Higgs Boson Property Measurements in the Diphoton Decay Channel at ATLAS

Jim Lacey

DESY FH Fellow Meeting

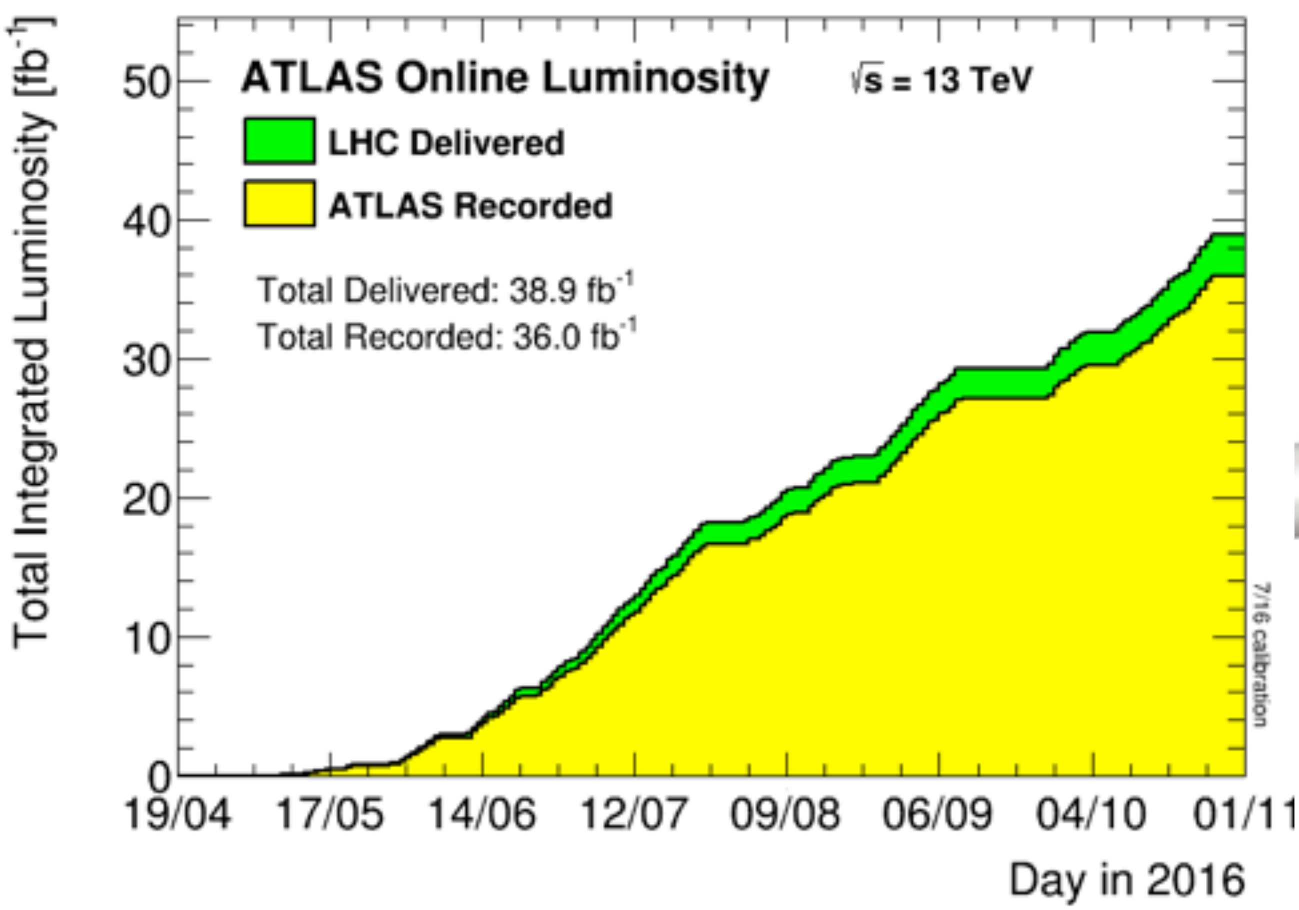
Nov. 29, 2016

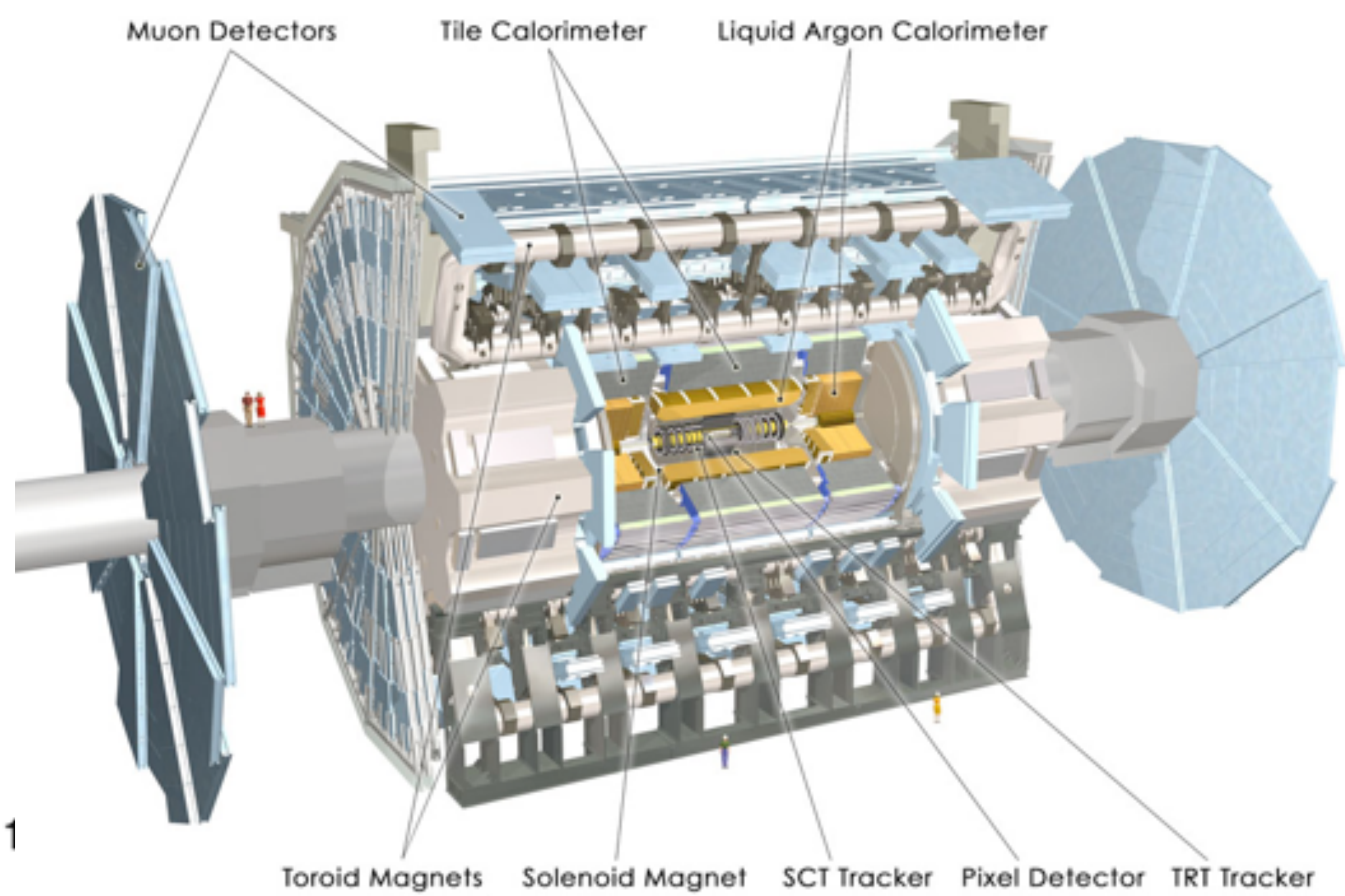
Run-II ATLAS & LHC

Run-II ATLAS data: *3.2 fb^{-1} (2015) + 33.2 fb^{-1} (2016) = 36.4 fb^{-1} ready for analysis!*

Data collected at a higher centre-of-mass energy (13 TeV):

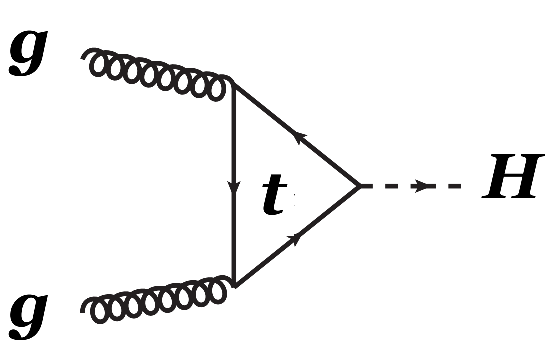
- *Increased sensitivity to Higgs boson production*
- *Increased sensitivity to tails of differential distributions*



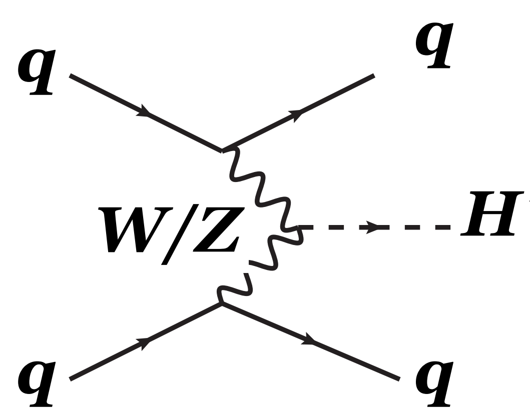


Higgs boson production & decay

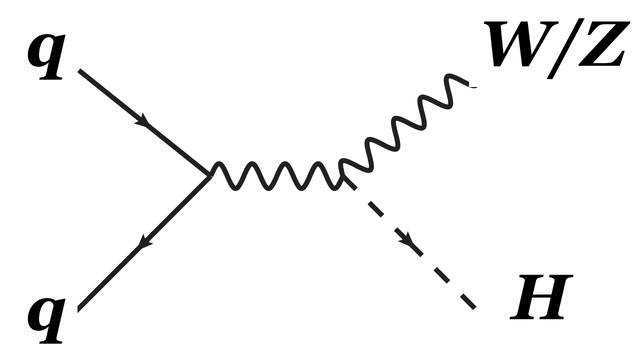
Production:



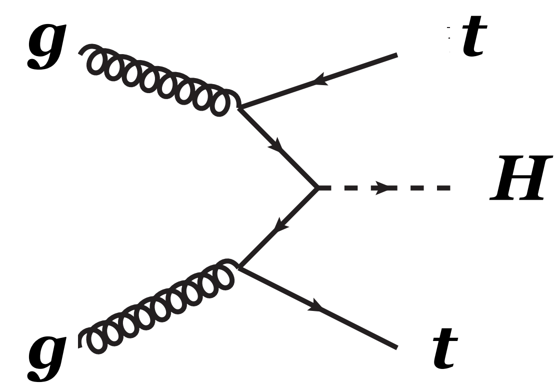
ggF: ~ 87%



VBF: ~ 7.2%



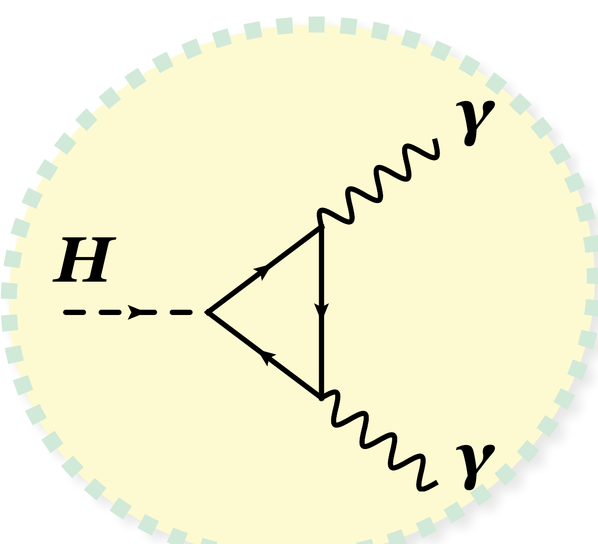
VH ≡ WH or ZH: ~ 5%



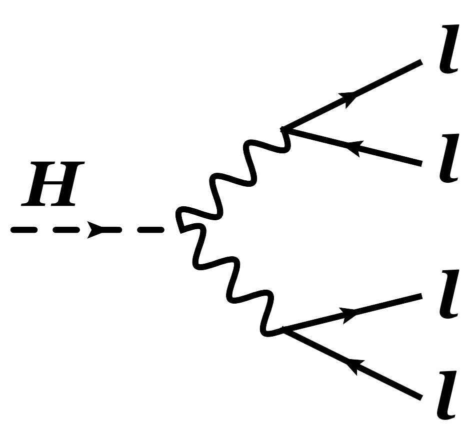
ttH: ~ 0.6%

Decay:

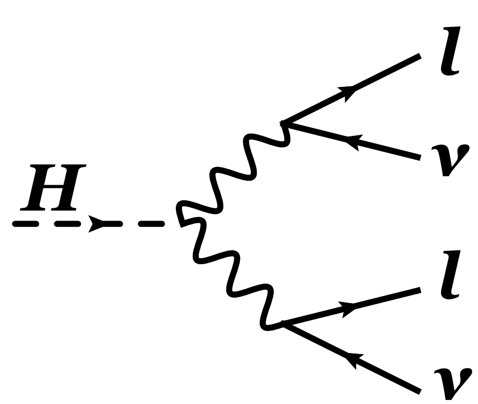
$l = e, \mu$



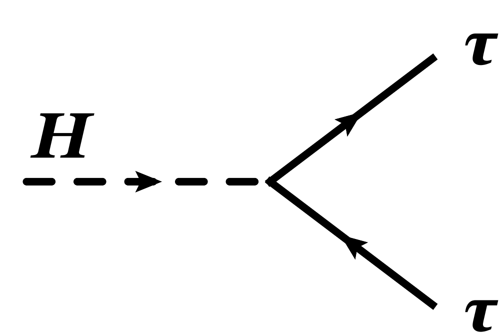
0.228%
$H \to \gamma\gamma$



0.013%
$H \to ZZ^* \to 4l$



1.09%
$H \to WW \to l\nu l\nu$

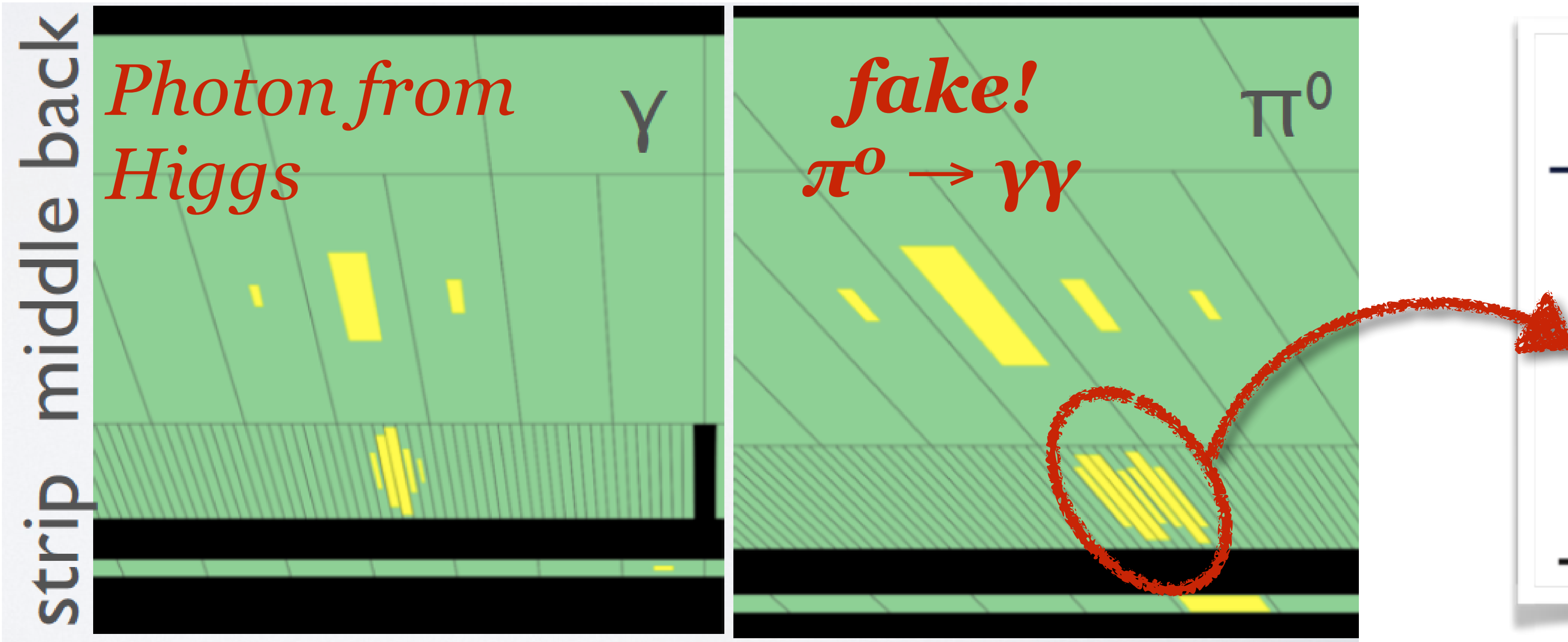


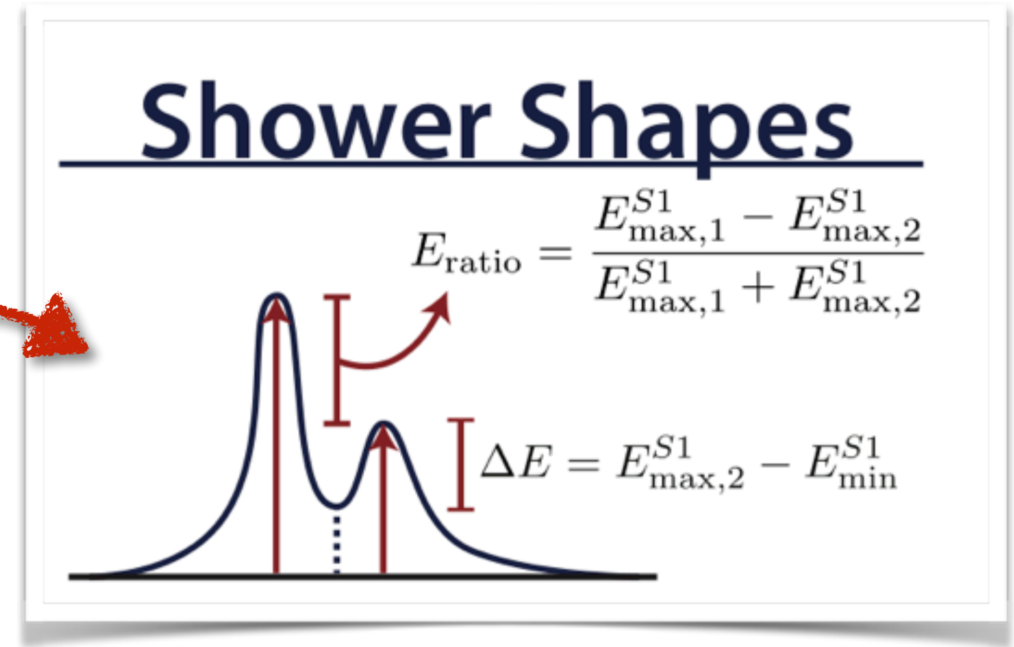
6.25%
$H \to \tau\tau$

In addition:

$H \to bb$	57.1%
$H \to WW^*$	22.1%
$H \to gg$	8.5%
$H \to cc$	2.9%
$H \to ZZ^*$	2.7%
. . .	

$H \rightarrow \gamma\gamma$ photon identification





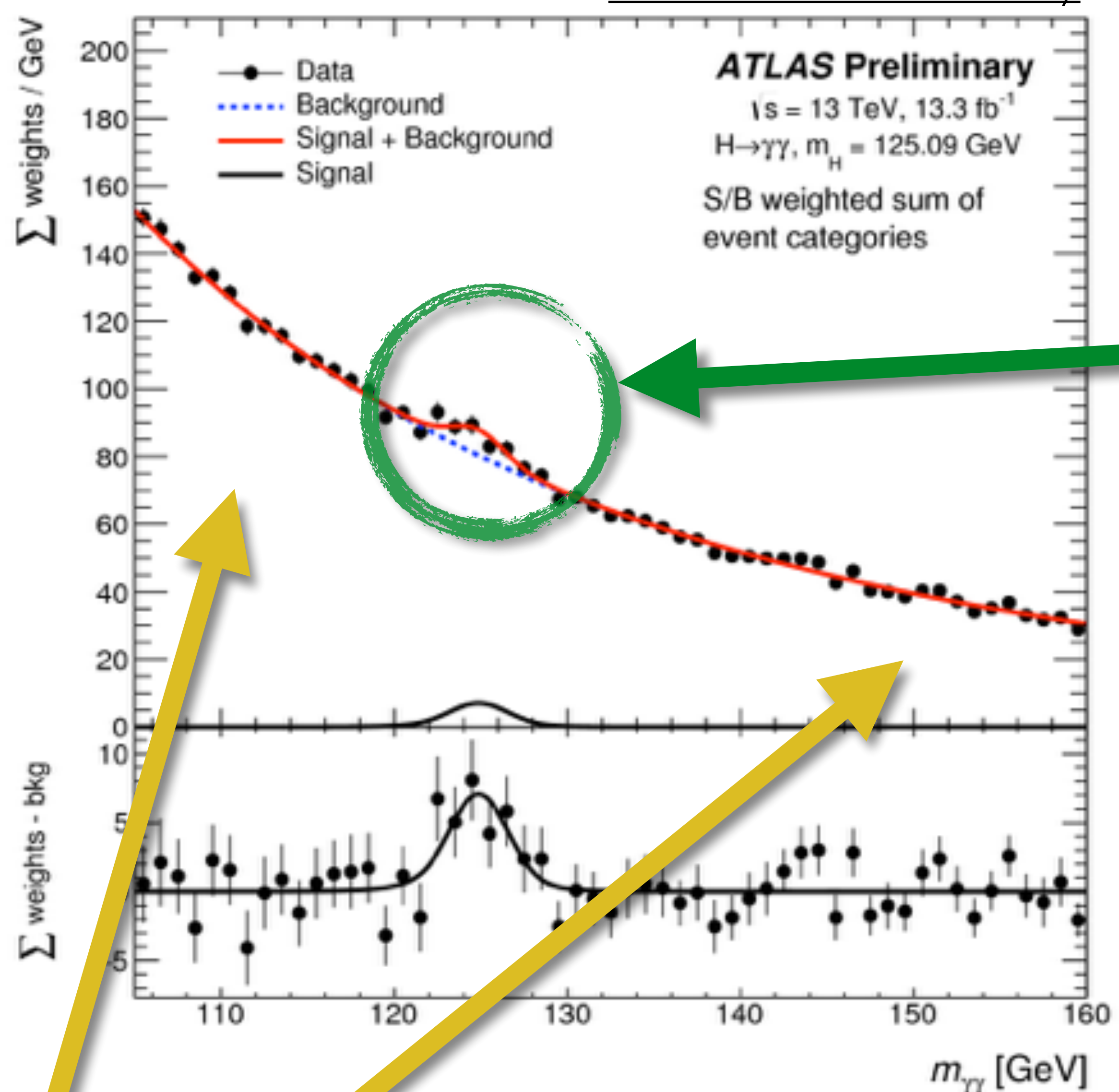
Discrimination against fake photons

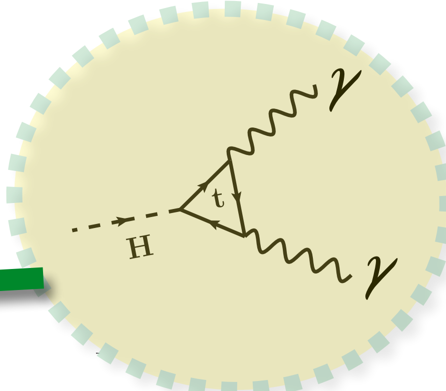
- *Many other particles (eg. π^0) can produce signals that are similar to photons produced by the Higgs boson*
- *Discrimination against such particles is achieved by examining the **shape of energy depositions** in the detector*

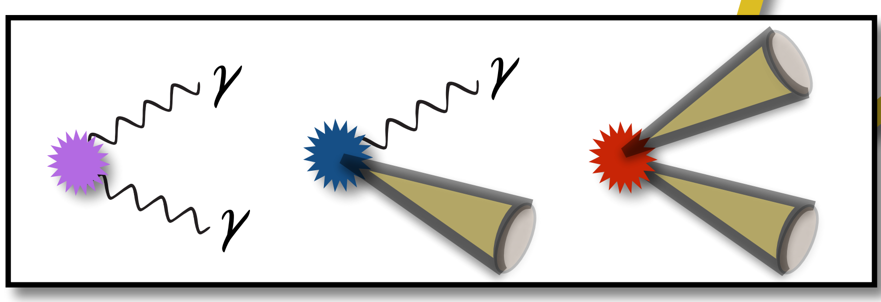
Photon identification is achieved using a set of variables that describe the shape of the energy deposition in the calorimeter

Signal & background

ATLAS-CONF-2016-067







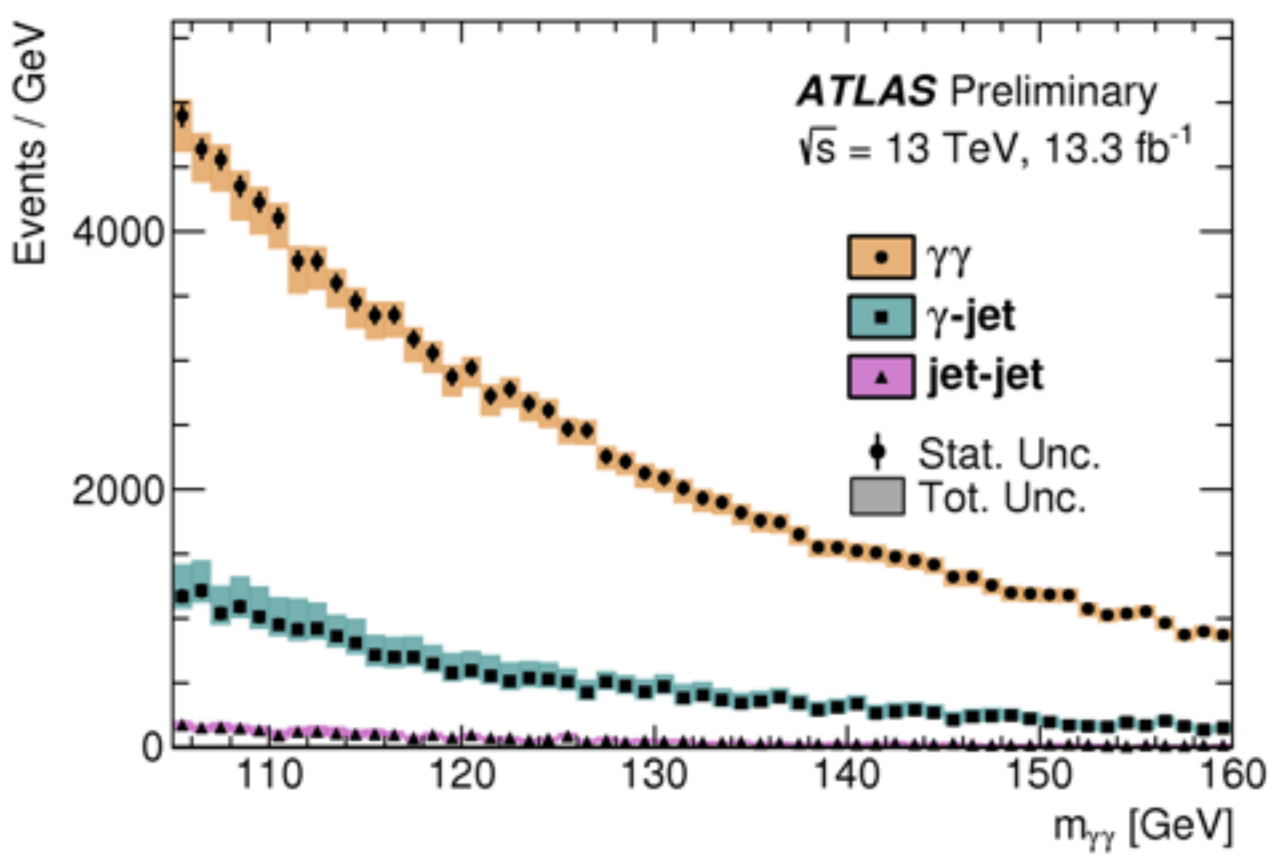
γγ, γ-jet, jet-jet

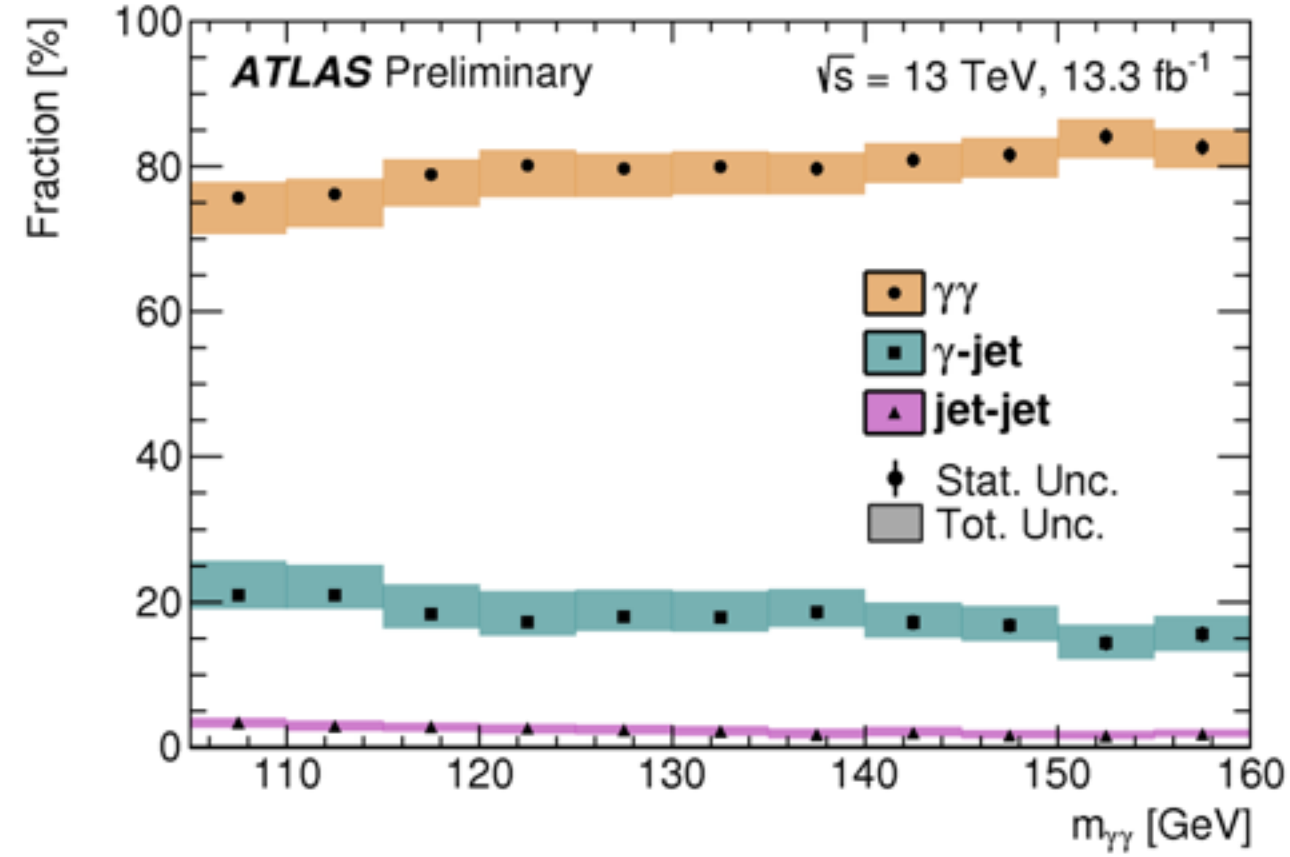
S + **B** fit to $m_{\gamma\gamma}$ spectrum: functional form for **S** + **B**

- minimize bkg bias / uncertainty
- account for uncertainties in the signal model via nuisance parameters

Diphoton background composition

ATLAS-CONF-2016-067





- **Data-driven background composition done for each fiducial region and bin measured**
- **Composition corresponding to the inclusive fiducial region shown above:**

80% γγ, 17% γ-jet, 3% jet-jet

Overview of Cross Sections

Cross section $\rightarrow$ $$\sigma_i = \frac{\nu_i^{\text{sig}}}{C_i \cdot A_i \cdot B \cdot \mathcal{L}_{\text{int}}}$$

Number of signal events measured in data

Correction for detector resolution and inefficiencies

Acceptance

Branching fraction

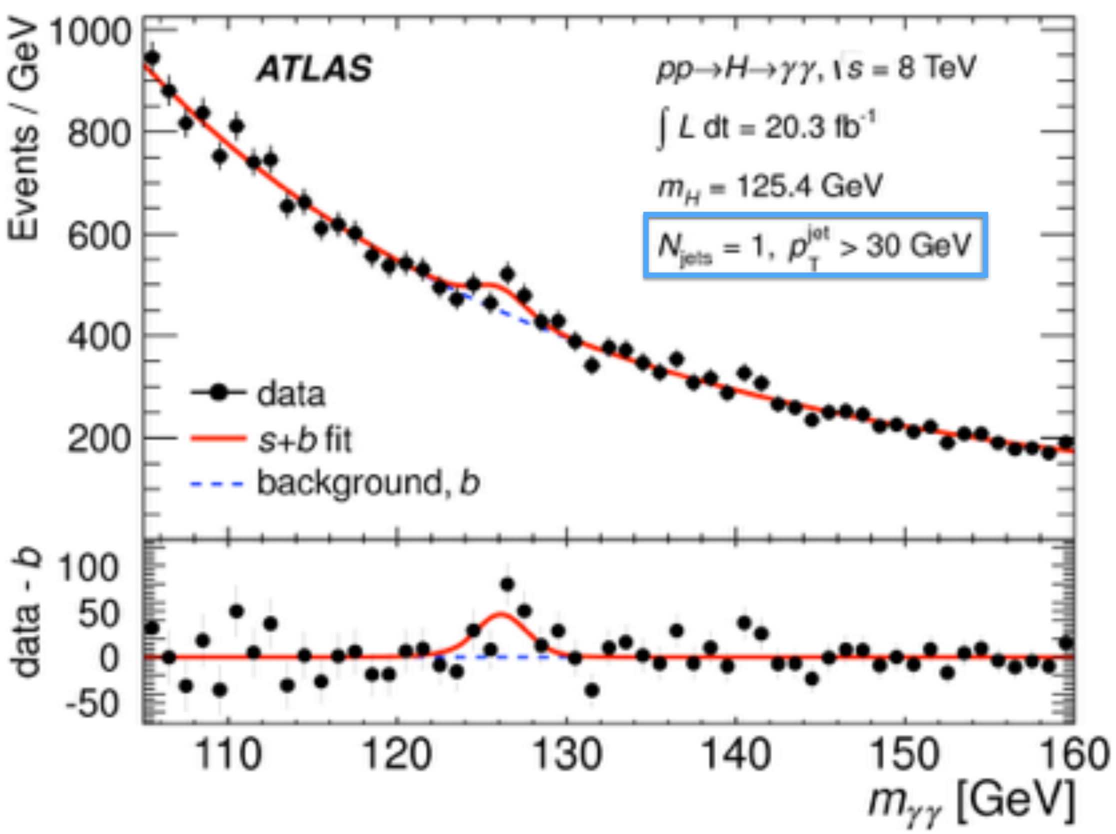
Integrated luminosity

Cross section in fiducial region or bin of a differential distribution $\rightarrow$ $$\sigma_{\text{fid},i} = \frac{\nu_i^{sig}}{C_i \cdot \mathcal{L}_{\text{int}}}$$

depends on event selection and decay channel $\rightarrow$ Goal: measure model independent detector-corrected event yields

Measuring Cross Sections

arXiv:1407.4222

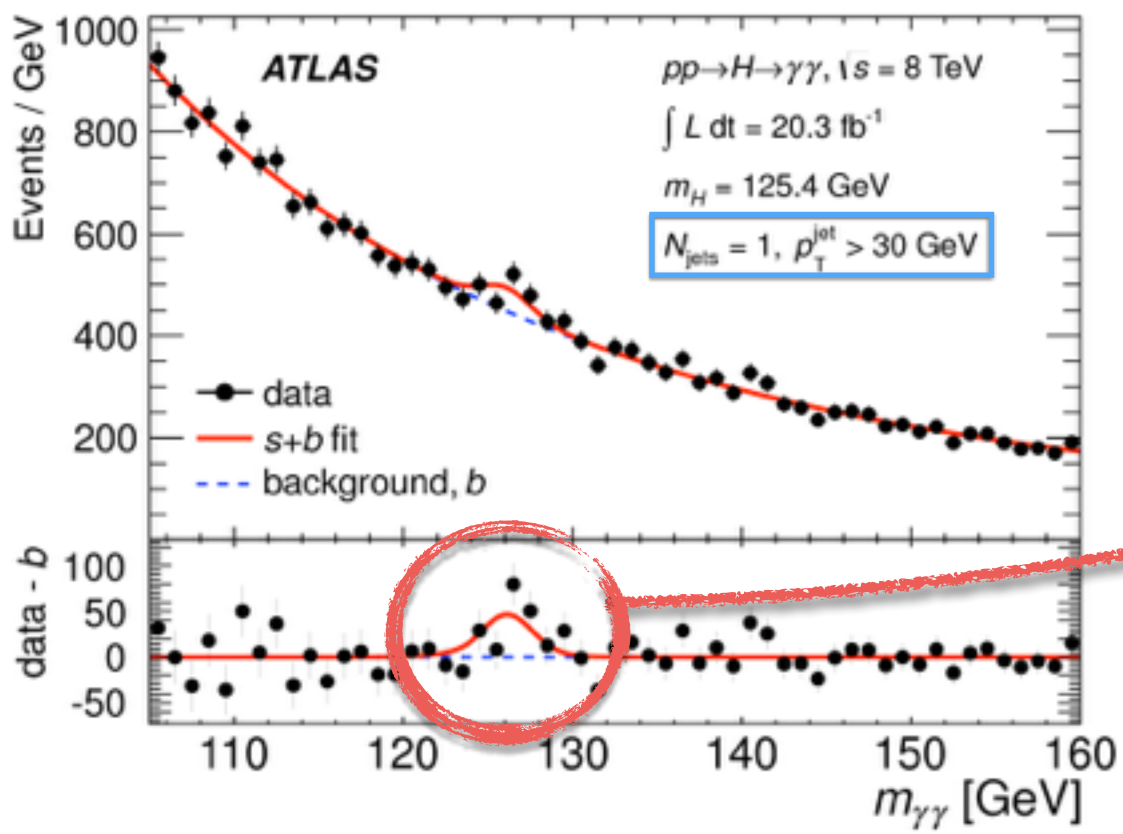


Categorize diphoton events into fiducial regions

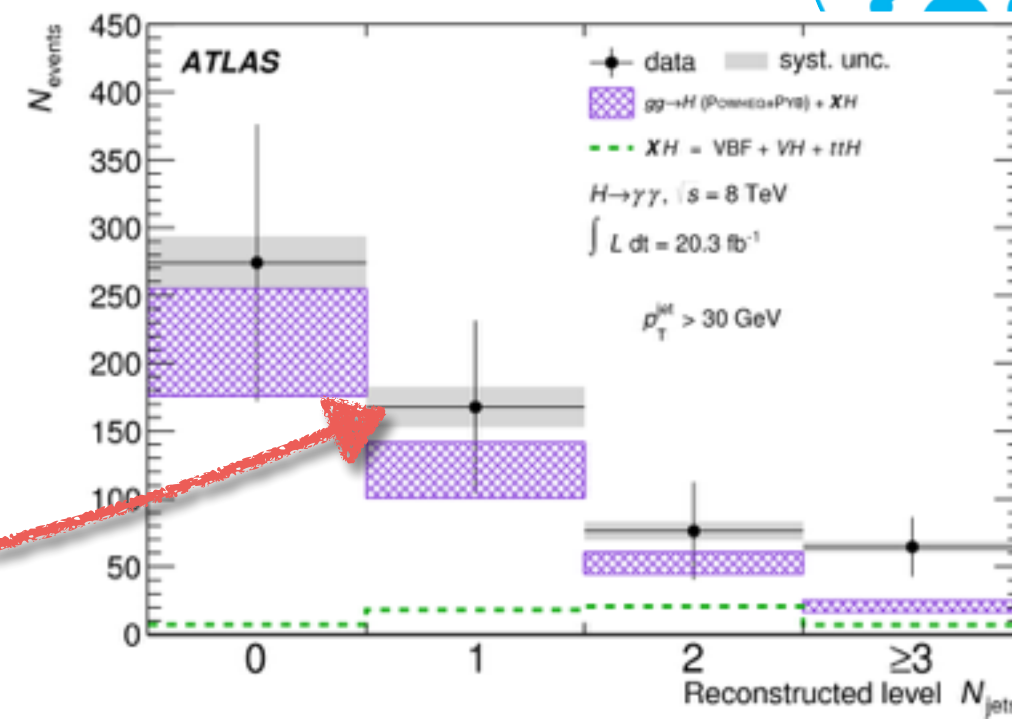
- *Truth-level fiducial definition chosen to mirror reco selection to minimize model dependence*

Measuring Cross Sections

arXiv:1407.4222



ν_i^{sig}



Categorize diphoton events into fiducial regions

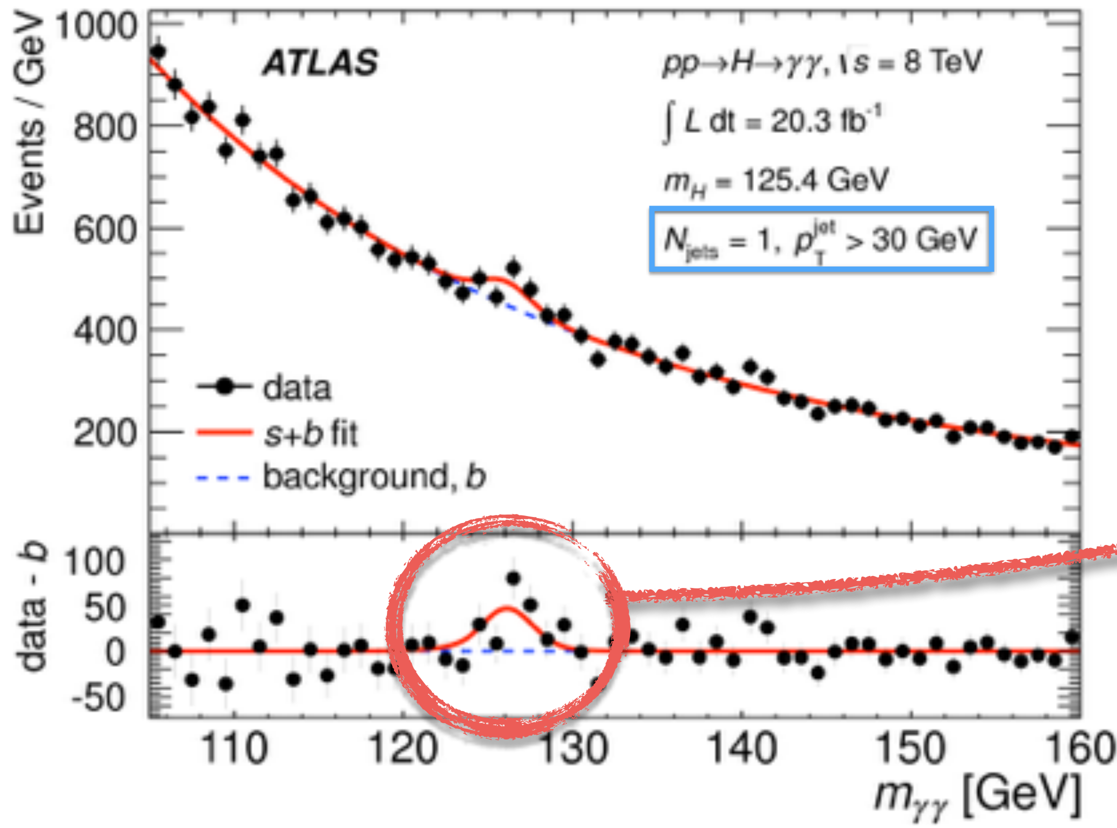
- *Truth-level fiducial definition chosen to mirror reco selection to minimize model dependence*

Extract *Higgs event yield* via a signal plus background fit to the $m_{\gamma\gamma}$ spectrum

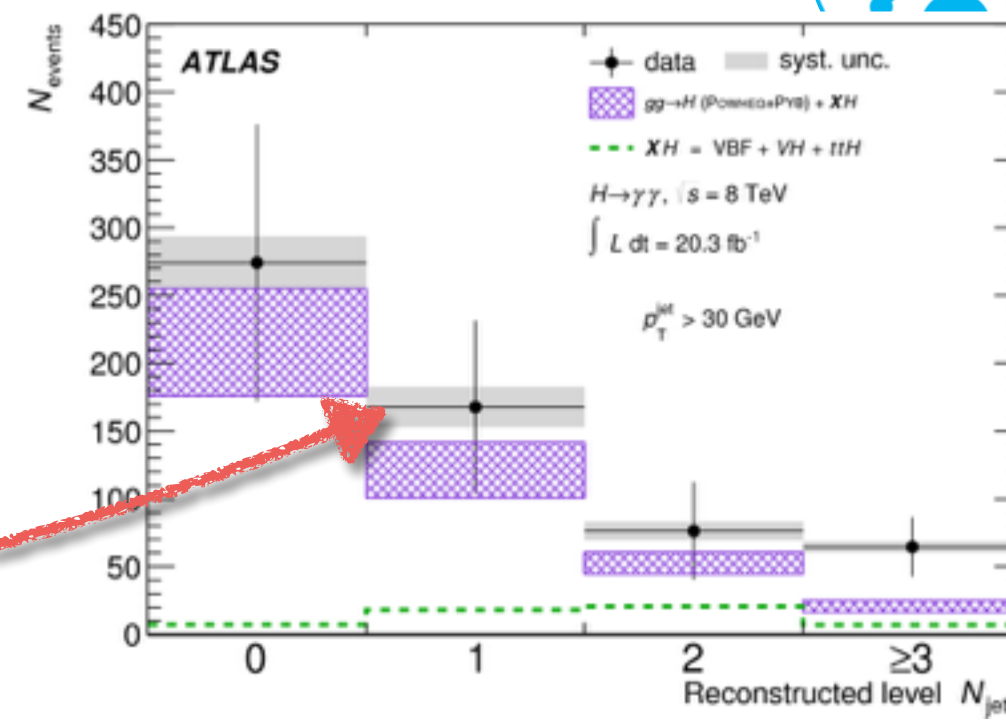
- *Higgs mass fixed to Run-I ATLAS+CMS best fit value ($m_H = 125.09 \pm 0.24$ GeV)*

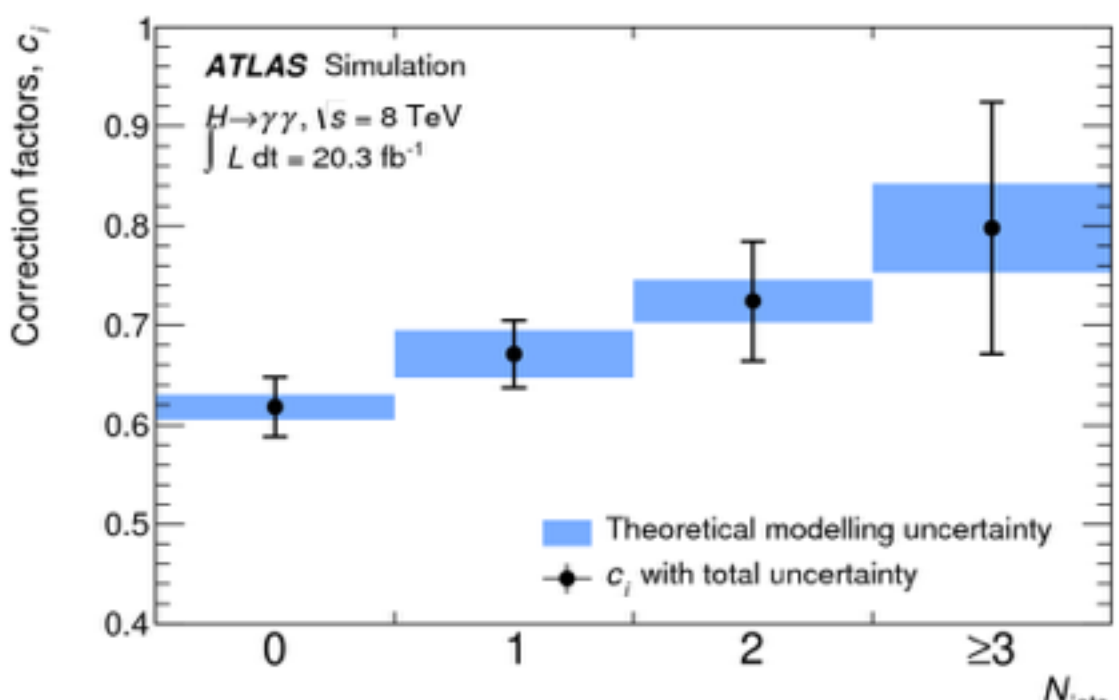
Measuring Cross Sections

arXiv:1407.4222



$$\nu_i^{\mathrm{sig}}$$





Correct signal yields for detector resolution and inefficiencies via unfolding

$$c_i = \frac{n_i^{det}}{n_i^{ptcl}}$$

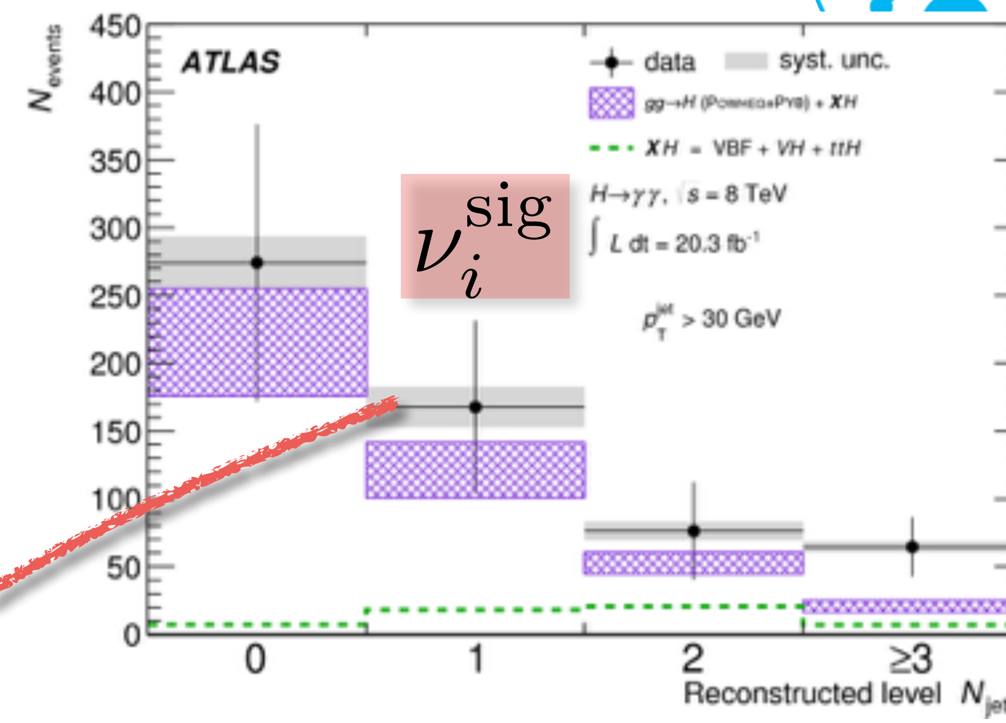
Measuring Cross Sections

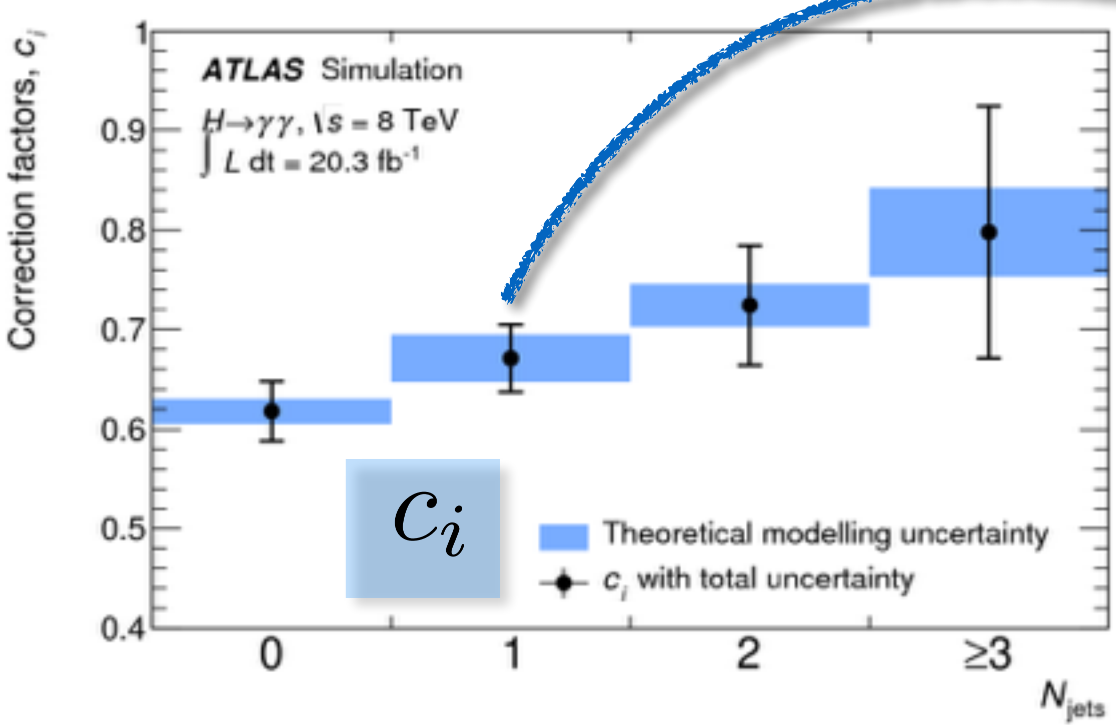
arXiv:1407.4222

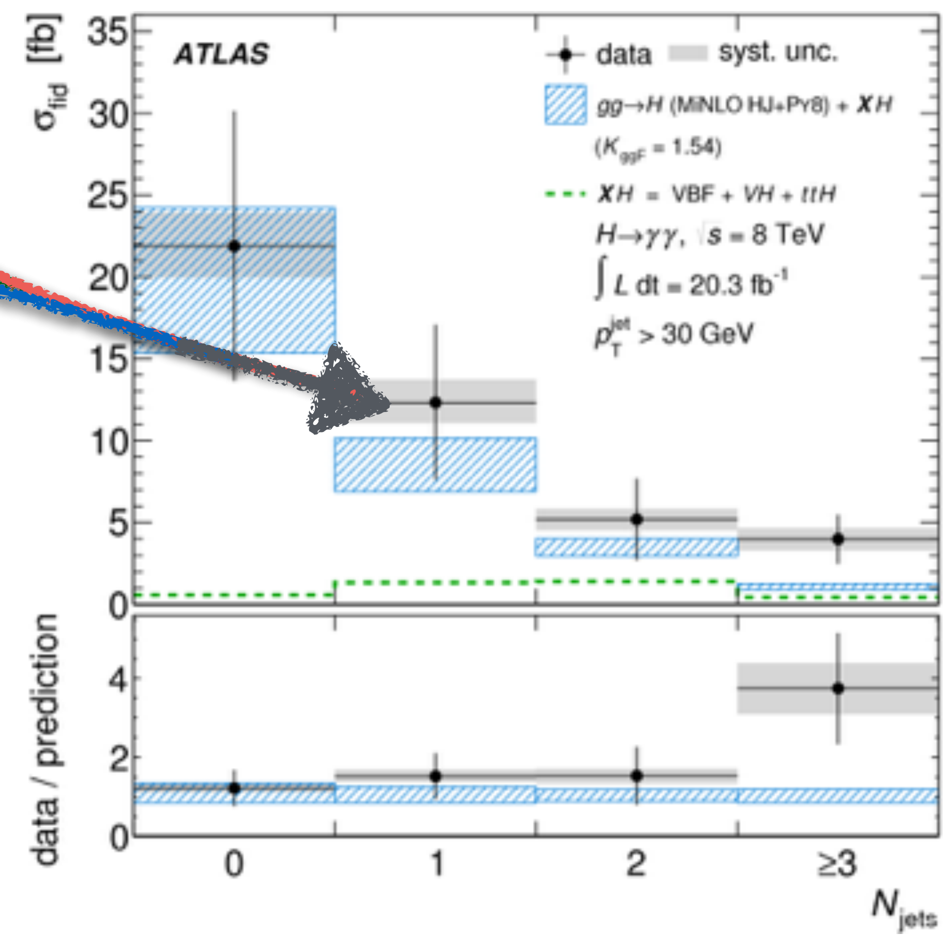
Apply correction for experimental effects and normalize to integrated luminosity

- *Cross section in a fiducial region or bin of a differential distribution*

$$\sigma_{\mathrm{fid},i} = \frac{\nu_i^{\mathrm{sig}}}{c_i \cdot \mathcal{L}_{\mathrm{int}}}$$

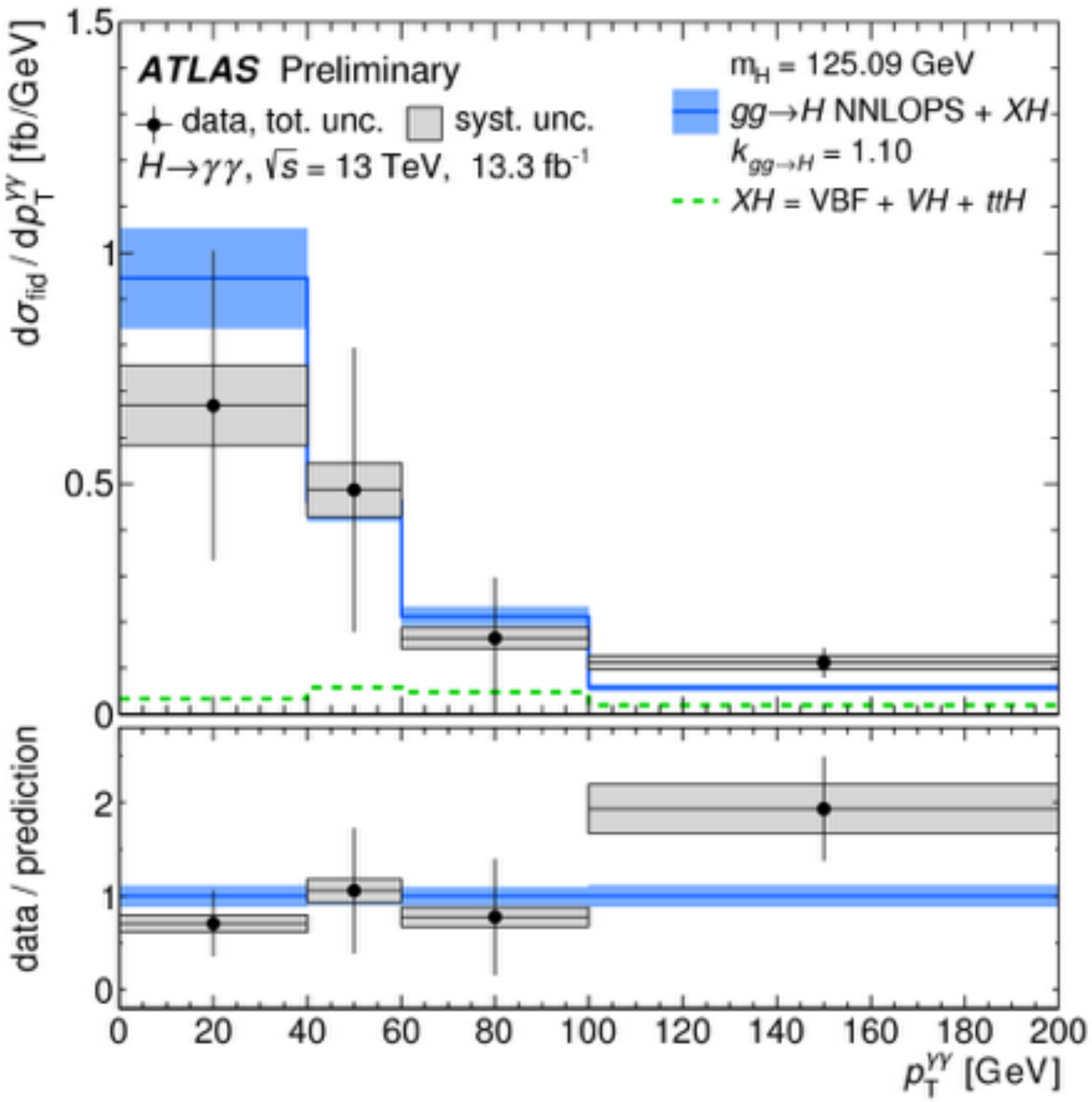


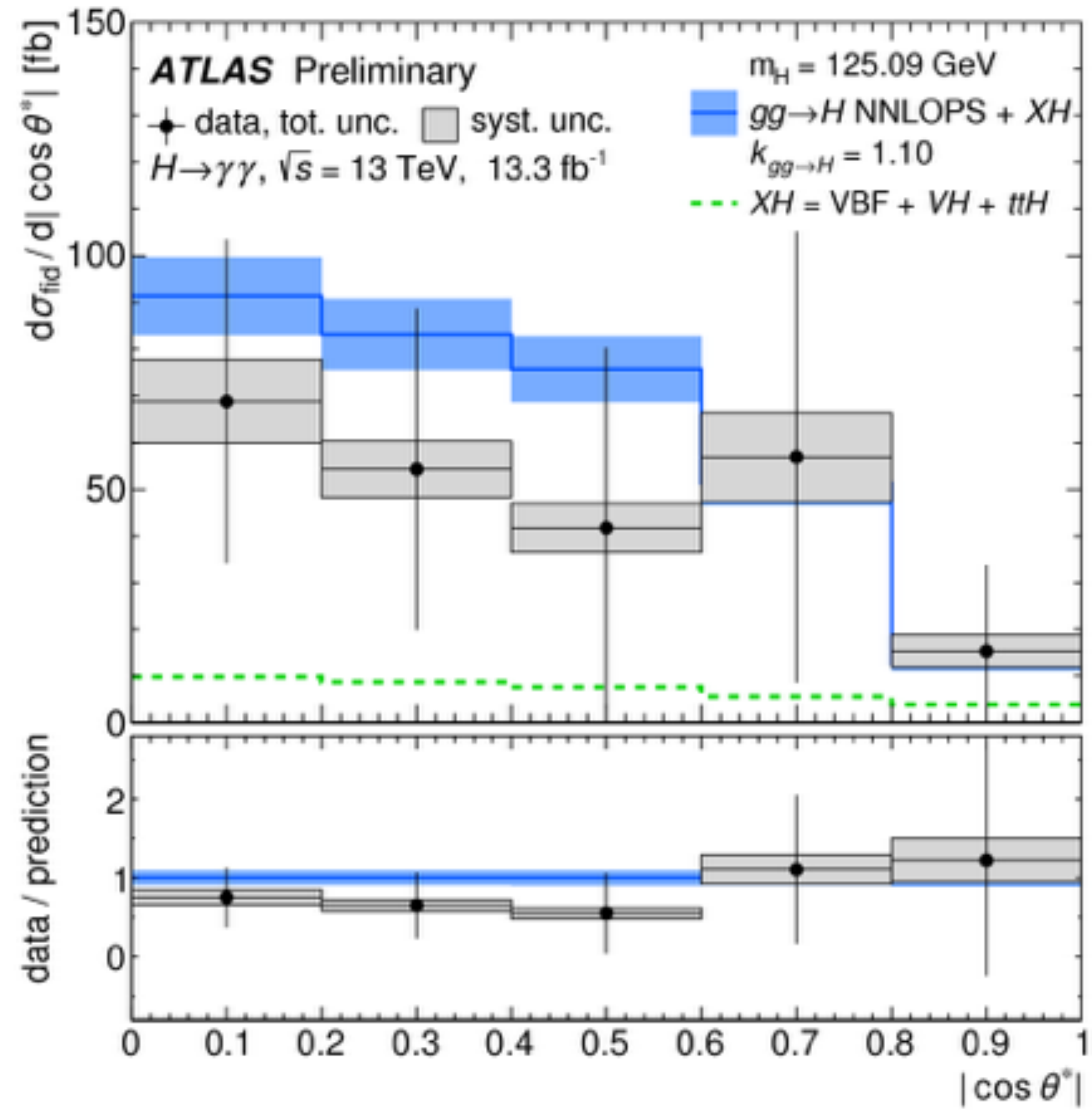




Higgs boson kinematics: $p_T^{\gamma\gamma}$

ATLAS-CONF-2016-067





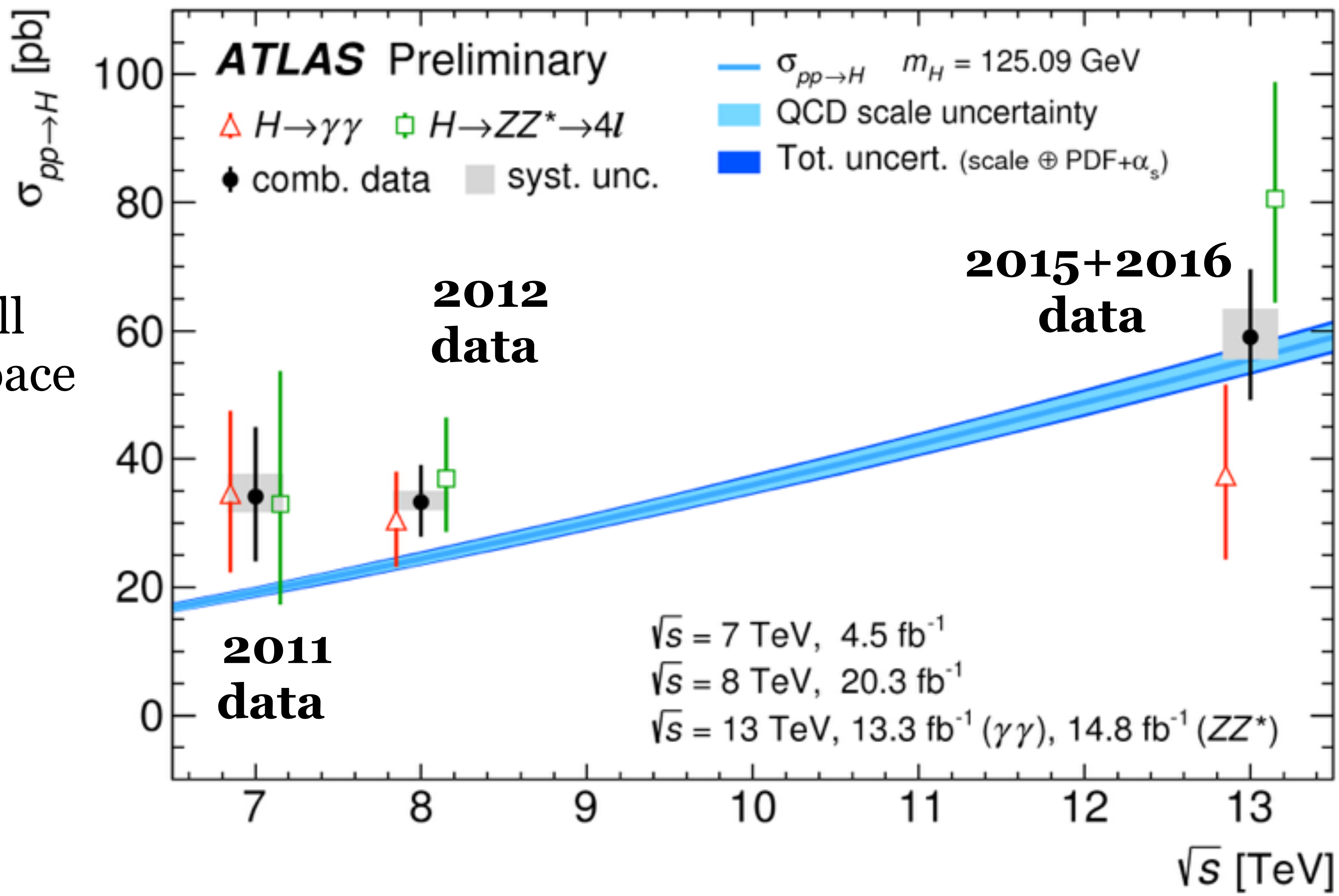
Good agreement between data and theory

- *somewhat harder Higgs p_T spectrum in data (also observed in Run-I), though not statistically significant given the uncertainties*
- *data supports theory hypothesis for a CP-even scalar particle*

Cross section vs. √s

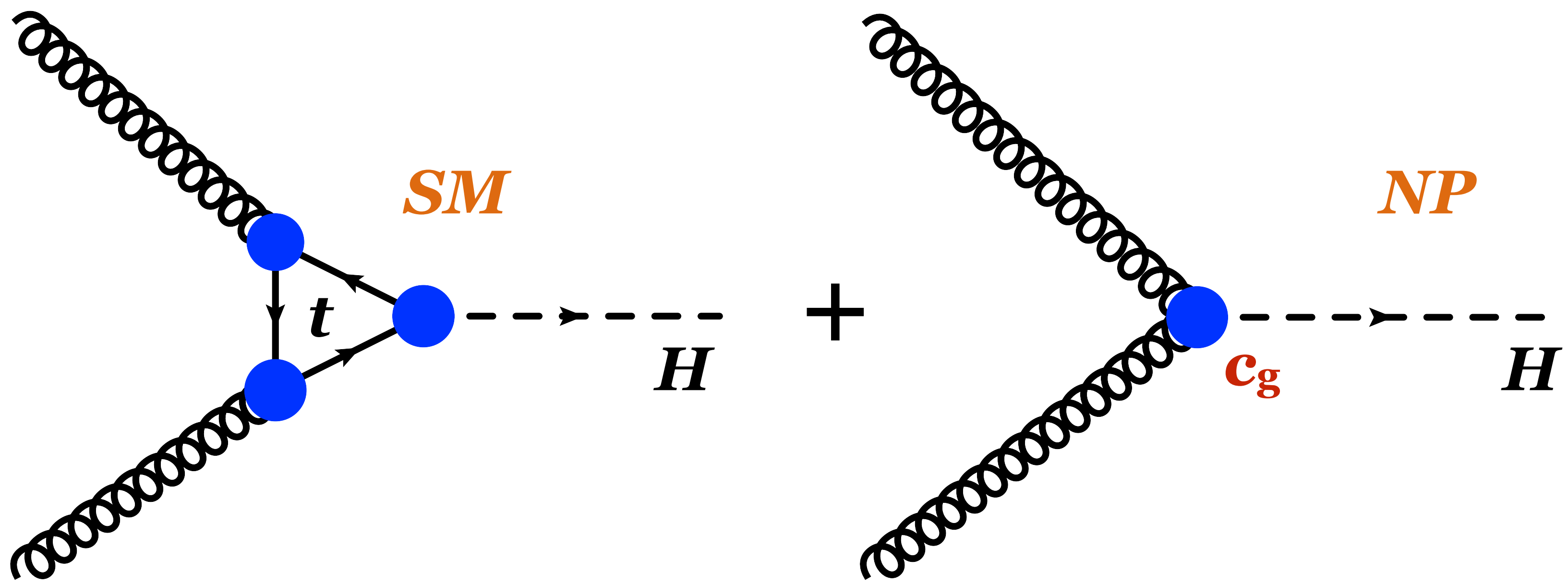
ATLAS-CONF-2016-067

σ in full phase-space



Measurements in agreement with theoretical predictions for a 125 GeV SM Higgs boson

Effective Field Theory

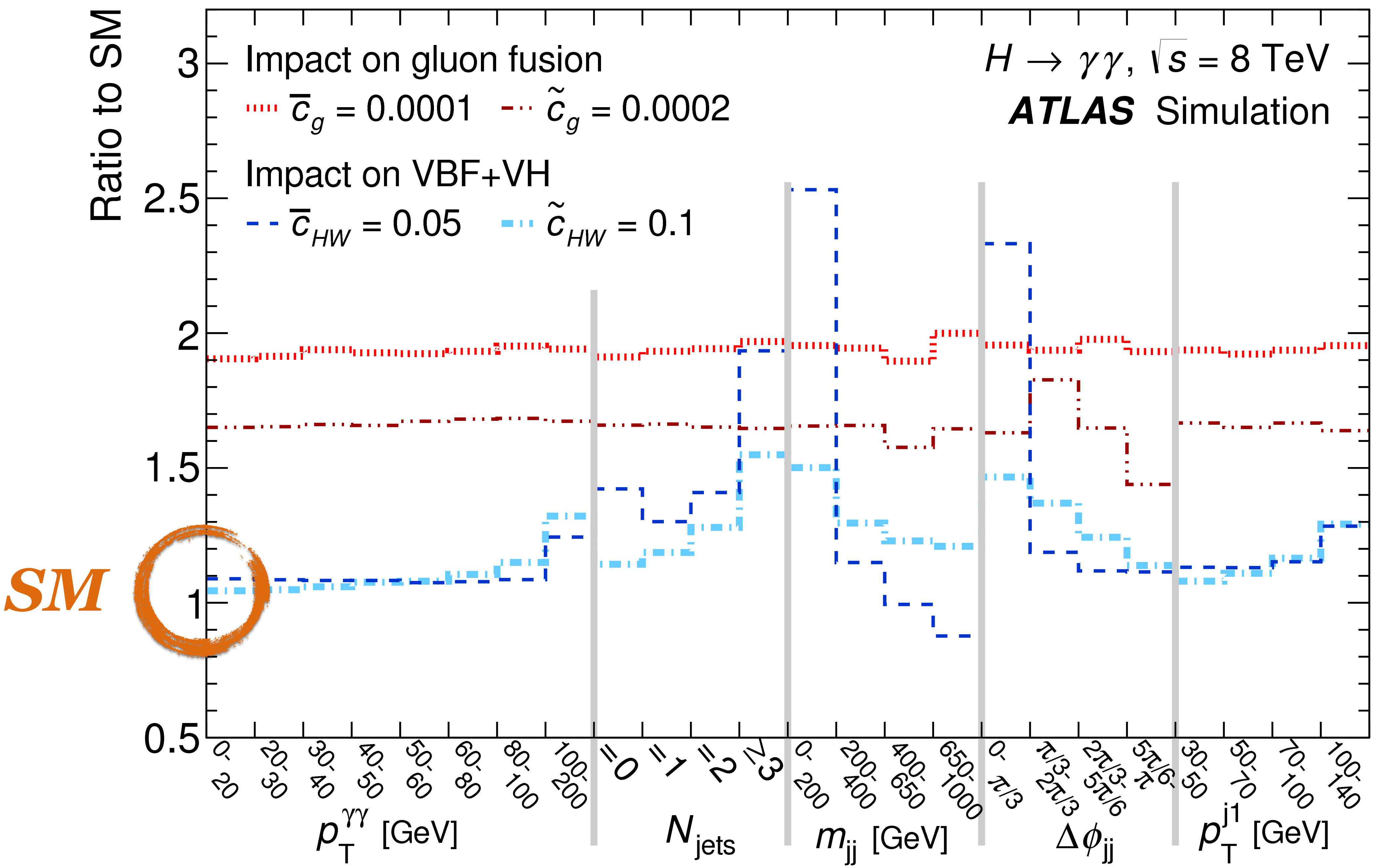


$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i \mathcal{O}_i = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SILH} + \mathcal{L}_{CP} + \mathcal{L}_{F_1} + \mathcal{L}_{F_2} + \mathcal{L}_G$$

- Probe BSM effects in Higgs sector using an effective field theory approach:
  - *Unfolded differential distributions sensitive to the event kinematics*
  - *Look for changes / distortions in the kinematic spectra of Higgs events due to new kinds / structures of the Higgs couplings due to new physics (NP)*

Effective Field Theory

arXiv:1508.02507



- Normalization differences for gluon fusion production mode
- Shape differences for VBF + VH production modes

Summary

- A number of cross section / Higgs property measurements have been made using both the Run-I and Run-II datasets
  - *No significant deviations from the SM are observed*
- Diphoton measurements combined with those from the 4l channel to improve precision
- 13 TeV dataset now ~2.7 times larger than ICHEP dataset
- New measurements in the pipeline
  - Precision tests of the SM and searches for new physics BSM

Thank you for your attention!

Backup

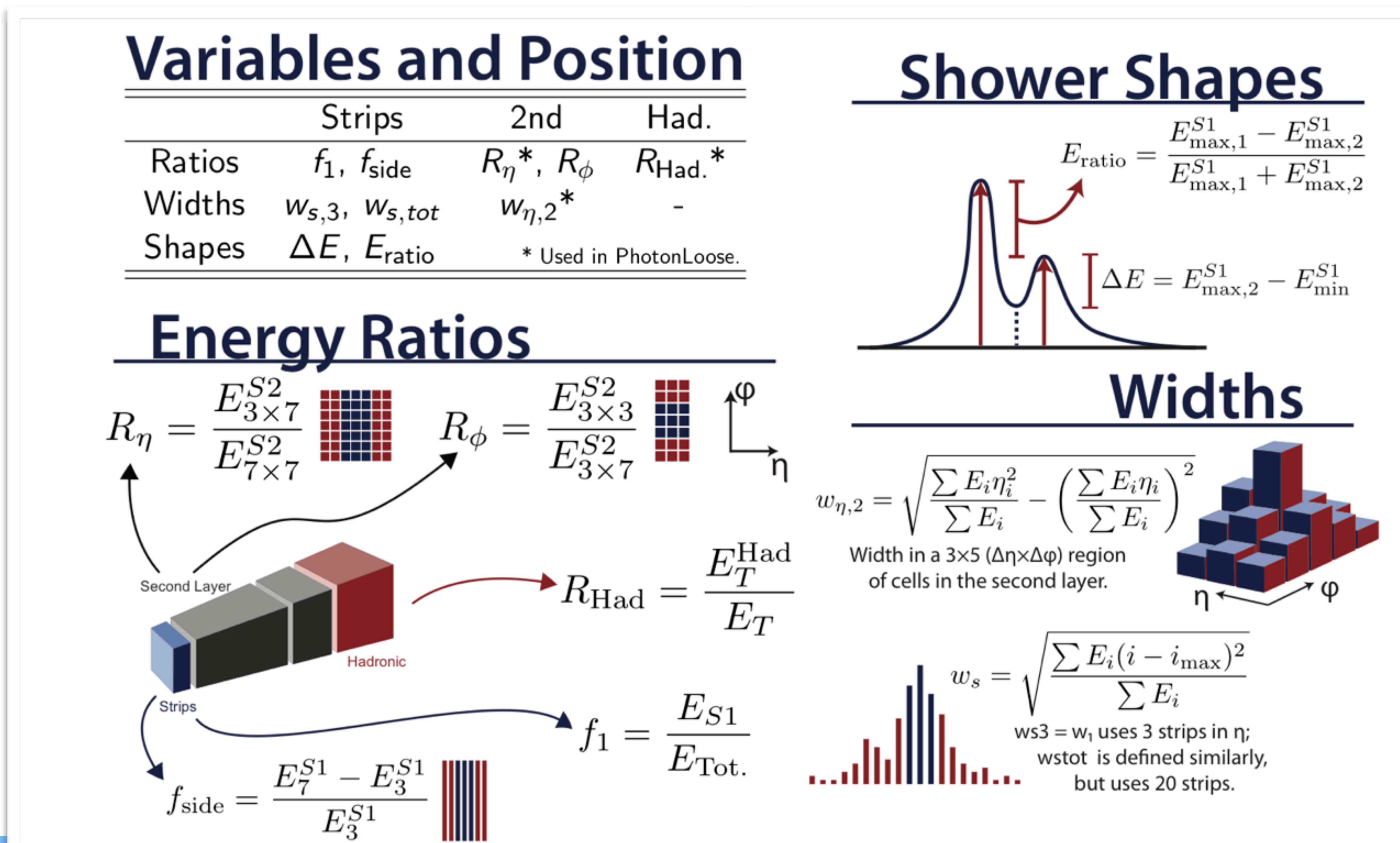
Photon Identification Inputs

- **Photon identification (ID) is achieved using nine (isEM) variables that describe the shape of the energy deposition in the calorimeter**

shapes depend on direction & conversion status

- **Photon ID inputs built from energy deposits in layers 1 & 2 of the EM calorimeter and energy leakage into the hadronic calorimeter**

ATL-COM-PHYS-2013-600



Event and Object selection

reconstruction-level selection:

- GRL and data quality
- trigger: HLT_g35_loose_g25_loose
- Consider 2 highest p_T photons
- $|\eta| < 2.37$ (exclude $1.37 \leq |\eta| < 1.52$)
- $p_T/m_{\gamma\gamma} > 0.35$ (0.25)
- Tight photon identification
- Isolated: eg. 13 TeV

  track: pTcone20<$0.05 \times p_T$

  calo: TopoETcone20<$0.065 \times p_T$
- $m_{\gamma\gamma} \in [105, 160)$ GeV

particle-level fiducial:

- Consider 2 highest pT photons
- $|\eta| < 2.37$

  (exclude $1.37 \leq |\eta| < 1.52$)
- $p_T/m_{\gamma\gamma} > 0.35$ (0.25)
- E_T charged ($\Delta R<0.2$)<$0.05 \times p_T$
- $m_{\gamma\gamma} \in [105, 160)$ GeV

Jets (anti-k_T, R=0.4):

- $p_T > 25$ GeV for $|\eta| < 2.4$
- $p_T > 30$ GeV for $2.4 < |\eta| < 4.4$
- Jet vertex tagger used to reject pile-up
- b-jet tagger to iden2fy heavy-flavour

Muons:

- $p_T > 10$ GeV and $|\eta| < 2.7$

Electrons:

- $p_T > 10$ GeV and $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$)

Missing transverse momentum:

- reconstructed from photons, jets, leptons and tracks

Fiducial Cross Sections

	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	- - -	$p_T > 30\,\mathrm{GeV}$, $\|y\| < 4.4$ $m_{jj} > 400\,\mathrm{GeV}$, $\|\Delta y_{jj}\| > 2.8$ $\|\Delta\phi_{\gamma\gamma,jj}\| > 2.6$	- - -
Leptons	-	-	$p_T > 15\,\mathrm{GeV}$ $\|\eta\| < 2.47$

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8\,^{+3.4}_{-4.4}$	[N^{3}LO + 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]

$m_{\gamma\gamma}$ background modelling

The total background contribution to the Higgs signal is obtained from data via a S+B fit to the $m_{\gamma\gamma}$ distribution in each fiducial region or bin of a differential distribution

- *Background template constructed from high stats $\gamma\gamma$ MC, utilizing data-driven templates for γ-jet and jet-jet contributions*
- *combined after normalizing to data-driven scale factors*
- *analytic model for the background*
  - *parameterization chosen that minimizes bias in the signal extraction*

Data-driven method to estimate background composition in the signal region

- *photon isolation and identification selection criteria inverted to define regions enriched with signal or background*
- *composition of bkg process entering the signal region estimated by extrapolating the process rates in the CR's into the signal region*

2x2D Sideband Method

Red: leading p_T photon

Blue: sub-leading p_T photon

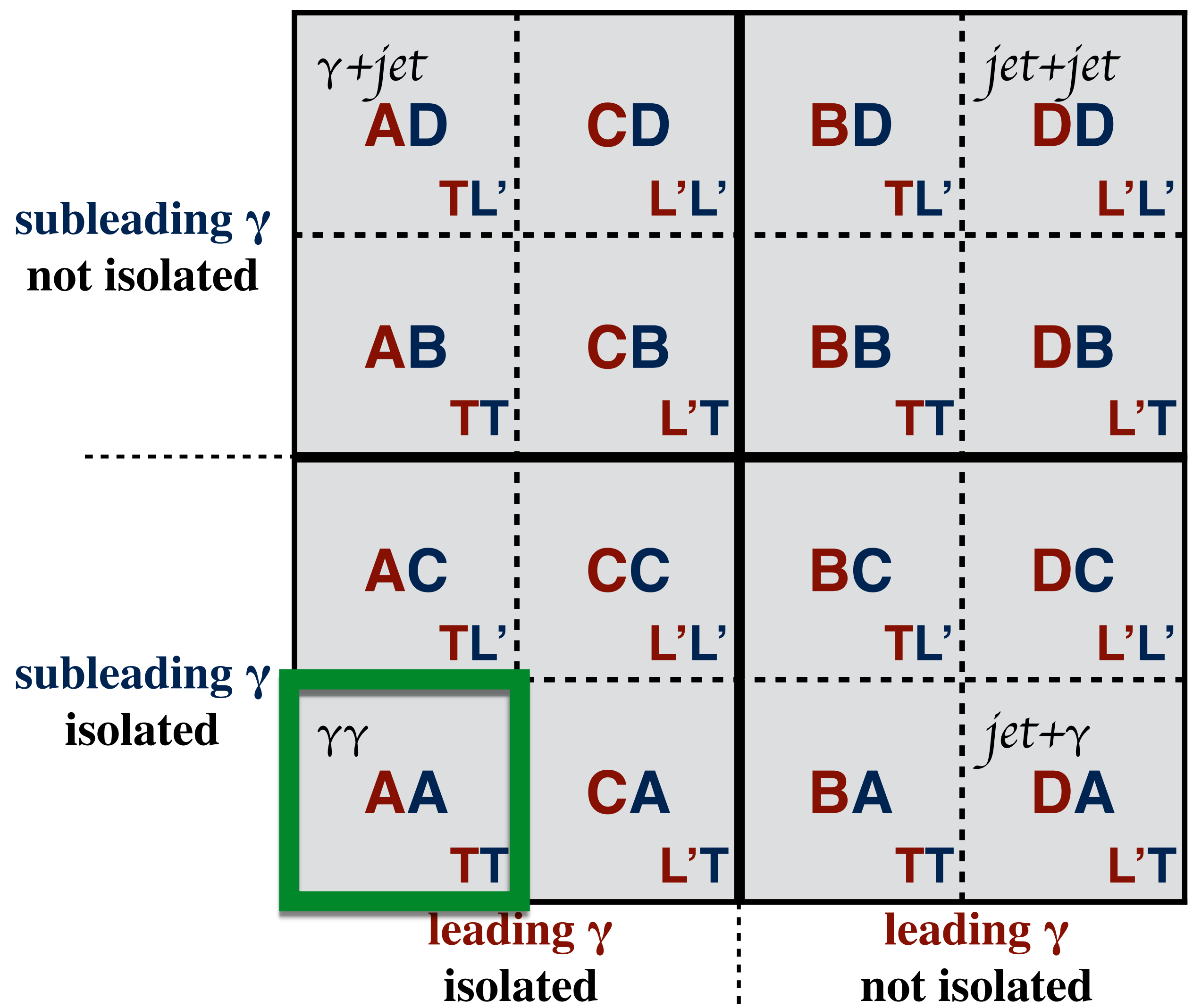
A: Tight and Isolated

B: Tight and not Isolated

C: not Tight and Isolated

D: not Tight and not Isolated

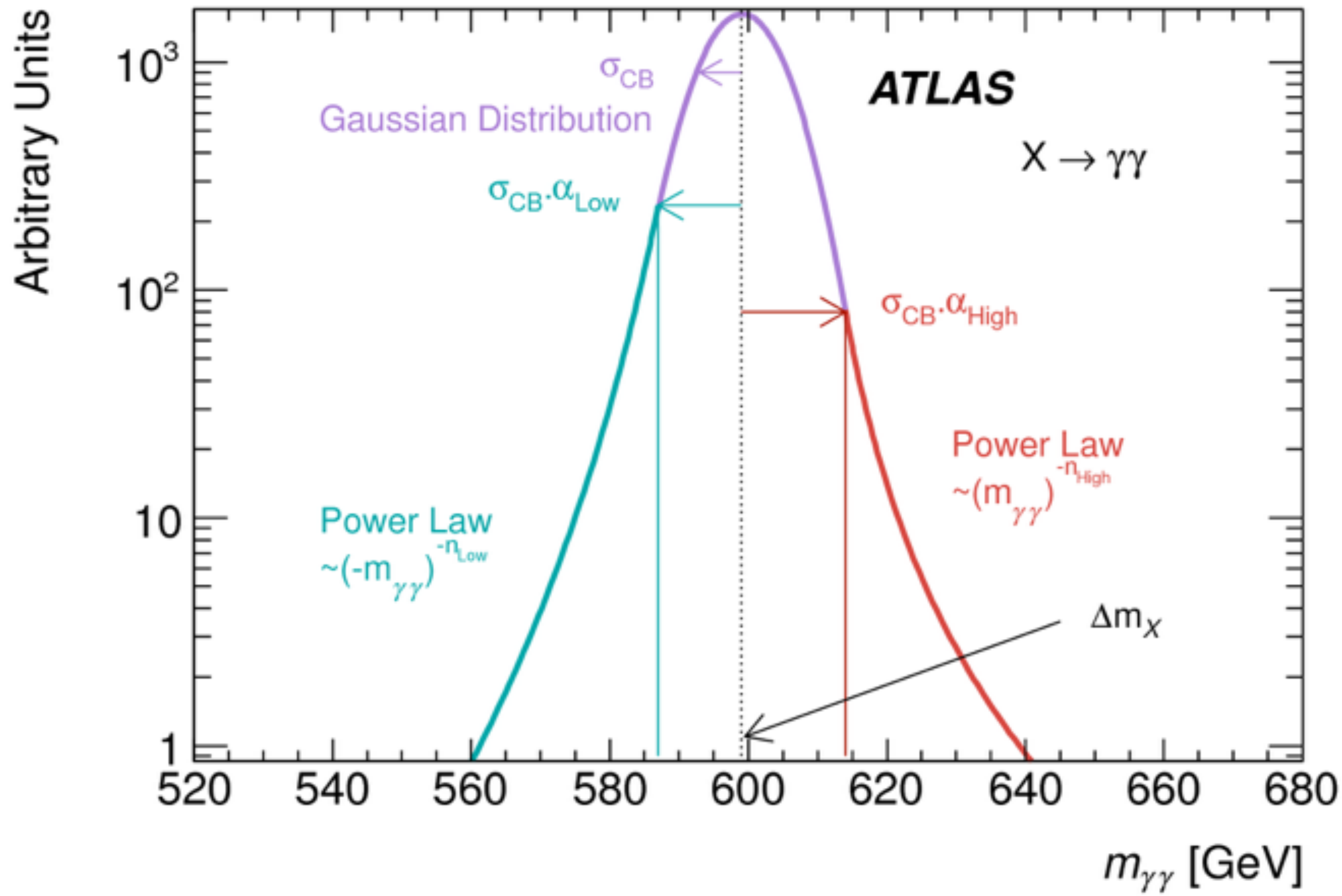
region	enriched with
DD	jet-jet
AD	γ-jet
DA	jet-γ
AA	γγ



- **1 signal region** and 15 background control regions
- **Photon efficiencies obtained from MC**
- solve 16 equations to extract the yields of each process entering the signal region, as well as the jet efficiencies

Signal model

arXiv:1407.6583



- Double-sided Crystal Ball function

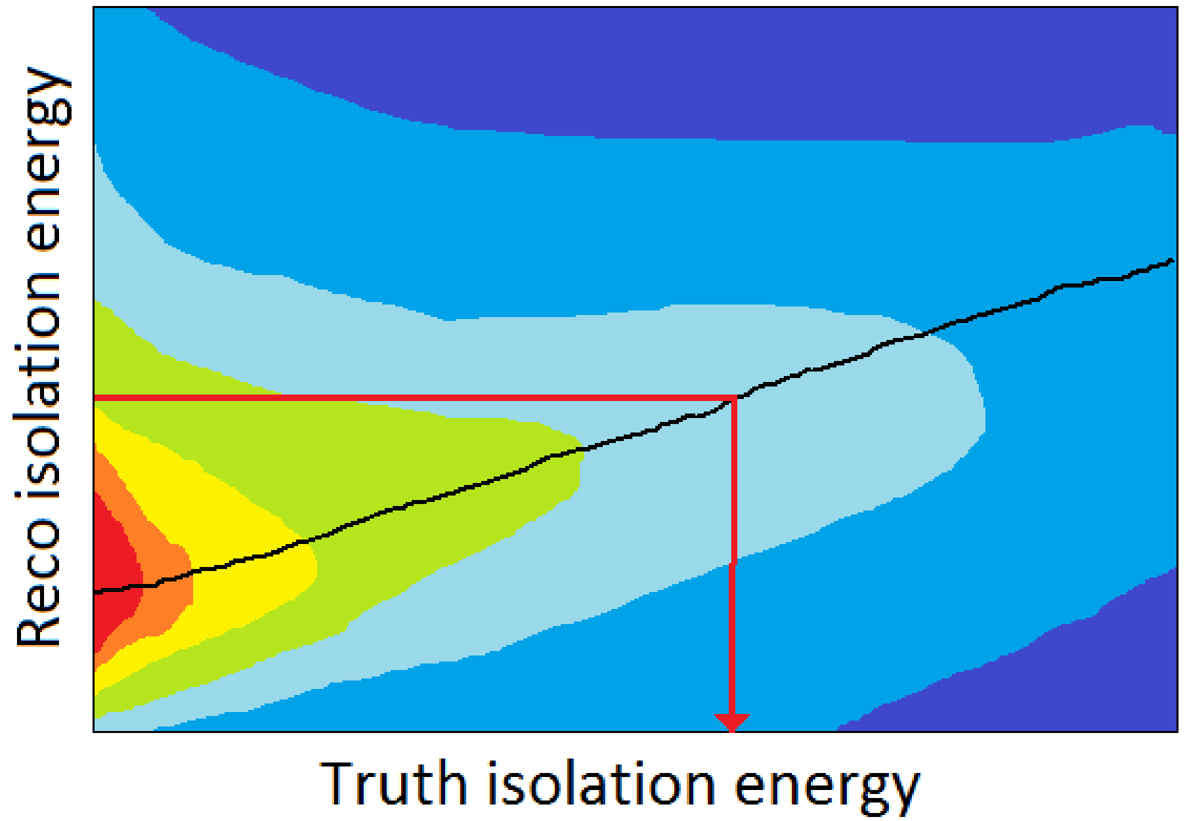
Gaussian core with power law tails

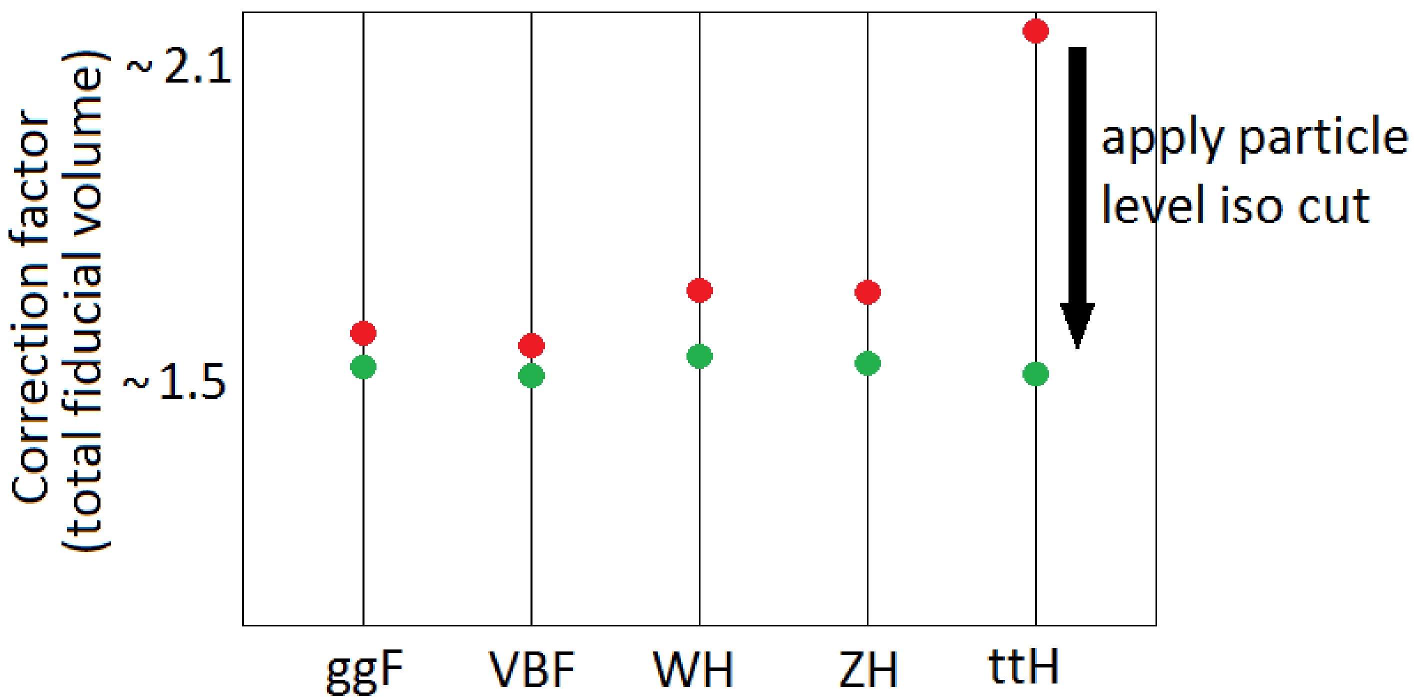
- Signal shape parameters determined from fitting simulated samples

Particle-level isolation

- Isolation is applied at detector-level
- map the detector-level isolation value to a corresponding particle-level isolation energy
- apply particle-level isolation to help mitigate the dependence of the correction factor on the production mode

E_T of the 4-vector sum of charged particles within a cone of R < 0.2



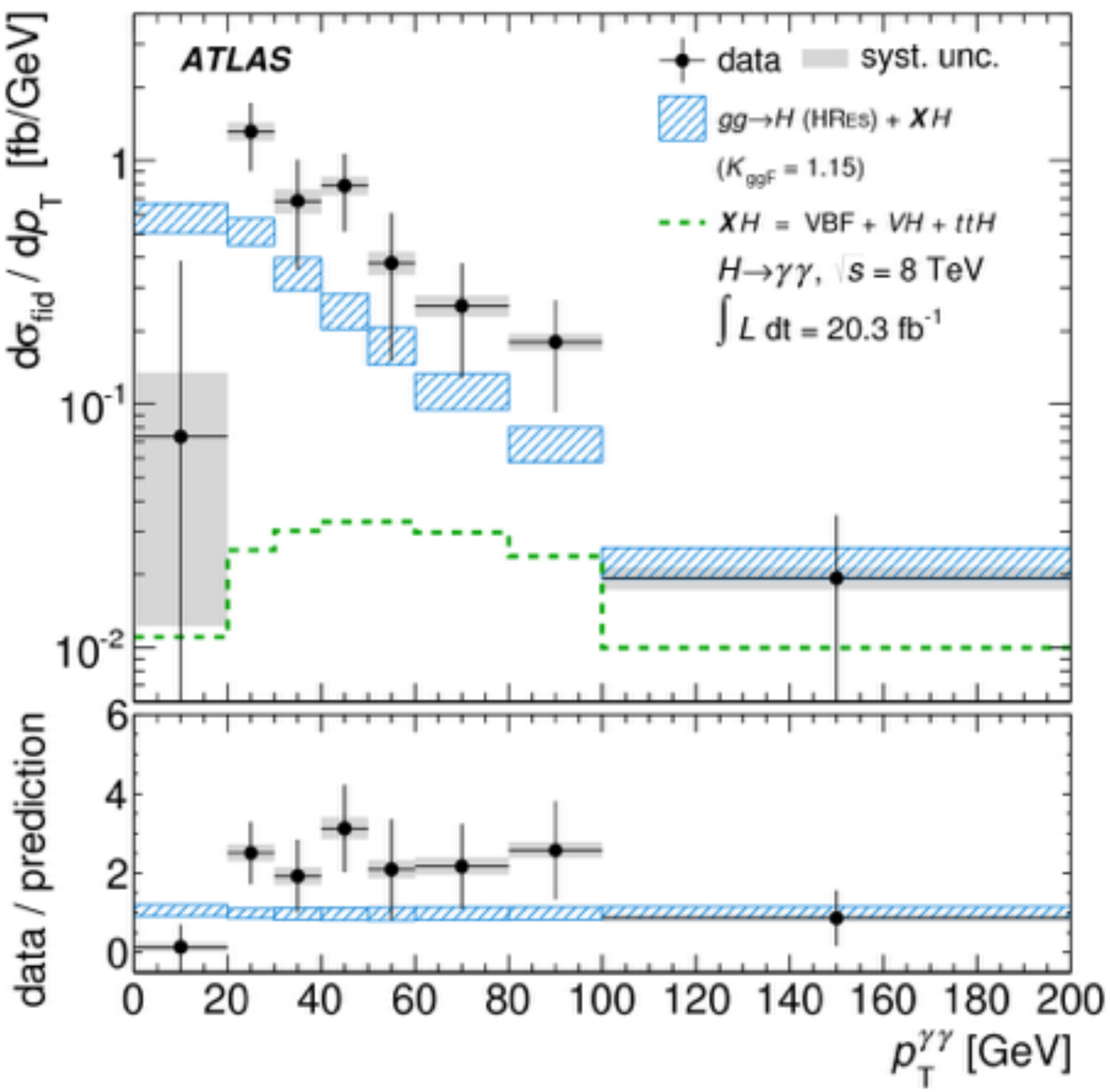


Handbook of LHC Cross Sections: YR4

Higgs boson kinematics: $p_T^{\gamma\gamma}$

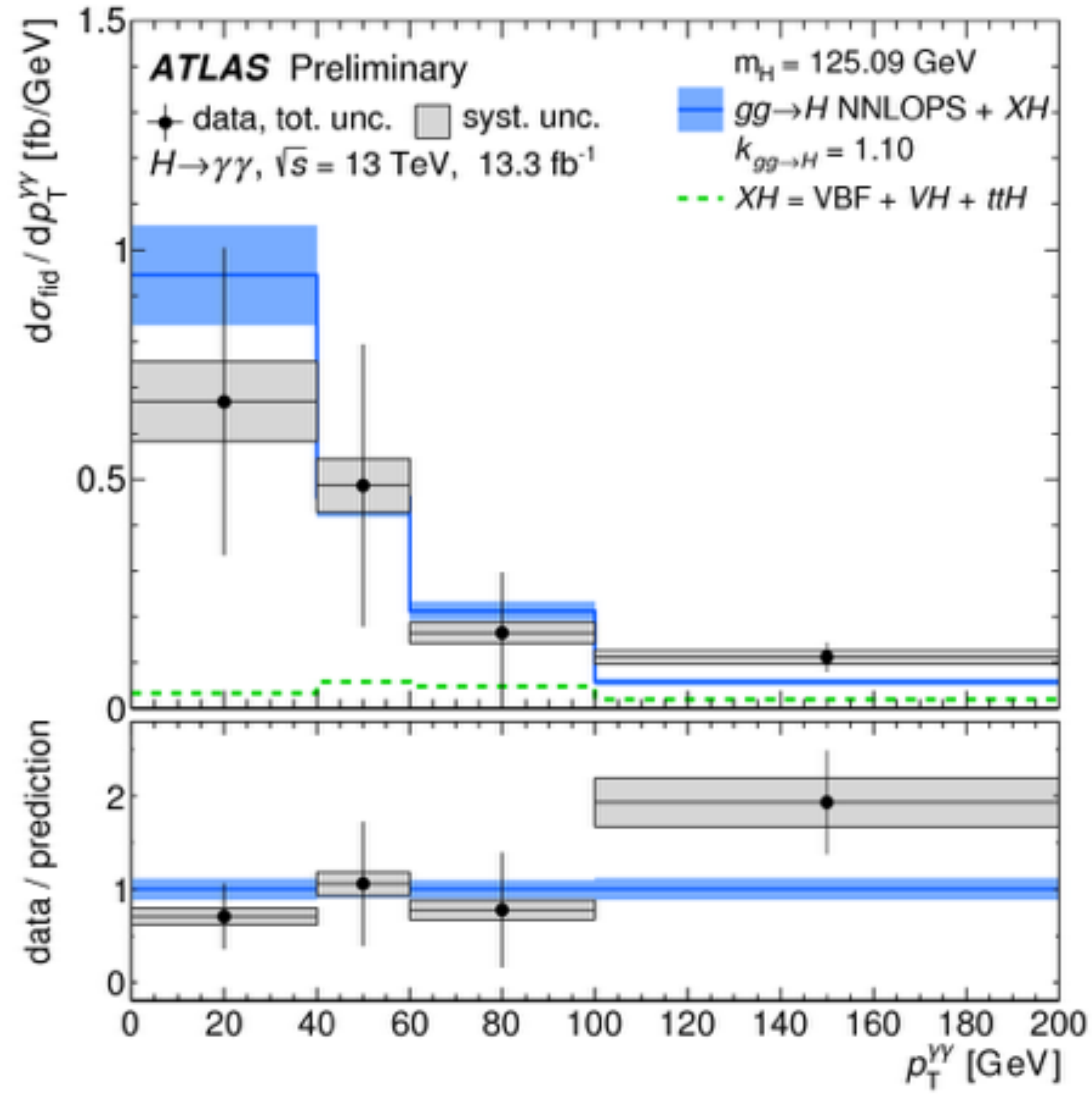
8 TeV

arXiv:1407.4222



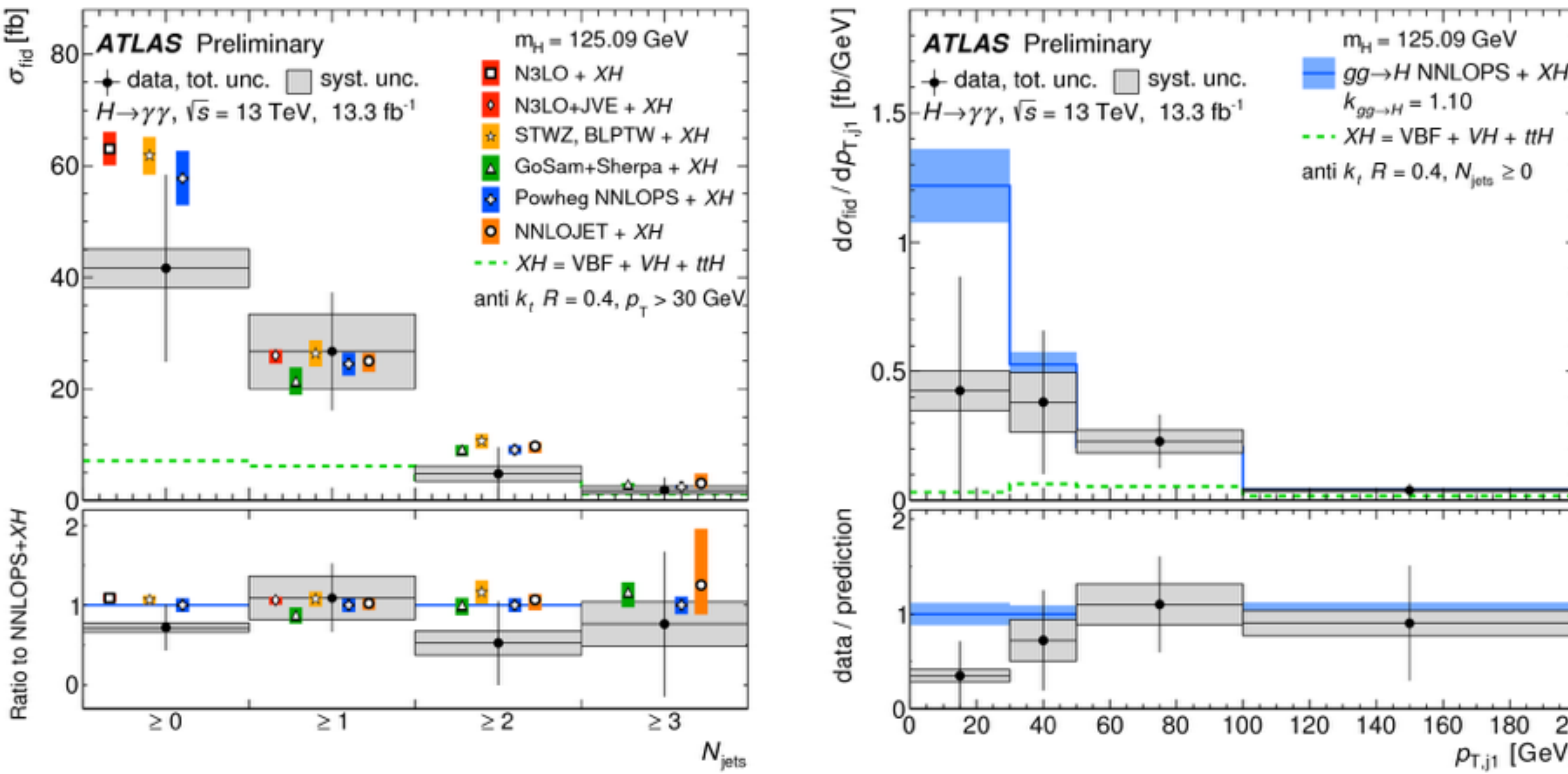
13 TeV

ATLAS-CONF-2016-067



Hadronic (Jet) Activity

ATLAS-CONF-2016-067



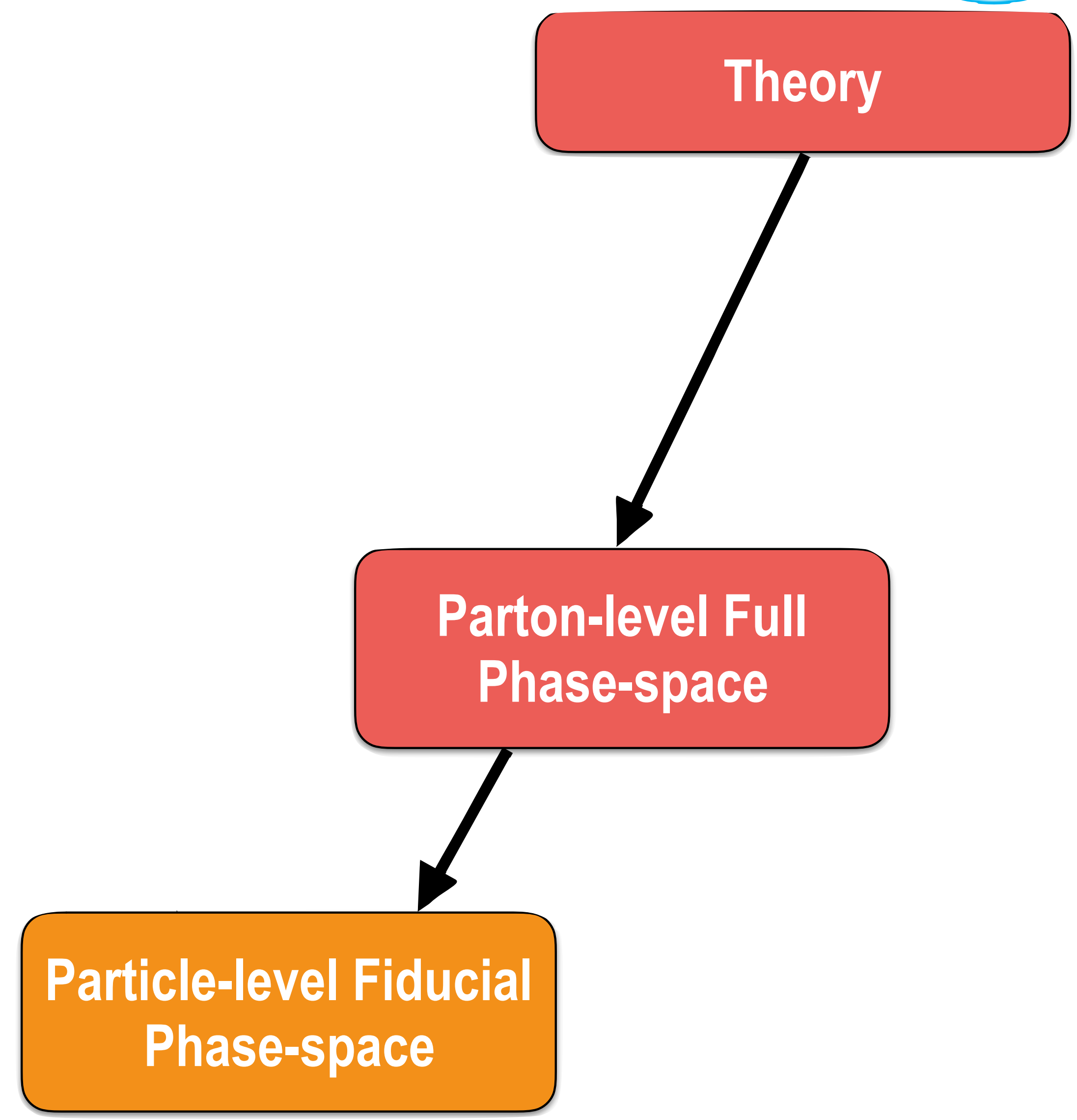
Good agreement between data and theory for variety of predictions

NP correction and acceptance factors

- **fiducial acceptance factors (α_{fid})**

  selection efficiency of the particle level fiducial volume (kinematic cuts and particle-level isolation)

  parton-level inclusive theoretical predictions ➜ particle-level fiducial predictions



- **α_{fid}: ratio between the fiducial and inclusive cross sections:**

$$\alpha_{\text{fid}} = \frac{\sigma^{\text{fid}}(pp \to H \to \gamma\gamma, \text{particle level})}{\sigma^{\text{inc}}(pp \to H \to \gamma\gamma, \text{parton or particle level})}$$

The Effective Lagrangian

$$\mathcal{L}_{\mathrm{SILH}} = \frac{c_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{c_T}{2v^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right] - \frac{c_6\lambda}{v^2}\left[\Phi^\dagger\Phi\right]^3$$

$$- \left[\frac{c_u}{v^2}y_u\Phi^\dagger\Phi\,\Phi^\dagger\cdot Q_L u_R + \frac{c_d}{v^2}y_d\Phi^\dagger\Phi\,\Phi Q_L d_R + \frac{c_l}{v^2}y_\ell\,\Phi^\dagger\Phi\,\Phi L_L e_R + \mathrm{h.c.}\right]$$

$$+ \frac{ig\,c_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\,c_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu}$$

$$+ \frac{2ig\,c_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\,c_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu}$$

$$+ \frac{g'^2\,c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}$$

$$\mathcal{L}_{CP} = \frac{ig\,\tilde{c}_{HW}}{m_W^2}D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\widetilde{W}^k_{\mu\nu} + \frac{ig'\,\tilde{c}_{HB}}{m_W^2}D^\mu\Phi^\dagger D^\nu\Phi\widetilde{B}_{\mu\nu} + \frac{g'^2\,\tilde{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu}$$

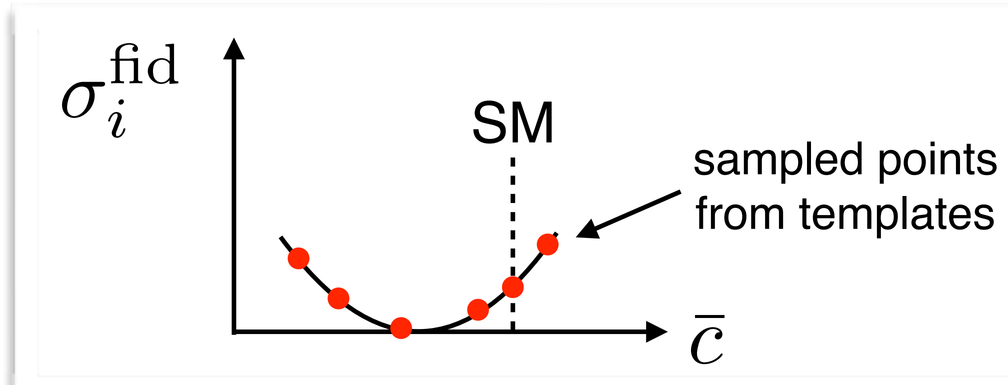
$$+ \frac{g_s^2\,\tilde{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}\widetilde{G}_a^{\mu\nu} + \frac{g^3\,\tilde{c}_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho\widetilde{W}^{\rho\mu k} + \frac{g_s^3\,\tilde{c}_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho\widetilde{G}^{\rho\mu c}$$

Additional terms that induce $\gamma\gamma H$, ggH, and VVH couplings

Limit-setting procedure

Differential cross section as a function of variable *X* for a specific choice of Wilson coefficient, c_i is given by:

$$\frac{d\sigma}{dX} = \sum_j \left(\frac{d\sigma_j}{dX}\right)^{\mathrm{ref}} \cdot \left(\frac{d\sigma_j}{dX}\right)^{\mathrm{MG5}}_{c_i} / \left(\frac{d\sigma_j}{dX}\right)^{\mathrm{MG5}}_{c_i=0}$$



Set 1-CL limits on Wilson coefficients by minimizing the χ2 between data and MC (perform scan across c_i):

$$\left[\vec{x}_{\mathrm{data}} - \vec{x}_{\mathrm{hypo}}(c_i)\right] C^{-1} \left[\vec{x}_{\mathrm{data}} - \vec{x}_{\mathrm{hypo}}(c_i)\right]$$

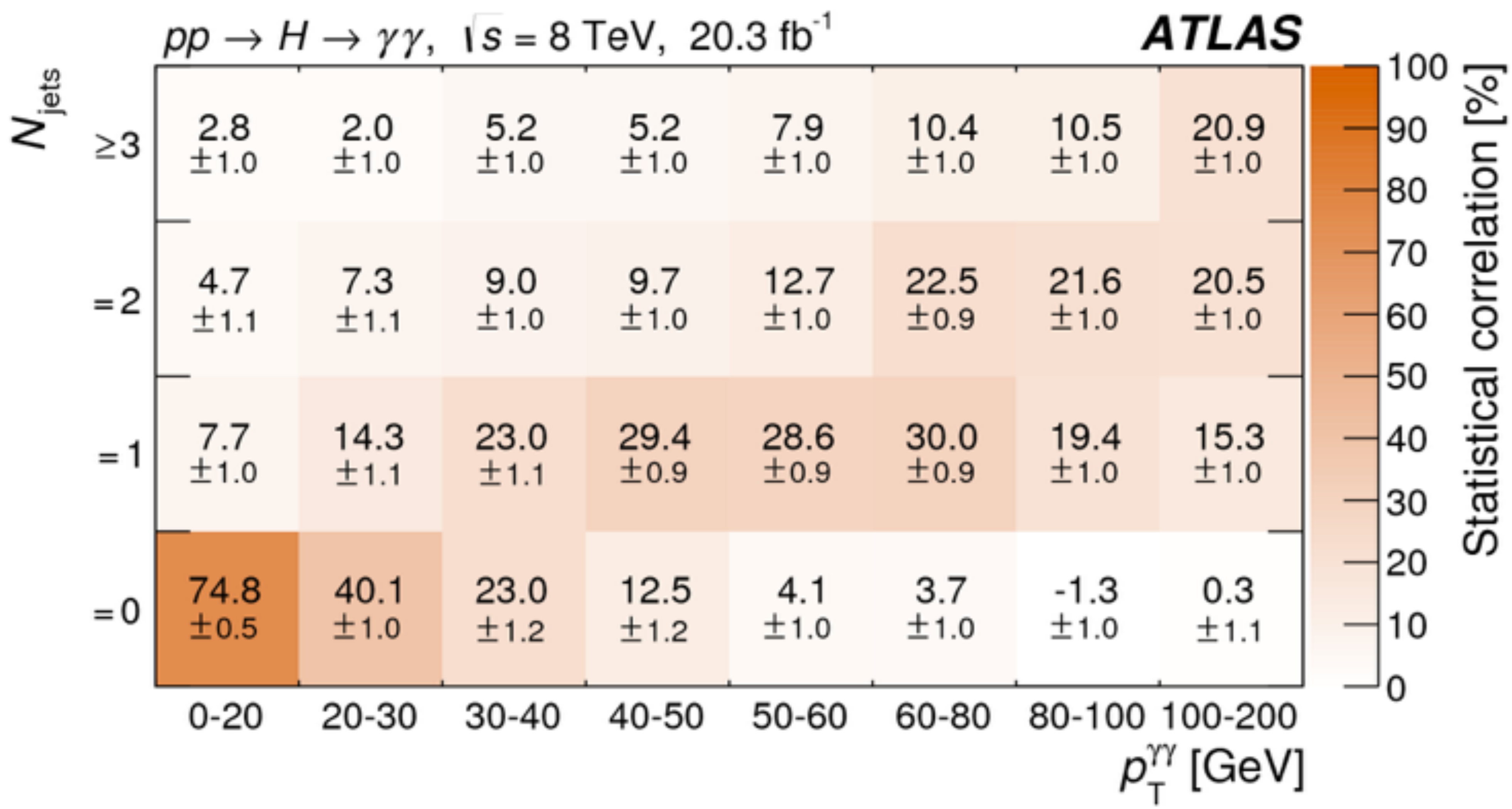
Vector of predictions from ProfDriver

Vector of measured cross sections

Full covariance matrix: $C_{\mathrm{stat.}} + C_{\mathrm{syst.}} + C_{\mathrm{theo.}}$

Statistical correlations

arXiv:1508.02507

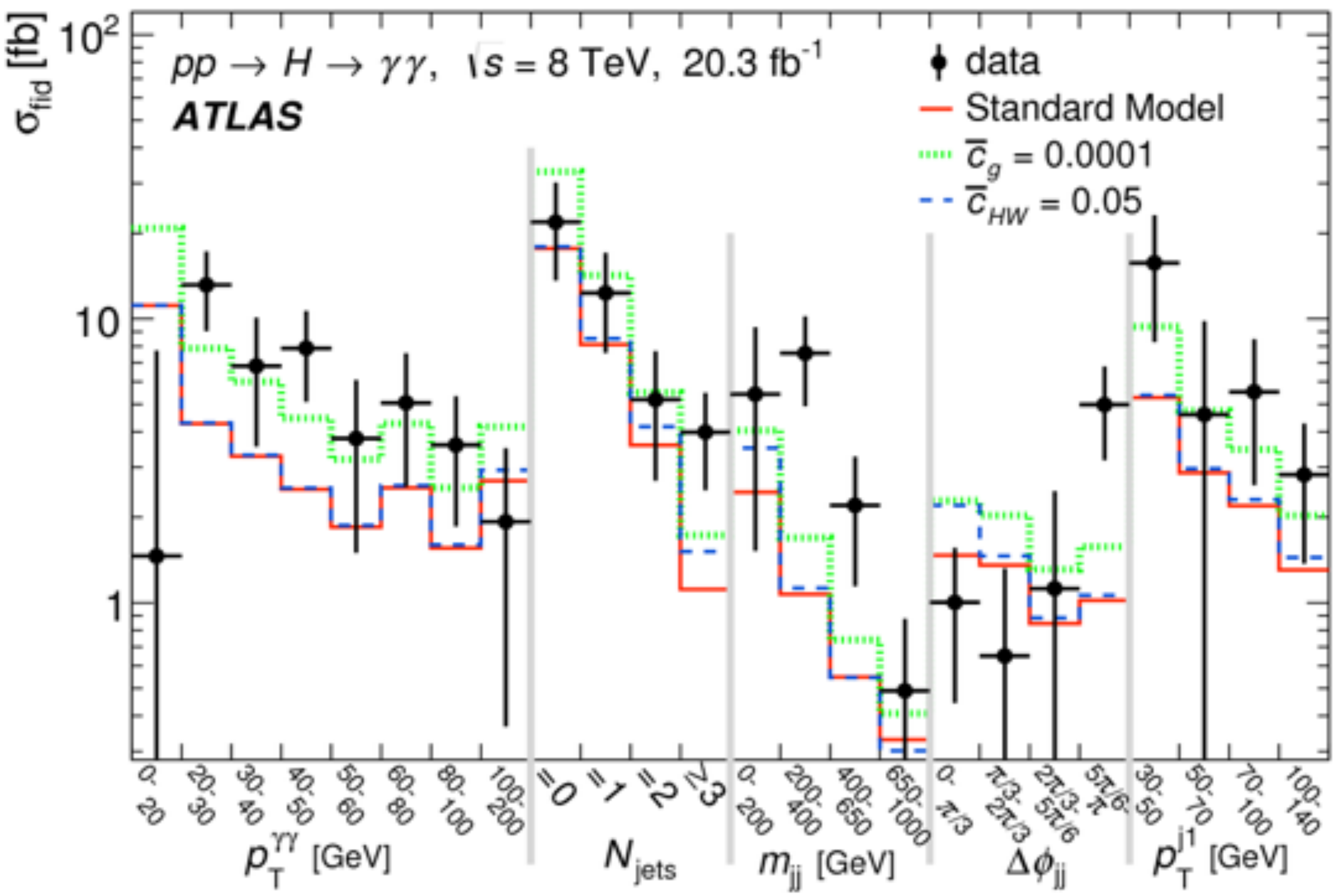


Same data used for the 5 input spectra

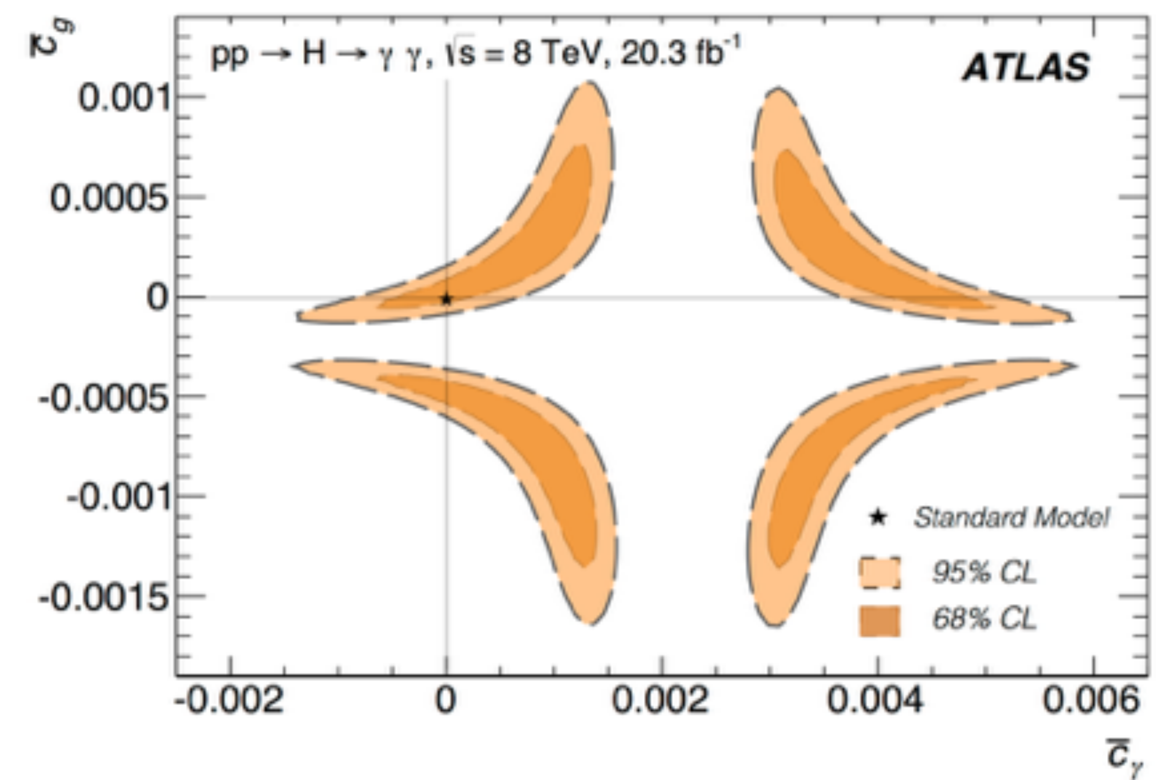
Estimate statistical correlations using bootstrapping procedure applied to the data:

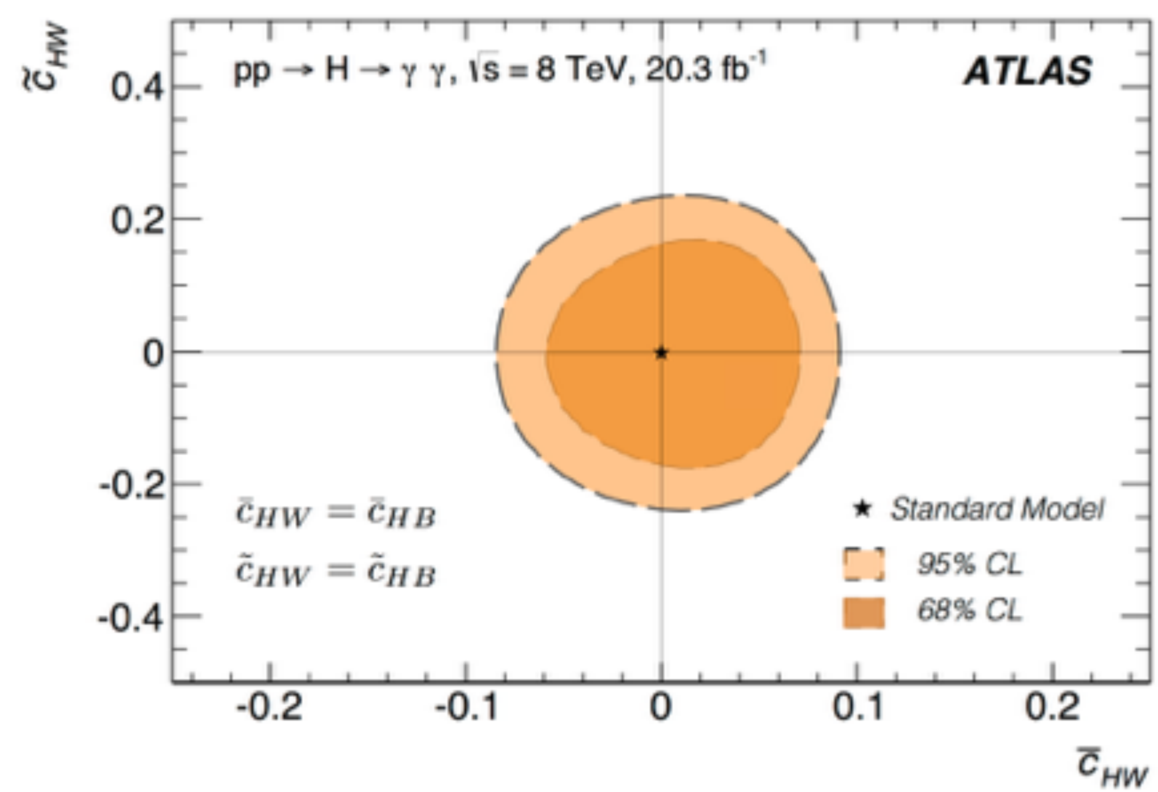
Fluctuate ATLAS data events according to a Poisson distribution and re-extract the Higgs signal

HEFT Using 8 TeV data



arXiv:1508.02507





Use five of the published Run-I differential spectra: p_T^H, N_{jets}, m_{jj}, $\Delta\phi_{jj}$, p_T^{j1}

- *Global fit to all distributions simultaneous*

Use Consider 6 coefficients: c_γ , c_g , c_{HW}+ CP-odd

- *Strong constraints on total c_γ, c_g*
- *Weak constraints on c_{HW}, CP-odd/even*