Higgs Physics – Lecture 1

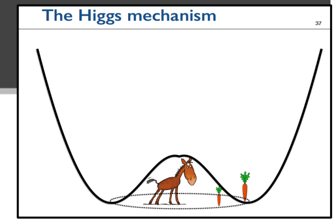
Higgs Physics at the LHC – Introduction

Ricardo Gonçalo – LIP

IDPASC Course on Physics at the LHC – LIP, 18 April 2016

Outlook

Monday, 18 April 2016

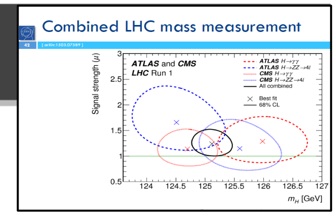


18:00 → 19:30 **Higgs Physics 1**

Introduction
Reminder of some shortcomings of the SM: masses, WW scattering.
The Higgs mechanism. Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
Previous searches at LEP and the Tevatron.

Speaker: Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Monday, 2 May 2016

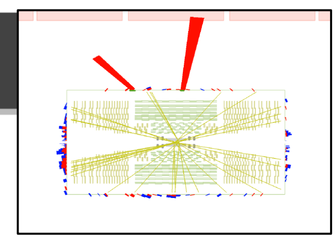


18:00 → 19:30 **Higgs Physics 2**

Combination of search results.
Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

Tuesday, 10 May 2016



18:00 → 19:30 **Higgs Physics 3**

Summary of results from the discovery in the different channels.
Case-study of the H->WW search at ATLAS.

Speaker: Patricia Conde Muino (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Monday, 16 May 2016

18:00 → 19:30 **Higgs Physics 4**

Speaker: Michele Gallinaro (LIP Lisbon)

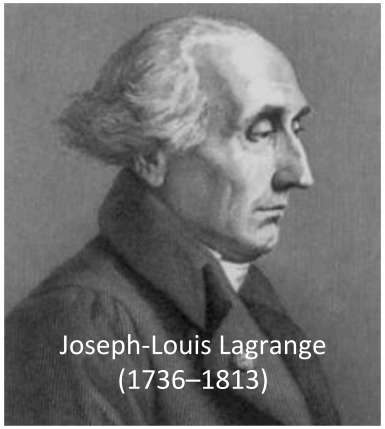
This lecture:

- Introduction:
  - Focus lecture on Standard Model (SM) and experimental searches for SM Higgs
- Reminder of some shortcomings of the SM:
  - Masses, WW scattering
- The Higgs mechanism
- Production and decay of the Higgs boson:
  - Early searches, searches at LEP, Tevatron and LHC
- Discovery at the LHC!

Introduction

or “Hard-core theory to set the scene”

Lagrangians in classical mechanics



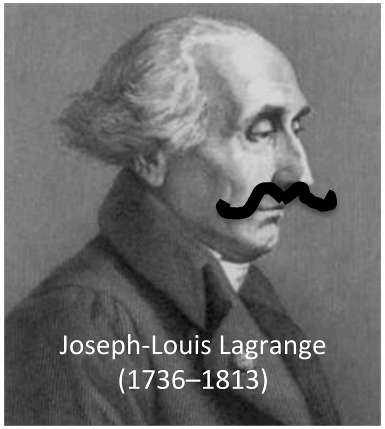
Equations of motion are derived from a scalar **Lagrangian** function of generalized coordinates and velocities (time derivatives):

$$L(q,\dot{q}) = T - V$$

and from Euler-Lagrange's equations:

$$\boxed{\frac{\partial L}{\partial q_j} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_j} = 0\,.}$$

Lagrangians in classical mechanics



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Example:

A particle in a conservative potential V is subjected to force: $F = -\nabla V(x,y,z)$

It's Lagrangian is:

$$L(x,y,z,\dot{x},\dot{y},\dot{z}) = \frac{1}{2}m(\dot{x}^2+\dot{y}^2+\dot{z}^2) - V(x,y,z)\,.$$

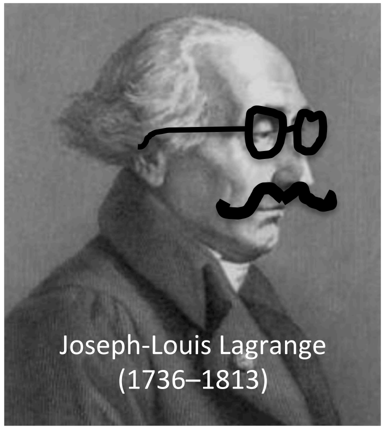
This gives the following terms in the Euler-Lagrange equations:

$$\frac{\partial L}{\partial x} = -\frac{\partial V}{\partial x}\,, \quad \frac{\partial L}{\partial \dot{x}} = m\dot{x}\,, \quad \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{x}}\right) = m\ddot{x}\,,$$

And we end up with the familiar equations of motion given by Newton's second law:

$$\boxed{m\ddot{x} = -\frac{\partial V}{\partial x}\,,}$$

Lagrangians in classical mechanics



Joseph-Louis Lagrange
(1736–1813)

Equations of motion are derived from a scalar **Lagrangian** function of generalized coordinates and velocities (time derivatives):

$$L(q,\dot{q}) = T - V$$

and from Euler-Lagrange's equation:

$$\boxed{\frac{\partial L}{\partial q_j} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_j} = 0\,.}$$

Why is this formulation useful? Example:

Coordinates not explicitly appearing in the Lagrangian indicate that the corresponding momentum is conserved:

The generalized momentum associated to coordinate q is:

$$p_i = \frac{\partial L}{\partial \dot{q}_i}.$$

e.g. for

$$L(x,y,z,\dot{x},\dot{y},\dot{z}) = \frac{1}{2}m(\dot{x}^2+\dot{y}^2+\dot{z}^2) - V(x,y,z)\,.$$

It's obvious that

$$p_z = \frac{\partial L}{\partial \dot{z}}\,, \quad p_s = \frac{\partial L}{\partial \dot{s}}\,, \quad p_\phi = \frac{\partial L}{\partial \dot{\phi}}\,,$$

So, if the Lagrangian doesn't depend on some coordinate $\boldsymbol{q_i}$, Euler-Lagrange's equation tells us that the corresponding momentum $\boldsymbol{p_i}$ is conserved:

$$\dot{p}_i = \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_i} = \frac{\partial L}{\partial q_i} = 0\,.$$

Parenthesis: quantum cooking

Non-relativistic quantum mechanics for a free particle:

From the usual energy-momentum relation: $$\frac{p^2}{2m} = E$$

Using the usual prescription: $$p \rightarrow \frac{\hbar^2}{i}\nabla \qquad E \rightarrow i\hbar\frac{\partial}{\partial t}$$

Gives **Schrödinger's** equation: $$\boxed{\frac{-\hbar^2}{2m}\nabla^2\psi = i\hbar\frac{\partial\psi}{\partial t}}$$

In relativistic notation the same recipe is written: $$p_\mu \rightarrow i\hbar\partial_\mu$$

The relativistic energy-momentum relation is now $$p^\mu p_\mu - m^2c^2 = 0$$

So in relativistic quantum mechanics we end up with **Klein-Gordon's** equation: (for spin-zero, free particles)

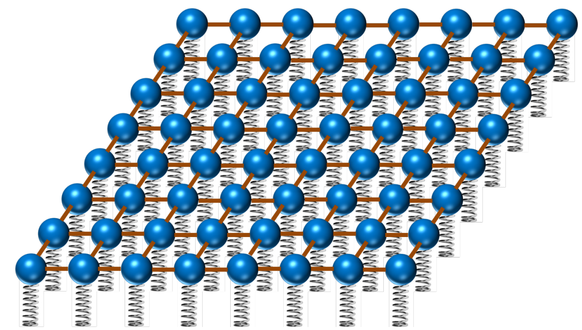
$$\boxed{-\hbar^2\partial^\mu\partial_\mu\psi - m^2c^2\psi = 0}$$

$$-\frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2} + \nabla^2\psi = \frac{m^2c^2}{\hbar^2}\psi$$

Now in quantum field theory…

We now have fields instead of the classical point-like particles

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. Particles are perturbations of this field!



The Lagrangian is now the integral of a ***Lagrangian density***, function of each field and its space and time derivatives

Lagrangian density: $\mathcal{L}(\phi, \nabla\phi, \partial\phi/\partial t, \mathbf{r}, t)$ Lagrangian: $L = \int \mathcal{L}\, \mathrm{d}^3\mathbf{x}\,.$

The Euler-Lagrange equation is now: $-\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \varphi)} \right) + \frac{\partial \mathcal{L}}{\partial \varphi} = 0.$

Note that in a relativistic theory we must treat space and time coordinates in an equal footing, so the time derivative in the classical equation is now ∂_μ

Example:

If we have a scalar field ϕ and a Lagrangian:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}\frac{m^2c^2}{\hbar^2}\phi^2$$

The terms in the Euler-Lagrange equation are:

$$\frac{\partial \mathcal{L}}{\partial \phi} = \frac{m^2c^2}{\hbar^2}\phi$$ and $$\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} = \partial^\mu \phi$$ and so: $$\partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} = \partial_\mu \partial^\mu \phi$$

And we end up with Klein-Gordon's equation

$$\boxed{\partial_\mu \partial^\mu \phi + \frac{m^2c^2}{\hbar^2}\phi = 0}$$

(with no need for cooking recipes)

Let's go back to the Klein-Gordon Lagrangian density for a second:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \boxed{\frac{1}{2}\frac{m^2c^2}{\hbar^2}\phi^2}$$

Notice that the ***mass term*** is the one which is ***second order*** *in the field.*
This is a general feature that we will exploit later

Gauge invariance

Take the Dirac Lagrangian (for spinor fields φ representing fermions)

$$\mathcal{L} = i\hbar c\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\bar{\psi}\psi$$

It is invariant under global gauge transformations like:

$$\psi \rightarrow e^{i\theta}\psi$$

Where θ is a constant. Now, what about ***local*** gauge transformations? If θ=θ(*x*) then the field derivative gives us extra terms:

$$\mathcal{L} \rightarrow \mathcal{L} - \hbar c(\partial_{\mu}\theta)\bar{\psi}\gamma^{\mu}\psi \quad \text{or} \quad \mathcal{L} \rightarrow \mathcal{L} + (q\bar{\psi}\gamma^{\mu}\psi)\partial_{\mu}\lambda$$

(with $\lambda(x) = -\frac{\hbar c}{q}\theta(x)$ and ***q*** the charge of the particle)

But we can now make the Lagrangian local-gauge invariant by adding an ***interaction term*** with a new **gauge** field $\boldsymbol{A_\mu}$:

$$\mathcal{L} = i\hbar c\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^2\bar{\psi}\phi - \boxed{(q\bar{\psi}\gamma^{\mu}\psi)A_{\mu}}$$

For this to work, the new field needs to transform like

$$A_\mu \to A_\mu + \partial_\mu \lambda$$

So that the last term cancels the change in the φ terms due to gauge transformations. But what has just happened? We have added a new field, and so a new particle to the Lagrangian. For this to make sense **we also need a new *free term*** for this field. We end up with:

$$\mathcal{L} = i\hbar c\bar{\psi}\gamma^\mu\partial_\mu\psi - mc^2\bar{\psi}\phi - \frac{-1}{16\pi}F^{\mu\nu}F_{\mu\nu} - (q\bar{\psi}\gamma^\mu\psi)A_\mu$$

Where $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

Now, the last 2 terms in the new Lagrangian correspond to **Maxwell's Lagrangian** and give all of electrodynamics!!

Demanding local gauge conservation resulted in obtaining a new field (the photon) and its interactions with the fermion fields. This is the blueprint of all Standard Model theories (called "Gauge theories").

Gauge theories are automatically renormalizable ('t Hooft & Veltman's Nobel prize) i.e. don't produce nonsense. BUT: notice there is no term depending on the square of the A_μ field:

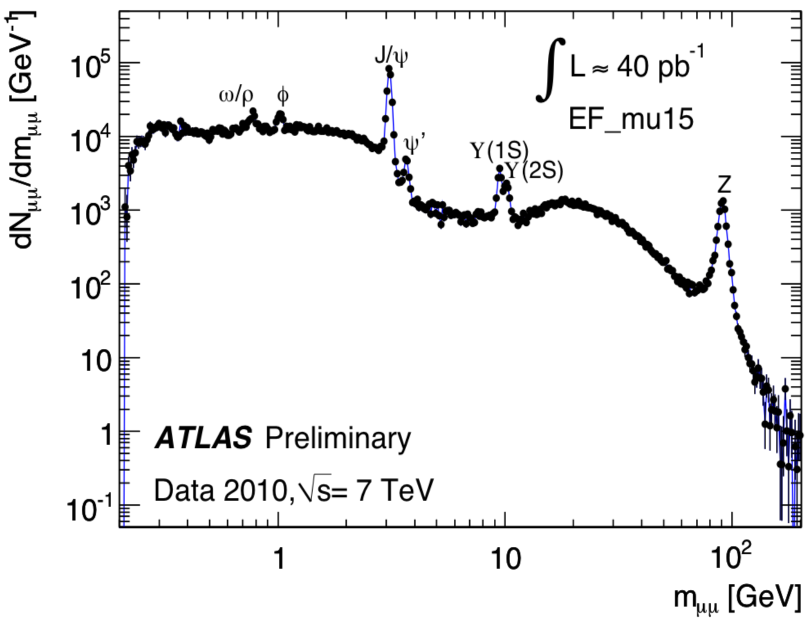
➔ There is **no mass term for the photon** – this is the beginning of the Higgs story!

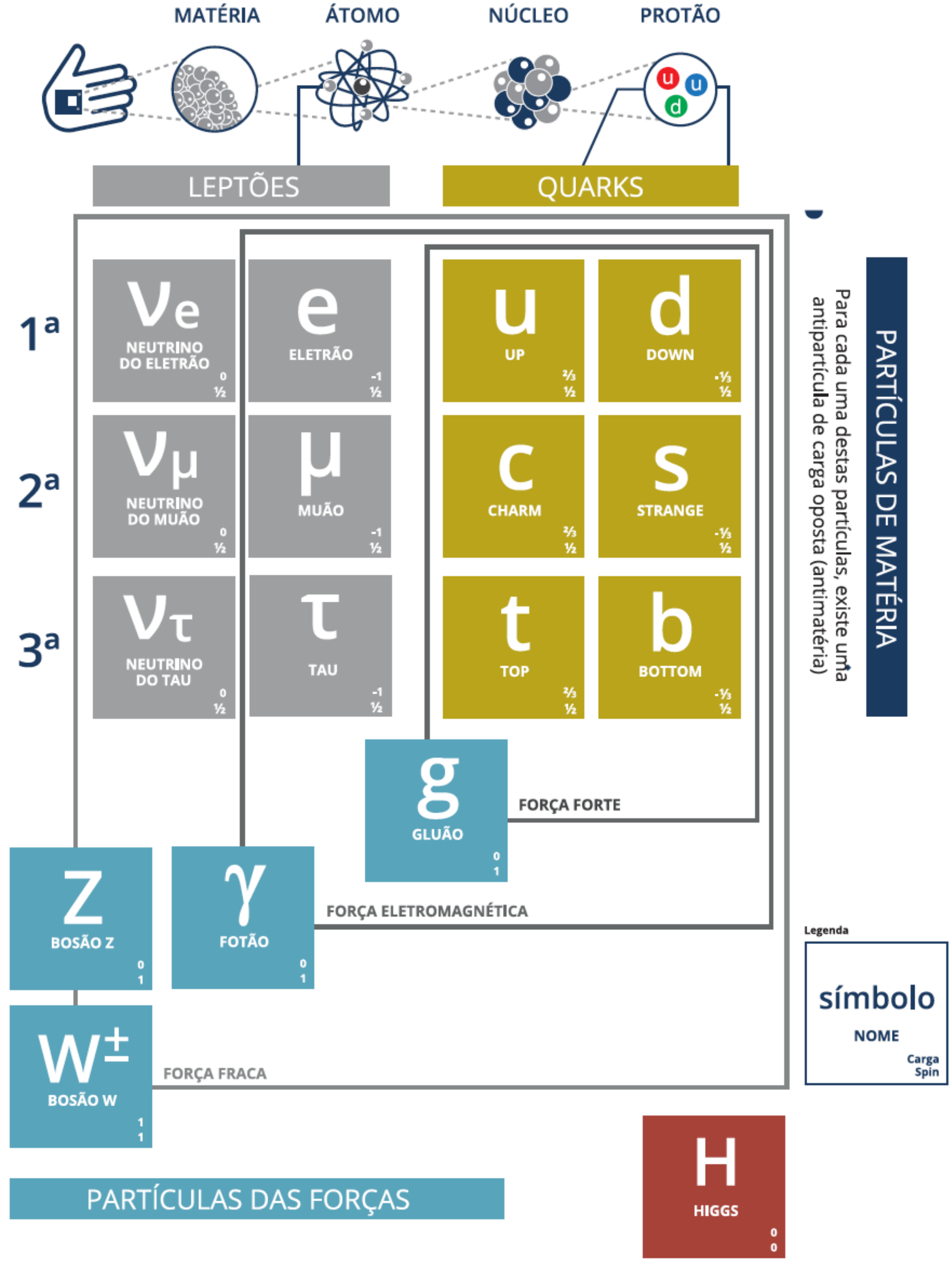
Shortcomings of the Standard Model

Elementary particle masses

WW scattering.

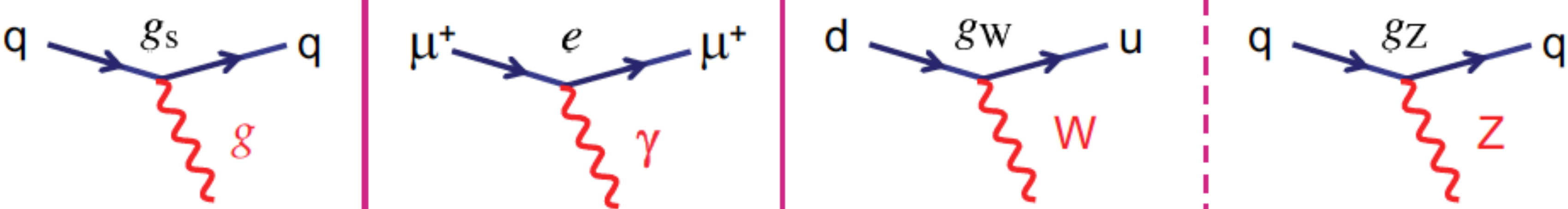
The Standard Model in 1 slide





Standard model interactions

The interaction of gauge bosons with fermions is (very) well described by the Standard Model



STRONG

Only quarks

Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM

All charged fermions

Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

WEAK CC

All fermions

Always changes flavour

WEAK NC

All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

W+, W-

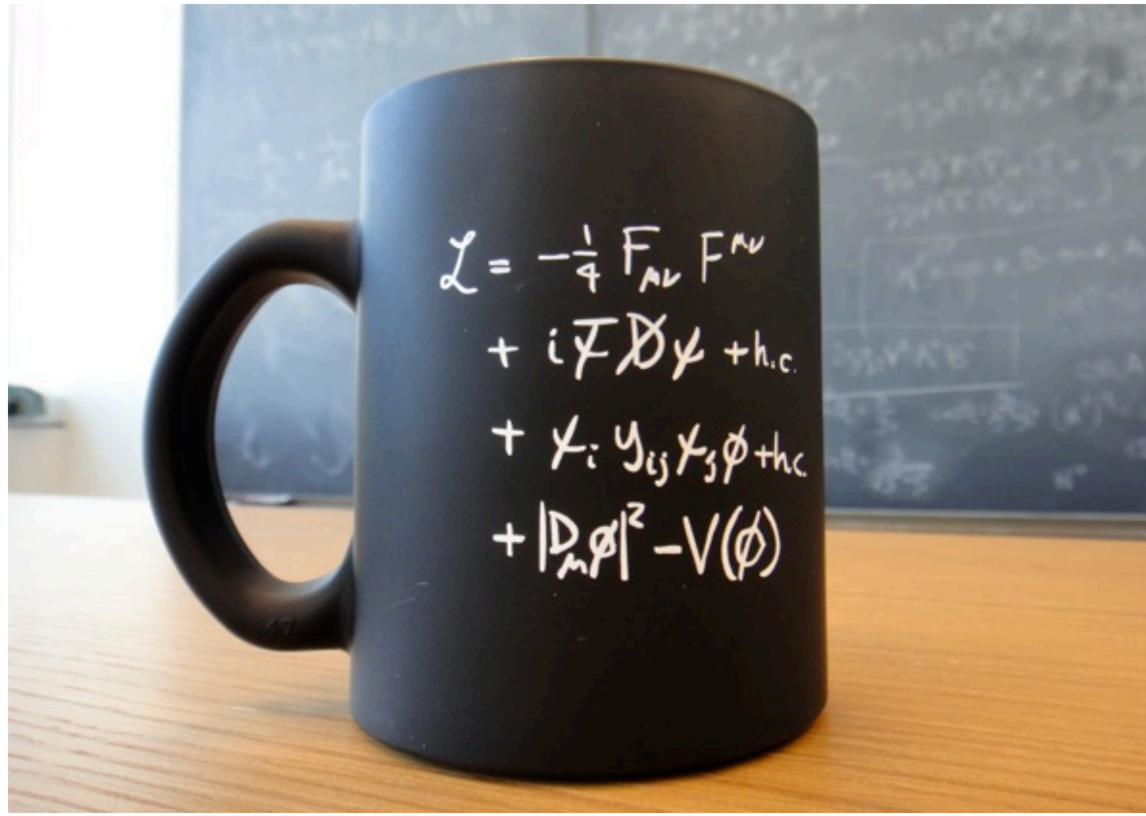
very massive

Z^0

very massive

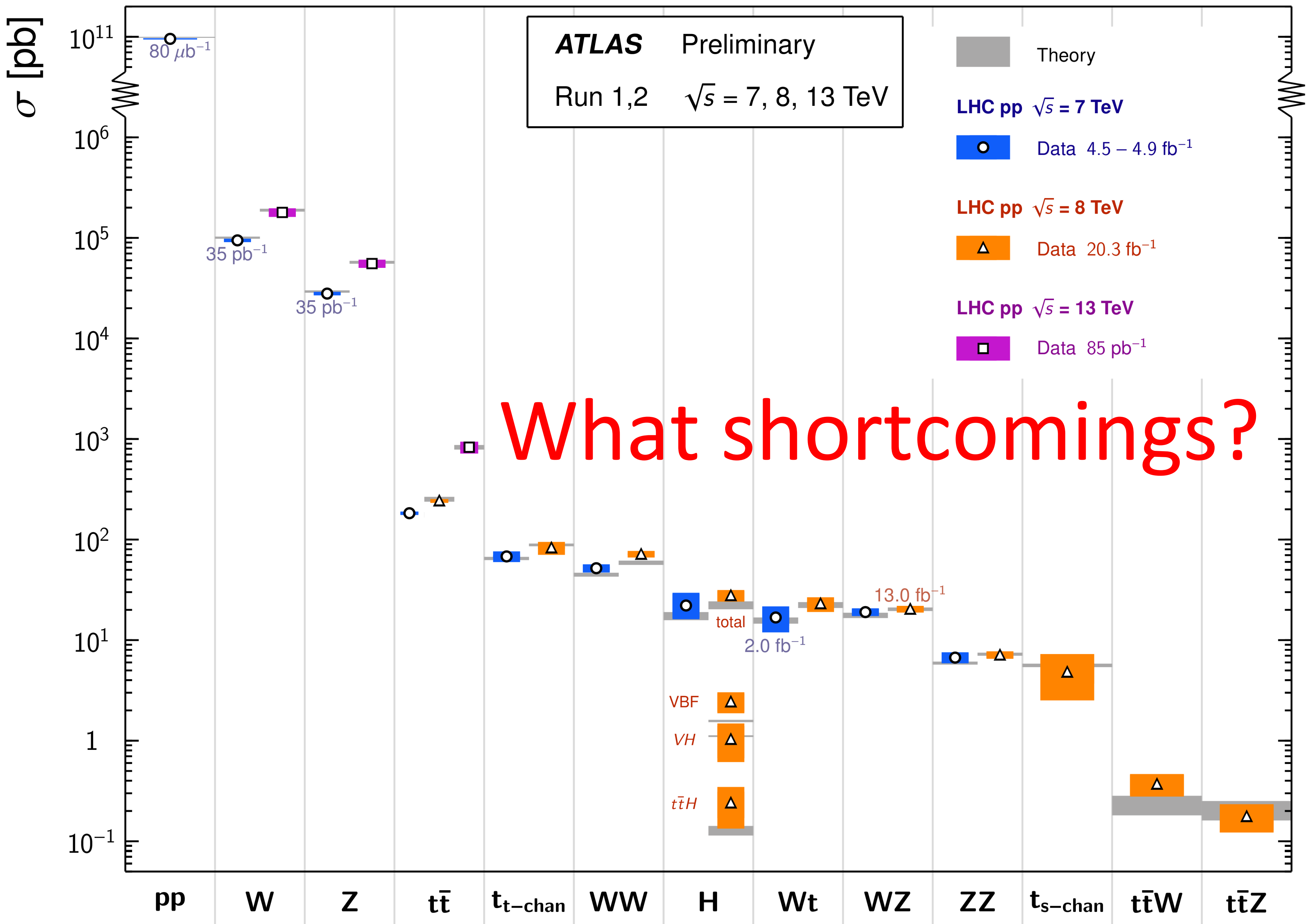
Back to Lagrangians… and coffee mugs

- Throughout history, we have been looking mostly at the second line
- Interactions between fermion matter particles transmitted by force carriers
- I.e. all of chemistry and most of physics
- Disclamer: gravity not on the mug



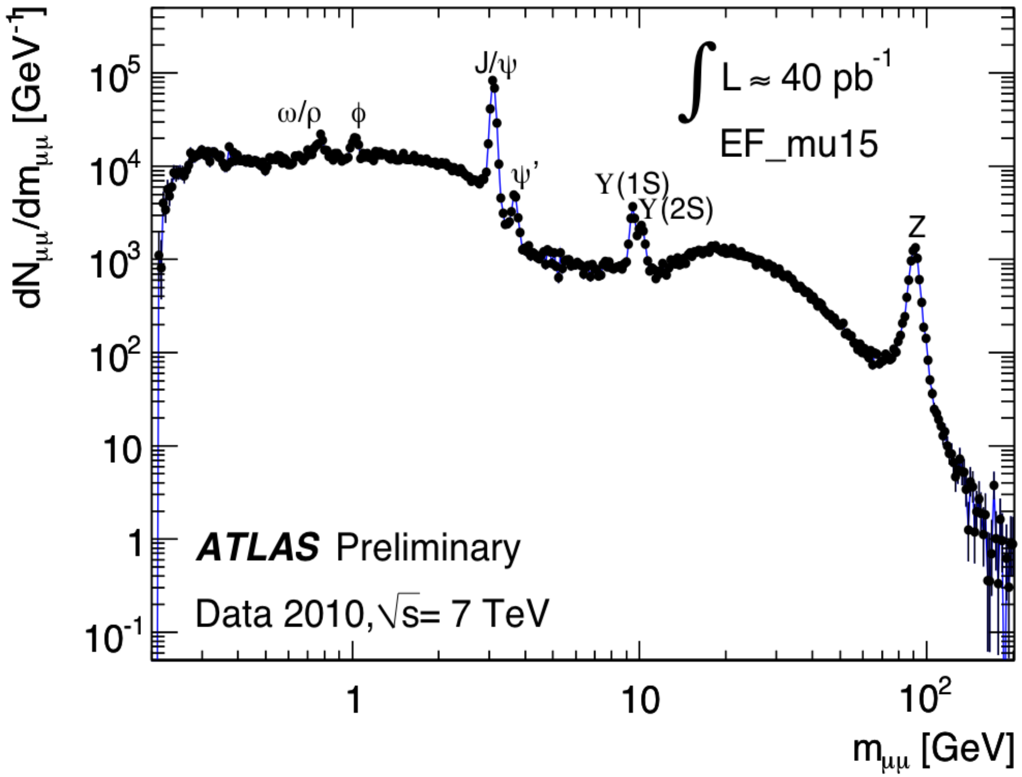
Standard Model Total Production Cross Section Measurements

Status: Nov 2015



Now the problems…

1. Mass of ~~elementary particles~~ and gauge bosons



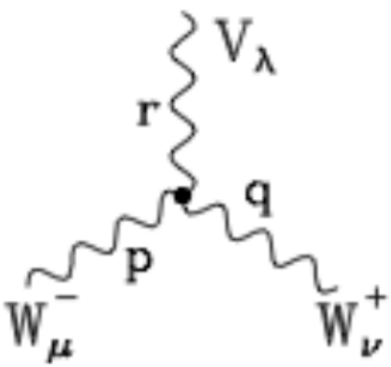
2. Longitudinal gauge-boson scattering (see below)

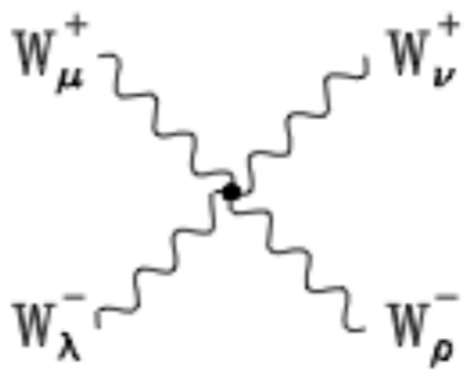
Pure gauge-boson interactions exist in SM

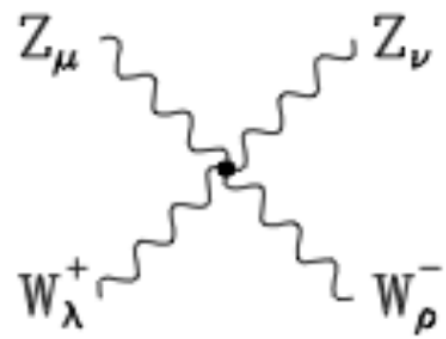
$$\mathcal{L}_{\text{gauge-fixing}} = -\frac{1}{4}W_{\mu\nu}^{\ \ i}W^{\mu\nu^i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

field-strength tensors for charged and neutral bosons

- **Triple and quartic gauge couplings can occur, and preserve gauge invariance**







etc.

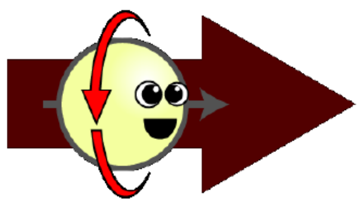
$+ig_V\ [(p-q)_\lambda g_{\mu\nu}+(q-r)_\mu g_{\nu\lambda}+(r-p)_\nu g_{\lambda\mu}]$
(all momenta incoming,
$g_A=e$, $g_Z=g_W\ \cos\theta_W$)

$+ig_W^2[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$

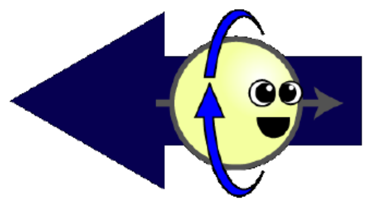
$-ig_W^2\cos^2\theta_W[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$

… and depending on polarization…

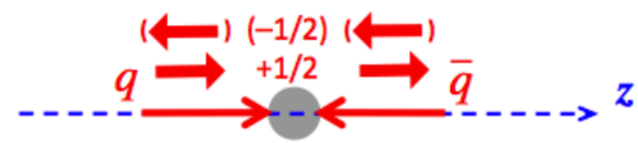
- **Photon-like polarizations are the most common in nature**
  - helicity conservation after an annihilation imposes transverse polarisation of vector-like states



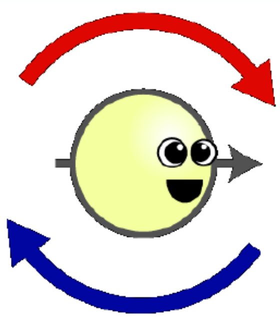
$$\varepsilon^{\mu}_{-} = \frac{1}{\sqrt{2}}(0, 1, -i, 0)$$



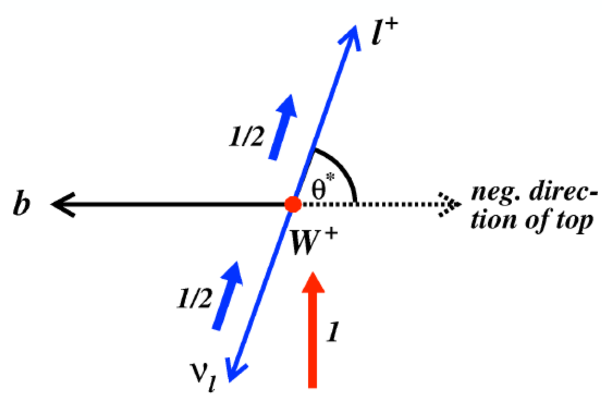
$$\varepsilon^{\mu}_{+} = \frac{1}{\sqrt{2}}(0, 1, i, 0)$$



$$|V\rangle = (1, \pm 1)$$



$$\varepsilon^{\mu}_{\mathrm{L}} = \frac{1}{m}(p_z, 0, 0, E)$$



Only massive vector bosons have longitudinal polarisations

- e.g. W's produced after a top quark decay acquire mostly (~60%) longitudinal polarisation

see lectures by M. Gallinaro
and A. Onofre

May have strange results!

The cross section for the scattering of longitudinally polarized W bosons grows with energy until it becomes unphysical

$$\sigma(W_L^+W_L^- \to W_L^+W_L^-) \sim s$$

This particular set of processes breaks unitarity for sufficiently large energy

For $s^{1/2} \simeq 1$ TeV interactions become strong unless underlying mechanism preserves unitarity

Possibility: an extra interaction with a scalar boson provides necessary cancellations

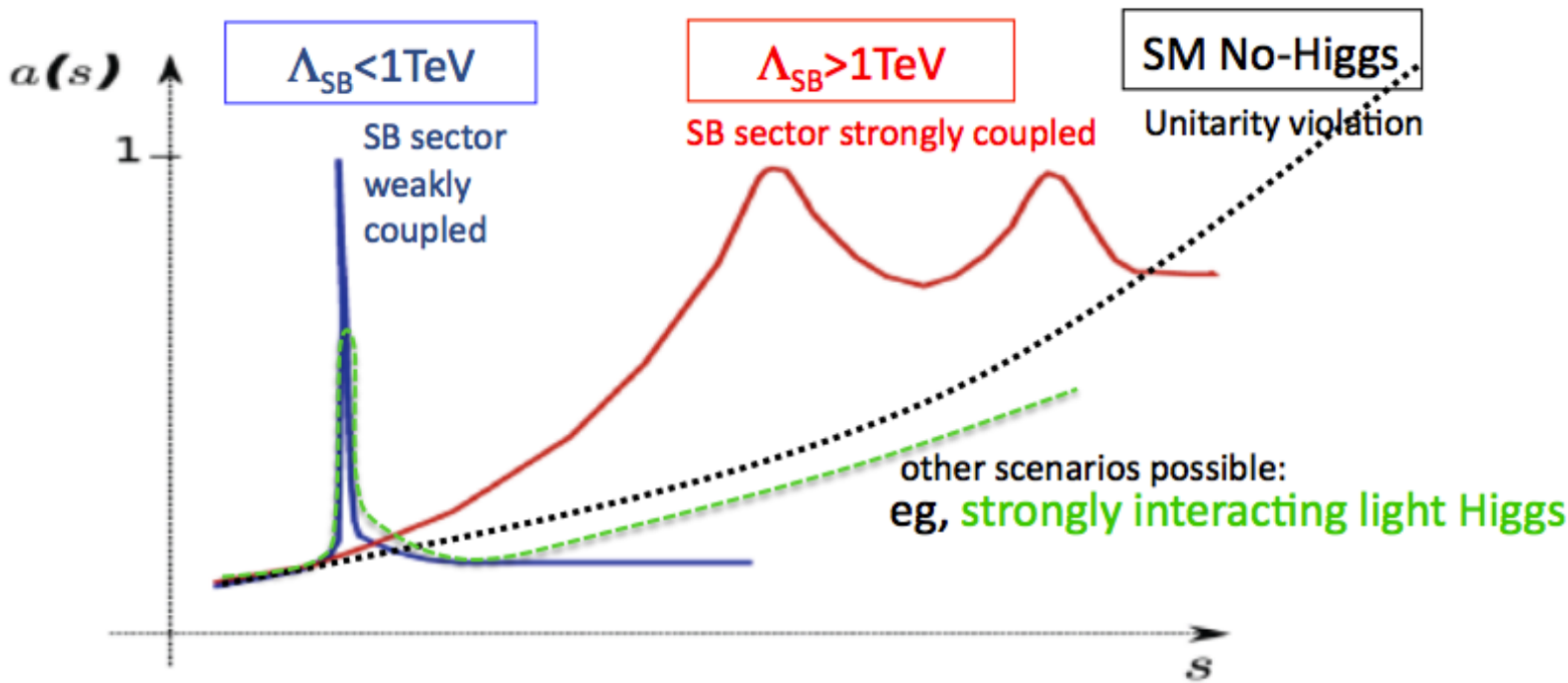
$$A(W^+W^- \to W^+W^-) \xrightarrow{s \gg M_W^2} \frac{1}{v^2}\left[s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right]$$

Possibilities (before Higgs discovery)

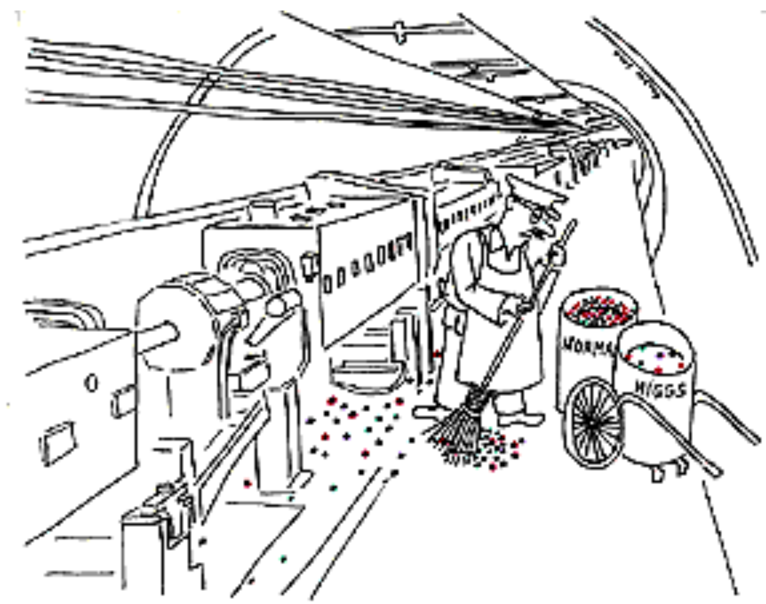
Depending on the nature of the scalar (or would it be absent)

- the scattering of vector bosons may be resonant, non-resonant, reveal strong behavior at large $s^{1/2}$

$\Rightarrow$ we need to scan a large energy range to test the mechanism which breaks EWK symmetry



The Higgs Mechanism



A new SU(2) doublet of spin-0 particles is added to the lagrangian

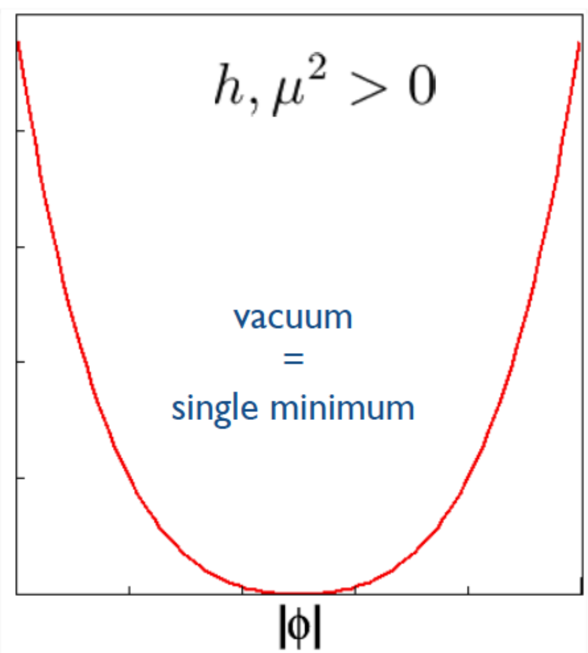
- 4 new degrees of freedom: doublet + anti-particles
- write down the interactions

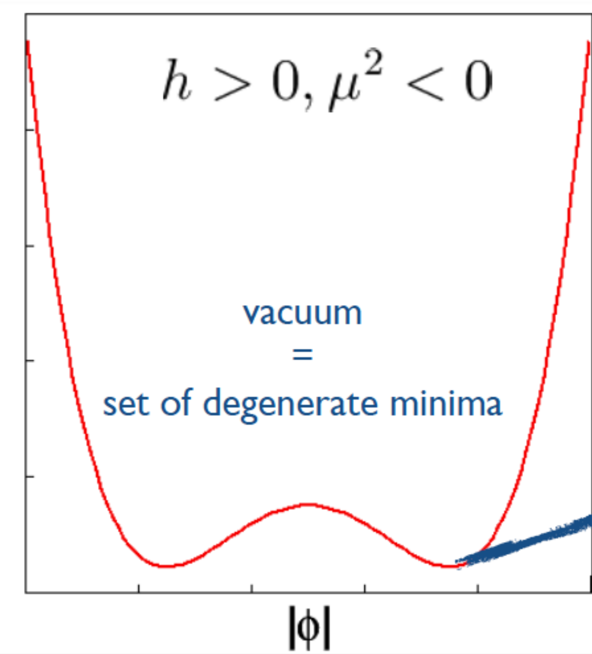
$$\begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix} \quad \begin{pmatrix} \varphi^{-} \\ \varphi^{*0} \end{pmatrix}$$

$$\mathcal{L}_{\text{higgs}} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

where V is a phase-symmetric potential

$$V(\phi) = \mu^2|\phi|^2 + h|\phi|^4$$





$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} = \frac{v}{2} > 0$$

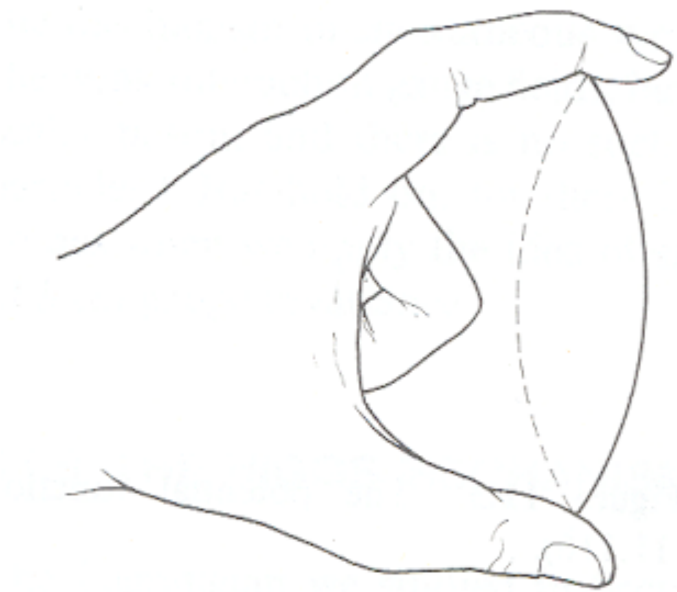
$$V(\phi_0) = -\frac{1}{4}hv^4$$

Electroweak symmetry breaking

- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass

- Electroweak symmetry is broken:
  - Photon does not have mass
  - W, Z have a large mass

- Higgs mechanism:
  - mass of W and Z results from the Higgs mechanism

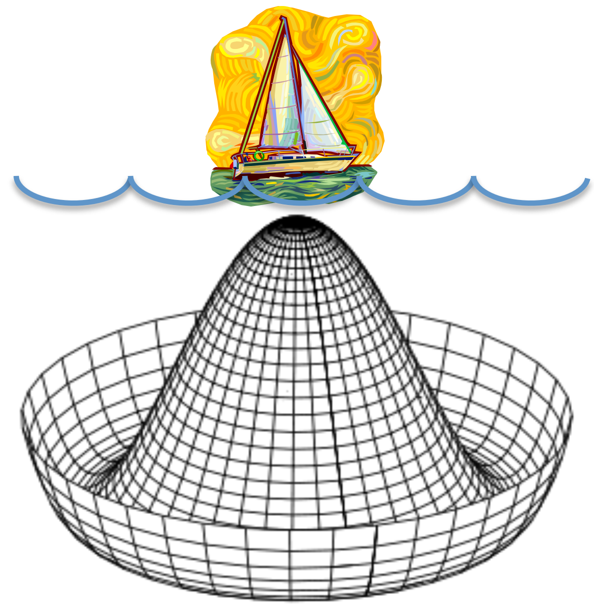


see J.Varela's lecture

Electroweak regime

Electroweak Lagrangian before spontaneous symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y.$$



Electroweak gauge bosons: B^0 W^0 $W^\pm$

$$\mathcal{L}_g = -\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$

Fermion kinetic terms

$$\mathcal{L}_f = \overline{Q}_i i \not{D} Q_i + \overline{u}_i i \not{D} u_i + \overline{d}_i i \not{D} d_i + \overline{L}_i i \not{D} L_i + \overline{e}_i i \not{D} e_i$$

$$\mathcal{L}_h = |D_\mu h|^2 - \lambda\left(|h|^2 - \frac{v^2}{2}\right)^2$$

Higgs term (note: vacuum expectation value zero before symmetry breaking)

$$\mathcal{L}_y = -y_{u\,ij}\epsilon^{ab}\, h^\dagger_b\, \overline{Q}_{ia} u^c_j - y_{d\,ij}\, h\, \overline{Q}_i d^c_j - y_{e\,ij}\, h\, \overline{L}_i e^c_j + h.c.$$

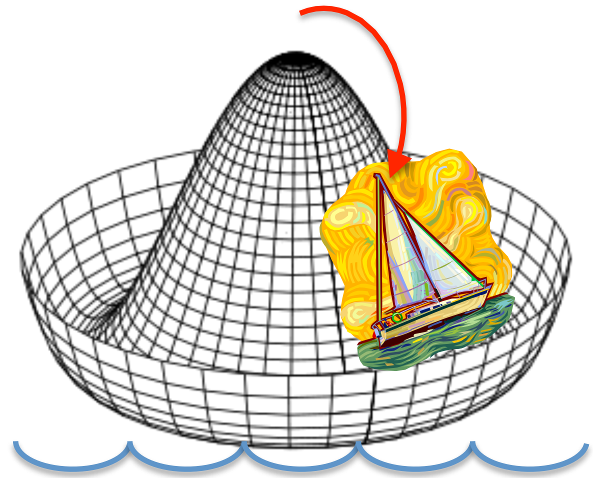
Yukawa interaction term between Higgs field and fermions

After the phase transition

After electroweak symmetry breaking

$$\mathcal{L}_{EW} = \mathcal{L}_K + \mathcal{L}_N + \mathcal{L}_C + \mathcal{L}_H + \mathcal{L}_{HV} + \mathcal{L}_{WWV} + \mathcal{L}_{WWVV} + \mathcal{L}_Y$$

Spontaneous symmetry breaking:
New bosons γ and Z^0 from W^0 and B^0

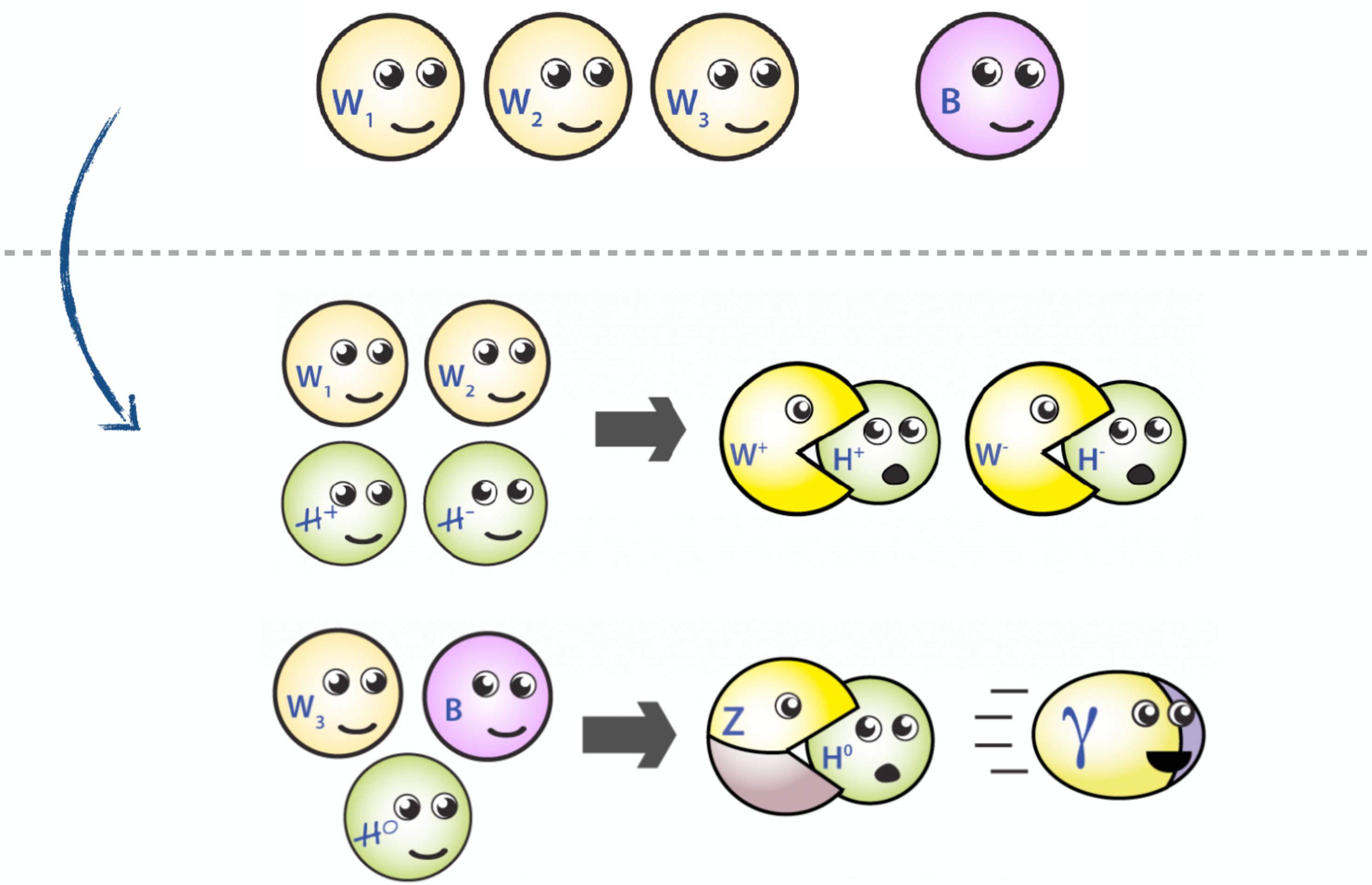


$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

Kinetic terms: **notice boson masses** for Z^0,$W^\pm$, H

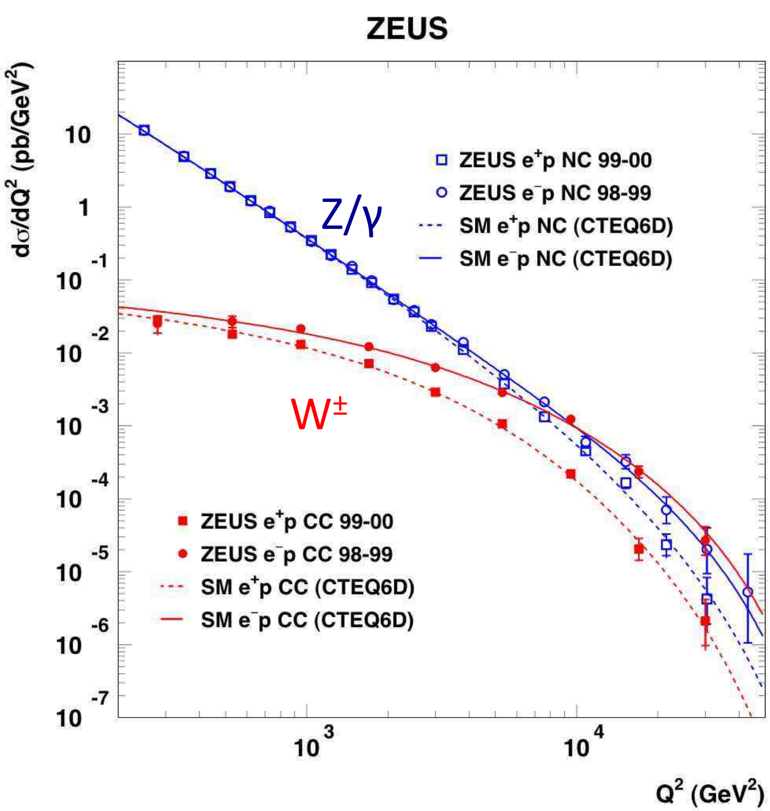
$$\mathcal{L}_K = \sum_f \overline{f}(i\partial\!\!\!/ - m_f)f - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} + \boxed{m_W^2 W^+_\mu W^{-\mu}}$$
$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \boxed{\frac{1}{2}m_Z^2 Z_\mu Z^\mu} + \frac{1}{2}(\partial^\mu H)(\partial_\mu H) - \boxed{\frac{1}{2}m_H^2 H^2}$$

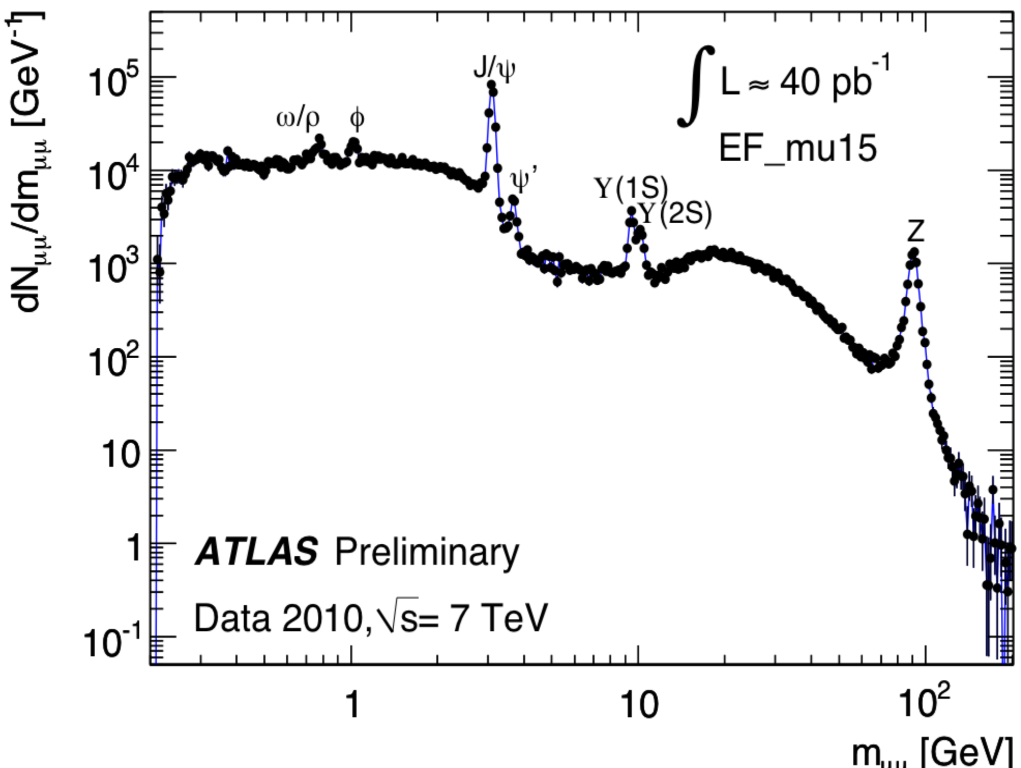
EWK Symmetry Breaking in Pictures



Why does it matter?

- Because it's real!
  - Data shows Higgs mechanism (or something like it) needed in the theory
- Because it may lead us to new discoveries and a new understanding of Nature!
  - "There is nothing so practical as a good theory" (Kurt Lewin)





Searches at: LEP, Tevatron and LHC

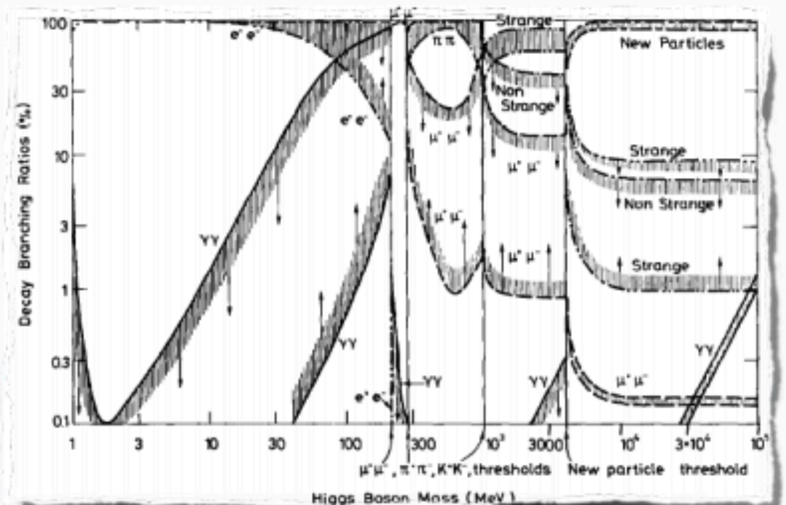
…or why did it take 50 years?

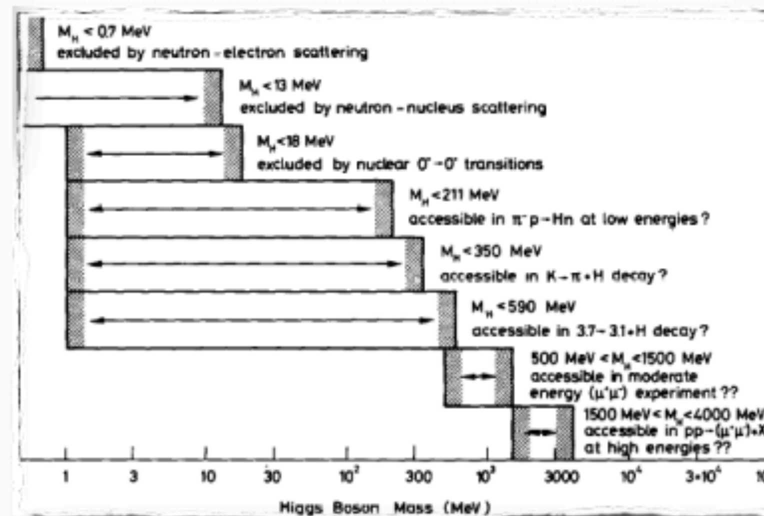
Before LEP

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975





We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Astrophysical constraints

- Effect on Cosmic Microwave background 0.1 eV < m_H < 100 eV

(Sato and Sato, 1975)

- Emission from stars: m_H > 0.7 m_e

(Sato and Sato, 1975)

Prog. Theor. Phys. Vol. 54 (1975), Sept.

Primordial Higgs Mesons and Cosmic Background Radiations

Katsuhiko SATO and Humitaka SATO

Research Institute for Fundamental Physics
Kyoto University, Kyoto

May 12, 1975

The unified theory of weak and electromagnetic interactions, proposed by Weinberg and Salam, has become a reliable one by the discovery of neutral currents in CERN and NAL. On the other hand, in this theory, the presence of neutral scalar meson, "Higgs meson", is also inevitable but its mass m_ϕ, is arbitrary in this theory.

Recently Kohler et al.[1] showed that Higgs meson cannot have a mass in the range 1.030 MeV$<m_\phi<$18.2 MeV by the experiment of 0^+ to 0^+ transition of ^{4}He. However the present day experiments, except for the above one, cannot rule out any range of mass, even a very small mass like 1 keV as discussed by Jackiw and Weinberg[2] and Resnick et al.[3]

Here, we will discuss a role of Higgs meson in the big-bang universe without such a speculative hypothesis and will give a constraint on its mass range derived from the observed cosmic background radiation.

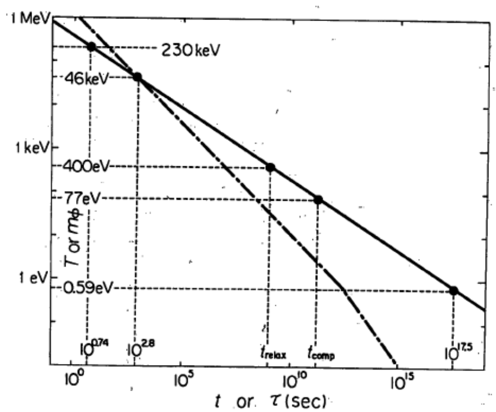


Fig. 1. Higgs meson mass (m_ϕ) versus decay life (τ) relation in a solid line and cosmic temperature (T) versus cosmic time (t) relation in a dot-dashed line. $t_{\rm relax}$ shows the end times of "free-free and Compton stage" where the spectrum always relaxes into the Planck one.

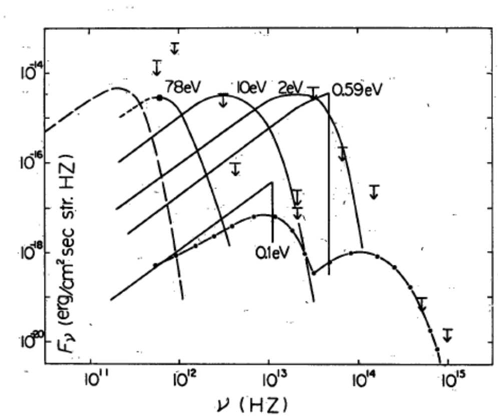


Fig. 2. Energy spectrum of the background radiation created by Higgs meson decay. The dashed curve represents the 2.7°K black body radiation. The observational upper limits of the flux are shown by the arrows and the theoretical estimations by Longair and Sunyaev[6] is shown by dot-dashed line.

Prog. Theor. Phys. Vol. 54 (1975), Nov.

Higgs Meson Emission from a Star and a Constraint on Its Mass

Katsuhiko SATO and Humitaka SATO

Research Institute for Fundamental Physics
Kyoto University, Kyoto

July 3, 1975

In the unified theory of weak and electromagnetic interaction,[1] a presence of Higgs meson is inevitable but its mass, m_ϕ, is arbitrary. In our previous paper,[2] we discussed the effect of the primordial Higgs mesons to the cosmic background radiation and obtained the constraint that the mass cannot be in the range 0.1 eV$<m_\phi<$100 eV. Here we discuss the Higgs meson emission from stars and it is argued that such a low mass range as $m_\phi<0.7\times$(electron mass) should be ruled out, otherwise this emission process would affect the evolution of stars drastically.

In the first paper, the effect of the φ→γγ decays from the primordial Higgs bosons on the cosmic microwave background spectrum are estimated, and conclusions on the excluded Higgs boson masses are drawn based on the limits on the fluxes in the CMB spectrum

In the second paper, the process γ+e→φ+e is considered and the effect to the star lifetime due to the energy loss are estimated (plus the non-observation of a γ-line from Higgs decays)

Searches in nuclear physics

The beginning of the 1970s started of with great excitement!

Two groups observed deviations in the X-ray spectrum of muonic atoms wrt QED expectations.

Dixit et al., Experimental test of the theory of muonic atoms, Phys.Rev.Lett. 27 (1971) 878-881

Walter et al., Test of quantum-electrodynamical corrections in muonic atoms, Phys.Lett. B40 (1972) 197-199

VOLUME 27, NUMBER 13 PHYSICAL REVIEW LETTERS 27 SEPTEMBER 1971

Experimental Test of the Theory of Muonic Atoms*†

M. S. Dixit and H. L. Anderson
Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

and

C. K. Hargrove and R. J. McKee
National Research Council of Canada, Ottawa, Canada

and

D. Kessler, H. Mes, and A. C. Thompson
Department of Physics, Carleton University, Ottawa, Canada

(Received 28 June 1971)

We have measured muonic x rays in the energy region 150 to 440 keV in nine elements with an absolute precision of 15 to 21 eV for transitions with small nuclear effects. Calculated transition energies were found to be consistently larger than those measured by an amount that varied from 15±16 eV at 157 keV to 137±22 eV at 438 keV. For these transitions, the principal correction to the Dirac energy is the vacuum polarization. The discrepancy, however, lies outside the expected validity of quantum-electrodynamic calculations and we are unable, at present, to offer an explanation for this effect.

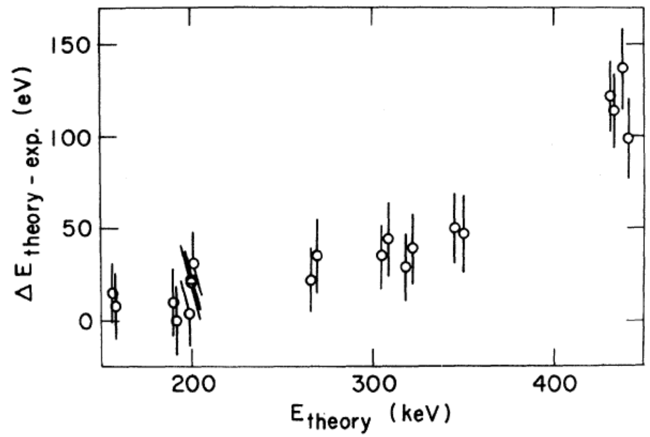


FIG. 1. The discrepancy $\Delta E_{\text{theo-expt}}$ (eV) plotted against the theoretical transition energies for 20 muonic x-ray transitions.

As expected a number of theory papers followed discussing potential sources of this effect, one being the production of a low mass Higgs boson, m_H~20 MeV

[1] S. Weinberg, Phys. Rev. Lett. 27, 1688 (1971).
[2] R. Jakiw and S. Weinberg, Phys. Rev. D 5, 2396 (1972).
[3] L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Phys. Rev. D 8, 172 (1973).
[4] M. K. Sundaresan and P. J. S. Watson, Phys. Rev. Lett. 29, 15 (1972).

Searches in particle decays

- SINDRUM Collaboration measured $\pi+ \rightarrow e^+ \nu e^+ e^-$ and searched for $H \rightarrow e^+ e^-$

[excluded 10 MeV < M_H < 110 MeV]
SINDRUM spectrometer experiment at the Paul Scherrer Institute (PSI) 590 MeV proton cyclotron.
Measurement of the Decay $\pi+ \rightarrow e+\nu e+e-$ and Search for a Light Higgs Boson
SINDRUM Collaboration (S. Egli (Zurich U.) et al.), Phys.Lett. B**222** (1989) 533

- CUSB Collaboration $\Upsilon \rightarrow H\gamma$

[excluded $2m_\mu < M_H$ < 5-6 GeV]
Investigated the radiative decay dependent on high order corrections of various states of the Y into a Higgs boson.
The search for a monochromatic photon sample from the decay $\Upsilon \rightarrow \gamma + X$.
It turned out that first order QCD corrections reduce the lowest order calculation by about 50%, and the effects of higher order corrections or relativistic corrections were not known.
CUSB also searched for Y decays to a photon plus a massless, invisible scalar.

- Crystal Ball collaboration looked for $J/\psi \rightarrow \gamma+$ massless scalar

The data were collected with the Crystal Ball Detector at the Stanford Linear Accelerator Center e'e storage ring facility SPEAR at the peak of the J/ψ resonance

[Edwards et al, Upper Limit for $J/\psi \rightarrow \gamma$+Axion, Phys.Rev.Lett. 48 (1982) 903]
These two results CUSB and Crystal Ball together excluded a massless and very light Higgs, which is also subject to radiative correction uncertainties

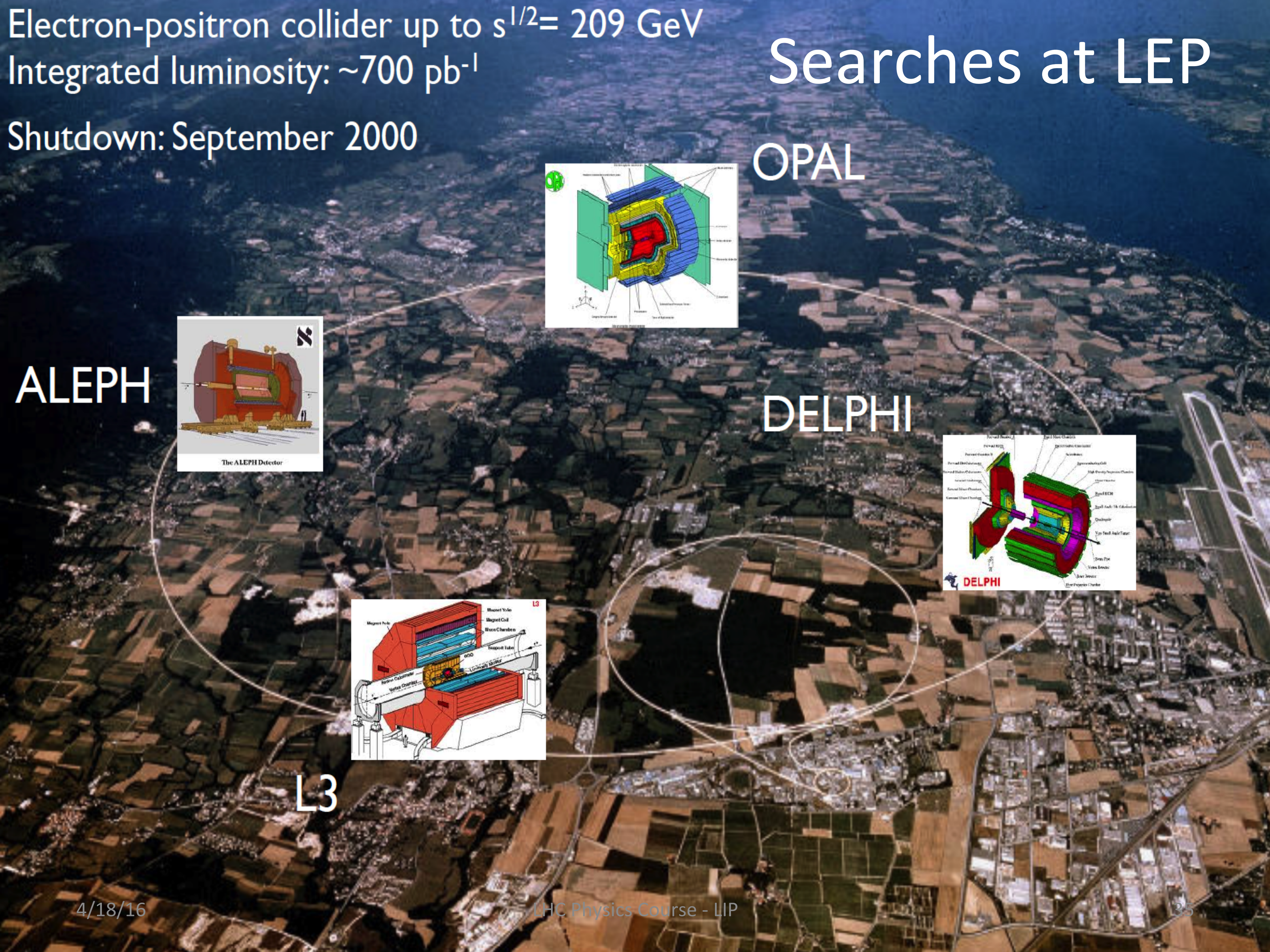
- CERN-Edinburgh-Orsay-Mainz-Pisa-Siegen (NA31) $K^0L \rightarrow \pi^0 H(\rightarrow ee)$

[excluded M_H < 50 MeV]
The NA31 experiment at the CERN Super Proton Synchrotron (SPS) searched for Higgs boson decays in e^+e^- in the decay $K^0_L \rightarrow \pi^0 H$.
These searches severely constrain the Higgs boson mass in the domain below 50 MeV by conferring an upper limit on the product of the branching ratios $Br(K0L \rightarrow \pi 0H) \times Br(H \rightarrow e+e-)$ of approximately 2×10^{-8}
Search for a Neutral Higgs Particle in the Decay Sequence $K0L \rightarrow \pi 0H$ and $H \rightarrow e^+e$
NA31 Collaboration (G.D. Barr (CERN) et al.), Phys.Lett. B235 (1990) 356

Searches at LEP

Electron-positron collider up to $s^{1/2} = 209$ GeV
Integrated luminosity: ~700 pb^{-1}

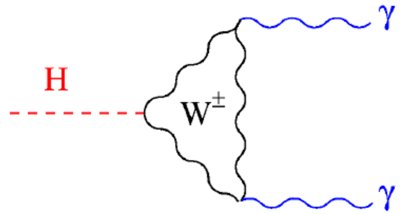
Shutdown: September 2000



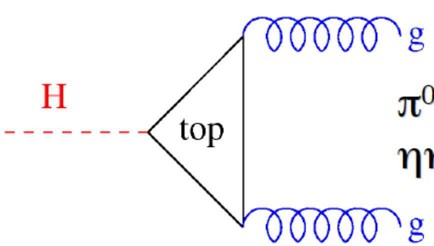
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

- ❑ $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;



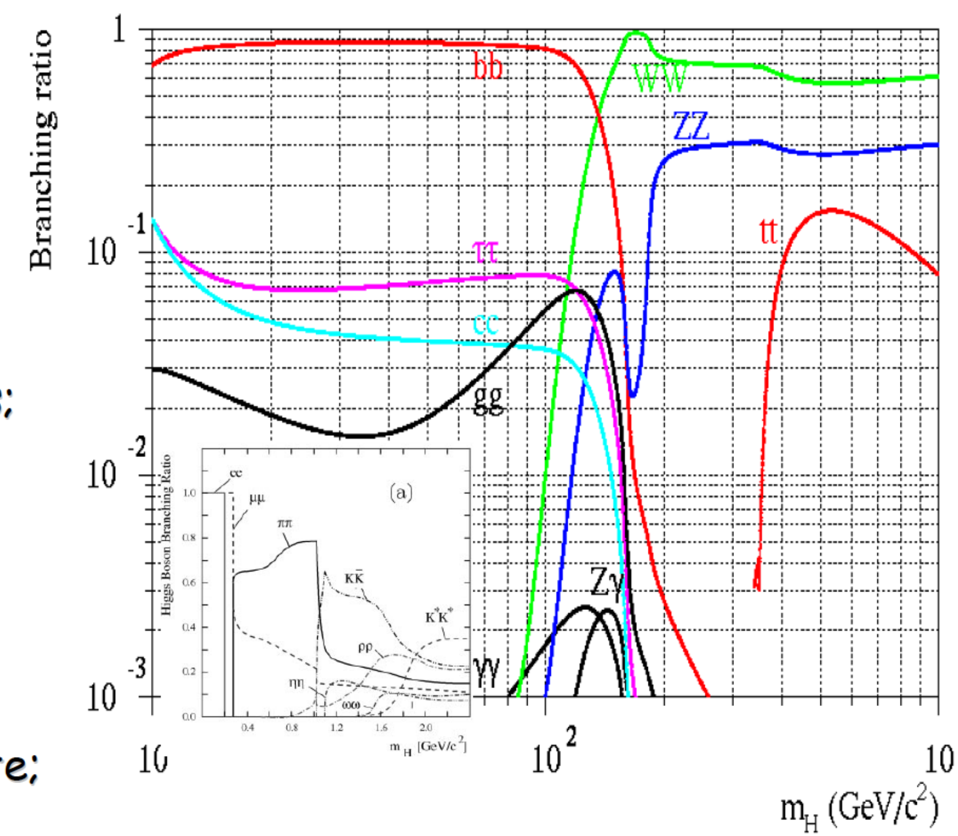
- ❑ $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- ❑ $m_H < 3$ - 4 GeV: $H \to gg$ dominates;



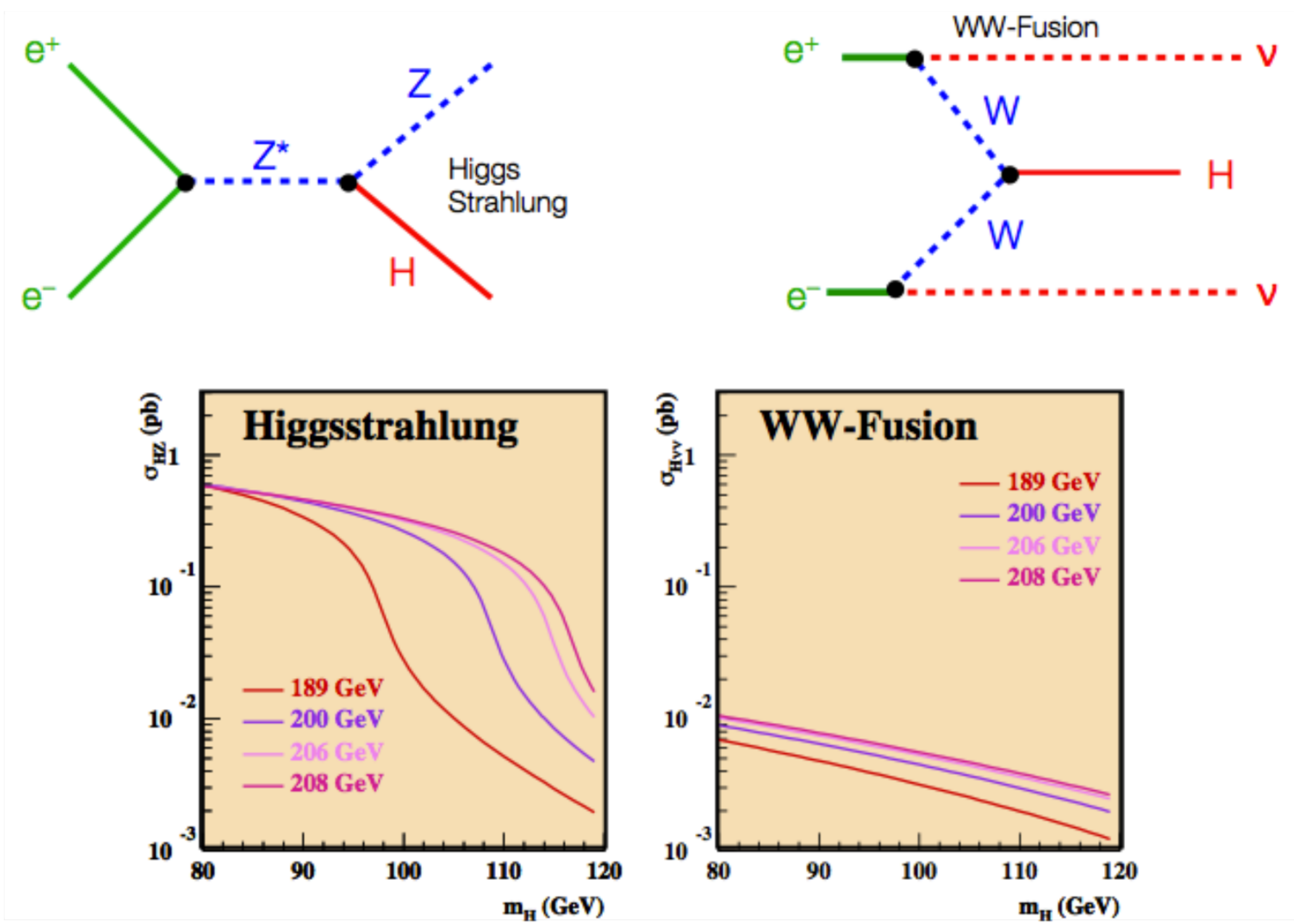
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, ... etc

- ❑ $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate;

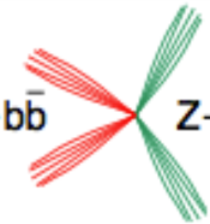
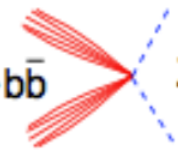
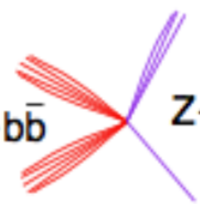
- ❑ $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Higgs decays: focus on 3rd generation

$H \to b\bar{b}$  $Z \to q\bar{q}$	4-jets	51%	$WW \to qqqq$ $ZZ \to qqqq$ QCD 4-jets
$H \to b\bar{b}$  $Z \to \nu\bar{\nu}$	missing energy	15%	$WW \to ql\nu$ $ZZ \to bb\nu\nu$
$H \to b\bar{b}$  $Z \to \tau^+\tau^-$	τ-channel	2.4%	$WW \to q\tau\nu$ $ZZ \to bb\tau\tau$ $ZZ \to qq\tau\tau$ QCD low mult. jets
$H \to \tau^+\tau^-$  $Z \to q\bar{q}$	τ-channel	5.1%	
$H \to b\bar{b}$  $Z \to e^+e^-$, $\mu^+\mu^-$	lepton channel	4.9%	$ZZ \to bbee$ $ZZ \to bb\mu\mu$

Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

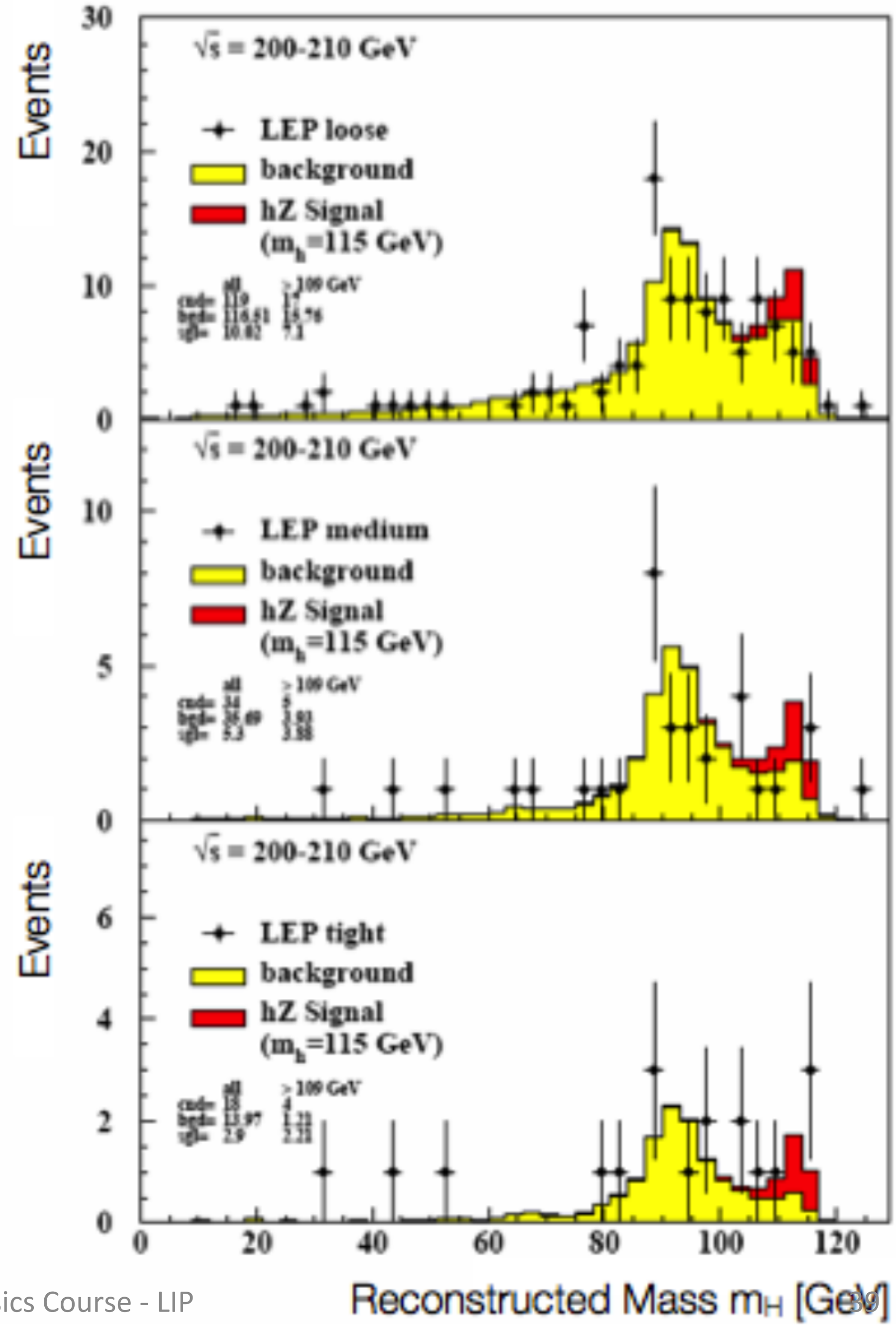
Expectation for m_H=115 GeV

- 8.4 events

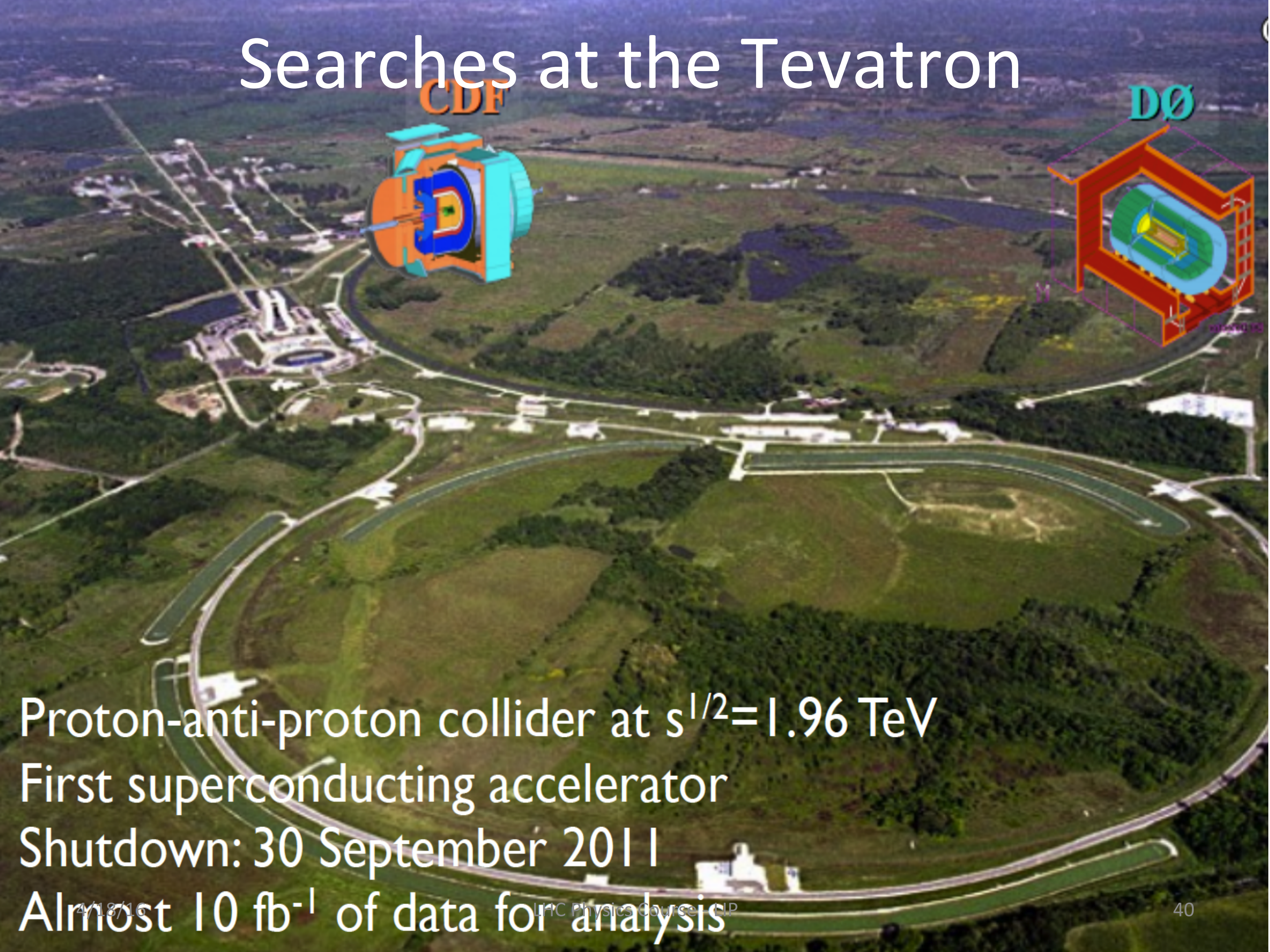
Corresponding excess was not observed

Final verdict from LEP

m_H>114.4 GeV @ 95% CL

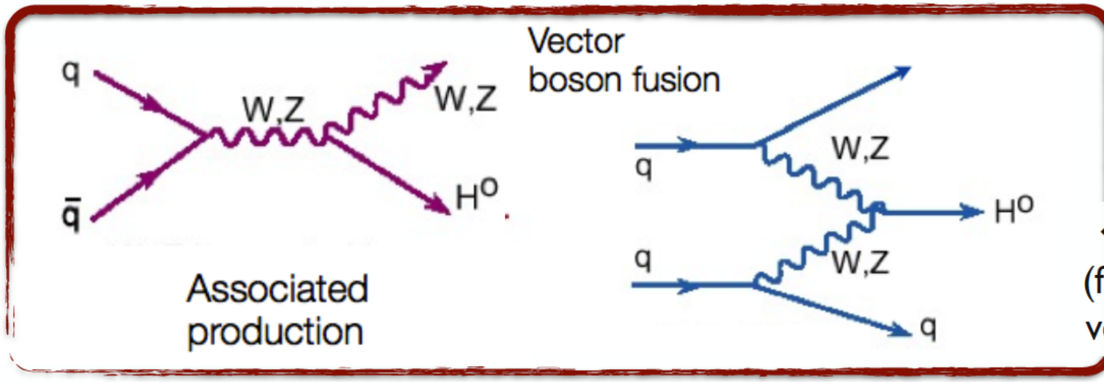


Searches at the Tevatron

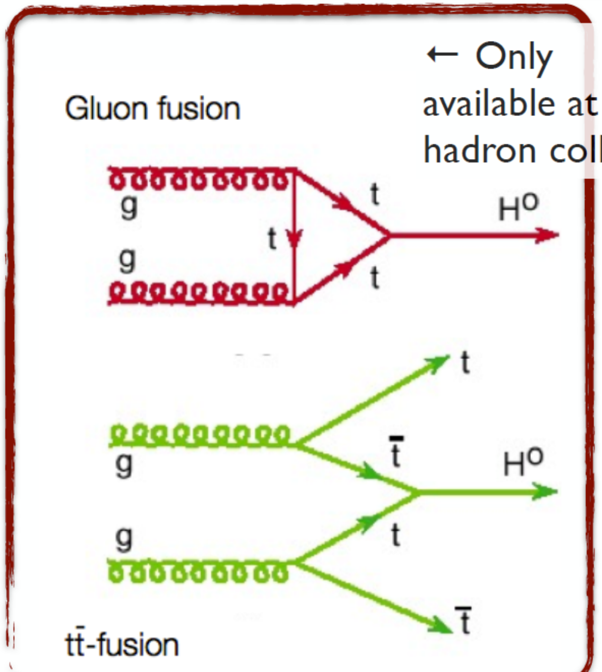


Proton-anti-proton collider at $s^{1/2}$=1.96 TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

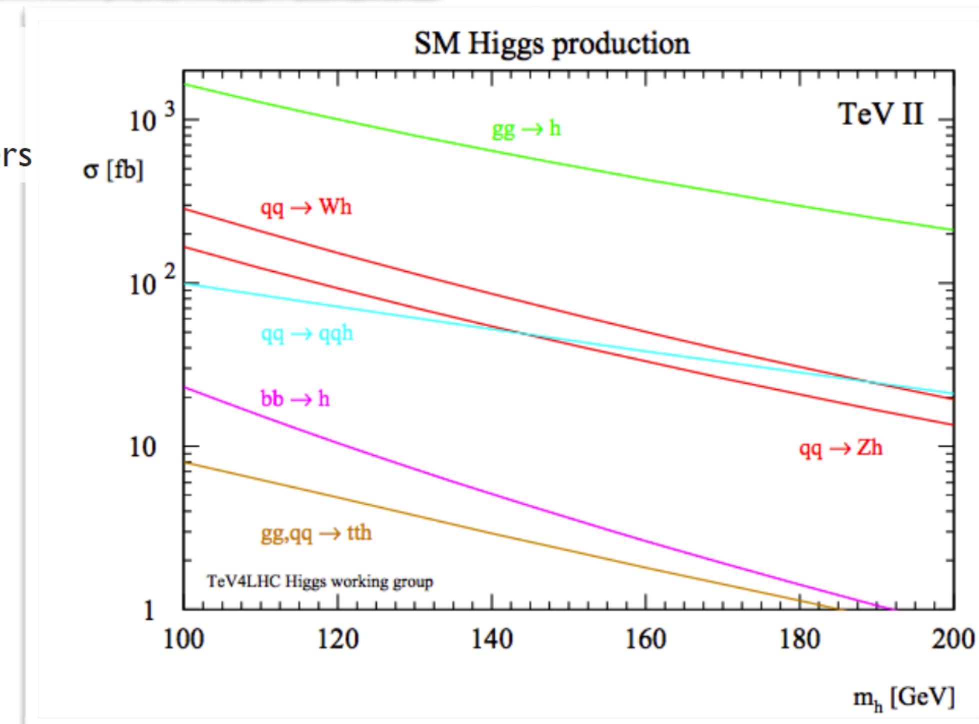
Higgs production at the Tevatron



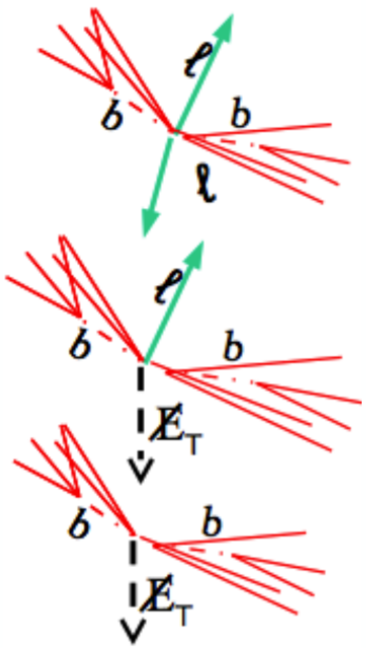
← (fermion annihilation and vector boson scattering)

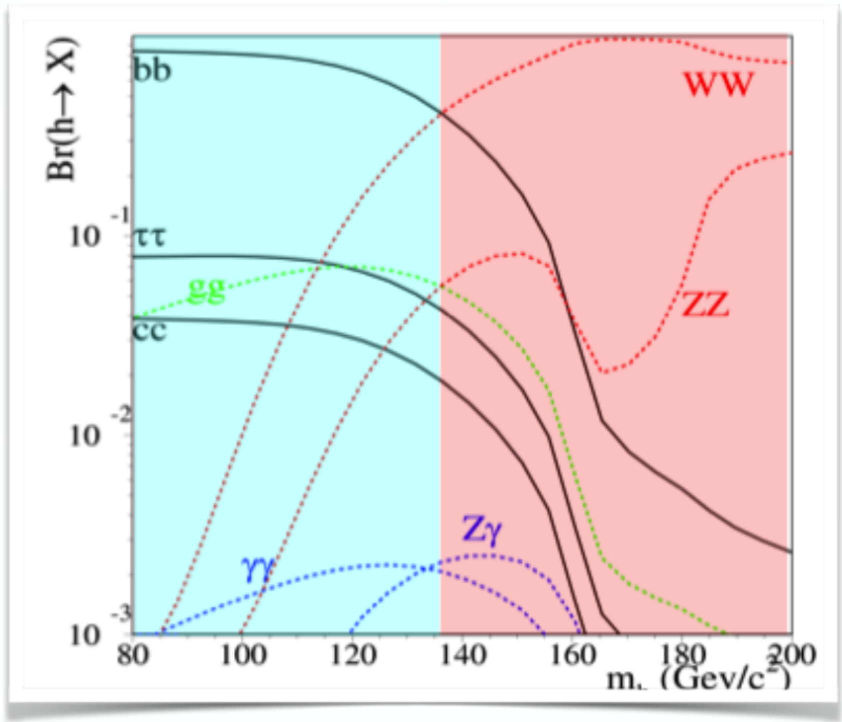


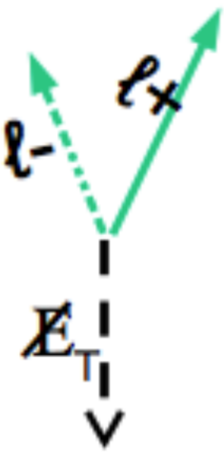
← Only available at hadron colliders



Most sensitive searches





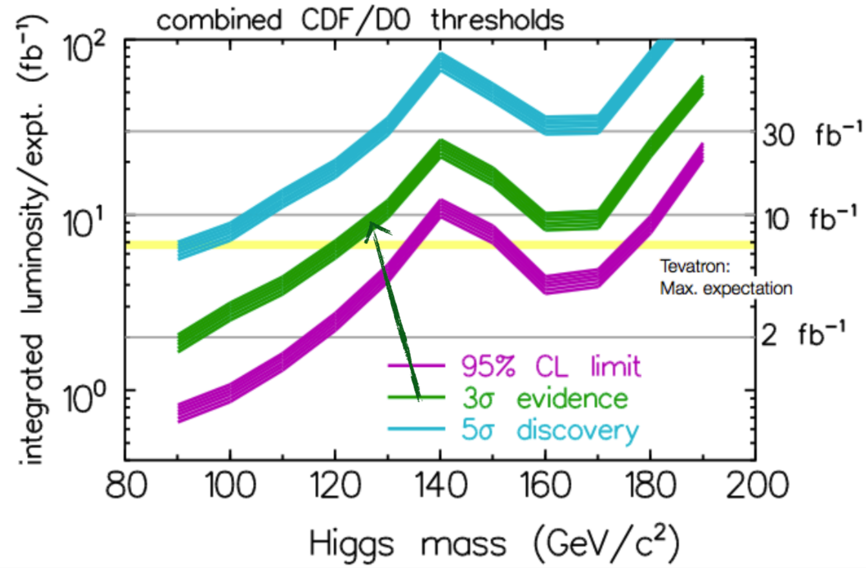


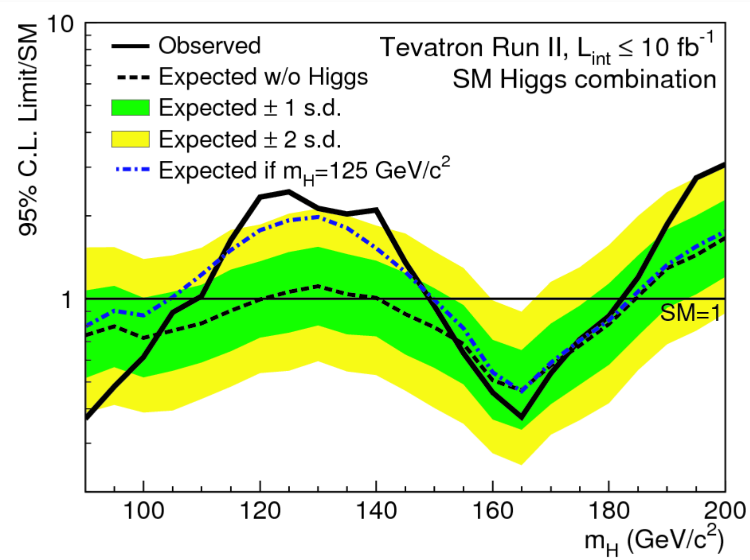
- At **low mass use h→bb final states**
  - associated production with W or Z
  - challenging: b-tagging, jet resolution
  - backgrounds: top, W/Z+heavy flavour di-bosons

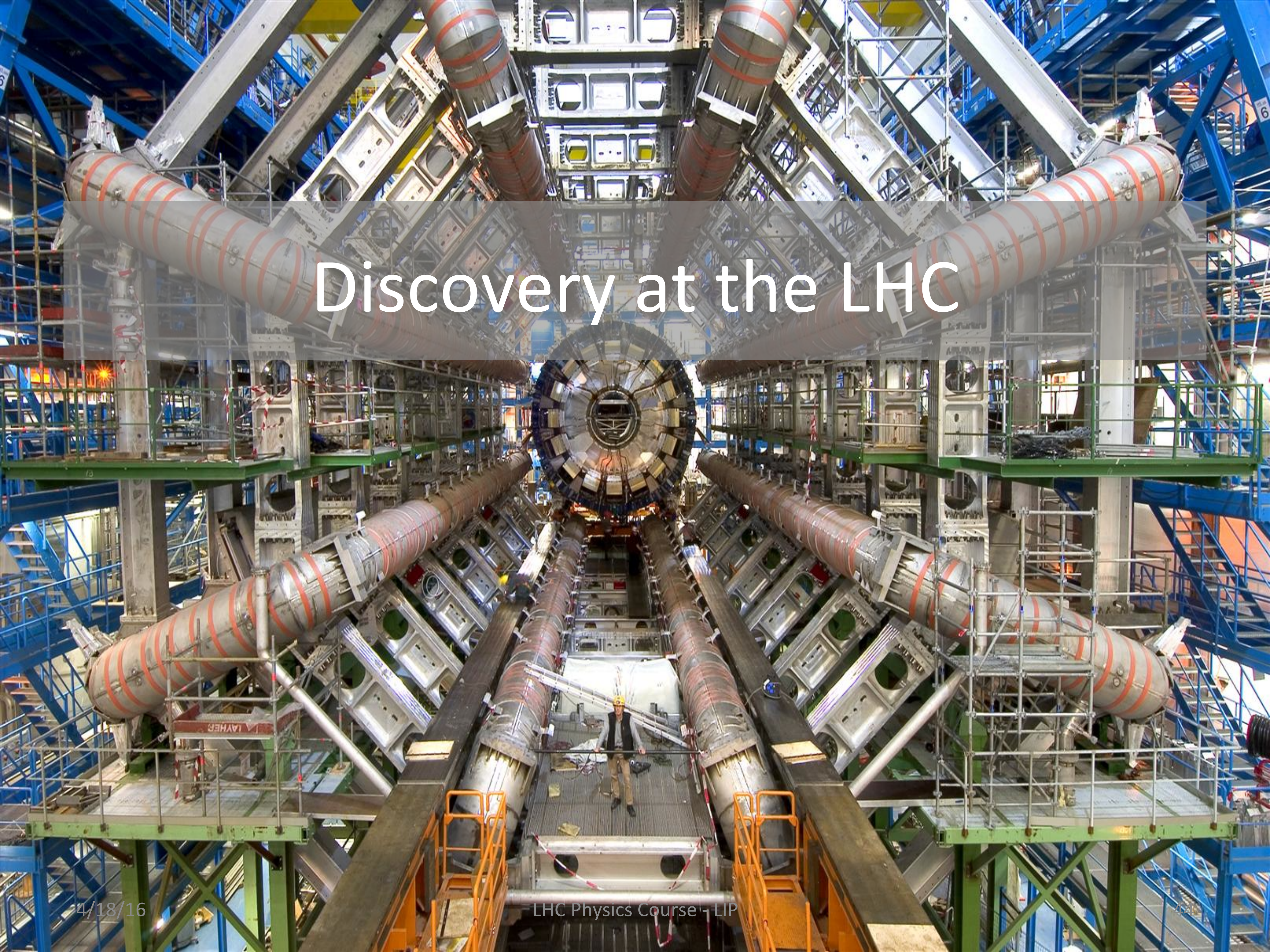
- At **high mass use H→WW final states**
  - benefit from high gluon-gluon cross section
  - challenging: lepton acceptance, missing energy
  - backgrounds: top, di-bosons

The final stand of the Tevatron

- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels
- By that time the LHC was collecting data and analysing it very fast
- The CDF and D0 experiments obtained a significant excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV
- Not enough to claim discovery, but consistent with the LHC results

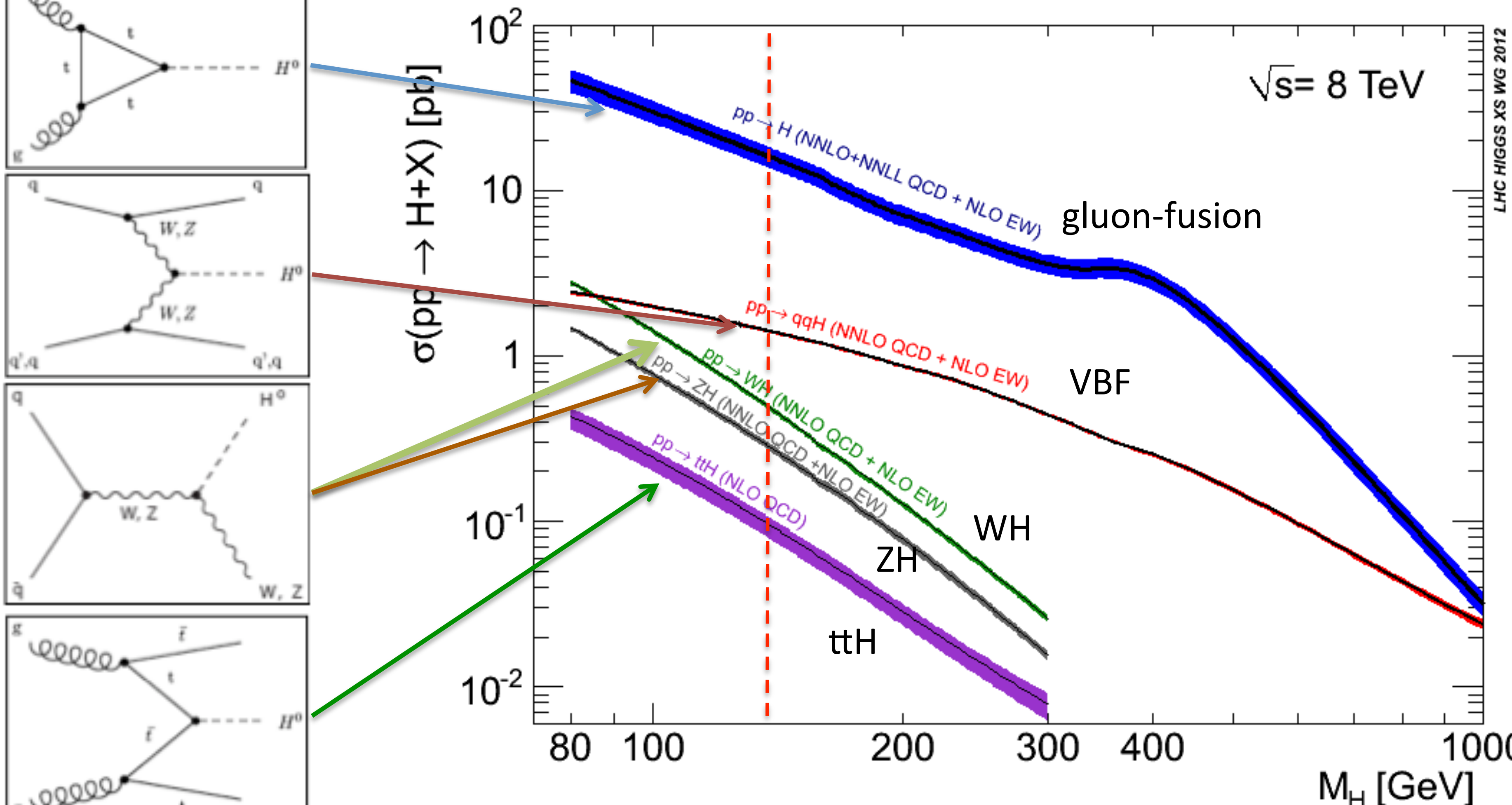




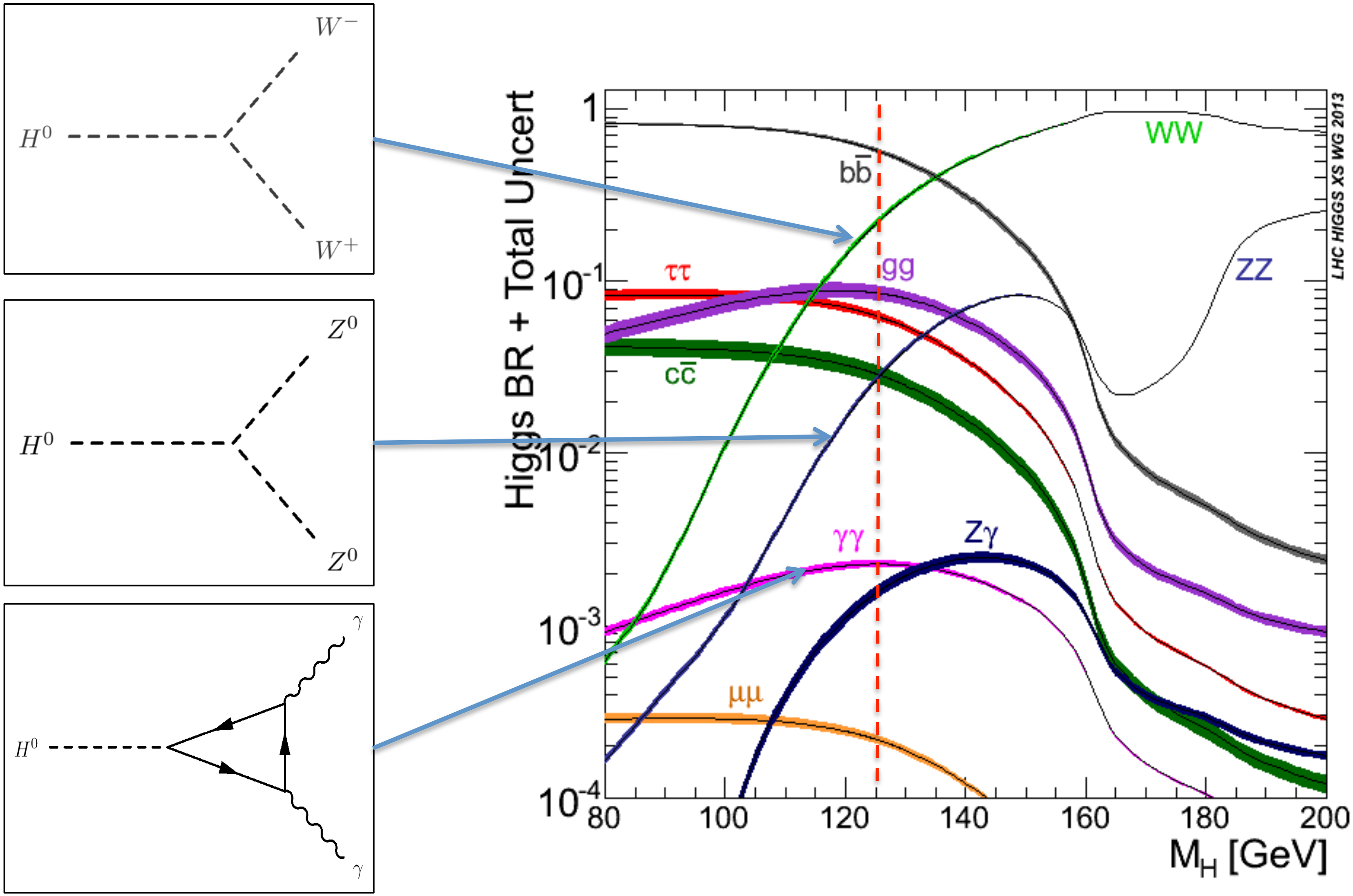


Discovery at the LHC

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



See previous lectures



W^-
H^0
W^+
Z^0
H^0
Z^0
γ
H^0
γ
Higgs BR + Total Uncert
LHC HIGGS XS WG 2013
WW
$b\bar{b}$
ττ
gg
ZZ
$c\bar{c}$
γγ
Zγ
μμ
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]

Discovery time!

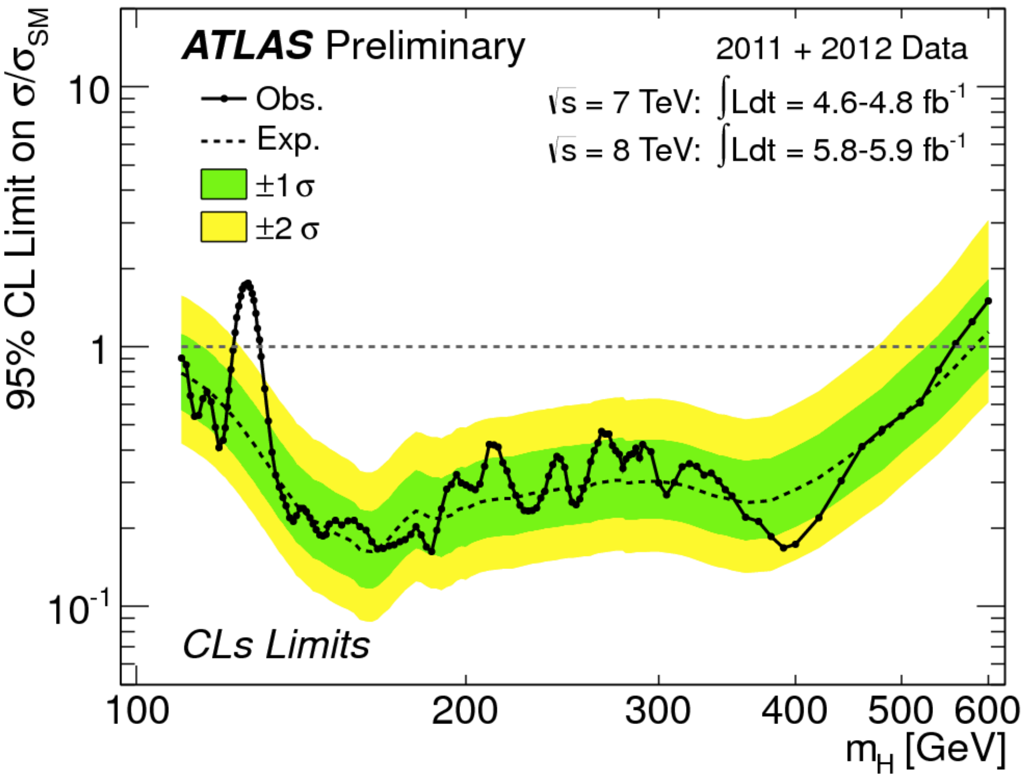
The Brazil Plot

Expected:

- Upper limit on σ(S+B)/σ(B) at 95% CL in Monte Carlo assuming B-only hypothesis

Observed:

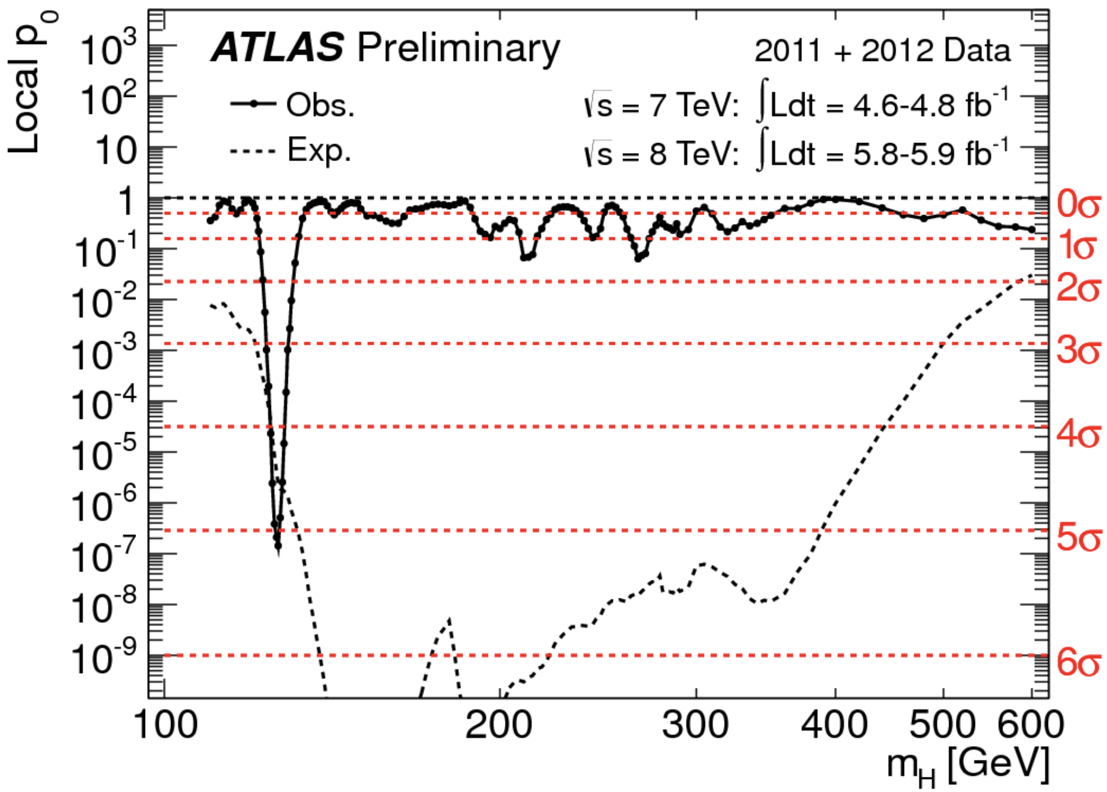
- Upper limit on σ(S+B)/σ(B) at 95% CL seen in data assuming B-only hypothesis



The *p0* Discovery Plot

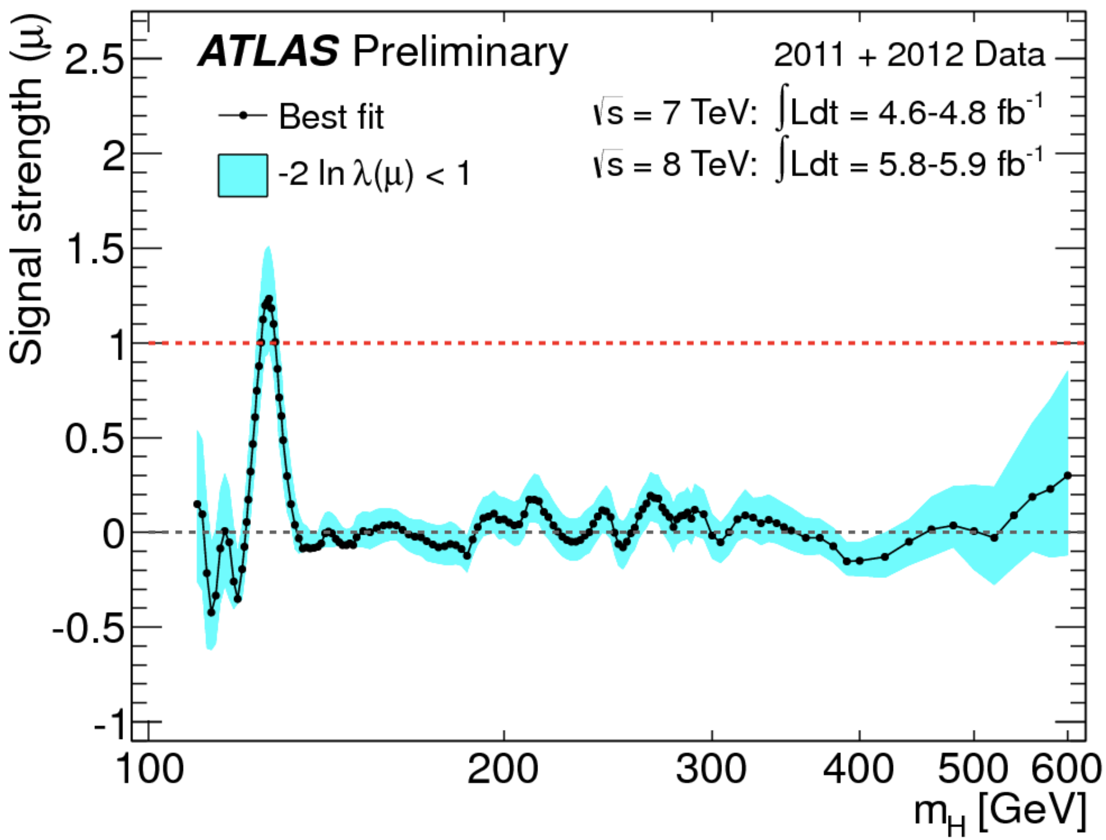
- **p0** is the probability that the background fluctuates to look like signal

- Translated into the one-sided Gaussian probability



The Cyan Band Plot – signal strength

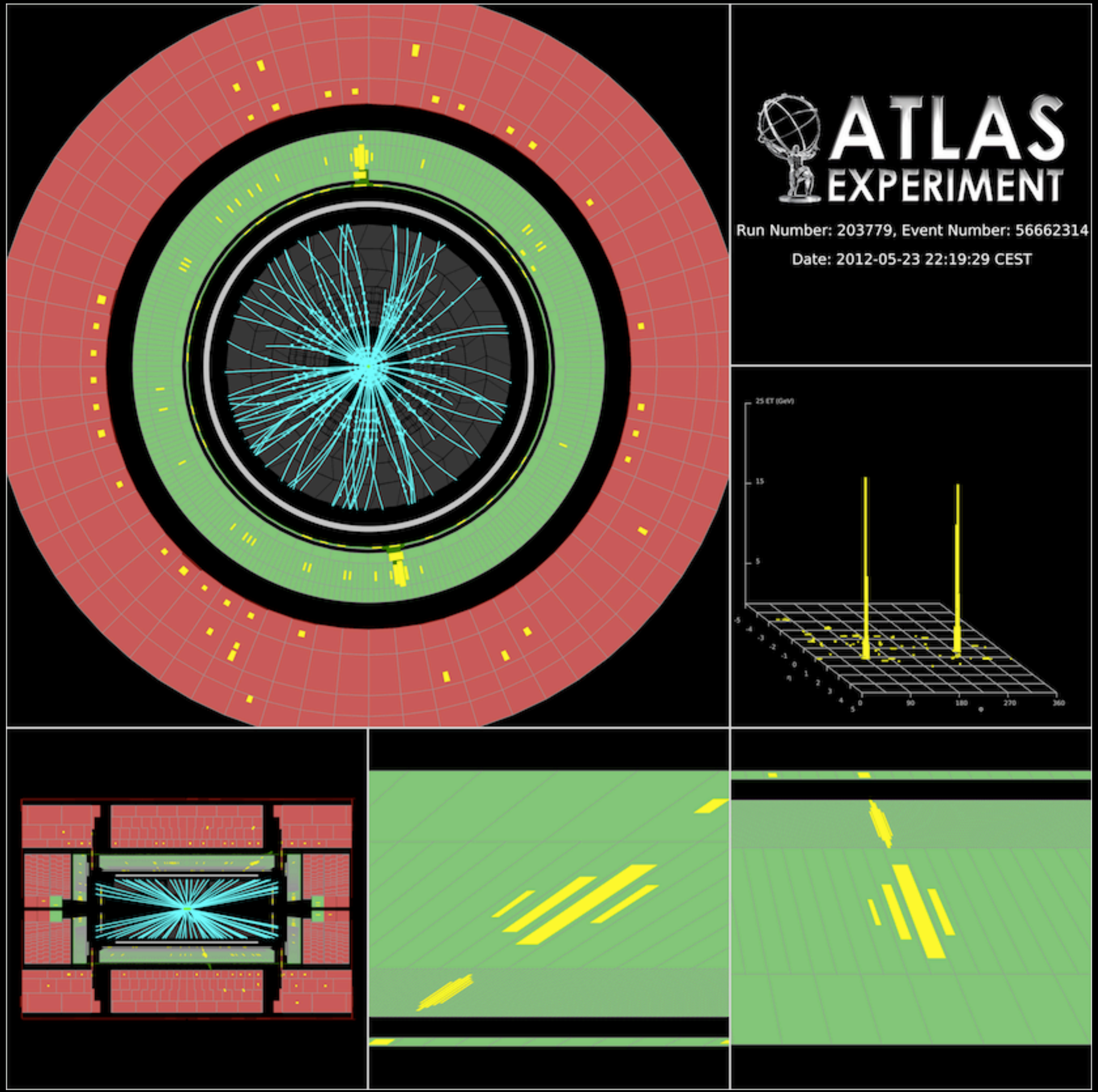
- Best fit of μ=σ(S+B)/σ(B) to data
- Error bands important…. As usual!



Blind Analysis

- To avoid unintended experimenter's bias in search for the Higgs boson
- The analysis strategy, event selection & optimization criteria for each Higgs search channel were **fixed** by looking at data control samples before looking at the signal sensitive region
  - Logistically quite painful
  - But the right thing to do !

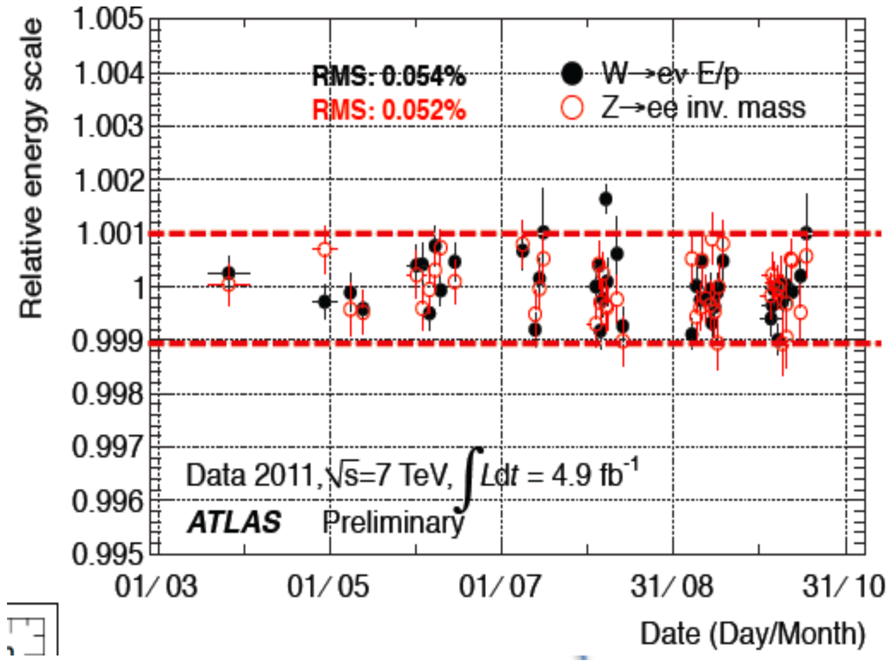
H->γγ

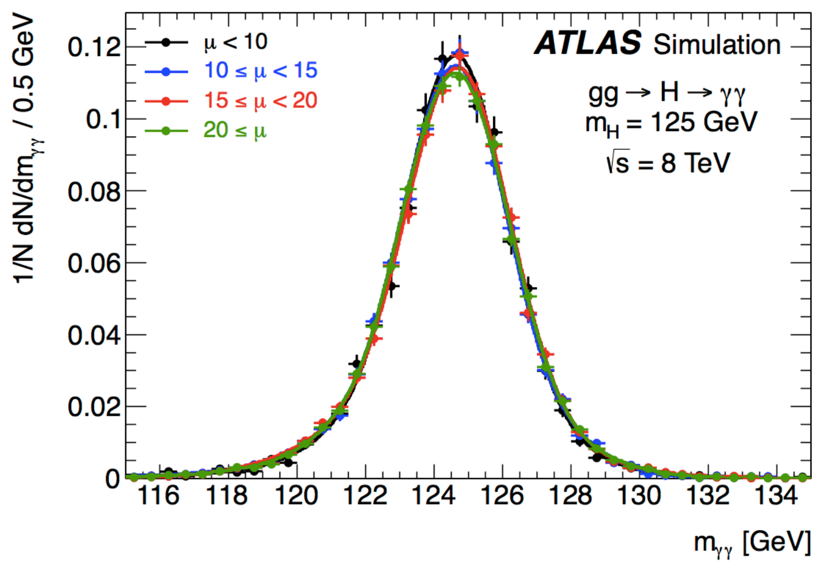


- $\sqrt{s}$ = 8 TeV
- *ET1 = 62.2 GeV*
- *ET2 = 55.5 GeV*
- *E1 = 66.9 GeV*
- *E2 = 99.2 GeV*
- *Mγγ = 126.9 GeV*

Diphoton mass reconstruction

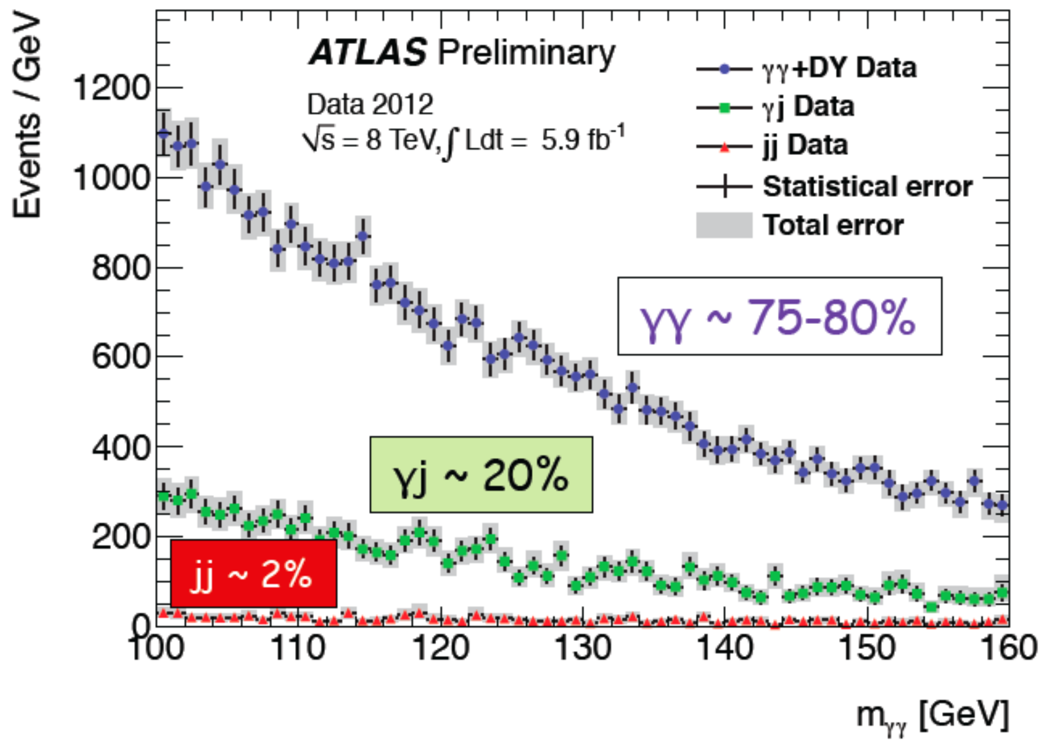
- $m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$
- Understanding of calorimeter E response (from Z, J/ψ -> ee, W -> eν data and MC):
  - E-scale at m_Z known to ~ 0.3%
  - Linearity better than 1% (few-100 GeV)
  - “Uniformity” (constant term of resolution): ~ 1% (2.5% for 1.37<|η|<1.8)
- High pile-up: many vertices distributed over
- σZ (LHC beam spot) ~ 5-6 cm => difficult to know which one has produced the γγ pair
- Primary vertex from:
  - EM calorimeter longitudinal (and lateral) segmentation
  - Tracks from converted photons
- Calorimeter pointing alone reduces vertex uncertainty from beam spot spread of ~ 5-6 cm to ~ 1.5 cm and is robust against pile-up
  - Good enough to make contribution to mass
- Resolution from angular term negligible
- Addition of track information (less pile-up robust) needed to reject fake jets from pile-up in 2j/VBF category





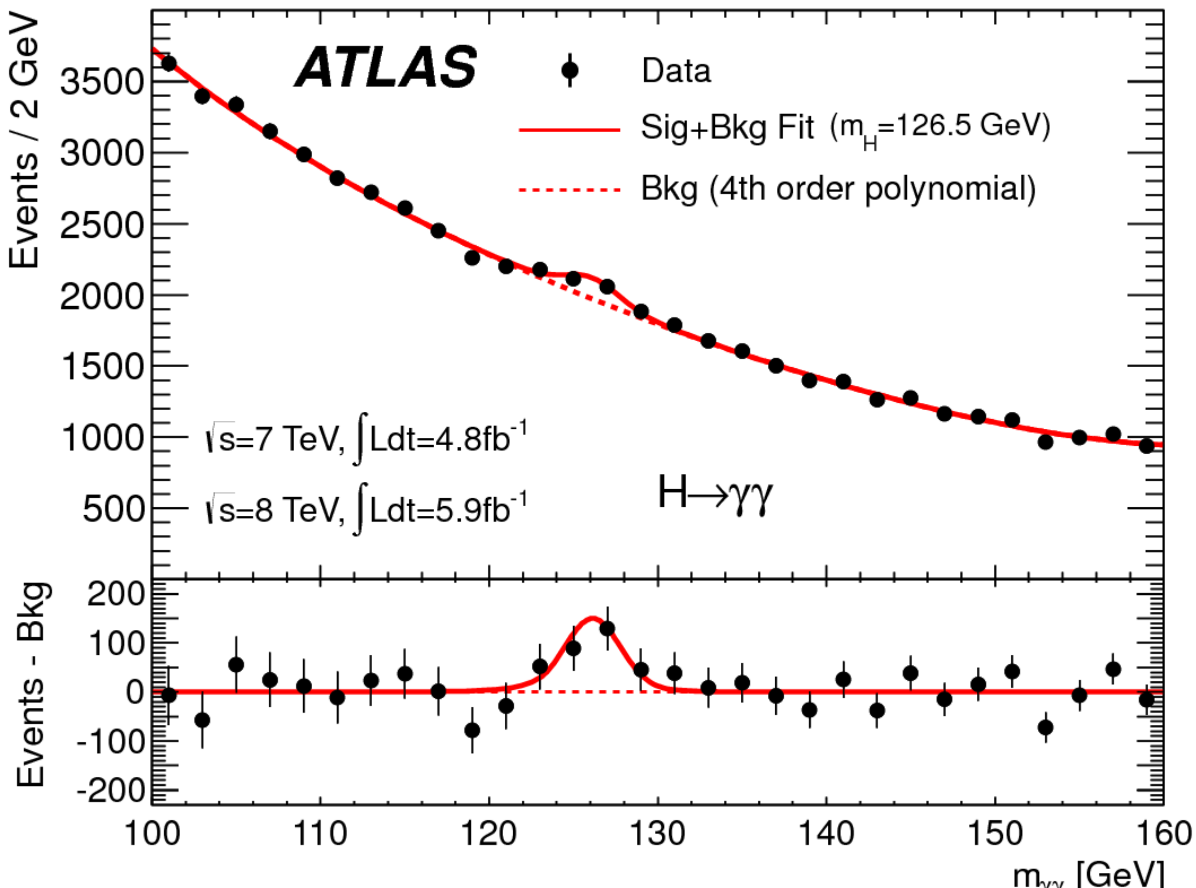
Backgrounds

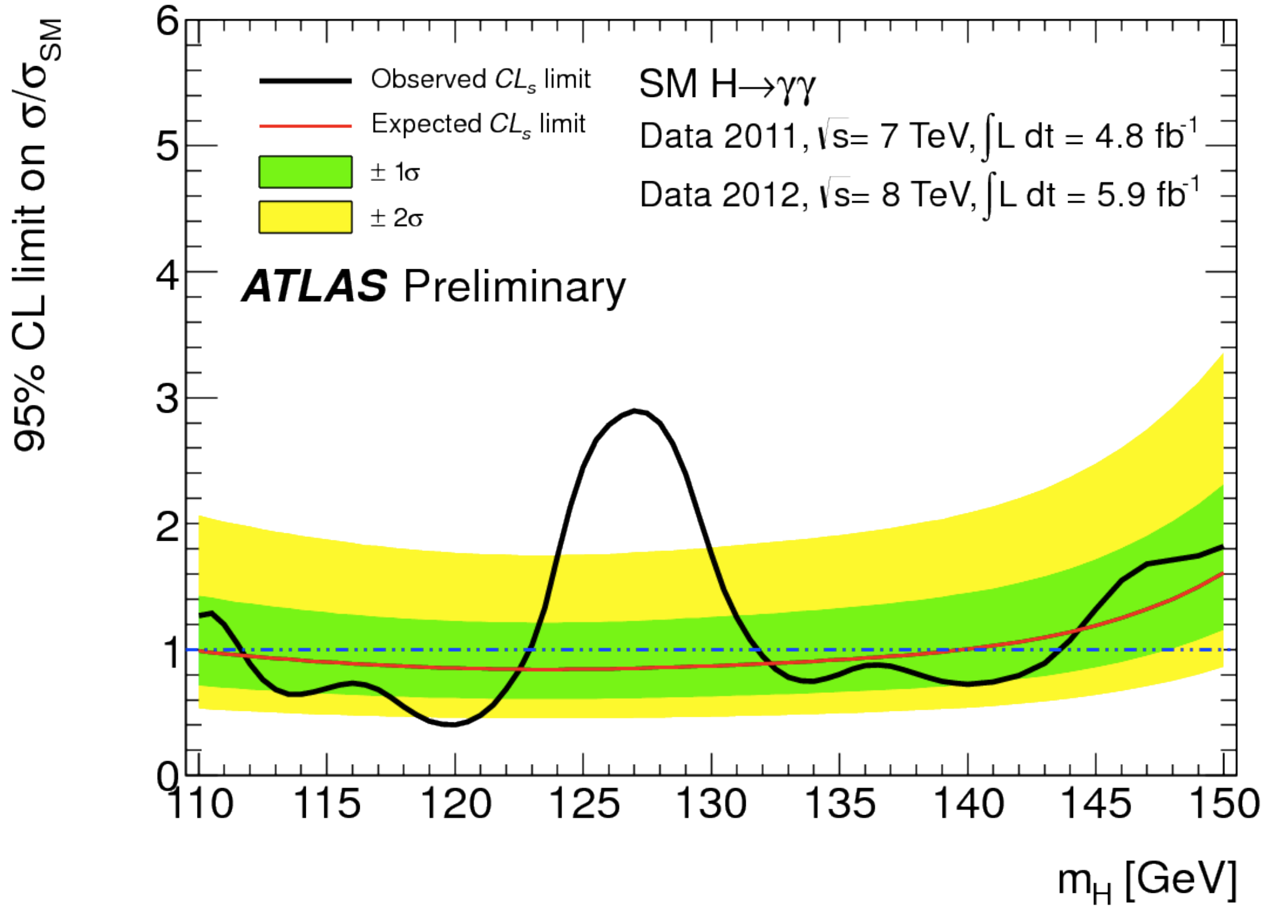
- Main backgrounds:
  - Continuum γγ production
  - Followed by γ mis-identification
- Smooth mγγ spectrum
  - Use sidebands to fit sum of backgrounds
- Confirm each background source by data-driven techniques
  - E.g. reverse quality cuts on photon identification



Results

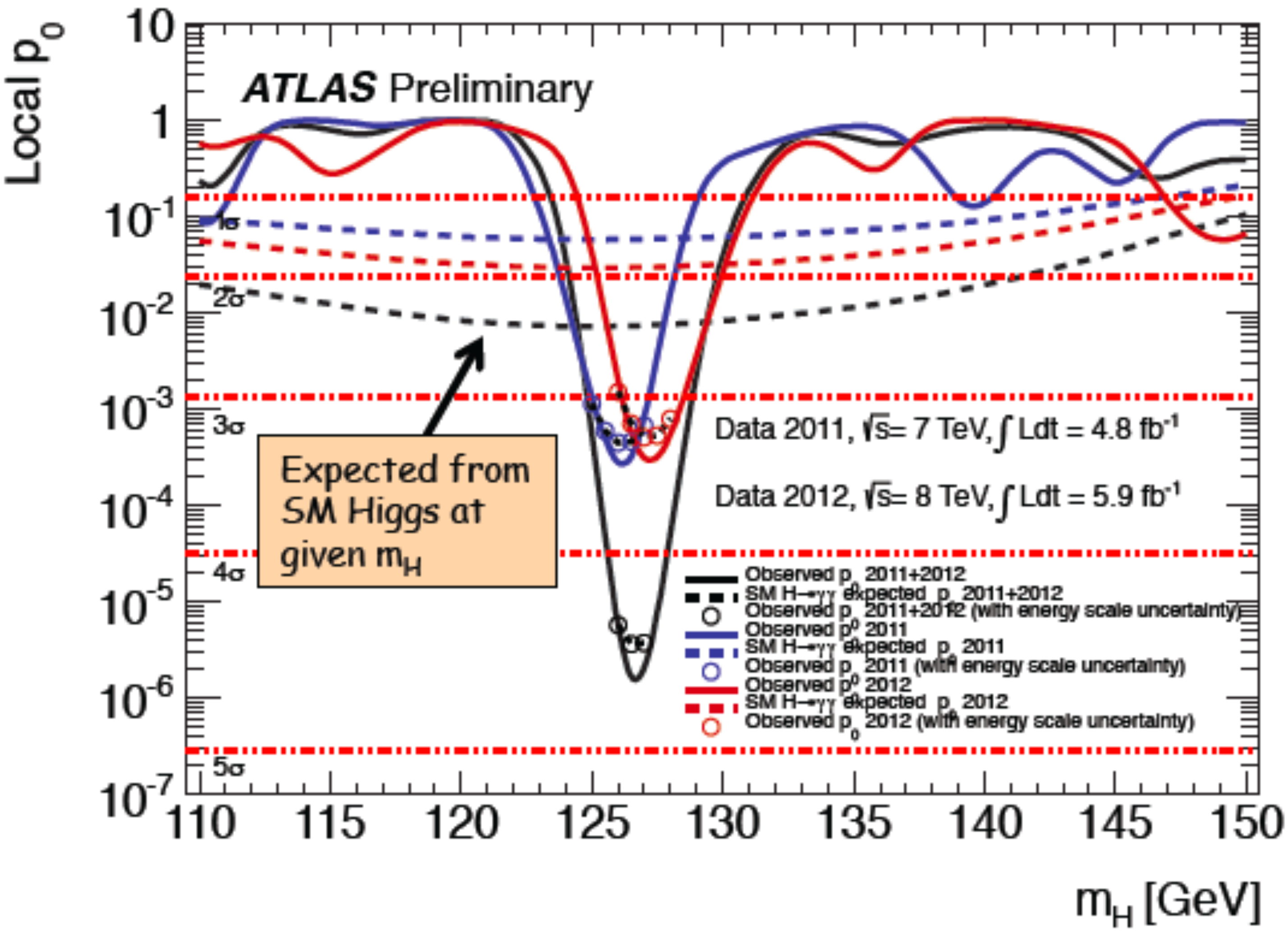
Combined $m_{\gamma\gamma}$ from all 10 categories and 7/8 TeV data





- Exclusion at 95% C.L. :
- Expected: 110 < mH < 139.5 GeV
- Observed: 112 < mH < 122.5 GeV 132 < mH < 143 GeV

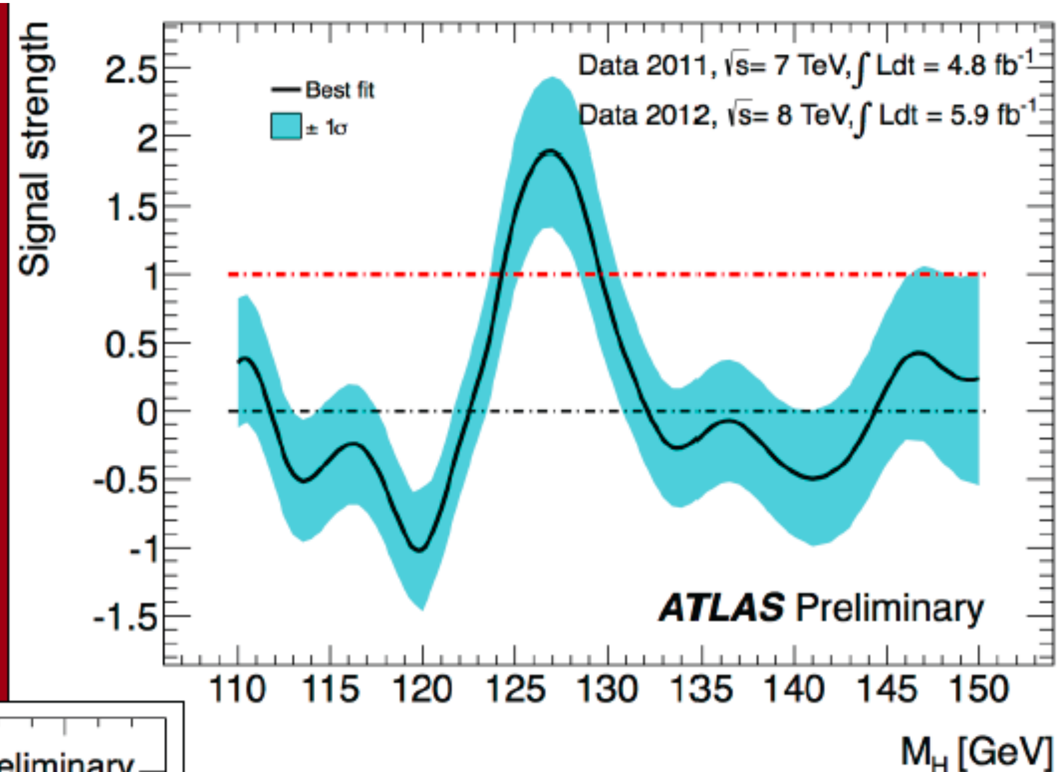
Results in more detail

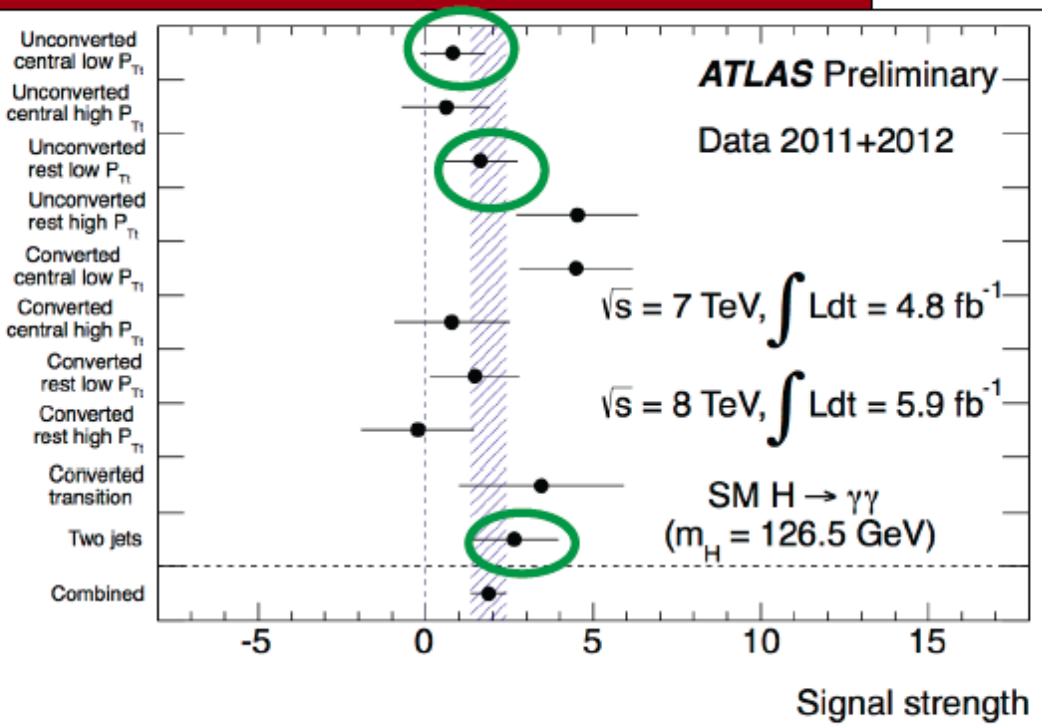


Fitted signal strength

Normalized to SM Higgs expectation at given m_H (μ)

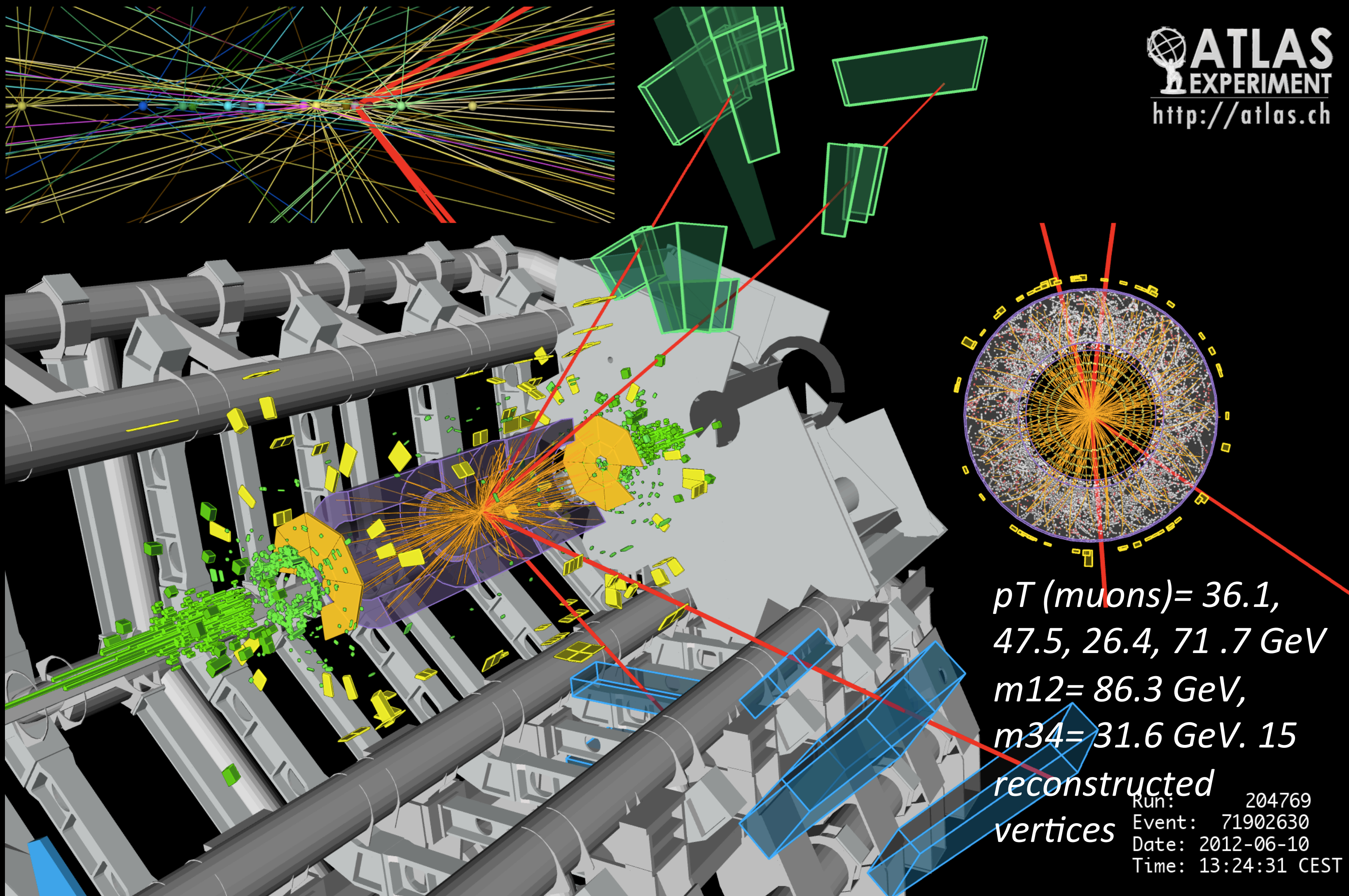
Best-fit value at 126.5 GeV: μ=1.9 ± 0.5





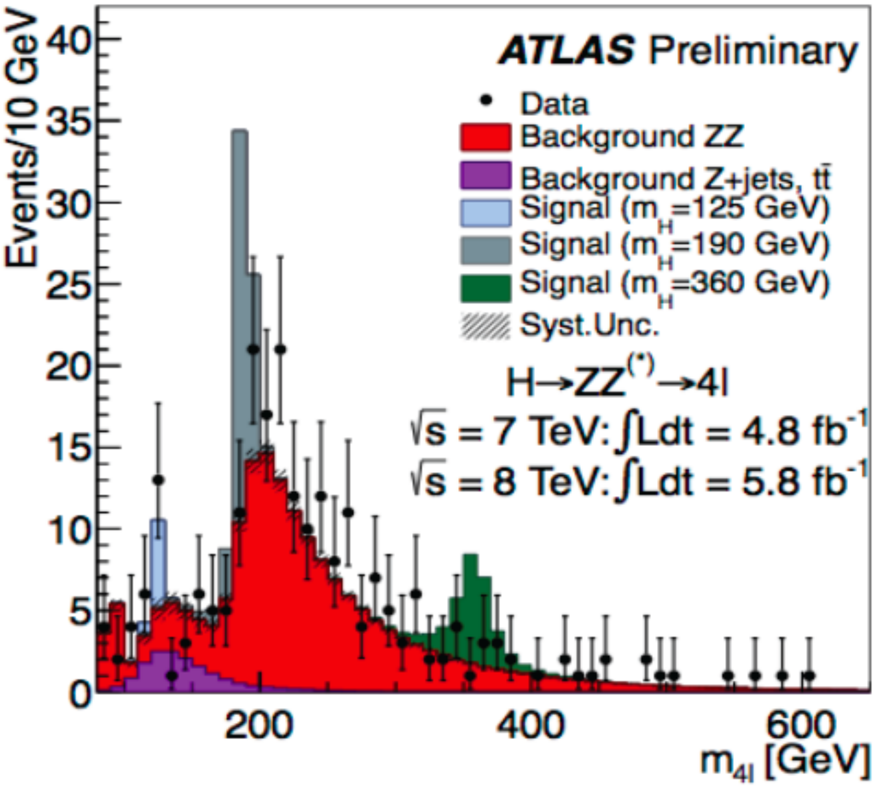
Consistent results from various categories within uncertainties (most sensitive ones indicated)

H->ZZ(*)->4l



pT (muons)= 36.1, 47.5, 26.4, 71 .7 GeV m12= 86.3 GeV, m34= 31.6 GeV. 15 reconstructed vertices

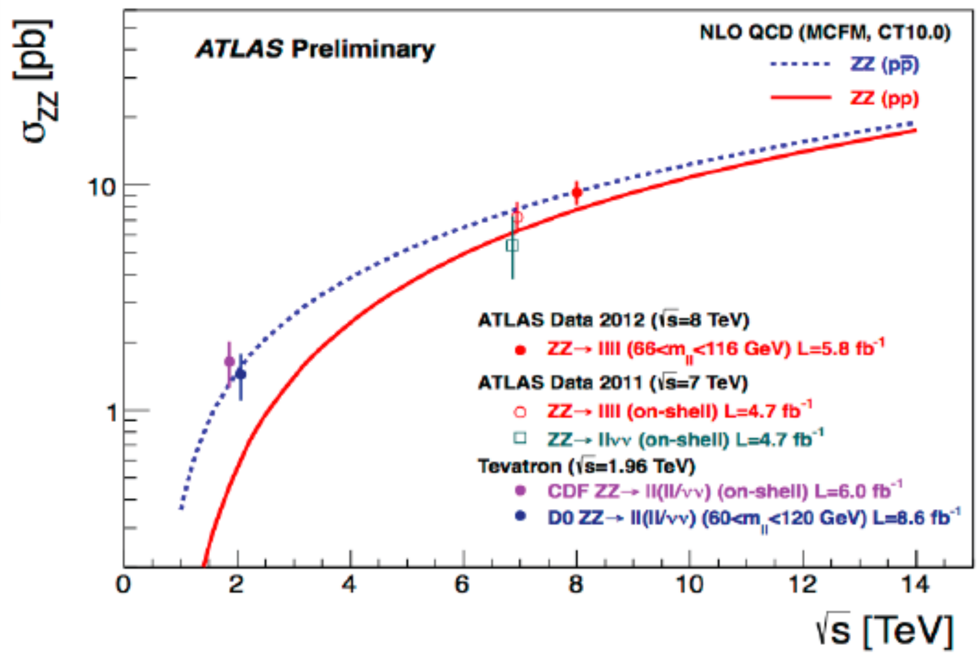
- The ”golden channel”:
  - Small rates, but high S/B
  - Can be fully reconstructed; mass resolution ~2% at 130 GeV
- Cross section times branching ratio (at mH=125 GeV):
- ~ 4 fb at √s=7 TeV
- ~ 5 fb at √s=8 TeV
- Backgrounds:
  - Irreducible: pp->ZZ(*)->4l
  - Reducible: Z+jets, Zbb, tt (sizeable at low Higgs masses)
- Suppress backgrounds with isolation and impact parameters cut on two softest
- Leptons
  - Mass range under consideration: 110 GeV to 600 GeV
  - Four final states: 4e, 4μ, 2e2μ, 2μ2e



m_{4l} > 160 GeV (dominated by ZZ background):
147 ± 11 events expected
191 observed

~ 1.3 times more ZZ events in data than SM prediction → in agreement with measured ZZ cross-section in 4l final states at $\sqrt{s}$ = 8 TeV

Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4 ± 0.4 pb

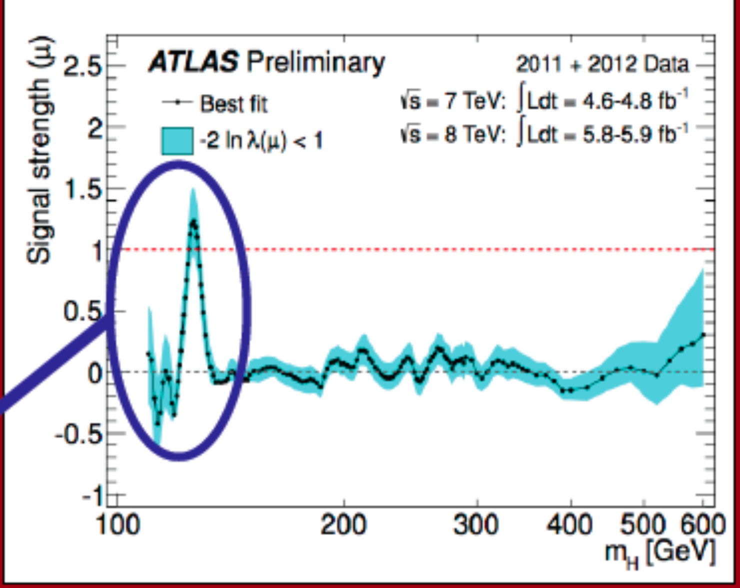


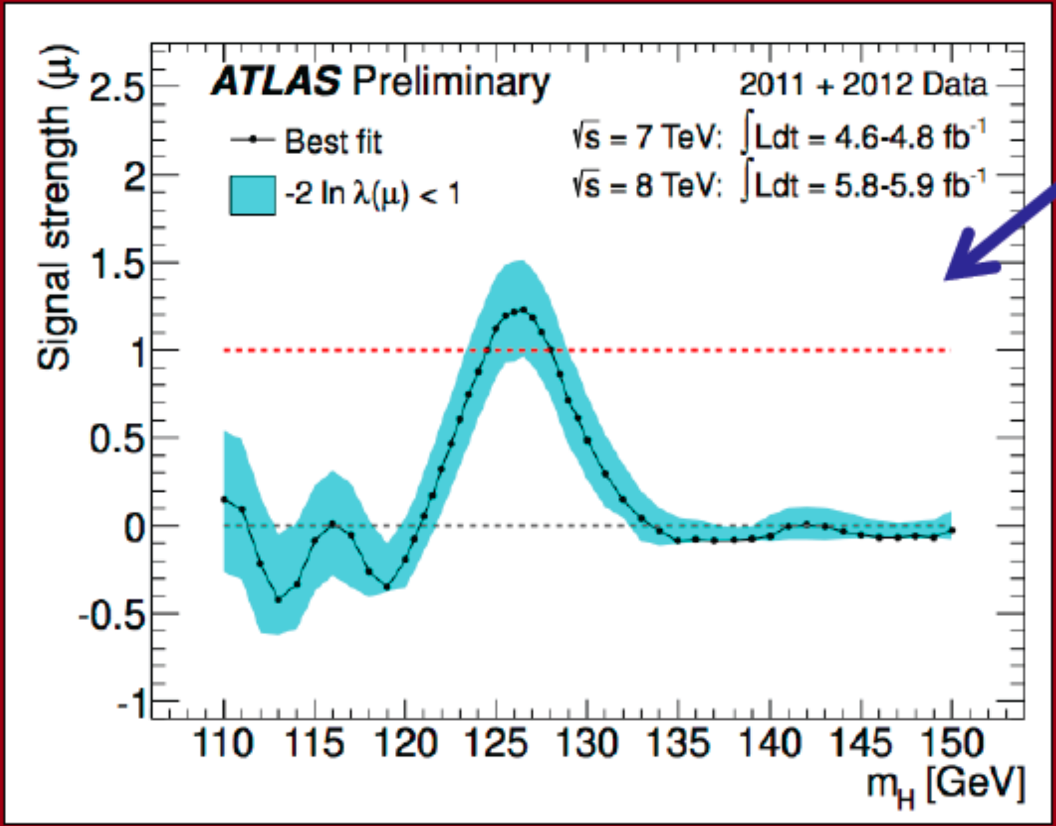
Discrepancy has negligible impact on the low-mass region < 160 GeV

(no change in results, if in the fit ZZ background is constrained within its uncertainty or left free)

Combined results: fitted signal strength

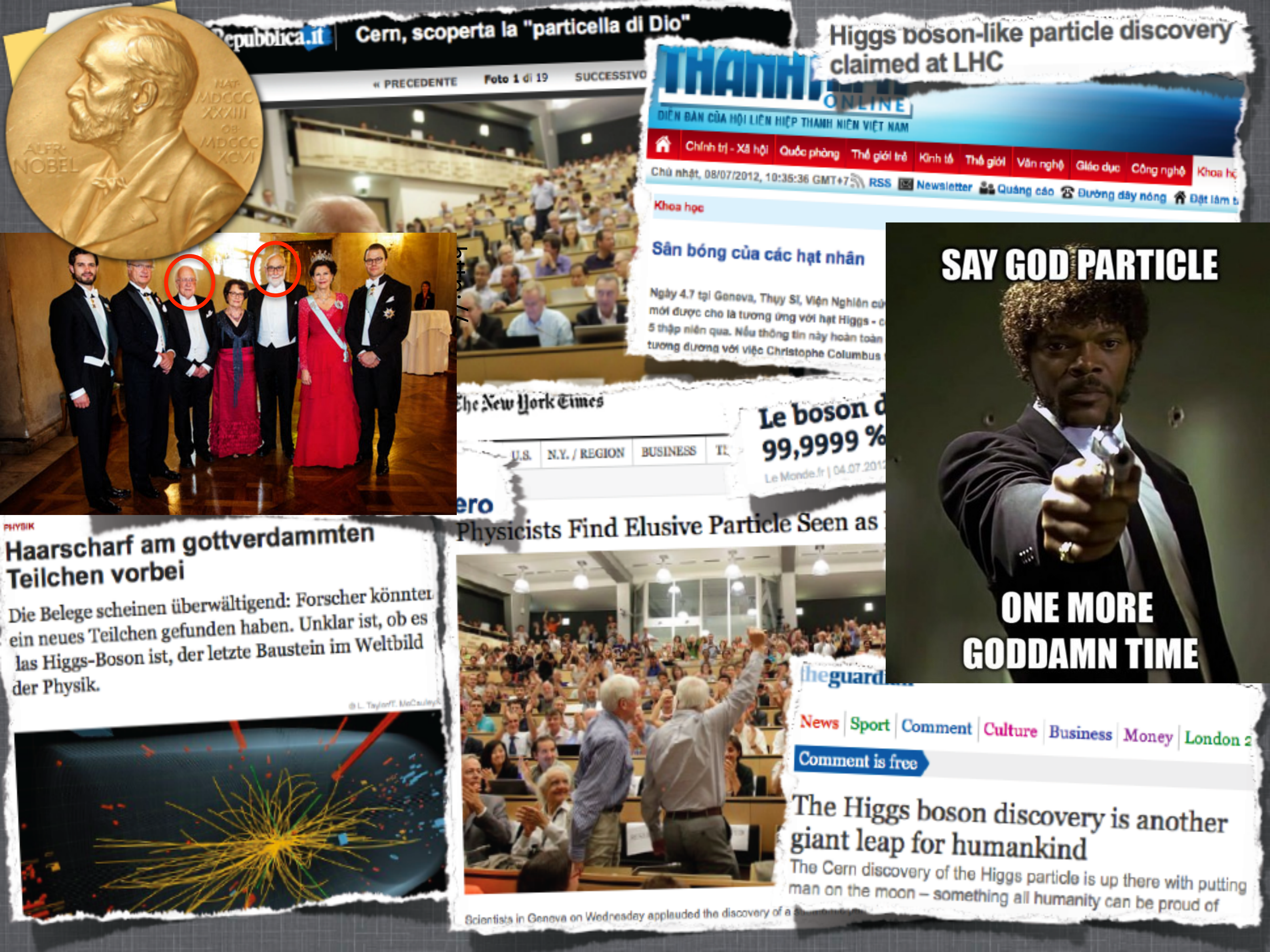
Normalized to SM Higgs expectation at given m_H (μ)





Best-fit value at 126.5 GeV:
$\mu = 1.2 \pm 0.3$

Good agreement with the expectation for a SM Higgs within the present statistical uncertainty



ALFR. NOBEL
NAT. MDCCCXXXIII OB. MDCCCXCVI
Repubblica.it
Cern, scoperta la "particella di Dio"
« PRECEDENTE
Foto 1 di 19
SUCCESSIVO
Higgs boson-like particle discovery claimed at LHC
ONLINE
DIỄN ĐÀN CỦA HỘI LIÊN HIỆP THANH NIÊN VIỆT NAM
Chính trị - Xã hội | Quốc phòng | Thế giới trẻ | Kinh tế | Thế giới | Văn nghệ | Giáo dục | Công nghệ | Khoa họ
Chủ nhật, 08/07/2012, 10:35:36 GMT+7 RSS Newsletter Quảng cáo Đường dây nóng
Khoa học
Sân bóng của các hạt nhân
SAY GOD PARTICLE
ONE MORE GODDAMN TIME
The New York Times
U.S. | N.Y. / REGION | BUSINESS
Le boson d
99,9999 %
Le Monde.fr | 04.07.2012
Physicists Find Elusive Particle Seen as
PHYSIK
Haarscharf am gottverdammten Teilchen vorbei
Die Belege scheinen überwältigend: Forscher könnten ein neues Teilchen gefunden haben. Unklar ist, ob es das Higgs-Boson ist, der letzte Baustein im Weltbild der Physik.
Scientists in Geneva on Wednesday applauded the discovery of a
theguardian
News | Sport | Comment | Culture | Business | Money | London 2
Comment is free
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

Where we stand now?

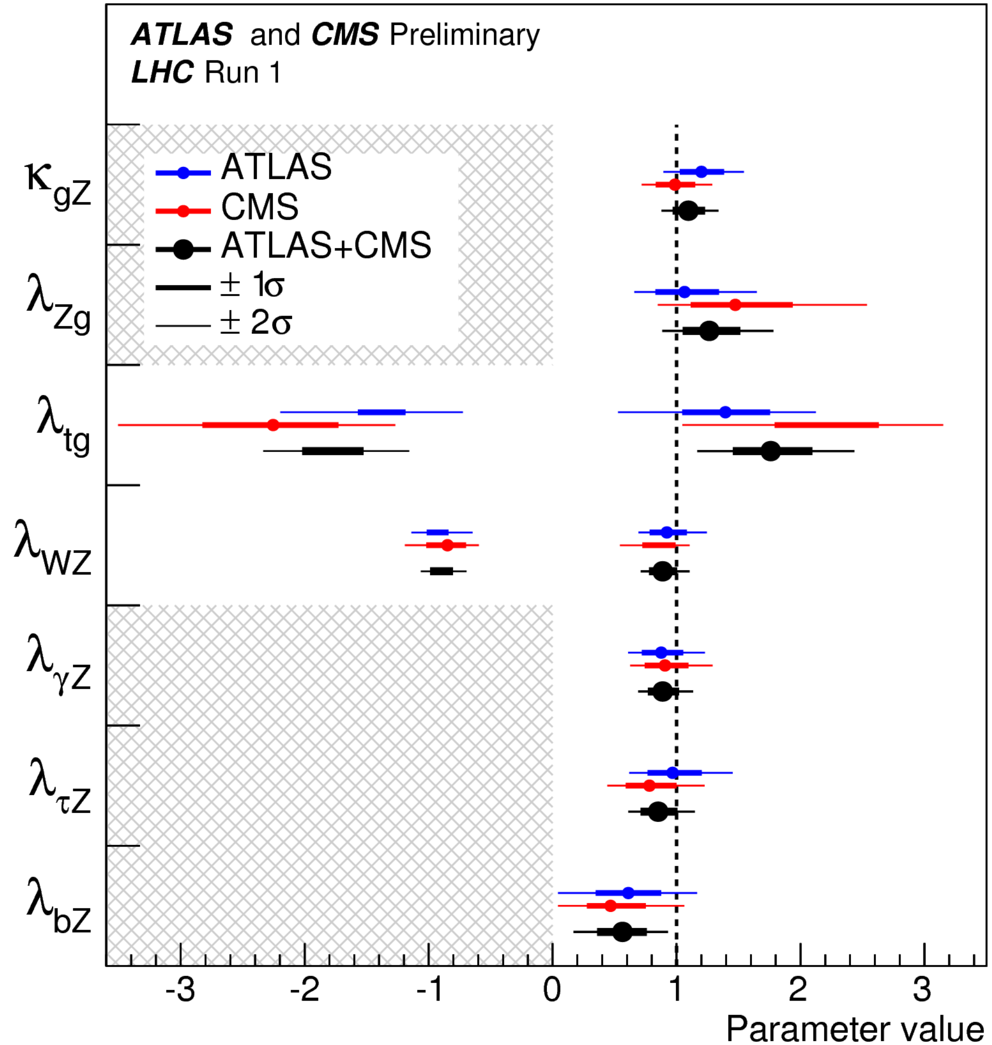
- Combination of ATLAS and CMS results in September 2015:
  - ATLAS-CONF-2015-044 / CMS-PAS-HIG-15-002, https://cds.cern.ch/record/2052552
- Used data recorded by the ATLAS and CMS detectors in 2011 and 2012, corresponding to integrated luminosities per experiment of 5 fb^{-1} at $\sqrt{s}$=7 TeV and 20 fb^{-1} at $\sqrt{s}$ = 8 TeV

- Results:
  - Combined signal strength: $\mu = 1.09 \pm 0.11$
  - $m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)$ GeV
  - Latest modes observed:
  - VBF observed at 5.4σ
  - H -> ττ decay observed at 5.5σ

- Bottom line is that this looks much like the SM Higgs boson (see next few slides)
  - **But the truth is out there! Keep looking!**

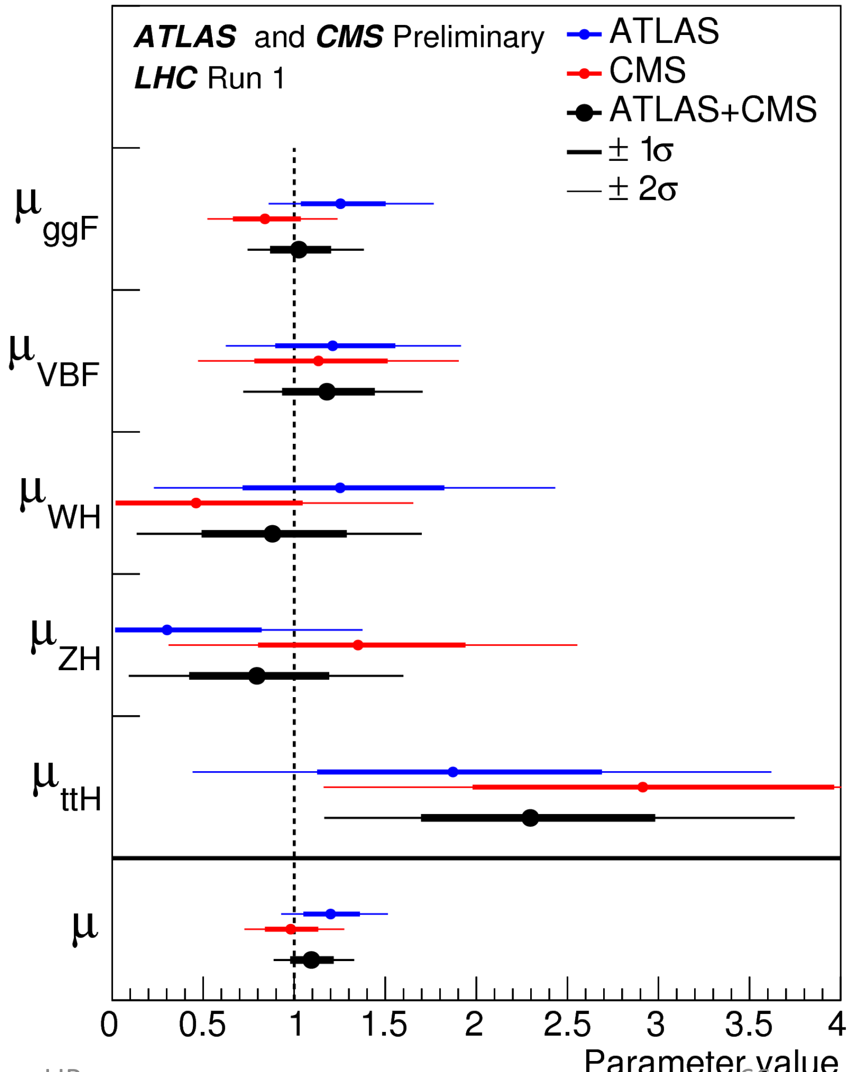
Higgs boson couplings

- Best-fit values of ratios of Higgs boson coupling modifiers
- The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals
- Hatched areas indicate the parameters which are assumed to be positive without loss of generality.



Signal strength

- Best-fit results for the production signal strengths
- Error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals.
- The measurements of the global signal strength μ are also shown.



Couplings versus mass

- Reduced coupling modifiers as a function of the particle mass:

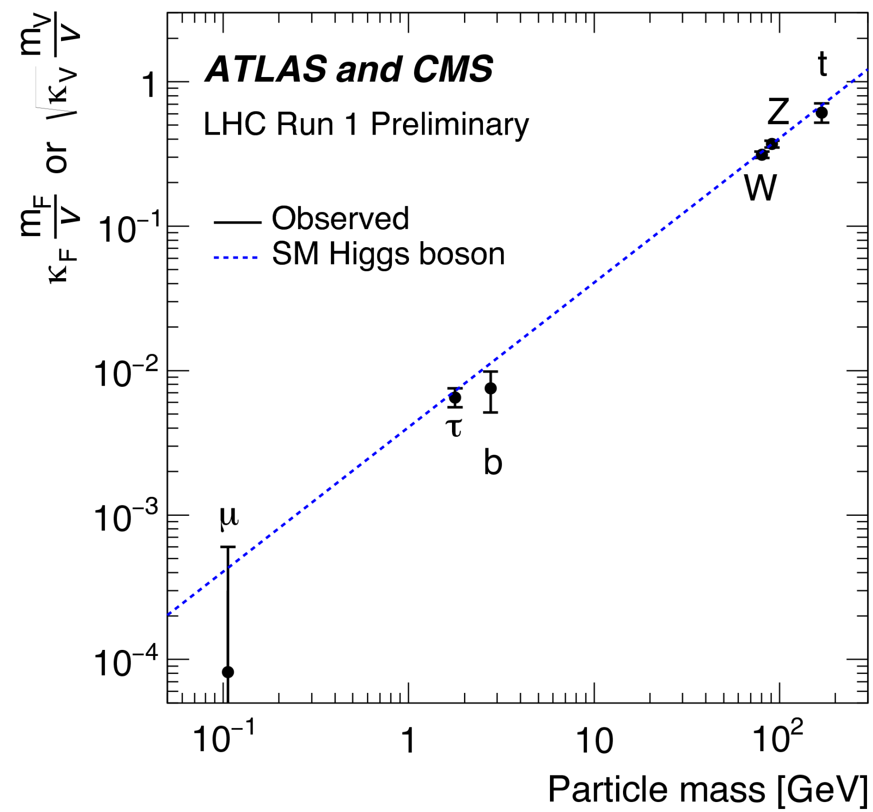
- For weak vector bosons:

$y_{V,i} = \sqrt{\kappa_{V,i}}\, g_{V/i}/2v = \sqrt{\kappa_{V,i}}\, m_{V/i}/v$

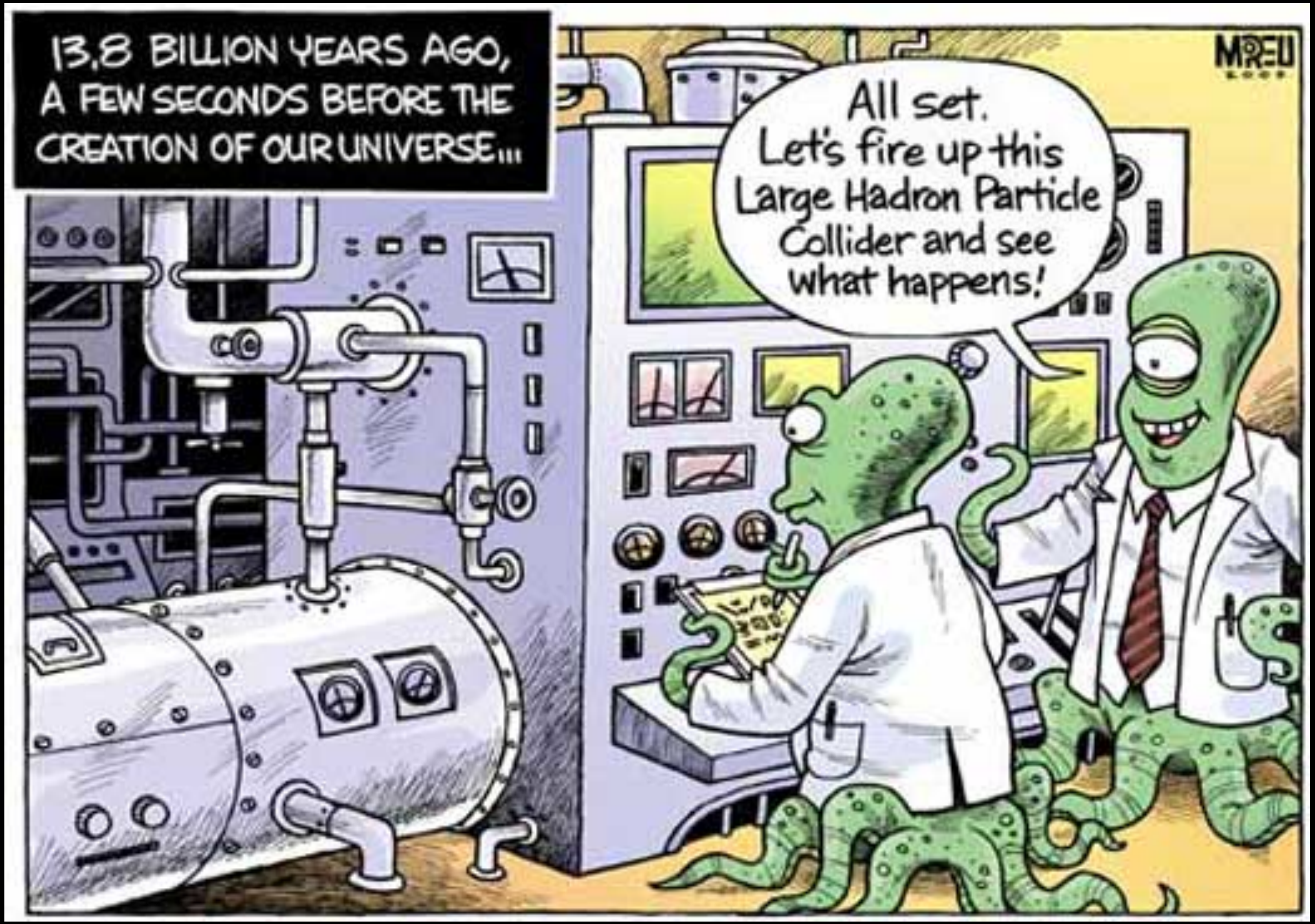
- For fermions:

$y_{F,i} = \kappa_{F,i} g_{F/i}/\sqrt{2} = \kappa_{F,i} m_{F/i}/v$

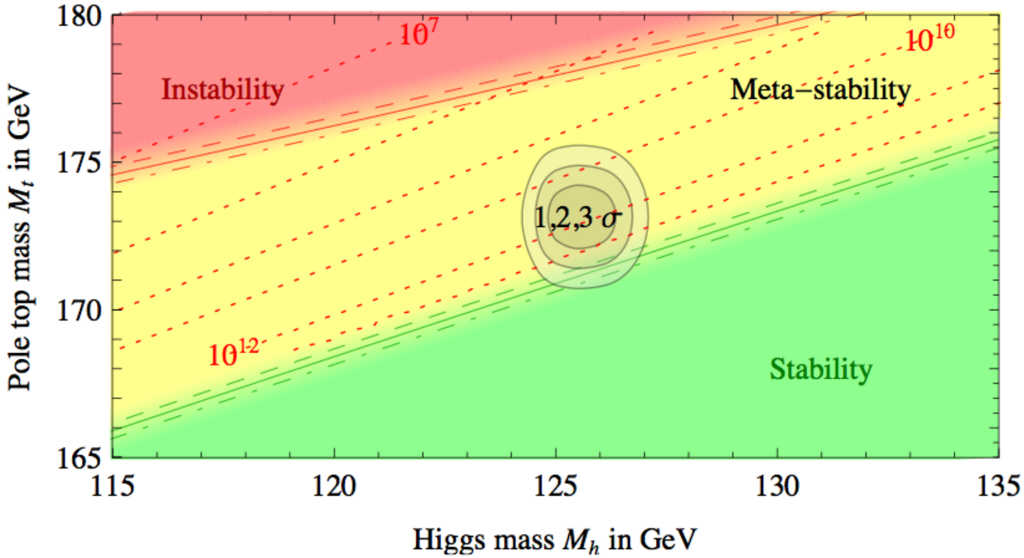
- Dashed line indicates the predicted dependence on the particle mass for the SM Higgs boson

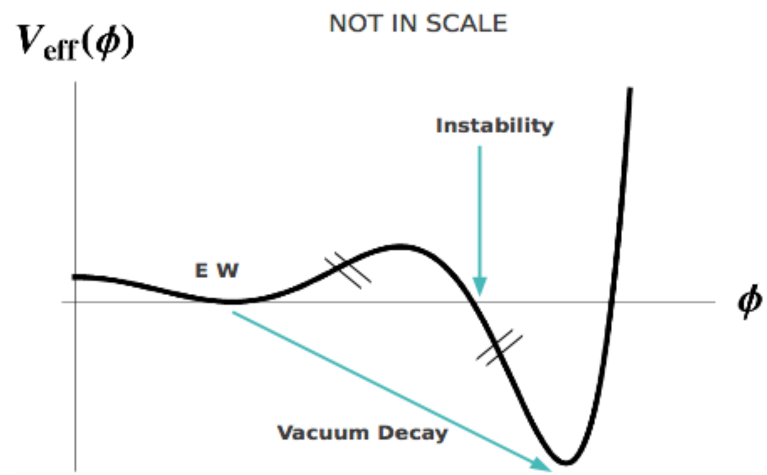


Is this the end?



A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

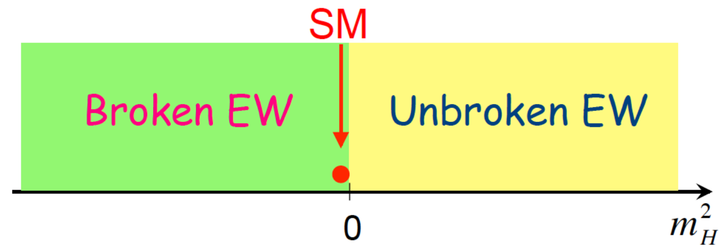
The universe seems to live near a critical condition

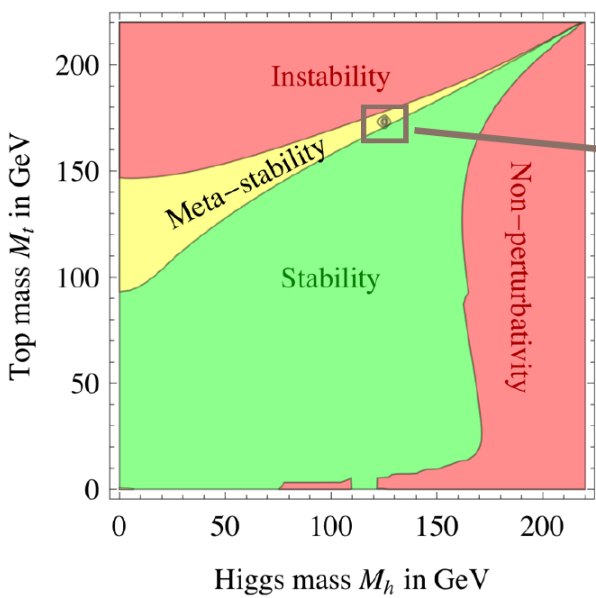
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?

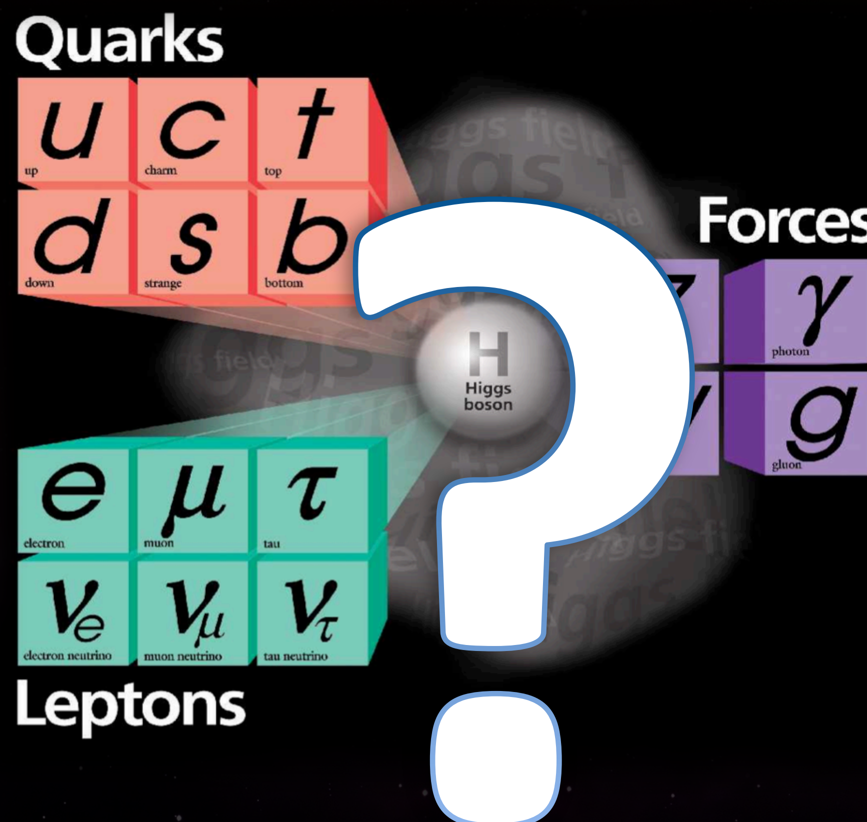




The End

Goldstein, 'Classical Mechanics', Addison-Wesley Publishing Company (1980)

D. Griffiths, 'Introduction to Elementary Particles ', John Wiley and Sons (1987)



Back to the big questions!!

Going beyond the standard model

But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

Many possible theories

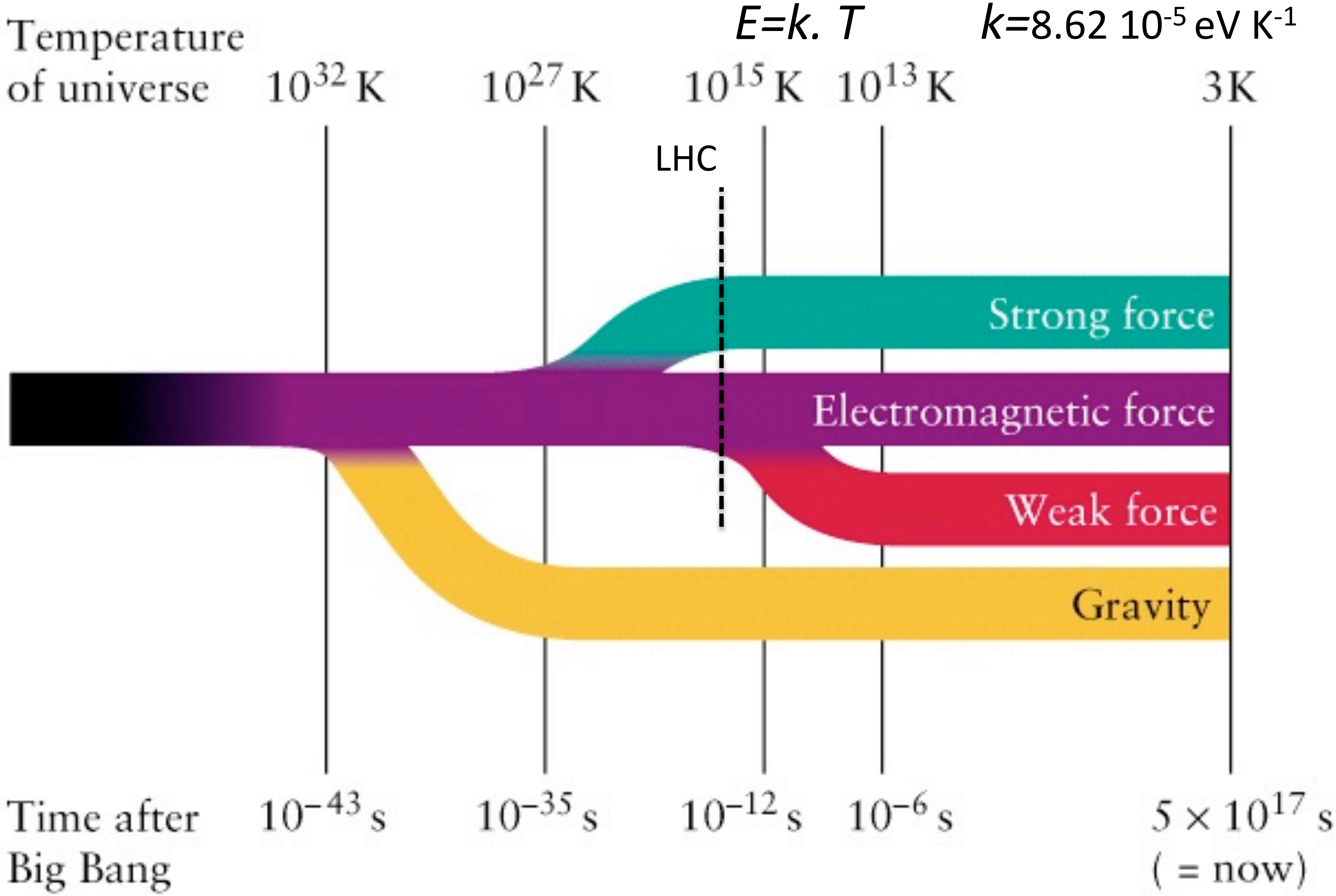
There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC

Forces and expansion of the Universe

$E = k.\,T$ k=8.62 10^{-5} eV K^{-1}

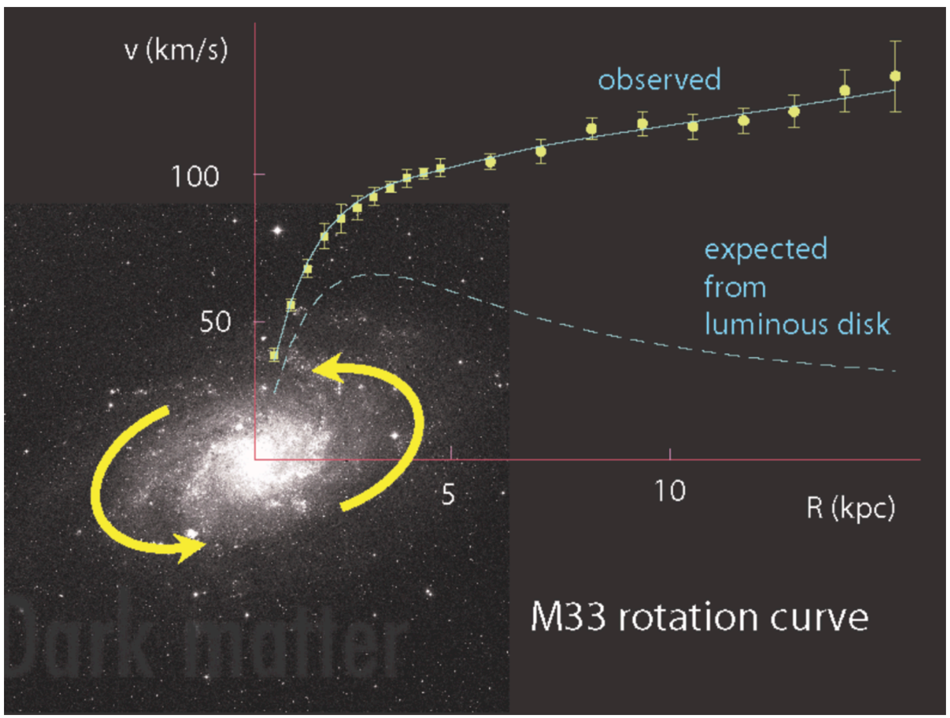


The dark side of the Universe

Long standing problem:

We know that ordinary matter is only ~4% of the matter-energy in the Universe.

What is the remaining 96%?



The LHC may help to solve this problem, discovering **dark matter**

- Most modes available with current lumi explored
- Precision: obvious signal in bosonic decays
  - Mass around 125GeV
  - Signal strength consistent with SM – some questions
  - Main alternatives to $J^P = 0^+$ discarded – questions remain
- Fermion couplings seen in $H\rightarrow\tau\tau$ (4σ)
- Evidence for VBF production (3σ)
- Mainly indirect sensitivity to ttH coupling through loops
- Many direct searches for other Higgses turned out nothing (yet)

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

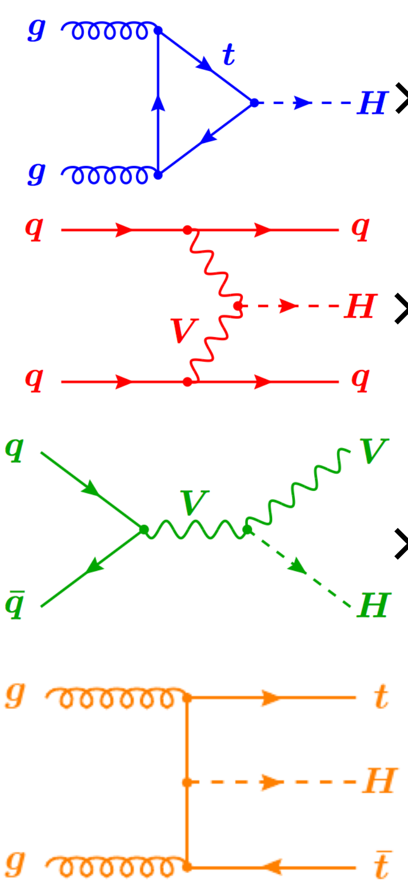
★ "seen" ☆ "tried" - "impossible"

	$H\rightarrow b\bar{b}$			$H\rightarrow\tau\tau$			$H\rightarrow WW$			$H\rightarrow ZZ$			$H\rightarrow\gamma\gamma$			$H\rightarrow Z\gamma$			$H\rightarrow$ inv.			$H\rightarrow\mu\mu$			$H\rightarrow c\bar{c}$ $H\rightarrow HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

See A.David and P.Conde's lectures

Combining Higgs Channels

Production



$\times\kappa_g^2$

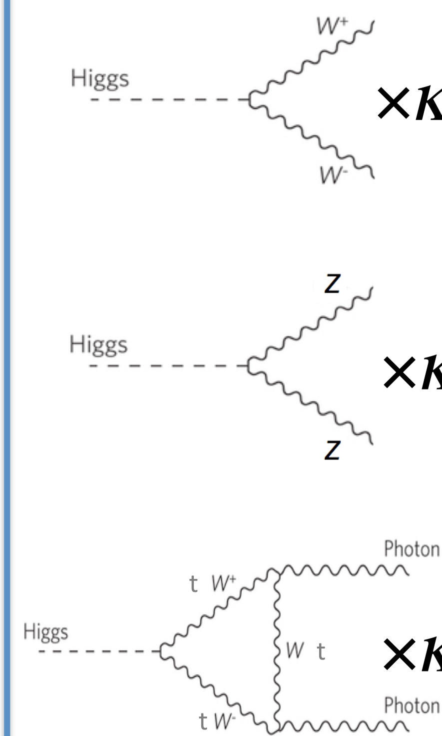
$\times\kappa_{W/Z}^2$

$\times\kappa_{W/Z}^2$

$\times\kappa_t^2$

$\times$

Decay



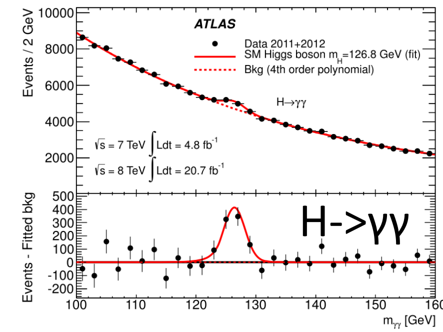
$\times\kappa_W^2$

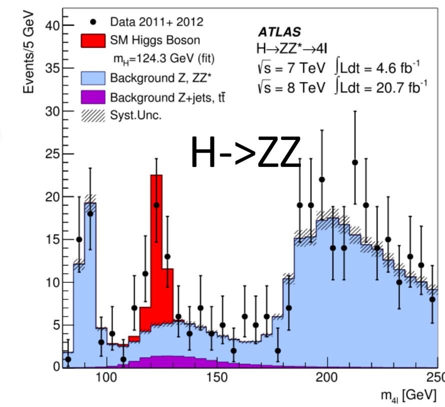
$\times\kappa_Z^2$

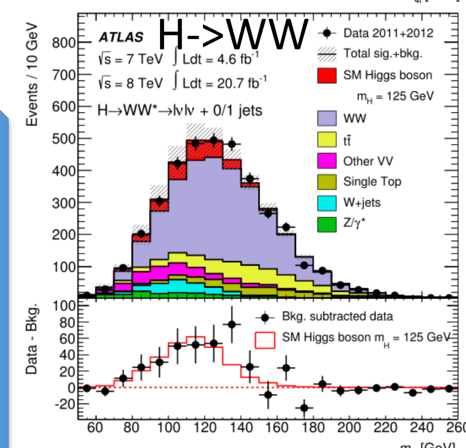
$\times\kappa_\gamma^2$

FIT

Backgrounds +







See A.David's lecture

A bit more technically

- **Assumptions:**
  - Single resonance (at $m_H = 125.5\text{GeV}$)
  - No modification of tensor structure of SM Lagrangian:
    - i.e. H has $J^P = 0^+$
  - Narrow width approximation holds
    - i.e. rate for process i ➔ H ➔ f is: $\sigma \times BR = \frac{\sigma_{i \to H} \times \Gamma_{H \to f}}{\Gamma_H}$
- **Free parameters** in framework:
  - Coupling scale factors: κ_j^2
  - Total Higgs width: κ_H^2
  - Or ratios of coupling scale factors: $\lambda_{ij} = \kappa_i / \kappa_j$

$$\sigma_i = \kappa_i^2 \cdot \sigma_i^{SM}; \Gamma_f = \kappa_f^2 \cdot \Gamma_f^{SM}; \Gamma_H = \kappa_H^2 \cdot \Gamma_H^{SM}$$

- Tree-level motivated framework
  - Useful for **studying deviations** in data with respect to expectations
    - E.g. extract coupling scale factor to weak bosons κ_V by setting $\kappa_W = \kappa_Z = \kappa_V$
  - Not same thing as fitting a new model to the data

Higgs boson mass

- **Mass:** around 125GeV
  - Used to be the only unknown SM-Higgs parameter, remember? ☺
- ATLAS: arXiv:1307.1427
  - $m_H^{H\text{->}4l}$ = 124.3 ±0.6(stat) ±0.5(sys)
  - $m_H^{H\text{->}\gamma\gamma}$ = 126.8 ±0.2(stat) ±0.7(sys)
  - Assuming single resonance:

    m_H = 125.5 ±0.2(stat) $^{+0.5}_{-0.6}$(sys)
- Tension between channels!
  - Compatibility P=1.5% (2.4σ)
  - Rises to 8% with square syst.prior

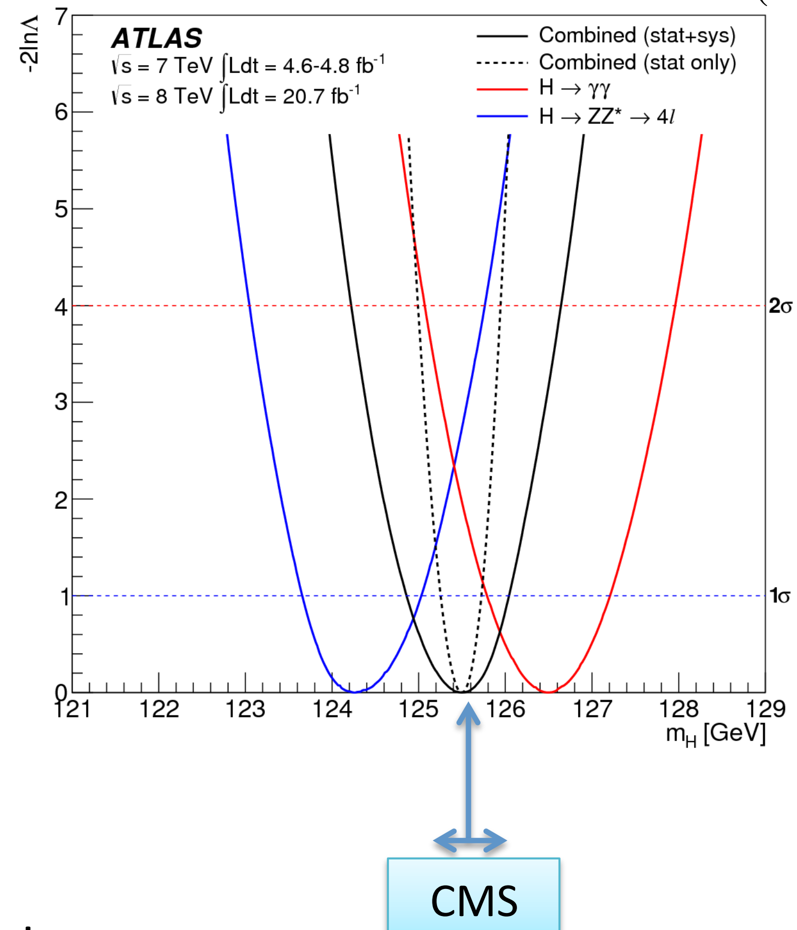
BUT:

- CMS: arXiv:1312.5353
  - $m_H^{H\text{->}4l}$ = 125.6 ±0.4(stat) ±0.6(sys)
- CMS: CMS-PAS-HIG-13-005
  - $m_H^{H\text{->}\gamma\gamma}$ = 125.4 ±0.5(stat) ±0.6(sys)

- Doesn't look like two different resonances!...

$$\Lambda = \frac{L(m_H)}{L(\hat{m}_H)}$$

ATLAS: arXiv:1307.1427

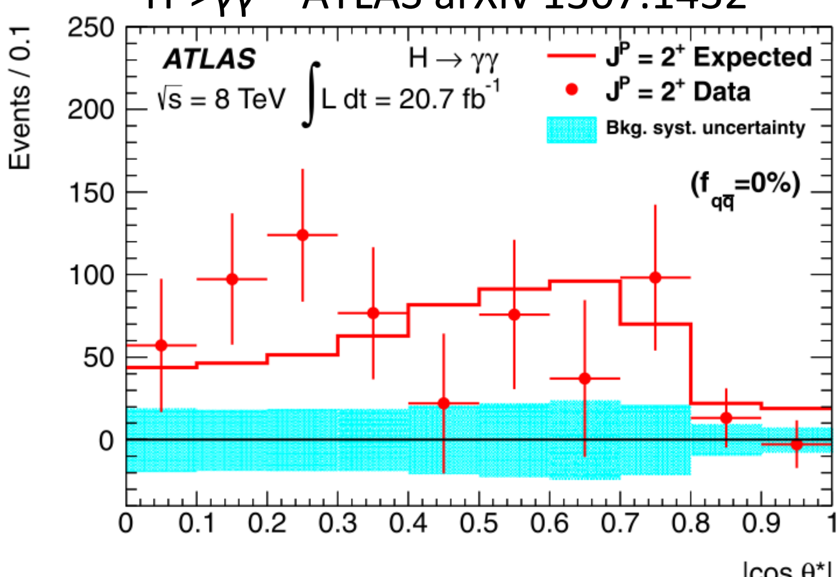


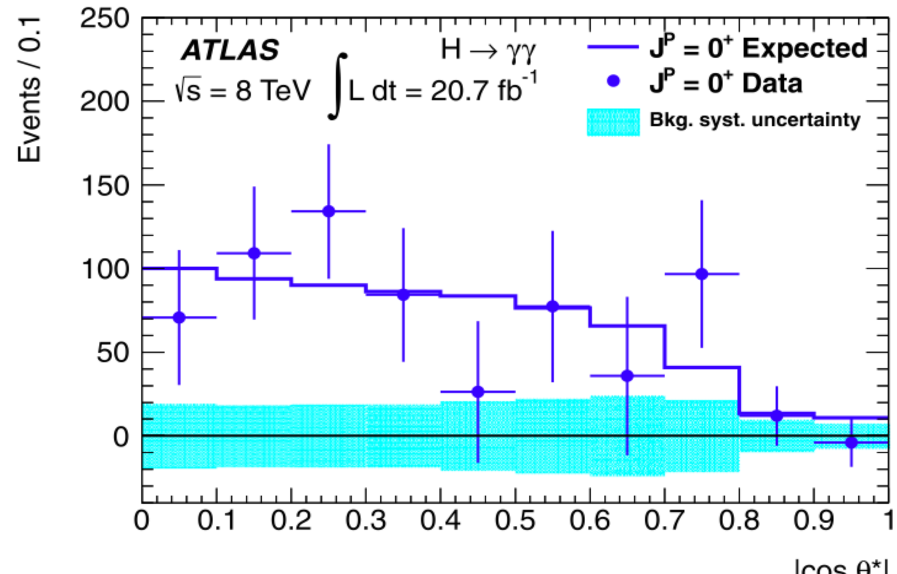
Spin and Parity

- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432)
- But note: Higgs could have CP-violating component!

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m^2_{\gamma\gamma}}$$

H->γγ – ATLAS arXiv 1307.1432





Direct Evidence of Fermion Couplings

- **Challenging** channels at the LHC!
  - Huge backgrounds (H->bb,H->ττ)
  - Or low rate: H->μμ

- ATLAS:

  4.1σ evidence of H->ττ decay 3.2σ exp.

  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 1.4 \pm 0.3(\text{stat}) \pm 0.4(\text{sys})$

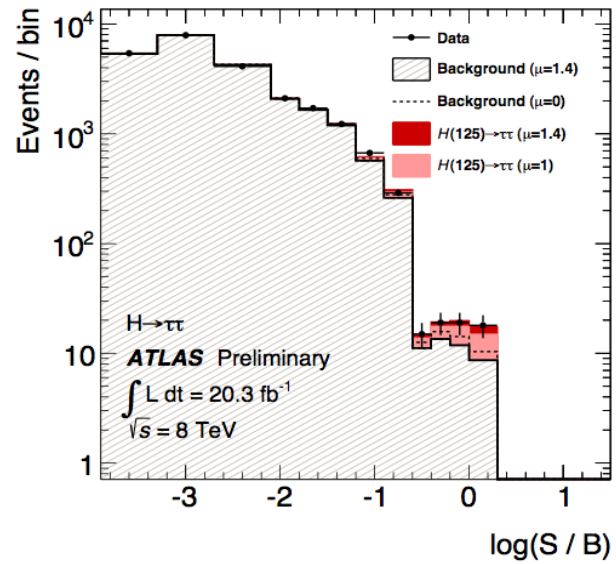
- CMS:
  - Combination of H->bb and H->ττ:

  3.8σ evidence (obs.) 4.4σ (expected)

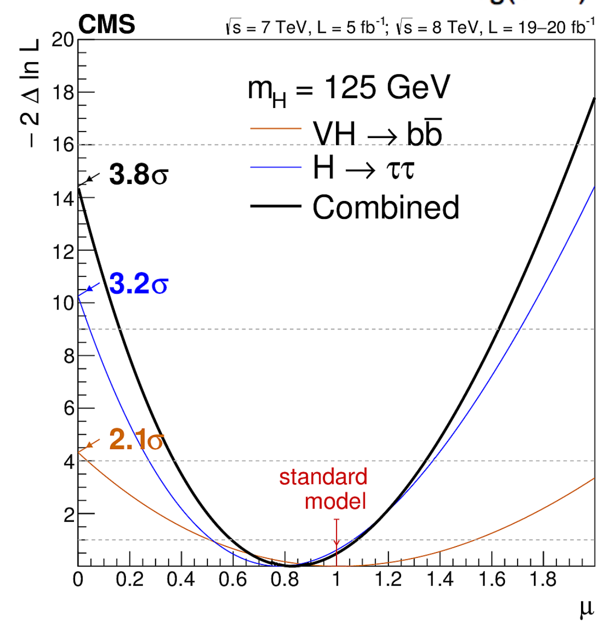
  $\mu = \boldsymbol{\sigma_{obs.}/\sigma_{SM}} = 0.83 \pm 0.24$

CMS 1401.6527

Channel ($m_H = 125\,\text{GeV}$)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$\text{VH} \to \text{b}\bar{\text{b}}$	2.3	2.1	1.0 ± 0.5
$\text{H} \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24



ATLAS-CONF-2013-108



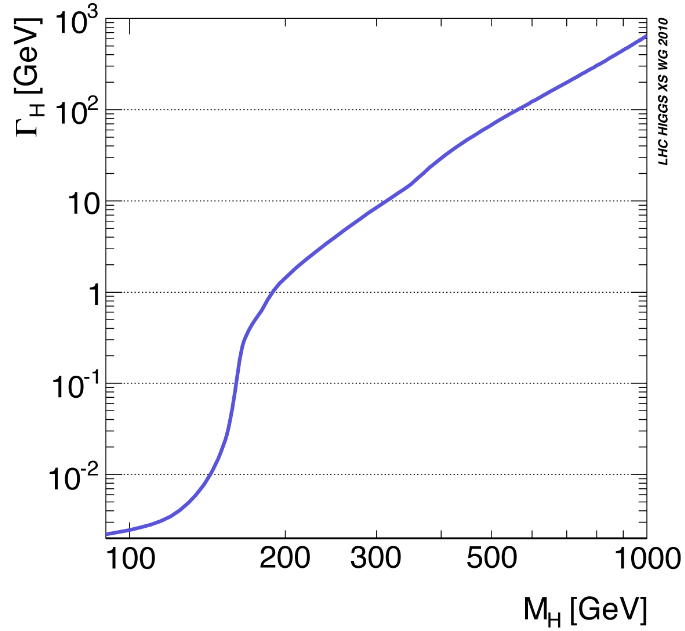
CMS 1401.6527

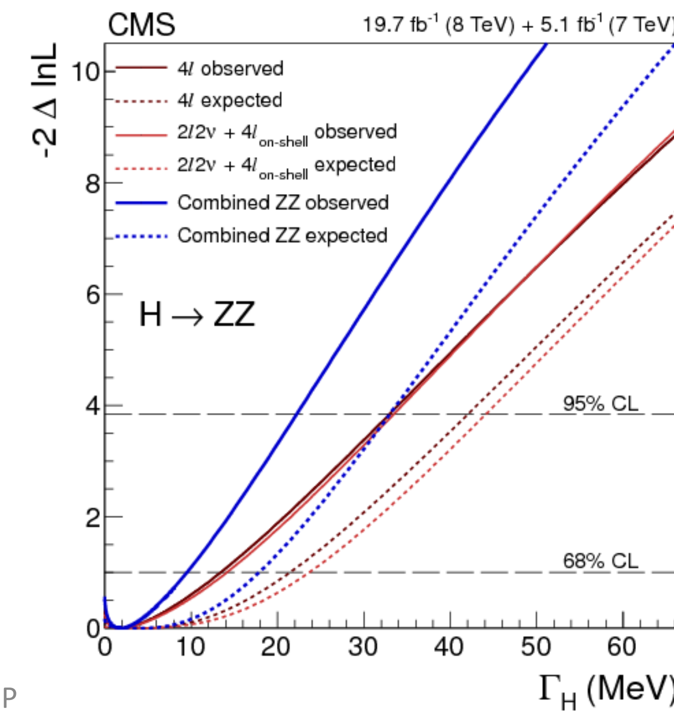
Higgs Width

- Total width not measurable at the LHC
  - Hadronic decays invisible in huge jet background
- Sensitivity can be achieved through "interferometric" measurement
  - **Use gg➞H➞ZZ with H on- or off-shell**
- Proof of principle done, although still very far from theoretically expected value (4MeV)
  - **Γ_H < 22 MeV at 95% CL**

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

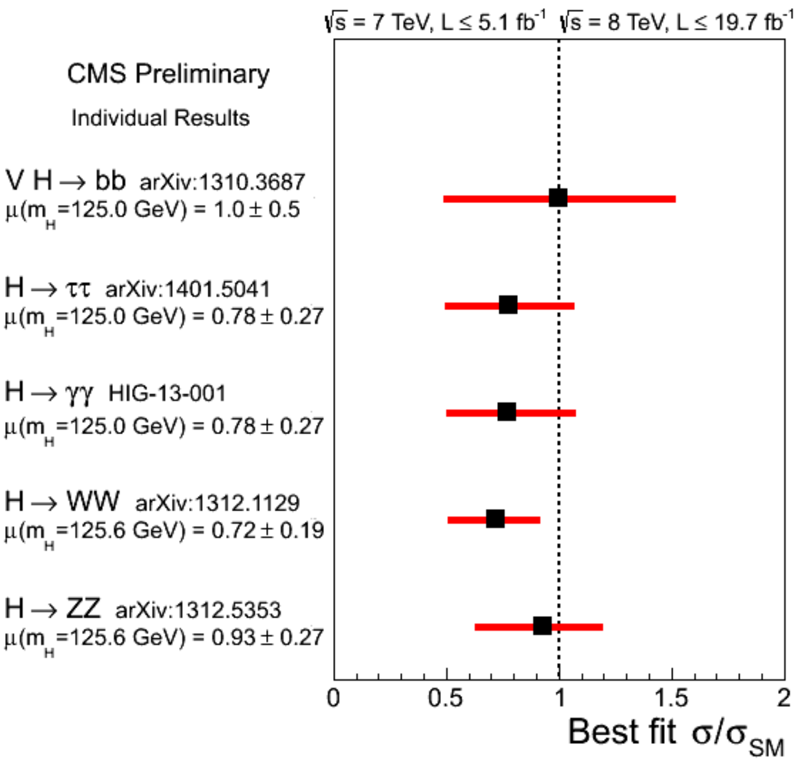
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

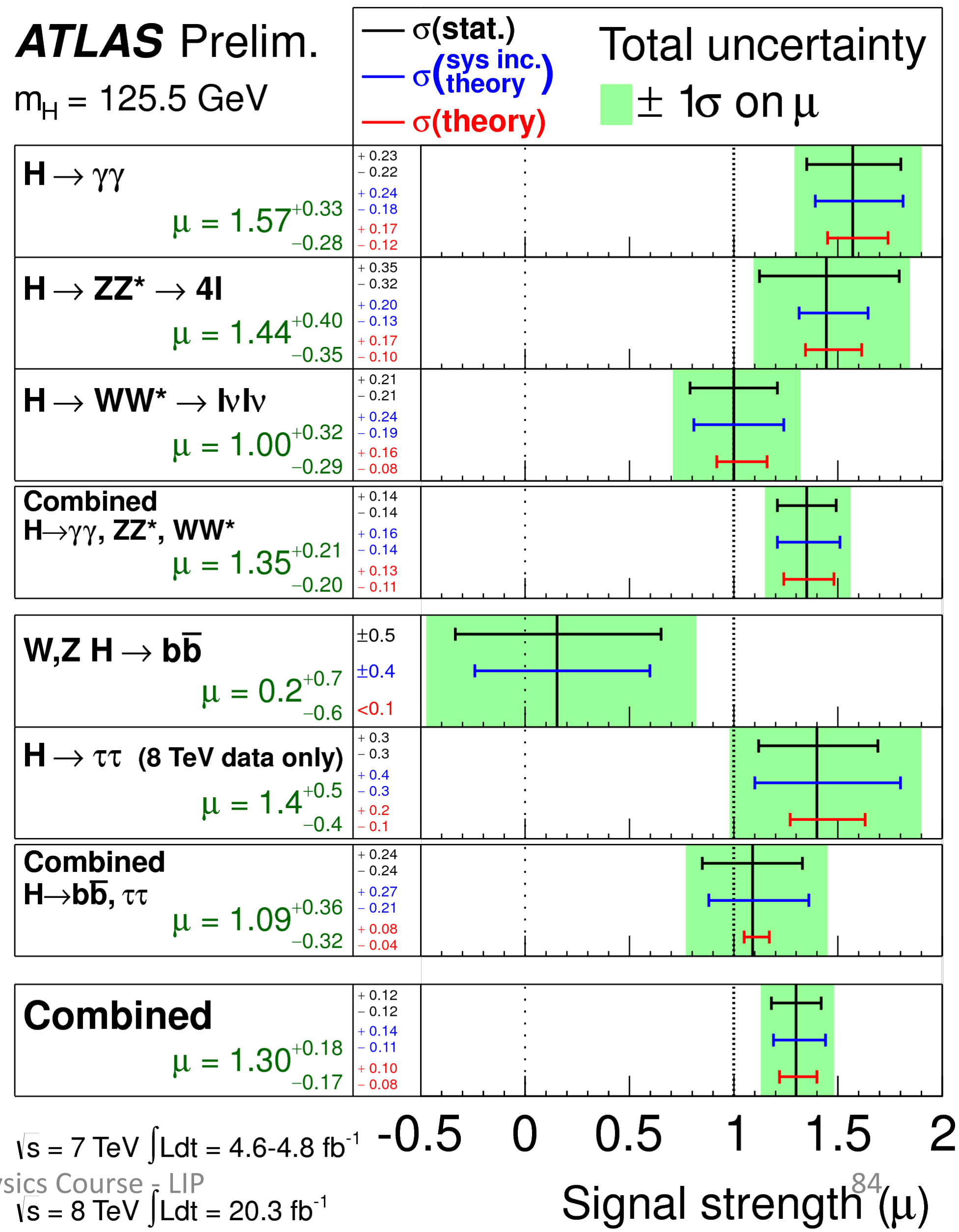




http://arxiv.org/pdf/1405.3455.pdf

Signal strength





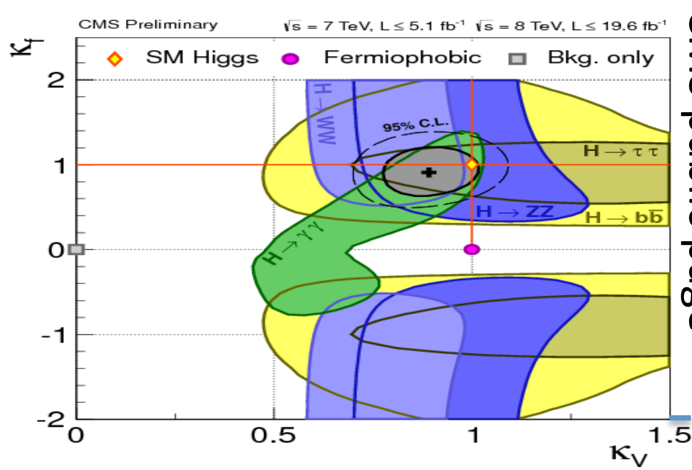
$$\mu = \frac{\sigma_{meas}}{\sigma_{SM}}$$

Take-home messages:

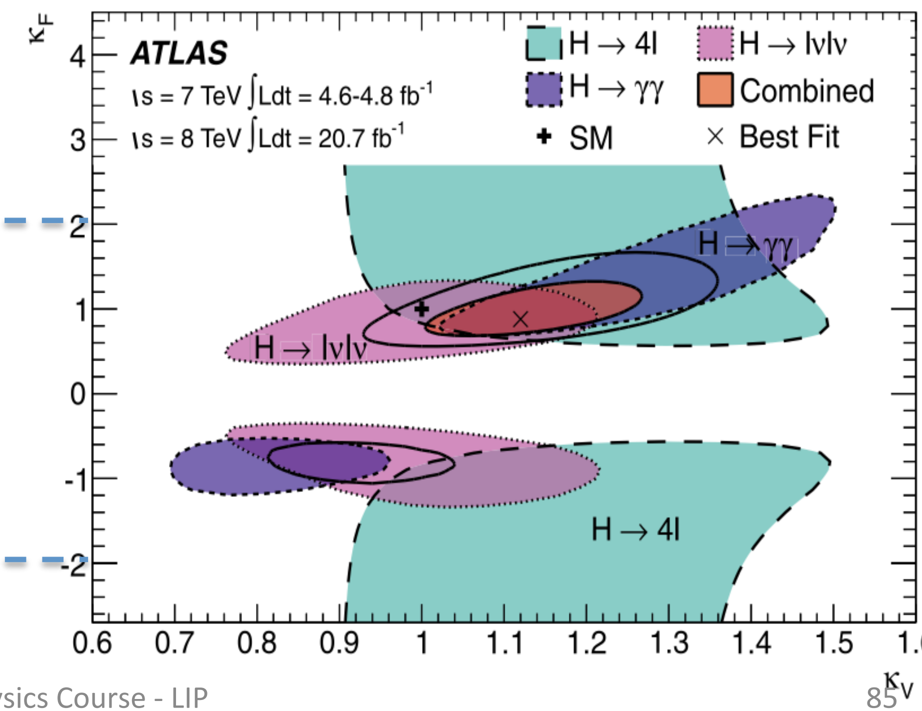
- Need more data!
- **Always run two experiments!**

Fermion and Boson couplings from fit

- Set one scale factor for all fermions (**κ_F** = κ_t = κ_b= κ_τ =…) and one for all vector bosons (**κ_V** = κ_Z = κ_W)
- Assume **no new physics**
- Strongest constraint to κ_F comes form gg->H loop
- ATLAS and CMS fits within 1-2σ of SM expectation (compatibility P=12%)
- Note ATLAS and CMS κ_V different – see signal strength below

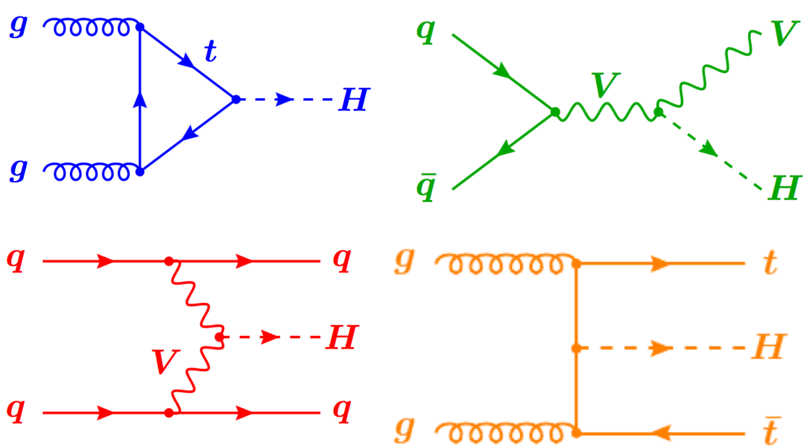


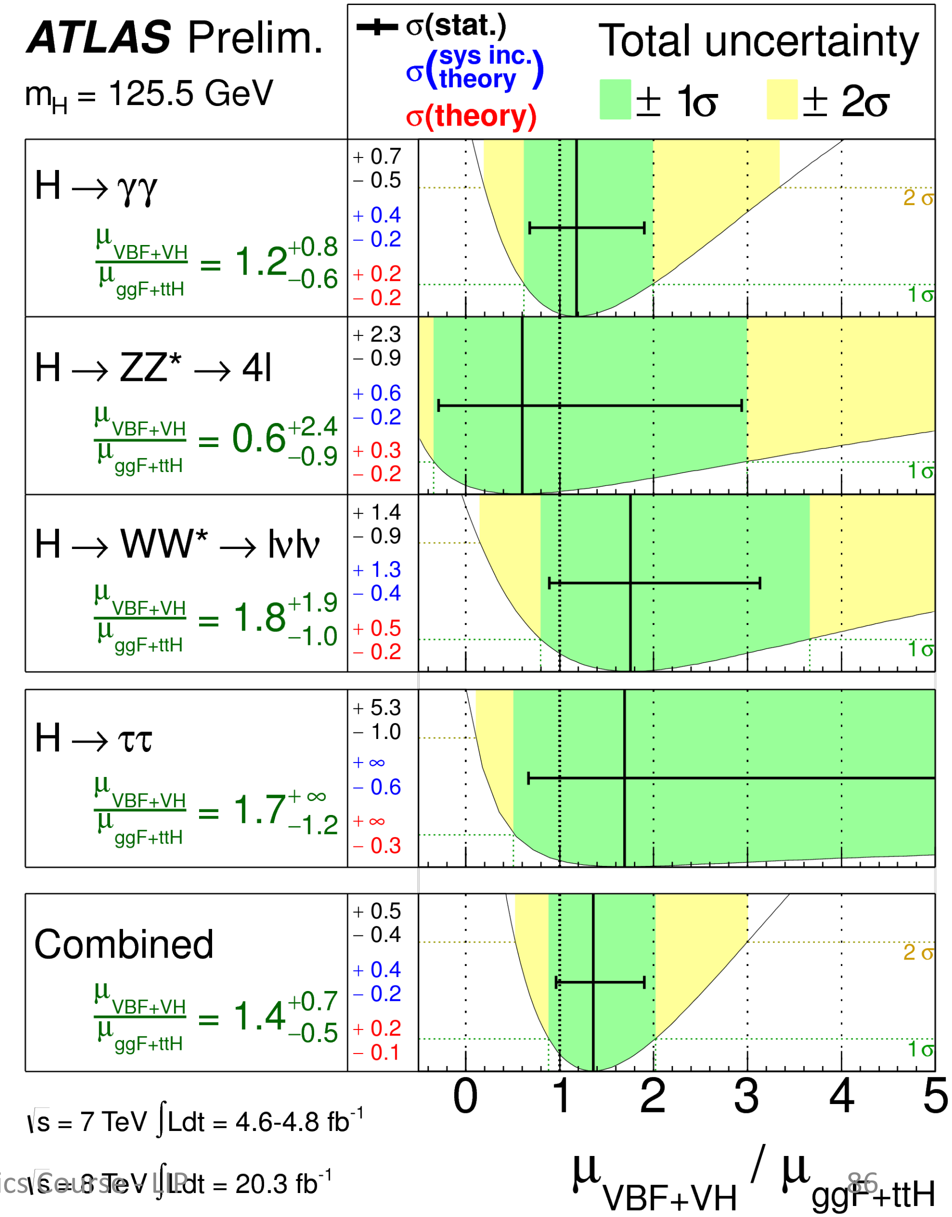
CMS public page



ATLAS 1307.1427

Production Modes

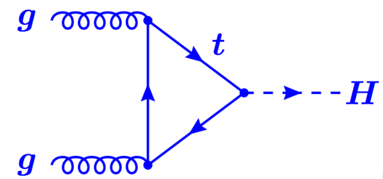


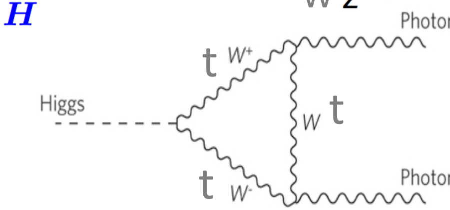


- Combination of channels allows consistency checks
- Evidence for VBF production (3σ)
- Sensitivity to top Yukawa coupling only through loops so far

New Physics in the Loops?

- New heavy particles may show up in **loops**
  - Dominant **gluon-fusion** through a (mostly) top loop production for H->ZZ, H->WW and H->γγ
  - **H->γγ decay** through top and W loops (and interference)

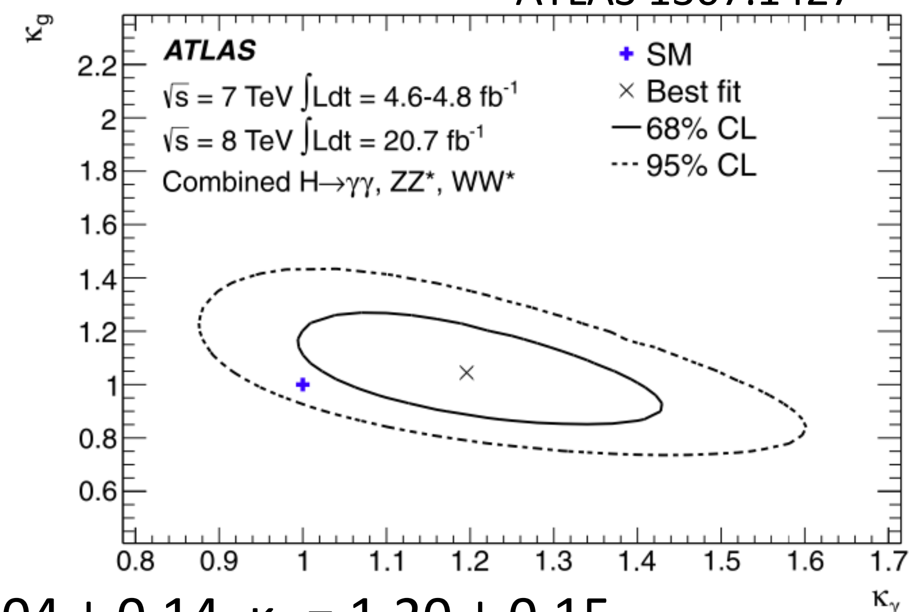




ATLAS 1307.1427

- Assume no change in Higgs width and SM couplings to known particles

- Introduce effective coupling scale factors:
  - κ_g and κ_γ for ggH and Hγγ loops



- Best fit values: $\kappa_g = 1.04 \pm 0.14$, $\kappa_\gamma = 1.20 \pm 0.15$
- Fit within 2σ of SM (compatibility P=14%)

Going beyond the Standard Model

Two Higgs Doublet Model (2HDM)

- No reason for simplest Higgs sector scenario to be true!
- One of the simplest alternatives: 2 Higgs doublets

$$\Phi_j = \begin{pmatrix} \phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix}$$

- Leads to 5 different Higgs bosons:
  - CP even (scalar): h, H
  - CP odd (pseudoscalar): A
  - charged: H^+, H^-
- Two doublets => two vacuum expectation values (mean field strength in the vacuum) – $\boldsymbol{v_1}$ **and** $\boldsymbol{v_2}$

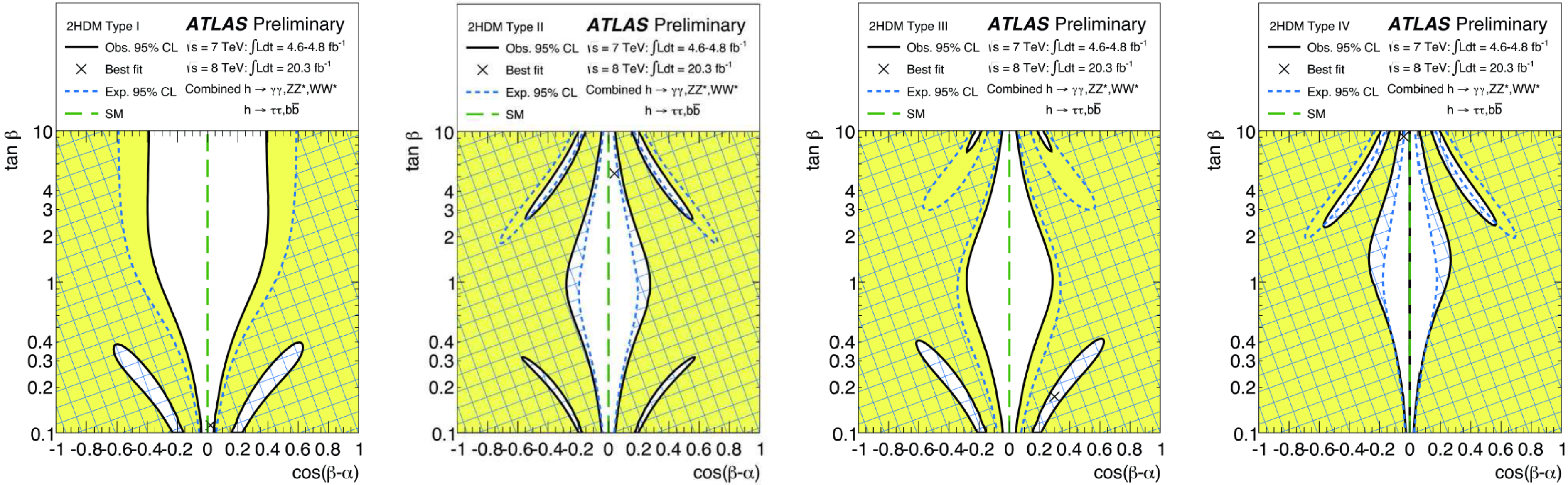
Two Higgs Doublet Model (2HDM)

- Free parameters:
  - 4 masses (Do we know one? Assume it's m_h)
  - tan β = v_1/v_2 ratio of v.e.v.'s
  - Mixing angle of h and H: α
- 4 possible Yukawa coupling arrangements ("types")
- Most common SUSY benchmark (MSSM) is based on Type II
- If cos(β-α) = 0, h = Standard Model H^0

	Type I	Type II	Lepton Specific	Flipped
κ_V	sin(β-α)	sin(β-α)	sin(β-α)	sin(β-α)
κ_u	cos(α)/sin(β)	cos(α)/sin(β)	cos(α)/sin(β)	cos(α)/sin(β)
κ_d	cos(α)/sin(β)	-sin(α)/cos(β)	cos(α)/sin(β)	-sin(α)/cos(β)
κ_l	cos(α)/sin(β)	-sin(α)/cos(β)	-sin(α)/cos(β)	cos(α)/sin(β)

Constraints from SM channels

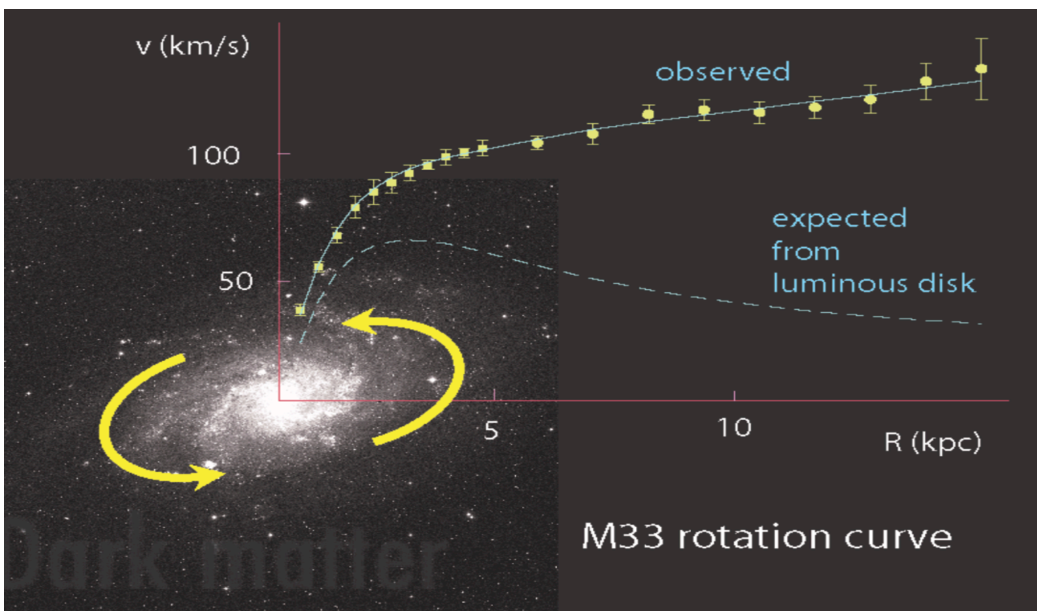
- What can our data already say about the 2HDM?
  - If it exists in Nature, then some of the measured rates (signal strength) are modified
  - Existing measurements can already rule out many possibilities
  - Used final states γγ, ZZ, WW, bb, ττ

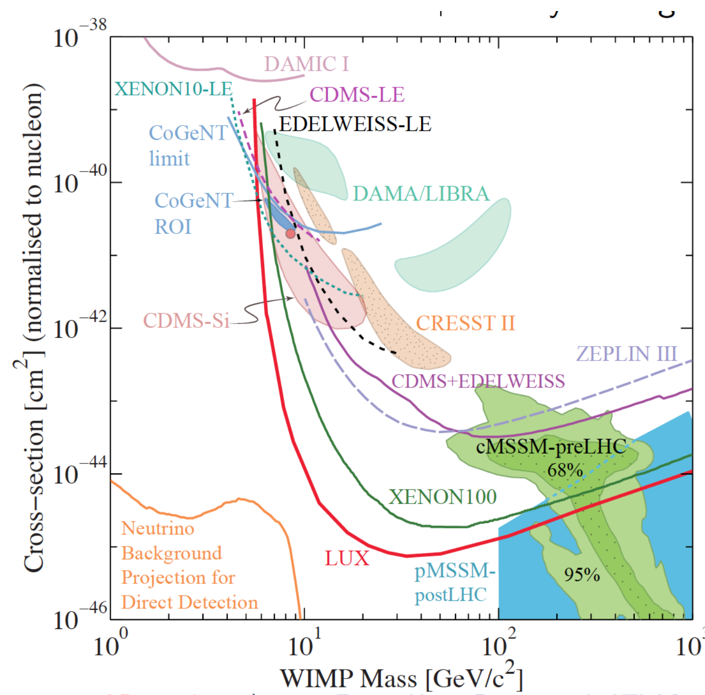


ATLAS-CONF-2014-010

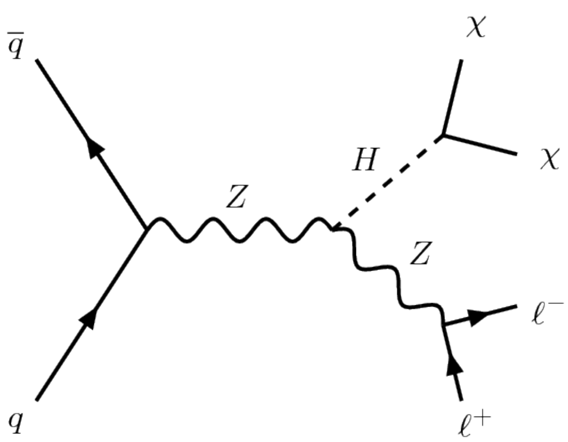
Invisible Higgs

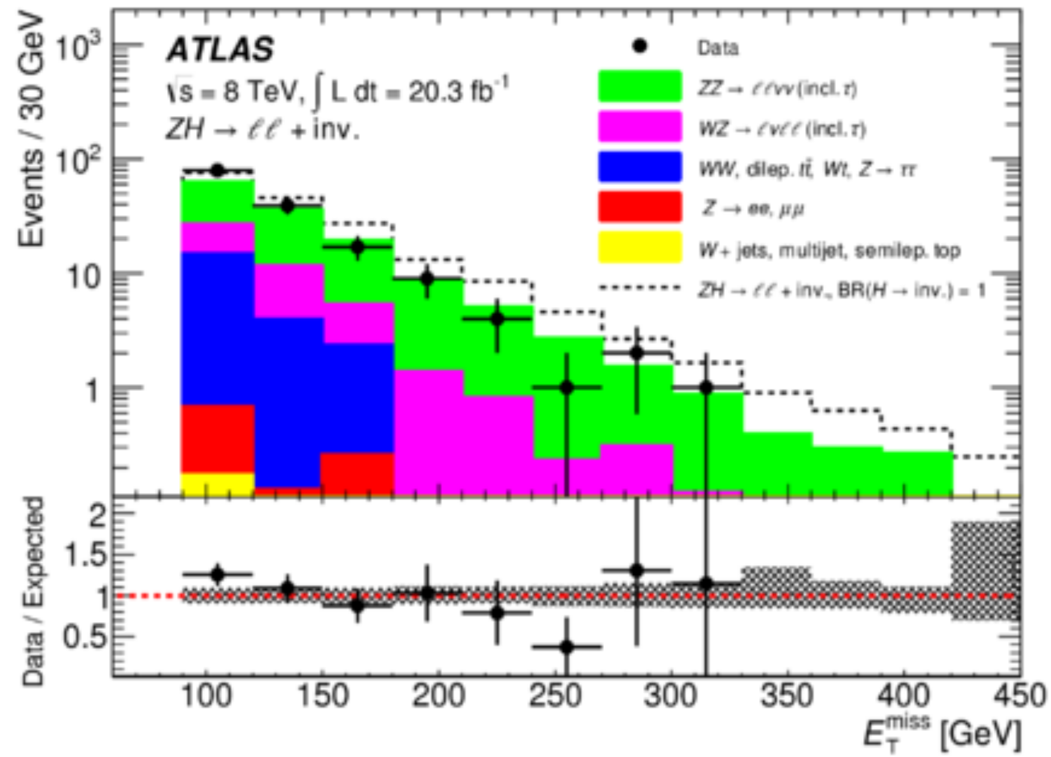
- Direct searches for Dark Matter usually hidden in deep caverns for low noise. But there is another way…
  - Dark matter has mass! Should couple to the Higgs. Do we see it?
  - Weakly interacting particles would leave no trace in detector – "Invisible" Higgs decays
  - Could be e.g. neutralinos in SUSY scenario
  - Would contribute to total Higgs width





Invisible Higgs





Require dileptons from Z

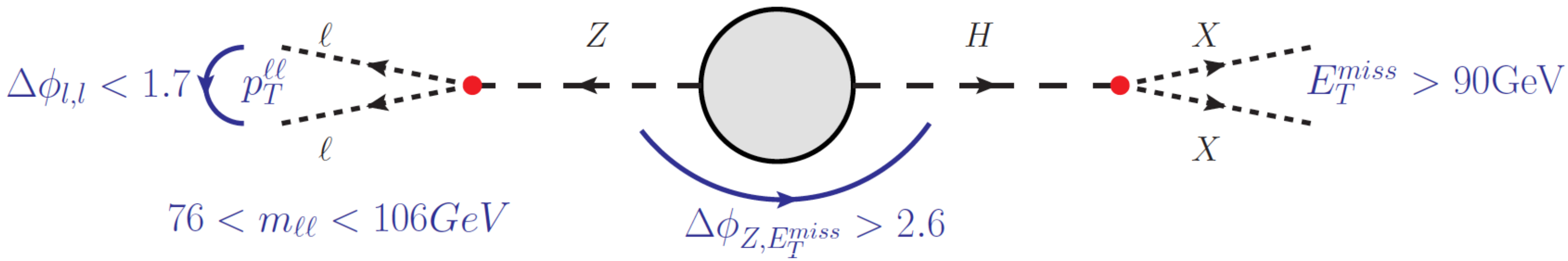
Back to back with Missing E_T and $p_T(\ell\ell)$

No jets

Main backgrounds ZZ, WZ

Claire Shepherd-Themistocleous - 26th Rencontres de Blois 2014

Z(H -> Invisible): Analysis Strategy

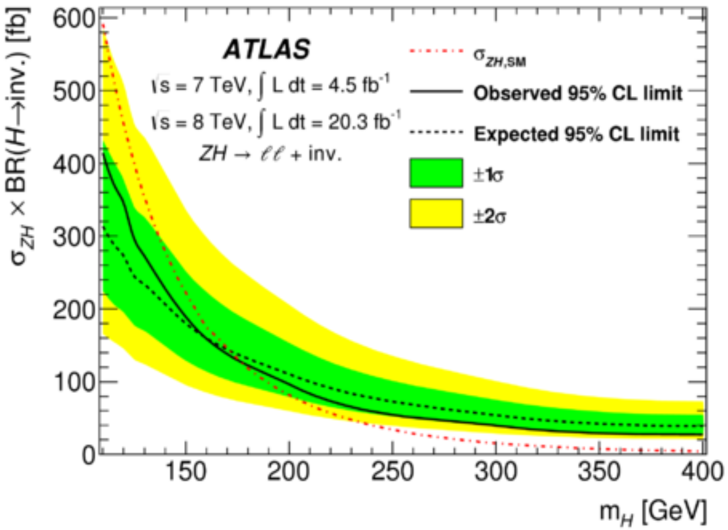


- Analysis cuts designed around the idea that the Z ($\ell\ell$ system) recoils off of the H (E_T^{miss}) for signal
- Most important background is Drell-Yan (Z) production with fake E_T^{miss} from mismeasured jets which is hard to estimate from MC
  - Estimated by 2 dimensional sideband fit of events failing one or both ❄

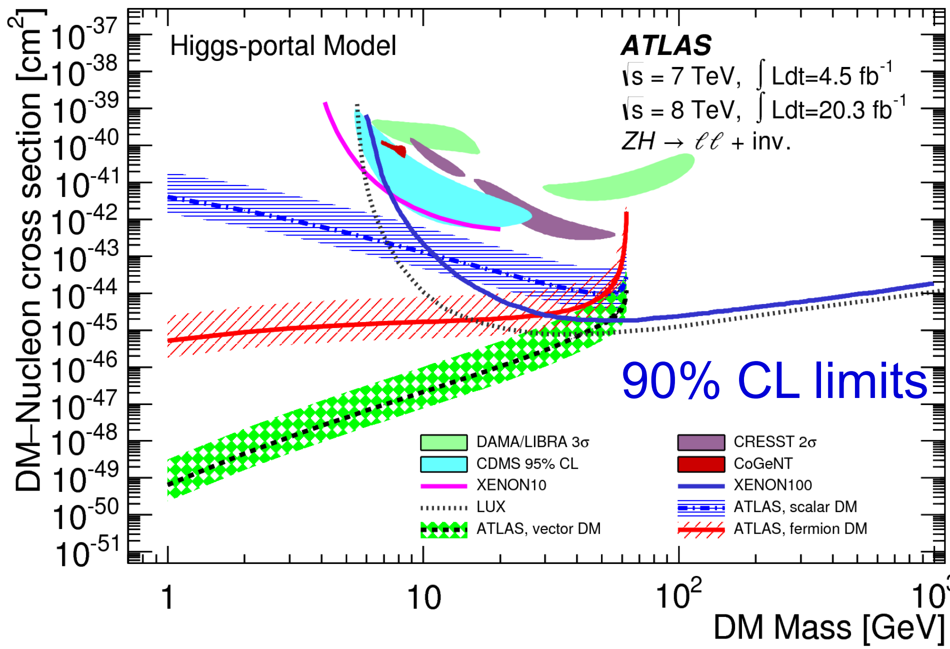
Requirement	Justification
$76 < m_{\ell\ell} < 106\text{GeV}$	Dilepton system consistent with $Z \to \ell\ell$
$E_T^{miss} > 90\text{GeV}$	Requiring the H to have p_T forces the Z to also have p_T
E_T^{miss} Cleaning Cuts	
$\Delta\phi_{\ell,\ell} < 1.7$	Boosted Z has leptons close together
$\Delta\phi_{Z,E_T^{miss}} > 2.6$	Z and H should be back-to-back
$\Delta\phi(E_T^{miss}, E_T^{miss,track}) < 0.2$	E_T^{miss} not correlated for background (E_T^{miss} from mismeasured jets) ❄
$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell} < 0.2$	Balance of Z and H momentum ❄
Central Jet Veto	Drell-Yan background tends to have one or more jets

R.Vanguri, Lake Louise Winter Institute 2015

Invisible Higgs



Upper limit Br to inv. 75%

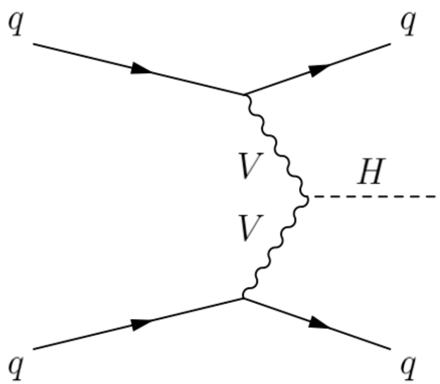


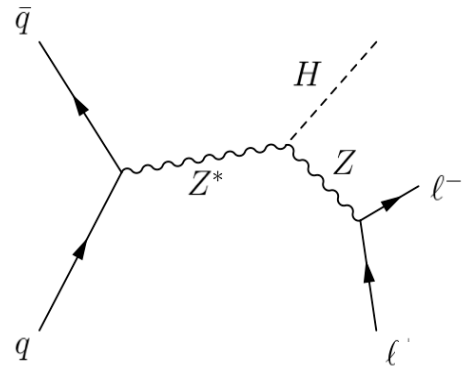
Upper limit interpreted as limit on DM-nucleon scattering cross section
Fox et al. Phys. Rev. D 85 050611

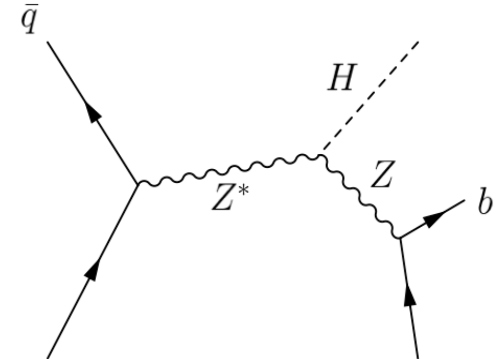
DM scenarios scalar, vector or Majorana fermion

Higgs-nucleon coupling 0.33 $^{+0.30}_{-0.07}$ Djouadi et al. Phys. Lett. B 709 65 (2012)

Invisible Higgs





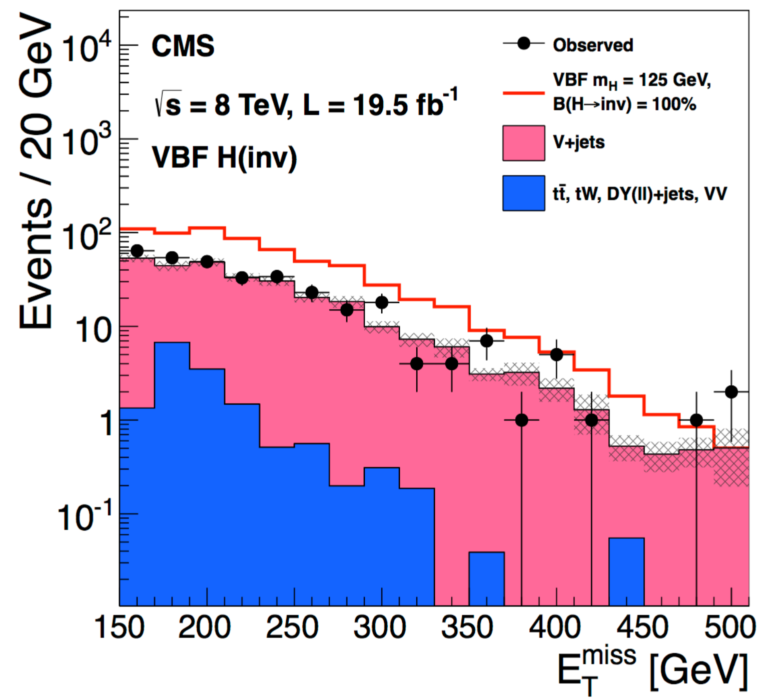


Other search channels:
Search in VBF and ZH , Z → ll and bb

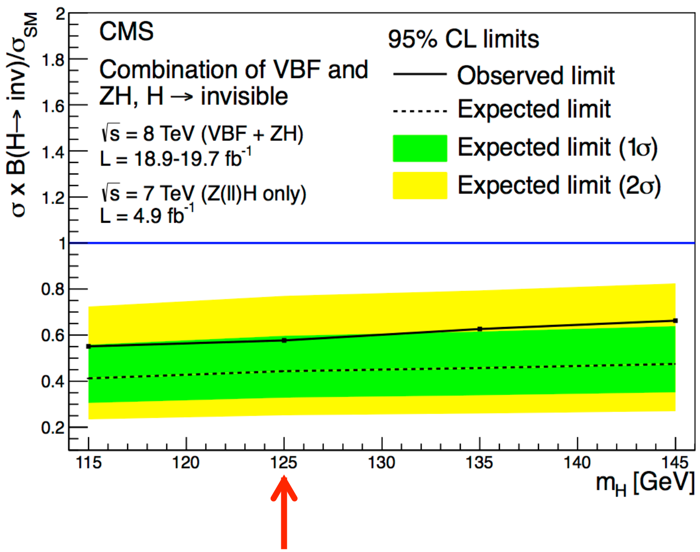
VBF mode requires 2 jets in forward region ($\Delta\eta_{jj} > 4.2$) , $E_t^{miss} > 130$ GeV

Central jet veto on any jet $p_T > 30$ GeV.

Dominant backgrounds
$Z(\nu\nu)$ + jets, $W(l\nu)$ + jets

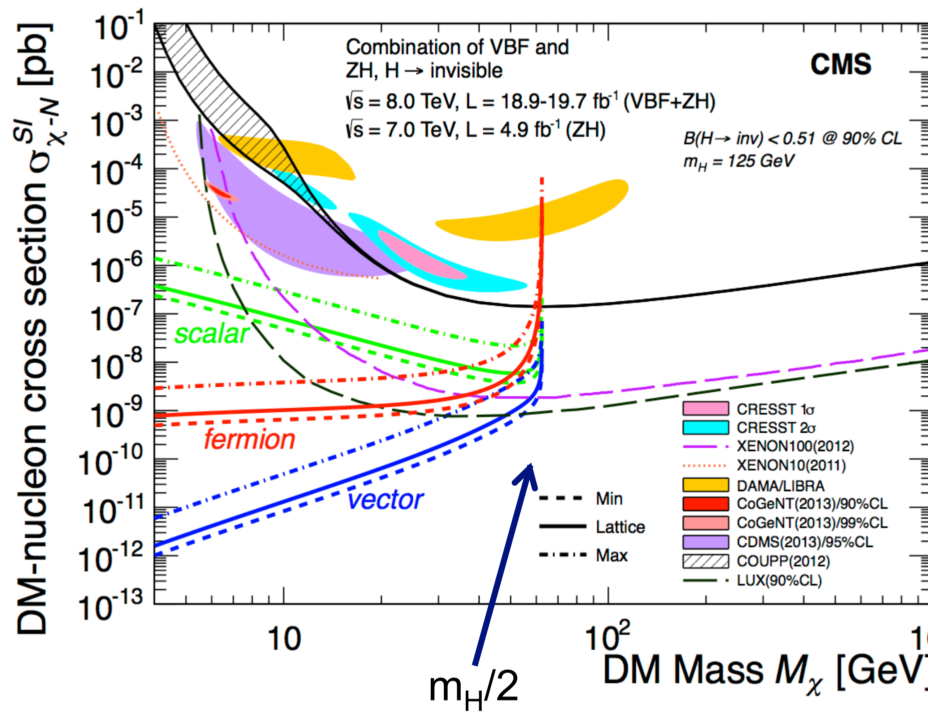


Invisible Higgs



Upper limit on Br to invisible 0.58 for Higgs mass 125 GeV

7 TeV 4.9 fb^{-1} 8 TeV ~ 19 fb^{-1}

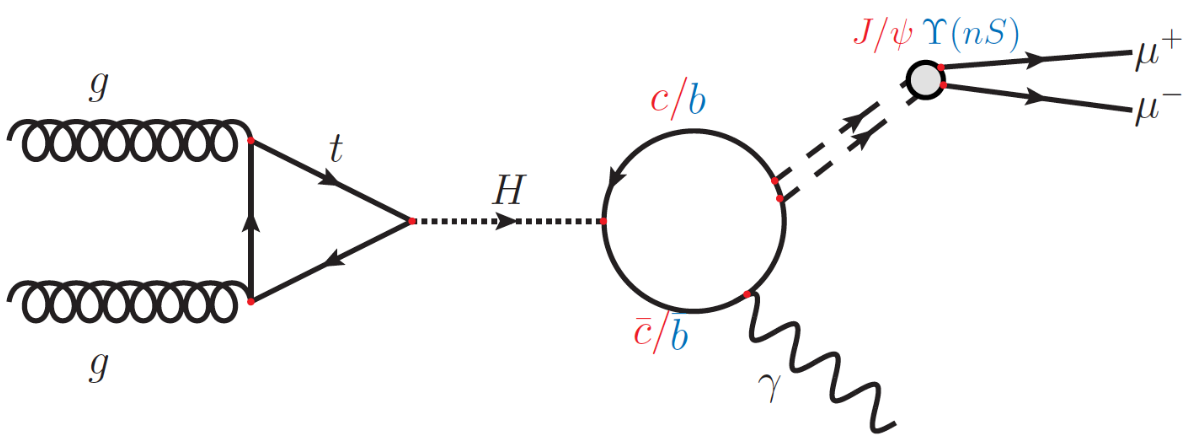


Higgs nucleon coupling 0.33 (range 0.26 - 0.63)

DM scenarios scalar, vector or Majorana fermion

Rare decays

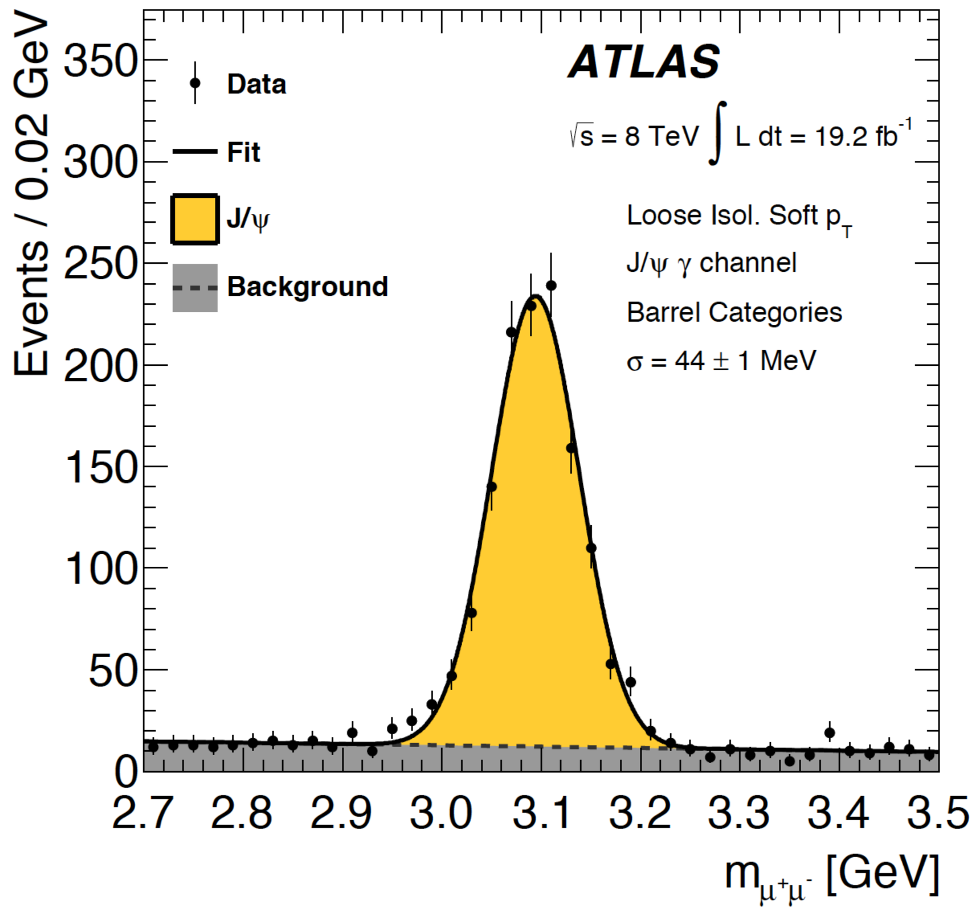
- Only way to probe Higgs decays to charm – charm Yukawa coupling – at LHC
- Deviations in coupling from SM value can lead to increase in branching fraction
- Analysis also probes Z decays to J/Ψ or ϒ(nS) plus γ – improved LEP limits by 2



Backgrounds

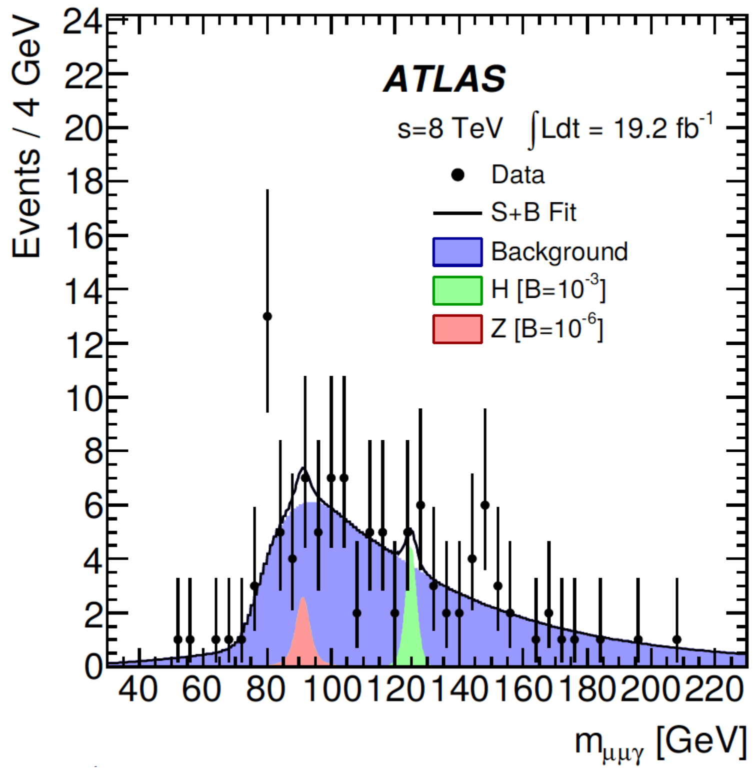
Dominant Backgrounds

- 56% Prompt J/ψ: Peaks in $m_{\mu\mu}$
  - $gg \to J/\psi g$ where g (jet) is misidentified as a γ
  - Suppressed by requiring γ be isolated since there is usually hadronic activity around a jet
- 41% Non-resonant: Smooth in $m_{\mu\mu}$
  - Production of a di-muon pair with invariant mass close to J/ψ



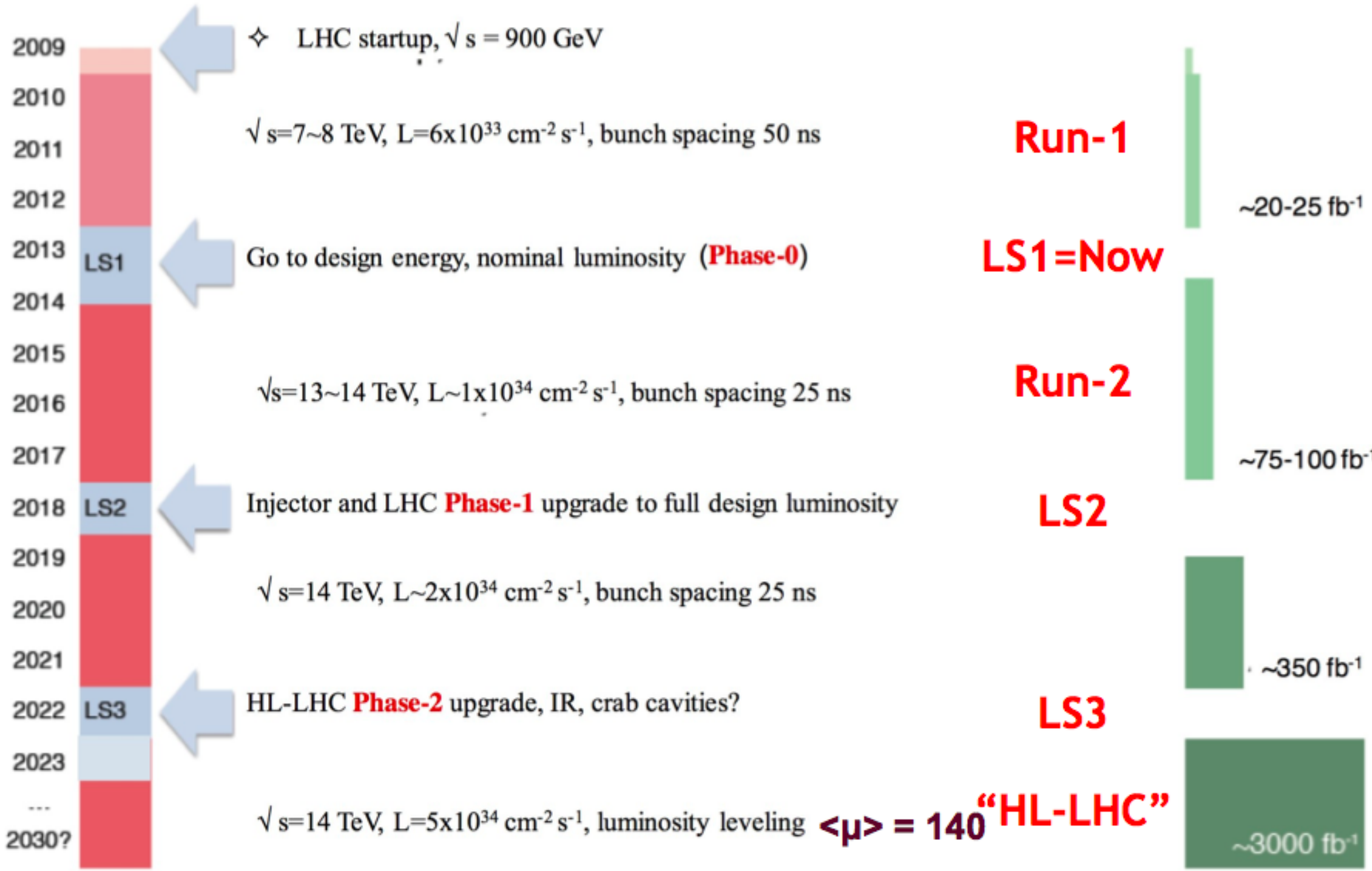
Results

- Upper limit set on branching fraction of H decay to J/Ψ plus γ at 95% confidence:
- Br (J/Ψ γ) < 1.5 x 10^{-3} (expected $1.2^{+0.6}_{-0.3}$ x 10^{-3})
- 540 ≈ SM Expectation



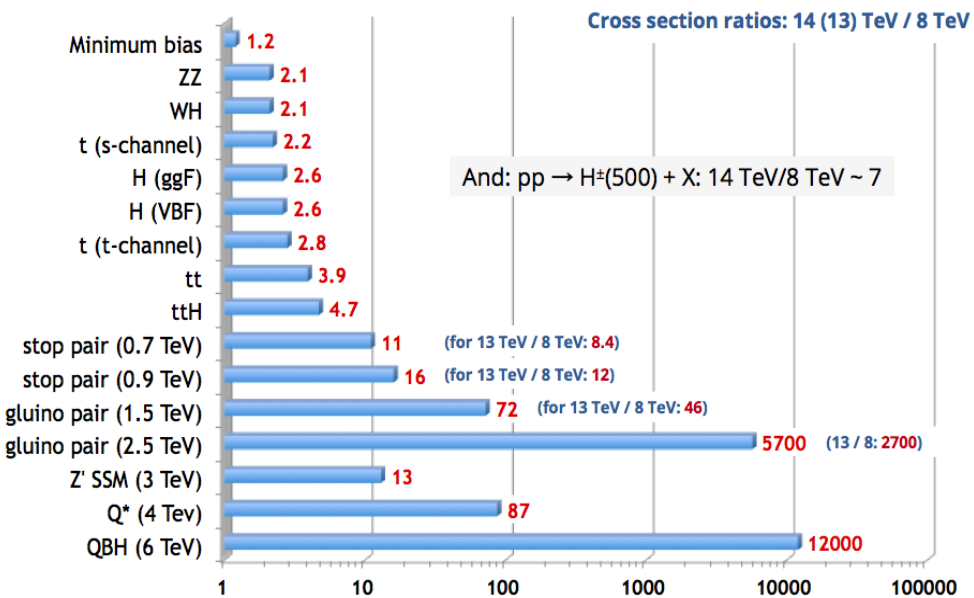
Looking into the future

Future LHC Running

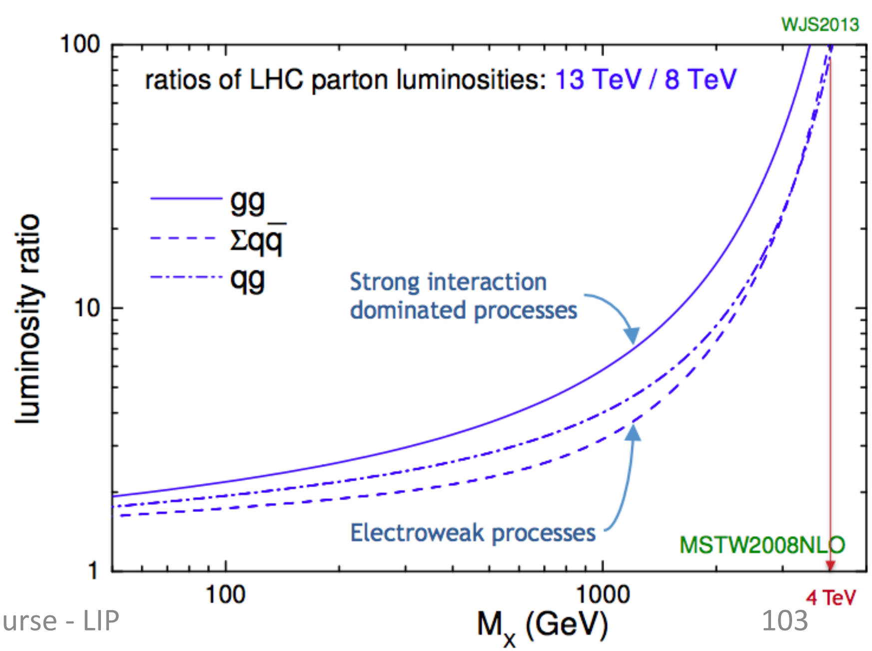


Not only more luminosity

- Higher centre of mass energy gives access to higher masses
- Hugely improves potential for discovery of heavy particles
- Increases cross sections limited by phase space
  - E.g. ttH increases faster than background (factor 4)
- But may make life harder for light states
  - E.g. only factor 2 increase for WH/ZH, H→bb and more pileup
  - Could be compensated by use of boosted jet techniques (jet substructure)



http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



Run II/High-Lumi LHC Programme

Precision AND searches!

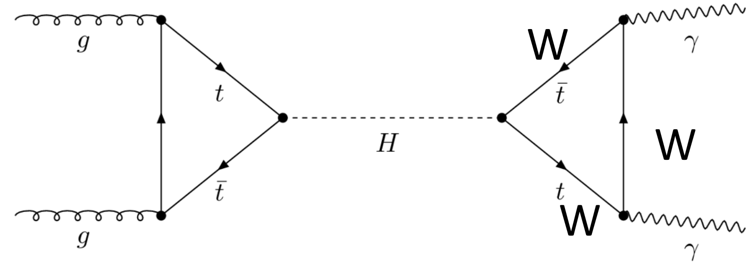
- Precision:
  - Continue to look for deviations wrt Standard Model
- Differential cross sections:
  - New physics in loops could modify event kinematics
- Complete measurement of properties:
  - E.g. CP quantum numbers:
  - Sensitivity in $H \rightarrow ZZ$ and VBF
  - Search for CP violation in Higgs sector
- Search for rare decay modes:
  - $H \rightarrow HH$ to access self coupling (long term!)
- Search for additional Higgs bosons:
  - E.g. 2-Higgs Doublet Model is a natural extension and predicted in SUSY

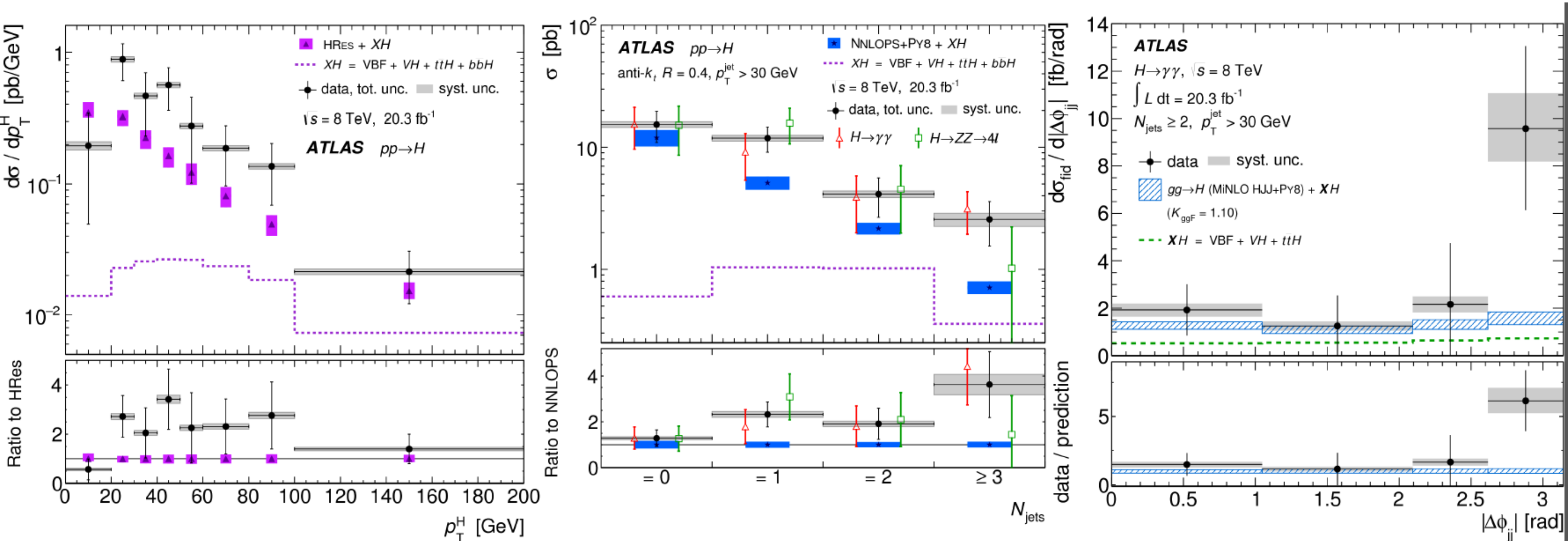
Luminosity	$H \rightarrow Z\gamma$	$H \rightarrow \mu\mu$	$H \rightarrow$ Invisible
300fb^{-1}	2.3 σ	2.3 σ	$Br < 23\%$
3000fb^{-1} HL-LHC	3.9 σ	7.0 σ	$Br < 8\%$

ATL-PHYS-PUB-2014-006 ATL-PHYS-PUB-2013-014 ATL-PHYS-PUB-2013-014

Higgs differential cross sections

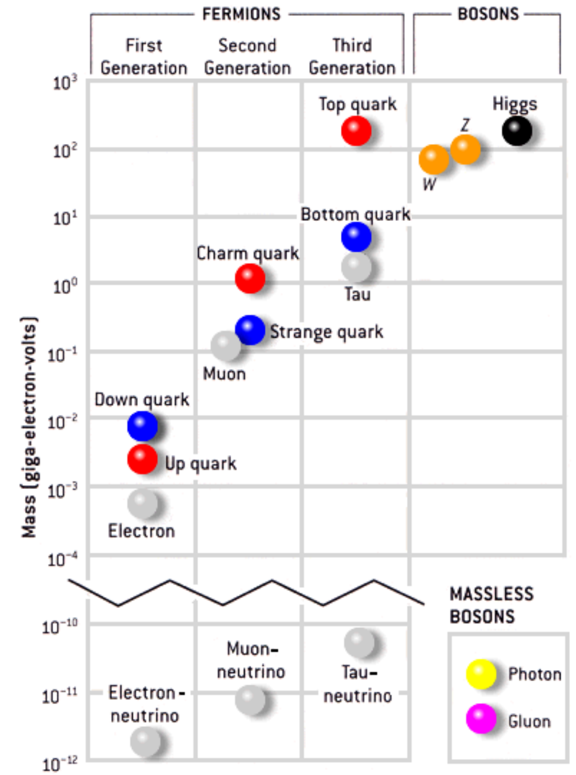
- Get access to the loop structure where there may be new physics
- ATLAS H→γγ and ZZ so far – more to come in run 2

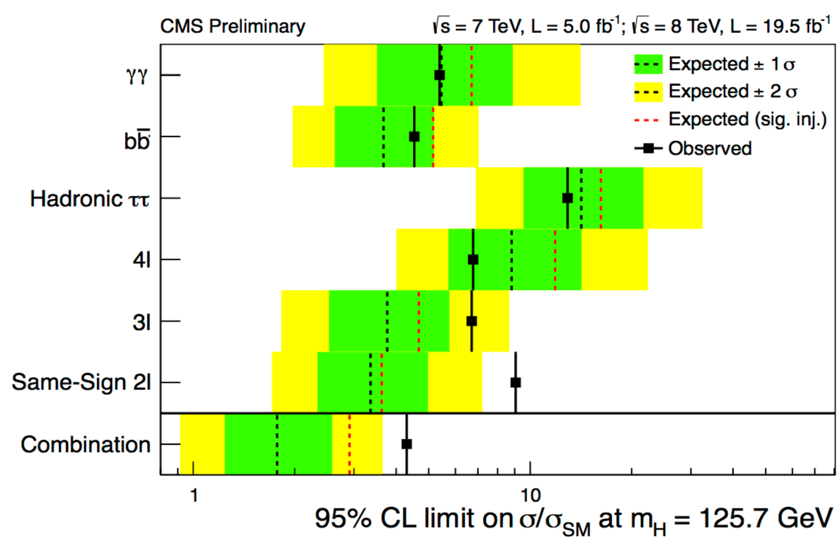


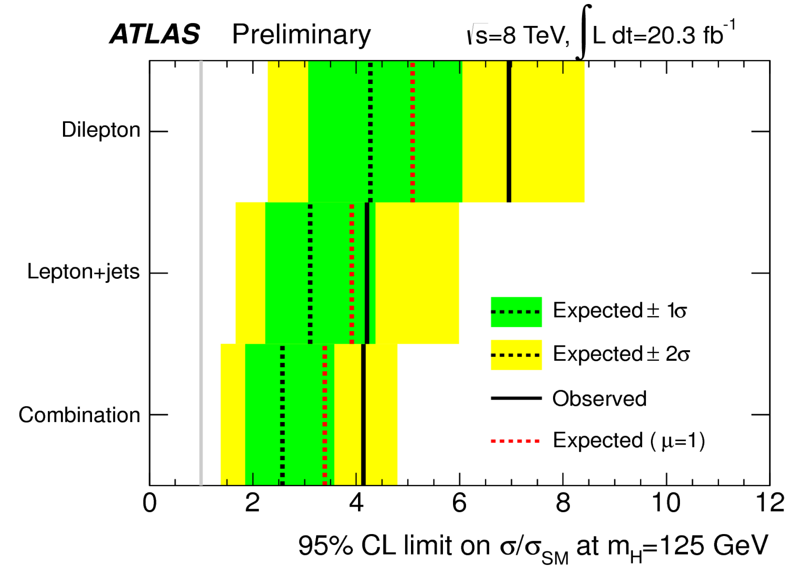


Another example: ttH

- Indirect constraints on top-Higgs Yukawa coupling from loops in ggH and ttH vertices
  - Assumes no new particles contribute to loops
- Top-Higgs Yukawa coupling can be measured directly
  - Allows probing for New Physics contributions in the ggH and γγH vertices
- Top Yukawa coupling $Y_t = \sqrt{2}M_t/vev = 0.996 \pm 0.005$
  - Does this mean top plays a special role in EWSB?

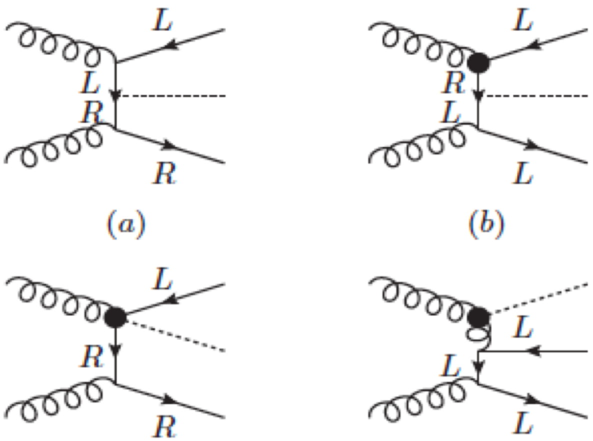




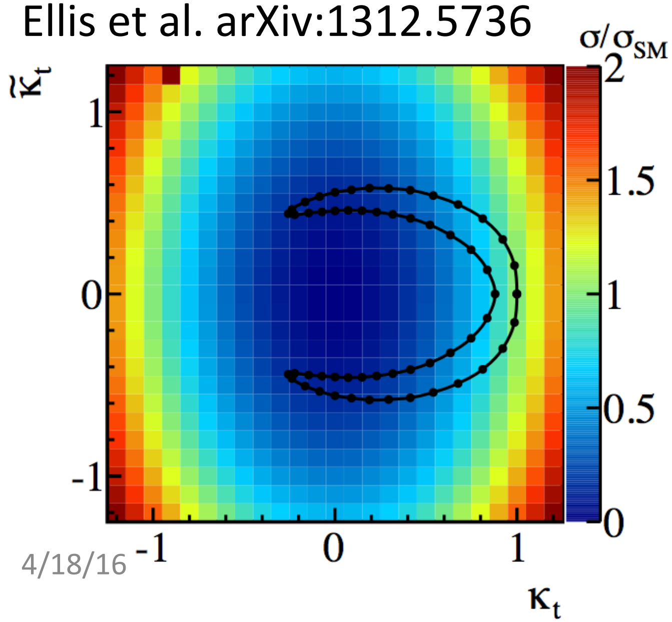


Sensitivity to New Physics

Degrande et al. arXiv:1205.1065



Ellis et al. arXiv:1312.5736



- Effective top-Higgs Yukawa coupling may deviate from SM due to new higher-dimension operators
  - Change **event kinematics –** go differential!
- ttH sensitive new physics: little Higgs, composite Higgs, Extra Dimensions,…
- In the presence of CP violation, Higgs-top coupling have scalar (κ_t)and pseudoscalar ($\tilde{\kappa}_t$)components
  - Strong dependence on ttH cross section
  - Note: Indirect constraints from electron electric dipole moment not taken into account (give $|\tilde{\kappa}_t| < 0.01$)

Summary

- Recapitulation:
  - Electroweak symmetry breaking
  - Higgs boson in Electroweak Lagrangian
  - Higgs boson production and decay at the LHC
  - The landscape at the end of LHC run I

- The Higgs sector beyond the Standard Model
  - Constraints from current data
  - Examples of rare and exotic channels

- Future Higgs measurements at LHC and beyond
  - Fundamental questions at the end of run I
  - Future LHC running – luminosity, energy, and physics reach
  - Higgs physics in future LHC analyses – Precision and Searches
  - An example: associated production with top-quark pair – SM and BSM