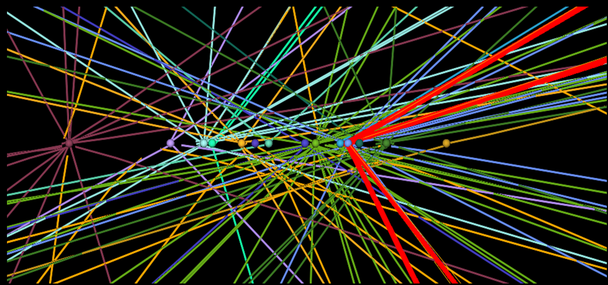
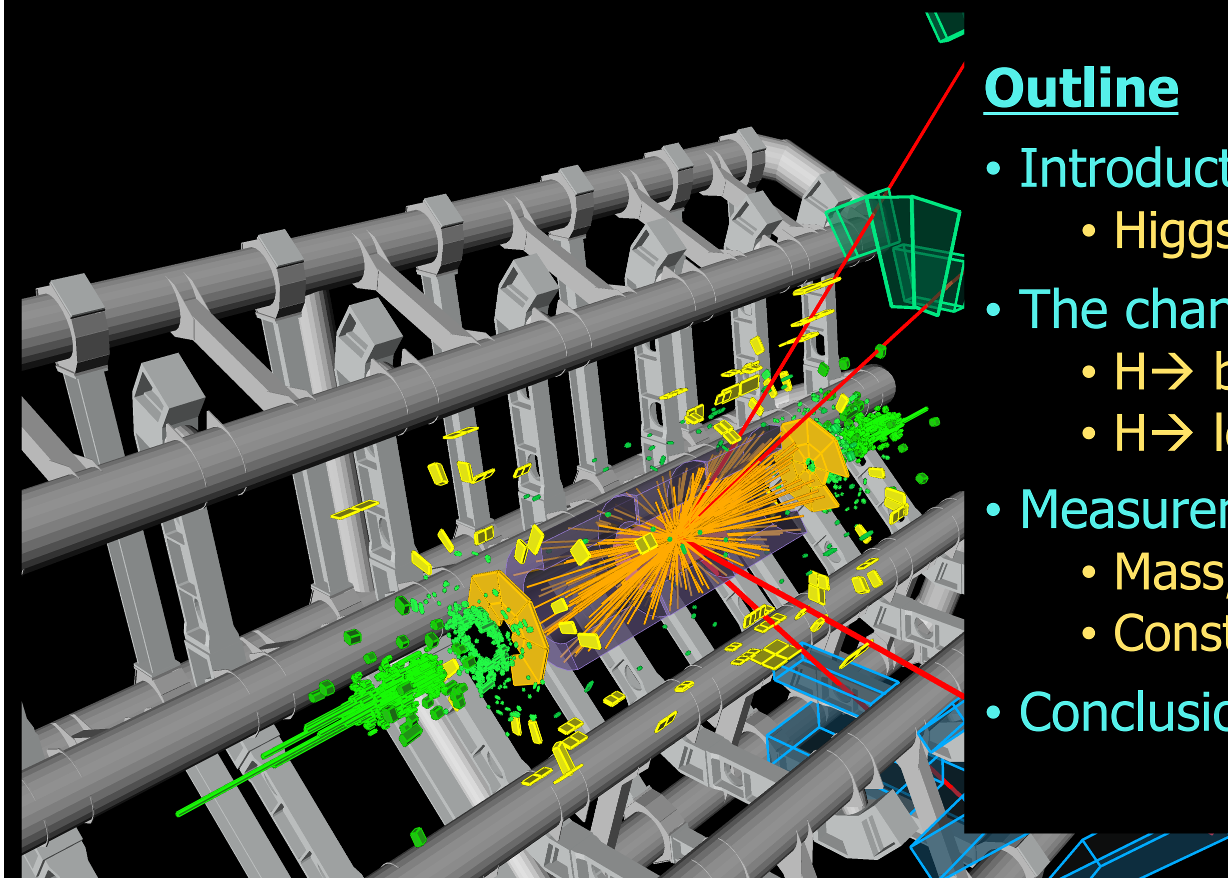


Higgs couplings at the LHC and constraints on New Physics

Gabriella Sciolla
Brandeis University

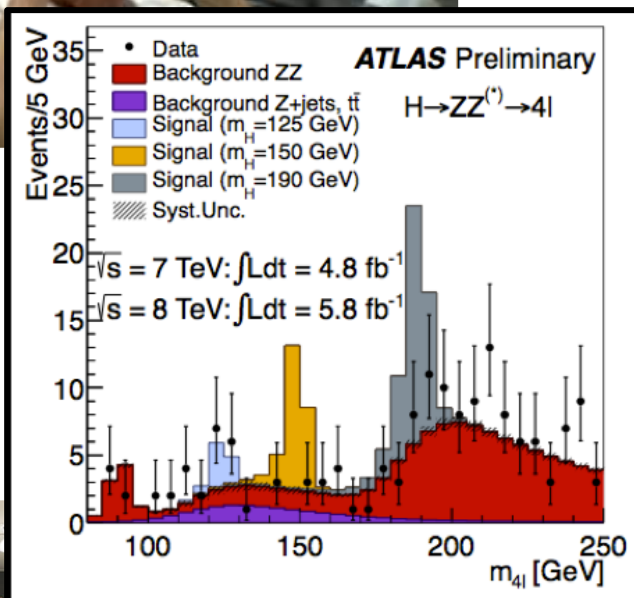


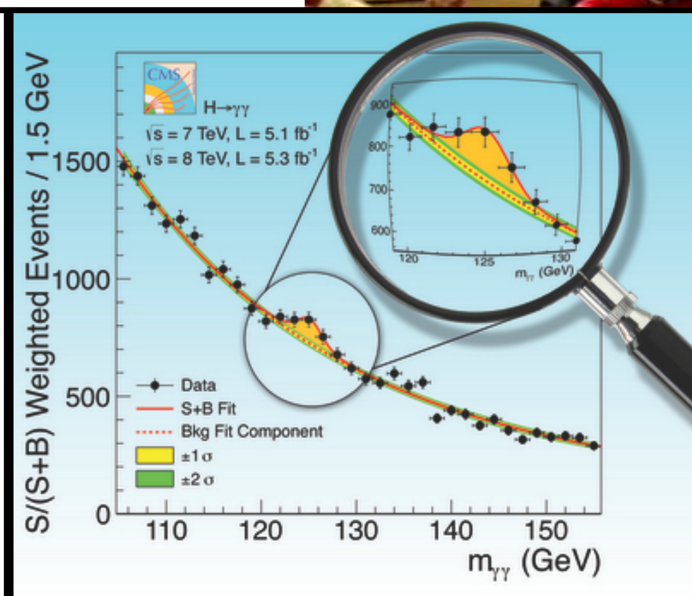
Outline

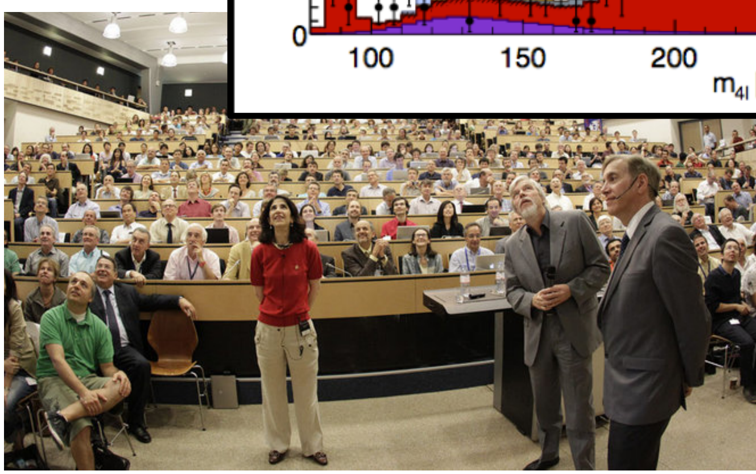
- Introduction
  - Higgs production and decay
- The channels of discovery
  - H→ bosons: $\gamma\gamma$, ZZ, WW
  - H→ leptons: $\tau\tau$, bb
- Measurements of Higgs properties
  - Mass, Spin/CP, x-sections, couplings
  - Constraints on NP
- Conclusion

PACIFIC 2014, Tahiti, Sep 17 2014

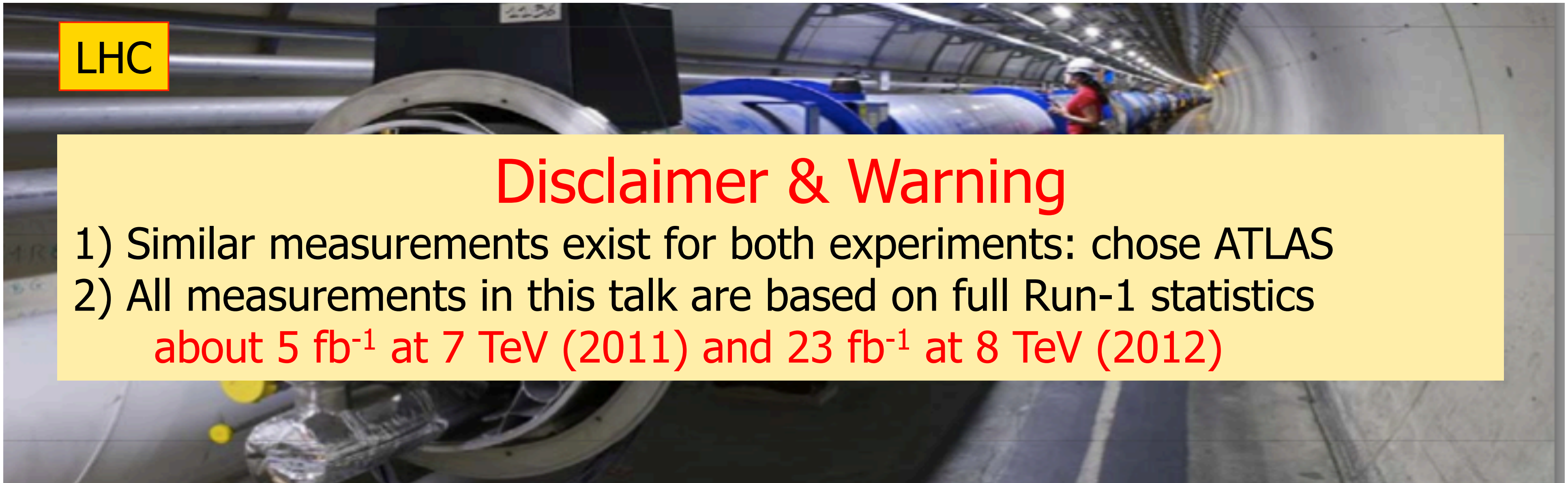
The discovery: Jul 4th 2012





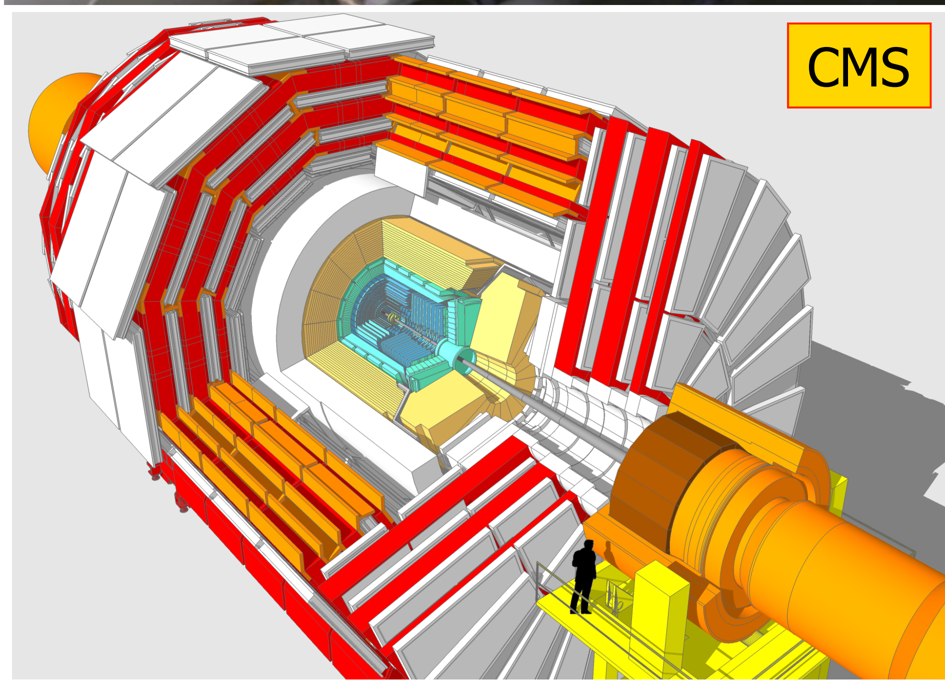


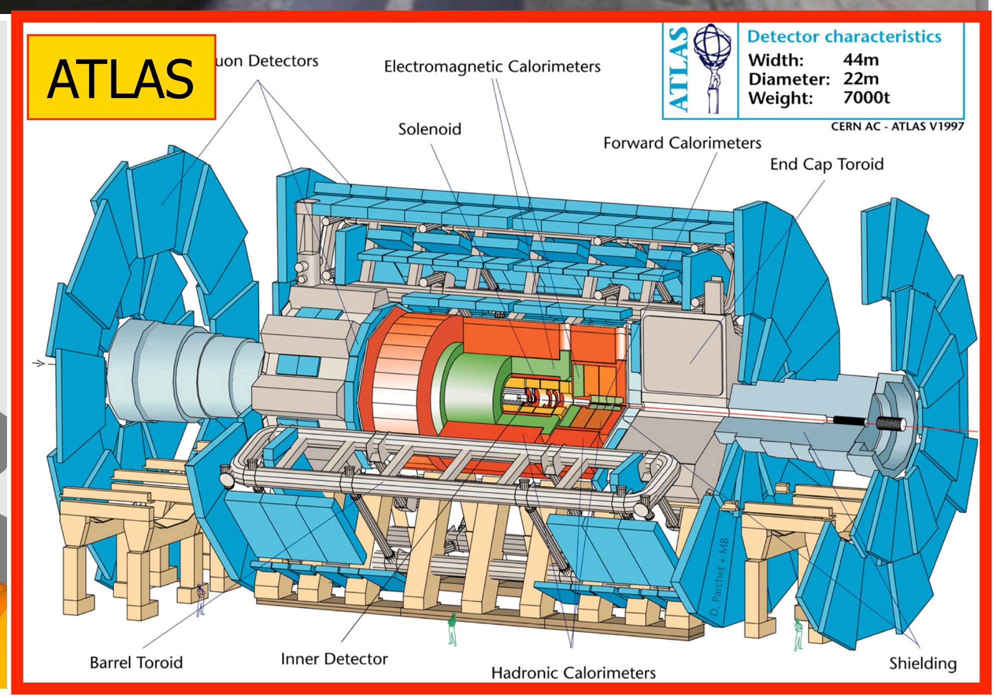
ATLAS and CMS at the LHC



Disclaimer & Warning

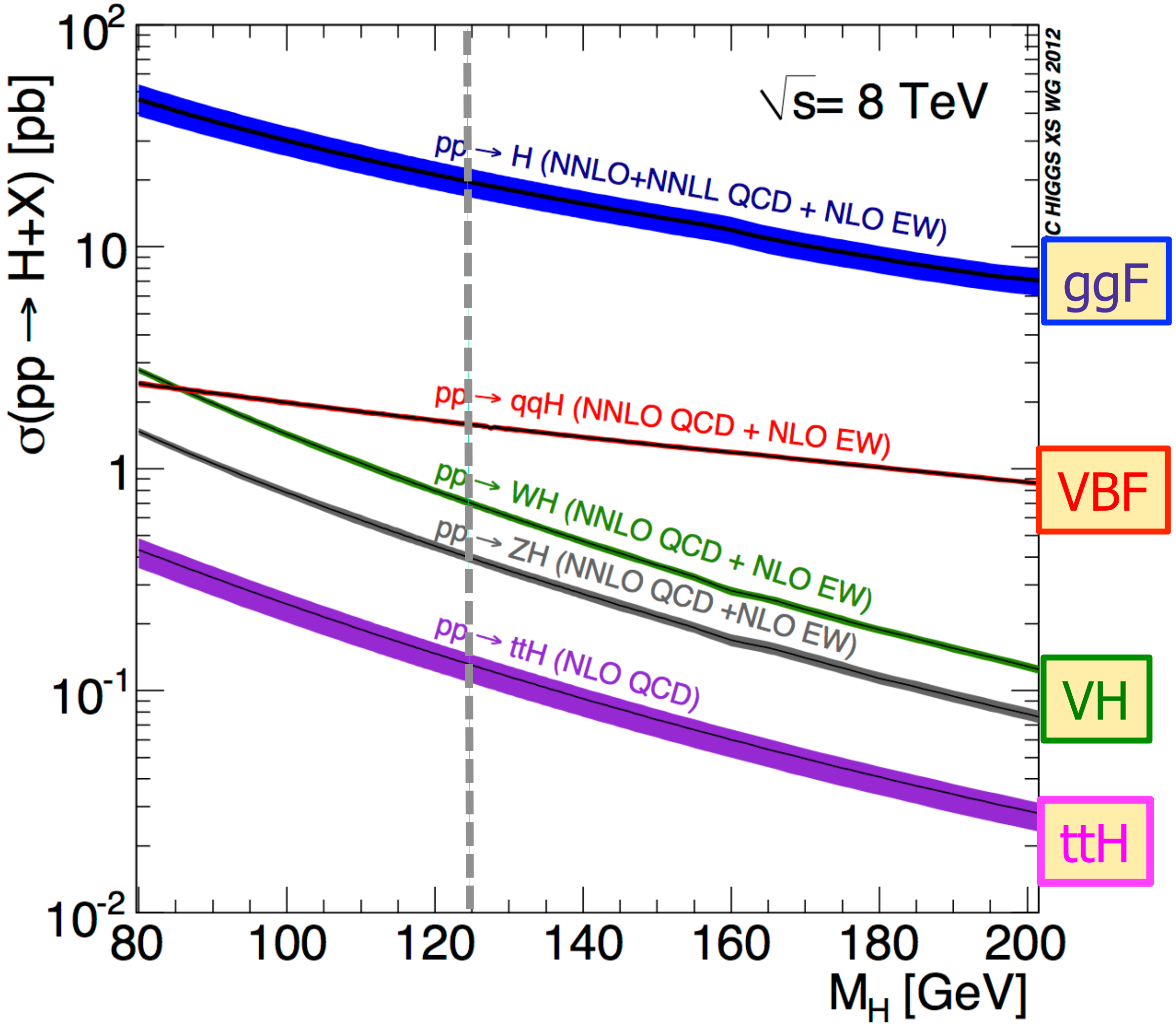
1) Similar measurements exist for both experiments: chose ATLAS
2) All measurements in this talk are based on full Run-1 statistics
   about 5 fb^{-1} at 7 TeV (2011) and 23 fb^{-1} at 8 TeV (2012)

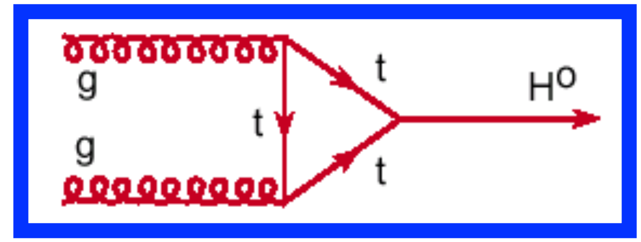


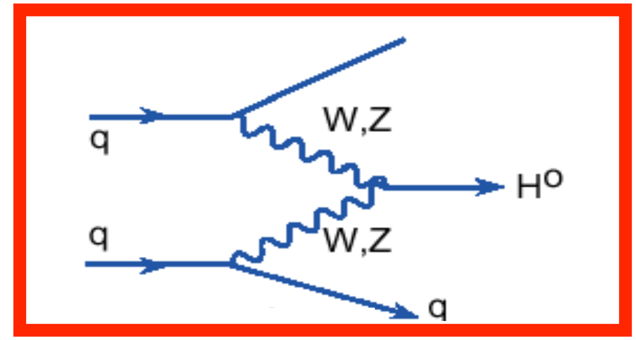


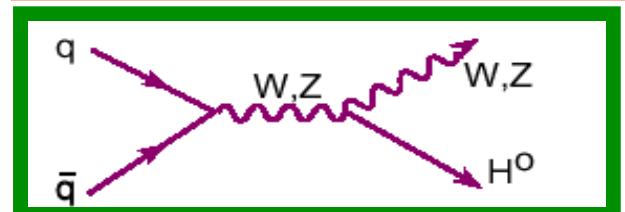
The Higgs at the LHC:

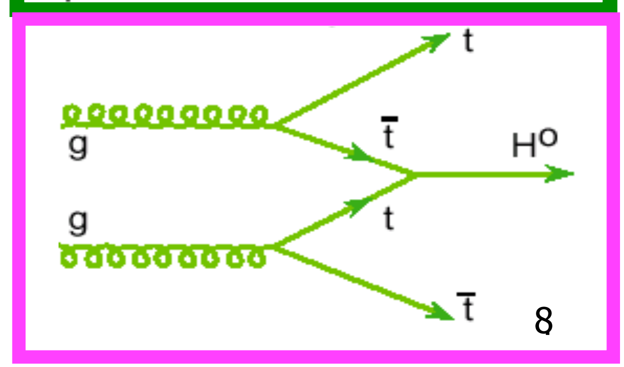
Production modes





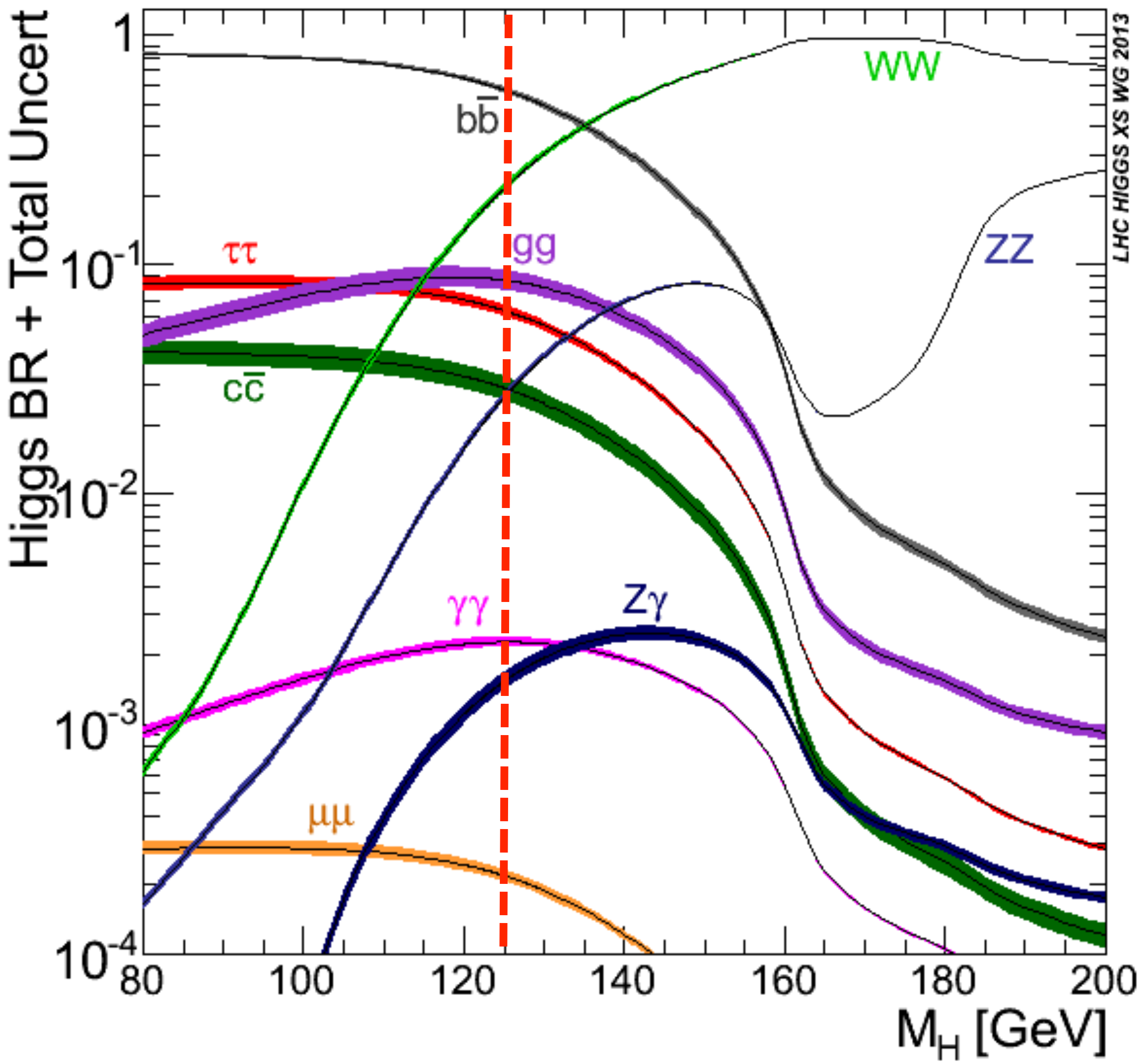






The Higgs at the LHC:

Decay modes



Decay Mode m_H=125.5	BR(%)
H→$b\bar{b}$	57
H→WW	22
H→ττ	7
H→ZZ	3
H→γγ	0.2

BR are only part of the story:

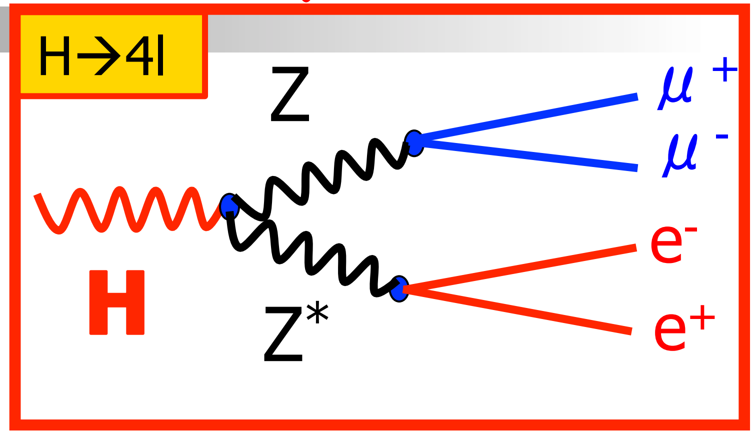
- Accessibility of final state
  - E.g.: Z→ll vs. Z→ ν ν
- BR of final state
  - E.g.: BR(Z→ll)~3%
- SM backgrounds

The channels of discovery

- Higgs → Vector Bosons
  - $H \to ZZ$
  - $H \to \gamma\gamma$
  - $H \to WW$
- Higgs → Fermions
  - $H \to \tau^+\tau^-$
  - $H \to b\bar{b}$

Phys. Rev. D. 90, 052004 (2014)

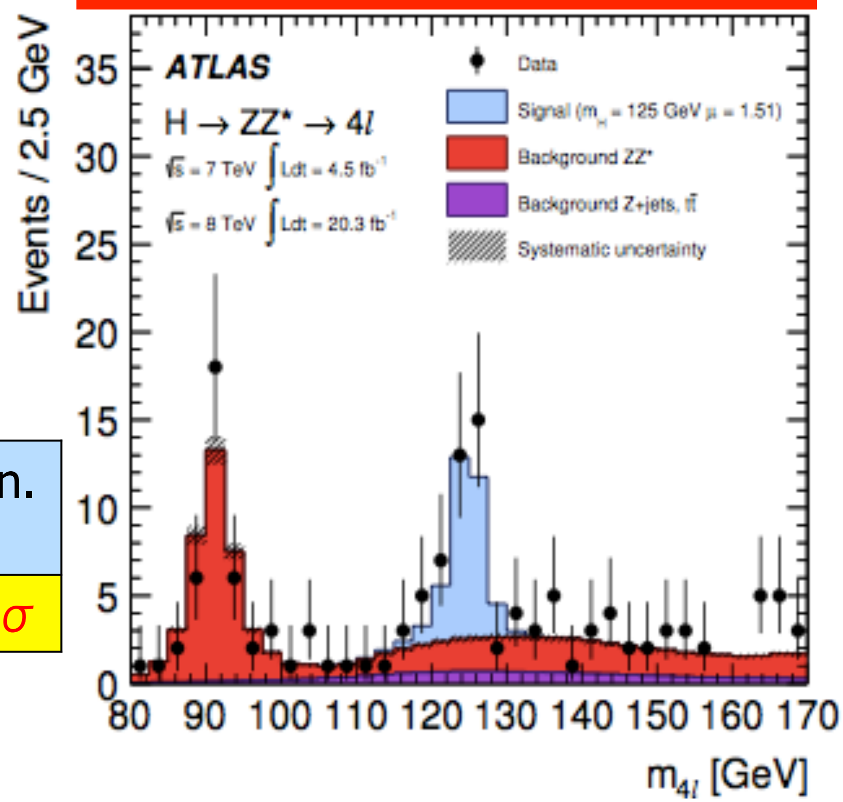
H→ZZ(*)→4 leptons (e or μ)



- The golden channel: S/B > 1:1
  - Small rates σ x BR ~ 2.5 fb
  - Very small backgrounds (SM diboson)
  - Final state is fully reconstructed
    - Can measure everything!
- Selection criteria
  - 4 isolated leptons $|\eta|<2.5$
  - p_T>20,15,10,6 GeV
  - One on-shell Z^0, m_{12}=[50,106] GeV

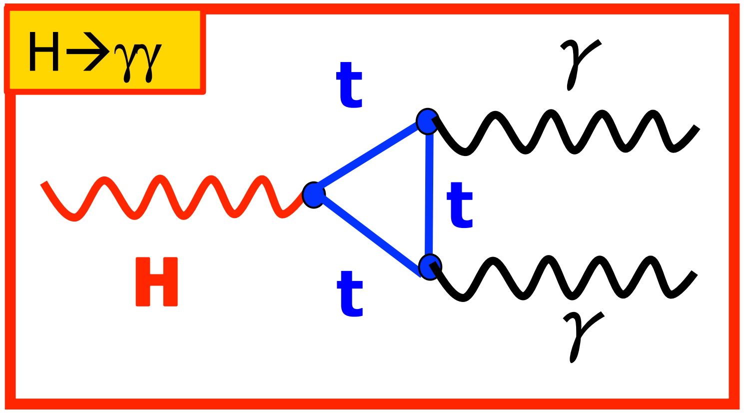
120-130 GeV	Expected Higgs	Expected backgr.	Observed in data	Sign.
5+20 fb^{-1}	16.2	10.4	37	8.1σ

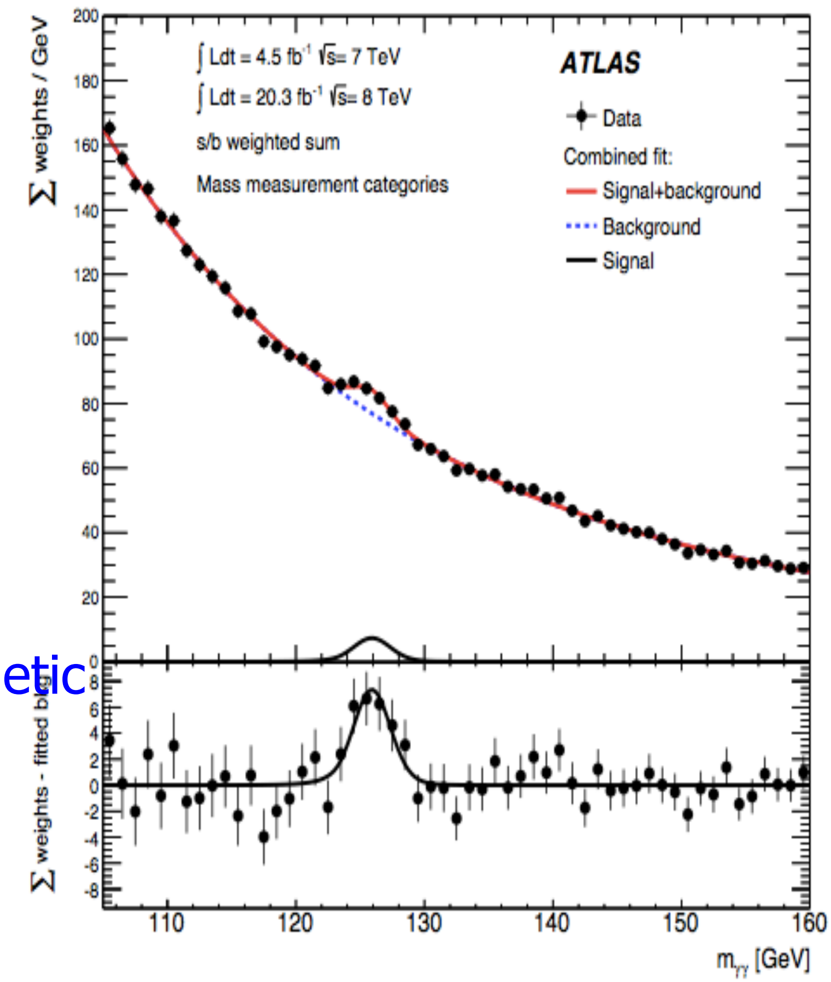
Was 6.6σ!



Phys. Rev. D. 90, 052004 (2014)

H→γγ





- Distinct kinematic signature
  - Two back-to-back γ, isolated & energetic
    - p_T>~40,30 GeV within $|\eta|$<2.5
    - Excellent energy (1.7 GeV) and angular (0.5°) resolution
- Experimental challenges
  - Small BR (~0.2%)
    - But rates (σ x BR ~ 50 fb)
  - Abundant SM background: S/B ~ 3%

Significance: 5.2 σ
(4.6 expected)

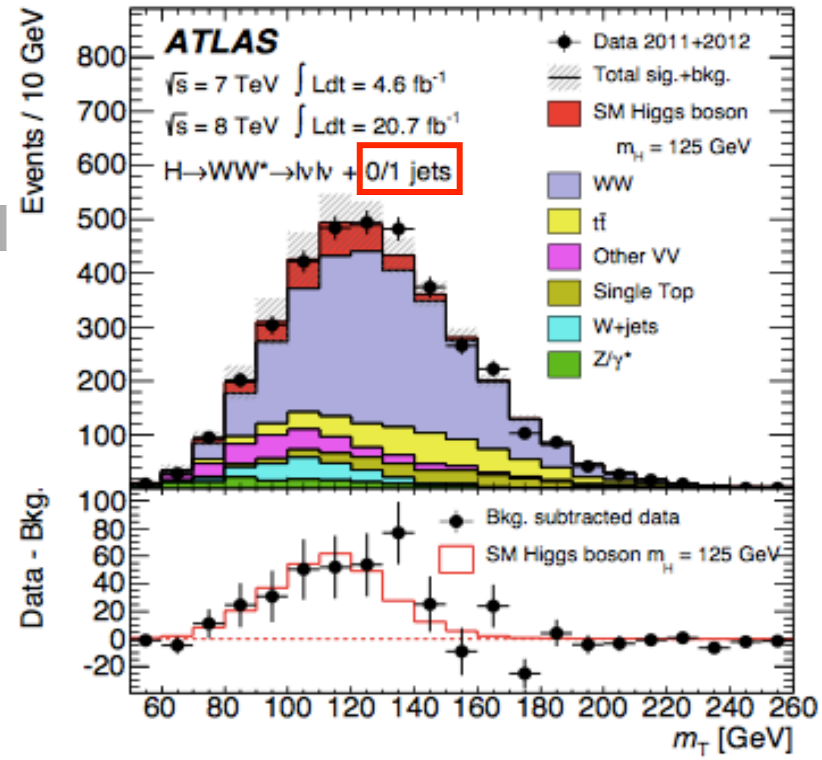
PLB 726 (2013) 88

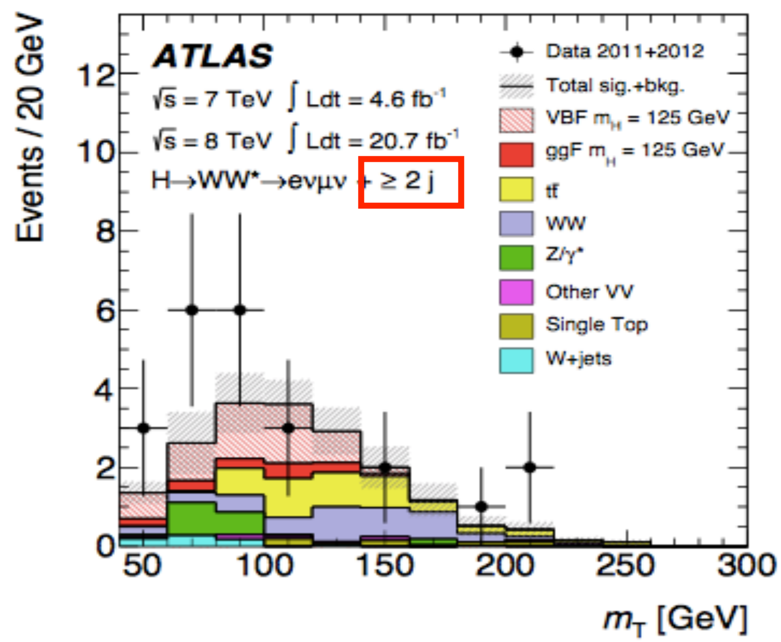
H→WW*→lνlν

- Large rates expected
  - σ x BR ~ 200 fb
- Significant backgrounds
  - SM WW, top, W+jets, WZ
- Missing particles in final state
  - Not all measurements possible
- Analysis strategy
  - Define categories according to lepton flavor (ee, eμ, μμ) and N_{jets}:
    - 0 and 1 jets: mainly ggF events
    - >= 2 jets: mainly VBF events

$$m_T = \sqrt{(E_T^{ll} + \not{E}_T)^2 - \left|\vec{p}_T^{ll} + \vec{\not{E}}_T\right|^2}$$

- $\text{Significance}_{mH=125}$: 3.8 σ (3.7 σ)





The channels of discovery

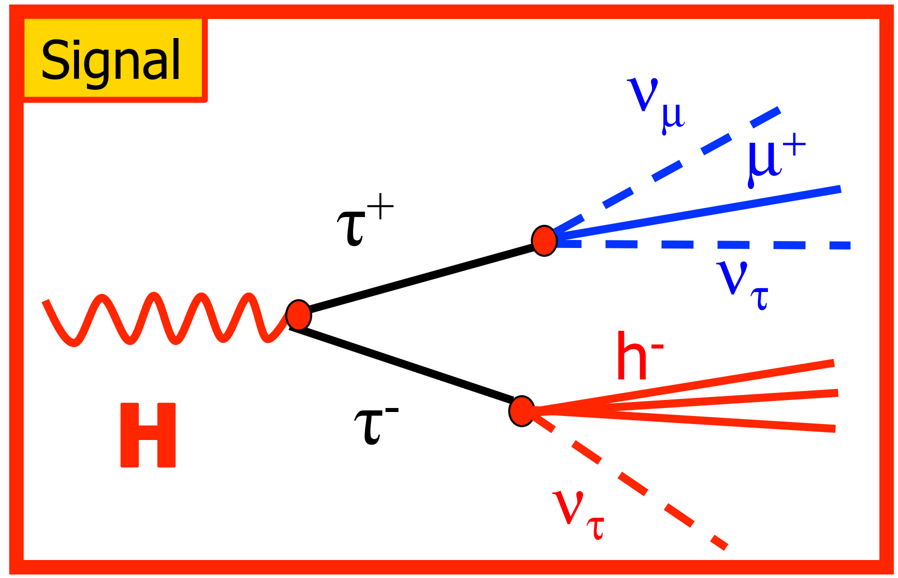
- Higgs → Vector Bosons
  - H→ $\gamma\,\gamma$
  - H→ZZ
  - H→WW

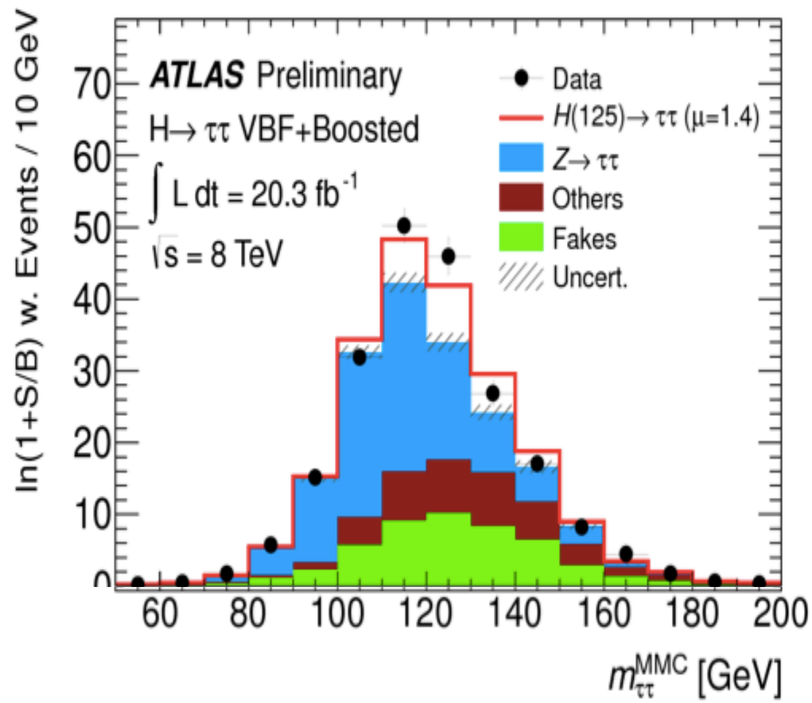
- Higgs → Fermions
  - H→ $\tau^+\tau^-$
  - H→ $b\bar{b}$

ATLAS-CONF-2013-108

$H \rightarrow \tau^+\tau^-$

- Large rates
  - σ x BR ~ 1500 fb
- Large backgrounds
  - $Z \rightarrow \tau\tau$, Z/W+jets, top,…
- Challenging final states
  - 2-4 neutrinos: large MET
- 3 final states:
  - lep-lep, lep-had, had-had
- Multivariate analysis: 9 variables BDT
  - $m_{\tau\tau}$, $\Delta R_{\tau\tau}$, m_{jj}, $\Delta\eta_{jj}$, p_T-sum, m_T, …
- Signal clearly visible in weighted mass
  - Event weight = ln(1+S/B)
- Observed significance: 4.1 σ
  - Expected 3.2 σ



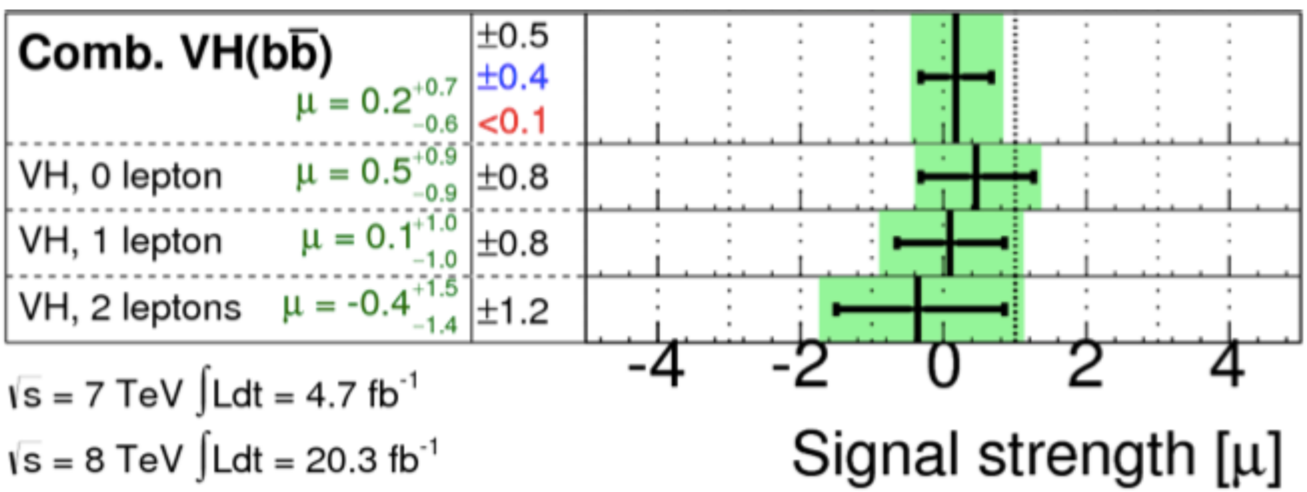


ATLAS-CONF-2013-079

H→$b\bar{b}$

- Highest Higgs BR (58%) but very high backgrounds
- Suppress backgrounds studying associated production in
  - ZH → νν+$b\bar{b}$ (Backgrounds: top, W/Z+heavy jets)
  - ZH → ll+$b\bar{b}$ (Backgrounds: Z+heavy jets)
  - WH → lν+$b\bar{b}$ (Backgrounds: top, W+heavy jets)
- No significant excess observed

$$\mu^{bb} = 0.2 \pm 0.5(stat) \pm 0.4(sys)$$



Beyond discovery:

measurement of Higgs properties

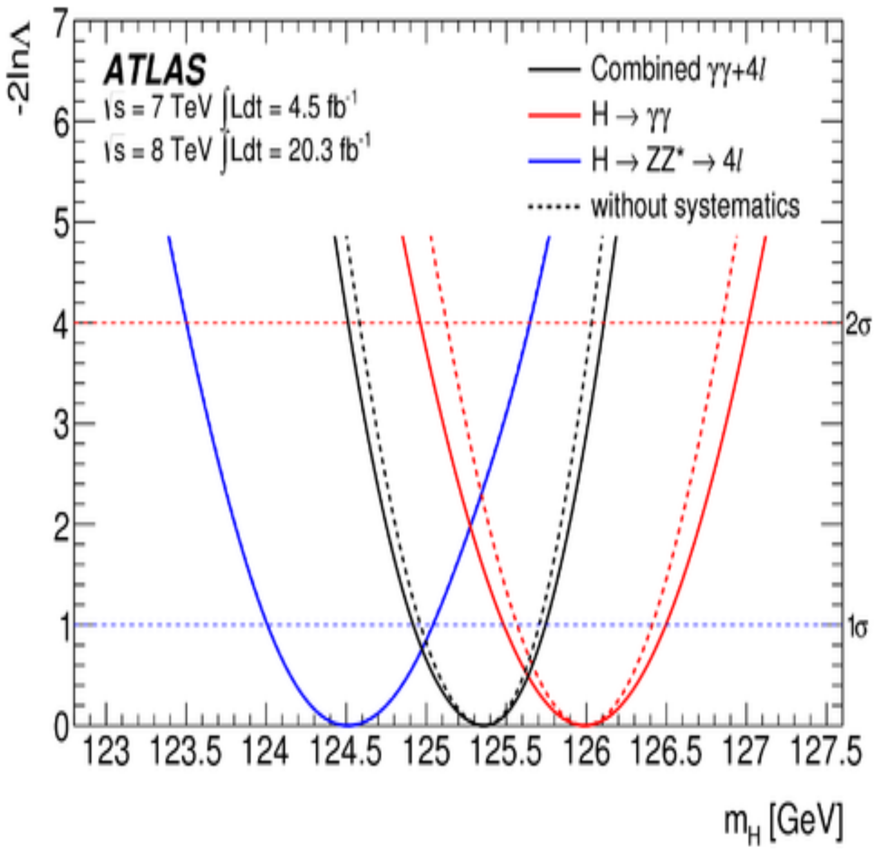
Combining channels is key!

Higgs property #1:

Phys. Rev. D. 90, 052004 (2014)

Higgs Mass

Not predicted by SM but important input to predict other quantities



$$m_H^{4l} = 124.51 \pm 0.52(stat) \pm 0.06(syst)\ \text{GeV}$$

$$m_H^{\gamma\gamma} = 125.98 \pm 0.42(stat) \pm 0.28(syst)\ \text{GeV}$$

Tension between two measurements?

$\Delta m_H = 1.47 \pm 0.67 \pm 0.28$ GeV

Probability=4.8% (2 σ)

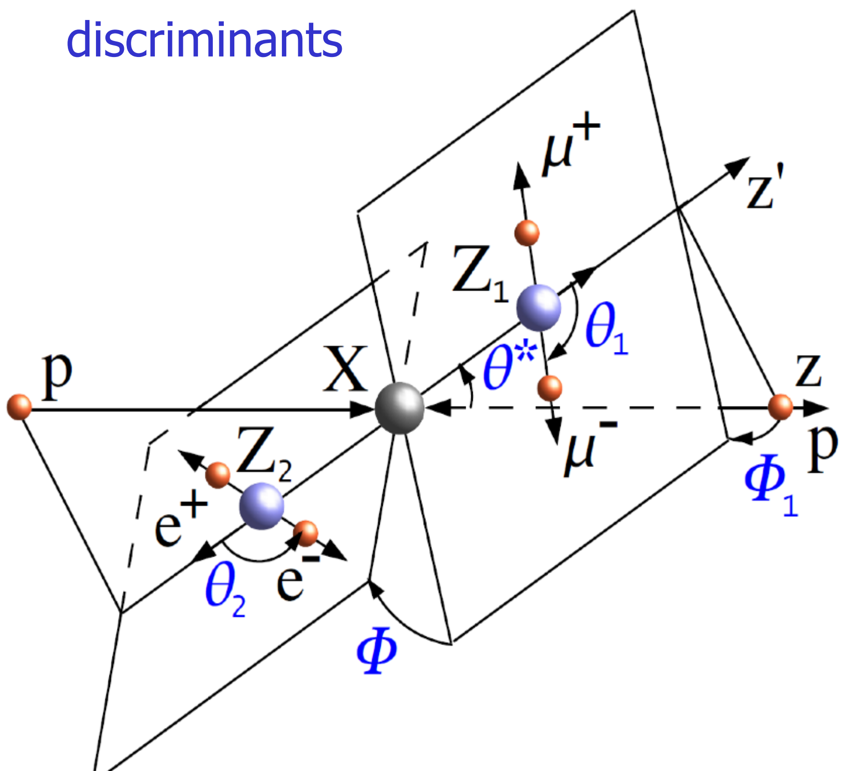
$$m_H^{ATLAS} = 125.36 \pm 0.37(stat) \pm 0.18(syst)\ \text{GeV}$$

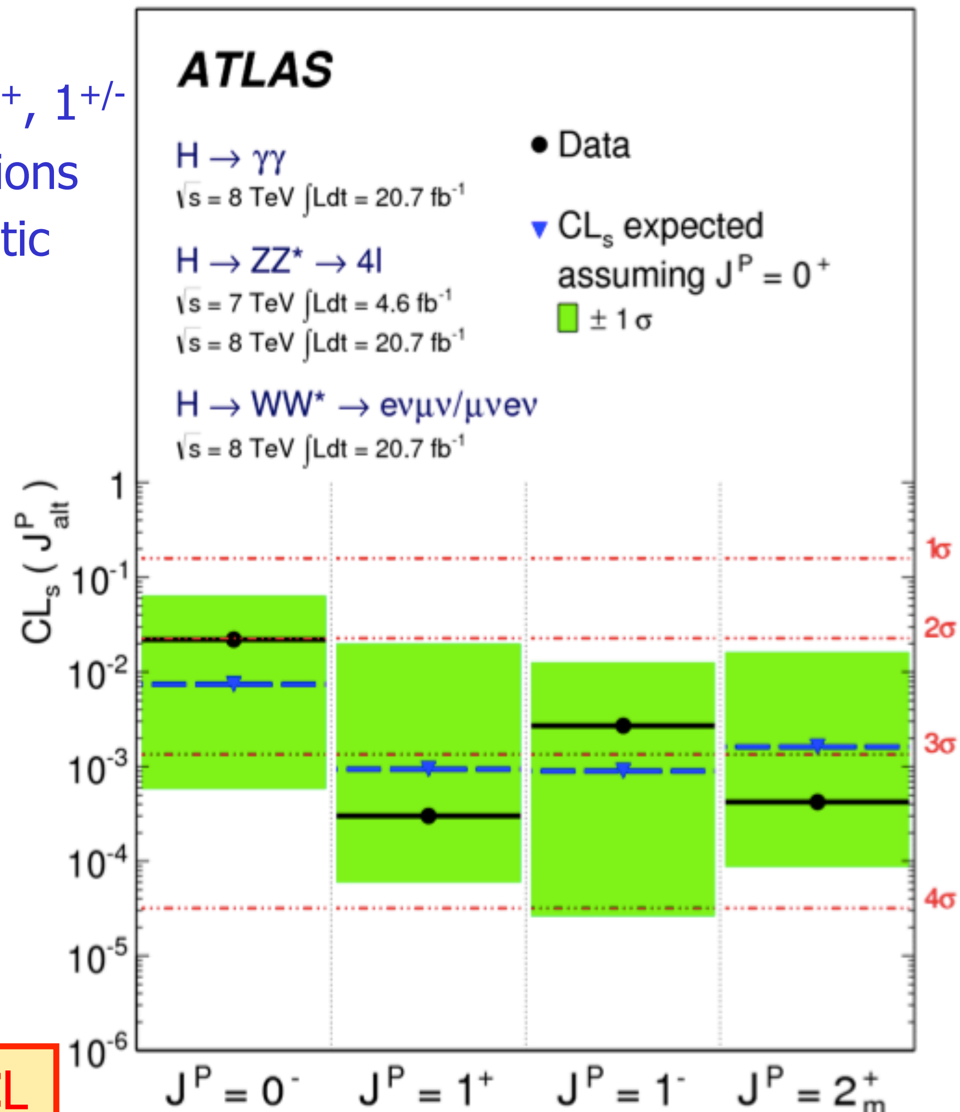
Higgs property #2:

Spin and Parity

Phys. Lett. B 726 (2013), 88-119

- For a Standard Model Higgs, $J^P = 0^+$
- Strategy: falsify other hypotheses 0^-, 2^+, $1^{+/-}$
- Spin and parity affect angular distributions
- Combine angular variables into kinematic discriminants





$J^P = 0^-$, $1^{+/-}$, 2^+ excluded @ >97.8% CL

ATLAS-CONF-2014-009

Higgs property #3:

cross-section x BR

To test SM compatibility, we measure signal strength μ

$$\mu \equiv \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

$$\mu_{VB} = 1.35^{+0.21}_{-0.20}$$

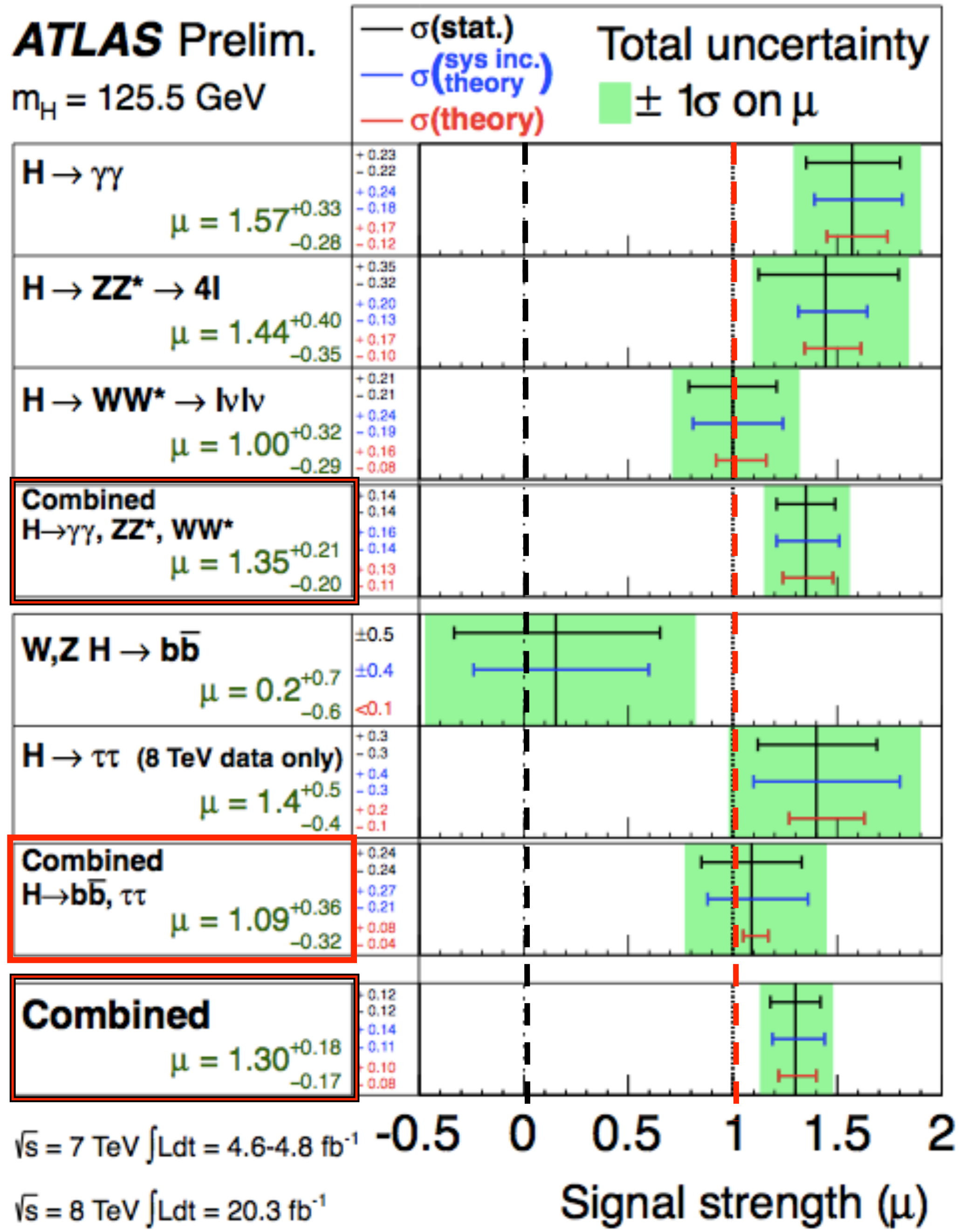
$$\mu_{F} = 1.09^{+0.36}_{-0.32}$$

→ Evidence of fermionic H decays: 3.7σ

- Average:

$$\mu = 1.30^{+0.18}_{-0.17}$$

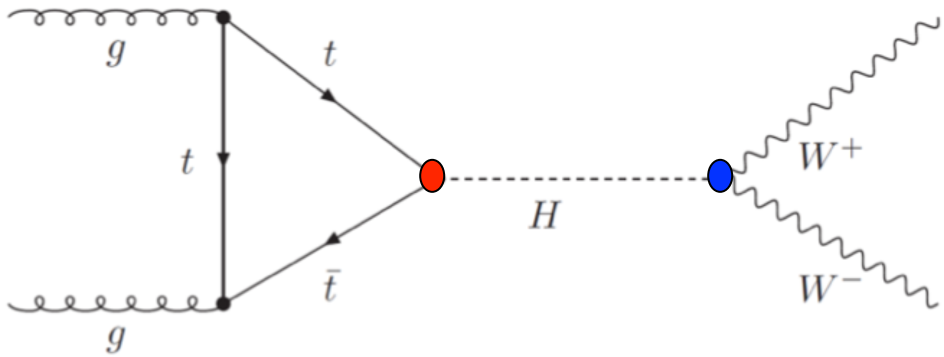
Compatible with SM



Higgs property #4:

Higgs couplings

- Couplings affect both production and decay mode:



H_{ff} in production and H_{VV} in decay

- Can we disentangle the couplings from the rest?
  - Couplings: g_X=coupling strength between H and particle X

$$g_{HFF} = \frac{\sqrt{2} m_F}{v}, \qquad g_{HVV} = \frac{2 m_V^2}{v},$$

v =246 GeV

- Measure deviations w.r.t. SM introducing parameters κ

$$g_{HFF} = \kappa_F g_{Hff}^{SM}, \qquad g_{HVV} = \kappa_V g_{HVV}^{SM}$$

If only SM: κ =1

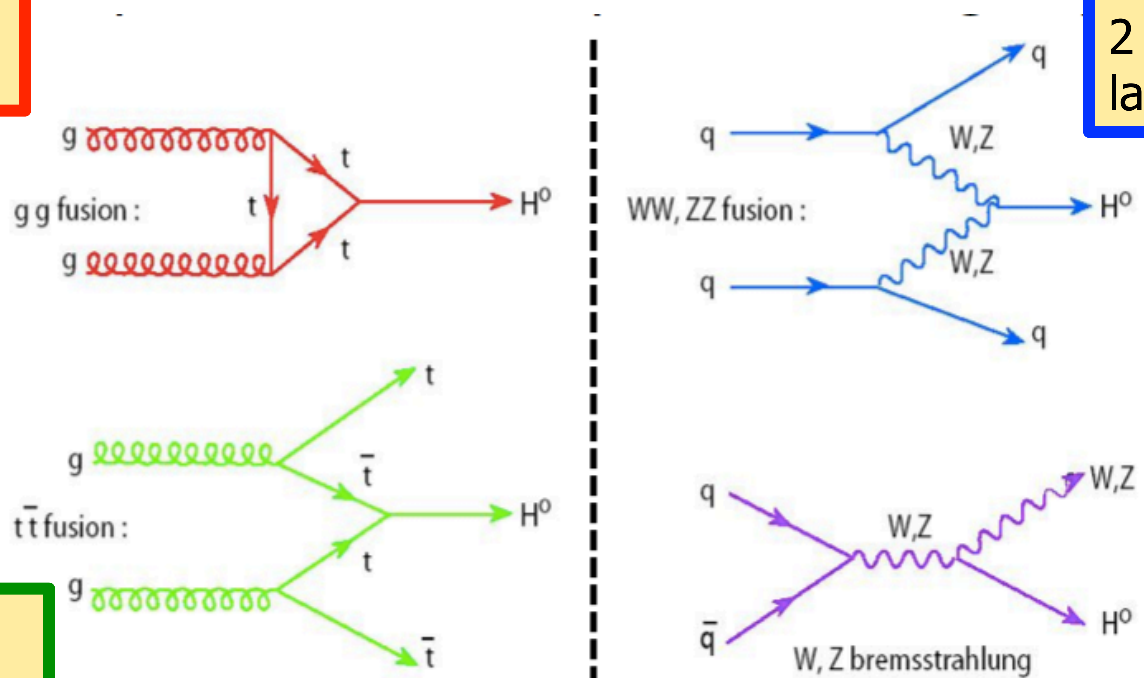
Beyond cross-sections:
Higgs Couplings

Different production modes to disentangle couplings of the Higgs to f or V

Kinematics used to define categories enriched in each production mode

ggF:
all the rest

VBF:
2 high-p_T forward jets,
large m_{jj} and $|\Delta\eta|$



ttH:
2 top quarks:
leptons, MET,
b jets, …

Strong Production
Fermion Coupling

Electroweak Production,
Vector Boson Coupling

VH:
High p_T μ/e , MET,
low-mass dijets

Higgs Couplings:

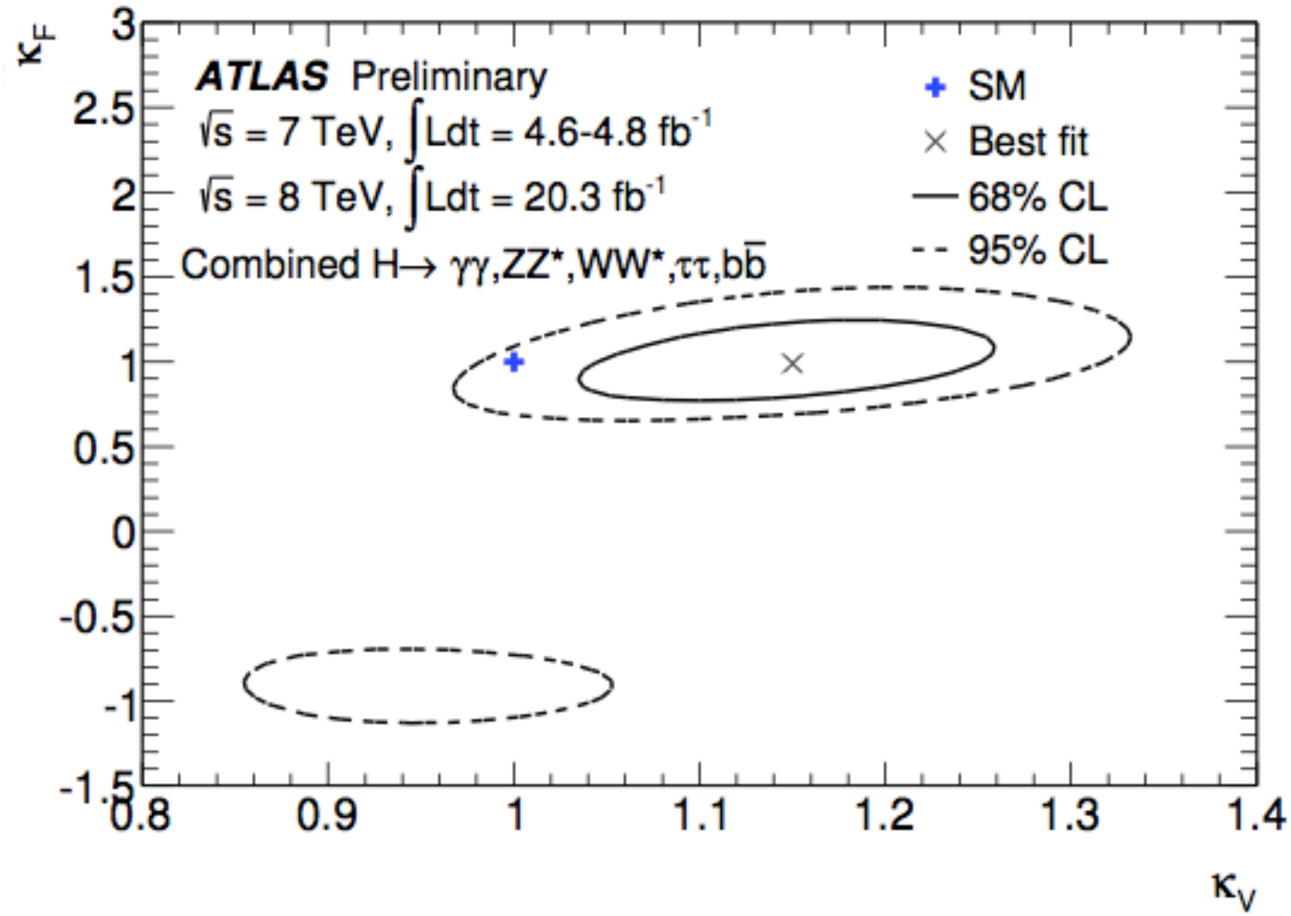
ATLAS-CONF-2014-009

Fermion and Boson couplings

- Assumption: same κ for all fermions κ_F , same κ for all vector bosons κ_V
- No BSM particles

$$\kappa_V = 1.15 \pm 0.08$$

$$\kappa_F = 0.99^{+0.17}_{-0.15}$$



2D compatibility with SM: 10%

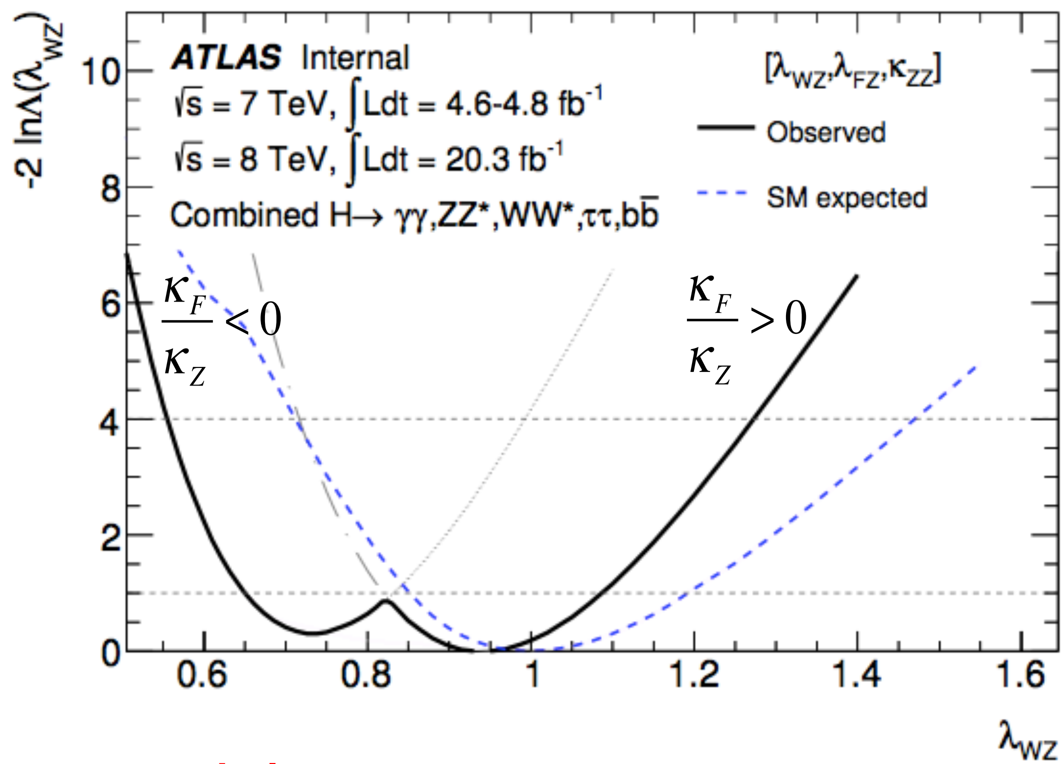
ATLAS-CONF-2014-009

Custodial Symmetry

- Assumption: same κ for all fermions κ_F , but in principle different κ for Z and W (κ_Z, κ_W)

- We measure

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.94^{+0.14}_{-0.29}$$



SM compatibility: 19%

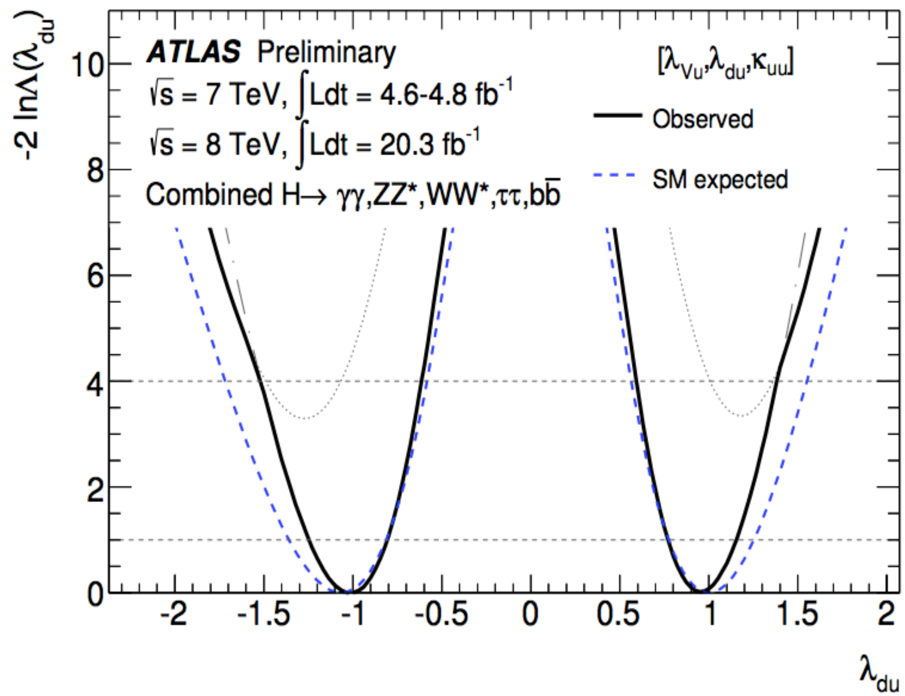
ATLAS-CONF-2014-009

Probing up/down fermion symmetry

- Assume same κ_V for bosons, but allow for different κ for up-type and down-type fermions
  - Asymmetry between κ_u and κ_d expected in some models (e.g.: some 2HDM)
    - Up-type: top from H→$\gamma\gamma$
    - Down-type: H→bb,$\tau\tau$

$$\lambda_{du} \equiv \frac{\kappa_d}{\kappa_u} = [0.78, 1.15]$$

SM compatibility: 20%



- Quark-lepton symmetry also tested
  - Compatibility with SM: 15%

ATLAS-CONF-2014-010

Simplified MSSM

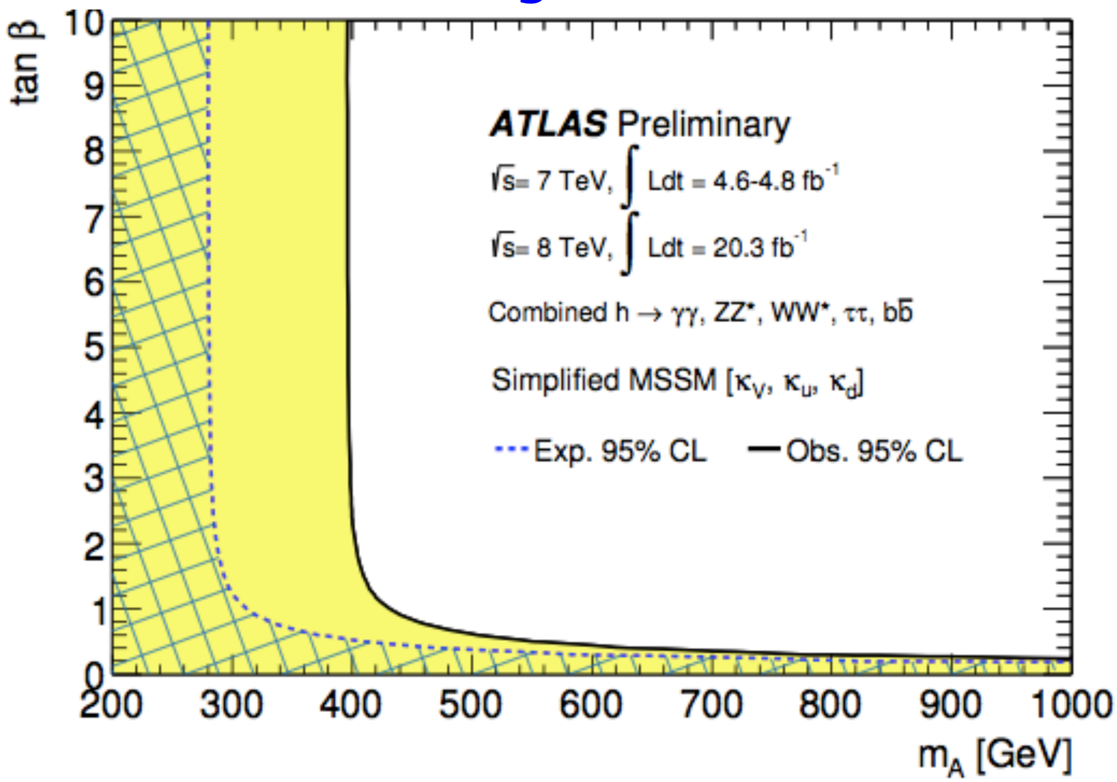
Couplings to VB, up-type and down-type fermions can be calculated in MSSM from the mass mixing matrix

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta},$$

A: CP- Higgs



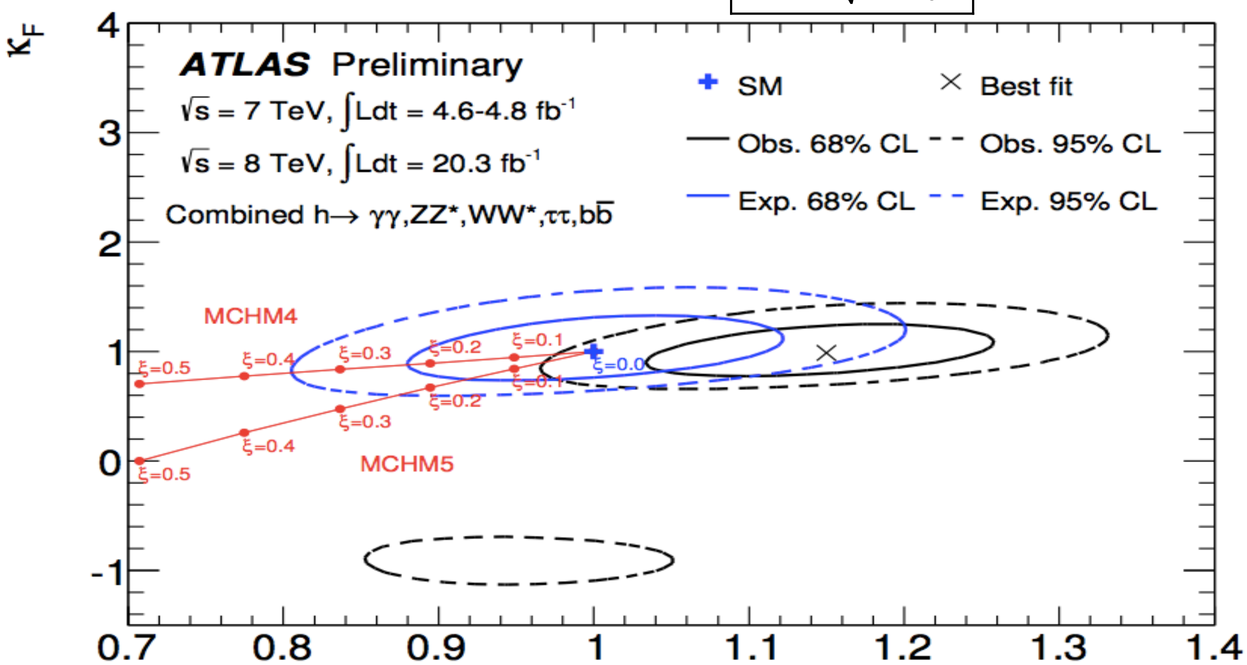
L. Maiani, A. Polosa, and V. Riquer, *Bounds to the Higgs Sector Masses in Minimal Supersymmetry from LHC Data*, arXiv:1305.2172 [hep-ph].

Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon, et al., *The post-Higgs MSSM scenario: Habemus MSSM?*, arXiv:1307.5205 [hep-ph].

ATLAS-CONF-2014-010

Minimal Composite Higgs Model (MCHM)

- Higgs boson is a composite, π-like particle
- Couplings modified as a function of the Higgs compositeness scale *f*
- In MCHM5 [2,3]: $\kappa_V = \sqrt{1-\xi}$ $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$ with $\xi = v^2 / f^2$



$$\xi < 0.15 @ 95\% C.L.$$

$$\rightarrow f > 640 GeV$$

[1]K. Agashe, R. Contino, A. Pomarol, *The minimal composite Higgs model*, Nucl. Phys. B 719 (2005) 165, arXiv:hep-ph/0412089

[2]R. Contino, L. Da Rold, A. Pomarol, *Light custodians in natural composite Higgs models*, Phys. Rev. D 75 (2007) 055014

[3]M. Carena, E. Ponton, J. Santiago, C. Wagner, *Electroweak constraints on warped models with custodial symmetry*, Phys. Rev. D76 (2007) 035006, arXiv:hep-ph/0701055

ATLAS-CONF-2014-010

2HDMs limits

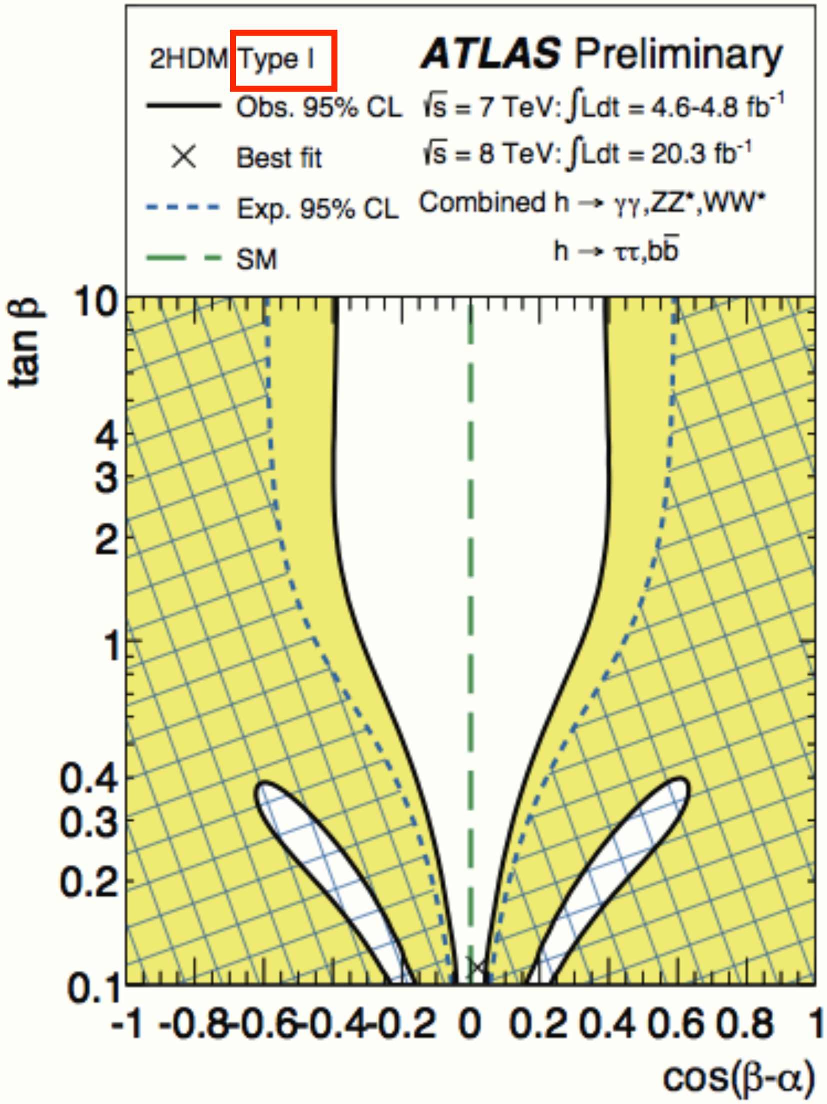
- In 2HDMs, we expect 5 Higgses ($H^{\pm}$, CP- A, 2 CP+: h, H)
- Parameters: $\tan\beta = \frac{v_1}{v_2}$; α: mixing angle between h,H
- 4 types of 2HDMs survive constraints from B physics
- Couplings can can be expressed as function of β and α:

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

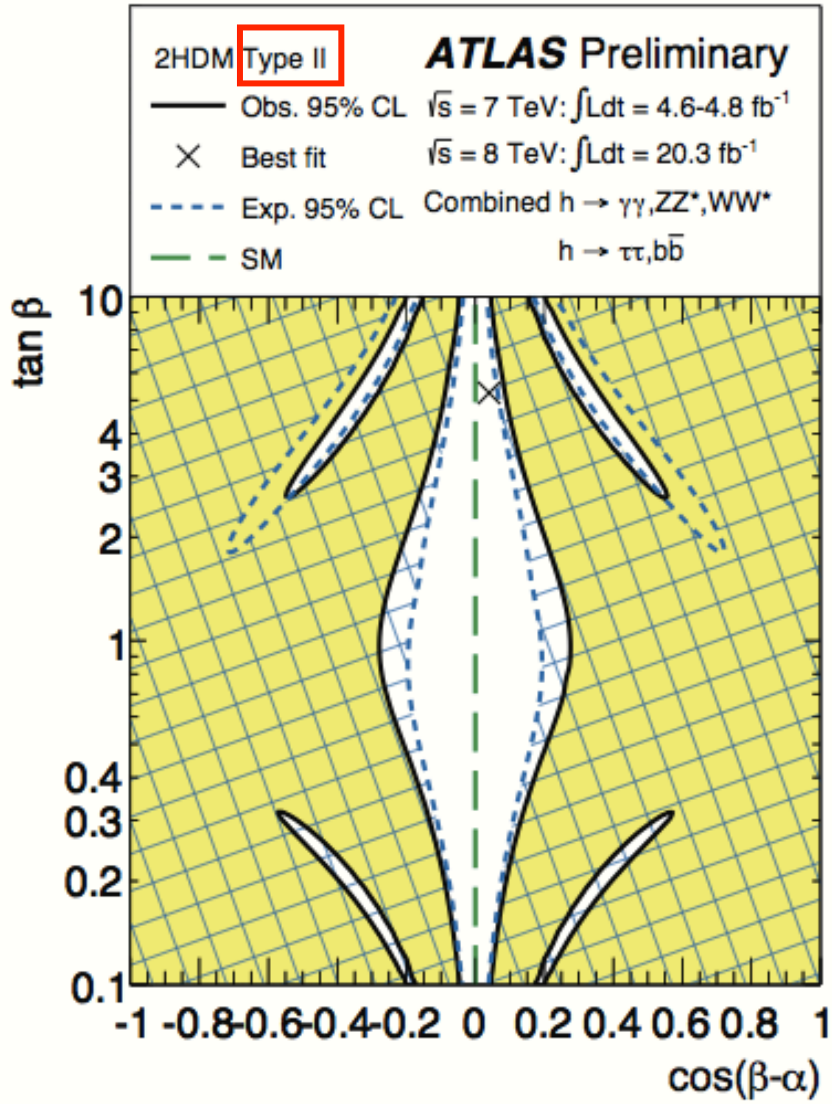
ATLAS-CONF-2014-010

2HDMs limits (cont)

$\tan\beta = \frac{v_1}{v_2}$; α: mixing angle (h,H)



Type I

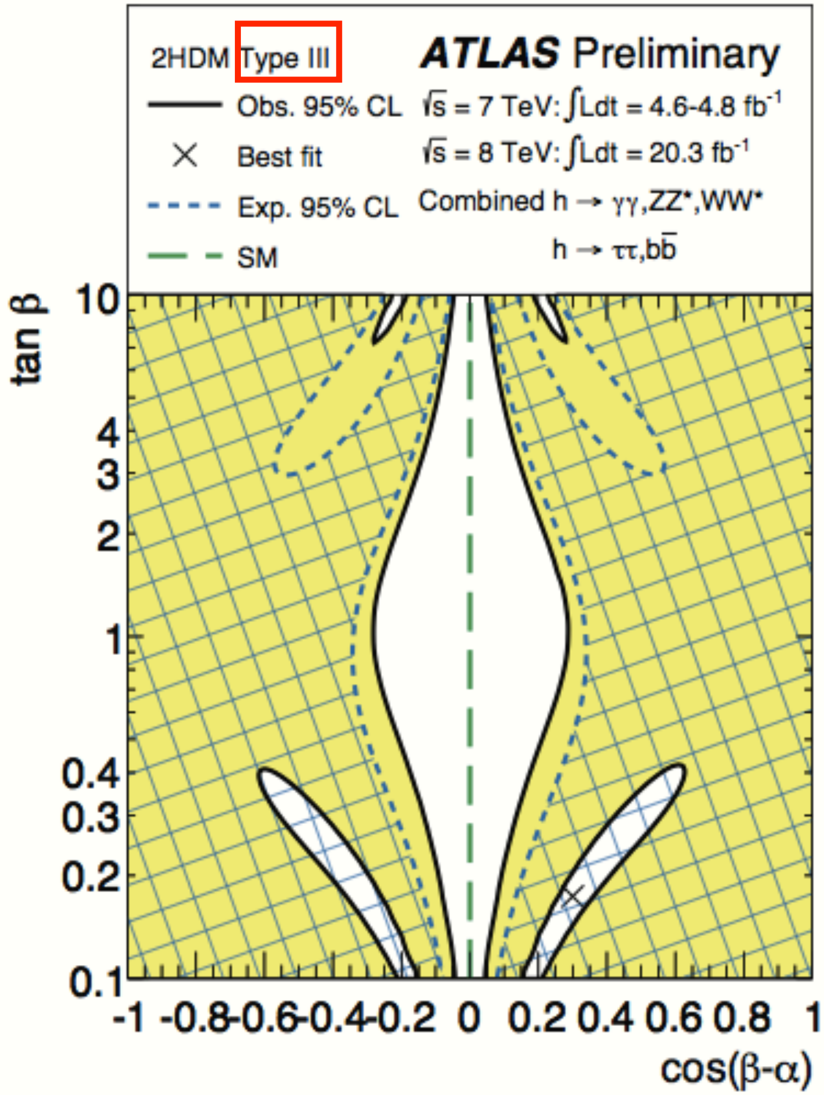


Type II

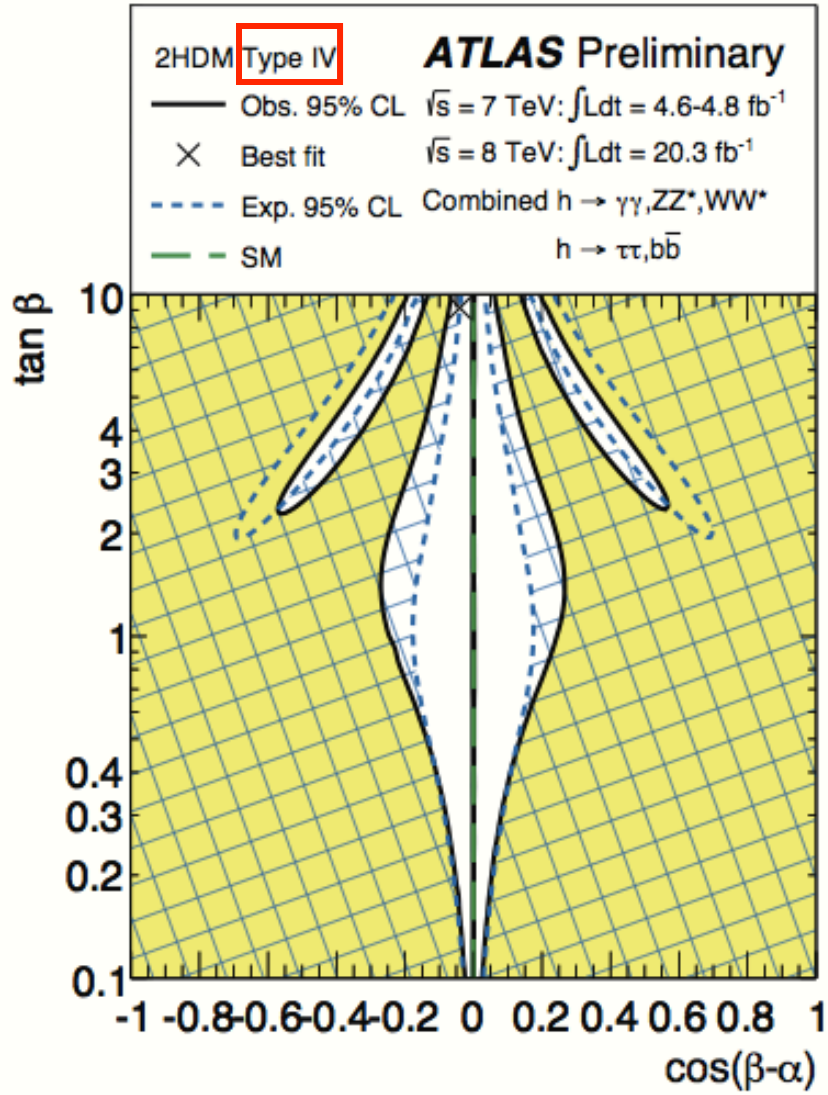
ATLAS-CONF-2014-010

2HDMs limits (cont)

$\tan\beta = \frac{v_1}{v_2}$; α: mixing angle (h,H)



Type III

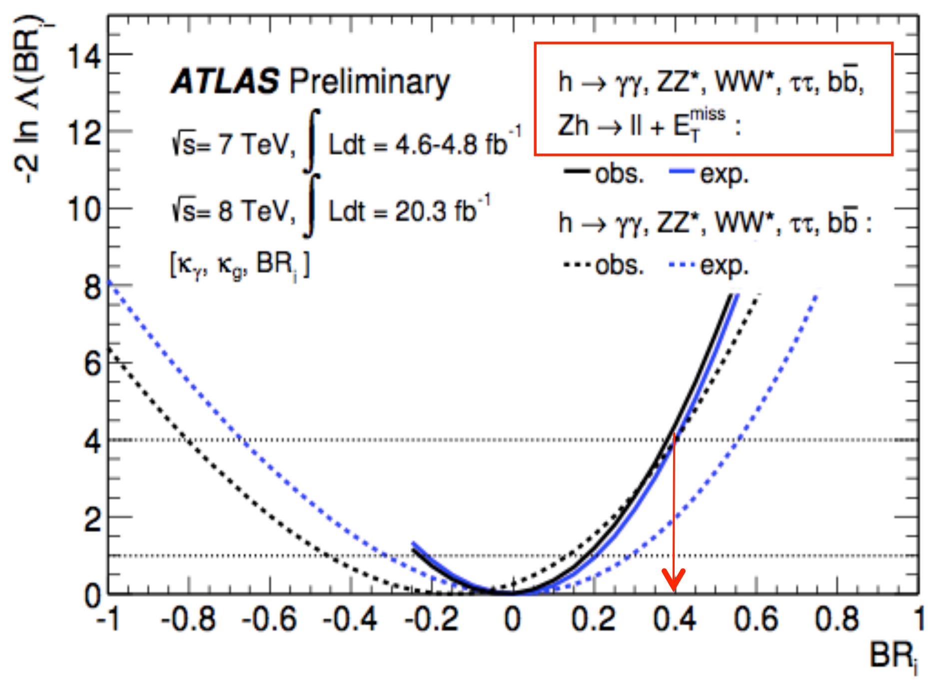


Type IV

ATLAS-CONF-2014-010

Higgs portal to DM

- Dark Sector couples very weakly to all SM particles but H
  - Coupling of Higgs to WIMP DM (χ) is a free parameter
- Calculate BR_{inv} = Br(H→$\chi\chi$) combining measurements of Higgs rates and limit on invisible H decays (ZH→$l^-l^+E_T^{miss}$)
  - Couplings of H to SM particles assumed to same as SM



$$BR_i = -0.02 \pm 0.20$$

$$\rightarrow BR_i < 0.37(0.39)@95\%C.L.$$

Limits on $\sigma_{\chi N}$ vs. m_χ

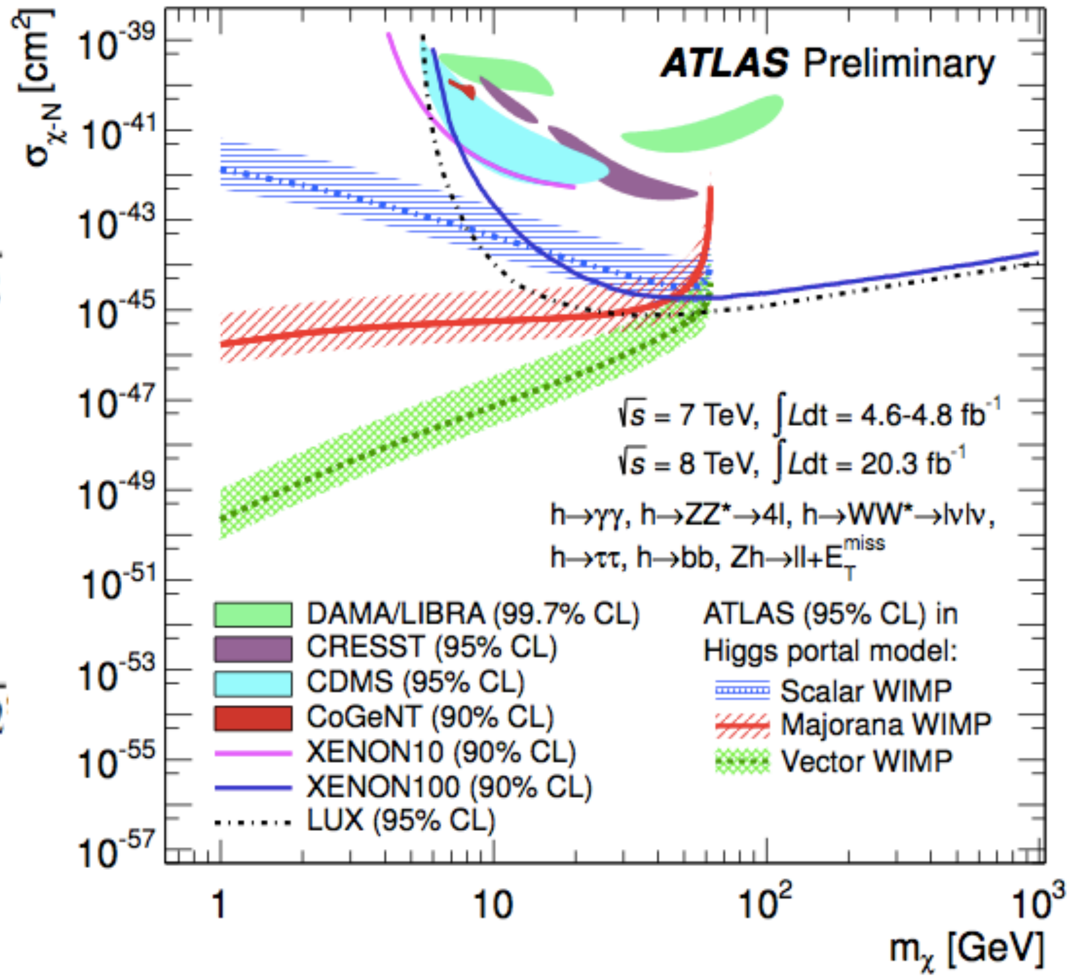
ATLAS-CONF-2014-010

Cross-section σ can be calculated for scalar (S), fermionic (f) and vector (V) WIMPs:

scalar S: $\sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$

fermion f: $\sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$

vector V: $\sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}$



Conclusion

- LHC Run-1 has been extremely successful in Higgs physics
  - Discovery in 2012!
  - Higgs is reconstructed in bosonic and fermionic channels
  - All production modes investigated
- Properties of the Higgs are being measured
  - Mass is known better than 400 MeV
  - Spin and parity seems to be consistent with SM $J^P=0^+$
  - Rates and Couplings look as expected
- So far, nothing inconsistent with the SM has been observed

  → First limits on New Physics are being set
- This is just the very beginning
  - Final analyses on Run-1 just coming out (not used for NP limits)
  - No combination between ATLAS and CMS yet
  - Run-2 will bring 13 TeV collisions and 300 fb^{-1}: stay tune!