Bosonic Higgs Decays

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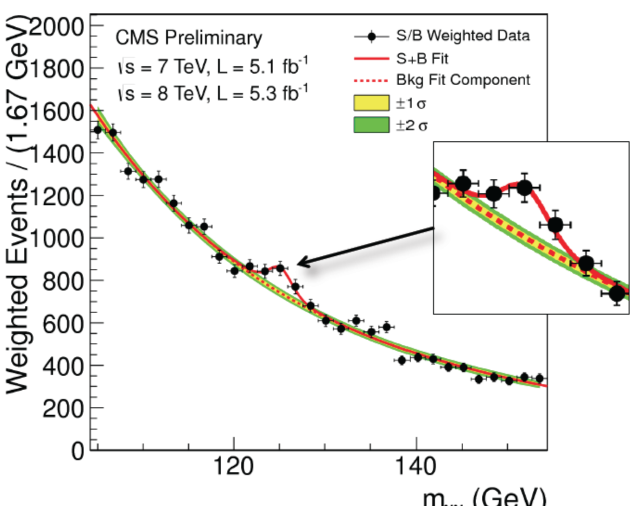
On behalf of the CMS and ATLAS Collaborations

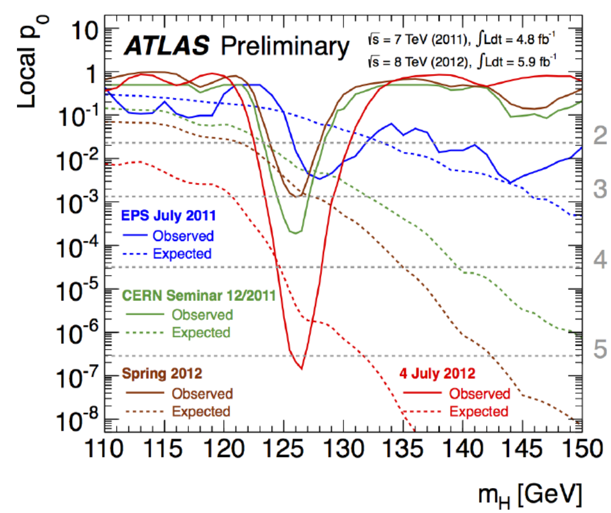
Thanks to Marco Pieri & Bing Zhou for good pptx slides on this topic.

PIC 2013: Physics in Collision,

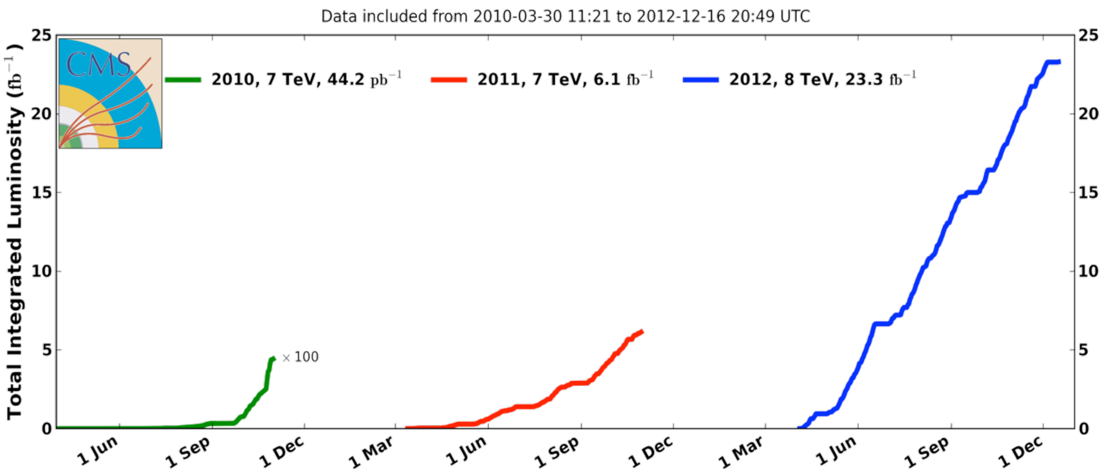
Sept. 3-7 2013,

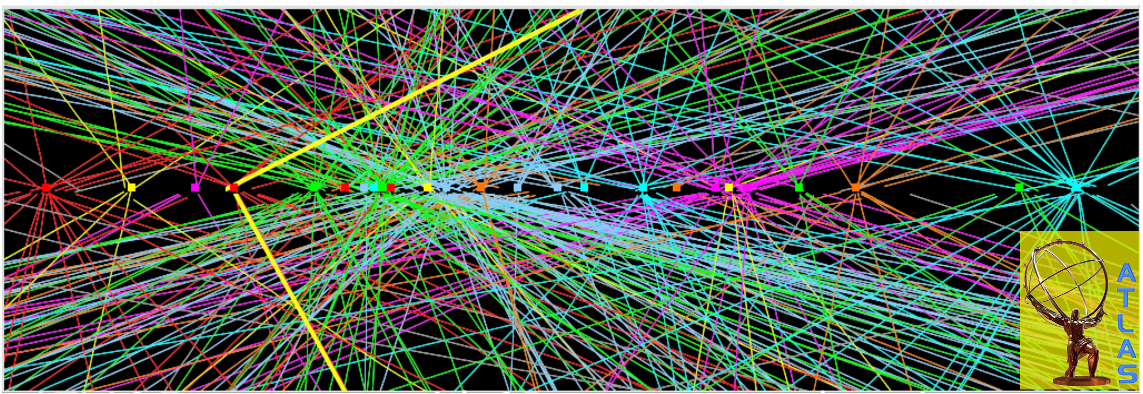
IHEP, Beijing, China





LHC Data: pp Collisions at 7 and 8 TeV



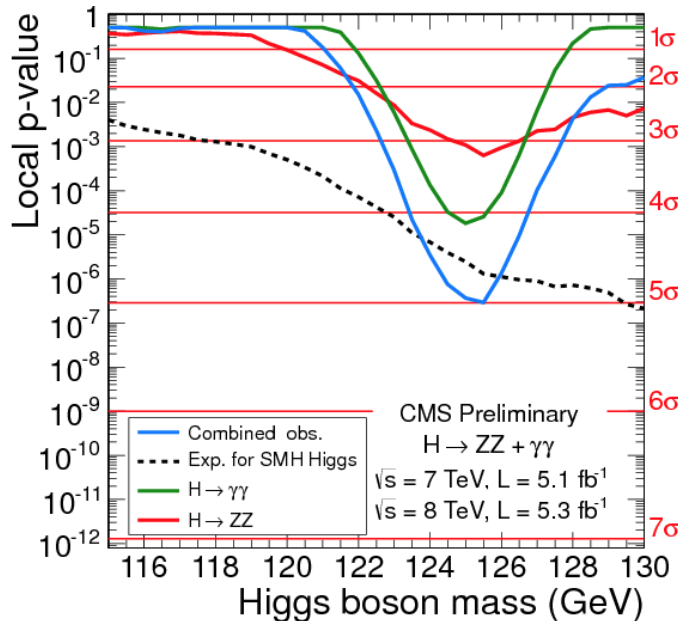


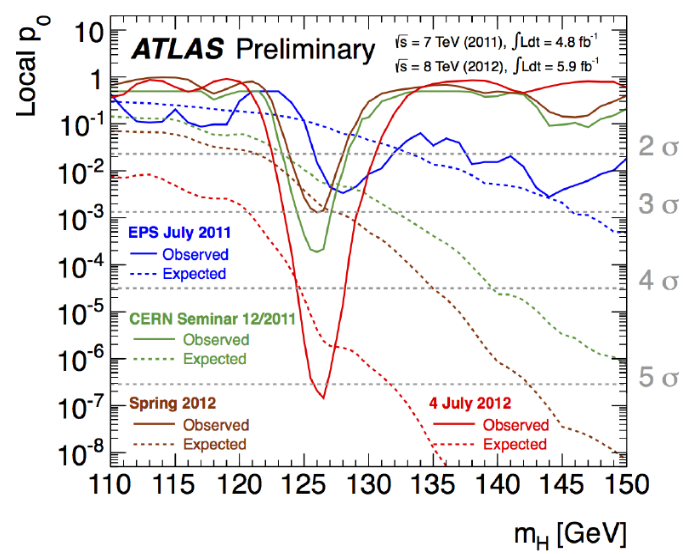
- Excellent performance of LHC in 2011 and 2012
  - Design 14 TeV @ 10^{34} $cm^{-2}s^{-1}$
  - Peak $\mathcal{L}$ = 7.7 x 10^{33} $cm^{-2}s^{-1}$
- ~25 fb^{-1} Int $\mathcal{L}$ pp collisions collected per experiment
- Very high data taking efficiency for both experiments
- More pileup than planned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

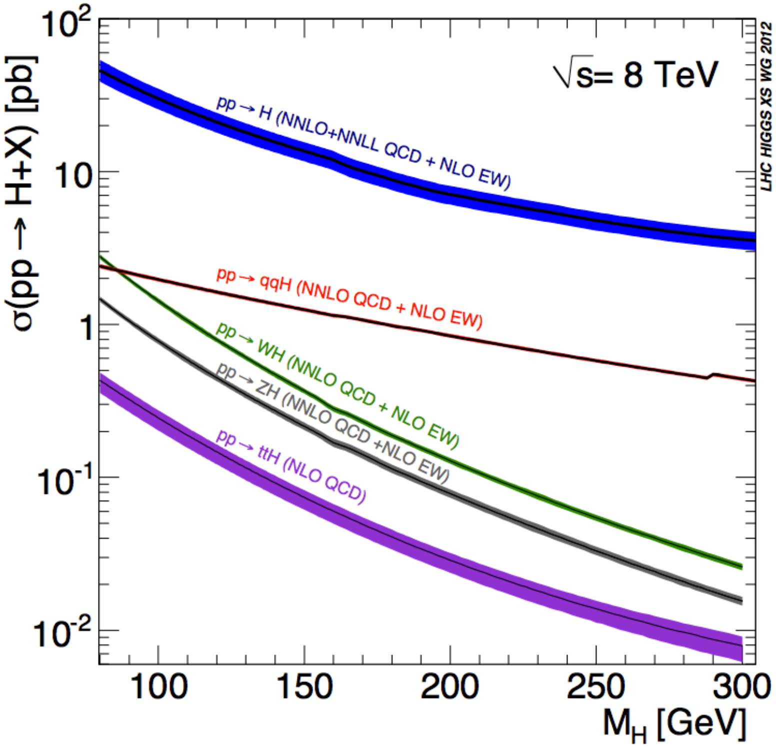
July 4, 2012: A "Higgs-like" Resonance

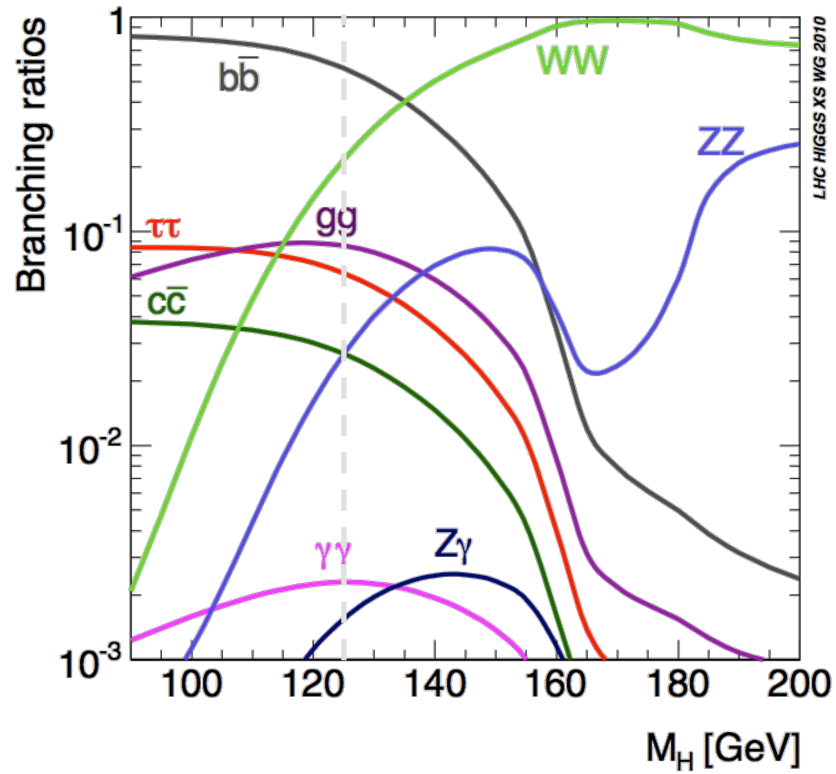
- Both Experiments had almost exactly 5σ when combining the channels that they analyzed.
  - Very lucky (sociologically) to get to 5σ at the same time
    - blind until just before CERN seminars
- Confirms (preposterous) SM Higgs Mechanism
  - But details of Higgs Sector still unclear
- M=125 is very 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.



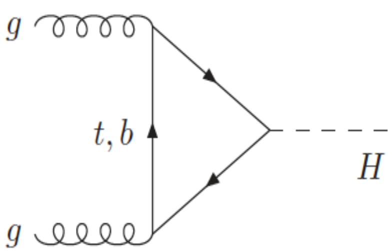


SM Higgs Production and Decay

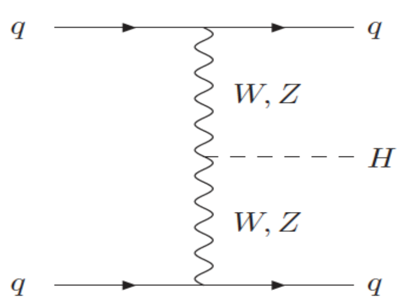




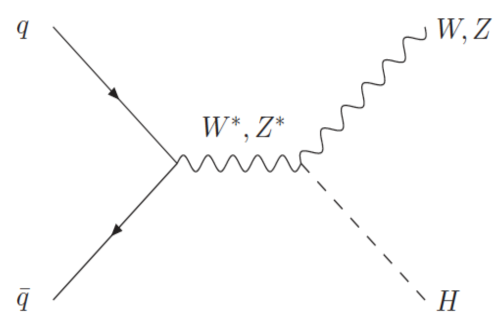
ggH



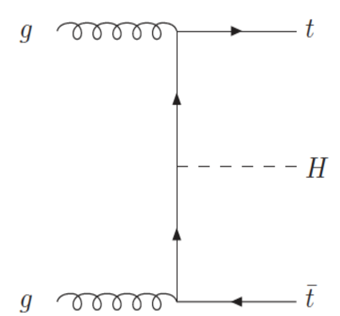
VBF



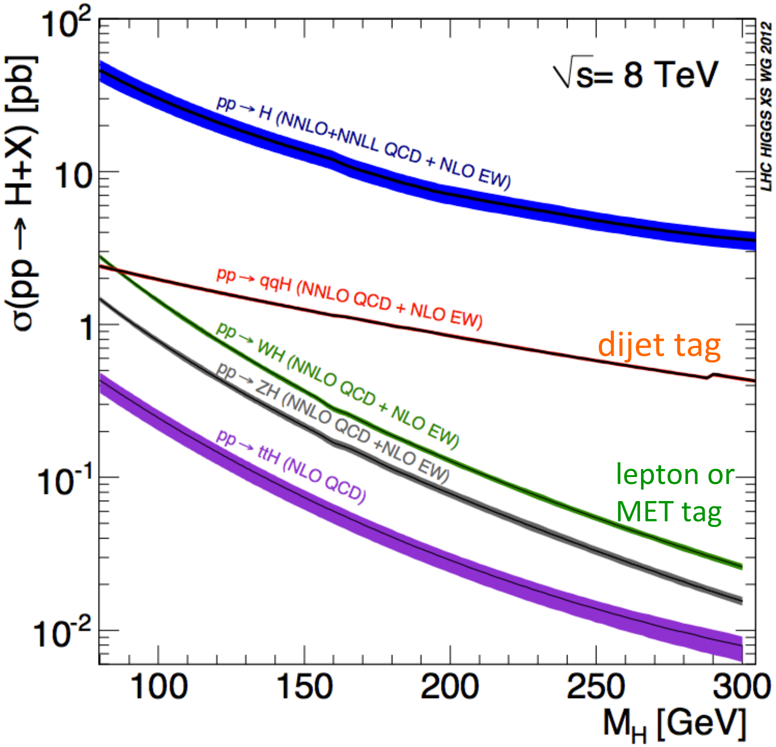
VH

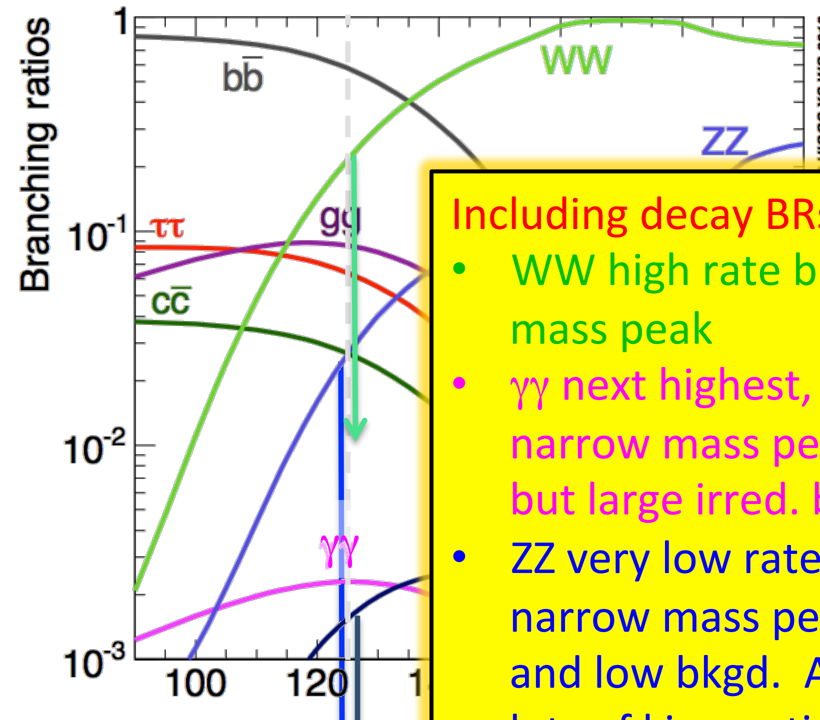


ttH



SM Higgs Production and Decay

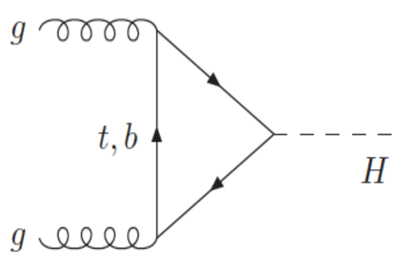




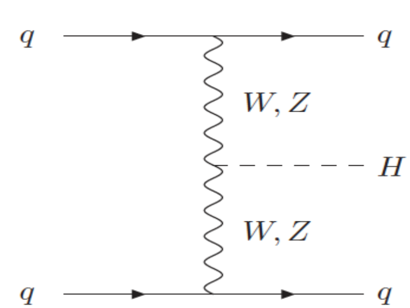
Including decay BRs

- 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

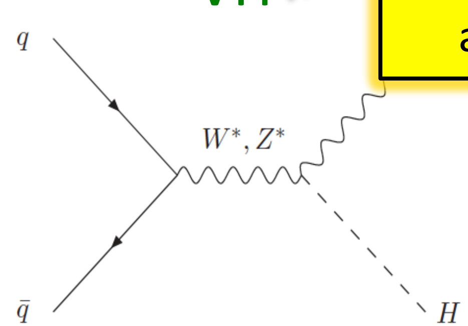
ggH

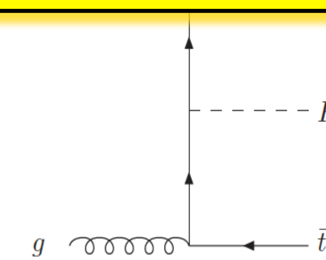


VBF



VH

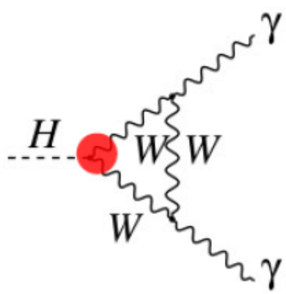


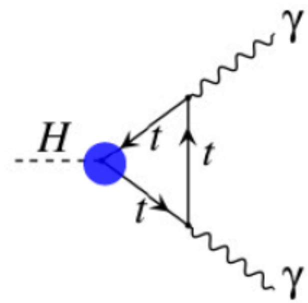


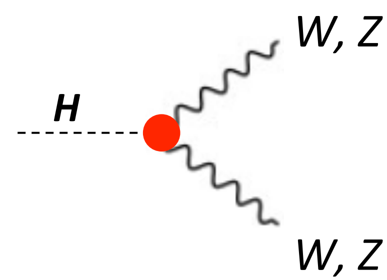
CMS Bosonic channels at 125 GeV

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
- $\gamma\gamma$ and ZZ -> 4ℓ with excellent mass resolution (1-2%):
- WW -> 2ℓ2ν with highest rate:
- Zγ -> $\ell\ell\gamma$ has low SM rate but good mass resolution



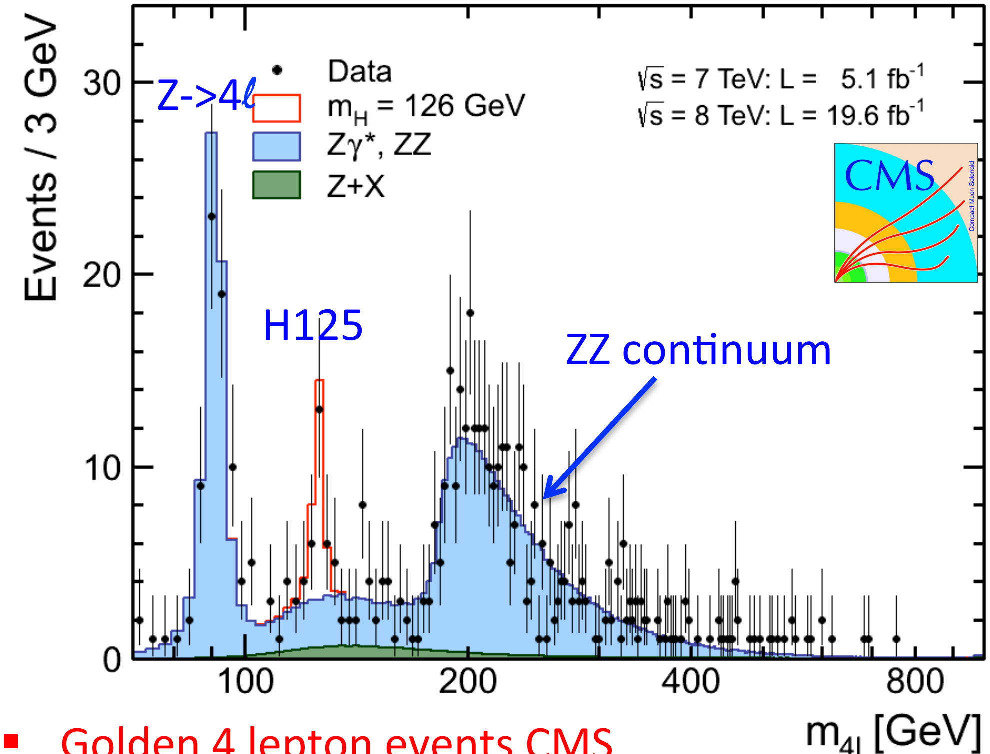


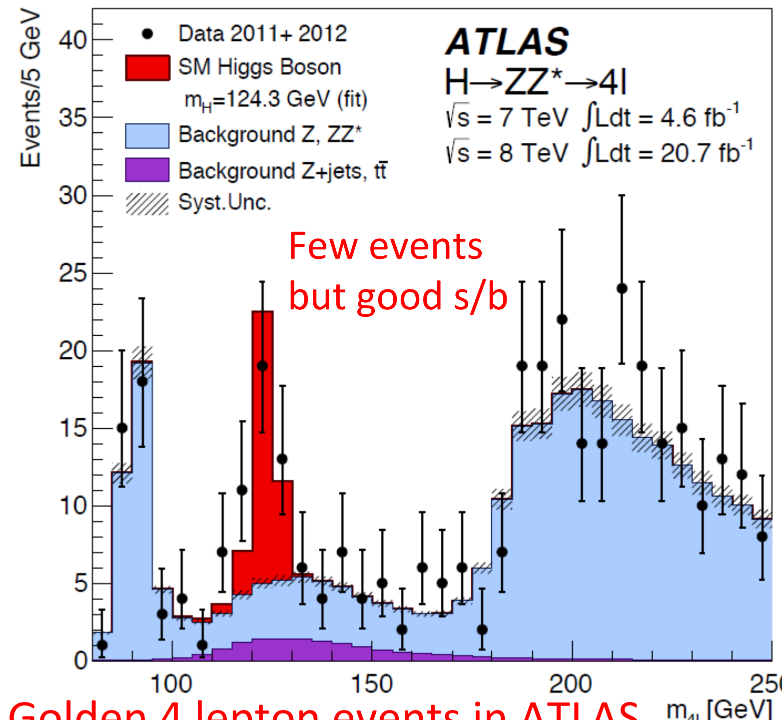


Higgs decay to $\gamma\gamma$ has interference between vector and fermion couplings

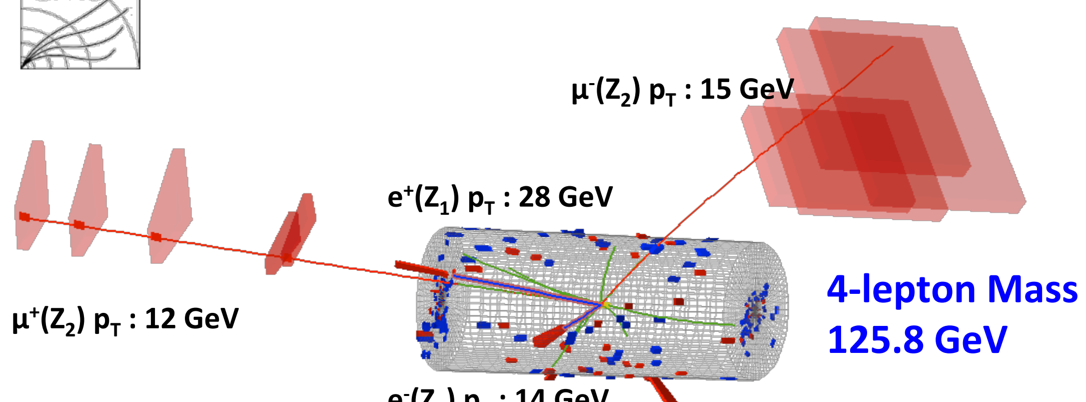
	Untagged	VBF	VH	ttH
H->γγ				
H->ZZ->4l	done		in progress	
H->WW-lvlv				
H->Zγ->llγ				

H → ZZ → 4ℓ: candidates

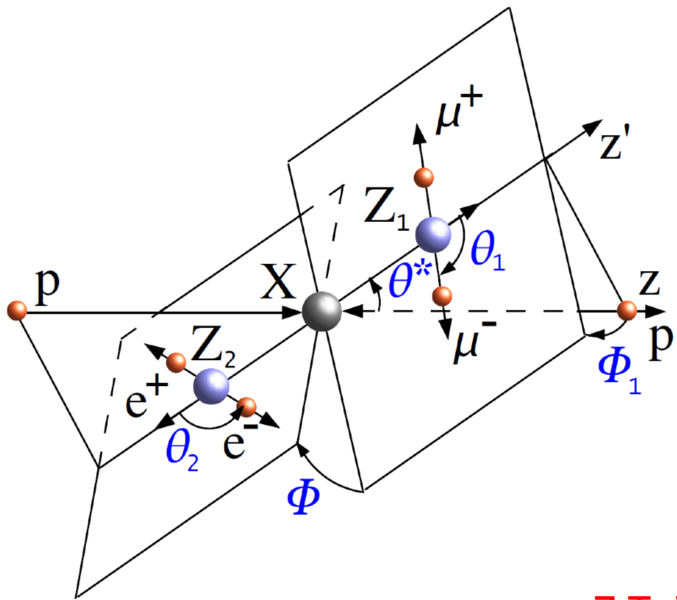




- Golden 4 lepton events CMS
  - Lepton ID efficiencies using Z.
  - Muon energy scale in constant B field is easy.
  - Energy scale and calibration for electrons (large effort) checked with Z→ee .
- Golden 4 lepton events in ATLAS
  - Huge effort on lepton ID efficiencies, and calibration of mass scale.



Measure 7 kinematic variables: K_D



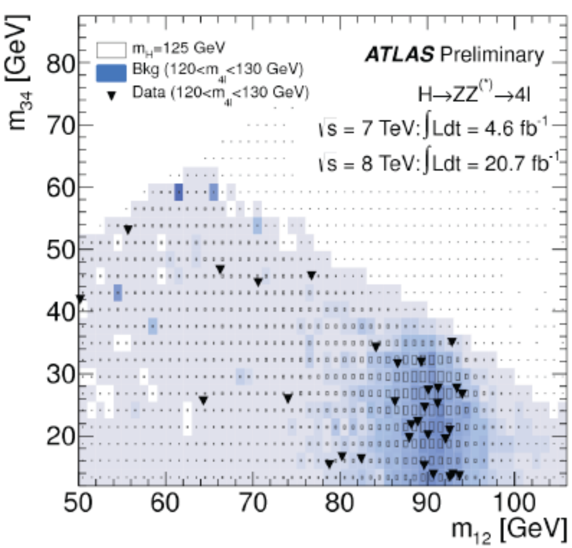
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

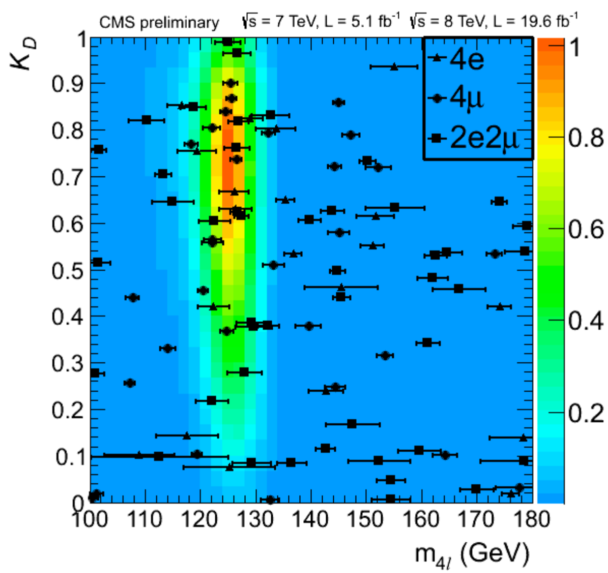
Kinematic Discriminants are useful to enhance signal over background or to test spin hypotheses…

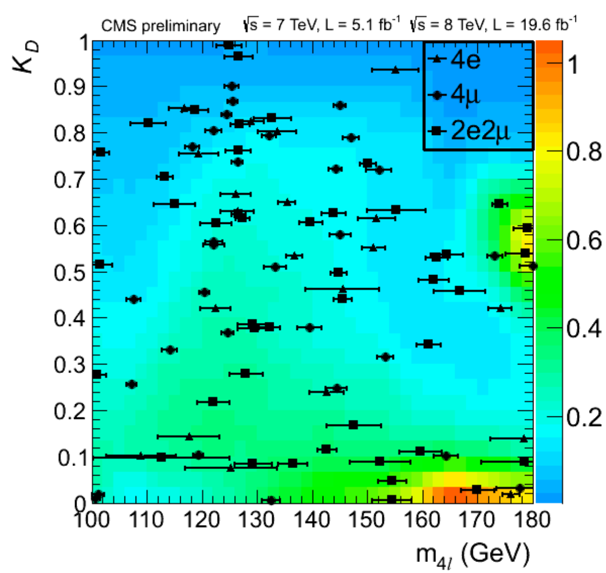
- Add a dijet category – to have sensitivity to VBF
- Use a 3D method in CMS (also using mass resolution)
  - Inclusive: Mass – K_D – P_{t4l}
  - dijet category: Mass – K_D – V_D (VBF discriminant)

7 TeV with signal expectation

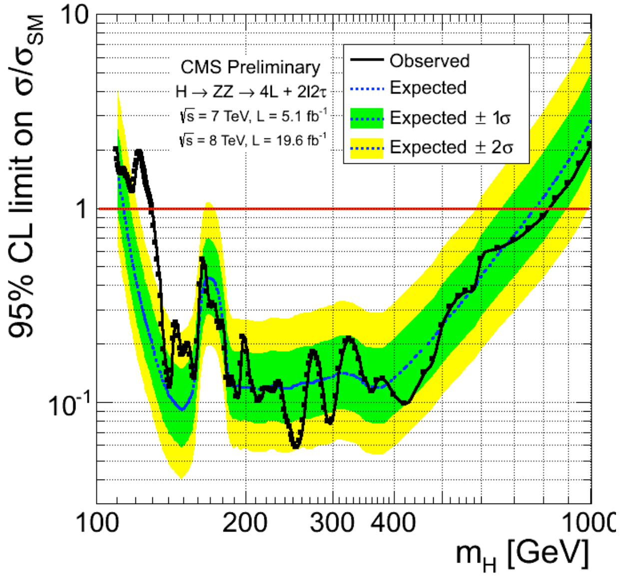
with bkgd expectation

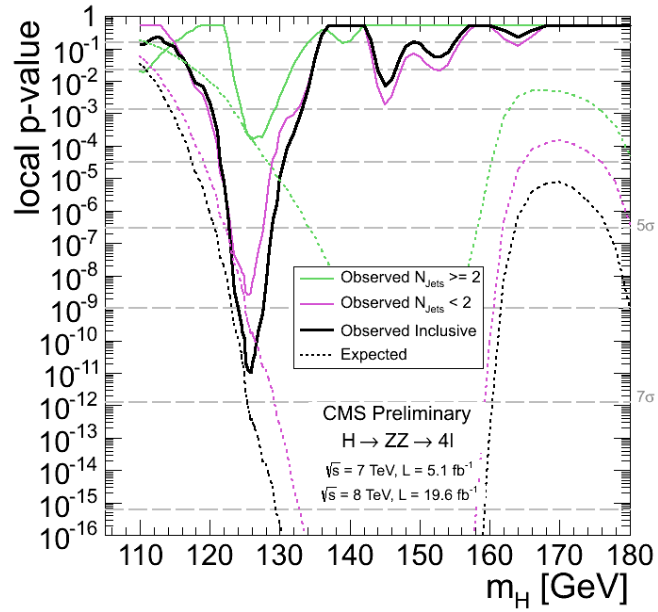






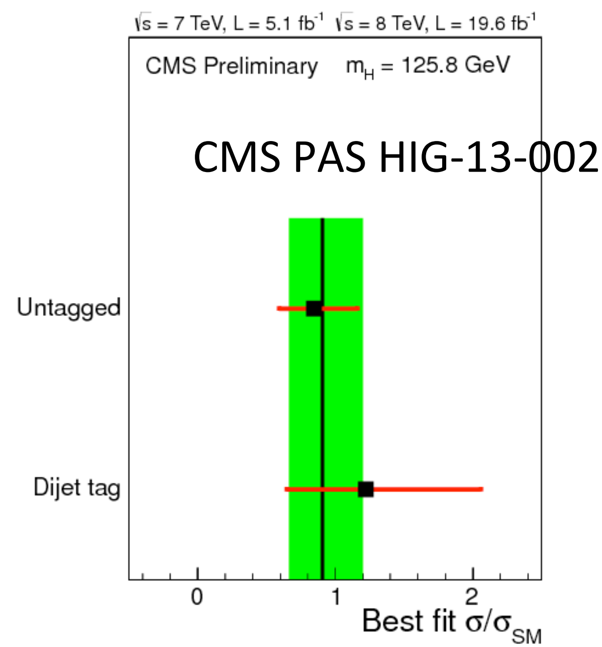
$H \rightarrow ZZ \rightarrow 4\ell$ (+$2\ell2\tau$): CMS results





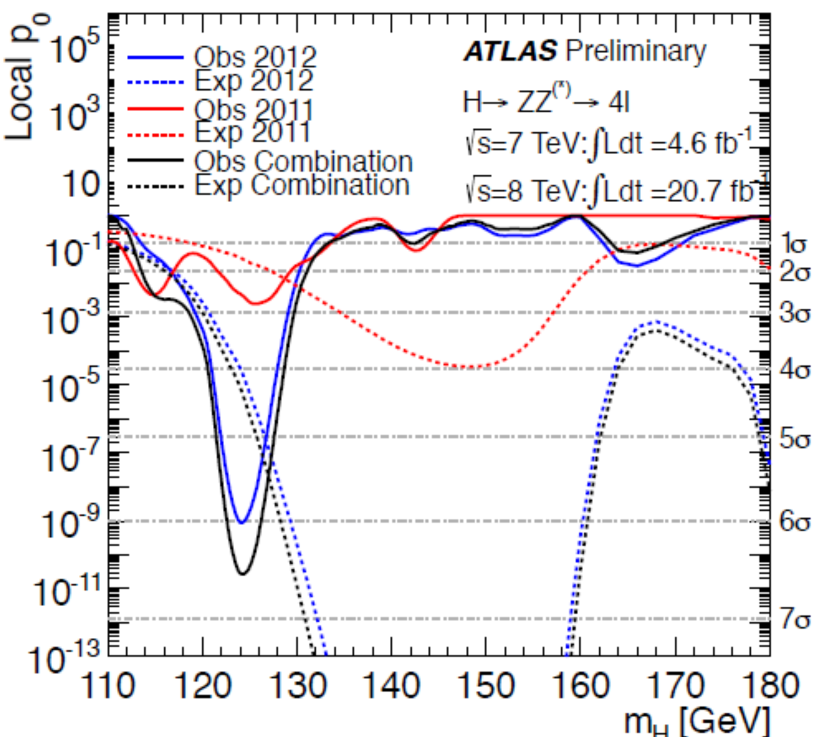
- Excess of events at 125.8 GeV
  - expected significance: 7.2σ ($P < 10^{-12}$)
  - observed significance: 6.7σ
  - Fitted $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$

Consistent results obtained with 1D and 2D fits



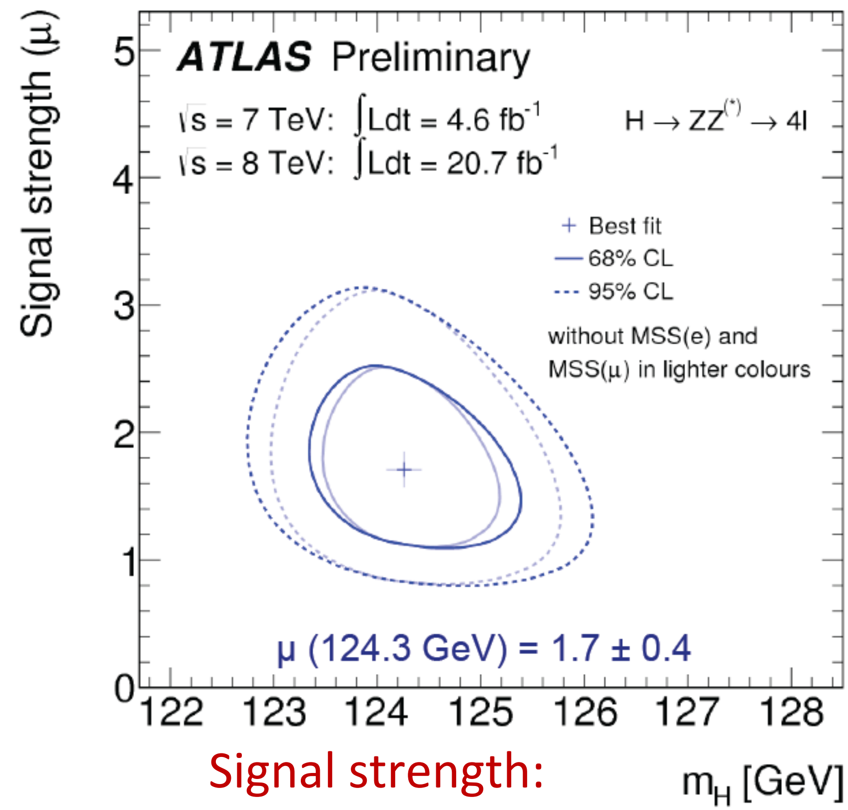
CMS PAS HIG-13-002

H→ ZZ*→ 4ℓ: 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

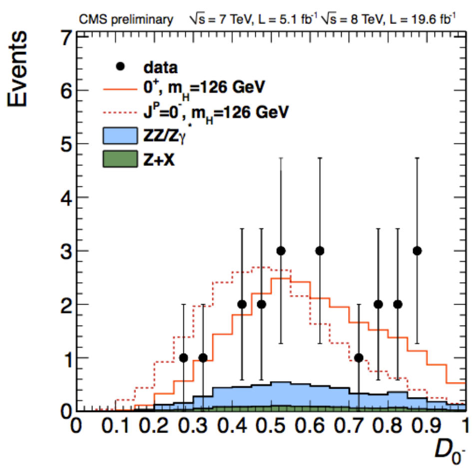
Compare Experiments based on expected sensitivity:

CMS: 7.2σ expected — ATLAS: 4.4σ

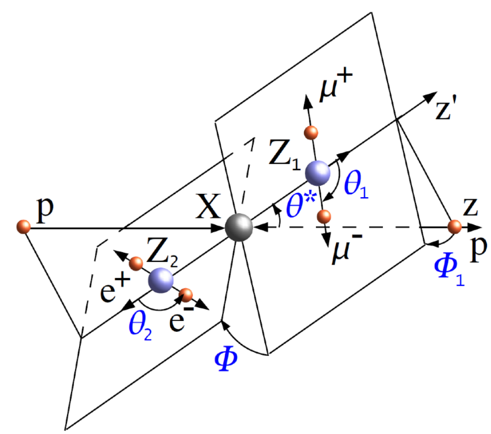
$\mu_{CMS} = 0.91^{+0.30}_{-0.24}$ — $\mu_{ATLAS} = 1.7^{+0.5}_{-0.4}$

CMS H→ ZZ*→ 4ℓ Spin-Parity Analysis

- 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.



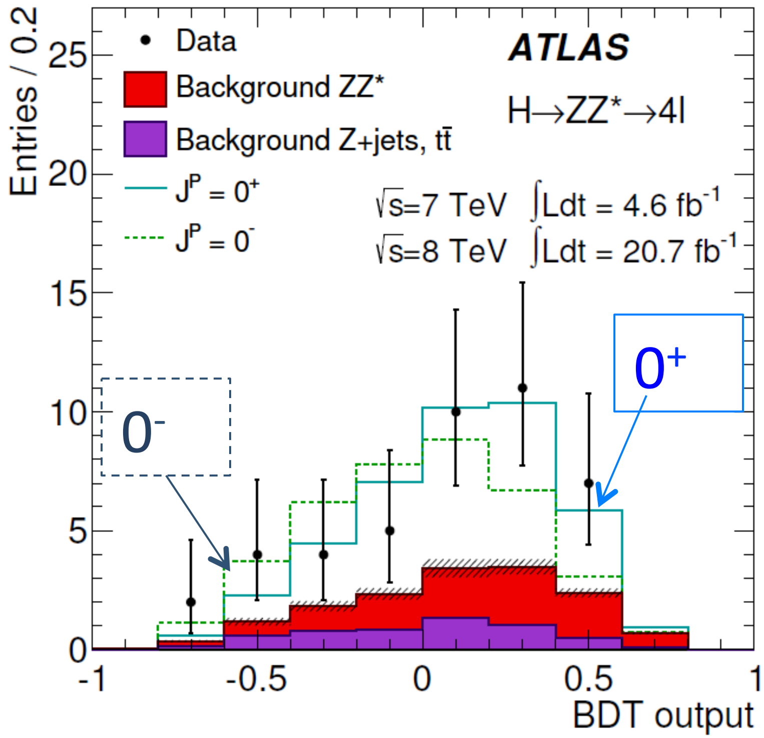
CMS PAS HIG-13-002

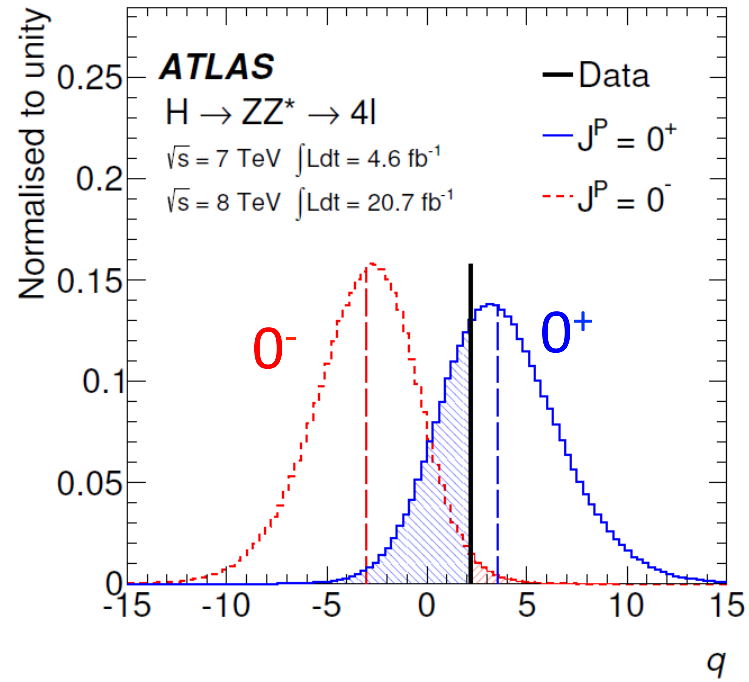


Data strongly favor $J^p = 0^+$

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$_s$):**

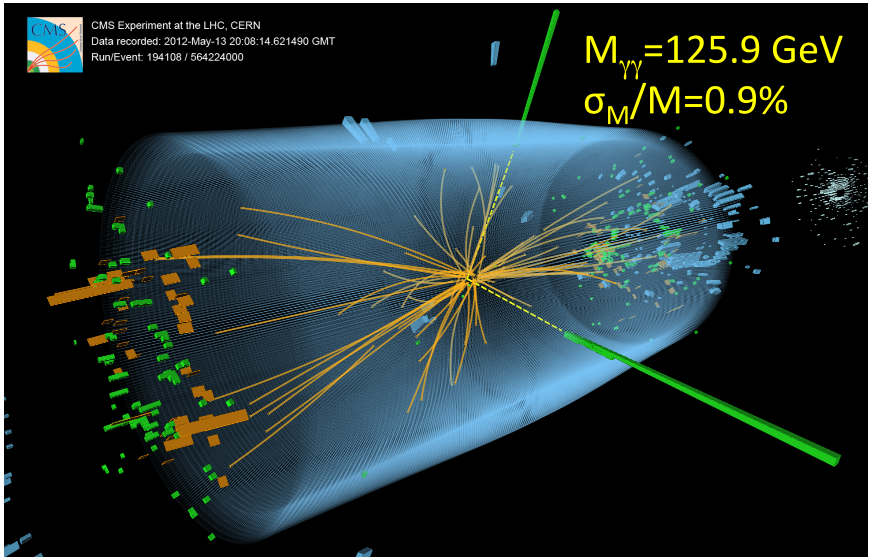
Observed 0$^-$ exclusion 97.8%

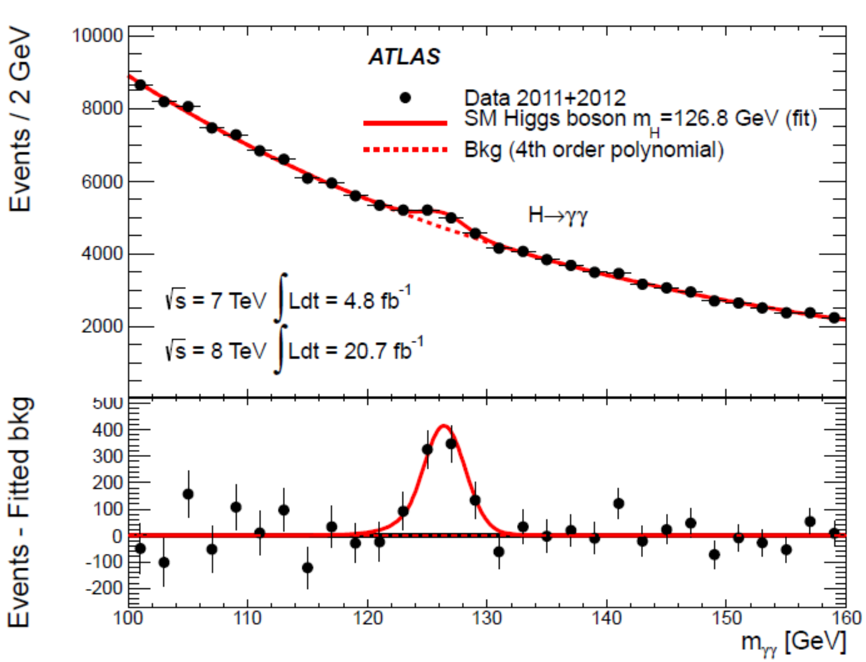
Observed 1$^+$ exclusion 99.8%

		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→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.

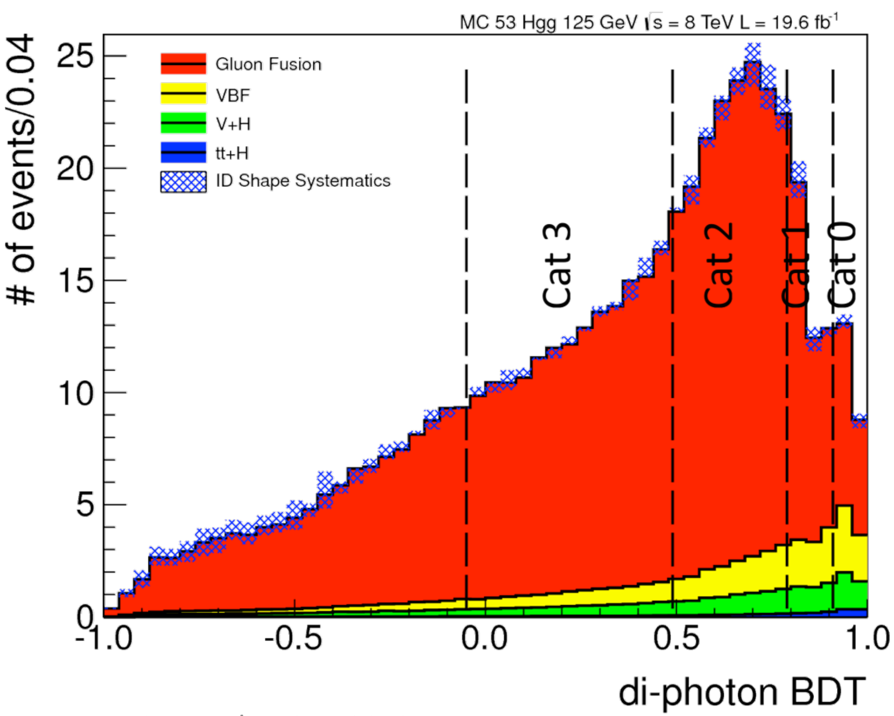


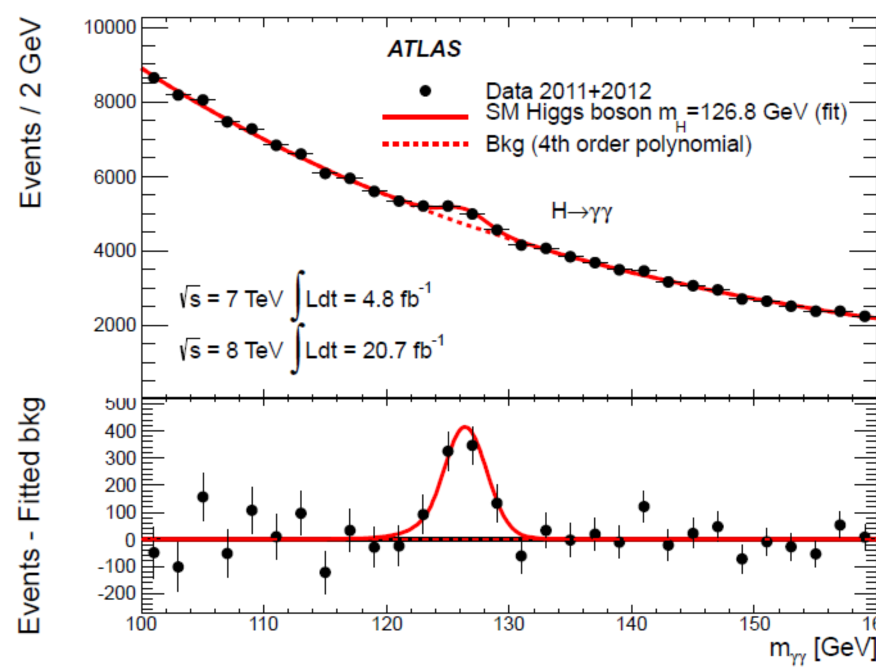


H→γγ Mass-Independent MVA Analysis

- 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

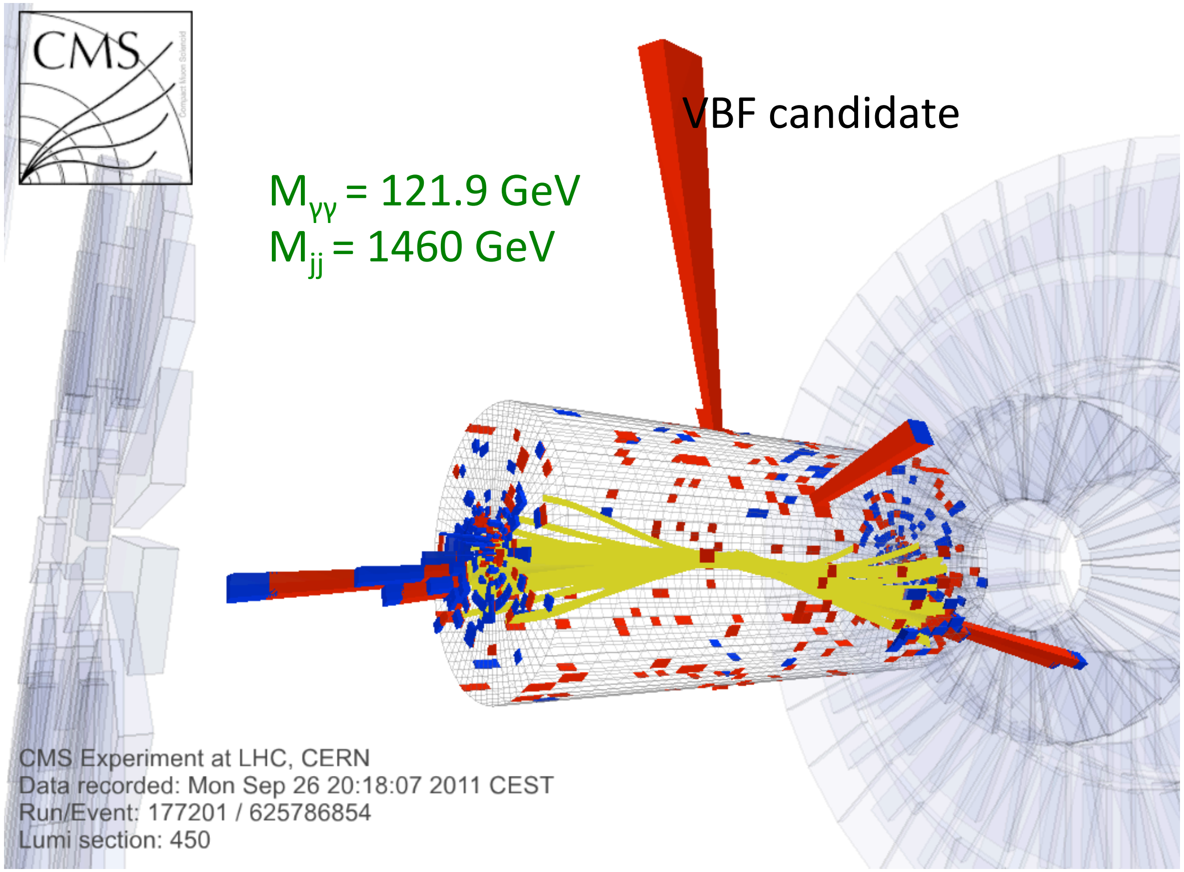
- ATLAS: Simple signature: two high-p_T isolated photons - E_T (γ_1, γ_2) > 40, 30 GeV ($\sqrt{s}$=8 TeV)
- Events divided into 14 categories based on production mode and S/B ratio in different detector region (increase sensitivity, also for coupling measurements)



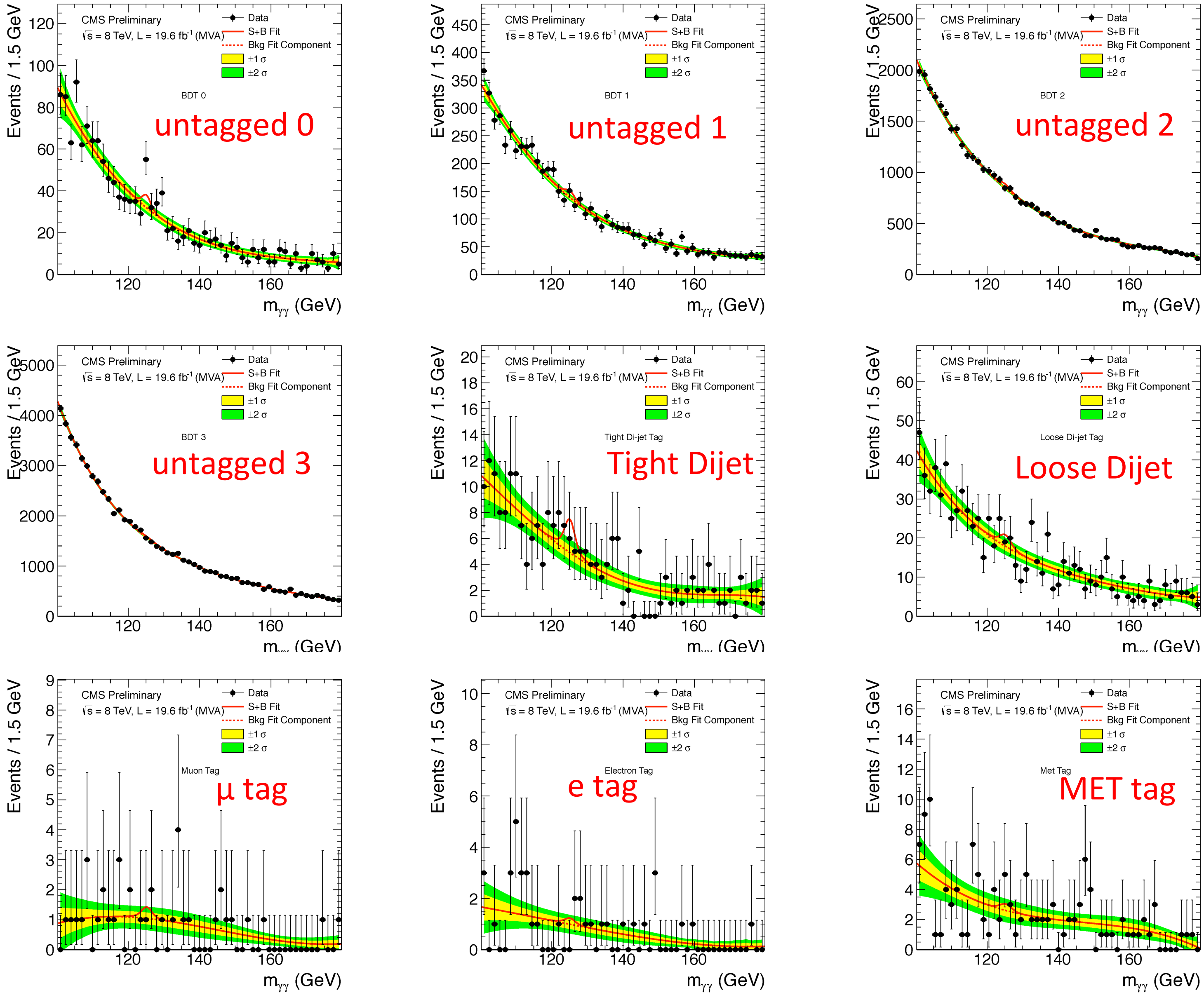


H→γγ Di-jet Tag

- 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

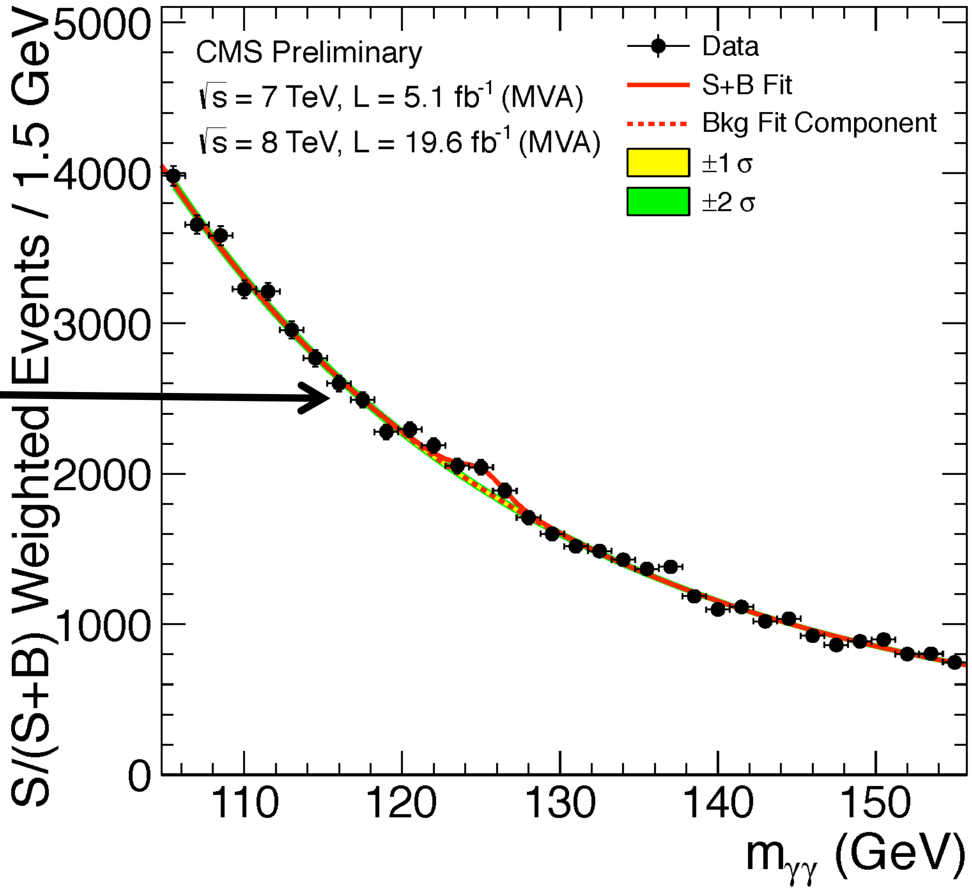


8 TeV Categories



H→γγ Weighted Mass Distribution

Weighed data events and BG model parametrizations

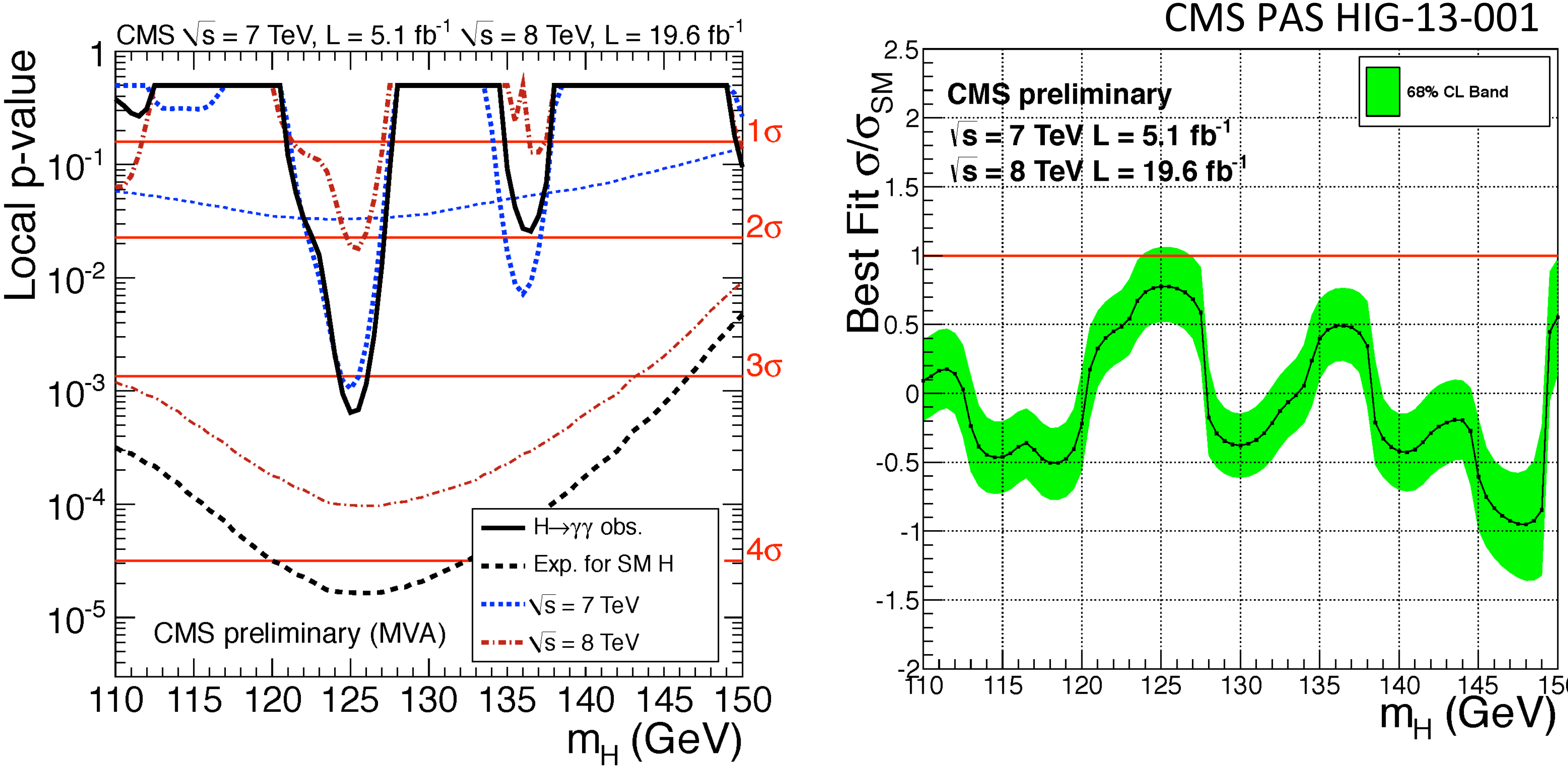


- **One weight per category.**
- Sum of mass distributions for each event class, weighted by S/(S+B)
- B is integral of background model over a constant signal fraction interval

- 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



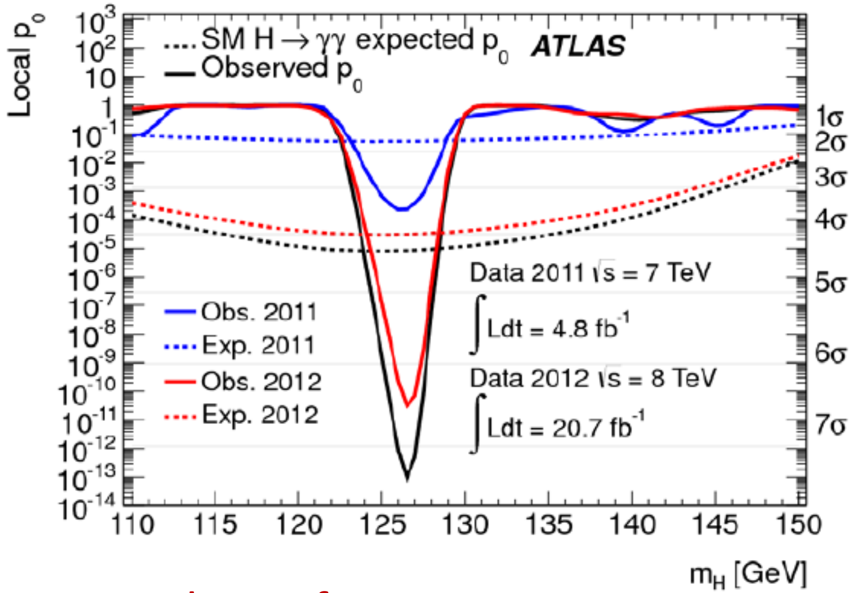
- Largest excess around 125 GeV
  - Local significance 3.2 σ at 125 GeV
  - Expected significance 4.2 σ at 125 GeV
  - Fitted σ/σ_{SM} at 125 GeV $0.78^{+0.28}_{-0.26}$

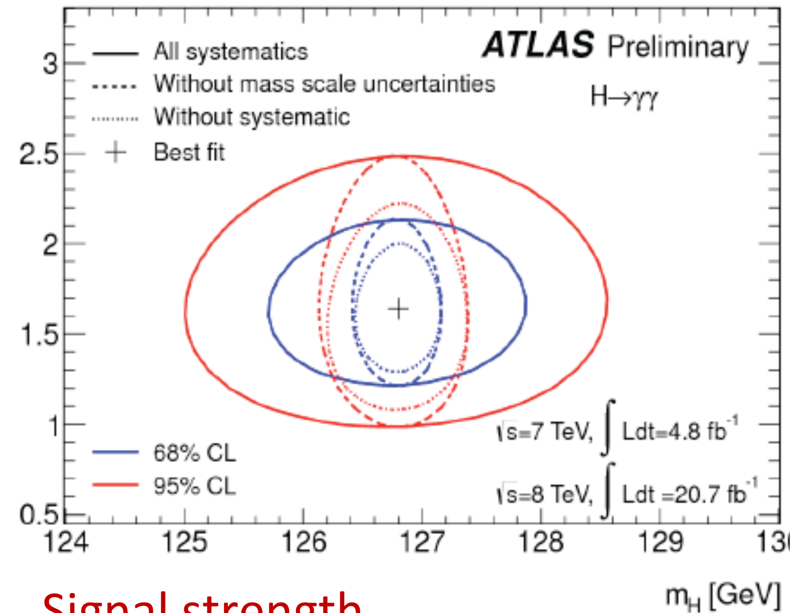
Consistent results from cut based: σ/σ_{SM} at 125 GeV $1.11^{+0.32}_{-0.30}$

(consistency check with bootstrap method).

$H \rightarrow \gamma\gamma$

arXiv:1307.1427 UCSD





Signal Significance :
7.4σ (4.3σ expected)

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

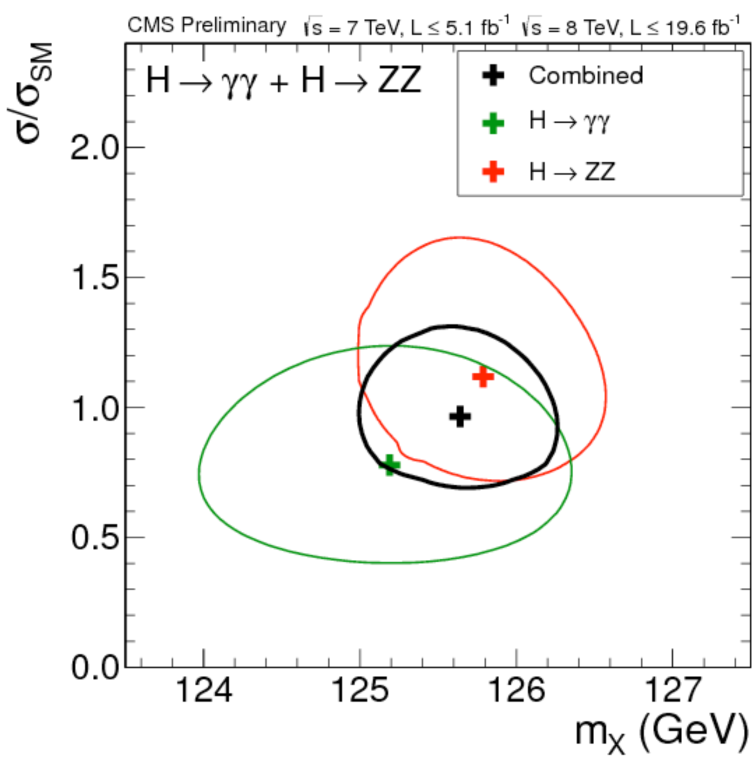
Obs (√s=8 TeV, $m_H^{rec} = 126.8$ GeV $\pm 2\sigma$)	Expected purity s/s+b (√s=8 TeV)	Main backgrounds
13931	370/13575 = 2.7%	γγ,γj and jj

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) ± 0.22(syst)

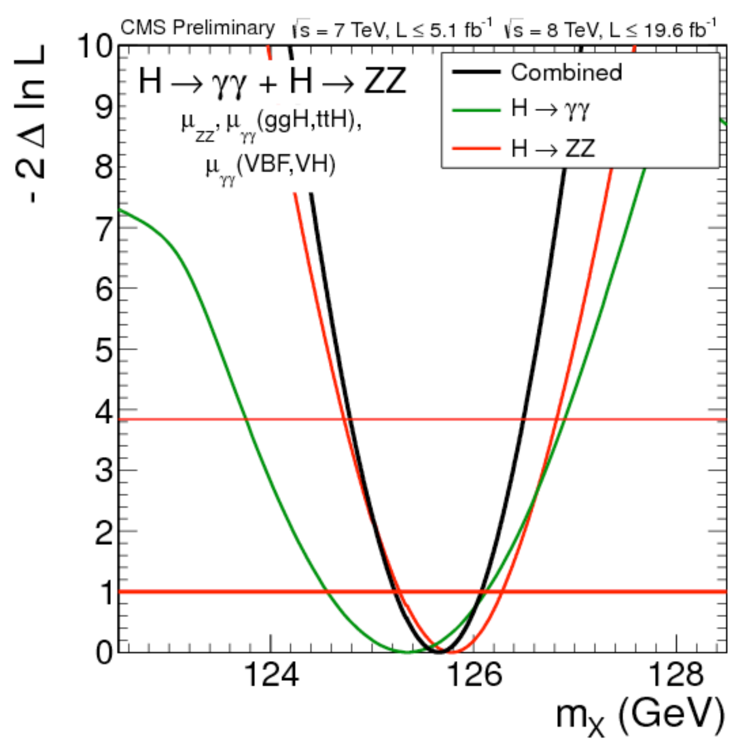
Combined Mass Measurement

- 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



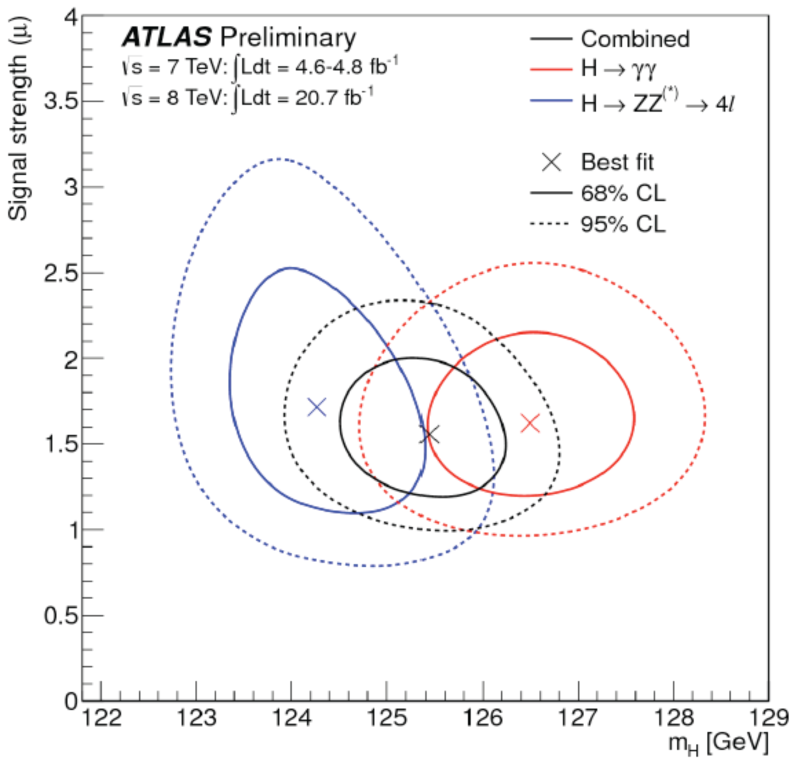
1D scan: mass

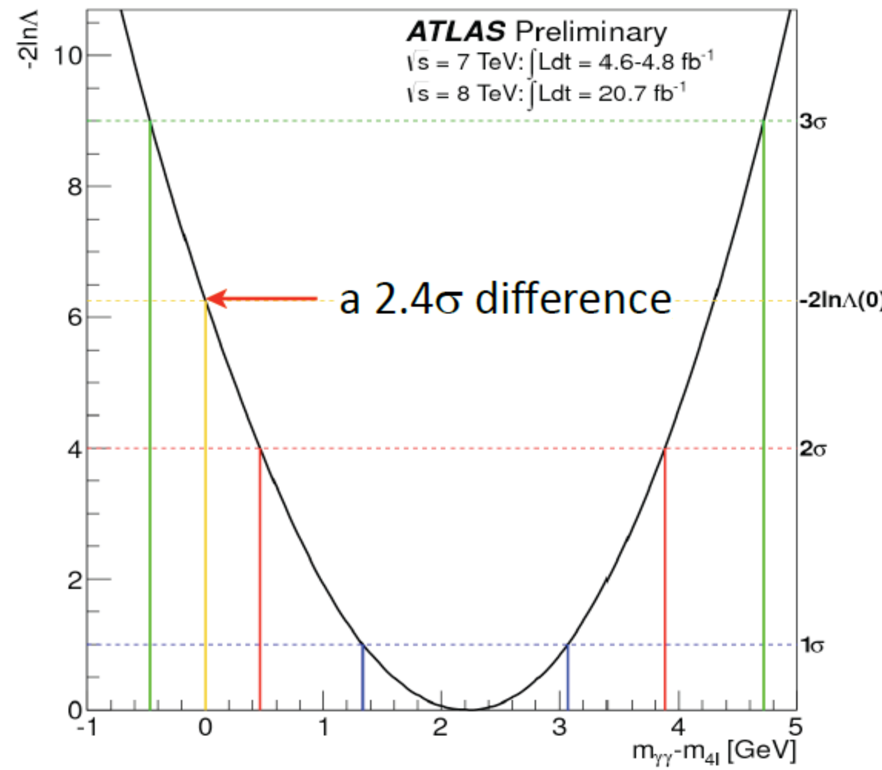


- $M_H = 125.7 \pm 0.3(\text{stat.}) \pm 0.3(\text{syst.})$ GeV

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)

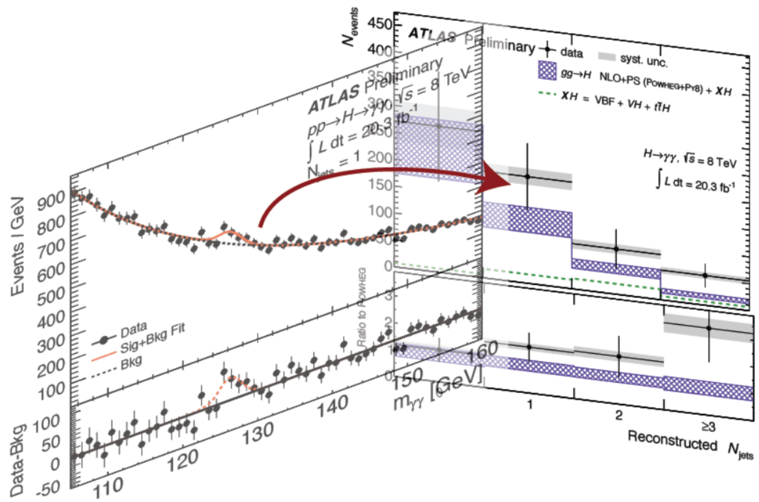
H→γγ Differential Cross-Sections

ATLAS-CONF-2013-072

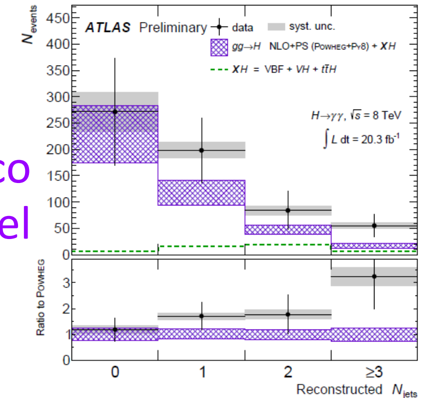
Study the kinematic distributions of H→ γγ events

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

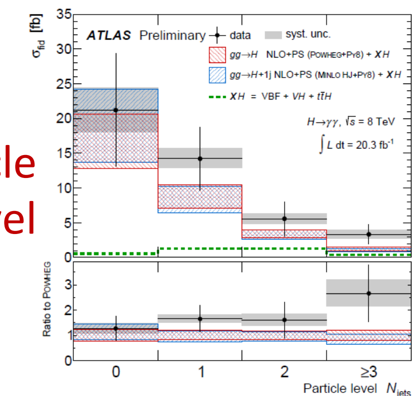
	Variable
Inclusive	$p_T^{\gamma\gamma}$
	$\lvert y^{\gamma\gamma}\rvert$
	$\lvert\cos\theta^*\rvert$
	N_{jets}
	p_T^{j1}
2-jets	$\Delta\varphi_{jj}$
	$p_T^{\gamma\gamma jj}$



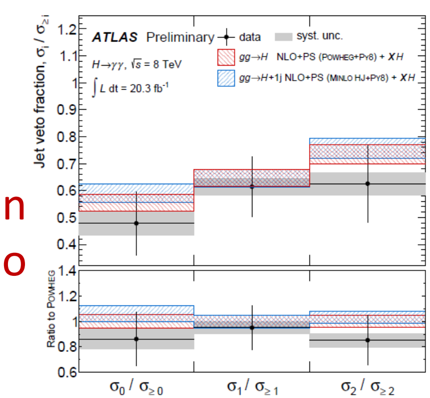
Reco level



Particle level



Cross-Section ratio



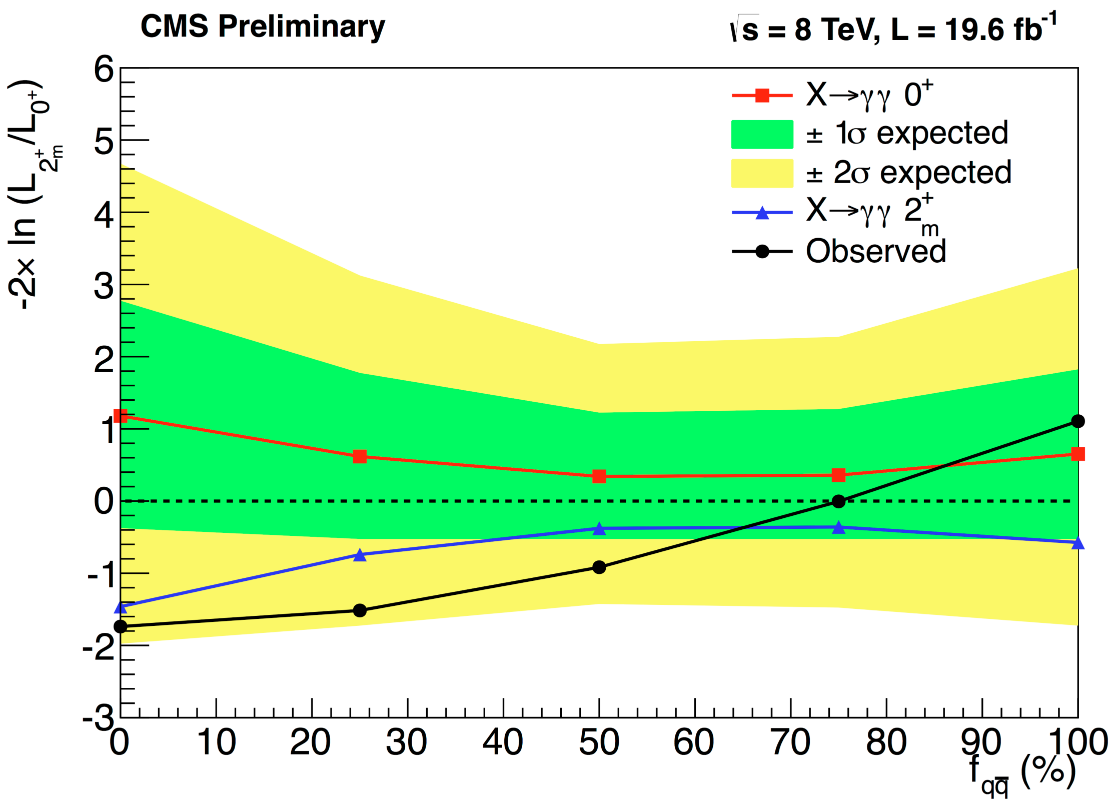
- **Bin events in variables of interest**
- **Background estimations from the mγγ side-band fit in each bin**
- **Estimate the systematics**
- **Background subtraction in each bin**
- **Unfold the reconstructed distributions to truth distributions**

(→ differential cross-sections)

- **ATLAS has fairly uniform acceptance**

$H \rightarrow \gamma\gamma$ spin analysis

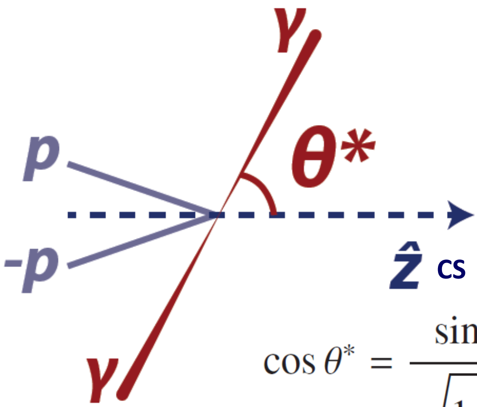
- Consider graviton-like hypothesis 2^+
- Production can be gg fusion or qq annihilation
- Sensitivity still rather low for high qq fraction



CMS PAS HIG-13-016

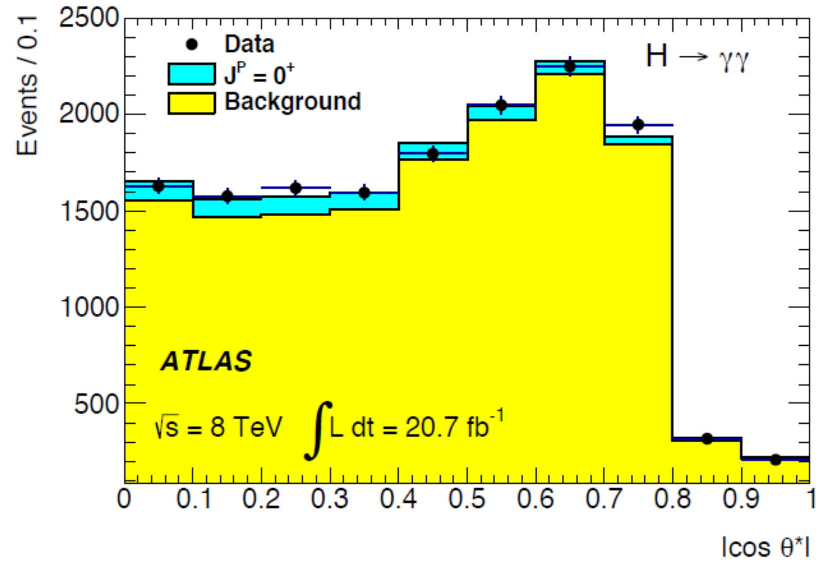
Spin Analysis with H→ γγ

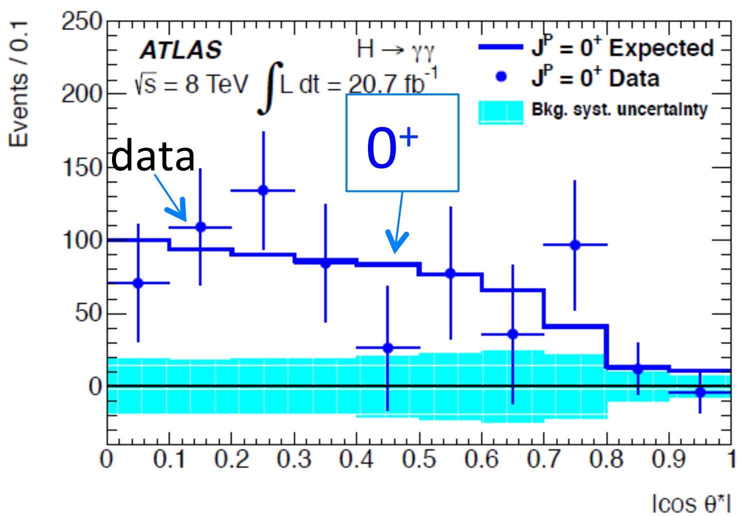
Polar angle θ^* of the photon decay in Collins-Soper frame, along with $m_{\gamma\gamma}$

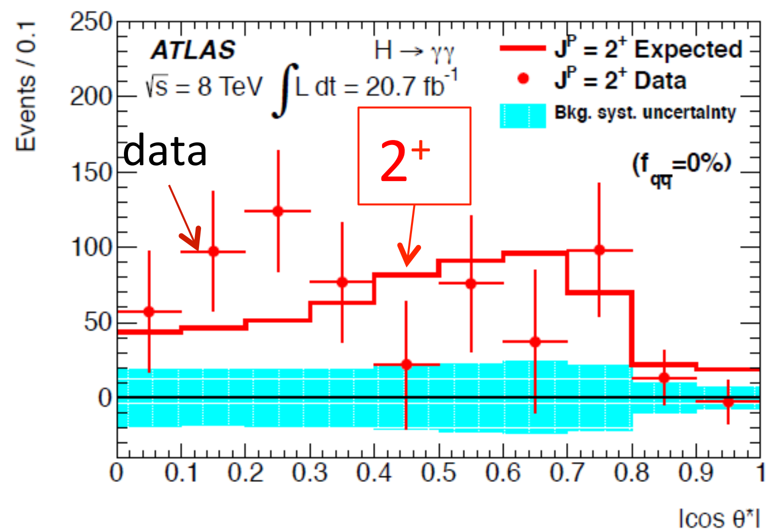


Z_{CS} bisects angle between the momenta of colliding hadrons

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







2^+ Hypothesis Exclusion in $H \rightarrow \gamma\gamma$

Method

- Binned likelihood using discriminants
  e.g. $\mathbf{m_{\gamma\gamma}}$ and $|\mathbf{\cos\theta^*}|$
- 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

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

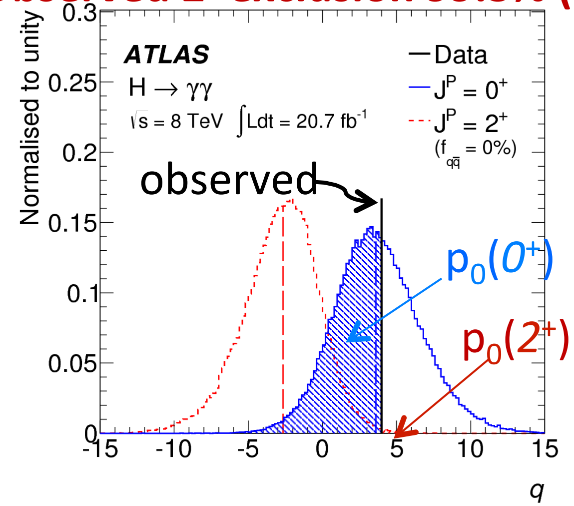
with μ fixed for a given J^P

- **Exclusion using (1 - $\mathbf{CL_S}$)**

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

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

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



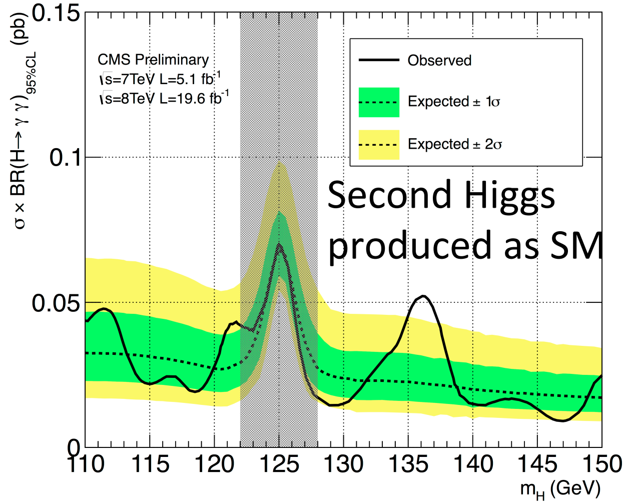
$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588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

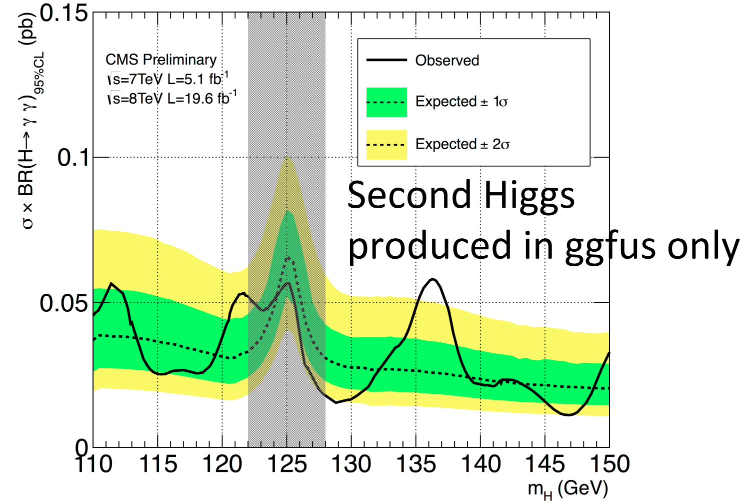
H→γγ - Double Higgs

- H125 used as additional BG

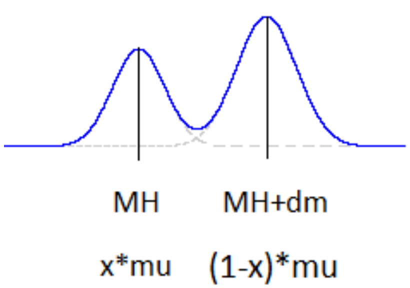
CMS PAS HIG-13-016

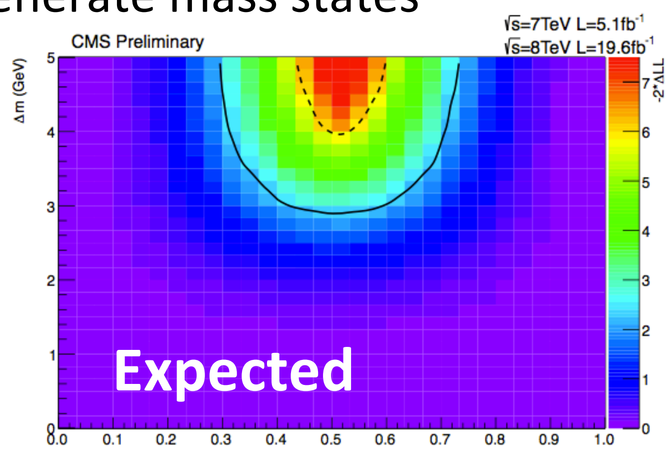
$M_{H'}$=136.5
Local significance 2.9 σ
Global significance <2σ

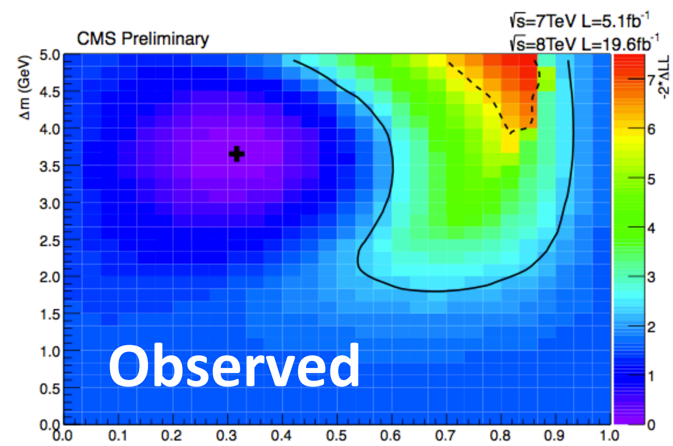




- Two nearly degenerate mass states







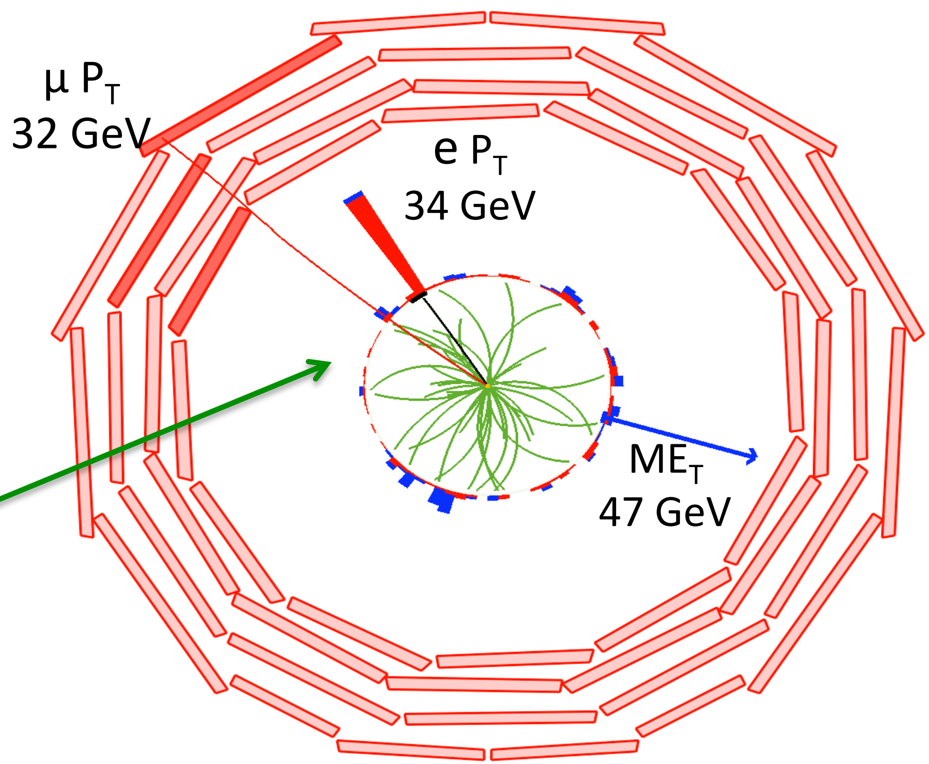
Allows to exclude parameters in the 2HDM when two Higgs boson interpreted as h,H or h,A

$H \rightarrow WW \rightarrow \ell\nu\ell\nu$

- 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 $\mathcal{L}$

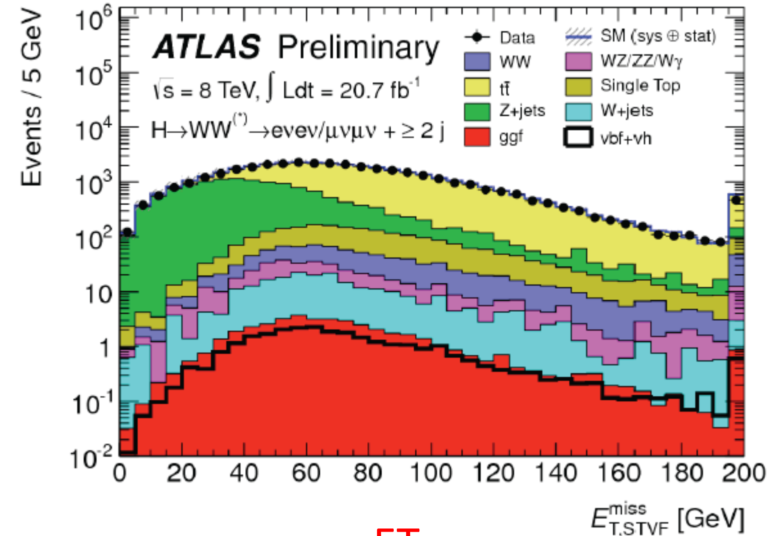
Scalar Higgs boson + V-A structure of W decay favors small Δϕ between the 2 charged leptons

H->WW->eμνν candidate

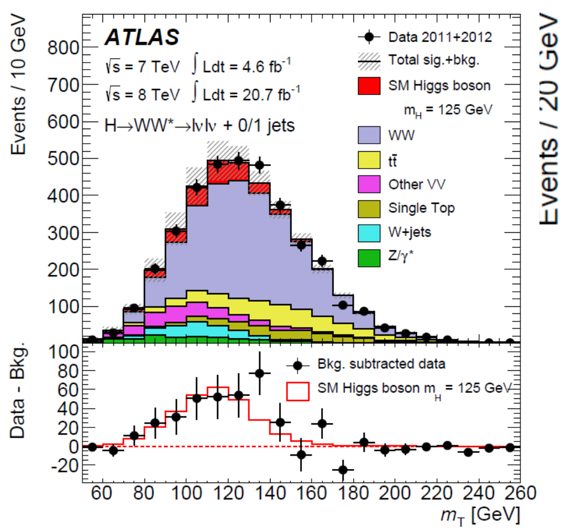


H→WW*→ℓνℓν

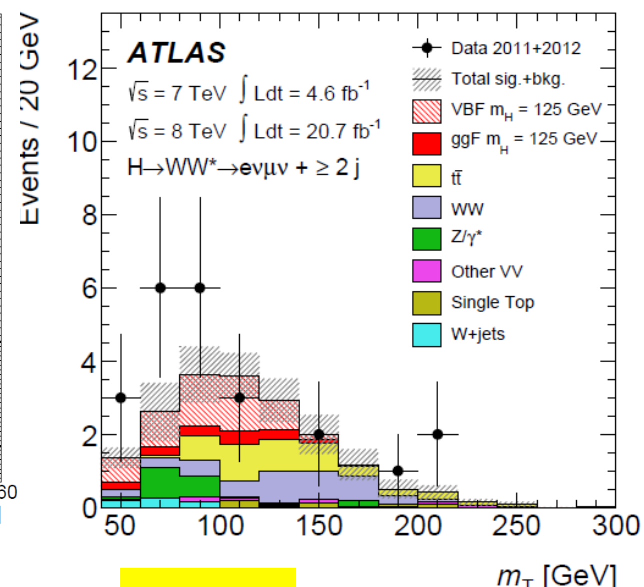
- $ee, e\mu, \mu\mu$ + 2ν final state
- N_{jet} classification (0,1, >= 2 jet) to separate ggF and VBF processes
- eμ channel most important (large DY bkgd for ee and μμ)
- Experimental challenges: E_T^{miss}, Njet
- final discriminant M_T



ET miss

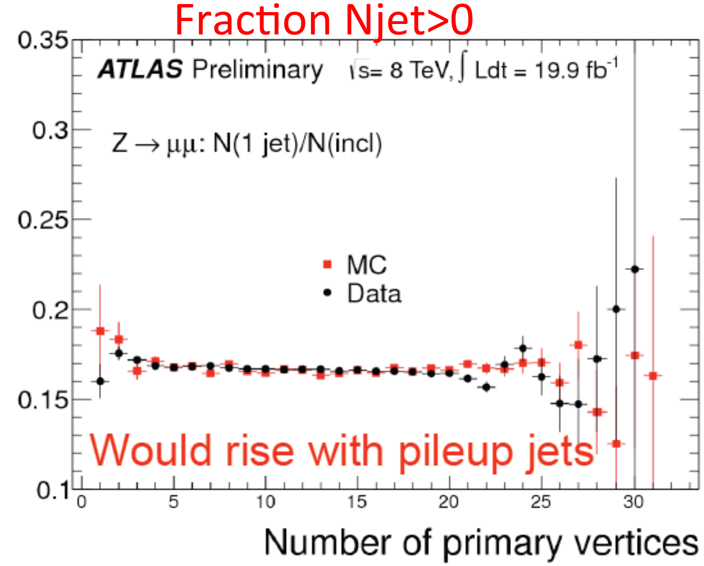


Njet =0,1



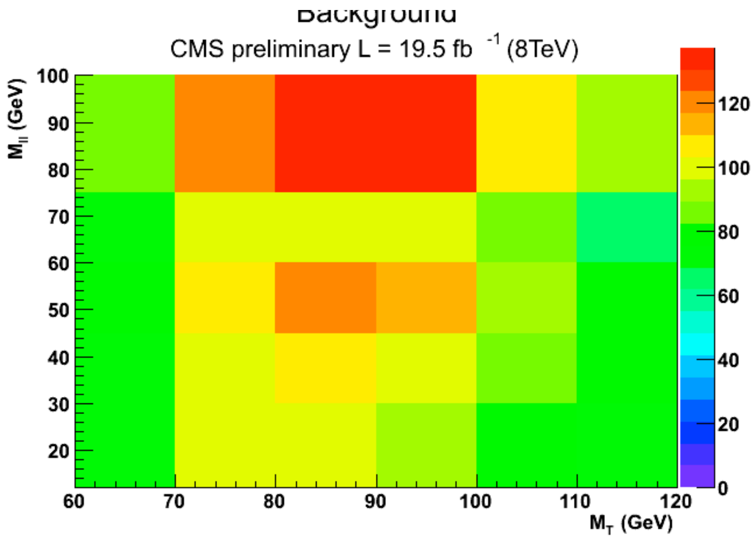
Njet = 2

Fraction Njet>0

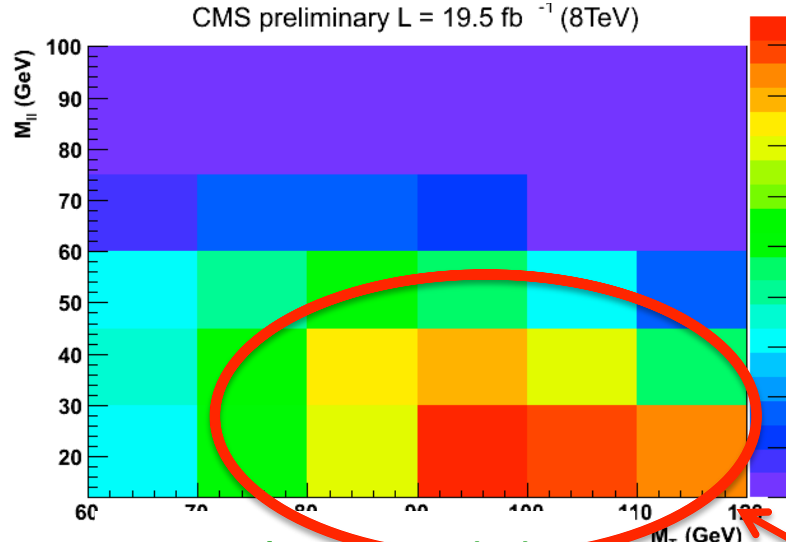


WW→ℓνℓν 2D analysis (0 jet bin)

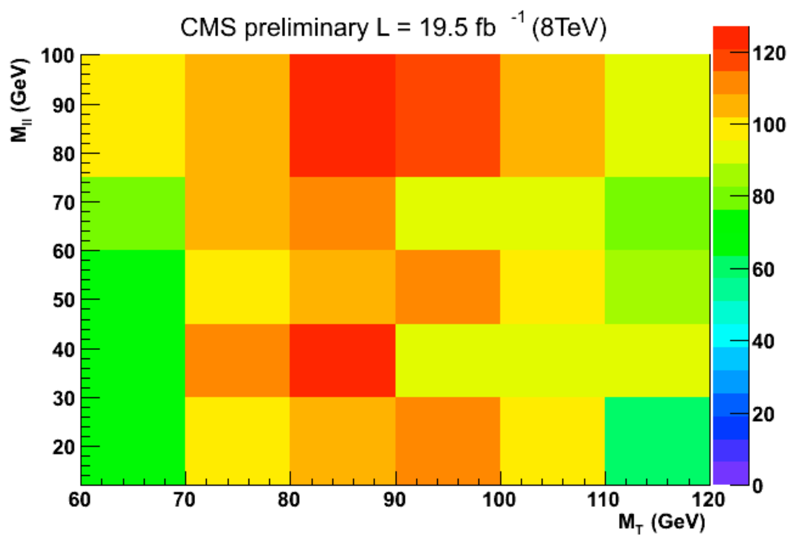
MC Background



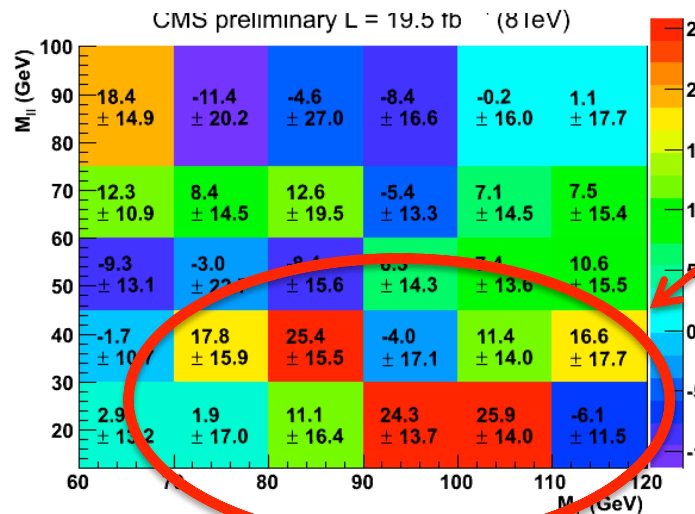
Higgs signal at 125 GeV



Data

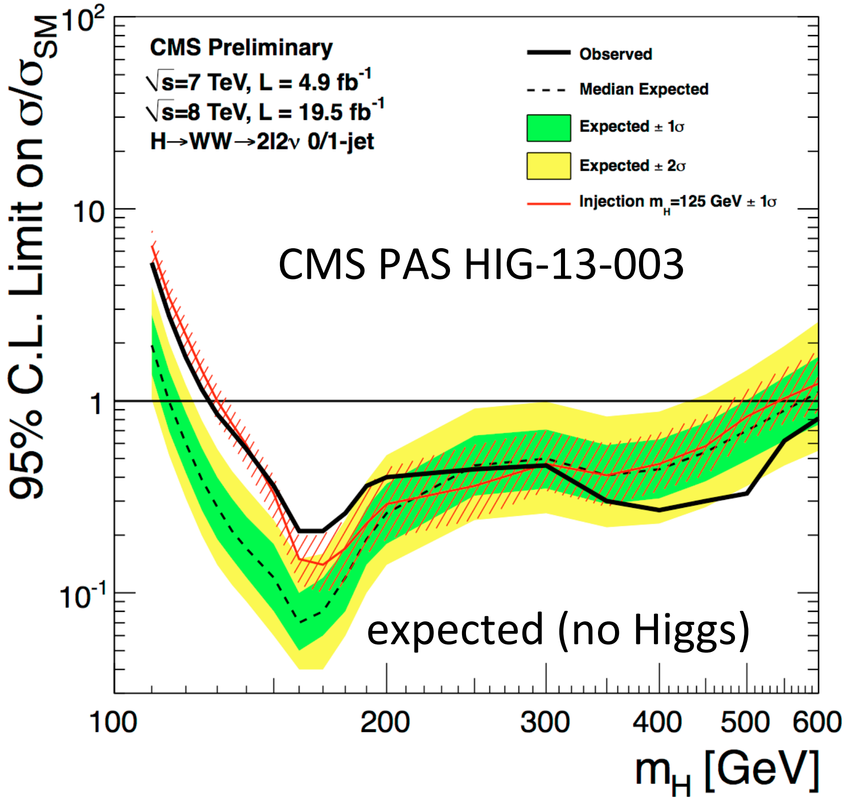


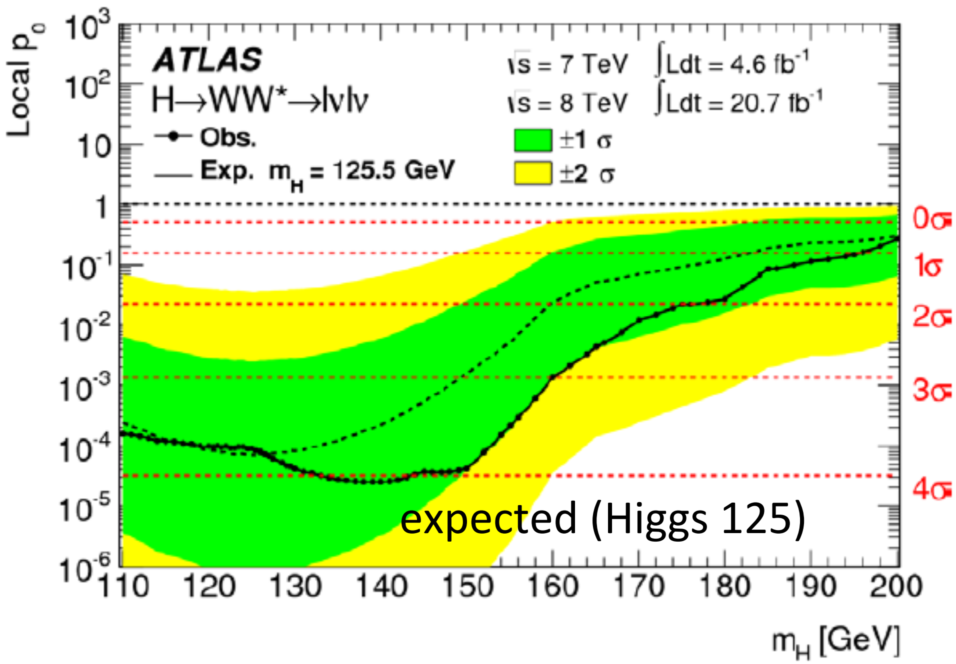
BG subtracted data



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

$$WH \rightarrow WWW^{*} \rightarrow 3\ell + \not{E}_T \quad ZH \rightarrow ZWW^{*} \rightarrow 4\ell + \not{E}_T$$

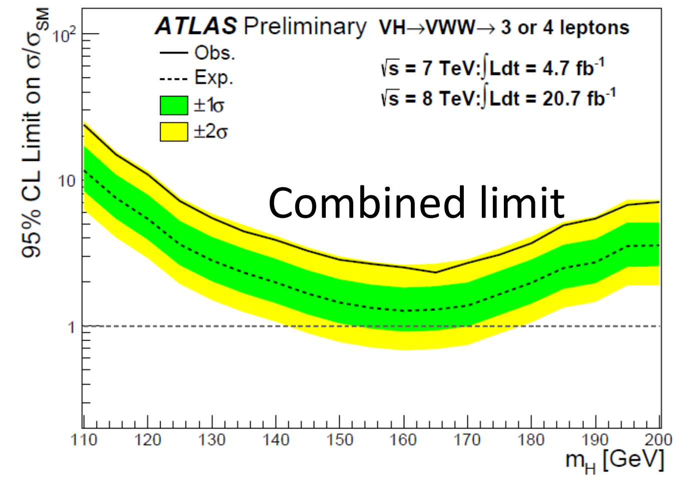
Lepton $p_T > 10-25$ GeV, $\not{E}_T^{rel} > 25-40$ GeV

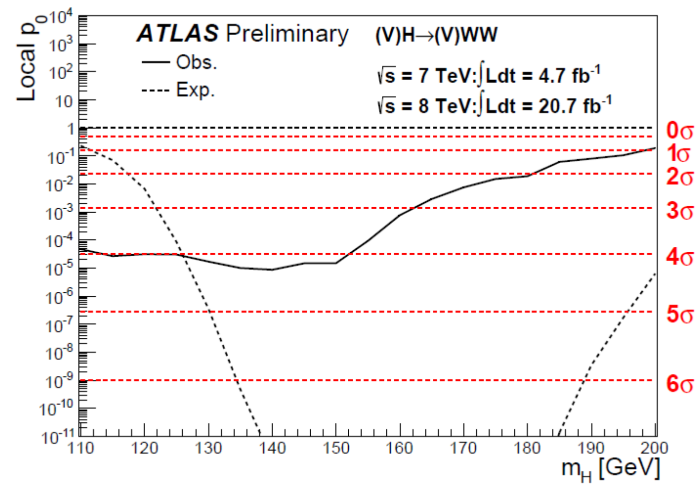
3ℓ analysis Data/MC, Total WWW contribution ~5.1 events

	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



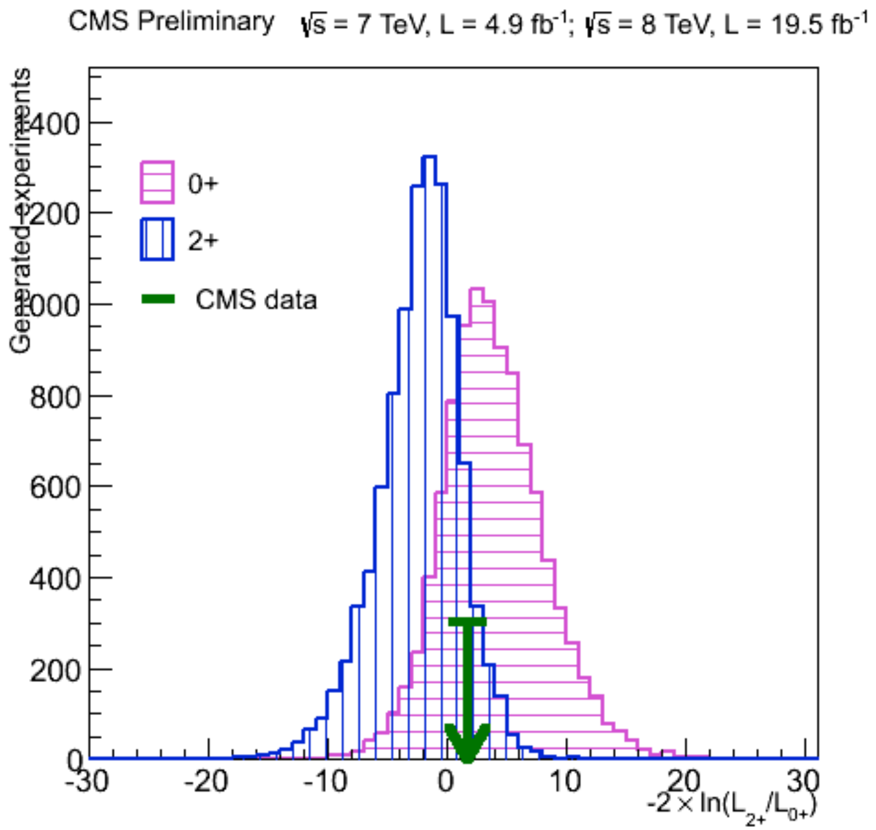


95% C.L. observed (expected) upper limit on the rate/SM at 125 GeV:
7.5 (4.0) for WH and 14.3 (9.6) for ZW

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

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

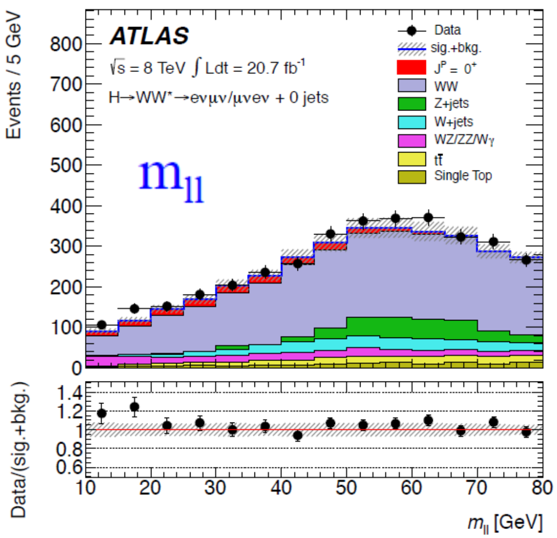
Spin 2 analysis

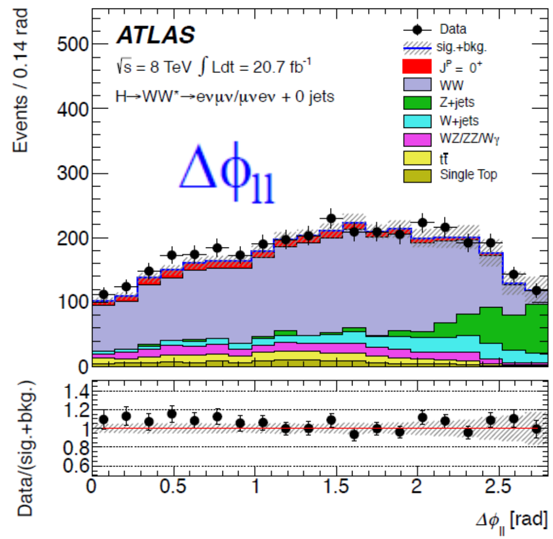


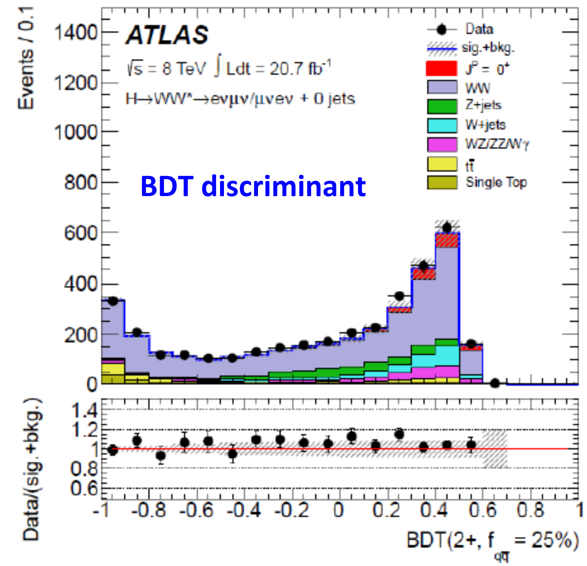
CMS PAS HIG-13-003

- 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*

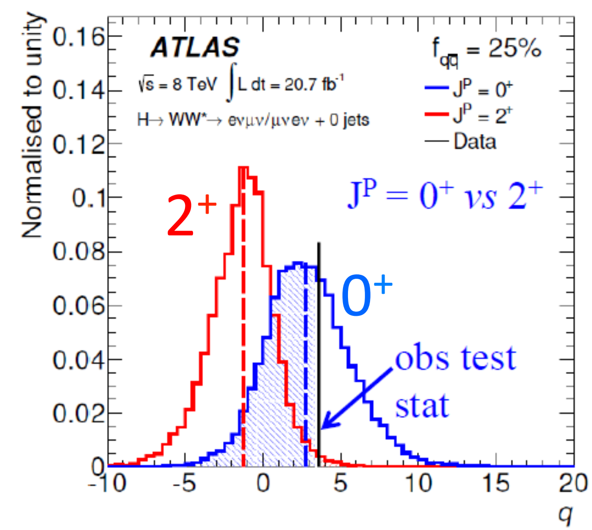






$J^P = 0^+ \ vs \ 2^+$

$f_{q\bar{q}}$	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	$3.6\cdot10^{-4}$	0.541	$1.7\cdot10^{-4}$	$3.6\cdot10^{-4}$
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



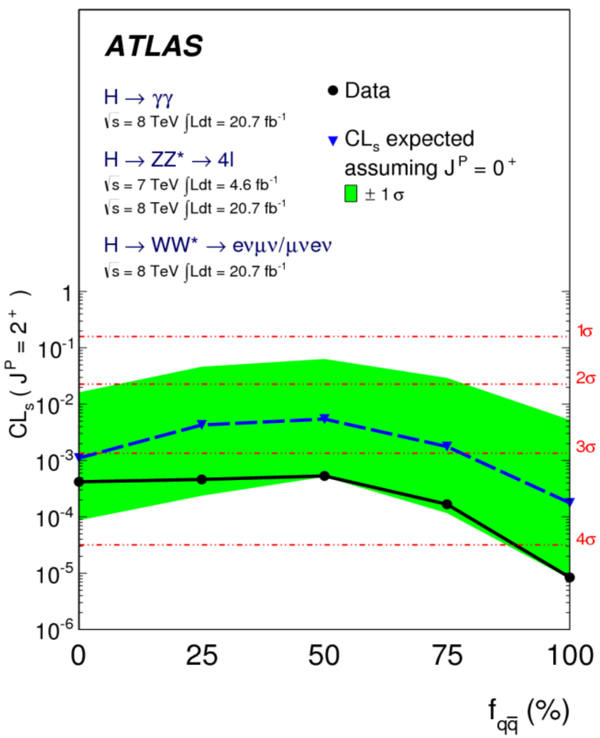
Exclusion **(1-CL$_s$):**

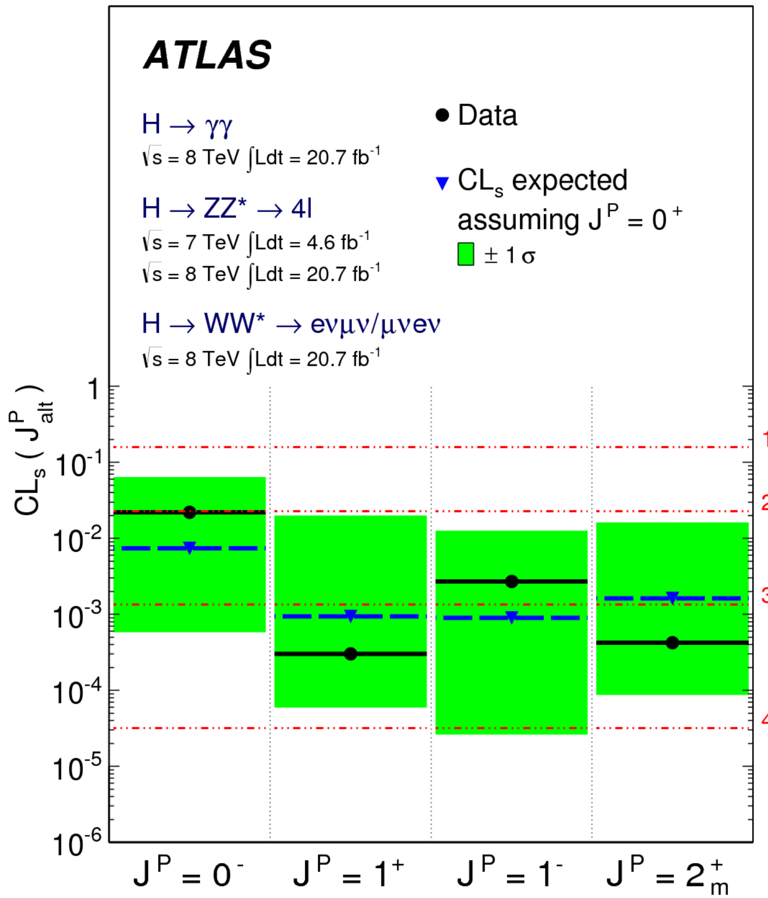
Observed 2$^+$ (qq=100%) exclusion 99.96%

Observed 2$^+$ (qq = 0%) exclusion 95.2%

Combined Spin-Parity Results

- 0^- hypothesis excluded at 97.8% CL in favor of 0^+ by $H \rightarrow ZZ^* \rightarrow 4\ell$ 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 $J^p = 0^+$

H→Zγ

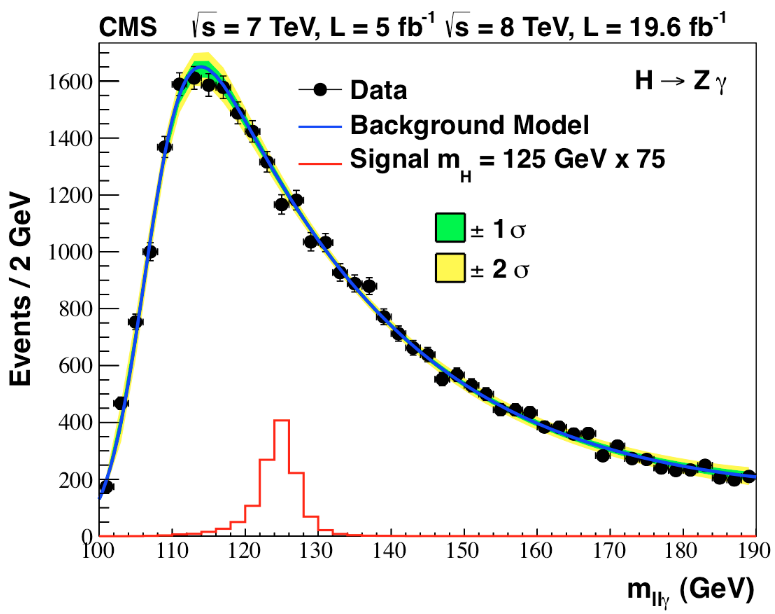
- Cross section similar to γγ
- Use Z->ee and Z->μμ (reduce cross section)
- Large BG from Drell Yan with ISR

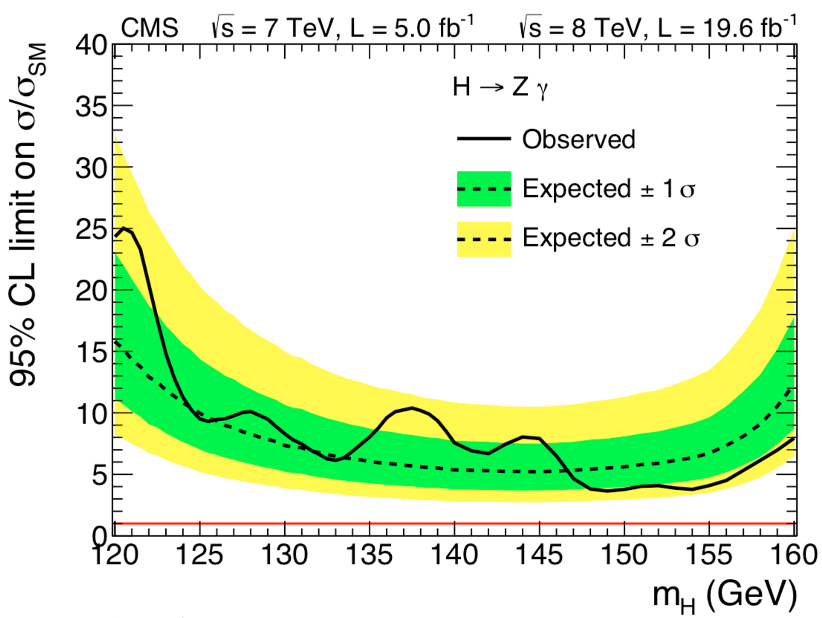
Models exist with BR(Zγ) >100 x SM while BR(γγ) is SM-like

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

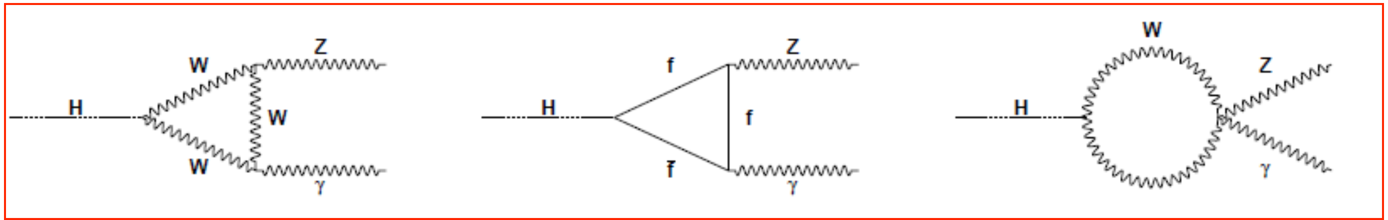
Sample	Integrated luminosity (fb^{-1})	Observed event yield for $100 < m_{\ell\ell\gamma} < 190$ GeV	Expected number of signal events for $m_H = 125$ GeV
2011 ee	5.0	2353	1.2
2011 $\mu\mu$	5.1	2848	1.4
2012 ee	19.6	12899	6.3
2012 $\mu\mu$	19.6	13860	7.0

arXiv:1307.5515





H→Zγ → ℓℓγ

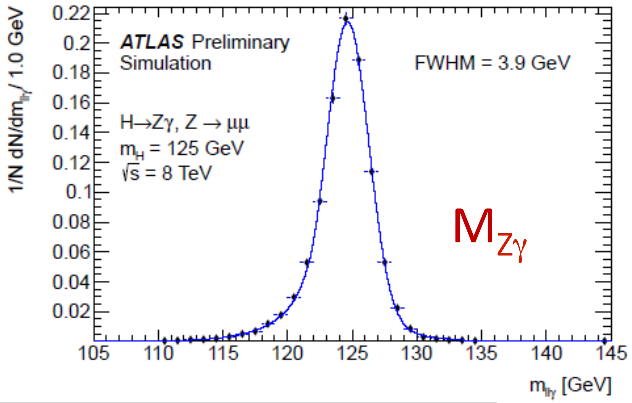


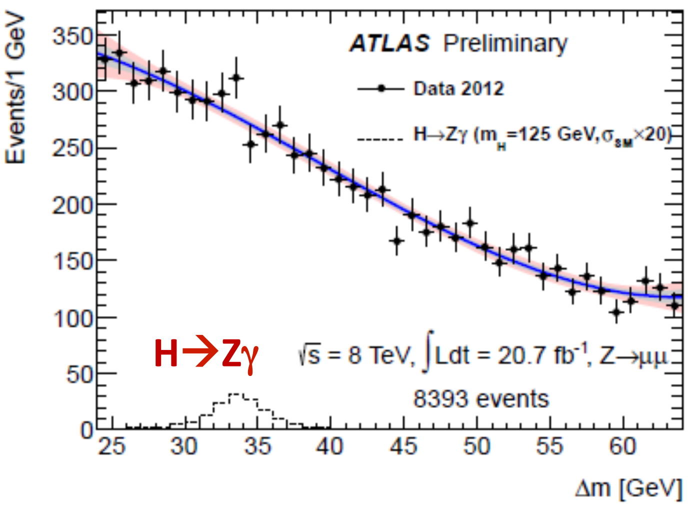
$BR(H\to Z\gamma)$=0.15%

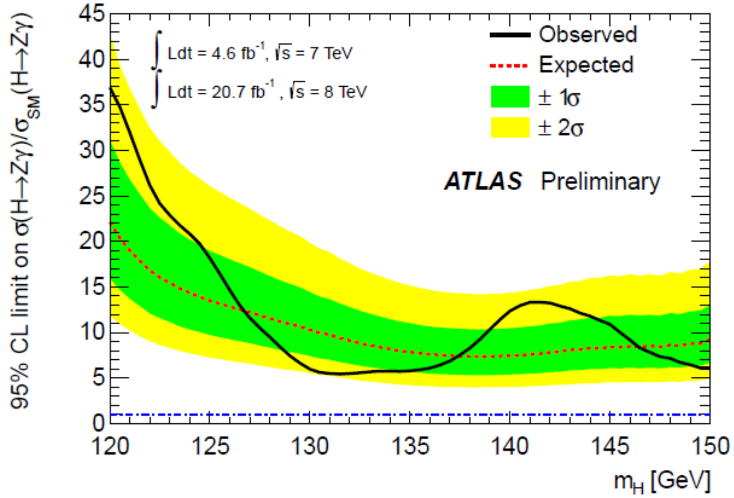
- H→Zγ is another high resolution channel
- Sensitive to new particles through loops
- For SM Higgs with mass = 125 GeV:

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

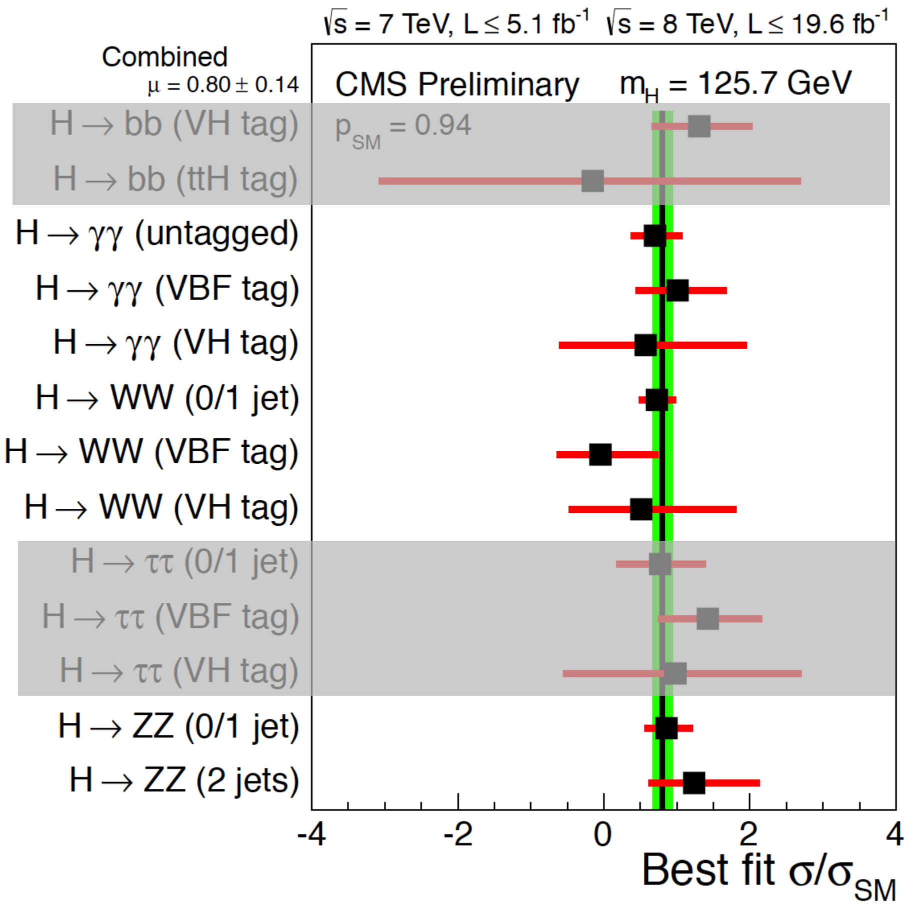
~ 55 events in 2011+2012 dataset

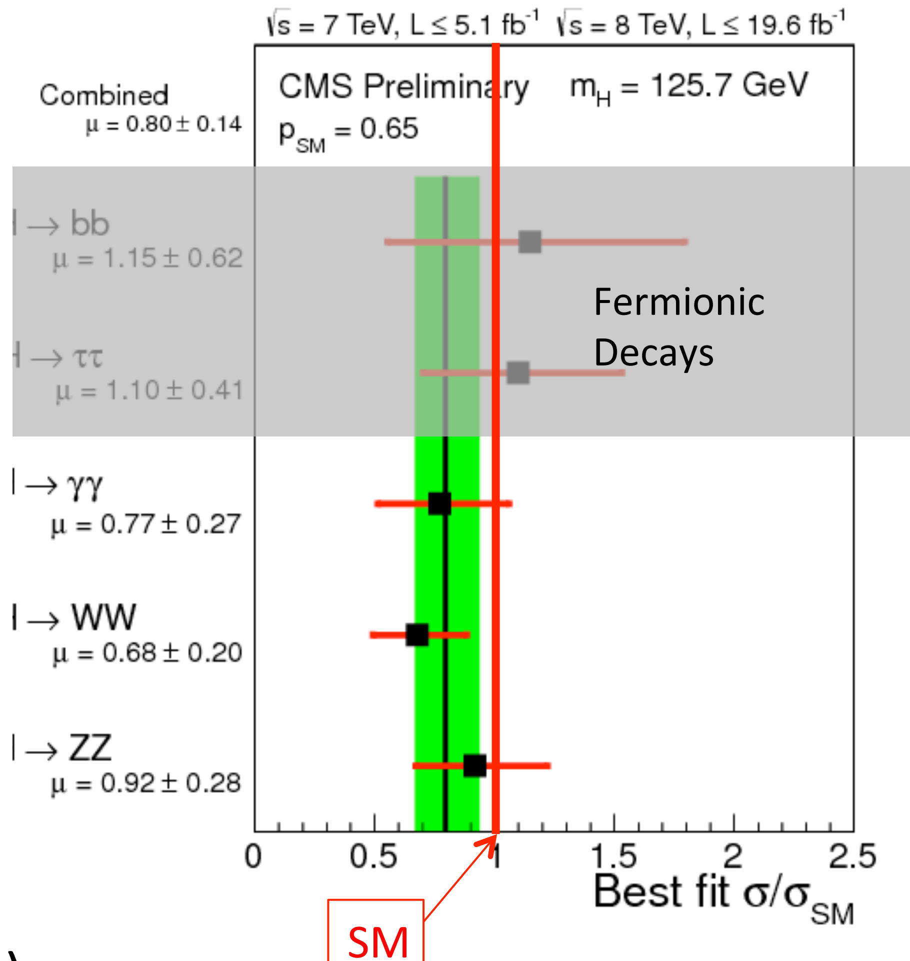






Summary of Measured Signal Strengths





- 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

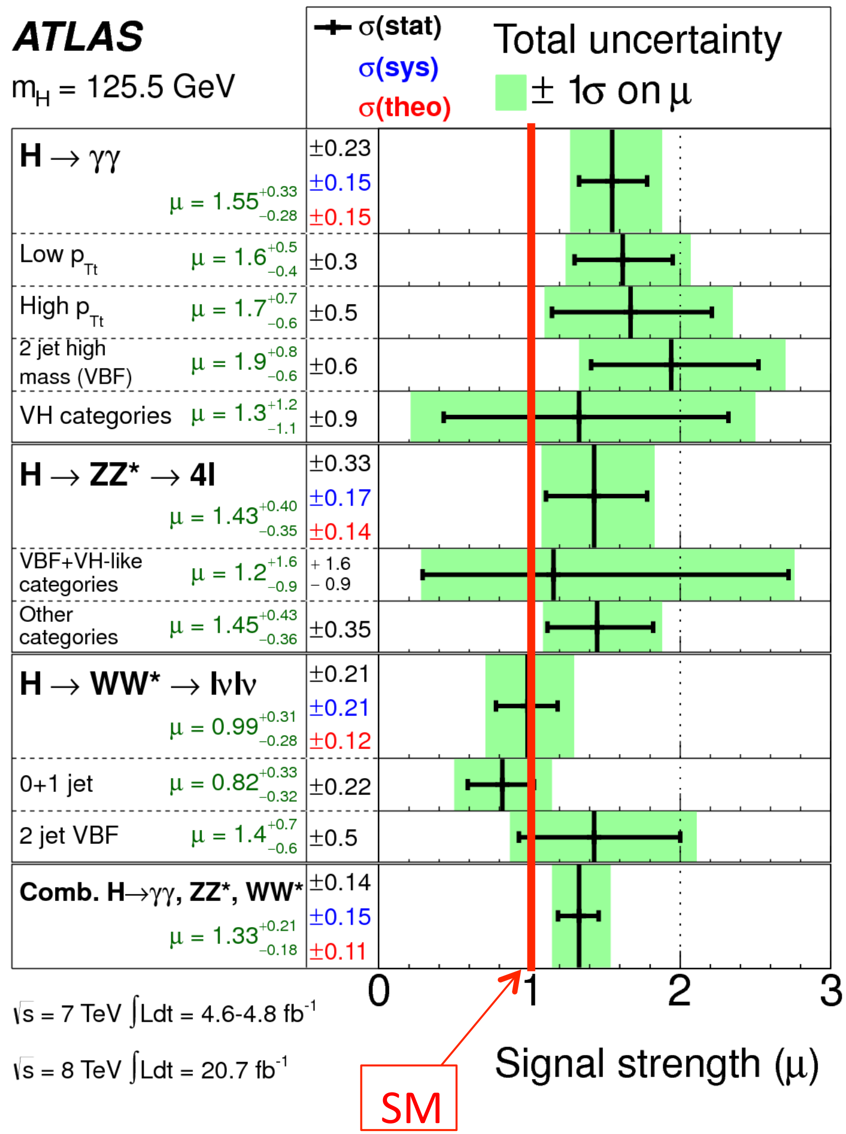
- **Variation due to m_H uncertainty: ±3%**
- **Compatibility with SM (μ=1): 7%**
- **Largest deviation $\mu_{\gamma\gamma}$: 1.9 σ**

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

ATLAS also sets preliminary (95%CL) limits:

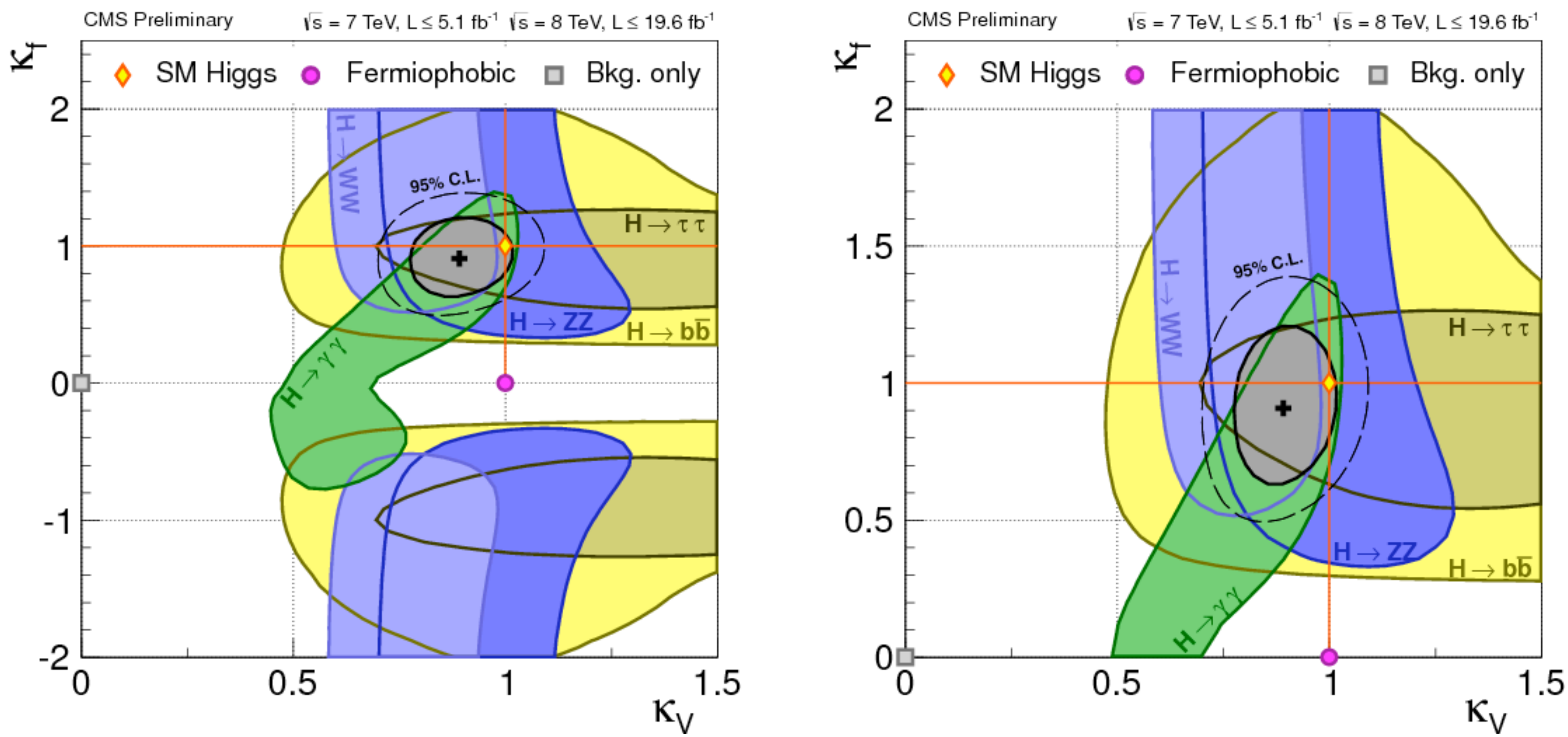
μ = 1.33 ± 0.14 (stat) ± 0.15 (sys) ± 0.11 (theo)

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



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 $\gamma\gamma$ is extremely important for coupling measurements

Vector vs Fermion Couplings

2-parameter benchmark model:

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

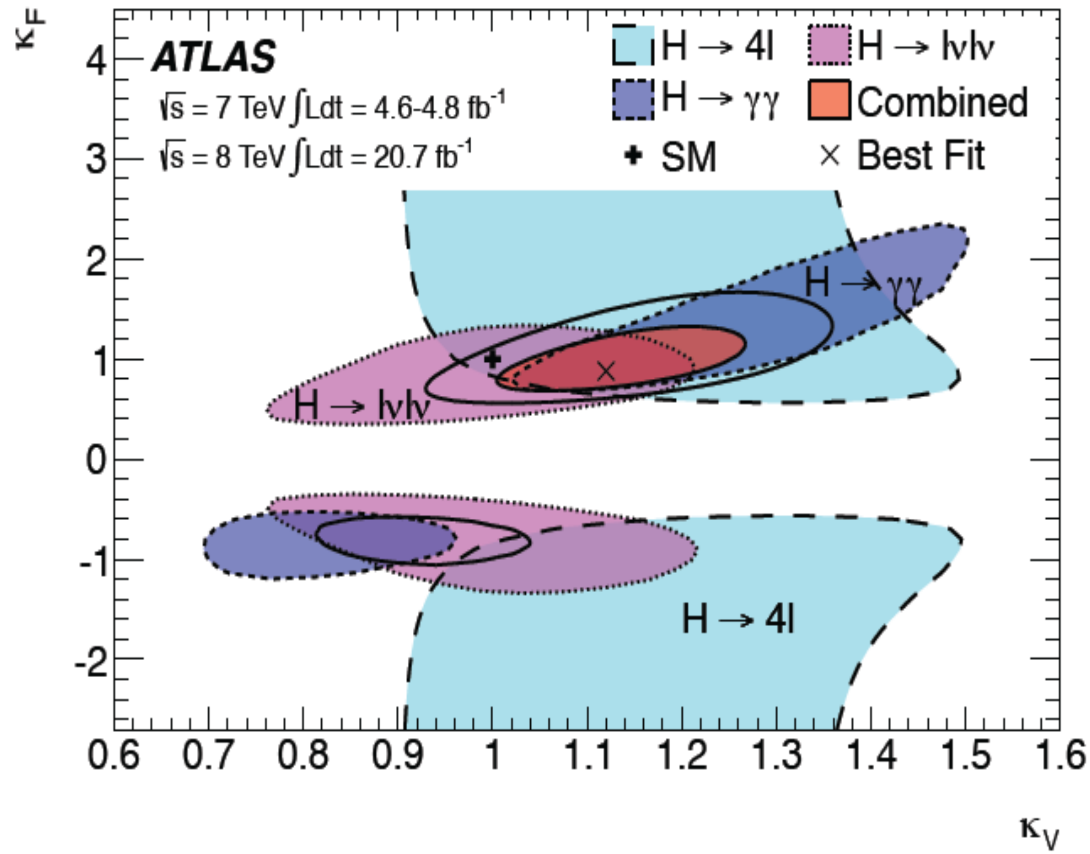
$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

(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)

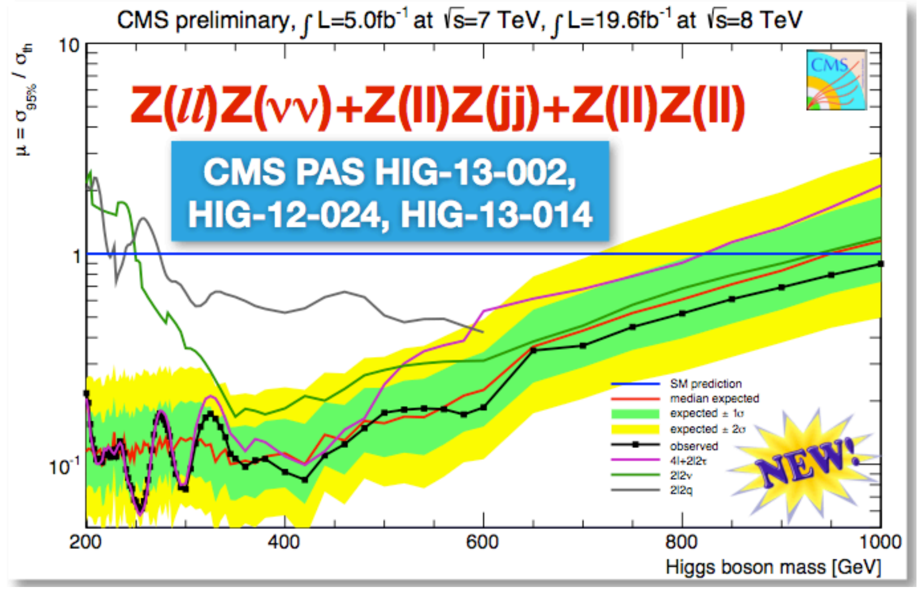
- ➢ **κ_F = 0 is excluded (>5σ)**

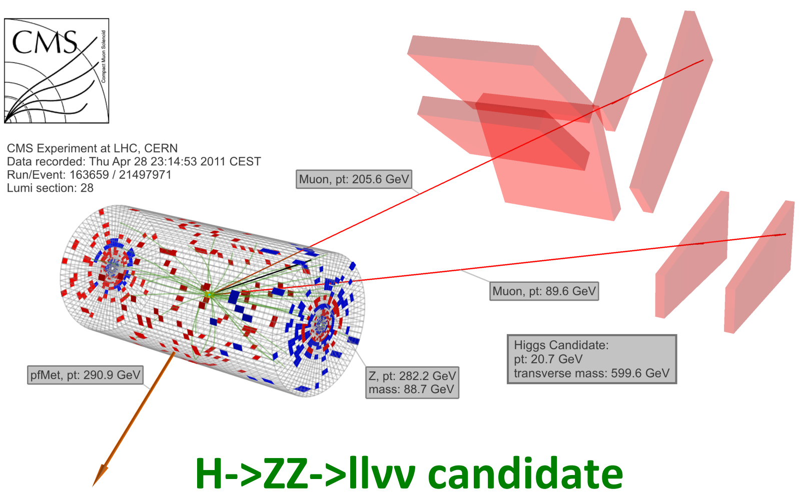
Double minimum from interference between vector(W) and fermion(top) in H→γγ



H→ZZ High Mass (SM) Higgs Search

- 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)





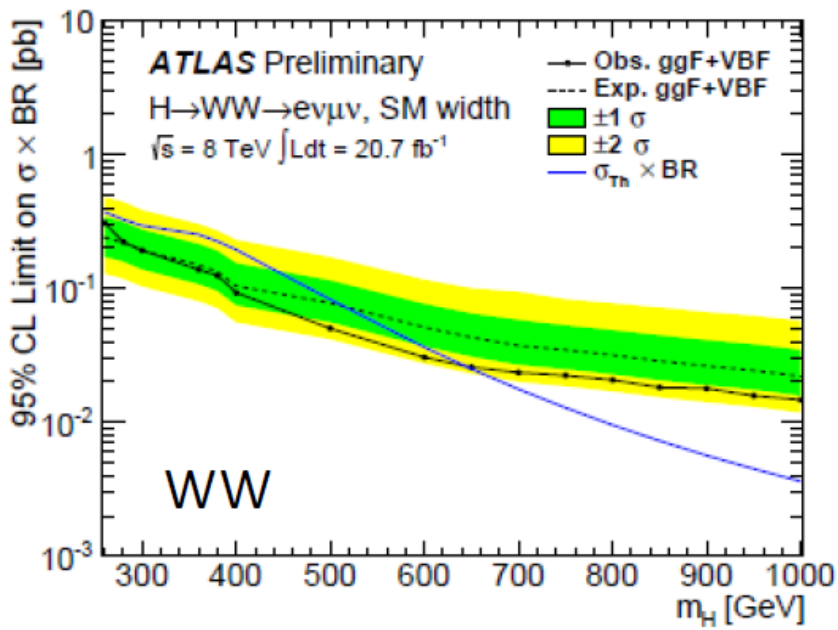
H->ZZ->llνν candidate

Search for High Mass H→ ZZ, WW

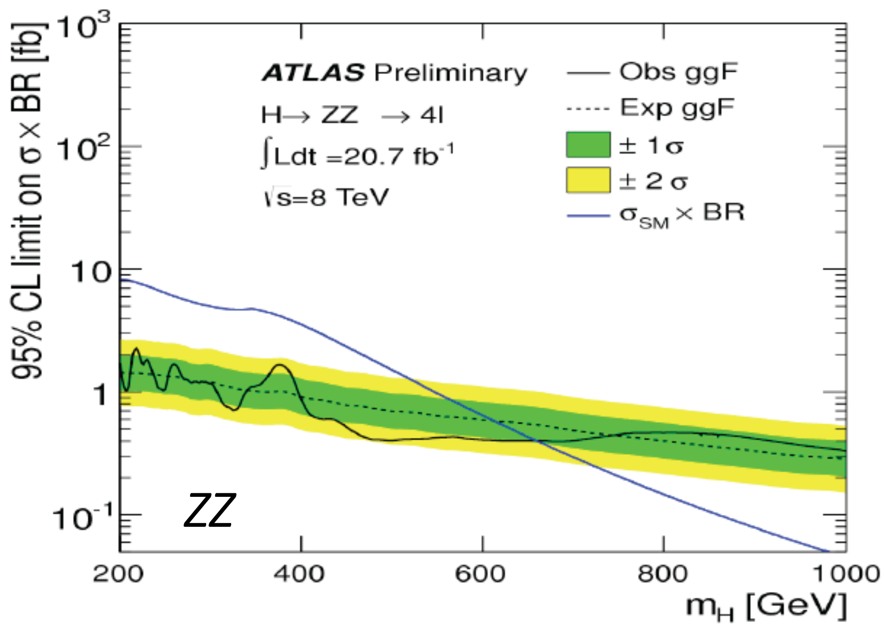
ATLAS-CONF-2013-067

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 of Higgs → Bosons

- By now we know we have found "a Higgs" Boson.
  - Branching ratios are about right,
  - 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

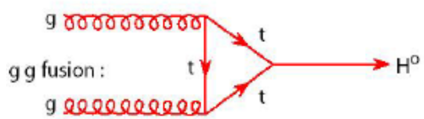
Backup Slides Need Cleanup

Coupling Measurements

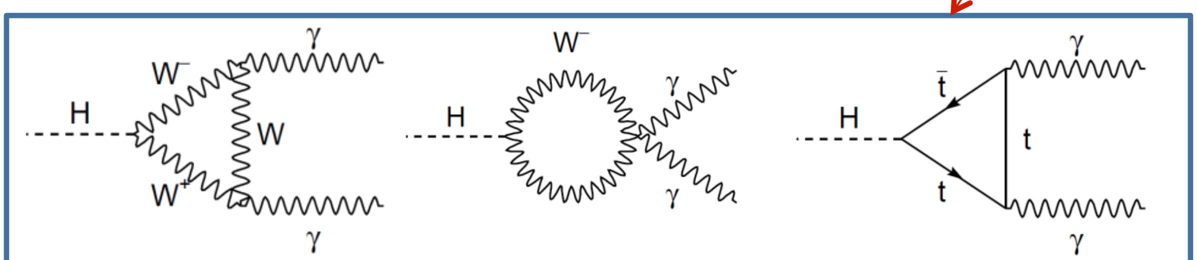
Coupling strengths κ_i & ratio: $\kappa_F = g_F/g_{F,SM}$, $\kappa_V = g_V/g_{V,SM}$, $\lambda_{ij} = \kappa_i / \kappa_j$

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
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 $H \to \gamma\gamma$



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

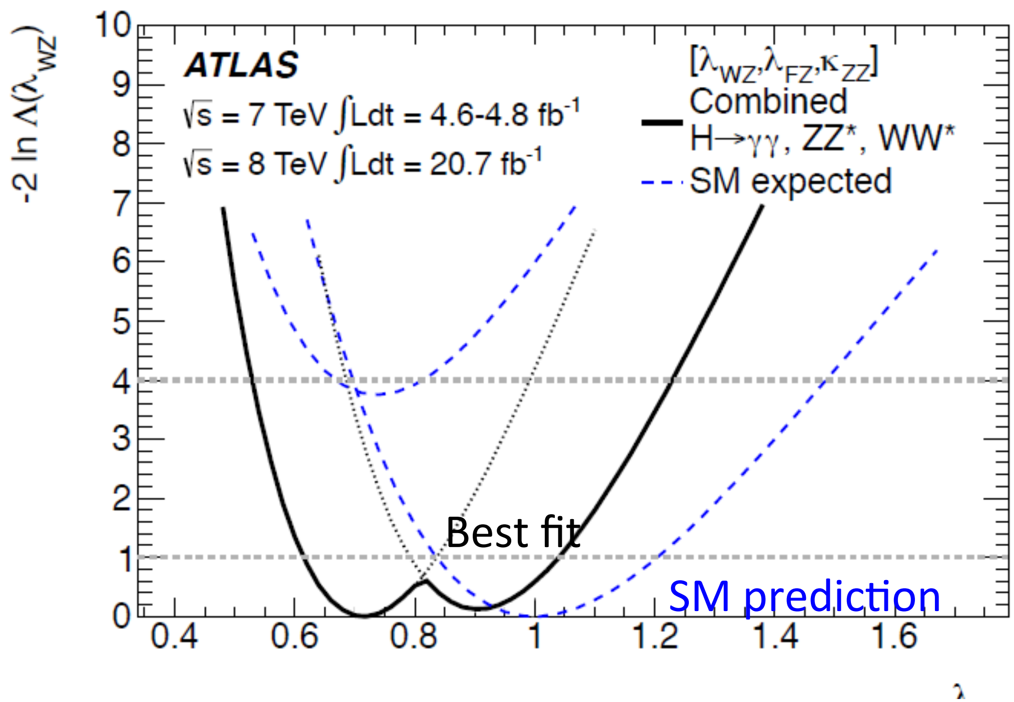


κ_g , κ_γ: loop coupling scale factors

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

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

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→ γγ, ZZ*, WW* analysis updates based on full 2011-2012 dataset ($4.6\ fb^{-1}$ @ 7TeV, $20.7\ fb^{-1}$ @ 8TeV)**
- Higgs mass from H→γγ and H→ZZ*→ 4ℓ
- 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 (γγ)
- ATLAS-CONF-2013-013 (ZZ*)
- ATLAS-CONF-2013-031 (WW*)
- ATLAS-CONF-2013-040 (Spin)
- ATLAS-CONF-2013-079 (VH → bb)
- ATLAS-CONF-2012-160 (H → ττ)
- ATLAS-CONF-2013-075 (WW*)
- ATLAS-CONF-2013-029 (γγ)

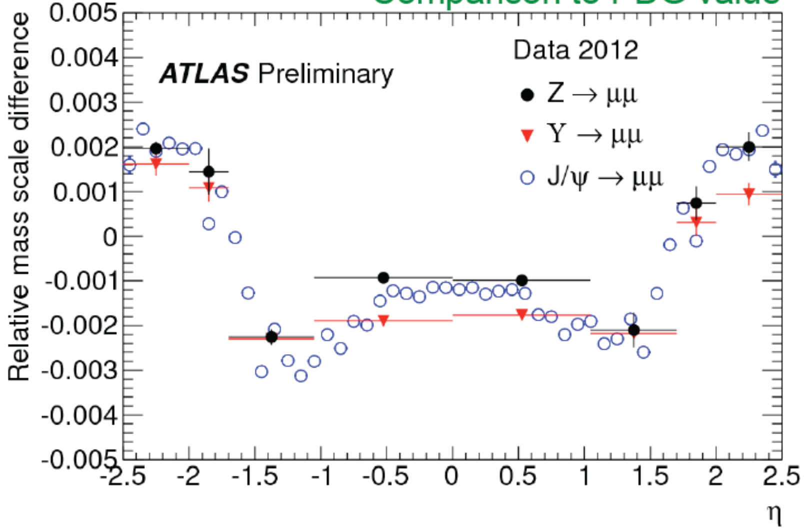
Searches:

- ATLAS-CONF-2013-009(Zγ)
- ATLAS-CONF-2013-010(μμ)
- ATLAS-CONF-2013-067(HMH→WW)
- ATLAS-CONF-2013-072 (diff σ H→γγ)
- ATLAS-CONF-2013-075(VH→WW)
- ATLAS-CONF-2013-080(tt +H→γγ)
- ATLAS-CONF-2013-081(t→cH)

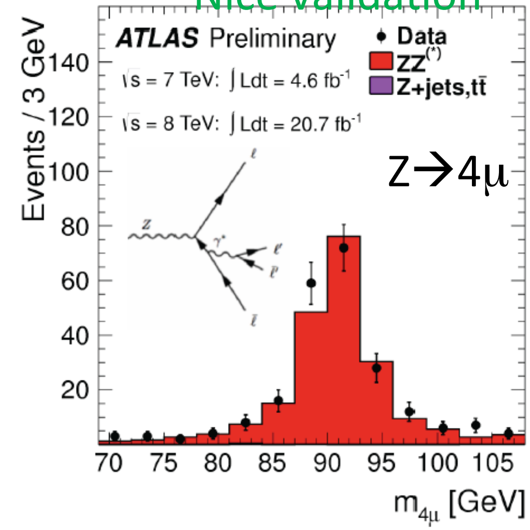
Lepton Energy/Momentum Calibration

Muons

Comparison to PDG value

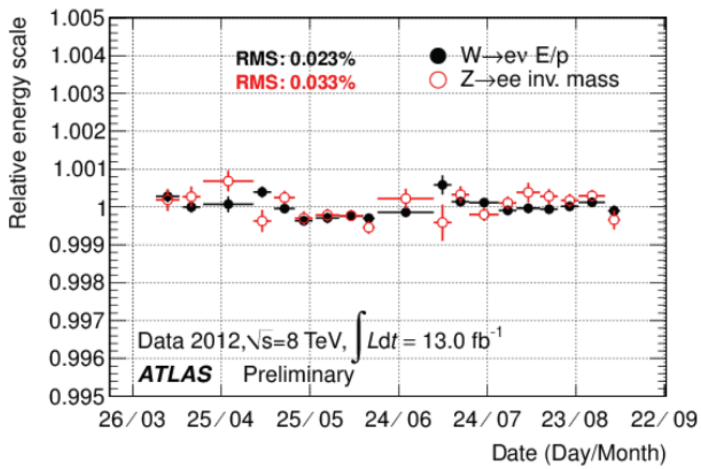


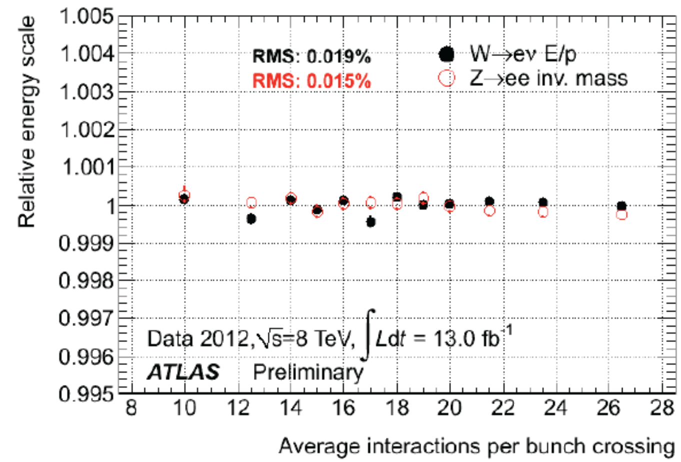
Nice validation



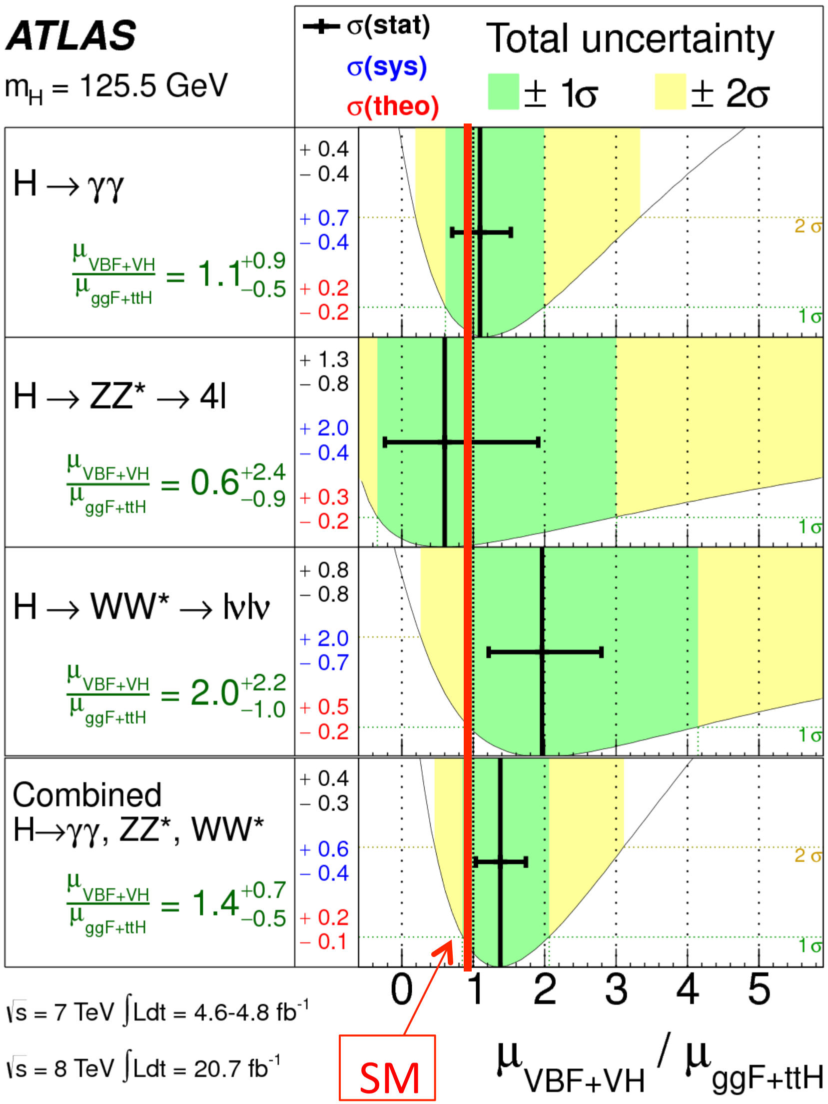
Electrons

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

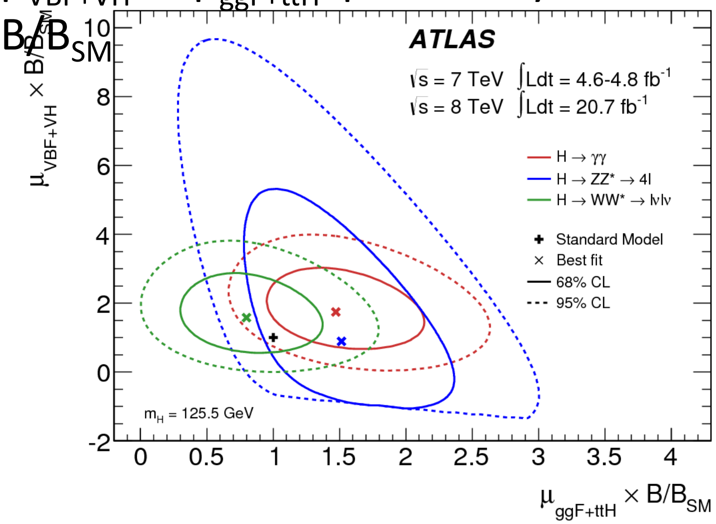


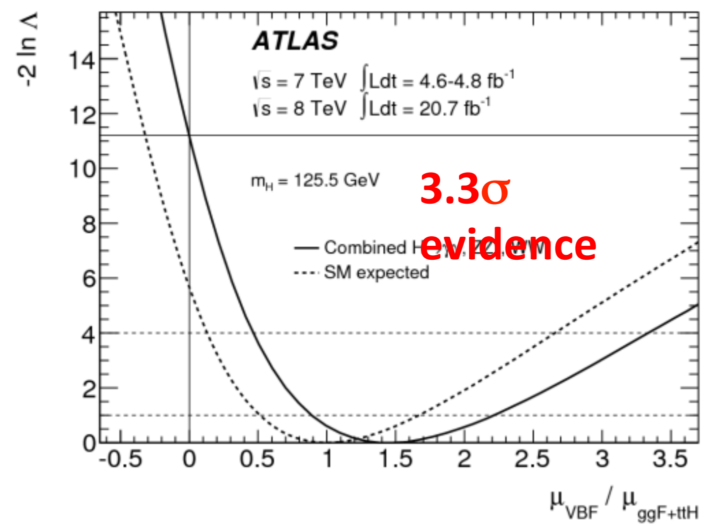


VBF vs. ggF Production



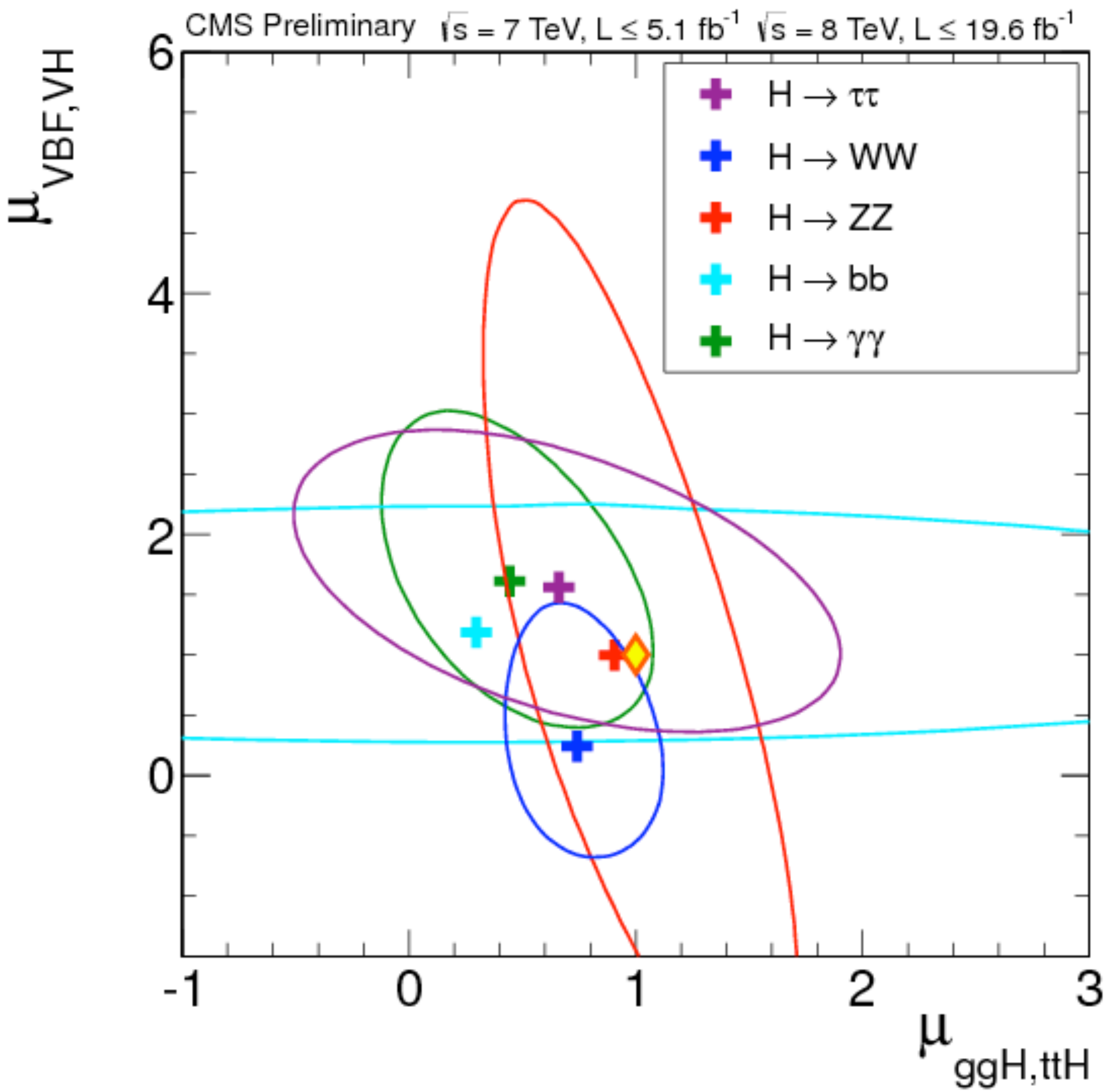
μ_{VBF+VH} vs $\mu_{ggF+ttH}$ potentially modified by B/B_{SM}





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

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

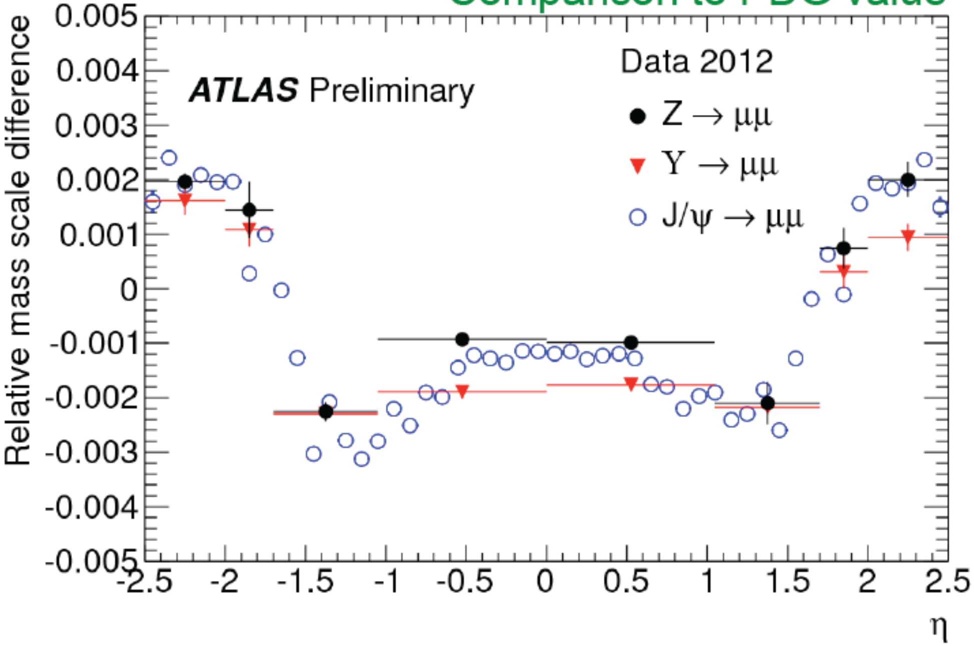


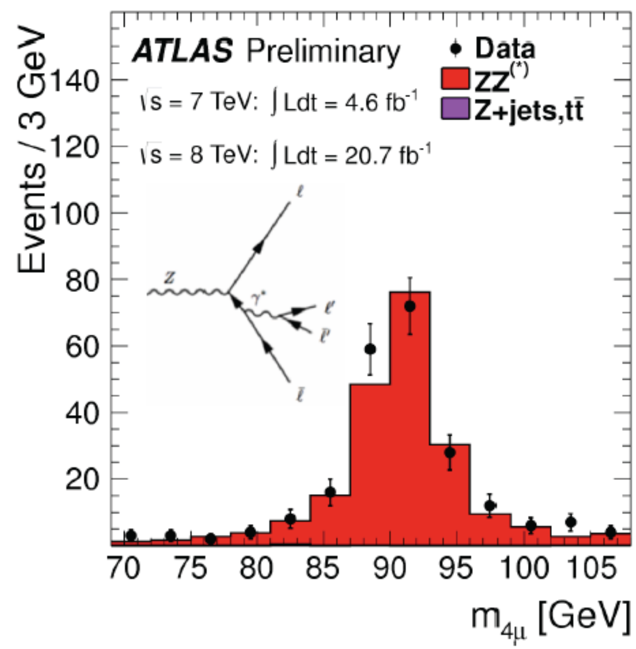
Energy Scale and Resolution

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

Comparison to PDG value



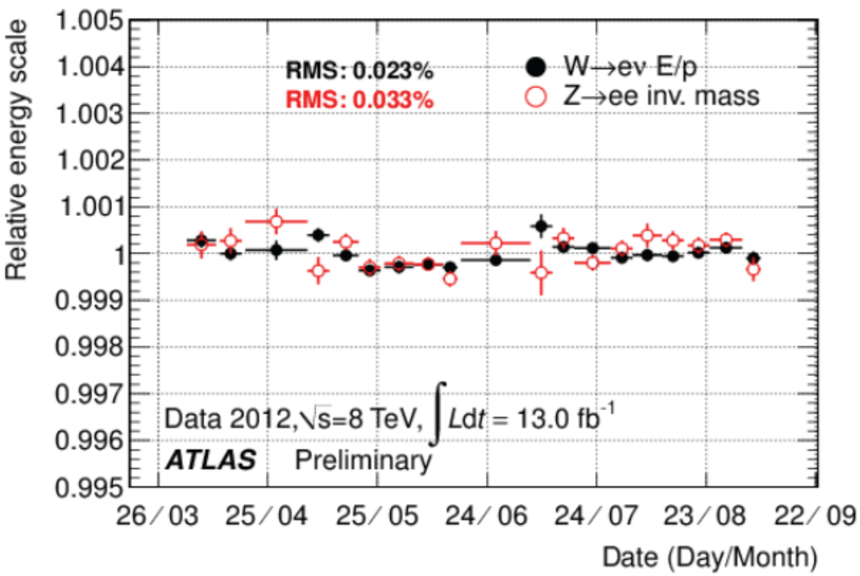


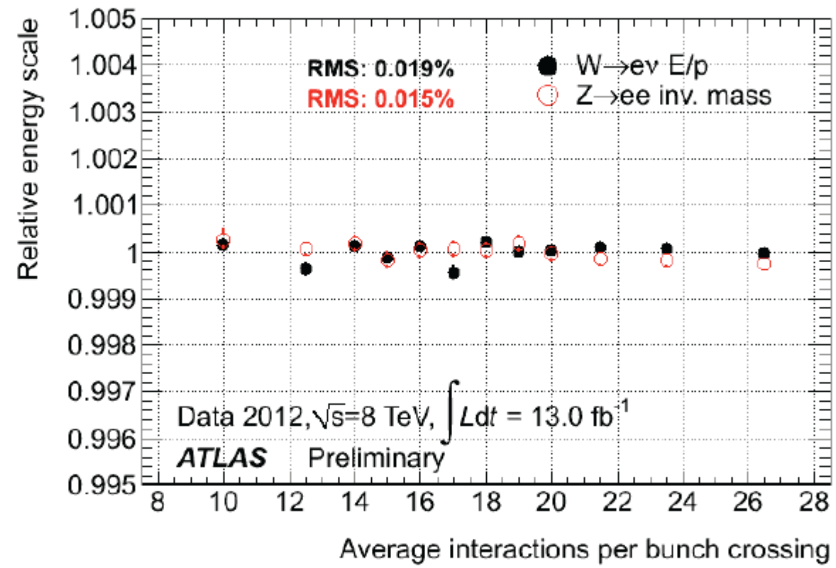
EM Colorimeter Calibration

- ❑ 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