Higgs boson results from ATLAS

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On behalf of the ATLAS collaboration

QFTHEP 2015 June25

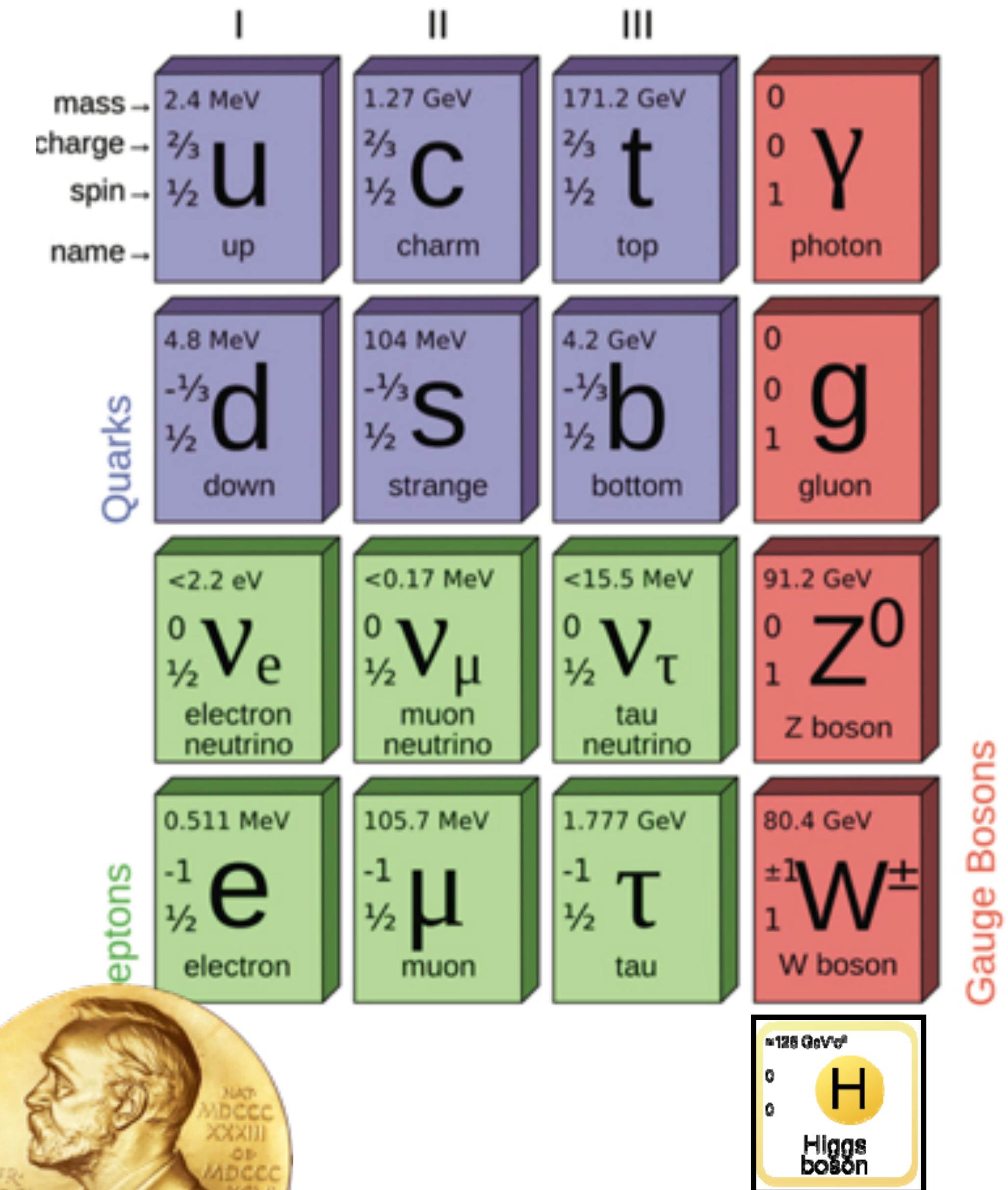
Higgs particle

- The Higgs particle was the missing corner stone of the SM and is responsible for the masses of elementary particles.

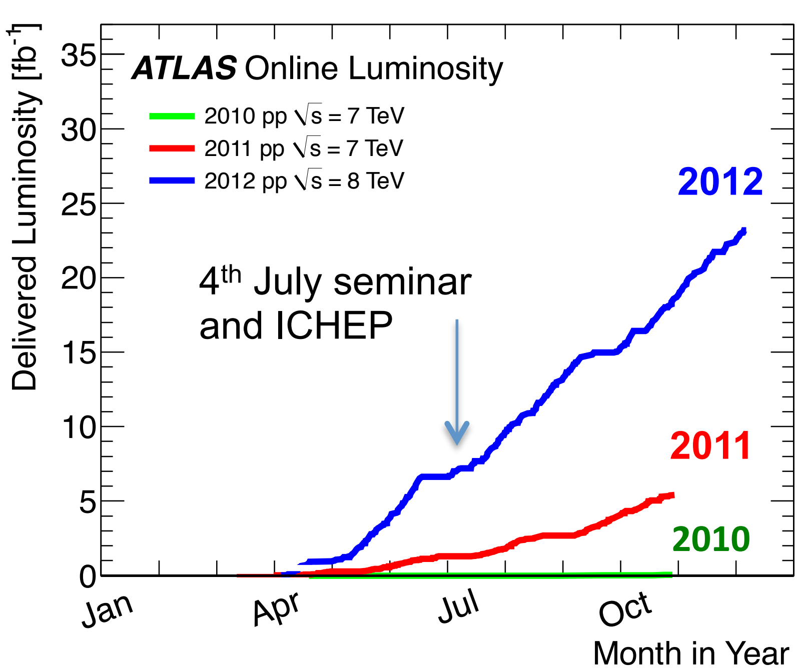
- **Born on 4th of July 2012:**
  - Higgs-like boson at ~125GeV
  - 5.9σ @ATLAS, 5σ @CMS (*PLB, 716, 2012*)

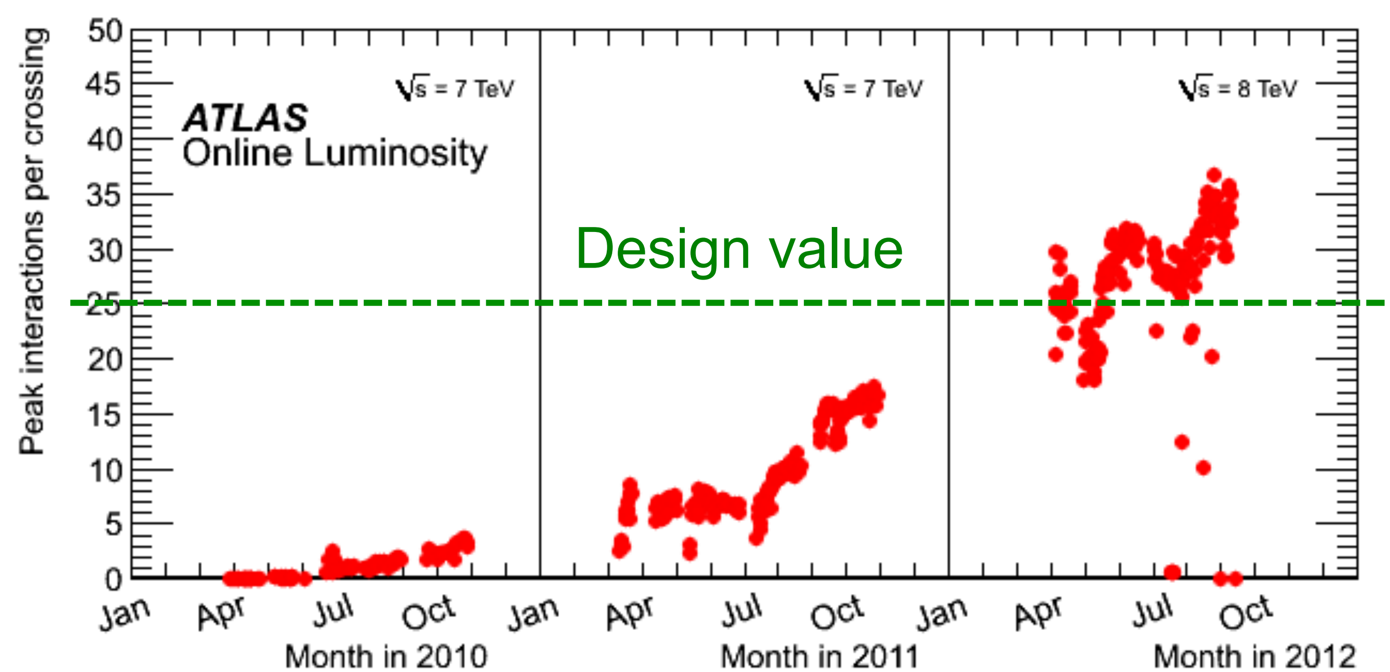
- October 2013: **Nobel prize** to Englert and Higgs

- **A new era of particle physics — measure the properties of the new particle**:
  - ★ mass, couplings and differential cross-sections, spin, CP, width ···



LHC and ATLAS

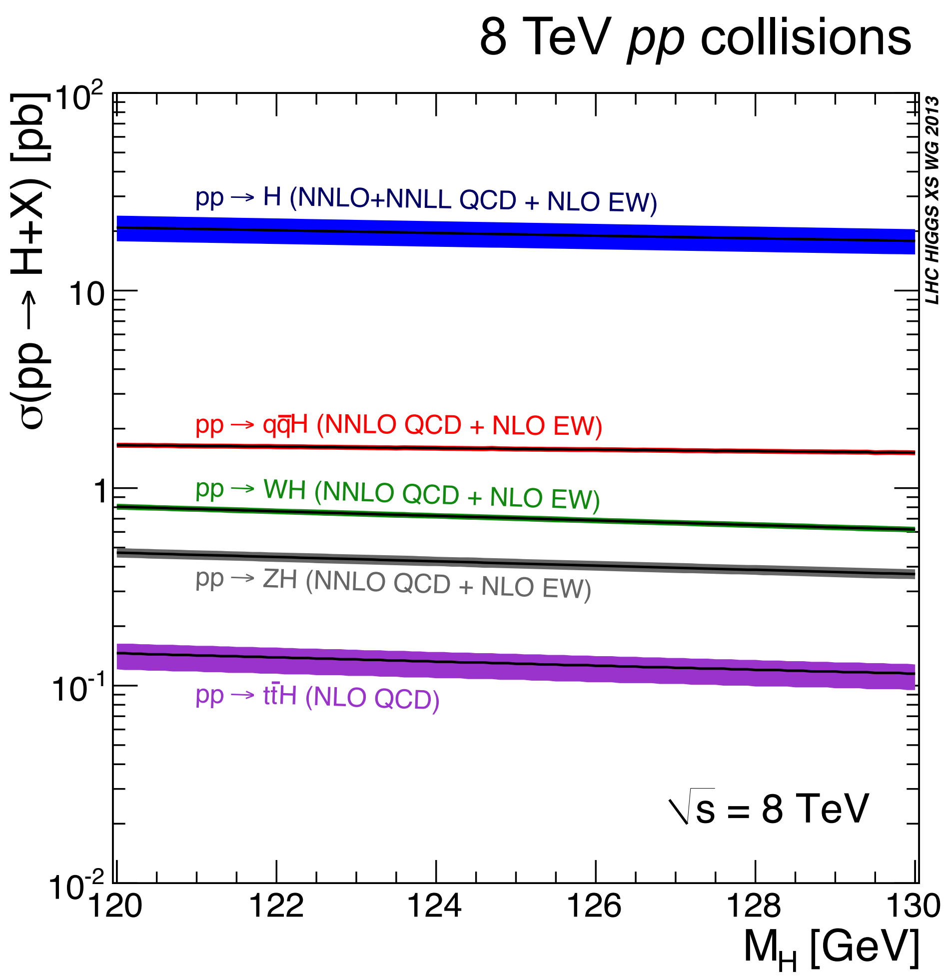


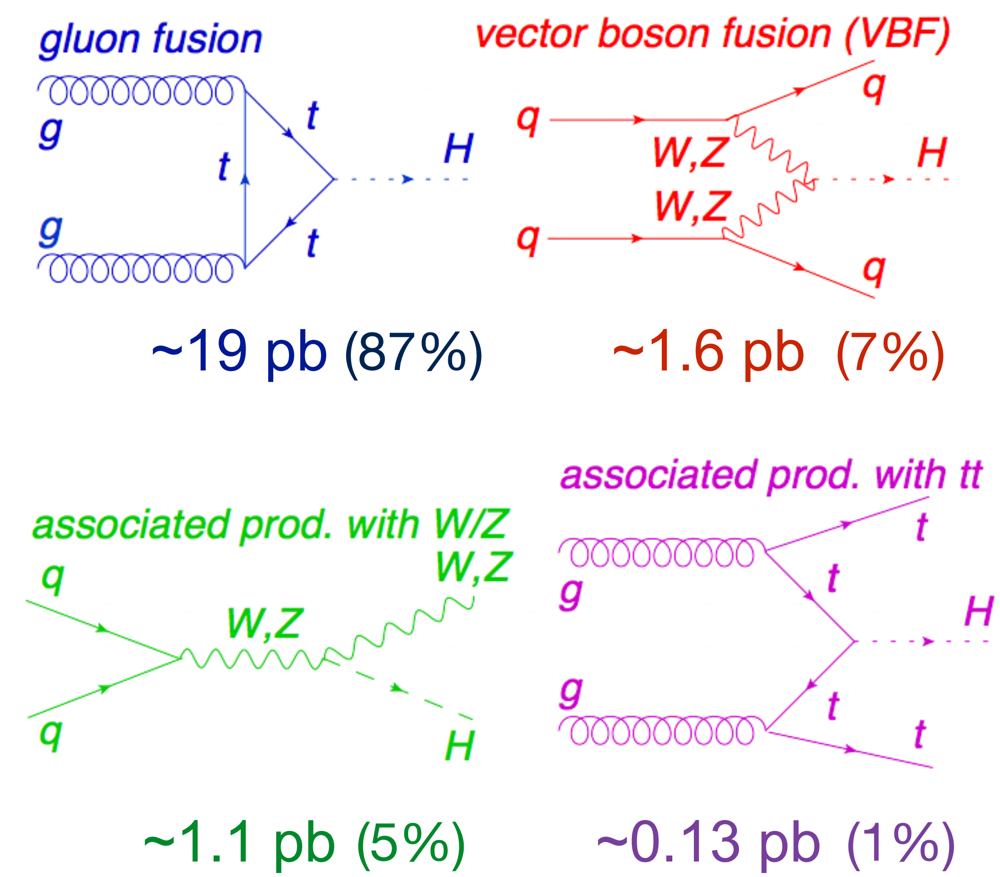


95%(90%) of recorded (delivered) luminosity was good for physics analysis

Challenges with high luminosity

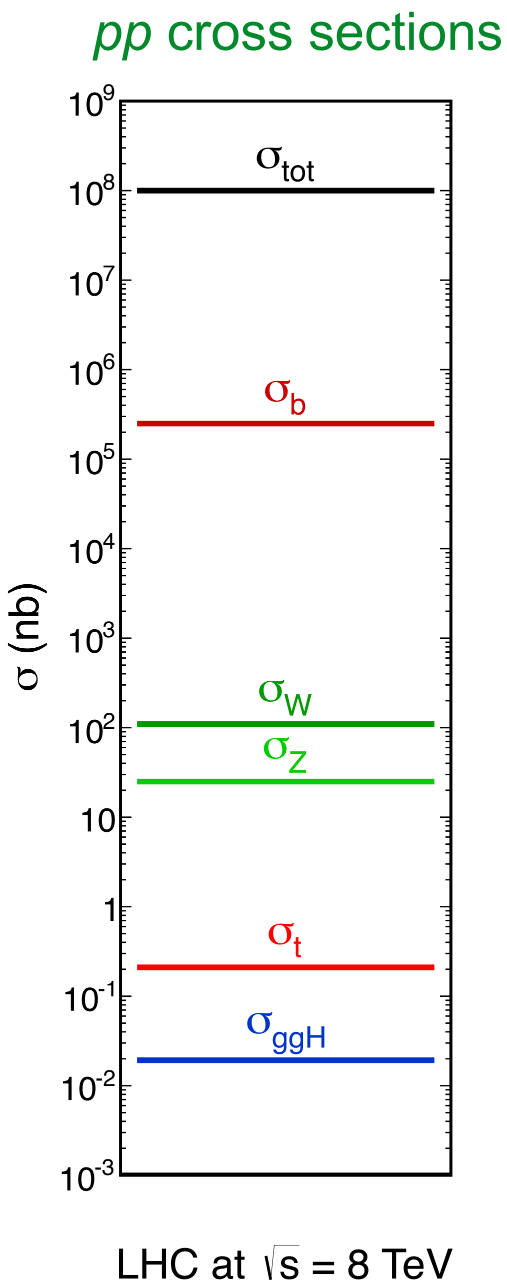
Higgs production at the LHC

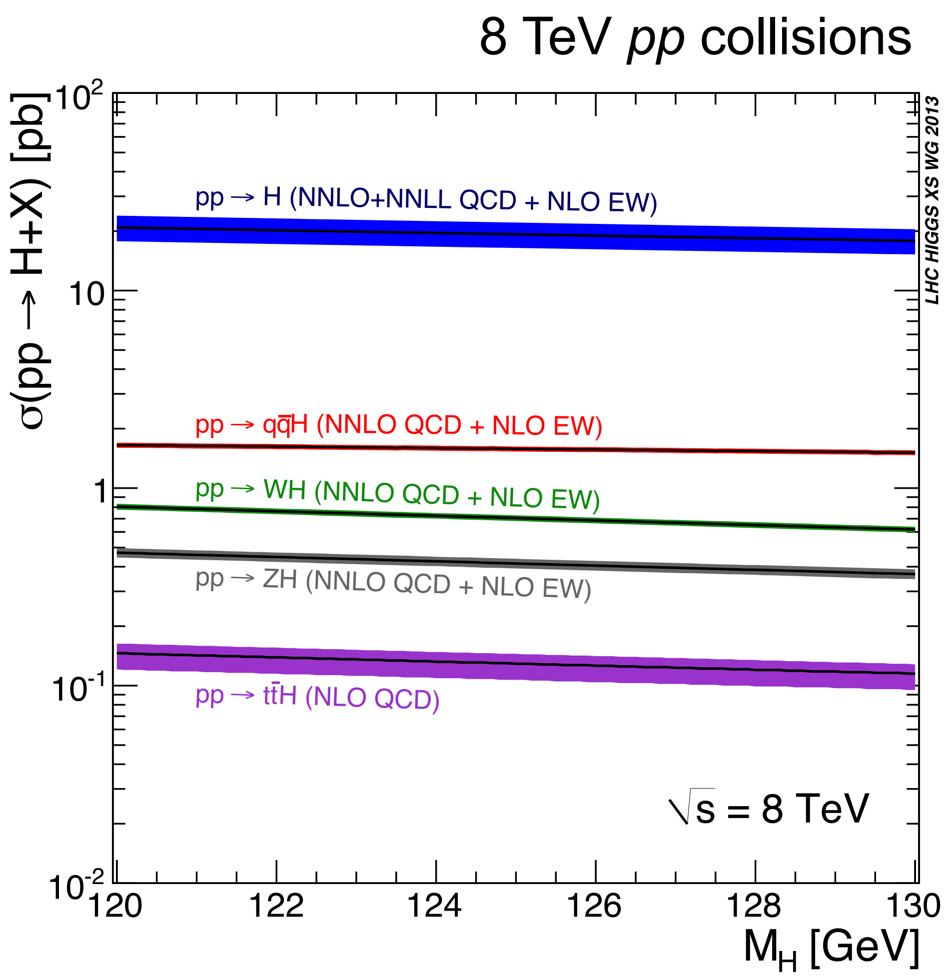


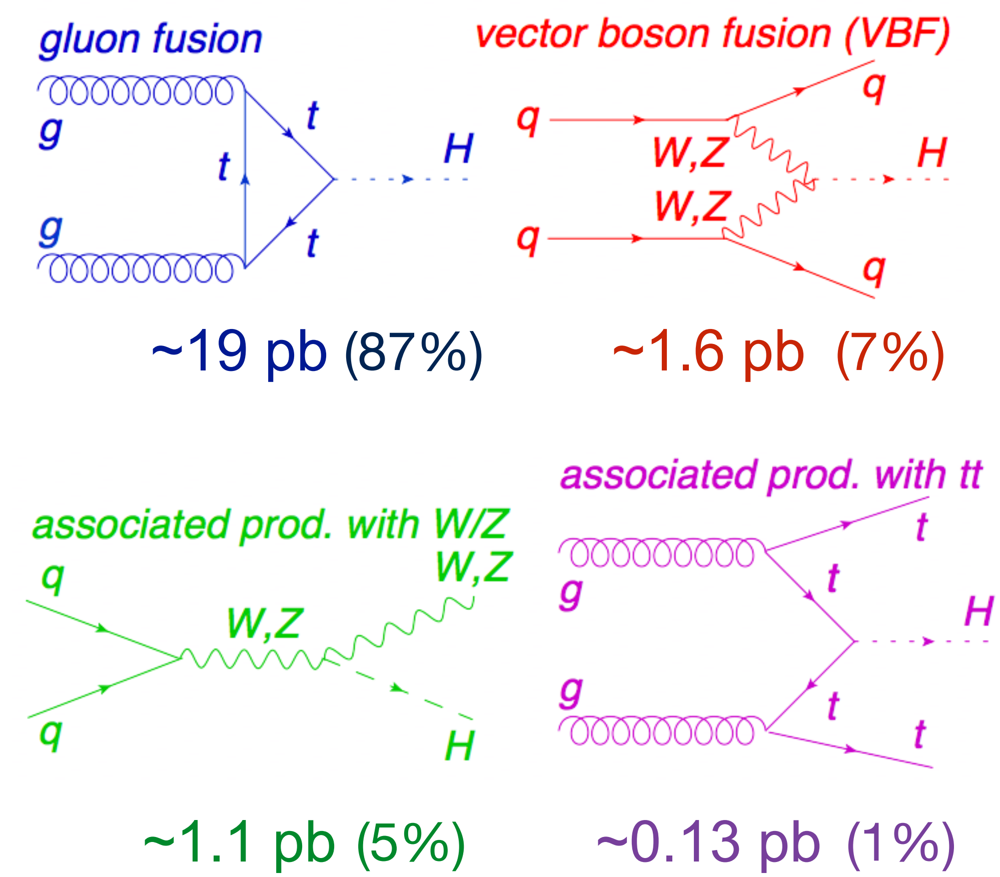


- ~500K Higgs bosons produced in the ATLAS detector

Higgs production at the LHC

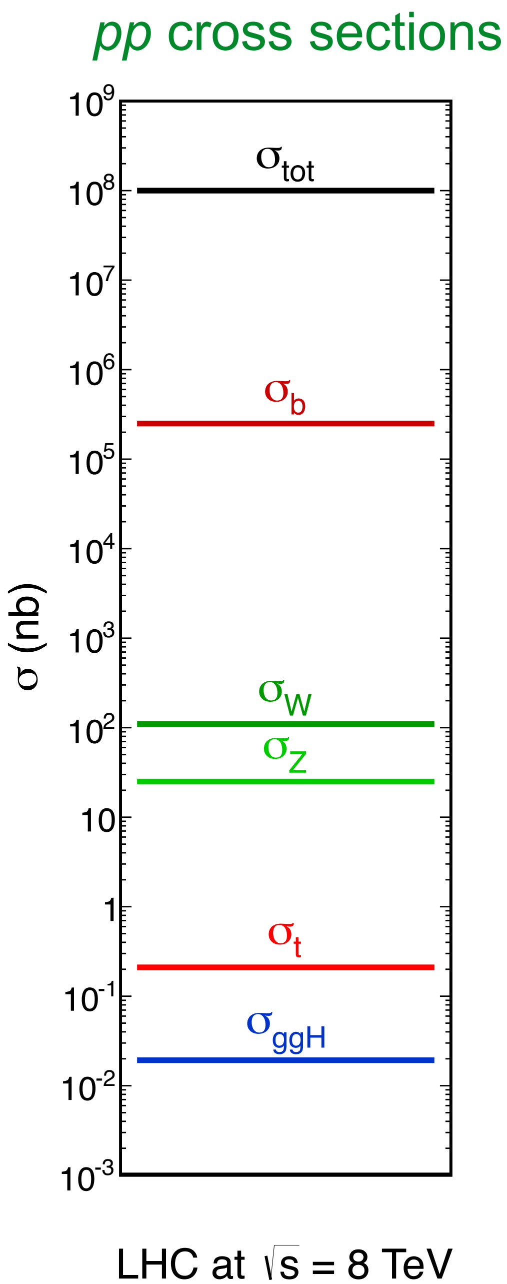






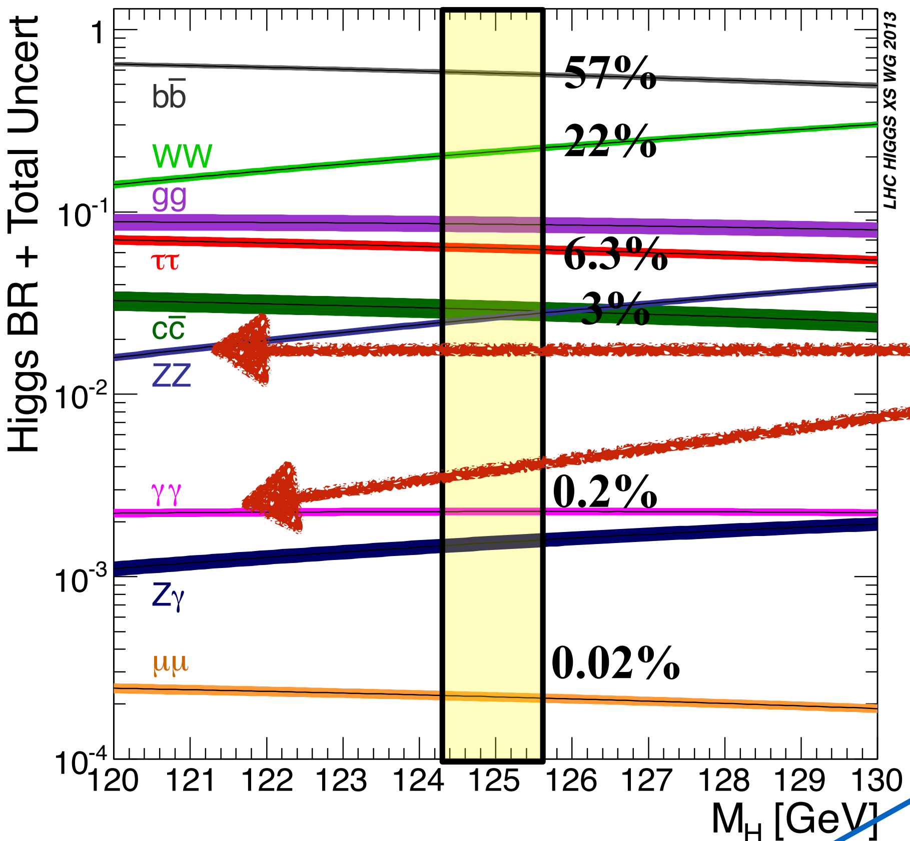
- ~500K Higgs bosons produced in the ATLAS detector
- **only one in ~10^{10} events will be a Higgs boson.**

Higgs production at the LHC



- ~500K Higgs bosons produced
- only one in ~10^{10} events will be a Higgs boson.

Higgs decays



Main discovery channels with excellent mass resolution

approximate event yield after selection

450 H→γγ
σ(m_H) ~ 1-2%
S/B ~ 3%

20 H→ZZ*(4l)
σ(m_H) ~ 1-2%
S/B ~ 1.6

500 H→WW*(2l2ν)
σ(m_T,H) ~ 20%
S/B ~ 15%

Higgs decays

$H \to \gamma\gamma$
exp. yield ~ 450
$\sigma(m_H)$ ~ 1-2%
S/B ~ 3%

$H \to ZZ^*(4l)$
exp. yield ~ 20
$\sigma(m_H)$ ~ 1-2%
S/B ~ 1.6

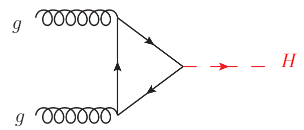
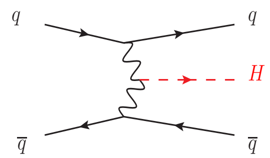
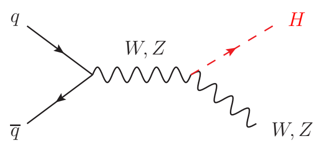
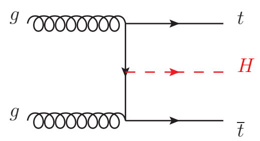
$H \to WW^*(2l2\nu)$
exp. yield ~ 500
$\sigma(m_{T,H})$ ~ 20%
S/B ~ 15%

$H \to \tau\tau$
exp. yield ~ 300
$\sigma(m_H)$ ~ 10-20%
S/B ~ 1-30%

$H \to bb$
exp. yield ~ 400
$\sigma(m_H)$ ~ 10-20%
S/B ~ 1-10%

Higgs field serves as the source of mass generation in the fermion sector through the Yukawa interaction.

Panorama of Higgs analysis

Channel	ggF 	VBF 	VH 	ttH 	Mass	CP	X-sec.	Width
$\gamma\gamma$	√	√	√	√	√	√	√	√
$ZZ^*(4l)$	√	√	√	√	√	√	√	√
$WW^*(l\nu l\nu)$	√	√	√	√		√	√	√
$\tau\tau$	√	√	√	√				
bb			√	√				
$Z\gamma$	√							
$\mu\mu$	√	√						
invisible	√	√	√					

❖ Experimental Strategy:

- ✦ **Investigate a large number of final states with dedicated event categories to separate different production modes (and to increase overall significance)**
- ✦ **Probe different kinds of the Higgs properties.**

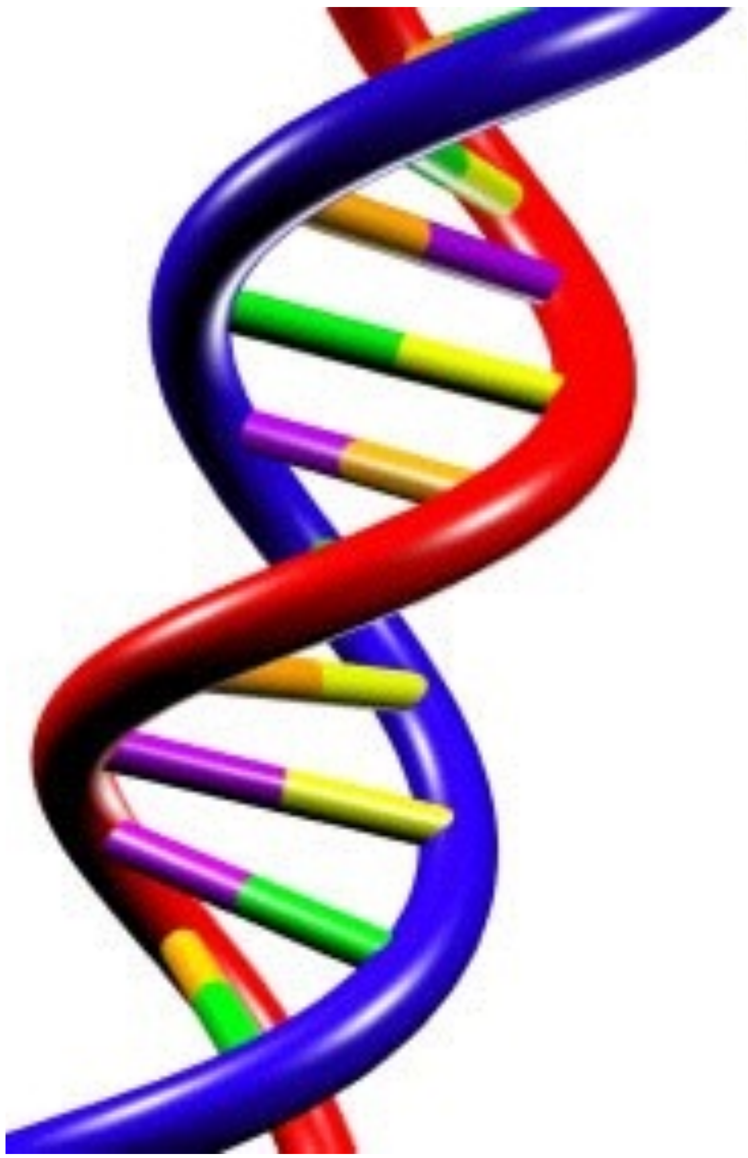
Higgs property measurement

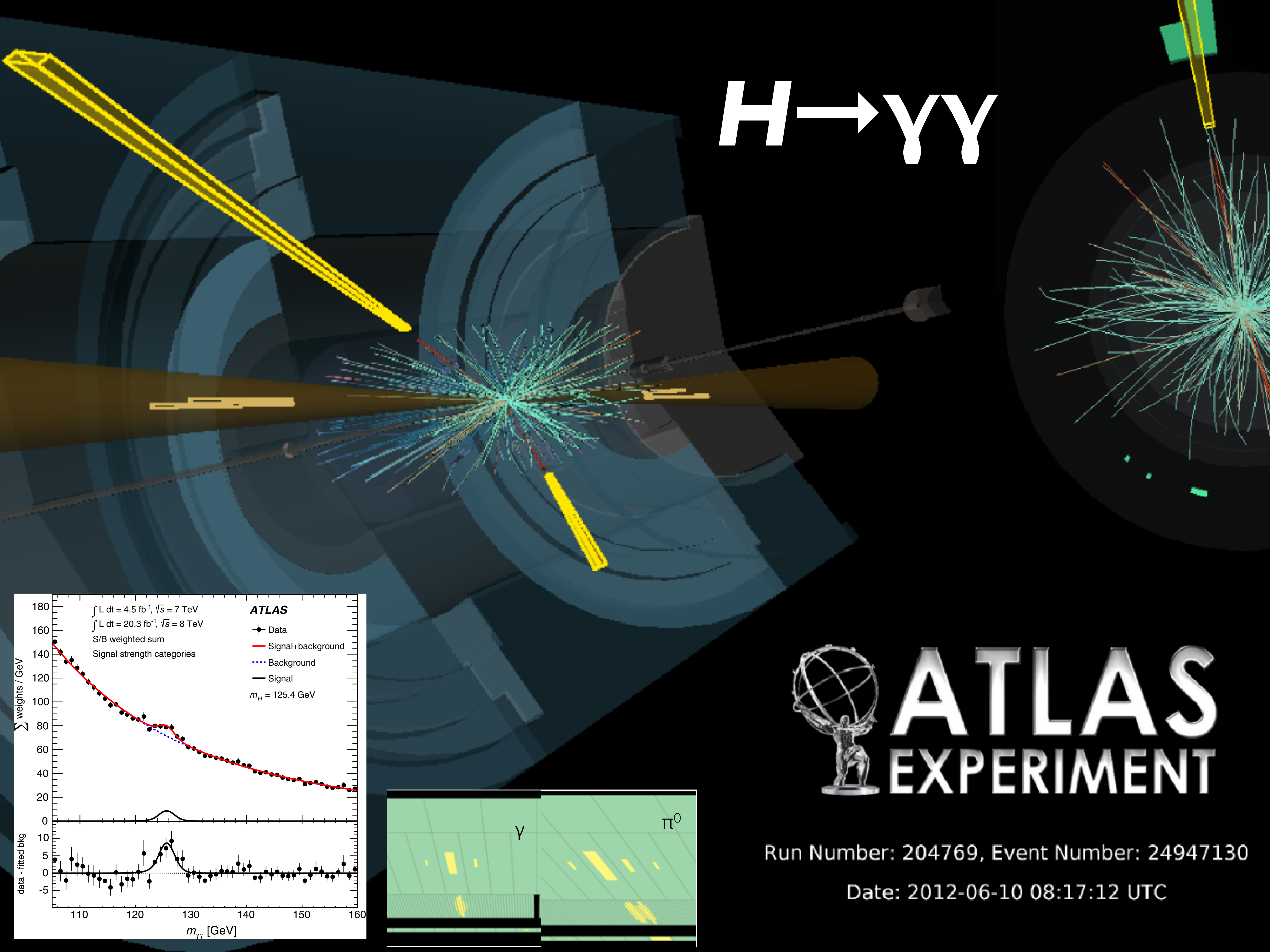
- ❖ Higgs Mass Measurement
- ❖ Coupling measurement
- ❖ Higgs invisible search
- ❖ Off-Shell behaviour
- ❖ Higgs Boson quantum numbers
- ❖ Fiducial and Differential cross section measurements

Higgs Mass Measurement

- The free and fundamental parameter of the SM Higgs sector

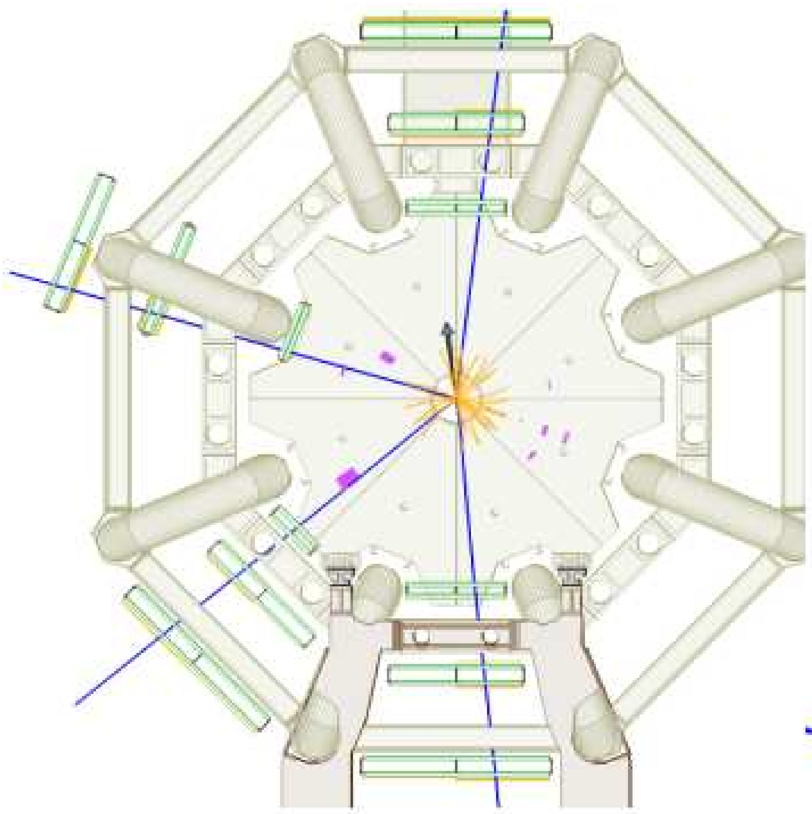
- Linked to Higgs properties, including the potential self-coupling.

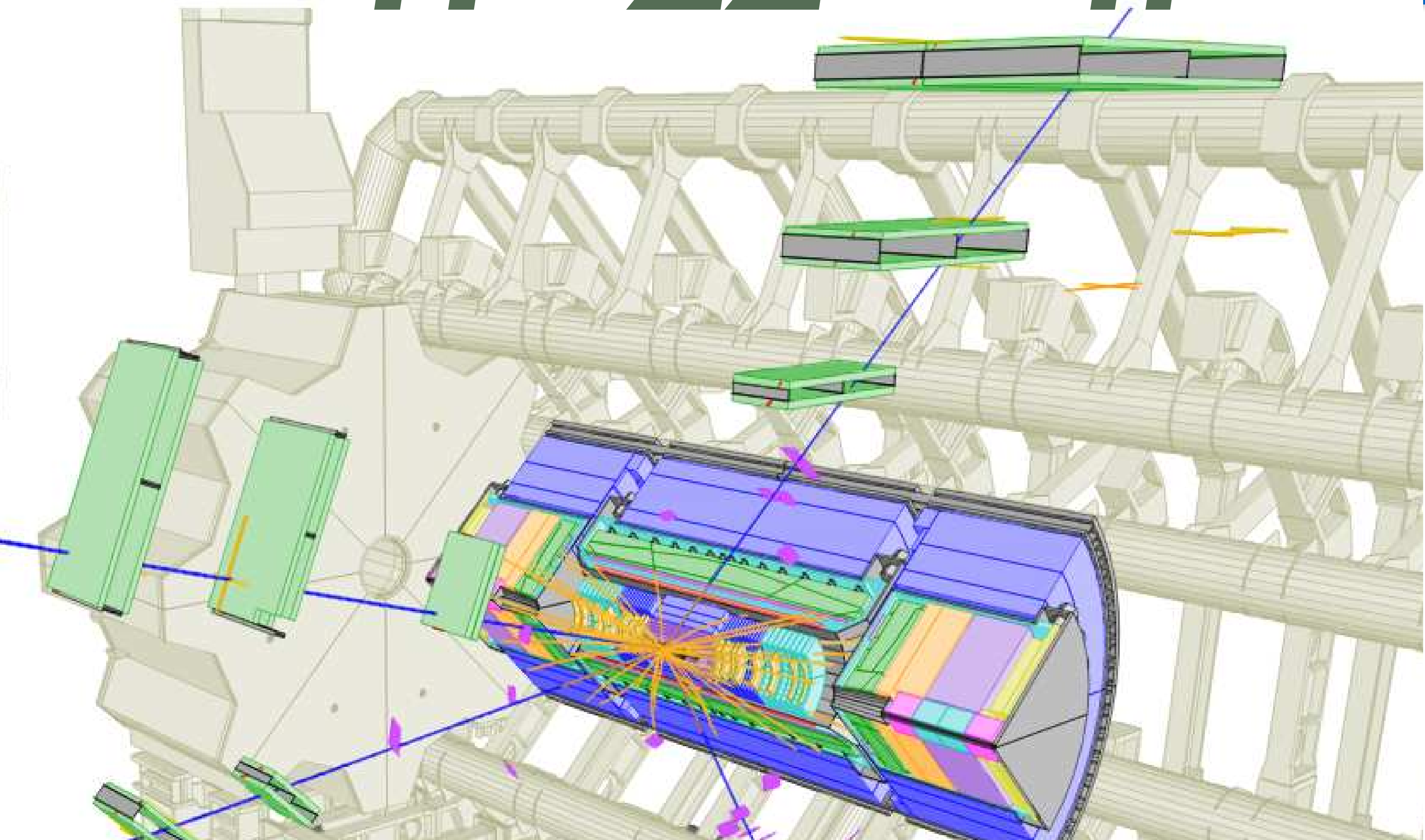




H→γγ
ATLAS EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC
∫L dt = 4.5 fb⁻¹, √s = 7 TeV
∫L dt = 20.3 fb⁻¹, √s = 8 TeV
S/B weighted sum
Signal strength categories
ATLAS
Data
Signal+background
Background
Signal
m_H = 125.4 GeV
∑ weights / GeV
data - fitted bkg
m_γγ [GeV]
γ
π⁰

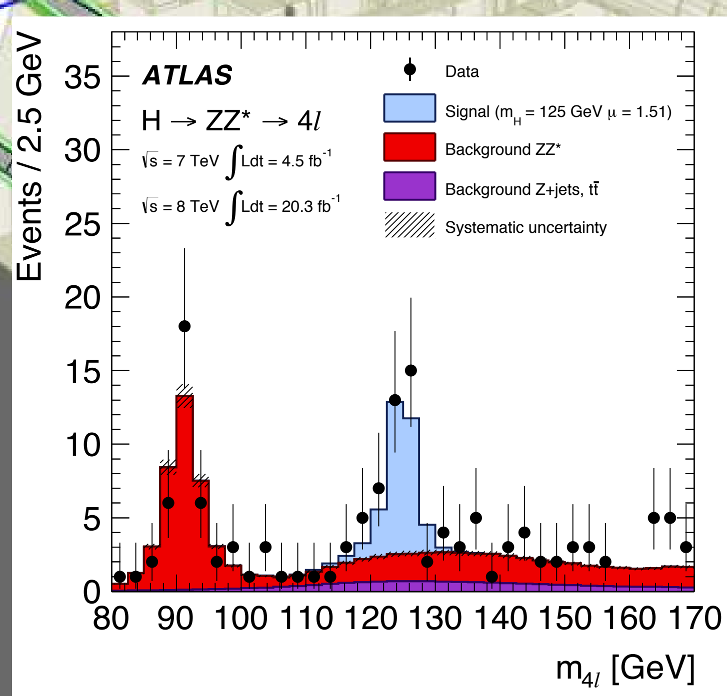
$H \to ZZ^* \to 4l$

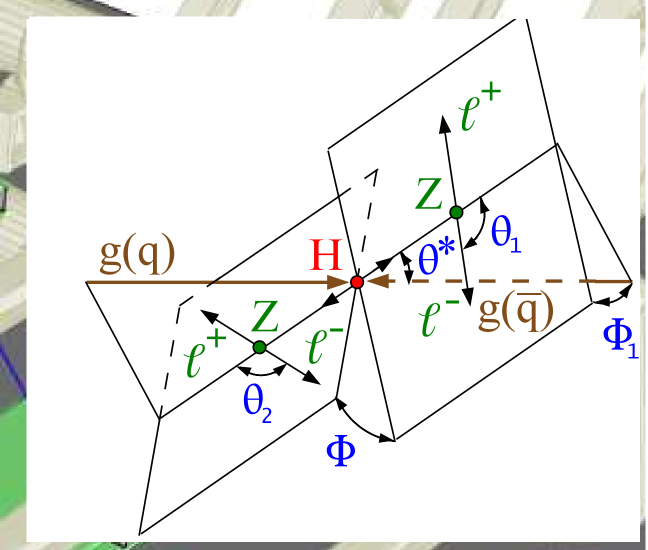




Run Number: 204769
Event Number: 82599793
Date: 2012-06-10, 13:12:52 CET

H –> ZZ* –> 4μ

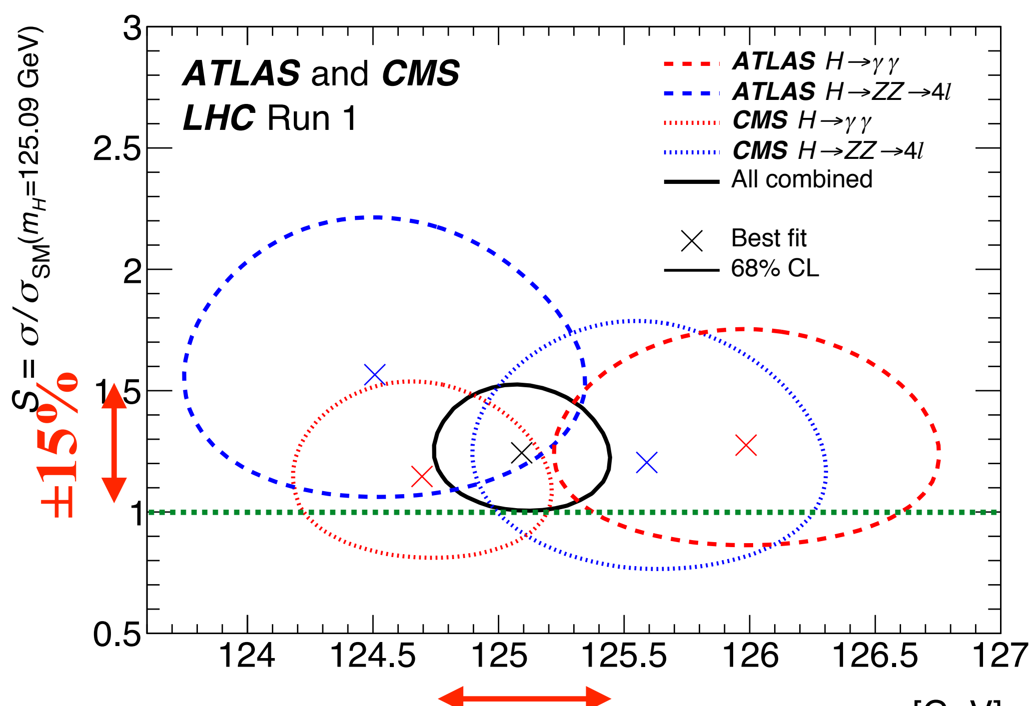


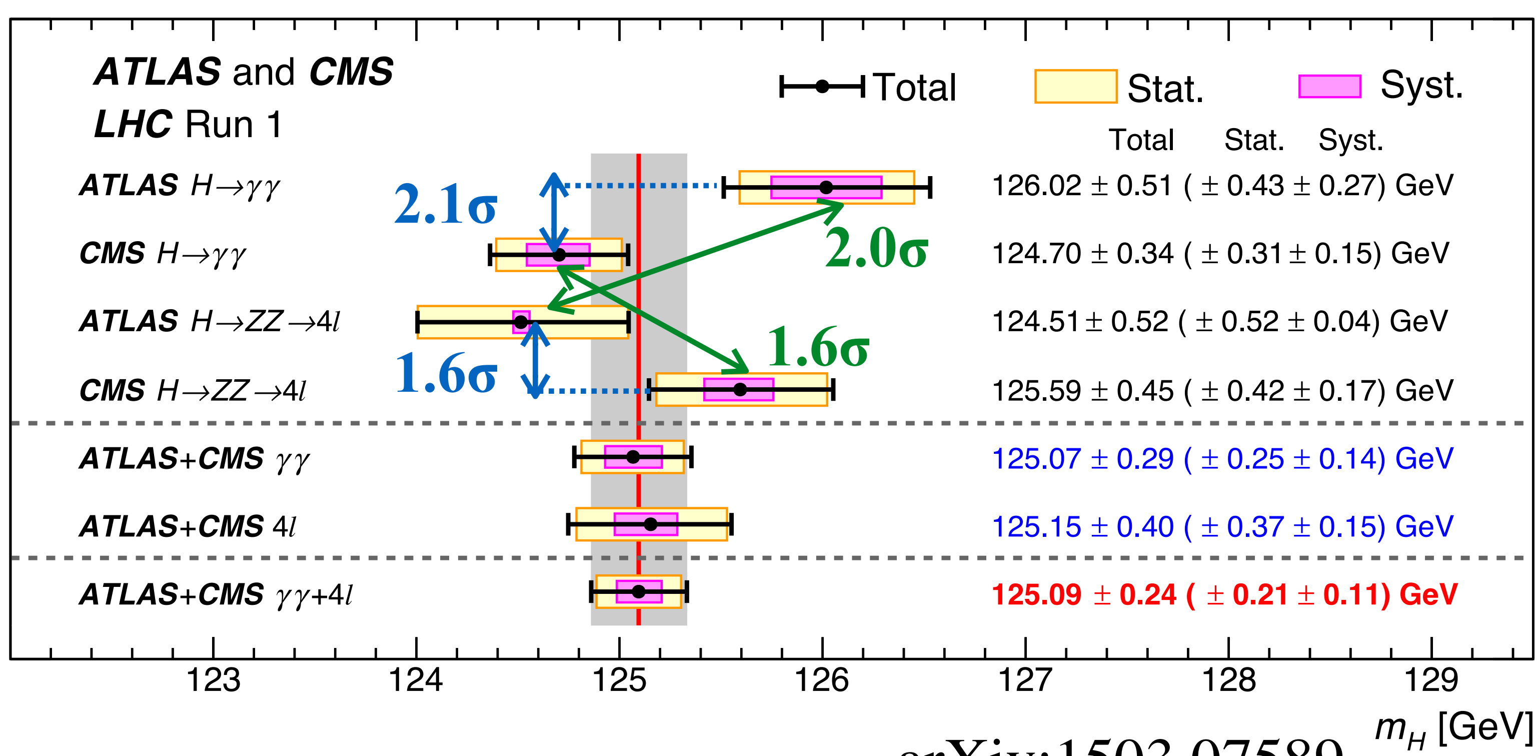


Higgs Mass

- Statistics dominated measurement.
- Systematic uncertainties dominated by energy/momentum calibration of photons (H→γγ) and electrons/muons(H→ZZ*(4l))
- Compatibility of the four measurement masses O(10%)
- Individual measurement compatible with ~2σ

First ATLAS and CMS Combination: m_H=125.09±0.21(stat.)± 0.11(sys.)GeV





arXiv:1503.07589

Higgs Boson Couplings

- **Predicted for all SM particles for a given Higgs mass.**
- **Determine Higgs boson phenomenology & experimental signatures.**
- **Sensitive to BSM phenomena coupling to Higgs sector.**

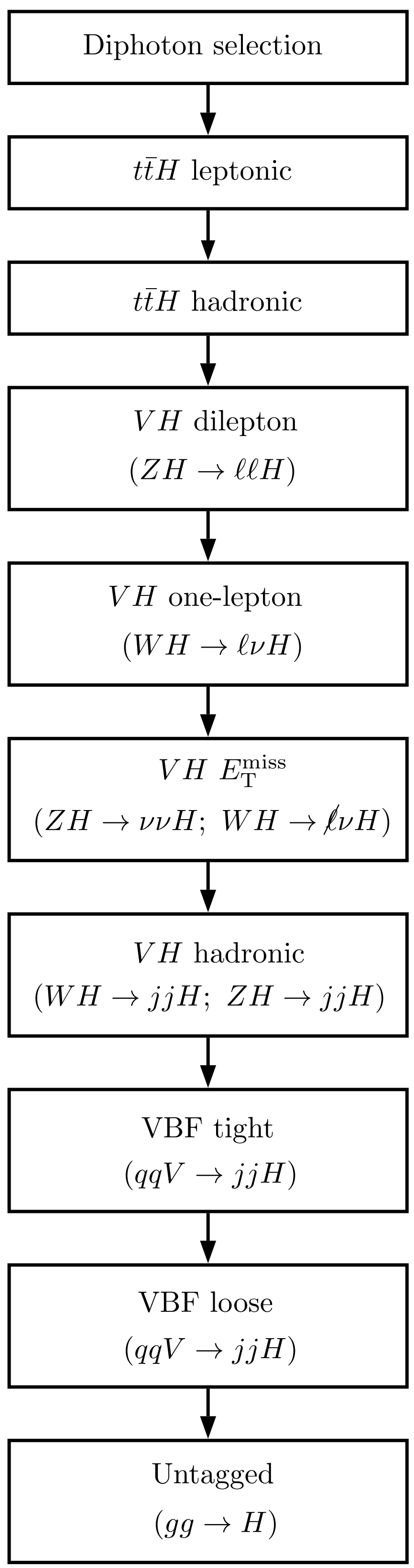
❖ **A straightforward consistency/deviation strategy is based on signal strength measurements in different production and decay modes:**

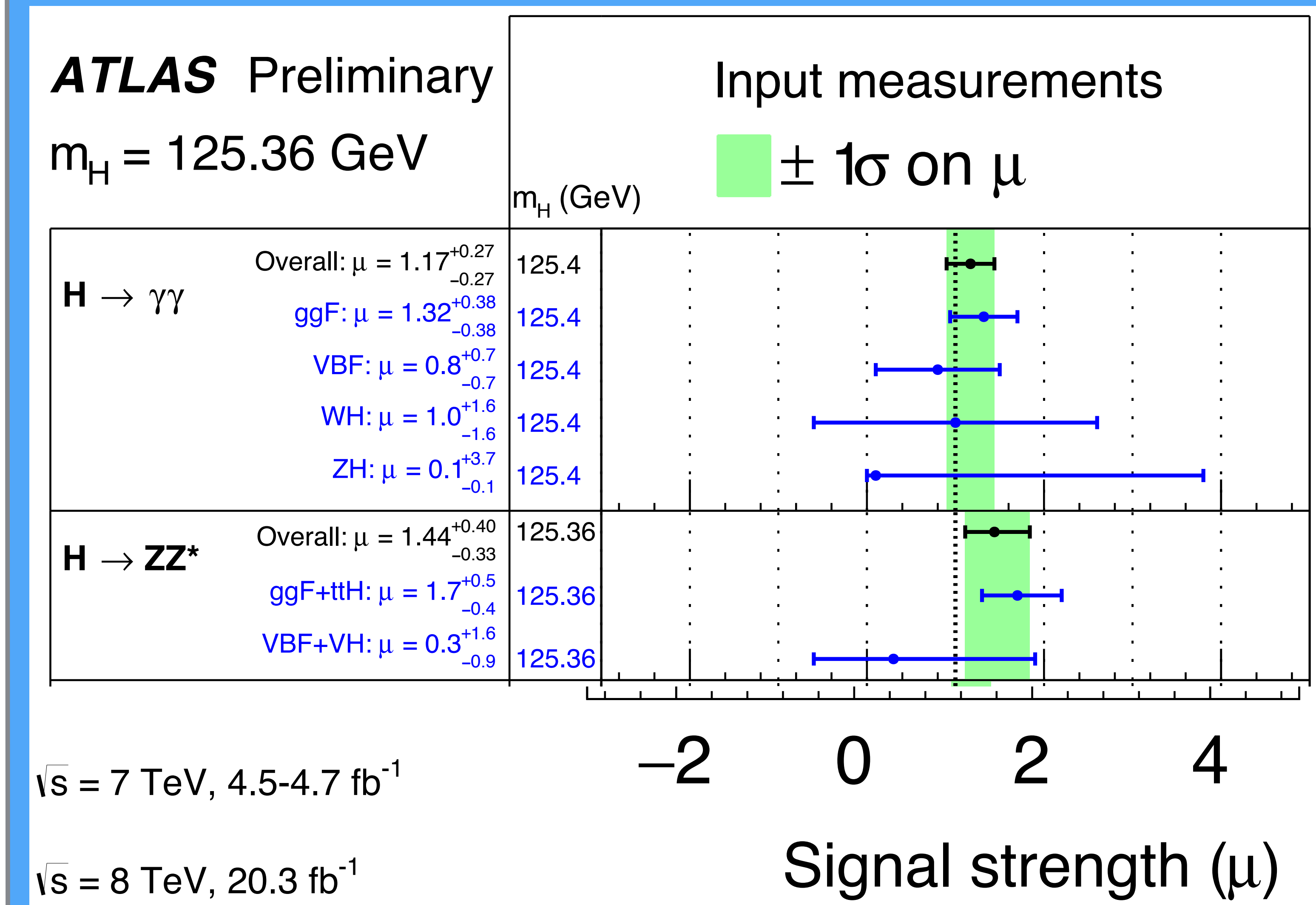
- The signal strength (μ) is defined as the ratio between the measured Higgs yield and the SM prediction.

$$\mu = \frac{N^{measured}}{N^{\mathrm{SM}}} = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

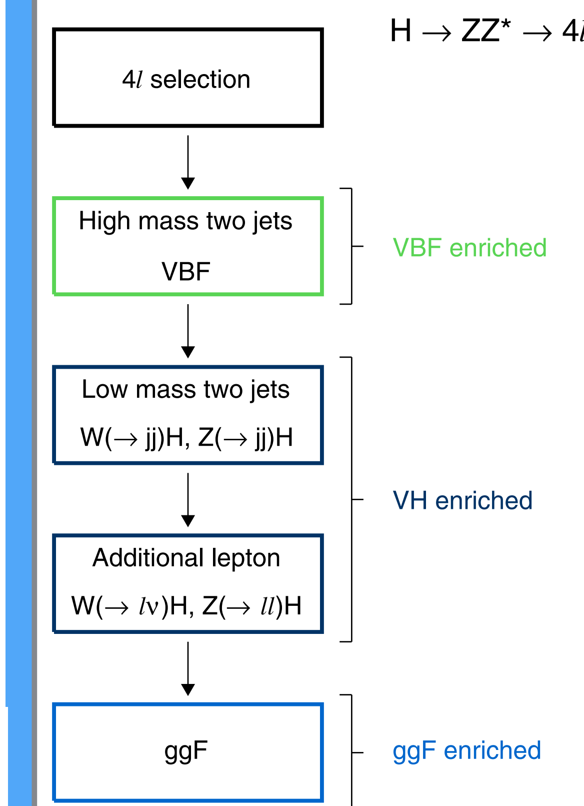
H→γγ and H→ZZ*(4l)

PRD 90(2014) 112015



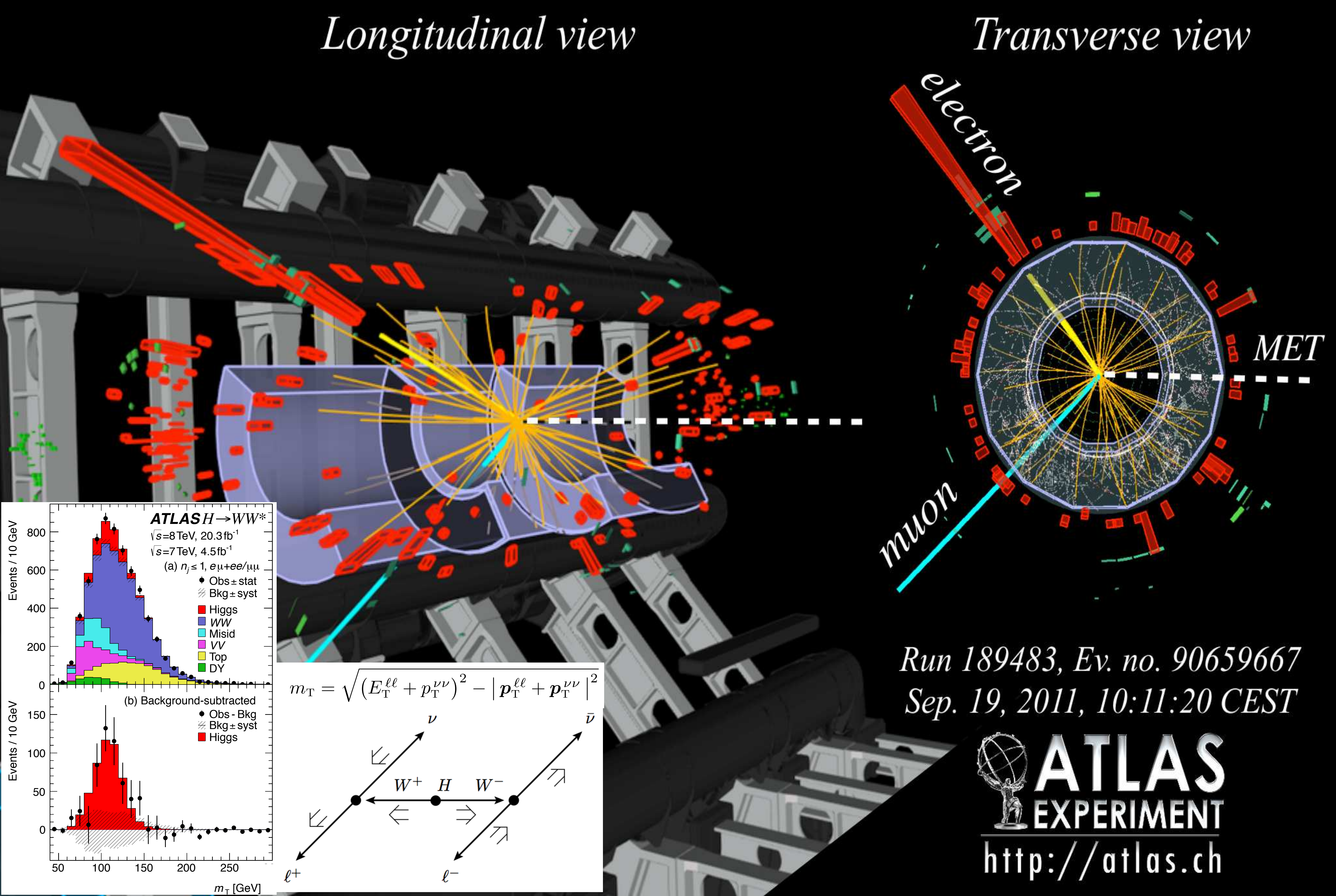


PRD 91(2015) 012006



	obs.(exp.) Significance
H→γγ	5.2σ(4.6σ)
H→ZZ*(4l)	8.1σ(6.2σ)

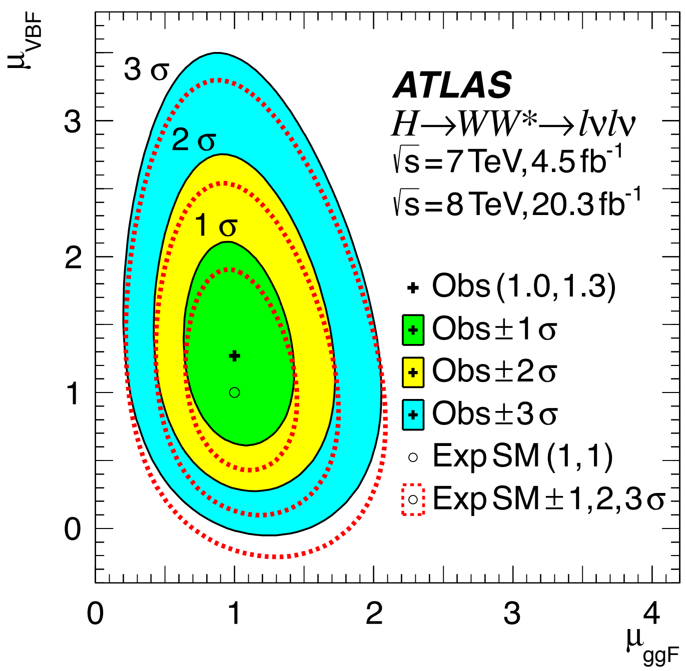
$H \to WW^* \to e\nu\mu\nu$ candidate and no jets



H→WW*(2l2ν)

- obs.(exp.) significance: 6.1σ(5.8σ)
- **Evidence for VBF** with obs.(exp.) significance of 3.2σ(2.7σ): Crucial to measure *VH* couplings in tree level processes
- Systematic (in particular theoretical uncertainty) play a very important role
  - N-jet categorization and VBF total cross section

arxiv:1412.2641



Source	Observed $\mu = 1.09$ Error +	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Experimental systematics	0.07	0.06	
Integrated luminosity	0.03	0.03	
Total	0.23	0.21	

-30 -15 0 15 30

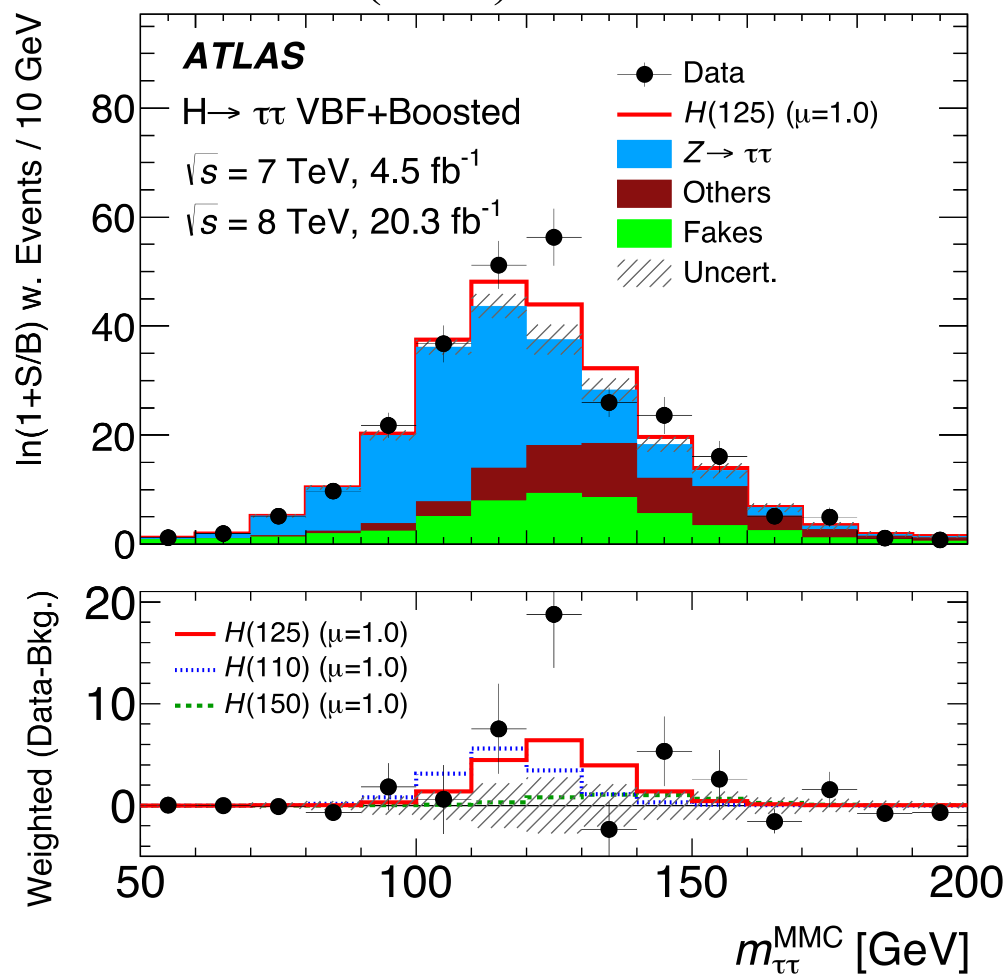
$$\mu = 1.09^{+0.23}_{-0.21} = 1.09^{+0.16}_{-0.15}(\text{stat.})^{+0.17}_{-0.14}(\text{syst.})$$

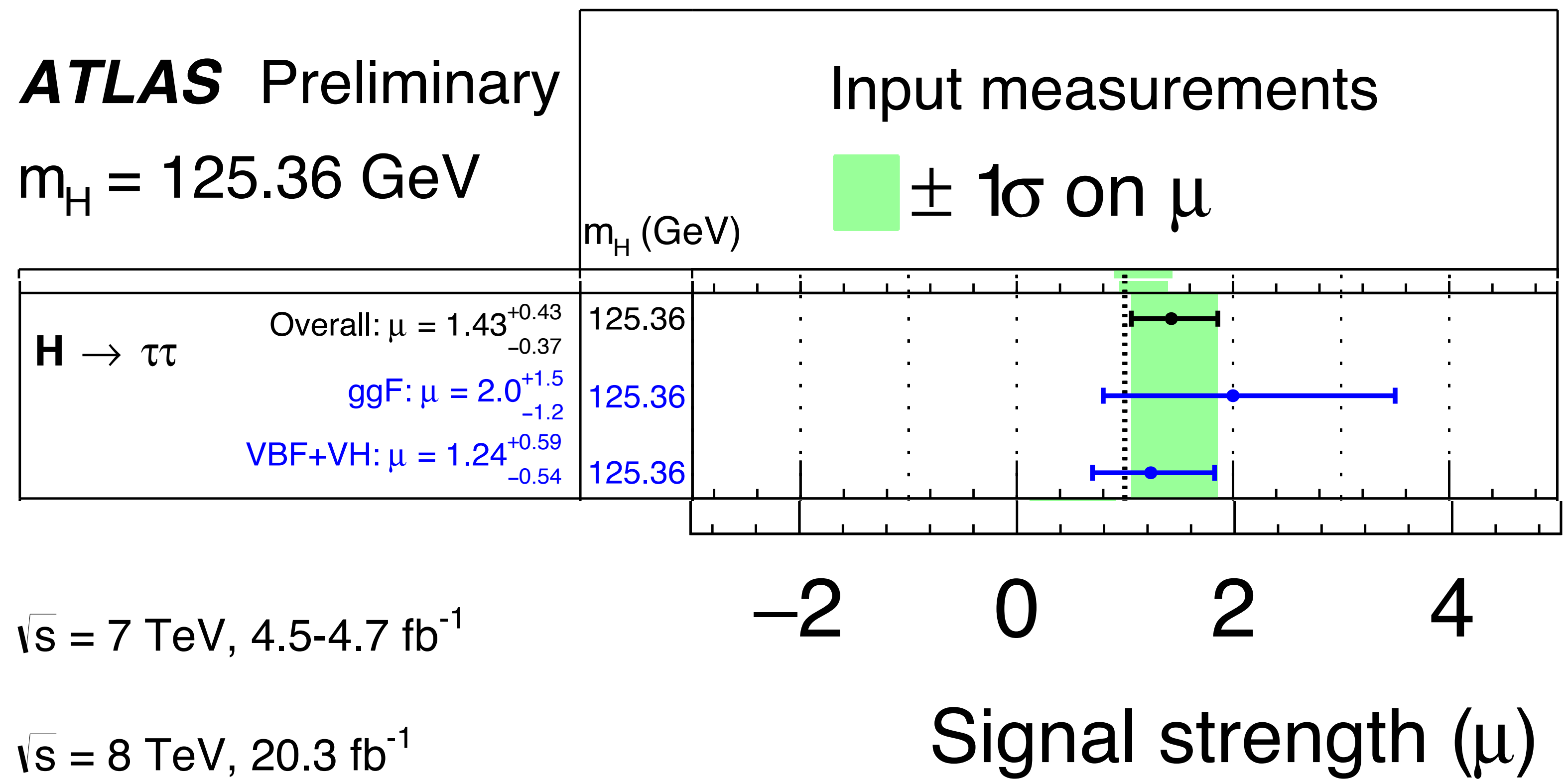
$$\mu_{ggF} = 1.02^{+0.29}_{-0.26} = 1.02 \pm 0.19(\text{stat.})^{+0.22}_{-0.18}(\text{syst.})$$

$$\mu_{VBF} = 1.27^{+0.53}_{-0.45} = 1.27^{+0.44}_{-0.40}(\text{stat.})^{+0.30}_{-0.21}(\text{syst.})$$

H→ττ

JHEP 04(2015) 117

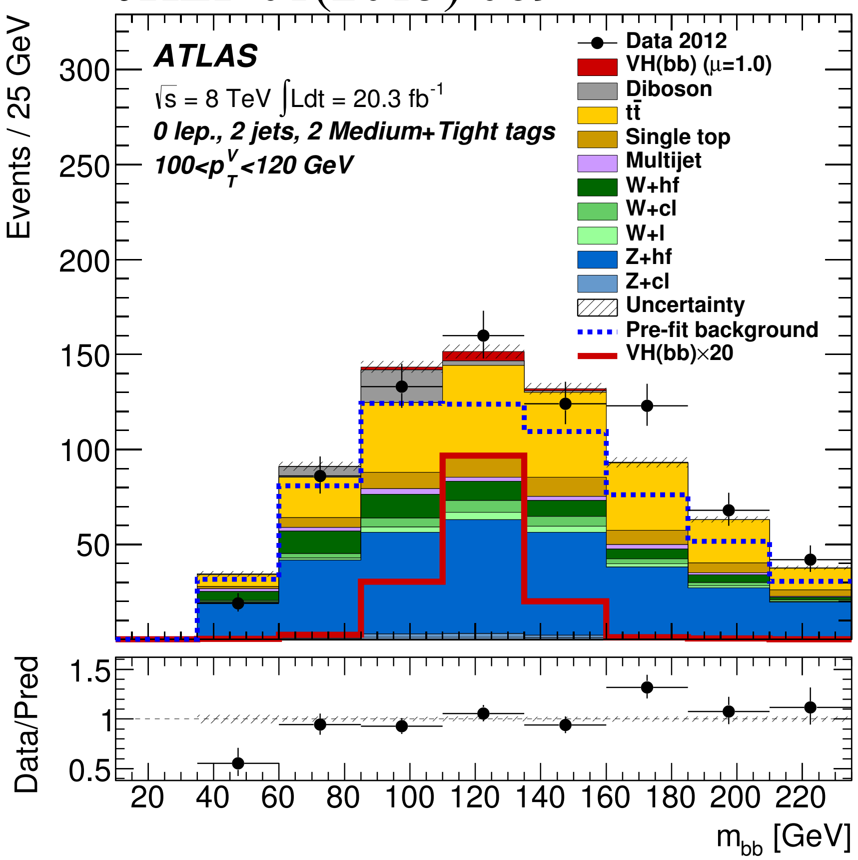


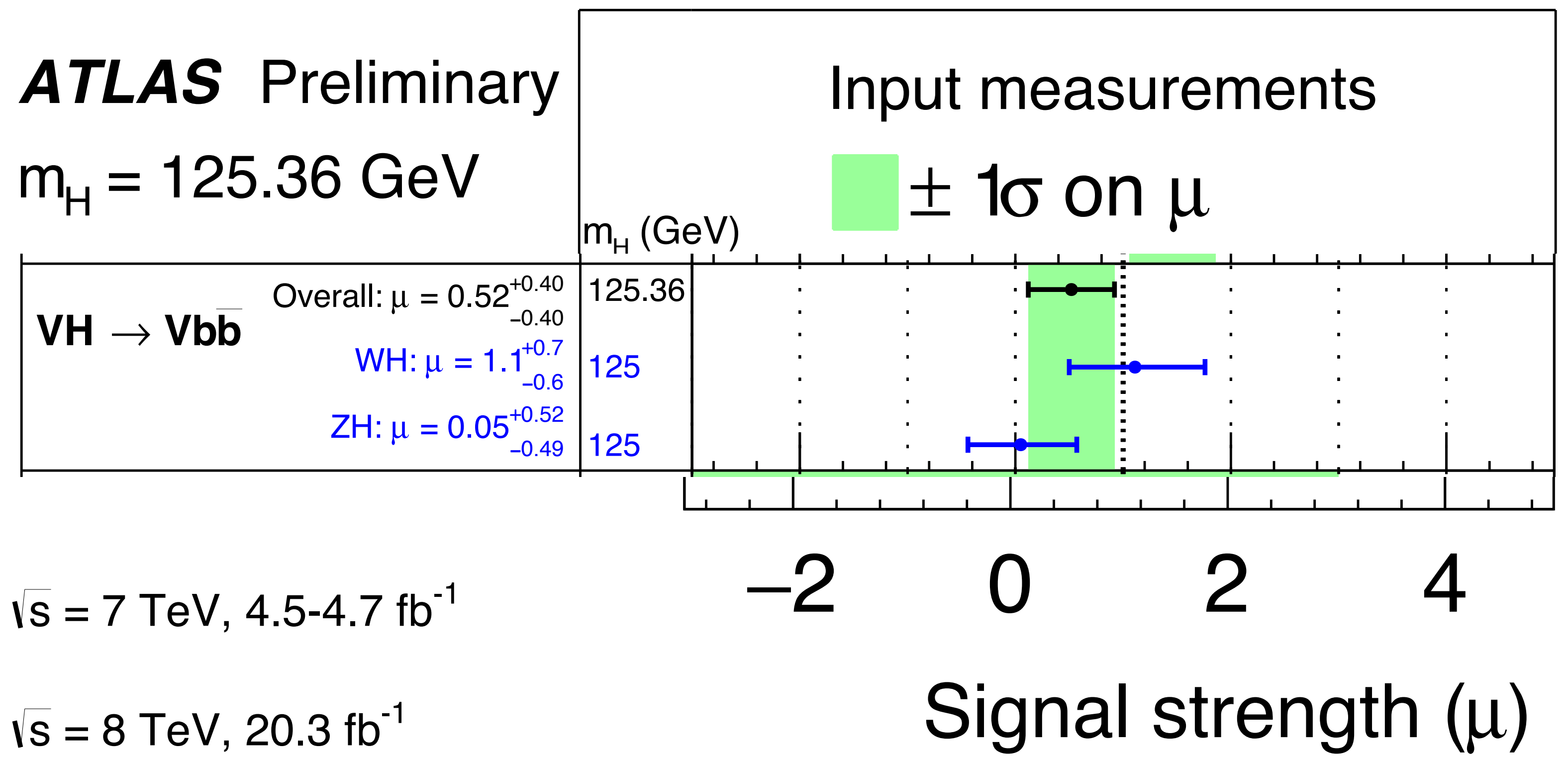


- **H→ττ:** include all τ decays
  - obs.(exp.) significance: 4.5σ(3.4σ)
  - **Evidence for Higgs-Yukawa coupling** as predicted in the SM.

H→bb

JHEP 01(2015) 069





- **H→bb:** due to overwhelming multi-jet backgrounds, need additional signature from exclusive production modes.
  - Signal: (W/Z)H with H→bb and V leptonic decay.
  - obs.(exp.) significance: 1.4σ(2.6σ)

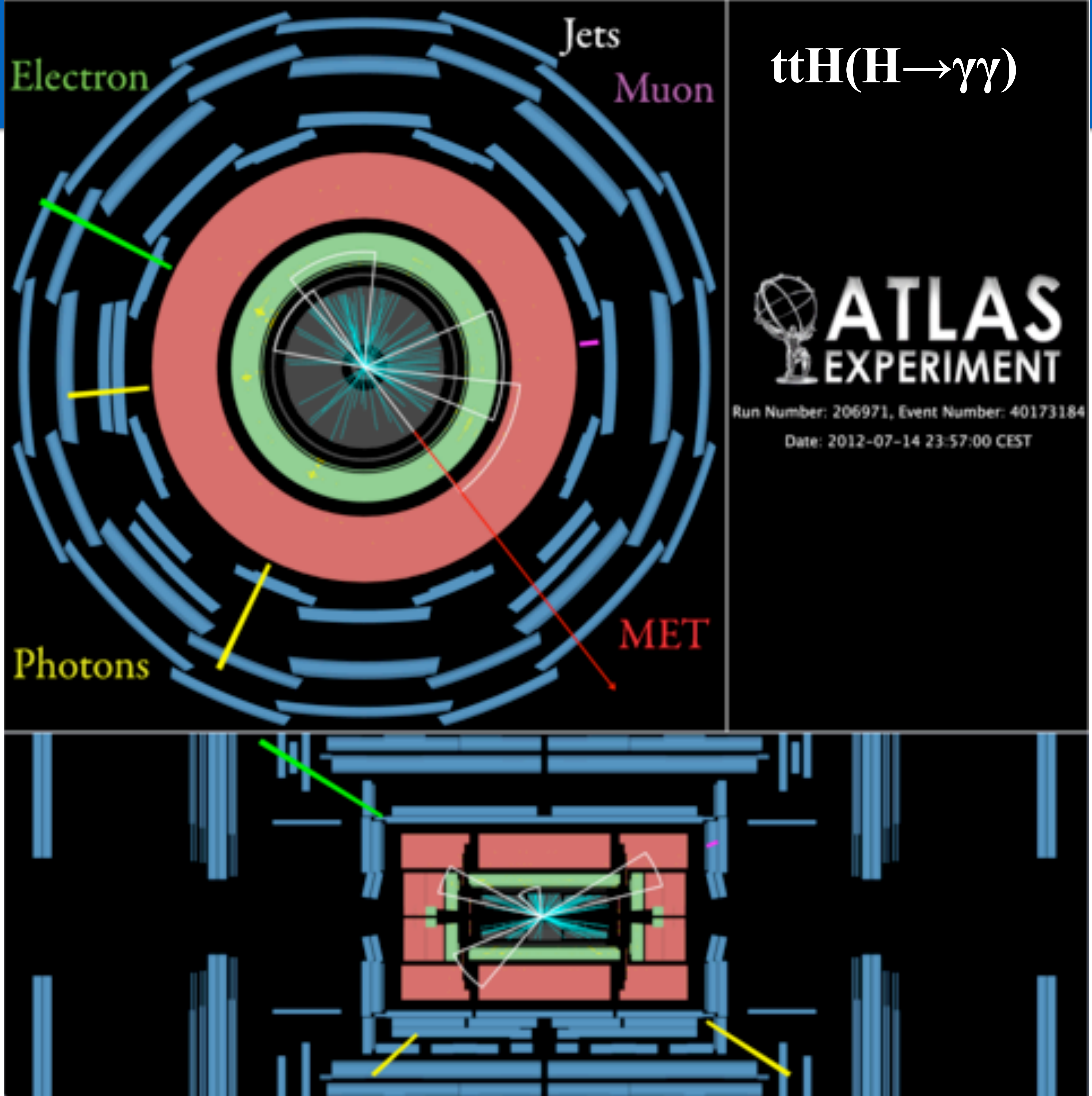
Searches for Rare Higgs Boson Production & Decays

❖ Searches for rare production modes

- ttH (direct access to top-Higgs Yukawa coupling)

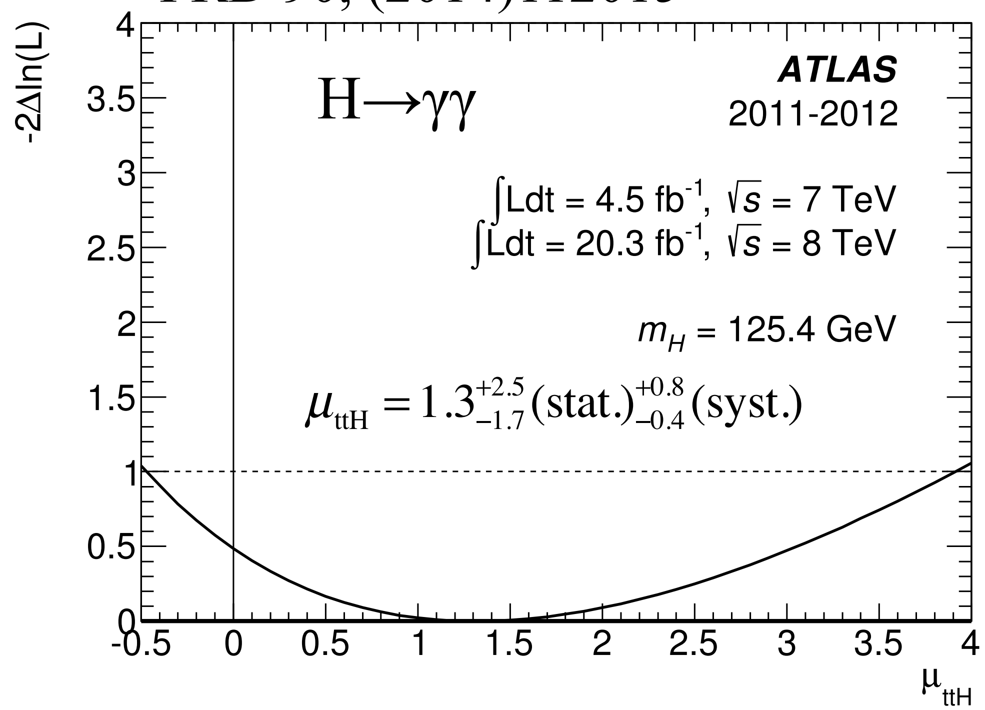
❖ Searches for rare SM decays

- $H \to \mu\mu$ (probe 2nd generation lepton coupling)
- $H \to Z\gamma$ (probe loop decay)

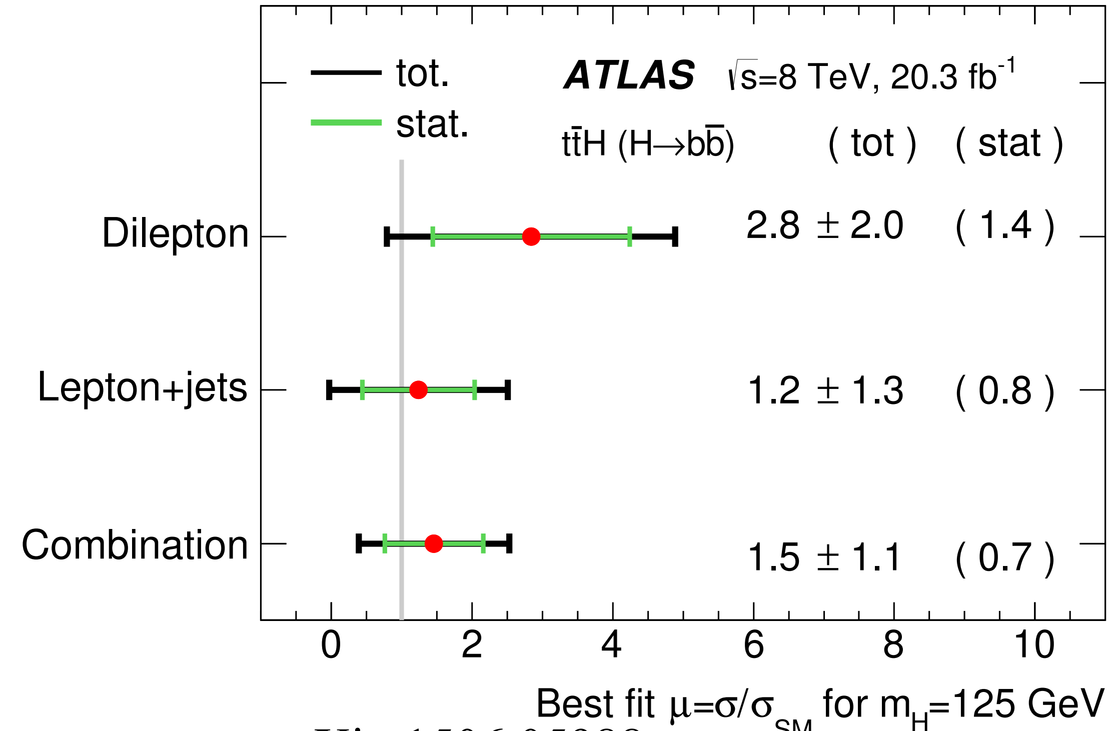

ttH(H→γγ)
Electron
Jets
Muon
Photons
MET
ATLAS EXPERIMENT
Run Number: 206971, Event Number: 40173184
Date: 2012-07-14 23:57:00 CEST

ttH Searches

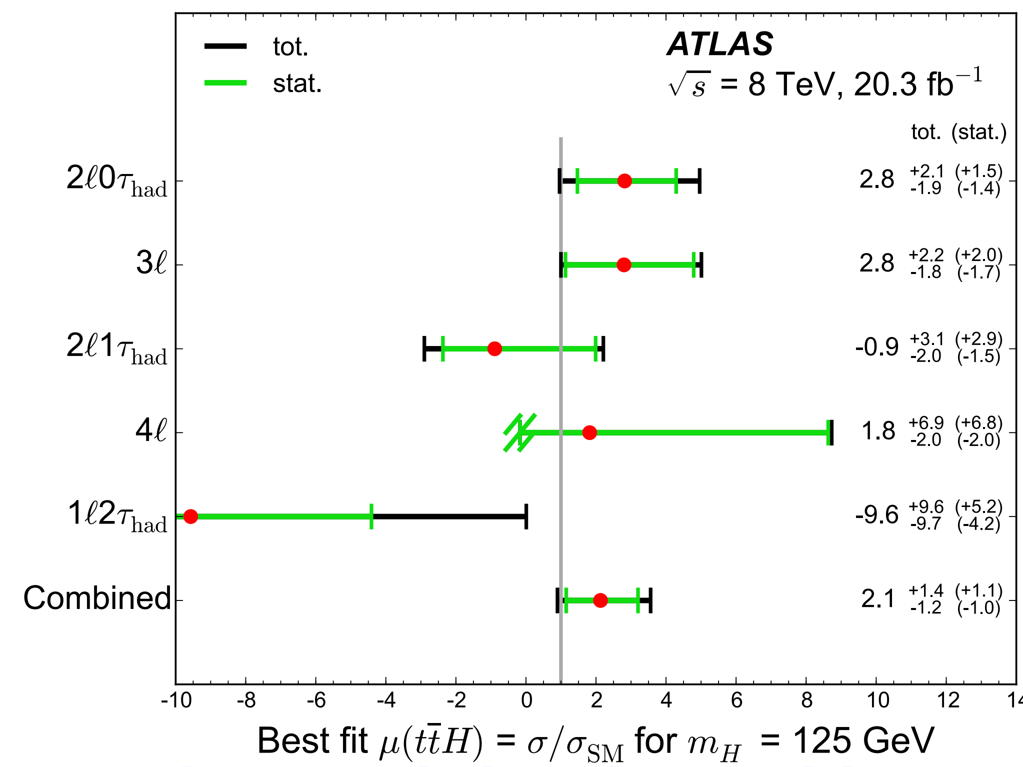
PRD 90, (2014)112015



arXiv:1503.05066



arXiv:1506.05988

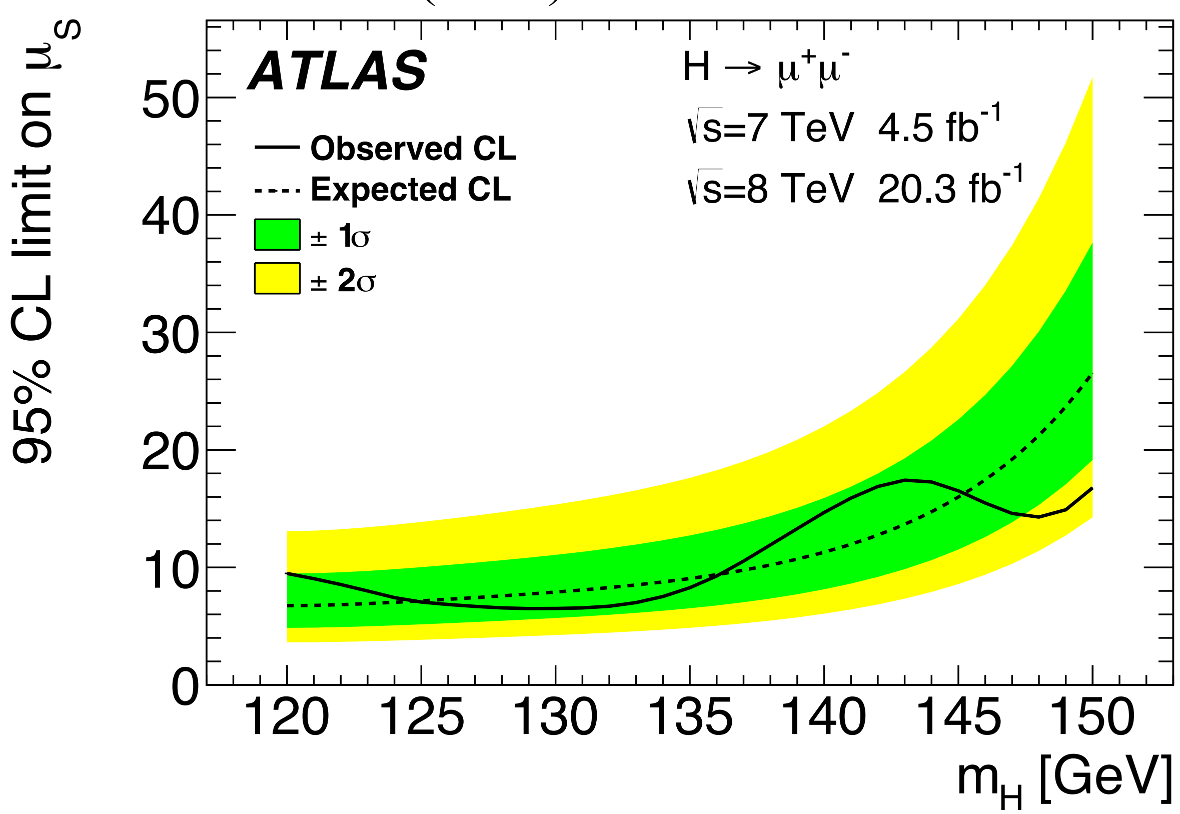


95% CL upper limit on signal strength (μ)		
	observed	expected
ttH(γγ)	5.6	4.9
ttH(bb)	3.4	2.2
ttH(multi-lepton)	4.7	2.4

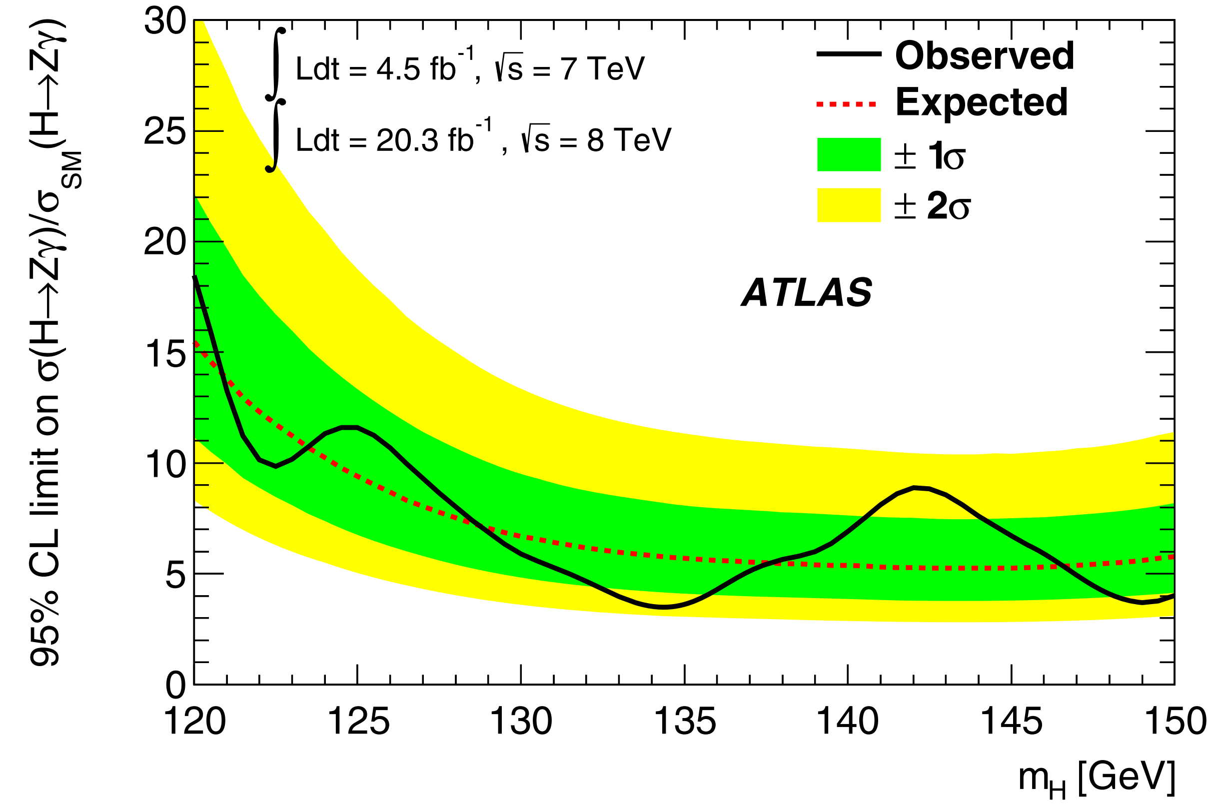
The results are compatible with the SM expectation and dominated by statistical uncertainties.

H→μμ and H→Zγ Searches

PLB 738 (2014) 68-86



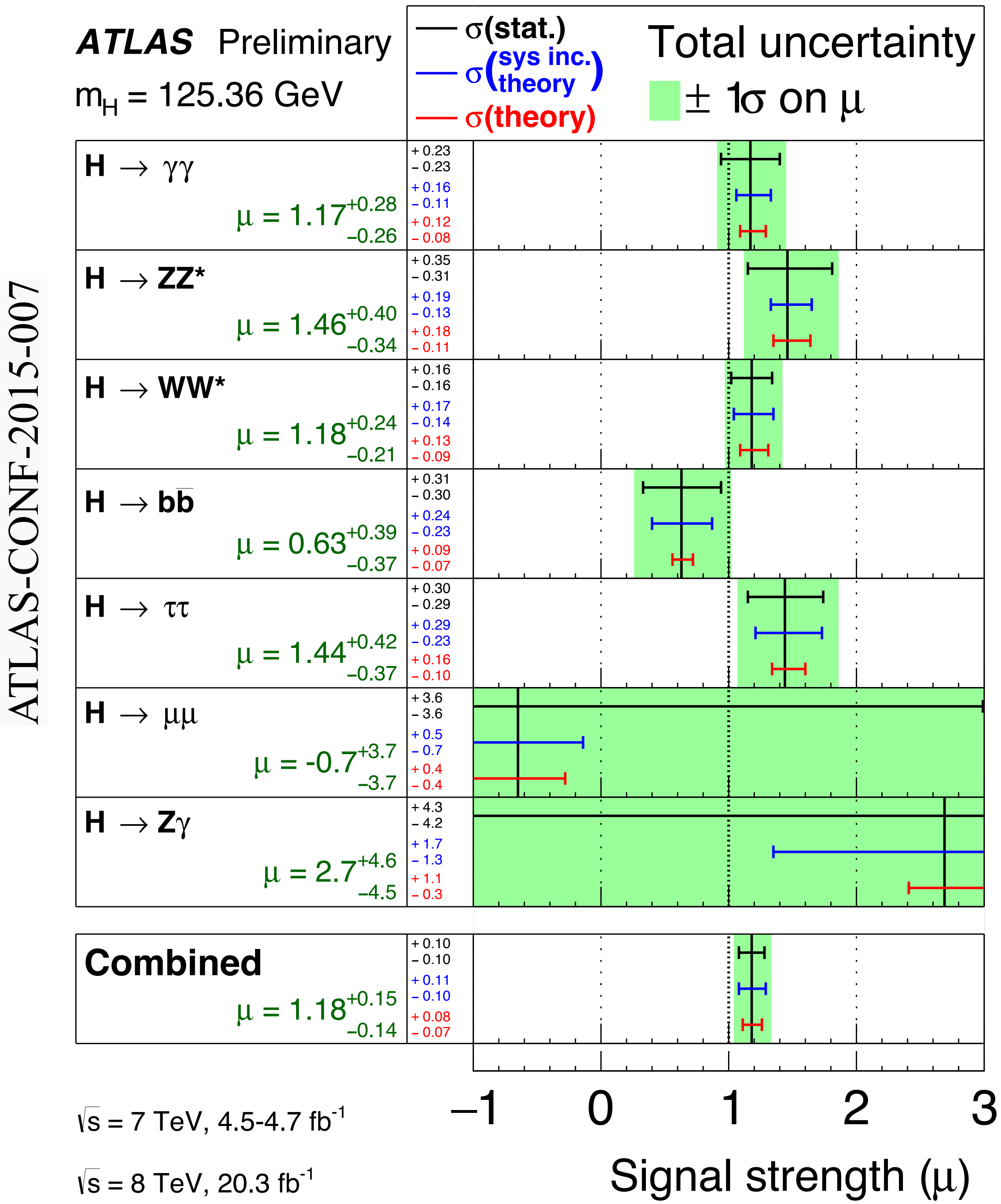
PLB 732 (2014) 8-27

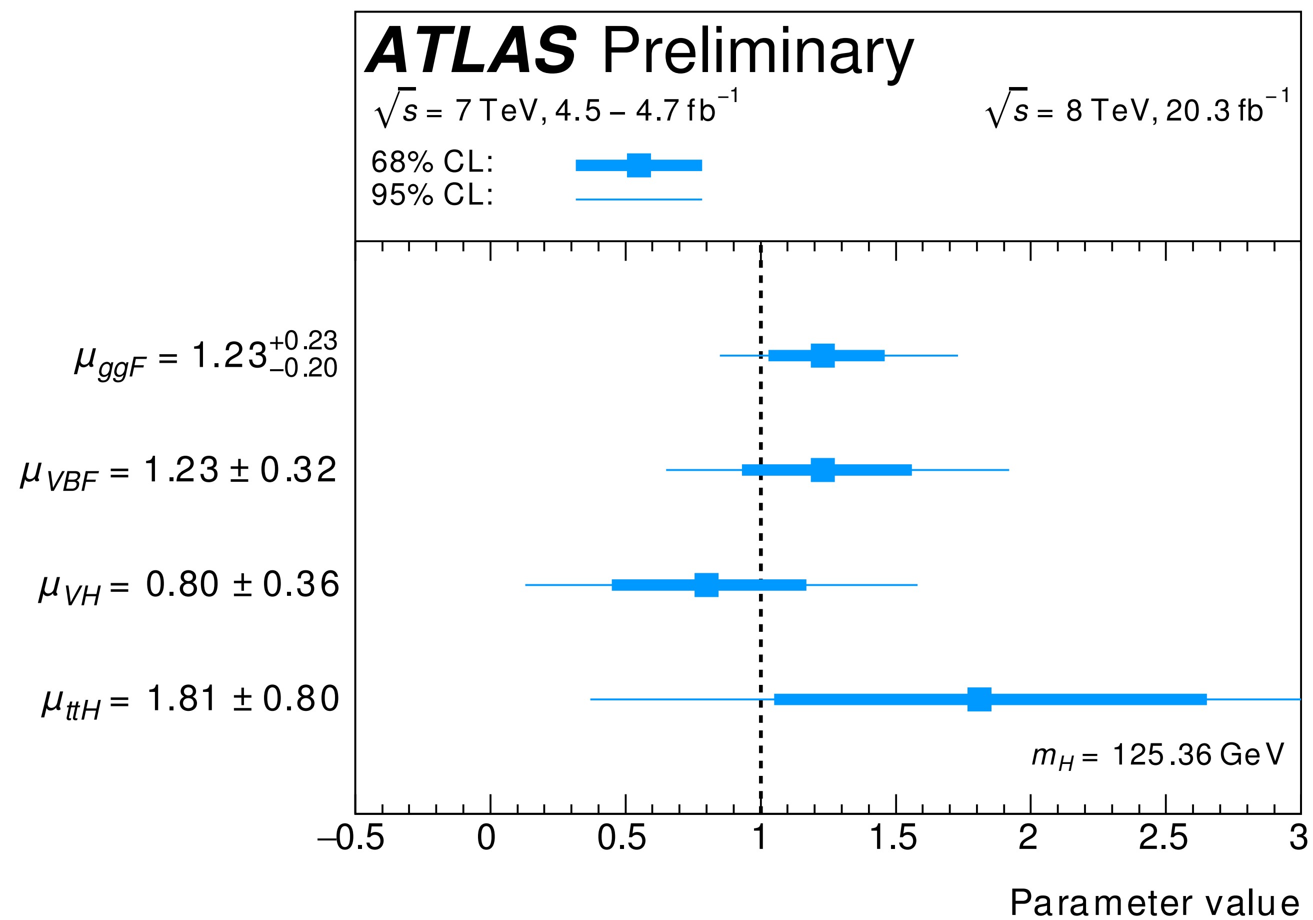


95% CL upper limit on signal strength (μ)		
	observed	expected
H→μμ	7.0	7.4
H→Zγ	11	9

- Searches are statistically limited
- Clear sign that Higgs boson does not couple universally to leptons (260×SM for H→μμ given the observed evidence of H→ττ)

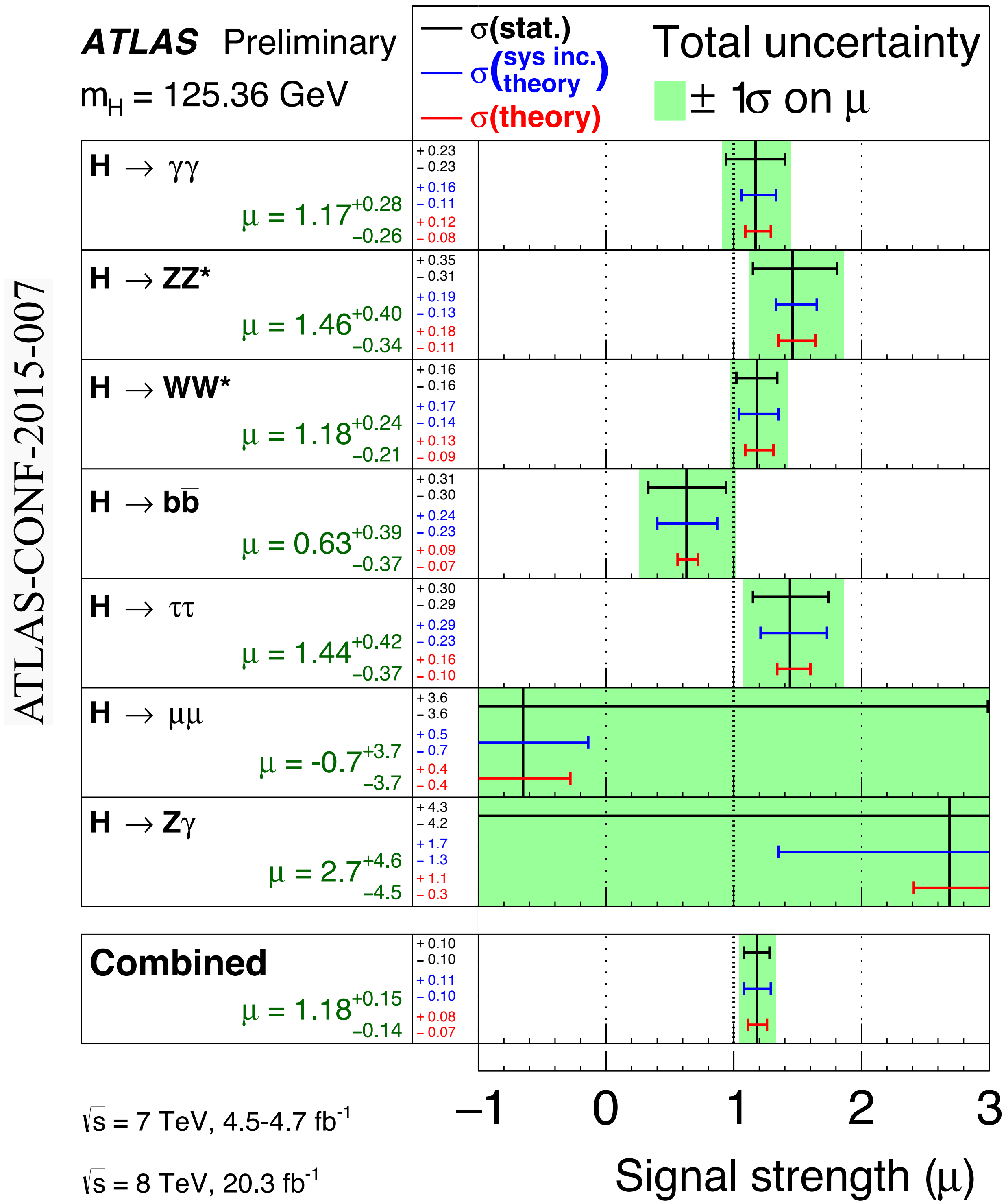
Summary of signal strength measurement





- All measurements of signal strength consistent with 1:
  - combined precision ~13%, theory uncertainty non-negligible

Summary of signal strength measurement



Re-parametrisation with the ratios to ggF(production) and WW(decay):

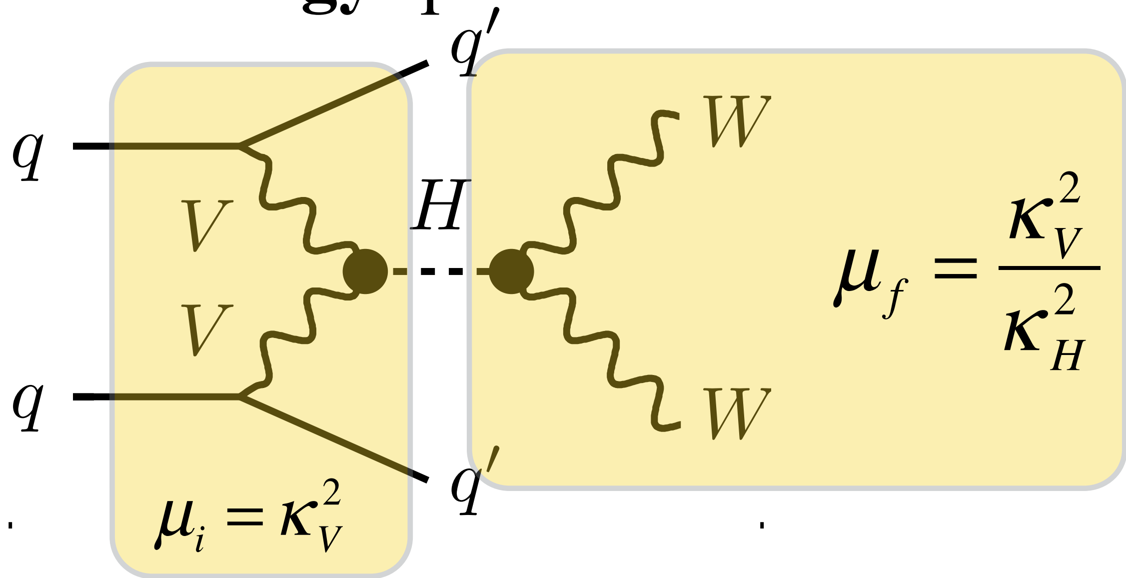
$$R_{i/\mathrm{ggF}} = \frac{\sigma_i/\sigma_{\mathrm{ggF}}}{\left[\sigma_i/\sigma_{\mathrm{ggF}}\right]_{\mathrm{SM}}} \qquad \rho_{f/WW^*} = \frac{\mathrm{BR}_f/\mathrm{BR}_{WW^*}}{\left[\mathrm{BR}_f/\mathrm{BR}_{WW^*}\right]_{\mathrm{SM}}}.$$

$\mu^{WW^*}_{\mathrm{ggF}}$	$1.15^{+0.28}_{-0.24}$		
Ratio of cross sections	Best-fit value	Significance (σ)	
		Observed	Expected
$R_{\mathrm{VBF/ggF}}$	$1.00^{+0.46}_{-0.34}$	4.3	3.8
$R_{VH/\mathrm{ggF}}$	$1.33^{+0.94}_{-0.68}$	2.6	3.1
$R_{ttH/\mathrm{ggF}}$	$1.90^{+1.12}_{-0.86}$	2.4	1.5

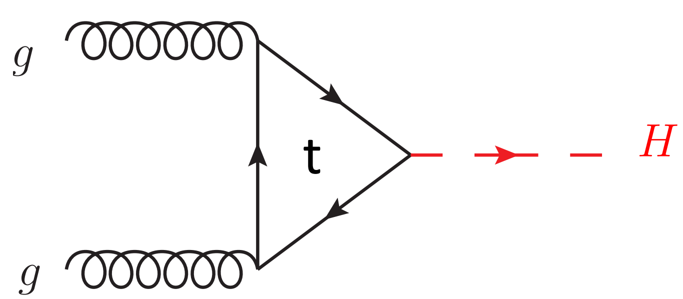
- All measurements of signal strength consistent with 1:
  - combined precision ~13%, theory uncertainty non-negligible

Higgs boson coupling scale factors

- **Assumptions:**
  - Single state, spin 0 and CP-even.
  - Narrow-width approximation: $(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \dfrac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$
- **Methodology:** parametrise deviations with coupling scale factors $\{\kappa_x\}$

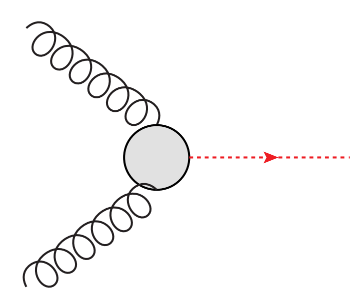


$$\Gamma_{\mathrm{H}}(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_{\mathrm{H}}^2(\kappa_j)}{(1 - \mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_{\mathrm{H}}^{\mathrm{SM}}$$



$\kappa_g^2 \propto 1.\times 06\kappa_t^2 - 0.07 \times \kappa_t\kappa_b + 0.01 \times \kappa_b^2$

Loop interaction



κ_g^2

- **Two fundamental options:**
  - Allow undetected/invisible decays (κ_{H} free) or only SM decays
  - Allow BSM particles in the loops or resolve the loop assuming SM field only

Scalar coupling deviations framework

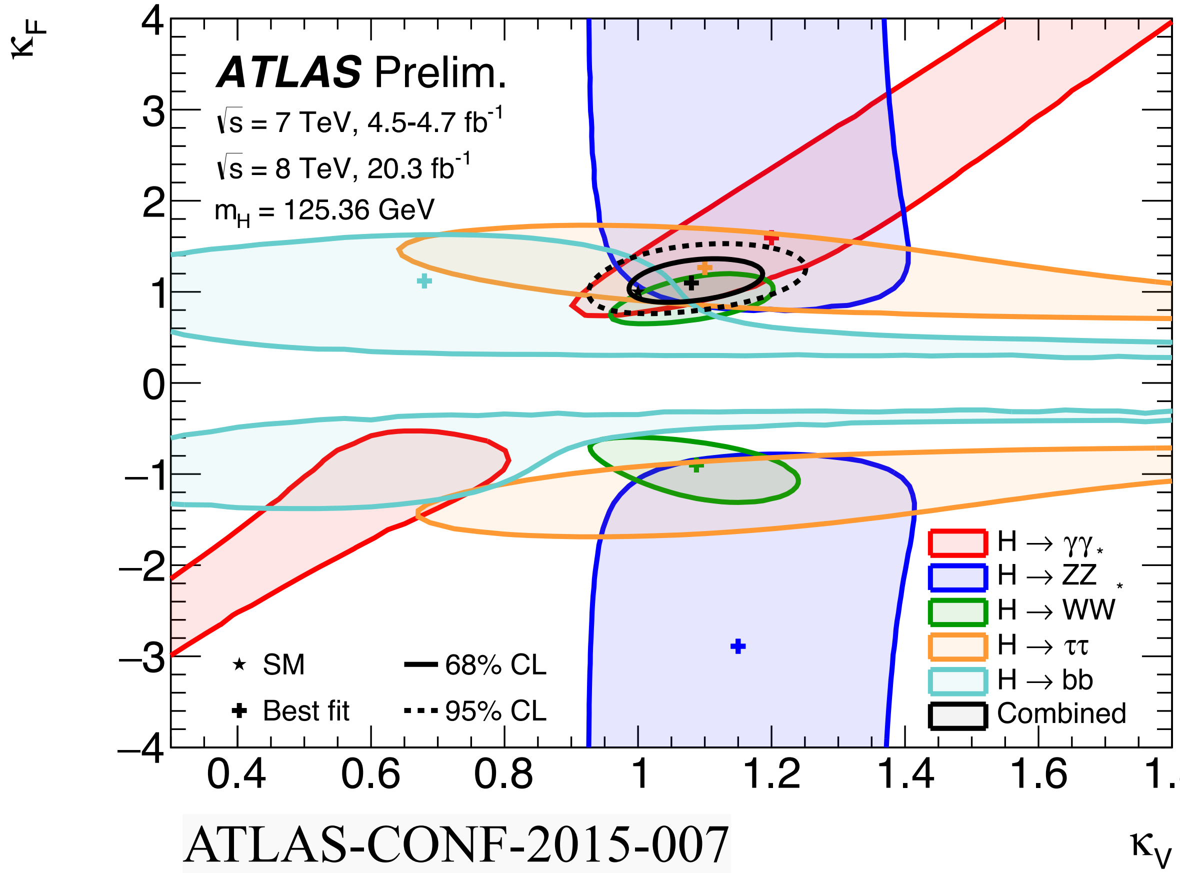
Production	Loops	Interference	Expression in terms of fundamental coupling strengths	
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06\cdot\kappa_t^2+0.01\cdot\kappa_b^2-0.07\cdot\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	-	-	$\sim$	$0.74\cdot\kappa_W^2+0.26\cdot\kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q}\to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg\to ZH)$	✓	$Z-t$	$\kappa_{ggZH}^2 \sim$	$2.27\cdot\kappa_Z^2+0.37\cdot\kappa_t^2-1.64\cdot\kappa_Z\kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_t^2
$\sigma(gb\to WtH)$	-	$W-t$	$\sim$	$1.84\cdot\kappa_t^2+1.57\cdot\kappa_W^2-2.41\cdot\kappa_t\kappa_W$
$\sigma(qb\to tHq')$	-	$W-t$	$\sim$	$3.4\cdot\kappa_t^2+3.56\cdot\kappa_W^2-5.96\cdot\kappa_t\kappa_W$
Partial decay width				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59\cdot\kappa_W^2+0.07\cdot\kappa_t^2-0.66\cdot\kappa_W\kappa_t$
$\Gamma_{Z\gamma}$	✓	$W-t$	$\kappa_{Z\gamma}^2 \sim$	$1.12\cdot\kappa_W^2+0.00035\cdot\kappa_t^2-0.12\cdot\kappa_W\kappa_t$
Total decay width				
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57\cdot\kappa_b^2+0.22\cdot\kappa_W^2+0.09\cdot\kappa_g^2+$ $0.06\cdot\kappa_\tau^2+0.03\cdot\kappa_Z^2+0.03\cdot\kappa_c^2+$ $0.0023\cdot\kappa_\gamma^2+0.0016\cdot\kappa_{Z\gamma}^2+0.00022\cdot\kappa_\mu^2$

Input analyses to the combinations: H→γγ, ZZ, WW, ττ, bb, μμ, Zγ and constraint on ttH and off-shell Higgs productions

Higgs Boson Coupling measurement

- Scaling coupling to fermions (κ_F) and vector bosons(κ_V):
  - All decay channels converging around SM expectation.
- Other benchmarks models:
  - different options on the loops and decays
  - custodial symmetry of W and Z
  - coupling to up/down-type fermions
  - coupling ratios

*only SM contribution to loop and total width



ATLAS-CONF-2015-007

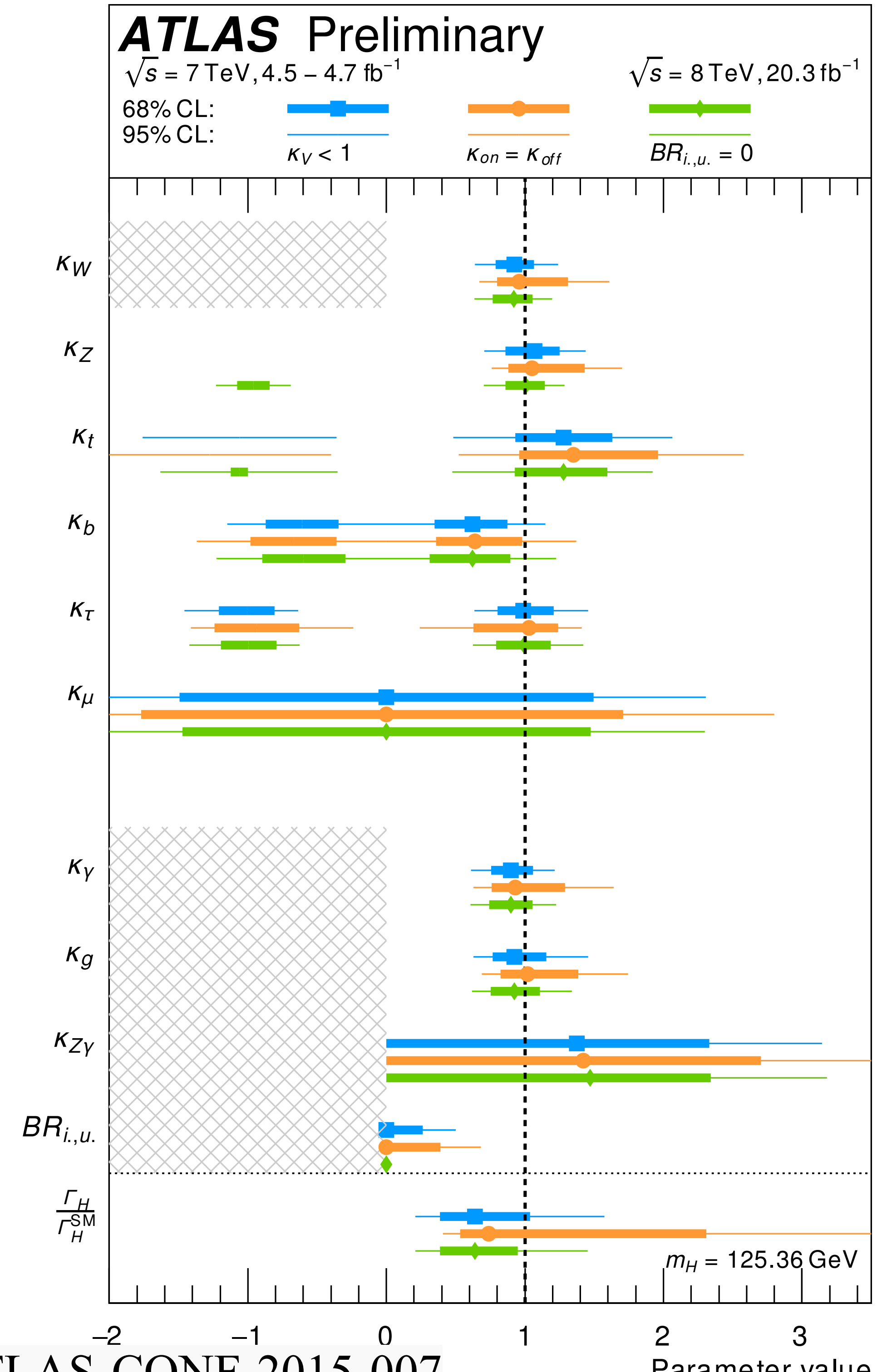
Best Fit values:

$$\kappa_V = 1.09^{+0.07}_{-0.07}$$
$$\kappa_F = 1.11^{+0.17}_{-0.15}$$

Couplings very consistent with SM predictions

Higgs Boson Coupling measurement

- Most general benchmark scenario with the consideration of all potential κ-scale factors:



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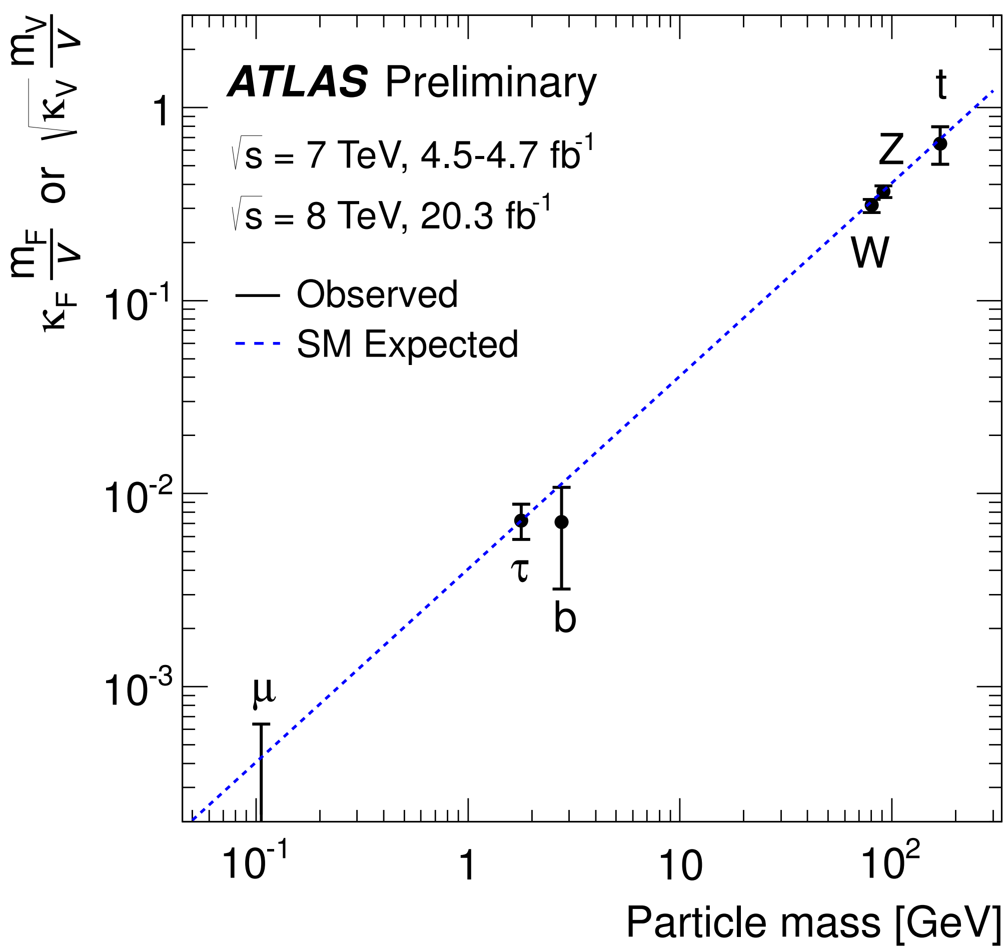
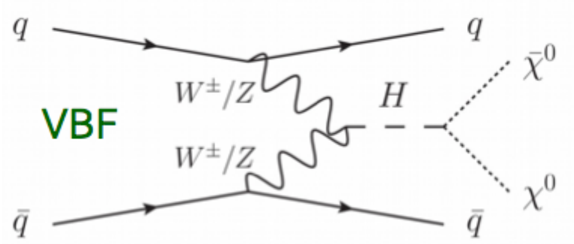
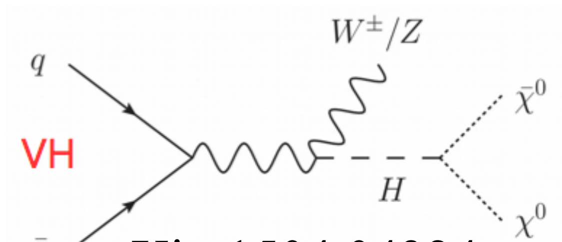


Measurements very compatible with SM prediction

Invisible Higgs Searches

ATLAS-CONF-2015-004

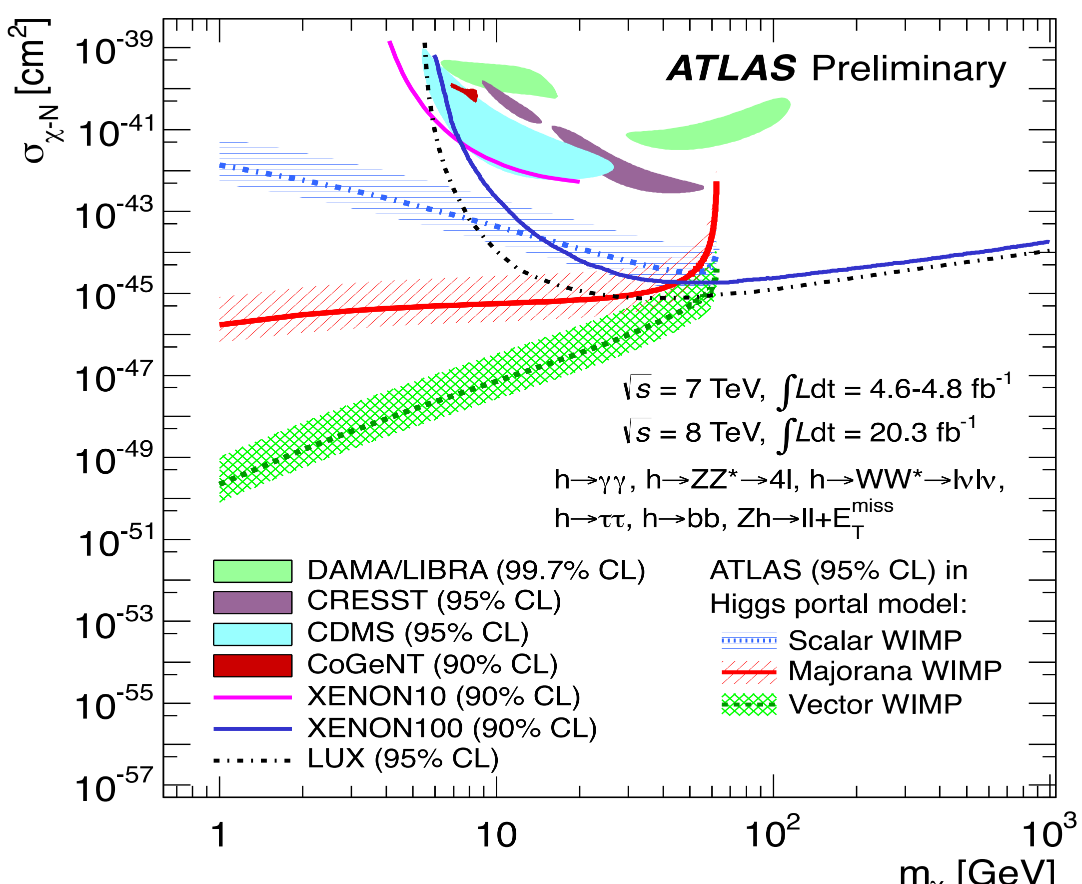




arXiv:1504.04324

With the assumption of SM coupling to known SM particle

- **VBF:** Br(H→inv)<0.29(0.35)@95% CL
- **ZH, Z→ee/μμ:** Br(H→inv)<0.75(0.62)@95% CL
- **VH, V→qq:** Br(H→inv)<0.78(0.86)@95% CL
- **Combination** between Zh→ll+MET and indirect measurement: Br(H→inv)<0.37(0.39)@95% CL



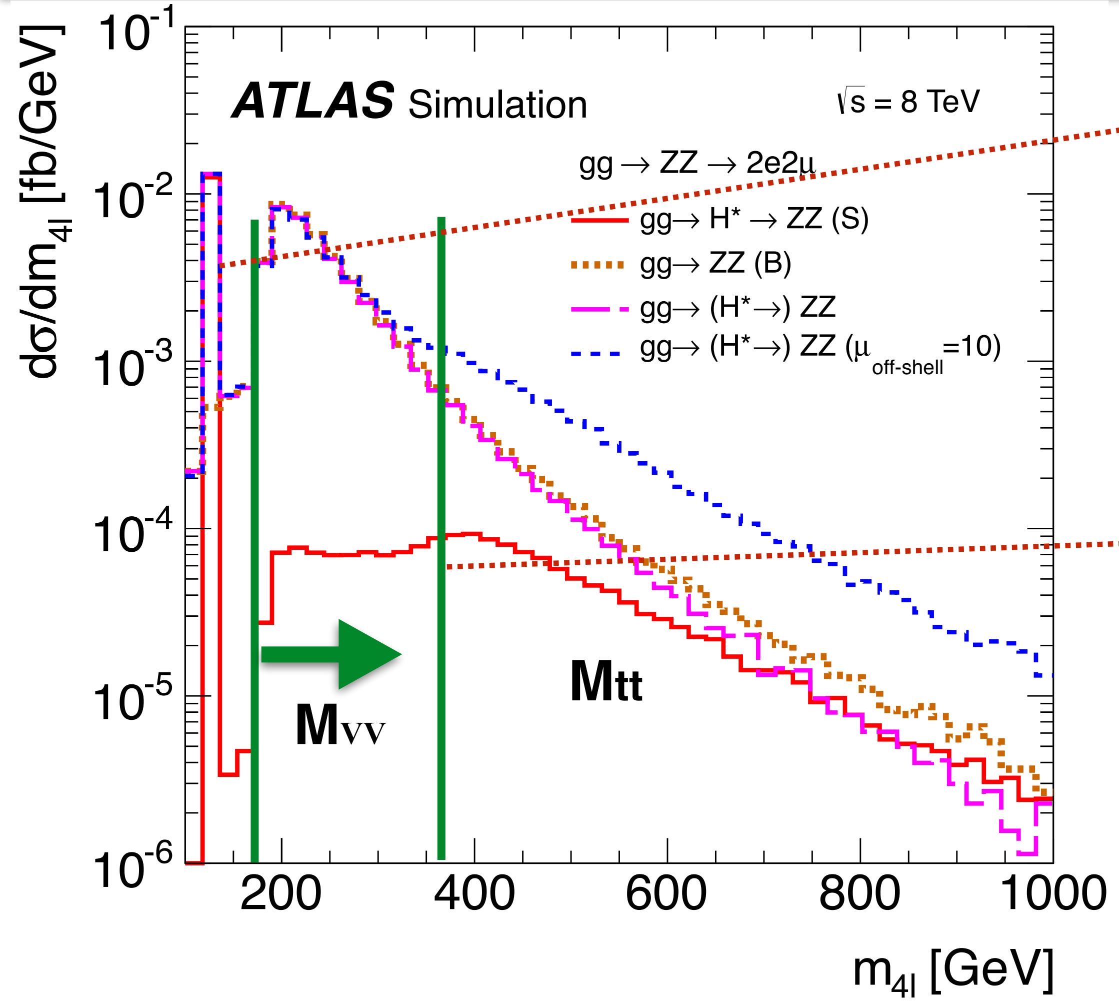
ATLAS-CONF-2014-010

*Combination with the indirect measurement of different channels with coupling scenario

- ❖ **In "Higgs portal" models, limits on Br(H→inv) can be translated to constraints on coupling λ(h, WIMP), then re-parametrized to scattering cross section $\sigma_{\chi\text{-N}}$.**

- ✦ Tight constraint on the DM at the low mass region

Off-Shell Behaviour and the Higgs Boson Width



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

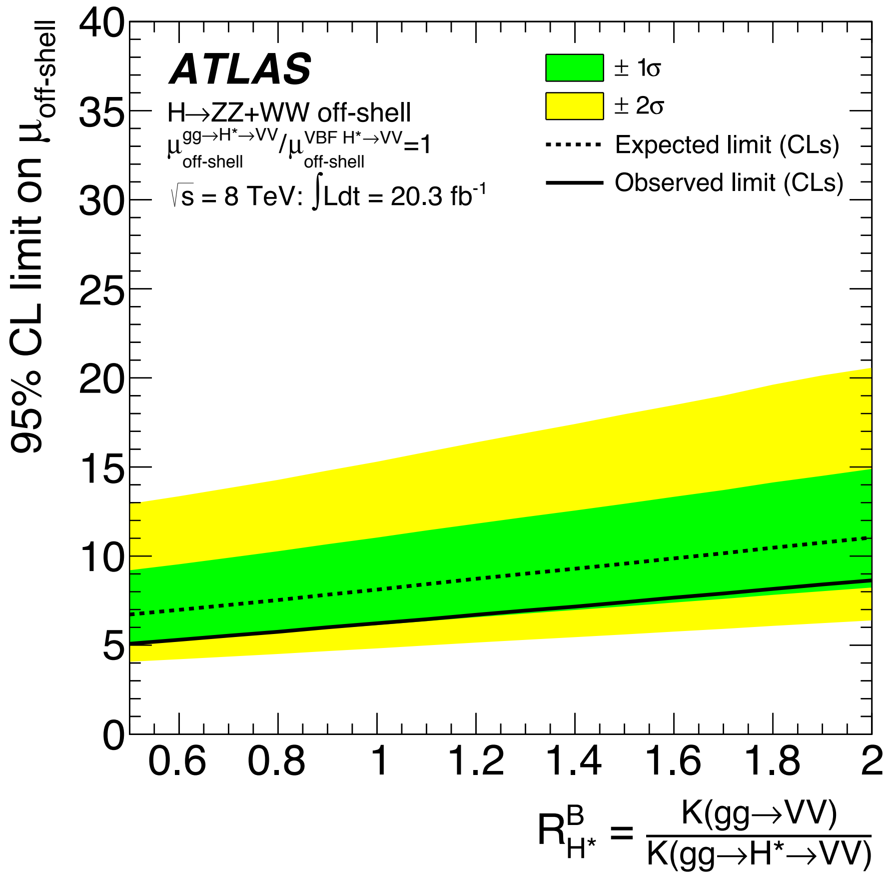
$$\mu_{offshell} = \mu_{onshell} \times \Gamma_H / \Gamma_H(SM)$$

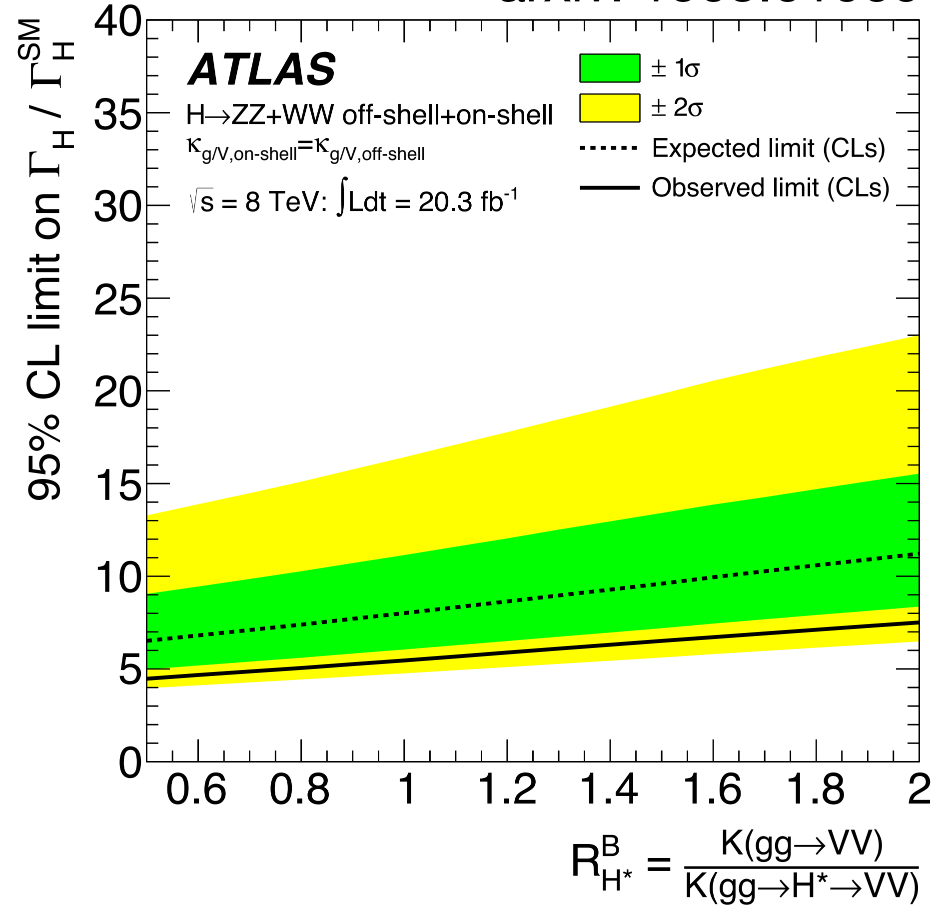
- **Measurement of the off-shell signal strength in H→WW and H→ZZ.**
- With the combination between on-shell and off-shell analysis:
  - Assuming the on-shell couplings are the same as the off-shell couplings, the coupling measurements can be reinterpreted as the **constraints on Γ_H**.
  - Assuming SM Higgs width, it can be reinterpreted as the **constraints on off-shell and on-shell coupling ratio** $\mu^{gg}_{offshell}/\mu^{gg}_{onshell}$

Off-Shell signal strength and the Higgs Boson Width Limit

expressed as a function of unknown K-factor ratio:

arxiv: 1503.01060



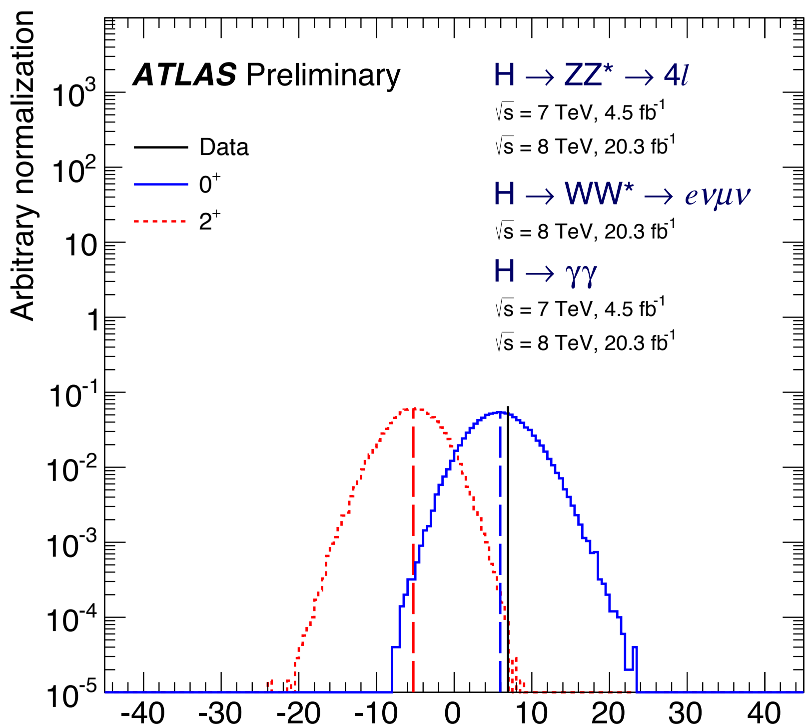


- **Assuming the unknown gg→VV k-factor is equal to signal k-factor:**
  - $\mu_{offshell}$ <6.2 (8.1) obs(exp) at 95%CL
  - Γ_H< 22.7 (33.0)MeV obs(exp) at 95%CL

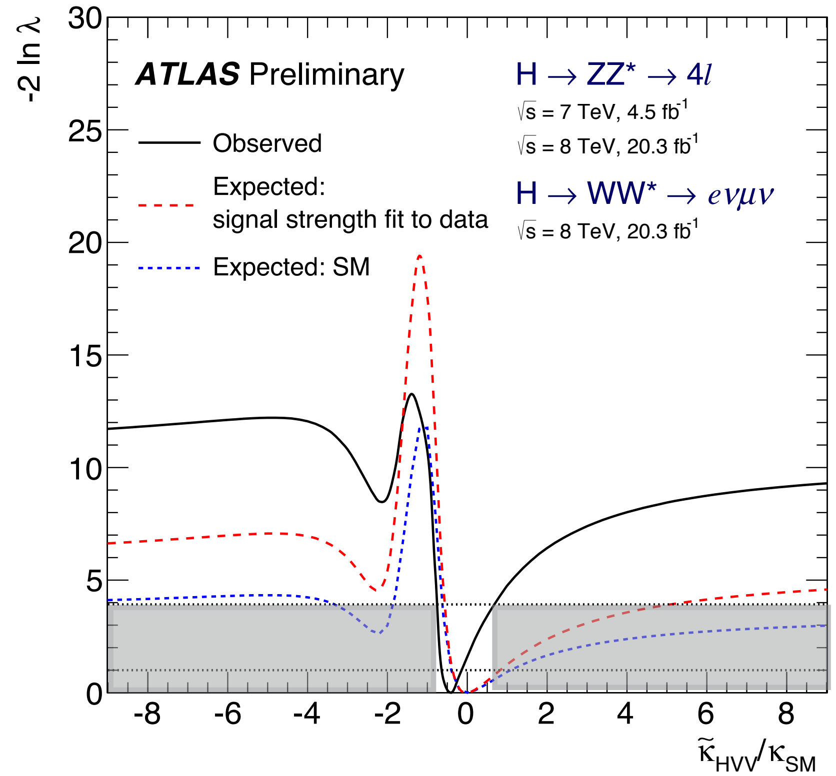
- **Direct Higgs width measurement at 95%CL:**
  - H→γγ: Γ_H<5.0(6.2)GeV
  - H→ZZ: Γ_H<2.6(6.2)GeV

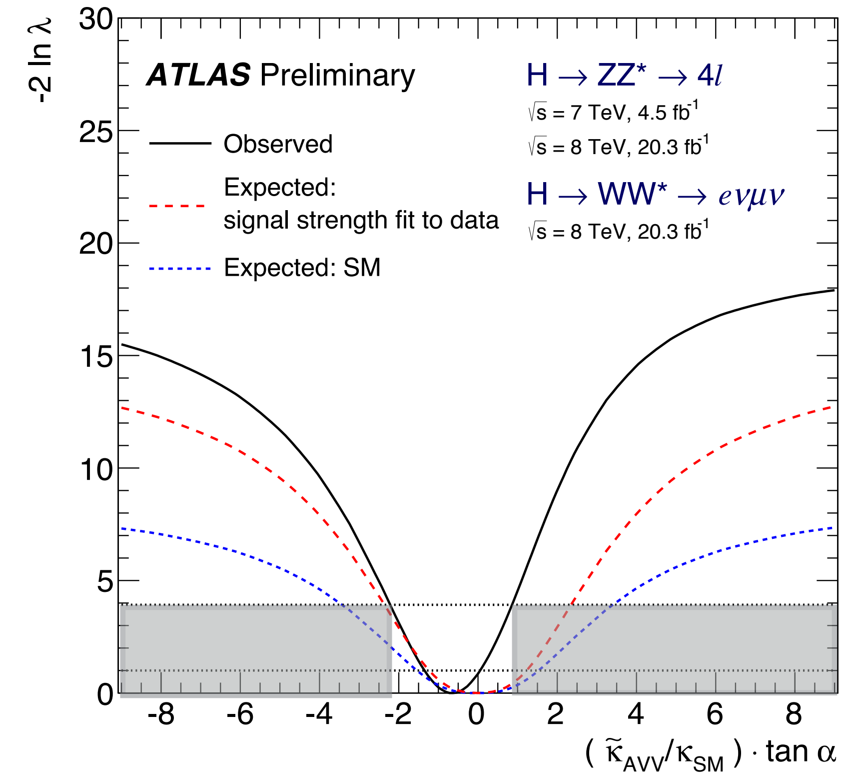
Higgs Boson Quantum Numbers

Clear SM prediction for Higgs Boson quantum Numbers: $J^{pc}=0^{++}$



*hypothesis test of spin-2





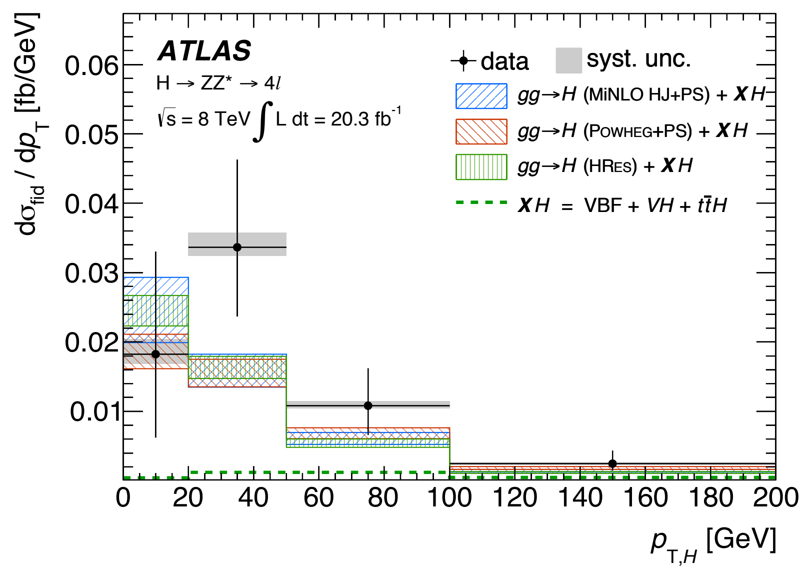
- All alternative hypothesises excluded to more than 99% CL: non-SM spin-0 models and spin-2 models with universal and non-universal coupling to fermions and bosons.
- Tensor structure of the HVV interaction in the spin-0 hypothesis is investigated.
- Higgs boson very SM-like: small non-SM admixture not yet excluded!

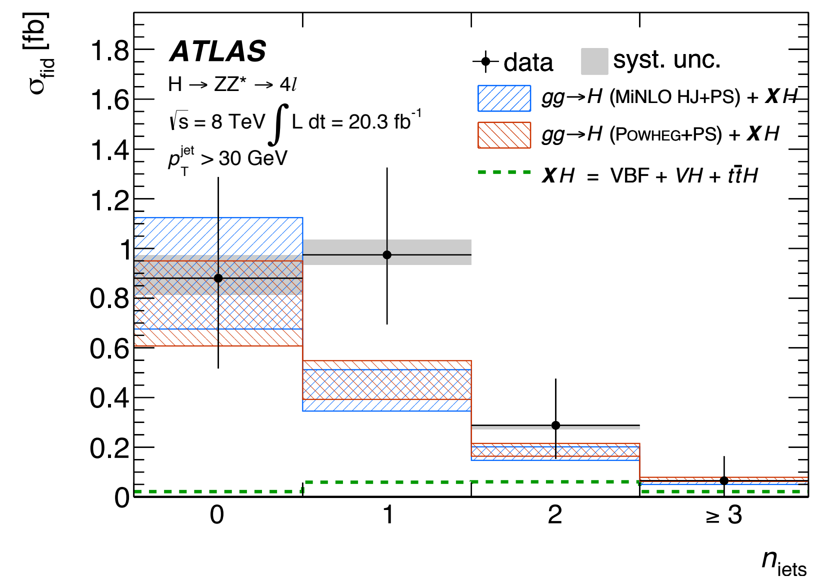
Fiducial and Differential cross section measurement

- **Measurement designed as model independent as possible.**
- **Direct comparison with theoretical predictions at particle level.**
- **A wide and diverse range of physical phenomena to be probed:**
  - Higgs boson kinematics, Jet activity, VBF-sensitive variables, Spin-CP sensitive variables

H→ZZ

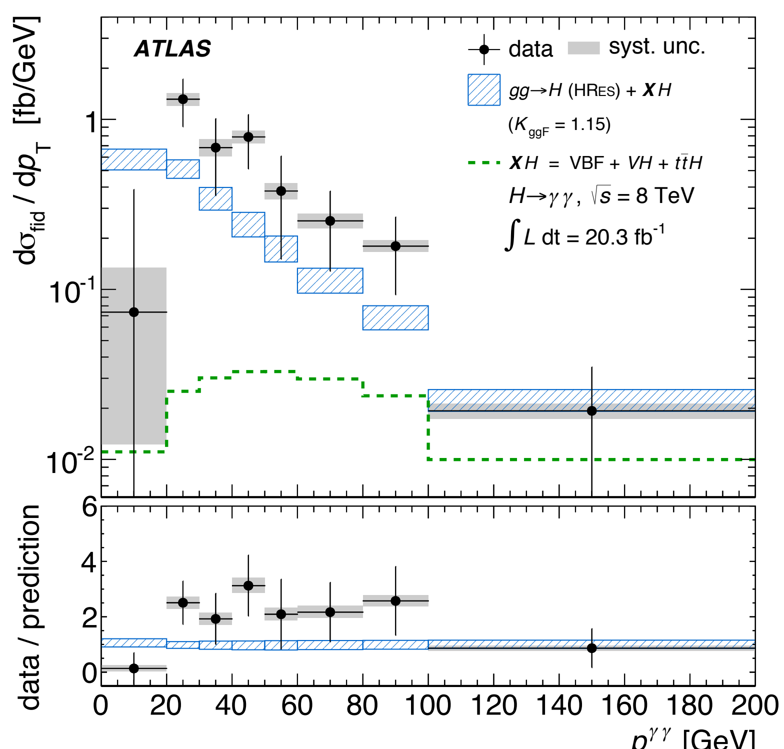
PLB 738 (2014)

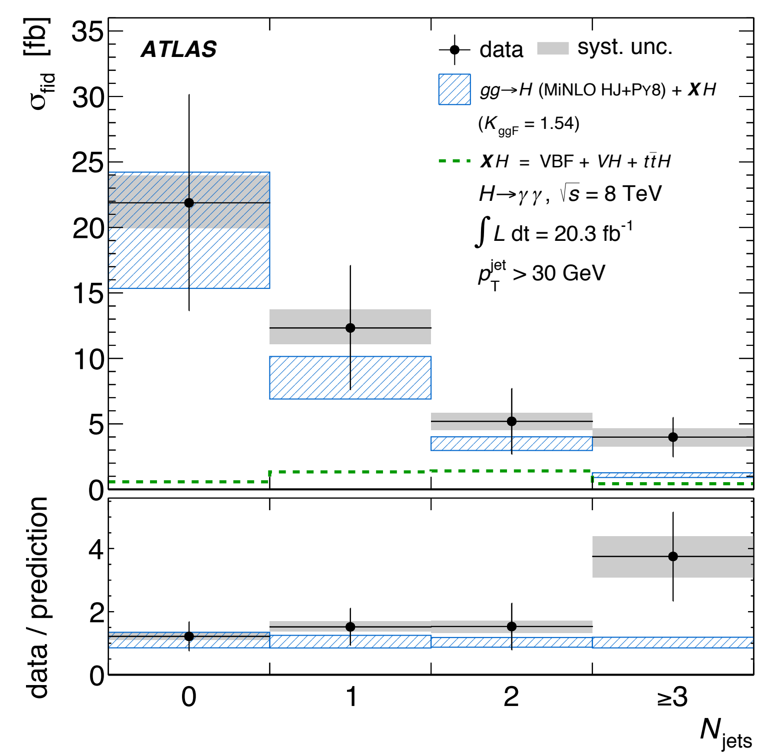




H→γγ

JHEP 09 (2014)

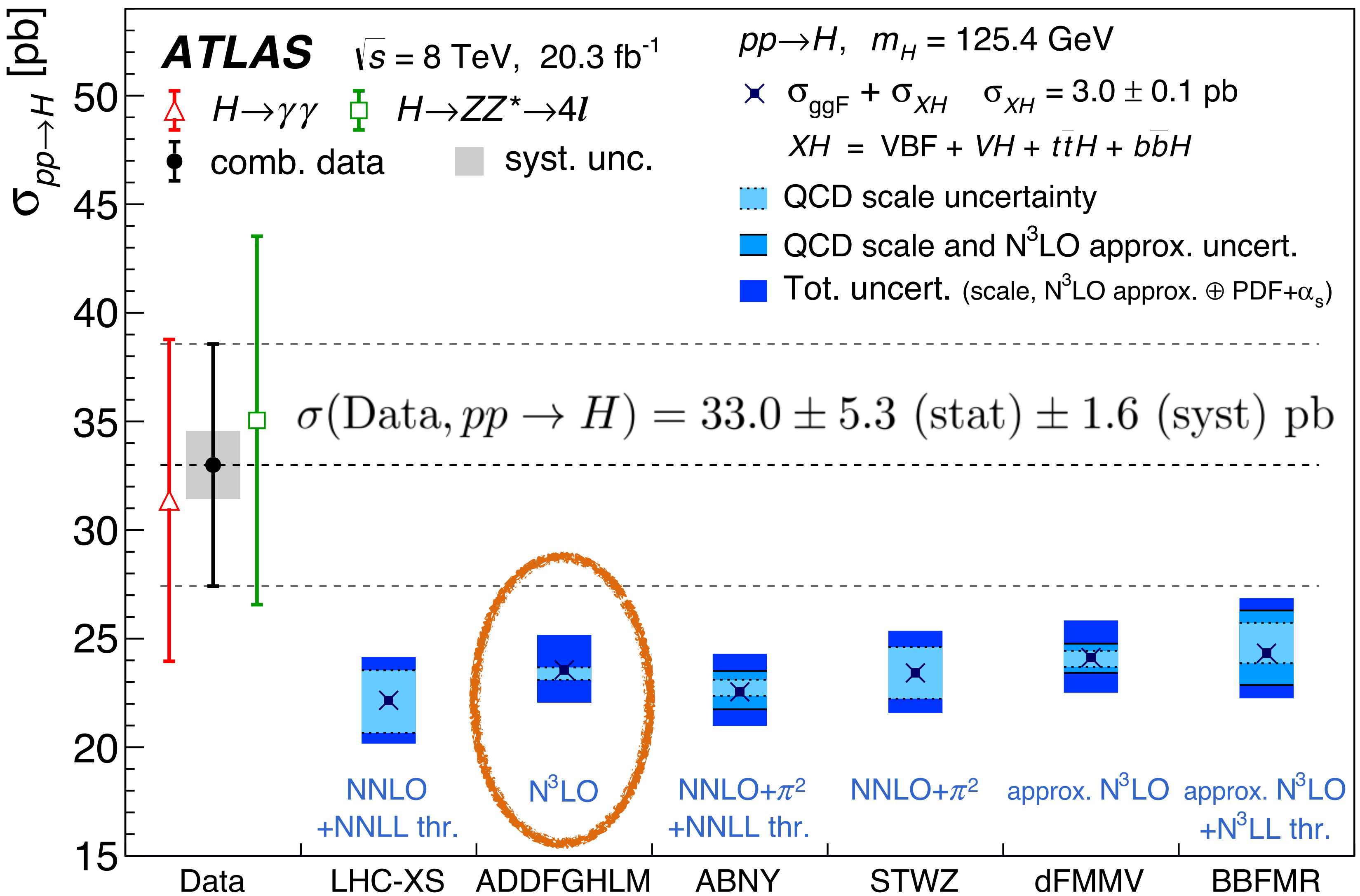




- **Dominated by statistical uncertainties**
- **Broadly in line with the theoretical expectations**

Inclusive pp→H cross section

arXiv:1504.05833



The measurement are comparable to the prediction

Summary: What have we learned?

- Higgs mass determined to 0.2%
- Higgs signal strength ~1, determined to 15%
- Higgs couplings tested for many scenarios and assumptions (consistent with SM), the combination between ATLAS and CMS is coming soon.
- Many non-Spin-0 and CP-odd hypotheses excluded
- Differential cross-section measurement at 8TeV

Higgs boson is so far very consistent with SM predictions, but still statistically limited.

LHC/HL-LHC Plan

$\sqrt{s}$ = 13 TeV
bunch spacing 25 ns

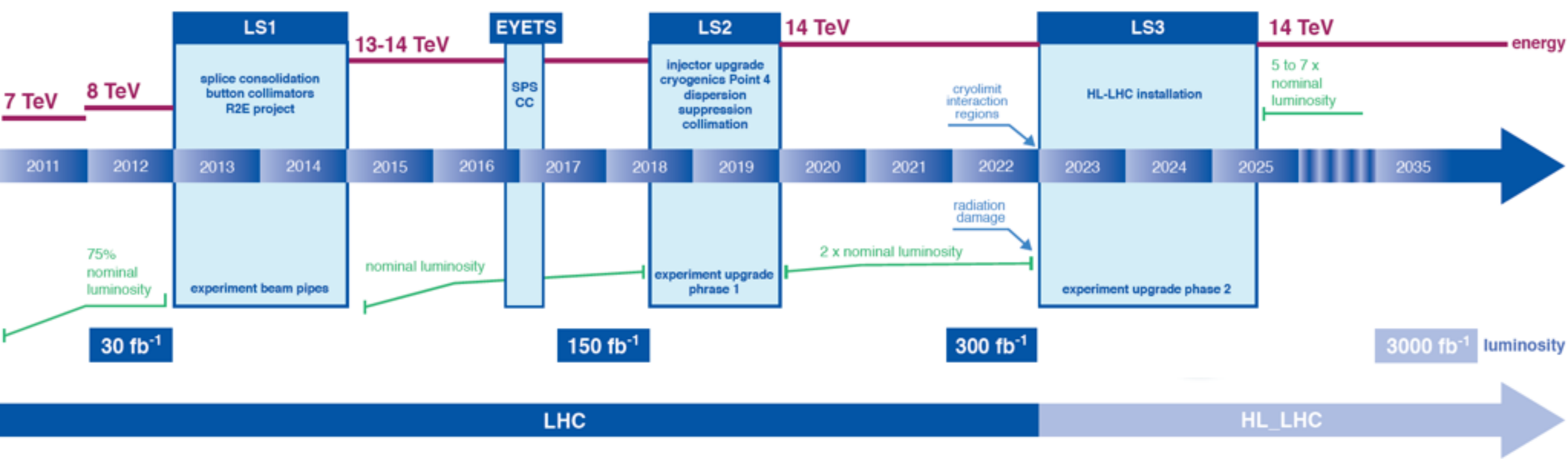
$\sqrt{s}$ = 14 TeV
LHC injector upgrade

New interaction region layout
Crab cavity

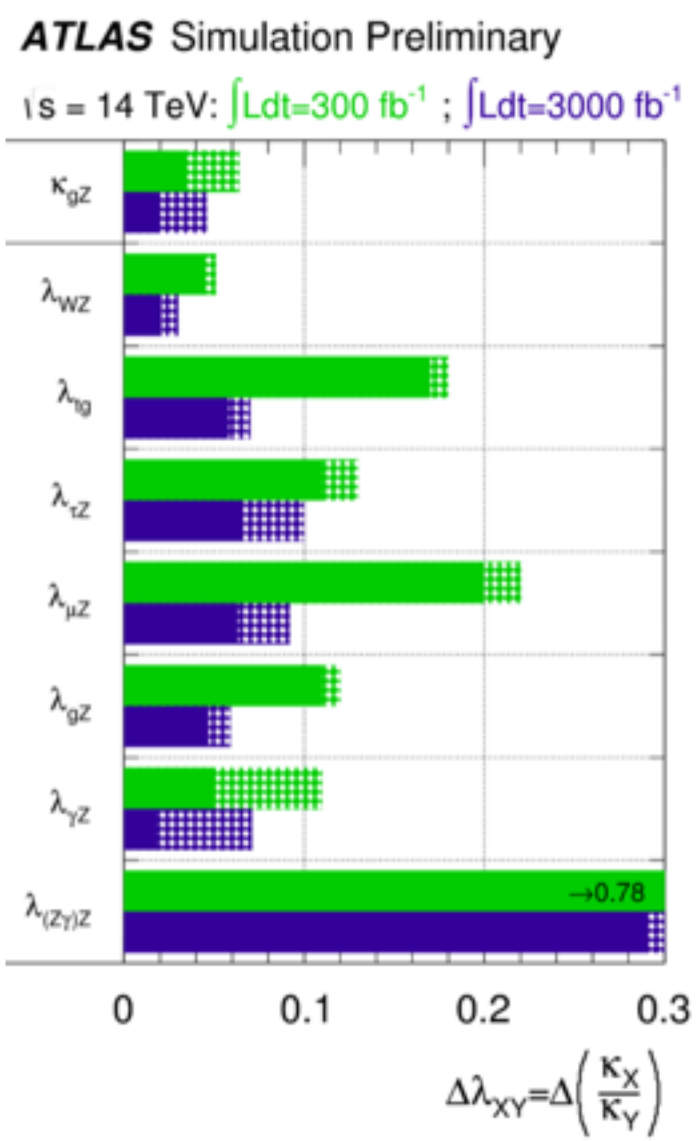
$\mathcal{L} \sim 1.6 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
Pile Up ~ 40

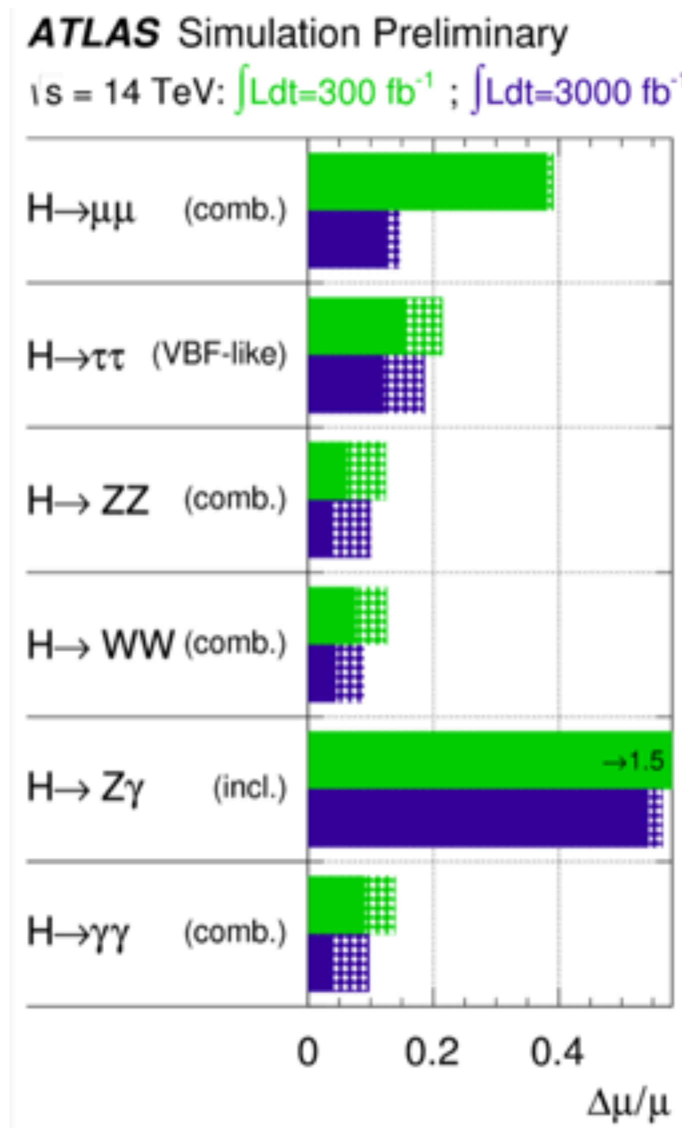
$\mathcal{L} \sim 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
Pile Up ~ 60

luminosity levelling
$\mathcal{L} \sim 5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
Pile Up ~ 140



Prospect of Higgs Boson coupling





- Offer a comprehensive physics programme
  - Expected to establish: H→bb, ttH , H→μμ , H→Zγ
  - 3000fb-1 offers physics significance better than 300fb-1
  - Theory uncertainties become dominant for many key processes


First Stable Beams
ATLAS EXPERIMENT
LHC Run2 is underway, more results to come very soon!
proton-proton collisions at 13 TeV
Run: 266904
Event: 9393006
2015-06-03 10:40:31 CEST