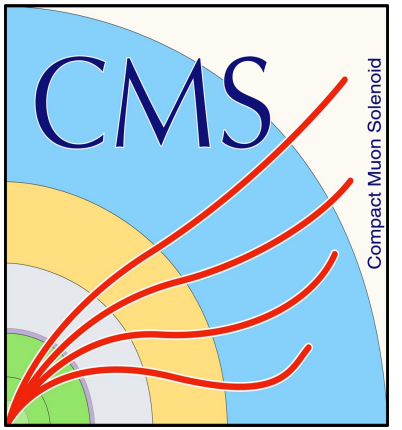
Standard Model Higgs results from ATLAS and CMS experiments

Jana Faltova
on behalf of ATLAS and CMS Collaborations



Epiphany 2016
7 – 9 January 2016, Krakow

Outline

- LHC collider
- ATLAS, CMS detectors
- Run1 and Run2 conditions
- Higgs boson
- Run1 results
- First Run2 measurements
- Conclusions

Large Hadron Collider (LHC)

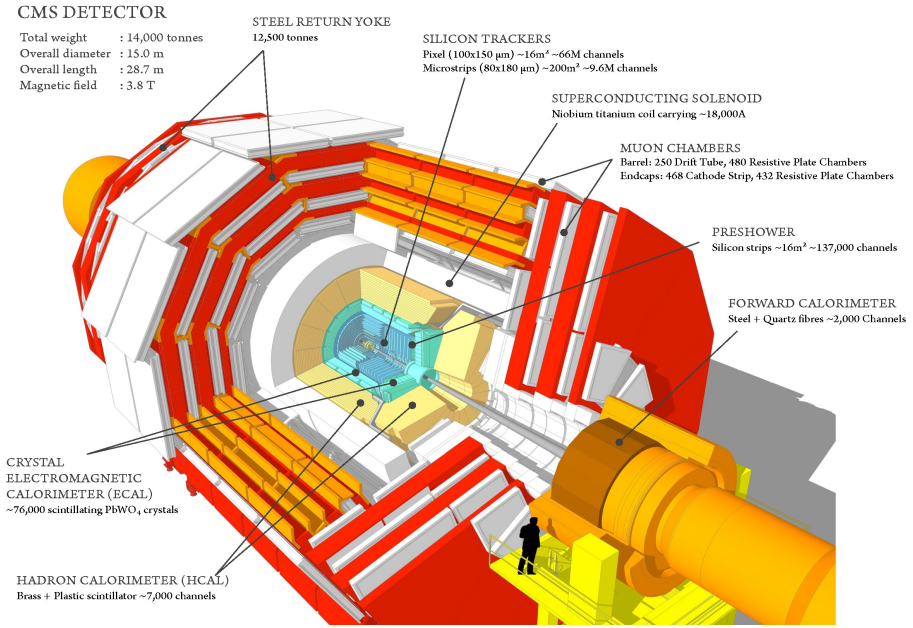
LHC at CERN

- 27 km long ring
- proton-proton and heavy ion collisions

Running conditions

- Run1 (2010 - 2012)
  - √s = 7, 8 TeV
  - 50 ns bunch spacing
- Run2 (since 2015)
  - √s = 13 TeV
  - 50 and 25 ns bunch spacing

ATLAS and CMS detectors

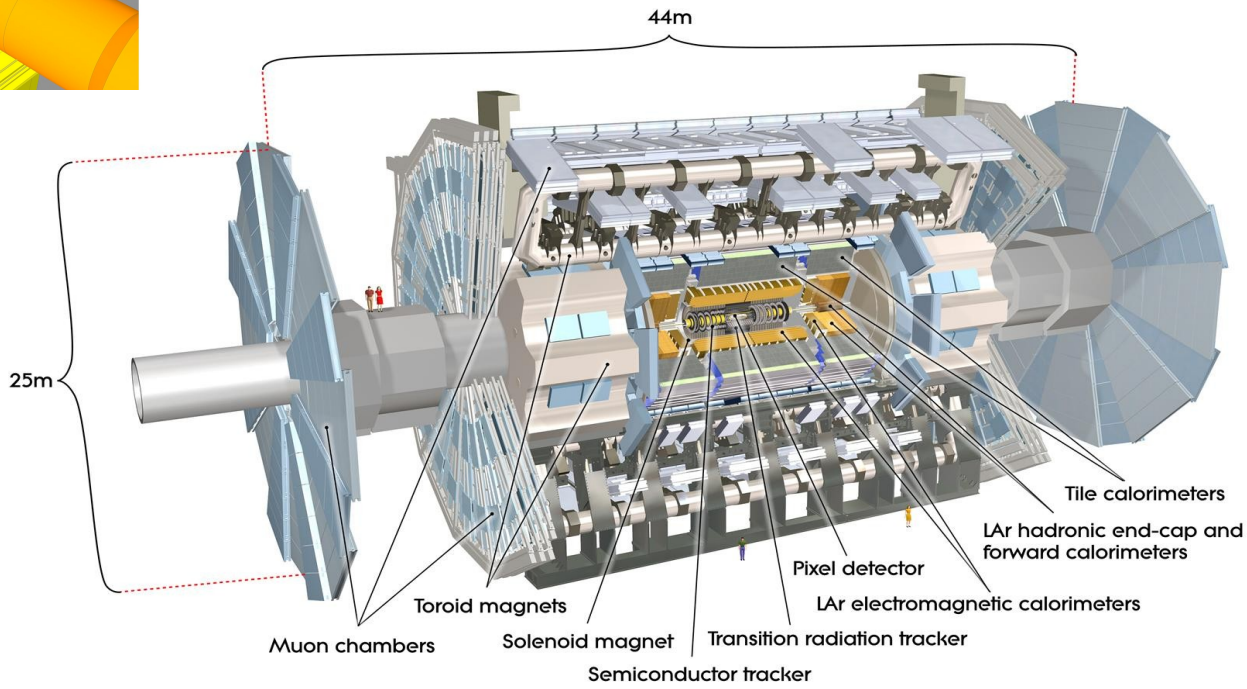


CMS in Run2

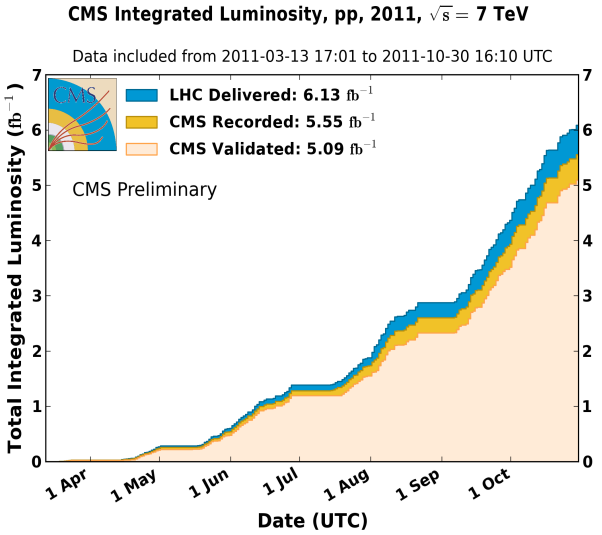
- Cold operation of Tracker
- Luminosity detectors
- 4th muon station
- New beam pipe

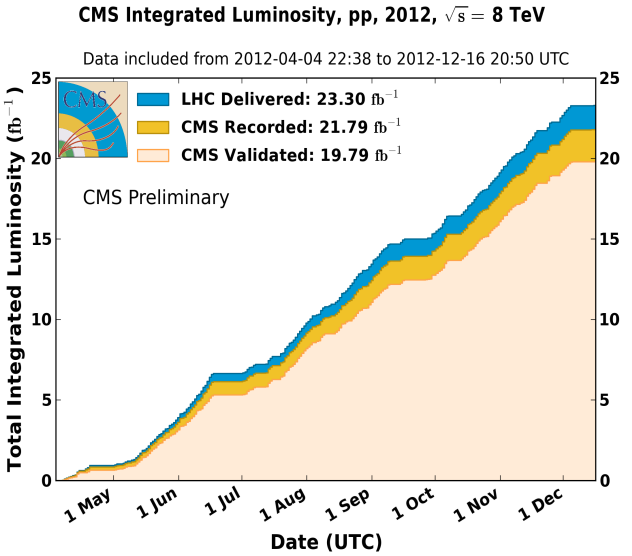
ATLAS in Run2

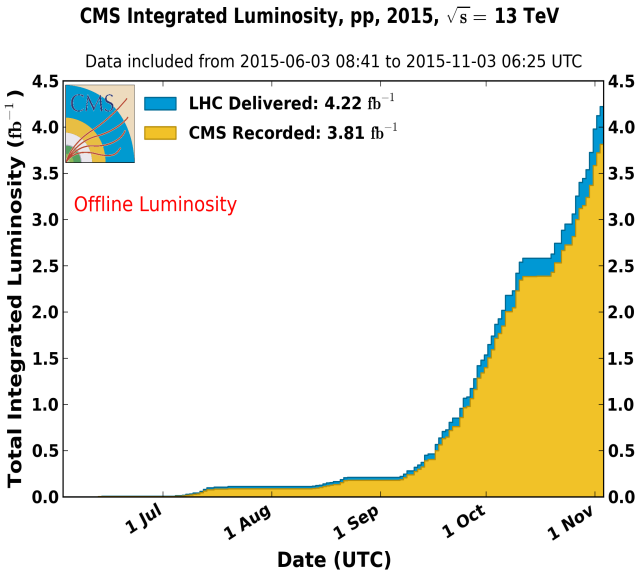
- 4th inner most layer of pixels (3.3 cm)
- Complete muon coverage
- Luminosity detectors
- Trigger



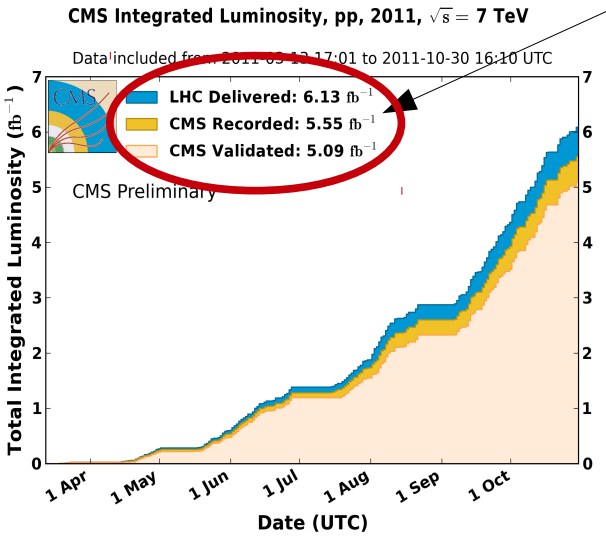
Luminosity in Run1 and Run2

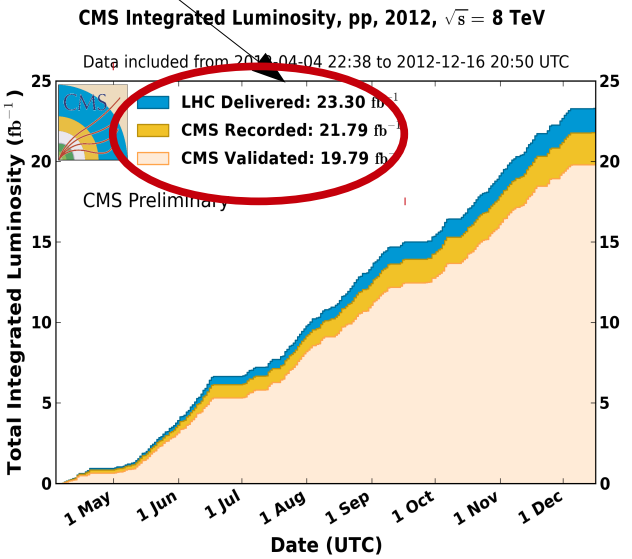


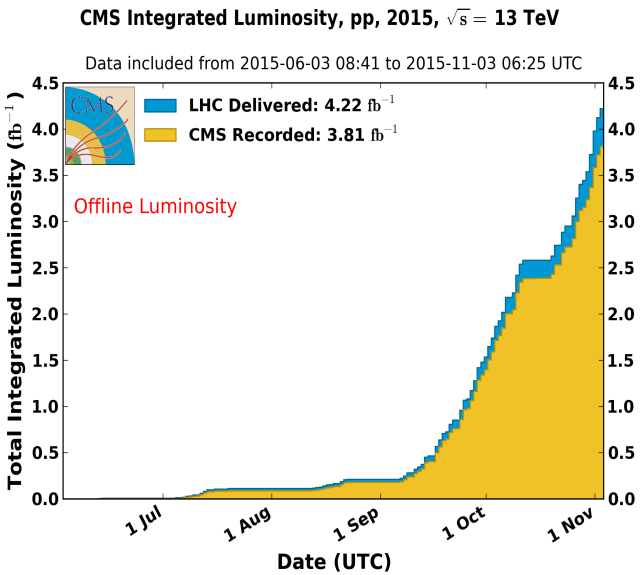




Luminosity in Run1 and Run2



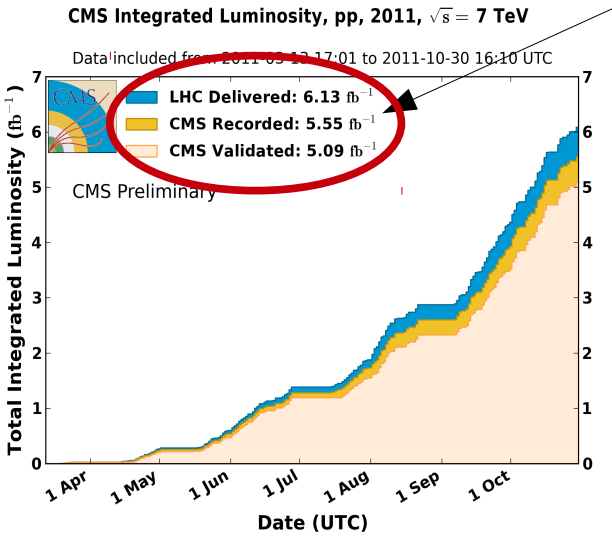


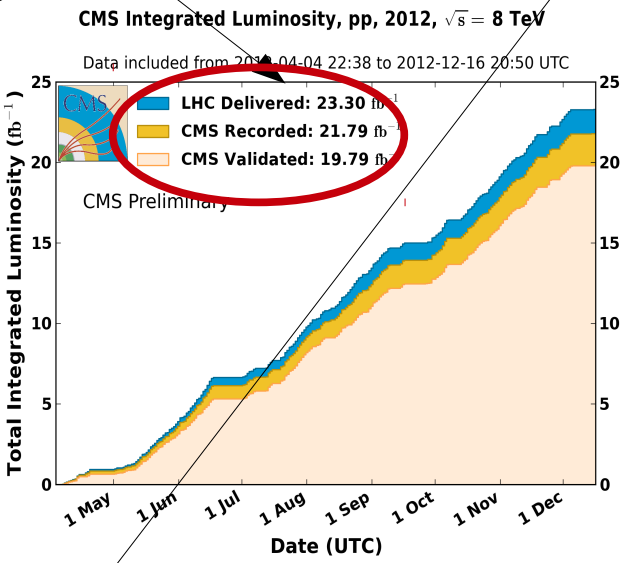


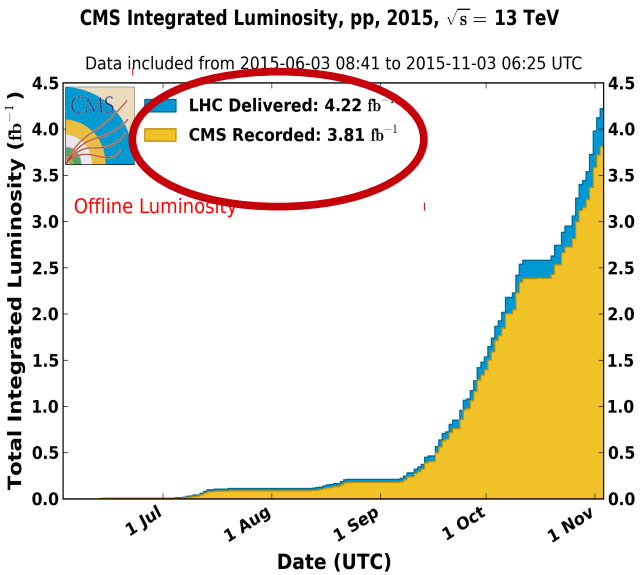
Good for physics analysis in Run1

- ATLAS: 4.6 fb^{-1} + 20.3 fb^{-1}
- CMS: 5.1 fb^{-1} + 19.8 fb^{-1}

Luminosity in Run1 and Run2







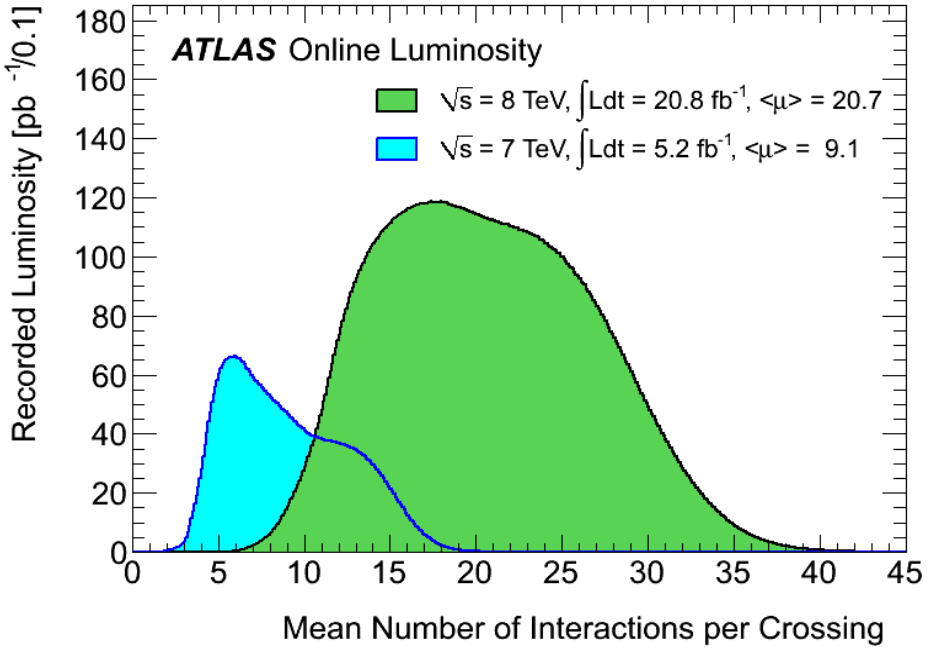
Good for physics analysis in Run1

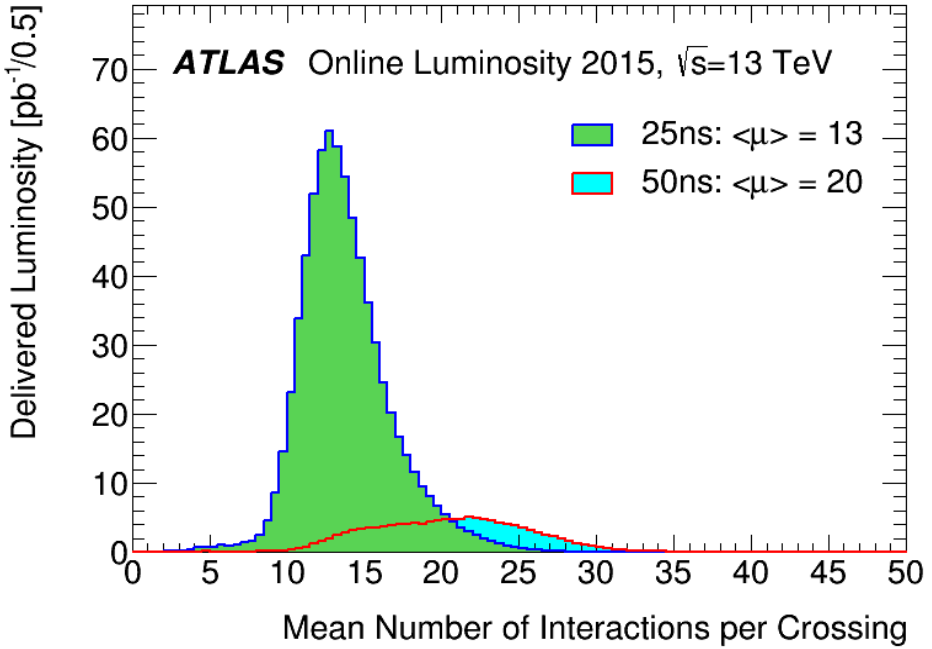
- ATLAS: 4.6 fb^{-1} + 20.3 fb^{-1}
- CMS: 5.1 fb^{-1} + 19.8 fb^{-1}

Good for physics analysis in Run2

- ATLAS: 3.2 fb^{-1}
- CMS: 2.6 fb^{-1} (magnet cryogenic supply issues)

Pileup in Run1 and Run2





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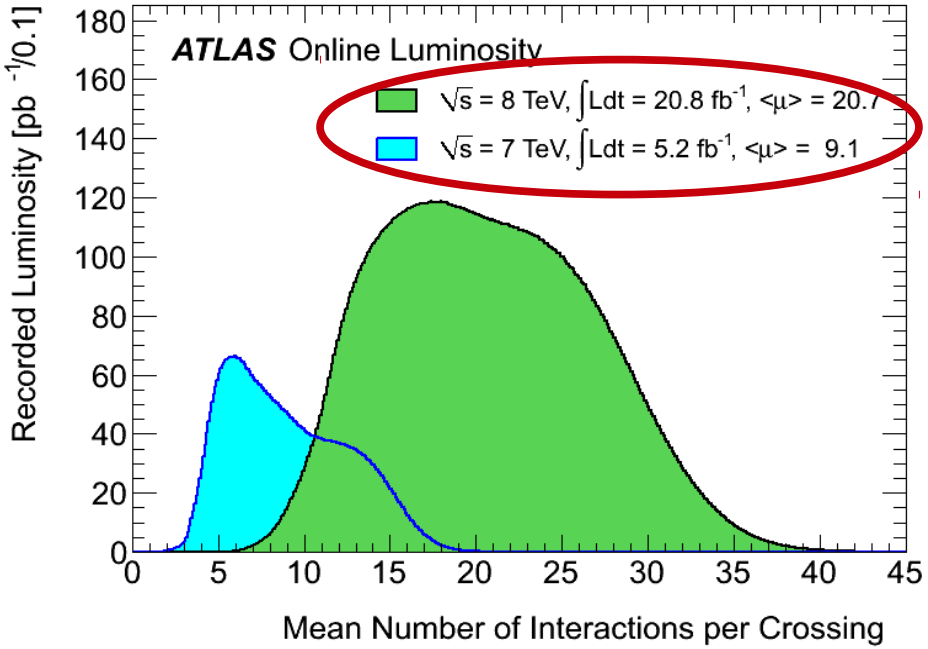
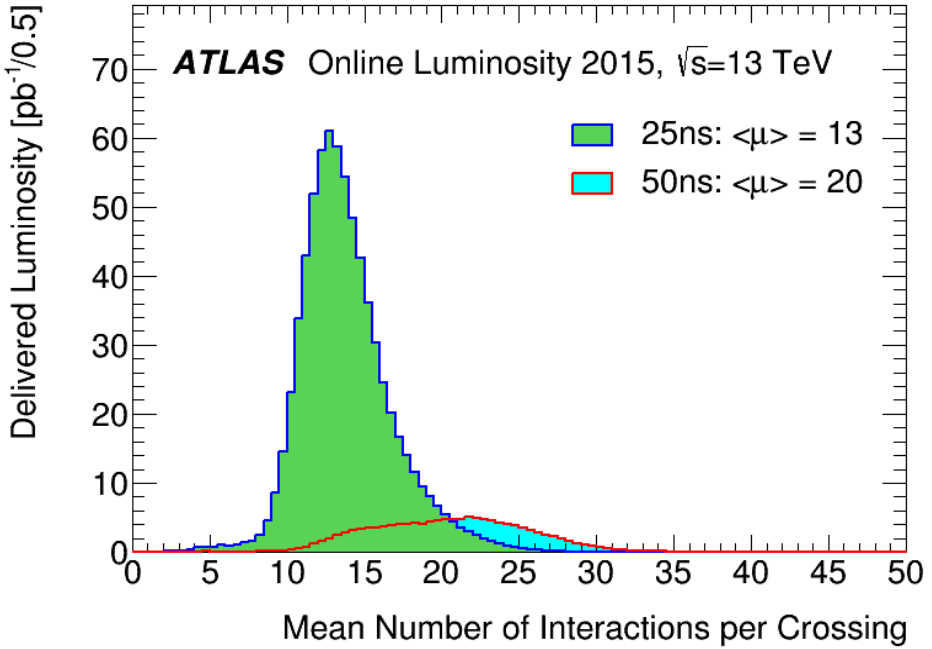
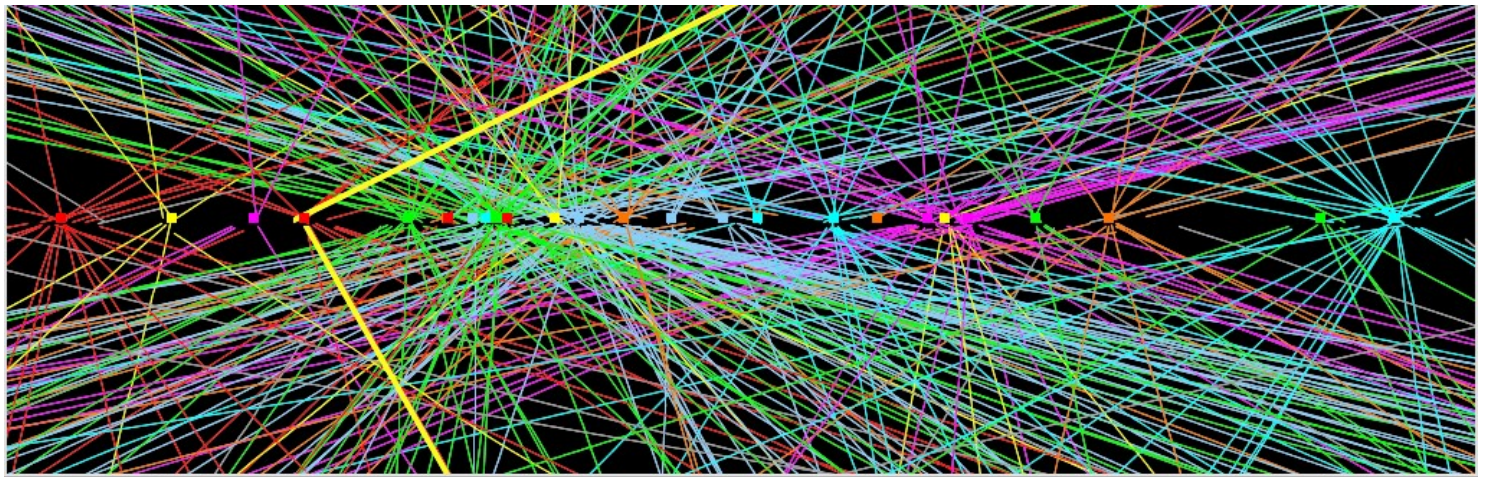
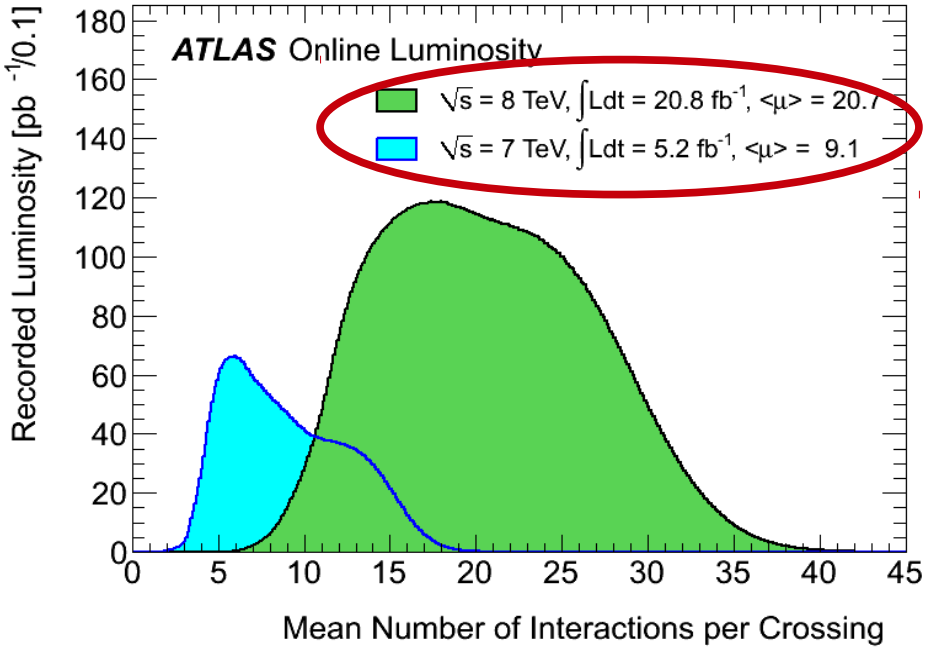


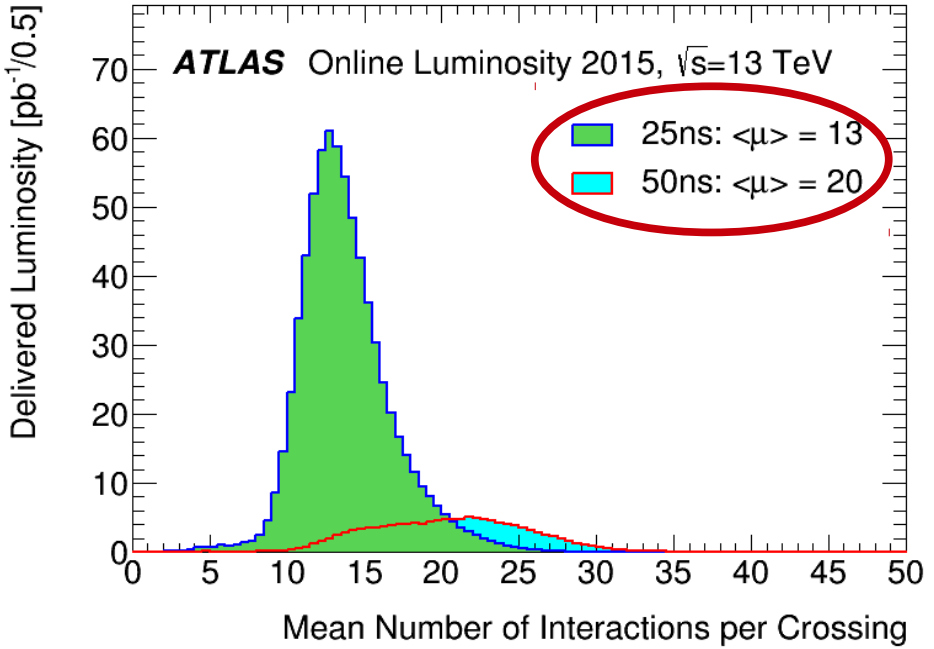


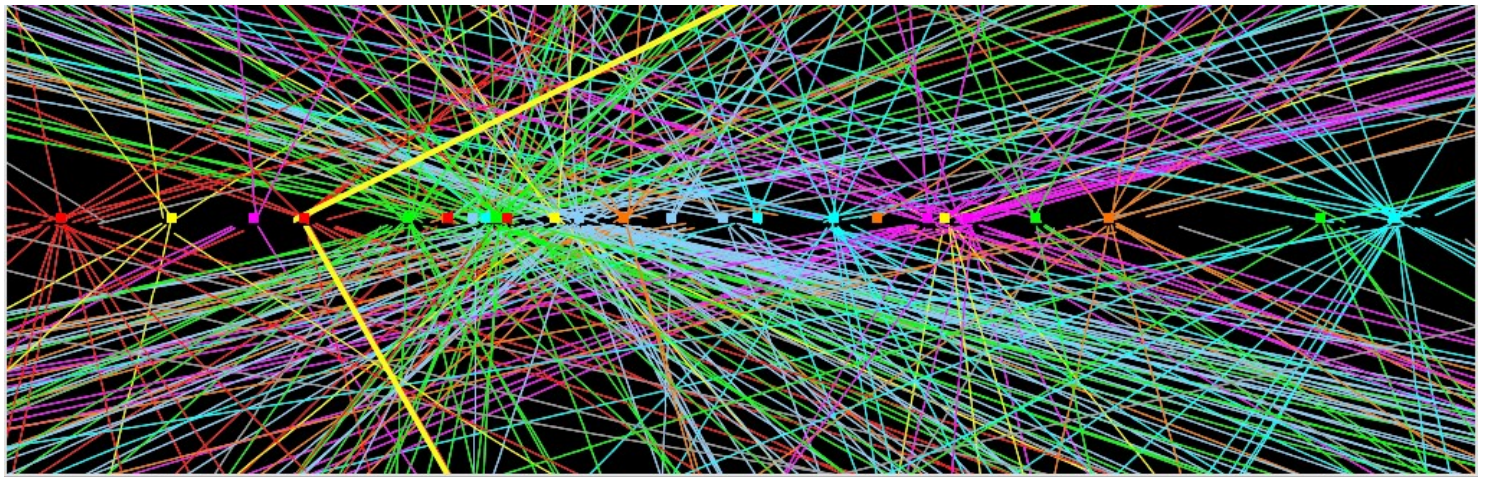


Event with 25 reconstructed vertices (Run1)

Pileup in Run1 and Run2





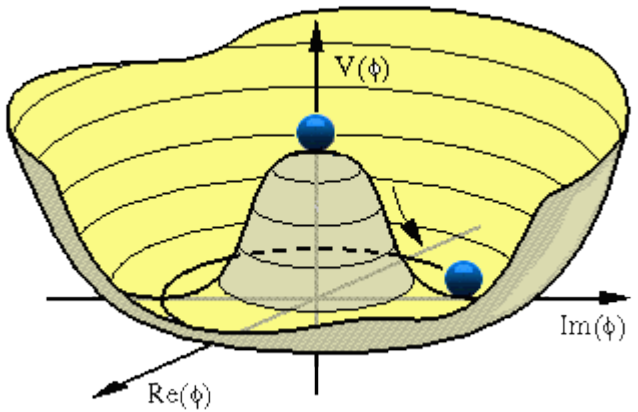


Event with 25 reconstructed vertices (Run1)

Standard Model (SM) and Higgs boson

Brout-Englert-Higgs mechanism

- Masses of particles via spontaneous symmetry breaking
- Cancellation of tree level divergences
- Higgs boson particle



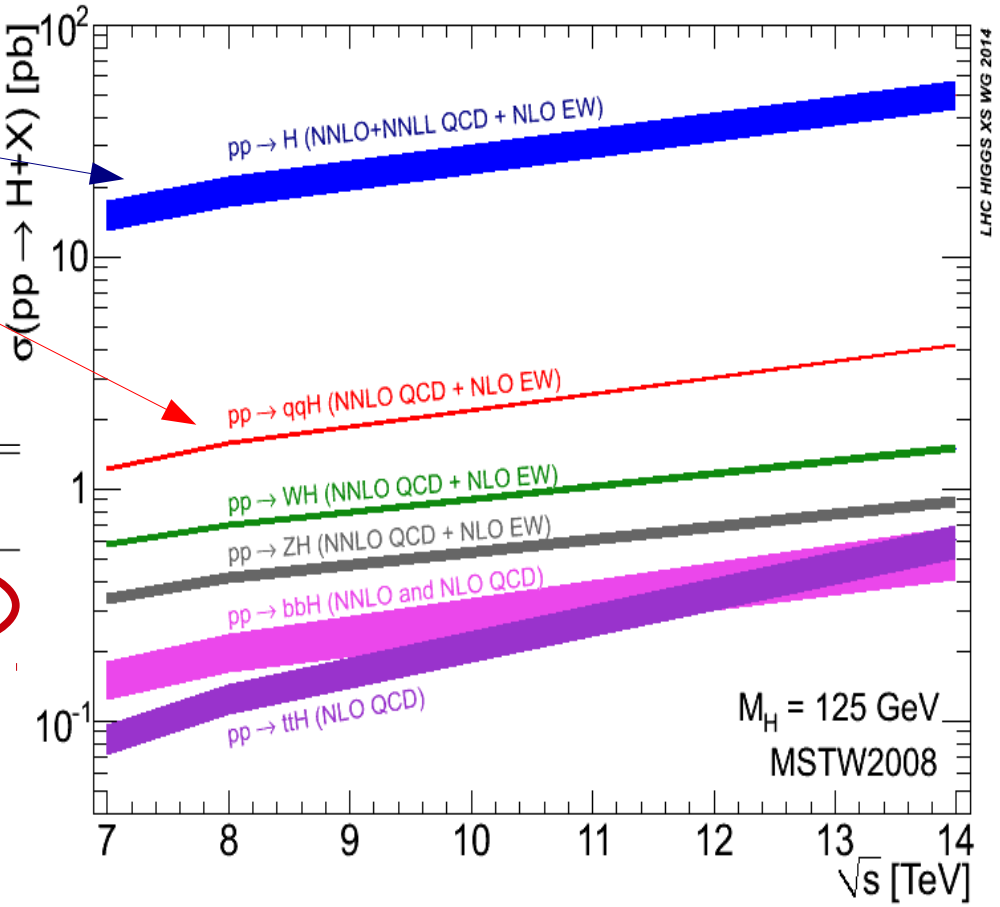
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Higgs production at LHC

Production modes

- gg fusion
- vector boson fusion
- associated production with W/Z boson, bb, tt

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	



Higgs production at LHC

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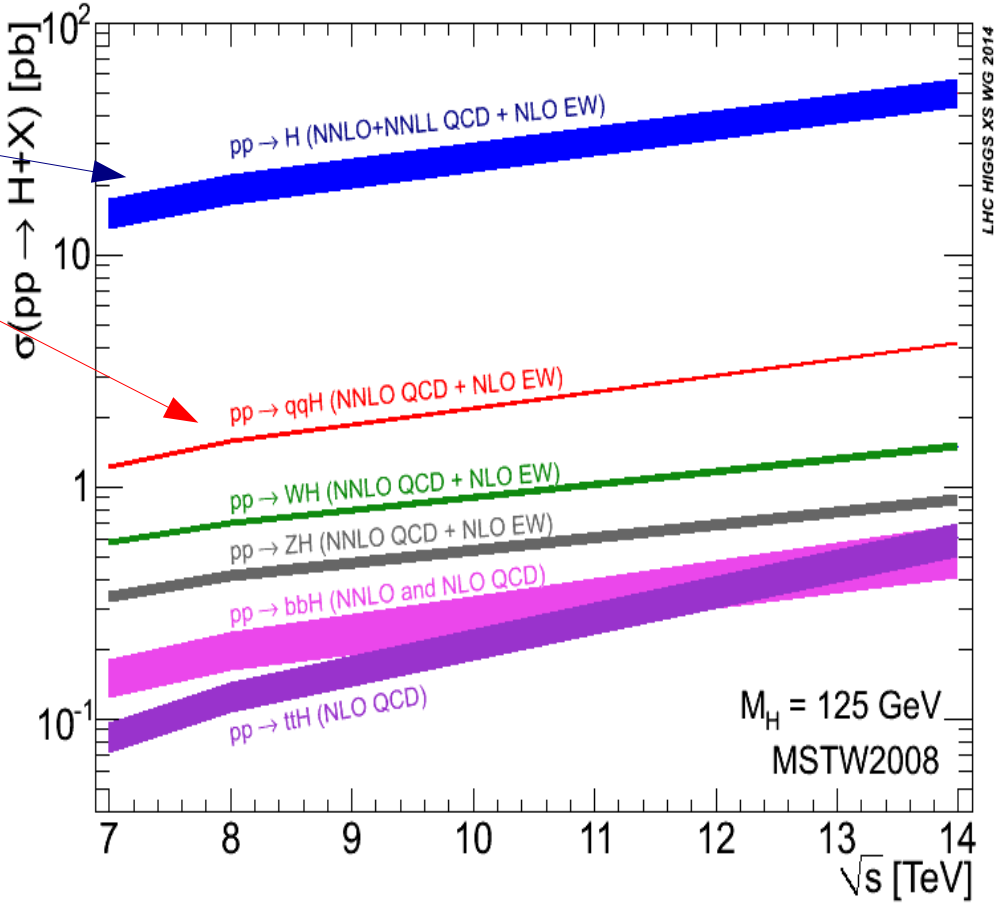


Increase by a factor of 2.3 from 8 to 13 TeV in gg fusion

- Even larger increase for ttH production

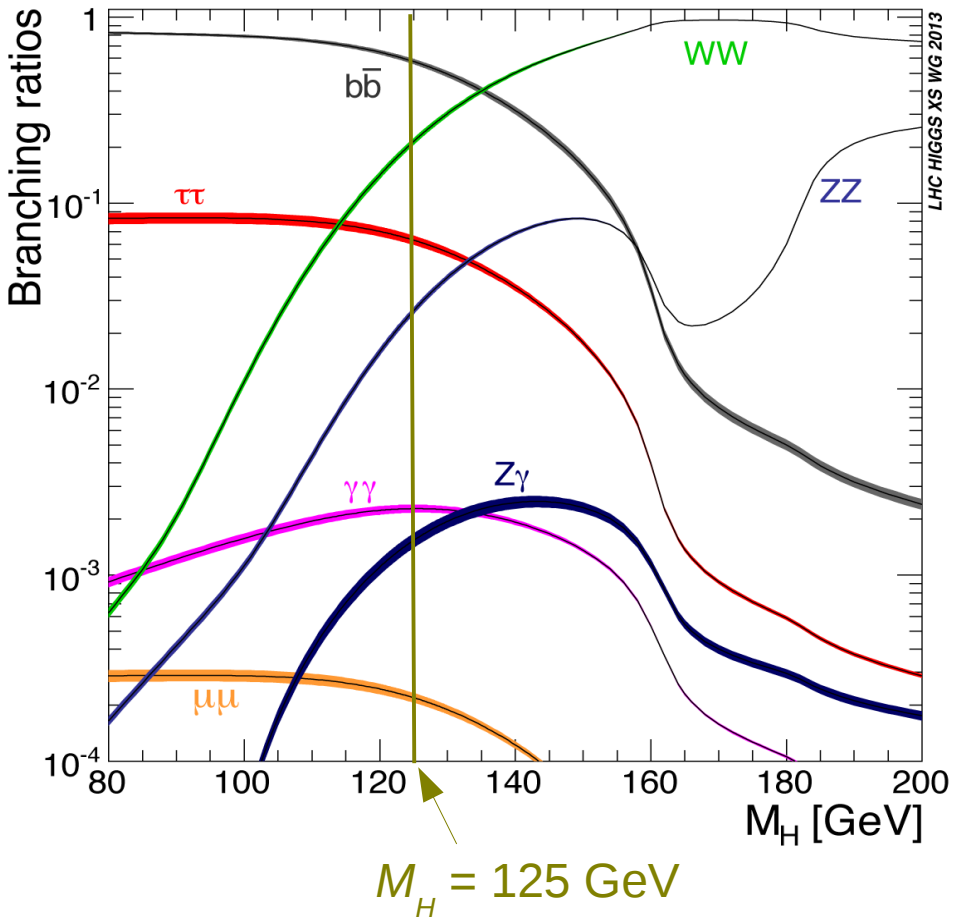
Higgs decays

Best mass resolution and good S/B

- $H \to \gamma\gamma$
- $H \to ZZ^* \to 4\text{leptons}$

M_H = 125 GeV

Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

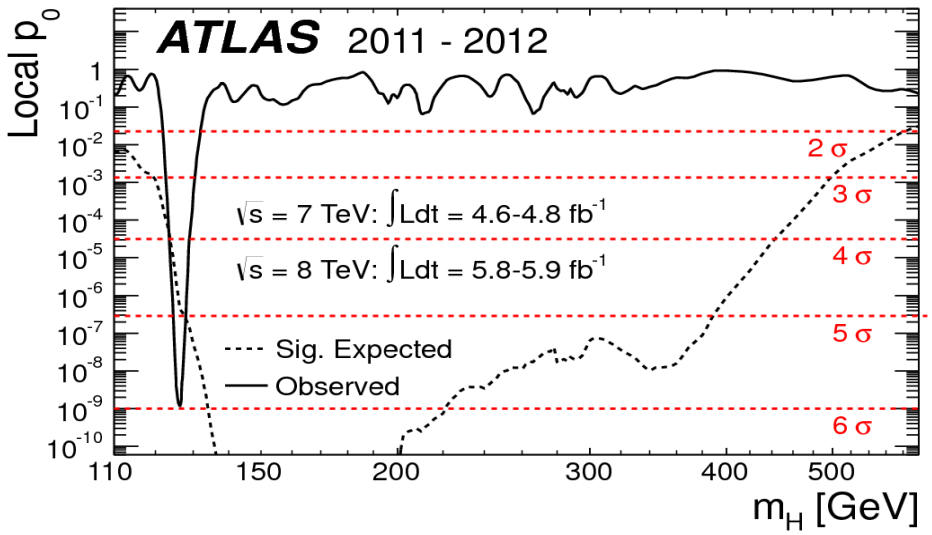


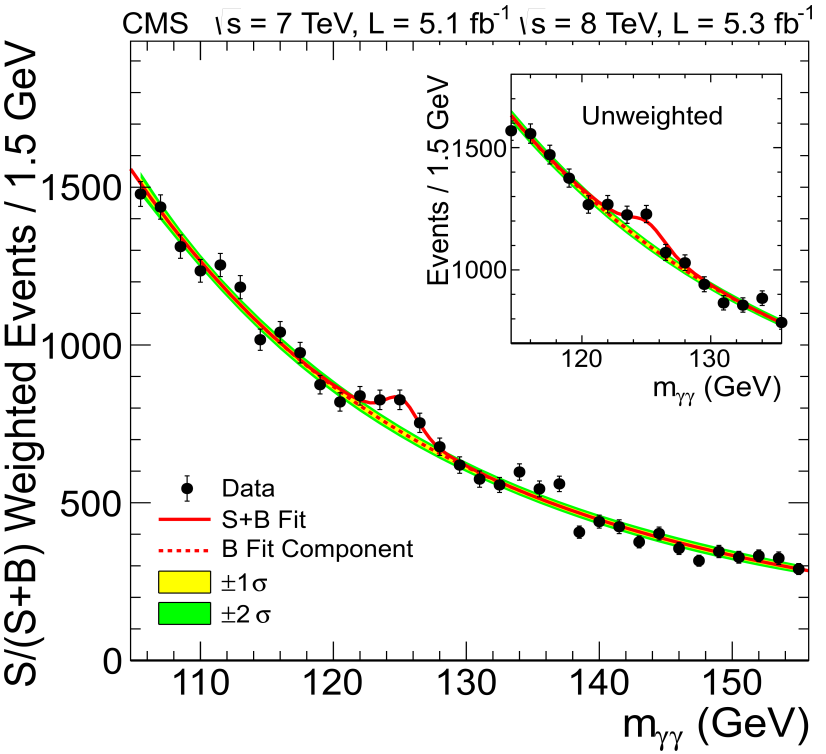
M_H = 125 GeV

Higgs boson at LHC

New resonance with mass around 125 GeV announced by ATLAS & CMS experiments in July 2012

Phys. Lett. B 716(2012)





Measurements of its properties show good agreement with SM Higgs boson

Nobel prize for Physics 2013 to F. Englert, P. Higgs

Mass of the Higgs boson (I.)

Phys. Rev. Lett. 114 (2015)

- Combination of ATLAS & CMS measurements
- Channels with best mass resolution used (H→γγ, H→ 4leptons)
- Simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments
- Mass measurement as independent as possible on the SM assumptions
- Maximization of profile likelihood ratios

$$\Lambda(m_H) = \frac{L\left(m_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+t\bar{t}H}(m_H), \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H), \hat{\hat{\mu}}^{4\ell}(m_H), \hat{\hat{\theta}}(m_H)\right)}{L\left(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}^{4\ell}, \hat{\theta}\right)}$$

μ^{i}_{j} (signal strengths): ratio of experimental and SM expected signal yields

- two factors for H→γγ (depending on the production mode) and one for H→ 4leptons

θ (nuisance parameters): systematic uncertainties

Mass of the Higgs boson (II.)

Phys. Rev. Lett. 114 (2015)

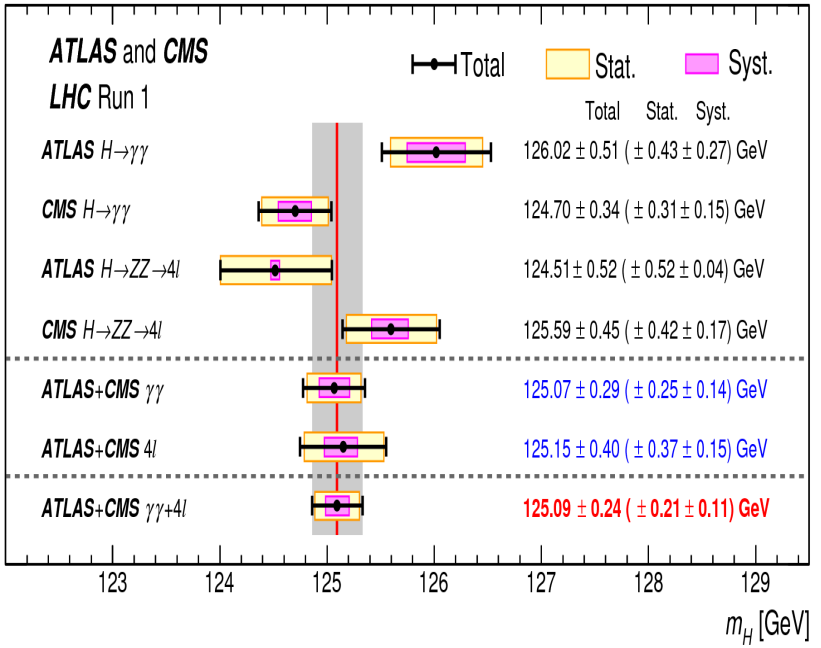
Result:

m_H = 125.09 ± 0.21 (stat) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV

- Total uncertainty dominated by statistical error
- Systematic uncertainty dominated by energy/momentum scale and resolution

Measurements are consistent with each other

- Between the different decay channels and between the two experiments



Production and decay strength (I.)

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

- Combination of ATLAS & CMS measurements
- Production and decay signal strength

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}, \mu^f = \frac{BR^f}{(BR^f)_{SM}}$$

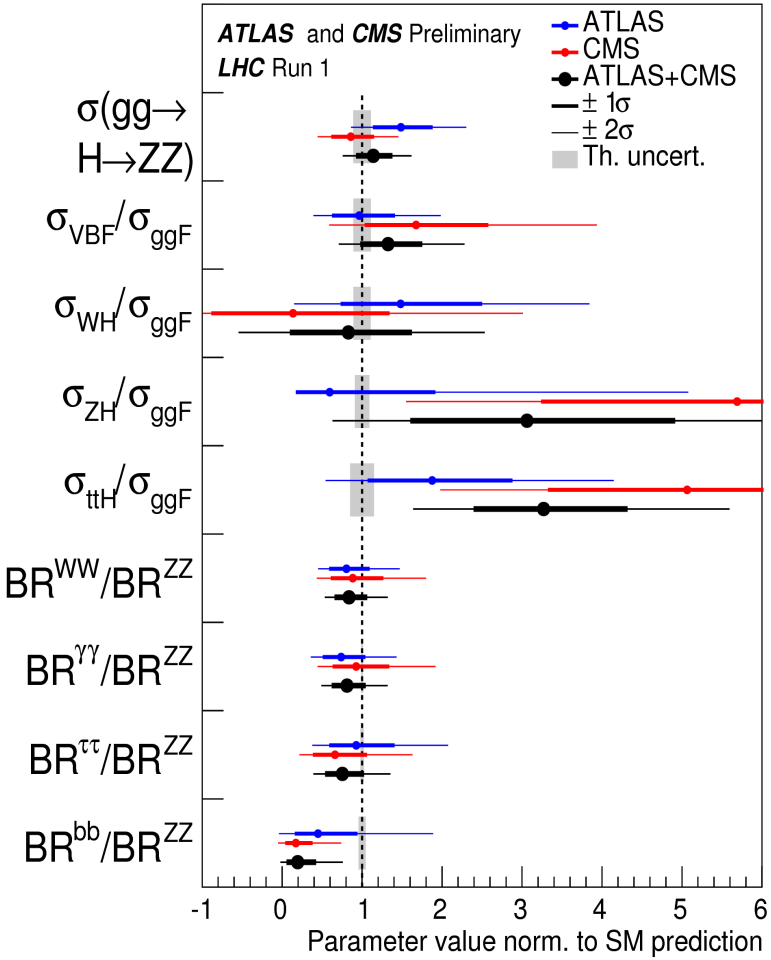
  - μ_i x μ^f measured experimentally

- Five production processes (ggH, VBF, WH, ZH, ttH)
- Six decay channels (H→γγ, H→ZZ, H→WW, H→ττ, H→b-bbar, H→μμ)
- Higgs boson mass fixed to 125.09 GeV

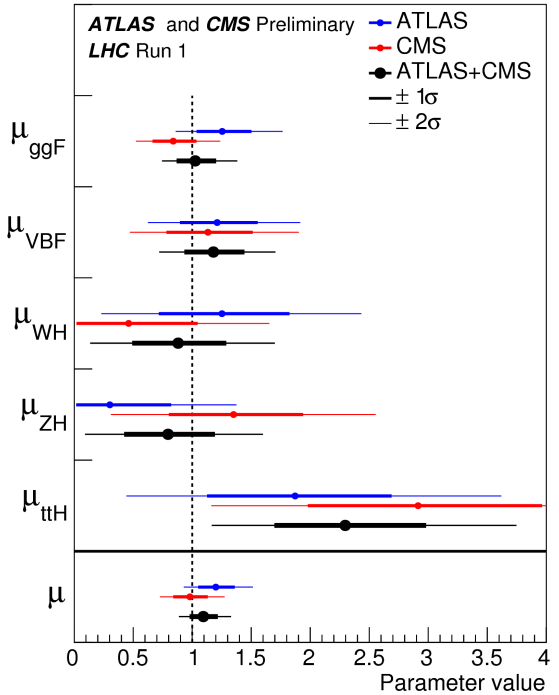
Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$ $(^{+0.26}_{-0.24})$	$1.12^{+0.25}_{-0.23}$ $(^{+0.24}_{-0.22})$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$ $(^{+0.33}_{-0.27})$	$1.05^{+0.32}_{-0.27}$ $(^{+0.31}_{-0.26})$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	[55, 56]	[57]	$1.23^{+0.23}_{-0.21}$ $(^{+0.21}_{-0.20})$	$0.91^{+0.24}_{-0.21}$ $(^{+0.23}_{-0.20})$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$ $(^{+0.37}_{-0.33})$	$0.89^{+0.31}_{-0.28}$ $(^{+0.31}_{-0.29})$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$ $(^{+0.39}_{-0.37})$	$0.81^{+0.45}_{-0.42}$ $(^{+0.45}_{-0.43})$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	[28, 62, 63]	[65]	$1.9^{+0.8}_{-0.7}$ $(^{+0.72}_{-0.66})$	$2.9^{+1.0}_{-0.9}$ $(^{+0.88}_{-0.80})$	2.7 (1.6)	3.6 (1.3)

Production and decay strength (II.)

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002



- Combined signal yield relative to SM expectation 1.09±0.11
- Observed significance of the VBF production mode at the level of 5.4σ (4.7 expected)
- H→ττ channel at the level of 5.5σ (5.0 expected)

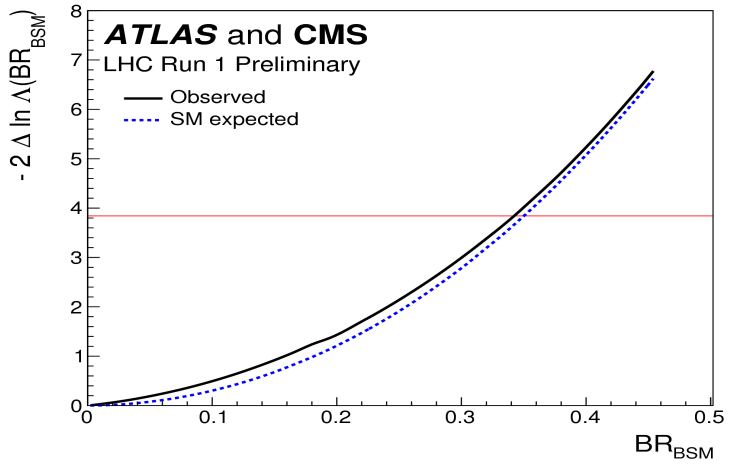


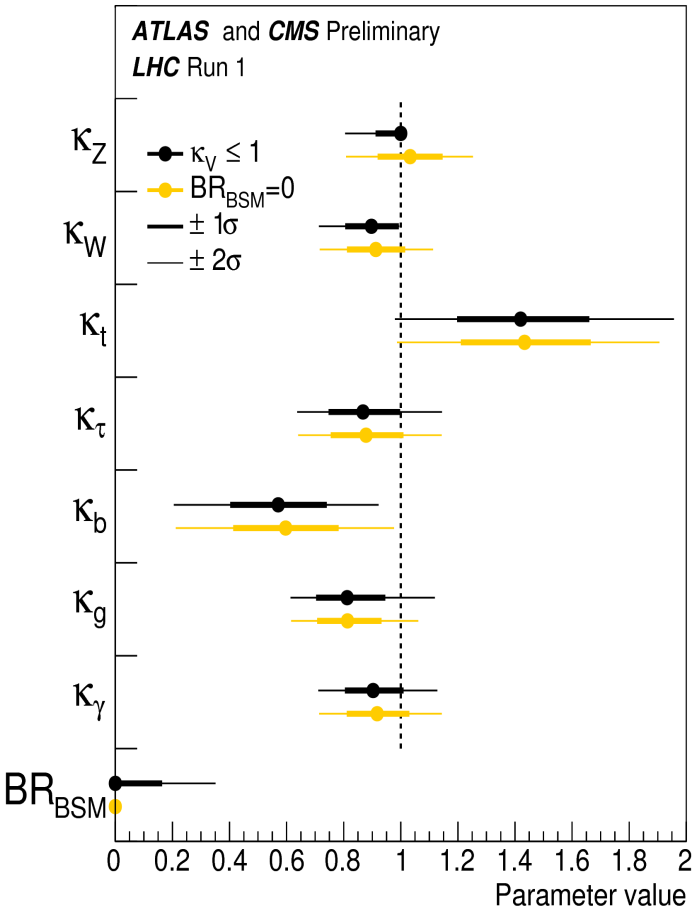
Data consistent with SM expectations

Constraints on Higgs boson couplings

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

- Testing of the couplings by allowing more generic models (BSM)
- Example: Parameterizations allowing contributions from BSM particles in loops and in decays
  - Fitting of 7 coupling modifiers κ_X + BR_{BSM}



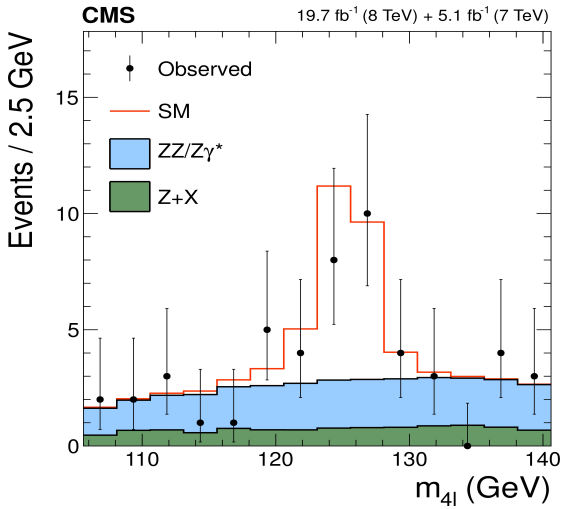


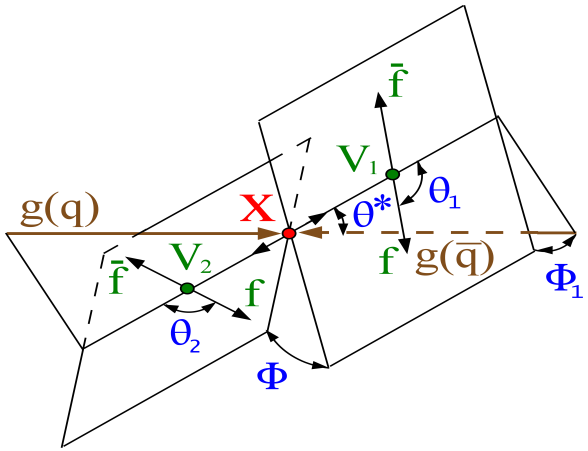
Data consistent with SM expectations

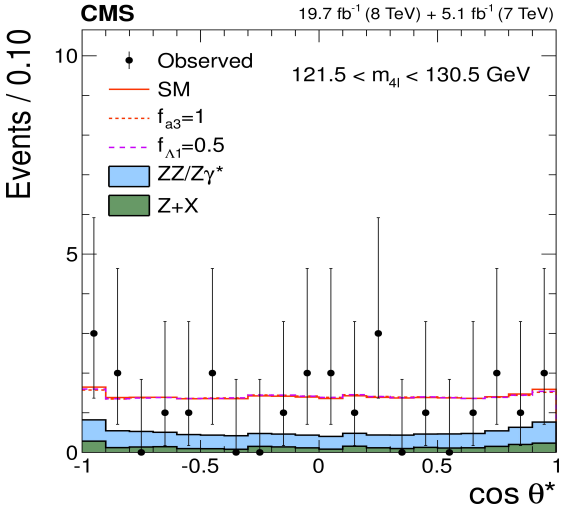
Spin & parity measurements (I.)

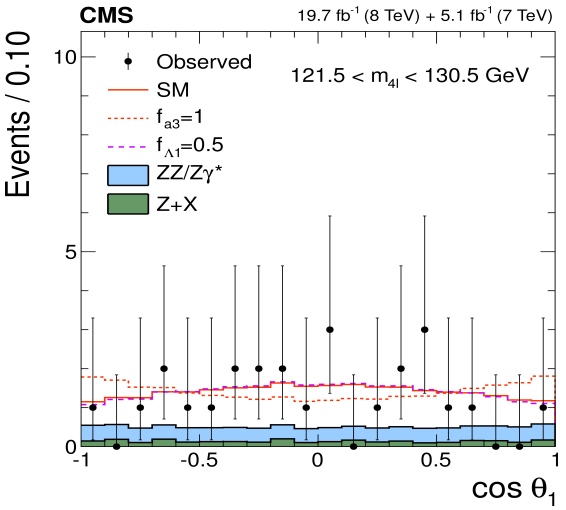
Phys. Rev. D 92 (2015)

- CMS measurements using the H→4leptons, H→WW→ℓνℓν, and H→γγ decay modes
- Different variables sensitive to the spin and parity of the Higgs boson built
- Examples from H→4leptons channel





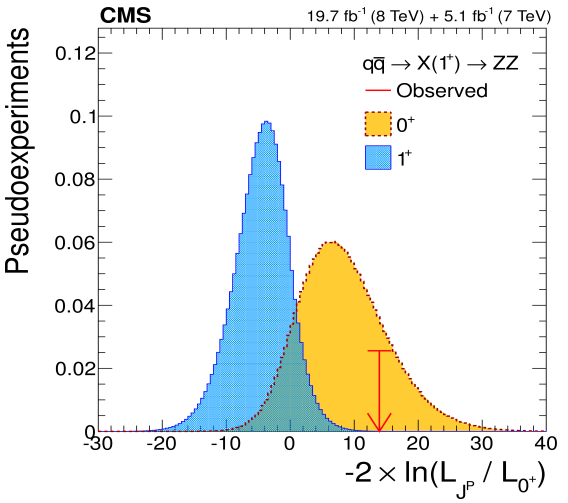




Spin & parity measurements (II.)

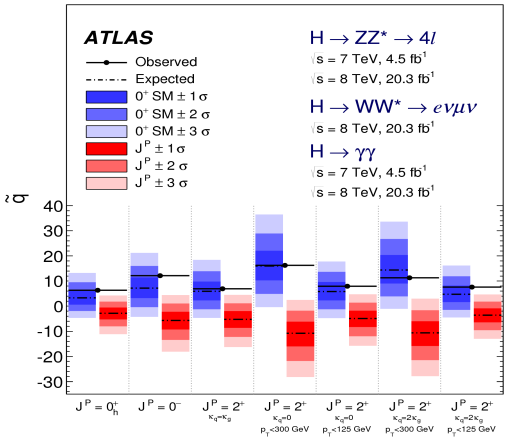
- Wide range of spin-two models excluded at 99% confidence level or higher
- Mixed-parity spin-one state is excluded at a confidence level of 99.999%
- All observations consistent with the expectations for a scalar SM-like Higgs boson ($J^{PC}=0^{++}$)

Phys. Rev. D 92 (2015)



- Similar conclusions in ATLAS

Eur. Phys. J. C75 (2015)



Summary of Run1 measurements

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.81 \pm 0.16$

$ZZ^* = 1.15^{+0.27}_{-0.23}$ (S = 1.2)

$\gamma\gamma = 1.17^{+0.19}_{-0.17}$

$b\bar{b} = 0.85 \pm 0.29$

$\mu^+\mu^- < 7.0$, CL = 95%

$\tau^+\tau^- = 0.79 \pm 0.26$

$Z\gamma < 9.5$, CL = 95%

$t\bar{t}H^0$ Production $= 2.5^{+0.9}_{-0.8}$

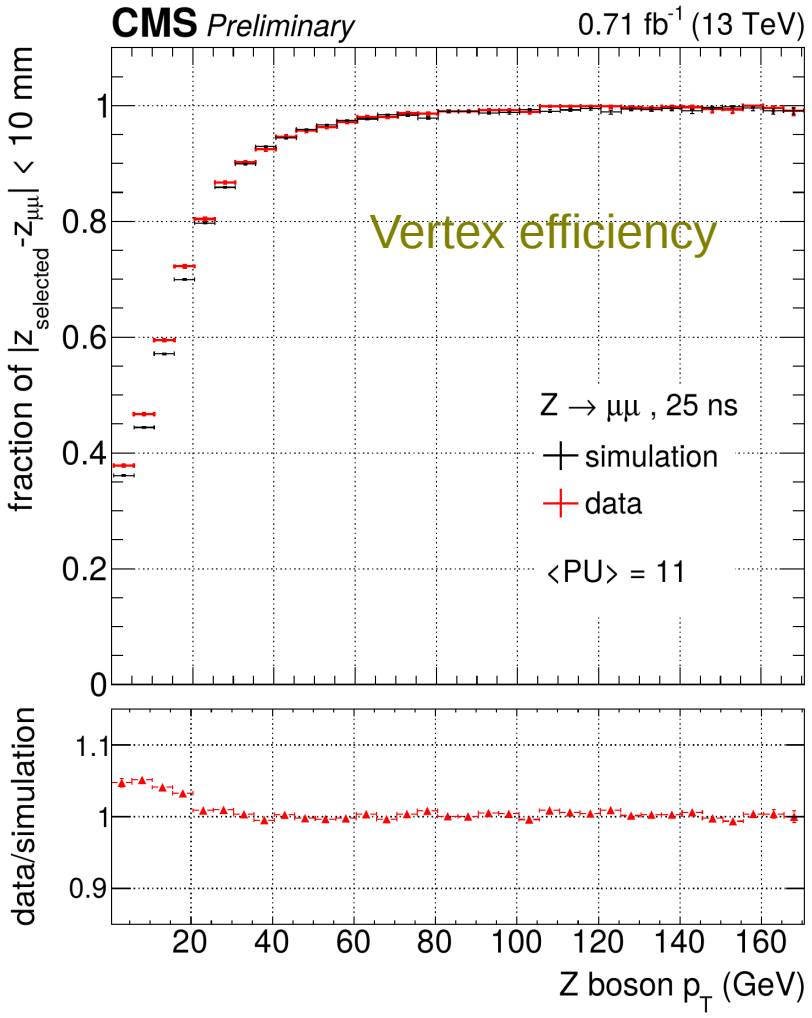
All results in agreement with the SM expectations

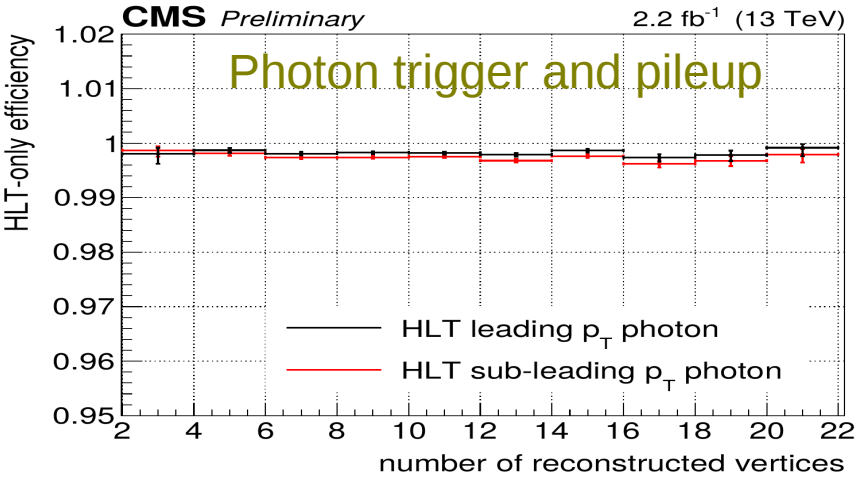
Analysis with current Run2 dataset

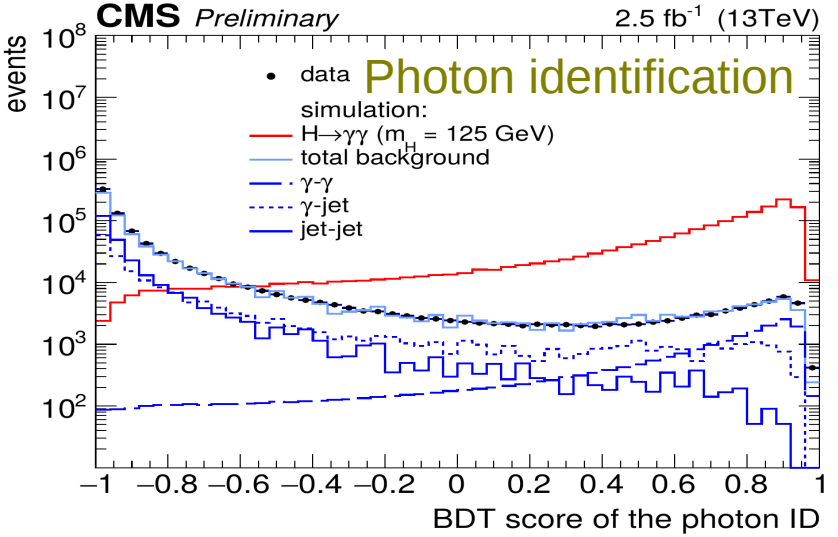
- Limited statistics compared to Run1 so far
- CMS
  - Preparation stage for the analysis with more data
  - Trigger, ID, selection efficiencies
  - Control regions checks
  - All Higgs boson analysis blinded at the moment
- ATLAS
  - Cross-section measurements with discovery channels ($H \rightarrow \gamma\gamma$, $H \rightarrow$ 4leptons)
  - Preparation stage for the rest of the analysis

H→γγ: Performance studies at CMS

- Search for a pair of well identified photons







Cross-section measurement

$$\sigma = \frac{N_S}{A\,C\,L_i}$$

σ - cross-section

N_s - extracted signal yield

C - correction factor

A - acceptance factor

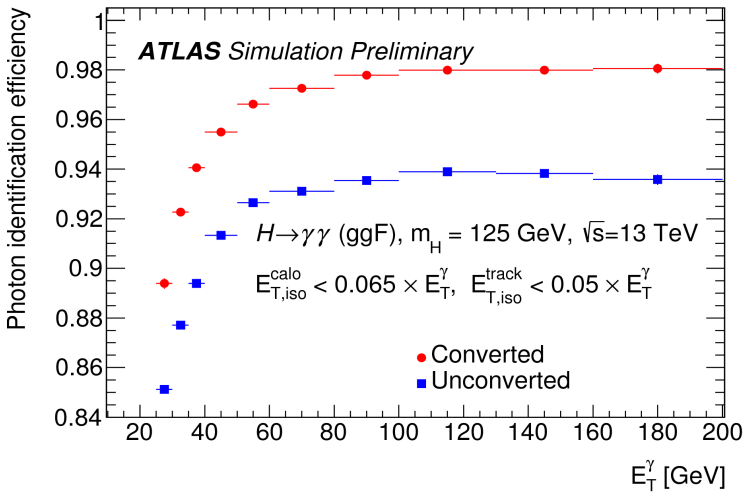
L_i - integrated luminosity

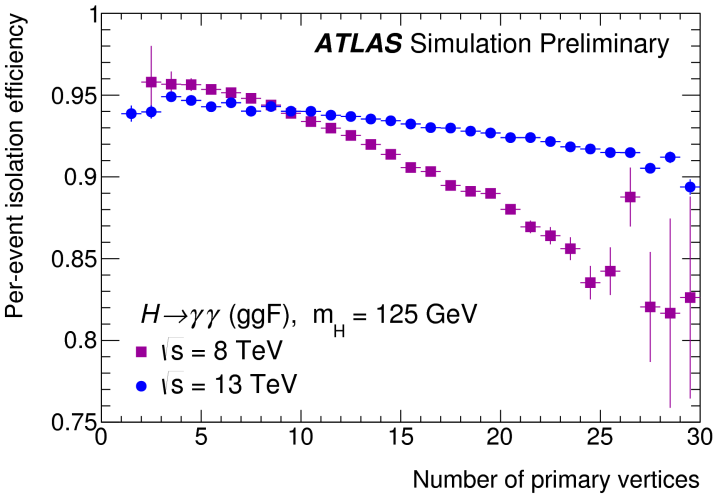
- Correction factor (C)
  - Accounts for detector resolution and efficiency
- Acceptance factor (A)
  - Efficiency of selection cuts at truth level

H→γγ analysis at ATLAS (I.)

ATLAS-CONF-2015-060

- Event selection
  - Two tight identified & isolated photons
  - Relative transverse energy cut ($E_T/m_{\gamma\gamma}$>0.35 / 0.25)

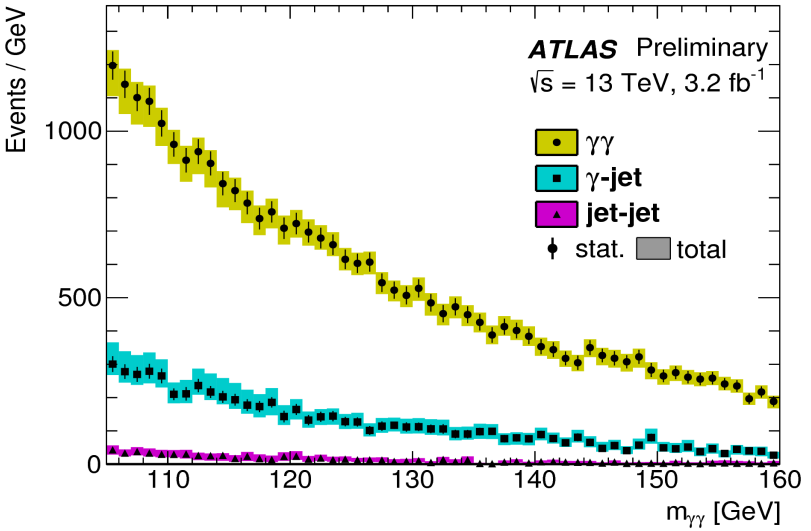




- Signal selection efficiency between 31 and 37% depending on the production mode

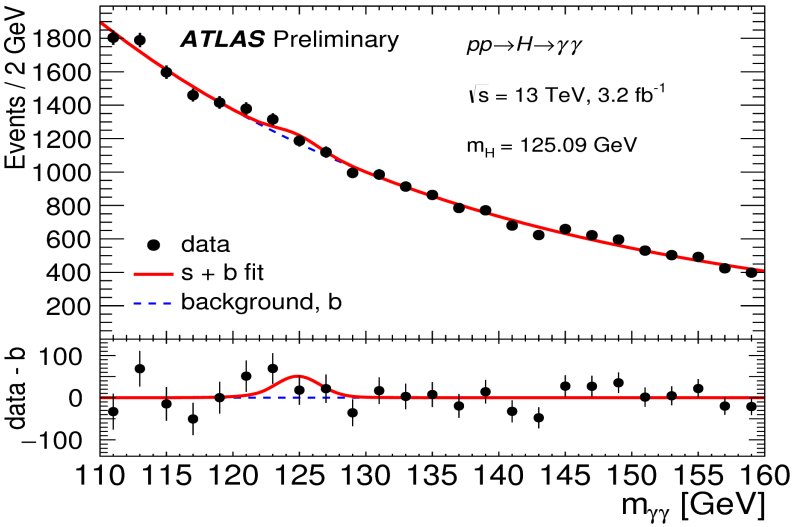
H→γγ analysis at ATLAS (II.)

- Main backgrounds
  - γγ continuum
  - γ+jet, jet+jet production



- Diphoton invariant mass spectrum fitted with signal + background model for the fixed Higgs boson mass 125.09 GeV

N_{exp} = 143 ± 71 (stat.)± $^{39}_{6}$ (syst.)
N_{S} = 113 ± 74 (stat.)± $^{43}_{25}$ (syst.)



H→γγ cross-section (I.)

- Correction factor
  - Defined as ratio of the expected number of events passing the selection requirement with the number of generated particle-level events in the fiducial volume
  - C = 0.68

Event Selection	
Two highest-p_{T} photons:	$\lvert\eta^{\gamma}\rvert < 2.37$
Relative-p_{T}:	$E^{\gamma}_{\mathrm{T},1}/m_{\gamma\gamma} \geq 0.35, E^{\gamma}_{\mathrm{T},2}/m_{\gamma\gamma} \geq 0.25$
Mass window:	$105\,\mathrm{GeV} \leq m_{\gamma\gamma} < 160\,\mathrm{GeV}$
Photon isolation:	$E_{\mathrm{T,iso}} < 0.1 \times E^{\gamma}_{\mathrm{T}} + 1\,\mathrm{GeV}$

Component	Uncertainty [%]
Photon energy scale	< 0.1
Photon energy resolution	< 0.1
Photon identification efficiency	± 2.6
Photon isolation efficiency	± 4.0
Trigger efficiency	± 0.4
Vertex selection	< 0.1
Theoretical modeling uncertainty	± 0.8
Total	± 4.8

H→γγ cross-section (II.)

- Acceptance factor
  - Fraction of H→γγ decays that pass the fiducial selection

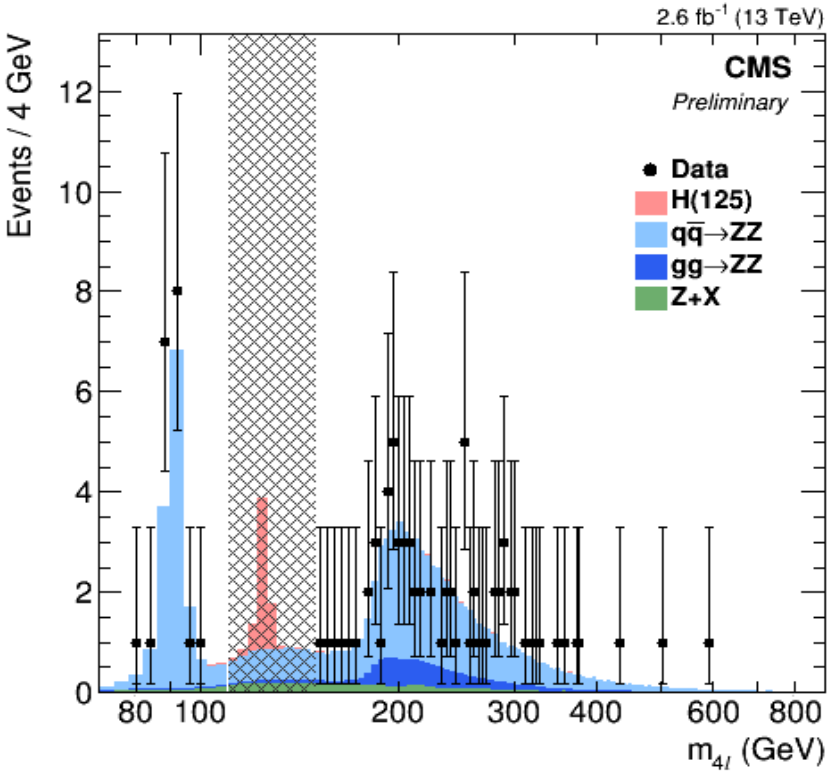
$\sqrt{s}$	$\mathcal{A}$
7 TeV	0.620 ± 0.007
8 TeV	0.611 ± 0.012
13 TeV	0.570 ± 0.006

- Cross-section results

$\sqrt{s}$	Measured total cross section [pb]	LHC-XS prediction [pb]
7 TeV	35 ± 12 (stat.) ± 4 (syst.) ± 1 (lumi.)	17.5 ± 1.6
8 TeV	30.5 ± 7.1 (stat.) $^{+2.6}_{-2.5}$ (syst.) ± 0.9 (lumi.)	22.3 ± 2.0
13 TeV	40 ± 26 (stat.) $^{+16}_{-10}$ (syst.) ± 2 (lumi.)	$50.9\ ^{+4.5}_{-4.4}$

H→4leptons at CMS

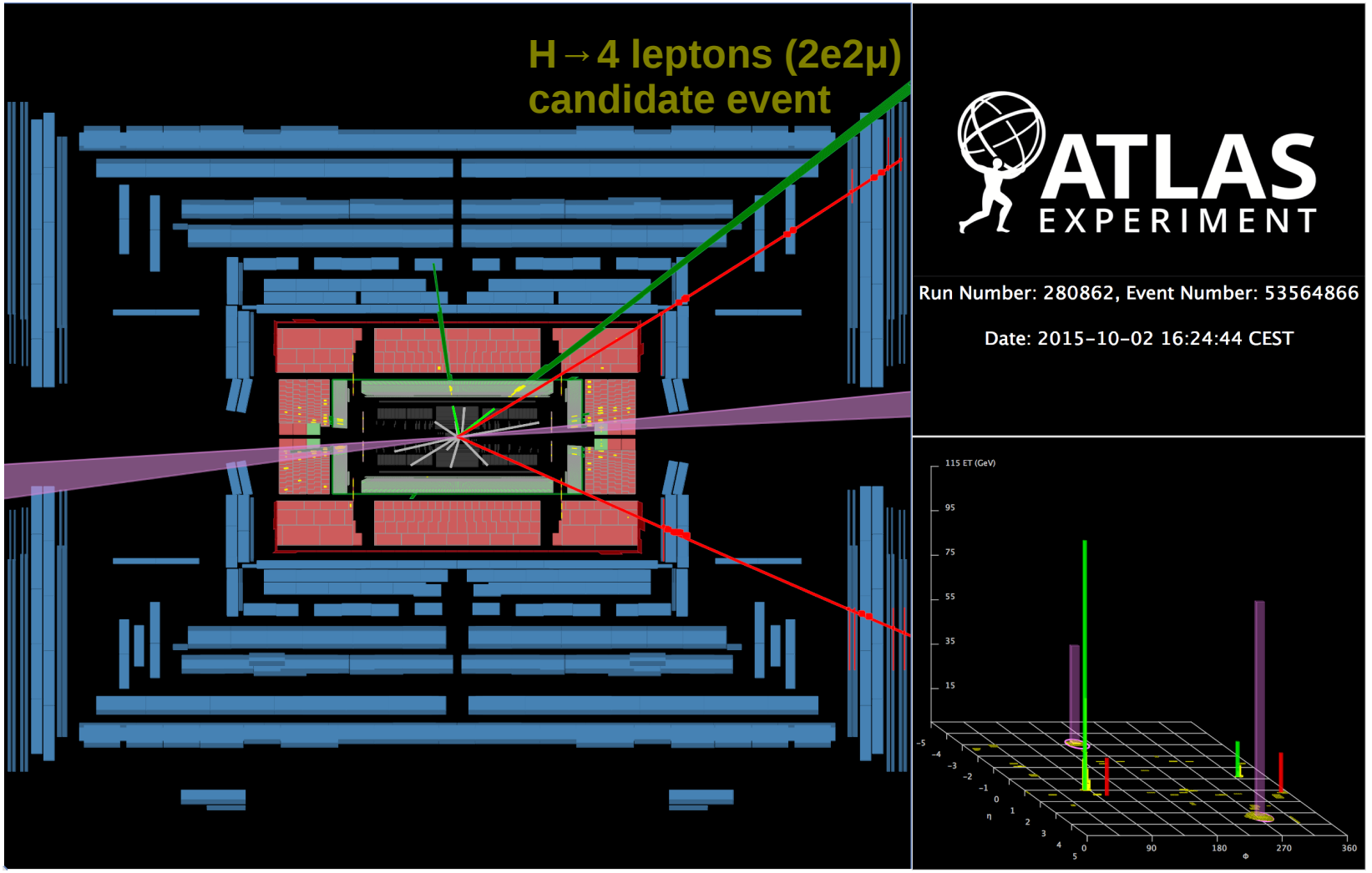
- Measurement of the fiducial cross section of the dominant background (ZZ* continuum)
- Blinded analysis at the moment
  - Mass spectrum matches well the expectations in the side band regions



H→4leptons analysis at ATLAS (I.)

ATLAS-CONF-2015-059

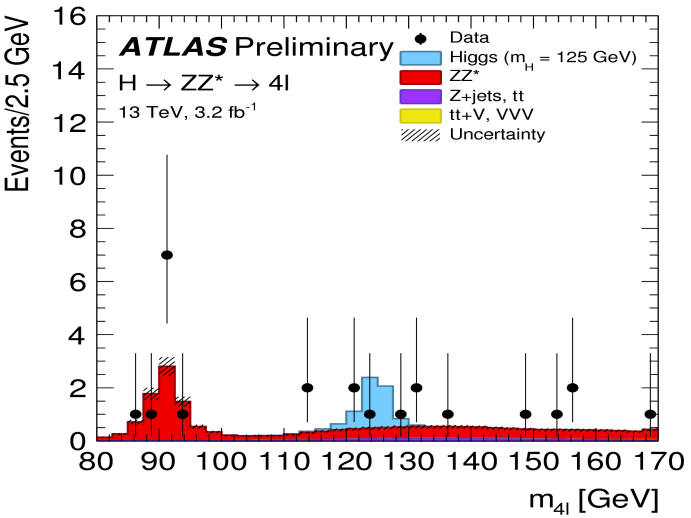
Event with 4 identified & isolated leptons and 2 jets



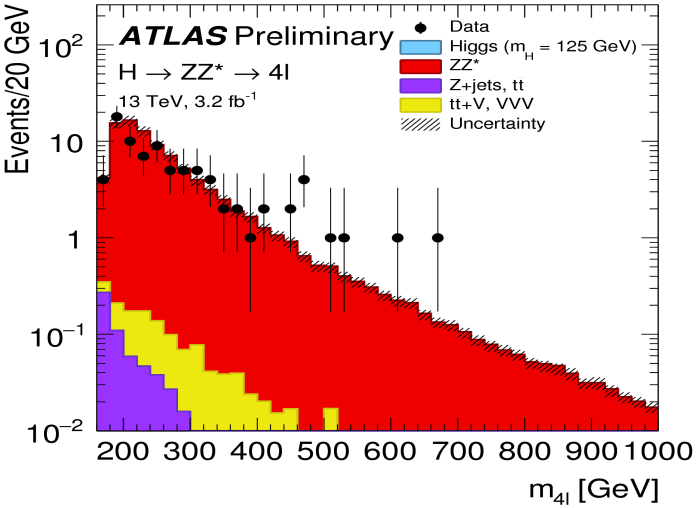
H→4leptons analysis at ATLAS (II.)

- Main backgrounds
  - ZZ* non-resonant diboson production
  - Z+jets, t-tbar

80 GeV <m_{4l}<170 GeV



160 GeV <m_{4l}<1000 GeV



Final state	Signal full mass range	Signal	ZZ^*	$Z+jets,\ t\bar{t}$ $t\bar{t}V, VVV,\ WZ$	S/B	Expected	Observed
4μ	1.79 ± 0.21	1.67 ± 0.20	0.64 ± 0.06	0.08 ± 0.03	2.3	2.39 ± 0.21	1
$2e2\mu$	1.19 ± 0.14	1.06 ± 0.13	0.44 ± 0.04	0.07 ± 0.03	2.1	1.57 ± 0.14	1
$2\mu 2e$	1.07 ± 0.16	0.96 ± 0.15	0.34 ± 0.05	0.09 ± 0.02	2.2	1.40 ± 0.16	2
$4e$	1.01 ± 0.15	0.88 ± 0.13	0.32 ± 0.05	0.09 ± 0.02	2.1	1.30 ± 0.14	0
Total	5.06 ± 0.60	4.57 ± 0.54	1.74 ± 0.19	0.34 ± 0.06	2.2	6.65 ± 0.58	4

H→4leptons cross-section

Acceptance & correction factor

	$\sqrt{s}$ [TeV]		
	7	8	13
$\mathcal{A}$ [%]	46.67 ± 0.23	45.98 ± 0.14	42.74 ± 0.24
$\mathcal{C}$ [%]	51.89 ± 0.36	55.32 ± 0.24	52.71 ± 0.45

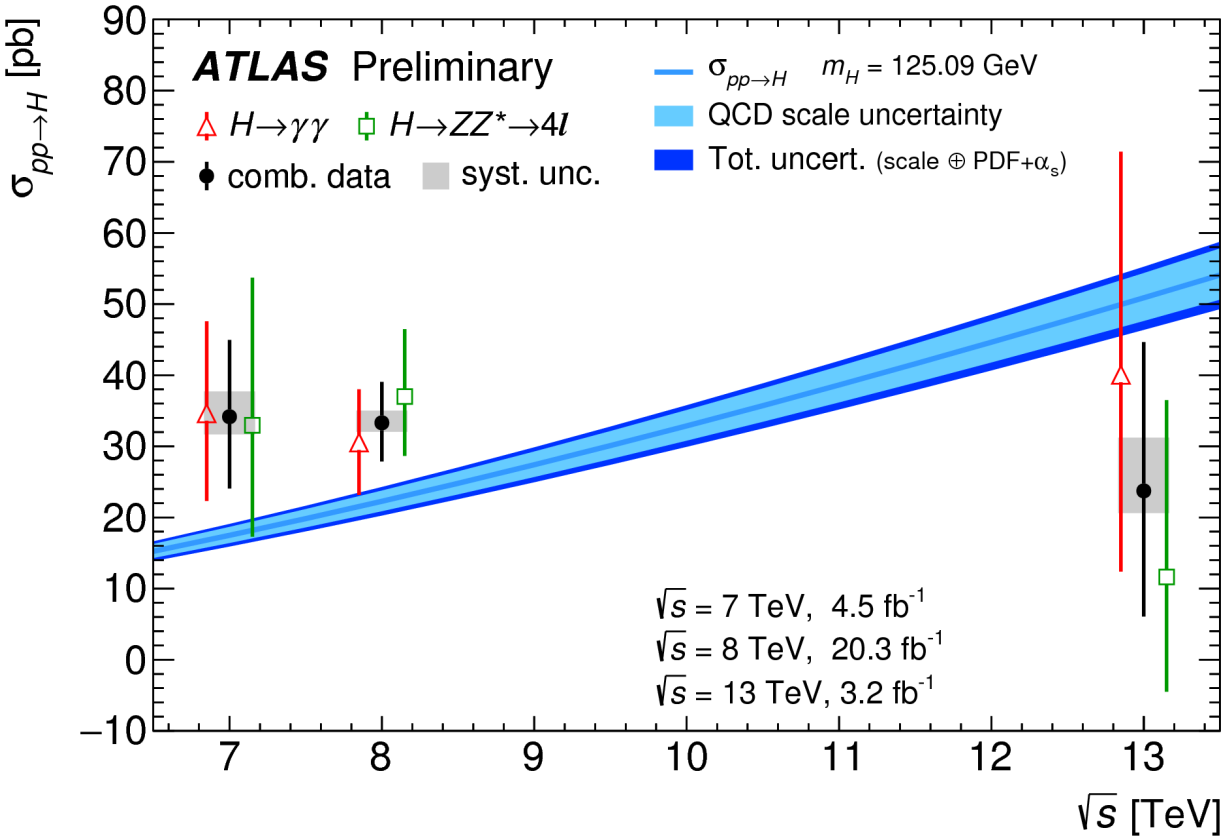
Cross-section results

Data set [TeV]	N_s	$\sigma^{\text{fid}}_{4\ell}$ [fb]	$\sigma^{\text{fid}}_{\text{theory}}$ [fb]	σ^{tot} [pb]	$\sigma^{\text{tot}}_{\text{theory}}$ [pb]
7	$4.5\ ^{+2.8}_{-2.2}$	$1.9\ ^{+1.2}_{-0.9}$	1.03 ± 0.11	$33\ ^{+21}_{-16}$	17.5 ± 1.6
8	$24.0\ ^{+6.0}_{-5.3}$	2.1 ± 0.5	1.29 ± 0.13	$37\ ^{+9}_{-8}$	22.3 ± 2.0
13	$1.0\ ^{+2.3}_{-1.5}$	$0.6\ ^{+1.3}_{-0.9}$	2.74 ± 0.28	$12\ ^{+25}_{-16}$	$50.9\ ^{+4.5}_{-4.4}$

Cross-section combination

ATLAS-CONF-2015-069

- Combination of H→γγ and H→4leptons cross-section measurements
- Comparison of 7, 8 and 13 TeV results



Conclusions

- Run1 measurements consistent with the SM expectations
  - First combined measurements by ATLAS and CMS for mass and couplings
- First Higgs boson measurements in Run2 performed with the ATLAS detector
  - Channels $H \rightarrow \gamma\gamma$ and $H \rightarrow 4$leptons
- Preparation of the analysis for larger dataset in ATLAS and CMS experiments
- Much more to come with more data
  - Different channels
  - CP, production & decay rates, differencial cross-section
  - Rare decays