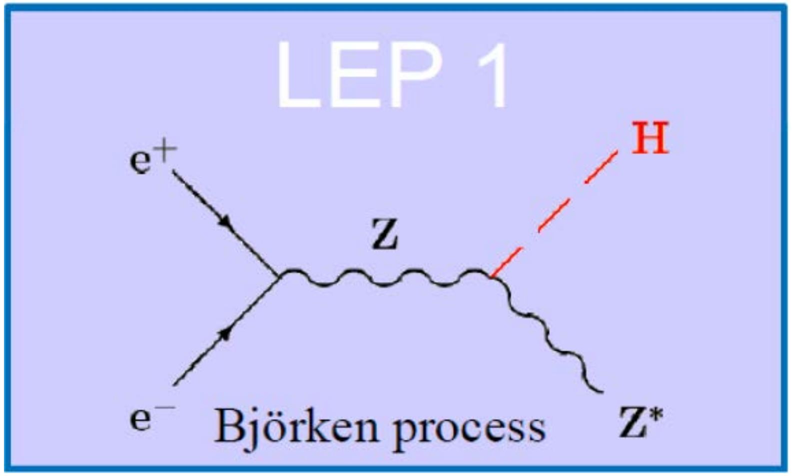
Large Electron Positron Collider at CERN

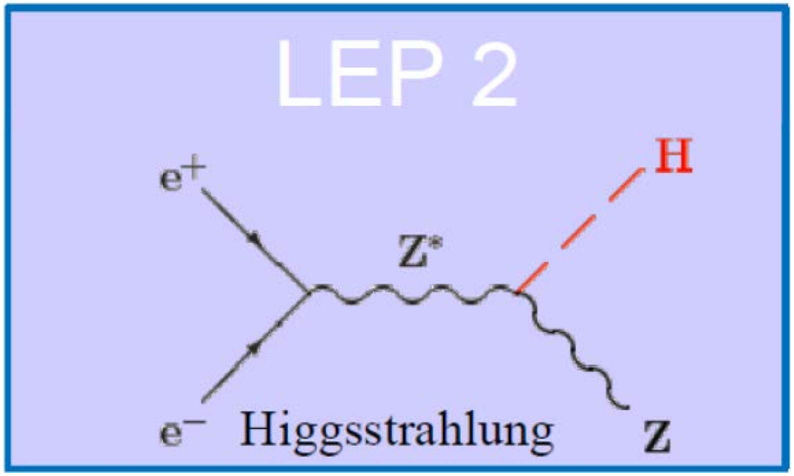
- Search for Higgs boson at LEP (e^+e^-, 26.7km)
- LEP1 (1989): $\sqrt{s}$ = 91 GeV
- LEP2 (2000): $\sqrt{s}$ = 209 GeV

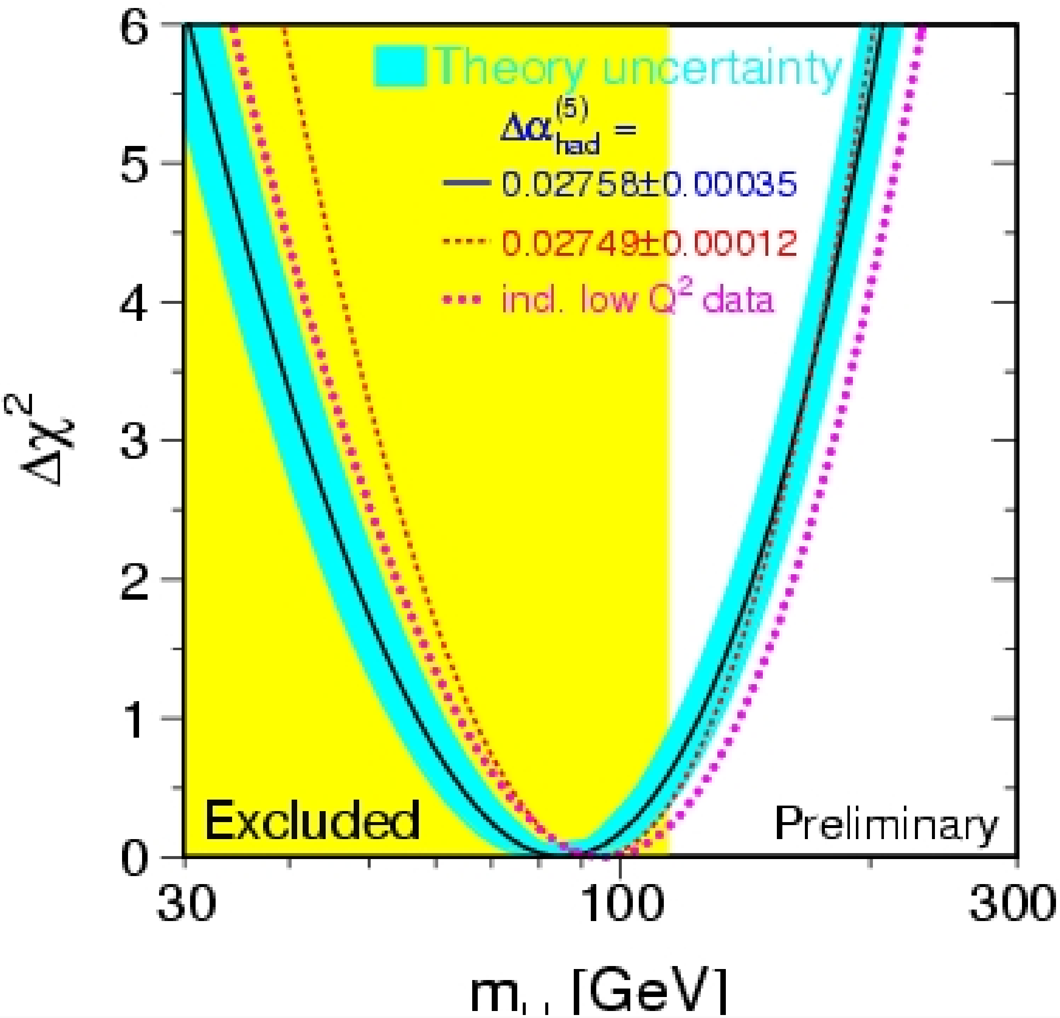
Search for Higgs boson at LEP

➔**Results: exclude $m_H < 114.4$ GeV/c^2 at 95% CL**

(Physics Letters B 565 (2003) 61-75)

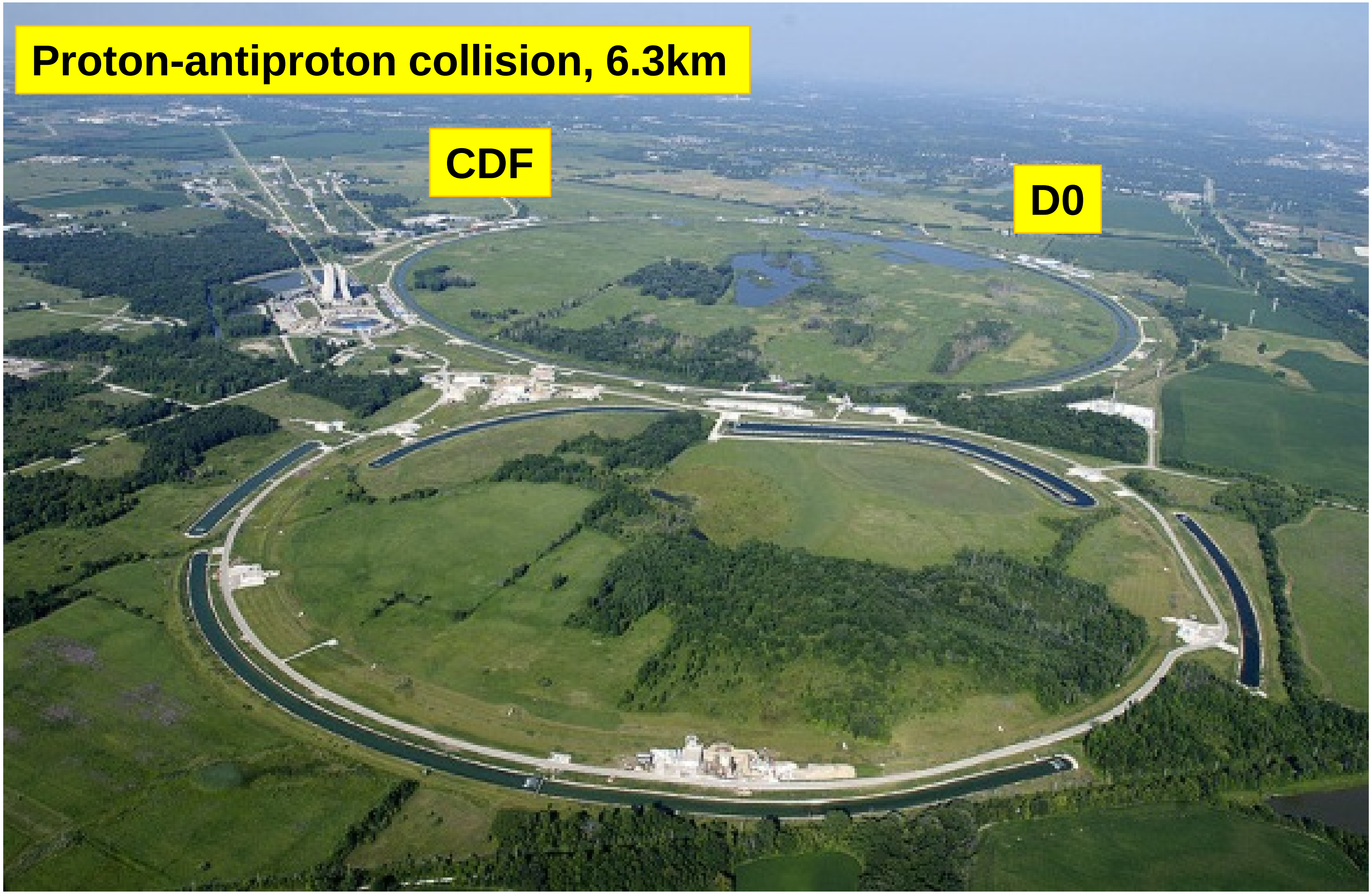






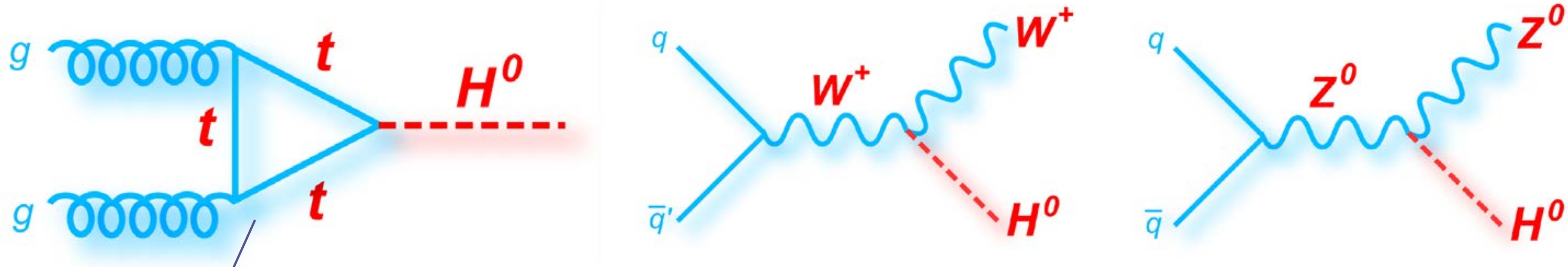
Tevatron at Fermilab (FNAL)

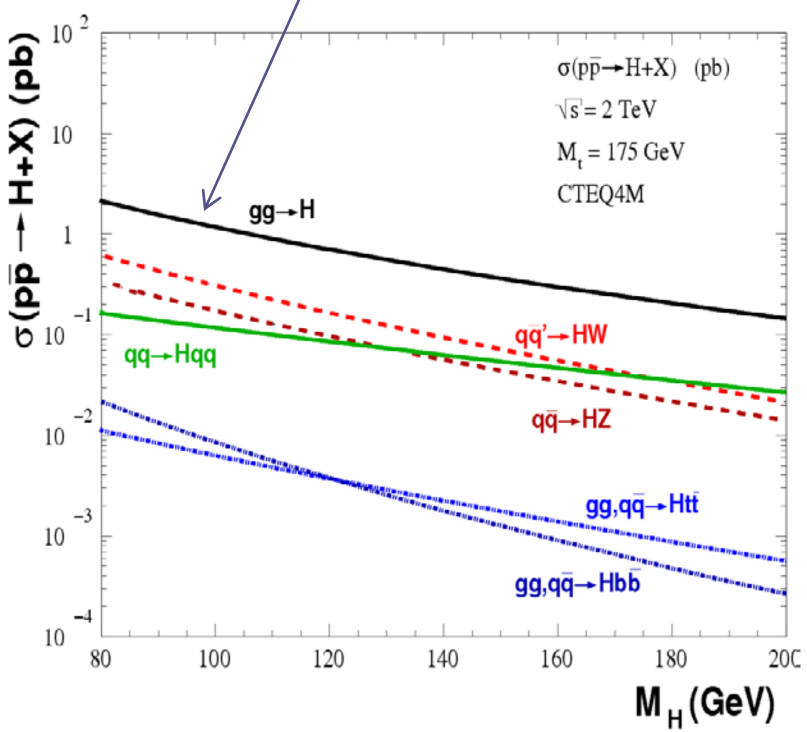
- Search for Higgs boson at Tevatron (1.96 TeV): 1983 – 2011

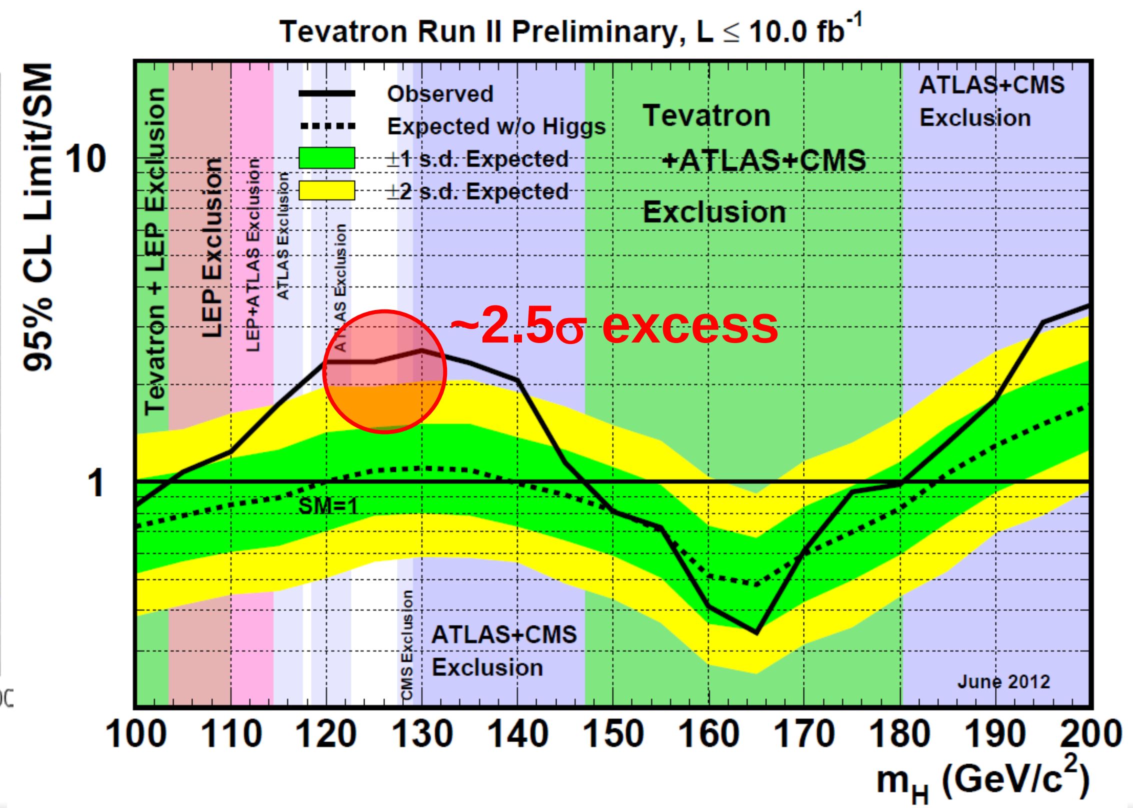


Search for Higgs boson at Tevatron

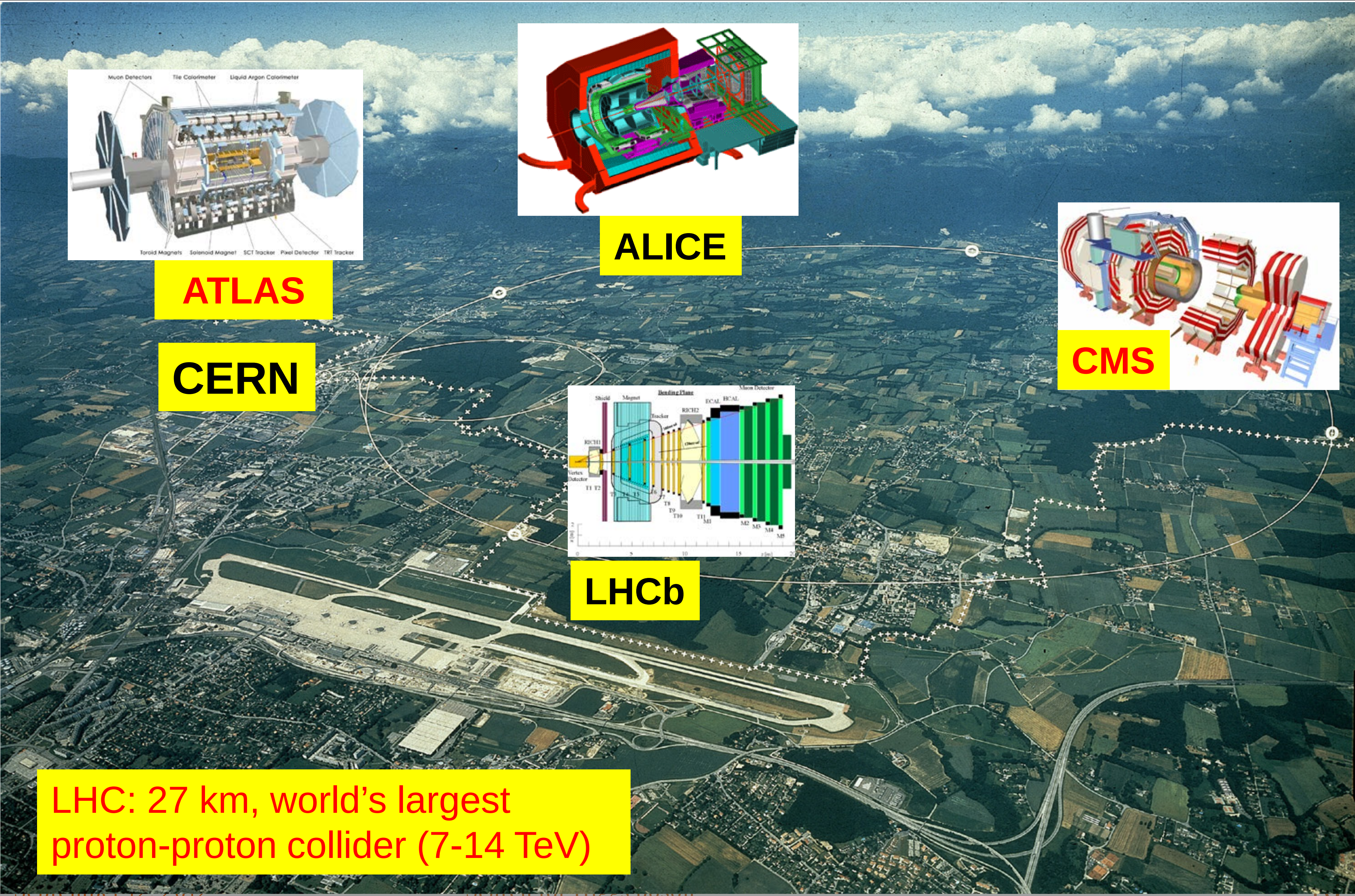
➔ Results (arXiv:1207.0449): 2.5σ excess at m_H=120-130 GeV







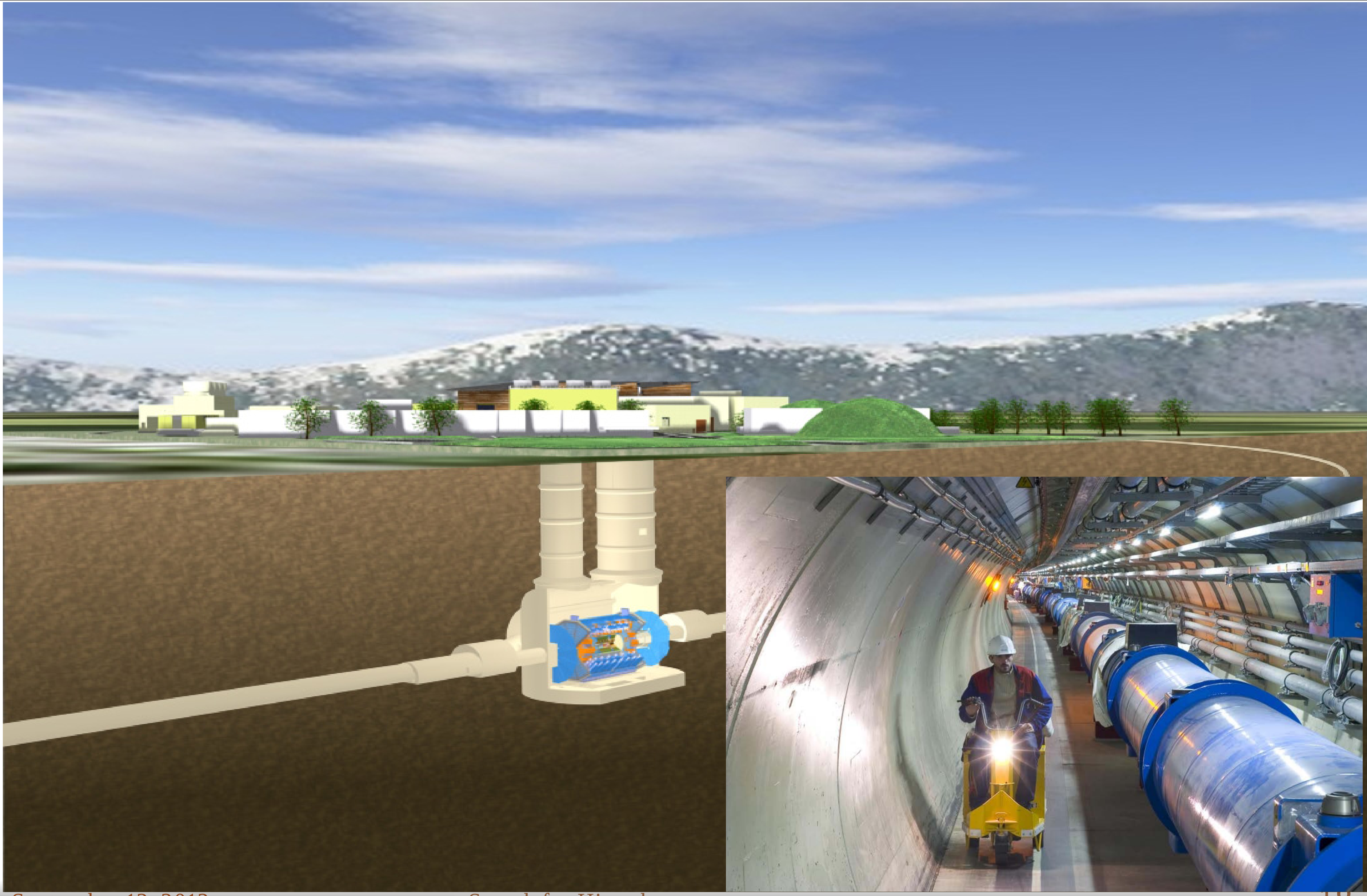
Large Hadron Collider at CERN



LHC: 27 km, world's largest proton-proton collider (7-14 TeV)

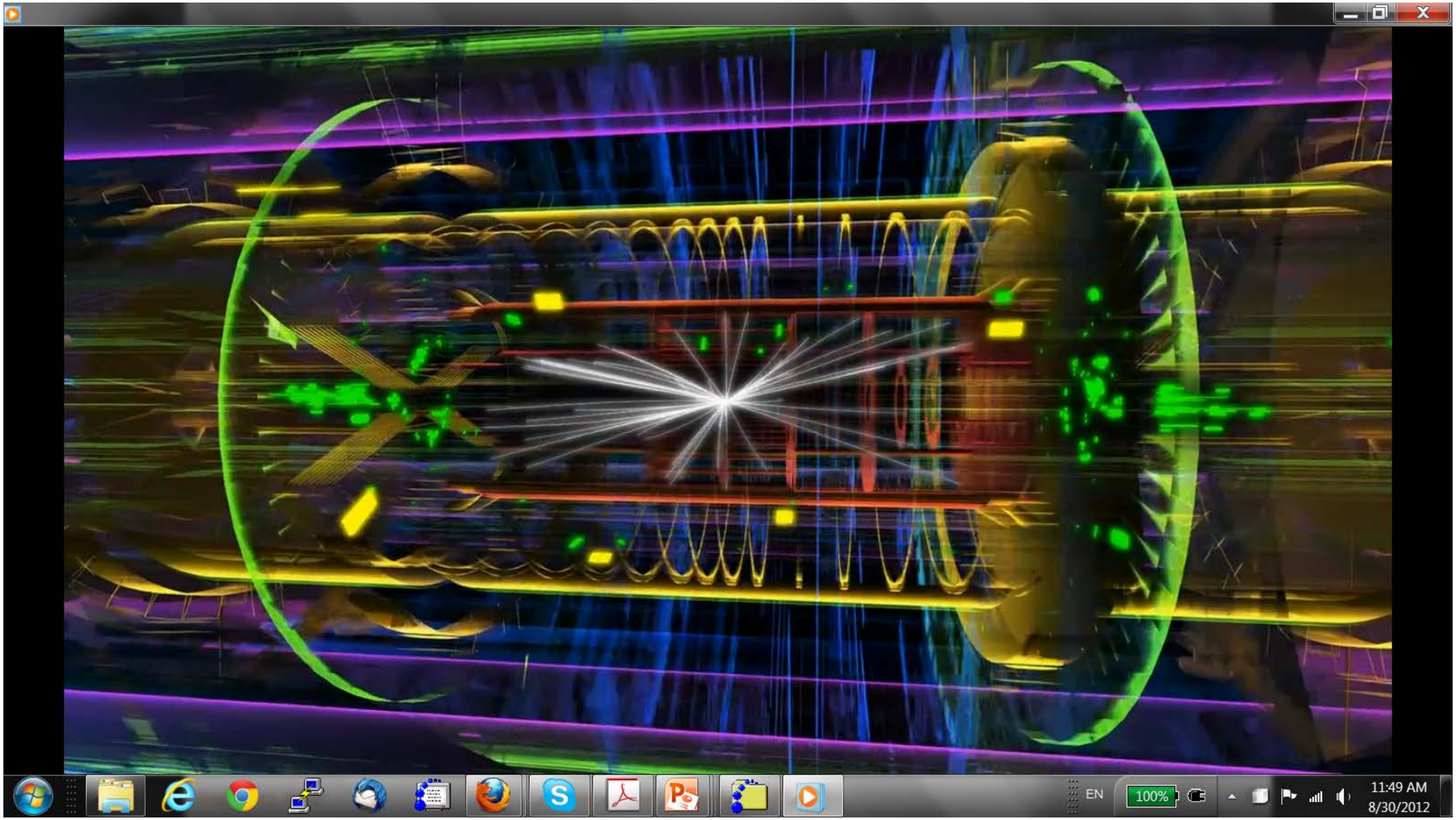
CERN

Tunnel (26.7 km)

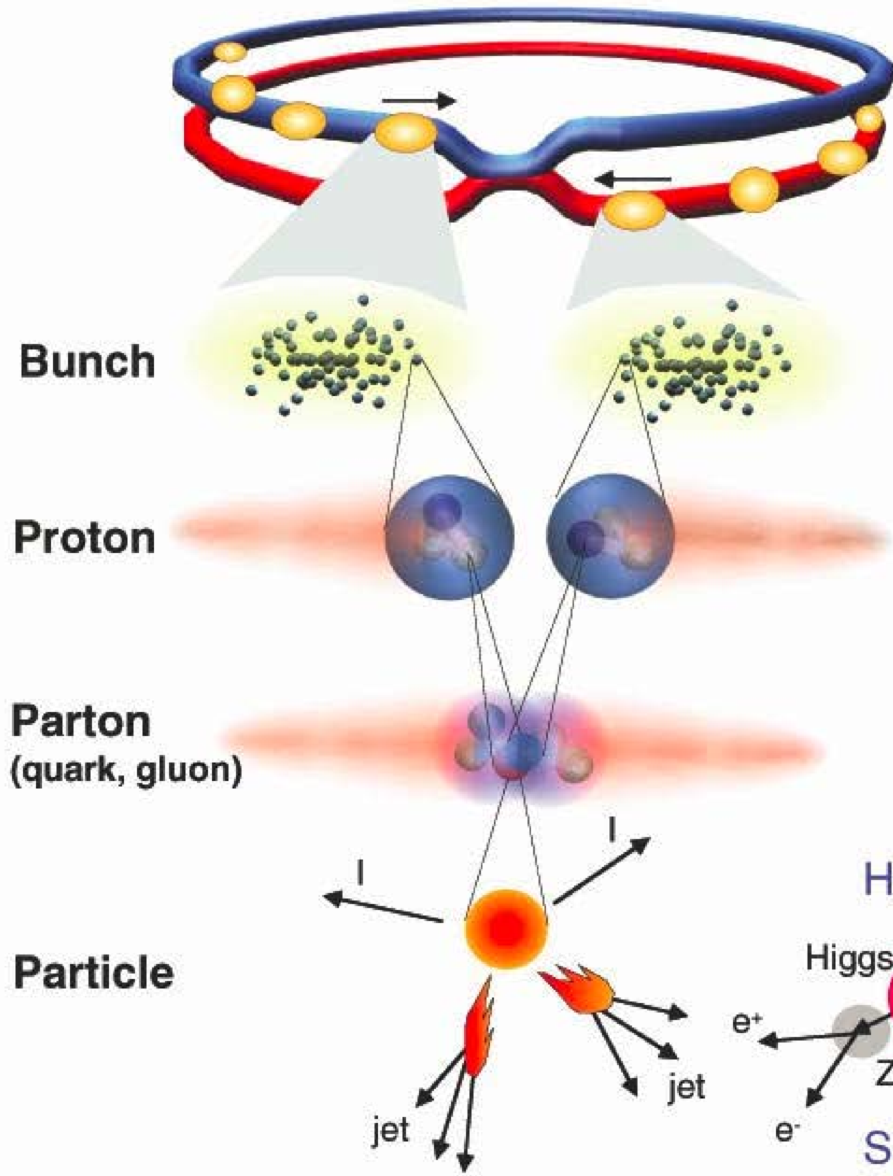


Particle Acceleration and Collision

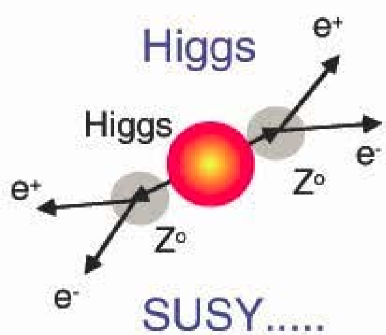
- Proton-proton collision at LHC



Collisions at LHC

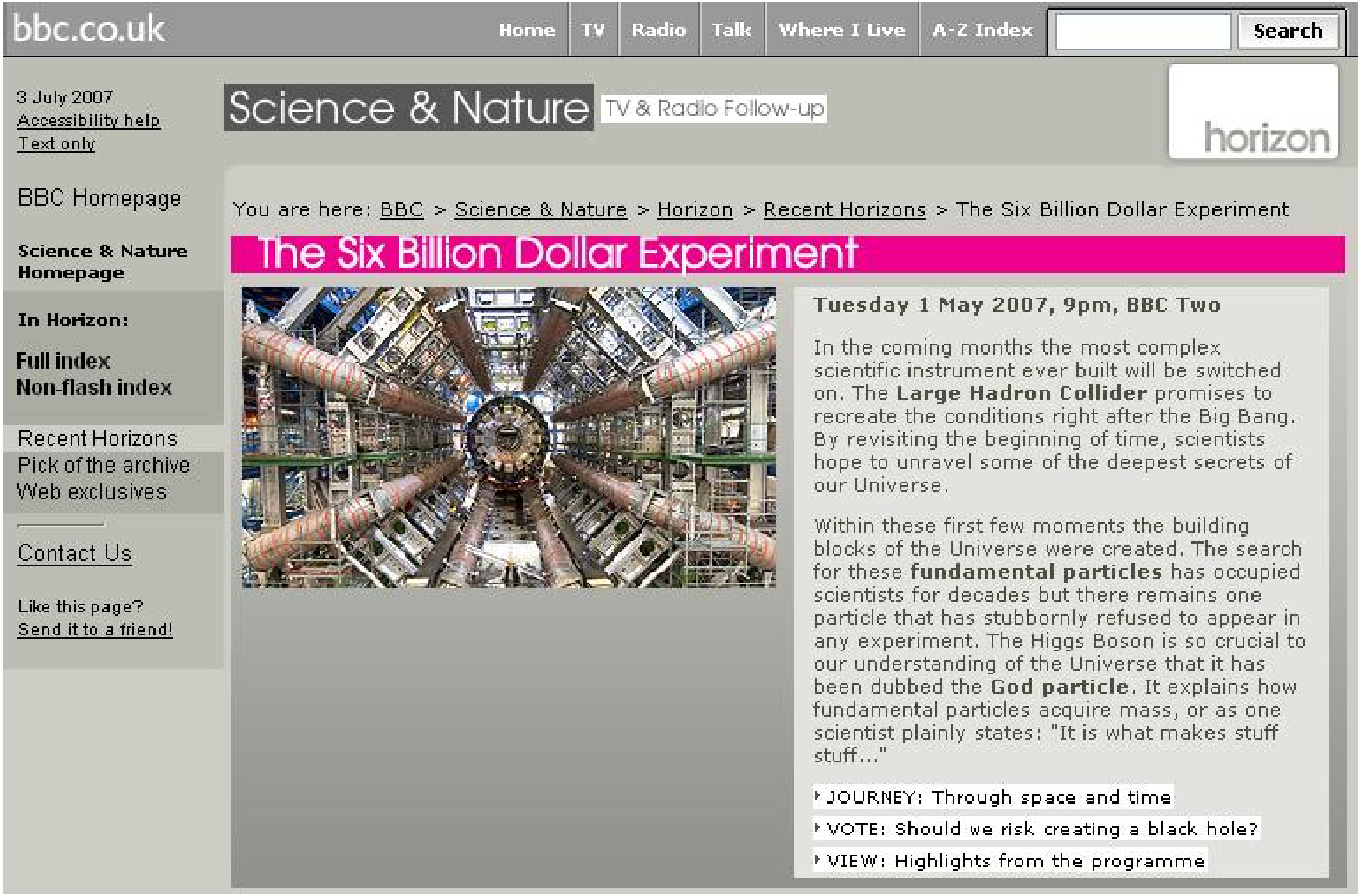


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz



Selection of 1 in 10,000,000,000,000

LHC on BBC



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The Six Billion Dollar Experiment

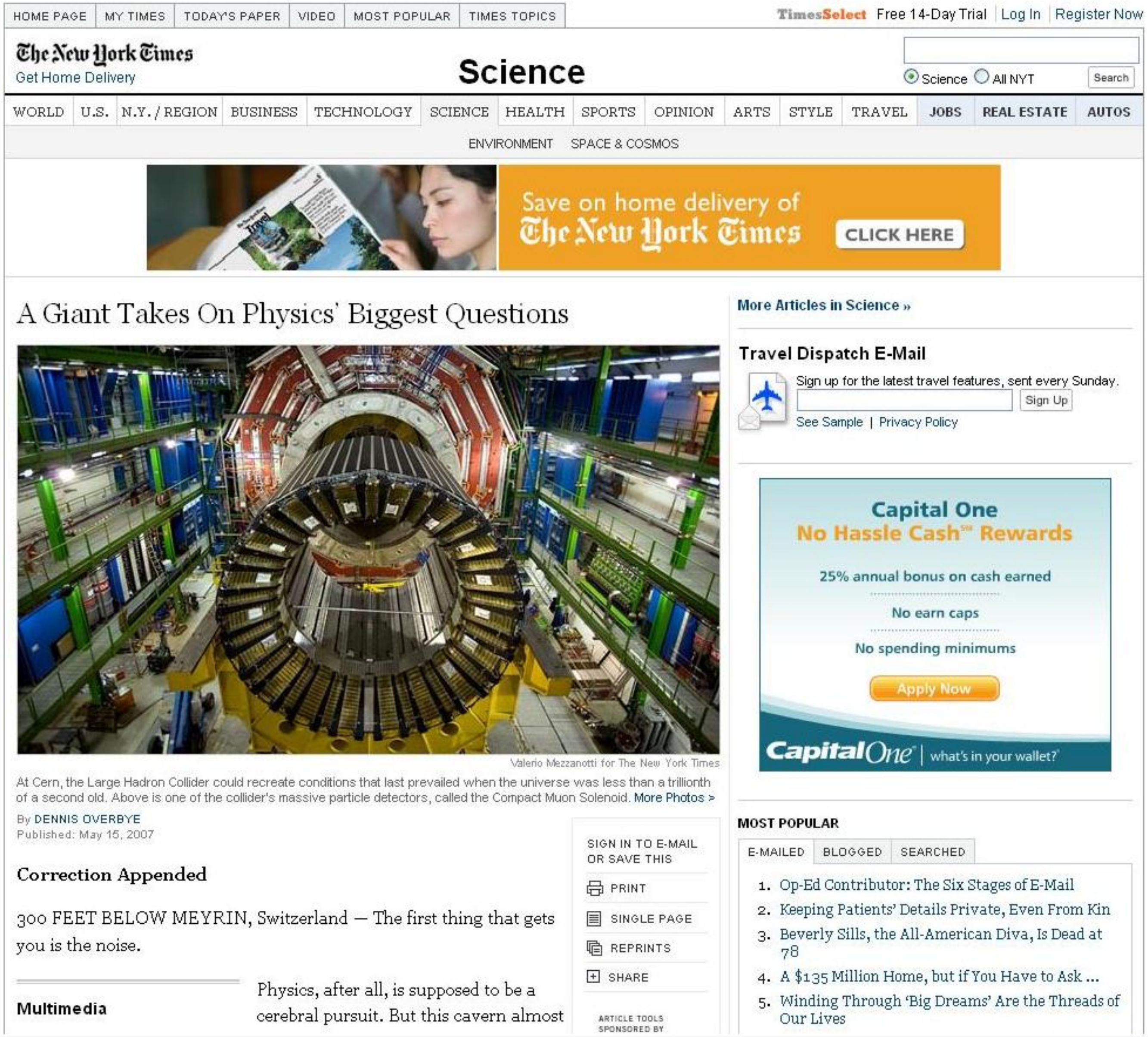
Tuesday 1 May 2007, 9pm, BBC Two

In the coming months the most complex scientific instrument ever built will be switched on. The **Large Hadron Collider** promises to recreate the conditions right after the Big Bang. By revisiting the beginning of time, scientists hope to unravel some of the deepest secrets of our Universe.

Within these first few moments the building blocks of the Universe were created. The search for these **fundamental particles** has occupied scientists for decades but there remains one particle that has stubbornly refused to appear in any experiment. The Higgs Boson is so crucial to our understanding of the Universe that it has been dubbed the **God particle**. It explains how fundamental particles acquire mass, or as one scientist plainly states: "It is what makes stuff stuff..."

- JOURNEY: Through space and time
- VOTE: Should we risk creating a black hole?
- VIEW: Highlights from the programme

LHC on New York Times



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A Giant Takes On Physics' Biggest Questions

Valerio Mezzanotti for The New York Times

At Cern, the Large Hadron Collider could recreate conditions that last prevailed when the universe was less than a trillionth of a second old. Above is one of the collider's massive particle detectors, called the Compact Muon Solenoid. More Photos >

By DENNIS OVERBYE
Published: May 15, 2007

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Correction Appended

300 FEET BELOW MEYRIN, Switzerland — The first thing that gets you is the noise.

Multimedia

Physics, after all, is supposed to be a cerebral pursuit. But this cavern almost

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ATLAS and CMS Collaborations

- **Detector: A Toroidal LHC ApparatuS (ATLAS)**
  - ~ 3000 physicists
  - ~ 1000 students
  - 175 institutes
  - 38 countries

- **Detector: Compact Muon Solenoid (CMS)**
  - ~ 3300 physicists
  - ~ 1500 students
  - 179 institutes
  - 41 countries

20+ years of worldwide collaborative efforts

Academic Ranking of World Universities (Top-25)

❑ Ranking of World U. by SJTU (2010) http://www.arwu.org/ARWU2010.jsp

Rank	University Name	Rank	University Name
1	Harvard U.	14	UC, San Diego
2	UC, Berkeley	15	U. Pennsylvania
3	Stanford U.	16	U. Washington
4	MIT	17	U. Wisconsin
5	U. Cambridge	18	John Hopkins U.
6	Caltech	19 (no physics)	UC, San Francisco
7	Princeton U.	20	U. Tokyo
8	Columbia U.	21	U. College London
9	U. Chicago	22	U. Michigan
10	U. Oxford	23	Swiss Federal Inst. of Technology, Zurich
11	Yale U.	24	Kyoto U.
12	Cornell U.	25	UIUC
13	UC, Los Angeles	26	Imperial College

ATLAS Member Institutes

- Ranking of World U. by SJTU (2010) http://www.arwu.org/ARWU2010.jsp

Rank	University Name	Rank	University Name
1 (ATLAS)	Harvard U.	14	UC, San Diego
2 (ATLAS)	UC, Berkeley	15 (ATLAS)	U. Pennsylvania
3 (ATLAS)	Stanford U.	16 (ATLAS)	U. Washington
4 (ATLAS)	MIT	17 (ATLAS)	U. Wisconsin
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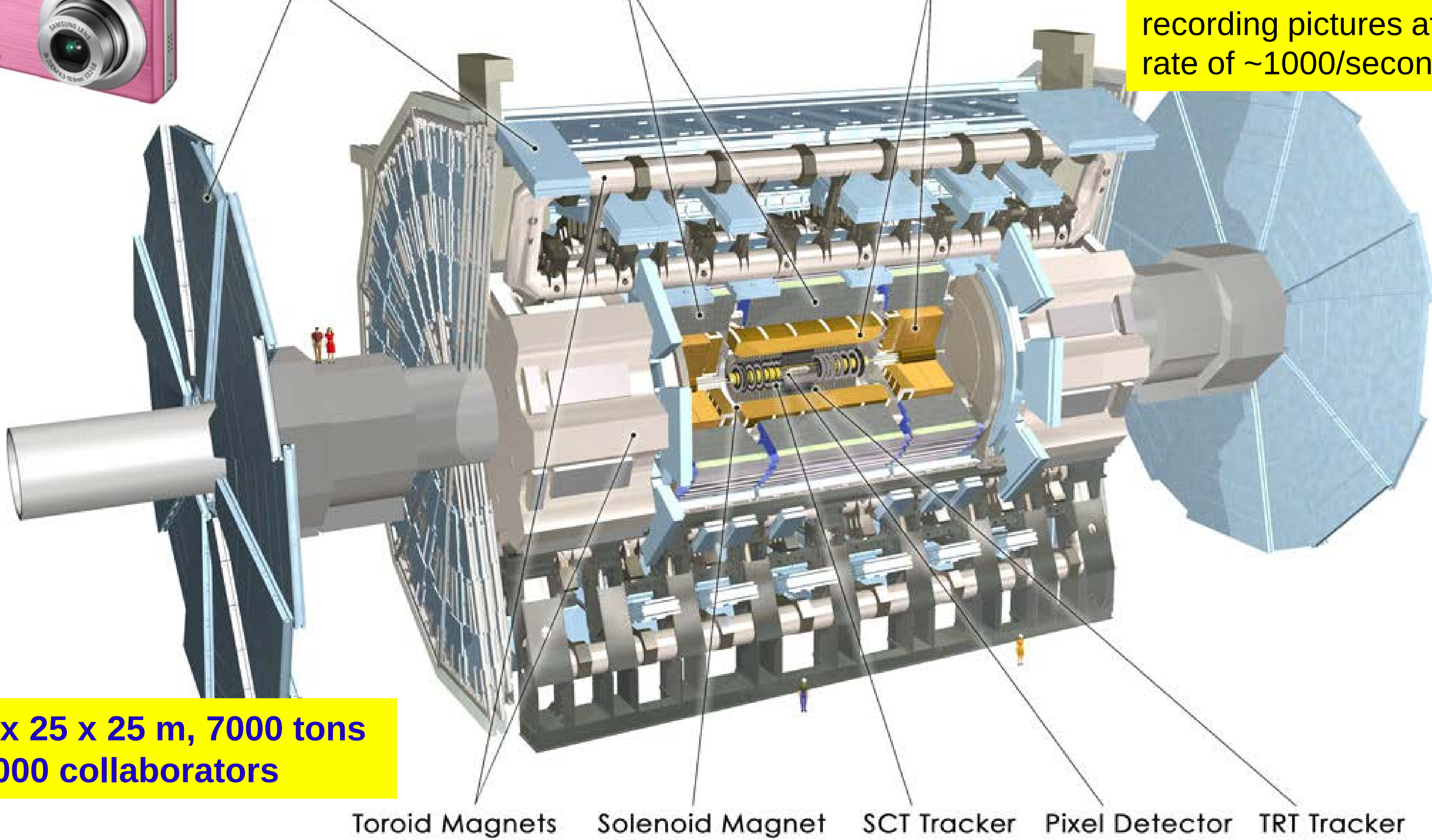
7	Princeton U.	20 (ATLAS)	U. Tokyo
8 (ATLAS)	Columbia U.	21 (ATLAS)	U. College London
9 (ATLAS)	U. Chicago	22 (ATLAS)	U. Michigan
10 (ATLAS)	U. Oxford	23	Swiss Federal Inst. Of Technology, Zurich
11 (ATLAS)	Yale U.	24 (ATLAS)	Kyoto U.
12	Cornell U.	25 (ATLAS)	UIUC
13	UC, Los Angeles	26	Imperial College

ATLAS and CMS Member Institutes

- Ranking of World U. by SJTU (2010) http://www.arwu.org/ARWU2010.jsp

Rank	University Name	Rank	University Name
1 (ATLAS)	Harvard U.	14 (CMS)	UC, San Diego
2 (ATLAS)	UC, Berkeley	15 (ATLAS)	U. Pennsylvania
3 (ATLAS)	Stanford U.	16 (ATLAS)	U. Washington
4 (ATLAS,CMS)	MIT	17 (ATLAS,CMS)	U. Wisconsin
5 (ATLAS)	U. Cambridge	18 (CMS)	John Hopkins U.
6 (CMS)	Caltech	19 (no physics)	UC, San Francisco
7 (CMS)	Princeton U.	20 (ATLAS)	U. Tokyo
8 (ATLAS)	Columbia U.	21 (ATLAS)	U. College London
9 (ATLAS)	U. Chicago	22 (ATLAS)	U. Michigan
10 (ATLAS)	U. Oxford	23 (CMS)	Swiss Federal Inst. Of Technology, Zurich
11 (ATLAS)	Yale U.	24 (ATLAS)	Kyoto U.
12 (CMS)	Cornell U.	25 (ATLAS)	UIUC
13 (CMS)	UC, Los Angeles	26 (CMS)	Imperial College

The ATLAS Detector: Huge Camera

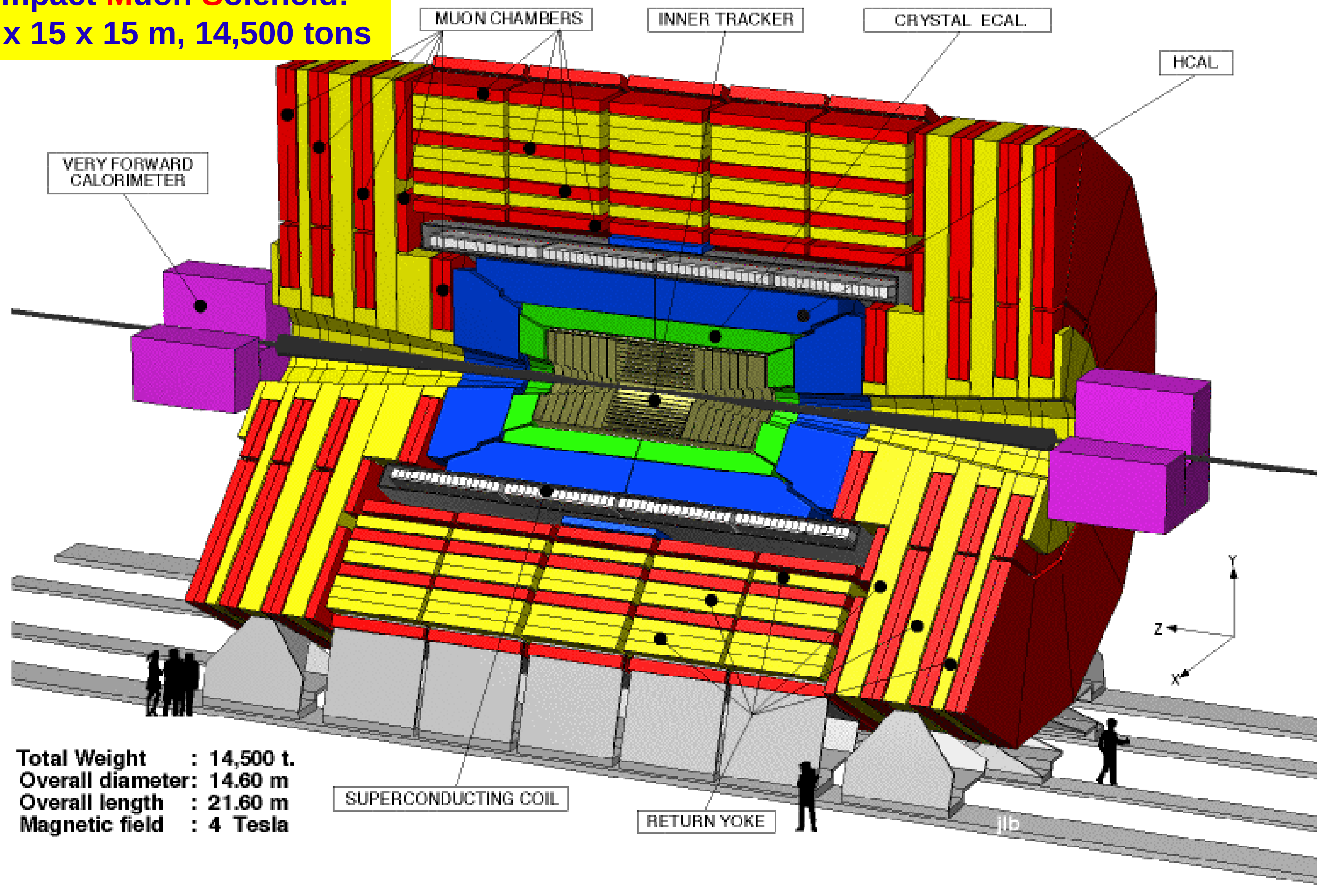


Taking pictures at a rate of 40 Millon/s and recording pictures at a rate of ~1000/second

46 x 25 x 25 m, 7000 tons
~3000 collaborators

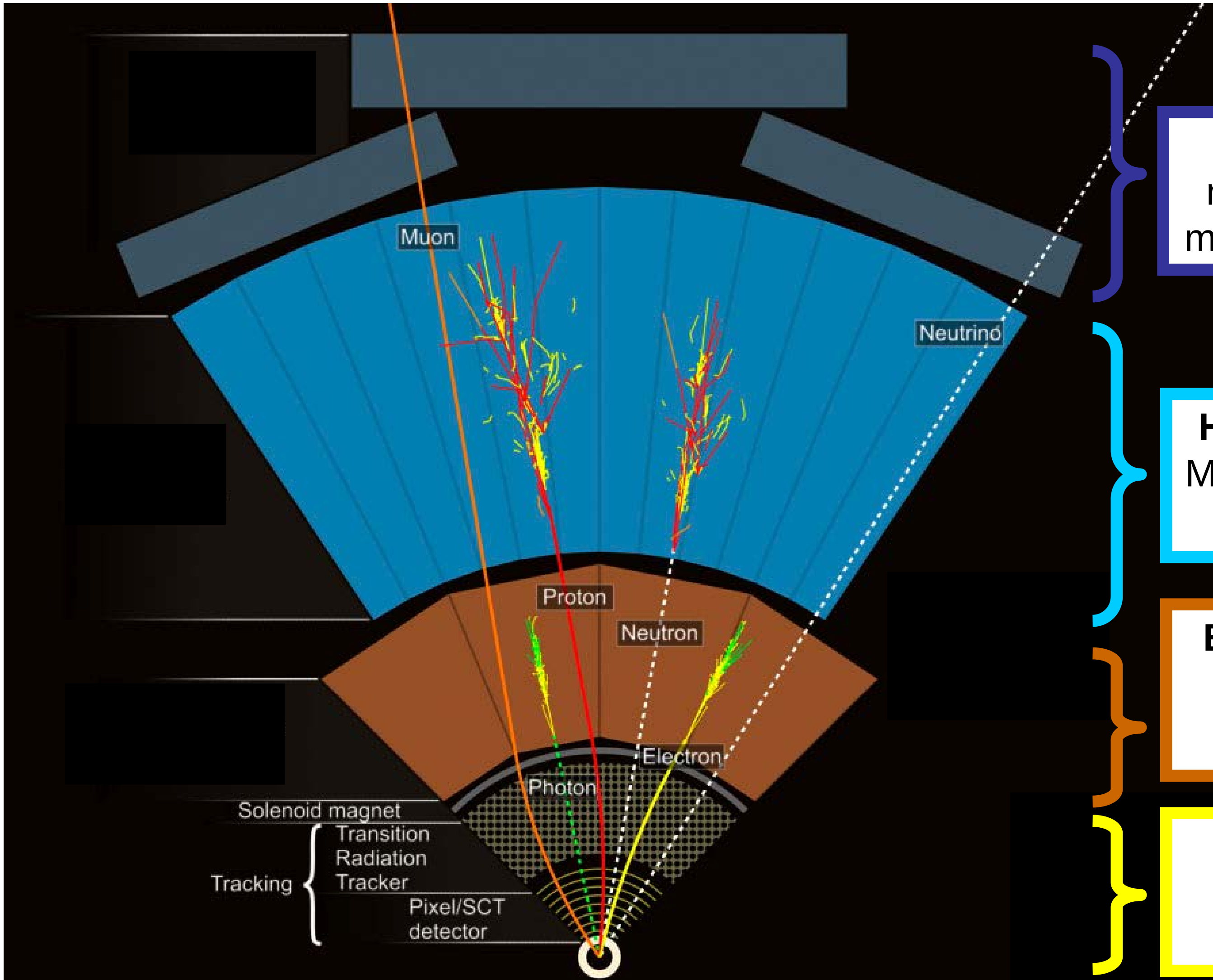
The CMS Detector

Compact Muon Solenoid:
21 x 15 x 15 m, 14,500 tons



Particle Detection

- Different particles have different signatures in detectors



Muon Spectrometer:
muon identification and momentum measurement

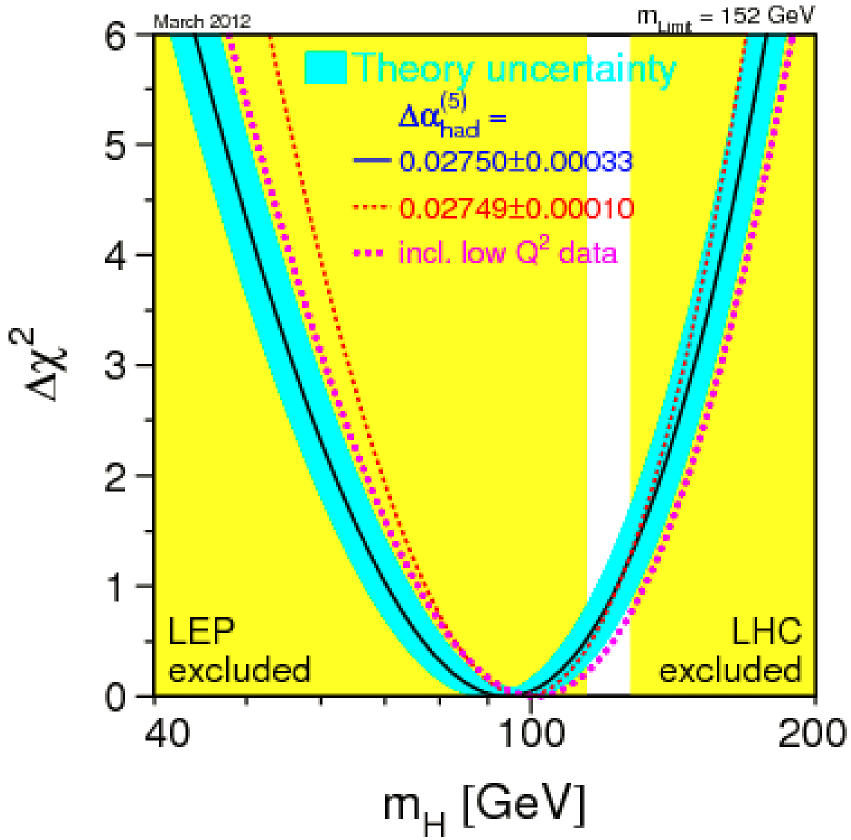
Hadronic calorimeter:
Measurement of jets and missing energy

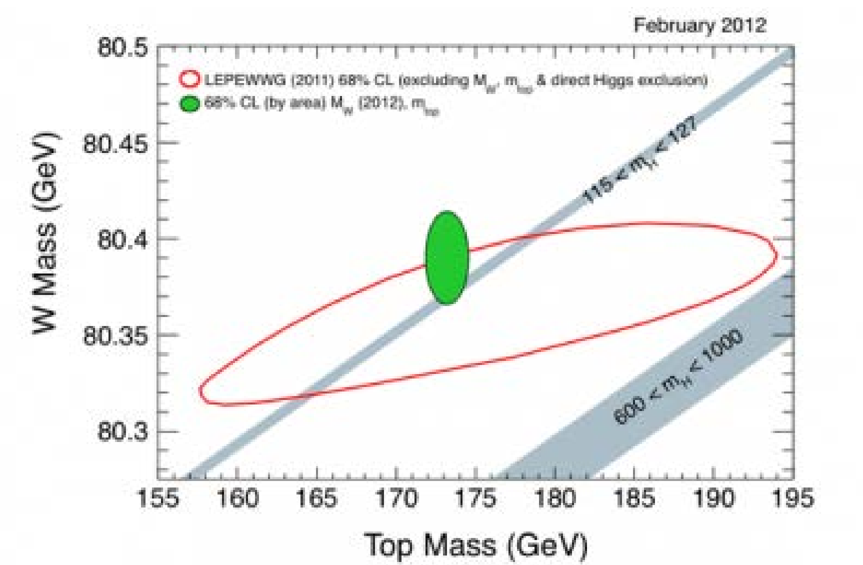
Electromagnetic calo:
e/γ identification and energy measurement

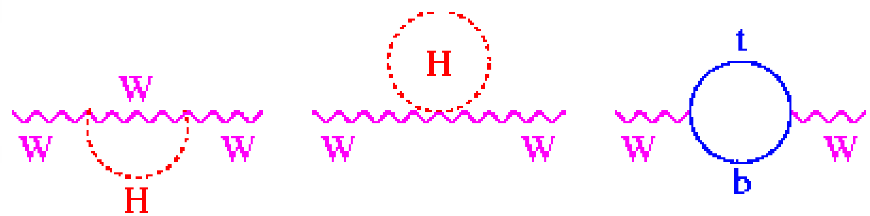
Tracking system:
Charged particle momentum, vertexing

Higgs Boson Mass Constraint

- Direct searches at LEP (2000):
  $m_H > 114.4$ GeV @ 95% C.L.
- Direct search at LHC (2012.3)
  $m_H < 127$ GeV @ 95% C.L.
- Precision electroweak data are sensitive to Higgs mass, global fit mass: $m_H = 94^{+29}_{-24}$ GeV



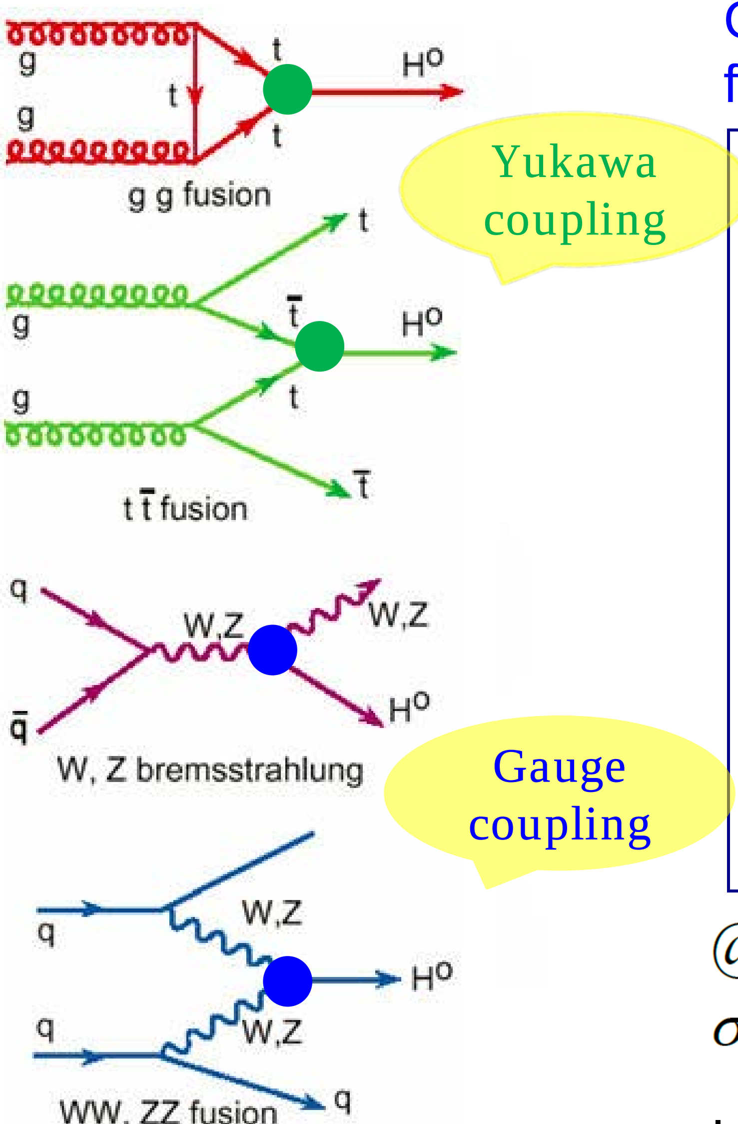




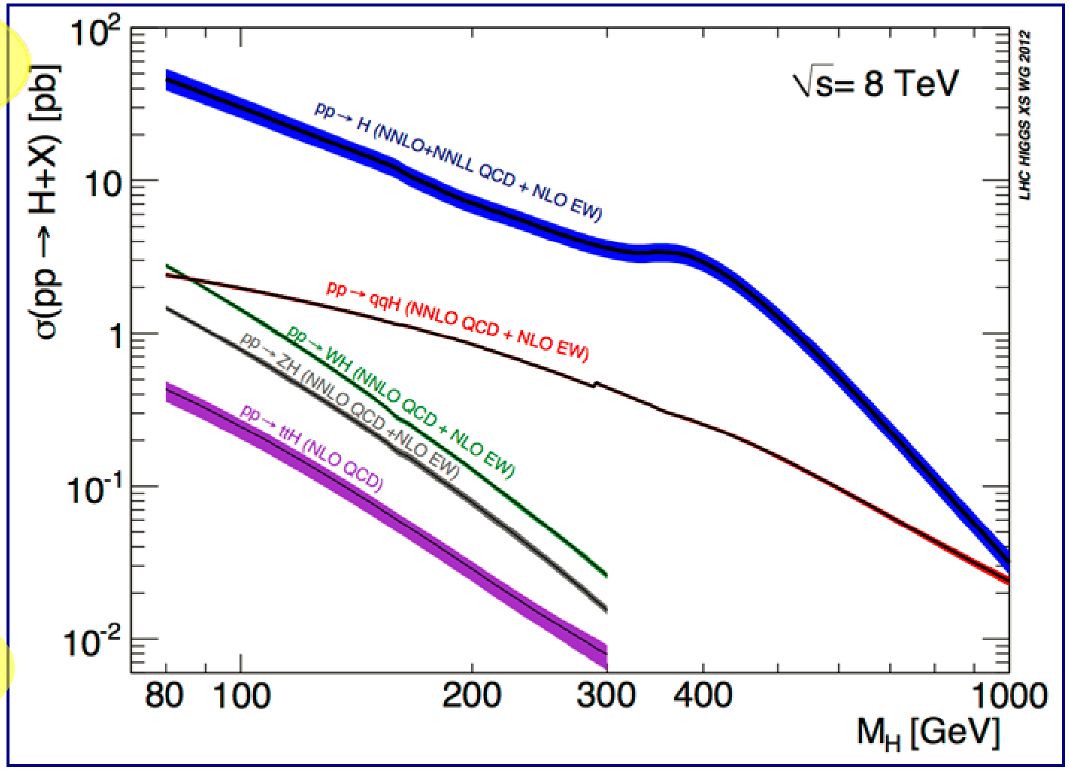
$M^2_W = M^2_Z(1-\sin^2\theta_w)(1+\Delta\rho)$

Radiative correction: $\Delta\rho(m_t, m_H, \alpha, \ldots)$

Higgs Boson Production at LHC



Gluon-gluon fusion gg→H and vector-boson fusion qq→qqH are dominant



$$@125\text{ GeV}:\ \sigma_{ggH}=19.5\text{ pb},\ \sigma_{VBF}=1.6\text{ pb},$$
$$\sigma_{WH}=0.70\text{ pb},\ \sigma_{ZH}=0.39\text{ pb},\ \sigma_{ttH}=0.13\text{ pb}$$

Inelastic pp cross section at 7 TeV is ~ 60 mb

Higgs Boson Width

➢ **Strong mass dependent**

Γ_H = 3.5 MeV @ 120 GeV

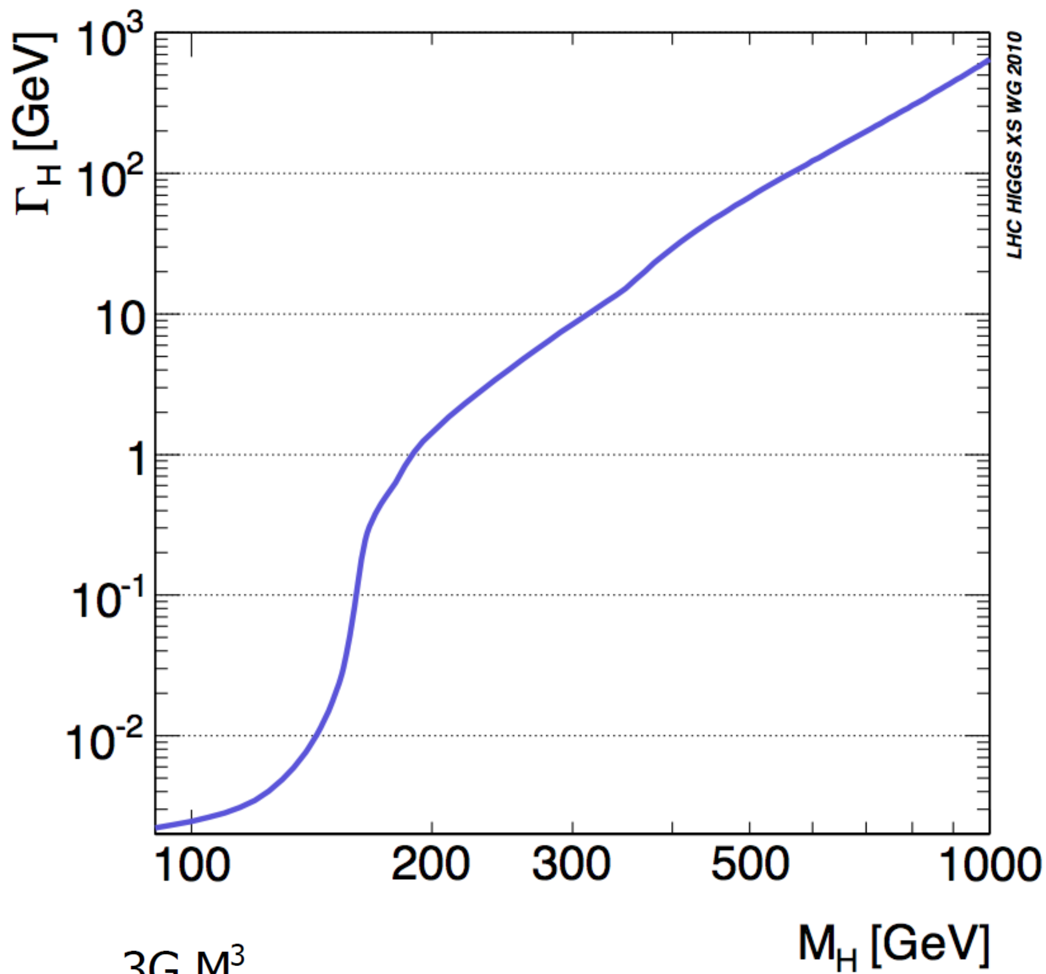
1.4 GeV @ 200 GeV

8.4 GeV @ 300 GeV

68.0 GeV @ 500 GeV

➢ At low mass region (<200 GeV), detector resolution dominates mass resolution

➢ At high mass, intrinsic width becomes dominant



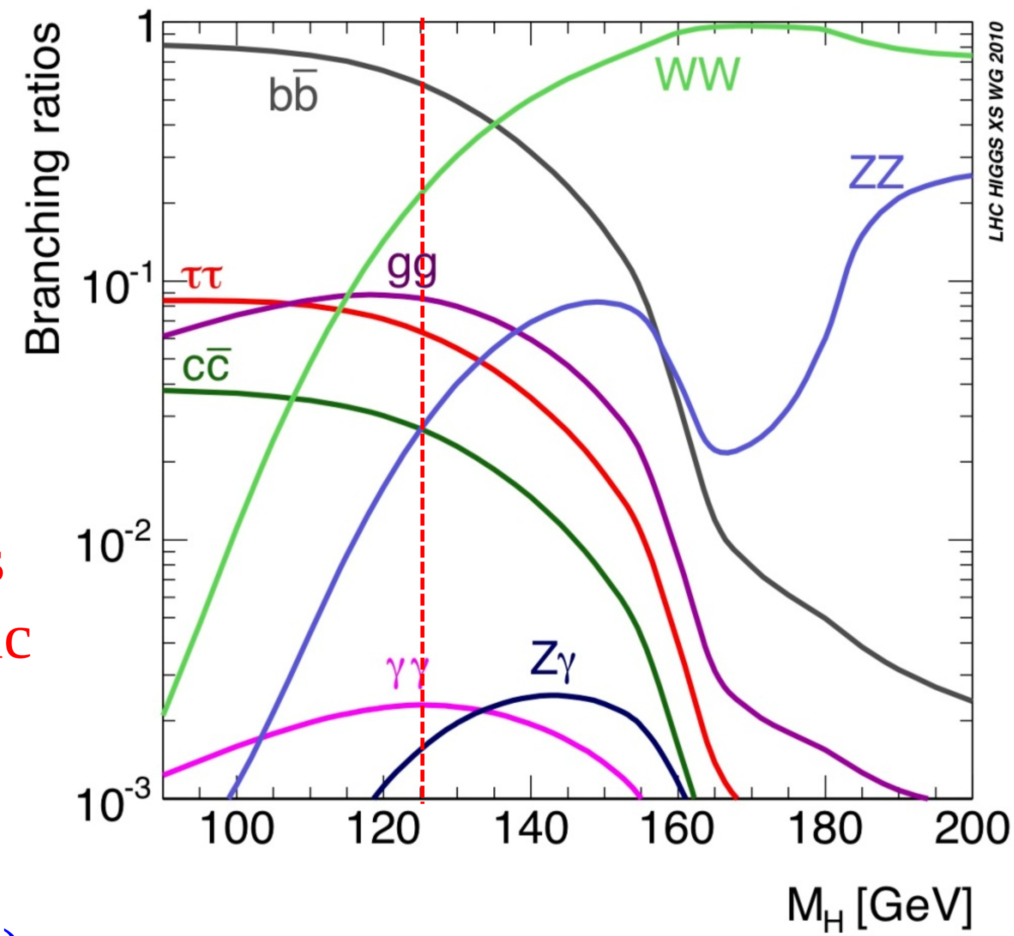
$$\Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}}$$

$$\approx 500\ \text{GeV} \cdot \left(\frac{M_H}{1\ \text{TeV}}\right)^3$$

Higgs Boson Decay

Higgs decay branching ratio at m_H=125 GeV

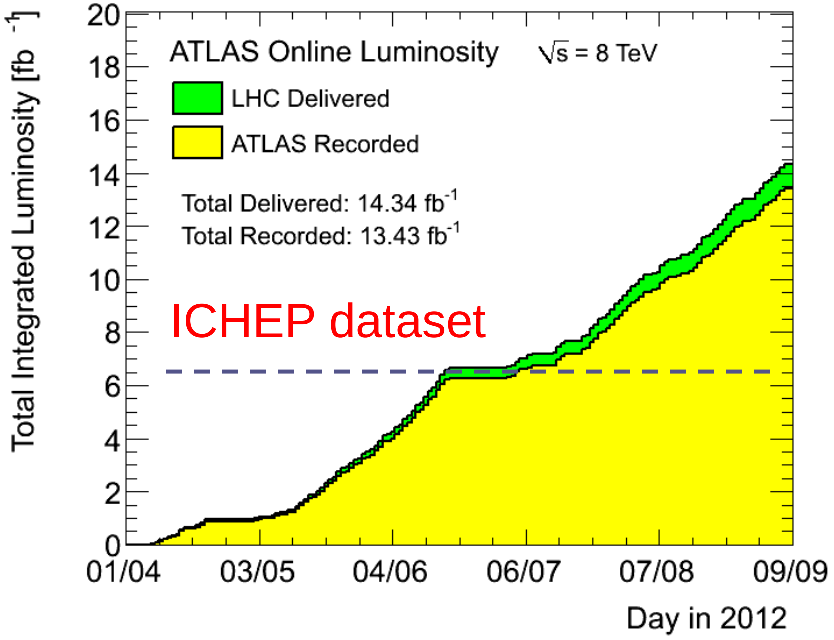
- bb: 57.7% (huge QCD background)
- WW: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% ("golden-plate", clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution, high sensitivity)

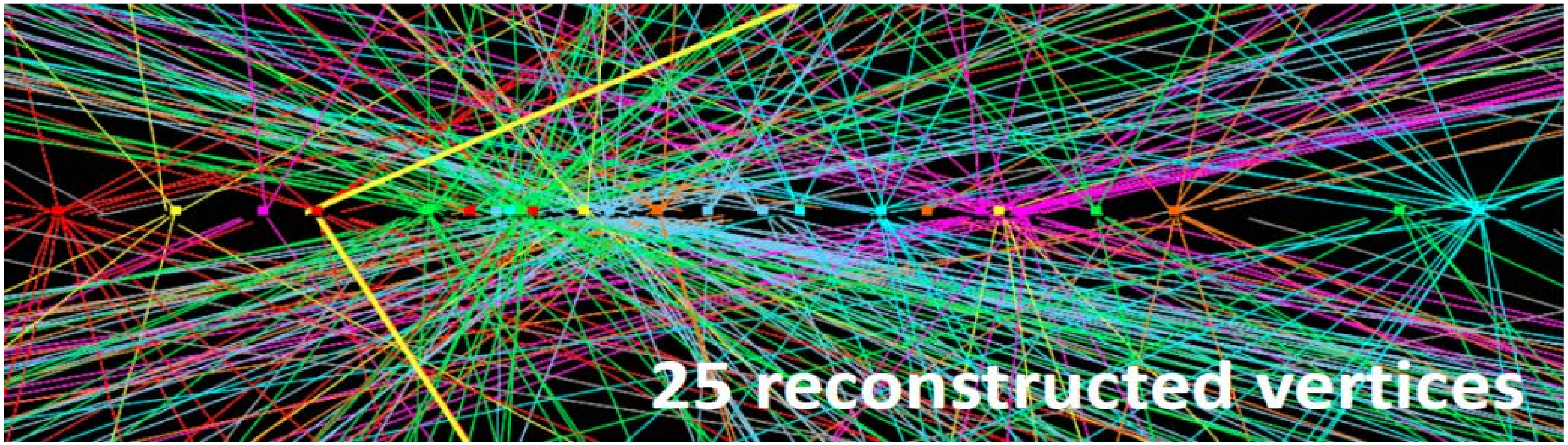


Higgs boson production rate:
1 out of 10^{12} collision events

ATLAS Data Samples

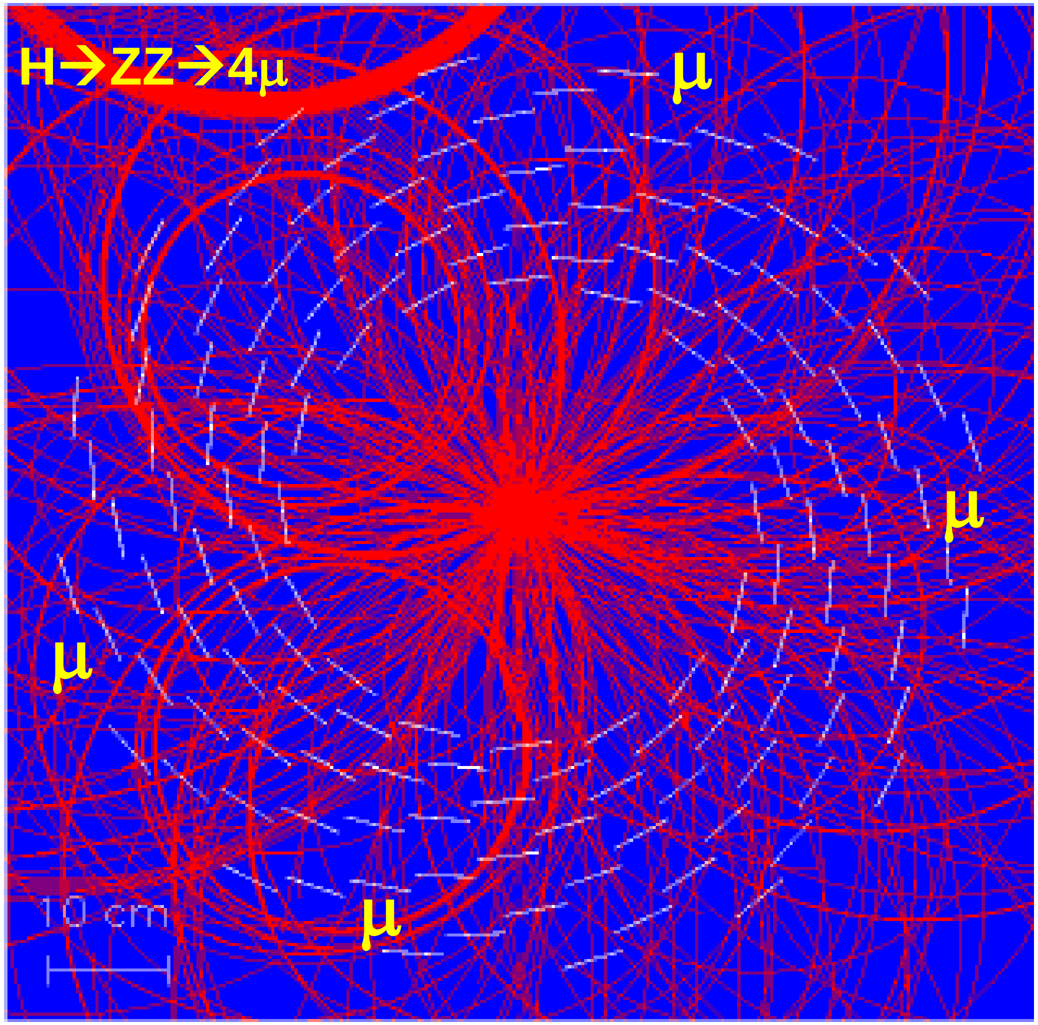
- **7 TeV data samples (2011)**
  - – 4.8 fb^{-1} for physics analysis
  - – Peak luminosity $3.6\times10^{33}cm^{-2}s^{-1}$
- **8 TeV data samples (2012)**
  - – 5.8 fb^{-1} for physics analysis
  - – Peak luminosity $6.8\times10^{33}cm^{-2}s^{-1}$
- **Data-taking efficiency: ~94%**
- **Significant pileup events**





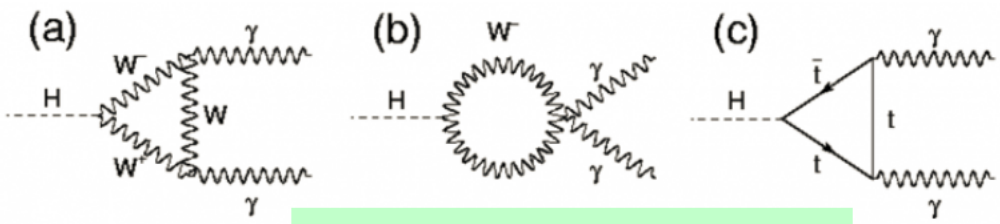
Major Challenge

- Large pileup events result in big challenge to the detector, reconstruction and particle identification !



Higgs → γγ

- **Very simple signature, but small rate Br(H→γγ) ~ 2×10^{-3};**
- **Important decay mode for the low mass region (100-140 GeV)**

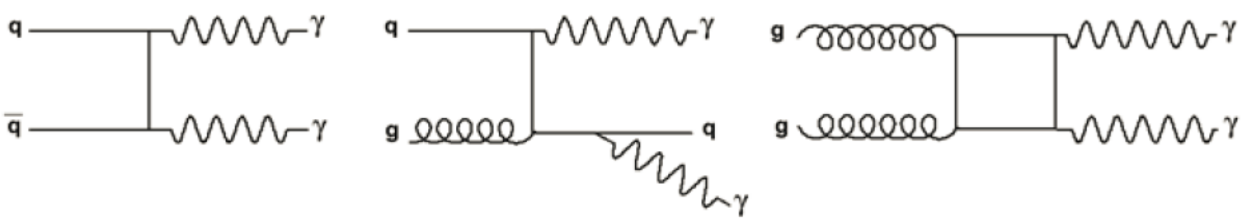


$$\sigma_H \times Br(H \to \gamma\gamma) \sim 50 \text{ fb}$$
$$@\ m_H = 125 \text{ GeV}$$

Decay through loops !

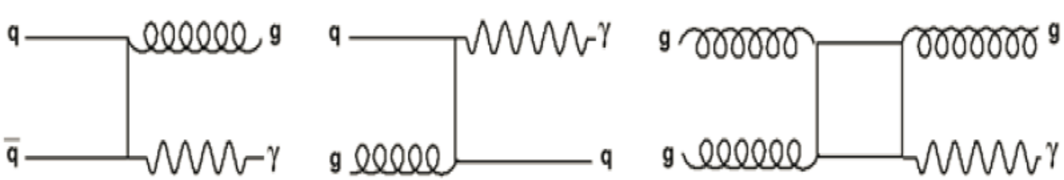
~500 events in 2011+2012 sample!

- **Irreducible background from γγ production**



$$\sigma(\gamma\gamma) \sim 40 \text{ pb}$$

- **Reducible background from γj and jj productions**



$$\sigma(\gamma j) \sim 3\times10^5 \text{ pb}$$
$$\sigma(jj) \sim 6\times10^8 \text{ pb}$$

Theoretical uncertainty $\Delta\sigma/\sigma \sim 30\%$ **, not reliable !**

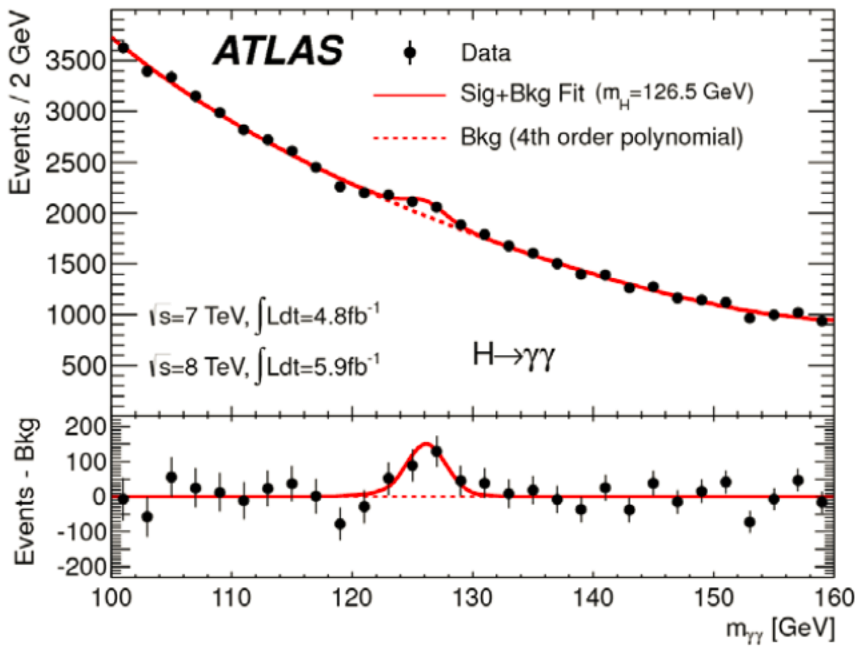
Higgs → γγ

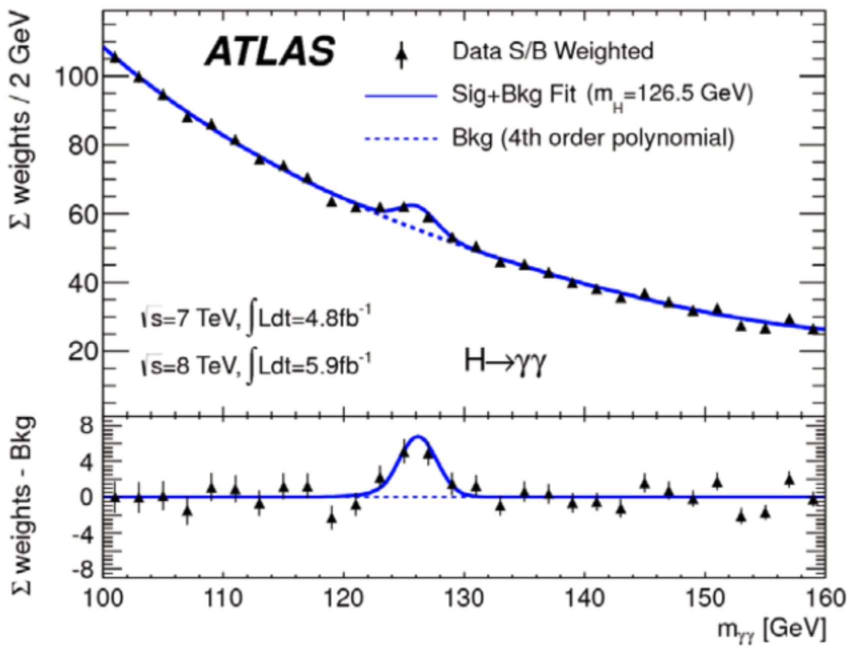
Diphoton mass $m_{\gamma\gamma}$ as the final discriminant variable

$$m^2 = 2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\Delta\phi_{\gamma\gamma}\right)$$

Model signal and background using analytical functions:

- **Signal: Crystal-Ball function (core) + Gaussian (outlier)**
- **Backgrounds: exponentials, polynomials, ...**





A total 59059 events selected, expect ~170 signal events at 126 GeV

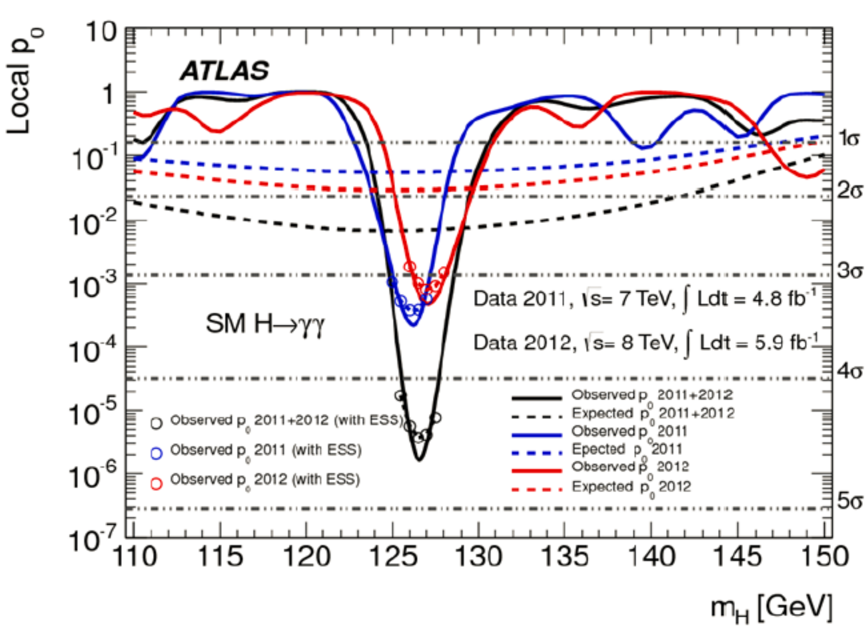
Higgs → γγ

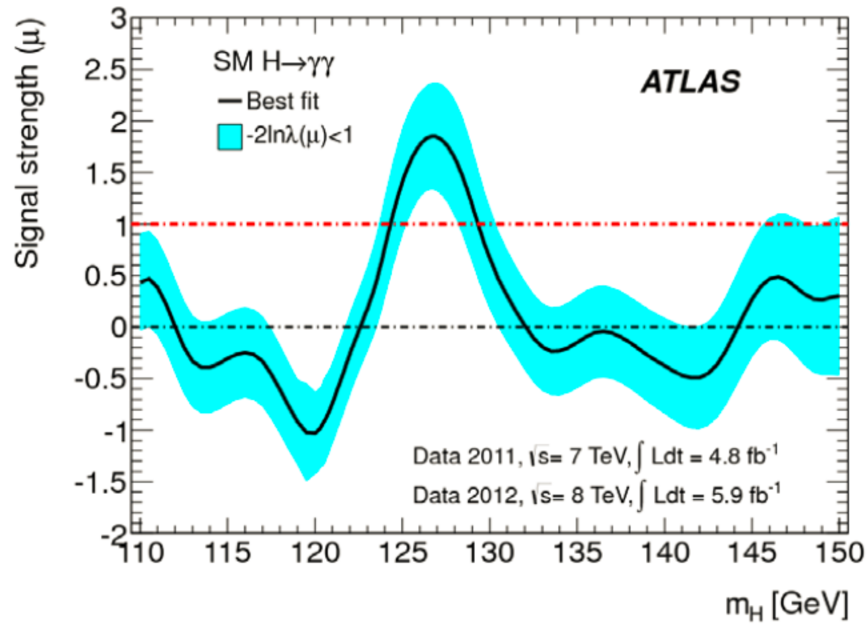
Consistent excesses in both 2011 and 2012 data

Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	126	3×10^{-4}	3.4σ	1.6σ
2012	127	5×10^{-4}	3.2σ	1.9σ
Combined	126.5	2×10^{-6}	4.5σ	2.5σ

A minimum p_0 at 126.5 GeV

$$p_0 = 2\times10^{-6} \quad \Rightarrow \quad 4.5\sigma$$

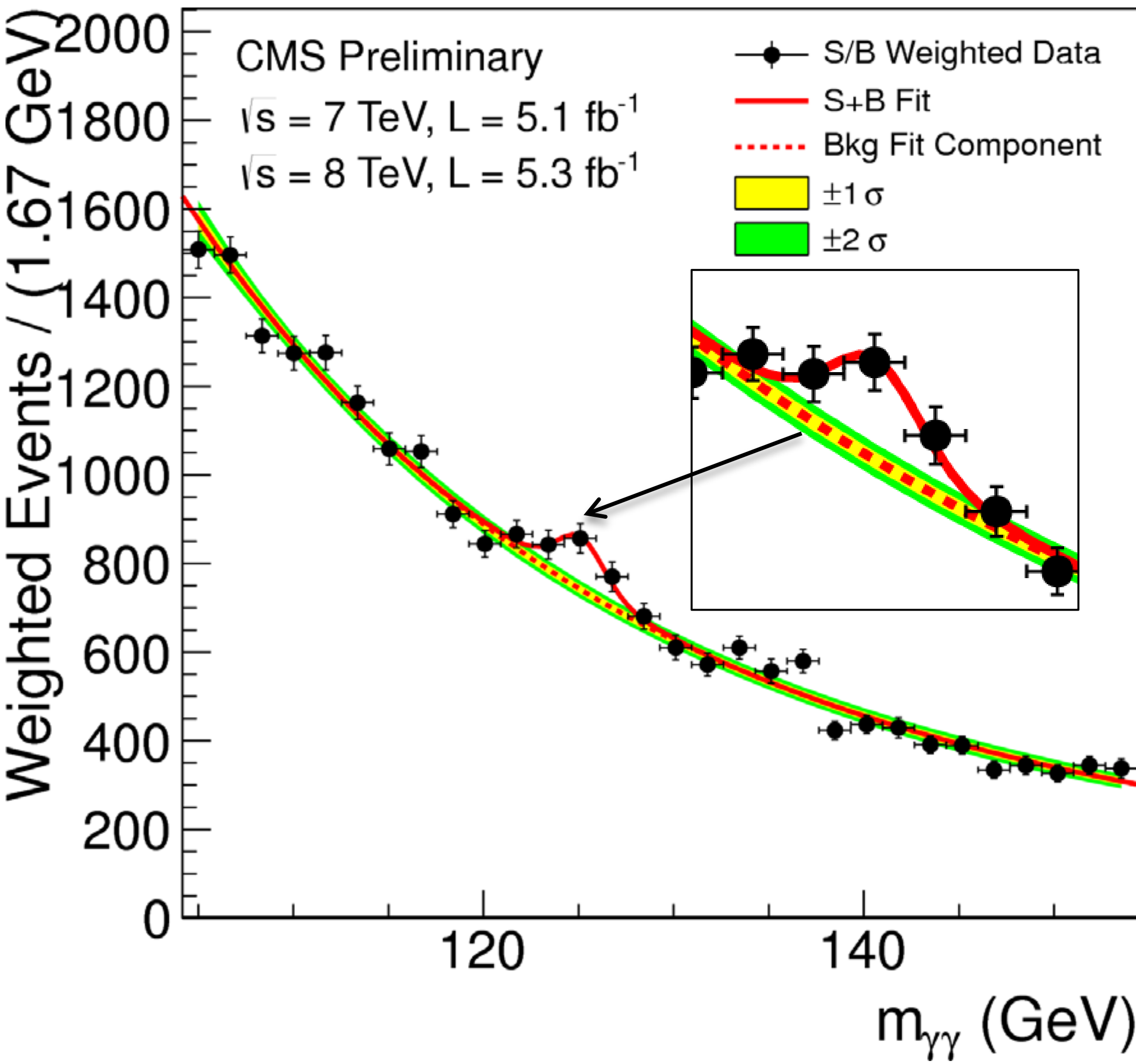


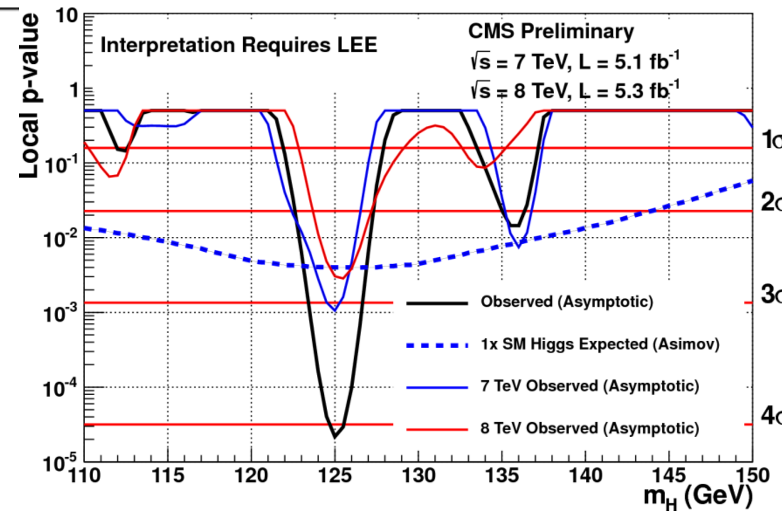


The measured signal strength, the excess relative to the SM expectation, at 126 GeV:

$$\mu = \frac{\sigma\cdot Br}{(\sigma\cdot Br)_{SM}} = 1.8\pm0.5$$

Results from CMS (H→γγ)



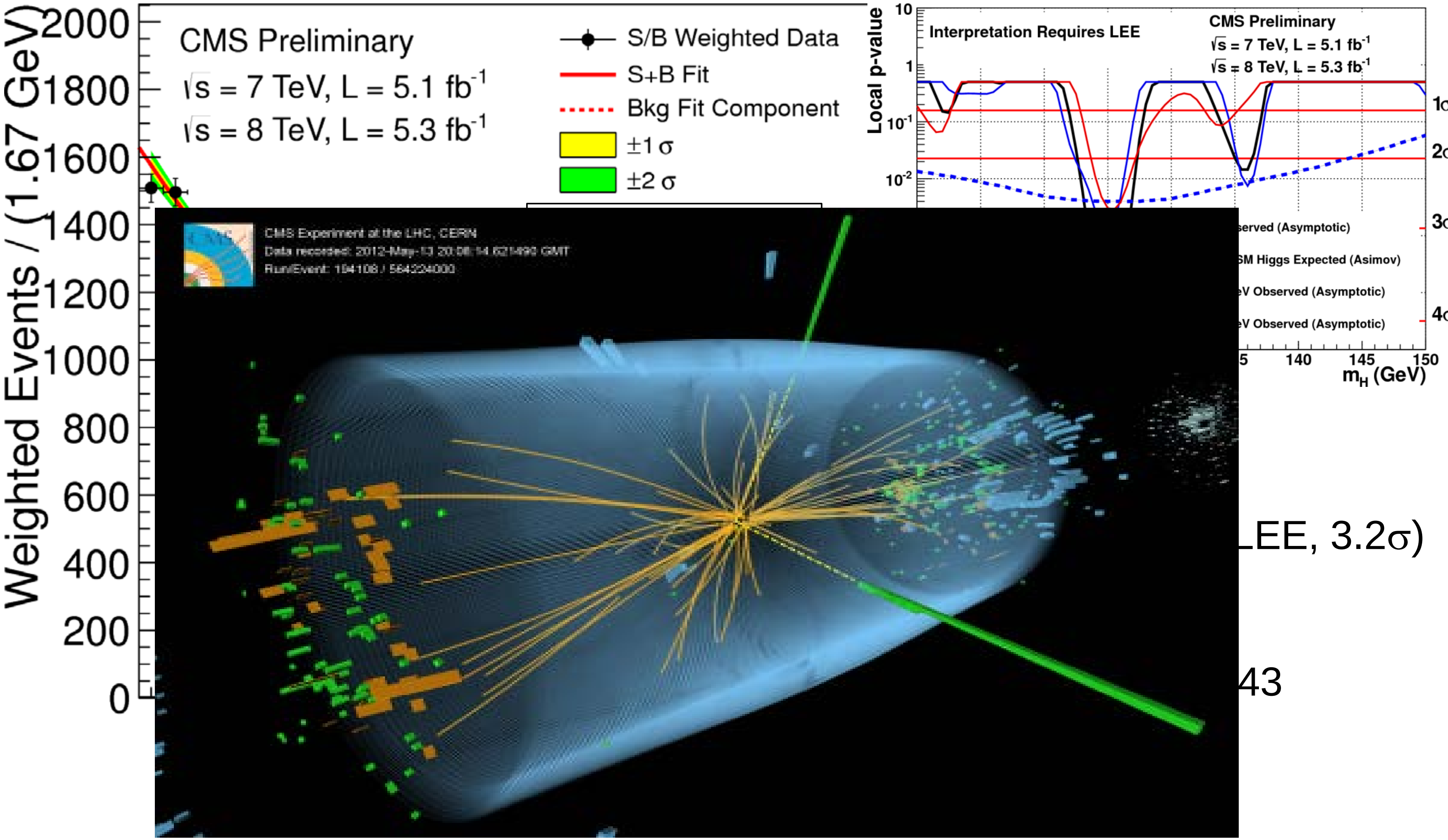


➔ Expected 2.5 σ

➔ Observed 4.1σ (LEE, 3.2σ)

➔ Signal strength:
$\sigma/\sigma_{SM} = 1.56 \pm 0.43$

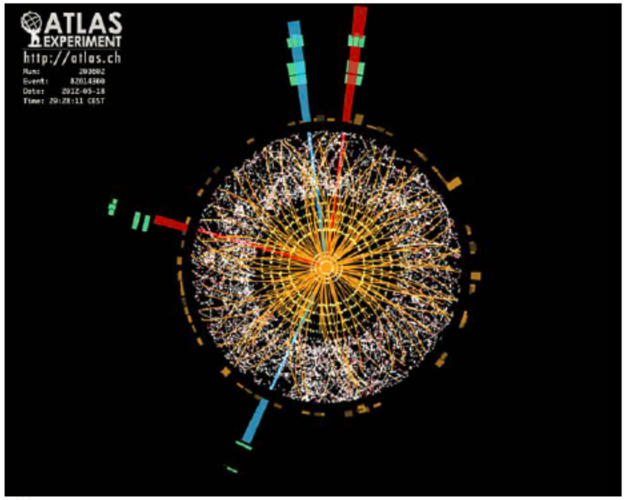
Results from CMS (H→γγ)



LEE, 3.2σ)

43

Higgs → ZZ* → 4ℓ: the golden channel



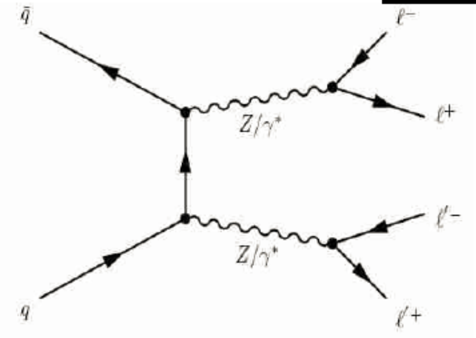
The gold-plated channel over a wide range of potential Higgs mass.

Clean signature:

- 4 isolated leptons, full reconstruction;
- Mass peak over backgrounds, good mass resolution.

Small backgrounds:

Irreducible SM ZZ* production and reducible Z+jets, top, …



$\ell = e, \mu$

But even smaller signal rate:

@125 GeV

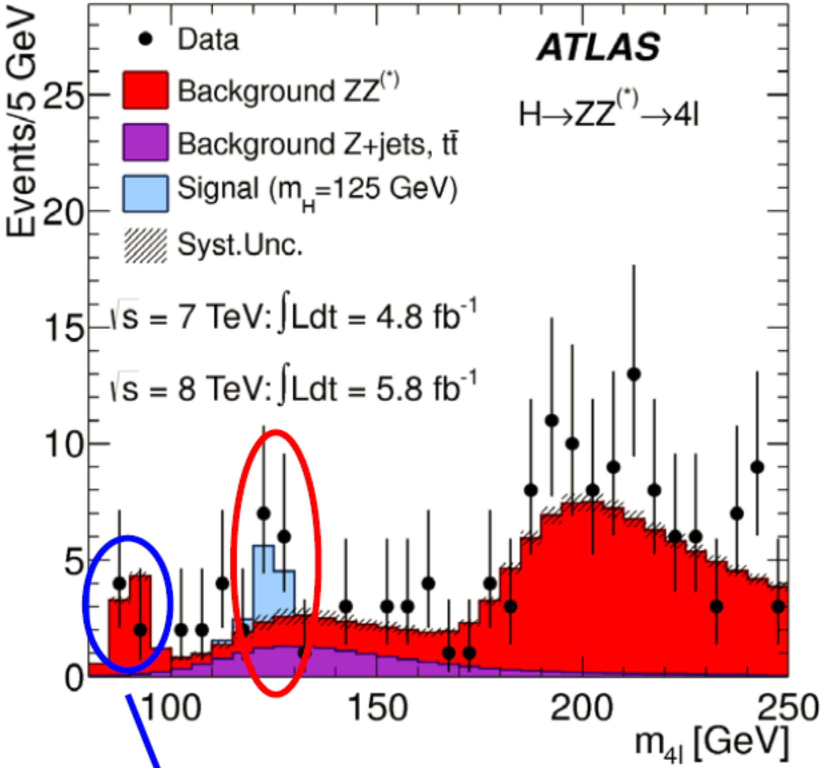
$$\mathrm{BR}(ZZ \to 4\ell) = 0.45\%,\ \mathrm{BR}(H \to ZZ^*) = 2.6\%$$
$$\Rightarrow\ \sigma_H \times \mathrm{BR}(H \to ZZ \to 4\ell) = 2.6\ \mathrm{fb}$$

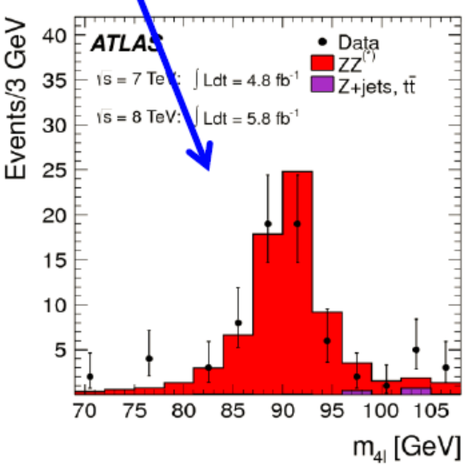
$\Rightarrow$ ~25 events in 2011+2012 samples

Selection efficiency to the 4th power of lepton efficiency:

0.7^4 ~ 0.25, 0.8^4 ~ 0.41 $\Rightarrow$ critical to improve lepton selection!

Higgs → ZZ* → 4ℓ





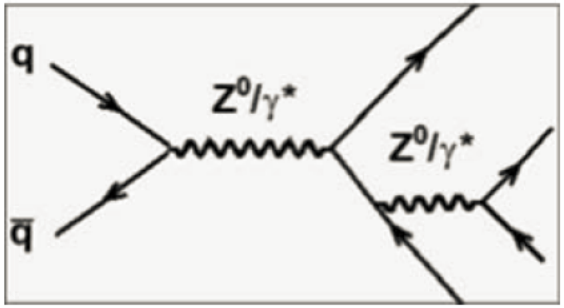
A small cluster of events populates around 125 GeV

In the region 125 ± 5 GeV

Dataset	2011	2012	2011+2012
Expected B only	2±0.3	3±0.4	5.1±0.8
Expected S m_H=125 GeV	2±0.3	3±0.5	5.3±0.8
Observed in the data	4	9	13

2011+ 2012	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1	0.5
Reducible/total background	5%	45%	55%

Single resonant contributions
Enhanced by relaxing mass and pT requirements



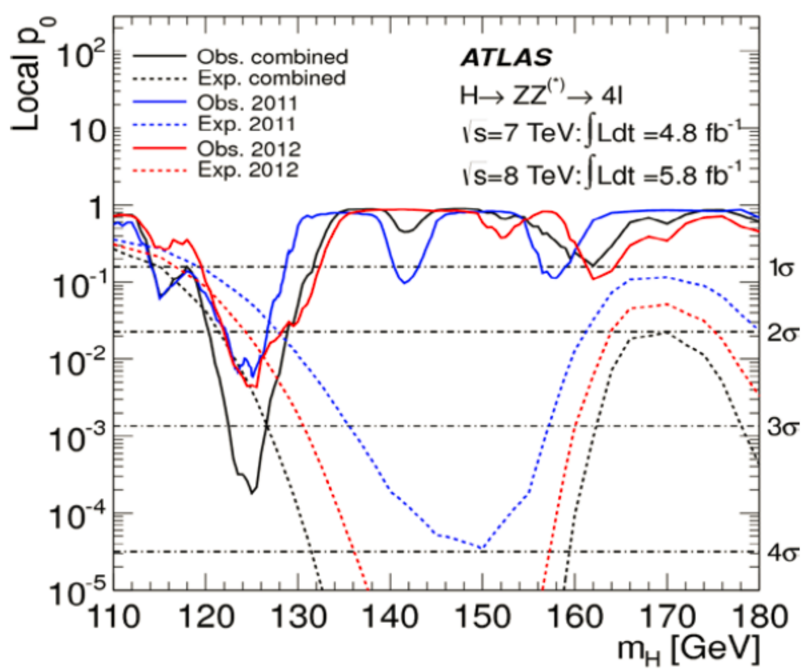
Higgs → ZZ* → 4ℓ

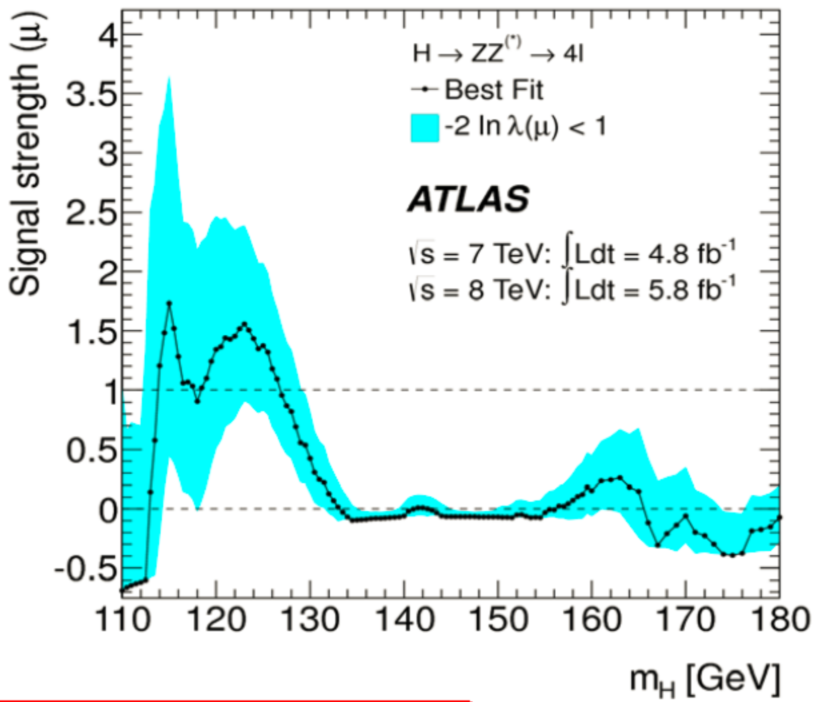
Consistent excesses in both 2011 and 2012 data

Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	125	0.6%	2.5σ	1.6σ
2012	125.5	0.5%	2.6σ	2.1σ
Combined	125	0.02%	3.6σ	2.7σ

A minimum p_0 at 125 GeV

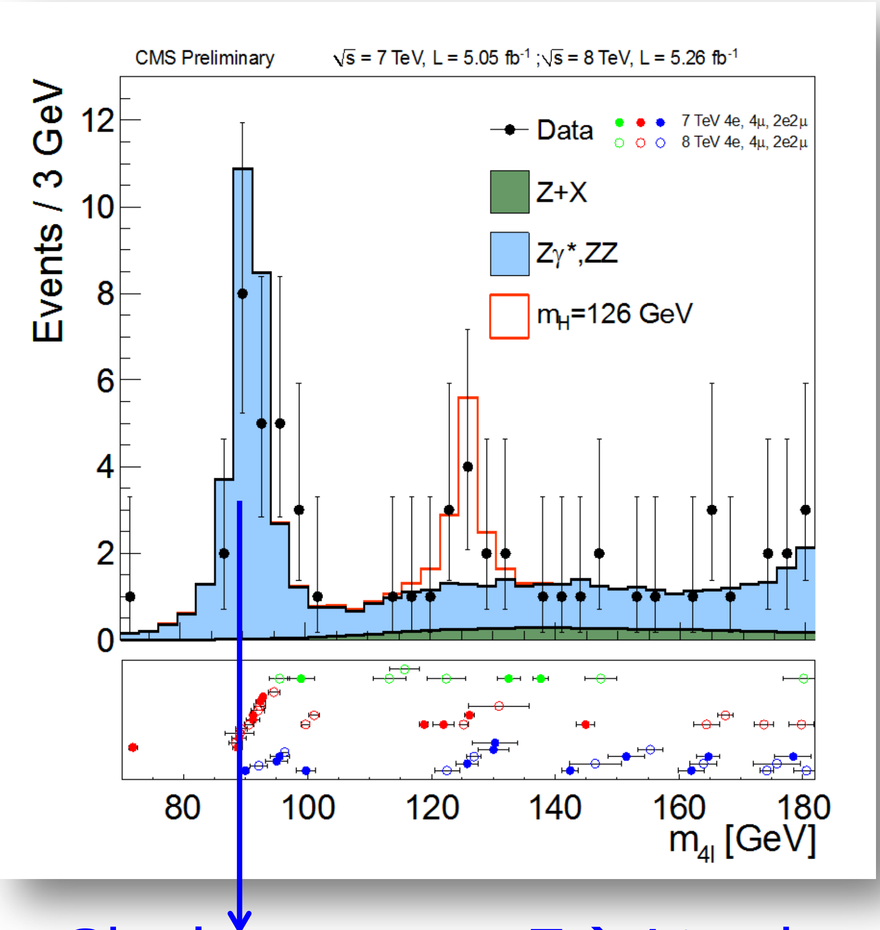
$$p_0 = 2\times10^{-4} \quad \Rightarrow \quad 3.6\sigma$$

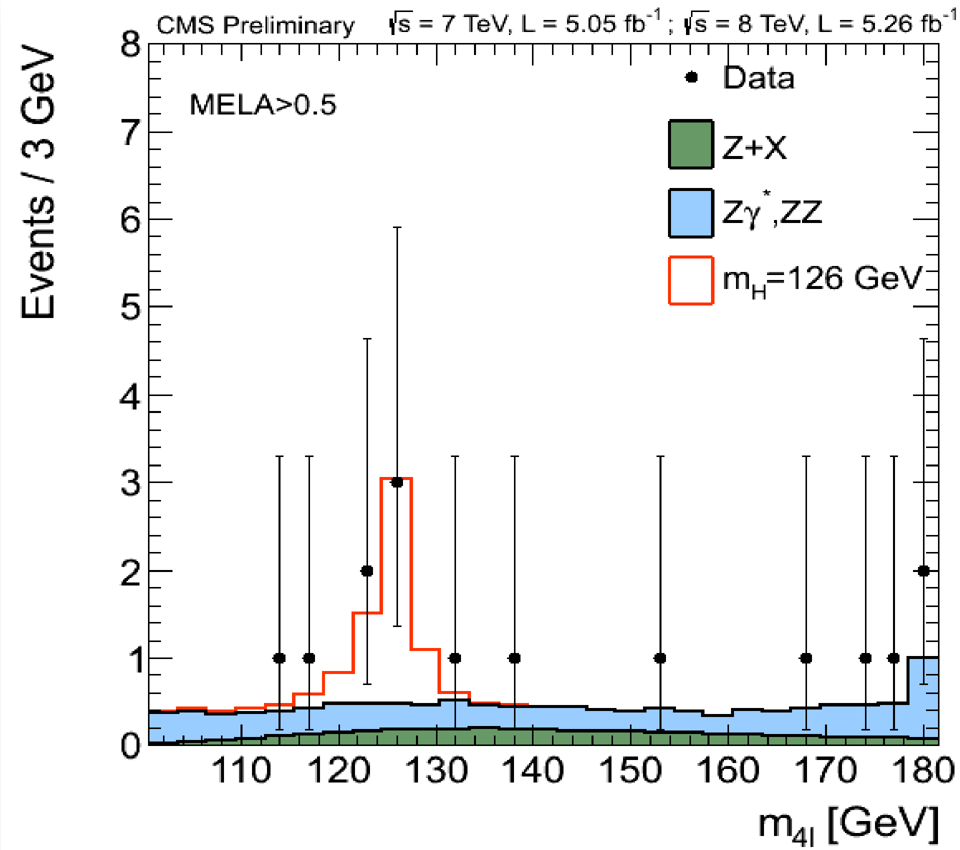




Signal strength at 126 GeV: μ=1.4 ± 0.6

Results from CMS (H→ZZ*→4ℓ)





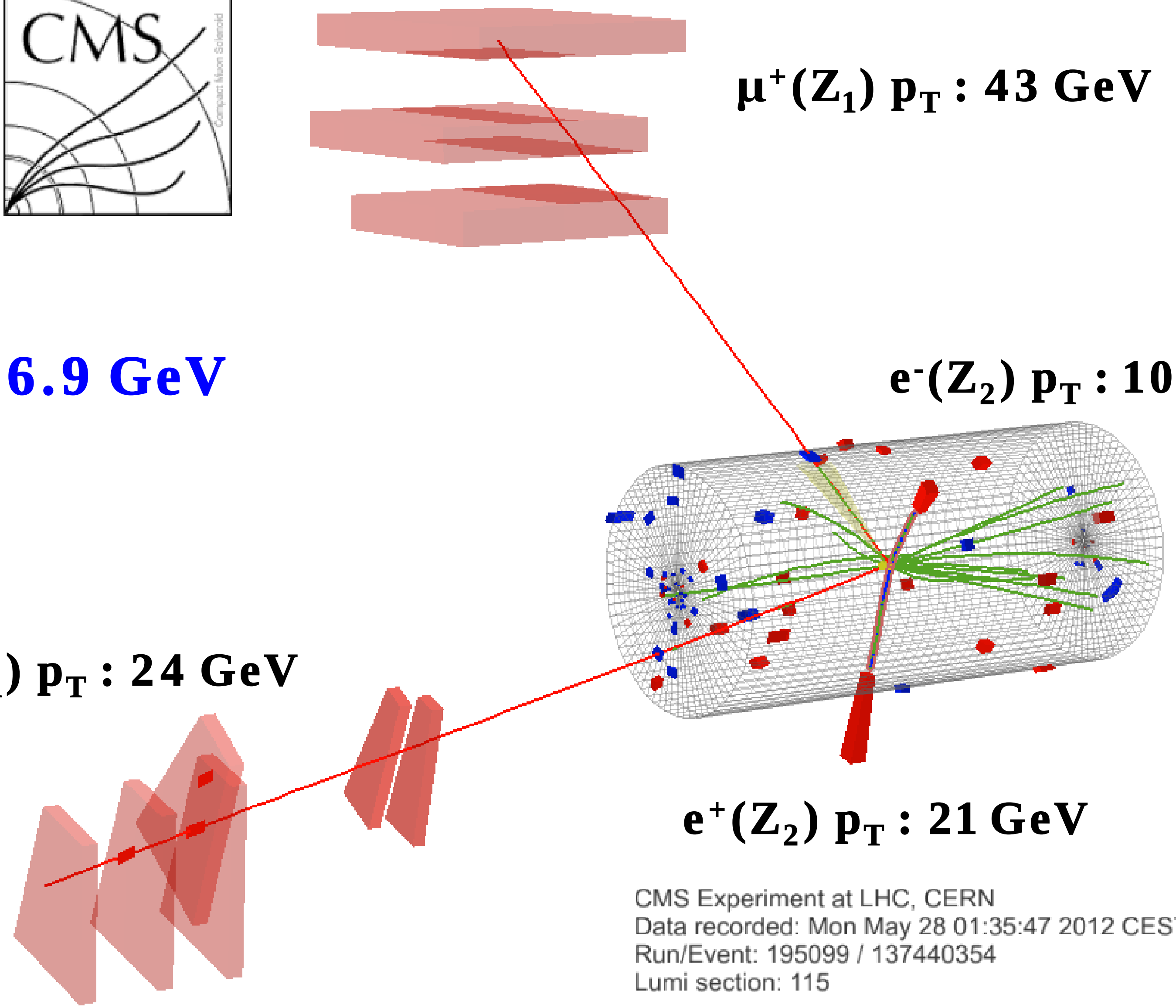
Single resonant Z→4ℓ using loose selection cuts

Enrich the Higgs signal by tightening the selection cuts

Significance: 3.8σ (expected), 3.2σ (observed)

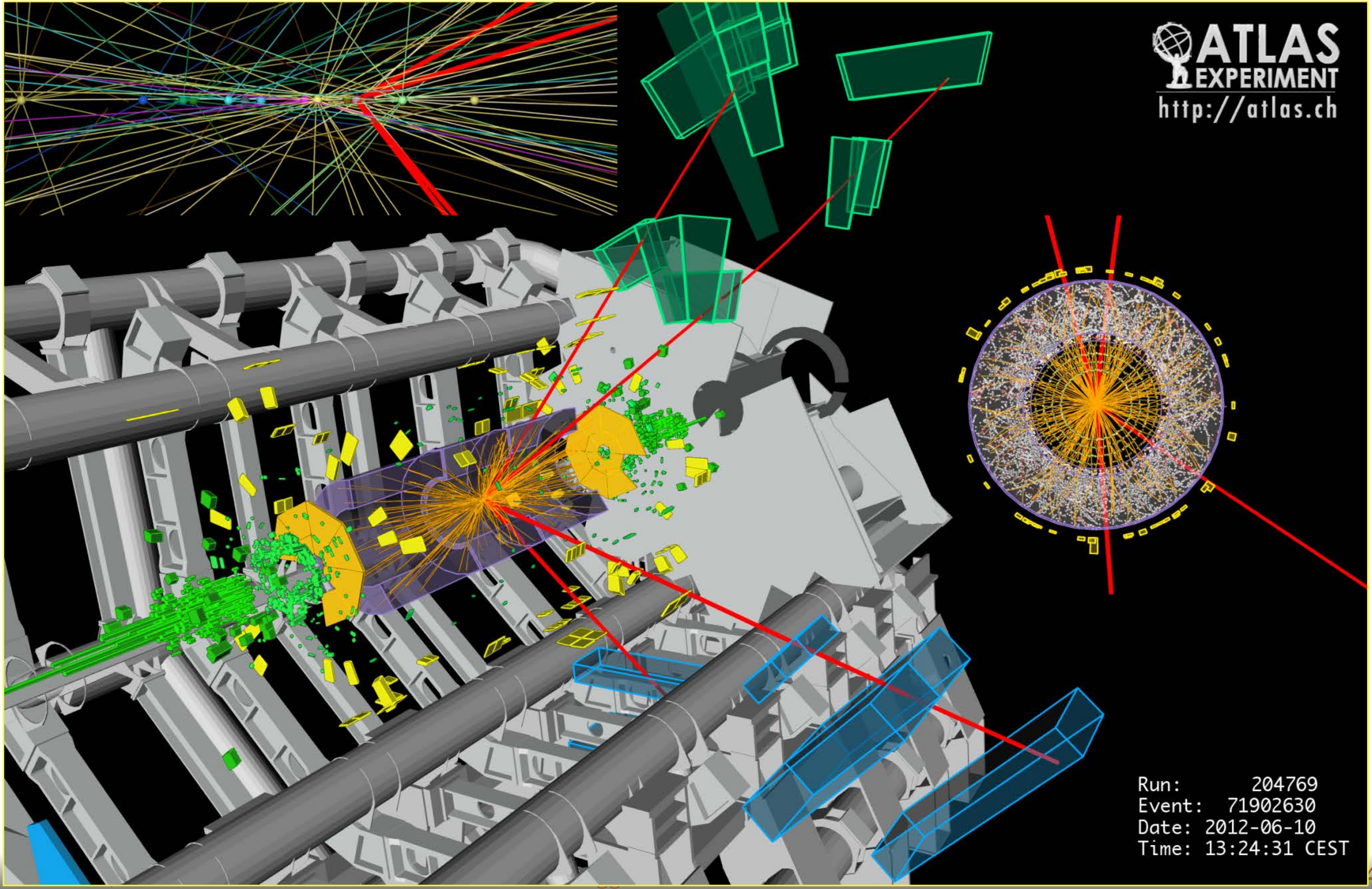
Candidate of H→ZZ*→4l (CMS)

M_{4l}=126.9 GeV



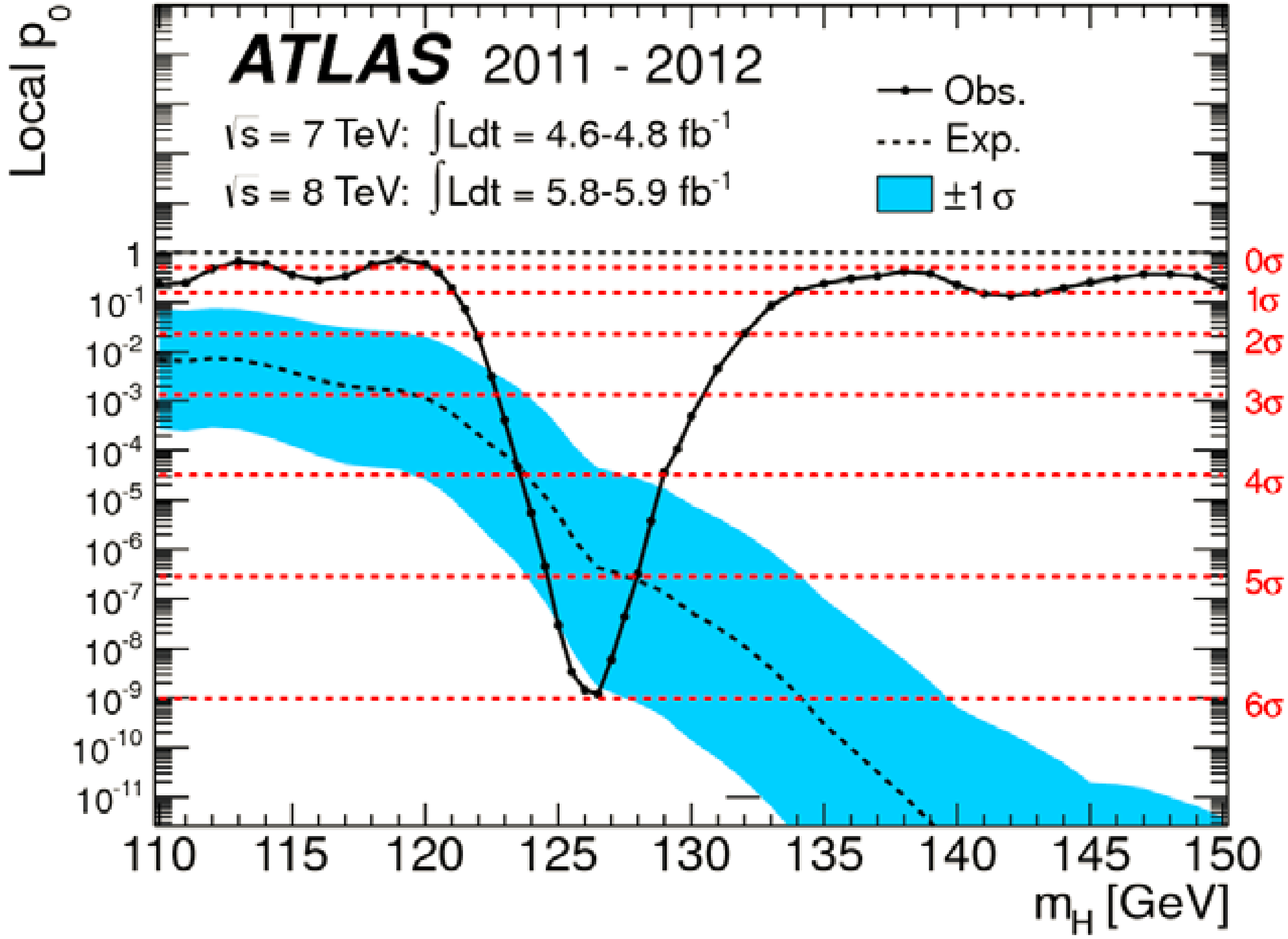
H → ZZ* → 4μ Candidate

- $M_{4\mu}$ = 125.1 GeV, M_{12} = 86.3 GeV, M_{34} = 31.6 GeV



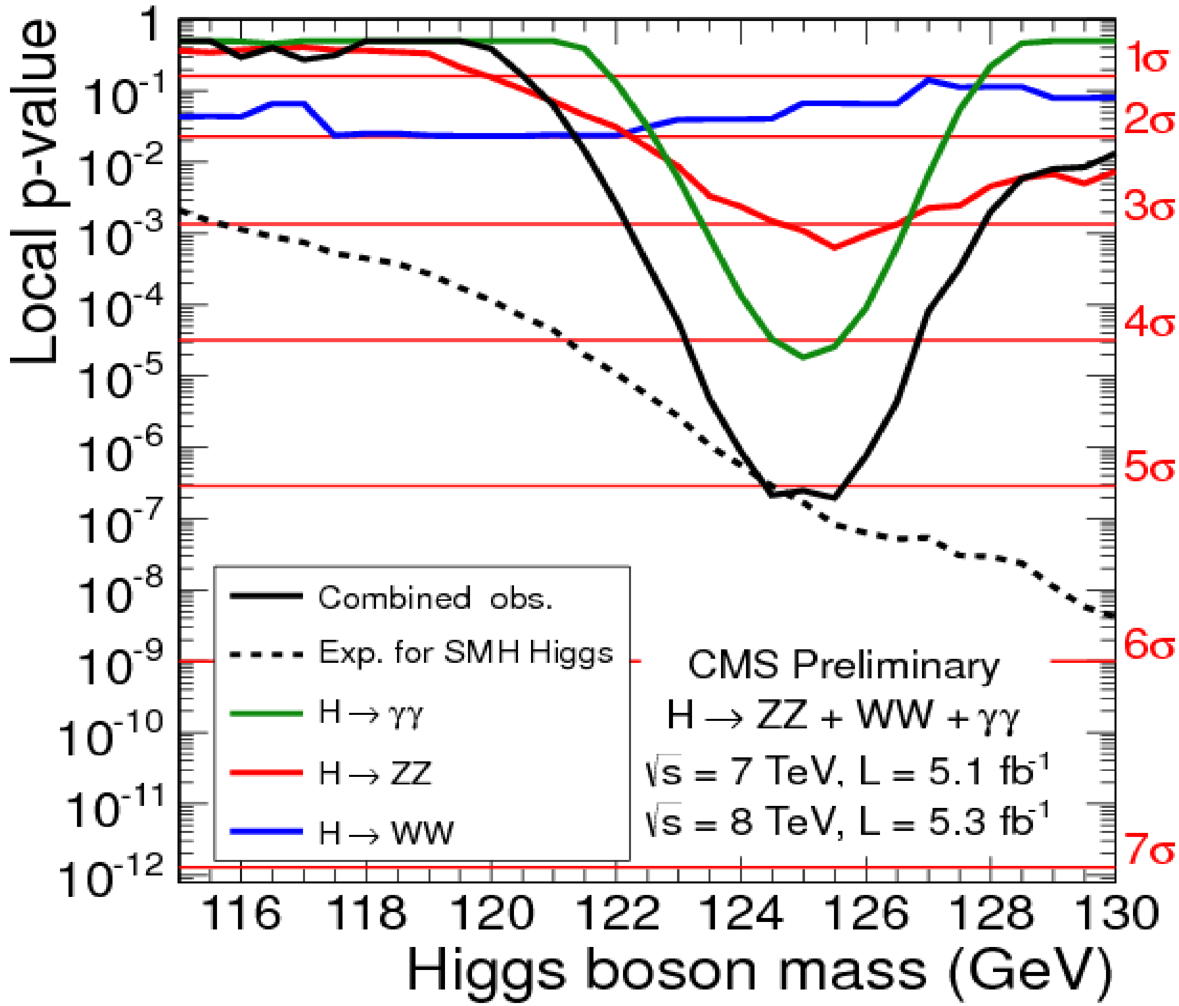
Combined Results from ATLAS

- ❑ **Observed significance 6.0σ (expected 5.0σ)**
- ❑ **Fitted mass: 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV**



Combined Results from CMS

- **Observed significance 5.1σ (expected 5.2σ)**
- **Fitted mass: 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV**



Observation of a New Particle !

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

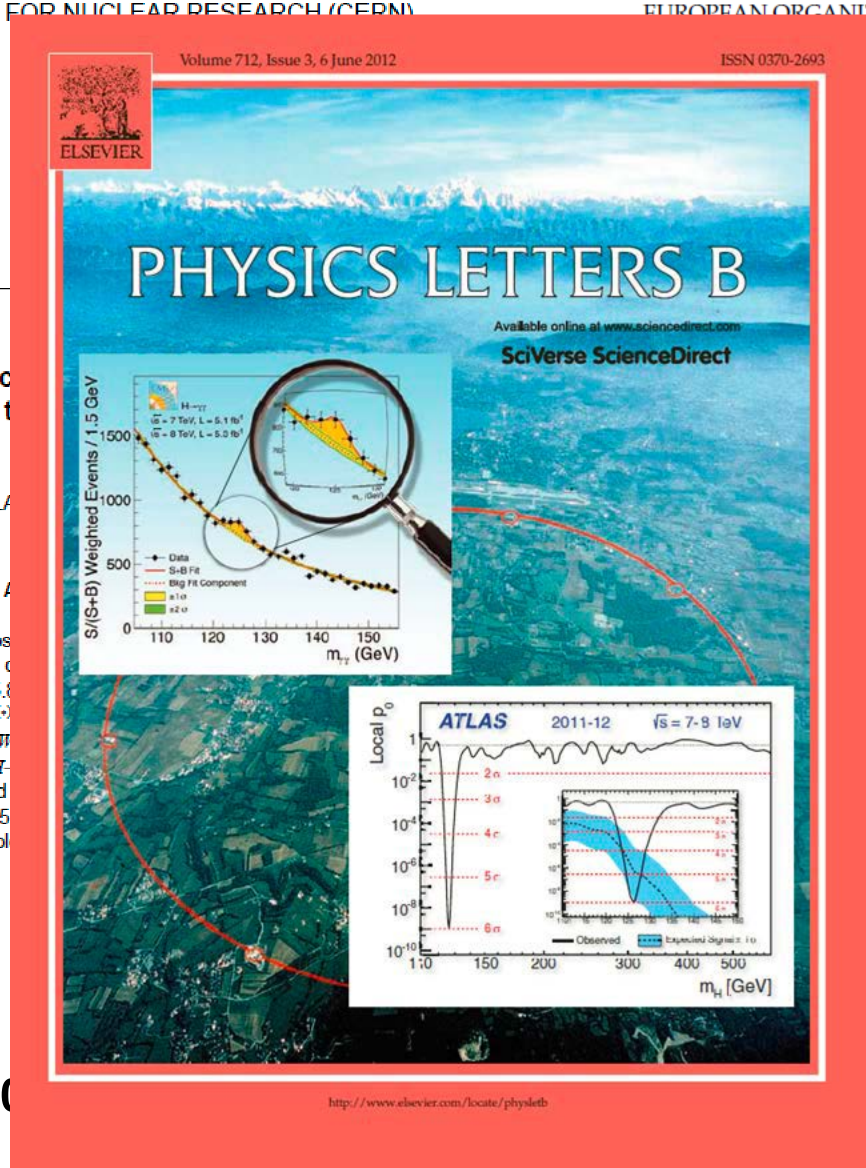
arXiv:1207.7214v1 [hep-ex] 31 Jul 2012

Observation of a New Partic
Model Higgs Boson with t

The ATL

A search for the Standard Model Higgs bos at the LHC is presented. The datasets used 4.8 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.8 channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)}$ published results of searches for $H \to ZZ^{(*)}$, W improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and H production of a neutral boson with a measured This observation, which has a significance of 5 fluctuation probability of 1.7×10^{-9}, is compatibl Higgs boson.

Phys. Lett. B 716 (20



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2012-220
2012/08/01

w boson at a mass of 125 GeV with the experiment at the LHC

he CMS Collaboration*

Abstract

searches for the standard model Higgs boson in proton- 7 and 8 TeV in the CMS experiment at the LHC, using to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and is performed in five decay modes: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, s observed above the expected background, a local signif- tions, at a mass near 125 GeV, signalling the production cted significance for a standard model Higgs boson of viations. The excess is most significant in the two decay solution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of) GeV. The decay to two photons indicates that the new different from one.

to the memory of our colleagues who worked on CMS but have since passed away.

ny contributions to the achievement of this observation.

Submitted to Physics Letters B

ett. B 716 (2012) 30-61

We have a discovery !!!

“We have now found the missing cornerstone of particle physics. We have a discovery. We have observed a new particle that is consistent with a Higgs boson.”

- Rolf Heuer

CERN Director

“It is an extraordinary achievement for the lab, and I am glad that it happened in my lifetime.” – Peter Higgs

It is a historic milestone, but only the beginning……

NEWS about the Higgs Boson (2012.7.4)

HOME PAGE | TODAY'S PAPER | VIDEO | MOST POPULAR | U.S. Edition

The New York Times

Science

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHN

Physicists Find Elusive Part

Scientists in Geneva on Wednesday applauded the discovery

By DENNIS OVERBYE
Published: July 4, 2012 | 122 Comments

The Higgs boson discovery is another giant leap for humankind

The Cern discovery of the Higgs particle is up there with putting man on the moon – something all humanity can be proud of

Themis Bowcock
guardian.co.uk, Wednesday 4 July 2012 12.45 BST
Jump to comments (...)

Scientists gather at Cern. Formal confirmation of the Higgs boson discovery is expected to follow in the next few months. Photograph: Denis Balibouse/Reuters

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27K Share

icle discovery

Prize for Higgs Mechanism

- **J. J. Sakurai Prize for Theoretical Particle Physics (2011)**

Peter W. Higgs
Phys. Lett. 12 (1964.9.15) 132
PRL 13 (1964.10.19) 508

F. Englert, R. Brout
PRL 13 (1964.8.31) 321

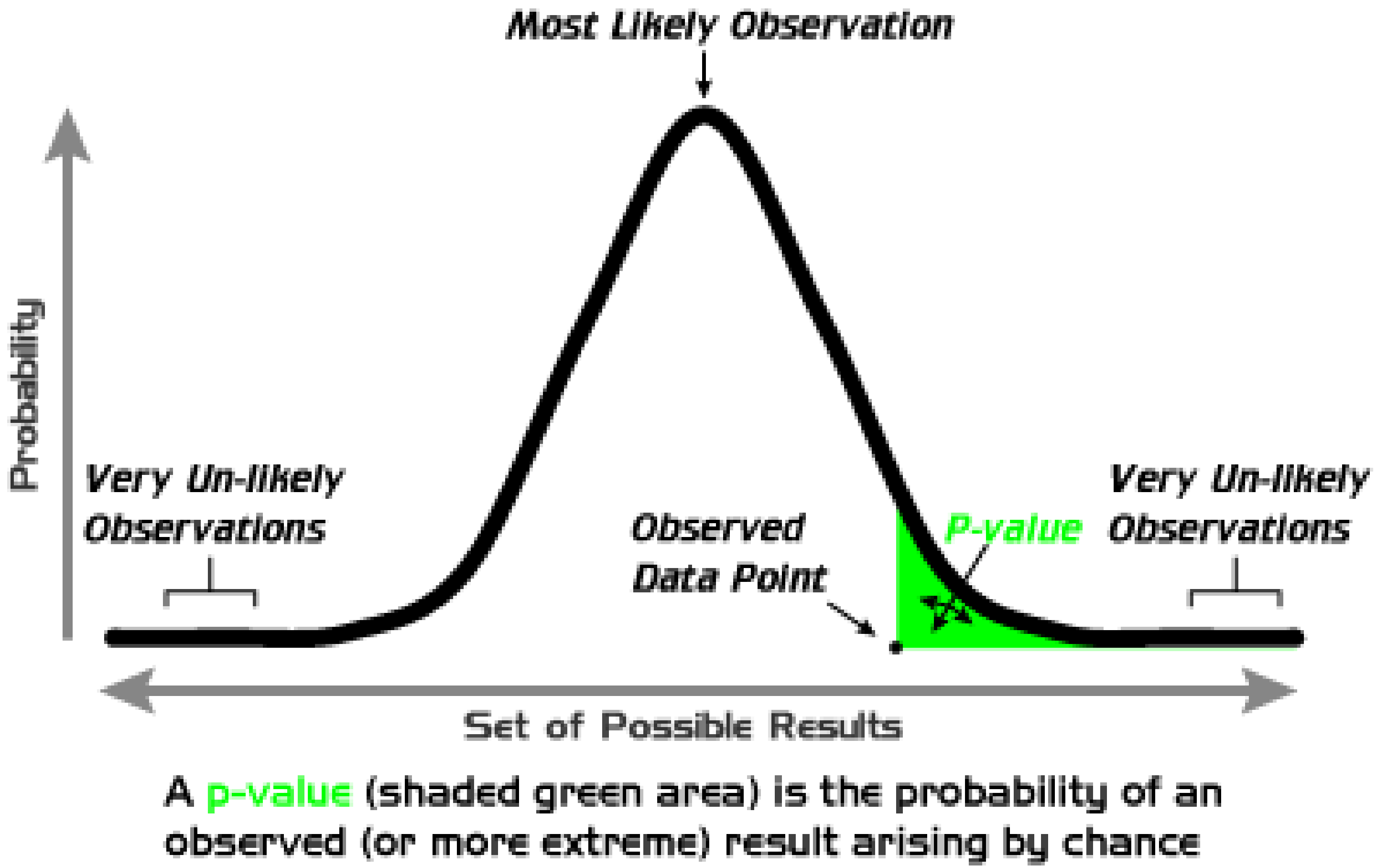
G.S. Guralnik, C.R. Hagen and
T.W.B. Kibble, PRL 13 (1964.11.16) 585

Who will win the Nobel Prize ?

Thank You !

谢谢大家 ！

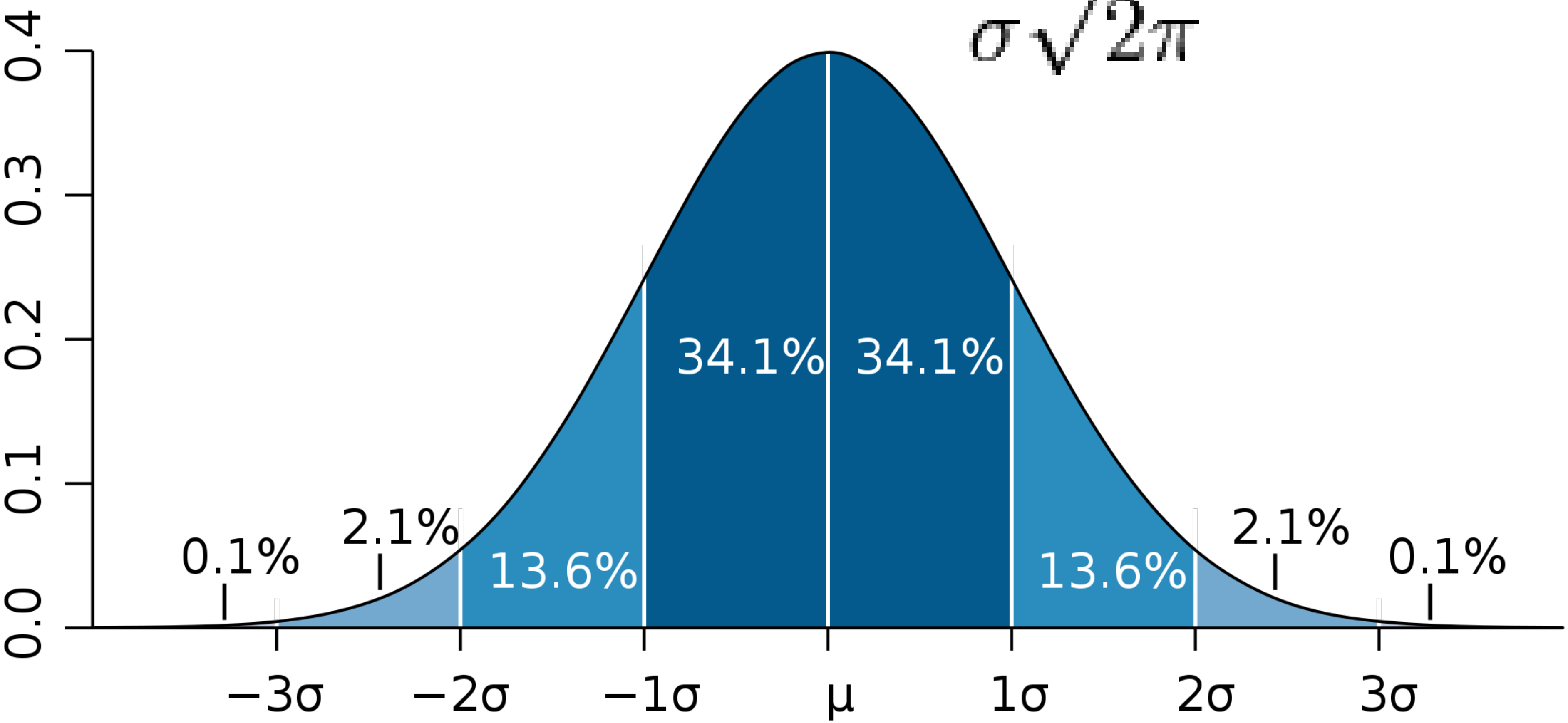
P-value


Most Likely Observation
Probability
Very Un-likely Observations
Observed Data Point
P-value
Very Un-likely Observations
Set of Possible Results
A p-value (shaded green area) is the probability of an observed (or more extreme) result arising by chance

Standard Deviation

- **Probability density function(PDF): Gaussian distribution**
- **μ: mean value**
- **σ: standard deviation**

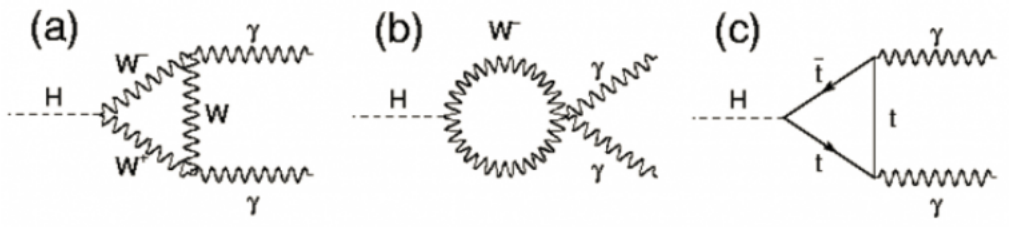
$$\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



What's Next ?

We have now discovered a Higgs-like new particle at 126 GeV

- Only observed in bosonic final states so far, its decay to fermonic final states has yet to be established;
- The overall production rate appears to be consistent with the Standard Model expectation, but is the higher than expected $H \rightarrow \gamma\gamma$ rate a statistical fluctuation? Or something new in the loop?



Some current activities:

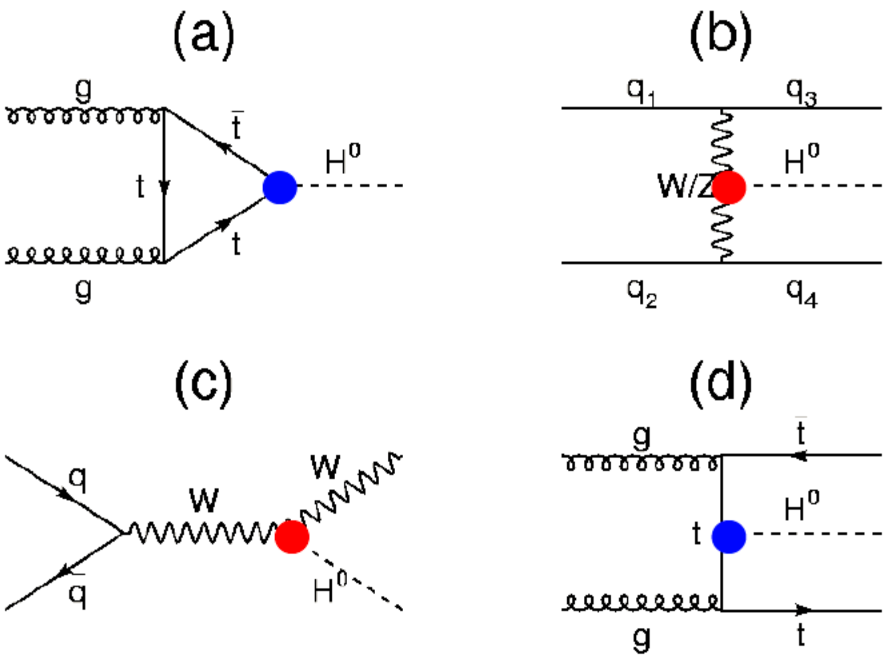
- Complete the analyses in $H \rightarrow \tau\tau$ and $H \rightarrow bb$ final states (Kracow?);
- Observe the particle in the VBF production mode
  Separate ggF and VBF processes, coupling measurements;
- Measurements of the particle properties: mass, spin and CP, …
- Improve the precision of the rate measurements;
- Continue the search for other Higgs-like particles

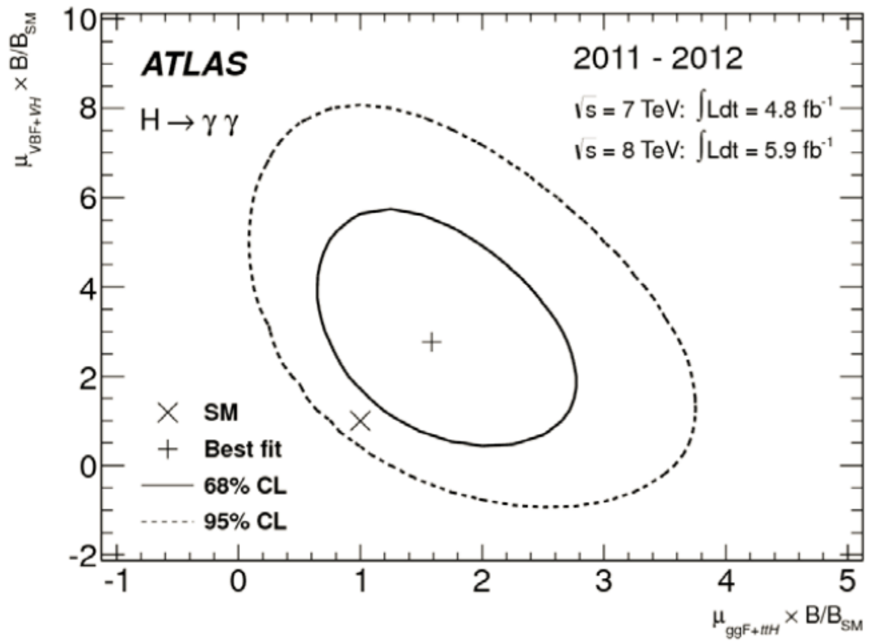
Next Step

Higgs has two types of coupling:

- To gauge bosons;
- Yukawa coupling to fermions

Isolating the two couplings through the study of both production and decay processes





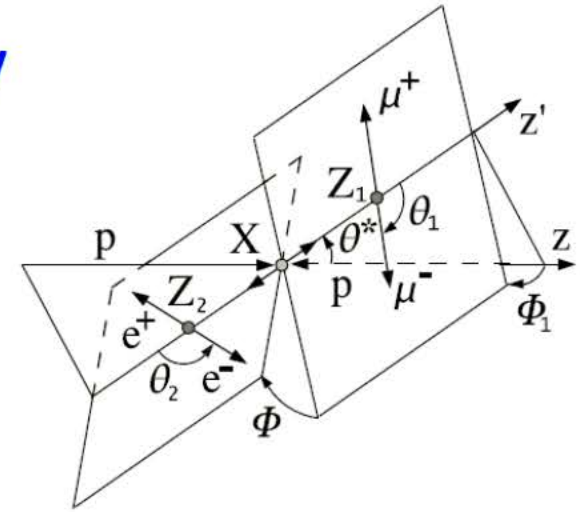
● "gauge" coupling

● Yukawa coupling

Higgs Spin and Parity

$H \to ZZ^* \to 4l$ final state is ideal for Higgs property measurement thanks to

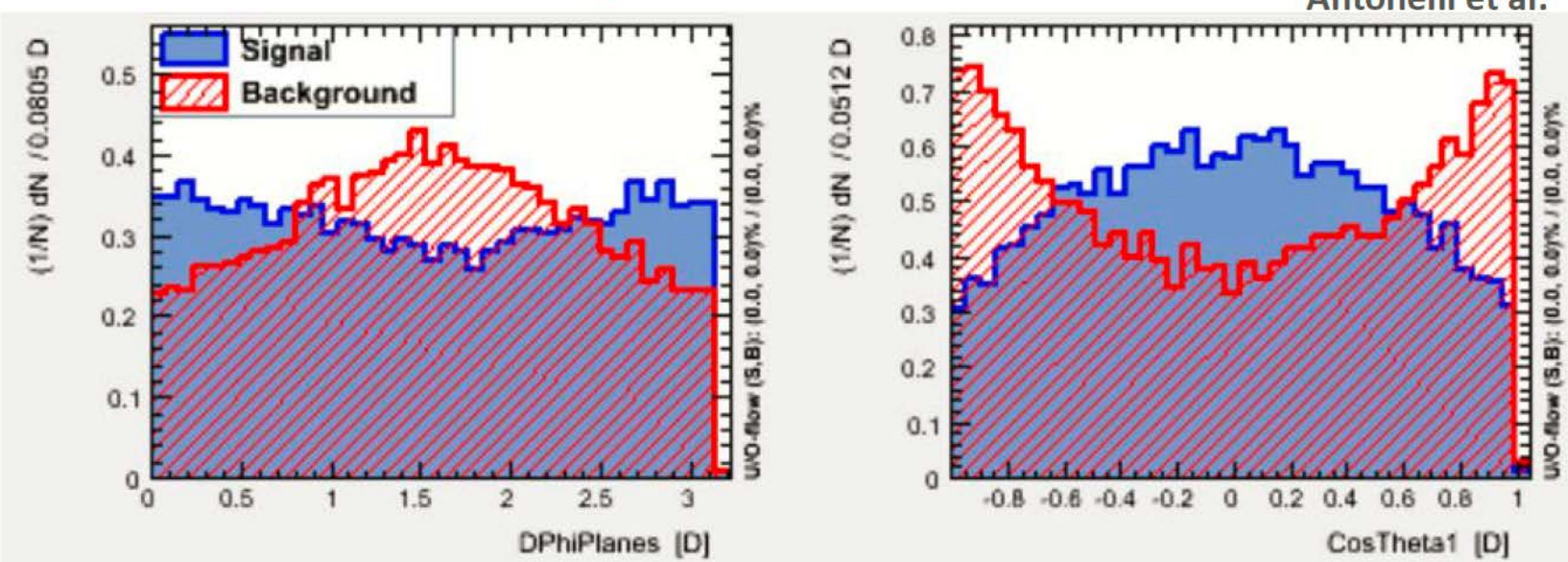
- full reconstruction, good resolution,
- low background



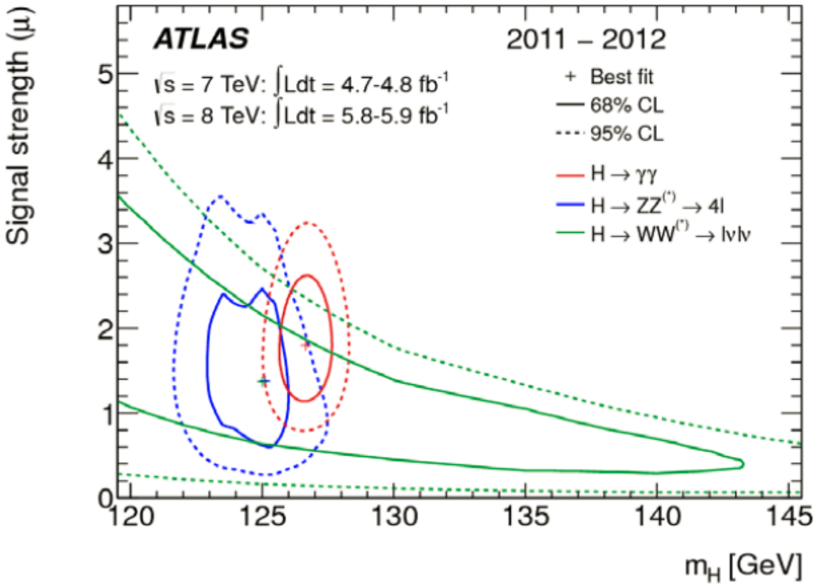
With 30 fb^{-1}, expect a ~3σ separation between 0^+ and 0^-.

JHU generator: 0^+ 0^-

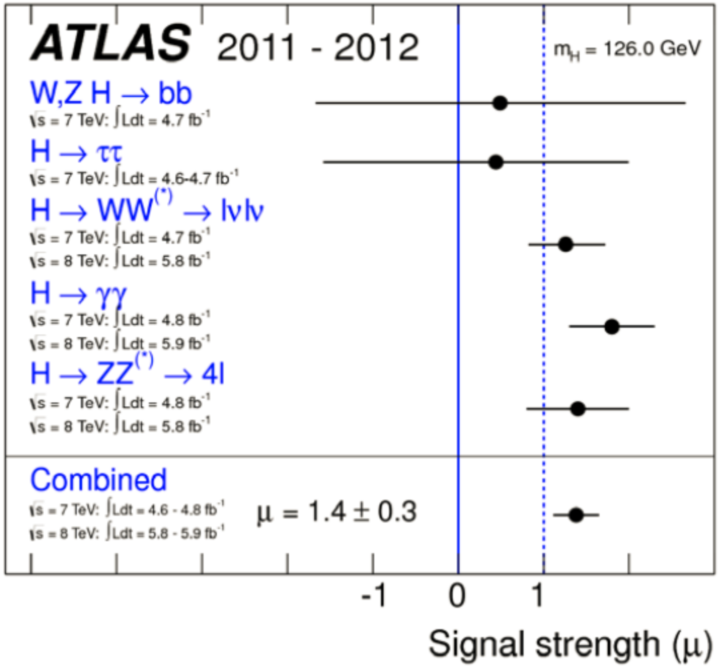
Antonelli et al.

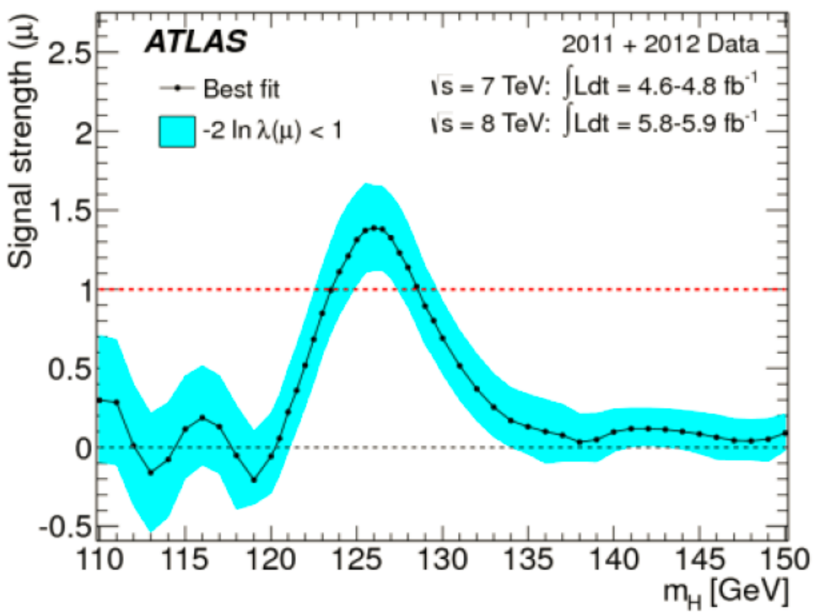


Combined Results from ATLAS



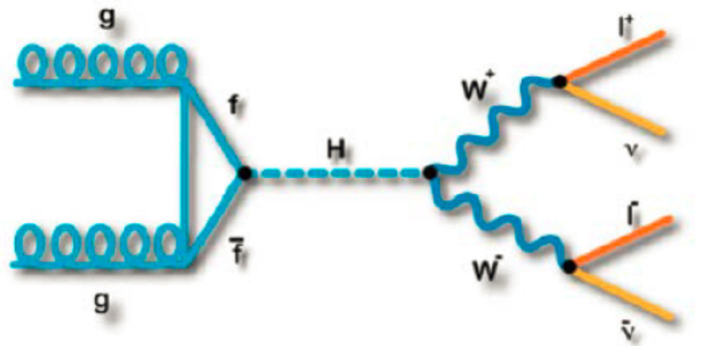
The best estimate of the mass:
m = 126.0 ± 0.4(stat) ± 0.4(sys) GeV





The signal strength at 126 GeV
μ=1.4±0.3

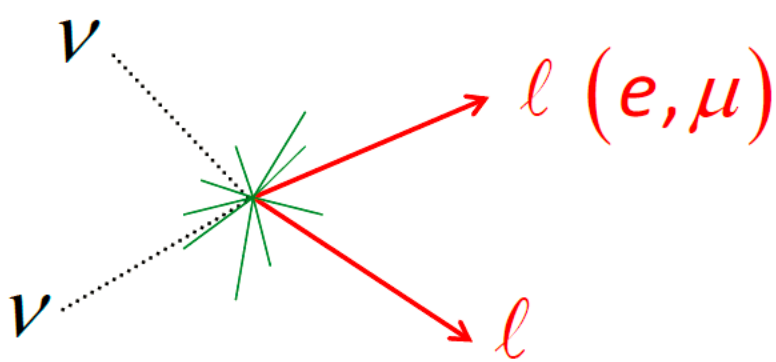
Higgs → WW* → ℓνℓν



$$\sigma(H \to WW^* \to \ell\nu\ell\nu) \approx 220 \text{ fb}$$

(8 TeV, m_H=125 GeV)

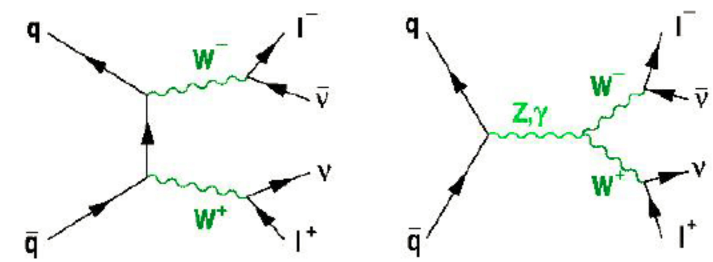
⇒ ~2300 events in 2011+2012 samples



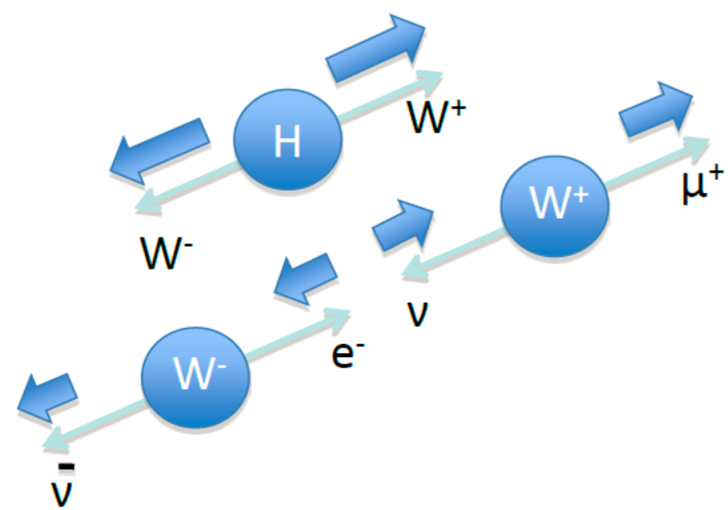
Main background:

WW, $t\bar{t}$, W/Z+jets, WZ/ZZ/Wγ,...

The SM WW is said to be "irreducible"



However, WW from the scalar Higgs is expected to have different kinematics

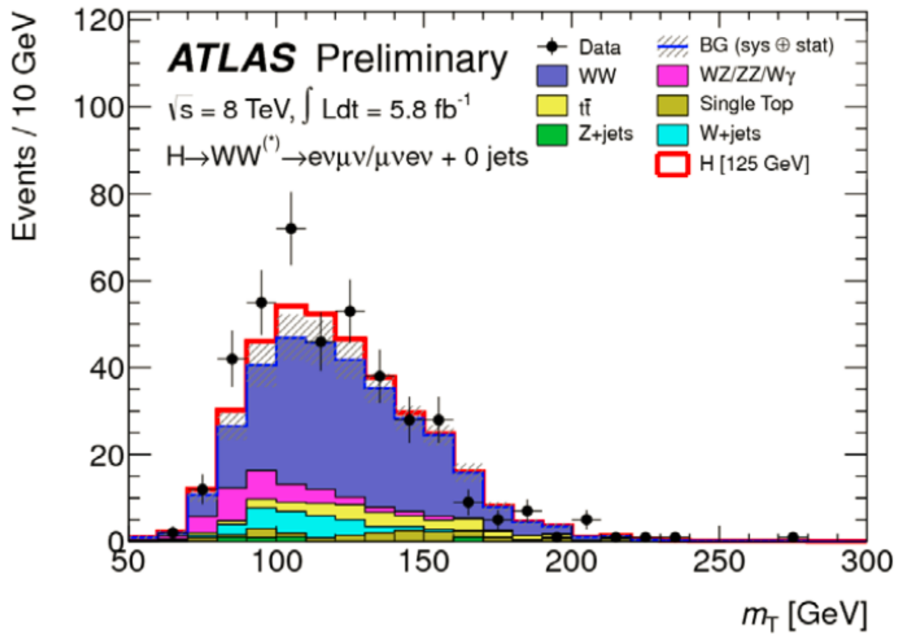


The spin correlation leads to a smaller average opening angle between the two leptons

Higgs → WW* → ℓνℓν

0-jet selections

$- p_T^{\ell\ell} > 30$ GeV;
$- m_{\ell\ell} < 50$ GeV;
$- \Delta\phi_{\ell\ell} < 1.8$



The transverse mass as the final discriminant

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}}\right)^2}$$

Fit mT to improve sensitivity

125 GeV: $0.75 m_H < m_T < m_H$ (illustration only)

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	20 ± 4	101 ± 13	12 ± 3	8 ± 2	3.4 ± 1.5	1.9 ± 1.3	15 ± 7	142 ± 16	185
$H+$ 1-jet	5 ± 2	12 ± 5	1.9 ± 1.1	6 ± 2	3.7 ± 1.6	0.1 ± 0.1	2 ± 1	26 ± 6	38
$H+$ 2-jet	0.34 ± 0.07	0.10 ± 0.14	0.10 ± 0.10	0.15 ± 0.10	-	-	-	0.35 ± 0.18	0

Significant excess over estimated background in both 0-jet and 1-jet channels !

Higgs → WW* → ℓνℓν

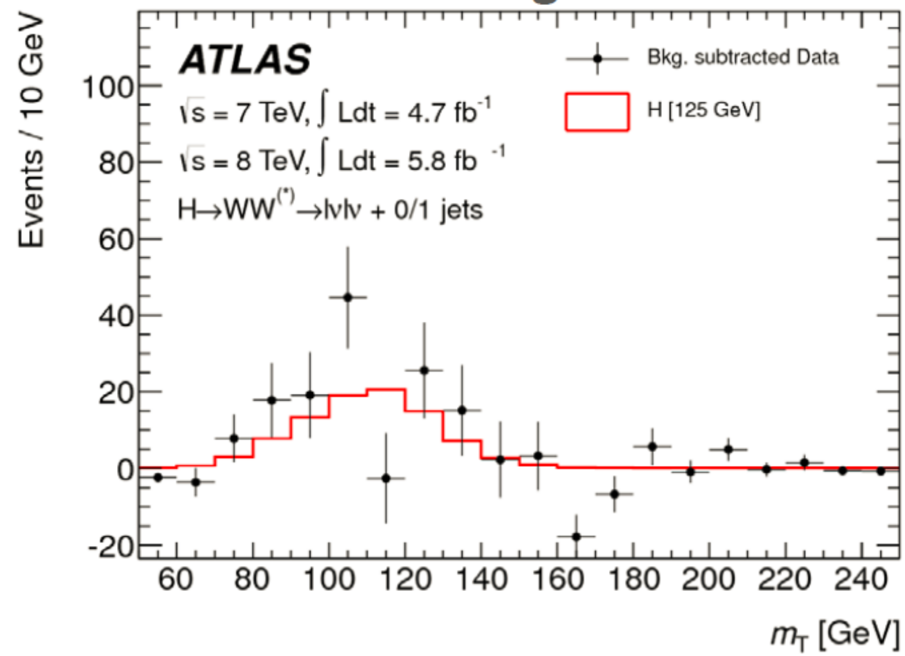
Combining with the published 2011 results (http://arxiv.org/abs/1206.0756)

A minimum p_0 value at 125 GeV

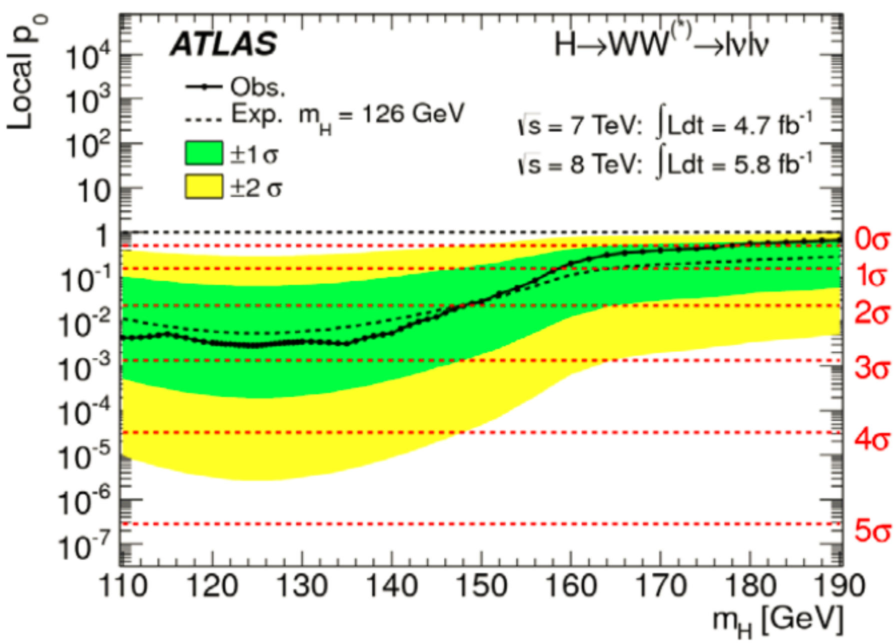
$$p_0 = 3\times10^{-3} \quad \Rightarrow \quad 2.8\sigma$$

$$(\text{Expected: } p_0 = 0.01 \text{ and } 2.3\sigma)$$

Data-background



Observed p-value and signal injection



$$\mu = \frac{\sigma\cdot Br}{(\sigma\cdot Br)_{SM}} = 1.3 \pm 0.5$$

$$2011:\ \mu = 0.5\pm0.6; \quad 2012:\ \mu = 1.9\pm0.7$$

Compatible within 1.5σ

Higgs Search Overview

High resolution channels: clean signature, full reconstruction, good mass resolution. ***updated with 2012 data for the July 4th seminar.***

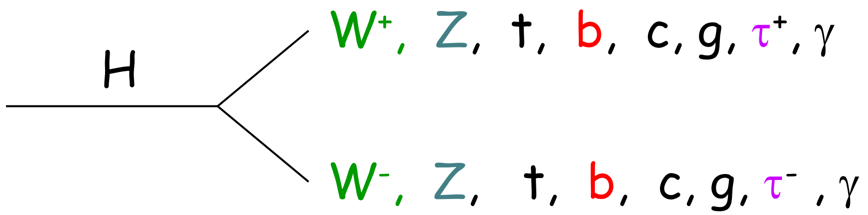
Channel	Mass range (GeV)	Key detector requirements	Main backgrounds
$H \rightarrow \gamma\gamma$	110-150	photon	$\gamma\gamma$, γj, jj
$H \rightarrow ZZ \rightarrow 4l$	110-600	lepton	ZZ, Z+jets, top
$H \rightarrow bb$ (WH/ZH)	110-130	jets, b-tagging	W/Z+jets, top
$H \rightarrow \tau\tau$ (ll, $l\tau_h$, $\tau_h\tau_h$)	100-150	lepton, jets, ETmiss	Z+jets, jets
$H \rightarrow WW \rightarrow l\nu l\nu$	110-600	lepton, jets, ETmiss, b-veto	WW, W/Z+jets, top, Wγ
$H \rightarrow WW \rightarrow l\nu qq$	300-600	lepton, jets, ETmiss, b-veto	W+jets, jets
$H \rightarrow ZZ \rightarrow ll\nu\nu$	200-600	lepton, ETmiss	Z+jets, ZZ, top
$H \rightarrow ZZ \rightarrow llqq$	200-600	lepton, jets, ETmiss, b-veto	Z+jets, ZZ, top

Low resolution channels: poor mass resolution, strong dependence on jet and ETmiss performance, ***only WW*→lvlv updated with 2012 data.***

	ATLAS	CMS
TRACKER	Si pixels + strips TRT → particle identification $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon ($\geq 10\ \lambda$) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. ($\geq 5.8\ \lambda$ + catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	MDT, CSC, RPC, TGC $\sigma/p_T \sim 7\%$ at 1 TeV standalone	DT, CSC, RPC $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

Higgs Boson Decays

The decay properties of the Higgs boson are fixed, if the mass is known:



$$\Gamma(H \to f\bar{f}) \;=\; N_C \frac{G_F}{4\sqrt{2}\pi}\, m_f^2(M_H^2)\, M_H$$

$$\Gamma(H \to VV) \;=\delta_V \frac{G_F}{16\sqrt{2}\pi}\, M_H^3\, (1 - 4x + 12x^2)\, \beta_V$$

where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta =$ velocity

$$\Gamma(H \to gg) \;=\frac{G_F\, \alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3}\, M_H^3\, \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_s}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) \;=\frac{G_F\, \alpha^2}{128\sqrt{2}\pi^3}\, M_H^3\, \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Higgs Boson:

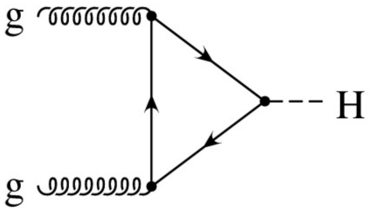
- it couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed

Yukawa Couplings

- Higgs couples to fermion mass

$$L_{Yukawa} = -\lambda_d Q_L \Phi d_R + hc$$
$$= -\lambda_d \left(\frac{v+h}{\sqrt{2}} \right) \bar{d} d h \rightarrow -\frac{m_d}{v} \bar{d} d h$$

  - $m_f = \lambda_f v/\sqrt{2}$
  - Yukawa ffh coupling doesn't vanish for v=0
  - Measuring Yukawa coupling doesn't prove VEV exists!

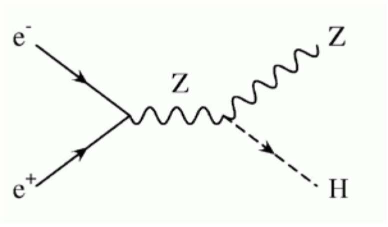


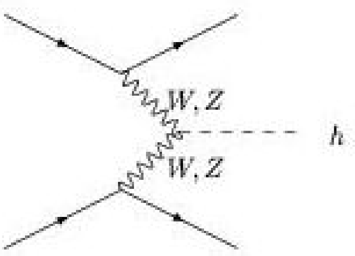
Gauge Higgs Couplings

- Higgs couples to gauge boson masses

$$(D_\mu \Phi)^+ (D_\mu \Phi) \to \left(\frac{gv}{2}\right)^2 W^{+\mu} W_\mu^- \left(1 + \frac{h}{v}\right) + \ldots.$$

- WWh coupling vanishes for v=0! Tests the connection of M_W to non-zero VEV



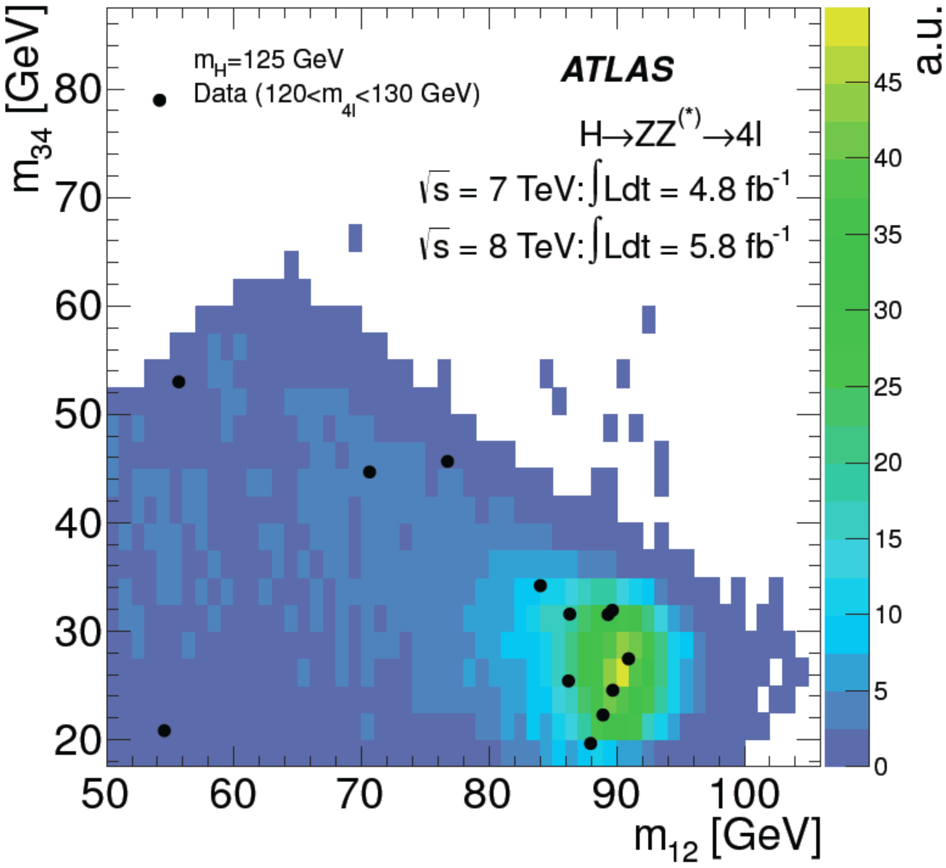


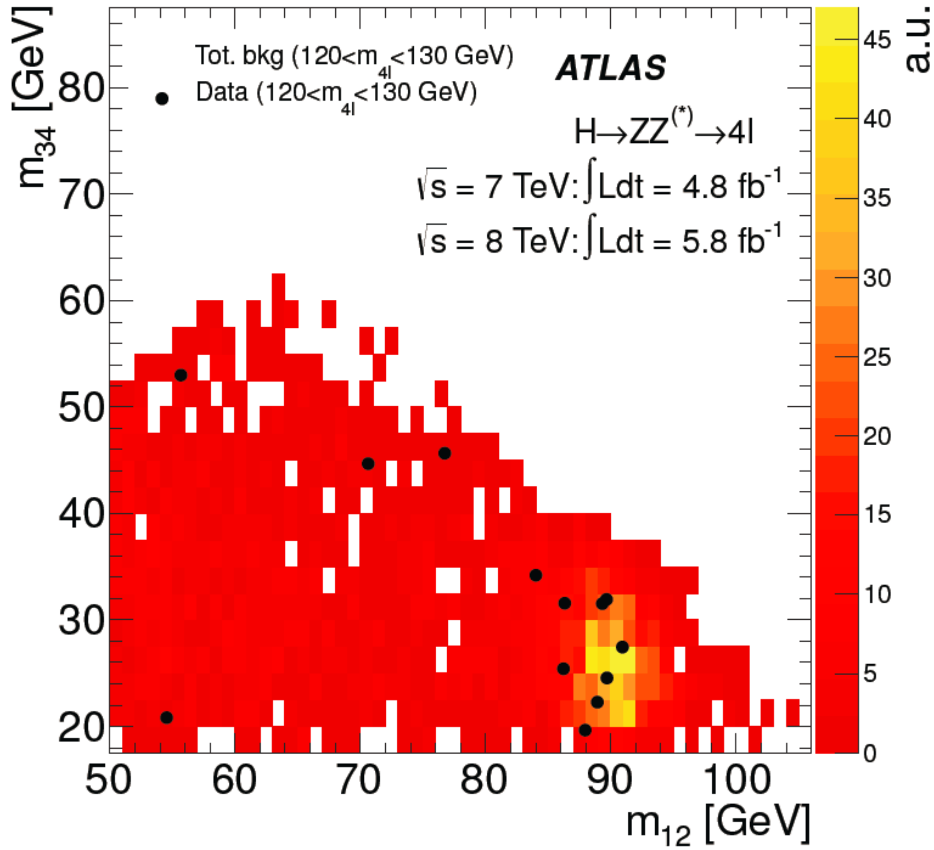
Selected H→ZZ*→4l Candidates

- Observed candidates with M_{4l} between 120 and 130 GeV

Signal m_H = 125 GeV

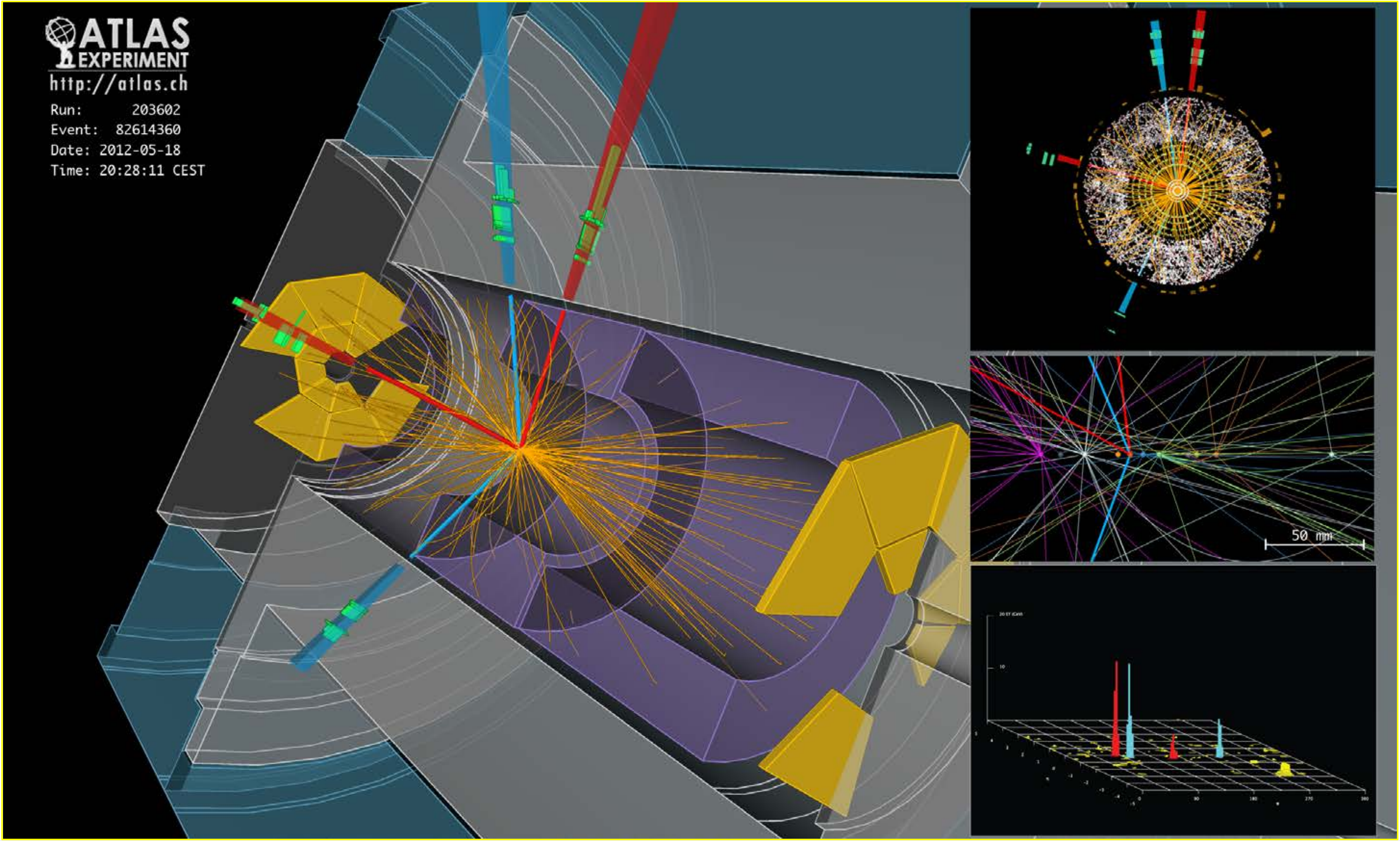
Total background: ZZ* Z+jets and ttbar





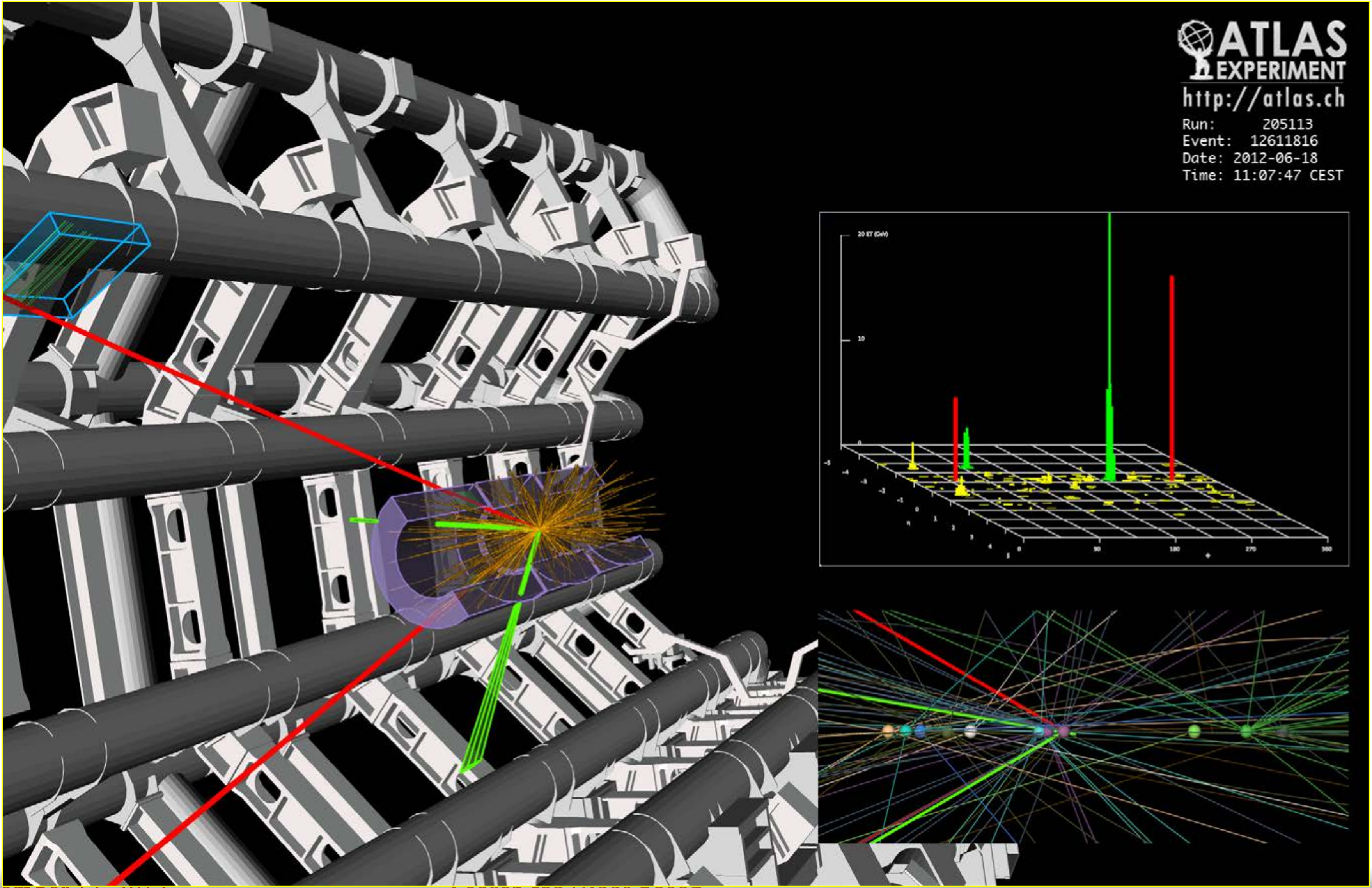
H → ZZ* → eeee Candidate

- M_{4e} = 124.6 GeV, M_{12} = 70.6 GeV, M_{34} = 44.7 GeV



H → ZZ* → 2e2μ Candidate

- $M_{2e2\mu}$ = 123.9 GeV, M_{12} = 87.9 GeV, M_{34} = 19.6 GeV

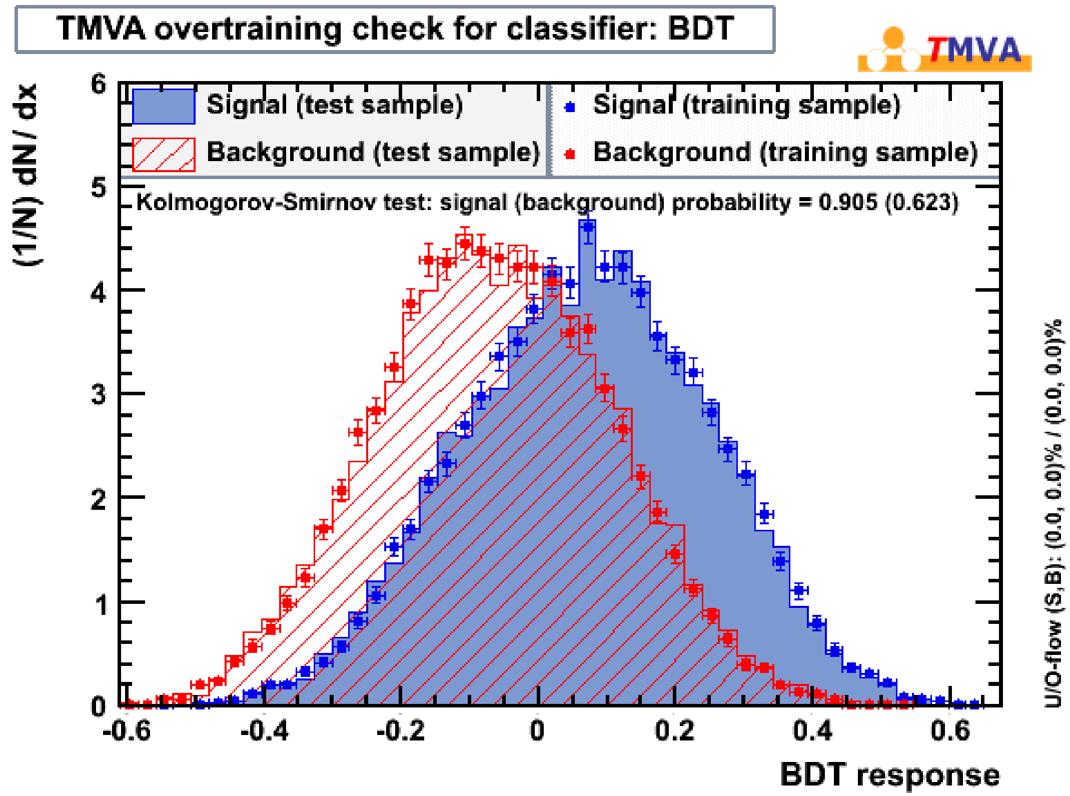


BDT Training and Test Results

- About 28K JHU H(0+) and 28K H(0-) events, one half for BDT training and another half and SM ZZ for test.

Selection Cuts:

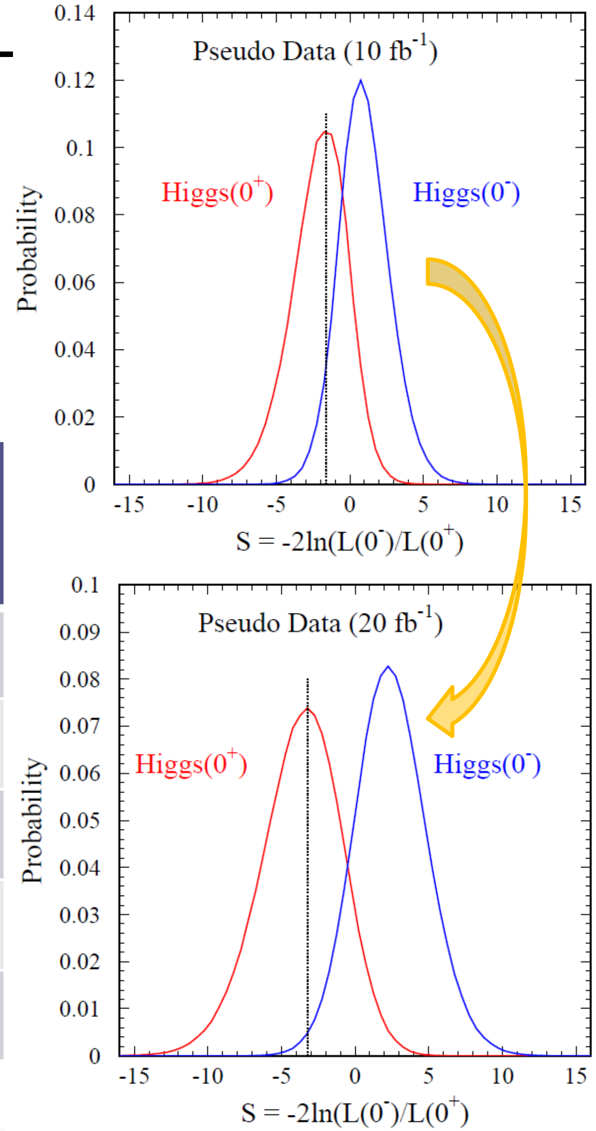
- 50 GeV < MZ1 < 106 GeV
- 17.5 GeV < MZ2 < 115 GeV
- Lepton pT:
  pT1 > 20 GeV, pT2 > 15 GeV,
  pT3 > 10 GeV, pT4 > 7 GeV
- |Eta| < 2.5
- dR > 0.1 (0.2) for same (different) flavor di-lepton
- **120 GeV < M_{ZZ} < 130 GeV**



Log-likelihood Ratio and Separation Power

- Using Binned Log-likelihood Ratio method to determine the separation power between Higgs 0+ and 0-
- 1M MC trials based on Poisson statistics
- Log-likelihood Ratio distributions
- Expected significance vs int. luminosity

Int. Luminosity (fb^{-1})	Significance (no ZZ, BDT)	Significance (with ZZ, BDT)
10 (N_s=6, N_b=5.5)	1.97 σ	1.45 σ
20 (N_s=12, N_b=11)	2.74 σ	1.98 σ
30 (N_s=18, N_b=16.5)	3.36 σ	2.40 σ
40 (N_s=24, N_b=22)	3.85 σ	2.77 σ
50 (N_s=30, N_b=27.5)	4.26 σ	3.10 σ



Discovery of SM Particles

- 1897 – e discovery, by J.J. Thompson (cathode ray tube, UK)
- 1919 – proton, Ernest Rutherford (UK)
- 1930 – neutron, James Chadwick (UK)
- 1936 – μ, Carl D. Anderson at Caltech
- 1947 – strange quark(K+=usbar, K-=subar)
- 1956 – ν_e discovery (nuclear reactor)
- 1962 – ν_μ discovery at BNL
- 1968 – u and d quark (quark model)
- 1974 – c quark (BNL, SLAC,J/ψ=ccbar)
- 1977 – tau discovery (SLAC)
- 1977 – b quark (Upsilon, FNAL)
- 1979 – gluon (DESY)
- 1983 – W and Z (CERN)
- 1995 – top quark
- 2000 – ν_τ discovery (Fermilab)