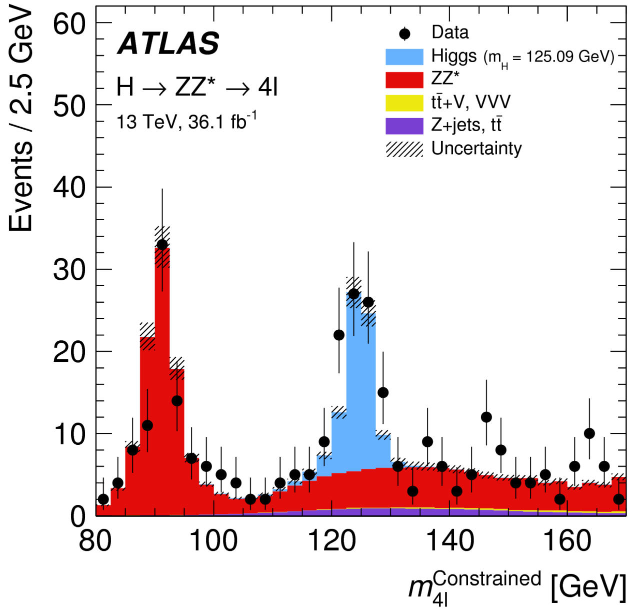
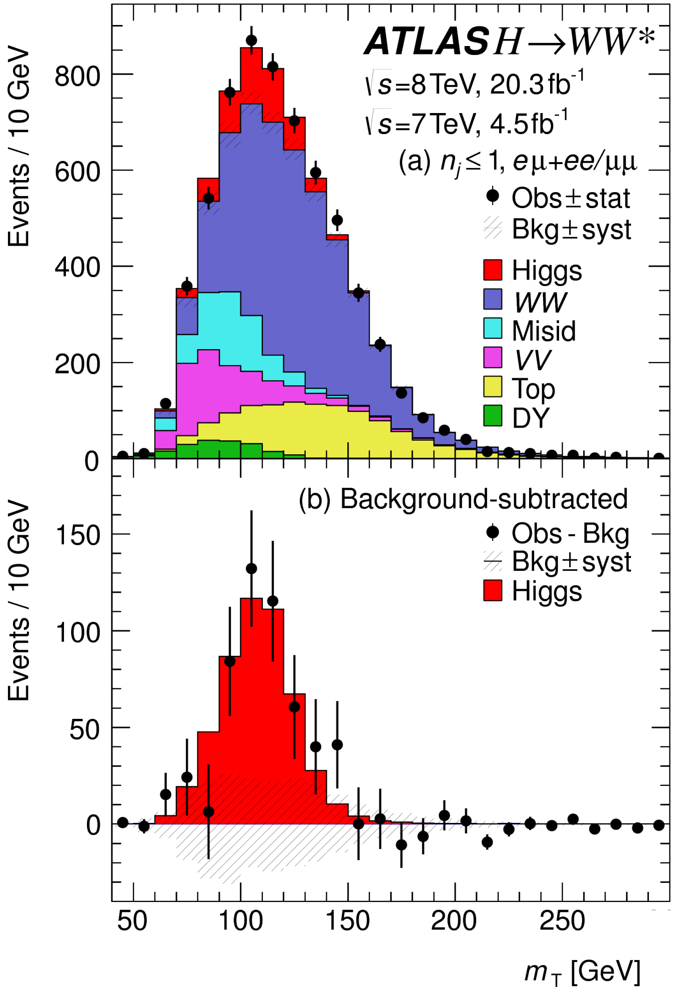
Measurements of the Standard Model Higgs boson with the ATLAS detector





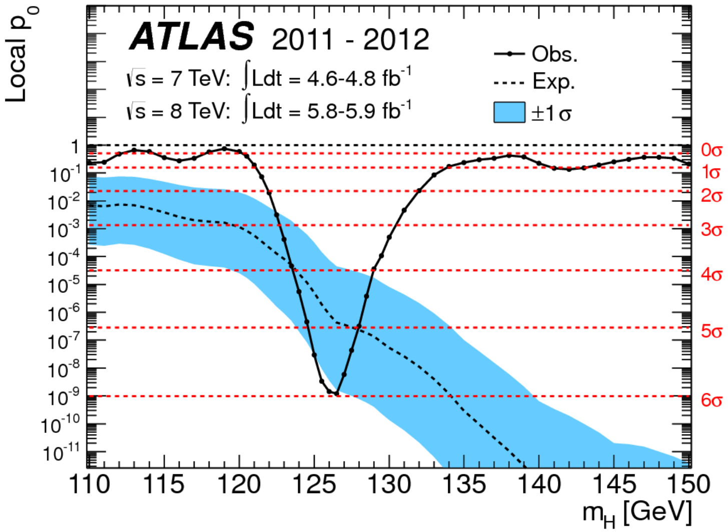
Kathrin Becker

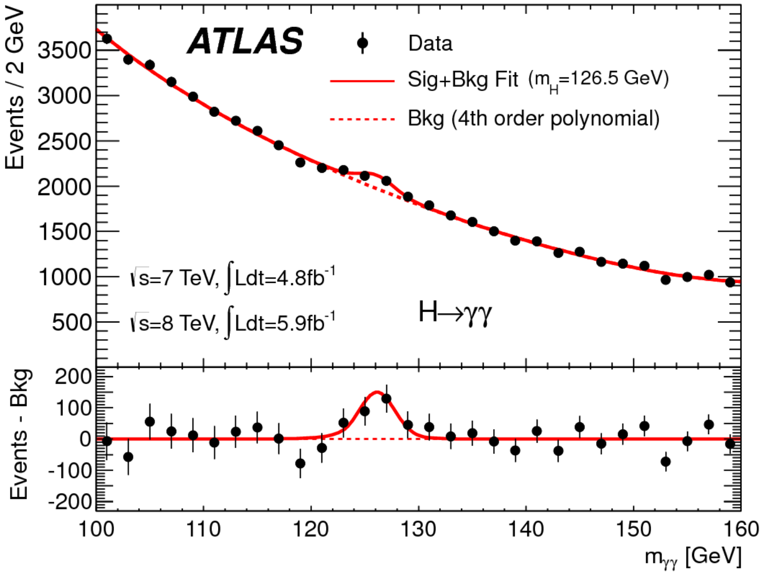
Seminar at University of Warwick,
08.03.2018

Higgs boson discovery in 2012

Highlight of LHC Run 1

- Observed significance: 5.9σ
- Dataset: 10.8 fb^{-1}
- Combination of three Higgs decays: $\gamma\gamma$, ZZ, and WW
- $\gamma\gamma$ strongest decay channel with 4.5σ



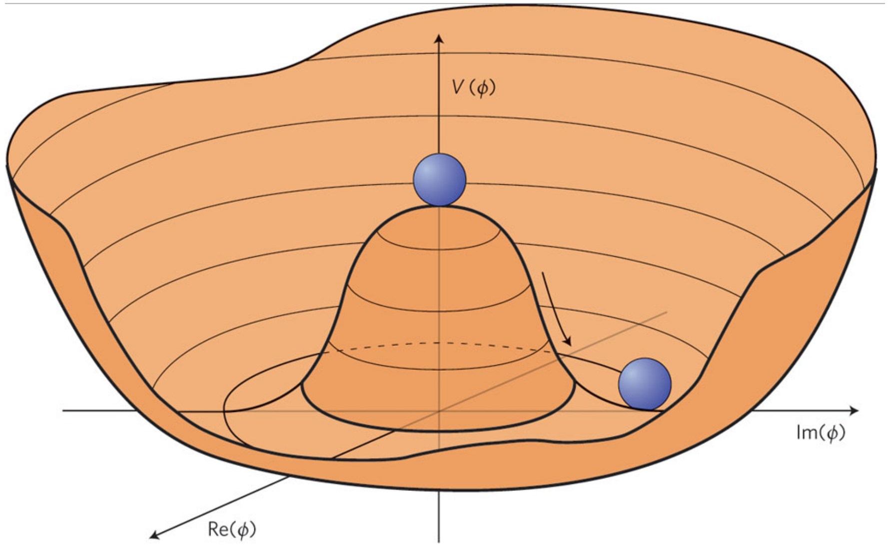


3 am, 4. July 2012 in front of CERN main auditorium

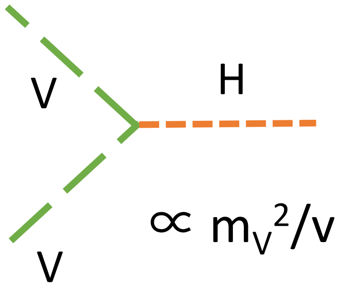
Nobel prize in physics 2013

For Peter Higgs and Francois Englert

Role of the Higgs boson in the SM

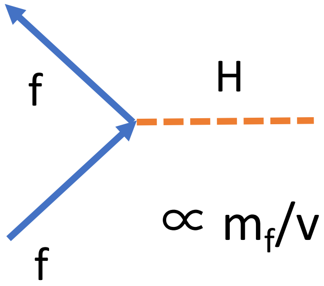


Gauge coupling:



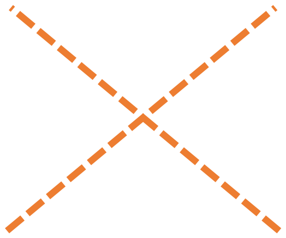
$\propto m_V^2/v$

Yukawa coupling:



$\propto m_f/v$

Self coupling:



$\propto m_H^2/v^2$

Higgs potential:

$$\boxed{V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4}$$

Higgs Vacuum Expectation Value:

$$\boxed{v = \frac{\mu}{\sqrt{\lambda}}}$$

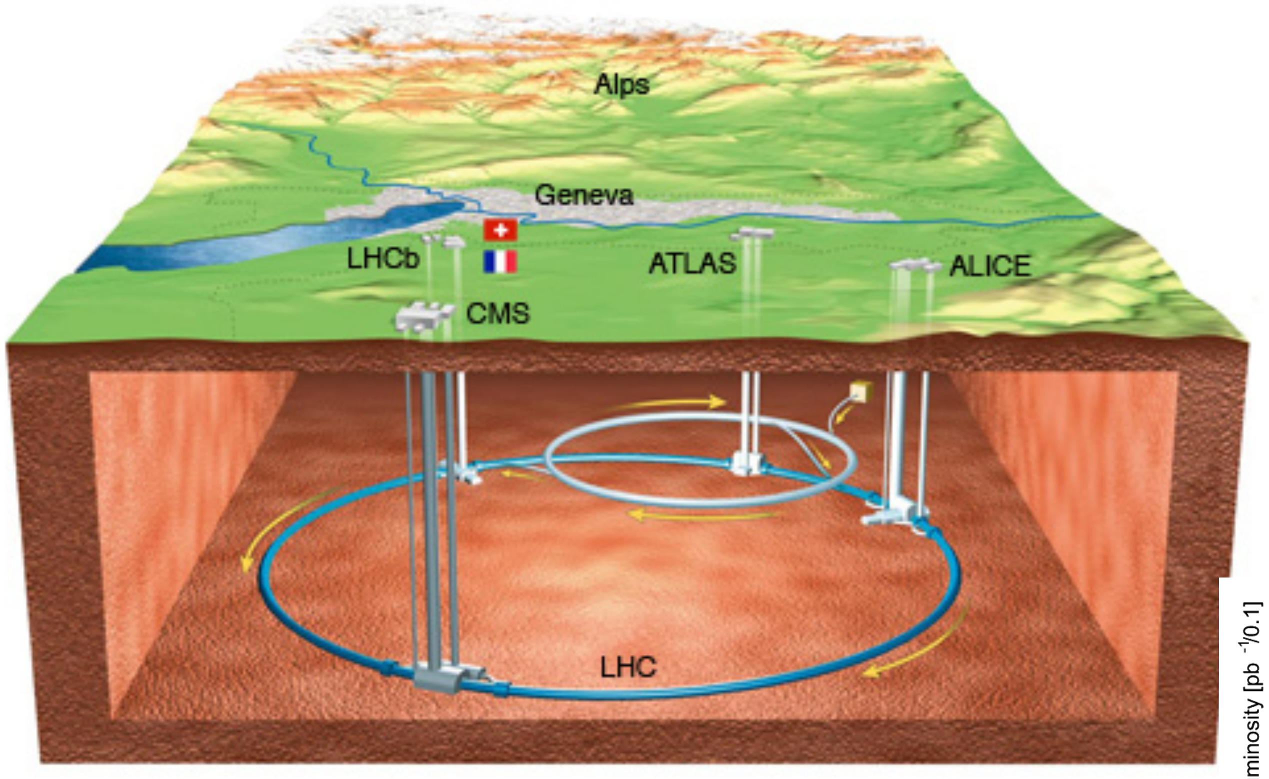
Experimental Setup: The machine and data

Year	CM energy	Integ. Lumi.
2010-2011	7 TeV	4.6 fb^{-1}
2012	8 TeV	20.3 fb
2015-2016	13 TeV	36.1 fb^{-1}
2015-2017	13 TeV	80 fb^{-1}

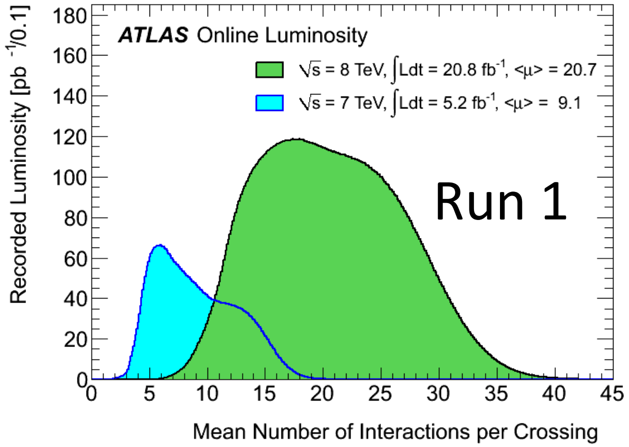
Run 1

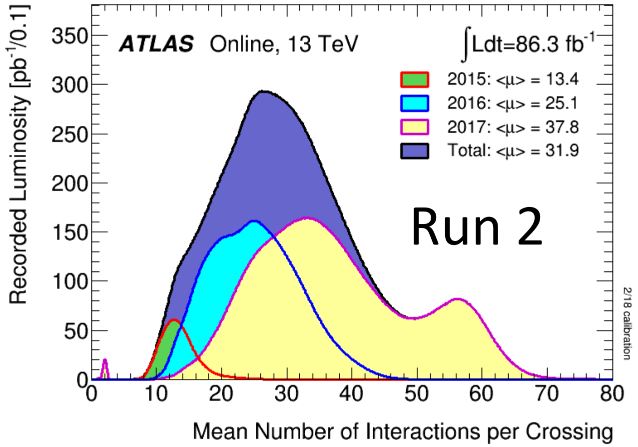
Run 2

Higher CM energy + higher luminosity
= more Higgs events

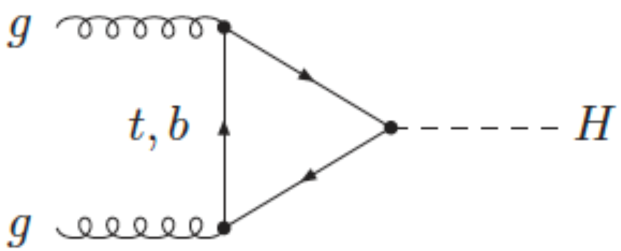


The LHC collides protons for the experiments!

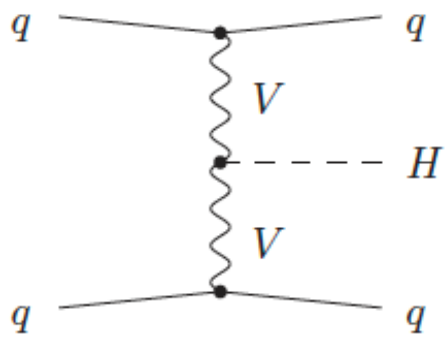




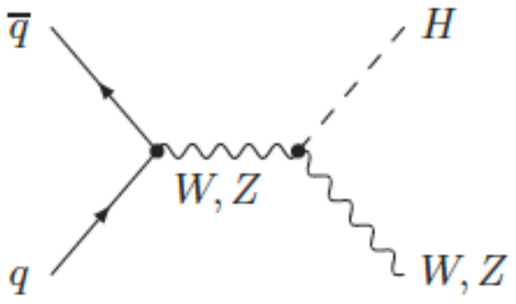
Higgs boson production in pp collisions



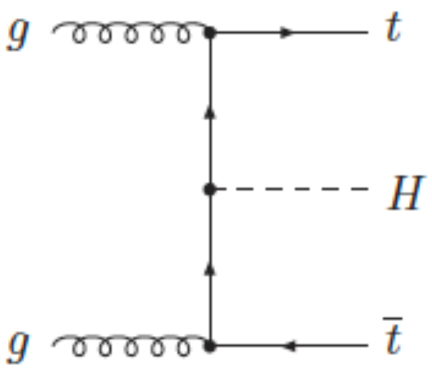
Gluon-gluon fusion (ggF)



Vector boson fusion (VBF)



Higgs-Strahlung (VH)



Top fusion (ttH)

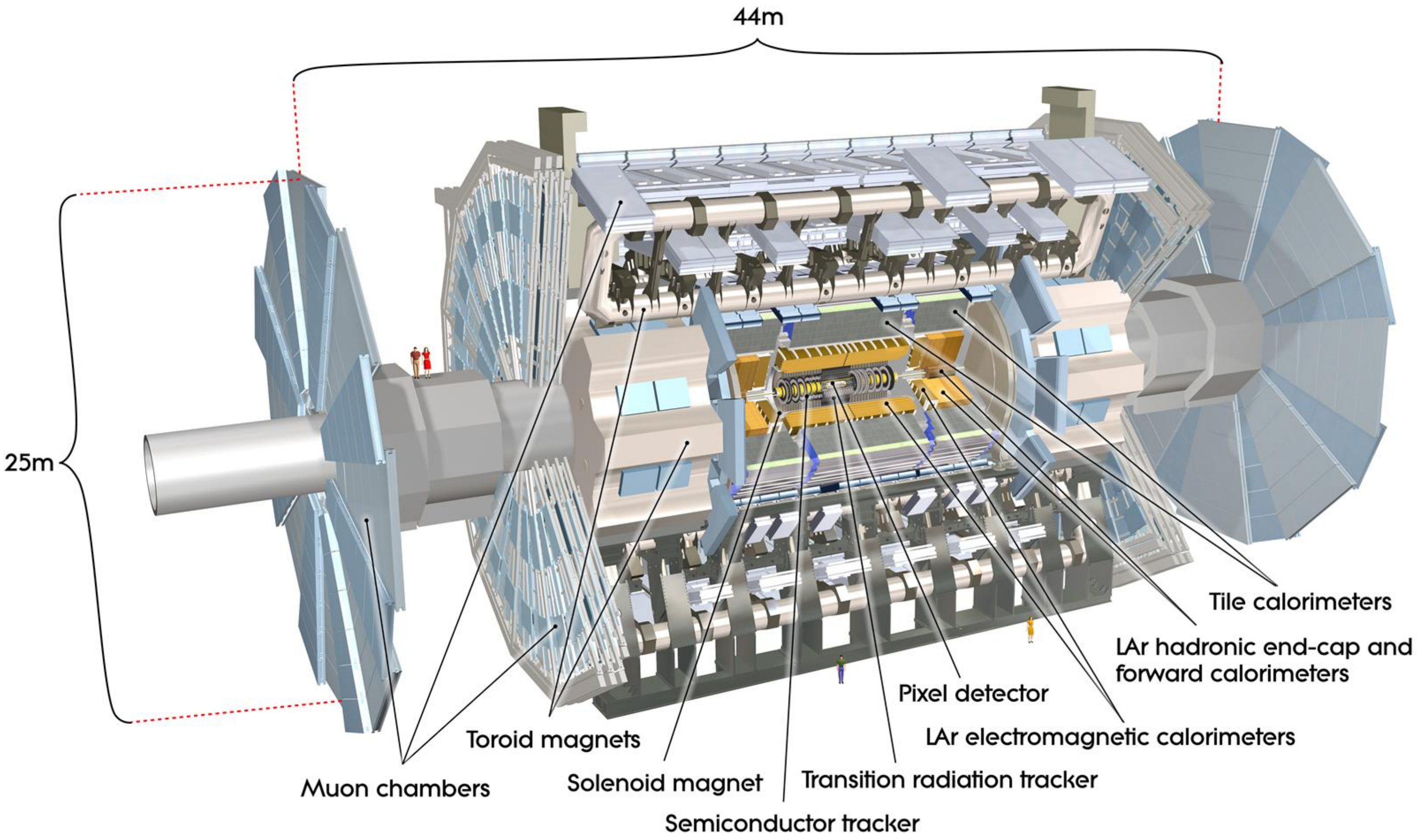
Cross sections and number of events:

m_H = 125 GeV	ggF	VBF	VH	ttH
σ(7 TeV)	16.8 pb	1.2 pb	0.9 pb	0.09 pb
σ(8 TeV)	21.4 pb	1.6 pb	1.1 pb	0.13 pb
σ(13 TeV)	48.5 pb	3.8 pb	2.3 pb	0.51 pb
N(7 TeV)	77k	6k	4k	0.5k
N(8 TeV)	434k	32k	23k	2.7k
N(13 TeV) 2015+2016	1751k	136k	81k	18k
N(13 TeV)	3882k	302k	180k	41k

Run 2 gives significant improvement in statistics!

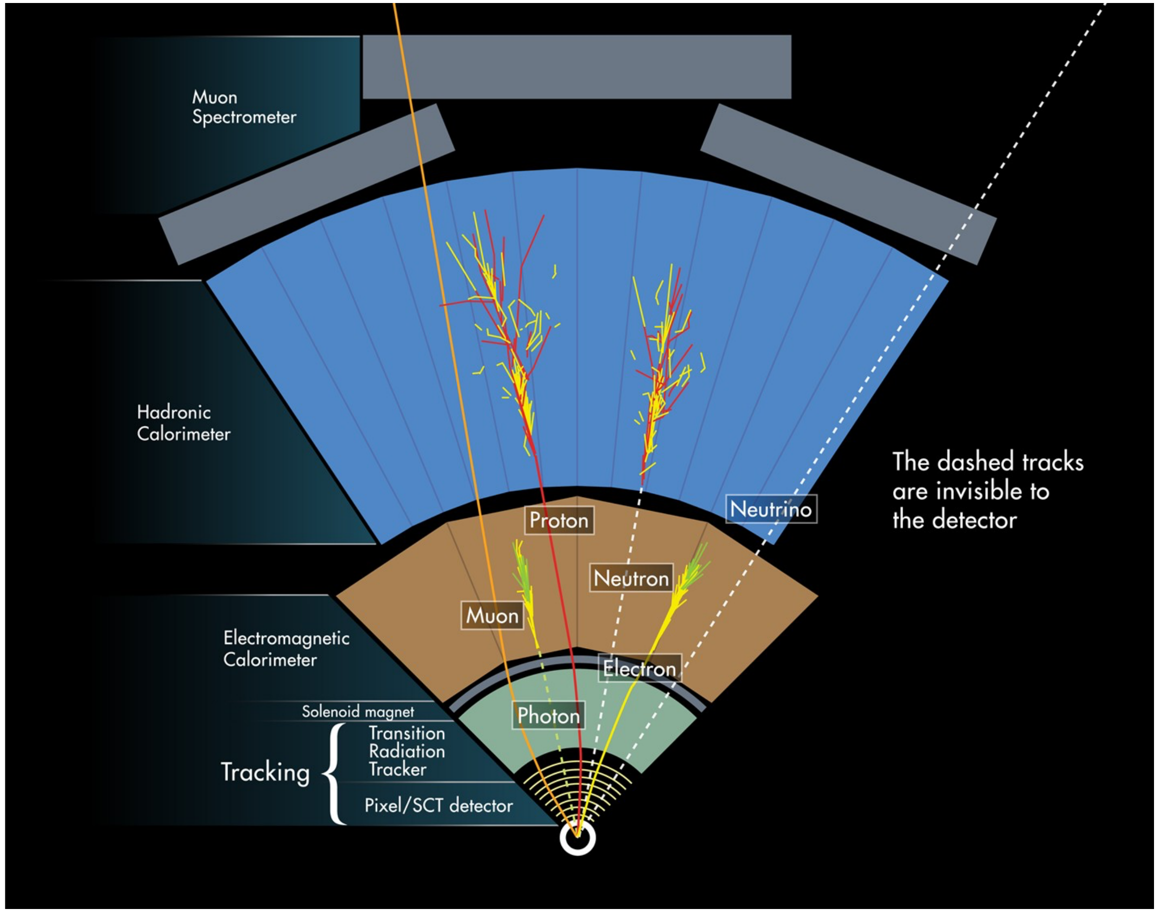
Experimental setup: The ATLAS detector

Multi-purpose detector: Onion setup



- Inside to outside:
  - Tracker
    - Silicon (pixel, strips)
    - Transition radiation (Xenon gas, to differ between electrons and pions)
  - Sampling calorimeter
    - Electromagnetic (LAr, Lead)
    - Hadronic (Steel, scintillator)
  - Muon spectrometer (gas tubes)
- Two magnets:
  - Solenoid surrounding tracker, 2T magnetic field
  - Toroid for muon spectrometer, 0.5T magnetic field

Which objects are available for analysis?



- Vertex
  - Reconstructed with tracks, super-important in times of up to 60 collisions
- Electrons
- Photons
- Muons

Good resolution, vertex matching, and reconstruction efficiency

- Jets
  - b-quark jets
  - Hadronically decaying τ
- Neutrinos = Missing transverse energy

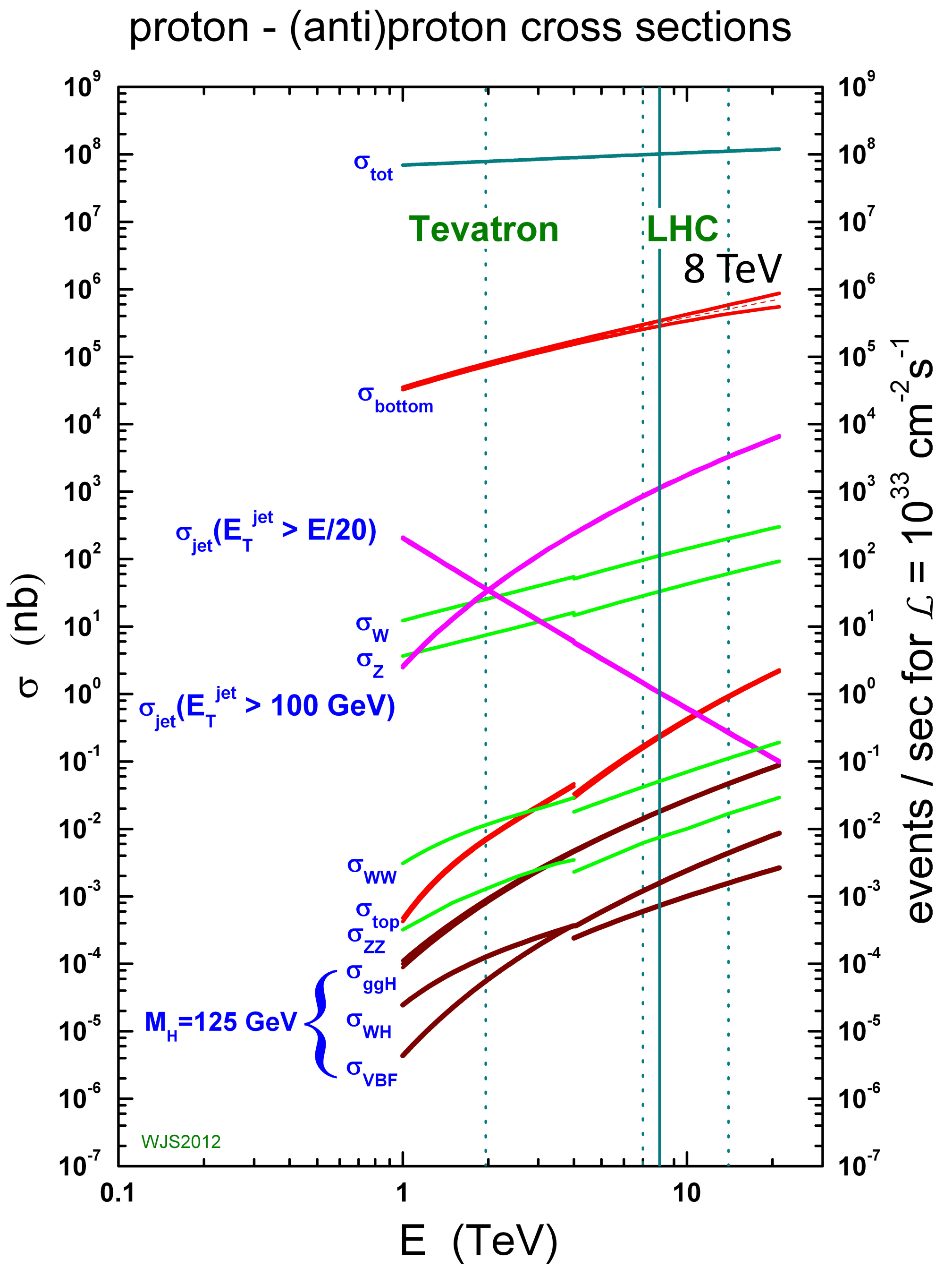
Low resolution and reco. efficiency, only partly vertex matched

Reminder: Energy in collision is unknown

Typical LHC pp collisions

- QCD production absolutely dominant at the LHC
- Single boson (W,Z) production already 5 orders of magnitude lower
  - Leptons and missing transverse energy can appear here
- Top-quark and diboson cross sections still larger than Higgs boson cross sections

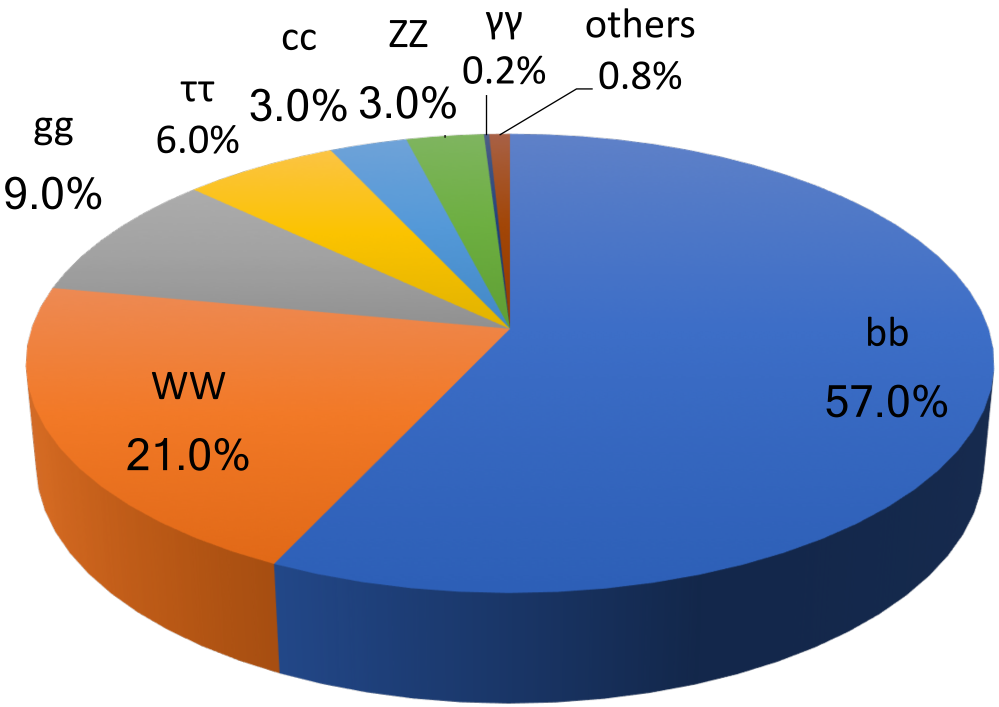
Advantageous to have leptons or photons in the final state of the Higgs decay to have a chance against the backgrounds!



Higgs boson decays – Measuring as many Higgs events as possible

- Main Higgs decays are very inconvenient for measurements at the LHC
  - bb: only for VH production and ttH production → Lepton from W/Z or top-decay
  - gg and cc decays difficult
  - WW: di-lepton mode → reduces BR again Resolution bad due to two neutrinos in the final state, many backgrounds
  - $\tau\tau$: τ leptonic or hadronic decays, low efficiency and resolution
- High mass resolution channels
  - ZZ → llll: low BR, great mass resolution
  - $\gamma\gamma$: good mass resolution and efficiency

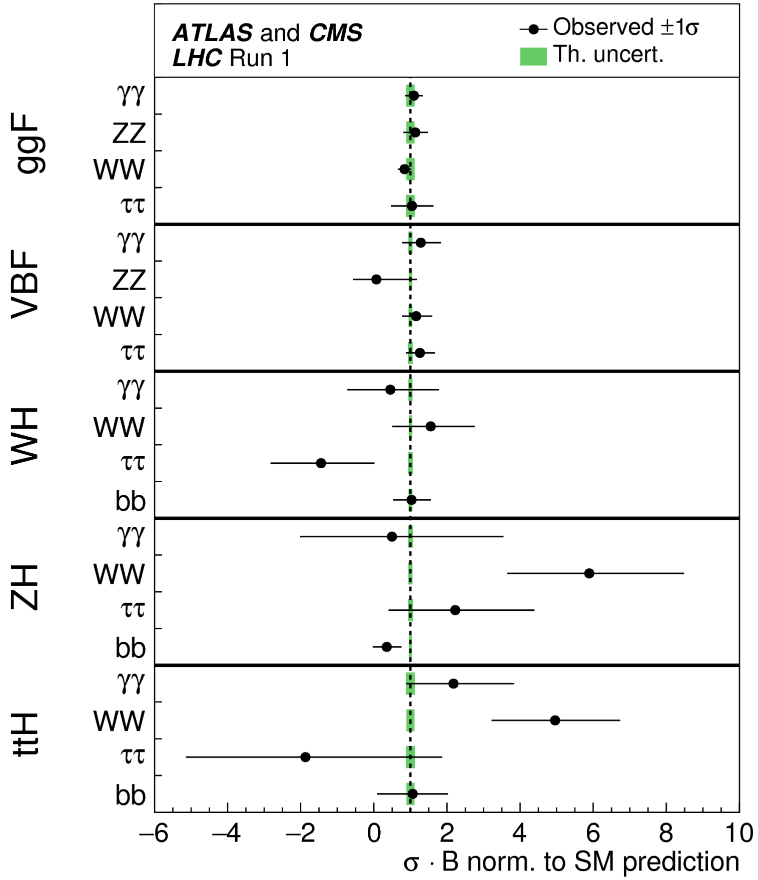
Higgs branching ratio (BR)



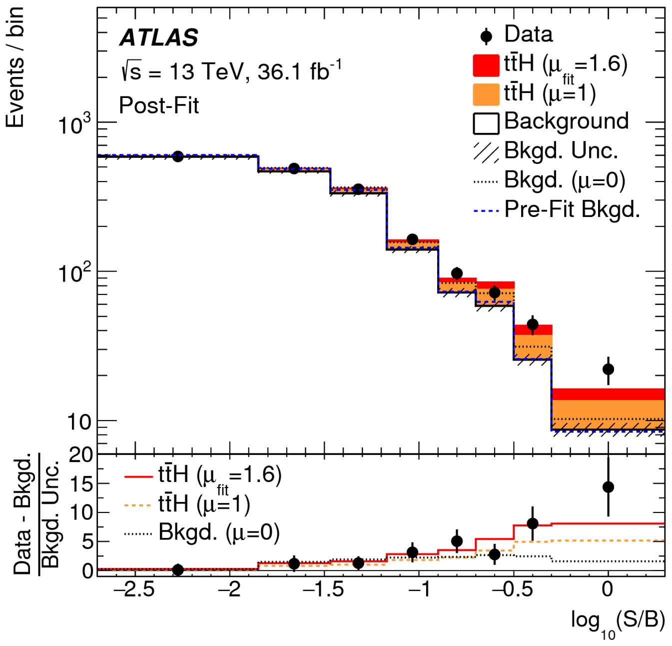
We extract only a fraction of the Higgs boson events produced by the LHC.
Analyses ongoing in most decay modes! Combination important!

Test of the Standard Model Higgs boson

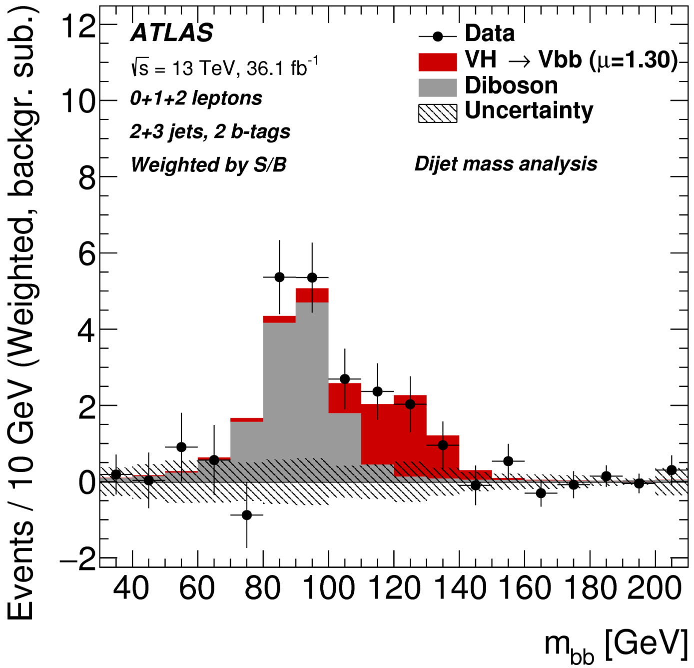
- Couplings of the Higgs boson to other particles
  - Accessible via production and decay modes
- Mass of the Higgs boson: 125.09 ± 0.24 GeV
- Spin/CP properties of the Higgs boson: Spin 0 / CP even favoured
- Higgs boson kinematics
  - Transverse momentum, rapidity
  - H+jets production
  - Properties of the jets in events with Higgs
- New physics could be hiding
  - Make sure results are not too SM dependent



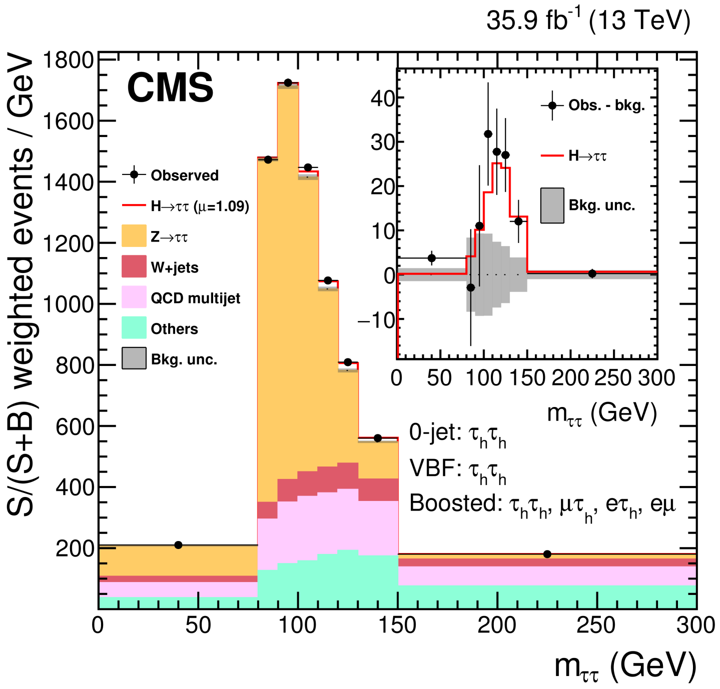
Highlights from Run 2 on the couplings



Evidence for top fusion production
Submitted to PRD (ATLAS)



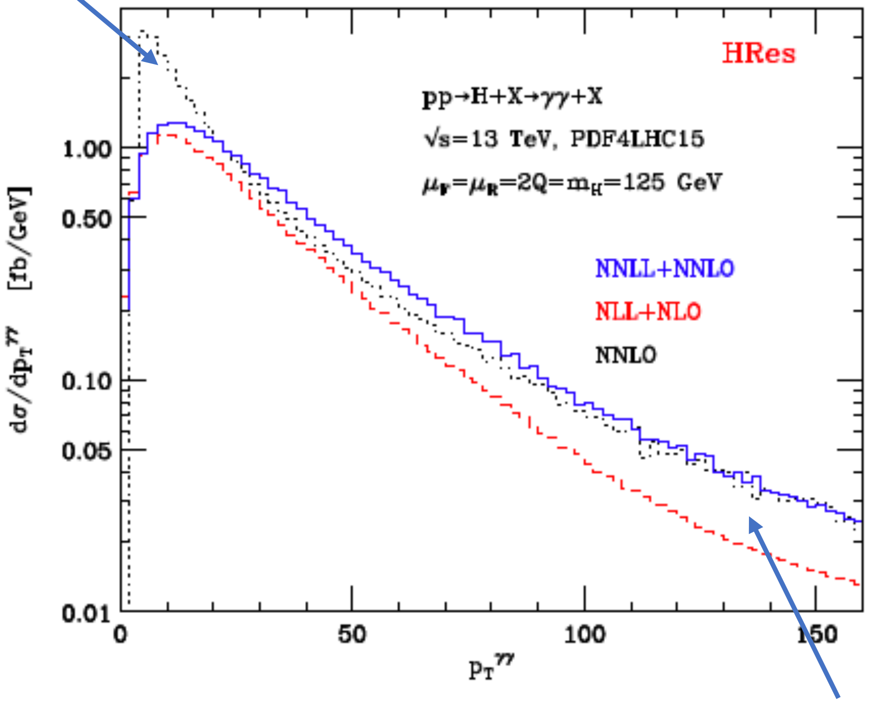
Evidence for VH(H→bb)
JHEP 12 (2017) 024 (ATLAS)
Accepted by PLB (CMS)



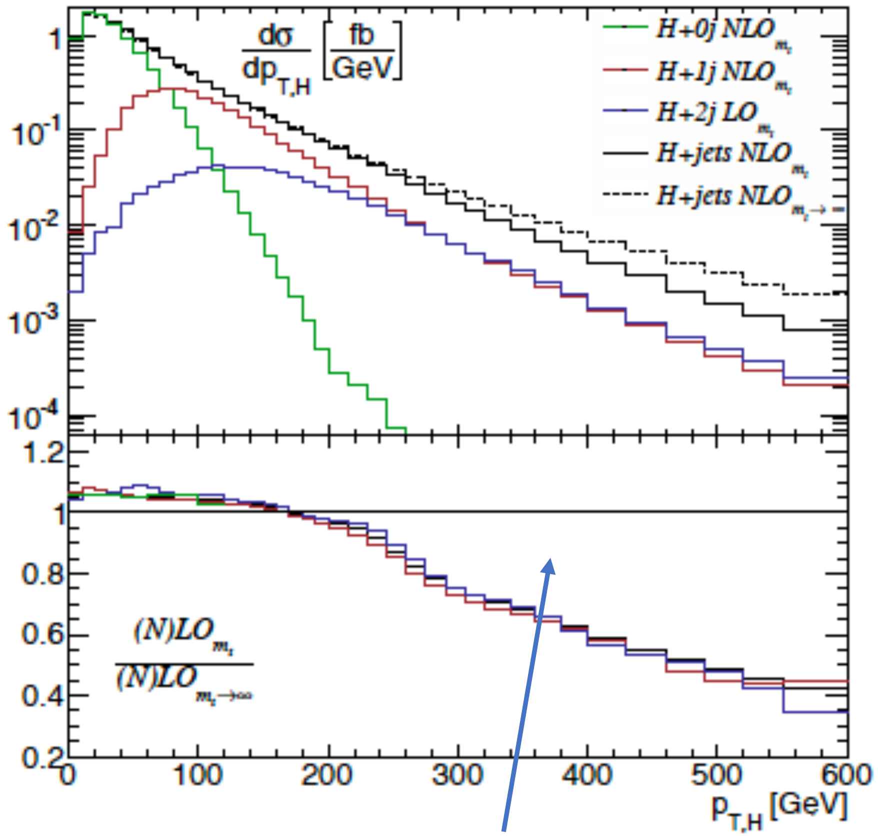
Observation of H→$\tau\tau$
Accepted by PLB (CMS)

Test of Higgs boson kinematics - p_T

resummation



Higher order QCD

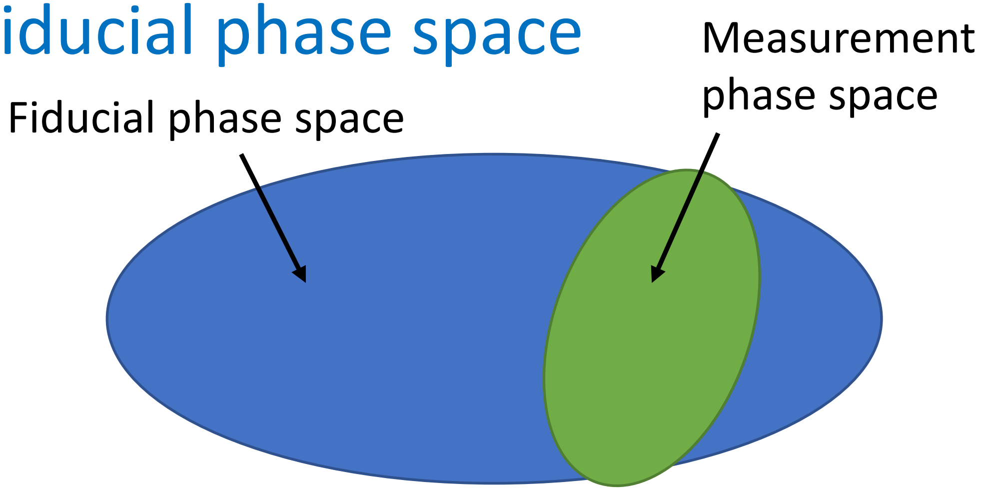


Top-quark mass dependence
→ Sensitivity to new physics

Measuring Higgs boson kinematics

- Measured differential cross sections in a fiducial phase space
  - Reduces dependence on the SM
  - Phase space different for each Higgs decay

Example with an experimentally difficult decay mode:
H→WW, 8 TeV, 20.3 fb^{-1}

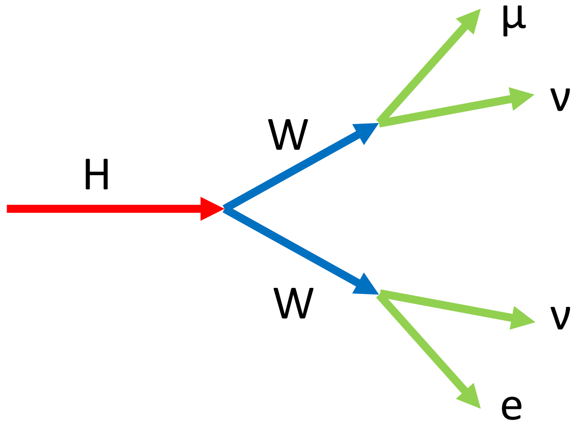


- Measure template cross sections in simple fiducial phase spaces
  - More model dependent, but easy to combine

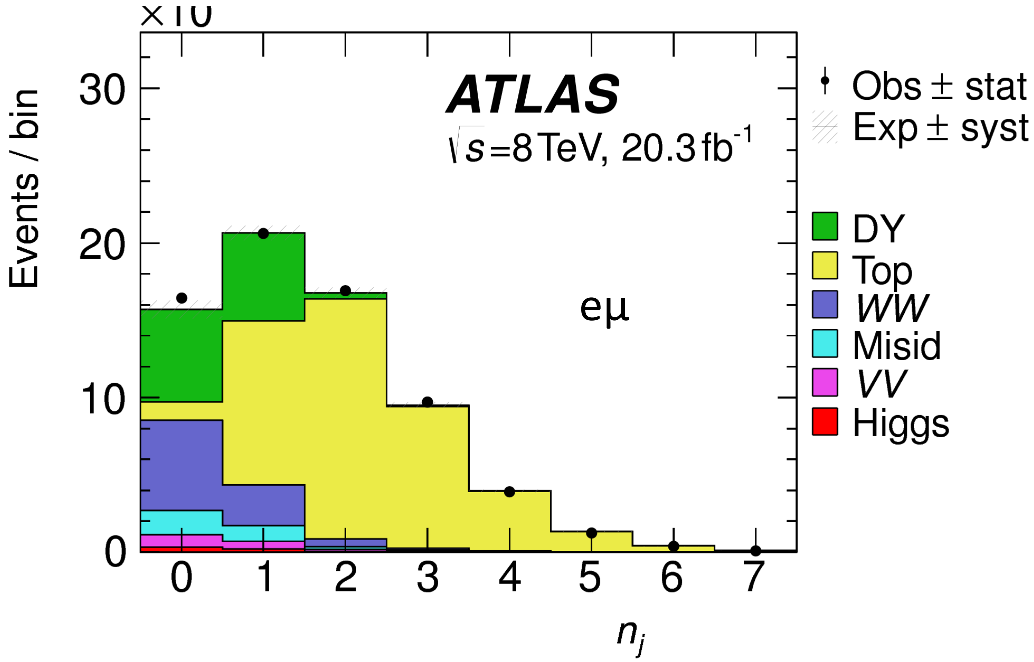
Example with an experimentally easier decay mode:
H→$\gamma\gamma$, 13 TeV, 36.1 fb^{-1}

Measuring kinematic distributions of the Higgs boson in H→WW

- Distributions
  - $d\sigma/dn_j$, $d\sigma/dp_T(j_1)$ to test higher order QCD
  - $d\sigma/dp_{T,H}$
  - $d\sigma/d|y_{ll}|$ to test PDFs



- Focus on gluon fusion production mode
- Leptonic (e, μ) decay of the W only
- Jet-binned analysis
  - 0 jets: WW production
  - 1 jet: WW and top-quark production
  - ≥2 jets: Top-quark production



Path to differential measurements

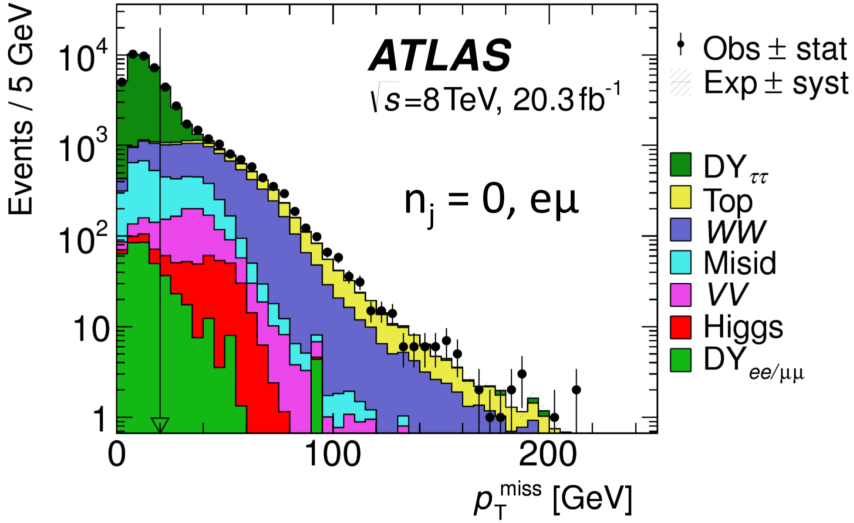
Event selection

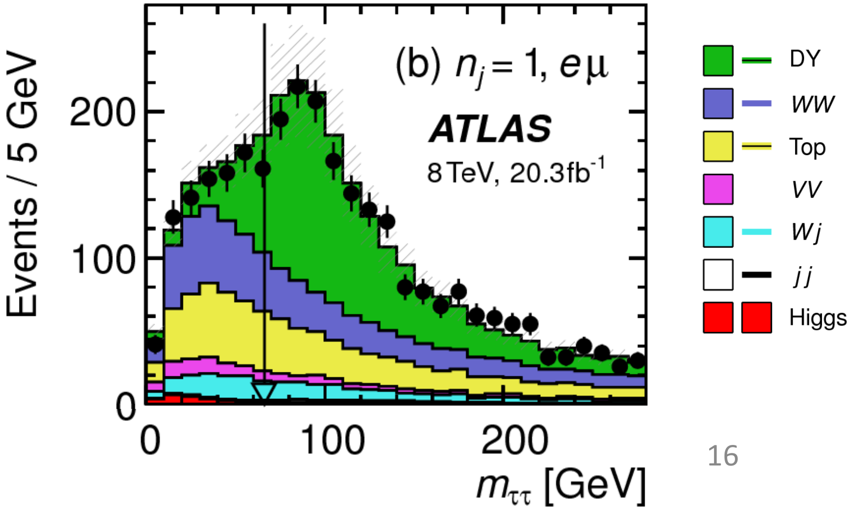
Background estimation

Correction for detector effects

Selection of WW→eνμν events

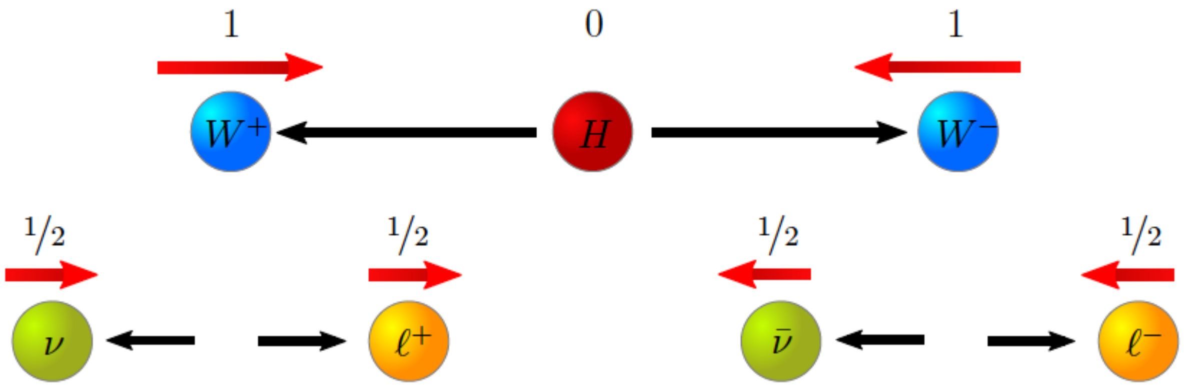
- Require large missing transverse momentum
  → suppress **QCD/DY background**
- Require exactly 2 opposite sign leptons
  → suppress **other diboson**
- Lepton isolation, $p_T(l_2)>15$ GeV
  → suppress **misidentified leptons**
- $m_{\tau\tau} < (m_Z - 25\ \text{GeV})$
  → suppress **Z→ττ production**
- veto events with b-quark jets
  → suppress **top-quark production**

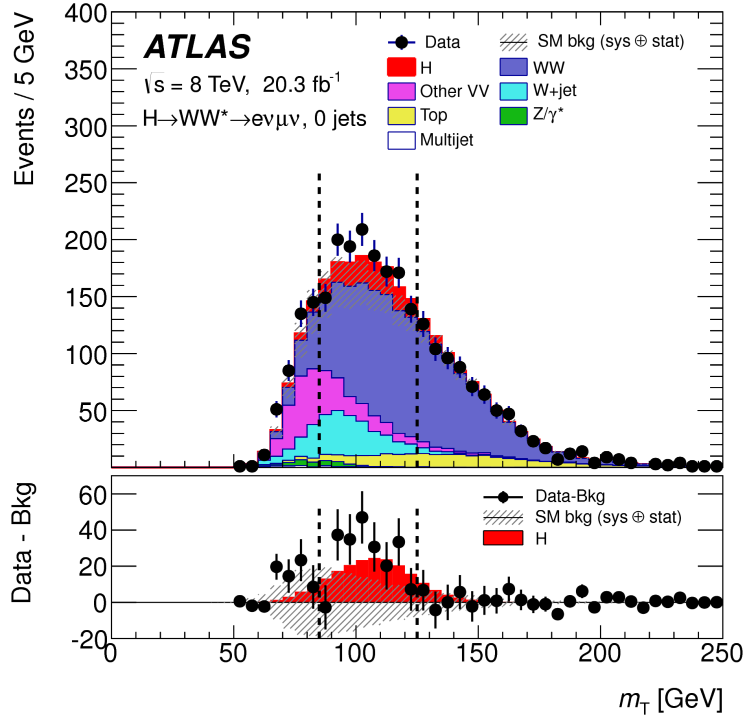




Selection of Higgs events

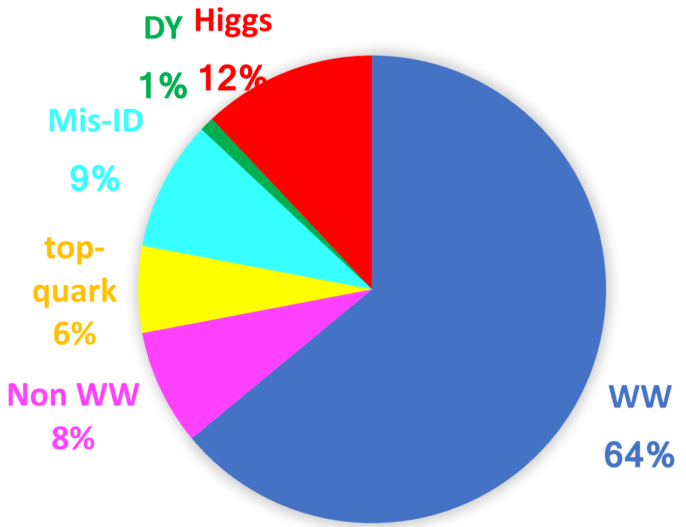
- Spin correlation of the two leptons
  - Spin 0 Higgs → leptons close together → Δϕ(l,l) and m(ll)
- Transverse mass: m_T(ll MET)
  - Enrich in Higgs events by window cut



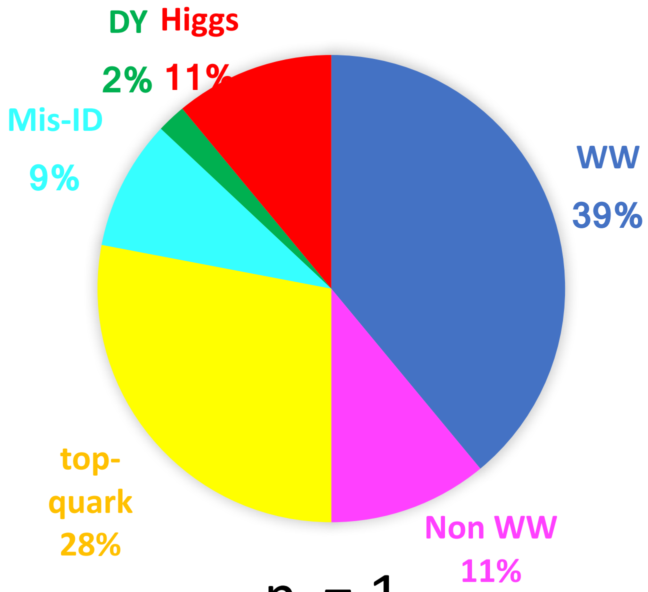


$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$$

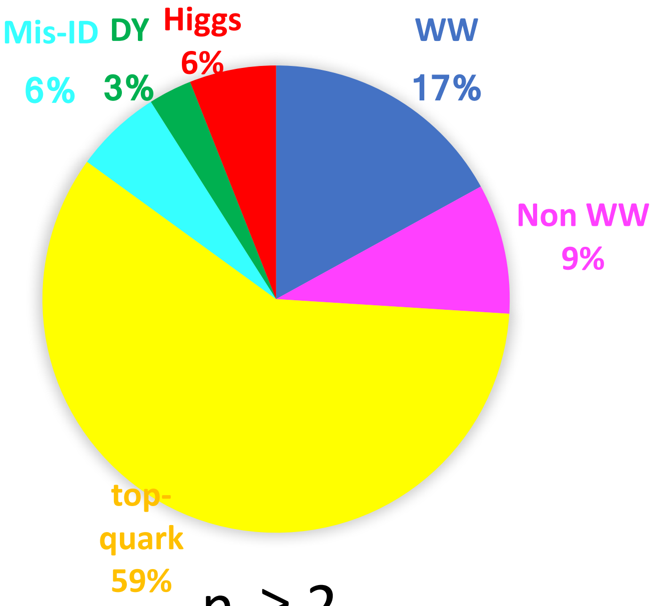
Composition of the signal regions



$n_j = 0$



$n_j = 1$



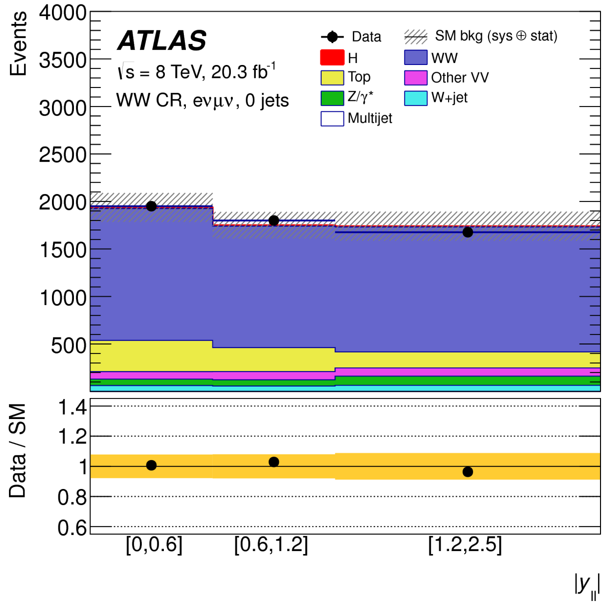
$n_j \geq 2$

Signal fraction at best 12%.
Normalize background as much as we can with data to keep uncertainties small.

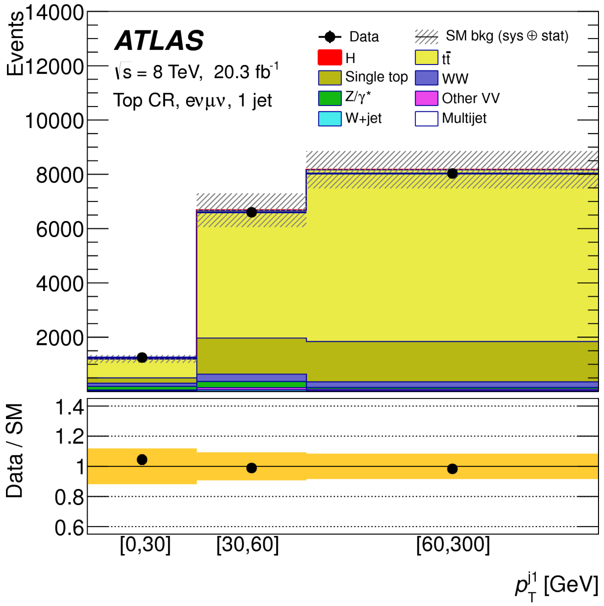
Background estimation

Define CR by reverting a selection criteria.
Close kinematics to the signal region and high purity are advantageous.
Total of 10 control regions in the analysis.

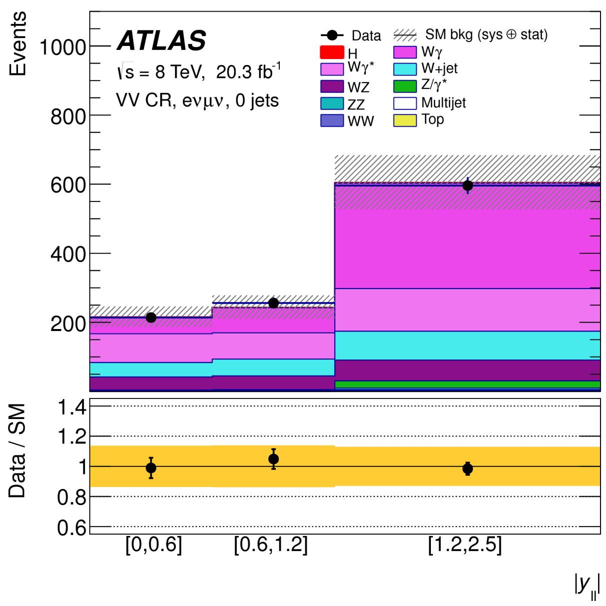
WW control region:
High m_{ll} events



Top control region:
Require b-quark jet



Other VV control region:
Require 2 same sign leptons



Estimation of mis-identified leptons

- Mis-identification probability ~10^{-4} → sizeable contribution of W+jets
- Define anti-ID leptons and apply the fake factor method:

Fake estimate in the SR

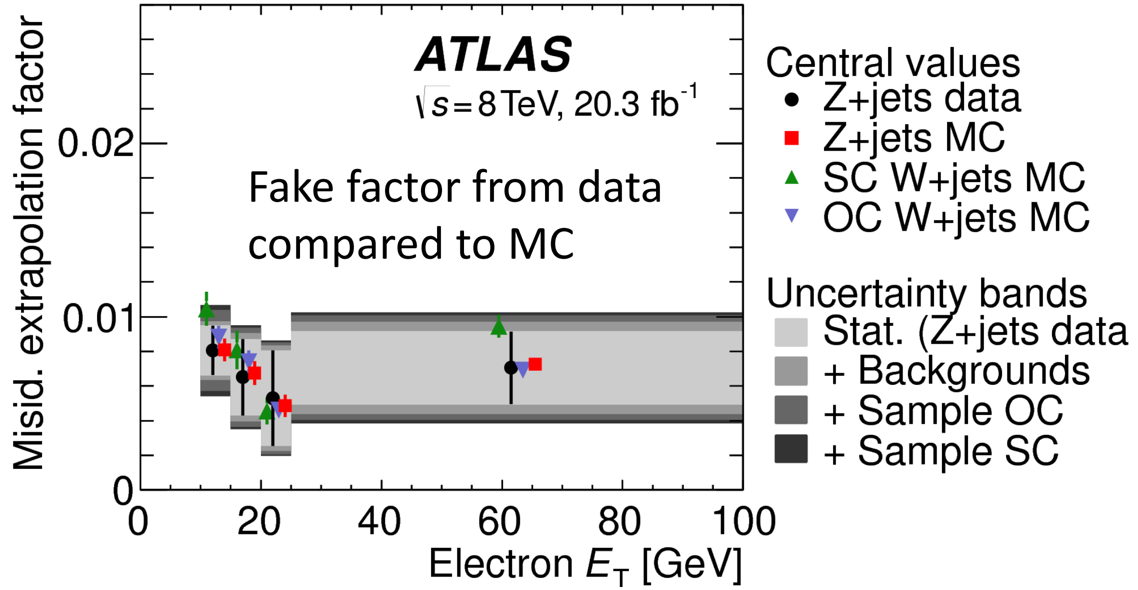
=

Fake factor = $N_{ID}/N_{anti\text{-}ID}$

x

W+jets control region
Replace ID with anti-ID leptons

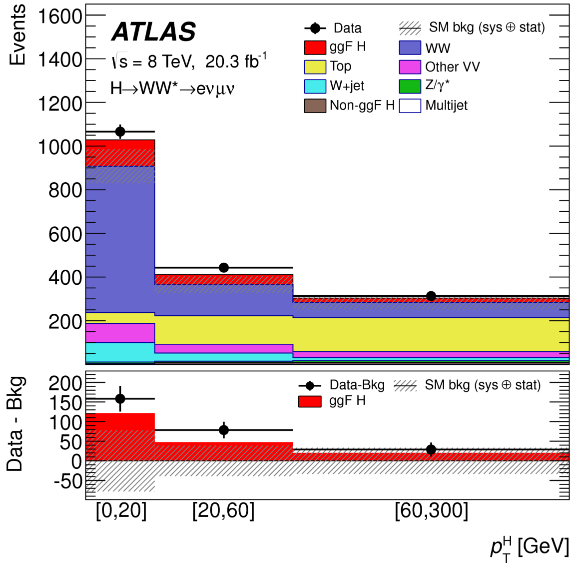
- Determine fake factor in Z+jets data
- Main uncertainties
  - Flavor composition of lepton fakes
  - Subtraction of the prompt background
  - Data statistics

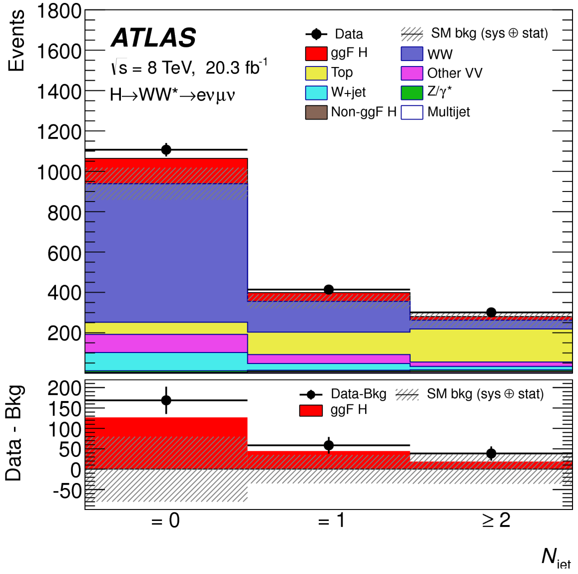


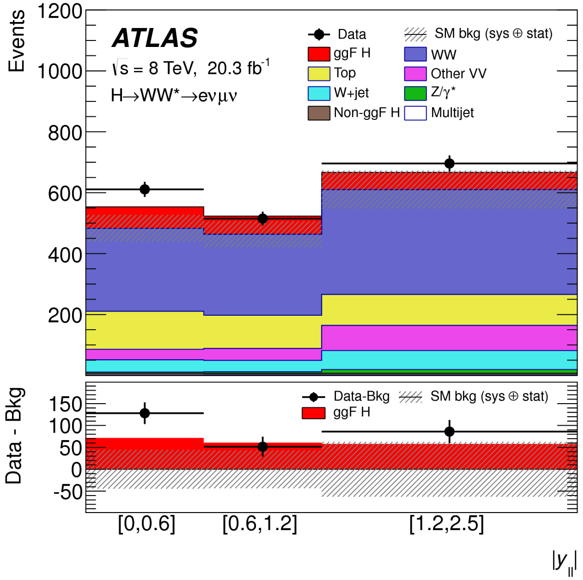
Fake factor from data compared to MC

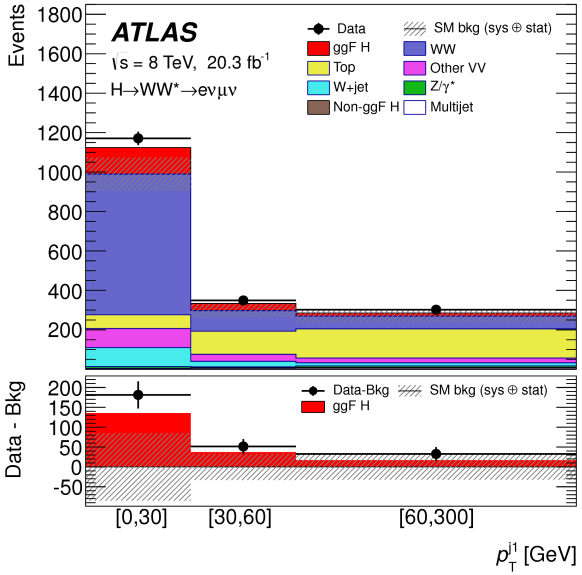
Measured distributions

- Distributions integrated over the 3 signal regions
- Signal statistics still limited
    - no more than three bins per distribution
- To extract the signal distribution, the normalized background is subtracted
    - This could be improved in the future









Correction for detector effects

- Theorist cannot compare their prediction to our measured distributions.
- Correct the distributions for efficiencies and resolutions of the measured objects using MC.
- Results quoted in a fiducial region (selection cuts applied on truth objects)

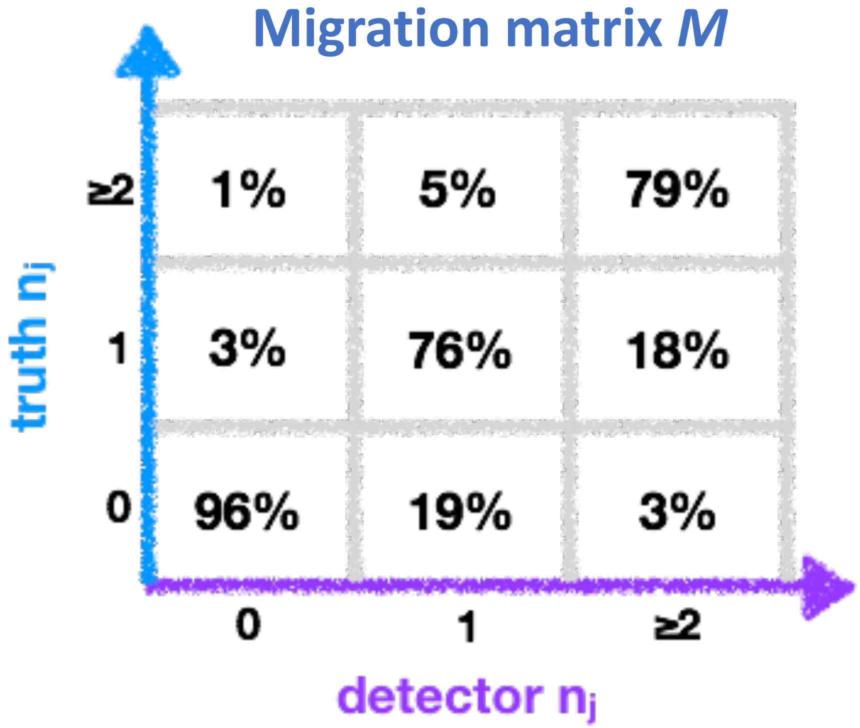
Migration matrix corrects resolution

Measured bin j

$$N_i^{\text{part}} = \frac{1}{\varepsilon_i} \cdot \sum_j \left(M^{-1}\right)_{ij} \cdot f_j^{\text{reco-only}} \cdot \boxed{\left(N_j^{\text{reco}} - N_j^{\text{bkg}}\right)}$$

Selection efficiency (14-43%)

Correction for measured events outside fiducial region ≈ 90%

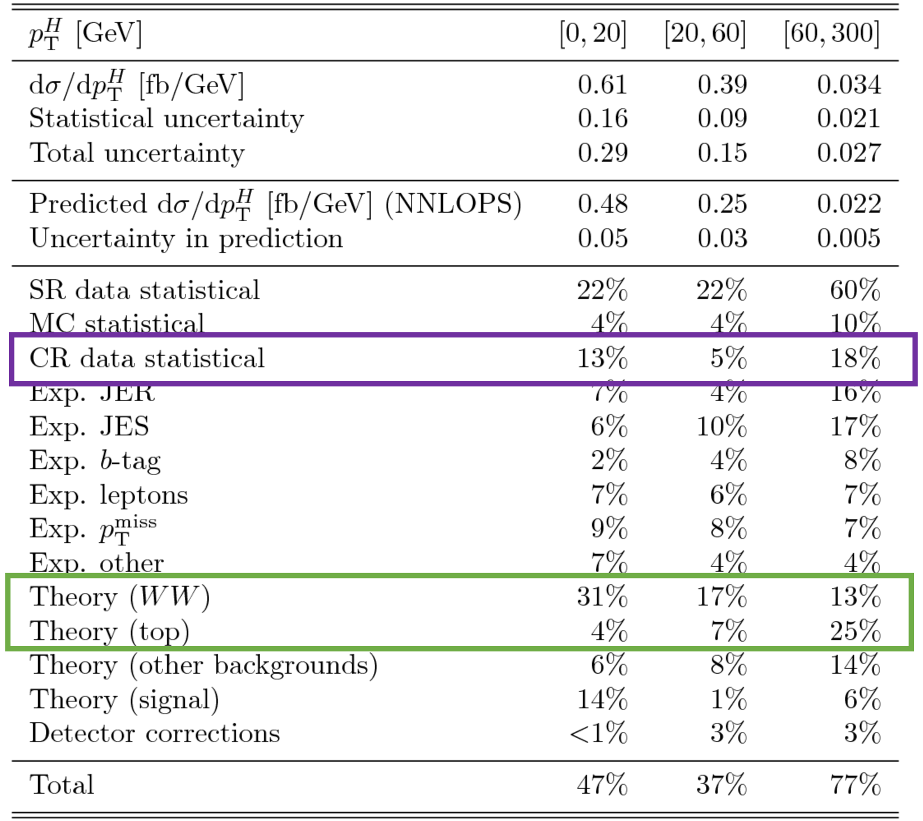


Migration matrix *M*

truth n_j			
≥2	1%	5%	79%
1	3%	76%	18%
0	96%	19%	3%
	0	1	≥2

detector n_j

Results and uncertainties: p_T of Higgs boson

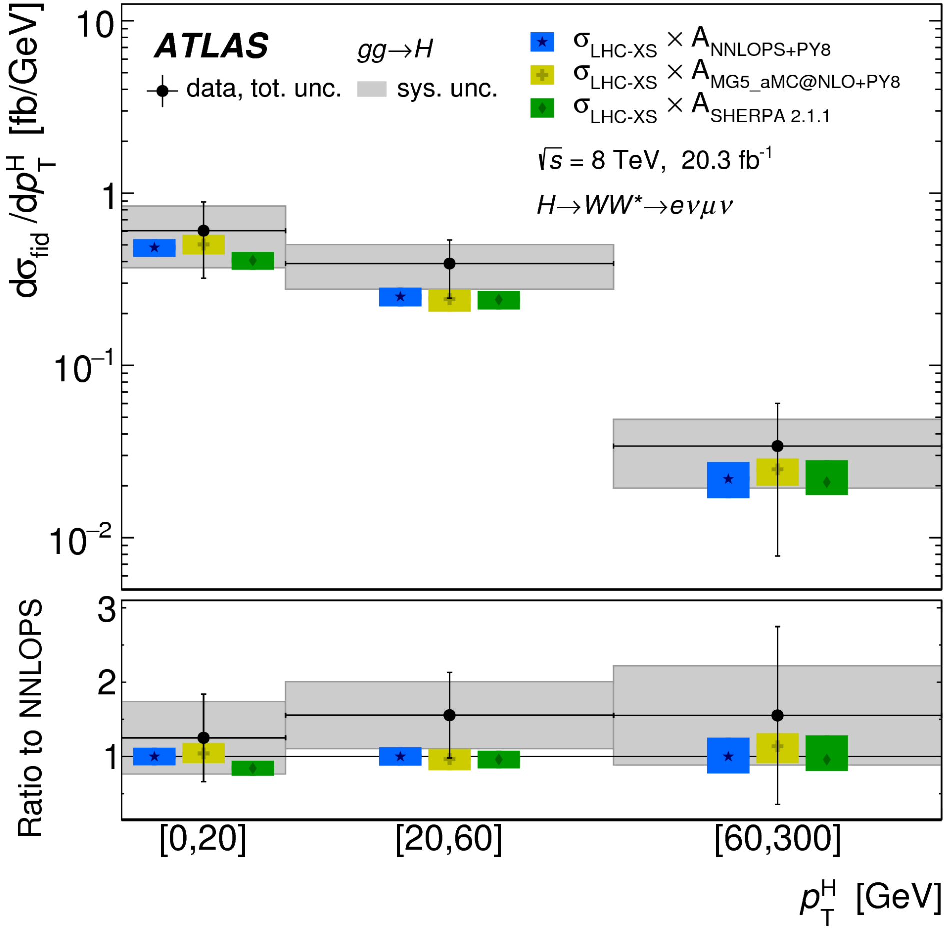


p_T^H [GeV]	[0, 20]	[20, 60]	[60, 300]
$d\sigma/dp_T^H$ [fb/GeV]	0.61	0.39	0.034
Statistical uncertainty	0.16	0.09	0.021
Total uncertainty	0.29	0.15	0.027
Predicted $d\sigma/dp_T^H$ [fb/GeV] (NNLOPS)	0.48	0.25	0.022
Uncertainty in prediction	0.05	0.03	0.005
SR data statistical	22%	22%	60%
MC statistical	4%	4%	10%
CR data statistical	13%	5%	18%
Exp. JER	7%	4%	16%
Exp. JES	6%	10%	17%
Exp. b-tag	2%	4%	8%
Exp. leptons	7%	6%	7%
Exp. p_T^{miss}	9%	8%	7%
Exp. other	7%	4%	4%
Theory (WW)	31%	17%	13%
Theory (top)	4%	7%	25%
Theory (other backgrounds)	6%	8%	14%
Theory (signal)	14%	1%	6%
Detector corrections	<1%	3%	3%
Total	47%	37%	77%

systematics dominated

stat. = syst.

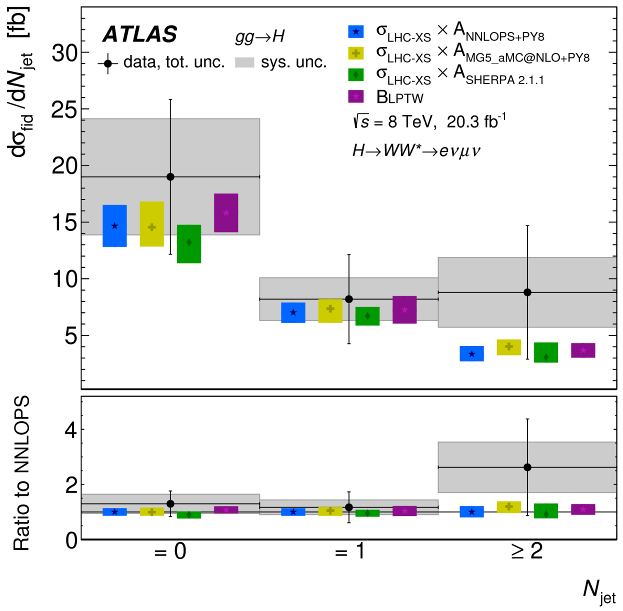
statistics dominated

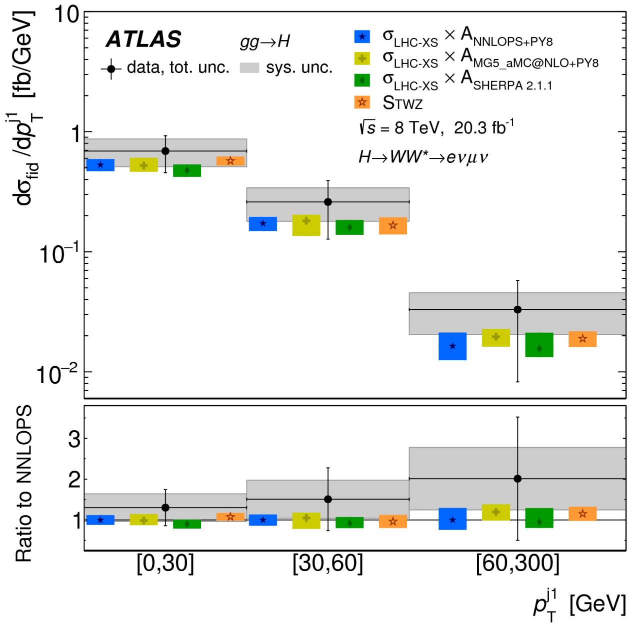


Discussion of results

- High statistics gluon fusion bins already systematics dominated
  - In the long run H→$\gamma\gamma$ and H→ZZ will be more precise (and already are)
- Low statistics bins are superior in sensitivity to H→ZZ
  - Similar or better compared to H→$\gamma\gamma$
  - Includes bins for high p_T Higgs boson and Higgs+jets production, sensitive to BSM heavy particles
  - Would be great to combined these bins

Fiducial and differential measurements are very complicated.
Define binned measurements that can be easily combined!





Combination of the Run 1 results

- Measuring the inclusive production cross section
- Extracting the signal strength $\mu = \sigma_{\text{measured}}/\sigma_{\text{theory}}$

Great for combination, can be extracted for all analyses.

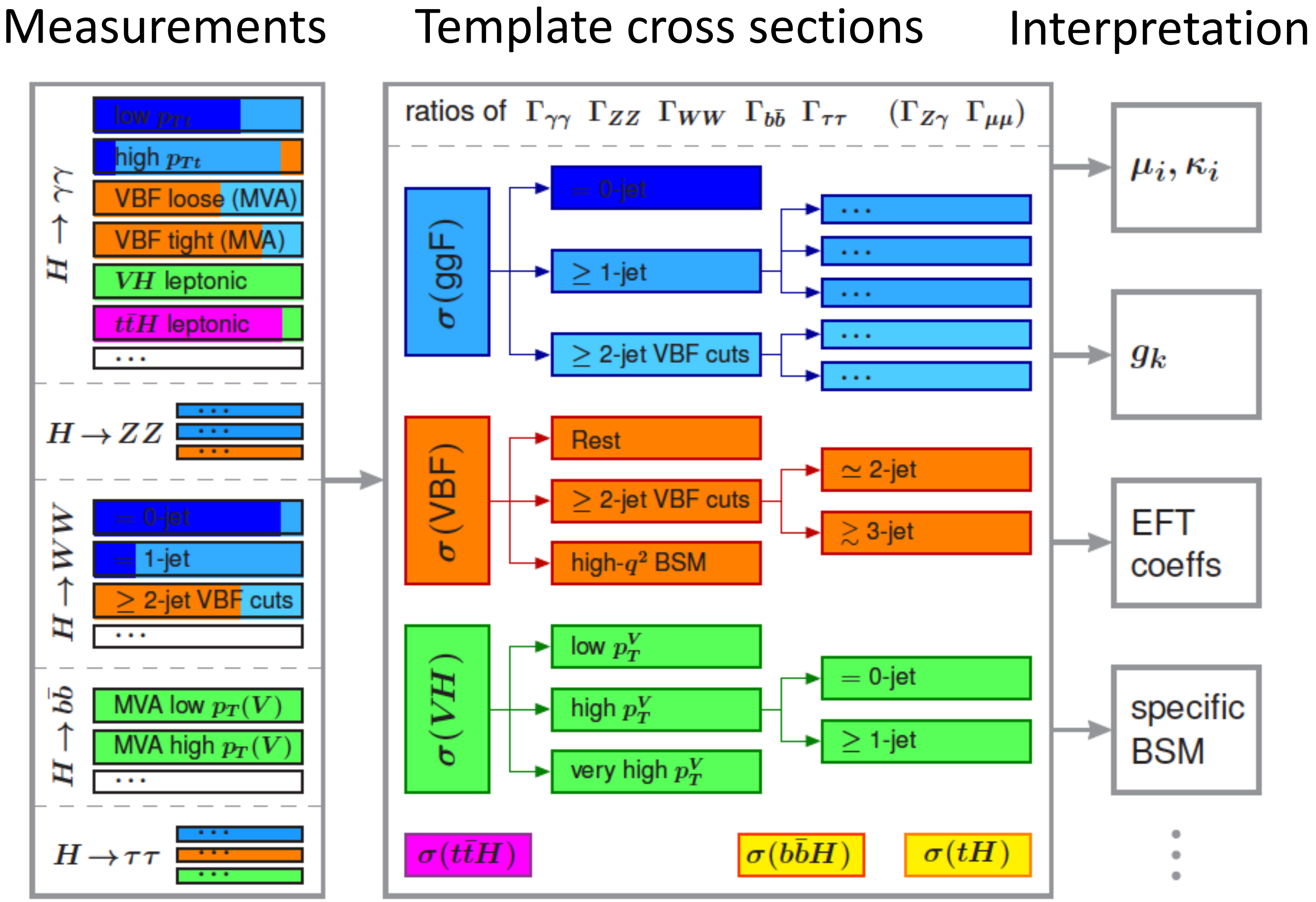
Extrapolated to the full phase space (model dependence)
Divide by theory cross section (uncertainties!)
No kinematic information of Higgs boson production.

Idea of “simplified template cross sections”

- Choose simple fiducial regions
  - For which theory uncertainties can evolve with time
  - Where BSM physics is most likely to appear
- Template with different regions defined for each production mode

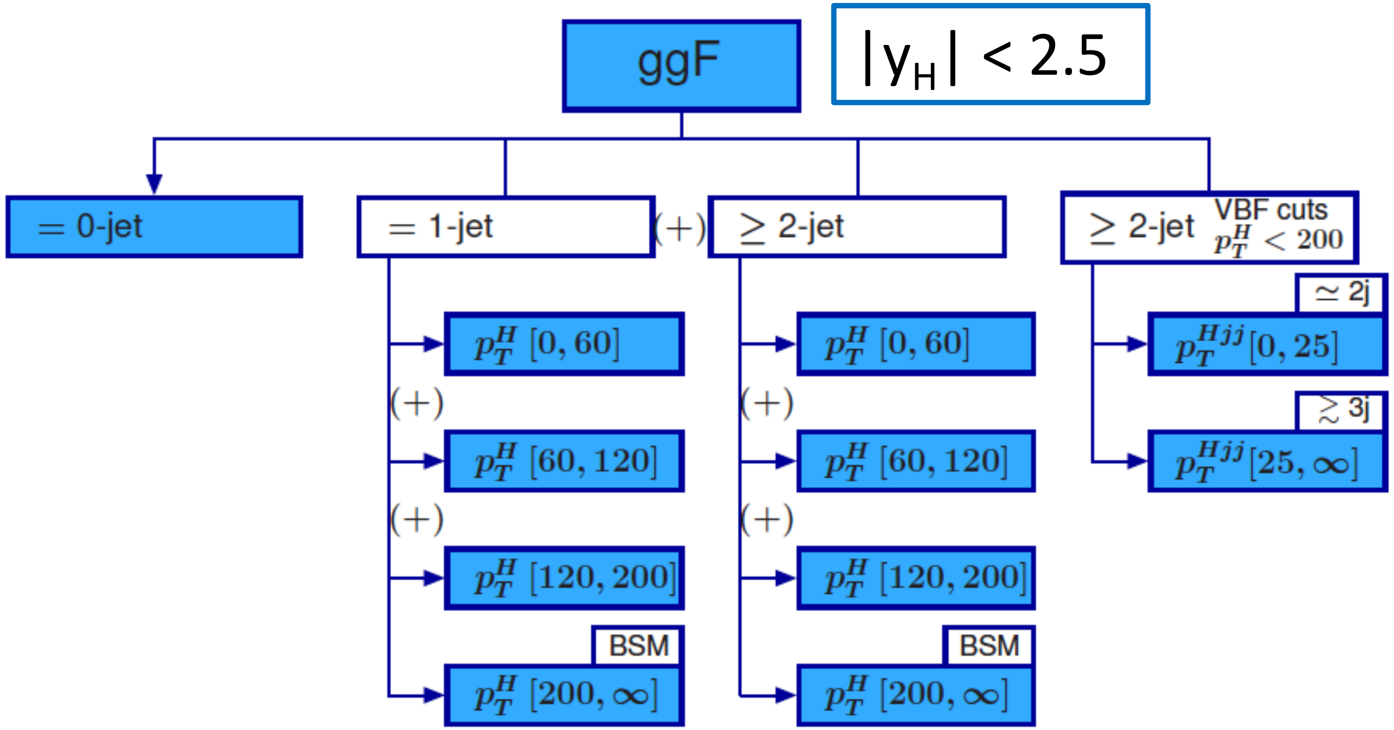
👍 Can still be combined between different decay channels

👎 Some assumptions on the SM still present



Closer look at the gluon fusion regions

- Simple fiducial regions for gluon fusion
- Split in number of jets
- Bin in p_T of the Higgs
- BSM bin for $p_{T,H} > 200$ GeV

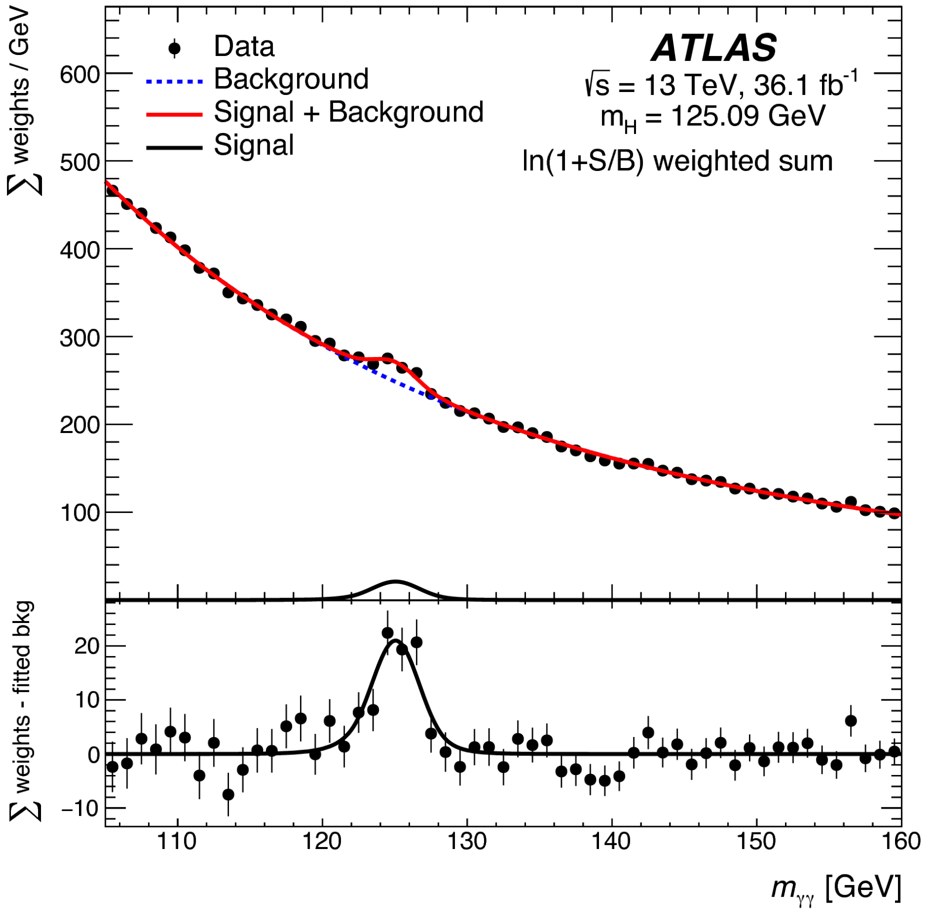


First results: Analysis in H→$\gamma\gamma$ with 36.1 fb^{-1}

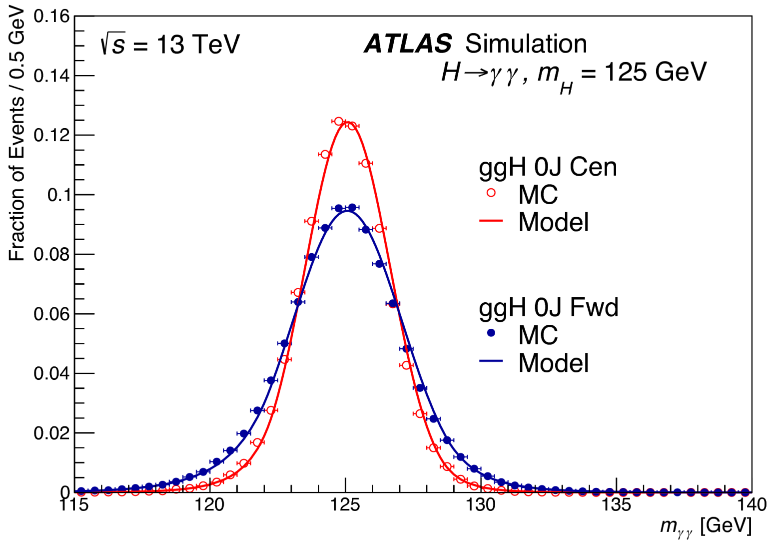
- Good photon reconstruction efficiency >84%, good energy resolution ≈1.5% on $m_{\gamma\gamma}$
- Allows to reconstruct narrow mass peak to identify and fit for Higgs events.

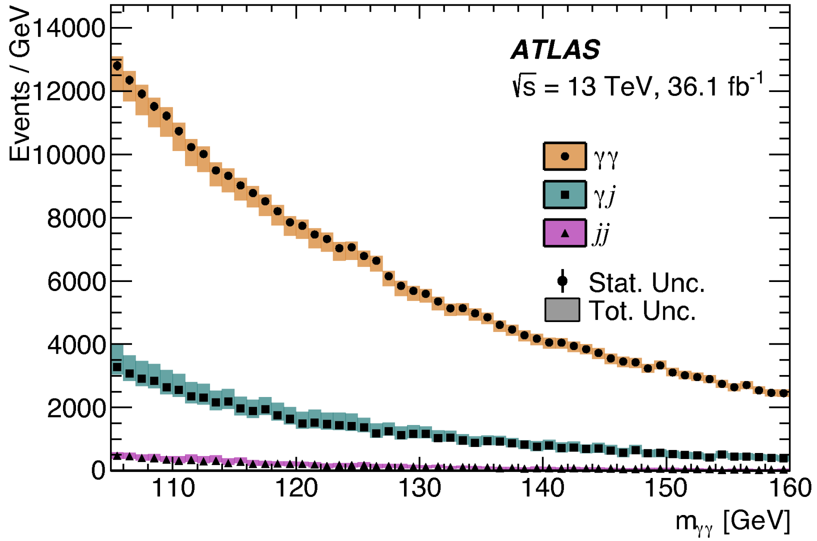
Selection

- 2 photons, $p_T > 25$ GeV, $|\eta| < 2.37$, $E_{T,\gamma}/m_{\gamma\gamma} > 0.35$ (0.25)
- Photons fulfill tight identification criteria and are matched to the collision vertex
- $m_{\gamma\gamma}$ within [105, 160] GeV
- Total selection efficiency for signal 42%



Signal and background modelling





Signal modelled by double-sided Crystal Ball function

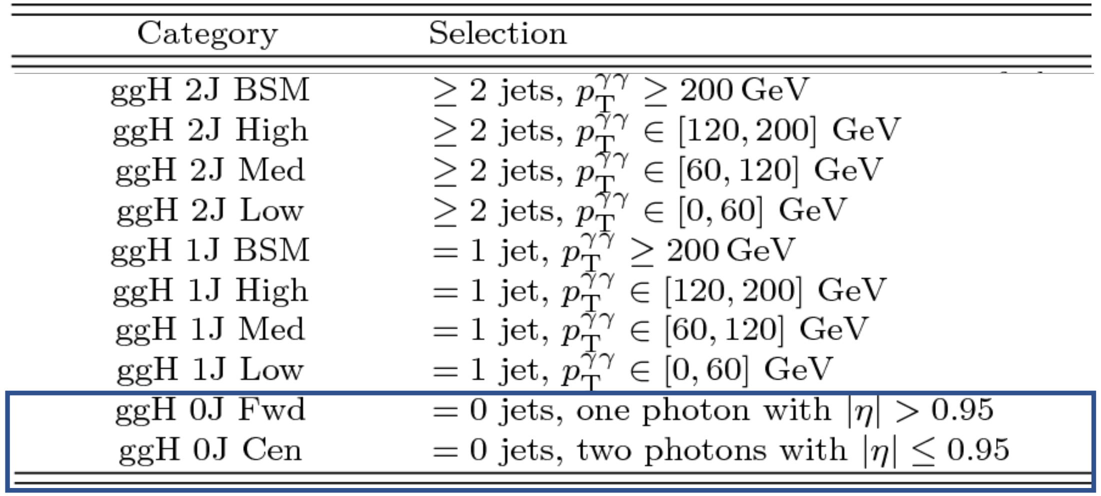
- Functional parameters determined with signal MC and fixed in data fit
- Variations allowed due to uncertainties (photon energy resolutions, scale, and mass of Higgs boson)

Background composition determined in 2D side-band method

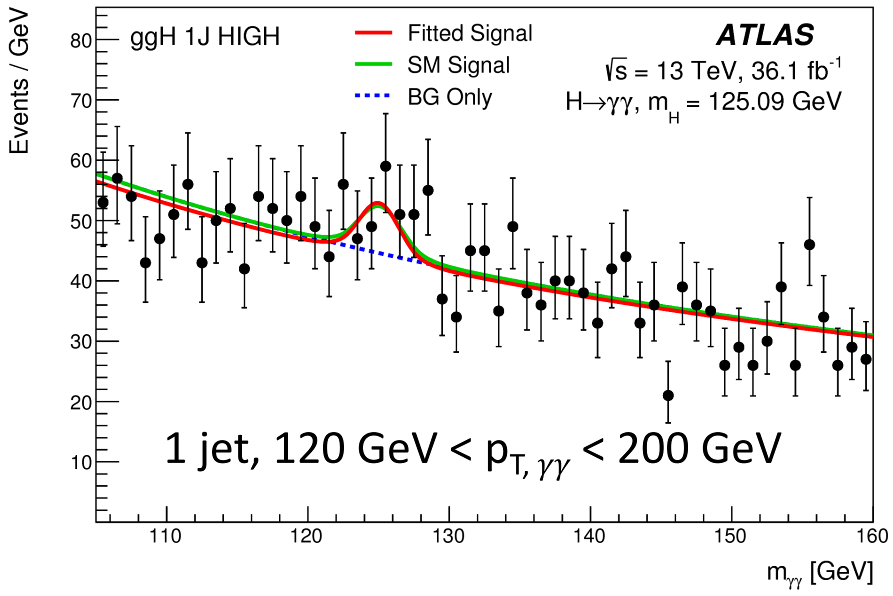
- Background described by empirical functional form
- Number of degrees of freedom validated on data sidebands

Categorisation

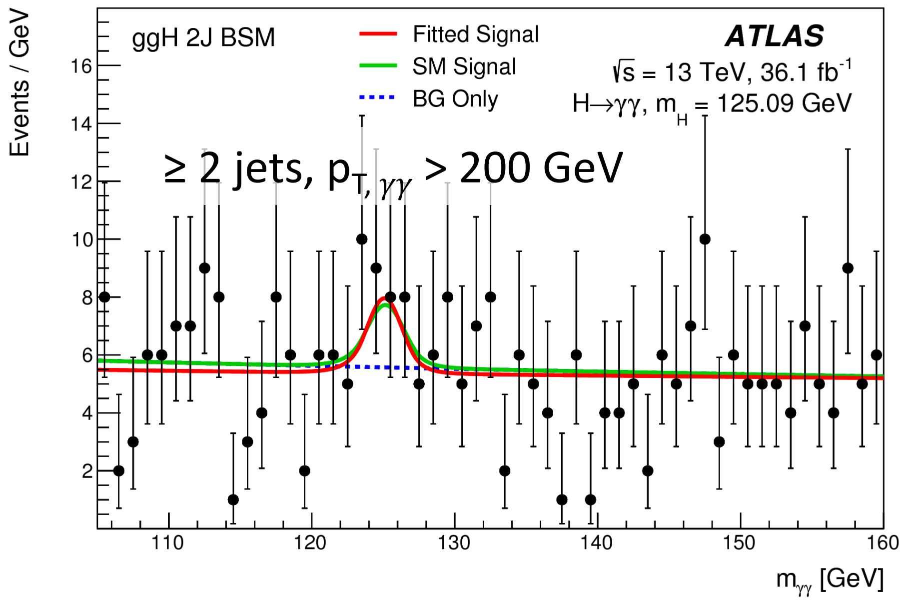
- 31 orthogonal categories defined for production modes and kinematic bins
- 10 categories for gluon fusion
  - 9 to match the fiducial regions
  - 1 for sensitivity
- Fit performed per category



Category	Selection
ggH 2J BSM	≥ 2 jets, $p_T^{\gamma\gamma} \geq 200$ GeV
ggH 2J High	≥ 2 jets, $p_T^{\gamma\gamma} \in [120, 200]$ GeV
ggH 2J Med	≥ 2 jets, $p_T^{\gamma\gamma} \in [60, 120]$ GeV
ggH 2J Low	≥ 2 jets, $p_T^{\gamma\gamma} \in [0, 60]$ GeV
ggH 1J BSM	$= 1$ jet, $p_T^{\gamma\gamma} \geq 200$ GeV
ggH 1J High	$= 1$ jet, $p_T^{\gamma\gamma} \in [120, 200]$ GeV
ggH 1J Med	$= 1$ jet, $p_T^{\gamma\gamma} \in [60, 120]$ GeV
ggH 1J Low	$= 1$ jet, $p_T^{\gamma\gamma} \in [0, 60]$ GeV
ggH 0J Fwd	$= 0$ jets, one photon with $\|\eta\| > 0.95$
ggH 0J Cen	$= 0$ jets, two photons with $\|\eta\| \leq 0.95$

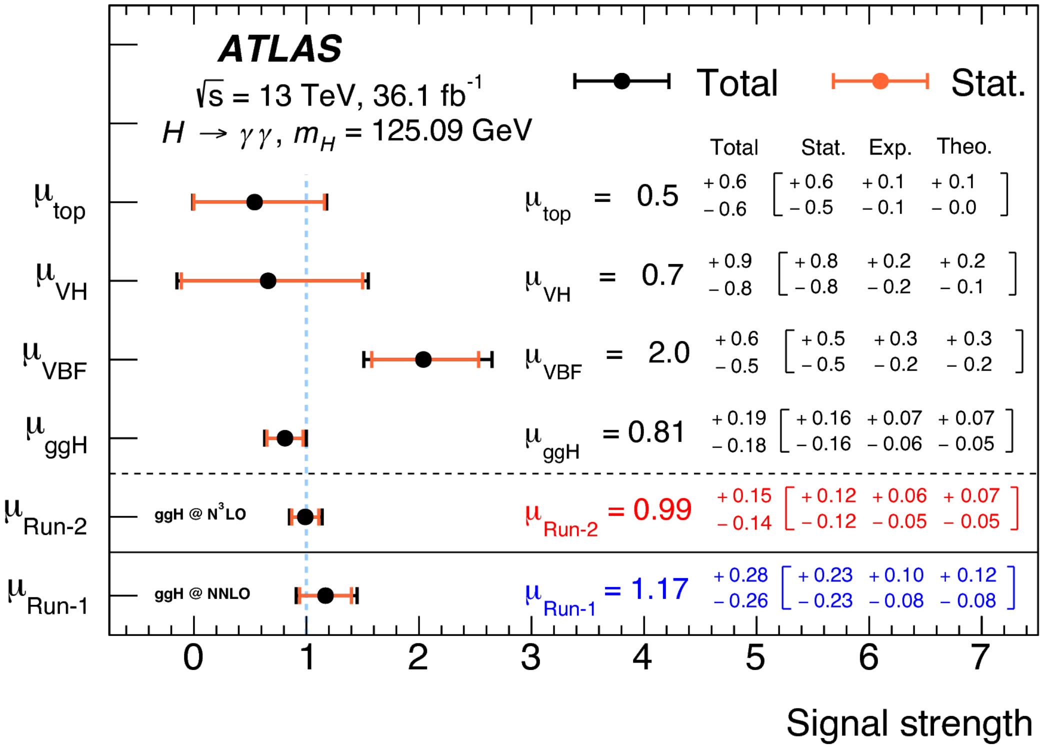


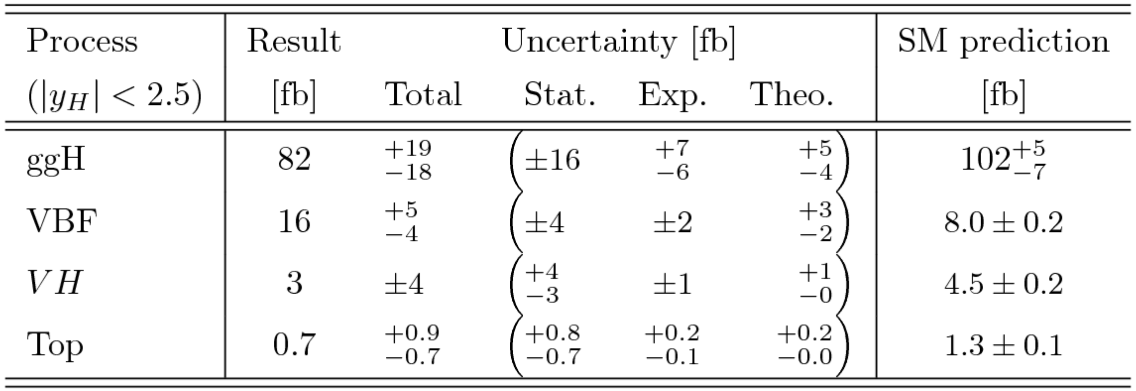
1 jet, 120 GeV < $p_{T,\gamma\gamma}$ < 200 GeV



≥ 2 jets, $p_{T,\gamma\gamma}$ > 200 GeV

Results for cross section and signal strength





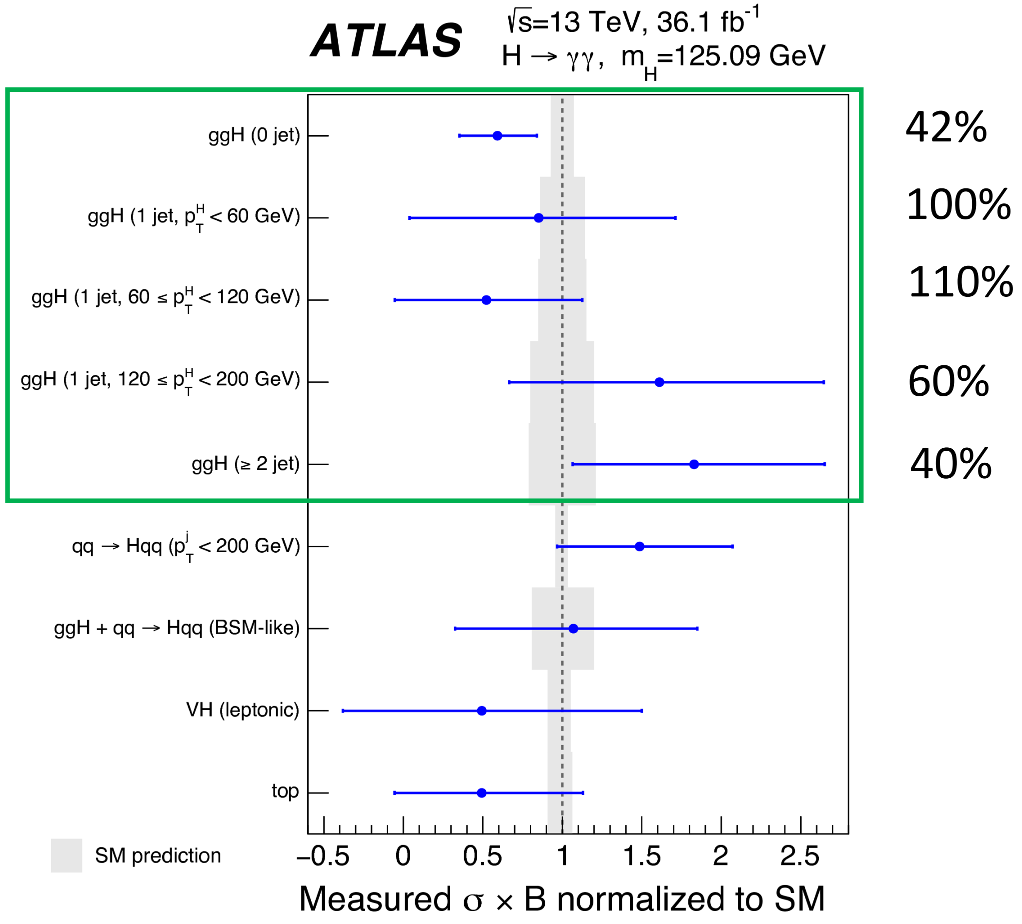
Process ($\lvert y_H\rvert < 2.5$)	Result [fb]	Uncertainty [fb] Total	 Stat.	 Exp.	 Theo.	SM prediction [fb]
ggH	82	$^{+19}_{-18}$	± 16	$^{+7}_{-6}$	$^{+5}_{-4}$	102^{+5}_{-7}
VBF	16	$^{+5}_{-4}$	± 4	± 2	$^{+3}_{-2}$	8.0 ± 0.2
VH	3	± 4	$^{+4}_{-3}$	± 1	$^{+1}_{-0}$	4.5 ± 0.2
Top	0.7	$^{+0.9}_{-0.7}$	$^{+0.8}_{-0.7}$	$^{+0.2}_{-0.1}$	$^{+0.2}_{-0.0}$	1.3 ± 0.1

- Statistics is still largest source of uncertainty.
- Improvements since Run 1 also in the experimental and theoretical uncertainties.
- Total uncertainty order 15%
- Theoretical uncertainty order 6%

Results for simplified template cross sections

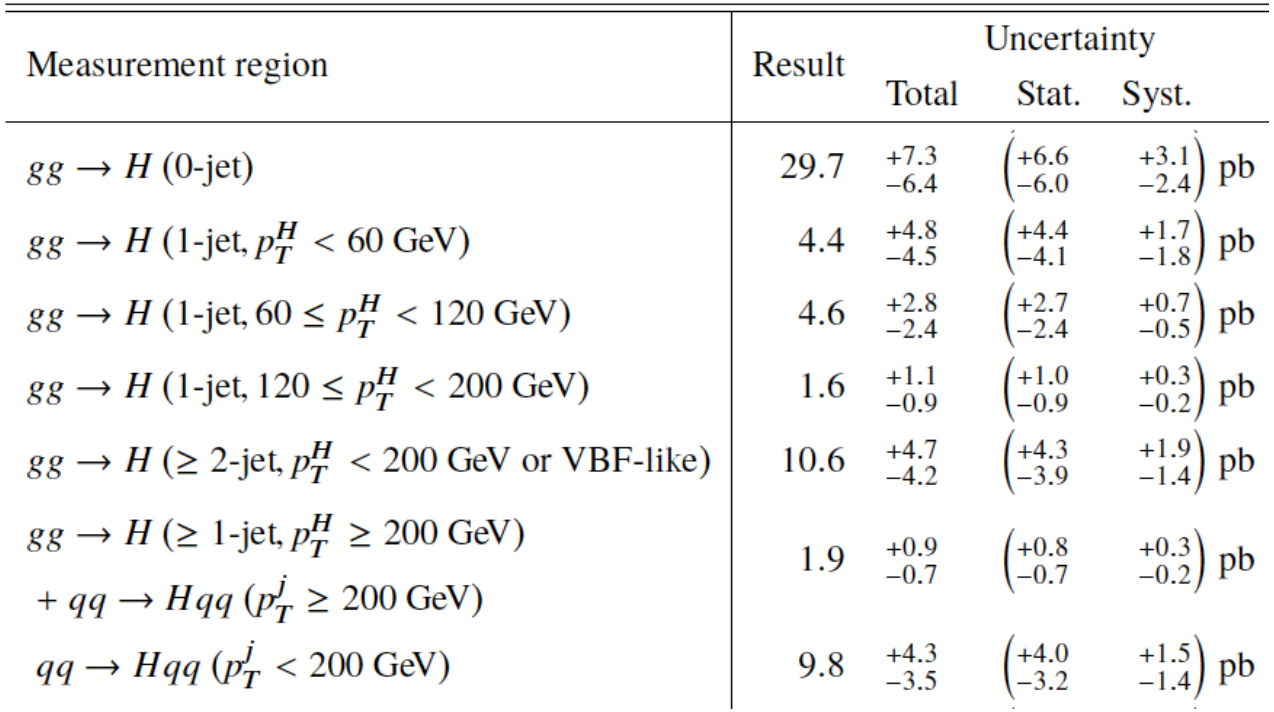
- Merge fiducial regions to achieve at least about 100% uncertainty per result.
- Dominated by statistical uncertainties
- Theoretical uncertainty much reduced compared to signal strength measurement
- Limit set on the BSM regions

H→$\gamma\gamma$ also measures differential cross sections with good sensitivity. Statistics dominated.



Combination with H→ZZ →4l

H→ZZ →4l analysis uses also $36.1\ \mathrm{fb}^{-1}$ of 2015+2016 data



	Measurement region	Result	Uncertainty Total	 Stat.	 Syst.	
Gluon fusion	$gg \to H$ (0-jet)	29.7	$^{+7.3}_{-6.4}$	($^{+6.6}_{-6.0}$	$^{+3.1}_{-2.4}$) pb	+25/-22%
	$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	4.4	$^{+4.8}_{-4.5}$	($^{+4.4}_{-4.1}$	$^{+1.7}_{-1.8}$) pb	>100%
	$gg \to H$ (1-jet, $60 \le p_T^H < 120$ GeV)	4.6	$^{+2.8}_{-2.4}$	($^{+2.7}_{-2.4}$	$^{+0.7}_{-0.5}$) pb	+61/-52%
	$gg \to H$ (1-jet, $120 \le p_T^H < 200$ GeV)	1.6	$^{+1.1}_{-0.9}$	($^{+1.0}_{-0.9}$	$^{+0.3}_{-0.2}$) pb	+69/-56%
	$gg \to H$ ($\ge$ 2-jet, $p_T^H < 200$ GeV or VBF-like)	10.6	$^{+4.7}_{-4.2}$	($^{+4.3}_{-3.9}$	$^{+1.9}_{-1.4}$) pb	+44/-40%
merged BSM	$gg \to H$ ($\ge$ 1-jet, $p_T^H \ge 200$ GeV) $+\ qq \to Hqq$ ($p_T^j \ge 200$ GeV)	1.9	$^{+0.9}_{-0.7}$	($^{+0.8}_{-0.7}$	$^{+0.3}_{-0.2}$) pb	+47/-37%
Vector boson fusion	$qq \to Hqq$ ($p_T^j < 200$ GeV)	9.8	$^{+4.3}_{-3.5}$	($^{+4.0}_{-3.2}$	$^{+1.5}_{-1.4}$) pb	+44/-36%

Interpretation of the template cross sections

Effective field theory approach

- Probe for deviations from the SM physics using an effective field theory approach at a large new physics scale $\Lambda >> E_{exp}, m_H$
- Particle content and symmetries as in the SM

Leading deformations of the SM

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

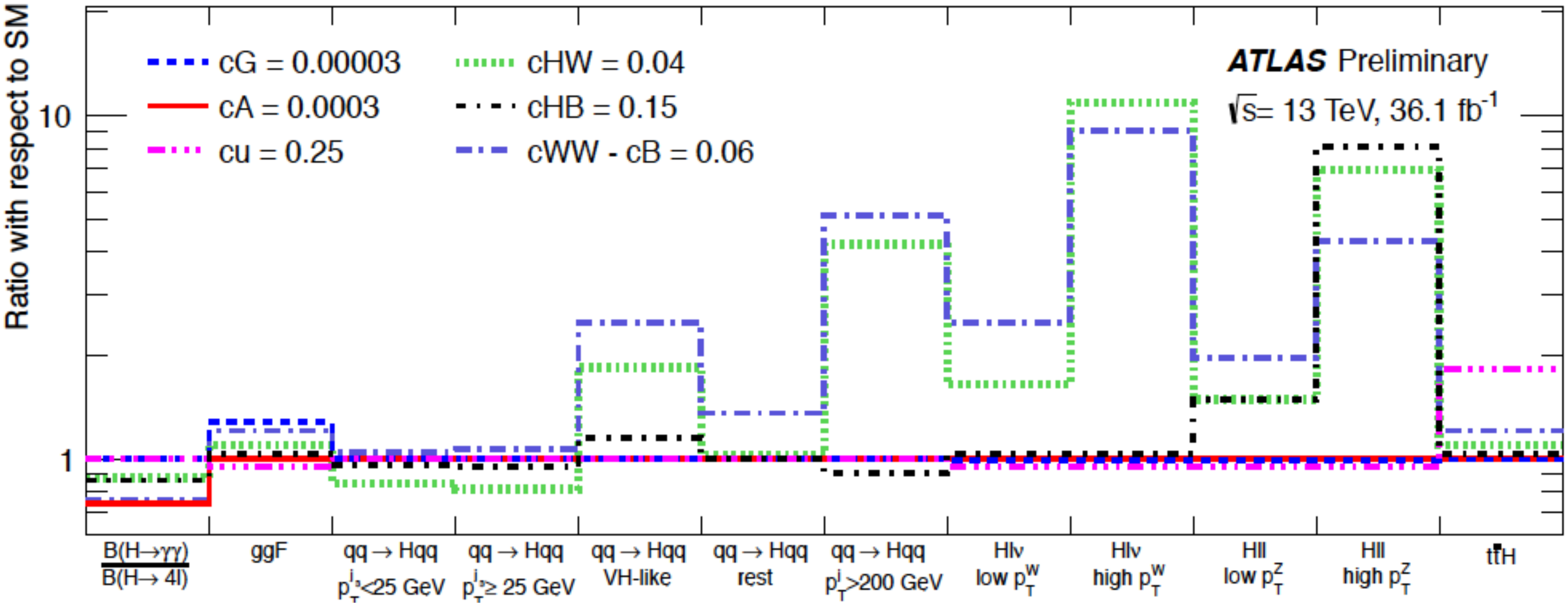
full theory

59 independent dim-6 operators if flavour universality.
2499 parameters for a generic flavour structure.

→ Can include cross-sections, template cross sections, even differential cross sections and test for deviations
Can combine different fields of SM measurements

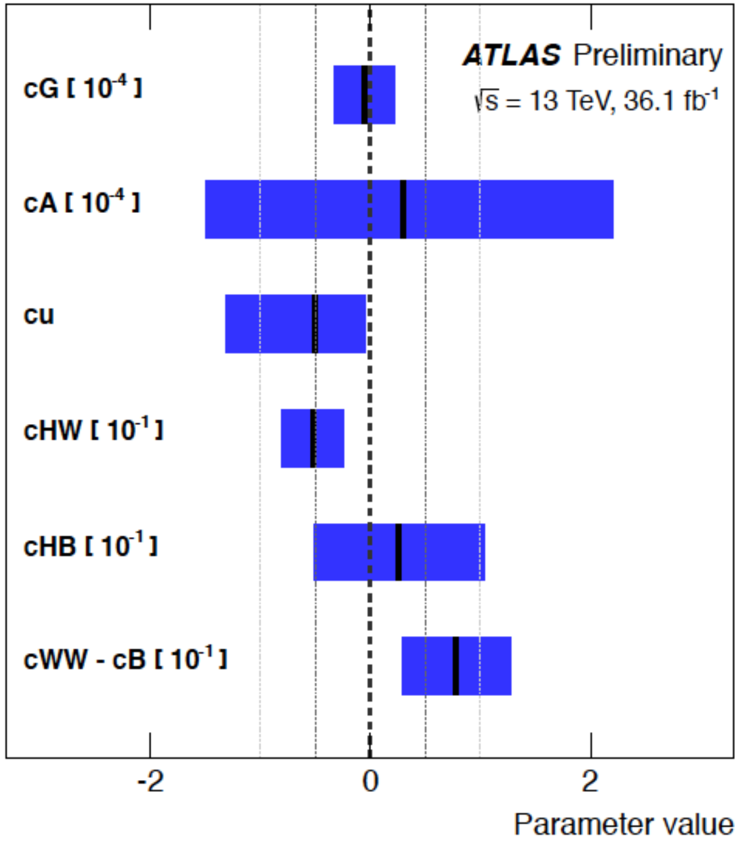
Interpretation of the template cross sections

- Different template cross section regions are sensitive to different dim-6 operators



Interpretation of the template cross sections

- Proof of concept performed
- Most stringent constraints on the effective couplings to photons and gluons
- Main point to improve is the theoretical EFT model which still misses physics components



Conclusion

- New Run 2 data is great for SM Higgs boson investigations
  - Huge increase in statistics
  - Understanding of the detector improves with time
  - Caveat: large number of pile-up collisions
- Statistics allows us to measure kinematic properties of the Higgs boson
  - More to come with the full Run 2 dataset
- Measurement done per Higgs decay mode
  - Several Higgs decay modes have similar sensitivity
    →Combination makes still sense and is worth the effort
  - Improvements on the way we combine are underway to make results less model-dependent

Thank you for your attention!

BACK-UP

BSM interpretation in Run 1

- Coupling strength (κ-framework)
- Coupling modifier κ_i and κ_f

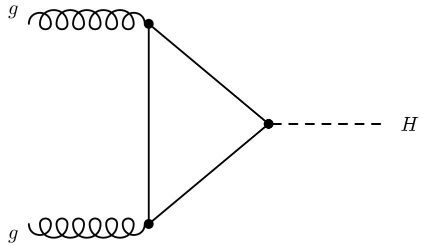
$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_H^2 \Gamma_H^{\mathrm{SM}}}$$

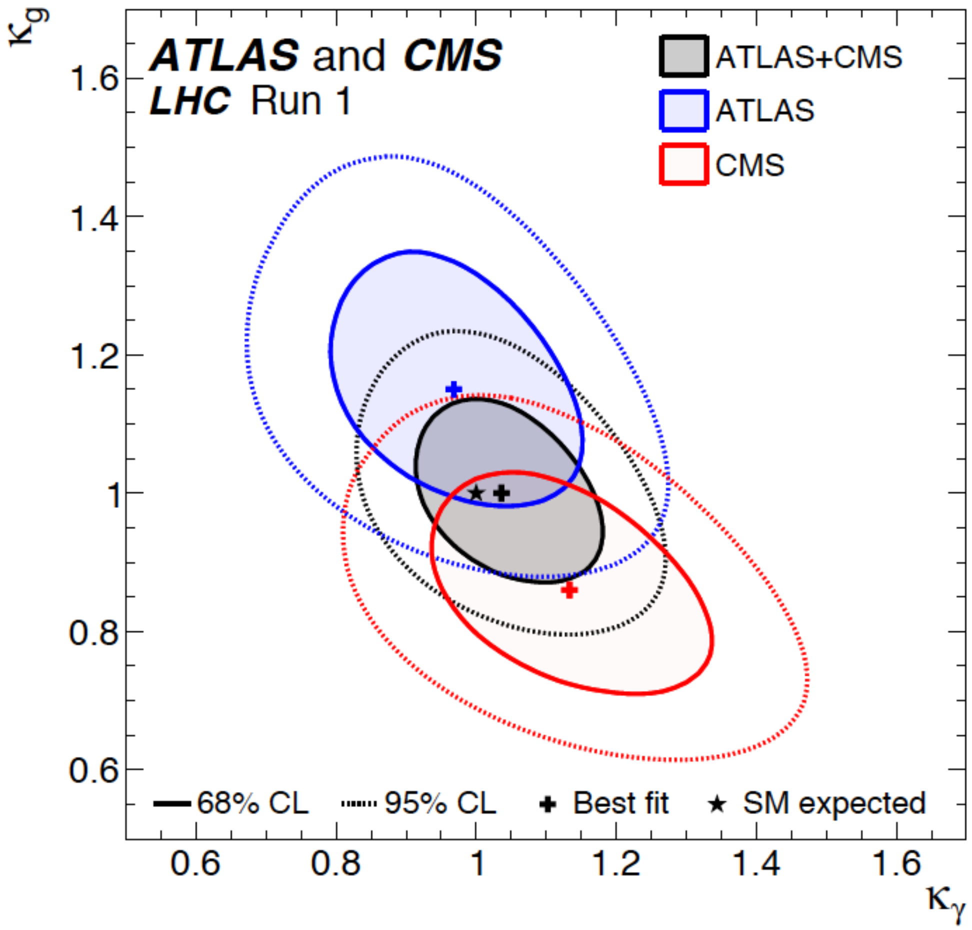
👍 Simple to understand and to apply

👎 Not a full theory description. Higgs physics only.
Can not use measured distributions to extract constraints
No combination with other SM measurements (top, electroweak)

New physics via heavy particles

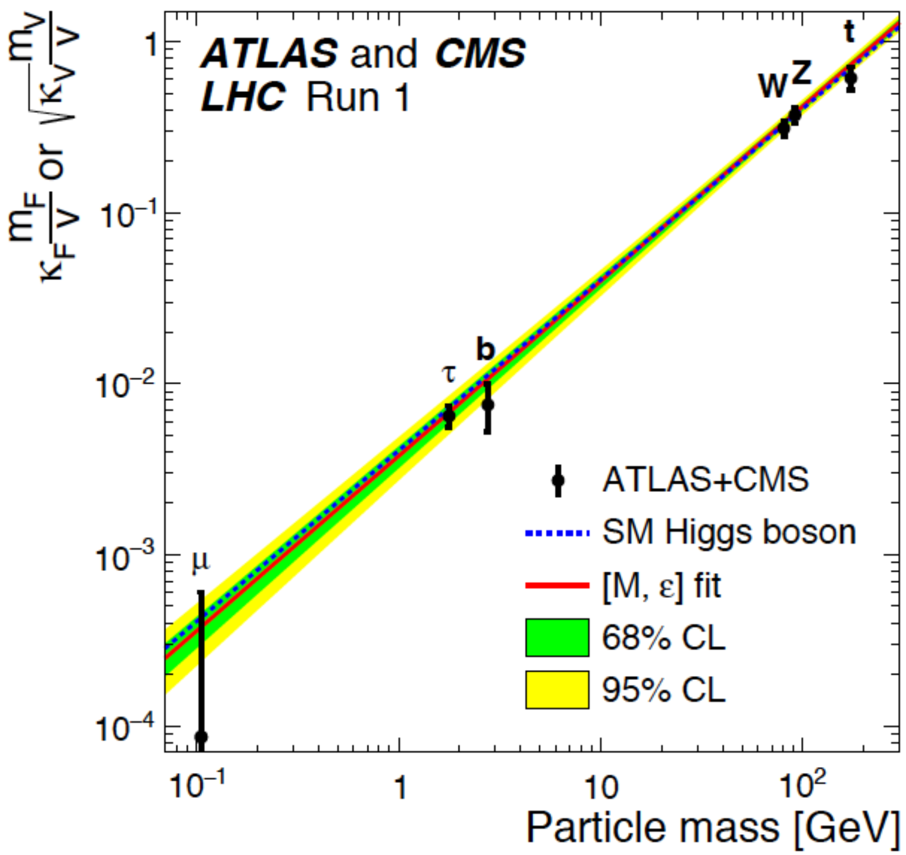
- Assumption: Higgs couplings to SM particles are described by the SM
- New heavy BSM particles enter via loops in the production
- Sensitivity via ggH production and H→γγ
- Compatibility of data with SM @82%





Couplings to Bosons and Fermions

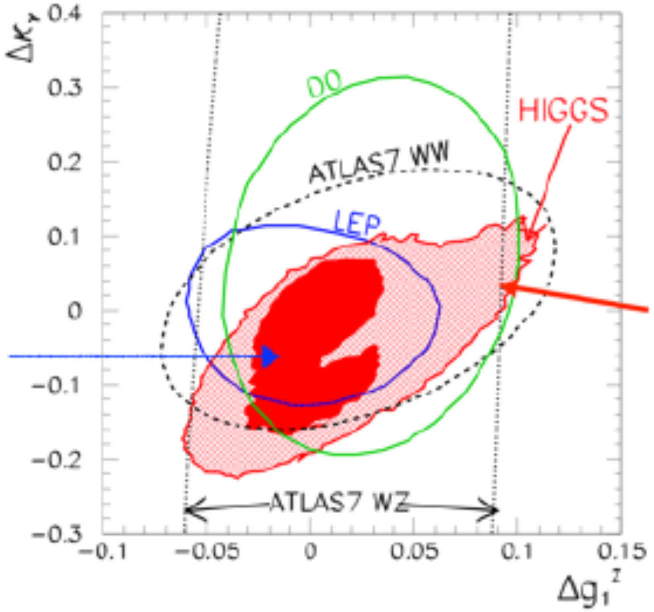
- Assumption:
  No new particle in the loop
- Parameterization of coupling modifier with the particle mass
- Good compatibility with the SM



Include more data with EFT approach

- Do global fits for EFT operators to the measurements
  - Include differential distributions
  - Include experimental data from other processes

rate + differential distributions



just rate

Higgs + Electroweak + LEP