Higgs searches at LHC

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LoopFest XII

Tallahassee, 13 May 2013

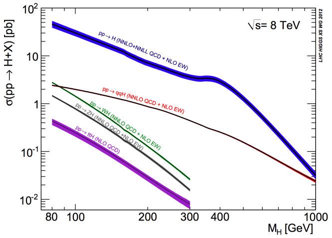
Outline

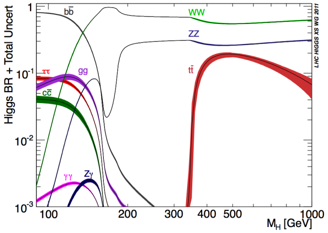
- SM Higgs boson search symphony
  - individual search channels and their grand combination

- Mass measurement
  - if X126 is the SM Higgs boson, its mass is the last SM parameter to measure

- Is X126 the SM Higgs boson?
  - What can we tell about the X126 width from the mass line shape?
  - Compatibility of event yields with the SM Higgs boson
  - Recast the event yields into "measurements" of couplings
  - Spin-parity properties
  - Is X126 one particle?

Search channels at low mass





CMS

🟧 7 TeV, 5 fb^{-1}

🟥 8 TeV, 5 fb^{-1}

🟥🟥 8 TeV, 12 fb^{-1}

🟥🟥🟥🟥 8 TeV, 20 fb^{-1}

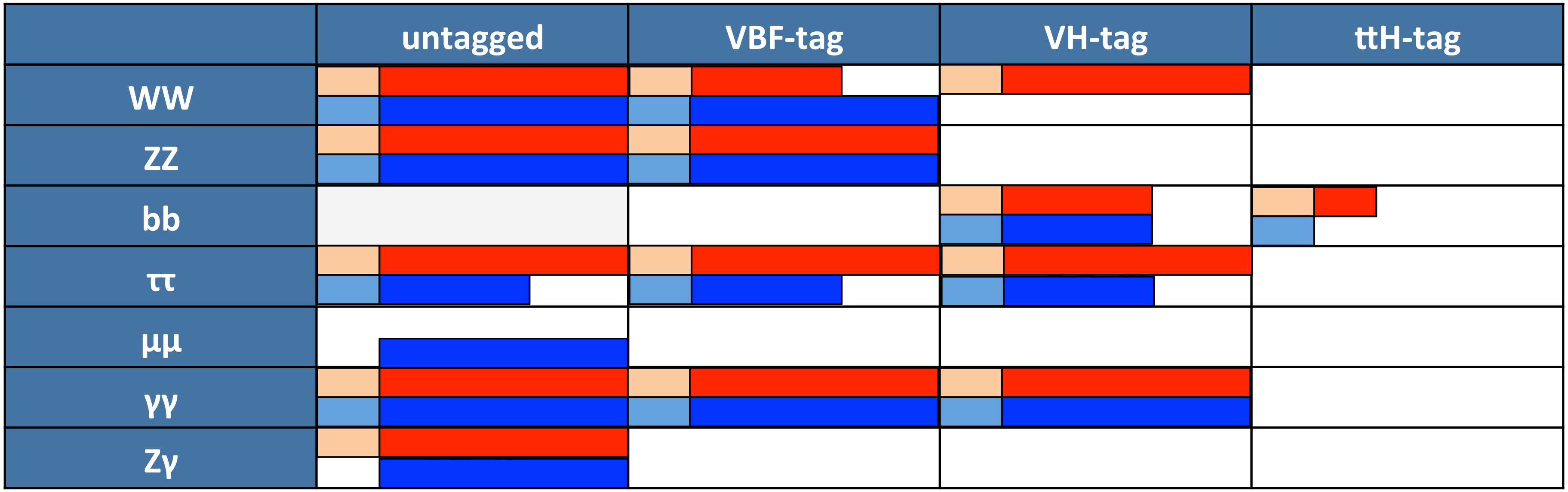
ATLAS

🔷 7 TeV, 5 fb^{-1}

🟦 8 TeV, 5 fb^{-1}

🟦🟦 8 TeV, 13 fb^{-1}

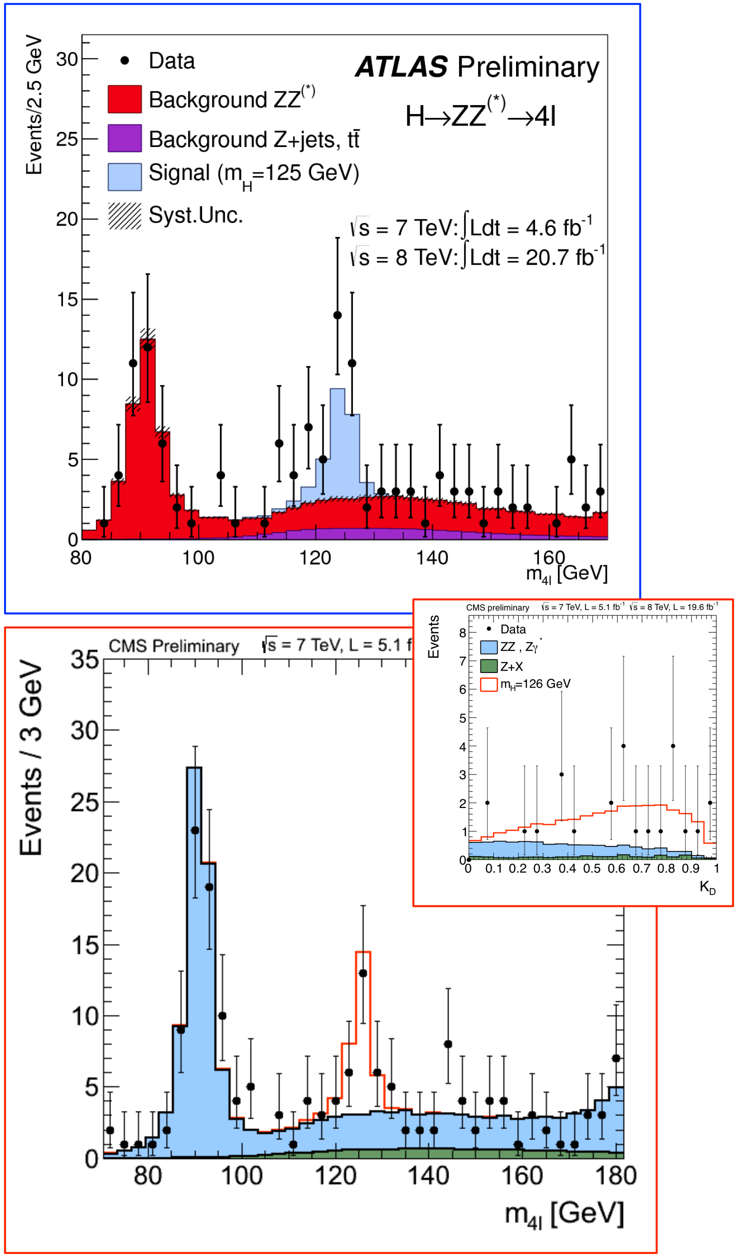
🟦🟦🟦🟦 8 TeV, 21 fb^{-1}



	untagged	VBF-tag	VH-tag	ttH-tag
WW	🟧🟥🟥🟥🟥 🔷🟦🟦🟦🟦	🟧🟥🟥 🔷🟦🟦🟦🟦	🟧🟥🟥🟥🟥	
ZZ	🟧🟥🟥🟥🟥 🔷🟦🟦🟦🟦	🟧🟥🟥🟥🟥 🔷🟦🟦🟦🟦		
bb			🟧🟥🟥 🔷🟦🟦	🟧🟥 🔷
ττ	🟧🟥🟥🟥🟥 🔷🟦🟦	🟧🟥🟥🟥🟥 🔷🟦🟦	🟧🟥🟥🟥🟥 🔷🟦🟦	
μμ	🟦🟦🟦🟦			
γγ	🟧🟥🟥🟥🟥 🔷🟦🟦🟦🟦	🟧🟥🟥🟥🟥 🔷🟦🟦🟦🟦	🟧🟥🟥🟥🟥 🔷🟦🟦🟦🟦	
Zγ	🟧🟥🟥🟥🟥 🟦🟦🟦🟦			

BEWARE: Tags are never pure; e.g. VBF-tags have 20%-80% of ggF, depending on analysis

H → ZZ → 4l



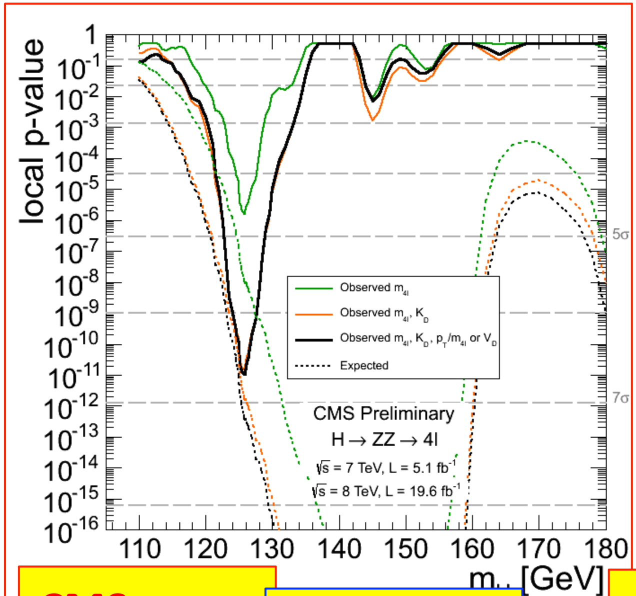
Analysis strategy:

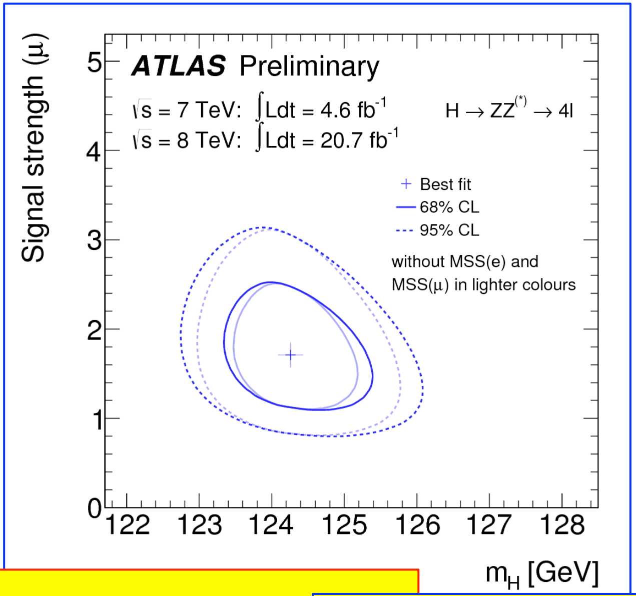
- four prompt leptons (low p_T is important!)
- **four-lepton mass** is the key observable
- split events into 4e, 4μ, 2e2μ channels:
  - different mass resolutions
  - different S/B rates (for reducible bkgd with "fake" leptons)
- CMS: add **ME-based discriminant K_D** (2^{nd} observ.)
- split events further into exclusive categories:
  - **untagged** (CMS: add a 3^{rd} observable: **four-lepton p_T/m**)
  - **di-jet tagged** (CMS: add a 3^{rd} observable: **$V_D(m_{jj}, \Delta\eta_{jj})$**)
- Backgrounds:
  - ZZ (dominant) from MC
  - reducible (with "fake" leptons): from control region

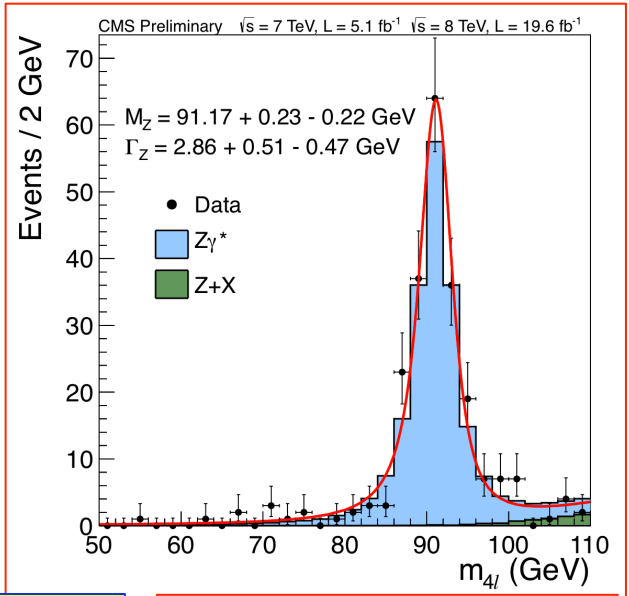
Analysis features to note:

- high S/B-ratio,
- but small event yield
- mass resolution = 1-2%

H → ZZ → 4l: results







CMS:
Z_{obs} = 6.7 σ
Z_{exp} = 7.2 σ

ATLAS:
Z_{obs} = 6.6 σ
Z_{exp} = 4.4 σ

CMS
$m_X = 125.8 \pm 0.5$
$\mu = 0.91^{+0.30}_{-0.24}$

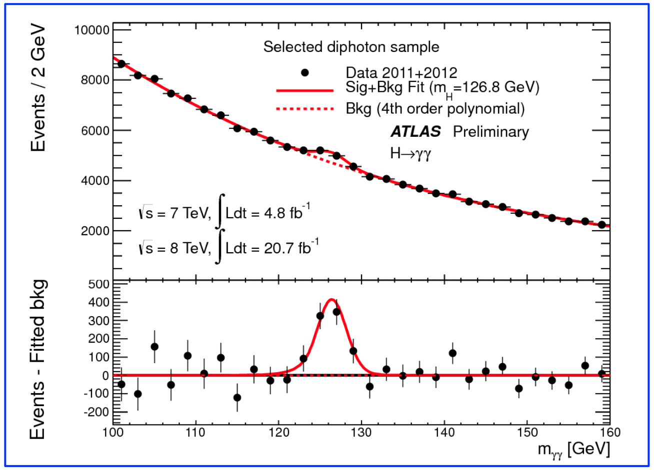
ATLAS
$m_X = 124.3 \pm 0.7$ GeV
$\mu = 1.7^{+0.5}_{-0.4}$

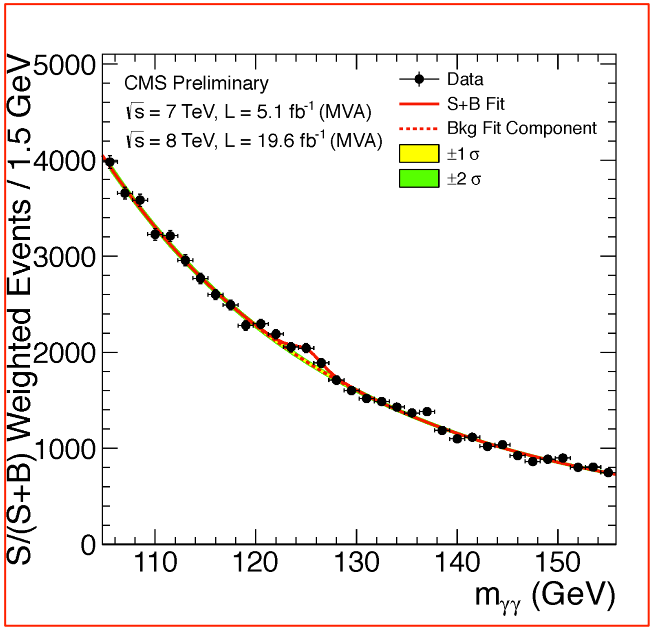
CMS
Z→4l standard candle
$m_Z = 91.2 \pm 0.2$ GeV
$\Gamma_Z = 2.9 \pm 0.5$ GeV

Points to note:

- **>5σ in one decay mode**
- di-jet tag does not help much in sensitivity (too few expected events), but is needed to assess the relative contributions of ggF and VBF production (will be shown later)
- ZZ→4l channel provides the **most accurate mass measurement** (CMS: event-by-event mass uncertainties improve the measurement by about 8%)
- signal strength is about equal to the expected
- Z→4l standard candle allows one to validate the mass (and future width) measurements

H → γγ



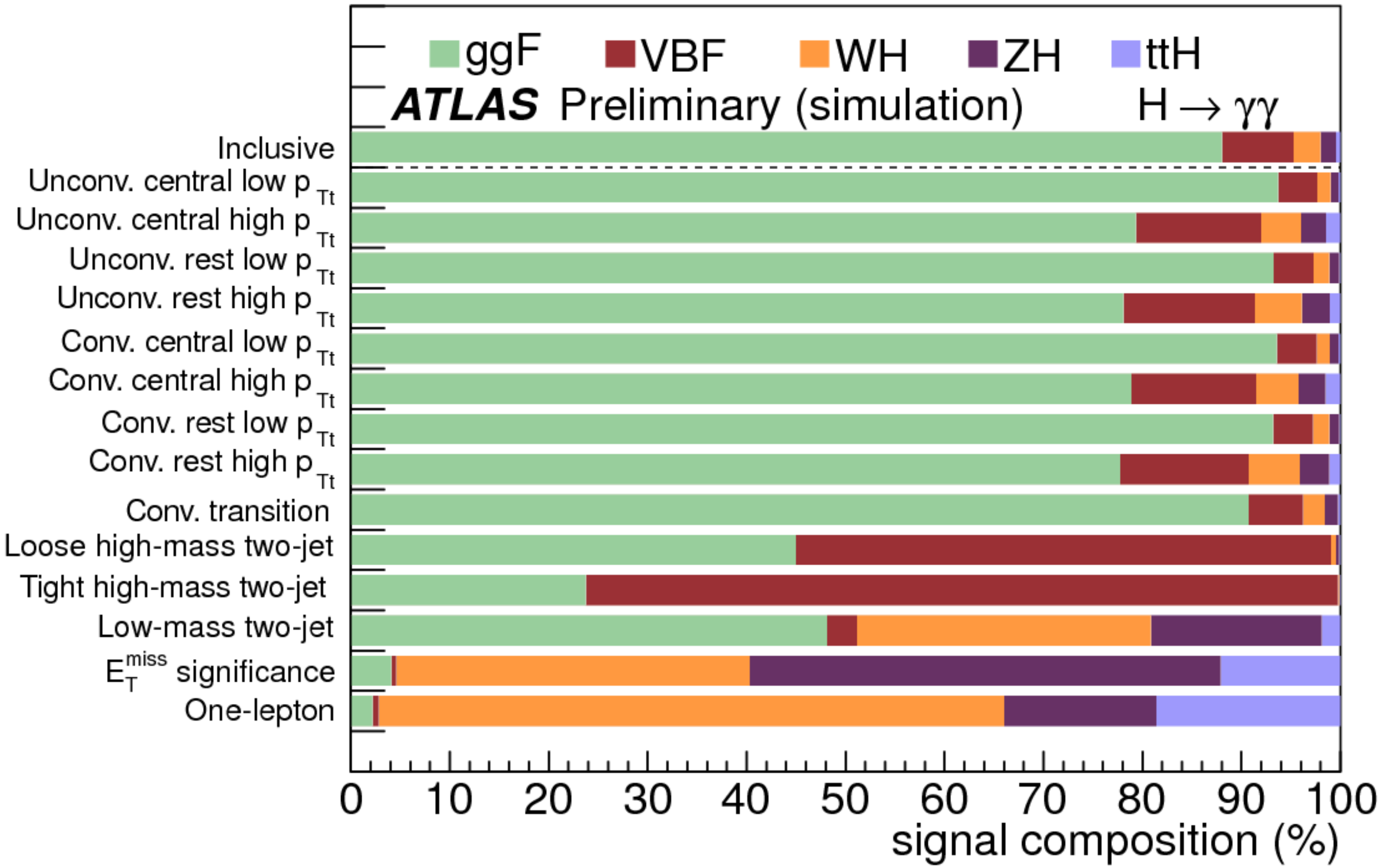


- Analysis strategy:
  - two isolated high-p_T photons
  - vertex
    - CMS: from recoiling charged particles
    - ATLAS: from photon pointing (longitudinal ECAL segmentation)
  - **di-photon mass** is the key observable
  - split events into exclusive categories:
    - untagged, and further divided into 4/9 classes based on
      - expected mass resolution
      - expected S/B-ratio
    - di-jet tagged (VBF), and further divided into 2 classes based on
      - expected S/B-ratio
    - ATLAS: low mass di-jet tag (VH)
    - MET-tagged (VH)
    - lepton-tagged (VH)
  - background: from $m_{\gamma\gamma}$-distribution sidebands

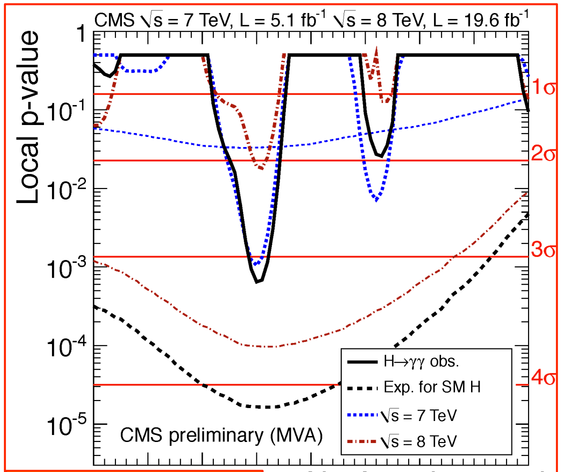
$m_{\gamma\gamma}$

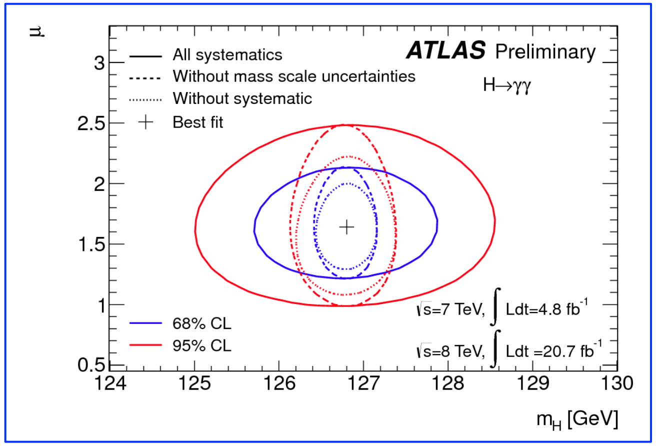
- Analysis features to note:
  - bad S/B-ratio,
  - but high event yield (500 events vs 20 for ZZ->4l)
  - di-photon mass resolution = 1-2%

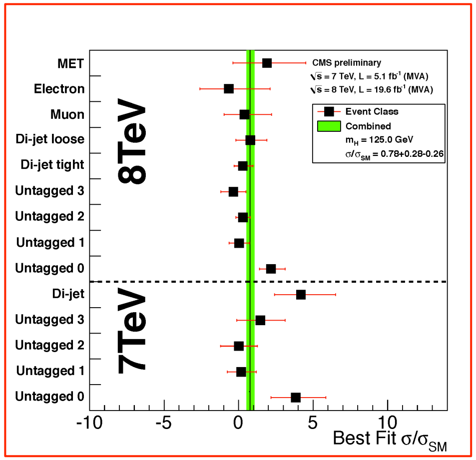
Word of caution: purity of tags



H → γγ: results







CMS:

Z_{obs} = 3.2 σ

Z_{exp} = 4.2 σ

ATLAS:

Z_{obs} = 7.4 σ

Z_{exp} = 4.1 σ

CMS

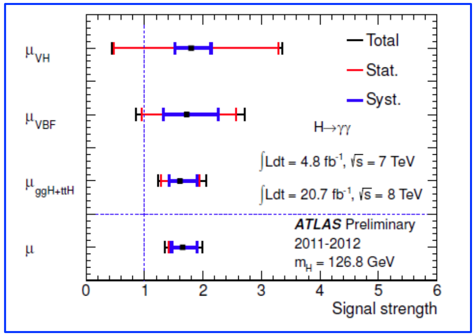
m_X = 125.4 ± 0.8

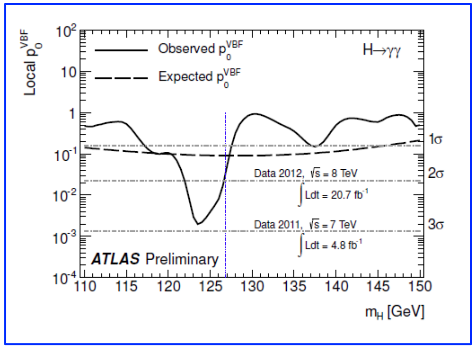
μ = 0.78 ± 0.27

ATLAS

m_X = 126.8 ± 0.7 GeV

μ = 1.65 ± 0.33

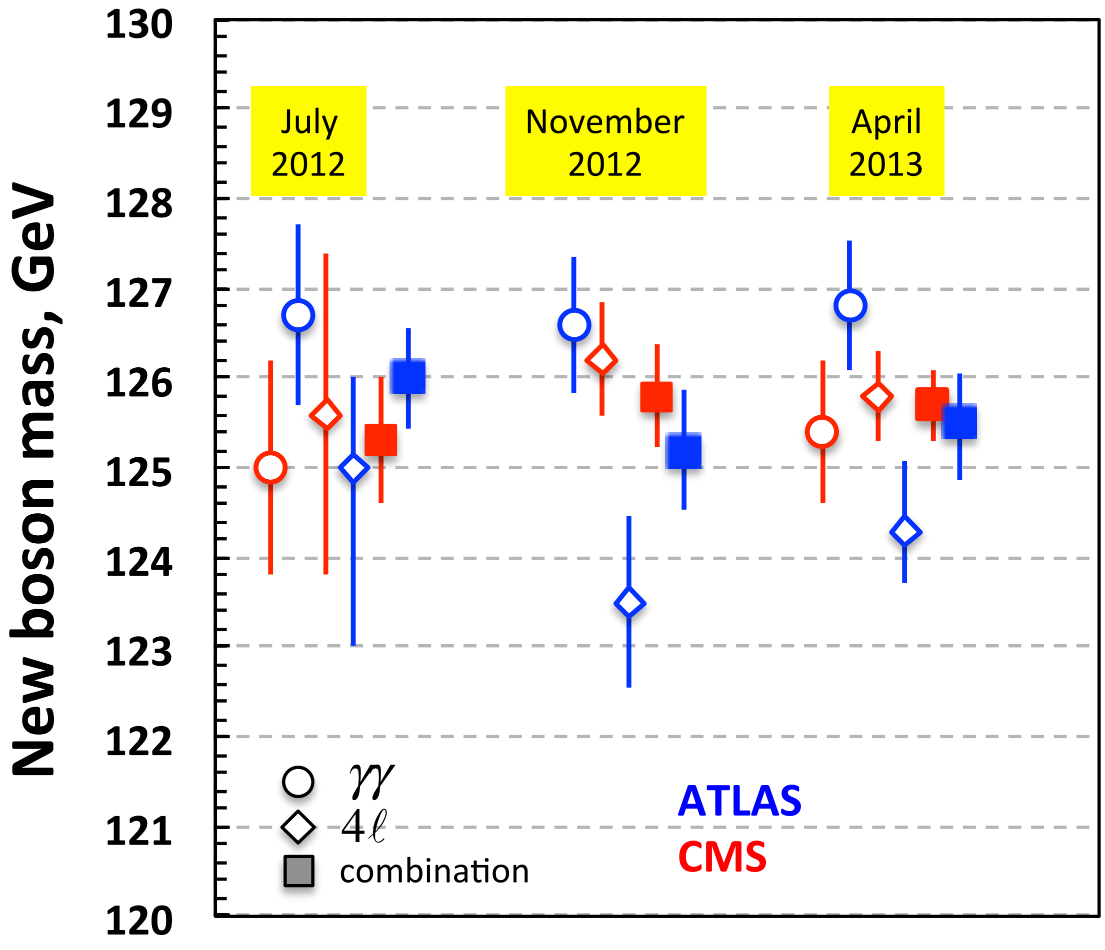




Points to note:

- CMS: significance is reduced compared to ICHEP:
    - ICHEP (10 fb^{-1}): **observed = 4.1**, expected = 2.7 ± 1
    - Moriond (25 fb^{-1}): **observed = 3.2**, expected = 4.2 ± 1
    - New data show fewer than expected signal-like events
    - The expected sensitivity evolves as sqrt(L)
- CMS: alternative analysis results: Z=3.9 (exp. 3.5) and μ = 1.11 ± 0.31
    - statistical correlation between two analyses is found to be 0.75
    - taking this into account, **stat significance of the difference in results is 1.5 σ**
- ATALS: γγ-signal stronger than expected (consistent with SM at 2.3σ)
- ATLAS: γγ-signal narrower than expected (stat consistency is 1.8σ)
- CMS and ATLAS: mass measurements limited by systematic uncertainties

Evolution of m_X with time

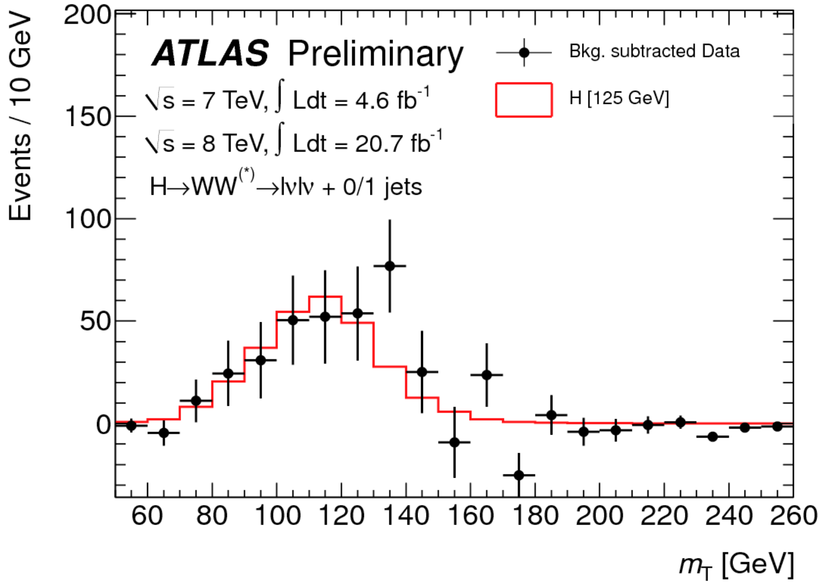


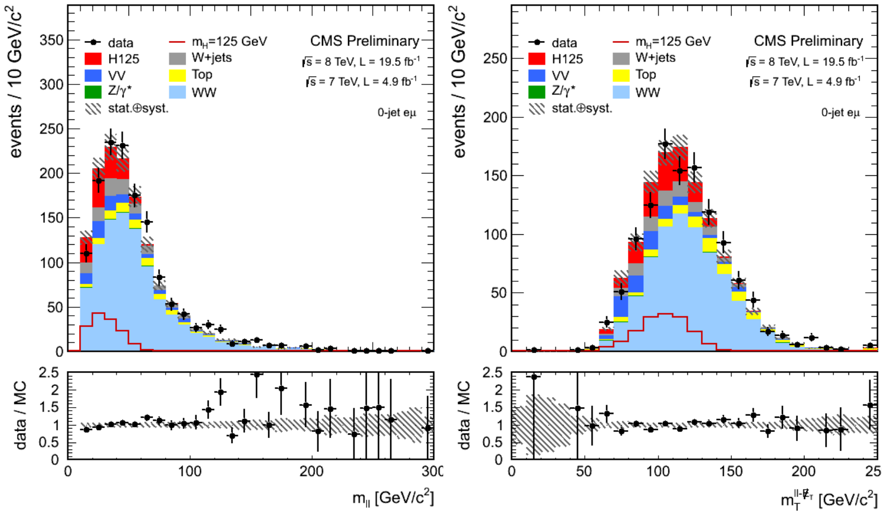
CMS: 125.7 ± 0.4 GeV
ATLAS: 125.5 ± 0.6 GeV

Points to note:

- mass uncertainties: 0.3-0.5%
- ATLAS and CMS overall best-fit values agree
- ATLAS has 2.3σ tension between γγ and 4l

H → WW → lνlν

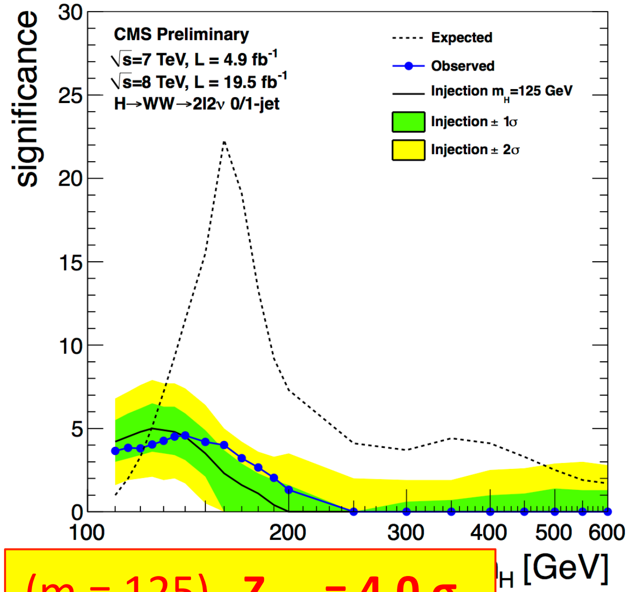




- Analysis strategy:
  - two prompt high-p_T leptons
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !
  - **ATLAS: m_T-distribution**
  - **CMS:**
    - Different-flavor: **2D distribution N(m_{ll},m_T)**
    - Same-flavor dileptons: **cut-based analysis**
  - Backgrounds (for low mass Higgs):
    - WW, tt, W+jets, DY+jets, Wγ: from control regions
    - ZW, ZZ: from MC (very small contribution)

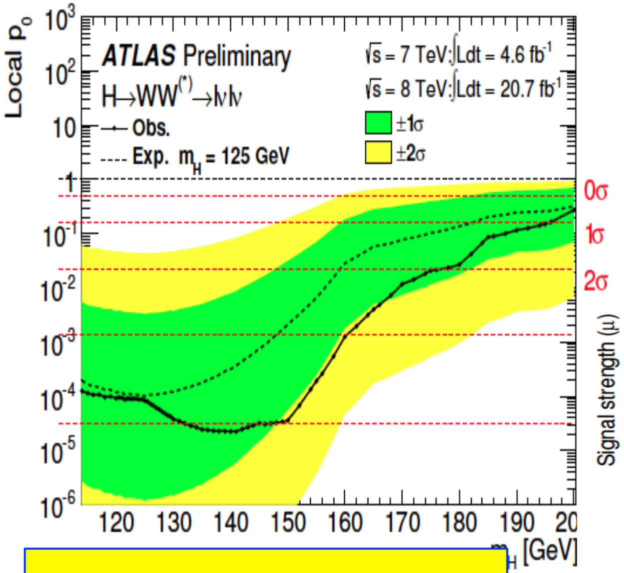
- Analysis features to note (m_H=125):
  - OK S/B-ratio
  - fair signal event yield (200 events)
  - poor mass resolution ≈20%

H → WW → lvlv: results



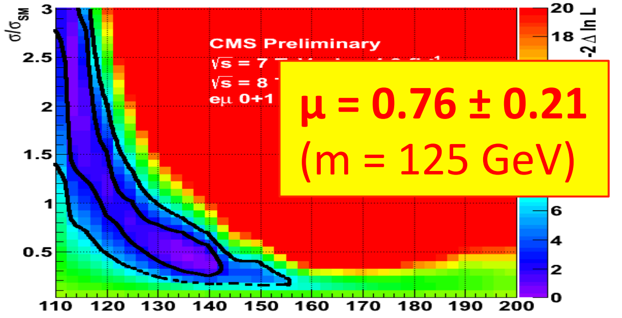
(m = 125) **Z_{obs} = 4.0 σ**

Z_{exp} = 5.0 σ



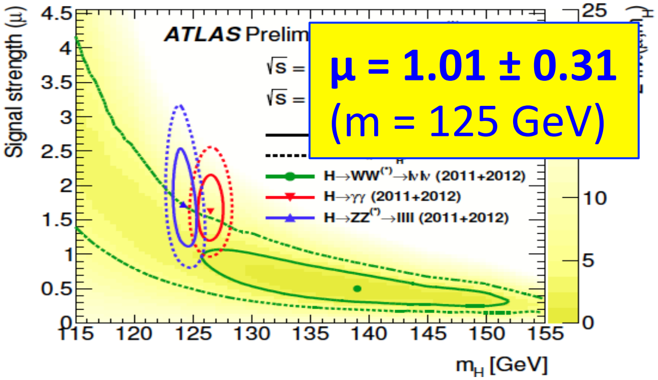
(m = 125) **Z_{obs} = 3.8 σ**

Z_{exp} = 3.7 σ



μ = 0.76 ± 0.21

(m = 125 GeV)



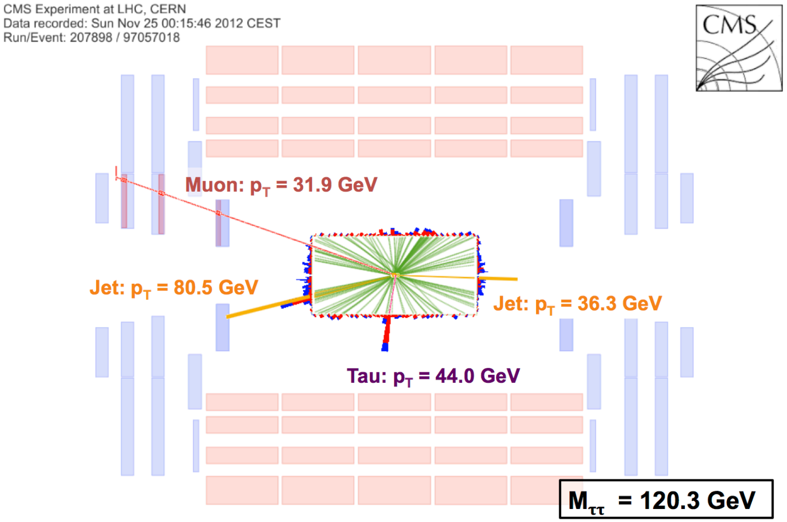
μ = 1.01 ± 0.31

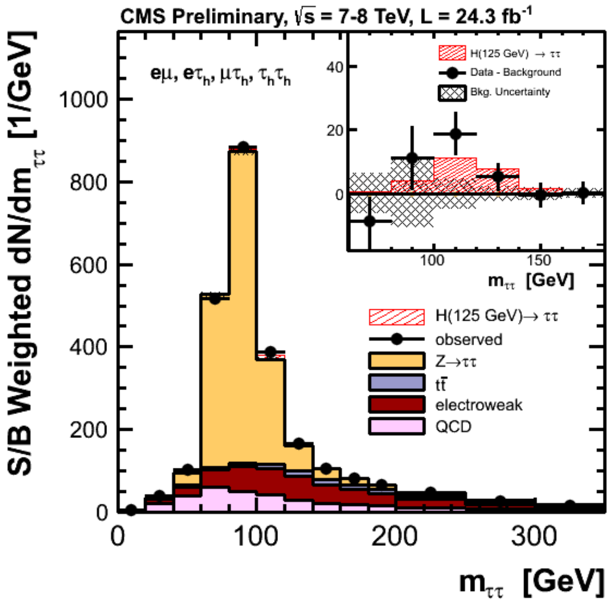
(m = 125 GeV)

Points to note:

- CMS and ATLAS see broad 4σ excesses in the low mass range
- poor mass resolution does not allow to pin down the mass and hence signal strength
- the broad accesses are consistent with **SM Higgs rate (m_H=125 GeV)** and the instrumental **mass resolution** (see injected signal)
- **curiosity:** both CMS and ATLAS have an extra 1σ excess between 130 and 200 GeV

H → ττ (CMS update since HCP)

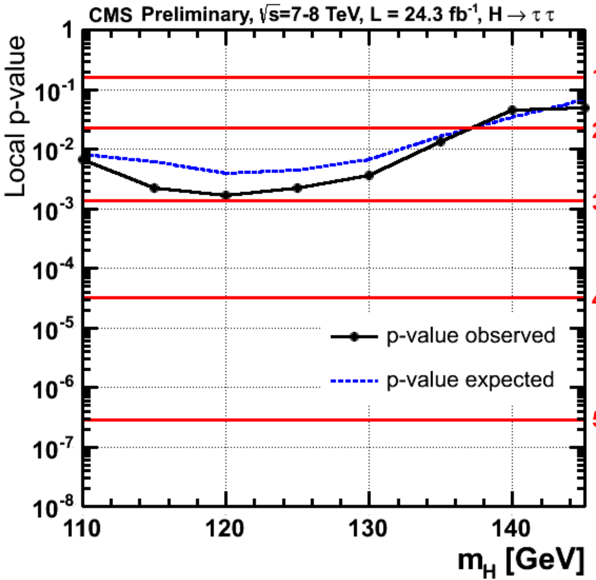




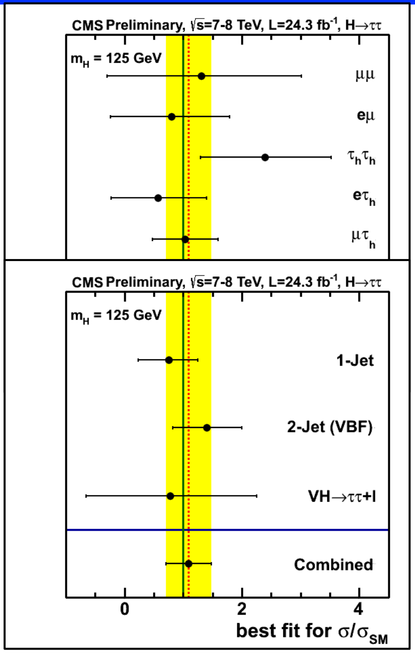
- Analysis strategy:
  - di-tau candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
  - MET
  - **DiTau mass (including MET)**: key distribution
  - split events into jet categories:
    - **2-jets (VBF-tag)**: best S/B-ratio
    - **1-jet (ggF, VH)**: acceptable S/B-ratio
    - untagged: control region (S/B≅0)
  - split 1-jet events further high/low p_T tau
    - different S/B rates
  - Backgrounds:
    - Z→ττ: Z→μμ (data) with a simulated μ-τ swap
    - Z→ee, W+jets, ttbar: MC for shapes, data for normalization
    - QCD: from control regions

- Analysis features to note (m_H=125):
  - poor S/B-ratio
  - small signal event yield
  - Higgs is on falling slope of Z-decays
  - poor mass resolution ≈15%

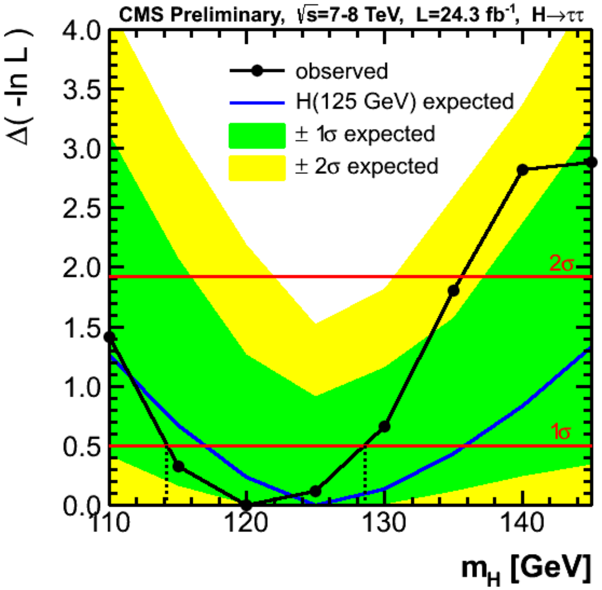
H → ττ: CMS results



Z_{obs} = 2.9 σ
Z_{exp} = 2.6 σ (m = 125)



μ = 1.1 ± 0.4
(m = 125 GeV)

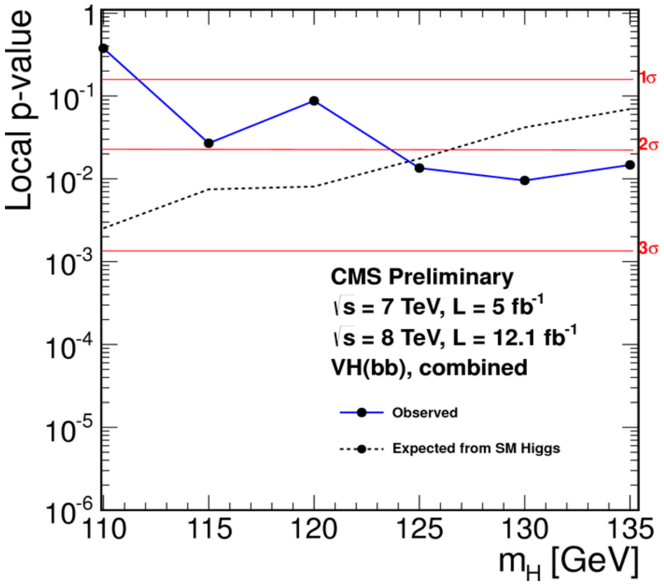


$m_X = 120^{+9}_{-7}$ GeV

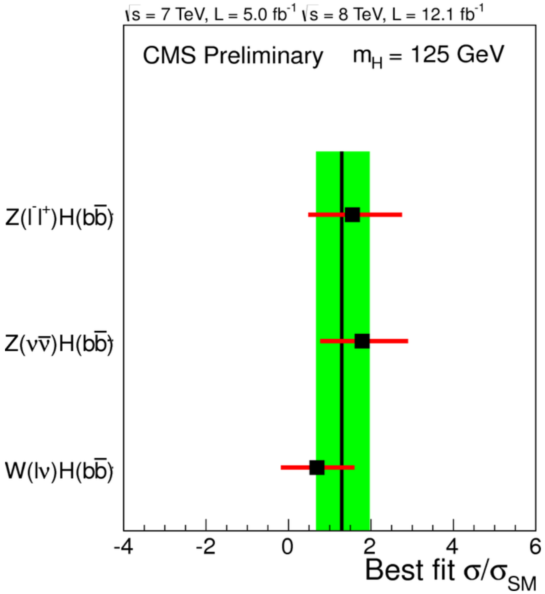
Points to note:

- broad access (poor mass resolution), consistent with **SM Higgs rate**
- close to reaching a 3σ-sensitivity: **fair sensitivity for measurements**
- 1-jet channel has a respectable weight in the search
- **VH(ττ) analysis is updated too**; its sensitivity can be seen in the μ-compatibility plot
- despite poor mass resolution, the TauTau channel is **not completely mass-blind** !
- ATLAS has not been using hadronic tau-decay yet (most sensitive channels in CMS)

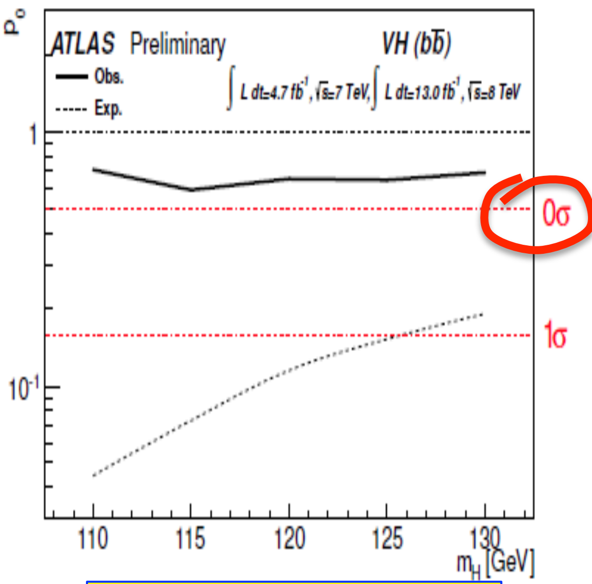
VH, H → bb: no updates since HCP (yet)



Z_{obs} = 2.2 σ
Z_{exp} = 2.1 σ (m = 125)



μ = 1.3 ± 0.7
(m = 125 GeV)

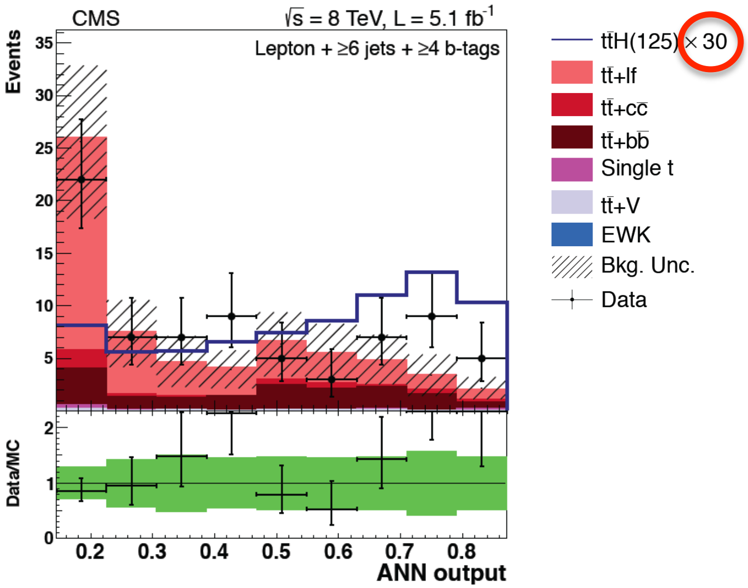


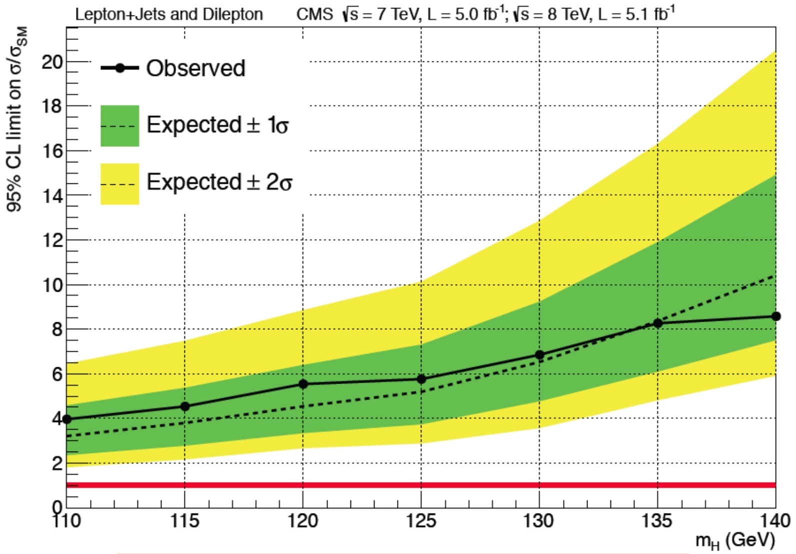
Z_{obs} = none
Z_{exp} = 1 σ (m = 125)

Brief summary:

- publicly available: **5 + 12 fb^{-1}**; update with the full lumi is expected shortly
- Event classification: 2 b-jets + (eν, μν, ee, μμ, νν); V has low/high-pT; events with high-pT: tight/loose b-tag
- **CMS: 2σ-excess** with a signal strength consistent with the SM Higgs boson: **μ = 1.3 ± 0.7**
- **ATLAS: deficit of events**, but statistically consistent with the expected SM Higgs boson signal
- mass resolution **≈10%**

ttH, H → bb: CMS update, but 5+5 fb^{-1} only



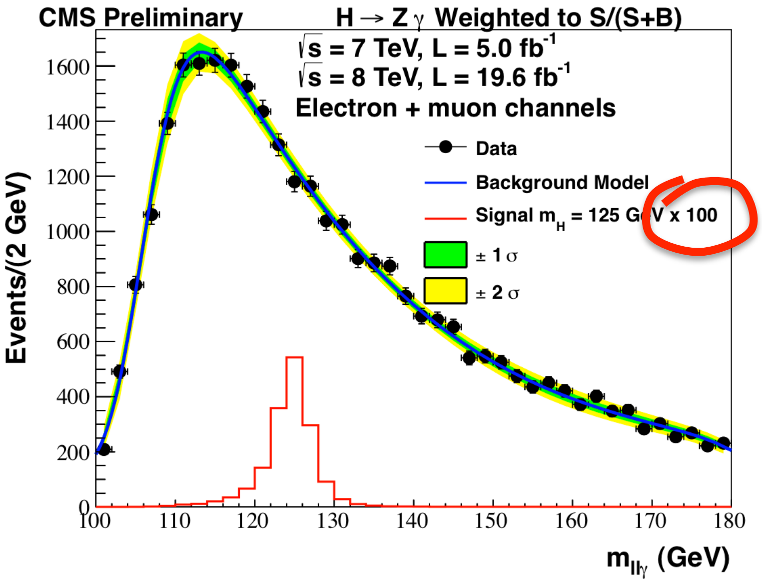


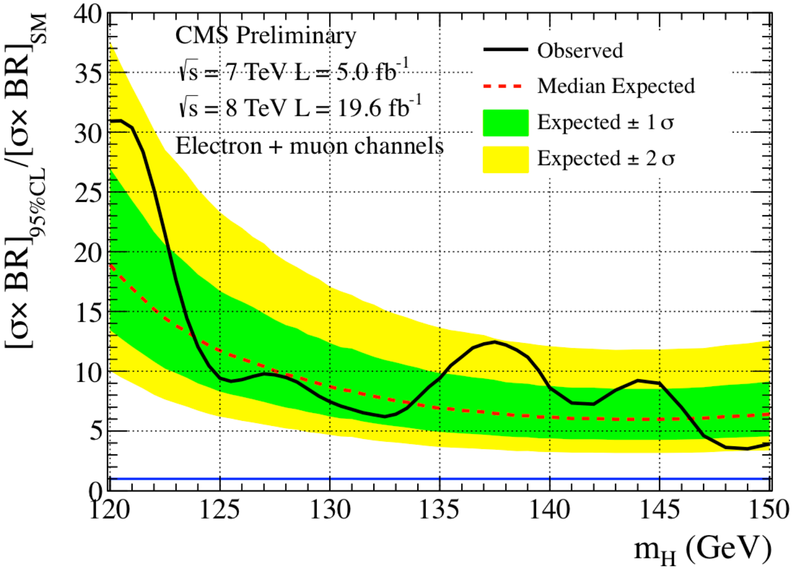
μ > 5.8 excluded at 95% CL
(m = 125 GeV)

Brief summary:

- publicly available: **5 + 5 fb^{-1}**; update with the full lumi is expected shortly
- Event classification: bb+(lνjjbb); bb+(lνlνbb); events are categorized based on # of jets and # of b-tags
- very small event rate; fair S/B-ratio
- MVA-shape analysis: exclude μ>5.8 at 95% CL
- To reach 2σ-sensitivity, **we need 30 times more data**

H → Zγ





Analysis strategy:

- two prompt leptons: Z→ee, Z→μμ
- isolated photon
- **dilepton-photon mass** is the key observable
- split events further into classes, based on "geography" of leptons/photon and photon cluster quality
  - different mass resolutions
  - different S/B-ratios
- Background: fit using sidebands

Analysis features to note:

- very poor S/B-ratio
- very small event yield
- mass resolution = 1-2%

Results:

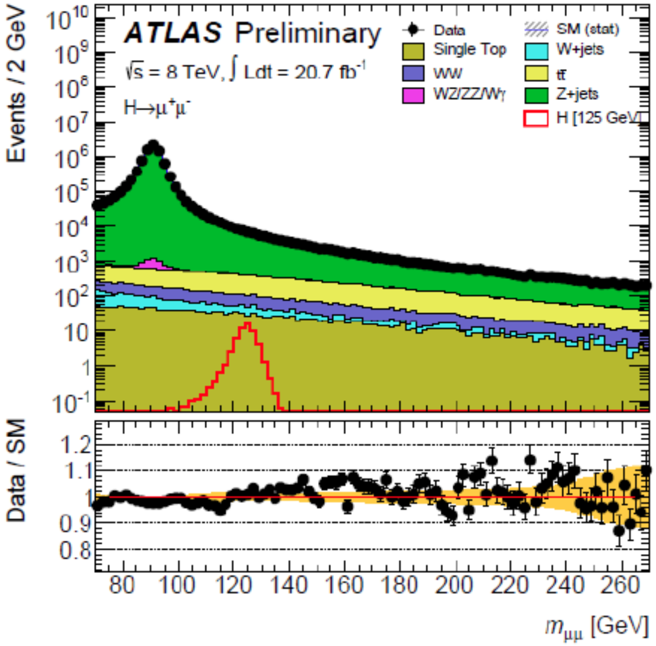
CMS (m_H=125): μ>10 is excluded at 95% CL

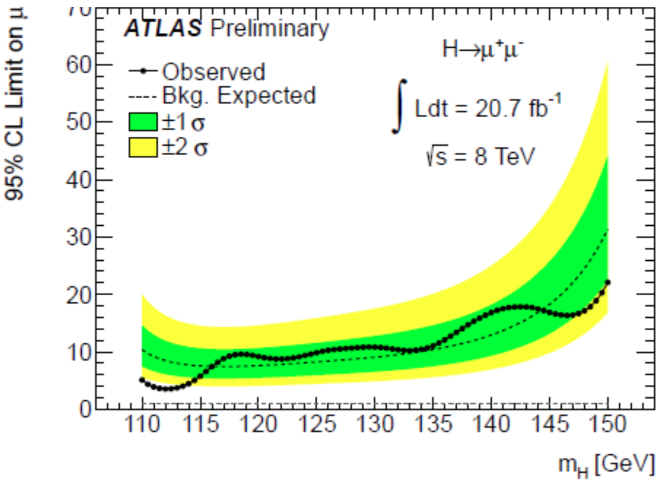
ATLAS (m_H=125): μ>18 is excluded at 95% CL

Points to note:

- **need 100 times more data** to reach 2σ-sensitivity

$H \rightarrow \mu\mu$ (ATLAS only)





Analysis strategy:

- two prompt muons: μμ
- **dimuon mass** is the key observable
- Background: fit using sidebands

Analysis features to note:

- very poor S/B-ratio
- very small event yield
- mass resolution = 2%

Results:

ATLAS (m_H=125): μ>10 is excluded at 95% CL

Points to note:

- **need 100 times more data** to reach 2σ-sensitivity

Significance of the excess near 125 GeV

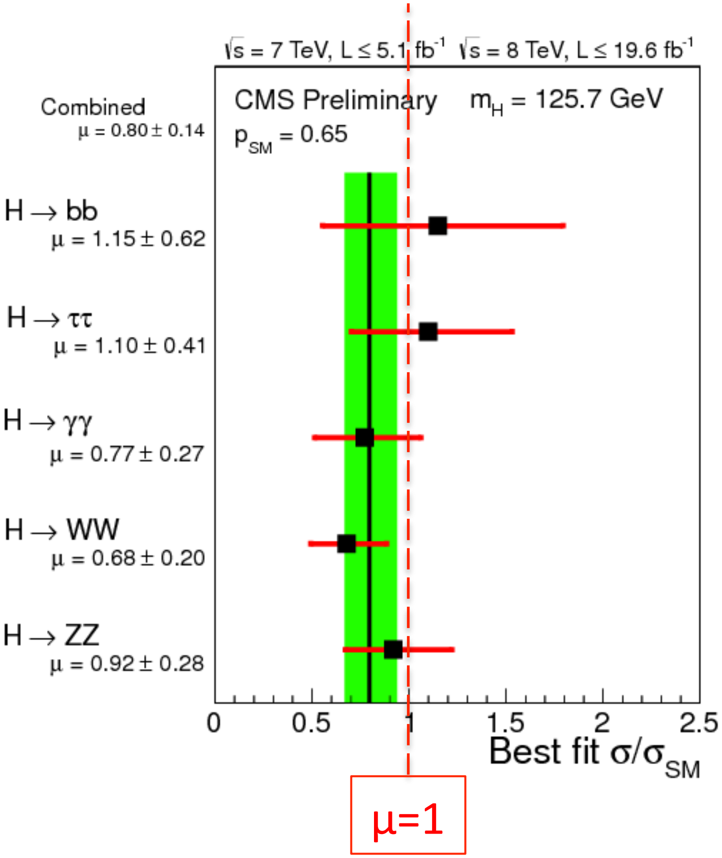
	ATLAS		CMS		
	expected	**observed**	expected	**observed**	observed
H→ZZ	4.4	**6.6**	7.1	**6.7**	
H→γγ	4.1	**7.4**	3.9	**3.2**	
H→WW	3.8	**3.8**	5.3	**3.9**	
H→ττ	1.6	**1.1**	2.6	**2.8**	3.4
H→bb	1.0	**0**	2.2	**2.0**	
combined	7.3	**10**	stopped computing		

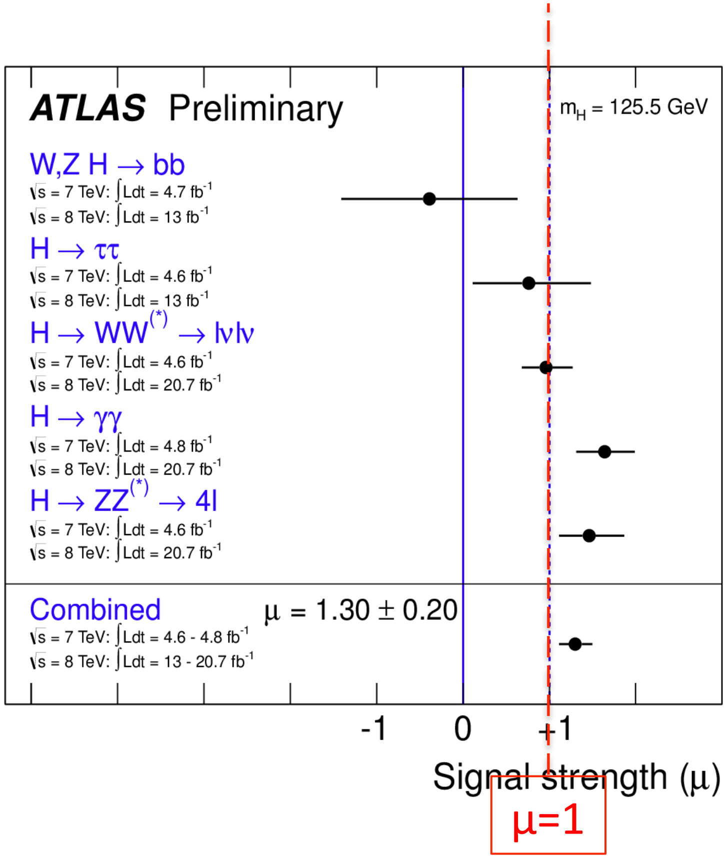
Higgs-like signal is certainly there beyond any reasonable and unreasonable doubt

Is X126 the SM Higgs boson?

- What can we tell about the X126 width from the mass line shape (not available)
- Compatibility of event yields with the SM Higgs boson
- Recast the event yields into "measurements" of couplings
- Spin-parity properties
- Is X126 one particle?

Consistency of event yields (2)





CMS best-fit signal strength

$\mu = 0.80 \pm 0.14$

ATLAS best-fit signal strength

$\mu = 1.30 \pm 0.20$

Is X126 the SM Higgs boson?

- What can we tell about the X126 width from the mass line shape (not available)
- Compatibility of event yields with the SM Higgs boson
- Recast the event yields into “measurements” of couplings
- Spin-parity properties
- Is X126 one particle?

Production × Decay parameterization

8 independent parameters to describe all currently relevant decays and production mechanisms:

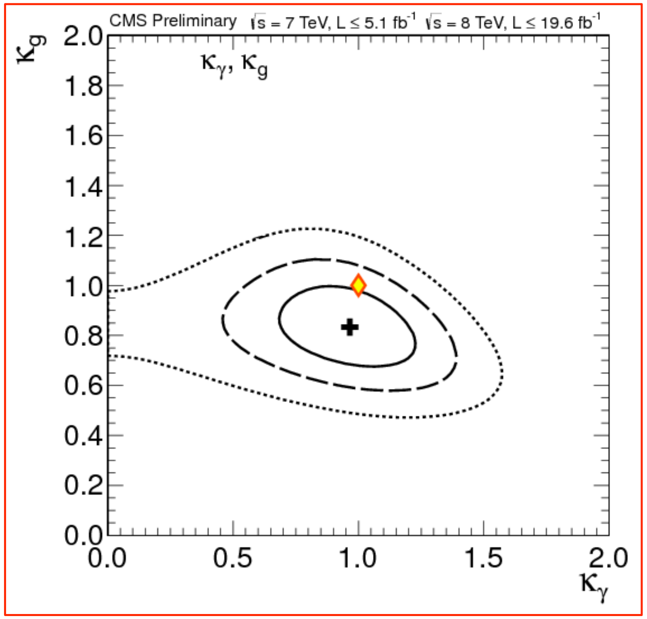
$$\sigma(xx \to H) \cdot BR(H \to yy) \;\propto\; \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{\mathrm{TOT}}}$$

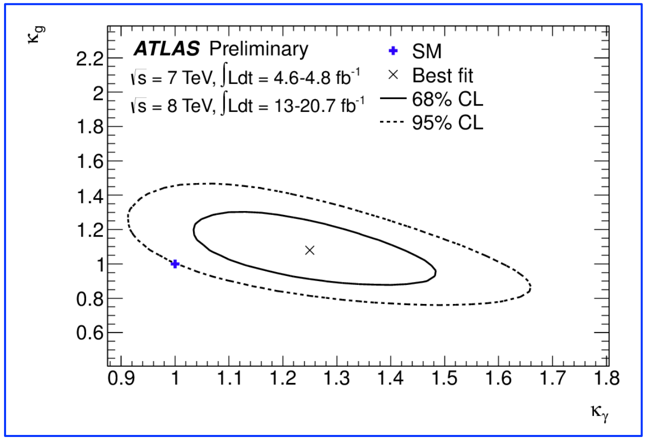
- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- Γ_{gg} (loop induced)
- Γ_{tt}
- Γ_{TOT} (including H → "invisible")
- **Zγ** and **μμ** still have too little sensitivity to affect anything in the combination

	untagged	VBF-tag	VH-tag	ttH-tag
WW	✓	✓	✓	
ZZ	✓	✓		
bb			✓	✓
ττ	✓	✓	✓	
γγ	✓	✓	✓	

For couplings of interest, introduce scaling factors *κ* w.r.t. the SM Higgs couplings

Look for new physics in loops: κ_g and κ_γ



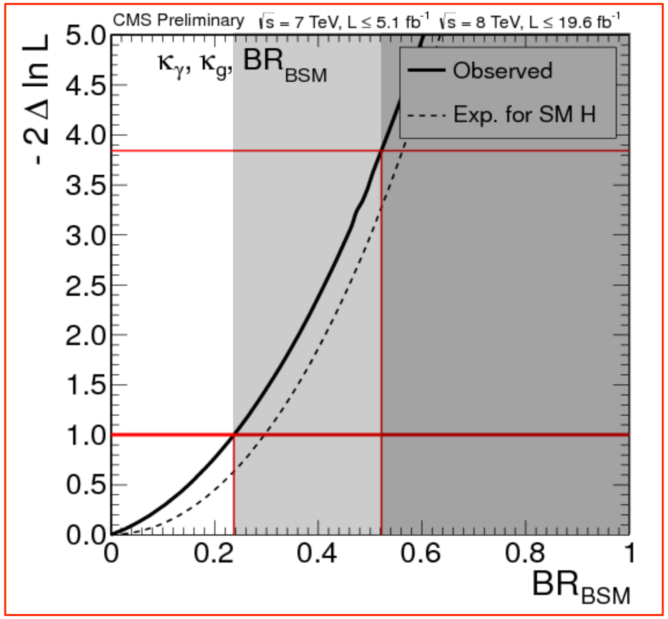


Two-parameter fit

- use all channels
- assume tree-level couplings = SM
- assume BR(BSM)=0
- **Fit for:** κ_γ , κ_g

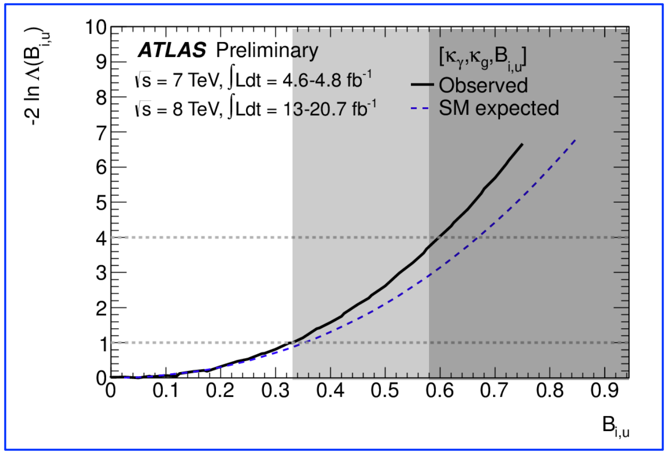
Data are consistent with (κ_γ; κ_g)=(1; 1)

Look for new physics: BR(BSM), κ_g , κ_γ



Three-parameter fit

- use all channels
- assume tree-level couplings = SM
- allow for BR(BSM) ≠ 0
- **Fit for: BR("invisible"), κ_γ , κ_g**



CMS: BR(BSM) < 0.52 at 95% CL

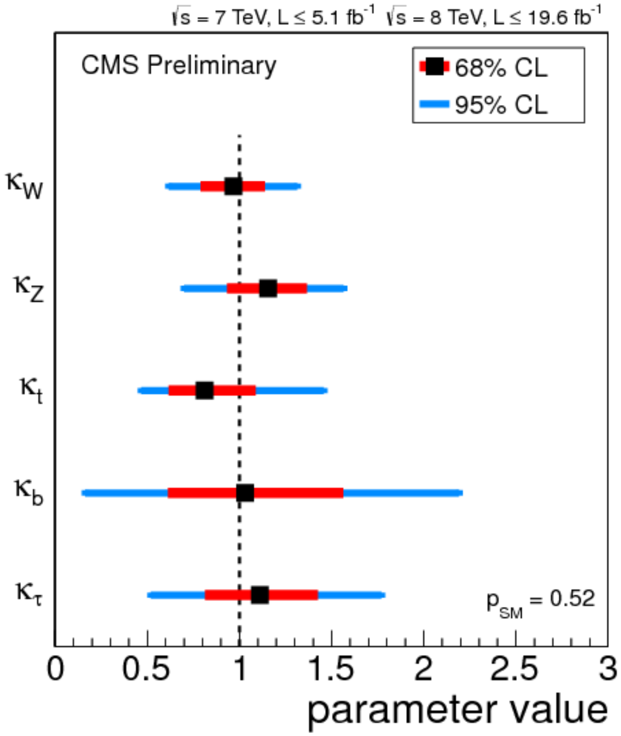
ATLAS: BR(BSM) < 0.58 at 95% CL

Direct ATLAS search for ZH→ (ll)+MET:
BR(inv)<0.65 at 95% CL
assuming SM HZZ coupling

CMS: C5 model (almost a measurement)

8 independent parameters to describe all currently relevant decays and production mechanisms:

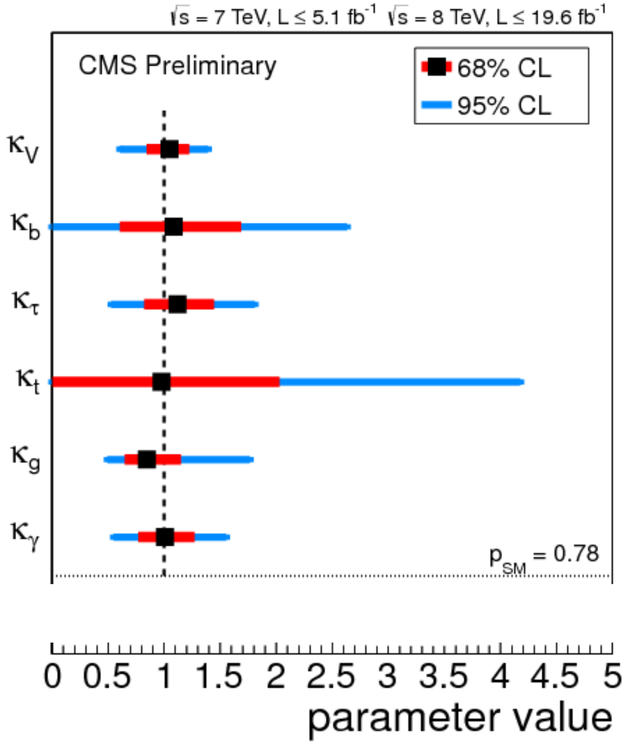
- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- $\Gamma_{\gamma\gamma}$ (loop is resolved) → κ_W, κ_t
- Γ_{gg} (loop is resolved) → κ_t, κ_b
- assume **BR(BSM)=0**
- Assume couplings to the 1st, 2nd, 3rd generations are modified the same way



CMS: C6 model (almost a measurement)

8 independent parameters to describe all currently relevant decays and production mechanisms:

- Γ_{ZZ} → κ_V
- Γ_{WW}
- $\Gamma_{\tau\tau}$ → κ_τ
- Γ_{bb} → κ_b
- $\Gamma_{\gamma\gamma}$ (loop induced) → κ_γ
- Γ_{gg} (loop induced) → κ_g
- Γ_{tt} → κ_t
- assume **BR(BSM)=0**
- Assume couplings to the 1st, 2nd, 3rd generations are modified the same way



Is X126 the SM Higgs boson?

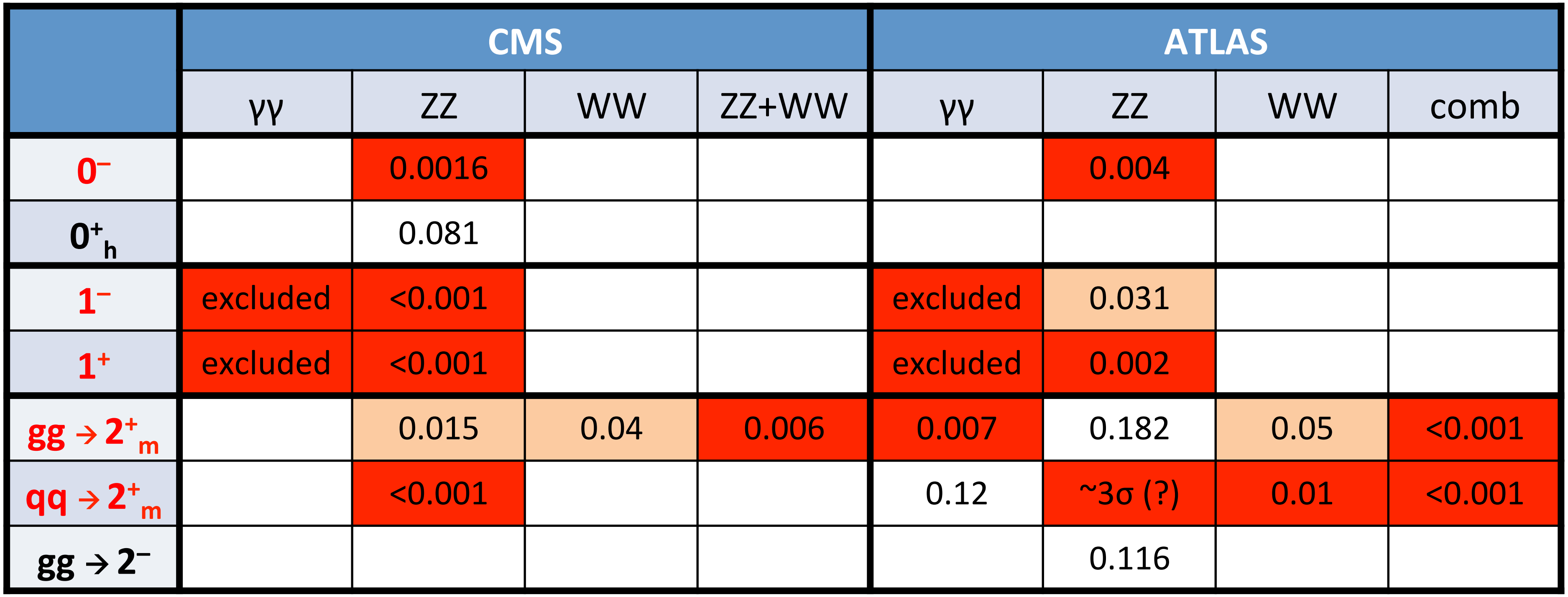
- What can we tell about the X126 width from the mass line shape (not available)
- Compatibility of event yields with the SM Higgs boson
- Recast the event yields into “measurements” of couplings
- Spin-parity properties
- Is X126 one particle?

Spin-parity (J^{CP})

CL_s values for testing J^{CP} state hypotheses vs SM-like Higgs boson (0^+_m)

🟧 $CL_s < 0.05$

🟥 $CL_s < 0.01$



	CMS				ATLAS			
	γγ	ZZ	WW	ZZ+WW	γγ	ZZ	WW	comb
0^-		0.0016				0.004		
0^+_h		0.081						
1^-	excluded	<0.001			excluded	0.031		
1^+	excluded	<0.001			excluded	0.002		
gg → 2^+_m		0.015	0.04	0.006	0.007	0.182	0.05	<0.001
qq → 2^+_m		<0.001			0.12	~3σ (?)	0.01	<0.001
gg → 2^-						0.116		

Example:
Spin-0 Lagrangian
(lowest dimension terms)

$$\mathcal{L} = X\left[\underset{\text{Higgs}}{\kappa_1}\frac{m_Z^2}{v}Z_\mu Z^\mu + \underset{0^+_h}{\frac{\kappa_2}{2v}}F_{\mu\nu}F^{\mu\nu} + \underset{0^-}{\frac{\kappa_3}{2v}}F_{\mu\nu}\tilde{F}^{\mu\nu}\right] + \ldots$$

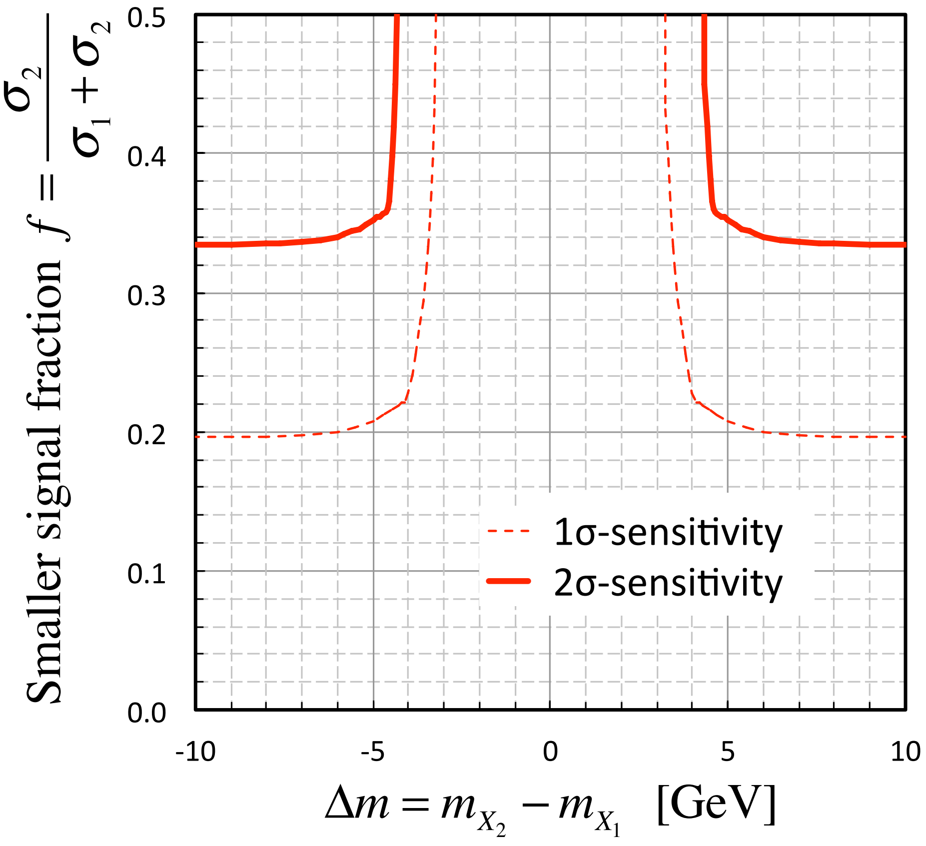
Is X126 the SM Higgs boson?

- What can we tell about the X126 width from the mass line shape (not available)
- Compatibility of event yields with the SM Higgs boson
- Recast the event yields into "measurements" of couplings
- Spin-parity properties
- Is X126 one particle?

Is X126 one particle?

What if X126 is two bosons with near degenerate masses?

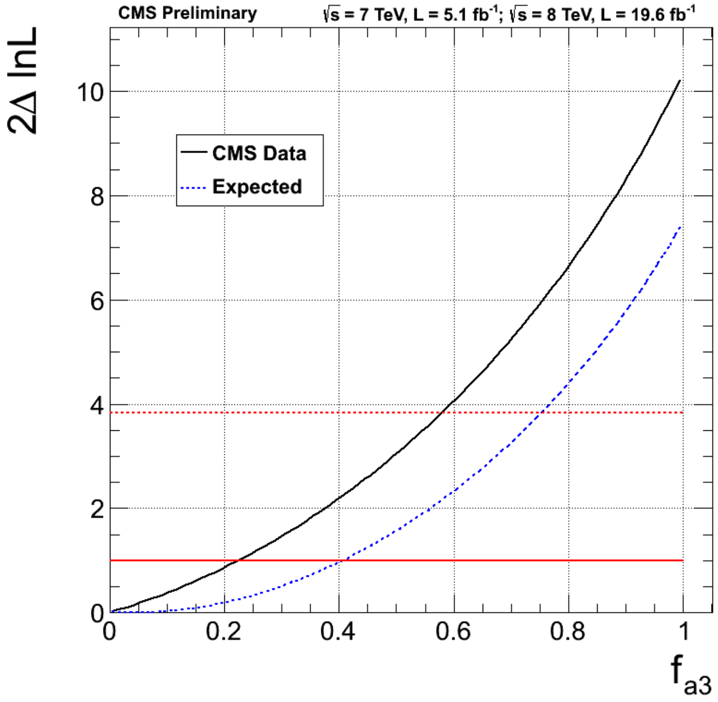
- What can we infer from the mass line shape?
  - **no public results yet**
  - **back-of-envelope for current dataset (HZZ4L):**
    - **no sensitivity, if Δm < 4 GeV**
    - **no sensitivity, if the smaller signal contributes with *f*<0.3**



Is X126 one particle?

What if X126 is two bosons with near degenerate masses?

- What can we infer from kinematics of decays?
  - CP-odd contribution (cross section fraction): **$f(0^-) < 0.58$ at 95% CL**
  - Non-zero $f(0^-)$ may be due to
    - a 0^- particle with a nearly the same mass;
    - a single particle $X = H(0^+) + A(0^-)$ with mixed CP-even/odd states
  - No public results on other $f(J^{CP})$ fractions



Summary

- In a **combined search** for the SM Higgs boson, **a significant excess of events near m_H=126 GeV** persists beyond any doubt and now has been **established in individual decay channels: ZZ, WW, γγ**

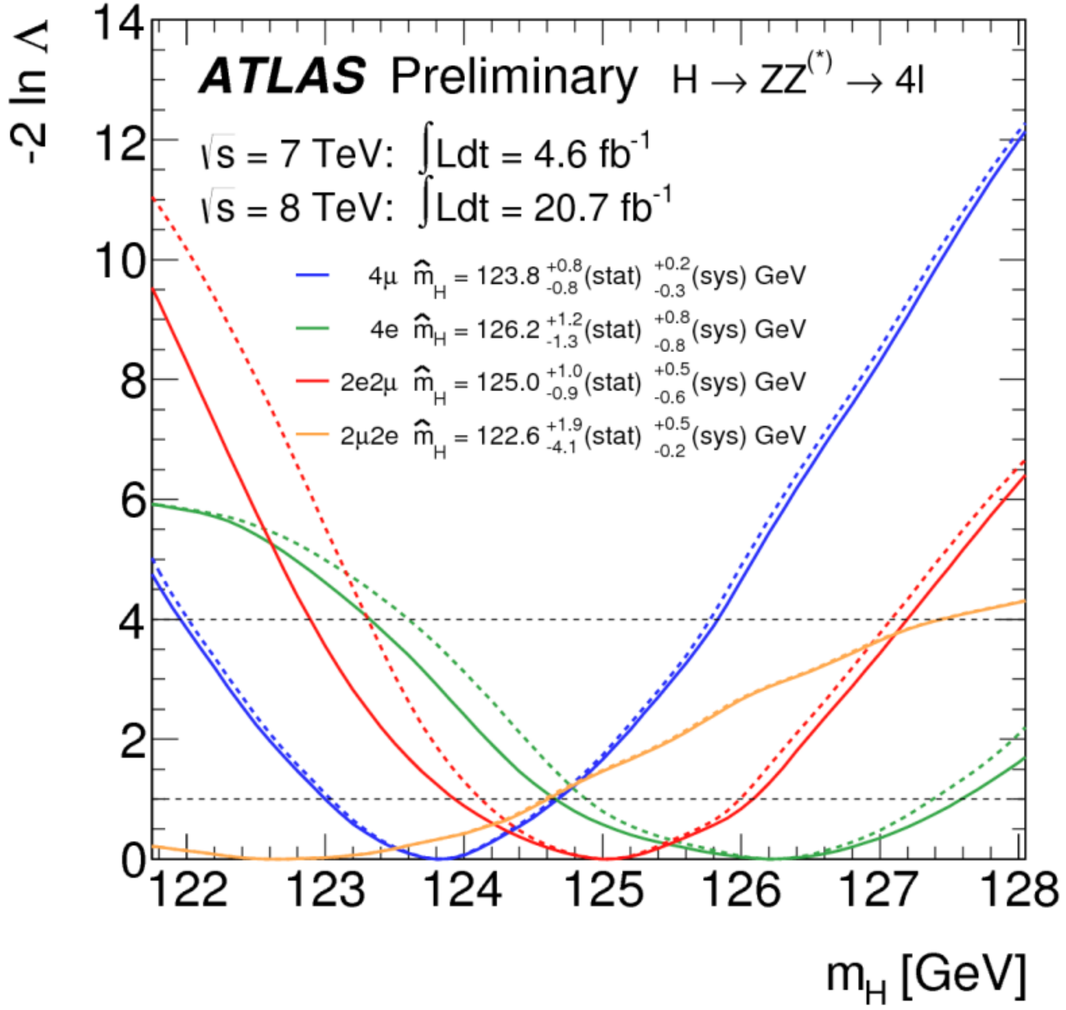
- **New boson's mass:**
  - **CMS:** **125.7 ± 0.4 GeV**
  - **ATLAS:** **125.5 ± 0.6 GeV**

- **Is X126 the SM Higgs boson?**
  - **event yields in all individual channels are consistent with the SM Higgs boson**
  - **couplings agree with the SM Higgs boson** with the current statistical accuracy: **20% (W & Z), 25% (t), 30% (τ), 60% (b)**
  - **no significant modifications for loop-induced couplings (deviations < 2σ)**
  - **BR(H→BSM) < 0.5 (approx.) at 95%CL**
  - **100% pure $J^{CP} = 0^-$, $1^{\pm}$, 2^+_m states are excluded at >99% CL**
  - **CP-odd fractional contribution: $f(0^-) < 0.58$ at 95% CL**

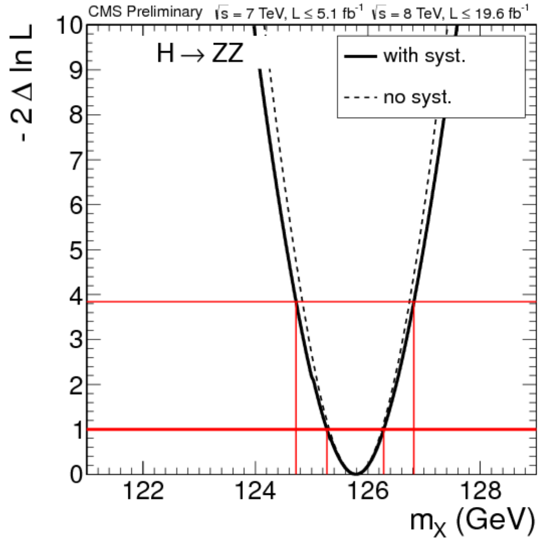
Conclusions

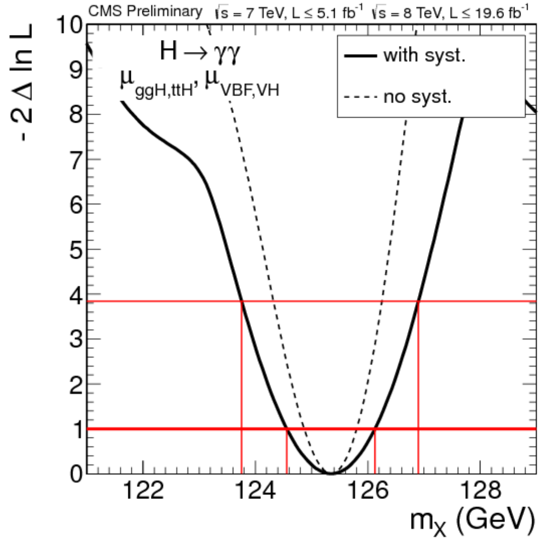
- **X126 looks very much like the SM Higgs boson… STILL?**
- **No signs for extra Higgs-like bosons… YET?**

Backup slides


ATLAS Preliminary H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
4μ m̂H = 123.8 +0.8 -0.8 (stat) +0.2 -0.3 (sys) GeV
4e m̂H = 126.2 +1.2 -1.3 (stat) +0.8 -0.8 (sys) GeV
2e2μ m̂H = 125.0 +1.0 -0.9 (stat) +0.5 -0.6 (sys) GeV
2μ2e m̂H = 122.6 +1.9 -4.1 (stat) +0.5 -0.2 (sys) GeV
-2 ln Λ
0
2
4
6
8
10
12
14
122
123
124
125
126
127
128
mH [GeV]

Mass measurement





- **A narrow resonance is seen with high significance in the two good mass resolution channels, ZZ(4l) and γγ**

ZZ(4l): m_X = 125.8 ± 0.5 (stat) ±0.2 (syst) GeV

main sources of systematic uncertainties:

  - electron energy scale: 0.3%
  - muon energy scale: 0.1%

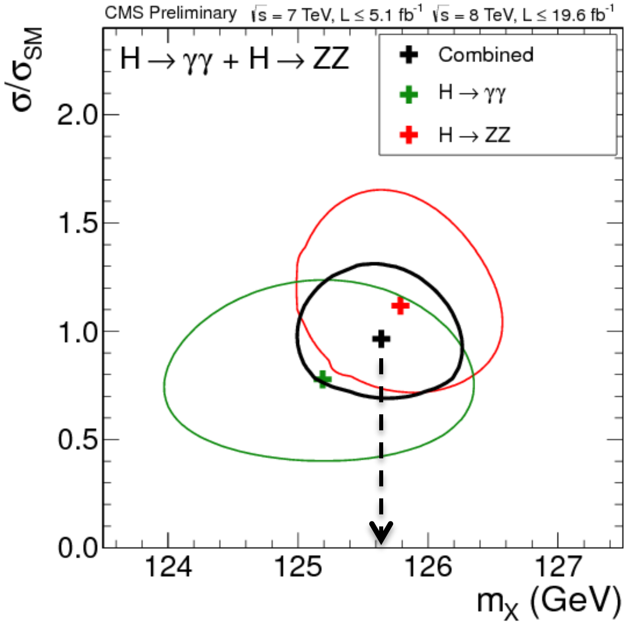
γγ: m_X = 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV

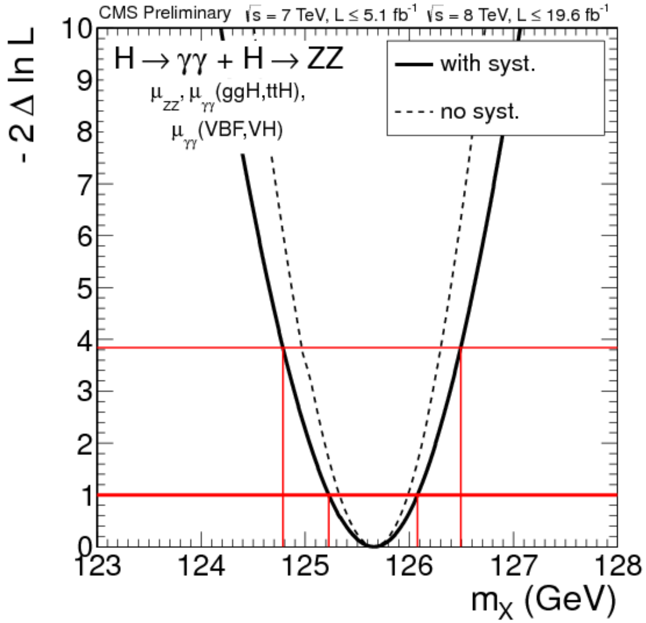
– main sources of systematic uncertainties:

  - electron-photon extrapolation
  - p_T scale extrapolation from $m_Z/2$ to $m_H/2$

- **Results are consistent with one particle X**
  → proceed with a combined mass measurement

Mass measurement





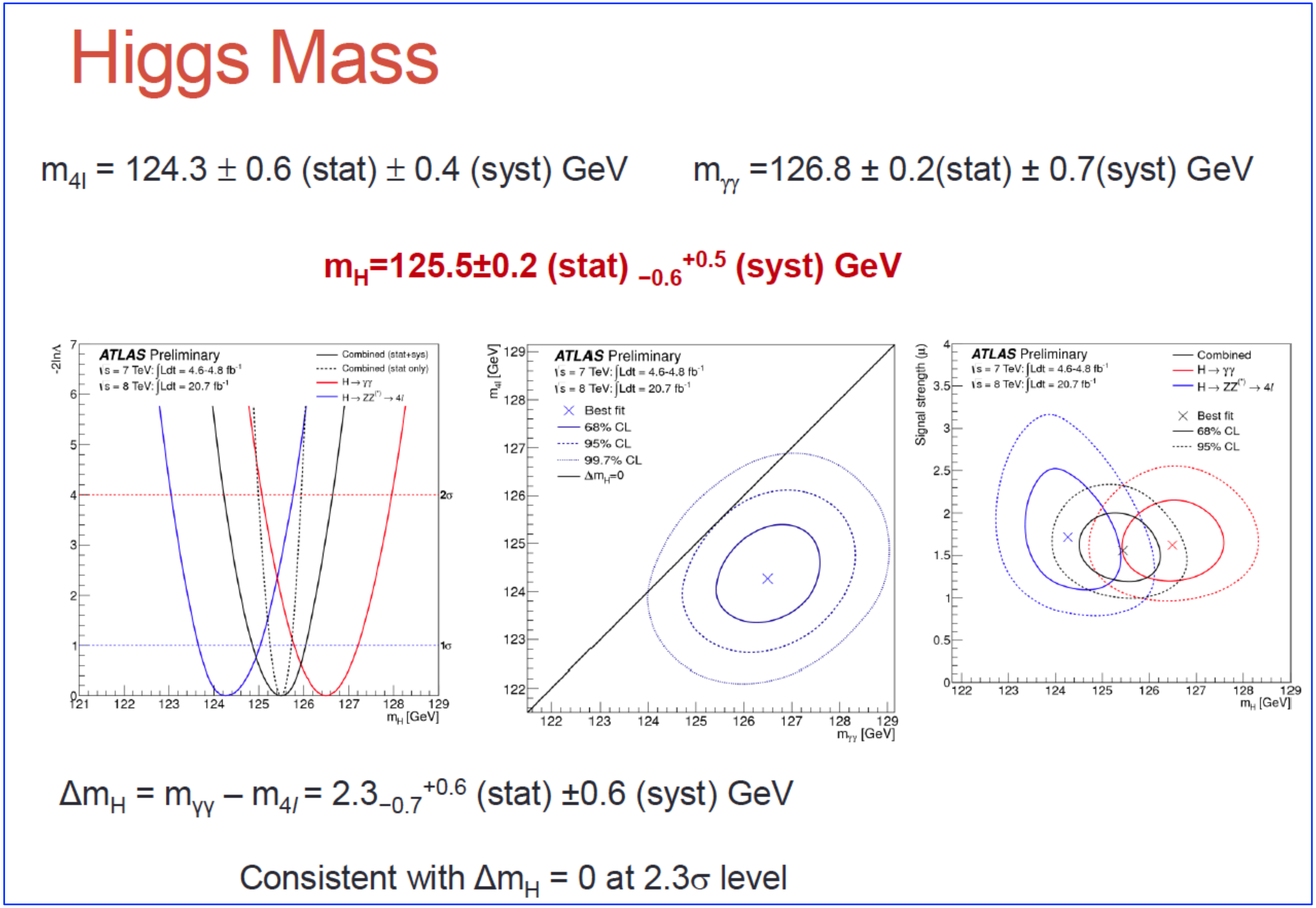
Assuming we indeed see one particle X, one can combine the two results

- either assuming the SM Higgs-like relationship for relative production rates (top plot)
- or letting relative event yields float free in the almost-model-independent fit (bottom plot):

m_X = 125.7 ± 0.4 (0.3%) GeV

= 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

Mass measurement in ATLAS



Higgs Mass

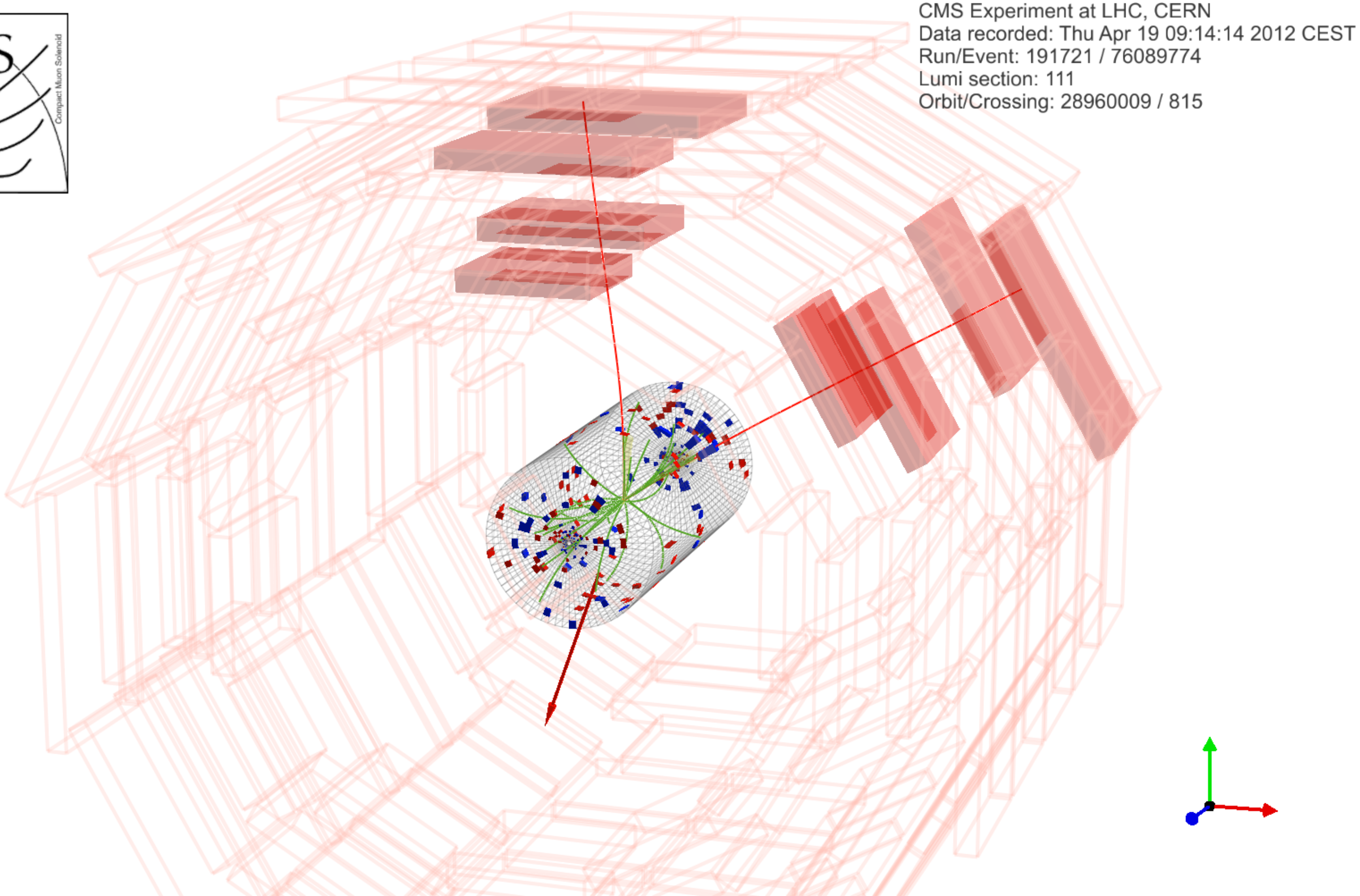
m_{4l} = 124.3 ± 0.6 (stat) ± 0.4 (syst) GeV $m_{\gamma\gamma}$ =126.8 ± 0.2(stat) ± 0.7(syst) GeV

m_H=125.5±0.2 (stat) $_{-0.6}^{+0.5}$ (syst) GeV

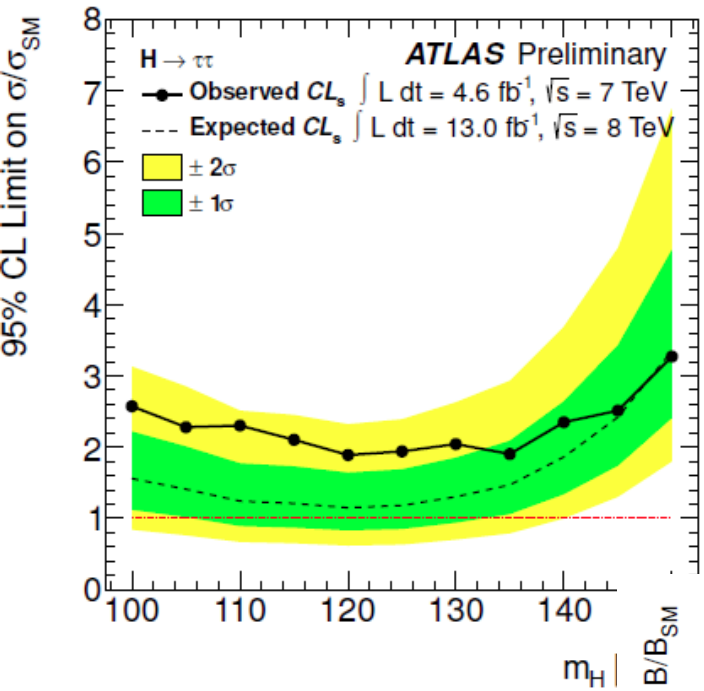
Δm_H = $m_{\gamma\gamma}$ – m_{4l} = $2.3_{-0.7}^{+0.6}$ (stat) ±0.6 (syst) GeV

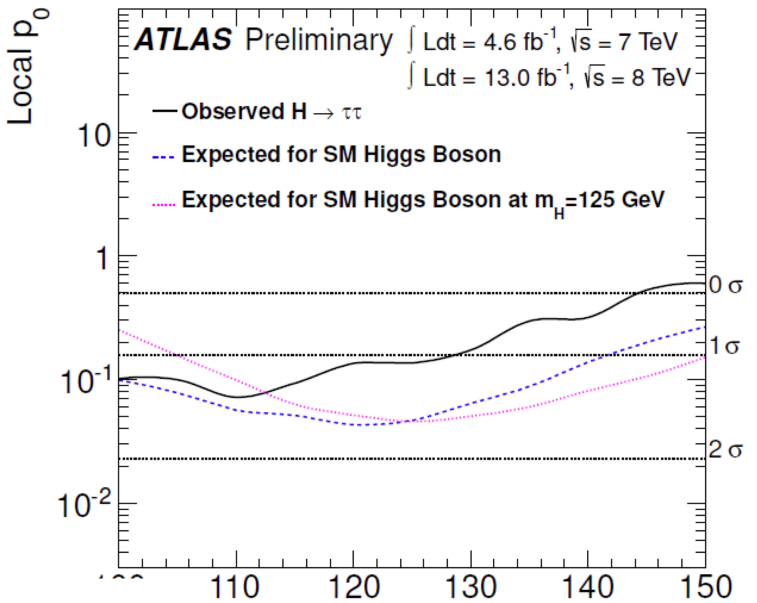
Consistent with Δm_H = 0 at 2.3σ level

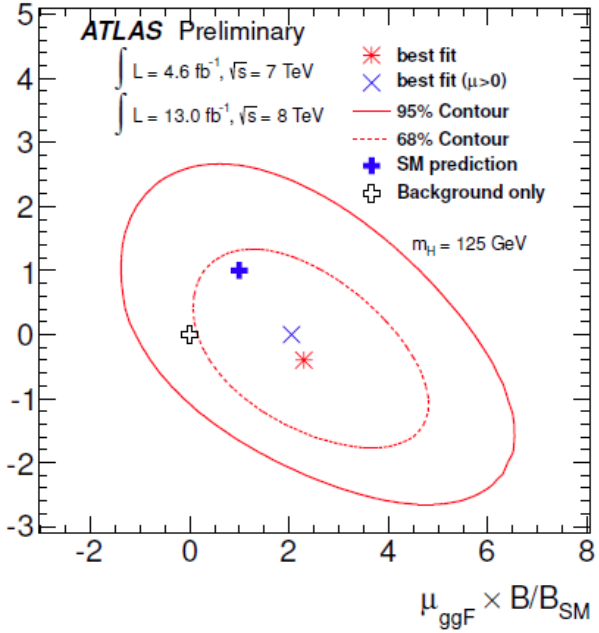
H → WW


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 2012 CEST
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815

ATLAS H → ττ







m_H [GeV]

μ_VBF+VH × B/B_SM

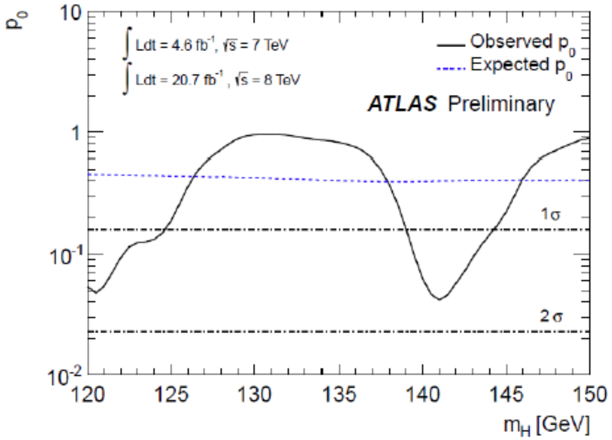
ATLAS H → Zγ

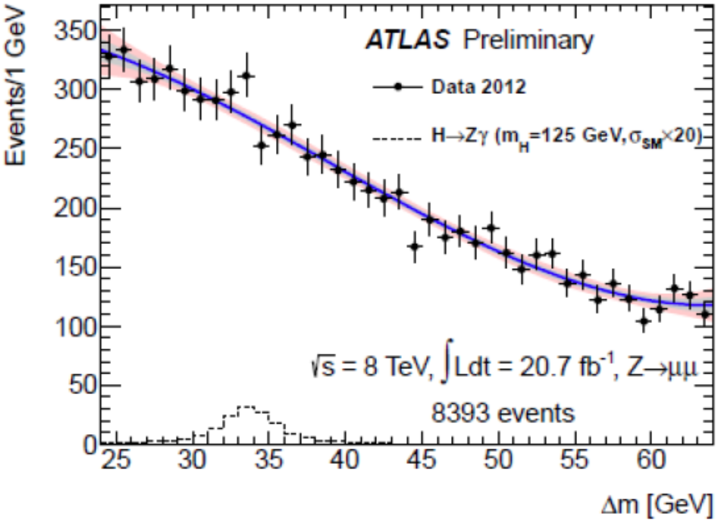
ATLAS-CONF-2013-009

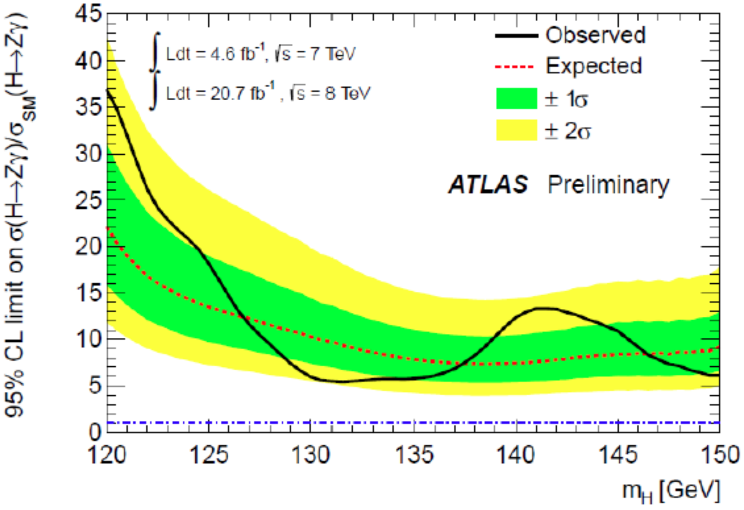
Higgs to Z + photon

Similar to diphoton channel
Loop production modes

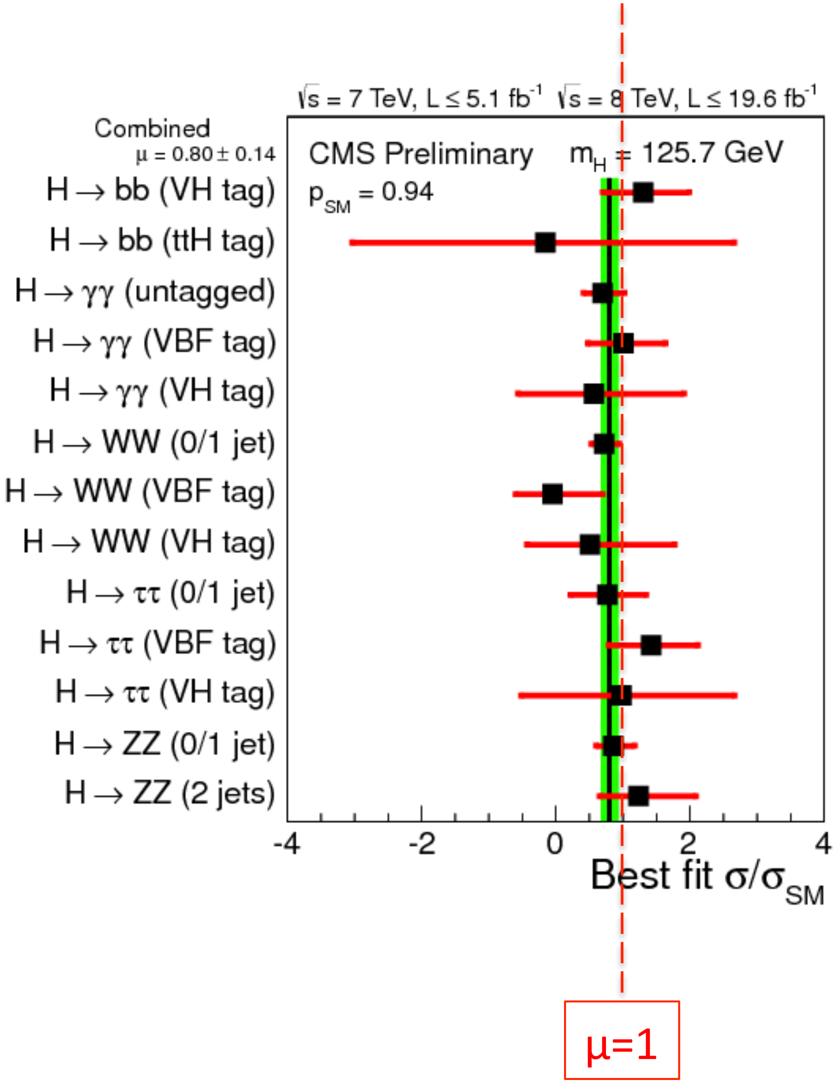
Relative rate to diphoton interesting and sensitive to BSM







Consistency of event yields (1)



Overall best-fit signal strength

μ = 0.80 ± 0.14

Sub-combinations grouped by (production tag) × (decay mode)

Consistency with the **SM Higgs**:

χ^2 / ndf = 6.2 / 13

asymptotic $P(\chi^2>6.2|ndf=13) = 0.94$

pseudo-experiments: P = 0.87

NB: VBF-tagged channels have large gg->H contributions

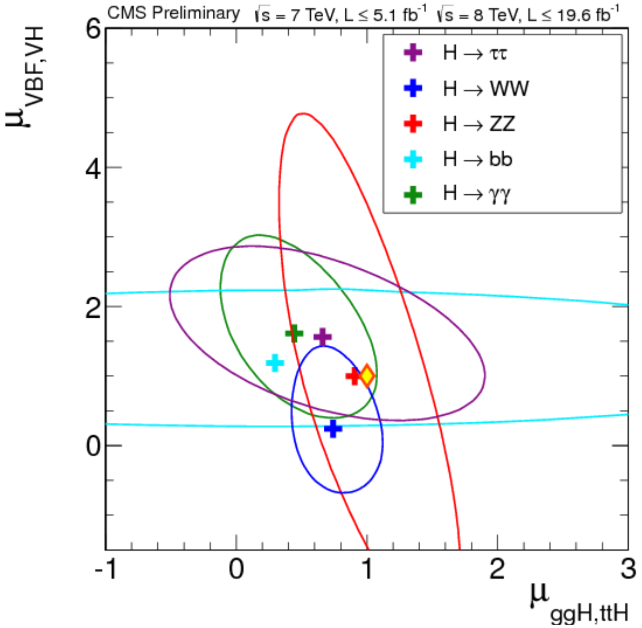
Couplings compatibility tests

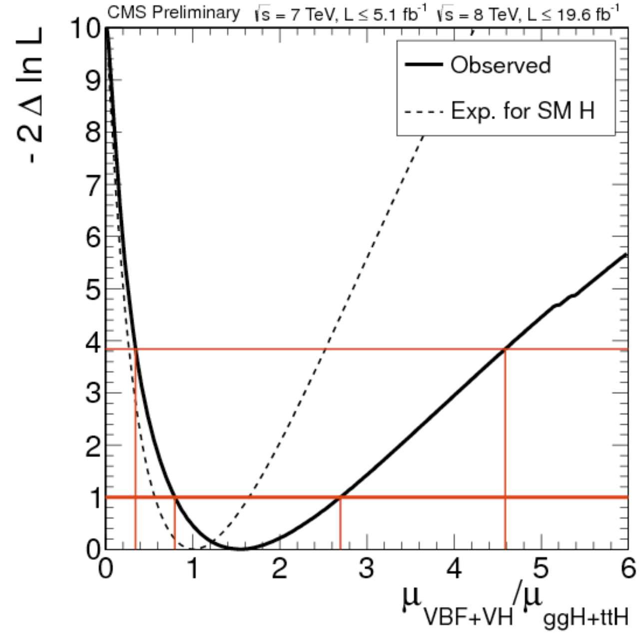
- Extraction of all 8 parameters is too early with the current data

- Instead, we go after coupling compatibility tests:
  - assume SM Higgs couplings
  - introduce **a limited number of scaling factor** for:
    - couplings (κ): $g_a = \kappa_a \cdot g_a^{\mathrm{SM}}$
    - or ratios of couplings (λ): $\left(g_a / g_b\right) = \lambda_{ab}\left(g_a^{\mathrm{SM}} / g_b^{\mathrm{SM}}\right); \quad \lambda_{ab} = \kappa_a / \kappa_b$
  - also can add and probe BR(H->BSM): $\Gamma_{\mathrm{TOT}} = \Gamma_{\mathrm{SM}} + \Gamma_{\mathrm{BSM}} = \dfrac{\Gamma_{\mathrm{SM}}}{1 - BR_{\mathrm{BSM}}}$

- **These are compatibility tests, not measurements of couplings:**
  - In SM, couplings are not free parameters
  - Any significant deviation of scaling factors from 1 would
    - imply new physics beyond SM
    - require a re-fit of event yields in the framework of particular BSM models

Consistency of event yields (3)



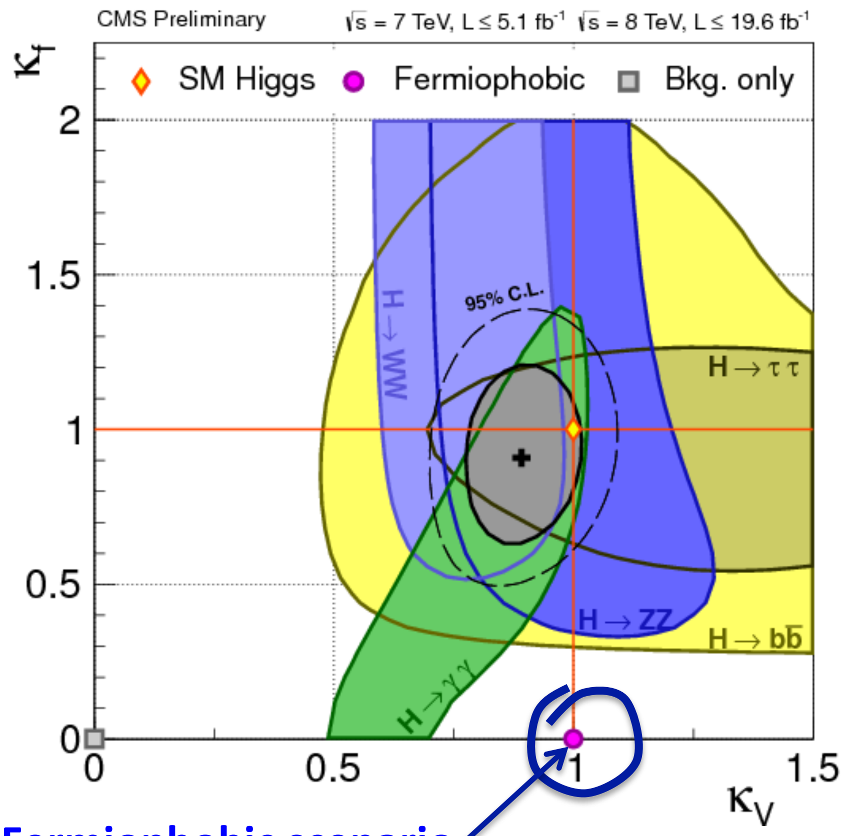


- Introduce two signal strengths **(μ_F, μ_V)** in each of the 5 decay channels:
  - μ_F scales the **fermion-coupling** induced production mechanisms (gg-fusion, ttH)
  - μ_V scales the **W/Z-coupling** induced production mechanisms (VBF, VH)

- **All channels give results consistent with the SM Higgs boson: (1,1)**

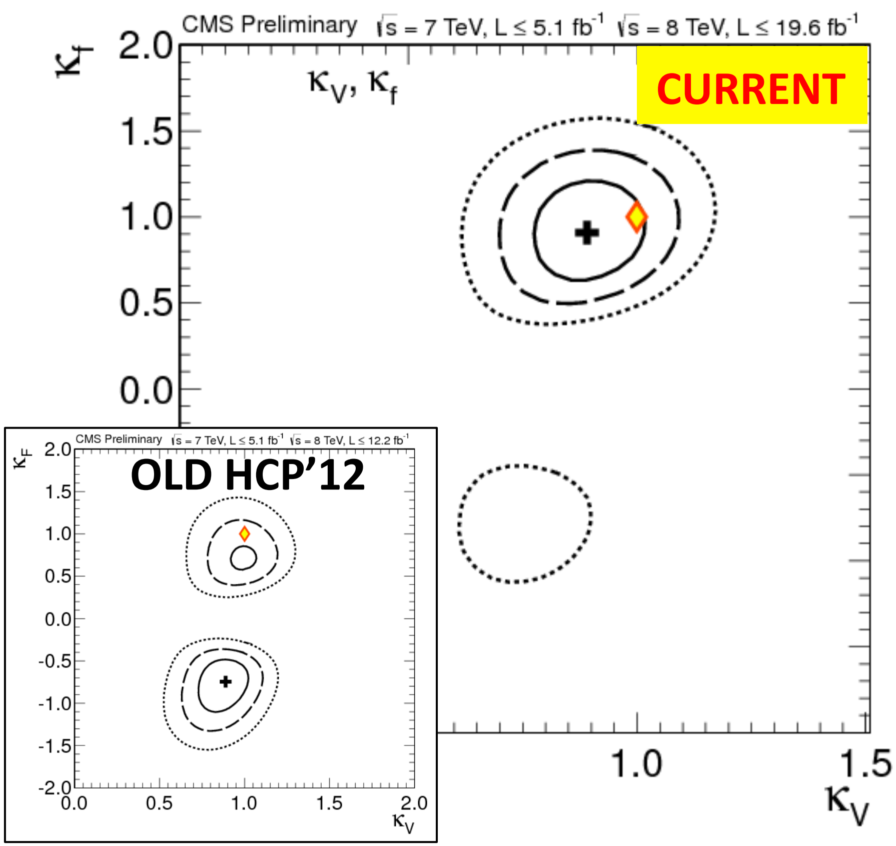
- These 2D-results obtained for individual decay channels cannot be combined: they are decoupled by independent BRs.
- But the ratios **μ_V/μ_F** can be combined as BRs cancel out in such ratios
- The need W/Z-coupling induced production mechanisms is established with >3σ significance

Two parameters: κ_V and κ_F



Fermiophobic scenario is reliably excluded

Data are consistent with (κ_V; κ_F)=(1; 1)

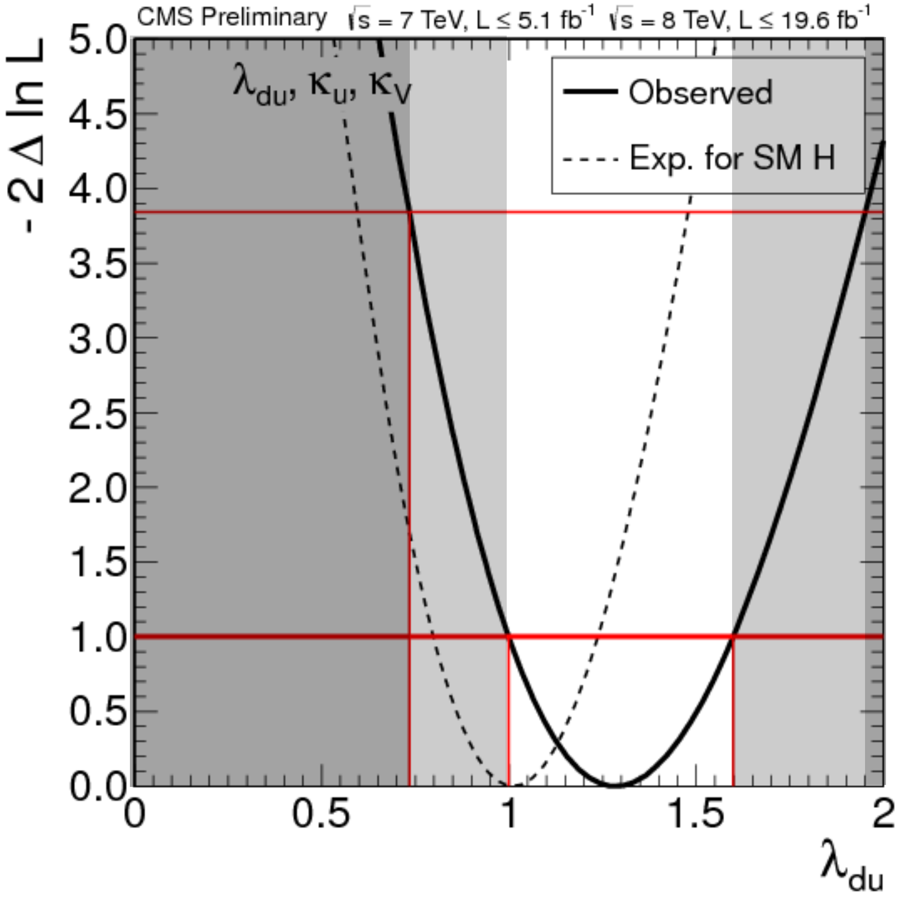


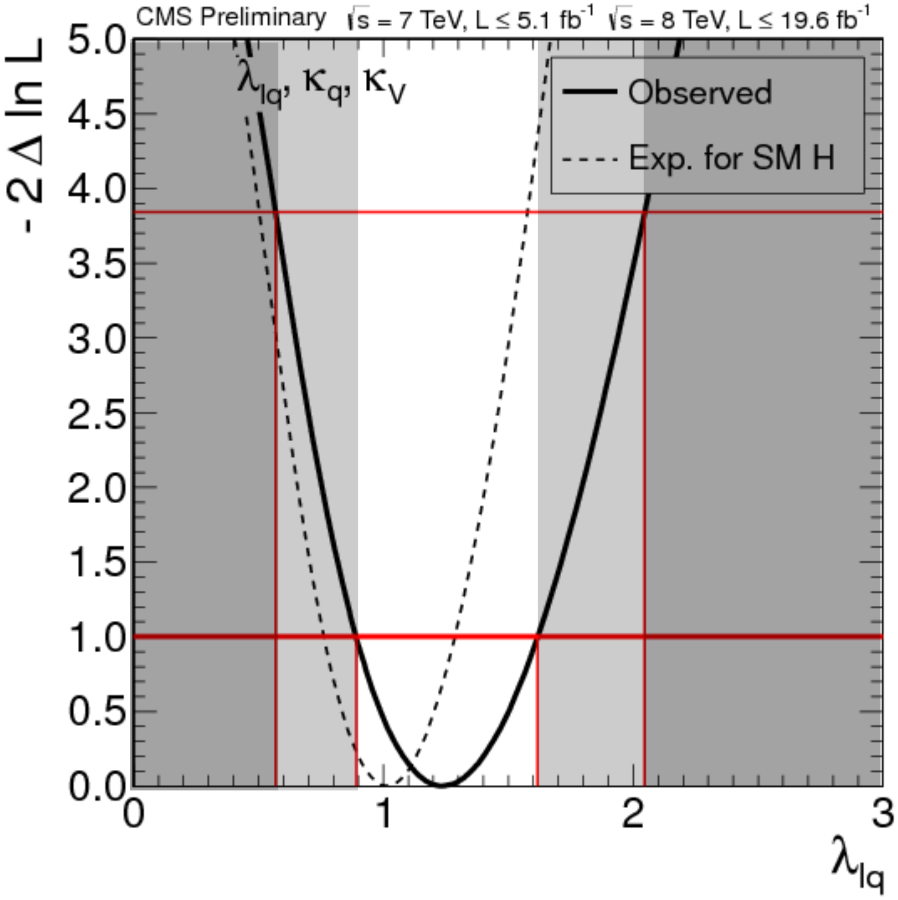
The previously seen global minimum of the likelihood in the (+; –) quadrant is gone, since the γγ-channel is no more enhanced

Asymmetry of couplings to fermions

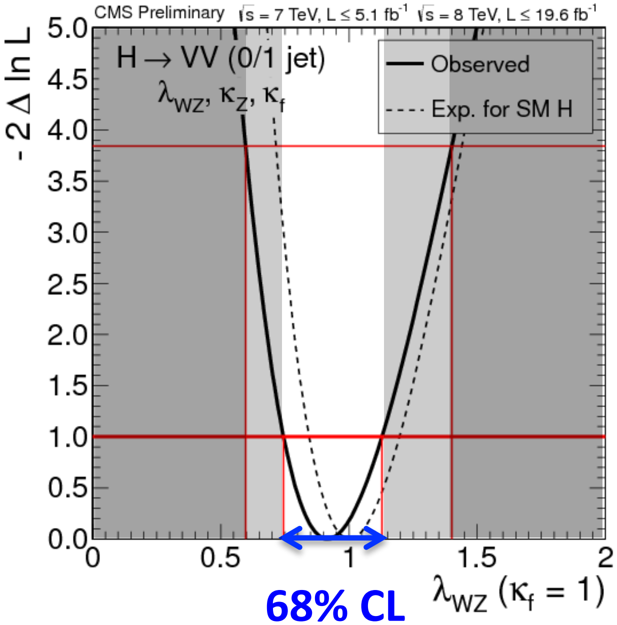
Ratio of coupling between down- and up-fermions

Ratio of coupling between leptons and quarks

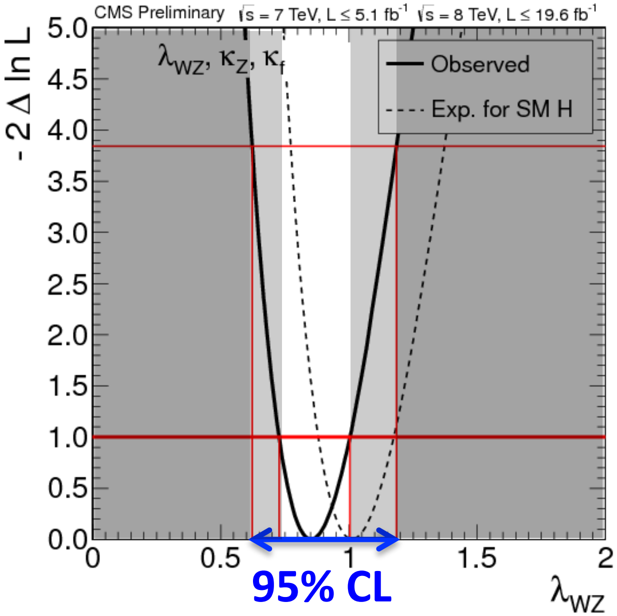




Custodial symmetry: λ_{WZ} and κ_Z (κ_F)



68% CL



95% CL

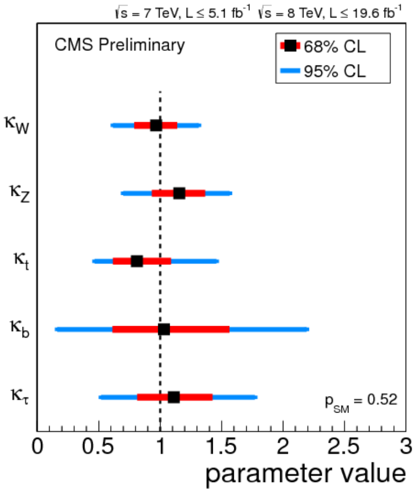
- **Custodial symmetry:** in SM, the ratio of couplings to W and Z bosons is almost not affected by loop corrections
- **Compatibility test No.1 (top plot):**
  - use **un-tagged WW and ZZ** channels
  - the ratio of signal event yields: $\sim g_W^2 / g_Z^2 = \lambda_{WZ}^2$
  - Assume SM coupling to fermions (κ_F=1); dependence on this assumption is weak
  - Fit for: λ_{WZ} and κ_Z
- **Compatibility test No.2 (bottom plot):**
  - use **all** channels
  - Assume a common scaling factor κ_F for all fermionic couplings
  - Fit for: λ_{WZ} and κ_Z, κ_F

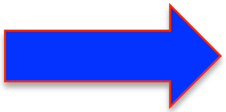
Data are consistent with the custodial symmetry

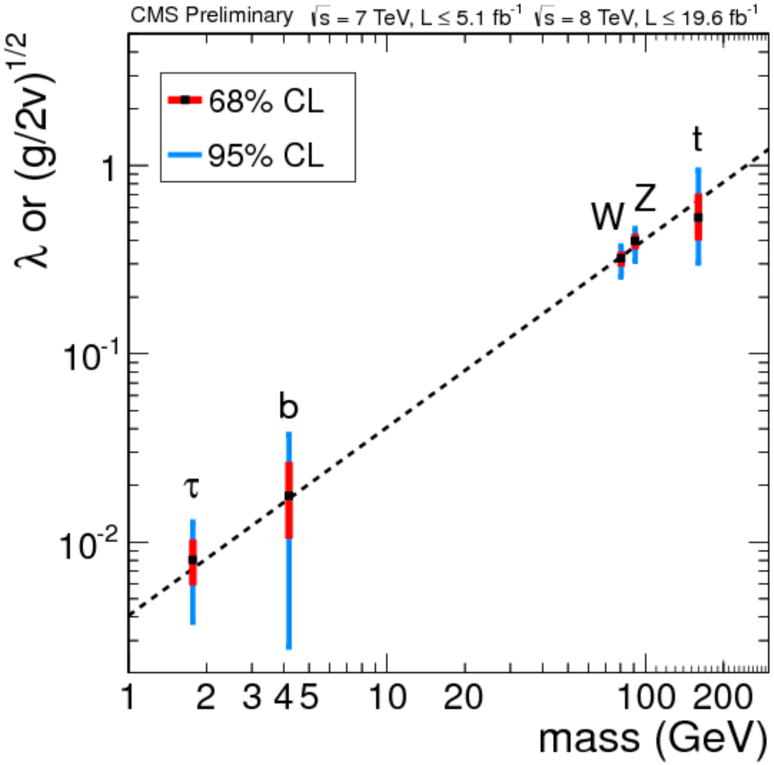
- **Further, we always use $\kappa_W = \kappa_Z$ (κ_V)**

CMS: C5 model (almost a measurement)

- Scale SM couplings by measured scale factors and plot modified couplings vs particle masses:
  - λ_f(Yukawa coupling) ~ m_f
  - $(g_V/2vev)^{0.5}$ ~ m_V







Note: the magnitude of couplings we try to assess range by a factor of 100! A test with 20+% accuracy is actually a very respectable test.

ZZ->4L J^{CP} analysis: discriminants

- Analysis considers alternative signal+background hypotheses, where signal *X* can be either gg→H or *xx* → J^{CP}
  - Construct two ME-based discriminating observables:

    where ME are complete LO matrix elements, and $m_X = m_{4\ell}$

$$KD(\mathrm{H;ZZ}) = \frac{\left|ME_{\mathrm{H}}(gg \to H \to 4\ell)\right|^2}{\left|ME_{\mathrm{ZZ}}(q\bar{q} \to 4\ell)\right|^2}$$

$$KD(J^{CP};\mathrm{ZZ}) = \frac{\left|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)\right|^2}{\left|ME_{\mathrm{ZZ}}(q\bar{q} \to 4\ell)\right|^2}$$

  - Extend KDs to include discriminating information from four-lepton mass:

$$D(H;ZZ) = \frac{\left|ME_X(xx \to H \to 4\ell)\right|^2 \cdot pdf(m_{4\ell} \,|\, m_H)}{\left|ME_{\mathrm{ZZ}}(q\bar{q} \to 4\ell)\right|^2 \cdot pdf(m_{4\ell} \,|\, ZZ)}$$

$$D(J^{CP};\mathrm{ZZ}) = \frac{\left|ME_{J^{CP}}(xx \to J^{CP} \to 4\ell)\right|^2 \cdot pdf(m_{4\ell} \,|\, m_{J^{CP}})}{\left|ME_{\mathrm{ZZ}}(q\bar{q} \to 4\ell)\right|^2 \cdot pdf(m_{4\ell} \,|\, ZZ)}$$

  - Without any loss of information, one can change “variables”:

$$D(\mathrm{H;ZZ})$$

$$D(J^{CP};\mathrm{H}) = \frac{D(\mathrm{J^{CP}};ZZ)}{D(\mathrm{H;ZZ})} = \frac{\left|ME_{J^{CP}}(xx \to \mathrm{J^{CP}} \to 4\ell)\right|^2}{\left|ME_{\mathrm{H}}(gg \to \mathrm{H} \to 4\ell)\right|^2}$$

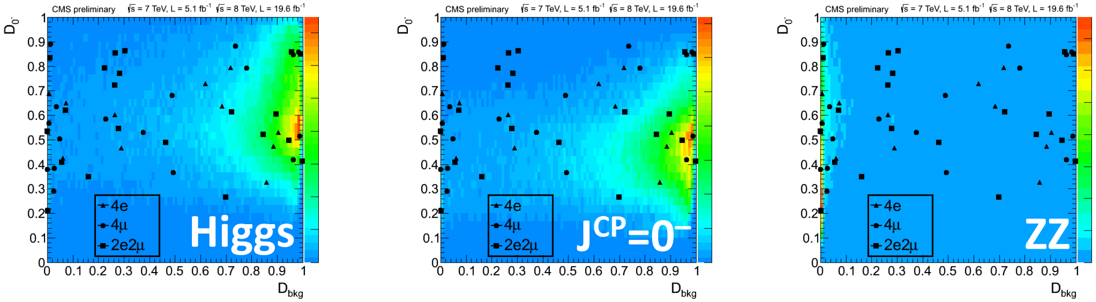
  - And again without any loss of information, compress discriminants to be between 0 and 1

$$D_{bkg} = \frac{1}{1 + const \cdot D(\mathrm{H;ZZ})}$$

$$D_{J^{CP}} = \frac{1}{1 + const \cdot D(J^{CP};\mathrm{H})}$$

ZZ->4L J^{CP} analysis: statistical analysis

- Build 2D-pdf's (templates) for different processes:



$$pdf\left(D_{bkg},\, D_{J^{CP}}\ \middle|\ \mathrm{H}\right) \leftarrow \text{from MC}$$

$$pdf\left(D_{bkg},\, D_{J^{CP}}\ \middle|\ \mathrm{J}^{CP}\right) \leftarrow \text{from MC}$$

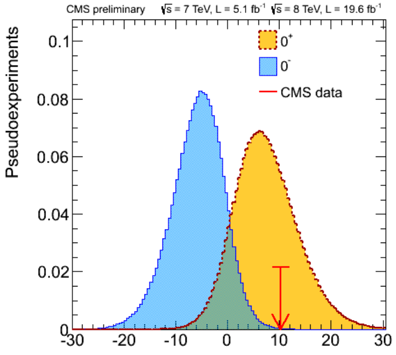
$$pdf\left(D_{bkg},\, D_{J^{CP}}\ \middle|\ ZZ\right) \leftarrow \text{from MC}$$

$$pdf\left(D_{bkg},\, D_{J^{CP}}\ \middle|\ reducible\ \text{bkg}\right) \leftarrow \text{from control region}$$

- Weigh templates by event rates to construct expected 2D-distributions for alternative signal+background hypotheses:
  - ZZ event rate: from MC
  - reducible background event rate: from control region
  - H and J^{CP} signal event rate: from two fits to data

$$\frac{\partial^2 N}{\partial D_{bkg} \partial D_{J^{CP}}}$$

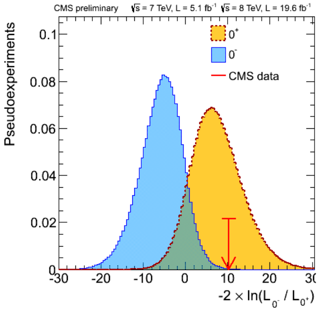
- Using 2D event distributions for alternative hypotheses, construct the usual log-likelihood-ratio test statistic and perform statistical analyses by generating pseudo-observations



$$q = -2\ln\frac{L\left(\text{observation}\ \middle|\ J^{CP} + bkg\right)}{L\left(\text{observation}\ \middle|\ H + bkg\right)}$$

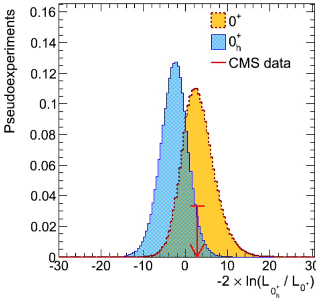
ZZ->4L J^{CP} analysis: results

$0^- \text{ vs } H$



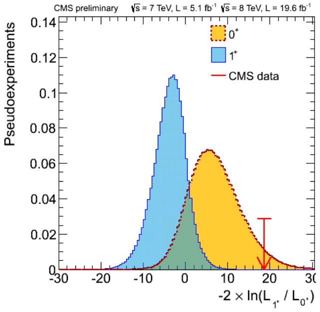
$CL_s = 0.0016$
excluded

$0_h^+ \text{ vs } H$



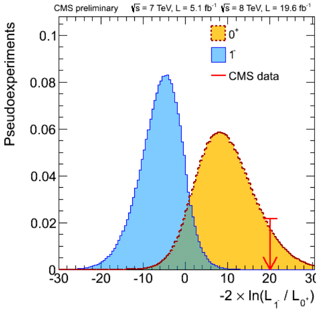
$CL_s = 0.081$
not yet

$q\bar{q} \to 1^- \text{ vs } H$



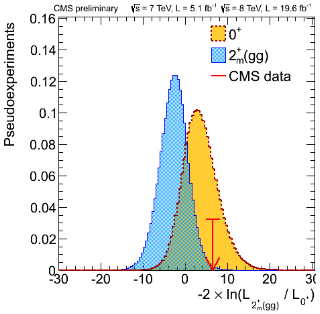
$CL_s < 0.001$
excluded

$q\bar{q} \to 1^+ \text{ vs } H$



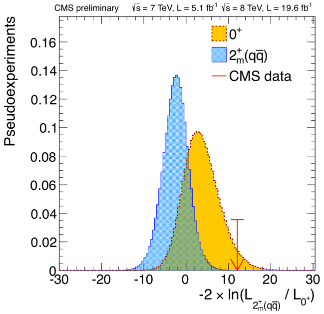
$CL_s < 0.001$
excluded

$gg \to 2_m^+ \text{ vs } H$



$CL_s = 0.015$
excluded

$q\bar{q} \to 2_m^+ \text{ vs } H$

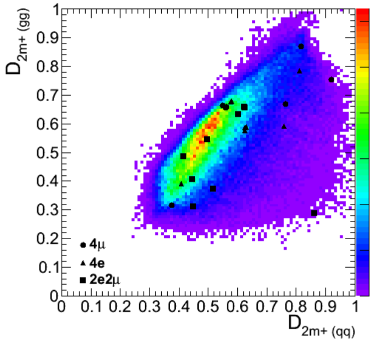


$CL_s < 0.001$
excluded

$$CL_S = \frac{P\left(q \geq q^{\text{obs}} \;\middle|\; J^{CP} + bkg\right)}{P\left(q \geq q^{\text{obs}} \;\middle|\; H + bkg\right)}$$

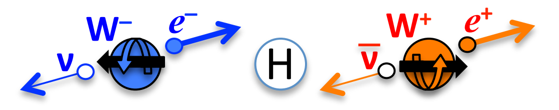
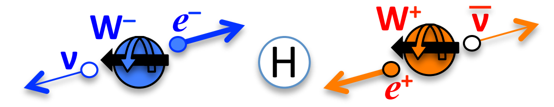
The observed test statistic value is

- consistent with the SM Higgs boson in all J^{CP} tests
- off the “SM Higgs median” in the same direction for all tests:
  - manifestation of correlations between kinematic properties of alternative J^{CP} bosons
  - CMS data “statistically lucky”: observed limits are a bit stronger than expected



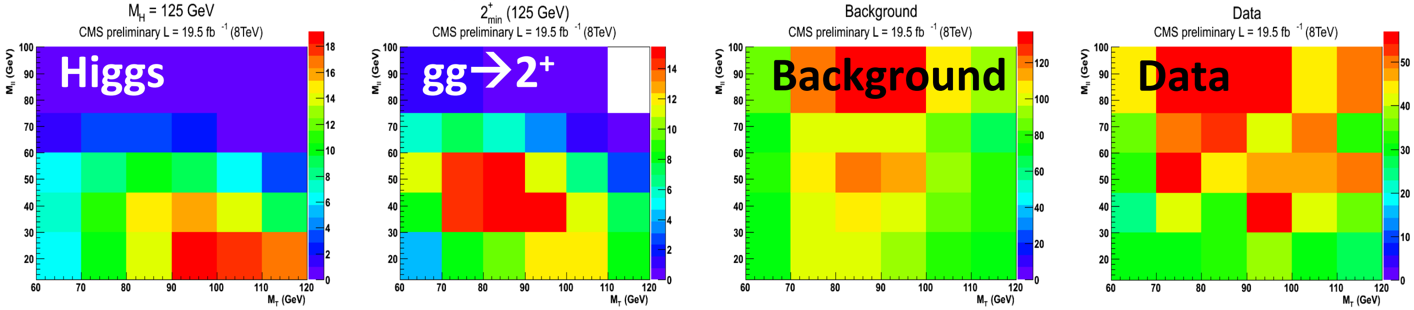
WW->2l2ν J^{CP} analysis

- Full event reconstruction is not possible, but:

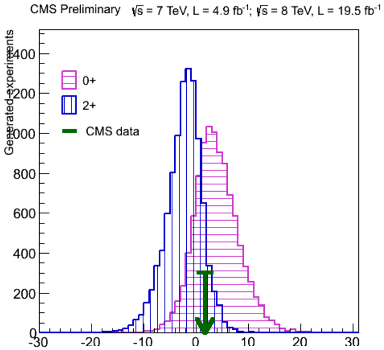
spin-0	leptons tend to go in one direction: **small m_{ll}**	
	neutrinos – in the other direction: **large MET**	
spin-2	leptons tend to go in opposite directions: **larger m_{ll}**	
	neutrinos also go in opposite directions: **smaller MET**	

- To test for alternative signal+background hypotheses, we build 2D-distributions

$$\frac{\partial^2 N}{\partial m_{\ell\ell}\,\partial E_T^{\text{mis}}}$$



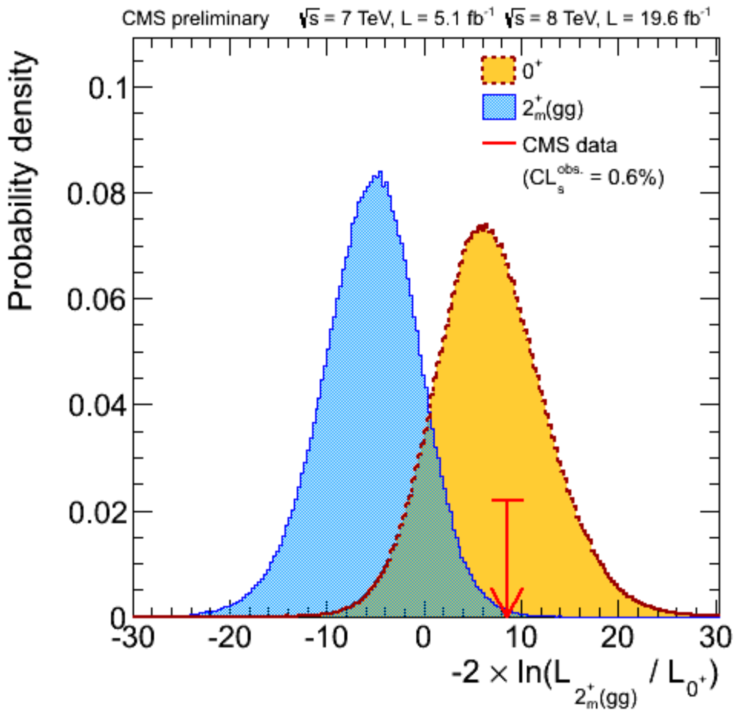
- Using 2D event distributions for alternative hypotheses, construct the usual log-likelihood-ratio test statistic and perform statistical analyses by generating pseudo-observations
  - **Observed CL_s=0.14** (data disfavor 2^+, but exclusion at 95% CL cannot be claimed)
  - Observed test statistic is **consistent with the SM Higgs boson**
  - Observed test statistic is off "SM H median expected" to the left ("unlucky fluctuation")



$$q = -2\ln\frac{L(\text{observation} \mid 2^+ + bkg)}{L(\text{observation} \mid H + bkg)}$$

ZZ+WW gg→2^+_m combination

	Expected 1-CL_s	Observed 1-CL_s
ZZ	93.1%	98.6%
WW	91.9%	86.0%
Combination	**98.8%**	**99.4%**



- ZZ and WW have similar sensitivities, 1- CL_s = 92%-93%
- **In combination, gg→2^+_m is excluded at 99% CL**