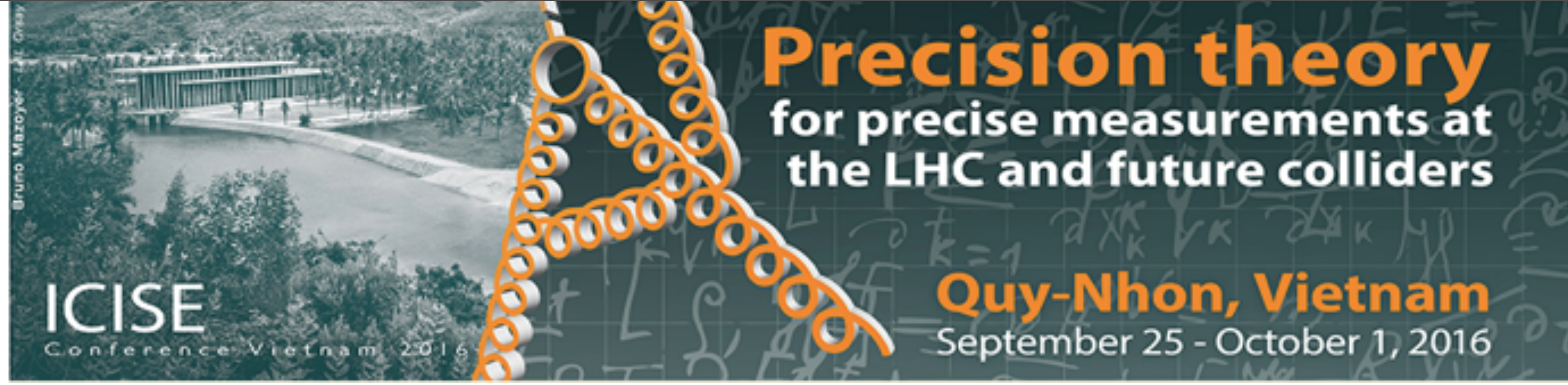


ATLAS expectations/improvements on Higgs from Run 2 (30-100 & 300 fb^{-1})

Oana Boeriu
University of Sheffield (UK)

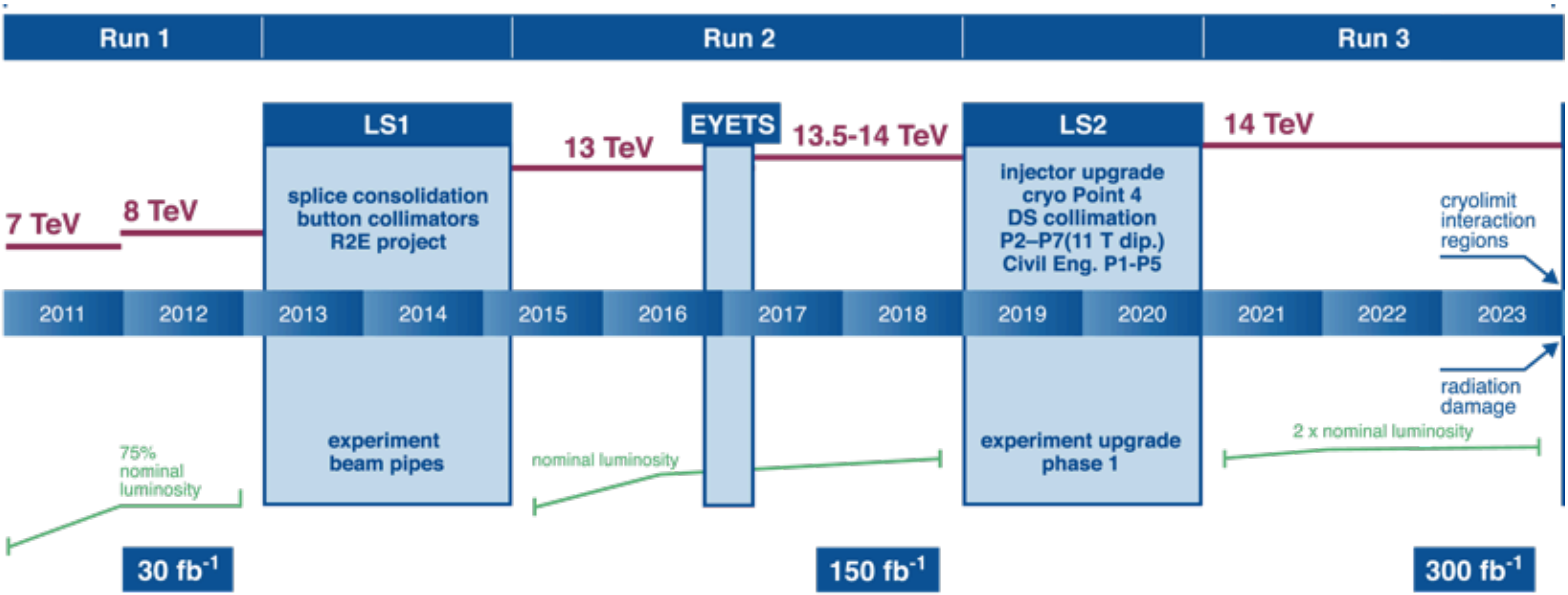
on behalf of the ATLAS Collaboration

Precision Theory, Vietnam, 29/9, Higgs Physics Part 1

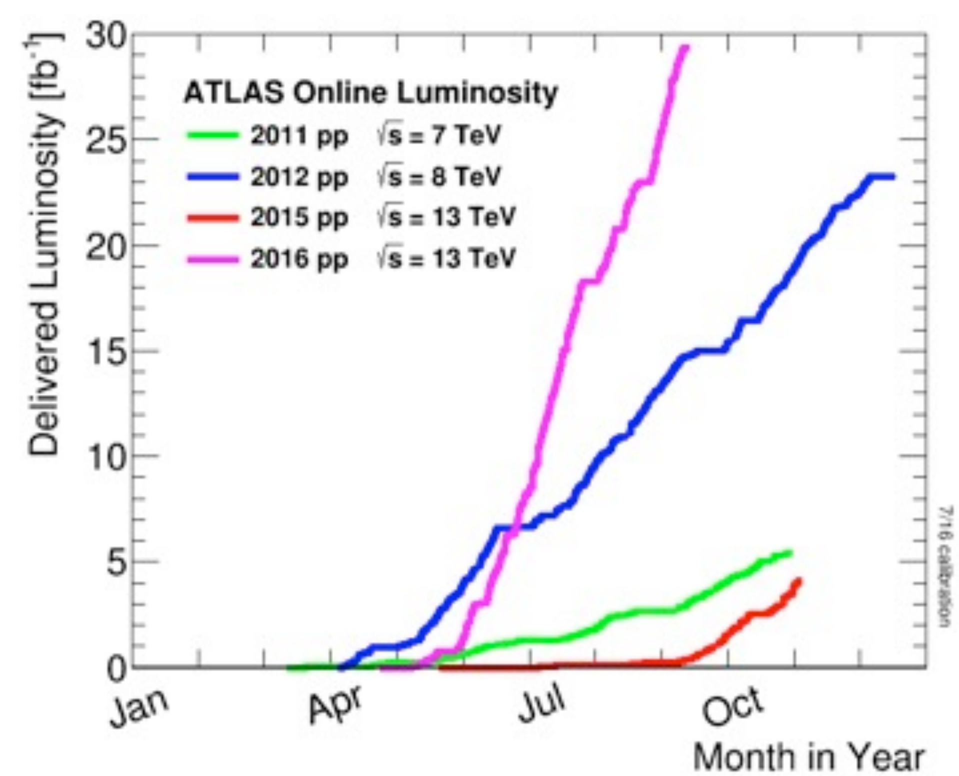
Outline

- LHC Schedule
  - Run 1 Higgs Results Highlights
- The ATLAS Detector in Run 2
- Run 2 Data Summary
  - Current Run 2 Higgs Boson Results
- Run 2 Physics Goals
  - Projections for Run 2 and Expected Results
- Summary

LHC Schedule



- **LHC performing beyond expectations**
- Current data expectations:
  - ~**35 fb^{-1}** @ 13 TeV **by end of 2016**
  - 150 fb^{-1} @ 13-13.5 TeV by end of Run 2, 2018
  - ~300 fb^{-1} @ 13-14 TeV by end of Run 3, 2023
  - ~3000 fb^{-1} @ 14 TeV > 2023



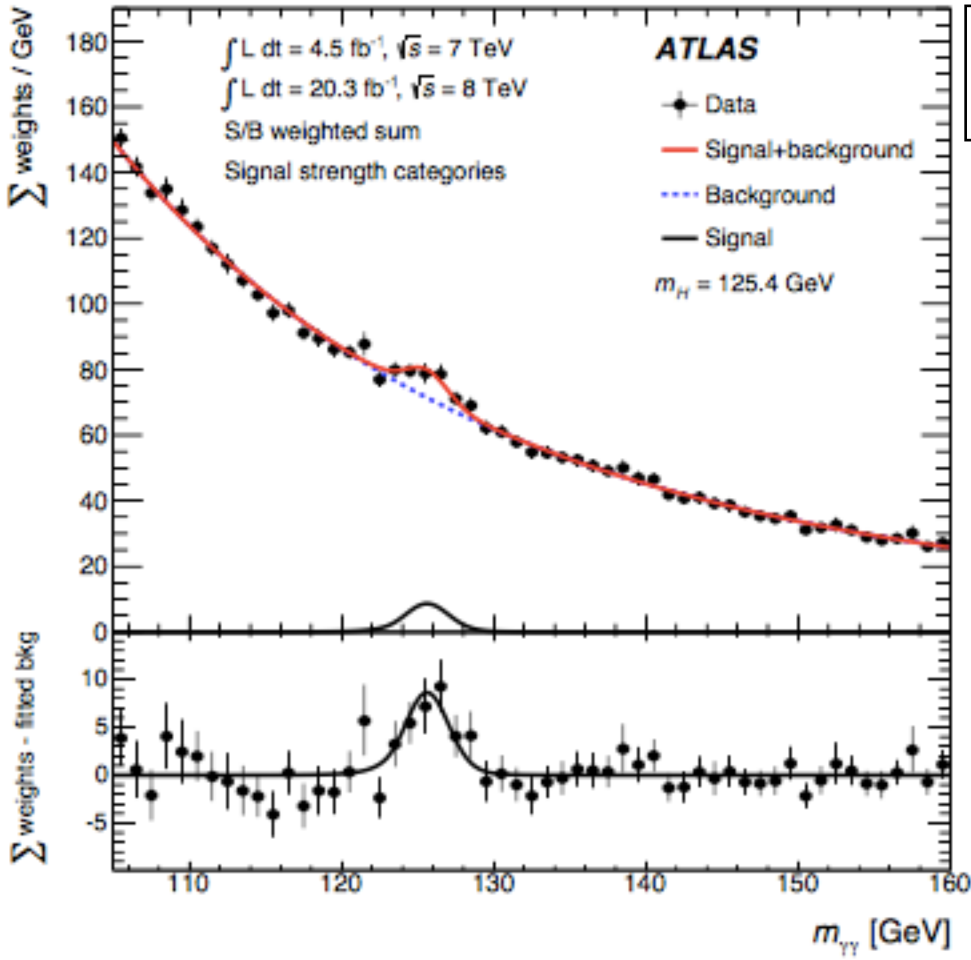
Run I Highlights

~25fb^{-1}

Run 1 H→γγ, H→4l

$$\mu = \frac{\sigma \times B}{\sigma^{SM} \times B^{SM}}$$

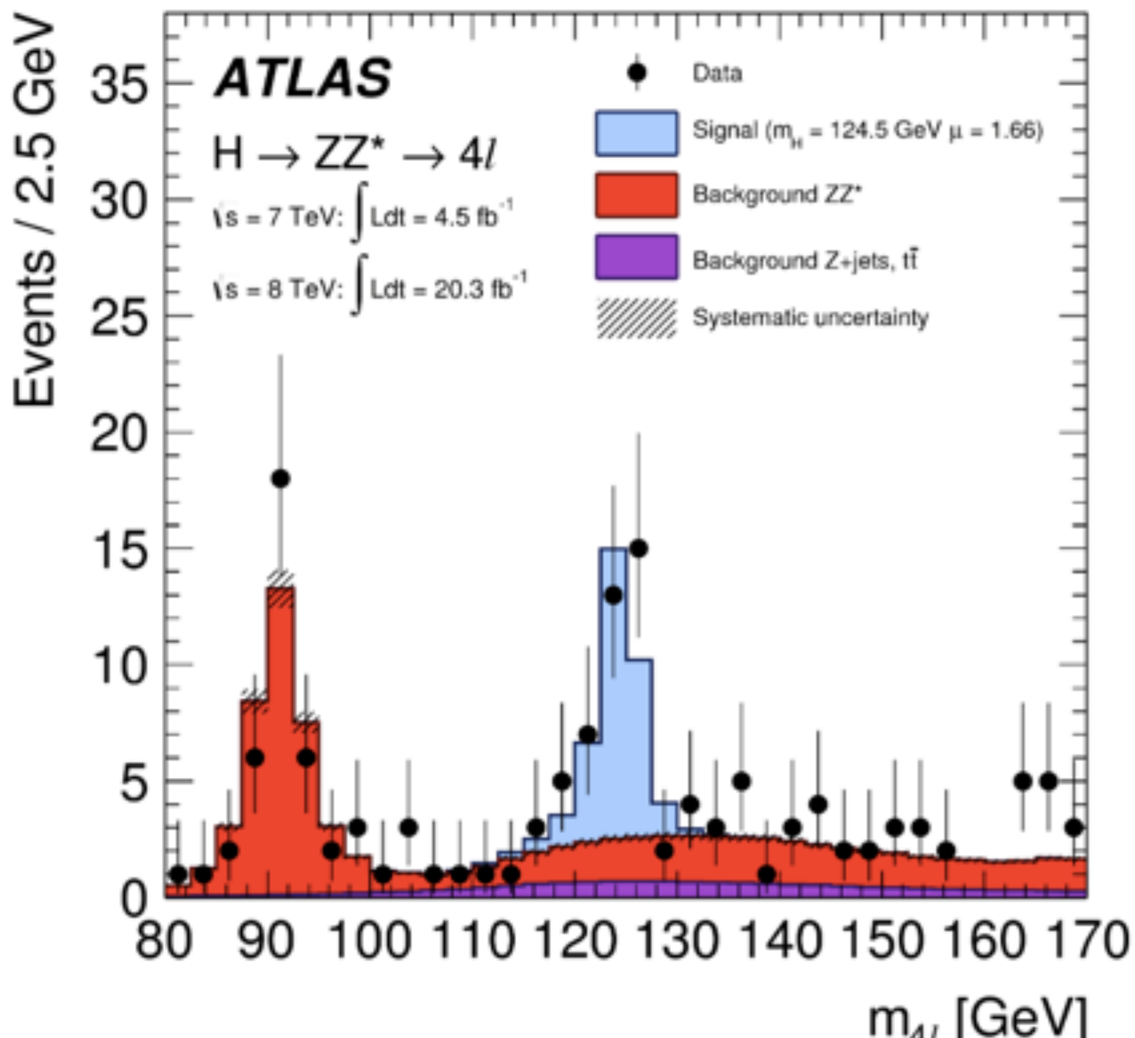
PRD 90 (2014) 112015



$$\mu = 1.17 \pm 0.23(\text{stat})^{+0.10}_{-0.08}(\text{syst})^{+0.12}_{-0.08}(\text{theory}) = 1.17 \pm 0.27,$$

Observed: 5.2σ
Expected: 4.6σ

PRD 90 (2014) 052004



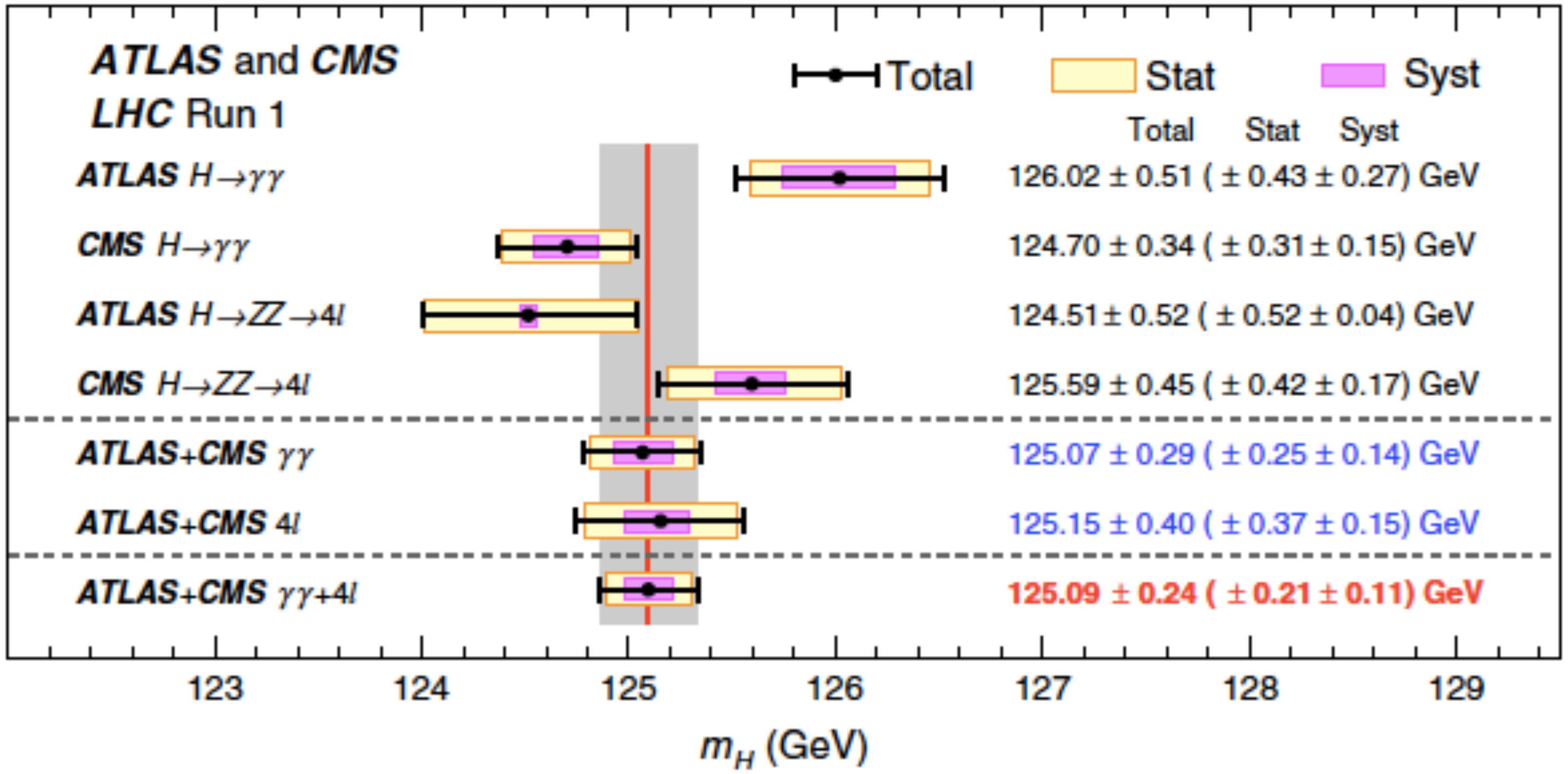
Observed: 8.1σ
Expected: 6.2σ

- H→WW* (PRD 92 (2015) 012006)
- H→bb (PRD (2015) 069)
- H→ττ (JHEP 04 (2015) 117)

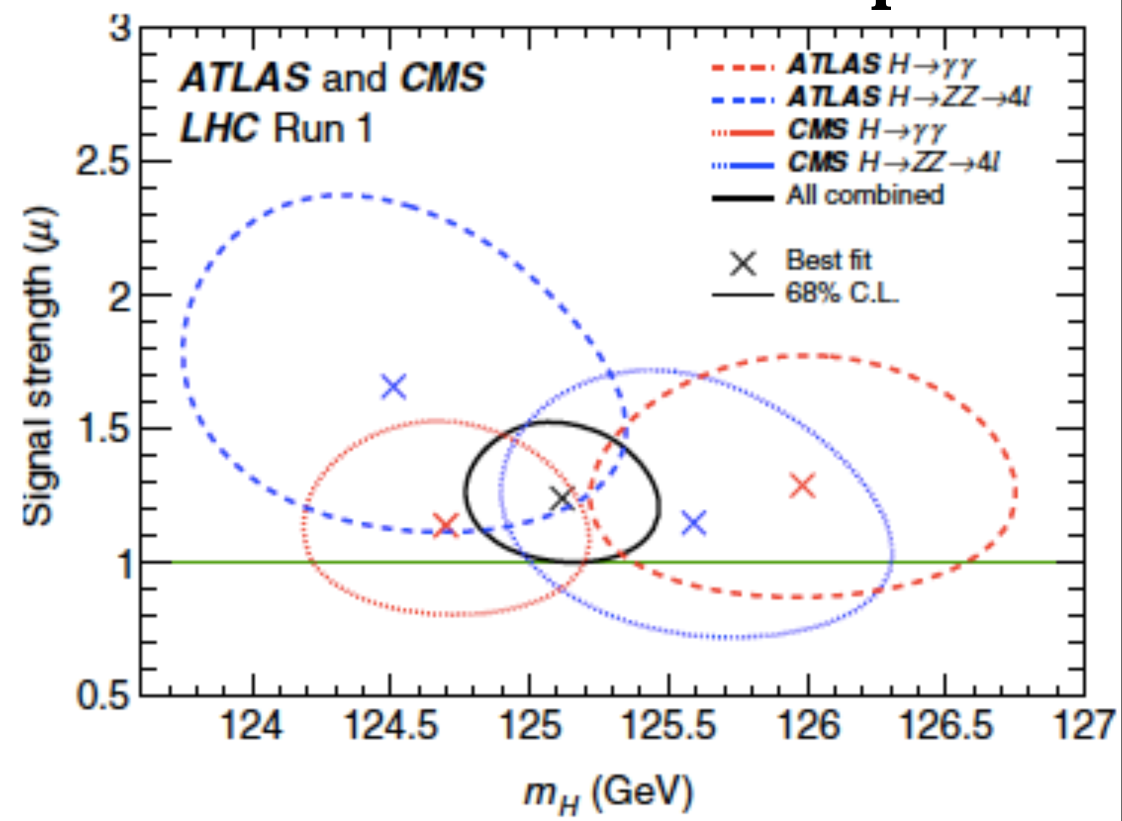
m_H = 125.36 ± 0.37(stat.) ±0.18 (syst.) GeV

PRL 114(2015) 191803

Run 1 Higgs Combination Results



Likelihood scans in 2D plane



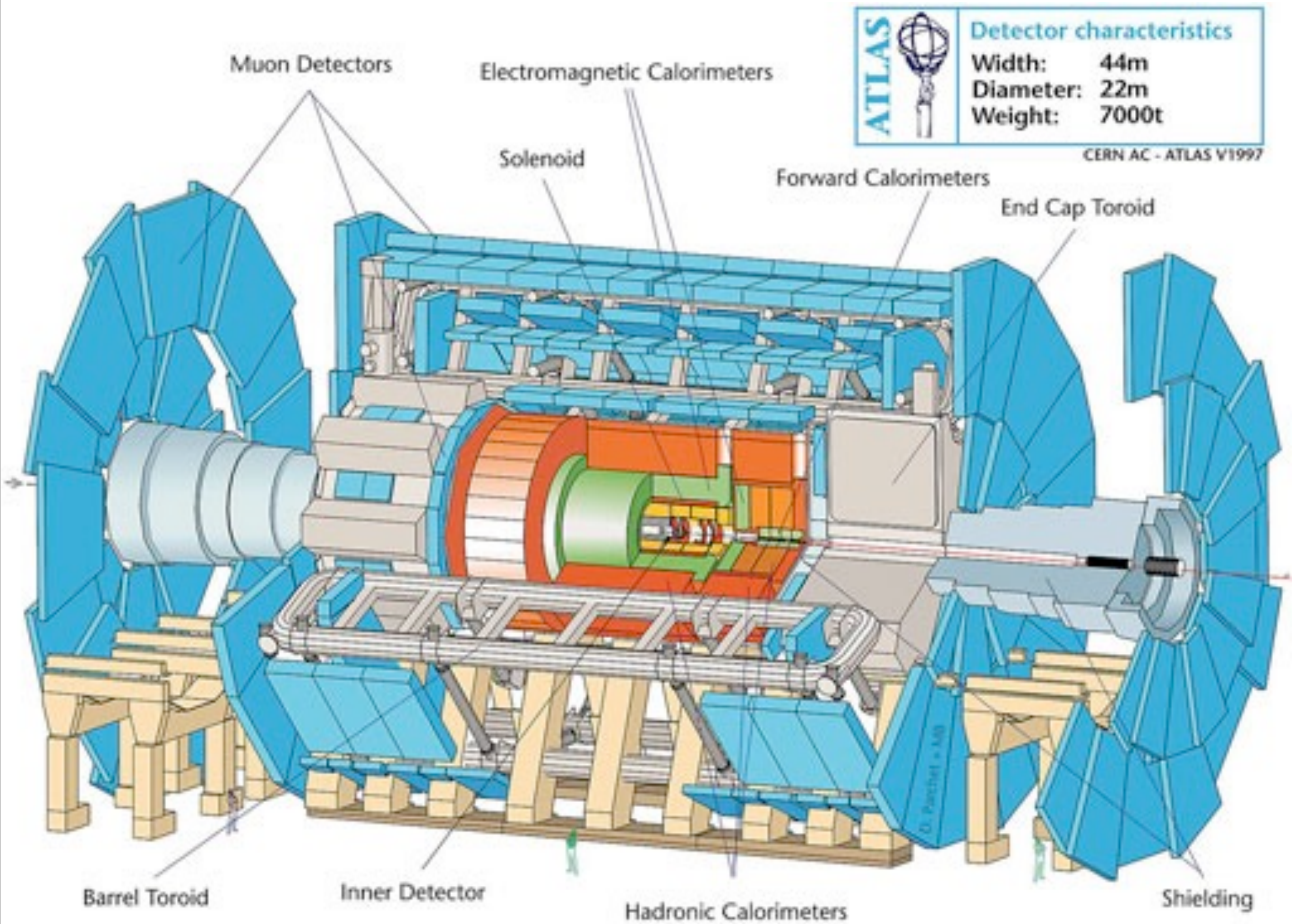
- Run 1 dataset: **~25 fb^{-1}** @ 7-8 TeV
  - Consistent with SM spin-CP expectation 0^+
- Alternative models (spin 2, neg. parity...) excluded at > 99.9% CL

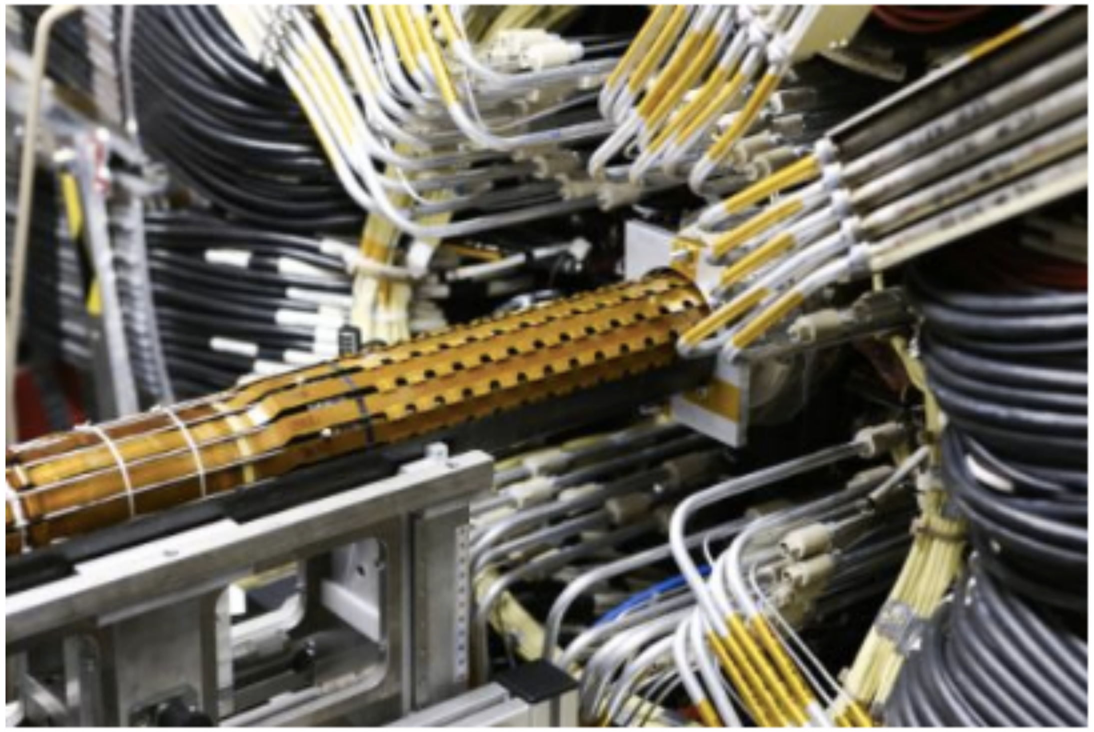
m_H=125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV

Run II Results

$\sim$13-15fb^{-1}

The ATLAS Detector in Run 2

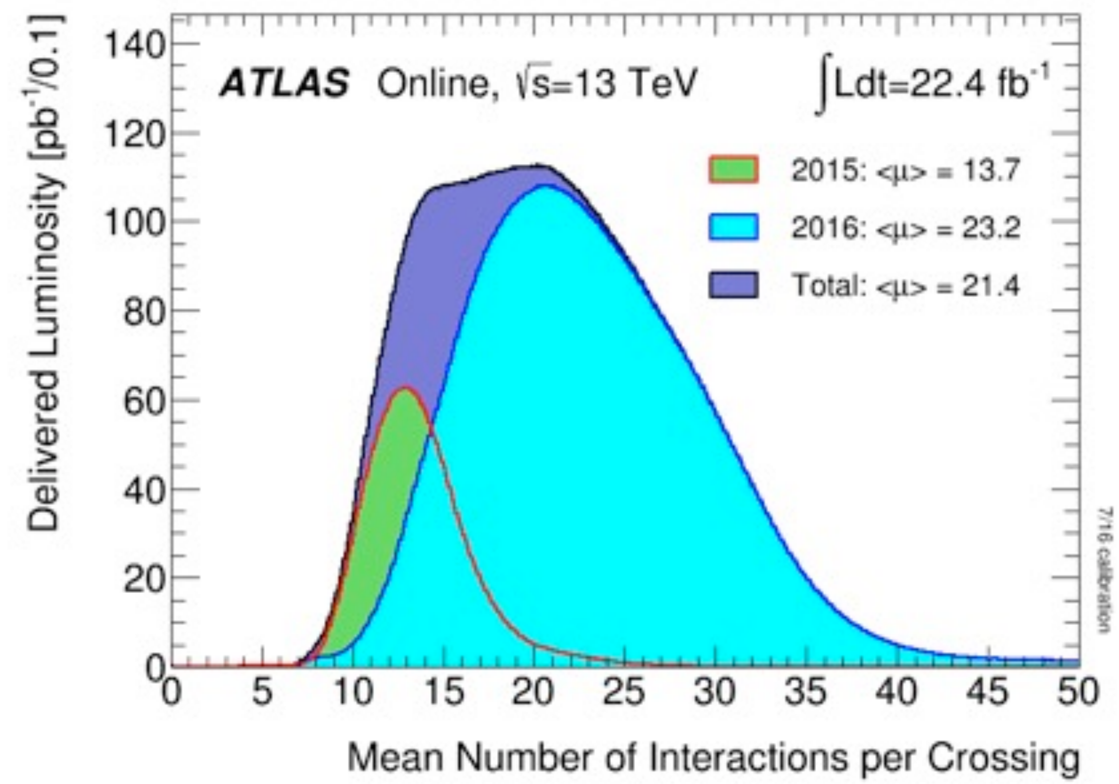


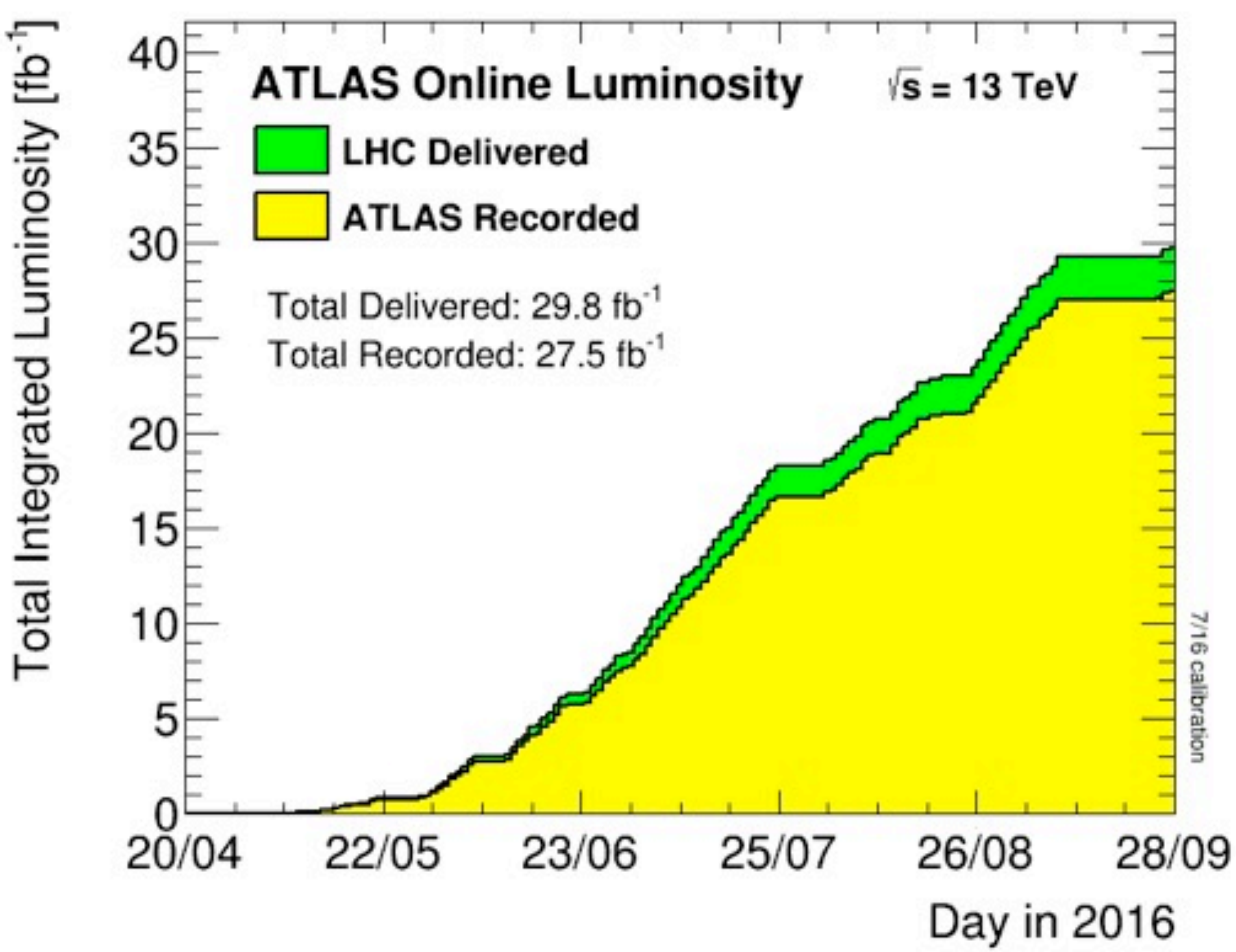


- The ATLAS detector has been significantly improved during the Long Shutdown 2013/2014:
  - **Infrastructure**: new beam pipe, improvements to magnets and cryogenic system
  - **Consolidation**: muon chambers and various repairs, upgrade of the Pixel L2 RO
  - **New detectors**: 4th silicon pixel layer (**IBL**) at 3.3 cm from interaction point
  - **Trigger/DAQ**: increase max **L1 (hardware)** rate from 75 kHz to 100 kHz and merge the two software trigger levels.

13 TeV Data Summary

- Instantaneous luminosities above the design value (1.2 x $10^{34}cm^{-2}\ s^{-1}$) ⇒ pile-up above design values
  - 92.3% overall ATLAS data taking efficiency in 2016 (95% lately)
- 25 ns bunch-crossing scheme

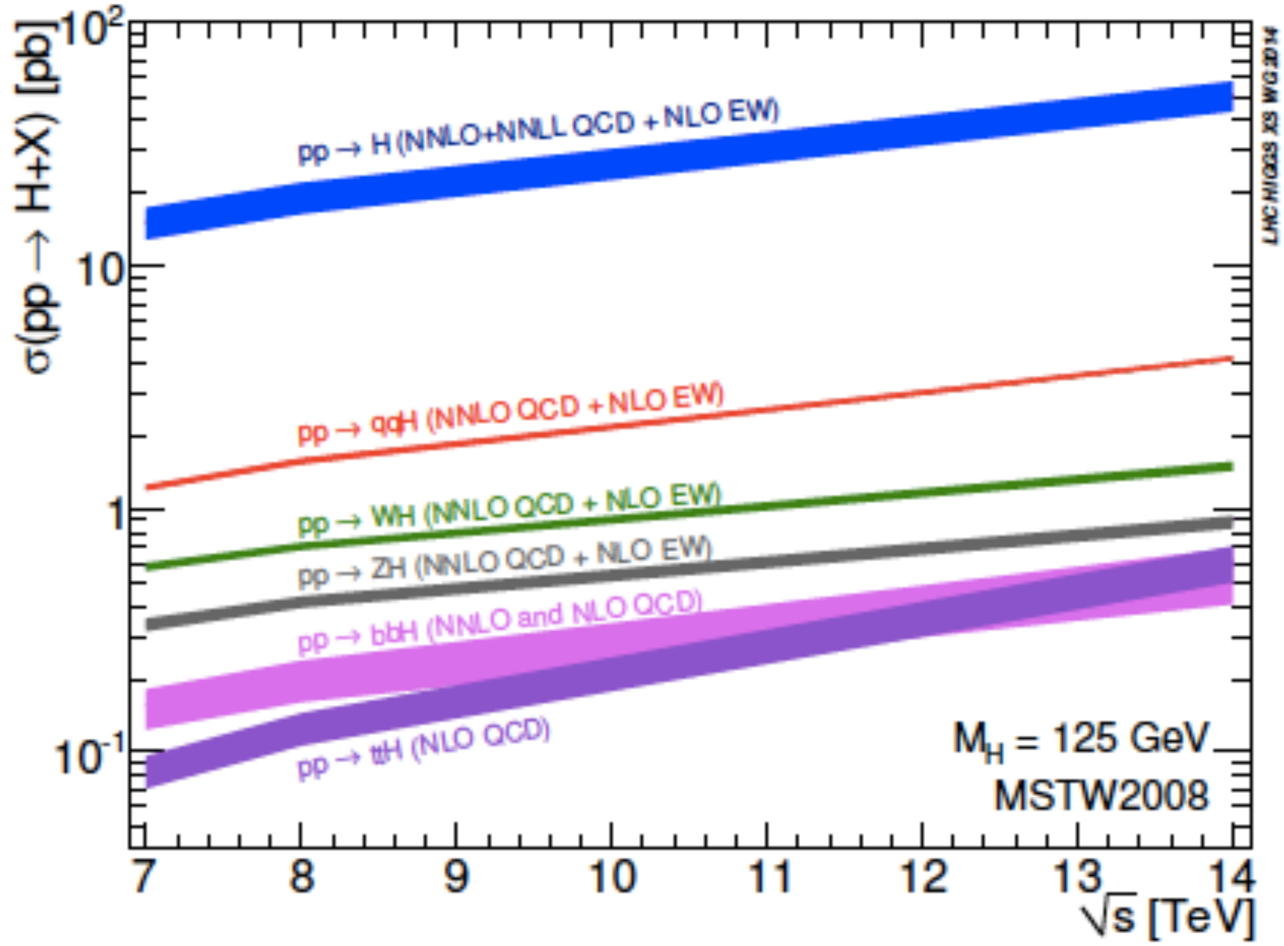




Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	98.2%
SCT Silicon Strips	6.3 M	98.7%
TRT Transition Radiation Tracker	350 k	97.2%
LAr EM Calorimeter	170 k	100%
Tile calorimeter	5200	100%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.7%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	383 k	99.8%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	357 k	99.7%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Chambers	383 k	96.6%
TGC Endcap Muon Chambers	320 k	99.6%
ALFA	10 k	99.9 %
AFP	188 k	98.8 %

Run 1 vs Run 2

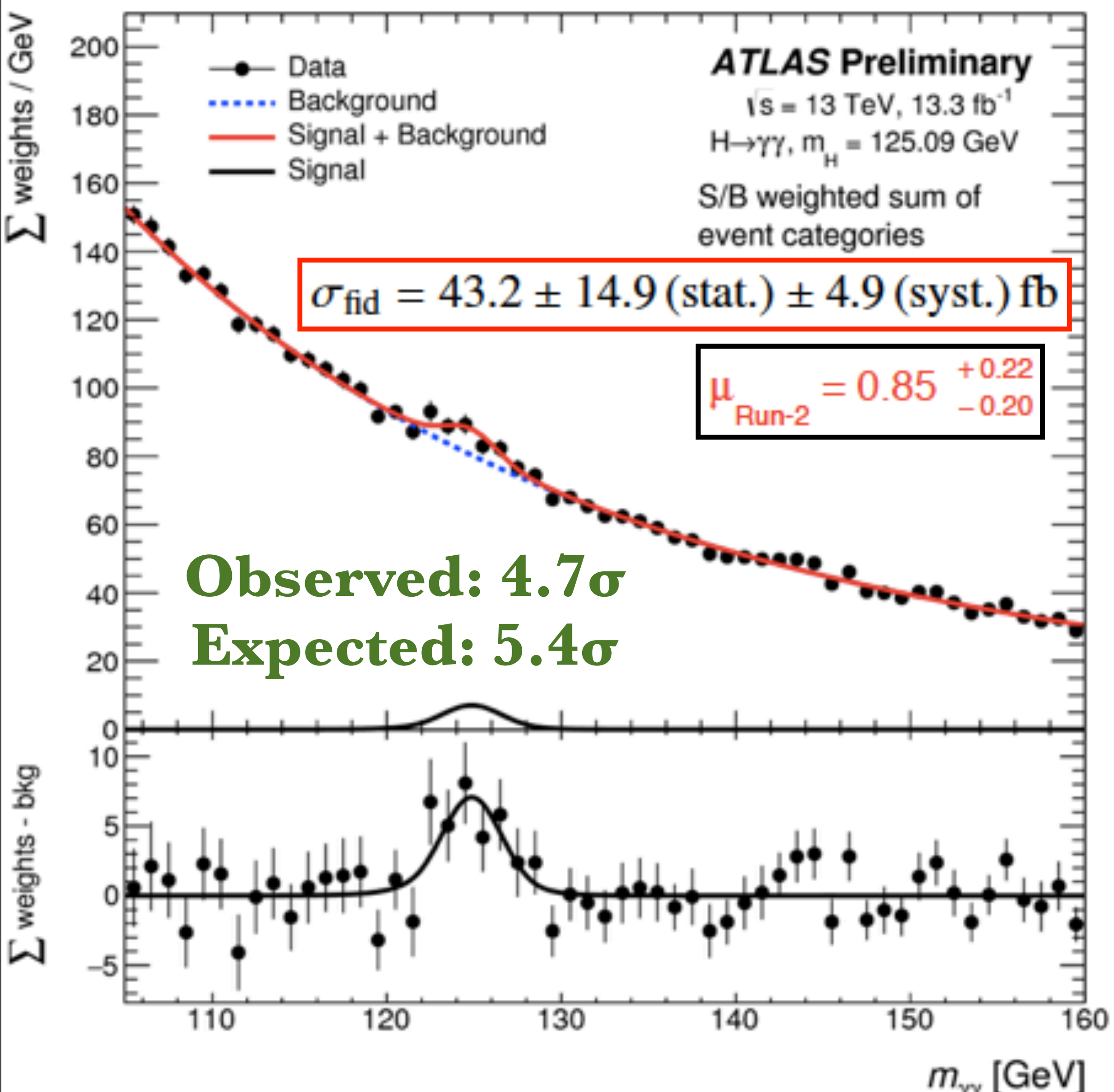
- $\sqrt{s}$ = 8 TeV ⇒ $\sqrt{s}$ = 13 TeV:
- ggF cross-sections increased by 2.3 times
- ttH production increases by 3.9 times



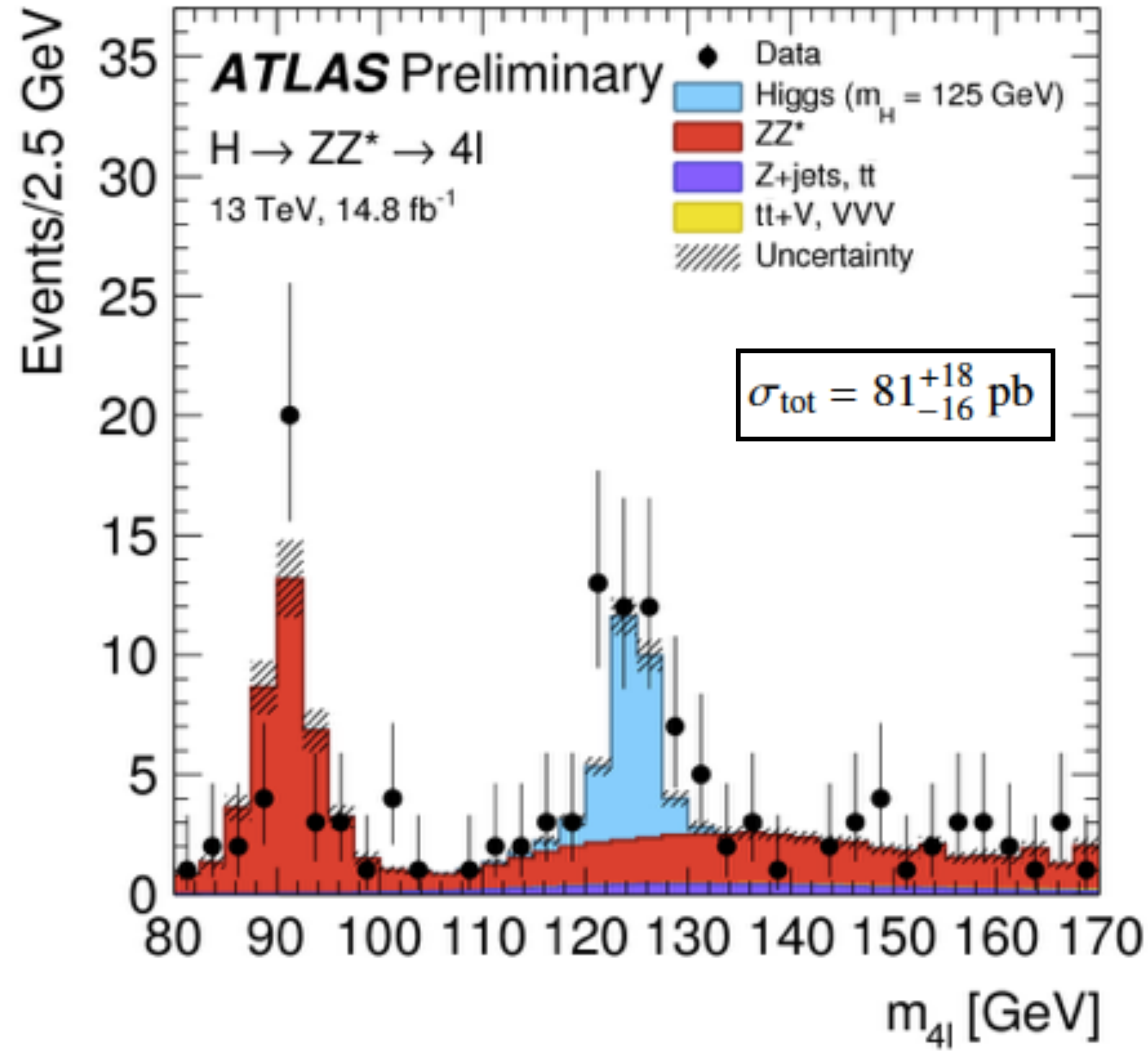
- **Run 1 analyses (7-8 TeV):**
  - measurements of mass and couplings
  - combined ATLAS+CMS results
  - spin^{CP}, width, differential cross-sections
- **Run 2 analyses (13 TeV):**
  - fiducial / total cross-section at 13 TeV
  - ttH, H→μμ

Current Run 2 Higgs Boson Results

ATLAS-CONF-2016-067

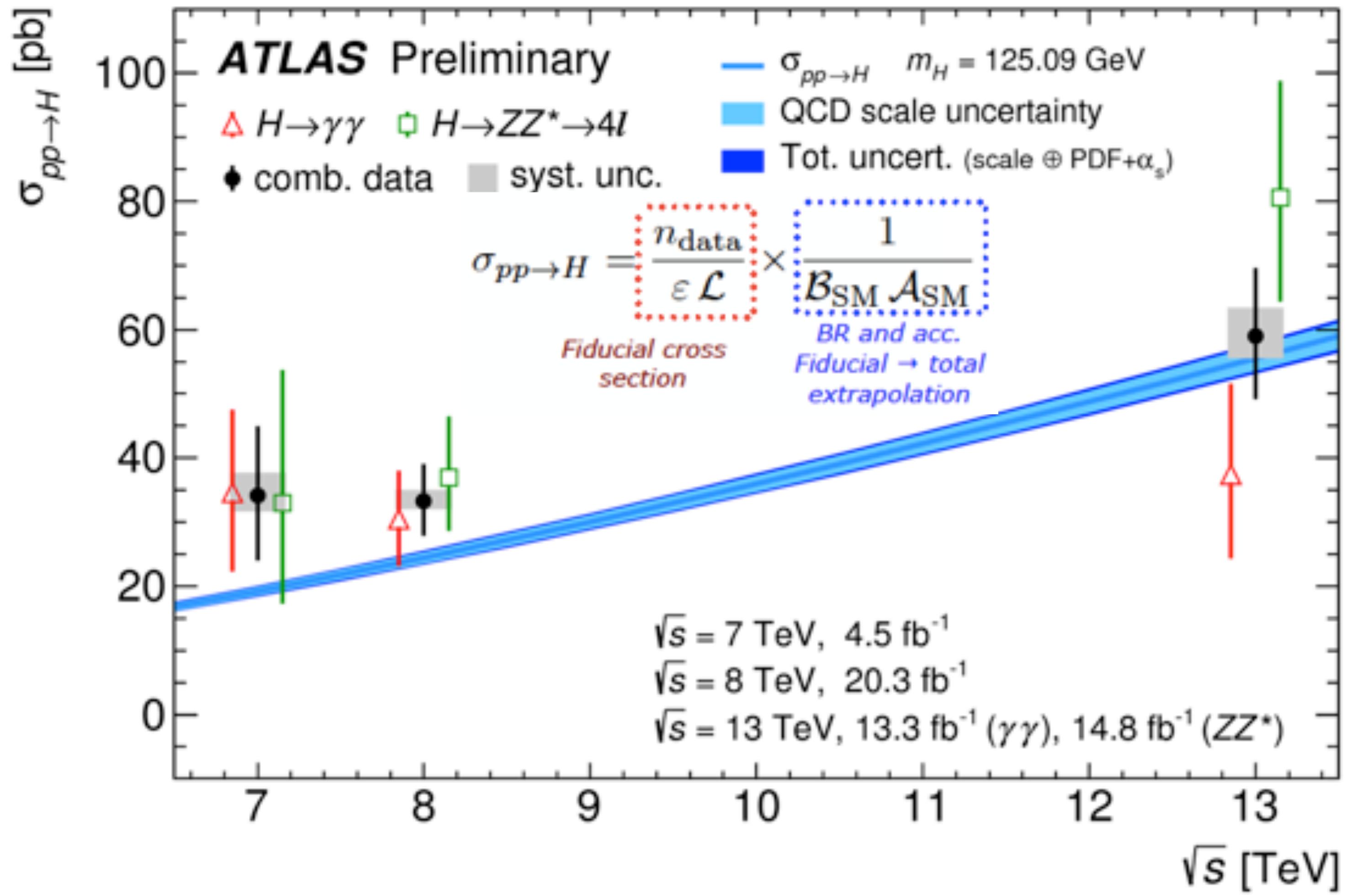


ATLAS-CONF-2016-079



- **Higgs boson production is re-observed at 13 TeV with γγ events (13.3 fb^{-1}) and 4*l* (14.8 fb^{-1}) using 13 TeV data.**
  - **all production modes targeted ggF, VBF, VH, ttH events**
  - **H→γγ: dominant syst. unc.: photon energy scale and resolution & background choice bias (smaller than statistical uncertainties)**
  - **H→ZZ*→4*l*: dominant systematic uncertainty: luminosity and lepton SF (smaller than statistical uncertainty)**

Higgs boson production and decays in $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ final states



Higgs boson production is observed with a local significance of about **10σ** (**8.6σ** expected)
- evidence for production via VBF is seen with a local significance of about **4σ** (**1.9σ** expected).

$$\mu = \frac{\sigma \times B}{\sigma^{SM} \times B^{SM}} \longrightarrow \mu = 1.13^{+0.18}_{-0.17}$$

pp → H + X in the full phase space:

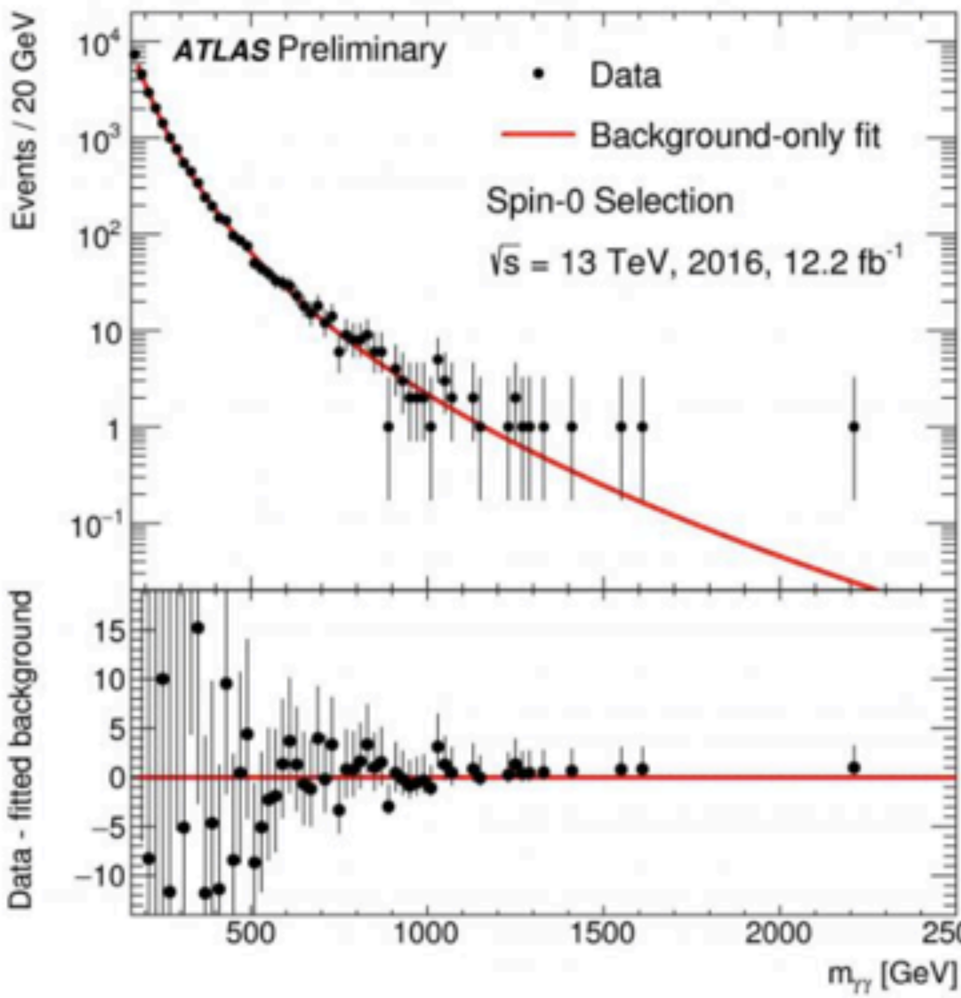
$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb

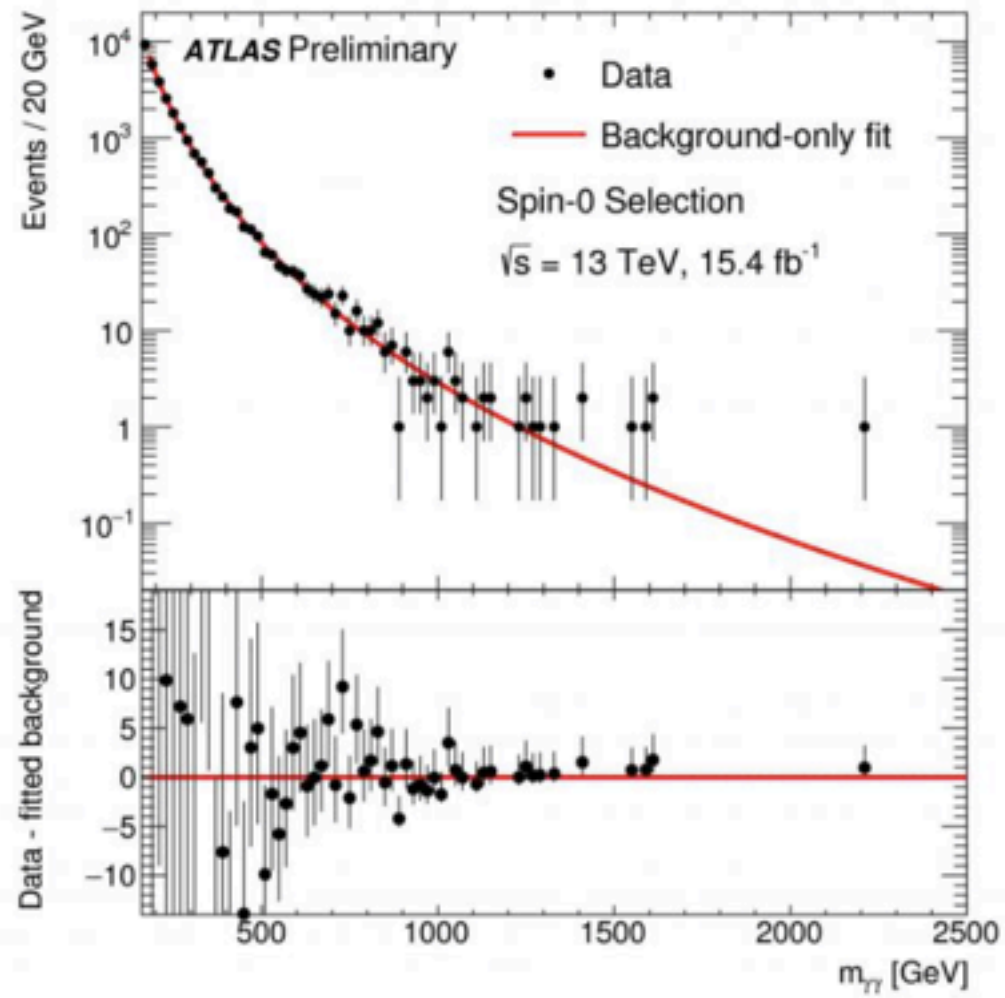
Combined results give observation of the Higgs boson at 13 TeV well above 5σ.

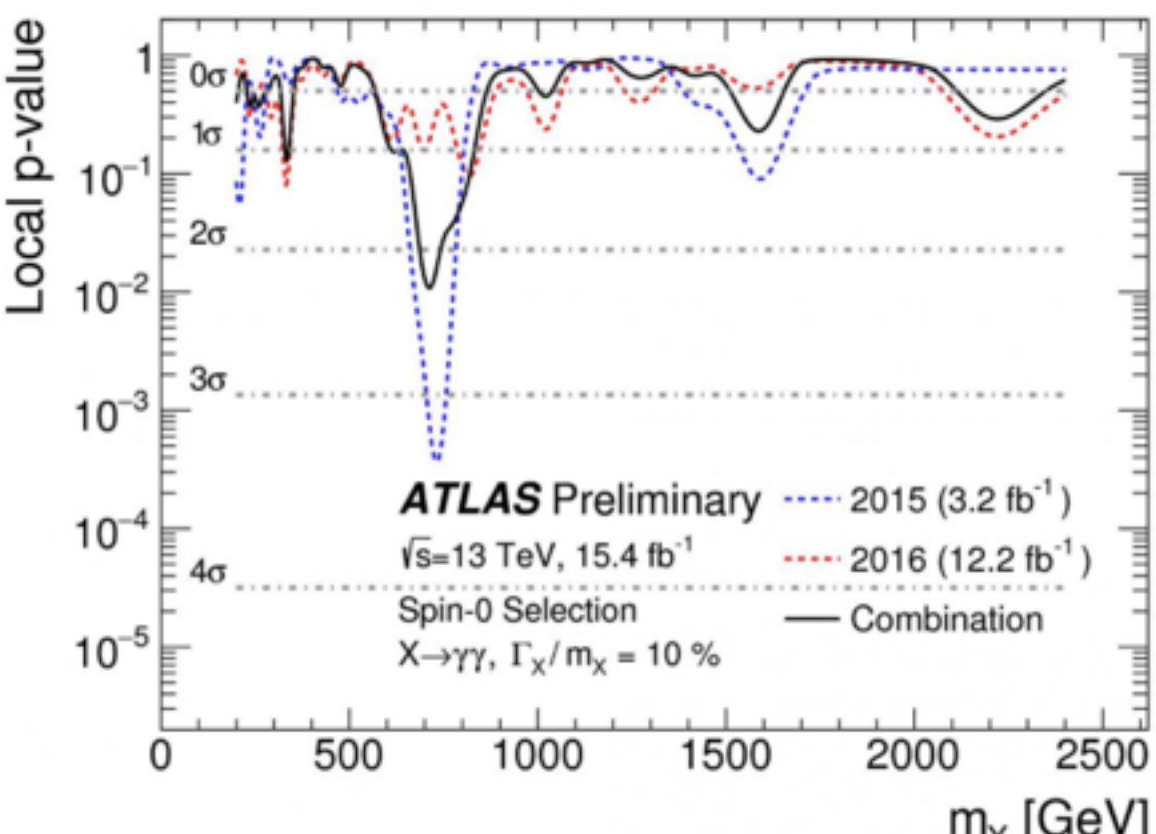
Decay channel	Total cross section ($pp \to H + X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

High Mass γγ Searches

ATLAS-CONF-2016-087







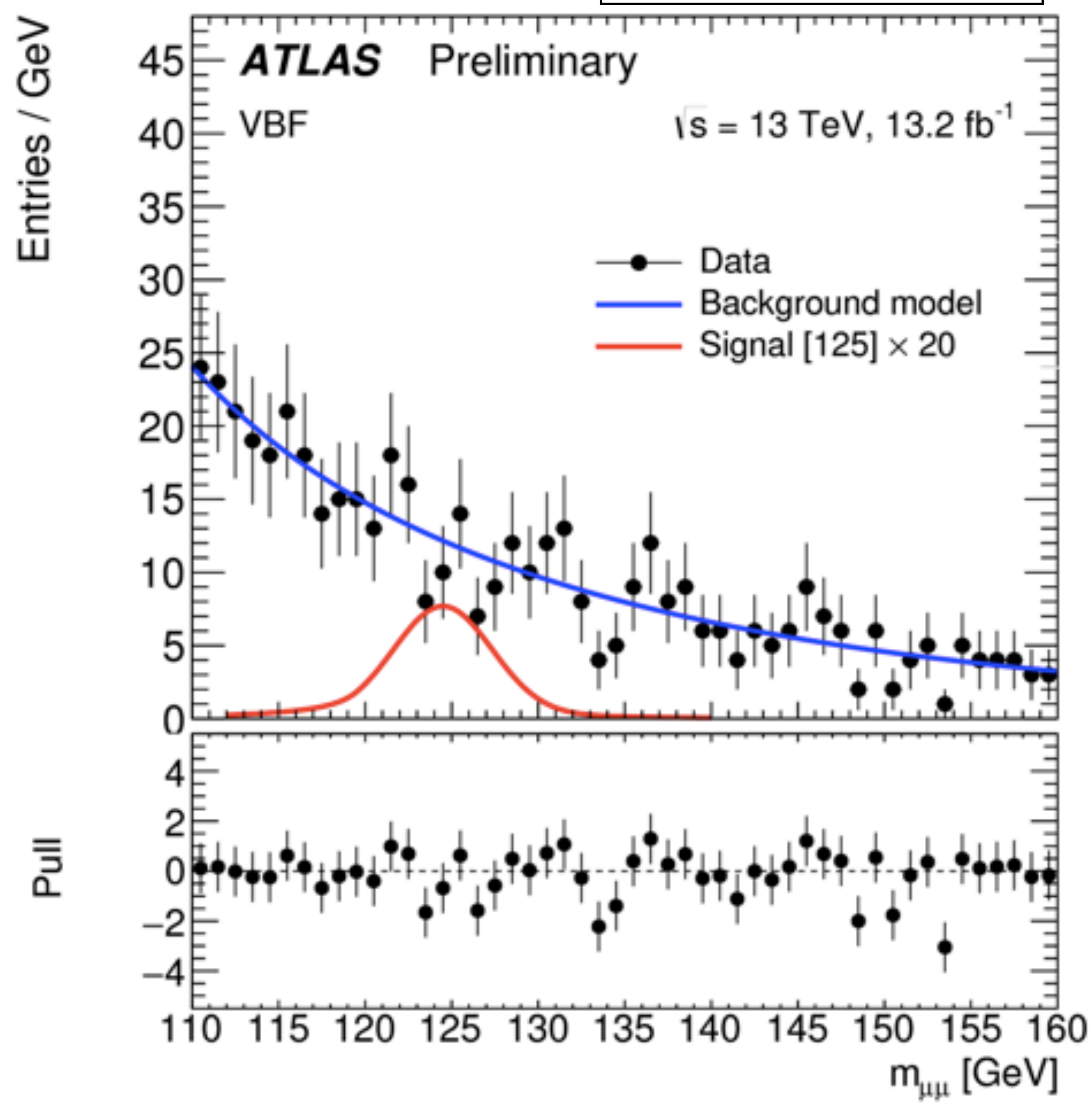
- **A broad excess found in the 2015 data around $m_{\gamma\gamma}$ =750 GeV**
- **Spin-0 analysis updated with combined 2015 + 2016 dataset**
- **No significant excess in 2016 data, compatibility between 2015 and 2016 datasets for signal cross-section @ 730 GeV: 2.7σ**
- **More work needed to complete the analysis in the extended acceptance of the spin-2 selection**

H→μμ Search Results

- A very **rare decay** in the SM
  - Probe Yukawa-coupling to 2nd-gen fermions and mass dependence
  - Test of the Higgs coupling to leptons
- **Signature**: Very clean signature from di-muon final state, but Z/γ*→μμ overwhelming irreducible background
- Search for peak in $m_{\mu\mu}$ spectrum over smoothly falling background
  - Categorize events according to VBF and ggF signature enriched

ATLAS	Upper limit x SM (expected)
Run 1	7.1 (7.2)
Run 2	4.4 (5.5)
Combined Run 1 and Run 2	3.5 (4.5)

ATLAS-CONF-2016-041



Combination with Run I:

$$\mu_S = -1.5^{+2.1}_{-2.4}$$

Run II

300 fb^{-1}

Run 2 & 3 Physics Goals

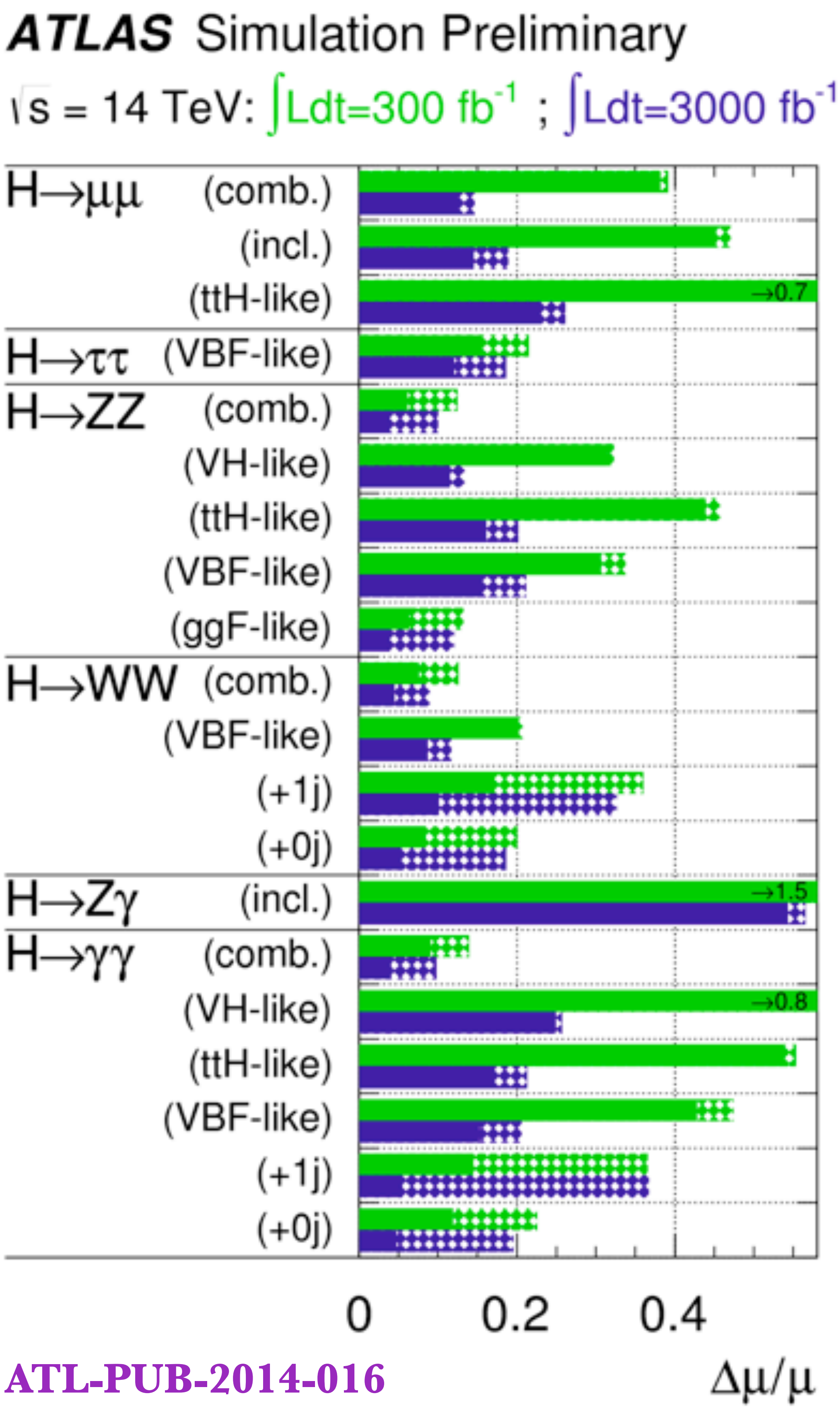
- Precise measurement of Higgs properties, in particular:
    - Higgs couplings (σ x BR) to gauge bosons at **2.5%**, to fermions (b, τ) at **7%** level. Needs also SM cross-sections theoretical improvements.
    - Sensitivity for CP-odd admixtures to scalar Higgs at **10-20%** level.
- Similar sensitivity of direct searches and indirectly from Higgs coupling measurements to:
    - extensions of the Higgs sector
    - dark matter couplings to Higgs

Event Yields Projections Run 2

$\mathcal{L}$ (fb^{-1})	All	H→γγ	H→ZZ→4l	H→WW*→$l\nu l\nu$
13.3	0.75M	600	20	400
150	8M	6800	225	4500
300	17M	13500	450	9000

- The peak instantaneous luminosity will be in the range:
  - 2-3 x 10^{34} cm^{-2} s^{-1}
  - expected pile-up ~**60**
- Projections for Run 3 (300 fb^{-1}) and HL-LHC (3000 fb^{-1}) are derived using MC hadron level samples with detector efficiency and resolution ("smearing") functions derived from full simulation of the expected upgraded detector and corresponding to the expected beam conditions.

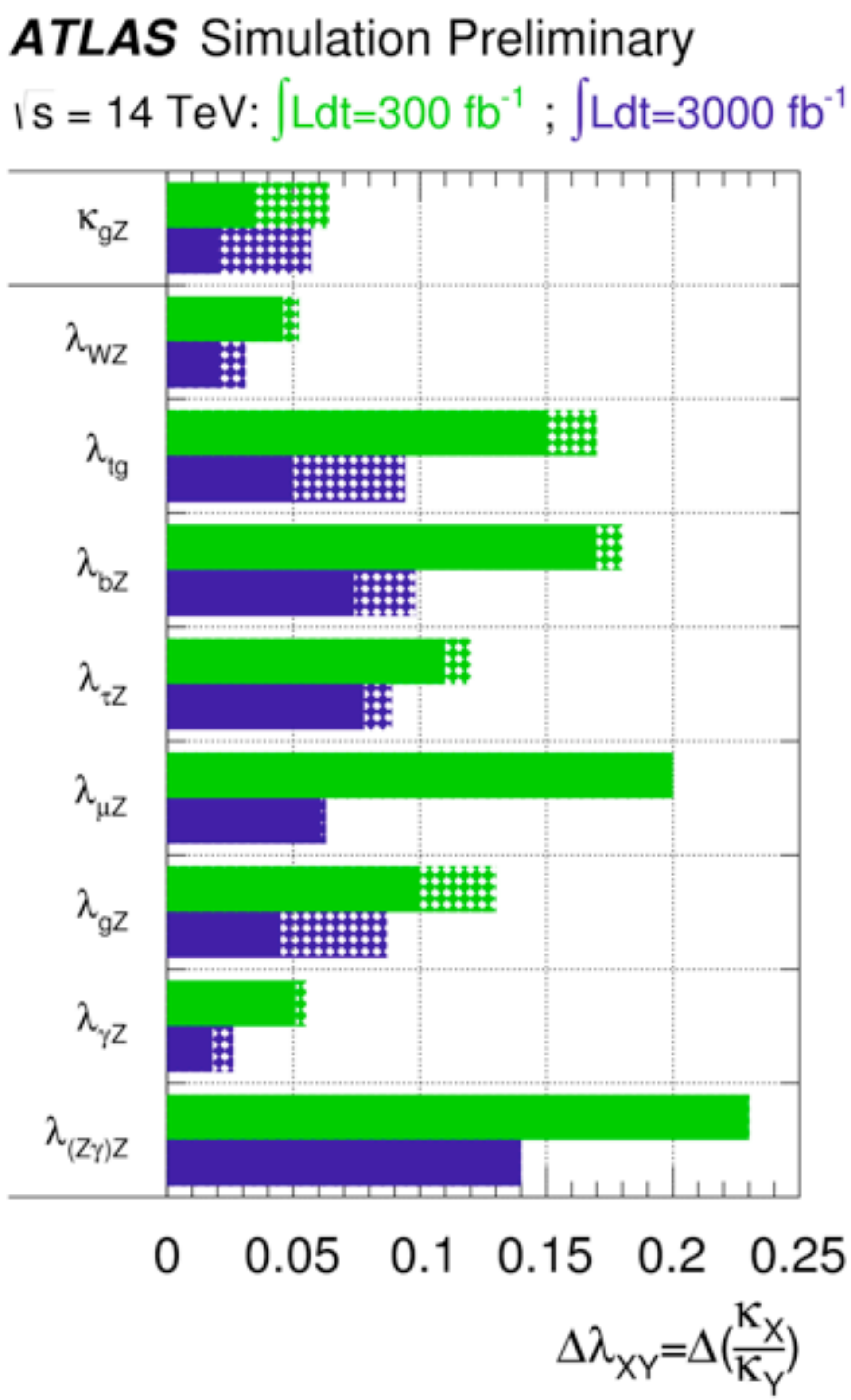
Higgs Signal Strength



ATL-PUB-2014-016

- **Relative uncertainty** on the total signal strength **μ** for all Higgs final states
- The **hashed areas** show the **increase of the estimated error due to current theory systematic uncertainties.**
- **Reducing the errors on the theory prediction is an important work ongoing in the theory community at present.**
- **Expecting ~2.5% (7%) precision in Higgs couplings to vector bosons (fermions) reachable with Run 2&3.**

Expected Higgs Couplings Results Run 2 & 3



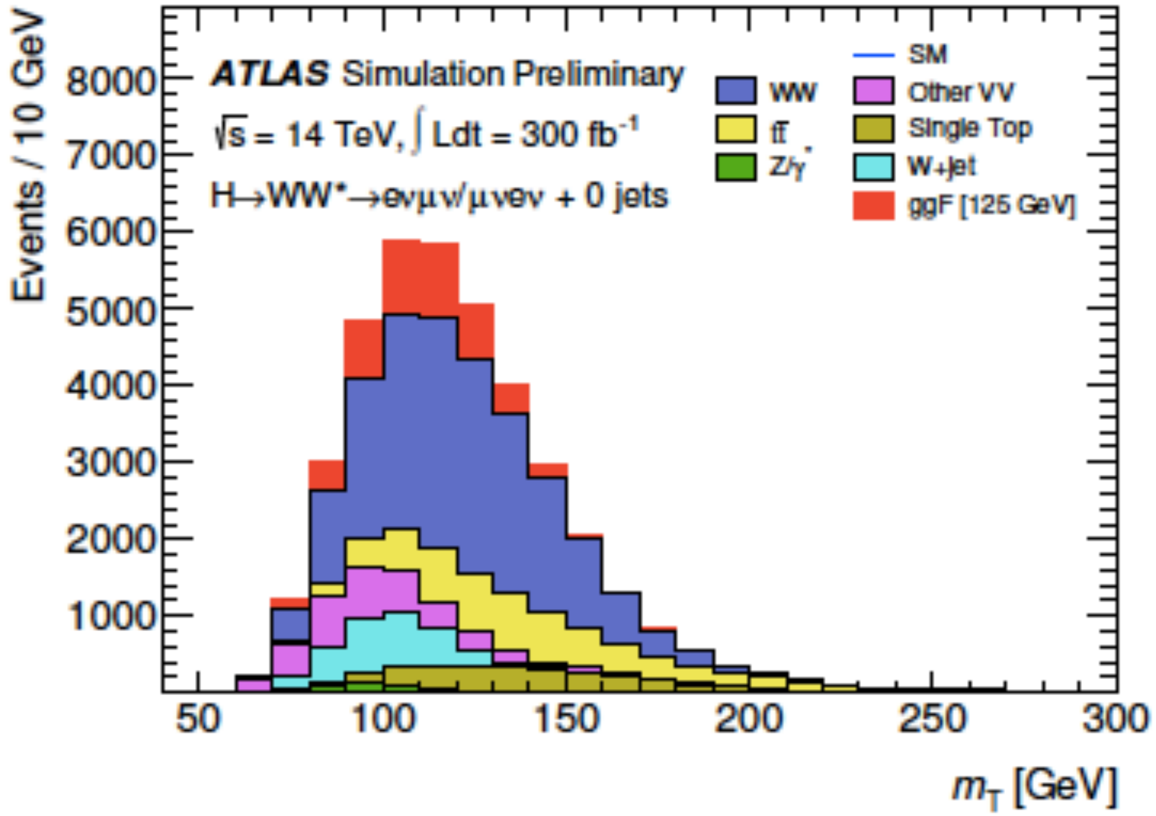
- **Relative uncertainty** expected for the determination of coupling scale factor ratios λ_{ij}

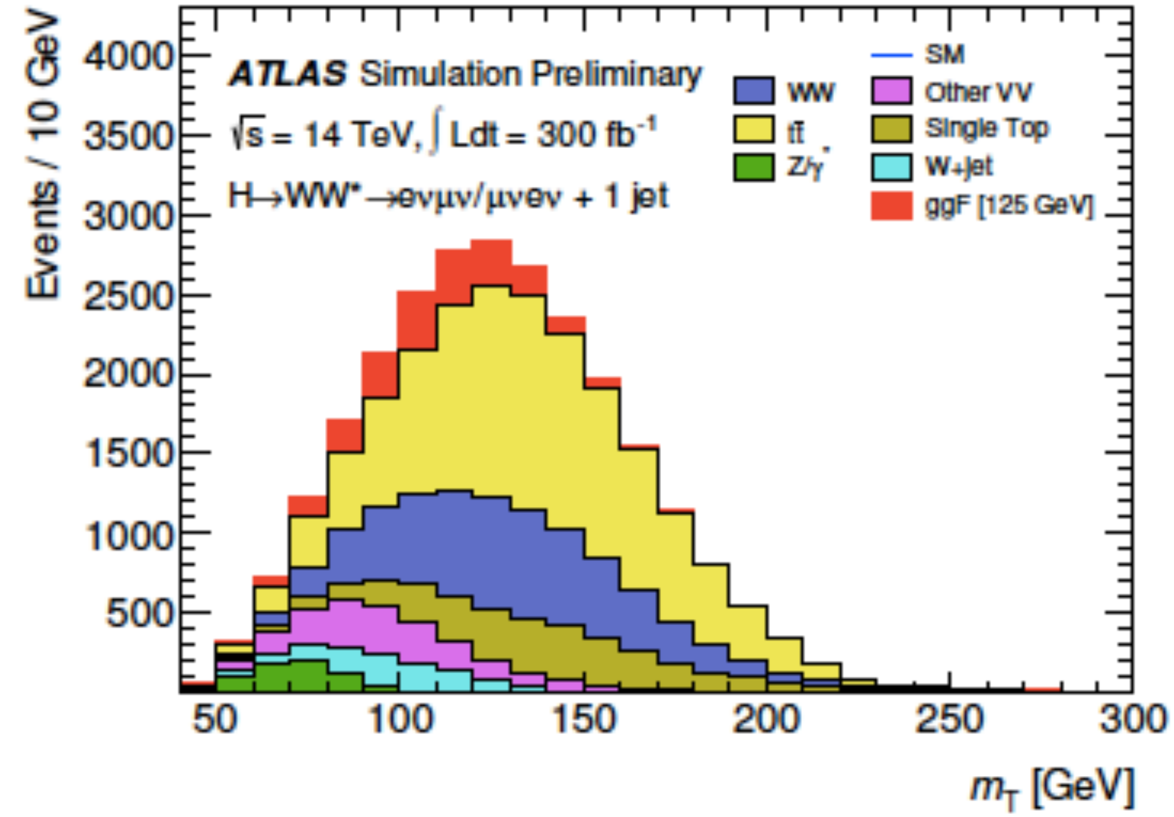
$$\lambda_{ij} = \kappa_i/\kappa_j$$

- Higgs boson signal strength (stat+exp. unc. only):
- **ICHEP 2016**, **13.3 fb^{-1}**, **18%** ($\gamma\gamma$+ZZ)
- **Run 2**, **150 fb^{-1}**, **~7%** ($\gamma\gamma$+ZZ)
- **Run 3**, **300 fb^{-1}**, **~2.5%**

• At LHC we can measure λ's in an almost model independent way
• in some cases some theory uncertainties cancel out: e.g. the ratio $\lambda_{\gamma Z}$ can be measured at ~2-3% (very important test of SM predictions)

H→WW→$l\nu l\nu$





* based on reconstructed events with 8 TeV extrapolated to the 14 TeV conditions by PDF re-weighting and emulation of the difference in performance of the ATLAS detector in the high pile-up environment.

- ggF and VBF production modes studied, final states with 0,1, ≥2 jets, for pu=50

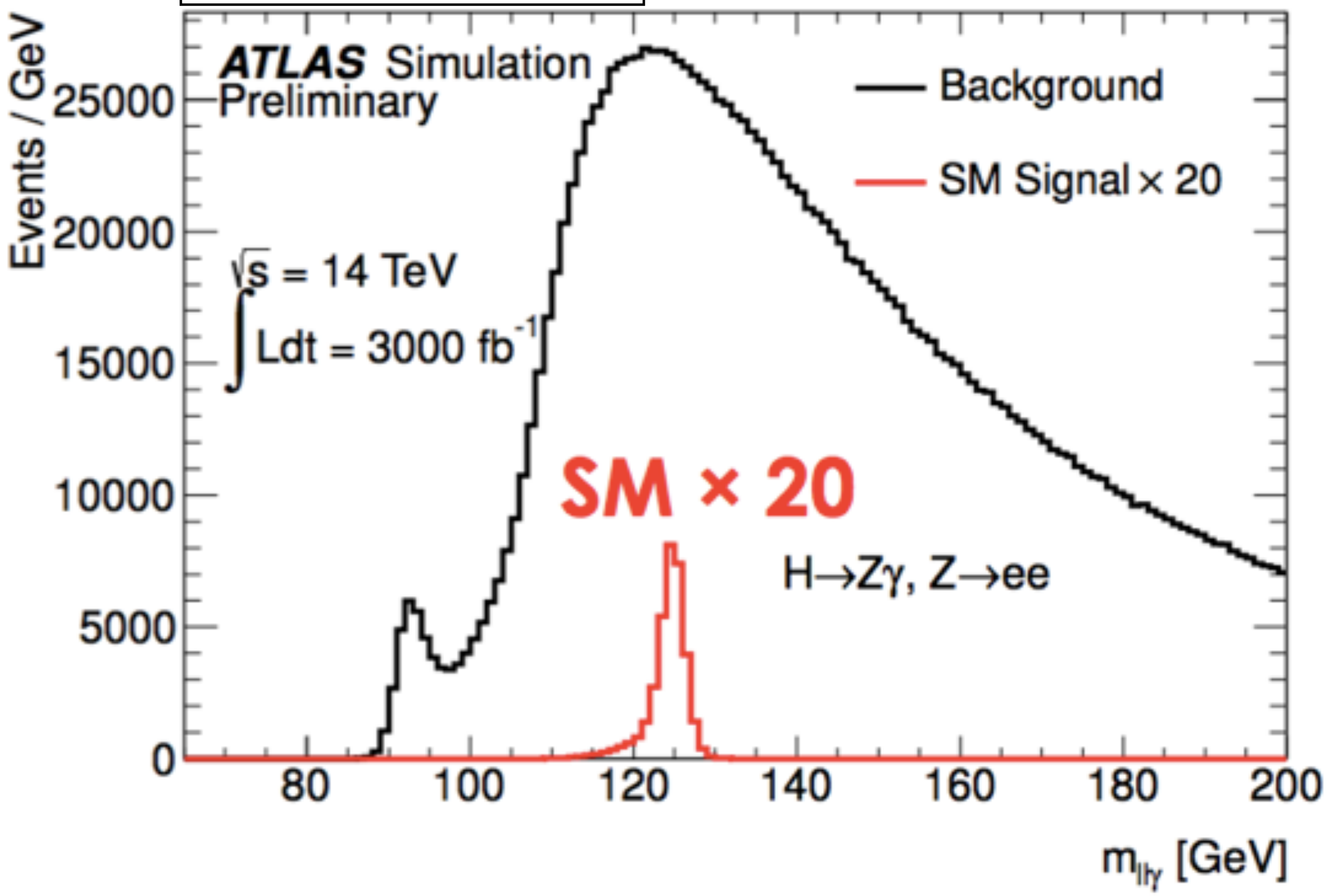
$N_{\rm jet}$	$N_{\rm bkg}$	$N_{\rm signal}$	$N_{\rm ggF}$	$N_{\rm VBF}$	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	$N_{Z+\rm jets}$	$N_{W+\rm jets}$
$=0$	34330	4380	4300	80	19000	3500	6000	2600	370	2860
$=1$	21460	1970	1740	230	5760	1800	9360	2850	710	980
≥ 2	101	62	5	57	12	4	60	5	12	8

The precision on the signal strength measurement

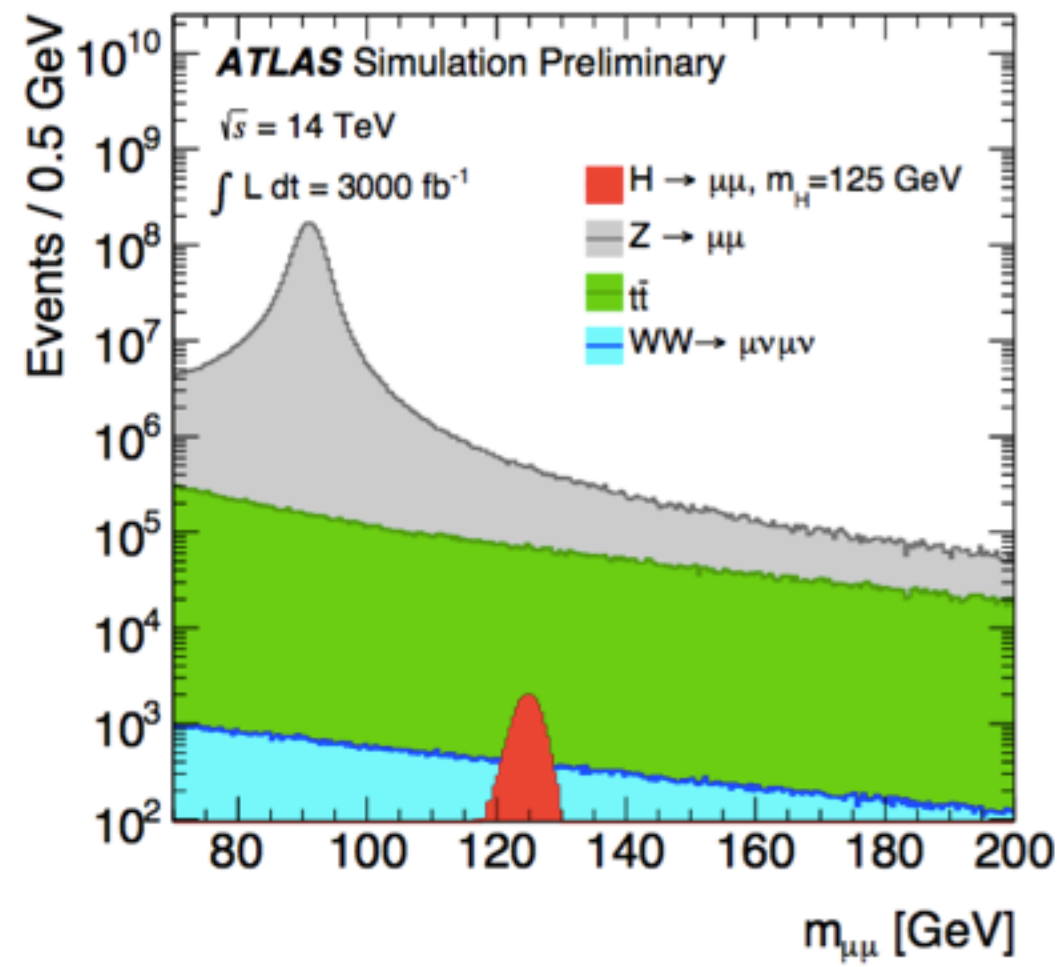
	$\mu_{\rm ggF}$	$\mu_{\rm VBF}$	$\mu_{\rm ggF+VBF}$
300 fb^{-1}	$1^{+0.18}_{-0.15}$	$1^{+0.25}_{-0.22}$	$1^{+0.14}_{-0.13}$
3000 fb^{-1}	$1^{+0.16}_{-0.14}$	$1^{+0.15}_{-0.15}$	$1^{+0.10}_{-0.09}$

Some Rare Higgs Decays

ATL-PUB-2014-006



ATL-PUB-2013-014



- During and after Run 3 (3000 fb^{-1}) we will have the opportunity to observe rare Higgs decays:
- H→μμ - right
  - SM sensitivity (1σ) expected with ~70 fb^{-1} (2018)) & 7σ expected with 3000 fb^{-1}
- H→Zγ→eeγ (left)

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

Summary

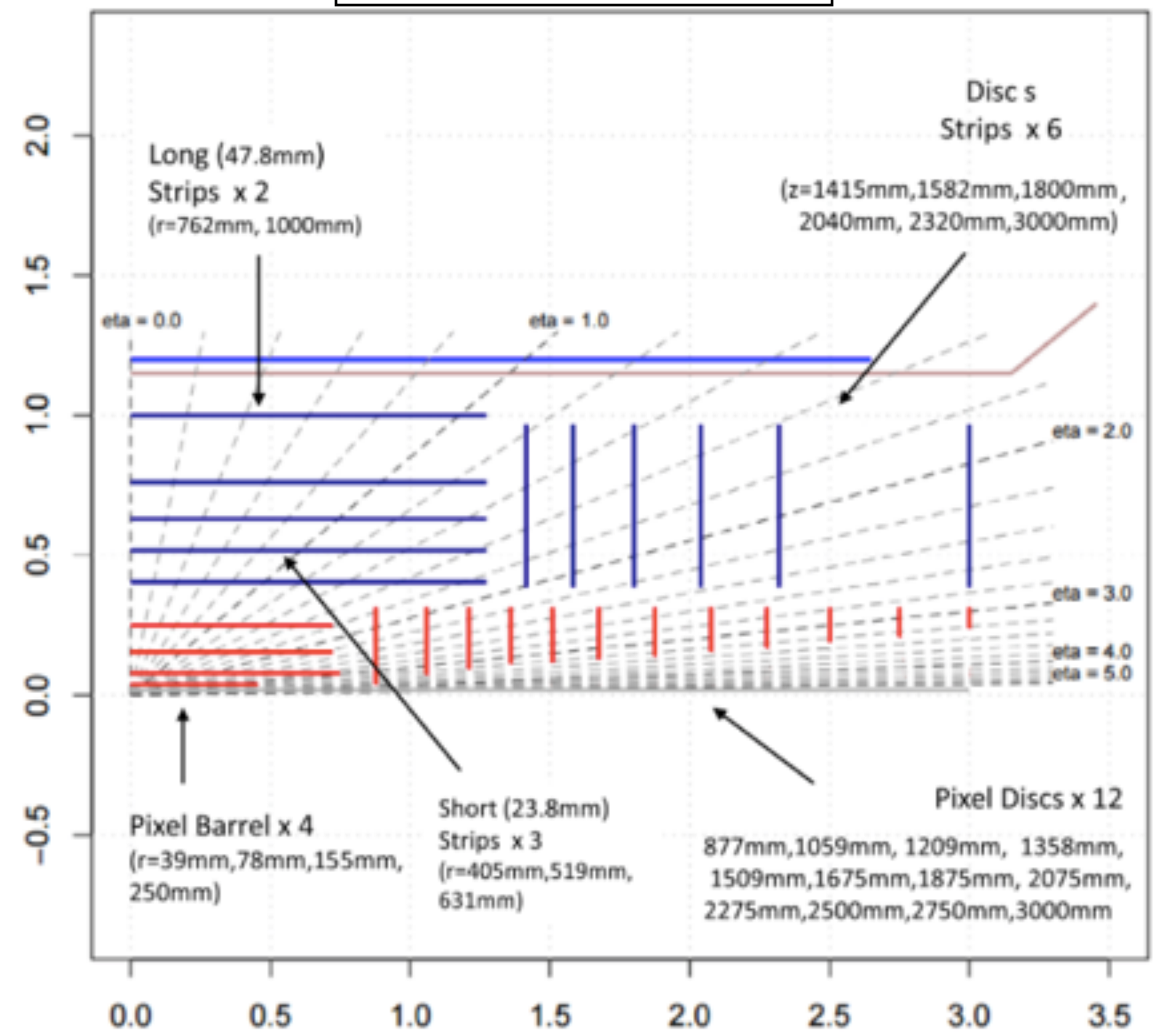
- LHC is currently delivering data above expectations
  - We have recorded **27.5 fb^{-1}** (**92.3%** overall ATLAS **efficiency**) in 2016
- The Higgs boson was re-observed in the $\gamma\gamma$+ZZ channels with **~10σ** (**8.6σ**) **observed** (**expected**) significance (ICHEP) 2016
- Preliminary measurements of the Higgs boson cross-section and couplings have been examined in first Run 2 results and are found to be consistent with SM expectations
- An increase in data statistics would allow future sensitivity for results on Higgs self coupling and rare Higgs decays.
- **Stay tuned for further 2016 results from Run 2 with ~40 fb^{-1}**

BACKUP

Detector Upgrades

- New **all-silicon tracker** with significantly improved forward coverage: $|\eta|<4$ (now 2.5)
  - Improved granularity of forward calorimeter
  - Improved triggering capabilities
  - New high-granularity timing detector in the forward region
- Will improve capabilities to suppress pileup, in particular in the forward region → enhanced precision to study events with VBF topology

CERN-LHCC-2015-020
LHCC-G-166



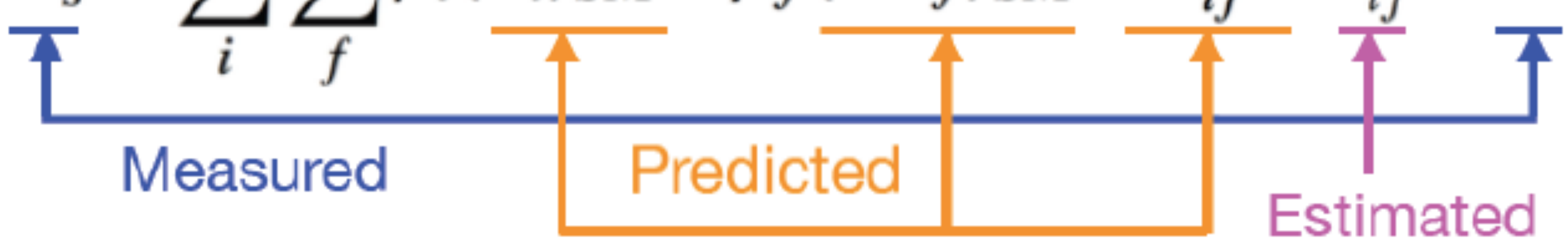
Production and decay strengths

- ATLAS uses parameters called production and decay strengths defined as the ratios between the actual production cross-sections/branching ratios and the SM predictions

Production (initial state) $$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}$$ Decay (final state)

- Maximum profile likelihoods used to determine these parameters from correlations between signal rates in various channels c:

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\mathrm{SM}} \times \mu_f (\mathrm{BR}_f)_{\mathrm{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$



H→μμ Uncertainties

	ggF signal	VBF signal
Experimental		
Luminosity	2.9%	
Muon efficiency	1%	
Muon momentum resolution	<1%	
Muon trigger	<1%	
Muon isolation	2%	
Jet energy scale	-	5%
Theoretical		
Higgs branching ratio	1.23%	
QCD scales	4%	0.8%
PDFs and α_s	1.9%	2.1%
ggF contribution to VBF	22% (VBF region only)	-
Multi-parton interactions	9%	4%
Higgs p_T distribution	22% for $p_T < 10$ GeV 13% for $p_T > 10$ GeV	-

Table 2: Main sources of experimental and theoretical uncertainties on the signal yield, except for the error from mismodeling bias. "QCD scale" indicates the theoretical uncertainty on the Higgs boson production due to missing higher-order corrections estimated by varying the QCD renormalisation and factorisation scales, while "PDFs and α_s" indicates the uncertainty due to parton distribution functions, as described in Ref. [24]. Higgs p_T distribution uncertainties in the $p_T < 10$ GeV and $p_T > 10$ GeV regions are anti-correlated. The ranges for the uncertainties cover the variations among different categories and data-taking periods. The impact of the signal systematic uncertainties on the signal strength measurement is less than 0.5%.

The total systematic uncertainty (in %) for the background processes at 300 fb^{-1} for H→WW

	$N_{jet} = 0$			$N_{jet} = 1$			$N_{jet} \geq 2$		
	14 TeV	ES	8 TeV	14 TeV	ES	8 TeV	14 TeV	ES	8 TeV
WW	1.5	5	5	5	-	6.5	10	10	30
VV	2	15	15	5	-	20	10	20	20
$t\bar{t}$	7	7	12	8	-	23	10	15	33
$tW/tb/tqb$	7	7	12	8	-	23	10	15	33
Z+jets	10	10	15	10	-	18	10	10	20
W+jets	20	30	30	20	-	30	20	100	30

Theoretical uncertainties at 8 TeV

	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
ggF QCD scale	17	37	43
ggF QCD acceptance	4	4	4
ggF PDF	8	8	8
ggF UE/PS	3	10	9
ggF total	19	39	44
VBF QCD scale	1	1	1
VBF QCD acceptance	4	4	4
VBF PDF	3	3	3
VBF UE/PS	3	10	3
VBF total	6	11	6

Coupling scale factors κ

The coupling scale factors κ_j are defined in such a way that the cross sections σ_j and the partial decay widths Γ_j associated with the SM particle j scale with κ_j^2 compared to the SM prediction [41]. With this notation, and with κ_H^2 being the scale factor for the total Higgs boson width Γ_H, the cross section for the $gg \to H \to \gamma\gamma$ process, for example, can be expressed as:

$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot B_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \qquad (2)$$

$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t\kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}}$$

$$\kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{Z\gamma}^{ij}}{\sum_{i,j} \Gamma_{Z\gamma}^{ij}}$$

$$\kappa_H^2 = \sum_{\substack{jj = WW,\, ZZ,\, b\bar{b},\, \tau^-\tau^+,\\ \gamma\gamma,\, Z\gamma,\, gg,\, t\bar{t},\, c\bar{c},\, s\bar{s},\, \mu^-\mu^+}} \frac{\kappa_j^2 \Gamma_{jj}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

Expected precision for Higgs couplings

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	3.2%	2.7%	2.5%	2.5%	1.9%	1.6%
2	$\kappa_V = \kappa_Z = \kappa_W$	3.3%	2.8%	2.7%	2.6%	1.9%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.6%	7.5%	7.1%	4.1%	3.5%	3.2%
3	κ_Z	8.4%	7.3%	6.8%	6.3%	5.0%	4.6%
	κ_W	8.0%	6.7%	6.2%	6.1%	4.8%	4.3%
	κ_t	11%	9.0%	8.3%	7.0%	5.6%	5.1%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	14%	13%	14%	11%	10%
	κ_μ	22%	20%	20%	10%	8.1%	7.5%
4	κ_Z	8.0%	7.0%	6.6%	5.2%	4.3%	4.0%
	κ_W	7.7%	6.8%	6.5%	4.9%	4.2%	3.9%
	κ_t	19%	18%	18%	7.7%	6.7%	6.3%
	$\kappa_d = \kappa_\tau = \kappa_\mu = \kappa_b$	16%	13%	12%	11%	8.2%	7.2%
	κ_g	8.9%	7.9%	7.5%	4.3%	3.8%	3.6%
	κ_γ	13%	9.3%	7.8%	9.3%	5.9%	4.2%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%
5	κ_Z	8.1%	7.1%	6.7%	6.2%	4.9%	4.4%
	κ_W	7.9%	6.9%	6.5%	5.9%	4.8%	4.4%
	κ_t	22%	20%	20%	10%	8.4%	7.8%
	$\kappa_{d3} = \kappa_\tau = \kappa_b$	18%	15%	13%	15%	11%	9.7%
	κ_μ	23%	21%	21%	11%	8.5%	7.6%
	κ_g	11%	9.1%	8.5%	6.9%	5.5%	4.9%
	κ_γ	13%	9.3%	7.8%	9.4%	6.1%	4.6%
	$\kappa_{Z\gamma}$	79%	78%	78%	30%	30%	29%

Table 18: Expected precision on Higgs coupling scale factors with 300 and 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV for selected parametrizations, assuming no new contributions to the Higgs total width beyond those in the Standard Model. The Higgs total width can still differ from its expected value in the Standard Model in the absence of any new decay modes if any of its couplings to SM particles differ from their expected values. Additional parametrizations explicitly including the b-quark coupling scale factor κ_b are possible in principle, but are not studied at the moment in the absence of $H \to b\bar{b}$ projections at high luminosity. The coupling scale factor κ_V represents the gauge bosons W and Z, κ_F all fermions, and κ_d and κ_{d3} all, respectively third generation, down-type fermions.