Measurement of fiducial and differential cross sections in the H→$\gamma\gamma$ decay channel with the ATLAS detector at 13 TeV

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Higgs Couplings 2016

ATLAS EXPERIMENT

ATLAS NOTE

ATLAS-CONF-2016-067

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CERN

Measurement of fiducial, differential and production cross sections in the $H \rightarrow \gamma\gamma$ decay channel with 13.3 fb^{-1} of 13 TeV proton-proton collision data with the ATLAS detector

The ATLAS Collaboration

Abstract

This note presents preliminary measurements of the Higgs boson properties measured in the $H \rightarrow \gamma\gamma$ decay channel using 13.3 fb^{-1} of proton-proton collision data taken at $\sqrt{s} = 13$ TeV by the ATLAS experiment at the LHC. Fiducial and differential cross section measurements are presented in a variety of phase space regions and as a function of several kinematic variables. The fiducial cross section is measured to be $\sigma_{\text{fid}} = 43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$ fb for a Higgs boson of mass 125.09 GeV decaying to two isolated photons that have transverse momentum greater than 35% and 25% of the diphoton invariant mass and each with absolute pseudorapidity $|\eta| < 2.37$, excluding the region $1.37 < |\eta| < 1.52$. The Standard Model prediction for the same fiducial region is $62.8^{+3.4}_{-4.4}$ fb. Finally, production cross section measurements for a Higgs boson rapidity $|y_H| < 2.5$ and in the full phase space are presented for gluon fusion, vector boson fusion, and Higgs boson production in association with a vector boson or a top-antitop pair. In addition, the signal strength, defined as the ratio of the observed signal yield to the expected signal yield, is measured for the same production processes as well as globally. No significant deviation from the Standard Model expectations is observed.

ATLAS-CONF-2016-067
08 August 2016

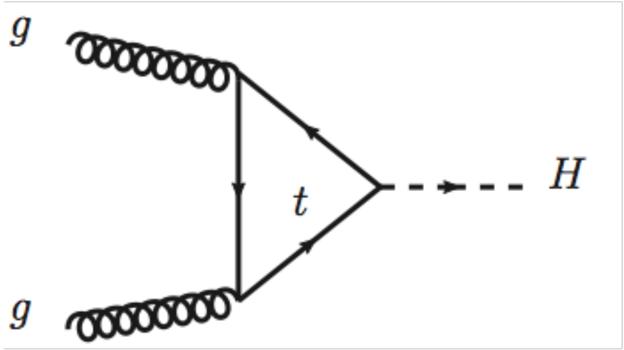
https://cds.cern.ch/record/2206210/files/ATLAS-CONF-2016-067.pdf

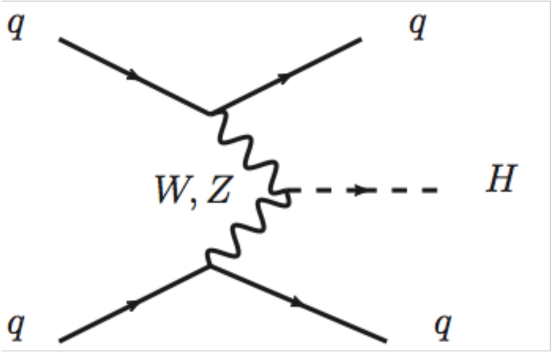
Outline

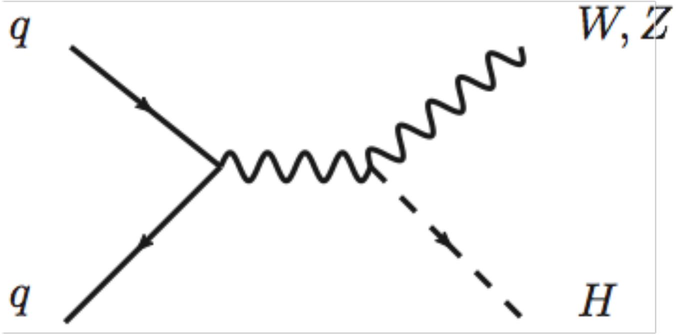
- Introduction and Objectives
- The ATLAS Detector
- Datasets and and Event Selection
- Signal & Background Modeling
- Fiducial and Differential Cross-Sections
- Simplified Templates & Event Categories
- Total Production Cross Section & Signal Strength
- Systematics Uncertainties and Their Impacts
- Summary

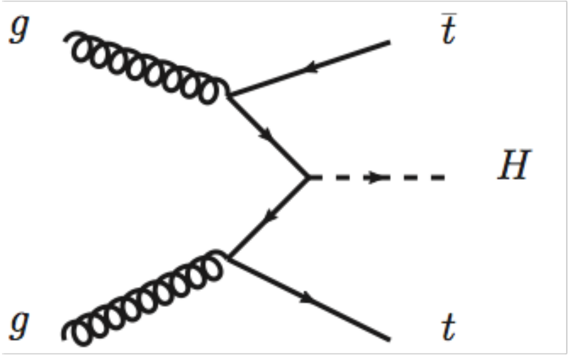
Introduction: Higgs boson production & decay at the LHC

Production ($\sqrt{s} = 13$ TeV):









ggF: ~ 88%

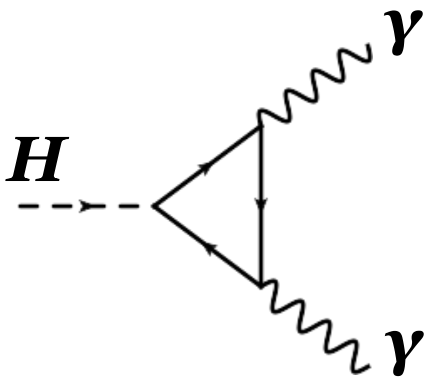
VBF: ~ 7.0%

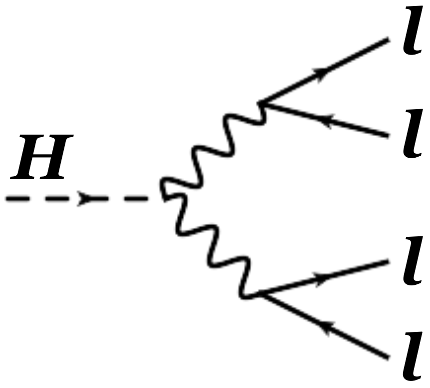
VH ≡ WH or ZH: ~ 4.1%

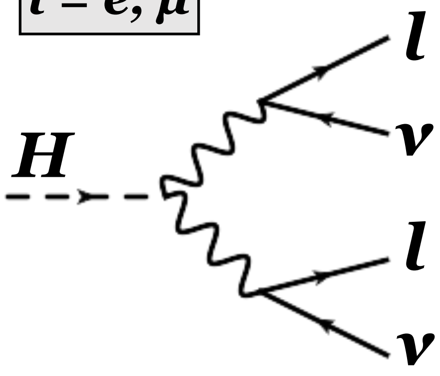
ttH: ~ 0.9%

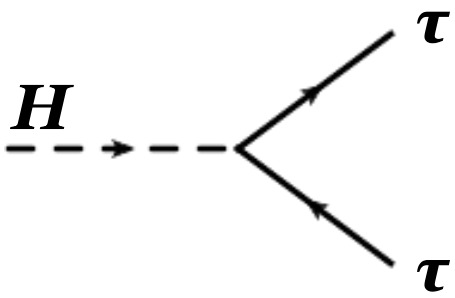
Decay ($m_H = 125$ GeV):

l = e, μ









0.228%
H→γγ

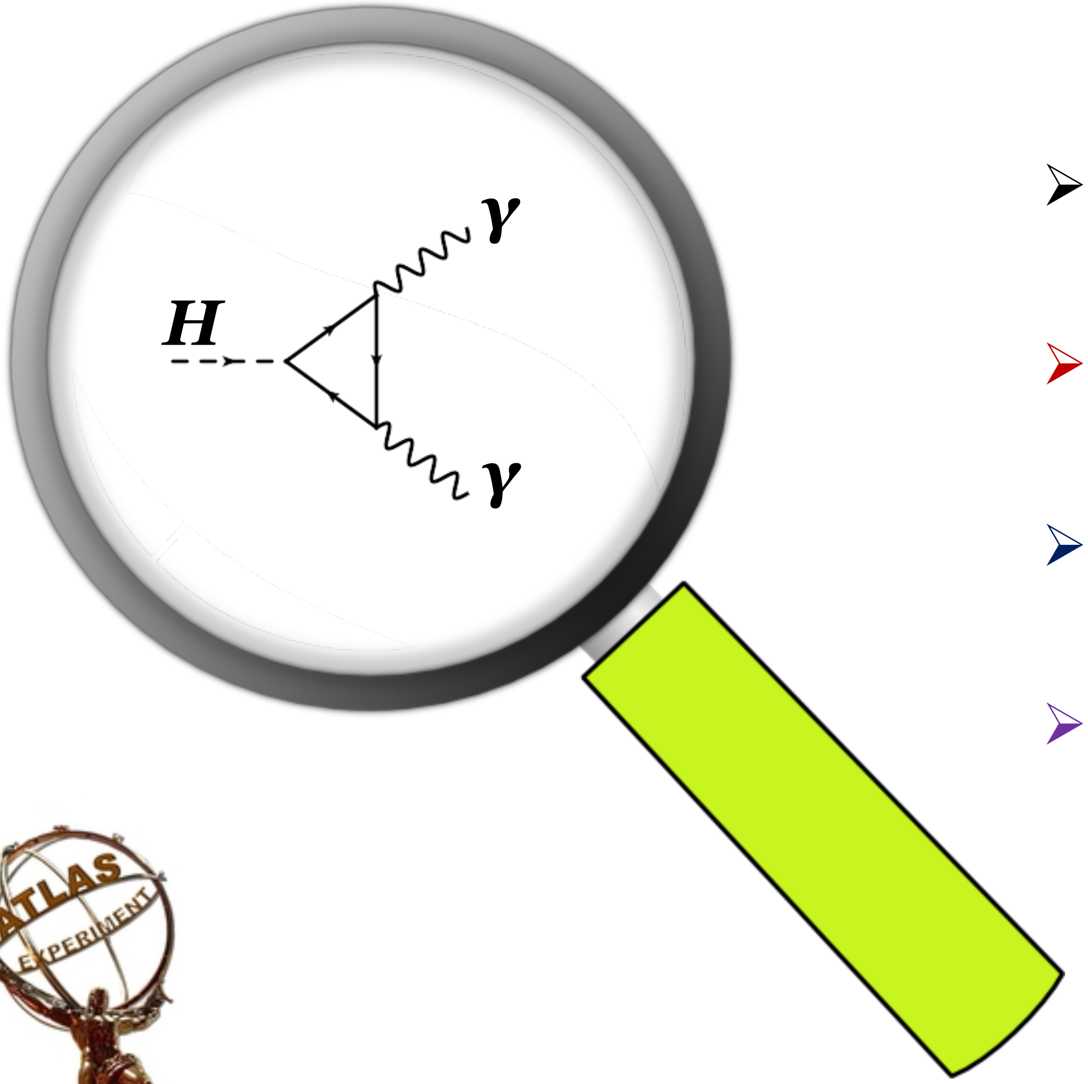
0.013%
H→ZZ*→4l

1.09%
H→WW→lνlν

6.25%
H→ττ

H→bb	*58%*
*H→WW**	*22%*
H→gg	*8.5%*
H→cc	*2.9%*
*H→ZZ**	*2.6%*
…	
H→Zγ	*0.15%*
H→μμ	*0.02%*

Objectives pp→ H → $\gamma\gamma$



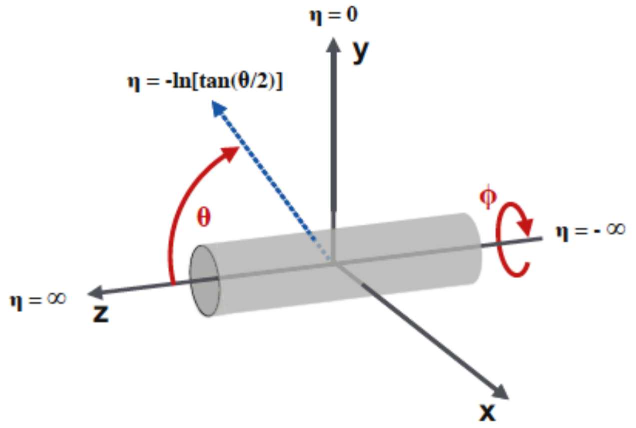
- After discovery, want to measure the properties of the Higgs boson and test the consistency of the SM with the **new** 13 TeV data
- Extract information about the Higgs boson's couplings to other particles
- A fiducial region, or a bin of a differential distribution, is a **specific area of phase space** to probe the Higgs properties
- Investigate production processes with simplified template cross sections
- Through unfolding, the measurements are corrected for experimental effects such as detector acceptance and resolution. Thus, designed to be as **model-independent** as possible to:
  - Allow direct comparison with theory predictions
  - Probe physics beyond the SM

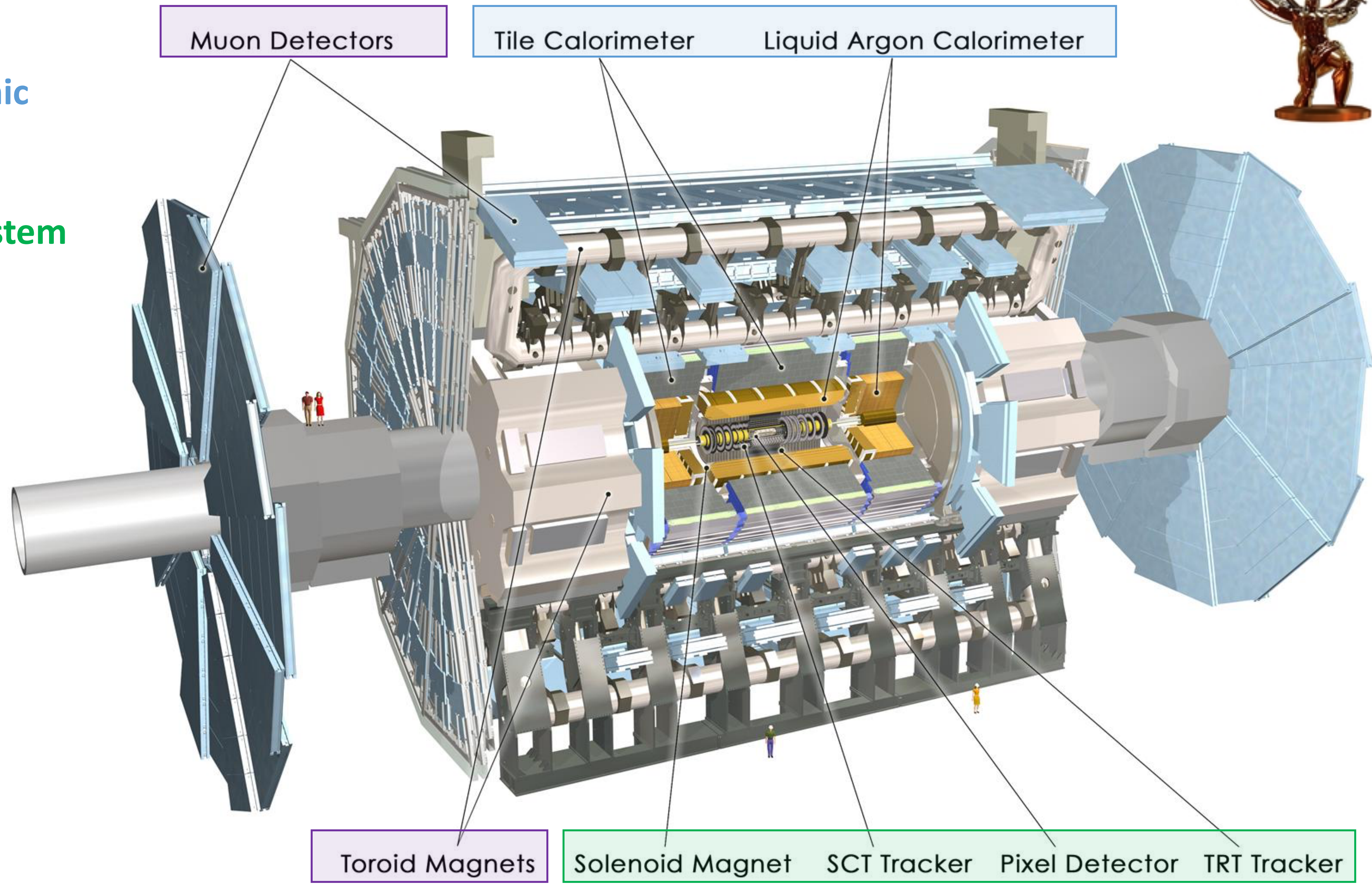
The ATLAS Detector

Electromagnetic and Hadronic Calorimeters

Charged particle tracking system

Muon spectrometer





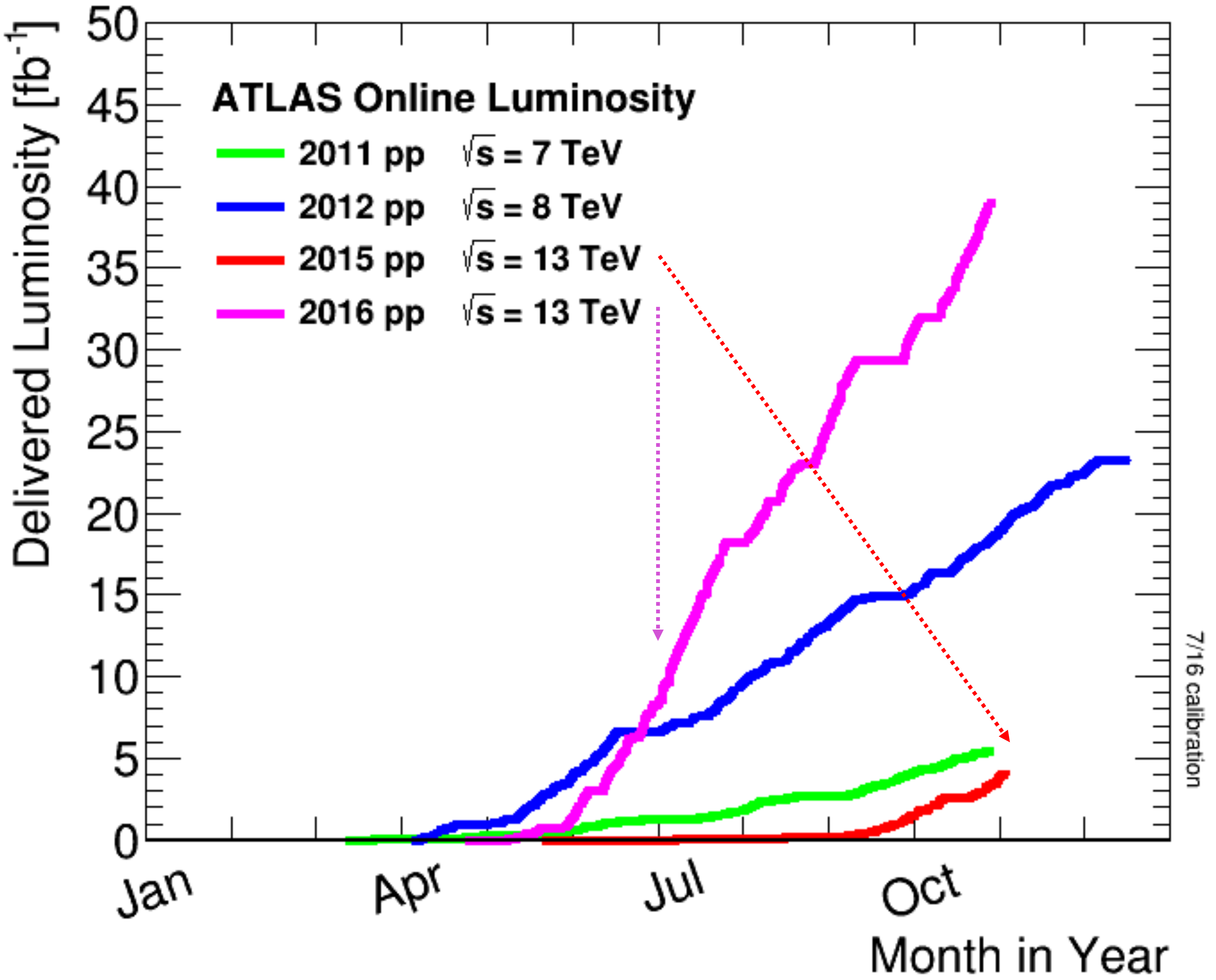
Dataset

ATLAS CONF 2016-067

$\sqrt{s}$ = 13 TeV

2015: 3.2 fb^{-1}
2016 10.1 fb^{-1}

Total: 13.3 fb^{-1}



Event Selection (*i.e.* baseline for photon candidates)

Reconstruction-level: In total 124137 diphoton events selected

Step 1:

Identify at least 2 “loose” photon candidates

- $E_T(\gamma_1) > 25$ GeV & $E_T(\gamma_2) > 25$ GeV
- $|\eta| < 2.37$ (excluding crack-region $1.37 \leq |\eta| < 1.52$)
- primary vertex with at least 2 tracks
- neural-network to identify diphoton primary vertex (redefine direction)

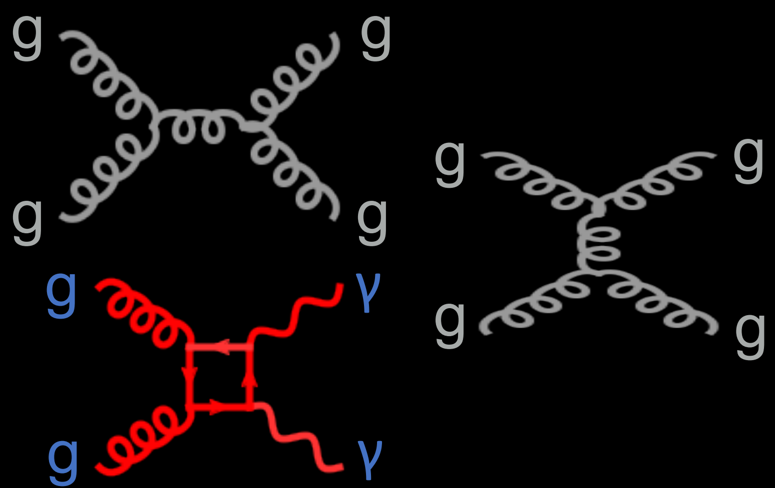
Step 2:

Use “tight” photon ID for both photon candidates

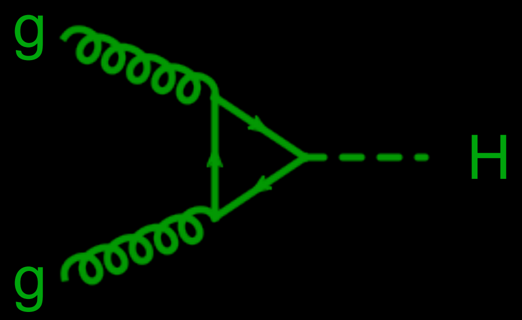
- $p_T(\gamma_1)/m_{\gamma\gamma} > 0.35$ & $p_T(\gamma_2)/m_{\gamma\gamma} > 0.25$
- Isolation requirements on both reconstructed photon candidates
- $m_{\gamma\gamma} \in [105, 160)$ GeV

Problem: Higgs production at the LHC is rare!

The vast majority of collision produced at the LHC do not contain any Higgs bosons



Examples of processes much, much more common than Higgs boson production

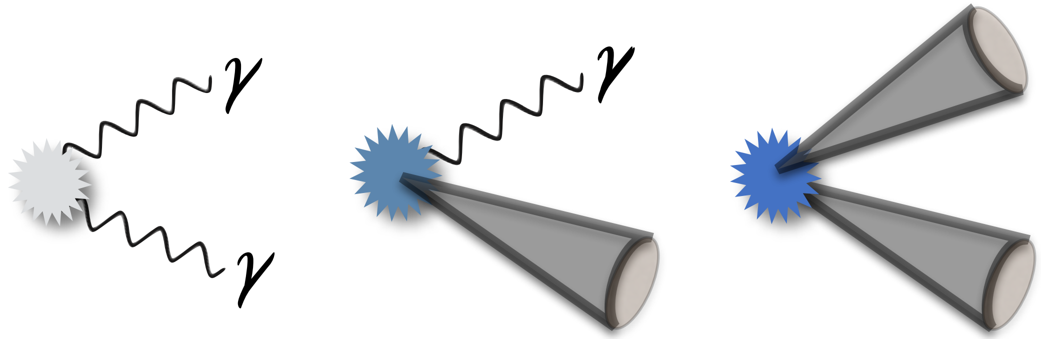


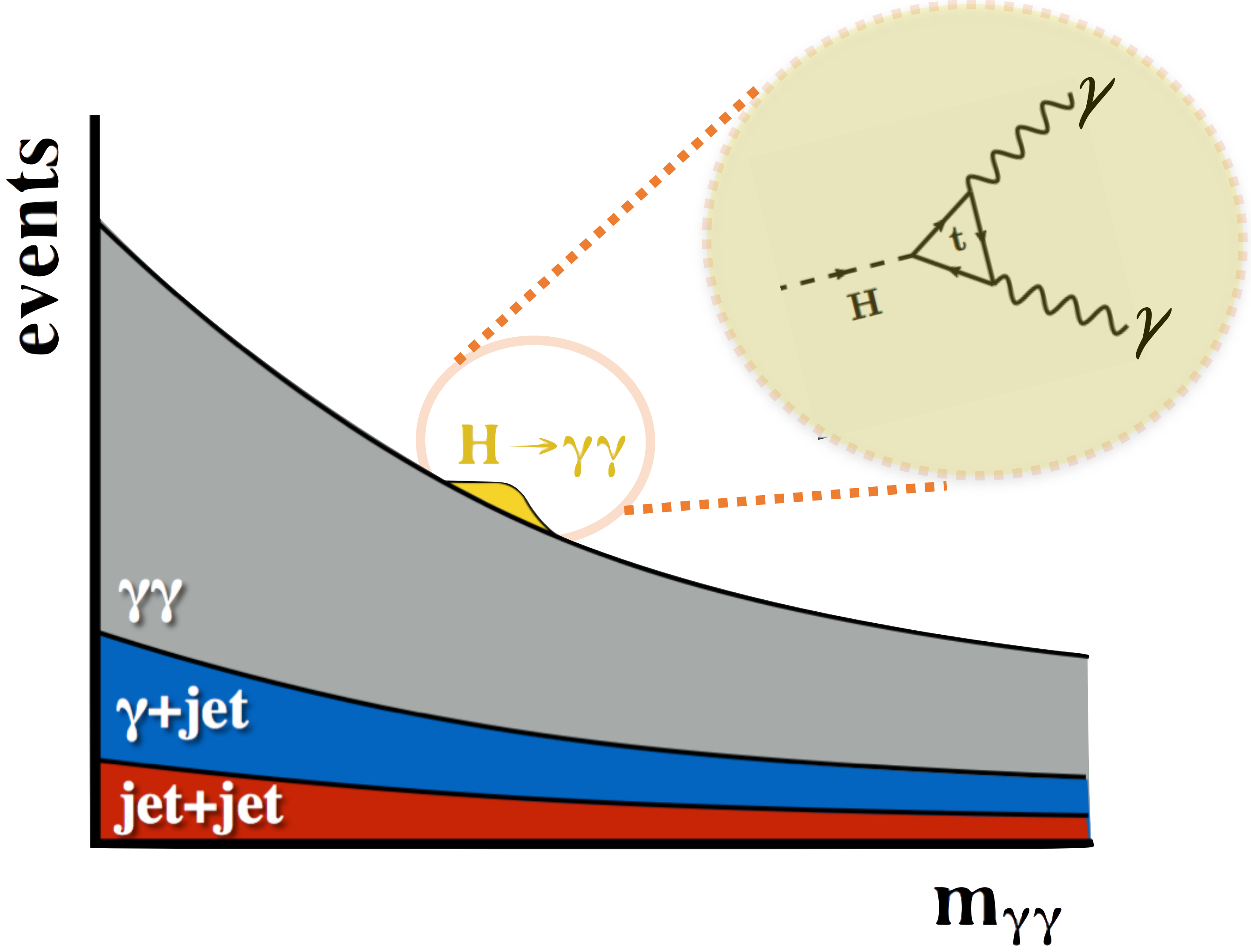
A Higgs boson is only produced in ***one collision out of 200 million***

H→γγ signature

- Higgs signal and SM background processes look identical, but background produces no peak!
- Background must be well modelled in order to minimize potential measurement biases

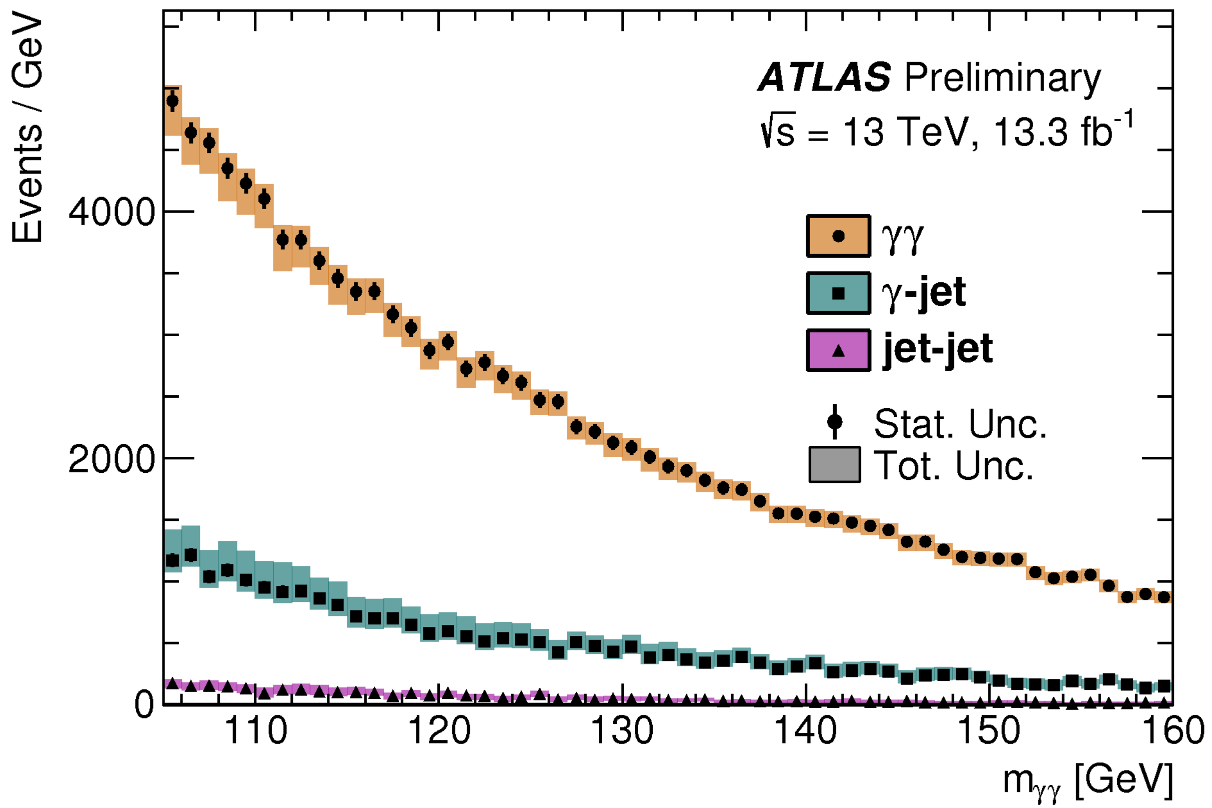
main backgrounds

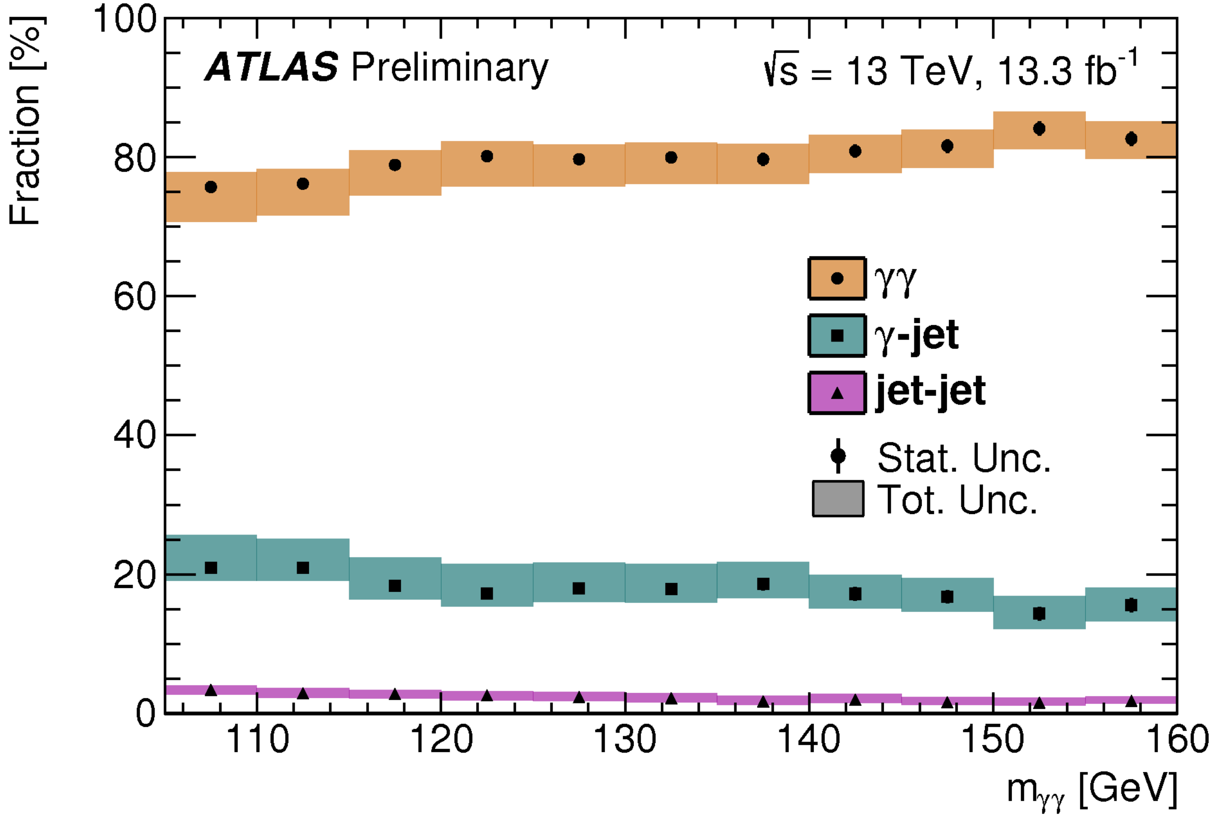




$$m_{\gamma\gamma} = \sqrt{2E_1E_2[1-\cos(\alpha)]}$$

Signal & Background Modeling





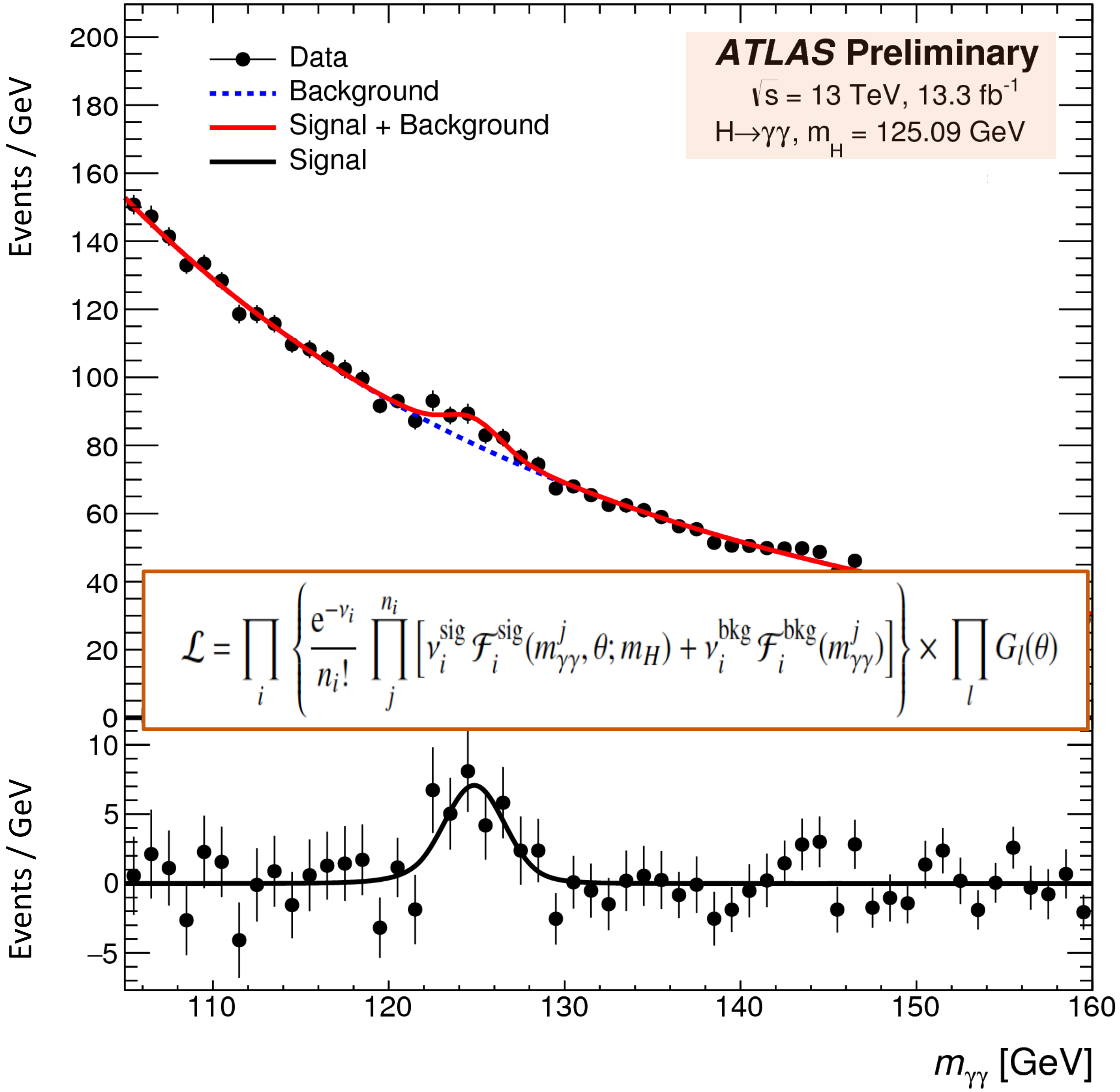
Data-driven background decomposition:

Extracted $\gamma\gamma$,γ-jet and dijet components as a function of $m_{\gamma\gamma}$

Fraction of $\gamma\gamma$,γ-jet and dijet events is $78.9 \pm 0.2\ ^{+1.9}_{-4.0}\ \%$, $18.6 \pm 0.2\ ^{+3.5}_{-1.7}\ \%$ and $2.5 \pm 0.1\ ^{+0.5}_{-0.4}\ \%$, respectively, integrated over the 105-160 GeV mass range

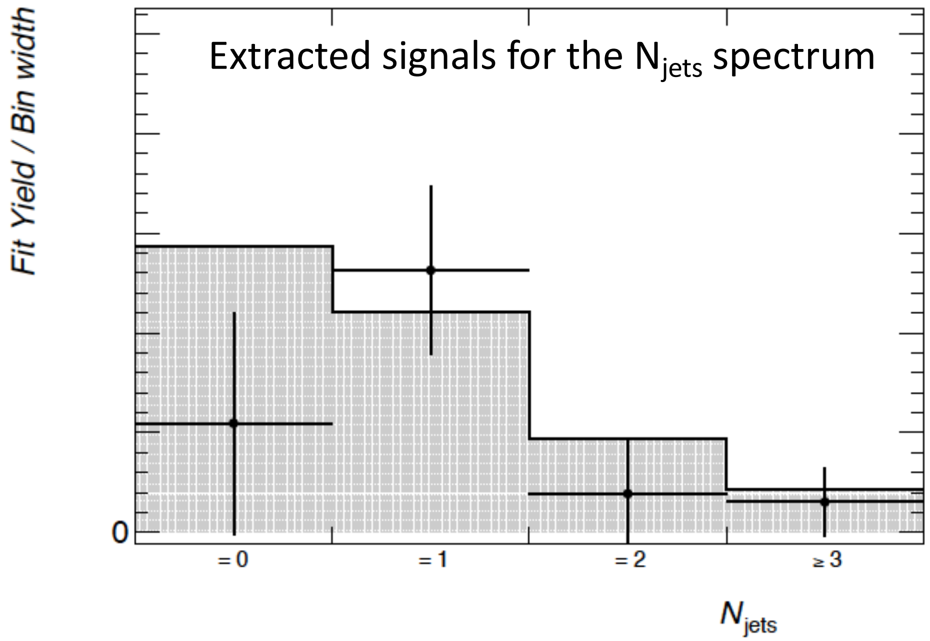
Event Yields per bin or region

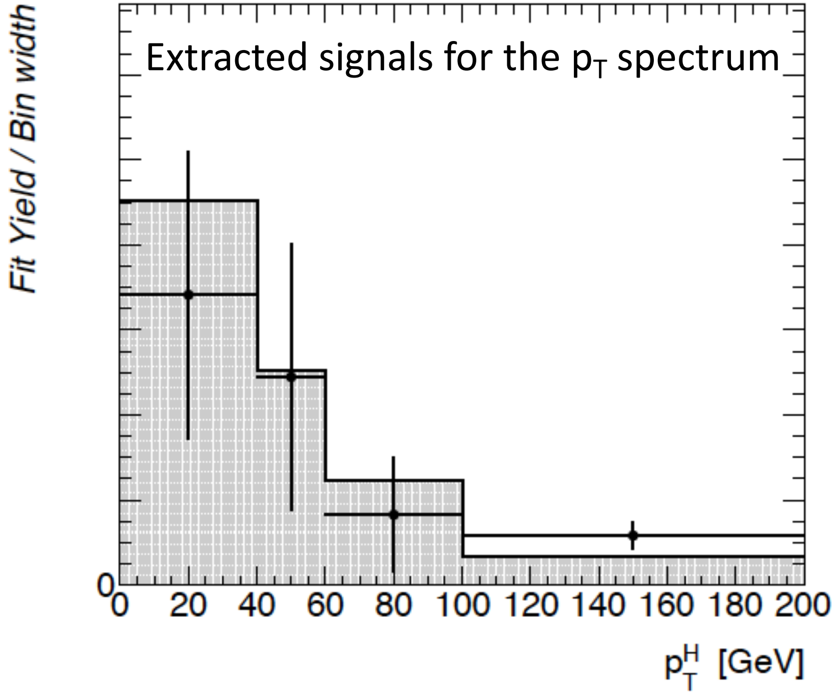
Use the ATLAS + CMS $\sqrt{s}$ = 7 & 8 TeV combined measurement of m_H = 125.09 GeV



$$\mathcal{L} = \prod_i \left\{ \frac{e^{-\nu_i}}{n_i!} \prod_j^{n_i} \left[\nu_i^{\mathrm{sig}} \mathcal{F}_i^{\mathrm{sig}}(m_{\gamma\gamma}^j, \theta; m_H) + \nu_i^{\mathrm{bkg}} \mathcal{F}_i^{\mathrm{bkg}}(m_{\gamma\gamma}^j) \right] \right\} \times \prod_l G_l(\theta)$$

Unbinned maximum likelihood fit to the $m_{\gamma\gamma}$ spectrum in each fiducial region or bin of a differential distribution





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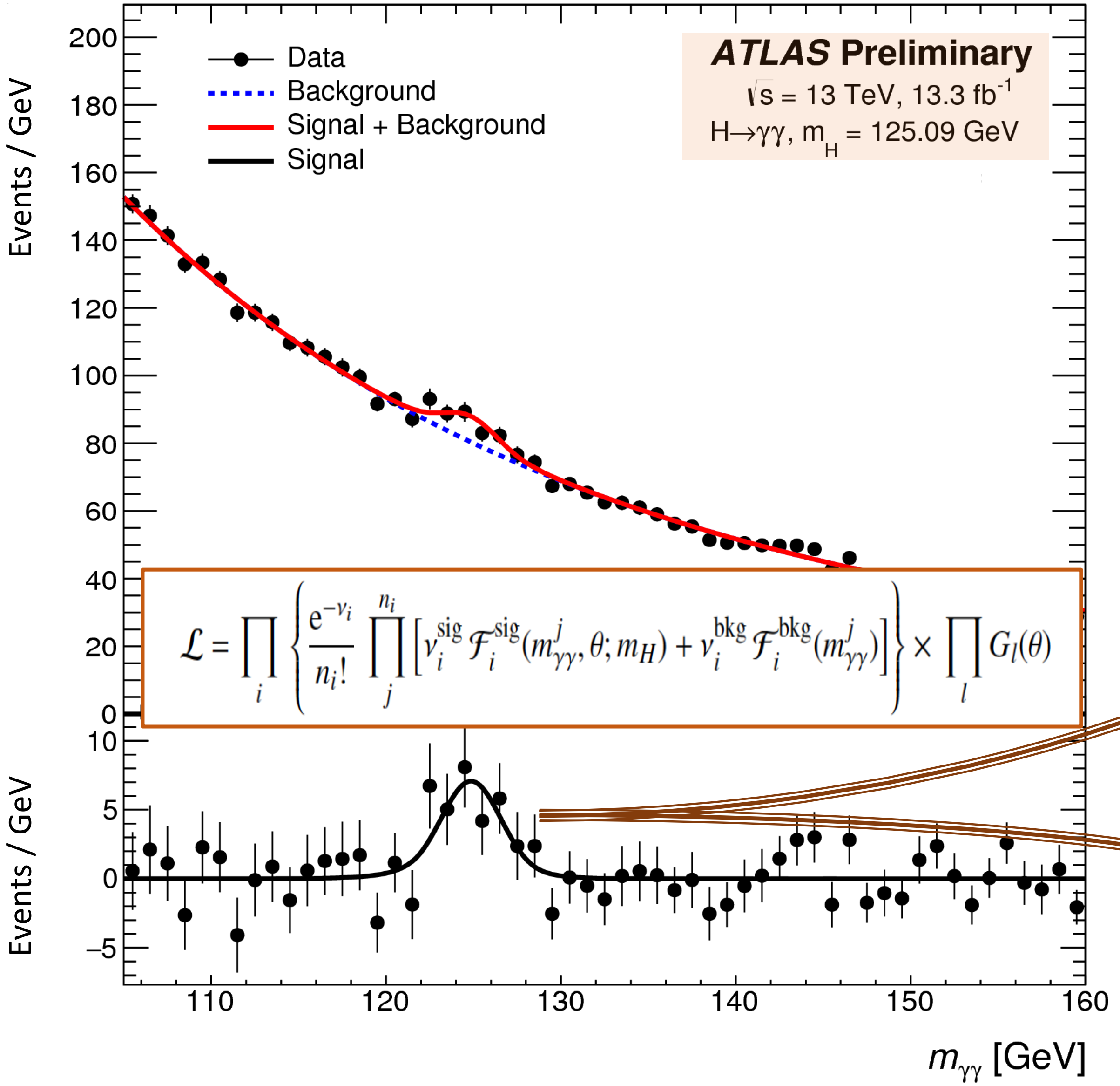

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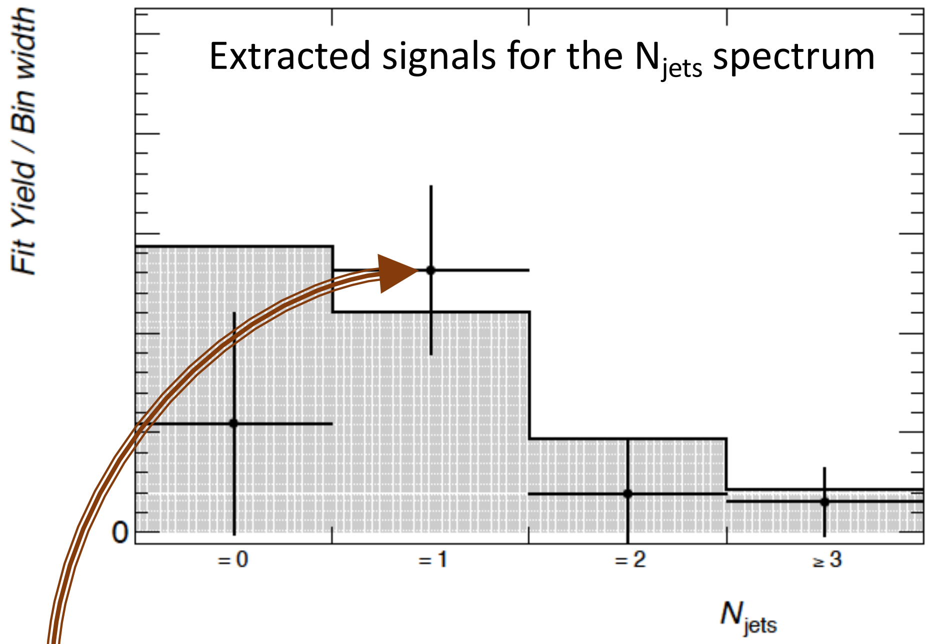
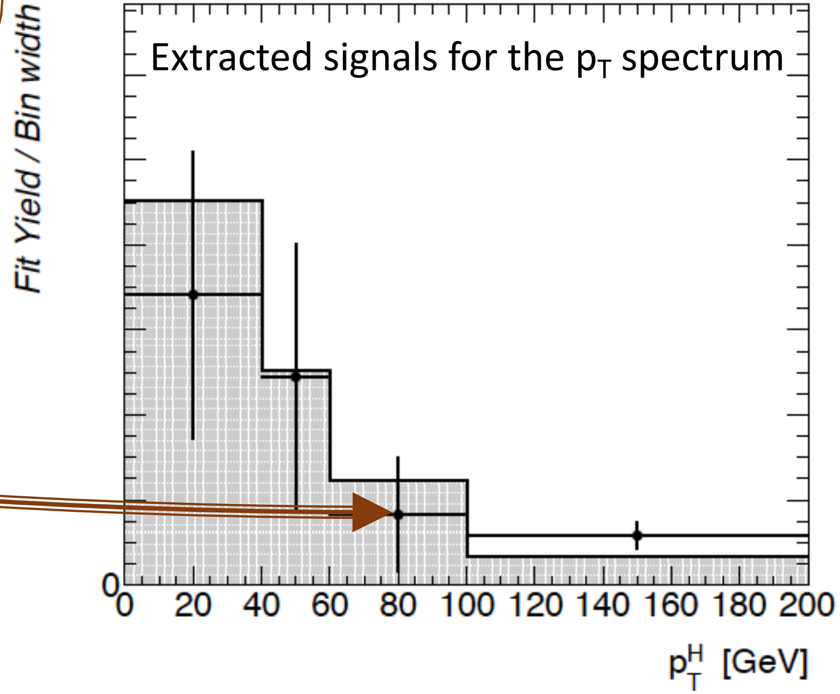
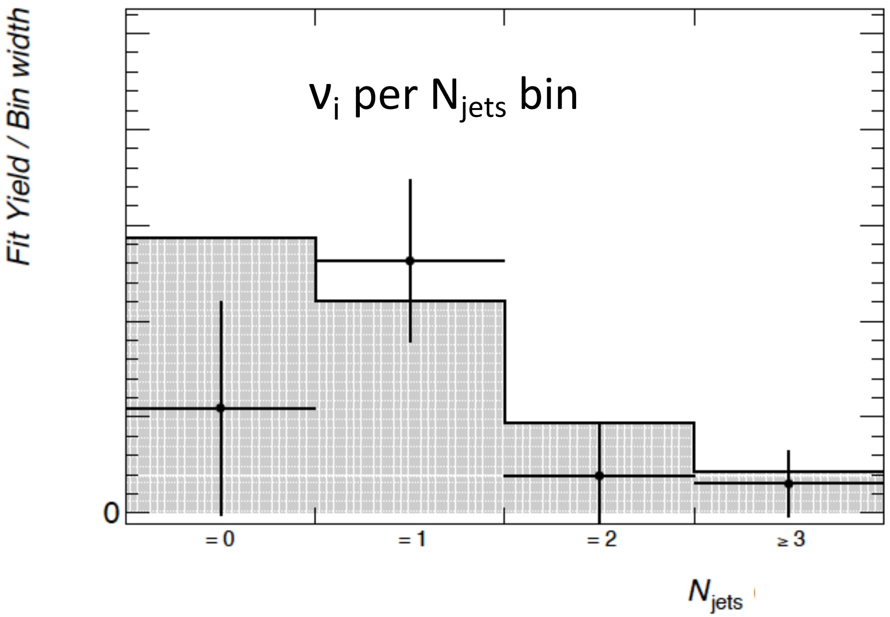
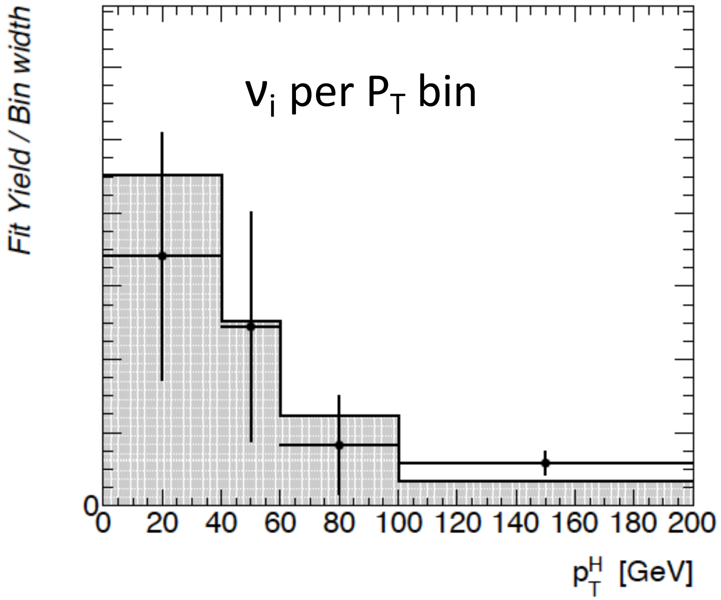




Fiducial & Differential Cross-Sections

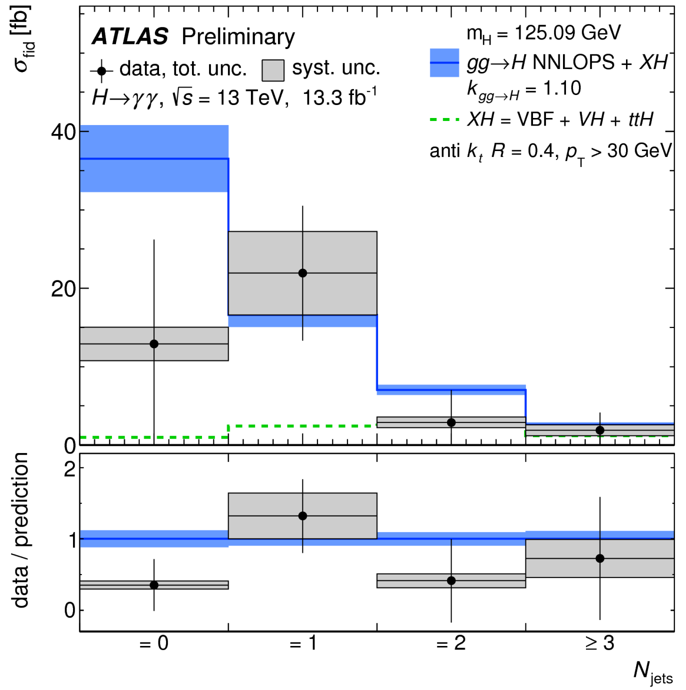


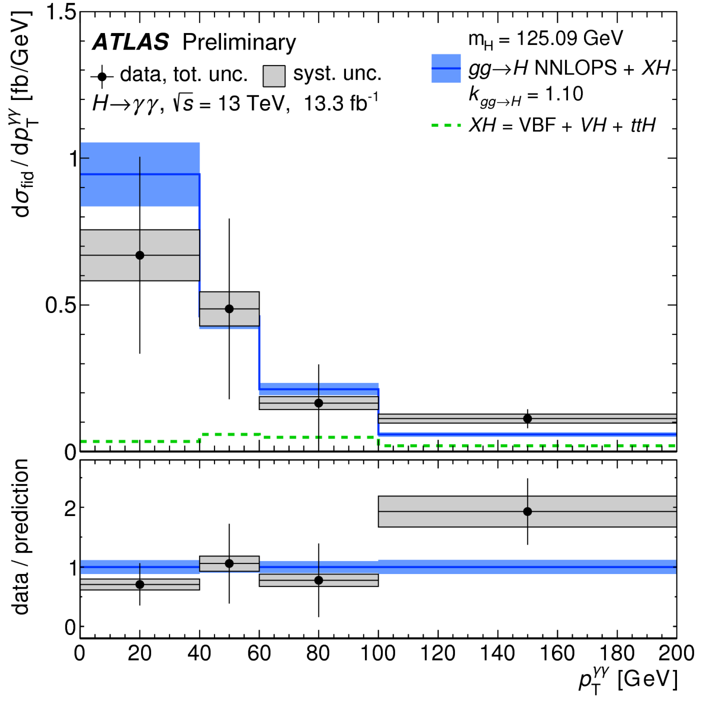


$$\sigma_{\text{fid}} = \frac{\nu_i^{\text{sig}}}{C_i\ \mathcal{L}_{\text{int}}}$$

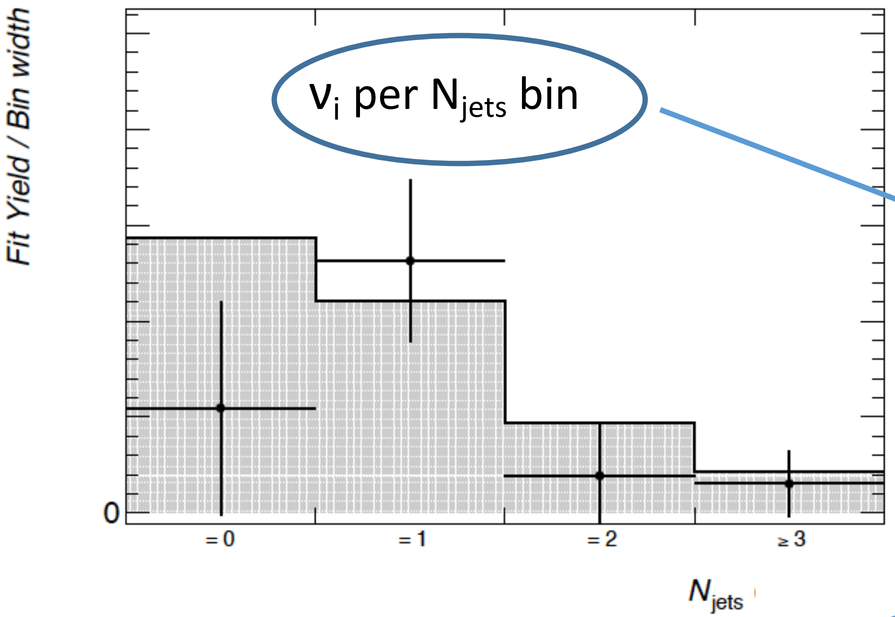
correction factor for detector effects

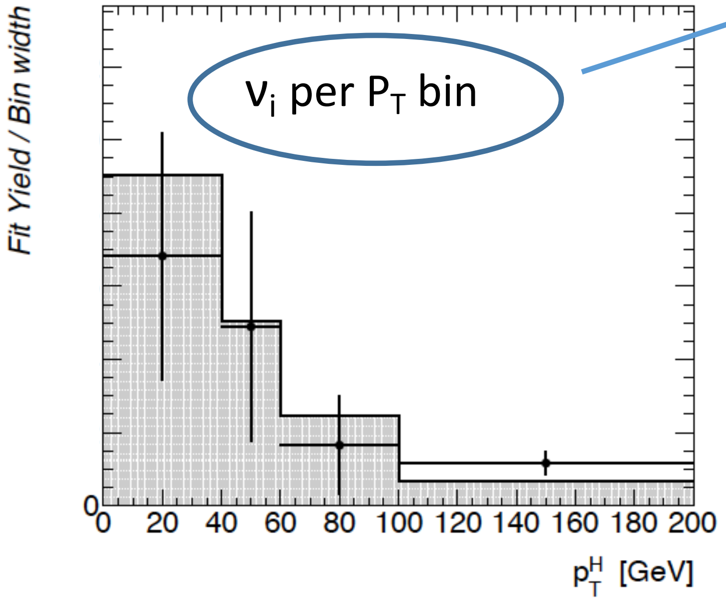
integrated luminosity





Fiducial & Differential Cross-Sections





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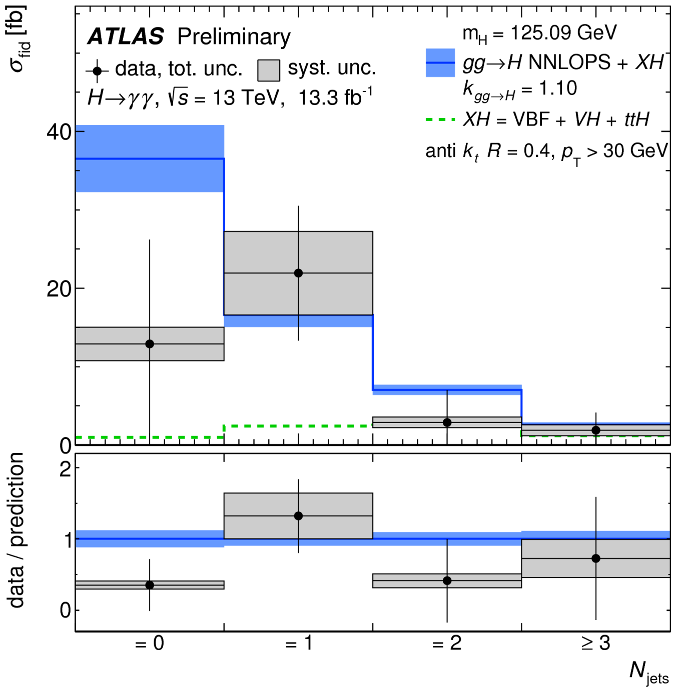
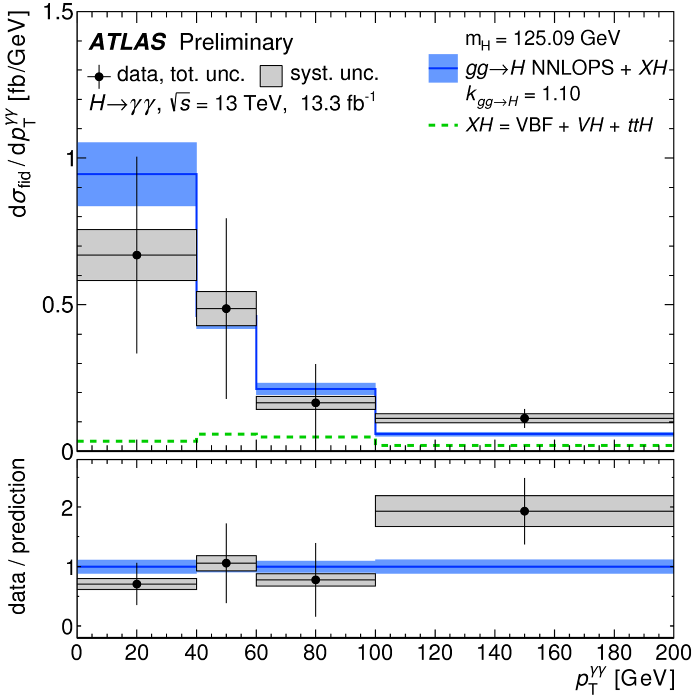
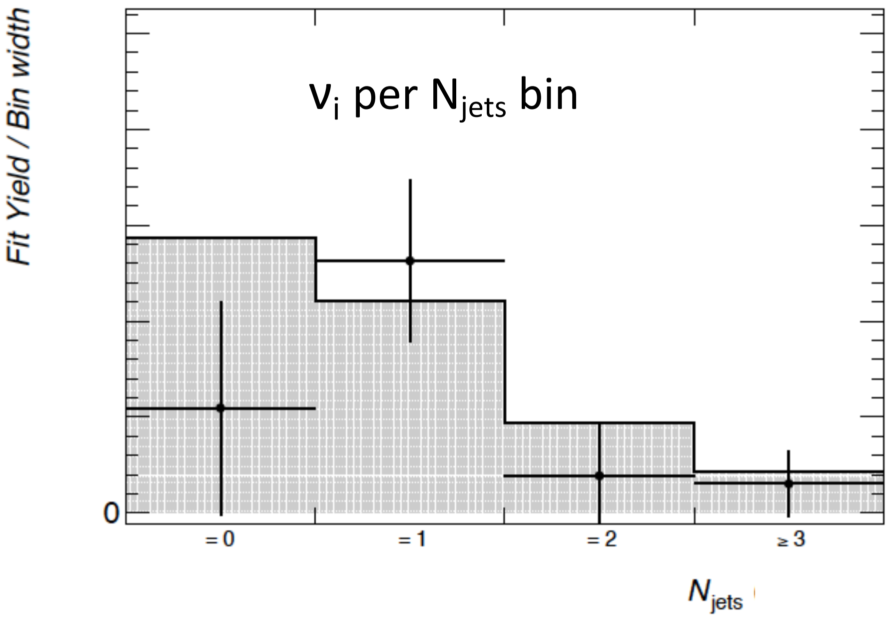
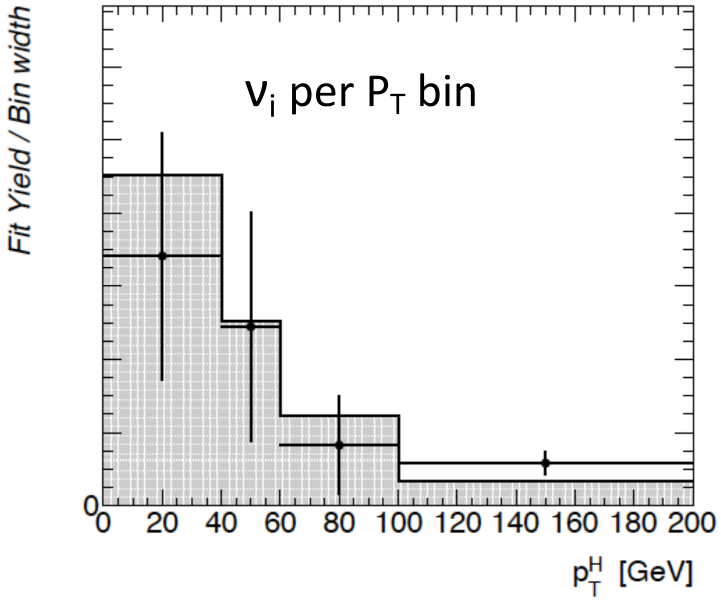




Fiducial & Differential Cross-Sections



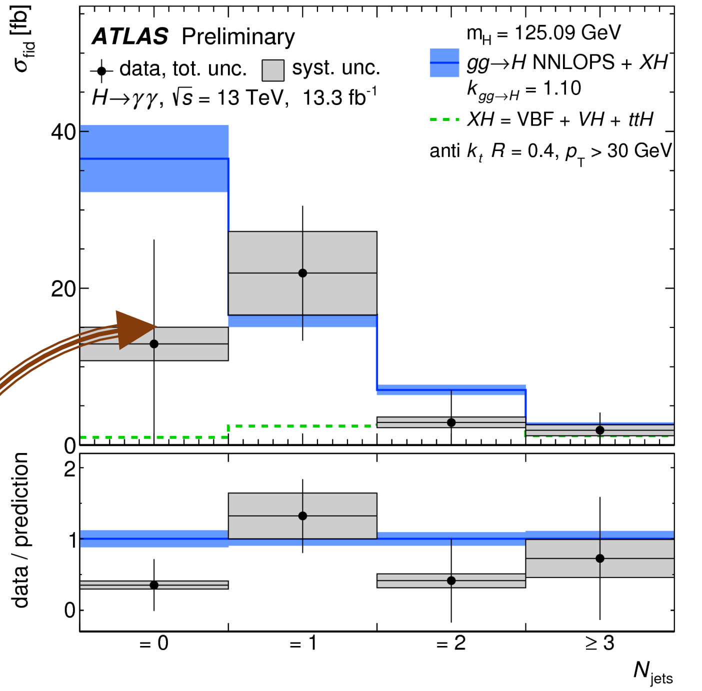


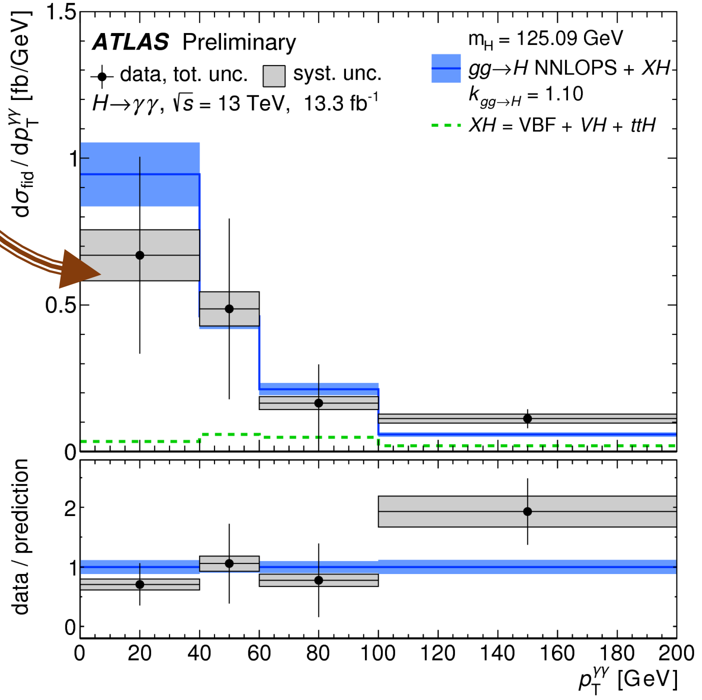
Particle-level cross-section measurements

$$\sigma_{\text{fid}} = \frac{\nu_i^{\text{sig}}}{C_i \ \mathcal{L}_{\text{int}}}$$

correction factor for detector effects

integrated luminosity



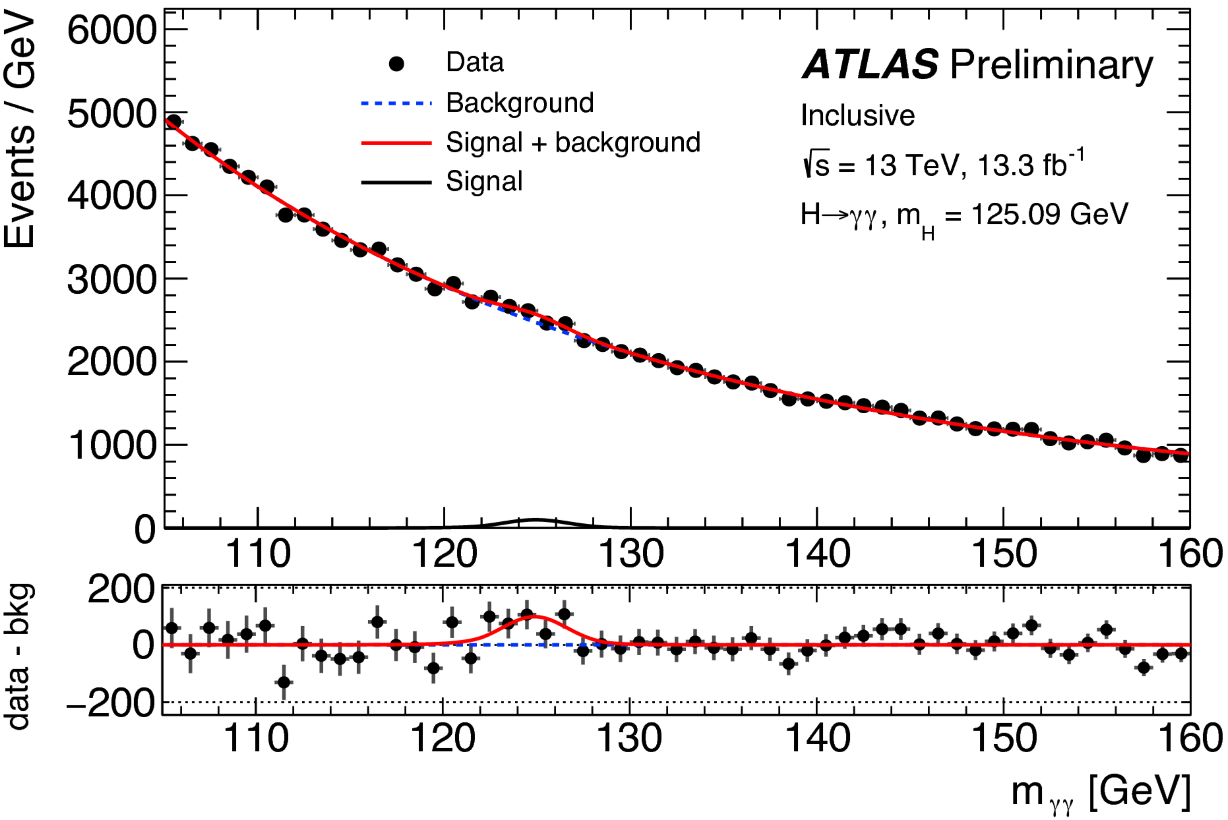


Diphoton invariant mass spectrum

Baseline

$p_T(\gamma_1)/m_{\gamma\gamma} > 0.35$ and $p_T(\gamma_2)/m_{\gamma\gamma} > 0.25$

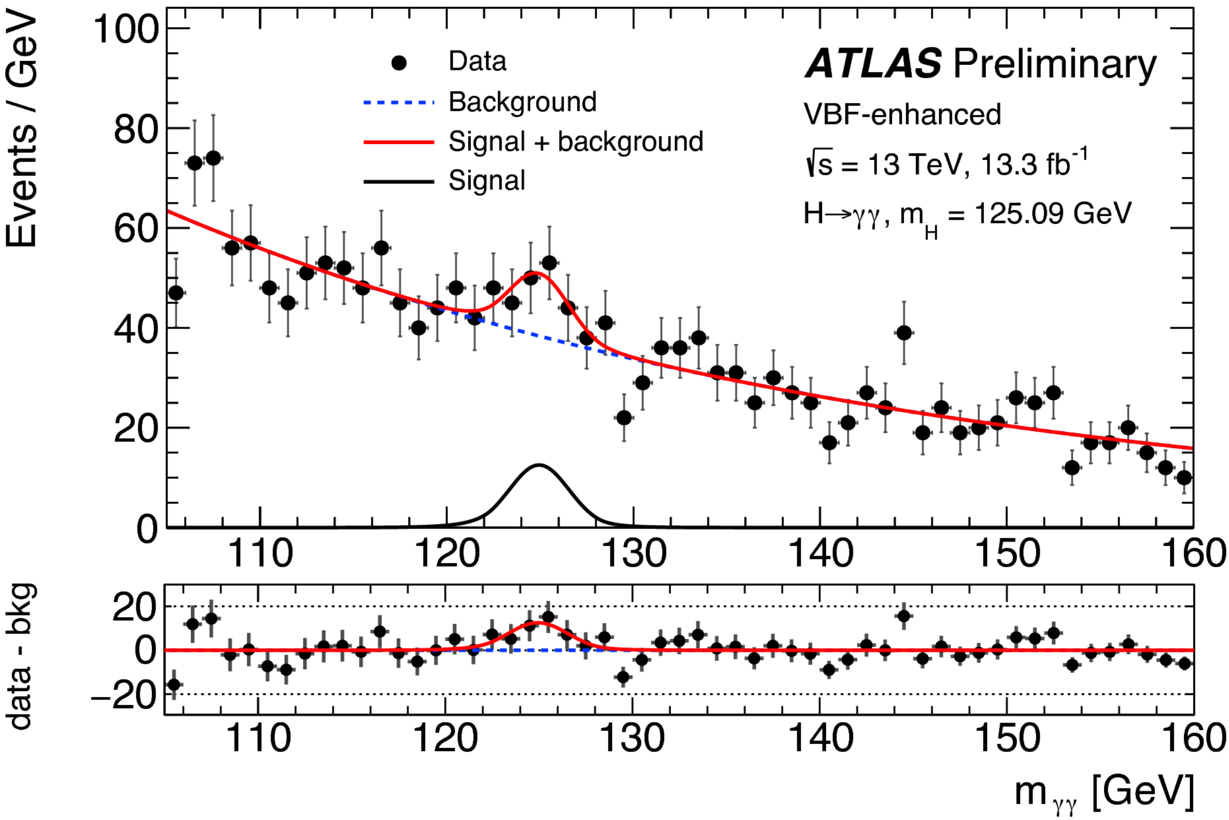
$|\eta| < 2.37$ (excluding crack-region $1.37 \leq |\eta| < 1.52$)



VBF-enhanced

$p_T(\text{jet}) > 30$ GeV, $|y(\text{jet})\} < 4.4$ and $m_{jj} > 400$ GeV

$|\Delta y_{jj}| > 2.8$ and $|\Delta\Phi_{\gamma\gamma,jj}| > 2.6$

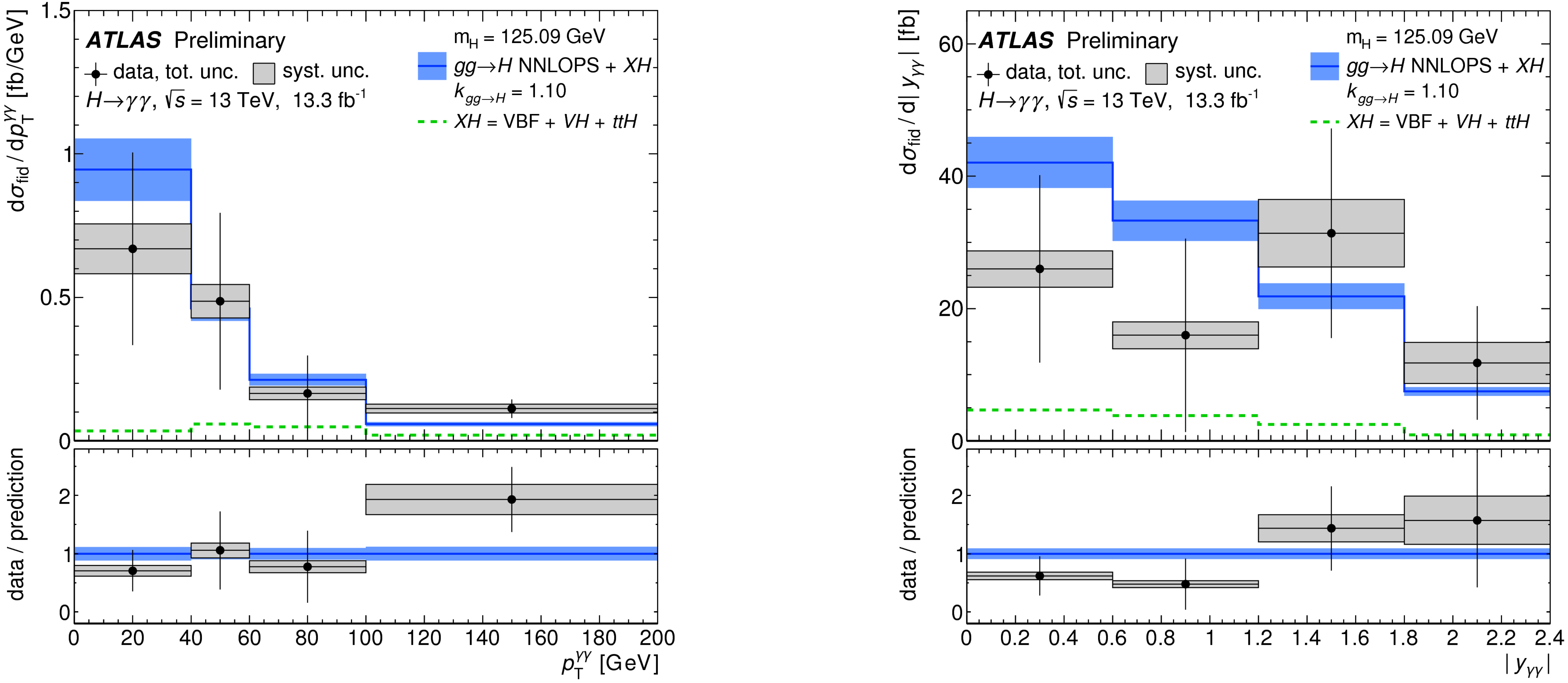


Cross Sections in Fiducial Phase Space Regions

	diphoton baseline	VBF enhanced	single lepton
Photons	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30\,\text{GeV}$, $\|y\| < 4.4$ $m_{jj} > 400\,\text{GeV}$, $\|\Delta y_{jj}\| > 2.8$ $\|\Delta\phi_{\gamma\gamma,jj}\| > 2.6$	- - -
Leptons	-	-	$p_T > 15\,\text{GeV}$ $\|\eta\| < 2.47$

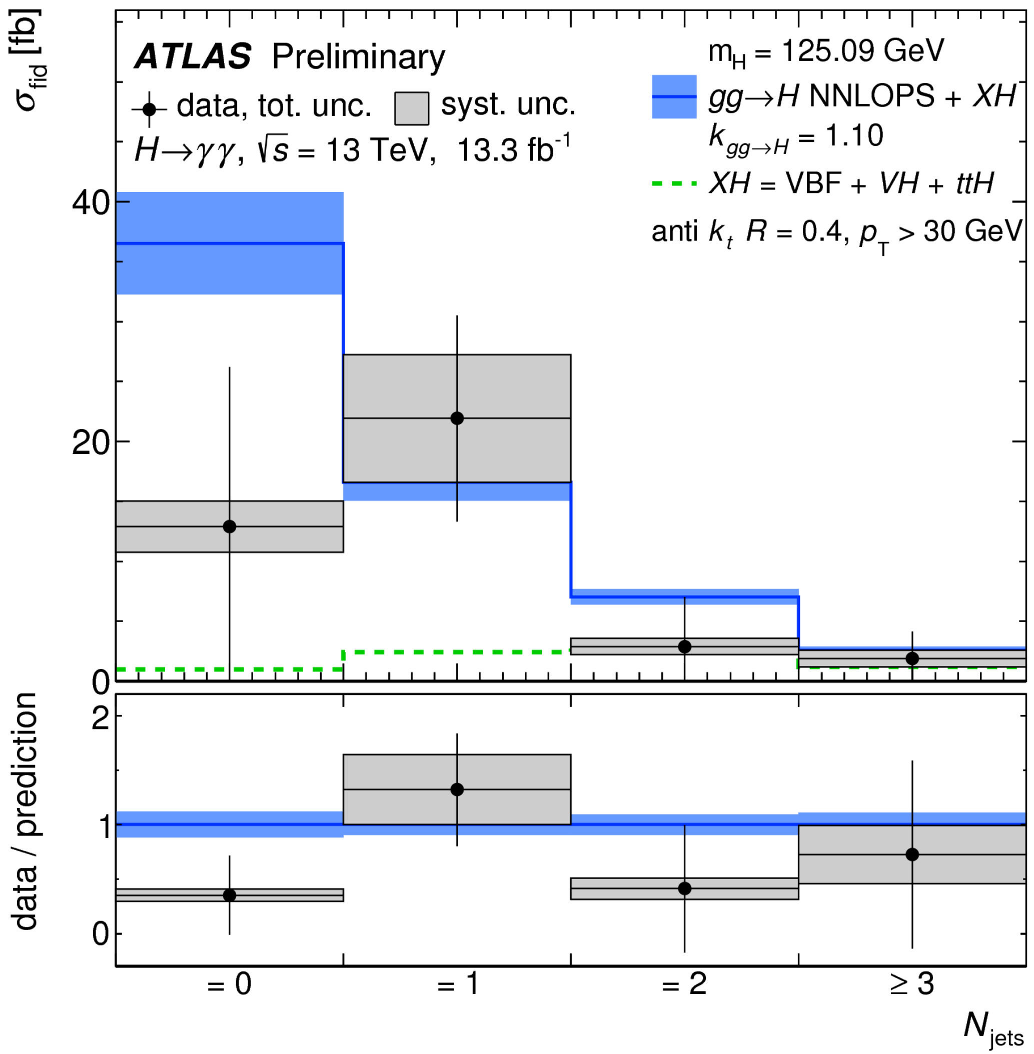
Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8\,^{+3.4}_{-4.4}$	$[\text{N}^3\text{LO} + \text{XH}]$
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	[NNLOPS + XH]

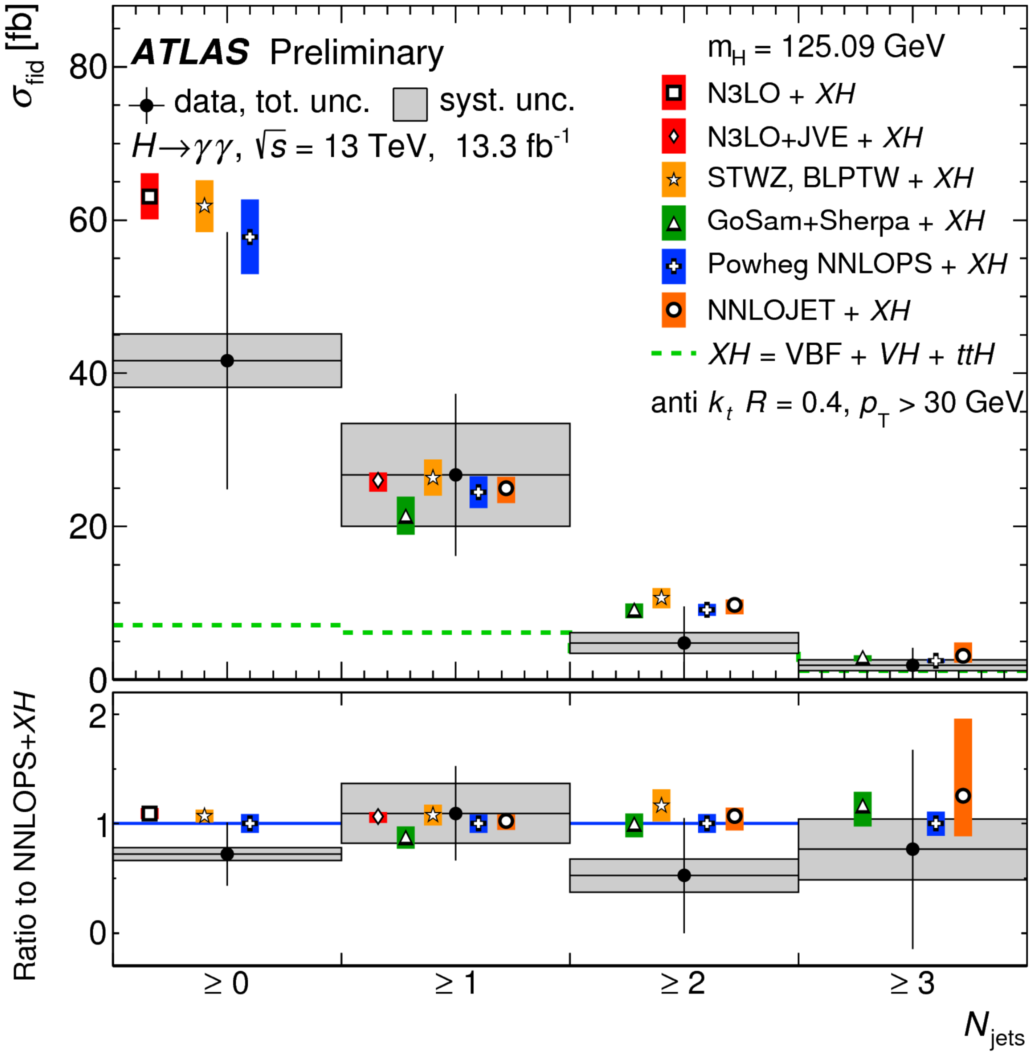
Higgs boson kinematics pp→ H → $\gamma\gamma$:



Good agreement data & SM prediction

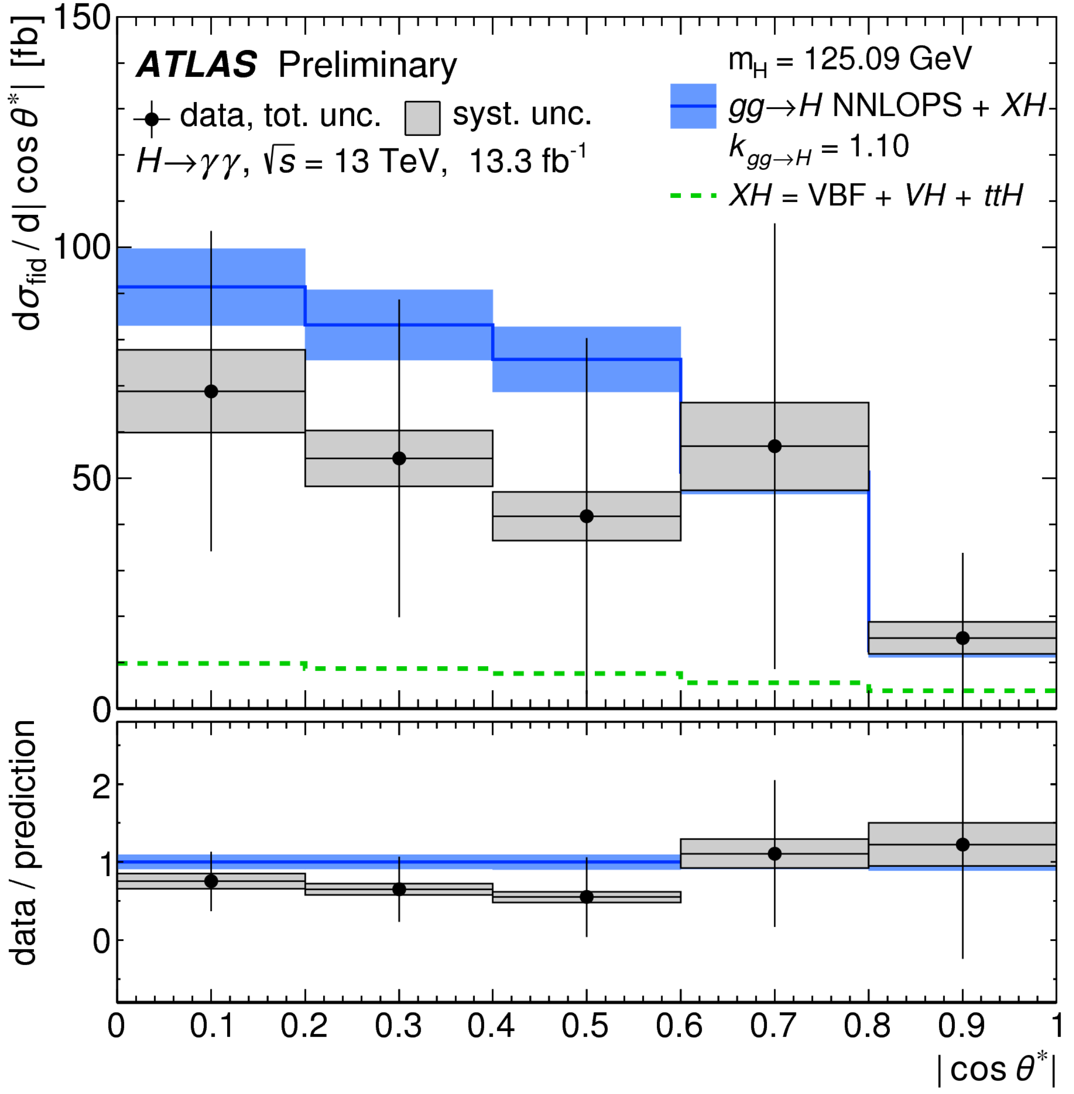
Jet activity (jet multiplicity): pp→ H → $\gamma\gamma$ + N_{jet}

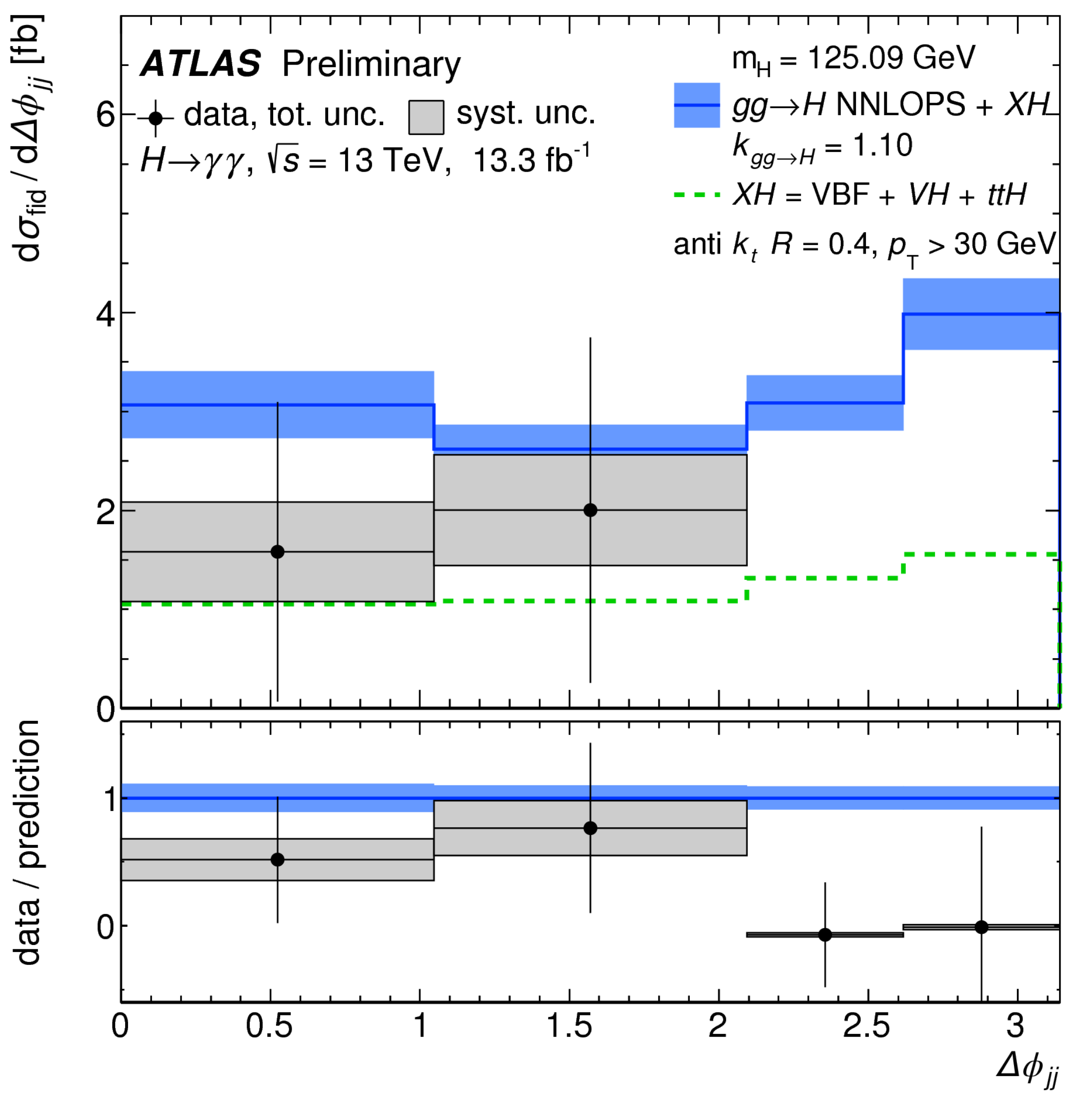




Good agreement data & SM prediction: deficit for N_{jet}=0 (left) – data compare to theory (right)

Angular Distributions





Data in agreement with SM expectation for scalar CP-even particle

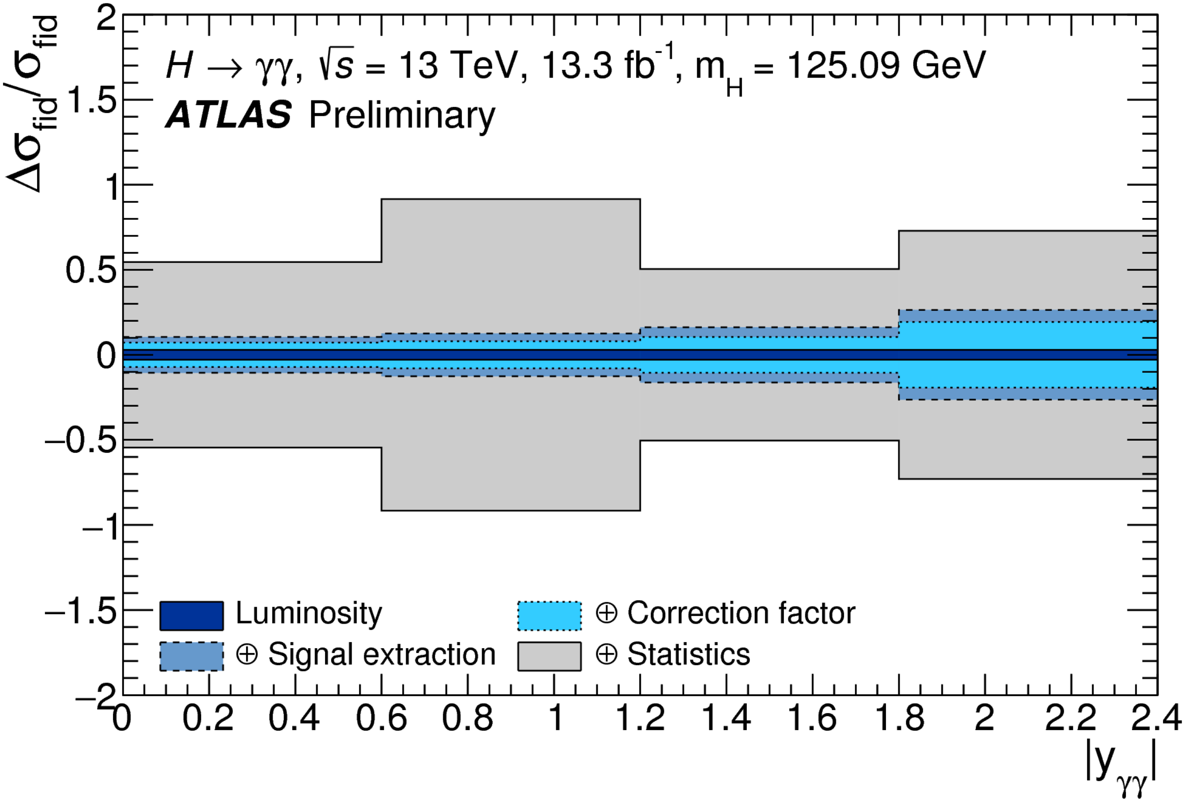
Systematics Uncertainties and Their Impacts

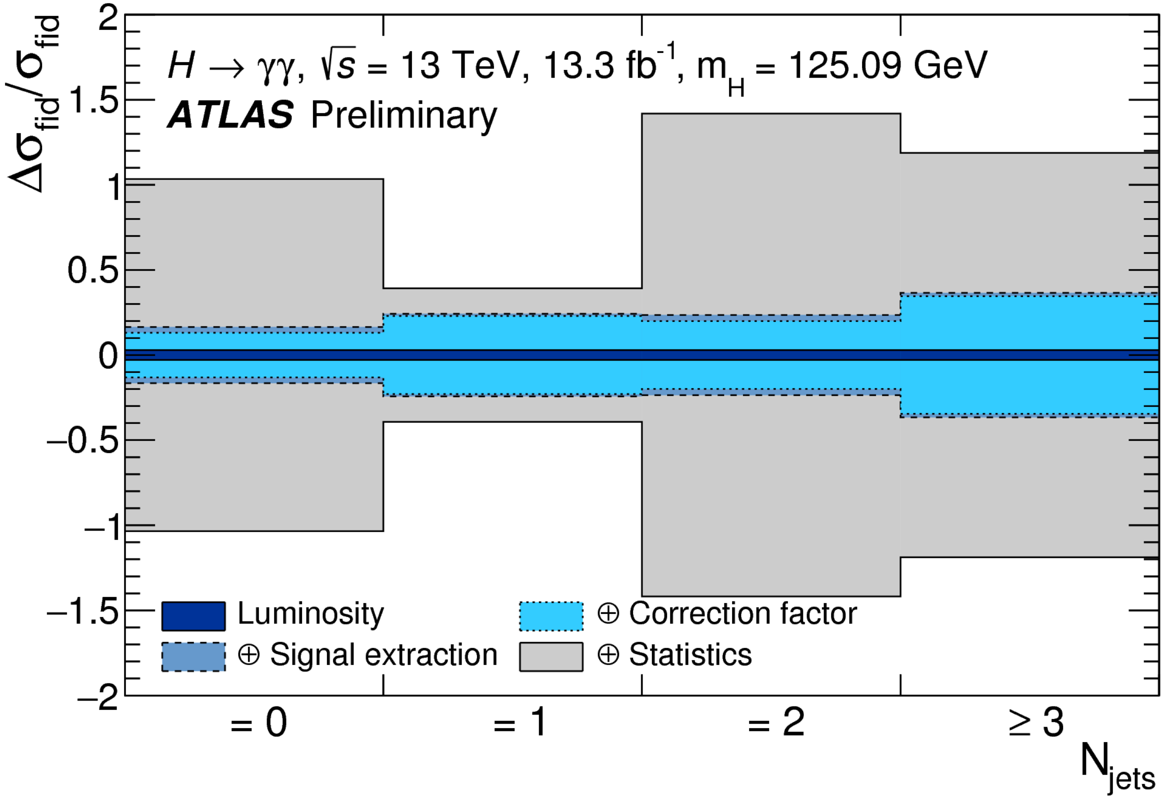
Photon energy resolution and background modeling are typically the main uncertainties

Jet energy calibration uncertainties important when jet activity

Source	Uncertainty on fiducial cross section (%)		
	Baseline	VBF-enhanced	single-lepton
Fit (stat.)	34.5	35.0	52.9
Fit (syst.)	9.0	11.1	9.3
Photon efficiency	4.4	4.4	4.4
Jet energy scale/resolution	-	9.4	-
Lepton selection	-	-	0.8
Pileup	1.1	2.0	1.4
Theoretical modelling	4.3	9.4	8.4
Luminosity	2.9	2.9	2.9

Dominated by statistical error !!!

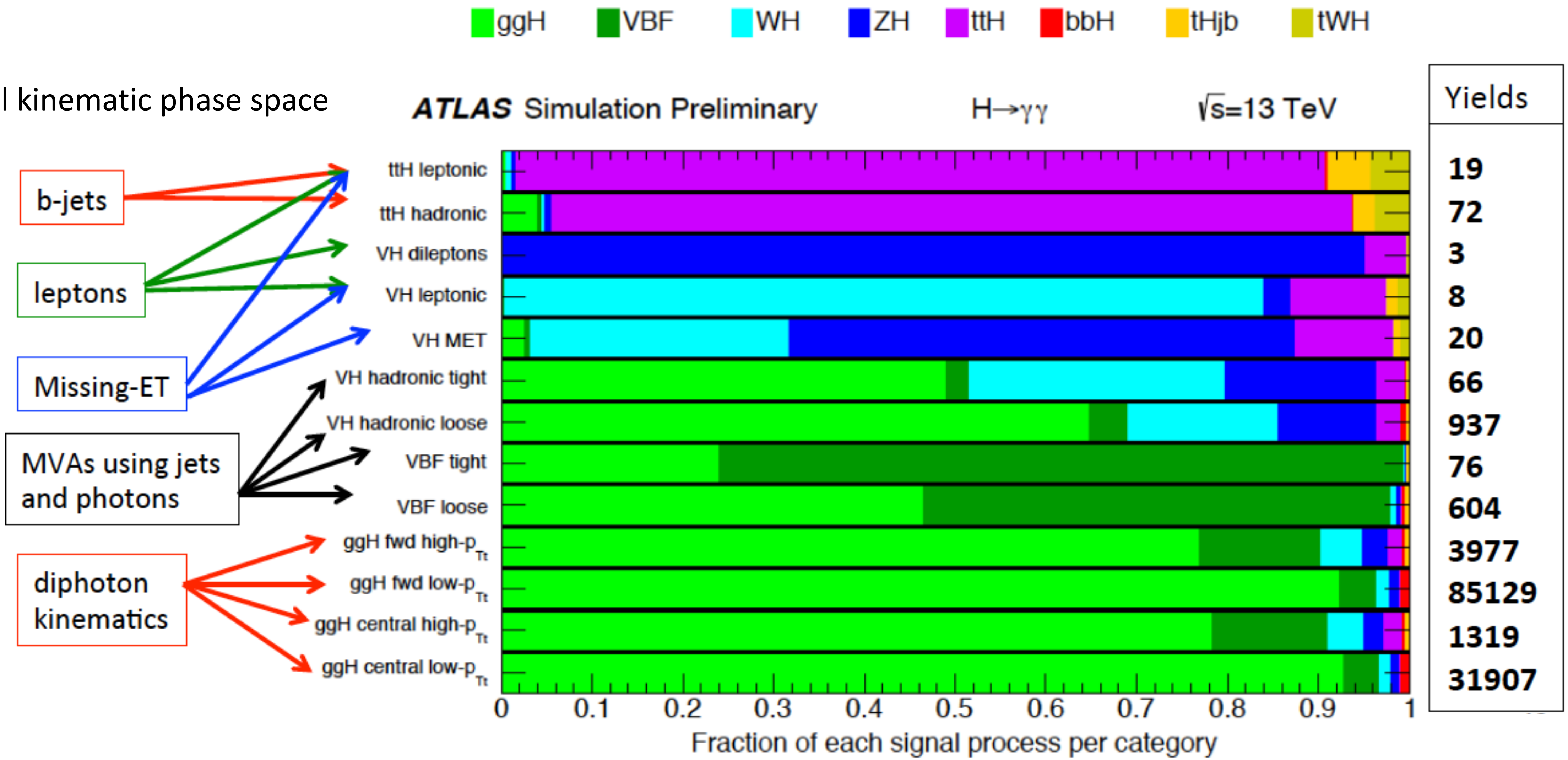




Simplified Template Cross Sections

Events are split into 13 orthogonal categories that exploit topological differences between production mechanisms

Full kinematic phase space



Procedure to get Signal Yields per category

Production cross section extracted by a combined fit to $m_{\gamma\gamma}$ specta

$$N_k^{\text{sig}} = \sum_i \sigma_i \cdot \mathcal{B}(H \to \gamma\gamma) \cdot \epsilon_{ik} \cdot A_{ik} \cdot \int L\,\mathrm{d}t$$

Signal yield in specified category

Production cross section times branching ratio for given process

Acceptance predicted by SM for given process in specified category

Dominant uncertainty again from photon energy scale/resolution in fit

Large uncertainty from theoretical modelling of acceptances, especially for gluon fusion in VBF-enriched categories

Production mode Cross Section

Total Higgs production cross section

$$\sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 65\,^{+32}_{-31}\ \text{fb}$$

$$\sigma_{\text{VBF}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 19.2\,^{+6.8}_{-6.1}\ \text{fb}$$

$$\sigma_{\text{VH}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 1.2\,^{+6.5}_{-5.4}\ \text{fb}$$

$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) = -0.28\,^{+1.44}_{-1.12}\ \text{fb}$$

Higgs production cross section ($|y_H|<2.5$)

$$\sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 63\,^{+30}_{-29}\ \text{fb}$$

$$\sigma_{\text{VBF}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 17.8\,^{+6.3}_{-5.7}\ \text{fb}$$

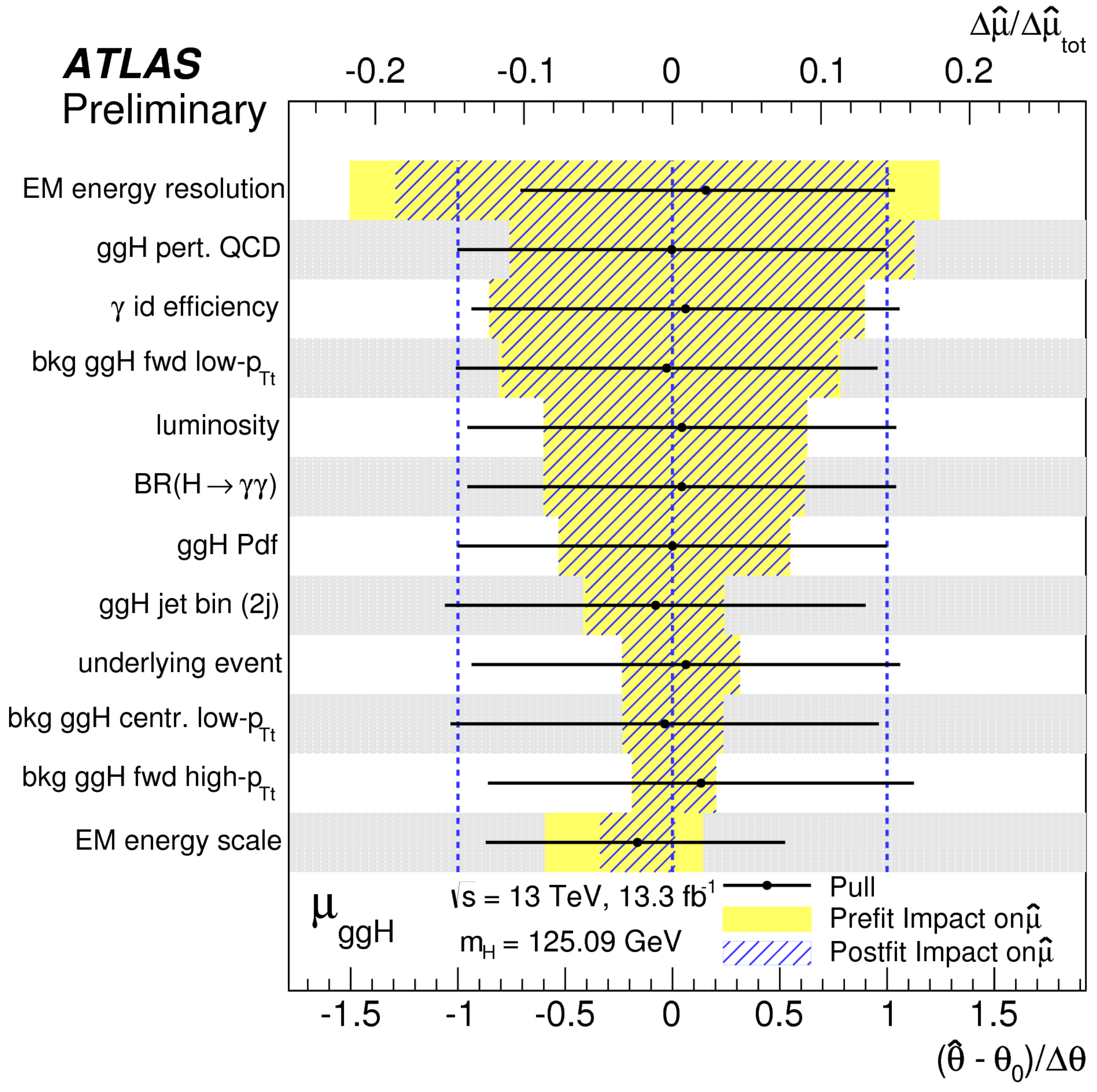
$$\sigma_{\text{VHlep}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 0.96\,^{+2.52}_{-1.90}\ \text{fb}$$

$$\sigma_{\text{VHhad}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = -2.3\,^{+6.8}_{-5.8}\ \text{fb}$$

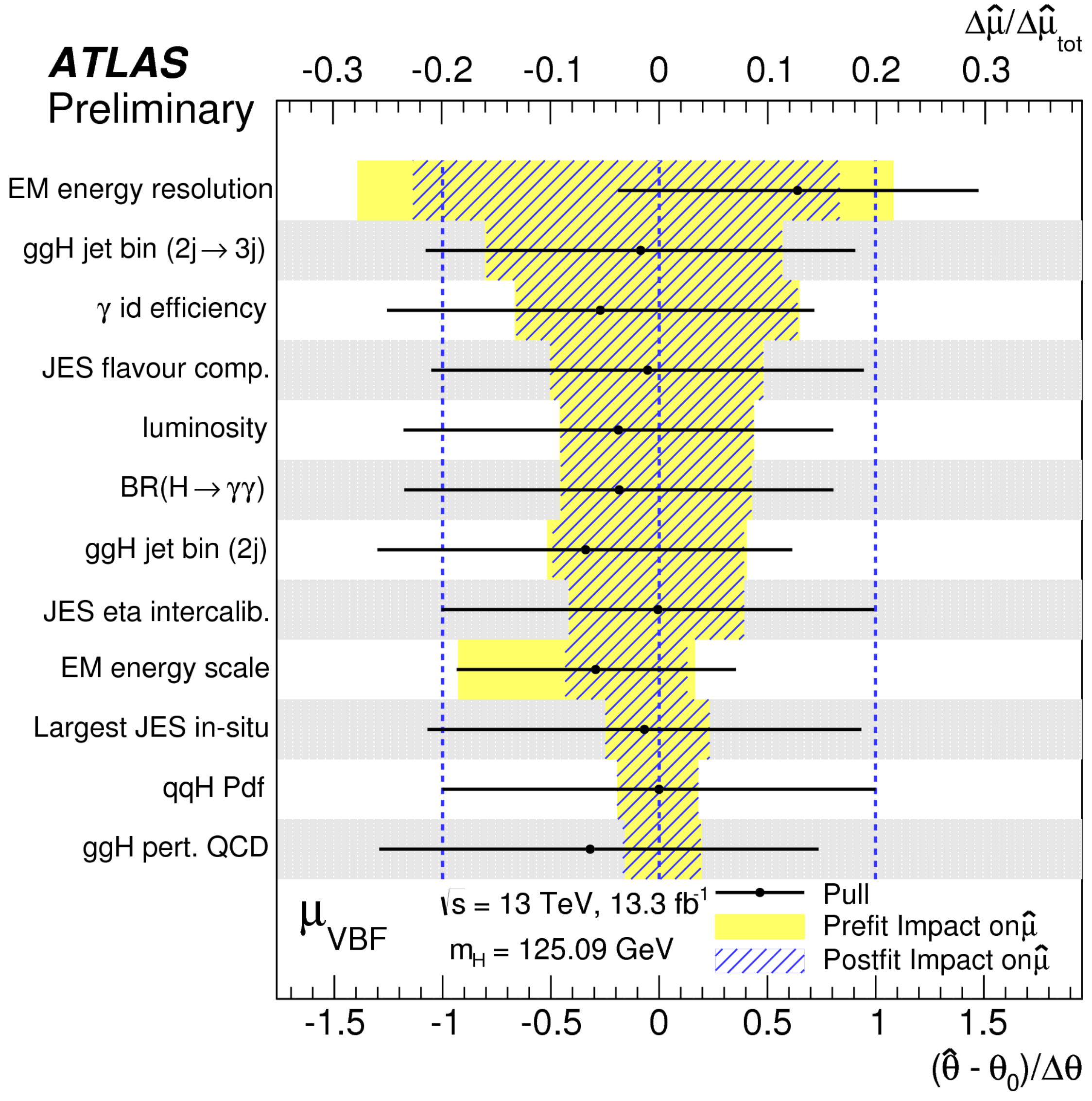
$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) = -0.28\,^{+1.43}_{-1.12}\ \text{fb}$$

Observed significance of $H \rightarrow \gamma\gamma$ signal is 4.7σ (SM expectation of 5.4σ

Systematic uncertainty signal strength measurements



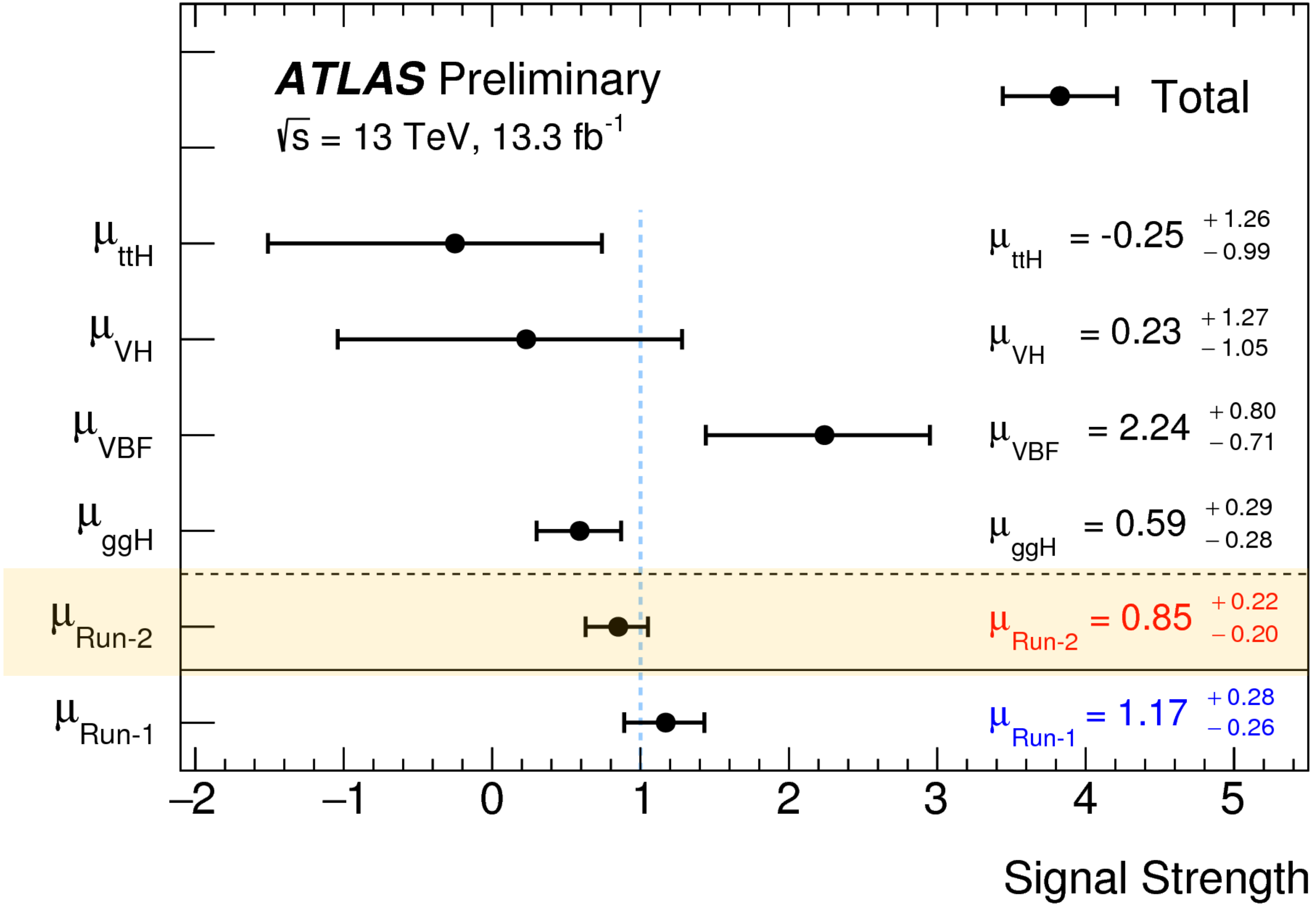
nuisance parameters ranking & pulls gluon fusion



nuisance parameters ranking & pulls VBF

Signal Strength

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



Summary

Since the 2012 discovery of the Higgs boson, focus has shifted to measuring its properties and testing the consistency of the Standard Model with data

First fiducial, differential and production cross section measurements of Higgs boson production in $H\rightarrow\gamma\gamma$ at 13 TeV with data collected in 2015 and early summer 2016

Two different but complementary approaches:

1. Fiducial and differential cross sections are the most model independent characterization of the events (from detector to particle-level fiducial phase space)
2. Production cross section and signal strengths probe the Higgs couplings directly

Conclusion pp $\rightarrow$ $H\rightarrow\gamma\gamma$:

- Analysis goal is to minimize the dependence on theoretical modelling
- Results statistically limited at the moment
- Comparison to theory predictions:
- Slightly “harder” observed in the Higgs transverse momentum spectrum
- Mild deficit observed in jet multiplicity spectrum at $N_{jet} = 0$
- All results consistent with the SM within statistical errors