Post-Higgsteria

Tom LeCompte

High Energy Physics Division
Argonne National Laboratory

(With thanks to the ATLAS and CMS Collaborations)

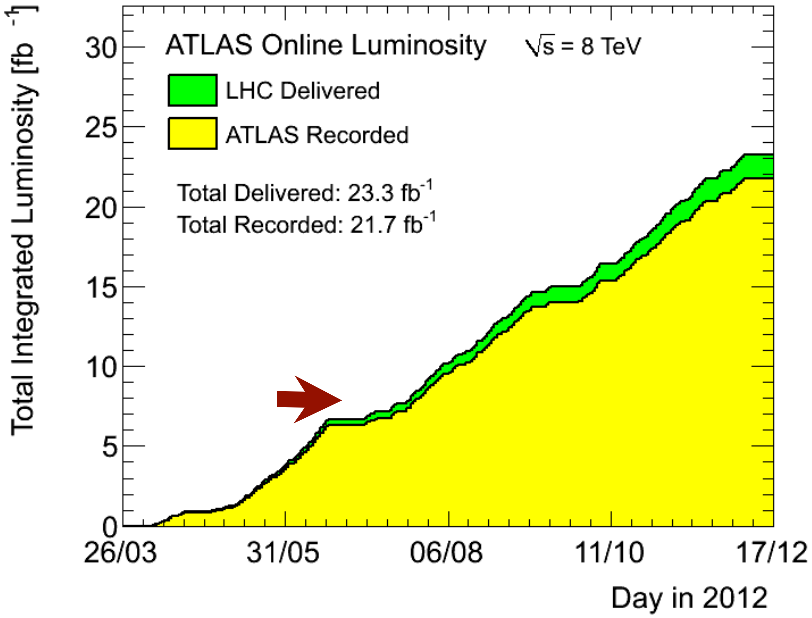
Yesterday's Summary

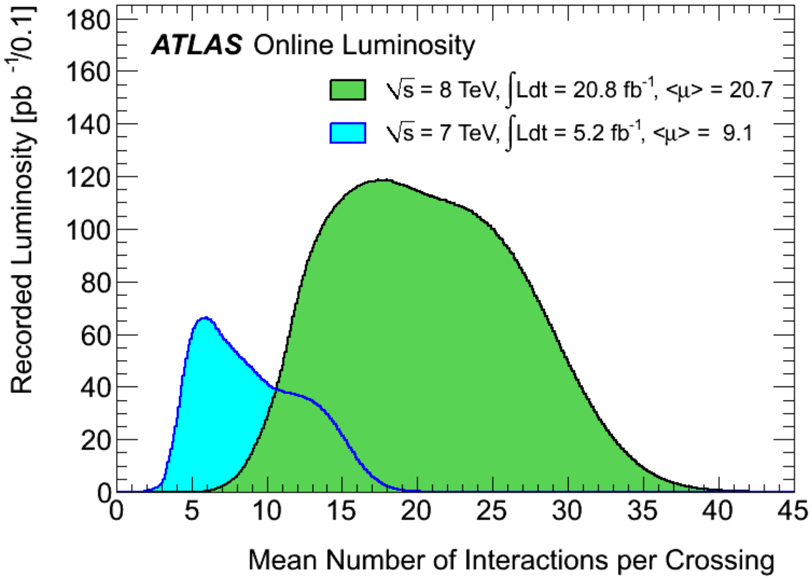
- A new boson is observed by both ATLAS and CMS, with independent ~5+ σ significance.
  - It's seen convincingly in 2 channels, and in both the 7 TeV and 8 TeV datasets.
  - Other channels provide weaker support, but do not contradict this.
- Its mass is somewhere between 125 and 126.5 GeV
  - An interesting number: too light to be heavy, and too heavy to be light
- This boson's properties match the SM Higgs Boson to within our ability to measure
  - In particular, it couples strongly to the electroweak boson sector (more later)

Today we are going to discuss the question: it's a boson. But is it the *Higgs* Boson?

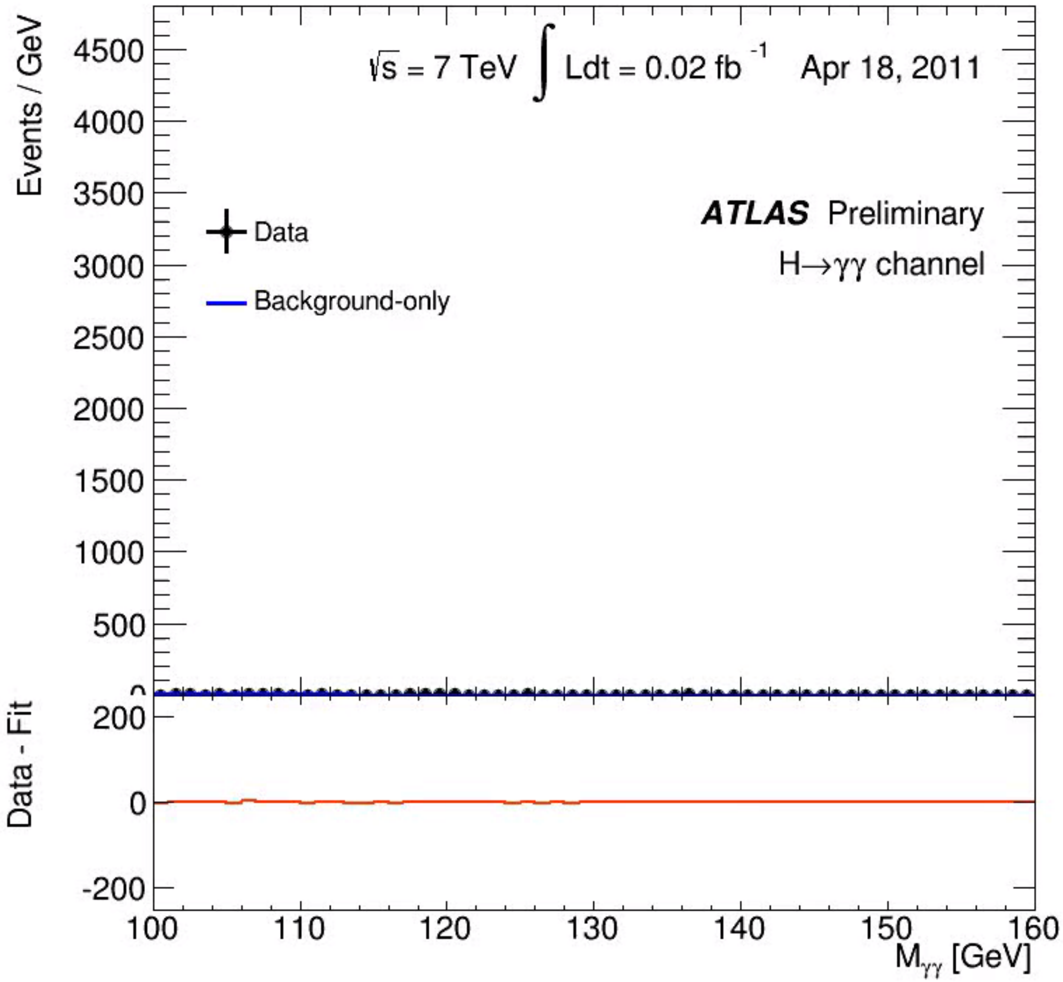
But first…the new data

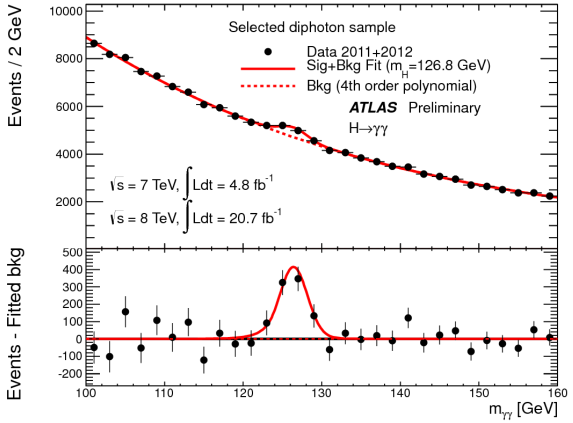
- Since the July 4th announcement
  - The 8 TeV dataset has almost quadrupled
  - The total dataset has roughly tripled
- The 8 TeV pileup is not substantially worse (19.1 vs. 20.7 events)
  - The biggest change is between 7 and 8 TeV, not early and late 8 TeV running
- Of course, there were some analysis tweaks and improvements too





Higgs to two photons

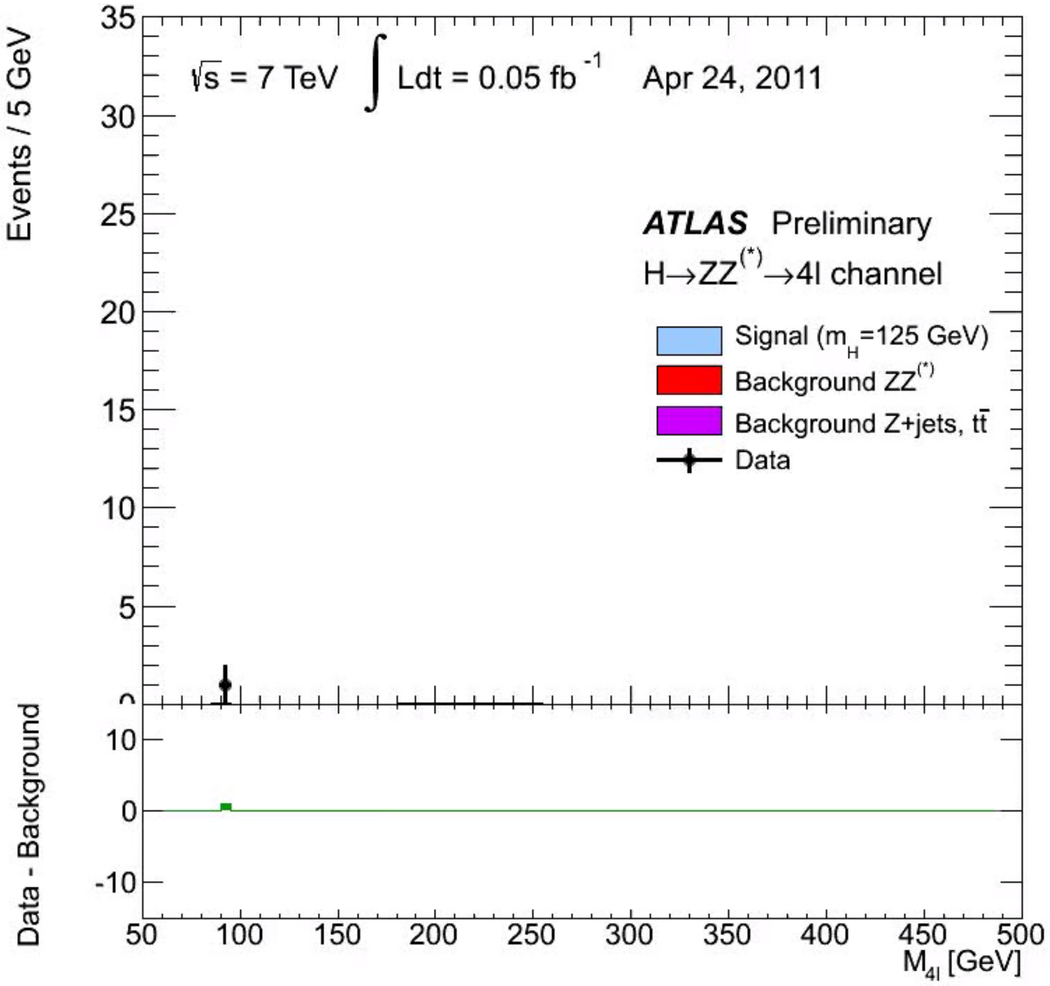


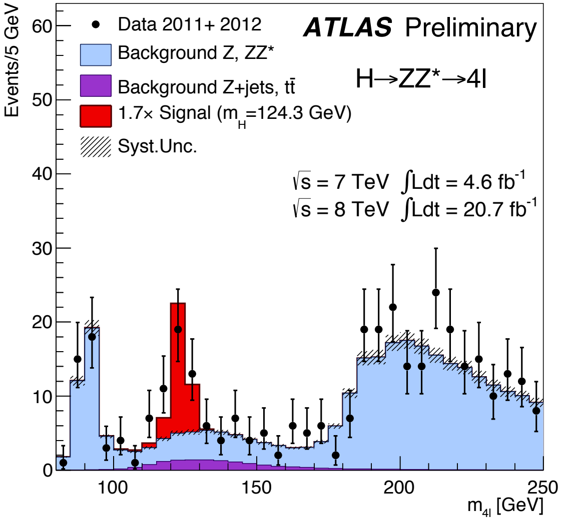


Was 4.5σ

Now 7.4σ

Higgs to ZZ*

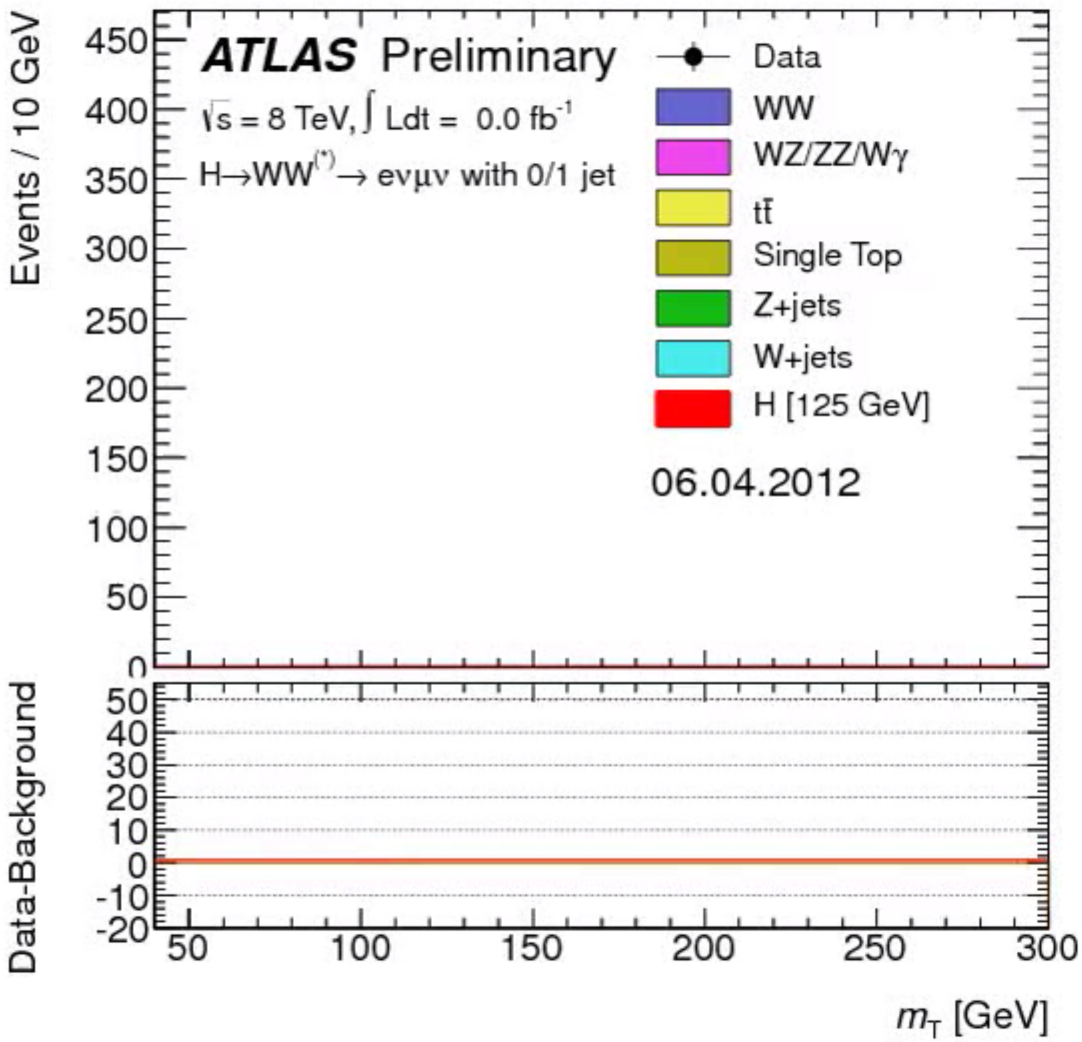


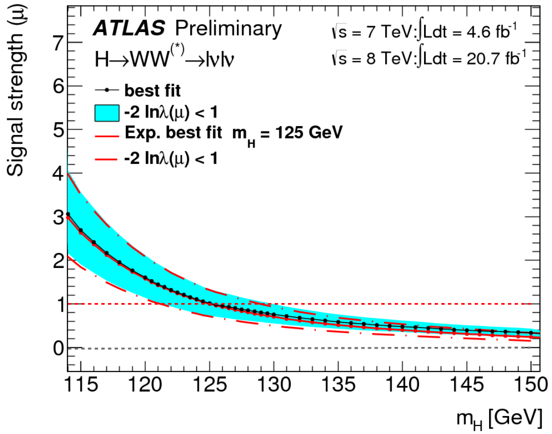


Was 3.4σ

Now 6.1σ

Higgs to WW*





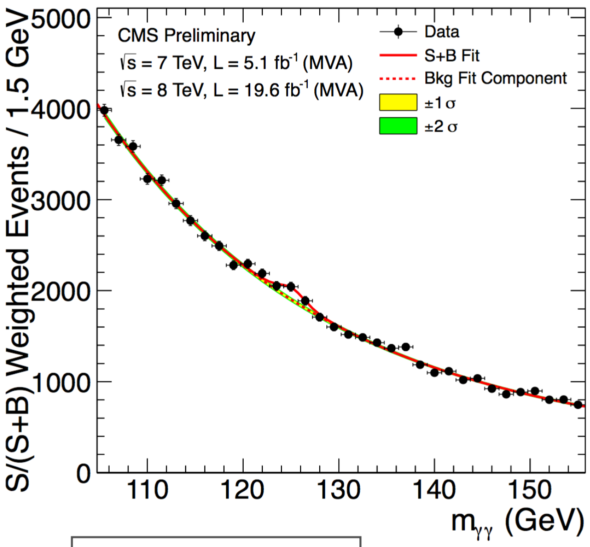
Was 2.8σ

Now 3.8σ

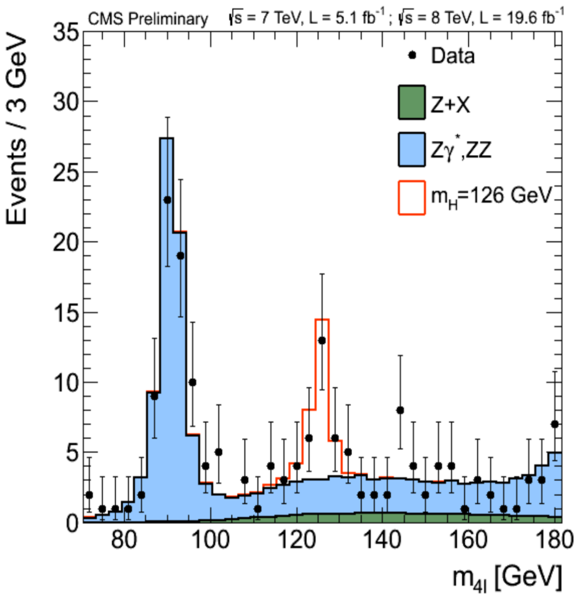
Putting it together

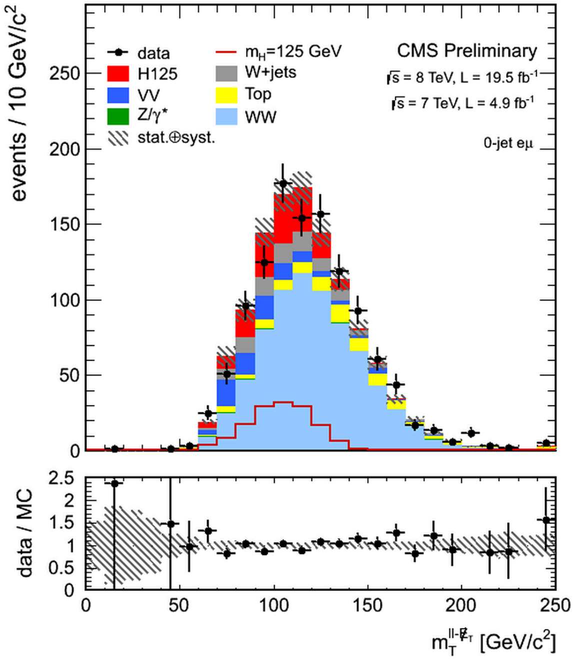
- ATLAS: 7.1σ + 6.4σ + 3.8σ – trials factor (80) = 9.6σ
- CMS: 3.2σ + 6.7σ + 3.9σ – trials factor (80) = 7.5σ
- Both (*one* trials factor): p = 10^{-39}, corresponding to 13σ

This really, really not a statistical fluctuation.



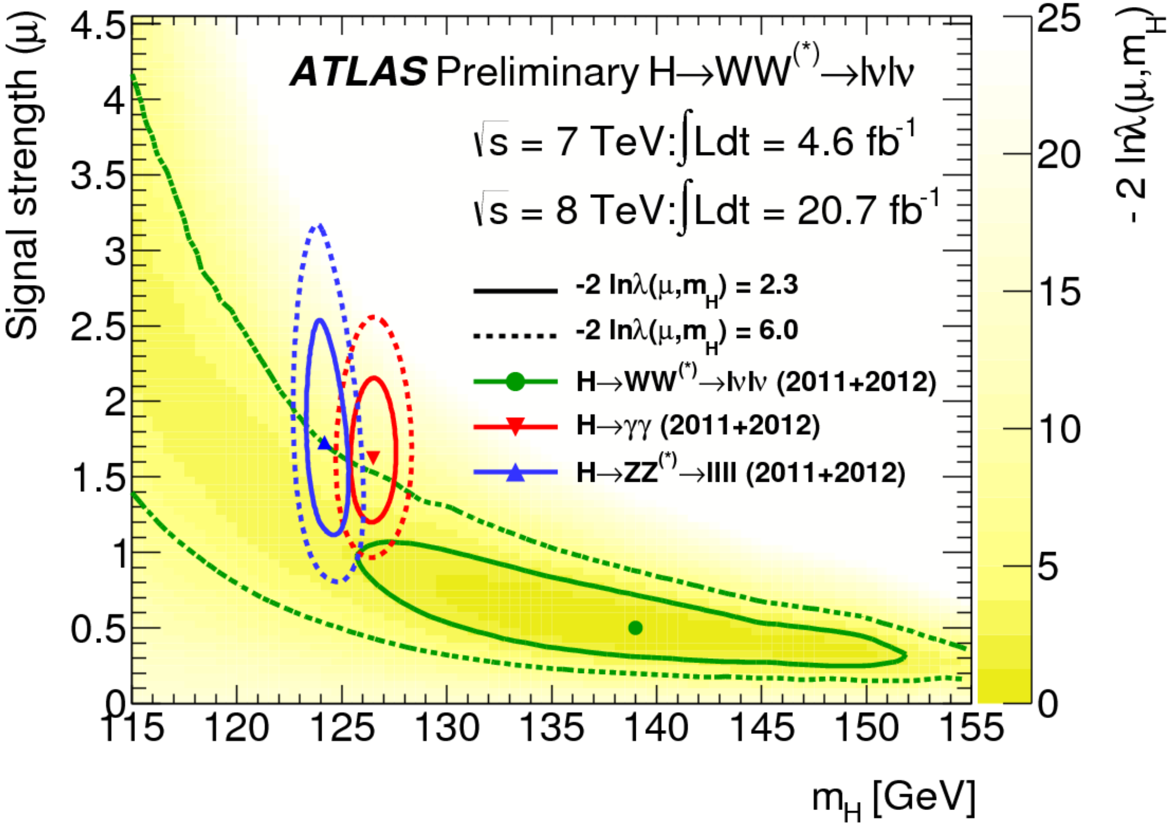
CMS Results





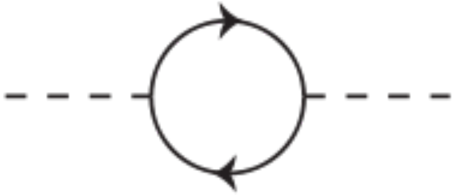
Consistency

- The WW* mass resolution is poor (30 GeV), because of the two missing neutrinos.
  - Mass and signal strength are correlated.
- Nevertheless, the agreement is pretty good between the three channels
  - Enough for us to conclude we are seeing one thing and not three things.



Called "The Banana Plot", for obvious reasons

The Higgs Mass Doesn't Make Any Sense



- The Higgs mass makes perfect sense – at tree level

- Radiative corrections are of order $\delta m^2(H) \sim \alpha_{weak} \Lambda^2/4\pi$
  - Where Λ^2 is the scale of new physics
  - There is potentially a lot of new physics up there – including gravity at the Planck scale
  - This will drive the Higgs mass up and up and up

- To keep the Higgs mass light, these new contributions must cancel

- e.g. $\delta m^2(H) = 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}933{,}023 - 36{,}127{,}890{,}984{,}789{,}307{,}394{,}520{,}932{,}878{,}928{,}917{,}398$

Thanks to
Michael Dine!

- This looks absurd, unless this is the result of some symmmetry
  - But that symmetry cannot be too exact, or the Higgs mass gets driven too low: perhaps even below the Z mass.

This is what I meant by "too light to be heavy, and too heavy to be light."

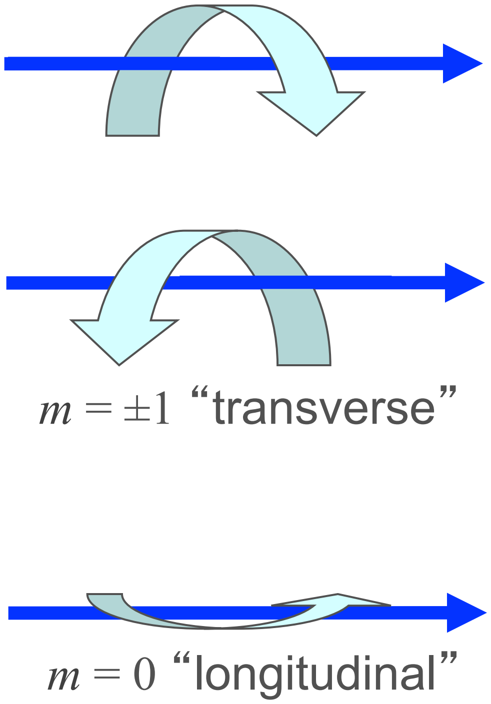
The Higgs Mechanism in Three Slides

- Write down a theory of massless weak bosons
  - The only thing wrong with this theory is that it doesn't describe the world in which we live
- Add a new doublet of spin-0 particles:
  - This adds *four* new degrees of freedom (the doublet + their antiparticles)

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

- Write down the interactions between the new doublet and itself, and the new doublet and the weak bosons in just the right way to
  - Spontaneously break the symmetry: i.e. the Higgs field develops a non-zero vacuum expectation value
    - Like the magnetization in a ferromagnet
  - Allow something really cute to happen

The Really Cute Thing



- The massless w^+ and ϕ^+ mix.
  - You get one particle with *three* spin states
    - Massive particles have three spin states
  - The W has acquired a mass

- The same thing happens for the w^- and ϕ^-

- In the neutral case, the same thing happens for one neutral combination, and it becomes the massive Z^0.

- The other neutral combination doesn’t couple to the Higgs, and it gives the massless photon.

- That leaves one degree of freedom left, and because of the non zero v.e.v. of the Higgs field, produces a massive Higgs.

How Cute Is It?

- There's very little choice involved in how you write down this theory.
  - There's one free parameter which determines the Higgs boson mass
  - There's one sign which determines if the symmetry breaks or not.
- The theory leaves the Standard Model mostly untouched
  - It adds a new Higgs boson – **which we can look for**
  - It adds a new piece to the WW → WW cross-section
    - This interferes destructively with the piece that was already there and restores unitarity

Is This The Higgs Boson?

- It must be a boson – it's undergoing a two-body decay to two spin-1 objects.
  - Making it a fermion requires a three-body decay.

- It must be spin-0 or spin-2.
  - Spin-1 is prohibited by spin-statistics
    - A spin-1 particle cannot decay to two identical massless spin-1 particles
    - Theorem by Yang and also Landau
  - Spin-2 is possible, but theoretically disfavored.

- This particle strongly (factor ~30x) prefers to decay to ZZ* and WW* than $\gamma\gamma$
  - Despite the fact that one Z or W must be way off-shell
  - This is naturally explained if this is a Higgs, because the longitudinal piece of the W or Z in a sense ***is*** the Higgs.

This particle may not be "the" Higgs. However, one cannot write a theory of EWSB that ignores this particle and have any hope of it being right.

A Goofy Model

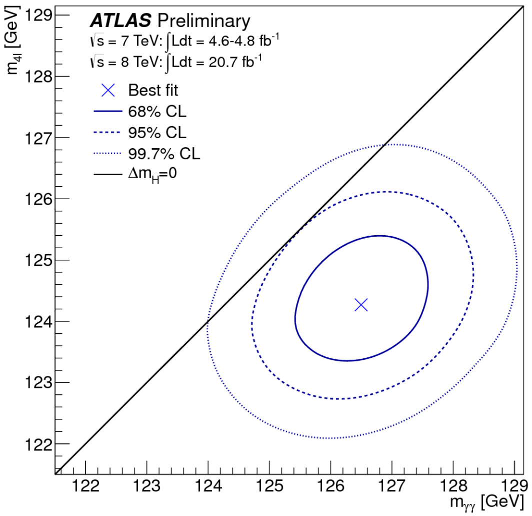
- Theory: This isn't the Higgs at all. It's a bound state of two new charged, colorless spin-½ fermions, weighing a ~TeV, and bound by a ~TeV.

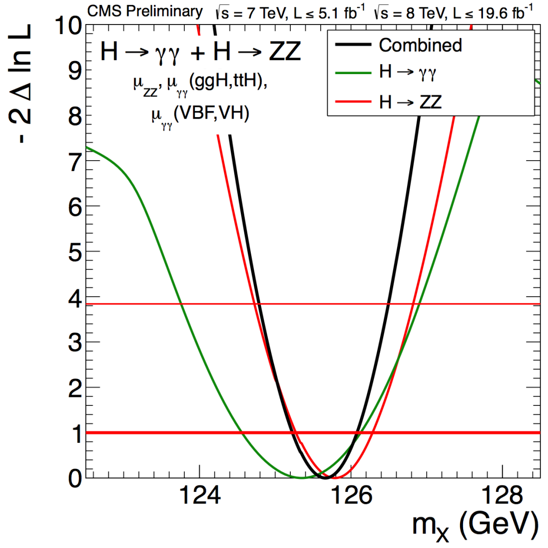
- Predictions:
  - There will be two states, a 0^- pseudoscalar (η^*) and a 1^- vector (ϕ^*).
  - There will not be any excited states
    - The potential looks a lot like a δ-function, which has only one bound state
  - These states will have almost the same mass (hyperfine splitting goes as 1/m)
  - The $\gamma\gamma$ decay is only from the η^*; the others can be from either state.
    - This is a consequence of the Landau-Yang theorem.

Testing the Goofy Model

- The Goofy Model predicts two states, one that decays to γγ and one that does not. How consistent are the masses in the γγ and ZZ* channels?
  - ATLAS (GeV):
    - Diphoton: 125.5 ± 0.7 ± 0.6
    - ZZ*: 124.3 ± 0.6 ± 0.5
    - Δm = 2.3 ± 0.7 ± 0.6
  - CMS (also GeV):
    - Diphoton: 125.4 ± 0.5 ± 0.6
    - ZZ*: 125.8 ± 0.5 ± 0.2
    - Δm = 0.4 ± 0.7 ± 0.6

The ZZ* measurements are driven by a small number of events. Historically, they have shown substantial scatter with time.





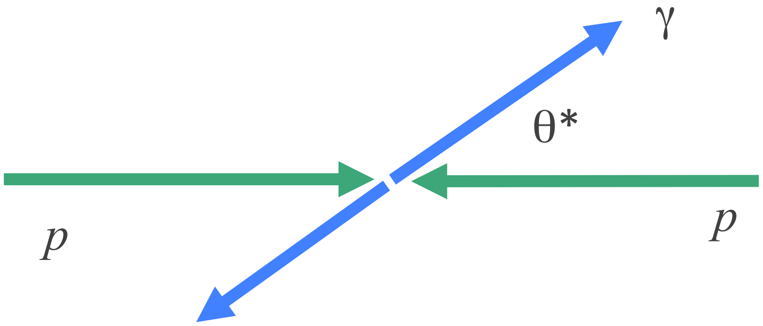
No significant evidence of two peaks. About one time in six, at least one of two experiments will see a result at least this different from Δm = 0.

Uncertainties have been symmetrized; selected for the Δm = 0 direction. The CMS Δm calculation is my own.

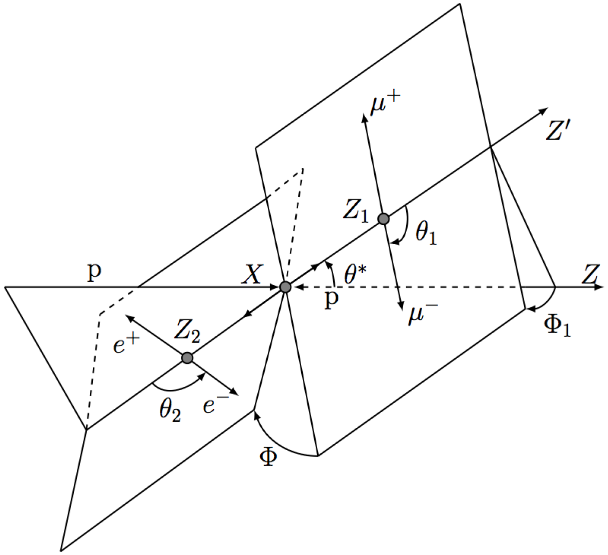
More Testing of the Goofy Model

- The Goofy Model makes a prediction of spin and parity: 0^- and 1^-
- The Standard Model also makes a prediction: 0^+

- In $\gamma\gamma$, there is exactly one unconstrained variable (θ^*)
- In ZZ*, there are a plethora of angles and masses (7 independent)
- Measuring these quantities allows us to infer the spin-parity



In the Collins-Soper frame

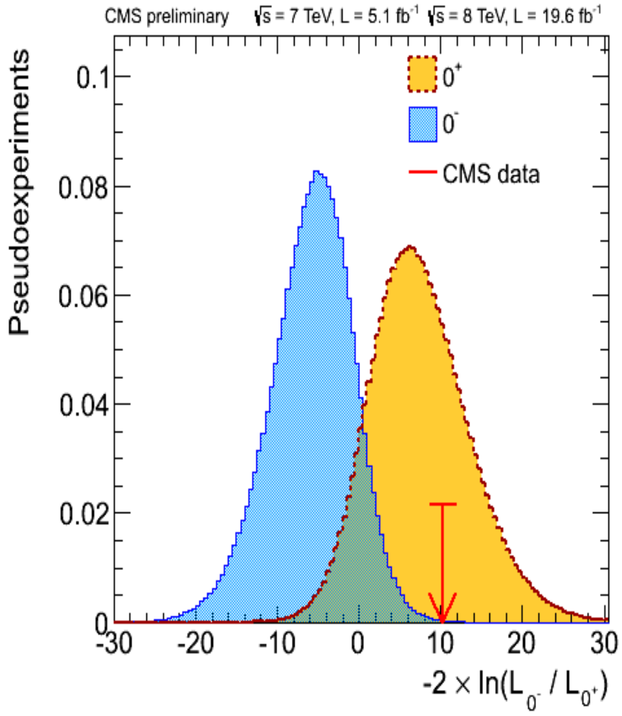


How This Works

- The experiments construct likelihoods for the various spin-parity hypotheses
  - Based on the 7 (or 1) observed variables
- They then look at these likelihood ratios for large numbers of Monte Carlo pseudoexperiments with a specified J^P hypothesis comapred to the SM 0^+ hypothesis…
- ..and then see where the data falls.

Here the CMS ZZ* observation (red arrow) is at a value where ~40% of the 0^+ pseudoexperiments are as large or larger, but only 0.16% of the 0^- pseudoexperiments are.

The data favor 0^+.



The Results:

J^P hypothesis	Channel	ATLAS	CMS
0^-	ZZ*	2.2%	0.16%
1^-	ZZ*	6%	<0.1%
	WW*	1.7%	
1^+	ZZ*	0.2%	<0.1%
	WW*	8%	
2^+_m	ZZ*	17%	1.5%
	WW*	5%	14%
	WW*	0.7%	

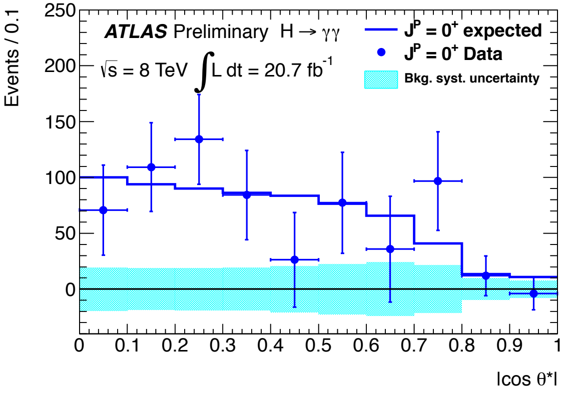
- The data clearly favor 0+
  - The SM Value…again
- The Goofy Model is in serious trouble

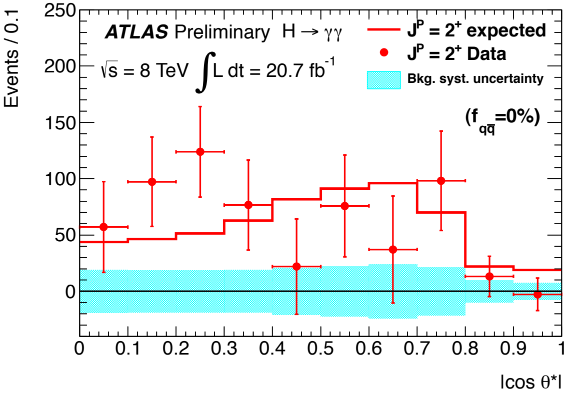
But why are the exclusions so different between the experiment?

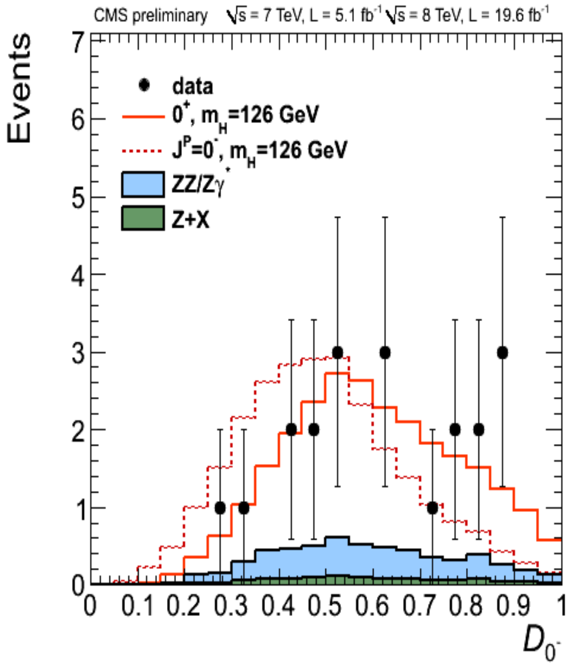
Behind the Curtain

- These are based on a few events – the position of a single event in a distribution can make a huge difference in the final answer.

- Likelihood ratios have the problem that they treat the case where p_0 = 50% and p_1 = 0.5% identically to the case where $p_0 = 10^{-9}$ and $p_1 = 10^{-11}$
  - The proponents call this a "feature"



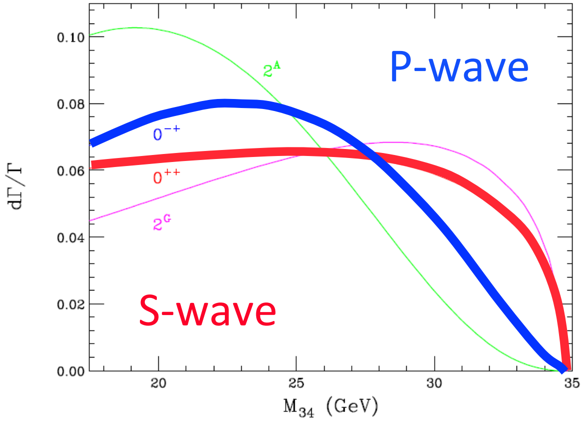




Opening the Black Box

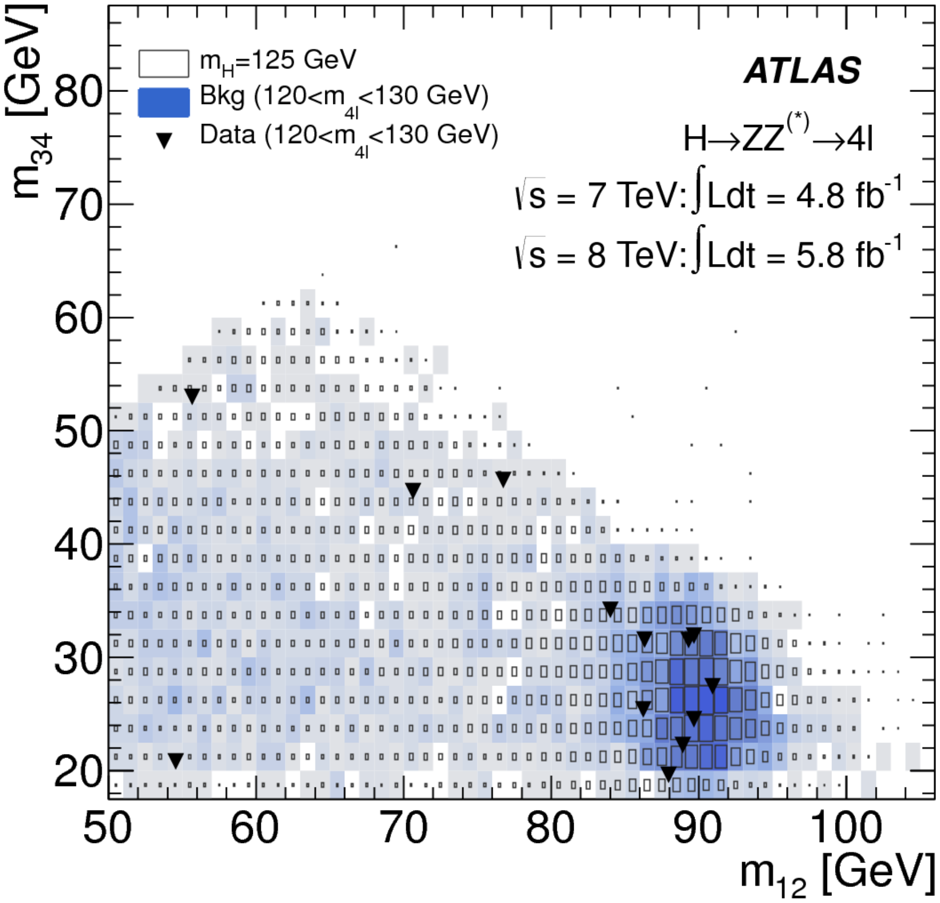
- This is not nearly as complicated as it looks.
- Think about conservation of energy in H → ZZ* decays:
  - $m(H) = m_{12} + m_{34}$ + kinetic energy
  - If $m_{12} = m(Z)$, m_{34} + kinetic energy = 35 GeV for a 126 GeV Higgs
    - Therefore, kinetic energy $= L^2/2I = 35 - m_{34}$
    - The m_{34} distribution serves as a proxy for the decay's orbital angular momentum

- As an example, consider 0^- - vs. 0^+
  - The 0^- is a P-wave decay and the 0^+ is S-wave.
    - The m_{34} distributions differ
  - These are both spin-0, so the Higgs decay angles are both isotropic – no separation
  - Unlike the W, the Z decays to leptons don't "remember" their spin very well (the decay is almost pure axial)
    - Again no (well, very little) separation
  - So the MVA is really mostly looking at a single variable



Historical Aside

- At the time of discovery, the data in hand were already enough to exclude most non-0^+ hypotheses.
- There is simply too many high mass Z*s in the data otherwise
- It's unusual to get this many high mass Z*s in the data even if the particle is 0^+
  - A statistical fluctuation that is somewhat unlikely in the 0^+ case, but very, very unlikely in the other cases.



We made no claim at the time – because our *expected* sensitivity was too low to make a distinction.

The Two Higgs Doublet Model

- This is a simple extension of the Higgs mechanism. Instead of one doublet, there are two.
  - This gives five scalar particles, usually called h^0, H^0, $H^\pm$, and A^0
    - Eight degrees of freedom minus three longitudinal components of the W&Z equals five
  - The A^0 is special – it does not couple to gauge bosons at tree level
    - This is not because it's a CP-odd *particle*, but because it's a CP-odd *Higgs*

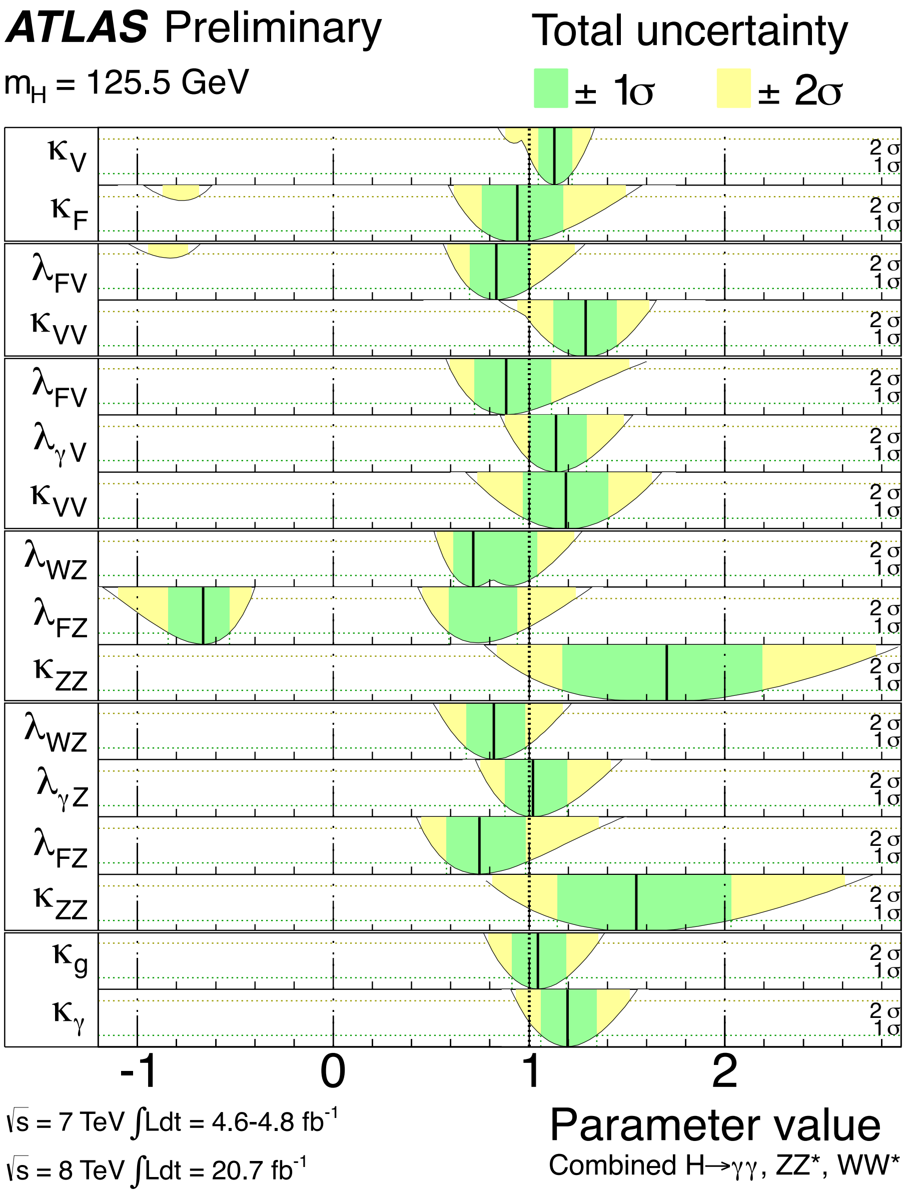
- There are special, limiting cases of this model
  - One Higgs couples to fermions, one to bosons ("Type I")
  - One Higgs couples to u-type quarks and one to d-type ("Type II")
    - Supersymmetry requires a 2HDM of this type
  - One couples to the top quark, one to the other quarks
  - The list goes on and on…

- This model is not particularly goofy

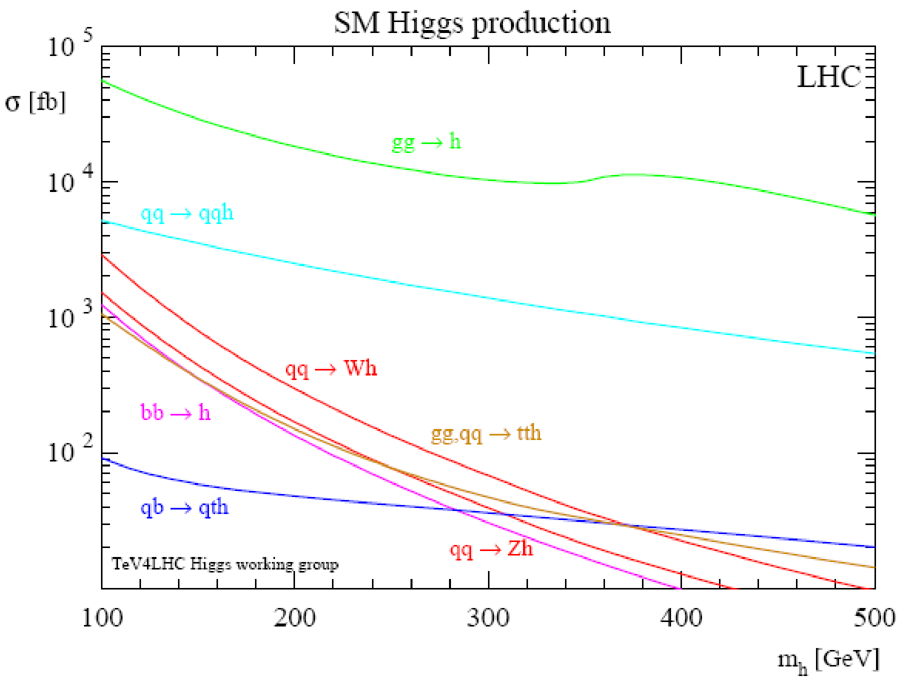
This serves as a prototype for models with a complex Higgs sector.

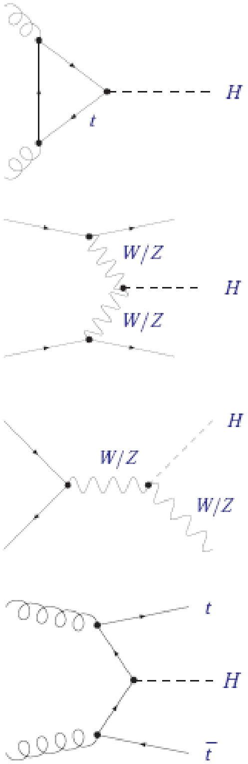
Testing the 2HDM

- Method 1 – discover SUSY
  - The less said about that, the better
- Method 2 – discover one of the additional Higgs bosons
  - Good plan – but no success yet
- <u>Method 3</u> – probe the couplings of the 125 GeV Higgs and look for discrepancies
  - Ongoing – see plot
  - However, this plot is **very misleading**. It looks like we are measuring 16 separate things, when we aren't.



What Information Do We Have?





gg-fusion

weak boson fusion

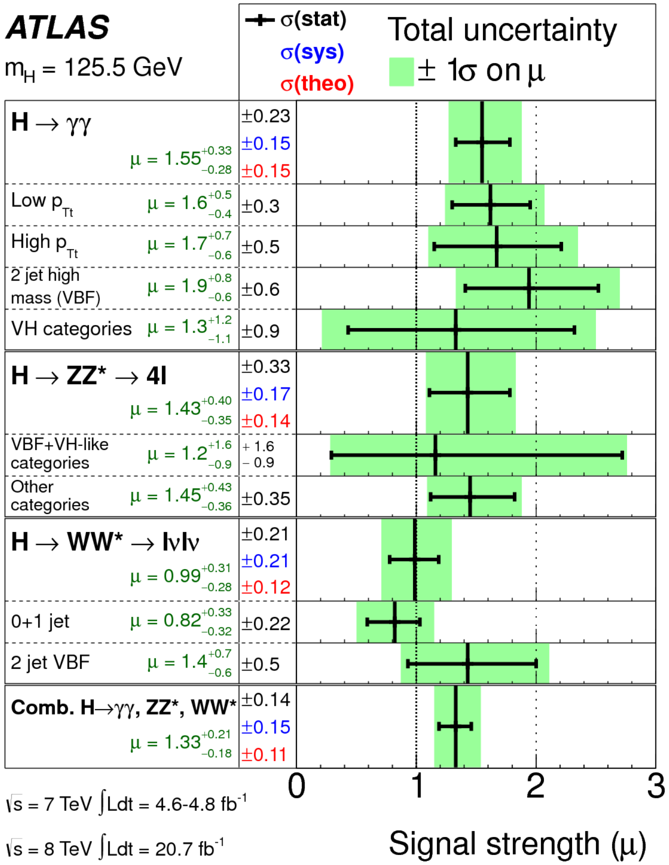
Higgs strahlung

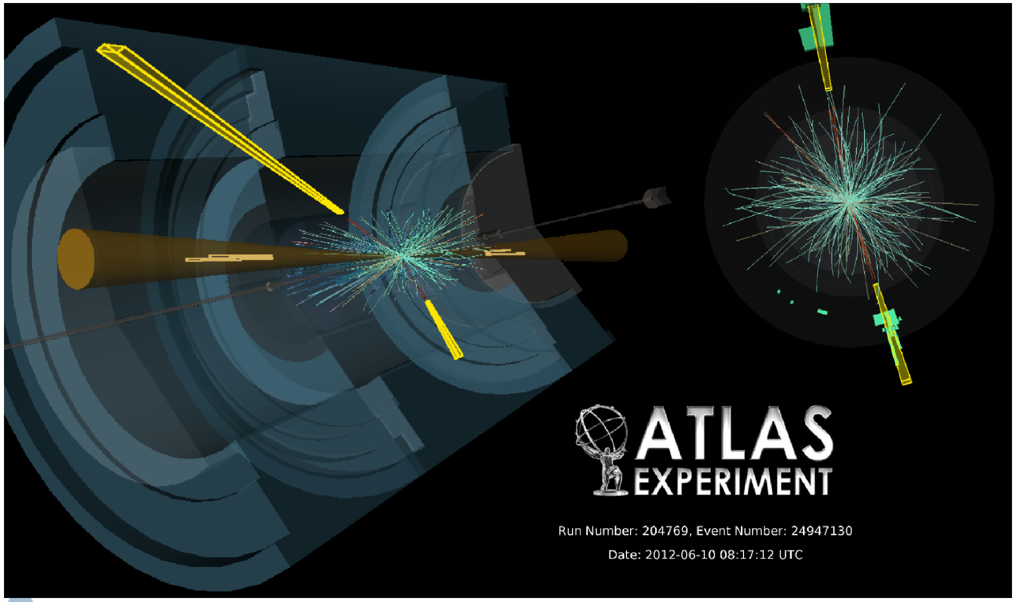
$t\bar{t}H$-channel

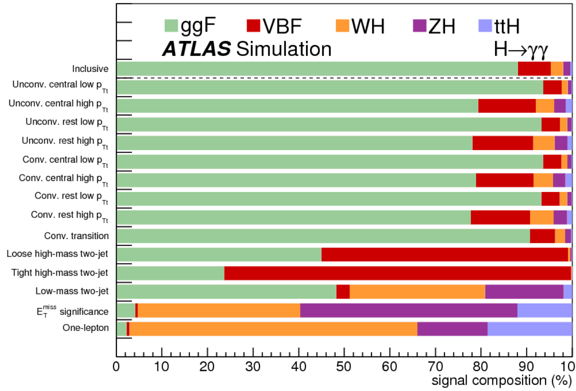
- Two facts to glean from yesterday's slide
  - The four production mechanisms give production information
  - Since gg dominates, the other channels have low yields and high uncertainties

Categorizing Production

- The basic idea:
  - If the event has a lepton, it’s VH
  - If the event has two forward jets, it’s VBF
  - Otherwise, it’s gg
- This can only be done statistically
- MVAs can make incremental improvements

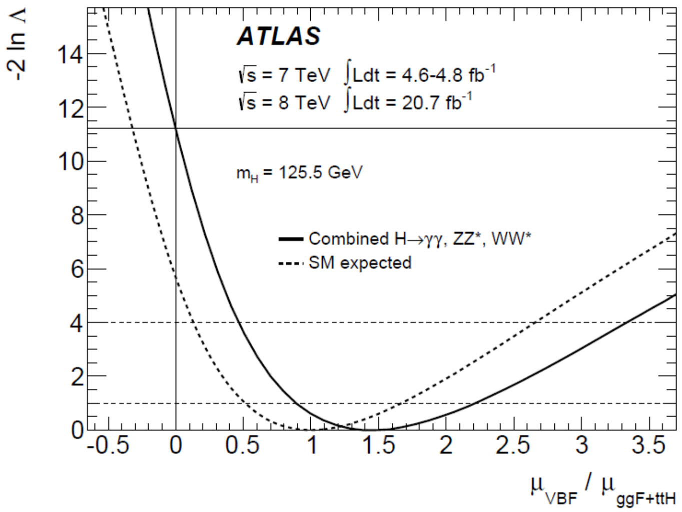


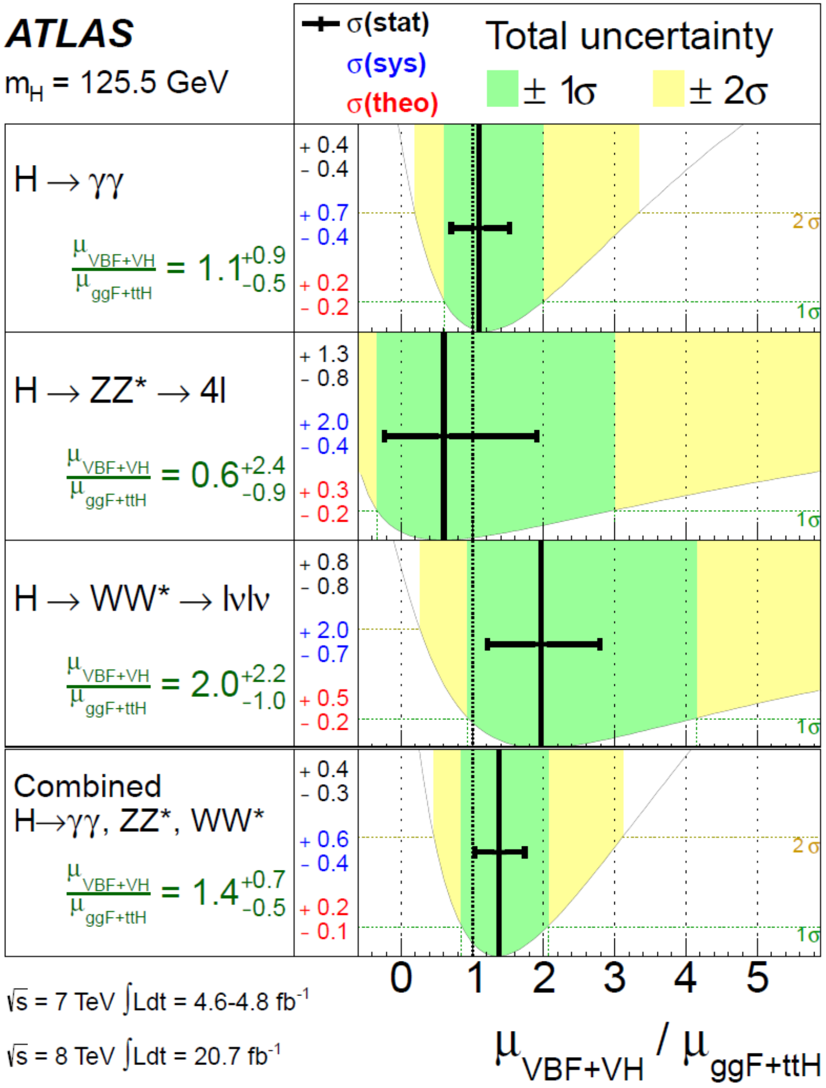




Do We See VBF Production?

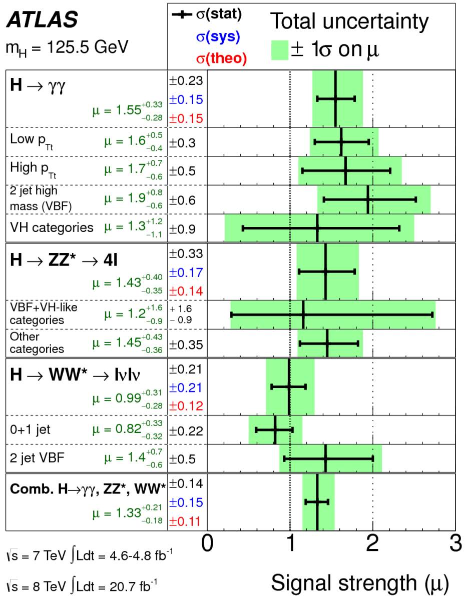
- Yes, at the 3.3σ level
- However, this requires the combination of all channels
  - No individual channel has a compelling signal by itself
- Also, this means *at best*, production rates via VBF can be determined to 30%.



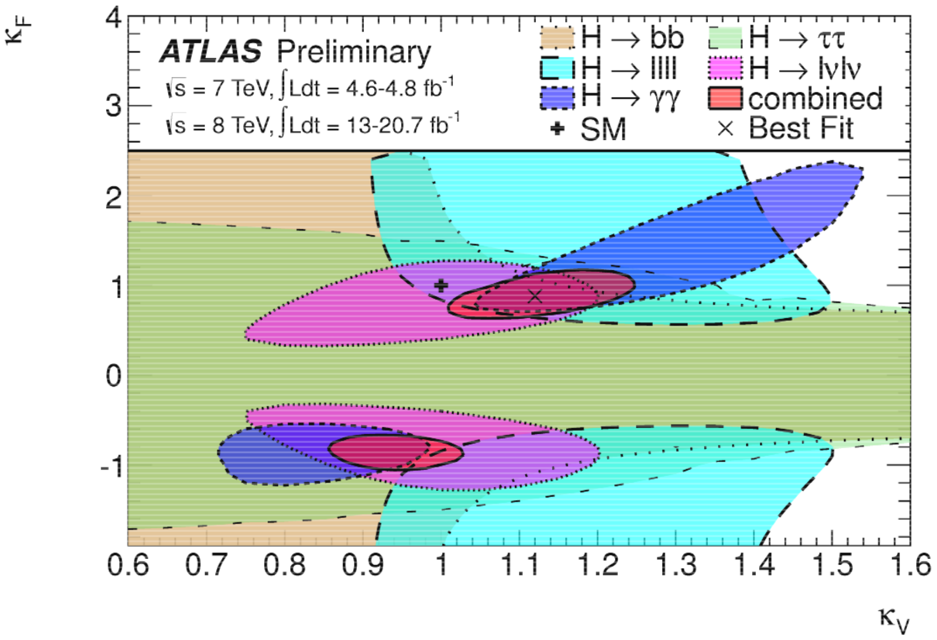


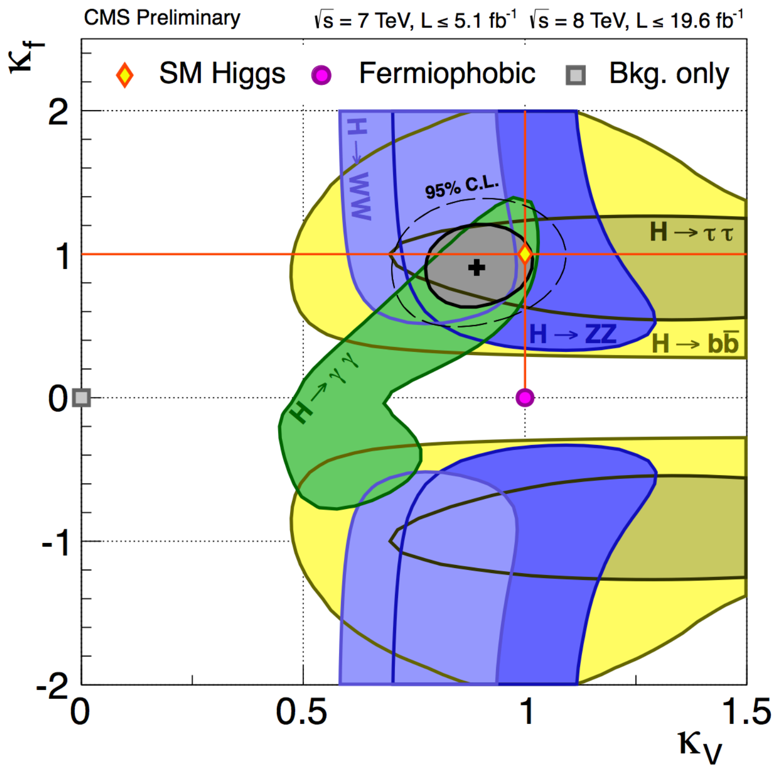
What Other Information Do We Have?

- We have yields – i.e. cross-sections times branching fractions – for the processes we observe:
  - $\gamma\gamma$, WW and ZZ.
- We have limits for the processes we haven't yet "discovered"
  - VH production and H → $\tau\tau$
  - These can be two-sided limits (if we can exclude $\sigma = 0$ at 95% CL but not 5σ)
  - Otherwise, these are upper bounds
- We combine these in…you guessed it…a giant fit.
  - However, we don't fit 16 values simultaneously
  - There's simply not enough information for that
    - There's even less information than it looks like.
      - Fermiophobic Higgs
  - We do limited fits, holding the other values to their SM values



Testing the Type I 2HDM





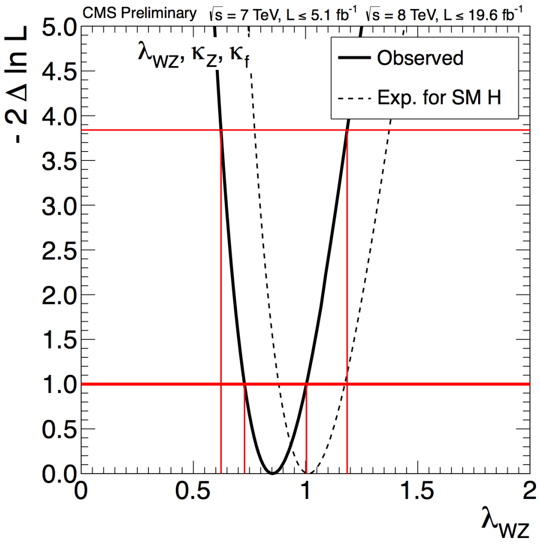
- Scale all fermionic couplings by κ_F and all bosonic couplings by κ_V
- Both experiments are consistent with the SM at the 10's of percent level

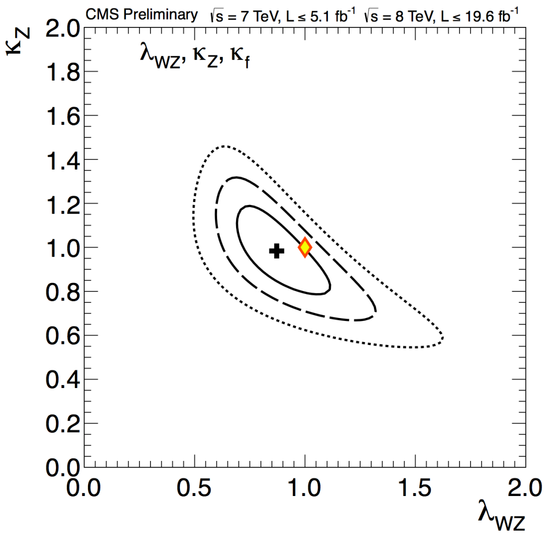
- The two allowed regions arises because of an uncertainty of the relative sign of two couplings
  - This happens when you have one large and one or more small

W and Z Relative Ratios

Scale the W and Z couplings by κ_W and κ_Z, and check that $\lambda_{WZ} = \kappa_W/\kappa_Z$ is consistent with 1.

(similar to last slide)



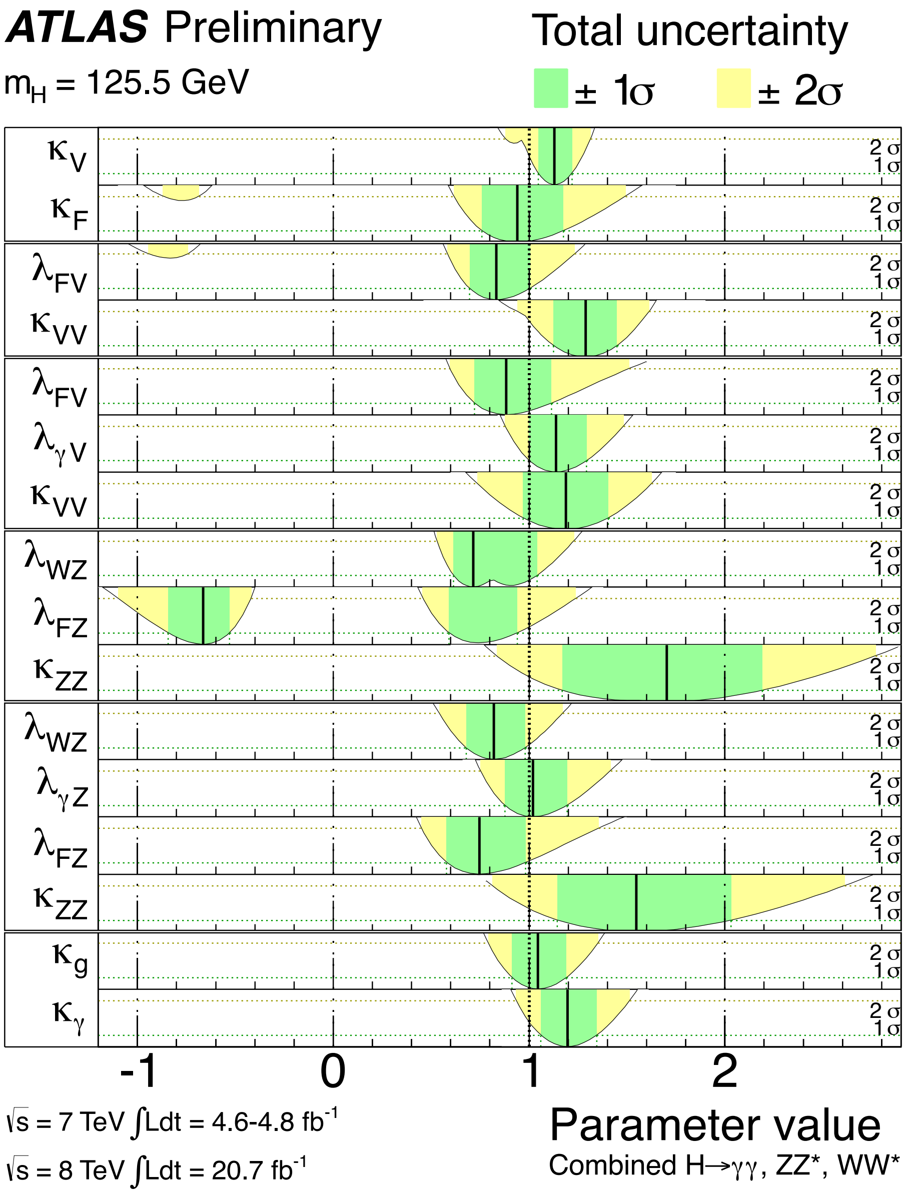


- This is called a test of "Custodial Symmetry"
  - This is essentially a Clebsch-Gordon coefficient. In the SM this is unity.
- While $\lambda_{WZ} = 1$ is compatible with the CMS data, so is $\lambda_{WZ} = 3/4$.
- ATLAS gets 0.82 ± 0.15

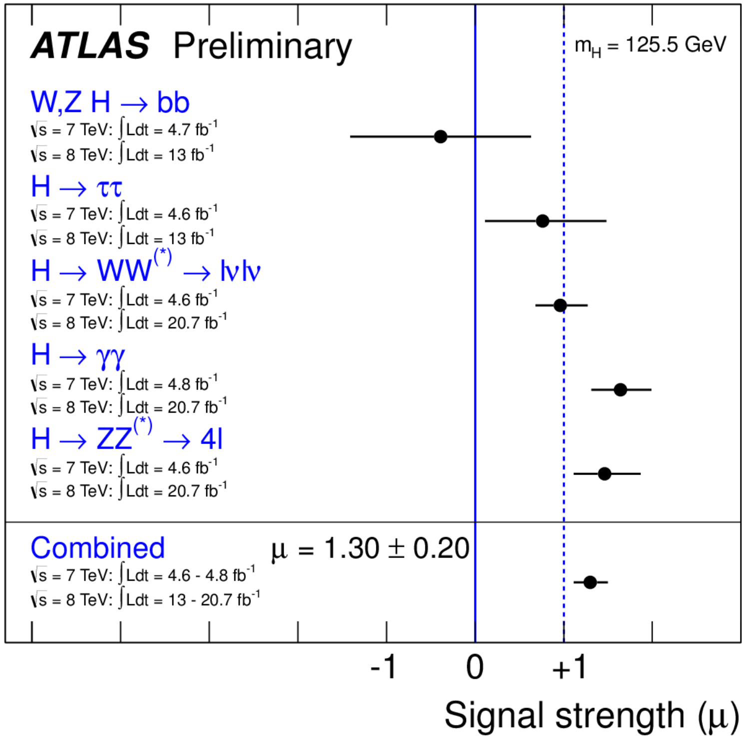
- For most successive results, we set $\lambda_{WZ} = 1$
  - This allows us to combine WW* and ZZ* data
  - You can decide for yourself if you think this is scientifically justified
    - For the record, I think it is – but this is part of the art of science.

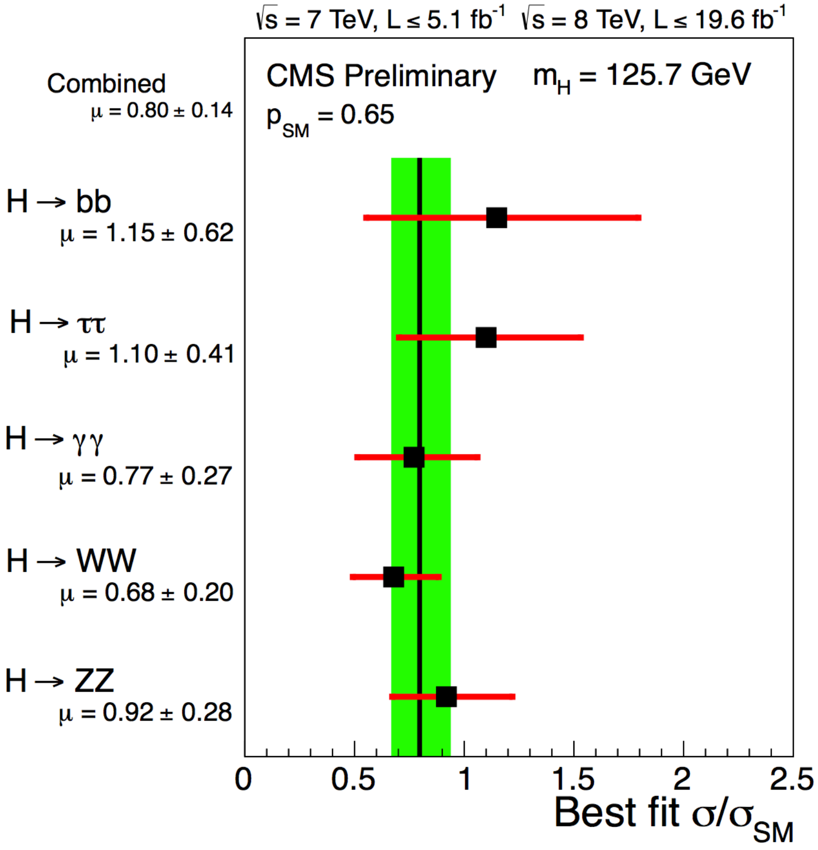
Understanding This Plot

- These are not sixteen measurements
- These are measurements of 2, 3 or 4 model parameters under varying assumptions
- All of these are consistent with the SM Higgs hypothesis at better than the 2σ level
- One cannot get a measure of the overall agreement by calculating a χ^2
  - The values are correlated



The Better Plots





- These are the principle inputs to the fits
- Since the inputs show no evidence for BSM physics, one should not be surprised that the fits do not either

A Few Words on 2HDMs

- Today, the only fermion we are reasonably sure couples to the Higgs is the top
  - We see it in gg fusion, and we infer that this is from a top quark loop
  - It sure would be nice to see others

- In a 2HDM, one Higgs looks more like the SM Higgs than the other
  - This is tautologically true
  - What is not, though, is that in most models that are compatible with observation, one looks *a lot* more like the SM Higgs than the other
  - That makes finding new physics by looking for coupling deviations difficult

- Searching for the other Higgs bosons is of very high priority

Conclusions

- The 125 GeV Higgs discovered a year ago is there in the new data
- We are sure it's a boson, and the evidence suggests that it's a scalar (0^+) boson.
- As far as we can tell, its couplings are consistent with the SM
  - The total cross-section is about right (ATLAS a little high, CMS a little low)
  - The fraction produced by VBF seems about right
  - The fermion/boson coupling strengths seem about right
    - This is a statement more about the top quark than the other fermions
  - The WW*/ZZ* ratio is a little off in both experiments, but we as a community have decided we can live with it
- The large coupling to WW* and ZZ* means this boson plays an important role in electroweak symmetry breaking
  - We do not know if this is a causative role
  - We do not know if this is a unique role
- It's mass makes no sense, and is a sign of new physics (somewhere…)
- The next logical step is the LHCs 13.X TeV run

$$\sigma \cdot \mathrm{BR}\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2}$$

$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}
\end{aligned}$$