SM Higgs boson at LHC

Marumi Kado and Andrey Korytov

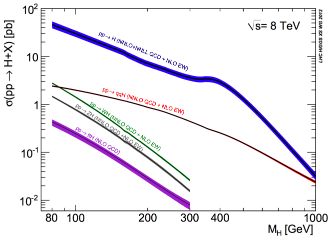
ÉCOLE DE PHYSIQUE
LES HOUCHES

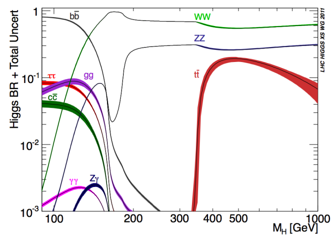
4 June 2013

Today's question: is X125 the SM Higgs boson?

- July 4, 2012 (5+5 fb^{-1}): **Discovery of the X125 boson**
  - Discovery of a new boson with mass near 125 GeV in **a combination** of multiple SM Higgs boson search channels…
- Today's question (5+20 fb^{-1}): **Properties of the X125 boson**
  - Status of **individual** SM Higgs boson search channels with more data
  - What is the mass and width of X125?
  - Compatibility of event yields with the SM Higgs boson
    - recast the event yields into measurements of **couplings**
    - unravel individual **(production)×(decay) cross sections**
    - indirect and direct limits on **non-SM like decays**
  - Spin-parity properties
  - Is X125 one particle?
- Today's experimenter's wish list

Summary 1: Current search channels at low mass



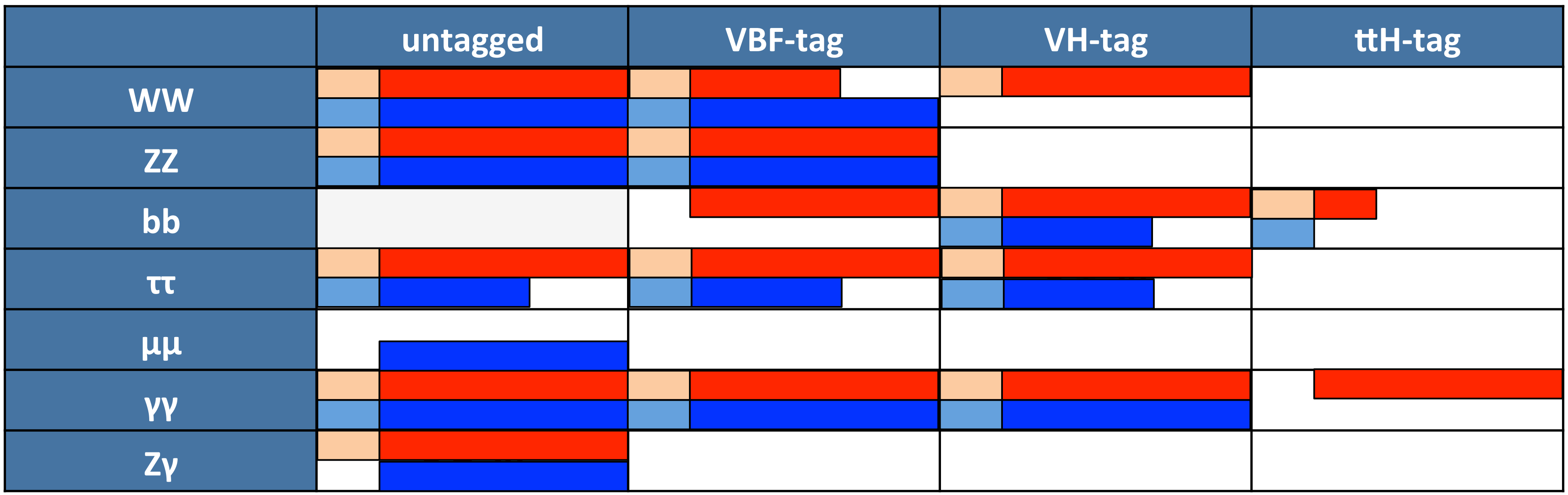


CMS

- 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}

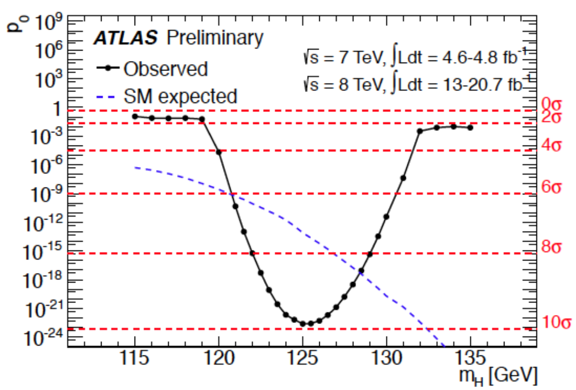


BEWARE: Tags are never pure; e.g. VBF-tags can have 20%-80% of ggF, depending on analysis

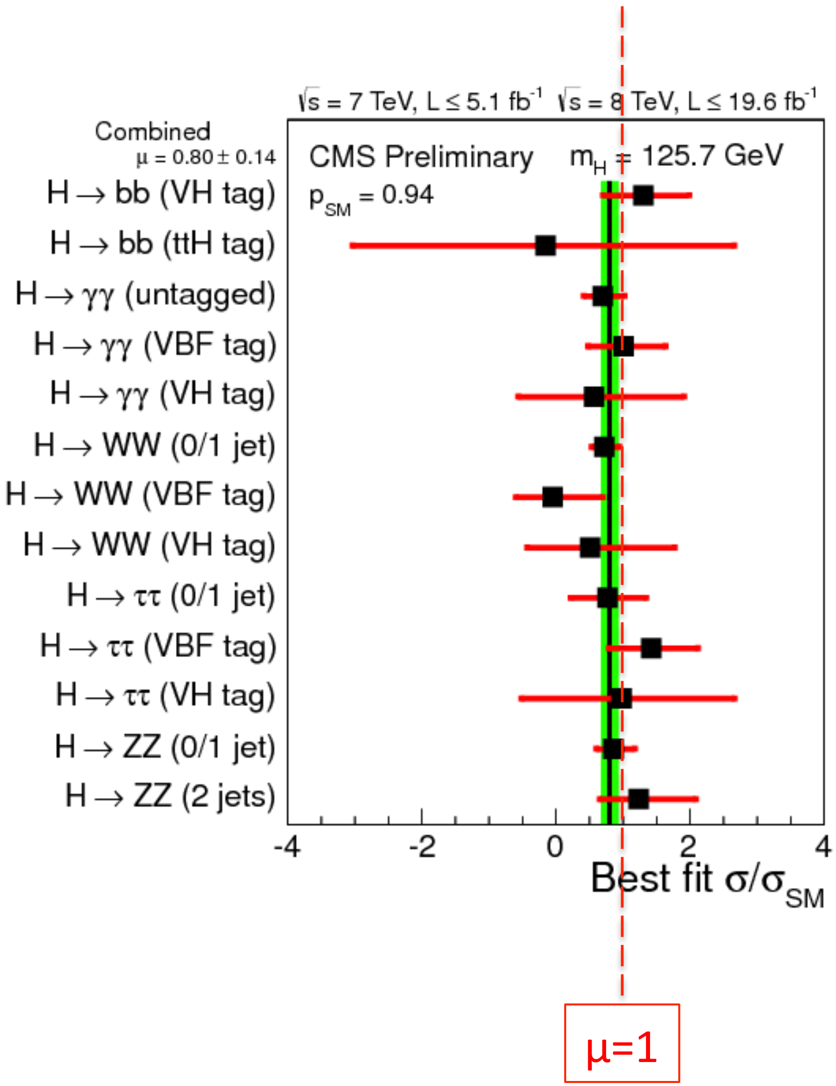
Summary 2: Significance of the excess near 125 GeV

	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**	2.1	**2.1**	
combined	7.3	**10**	stopped computing		

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



Summary 3A: Consistency of event yields with SM Higgs



Overall best-fit signal strength

μ = 0.80 ± 0.14

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

Consistency with the **SM Higgs**:

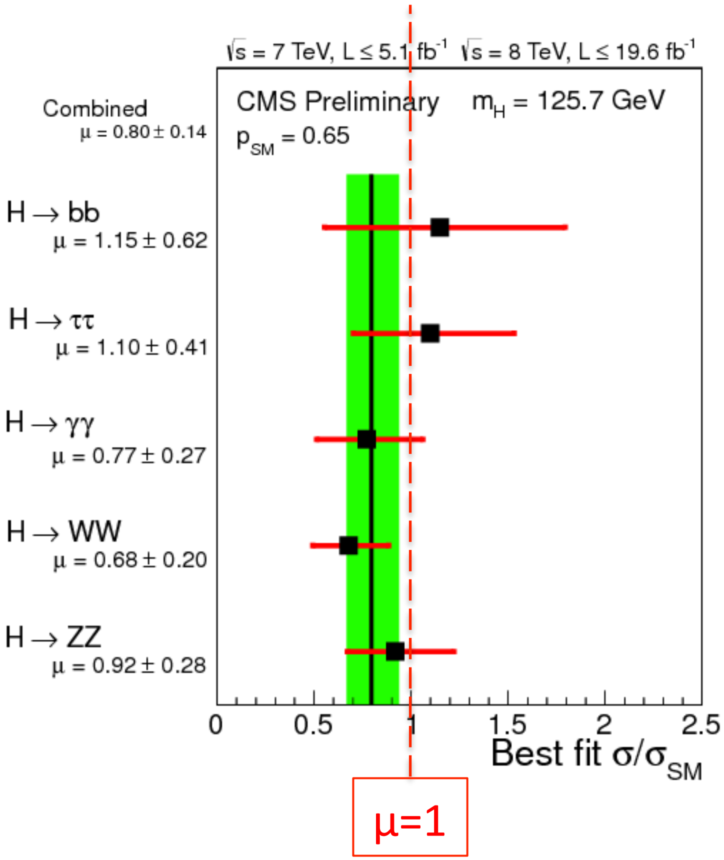
χ^2 / ndf = 6.2 / 13

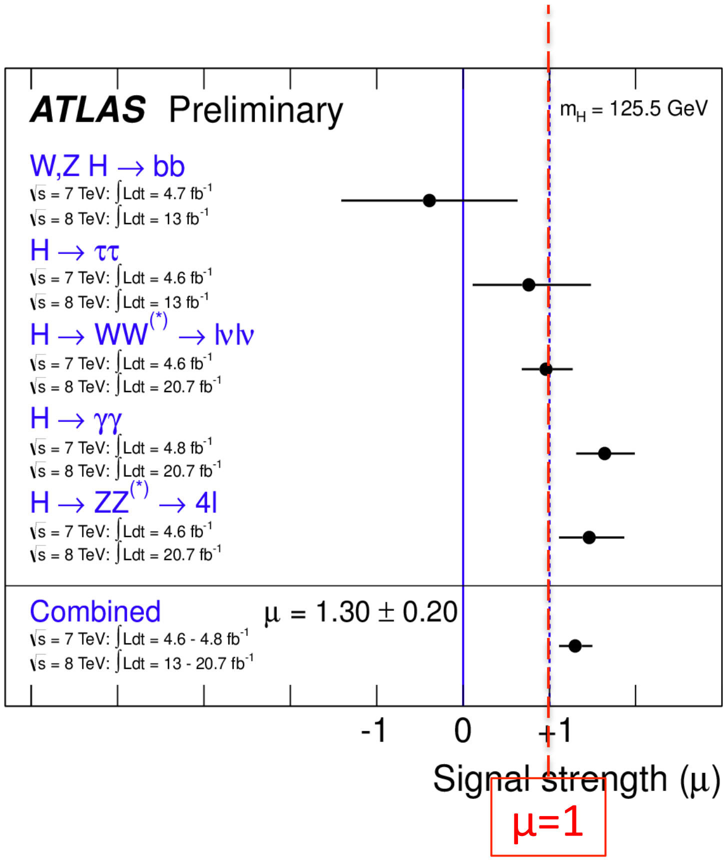
asymptotic $P(\chi^2 > 6.2 | ndf = 13) = 0.94$

pseudo-experiments: P = 0.87

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

Summary 3B: Consistency of event yields with SM Higgs





CMS best-fit signal strength

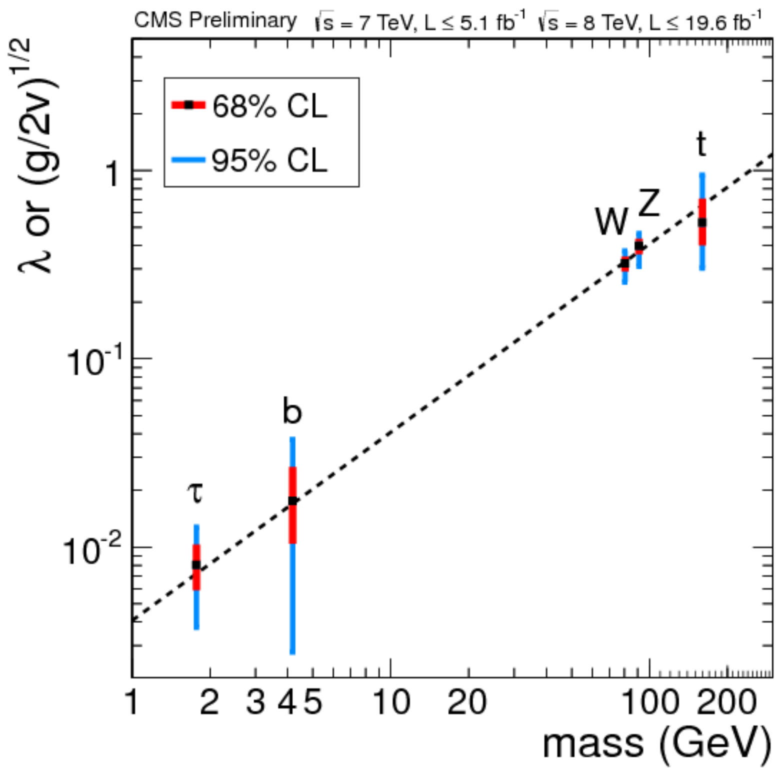
μ = 0.80 ± 0.14

ATLAS best-fit signal strength

μ = 1.30 ± 0.20

Summary 4: Current sensitivities for couplings

- Recast event yields into **SM Higgs boson couplings with no extra degrees of freedom**



Points to note:

- **X125 seems to couple to W, Z, t, b, τ very much like the SM Higgs boson**
- **Current precision of the coupling measurements: 20% (W & Z), 25% (t), 30% (τ), 60% (b)**
- **Beware: these "measurements" have STRONG correlations**

Summary 5: Current sensitivities for signal strength

- Current cross section sensitivities: **±δμ × (SM Higgs boson CS)**
- When ATLAS and CMS sensitivities are available, the best one is shown
- Majority will improve as **sqrt(1/data)**, assuming no changes in the analysis
- Circled channels will improve much faster (good S:B, but very small S)

	ggF	VBF	VH	ttH
WW	**±0.4**	**±0.7**	**±1.5**	
ZZ	**±0.5**	**±2.4**		
bb		**±1.4** (20 fb^{-1})	**±0.5**	**±2.5** (10 fb^{-1})
ττ	**±0.5**	**±0.6**	**±1.5**	
μμ	±4 (21 fb^{-1})			
γγ	**±0.4**	**±0.9**	**±1.3**	**±2.5** (20 fb^{-1})
Zγ	±6			

Points to note:

- **We can provide a few very meaningful (δμ<0.5) measurements of individual (production)×(decay) cross sections**
- **Quite a few more will open up in the next LHC run (2015-2017): ≈14 TeV, 100 fb^{-1}**

	ggF, VBF	VH	ttH
lumi	× 4		
signal cross section	× 2.5	× 2	× 5
signal events	**× 10**	**× 8**	**× 20**

Summary 6: Alternative spin-parity states

CL_s values for testing J^{CP} state hypotheses vs SM-like Higgs boson

- (light orange) $CL_s < 0.05$
- (red) $CL_s < 0.01$

	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		
~~$gg \to 2^+_m$~~		0.015	0.04	0.006	0.007	0.182	0.05	<0.001
~~$qq \to 2^+_m$~~		<0.001			0.12	~3σ (?)	0.01	<0.001
$gg \to 2^-$						0.116		

Example:
Spin-0 Lagrangian
(lowest dimension terms)

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

κ_1: Higgs; κ_2: 0^+_h; κ_3: 0^-

A few highlights

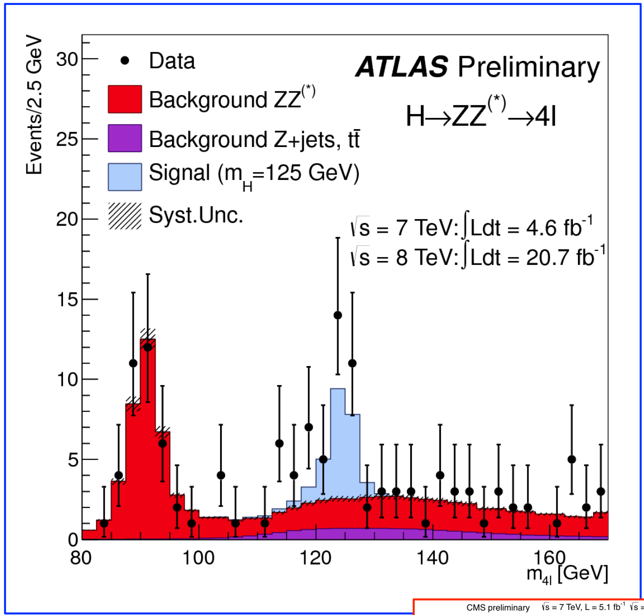
- **Main five channels (should be measurable with >2σ now):**
  - **H→ZZ(4l)**
  - **H→γγ**
  - **H→WW(lνlν)**
  - **H→ττ**
  - **VH, H→bb**

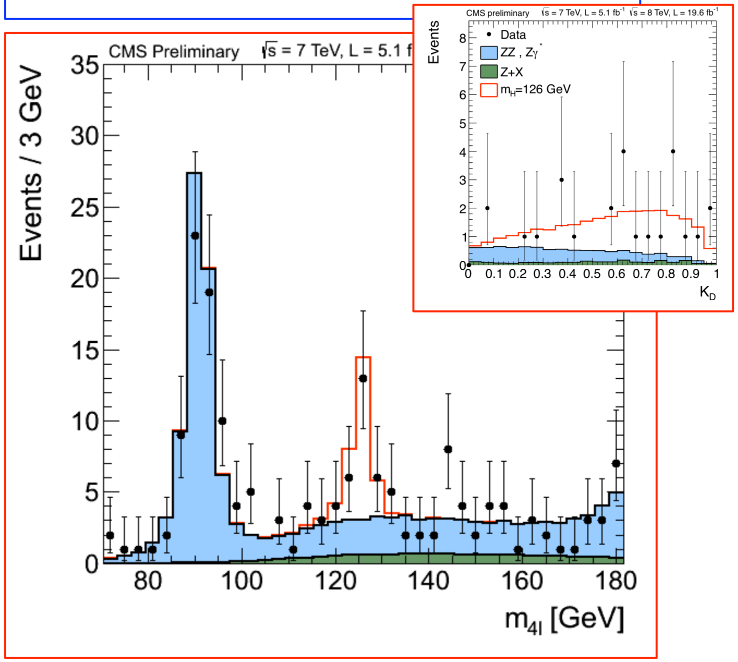
(H→ZZ(4l), H→γγ → mass measurements; H→ZZ(4l), H→γγ, H→WW(lνlν) → spin-parity measurements)

- Results for less sensitive channels are in back-up slides
  - H→Zγ (loop)
  - H→μμ (2nd gen *f*)
  - ttH, H→bb
  - ttH, H→γγ
  - VBF H→bb

(H→Zγ, H→μμ → potential for BSM physics discovery (if observed too early); ttH, H→bb and ttH, H→γγ → will be important for top-quark coupling measurements independent from gluon fusion)

$H \rightarrow ZZ \rightarrow 4l$

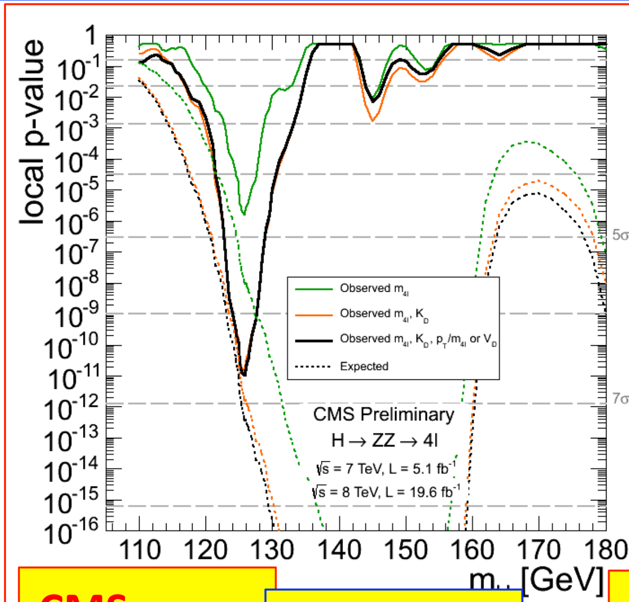


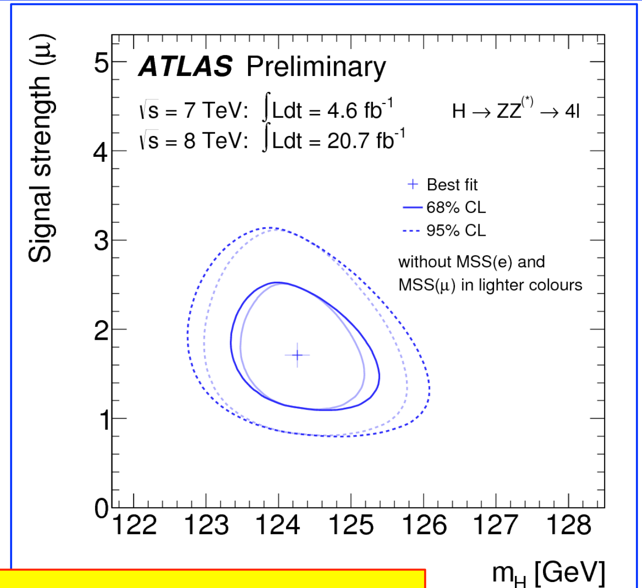


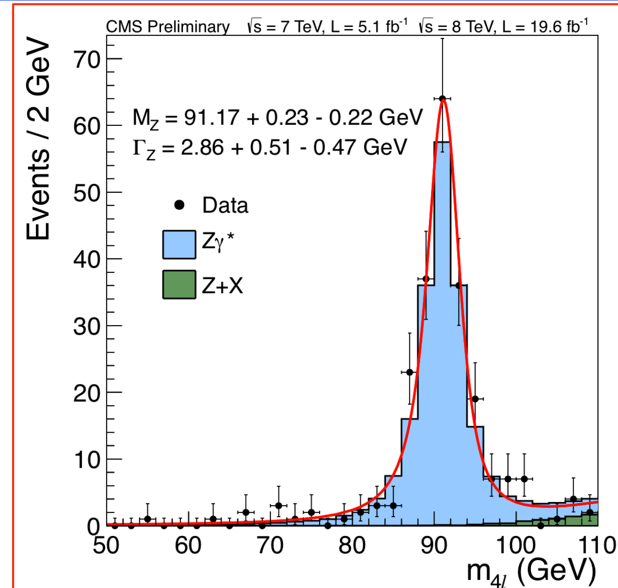
- **Analysis strategy:**
  - four prompt leptons (low p_T is important!)
  - **four-lepton mass** is the key observable
  - split events into 4e, 4μ, 2e2μ channels:
    - different mass resolutions
    - different S/B rates (for reducible bkgd with "fake" leptons)
  - CMS: add **ME-based discriminant 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 (about 2:1)
  - but small event yield (about 20 events)
  - good 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
$\mu = 1.7^{+0.5}_{-0.4}$

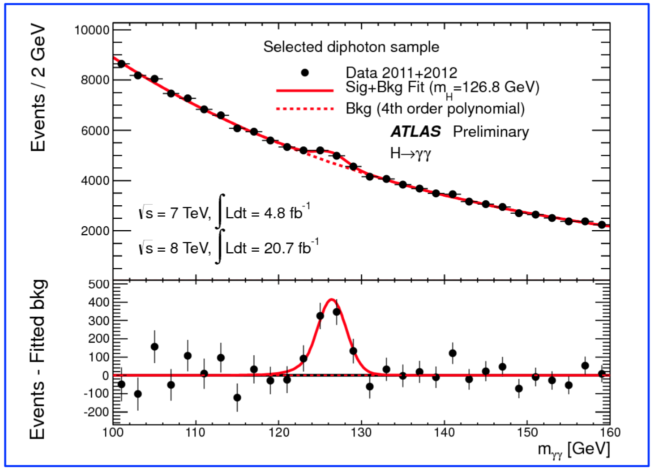
CMS
Z→4l standard candle
$m_Z = 91.2 \pm 0.2$ GeV
$\Gamma_Z = 2.9 \pm 0.5$ GeV

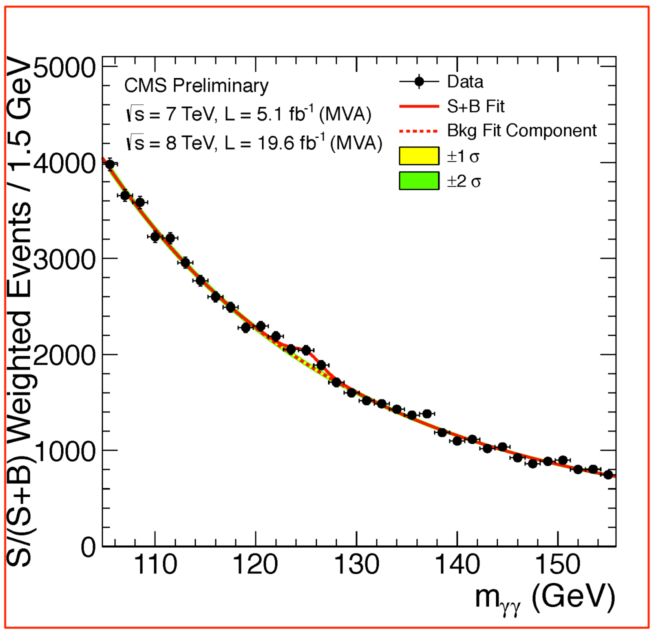
Points to note:

- **>5σ in one decay mode**
- signal strength is about equal to the expected
- 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
- ZZ→4l channel provides now the **most accurate mass measurement**
- Z→4l standard candle allows one to validate the mass measurements

ATLAS-CMS consistency
- Δm: 1.7σ
- Δμ: 1.6σ

H → γγ

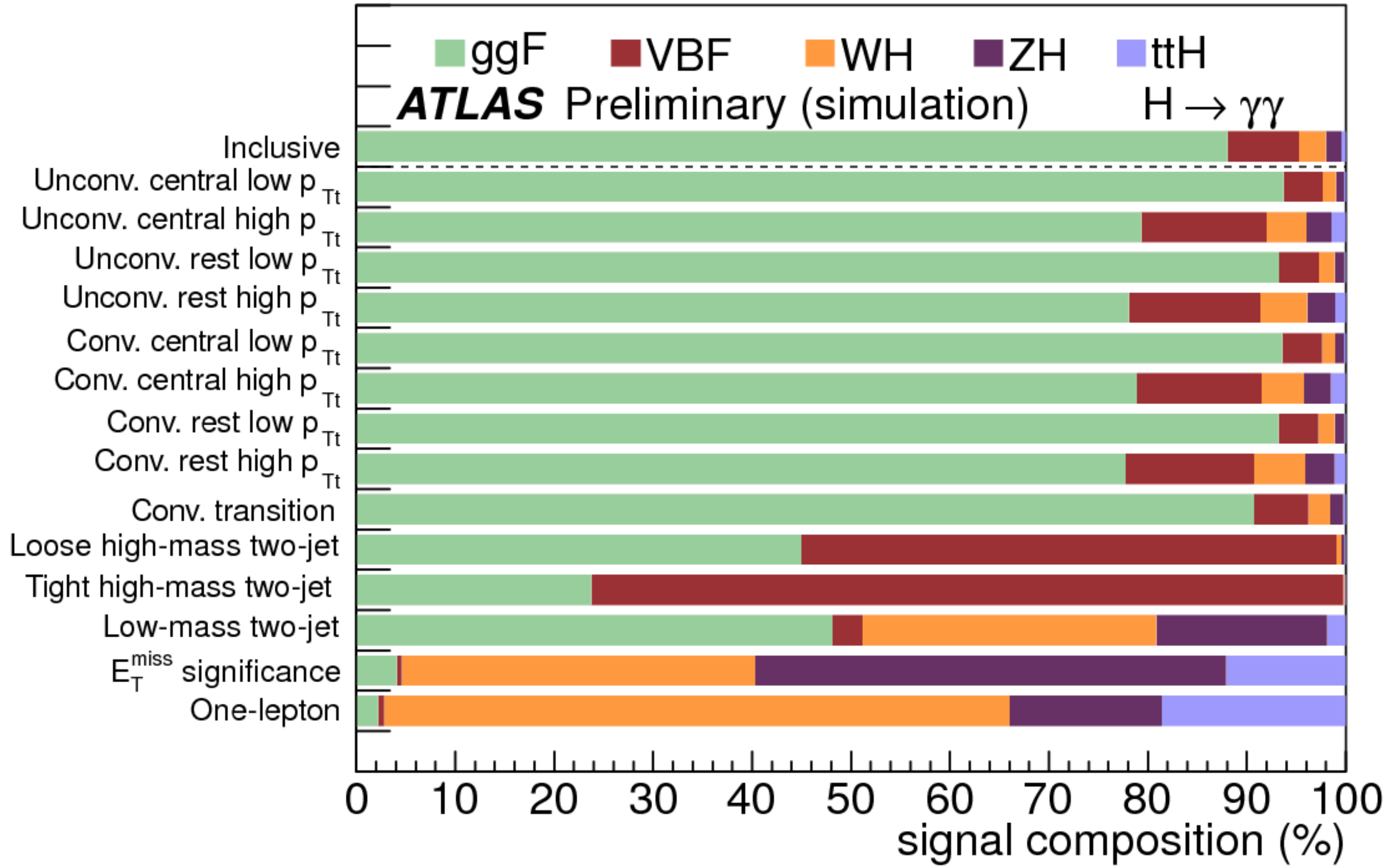




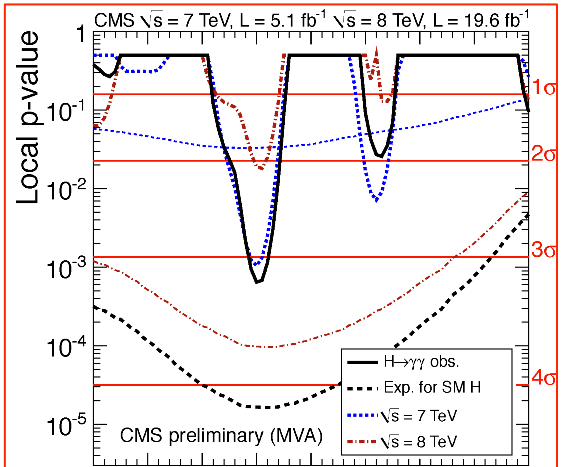
- **Analysis strategy:**
  - two isolated high-p_T photons → $m_{\gamma\gamma}$
  - vertex
    - CMS: from recoiling charged particles
    - ATLAS: from photon pointing (longitudinal ECAL segmentation)
  - **di-photon mass** is the key observable
  - split events into exclusive categories:
    - untagged, 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

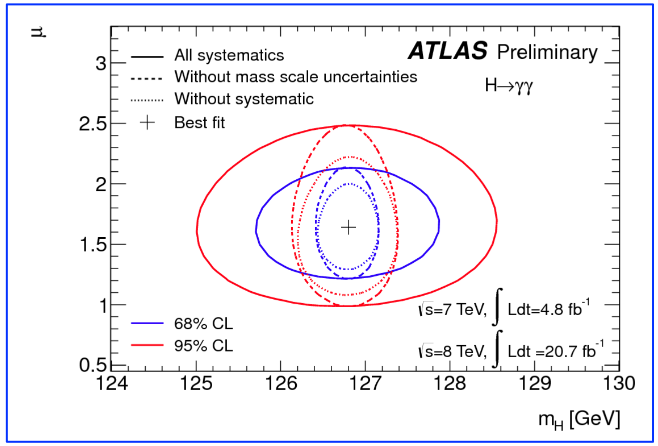
- **Analysis features to note:**
  - bad S/B-ratio (1:20)
  - but high event yield (500 events vs 20 for ZZ->4l)
  - good mass resolution = 1-2%

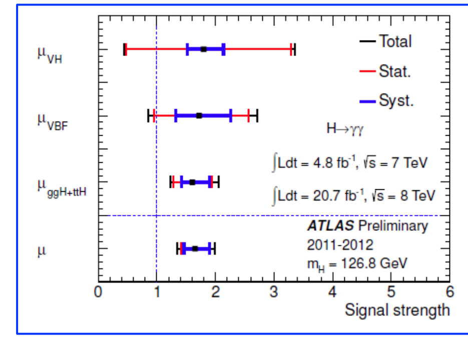
Word of caution: purity of tags

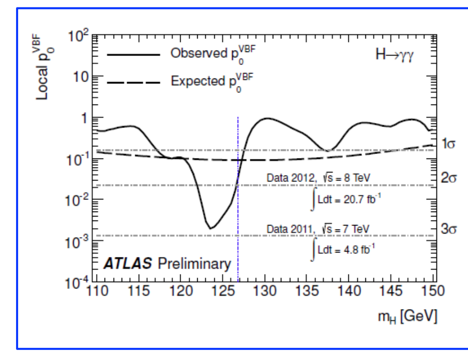


H → γγ: results









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

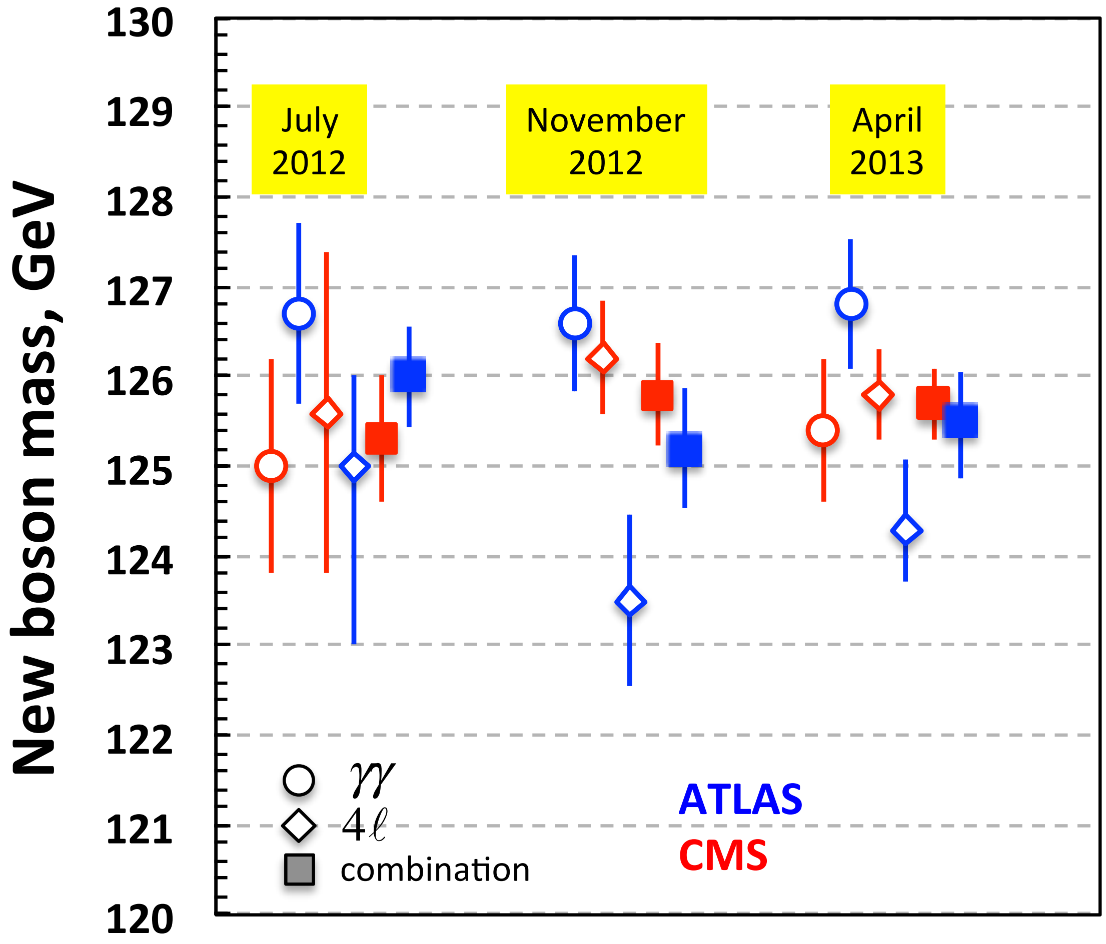
ATLAS
m_X = 126.8 ± 0.7 GeV
μ = 1.65 ± 0.33

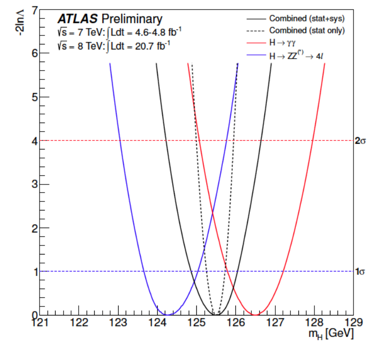
ATLAS-CMS consistency
- Δm: 1.3σ
- Δμ: 2.0σ

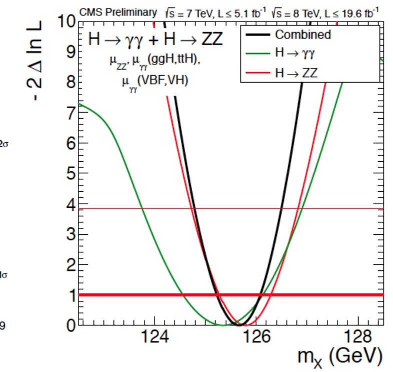
Points to note:

- 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





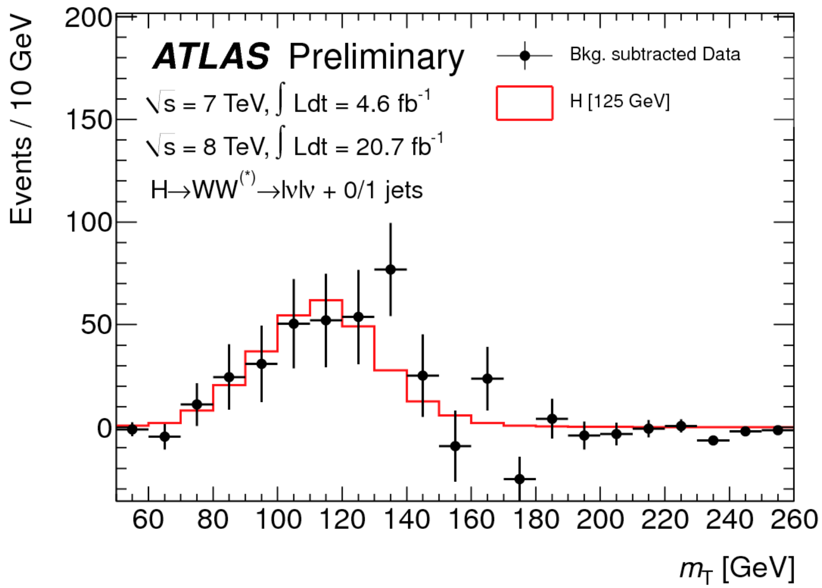


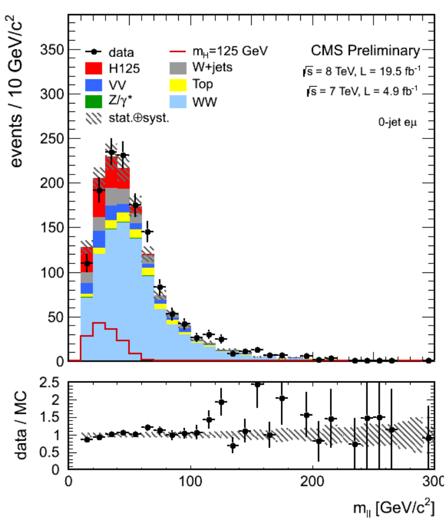
ATLAS: 125.5 ± 0.6 GeV
CMS: 125.7 ± 0.4 GeV

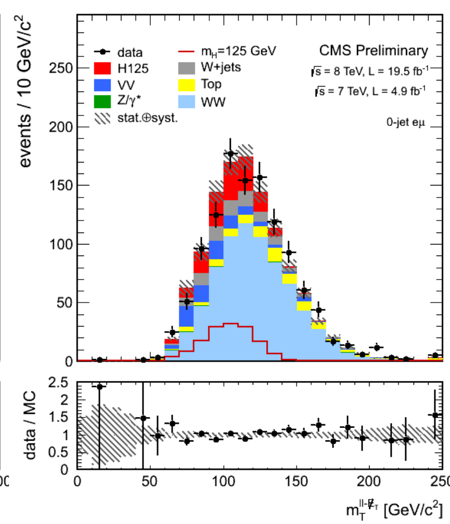
Points to note:

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

H → WW → lνlν



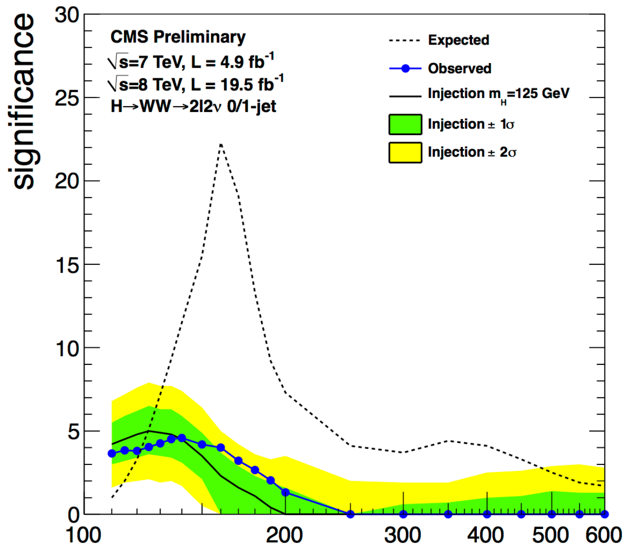




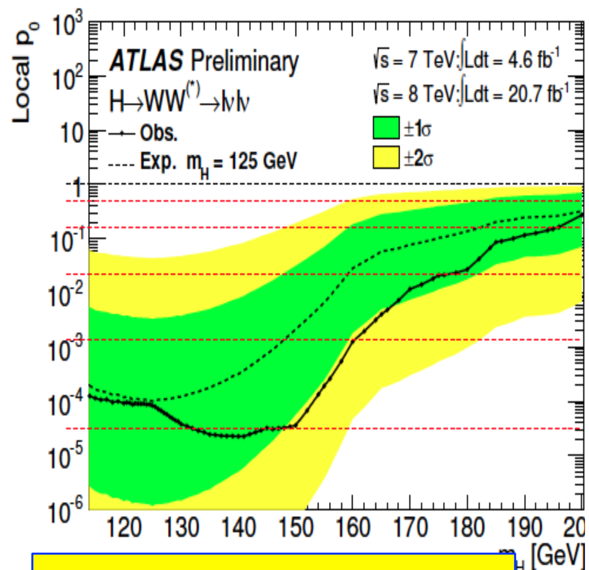
- Analysis strategy:
  - two prompt high-p_T leptons
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !
  - **ATLAS: m_T-distribution**
  - **CMS:**
    - Different-flavor: **2D distribution N(m_T, m_{ll})**
    - 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):**
  - fair S/B-ratio (>1:10)
  - fair signal event yield (200 events)
  - poor mass resolution ≈20%

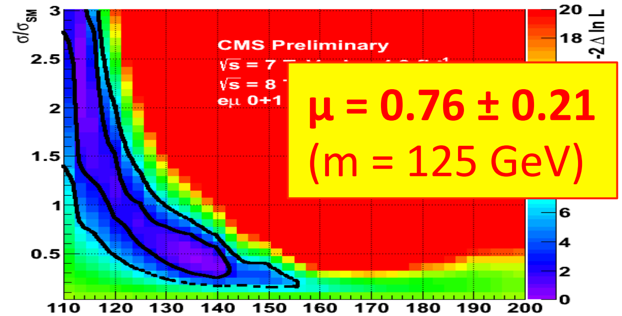
H → WW → lνlν: results



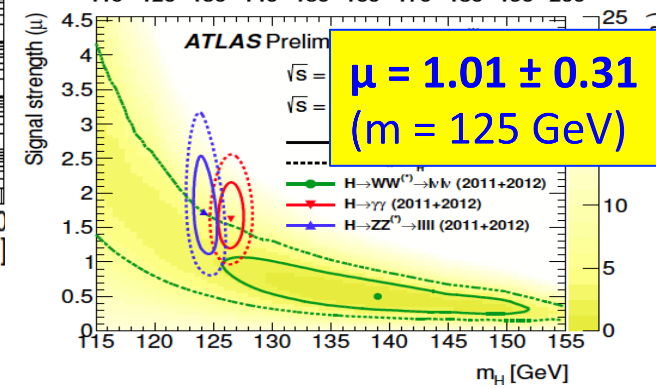
(m = 125) Z_{obs} = 4.0 σ
Z_{exp} = 5.0 σ



(m = 125) Z_{obs} = 3.8 σ
Z_{exp} = 3.7 σ



μ = 0.76 ± 0.21
(m = 125 GeV)

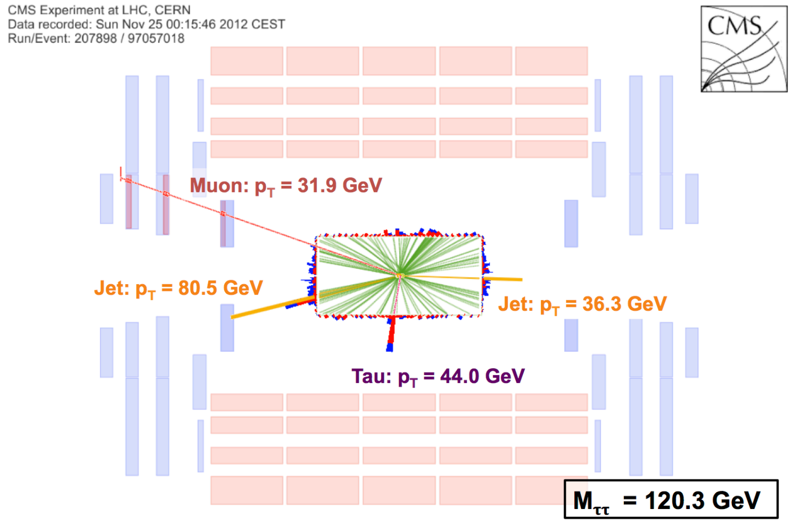


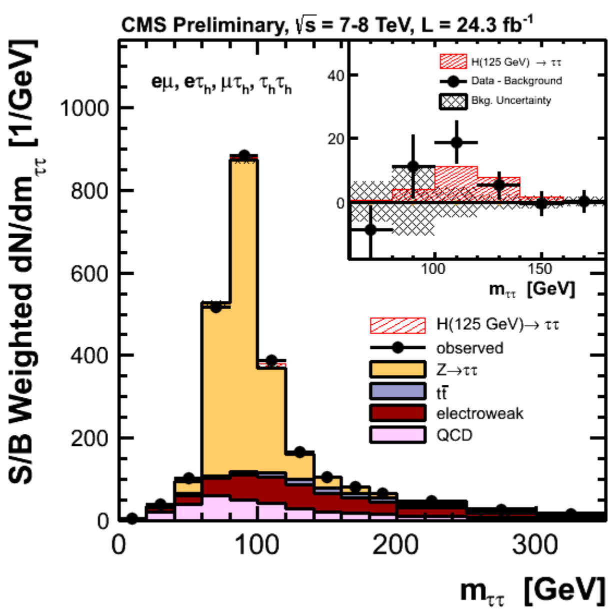
μ = 1.01 ± 0.31
(m = 125 GeV)

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

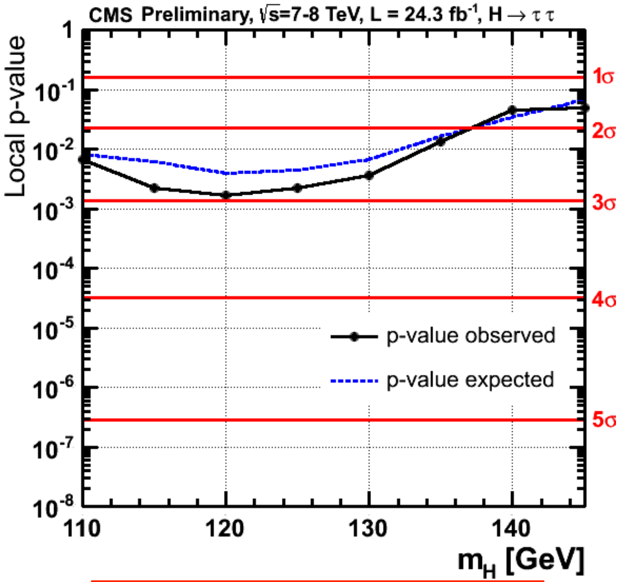




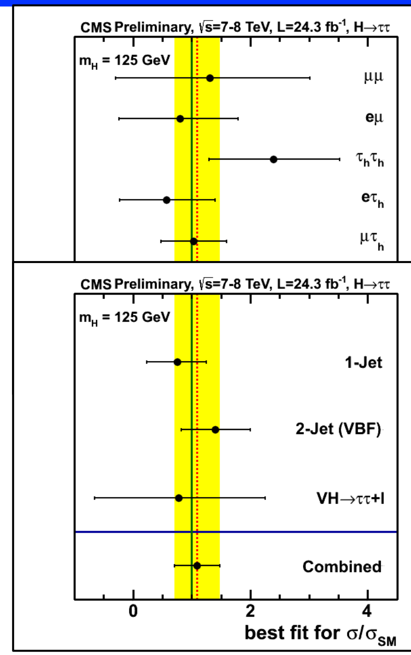
- Analysis strategy:
  - di-tau candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
  - MET
  - **DiTau mass (including MET)**: key distribution
  - split events into jet categories:
    - **2-jets (VBF-tag)**: best S/B-ratio
    - **1-jet (ggF, VH)**: acceptable S/B-ratio
    - untagged: 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 (1:40)
  - small signal event yield
  - Higgs is on the falling slope of Z-decays (bad!)
  - poor mass resolution ≈15%

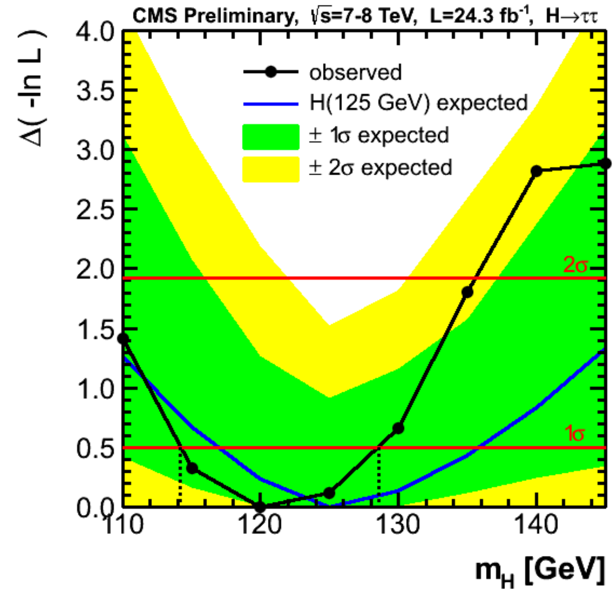
H → ττ: CMS results



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



μ = 1.1 ± 0.4
(m = 125 GeV)



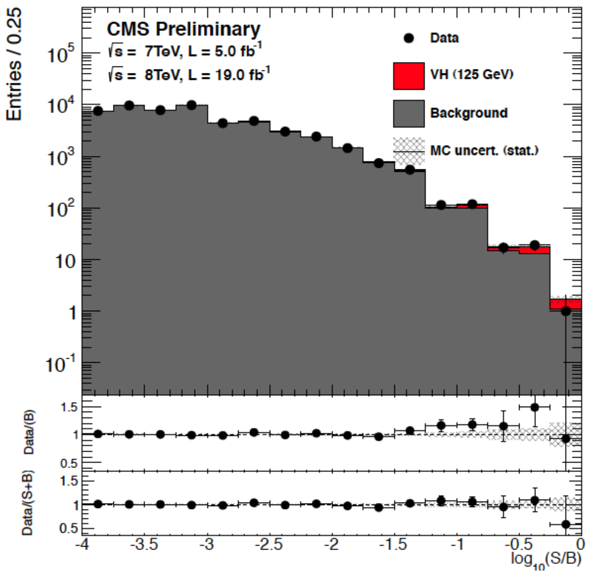
$m_X = 120^{+9}_{-7}$ GeV

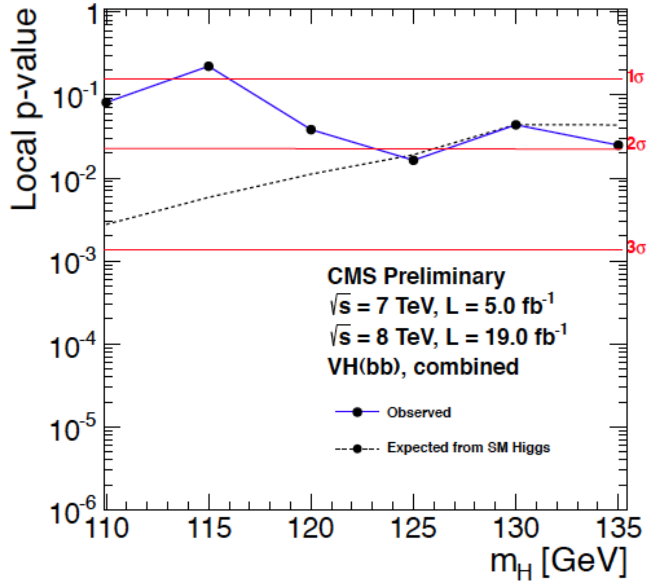
Points to note:

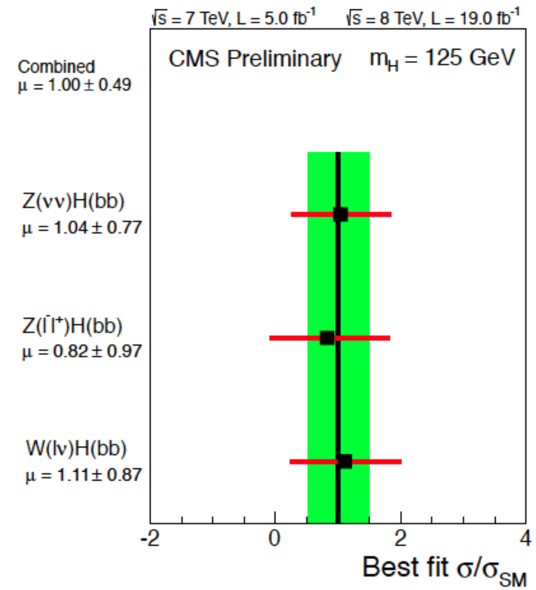
- broad access (poor mass resolution), consistent with **SM Higgs rate**
- **fair sensitivity for measurements**
- 1-jet channel has a respectable weight in the search
- **VH(ττ) analysis is updated too**; its sensitivity can be seen in the μ-compatibility plot
- despite poor mass resolution, the H→ττ channel is **not completely mass-blind** !

ATLAS (5+13 fb^{-1}): at m=125, **Z=1.1σ, μ=0.7±0.7**

VH, H → bb: CMS update since HCP







S/B-ratios from BDT(m_H=125)

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

μ = 1.0 ± 0.5
(m = 125 GeV)

Brief summary:

- Event classification: 2 b-jets + V(eν, μν, ee, μμ, νν); V with low/**high-p_T**; events with high-p_T: tight/loose b-tag
- mass resolution: **10%**
- **2.1σ-excess** with a signal strength consistent with the SM Higgs boson: **μ = 1.0 ± 0.5**

ATLAS (5+13 fb^{-1}): no access (μ = -0.4 ± 1.1), still stat. consistent with SM Higgs presence

Recast: event yields → couplings

Production × Decay parameterization

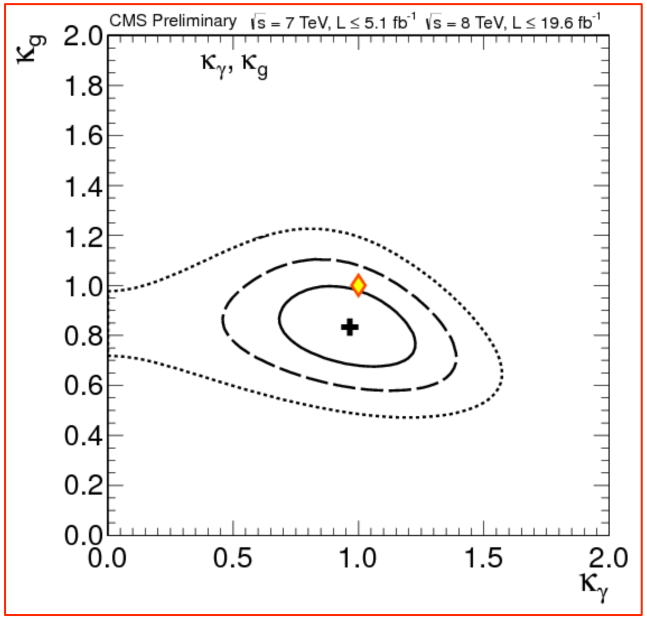
8 independent parameters to describe all currently relevant decays and production mechanisms: $\sigma(xx \to H) \cdot BR(H \to yy) \propto \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{\mathrm{TOT}}}$

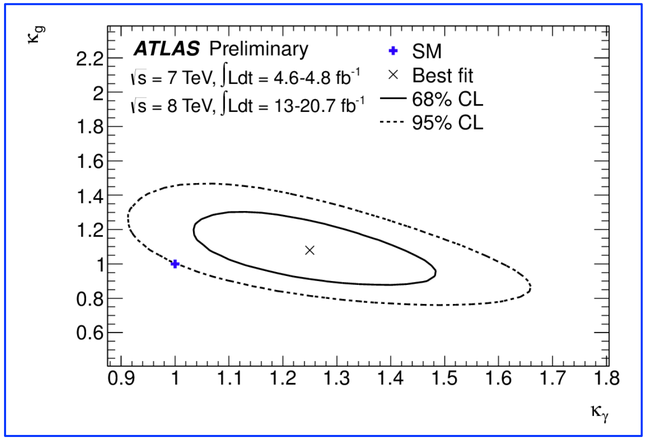
- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- Γ_{gg} (loop induced)
- Γ_{tt}
- Γ_{TOT} (including H → "invisible")
- **Newer channels** still have too little sensitivity to affect anything in the combination (two more parameters will be needed: $\Gamma_{Z\gamma}$ and $\Gamma_{\mu\mu}$)

	untagged	VBF-tag	VH-tag	ttH-tag
WW	✔	✔	✔	
ZZ	✔	✔		
bb		✔	✔	✔
ττ	✔	✔	✔	
γγ	✔	✔	✔	✔
Zγ	✔			
μμ	✔			

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



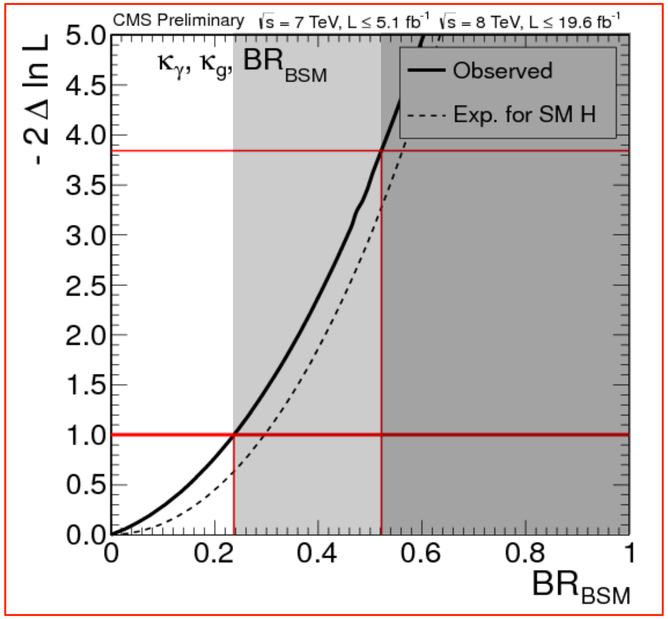


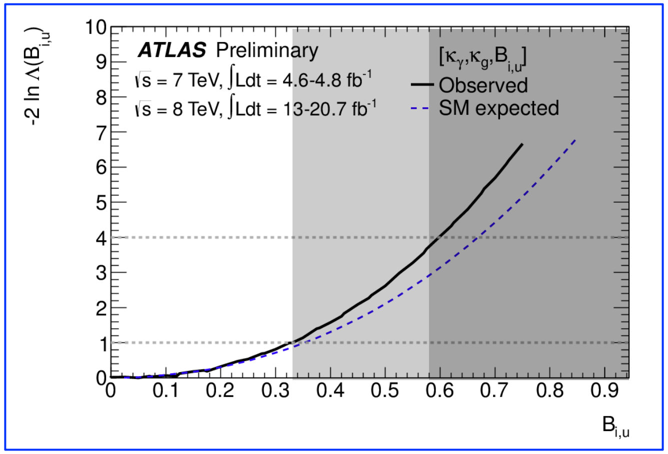
Two-parameter fit

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

Data are consistent with $(\kappa_\gamma; \kappa_g)=(1; 1)$

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**

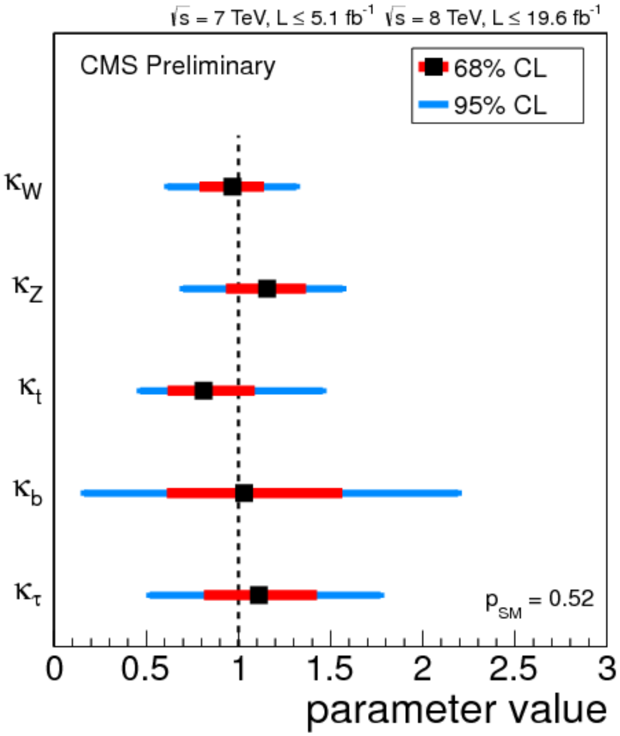
CMS: BR(BSM) < 0.52 at 95% CL
ATLAS: BR(BSM) < 0.58 at 95% CL

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

CMS: C5 model (almost a measurement)

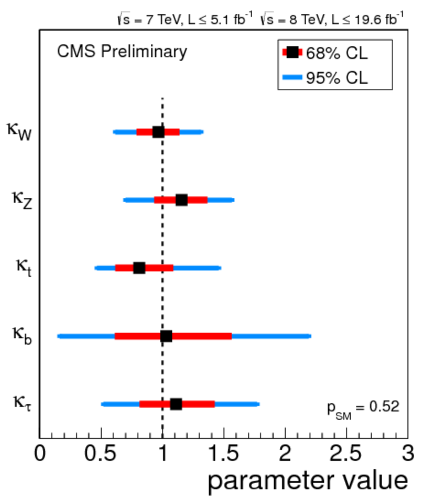
8 independent parameters to describe all currently relevant decays and production mechanisms:

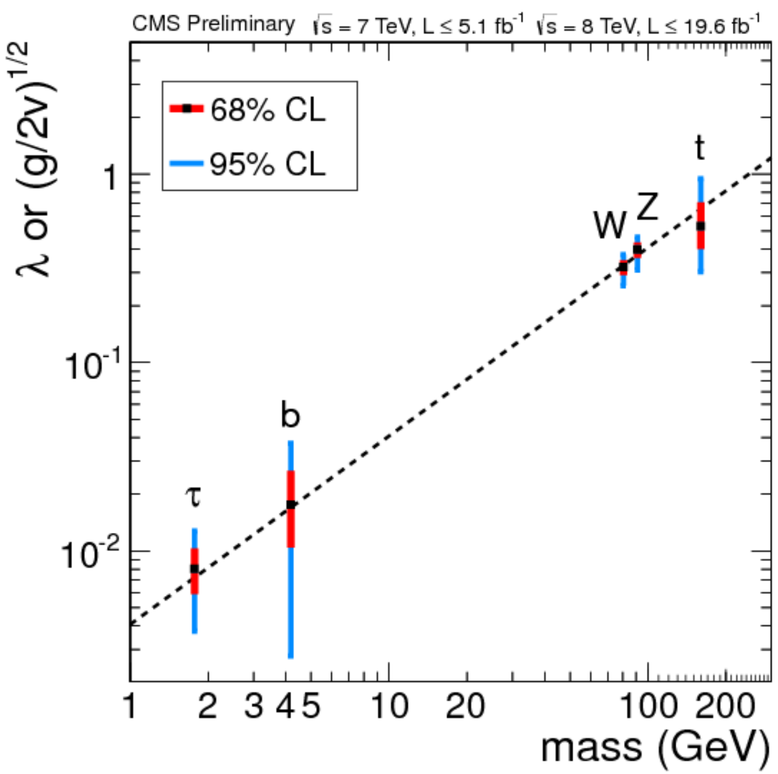
- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- $\Gamma_{\gamma\gamma}$ (loop is resolved) → κ_W, κ_t
- Γ_{gg} (loop is resolved) → κ_t, κ_b
- assume **BR(BSM)=0**
- Assume couplings to the 1st, 2nd, 3rd generations are modified the same way



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



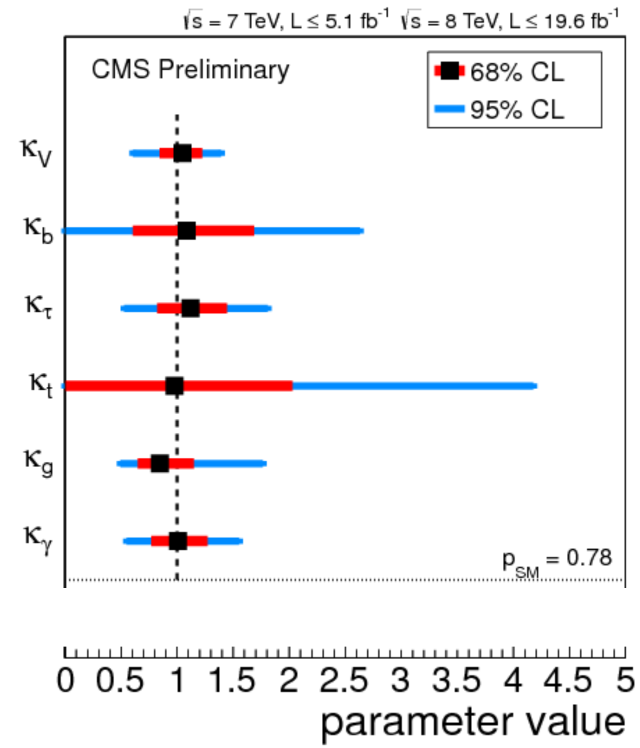


Note: the magnitude of couplings we try to assess range by a factor of 100!
A test with 20+% accuracy is actually a very respectable test.

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

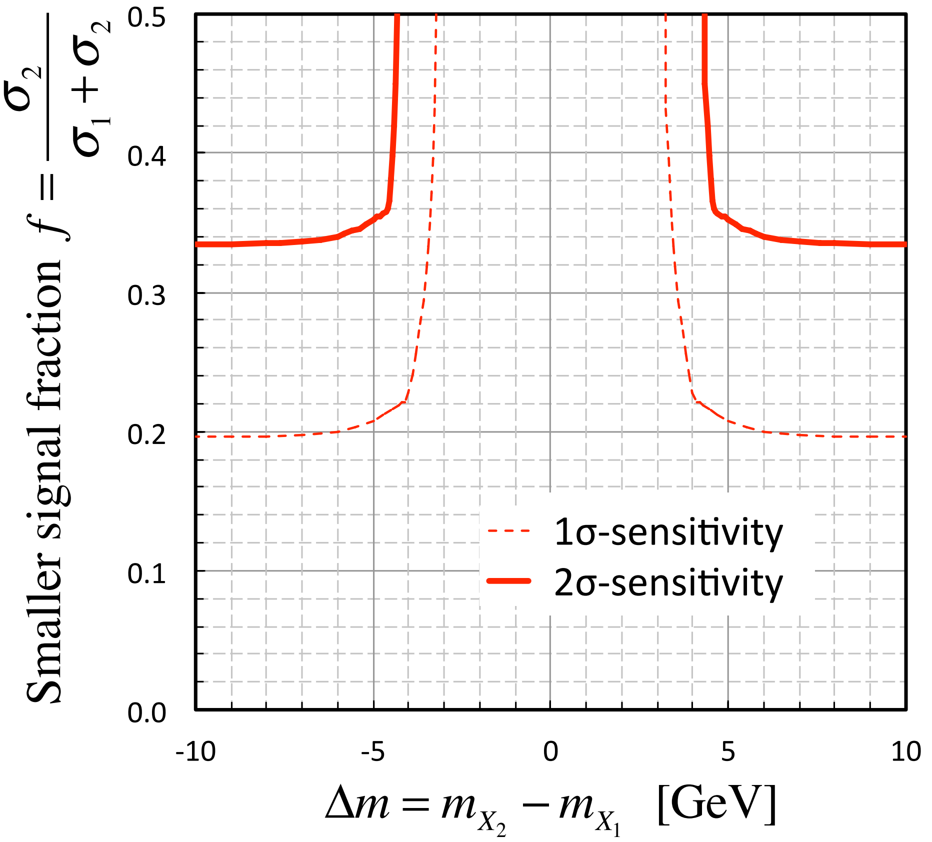


Is X125 one particle?

Is X125 one particle? (mass lineshape)

What if X125 is two bosons with near degenerate masses?

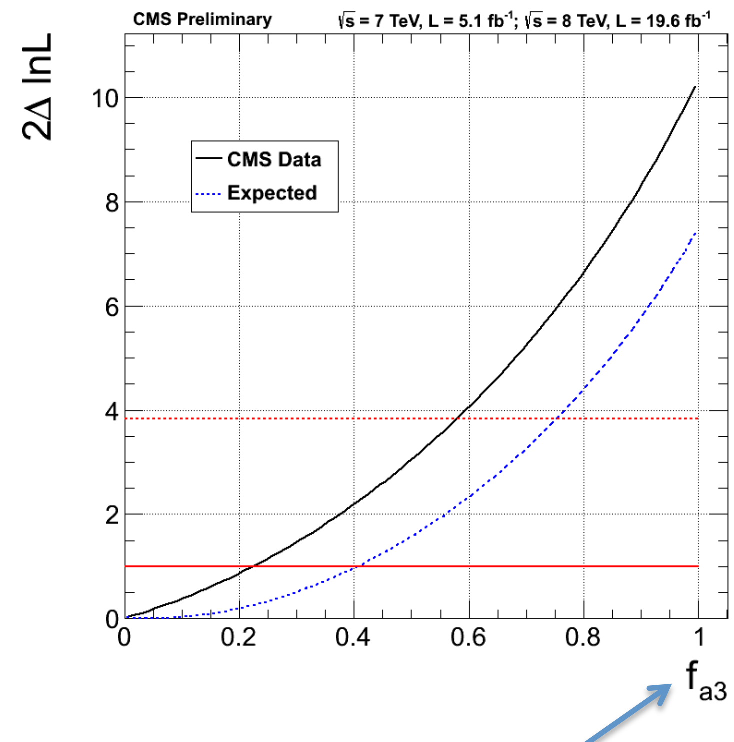
- What can we infer from the mass line shape?
  - **no public results yet**
  - **back-of-envelope for current dataset (HZZ4L):**
    - **no sensitivity, if Δm < 4 GeV**
    - **no sensitivity, if the smaller signal contributes with *f*<0.3**



Is X125 one particle? (J^{CP})

What if X125 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



$$f_{a3} = f(0^-) = \frac{\sigma(0^-)}{\sigma(0^-)+\sigma(0^+_m)}$$

Experimental status 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 X125 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**

Today's experimenter's wish list

Entering the Higgs Precision Era

Precision signal

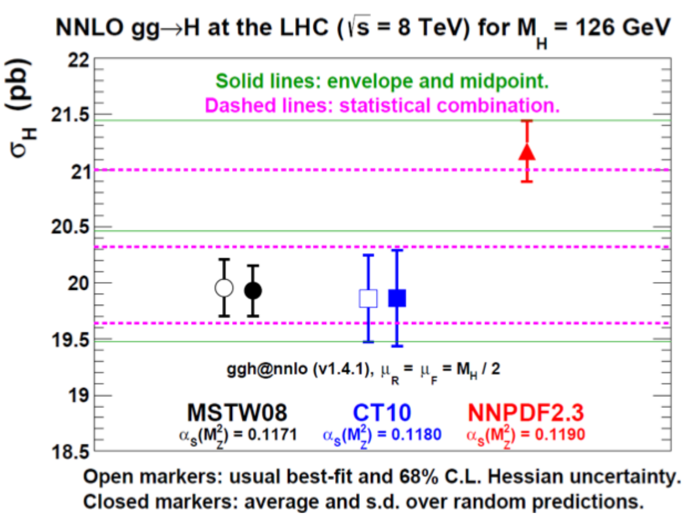
- Change of paradigm: from search to PRECISION signal measurements
  - Precise assessment of TH uncertainties, strategies to reduce them
  - Fiducial cross sections: define fiducial regions
  - Total cross sections: acceptance uncertainties
  - What are Important (fiducial) differential CSs (p_T, Y, etc…)
  - Define ratio measurements in these variables

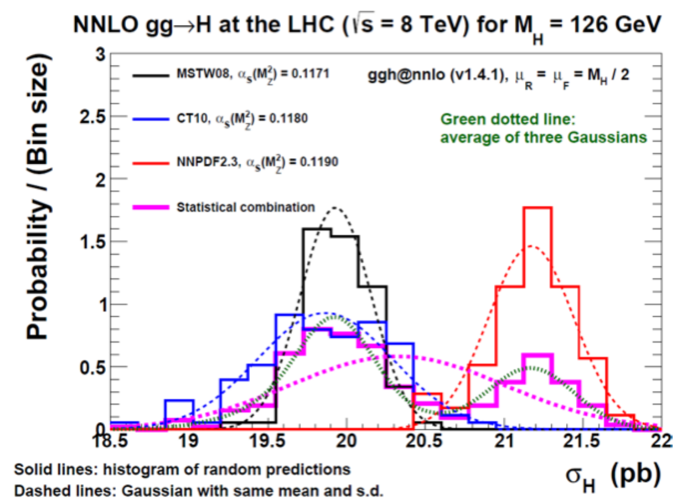
Precision Backgrounds

- Still searching (or first first measurements)
  - H_{125} direct couplings to main fermions (tau and b)
  - H_{125} direct top Yukawa couplings
  - H_{125} rare and invisible decays
  - Additional states of the EWSB sector…

TH Uncertainties (Signal)

- Treatment of TH systematic uncertainties:
  - Paradigm for measurements: profiling (systematic uncertainties are treated statistically).
  - What is the best model for TH systematic uncertainties?
- PDF uncertainties:
  - Correlation model of the uncertainties can always be refined (signal-background, background-background): is it time to improve on the simple scheme set up in 2011 (Joey Huston et al)?
  - PDF4LHC envelope?
  - (Plots shown below are for illustration purpose only; thy are out of date and use inconsistent values α_S)





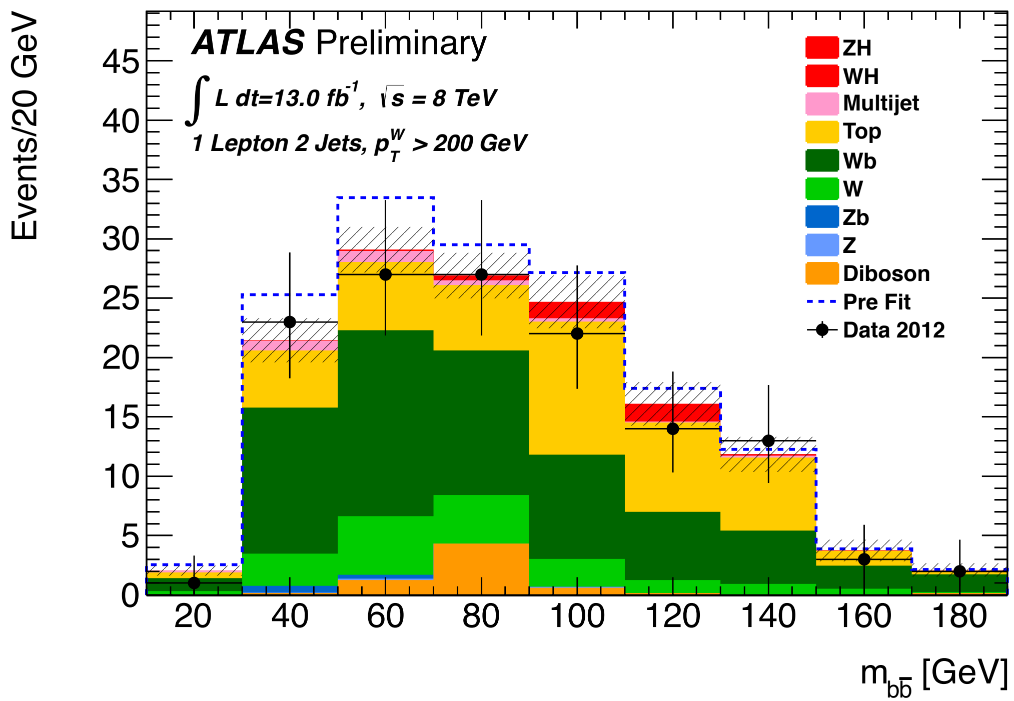
TH Uncertainties (Signal)

- Jet bin uncertainties, VBF phase space in particular:
  - Improvements TH uncertainty treatment?
  - Can we converge on a "standardized" set of VBF criteria?
  - Can the ggF uncertainty be constrained from 2-jet slightly larger phase space?
- PS and underlying event:
  - Common definition of tunes to use for UE
  - PS systematic uncertainties common strategy
- Interference:
  - yy full NLO interference estimate?
  - Can interferometry (mass shift measurement to bound Higgs width) really work (**arXiv:1305.3854**)?

Background: Striking Examples (1)

- **VH, H→bb**

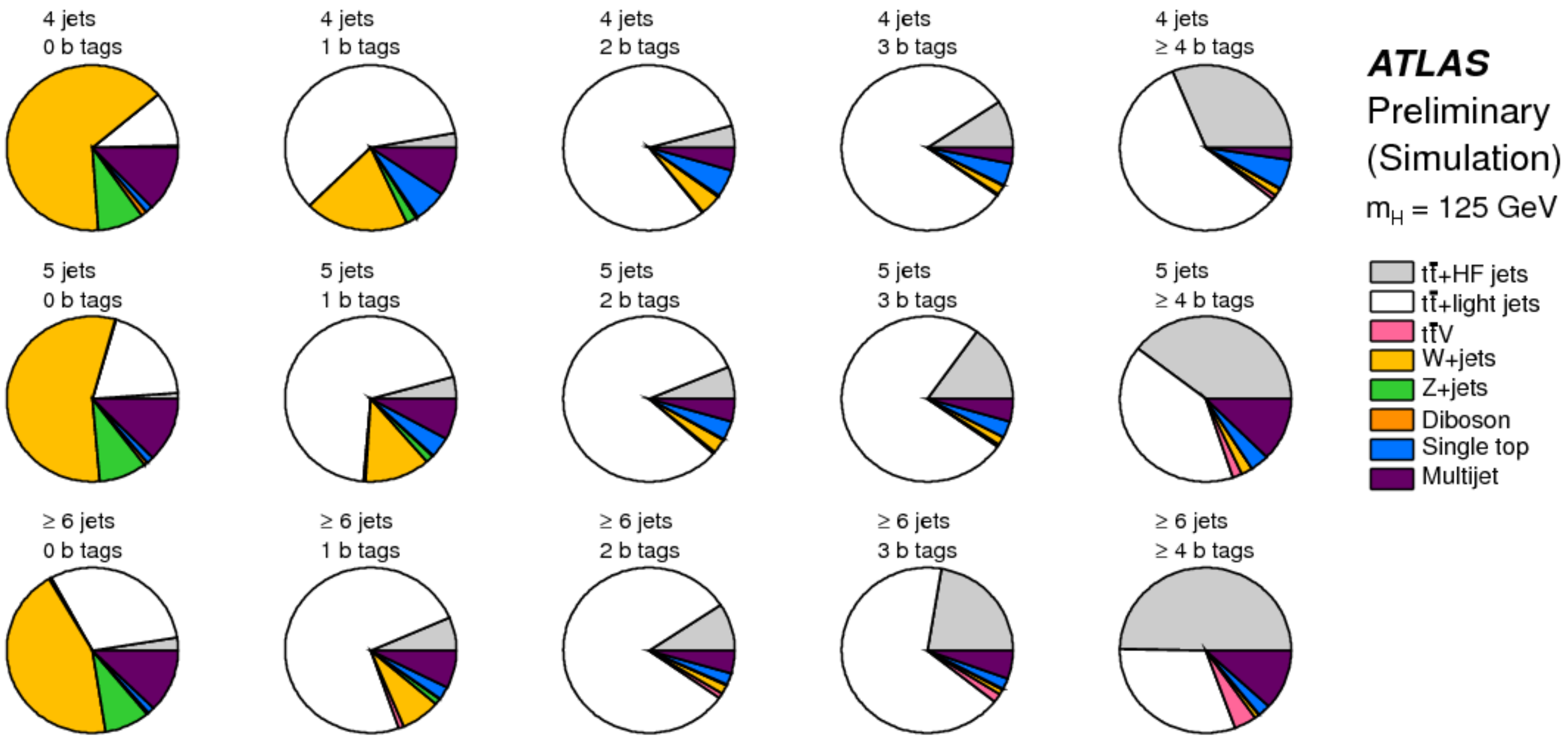
  Description of:
  - pT in W+jets, Z+jets, tt (ISR)
  - Simulation/Understanding of gluon splitting
  - Simulation of close-by jets?
  - PDF uncertainties
  - UE and PS



Backgrounds: Striking Examples (2)

- **tt̄H, H→bb**

  Description of backgrounds many control regions (including correlations!):
  - p_T in W+jets, Z+jets, **tt+jets (both light and HF)**
  - Simulation/Understanding of gluon splitting
  - Simulation of close-by jets?
  - PDF uncertainties
  - UE and PS



Tools

- Validation work on the recent tools:
  - MINLO (Multi scale Improved NLO **arXiv:1206.3572**)
  - HEJ (**arXiv:1101.5394)**
  - NLO ME-PS matching: MeNLOPS (**arXiv:1004.1764)**
  - **Madgraph5 and aMC@NLO (amcatnlo.web.cern.ch)**
  - PowHel (Powheg+Helac) for complex process tt+jets/HF
  - HRes
  - 2yNNLO

- Specific requests for the diphoton channel:
  - Public release of 2yNNLO?
  - Fragmentation (NNLO)?

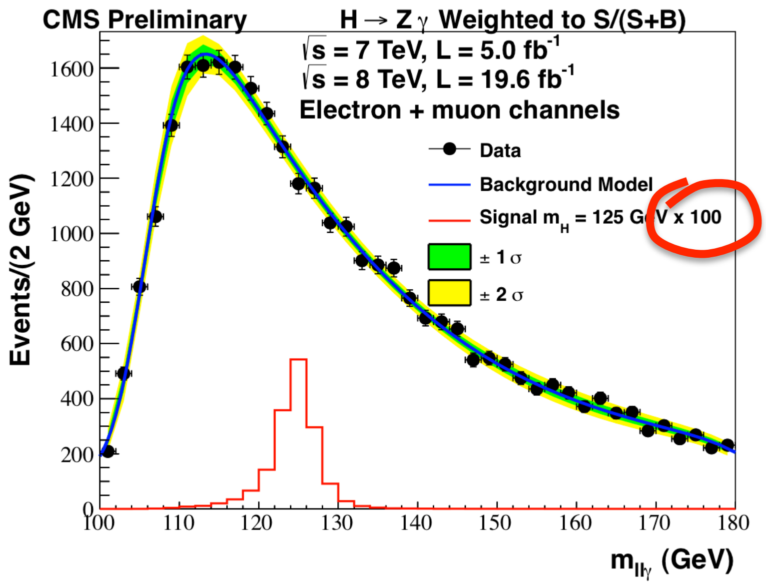
Summary

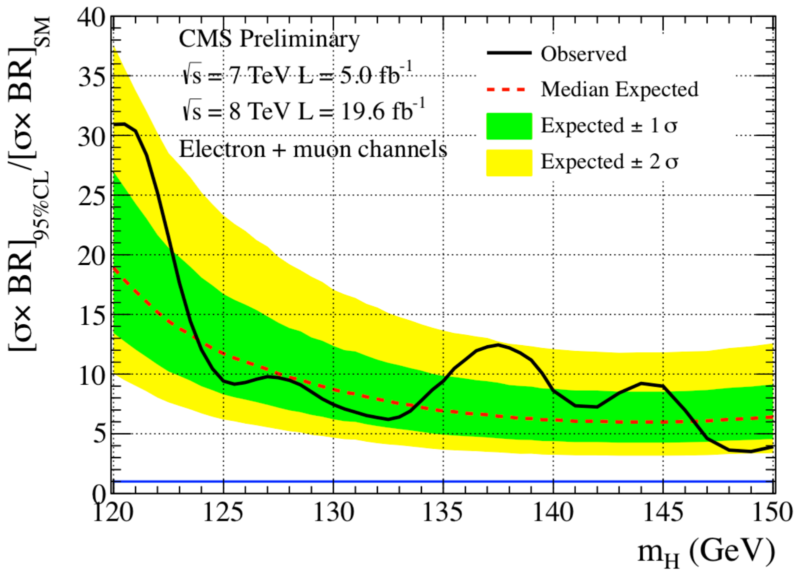
We have high hopes for making progress here at Les Houches…

at least on some items on the wish list

Backup I: less sensitive channels

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:

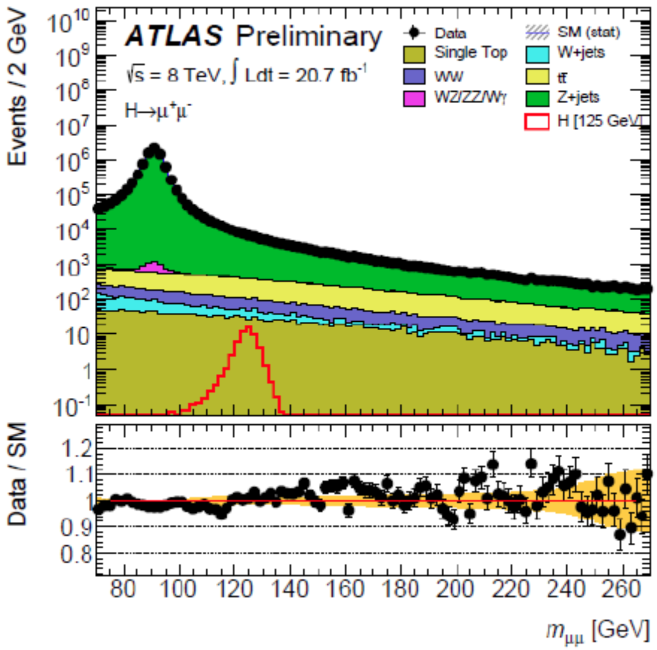
CMS (m_H=125): μ>10 is excluded at 95% CL

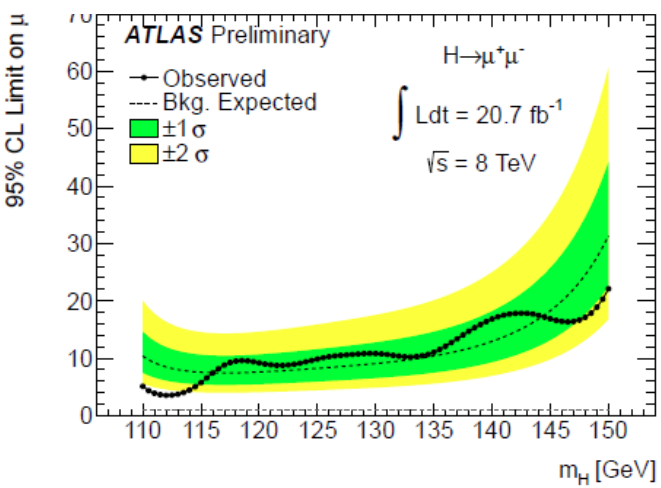
ATLAS (m_H=125): μ>18 is excluded at 95% CL

Points to note:

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

H → μμ: ATLAS results





Analysis strategy:

- two prompt muons: μμ
- **di-muon 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%

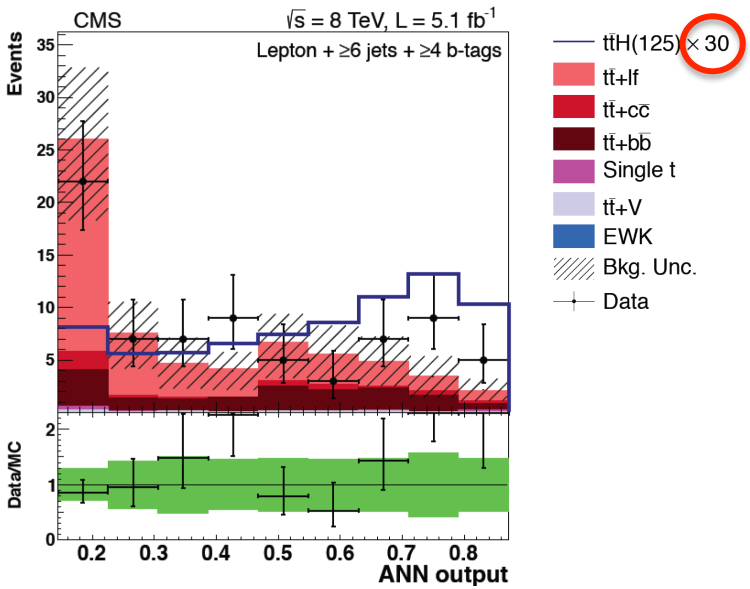
Results:

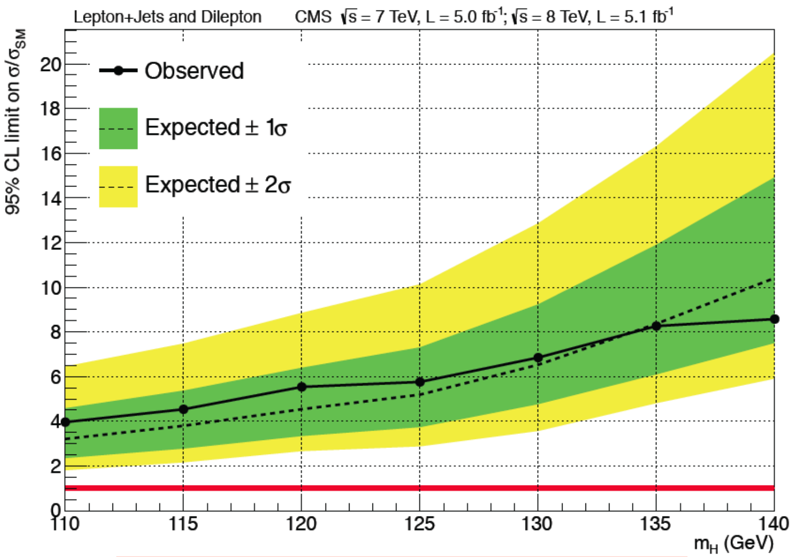
ATLAS (m_H=125): μ>10 is excluded at 95% CL

Points to note:

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

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



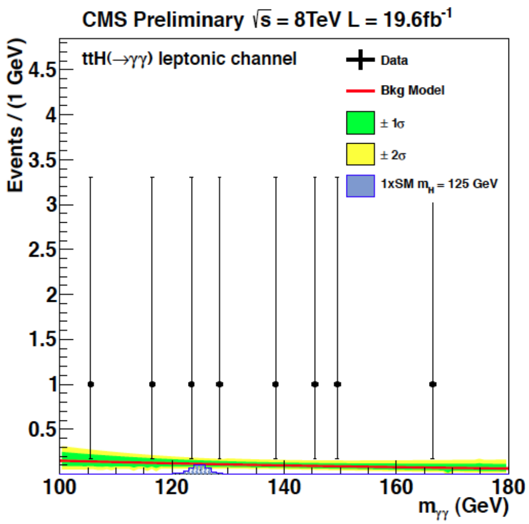


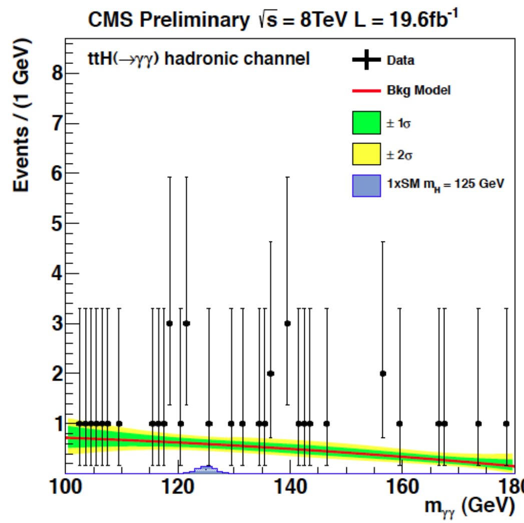
μ > 5.8 excluded at 95% CL
(m = 125 GeV)

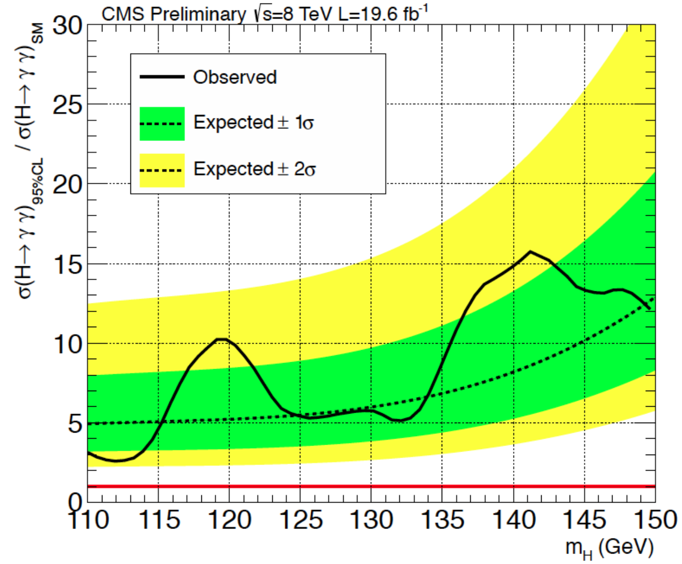
Brief summary:

- 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 25 times more data**

ttH, H → γγ: CMS results





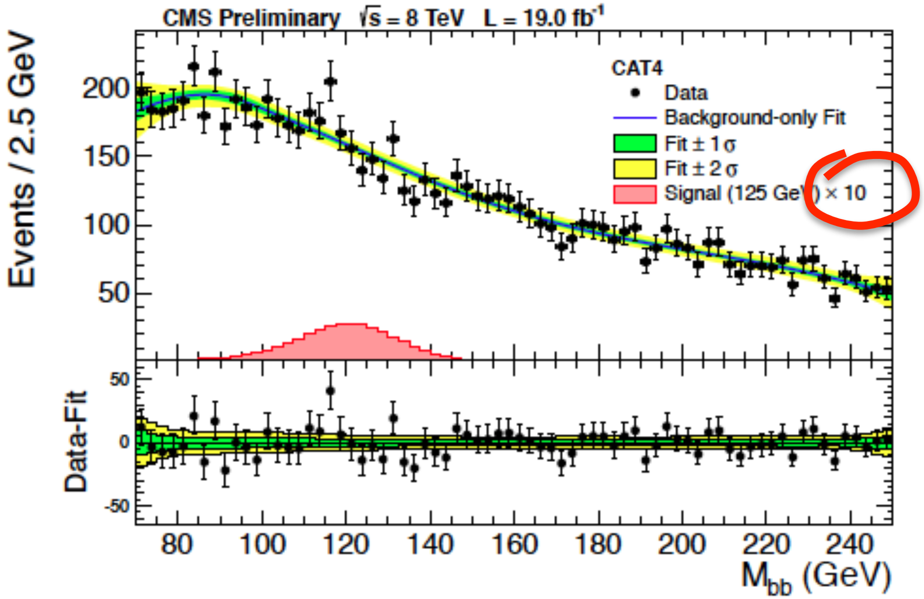


μ > 5.4 excluded at 95% CL
(m = 125 GeV)

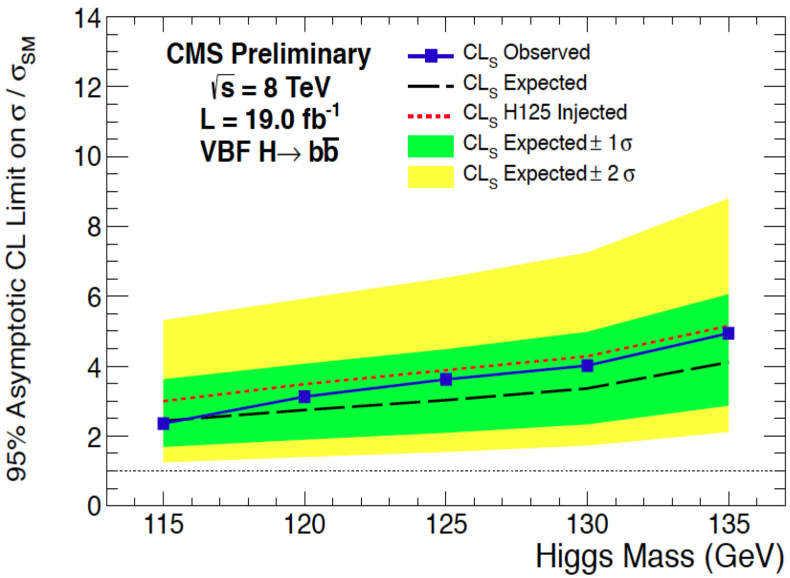
Brief summary:

- **8 TeV, 19 fb^{-1}**
- **analysis strategy:** narrow $m_{\gamma\gamma}$ bump a la the canonical H→γγ analysis (**not limited by systematics!**)
- event classification: γγ+(lνb,jjb): , ≥2 jets, ≥1 b-tag; γγ+(jjb,jjb): ≥5 jets, ≥1 b-tag;
- good S/B-ratio**: about 1:3**
- very small event rate: **1.1 events**
- exclude μ>5.4 at 95% CL (expected limit 5.3)
- to reach 2σ-sensitivity, **we need only 4 times more data**

VBF, H → bb: CMS results



Best NN-output category

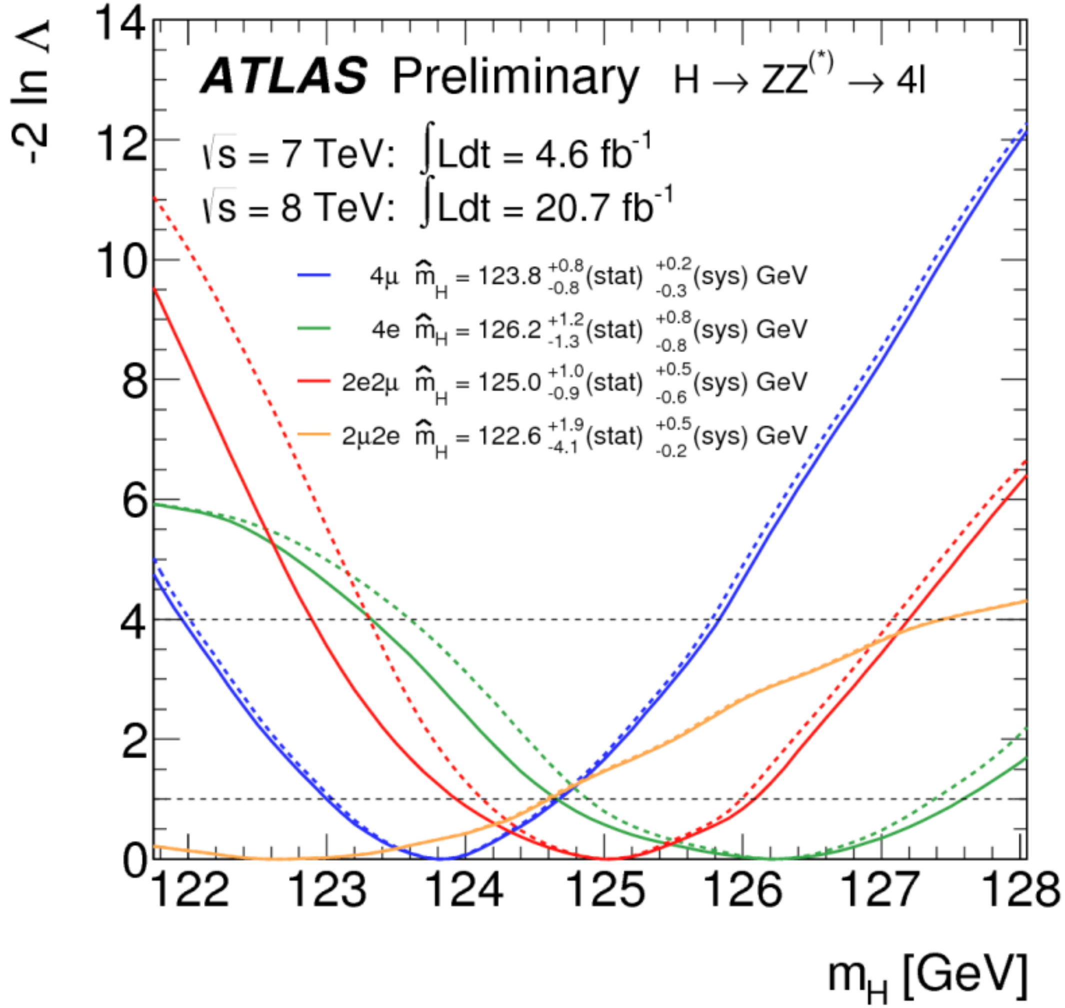


μ > 3.6 excluded at 95% CL
μ = 0.7 ± 1.4
(m = 125 GeV)

Brief summary:

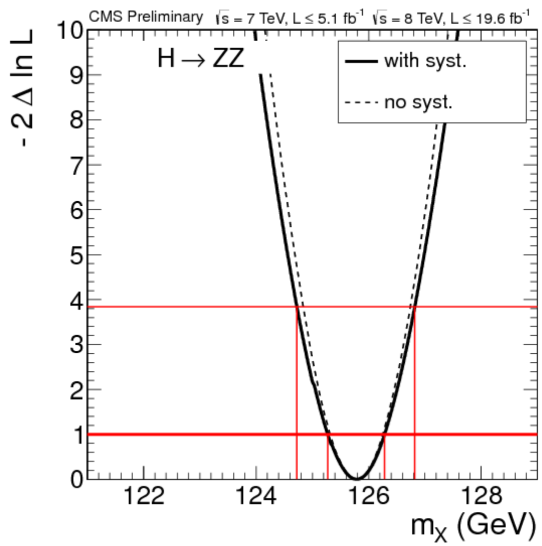
- Event selection: bb + $(jj)_{VBF}$
- **NN:** b-tags, relative jet kinematics, **q/g-jets**, **soft energy flow**, etc.
- Four event classes based on NN-output
- m_{bb} distributions for Z and tt are from simulation, QCD – data-driven
- **very challenging S:B (1:50)**
- To reach 2σ-sensitivity, **we need 10 times more data**

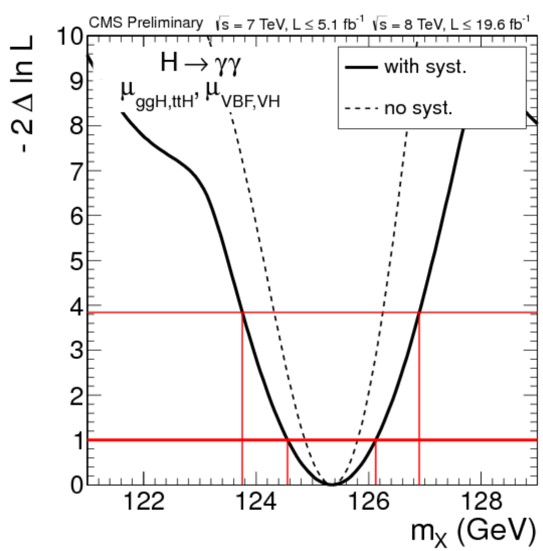
Back-up II: bits and pieces



ATLAS Preliminary $H \rightarrow ZZ^{(*)} \rightarrow 4l$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 20.7 fb^{-1}
4μ $\hat{m}_H = 123.8^{+0.8}_{-0.8}$(stat) $^{+0.2}_{-0.3}$(sys) GeV
$4e$ $\hat{m}_H = 126.2^{+1.2}_{-1.3}$(stat) $^{+0.8}_{-0.8}$(sys) GeV
$2e2\mu$ $\hat{m}_H = 125.0^{+1.0}_{-0.9}$(stat) $^{+0.5}_{-0.6}$(sys) GeV
$2\mu 2e$ $\hat{m}_H = 122.6^{+1.9}_{-4.1}$(stat) $^{+0.5}_{-0.2}$(sys) GeV
$-2 \ln \Lambda$
m_H [GeV]

Mass measurement in CMS





- **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

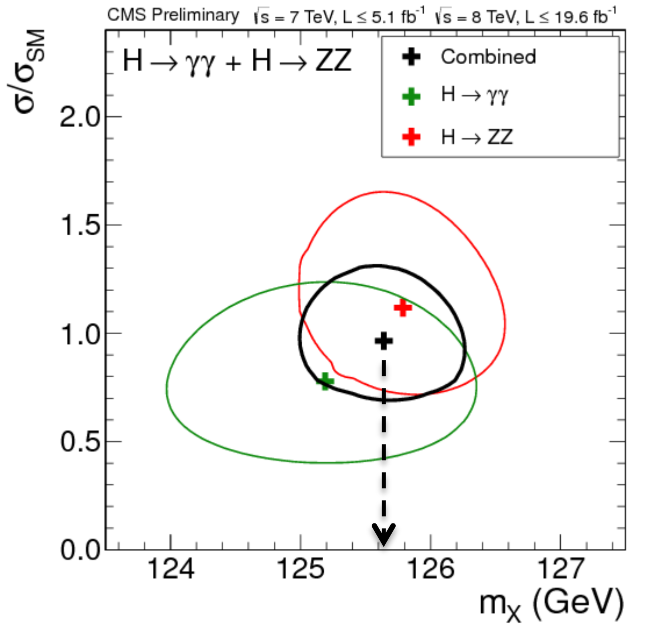
main sources of systematic uncertainties:
  - electron energy scale: 0.3%
  - muon energy scale: 0.1%

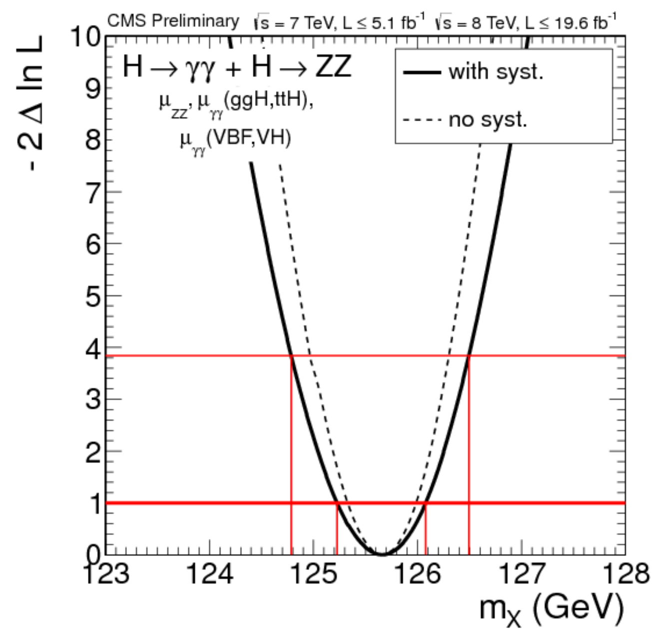
γγ: m_X = 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV

– 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 in CMS





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

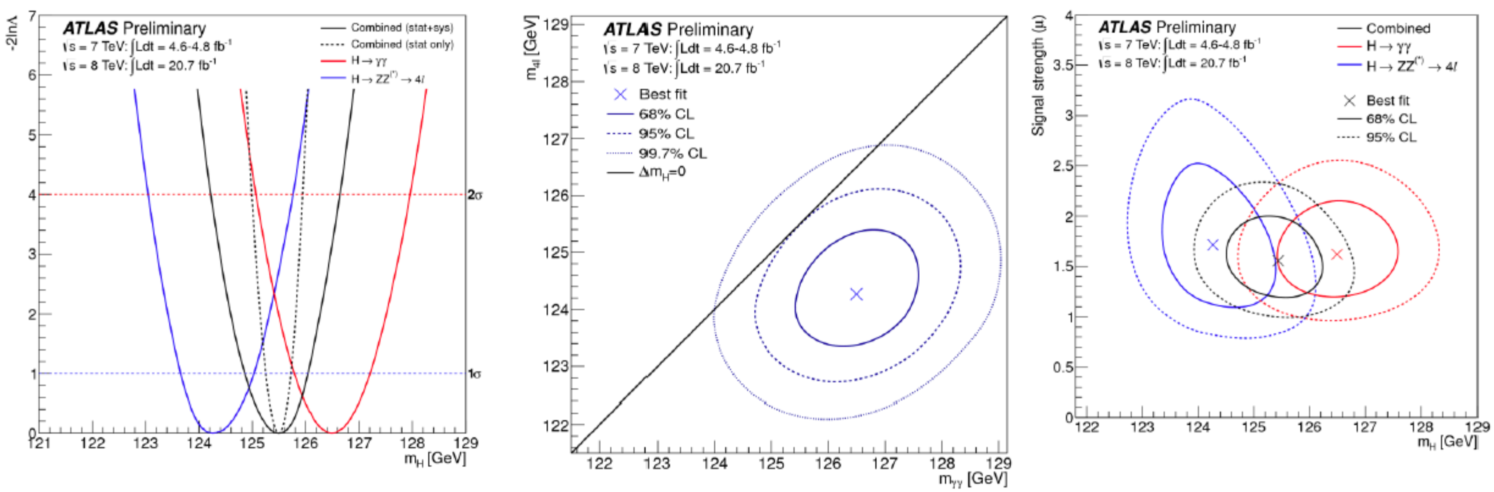
= 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

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

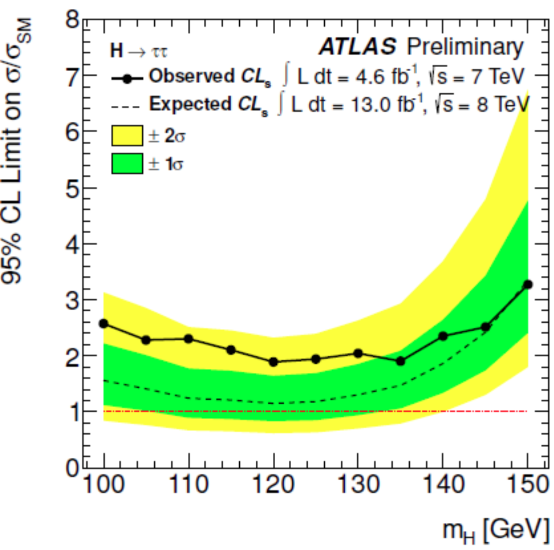
m_H=125.5±0.2 (stat) $_{-0.6}^{+0.5}$ (syst) GeV



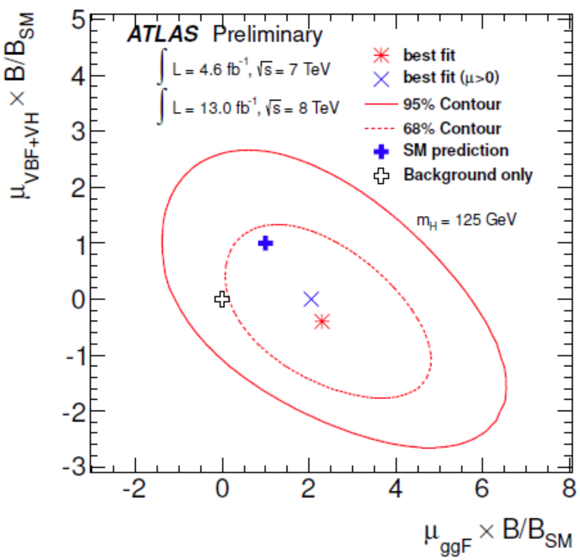
$\Delta m_H = m_{\gamma\gamma} - m_{4l} = 2.3_{-0.7}^{+0.6}$ (stat) ±0.6 (syst) GeV

Consistent with $\Delta m_H = 0$ at 2.3σ level

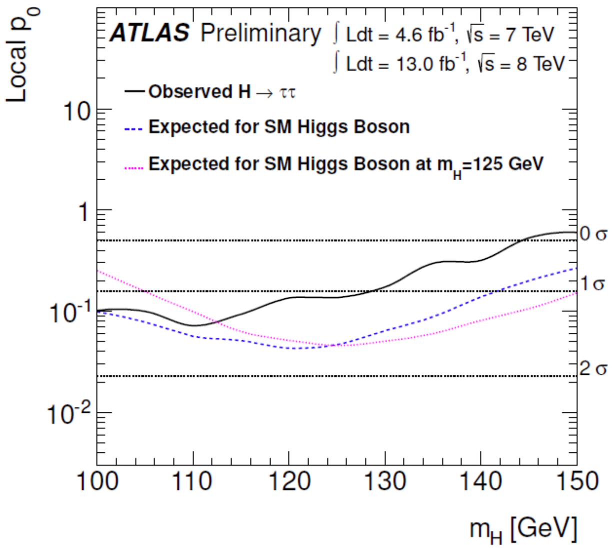
ATLAS H → ττ



H → ττ
ATLAS Preliminary
Observed CL_s ∫ L dt = 4.6 fb^{-1}, √s = 7 TeV
Expected CL_s ∫ L dt = 13.0 fb^{-1}, √s = 8 TeV
± 2σ
± 1σ
95% CL Limit on σ/σ$_{SM}$
m_H [GeV]



ATLAS Preliminary
∫ L = 4.6 fb^{-1}, √s = 7 TeV
∫ L = 13.0 fb^{-1}, √s = 8 TeV
best fit
best fit (μ>0)
95% Contour
68% Contour
SM prediction
Background only
m_H = 125 GeV
$\mu_{VBF+VH} \times B/B_{SM}$
$\mu_{ggF} \times B/B_{SM}$



ATLAS Preliminary ∫ Ldt = 4.6 fb^{-1}, √s = 7 TeV
∫ Ldt = 13.0 fb^{-1}, √s = 8 TeV
Observed H → ττ
Expected for SM Higgs Boson
Expected for SM Higgs Boson at m_H=125 GeV
Local p_0
0 σ
1 σ
2 σ
m_H [GeV]

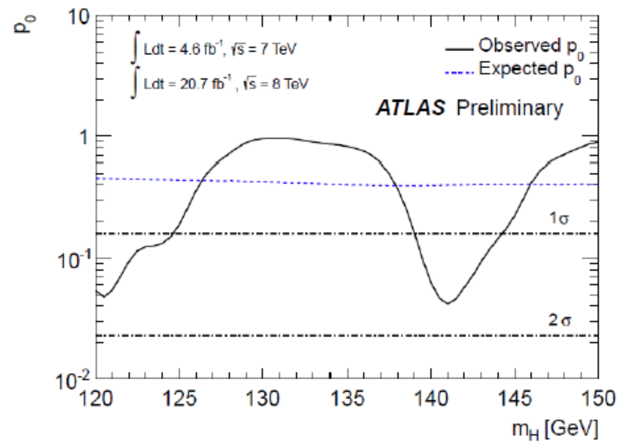
ATLAS H → Zγ

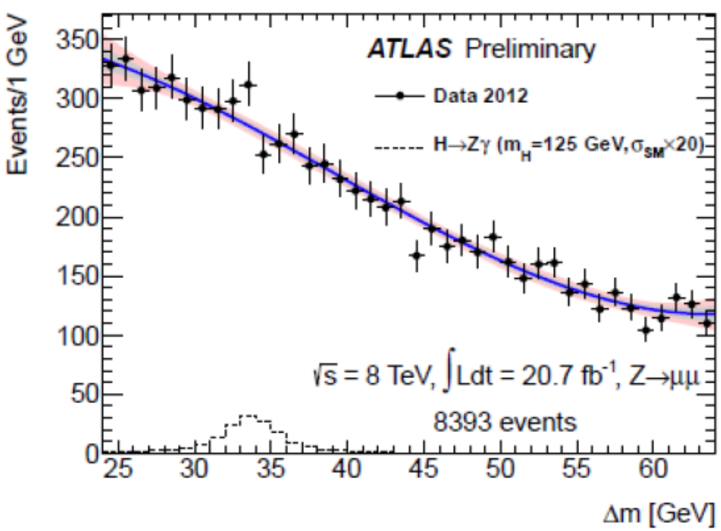
ATLAS-CONF-2013-009

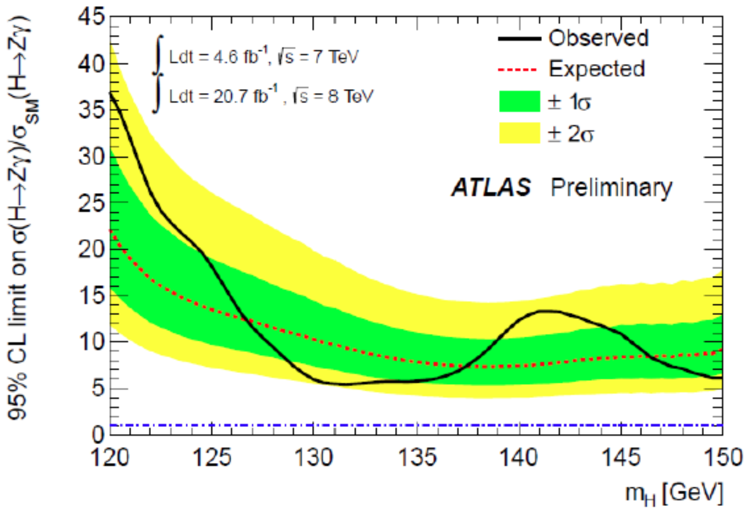
Higgs to Z + photon

Similar to diphoton channel
Loop production modes

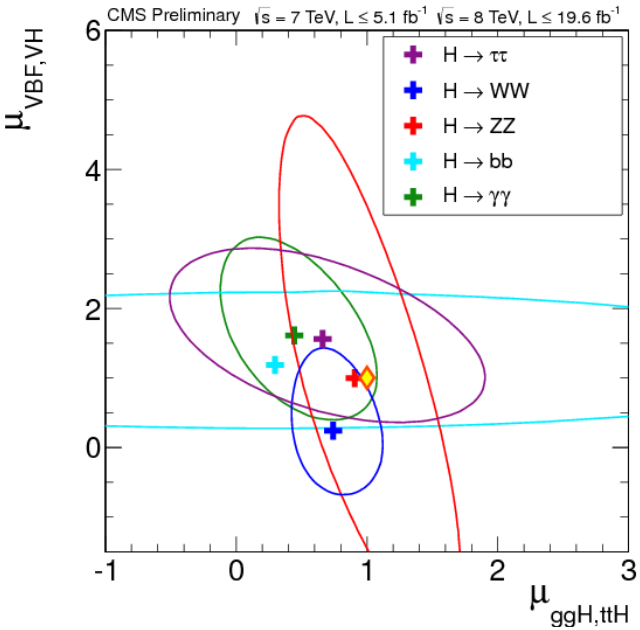
Relative rate to diphoton interesting and sensitive to BSM

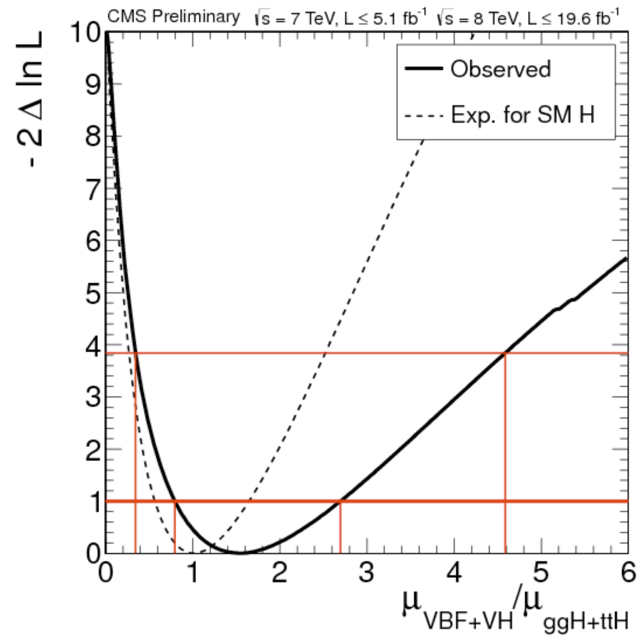






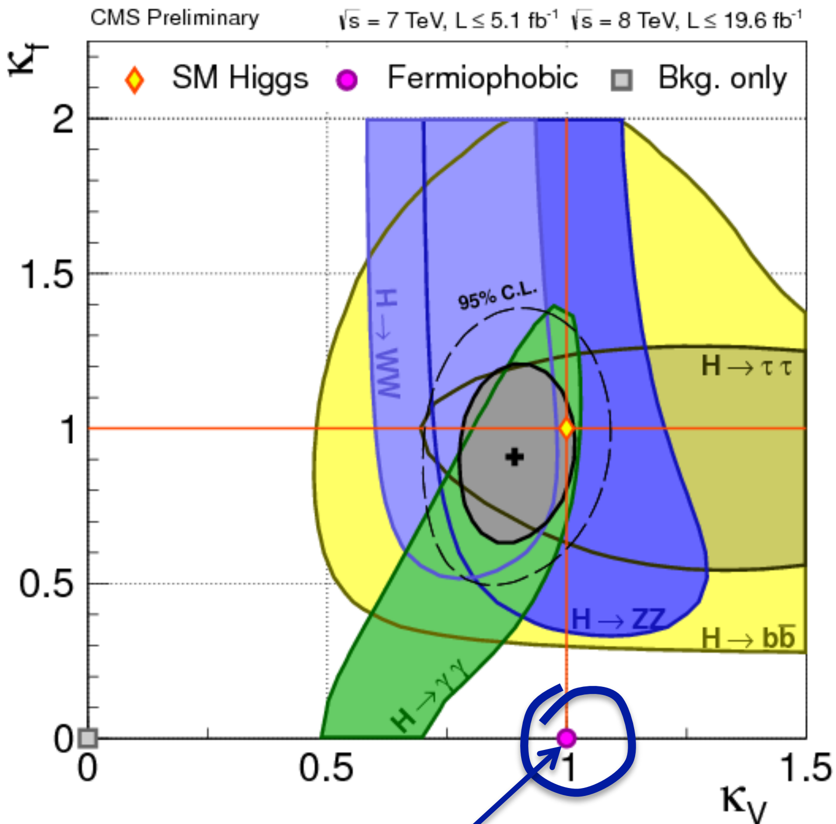
Consistency of event yields (3)





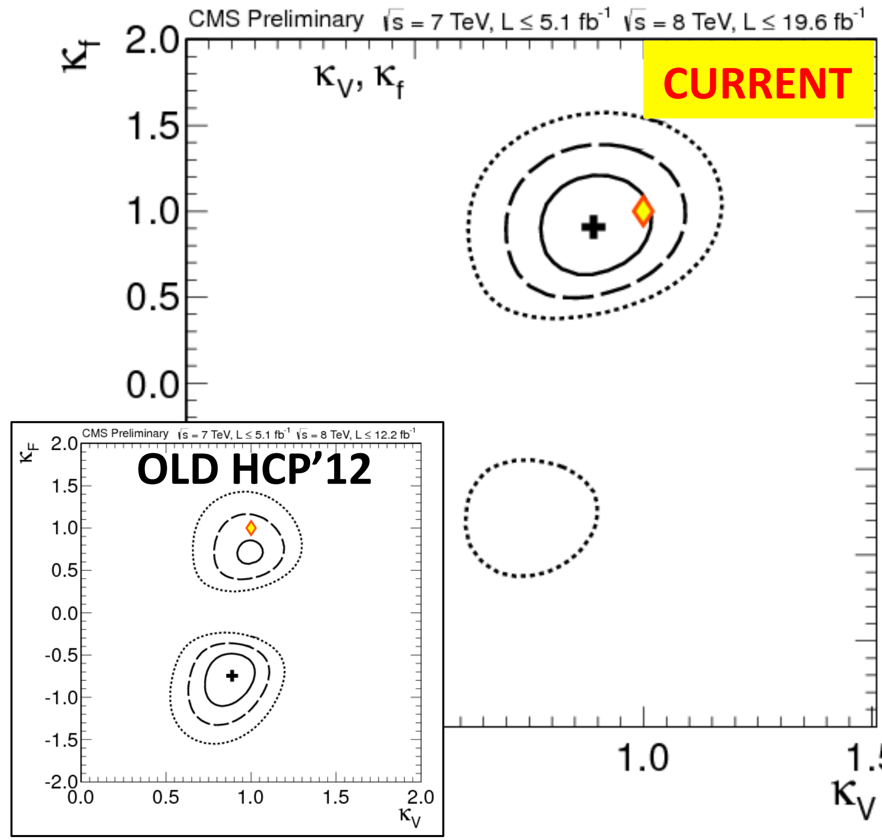
- Introduce two signal strengths **(μ_F, μ_V)** in each of the 5 decay channels:
  - μ_F scales the **fermion-coupling** induced production mechanisms (gg-fusion, ttH)
  - μ_V scales the **W/Z-coupling** induced production mechanisms (VBF, VH)
- **All channels give results consistent with the SM Higgs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

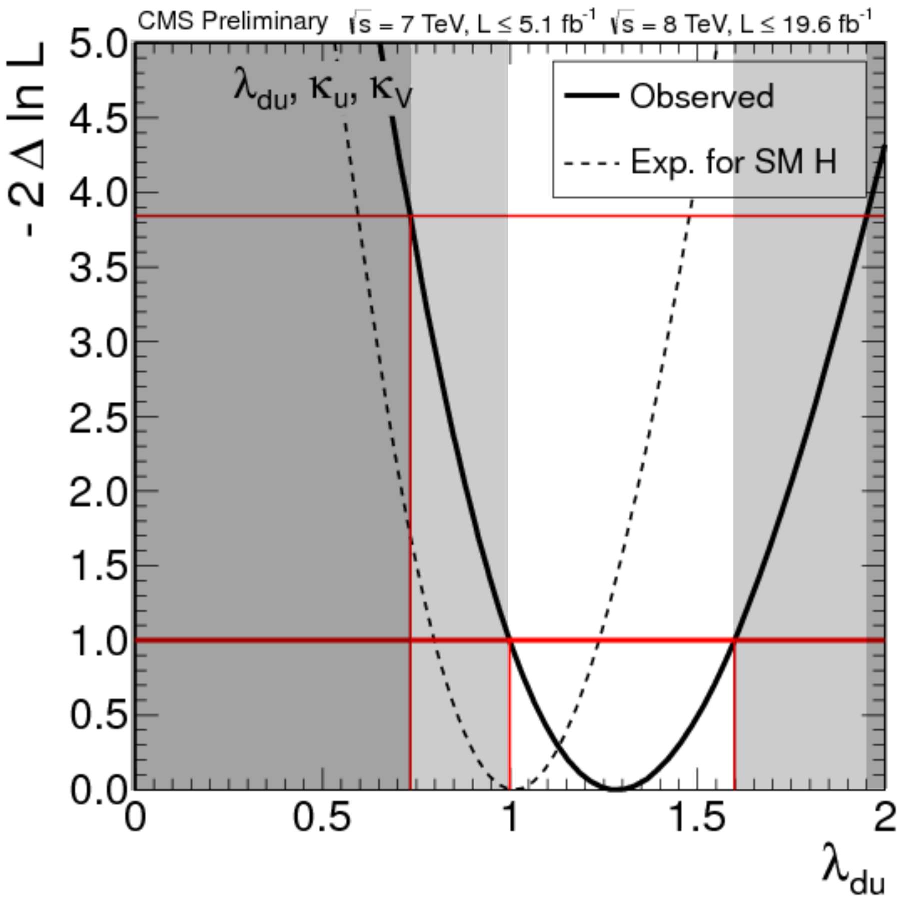
Data are consistent with (κ_V; κ_F)=(1; 1)



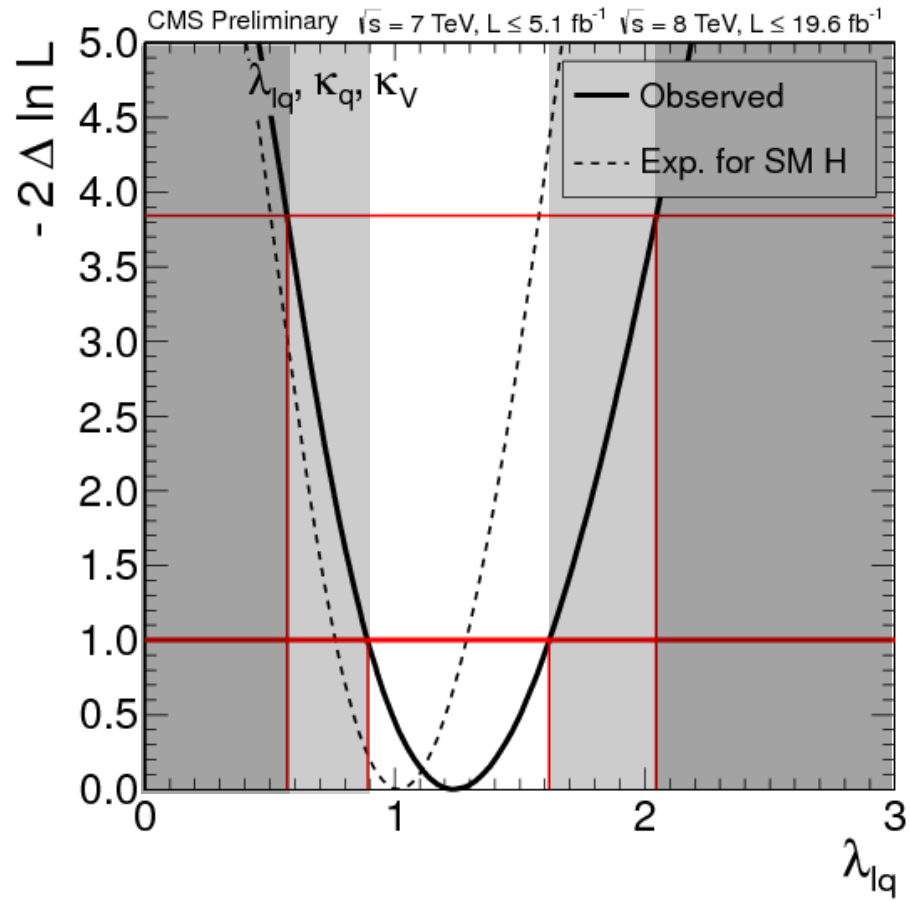
The previously seen global minimum of the likelihood in the (+; –) quadrant is gone, since the γγ-channel is no more enhanced

Asymmetry of couplings to fermions

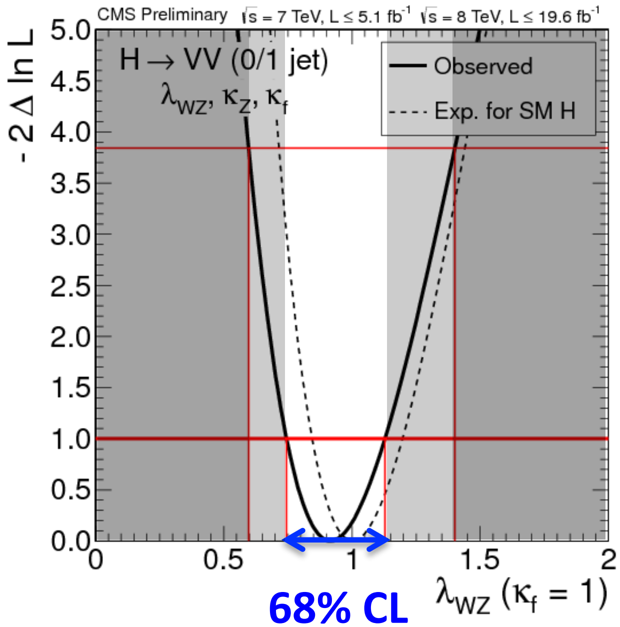
Ratio of coupling between down- and up-fermions

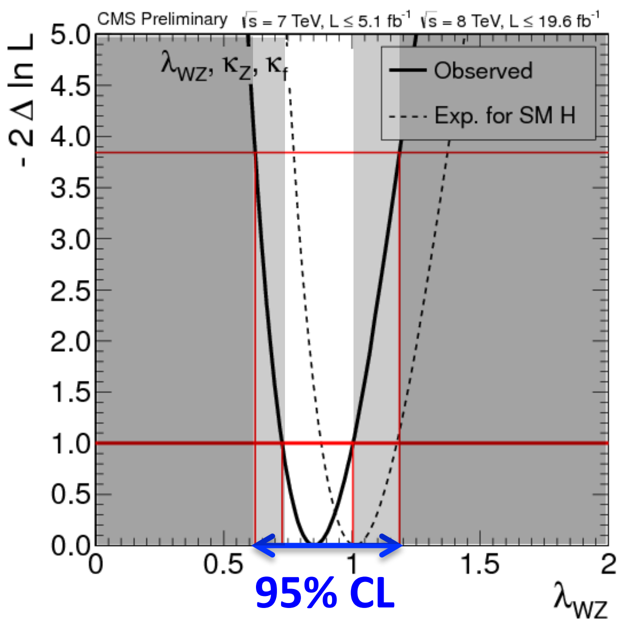


Ratio of coupling between leptons and quarks



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





- **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)**

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 $m_X = m_{4\ell}$
  - Extend KDs to include discriminating information from four-lepton mass:
  - Without any loss of information, one can change "variables":
  - And again without any loss of information, compress discriminants to be between 0 and 1

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

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

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

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

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

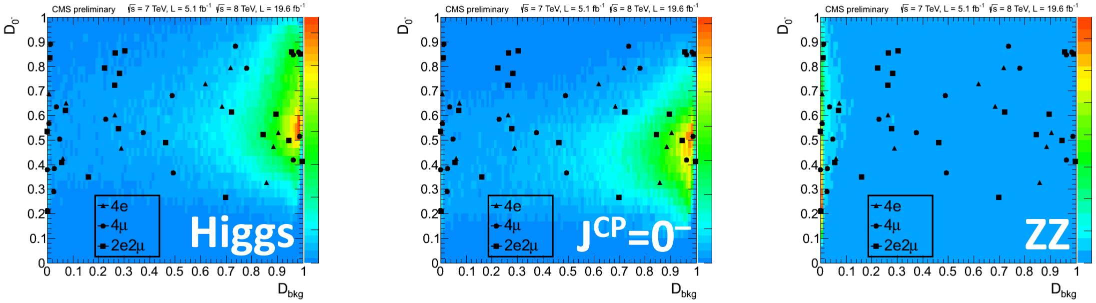
$$D(J^{CP};\mathrm{H}) = \frac{D(\mathrm{J^{CP};ZZ})}{D(\mathrm{H;ZZ})} = \frac{\left|ME_{J^{CP}}(xx \to \mathrm{J^{CP}} \to 4\ell)\right|^2}{\left|ME_{\mathrm{H}}(gg \to \mathrm{H} \to 4\ell)\right|^2}$$

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

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

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

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

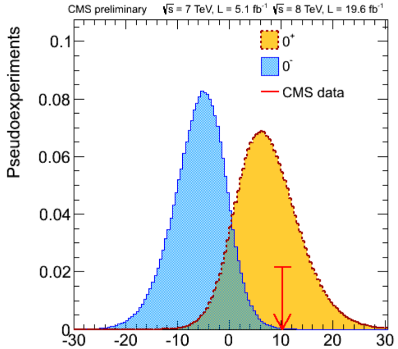


$$pdf\left(D_{bkg}, D_{J^{CP}} \mid \mathrm{H} \right) \leftarrow \text{from MC}$$
$$pdf\left(D_{bkg}, D_{J^{CP}} \mid \mathrm{J^{CP}} \right) \leftarrow \text{from MC}$$
$$pdf\left(D_{bkg}, D_{J^{CP}} \mid ZZ \right) \leftarrow \text{from MC}$$
$$pdf\left(D_{bkg}, D_{J^{CP}} \mid reducible\ \text{bkg} \right) \leftarrow \text{from control region}$$

- 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

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

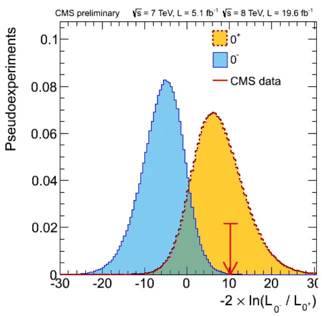
- Using 2D event distributions for alternative hypotheses, construct the usual log-likelihood-ratio test statistic and perform statistical analyses by generating pseudo-observations



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

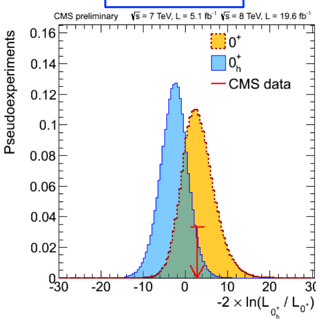
ZZ->4L J^{CP} analysis: results

$0^- \text{ vs } H$



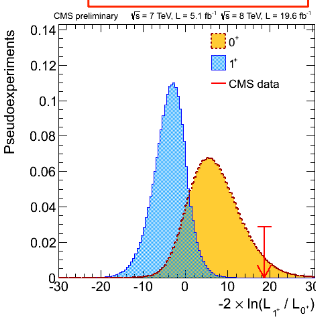
$CL_s = 0.0016$ excluded

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



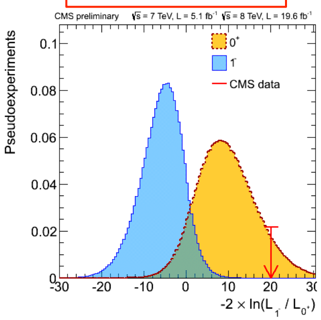
$CL_s = 0.081$ not yet

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



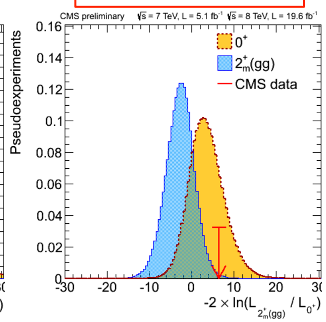
$CL_s < 0.001$ excluded

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



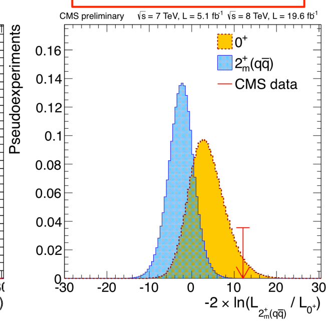
$CL_s < 0.001$ excluded

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



$CL_s = 0.015$ excluded

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

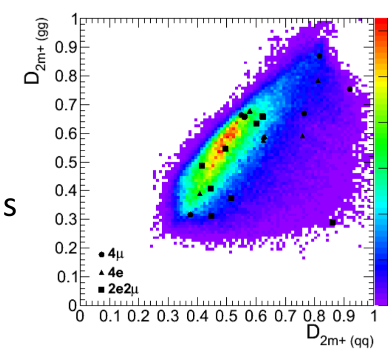


$CL_s < 0.001$ excluded

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

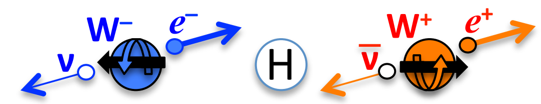
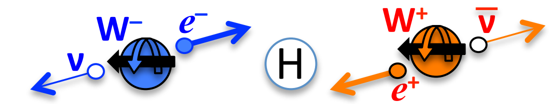
The observed test statistic value is

- 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

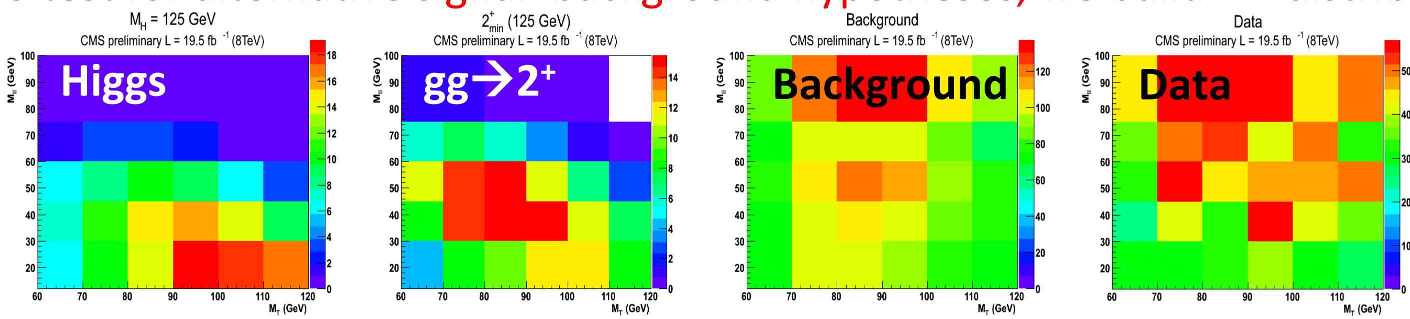


WW->2l2ν J^{CP} analysis

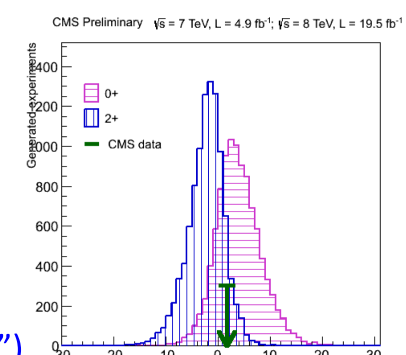
- Full event reconstruction is not possible, but:

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



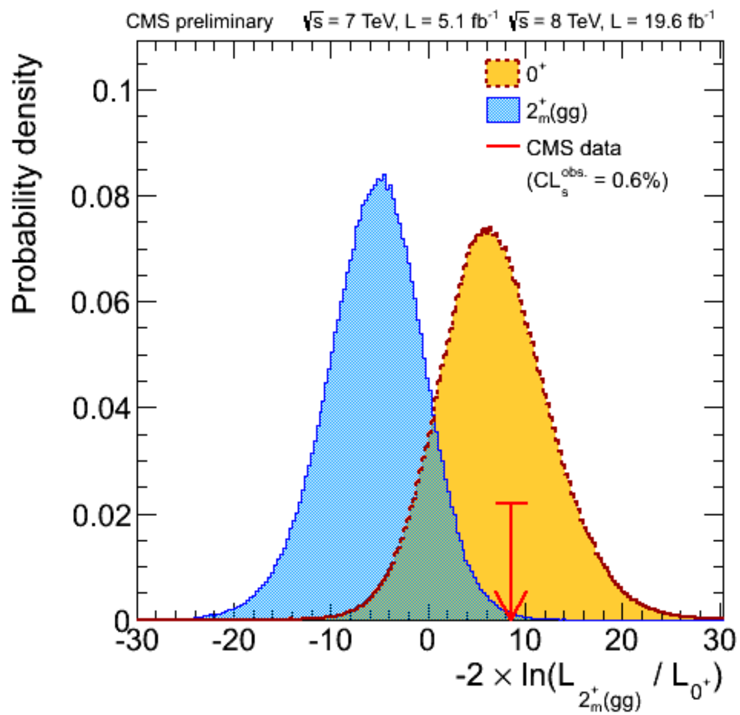
- Using 2D event distributions for alternative hypotheses, construct the usual log-likelihood-ratio test statistic and perform statistical analyses by generating pseudo-observations
  - **Observed CL_s=0.14** (data disfavor 2^+, but exclusion at 95% CL cannot be claimed)
  - Observed test statistic is **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 $gg \rightarrow 2^+_m$ 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, $gg \rightarrow 2^+_m$ is excluded at 99% CL**