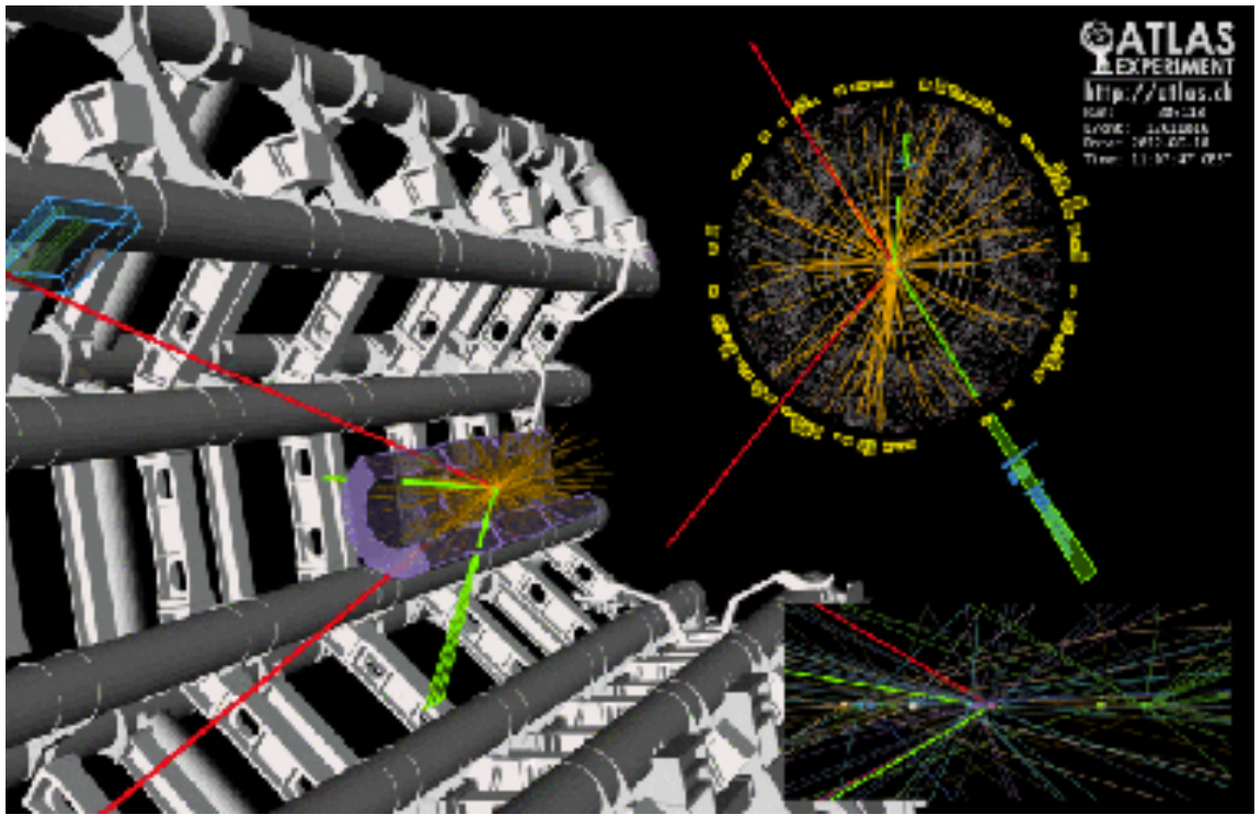
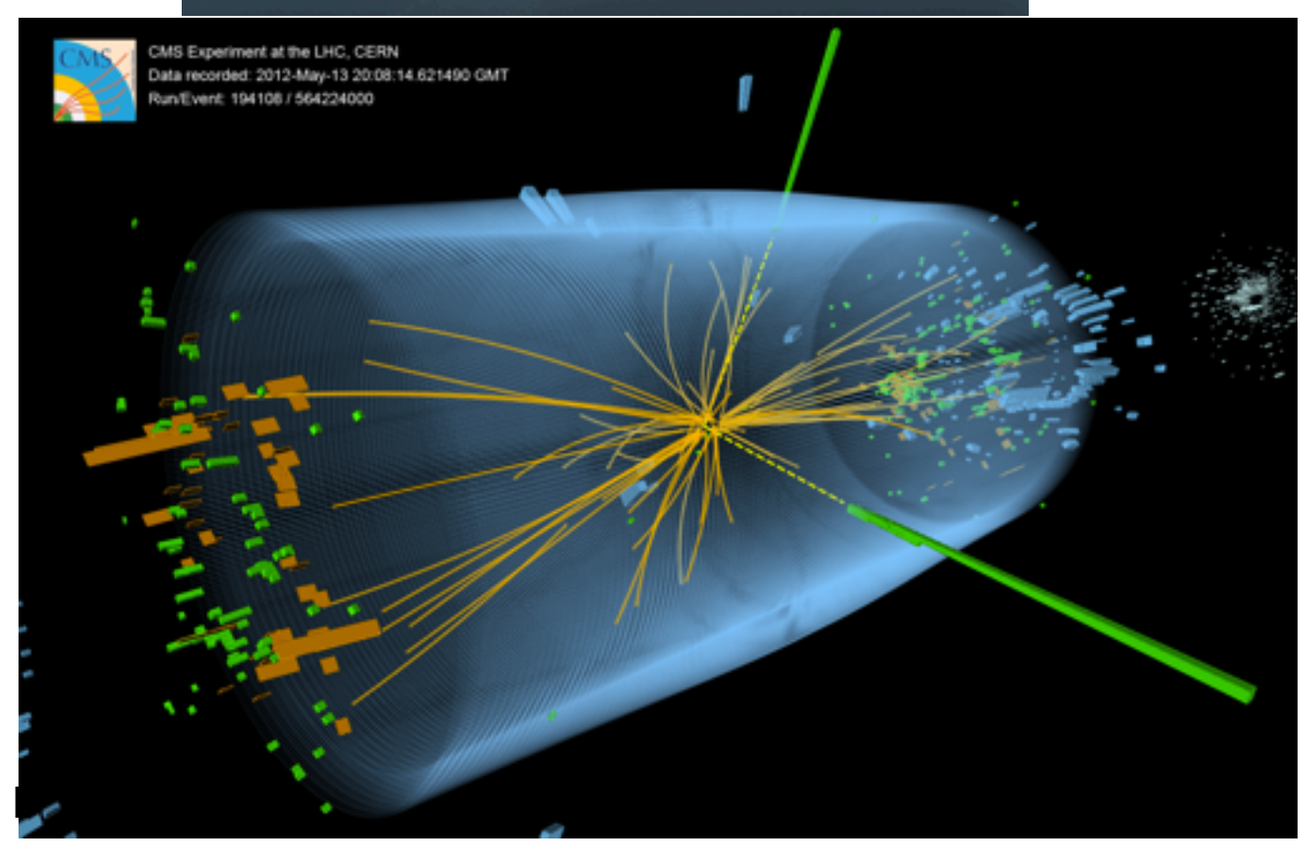


Recent Results on Higgs Physics from ATLAS and CMS

Michele de Gruttola (U of Florida) on behalf of ATLAS and CMS collaboration

11/06/2014, FNAL



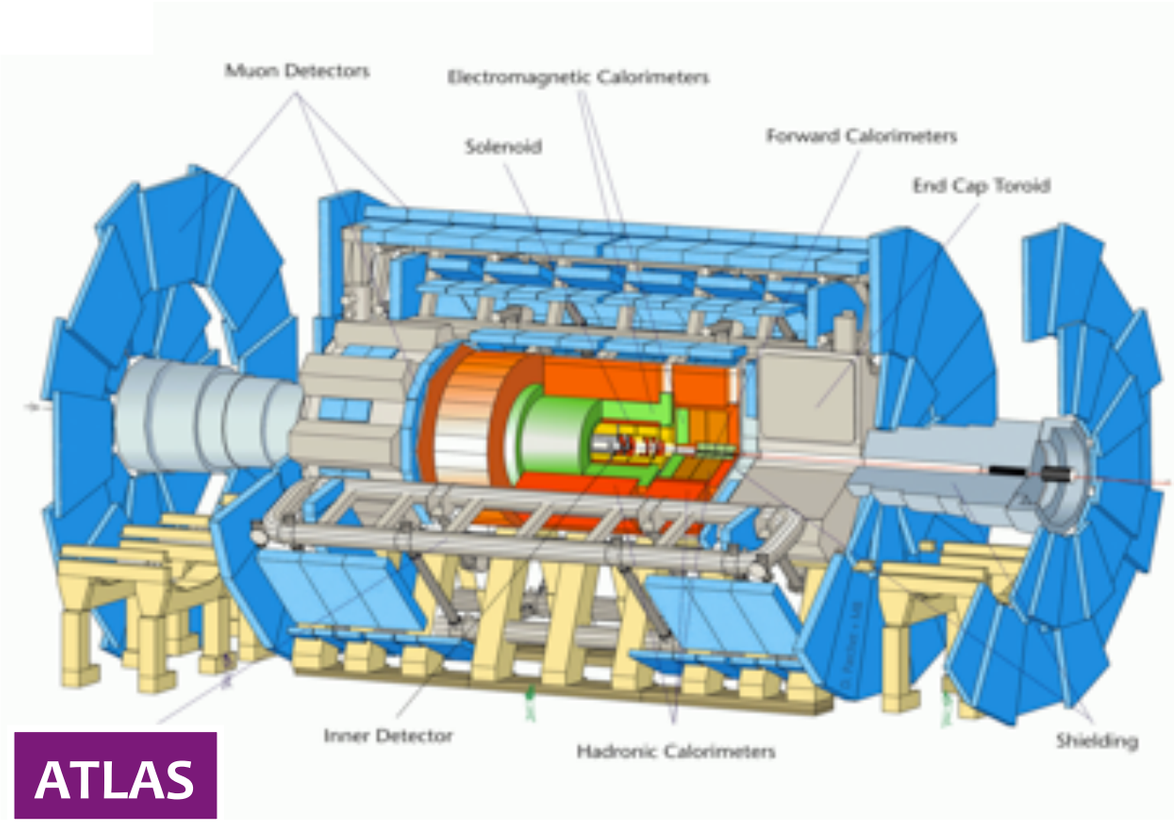
Introduction

- Prologue
- Higgs observables
- Recent results from CMS and ATLAS
- Prospects
- NEW! means new from Moriond14

Disclaimer: BSM Higgs results will be discussed in detail in next talk

Prologue(1)

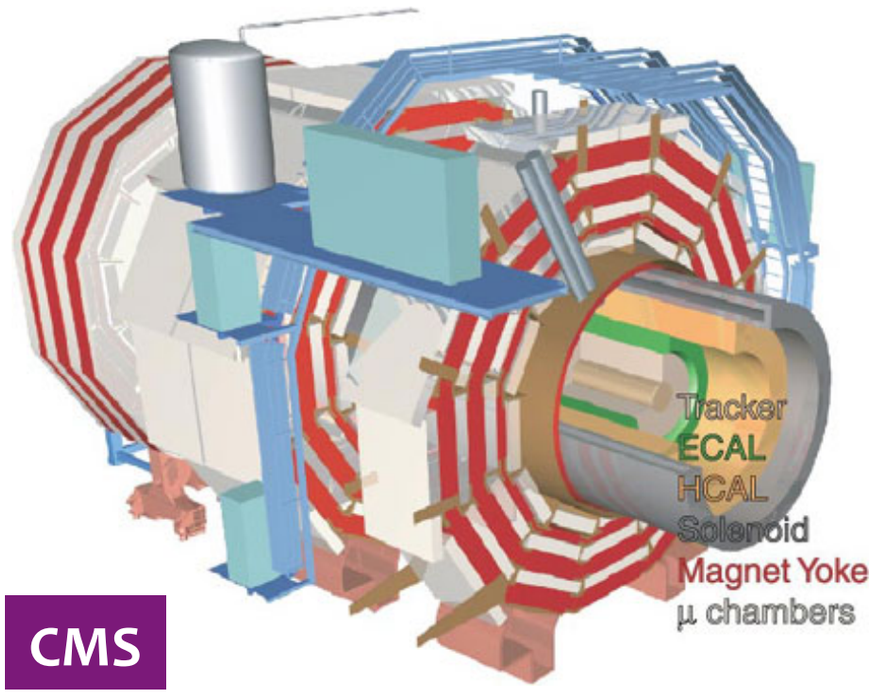
>10 years of hard work in design and construction!



ATLAS

Length : ~45 m
Diameter : ~24 m
Weight : ~ 7,000 tons
Electronic channels : ~ 10^8
Solenoid : 2 T
Air-core toroids

Excellent Standalone Muon Detector and Hadron calorimeter



CMS

Length : ~22 m
Diameter : ~14 m
Weight : ~ 12,500 tons
Solenoid : 4 T
Fe yoke
Compact and modular

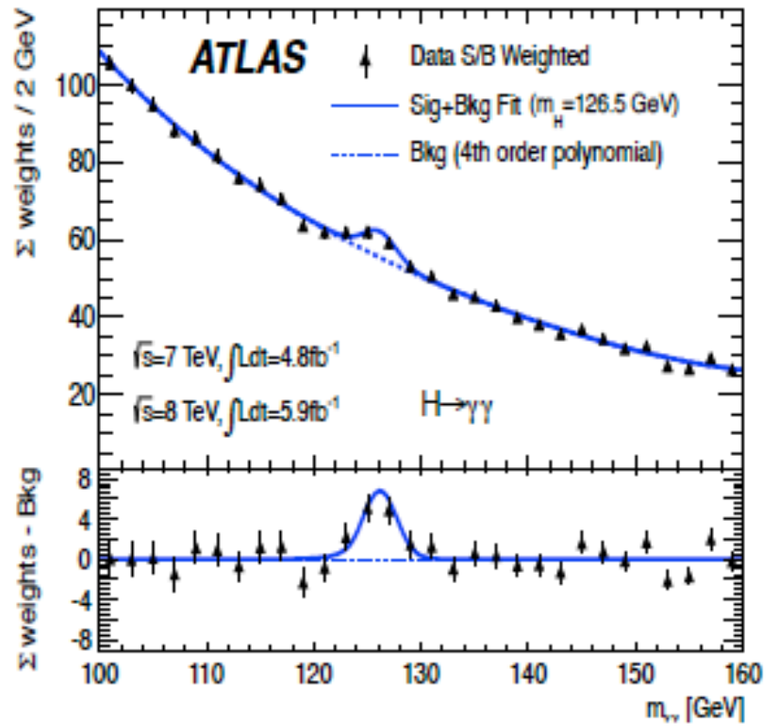
Excellent EM Calorimeter And tracking

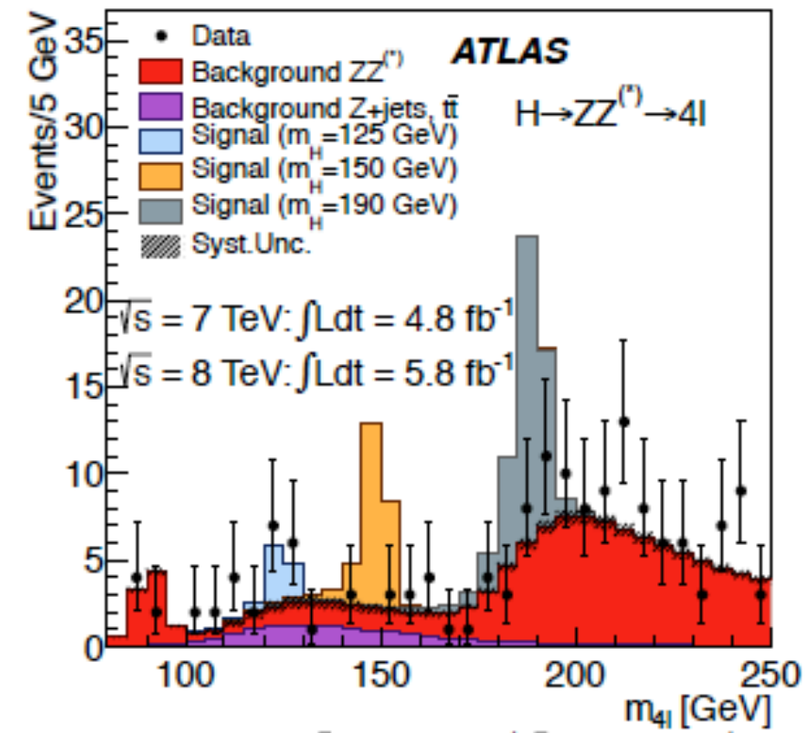
Prologue (2)

Prologue (3)

ATLAS

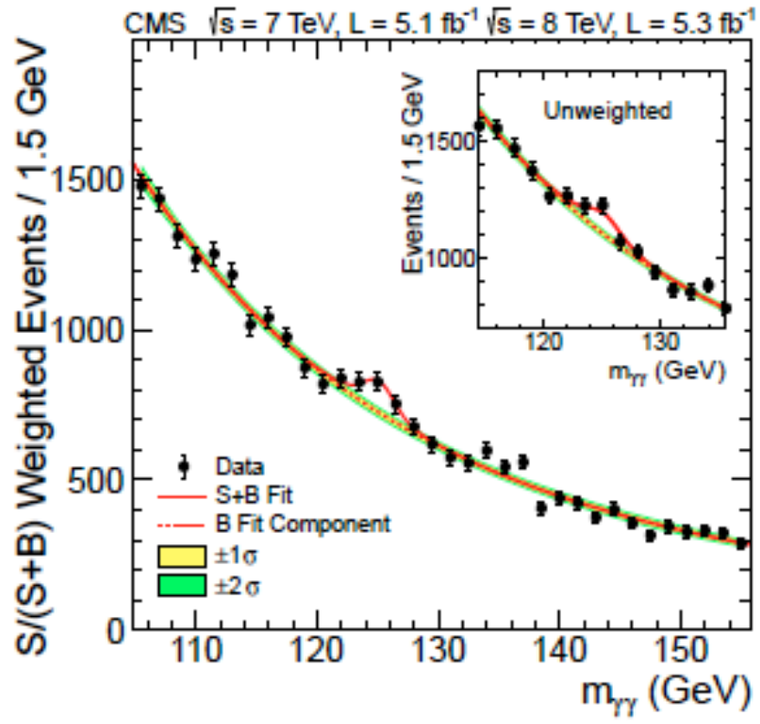
Phys.Lett. B716 (2012) 1-29

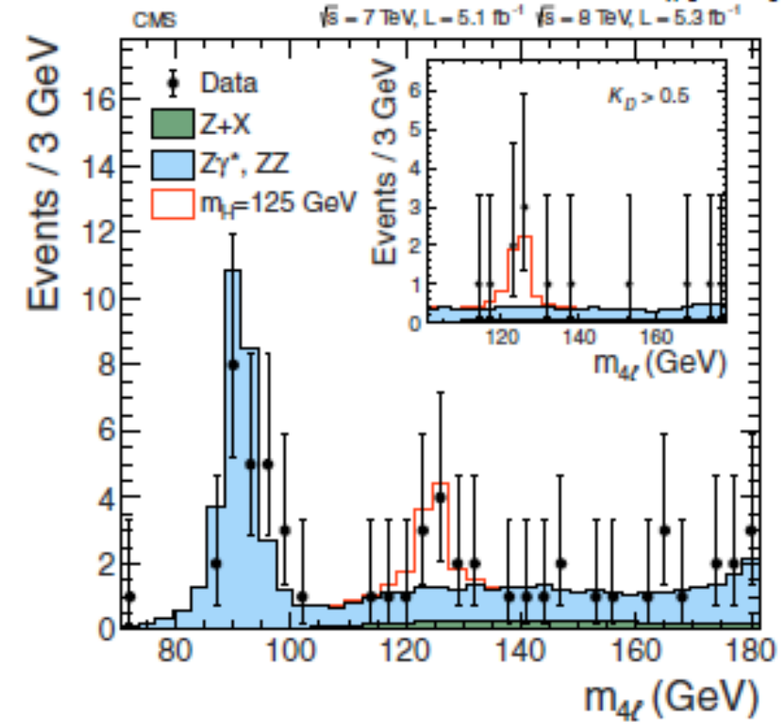




CMS

Phys.Lett. B716 (2012) 30-61





JULY 2012

Discovery at $M_X \sim 125$ GeV, in both ATLAS and the CMS experiments combining $X \rightarrow \gamma\gamma$ and ZZ* channels (additional evidence from $X \rightarrow WW^*$)

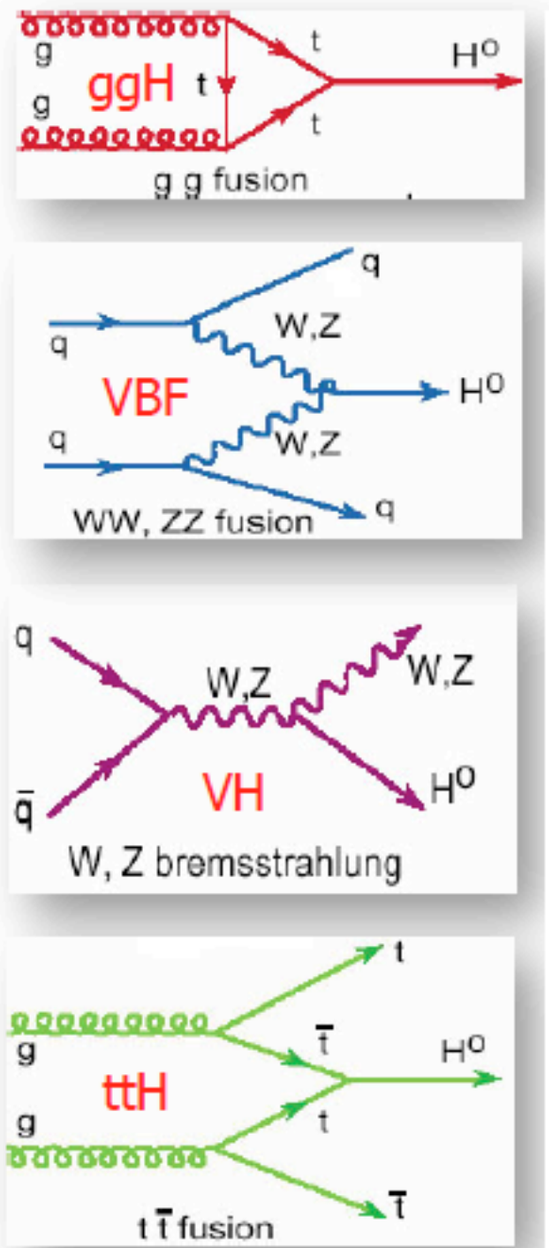
N = L ε σ Higgs production

87%

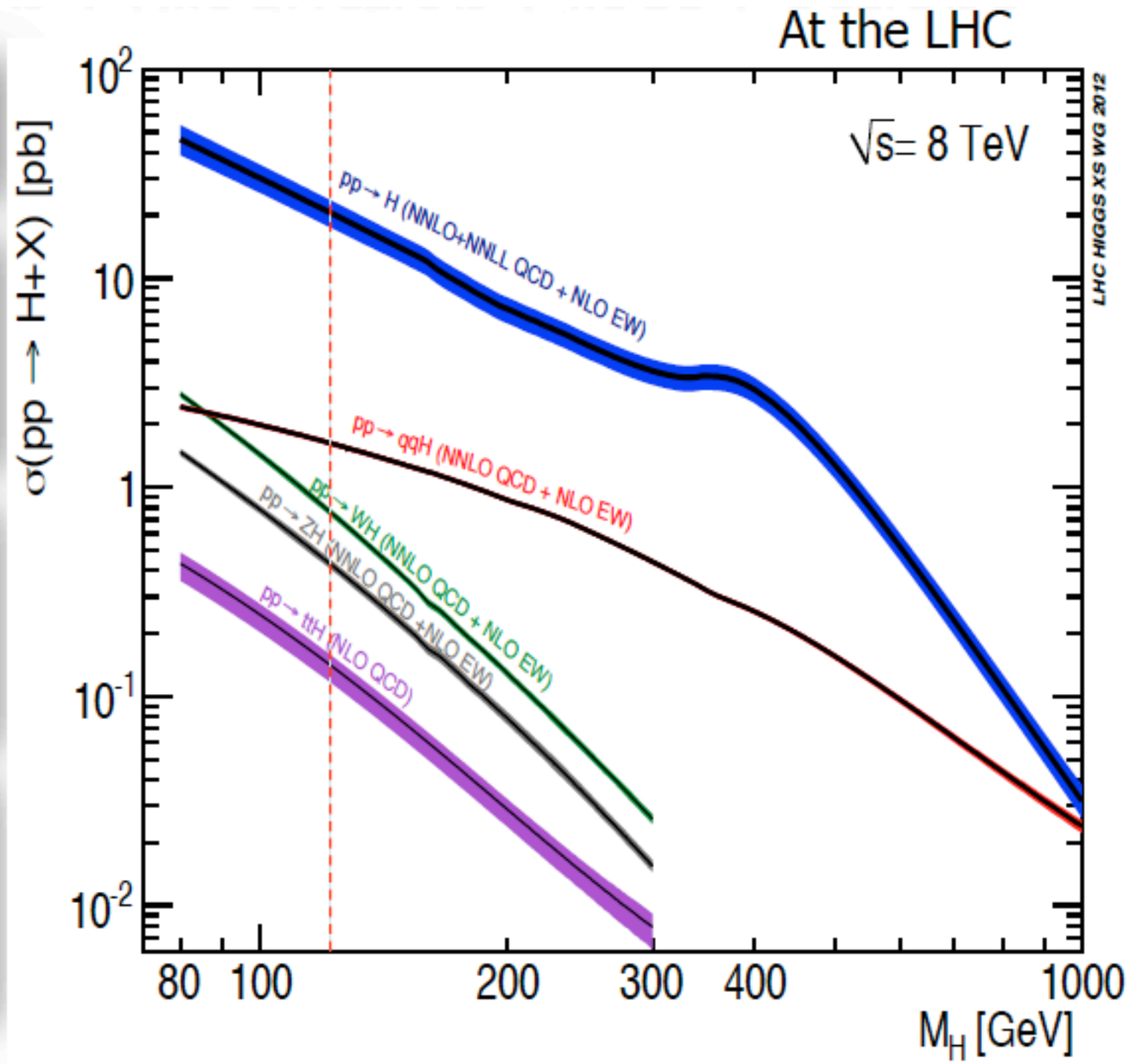
7.1%

4.9%

0.6%



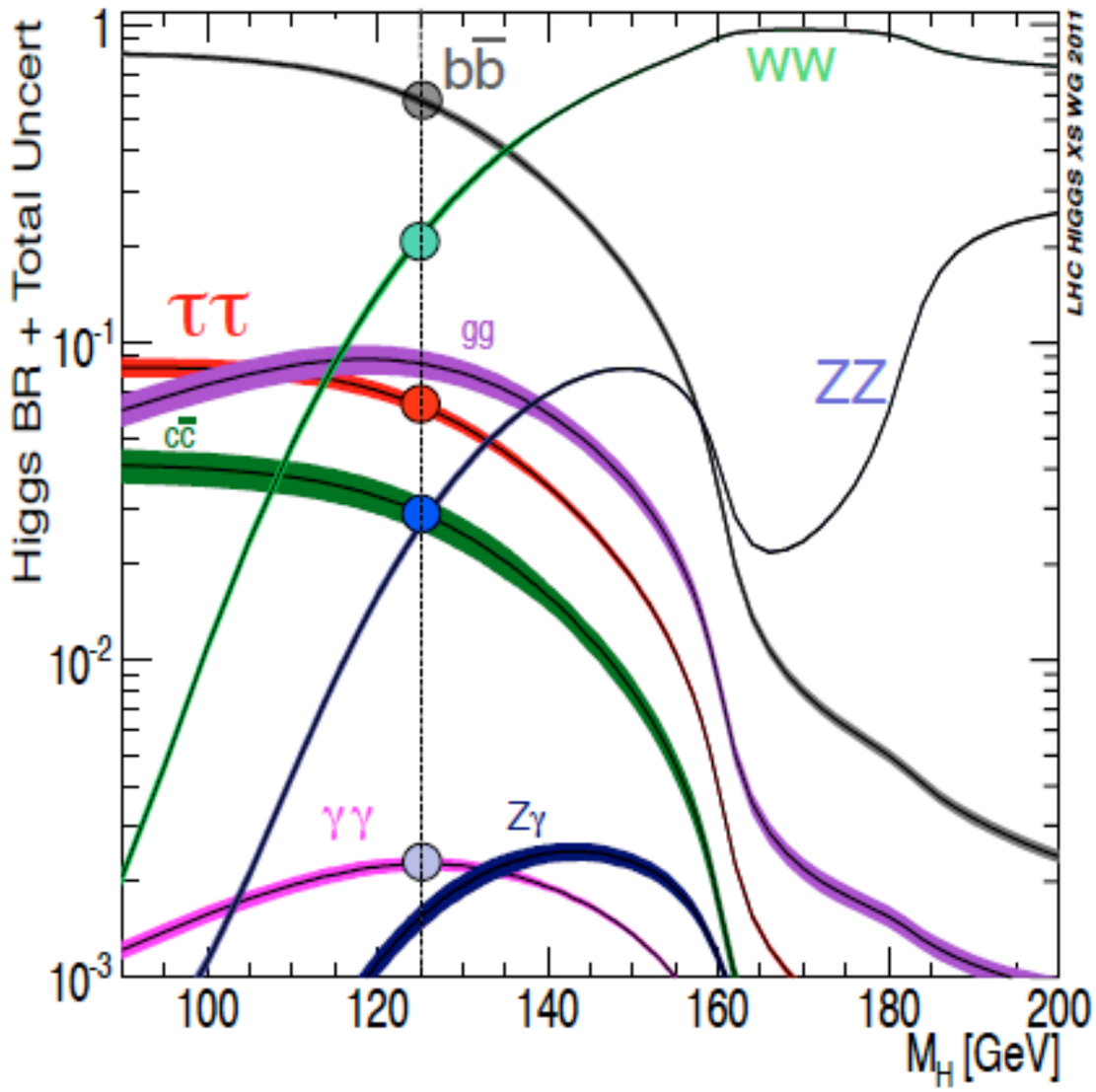
σ/σ_{tot} (M_H = 125 GeV)



But this is only part of the story…..

Michele de Gruttola

σ x BR: Higgs decays



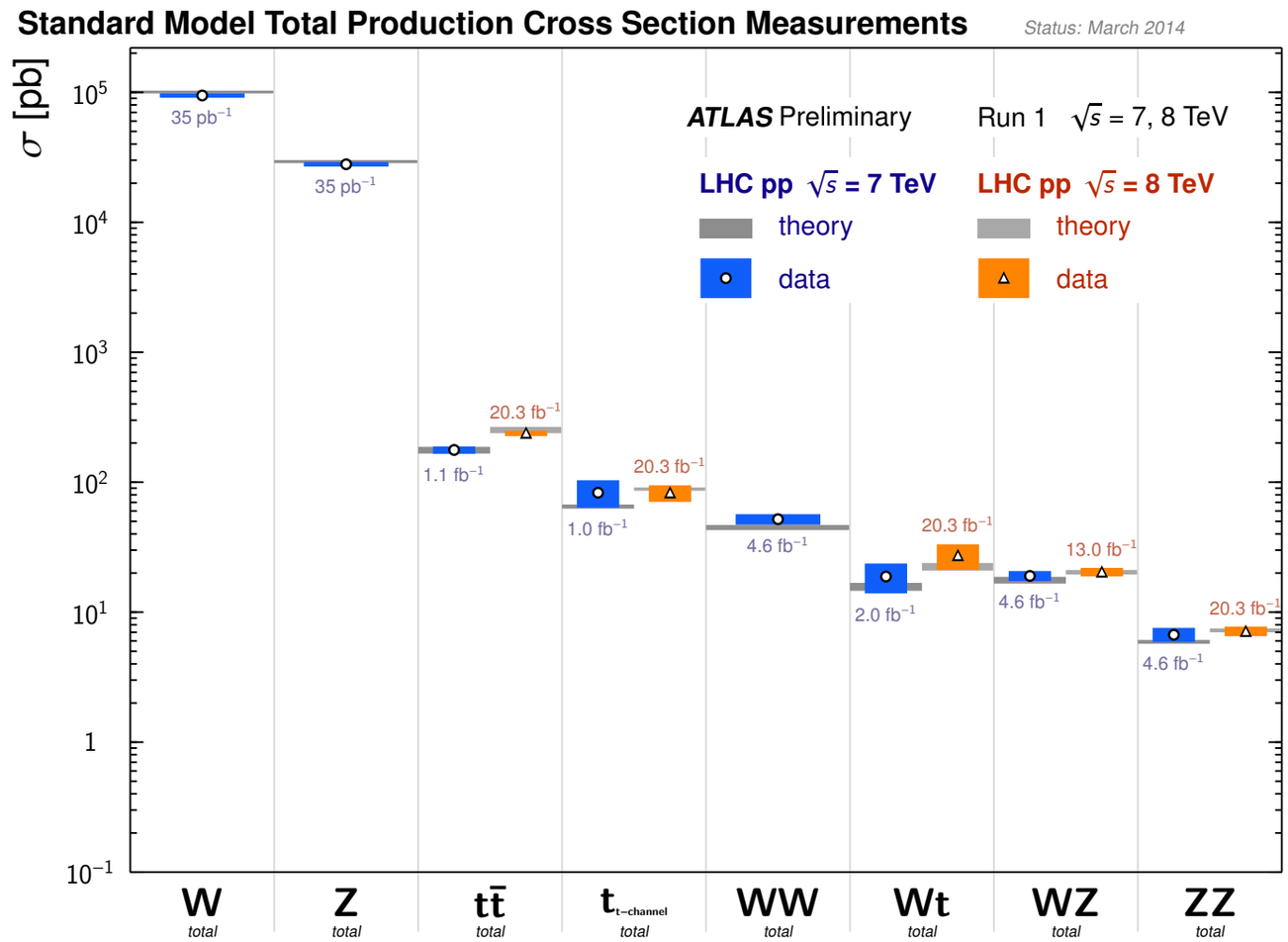
ΔM/M ~ 1-2%	High resolution
H → γγ	Rare, S/B < 1
H → ZZ* → 4ℓ	Very rare, S/B >> 1
ΔM/M ~ 10-20%	Medium resolution
H → bb	Abundant, S/B << 1
H → ττ	Abundant, S/B < 1
ΔM/M > 30%	Low resolution
H → WW* → 2ℓ2ν	Very abundant, S/B < 1

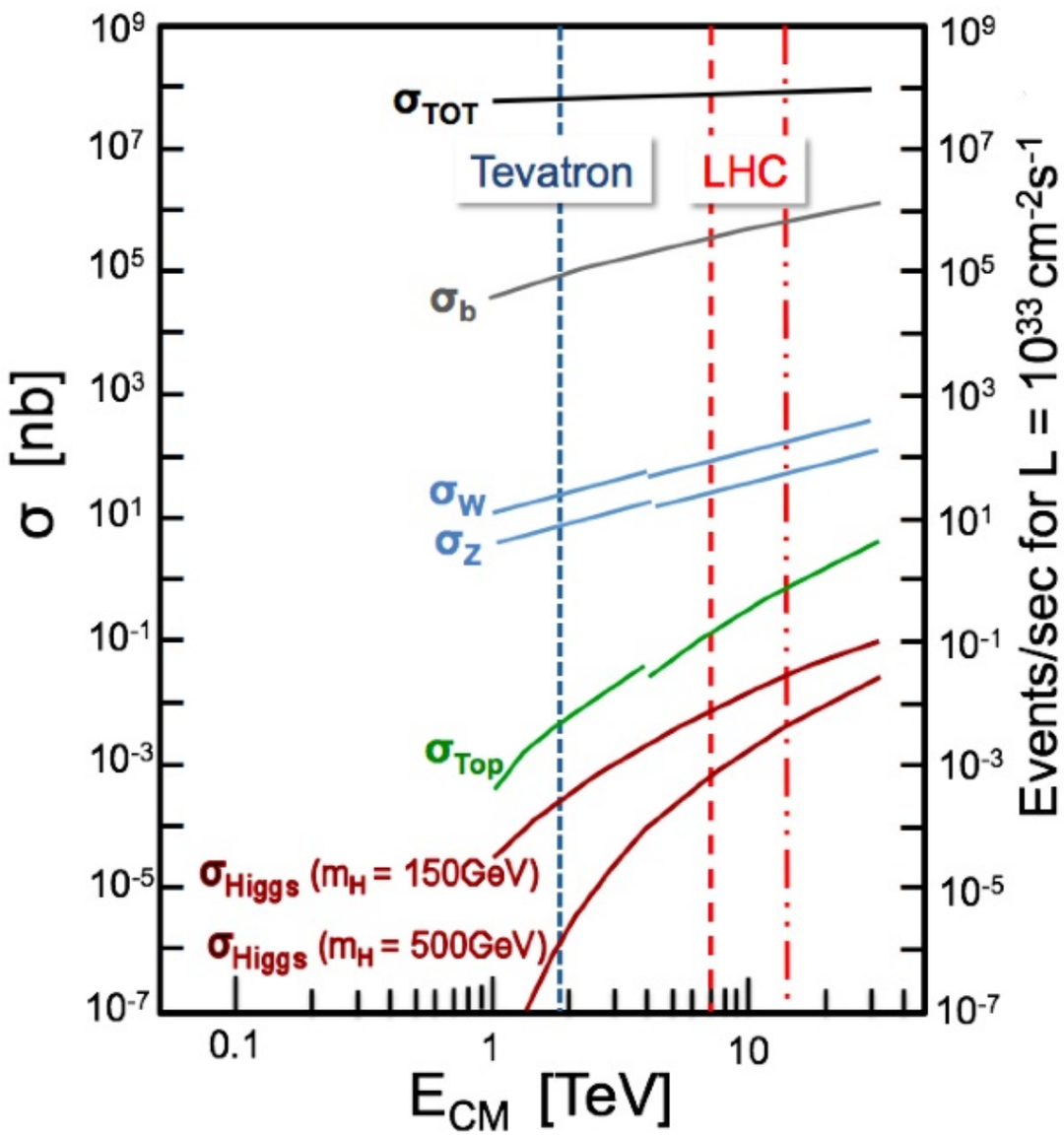
4 production modes × 5 decay modes (γγ, ZZ, WW, ττ, bb)

~ 100 exclusive final states (production, decay, event categories) are contributing for M_H ~ 125 GeV !

Third part of the story: the bkg!

ATLAS and CMS demonstrated they can measure SM bkgs very well!





The V, di-top, top and VV are "must" measurements to perform before searching for H....

Michele de Gruttola

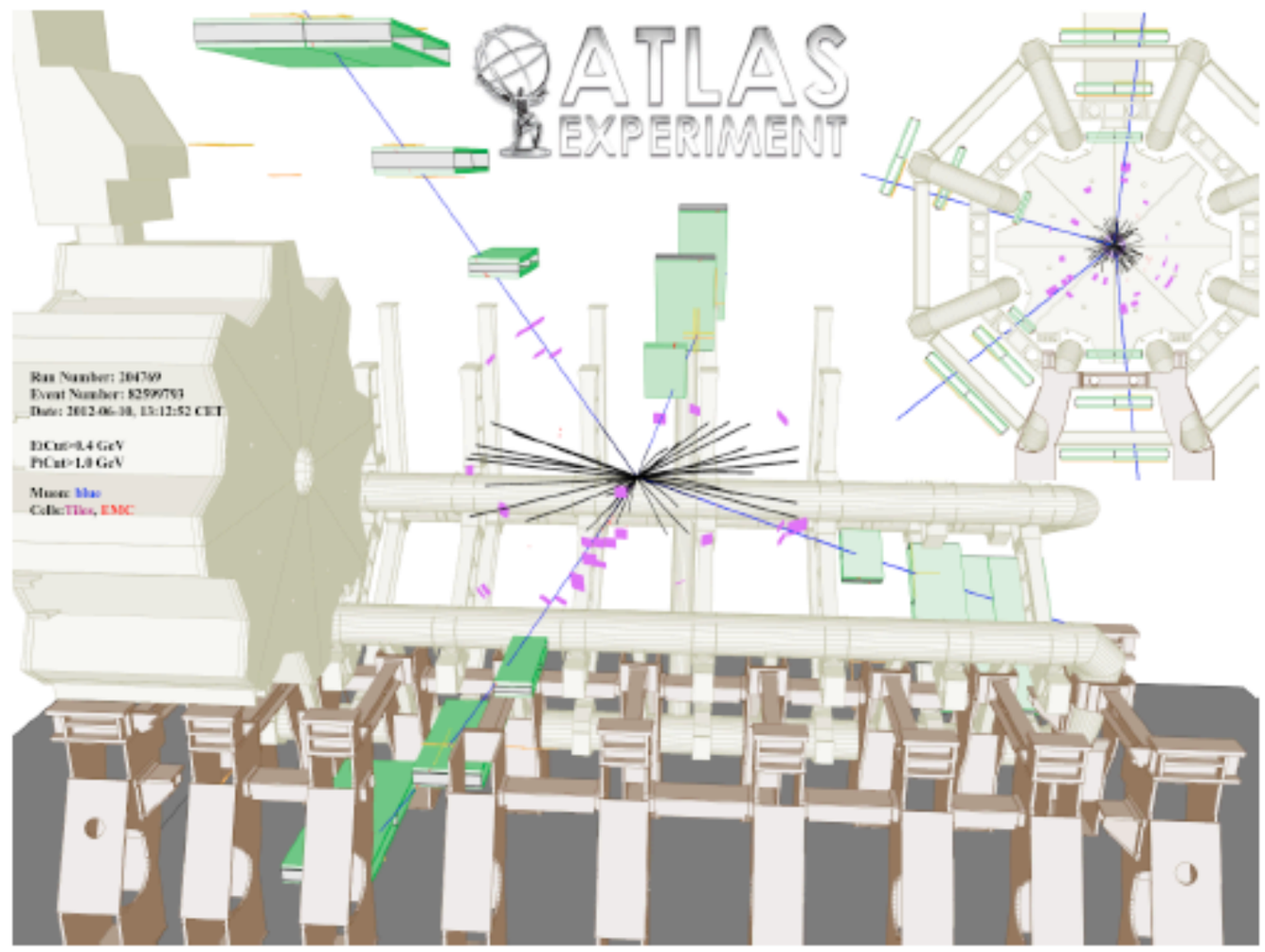
H->ZZ*->4l

The "golden" channel – Narrow peak over a locally flat continuum
Very high mass resolution and S/B >> 1
Very low rates (σ x β ~ 0.8 fb at 125 GeV)

Signature:
Four isolated leptons from
Common primary vertex

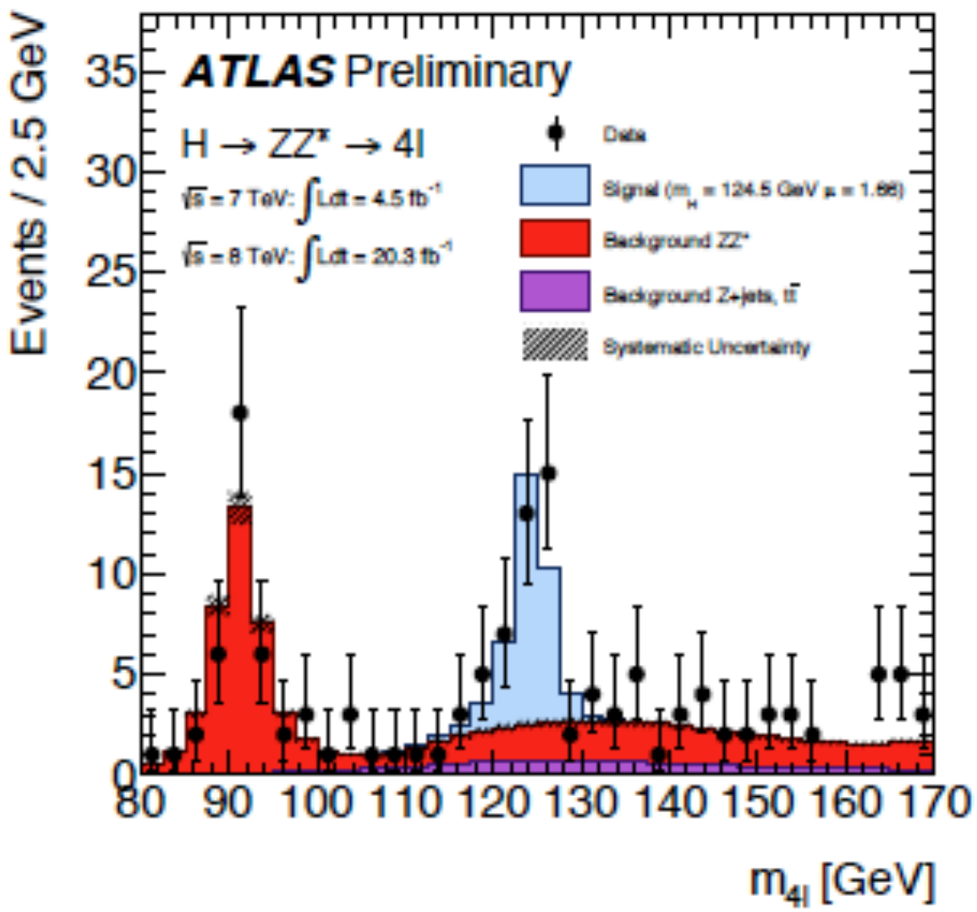
Analysis key:

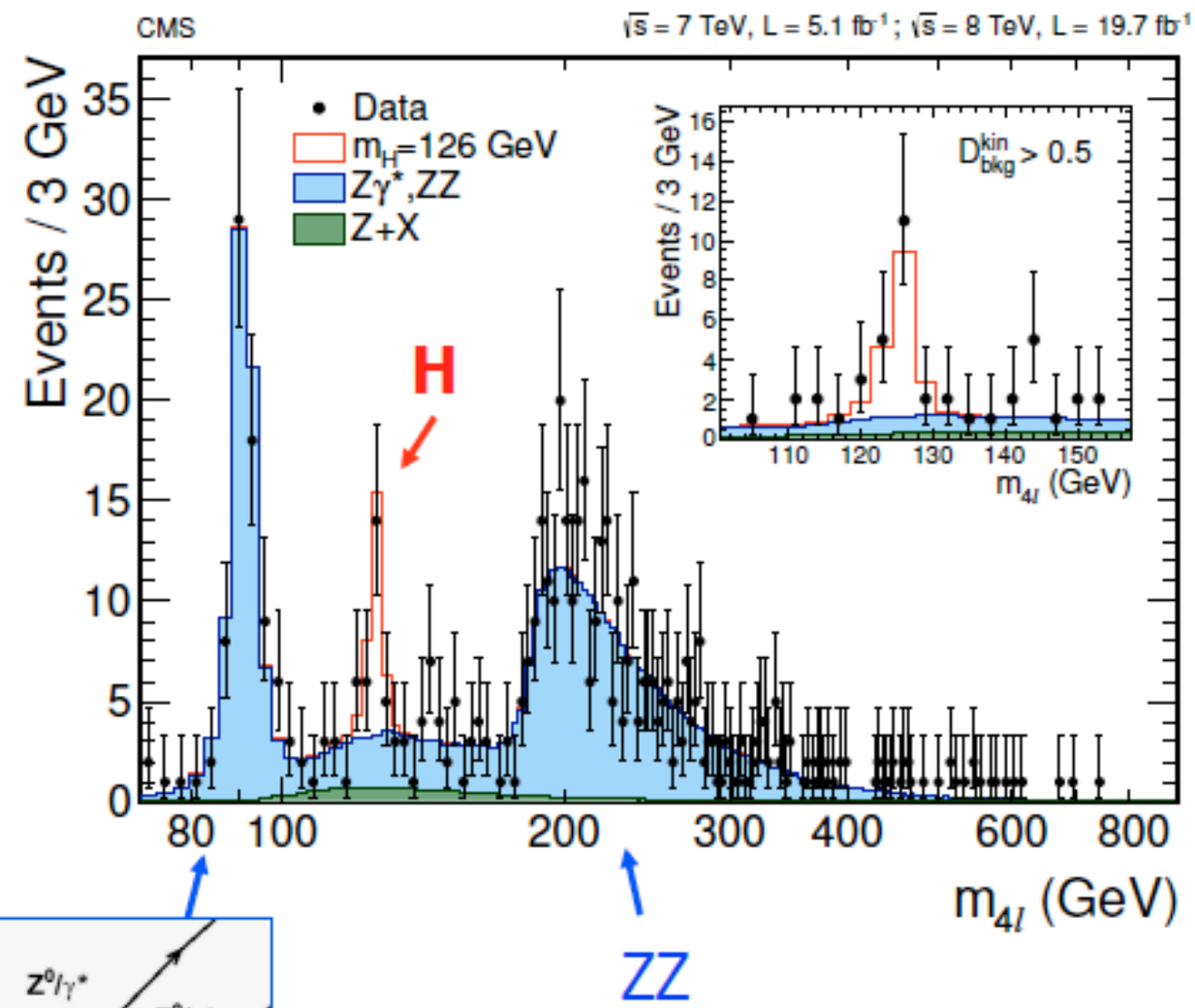
- Precision on lepton (E,**P**) & highest possible ε_ℓ down to lowest P_T
- Maintain the reducible background well below the ZZ* continuum

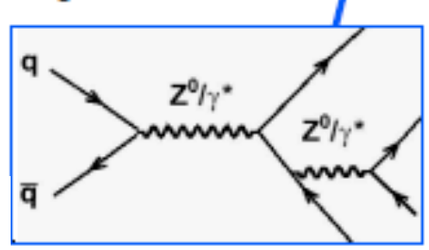


Discriminating variables:
$M_{4\ell}$
Kinematic Discriminant (e.g. M_{Z1}, M_{Z2}, 5 angles from decay chain)

4l mass







NEW!

m_H=124.51±0.52±0.04 GeV

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

ATLAS: new regression technique for photon and electron energy

new: Run I "legacy analysis"

$125.6 \pm 0.4(stat) \pm 0.2(syst.)$

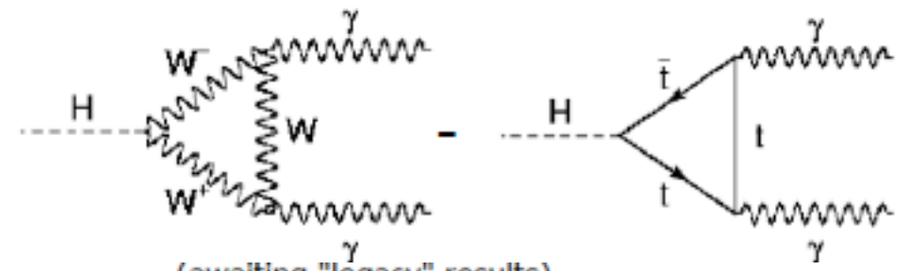
Obs. 6.8σ (exp. 6.7σ)

CMS, arXiv:1312.5353 (PRD 2014)

H->γγ

Narrow peak over falling ~ monotonic background
Very high mass resolution but S/B < 1
in gg-fusion production mode

Low rates ($\sigma \times \beta \sim 48.6$ fb at 125 GeV);

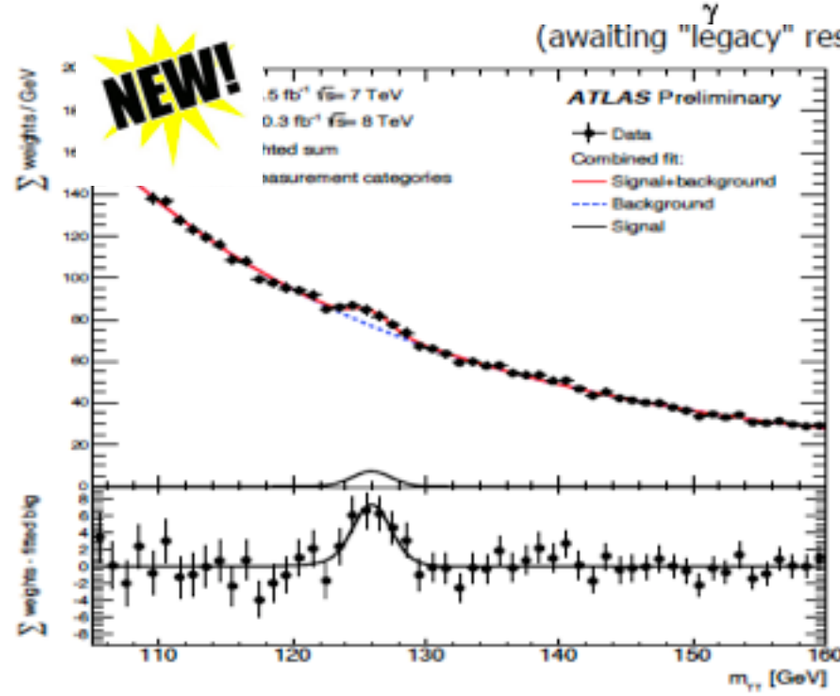


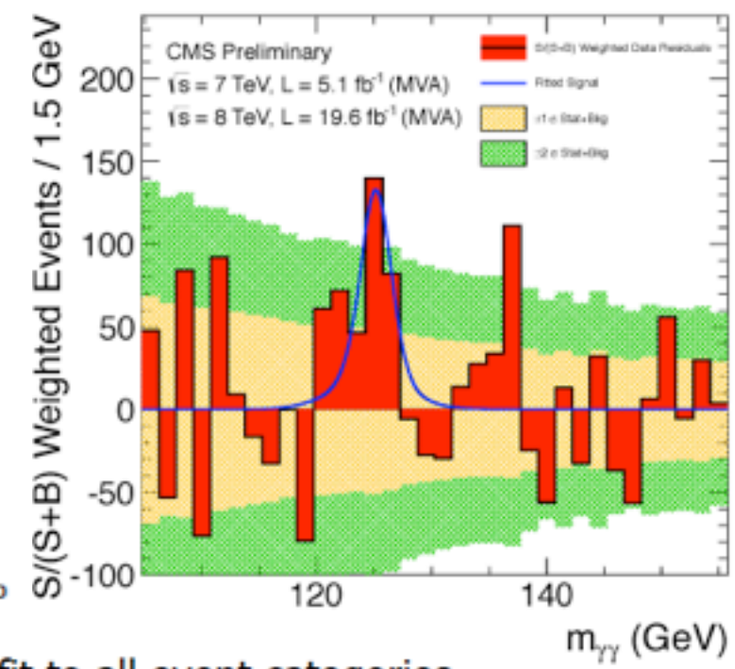
(awaiting "legacy" results)

Signature:
Two isolated photons

Analysis key:
Photon E measurement (ECAL
Photon angles
(ECAL and primary vertex)
Photon ID and Isolation

Discriminating variables:
$M_{\gamma\gamma}$, $P_{T\gamma}$
Event categorization
(Optimize sensitivity to different $M_{\gamma\gamma}$ resolution, or different production modes)





- Signal extracted from simultaneous S+B fit to all event categories with S/B varying from ~ 1/1 to 1/20
- $M_{\gamma\gamma}$ systematics dominated by uncertainty on E_γ scale (extracted via Z → ee)

m_H=125.98±0.42±0.28 GeV

- previous: m_H=126.8±0.2±0.7 GeV

$125.4 \pm 0.5(stat) \pm 0.6(syst.)$
Obs. 3.2σ (exp. 4.2σ)

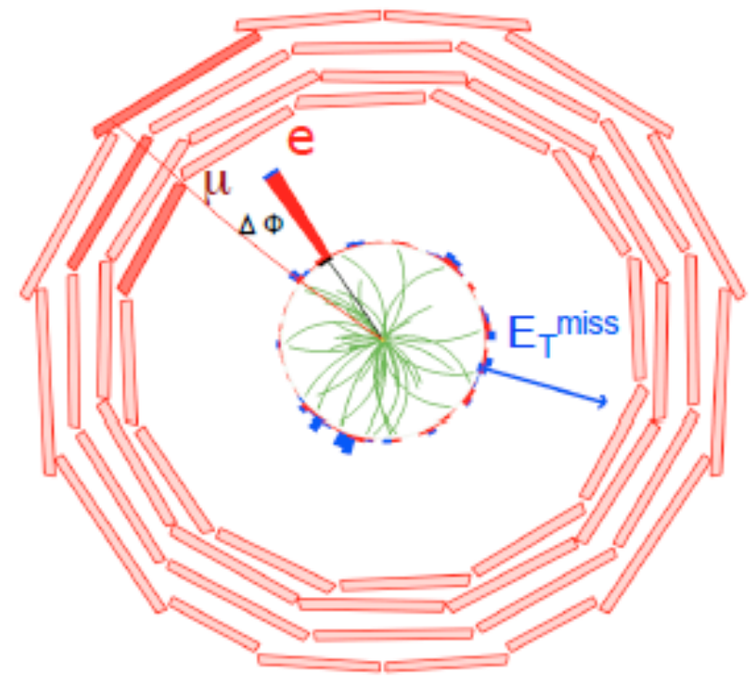
PAS HIG-13-001 (March 2013)

H->WW

Large rates ($\sigma \times \beta \sim 200$ fb at 125 GeV) and low mass resolution

Signature:

Two opposite sign isolated high P_T leptons and missing E_T



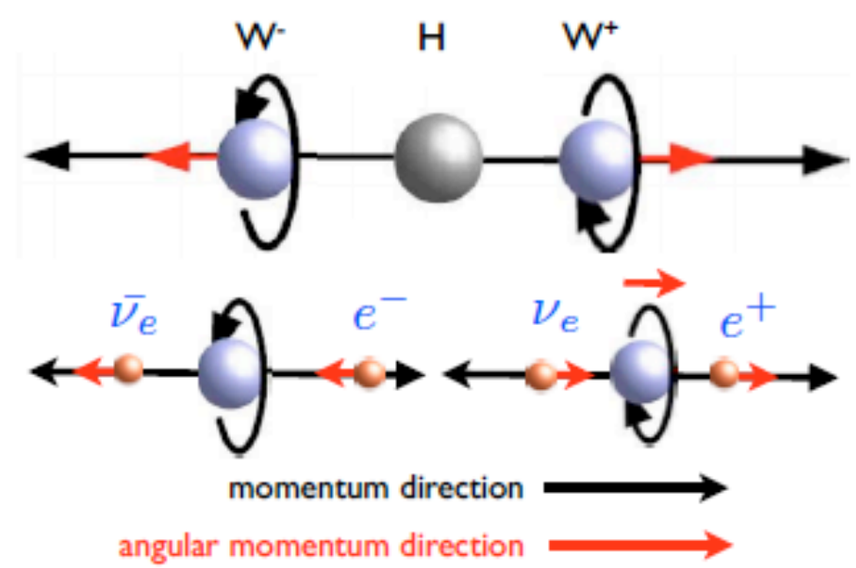
Analysis key:

Backgrounds from control regions with data

- Irreducible $qq/\gamma\gamma \rightarrow$ non-resonant WW*
- Reducible: top, W+jets, di-boson, DY, ...

Discriminating variables: $P_{T\ell\ell}$, M_ℓ M_T, $\Delta\Phi_\ell$

Small M_ℓ & small opening angle $\Delta\Phi_\ell$ (especially for on-shell W's) exploits the scalar H nature and V-A structure of EWK interaction $\Leftrightarrow$



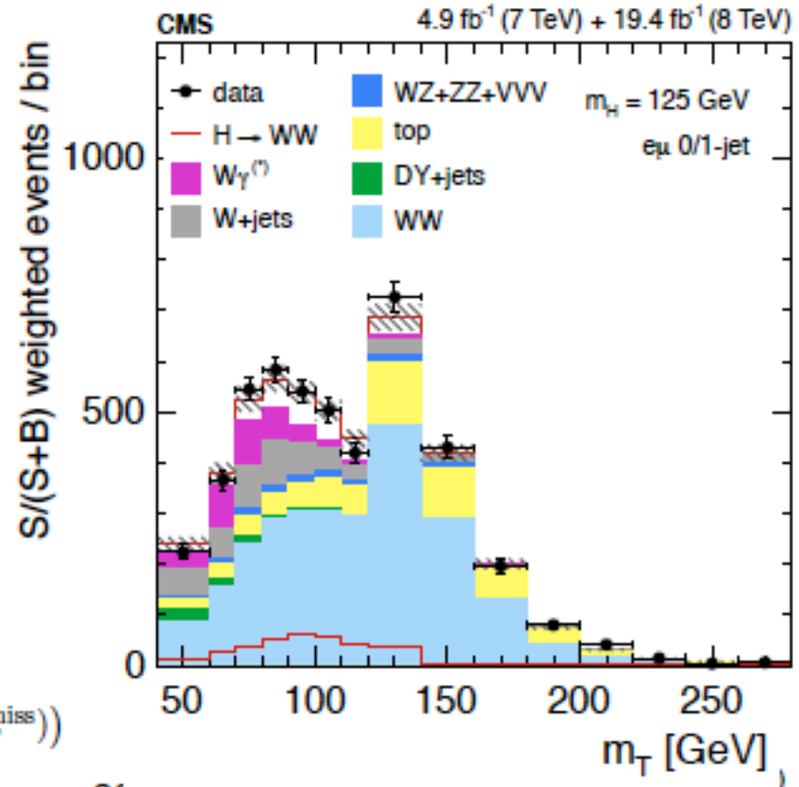
H->WW

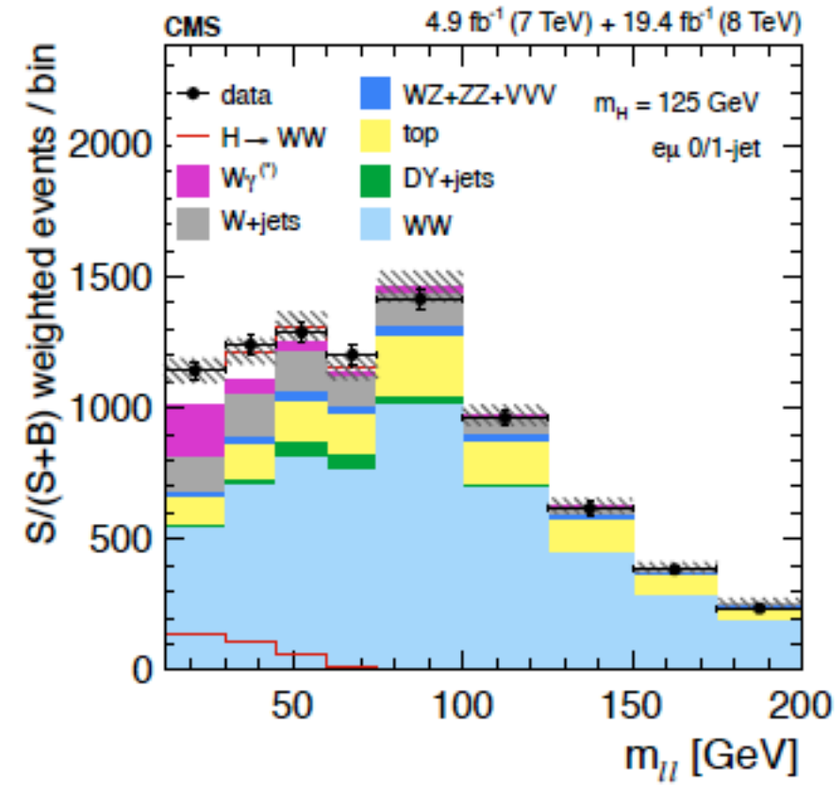
New:
Run I "legacy analysis"

e.g.

eμ channel
0 + 1 jets

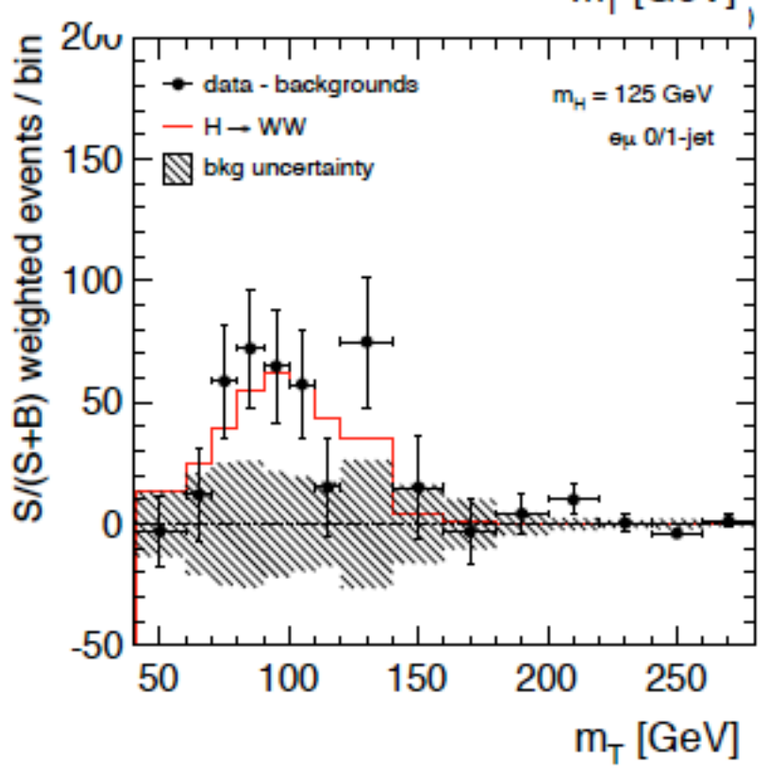
$m_T^2 = 2p_T^{\ell\ell} E_T^{miss}(1-\cos\Delta\phi(\ell\ell, \vec{E}_T^{miss}))$

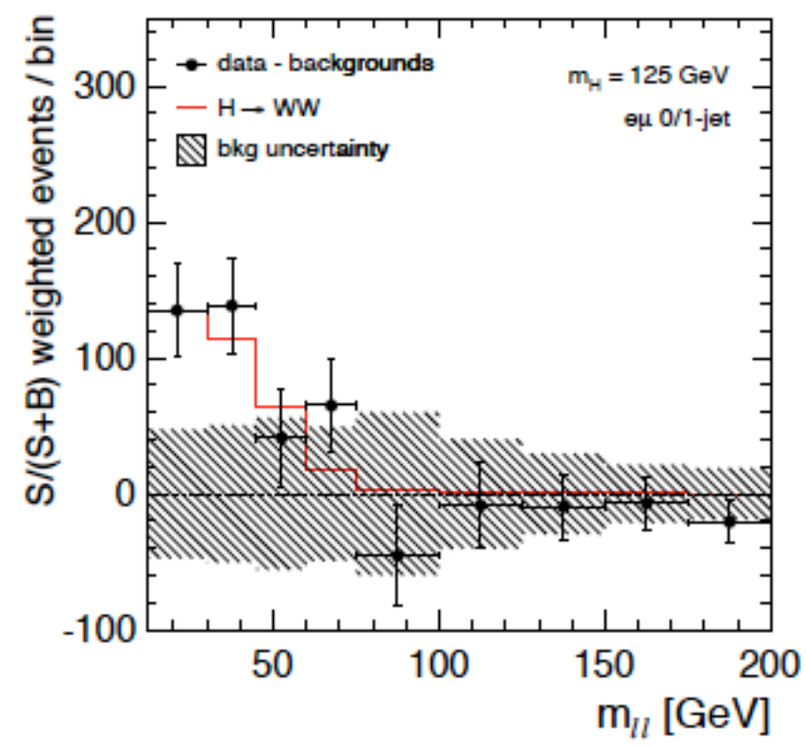




The interpretation uses 2D templates in m_T vs $m_{\ell\ell}$ plane

Obs. 4.3σ
(exp. 5.8σ)





CMS JHEP01(2014)096

H->fermions

Large rates ($\beta_{H \to bb}$ ~ 58%) and medium mass resolution

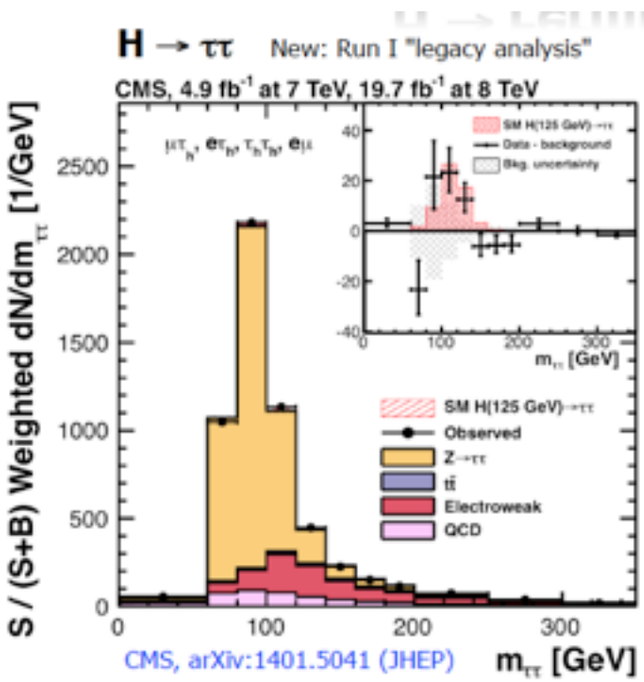
Signature:

$H \to bb$ ggH, $H \to bb$ is saturated by QCD background ⇒ focus on WH and ZH prod. with b-tagged jets and ≥ 1 lepton

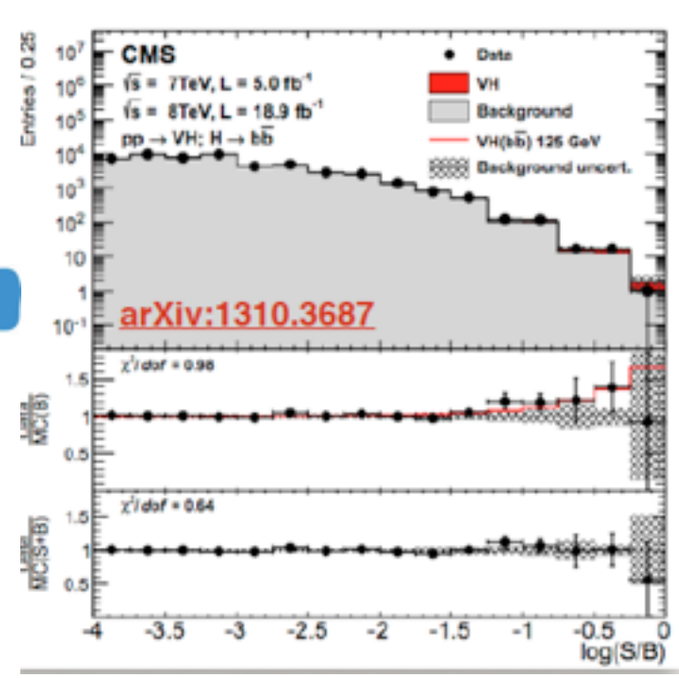
$H \to \tau\tau$ Exploit production and τ lepton decay dependent categorisation

Analysis key:

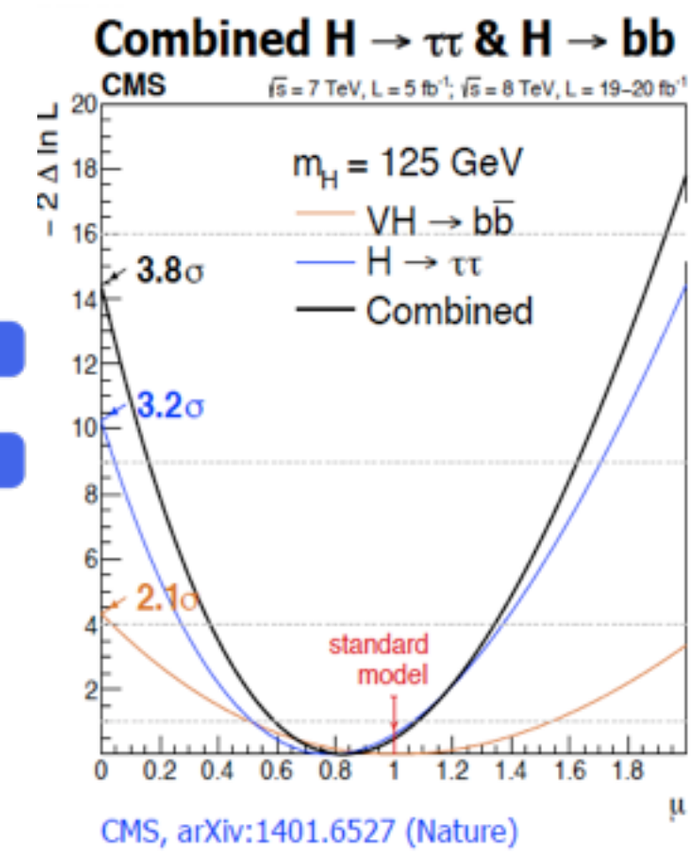
Mass discrimination against background from Z/W + heavy flavours



$H \to \tau\tau$	ATLAS	CMS
Sign. strength	$1.4^{+0.5}_{-0.4}$	0.78 ± 0.27
Significance	4.1σ (exp 3.2σ)	3.2σ (exp 3.7σ)



CMS, VH->bb, 2σ obs

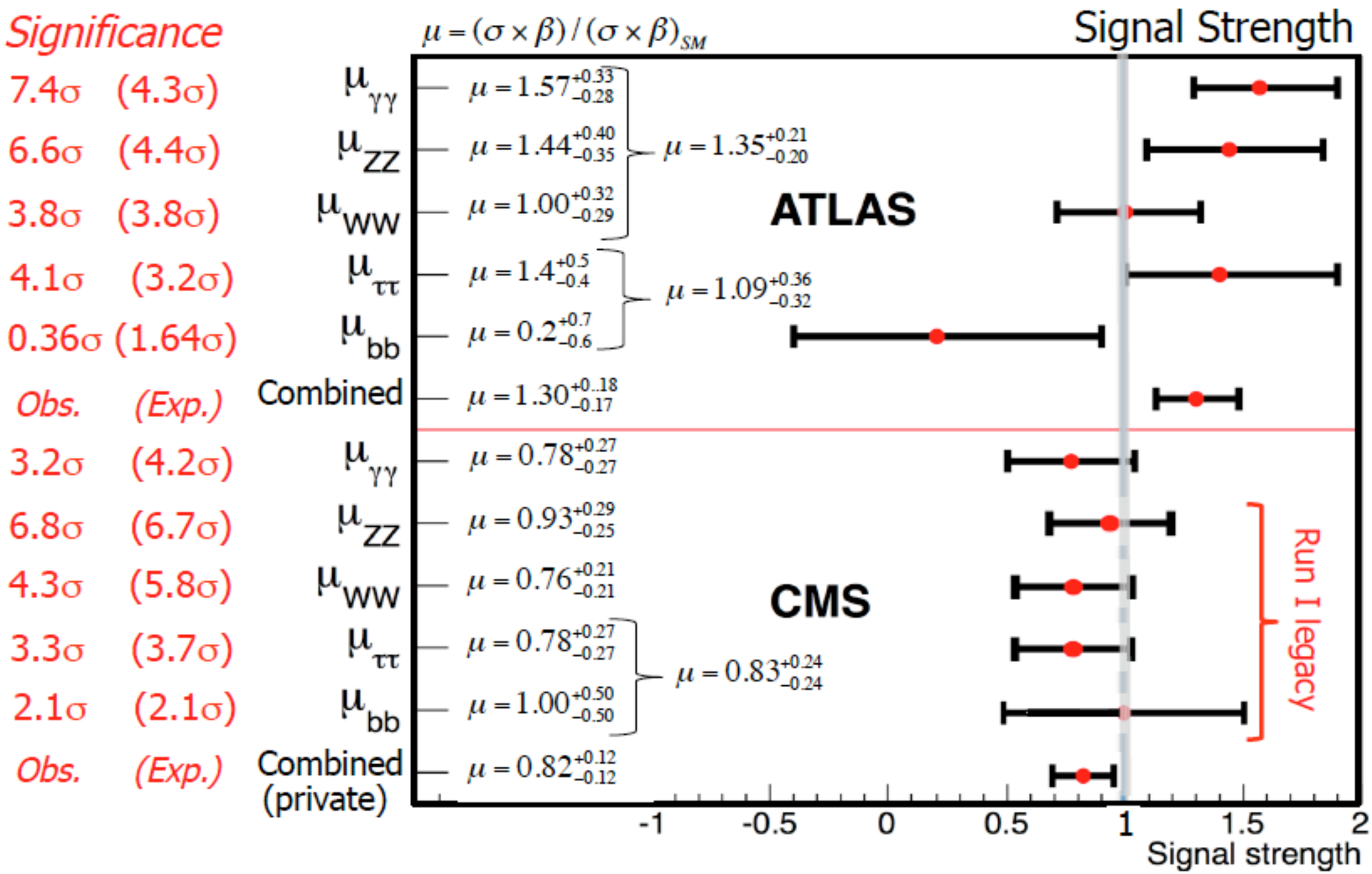


$\mu_{comb.}$ = 0.83 ± 0.24

Obs. 3.8σ (exp. 4.4σ)

Evidence for H-> fermions (CMS) !

Putting it all together: mu



Mass

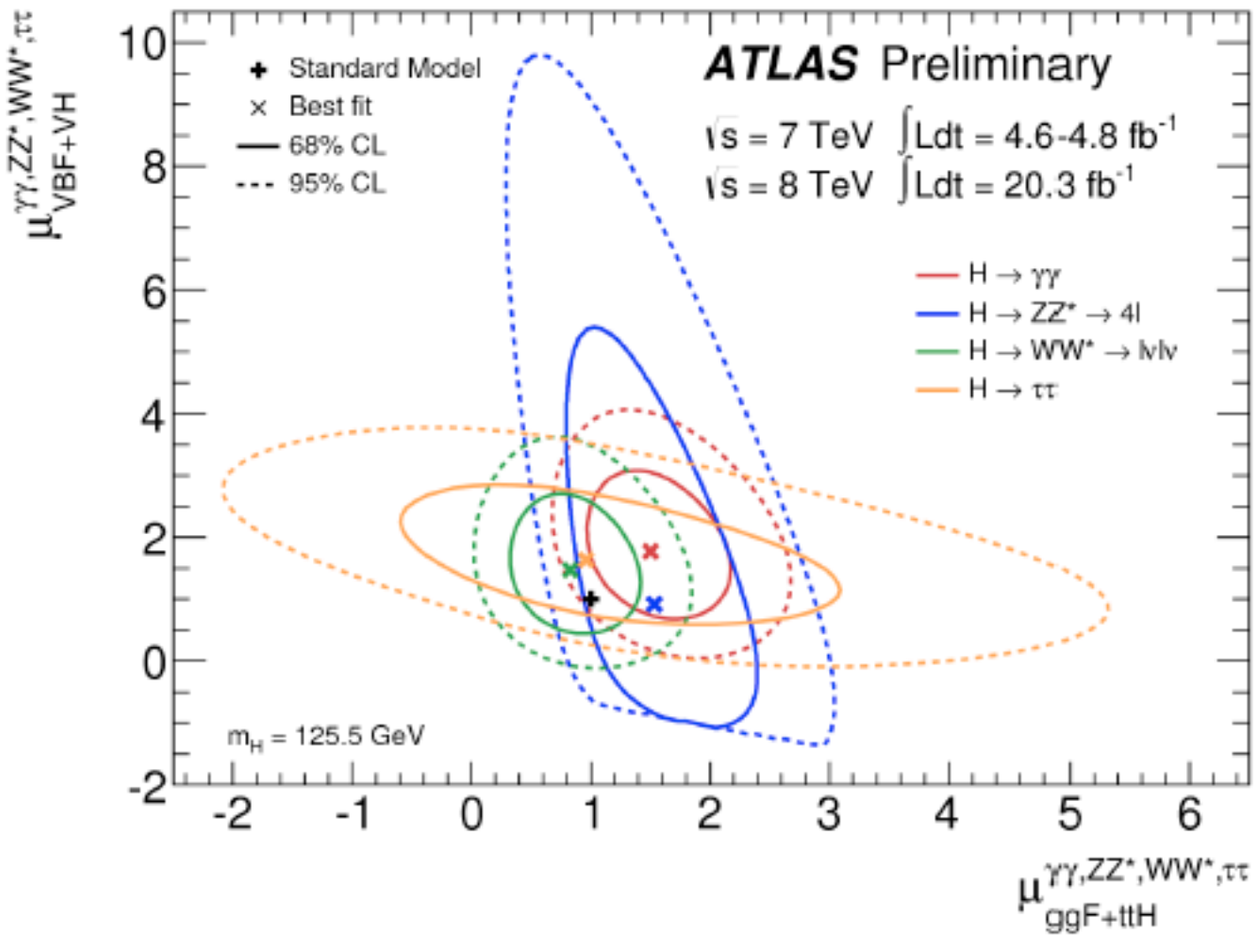
ATLAS $\gamma\gamma$+ZZ combined
$125.5 \pm 0.2(stat) \pm 0.55(syst.)$

CMS $\gamma\gamma$+ZZ combined*
$125.7 \pm 0.3(stat) \pm 0.3(syst.)$

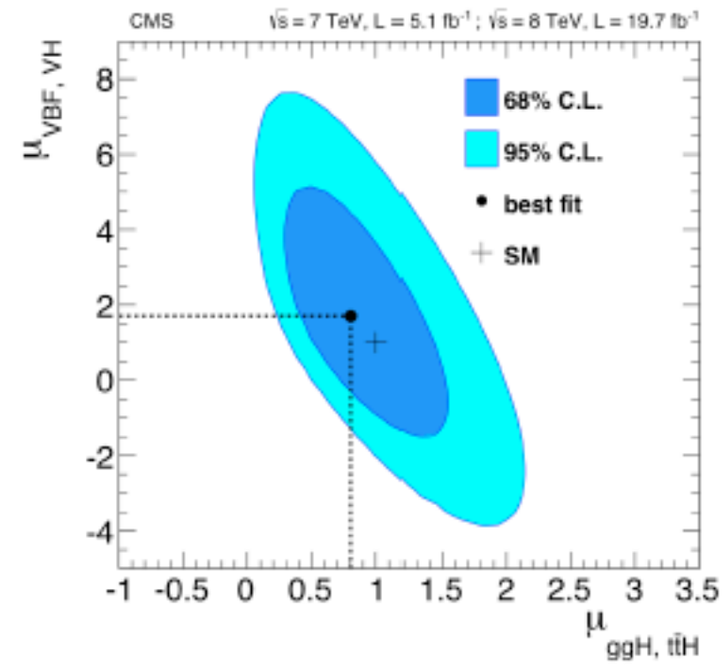
* Results as of Moriond 2013

Putting it all together: prod modes

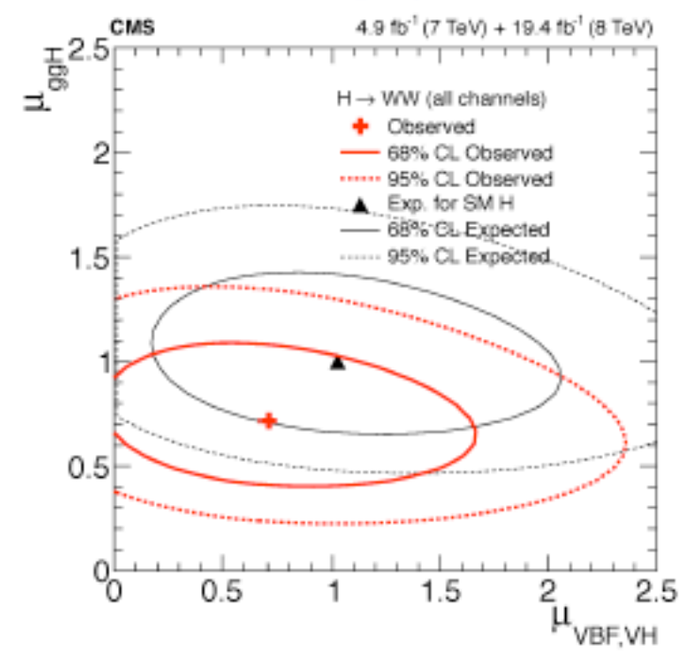
New combination: ATLAS CONF-2014-009



CMS H → ZZ "legacy": arXiv-1312.5353 (PRD)



CMS H → WW "legacy": JHEP01-2014-096



The ratio $\mu_{VBF+VH} / \mu_{ggH+ttH}$ is indep. of decay

ATLAS profiles $\mu_{VH} / \mu_{ggH+ttH}$

$$\mu_{VBF} / \mu_{ggH+ttH} = 1.4 \pm 0.3(stat.)^{+0.6}_{-0.4}(syst.)$$

CMS profiles VH, ggH, ttH

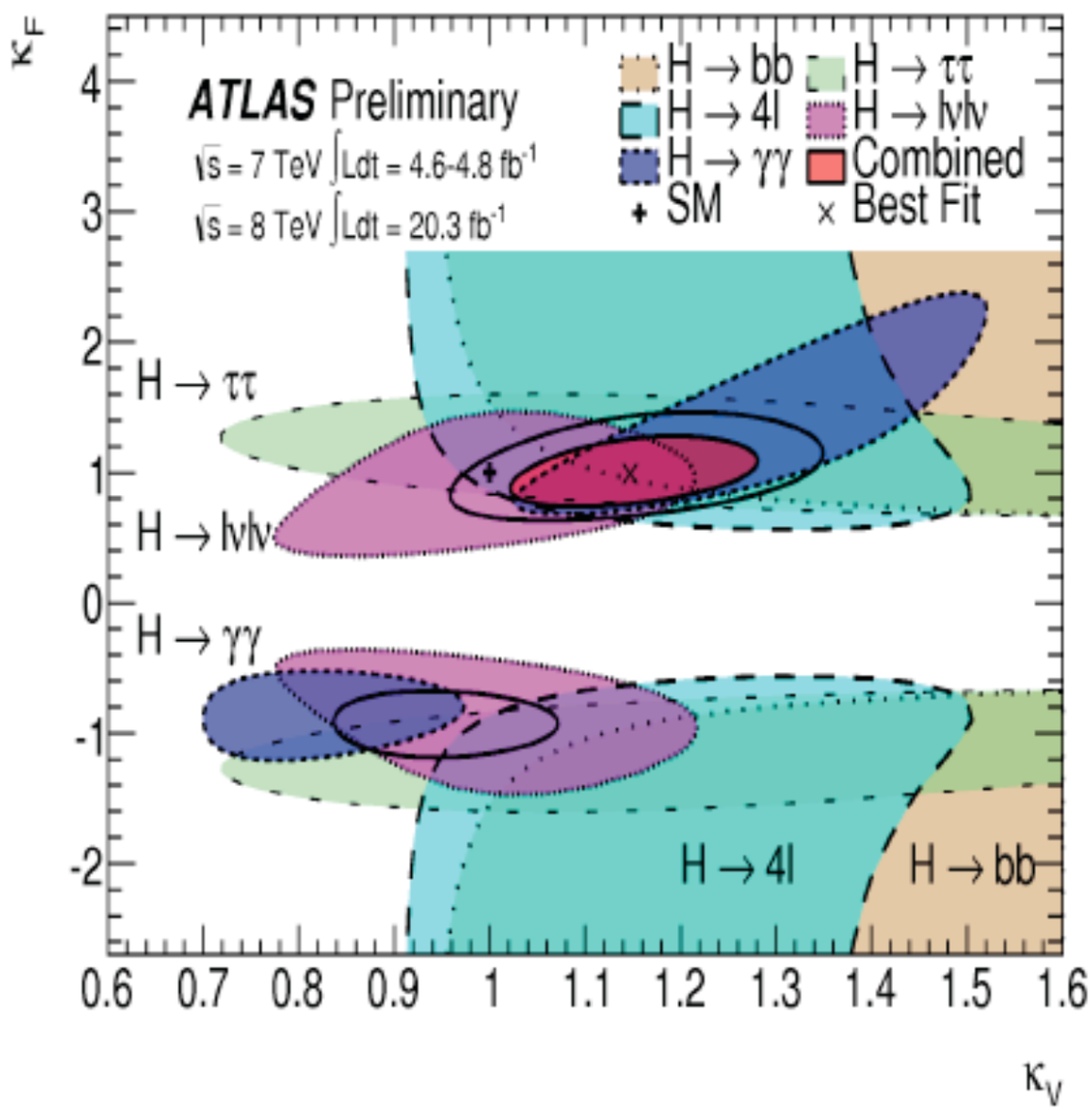
$$\mu_{VBF} = 0..95 \pm 0.5$$

$\mu_{VBF} = 0$ is excluded at ~3σ level

Also CMS Combination from spring 2013 in PAS-13-005

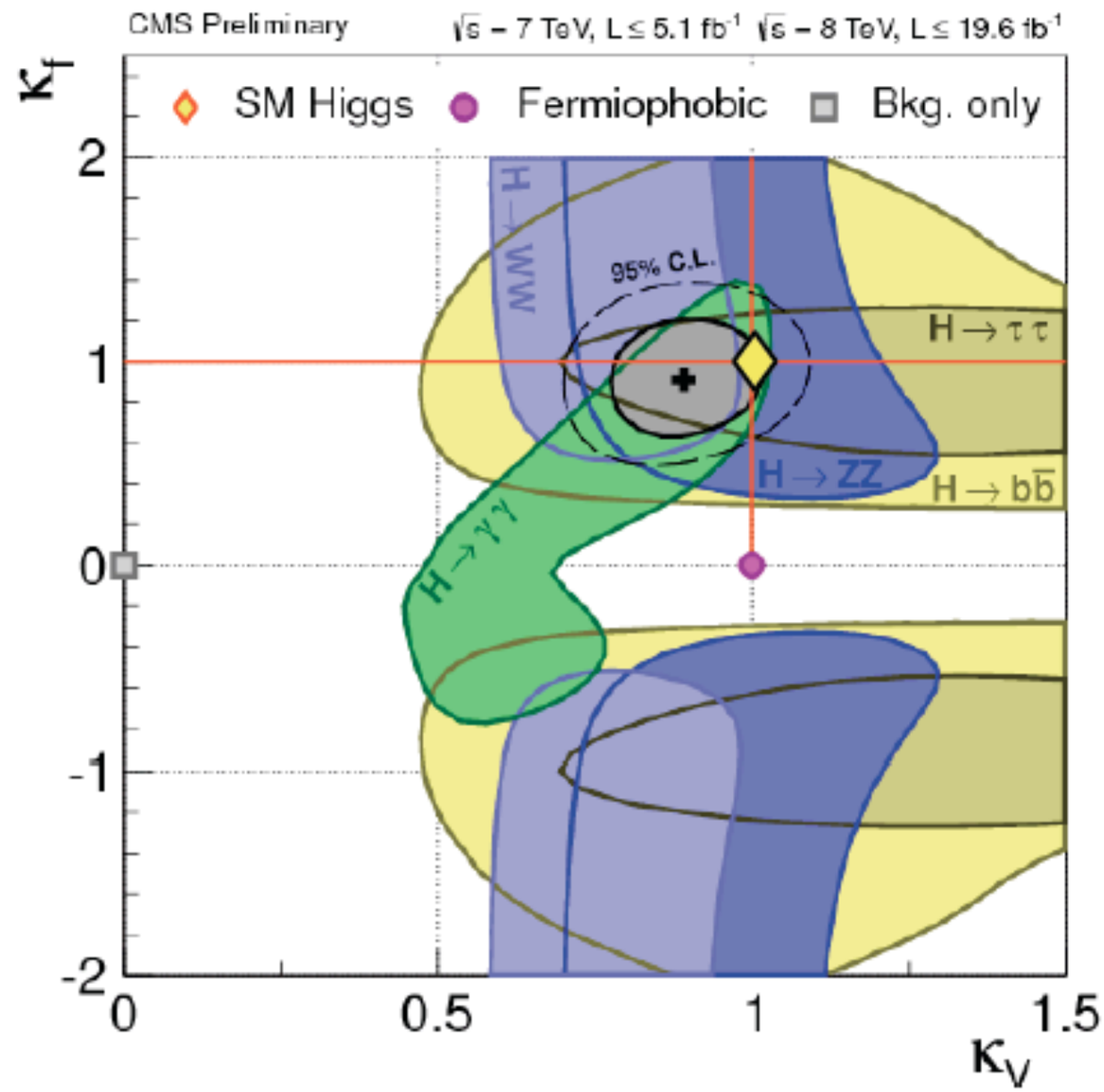
Putting it all together: coupling to fermions and bosons

ATLAS



New: ATLAS CONF-2014-009

CMS



CMS PAS-HIG-13-005 Moriond 2013

also here compatible with SM within uncertainty

Higgs boson decay width (1)

Direct

- Measurement of resonance width limited by experimental precision

  e.g. Limits at 95%CL from CMS $\Gamma < 4.9$ GeV from $H \to \gamma\gamma$
  $\Gamma < 3.4$ GeV from $H \to 4\ell$

  "Results consistent with a single narrow resonance"
- For a Higgs boson at $M_H \sim 125$ GeV, total width $\Gamma_H \sim 4.2$ MeV
  $\Gamma_H \ll M_H$ & $\Gamma_H \ll \Delta M_H^{meas}$

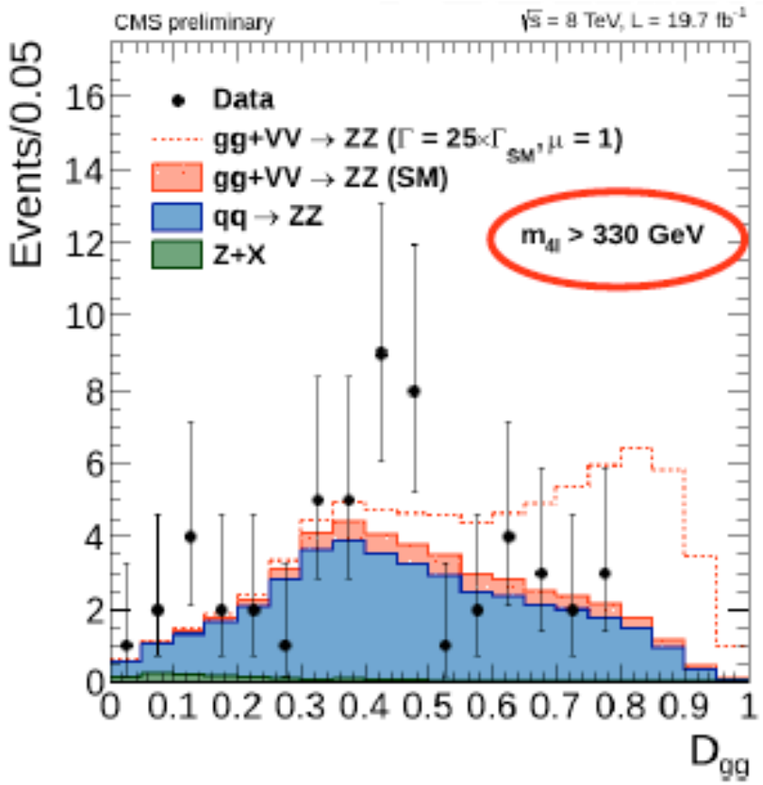
  "Direct measurements of Γ_H seems a priori impossible at the LHC ..."

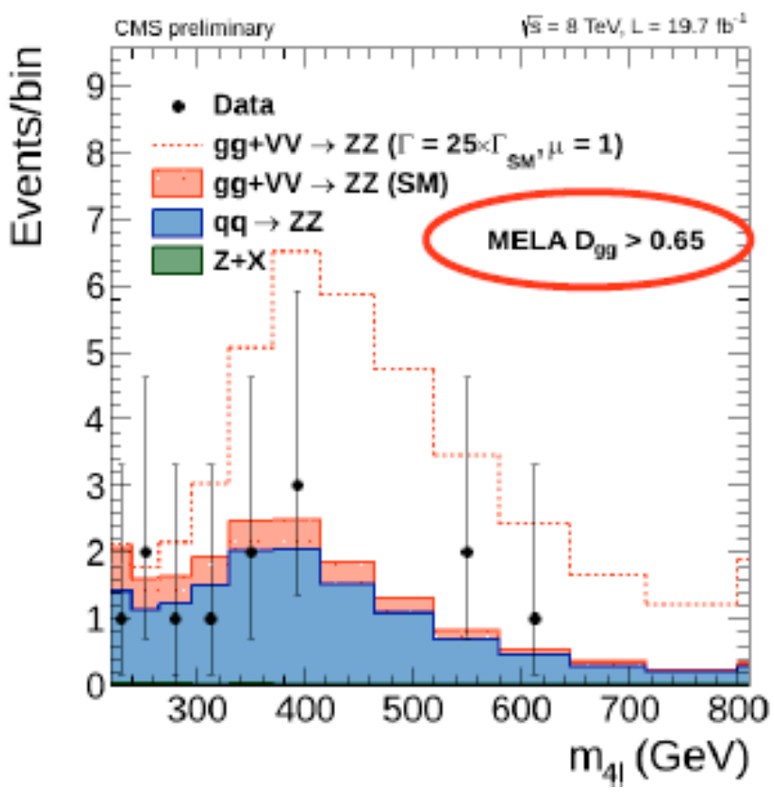
Give up ? ... Not quite ...

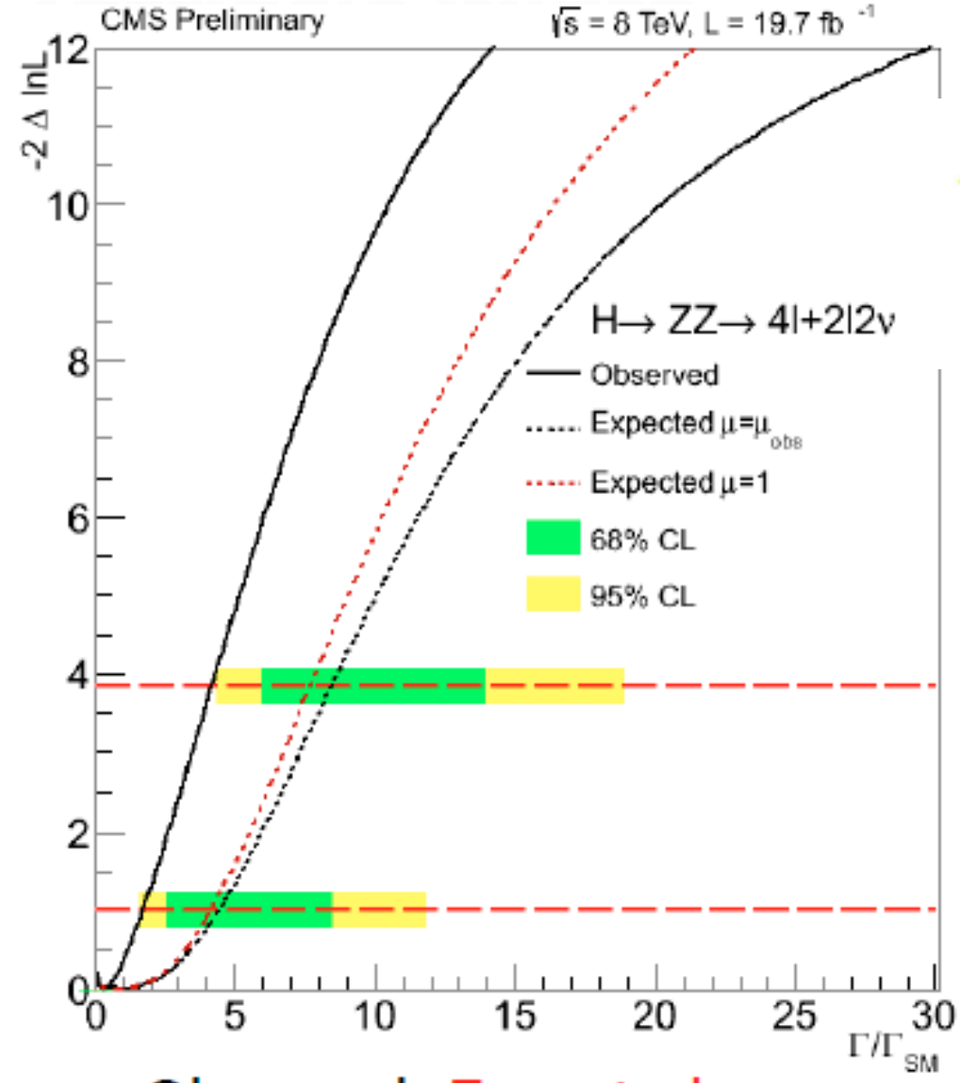
Indirect

- Two possible techniques at the LHC
  - By "interferometry": exploit the effect (change of sign) of the interference around the resonance peak (e.g. slight shift of $M_{\gamma\gamma}$) ...
    $\Rightarrow$ requires very large statistics (Run II and beyond)
  - By the "propagator": exploit relative intensity of the on- and off-peak signal, taking interference with irreducible background into account.
    $\Rightarrow$ already exploitable with Run I data in the $H \to 4\ell$ channel

Higgs boson decay width (1)







	Observed	Expected	
$r = \Gamma/\Gamma_{SM} < 4.2$	8.5		95% CL
$\Gamma < 17.4$ MeV	35.3 MeV		95% CL

Best fit : $r = \Gamma/\Gamma_{SM} = 0.3\ ^{+1.5}_{-0.3}$

$\Gamma = 1.4\ ^{+6.1}_{-1.4}$ MeV

ttH

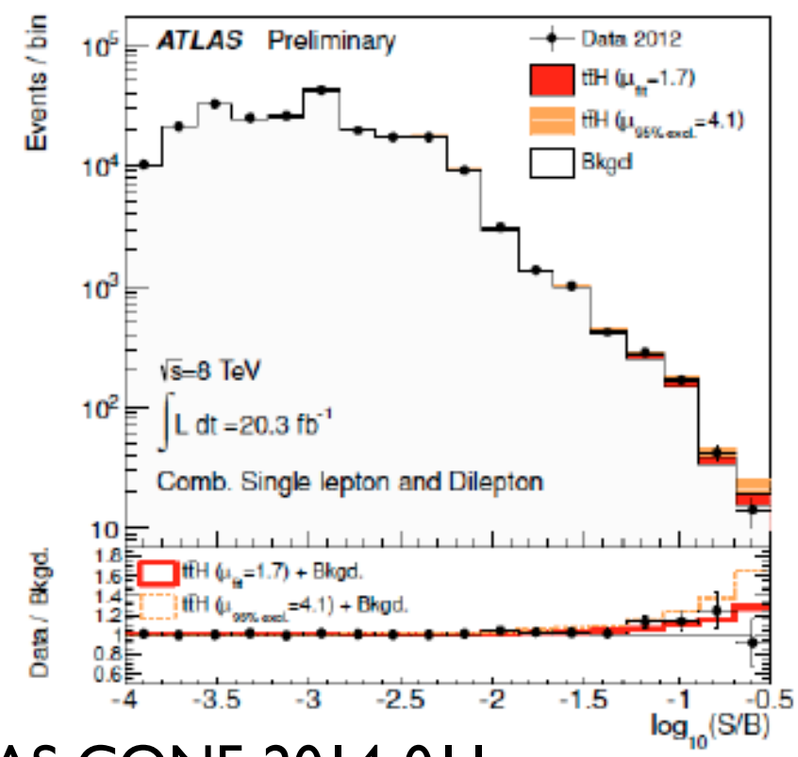
- Direct study of top Yukawa coupling
- exploring all accessible Higgs decay modes
- Approaching SM sensitivity

ATLAS

NEW!

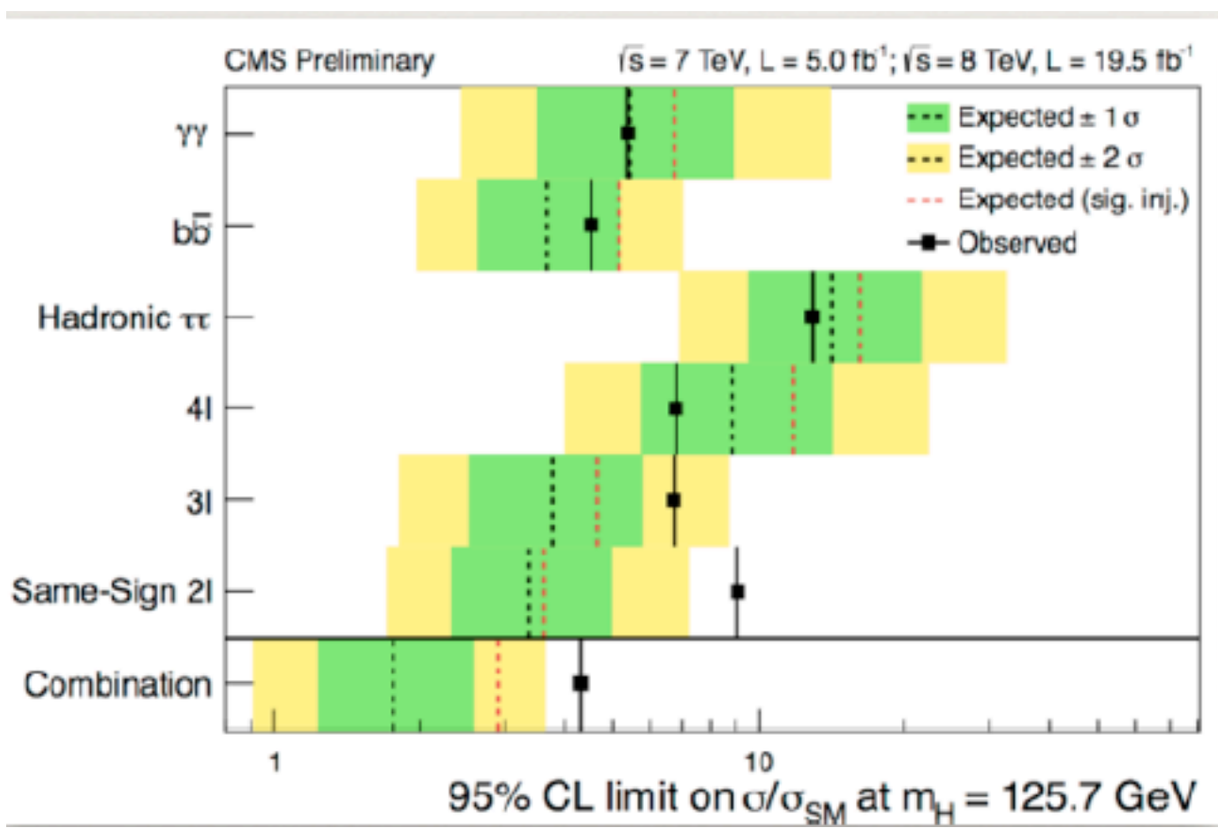
Search for ttH, H→bb

- results:
- μ=1.7±1.4, consistent between 2 channel



ATLAS CONF-2014-011

CMS



Higgs spin and parity

- The spin-parity of the Higgs boson candidate (assuming pure J^P state) can be tested in di-boson decay channels or via associated production

$H \to \gamma\gamma$ ATLAS, CMS

Test 0^+ against 2^+ states

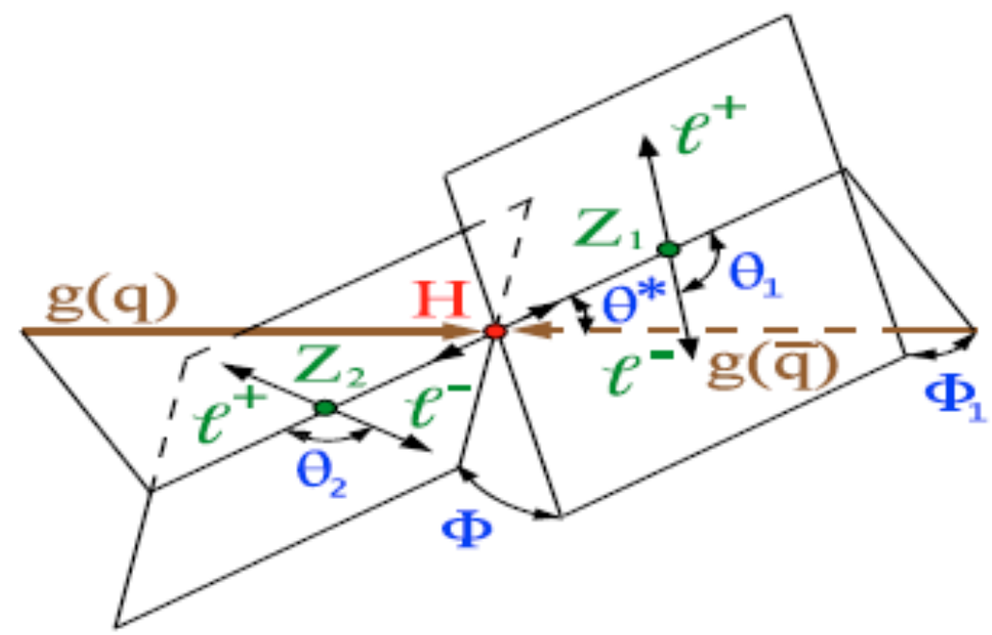
e.g. exploit the prod. dependent scattering angle in the Collins-Sopper frame

$$\cos(\theta^*_{CS}) = 2 \times \frac{E_2 p_{z1} - E_1 p_{z2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + p^2_{T\gamma\gamma}}}$$

$H \to ZZ^* \to 4l$ ATLAS, CMS

Test 0^+ against spin 0^-, $1^\pm$ and $2^\pm$ states

e.g. exploit mostly the angular correlations in the decay chain



$H \to WW^* \to 2\ell\, 2\nu$ ATLAS, CMS

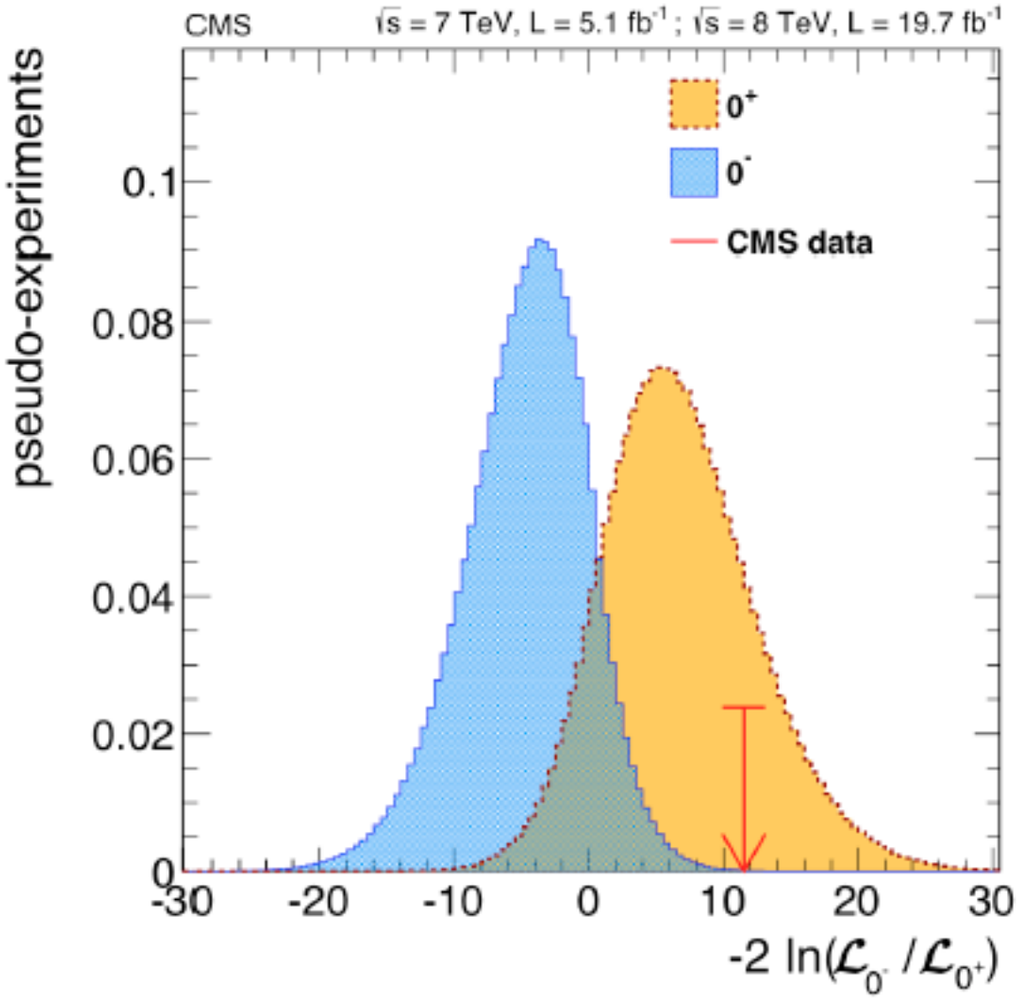
Test 0^+ against 0^- or 2^+

e.g. exploit the prod. dependent 2D distributions in m_T and $M_{\ell\ell}$

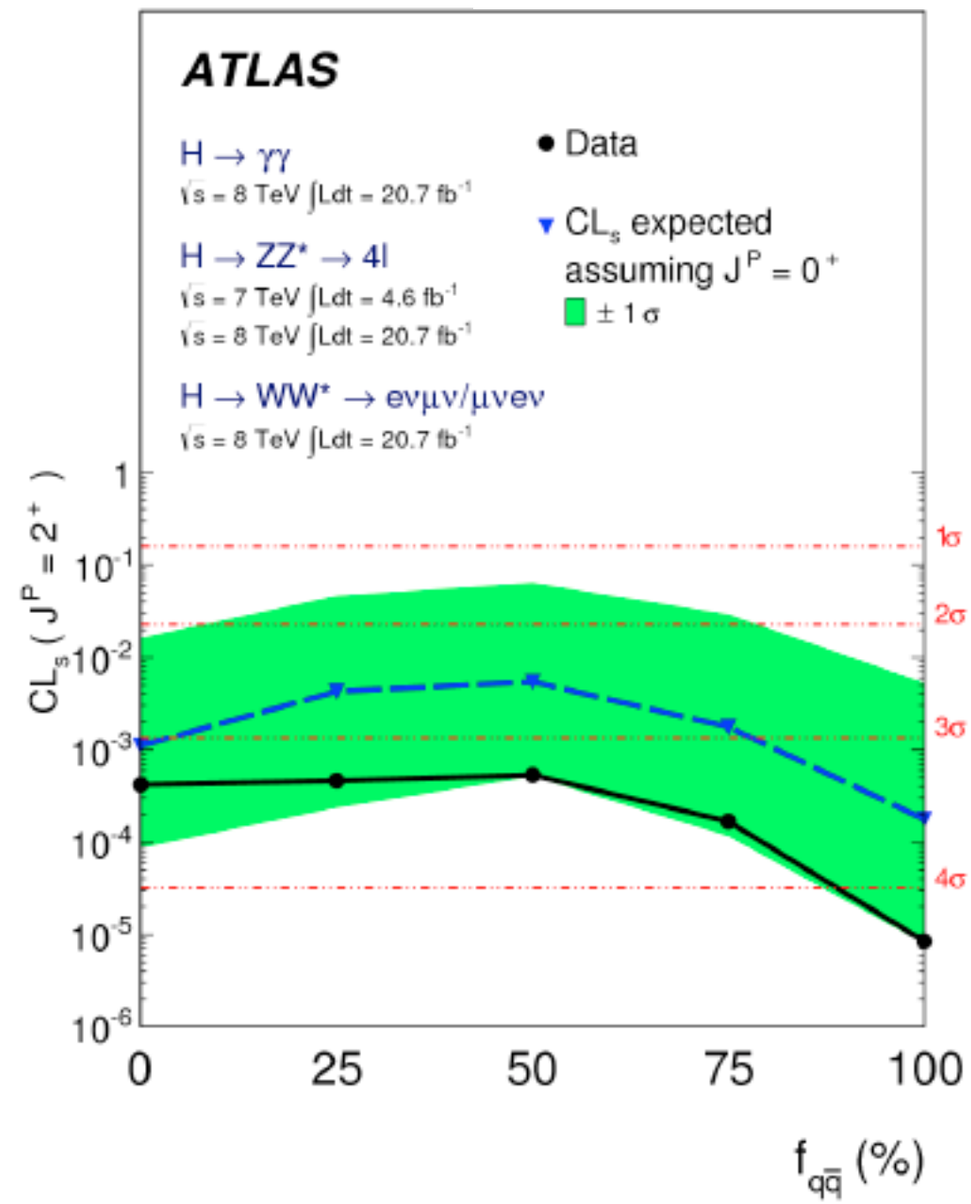
ATLAS PLB726 (2013) 120-144.
CMS PRD110 (2012) 081803 arXiv:1312.5353 & 1129, PAS-HIG-13-016

Higgs spin an parity

ATLAS PBL 726 (2014) 120-144.



CMS arXiv:1312.5353 (PRD 2014)



Spin 0 nature of the boson, 0+ strongly preferred

Higgs couplings

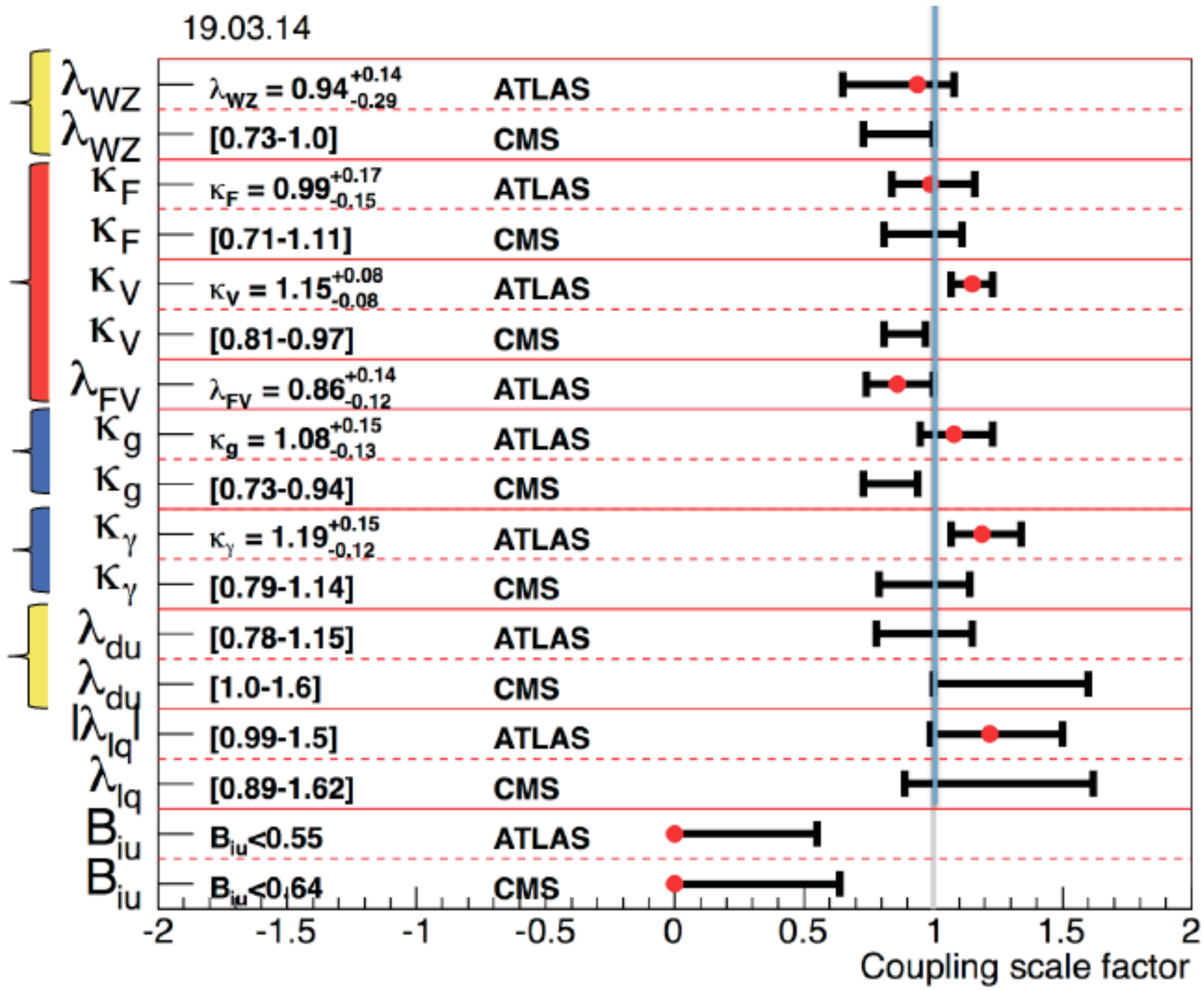
Custodial Symmetry

Coupling to fermions ($\propto M_f$) and bosons ($\propto M_V^2$)

Heavy quarks in the prod. loop

W boson and top quark in the loop

Flavour Symmetry



ATLAS CONF-2014-009

CMS PAS-HIG-13-005 Moriond 2013

Table from E. Gross, Moriond 2014

Projection of coupling

κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics

κ_W, κ_Z: vector bosons

κ_t, κ_b: up- and down-type quarks

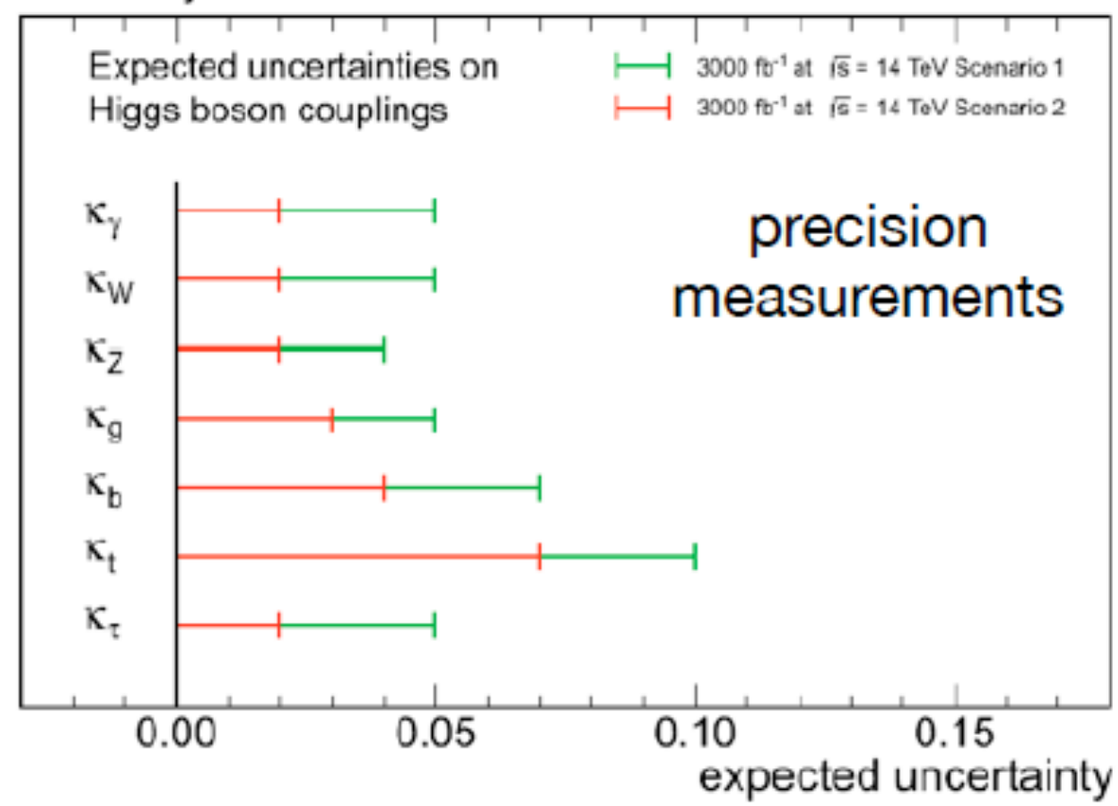
κ_τ, κ_μ: charged leptons

total width from sum of partial widths

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ $1/\sqrt{L}$

coupling precision 2-10 %
factor of ~2 improvement from HL-LHC

CMS Projection



precision measurements

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

from Snowmass, ECFA process

but we need some expensive maquillage

current Phase1 Phase2

Run1 2015-2X 2030

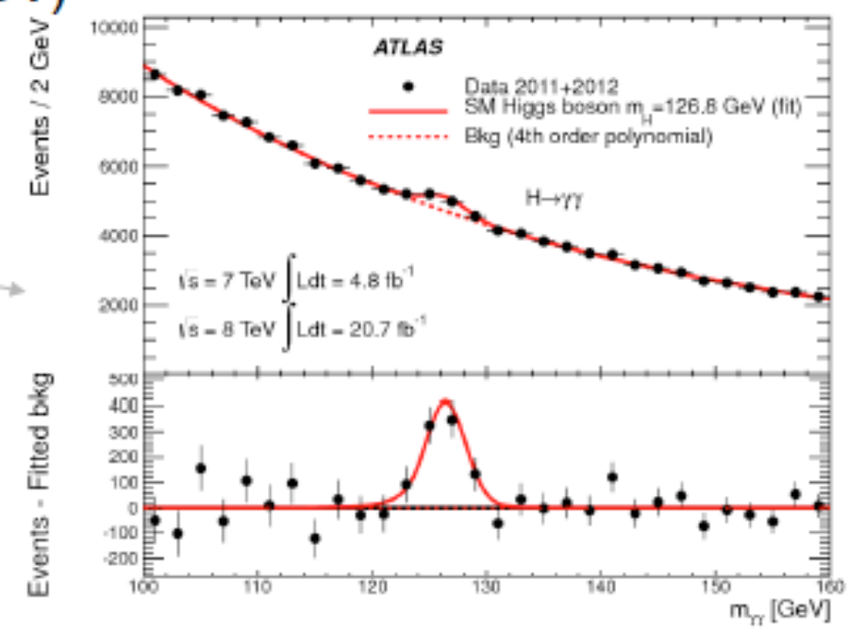
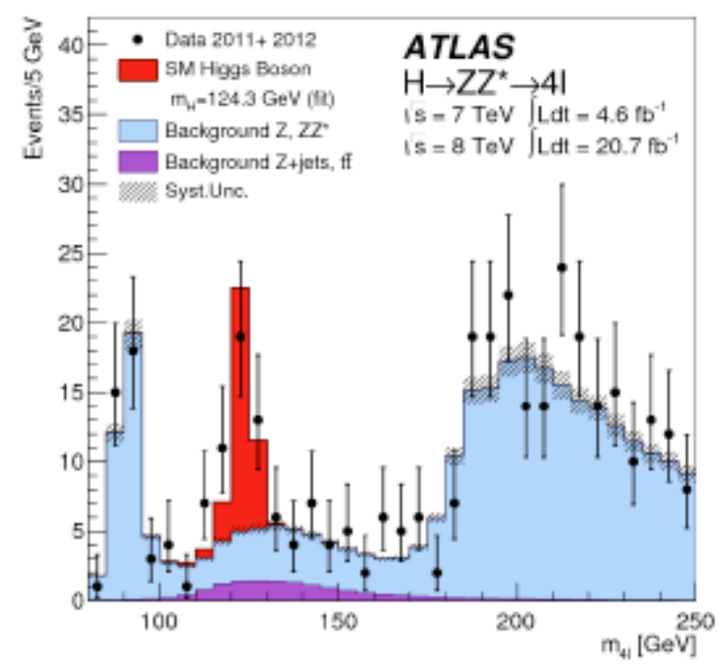
Conclusions

- Wide range of Higgs production and decay channel studied by CMS and ATLAS
- All signatures so far compatible with SM
  - future precision measurements can unveil its nature
- CMS and ATLAS are finalizing Run1 results and preparing for Run2 (and also Stage2 of the detectors)
  - we need to enforce the development of
    - new detectors - yes there will be brand-new ATLAS and CMS!
    - new analysis techniques to cope with high lumi!

BACK-UP

New ATLAS mass meusurements

- measurement possible using high-resolution channels: $H \to ZZ^* \to 4l$ ($\sigma_m \sim 1.6$-2.4 GeV) and $H \to \gamma\gamma$ ($\sigma_m \sim 1.7$ GeV)

- previous result (7+8 TeV): PLB 726, 88 (July 2013)
  - $m_H = 125.5 \pm 0.2^{+0.5}_{-0.6}$ GeV
  - 2.4σ tension: $\Delta m = 2.3^{+0.6}_{-0.7} \pm 0.6$ GeV

- changes in new measurement:
  - new e/γ calibration
  - improved e/γ and μ energy scale uncertainties
  - event classification optimised for best σ_m in $H \to \gamma\gamma$, independent of model of production
  - improved expected statistical uncertainty in $H \to ZZ^*$ with 2D likelihood fit