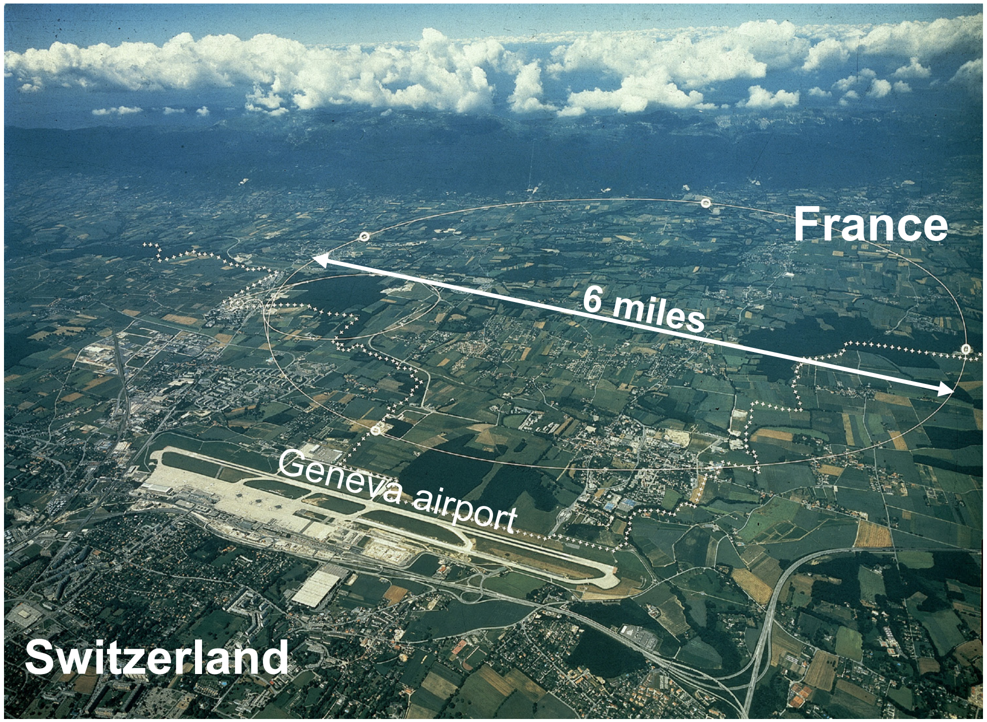
SM Higgs boson results (LHC Run I)

Andrey Korytov (for ATLAS and CMS collaborations)

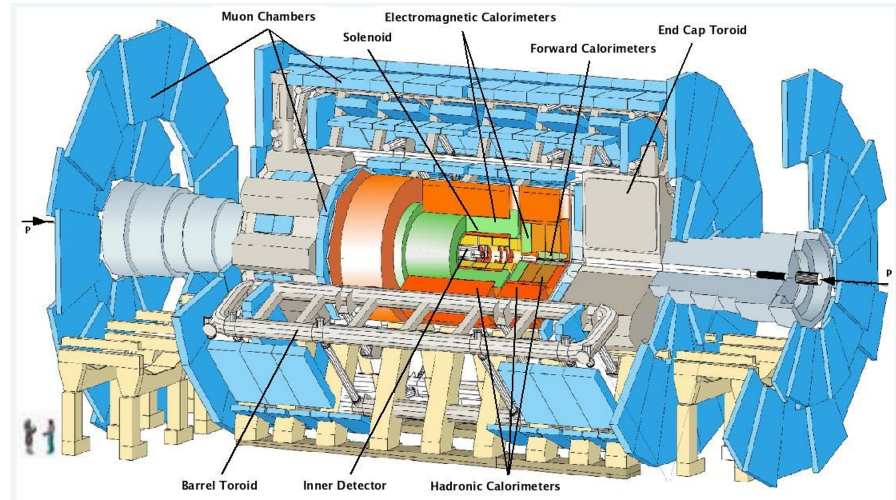


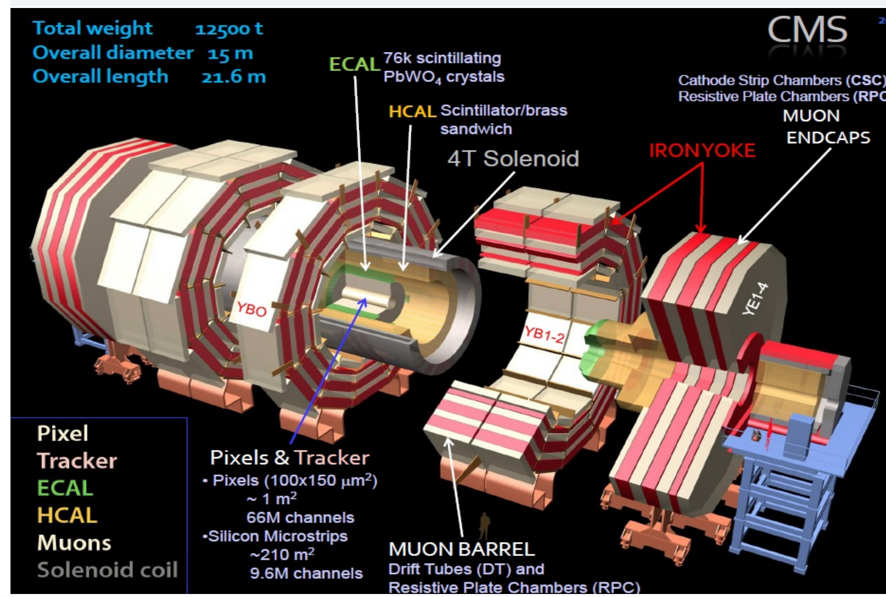
LHC Run I (2010 – 2012)

7 TeV: ~ 5 fb^{-1}

8 TeV: ~ 20 fb^{-1}

(many final results have been just released)





Outline

- Introductory remarks
- Observation of or evidence for Higgs boson in the five main decay channels
    - $H \to ZZ \to 4l$
    - $H \to \gamma\gamma$

      mass (from $H \to ZZ \to 4l$ and $H \to \gamma\gamma$)
    - $H \to WW \to 2l2\nu$
    - $H \to \tau\tau$
    - $H \to bb$
- Searches for rare decay/production modes
    - rare decays: $H \to \mu\mu$, $Z\gamma$, invisible, γQ [$\gamma J/\psi$, $\gamma \Upsilon$]
    - rare production: $pp \to ttH$, $pp \to tHq$
- Properties of the H(125) boson
    - couplings (and BSM implications)
    - spin-parity properties
    - limits on width from probing the far off-shell production
    - differential cross sections: $d\sigma/dp_T$, σ(H + n jets)

References

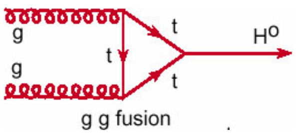
new results from the last 6 months are highlighted in pink

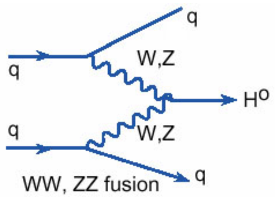
Analysis	ATLAS	CMS
H → ZZ → 4l	Phys. Rev. D91 (2014) 012006	Phys. Rev. D89 (2014) 092007
H → γγ	Phys. Rev. D90 (2014) 112015	Eur. Phys. J. C74 (2014) 10, 3076
H → WW → 2l2ν	arXiv:1412.2641	JHEP 1401 (2014) 096
H → ττ	arXiv:1501.04943	JHEP 1405 (2014) 104
H → bb	JHEP 01 (2015) 069	Phys.Rev. D89 (2014) 012003, CMS PAS HIG-13-011
H → μμ	Phys. Lett. B738 (2014) 68	arXiv:1410.6679
H → Zγ	Phys. Lett. B732 (2014) 8	Phys. Lett. B726 (2013) 587
H → invisible	Phys. Rev. Lett. 112 (2014) 201802	Eur. Phys. J. C74 (2014) 2980
H → Qγ [Q=J/ψ, Υ]	arXiv:1501.03276	
pp → ttH	Phys. Lett. B740 (2015) 222, ATLAS-CONF-2014-011	JHEP 1409 (2014) 087, arXiv:1502.02485
pp → tHq		CMS PAS HIG-14-001, CMS PAS HIG-14-015
mass	Phys.Rev. D90 (2014) 052004	arXiv:1412.8662
combination (couplings, BSM)	update is coming soon	arXiv:1412.8662
spin-parity	Phys.Lett. B726 (2013) 120	arXiv:1411.3441, Phys. Rev. D89 (2014) 092007
anomalous decay amplitudes	coming soon	arXiv:1411.3441
width via off-shell production	ATLAS-CONF-2014-042	Phys. Lett. B736 (2014) 64
differential cross sections	JHEP 09 (2014) 112, Phys. Lett. B738 (2014) 234	coming soon

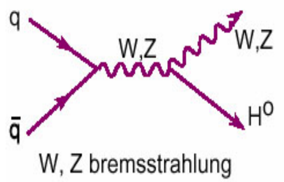
SM Higgs boson production: pp → H

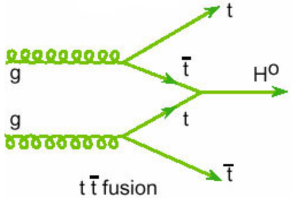
coupling to Higgs boson ~ particle's mass

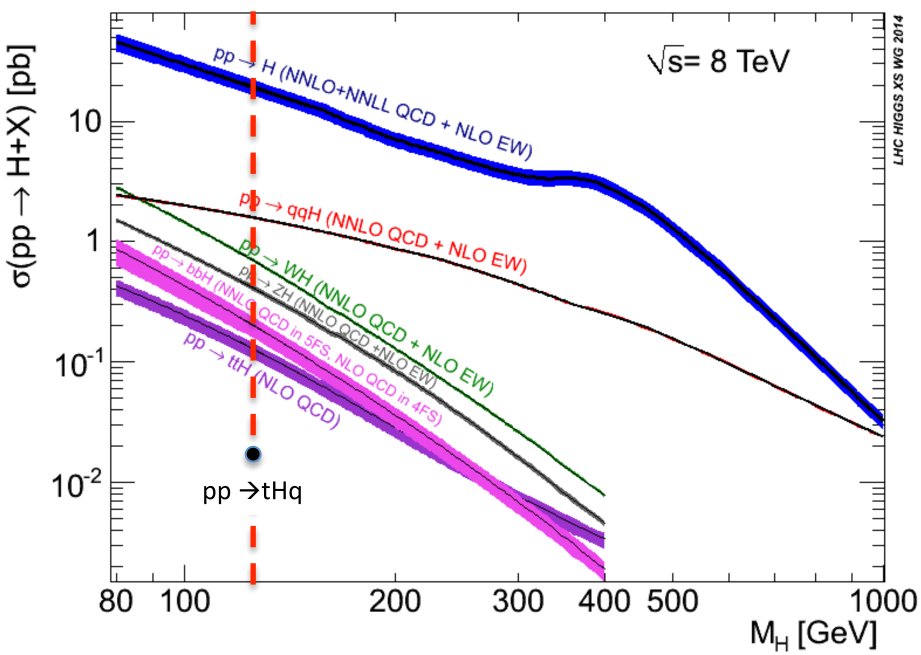
- light quarks and gluons in protons → small/no direct coupling to Higgs boson
- → first produce massive particles, to which Higgs would couple more willingly…

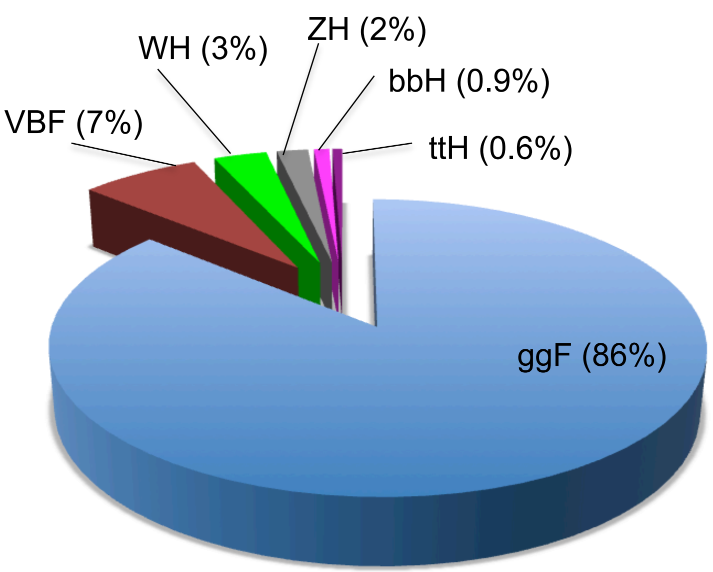












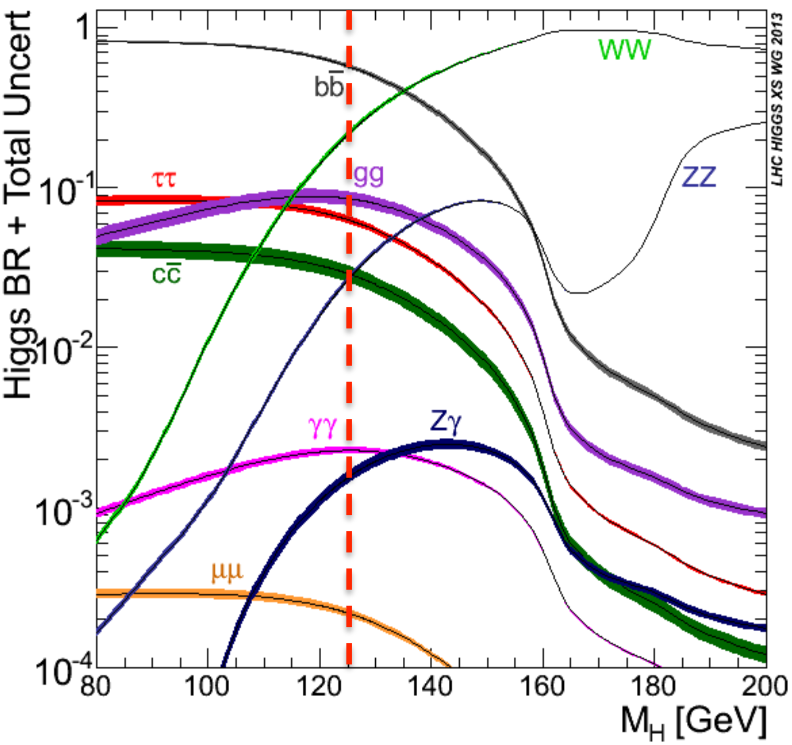
m_H=125 GeV

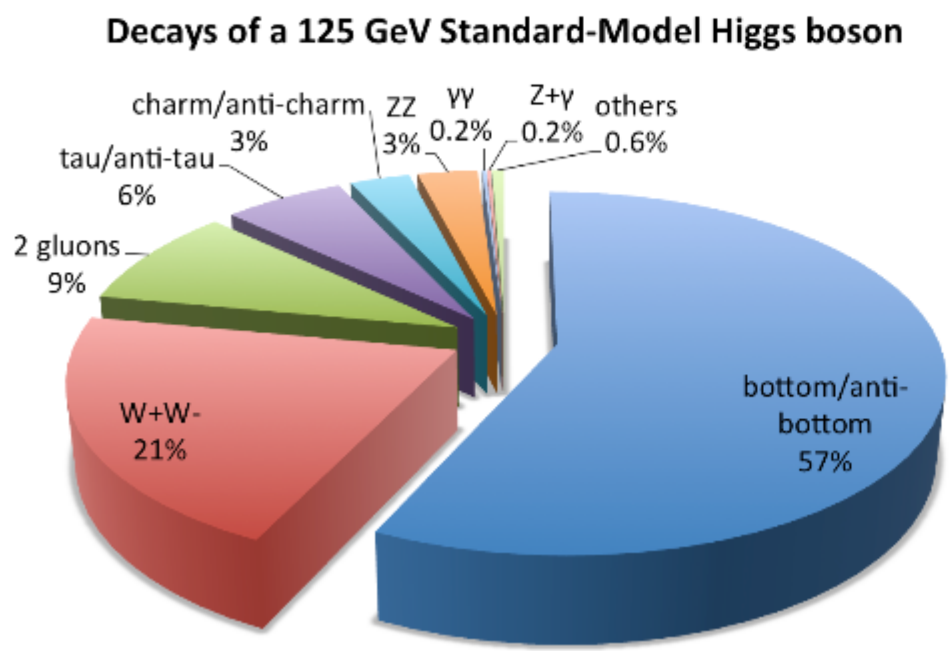
SM Higgs boson decays

coupling to Higgs boson ~ particle's mass

➔ **H "likes" to decay to the heaviest kinematically allowed pair of particles ($m < m_H/2$)**

- **H → WW*, ZZ* do not drop out sharply for $m_H < 2m_W$ and $m_H < 2m_Z$**
- **H → gg, γγ, Zγ (massless final states) are possible via loops with top and W**

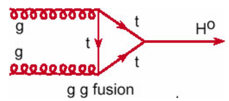


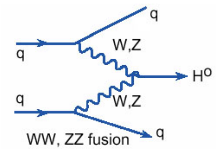


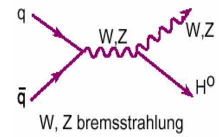
SM Higgs events in Run I (per experiment)

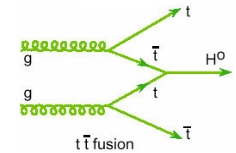
Total number of inelastic pp-collisions produced in Run I: 1.5×10^{15}

Total produced Higgs bosons (m_H=125 GeV): 560,000









	m_H=125 GeV (l=e/μ)		ggF (86%)	VBF (7%)	VH (5%)	bbH (0.9%)	ttH (0.6%)
✓	H → ZZ → 4l	0.013%	72				
✓	H → γγ	0.23%	1,300				
✓	H → WW → lνlν	1.1%	6,100				
✓	H → ττ	6.3%	35,000				
?	H → bb	58%	✗ 270,000	42,000			
–	H → μμ	0.022%	120				
–	H → Zγ → 2l γ	0.010%	56				
–	H → J/ψγ → μμ γ	1.7×10^{-7}	0.1				
–	invisible	0.11%	✗ 590 (too small S/B at LHC, unless there is BSM H→inv)				
	all others	37%	✗ 200,000 (deemed not feasible at LHC)				

all event counts are before:
- detector acceptance
- reconstruction efficiency
- event selection efficiency

LHC future

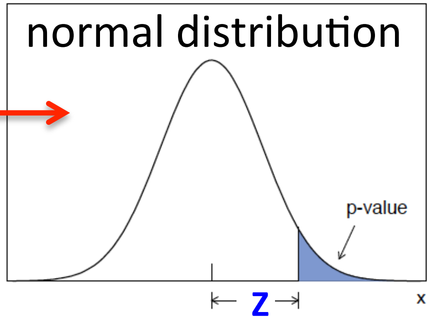
LHC operation in 2010-2012 and projections for the future.

Run period	$\sqrt{s}$ (TeV)	Peak $\mathcal{L}$ (cms^{-2}s^{-1})	$\mathcal{L}_{int}$ (fb^{-1})	
2010-2011	7	0.4×10^{34}	5	
2012	8	0.7×10^{34}	20	
Long Shutdown (LS1)				
2015-2018	13	1×10^{34}	100	→ **(2.3× σ)(4× L) = 10× H**
Long Shutdown (LS2)				
2020-2022	14	1.6×10^{34}	300	→ **(2.6× σ)(12× L) = 30× H**
Long Shutdown (LS3)				
2025-2030+	14	5×10^{34}	3000	→ **(2.6× σ)(120× L) = 300× H**

Signal presence inference

p-value and significance (Z)

$$p\text{-value} = P(\, n \geq n_{obs} \mid b \,)$$



p-value	Z
2.3×10^{-2}	2
1.4×10^{-3}	3
3.2×10^{-5}	4
2.9×10^{-7}	**5**
1.0×10^{-9}	6
1.3×10^{-12}	7

signal strength (μ) – common scale factor for signal event yields

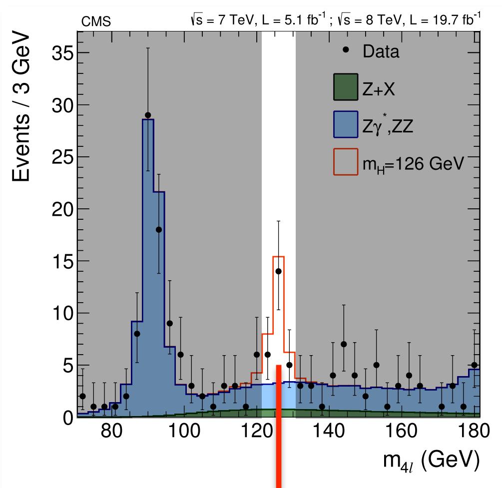
$$n_{\text{expected}} = \mu \cdot [\, \sigma_{\text{SM H}} \cdot B(\text{H}_{\text{SM}} \to xx) \cdot L \cdot \varepsilon \,] + n_{\text{background}}$$

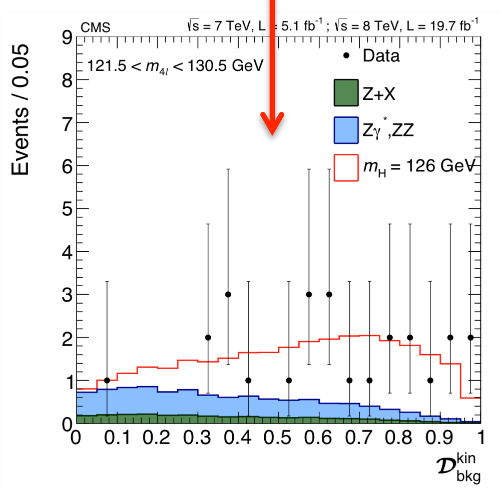
95% CL limits on signal strength (in absence of a significant excess):

$$\mu \text{ is excluded at 95\% CL, if: } \quad \frac{P(\, n \leq n_{obs} \mid b + \mu \cdot s \,)}{P(\, n \leq n_{obs} \mid b \,)} < 0.05$$

Five main channels

σ×B×L = 72 events   H → ZZ → 4l (golden channel)





Event Selection Strategy

- **4 "tight" leptons** (4e, 4μ, 2e2μ, low p_T is important!)
- **final key observables:**
  - **four-lepton mass is the key observable**
  - **ME-kinematic discriminant** (+20% sensitivity)
  - **VBF/VH categories** (<1 expected events)

$$d = \frac{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4\middle|\mathrm{H}\right)\right|^2}{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4\middle|ZZ\right)\right|^2}$$

Backgrounds

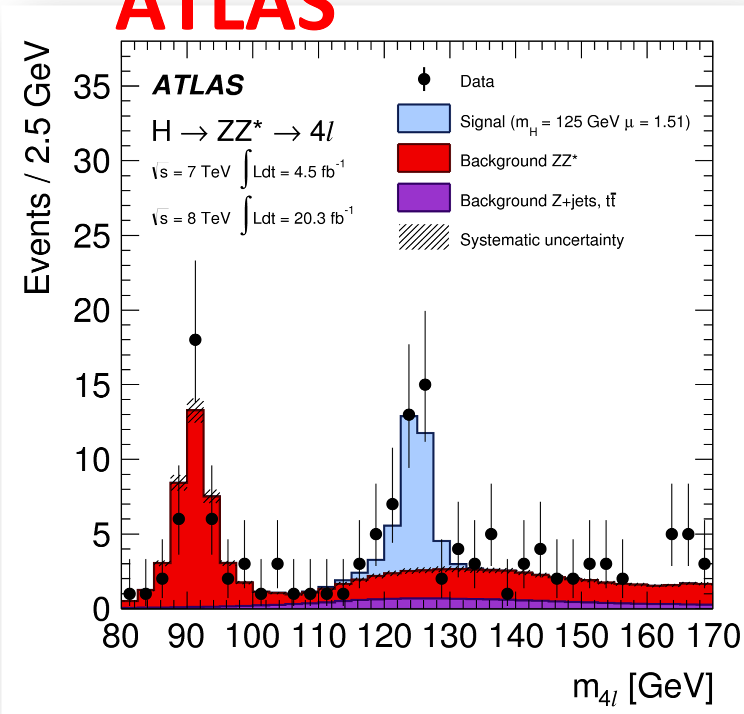
- **ZZ (dominant):** *EWK well calculable process (use MC)*
- **reducible (WZ+jets, Z+jets, tt, WW+jets, …):** *data-driven*

Analysis features to note

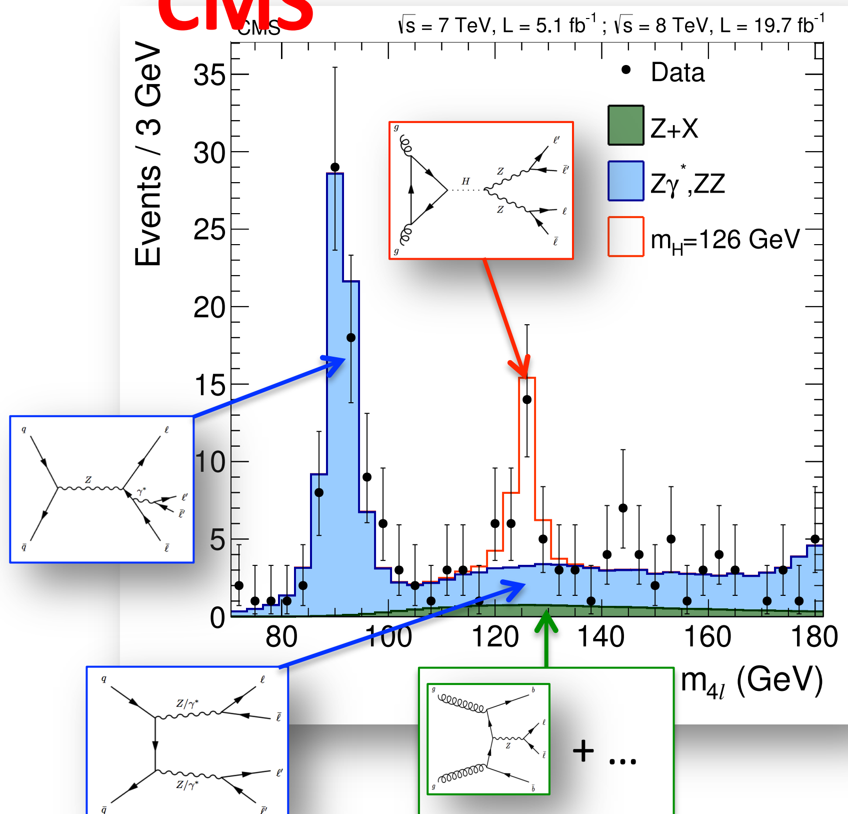
- **small event yield: 20 events**
- **high S/B-ratio: better than 2:1** (best among all)
- **good mass resolution (instrumental): 1-2%**
- **four-body decay, fully reconstructed: spin-parity studies**

H → ZZ → 4l results

ATLAS



CMS



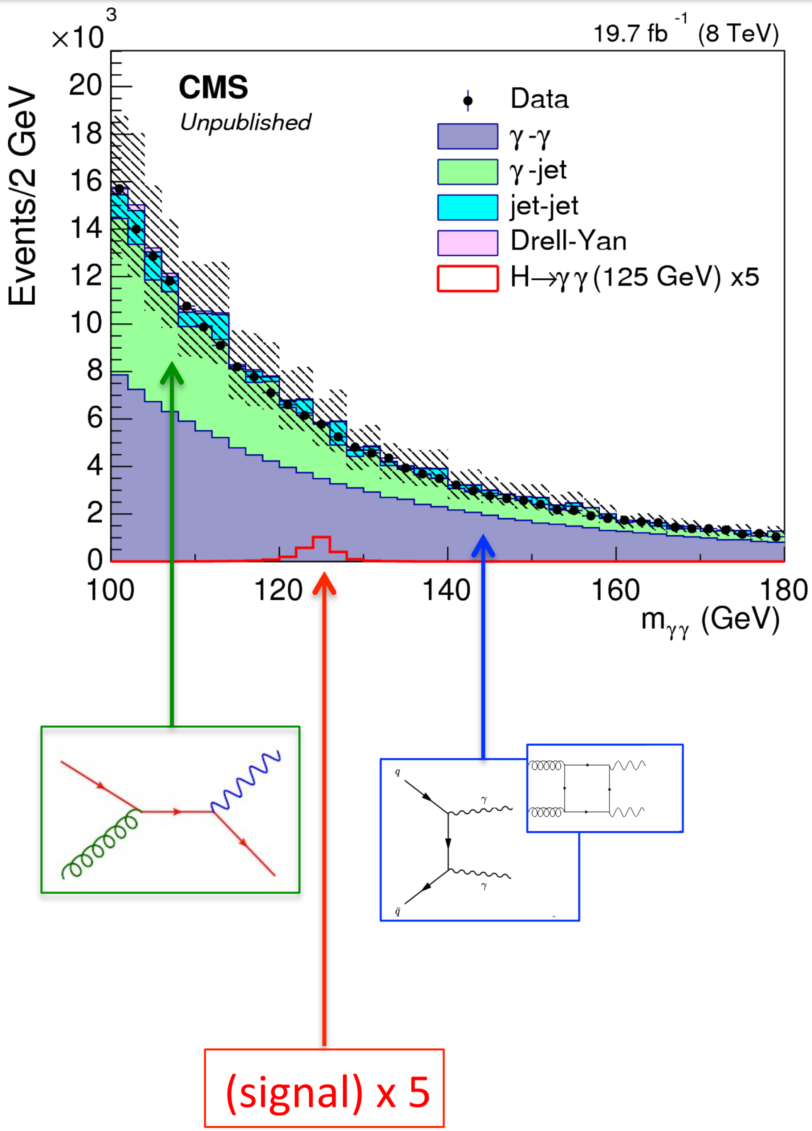
significance = 8.2 (expected 5.8)
signal strength μ = 1.7 ± 0.4
m_H = 124.5 ± 0.5 GeV
Γ_H < 2.6 GeV at 95% CL

μ = 1.4 ± 0.4
@ m_H=125.4

significance = 6.7 (expected 7.2)
signal strength μ = 0.9 ± 0.3
m_H = 125.6 ± 0.4 GeV
Γ_H < 3.4 GeV at 95% CL

σ×B×L = 1.3K events

H → γγ



Event Selection Strategy

- 2 “tight” high-p_T photons → $m_{\gamma\gamma}$
- vertex:
  - CMS: recoiling charged particles only
  - ATLAS: pointing EM showers (thanks to longitudinal segmentation of the EM calorimeter)
- key observable: di-photon mass
- split events into exclusive categories:
  - di-jet/MET/e/μ tagged (VBF and VH like)
  - untagged events are further sorted into a number of classes based on the quality of photons

Backgrounds

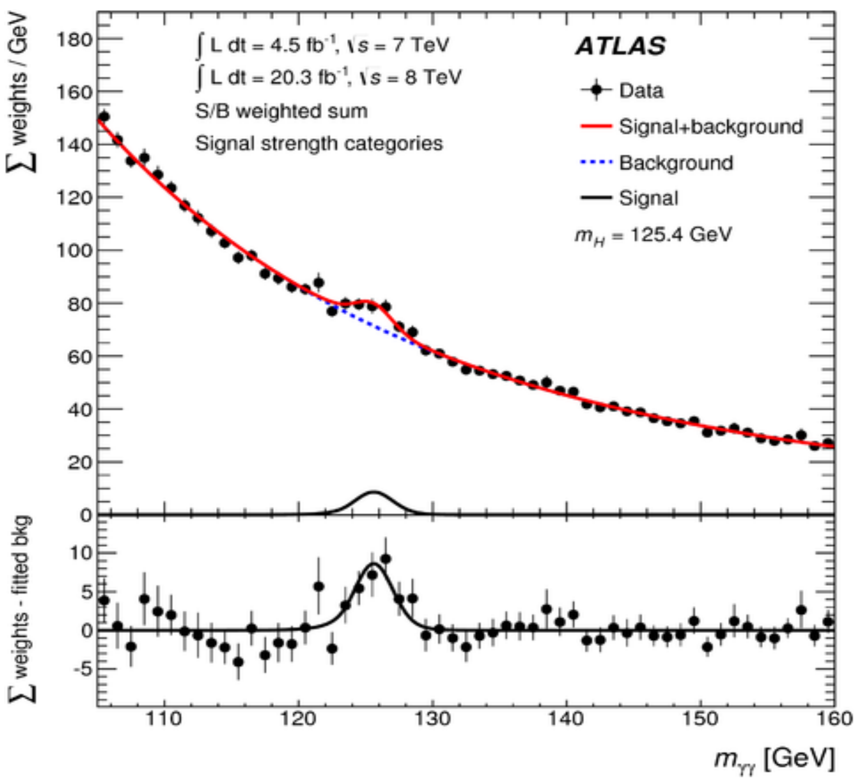
- 70% from prompt γγ, 30% from jet+γ, …
- *entire background = fit of $m_{\gamma\gamma}$-distribution fit*

Analysis features to note

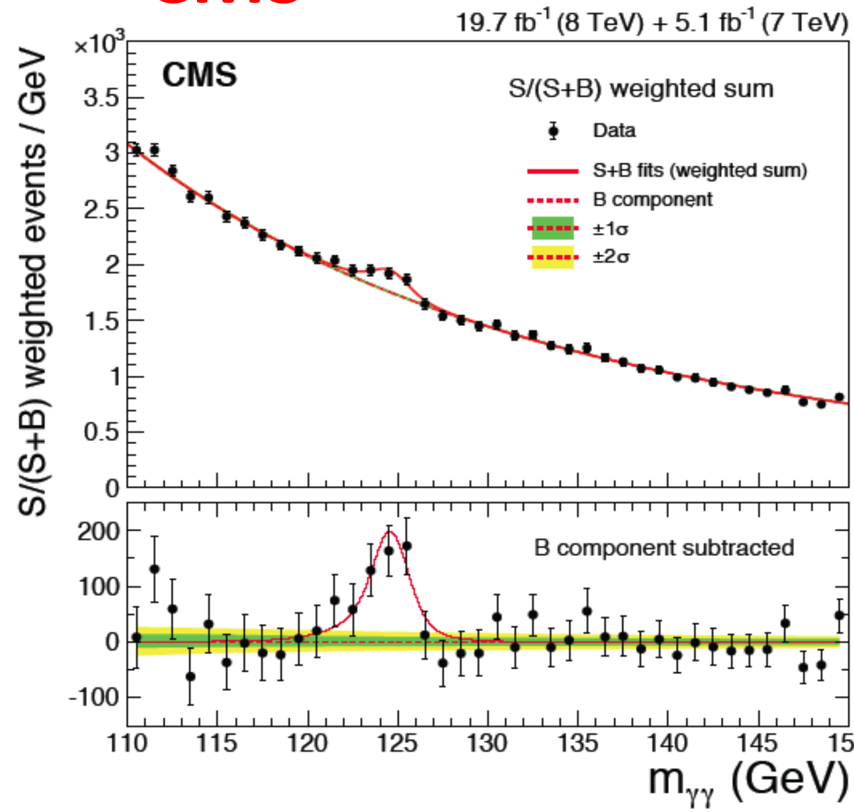
- fairly high event yield: 470 events
- bad “effective” S/B-ratio: 1:20
- good mass resolution (instrumental): 1-2%

H → γγ results

ATLAS



CMS



significance = 5.2 (expected 4.6)
signal strength μ = 1.2 ± 0.3

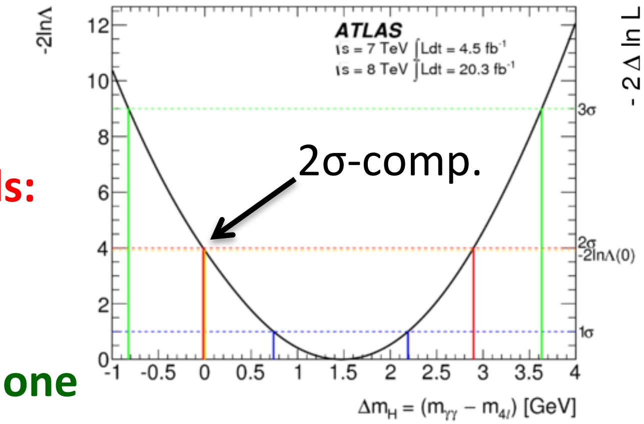
@ m_H=125.4

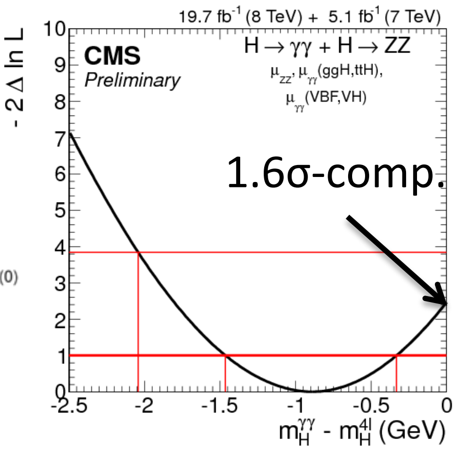
m_H = 126.0 ± 0.5 GeV
Γ_H < 5.0 GeV at 95% CL

significance = 5.7 (expected 5.2)
signal strength μ = 1.1 ± 0.3
m_H = 124.7 ± 0.4 GeV
Γ_H < 3.4 GeV at 95% CL

Combined ZZ + γγ mass measurement

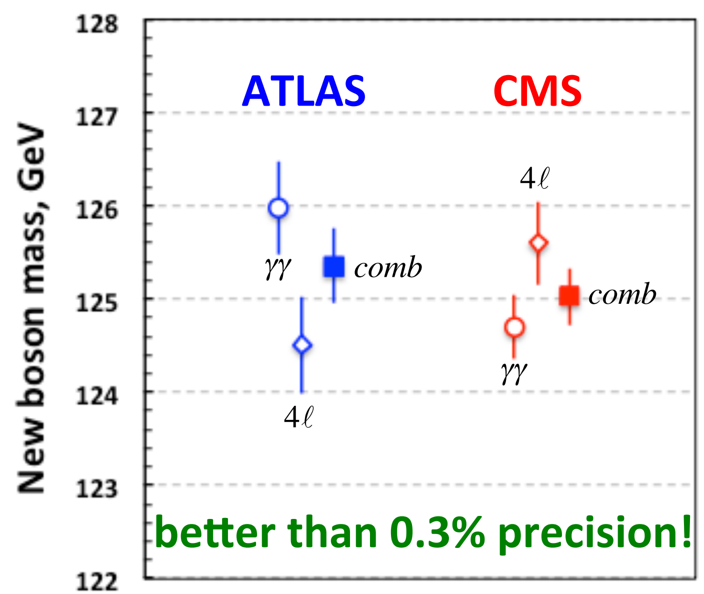
A narrow resonance
is seen with high significance
in the two good-mass-resolution channels:
ZZ(4l) and γγ





Mass measurements are consistent with one particle:

- ATLAS: 2.0σ-compatibility
- CMS: 1.6σ-compatibility

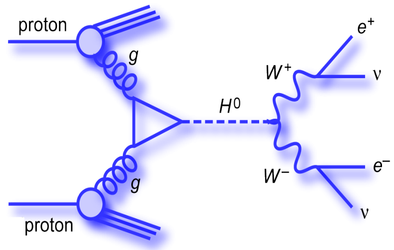


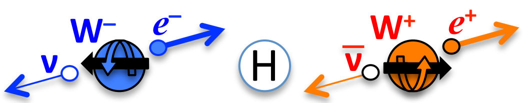
Proceed with a combined mass measurement

Do not assume that ZZ and γγ event rates are tied to each other by the SM expectations

ATLAS: m_H = 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV
CMS: m_H = 125.03 ± 0.27 (stat) ± 0.14 (syst) GeV

σ×B×L = 6.1K evts   H → WW → lνlν

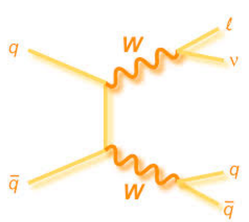


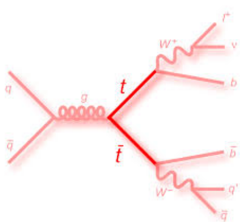


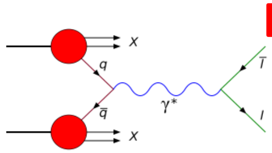
Higgs (spin=0) ==> small dilepton mass

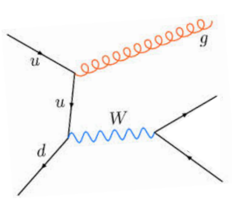
Event Selection Strategy

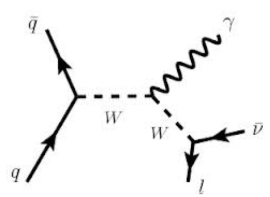
- two "tight" leptons (ee, μμ, eμ) + MET
- main discriminating observables:
  - m_T - transverse mass m_T = inv. mass of $\left(m_{\ell\ell}, \vec{p}_T^{\,\ell\ell}\right)$ and $\left(0, \vec{p}_T^{\,miss}\right)$
  - m_{ll} - di-lepton mass (tends to be small for H→WW)
  - p_T of sub-leading lepton (tends to be small for H→WW*)
- split events into exclusive categories:
  - untagged: 0- and 1-jet separately (tt background!)
  - VBF di-jet tag
  - ATLAS: gg-fusion di-jet tag
  - CMS: VH di-jet tag, WH -> 3l3ν, ZH -> 2l+lν+jj











Backgrounds (many!)

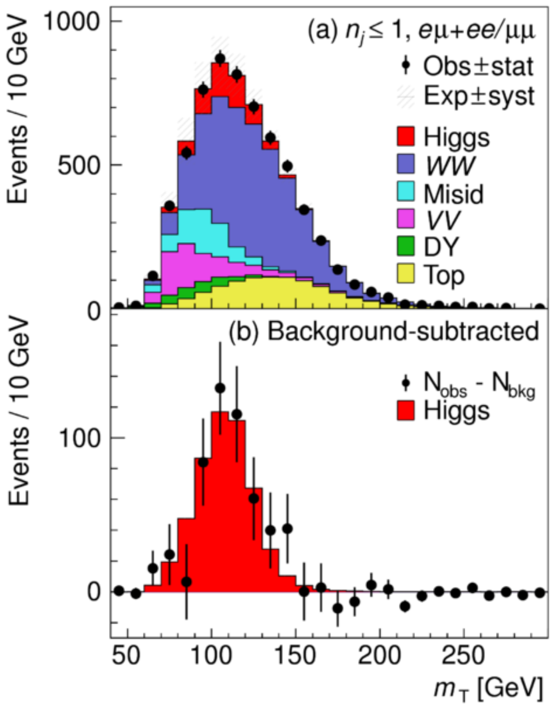
- WW, tt, DY+jets, W+jets, Wγ: *data-driven*
- ZW, ZZ: *from simulation*

Analysis features to note

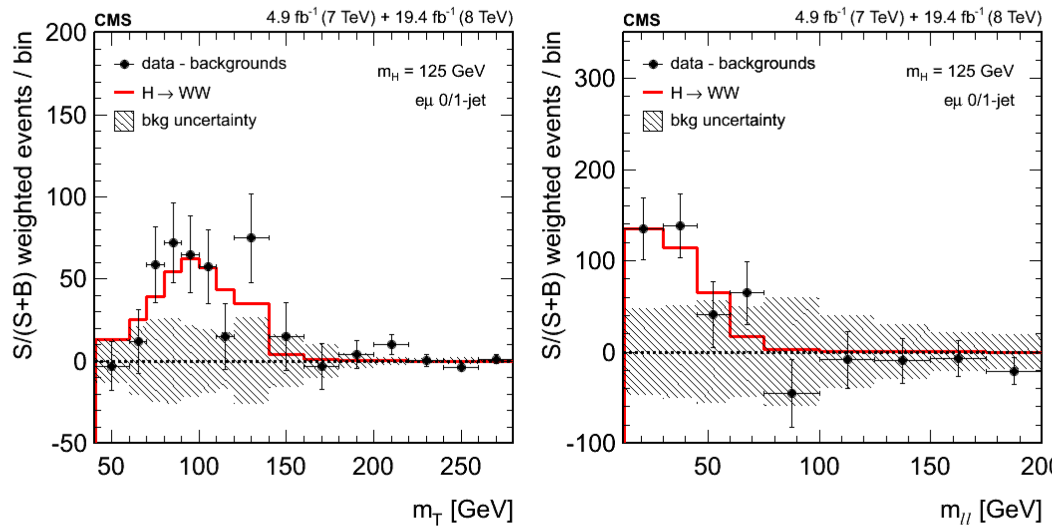
- fair signal event yield: **270**
- not-too-good "effective" S/B-ratio: **1:10**
- poor mass resolution (neutrinos!): **15%**

H→WW→2l2ν

ATLAS



CMS



significance: 6.1 (expected 5.8)
signal strength: μ = 1.1 ± 0.2 @ m_H=125.4

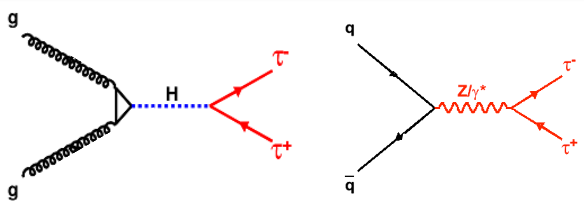
significance: 4.3 (expected 5.8)
signal strength: μ = 0.7 ± 0.2 @ m_H=125.6

m_H = 128 ± ?? GeV mass uncertainty not quoted

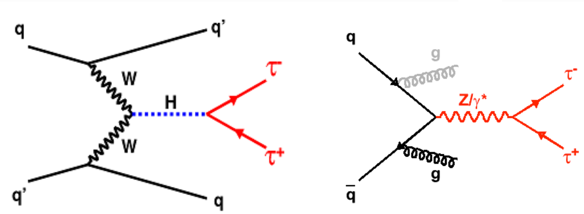
m_H = 128 ± 6 GeV

σ×B×L = 35K events

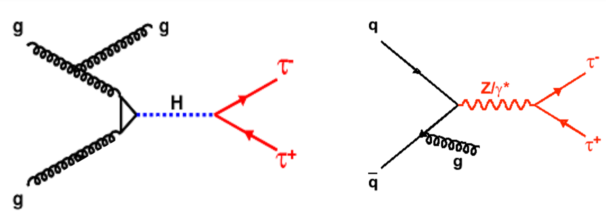
H → ττ



Drell-Yan is too large…



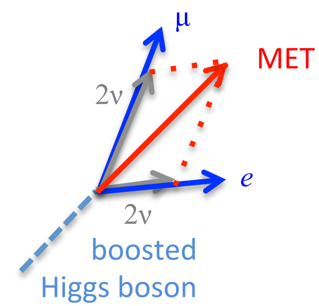
VBF-like jets: DY is suppressed a lot



1 jet: DY gets suppressed more

Event Selection Strategy

- **di-tau candidates ($e\tau_h$, $\mu\tau_h$, $e\mu$, ee, $\mu\mu$, $\tau_h\tau_h$) + MET**
- **key observable: di-tau mass (including MET)**
- **most-important event categories:**
  - **2-jets (VBF-tag):** usual reasons
  - **1-jet:** *gg→H vs qq→Z*
  - **high/low $p_T(\tau\tau)$:**
    - *better di-tau mass resolution*
    - *also, helps with gg→H vs qq→Z*



Backgrounds (many!)

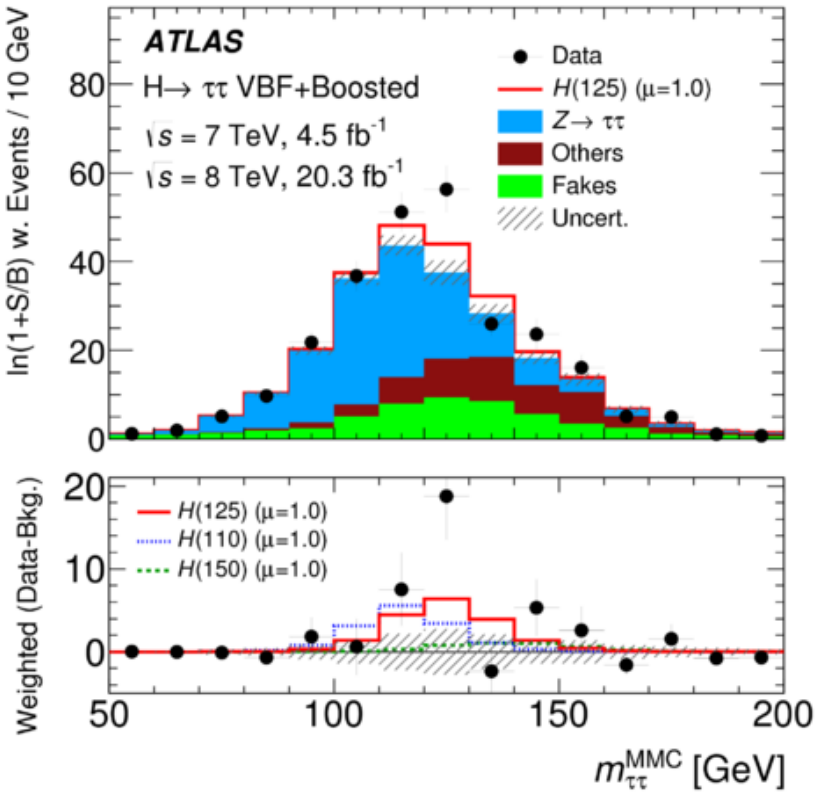
- **Z→ττ, Z→ee, tt, W-jets, QCD:** *from control regions*
- **di-bosons:** *from simulation*

Analysis features to note

- **small signal event yield: 400 events**
- **poor "effective" S/B-ratio: 1:50**
- **Higgs boson "blip" is on the falling slope of the Z peak**
- **mass resolution (neutrinos!): 10%($\tau_h\tau_h$), 15%($l\tau_h$), 20%(ll)**

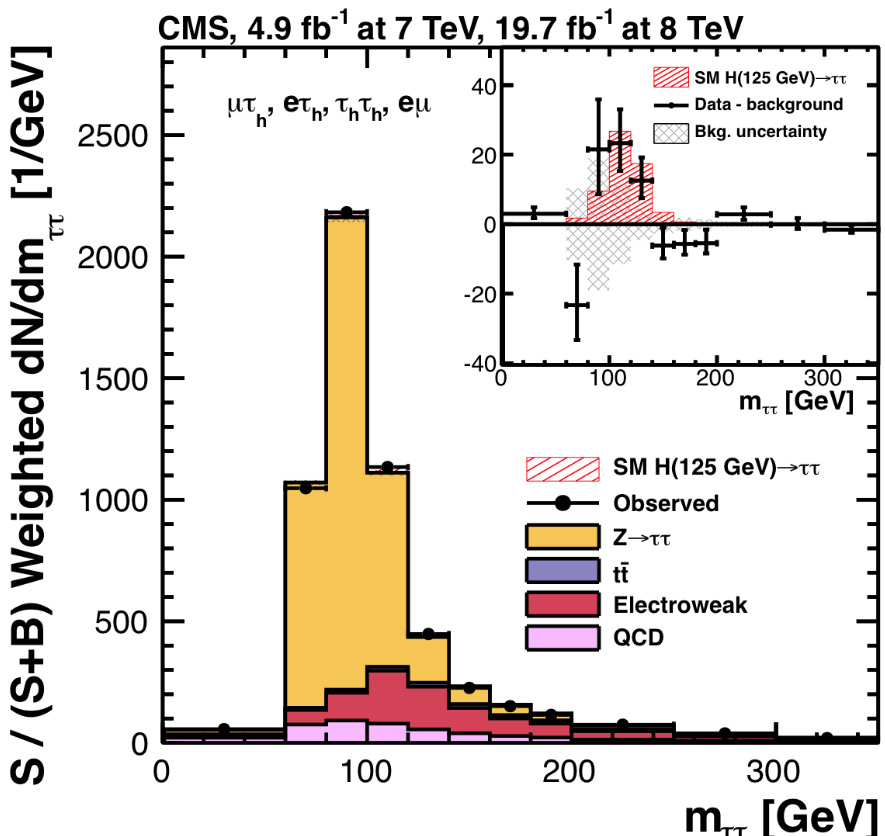
H→ττ

ATLAS



significance: 4.5 (expected 3.4)
signal strength: μ = 1.4 ± 0.4 @ m_H=125.4

CMS

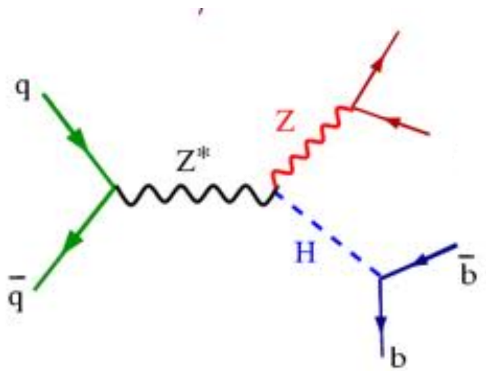


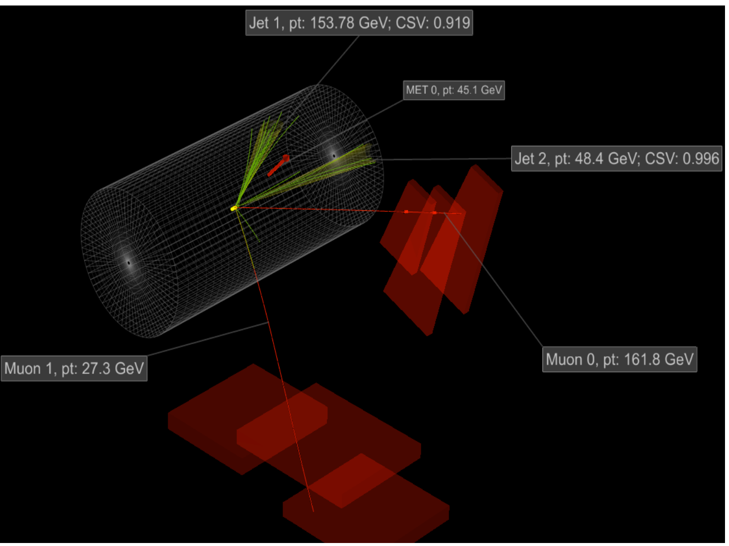
significance: 3.2 (expected 3.7)
signal strength: μ = 0.8 ± 0.3 @ m_H=125

m_H = 122 ± 7 GeV

σ×B×L = 310K events

H→bb





Event Selection Strategy

- **Two b-tagged jets** (QCD bkg is huge!!!)
- **Target VH production** (**16K events**); split into categories:
  - **Z(νν)-tag: ~30 events**
  - **Z(ll)-tag: ~10 events**
  - **W(lν)-tag: ~20 events**
  - **CMS: W(τ_hν)-tag (1 event)**

after all selection cuts

- **split event further by p_T(V)**
  - **higher p_T(V): better S:B, better δm_{bb}**
- **key observable:**
  - **MVA of many observables (** **m_{jj} is the most important)**

Main backgrounds (many!)

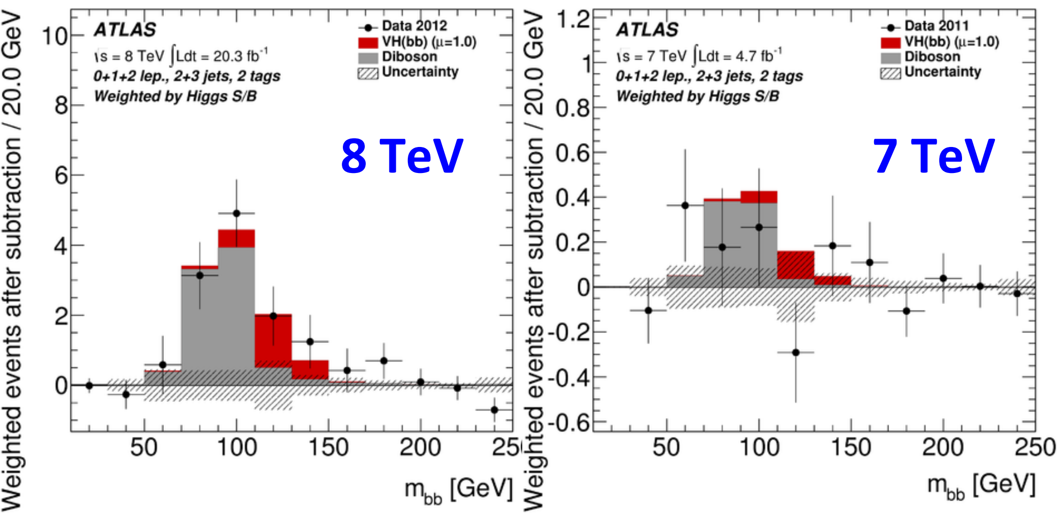
- **Vbb, V+jets, ttbar, single-top:** *from control regions*
- **di-boson:** *from simulation*

Analysis features to note

- **small signal event yield: 60 events**
- **poor "effective" S/B-ratio = 1:20**
- **not-too-good mass resolution (jets): 10%**

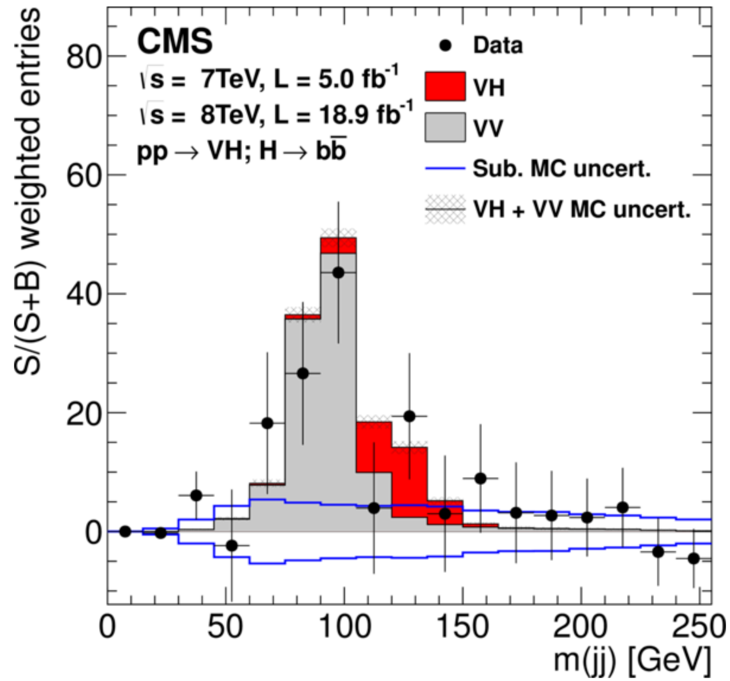
pp → VH, H→bb

ATLAS



significance: 1.4 (expected 2.6)
signal strength: μ = 0.5 ± 0.4 @ m_H=125.4

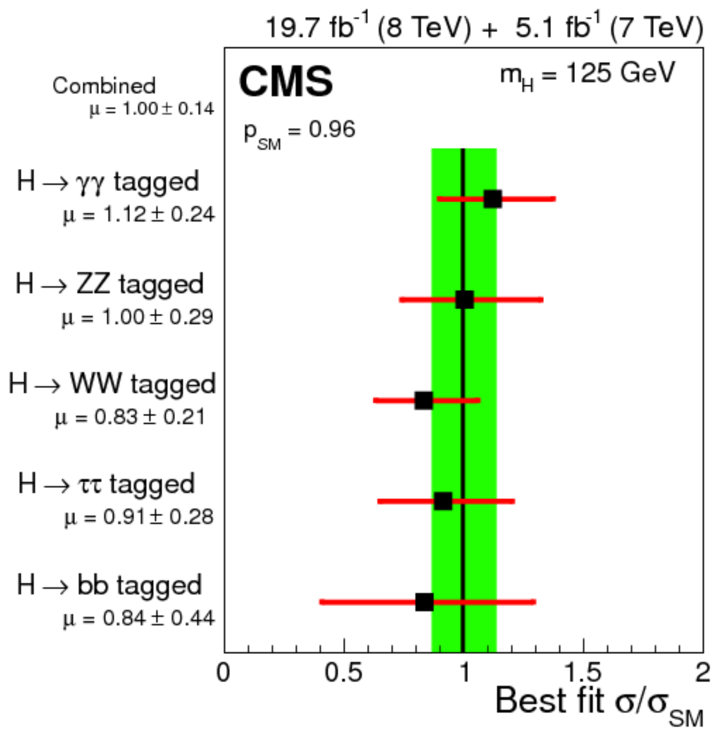
CMS

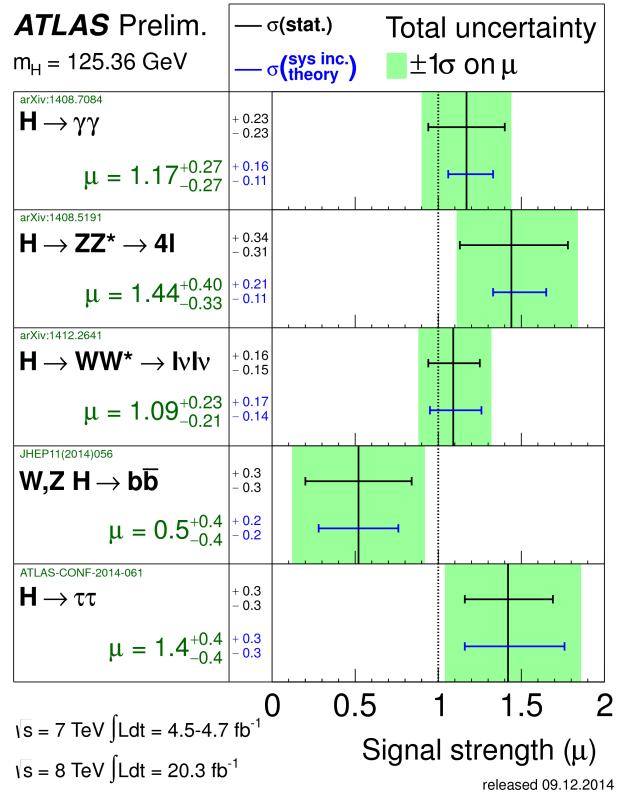


significance: 2.1 (expected 2.0)
signal strength: μ = 1.0 ± 0.5 @ m_H=125

CMS also has a preliminary result for VBF H→bb:
At m_H=125: μ = 0.9 ± 1.9 (<4.9 @ 95% CL)

Main five channels: best-fit signal strengths μ





CMS: μ = 1.00 ± 0.09 (stat) ± 0.07 (syst) ± 0.08 (theory)
ATLAS: μ = 1.30 ± 0.12 (stat) ± 0.09 (syst) ± 0.10 (theory)

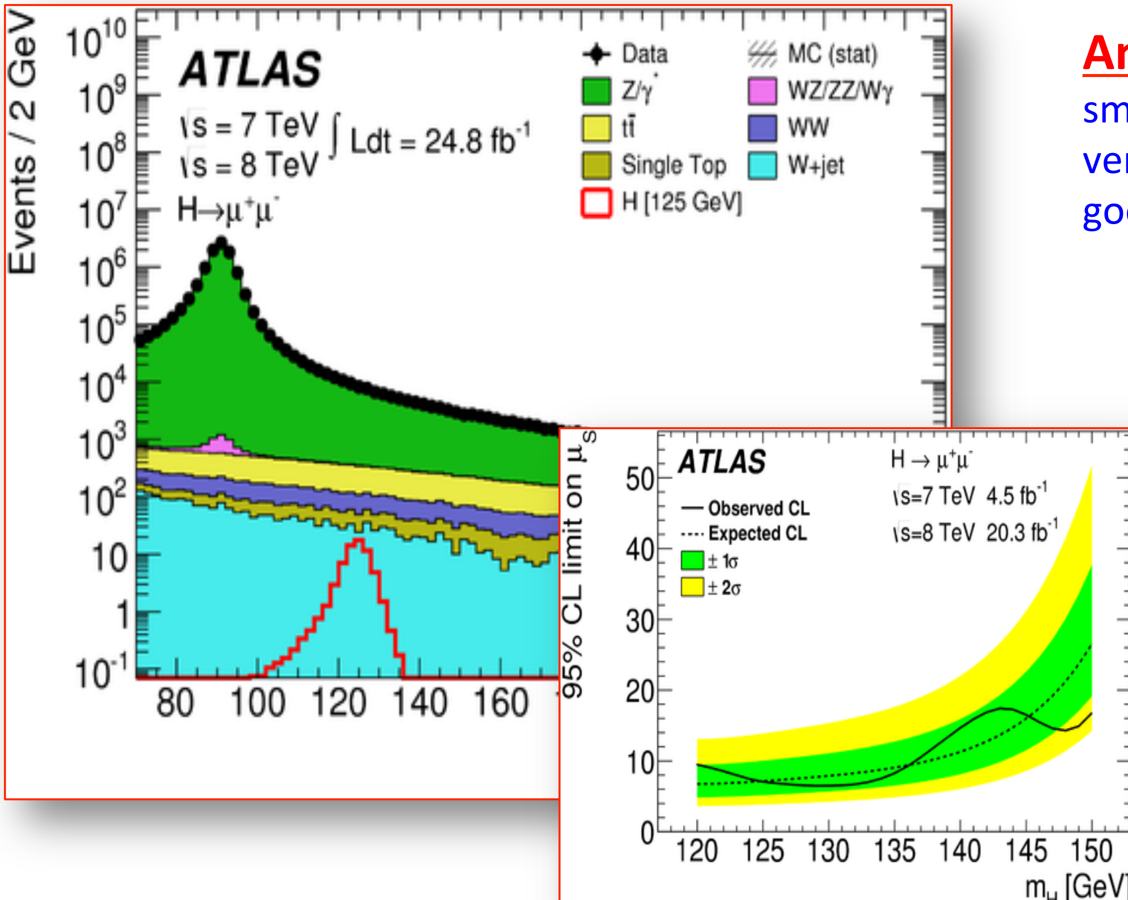
[to be updated soon]

NB: experimental precision is already comparable to theoretical uncertainties on cross sections

Rare decays and production modes

Search for rare decays H→μμ

σ×B×L = 120 events



Analysis features to note

small signal: **~45 events**

very bad "effective" S/B-ratio: **~1:150**

good mass resolution: **1-2%**

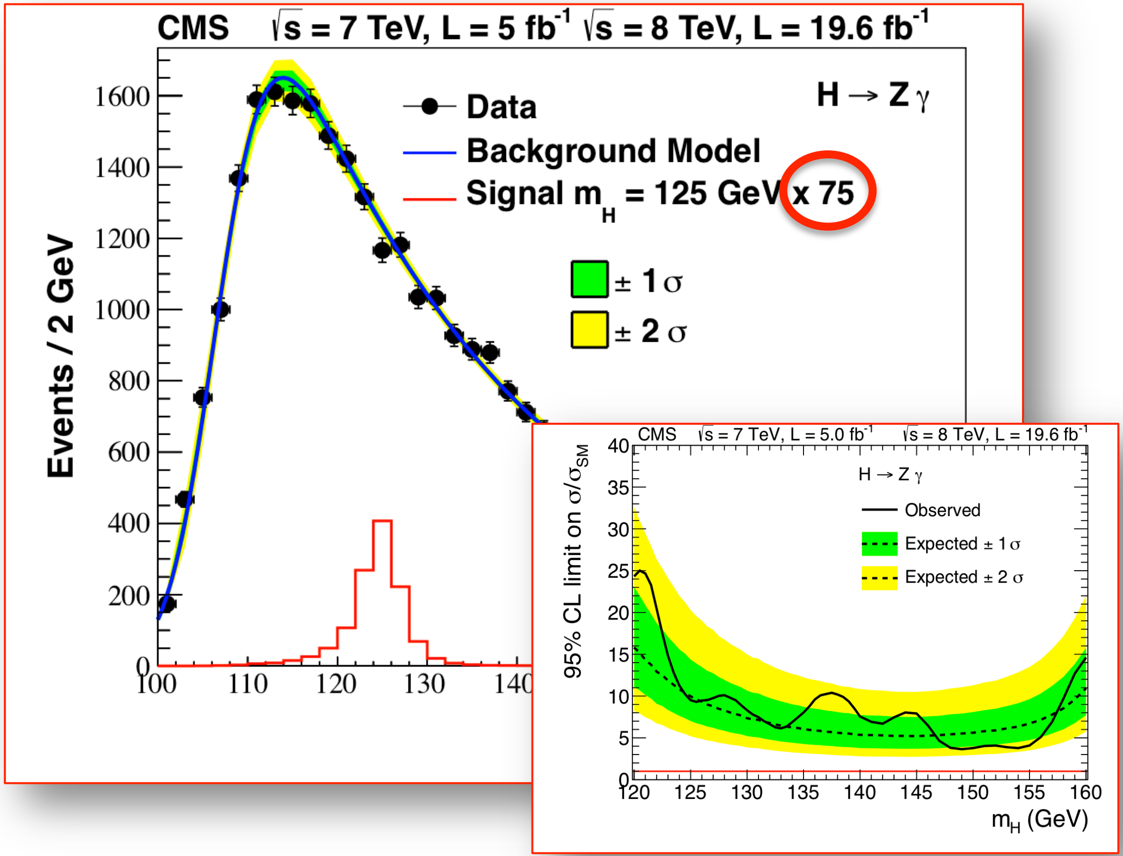
ALTAS: μ < 7.0 (7.2 exp.)

CMS: μ < 7.4 (6.5 exp.)

Naively, 50ˣ more data for a 2σ-signal

Search for rare decays H→Zγ

σ×B×L = 56 events



Analysis features to note

small signal: ~**15 events**

very bad "effective" S/B-ratio: ~**1:200**

good mass resolution: **1-2%**

ALTAS: μ < 11 (9 exp.)

CMS: μ < 10 (10 exp.)

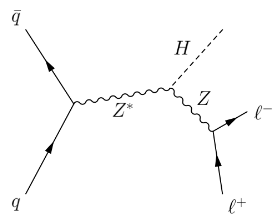
Naively, 100ˣ more data for a 2σ-signal

Search for rare H → inv

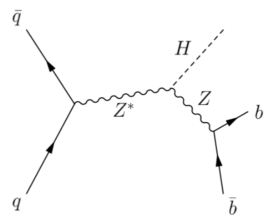
SM: B(H→ZZ→inv) = 0.0011 (not observable at LHC)

σ×B×L = 590 events

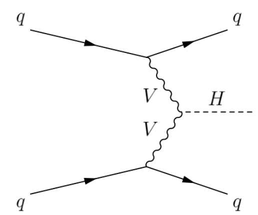
BSM: B(H→χχ) = ???



ATLAS and CMS



CMS



CMS

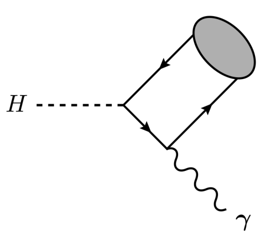
ATLAS: B(H → inv) < 0.75 (expected <0.62)
CMS: B(H → inv) < 0.58 (expected <0.44)

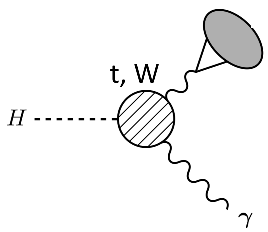
interesting connection to direct Dark Matter searches

See talks by *Luca Mastrolorenzo* and *Rami Vanguri* for details

Search for rare H→ J/ψ γ and H→Υγ

Probe of a Higgs-charm coupling?

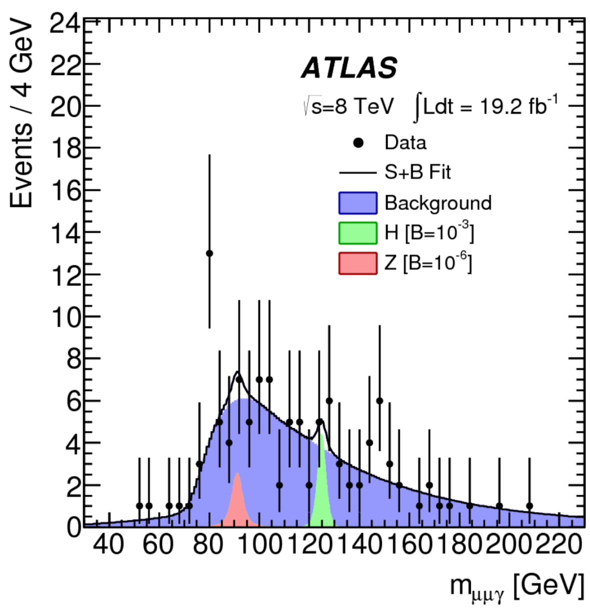




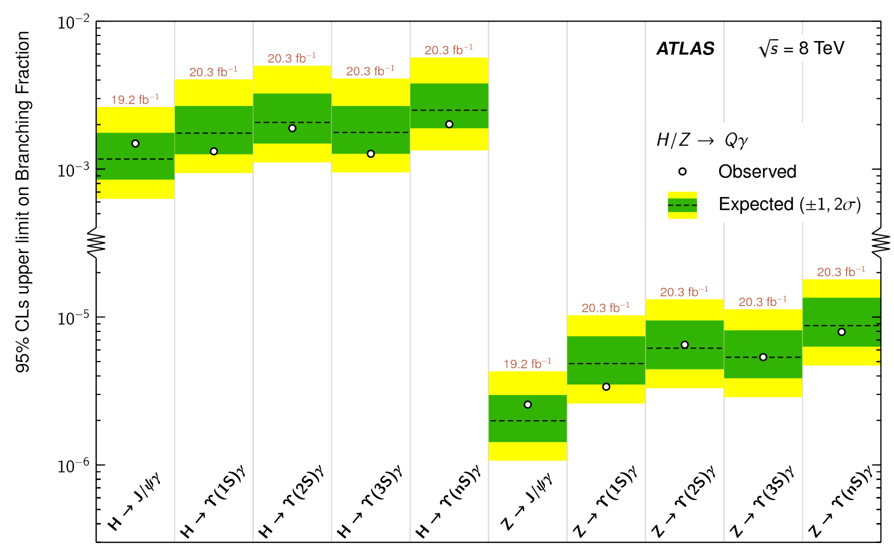
SM Higgs: B(H → J/ψ γ) = 2.8×10^{-6}

B(J/ψ → μμ) = 0.06

σ×B(μμγ)×L = 0.1 events



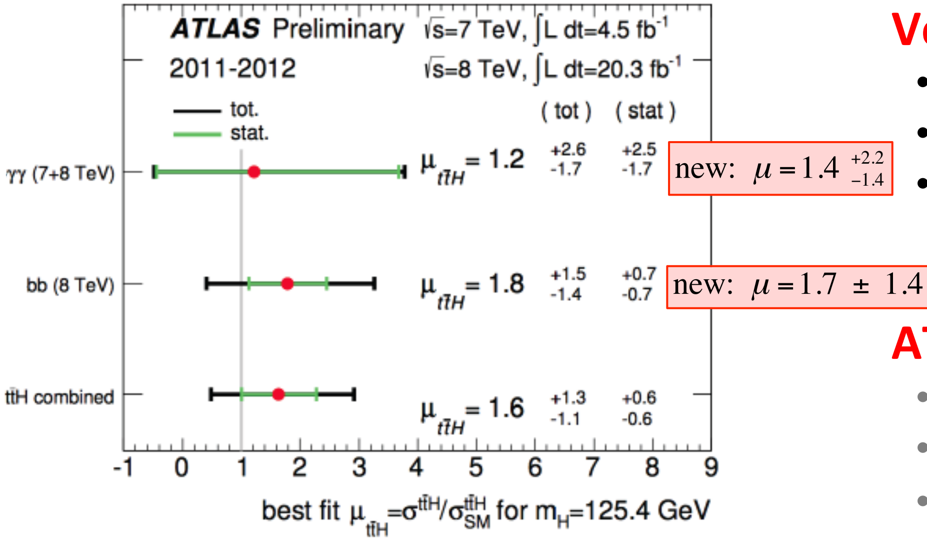
| $m_{\mu\mu} - m_{J/\psi}$ | ≤ 0.2 GeV

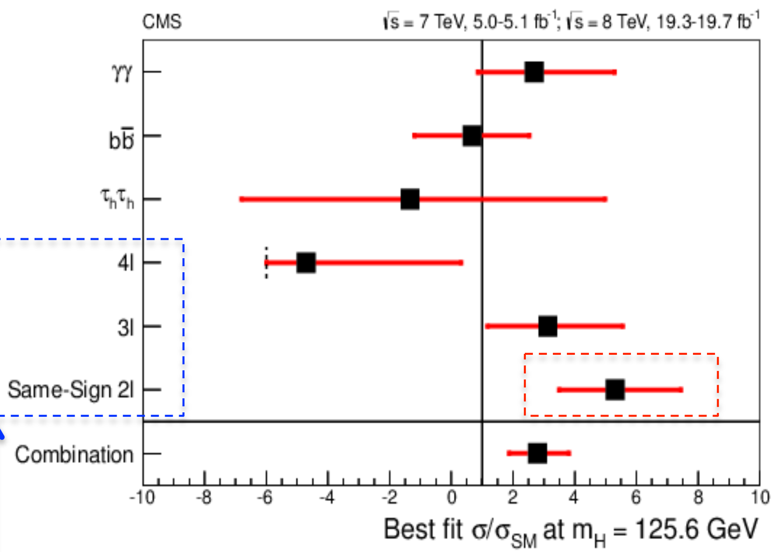


ATLAS: B(H → J/ψγ) < 1.5 × 10^{-3}

Not too promising even for HL-LHC…

Search for rare pp → ttH production





multi-leptons:
H → WW/ZZ/ττ + leptons from t → Wb

Very challenging search

- very few events are expected: σ×L = 3K events
- tt background is BAD: ttH : tt ≈ 1 : 2,000
- all other Higgs production mechanisms (99.4%) must be suppressed as well

ATLAS (to be updated soon)

- expected sensitivity: 0.7σ
- 1σ-excess observed
- μ = 1.6 ± 1.4
- results are compatible with signal and no-signal

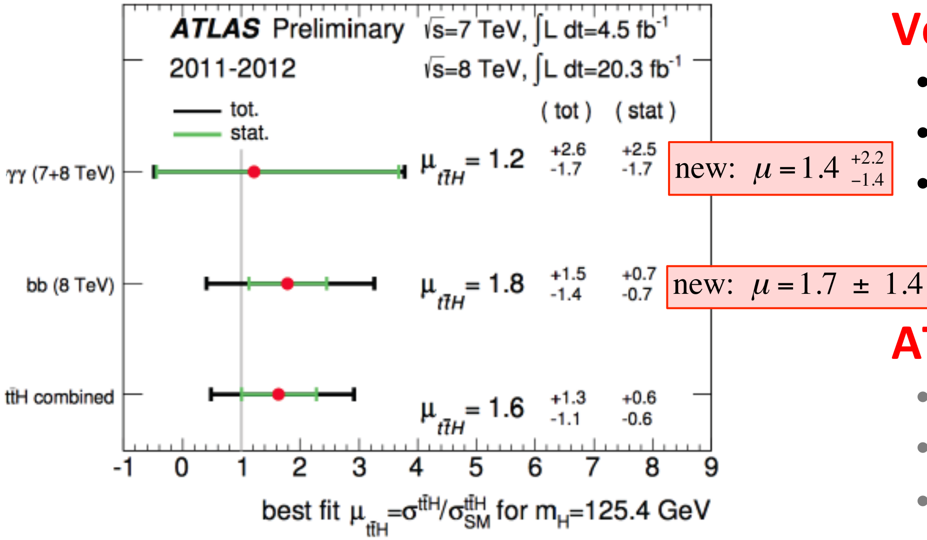
CMS

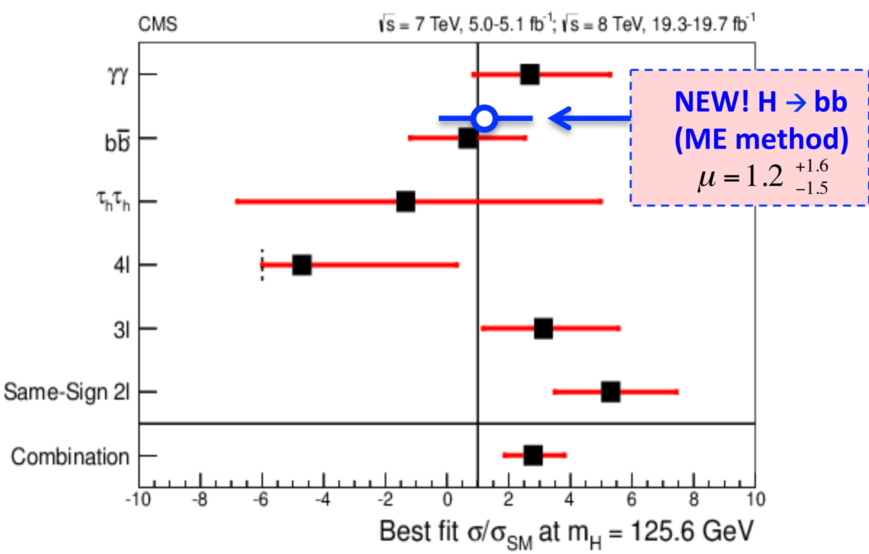
- expected sensitivity: 1.2σ
- 3.4σ-excess observed
- μ = 2.8 ± 1.0
- 2% compatibility with SM signal (2σ)

More data are needed

Just before LHC start-up, prospects for measuring ttH were thought to be very slim. Now this channel looks feasible!

Search for rare pp → ttH production





Very challenging search

- **very few events are expected: σ×L = 3K events**
- **tt background is BAD: ttH : tt ≈ 1 : 2,000**
- **all other Higgs production mechanisms (99.4%) must be suppressed as well**

ATLAS (to be updated soon)

- expected sensitivity: 0.7σ
- 1σ-excess observed
- μ = 1.6 ± 1.4
- results are compatible with signal and no-signal

CMS

- expected sensitivity: 1.2σ
- 3.4σ-excess observed
- μ = 2.8 ± 1.0
- 2% compatibility with SM signal (2σ)

More data are needed

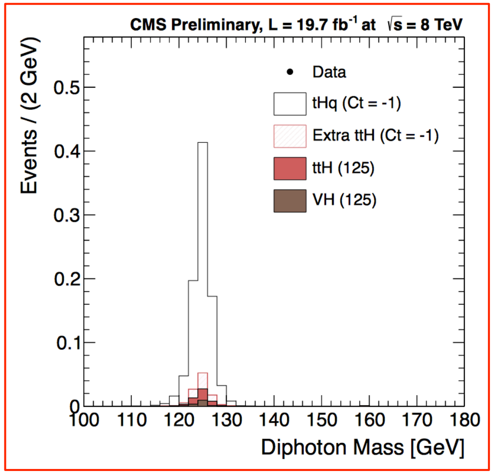
Just before LHC start-up, prospects for measuring ttH were thought to be very slim. Now this channel looks feasible!

Search for rare pp → tHq production

Very challenging search

- two diagrams nearly cancel out (negative interference)
- cross section: 18 fb
- pp→tHq→(blν)(γγ)q: σ×L = 0.2 events
- pp→tHq→(blν)(bb)q: σ×L = 60 events
- should one flip relative sign of Higgs-top and Higgs-W couplings, cross section becomes 234 fb (13$^{\times}$ SM !!!)

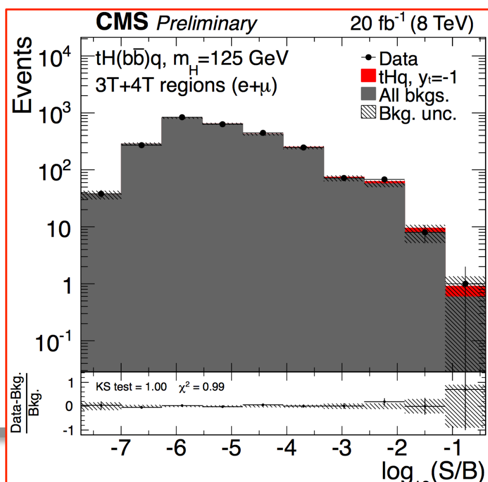
H → γγ



pp→tHq→(blν)(γγ)q

- expected limits (SM): μ < 4.1×13 = 52 at 95% CL
- observed limit (SM): μ < 4.1×13 = 52 at 95% CL

H → bb



pp→tHq→(blν)(bb)q

- expected limits (SM): μ < 5.2×13 = 66 at 95% CL
- observed limit (SM): μ < 7.6×13 = 97 at 95% CL

Future (SM Higgs)

H→γγ may be feasible in future (currently, stat limited with zero bkg)

H→bb: not clear (already systematics limited)

Couplings (and BSM implications)

Combination for couplings

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

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

- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- $\Gamma_{\mu\mu}$
- Γ_{gg} (loop induced)
- Γ_{tt}
- $\Gamma_{TOT} = \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{bb} + \ldots + \Gamma_{BSM}$
- gray: not yet used in combination
- **Note degeneracy: scaling Γ_{TOT} by κ^2 and all Γ_{xx} and Γ_{yy} by κ does not change rates**

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

Couplings: compatibility with SM

- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- $\Gamma_{\mu\mu}$ → κ_μ
- $\Gamma_{\gamma\gamma}$ (loop) → κ_W, κ_t
- Γ_{gg} (loop) → κ_t, κ_b
- Assume:
  - $\Gamma_{BSM}=0$, or B(H→BSM)=0
  - couplings to the 1st, 2nd, 3rd generations are modified the same way

Couplings: compatibility with SM

- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
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- $\Gamma_{\mu\mu}$ → κ_μ
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- Assume:
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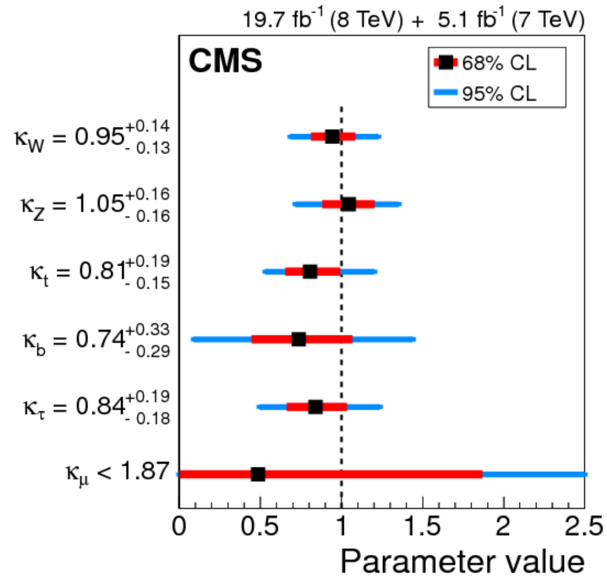

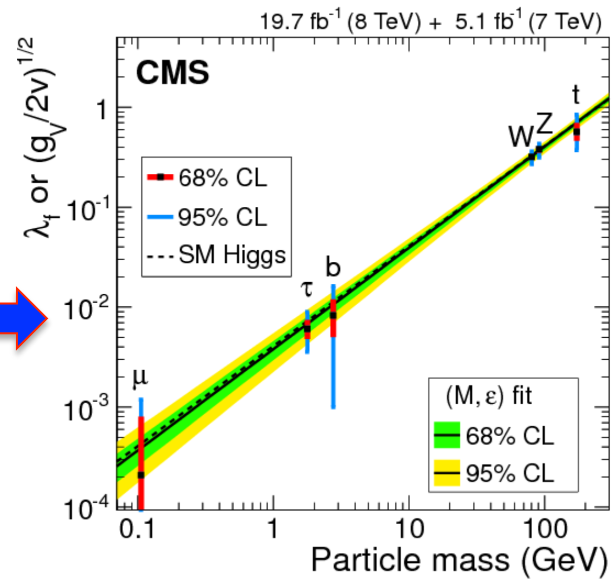

Summary:

- Good compatibility with the SM Higgs couplings (current accuracy: 20-50%)
- NB: range of couplings tested is $O(10^3)$

Couplings: search for new physics

- Γ_{ZZ} — custodial symmetry
- Γ_{WW} — assume: $\kappa_Z = \kappa_W$ → κ_V
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- Γ_{tt} → κ_t
- Γ_{gg} (allow BSM in loop) → κ_g
- $\Gamma_{\gamma\gamma}$ (allow BSM in loop) → κ_γ
- assume B(H→BSM)=0

Couplings: search for new physics

- Γ_{ZZ} — custodial symmetry
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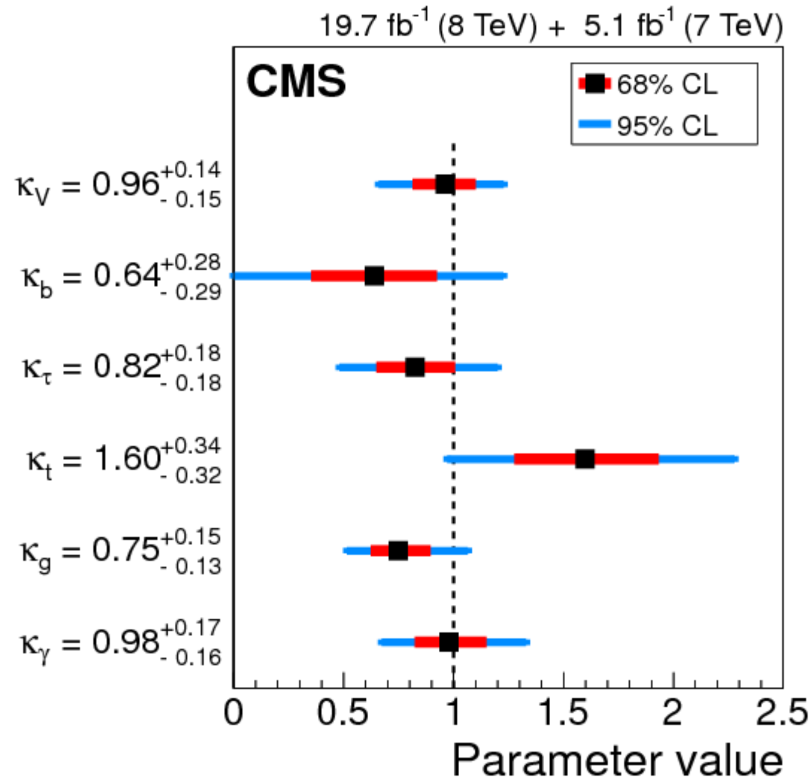


Summary:

- κ_g and κ_γ remain close to 1, implying no new physics in the loops
- accuracy on the top-quark coupling is now solely defined by the ttH analysis

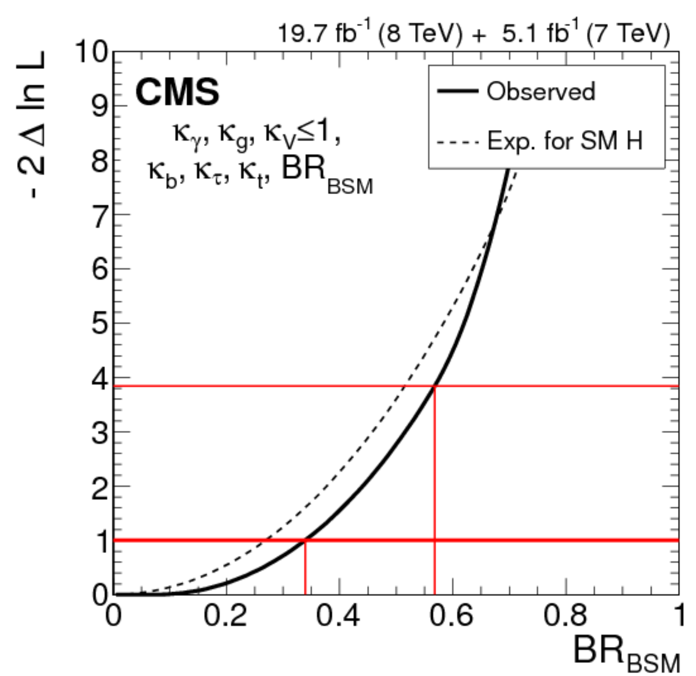
Couplings: search for new physics

- Γ_{ZZ} custodial symmetry
- Γ_{WW} assume: $\kappa_Z = \kappa_W$ → κ_V
- $\Gamma_{\tau\tau}$ → κ_τ
- Γ_{bb} → κ_b
- Γ_{tt} → κ_t
- $\Gamma_{\gamma\gamma}$ (allow BSM in loop) → κ_γ
- Γ_{gg} (allow BSM in loop) → κ_g
- allow B(H→BSM) ≠ 0

- assume: $k_V \leq 1$
  - some constrain is needed to remove the degeneracy in $\sigma(xx \to H) \cdot BR(H \to yy) \propto \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{TOT}}$
  - $k_V \leq 1$ is natural: $k_V > 1$ overshoots the unitarity recovery in WW scattering with no remedy

Couplings: search for new physics

- Γ_{ZZ}
- Γ_{WW} assume: $\kappa_Z = \kappa_W$ → κ_V
- $\Gamma_{\tau\tau}$ → κ_τ
- Γ_{bb} → κ_b
- Γ_{tt} → κ_t
- $\Gamma_{\gamma\gamma}$ (allow BSM in loop) → κ_γ
- Γ_{gg} (allow BSM in loop) → κ_g
- allow B(H→BSM) ≠ 0



- **assume**: $k_V \leq 1$
  - some constrain is needed to remove the degeneracy in $\sigma(xx \to H) \cdot BR(H \to yy) \propto \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{TOT}}$
  - $k_V \leq 1$ is natural: $k_V > 1$ overshoots the unitarity recovery in WW scattering with no remedy

Result: B(H→BSM) < 0.57

NB: With all other couplings ~SM-like, this implies that $\Gamma_{TOT} < \Gamma_{SM}/(1\text{-}0.57) \sim 2.5\ \Gamma_{SM}$

[this is a back-of-envelope estimate; the actual result will come out in near future]

Spin-parity properties

Spin-parity of H(125) [on example of H→ZZ]

Spin=0:

pseudo-scalar (0^-)

$$\mathcal{L} \sim \kappa \frac{m_Z^2}{v} X Z^\mu Z_\mu + \frac{X Z^\mu \Box Z_\mu}{\Lambda_\alpha} + \frac{X Z^{\mu\nu} Z_{\mu\nu}}{\Lambda_\beta} + \frac{X Z^{\mu\nu} \tilde{Z}_{\mu\nu}}{\Lambda_\gamma} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

SM Higgs (κ=1)

Dim-5 operators need some scale Λ in denominator

Spin=1: (forbidden for H→γγ)

$$L(X_{J=1}VV) \sim b_1^{VV} \partial_\mu X_\nu Z^\mu Z^\nu + b_2^{VV} \epsilon_{\alpha\mu\nu\beta} \partial^\beta X^\alpha Z^\mu Z^\nu$$

vector (1^-) **pseudo-vector (1^+)**

Dim-4 operators: no suppression is needed

Spin=2:

$$L(X_{J=2}VV) \sim -c_1^{VV} X_{\mu\nu} Z^{\mu\alpha} Z_\alpha^\nu + \frac{c_2^{VV}}{\Lambda^2} \left(\partial_\alpha \partial_\beta X_{\mu\nu}\right) Z^{\mu\alpha} Z^{\nu\beta} + \frac{c_3^{VV}}{\Lambda^2} X_{\beta\nu} \left[\partial^\alpha, \left[\partial^\beta, Z^{\mu\nu}\right]\right] Z_{\mu\alpha}$$
$$+ \frac{c_4^{VV}}{2\Lambda^2} X_{\mu\nu} \left[\partial^\mu, \left[\partial^\nu, Z^{\beta\alpha}\right]\right] Z_{\alpha\beta} + c_5^{VV} m_V^2 X_{\mu\nu} Z^\mu Z^\nu + \frac{2c_6^{VV} m_V^2}{\Lambda^2} \partial_\alpha X_{\mu\nu} \left[\partial^\mu, Z^\nu\right] Z^\alpha$$
$$- \frac{c_7^{VV} m_V^2}{2\Lambda^2} X_{\mu\nu} \left[\partial^\mu, \left[\partial^\nu, Z_\alpha\right]\right] Z^\alpha + \frac{c_8^{VV}}{2\Lambda^2} X_{\mu\nu} \left[\partial^\mu, \left[\partial^\nu, \tilde{Z}^{\alpha\beta}\right]\right] \tilde{Z}_{\alpha\beta}$$
$$- \frac{c_9^{VV} m_V^2}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \partial^\sigma X^{\mu\alpha} Z_\nu \partial_\alpha Z^\rho + \frac{c_{10}^{VV} m_V^2}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} \partial^\rho \partial^\beta X^{\mu\alpha} \left[\partial^\sigma, \left[\partial_\alpha, Z^\nu\right]\right] Z_\beta$$

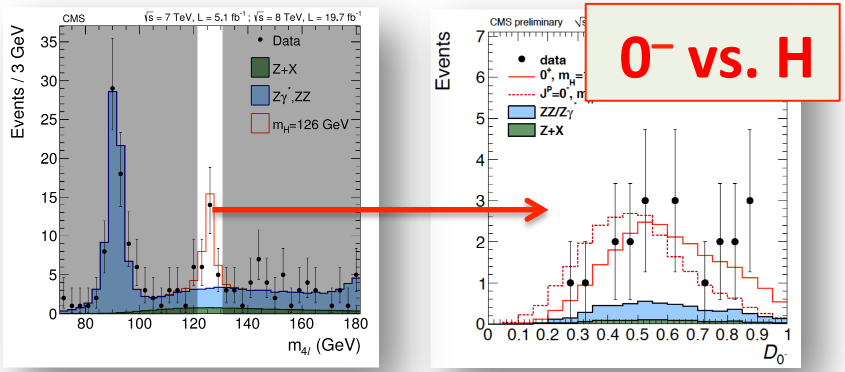
- **10 distinct terms**
- **c_5-term is dim-3**
- **all others: dim-5 or 7**
- **graviton-like sate: $c_5 = c_1$ (the state is denoted as 2^+_m)**

Spin-parity tests: X(J^P) vs. H(0^+)

H→ZZ→4l

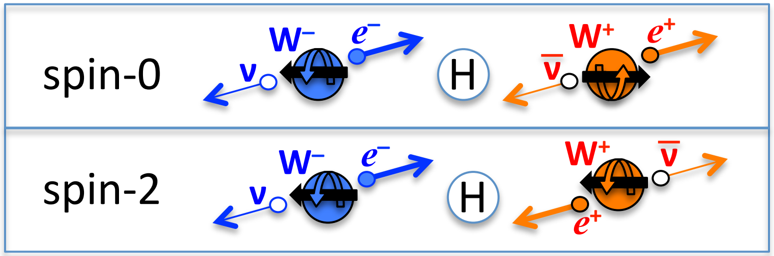
- 4l system is fully reconstructed
- use ME-based discriminator

$$d = \frac{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4|\mathrm{H}\right)\right|^2}{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4|J^P\right)\right|^2}$$



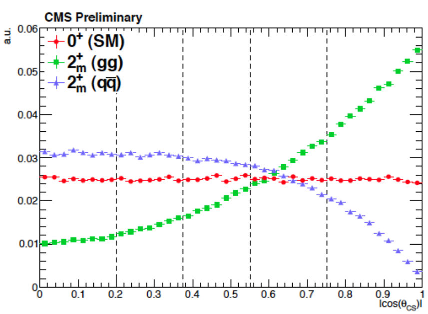
H→WW→lνlν

- di-lepton angle and mass are sensitive to the spin of the decaying X(J^P)



H→γγ

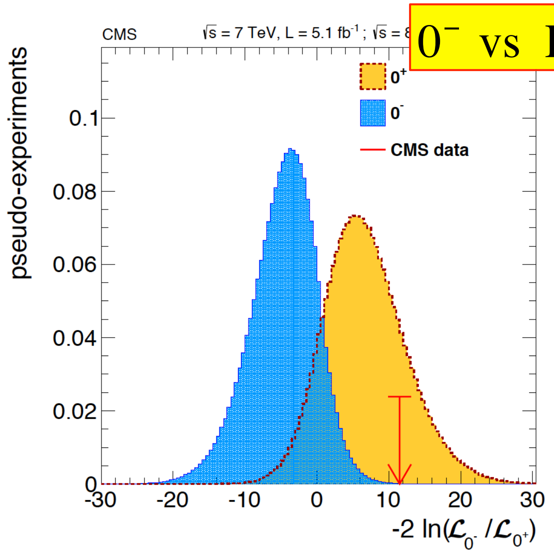
- J=1 forbidden (Landau-Yang theorem)
- cosθ* is the only variable sensitive to J^P information at leading order



- shown distributions: before acceptance and reconstruction
- after acc x reco, discrim. power lessens
- poor S:B makes measurements difficult

Spin-parity results: X(J^P) vs. H(0^+)

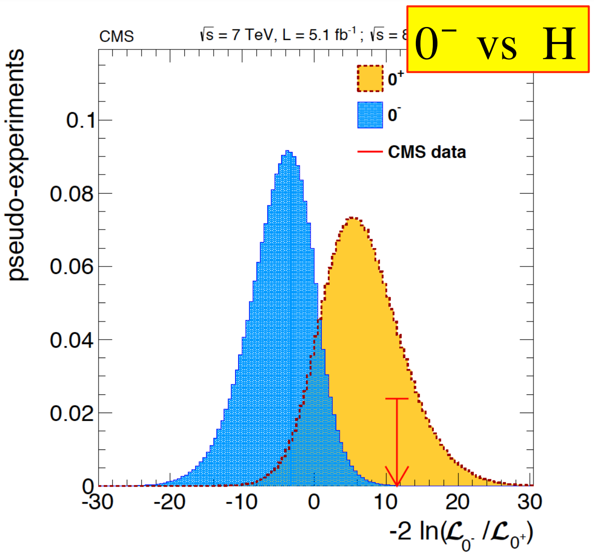
0^- vs H



excluded at 99.9% CL

Test Statistic $q = -2\ln\frac{L(data|J^P + bkg)}{L(data|H + bkg)}$

Spin-parity results: X(J^P) vs. H(0^+)



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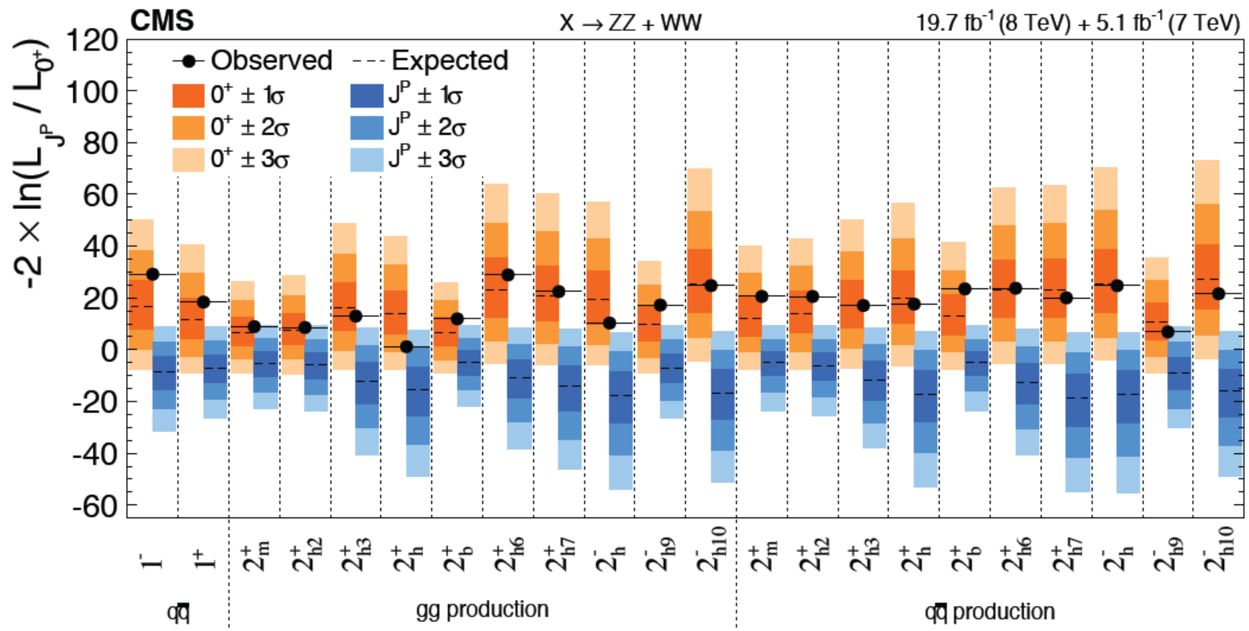


$$\text{Test Statistic } q = -2\ln\frac{L(data|J^P + bkg)}{L(data|H + bkg)}$$

CMS:

- **data are better than ±1.5σ compatible with 0^+ in all tests**
- **data is incompatible with 0^-, $1^\pm$, ten J=2 models at the level of 3σ or higher**

ATLAS results for 0^-, $1^\pm$, and 2^+_m are similar

J=0: anomalous decay amplitudes?

Generic Lagrangian for spin-zero X→ZZ:

pseudo-scalar

$$\mathcal{L} \sim \kappa \frac{m_Z^2}{v} X Z^\mu Z_\mu + \frac{\alpha}{v} X Z^\mu \Box Z_\mu + \frac{\beta}{v} X Z^{\mu\nu} Z_{\mu\nu} + \frac{\gamma}{v} X Z^{\mu\nu} \tilde{Z}_{\mu\nu} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

SM Higgs (κ=1)

Dimension-five operators: one needs to put some scale Λ in the denominator (they can be though of as effective Lagrangians for loop-induced decays)

Kinematic distributions of leptons differ for each of these terms
→ Use ME-based discriminants to test for admixtures of anomalous amplitudes in X→ZZ
→ interference with the SM Higgs term is important

Present experimental constraints (CMS):

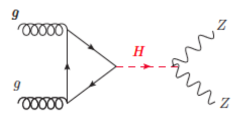
	α/κ	β/κ	γ/κ
allowed range at 95% CL	[-1.2, 1.5]	[-∞, 0.69] [1.9, 2.3]	[-2.2, 2.1]
expected SM loop contributions	$< O(10^{-2})$	$< O(10^{-2})$	$< O(10^{-10})$

Limits on total width from constraints on off-shell production

Width limits from off-shell H*→ZZ

Breit-Wigner production gg→H→ZZ:

$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$



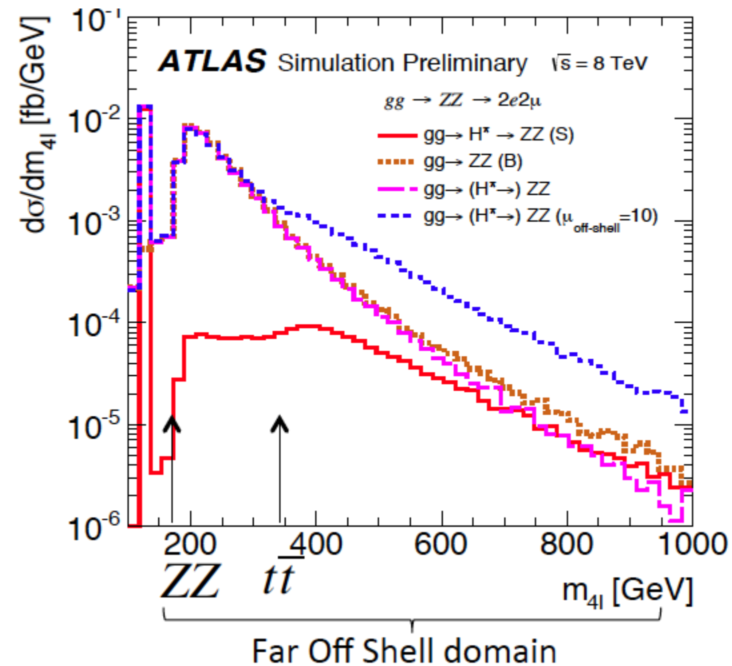
F(m) depends on:

- phase space for H→ZZ
- partonic gg-luminosity
- g_g coupling evolution with m_{H*}

On-peak and off-peak cross sections:

$$\sigma^{\text{on-shell}} = \int_{|m-m_H| \leq n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$$



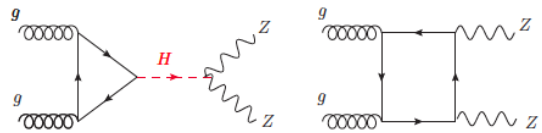
Off-peak to on-peak ratio is proportional to Γ_H (red curve on the plot)

$$\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H$$

Width limits from off-shell H*→ZZ

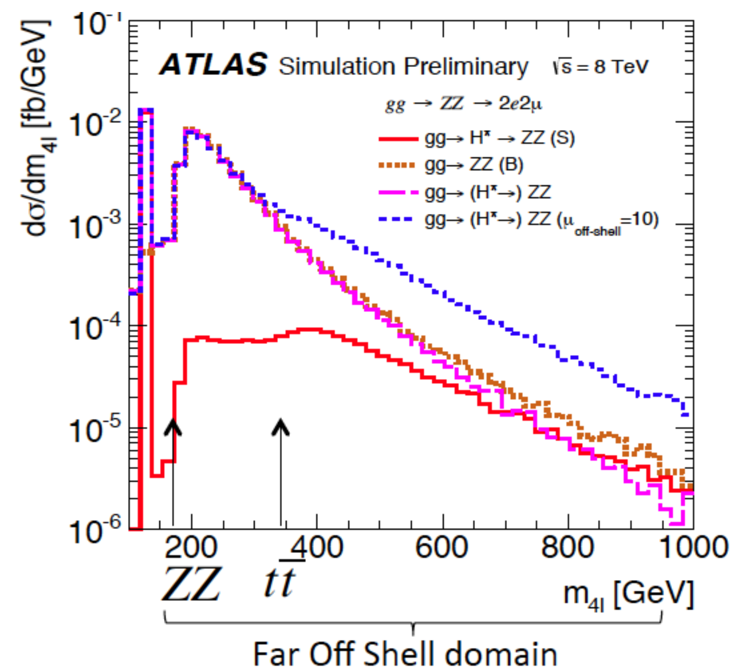
Technical, but very important, detail:

- one must include negative interference between gg→H*→ZZ and gg→(box)→ZZ



- off-shell production: $\sigma_{gg\to H^*\to ZZ} + \sigma_{gg\to(box)\to ZZ} + \sigma_{interference}$
  because of the negative interference,
  - narrow SM Higgs boson implies a deficit of events wrt to pure ZZ background: magenta vs brown
  - wide boson results in an excess of events wrt to the pure ZZ background: blue vs brown

- K-factor on gg→(box)→ZZ is large and not well known



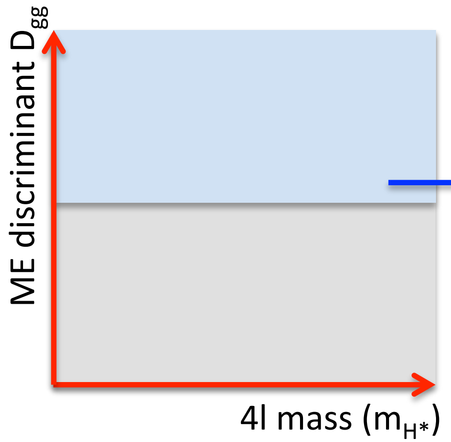
CAVEATS (model-dependent assumptions):

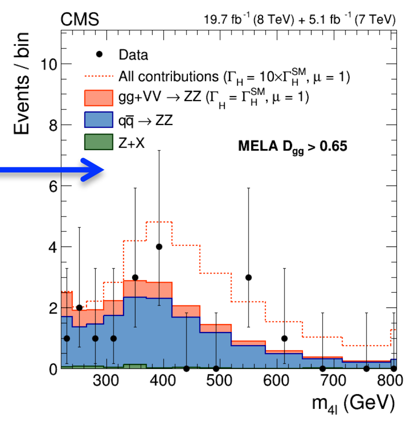
- gg → H is the dominant production mechanisms (e.g., not qq → H)
- evolution of $g_{ggH}(m_{H^*})$ depends on what is in the loop: assume top-loop dominance
- off-peak production depends on tensor structure of H→ZZ: assume SM-like 0^+

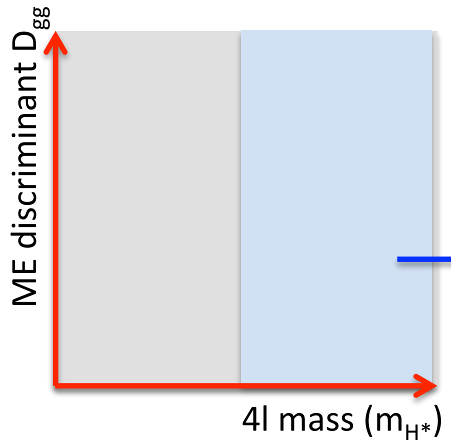
Width limits from off-shell $H^* \to ZZ$

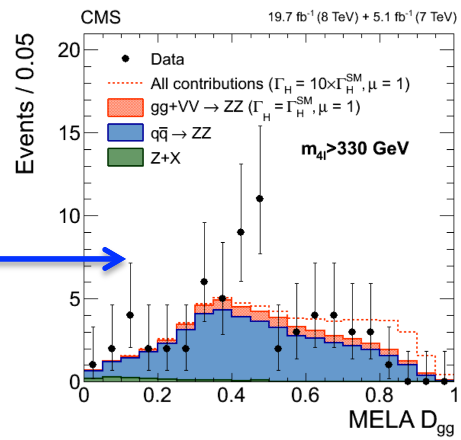
Analysis strategy:

- for large Γ_H, expect an excess of events at high m_{ZZ}
- use ME discriminant D_{gg}, $gg \to (box+H) \to ZZ \to 4l$ vs. $qq \to ZZ \to 4l$, to improve sensitivity









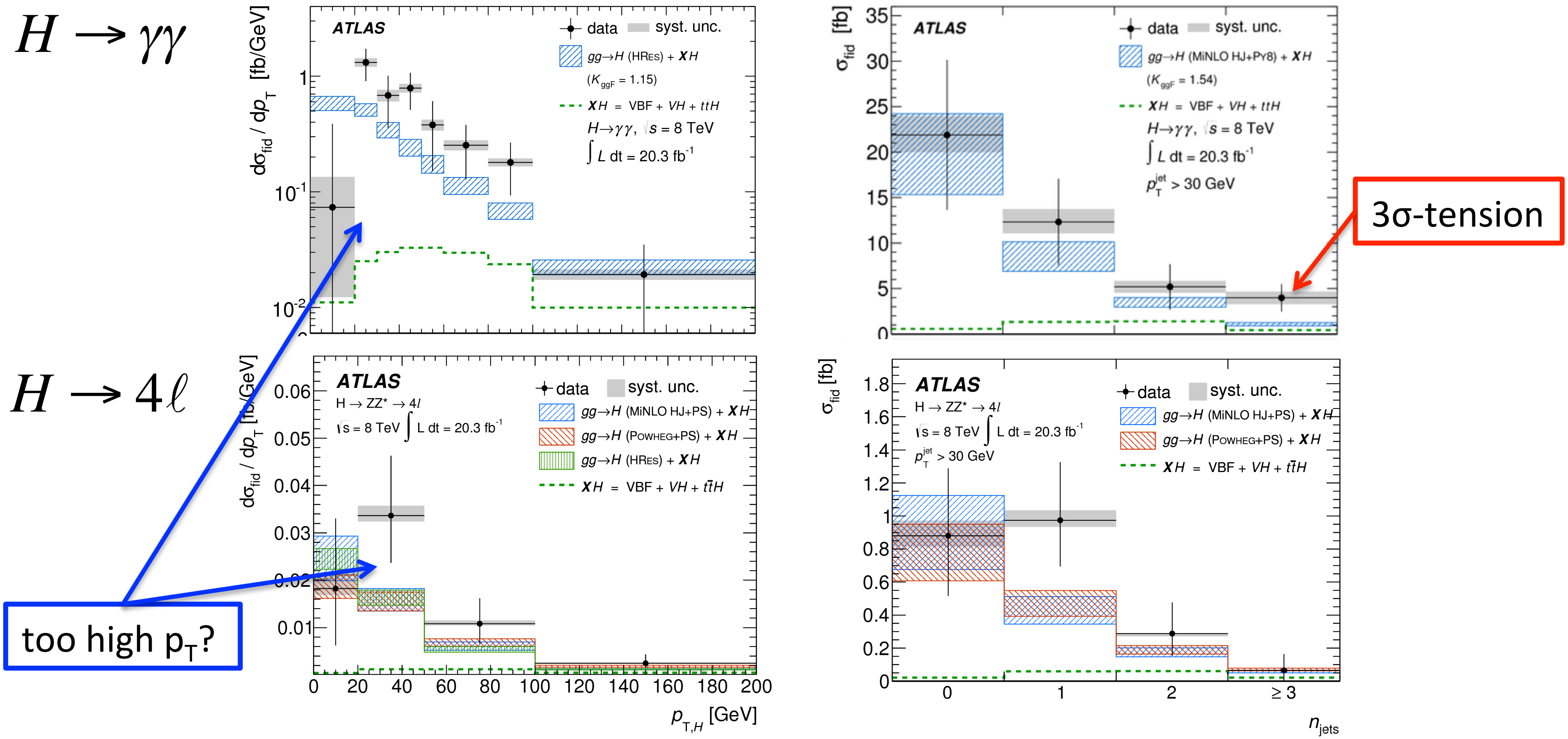
- include $H \to ZZ \to 2l2\nu$ for probing the off-shell event rate at high m_{ZZ} (as sensitive as 4l)

Results:

CMS	$\Gamma_H < 5.4\ \Gamma_{SM}$	(expected limit with SM Higgs: <8.0)
ATLAS	$\Gamma_H < 5.7\ \Gamma_{SM}$	(expected: <8.5)

Differential cross sections

Differential cross sections



Higgs p_T distributions are sensitive to new physics in loops

Higgs exclusive N-jet cross sections are of a particular challenge in theory

CMS results are coming soon

Summaries

quantitative

qualitative

Summary (quantitative)

The H(125) boson is reliably established in $H \to ZZ$, $H \to \gamma\gamma$, $H \to WW$, $H \to \tau\tau$ decay channels
There is a "hint" for $H \to bb$

- H(125) mass m_H = 125.4 ± 0.4 GeV (ATLAS)
  125.0 ± 0.3 GeV (CMS)
- signal strengths (all decay modes, all production tags) are consistent with SM Higgs
- $\mu_{overall}$ = 1.30 ± 0.18 (ATLAS) [to be updated soon]
  1.00 ± 0.14 (CMS)
- five couplings to W, Z, t, b, τ are measured with 20-30% and agree with SM Higgs boson
- no exotic decay rates (nor exotic decays) are seen: invisible, μμ, ee, Zγ, $H \to \tau\mu$ (LFV!)
- 0^+ is consistent with data, alternative J^P states are excluded (>3σ)
  limits on fractional non-0^+ states in the "bump" are set
- $\Gamma < 5.4\ \Gamma_{SM}$ (from measuring off-shell event rates with some model-dependent assumptions)
- differential cross sections: look OK (but very limited statistics)

Summary (qualitative)

- H(125) looks just like the SM Higgs boson…
- Ahead: painstaking search for small deviations

- And, of course, we must look elsewhere!
  - exotic H(125) decay [e.g., H→τμ]
  - exotic production modes for H(125) [e.g., t→cH]
  - more Higgs bosons [neutral, charged, double-charged]