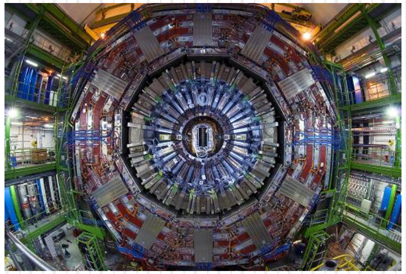
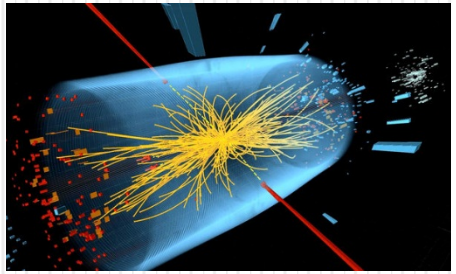
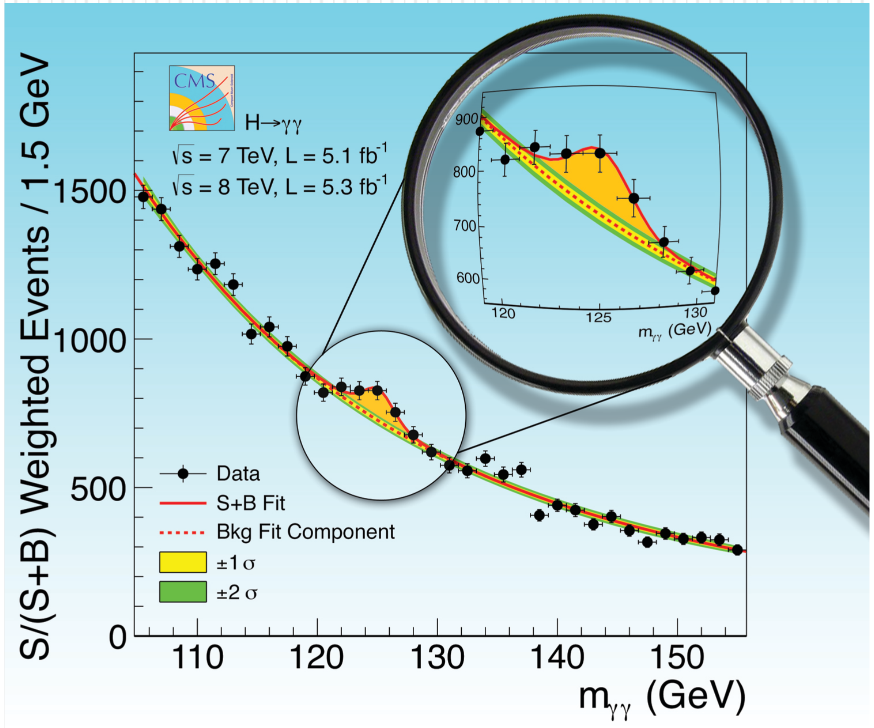


Nature of the New Boson: a lonely Higgs, or one of many cousins?



Jim Olsen

Princeton University

Colloquium of the School of Physics and Astronomy

Queen Mary University of London

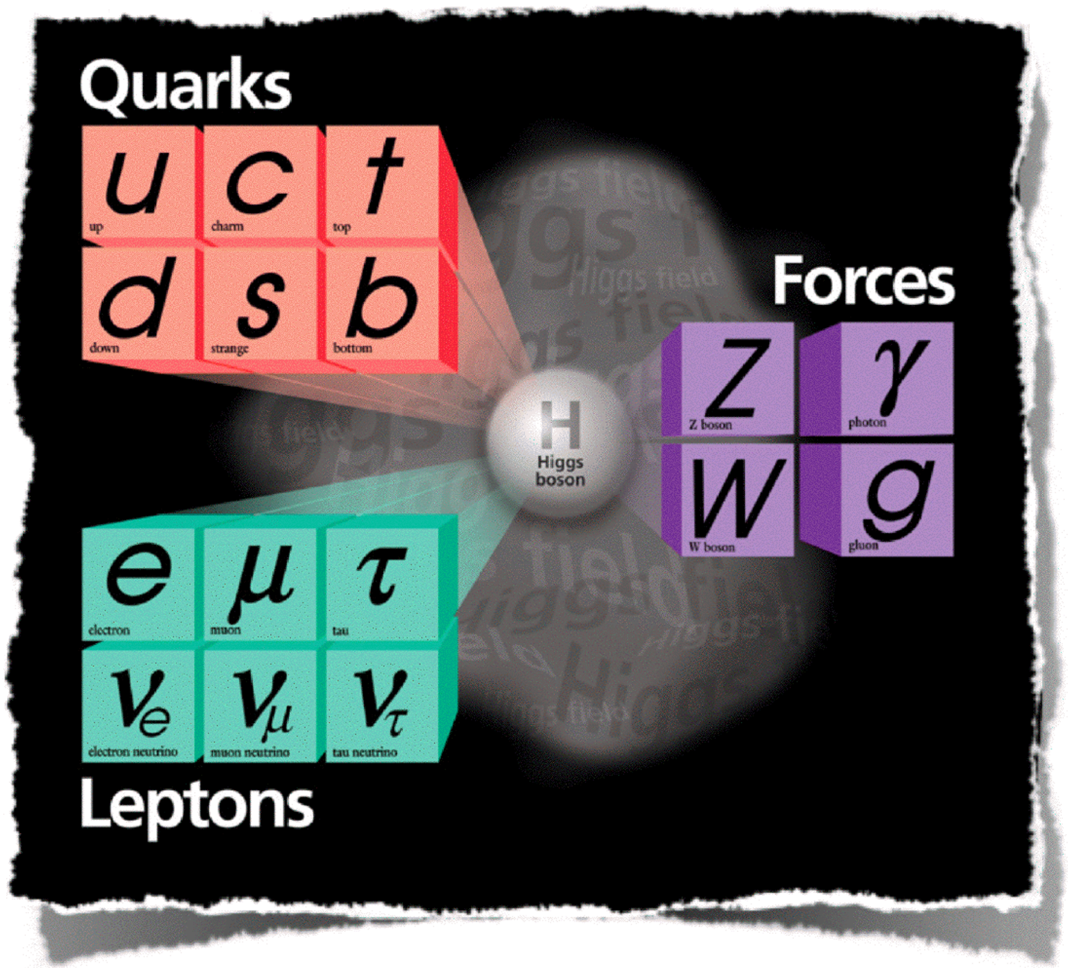
January 17, 2014

Outline

- Why do we need any Higgs bosons?
- Search for the Higgs boson
- Discovery of "a Higgs boson"
- Nature of the new boson
- Is there more than one Higgs boson?
- Future prospects in Higgs physics at the LHC

Why do we need any Higgs bosons?

One field to rule them all…



Standard Model

Fundamental matter:

quarks and leptons

Symmetries:

$U(1)_Y$, $SU(2)_L$, $SU(3)_C$

Local gauge invariance:

gauge bosons (force carriers)

Higgs field:

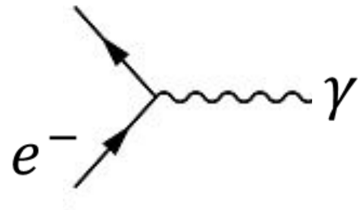
spontaneous EWK symmetry breaking and the Higgs boson

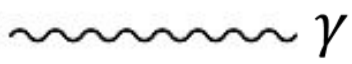
What's the problem?

Dirac Lagrangian:

$$\mathcal{L} = \underbrace{\left[i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi\right]}_{\text{Free fermions}} - \underbrace{\left(e\bar{\psi}\gamma^{\mu}\psi\right)A_{\mu}}_{\text{Gauge interaction}} - \underbrace{\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^{\nu}A_{\nu}}_{\text{Free gauge bosons}}$$

Free fermions | **Gauge interaction** | **Free gauge bosons**





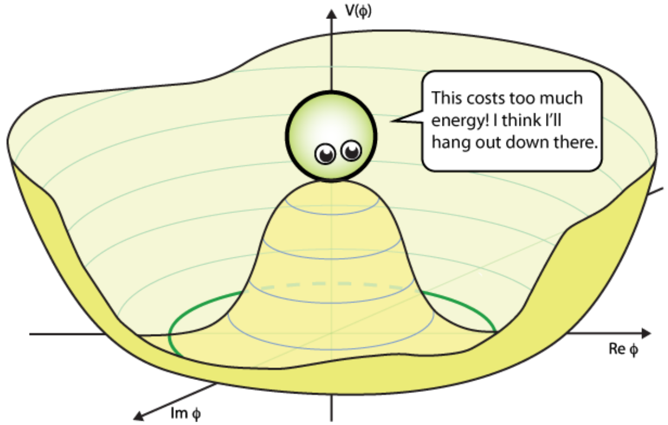
"Local gauge invariance": $\mathcal{L}$ should be invariant under $\psi \rightarrow e^{i\theta(x)}\psi$,

but $m_A^2 A^{\nu}A_{\nu}$ is not gauge invariant $\longrightarrow$ need $m_A = 0$!

So it works for EM and QCD, but W and Z bosons are massive (~100 GeV). Need a mechanism to give mass to the W and Z.

The Higgs* Mechanism (1964)

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - \overbrace{\left(-\mu^2 \phi^2 + \lambda \phi^4\right)}^{V(\phi)} - \tfrac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

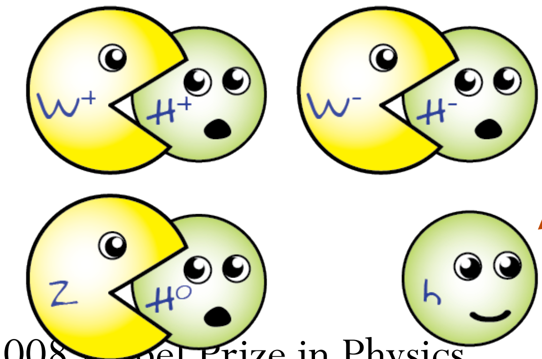


F. Tanedo

$$\phi = \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \Rightarrow \begin{pmatrix} v + h \\ 0 \end{pmatrix}$$

Spontaneous symmetry breaking (v = "vev")

3 degrees of freedom are "eaten" by the $W^\pm$ and Z^0, thus acquiring mass, while the photon remains massless:



The "SM Higgs boson" is the 4th degree of freedom, with mass

$$m_h = \sqrt{2\lambda} v$$

2008 Nobel Prize in Physics

2013 Nobel Prize in Physics

* actually, the Nambu-Goldstone-Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Properties of "the SM Higgs boson"

A single **elementary** scalar particle ($J^P = 0^+$), quantum of the field that gives mass to the W and Z, plus quarks and leptons

Mass: $m_h = \sqrt{2\lambda}v$ $v = \left(\sqrt{2}G_F\right)^{-\frac{1}{2}} \cong 246\ \mathrm{GeV}$

Because λ is not predicted, the Higgs boson mass m_h is a free parameter in the Standard Model

Interaction: couples to particles according to their mass, including self-coupling (h* → hh)

$$m_W = \frac{gv}{2},\ m_f = \frac{g_f v}{\sqrt{2}}$$

Is this the only possibility?

Additional Higgs fields ϕ_i ➡ $2m_W = \sum_i g_i v_i$

Composite Higgs: top-quark condensate

Technicolor: new gauge interactions

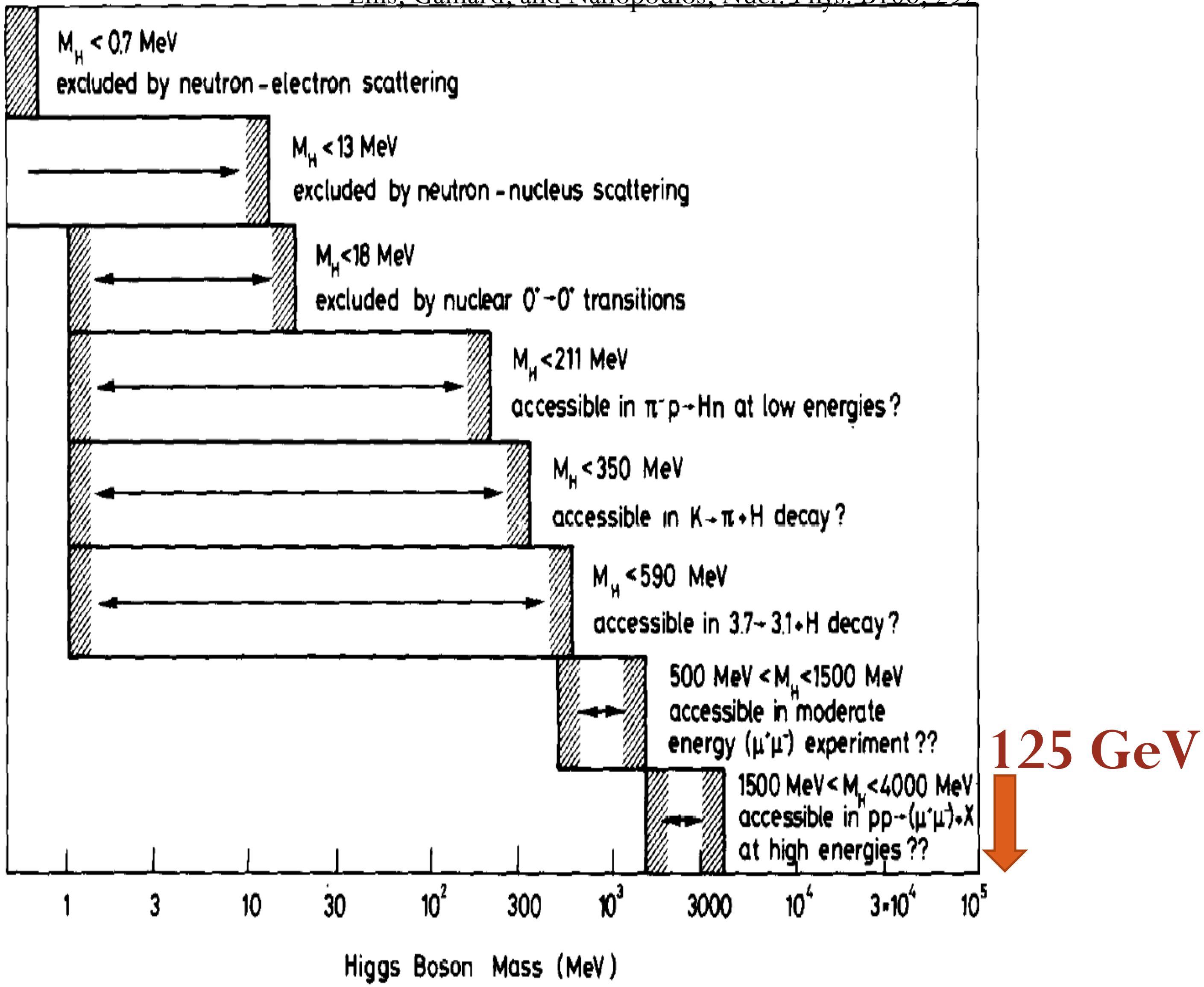
Extra dimensions

…

Search for the Higgs boson

Higgs Hunting: 1975

Ellis, Gaillard, and Nanopoulos, Nucl. Phys. B106, 292



Bounds on the SM Higgs Mass: ~1980

Mass of the Higgs Boson*

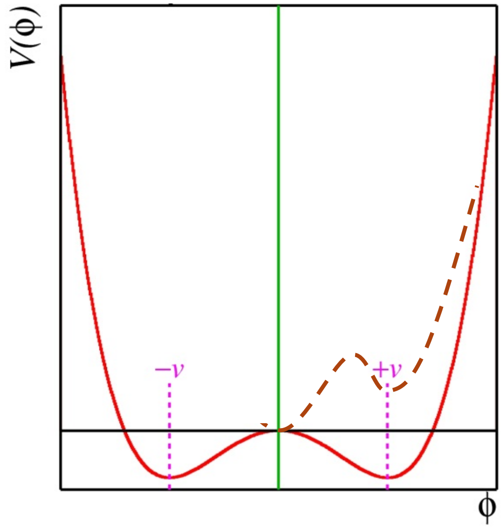
Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 December 1975)

The stability of the vacuum sets a lower bound of order $\alpha G_F^{-1/2}$ on the Higgs-boson mass. For the simplest SU(2) ⊗ U(1) model, this lower bound is $1.738 \alpha G_F^{-1/2}$, or 3.72 GeV.

and A. Linde, JETP Lett. 23 (1976) 64

Requiring $V(v) < V(0)$ gives:

$$m_H > \left[\frac{3(2m_W^4 + m_Z^4) - 4\sum m_l^4 - 12\sum m_q^4}{16\pi^2}\right]^{\frac{1}{2}} > 7\text{ GeV}$$



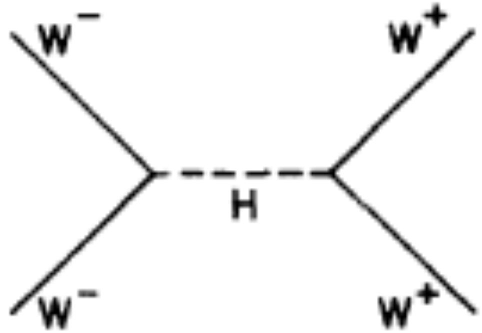
PHYSICAL REVIEW D VOLUME 16, NUMBER 5 1 SEPTEMBER 1977

Weak interactions at very high energies: The role of the Higgs-boson mass

Benjamin W. Lee,* C. Quigg,† and H. B. Thacker
Fermi National Accelerator Laboratory,‡ Batavia, Illinois 60510
(Received 20 April 1977)

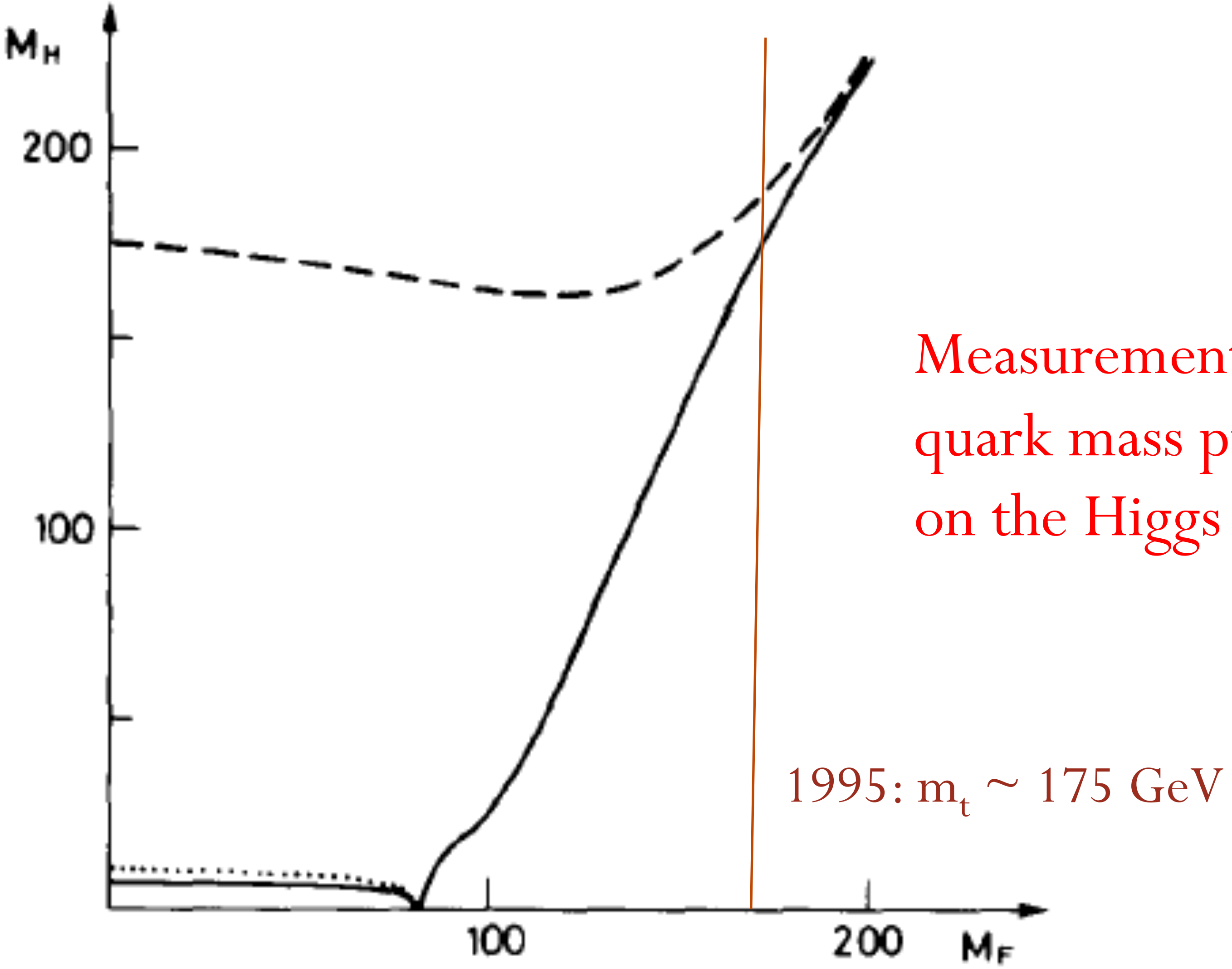
We give an *S*-matrix-theoretic demonstration that if the Higgs-boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{1/2}$, parital-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

$$M_H \leq M_c = (8\pi\sqrt{2}/3G_F)^{1/2} \simeq 1\text{ TeV}/c^2$$



By 1980 we knew the Higgs mass was 7 < m_h < 1000 GeV

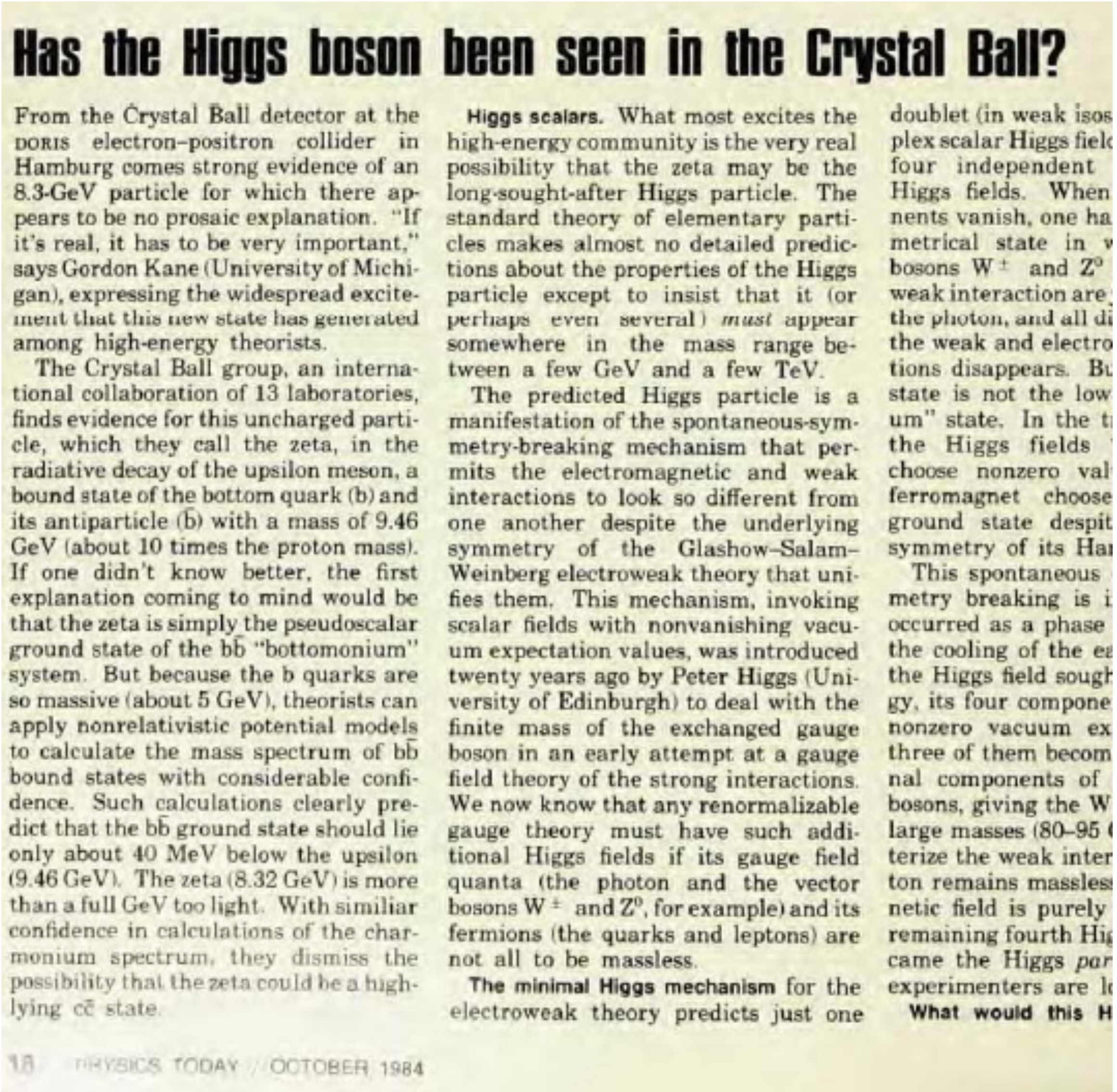
Role of the Top Quark



Measurement of the top quark mass puts a bound on the Higgs mass

Cabibbo, Maiani, Parisi, Petronzio, Nucl. Phys. B158 (1979) 295

1984: Higgs boson found, not!



Has the Higgs boson been seen in the Crystal Ball?

From the Crystal Ball detector at the DORIS electron–positron collider in Hamburg comes strong evidence of an 8.3-GeV particle for which there appears to be no prosaic explanation. "If it's real, it has to be very important," says Gordon Kane (University of Michigan), expressing the widespread excitement that this new state has generated among high-energy theorists.

The Crystal Ball group, an international collaboration of 13 laboratories, finds evidence for this uncharged particle, which they call the zeta, in the radiative decay of the upsilon meson, a bound state of the bottom quark (b) and its antiparticle ($\bar{b}$) with a mass of 9.46 GeV (about 10 times the proton mass). If one didn't know better, the first explanation coming to mind would be that the zeta is simply the pseudoscalar ground state of the $b\bar{b}$ "bottomonium" system. But because the b quarks are so massive (about 5 GeV), theorists can apply nonrelativistic potential models to calculate the mass spectrum of $b\bar{b}$ bound states with considerable confidence. Such calculations clearly predict that the $b\bar{b}$ ground state should lie only about 40 MeV below the upsilon (9.46 GeV). The zeta (8.32 GeV) is more than a full GeV too light. With similiar confidence in calculations of the charmonium spectrum, they dismiss the possibility that the zeta could be a high-lying $c\bar{c}$ state.

Higgs scalars. What most excites the high-energy community is the very real possibility that the zeta may be the long-sought-after Higgs particle. The standard theory of elementary particles makes almost no detailed predictions about the properties of the Higgs particle except to insist that it (or perhaps even several) *must* appear somewhere in the mass range between a few GeV and a few TeV.

The predicted Higgs particle is a manifestation of the spontaneous-symmetry-breaking mechanism that permits the electromagnetic and weak interactions to look so different from one another despite the underlying symmetry of the Glashow–Salam–Weinberg electroweak theory that unifies them. This mechanism, invoking scalar fields with nonvanishing vacuum expectation values, was introduced twenty years ago by Peter Higgs (University of Edinburgh) to deal with the finite mass of the exchanged gauge boson in an early attempt at a gauge field theory of the strong interactions. We now know that any renormalizable gauge theory must have such additional Higgs fields if its gauge field quanta (the photon and the vector bosons $W^{\pm}$ and Z^0, for example) and its fermions (the quarks and leptons) are not all to be massless.

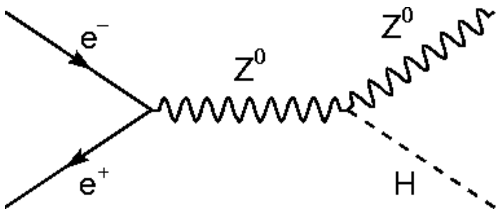
The minimal Higgs mechanism for the electroweak theory predicts just one doublet (in weak isos plex scalar Higgs fiel four independent Higgs fields. When nents vanish, one ha metrical state in bosons $W^{\pm}$ and Z^0 weak interaction are the photon, and all di the weak and electro tions disappears. Bu state is not the low um" state. In the t the Higgs fields choose nonzero val ferromagnet choose ground state despit symmetry of its Ha

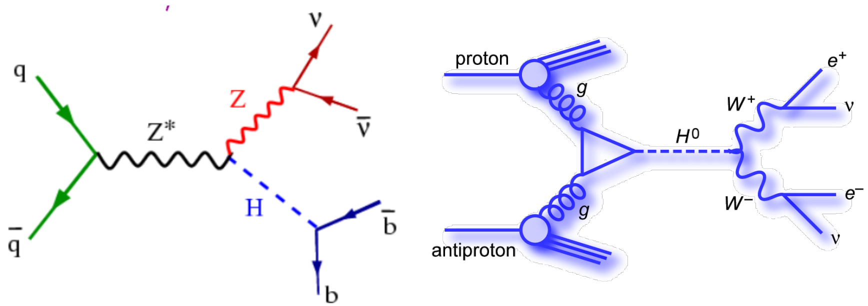
This spontaneous metry breaking is i occurred as a phase the cooling of the ea the Higgs field sough gy, its four compone nonzero vacuum ex three of them becom nal components of bosons, giving the W large masses (80–95 terize the weak inter ton remains massles netic field is purely remaining fourth Hi came the Higgs *par* experimenters are l

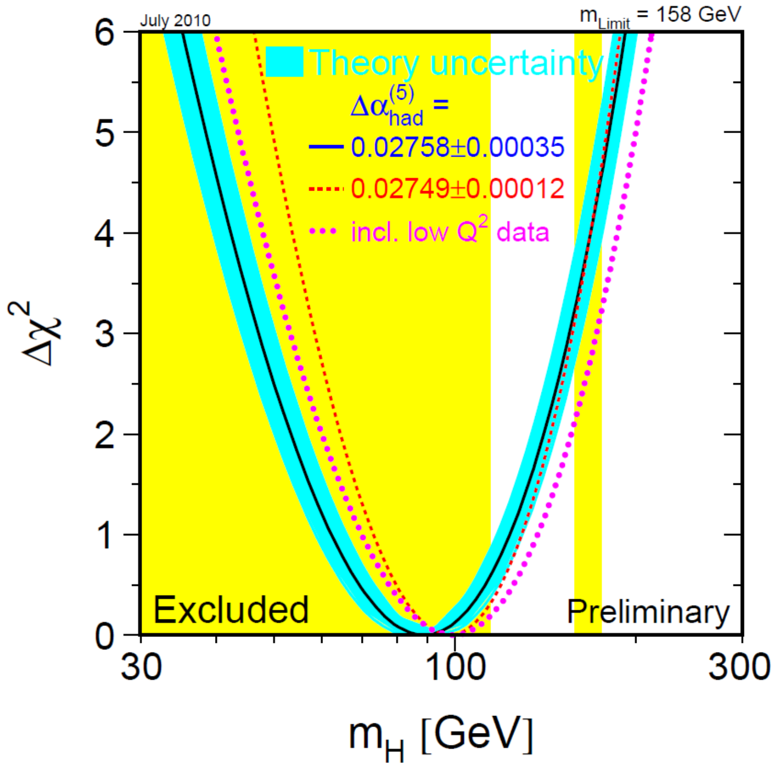
What would this H

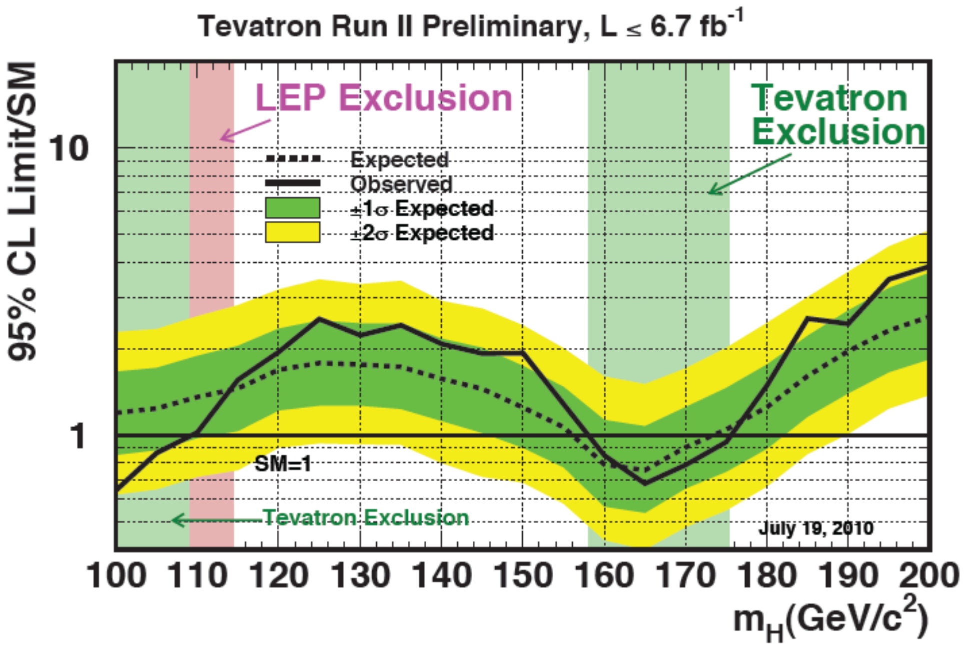
$$\Upsilon \rightarrow \gamma + X$$

Pre-LHC: LEP and Tevatron





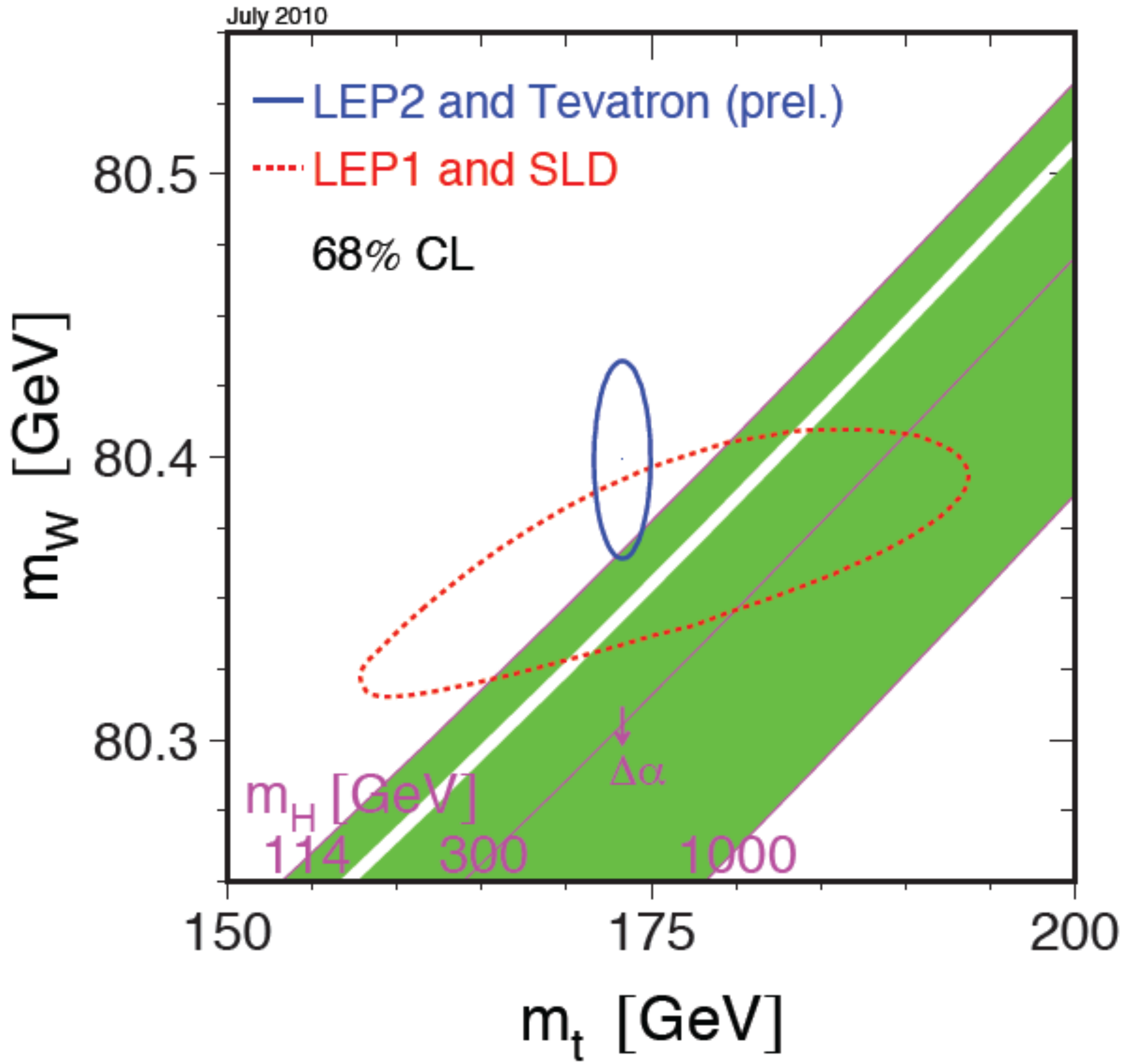




$m_h > 114.4$ GeV

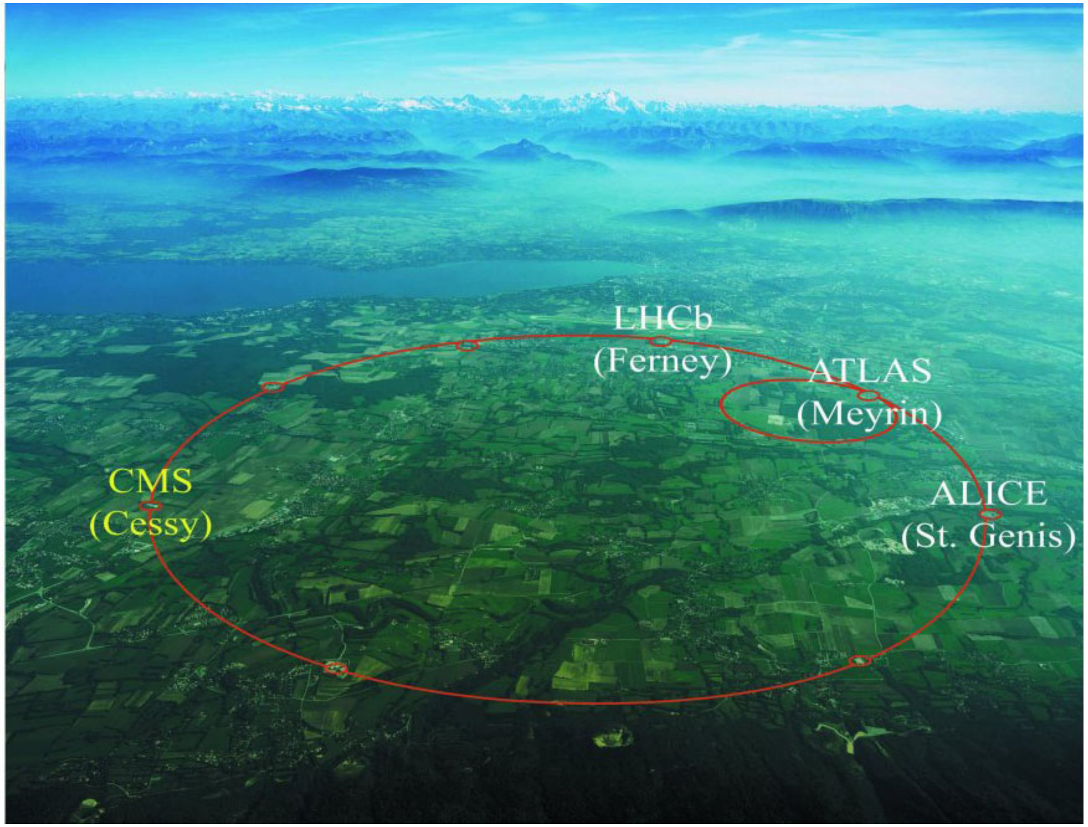
$m_h < 158$ or > 175 GeV

At the dawn of the LHC era



Discovery of “a Higgs boson”

Large Hadron Collider



pp collider inside the 27km LEP tunnel (1998-2008)

Highest energy collider ever built (8 trillion electron volts)

1232 superconducting dipole magnets with B > 8 Tesla

Magnets are colder than space

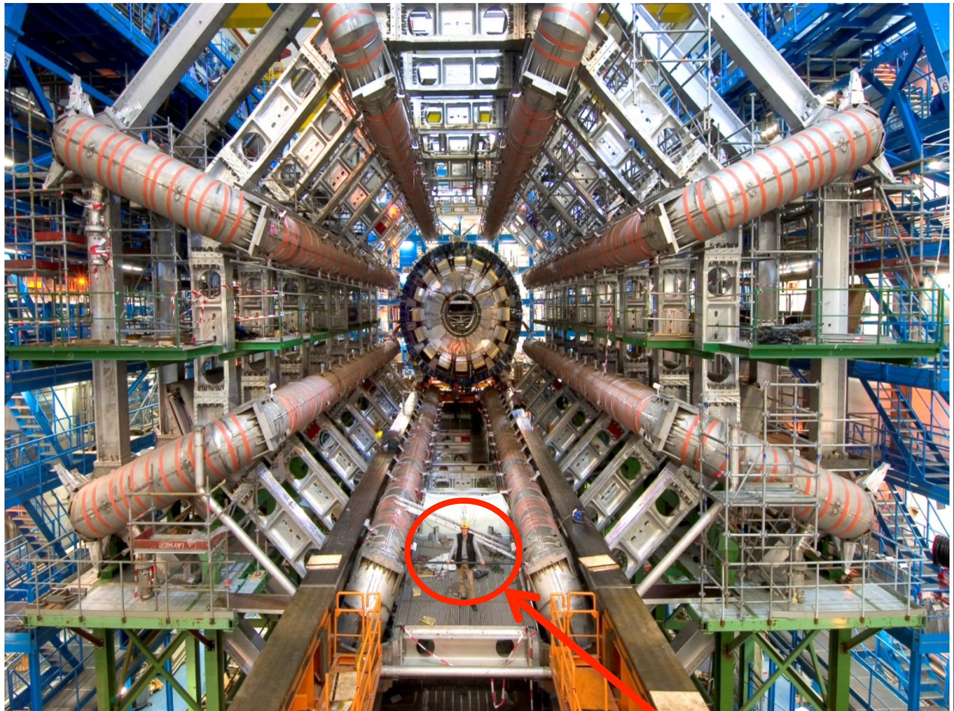
World's largest cryogenic plant

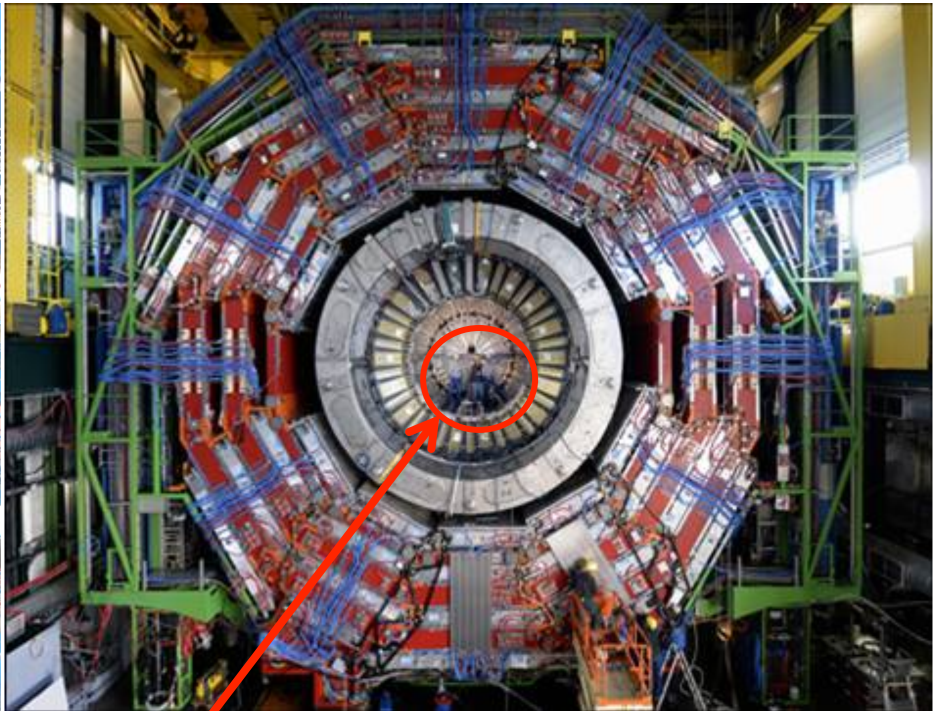
Roughly 750,000 Higgs bosons have been produced by the LHC

ATLAS and CMS

~3000 scientist, engineers, and students working on **each** experiment

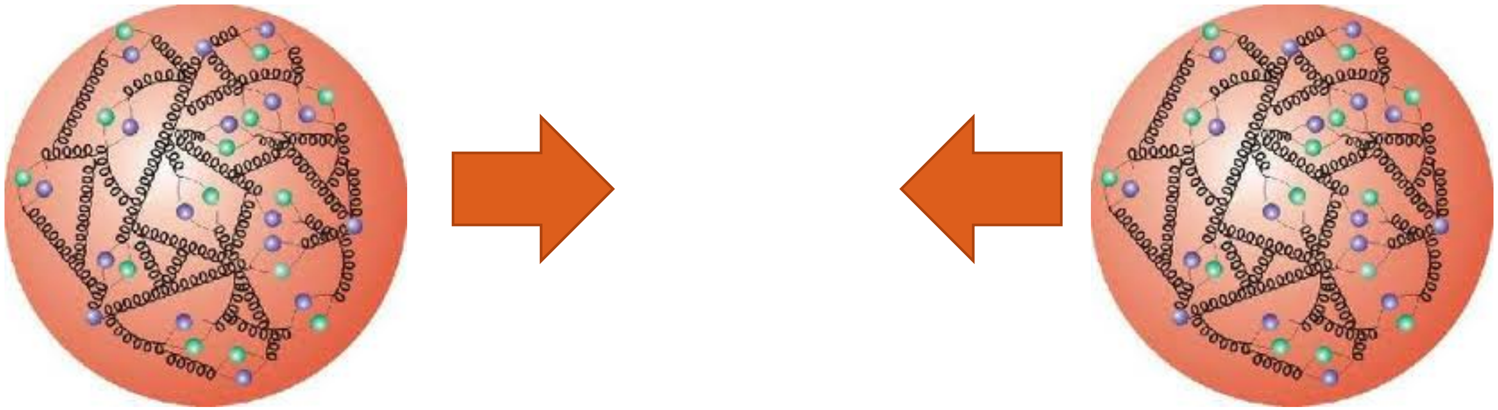
Giant multipurpose particle detectors designed to find or exclude the Higgs boson and signs of physics beyond the SM



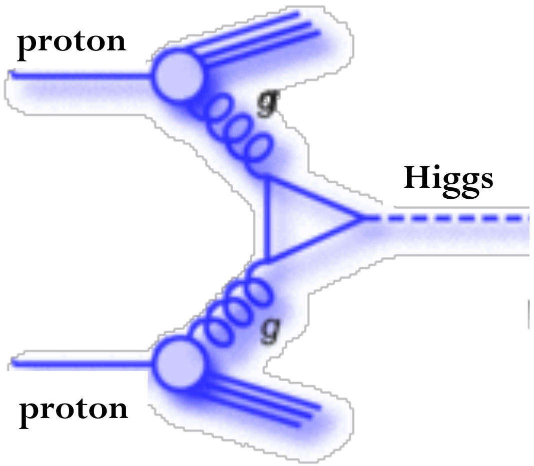


Humans

Creating a Higgs boson

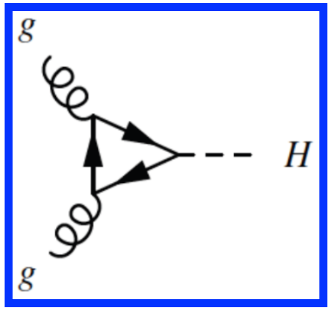


Proton Proton

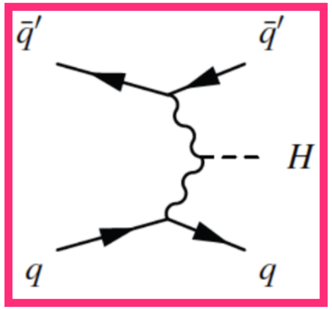


The most probable way to create a Higgs boson is via “gluon fusion”. This happens more than 500 times per hour at the LHC.

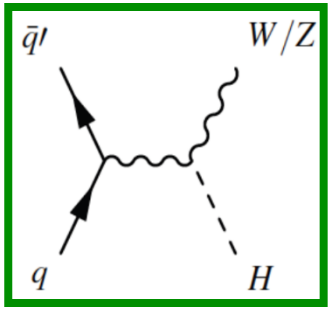
SM Higgs Production at the LHC



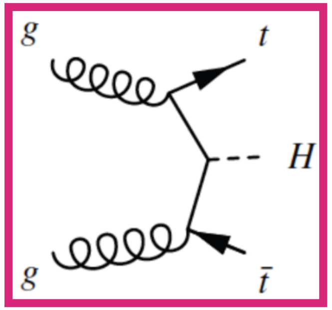
Gluon Fusion



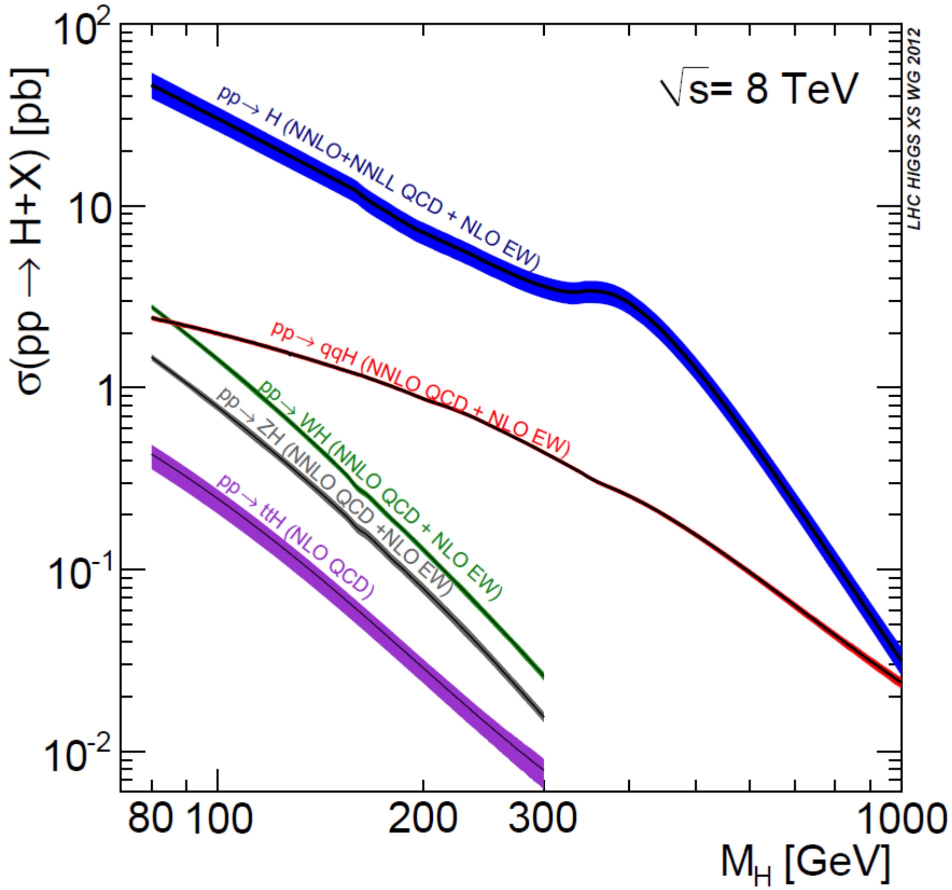
Vector-Boson Fusion



Higgs-strahlung

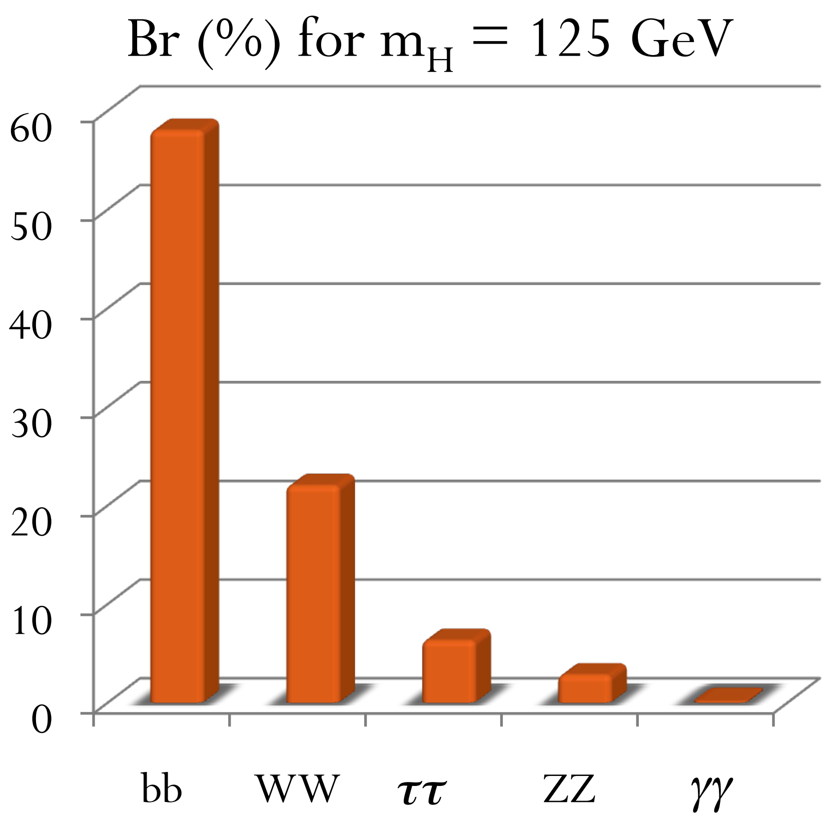


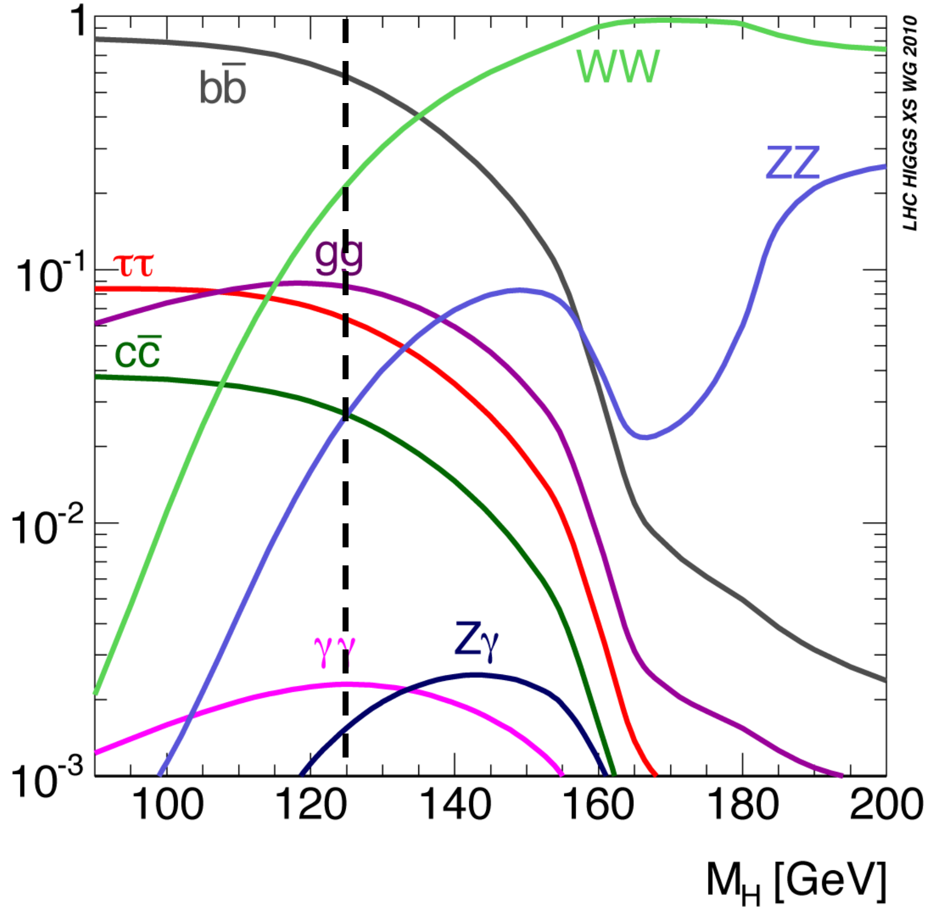
Top Fusion (tt̄H)



LHC in 2012 at record luminosity (7×10^{33} $cm^{-2}s^{-1}$) and energy (8 TeV) was producing SM Higgs bosons (M_H = 125 GeV) at a rate **~750/hr**

How does it decay?





Fortuitous! Only region in m_h where

- Cross sections are large
- Fermion decays (bb+**ττ**) are accessible
- Natural width is negligible

What does it look like?

@Low mass

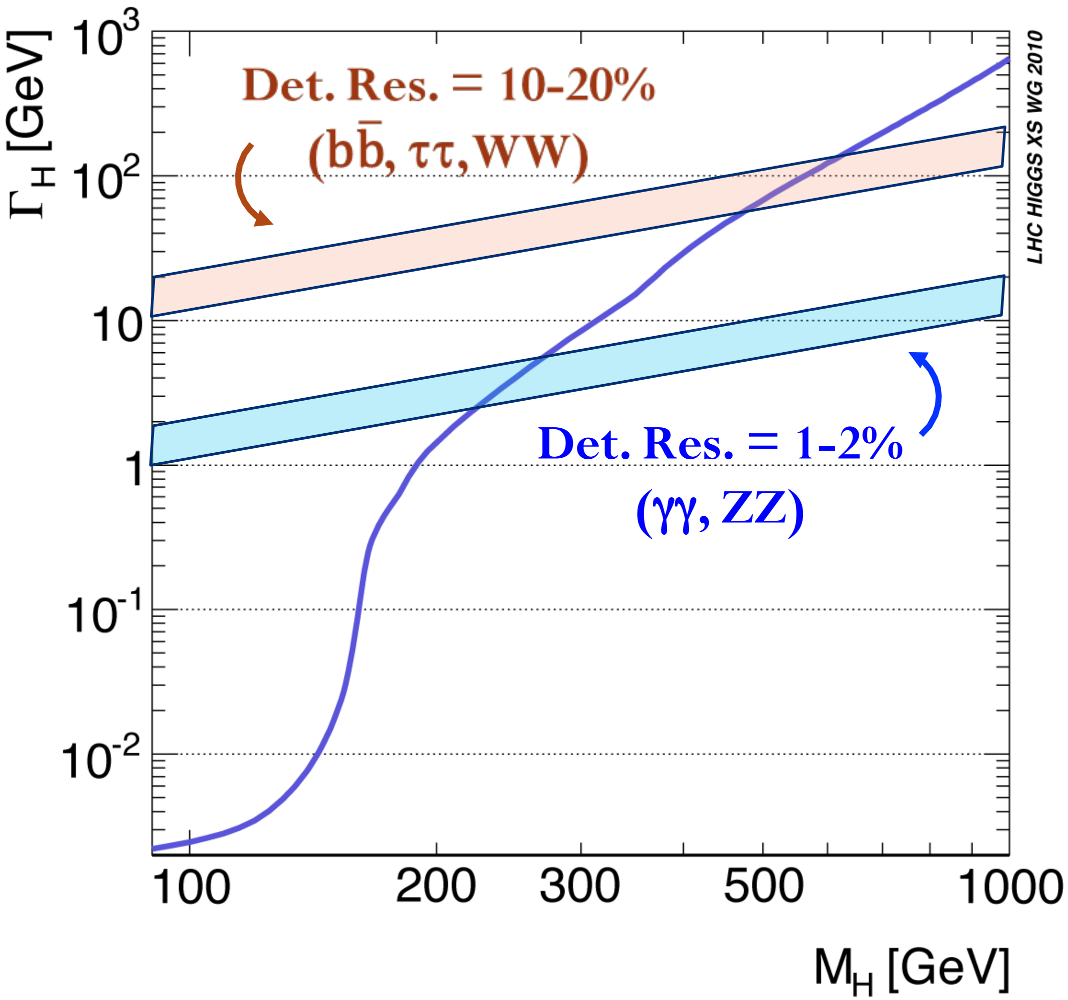
Narrow! $\Gamma_H / m_H \sim 10^{-5}$

Observed width dominated by ***detector resolution***

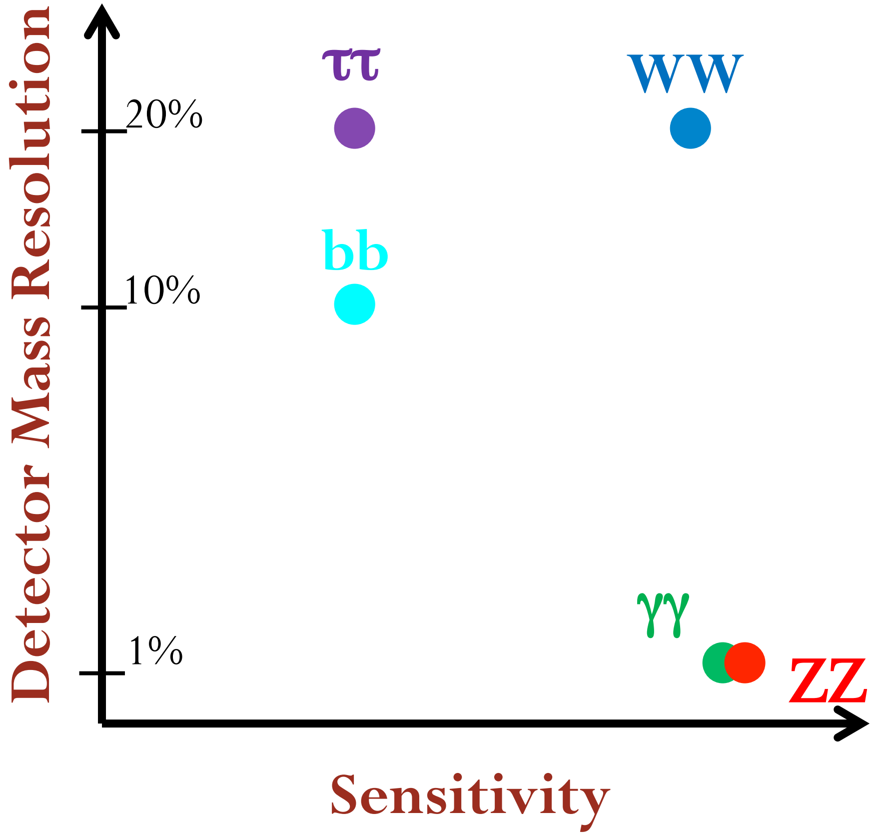
@High mass

Higgs becomes a broad resonance dominated by ***natural width***

Theory input is critical



SM Higgs Analyses @ LHC



Three classes of SM analysis:

1) High sensitivity, high resolution

γγ, ZZ

2) High sensitivity, low resolution

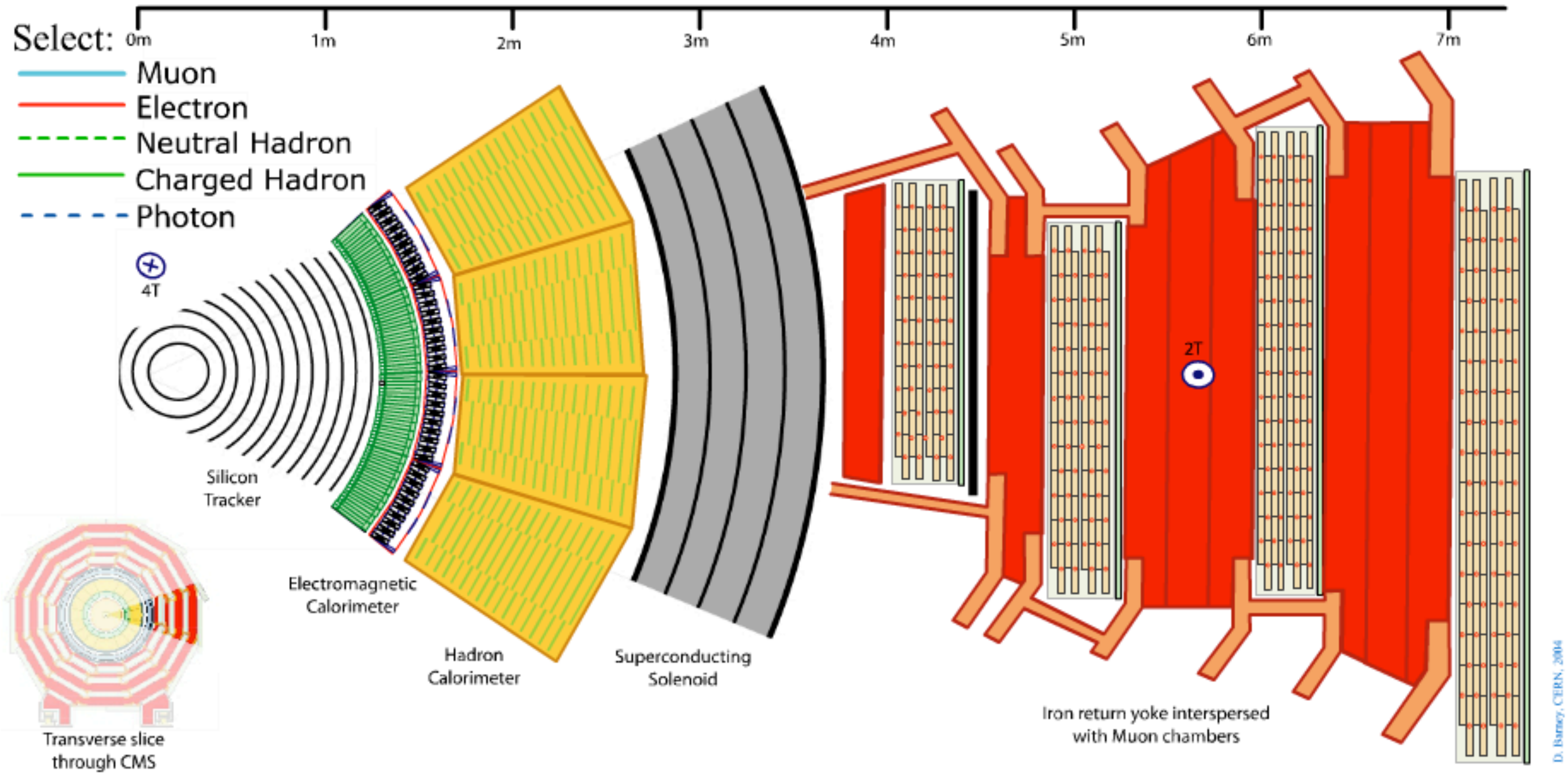
WW

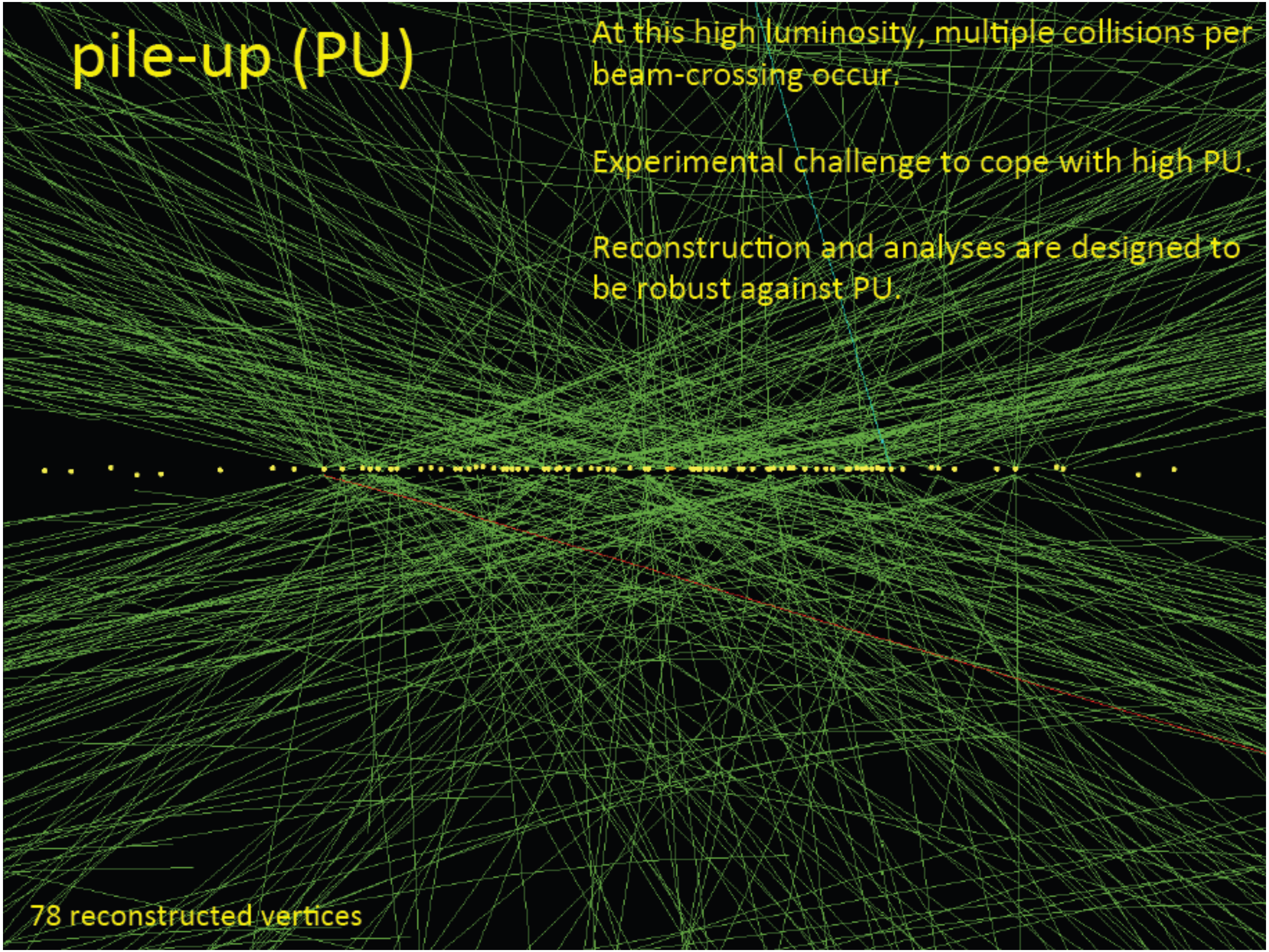
3) Low sensitivity, low resolution

ττ, bb

Need **multi-purpose detectors** like ATLAS and CMS to find the Higgs boson at the LHC!

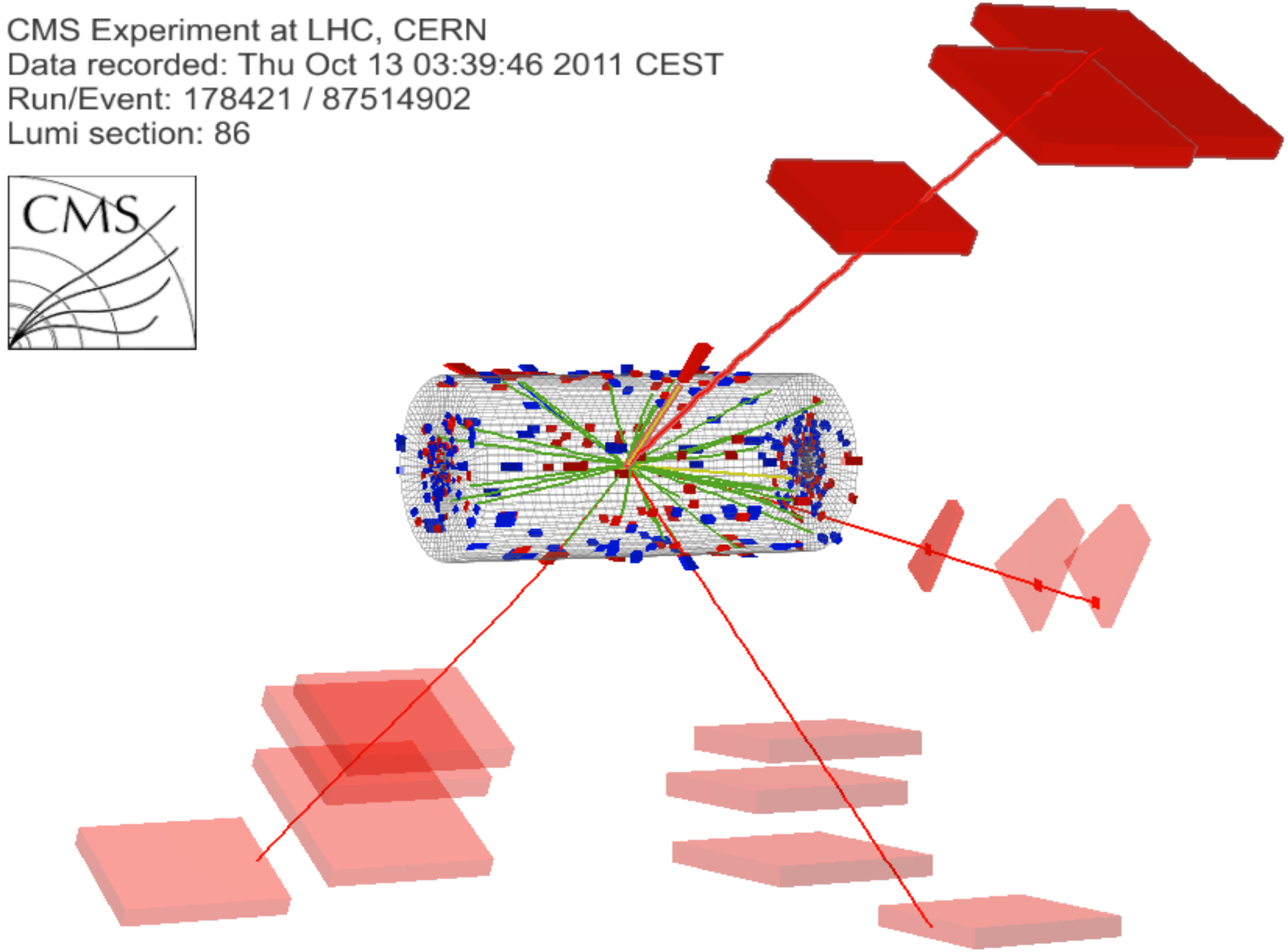
Example: a slice of CMS



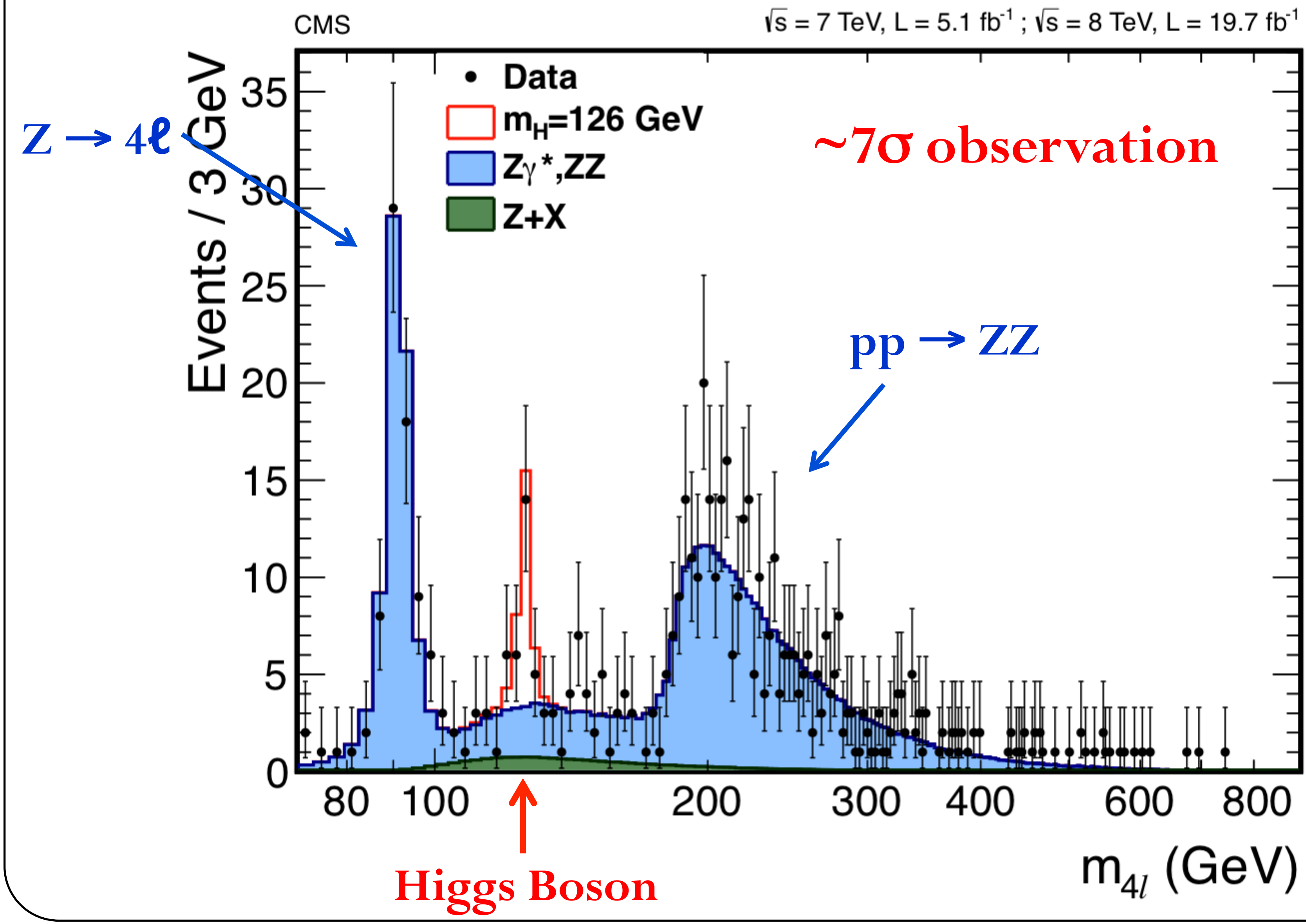

pile-up (PU)
At this high luminosity, multiple collisions per beam-crossing occur.
Experimental challenge to cope with high PU.
Reconstruction and analyses are designed to be robust against PU.
78 reconstructed vertices

What it’s like to be an experimentalist at the LHC:

Golden channel: $H \to ZZ^* \to 4\mu$



Golden Channel: $H \rightarrow ZZ^{*} \rightarrow 4\ell$



A note on statistics

Probability		Interpretation
$"3\sigma" \Rightarrow 1.35\times10^{-3}$		"Evidence"
$"4\sigma" \Rightarrow 3.15\times10^{-5}$		"Strong / Compelling Evidence"
$"5\sigma" \Rightarrow 2.85\times10^{-7}$		"Observation"

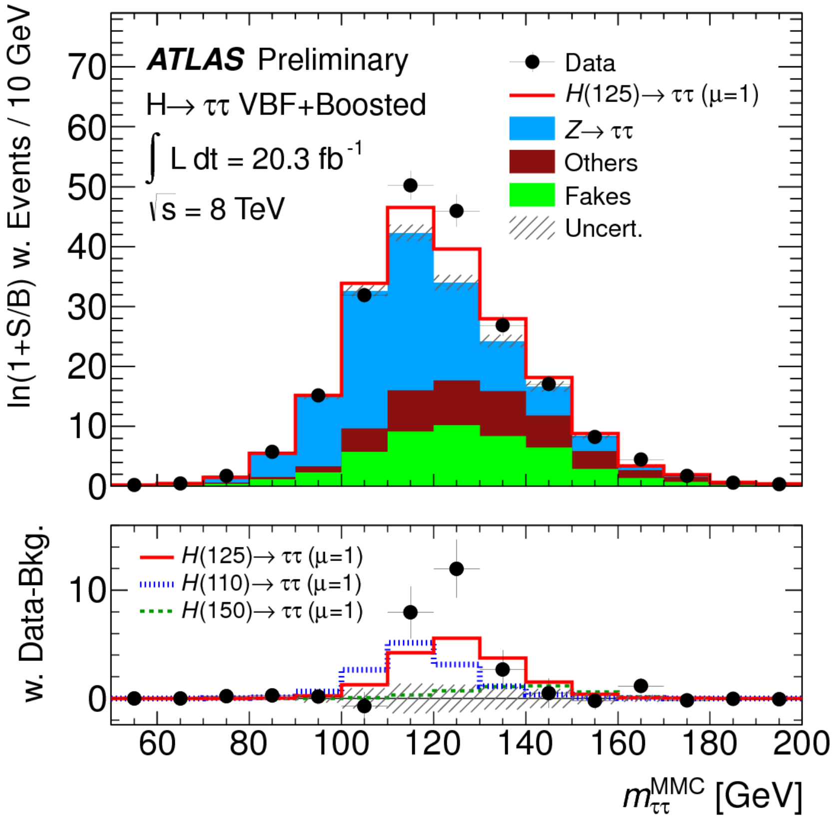
Significance (σ) by decay channel

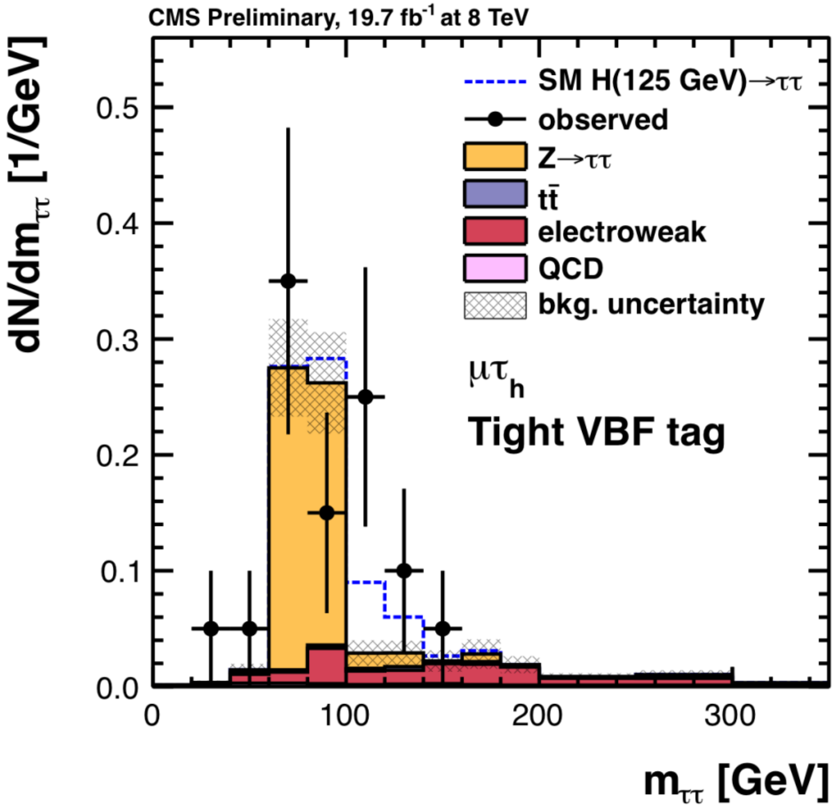
Channel	ATLAS (expected)	ATLAS (observed)	CMS (expected)	CMS (observed)
$h \to \gamma\gamma$	4.1	**7.4**	4.2	**3.2**
$h \to ZZ$	4.4	**6.6**	6.7	**6.8**
$h \to WW$	3.7	**3.8**	5.8	**4.3**
$h \to \tau\tau$	3.2	**4.1**	3.6	**3.4**
$h \to bb$	1.6	**~0**	2.1	**2.1**

First "clear, strong, compelling" evidence for fermionic decays

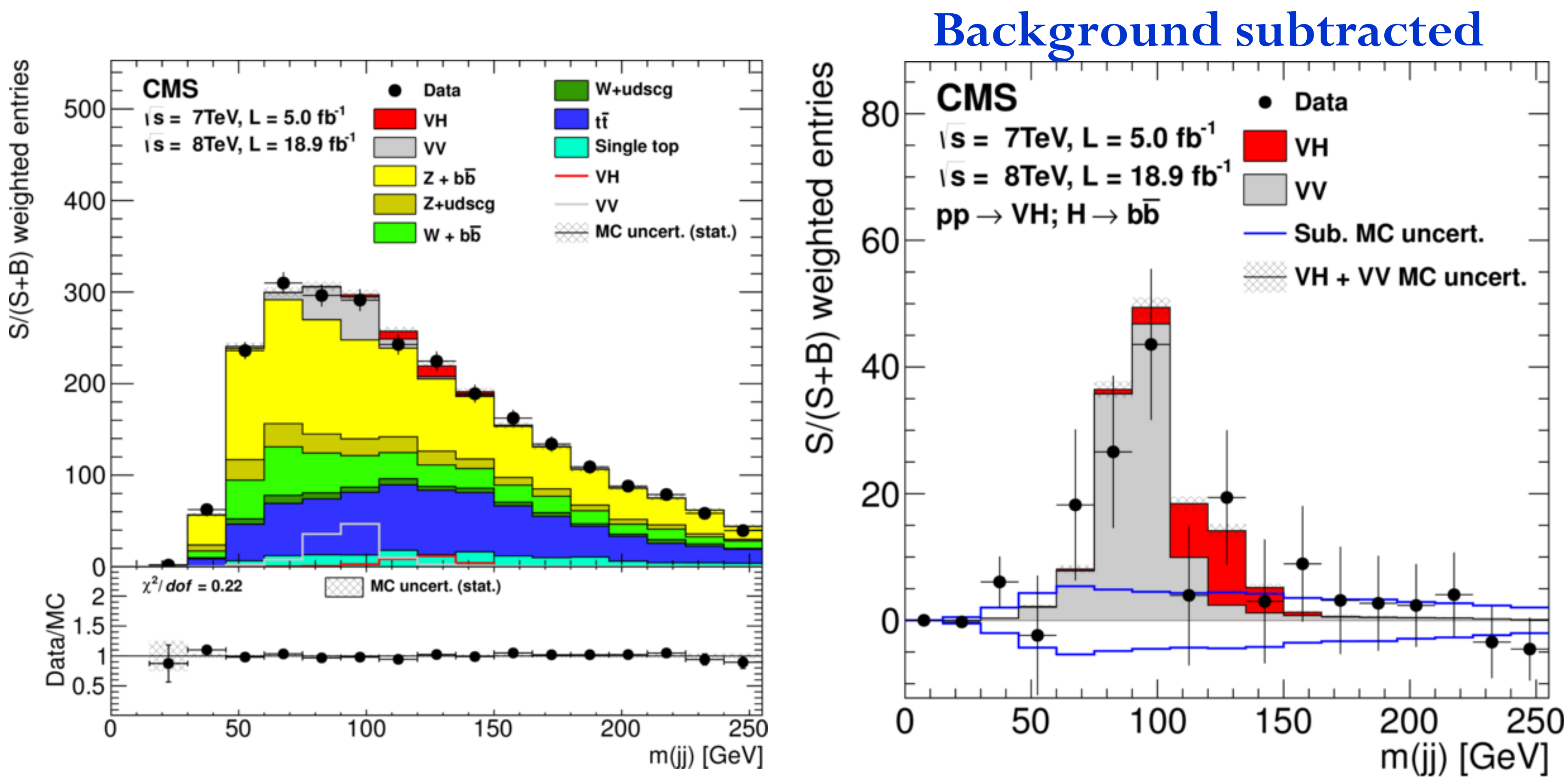
H → ττ: ATLAS and CMS

End of 2013: ATLAS and CMS showed updated results on the full LHC dataset





H → bb ?

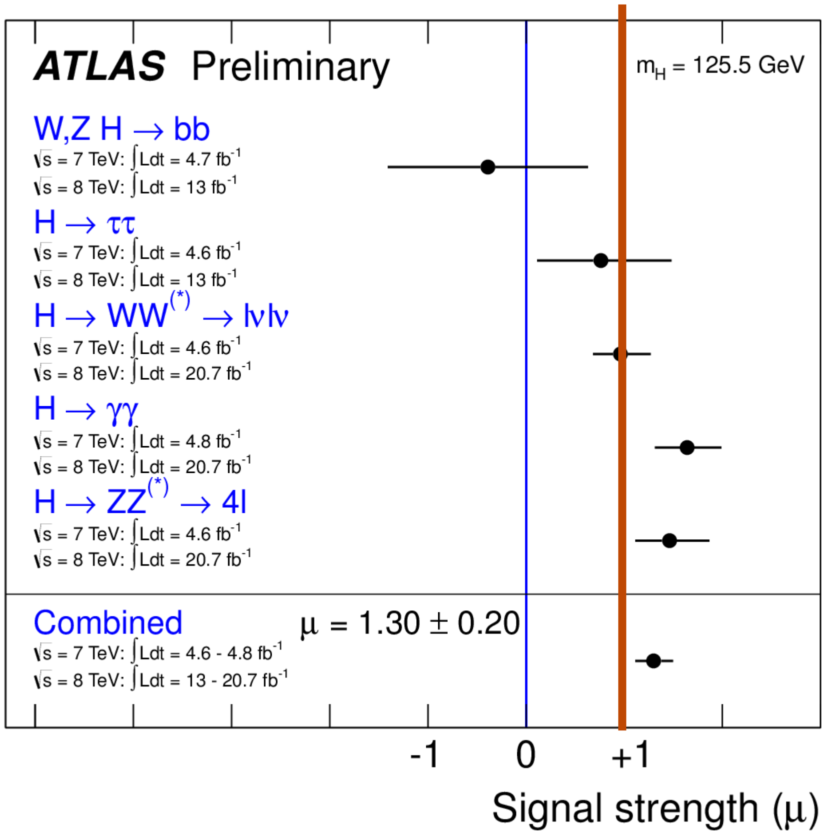


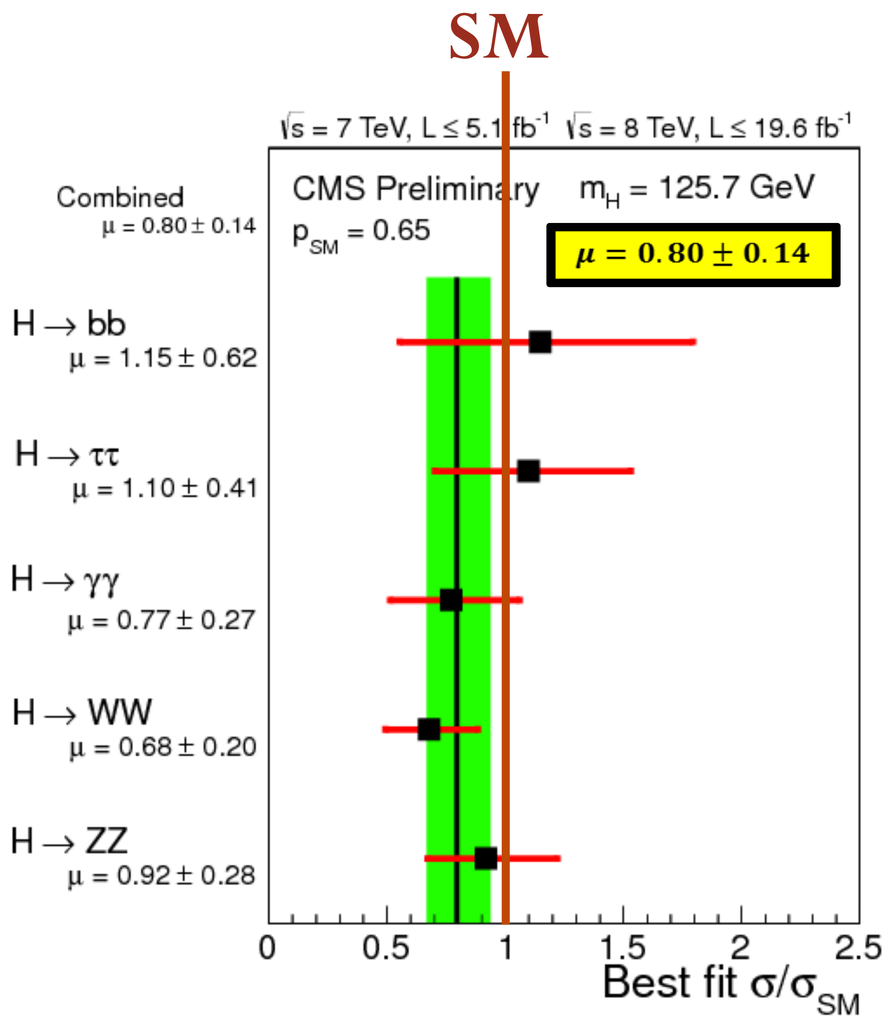
Z → bb peak (grey) observed, but only a hint of Higgs (red)

Nature of the New Boson

Signal strength by decay channel

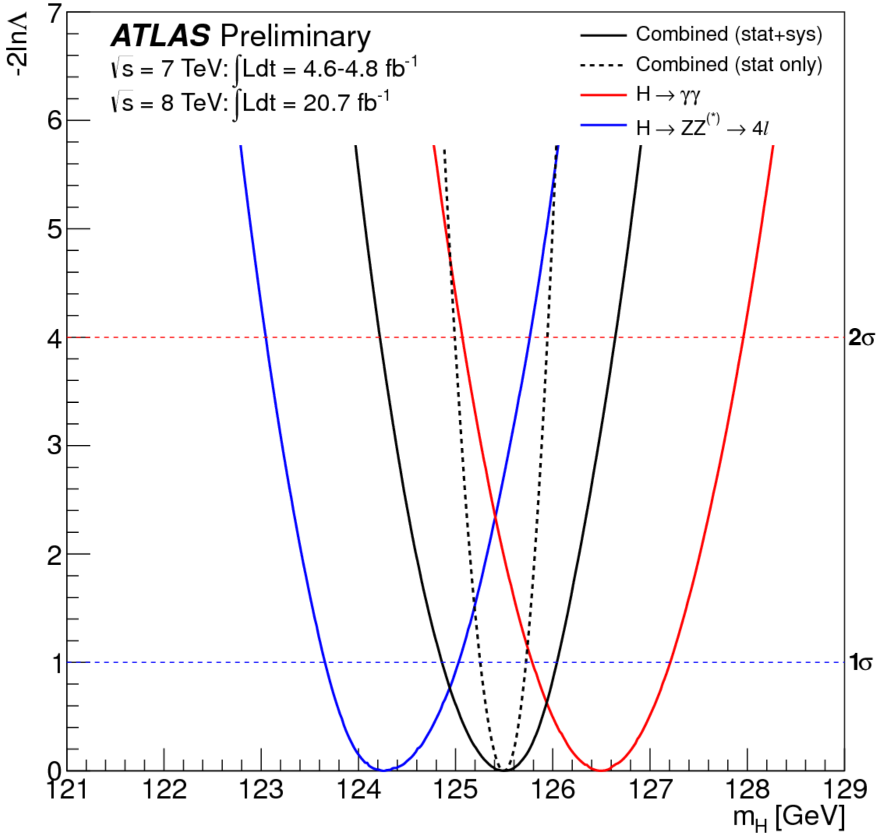
$$\mu \equiv \sigma \times \mathrm{Br}/\sigma_{SM} \times \mathrm{Br}_{SM}$$

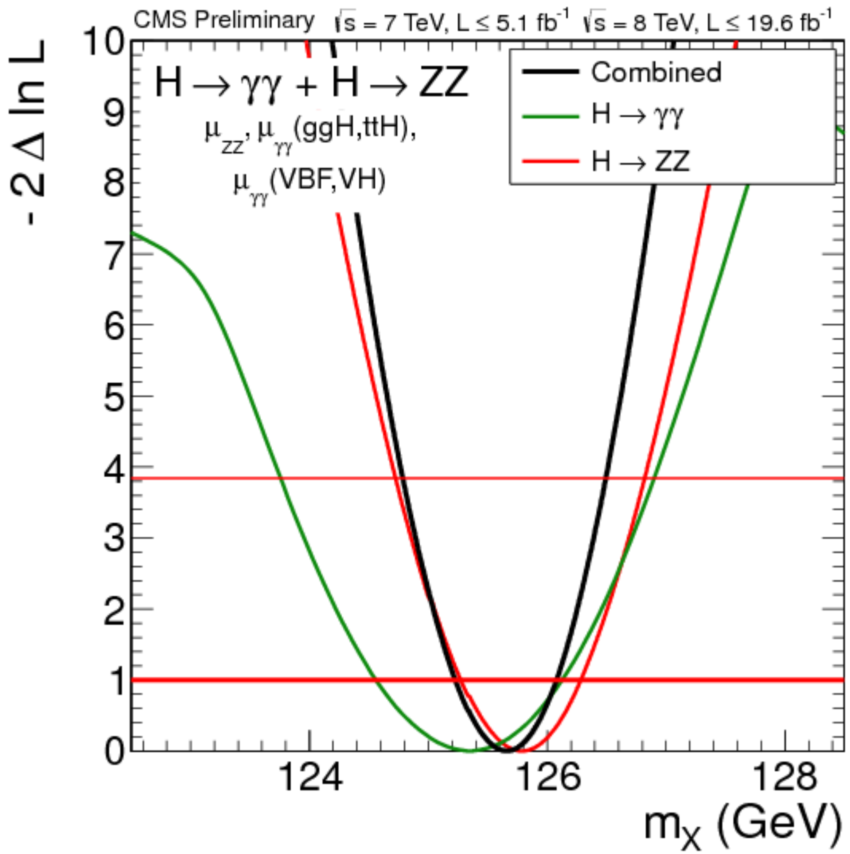




Both experiments are consistent with the SM expectation

Mass (GeV) from γγ and ZZ

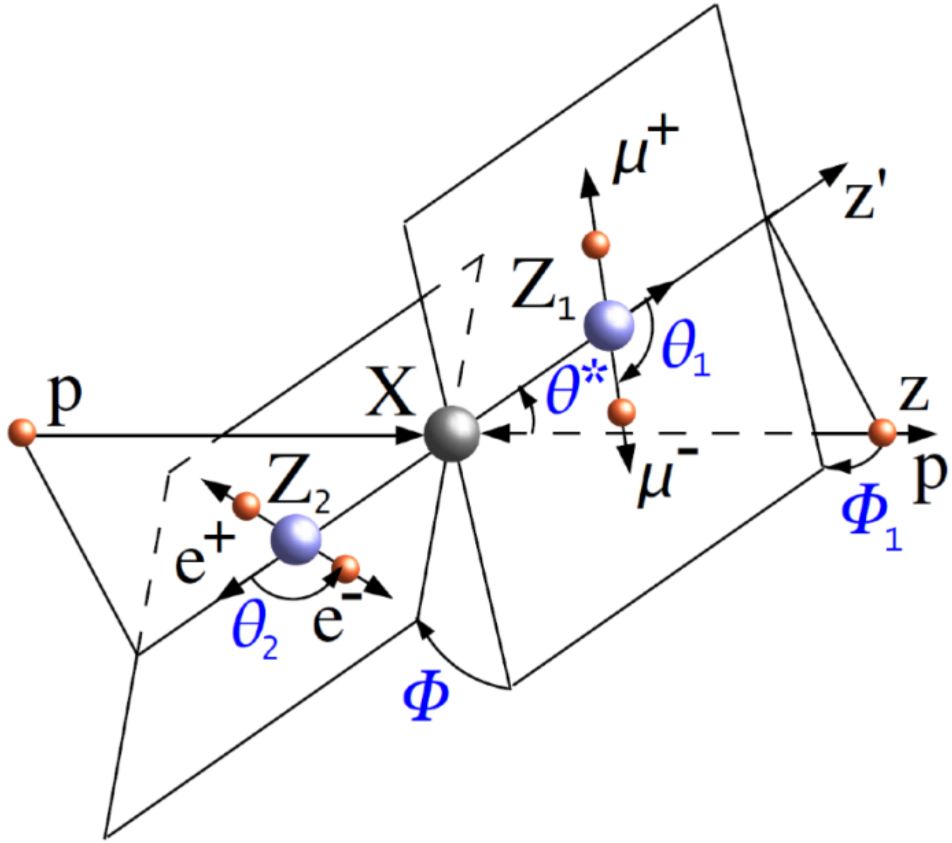


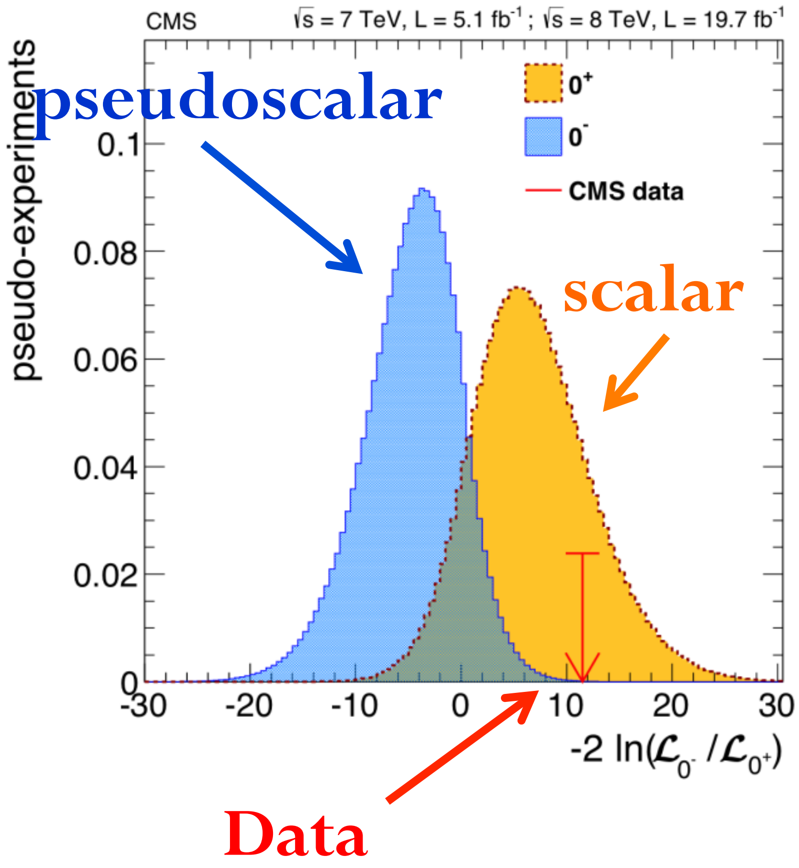


$$m_H = 125.5\ \pm 0.2\ (\text{stat})\ \pm 0.5\ (\text{syst})$$

$$m_H = 125.7\ \pm 0.3\ (\text{stat})\ \pm 0.3\ (\text{syst})$$

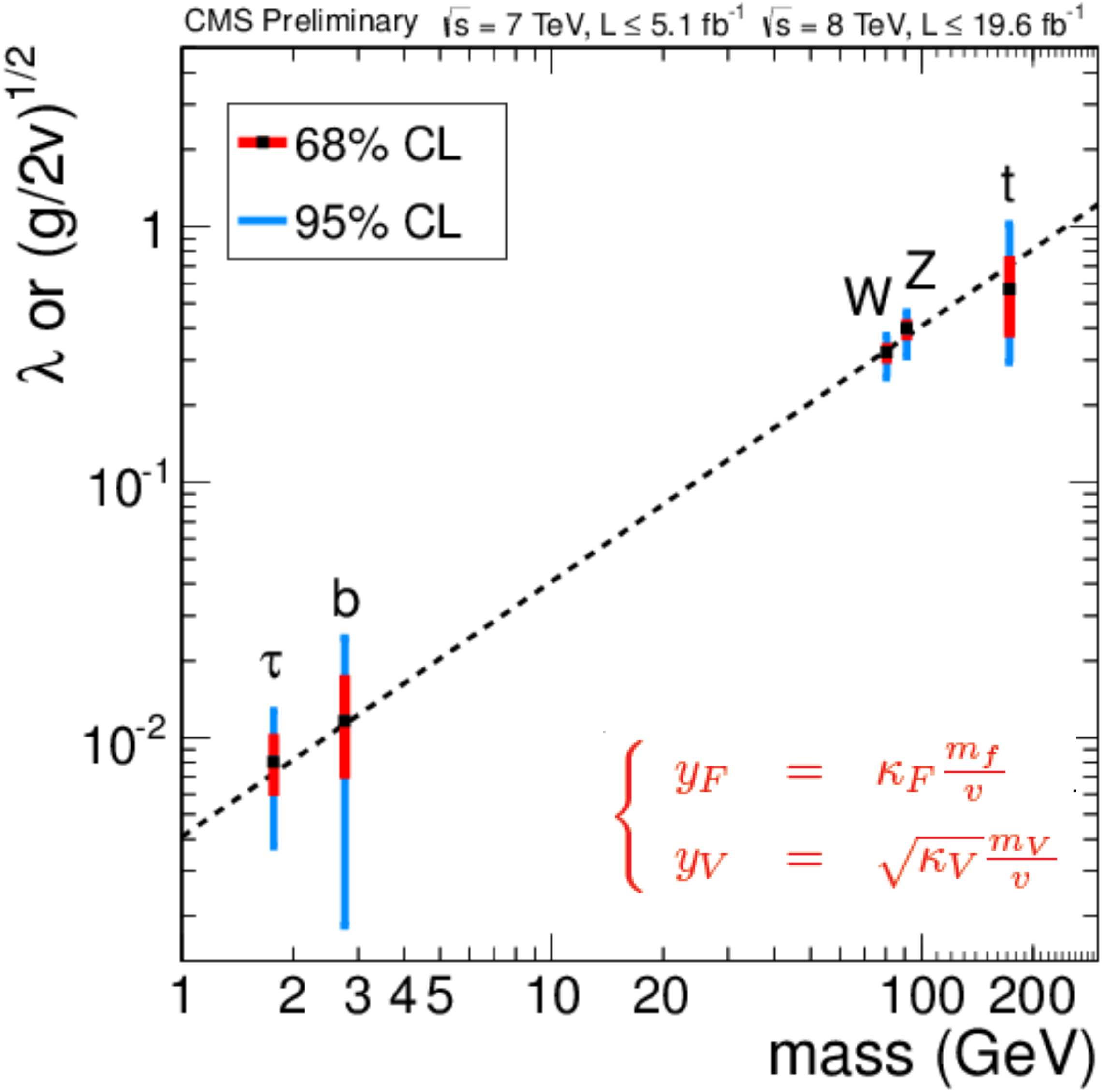
Spin and parity





All data from ATLAS and CMS to date disfavor alternative J^P hypotheses

Couplings of the Higgs boson



New results indicate that particle discovered at CERN is a Higgs boson

- CERN

ISSUES AND EXPERTS

Higgs boson and new pope confirmed

March 14, 2013

Tweet Facebook Email Print

'God particle' is for real

Scientists are confirming that a new subatomic particle discovered at the world's most powerful particle accelerator is indeed an elusive Higgs boson, also referred to as 'the God particle.' It was discovered during experiments at the Large Hadron Collider (LHC) at CERN, Switzerland last July. Scientists, who say they have a "long way to go" to know what kind of Higgs boson it is, are reporting the confirmation at the Moriond physics conference in Italy this week. The Higgs boson is the only particle in the Standard Model of Physics that has never been observed. SFU physicists **Dugan O'Neil, Bernd Stelzer** and **Michel Vetterli** are involved with ATLAS – one of two international physics experiments involving the LHC– and can comment on the news. Vetterli is currently at CERN where he'll spend the next year and can also do Skype interviews.

Michel Vetterli, +41 22 767 4368; vetz@triumf.ca; mikevetterli (Skype)
Dugan O'Neil, 778.782.5623; dugan_oneil@sfu.ca
Bernd Stelzer, 778.782.7731; stelzer@sfu.ca
Background: http://at.sfu.ca/eUnDFV

First non-European pope chosen

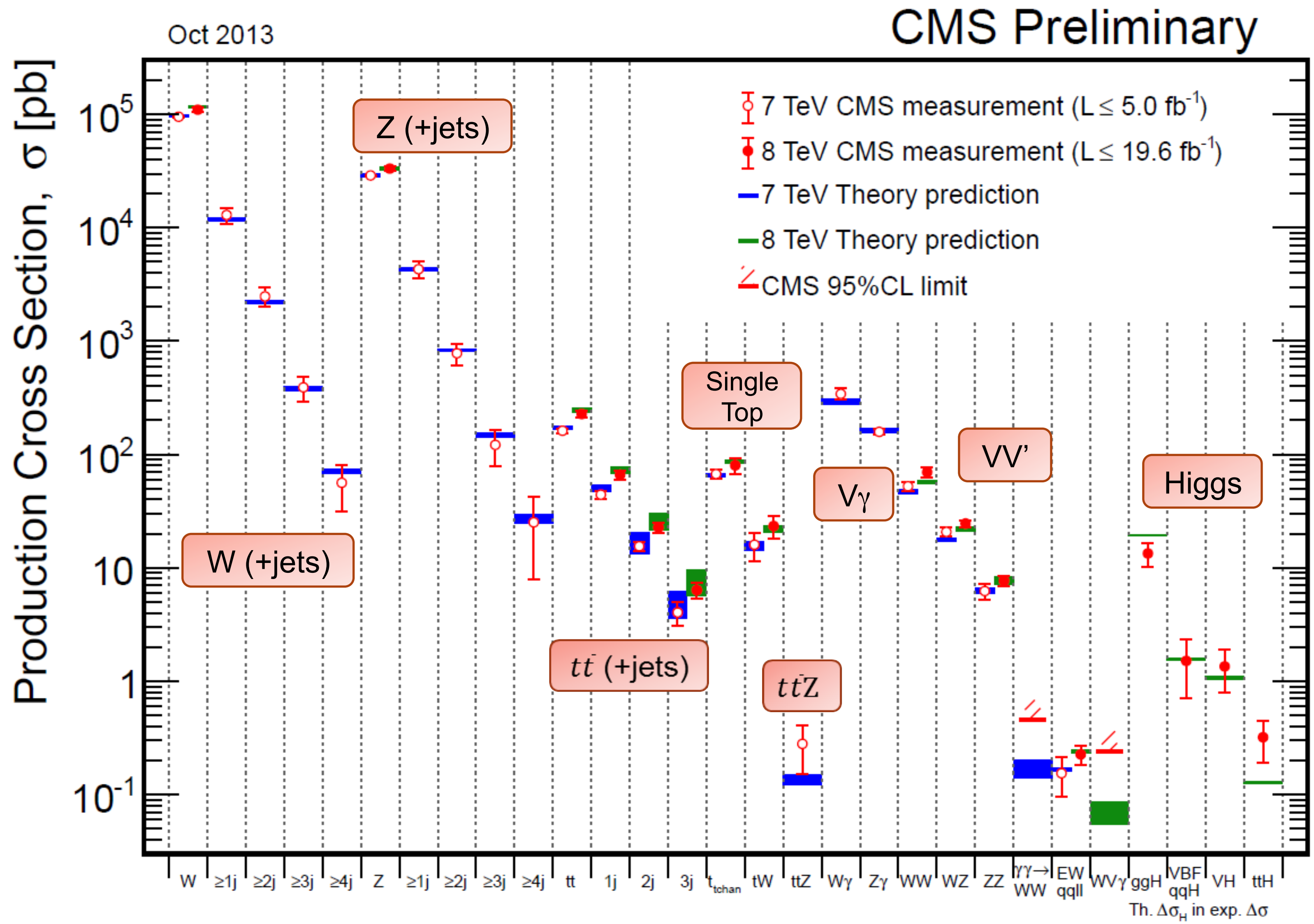
Jorge Mario Bergoglio of Argentina was elected yesterday as the new pope to lead the Roman Catholic Church. **Donald Grayston**, a retired religious studies professor at SFU, says that it is interesting the new pope comes from the new world.

"I don't think the Curia is ready to let go of its stranglehold on change," says Grayston. "But I'm betting that the non-Curia cardinals wanted to elect someone who could tackle the Curia. I see it as very appropriate, given that 40-percent of the world's Catholics live in Latin America."

Is there more than one Higgs boson?

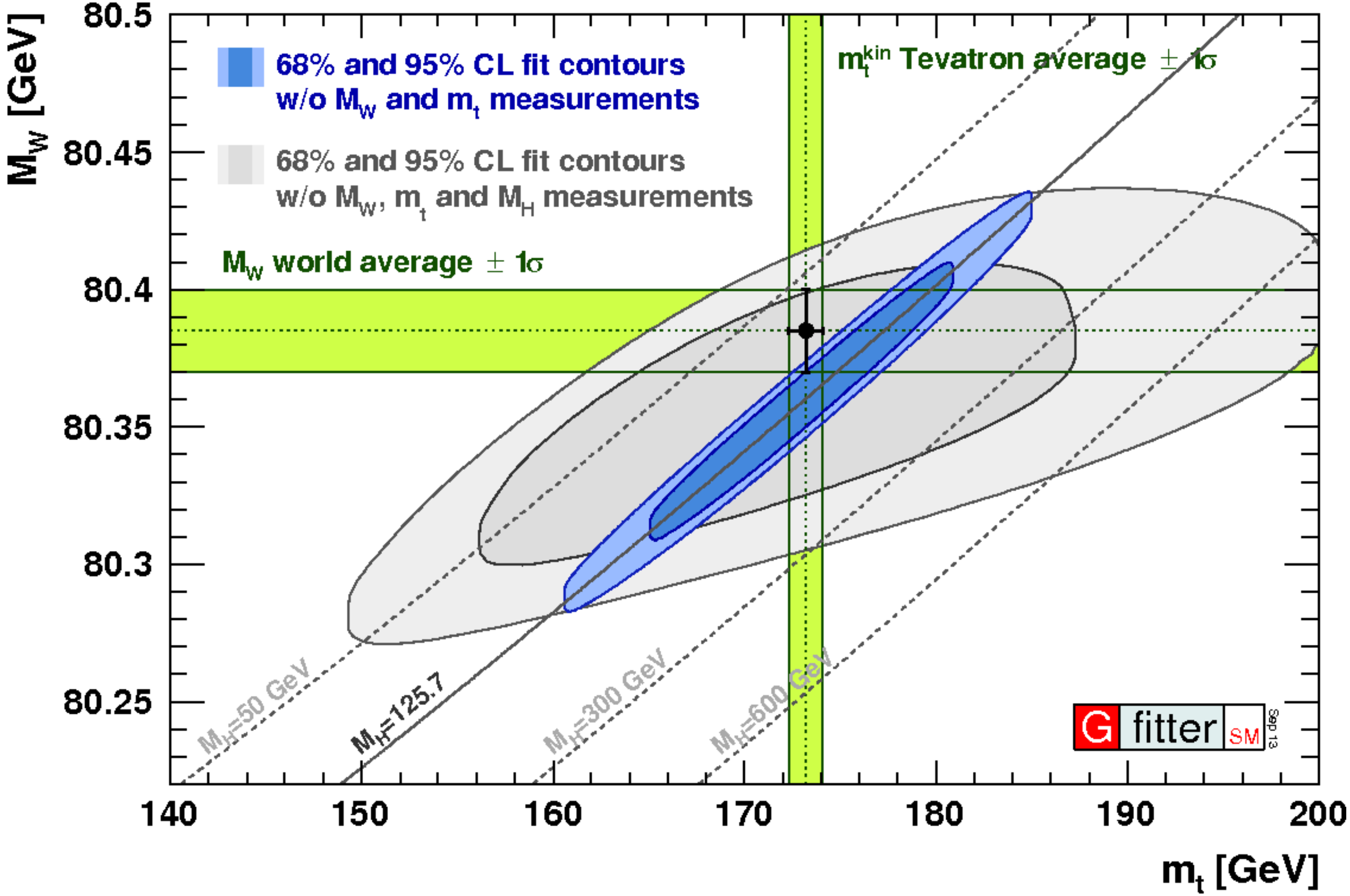
(Is there **anything** else besides SM?)

Standard Model: Mission Accomplished?

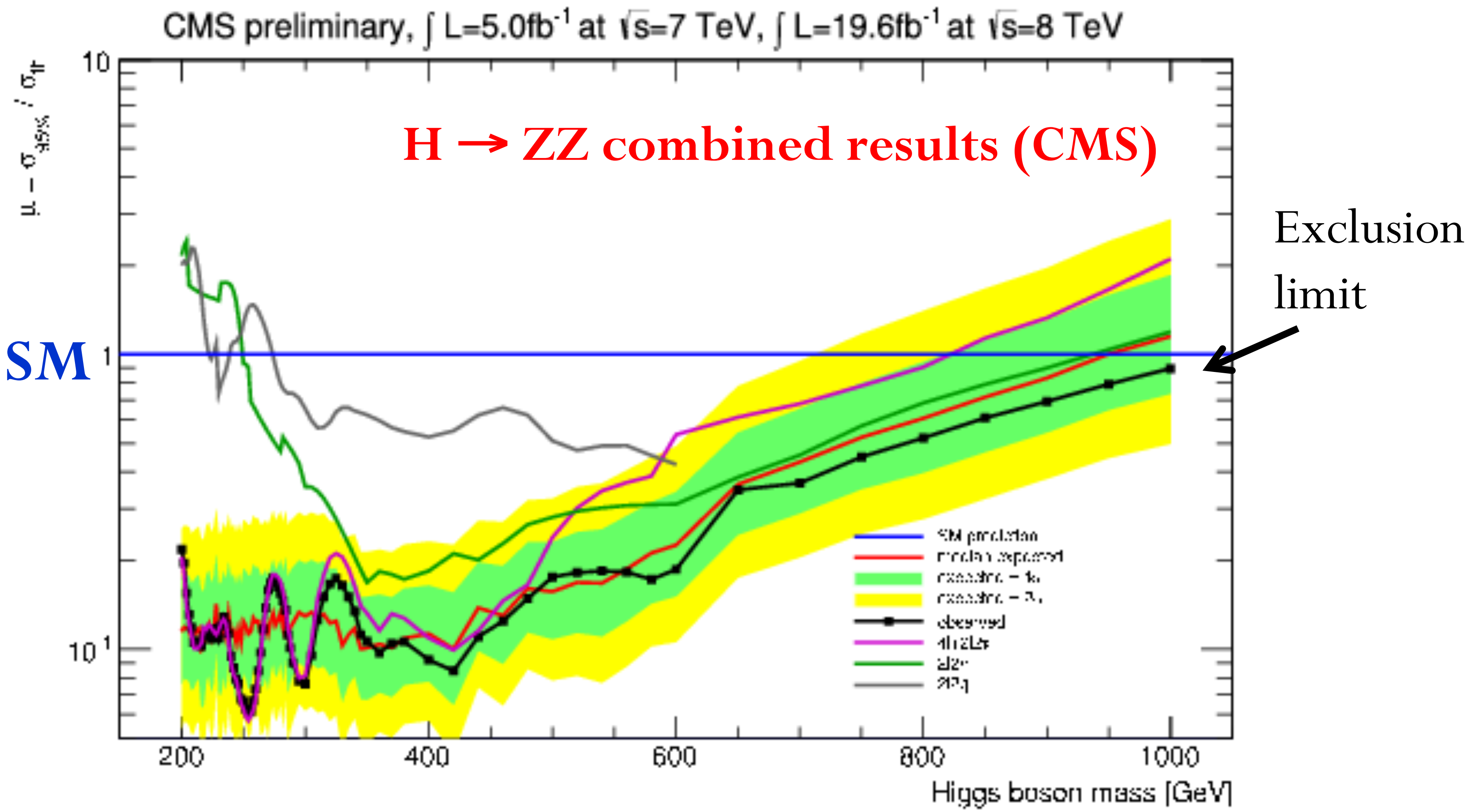


Exquisite agreement over 6 orders of magnitude!

Standard Model: Mission Accomplished?



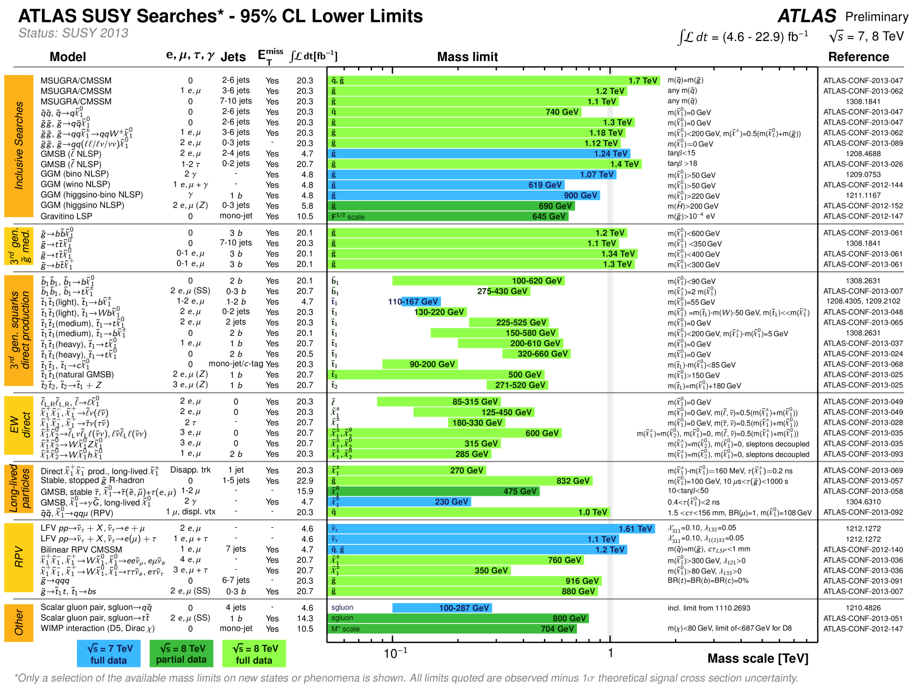
Search for a high-mass Higgs Boson



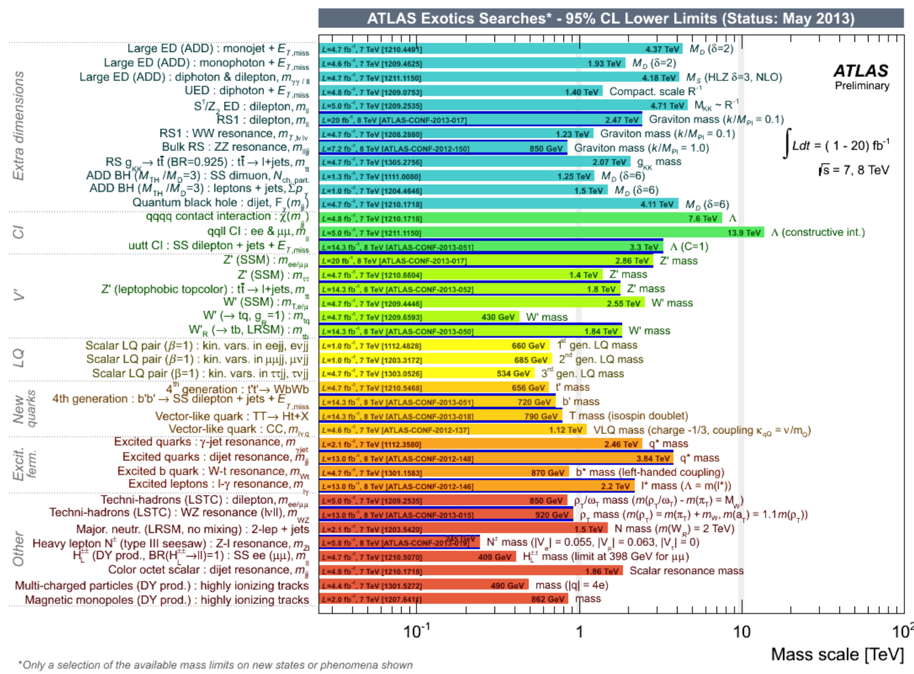
No sign of a SM Higgs boson up to ~1000 GeV

Search for "everything else"

Supersymmetry



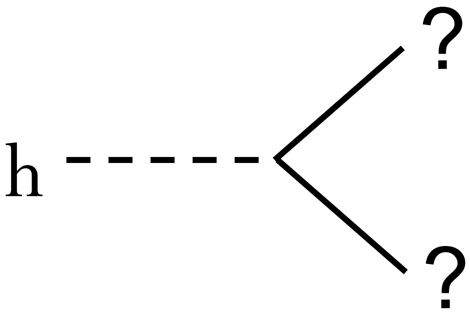
"Exotica"



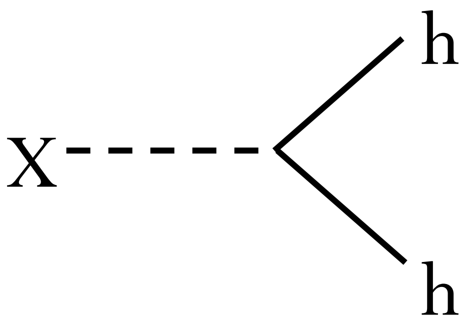
Many many many searches, no sign of any physics beyond the SM

Experimental Perspective

We have a new particle, h(126), use it as a 'scout' to search for other particles:



Exotic (invisible) decays, e.g. dark matter



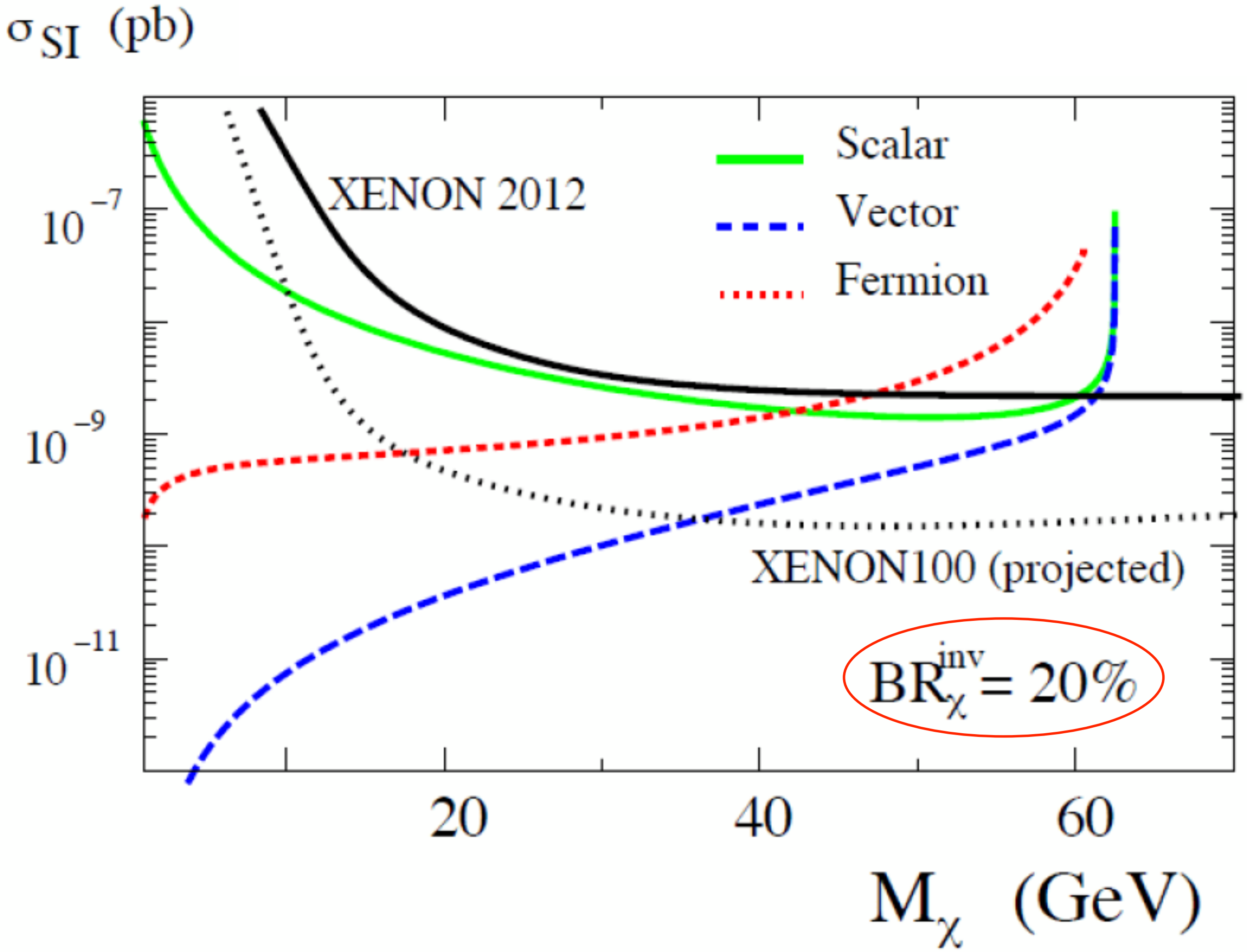
Heavy resonances (Higgs, SUSY, Exotica) decaying to the observed Higgs boson

Theoretical Perspective

- The SM is not complete, there are specific questions to answer. Some examples:
  - Higgs mass: is our universe 'fine-tuned'?
  - Why is the EWK scale so far from the GUT scale?
  - What is the nature of dark matter?
- An extended Higgs sector could help in answering some of these questions
  - Models with additional Higgs bosons:
    - MSSM: H, h, A, H^+, H^-
    - NMSSM: add a singlet
  - "Higgs portal" coupling to dark matter

ATLAS and CMS are searching for all of these

Dark matter search: h(126) → invisible



Best limit from the LHC so far (CMS): $BR_{inv} < 0.54$ (95% C.L.)

Additional Higgs bosons

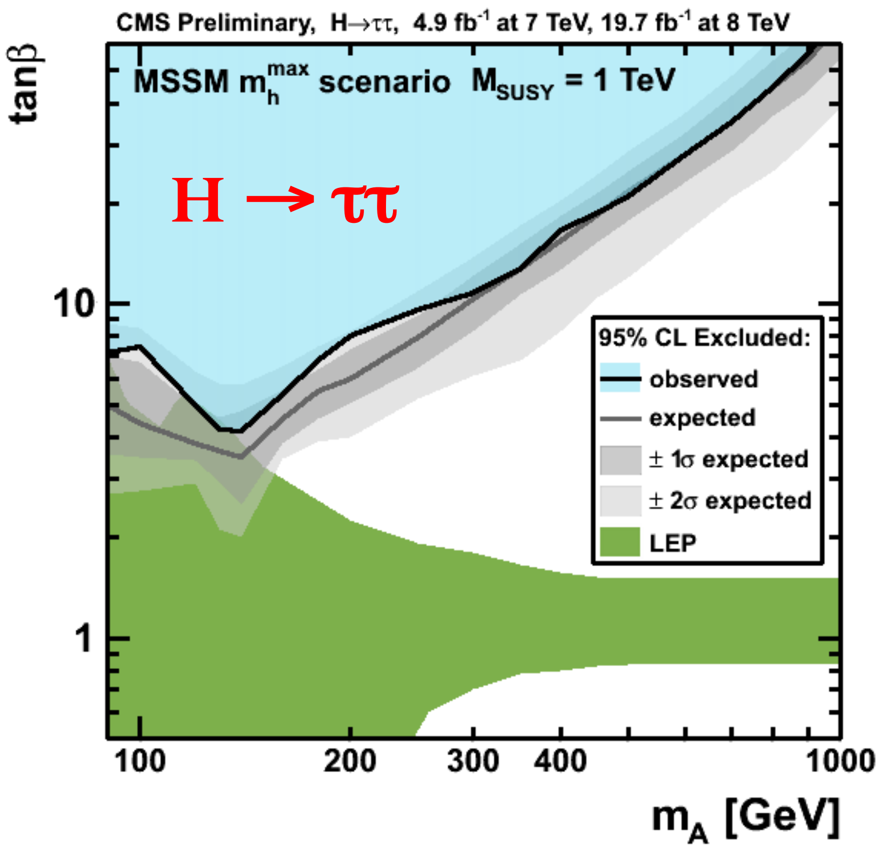
Extensions of the SM (e.g., SUSY) naturally include additional scalar doublets, leading to multiple Higgs bosons:

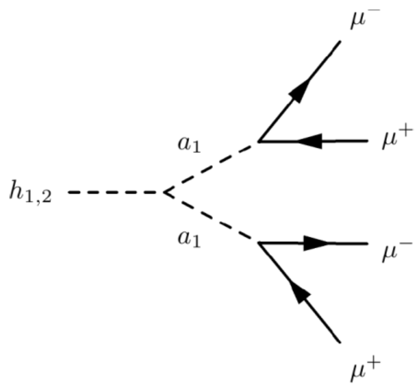
ϕ_1, ϕ_2: 8 degrees of freedom ⇨ three go to the W, Z masses, leaving five physics Higgs bosons

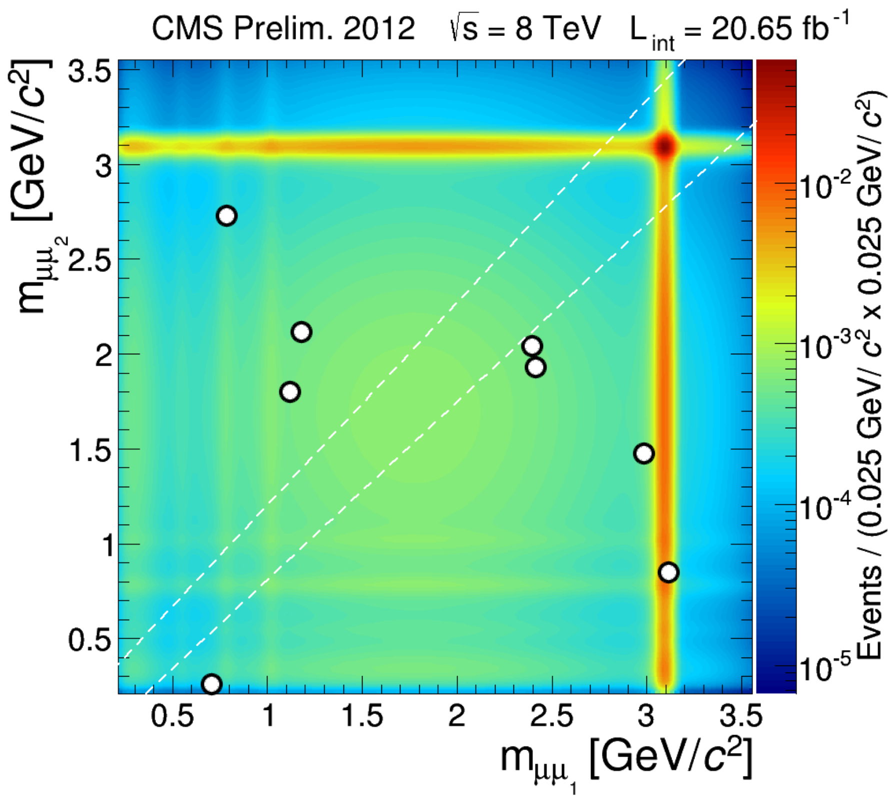
$$H^+,\ H^-,\ H,\ h,\ A$$

The Higgs boson we found could be H or h (looks like A is ruled out from spin-parity measurements), we search for additional Higgs bosons above and below h(126).

Searching for another neutral Higgs







Summary

- The new particle @ "126 GeV" is observed to decay to all gauge bosons, and in the right proportion
- Consistent mass between CMS and ATLAS
- Now "clear, strong, compelling" evidence for $H \rightarrow \tau\tau$
- Spin-parity measurements disfavor alternative hypotheses
- Signal strength and couplings consistent with the SM
- No sign for any other SM-like Higgs boson
- No sign of (any of) the beyond-SM Higgs bosons

If it is not the SM Higgs boson it certainly is a good actor!

Continuing studies of h(126), looking for new Higgs particles

LHC Schedule: 2015 – 2035

Run 2: 13 TeV and 10x more data

→ Extend searches, Higgs physics becomes precision physics

"It is not the end. It is not even the beginning of the end. It is, perhaps, the end of the beginning."

–Winston Churchill