大加速器

“上帝粒子”发现后的“中国梦”

上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

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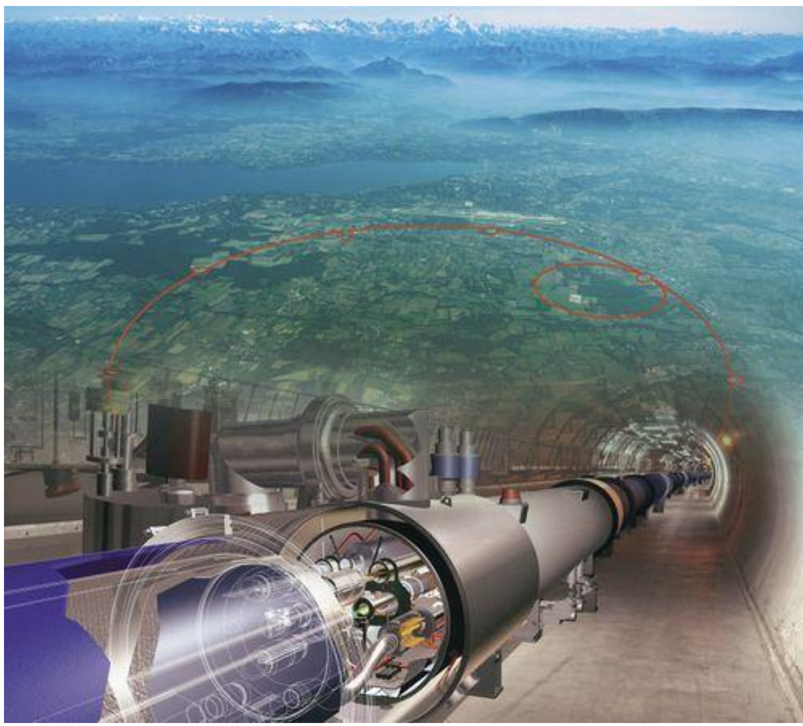
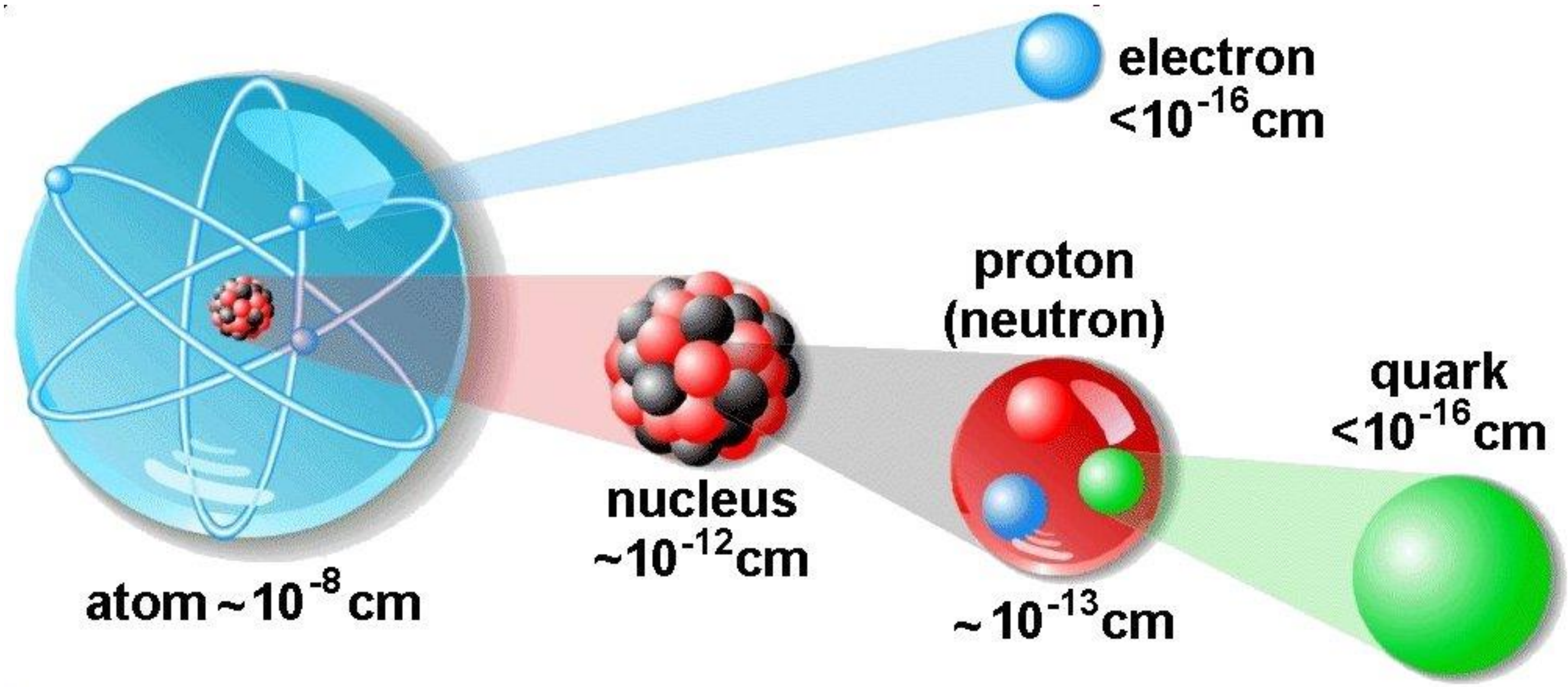
2014年10月20日



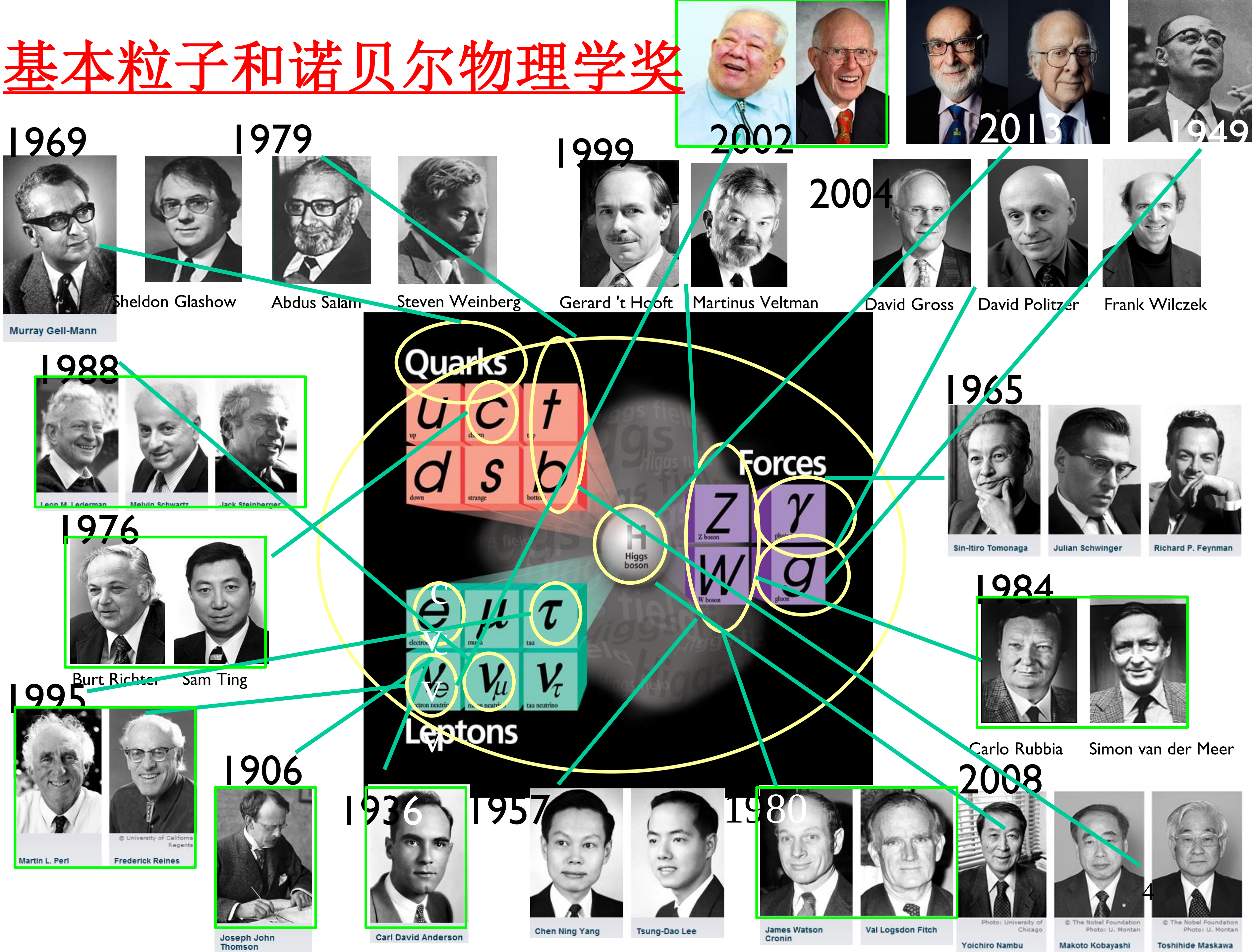
报告大纲

- 简要介绍粒子物理标准模型
- 基本粒子质量产生机制-希格斯机制
- 回顾希格斯粒子的寻找历史
- 如何在LHC上发现希格斯玻色子
- 后希格斯时代 - “Higgs Factory”
- 中国高能物理的前景和展望

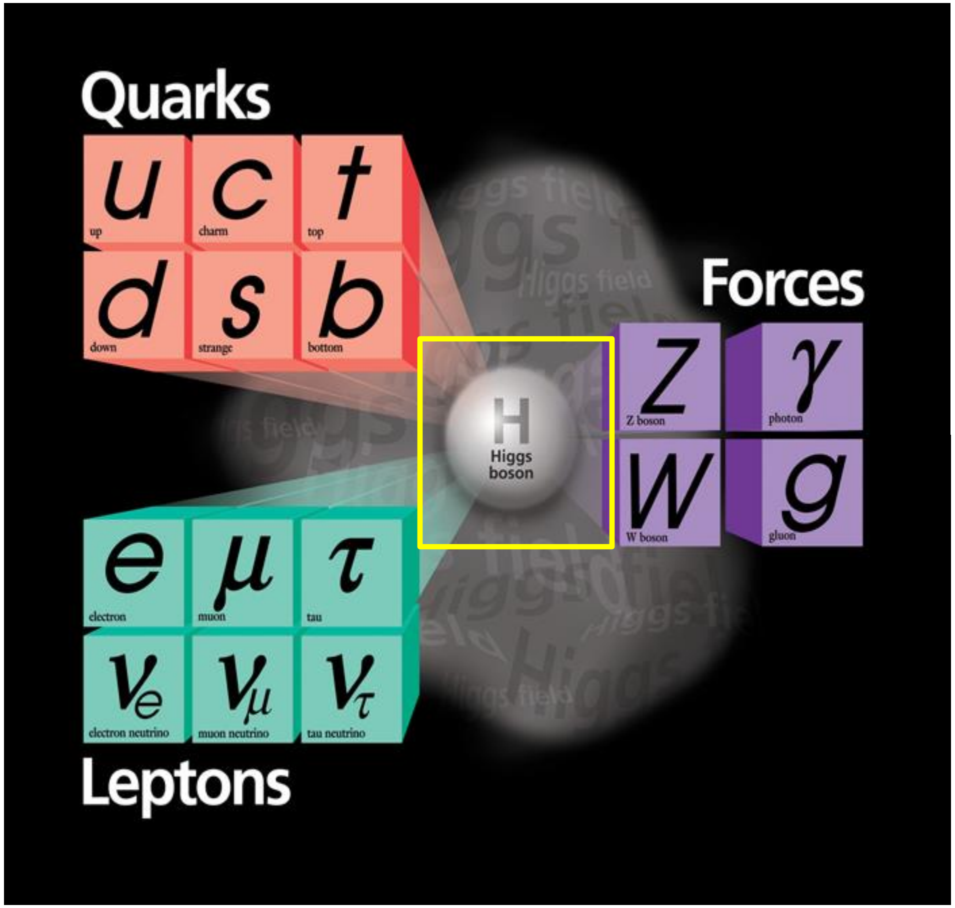
研究物质最基本的结构


electron
<10-16cm
proton
(neutron)
quark
<10-16cm
nucleus
~10-12cm
atom ~10-8 cm
~10-13cm

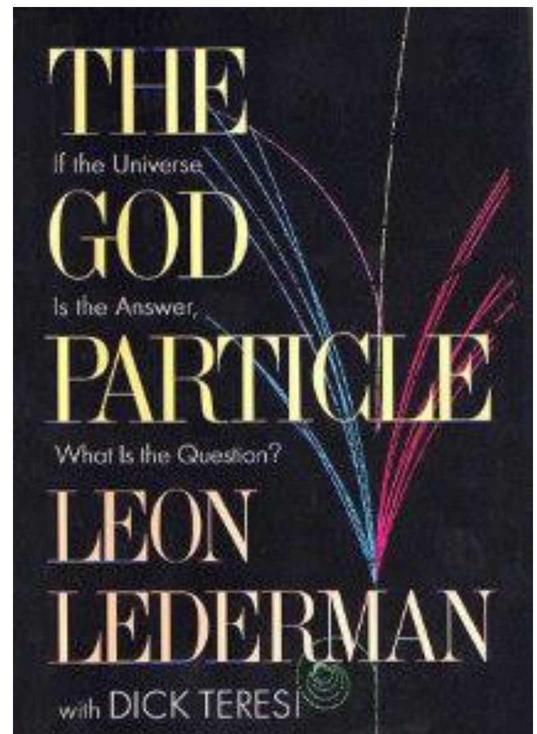
基本粒子和诺贝尔物理学奖



探索基本粒子质量的起源



➔**Higgs** 玻色子用来解释基本粒子的质量来源，是粒子物理标准模型中最后被发现的关键粒子，常被媒体称为“上帝”粒子。



➔寻找**Higgs** 玻色子是大型国际高能对撞机实验 (LEP, Tevatron, LHC) 的主要物理目标。

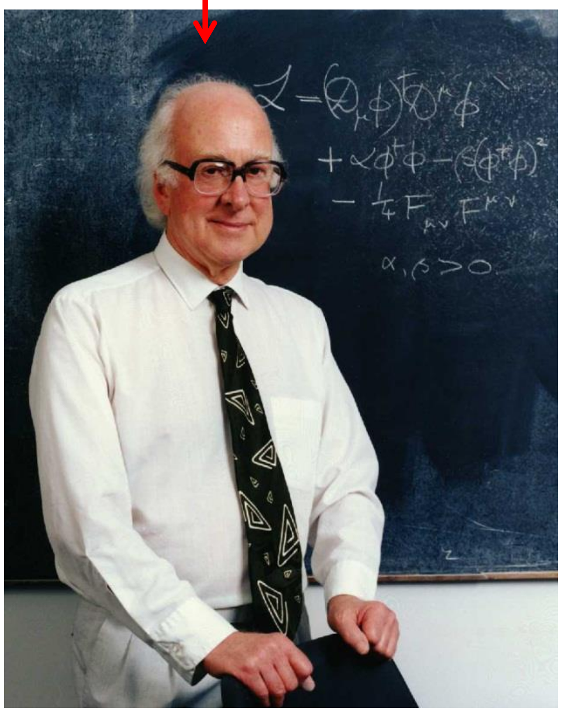
Higgs Mechanism (1964)

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

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

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

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



Higgs Mechanism

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L=-\tfrac{1}{2}(\nabla\varphi_1)^2-\tfrac{1}{2}(\nabla\varphi_2)^2 -V(\varphi_1^2+\varphi_2^2)-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

$$\nabla_\mu\varphi_1=\partial_\mu\varphi_1-eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2=\partial_\mu\varphi_2+eA_\mu\varphi_1,$$

$$F_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2)=0$, $V''(\varphi_0^2)>0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}=0, \quad (2a)$$

$$\{\partial^2-4\varphi_0^2V''(\varphi_0^2)\}(\Delta\varphi_2)=0, \quad (2b)$$

$$\partial_\nu F^{\mu\nu}=e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0A_\mu\}. \quad (2c)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu=A_\mu-(e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu}=\partial_\mu B_\nu-\partial_\nu B_\mu=F_{\mu\nu}, \quad (3)$$

into the form

$$\partial_\mu B^\mu=0, \quad \partial_\nu G^{\mu\nu}+e^2\varphi_0^2B^\mu=0. \quad (4)$$

Equation (4) describes vector waves whose quant have (bare) mass $e\varphi_0$. In the absence of the gau field coupling $(e=0)$ the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In pass ing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y=0$, $I_3=0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

massive vector bosons. There are two $I=\frac{1}{2}$ vector doublets, degenerate in mass between $Y=\pm1$ but with an electromagnetic mass splitting between $I_3=\pm\frac{1}{2}$, and the $I_3=\pm1$ components of a $Y=0$, $I=1$ triplet whose mass is entirely electromagnetic. The two $Y=0$, $I=0$ gauge fields remain massless: This is associated with the residual unbroken symmetry under the Abelian group generated by Y and I_3. It may be expected that when a further mechanism (presumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

[1] P. W. Higgs, to be published.
[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).
[3] P. W. Anderson, Phys. Rev. 130, 439 (1963).

[4] In the present note the model is discussed mainly in classical terms; nothing is proved about the quantized theory. It should be understood, therefore, that the conclusions which are presented concerning the masses of particles are conjectures based on the quantization of linearized classical field equations. However, essentially the same conclusions have been reached independently by F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964): These authors discuss the same model quantum mechanically in lowest order perturbation theory about the self-consistent vacuum.

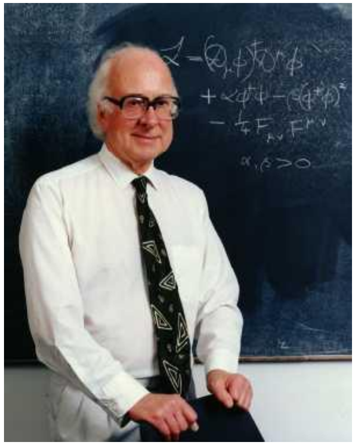
[5] In the theory of superconductivity such a term arises from collective excitations of the Fermi gas.

[6] See, for example, S. L. Glashow and M. Gell-Mann, Ann. Phys. (N.Y.) 15, 437 (1961).

[7] These are just the parameters which, if the scalar octet interacts with baryons and mesons, lead to the Gell-Mann–Okubo and electromagnetic mass splittings: See S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).

[8] Tentative proposals that incomplete SU(3) octets of scalar particles exist have been made by a number of people. Such a rôle, as an isolated $Y=\pm1$, $I=\frac{1}{2}$ state, was proposed for the κ meson (725 MeV) by Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 11, 42 (1963). More recently the possibility that the σ meson (385 MeV) may be the $Y=I=0$ member of an incomplete octet has been considered by L. M. Brown, Phys. Rev. Letters 13, 42 (1964).

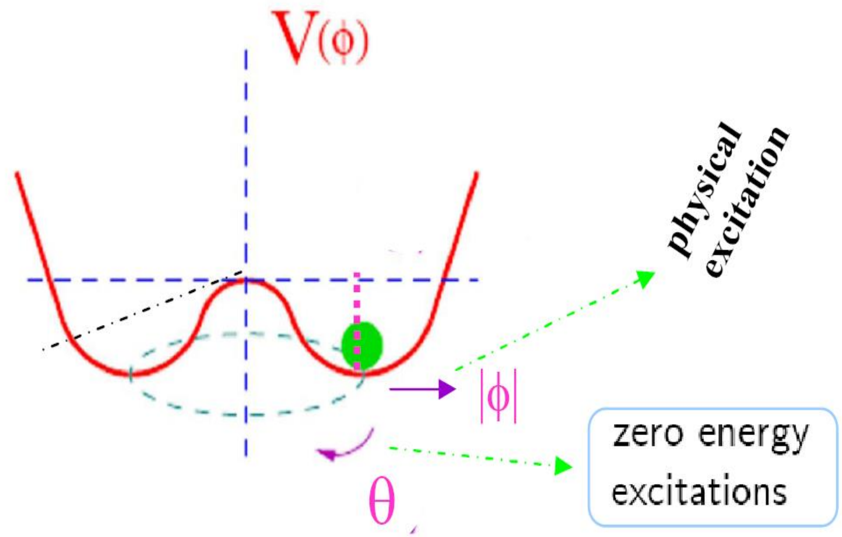
[9] In the theory of superconductivity the scalar fields are associated with fermion pairs; the doubly charged excitation responsible for the quantization of magnetic flux is then the surviving member of a U(1) doublet.



Higgs Mechanism in SM:

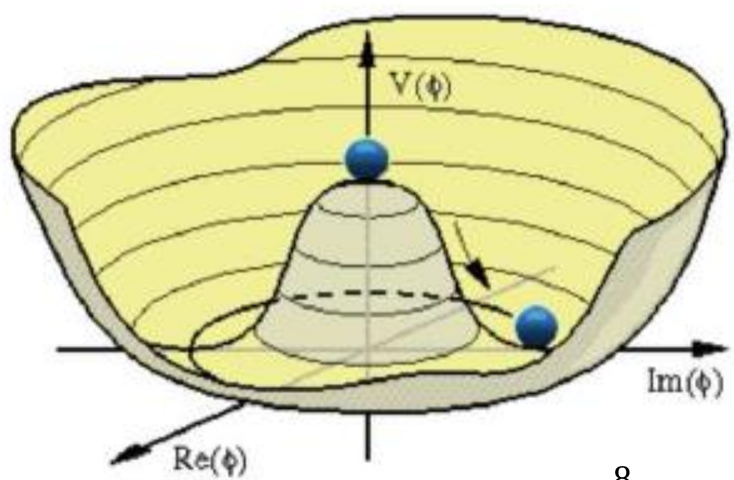
$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

$$\phi = \begin{pmatrix} iG^+ \\ \frac{v+h-iG^0}{\sqrt{2}} \end{pmatrix} =$$

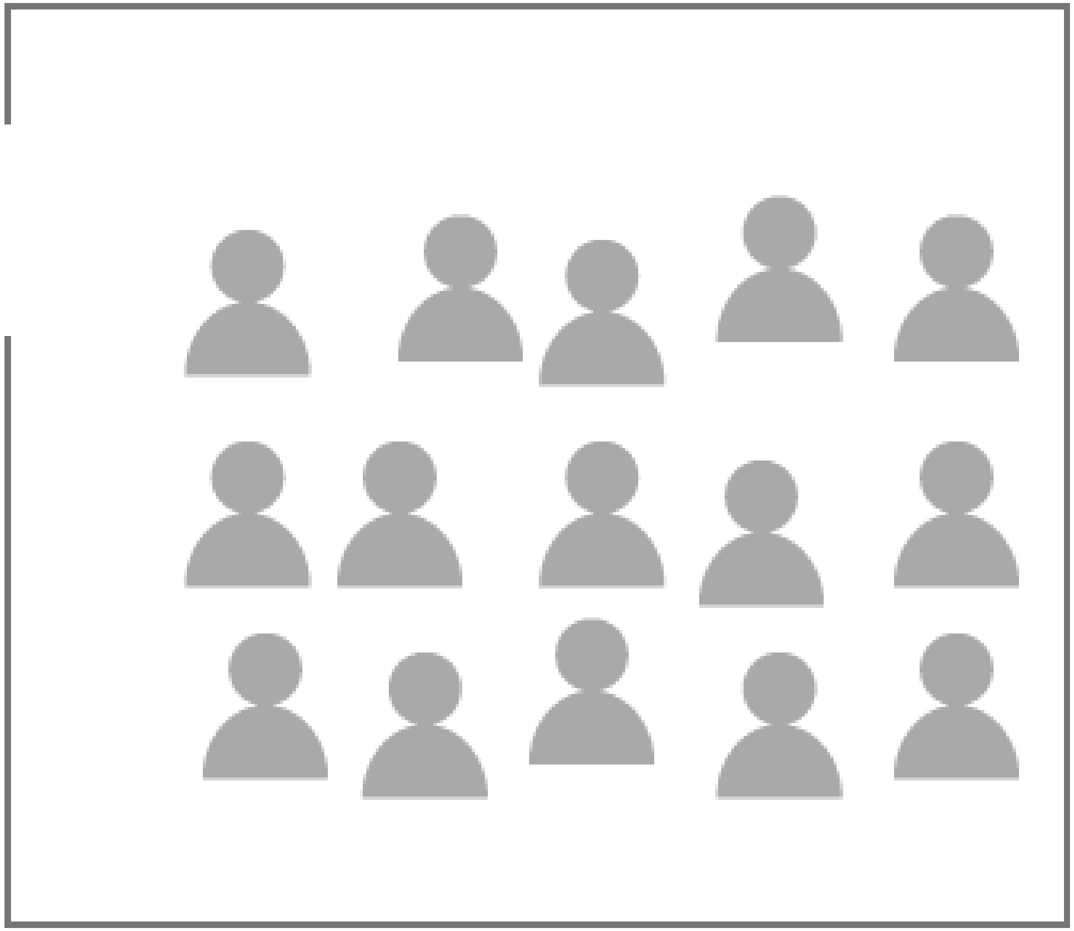


- 连续对称性的自发破缺导致零能激发，会产生零静止质量的标量粒子－Goldstone boson，它被静止质量为零的规范场粒子（两个横向极化自由度）“吃掉”，转化成规范场的纵向极化分量的自由度，使得规范场粒子具有三个极化自由度，变成具有静止质量的粒子。

- 剩下一个物理激发态：希格斯粒子



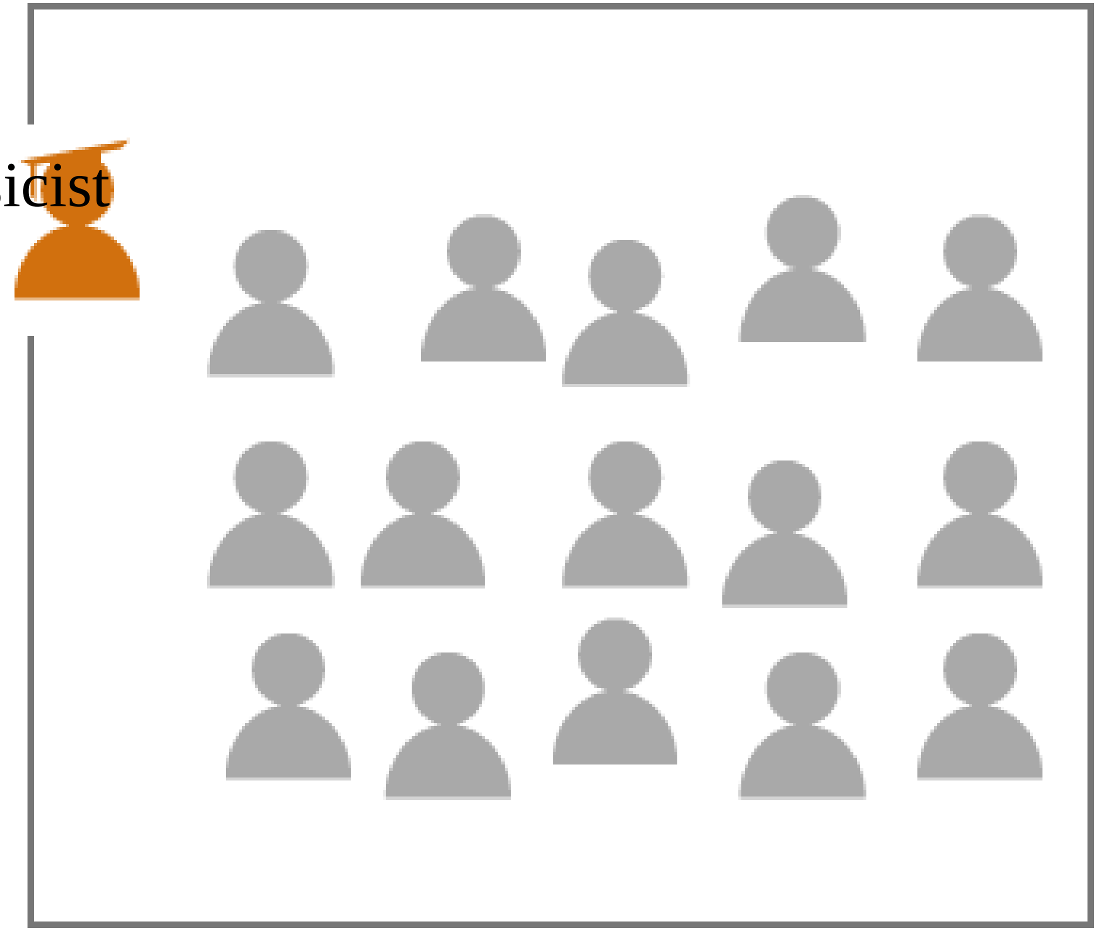
Cartoon Explanation of the Higgs Boson



Physicists
"Higgs field"

Cartoon Explanation of the Higgs Boson

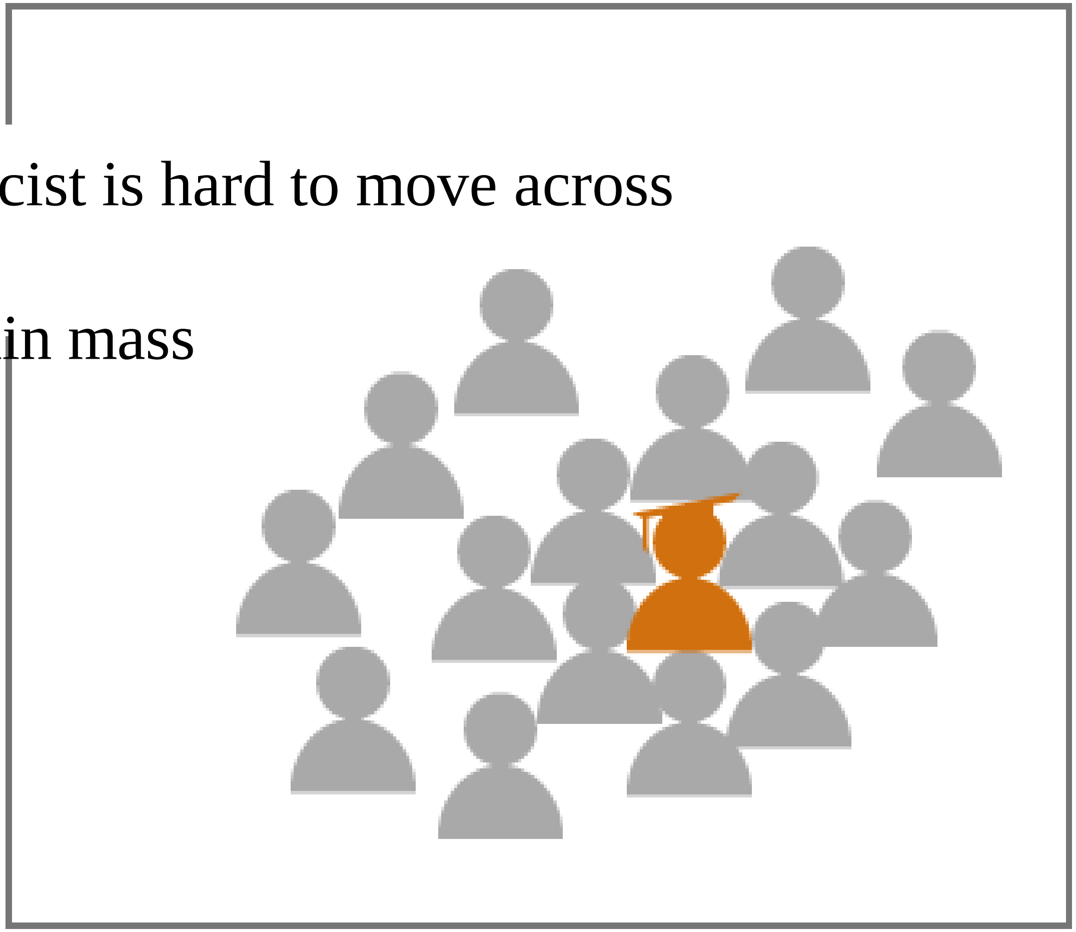
A famous physicist
“Particle”



Physicists
“Higgs field”

Cartoon Explanation of the Higgs Boson

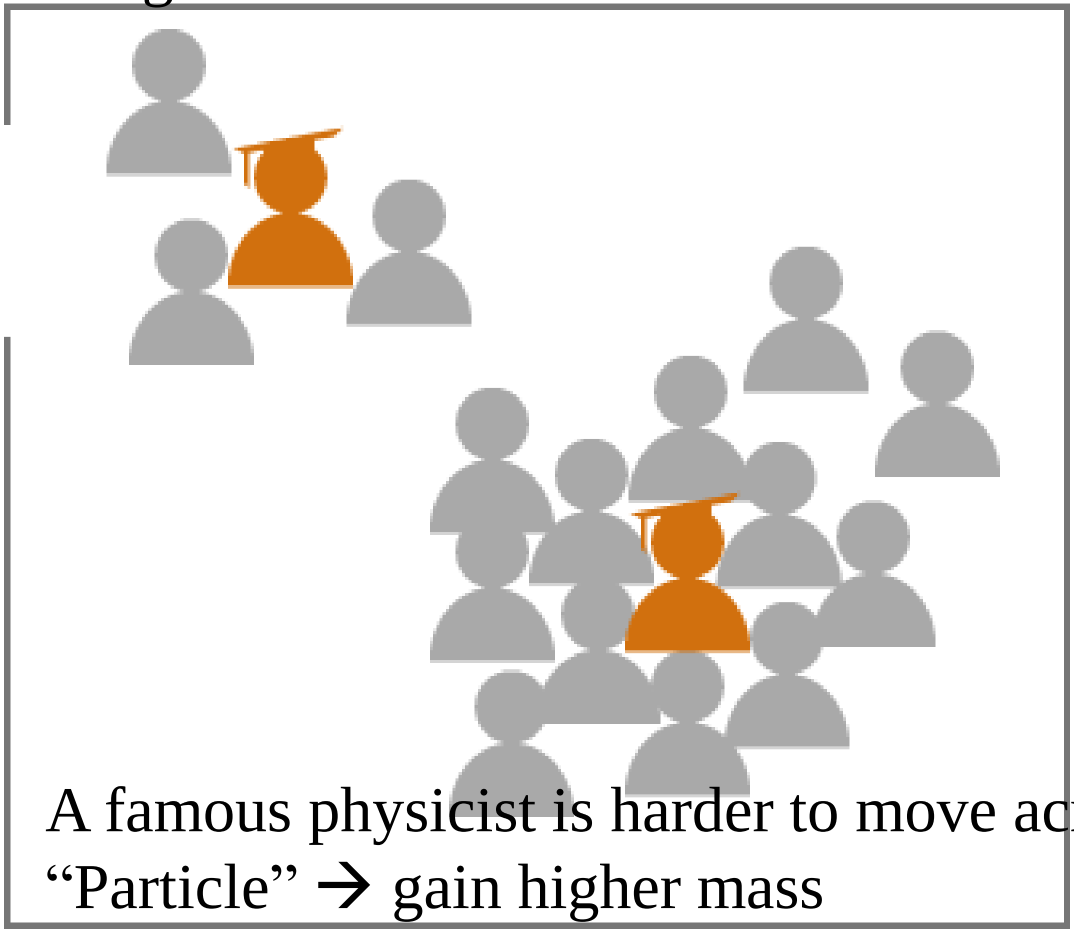
A famous physicist is hard to move across the room.
"Particle" → gain mass



Physicists
"Higgs field"

Cartoon Explanation of the Higgs Boson

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



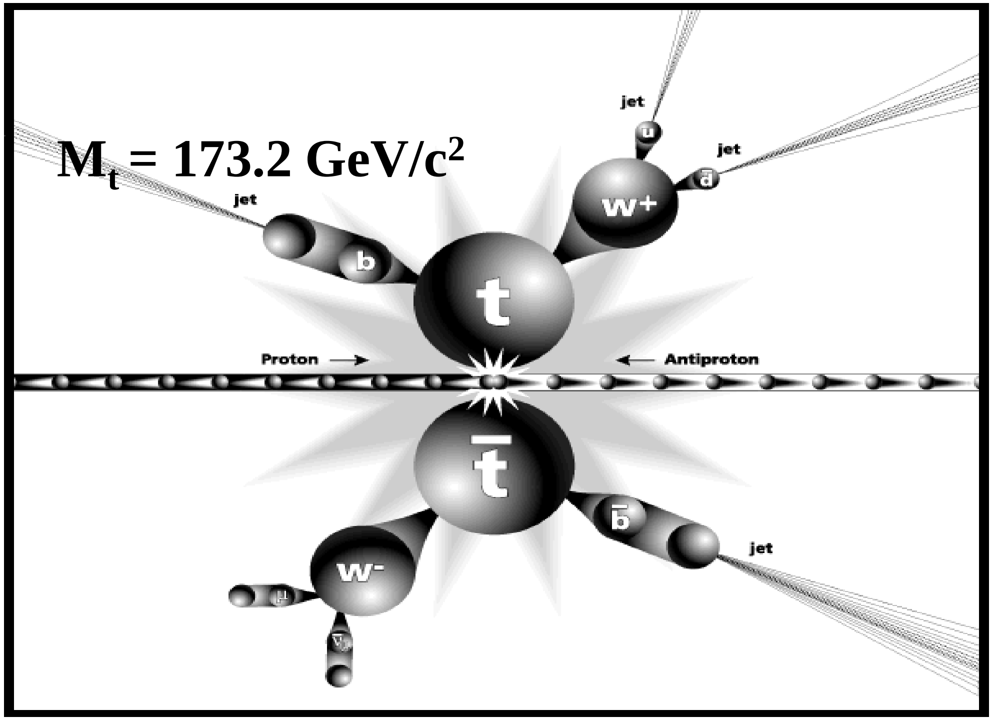
Physicists
“Higgs field”

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

Source: Cern/UCL

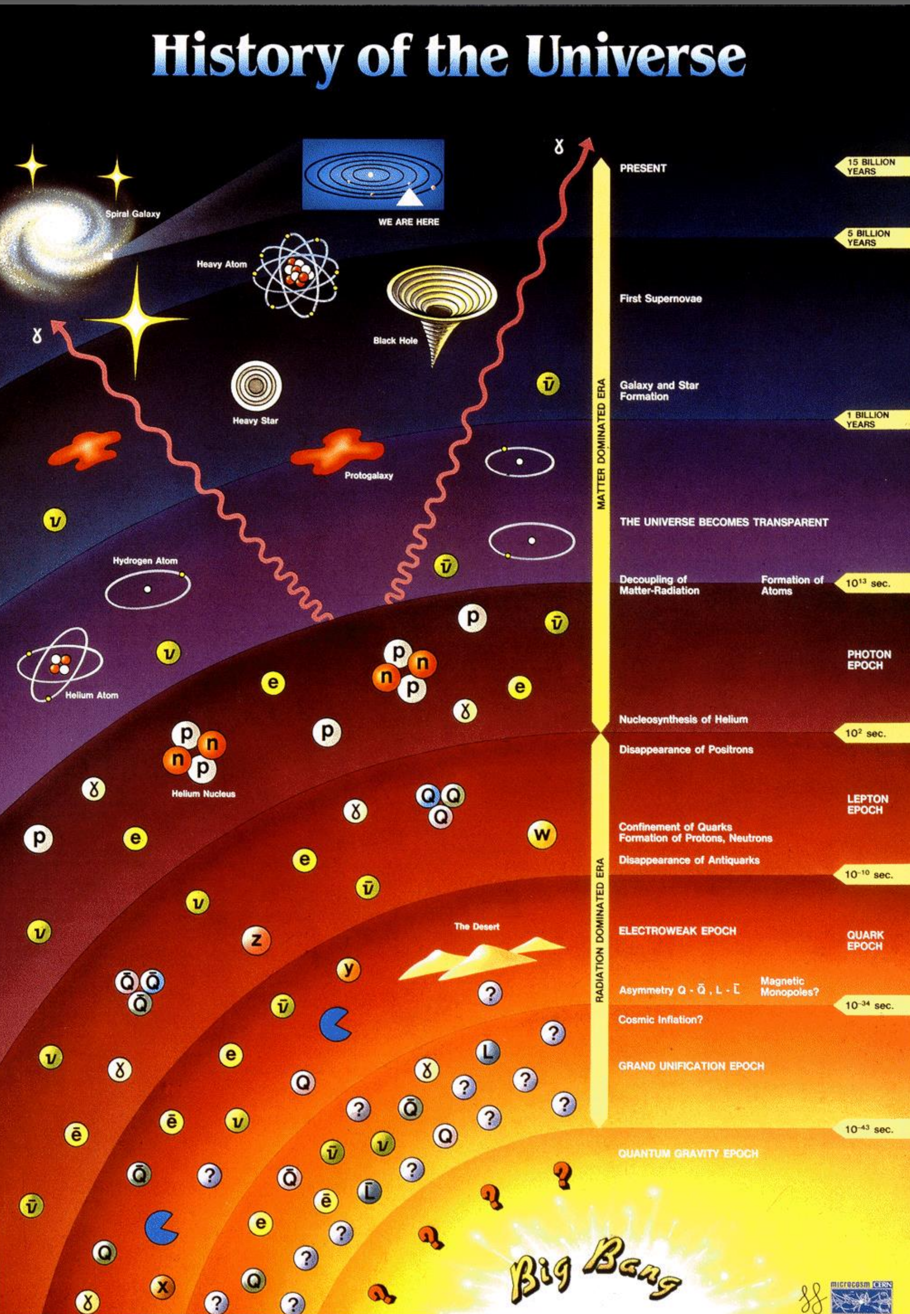
研究工具: 高能对撞机

- **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**

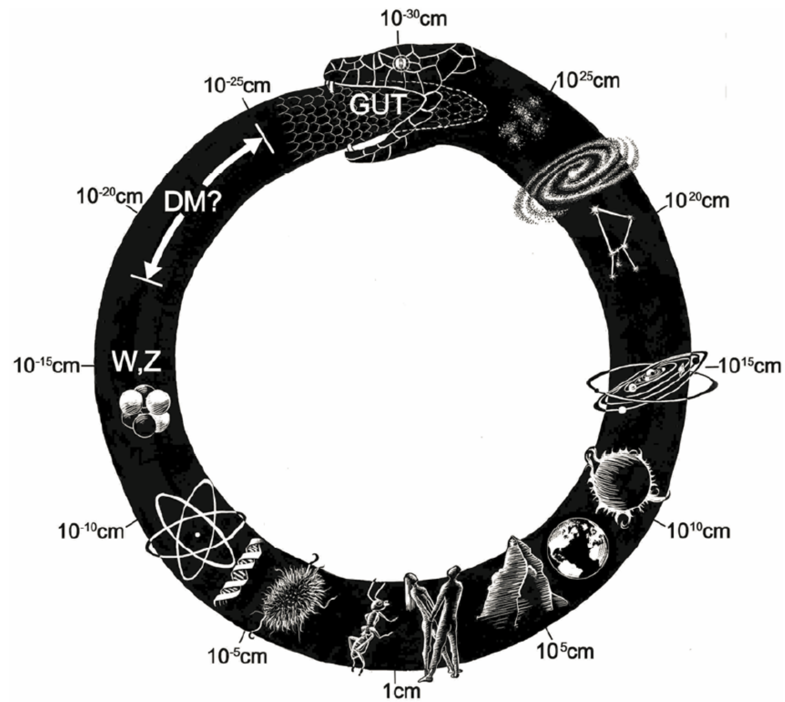


Tevatron at Fermi National Accelerator Laboratory (Fermilab)

高能对撞机: 模拟宇宙大爆炸



- Higher energy beam collisions ↔ higher temperature ($E = \kappa T$)
- **High energy collider to recreate the Big Bang in Lab.**



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

Brief History of the Higgs Search

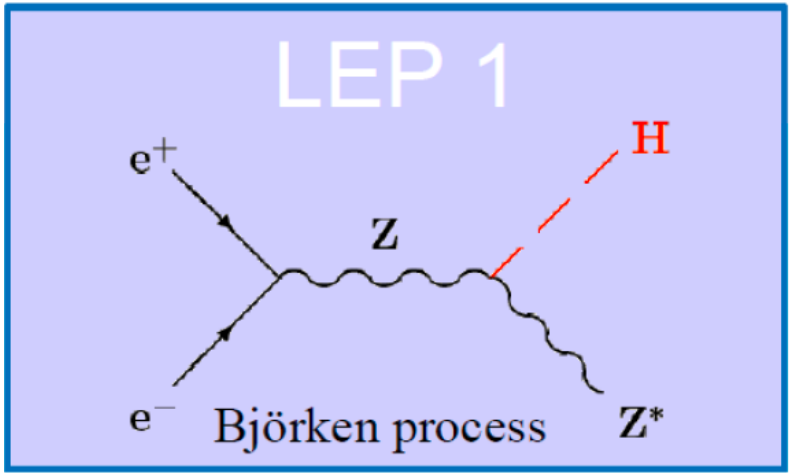
- 1964 Brout & **Englert, Higgs**, Guralnik, Hagen & Kibble
- 1967 Weinberg, Salam, Glashow integrated it in the SM
- 1973 Exp. Confirmation of weak neutral current(Z) of the SM (**Nobel Prize in 1979**)
- 1983 Discovery of W and Z bosons at CERN

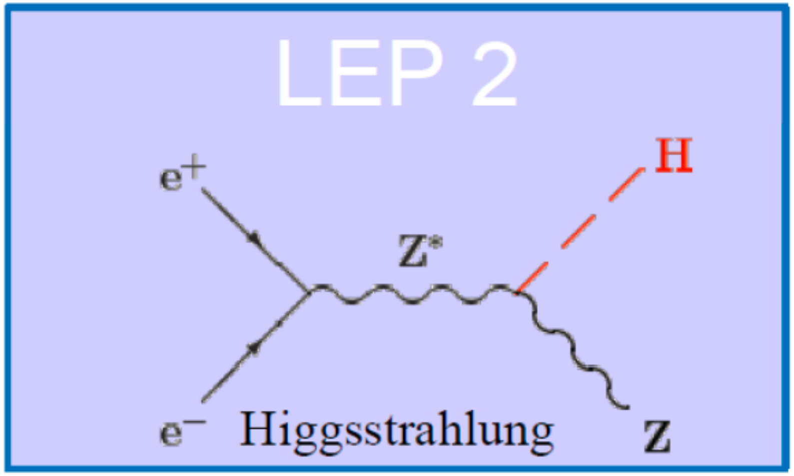
  (Nobel Prize in 1984) , closely linked to the Higgs boson
- 1993 CERN/LEP1 studies Z's and rules out m_H<53 GeV
  – And indirectly excludes m_H > 300 GeV
- 2000 CERN/LEP2 lower limit reaches 114.4 GeV
- 2012 Fermilab/Tevatron observed ~2.5σ excess at [120,130]
- **2012.7 Discovery of the Higgs boson at LHC**
- **2013.10 Nobel Prize in Physics**

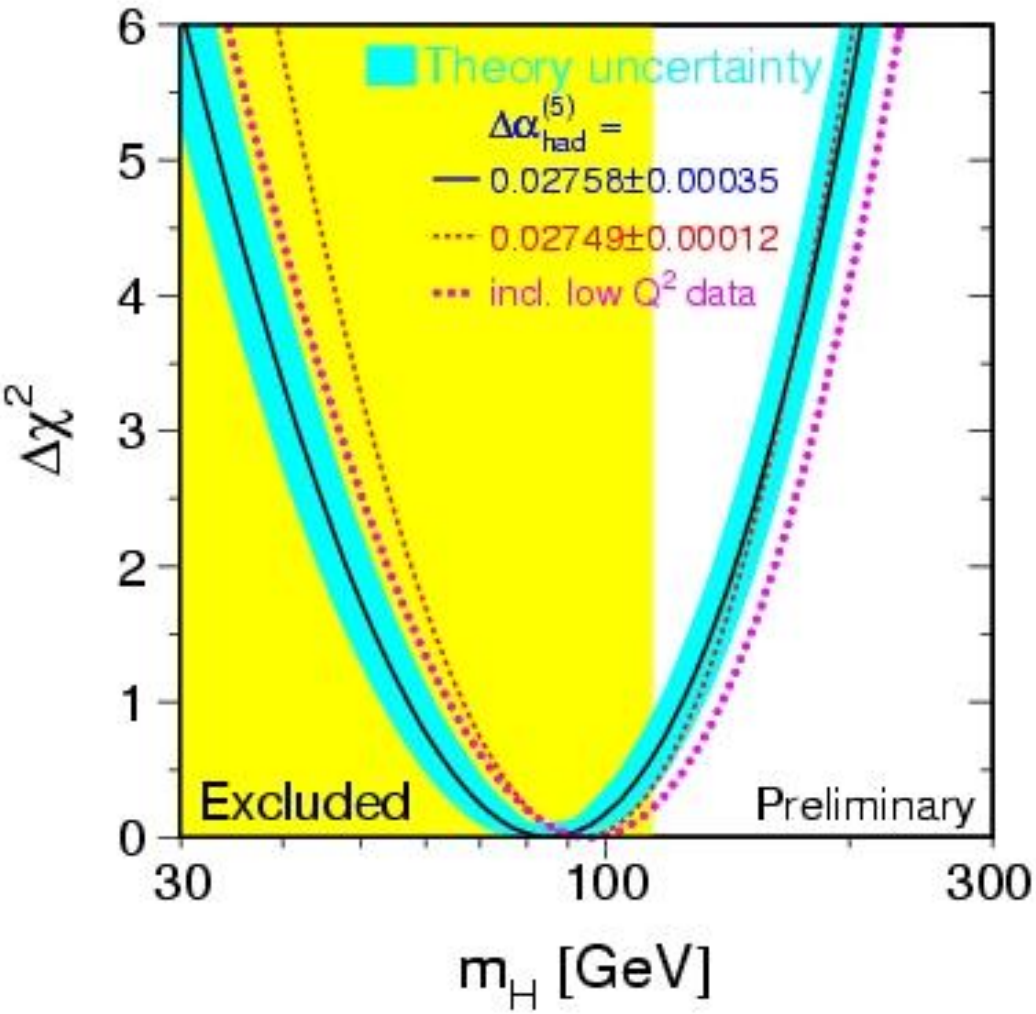
Search for Higgs boson at LEP

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

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

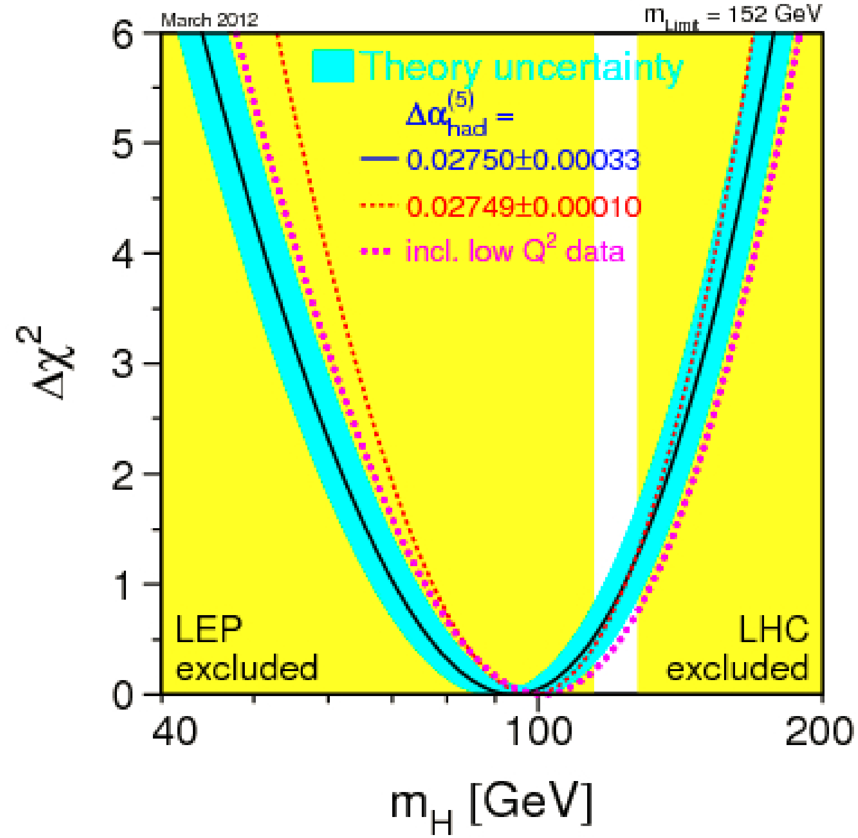


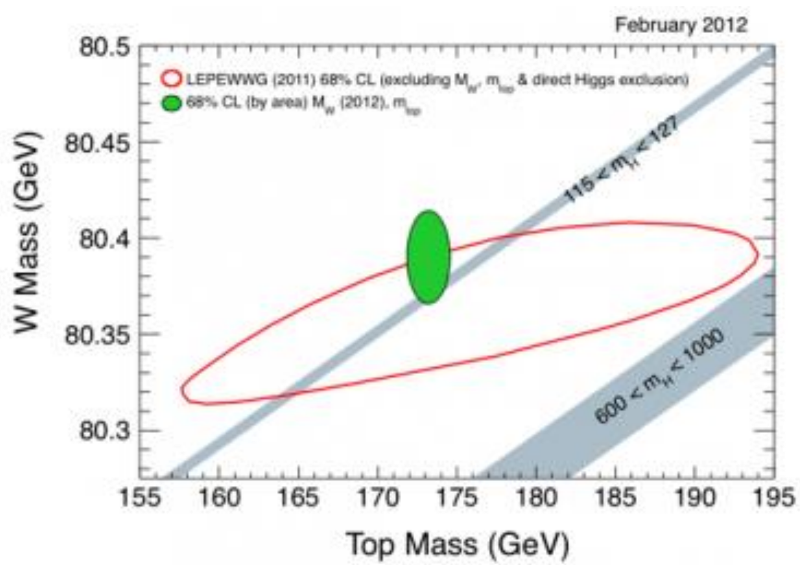


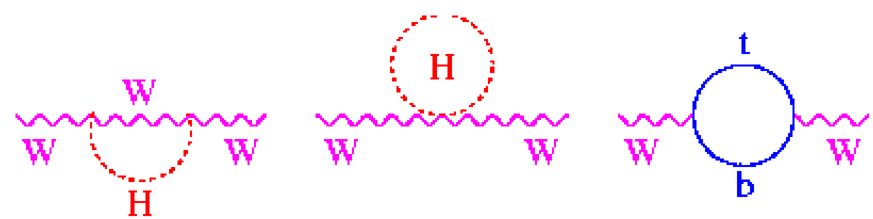


Searches for Higgs Boson at LEP and LHC

- 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





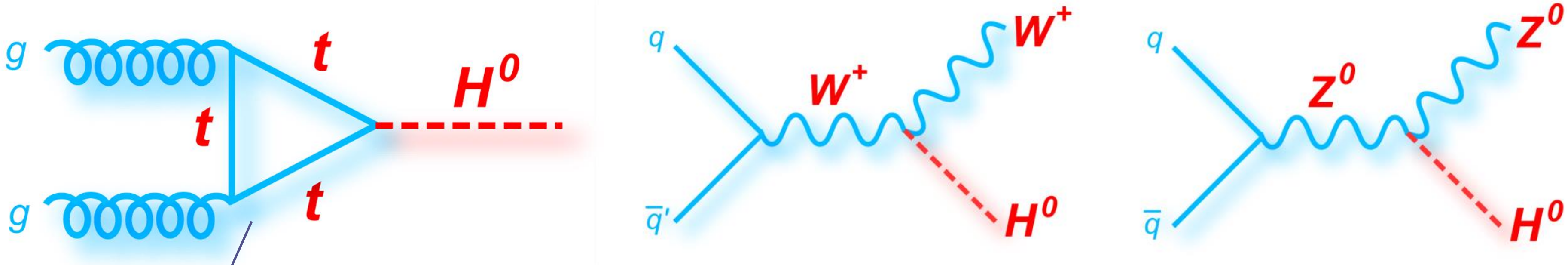


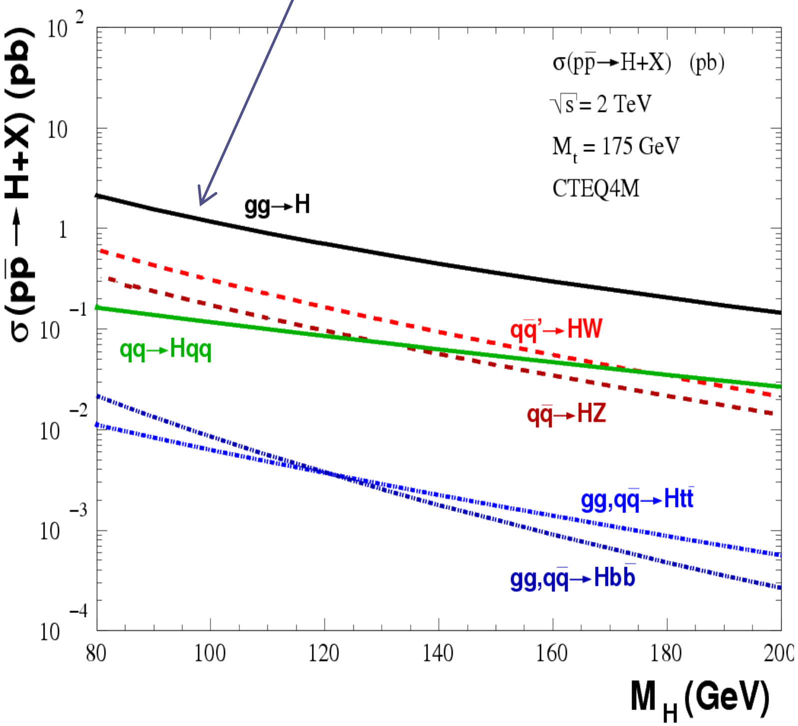
$M^2_W = M^2_Z(1-\sin^2\theta_w)(1+\Delta\rho)$

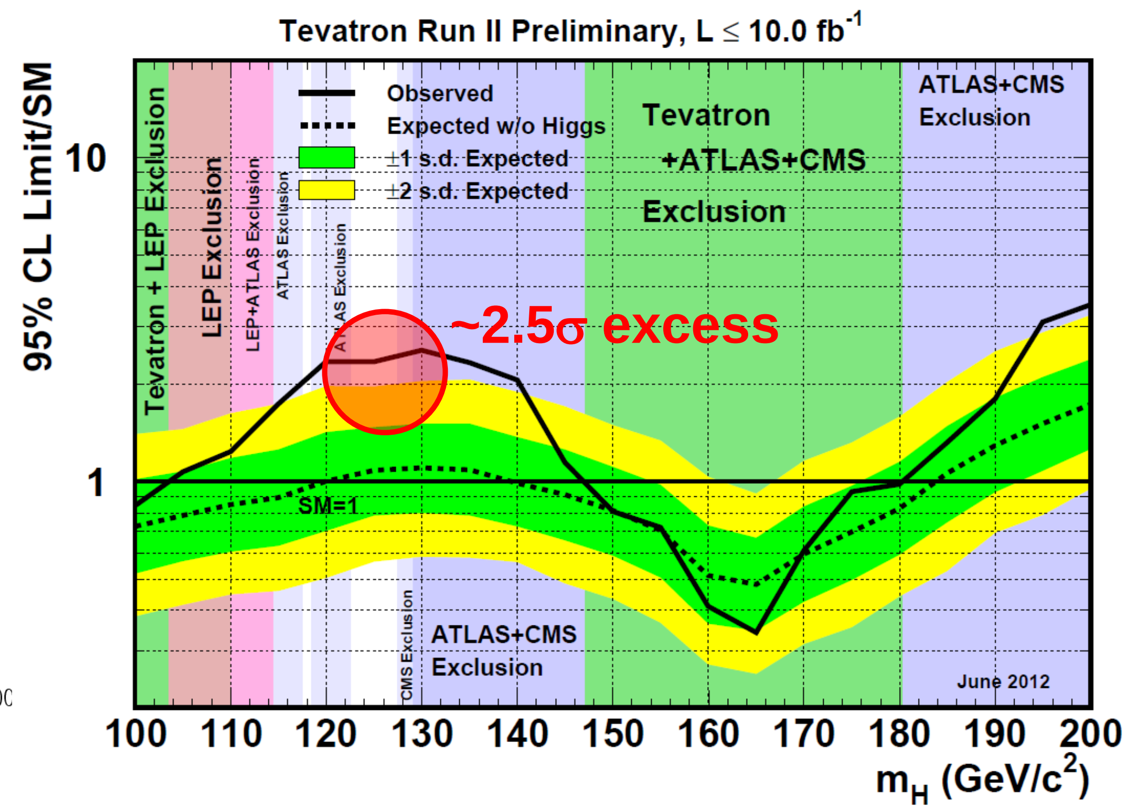
Radiative correction: $\Delta\rho(m_t, m_H, \alpha, \ldots)$

Search for Higgs boson at Fermilab/Tevatron

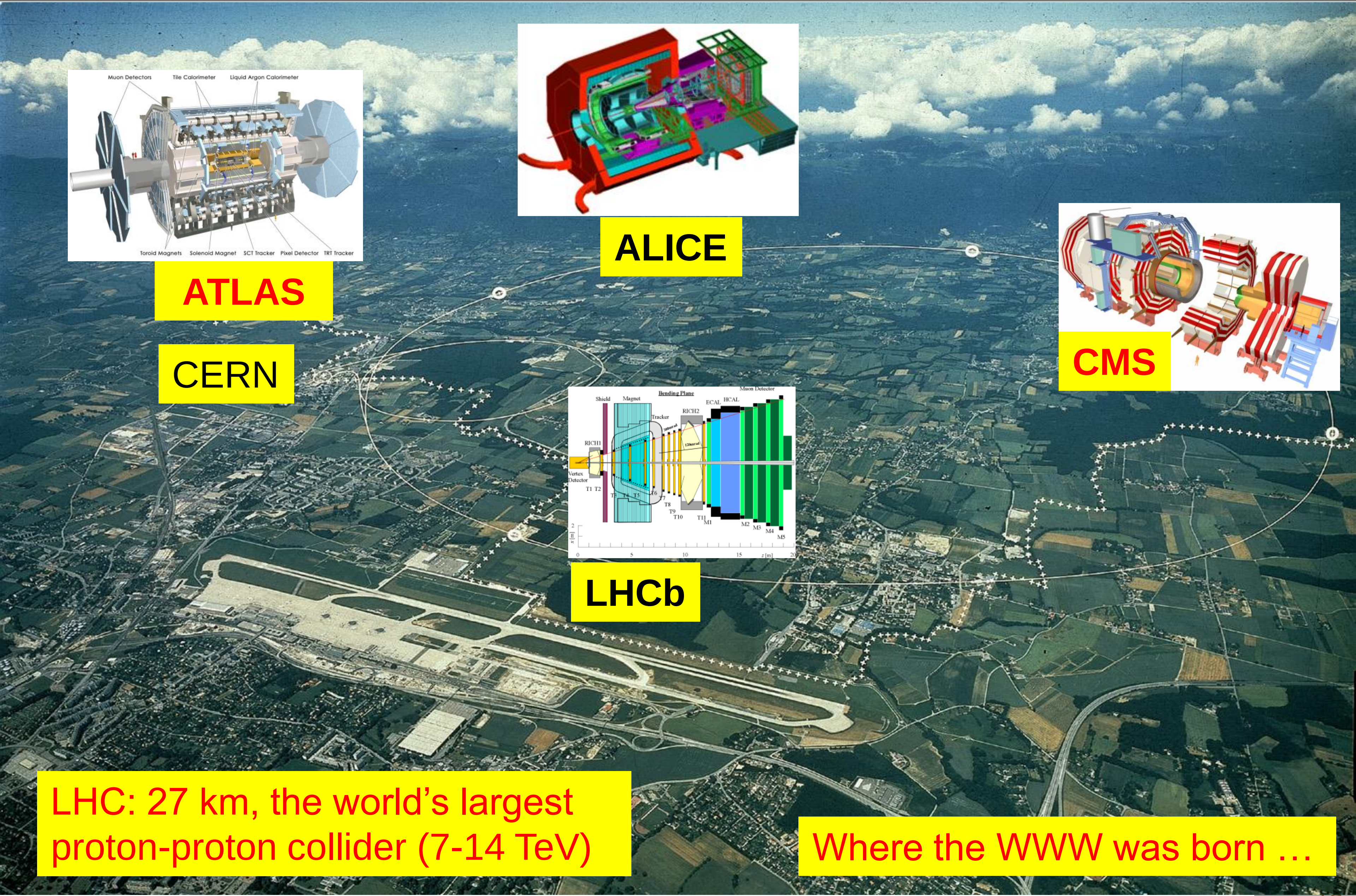
➔ Results (arXiv:1207.0449): 2.5σ excess at m_H=120-130 GeV







Large Hadron Collider at CERN



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

Where the WWW was born …

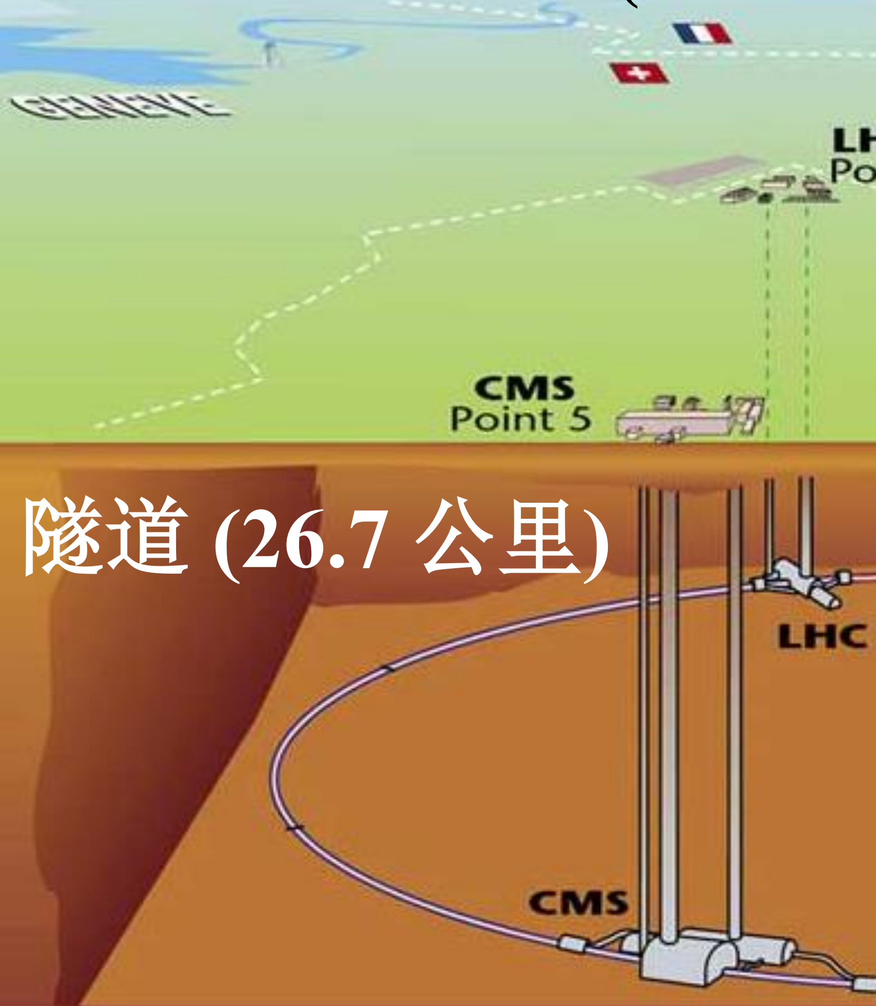
The birth of the WWW at CERN

- Tim Berners-Lee, a British scientist at CERN, invented the World Wide Web (WWW) in 1989. The web was originally conceived and developed to meet the demand for automatic information-sharing between scientists in universities/institutes around the world.

CERN是万维网的诞生地！

欧洲核子研究中心(CERN)大型强子对撞机 (LHC)

LHC是目前世界上最大和能量最高的强子对撞机 (7-14 TeV)
ATLAS Collaboration (38 countries, 174 institutes, ~ 3000)
CMS Collaboration (41 countries, 179 institutes, ~3300)



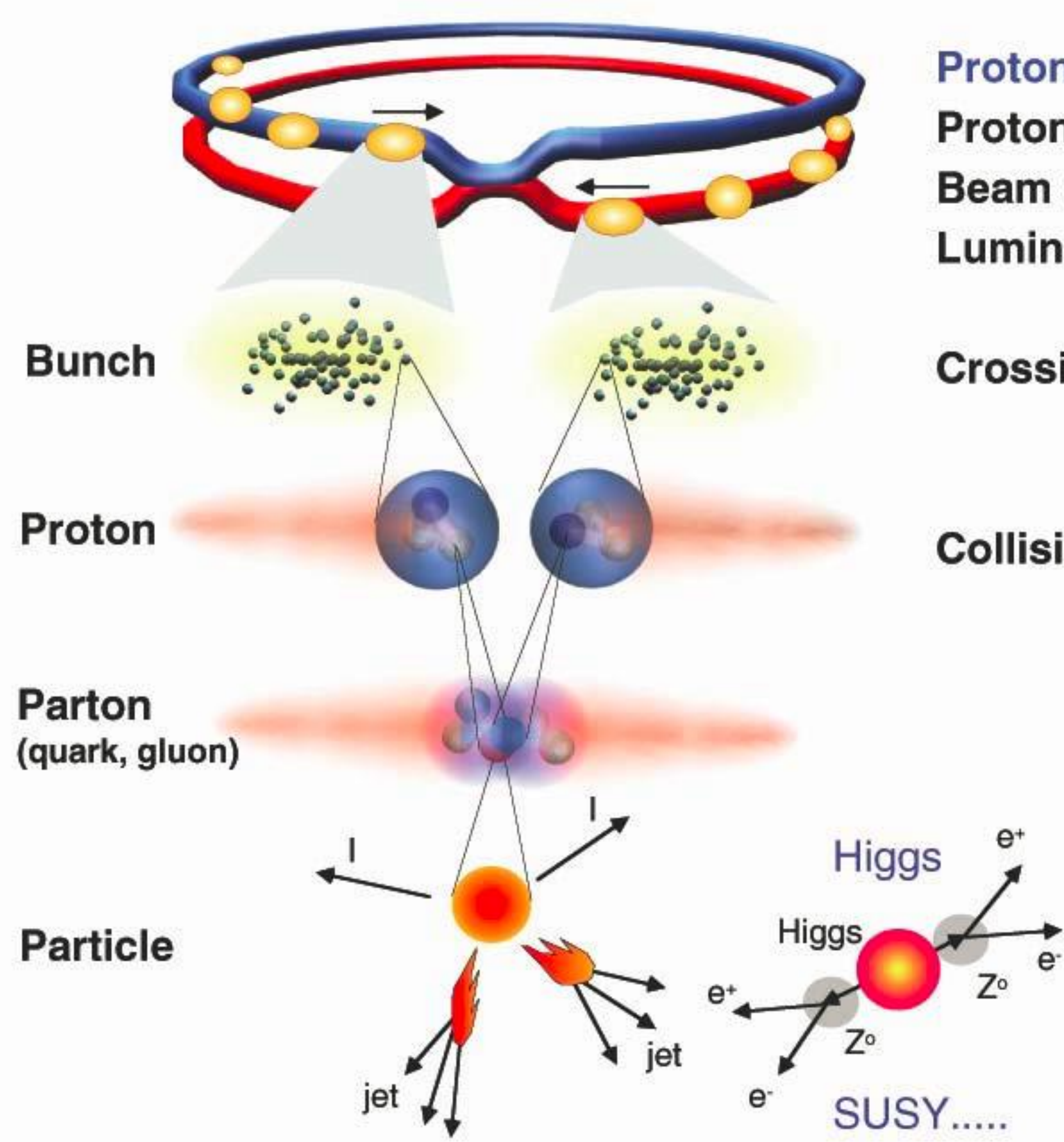
隧道 (26.7 公里)

ATLAS and CMS Member Institutes

- Ranking of World U. by SJTU: 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

LHC：质子-质子对撞

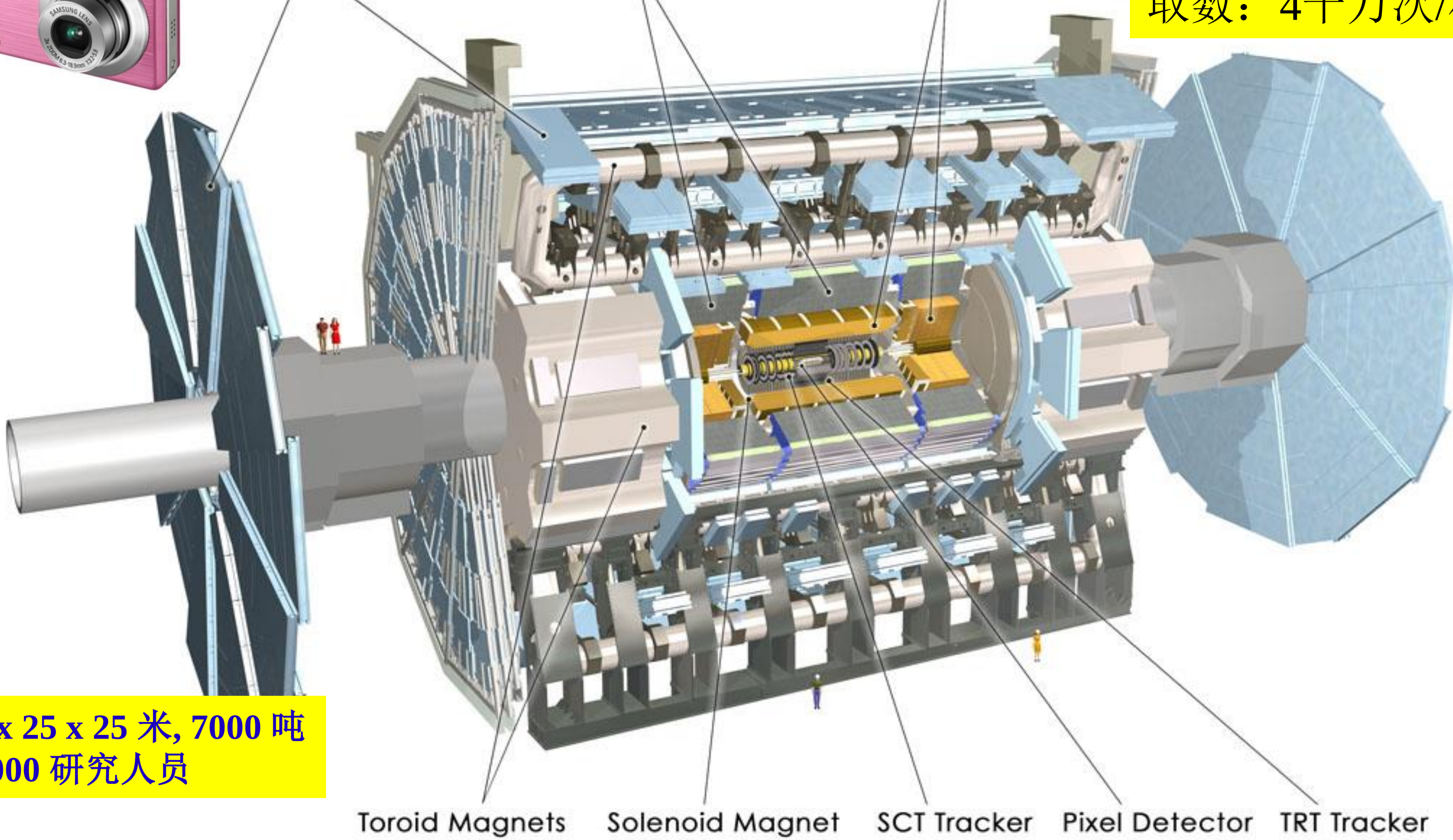


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

Higgs → ZZ* → 4l 产生几率为10万亿分之一

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

The ATLAS Detector: Huge Camera

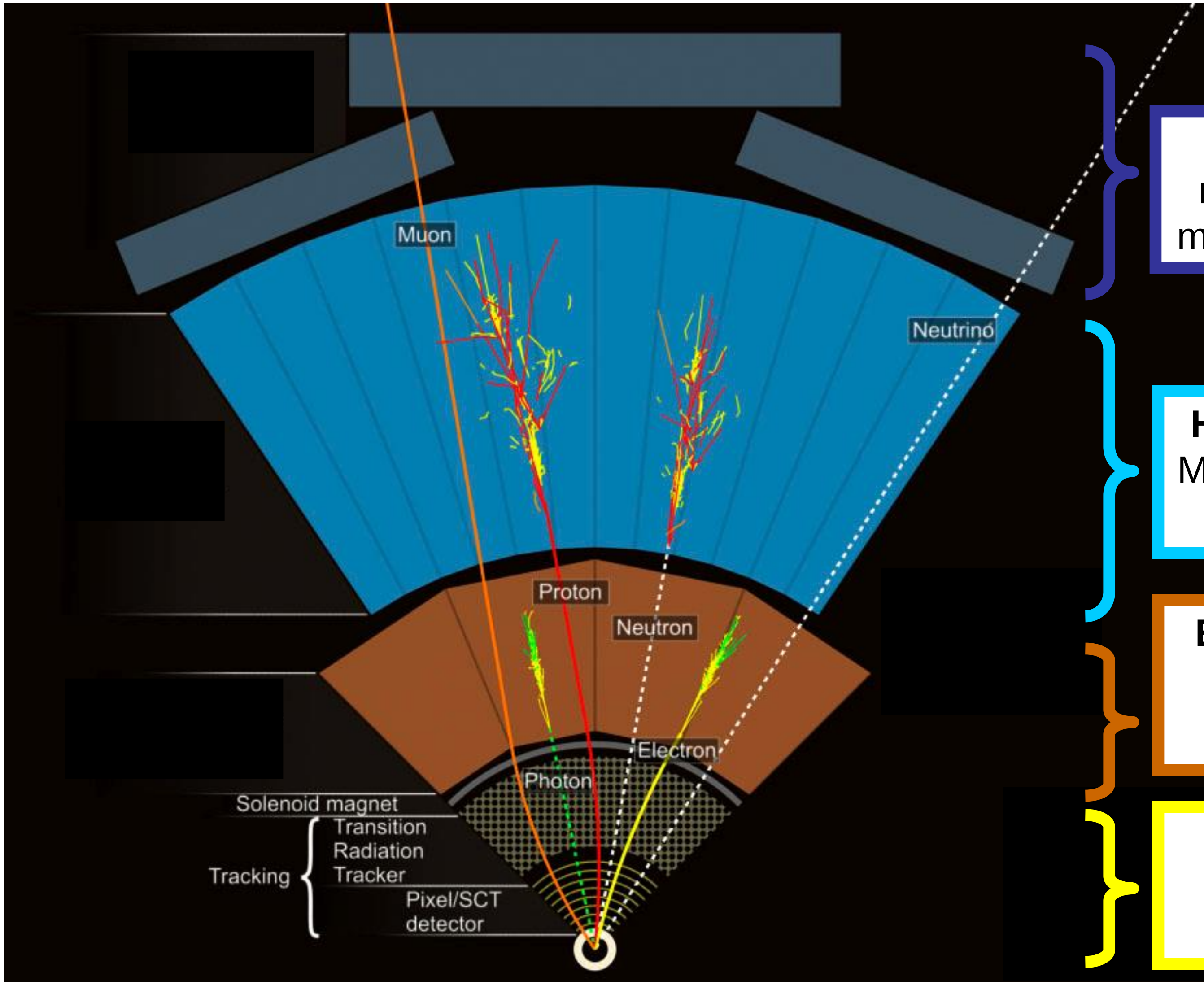


取数：4千万次/秒

46 x 25 x 25 米, 7000 吨
~3000 研究人员

Particle Detection

- ❑ Different particles have different signatures in detectors



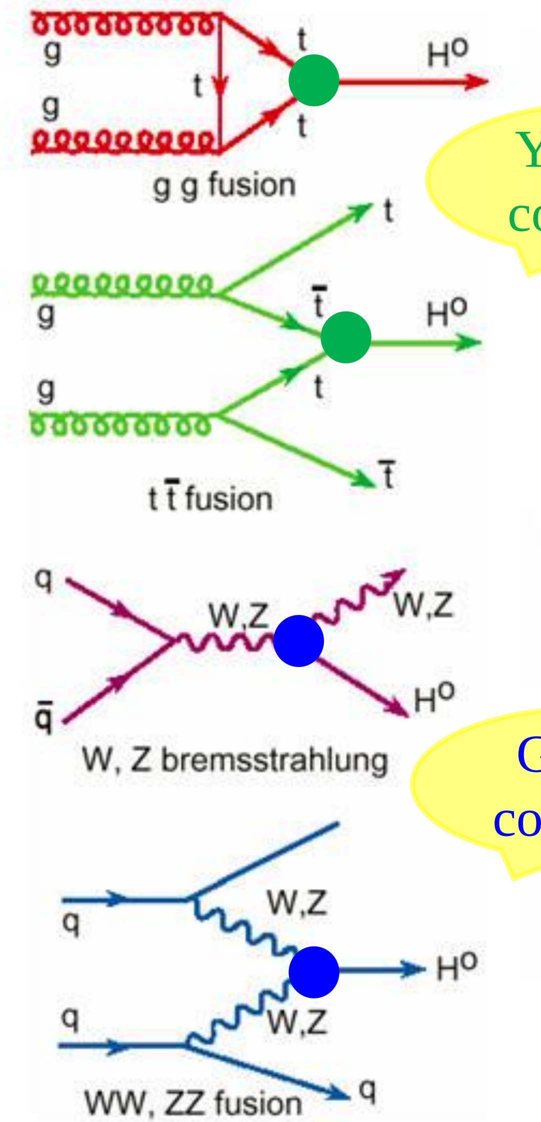
Muon Spectrometer:
muon identification and
momentum measurement

Hadronic calorimeter:
Measurement of jets and
missing energy

Electromagnetic calo:
e/γ identification and
energy measurement

Tracking system:
Charged particle
momentum, vertexing

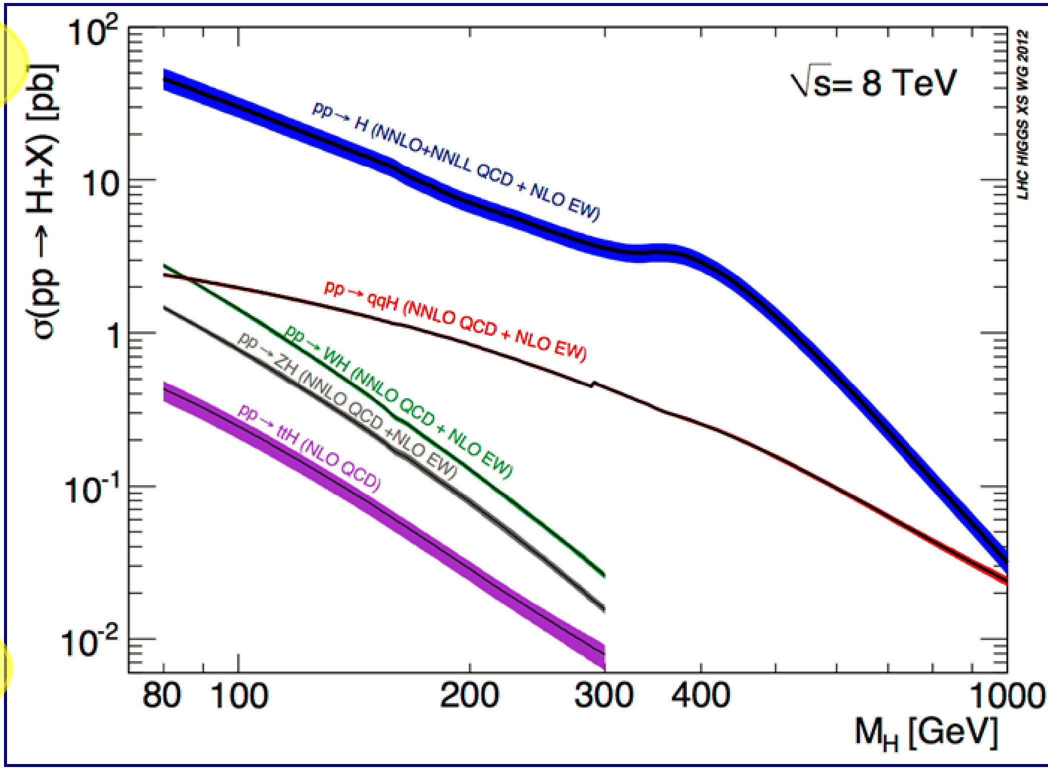
Higgs Boson Production at LHC



Yukawa coupling

Gauge coupling

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



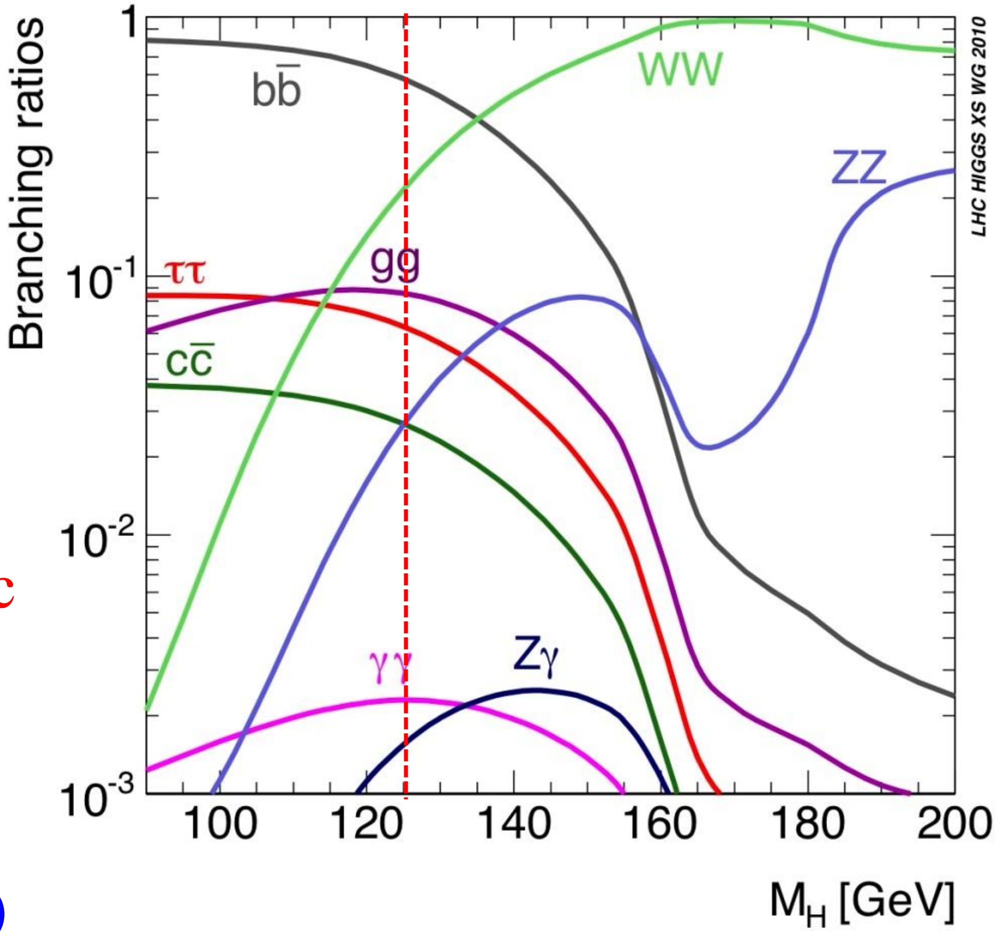
$$@125\text{ GeV: } \sigma_{ggH} = 19.5\text{ pb},\ \sigma_{VBF} = 1.6\text{ pb},$$
$$\sigma_{WH} = 0.70\text{ pb},\ \sigma_{ZH} = 0.39\text{ pb},\ \sigma_{ttH} = 0.13\text{ pb}$$

Inelastic pp cross section at 7 TeV is ~ 60 mb

Higgs Boson Decay

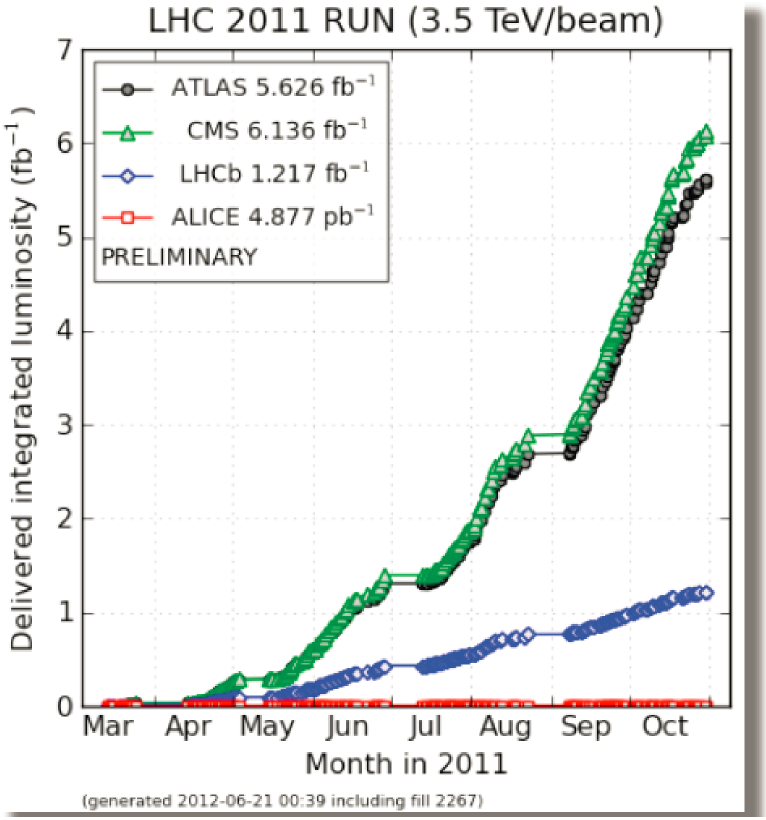
Higgs decay branching ratio at m_H=125 GeV

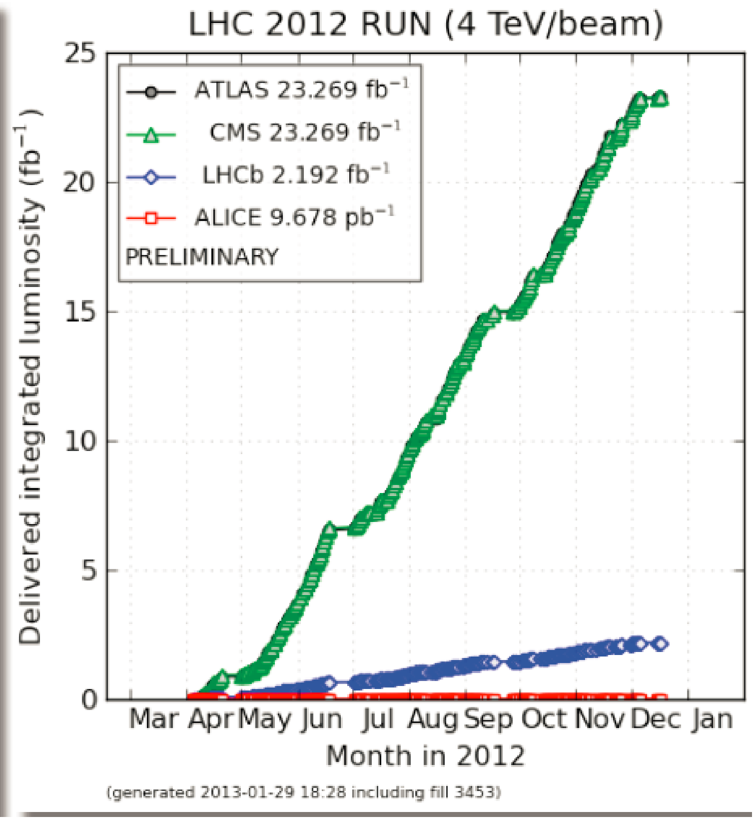
- bb: 57.7% (huge QCD bkgd)
- WW: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% (“gold-plated”, clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution,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

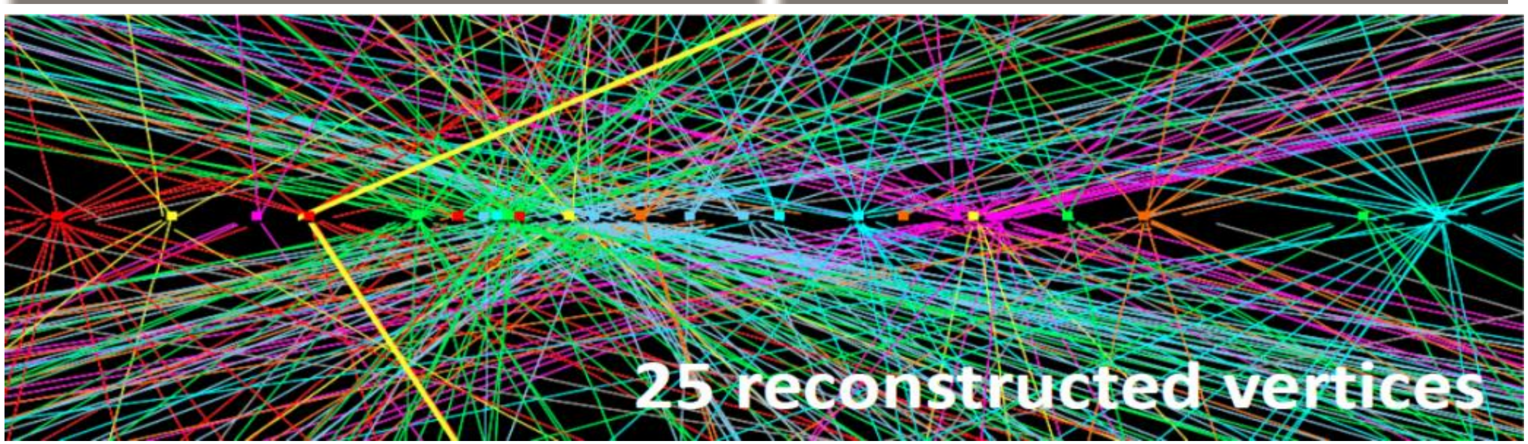


Higgs boson production rate: 1 out of 10^{12} collision events

LHC Data Samples and Major Challenges

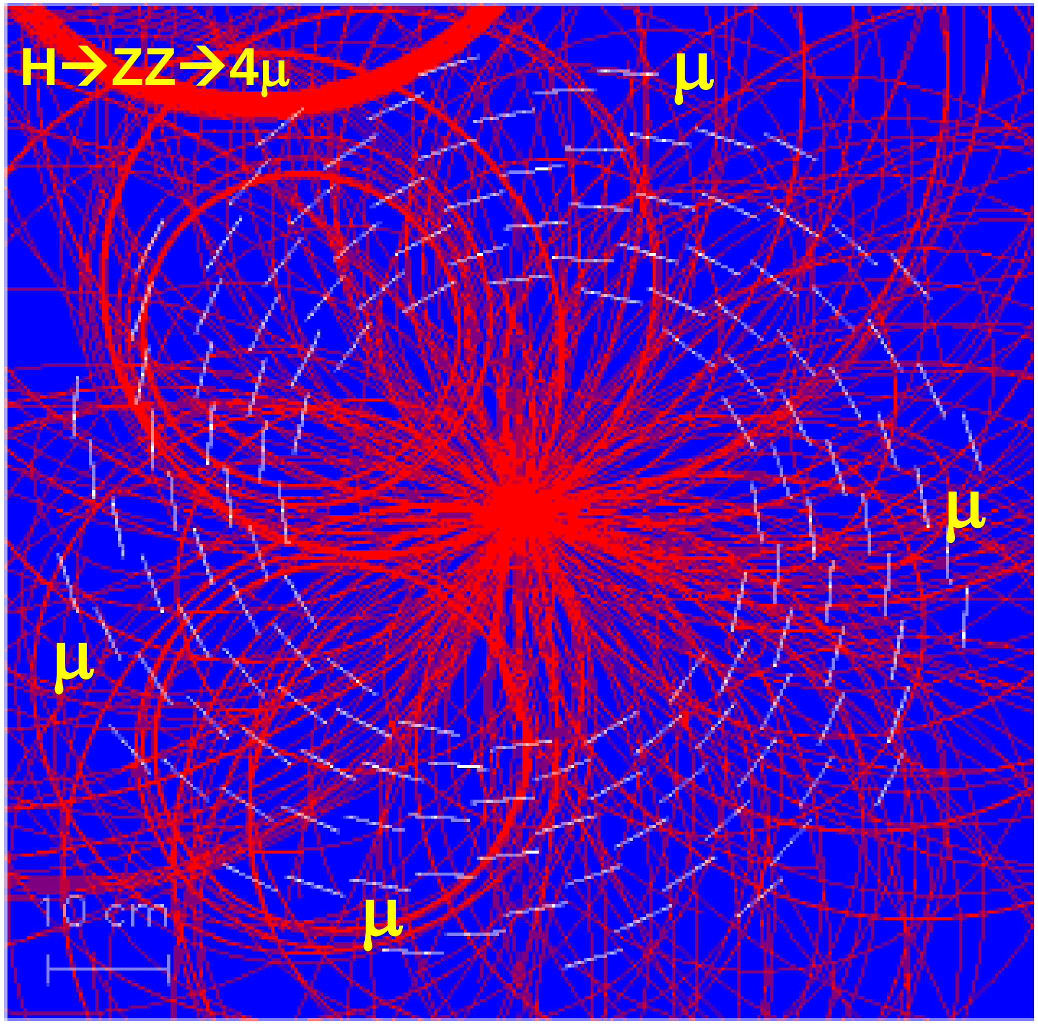






Major Challenge (Large Pileup)

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



Boosted Decision Trees (BDT)

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Nuclear Instruments and Methods in Physics Research A 543 (2005) 577–584
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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Received 16 November 2004; accepted 9 December 2004
Available online 25 January 2005

Abstract

The efficacy of particle identification is compared using artificial neutral networks and boosted decision trees. The comparison is performed in the context of the MiniBooNE, an experiment at Fermilab searching for neutrino oscillations. Based on studies of Monte Carlo samples of simulated data, particle identification with boosting algorithms has better performance than that with artificial neural networks for the MiniBooNE experiment. Although the tests in this paper were for one experiment, it is expected that boosting algorithms will find wide application in physics.

PACS: 29.85.+c; 02.70.Uu; 07.05.Mh; 14.60.Pq

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

1. Introduction

The artificial neural network (ANN) technique has been widely used in data analysis of High Energy Physics experiments in the last decade. The use of the ANN technique usually gives better results than the traditional simple-cut techniques. In this paper, another data classification technique, *boosting*, is introduced for data analysis in the MiniBooNE experiment [1] at Fermi National Accelerator Laboratory. The MiniBooNE experiment is designed to confirm or refute the evidence for $\nu_\mu \to \nu_e$ oscillations at $\Delta m^2 \simeq 1\,\mathrm{eV}^2/c^4$ found by the LSND experiment [2]. It is a crucial experiment which will imply new physics beyond

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Studies of boosted decision trees for MiniBooNE particle identification

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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

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.

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

1. Introduction

In High Energy Physics (HEP) experiments, people usually need to select some events with specific interest, so called signal events, out of numerous background events for study. In order to increase the ratio of signal to background, one needs to suppress background events while keeping high signal efficiency. To this end, some advanced techniques, such as AdaBoost [1], ε-Boost [2], ε-LogitBoost [2], ε-HingeBoost, Random Forests [3] etc., from Statistics and Computer Sciences were introduced for signal and background event separation in the MiniBooNE experiment [4] at Fermilab. The MiniBooNE experiment is designed to confirm or refute the evidence for $\nu_\mu \to \nu_e$ oscillations at $\Delta m^2 \simeq 1\,eV^2/c^4$ found by the LSND experiment [5]. It is a crucial experiment which will imply new physics beyond the standard model if the LSND signal is confirmed. These techniques are tuned with one sample of Monte Carlo (MC) events, the training sample, and then tested with an independent MC sample, the testing sample. Initial comparisons of these techniques with artificial neural networks (ANN) using the MiniBooNE MC samples were described previously [6]. This work indicated that the method of boosted decision trees is superior to the ANNs for Particle Identification (PID) using the MiniBooNE MC samples. Further studies show that the boosted decision tree method has not only better event separation, but is also more stable and robust than ANNs when using MC samples with varying input parameters.

It is important to verify that the resultant algorithm is not sensitive to small biases in the inputs, i.e., that it is robust. For MiniBooNE about two dozen MC data sets, each having a geometrical or physical parameter changed by about one standard deviation, are generated. It is then checked that, if the algorithm is trained with a central value MC data set, the results do not strongly differ when the resulting algorithm is applied to these varied sets. These tests are ongoing, but it appears that the boosting method is quite robust, in part due to using many PID variables.

The boosting algorithm is one of the most powerful learning techniques introduced in the past decade [7–10]. The motivation for the boosting algorithm is to design a procedure that combines many "weak" classifiers to achieve a final powerful classifier. In the present work numerous trials are made to tune the boosted decision trees, and comparisons are made for various algorithms. For a large number of discriminant variables, several

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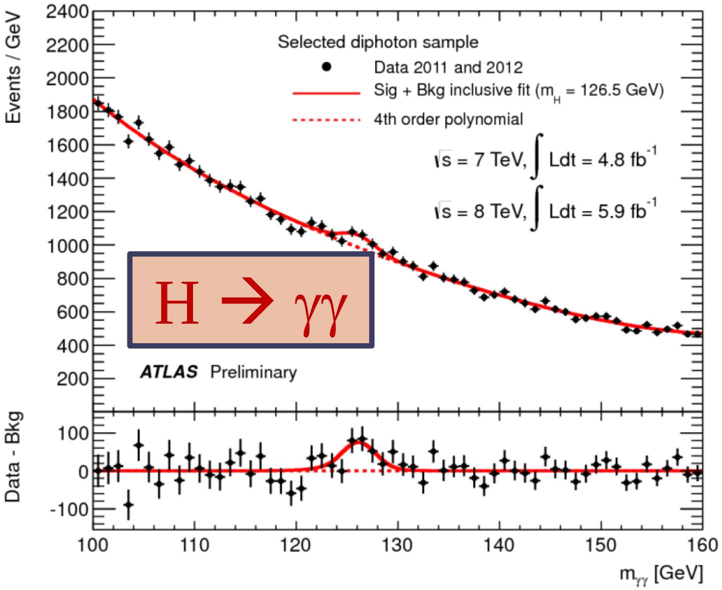
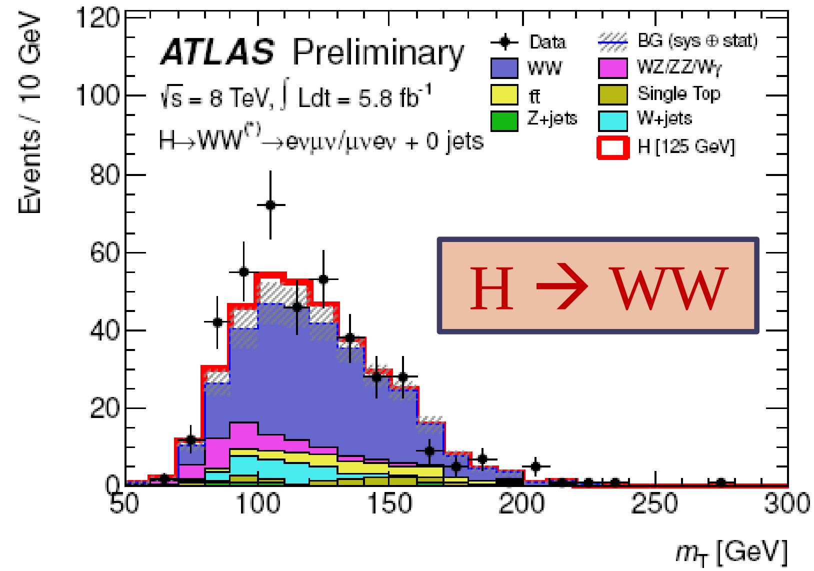
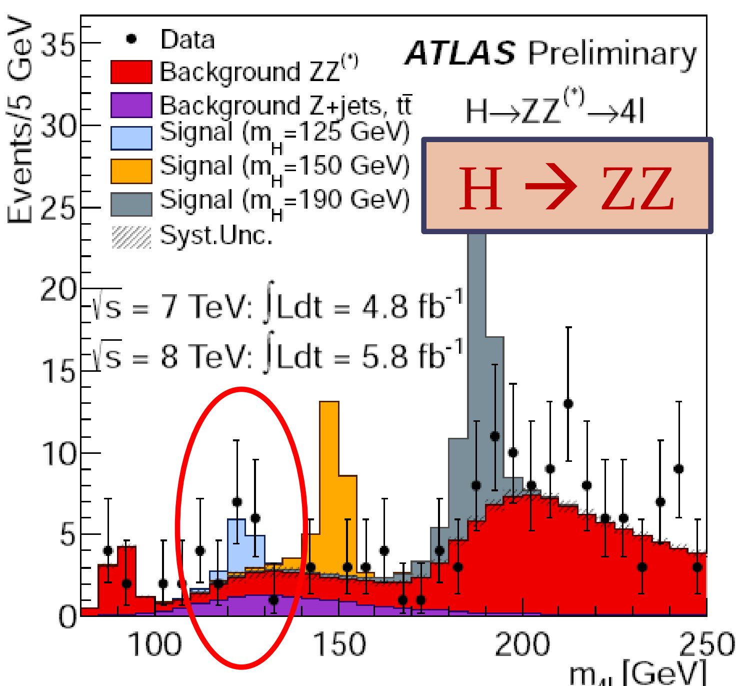
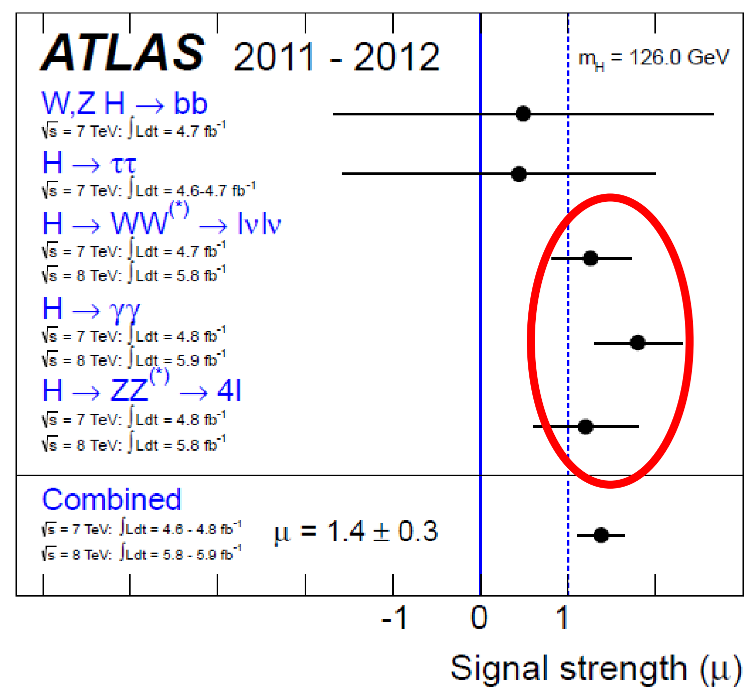
doi:10.1016/j.nima.2005.09.022

Observation of a new Particle (July 4, 2012)

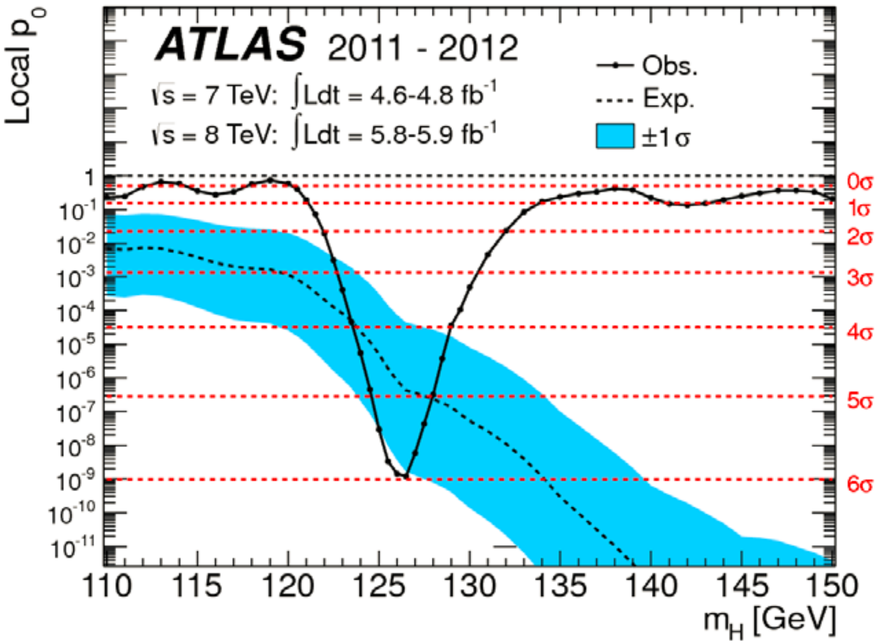








Strong Evidence for a New Particle



❑ **2012 ICHEP (summer)**

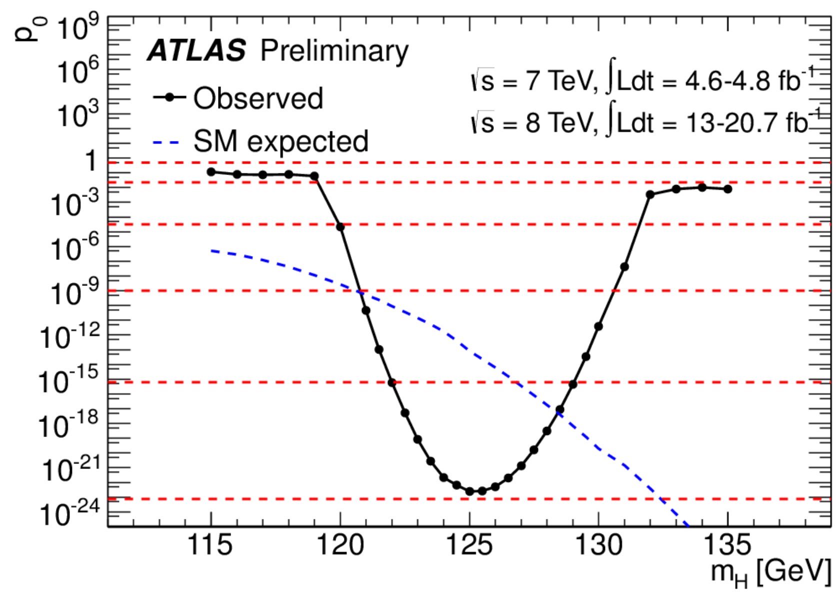
➔ Significance 6.0σ (exp 5.0σ)

➔ M_H=126.0±0.4±0.4 GeV

❑ **2012 Full Datasets**

➔ Significance 9.9σ (exp 7.5σ)

➔ M_H=125.5±0.2±0.6 GeV



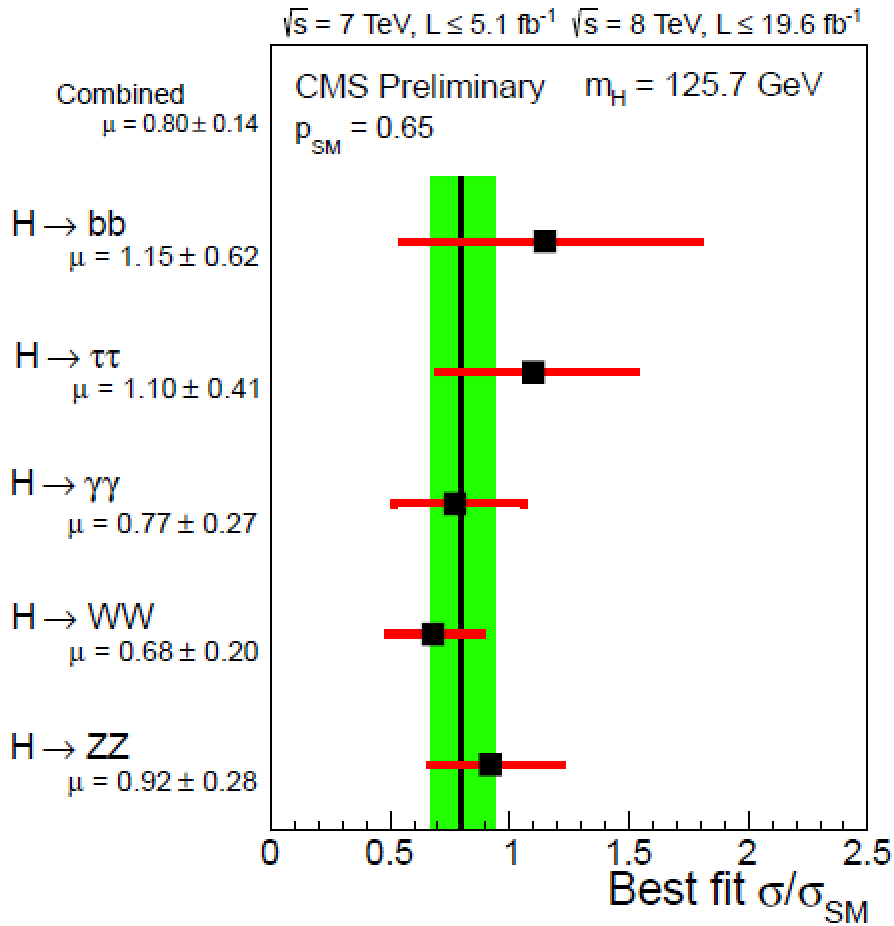
Update of Higgs Signal Strength

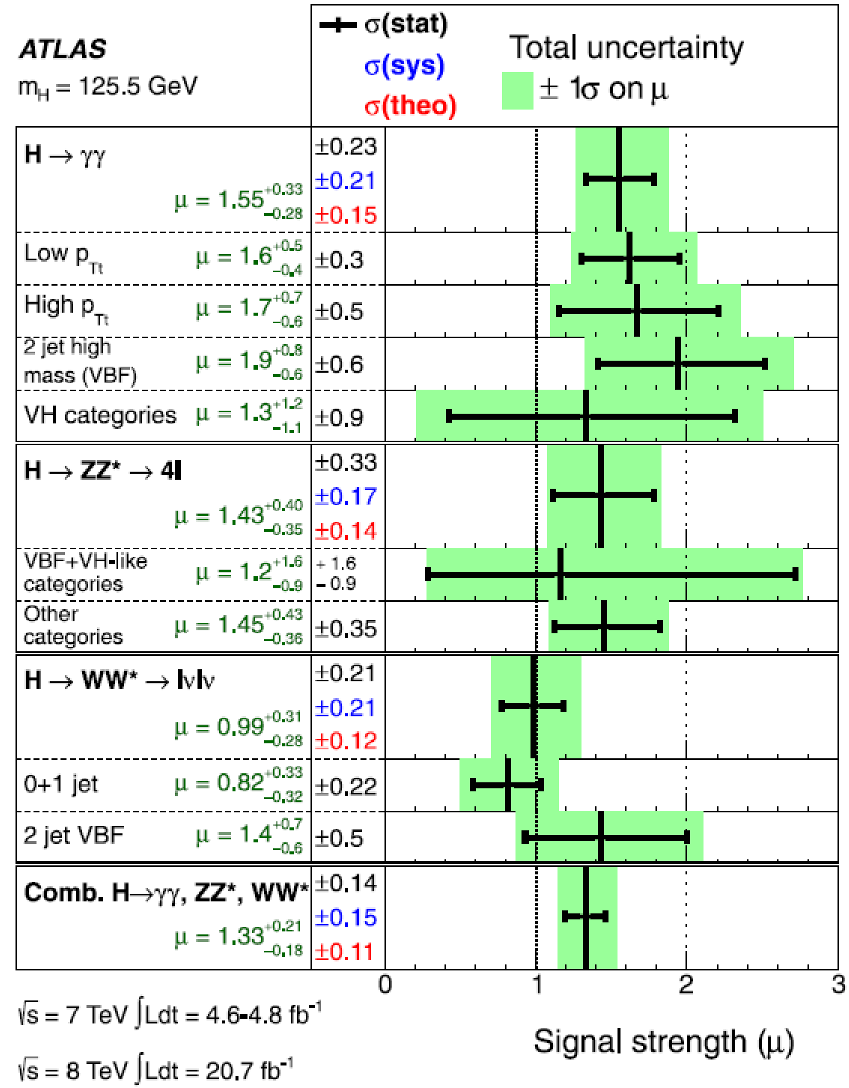
➔ **Signal strength: μ=1.3±0.2(ATLAS)**
➔ **μ = 0.8 ±0.14 (CMS)**

PLB726（2013）88-119
PLB726（2013）120-114

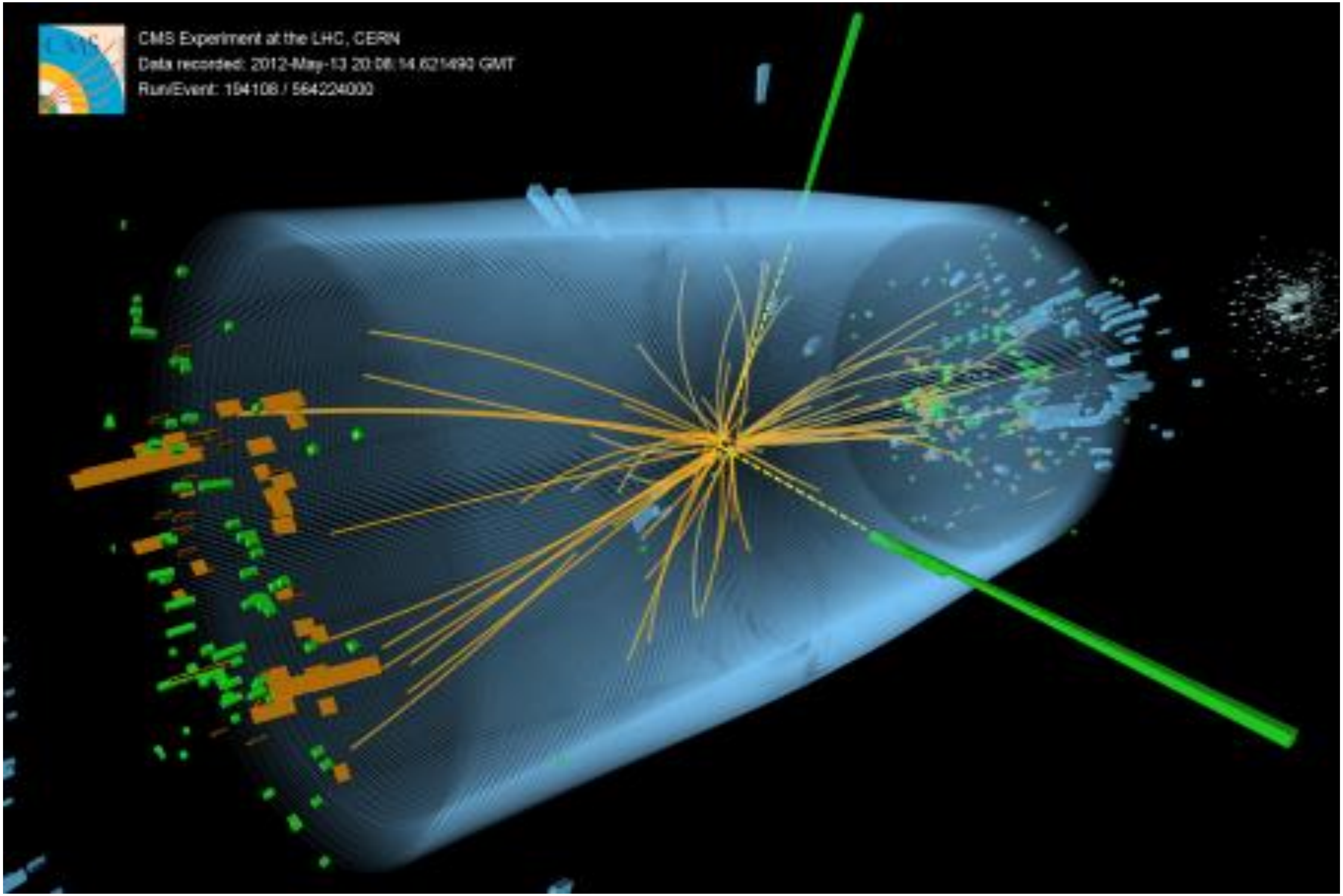
$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

CMS-HIG-13-005
JHEP 06 (2013) 081



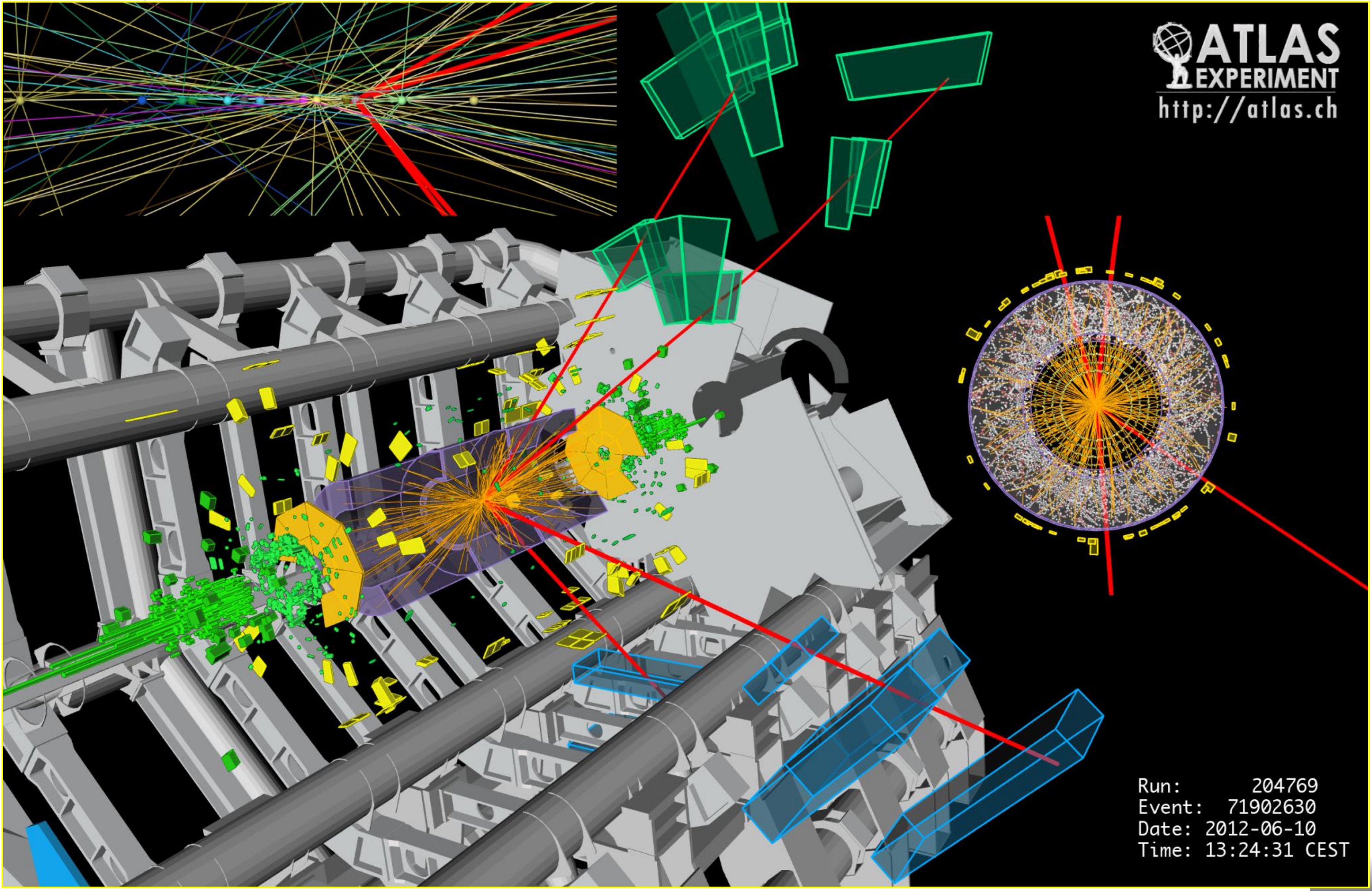


CMS H→γγ Candidate

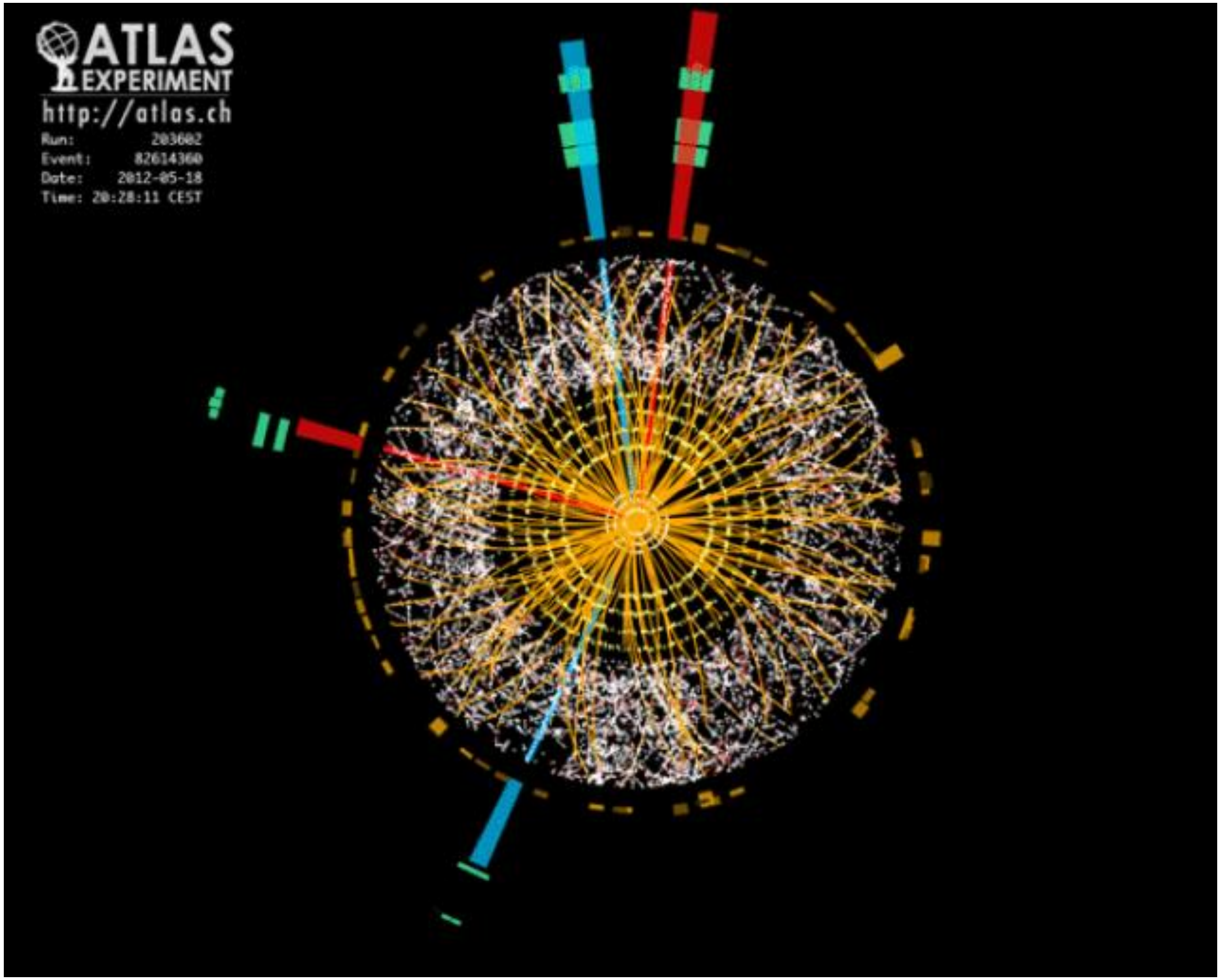


ATLAS H → ZZ* → 4μ Candidate

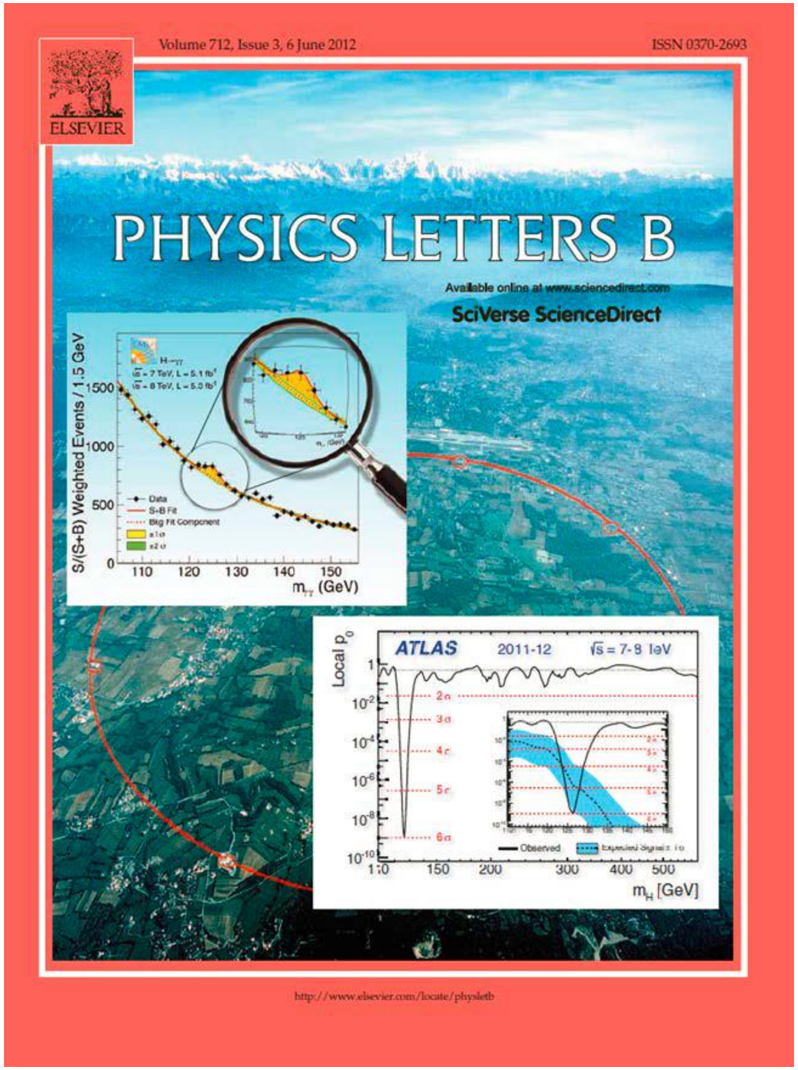
- $M_{4\mu}$ = 125.1 GeV, M_{12} = 86.3 GeV, M_{34} = 31.6 GeV



Higgs →ZZ* →4l Candidates Evolution



Discovery of the Higgs Boson



Phys. Lett. B 716 (2012) 1-29 (ATLAS)

Phys. Lett. B 716 (2012) 30-61 (CMS)

http://www.sciencemag.org/site/special/btoy2012/

NEWS: Higgs Boson (2012.7.4)

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The New York Times

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Physicists Find Elusive Part

Scientists in Geneva on Wednesday applauded the discovery

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

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27K Share

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

...ticle discovery

SS

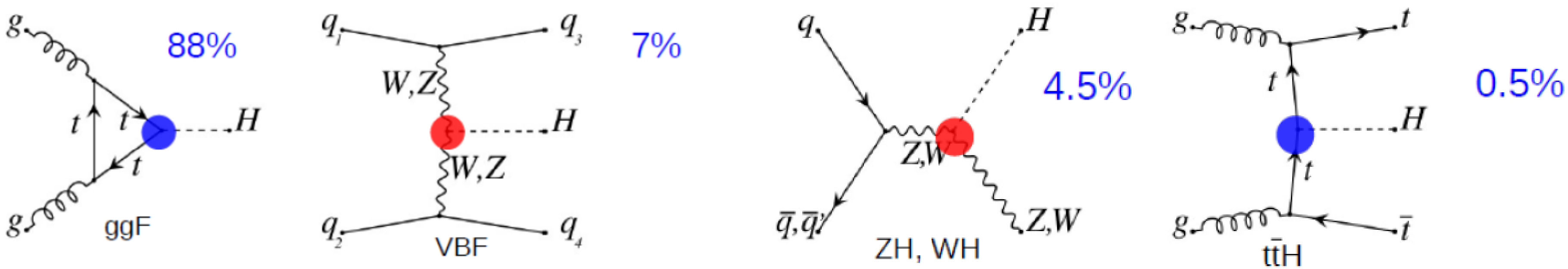
RAGE

inars at CERN

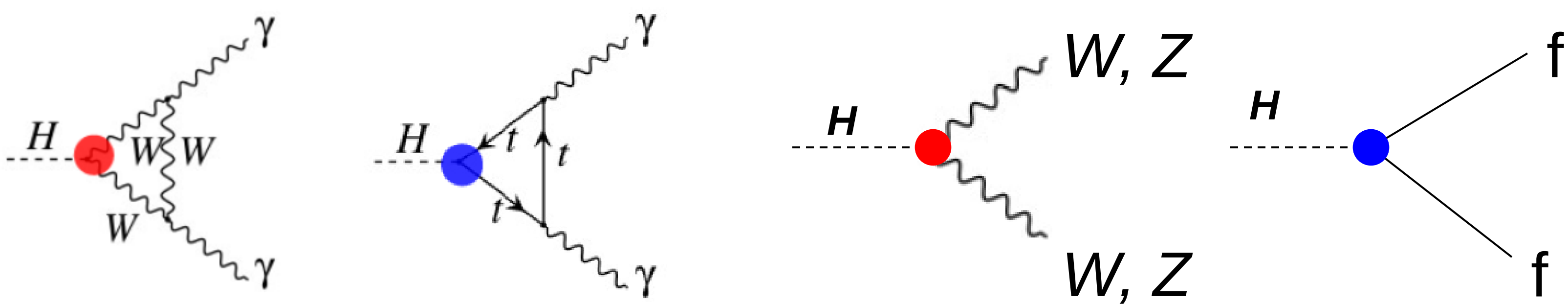
CERN black board, Jul 2012

Is it the SM Higgs Boson?

- **Higgs production (m_H = 125 GeV)**



- **Higgs decays**



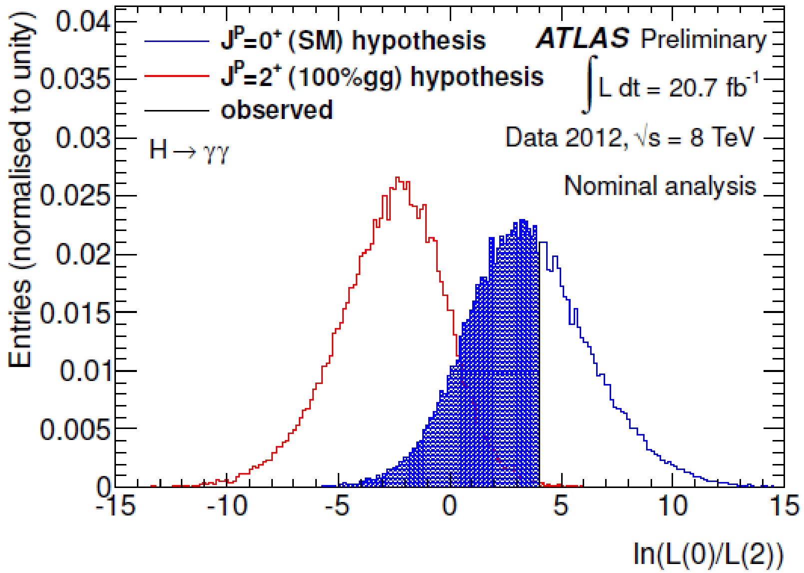
- **Couplings (new force!)**
- **Spin (0) and Parity (Even)**

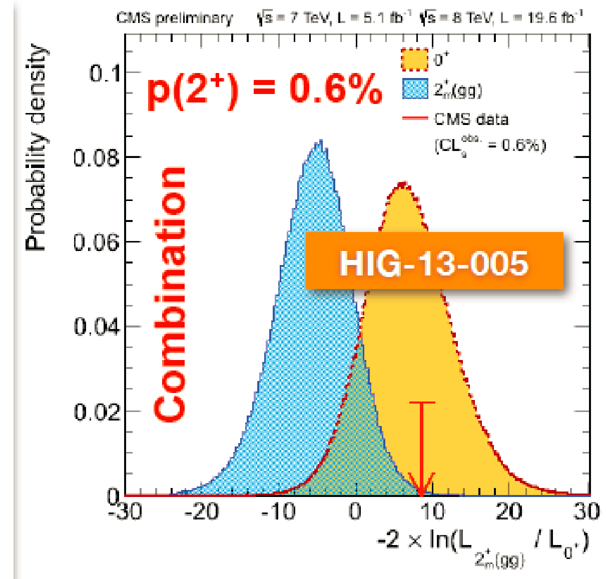
● : fermions
● : vector bosons

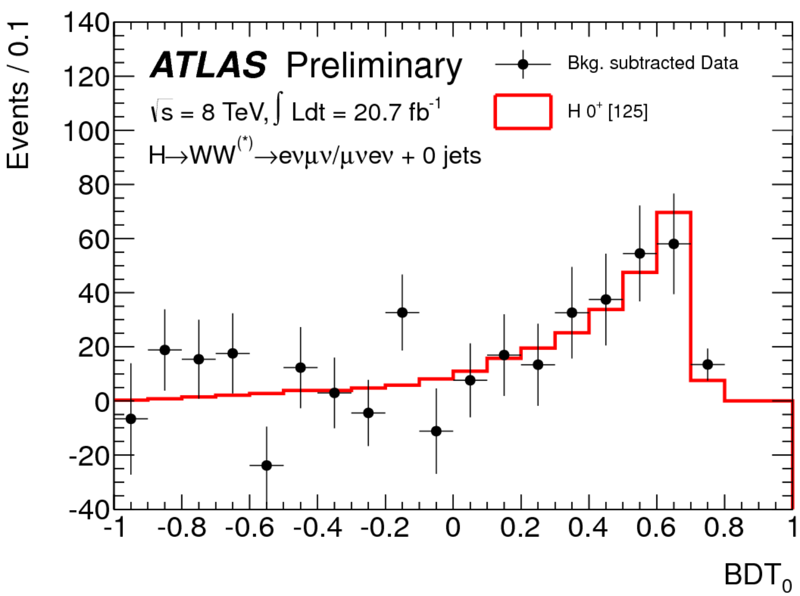
g_F (Yukawa coupling) $=\sqrt{2} \times m_F/\nu$
g_V (Gauge coupling) $= 2m_V^2/\nu$
(ν is the vacuum expectation value)

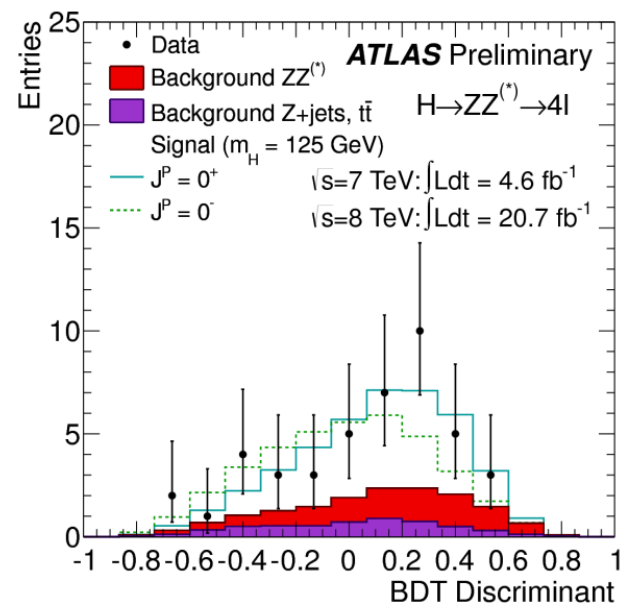
Higgs Spin and CP

- ATLAS/CMS strongly prefer Higgs with spin 0 and CP even (SM Higgs).









It is the SM Higgs Boson !!!

- **ATLAS and CMS Results are consistent with the SM Higgs boson which has spin 0 and CP even.**

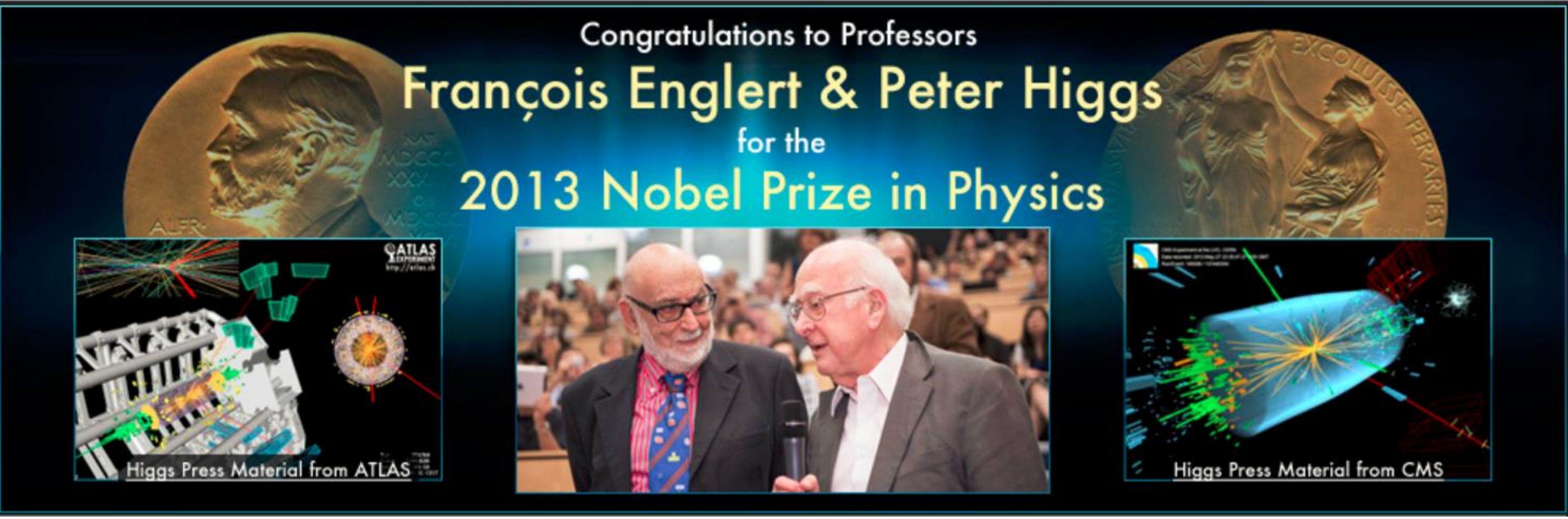
	ATLAS	CMS
Mass	125.5 ± 0.2(stat) ± 0.6(syst)	125.7 ± 0.3(stat) ± 0.3(syst)
Data favors 0^+ vs		
Spin 0^-	97.8% CL	99.8% CL
Spin 1	99.7% CL	99.9% CL
Spin 2^+	99.9% CL	99.4% CL (100%gg)

- **Each experiment:**
  - **Couplings to bosons determined at** the 10% level
  - **Rejecting zero couplings to fermions** at >5σ

- **Observation of**
  - **VBF production** at 3.3σ (ATLAS)
  - **VBF+VH production** at 3.2σ (CMS)

PLB726（2013）88-119
PLB726（2013）120-114
JHEP 06 (2013) 081
CMS-HIG-13-005

Nobel Prize in Physics in 2013



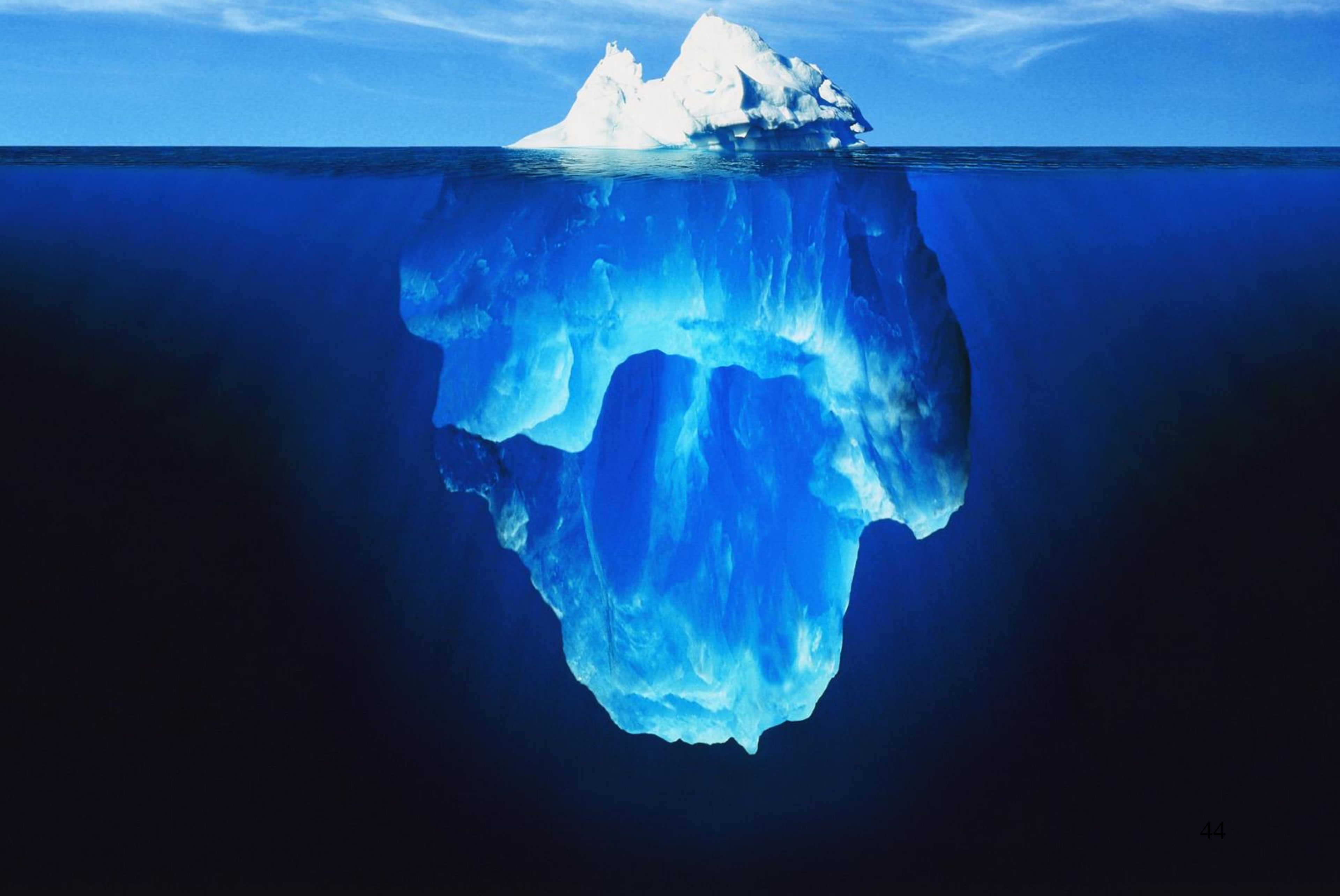
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***

➔中国组在探测器建造和**Higgs**发现中做出了重要贡献

ATLAS实验组：高能所、中国科大、南京大学、山东大学、上海交大

CMS实验组：　　高能所、北京大学

After the discovery of the Higgs boson



Looking Forward

- Before the Higgs discovery, all known elementary particles had ***spin 1 (Bosons) or spin ½ (Fermions).***

- The Higgs boson has ***spin 0***, so it is not only a new particle, but ***a new type of elementary particle***

- For this reason, many see the discovery of the Higgs boson as one of the most important steps forward in physics in the last half a century:

  it opens a new era of physics

新粒子的发现 → "粒子工厂"

CERN/UA1,UA2
1983 发现W, Z

→

CERN/LEP (1989-2000)
W, Z 玻色子工厂(SMEW)

Fermilab/L. Lederman
1977 发现b夸克($\Upsilon, \bar{b}b$)

→

SLAC/BaBar (1999-2008)
KEK/Belle (1999-2010)
B夸克工厂 (CPV)

BNL/Samuel Ting(1974, J)
SLAC/B. Richter (1974,ψ)
SLAC/M. Perl (1975,τ)

→

CESR/CLEO(2001-2008)
中国IHEP/BEPC(2003-)
τ-c 工厂 (SMEW)

CERN/LHC
(2012, Higgs)

→

希格斯工厂？
日本ILC (30km)
CERN/TLEP (80-100km)
中国CEPC(50-70km)

After the Higgs Discovery ……

Higgs Factories are proposing in
Japan (ILC), Europe (FCC) and China (CEPC)…

顶级物理学家北京座谈

大加速器：上帝粒子发现后的“中国梦”

科技日报北京2月24日电（记者高博）2月23日晚，争睹大师风采的年轻人挤爆了清华大学主报告厅。中科院高能物理所和清华大学等院校联合举办的论坛，请来世界一流的物理学家，谈基础物理学的未来发展。演讲者都看好中国科学家的未来对撞机构想。

论坛的主题是“希格斯子发现后，基础物理学的方向”，由丘成桐教授主持。发表演讲的外国专家有七位，包括两位物理诺奖得主——大卫·格罗斯和格拉德·霍夫特，还有菲尔兹奖和基础物理学奖得主，弦论大师爱德华·维腾、基础物理学奖得主尼玛·阿尔卡尼-哈米德、基础物理学奖获得者约瑟夫·英坎德拉、狄拉克奖和樱井奖获得者卢西亚诺·迈阿尼、加州伯克利大学和日本东京大学教授村山齐。

潘诺夫斯基实验粒子物理学奖获得者、中科院高能所所长王贻芳也出席演讲。他表示，中国科学家已经提出建设新的对撞机，而且成本是中国可以承受的。本论坛也是2月24日至25日在中科院高能所举行的未来环形正负电子对撞机研讨会的开幕式。

希格斯子发现后，中国科学家于2012年提出建造下一代环形正负电子对撞机（CEPC）并适时转为质子对撞机（SPPC）的方案。

对撞机是物理学家探讨宇宙基本成分的最重要工具。能量超高的两束粒子流对撞，溅出日常观察不到的“碎片”，从而检验基本粒子假说。

CEPC如能实现，则将成为同类型机器中能量最高的，它旨在精确测量希格斯粒子的性质，以及搜索基本子标准模型背后更基础的物理规律；如果它继续升级为SPPC，则比如今最厉害的大型强子对撞机（LHC）的能量高出一个数量级。

“（中国设想的）这个加速器第一步可以进行正负电子湮灭的对撞实验。”阿尔卡尼-哈米德说，“这个阶段会产生很多希格斯子，从而带动相关研究。第二步我们可以在加速器上进行质子—质子的对撞实验。由于质子的静质量比电子大很多，我们可以探测更高的能量区域，从而观察更微观的尺度。”

“LHC已经巩固了标准模型，但其他理论必须通过更高能的对撞机实验去验证。”大卫·格罗斯说，“现在中国有一个很好的机会在自然科学基础研究方面起领导作用……我把这个梦想叫做‘中国大加速器（The Great Accelerator）’。这会和长城（The Great Wall）一样引人瞩目，会比长城作用更大。如果中国建造了加速器，世界上的许多科学家会来这儿帮忙和工作。”其他几位发言者的意见也都类似。

王贻芳说：“CEPC＋SPPC预计经费占国家GDP的比例，比三十年前中国政府决定建设高能所的北京正负电子对撞机占当时国内GDP的比例还低。20年后，中国将成为世界最大的经济体，也很有理由建造世界最大的加速器。”

“只有有了一个世界最先进的科研项目，才能吸引青年学者和世界顶级科学家来工作。”王贻芳认为，“世界上有个先例非常成功，就是日内瓦的欧洲核子中心，自从它有了世界上最大最先进的加速器后，欧洲就代替美国成为了世界高能物理的中心。这是美国结束了得克萨斯州的超级超导加速器的后果，是美国的悲哀。希格斯子发现后，中国有了一个机会：利用成熟的环形加速器技术，就可以建造一个希格斯子工厂，来研究世界上最先进的研究课题。只有研究清楚了希格斯的性质，才有可能了解粒子物理未来的方向。”

丘成桐说：“今天我们讨论希格斯子，也有人叫它‘上帝’粒子。今天我们也有一个‘上帝’赐给的良机，就是参加建造下一个大型对撞机，叫作希格斯子工厂或扩展成质子对撞机。今天我们高兴地看到这么多的学生来参加讨论。你们是建造下一个机器和建立一流科学的参与者。”

- 2004年诺贝尔物理学奖得主David Gross说：“现在中国有一个很好的机会在自然科学基础研究方面起领导作用……我把这个梦想叫做‘中国大加速器（The Great Accelerator）’。这会和长城（The Great Wall)一样引人瞩目，会比长城作用更大”。
- 潘诺夫斯基粒子物理学奖获得者、高能所所长王贻芳认为：“只有有了一个世界最先进的科研项目，才能吸引青年学者和世界顶级科学家来工作。…日内瓦的欧洲核子研究中心自从有了世界上最大最先进的加速器后，欧洲就代替美国成为世界高能物理中心。…希格斯发现后，中国有了一个机会，利用成熟的环形加速器技术，就可以建造一个希格斯工厂，来研究世界上最先进的研究课题。只有研究清楚了希格斯的性质，才有可能了解粒子物理未来的方向。”

CEPC-SppC优先纳入“率先计划”

➔ 习近平总书记2013年7月17日在中科院高能所考察工作时的讲话，“希望中国科学院不断创新成果、出创新人才、出创新思想，

- 率先实现科学技术跨越发展，
- 率先建成国家创新人才高地，
- 率先建成国家高水平科技智库，
- 率先建设国际一流研究机构。

➔ 中国科学院力推“率先计划”，规划中科院跨越发展新方向

大型环形正负电子对撞机（CEPC）已被优先纳入到“率先计划”，获得高能物理学界支持和推动。

CEPC-SPPC 预研启动

- ❑ 环形正负电子对撞机(CEPC)-超级质子质子对撞机(SPPC)
  - 2013年9月13日正式在北京召开启动会
  - 成立Institutional Board (IB) 、项目执行委员会(Steering Committee)、项目经理 (Project Manager)和理论、实验和加速器组的召集人(conveners)
- ❑ CEPC-SPPC 项目初步时间表
  - 2014年：项目黄皮书(pre-CDR)
  - 2015-2020年：预研项目建议书(TDR)
  - 2021-2027年：开始CEPC工程建设
  - 2028-2035年：开始CEPC运行取数
  - 2036-2042年：SPPC启动工程建设
  - 2042-2050年：SPPC (50-100TeV) 运行

- ❑ CEPC项目估算：建造约200-300亿元，每年运行费约20-30亿元
  - **50-100 公里长的环形对撞机**

（GDP占比: LHC~0.03%, LEP~0.02%, ILC~0.02%, BEPC~0.01%, CEPC~0.005%）

A Series of CEPC Workshops

CEPC in the News

【Xinhua Net】Chinese scientists plan better machine to hunt “God particle”

【新华网】中国科学家提出建设下一代环形正负电子对撞机探索“上帝粒子”奥秘”

【中新网】中国科学家酝酿建造下一代环形正负电子对撞机

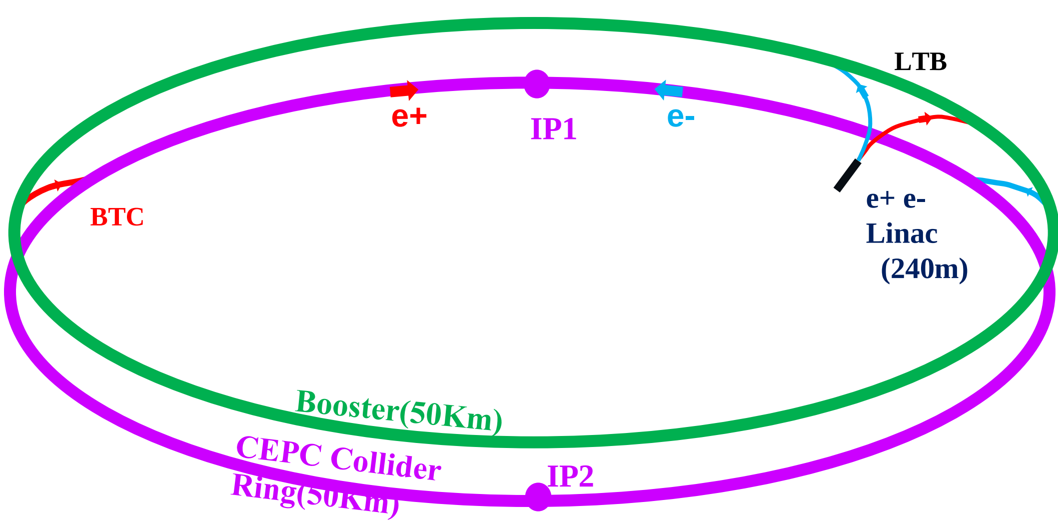
【科技日报】“中国建大加速器，将激励一代人”; 【中国科学报】基础物理何去何从

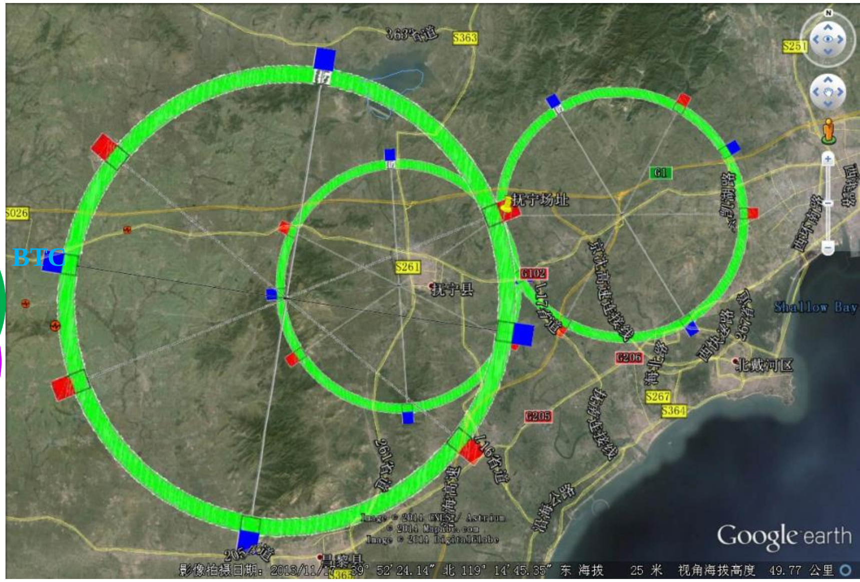
【科技日报】大加速器：上帝粒子发现后的“中国梦”

【中国科学报】“率先行动”:书写时代新篇章

【AIP - Physics Today】Particle physicists brainstorm long-term collider options

【Nature】China plans super collider

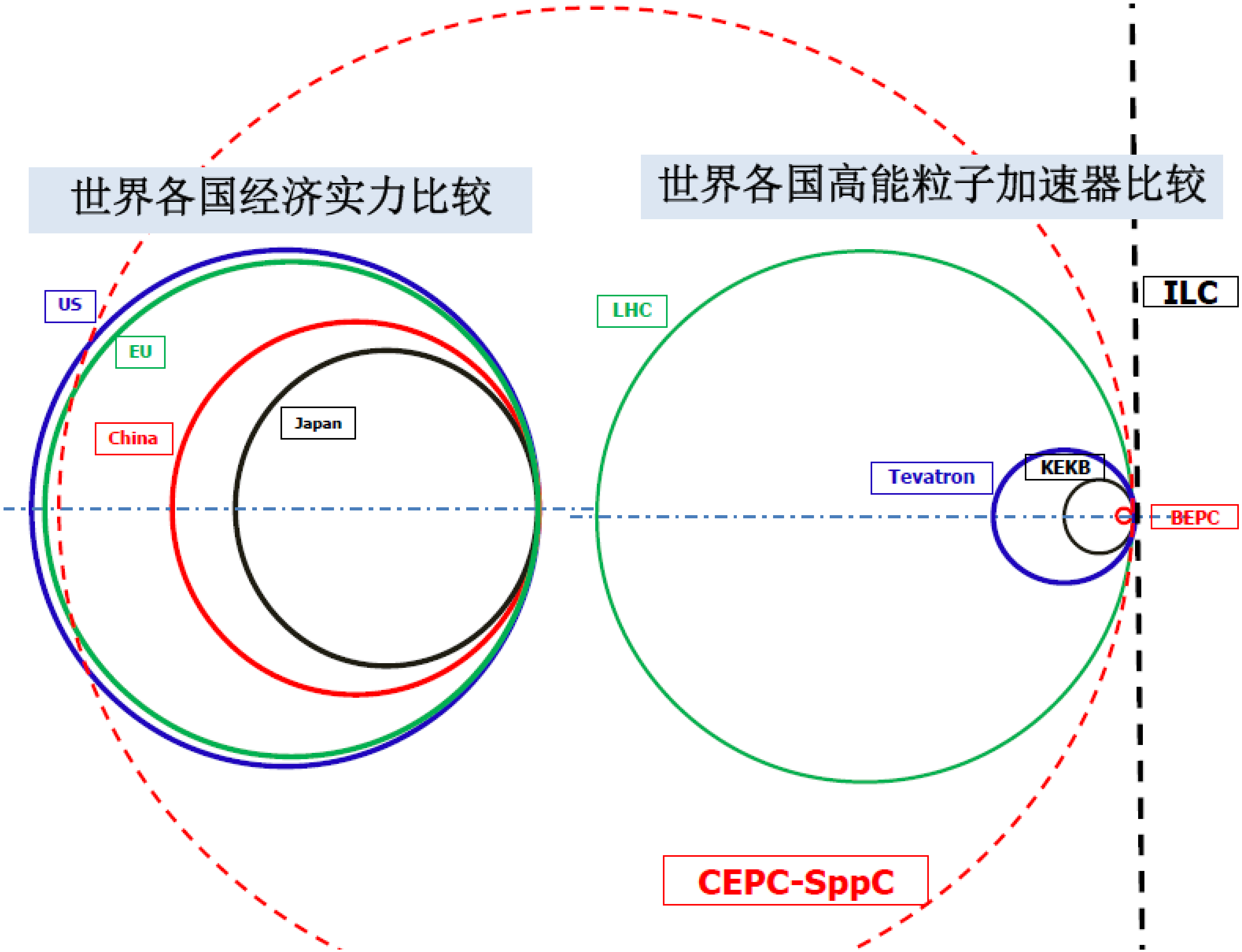




CEPC 简介

目　录

Our Dream: from BEPC to CEPC



各国粒子物理发展计划

- 日本
  - 完成超级B工厂改造，开始BELLE-II实验（~2018年）
  - 国际直线对撞机(ILC，~ 2020)
  - HyperK（有可能会放弃，如果做ILC的话）
- 欧洲
  - 继续运行大型强子对撞机(LHC)及其改进（至 ~ 2030年）
  - ILC、长基线中微子等与美国、日本合作
  - 探索未来环形高能加速器的可能：FCC
    - 如果日本做ILC，直接做 FCC-hh，否则有一个FCC-ee的阶段，并考虑FCC-eh 的可能性
- 美国
  - 长基线中微子设施(LBNF)
  - 积极参与未来能量前沿大型加速器(ILC，FCC，CEPC)

中国的难得机会

- 科学上： e^+e^- + pp 均领先世界
- 技术上：不是高不可攀
- 经济上：也许可以承受
- 预期成果：至少可以在高能物理领域领先国际，成为世界中心，国际关注的焦点，国家科技发展的一个标志。更多的可能包括：重大科学发现，重大技术进步，。。。

中国梦：建设象CERN一样的国际科学城

BEPC的选择使我们从零起步到今天在国际高能物理学界占有一席之地。在经济规模即将达到世界第一时，我们能否为30年后的中国规划一个蓝图，成为世界高能物理领域的领跑者 ？

机会只有10年: 2020年左右开始建设，2030年开始运行

现实中：2030年之前

欧洲忙于LHC，无法腾出手来

日本由于ILC，无法掉头

美国尚未走出SSC的阴影，也缺乏共识，很难较快改变

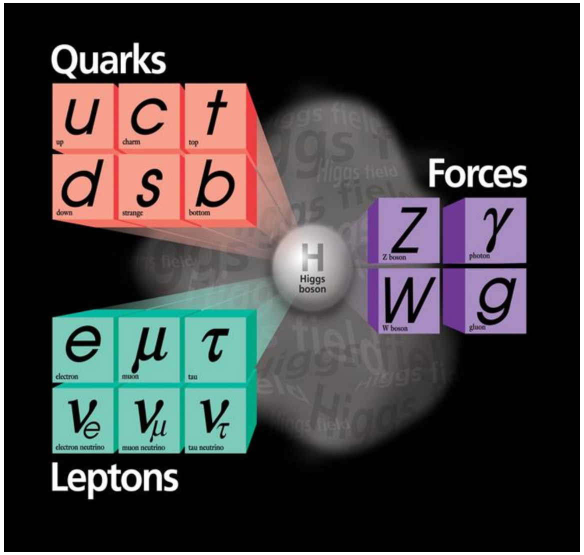
失去这个机会，不知何时才有下一次使我们能超越欧美日？

基本粒子百年重大发现 vs 大国兴衰

- 1897 – e discovery, J.J. Thompson (英国)
- 1919 – proton, Ernest Rutherford (英国)
- 1930 – neutron, James Chadwick (英国)
- 1936 – μ, Carl D. Anderson (Caltech, 美国)
- 1956 – ν_e discovery (Homestake, 美国)
- 1962 – ν_μ discovery (BNL, 美国)
- 1968 – u and d quark (quark model, 美国)
- 1968 – strange quark(Kaon, 美国)
- 1974 – c quark (J/ψ, BNL, SLAC, 美国)
- 1977 – tau discovery (SLAC, 美国)
- 1977 – b quark (Upsilon, Fermilab, 美国)
- 1979 – gluon (DESY, 德国)
- 1983 – W and Z (CERN, 欧洲)
- 1988 – atmospheric neutrino oscillation (日本)
- 1995 – top quark (Fermilab, 美国)
- 2000 – ν_τ discovery (Fermilab, 美国)
- 2001 – solar neutrino oscillation (SNO, 加拿大)
- 2012 – Higgs boson (CERN/LHC, 欧洲)
- 2012 – reactor neutrino oscillation (Dayabay, 中国)
- 2013 – Zc(3900) four-quark state (BESIII, 中国）

英国
“日不落帝国”

二战后美国成为
世界超级强国



总结和展望

- 用高能对撞机探索基本粒子质量的起源
  - 1964年 理论上预言希格斯粒子的存在
  - 2012年 在CERN/LHC实验上发现希格斯粒子，中国科学家对实验上发现希格斯粒子做出了重要贡献
  - 2013年 Francois Englert 和 Peter W. Higgs 因为理论上预言希格斯粒子而获得诺贝尔物理学奖
- 中国将在粒子物理领域有更大的发展
  - 目前中国正面临快速发展高能对撞机物理战略机遇期，物理学界要形成共识，抓住难得的机会，积极推动在中国本土建造50-70公里长的大型环形正负电子对撞机（CEPC，希格斯工厂）-超级质子质子对撞机（SPPC）。
  - 希望中国早日建成世界级的高能物理研究中心，在基础科学领域取得重大突破，为未来基础物理学指引方向，成为基础科学领域的领跑者，实现科技强国的“中国梦”。

谢谢大家！

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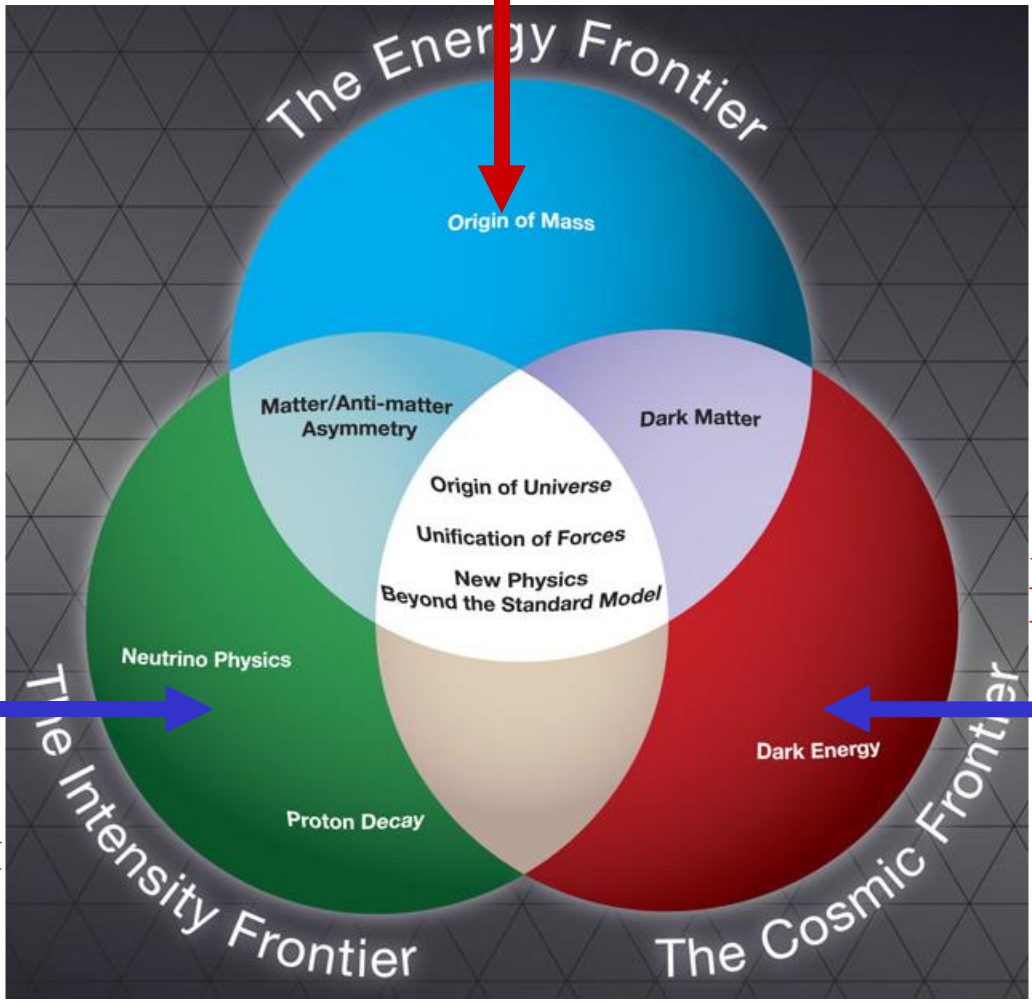
职位： 教授，博导，粒子物理学科带头人
入选上海“千人计划”
入选中组部“青年千人计划”
CEPC 执行委员会核心成员

研究领域： 高能对撞机物理，
Higgs，SUSY和暗物质，
超标准模型物理探索

联系方式：13764927109
Email: Haijun.Yang@sjtu.edu.cn

研究物质世界的三大前沿

高能量前沿 (上海交大参与LHC/ATLAS实验，CEPC-SPPC)



上海交大主导中国PandaX暗物质实验

高强度前沿

上海交大参与中国大亚湾中微子实验

宇宙学前沿

主要合作单位

- 欧洲核子研究中心(CERN)
- 美国费米国立加速器实验(Fermilab)
- 美国阿贡国家实验室(ANL)
- 美国布鲁海文国家实验室(BNL)
- 美国密歇根大学(University of Michigan)
- 中国科学院高能物理研究所(IHEP)
- 中法粒子物理联合实验室(FCPPL)

上海交大参与的研究工作

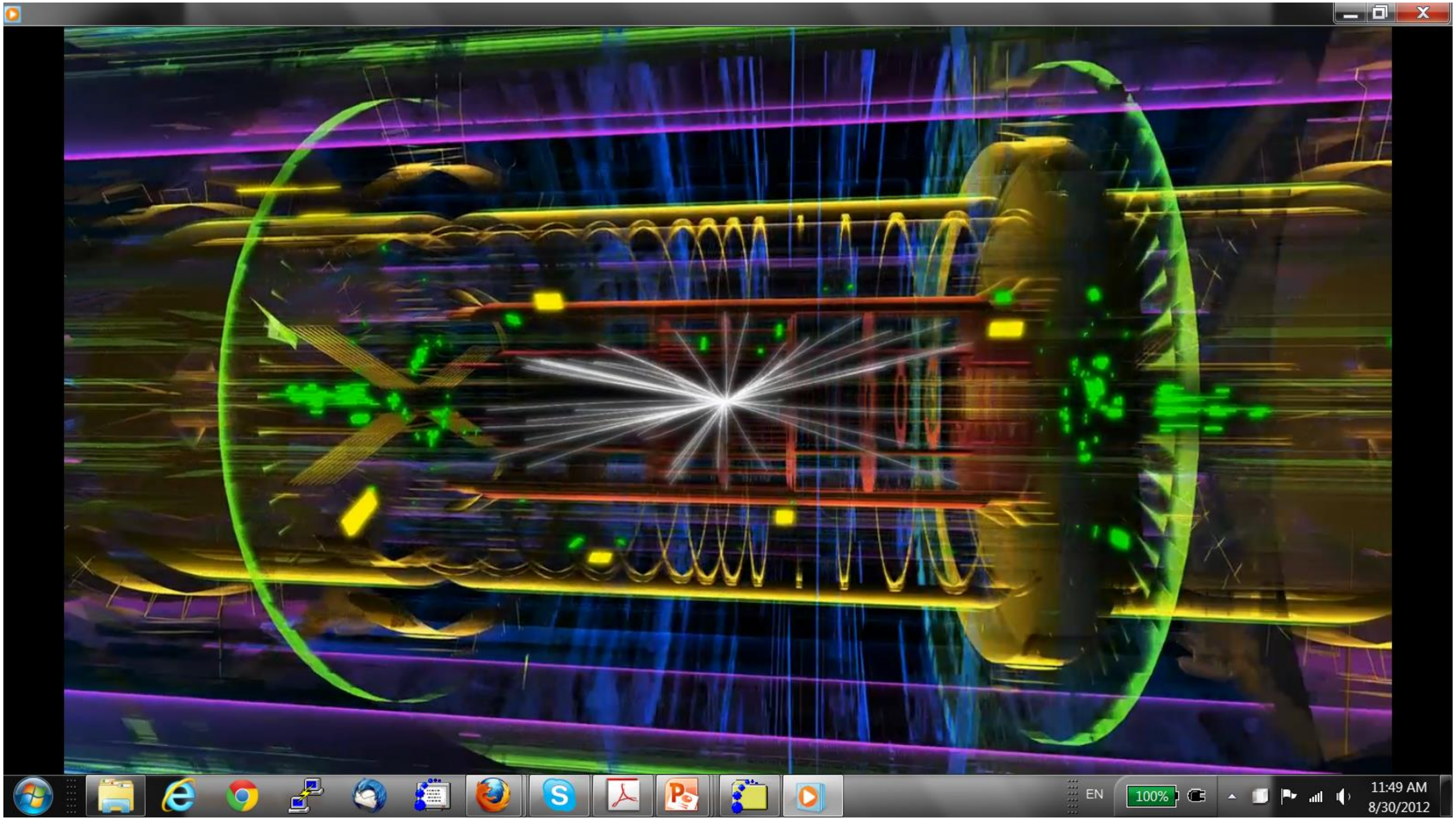
- **欧洲核子中心LHC/ATLAS国际合作实验：**
  - 研究Higgs的属性
  - 寻找 SUSY、暗物质粒子
  - 精确检验标准模型及探索新物理现象

- **中国CEPC-希格斯工厂预研**
  - 粒子探测器的模拟，材料选型、尺寸和性能的优化等
  - Higgs信号产生、模拟、重建和分析(LCIO-MOKKA)
  - 电磁量能器和强子量能器(RPC)的预研等

- 有广泛的国内外合作研究、联合培养机会

LHC：粒子加速和对撞

❑ 质子-质子对撞示意图



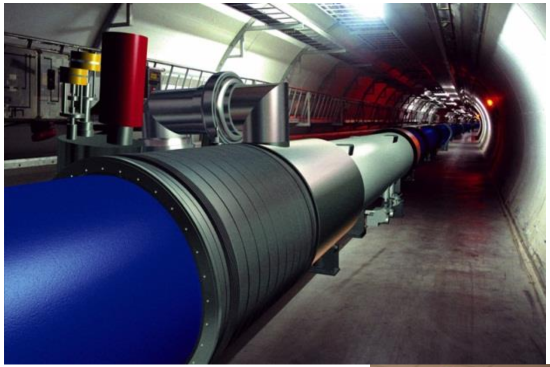
Concluding Remarks

To imitate J.F. Kennedy's famous speech in 1961 when he announced the US will send man to the moon in a decade, one can say:

We choose the CEPC-SPPC as our next project, ***not because it is easy, but because it is hard****, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win.*

大型对撞机实验的技术创新和转化

前沿基础研究依赖于先进技术和尖端技术强有力的支撑，如强子对撞机实验：



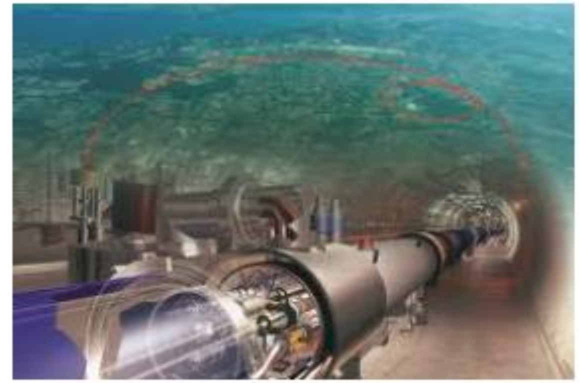
- 低温超导技术
- 超高真空技术
- 高能粒子加速技术
- 新型和高效的粒子探测技术

- 高速电子学读出技术
- 高性能计算机数据处理和分析技术

- 大型复杂装置的管理技术
- 研究人员协同创新和管理技术

- ……..

Energy Frontier Facilities

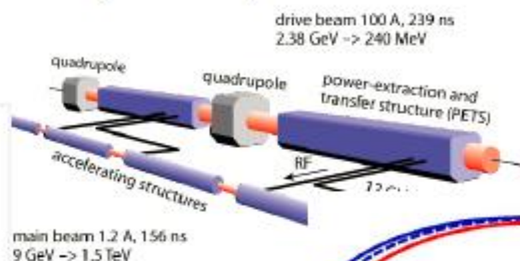


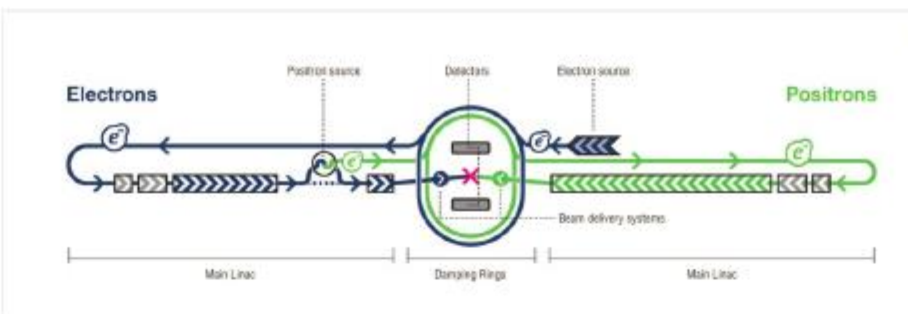
pp colliders:

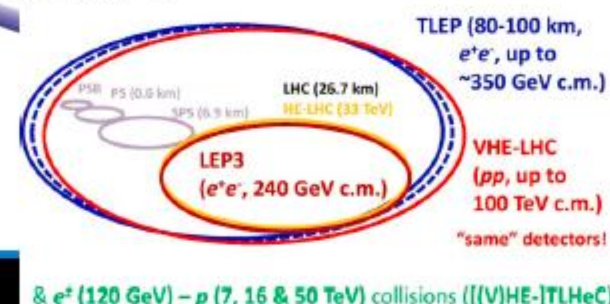
- LHC at 14 TeV with 300 fb^{-1}
- HL-LHC at 14 TeV with 3000 fb^{-1}
- HE-LHC at 33 TeV and VLHC at 100 TeV

e^+e^- colliders:

- Linear: ILC 250/500/1000 GeV, CLIC 350/1400/3000 GeV
- Circular: TLEP @ 240 and 350 GeV

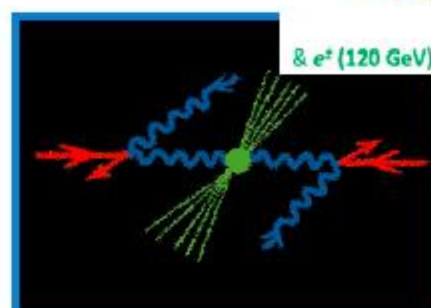




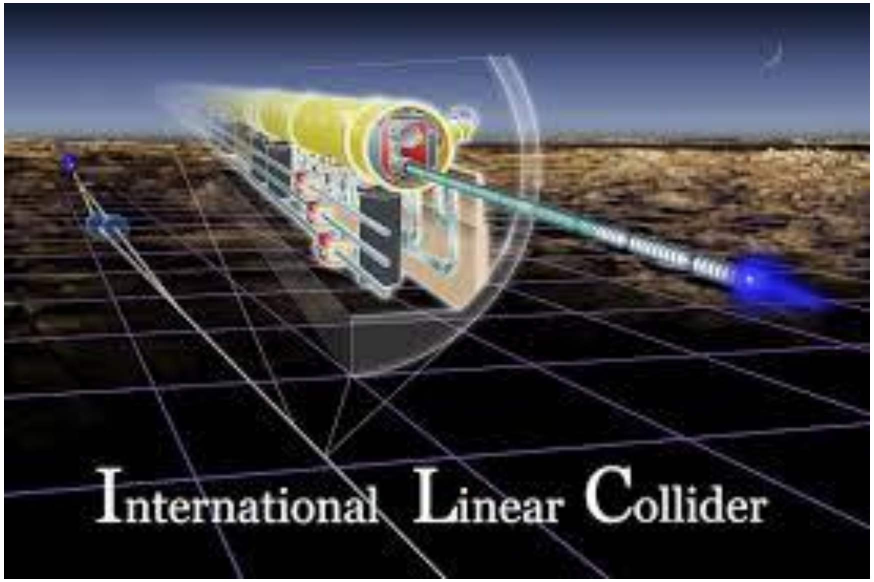


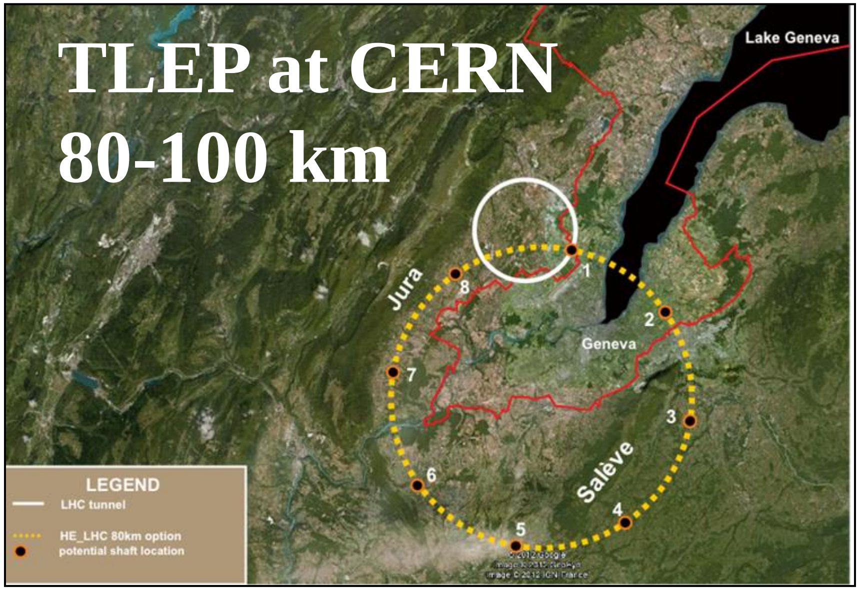
Others:

- $\mu^+\mu^-$ collider
- $\gamma\gamma$ collider



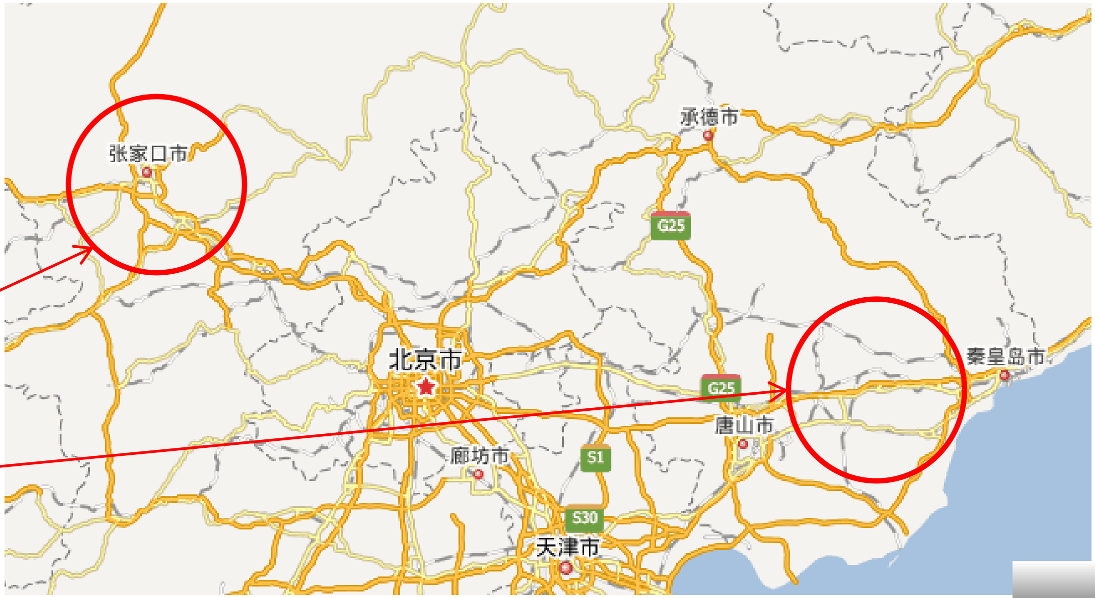
Next Generation High Energy Colliders





- Kitakami mountain in Tokoku (30km)

中国CEPC-SPPC
50-70公里，选址：
-张家口新区
-秦皇岛抚宁



World HEP Planning Status

- All three regions – Europe, North America and Asia – have been carrying out strategic HEP planning in the last 1-1/2 years since the Higgs discovery.
- **European Strategic Plan** – identified four high priority items:
  - LHC and luminosity upgrade
  - New energy frontier lepton and proton accelerators (CLIC and FCC/TLEP)
  - Support for the ILC in Japan
  - Support for neutrino experiments in the US and Japan
- **US Snowmass meeting and P5 process:**
  - P5 draft report due in March, final report in May
  - Full support for the LHC and upgrade
  - Fermilab will be a neutrino/muon lab (LBNE, NOvA, MicroBooNE, muon g-2, mu2e, etc.)
- **Japan's plan:**
  - To host the ILC – but need support from the Japanese government and non-HEP science communities
  - Also need support from foreign countries for cost sharing (~50%)
  - First stage of the ILC can be 250 GeV for Higgs factory
- **China's plan:**
  - Dig a big circular tunnel (which is cheap and almost trivial in China)
  - First use it for CEPC, a Higgs factory
  - Then use it for SppC, a world no.1 energy frontier machine

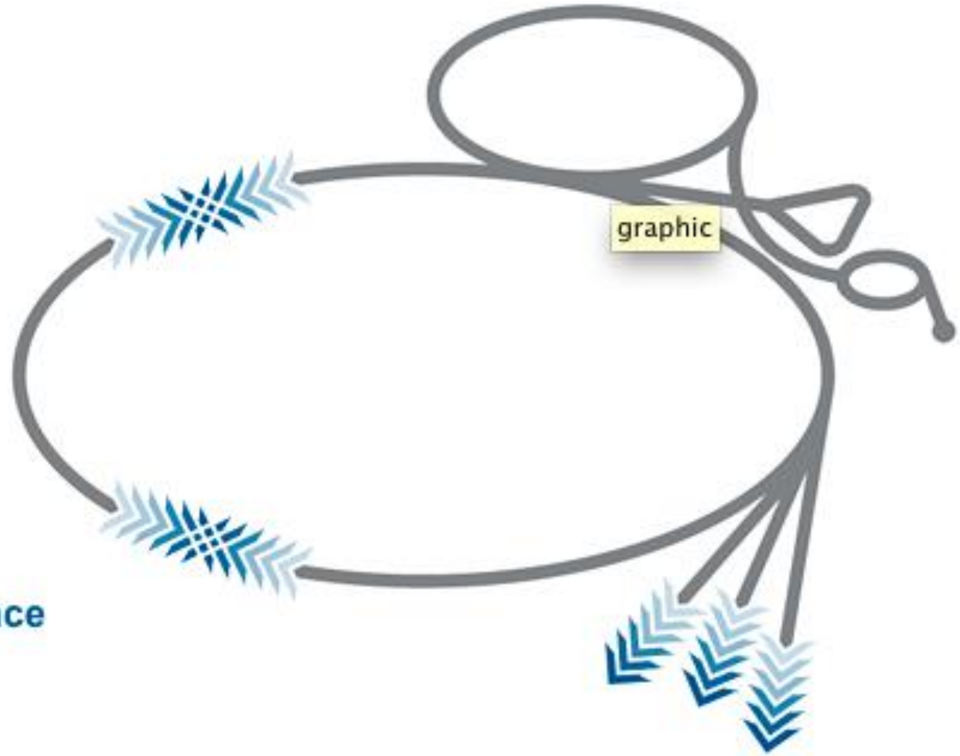
Comments

- CERN is busy with the LHC and its upgrade.
- US seems to be content with leading the intensity frontier and has no plan to build a big accelerator in the near future.
- Japan has hands full with the ILC.
- Therefore, there is a **window of opportunity** for China to become a world leader in HEP by constructing a big ring collider as a Higgs factory and upgradable to a pp collider.
- CERN's FCC is both a competitor and collaborator. If we work with the FCC team properly, it can be a big help.
- ICFA's statement on February 21, 2014:

"***ICFA supports studies of energy frontier circular colliders and encourages global coordination***."

TevatronImpact

A symposium celebrating extraordinary contributions to science, technology & society



June 11, 2012

Ramsey Auditorium

Fermilab

Batavia, Illinois, USA

1:00 p.m. Symposium

6:00 p.m. Reception

Featuring speakers honoring three decades of Tevatron history and a performance by Winifred Haun & Dancers

Watch the symposium live

Registration not required to attend

Please also join us for the 45th Fermilab Users' Meeting
Showcasing recent results from Fermilab's experimental program
June 12–13, 2012

What did the Tevatron cost?

- Tevatron accelerator
  - $120M (1983) = $277M (2012 $)
- Main Injector project
  - $290M (1994) = $450M (2012 $)
- Detectors and upgrades
  - Guess: 2 x $500M (collider detectors) + $300M (FT)
- Operations
  - Say 20 years at $100M/year = $2 billion
- Total cost = **$4 billion**

Balance sheet

- 20 year investment in Tevatron ~ $4B
- Students $4B
- Magnets and MRI $5-10B } ~ $50B total
- Computing $40B

Very rough calculation – but confirms our gut feeling that investment in fundamental science pays off

I think there is an opportunity for someone to repeat this exercise more rigorously

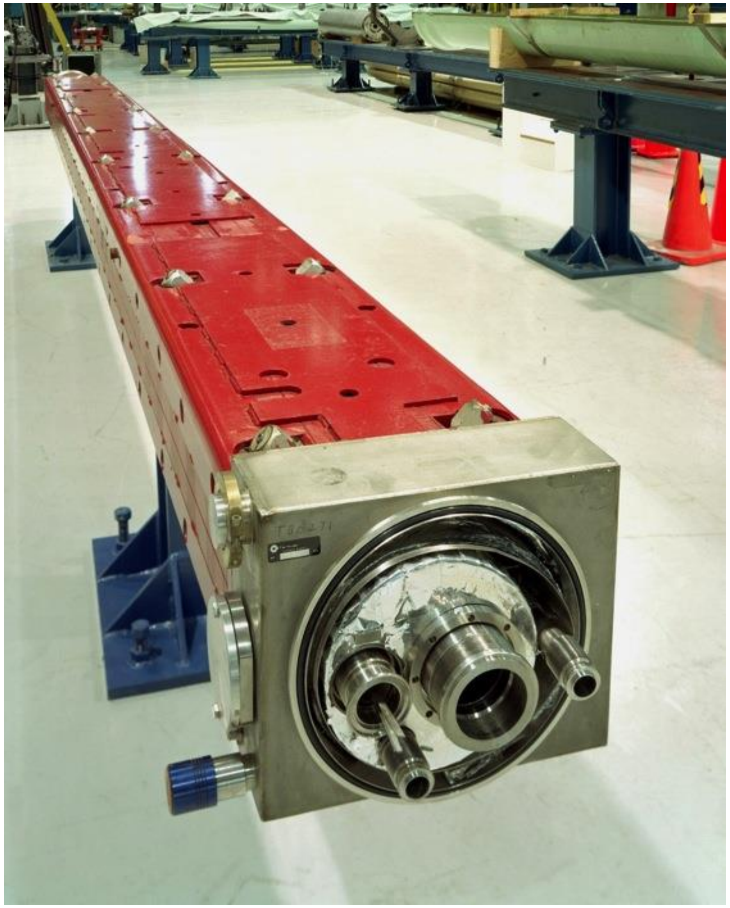
cf. STFC study of SRS Impact

http://www.stfc.ac.uk/2428.aspx

PhD Student Training

- Value of a PhD student
  - $2.2M (US Census Bureau, 2002) = $2.8M (2012 $)
- Number of students trained at the Tevatron
  - 904 (CDF + DØ)
  - 492 (Fixed Target)
  - 18 (Smaller Collider experiments)
  - 1414 total
- Financial Impact = **$3.96 billion**

Superconducting Magnets



- Tevatron was the first installation of mass-produced superconducting magnets on an industrial scale

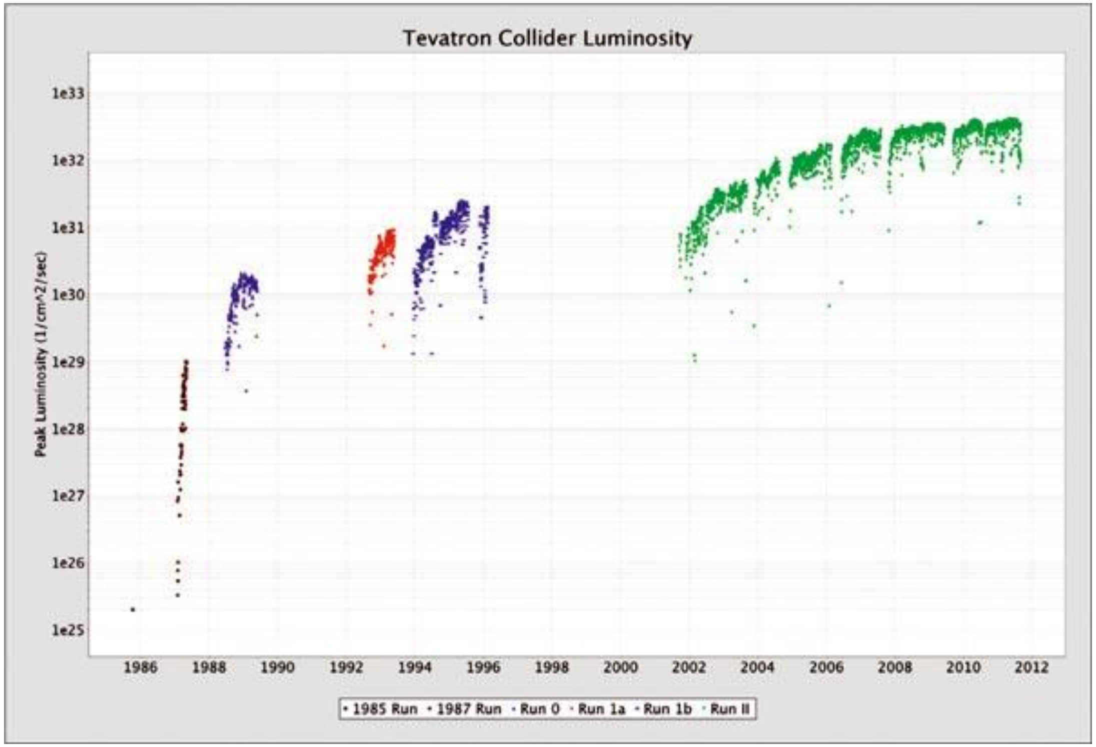
Superconducting Magnets

- National medal of Technology (1989)
- Historic engineering landmark (1993)

Superconducting Magnets

- Current value of SC Magnet Industry
  - $1.5 Billion p.a.
- Value of MRI industry (the major customer for SC magnets)
  - $5 Billion p.a.
- This industry would probably have succeeded anyway – what we can realistically claim is that the large scale investment in this technology at the Tevatron significantly *accelerated* its development
  - Guess – one to two years faster than otherwise?
- Financial Impact = **$5-10 billion**

Computing



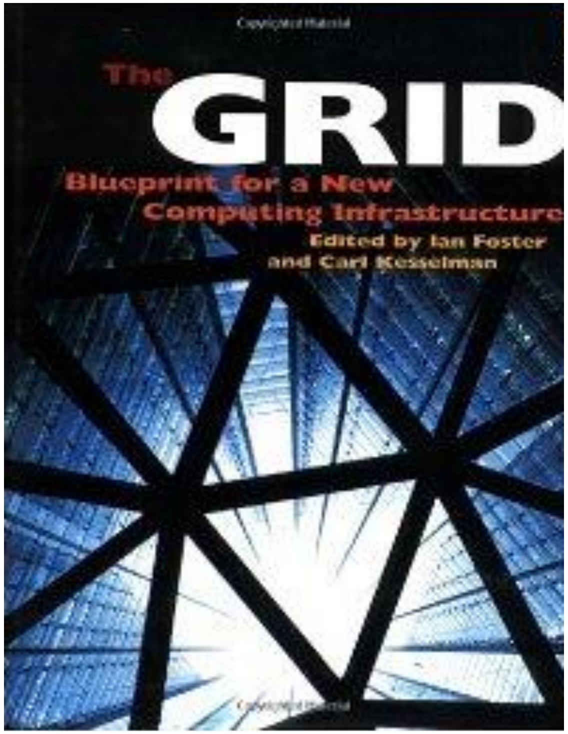
- Increases in luminosity – driven by physics – created the challenge of processing ever larger datasets

Computing – Linux PC farms

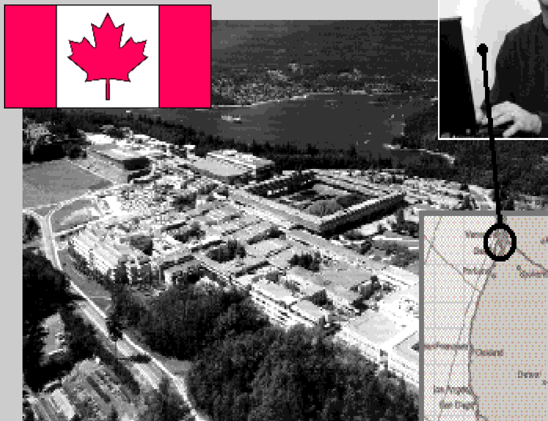
- MicroVAXes
- Unix Farms in Run I
- Computing requirements for Run II led to pioneering adoption of PC Farms running Linux for large scale data handling
  – Fermilab PC Farm Exhibit in Supercomputing Conference SC 1997
  – Linux Torvalds and Red Hat CEO Robert Young visit Fermilab; Fermi Linux released 1998
- More than 90% of the world's supercomputers now use Linux

Distributed Computing

- Concept of Computing as a Utility
  - "The Grid" (1998)
- Grid resources used for Monte Carlo generation and large scale reprocessing of Run II data
  - DØ data shipped over the internet to Canada, France, Germany, Netherlands UK, and US universities, and processed data shipped back



DZero

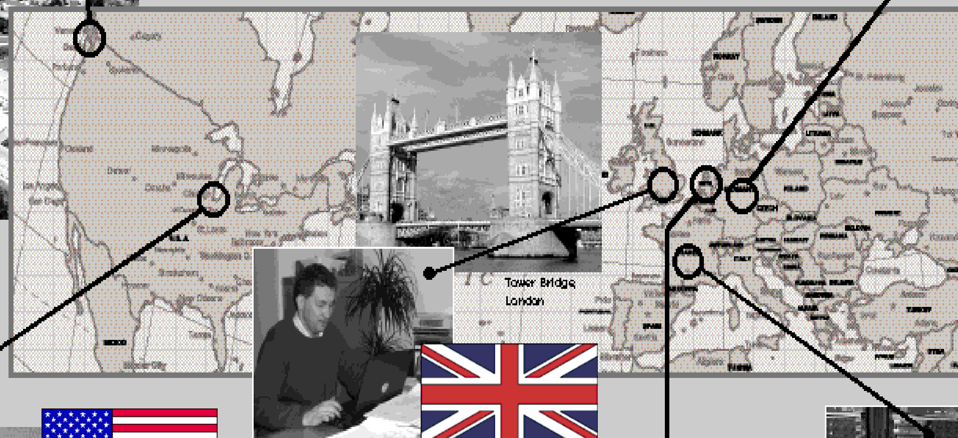


SFU campus on Burnaby Mountain, Vancouver

"You can't make the Grid work without motivation. It's one thing to have a vision, and it is another thing to stay up to three in the morning to make things work because they need to get done. DZero is a real application. We need to get the physics results out."
– Dugan O'Neil, Simon Fraser University, Canada

Wuppertal's landmark, the elevated train line

"In the past, particle physics collaborations have used remote computing sites to carry out Monte Carlo simulations. We are now one of the first experiments to process real data at remote sites. The effort has opened up many new computing resources. The evaluation of our experience will provide valuable input to the Grid development."
– Daniel Wicke, University of Wuppertal, Germany



Tower Bridge, London

Street scene in Lyon

"The machines at Imperial College, for example, are shared across the whole college, so it takes grid software to keep it all running smoothly." – Gavin Davies, Imperial College London, UK

"With the SAM software developed by the Fermilab Computing Division and DZero, a user doesn't know whether the data is stored on tape or on disk, whether it is located at Fermilab or at Karlsruhe."
– Wyatt Merritt (left), with Mike Diesburg and Amber Boehnlein, Fermilab, U.S.A.

Chicago skyline

"We've participated in large-scale Monte Carlo production in the past, but data reprocessing involves large volumes of data to be transferred in both directions on a scale that was simply unthinkable a few years ago. It will open new possibilities that we are only beginning to explore."
– Patrice Lebrun (right), with Tibor Kurca, CCIN2P3, Lyon, France

Amsterdam, famous for its canals

"The re-processing was a major milestone for DZero. For us it is also important that we have been able to show that we can really use the LHC Computing Grid for DZero processing. We saw jobs submitted from Wuppertal being executed on our CPUs, and we executed jobs in Karlsruhe, at Rutherford Appleton Laboratory and a few more places."
– Kors Bos (front row, second from left) and the Scientific Computing team at NIKHEF, Amsterdam, Netherlands

Cloud Computing

- Remotely accessible Linux farms are now a commercial service
  - Amazon EC2

Cloud Computing

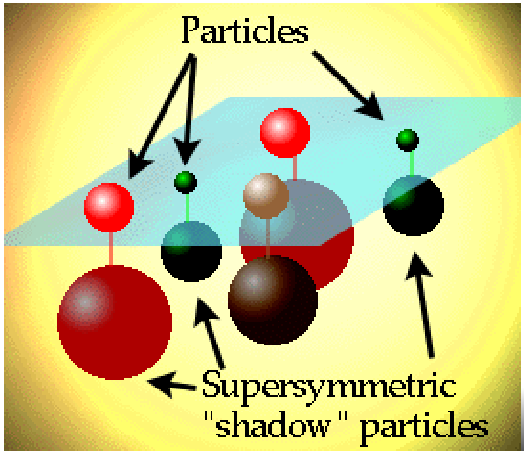
- Value of Cloud Computing Industry today
  - $150 Billion p.a. (Gartner)
- This industry would definitely have succeeded anyway – but let's assume that the stimulus given by the Tevatron experiments, work with Red Hat etc. gave just a *3 month* speed-up to its development
- Financial Impact = **$40 billion**

Looking Forward

- ***Simplest guess:***
  - Have spin-0 quarks and spin-0 leptons, i.e., scalar quarks/leptons
- ***How do they behave ?***
  - Similar to ordinary quarks and leptons, they are likely to decay into each other via weak interaction
  - Unlike ordinary quarks and leptons, they are quite heavy
- ***How many spin-0 quarks and leptons*** may be expected ?
  - Simple guess is as many as ordinary quarks and leptons
  - If this is true, we may envisage some sort of symmetry between fermions (ordinary quarks and leptons) & bosons (scalar quarks and scalar leptons)

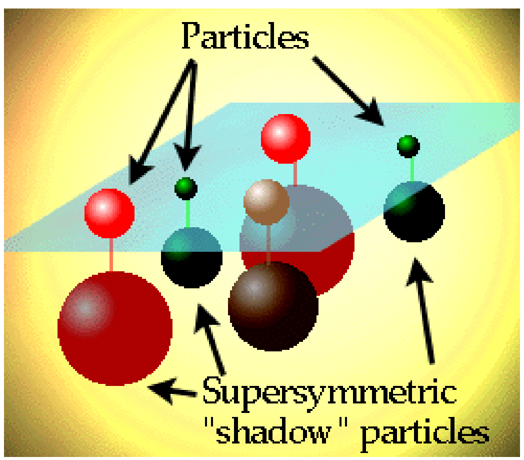
➢ ***Is this supersymmetry ?***

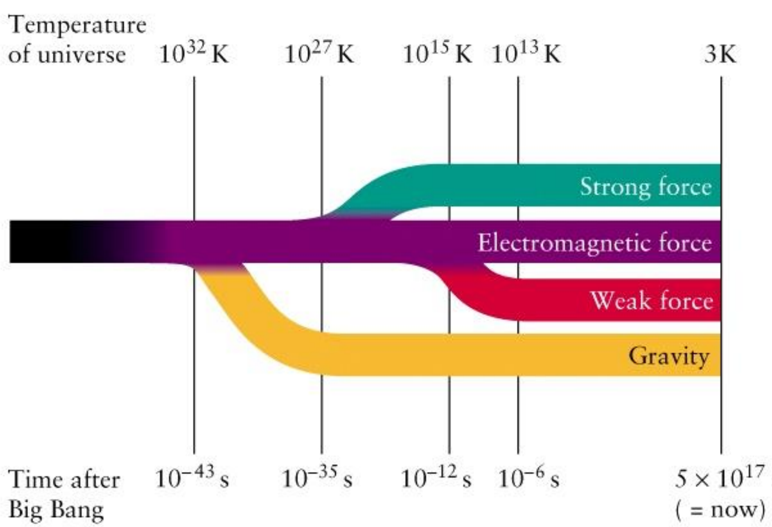
Maybe, or maybe not !

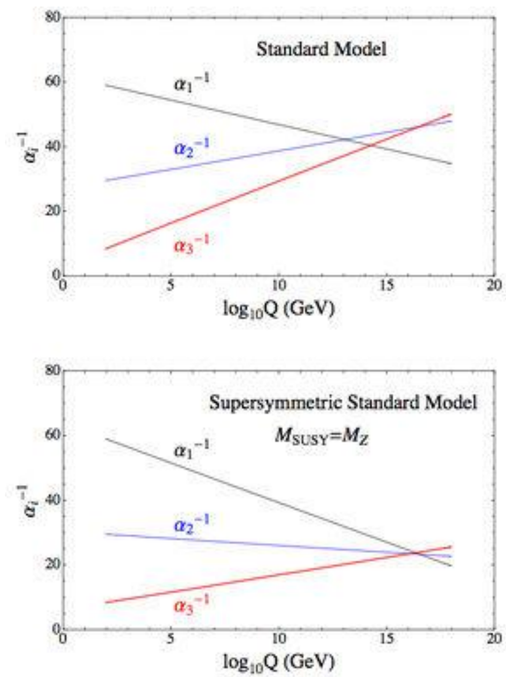


寻找超对称理论预言的粒子

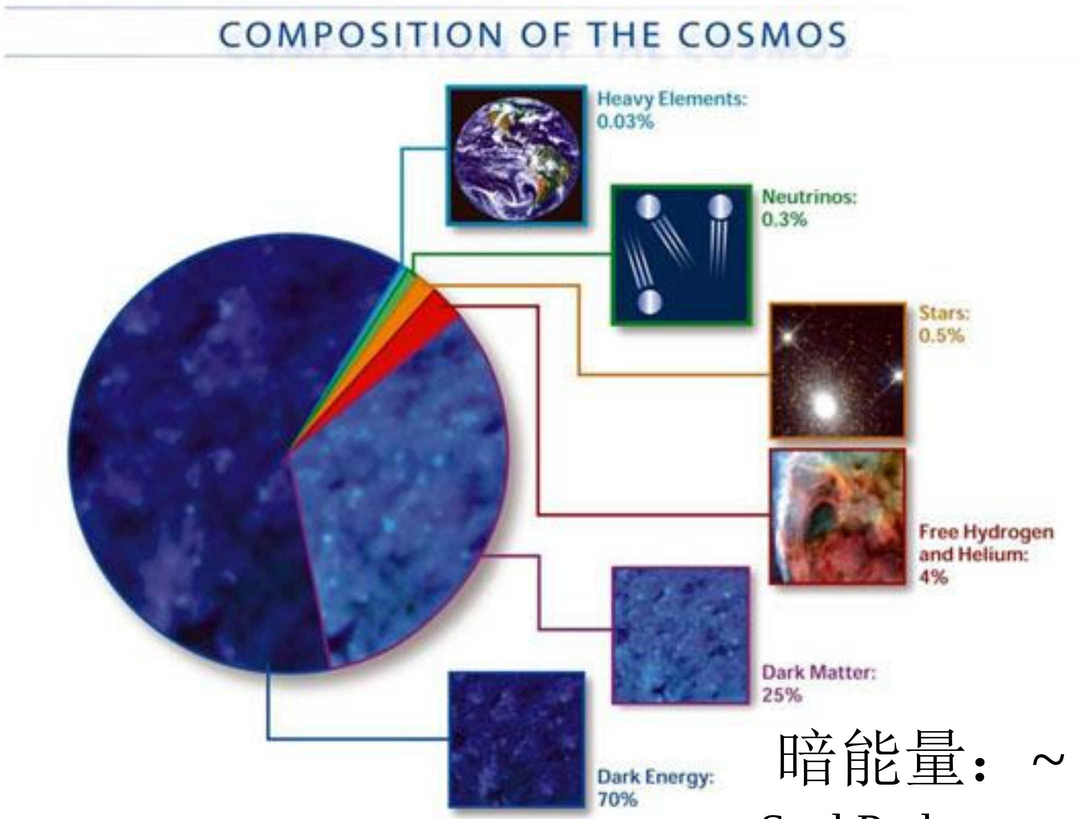
超对称理论认为费米子与玻色子之间具有某种对称性，标准模型粒子都有相对应的自旋相差1/2的超对称粒子。如果超对称粒子的质量在100GeV-TeV 能区，有可能在LHC产生并发现超对称粒子。超对称理论有助于解决强，弱和电磁相互作用力的大统一。







用高能对撞机产生和寻找暗物质



可见物质：
~ 5%

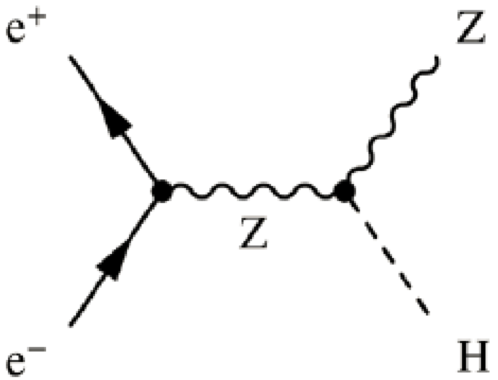
暗物质：~ 25%

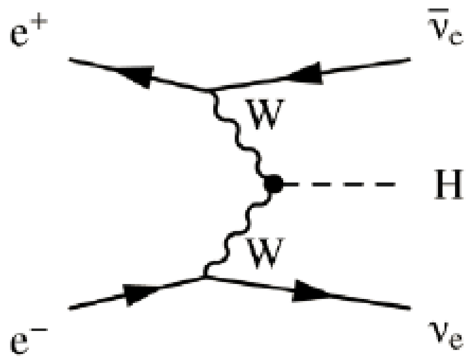
暗能量：~ 70% (→宇宙加速膨胀)

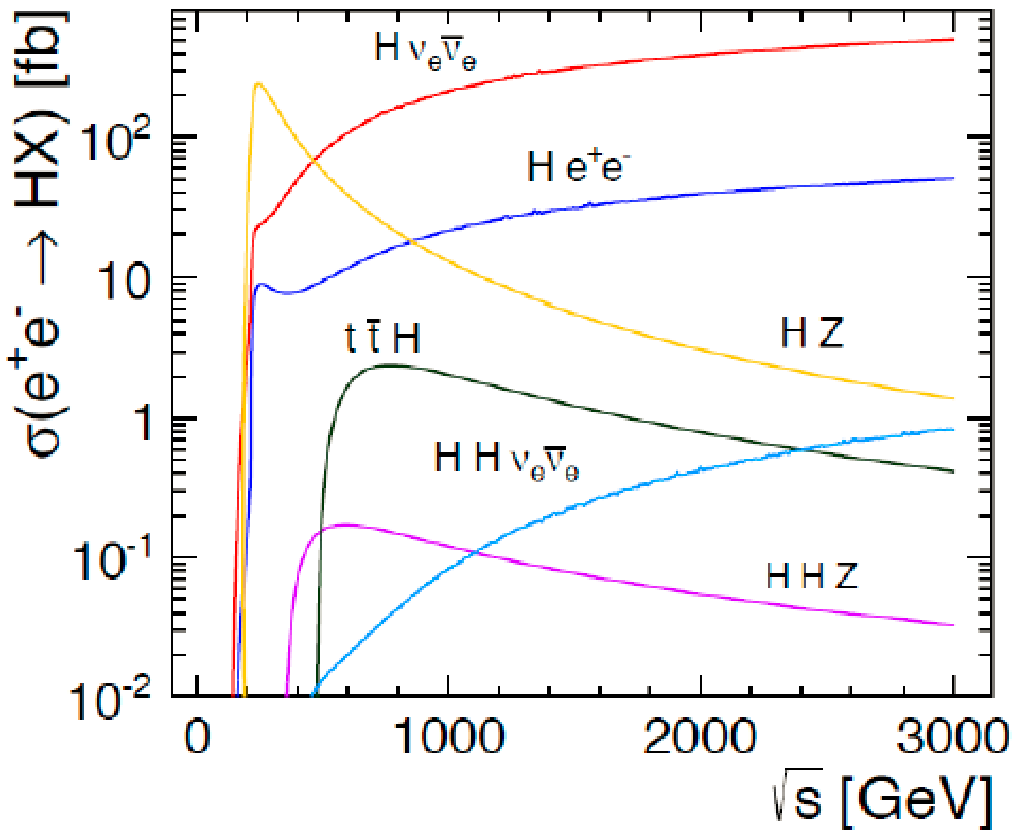
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess
Nobel Prize in physics, 2011

➔ LHC有可能产生质量小于1 TeV 的超对称理论预言的粒子，这些粒子会衰变到最轻的超对称粒子(LSP)，LSP是暗物质的候选粒子。

Higgs Production at Lepton Colliders





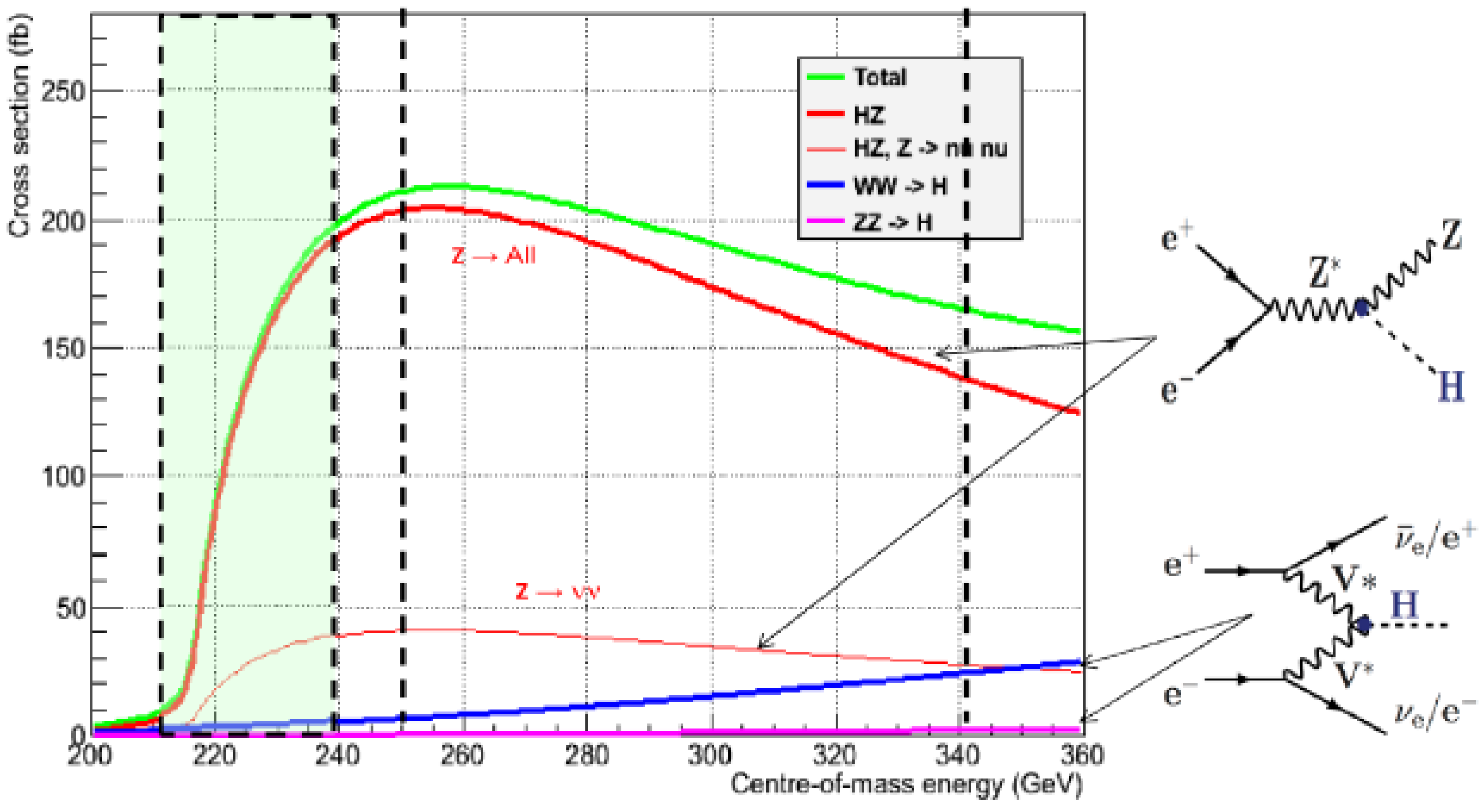


Cross sections for $m_H = 125$ GeV

$\sqrt{s}$	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$ (fb)	300	129	500	13	6	1
$\sigma(e^+e^-) \to \nu\nu H)$ (fb)	18	30	75	210	309	484

With polarized beams $\mathcal{P}(e^-, e^+) = (-0.8, 0.3)$

Higgs Production at e^+e^- Collider



σ(HZ, 240 GeV) ~ 200fb with non-polarized beam

L ~ 10^{34} $cm^{-2}s^{-1}$ ~ $100fb^{-1}/y$; Nominal luminosity $500fb^{-1}$ ~ 10^5 Higgs/IP

Benchmark: 100 k Higgs, but can be (largely) increased

Beam polarization can enhance the Higgs productivity by ~ 50% at ILC, and reduce the SM Background at the same time. However, it's not crucial for Higgs measurement 4

Why e^+e^- Higgs Factory

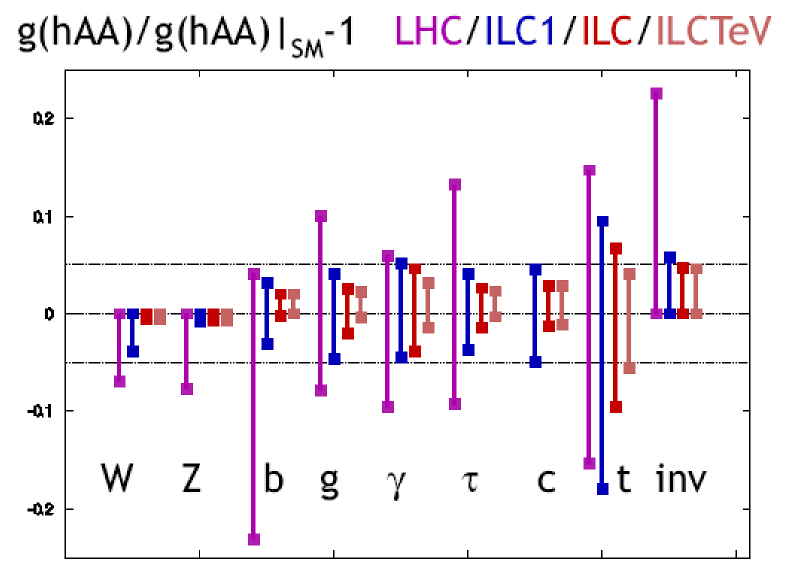


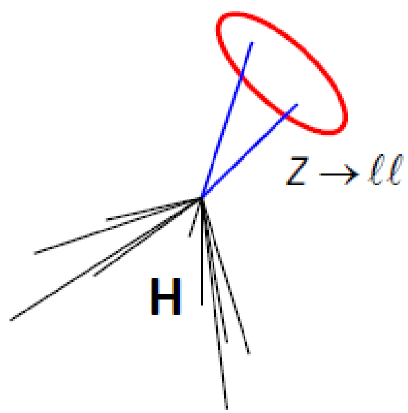
Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

- ❑ Precise verify the SM- searching for possible new physics, Higgs couplings must be measured to better than a few % to reveal TeV scale new physics.
- ❑ LHC: high productivity, huge backgrounds and systematics, ultimate precision in Higgs coupling limited to 10-20%.
- ❑ e^+e^- machine: low background – trigger-less mode, well known ISR, allow to measure σ and BR separately via Z recoil to tag Higgs events.

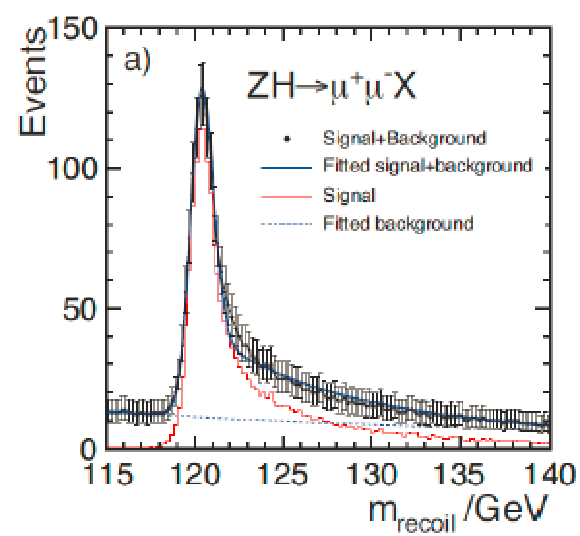
$e^+e^- \rightarrow ZH$ with

$Z \rightarrow \ell^+\ell^-$

$H \rightarrow X$



$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_{\ell\ell}\right)^2 - \left|\vec{p}_{\ell\ell}\right|^2$$



Observables and Expected Accuracy

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
$\Delta g_{HWW} / g_{HWW}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

Typical Sensitivities to test BSM Physics

How large are potential deviations from BSM physics? How well do we need to measure them to be sensitive?

To be sensitive to a deviation Δ, the measurement precision needs to be much better than Δ, at least Δ/3 and preferably Δ/5!

Since the couplings of the 125 GeV Higgs boson are found to be very close to SM ⇒ deviations from BSM physics must be small.

Typical effect on coupling from heavy state M or new physics at scale M:

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 5\% \text{ @ } M \sim 1 \text{ TeV}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, ...)

Typical sizes of coupling modification from some selected BSM models

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

交大参与的研究工作

- **欧洲核子中心LHC/ATLAS国际合作实验：**
  - 研究Higgs的属性
  - 寻找 SUSY、暗物质粒子
  - 精确检验标准模型及探索新物理现象
- **中国CEPC-SPPC预研**
  - 粒子探测器的模拟，材料选型、尺寸和性能的优化等
  - Higgs信号产生、模拟、重建和分析
  - 电磁量能器和强子量能器(RPC)的预研等
- **有广泛的国内外合作研究、联合培养机会**

感兴趣的同学请联系我！
粒子所411B, 13764927109
haijun.yang@sjtu.edu.cn

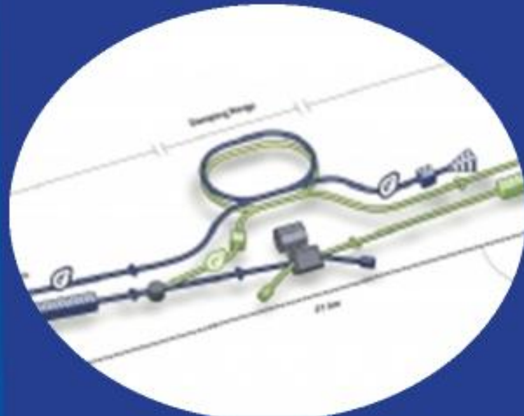
CERN, Geneva, Switzerland

J. Ellis
SUSY2013

Let us be patient …

- If you have a problem, postulate a new particle:
  - QM and Special Relativity: Antimatter
  - Nuclear spectra: Neutron
  - Continuous spectrum in β decay: Neutrino
  - Nucleon-nucleon interactions: Pion
  - Absence of lepton number violation: Second neutrino
  - Flavour SU(3): Ω^-
  - Flavour SU(3): Quarks
  - FCNC: Charm
  - CP violation: Third generation
  - Strong dynamics: Gluons
  - Weak interactions: $W^\pm$, Z^0
  - Renormalizability: H (48 years)
  - **Naturalness: Supersymmetry? (40 years)**

Linear Colliders



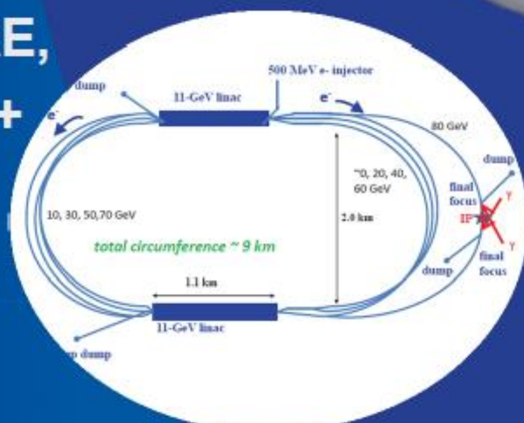
- ILC
- CLIC
- SLC-type
- Adv. Concepts

Circular e^+e^- Colliders

- LEP3
- TLEP
- Super-Tristan
- FNAL Site-filler
- IHEP, +
- …

Higgs Factories

- SAPPHIRE,
- CLICHÉ, +
- …



γ-γ Colliders

Muon Colliders

下一代高能对撞机

- CERN/LEP – W, Z factory (1989 – 2000)
- Fermilab/Tevatron – discovery of top quark (1985 - 2011)
- CERN/LHC – discovery of Higgs, top factory (2009-2030)
- SLAC/BaBar – b factory (1999-2008, CP violation)
- KEK/Belle – b quark factory (1999-2010, CP violation)
- IHEP/BEPCII – τ-c factory (1988-)
- Fermilab/ProjectX – neutrino factory
- KEK/J-PARC neutrino factory(2009)

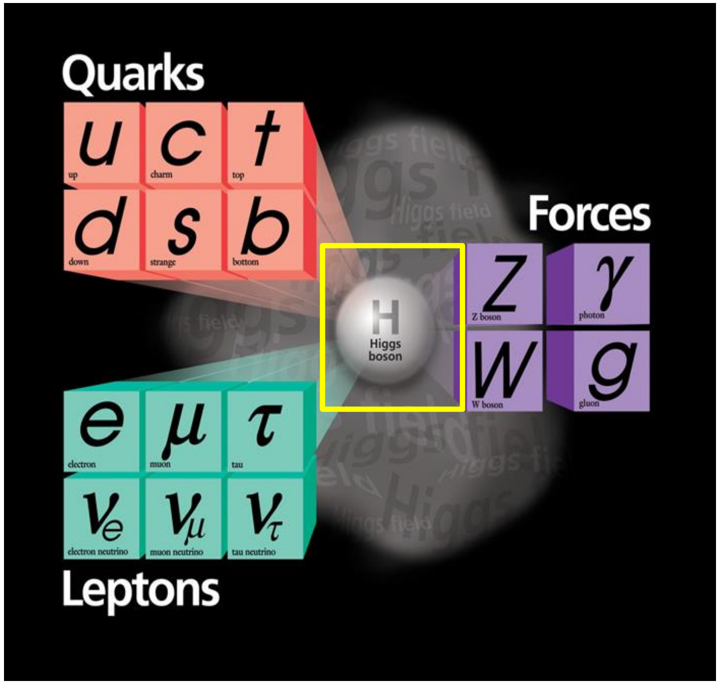
Discovery of Higgs at LHC in 2012

Higgs factory

➔ ILC (Japan, 30km)

➔ TLEP (Europe, 80-100km)

➔ CEPC-SPPC (China, 50-70km)



《创新2050：科学技术与中国的未来》（2009）
（中国科学院战略研究系列报告）

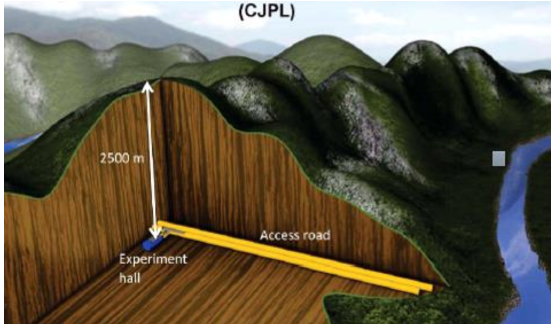
- 可能出现革命性突破的4个基本科学问题：

- 暗物质、暗能量被列为第一

报告指出："揭开暗物质、暗能量之谜，将是人类认识宇宙的又一次重大飞跃，可能导致一场新的物理学革命。

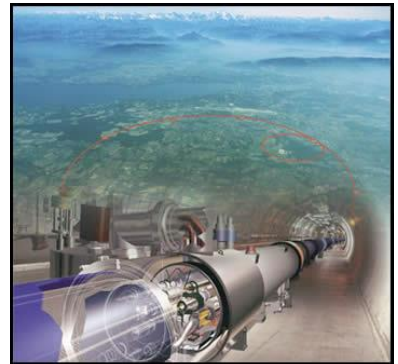
- 交大物理与天文系把暗物质和暗能量的研究作为重点发展方向之一。

直接探测



季向东， Giboni
倪凯旋， 刘江来
符长波， 刘 湘
James Loach

大型加速器



杨海军
李 亮

天文观测

徐海光， 王 斌
张 骏， 刘当波
刘成则， 武向平

1. 主导大型暗物质探测实验PandaX

2. 参加LHC/ATLAS，在加速器上寻找暗物质产生

3. 参加21CMA/南极天文台，研究暗物质太空分布

交大暗物质和暗能量研究群体

何小刚
顾佩洪

4. 理论研究：暗物质和暗能量的起源

2012年评为教育部创新群体

LHC on BBC

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3 July 2007
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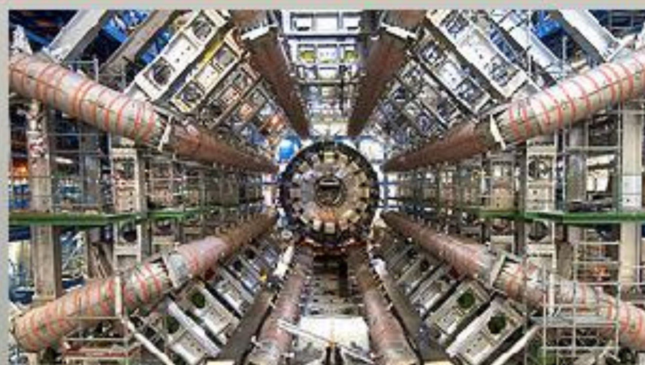
The Six Billion Dollar Experiment



Tuesday 1 May 2007, 9pm, BBC Two

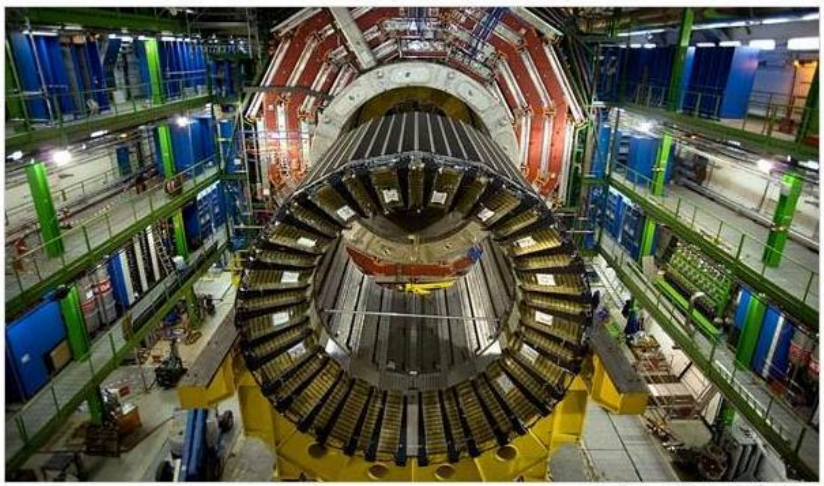
In the coming months the most complex scientific instrument ever built will be switched on. The **Large Hadron Collider** promises to recreate the conditions right after the Big Bang. By revisiting the beginning of time, scientists hope to unravel some of the deepest secrets of our Universe.

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

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

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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5. Winding Through 'Big Dreams' Are the Threads of Our Lives

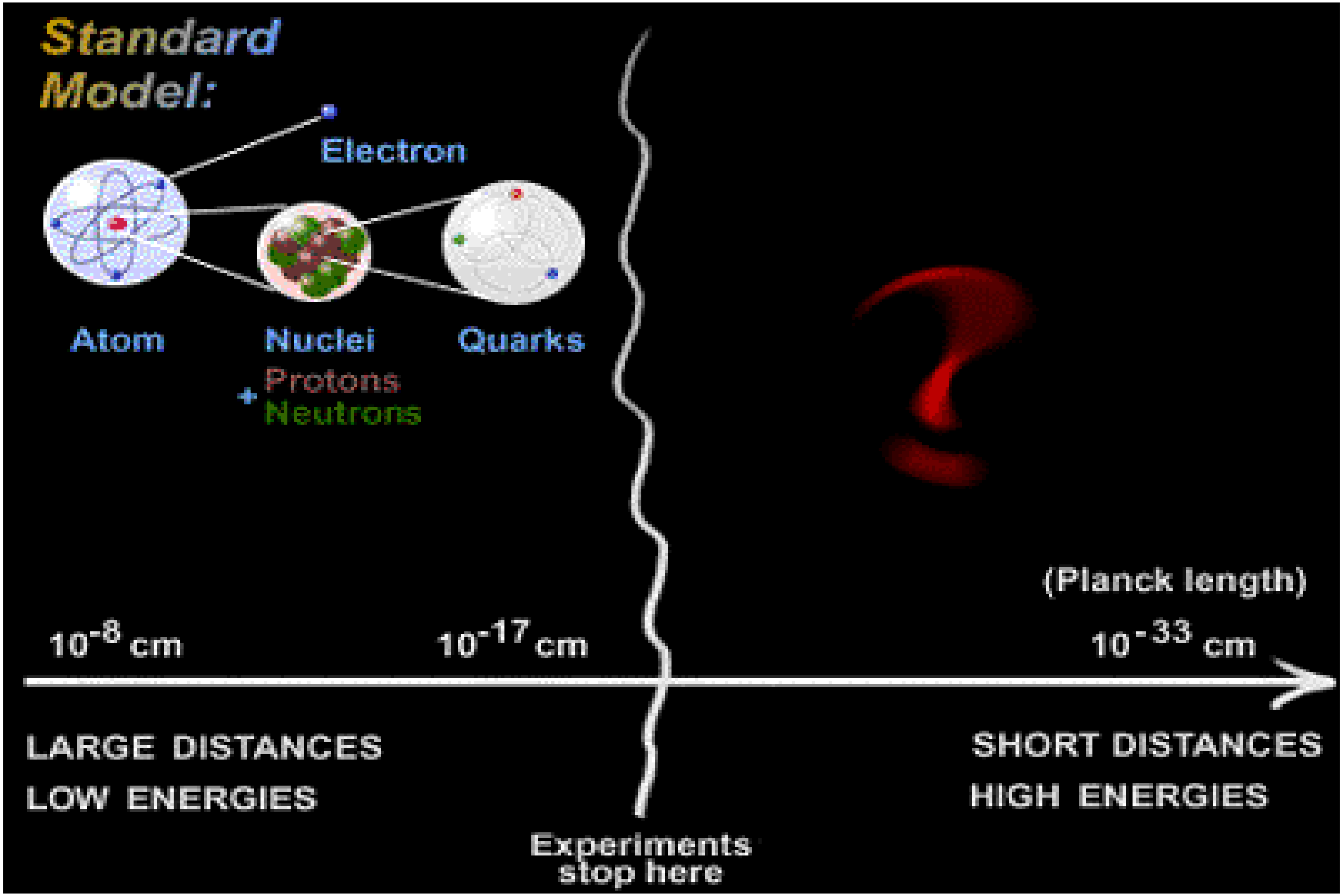
ATLAS and CMS Collaborations

- **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

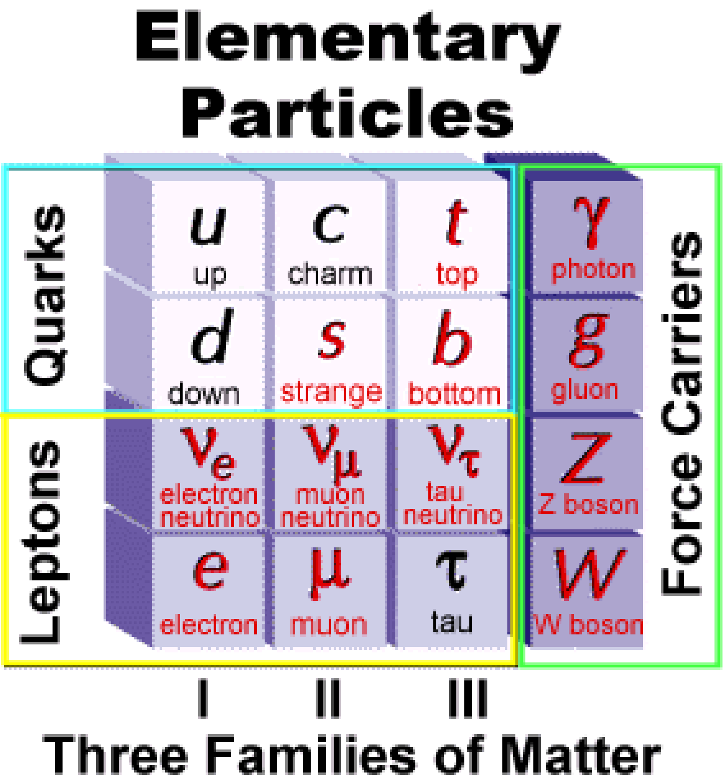
20+ years of worldwide collaborative efforts

探索物质最深层次的结构



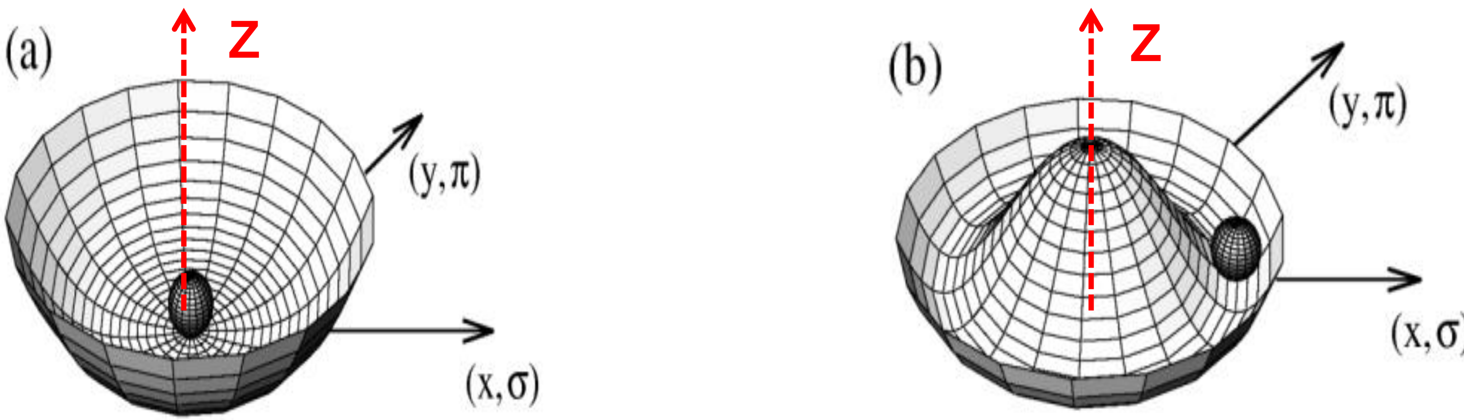
基本粒子百年重大发现

- 1897 – e discovery, J.J. Thompson (英国)
- 1919 – proton, Ernest Rutherford (英国)
- 1930 – neutron, James Chadwick (英国)
- 1936 – μ, Carl D. Anderson (Caltech, 美国)
- 1956 – ν_e discovery (Homestake, 美国)
- 1962 – ν_μ discovery (BNL, 美国)
- 1968 – u and d quark (quark model, 美国)
- 1968 – strange quark(Kaon, 美国)
- 1974 – c quark (J/ψ, BNL, SLAC, 美国)
- 1977 – tau discovery (SLAC, 美国)
- 1977 – b quark (Upsilon, Fermilab, 美国)
- 1979 – gluon (DESY, 德国)
- 1983 – W and Z (CERN, 欧洲)
- 1988 – atmospheric neutrino oscillation (日本)
- 1995 – top quark (Fermilab, 美国)
- 2000 – ν_τ discovery (Fermilab, 美国)
- 2001 – solar neutrino oscillation (SNO, 加拿大)
- 2012 – reactor neutrino oscillation (Dayabay, 中国)
- 2012 – Higgs boson (CERN/LHC, 欧洲)



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.

[4] F. Englert, R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. 13 (1964) 321.
[5] P.W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. 12 (1964) 132.
[6] P.W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. 13 (1964) 508.
[7] G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Global conservation laws and massless particles, Phys. Rev. Lett. 13 (1964) 585.

Higgs Properties Measurement with Full Datasets

- **$H \to \gamma\gamma$, ZZ*, WW* analyses update using full datasets collected in 2011-2012**
  - **4.6 fb^{-1} @ 7TeV**
  - **20.7 fb^{-1} @ 8TeV**

- Higgs mass from $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$
- Signal strengths ($\mu = \sigma/\sigma_{SM}$)
- Sensitivity to VBF
- Higgs Couplings
- Higgs Spin and parity

New ATLAS Higgs Papers

arXiv:1307.1427, PLB726(2013)88-119 (Mass, Couplings)
arXiv:1307.1432, PLB726(2013)120-144 (Spin-parity)

New ATLAS Higgs Pub Notes

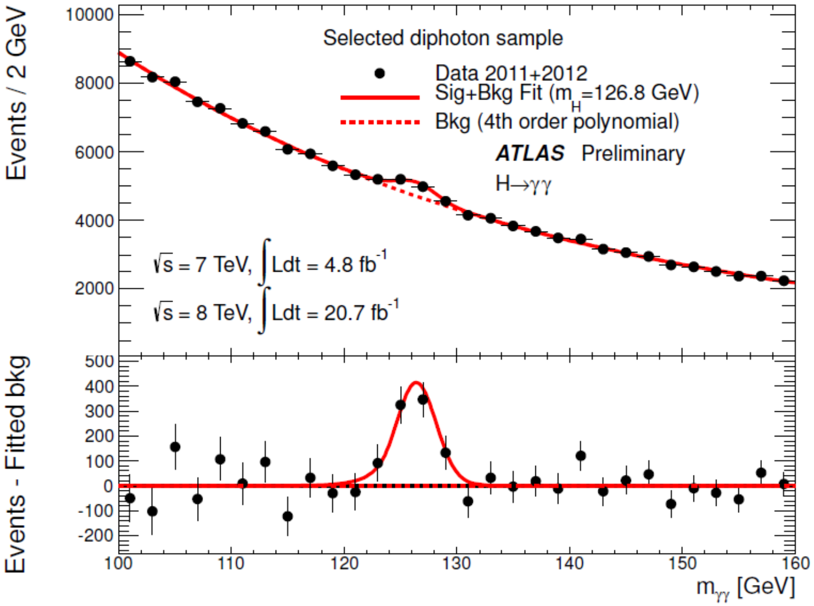
Property measurement:

- ATLAS-CONF-2013-012 ($\gamma\gamma$)
- ATLAS-CONF-2013-013 (ZZ*)
- ATLAS-CONF-2013-031 (WW*)
- ATLAS-CONF-2013-040 (Spin)
- ATLAS-CONF-2013-079 ($VH \to bb$)
- ATLAS-CONF-2012-160 ($H \to \tau\tau$)
- ATLAS-CONF-2013-075 (WW*)
- ATLAS-CONF-2013-029 ($\gamma\gamma$)
- ATLAS-CONF-2013-108 ($\tau\tau$)

Searches:

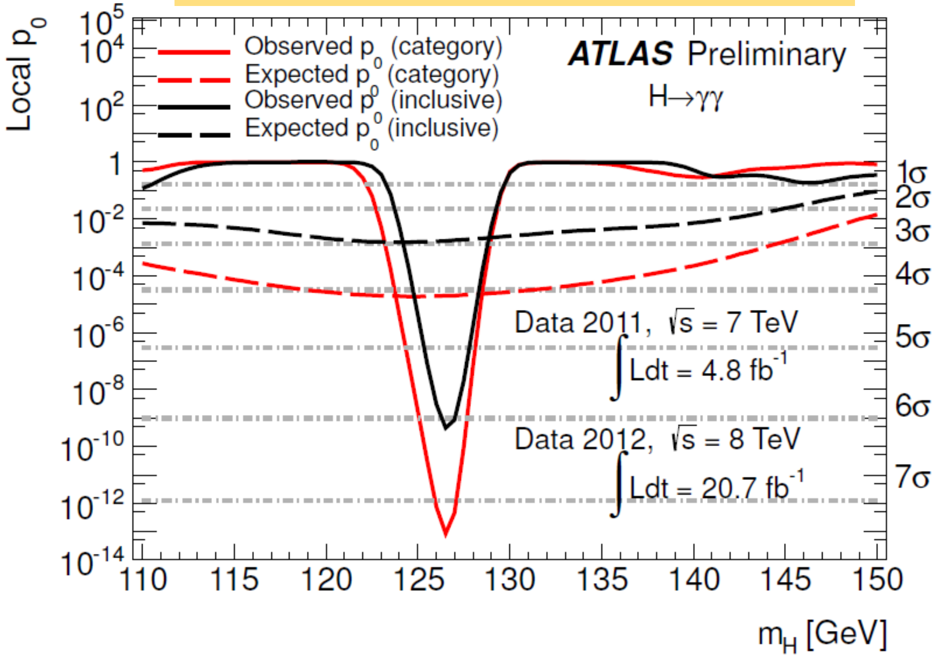
- ATLAS-CONF-2013-009($Z\gamma$)
- ATLAS-CONF-2013-010($\mu\mu$)
- ATLAS-CONF-2013-067(HMH→WW)
- ATLAS-CONF-2013-072 (diff σ $H \to \gamma\gamma$)
- ATLAS-CONF-2013-075(VH→WW)
- ATLAS-CONF-2013-080(tt +$H \to \gamma\gamma$)
- ATLAS-CONF-2013-081($t \to cH$)

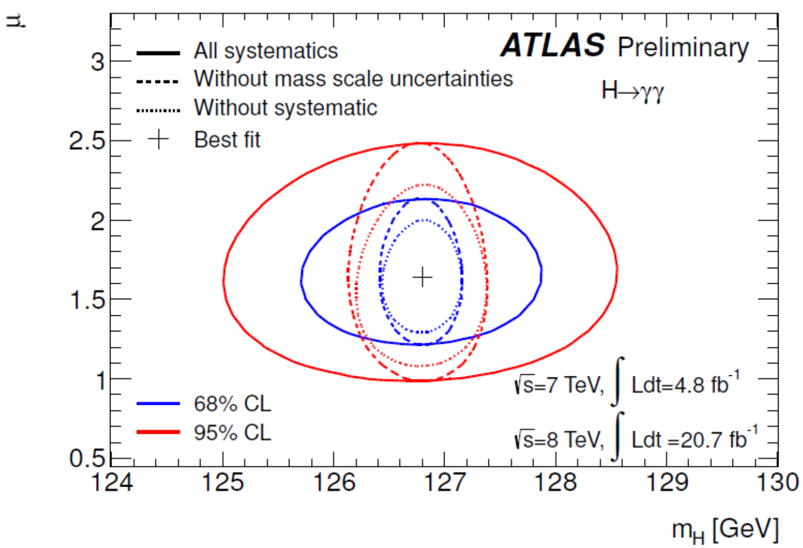
Update of H → γγ



Higgs Significance

- **Expected 4.1σ**
- **Observed 7.4σ**



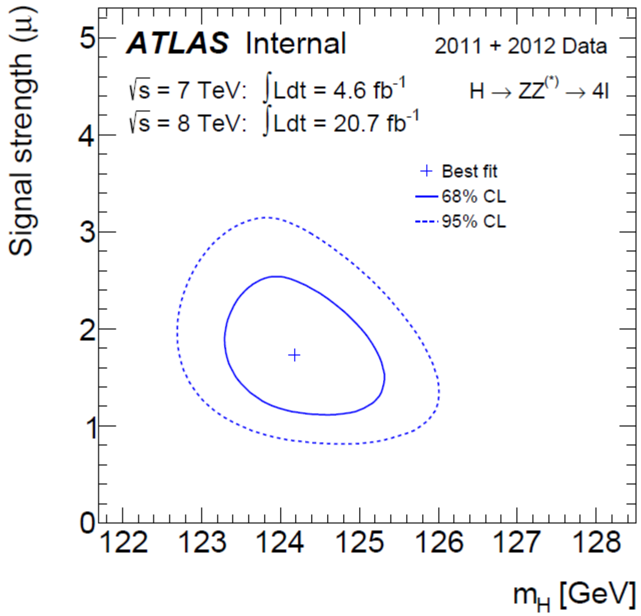


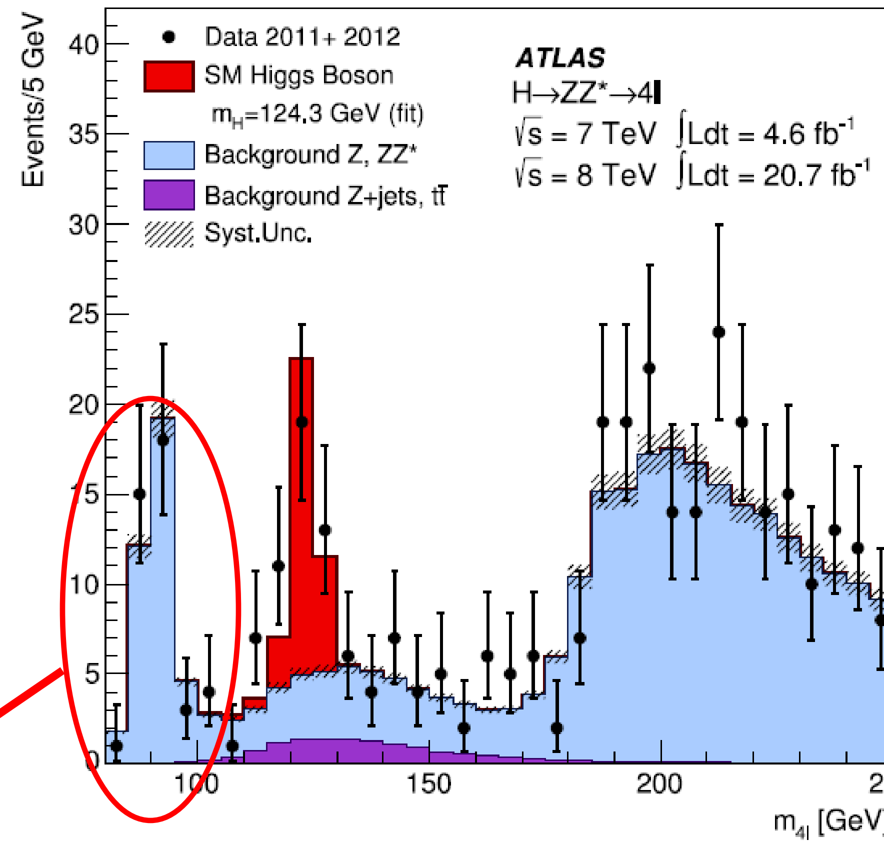
Best fitted mass:
M_H = 126.8 ±0.2(stat) ± 0.7(syst) GeV

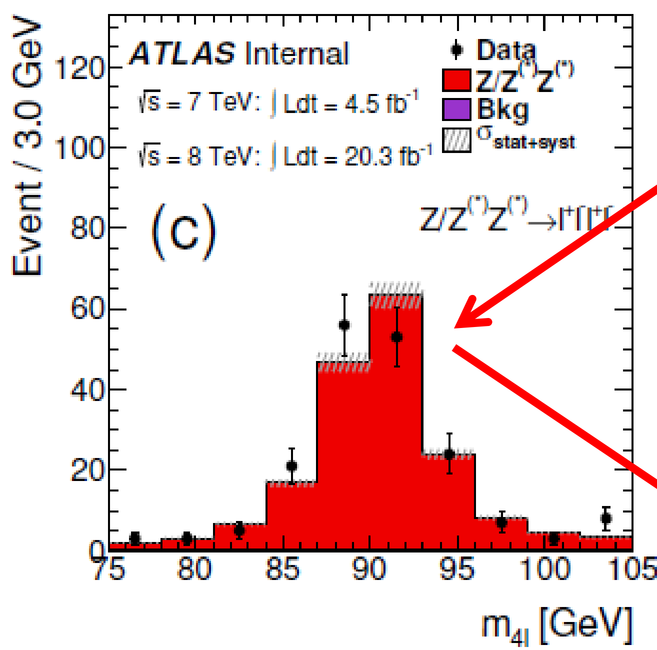
Best fitted Signal strength

$$1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst})$$

Update of H→ZZ*→4l







Best fit mass:
M_H = 124.3 ±0.6(stat) ± 0.3(syst) GeV

Best fit signal strength:
μ = 1.7 + 0.5 (– 0.4) @ 124.3 GeV
μ = 1.5 ± 0.4 @ 125.5 GeV

$$\Gamma_{Z\to 4\ell}/\Gamma_Z = (4.43 \pm 0.34\ (\mathrm{stat}) \pm 0.16\ (\mathrm{syst})) \times 10^{-6}$$

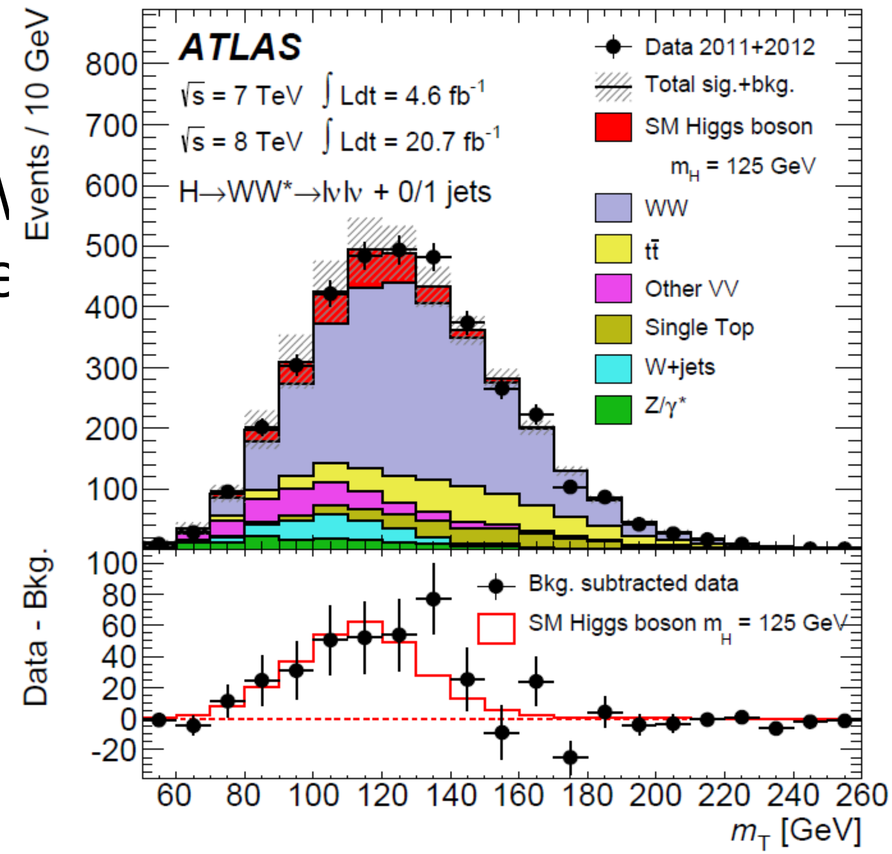
Update of H → WW* → ℓνℓν

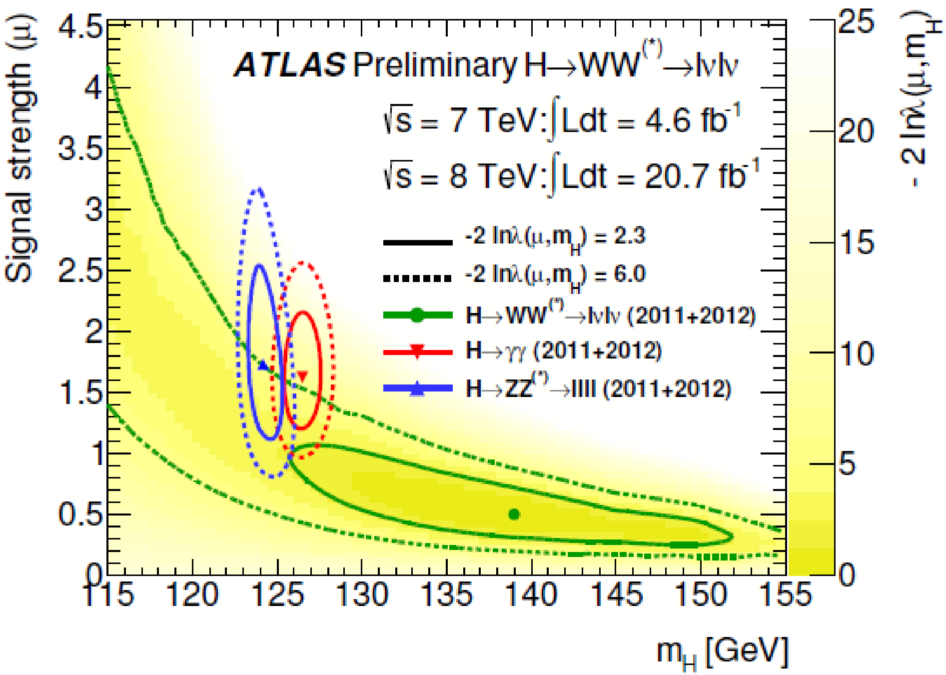
- Final discriminant

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\rm miss}\right)^2 + |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\rm miss}|^2}$$

Due to spin correlation between W
The signal has the following prope

Large $P_T(ll)$, small m_{ll}, small $\Delta\phi_{ll}$



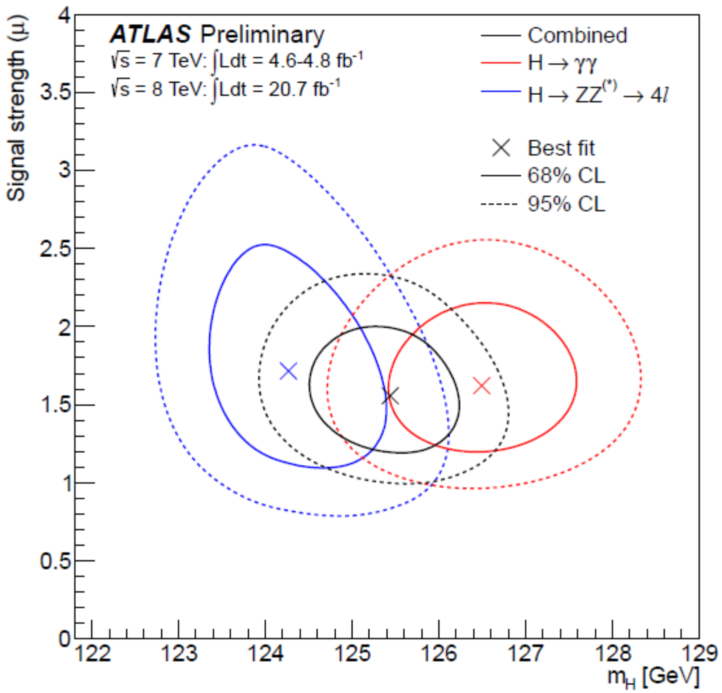


ATLAS best-fit signal strength:

ICHEP($4.6+5.8\ fb^{-1}$): μ = **1.3 ± 0.5**

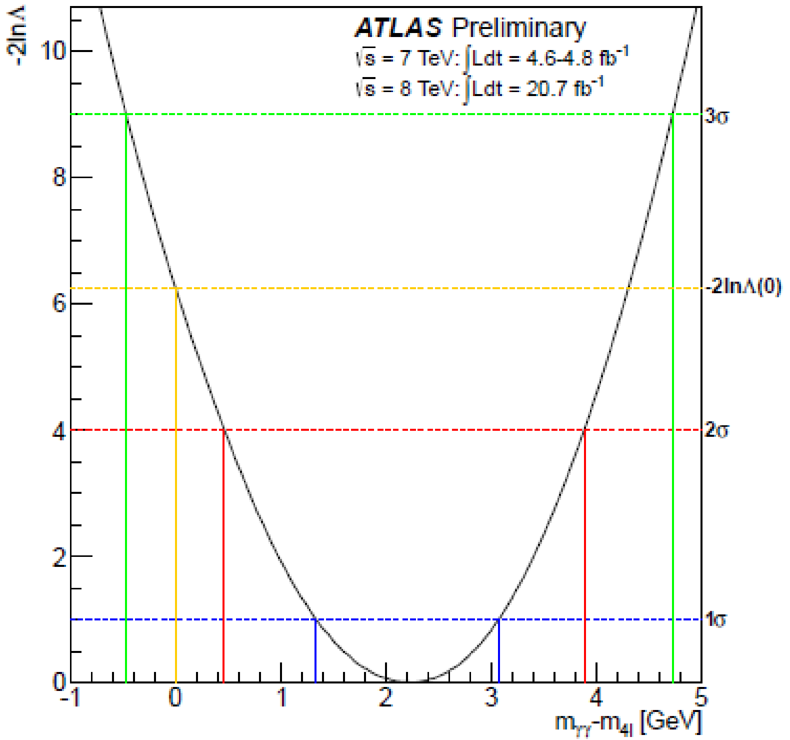
2012 ($4.6+20.7\ fb^{-1}$): μ = **1.0 ± 0.3**

Higgs Mass Measurements



$$\Lambda(\Delta m_H) = \frac{L(\Delta m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(\Delta m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(\Delta m_H)\,,\,\hat{\hat{m}}_H(\Delta m_H)\,,\,\hat{\hat{\theta}}(\Delta m_H))}{L(\Delta\hat{m}_H,\hat{\mu}_{\gamma\gamma},\hat{\mu}_{4\ell},\hat{m}_H,\hat{\theta})}$$

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$



Best fit mass for H → γγ and 4l

M_H (γγ)= 126.6 ± 0.2(stat) ± 0.7(syst) GeV

M_H (4l)= 124.3 ± 0.6(stat) ± 0.3(syst) GeV

Best fit mass for combination:

ATLAS: 125.5 ± 0.2(stat) ± 0.6(syst) GeV

CMS:125.7 ± 0.3(stat) ± 0.3(syst) GeV

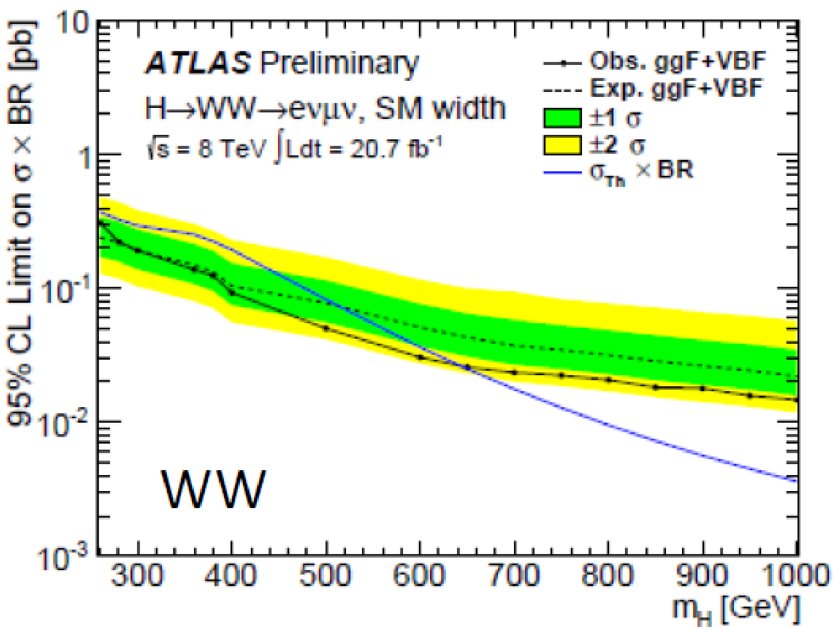
Mass compatibility: 1.2%, 2.5σ

Search for High Mass H → WW, ZZ

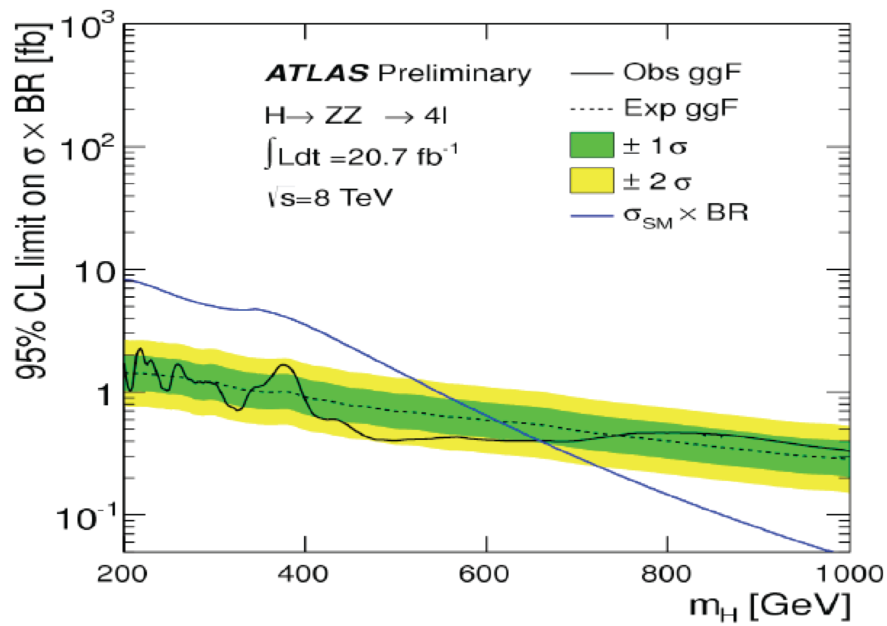
- **Extend the Higgs search to high mass assume SM-like width and decay.**

ATLAS-CONF-2013-067

WW → lνlν*



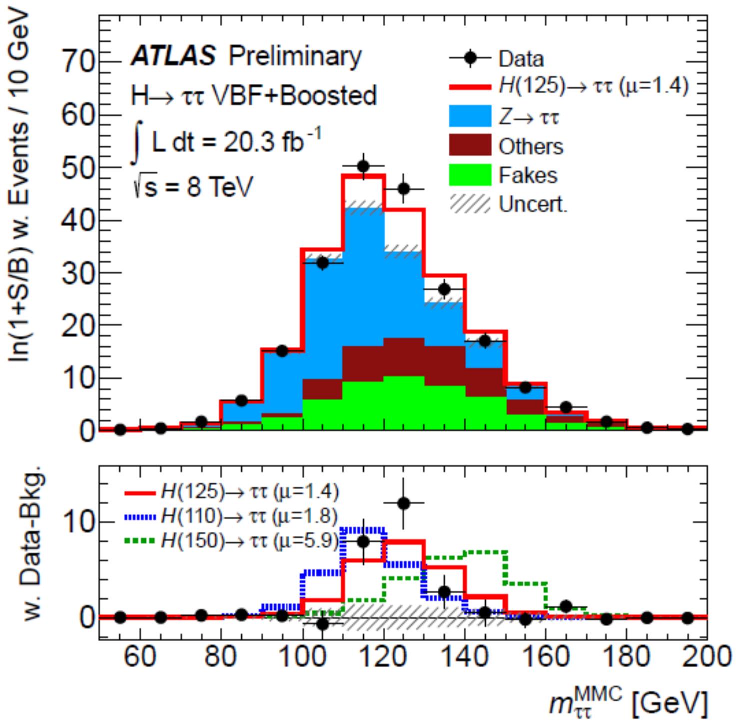
ZZ → 4l*

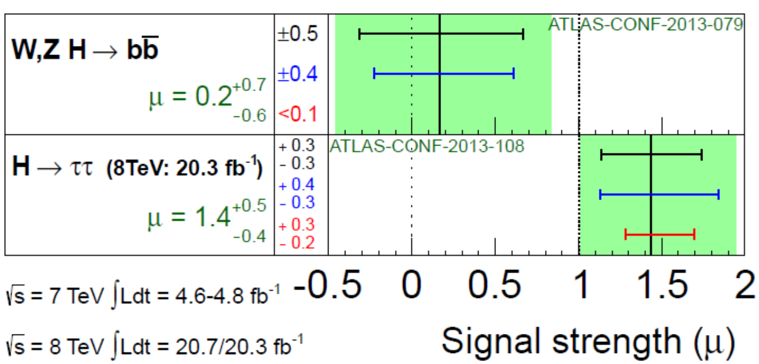


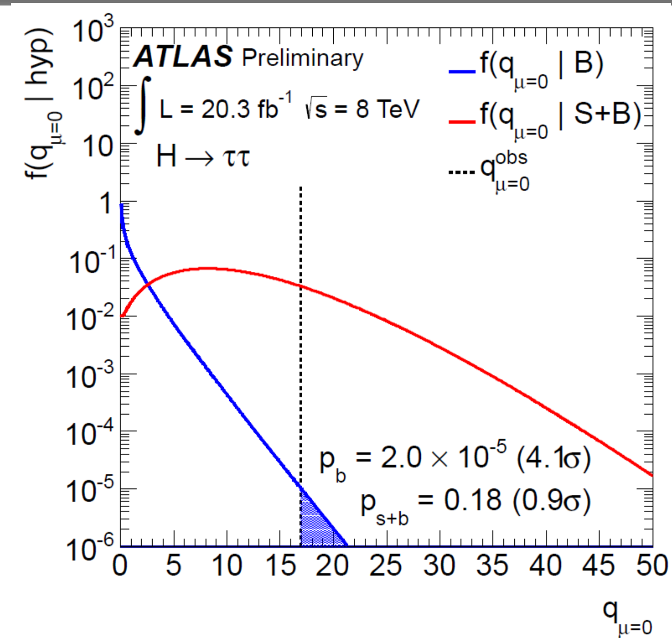
95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

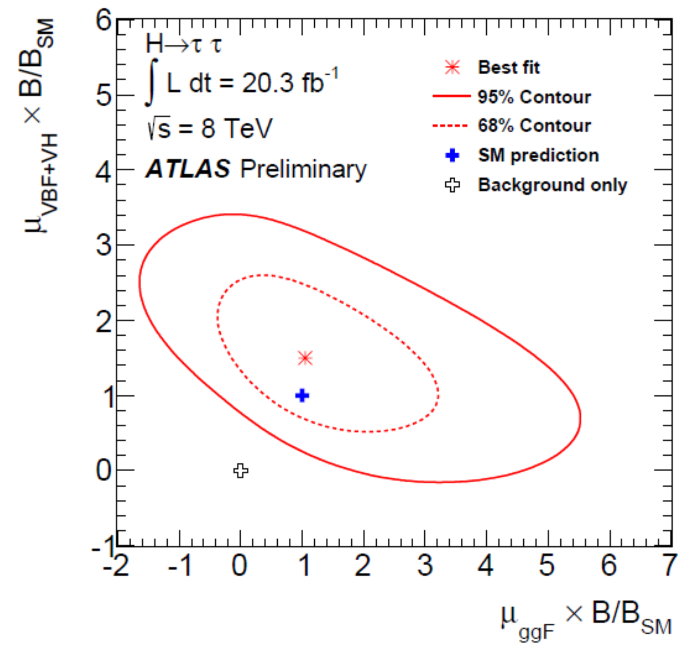
Latest Update of H → ττ

➔ **Observed 4.1σ, expected 3.2σ for 125 GeV Higgs.**

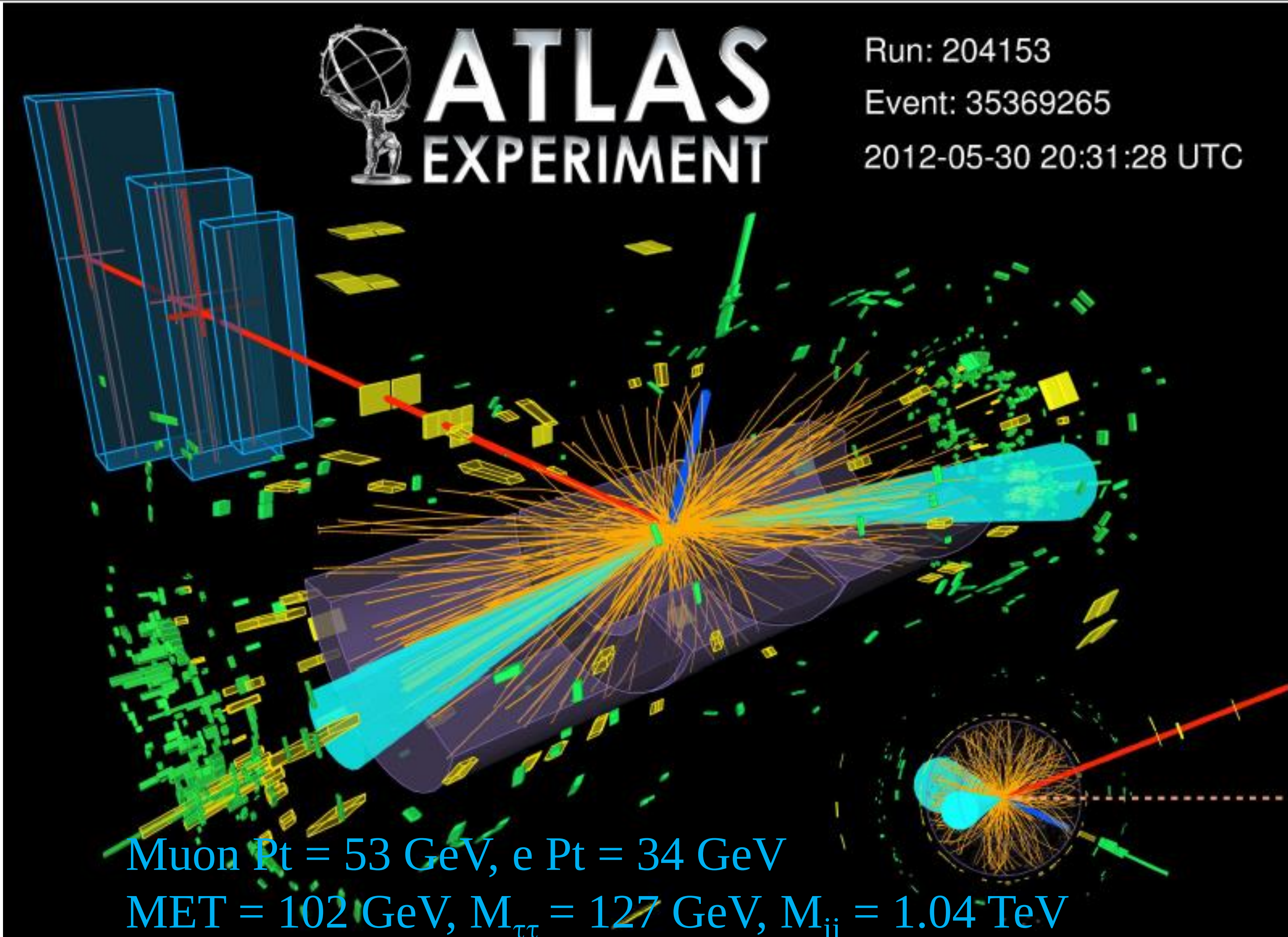








Candidate of VBF H → ττ



Muon Pt = 53 GeV, e Pt = 34 GeV

MET = 102 GeV, $M_{\tau\tau}$ = 127 GeV, M_{jj} = 1.04 TeV

Update of Higgs Signal Strength

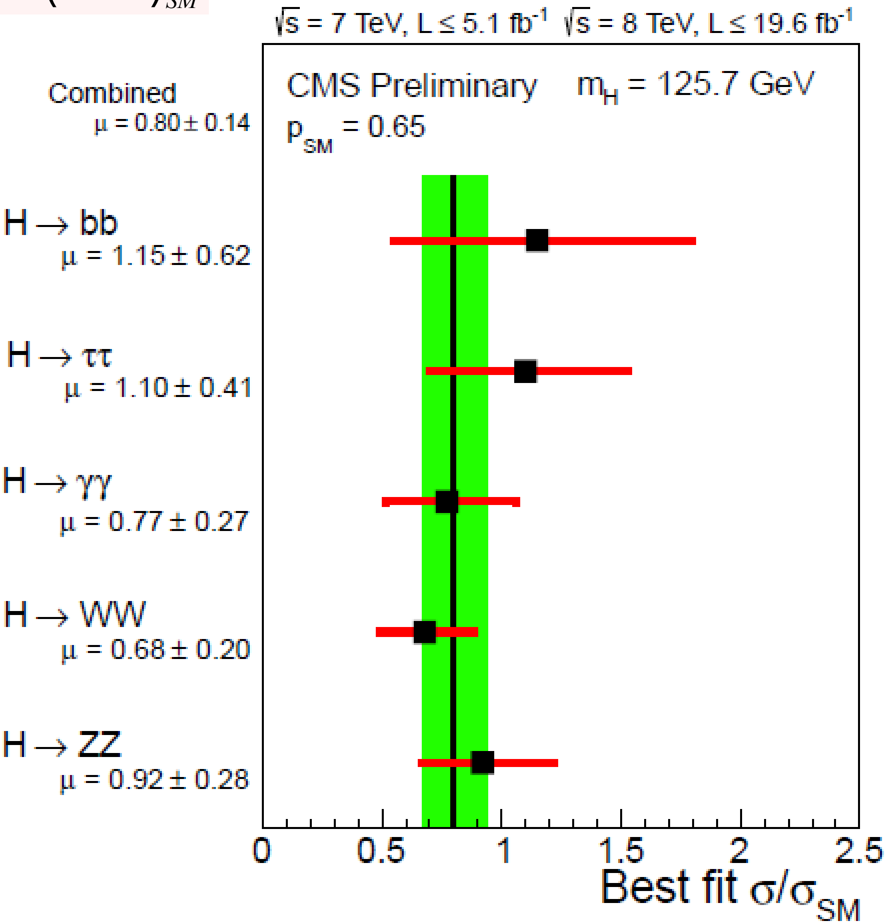
➔ **Signal strength: μ=1.3±0.2(ATLAS)**

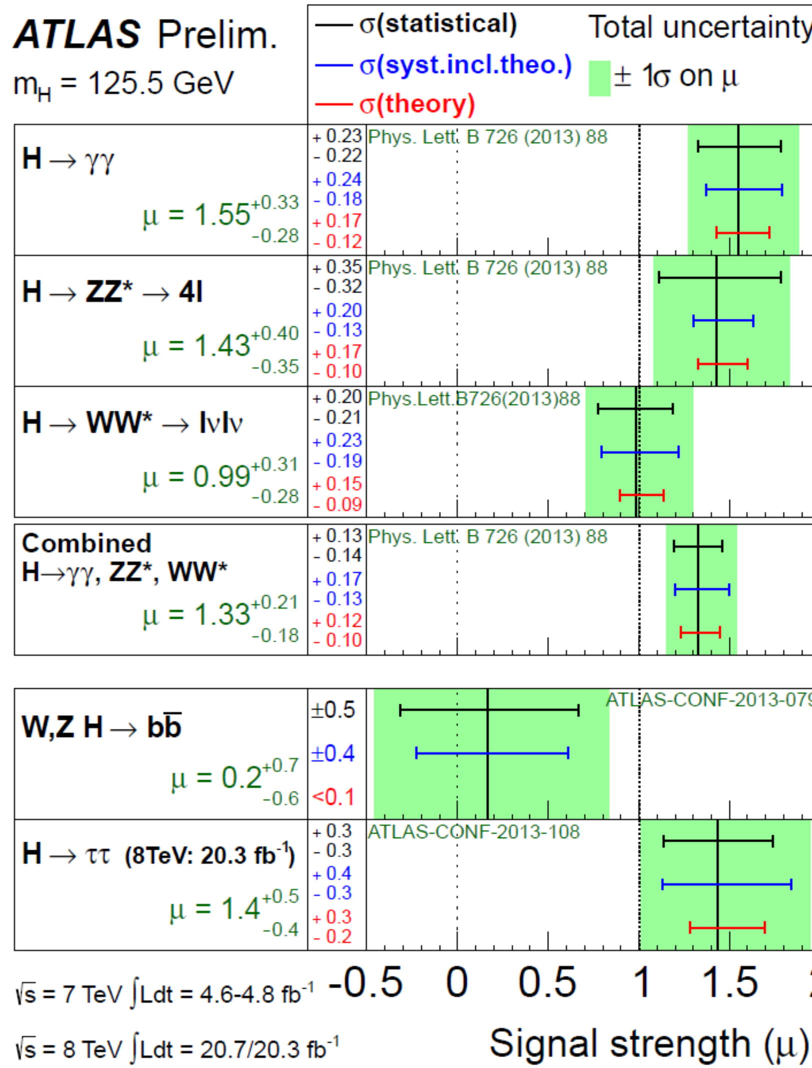
➔ **μ = 0.8 ±0.14 (CMS)**

ATLAS-CONF-2013-034
ATLAS-CONF-2013-108

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

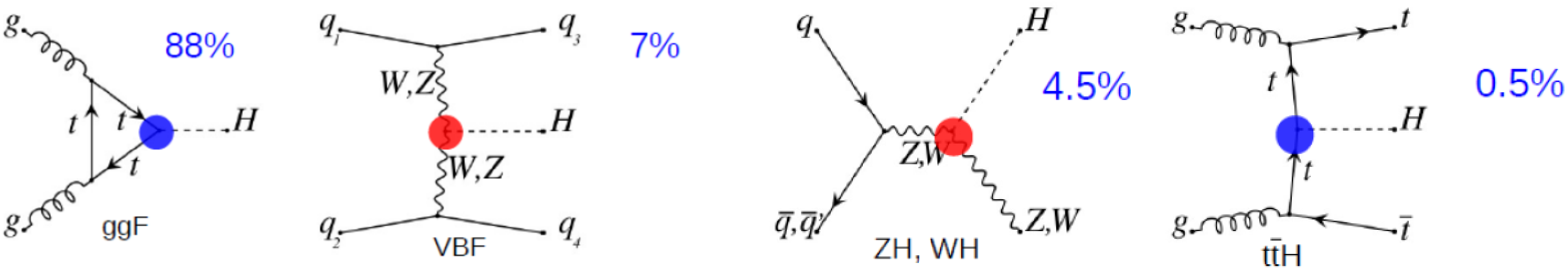
CMS-HIG-13-005



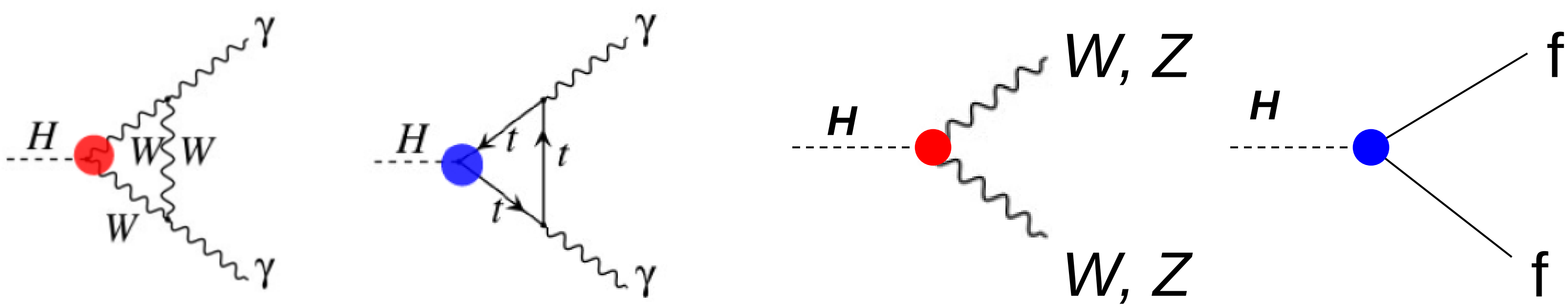


Is it the SM Higgs Boson?

- **Higgs production (m_H = 125 GeV)**



- **Higgs decays**



- **Couplings (new force!)**

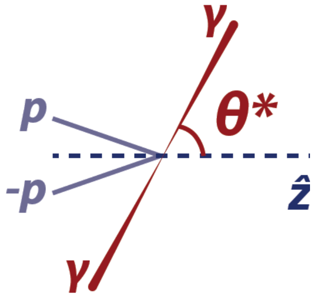
● : fermions
● : vector bosons

g_F (Yukawa coupling) $= \sqrt{2} \times m_F/\nu$
g_V (Gauge coupling) $= 2m_V^2/\nu$
(ν is the vacuum expectation value)

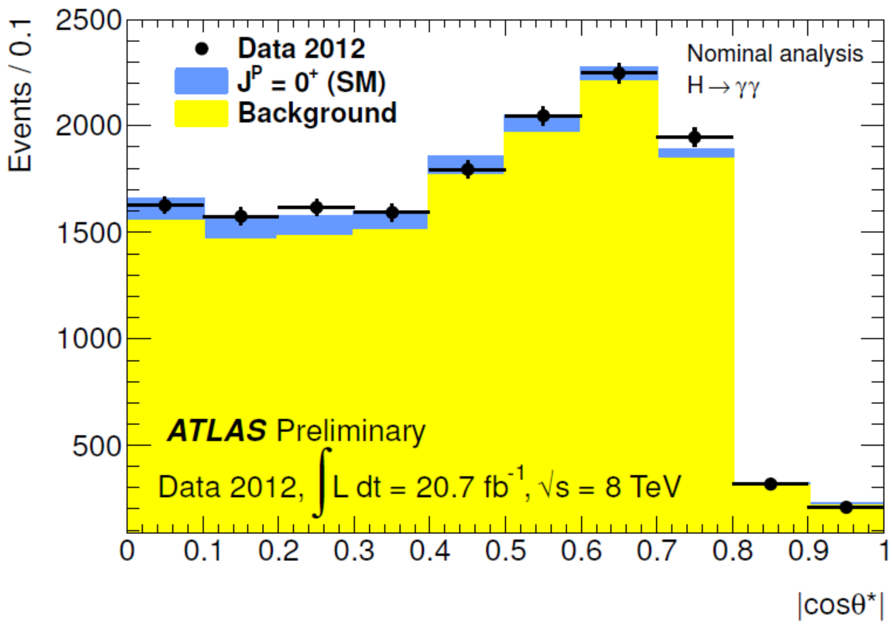
- **Spin and Parity**

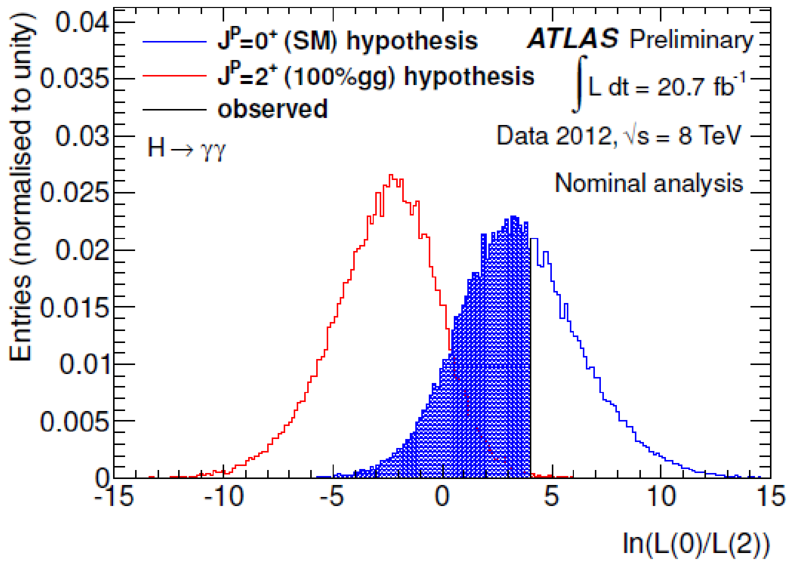
Spin for H → γγ

- ❑ Using events in signal mass window [123.6, 128.6] GeV
- ❑ The photon polar angle |cosθ*| in the resonance rest frame (Collins-Soper frame) is sensitive to the spin of Higgs.



$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



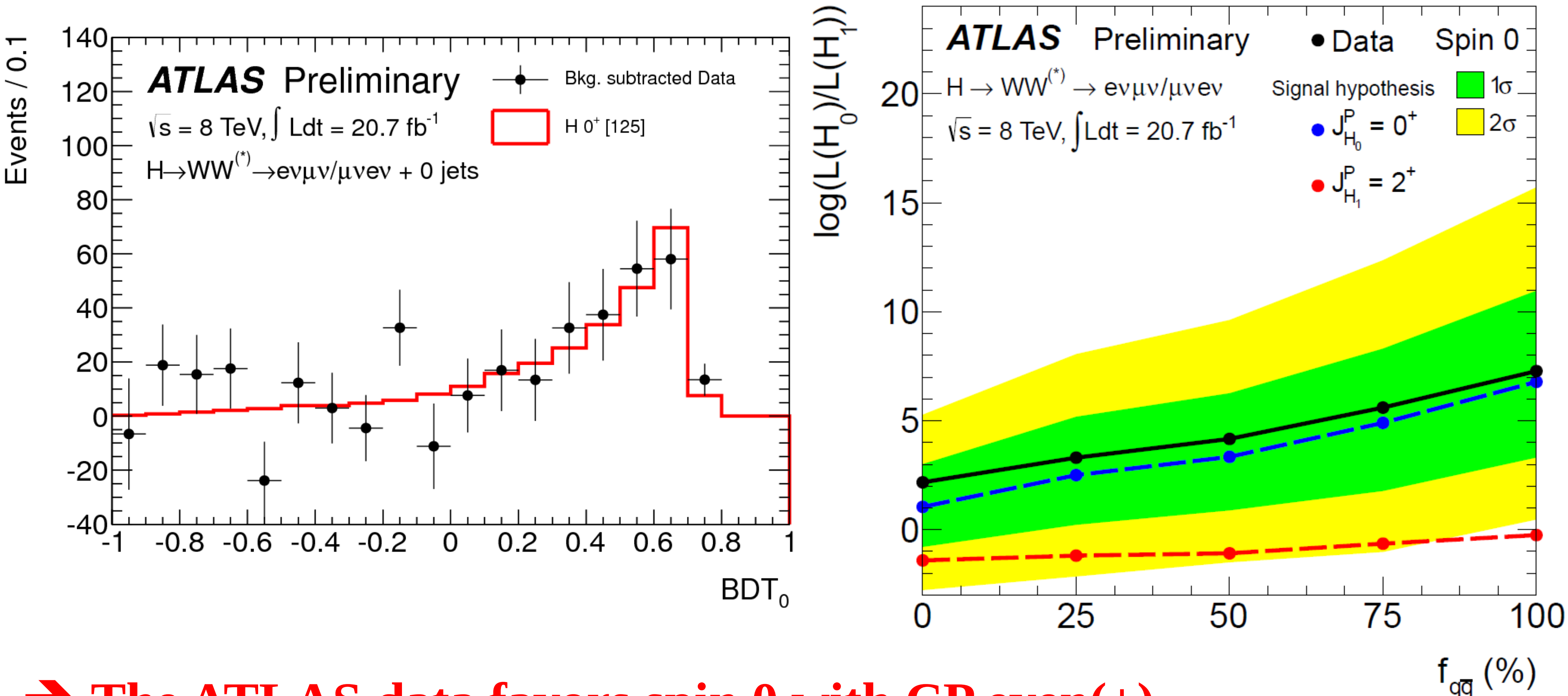


➔**Data agree with spin 0^+ hypothesis (1-CL_b) ~ 58.8%.**

➔**Spin 2 is disfavored at 99.3% C.L. (or 2.9σ).**

Spin for H → WW

- Combine several variables in a MVA discriminant (Boosted Decision Trees, BDT)
- Variables used: m_{ll}, P_T^{ll}, $\Delta\varphi_{ll}$, m_T

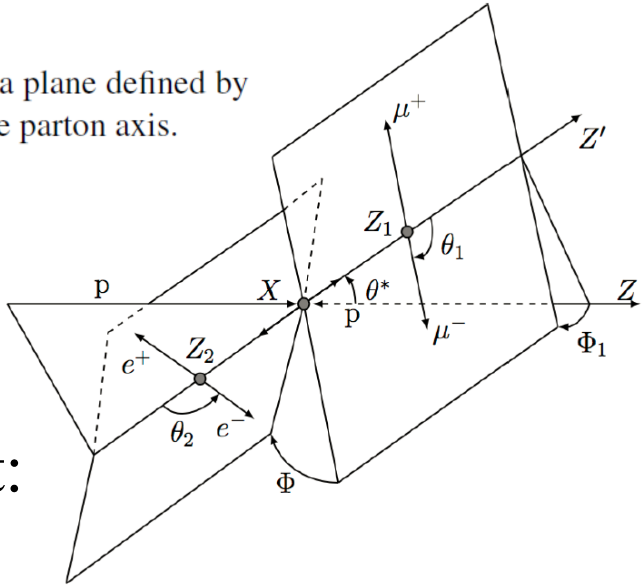


➔ The ATLAS data favors spin 0 with CP even(+).

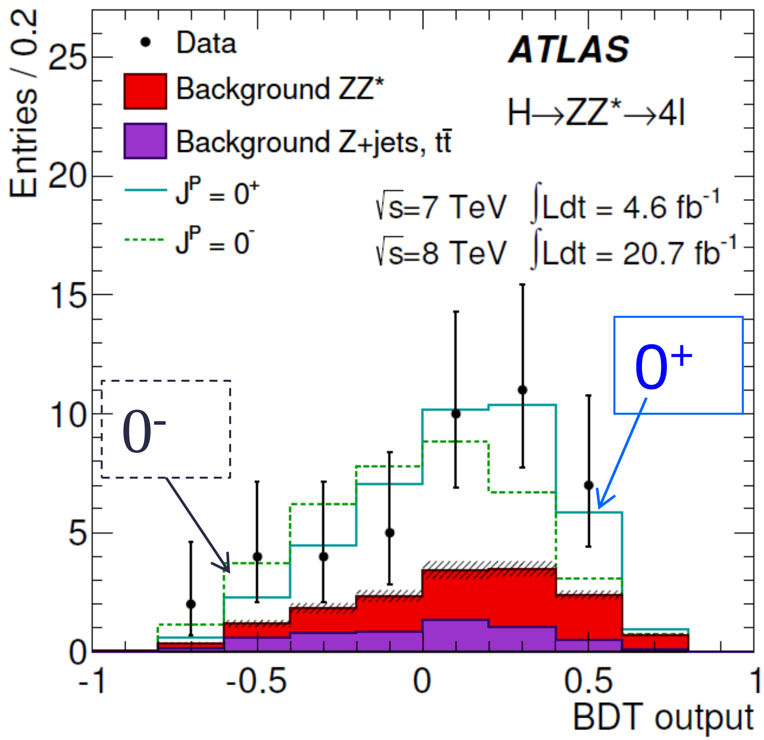
H→ZZ*→4l : Spin and CP

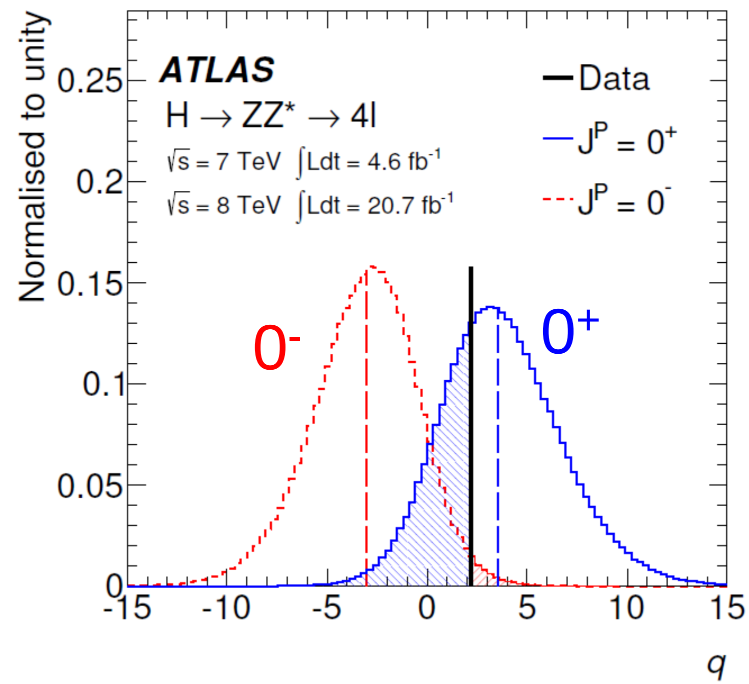
- Fully reconstructed final state allows measuring Spin/CP:
  - Five kinematic angles (production, decay)
  - Invariant mass of the primary Z and the secondary Z

- θ_1 (θ_2) is the angle between the negative final state lepton and the direction of flight of Z_1 (Z_2) in the Z rest frame.
- Φ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
- Φ_1 is the angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the Z_1 in the four lepton rest frame and the positive direction of the parton axis.
- θ^* is the production angle of the Z_1 defined in the four lepton rest frame.



- Discriminate 0^+ (SM) hypothesis against:
  - 0^- (CP odd), 1^+, 1^-
  - 2^- (pseudo-tensor)
  - 2^+_m (graviton-like tensor, minimal coupling)





BDT analysis variables:

m_{Z1}, m_{Z2} from Higgs --> ZZ* →4l
+ production and decay angles

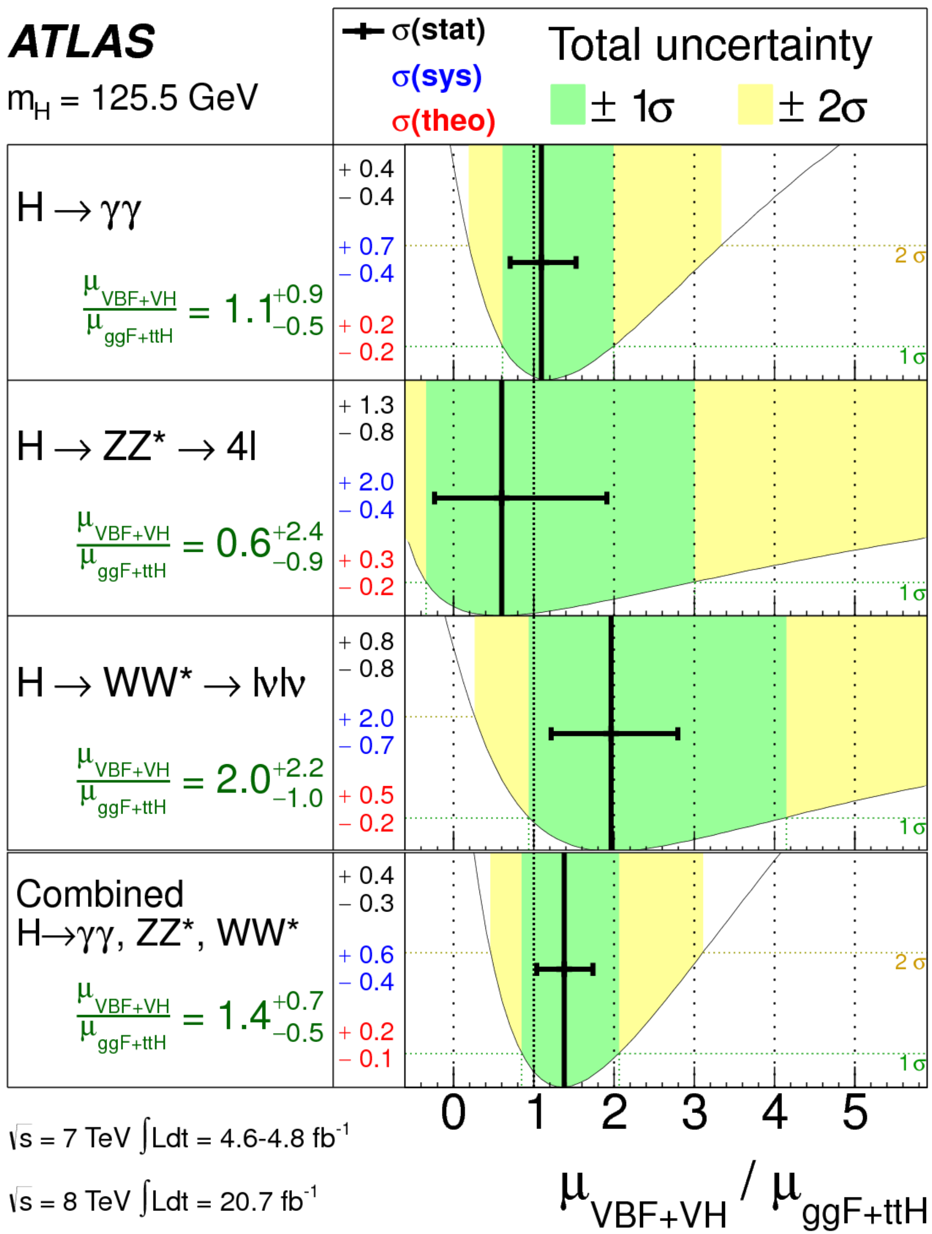
Exclusion (1-CL_s):

Observed 0^- exclusion 97.8%

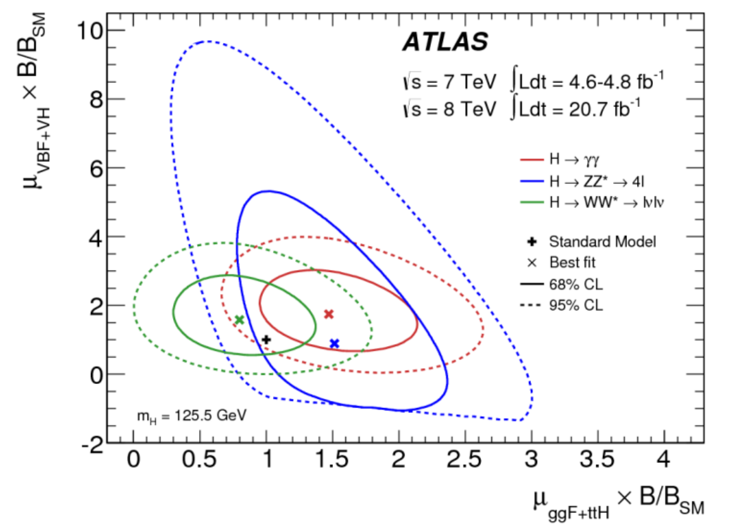
Observed 1^+ exclusion 99.8%

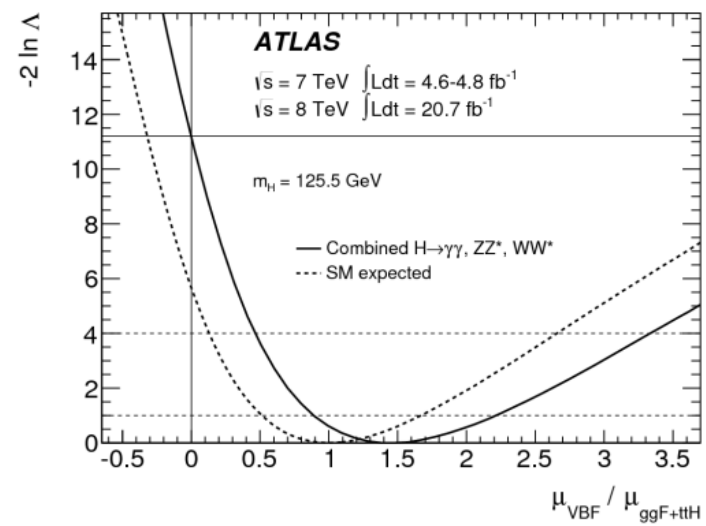
		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

Higgs Production: ggF vs.VBF



μ_{VBF+VH} vs $\mu_{ggF+ttH}$ potentially modified by B/B_{SM}





$\mu_{VBF+VH} / \mu_{ggF+ttH}$ =
1.4+0.4-0.3(stat)+0.6-0.4(sys)

Fermion and Vector Couplings

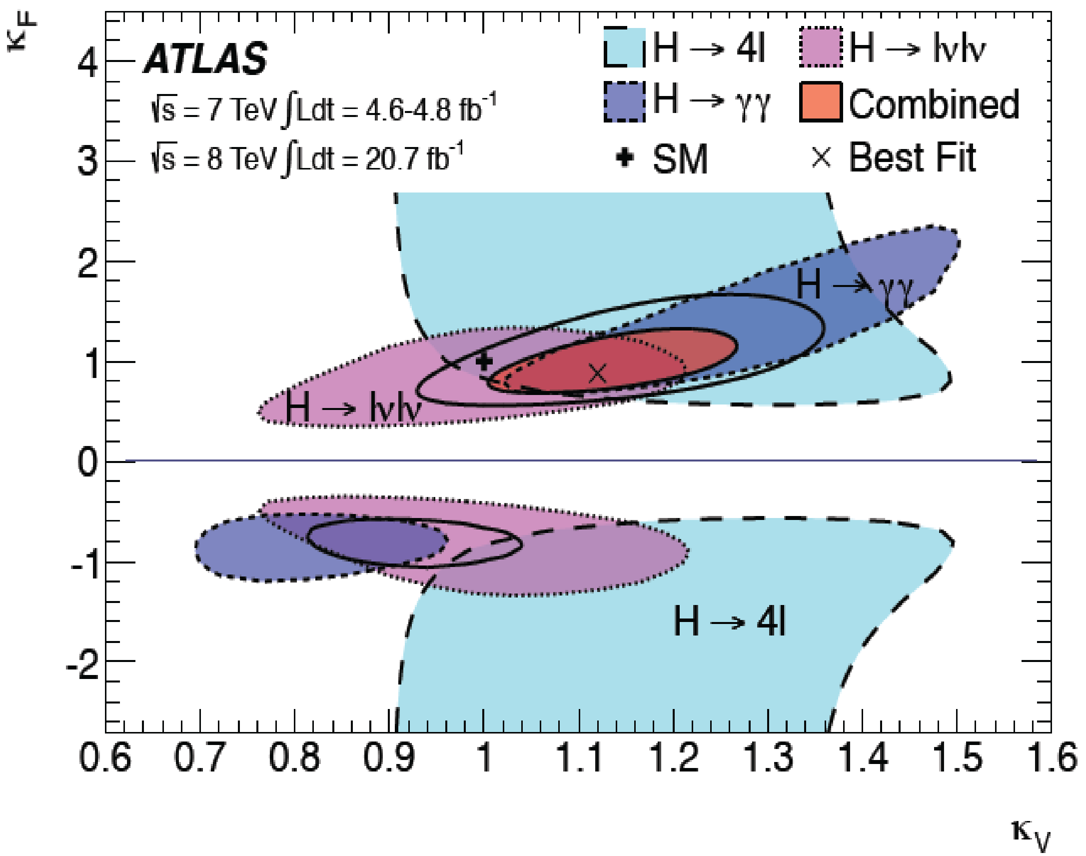
2-parameter benchmark model:
$\kappa_V = \kappa_W = \kappa_Z$ (>0)
$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$
(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

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

Assume no BSM contributions to loops: gg→ H and H→$\gamma\gamma$, and no BSM decays (no invisible decays)

- **κ_F = 0 is excluded (>5σ)**

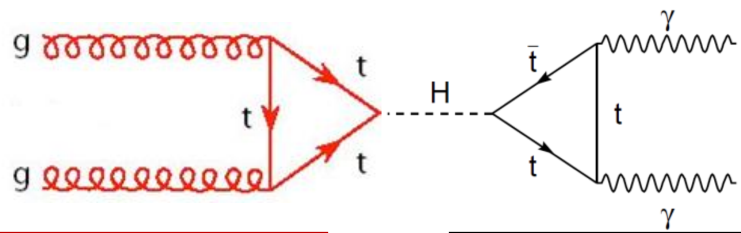
Double minimum from interference between vector(W) and fermion (top) in H→$\gamma\gamma$



Constraints on BSM Loops

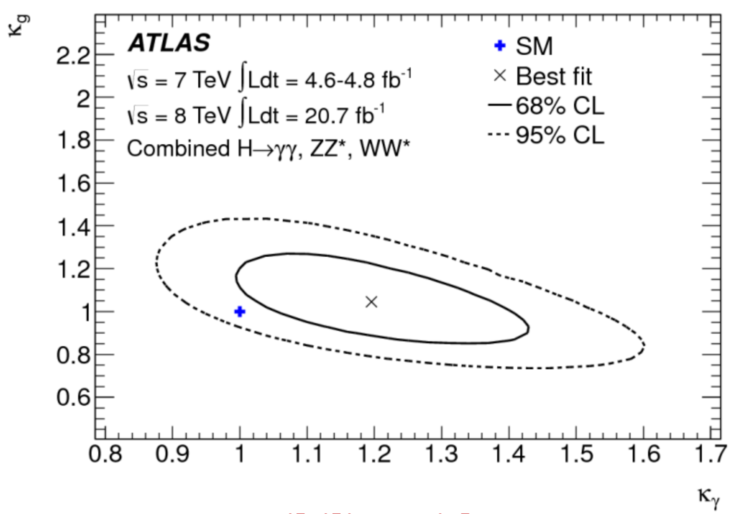
New heavy particles may contribute to loops

- Introduce effective κ_g, κ_γ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b$, κ_τ etc set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width

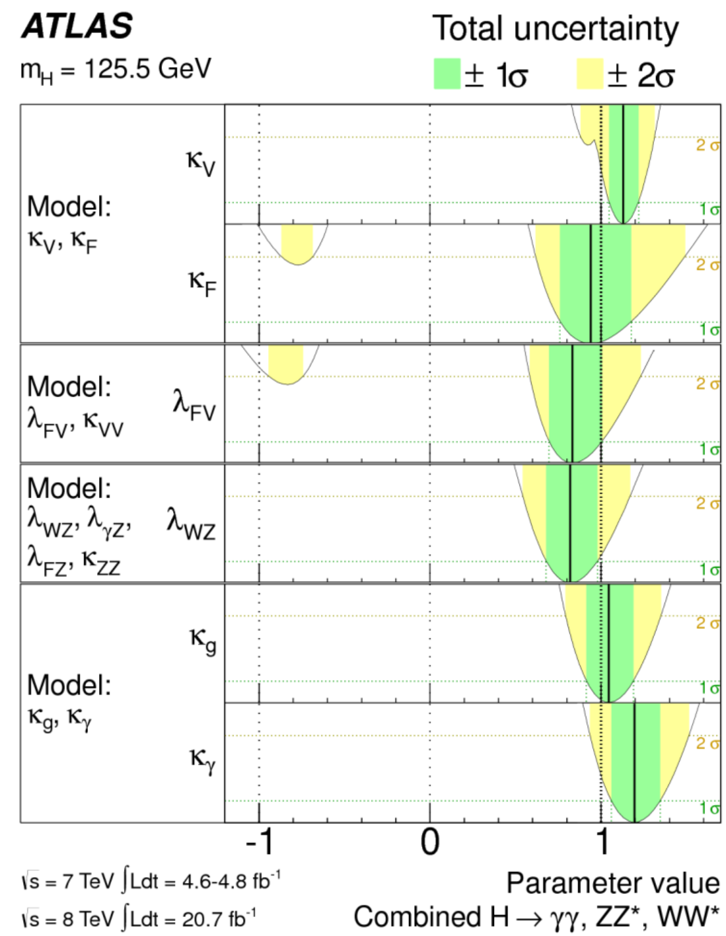


$\kappa_g = 1.04 \pm 0.14$

$\kappa_\gamma = 1.20 \pm 0.15$



2D Compatibility with SM: 14%



Couplings tested for anomalies w.r.t. fermion and boson, W/Z and vertex loop contributions at ±10-15% precision

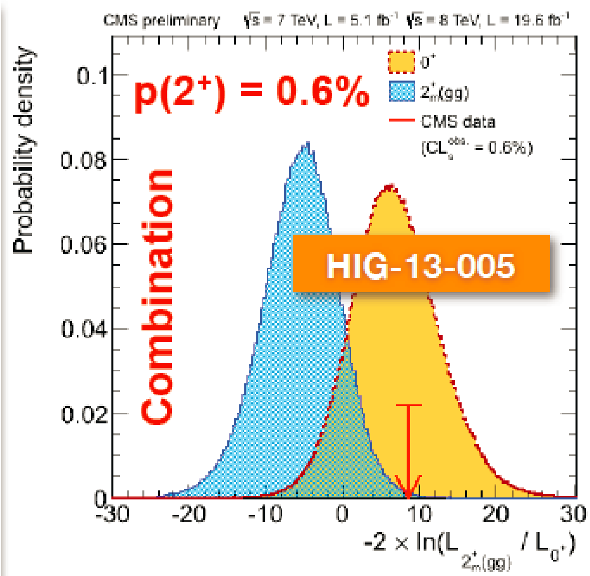
It is the SM Higgs Boson !!!

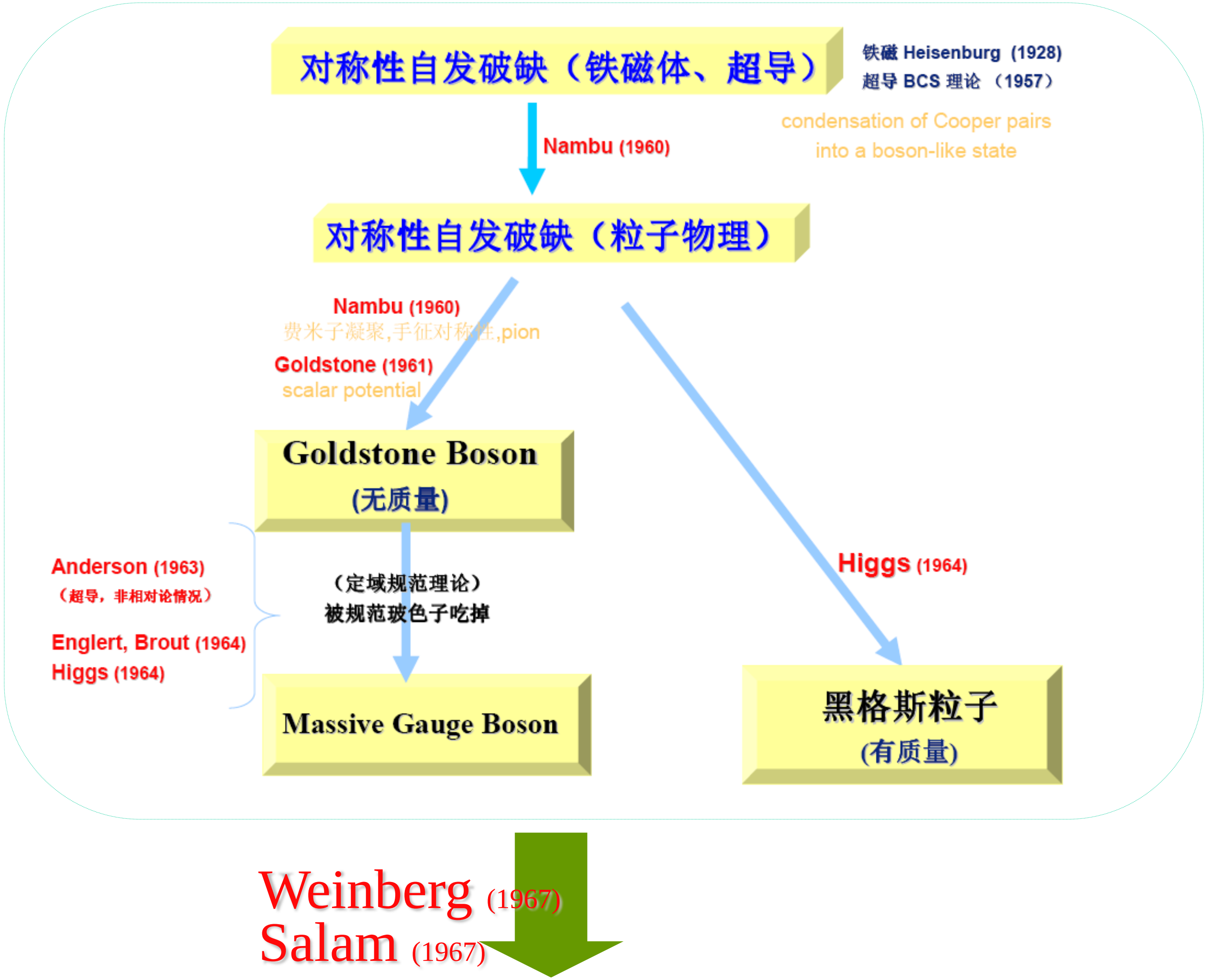
- **ATLAS and CMS Results are consistent with the SM Higgs boson which has spin 0 and CP even.**

	ATLAS	CMS
Mass	125.5 ± 0.2(stat) ± 0.6(syst)	125.7 ± 0.3(stat) ± 0.3(syst)
Data favors 0^+ vs		
Spin 0^-	97.8% CL	99.8% CL
Spin 1	99.7% CL	99.9% CL
Spin 2^+	99.9% CL	99.4% CL (100%gg)

- **Each experiment:**
  - **Couplings to bosons determined at** the 10% level
  - **Rejecting zero couplings to fermions** at >5σ

- **Observation of**
  - **VBF production** at 3.3σ (ATLAS)
  - **VBF+VH production** at 3.2σ (CMS)





SU(2) x U(1) 电弱理论

In 1967 Steven Weinberg [44] finally tied the pieces together.
Abdus Salam [45] presented essentially the same model in a Nobel Symposium about half a year later.