SM Higgs searches – Moriond/Aspen 2013 highlights

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❑ ***Disclaimer***

➢ *Many SM Higgs search updates presented this round (some of them late last week.. !)*

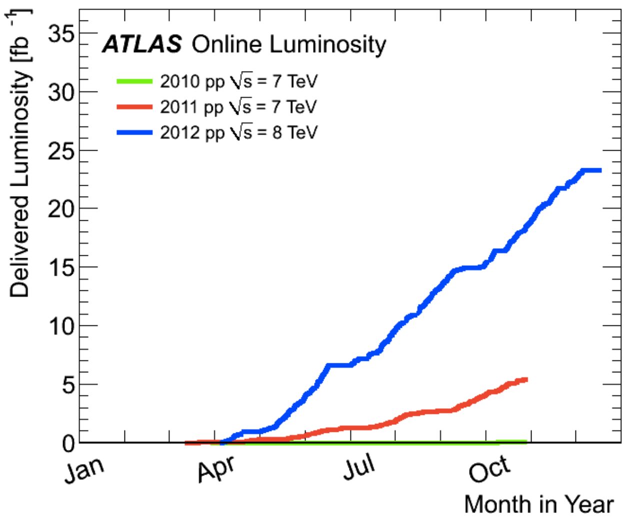
1. ATLAS-CONF-2013-009
2. ATLAS-CONF-2013-010
3. ATLAS-CONF-2013-012
4. ATLAS-CONF-2013-013
5. ATLAS-CONF-2013-014
6. ATLAS-CONF-2013-029
7. ATLAS-CONF-2013-030
8. ATLAS-CONF-2013-034

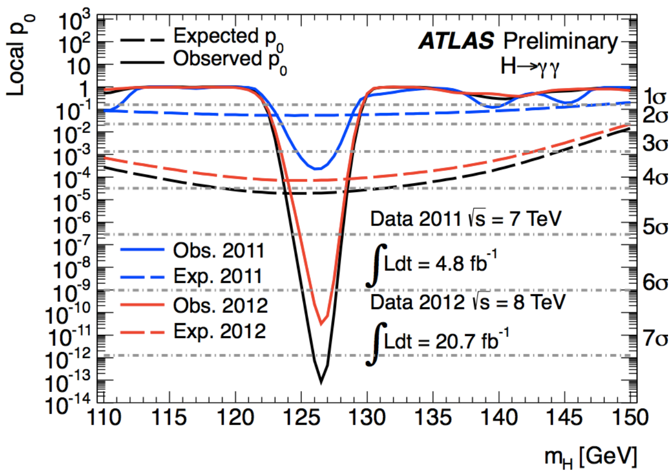
1. HIG-12-001-pas
2. HIG-12-002-pas
3. HIG-12-003-pas
4. HIG-12-004-pas
5. HIG-12-006-pas
6. HIG-12-009-pas

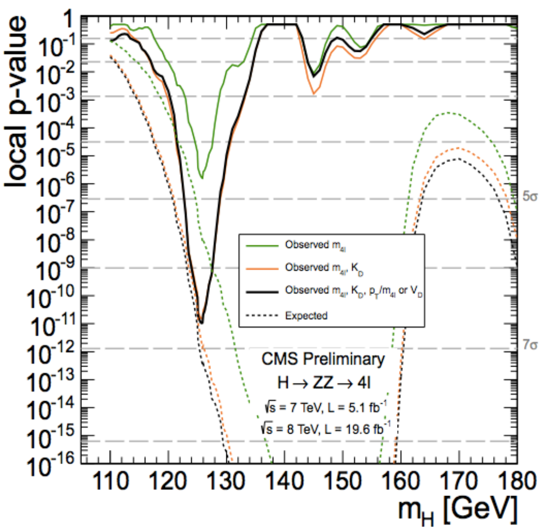
❑ Each of these being ~ 40 pages long (>500 condensed pages!), it's a bit too much to read over the weekend… so bear with me as I try to summarize as best as I can… ☺

❑ INTRO

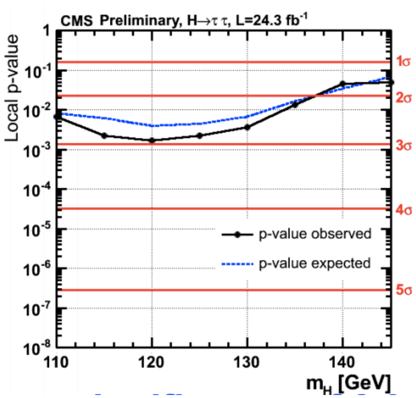
- ❑ ***The LHC has delivered an spectacular ~25 fb^{-1} of integrated luminosity with ~5 fb^{-1} of 7 TeV and ~20 fb^{-1} of 8 TeV data***
- ❑ ***Three main SM search analyses : H→4 leptons, H→2 photons and H→WW→lvlv have been updated to the full 2011+2012 dataset and presented in Moriond and/or in Aspen last week***
- ➢ ***The 2 high sensitivity channels can claim discovery on their own !***
- ➢ ***First measurements on properties (strength/couplings/spin) of resonance beginning to gain maturity !***



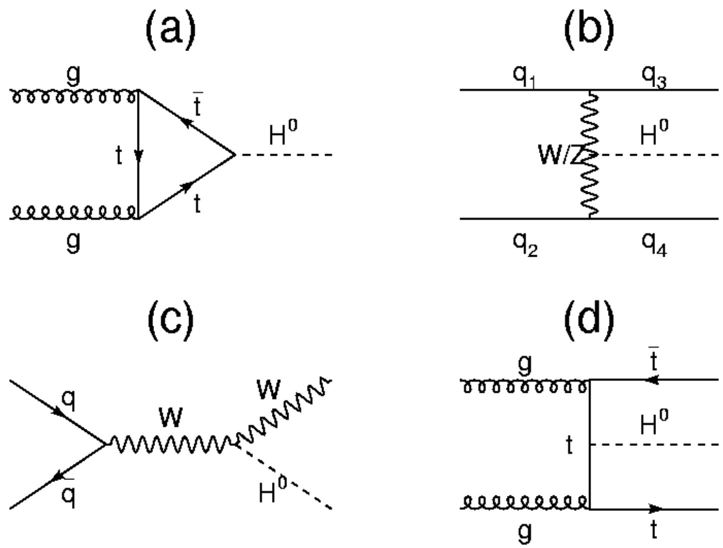




H→ττ

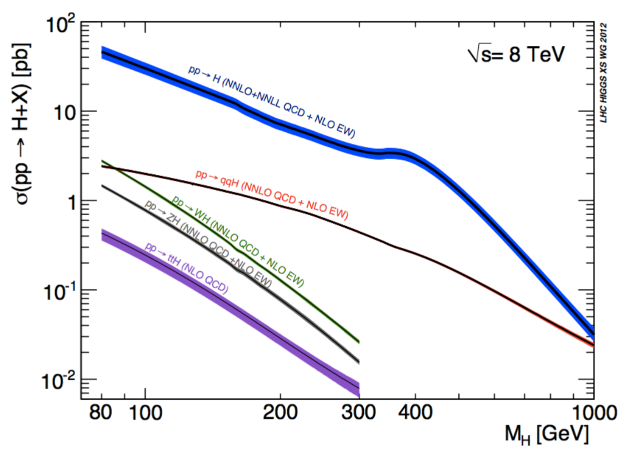


Standard Model Higgs production mechanisms at the LHC

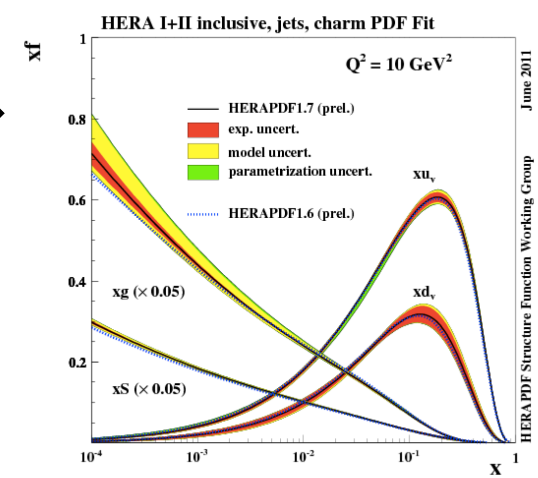


a) **Gluon-gluon fusion – dominant mechanism (high s → low x where pdfs dominate**
b) **VBF – one order of magnitude smaller cross section. Two jets in the final state**
c) **Associated Higgs production – leptons and possibly MET**
d) **ttbar + higgs (3 orders of magnitude smaller cross section)**

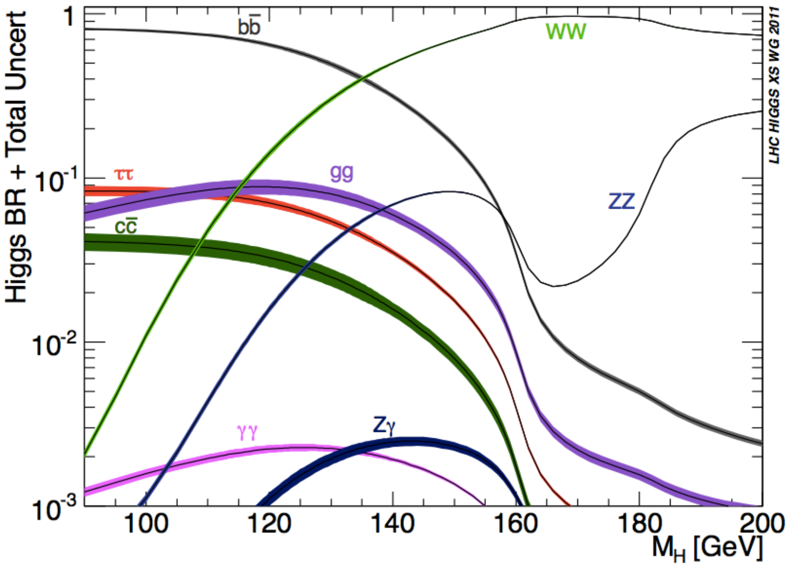
Expected cross sections (8 TeV)



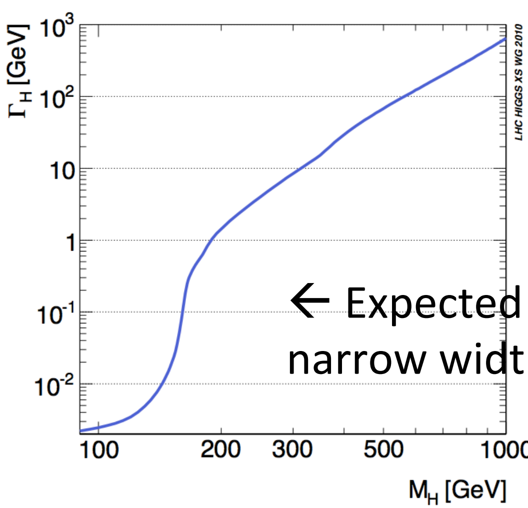
- ❑ At low x gluon PDF dominates →
- ❑ Relatively large uncertainty
- ← Cross section estimates with uncertainty



Standard Model Higgs Decay Channels

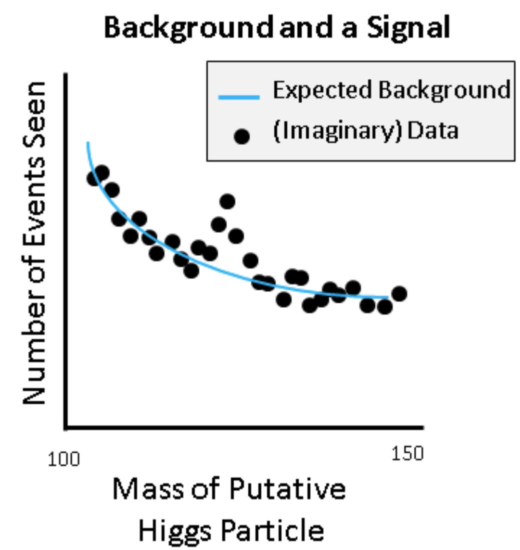


- At m_H > 130 GeV WW decay mode becomes important (limited by large backgrounds and low mass resolution)
- At mass 100 < m_H < 600 GeV ZZ can provide very clean signal (golden channel)
- At mass 100 < m_H < 160 GeV di-photon has 0.2% branching ratio fraction
  -- but "simple" final state and "easy" to spot

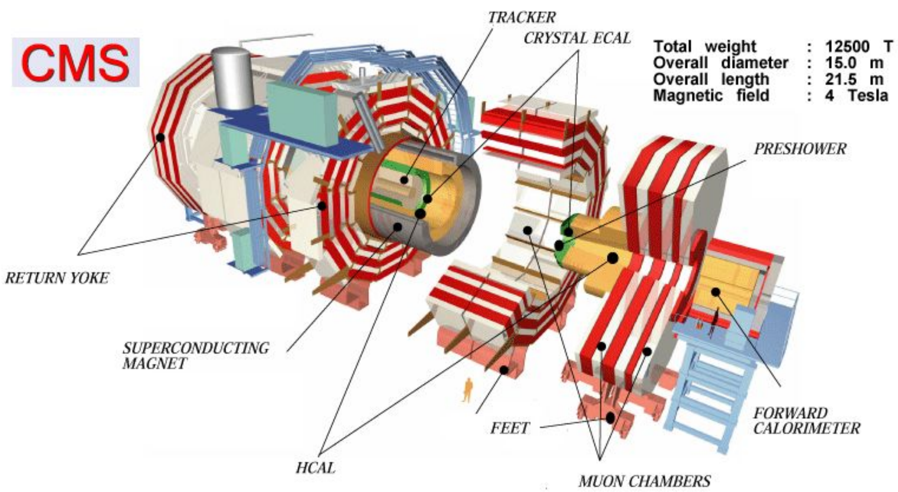


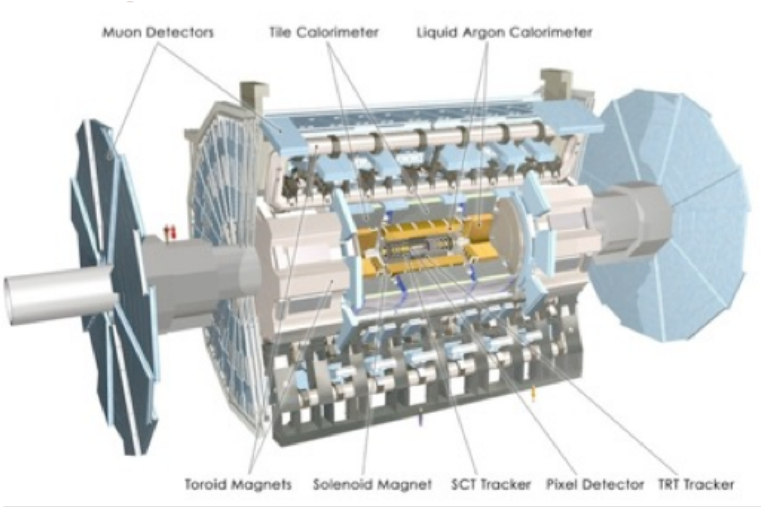
← Expected narrow width

- In channels where mass can be reconstructed, we expect to see peak whose width is dominated by detector resolution



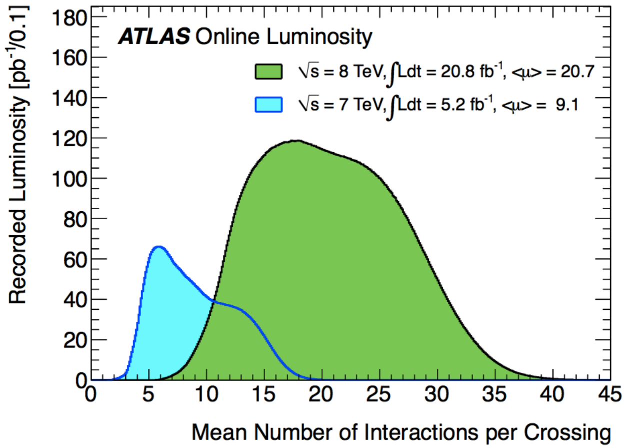
Discovery of resonance made possible by these machines :



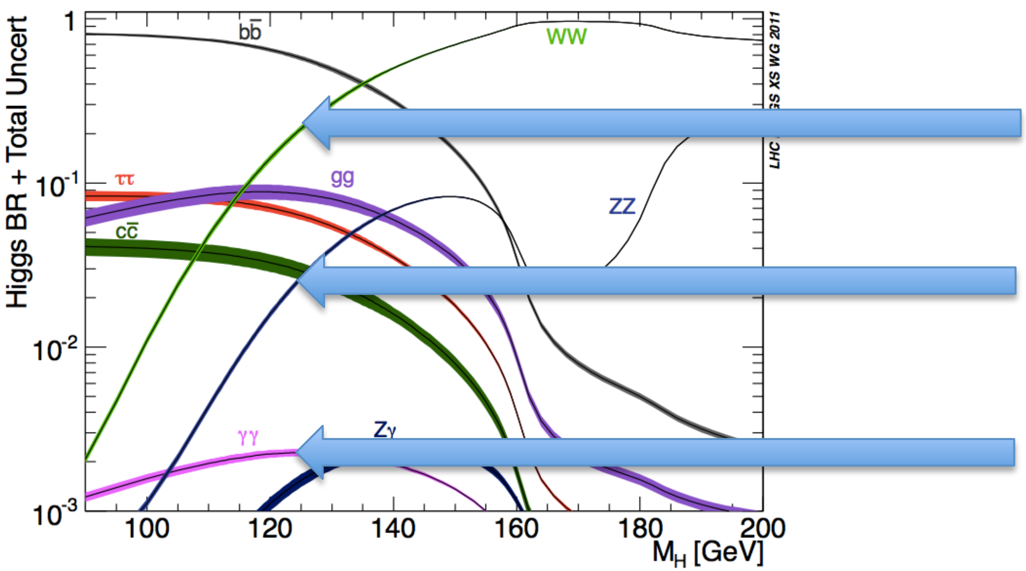


- **Similar detector set-up**
  - Inner detector used for tracking (pixel and strip detectors) < Strong magnetic field
  - Electromagnetic and Hadronic calorimeters calorimeter
  - Muon tracking chambers

- *For every hard interaction, we expect 20 additional, less energetic collisions per bunch crossing – huge challenge !*



- I will describe the analysis for the three higher resolution channels and give an overview of how and what we have been able to measure about the new particle



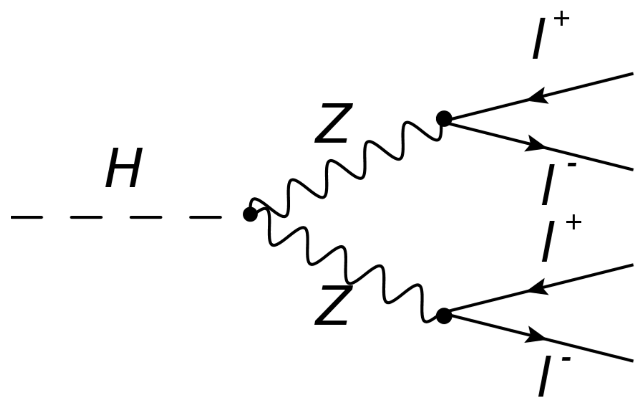
- **WW leptonic decay –** ***abundant but "dirty"***
- **ZZ leptonic decay –** ***very clean but very rare***
- **Diphoton decay –** **relatively** ***clean but relatively rare***

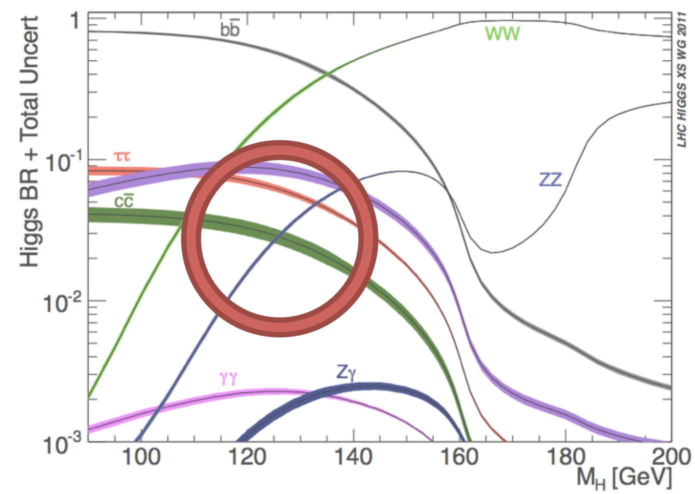
- **Other interesting updates (which I will only briefly mention)**

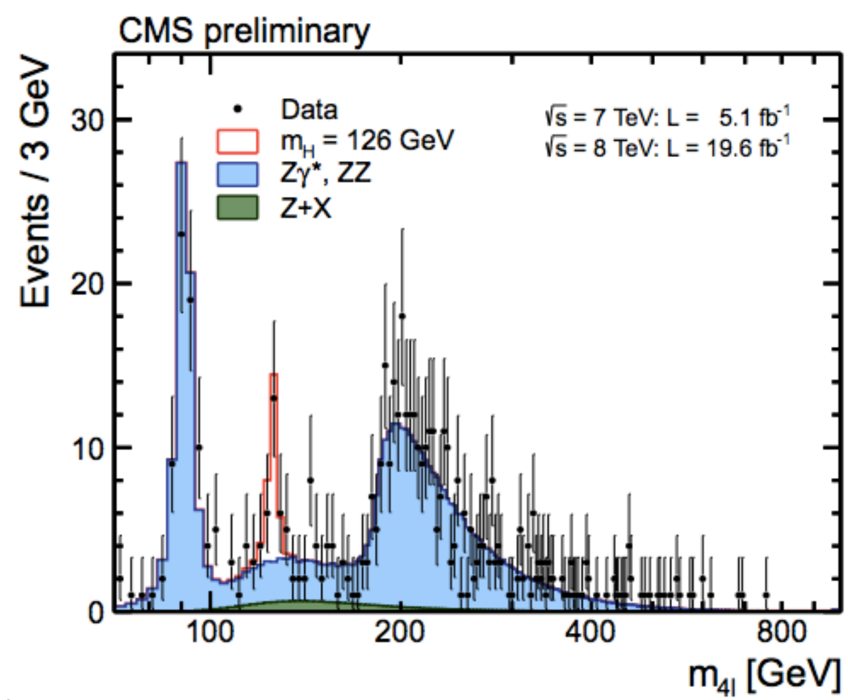
- H→ττ
- H→bb^{bar}
- H→Zgamma
- H→ZH (invisible decays)
- WH→WWW→3l3ν

These are very interesting as the (for example) probe the direct coupling of Higgs to fermions, but I will only show them in the context of combined fits to Higgs properties

Higgs to → 4 leptons (golden channel) - Intro



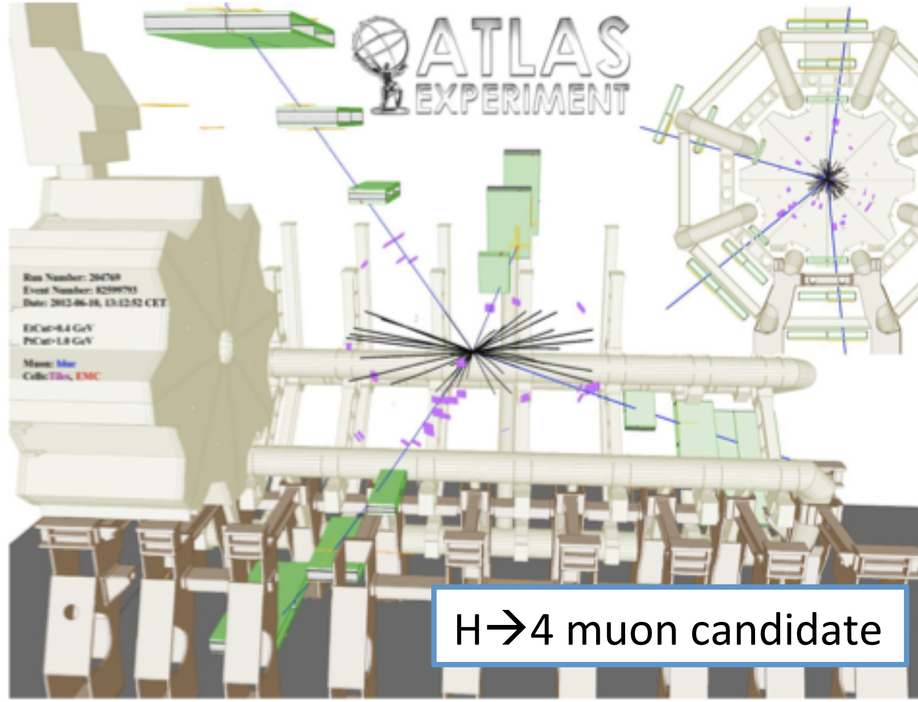




- ❑ **Advantages:**
  - →Good invariant mass resolution
  - →Easy-to-spot excess
  - →Three different decay modes ***(2e + 2μ), (4e) and 4μ)***
- ❑ ***Disadvantages*** *: low stats (~0.1 H→ branching to 4 leptons)*
- ❑ ***Main backgrounds are:***
  -- SM Z to 4 leptons, (Z^*/γ^*) (Z^*/γ^*), Z+jets
- ❑ ***MC-background description validated from data bkg enhanced regions whenever possible***

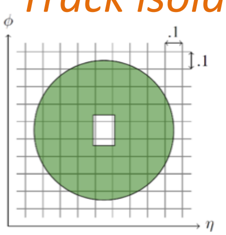
Higgs to → 4 leptons (golden channel) – Object definition (CMS & ATLAS)

- ***Electron--> track-EMC match***
  → GSF to compensate for brem
- ***Muon → ID-muon chamber track match***
  → nearby photons added (~4%)



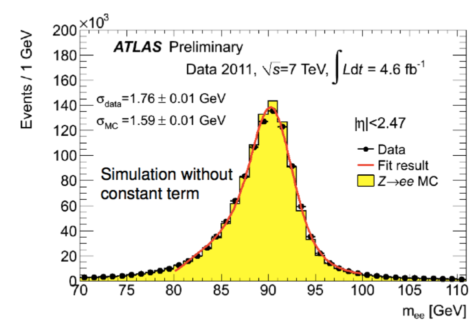
- ***Background/pile-up impact is reduced by :***

- **Impact parameter cuts on tracks**
- *EMC isolation (on muon and el)*
- *Track isolation (on muon and el)*



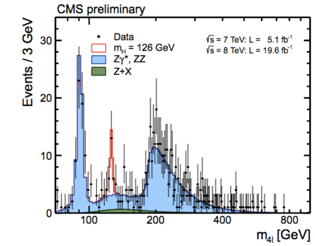
→ Isolation corrected for pileup and leakage

→ Final energy calibration from Z electrons

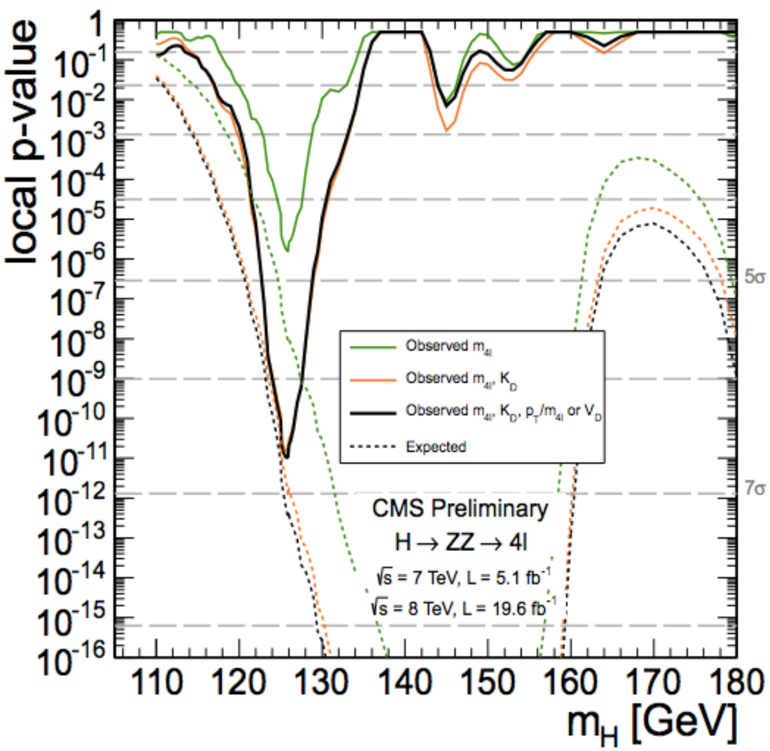


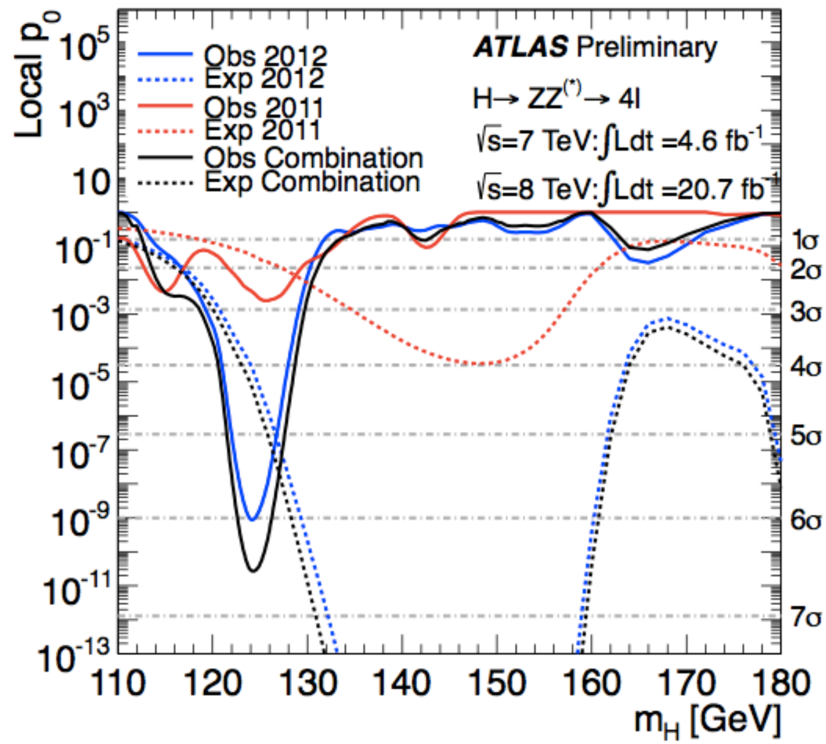
- *Shower shapes/energy deposits in EMC must be consistent with electron/muon expected*
- *Variables fed to multivariate approach by CMS*

Higgs to → 4 leptons (golden channel) – results (discovery)



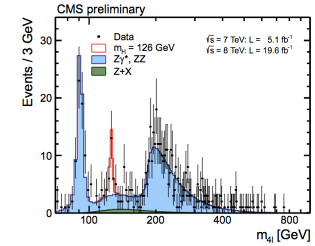
- Higgs→4 lepton channel can establish discovery by itself (p0 value > 5 sigma)



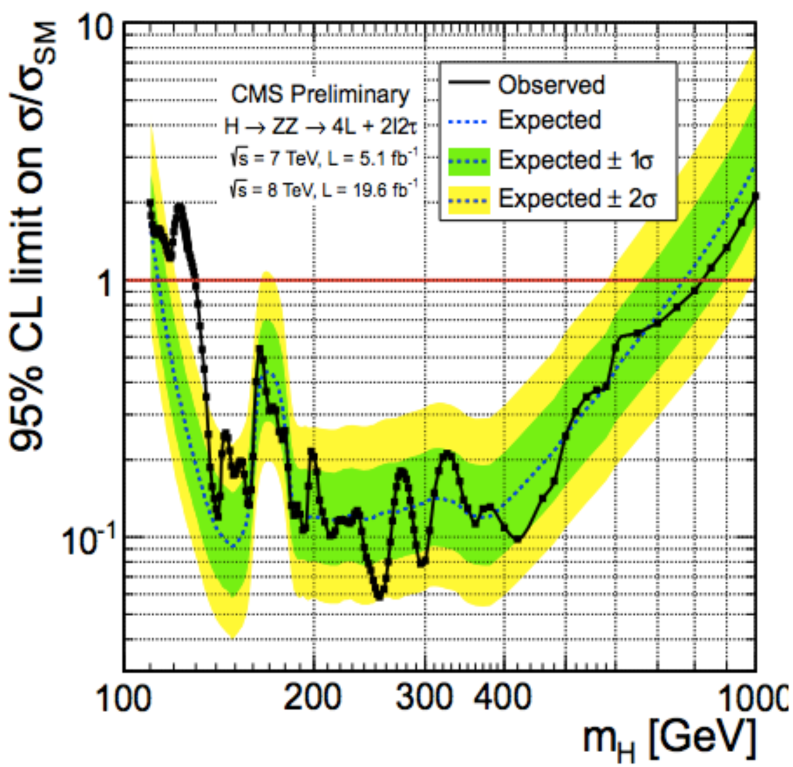


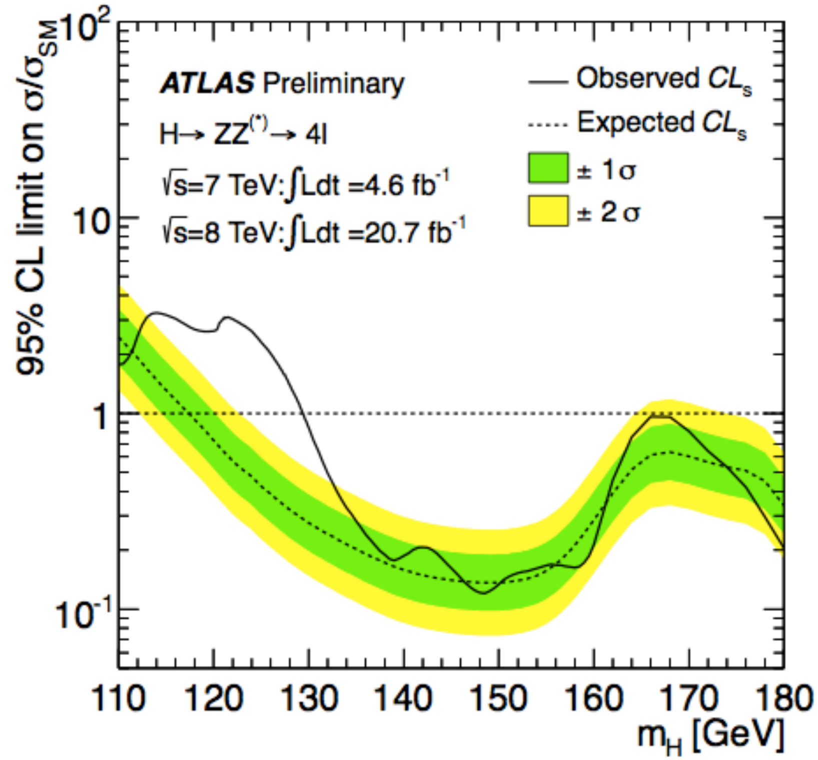
- p0-value plot represents **the probability of the background-only assumption (SM without Higgs) to fluctuate upwards and fake the signal we observe**

Higgs to → 4 leptons (golden channel) – results (exclusion)



- **Additional SM-like higgs excluded in 130-827 GeV mass region (CMS)**

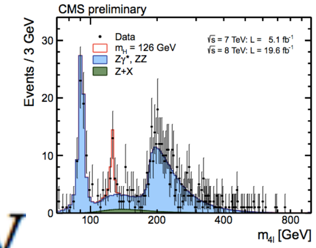




- ***Couplings and spin measurements on upcoming slides…***

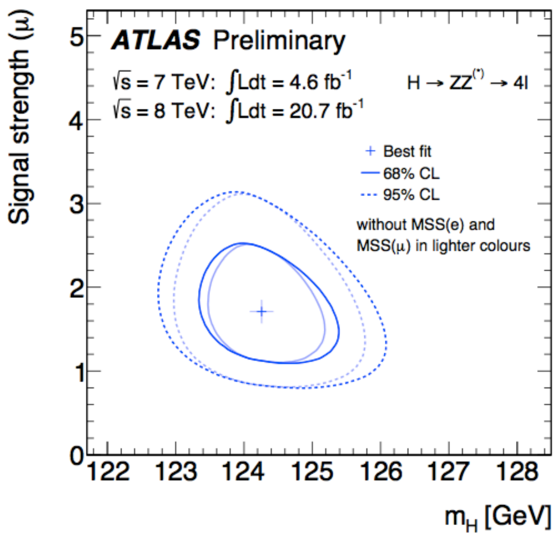
Higgs to → 4 leptons (golden channel) – results

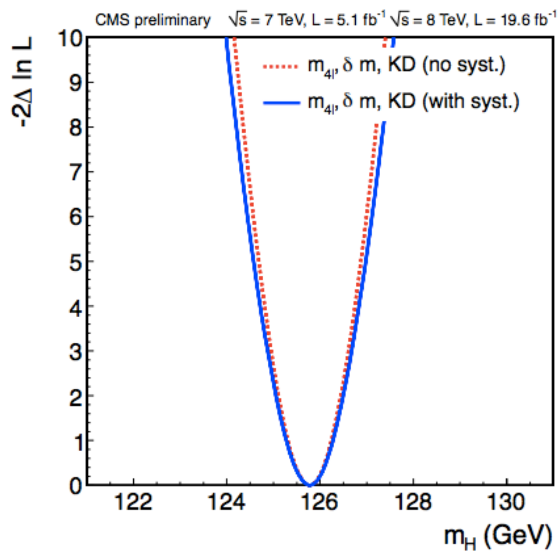
mass and signal strength: ATLAS-CMS comparison

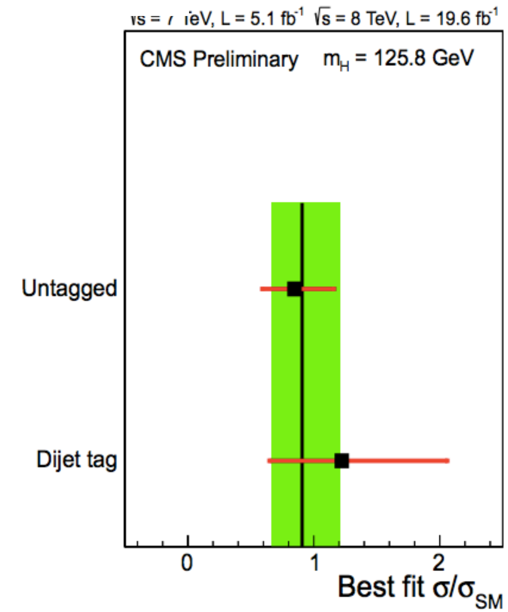


CMS → $m_H = 125.8 \pm 0.5\ \text{(stat.)}\ \pm 0.2\ \text{(syst.) GeV}$

ATLAS → $m_H = 124.3^{+0.6}_{-0.5}\ \text{(stat)}^{+0.5}_{-0.3}\ \text{(syst) GeV}$





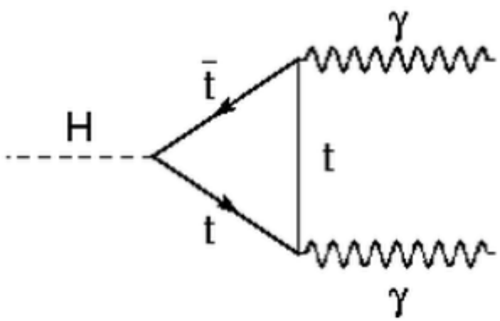


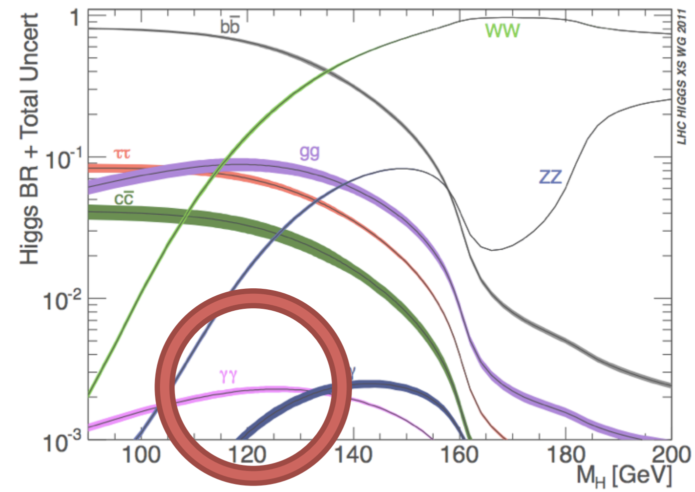
Signal strength CMS = $\mu = 0.91^{+0.30}_{-0.24}$

Signal strength ATLAS = $\mu = 1.7^{+0.5}_{-0.4}$

- ***No significant tension between measurements or between either and the SM prediction***
- ***I'll show spin in later slides***

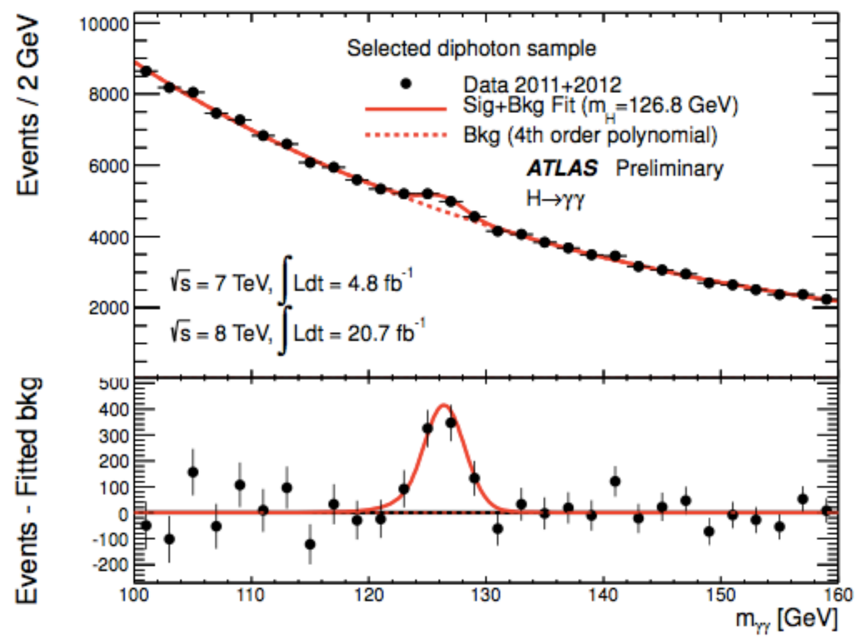
Higgs decay to 2 photons -- Introduction





Advantages :

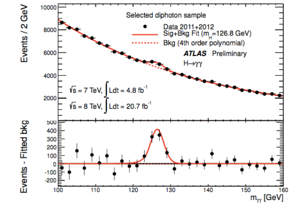
- ➢ **Good mass resolution (~1.8 GeV)**
- ➢ **"Easy" background functional form (falling exponential to 1st approx)**

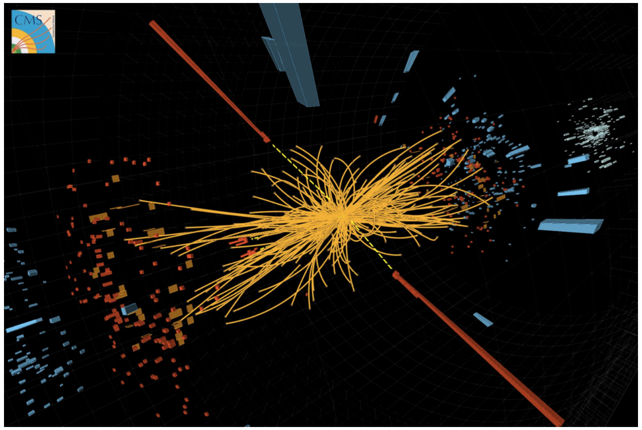


Challenges :

- ❑ **Low branching fraction (need to maximize sensitivity of analysis)**
- ❑ **Large QCD backgrounds**
- ❑ **Non-trivial energy calibration and primary vertex determination**

Higgs decay to 2 photons – Object definition

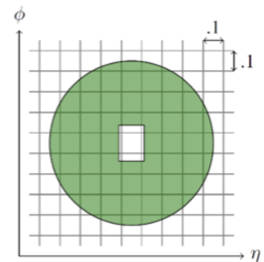


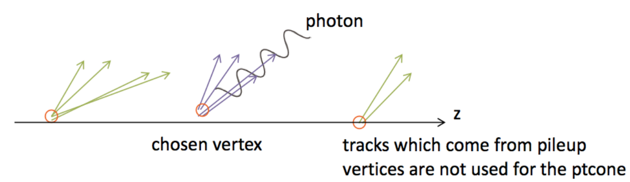


$$m_{\gamma\gamma}^2 = 2*E_1E_2(1 - \cos\alpha)$$

- Photons may convert in the Inner detector – conversion vertex can be detected (ambiguity with electron track requires careful analysis of tracks)

- Track pT based isolation + EMC based isolation (ATLAS + CMS)



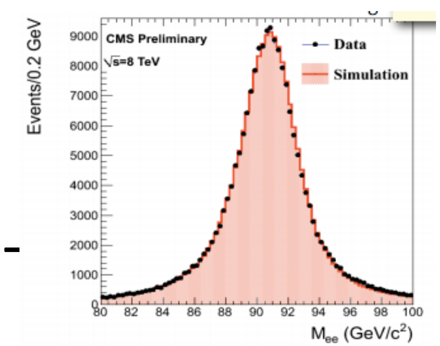


- Shower-shape based selection (ATLAS + CMS)

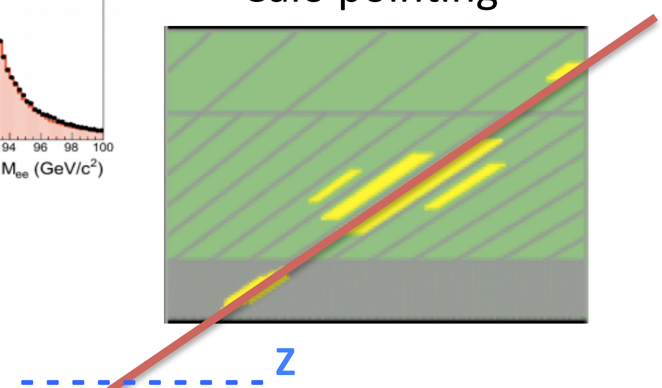
Invariant mass relies on :

- **Energy calibration** (in ATLAS extrapolated from Z peak electrons)

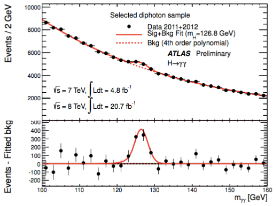
- **Primary vertex** (needed for photon position) – similar for ATLAS and CMS
  - **Calorimeter 'pointing' (only ATLAS)**
  - **Σ tracks pT², Σ tracks pT**
  - **Conversion vertex**
  - **Mean vertex position**



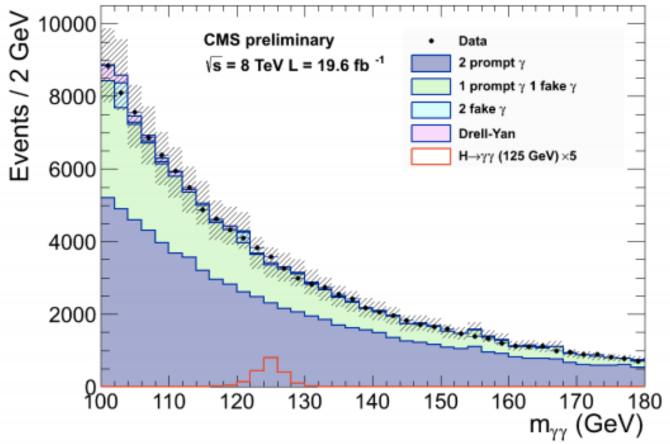
Calo pointing



Higgs decay to 2 photons – Background modeling



- **In order to Test Photon ID performance and validate MC bkg modeling several data-driven background decomposition techniques are used**



- ❑ 75% diphoton background
- ❑ 24% gamma-jet background
- ❑ ~1% jet-jet background

- **Signal is modeled by a CB + broad Gaussian distribution** (dominated by signal resolution)
- Background functional form can be more complex than simple exponential: exponential polynomial or Bernstein polynomial where the aim is:
  - → Have enough flexibility to adjust to background shape but not too much
  - → Does not introduce a bias (spurious signal) -- thorough check using MC models
- **Actual background shape is obtained from fitting these functional forms** (tested on MC) **directly to the data** distribution

Higgs decay to 2 photons – Expected number of SM Higgs events

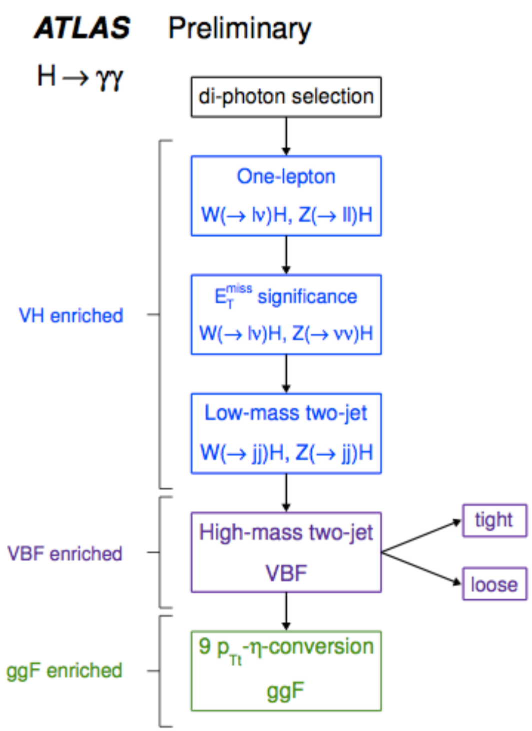
- With ~20 fb^{-1} of 8 TeV data we expect to have a significant amount of VBF from SM, and some VH and ttH

$\sqrt{s}$	m_H [GeV]	$gg \to H$ $\epsilon(\%)$	$gg \to H$ N_{evt}	VBF $\epsilon(\%)$	VBF N_{evt}	WH $\epsilon(\%)$	WH N_{evt}	ZH $\epsilon(\%)$	ZH N_{evt}	ttH $\epsilon(\%)$	ttH N_{evt}	Total N_{evt}
8 TeV	110	30.4	352.5	30.4	25.6	25.4	12.8	26.6	7.23	24.5	2.11	400.4
	115	32.1	364	33.1	27.5	[illegible]	[illegible]	28.3	7.12	25.6	2.09	413.5
	120	[illegible]	363.9	34.4	28.6	29.9	11.9	29.8	6.79	27.5	2	413.4
	125	35.7	352.9	36.3	28.8	30.9	11	32.4	6.29	28.4	1.87	401
	130	[illegible]	331.7	38.1	28.2	32.4	9.85	33	5.65	29.7	[illegible]	377.1
	135	38.4	301.2	39.4	26.5	34.1	8.49	33.9	4.91	30.4	1.47	342.6
	140	39.3	261.9	41	23.9	35	7.02	35.4	4.1	31.8	1.24	298.2
	145	40.7	214.8	42.3	20.3	35.9	5.48	36.5	3.25	32.9	0.983	244.8
	150	41.2	160.4	43.1	15.6	37	3.95	36.9	2.4	32.9	0.726	183.2

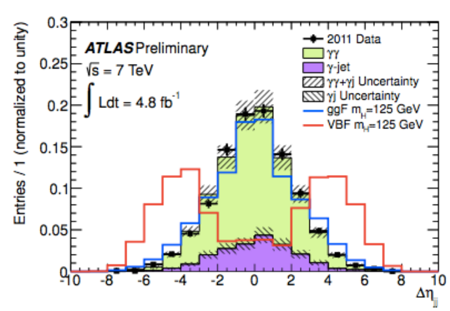
- **VBF events are characterized by 2 forward jets in final state (next slide)**
- **VH events are characterized by the presence of at least one lepton (electron or muon) in the final state,** two jets of relatively low inv mass, or MET

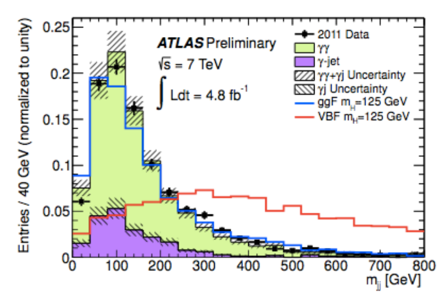
Higgs decay to 2 photons – Categories

- The data sample can be broken down into categories
  - → to maximize detector sensitivity (resolution) and S/B ratio
  - → to gain sensitivity to individual production modes (ggF, VBF, VH..)



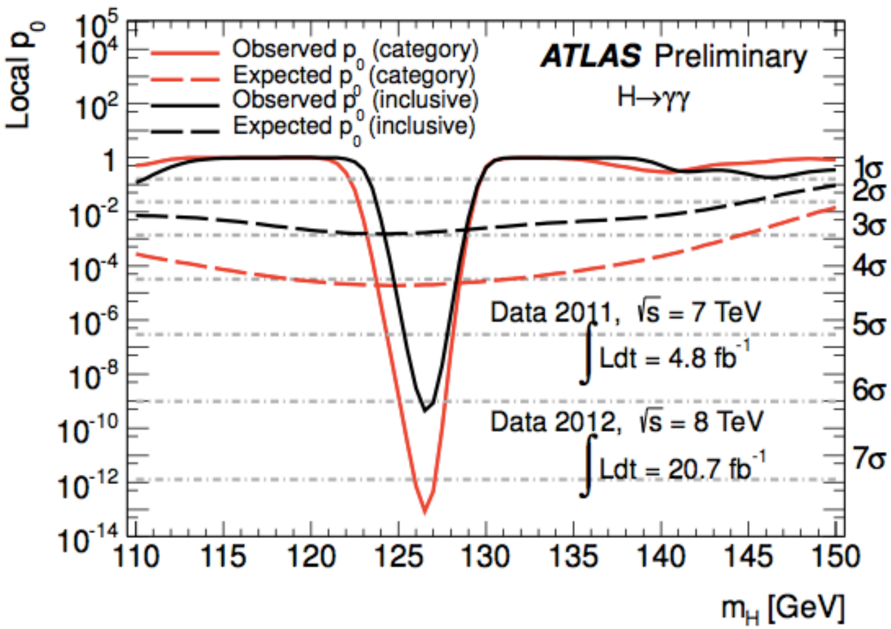
- The VBF-enriched category, for example, exploits the expected properties of the 2 forward jets based

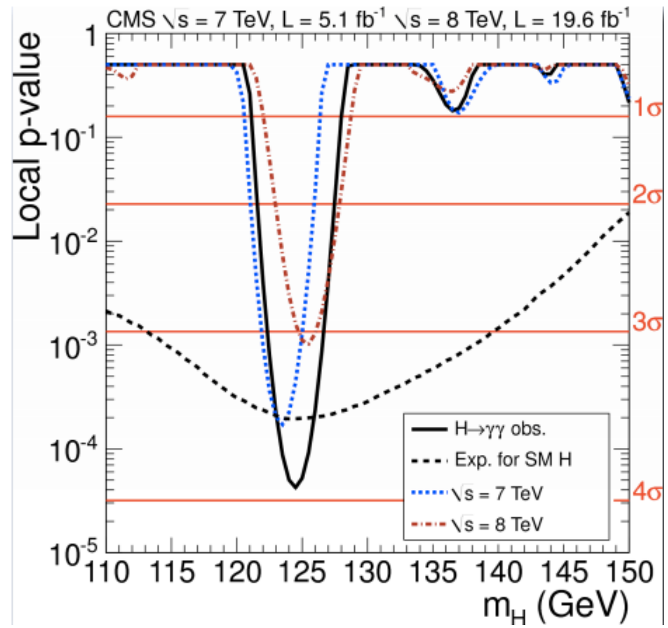




Higgs decay to 2 photons – properties (mass)

- P0 values show significant excess around the same mass value point



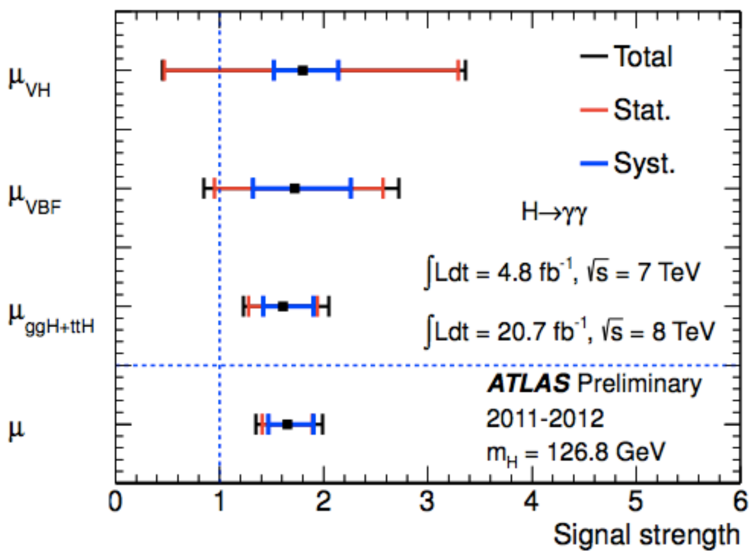


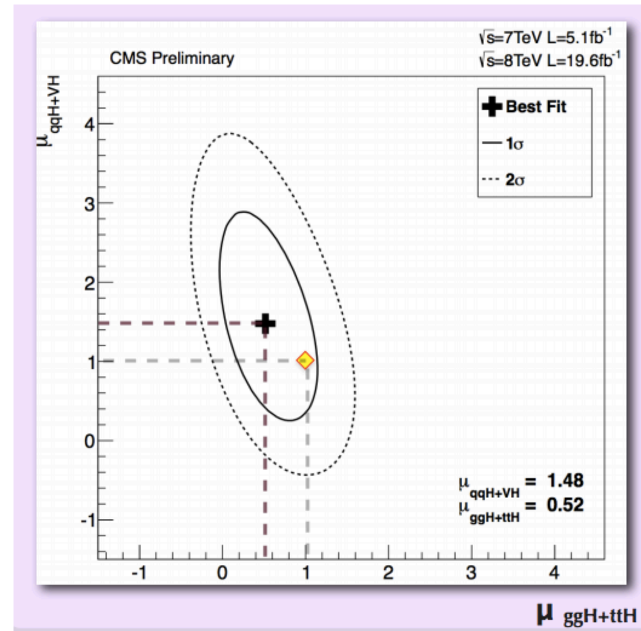
Mass determined from best m_H fit with μ a free parameter
ATLAS m_H = 126.8 +- 0.2 (stat) +- 0.7 (syst) GeV
CMS m_H = 125.4 +- 0.5 (stat) +- 0.6 (syst) GeV

- **Both experiments measure consistent results for the mass in this channel**

Higgs decay to 2 photons – properties (signal strengths)

- The signal strength is fitted separately for the different Higgs production modes

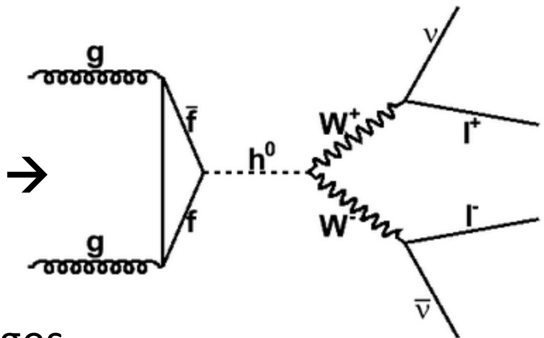


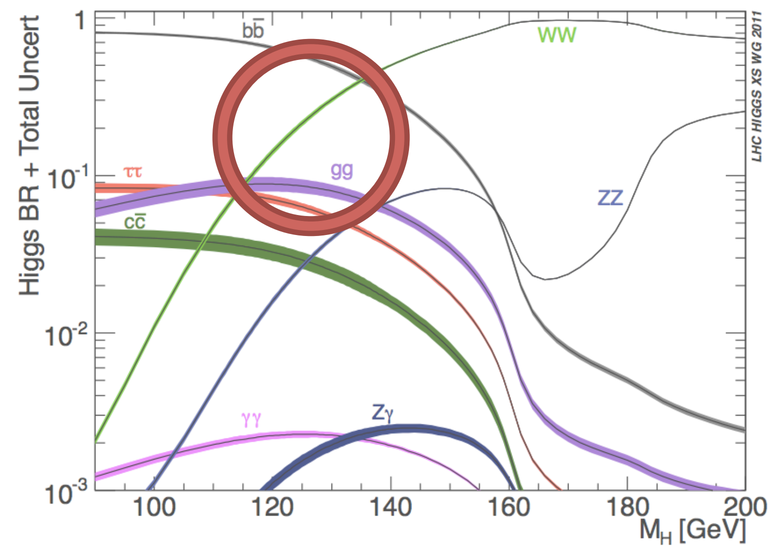


ATLAS mu = $1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}(\text{syst})$

CMS mu = 1.11+- 0.31 (cut-based) and 0.78 +- 0.27 (MVA based)

Higgs decay to (WW) two leptons and two neutrinos

(ggF) → 



- ❑ Advantages
- → Large branching fraction
- *→ Different decay modes*
- ❑ *Disadvantages*
  - *→ high SM backgrounds (WW, Wjet, ttbar..)*
  - *→ MET in final state (low mass resolution)*

Analysis strategy

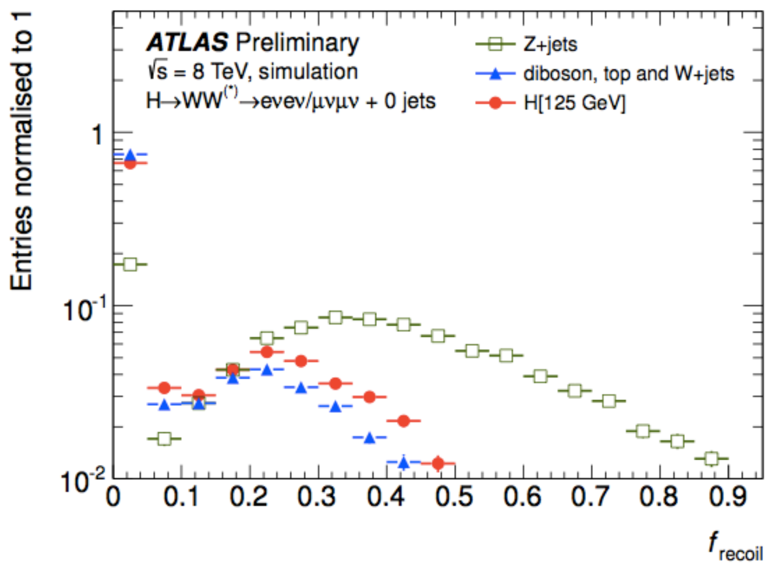
- Select events with two leptons and large MET
- *Customize cuts depending on channel*
- Check for (broad) excess in M_T or M_{ll} distributions

N jets	eν + eν	eν + μν	μν + μν
0-1	**ggF dominated** *Large DY bkg* *Large WW bkg* *-- strong MET*	**ggF dominated** *Small DY bkg* *Large WW bkg* *-- weak MET*	**ggF dominated** *Large DY bkg* *Large WW bkg* *-- strong MET*
2	**VBF dominated** *Large DY bkg* *Large ttbar bkg* *-- low stats*	**VBF dominated** *Small DY bkg* *Large ttbar bkg* *-- low stats*	**VBF dominated** *Large DY bkg* *Large ttbar bkg* *-- low stats*

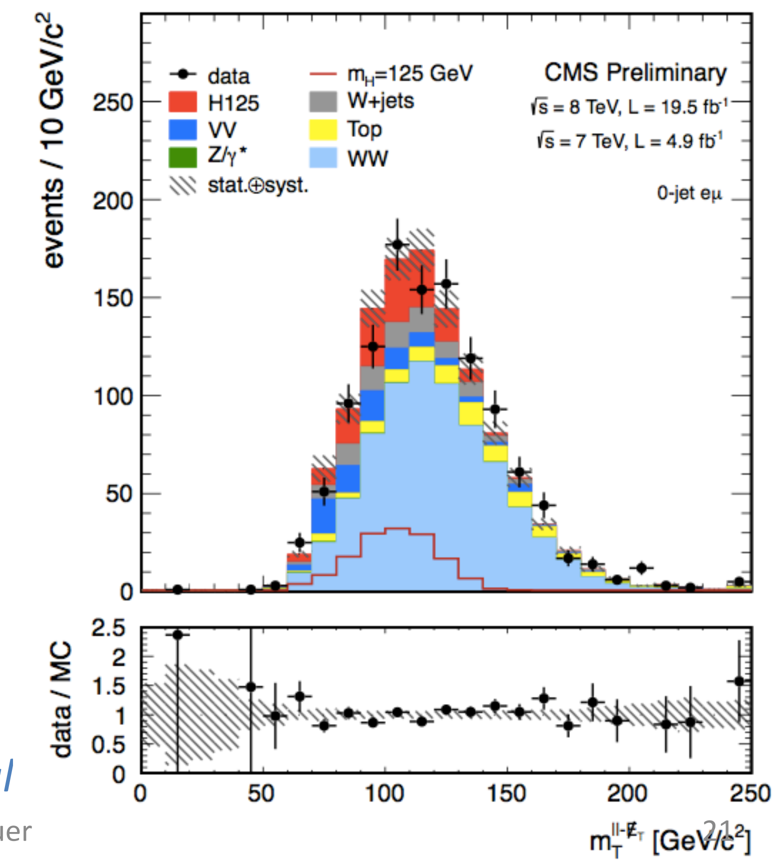
Higgs decay to (WW) two leptons and two neutrinos

- A number of sophisticated **topological variables are developed to reject background**
  -- (relative MET, relative P_{Tmiss}, f_{recoil}, b-tagging, etc..) in ATLAS
  -- multivariate techniques are deployed based on projected MET and other topo variables

➢ *F_{recoil} defined as fraction lepton (+ jet p_T) / sum p_T of jets in opposite phi quadrant*



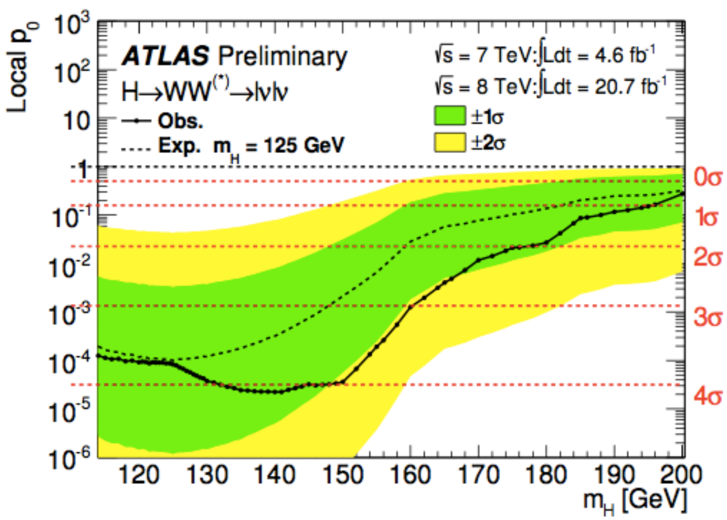
(d) f_{recoil} for $N_{\mathrm{jet}} = 0$, $ee + \mu\mu$



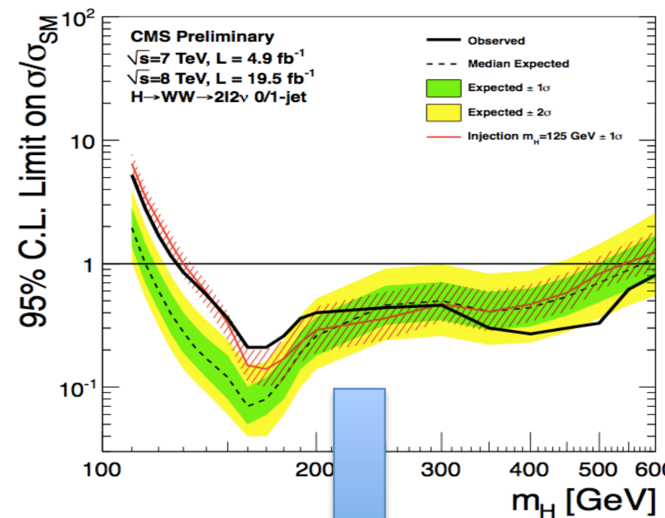
- *MC background description is validated using background control regions in data as much as possible (some error from extrapolation to signal regions)*

Higgs decay to (WW) two leptons and two neutrinos - results

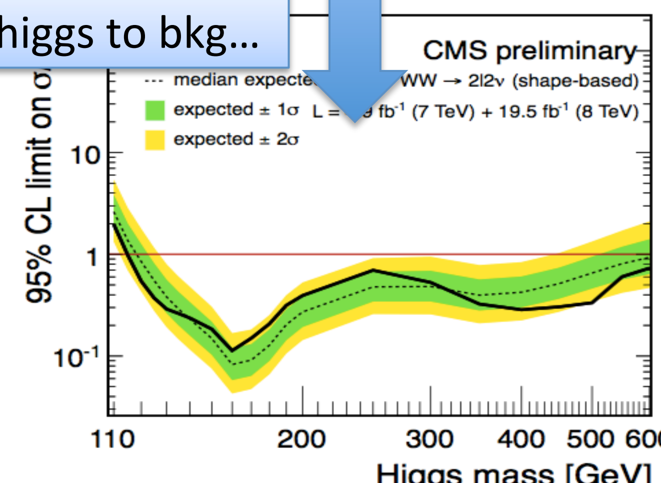
- ❑ p0 value around 10^{-4}



- ❑ SM excluded from 128-600 GeV



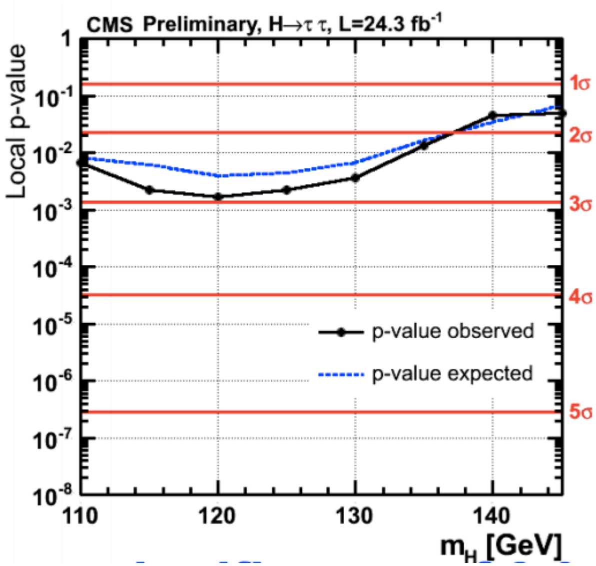
If we add SM higgs to bkg…

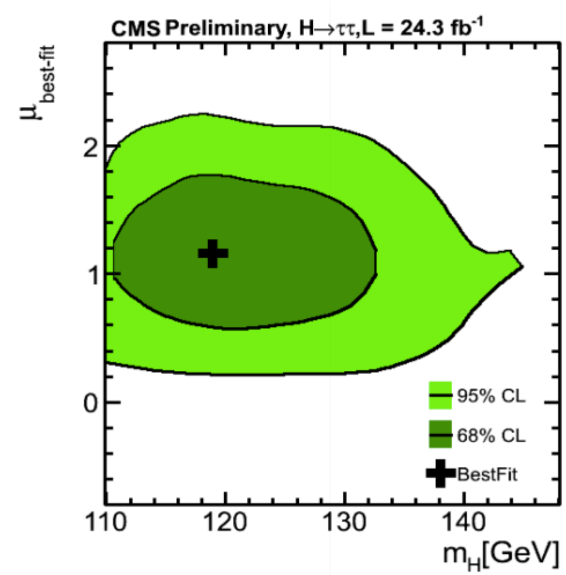


- ❑ ***Despite challenging environment this channel has strong exclusion limits and also evidence for signal***
- ❑ *Can also be used to check spin of resonance (later in this talk…)*

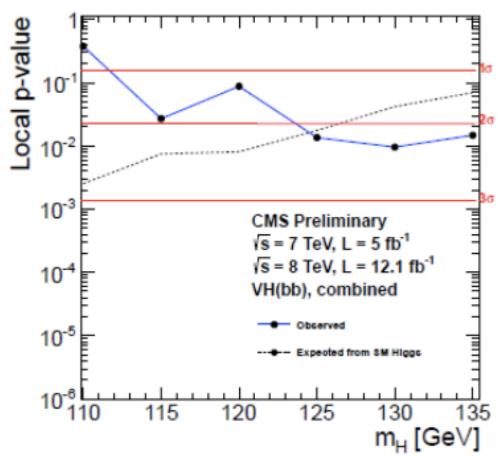
Higgs to fermions – results (end of analysis description section of talk)

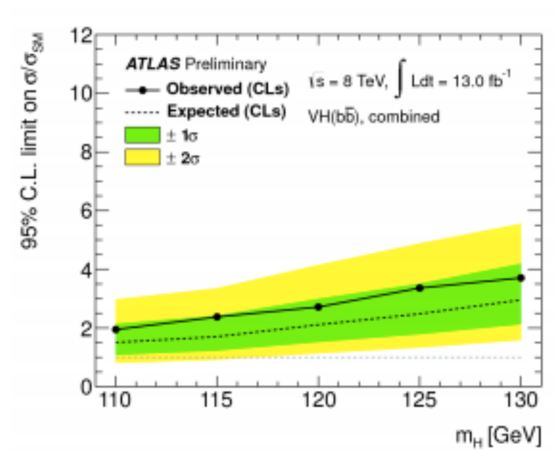
H→ττ





H→bbbar





- ❑ **Particle beginning to show up in fermionic channels !**

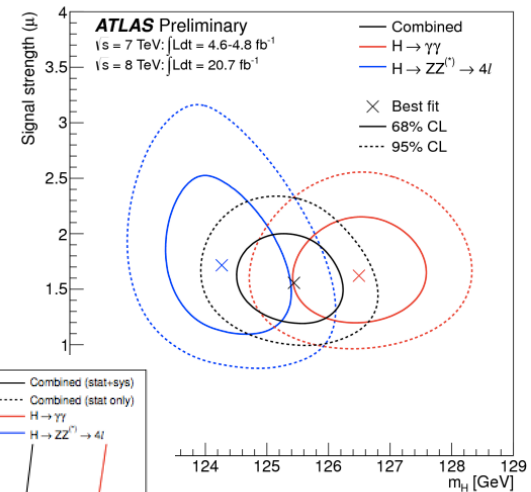
The latest results

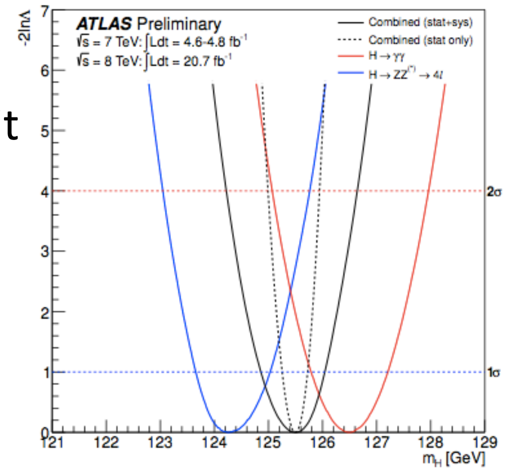
How a theorist feels following ATLAS and CMS presentations....

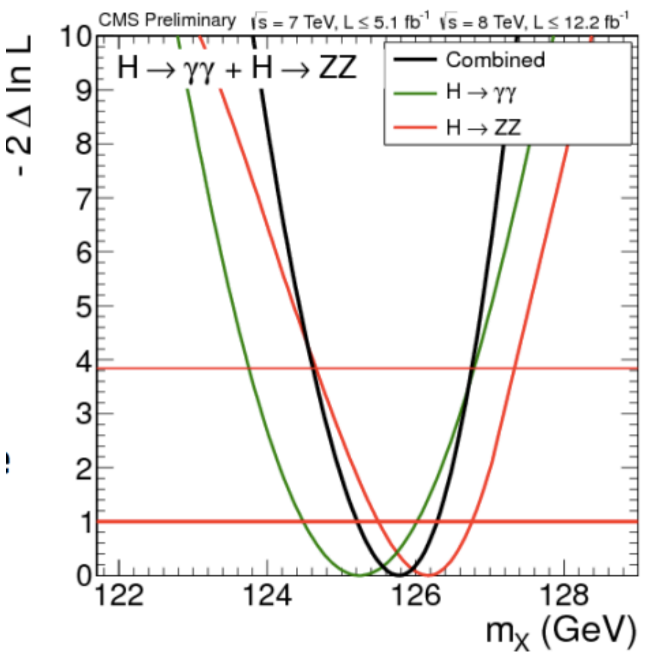
(I grabbed this from one of the talks given at Aspen…)

Properties of new resonance – Mass

- H→4l and H→2photon channels give
  Δm = 2.3+0.6 (stat) ± 0.6 (sys) GeV
- We can check *how likely it is for a single mass to produce this Δm* by looking at the profile likelihood of Δm = 0 vs Δm = 2.3
  - ➢ 1.2-8%, depending on how conservative you are with the erros in the likelihood fit







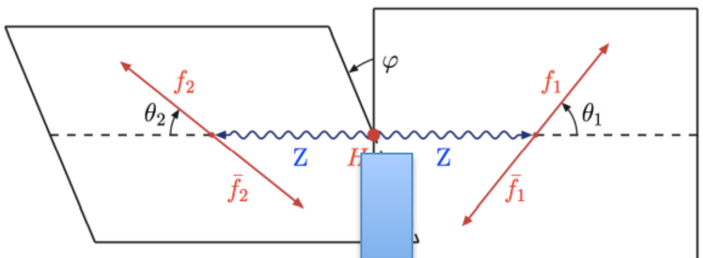
- Central values swapped between ATLAS and CMS
- **Combined values are very compatible**

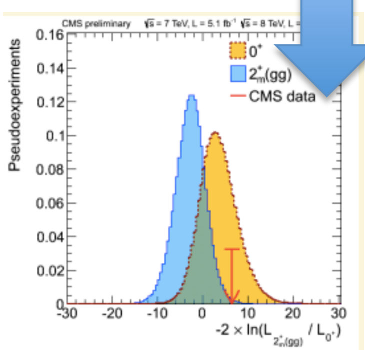
→ CMS combined mass
m_H = 125.8 +/- 0.4 (stat) +/- 0.4 (syst) GeV
→ ATLAS combined mass
m_H = 125.5 ± 0.2 (stat) +0.5 (sys) GeV

Properties of new resonance – SPIN and parity

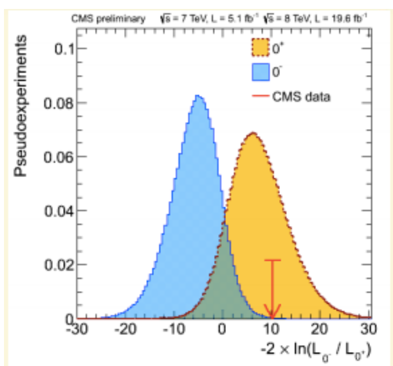
- ❑ **Goal** : test specific models for the spin of the newly discovered particle
  - → **Spin 0^+ for Standard Model vs, i.e. Spin 2^+ : Graviton with minimal couplings**
- ❑ **Define discriminating variable and fit bkg/signal to check likelihood profile of signal**

Higgs to 4 leptons (lepton to Z or angle between 2 lepton-Z planes)



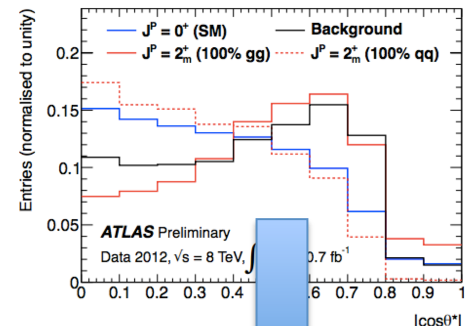


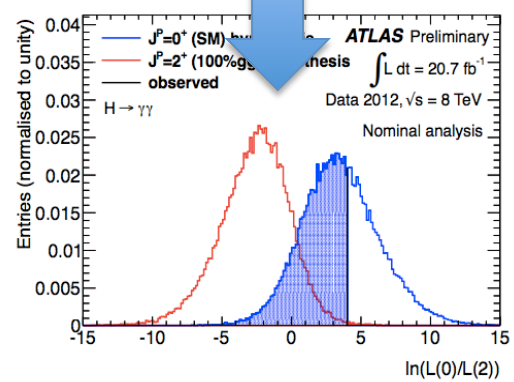
CL$_s$ ($2^+_{m\,gg}$) : 1.5%



CL$_s$ (0^-) : 0.16%

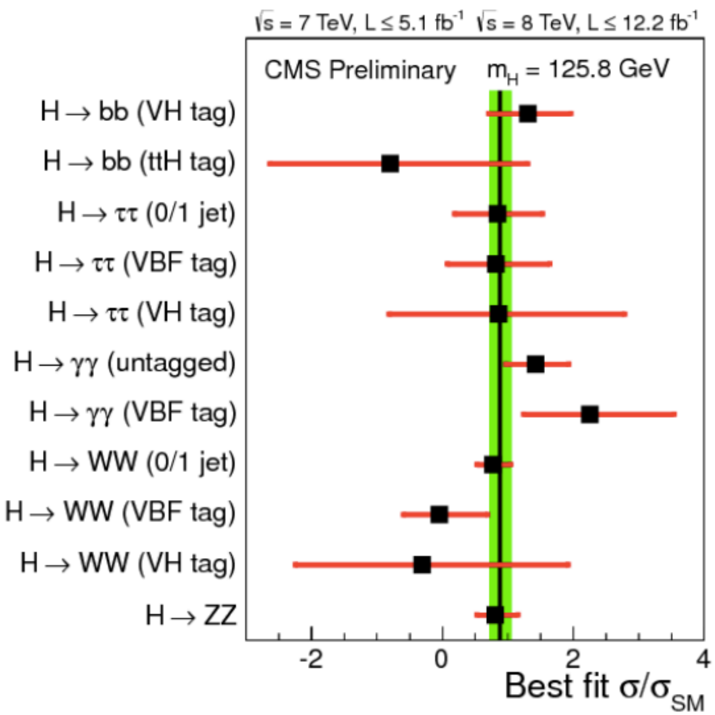
Higgs to 2 photons (can use cosθ*)



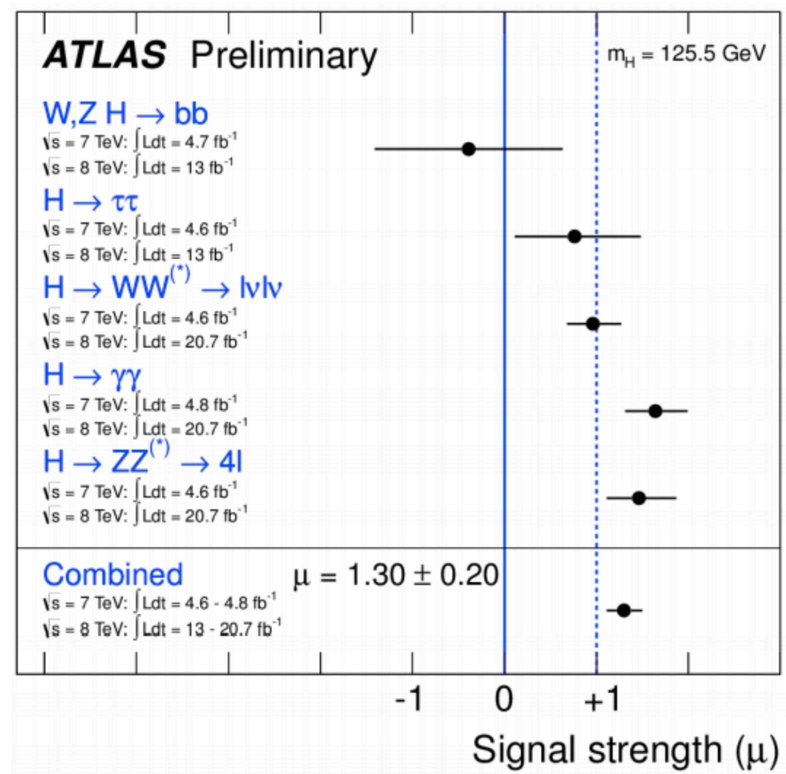


- ➢ **Measurements in other channels (i.e. WW) also favour Spin 0^+ while strongly disfavour spin-2 hypthesis**

Properties of new resonance – Signal Strength



σ/σ_{SM} = 0.88 +/- 0.21



- ❑ **Combined signal strength within 2 sigma from SM and from each other**

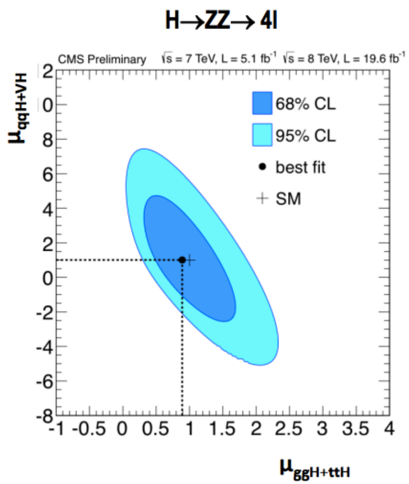
→ **ATLAS : consistency of μ=1.3 with SM (μ=1) is of 9% (with more conservative treatment of systematics it goes up to 40%)**

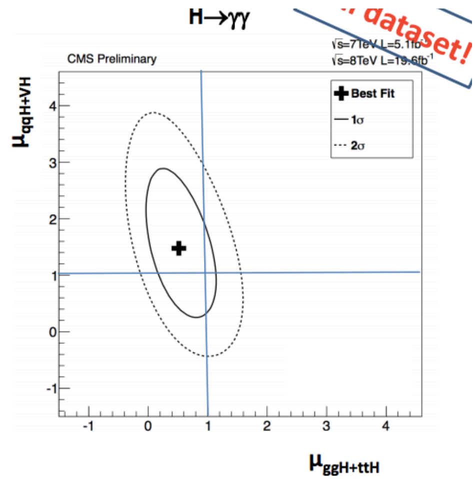
→ **CMS : measured μ=0.88 within 1 sigma of SM (μ=1)**

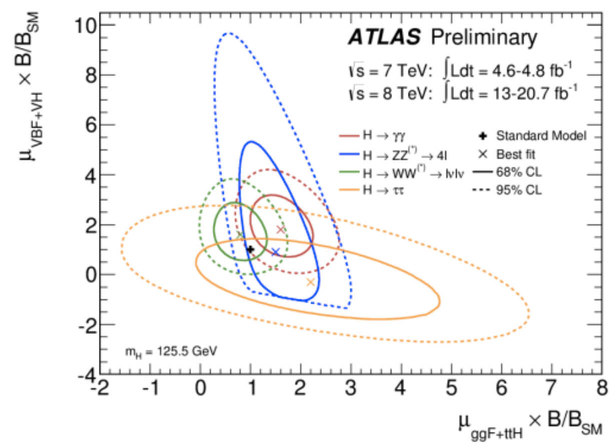
Properties of new resonance – Signal Strengths

- **Global μ fit does not give any information about individual production modes**
- *Higgs signal strengths for different production processes are measured*

- Group together production signal strengths:
  - Fermion-mediated: $\mu_{ggF+ttH} \equiv \mu_{ggF} = \mu_{ttH}$ – ttH,VH rates subdominant
  - Boson-mediated: $\mu_{VBF+VH} \equiv \mu_{VBF} = \mu_{VH}$



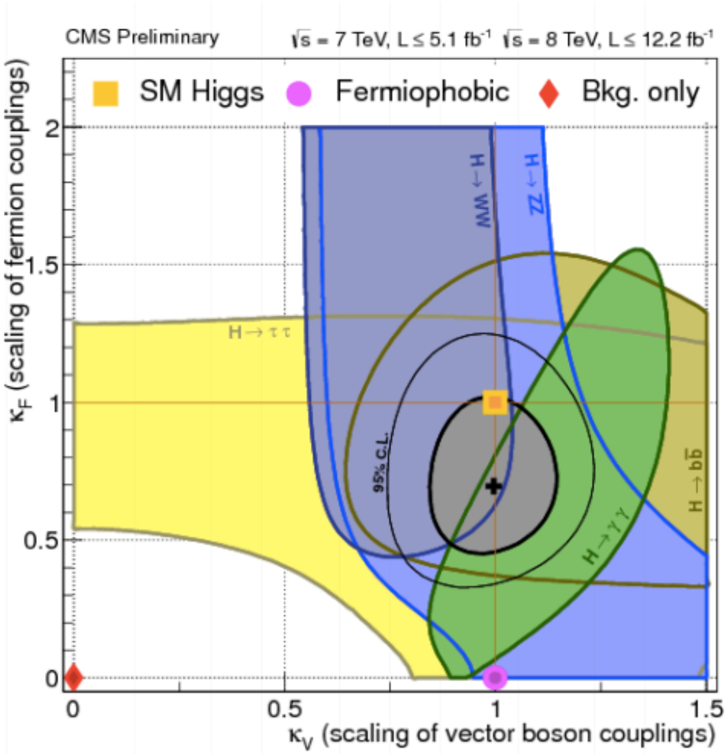




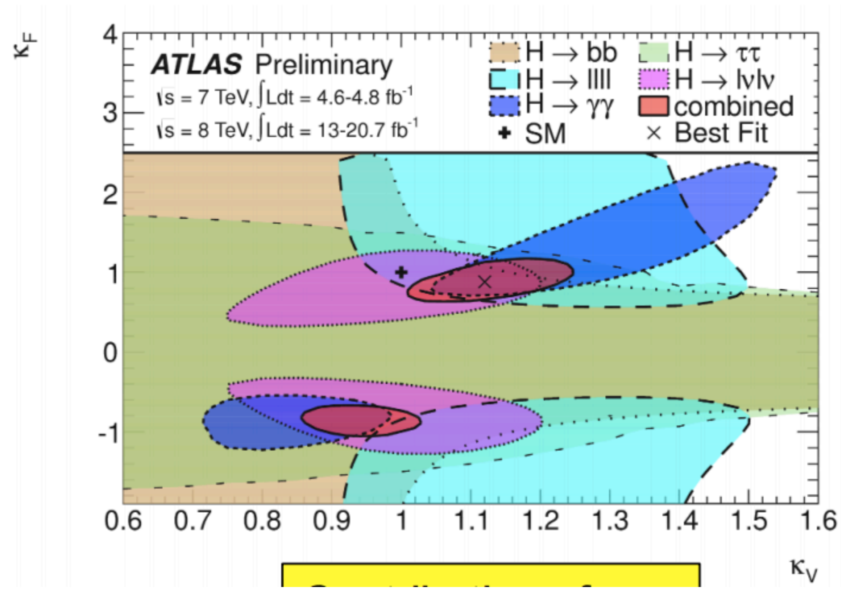
- ❑ We can take ratios of $R = \mu_{VBF+VH}/\mu_{ggF+ttH}$ such that the BF cancels out in each channel
  - → combined R for all channels = 1.2+-0.6 (compatible with SM)
  - → test $\mu_{VBF+VH} = 0$ assumption and find it is disfavoured with a p-value of 0.05%
  - → of test μ_{VBF} alone (assume VH =0), being disfavoured by a p-value of 0.09%
- ❑ This can be flipped around by taking ratios of the same production mode in different channels (test BFs). Results are $\rho_{\gamma\gamma/ZZ} \sim \rho_{\gamma\gamma/WW} \sim \rho_{ZZ/WW} \sim 1$ (consistent w/ SM)

Properties of new resonance – Signal Strengths

- In order to treat production and decay modes consistently, we can look at what is called *κ-factors = scales of the SM couplings without changing tensor structure of SM*
- Presented here as a measure of fermionic and bosonic *κ-factors (κ_F vs κ_V)*



- No significant deviation from *κ = 1 observed*
  → Near the 1 sigma level in both CMS and ATLAS



Summary and conclusions

- A number of updates with the full 2011+2012 have been presented in Aspen/ Moriond last week
- The high resolution channels can claim discovery on their own

Properties analyses for new resonance gaining maturity

- Mass agreement between all channels points to single particle
- Spin analyses point to 0^+ particle (CP even boson)
- Signal strengths in different production and decay modes see no significant tension with Standard Model and agree well between CMS and ATLAS experiments
- **We cannot claim SM Higgs yet, but so far it definitely looks like it…**