Adam Falkowski

Introduction to Physics beyond the Standard Model

Part 2: The Higgs Boson

Osaka, 19 May 2014

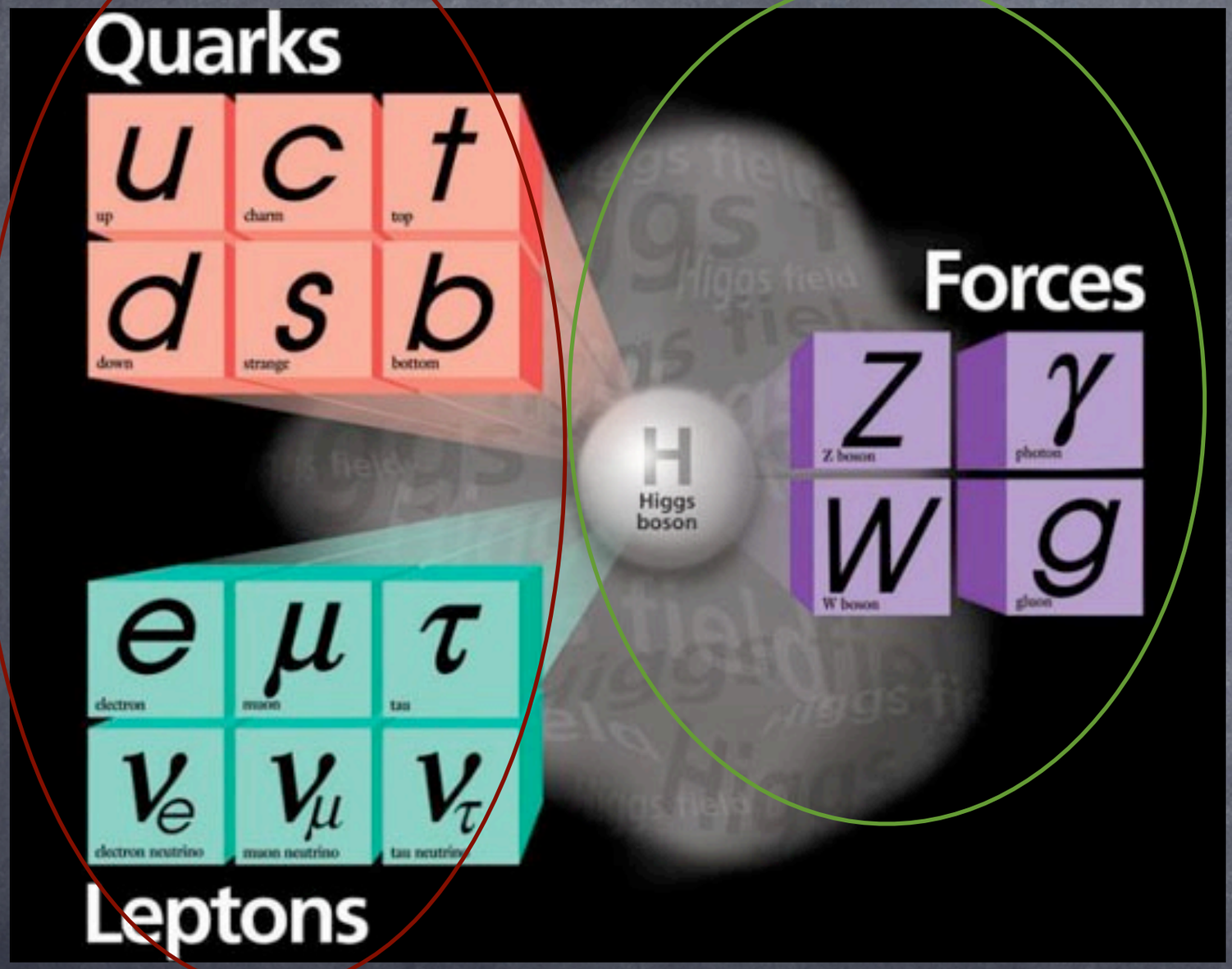
Plan

- What is the Higgs boson and why is it there
- Where do we stand and what experimental data do we have
- How theorists interpret the data

WHERE DO WE STAND

Fermions

Bosons



SU3xSU2xU1
local symmetry

known particles so far

What is the Higgs boson?

What is the Higgs boson?

- God particle
- Particle that gives mass to other particles
- Oscillations of the field that gives mass to other particles
- Particle that ensures consistency of theories with massive vector bosons

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What is the Higgs boson?

- ~~God particle~~
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- Particle that ensures consistency of theories with massive vector bosons

- There can be mass without Higgs, e.g. RH neutrino Majorana masses, proton mass in QCD, etc.
- Actually most of mass in the Universe probably does not originate from Higgs
- There can even be mass of SM vector bosons and fermion without Higgs, e.g. technicolor theories

What is the Higgs boson?

- ~~God particle~~
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- Oscillations of the field that breaks EW symmetry and gives mass to fundamental particles
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Symmetric potential develops instability

$$V(|H|) = -m_H^2|H|^2 + \lambda|H|^4$$

$$|H|^2 \equiv H^\dagger H$$

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\lambda v^2 = m_H^2$$

Spontaneous symmetry breaking

Masses for W and Z bosons via ABEH mechanism

$$m_W = \frac{g_L v}{2} \qquad m_Z = \frac{\sqrt{g_L^2 + g_Y^2}\, v}{2}$$

gL, gY are known couplings of SU(2)L x U(1)Y

It follows v = 246 GeV

What is the Higgs boson?

graphics
by Flip Tanedo

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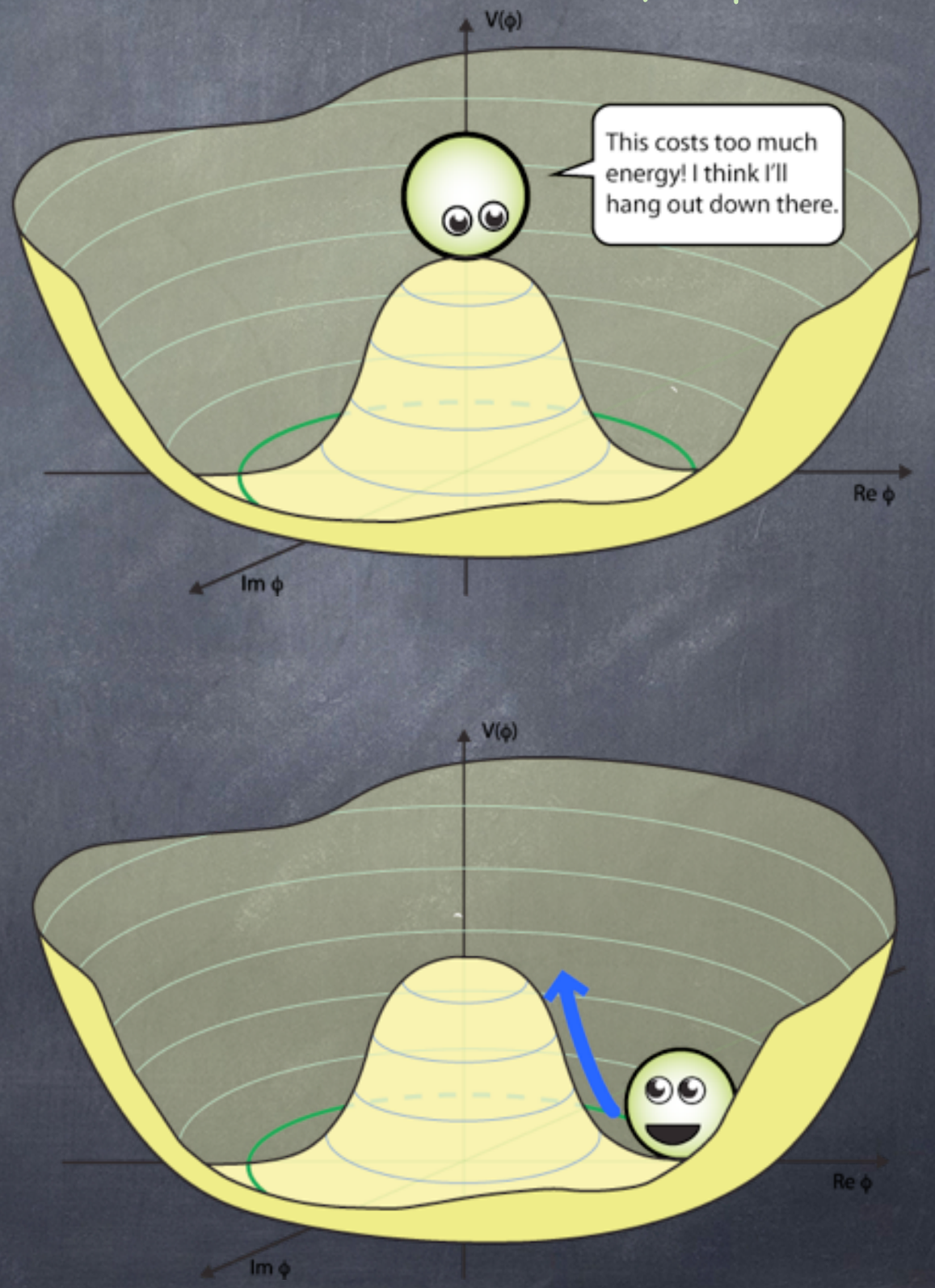

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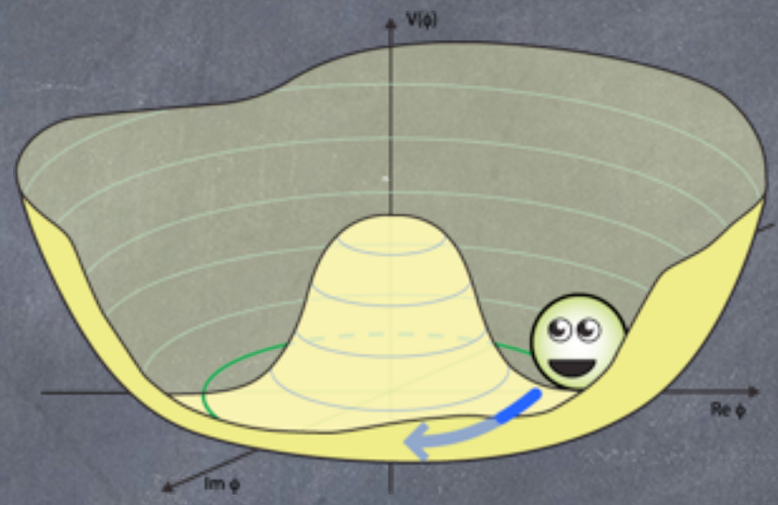
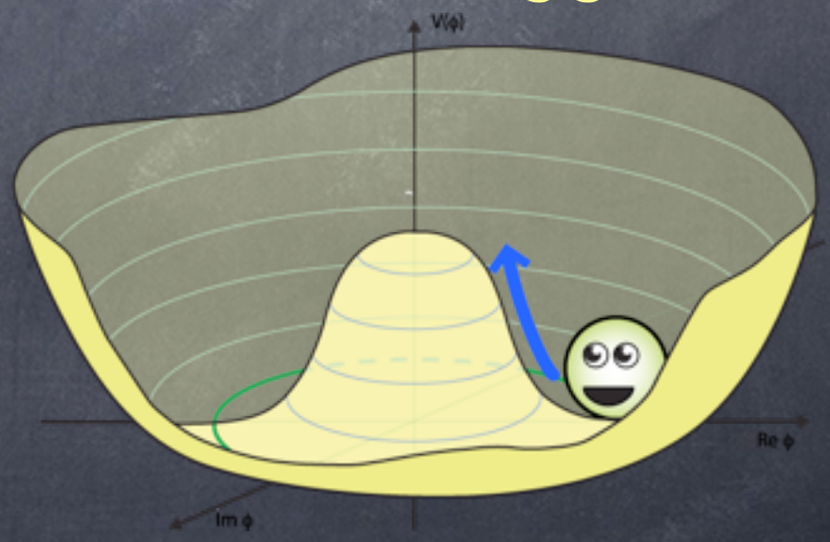


Massless unphysical Goldstone boson

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}G^+ \\ v + h + iG^0 \end{pmatrix}$$

Massive Higgs boson



$$m_h^2 = 2\lambda v^2$$

graphics by Flip Tanedo

What is the Higgs boson?

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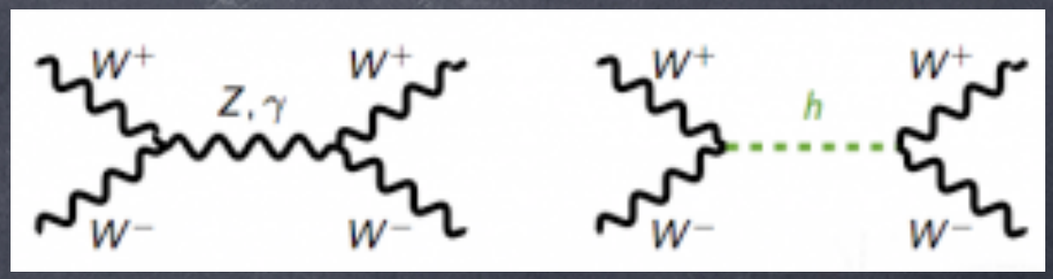
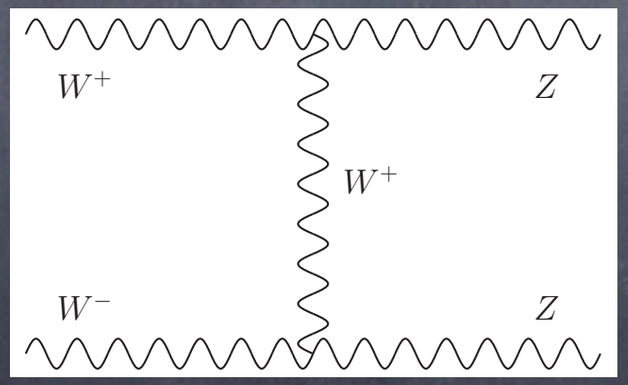
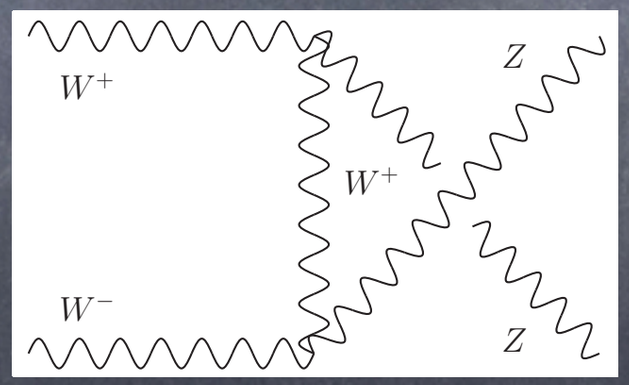
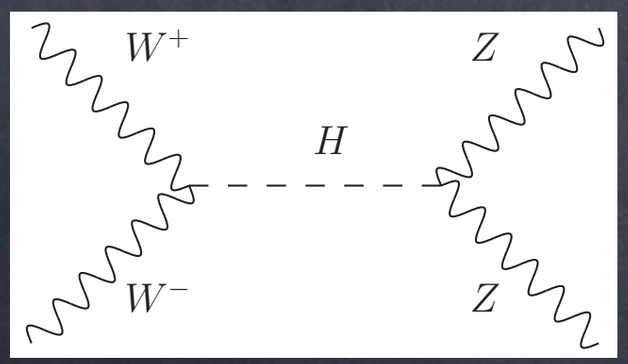


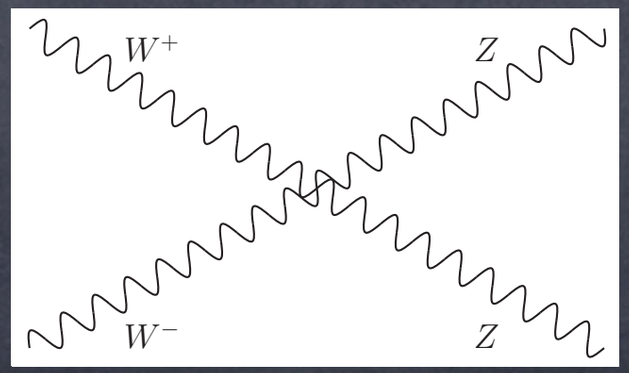
What is the Higgs boson?

- Separately, WW scattering amplitudes without Higgs grow as collision energy squared
- This would lead to perturbative unitarity violation at energies of order 1 TeV
- But amplitudes with Higgs exchange precisely cancel that growing terms, leading to total amplitude asymptoting to a constant at high energies
- Thanks to that, SM is perturbatively unitary up to very high energy scales (infinite scales, if we ignore gravity)
- A Higgs boson is not the only way to ensure perturbative unitarity, but it is the simplest and most efficient way









What is the Higgs boson?

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \dots \\ v + h + \dots \end{pmatrix}$$

$$\mathcal{L}_{\rm SM} = D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 + \left(\frac{y_{ij}}{\sqrt{2}} H \bar{\psi}_i \psi_j + \text{h.c.} \right) + \dots$$

No Higgs

Couplings to EW gauge bosons

Self-Couplings

Couplings to fermions

$$\left(\frac{h}{v} + \frac{h^2}{2v^2} \right) \left(2 m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu \right)$$

Ensures unitarity of VV->hh scattering

Ensures unitarity of VV->VV scattering

$$-\frac{m_h^2}{2v} h^3 - \frac{m_h^2}{8v^2} h^4$$

Ensures unitarity of VV->VVVV... scattering

$$-\frac{h}{v} \sum_f m_f \bar{f} f$$

Ensures unitarity of VV->ff scattering

Where do we stand

We know a Higgs particle has been discovered...

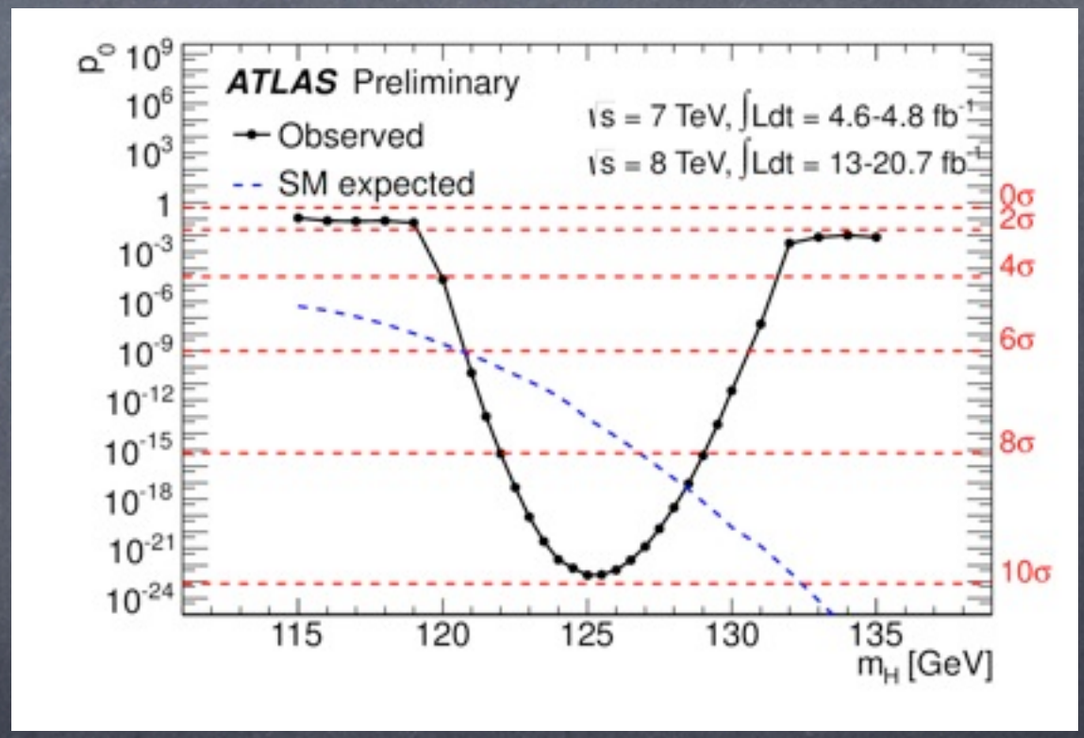
We know a Higgs particle has been discovered...

...because LHC experimentalists told us so

Significance in CMS, from CMS-PAS-HIG-13-005

	Significance (m_H = 125.7 GeV)		
Combination	**Expected (pre-fit)**	**Expected (post-fit)**	**Observed**
H→ZZ	7.1 σ	7.1 σ	6.7 σ
H→γγ	4.2 σ	3.9 σ	3.2 σ
H→WW	5.6 σ	5.3 σ	3.9 σ
H→bb	2.1 σ	2.2 σ	2.0 σ
H→ττ	2.7 σ	2.6 σ	2.8 σ
H→ττ and H→bb	3.5 σ	3.4 σ	3.4 σ

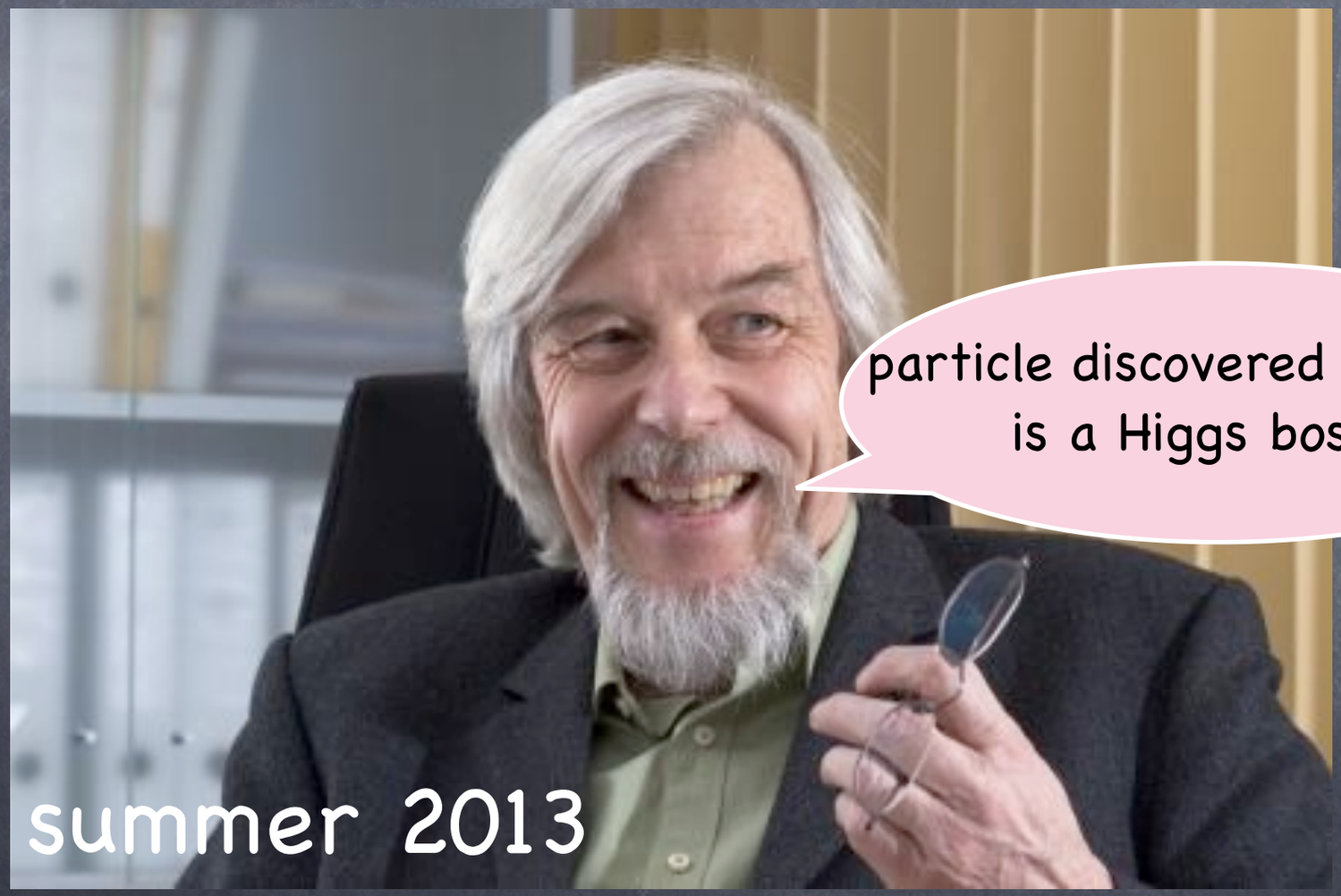
Significance in ATLAS from ATLAS-CONF-2013-034



summer 2013

We know a Higgs particle has been discovered...

...because CERN DG told us so

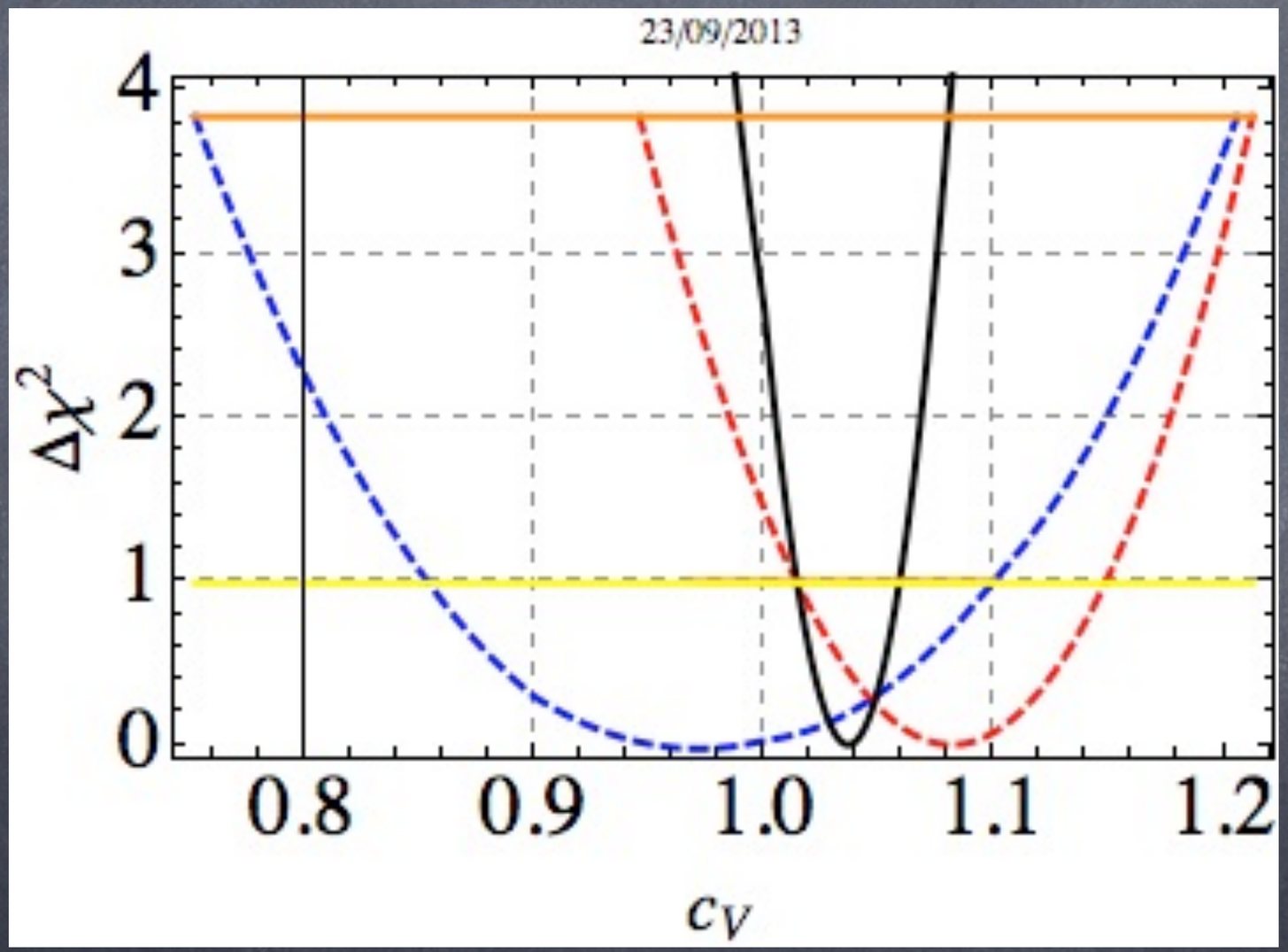


We know a Higgs particle has been discovered...

...because Nobel Committee told us so

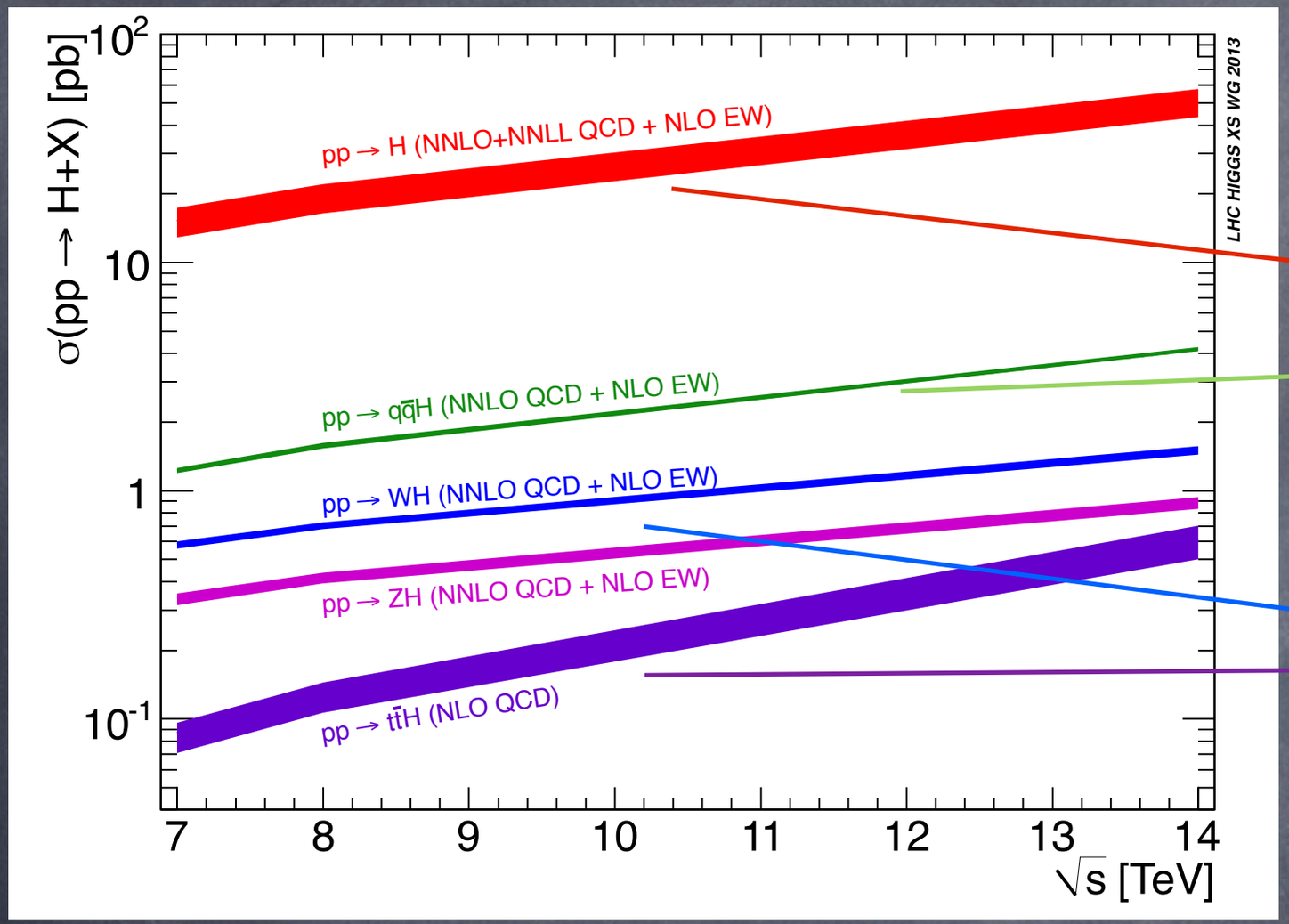
We know a Higgs particle has been discovered...

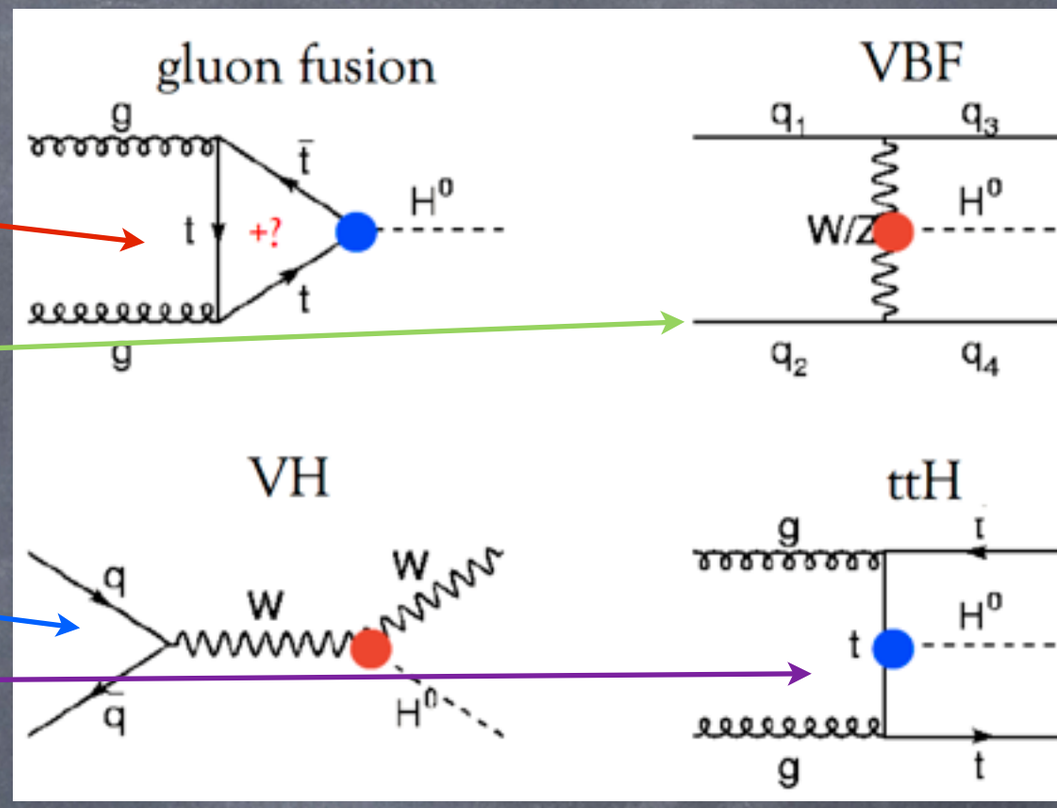
...because I told you so ;)



What are have we been looking for

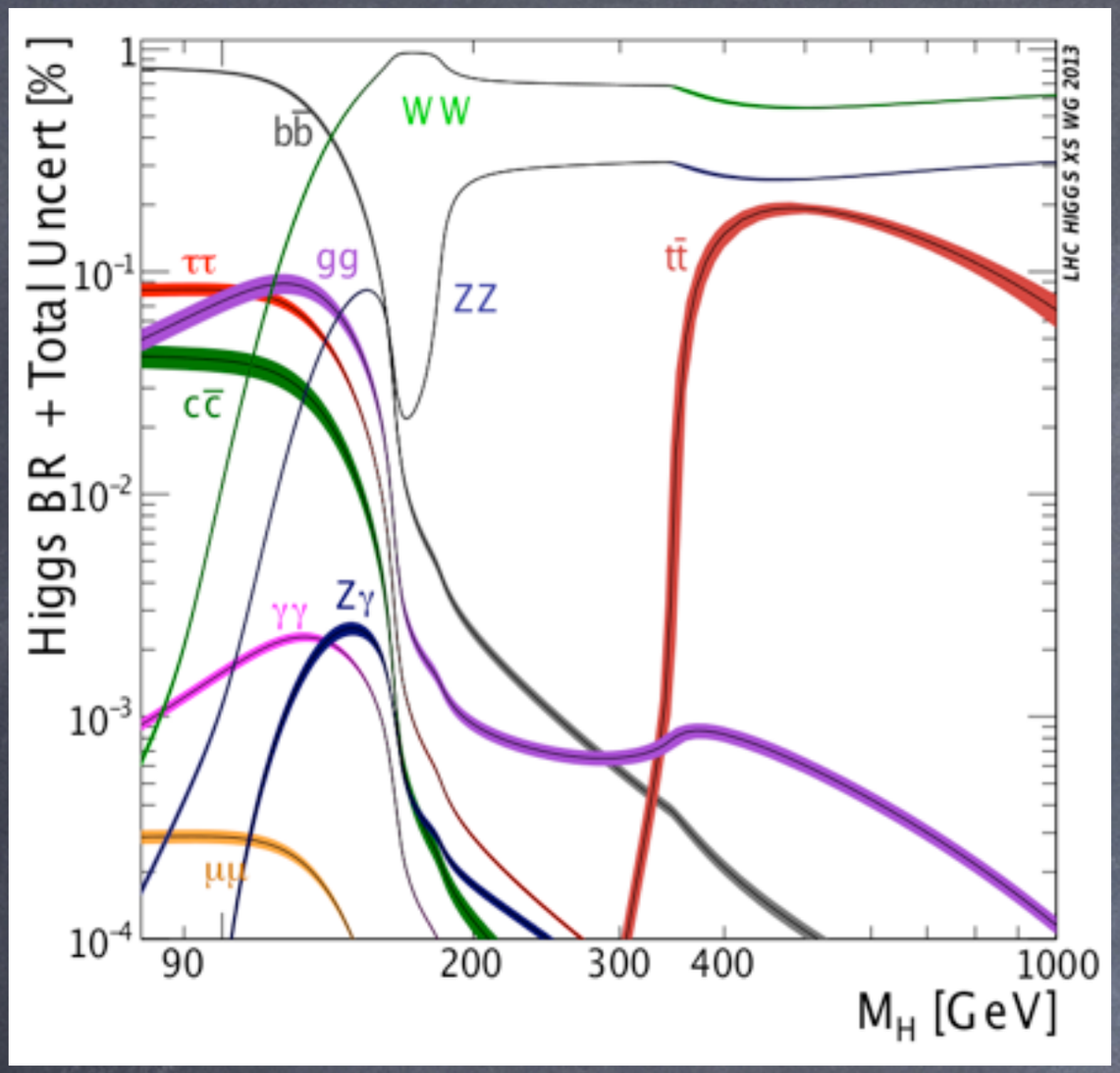
Higgs: Production





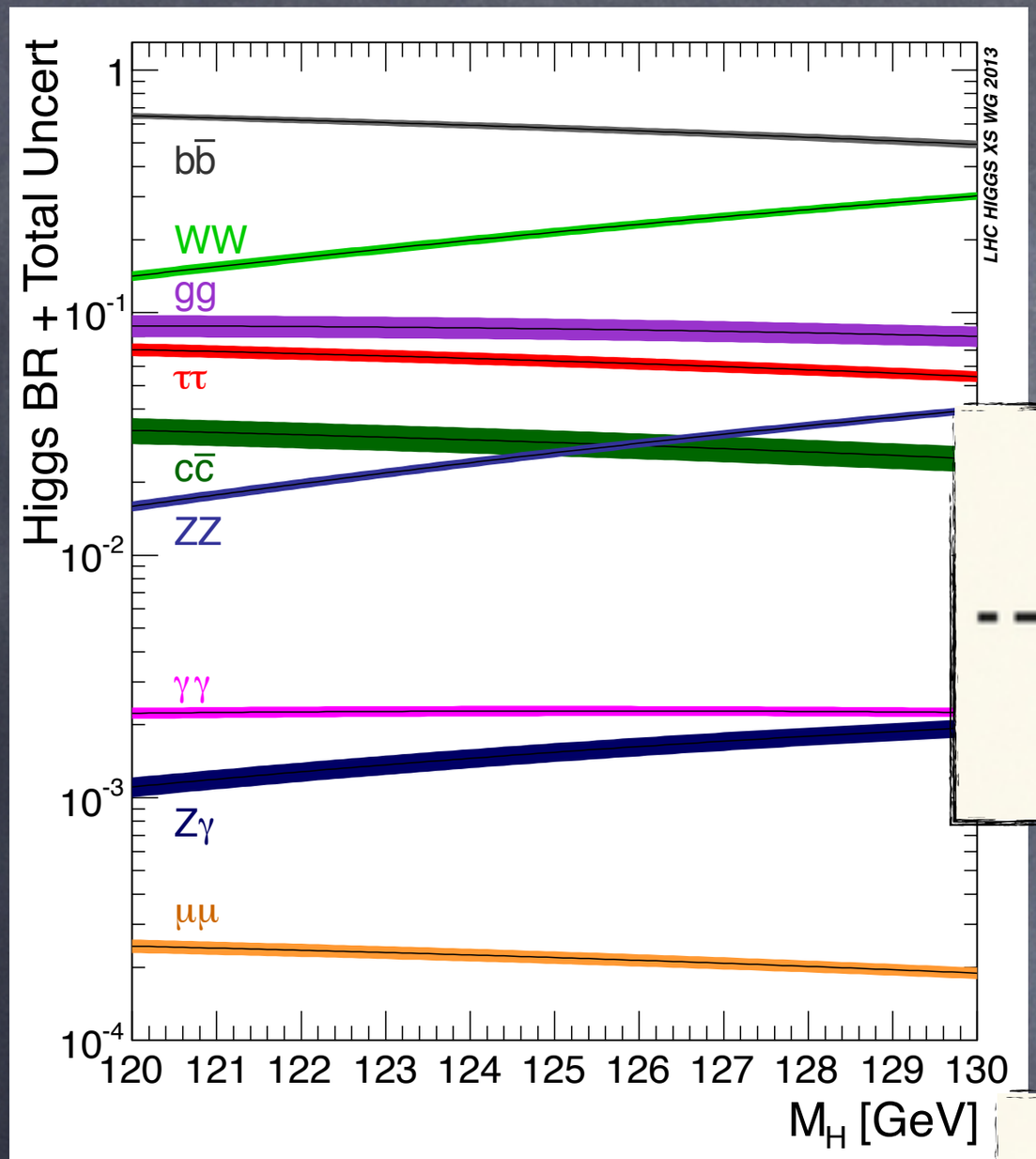
- Fairly large production cross section
- About a million Higgs bosons produced so far at LHC!
- Several distinct production mechanisms that can be experimentally separated

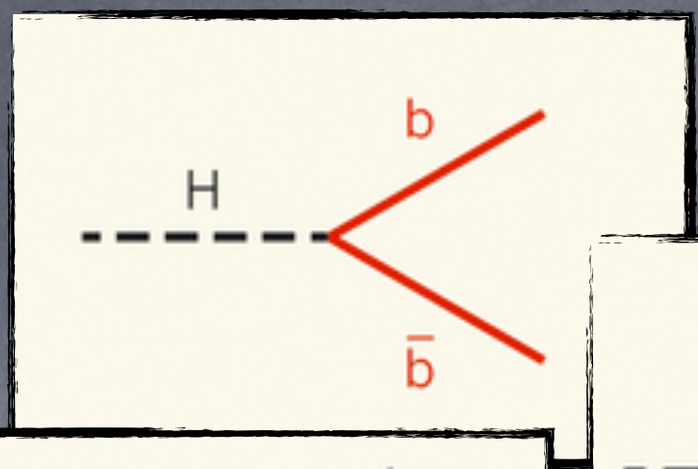
Higgs: Decay

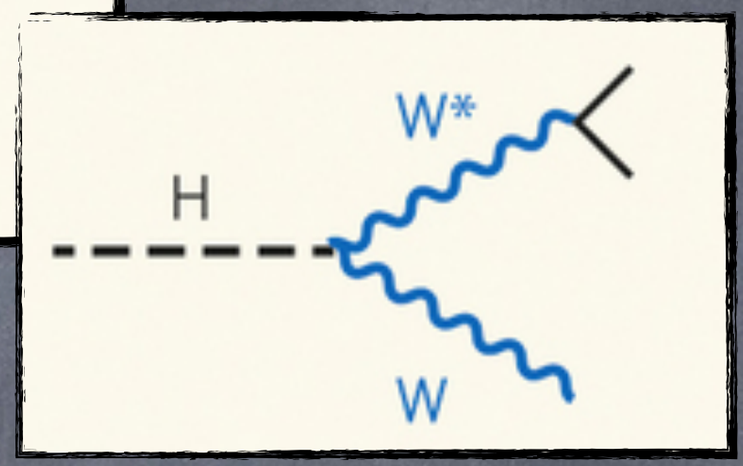


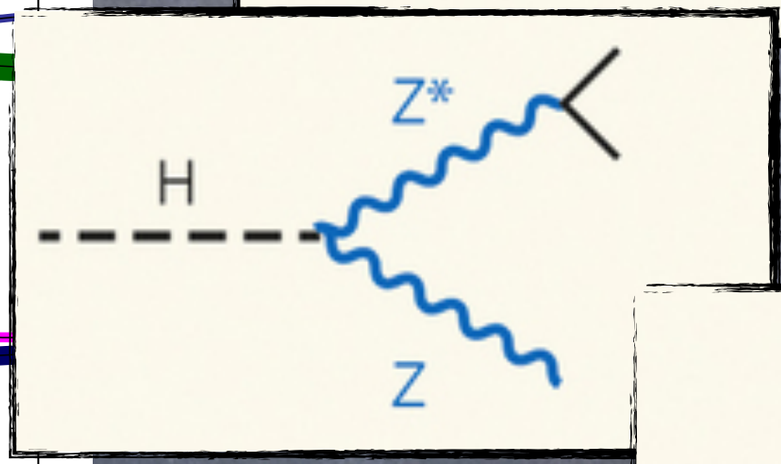
- Roughly, Higgs decays to the heaviest pair of SM particles that is kinematically available
- Heavy Higgs would decay mostly to massive gauge bosons and top quarks
- Light Higgs would decay mostly to b-quarks and tau leptons
- Intermediate mass Higgs (~125 GeV) is the best of all possible worlds for experimentalists

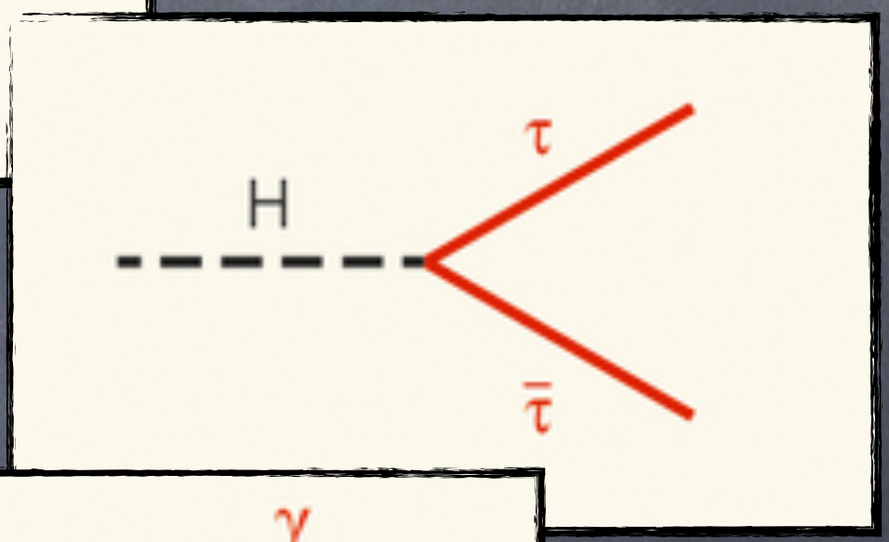
Higgs: Decay

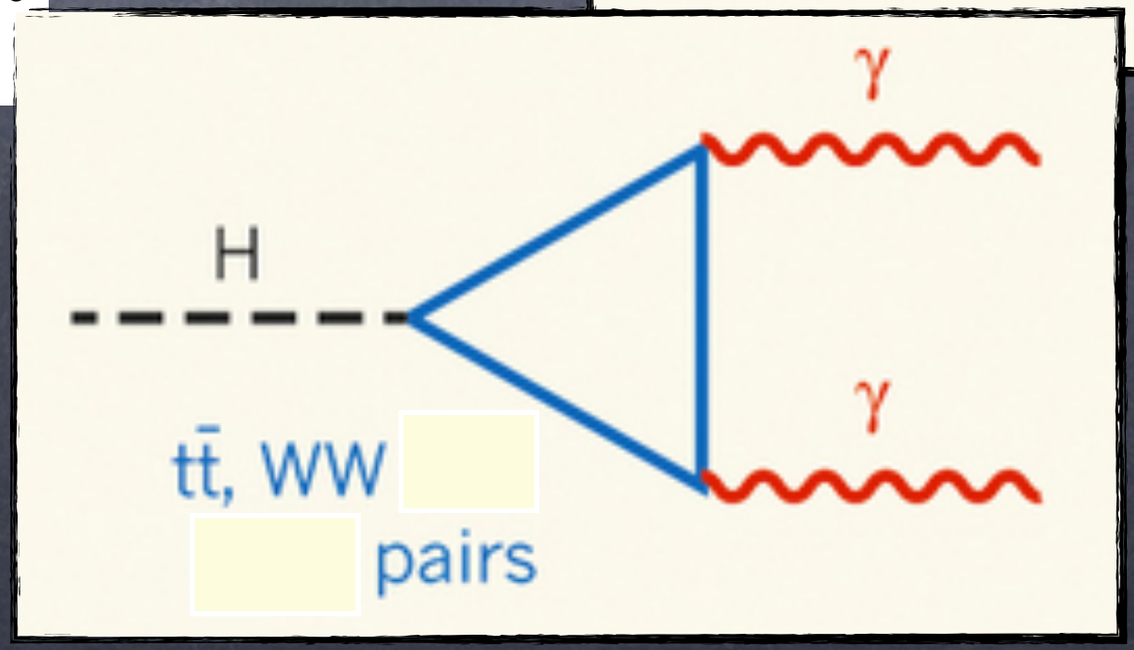

Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
bb̄
WW
gg
ττ
cc̄
ZZ
γγ
Zγ
μμ
LHC HIGGS XS WG 2013
120 121 122 123 124 125 126 127 128 129 130
M_H [GeV]


H
b
b̄


H
W*
W

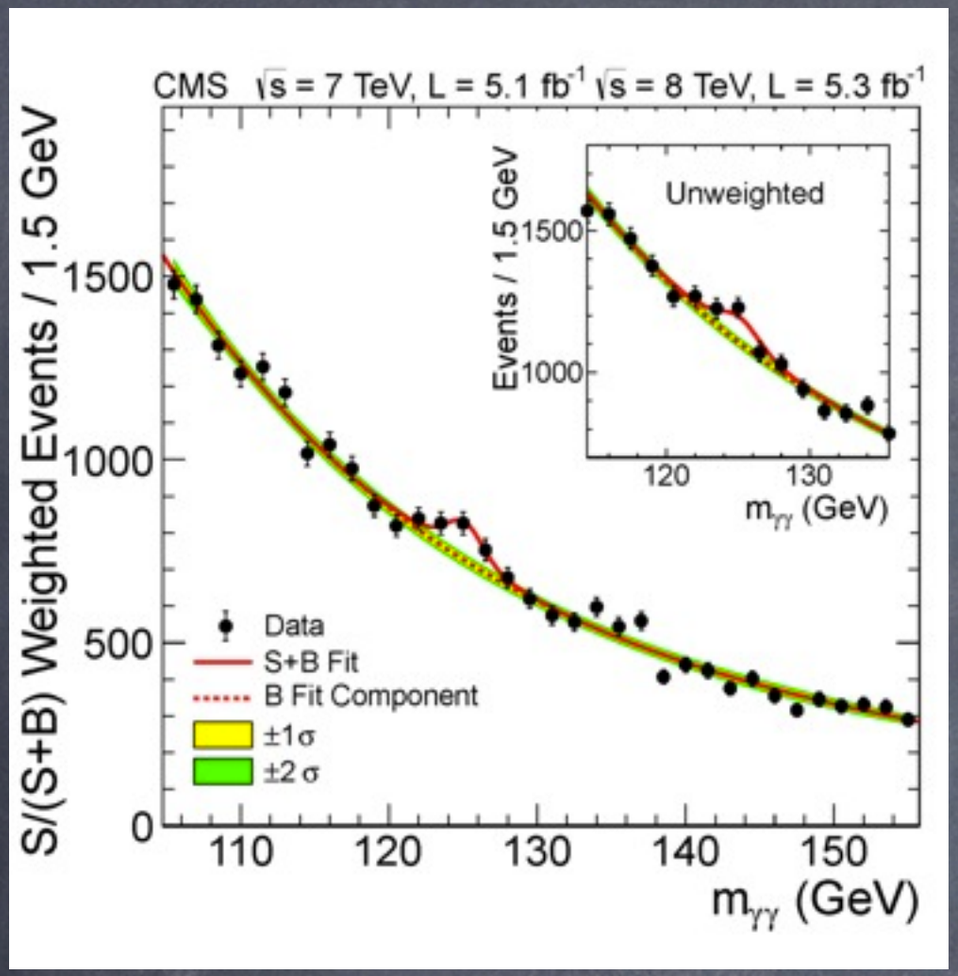

H
Z*
Z


H
τ
τ̄

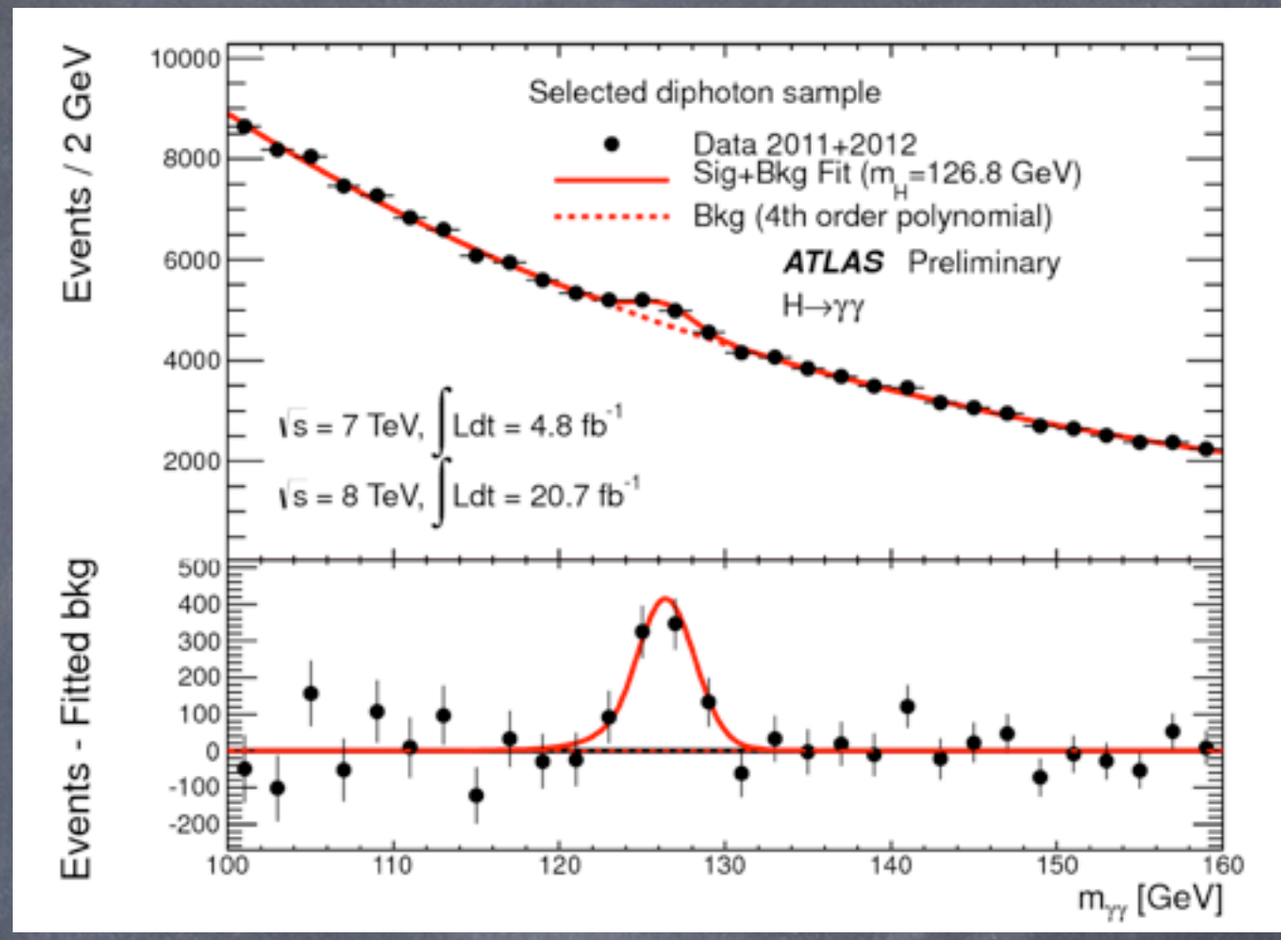

H
γ
γ
tt̄, WW
pairs

What experimental data have we got so far

Higgs: diphoton channel



γγ



- Small deficit of inclusive rate:

$\mu = 0.77 \pm 0.27$

- Interesting excess in 7 TeV data in not borne out in 8 TeV
- Mass measured at:

$m_h = 125.0 \pm 0.7$ GeV

Larger rate and slightly smaller mass for cut based analysis

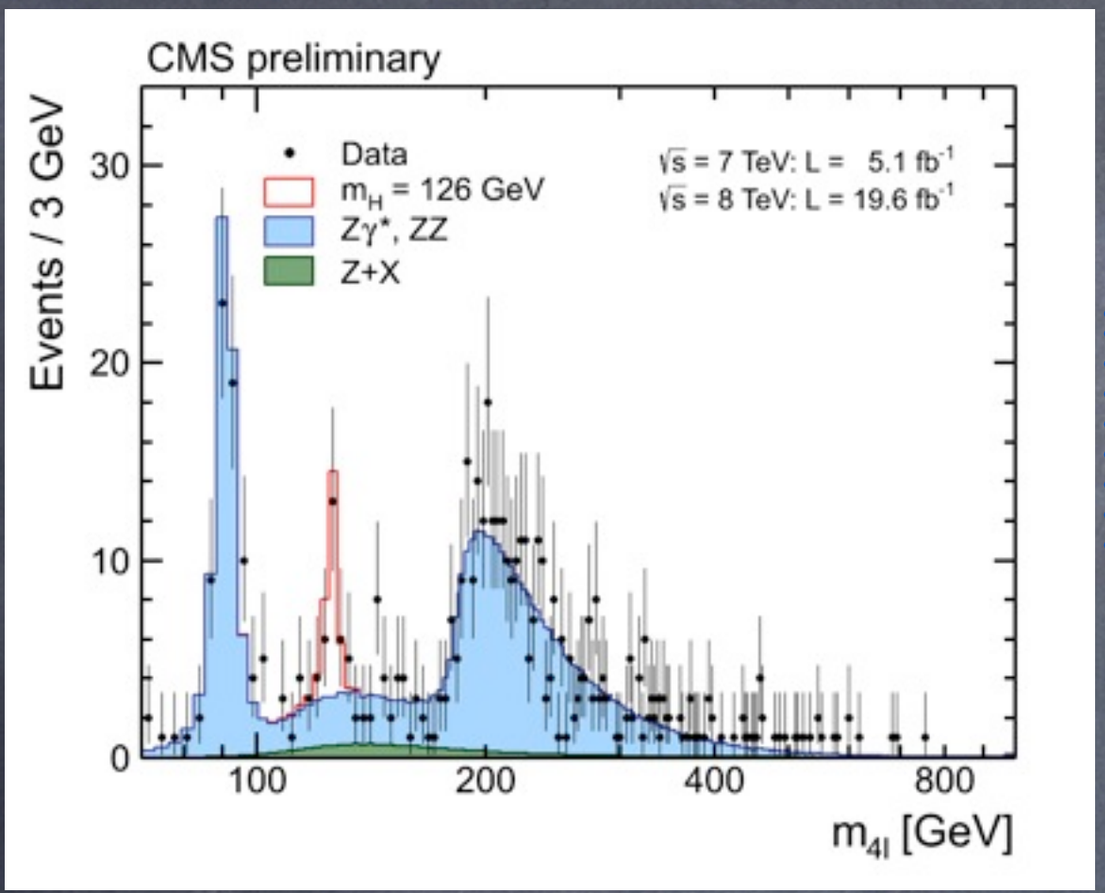
- ~2σ excess of inclusive rate:

$\mu = 1.65 \pm 0.32$

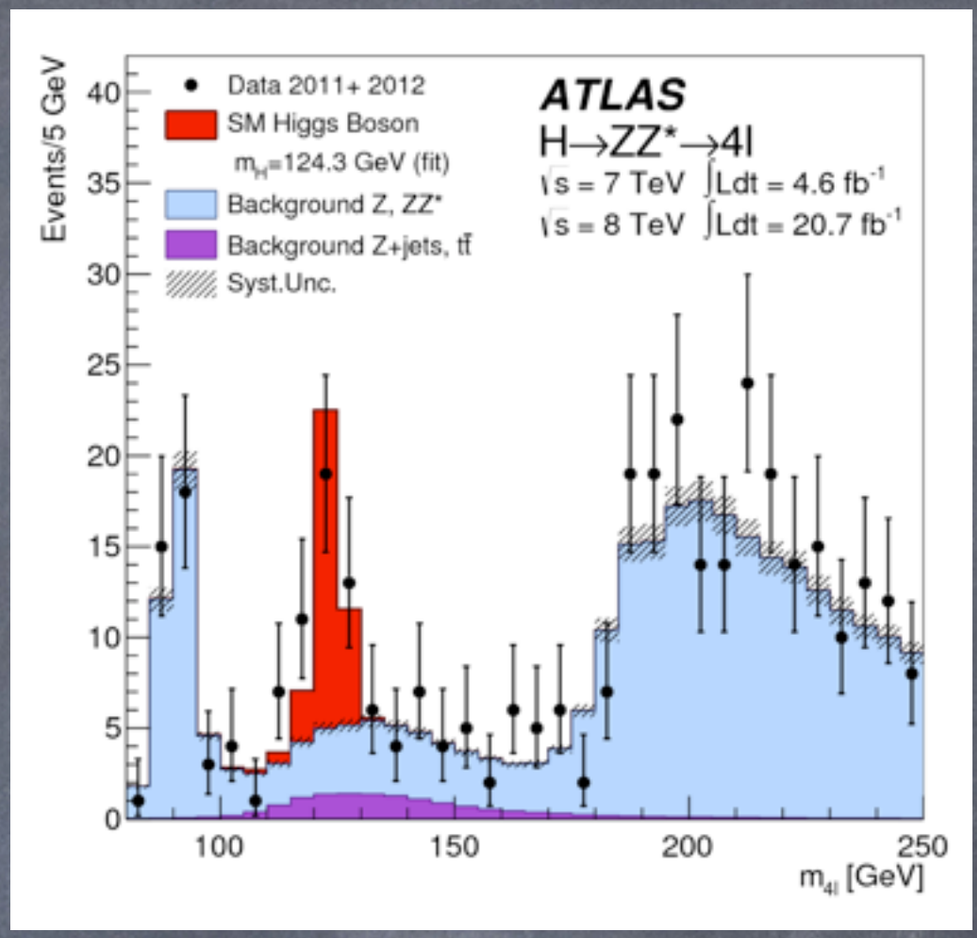
- Excess quite stable from 7 to 8 TeV
- Best fit mass measured at:

$m_h = 126.8 \pm 0.2 \pm 0.7$ GeV

Higgs: what do we know from experiment



ZZ

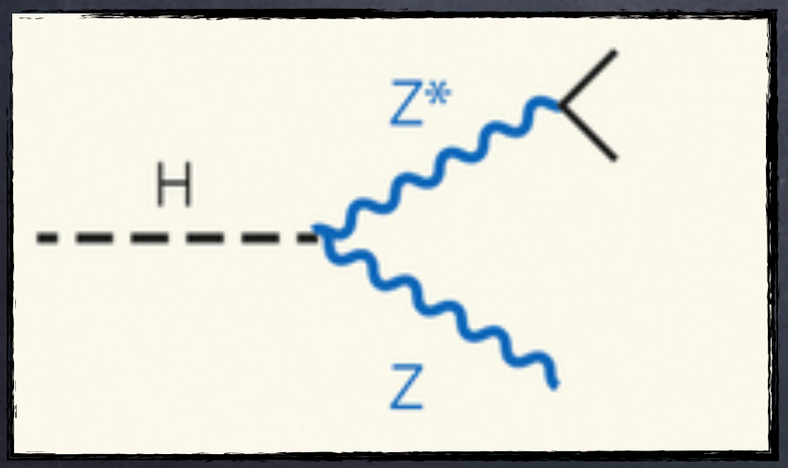


- Rate in good agreement with SM:

$\mu = 0.92 \pm 0.28$

- Mass measured at:

$m_h = 125.8 \pm 0.6$ GeV



- Rate in decent agreement with SM

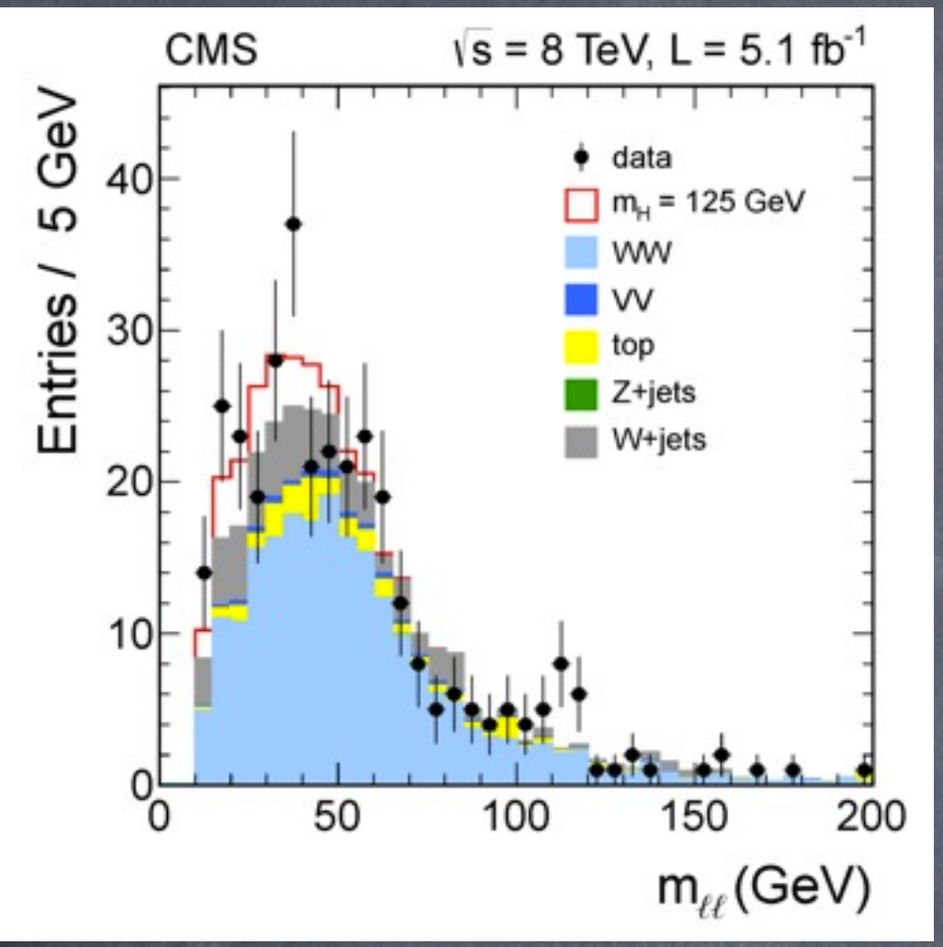
$\mu = 1.7 \pm 0.4$

- Best fit mass measured at:

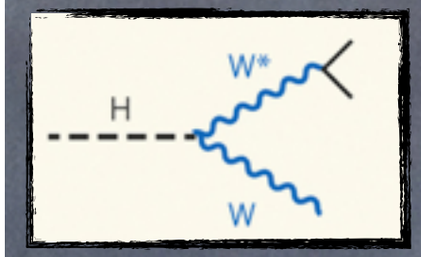
$m_h = 124.3 \pm 0.7$ GeV

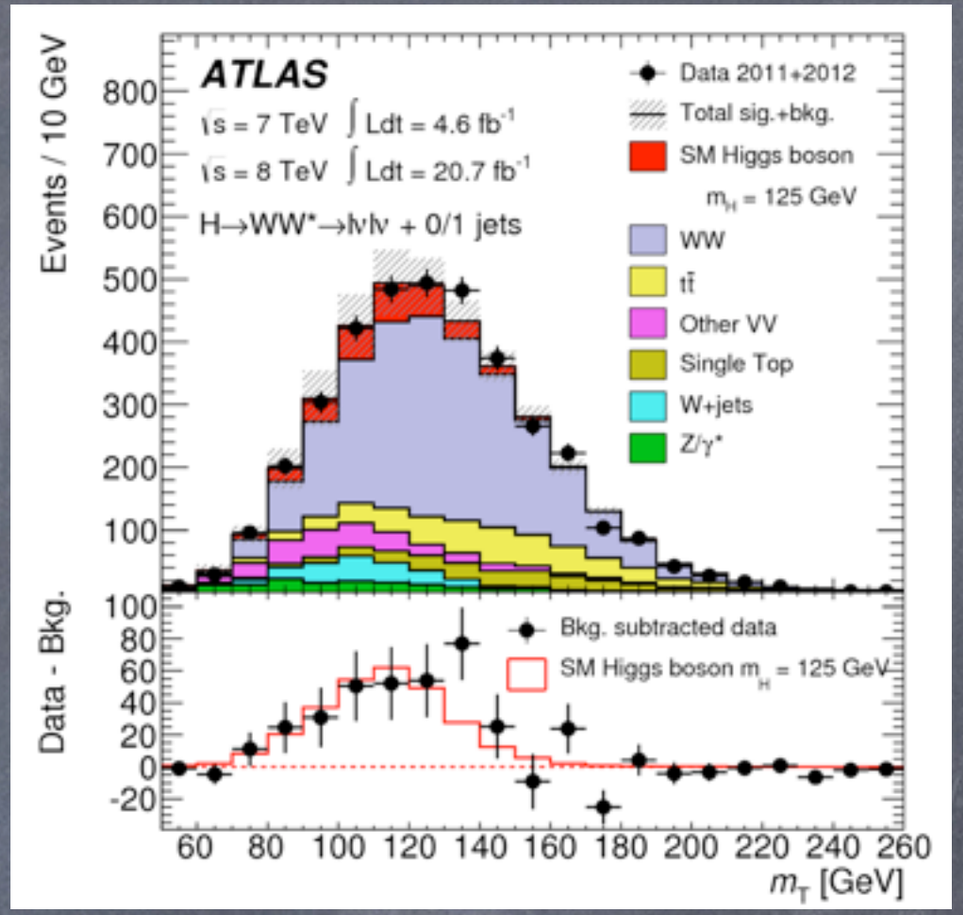
(for m_h = 125.5 GeV: μ=1.41+0.42-0.33)

Higgs: WW channel



WW





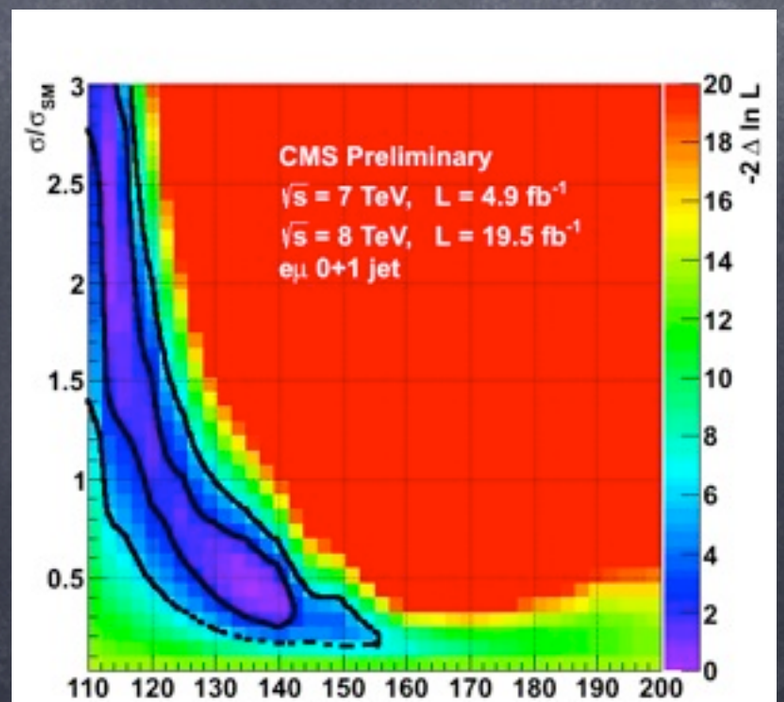
- Rate in decent agreement with SM

μ = 0.72±0.20

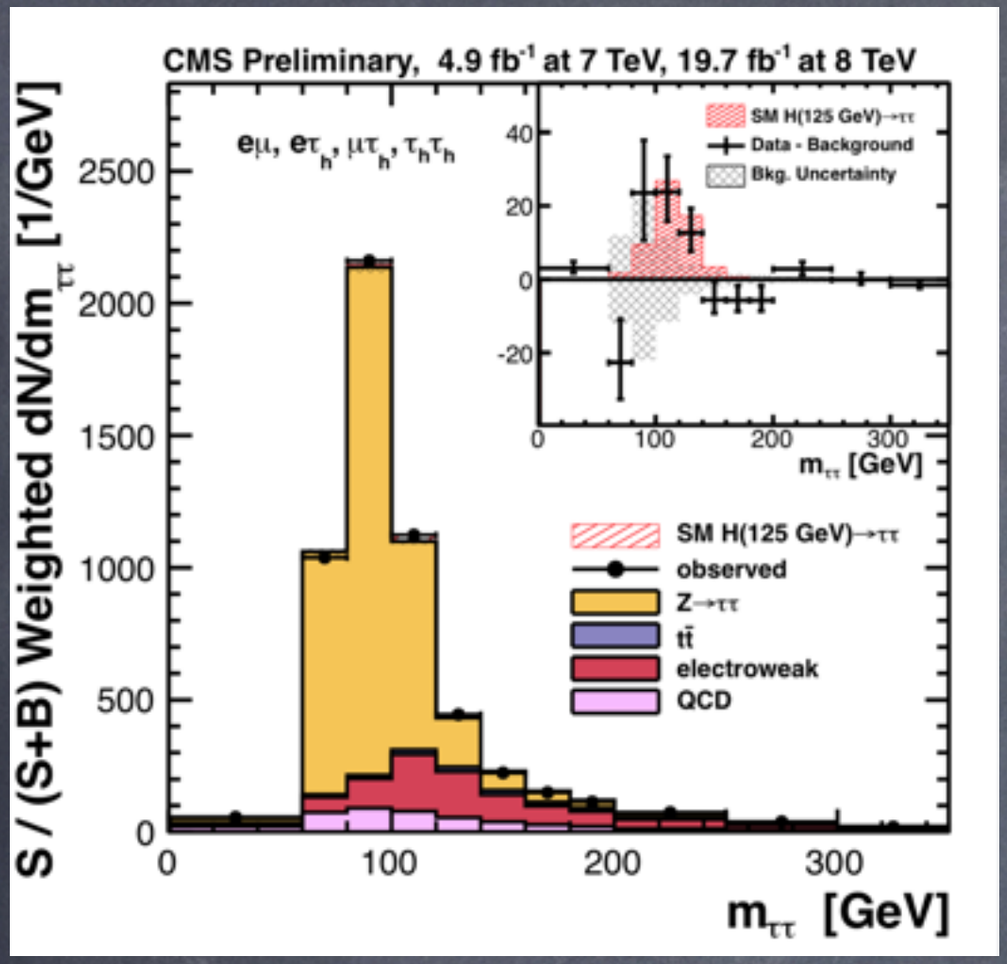
- Rate in perfect agreement with SM

μ = 0.98±0.30

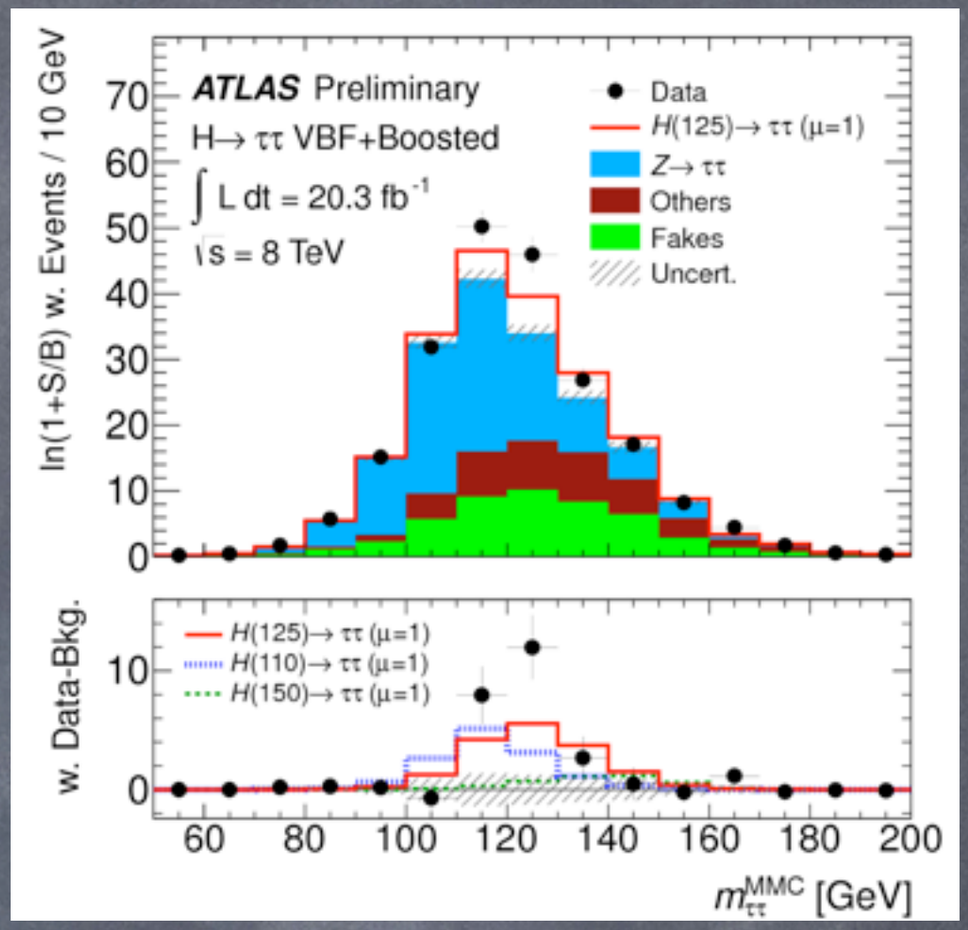
Mass resolution much worse in this channel



PROGRESS IN ττ CHANNEL



ττ



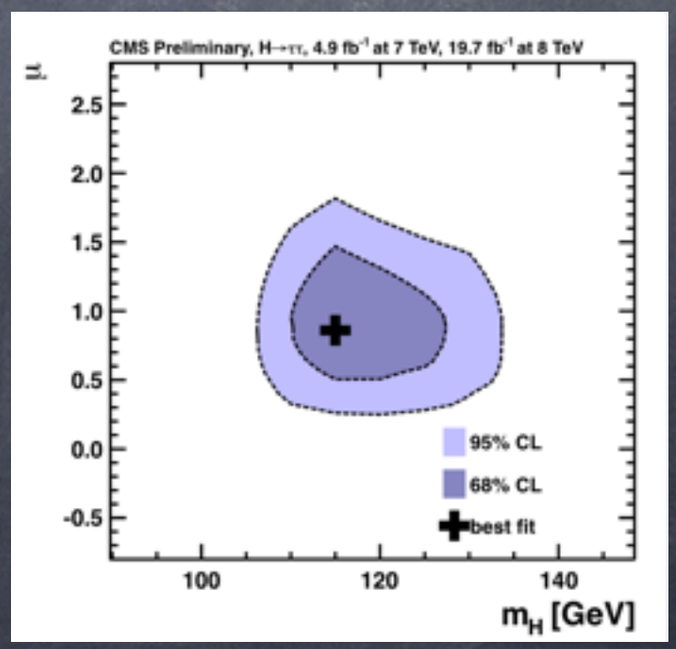
- Rate in good agreement with SM

μ = 0.87±0.29

- Rate slightly larger than in SM

μ = 1.4-0.4+0.5

Mass resolution much worse in this channel

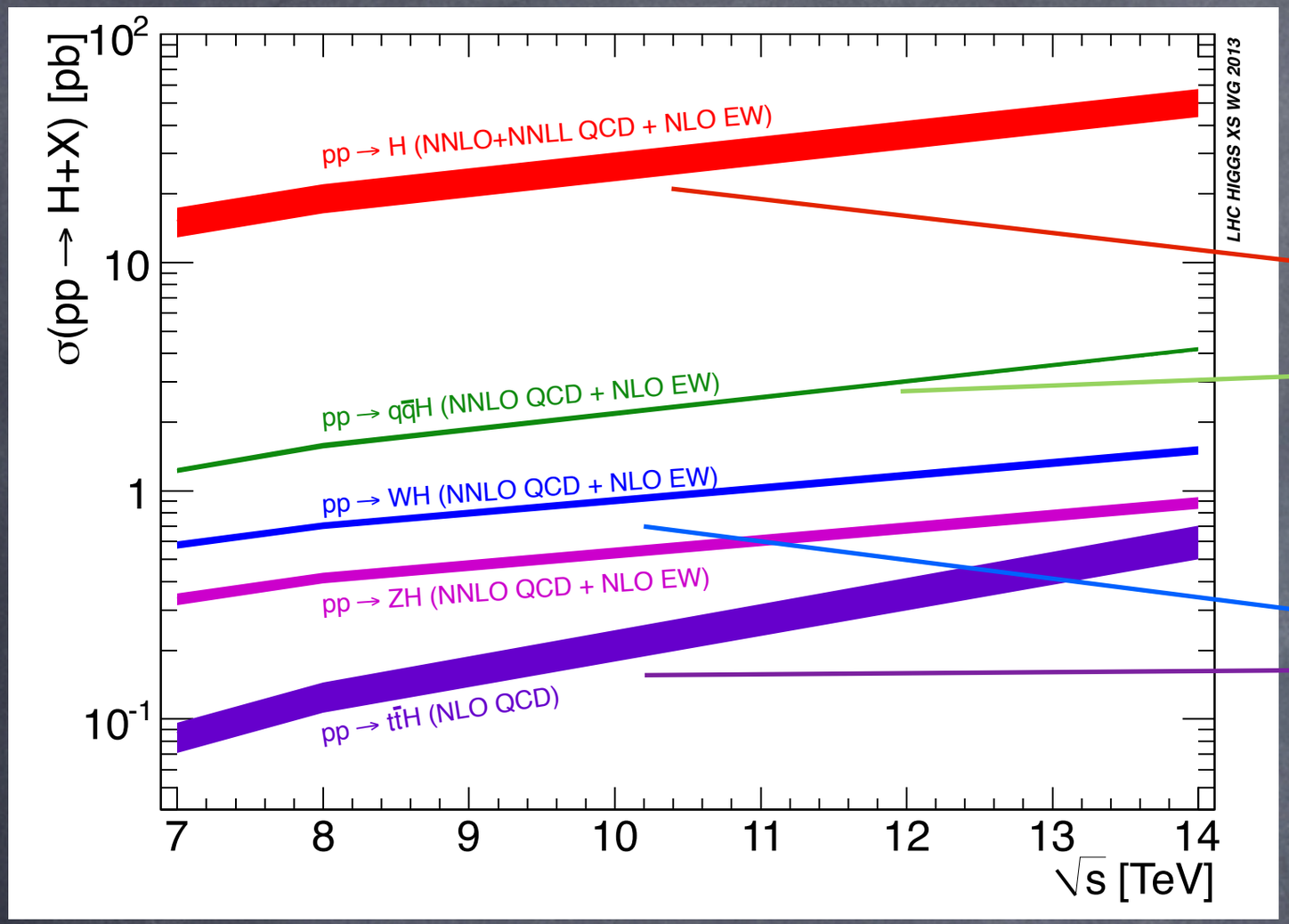


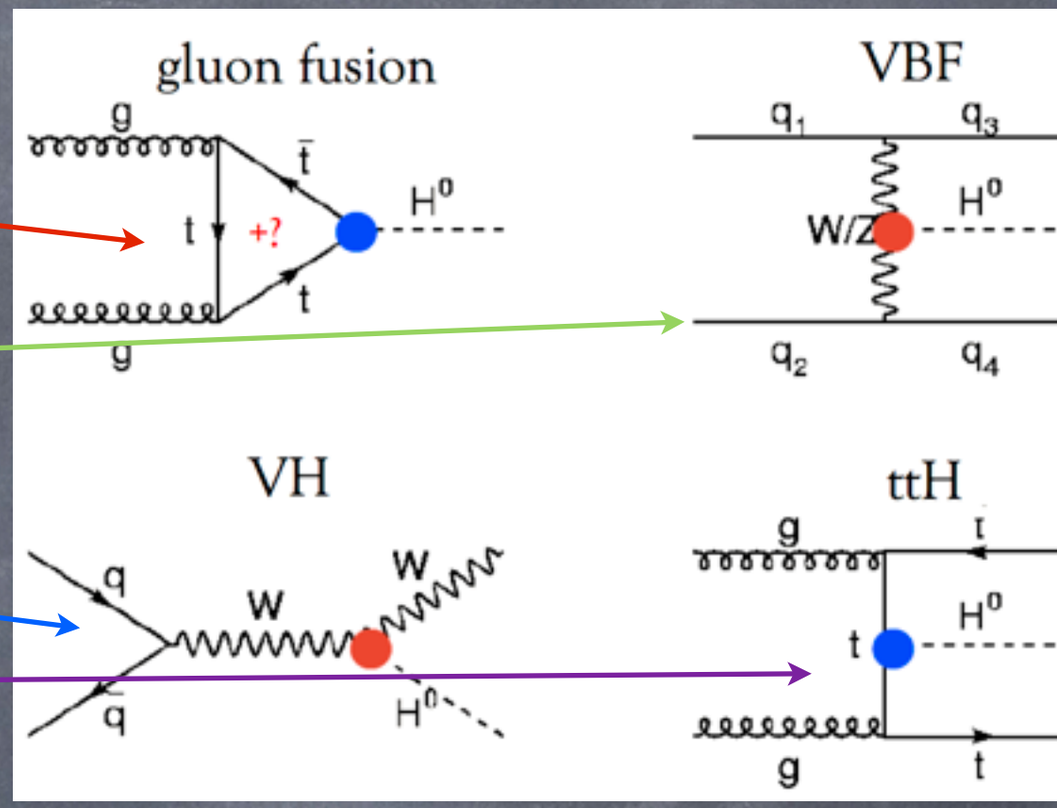
Higgs: other channels

Besides,

- Searches in the h→bb+W/Z channel not conclusive yet
- Two other channels h→ Zγ, h→μμ have not reached sensitivity to the signal expected from the SM Higgs bosoh

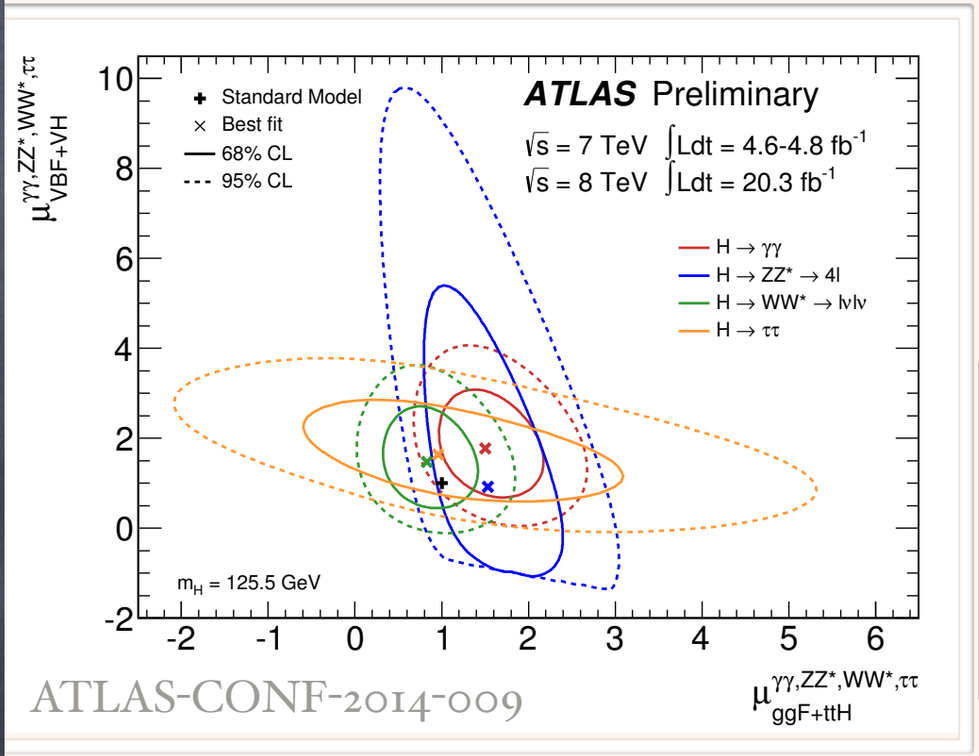
Higgs: Production



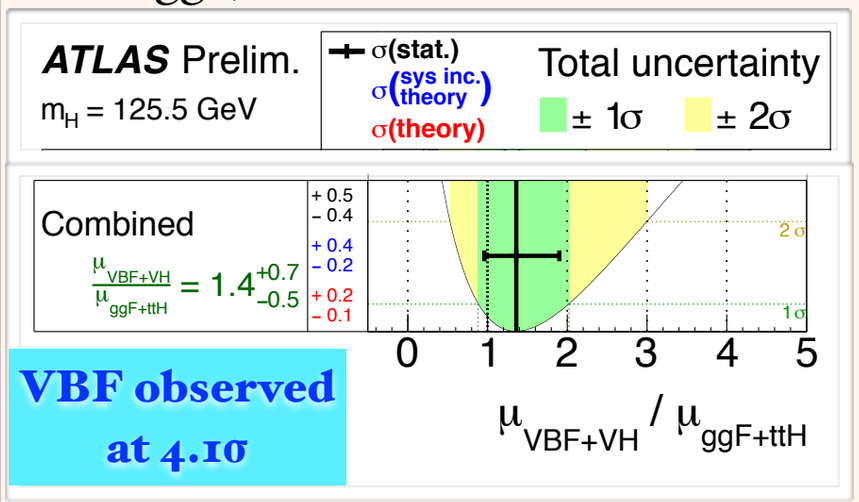


- Fairly large production cross section
- About a million Higgs bosons produced so far at LHC!
- Several distinct production mechanisms that can be experimentally separated

Probe of the production mechanism.



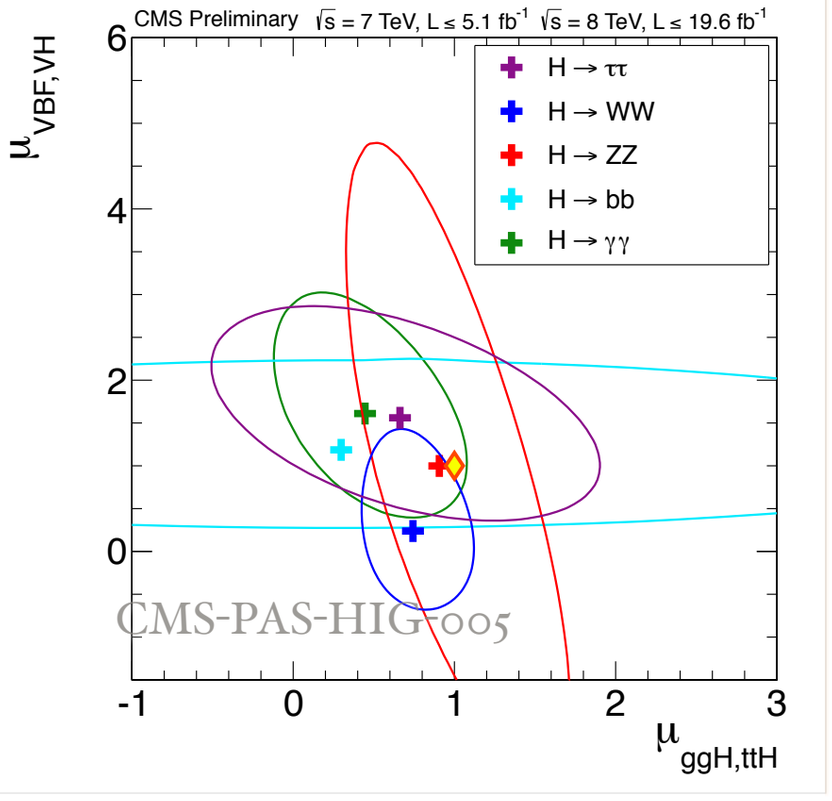
Combined fit to all categories, assuming the same signal strength for low sensitive production modes (ttH, VH) and the high sensitive ones (ggF, VBF).

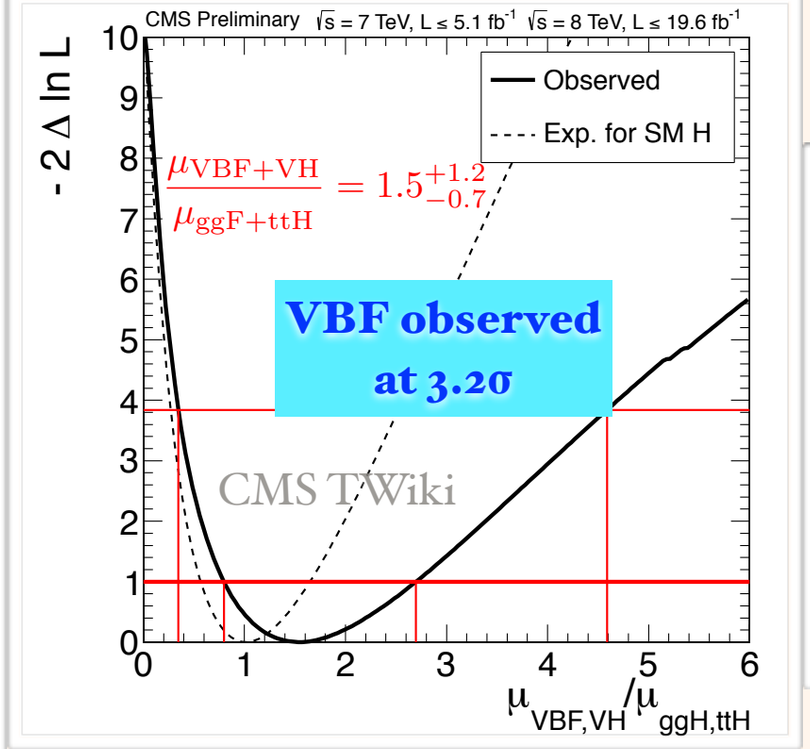


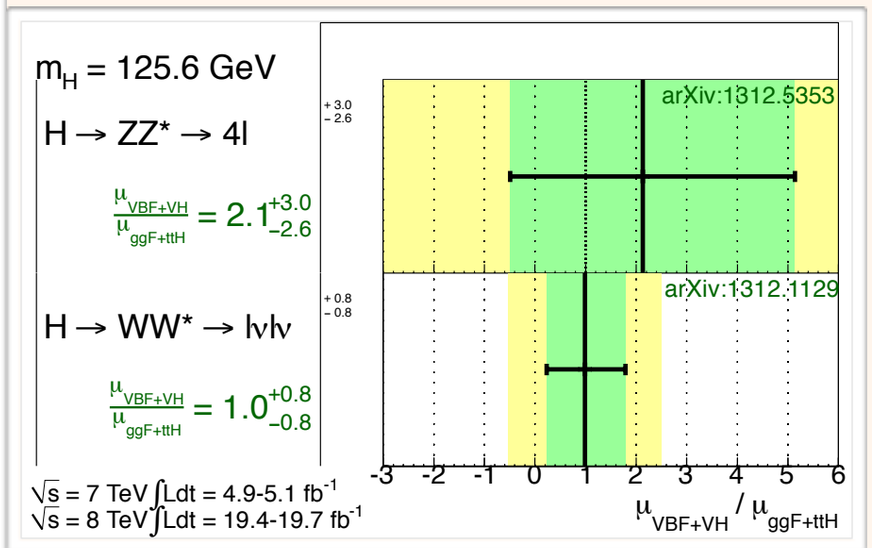
i: bin of the likelihood fit.

$$N^i_{sig.} = \mu_{ggF+ttH}\left(N^i_{ggF} + N^i_{ttH}\right) + \mu_{VBF+VH}\left(N^i_{VBF} + N^i_{VH}\right)$$

CMS updates (personally recomputed using published inputs)





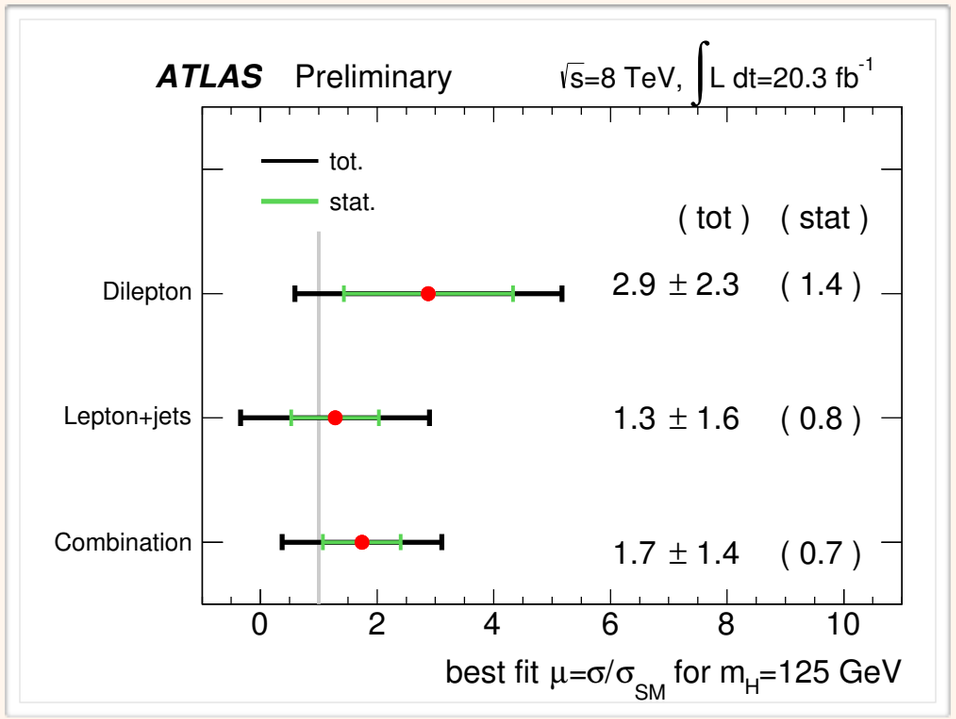


ttH couplings

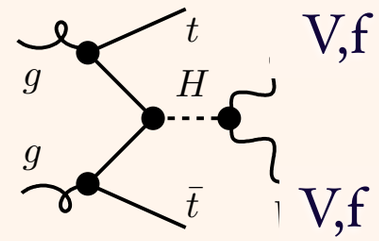
ATLAS

gg→ttH (H→bb)→WbWb bb→ lν lνbb, lνqqbb

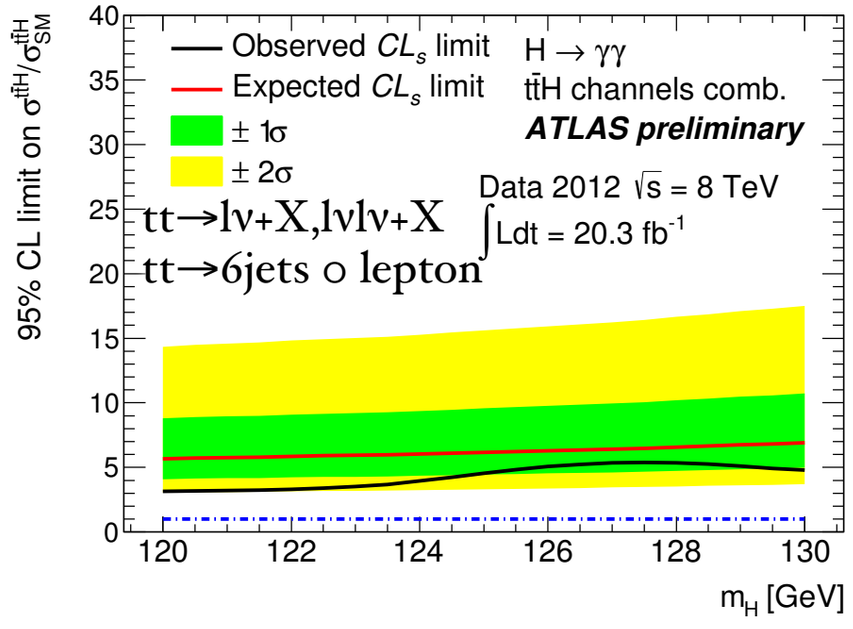
- Data divided in jet multipli-cities and n. of b-tagged jets categories (9 single-lepton, 6 di-lepton).
- NN used as primary discriminant.



H→γγ



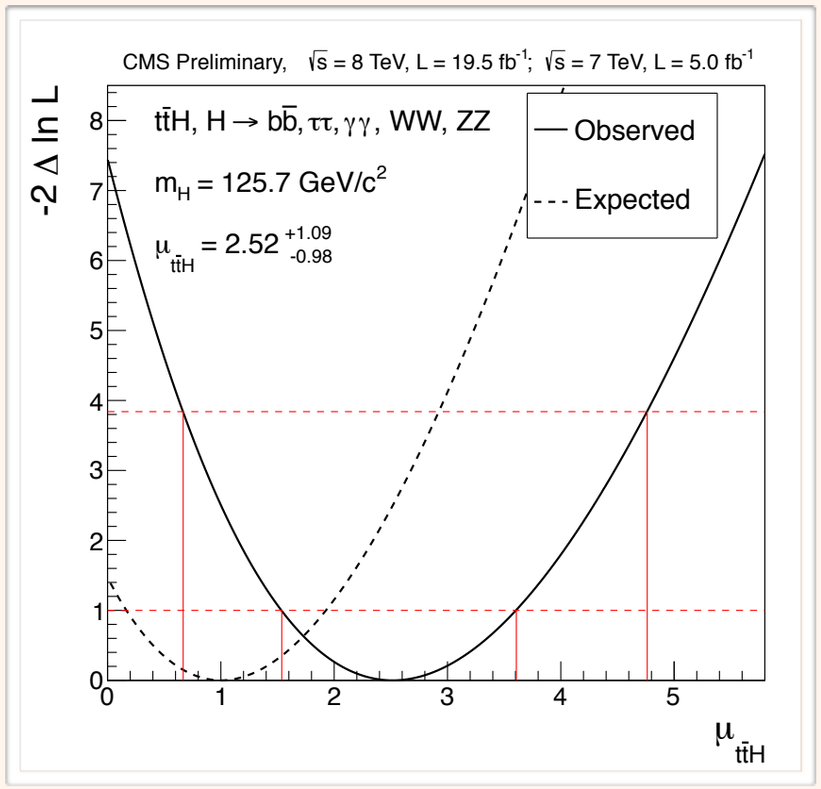
ttH production

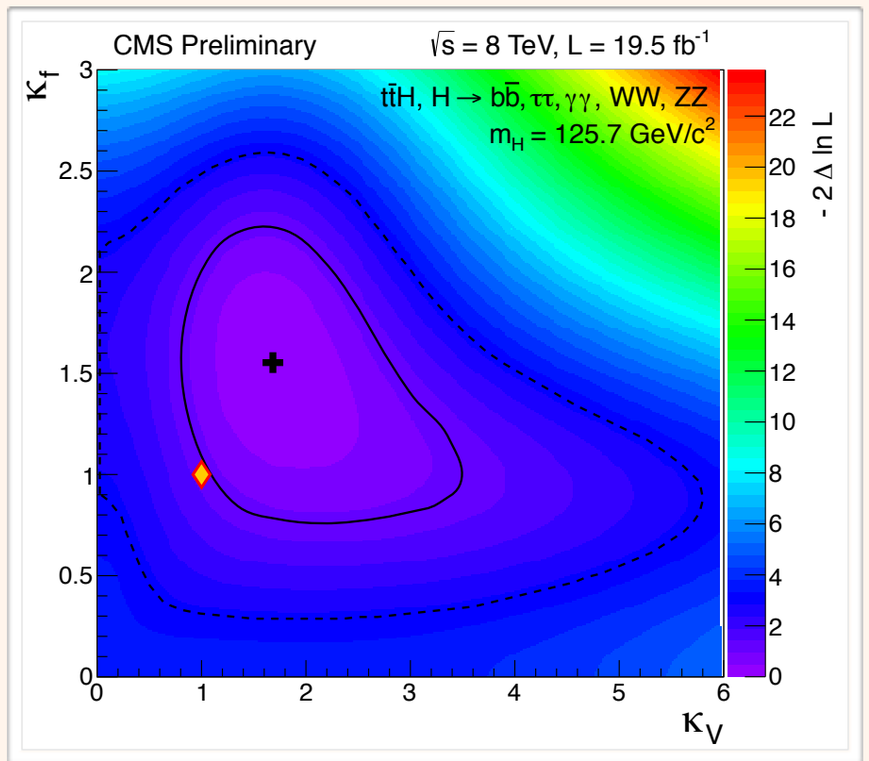


CMS

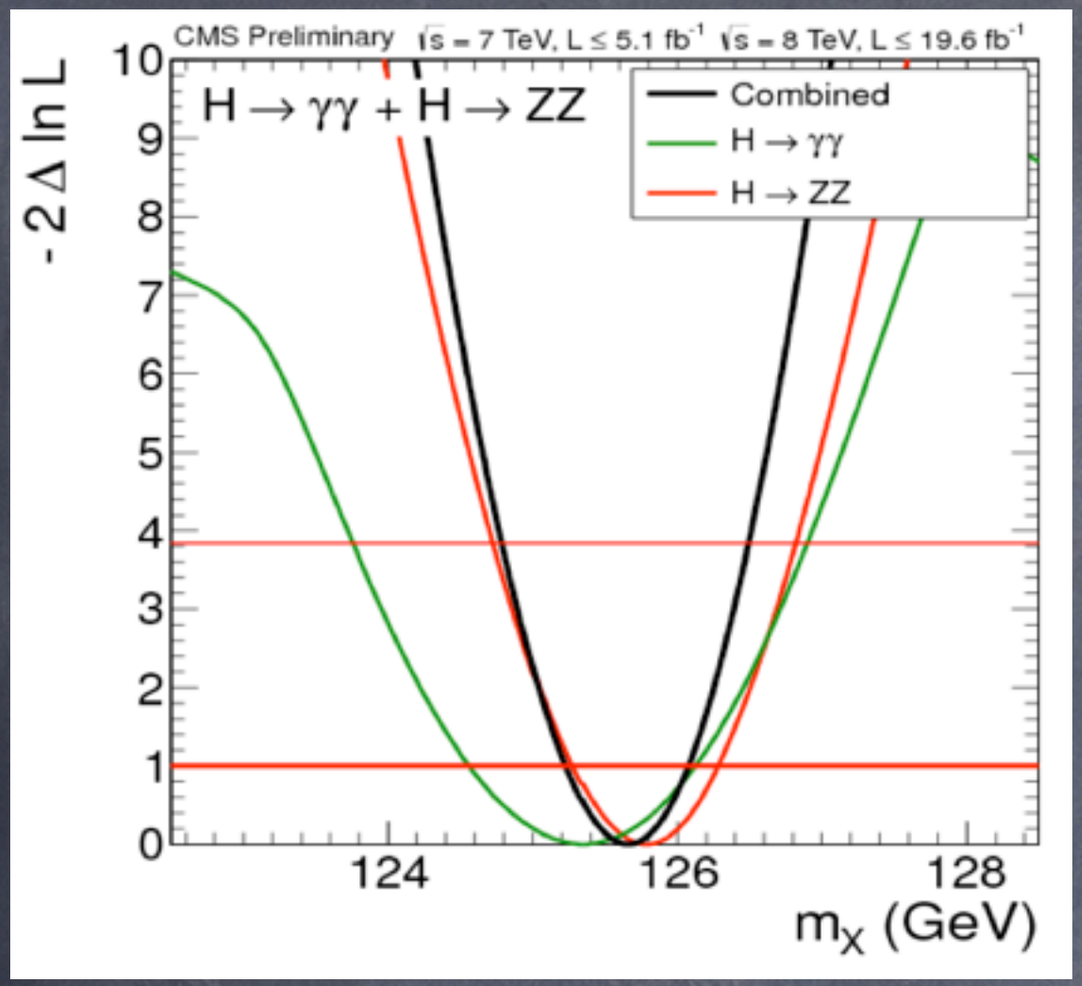
Exploit many reco final states.

ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

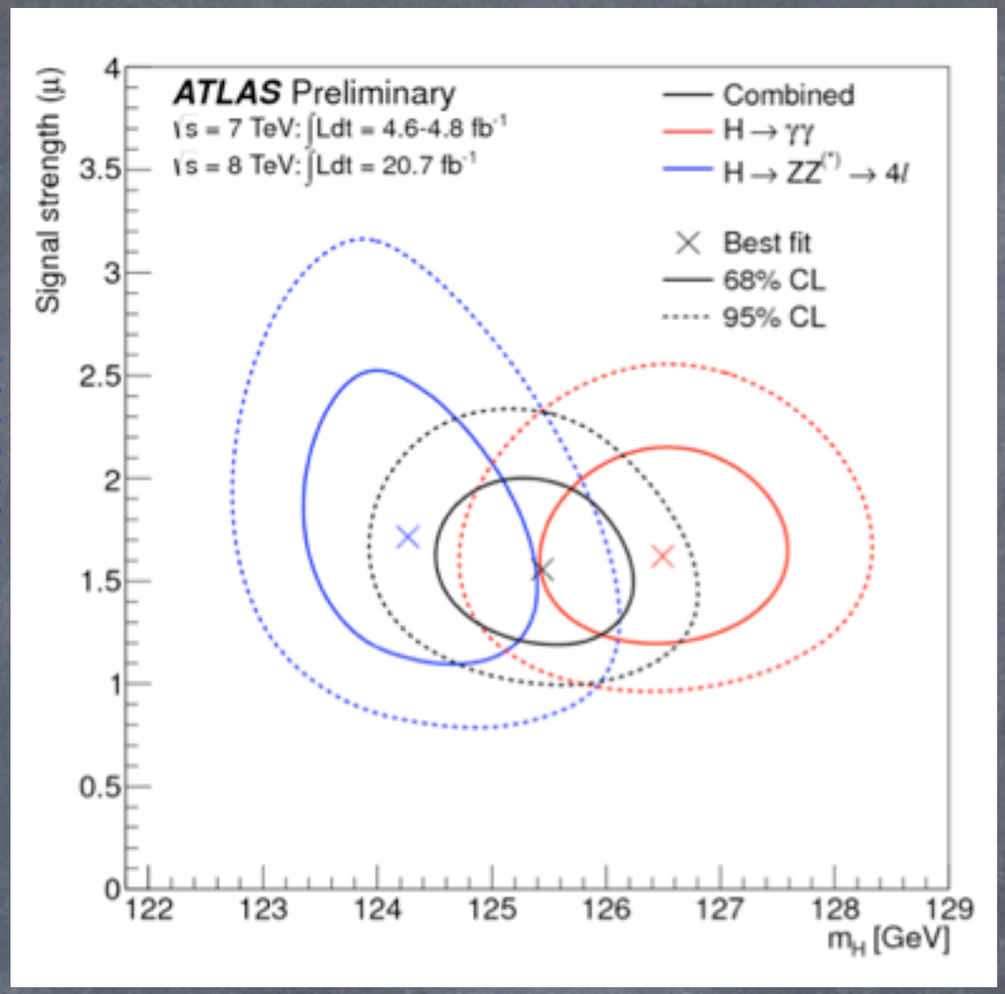




Higgs: mass measurement



m_h



Systematic error? Fluctuation? Anyway, less worrying than last year...

Mass combination:

$m_h = 125.7 \pm 0.4$ GeV

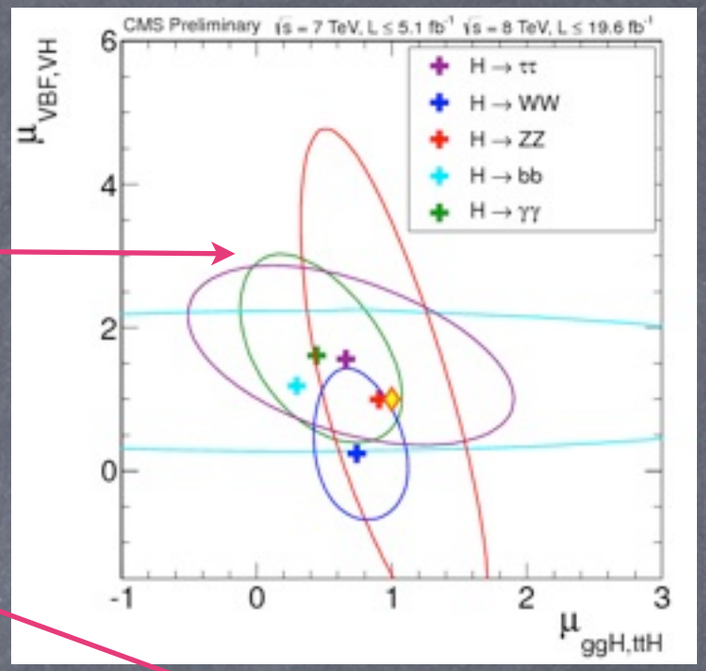
Mass combination:

$m_h = 125.5 \pm 0.6$ GeV

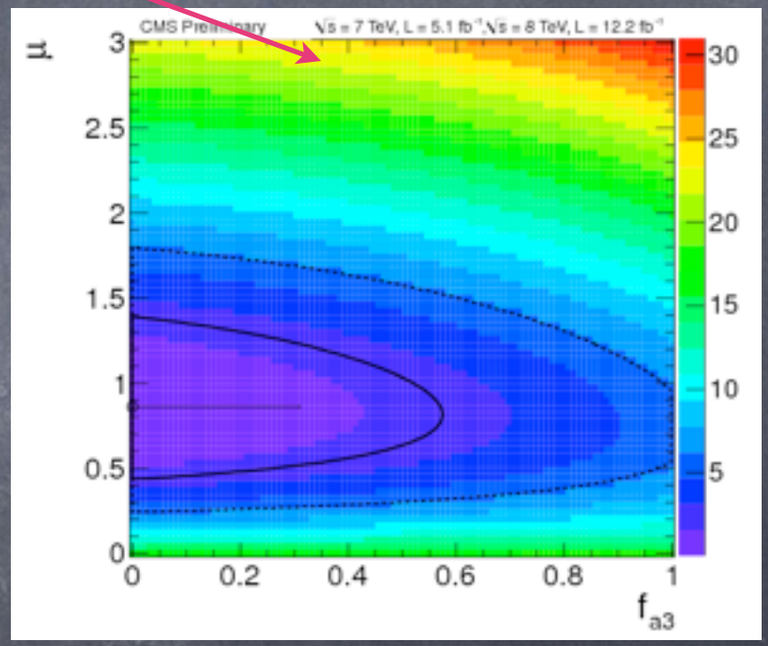
In spite of some jitters in ATLAS, experiments agree
that m_h is likely between 125 and 126 GeV
In this talk $m_h = 125.6$ GeV

WHAT HAVE THE EXPERIMENTALISTS EVER DONE FOR US ?

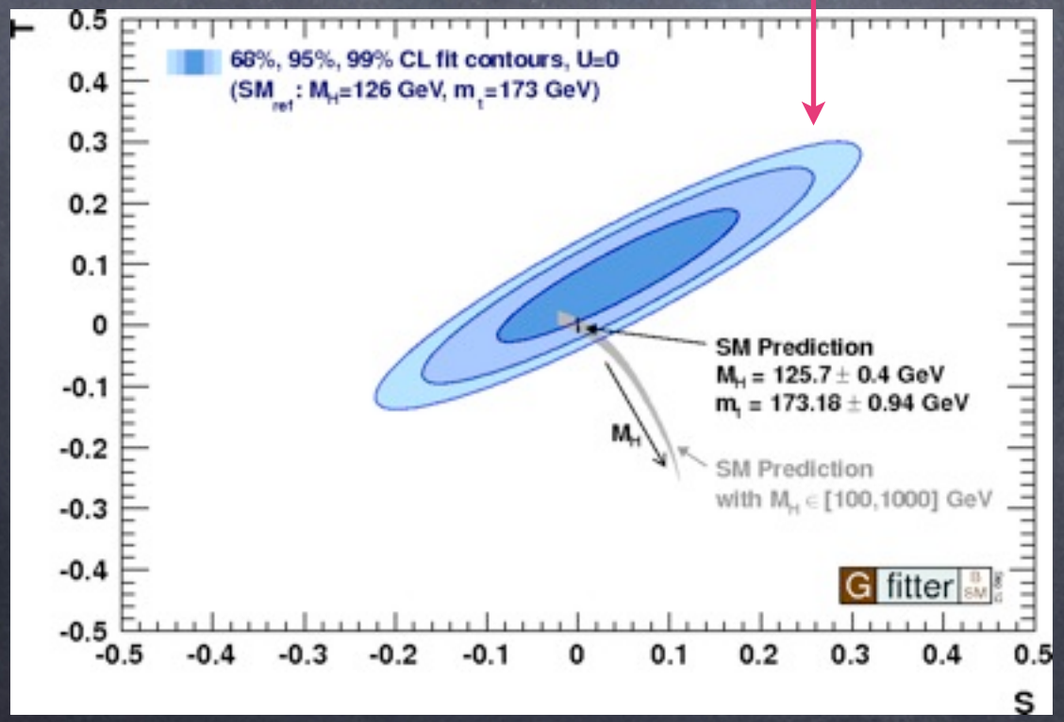
- Higgs production rates, split into separate production and decay channels



- Some information about tensor structure of the Higgs couplings



- Constraints on precision observables where Higgs enters indirectly



How we interpret that

Understanding Higgs Data

- Before 2012, the last free parameter in the SM had been the Higgs mass and we've already pinpointed it with a fantastic precision (no need to know better really ;)

- All the Higgs couplings and self-couplings can be expressed in terms of previously measured parameters

- Nothing left to do :), at least in the context of the SM

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \cdots \\ v + h + \ldots \end{pmatrix}$$

$$\mathcal{L}_{\rm SM} = D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 + \left(\frac{y_{ij}}{\sqrt{2}} H \bar{\psi}_i \psi_j + \text{h.c.} \right) + \ldots$$

No Higgs

Couplings to EW gauge bosons

$$\left(\frac{h}{v} + \frac{h^2}{2v^2} \right) (2 m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu)$$

Ensures unitarity of VV->hh scattering

Ensures unitarity of VV->VV scattering

Self-Couplings

$$-\frac{m_h^2}{2v} h^3 - \frac{m_h^2}{8v^2} h^4$$

Ensures unitarity of VV->VVVV... scattering

Couplings to fermions

$$-\frac{h}{v} \sum_f m_f \bar{f} f$$

Ensures unitarity of VV->ff scattering

Simplified Effective Higgs Lagrangian

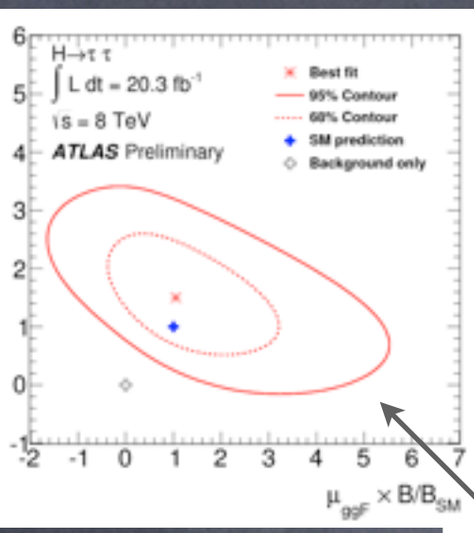
$$\mathcal{L}_{h,\mathrm{sim}} = \frac{h}{v}\Big(\quad 2c_V m_W^2 W_\mu^+ W_\mu^- + c_V m_Z^2 Z_\mu Z_\mu$$
$$- c_u \sum_{q=u,c,t} m_q \bar{q} q - c_d \sum_{q=d,s,b} m_q \bar{q} q - c_l \sum_{l=e,\mu\tau} m_l \bar{l} l$$
$$+ \frac{1}{4} c_{gg} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu} \gamma_{\mu\nu}$$
$$- \frac{1}{2} c_{WW} W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z_{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z_{\mu\nu} \Big)$$

$$c_{WW} = c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} \qquad c_{ZZ} = c_{\gamma\gamma} + \frac{c_w^2 - s_w^2}{c_w s_w} c_{Z\gamma}$$

- Simpler effective theory with 7 free parameters
- <ALL> these parameters are meaningfully constrained by current Higgs data
- Limit of SM+SILH with constraints $\bar{c}_T = \bar{c}_6 = 0 \qquad \bar{c}_{HW} + \bar{c}_{HB} = 0 \qquad \bar{c}_B + \bar{c}_{HB} = 0$
- Standard Model limit: $c_V = c_f = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$

Global Fit to Higgs Couplings

Higgs: the story so far



ATLAS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$1.55^{+0.33}_{-0.29}$	[5, 6]
	ZZ	$1.41^{+0.42}_{-0.33}$	[5, 7]
	WW	$0.98^{+0.33}_{-0.26}$	[5, 8]
	$\tau\tau$	$1.4^{+0.4}_{-0.5}$	[9]
VH	bb	$0.2^{+0.7}_{-0.6}$	[10]
ttH	bb	2.69 ± 5.53	[11]
	$\gamma\gamma$	-1.39 ± 3.18	[12]
inclusive	$Z\gamma$	2.96 ± 6.69	[13]
	$\mu\mu$	1.75 ± 4.26	[14]

CMS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$0.77^{+0.29}_{-0.26}$	[15]
	ZZ	$0.92^{+0.29}_{-0.24}$	[16]
	WW	$0.68^{+0.21}_{-0.19}$	[16]
	$\tau\tau$	0.87 ± 0.29	[17]
VH	bb	1.00 ± 0.49	[18]
VBF	bb	0.7 ± 1.4	[19]
ttH	bb	$1.0^{+1.9}_{-2.0}$	[20]
	$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$	[20]
	$\tau\tau$	$-1.4^{+6.3}_{-5.5}$	[20]
	multi-ℓ	$3.7^{+1.6}_{-1.4}$	[21]
inclusive	$Z\gamma$	-0.21 ± 4.86	[22]
	$\mu\mu$	$2.9^{+2.8}_{-2.7}$	[23]

7 parameter fit

$$c_V = 1.04^{+0.03}_{-0.03}$$

$$c_u = 1.30^{+0.23}_{-0.27}$$

$$c_d = 1.03^{+0.27}_{-0.17}$$

$$c_l = 1.10^{+0.18}_{-0.15}$$

$$c_{gg} = \frac{g_s^2}{16\pi^2}\left(-0.48^{+0.44}_{-0.17}\right)$$

$$c_{\gamma\gamma} = \frac{e^2}{16\pi^2}\left(0.2^{+2.8}_{-3.3}\right)$$

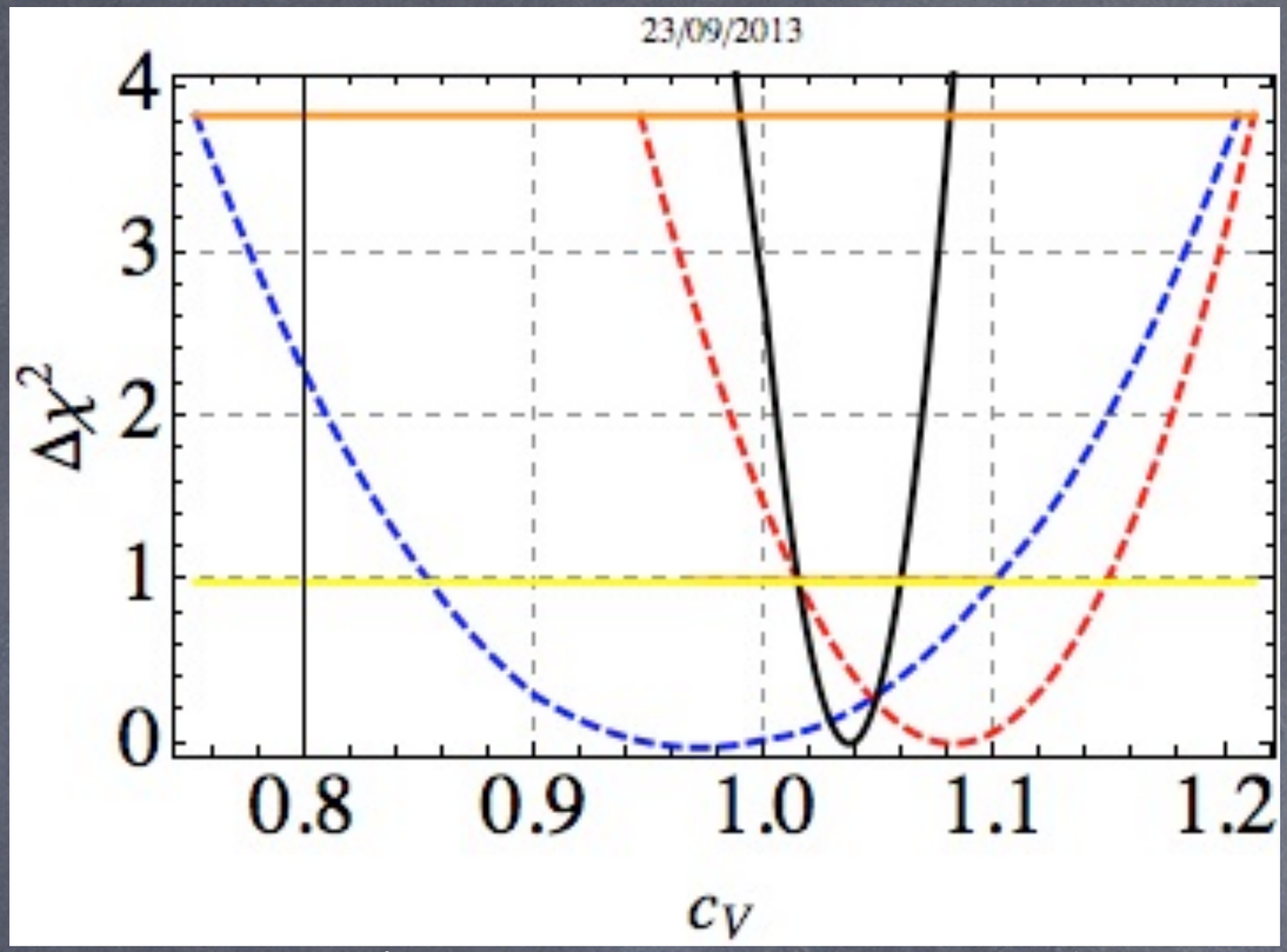
$$c_{Z\gamma} = \frac{e g_L}{\cos\theta_W 16\pi^2}\left(4^{+10}_{-19}\right)$$

using only Higgs data:

$$c_V = 1.03^{+0.08}_{-0.08}$$

$\Delta\chi^2 = \chi^2_{SM} - \chi^2_{min} \approx 5.5$,
with 7 d.o.f.
SM hypothesis is
a perfect fit

7 parameter fit



- Overwhelming evidence it is a Higgs boson (particle coupled to mass of W and Z)
- Statement independent of possible higher order couplings to W and Z
- Smells like the Higgs boson