Summary of LHC Higgs Results

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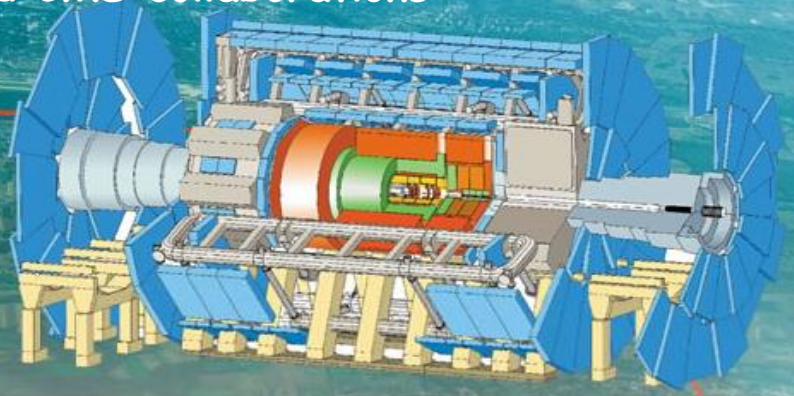
On behalf of the ATLAS and CMS collaborations



22 November 2013 - PASCOS 2013@Taipei

Bibliography used

ATLAS

Phys.Lett. B 716 (Discovery)

Phys.Lett. B 726 (Spin, Couplings)

ATLAS-CONF 2013-040 (Spin Combi.)

ATLAS-CONF-2013-034 (Coupling Combi.)

ATLAS-CONF 2013-014 (Mass Combi.)

ATLAS-CONF 2013-029 (γγ Spin)

ATLAS-CONF 2013-031 (WW* Spin)

ATLAS-CONF 2013-030 (WW*)

ATLAS-CONF 2013-012 (γγ)

ATLAS-CONF 2013-013 (ZZ*)

ATLAS-CONF 2013-079 (VH,H→bb)

ATLAS-CONF 2013-072 (H ->γγ, diff σ)

ATLAS-CONF 2013-075 (VH,H→WW)

ATLAS-CONF-2013-011 (Z(ll)H, H→Inv)…

CMS

Phys. Lett. B 716 (Discovery)

Phys. Rev. Lett. 110 (ZZ*, Spin)

CMS-PAS-HIG-13-005 (Mass, Couplings)

CMS-PAS-HIG-13-016 (Properties γγ)

CMS-PAS-HIG-13-001 (γγ)

CMS-PAS-HIG-13-003 (WW*)

CMS-PAS-HIG-13-002 (ZZ*, Spin)

CMS-PAS-HIG-13-012 (H→bb)

CMS-PAS-HIG-13-013(VBF, H→Inv)

CMS-PAS-HIG-13-018 (Z(ll)H, H→Inv)

CMS-PAS-HIG-13-018 (Z(bb)H, H→Inv)

CMS-PAS-HIG-13-004 (ττ)…

LHC Higgs Cross Section Working Group

http://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

arXiv:1307.1347 (CERN Yellow Report 3: σ, BR, coupling, spin/CP…)

Higgs Talks at Pascos2013

More complete information can be found in the following presentations given in parallel sessions:

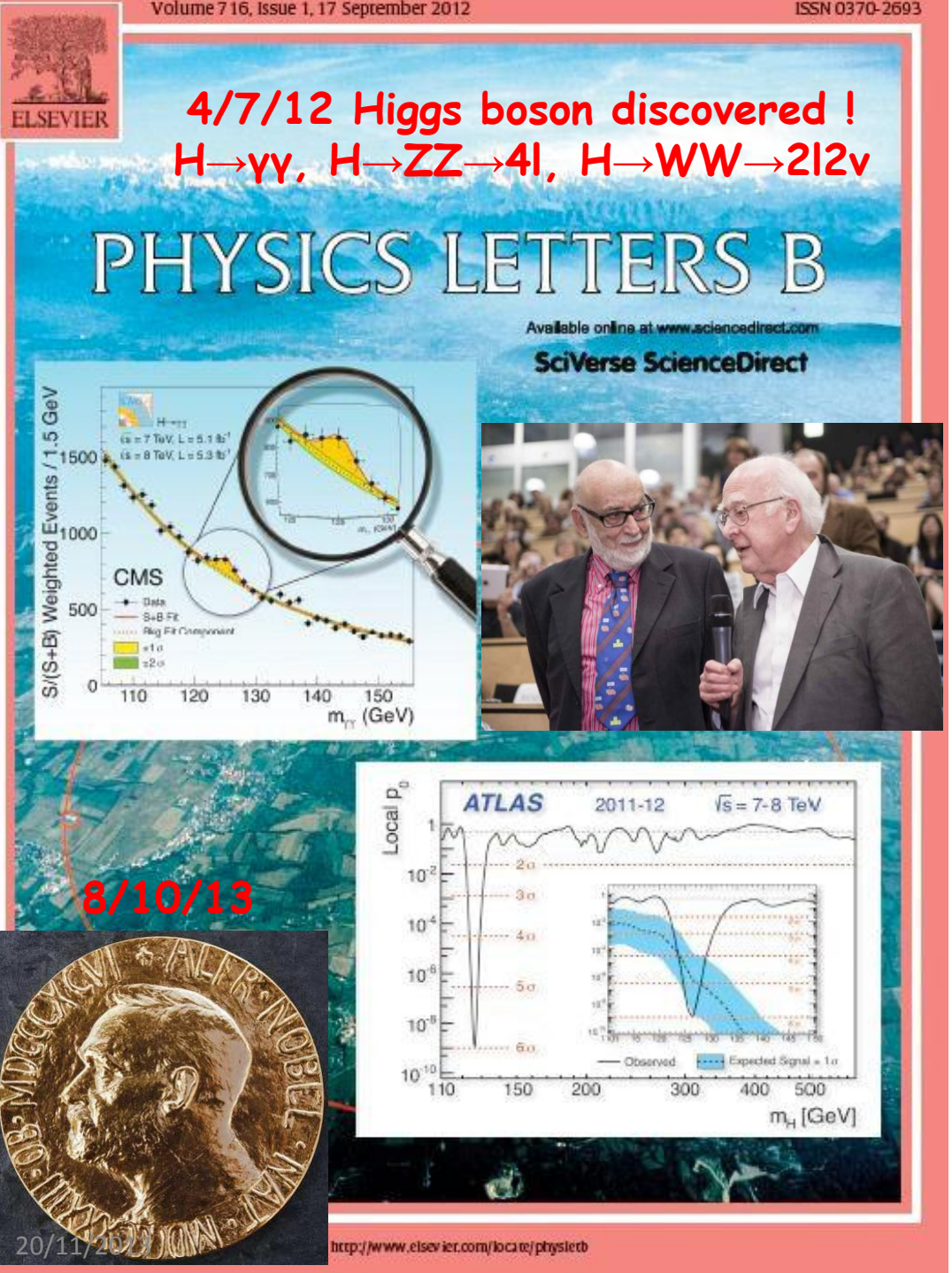
- F. Bernlocher: Higgs mass and coupling properties (ATLAS)
- R. Di Nardo: Higgs spin and parity properties (ATLAS)
- R. Castello: Higgs properties (CMS)

- A. Palma: Higgs into bosons (ATLAS)
- G. Cerati : Higgs into bosons (CMS)

- K. Hanagaki: Higgs into fermions (ATLAS)
- P. Azzuri : Higgs into fermions (CMS)

- A. Kotwal: BSM Higgs (ATLAS)
- C. Asawatangtrakuldee: BSM Higgs (CMS)

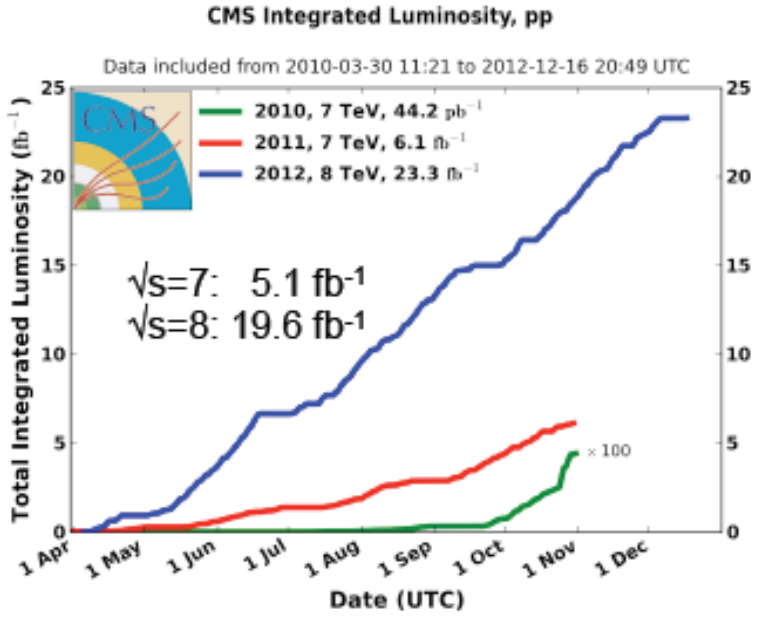
- T. Baroncelli: Higgs rare decays (ATLAS)
- O. Bondu: Future prospects for Higgs (CMS)
- and others….

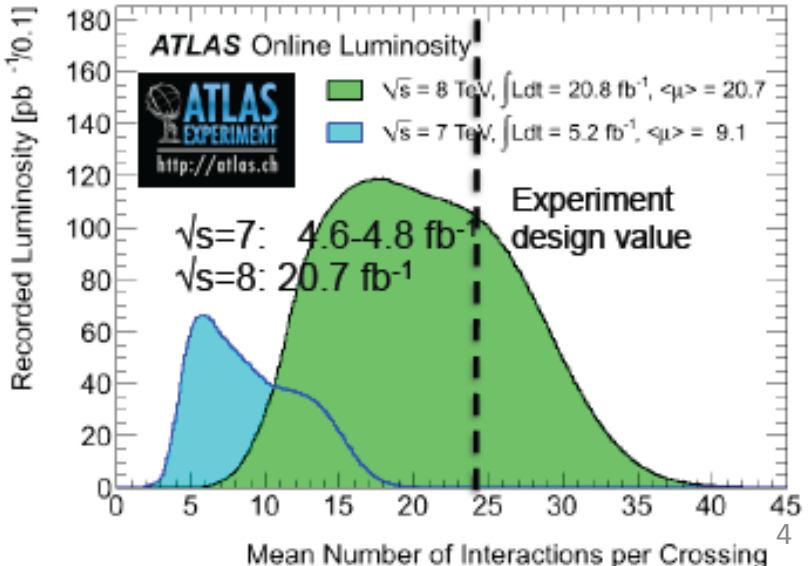


Now "LHC-Run1" data analyzed:

2011~5fb^{-1}@7Tev Outstanding

2012~20fb^{-1}@8Tev LHC !

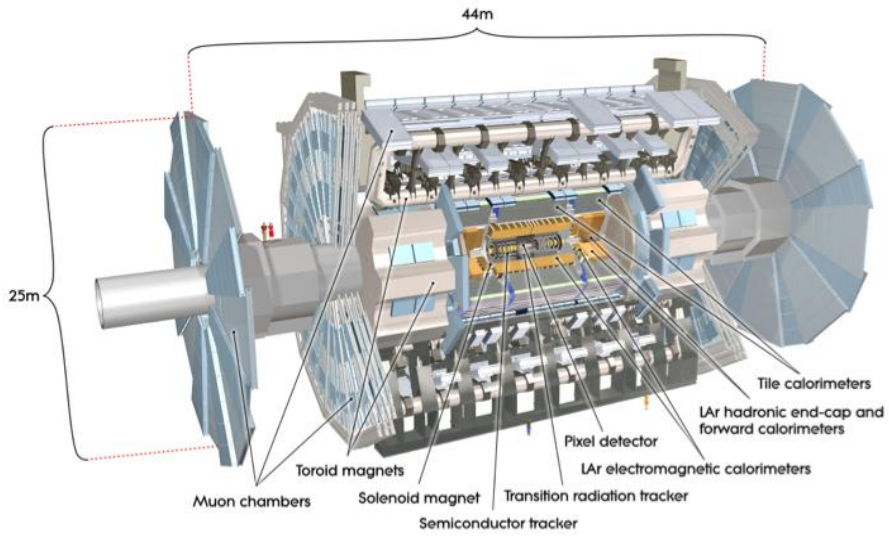


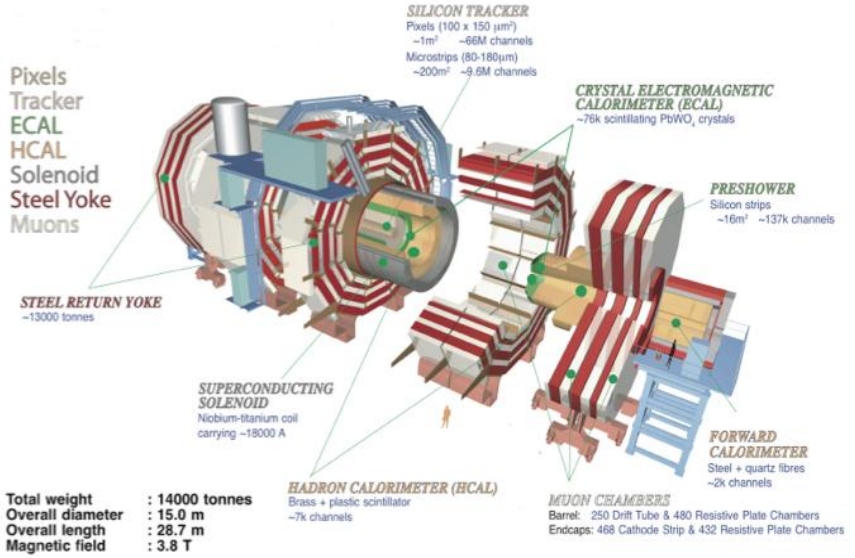


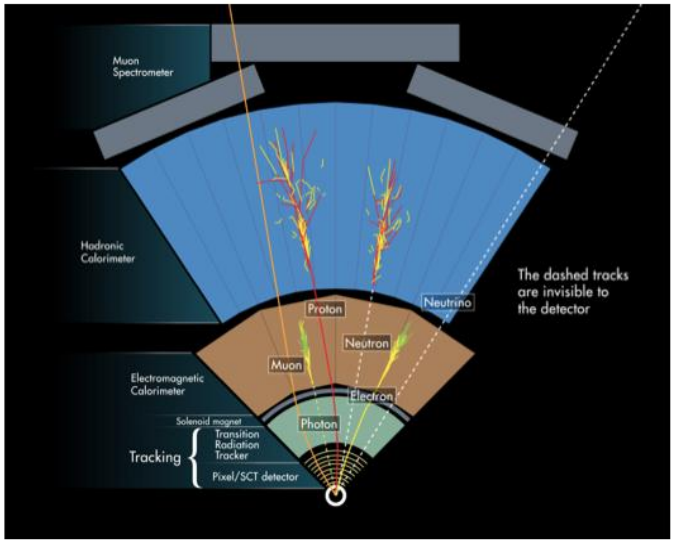
ATLAS and CMS detectors

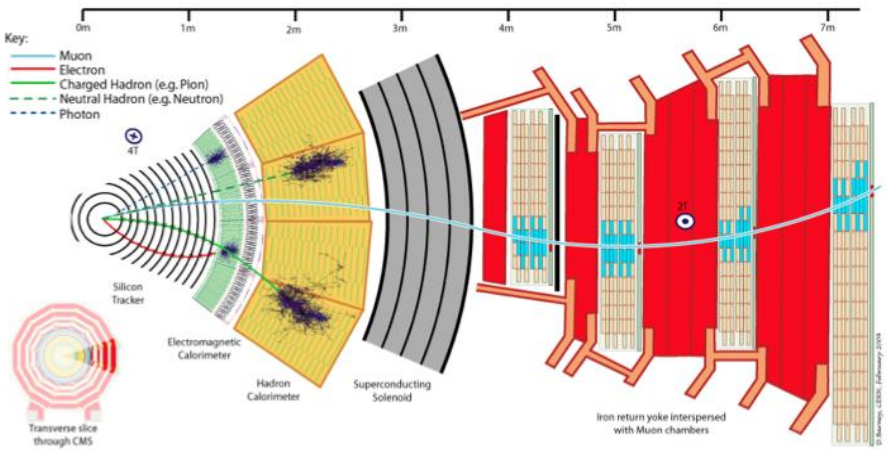
See also I. Wingerter-Seez (ATLAS) and S. Ganjour (CMS) plenary talks

Outstanding detector performance !



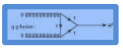




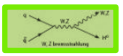


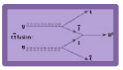
Higgs boson production

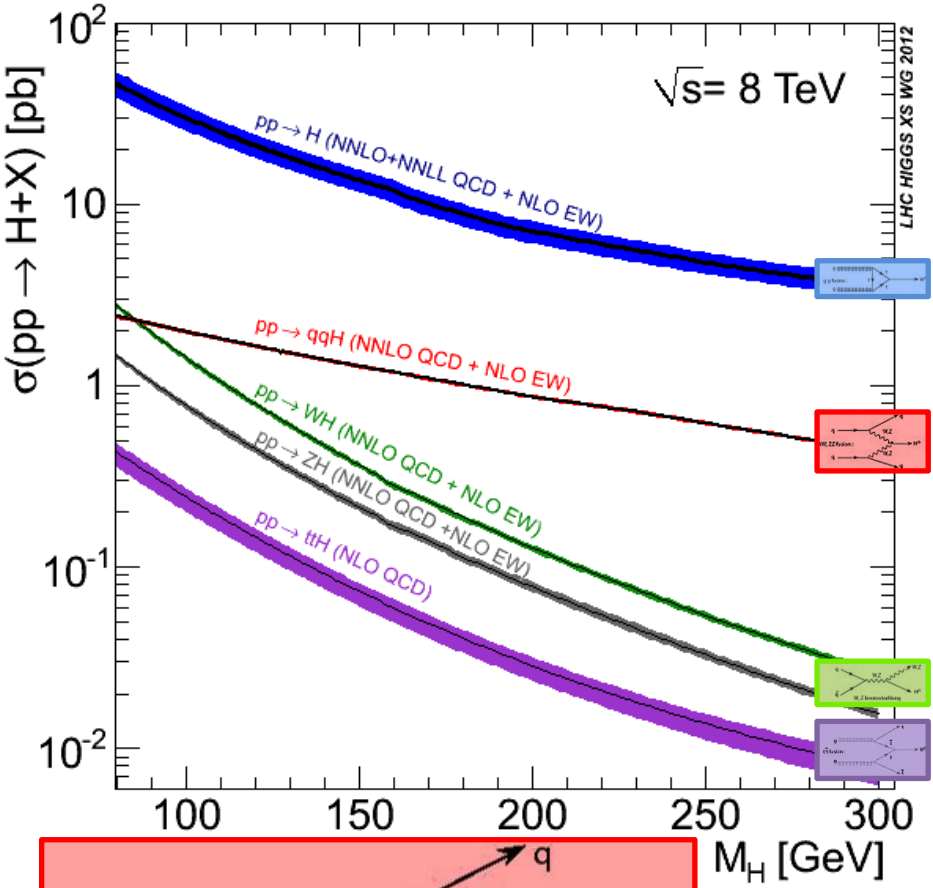
m_H=125.5 GeV, σ = 21.84 pb @ 8TeV

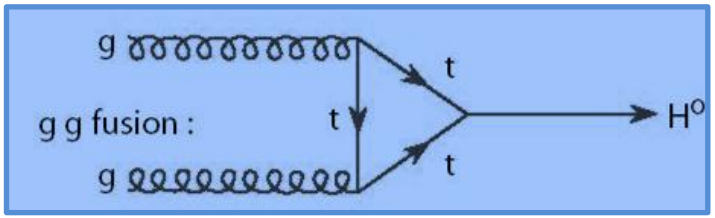

ggF, 19pb, 87%


VBF, WW, ZZ Fusion: 1.6pb, 7.3%

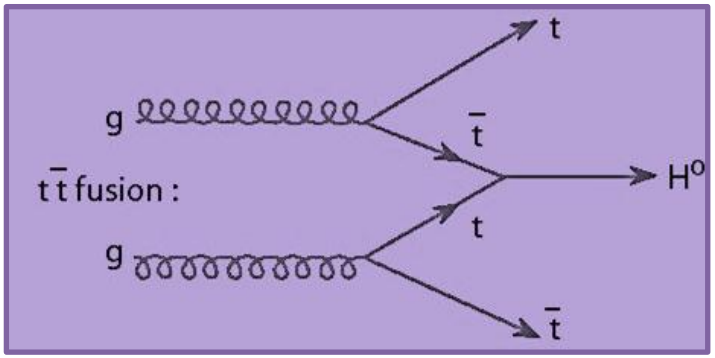

W/ZH, 0.70pb, 0.41pb

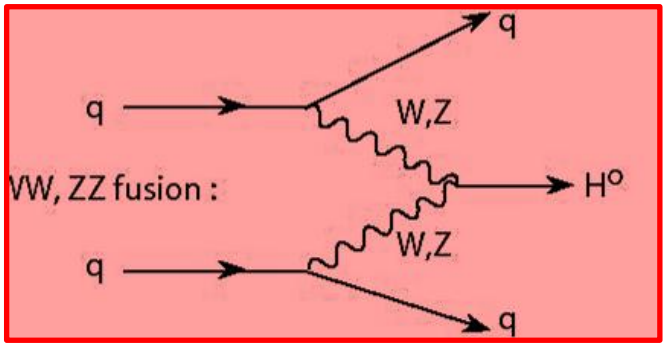

ttH: 0.13pb

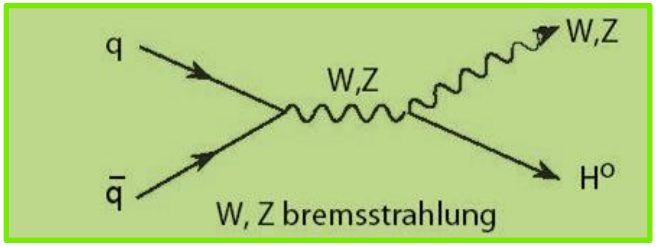




Fermion Coupling



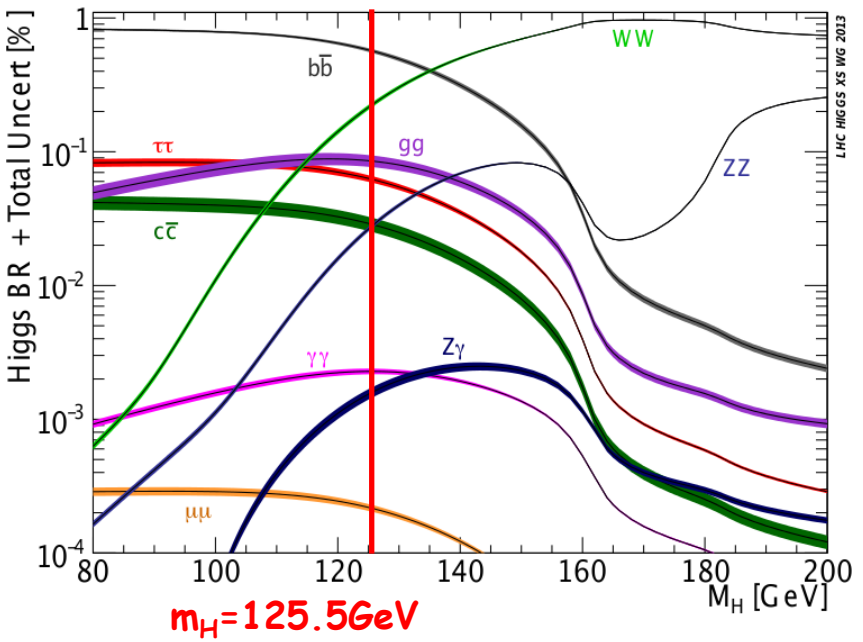


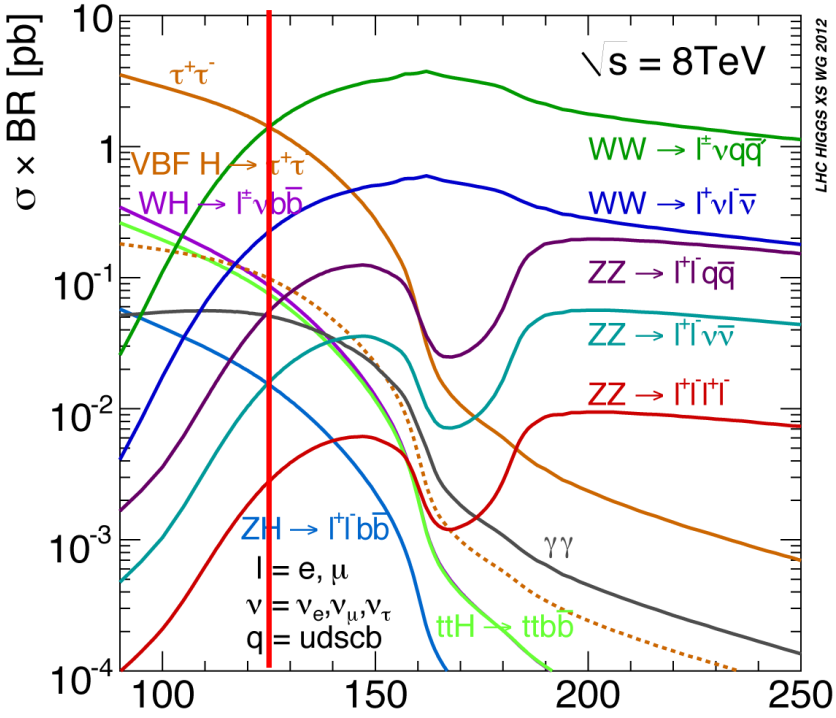


Vector Boson Coupling

Higgs boson decays

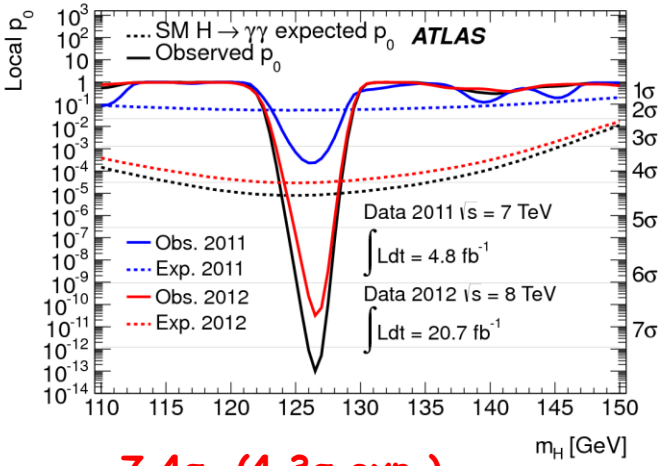
- H→bb, 56.9% (@125.5GeV), Yukawa coupling
- H→WW(*), 22.3%, Gauge Coupling
  - H→WW(*)→2l2ν
- H→ττ, 6.2% Yukawa Coupling
- H→γγ, 0.23% Yukawa/Gauge (loop) Coupling
- H→ZZ(*), 2.8%, Gauge coupling
  - H→ZZ(*)→4l
- H→Zγ, 0.16%
- H→μμ, 0.02%





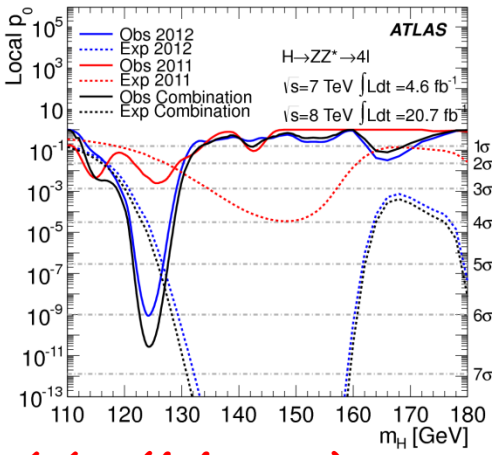
Higgs discovery channels update with "Run-1" statistic

Phys.Lett. B 726



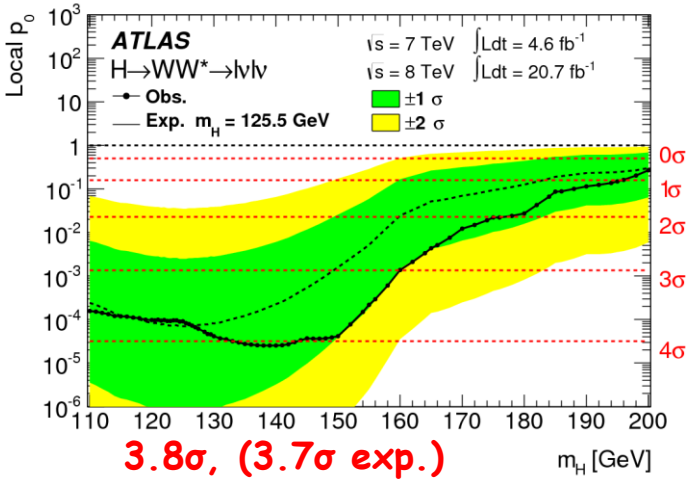
7.4σ, (4.3σ exp.)

H→γγ



6.6σ, (4.4σ exp.)

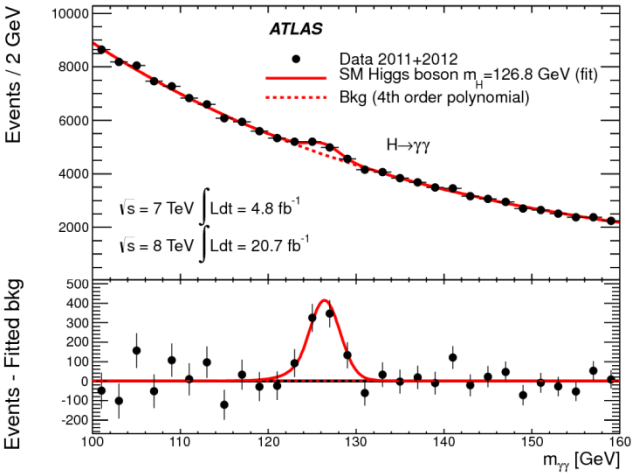
H→ZZ→4l



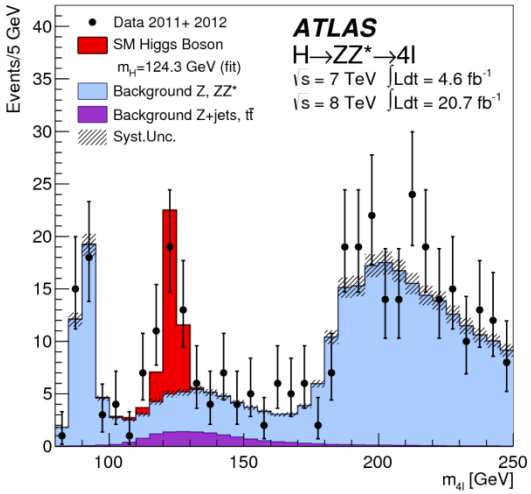
3.8σ, (3.7σ exp.)

m_H=125.5 GeV

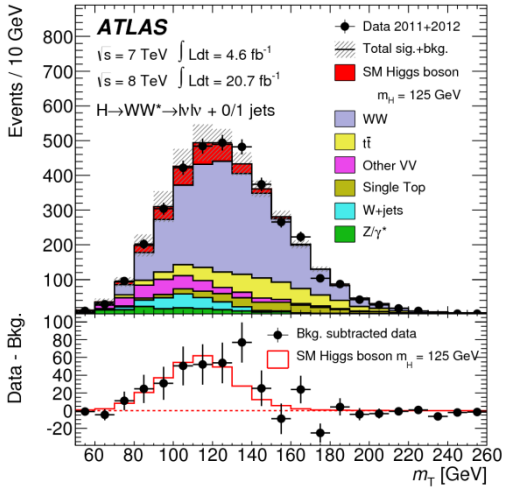
H→WW→2l2ν



$m_H = 126.8 \pm 0.2_{stat} \pm 0.7_{sys}$ GeV

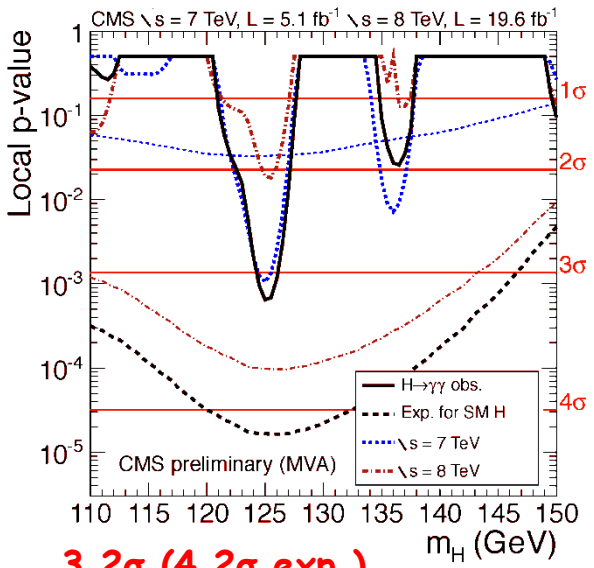


$m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV



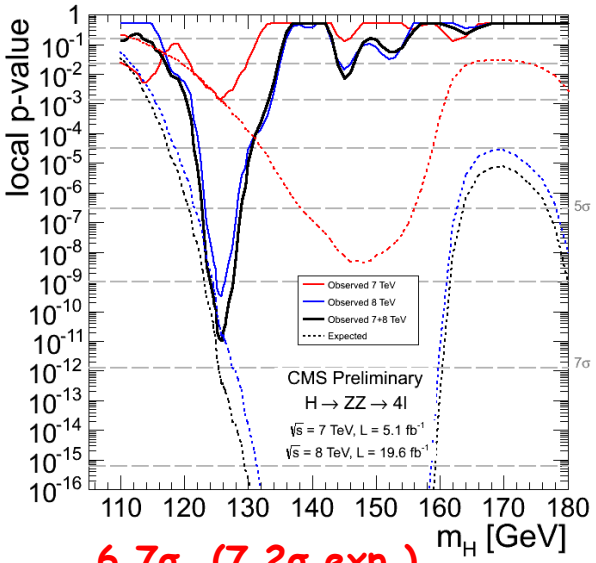
$$m_T = \sqrt{(ET^{ll}+E^{Miss}_T)^2-(\vec{P}_T^{\,ll}+\vec{P}^{Miss}_T)^2}$$

H→γγ



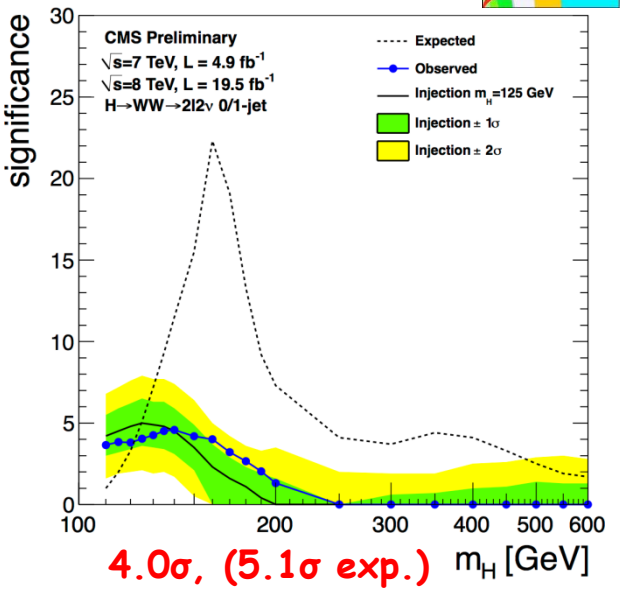
3.2σ (4.2σ exp.)

H→ZZ→4l



6.7σ, (7.2σ exp.)

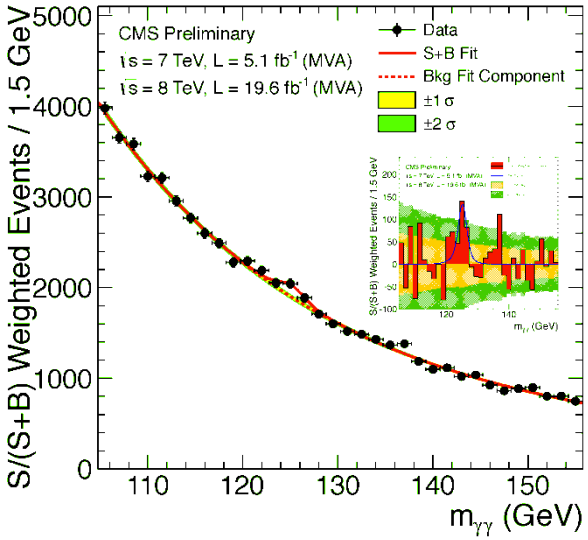
H→WW→2l2ν



4.0σ, (5.1σ exp.)

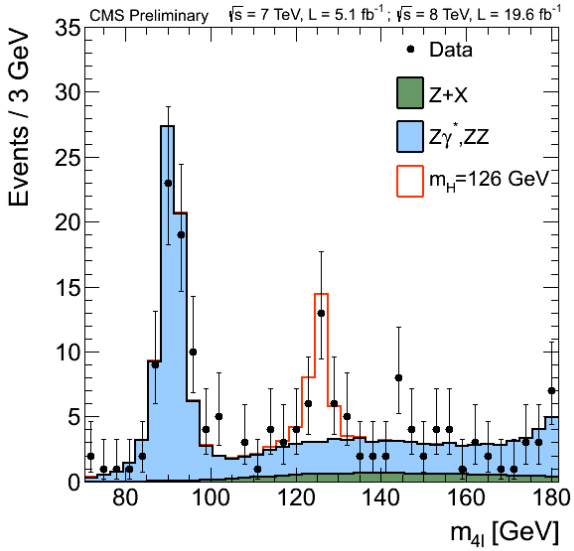
m_H=125GeV CMS-PAS-HIG-003

CMS-PAS-HIG-001

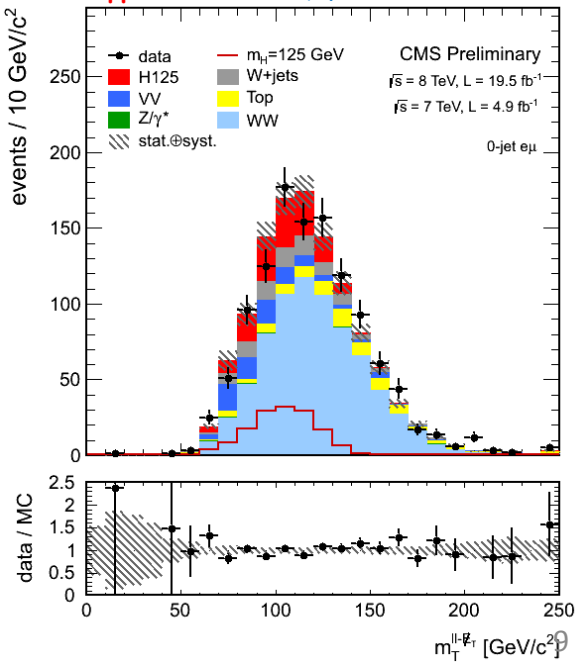


m_H=125.4±0.5$_{stat}$±0.6$_{sys}$ GeV

CMS-PAS-HIG-002

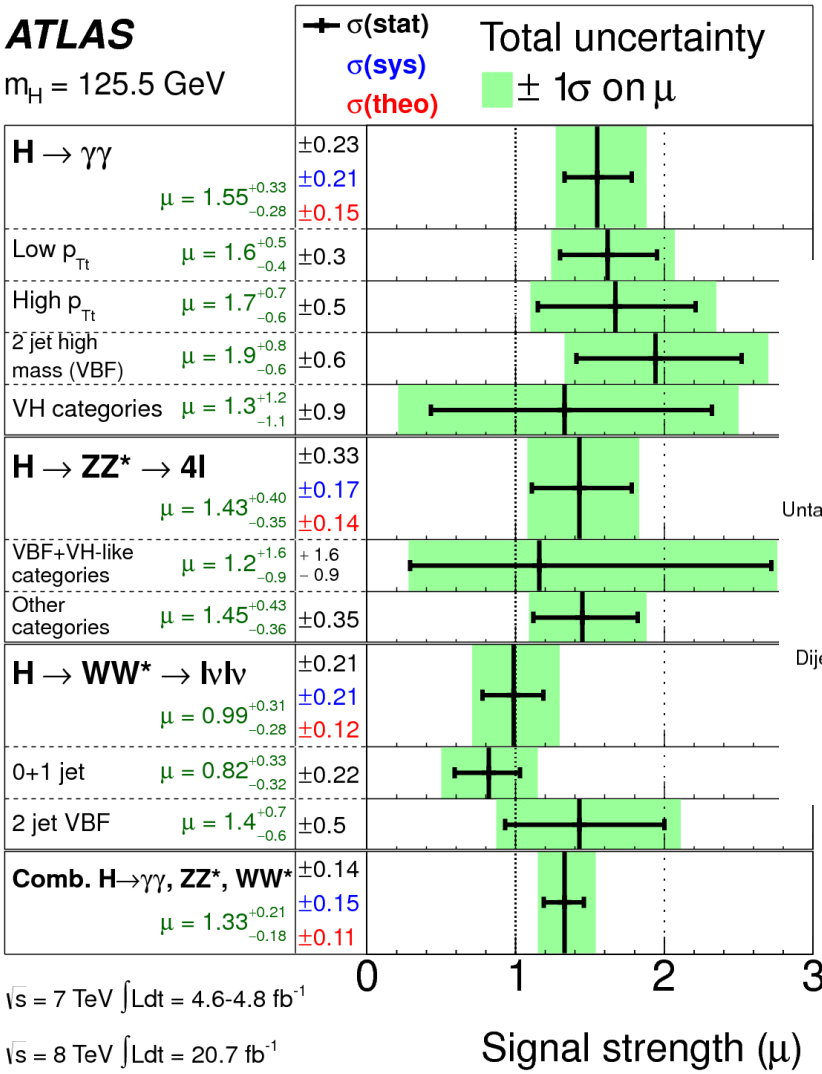


m_H=125.8±0.5$_{stat}$±0.2$_{sys}$ GeV



Signal Strength

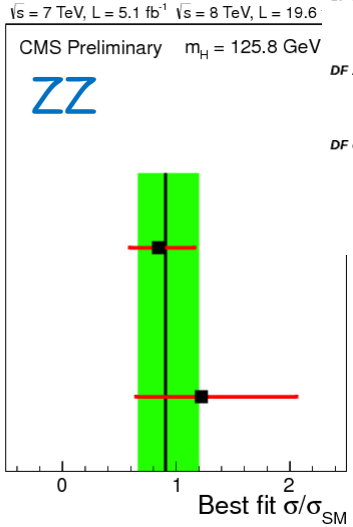
$$\mu = \frac{\sigma^{obs}}{\sigma_{SM}}$$

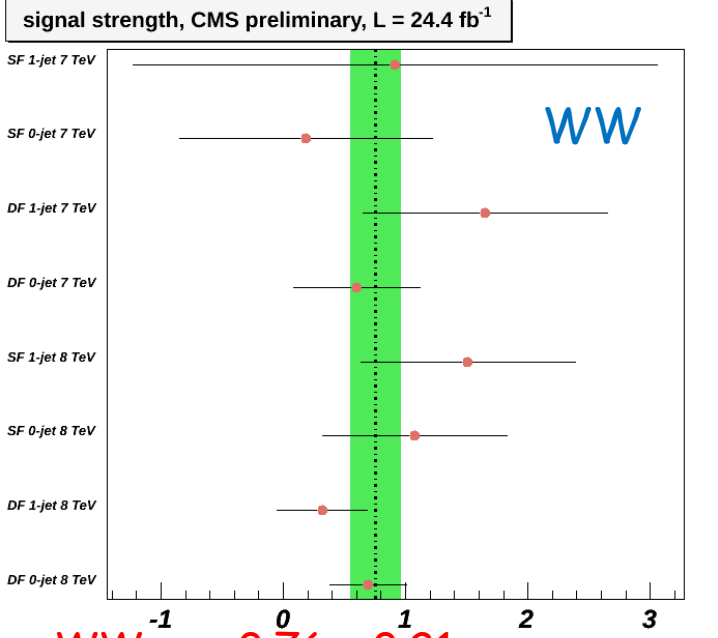


WW: $\mu = 0.99^{+0.31}_{-0.28}$

ZZ: $\mu = 1.43^{+0.40}_{-0.35}$

γγ: $\mu = 1.55^{+0.33}_{-0.28}$

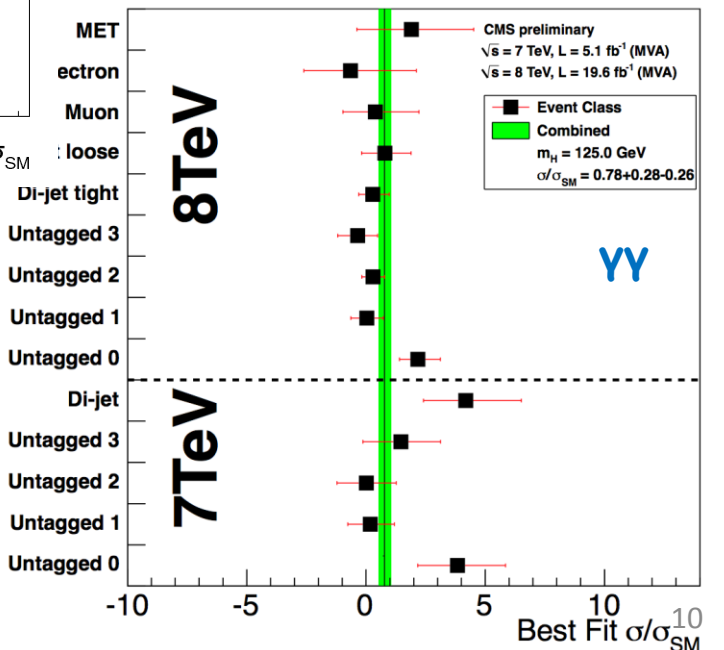




WW: $\mu = 0.76 \pm 0.21$

ZZ: $\mu = 0.91^{+0.30}_{-0.24}$

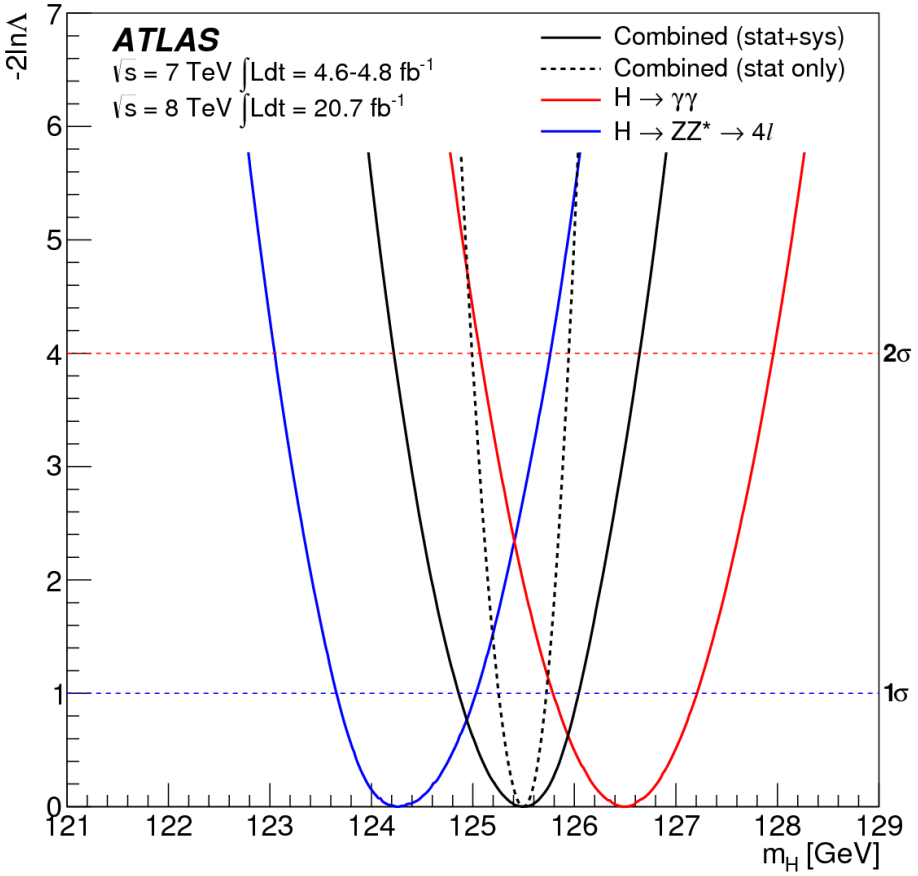
γγ: $\mu = 0.78^{+0.28}_{-0.26}$



Higgs Mass measurement

$m_H^{\gamma\gamma} = 126.8 \pm 0.2_{stat} \pm 0.7_{sys}$ GeV

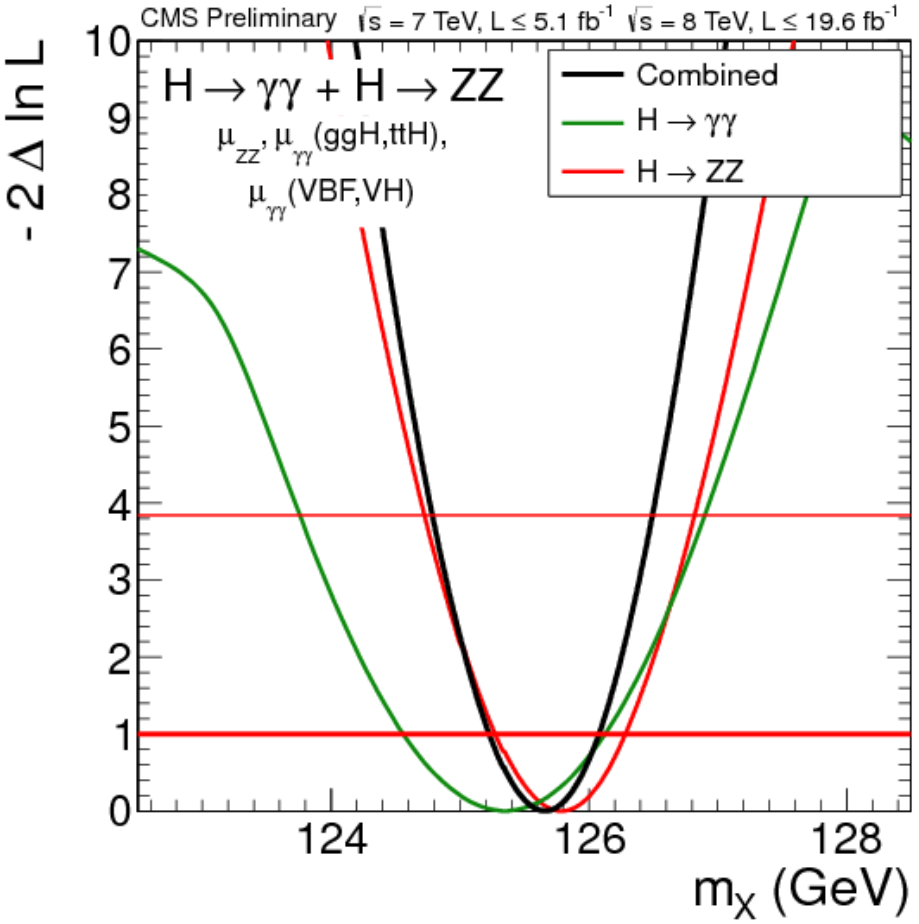
$m_H^{4l} = 124.3^{+0.6}_{-0.5\ stat}{}^{+0.5}_{-0.3sys}$ GeV



$m_H = 125.5 \pm 0.2_{stat}\ ^{+0.5}_{-0.6sys}$ GeV

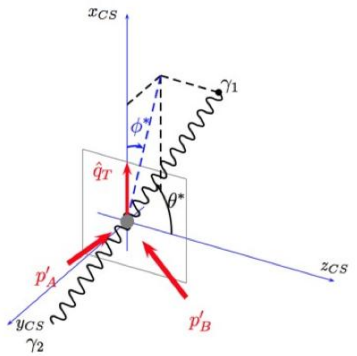
$m_H^{\gamma\gamma} = 125.4 \pm 0.5_{stat} \pm 0.6_{sys}$ GeV

$m_H^{4l} = 125.8 \pm 0.5_{stat} \pm 0.2_{sys}$ GeV



$m_H = 125.7 \pm 0.3_{stat} \pm 0.3_{sys}$ GeV

Spin and Parity



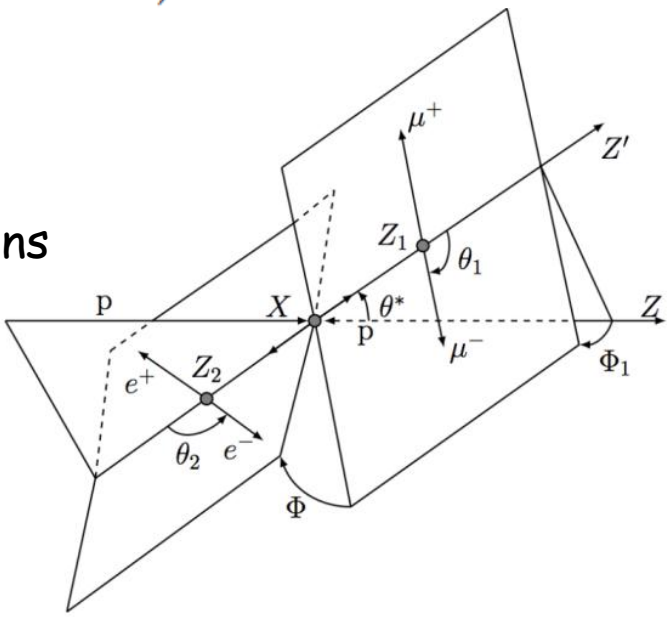
SM Higgs predicted $J^P = 0^+$

Studied in three decay modes:

- $H \to \gamma\gamma$ Fully reconstructed:
  - Use of production angle
  - Background understanding critical

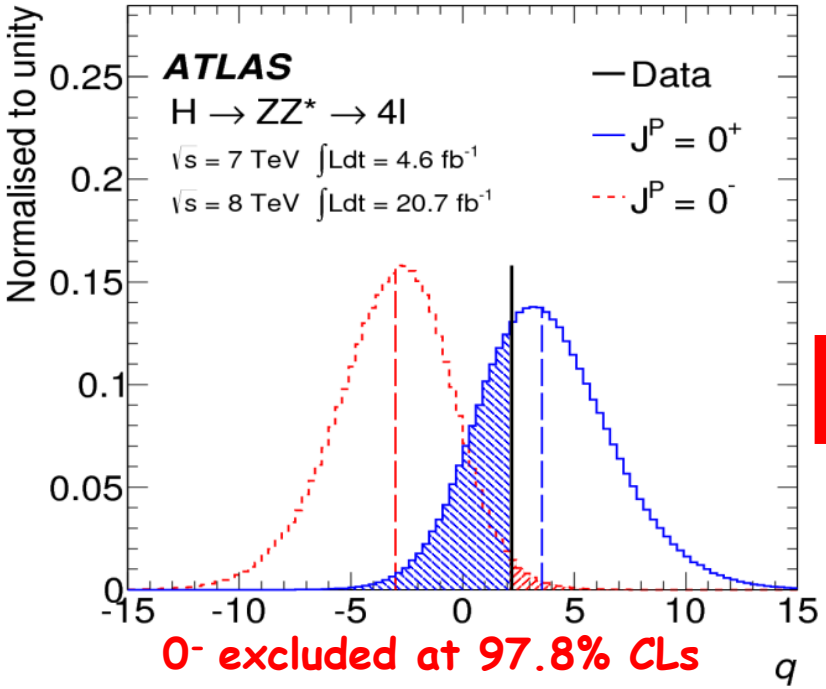
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

- $H \to ZZ^{(*)} \to 4l$ Fully reconstructed:
  - Use of up to 5 angular and 2 mass distributions
  - and BDT or ME Discriminant if all combined



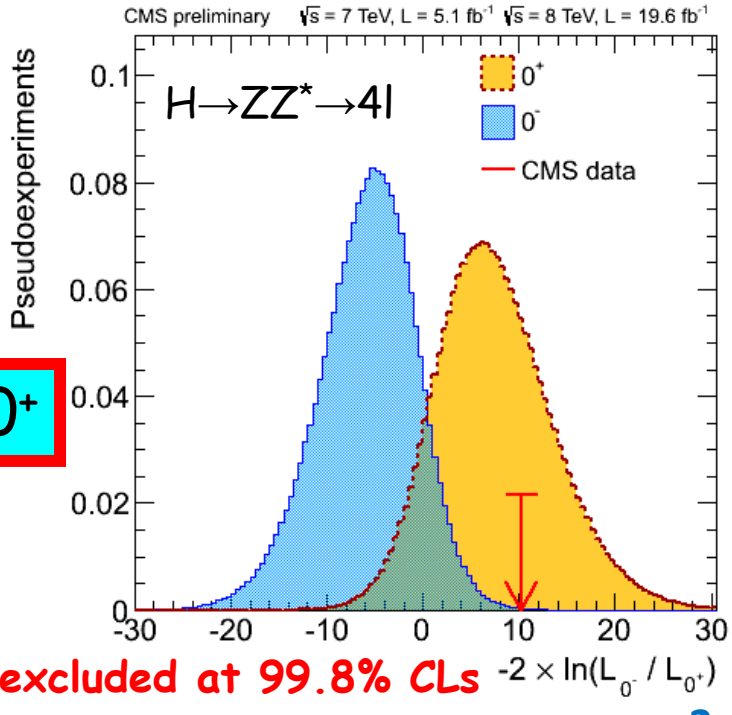
- $H \to WW^{(*)} \to 2l2\nu$
  - direct angle calculation not possible
  - Use kinematic distribution such as $\Delta\varphi_{//}$, $M_{//}$
  - Combined BDT or 2D fit

- Different models for J^P compared to SM Higgs 0^+



0⁻ excluded at 97.8% CLs

$J^P = 0^-$ vs 0^+



0⁻ excluded at 99.8% CLs

= 2q

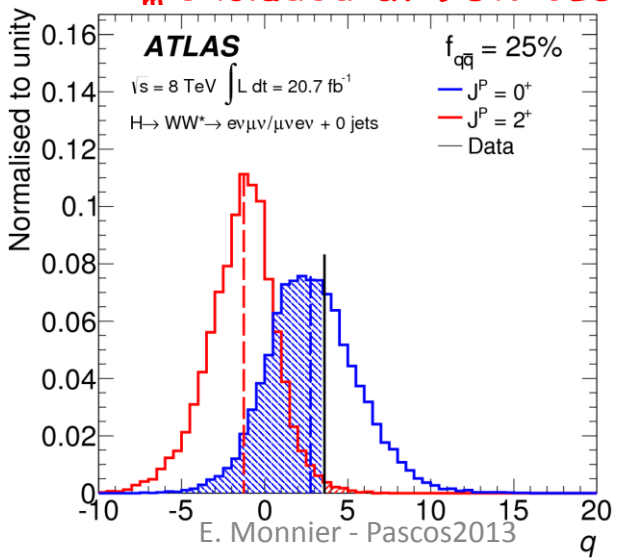
H→ZZ*→4l channel also used in ATLAS and CMS to probe 1^{+-}, 2^+_m

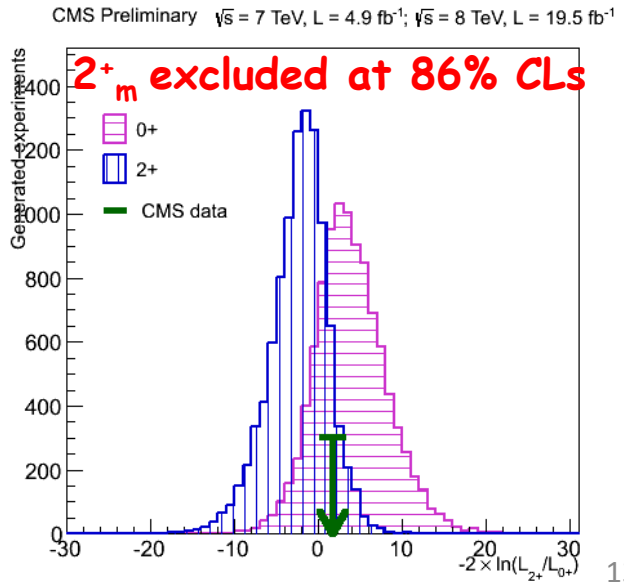
All favor 0^+ Hypothesis

2^+_m excluded at 98% CLs

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

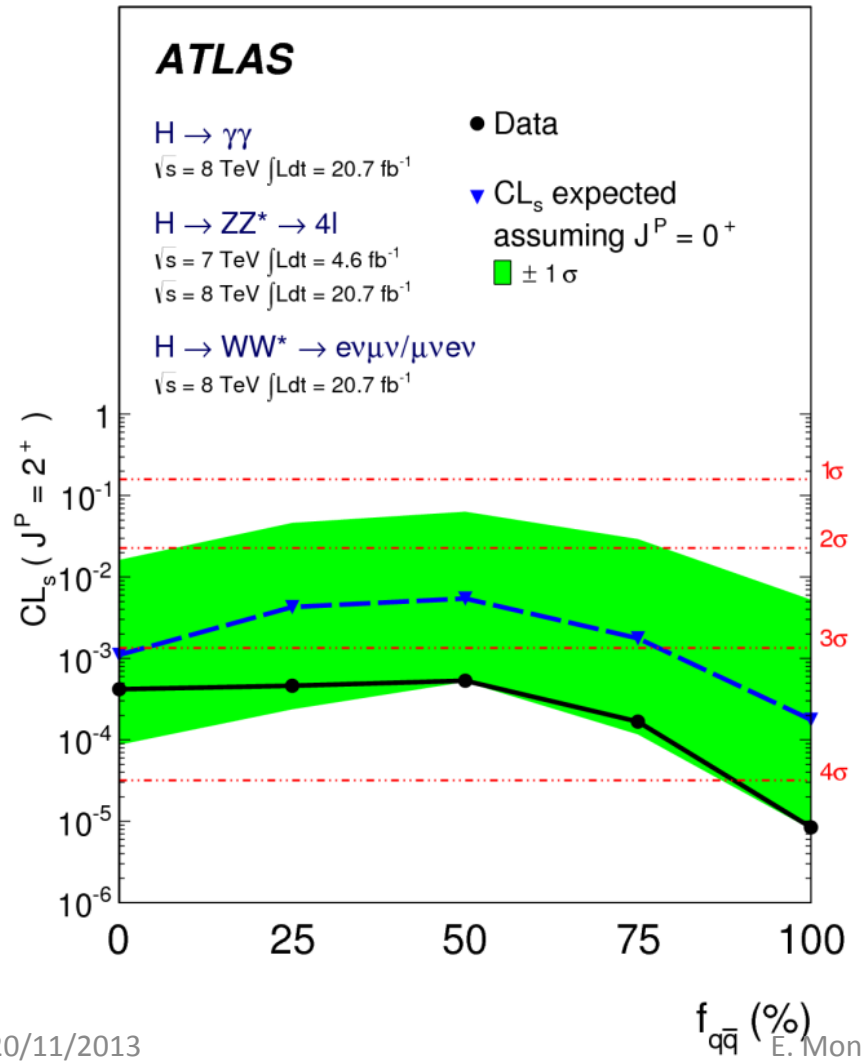
H→WW*→2l2ν
used to probe 1^{+-}, 2^+_m



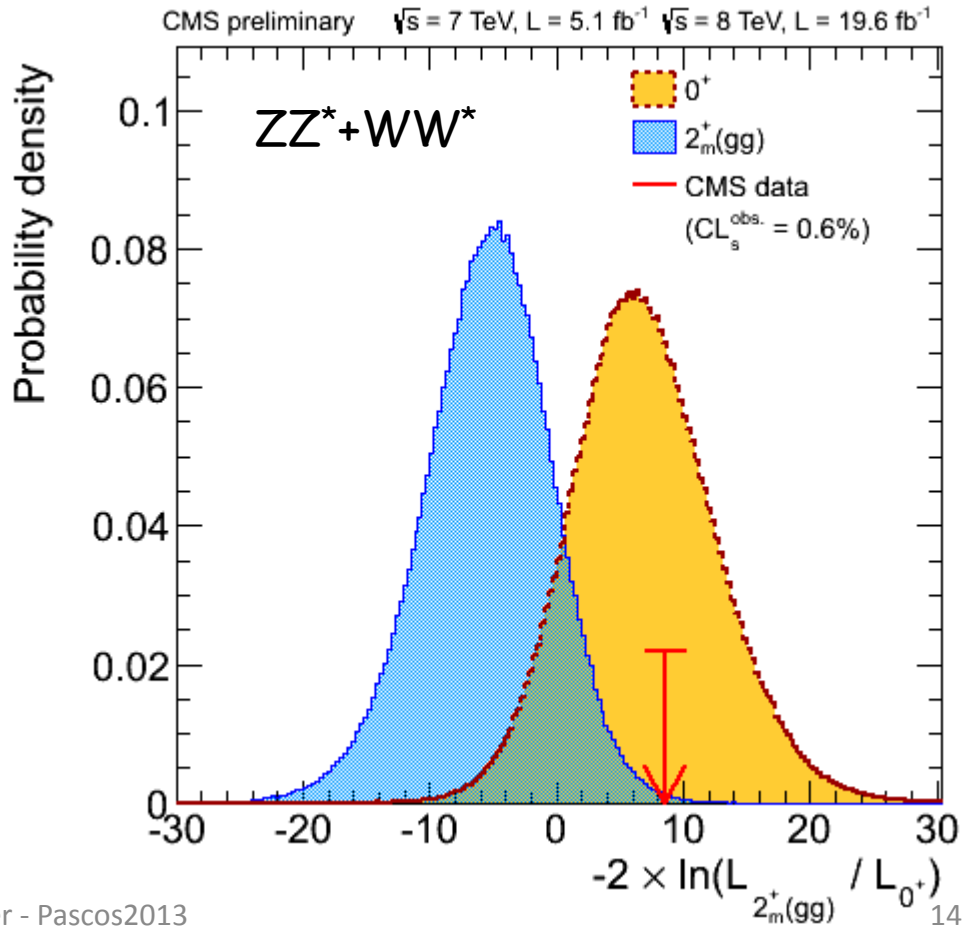


$J^P = 2^+_m$ vs 0^+

- Graviton inspired model, produced via gg or qq with a fraction f_{qq} and minimal coupling: Minimal model 2^+_m tested (LO QCD): f_{qq} =4%)

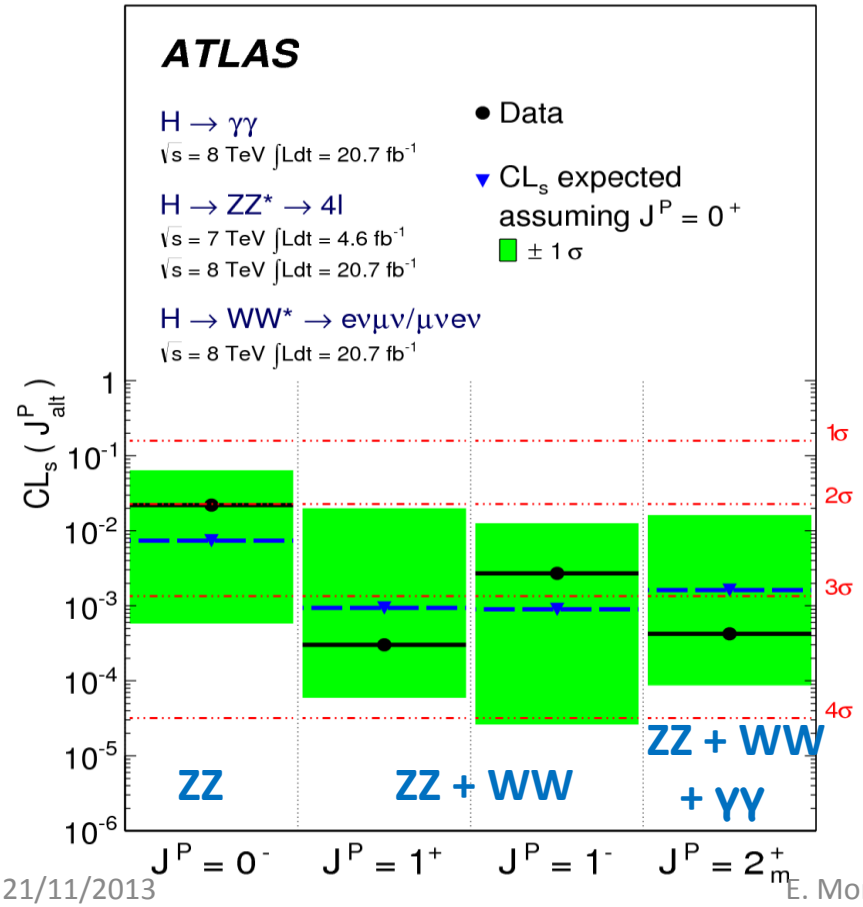


2^+_m excluded at > 99% CLs
All favor 0^+ Hypothesis



Spin Overview

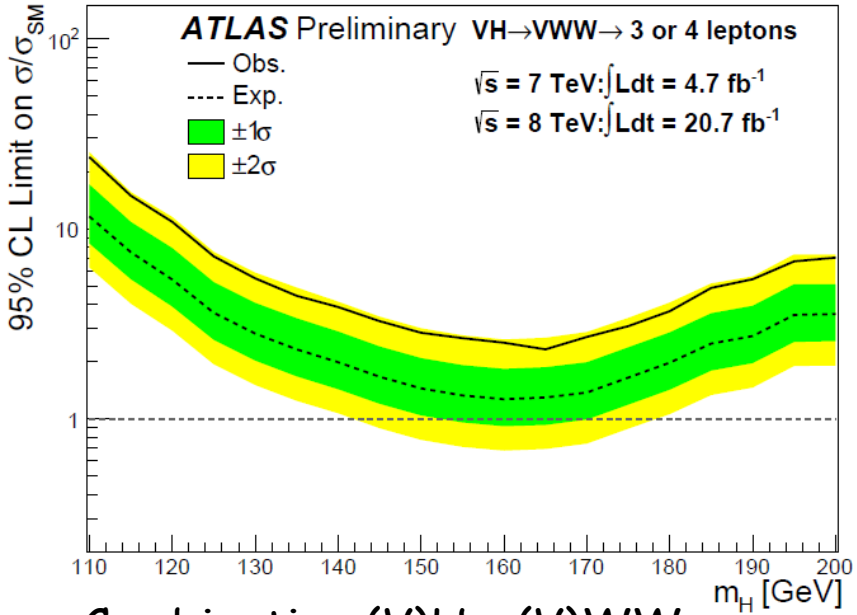
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ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

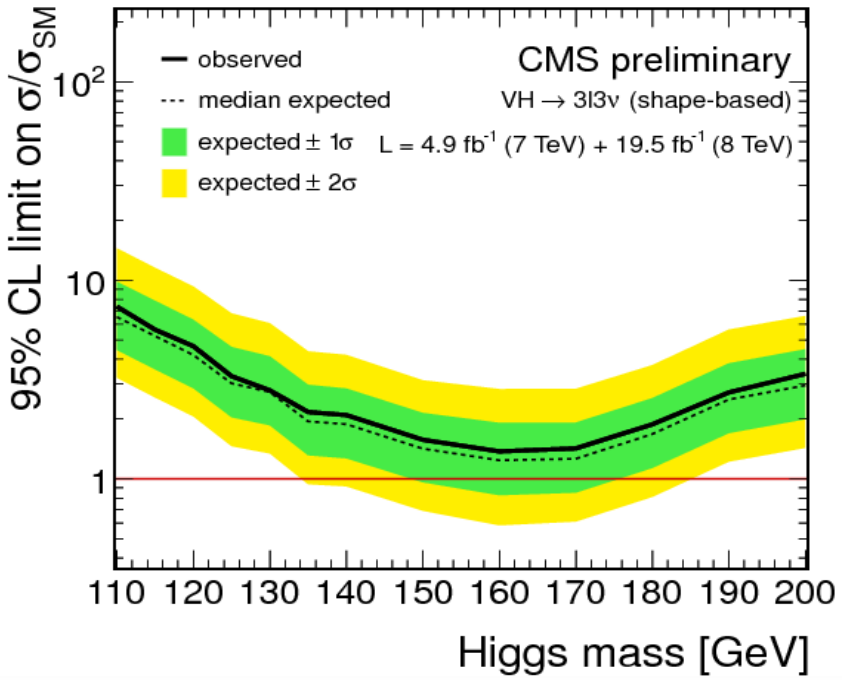


CMS $H \to ZZ^* \to 4l$
Not conclusive yet for $H \to \gamma\gamma$

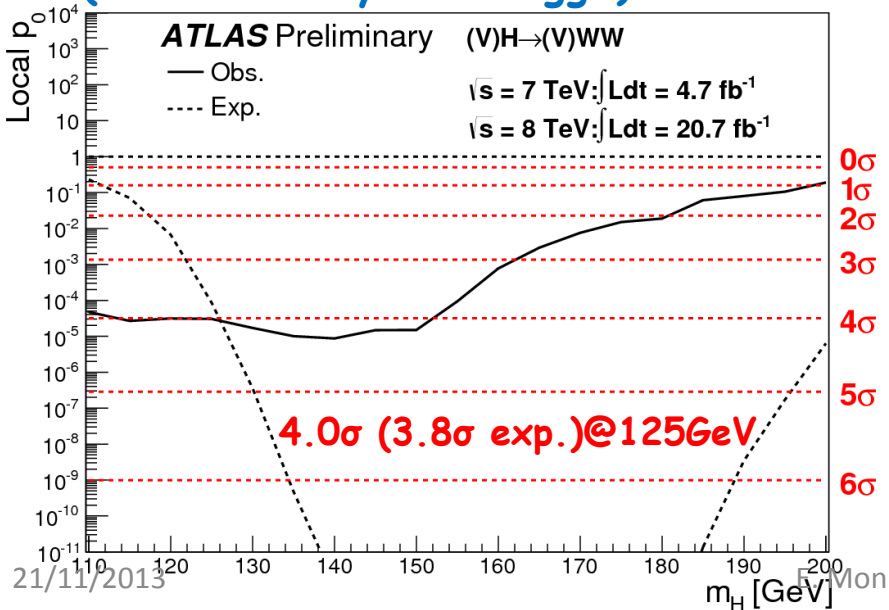
- ATLAS and CMS strongly favor $J^P = 0^+$
- Other models excluded @ > 95% CLs

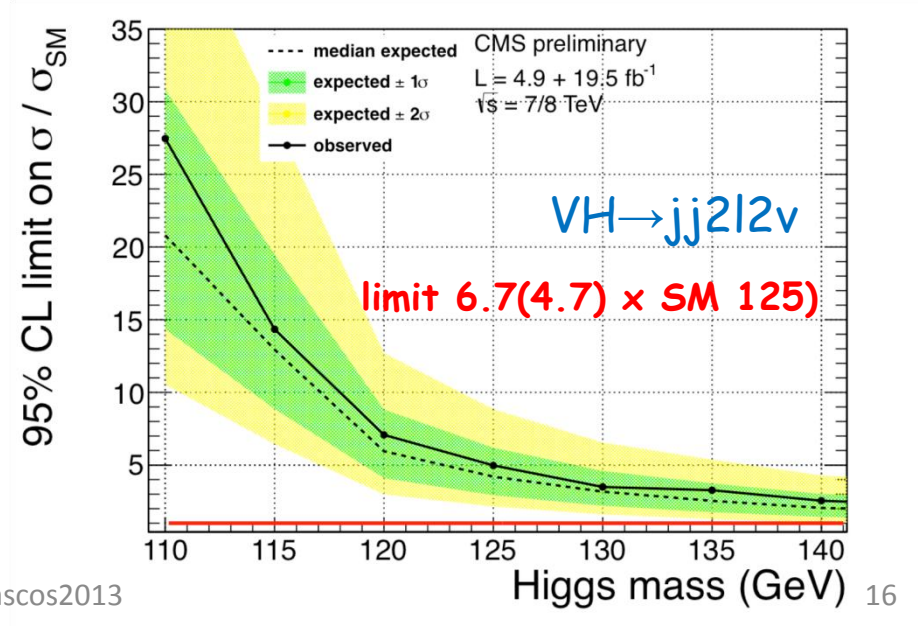
Associated productions: VH(WW)



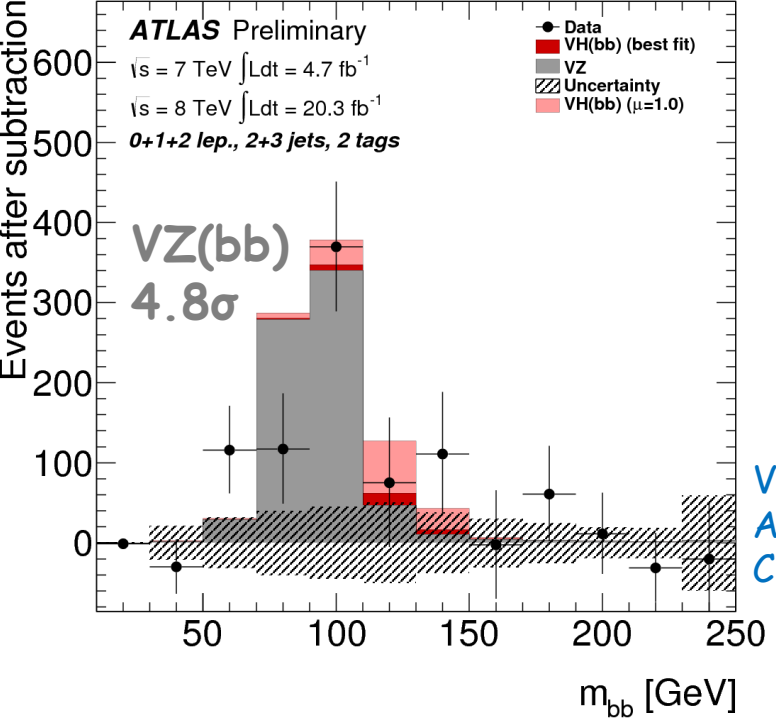


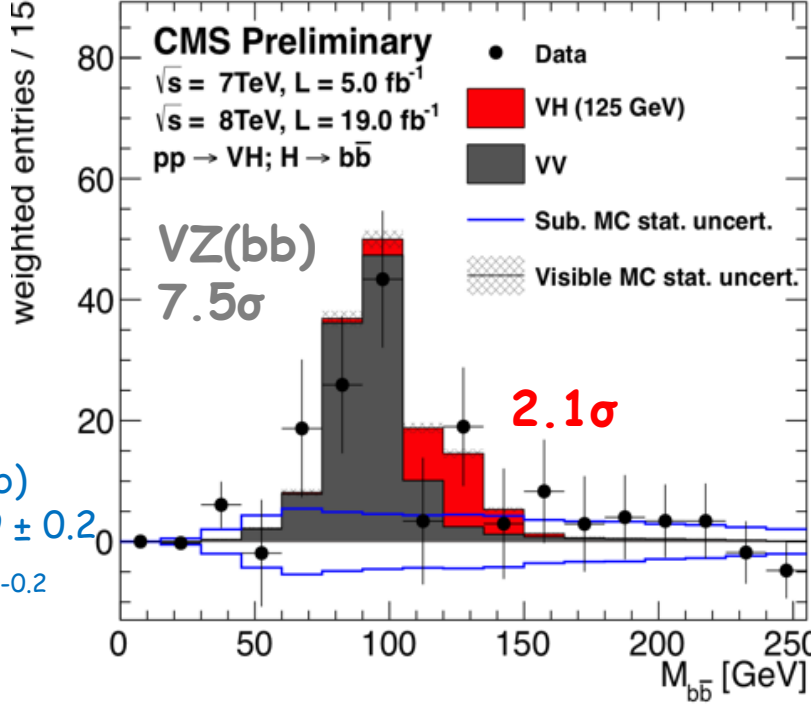
Combination (V)H→(V)WW
(Dominated by VBF & ggF)





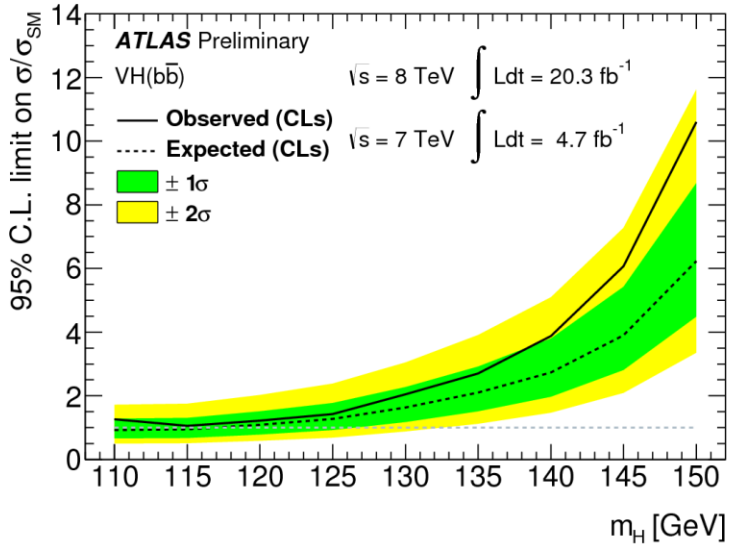
VH(bb)



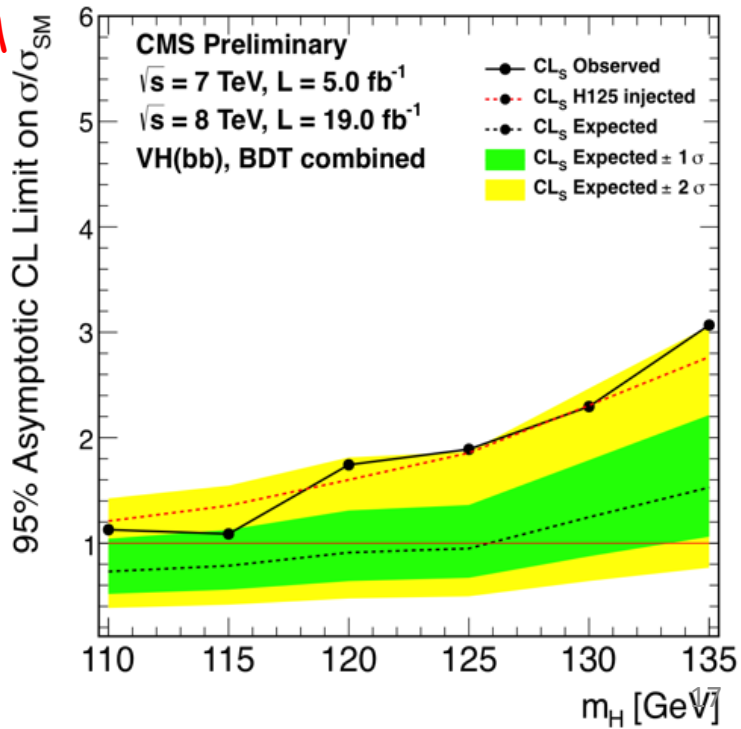


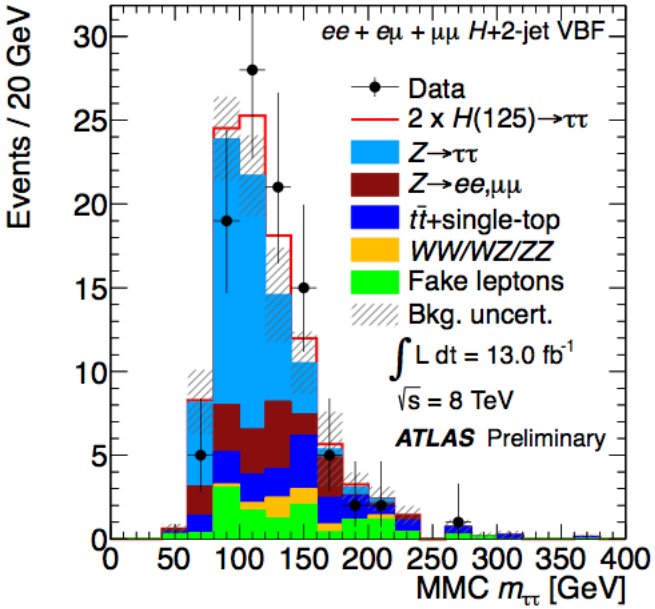
Validated with VZ(bb)
ATLAS: 4.8σ, μ = 0.9 ± 0.2
CMS: 7.5σ, μ = $1.2^{+0.3}_{-0.2}$

ATLAS: limit 1.4(1.3) × SM
μ(125.5) = $0.2^{+0.7}_{-0.6}$



CMS: 1.9(1.0) × SM
μ(125) = 1.0 ± 0.5





H→ττ

Search in exclusive categories, ll, lh, hh and jets (0,1,2)

Optimized ττ mass reconstruction

ATLAS:

1.1σ (1.7σ exp.)

$\mu(125.5) = 0.7^{+0.7}_{-0.6}$

Full stat soon !

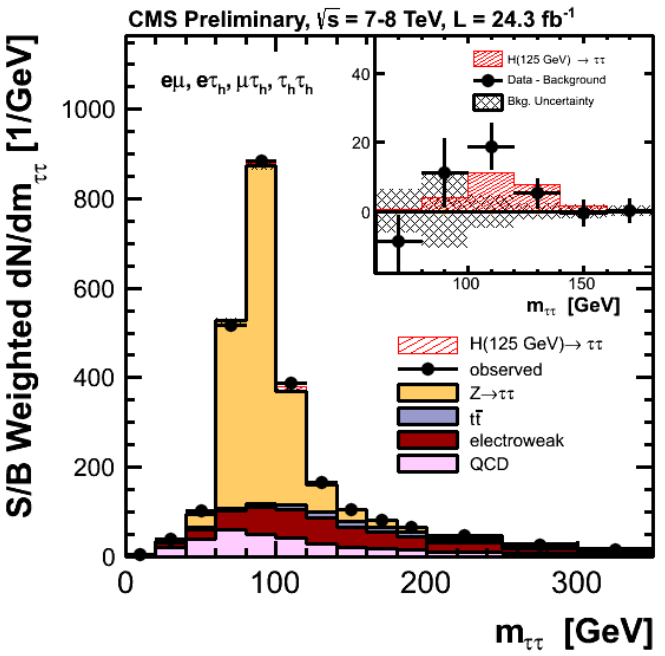
CMS:

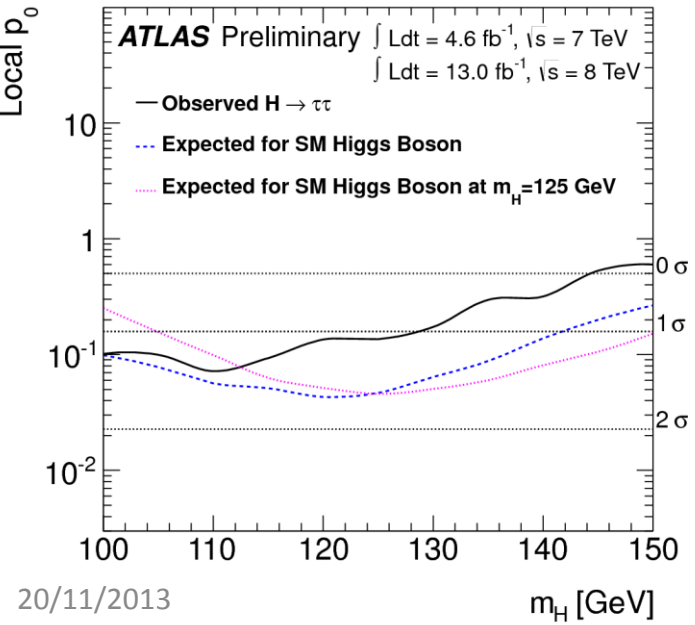
2.8σ (2.6σ exp.)

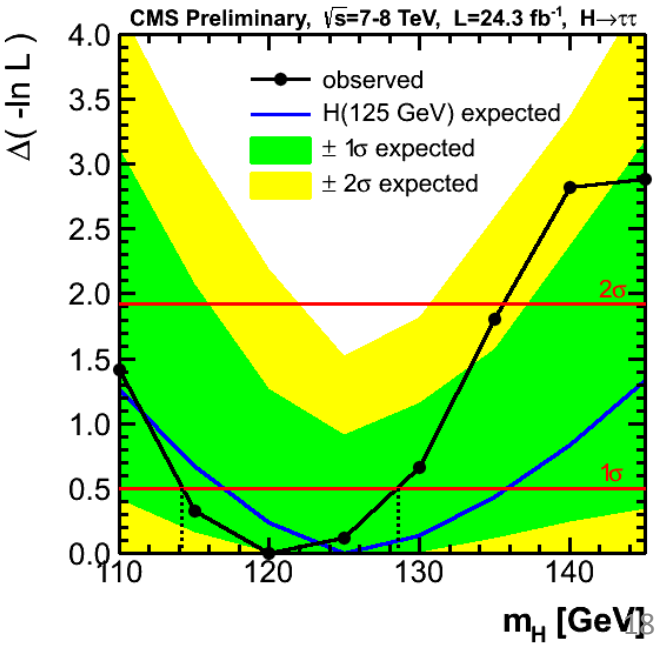
$\mu(125) = 1.1 \pm 0.4$

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

ττ + bb: 3.4σ

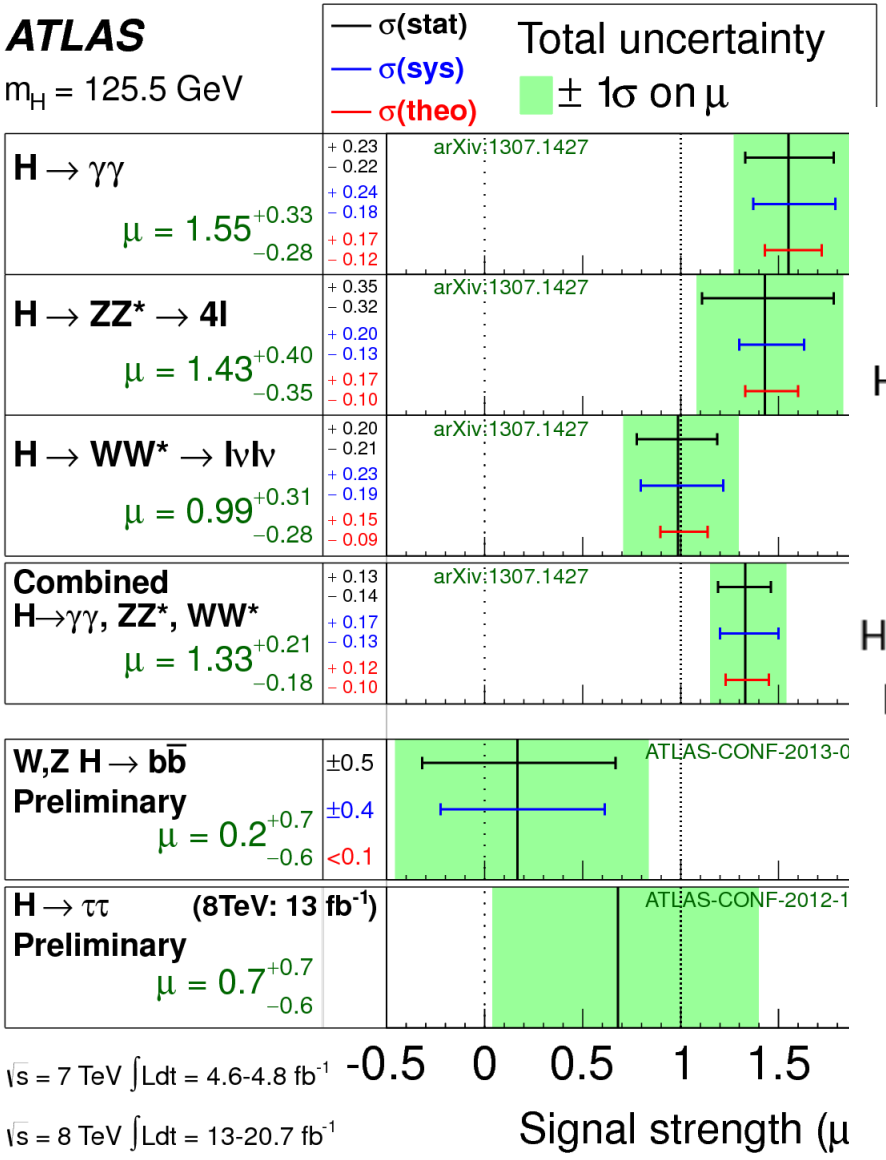




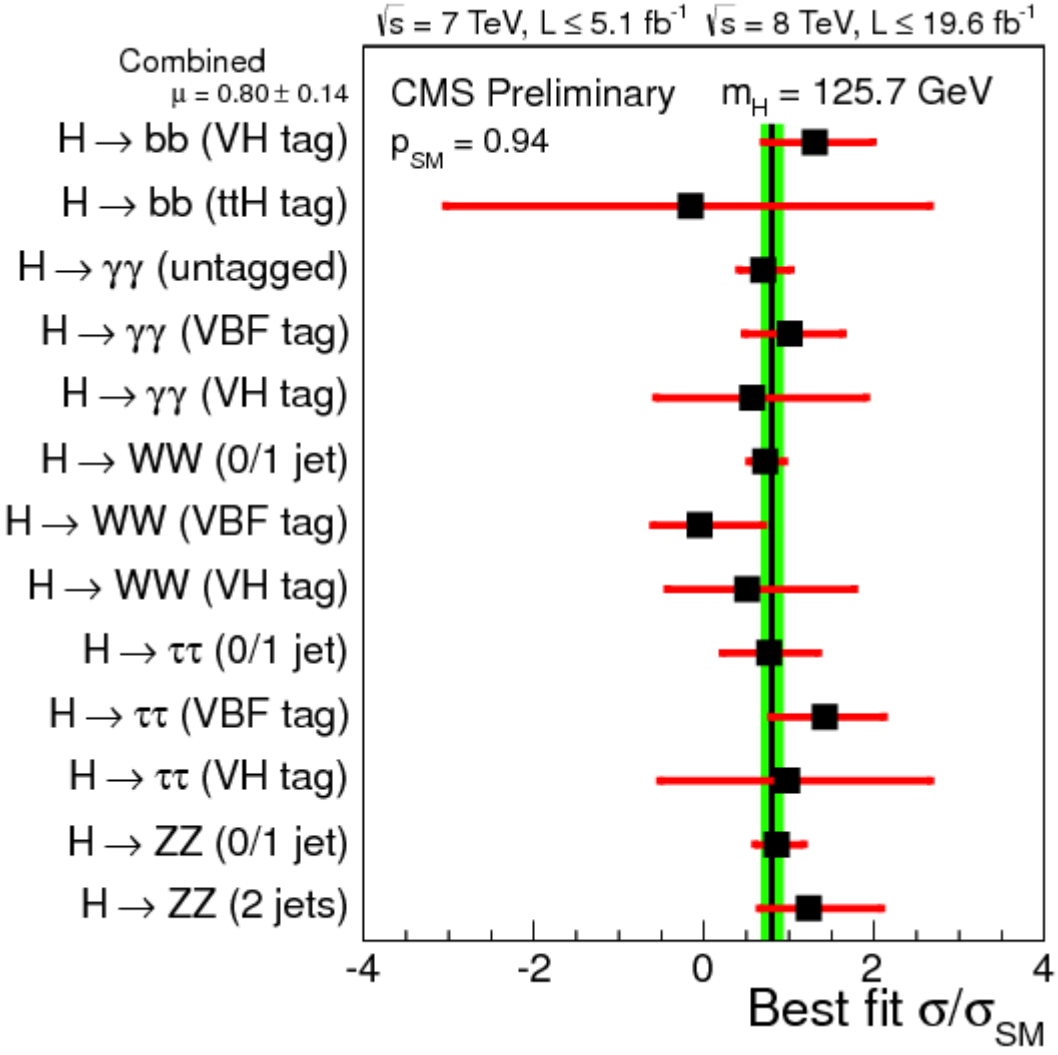


Signal Strength Summary

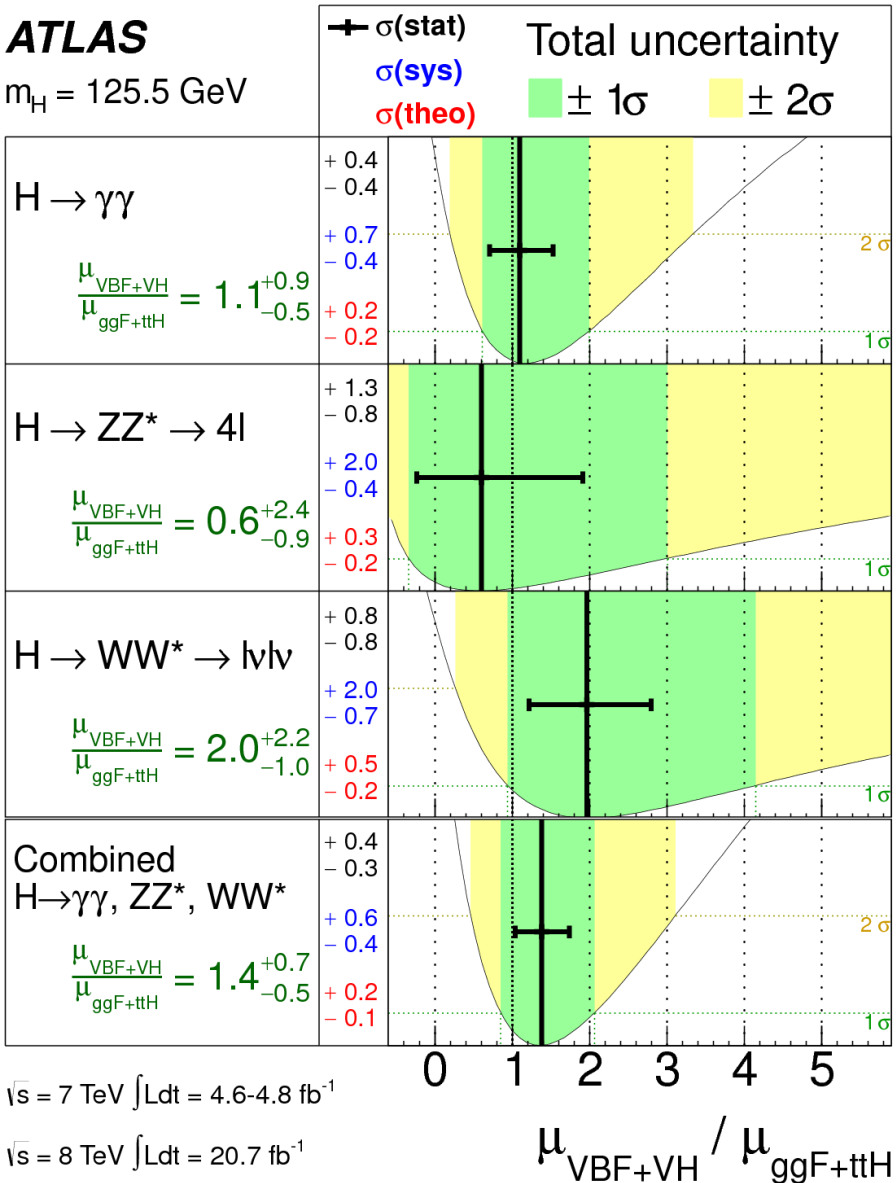
$\mu = 1.23 \pm 0.18$

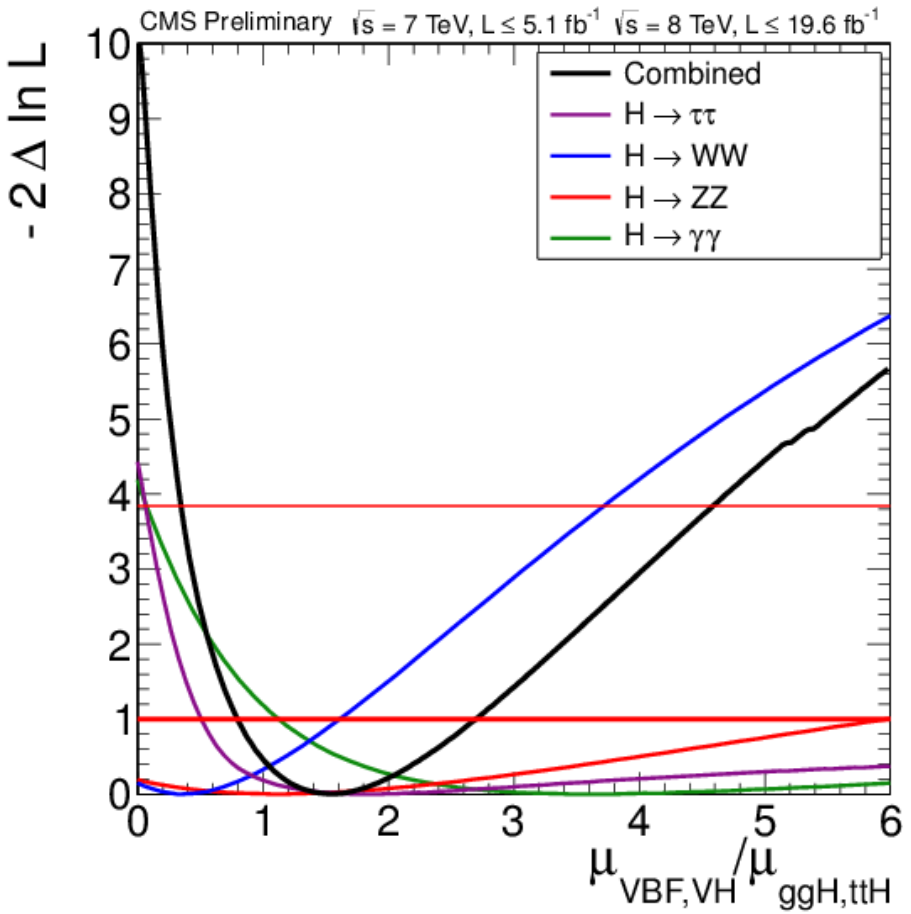


$\mu = 0.80 \pm 0.14$

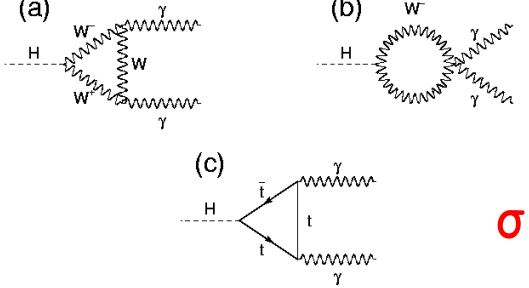


Coupling studies: VBF+VH/ggF+ttH

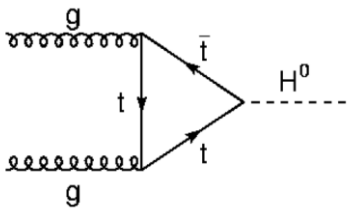




- ATLAS evidence for VBF production: 3.3σ
- CMS evidence for V-type production: 3.2σ

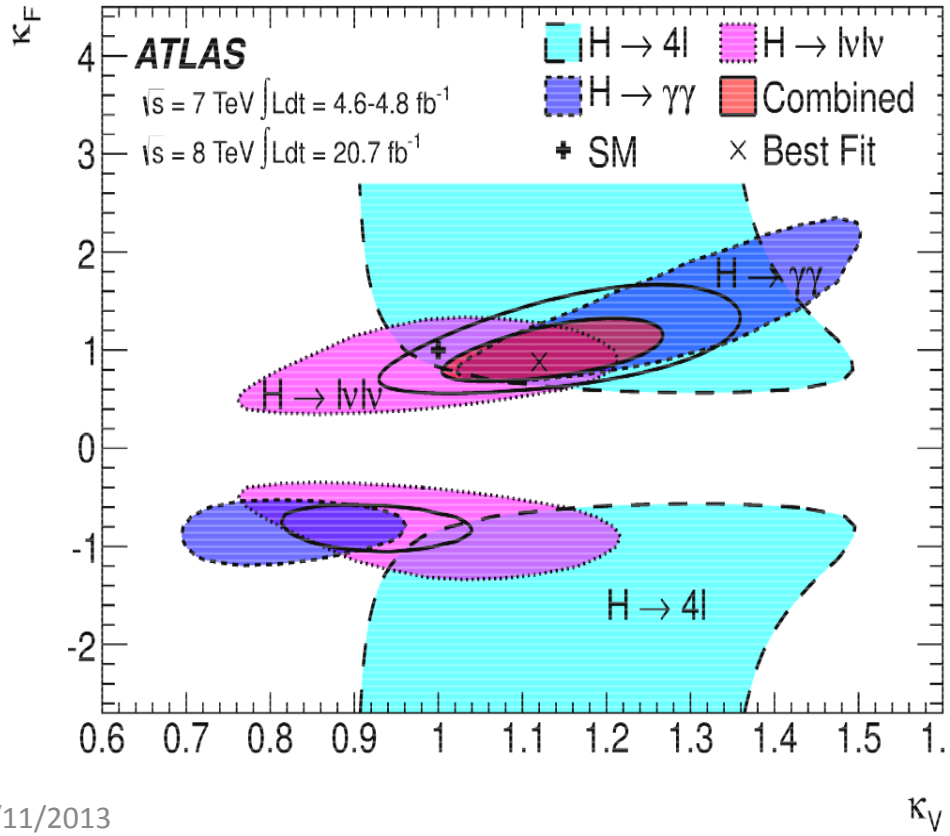


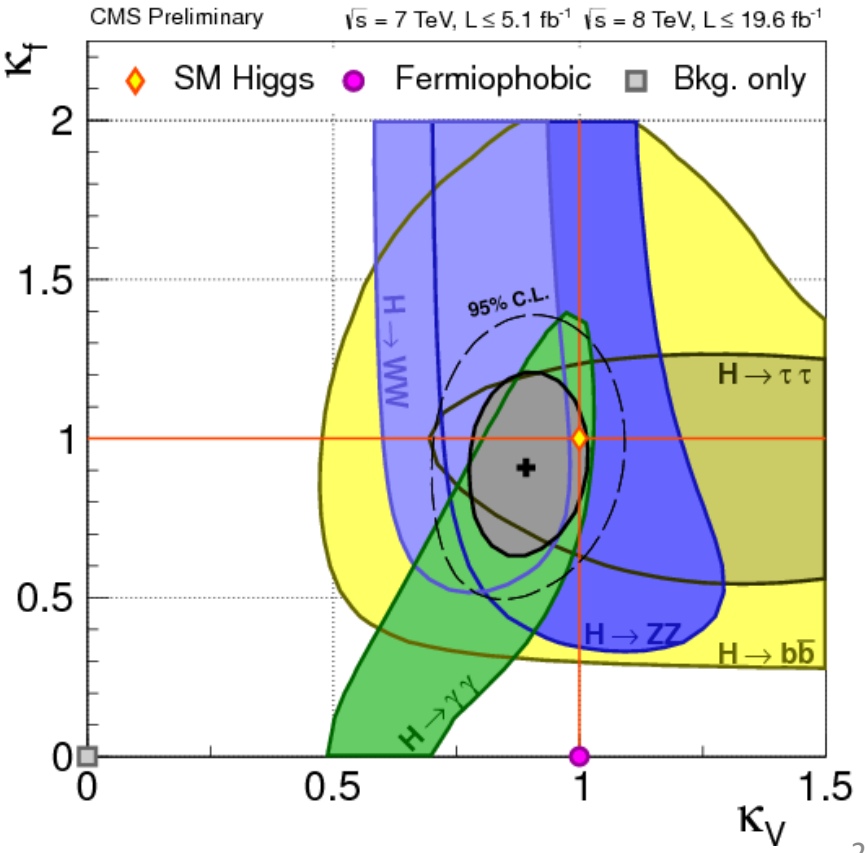
Coupling: strength of κ_V vs κ_F



$$\sigma * BR(ii \to H \to ff) = \frac{\sigma_{ii}.\Gamma_{ff}}{\Gamma_H} \; ; \; \mu = \frac{\sigma^{obs}}{\sigma_{SM}} = \frac{\kappa^2_i.\kappa^2_f}{\kappa^2_H}$$

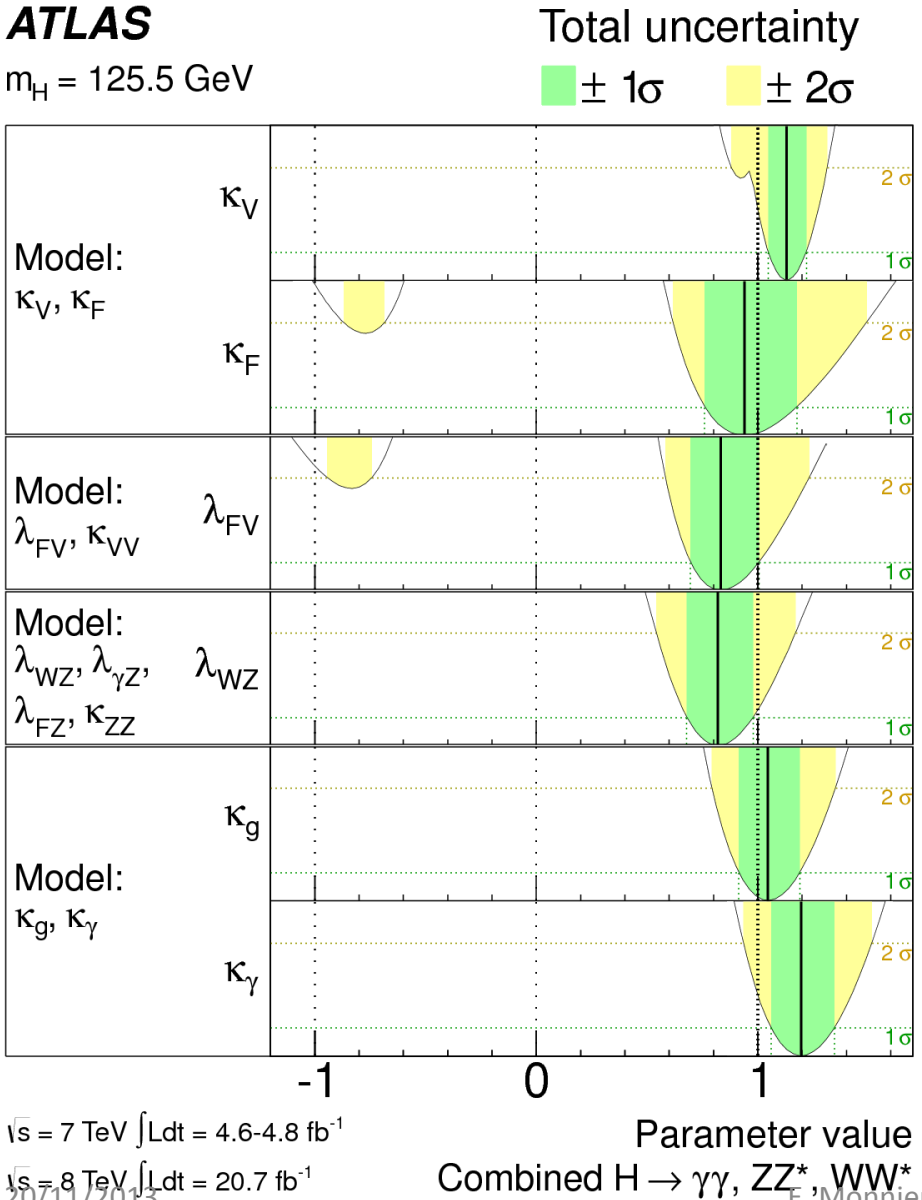
- κ is a scale factor for a SM coupling, =1 if compatibility with SM Higgs.
- Simplification: universality of κ for fermions, κ_F, for bosons, κ_V and $\kappa_g = \kappa_F$
- $\kappa_\gamma^2 = (1.26\kappa_V - 0.26\kappa_F)^2$ and $\kappa_H^2 = 0.75\kappa_F^2 + 0.25\kappa_V^2$ (at m_H = 125.5)
- Evidence for both fermion and boson coupling (κ_F and κ_V >0)

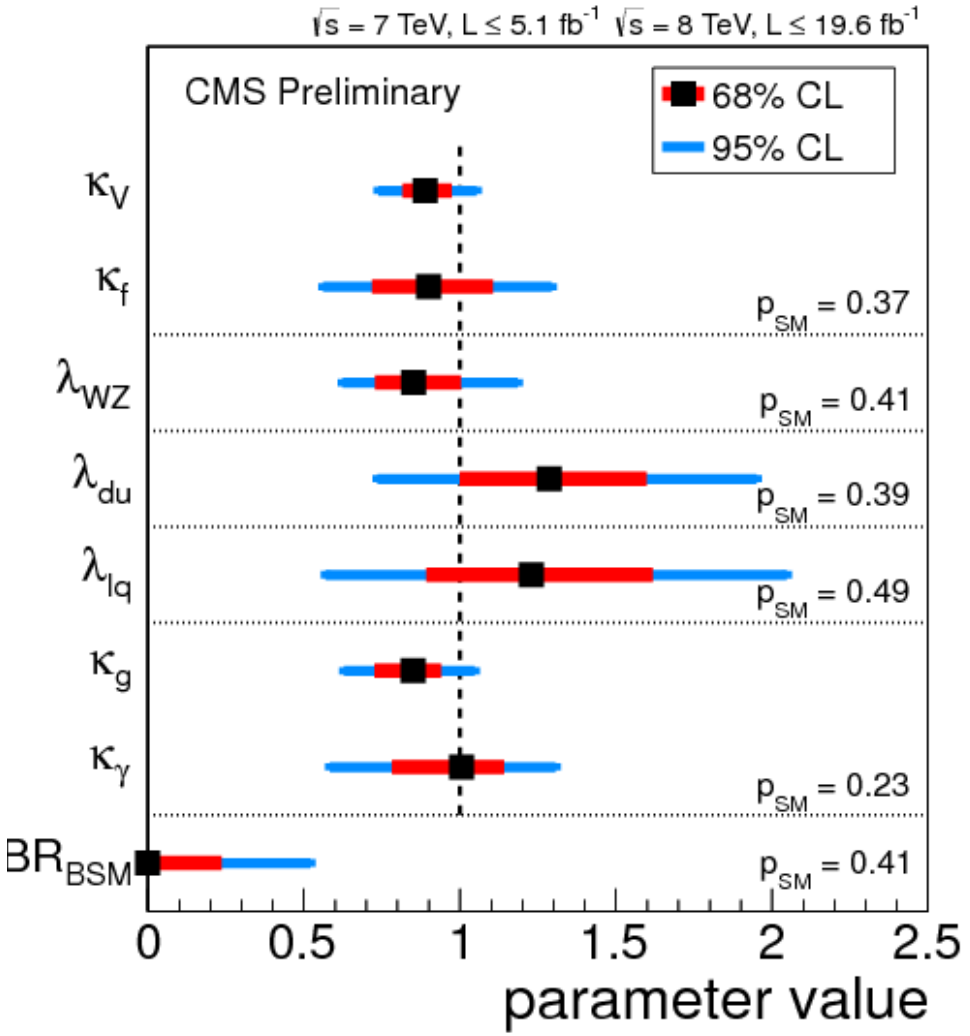




Coupling: additional tests

- Test of κ_Z vs κ_W: λ_{WZ}
- Test of κ_g vs κ_γ...

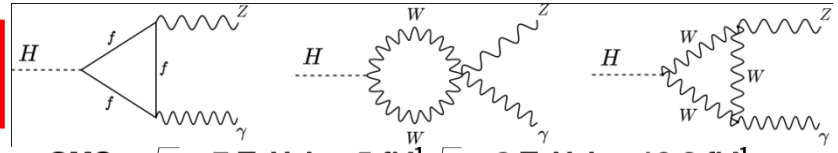


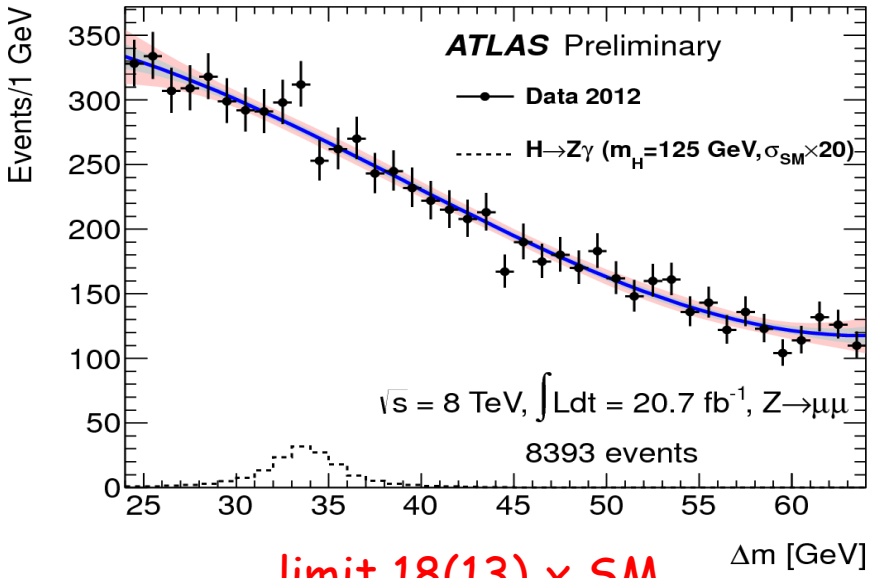


All compatible with SM

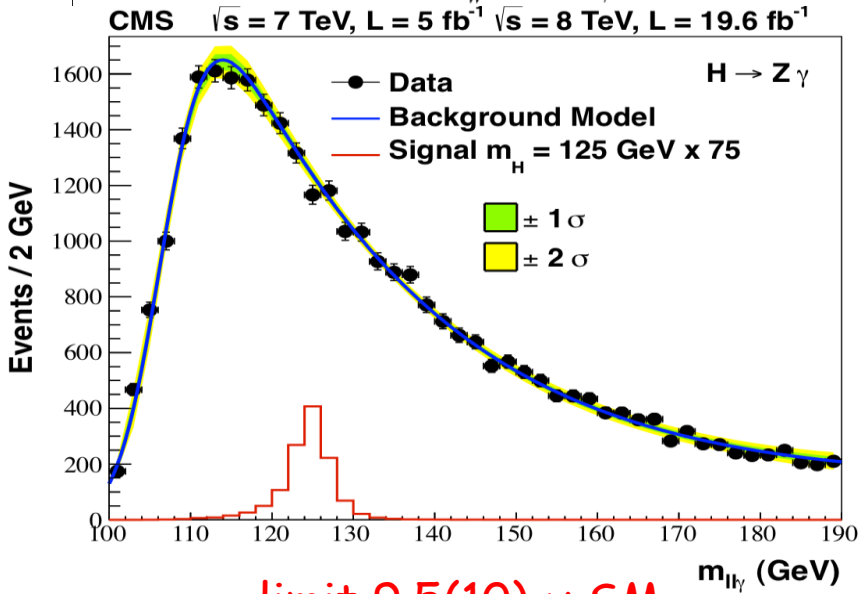
Sensitive to new physics

H to Zγ

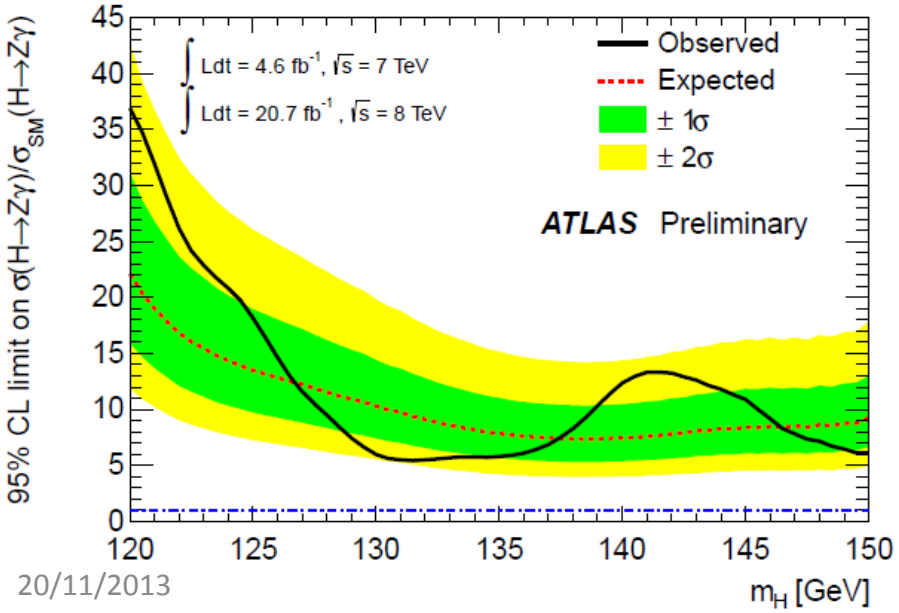


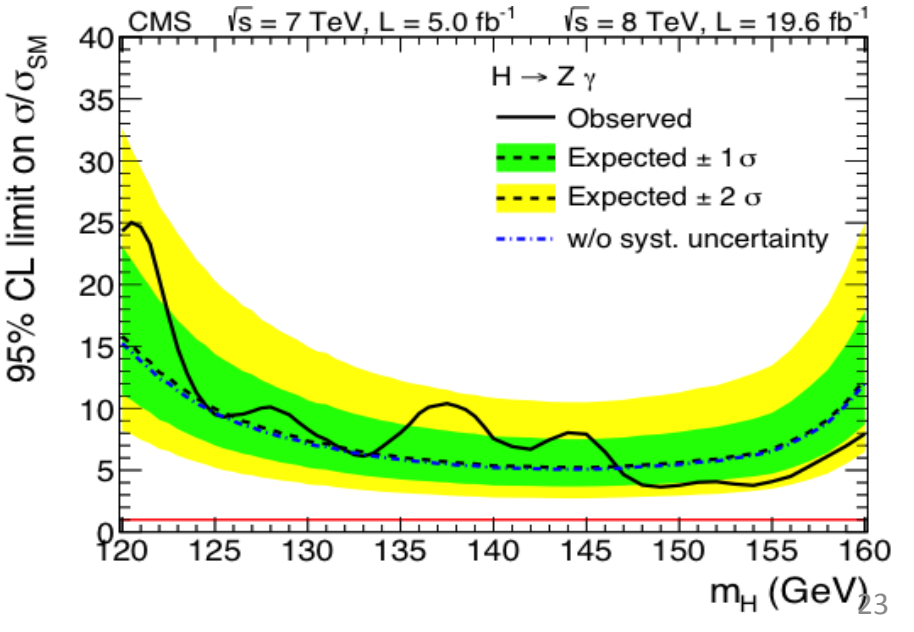


limit 18(13) x SM



limit 9.5(10) x SM

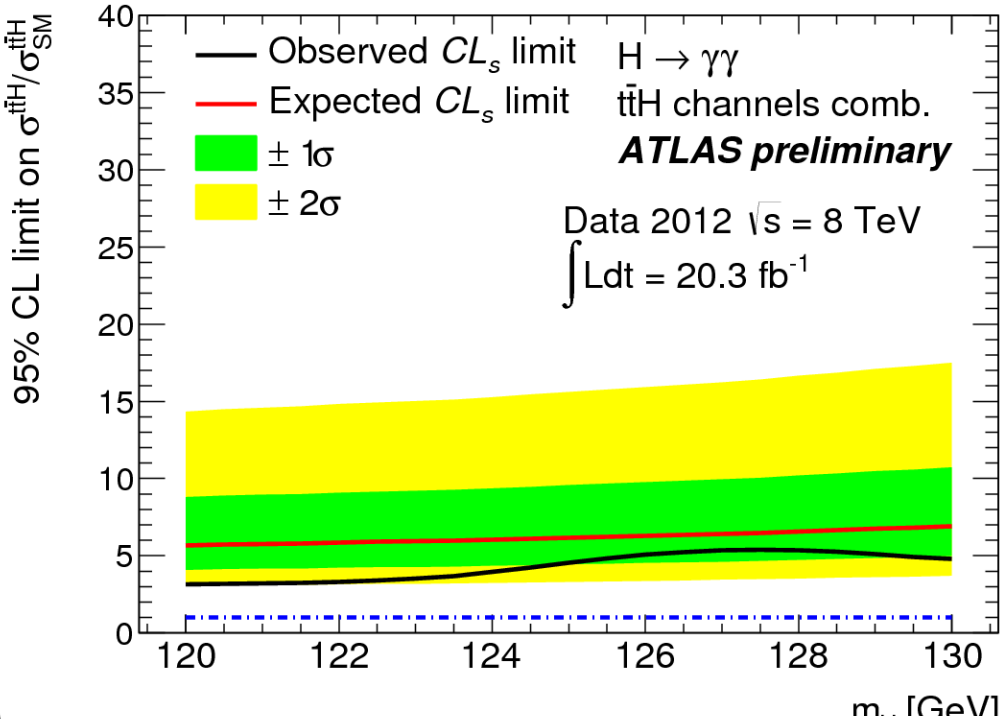


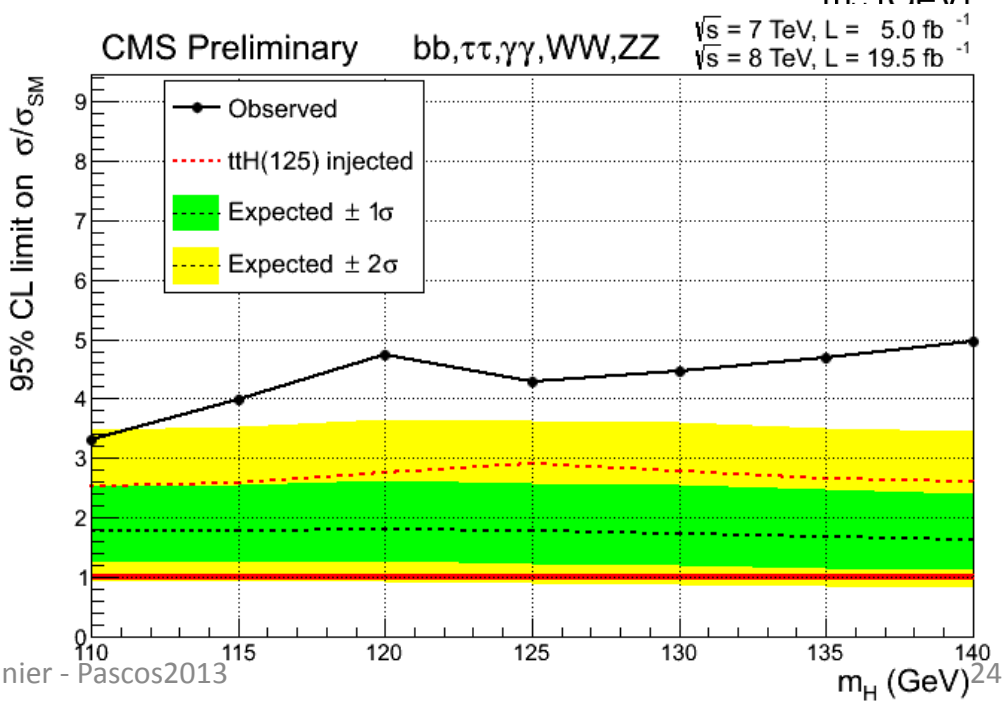


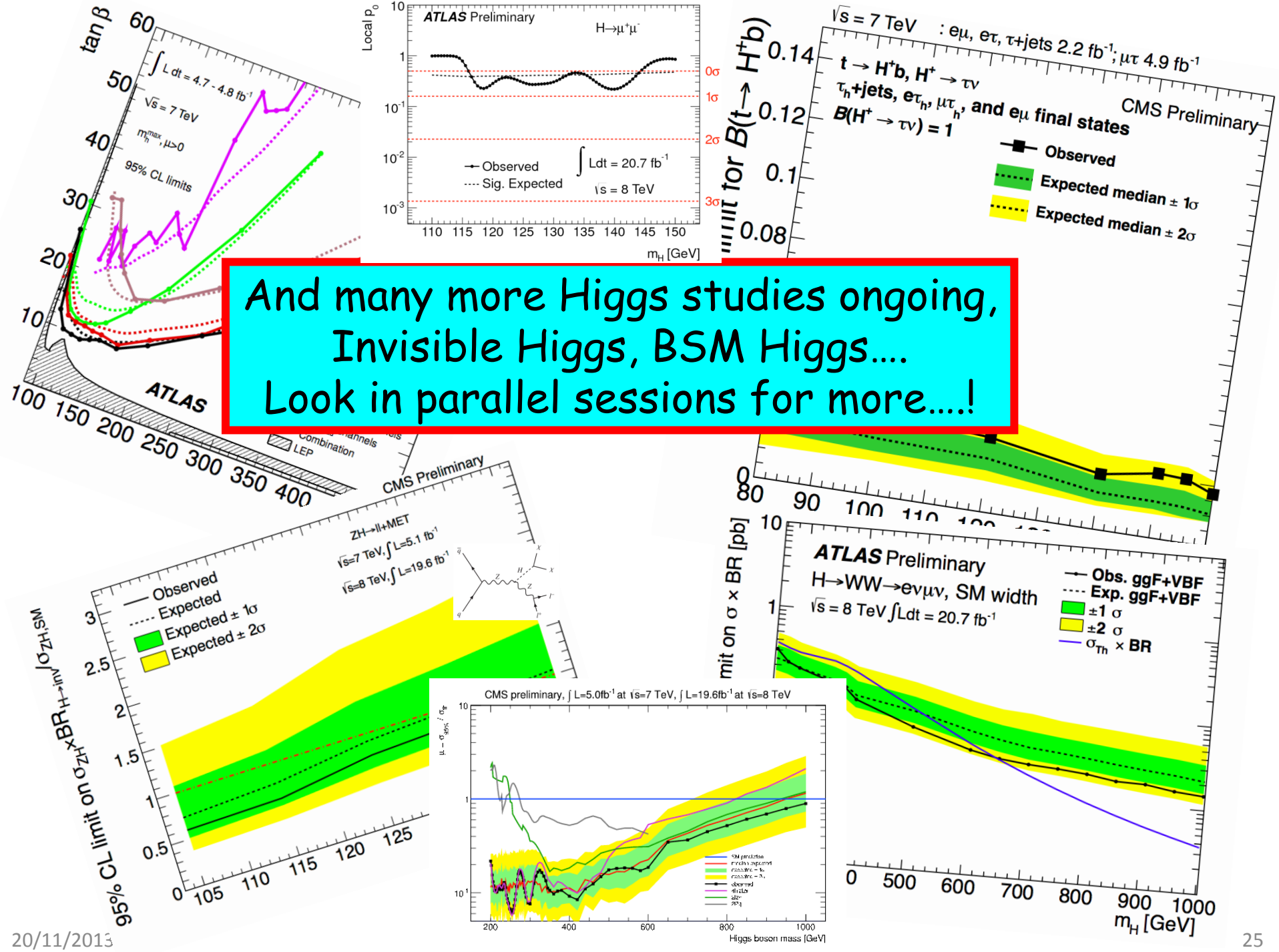
ttH

Very Challenging mode
Low rate
Complex state
Large Background

- Direct access coupling H to Top
- ttH(bb):
  - 7TeV ATLAS: 13.1 (10.5) x SM
  - Run1 CMS: 5.2 (4.1) x SM
- ttH(γγ):
  - Run1 ATLAS: 5.3 (6.4) x SM
  - Run1 CMS: 5.4 (5.3) x SM
- ttH γγ, bb,ττ, WW, ZZ combination:
  - Run1 CMS: 4.3 (1.8) x SM






And many more Higgs studies ongoing,
Invisible Higgs, BSM Higgs….
Look in parallel sessions for more….!
ATLAS Preliminary
H→μ⁺μ⁻
Observed
Sig. Expected
∫ Ldt = 20.7 fb⁻¹
√s = 8 TeV
m_H [GeV]
CMS Preliminary
√s = 7 TeV : eμ, eτ, τ+jets 2.2 fb⁻¹; μτ 4.9 fb⁻¹
t → H⁺b, H⁺ → τν
τ_h+jets, eτ_h, μτ_h, and eμ final states
B(H⁺ → τν) = 1
Observed
Expected median ± 1σ
Expected median ± 2σ
ATLAS
∫ L dt = 4.7 - 4.8 fb⁻¹
√s = 7 TeV
95% CL limits
tan β
CMS Preliminary
ZH→ll+MET
√s=7 TeV, ∫ L=5.1 fb⁻¹
√s=8 TeV, ∫ L=19.6 fb⁻¹
Observed
Expected
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ_ZH x BR_H→inv / σ_ZH,SM
ATLAS Preliminary
H→WW→eνμν, SM width
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Obs. ggF+VBF
Exp. ggF+VBF
±1 σ
±2 σ
σ_Th x BR
m_H [GeV]
CMS preliminary, ∫ L=5.0fb⁻¹ at √s=7 TeV, ∫ L=19.6fb⁻¹ at √s=8 TeV
Higgs boson mass [GeV]

Conclusion

More than one year after the Higgs discovery and ~ 25 fb^{-1} looked at:

- Higgs saga continues and more decays found or about to be.
- Mass at 3 per mill
- Evidence for scalar nature 0^+, coupling to fermion, V-mediated and VBF production
- Coupling and all other properties compatible with SM
- All converge toward SM Higgs for now, no evidence for New Physics
- Full Run1 stat now being look at with improved detector performances, more new or more precise results still expected in 2014
- In 2015 start run2 with higher E_{CM} and Luminosity, so higher Higgs statistics (2.6 to 4.7xσ_H@8TeV) to study it and search for new phenomena.
- **A bright future is ahead of us !!**