Measurement of Higgs Production and Decay in CMS and ATLAS

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On behalf of the CMS and ATLAS Collaborations

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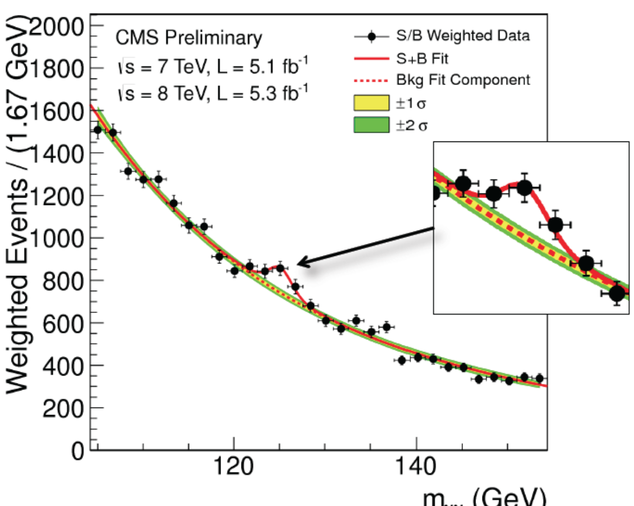

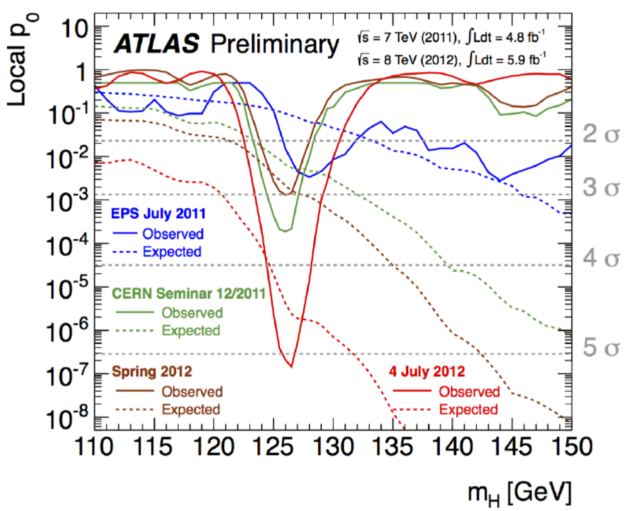

Measurement of Higgs Production and Decay in CMS and ATLAS (with emphasis on bosonic decay modes)

James G. Branson

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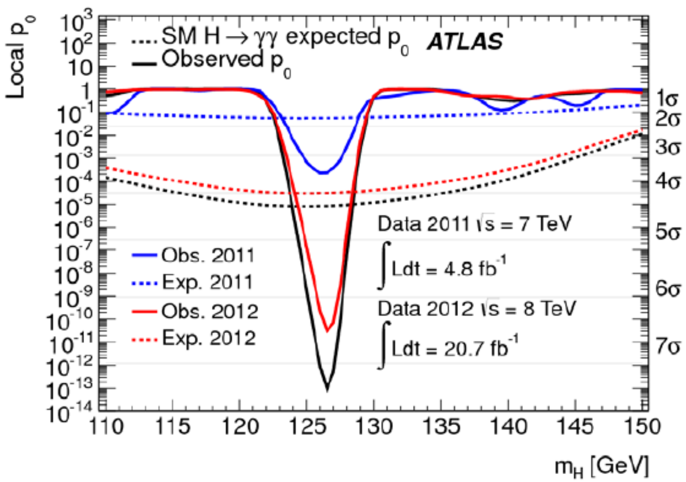
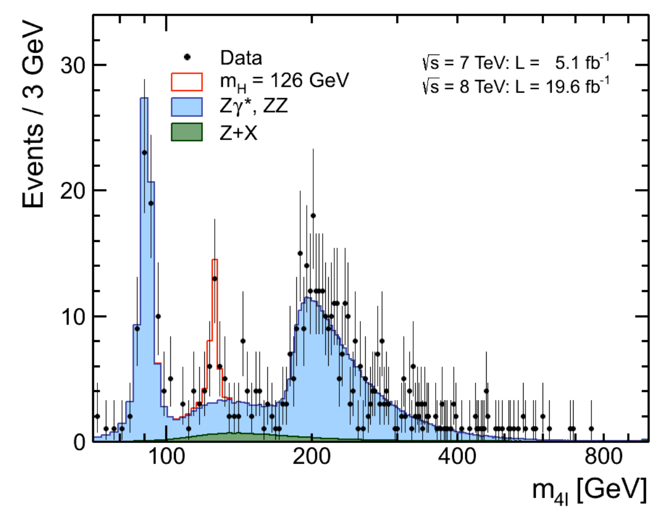
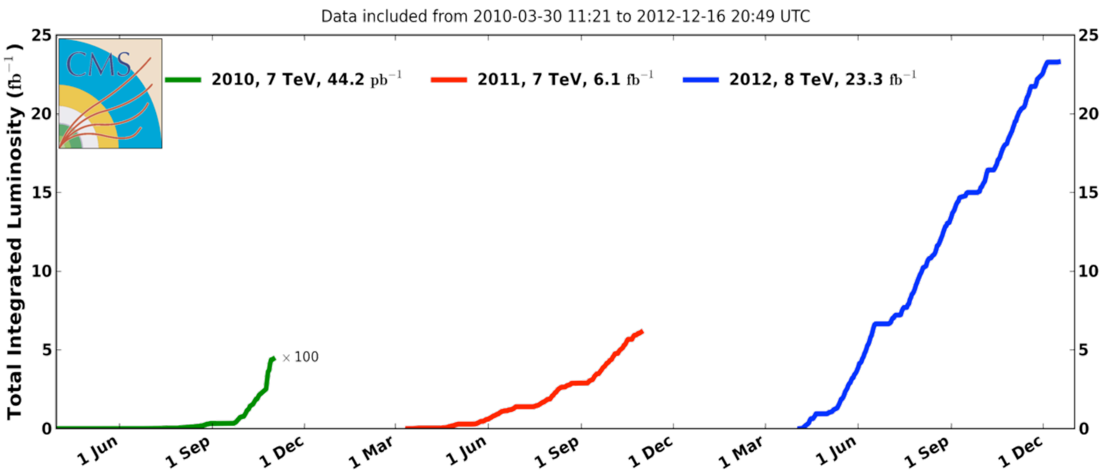
ABSTRACT

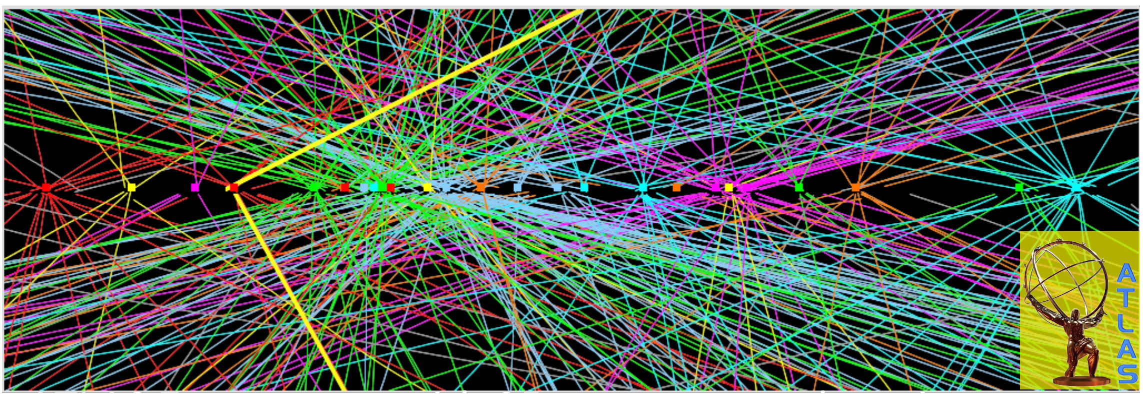
On July 4, 2012, both CMS and ATLAS showed Higgs search results at CERN. Each experiment had a narrow resonance with a mass around 125 with a significance of almost exactly 5σ when combining the channels analyzed (which seems very lucky sociologically). The discovery of a resonance in the modes expected for the SM Higgs indicated that the somewhat preposterous SM Higgs Mechanism was correct, but the details were still unclear. A Higgs mass of around 125 is very interesting since it is consistent with EW measurements in the SM, allows measurement of many decay modes, is consistent with the prediction of SUSY and it is possible in (new) composite Higgs models. It was decided that the LHC run at 8 TeV should be extended to determine whether this resonance was the Higgs. With substantial additional luminosity, we have begun to measure the couplings of this particle and can now say that it is a Higgs-like particle. In this seminar, I summarize the measurements of CMS and ATLAS with an emphasis on the bosonic decay modes (ZZ, $\gamma\gamma$, and WW). I also summarize what we have measured concerning the spin and parity of the resonance. Finally I discuss what we know about the couplings and what can be done in future runs at higher energy and higher luminosity.





LHC Data: pp Collisions at 7 and 8 TeV



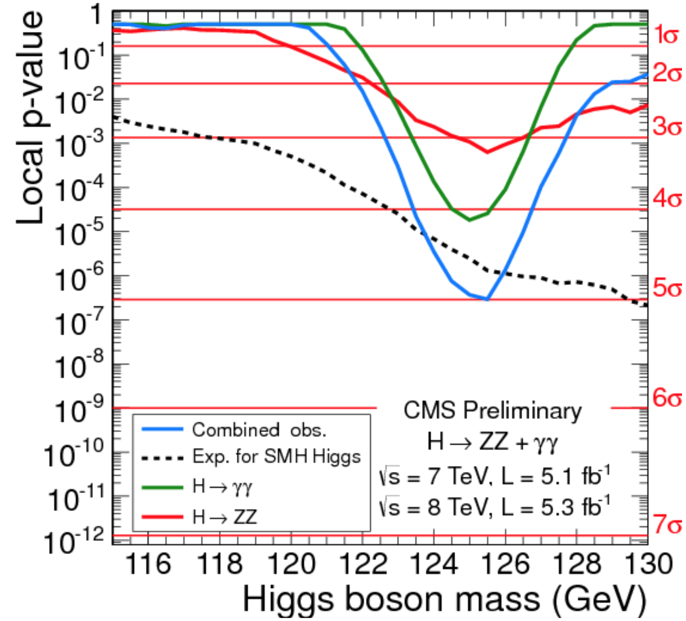


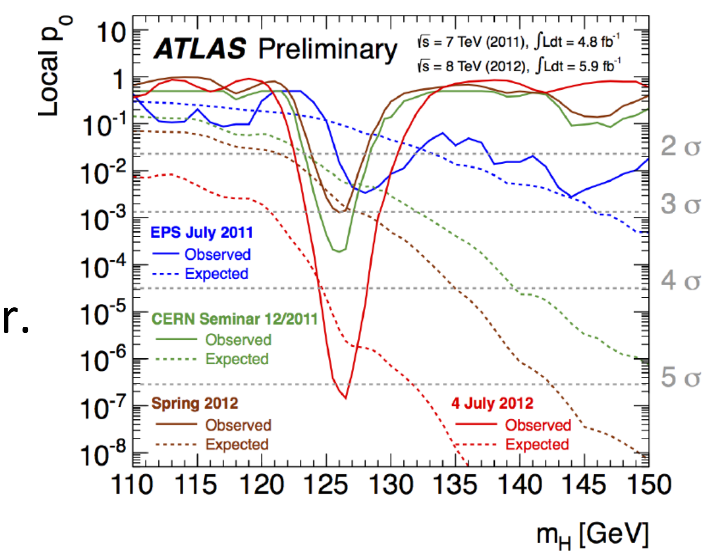
- Excellent performance of LHC in 2011 and 2012
  - Design 14 TeV @ 10^{34} cm^{-2}s^{-1}
  - Peak $\mathcal{L}$ = 7.7 x 10^{33} cm^{-2}s^{-1}
- ~25 fb^{-1} Int $\mathcal{L}$ pp collisions collected per experiment
- Very high data taking efficiency for both experiments
- More pileup than planned at design luminosity due to 50 nsec crossing interval.

- Effects of pileup:
  - Trackers do an excellent job of distinguishing different vertices . They see only in-time tracks.
  - Calorimeters see in-time pileup as normal energy. Particle flow algorithms help. Energy from previous bunch crossings affect the pulse shape and baseline subtraction.
  - Slightly deteriorates energy resolution for electrons, photons and jets. Apply corrections event by event.
  - Adds energy in isolation cone. Corrected for pileup energy estimated event by event.
  - We can go to higher luminosity.

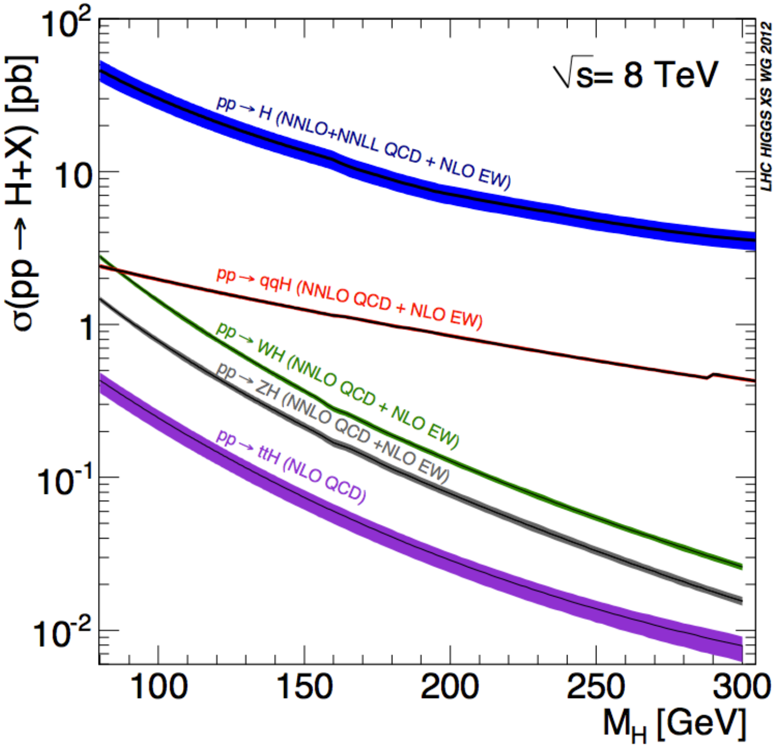
July 4, 2012: A "Higgs-like" Resonance

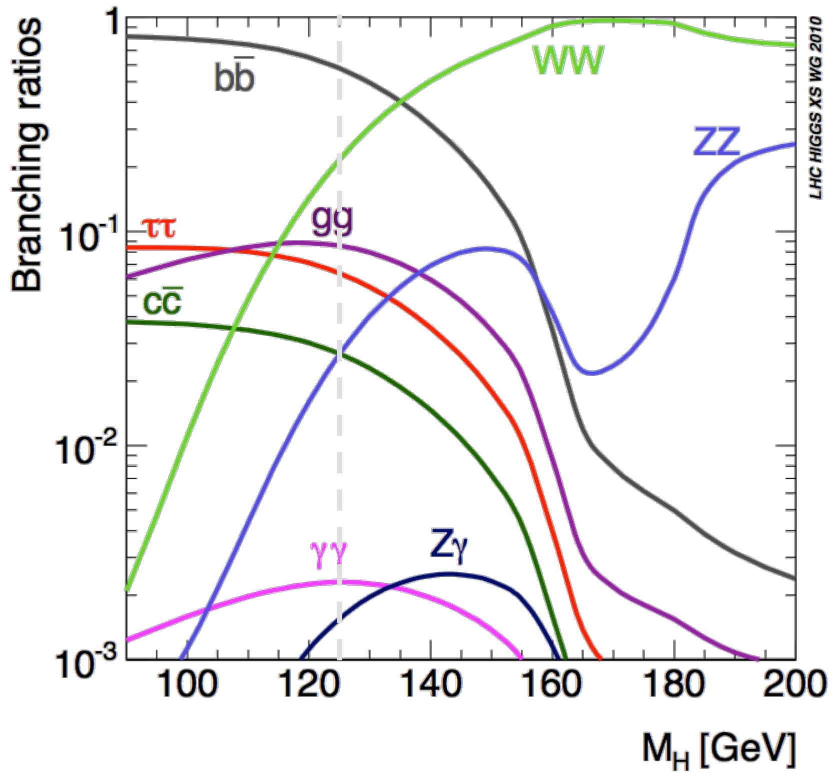
- Both Experiments had almost exactly 5σ when combining the channels that they analyzed.
  - Very lucky (sociologically) to get to 5σ at the same time
    - blind until just before CERN seminars
- Confirms (preposterous) SM Higgs Mechanism
  - But details of Higgs Sector still unclear
- M=125 is very interesting
  - Consistent with EW measurements
  - Allows measurement of many decay modes
  - Light Higgs is a prediction of SUSY
    - but 125 close to the limits of MSSM
  - Possible in (new) composite Higgs models
- Its NOT a revolution (its SM!) but:
  - the origin of mass is (mainly) in this scalar
  - our first (fundamental?) scalar found
- We have begun to measure the couplings,
- And to search for other particles in the Higgs sector.
- A lot of measurements to make at higher energy and higher luminosity LHC.



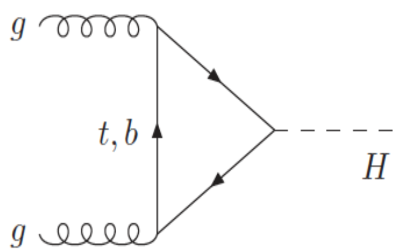


SM Higgs Production and Decay

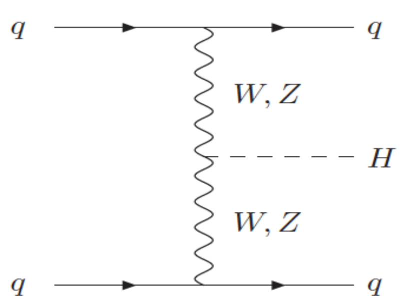




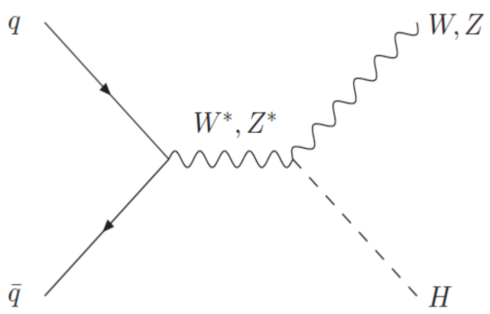
ggH



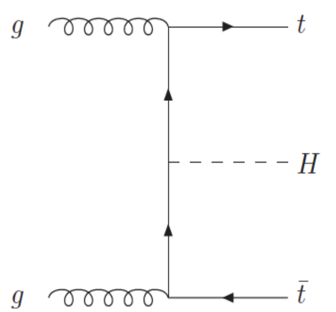
VBF



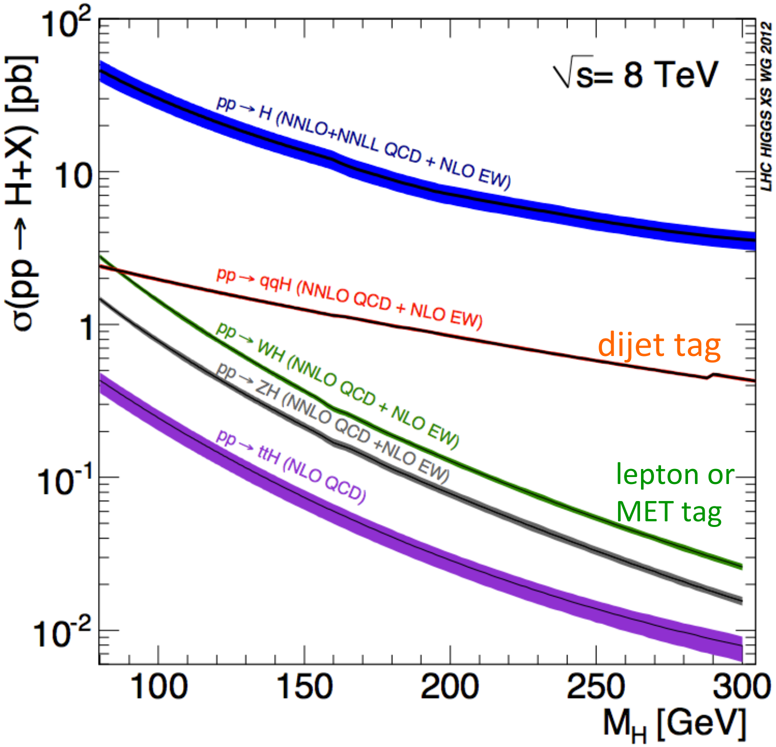
VH

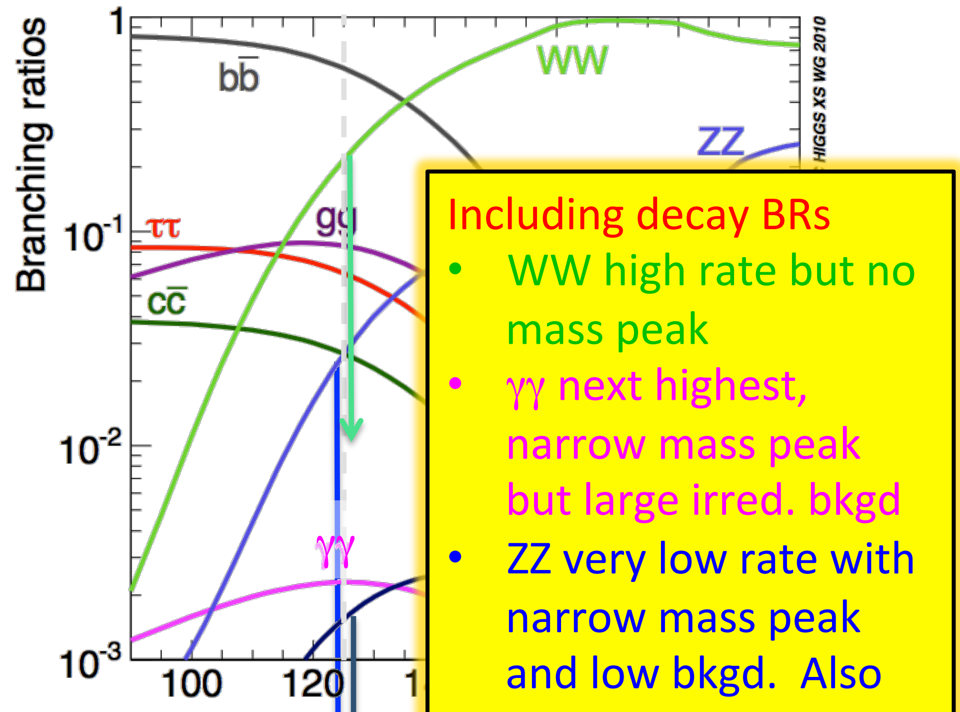


ttH



SM Higgs Production and Decay

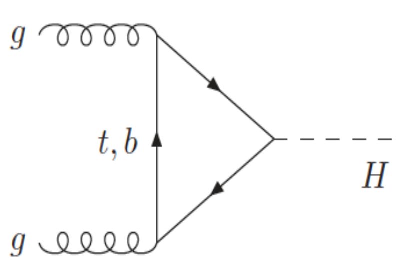




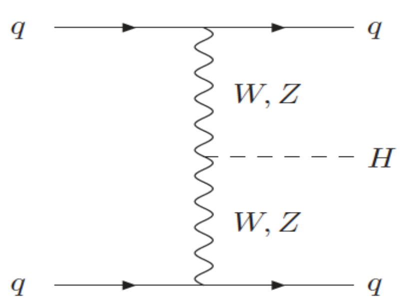
Including decay BRs

- WW high rate but no mass peak
- γγ next highest, narrow mass peak but large irred. bkgd
- ZZ very low rate with narrow mass peak and low bkgd. Also lots of kinematic info
- Zγ very low rate, narrow mass peak and large irred. bkgd

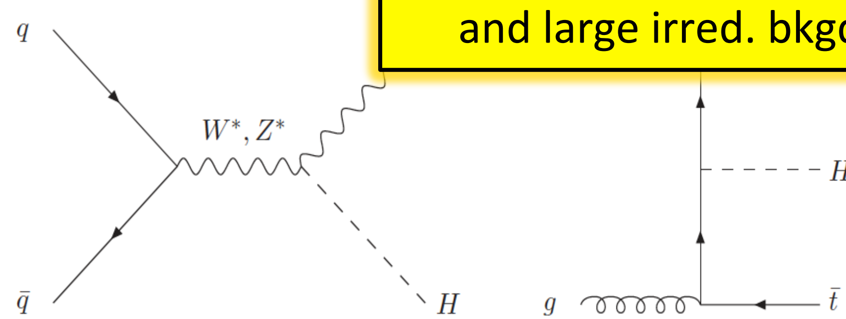
ggH



VBF



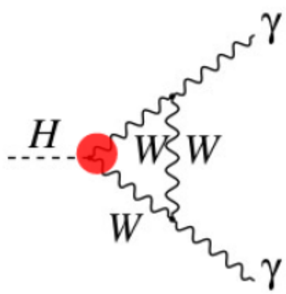
VH

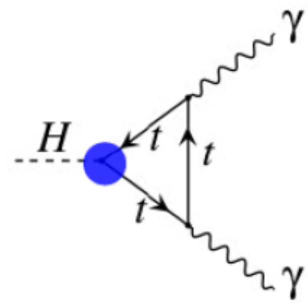


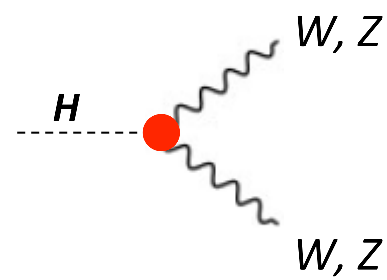
CMS Bosonic channels at 125 GeV

Channel	Int Luminosity 7 + 8 TeV (fb^{-1})	Mass resolution	Expected sensitivity	Observed error on σ/σ_{SM}
$\gamma\gamma$	5.1 + 19.6	1%	4.2 σ	0.27
ZZ→4ℓ	5.1 + 19.6	1.5%	7.2 σ	0.26
WW→2ℓ2ν	4.9 + 19.5	~20%	5.1 σ	0.21
Zγ	5.0 + 19.6	~2%	Tiny for SM	~5

- 3 channels with similar σ_μ
- γγ and ZZ→4ℓ with excellent mass resolution (1-2%):
- WW→2ℓ2ν with highest rate:
- Zγ→ℓℓγ has low SM rate but good mass resolution



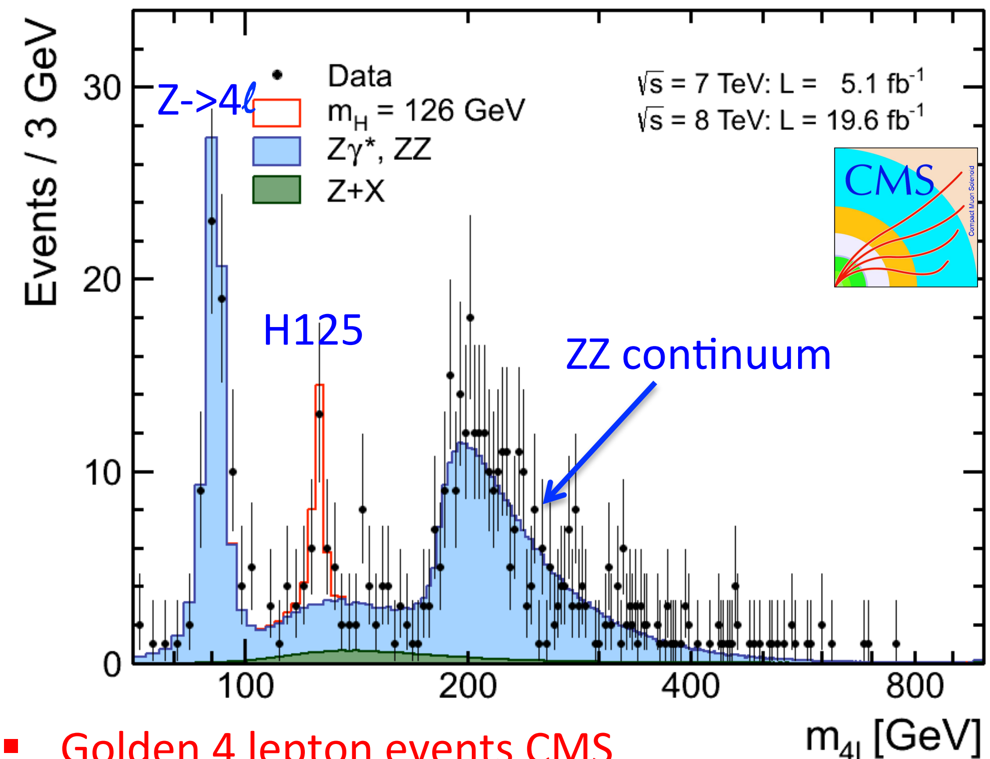


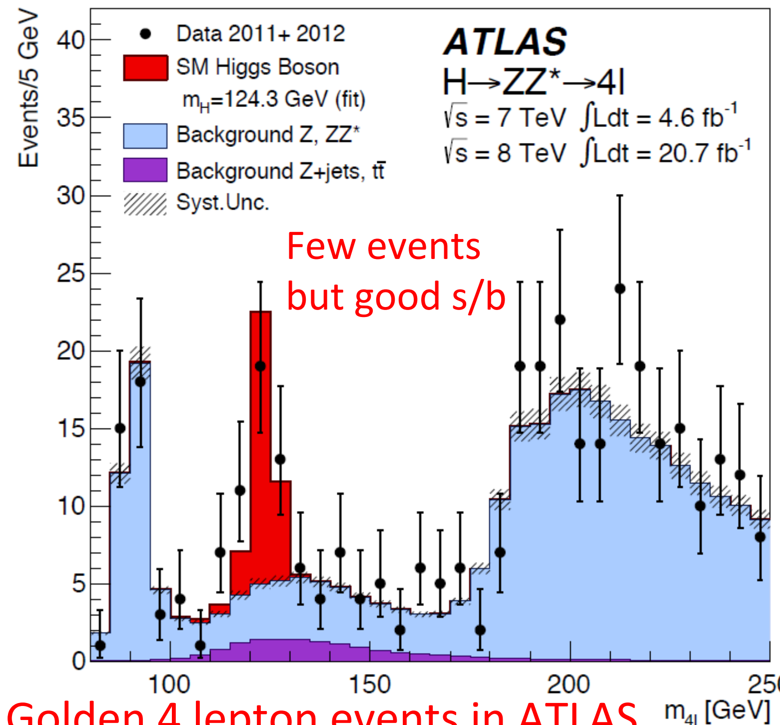


Higgs decay to γγ has interference between vector and fermion couplings

	Untagged	VBF	VH	ttH
H->γγ				
H->ZZ->4l	done		in progress	
H->WW-lvlv				
H->Zγ->llγ				

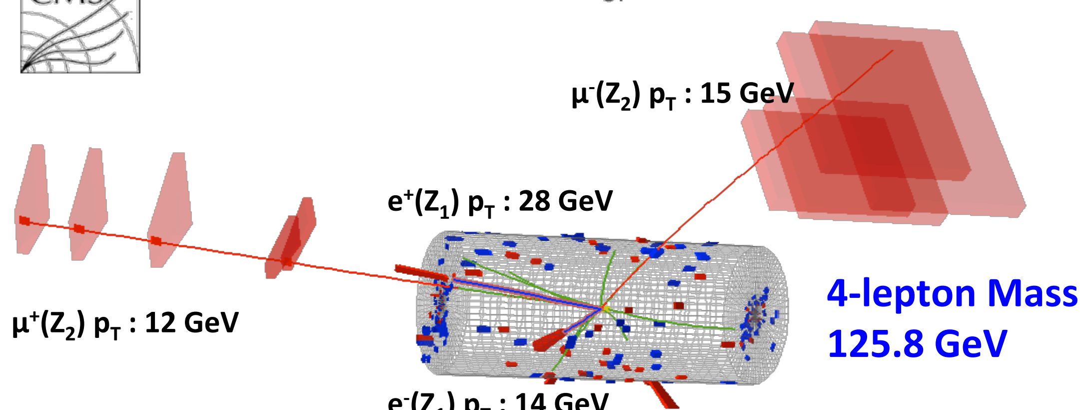
H → ZZ → 4ℓ: candidates



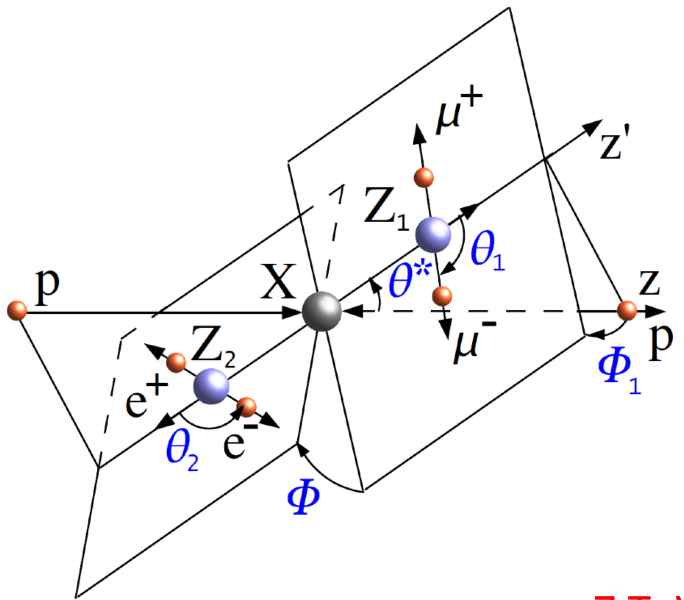


- Golden 4 lepton events CMS
  - Lepton ID efficiencies using Z.
  - Muon energy scale in constant B field is easy.
  - Energy scale and calibration for electrons (large effort) checked with Z→ee .

- Golden 4 lepton events in ATLAS
  - Huge effort on lepton ID efficiencies, and calibration of mass scale.



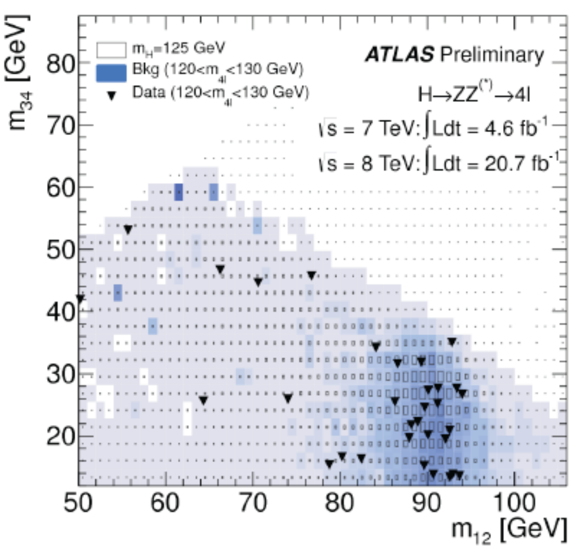
Measure 7 kinematic variables: K_D



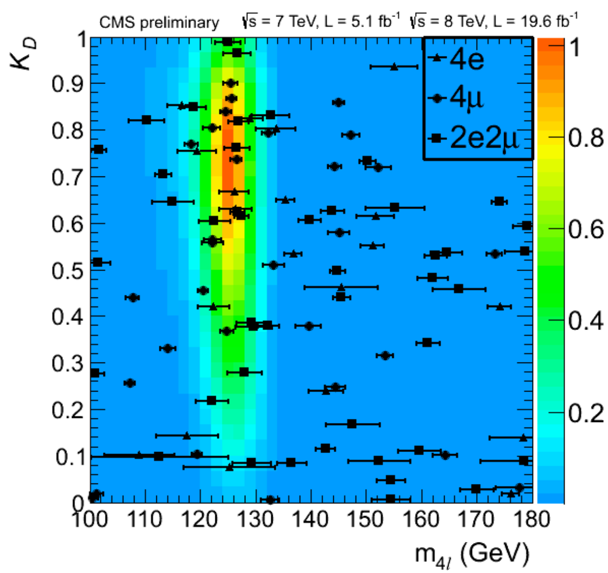
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

Kinematic Discriminants are useful to enhance signal over background or to test spin hypotheses…

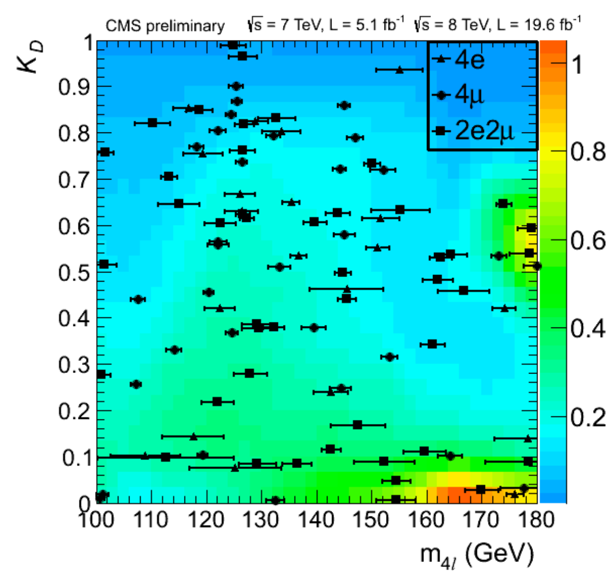
- Add a dijet category – to have sensitivity to VBF
- Use a 3D method in CMS (also using mass resolution)
  - Inclusive: Mass – K_D – P_{t4l}
  - dijet category: Mass – K_D – V_D (VBF discriminant)



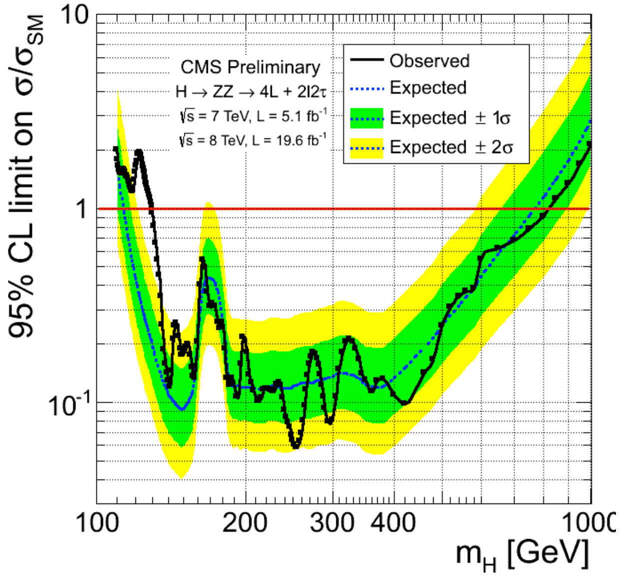
7 TeV with signal expectation

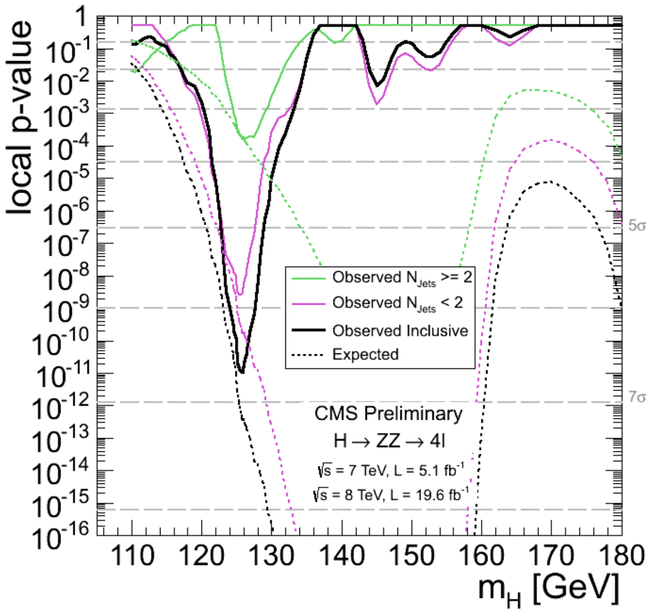


with bkgd expectation

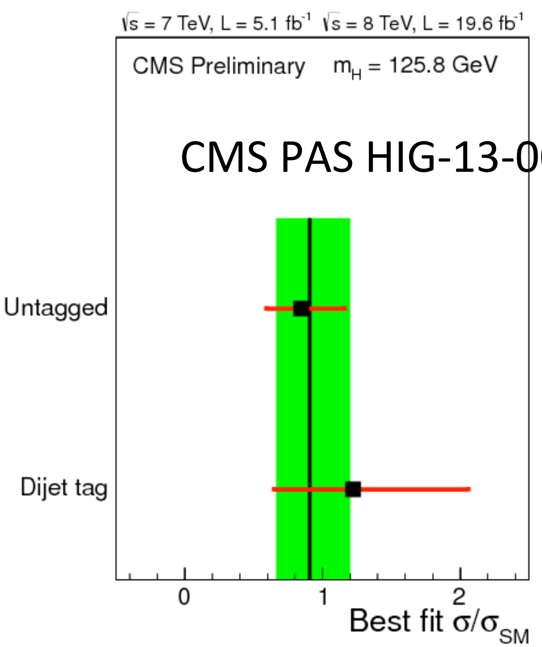


$H \to ZZ \to 4\ell$ (+2ℓ2τ): CMS results





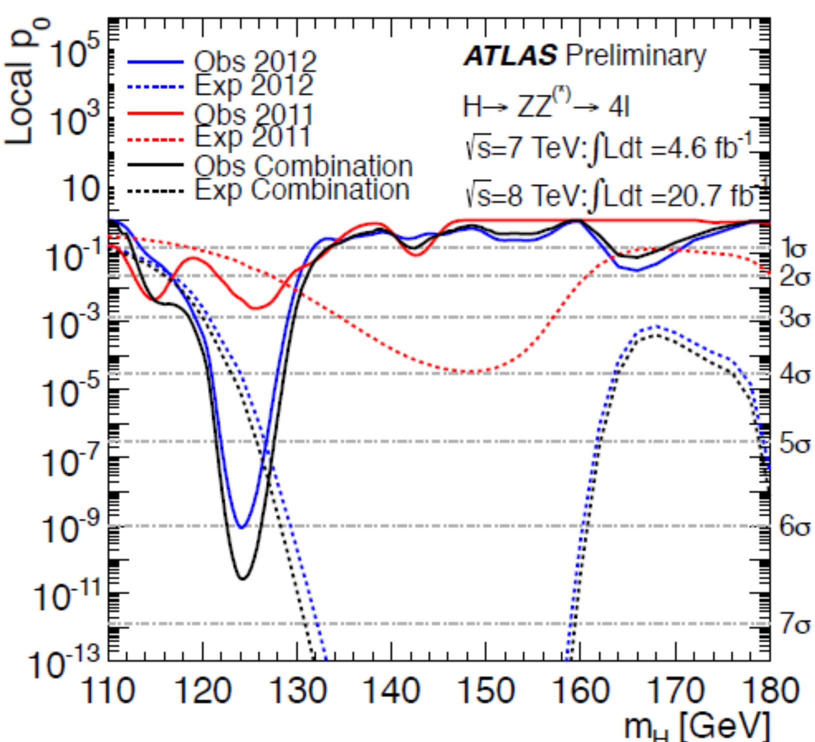
- Excess of events at 125.8 GeV
  - expected significance: 7.2σ ($P < 10^{-12}$)
  - observed significance: 6.7σ
  - Fitted $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$

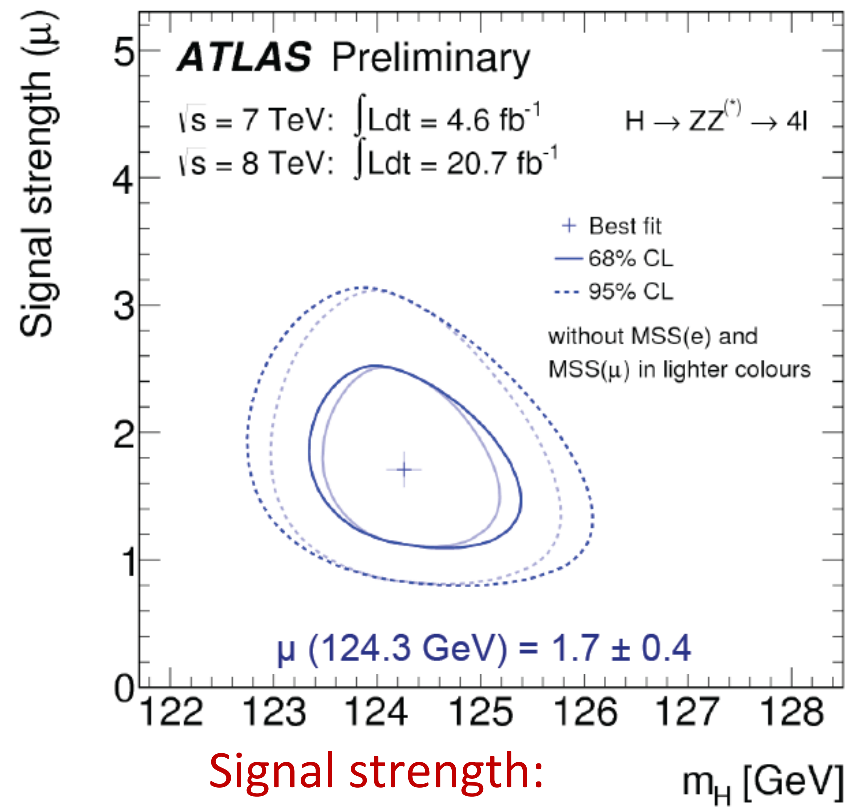


CMS PAS HIG-13-002

Consistent results obtained with 1D and 2D fits

$H \rightarrow ZZ^* \rightarrow 4\ell$: ATLAS Results





Signal Significance :
6.6σ (4.4σ expected)

arXiv:1307.1427

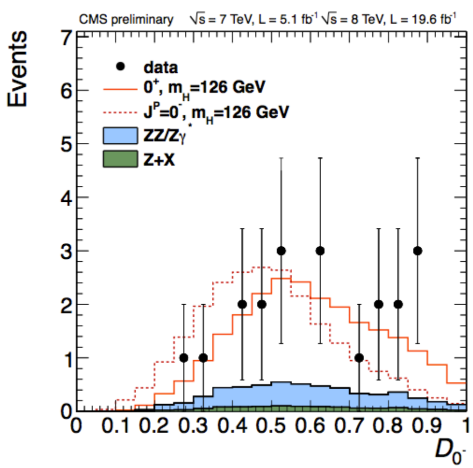
Signal strength:
$\mu = 1.7^{+0.5}_{-0.4}$
at mass = 124.3 GeV

Compare Experiments based on expected sensitivity:

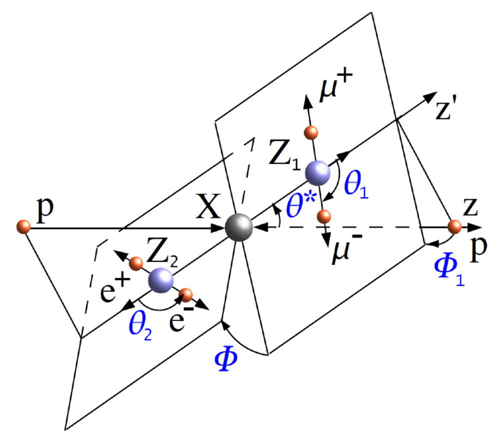
CMS: 7.2σ expected — ATLAS: 4.4σ

$\mu_{CMS} = 0.91^{+0.30}_{-0.24}$ — $\mu_{ATLAS} = 1.7^{+0.5}_{-0.4}$

- Spin and parity can be probed using angular distributions
- H→ZZ is the best channel as all angles are measured
  - Using discriminators similar to K_D we can distinguish between scalar and pseudo-scalar and different spin hypotheses
  - Derive kinematic discriminants for each of 6 possible J^P particles.
  - All but one other 0^+ origin are excluded at >98% CL.



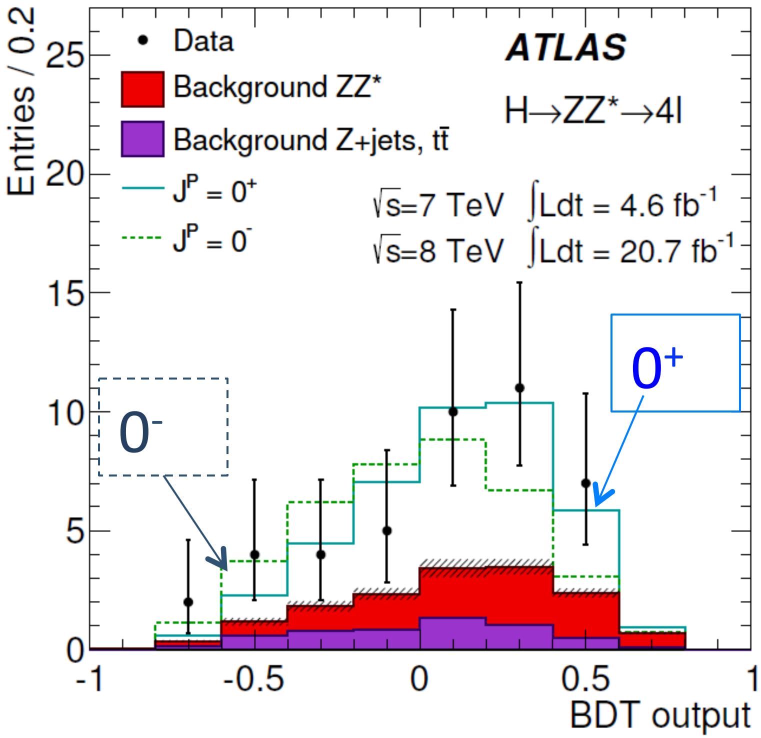
CMS PAS HIG-13-002

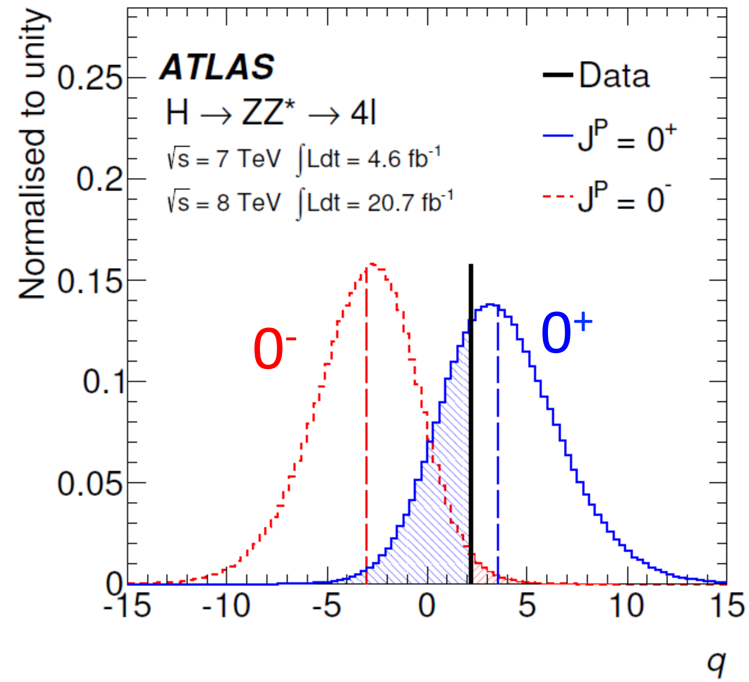


Data strongly favor $J^p = 0^+$

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

ATLAS H→ ZZ*→ 4ℓ J^P Analysis





BDT analysis variables:

m_{Z1}, m_{Z2} from Higgs --> ZZ* →4ℓ
+ production and decay angles

Exclusion **(1-CL_s):**

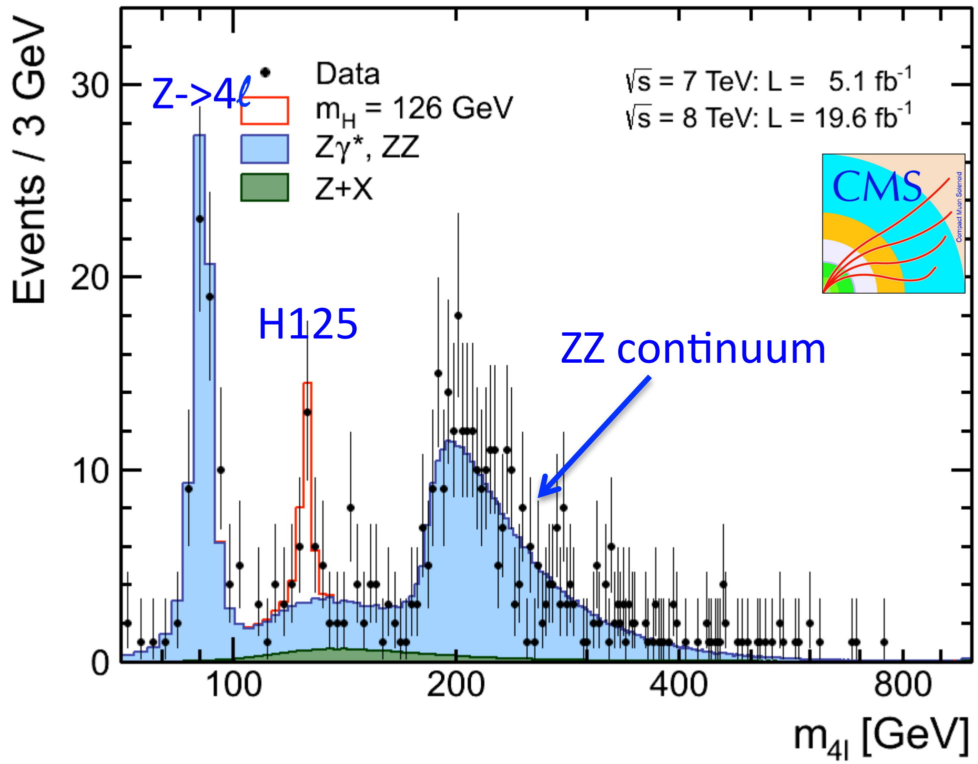
Observed 0^- exclusion 97.8%

Observed 1^+ exclusion 99.8%

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

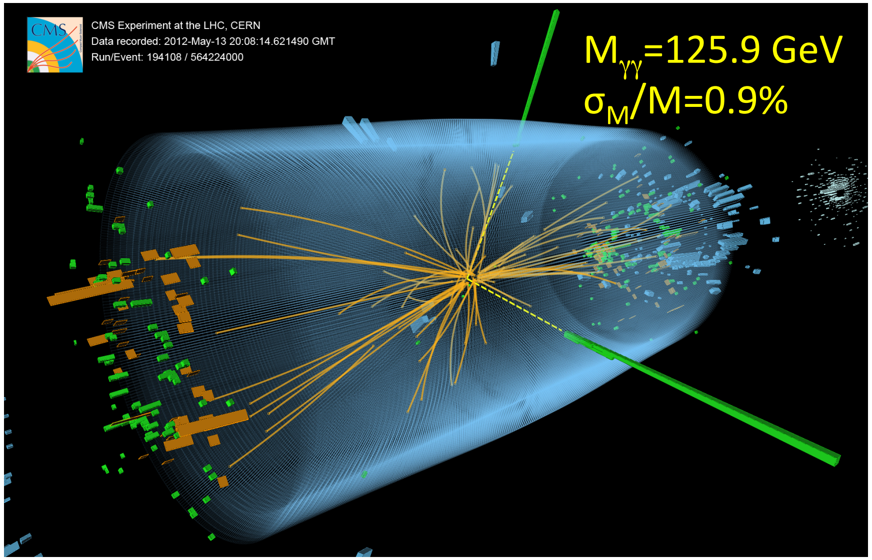
H→ ZZ*→ 4ℓ is Still Golden

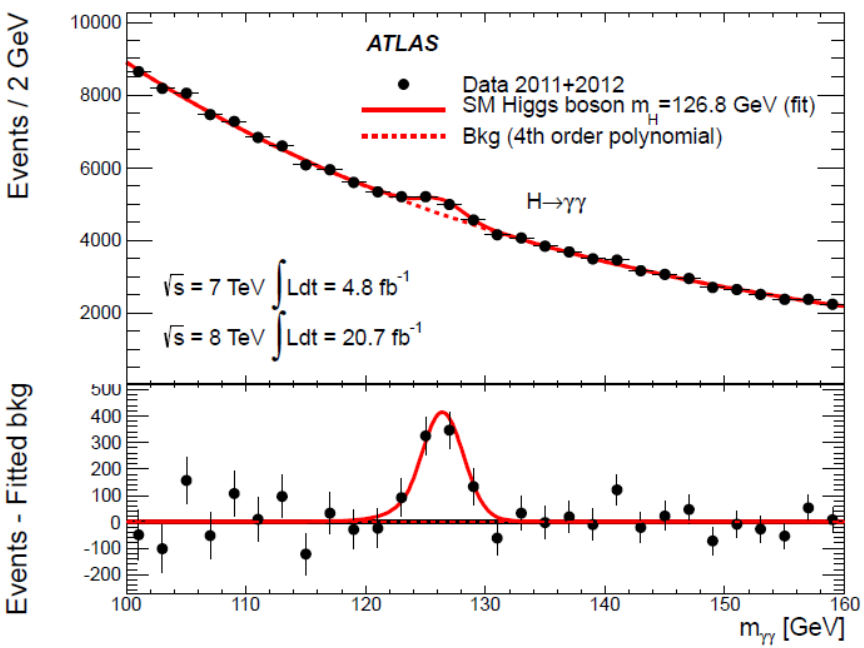
- We are at very low statistics in this channel.
- This analysis will not be limited by systematic error for a long time.



H→γγ is a Systematically Safe Analysis

- Signal model well tested with Z→ee (or μμ)
  - Photon resolution better than e
  - photon ID
  - vertex choice (μμ)
  - Small step using MC from e to γ & from 91 to 125 GeV
- Bkgd determined by fit to data
  - have carefully studied parameterizations needed
  - no use of MC to get background
- This channel will be statistics dominated even for large increases in luminosity.
  - Statistical error is dominated by error on background events under the peak.

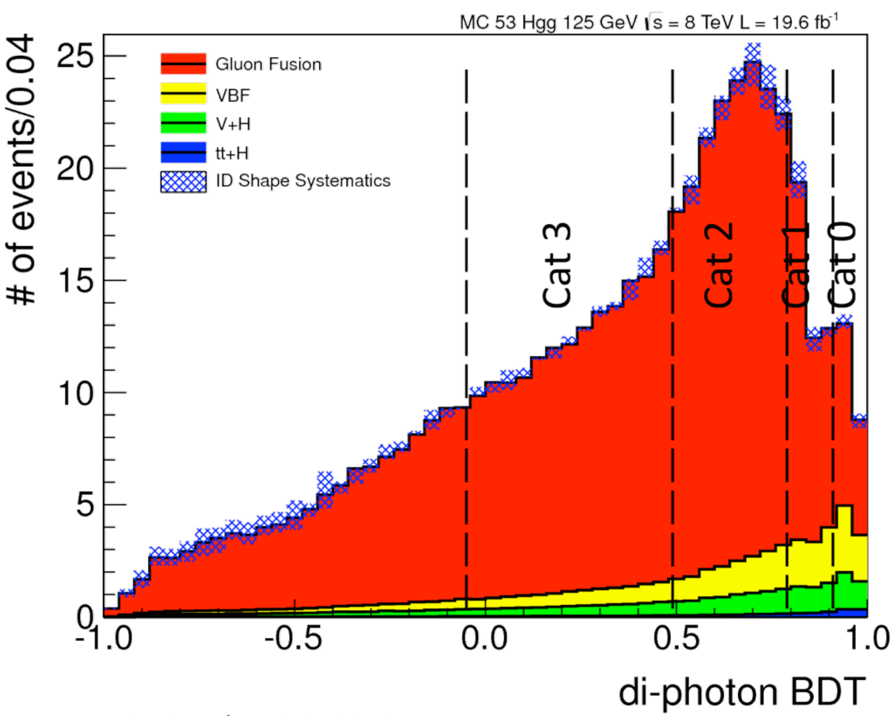


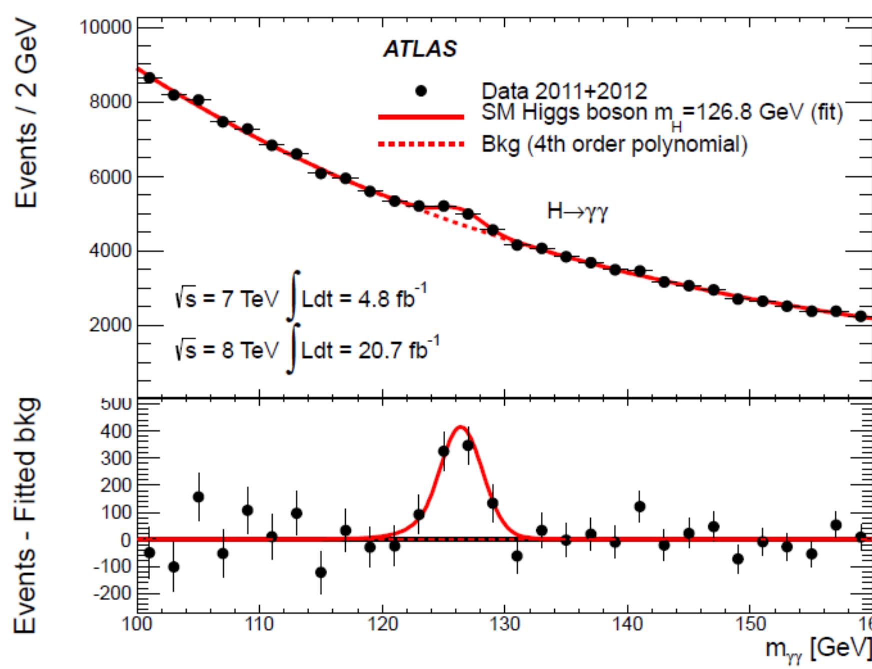


H→γγ Mass-Independent MVA Analysis

- CMS: 4 event categories based on a diphoton Boosted Decision Tree (BDT)
  - cut on MVA does not alter mass shape significantly over the full mass range
  - Separates events with different s/b, including resolution
- BDT inputs:
  - Kinematics, photon Id classifier, estimated mass resolution
- Additional categories for di-jet, lepton, and MET tags
  - 9 categories in all

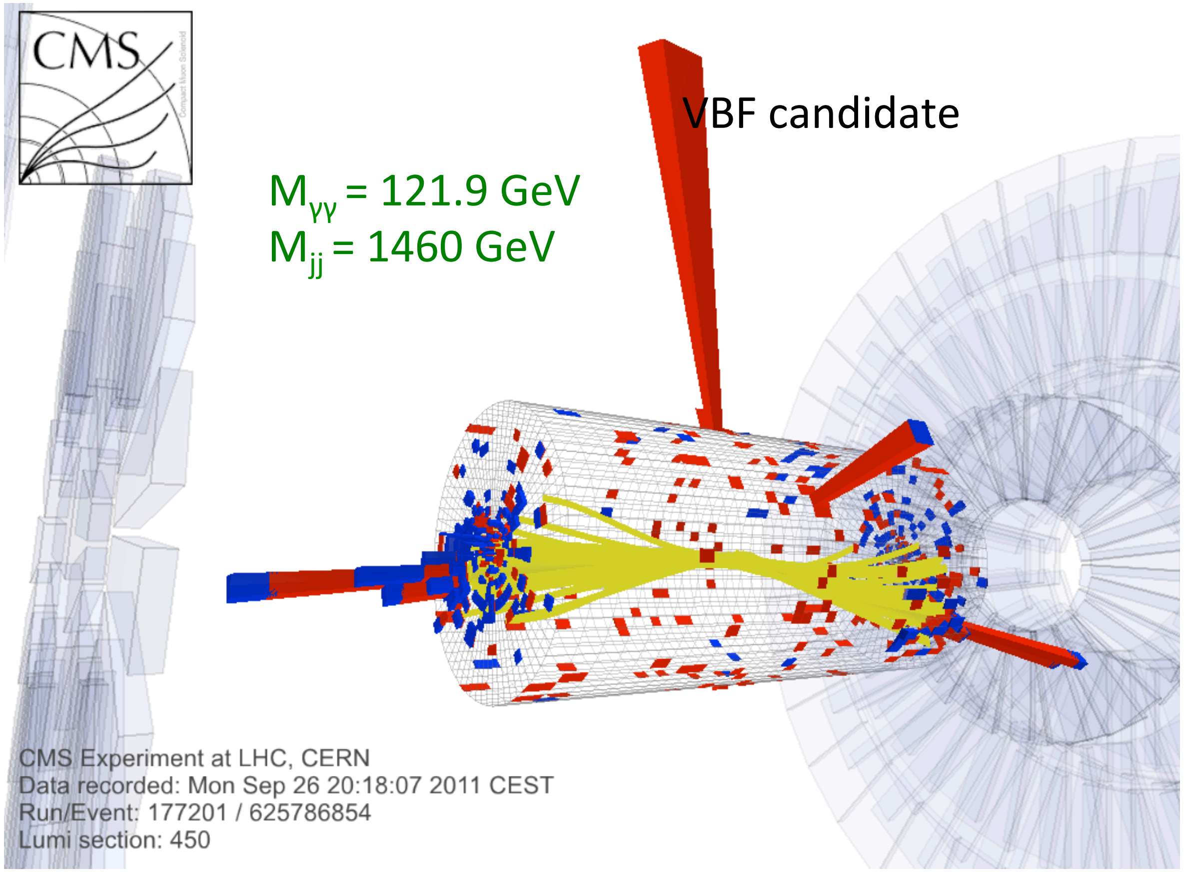
- ATLAS: Simple signature: two high-p_T isolated photons - $E_T(\gamma_1, \gamma_2) > 40, 30$ GeV ($\sqrt{s}$=8 TeV)
- Events divided into 14 categories based on production mode and S/B ratio in different detector region (increase sensitivity, also for coupling measurements)



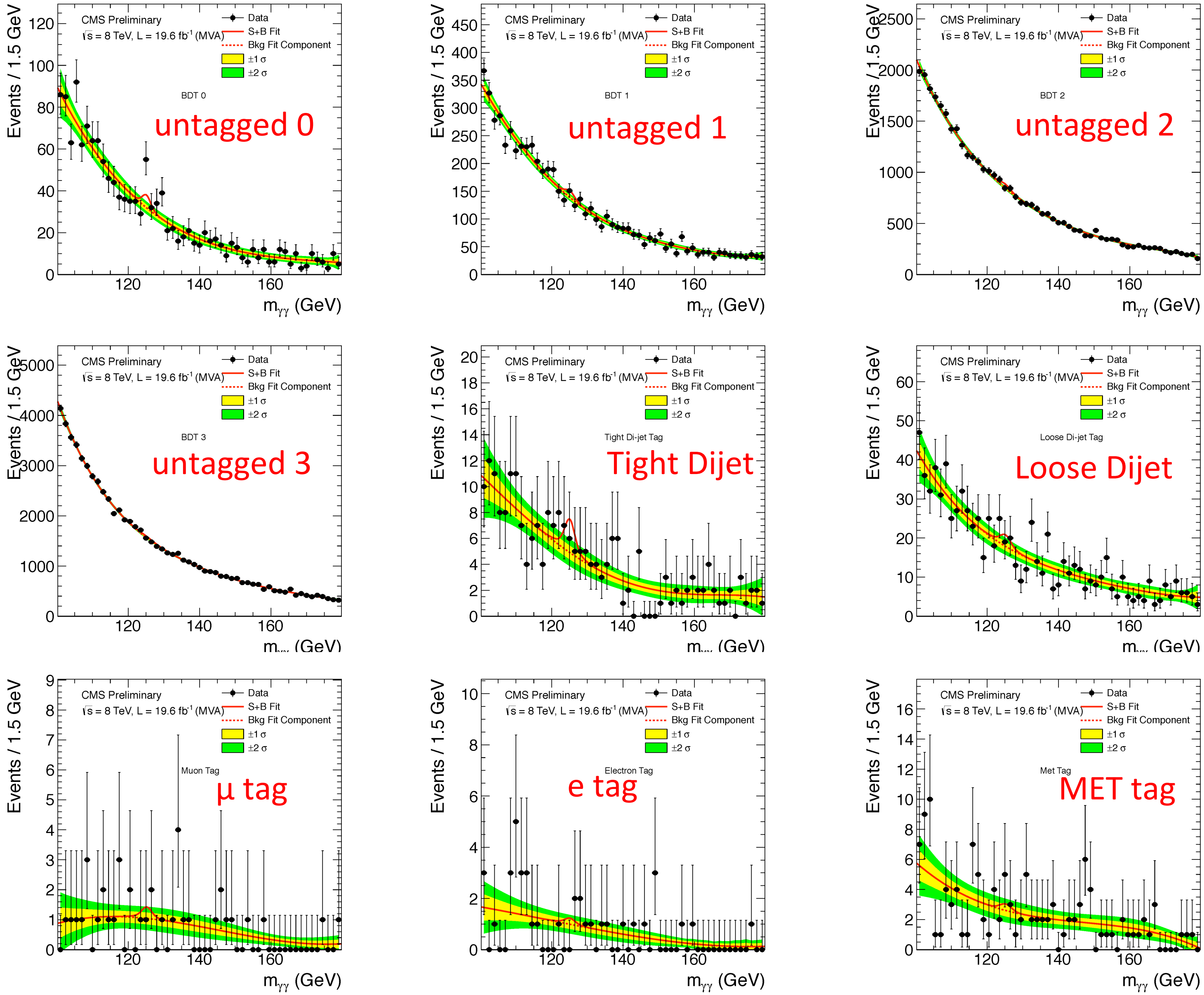


H→γγ Di-jet Tag

- Di-Jet tag enhances VBF production significantly
  - Most important variables are M_{jj}, P_{Tjet}, $\Delta\eta$
  - di-jet BDT used to improve tag
  - H→γγ gives the best VBF measurement

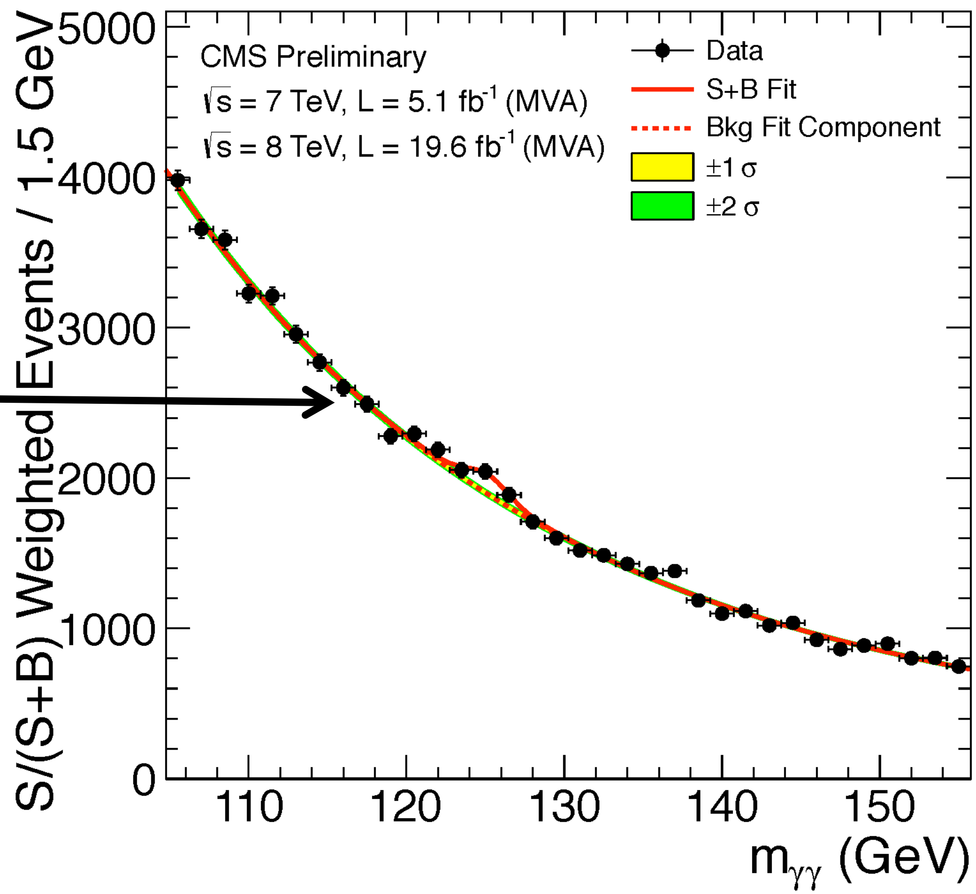


8 TeV Categories



H→γγ Weighted Mass Distribution

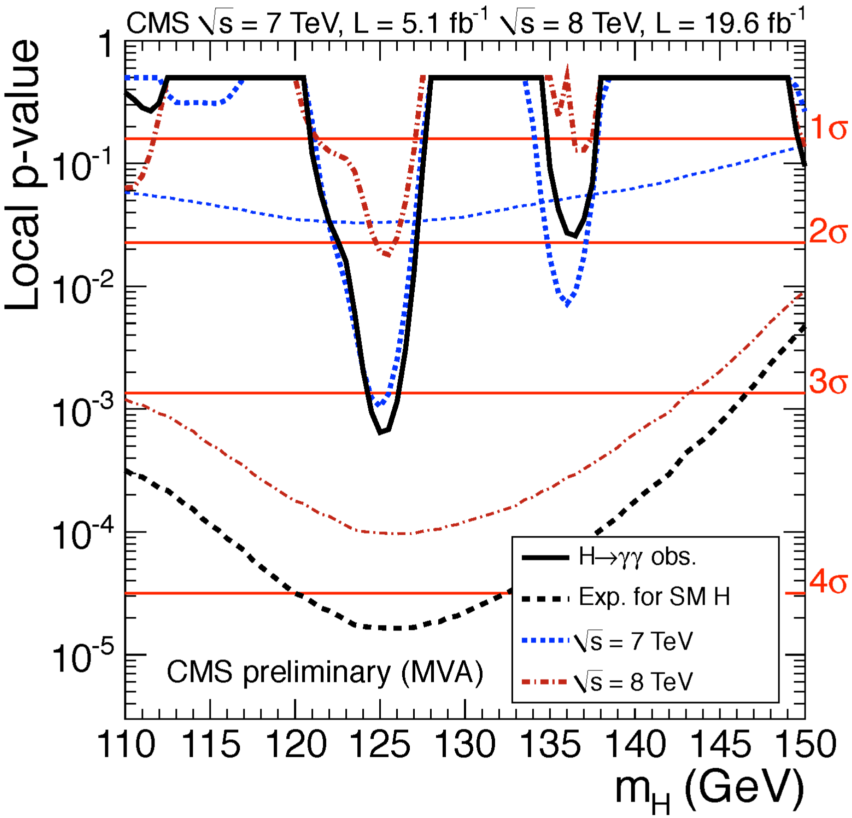
Weighed data events and BG model parametrizations



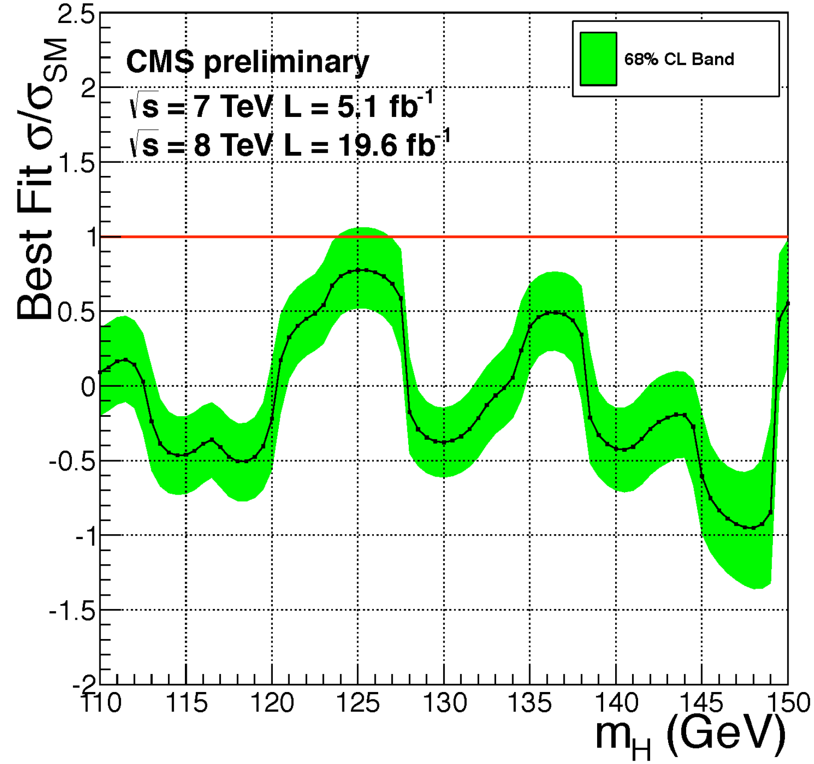
- **One weight per category.**
- Sum of mass distributions for each event class, weighted by S/(S+B)
- B is integral of background model over a constant signal fraction interval

- This plot is not used in the analysis and it is for illustration only, it adds all event classes together

H→γγ Results: p-values



CMS PAS HIG-13-001



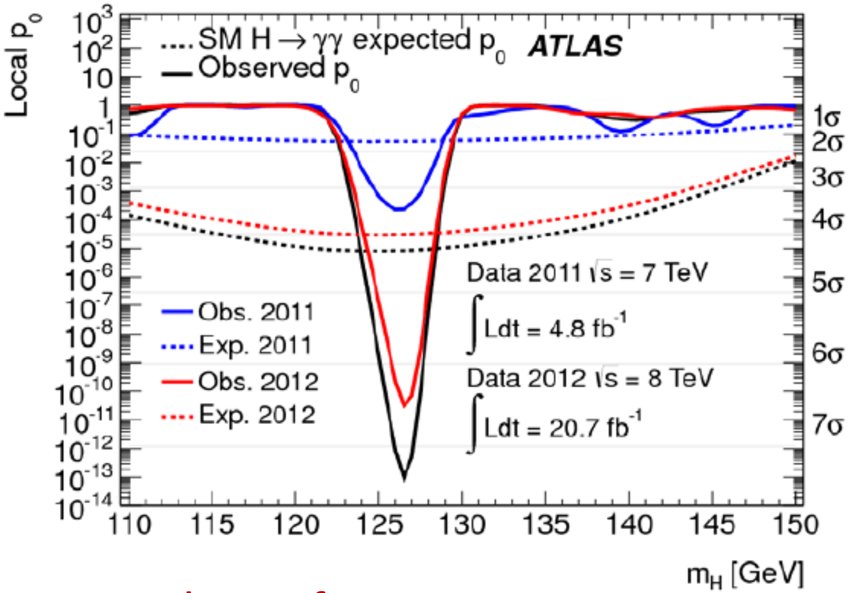
- Largest excess around 125 GeV
  - Local significance 3.2 σ at 125 GeV
  - Expected significance 4.2 σ at 125 GeV
  - Fitted σ/σ_{SM} at 125 GeV $0.78^{+0.28}_{-0.26}$

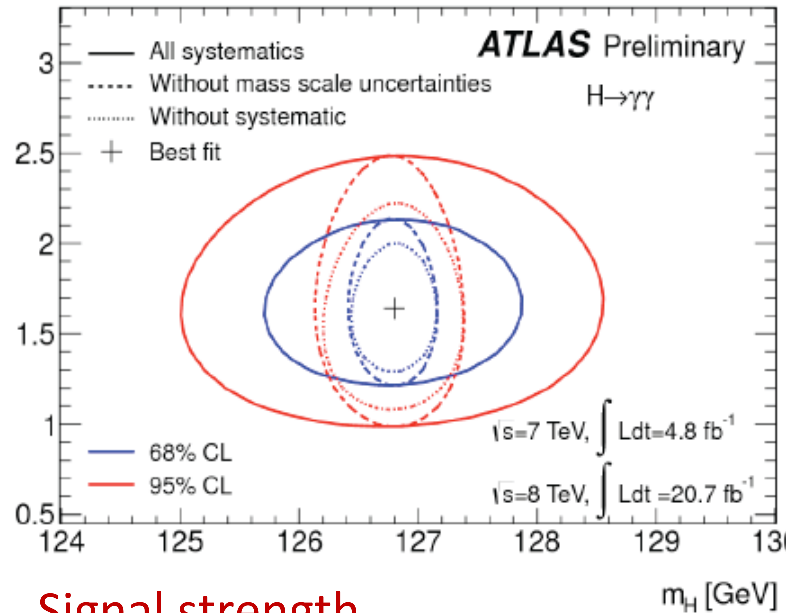
Consistent results from cut based: σ/σ_{SM} at 125 GeV $1.11^{+0.32}_{-0.30}$

(consistency check with jackknife method).

H→ γγ

arXiv:1307.1427





Signal Significance :
7.4σ (4.3σ expected)

Signal strength
$\mu = 1.57 \pm 0.24(stat) \pm 0.22(syst)$
at mass = 126.8 GeV

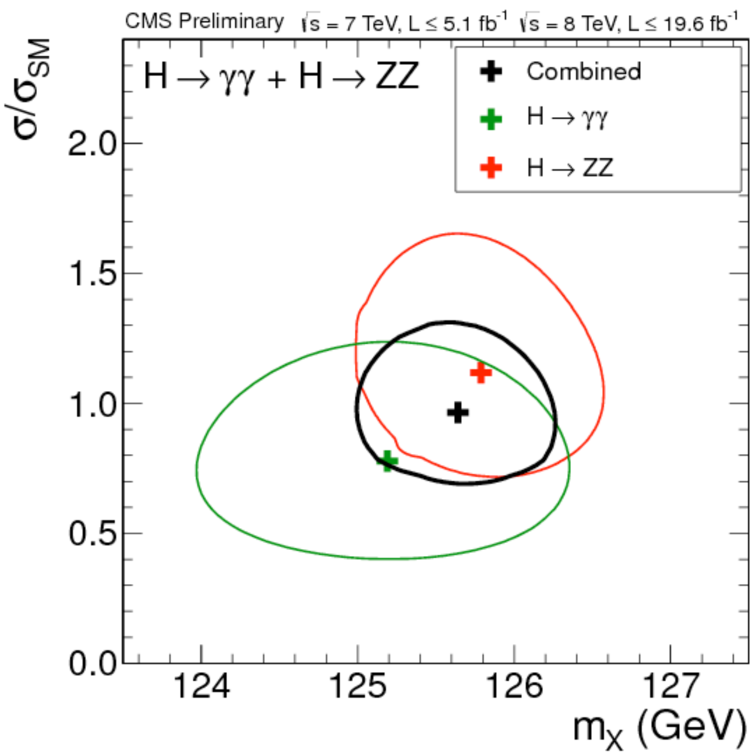
Obs ($\sqrt{s}$=8 TeV, m_H^{rec} = 126.8 GeV $\pm 2\sigma$)	Expected purity s/s+b ($\sqrt{s}$=8 TeV)	Main backgrounds
13931	**370/13575 = 2.7%**	**γγ,γj and jj**

Compare Experiments based on expected sensitivity: CMS: 4.2σ, ATLAS: 4.3σ.
$\mu_{CMS} = 0.78^{+0.28}_{-0.26}$ (includes stat & syst) $\mu_{ATLAS} = 1.57 \pm 0.24(stat) \pm 0.22(syst)$

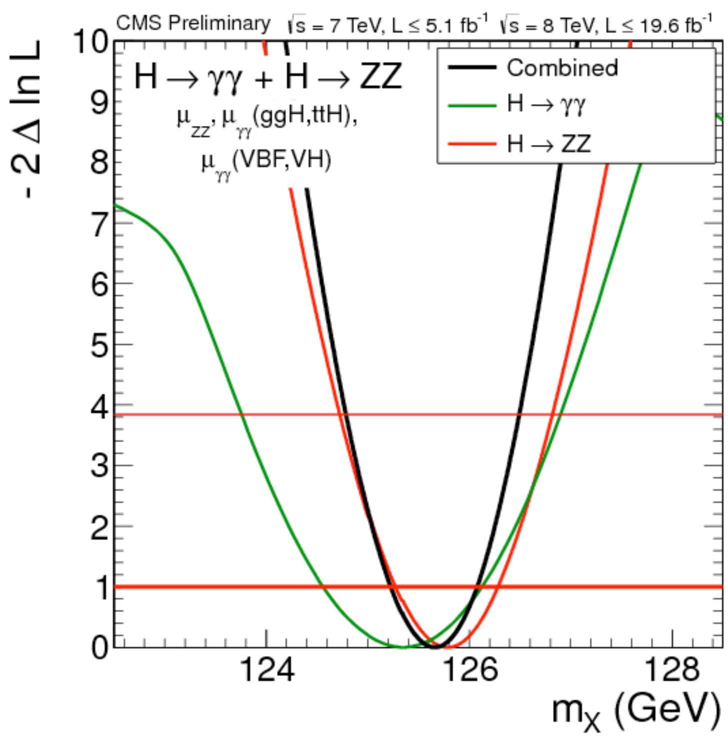
Combined Mass Measurement

- Mass can be measured with higher precision with $\gamma\gamma$ and ZZ
  - To reduce model dependence, allow for free cross section in different channels and fit for the common mass
  - Note: Fit to ZZ is simpler in this combined fit so fit-μ is different

2D scan μ vs mass



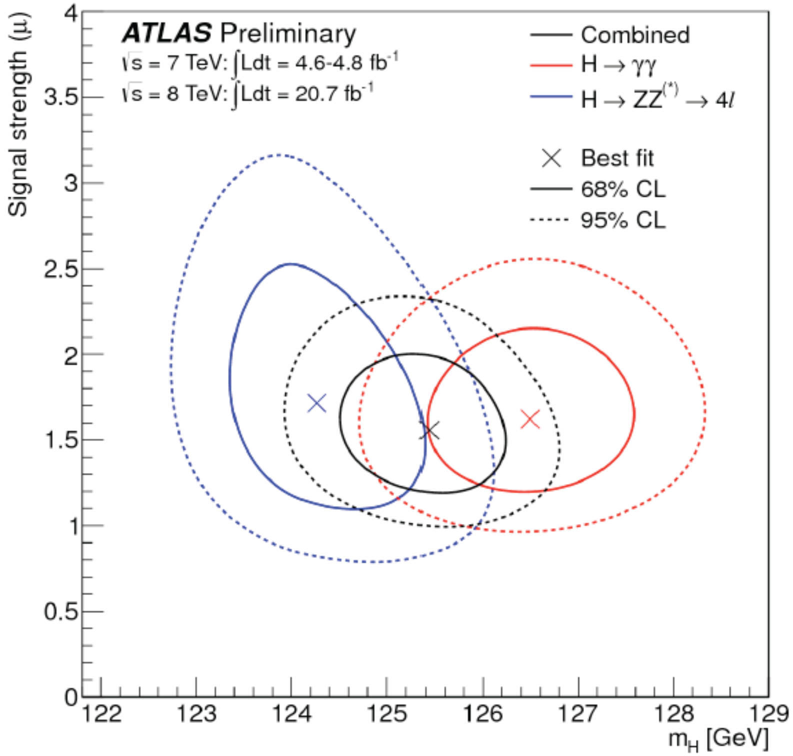
1D scan: mass

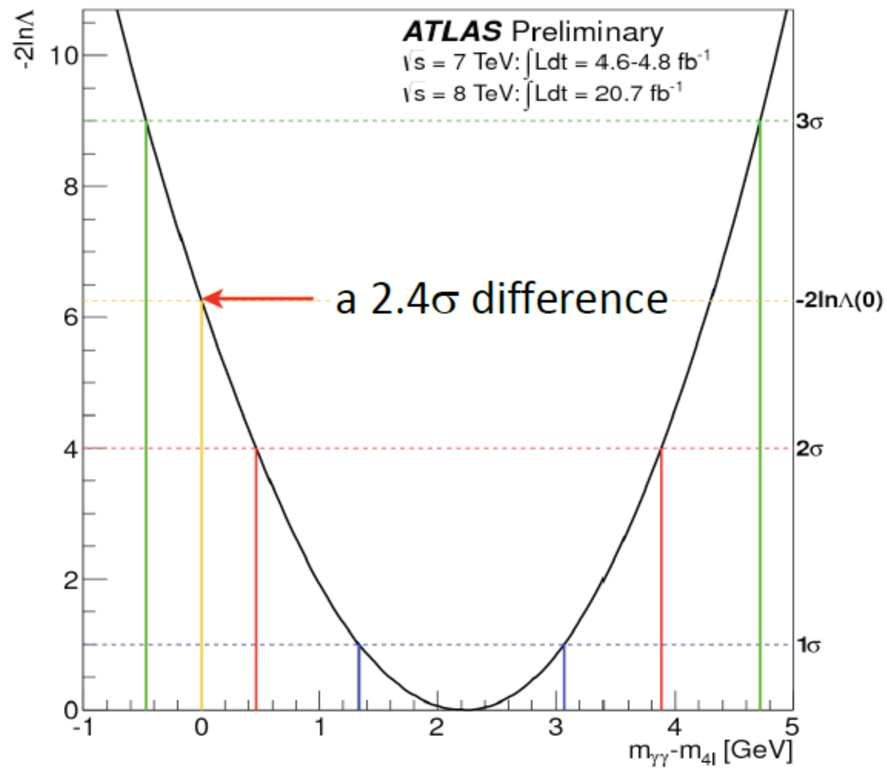


- $M_H = 125.7 \pm 0.3(\text{stat.}) \pm 0.3(\text{syst.})$ GeV

Mass Combination (4ℓ, γγ)

Combined mass measurement m_H = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV





$$m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst) \text{ GeV}$$

$$m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst) \text{ GeV}$$

Two measurements are 2.3 GeV apart:

$$\Delta m_H = 2.3^{+0.6}_{-0.7}(stat) \pm 0.6(syst) \text{ GeV}$$

Prob. to observe Δm≥2.3 GeV ~ 1.5% (2.4σ)

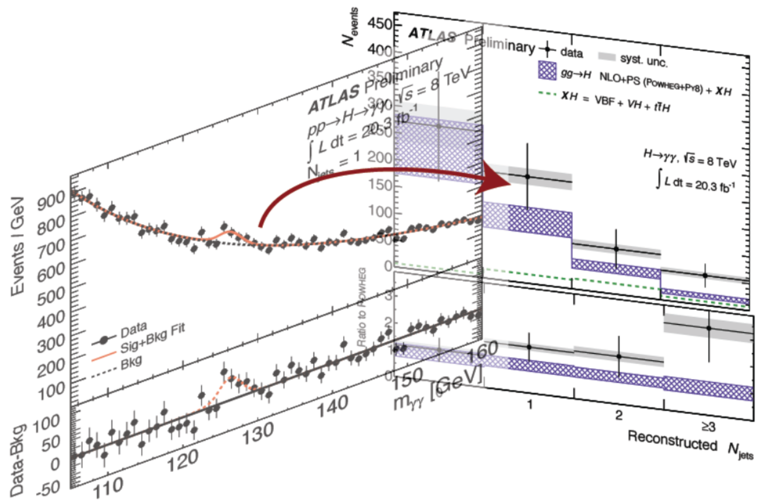
H→γγ Differential Cross-Sections

ATLAS-CONF-2013-072

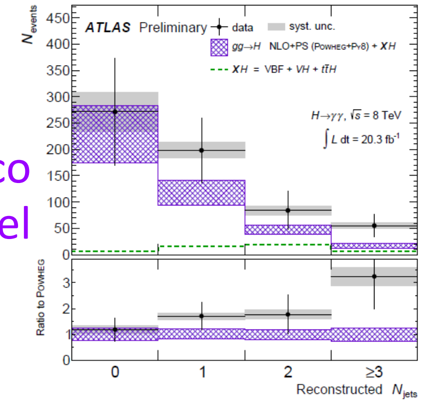
Study the kinematic distributions of H→ γγ events

To unfold the experimental measured distributions to particle level distributions (differential dσ/ dx)

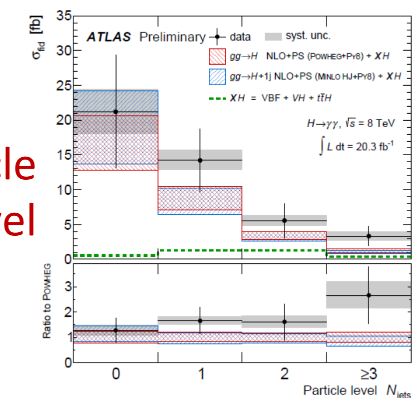
	Variable
Inclusive	$p_T^{\gamma\gamma}$
	$\lvert y^{\gamma\gamma}\rvert$
	$\lvert \cos\theta^*\rvert$
	N_{jets}
	p_T^{j1}
2-jets	$\Delta\varphi_{jj}$
	$p_T^{\gamma\gamma jj}$



Reco level

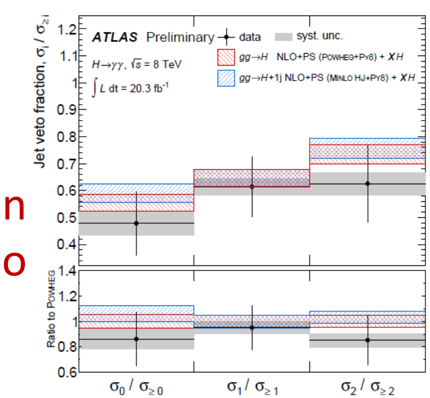


Particle level



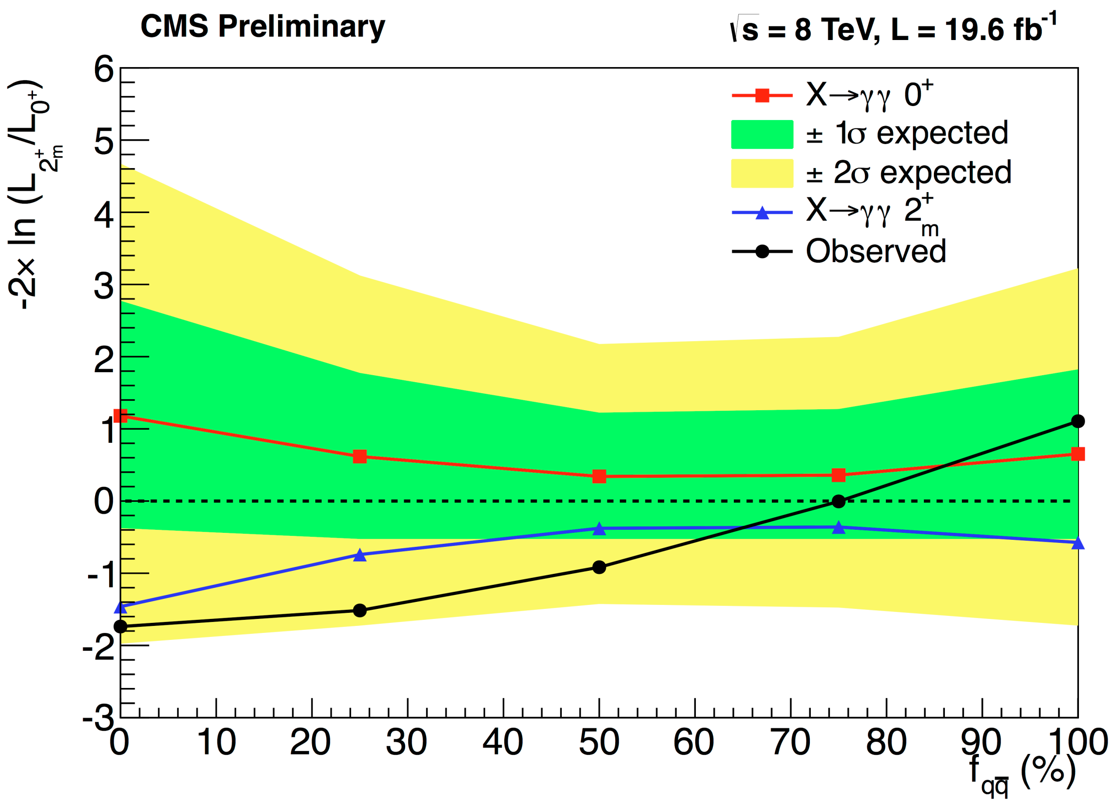
- **Bin events in variables of interest**
- **Background estimations from the mγγ side-band fit in each bin**
- **Estimate the systematics**
- **Background subtraction in each bin**
- **Unfold the reconstructed distributions to truth distributions (→ differential cross-sections)**
- **ATLAS has fairly uniform acceptance**

Cross-Section ratio



$H\rightarrow\gamma\gamma$ spin analysis

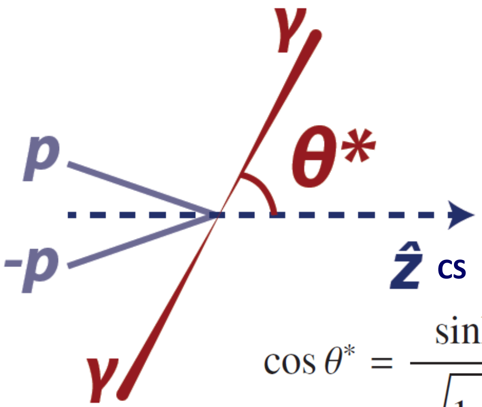
- Consider graviton-like hypothesis 2^+
- Production can be gg fusion or qq annihilation
- Sensitivity still rather low for high qq fraction



CMS PAS HIG-13-016

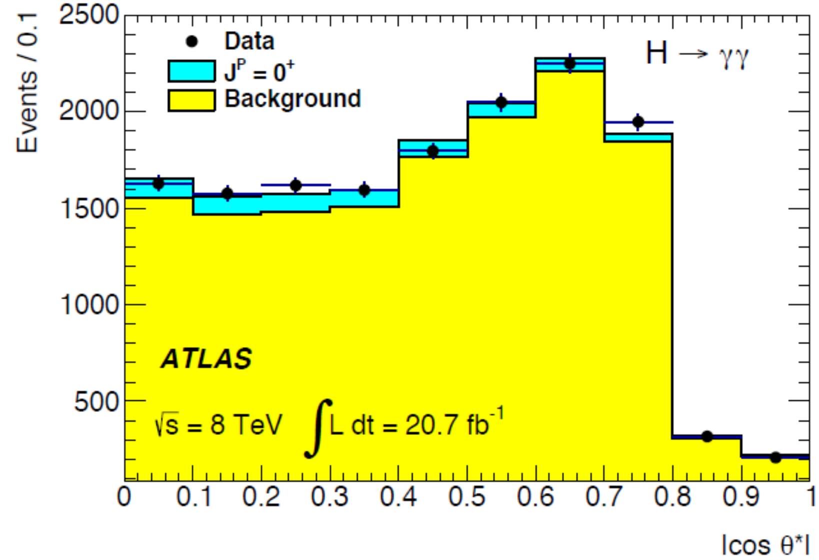
Spin Analysis with H→ γγ

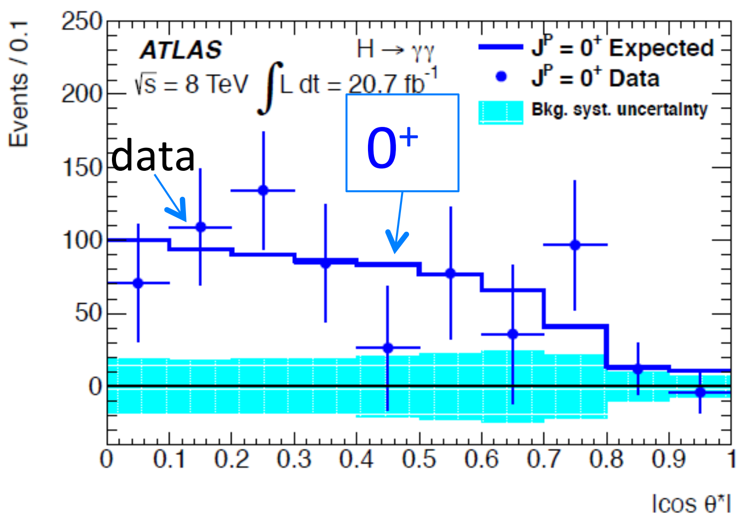
Polar angle θ^* of the photon decay in Collins-Soper frame, along with $m_{\gamma\gamma}$

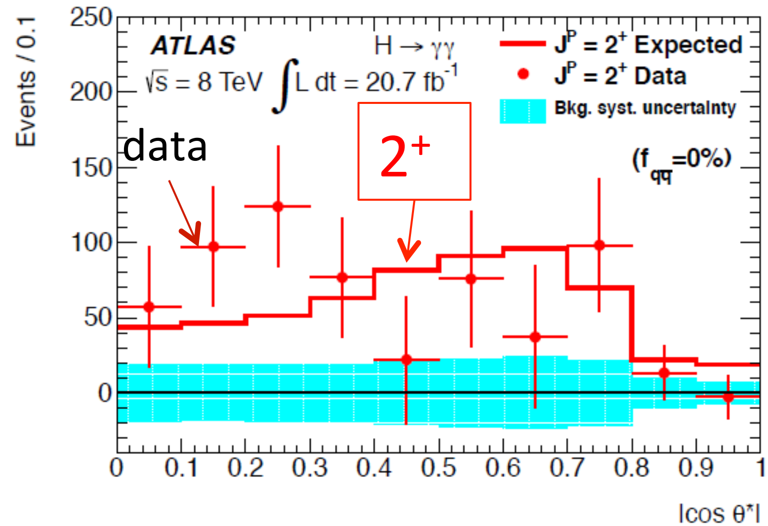


Z_{CS} bisects angle between the momenta of colliding hadrons

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$







2^+ Hypothesis Exclusion in H→ γγ

Method

- Binned likelihood using discriminants
  e.g. $\mathbf{m_{\gamma\gamma}}$ and **|cos θ*|**
- Poisson probability given a signal ***S*** scaled by strength μ and background ***B*** with nuisance parameters θ and constraints from auxiliary
- measurements *A* for each channel

Ratio of likelihoods test statistic

$$q = \log(L(0^+)/L(J^P_{alt}))$$

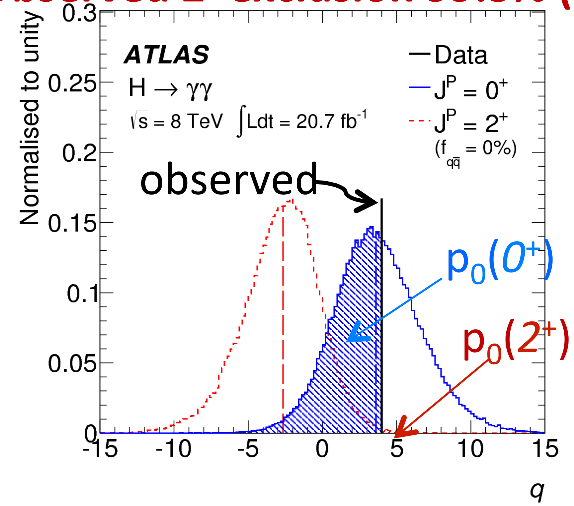
with μ fixed for a given J^P

- **Exclusion using (1 - CL_S)**

$$CL_S = p_0(J^P_{alt}) / (1-p_0(0^+))$$

$$\mathcal{L}(J^P,\mu,\theta) = \prod_j^{N_{\mathrm{chann.}}} \prod_i^{N_{\mathrm{bins}}} P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta)$$

Observed 2^+ exclusion 99.3% (1-CL_S)

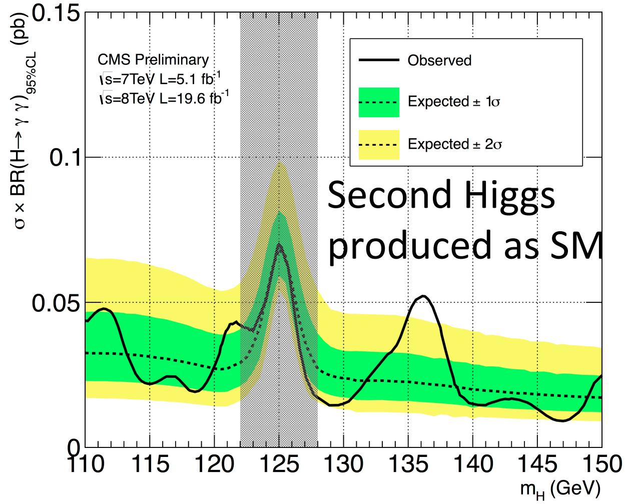


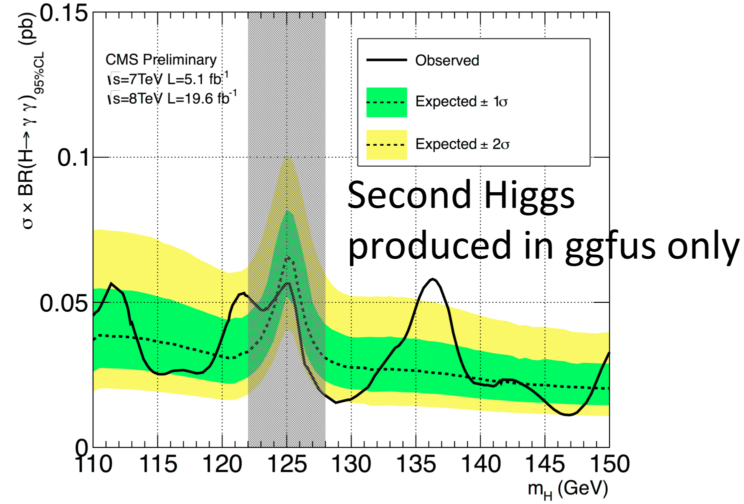
$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

H→γγ - Double Higgs

- H125 used as additional BG

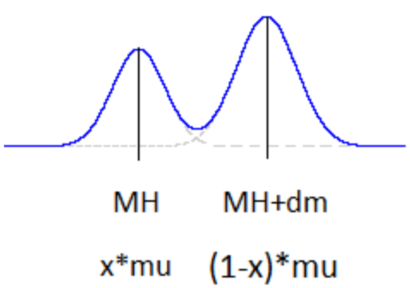
CMS PAS HIG-13-016

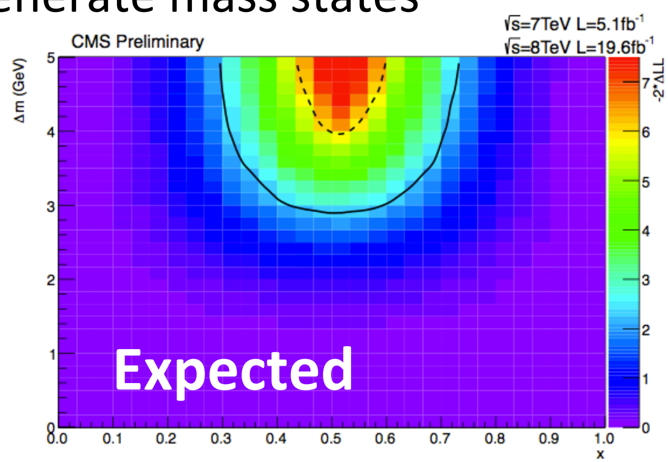


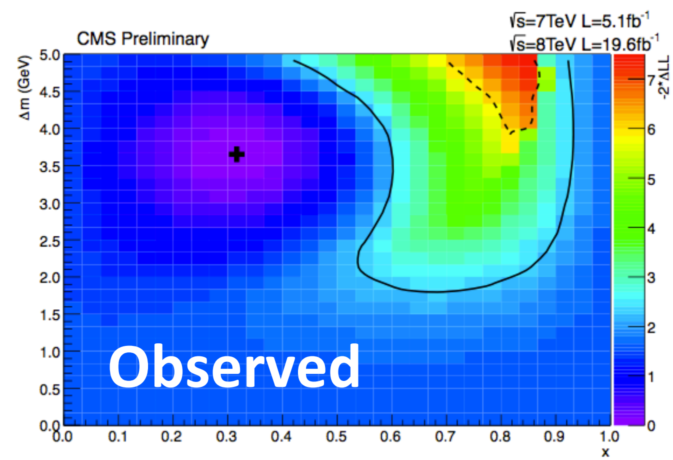


$M_{H'}$=136.5
Local significance 2.9 σ
Global significance <2σ

- Two nearly degenerate mass states







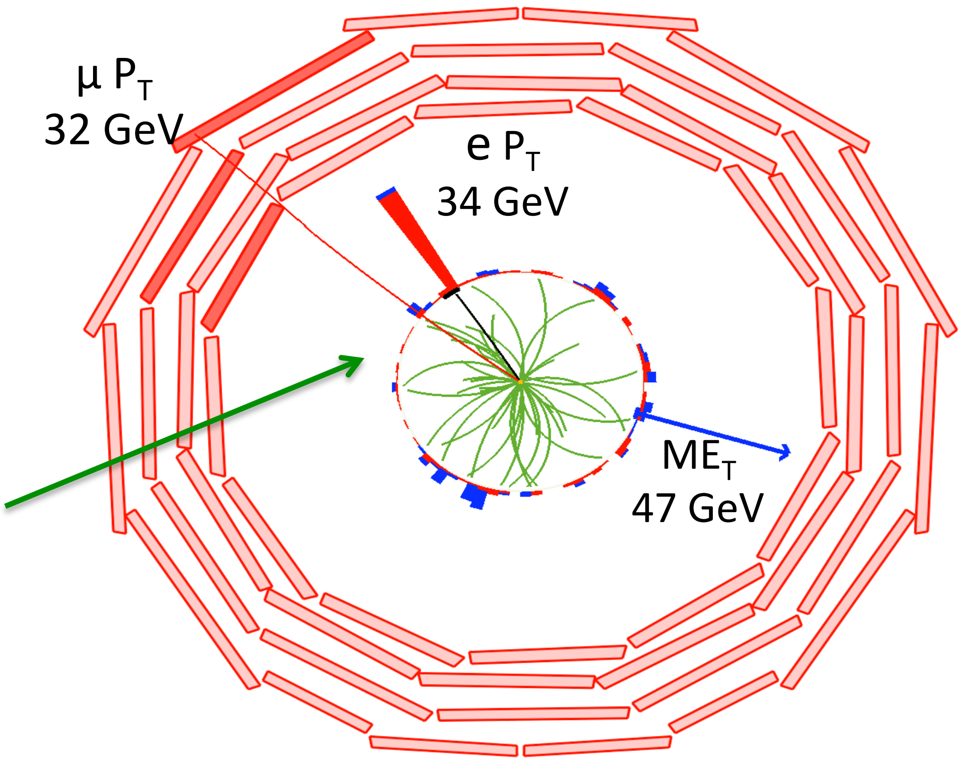
Allows to exclude parameters in the 2HDM when two Higgs boson interpreted as h,H or h,A

H→WW→ℓνℓν

- Two high p_T isolated leptons + **MET**
- No narrow mass peak
- Most sensitive channel around $2M_W$
  - Also at 125 GeV it gives the smallest error on μ
- Main backgrounds
  - WW (irreducible)
  - Z+jets, WZ, ZZ, tt, W + jets
- BG estimation is crucial
  - Main BG estimated from data
  - Less clear how this scales with $\mathcal{L}$

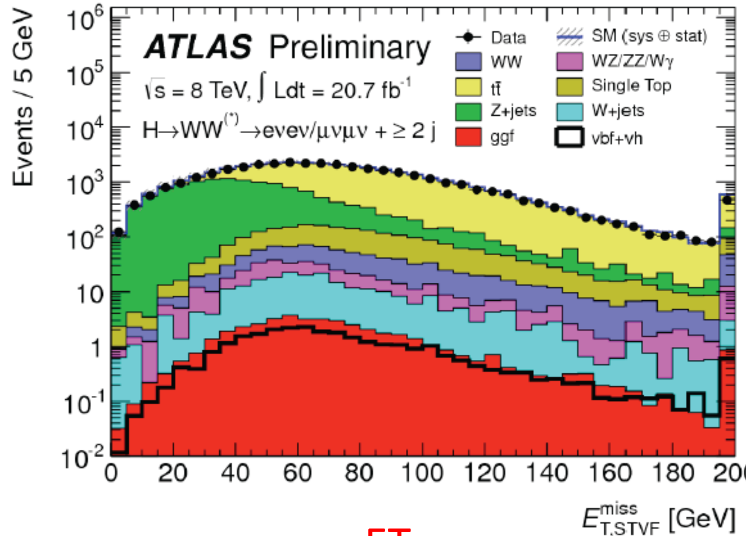
Scalar Higgs boson + V-A structure of W decay favors small Δϕ between the 2 charged leptons

H->WW->eμνν candidate

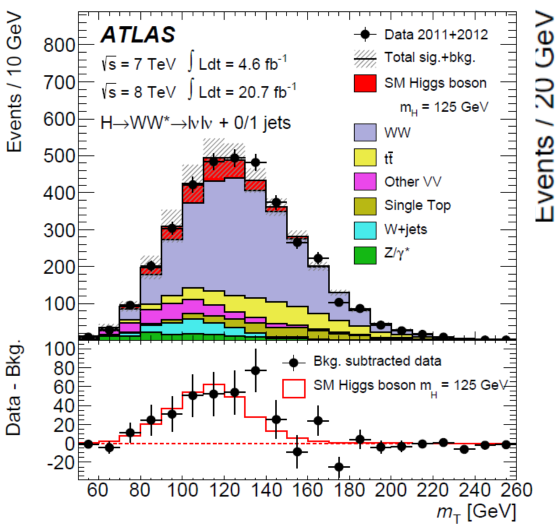


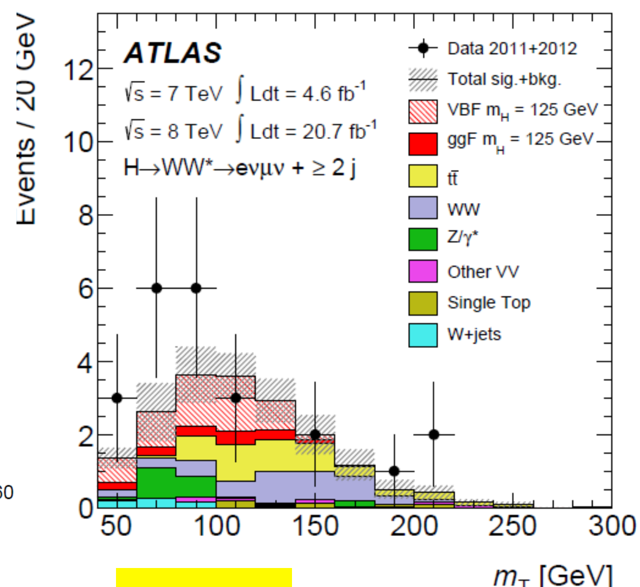
H→WW*→ℓνℓν

- ❑ *ee,eμ,μμ* + 2ν final state
- ❑ N_{jet} classification (0,1, >= 2 jet) to separate ggF and VBF processes
- ❑ eμ channel most important (large DY bkgd for ee and μμ)
- ❑ Experimental challenges: E_T^{miss}, Njet
- ❑ final discriminant M_T



ETmiss

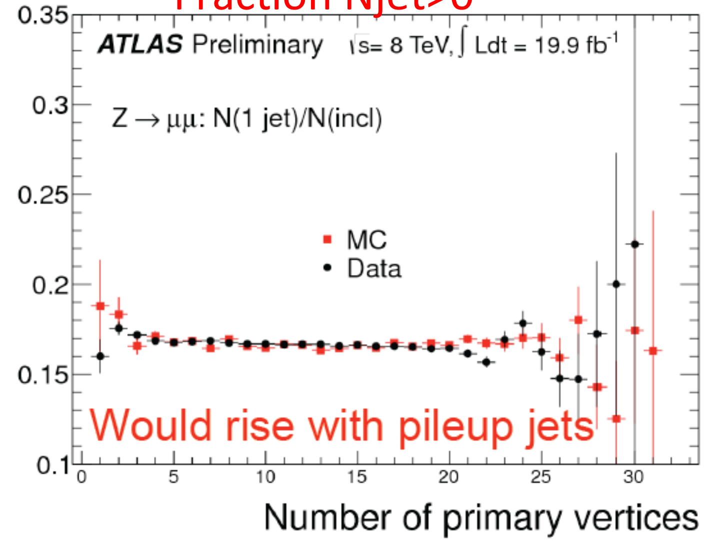




Njet =0,1

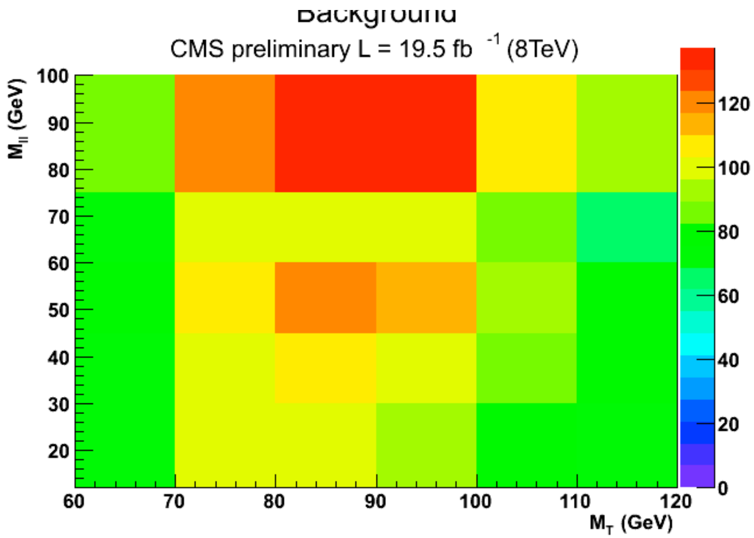
Njet = 2

Fraction Njet>0

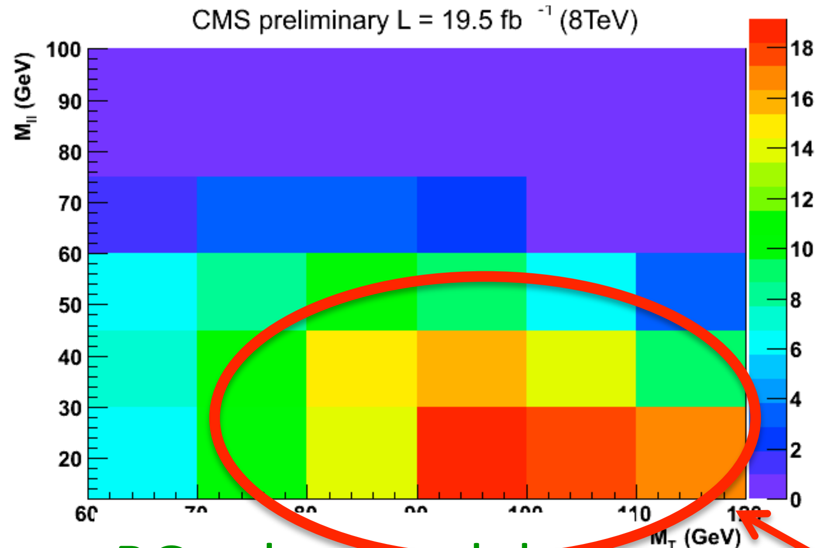


WW→ℓνℓν 2D analysis (0 jet bin)

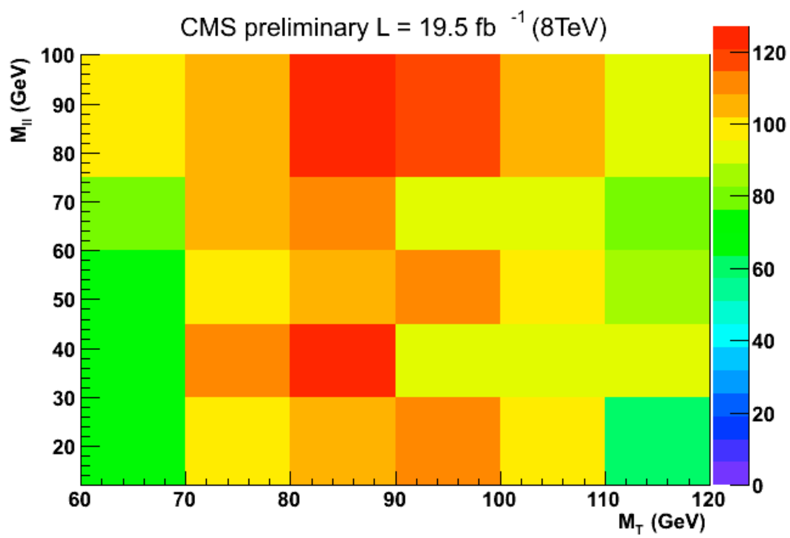
MC Background



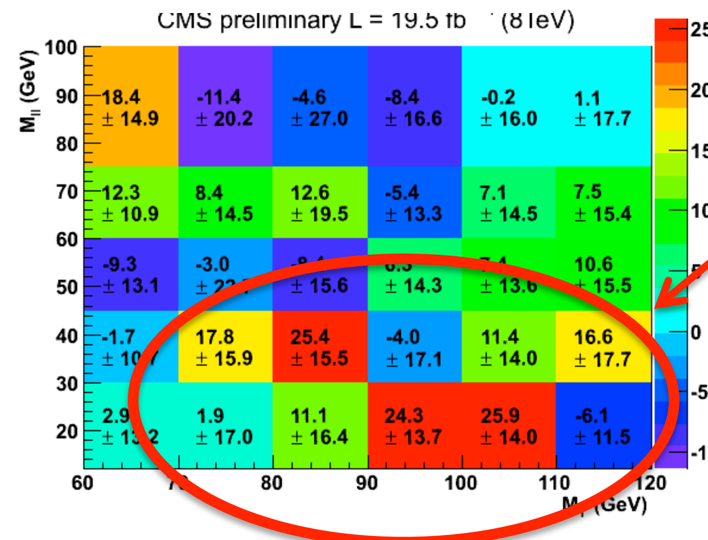
Higgs signal at 125 GeV



Data

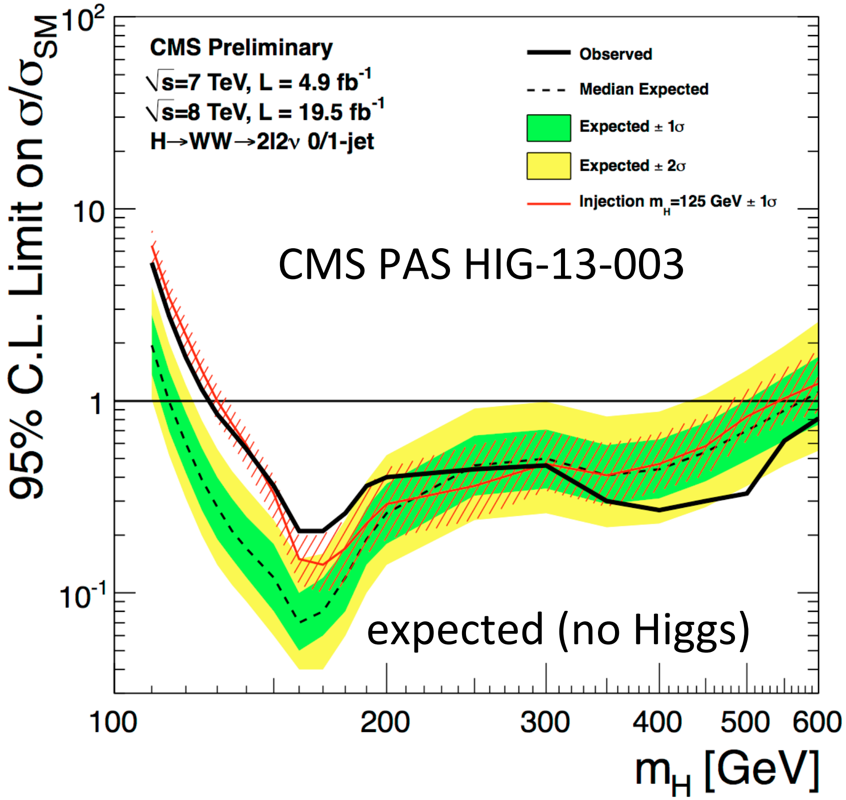


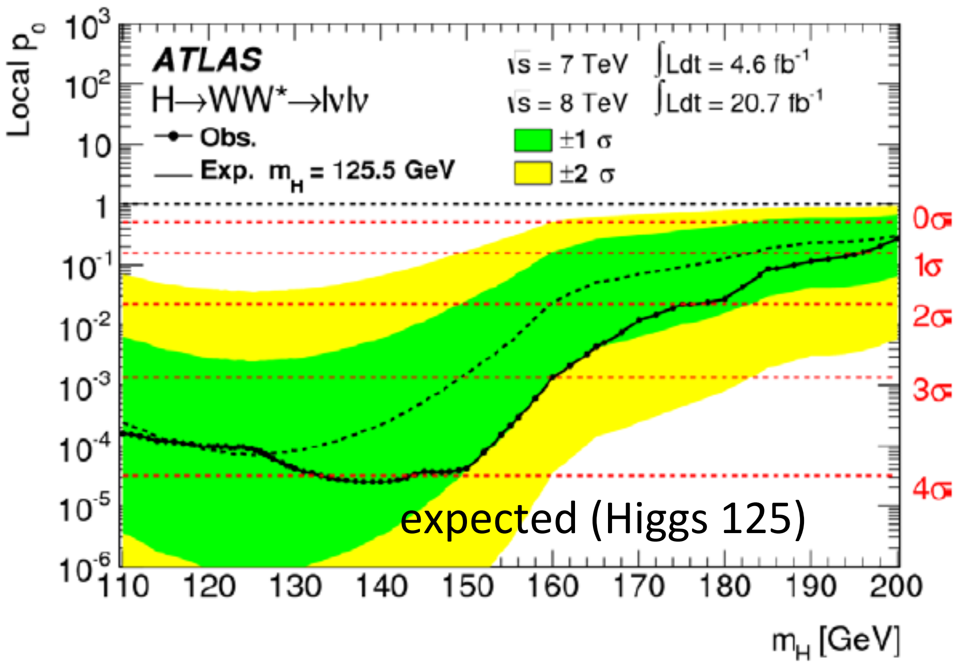
BG subtracted data



Signal region

H→WW→ℓνℓν: results





- CMS: Broad excess consistent with 125 GeV
  - expected significance: 5.1 σ
  - observed significance: 4.0 σ
  - Fitted $\sigma/\sigma_{SM} = 0.76 \pm 0.21$
- ATLAS: Broad excess consistent with 125 GeV
  - expected significance: 3.8 σ
  - observed significance: 3.8 σ
  - Fitted $\sigma/\sigma_{SM} = 0.99 \pm 0.30$

Z/W (→ll/lν) + H (→WW*→ℓνℓν)

ATLAS-CONF-2013-075

$WH \rightarrow WWW^{*} \rightarrow 3\ell + E_T \quad ZH \rightarrow ZWW^{*} \rightarrow 4\ell + E_T$

Lepton $p_T > 10-25$ GeV, $E_T^{rel} > 25-40$ GeV

3ℓ analysis Data/MC, Total WWW contribution ~5.1 events

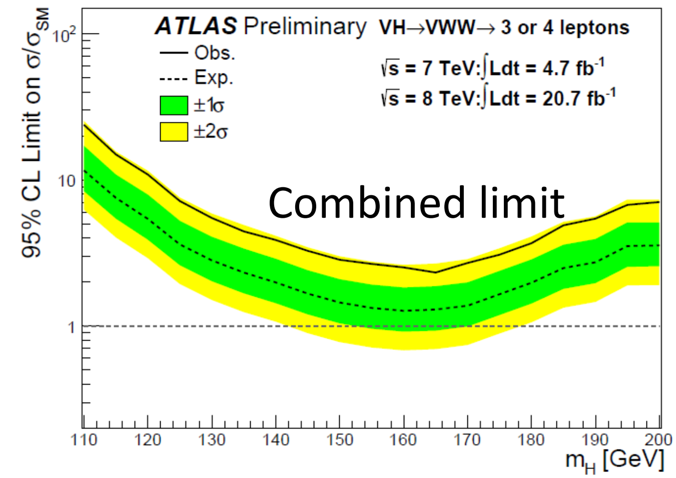
	Data	MC	Data/MC
WZ^* CR	439	438 ± 24	1.00 ± 0.07
ZZ^* CR	244	210 ± 40	1.15 ± 0.23
Z+jets CR	828	860 ± 40	0.96 ± 0.06
Top CR	6	6.2 ± 1.1	1.0 ± 0.4

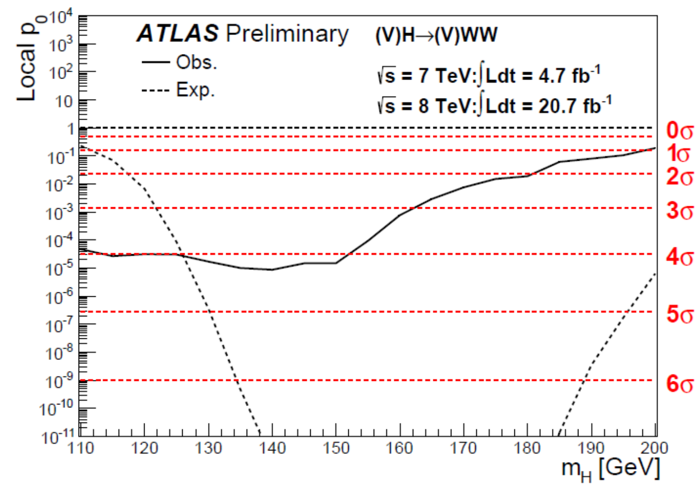
4ℓ analysis Data/MC, ZWW contribution ~0.6 events

	$Z(H \rightarrow WW)$	Data	MC	Data/MC
ZZ CR	0.03 ± 0.00	100	100.00 ± 3.19	1.00 ± 0.10

95% C.L. observed (expected) upper limit on the rate/SM at 125 GeV:
7.5 (4.0) for WH and 14.3 (9.6) for ZW

Observed small excess at 125 GeV:
1.7σ (WH→WW), 1.5σ (ZH→WW)

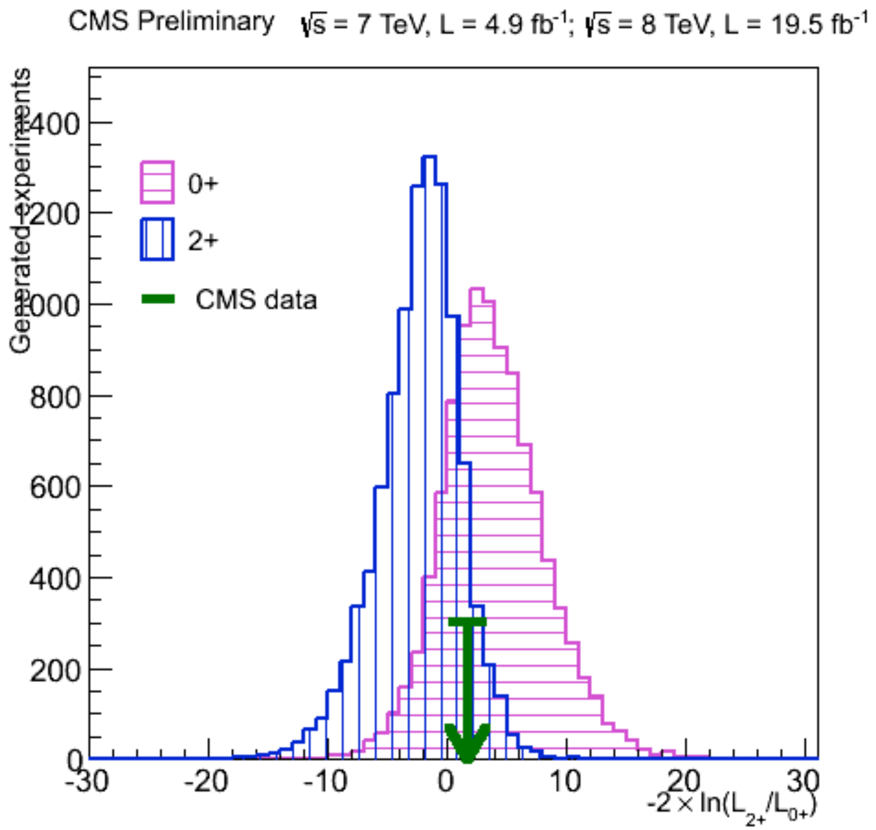




significance (σ)	VH	$H \rightarrow WW^{(*)}$ [6]	Combined
expected	0.7	3.7	3.8
observed	2.0	3.8	4.0

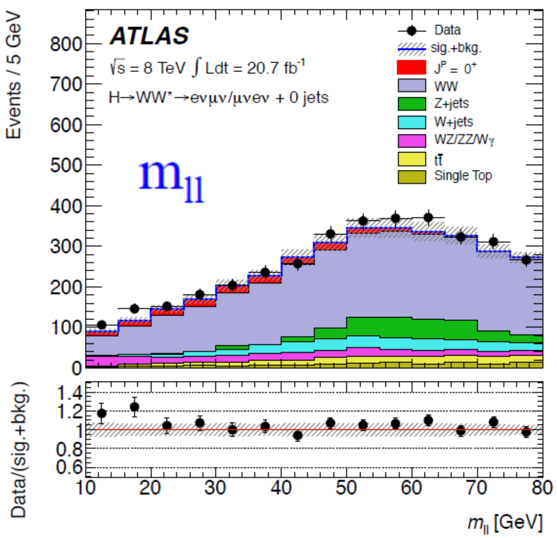
Spin 2 analysis

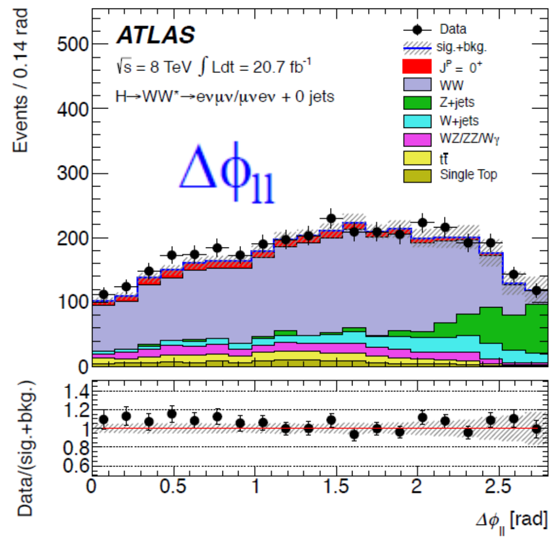
CMS PAS HIG-13-003

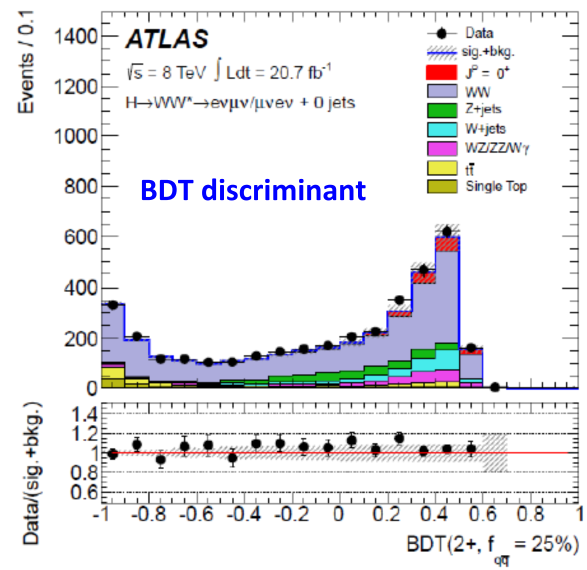


- Use 0-jet and 1-jet bins
- Limited sensitivity (expected < 2σ)
- Observed result disfavours 2^{+}_{min} hypothesis at 12-14% probability

Spin Analysis With H→ WW*

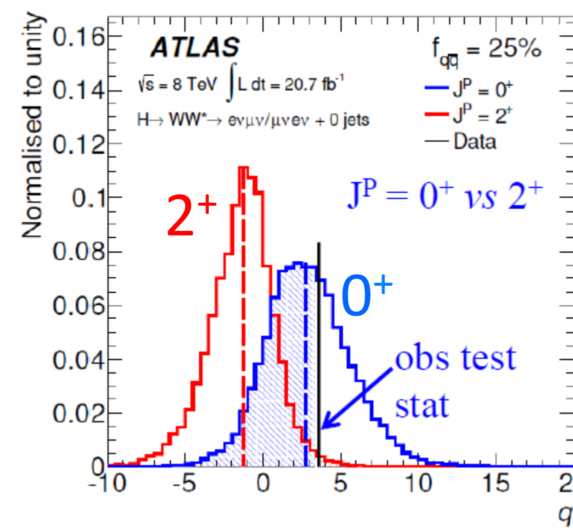






$J^P = 0^+ \; vs \; 2^+$

$f_{q\bar{q}}$	2⁺ assumed Exp. $p_0(J^P = 0^+)$	0⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048



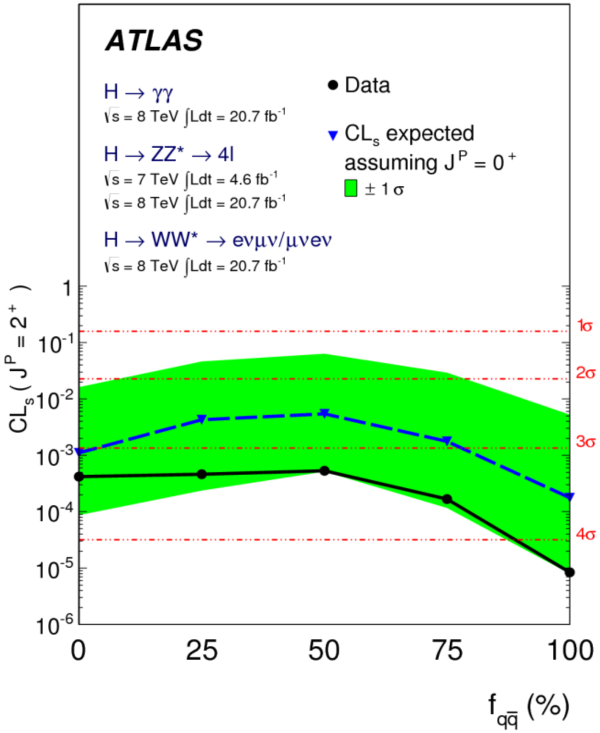
Exclusion **(1-CL_s):**

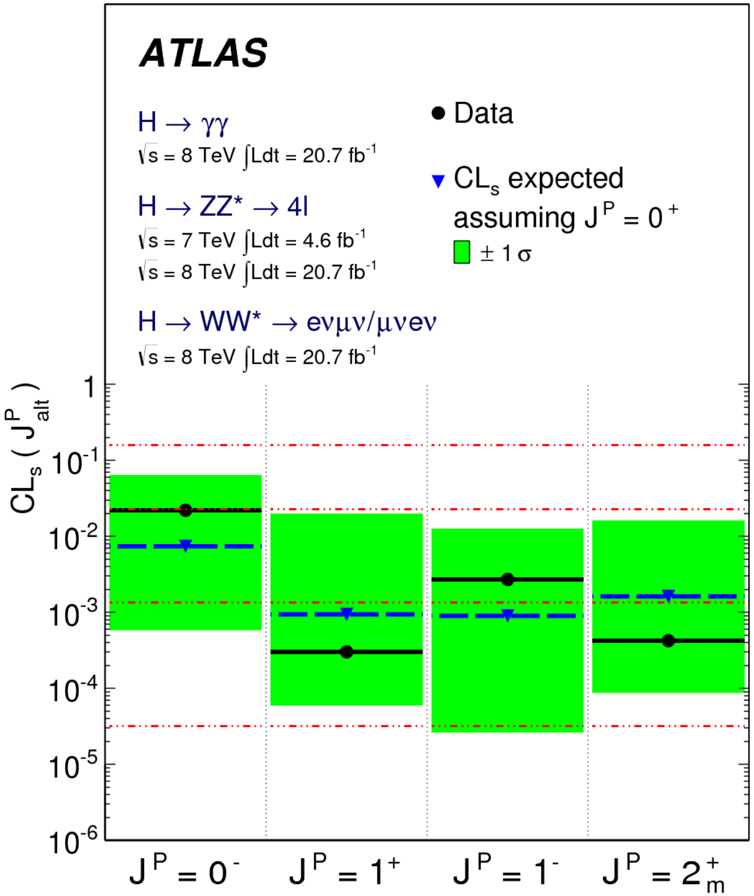
Observed 2⁺ (qq=100%) exclusion 99.96%

Observed 2⁺ (qq = 0%) exclusion 95.2%

Combined Spin-Parity Results

- 0^- hypothesis excluded at 97.8% CL in favor of 0^+ by H→ ZZ*→ 4ℓ analysis
- 1^+ and 1^- excluded at 99.7% CL, respectively by WW and ZZ analysis
- 2^+ excluded at 95.2% to 99.96% CL





Combine: ZZ ZZ, WW ZZ, WW, γγ

Data favor of $J^P = 0^+$

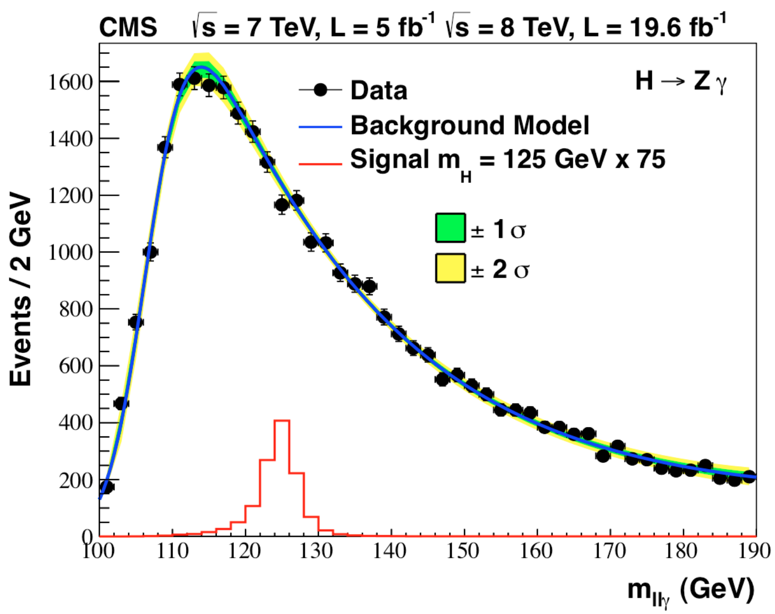
- Cross section similar to γγ
- Use Z->ee and Z->μμ (reduce cross section)
- Large BG from Drell Yan with ISR

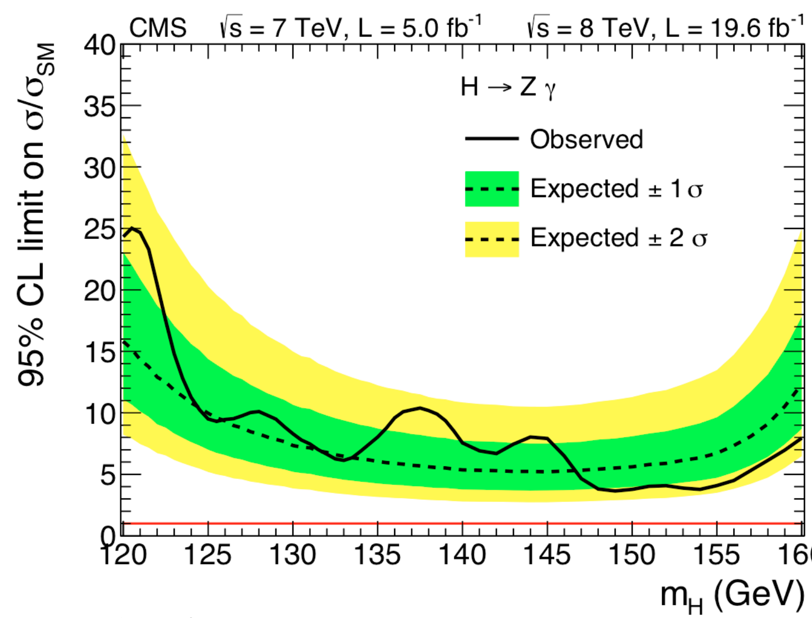
Models exist with BR(Zγ) >100 x SM while BR(γγ) is SM-like

Table 1: Observed and expected event yields for a 125 GeV SM Higgs boson.

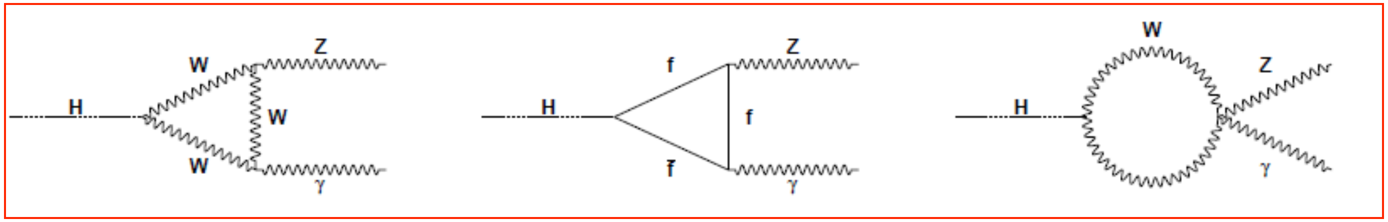
Sample	Integrated luminosity (fb^{-1})	Observed event yield for $100 < m_{\ell\ell\gamma} < 190$ GeV	Expected number of signal events for $m_H = 125$ GeV
2011 ee	5.0	2353	1.2
2011 $\mu\mu$	5.1	2848	1.4
2012 ee	19.6	12899	6.3
2012 $\mu\mu$	19.6	13860	7.0

arXiv:1307.5515





H→Zγ → ℓℓγ

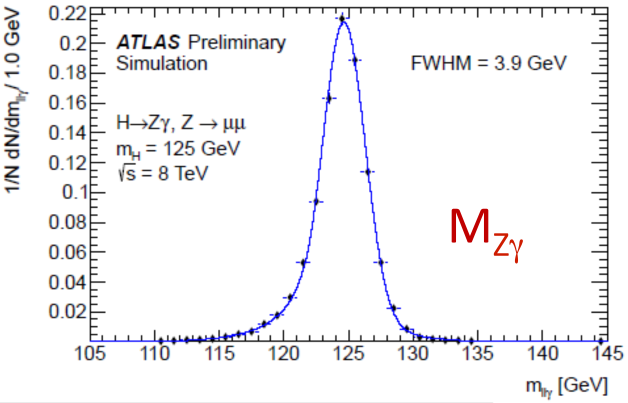


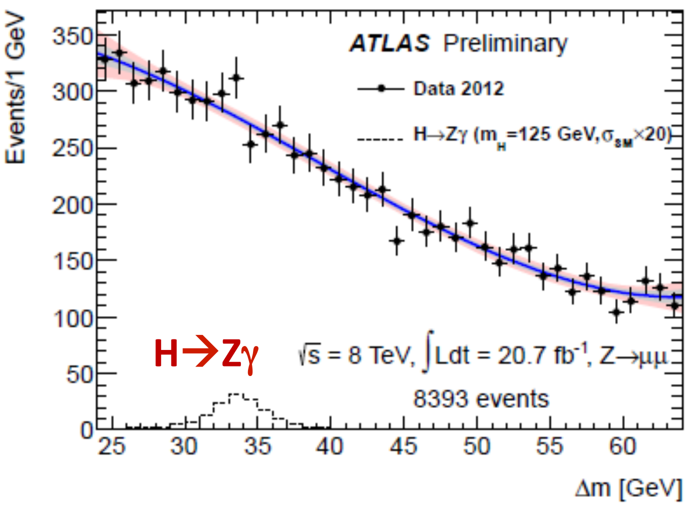
$BR(H \to Z\gamma)$=0.15%

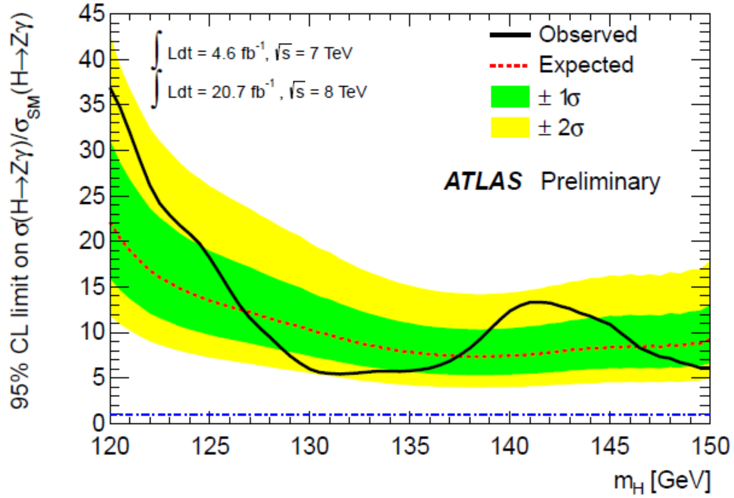
- **H→Zγ** is another high resolution channel
- Sensitive to new particles through loops
- For SM Higgs with mass = 125 GeV:

$\sigma_H \times Br(H \to Z\gamma \to \ell\ell\gamma) \sim 2.3$ fb

~ 55 events in 2011+2012 dataset







H→bb, $\tau\tau$

- No narrow mass peak.
- Rather low s/b.
- But we have large signals to work with.

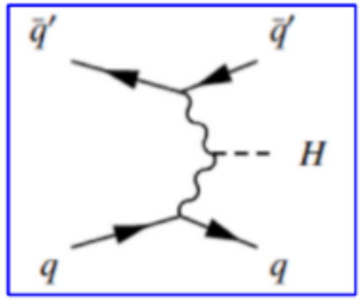
- These analyses have significant systematic errors, but the measurements can be made, particularly for well tagged modes.

H→bb

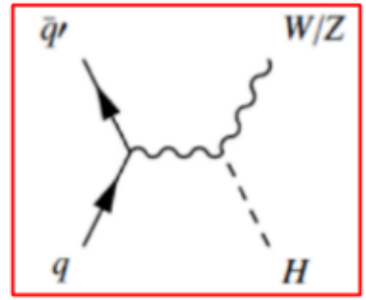
Which production mode for *bb* final state ?

All but gluon fusion

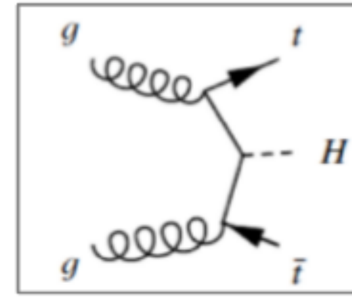
$\sigma_{tot}(b\bar{b}) \sim 10^7$ pb



qqbb final state
high bkg rate



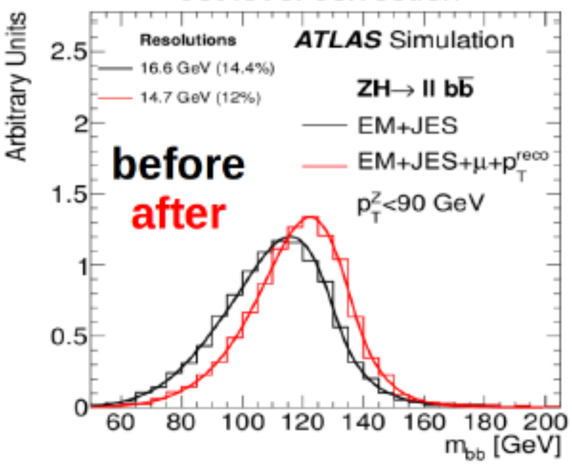
W/Z signature
most sensitive



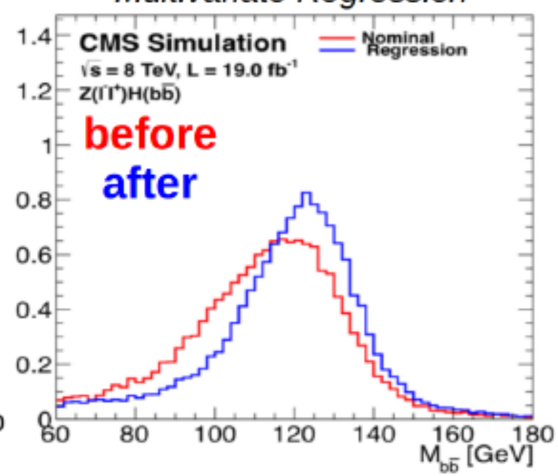
dedicated search, **see later**

Relevant observable : m_{bb}

ATLAS : method based on Jet level correction



CMS : method based on Multivariate Regression



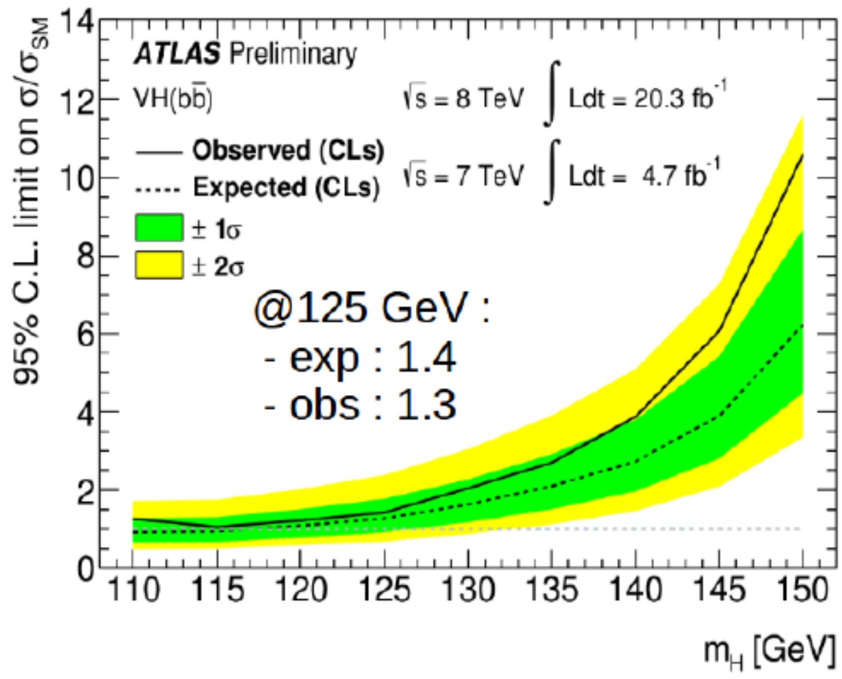
Refined energy scale and resolution for *b*-jets

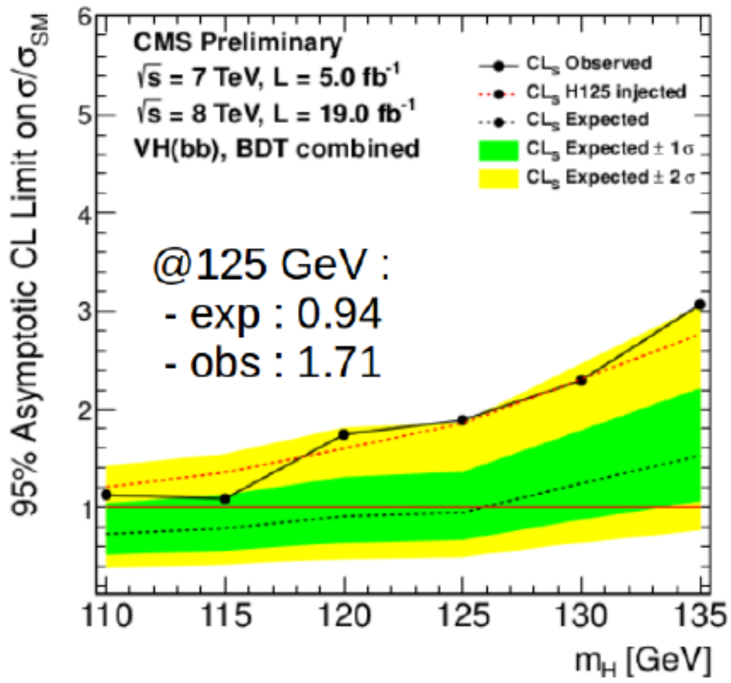
- jet kinematics
- soft lepton properties
- ...

Improvement : $\sim 10 - 15\%$

References : ATLAS-CONF-2013-079, CMS PAS HIG-13-012, CMS PAS HIG-13-011

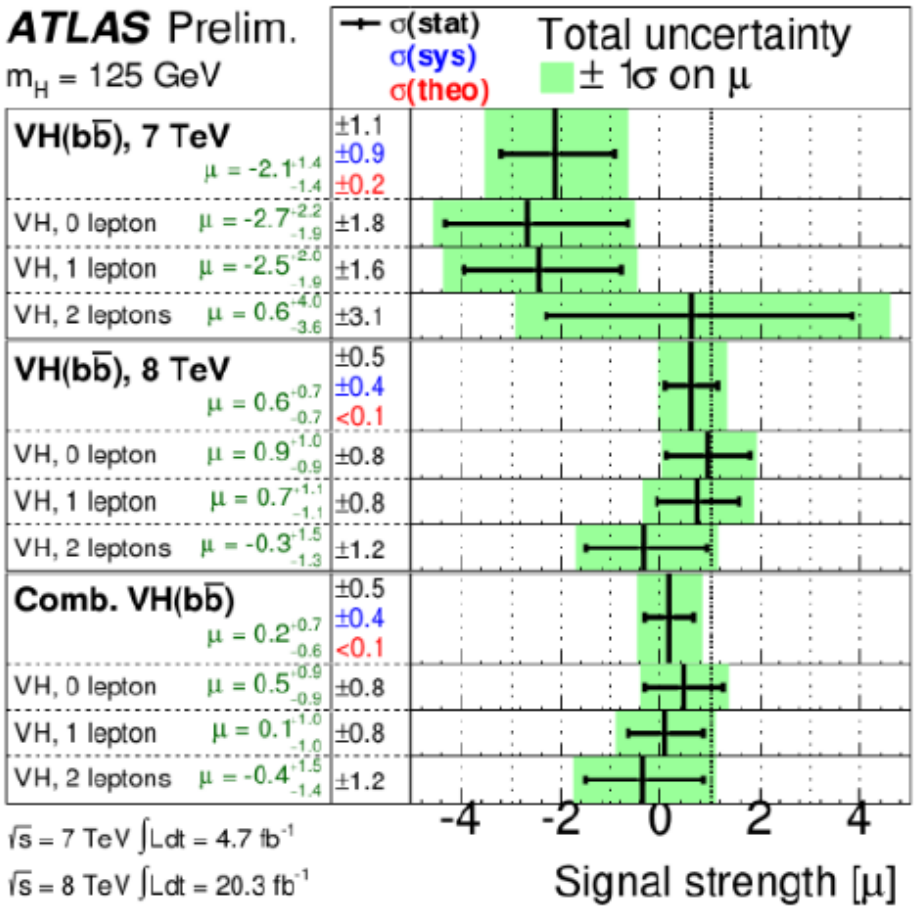
95% CL Limits on *VH*(*bb*)

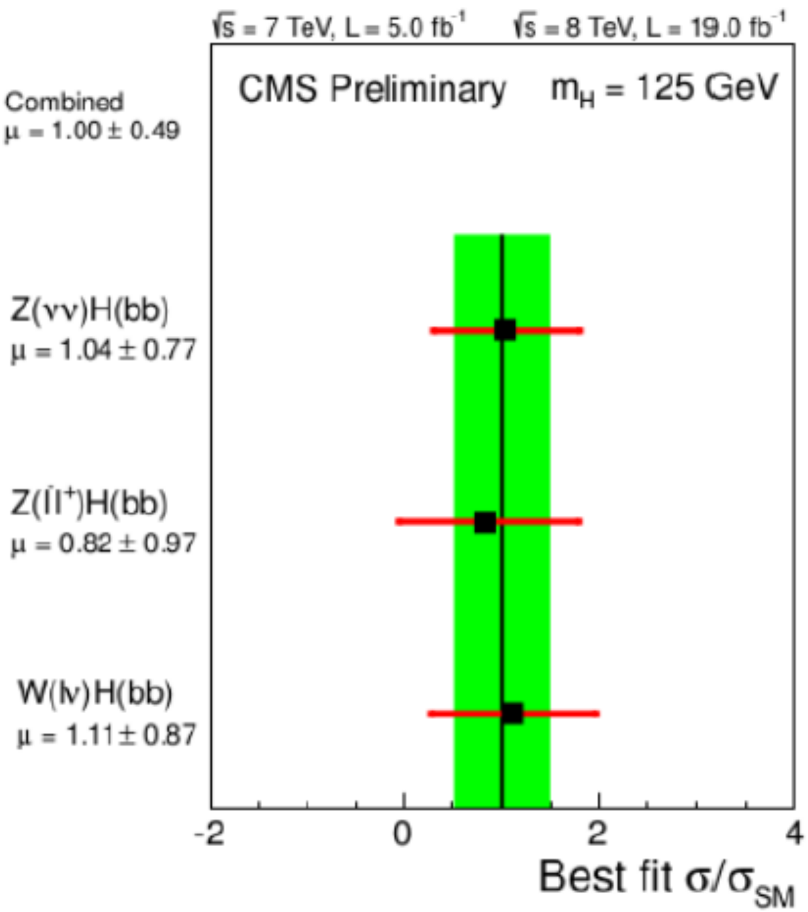




Excess observed in CMS but not ATLAS.

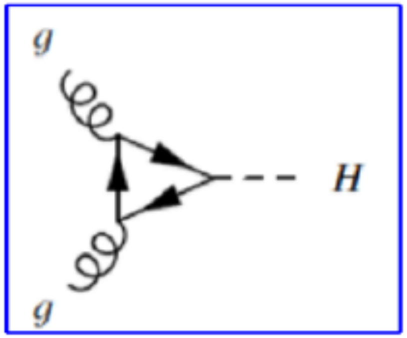
Measured m in *VH→Vbb*



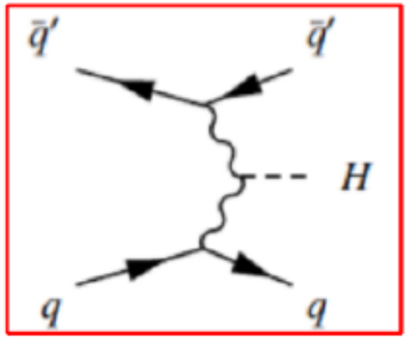


H→ττ Modes

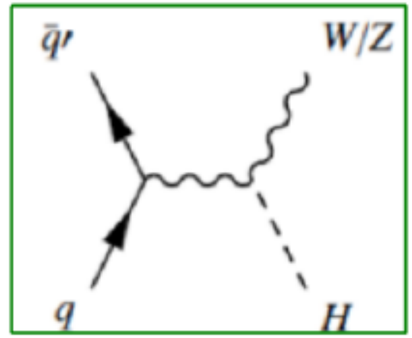
Which production mode ? All of them are exploited



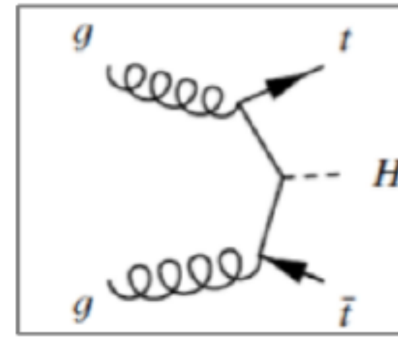
mostly sensitive for
high $p_T(\tau,\tau)$



tagging jets
most sensitive



lower rate, **less sensitive**

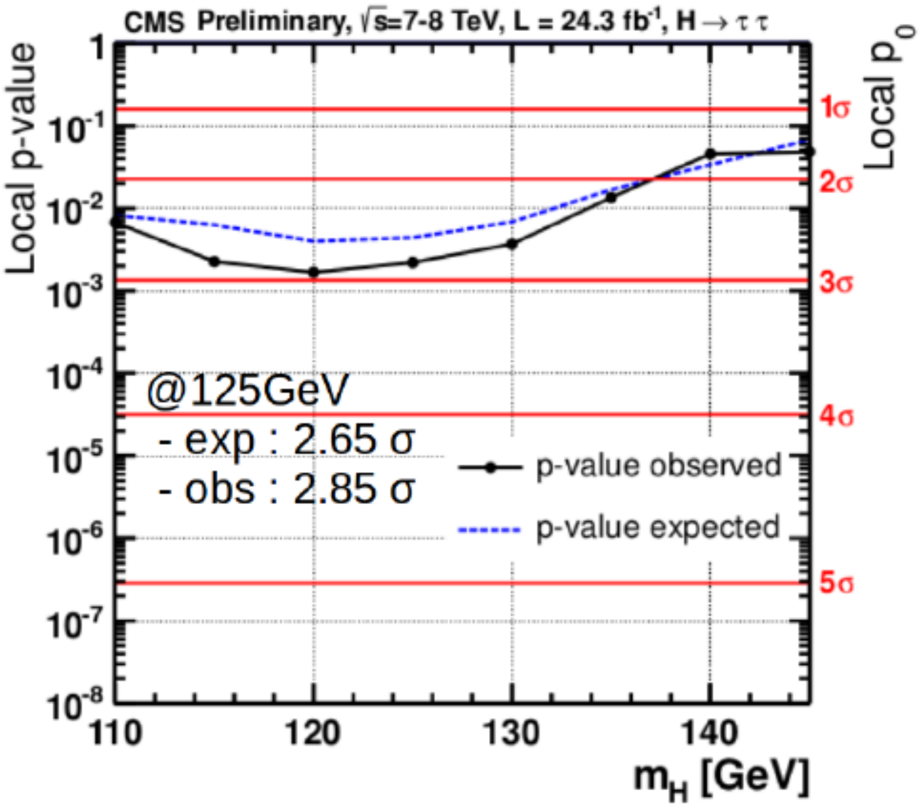


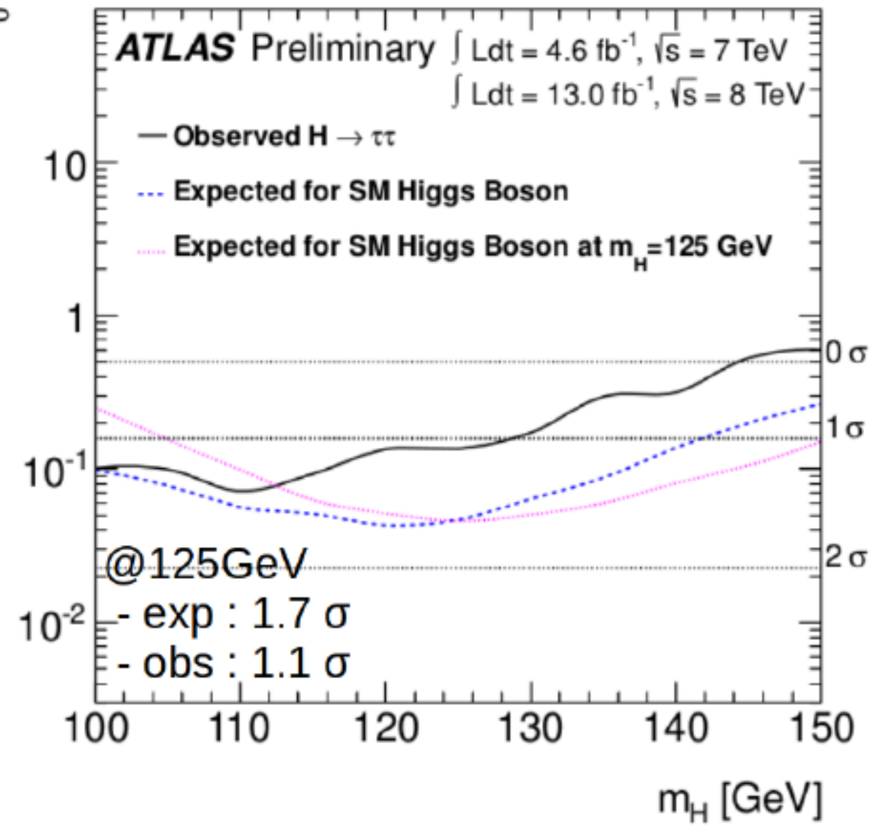
dedicated search, **see later**

Experimental challenges for $H \to \tau\tau$:

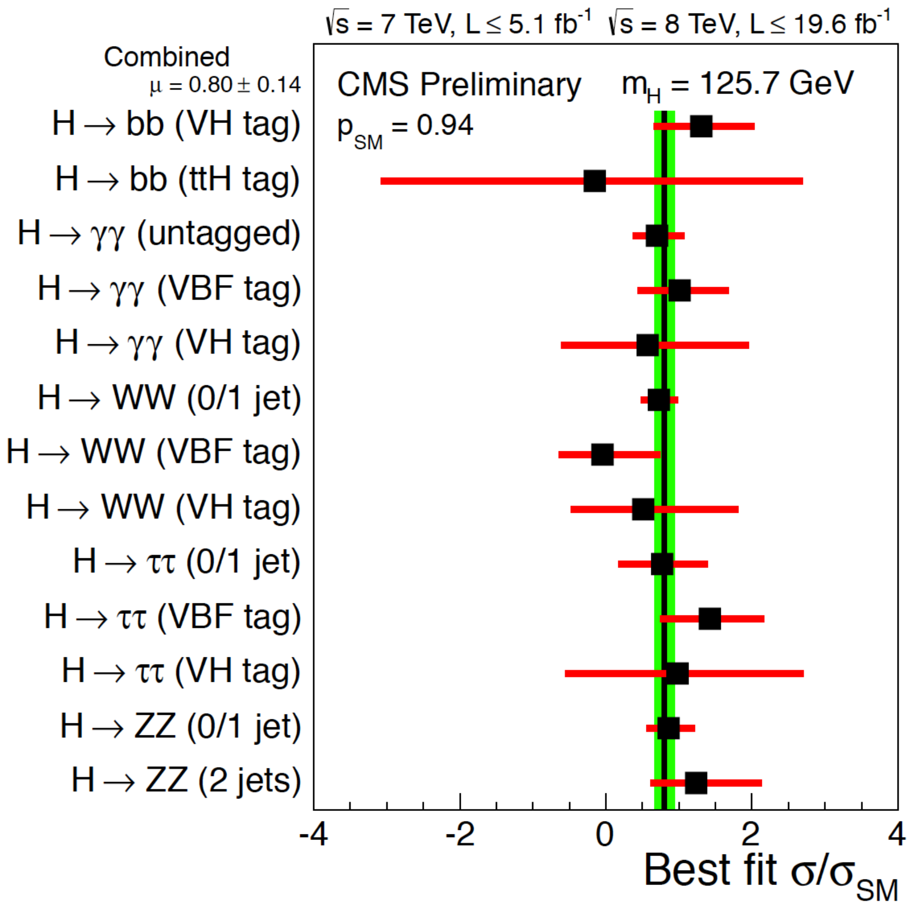
- Decay of τ pair into stable particles leads to 3 different final states
- Reconstruction of (τ,τ) invariant mass (escaping neutrinos)
- Energy scale determination of hadronic τ decays (and its uncertainty)

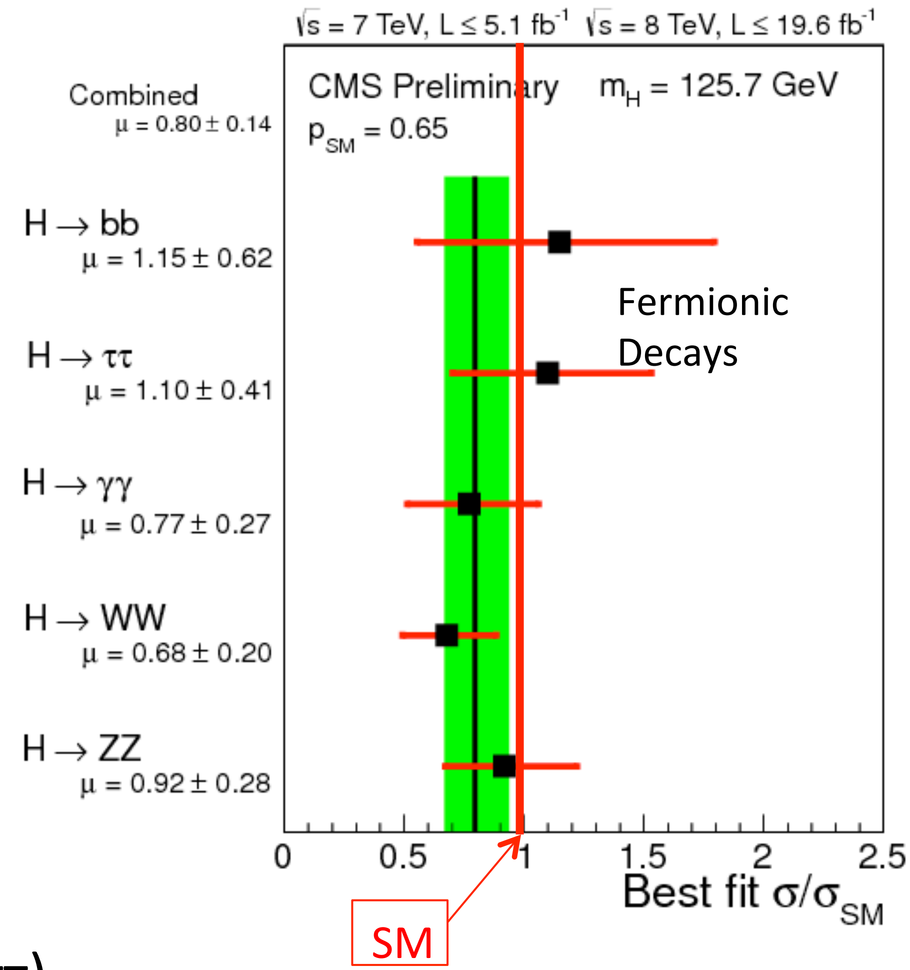
H→ττ P-Values


CMS Preliminary, √s=7-8 TeV, L = 24.3 fb⁻¹, H → τ τ
Local p-value
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
1σ
2σ
3σ
4σ
5σ
@125GeV
- exp : 2.65 σ
- obs : 2.85 σ
p-value observed
p-value expected
110
120
130
140
m_H [GeV]


ATLAS Preliminary ∫ Ldt = 4.6 fb⁻¹, √s = 7 TeV
∫ Ldt = 13.0 fb⁻¹, √s = 8 TeV
Local p₀
Observed H → ττ
Expected for SM Higgs Boson
Expected for SM Higgs Boson at m_H=125 GeV
10
1
10⁻¹
10⁻²
0 σ
1 σ
2 σ
@125GeV
- exp : 1.7 σ
- obs : 1.1 σ
100
110
120
130
140
150
m_H [GeV]

Summary of Measured Signal Strengths





- The fitted μ (including bb and ττ) at 125.7 GeV is:
  - $\sigma/\sigma_{SM} = 0.80 \pm 0.14$

Comparison of channels for M_H=125.7 GeV

CMS PAS HIG-13-005

Higgs Signal Strength

Signal strength $\mu = \sigma/\sigma_{SM}$

Combination of diboson final states

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ(*) \rightarrow 4\ell$

$H \rightarrow WW(*) \rightarrow \ell\nu\ell\nu$

measured at combined m_H=125.5 GeV

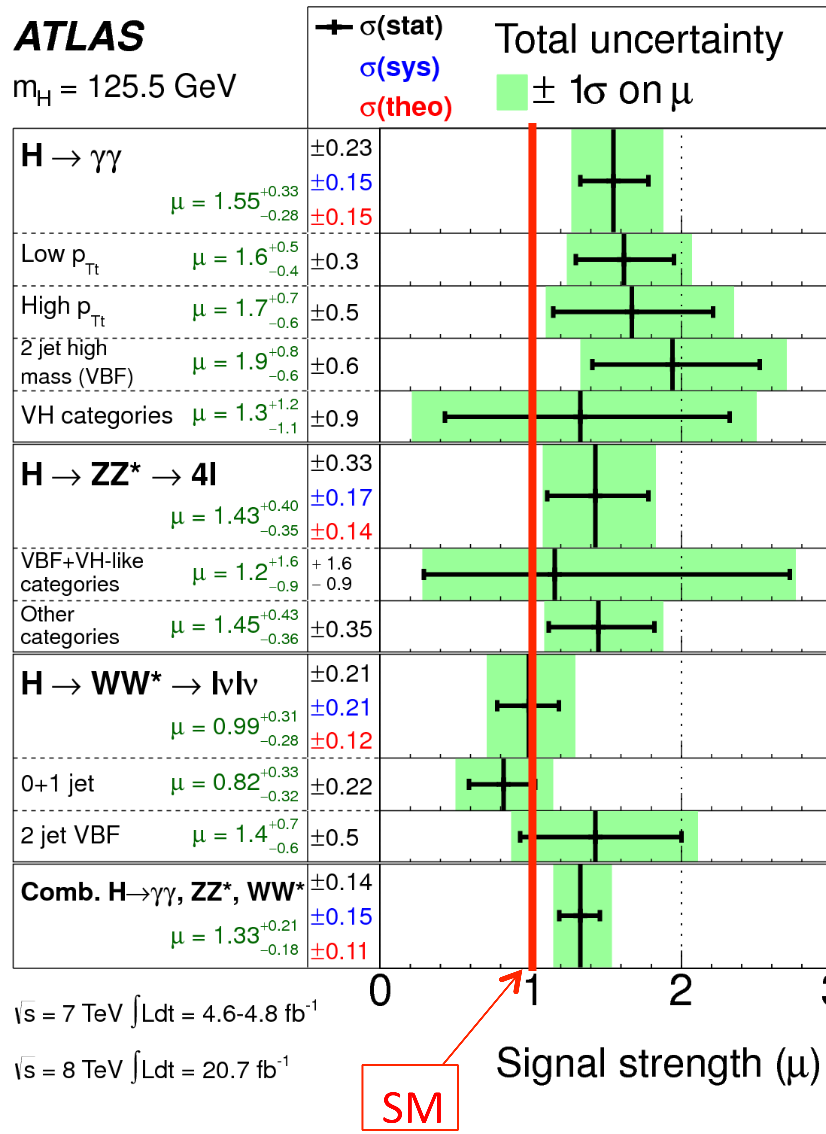
- **Variation due to m_H uncertainty: ±3%**
- **Compatibility with SM (μ=1): 7%**
- **Largest deviation $\mu_{\gamma\gamma}$: 1.9 σ**

Including preliminary μ_{bb}, $\mu_{\tau\tau}$: μ=1.23 ± 0.18

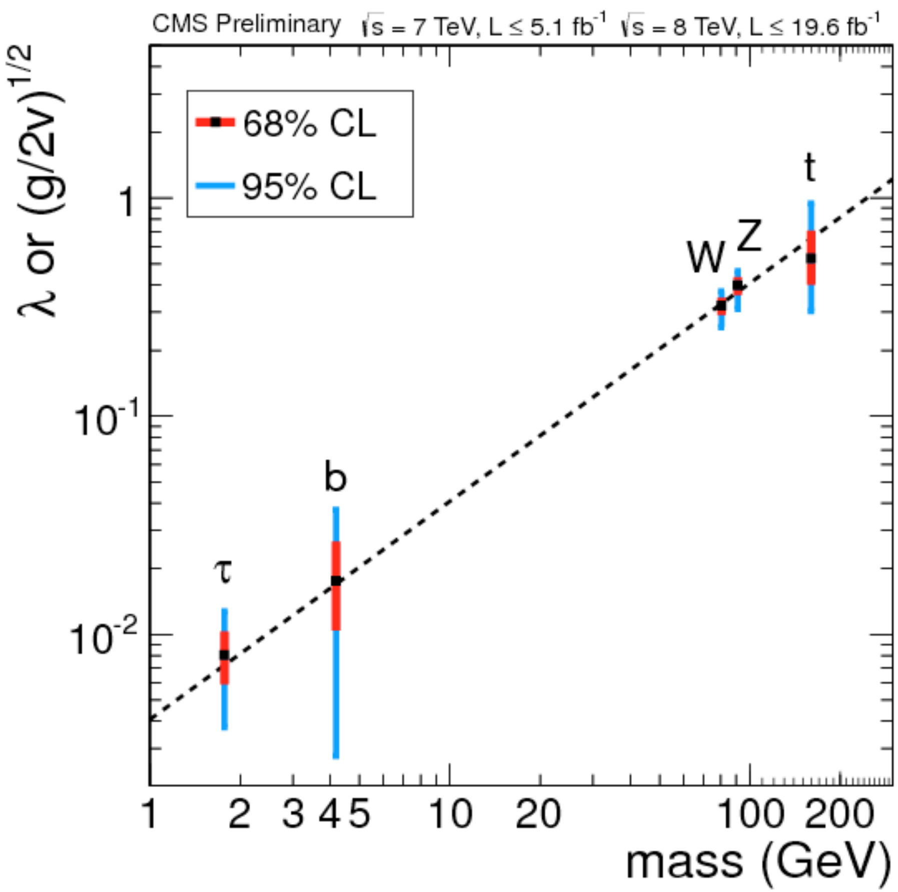
ATLAS also sets preliminary (95%CL) limits:

μ = 1.33 ± 0.14 (stat) ± 0.15 (sys) ± 0.11 (theo)

$H \rightarrow Z\gamma$: μ<18.2 (4.6 fb^{-1} + 20.7 fb^{-1})



The Higgs Should Couple to Mass



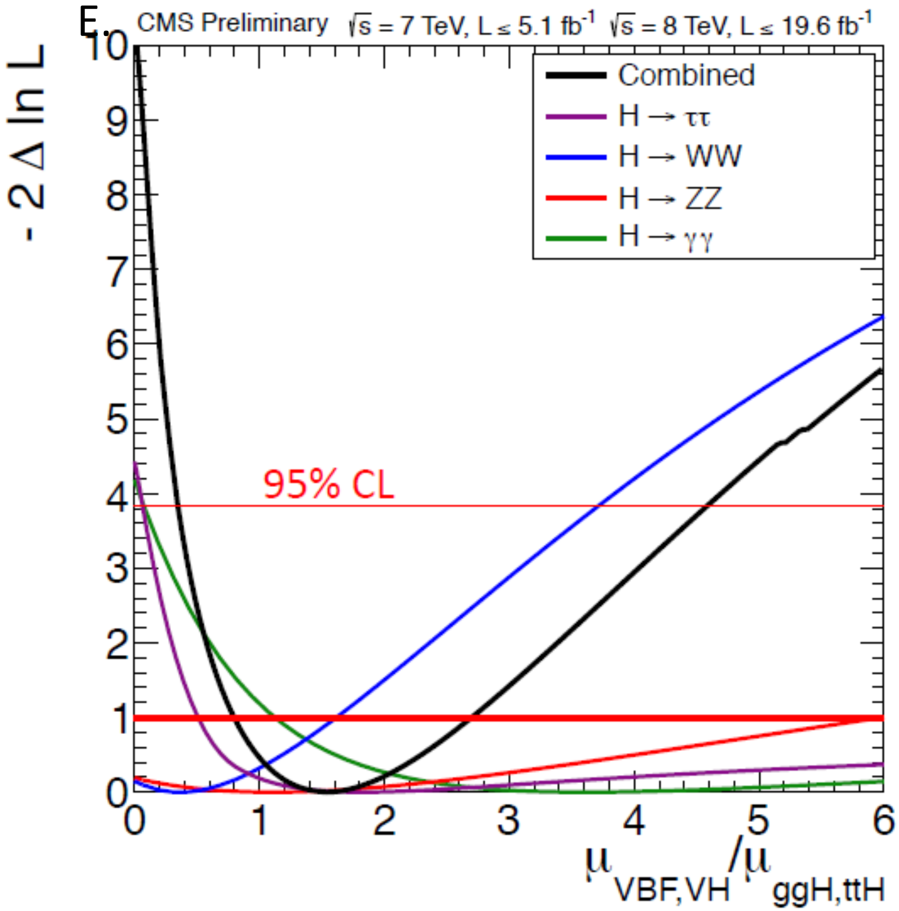
- Violates universality of couplings to different generations.
- The measured couplings support the coupling to mass.
- While Higgs to μμ is not yet observed, it is limited to be below about 5 times the SM expectation.
  - another factor of 10 on this plot.

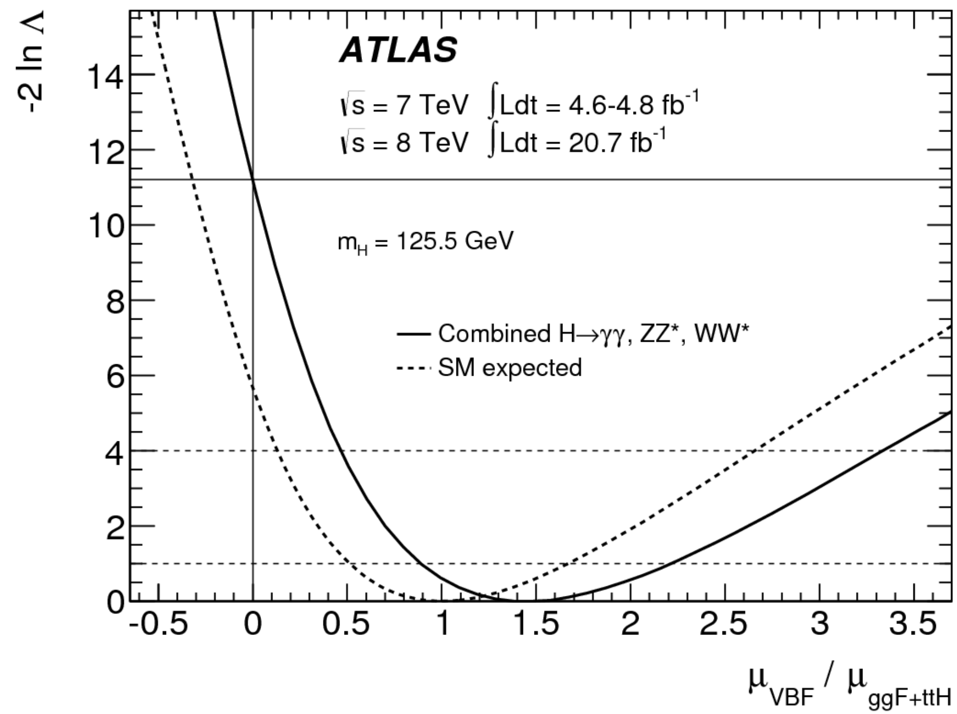
Evidence for VBF and VH production

Combine results from separate decay mode to disentangle production modes:
Fit to $\mu_{VBF+VH}/\mu_{ggH+ttH}$ in different channels (independent on Branching Ratios)

- **CMS** : Evidence for VBF+VH production **3.2σ**
- **ATLAS**: Evidence for VBF production (VH 'profiled') **3.3σ**

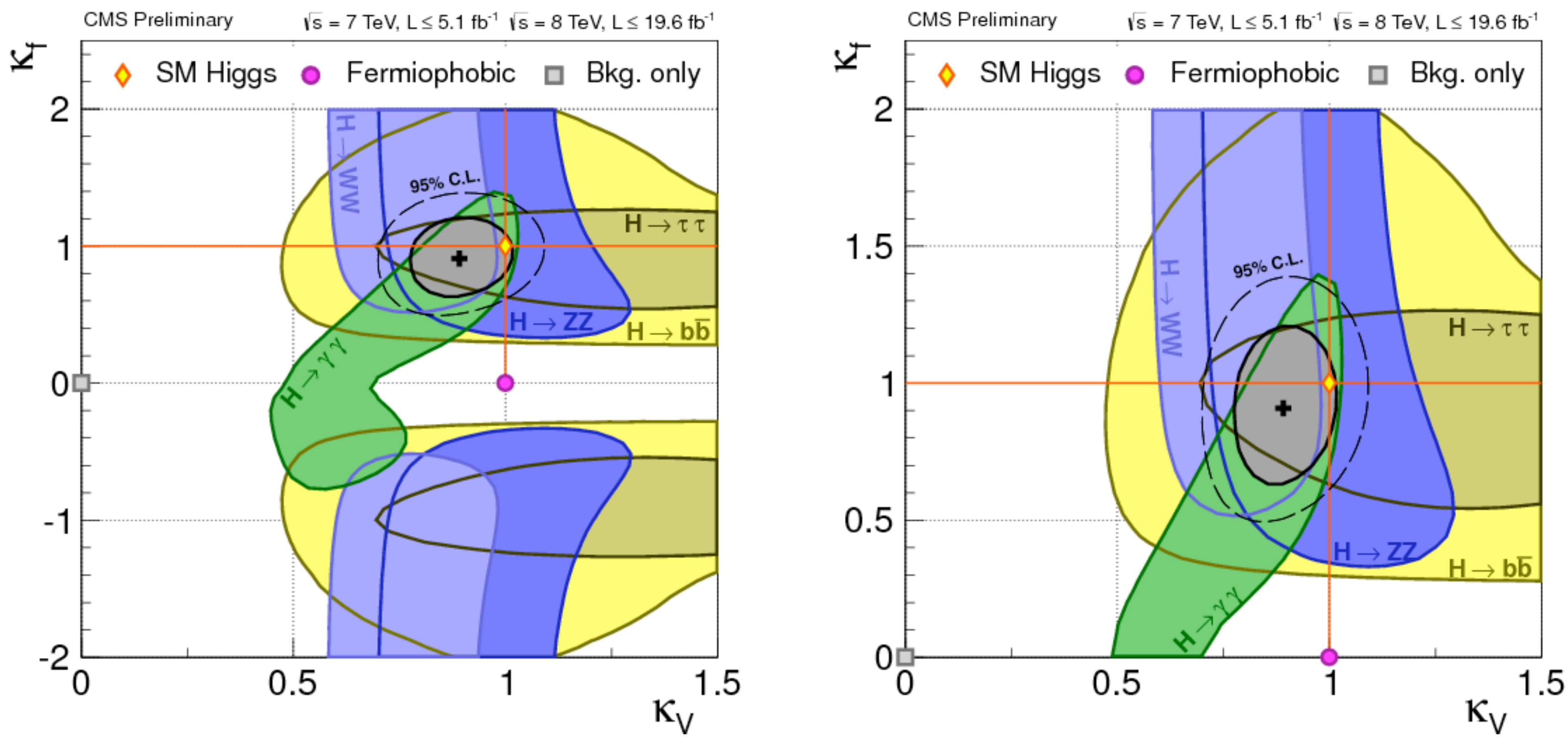
VBF and VH production compatible with SM prediction





CMS: κ_V, κ_f Contours

- Vector and fermion couplings are scaled by two scale factors , κ_V and κ_F
- Agree with SM at ~1 σ
- $\kappa_F < 0$ excluded at 95% CL



The green thumb of γγ is extremely important for coupling measurements

Vector vs Fermion Couplings

2-parameter benchmark model:

$\kappa_V = \kappa_W = \kappa_Z$ (>0)

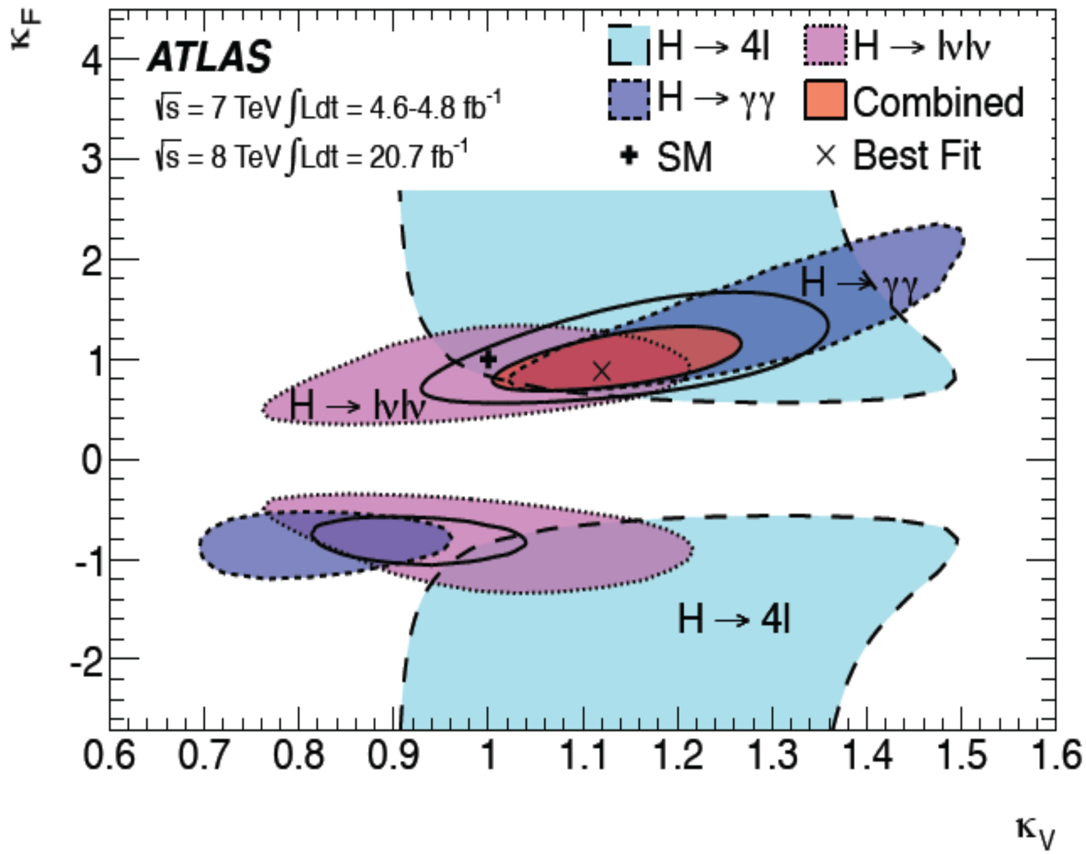
$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

Assume no BSM contributions to loops: gg→ H and H→γγ, and no BSM decays (no invisible decays)

- **κ_F = 0 is excluded (>5σ)**

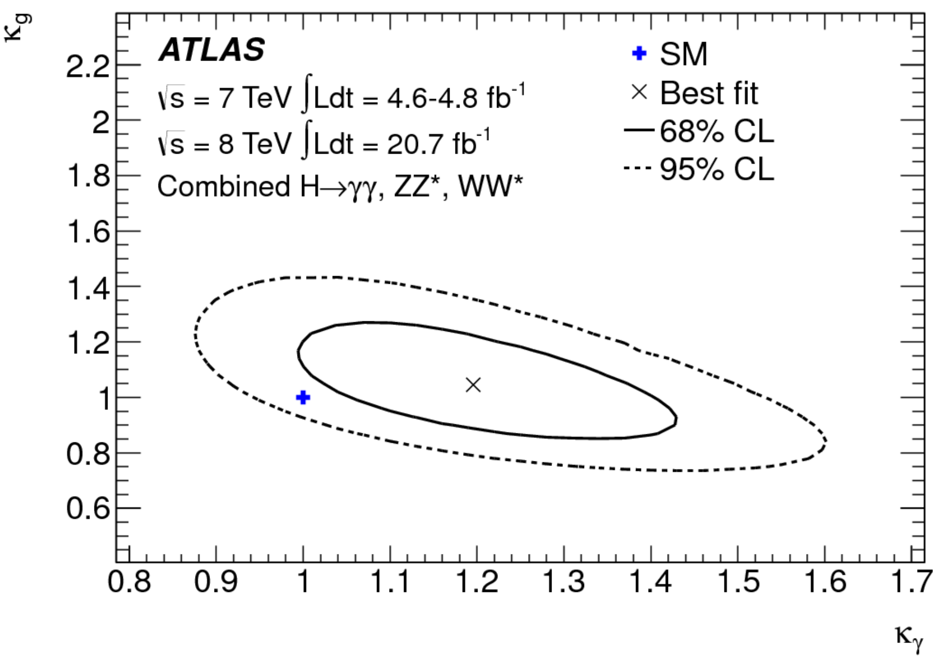
Double minimum from interference between vector(W) and fermion(top) in H→γγ

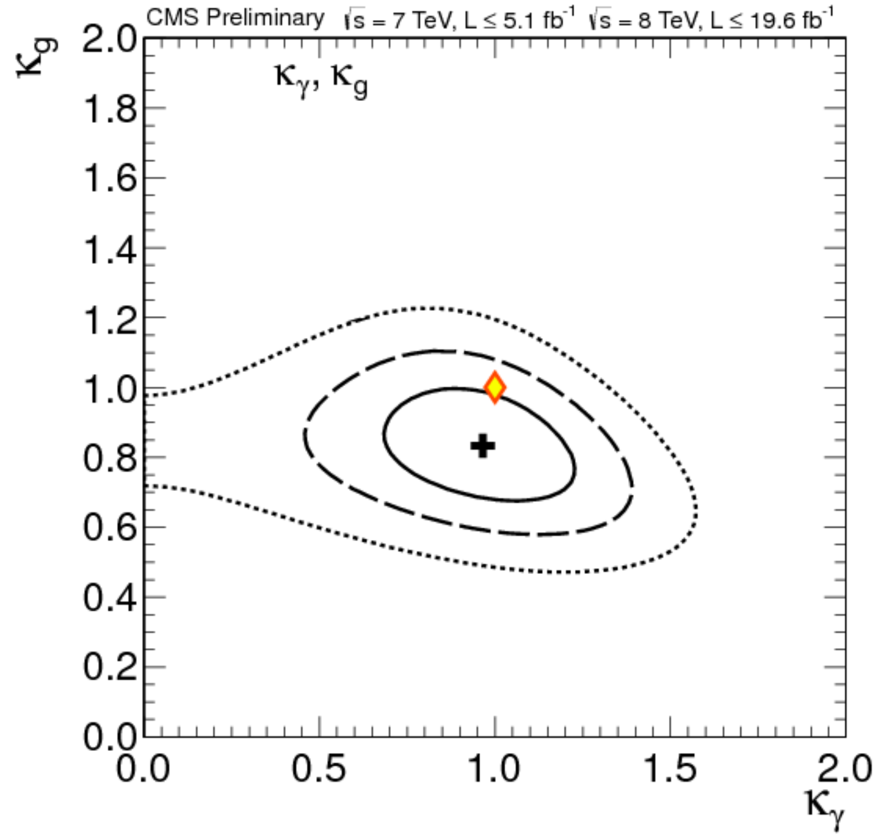


New particles in the loops

Fix all non-loop κ_i to SM value: $\kappa_V = \kappa_F = 1$

- Assume new particles do not contribute to Γ_H
- Directly measure effective κ_g and κ_γ – test non SM contributions





- Both experiments: compatible with SM predictions at ~10-15%
  - **ATLAS**: κ_g = (1.04 ± 0.14) at 68% CL - κ_γ = (1.20 ± 0.15) at 68% CL
  - **CMS** : κ_g [0.63,1.05] at 95% CL - κ_γ [0.59,1.30] at 95% CL

Contribution to the width from BSM

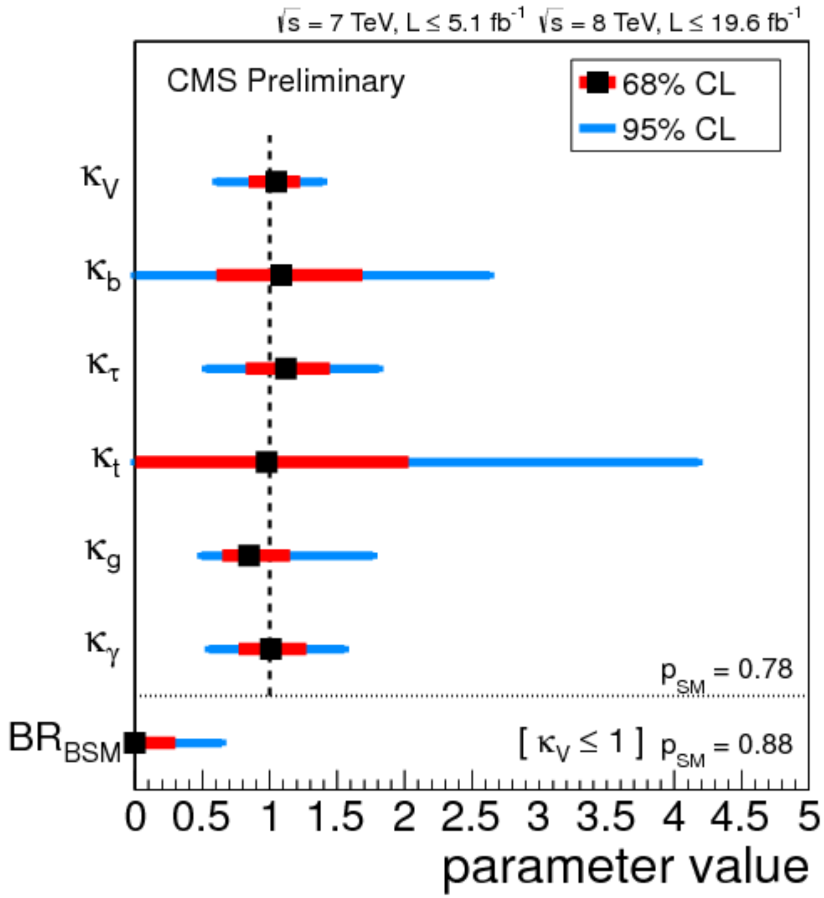
- Limits from direct searches ($ZH \rightarrow ll$ – invisible)
  ATLAS: $BR_{inv} < 0.65$ @ 95% CL
  CMS : $BR_{inv} < 0.75$ @ 95% CL

- $\Gamma_H = \Gamma_{SM} + \Gamma_{BSM} \rightarrow BR_{BSM} = \Gamma_{BSM} / \Gamma_H$

- BR_{BSM} is sensitive to invisible and undetectable decay modes ($H \rightarrow$ light hadrons)

- **ATLAS**
  Assume tree level couplings: $\kappa_b = \kappa_W ... =1$
  $\Gamma_{SM} \sim 0.9 + 0.1\ \kappa_g$
  3 fitted parameters: κ_γ , κ_g and BR_{BSM}
  - $BR_{BSM} < 0.6$ @ 95% C.L.

- **CMS**
  Assume $\kappa_V \leq 1$ (motivated by EWSB)
  7 fitted parameters: $\kappa_V, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\gamma, \kappa_g$ and BR_{BSM}
  - $BR_{BSM} < 0.64$ @ 95% C.L.

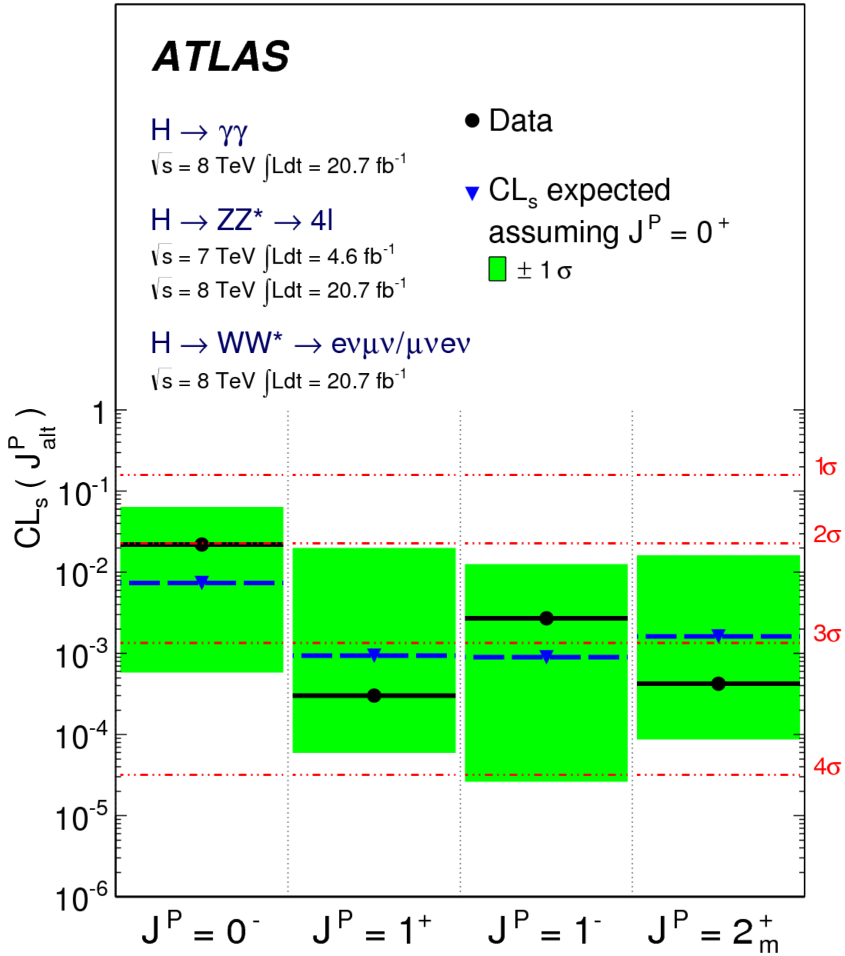


Summary of Spin/Parity Measurements

CMS

CL_s	$ZZ \rightarrow 4l$	$WW \rightarrow 2l2\nu$	Comb ZZ-WW	$\gamma\gamma$
0^-	0.16 %	-	-	-
1^-	< 0.1%			
1^+	< 0.1%			
$2_m^+(gg)$	1.5%	14%	0.6%	60.9%
$2_m^+(q\bar{q})$	0.1%	-	-	16.9%

Tests strongly favor SM 0+ hypothesis
Many alternative models tested:
Excluded at > 98% CL



Beyond hypothesis testing: 0^+ versus 0^-

CMS estimates contribution of CP-violating amplitude to $H \to ZZ^*$ decay

Most general spin 0 $H \to VV$ amplitude

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A$$

CP odd amplitude

0^+ decays dominated by A_1 amplitude, 0^- decays dominated by A_3 amplitude

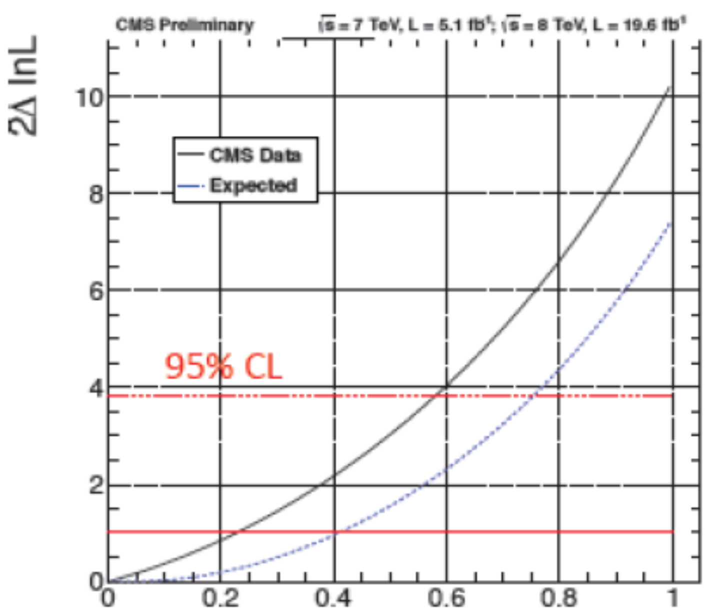
Take separate 2D template for 0^+ and 0^- and fit to data for their relative presence

$$f_{a3} = |A_3|^2 / |A_1|^2 + |A_3|^2$$

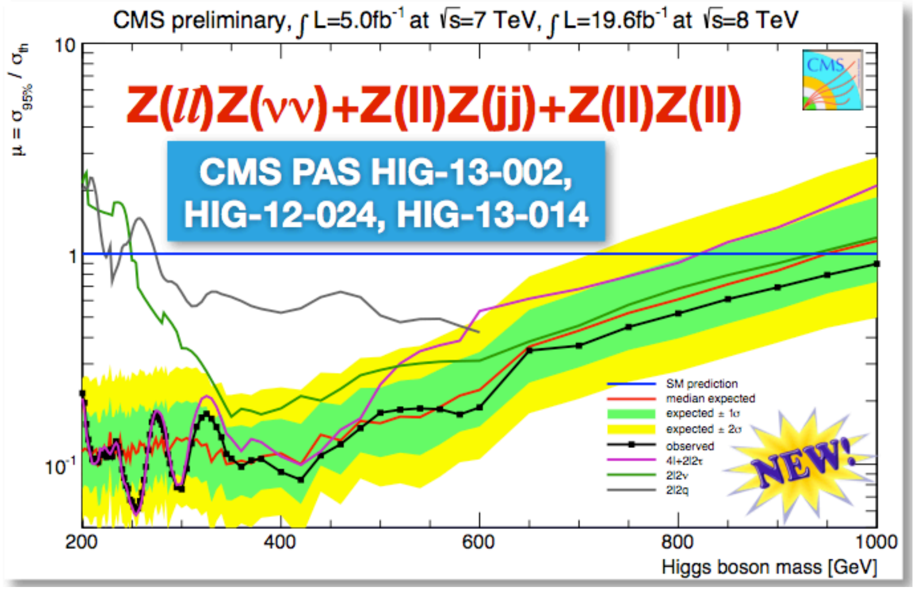
- check presence of CP violation (a_2: assume zero)
- interference term has negligible effect on observable or yields

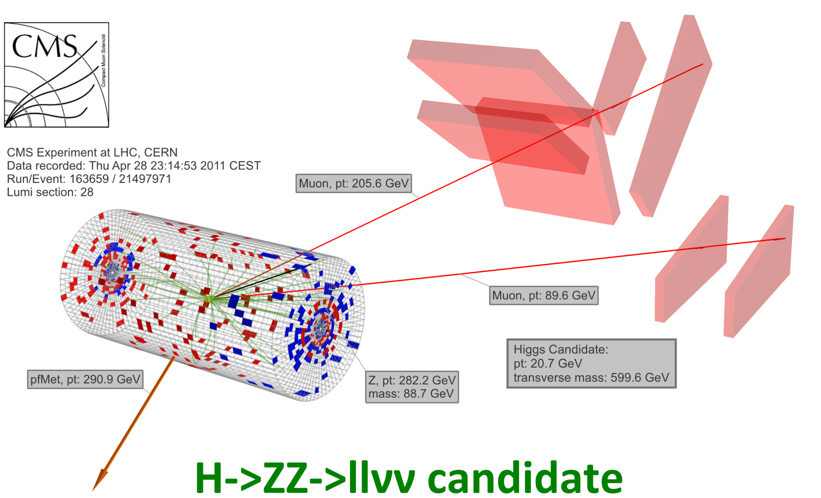
CMS: $H \to ZZ^* \to 4l$

$f_{a3} = 0.00^{+0.23}_{-0.00}$ $\quad$ $f_{a3} < 0.58$ @ 95% CL



- H→ZZ→ℓℓνν is the most sensitive channel for high mass search
  - Mass resolution 7%
  - Main backgrounds
    - ZZ (irreducible), Z+jets, tt, WZ
  - No signal observed with full dataset
- Combine with other ZZ channels
  - H→ZZ→4ℓ
  - H→ZZ→2ℓ2τ
  - H→ZZ→2ℓ2j
  - SM-like Higgs excluded 200<m<1000
    - the full mass range studied
- (Not a multi-Higgs model, just SM)





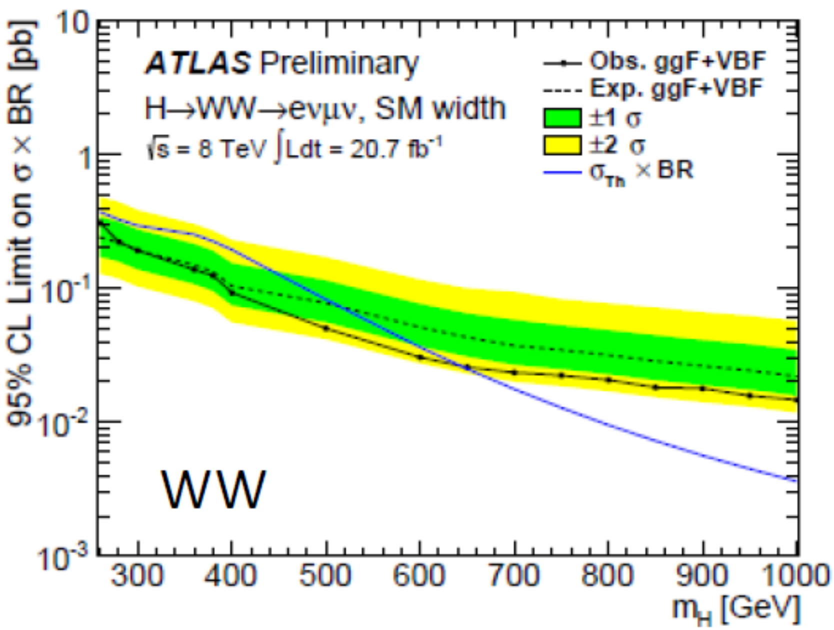
H->ZZ->llνν candidate

Search for High Mass H→ ZZ, WW

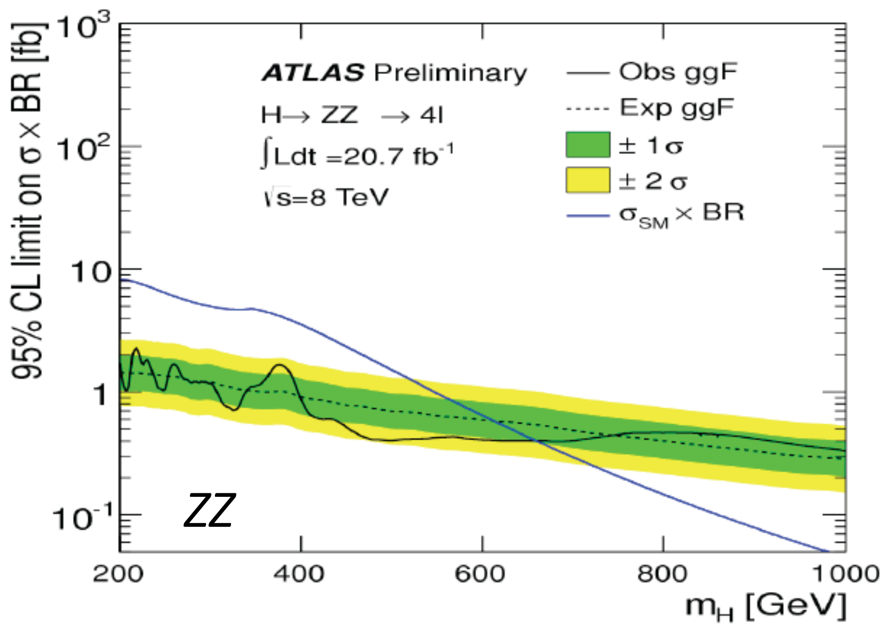
ATLAS-CONF-2013-067

Extend the Higgs search to high mass assume SM-like width, and decay to

*WW** → *lνlν*



*ZZ** → 4ℓ



95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

Summary

- By now we know we have found “a Higgs” Boson.
  – Branching ratios are about right, (mass)
  – and it seems to be 0^+ (in both CMS and ATLAS)
- This discovery confirms the SM Higgs mechanism,
  – but we can measure a lot more for m = 125,
  – and SUSY Higgs, composite Higgs, other BSM Higgs are still possible and discoverable.
- Many other measurements have begun.
  – not all shown here,
  – but we have a good start,
  – and 14 TeV will be better.
- We will run at higher energy and Luminosity.
  – the future is bright for Higgs Physics at LHC (and beyond).

Backup

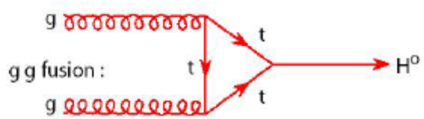
Backup Slides Need Cleanup

Coupling Measurements

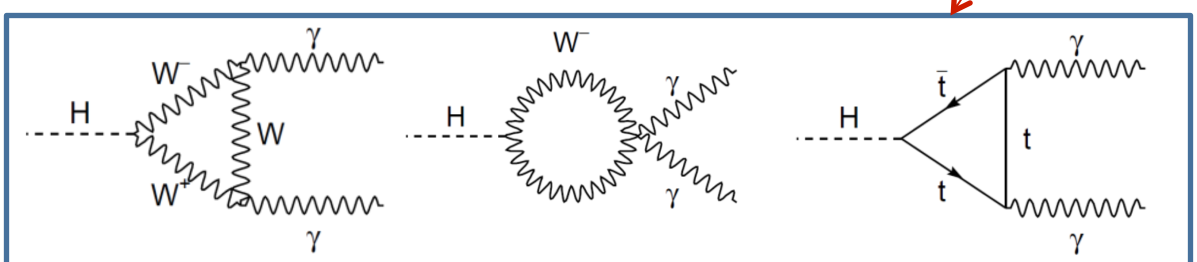
Coupling strengths κ_i & ratio: $\kappa_F = g_F/g_{F,SM}$, $\kappa_V = g_V/g_{V,SM}$, $\lambda_{ij} = \kappa_i/\kappa_j$

Model	Probed couplings	Parameters of interest	Functional assumptions					Example: $gg \to H \to \gamma\gamma$
			κ_V	κ_F	κ_g	κ_γ	κ_H	
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F,\kappa_V)/\kappa_H^2(\kappa_F,\kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV},\lambda_{FV},\lambda_{FV},1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g,\kappa_\gamma)$

Example $H \to \gamma\gamma$



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

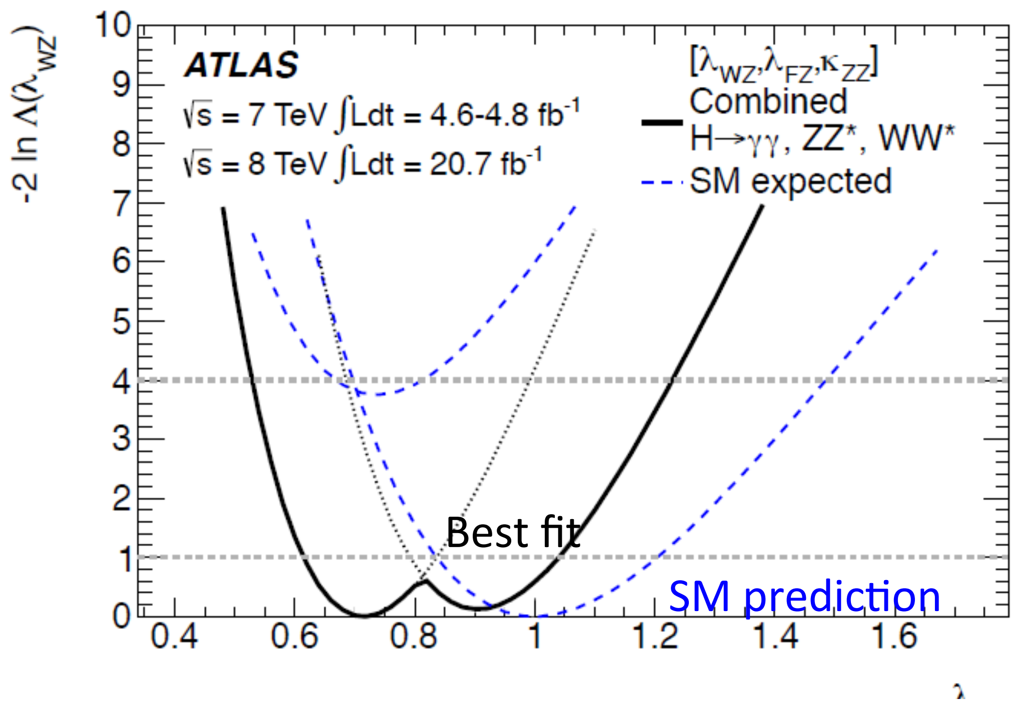


κ_g, κ_γ: loop coupling scale factors

κ_H is the total Higgs width scale factor

$$\kappa_\gamma^2 = |1.28\,\kappa_W - 0.28\,\kappa_t + \ldots|^2$$

W vs Z Coupling (Custodial Symmetry)



λ_{WZ} consistent with SM

$$\lambda_{WZ} = 0.82 \pm 0.15$$

Indirect indication "Higgs-like" boson is EW doublet (since λ_{WZ} = 0.5 for triplet)

Ratio of W/Z couplings (λ_{WZ}), with:

- Fermion couplings grouped together
- Total width left free
- Extra degree to allow to absorb deviation from the SM in the H → γγ loop

λ_{WZ} consistent with the SM

Both experiments have a comprehensive analysis of all channels combined.

New -- After the Higgs Discovery

- **$H \rightarrow \gamma\gamma$, ZZ*, WW* analysis updates based on full 2011-2012 dataset (4.6 fb^{-1} @ 7TeV, 20.7 fb^{-1} @ 8TeV)**

- Higgs mass from $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^* \rightarrow 4\ell$
- Signal strengths ($\mu = \sigma/\sigma_{SM}$)
- Sensitivity to vector boson fusion (VBF)
- Comparison of decay rates
- Couplings
- Spin and parity
- Searches in rare decay modes

New ATLAS Higgs Papers

arXiv:1307.1427 Sub. Phys. Lett. B (Mass, Couplings)
arXiv:1307.1432 Sub. Phys. Lett. B (Spin-parity)

New ATLAS Higgs Pub Notes

Property measurement:

- ATLAS-CONF-2013-012 ($\gamma\gamma$)
- ATLAS-CONF-2013-013 (ZZ*)
- ATLAS-CONF-2013-031 (WW*)
- ATLAS-CONF-2013-040 (Spin)
- ATLAS-CONF-2013-079 ($VH \rightarrow bb$)
- ATLAS-CONF-2012-160 ($H \rightarrow \tau\tau$)
- ATLAS-CONF-2013-075 (WW*)
- ATLAS-CONF-2013-029 ($\gamma\gamma$)

Searches:

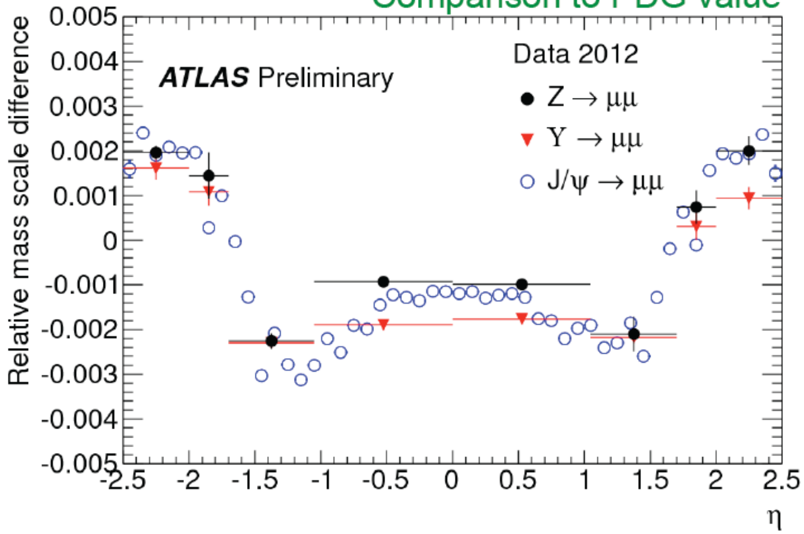
- ATLAS-CONF-2013-009($Z\gamma$)
- ATLAS-CONF-2013-010($\mu\mu$)
- ATLAS-CONF-2013-067($HMH \rightarrow WW$)
- ATLAS-CONF-2013-072 (diff σ $H\rightarrow\gamma\gamma$)
- ATLAS-CONF-2013-075($VH\rightarrow WW$)
- ATLAS-CONF-2013-080($tt + H\rightarrow\gamma\gamma$)
- ATLAS-CONF-2013-081($t\rightarrow cH$)

Lepton Energy/Momentum Calibration

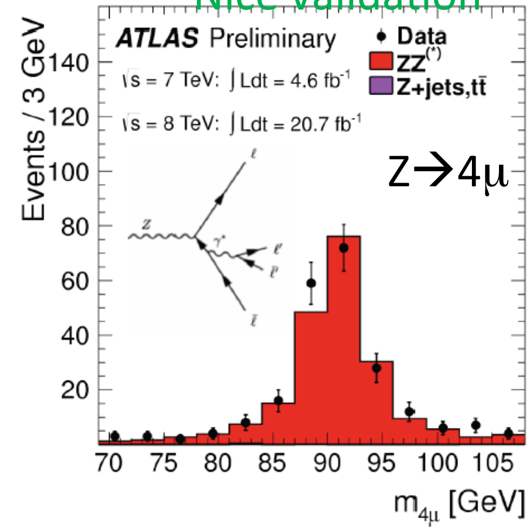
UCSD

Muons

Comparison to PDG value

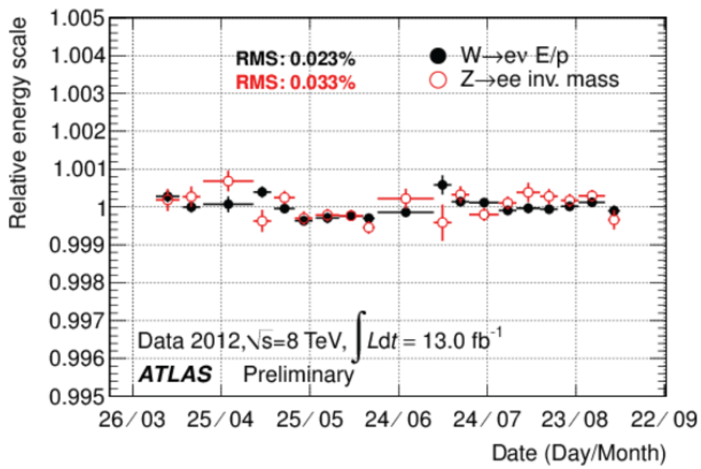


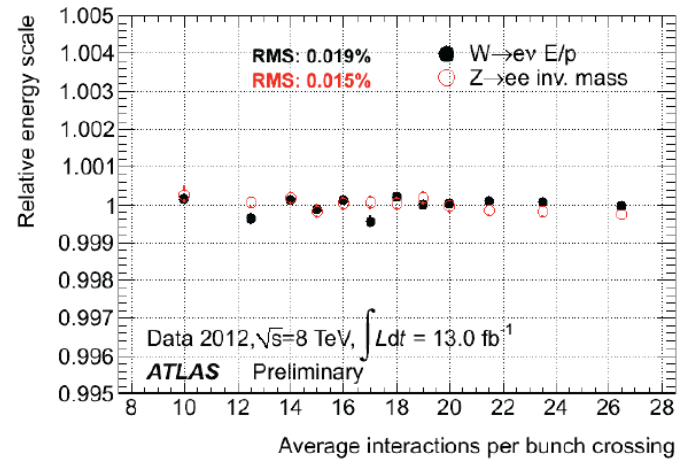
Nice validation



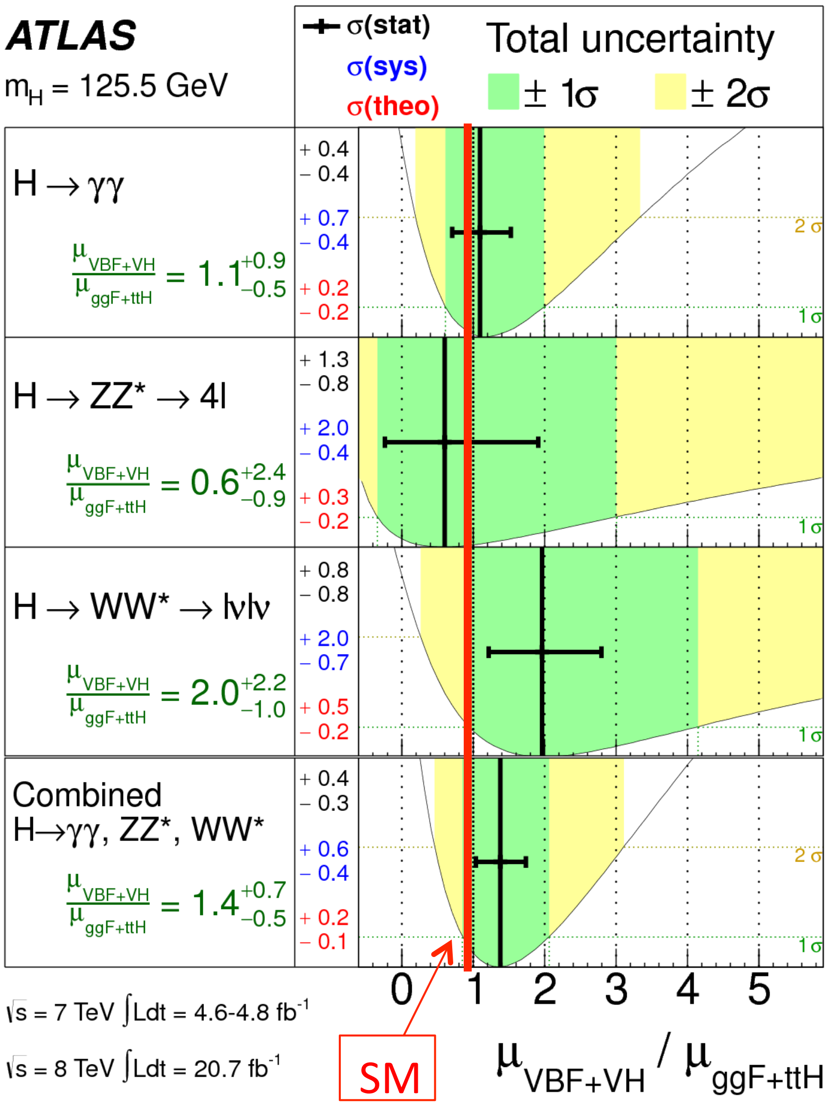
Electrons

Stability of EM calorimeter response vs time/pile-up better than 0.1%

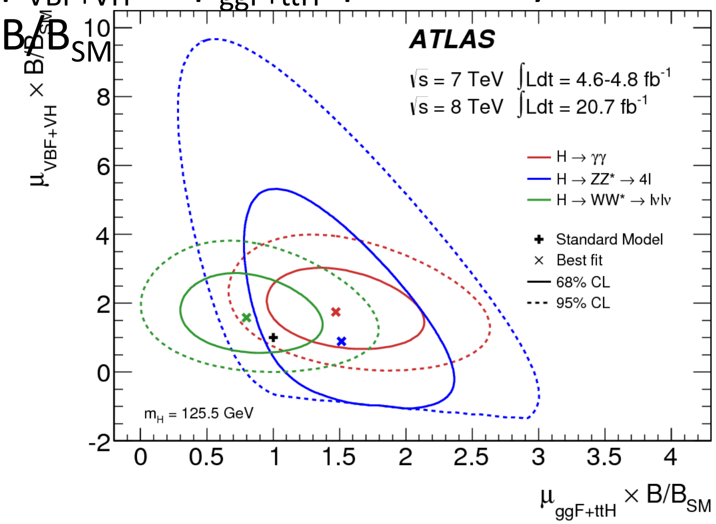


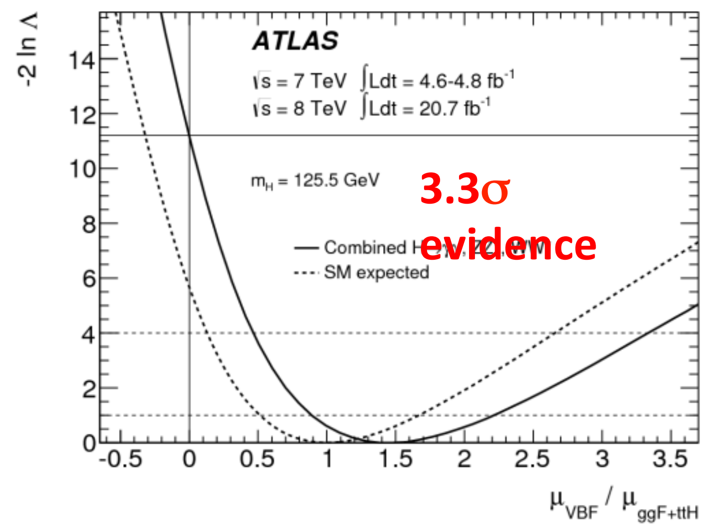


VBF vs. ggF Production



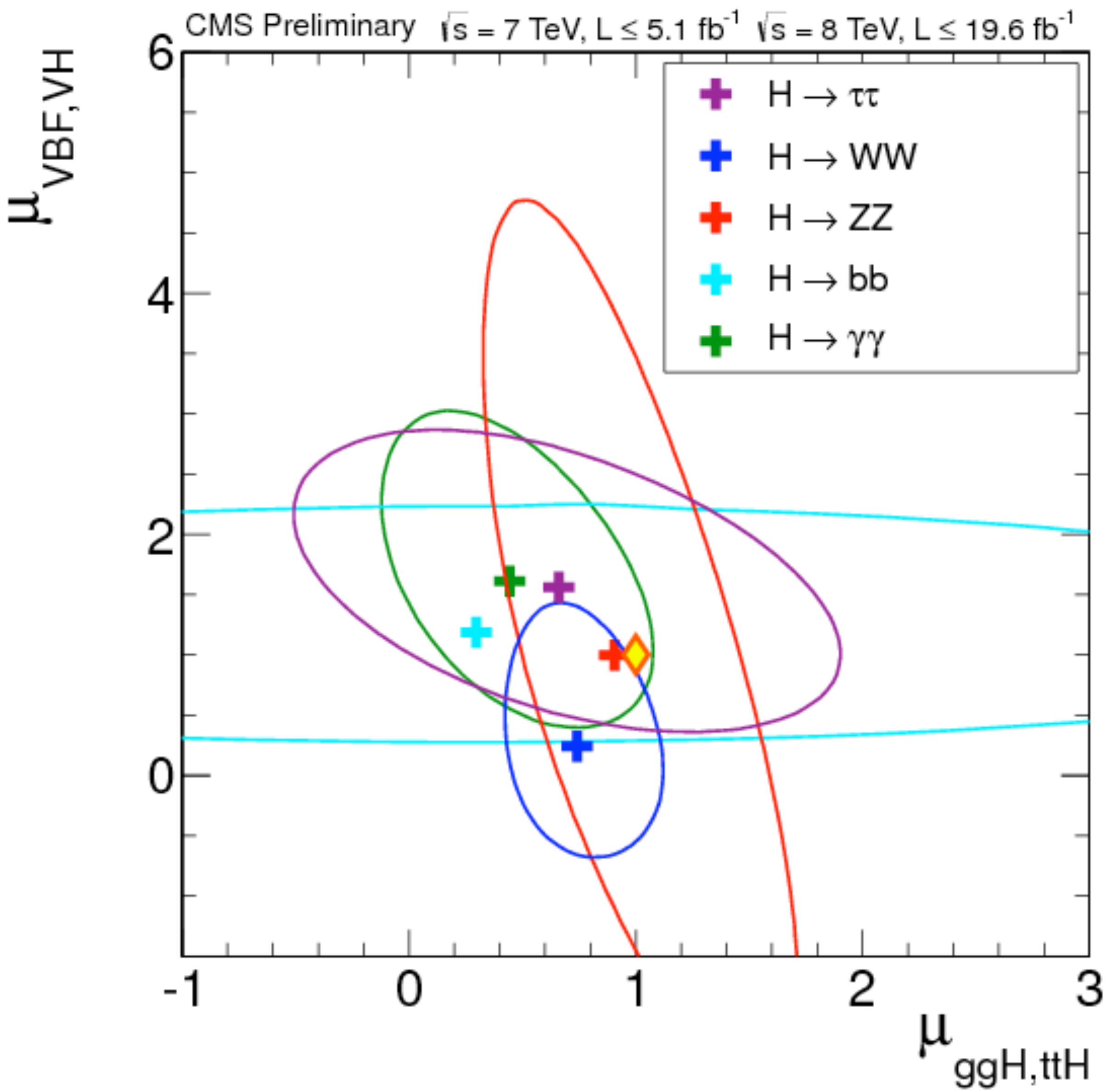
μ_{VBF+VH} vs $\mu_{ggF+ttH}$ potentially modified by B/B_{SM}





$\mu_{VBF+VH} / \mu_{ggF+ttH}$ = 1.4+0.4-0.3(stat) +0.6-0.4(sys)

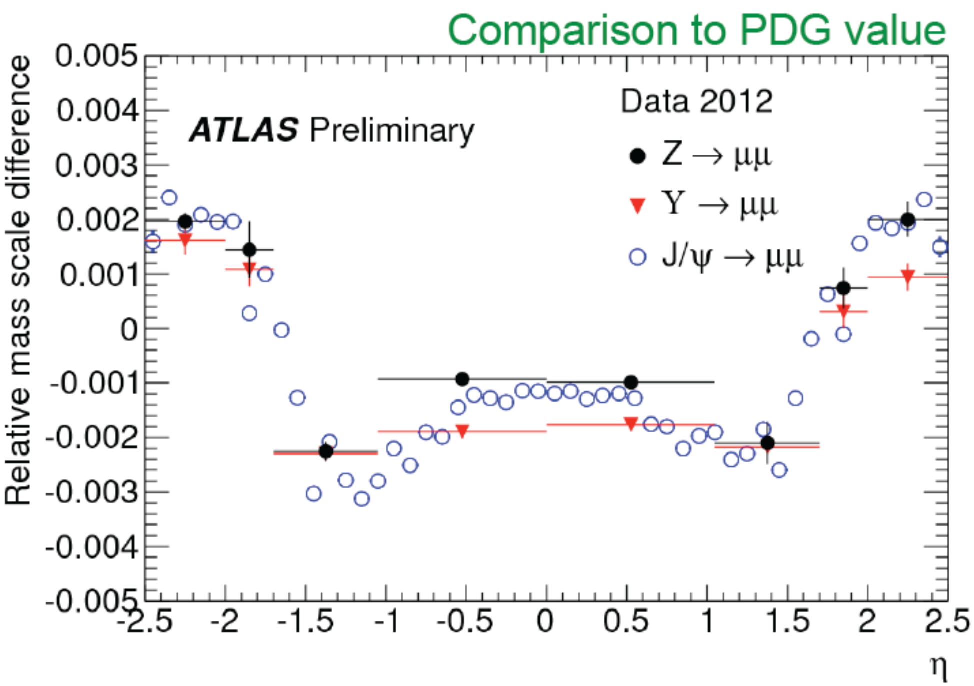
$\mu_{ggH,ttH}$ vs $\mu_{VBF,VH}$

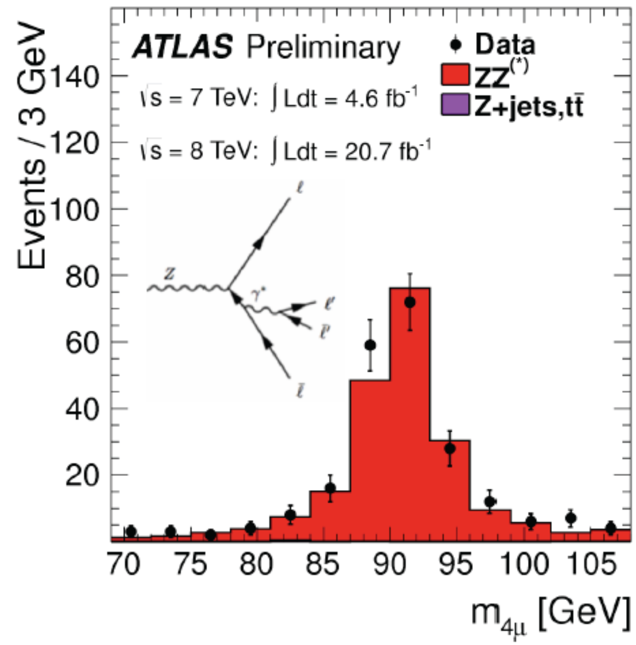


Energy Scale and Resolution

Muon energy scale and resolution corrections and systematic uncertainties determined from large Z, J/ψ and Y samples

- Resolution correction (0.2-1.3%), scale correction (< 0.1%)
- Independent measurements from Muon Spectrometer and inner tracker
- Probe global and local scale biases, overall uncertainty on 4μ scale 0.2%
- Calibration using Z→ 4μ mass peak



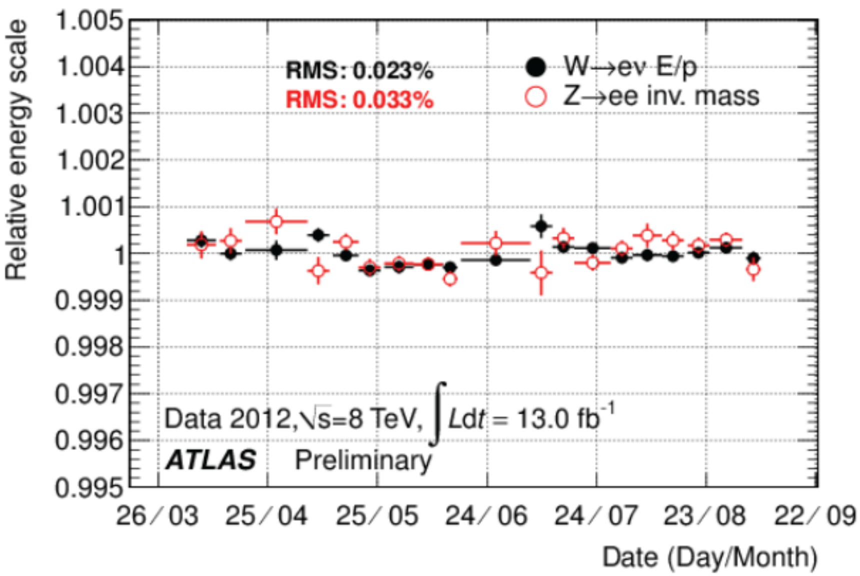


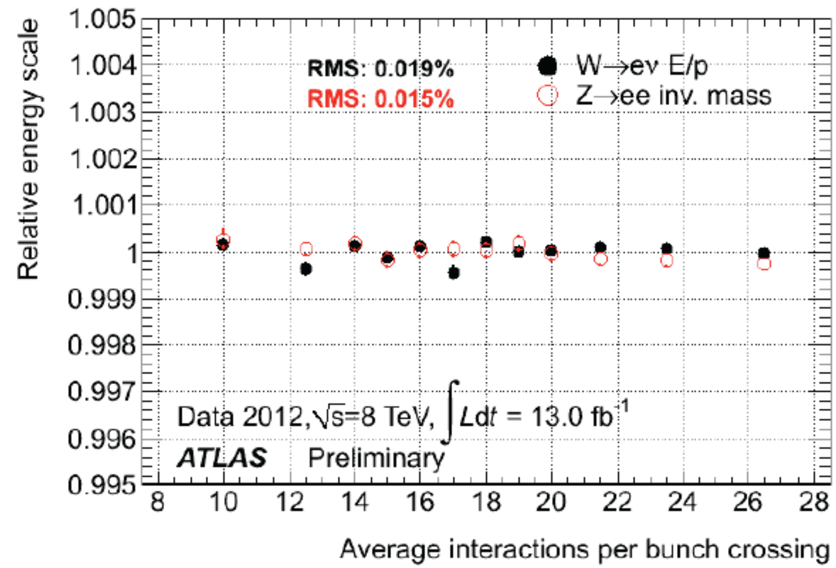
EM Colorimeter Calibration

- In-situ energy calibration results and their stability checked with different methods
  (E/P with W→ eν, J/ψ → ee)

- Uncertainty on the diphoton mass scale 0.6%, largely contributions
  - Material effects (separately for volumes for |η| < 1.8, and |η| > 1.8)
  - Uncertainty on the in-situ calibration method

Stability of EM calorimeter response vs time/pile-up better than 0.1%





Photon Energy Calibration

- ❑ MC based calibration at cluster level tuned in test beams
- ❑ Need accurate material description for e→ g extrapolation
  (Cross checked with EM shower shapes, photo conversions, hadronic interactions and e/p,…)
- ❑ Energy scale corrections from Z decay to electrons. Cross checked at the lower energy spectrum with radiative Z decays