Latest ATLAS Results in $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ Differential Cross Sections and Couplings

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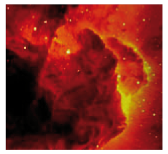
LHC Physics Discussion: Higgs

May 7, 2018

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676



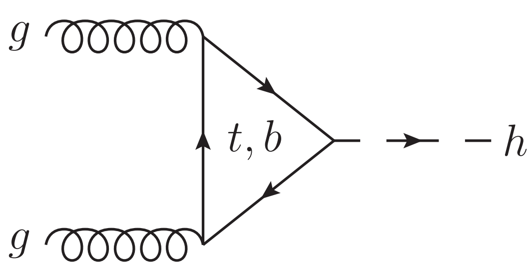
Latest ATLAS 13 TeV Results

- ***Measurements of Higgs boson properties in the $\gamma\gamma$ decay channel (36 fb^{-1})***
  - arXiv:1802.04146 (Feb 12, 2018 – Submitted to PRD)
  - Adds to previous conference note (ATLAS-CONF-2017-045 – July 2017)

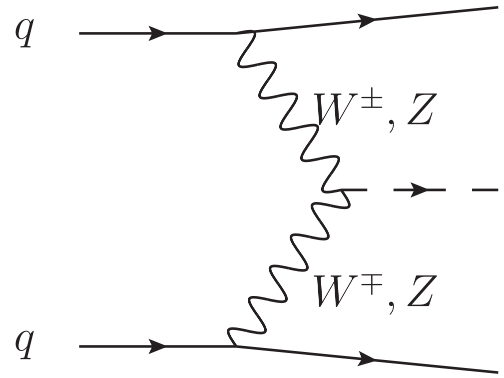
- ***Combination of Fiducial and Differential Cross Sections ($\gamma\gamma$ and 4ℓ) (36.1 fb–1)***
  - Conference note: http://cdsweb.cern.ch/record/2308390 (Mar 12, 2018)
  - Paper in final stages of preparation
  - Last differential combination of $\gamma\gamma$ and ZZ results was in December 2015 (3.2 fb^{-1})

- **Brief outline:**
  - Motivate differential cross sections and couplings (STXS)
  - Introduce $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$ analyses
  - Describe differential cross section measurements and combination
  - Focus on $H\rightarrow\gamma\gamma$ Couplings Results

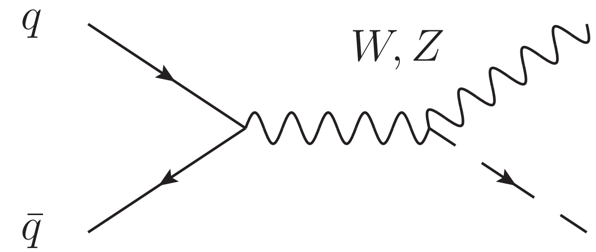
Higgs Physics, H→γγ and H→ZZ



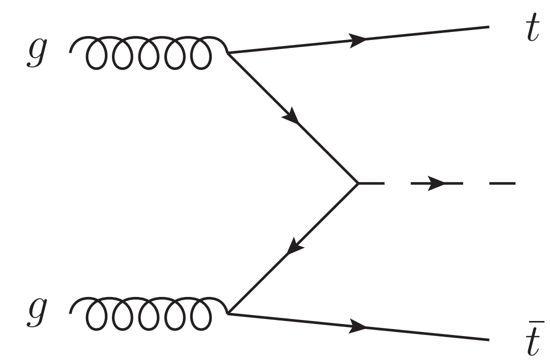
gluon fusion (87%)



vector boson fusion (7%)



"higgstrahlung" (4%)



ttH (2%)

- H→ZZ→4ℓ channel
  - "Golden" – low backgrounds with 4 leptons (e,μ)
  - Very low branching ratio:
    - ~57 final events in 35 fb^{-1}
  - Fully reconstructed final state, lots of angles
- H→γγ channel
  - Higher branching ratio → 1740 final events
  - … but much larger backgrounds (SM γγ, γj, jj)
  - Fully reconstructed final state

Higgs Decay Modes / BRs

Decay Mode	Branching ratio (%)
$H \to b\bar{b}$	57.1
$H \to WW$	22.1
$H \to gg, cc, ss, tt$	11.4
$H \to \tau\tau$	6.25
$H \to ZZ$	2.74 ×BR(ZZ→4ℓ)=0.0125%
$H \to \gamma\gamma$	0.228
$H \to Z\gamma$	0.157
$H \to \mu\mu$	0.021

Precision Measurements with the Higgs

- Total Cross Section
  - Extrapolate outside of detector's reach
  - ***A***cceptance factor can be quite model dependent

$$\sigma_{\text{total}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}_{\text{int}} \cdot C \cdot A \cdot BR}$$

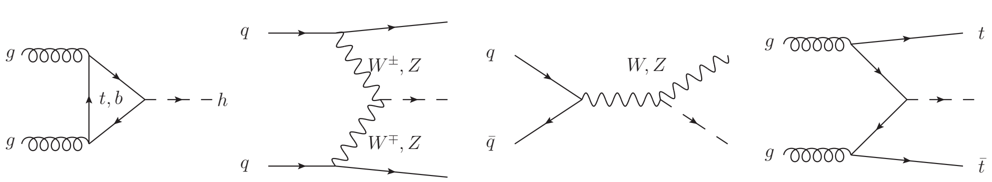
- Fiducial Cross Sections - a measurement that lasts
  - A cross section in a phase space matching analysis cuts
  - ***C***orrection factor for detector effects typically small
  - Rivet routine to allow theorists to run their favorite generator and apply fiducial selection

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}_{\text{int}} \cdot C}$$

- Fiducial Differential Cross Sections
  - Gets the shape of interesting variables
  - Deal with bin migrations by unfolding data distributions
    - E.g. Correction factors for each bin

e.g. $$\sigma_i^{\text{fid}} = \frac{N_{\text{data},i} - N_{\text{bkg},i}}{\mathcal{L}_{\text{int}} \cdot C_i}$$

- Measurements of Production modes (couplings)
  - Use lepton multiplicity, jet topologies, etc. to probe production modes
  - Details covered later



Differential Cross Sections

- Motivating the Higgs variables
- Introduction to the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4\ell$ analyses
- Differential Cross section results
- Combination

Differential XS: Which Variables and Why?

Sarah Heim

Higgs kinematic variables:

- Higgs p_T
- Higgs rapidity

QCD calculations

PDF

production modes

Decay variables (assuming $H \to ZZ^* \to 4l$)

- m_{12}, m_{34}
- angles

spin/cp

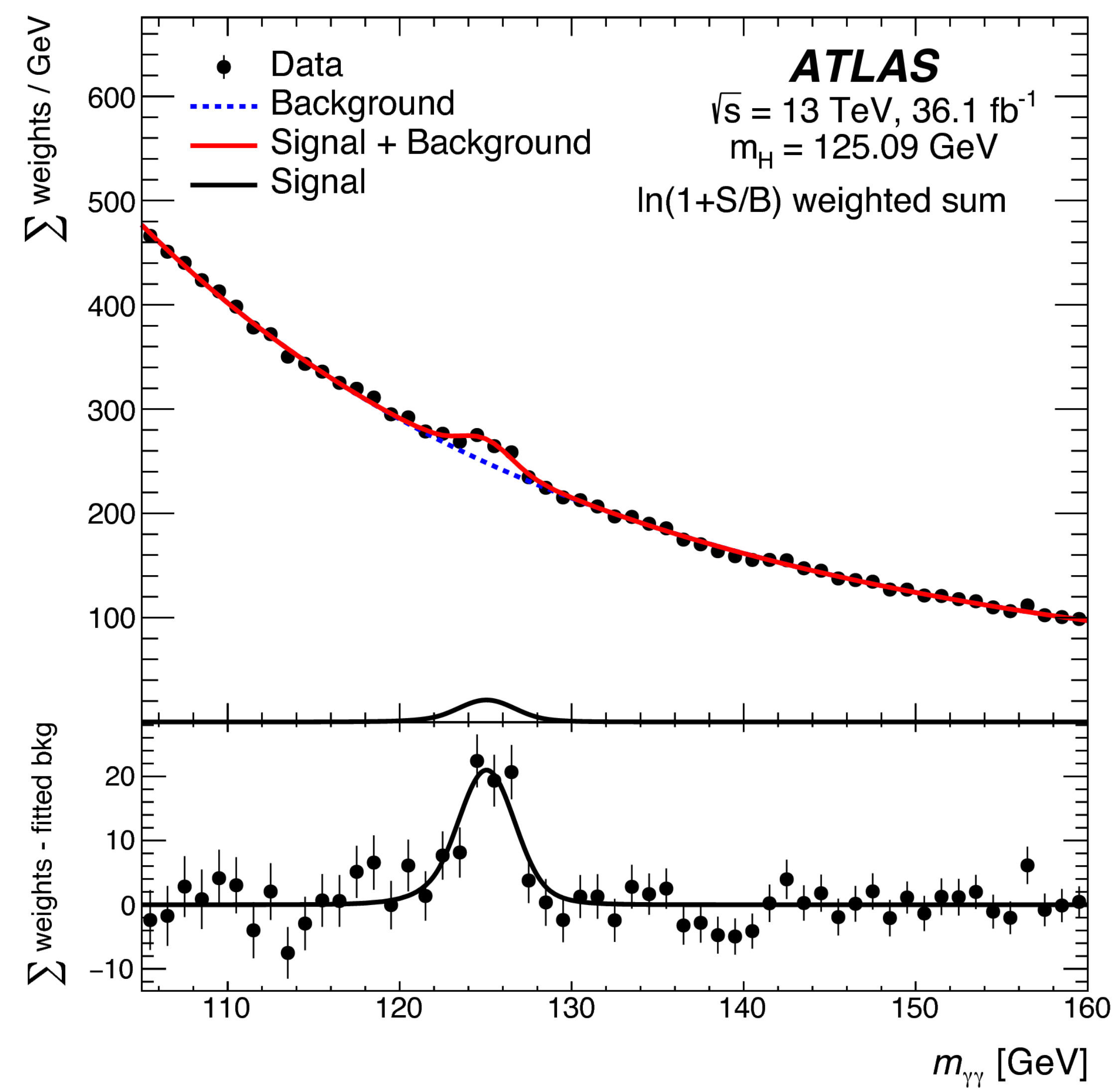
Jet variables

- # of jets, jet p_T
- dijet variables: m_{jj}, angles between jets

Modeling of hard quark and gluon radiation

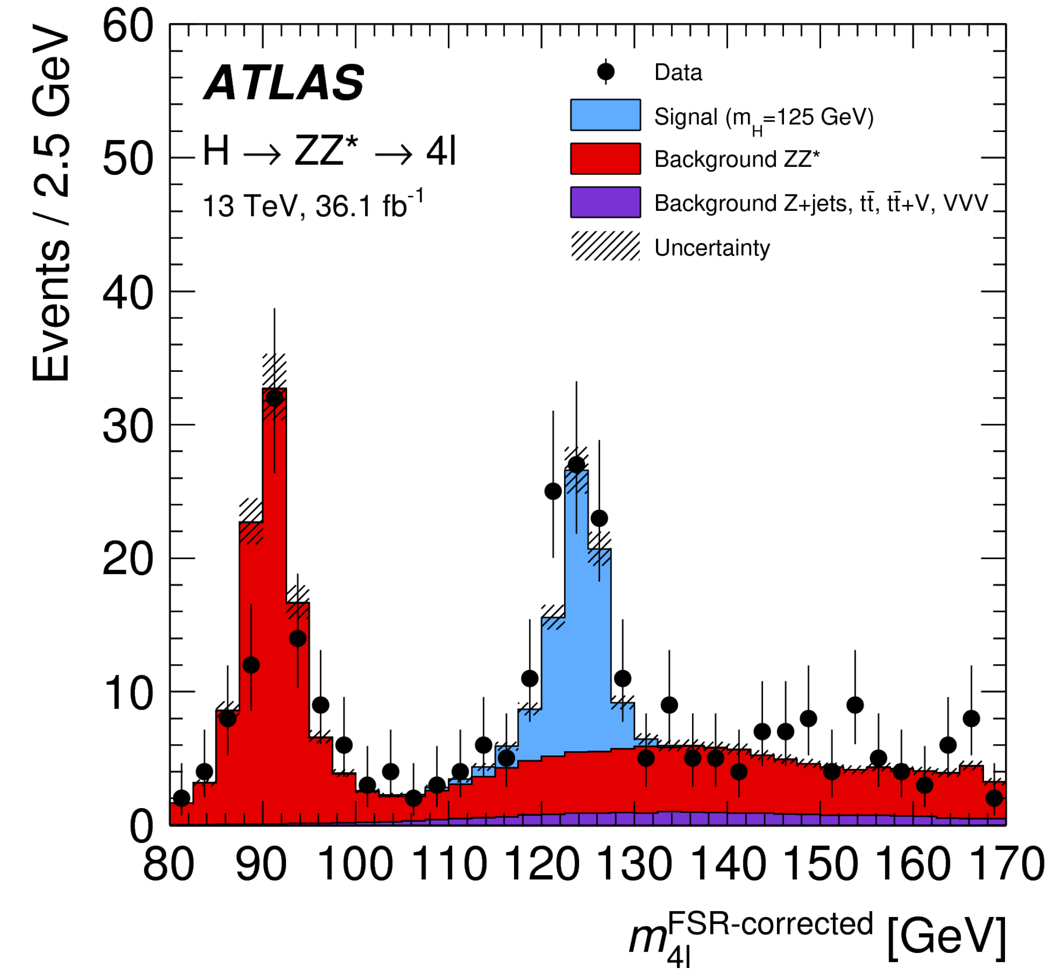
$H \to \gamma\gamma$ Channel – General Introduction

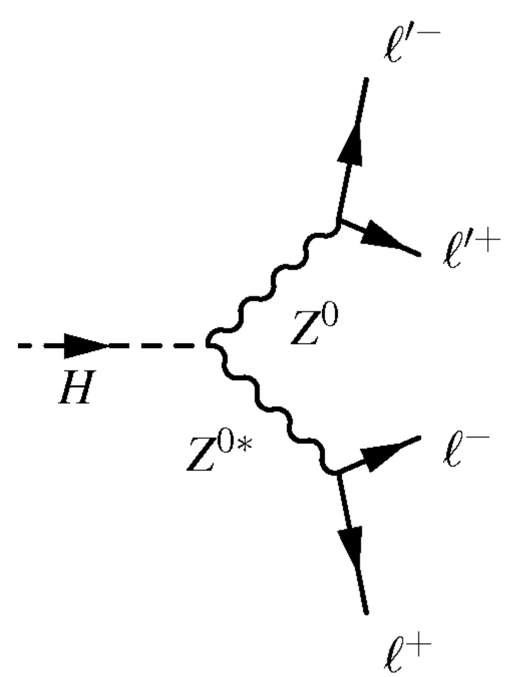
- Trigger events with asymmetric diphoton trigger (35 GeV, 25 GeV thresholds)
- Select 2 tight, isolated photons
- Split up events:
  - Categorize events according to topology (number of leptons, jets, event kinematics with BDTs...)
  - Differential bins of variables with interesting physics
- In each bin/category, model the background $m_{\gamma\gamma}$ distribution using a falling function or a polynomial
  - ... with as few degrees of freedom (DOF) as is required
- Perform your S+B fit of $m_{\gamma\gamma}$ distribution on data
  - Signal is modeled using double-sided Crystal Ball



H→ ZZ→ 4ℓ – General Introduction

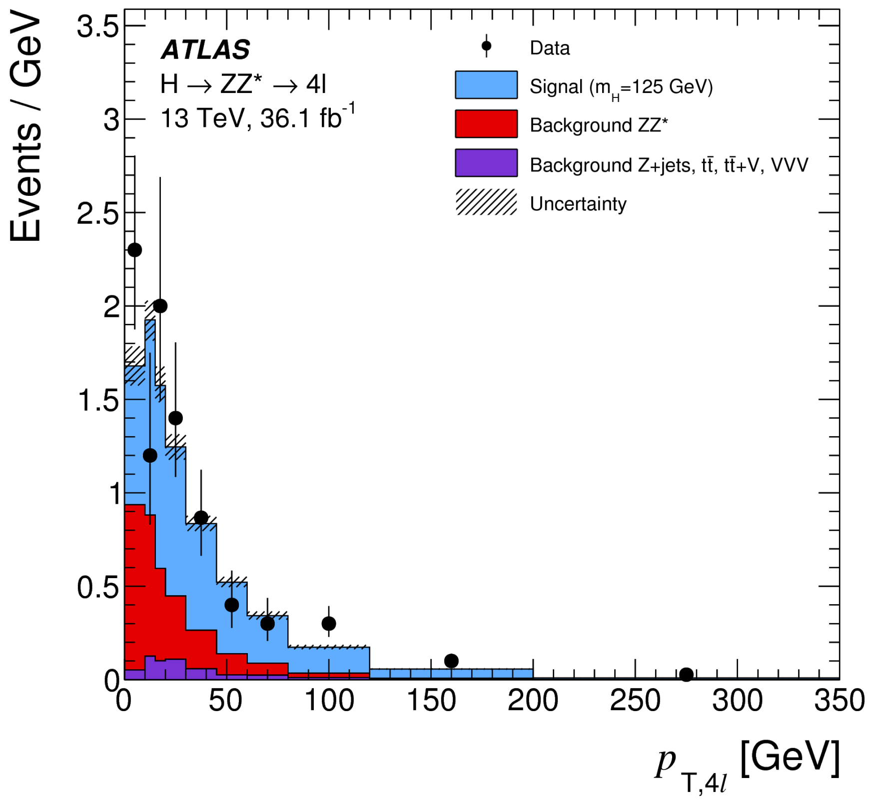
- Fast Facts:
  - electrons, muons, not taus
  - Fully reconstruct the final state
  - signal/background ~2 (115-130 GeV window)
- Event selection:
  - 4 leptons, very loose identification, isolation
  - Form 2 opposite sign, same flavor pairs
    - "Z_{12}" consistent with on-shell Z; "Z_{34}" with off-shell Z
  - Constrain Z_{12} kinematically to M_Z
- Background estimates:
  - Irreducible from SM Z(*)Z(*)→4ℓ, ttV, VVV
    - modeled using simulation
  - <u>Reducible from Z+jets and ttbar (and WZ), modeled using data-driven methods</u>



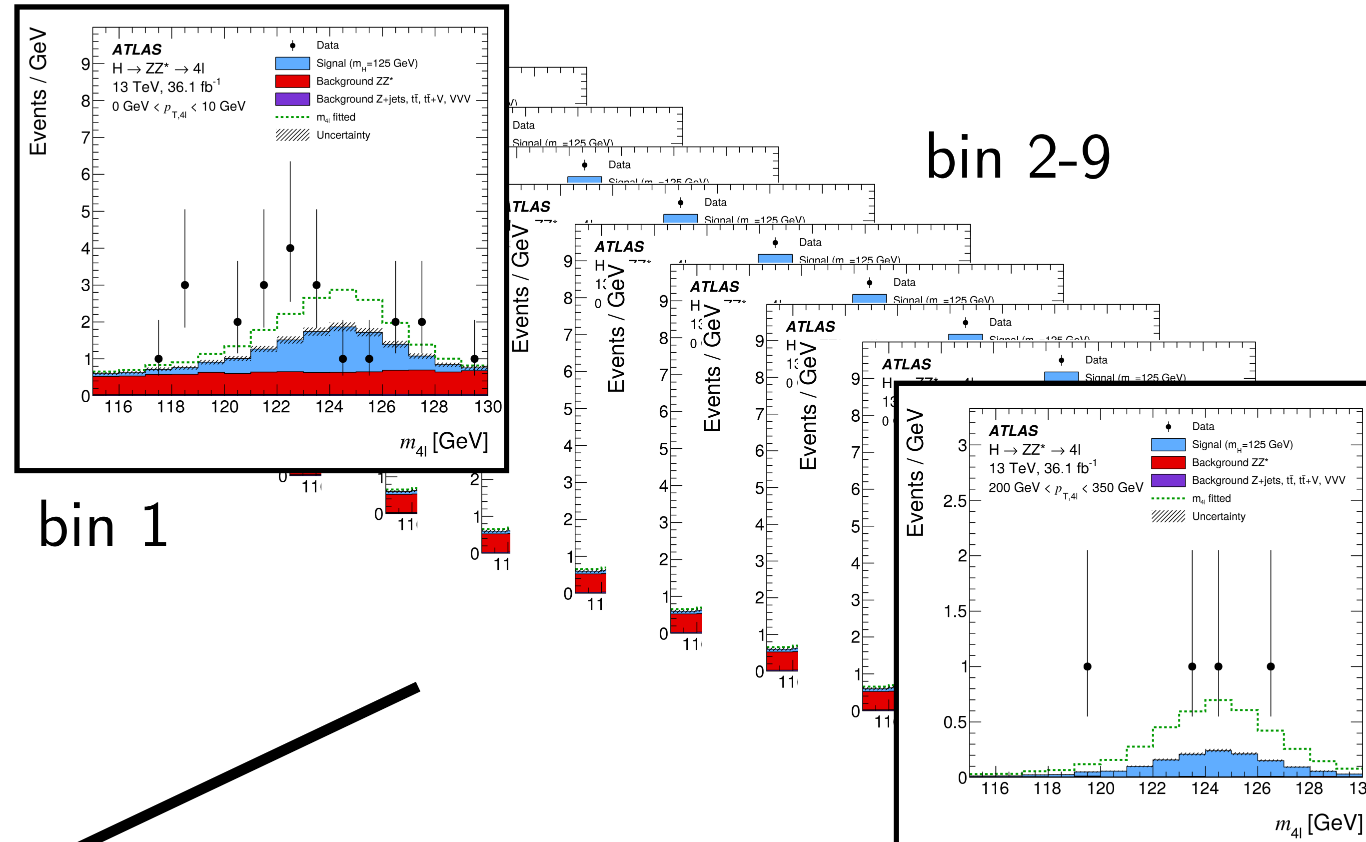


Obtaining a differential distribution: $H \to ZZ^* \to 4\ell$

Reconstructed Distribution



Obtain signal in each bin using fits in $m_{4\ell}$

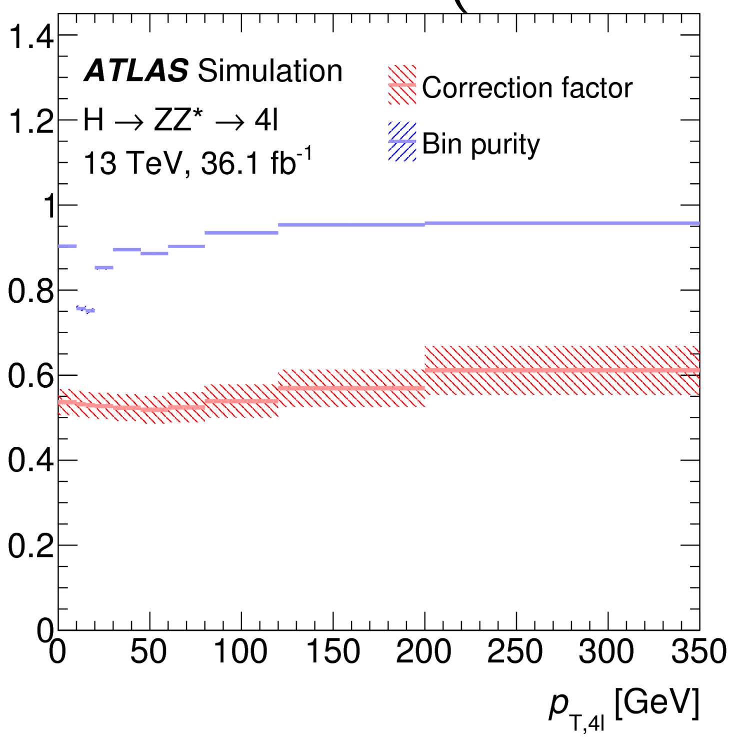


bin 1

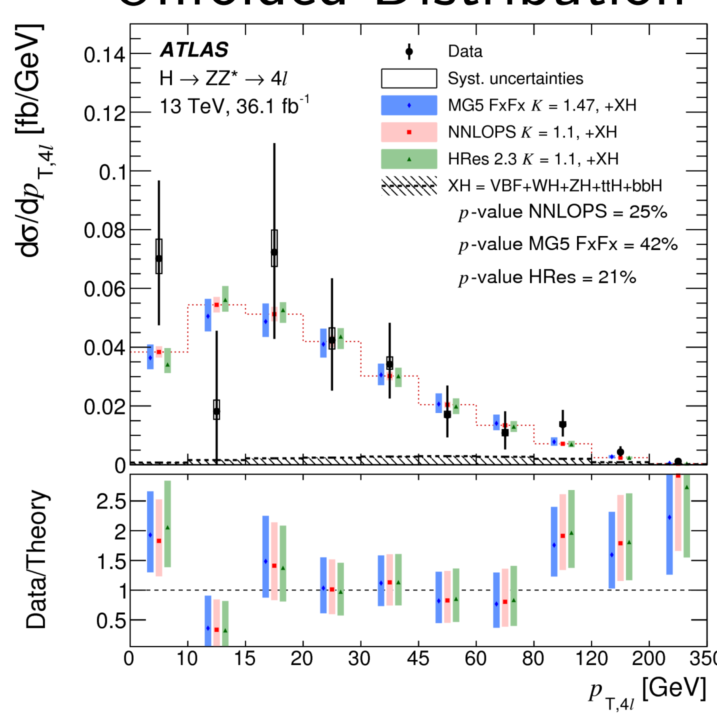
bin 2-9

bin 10

Correct for detector effects (correction factors)



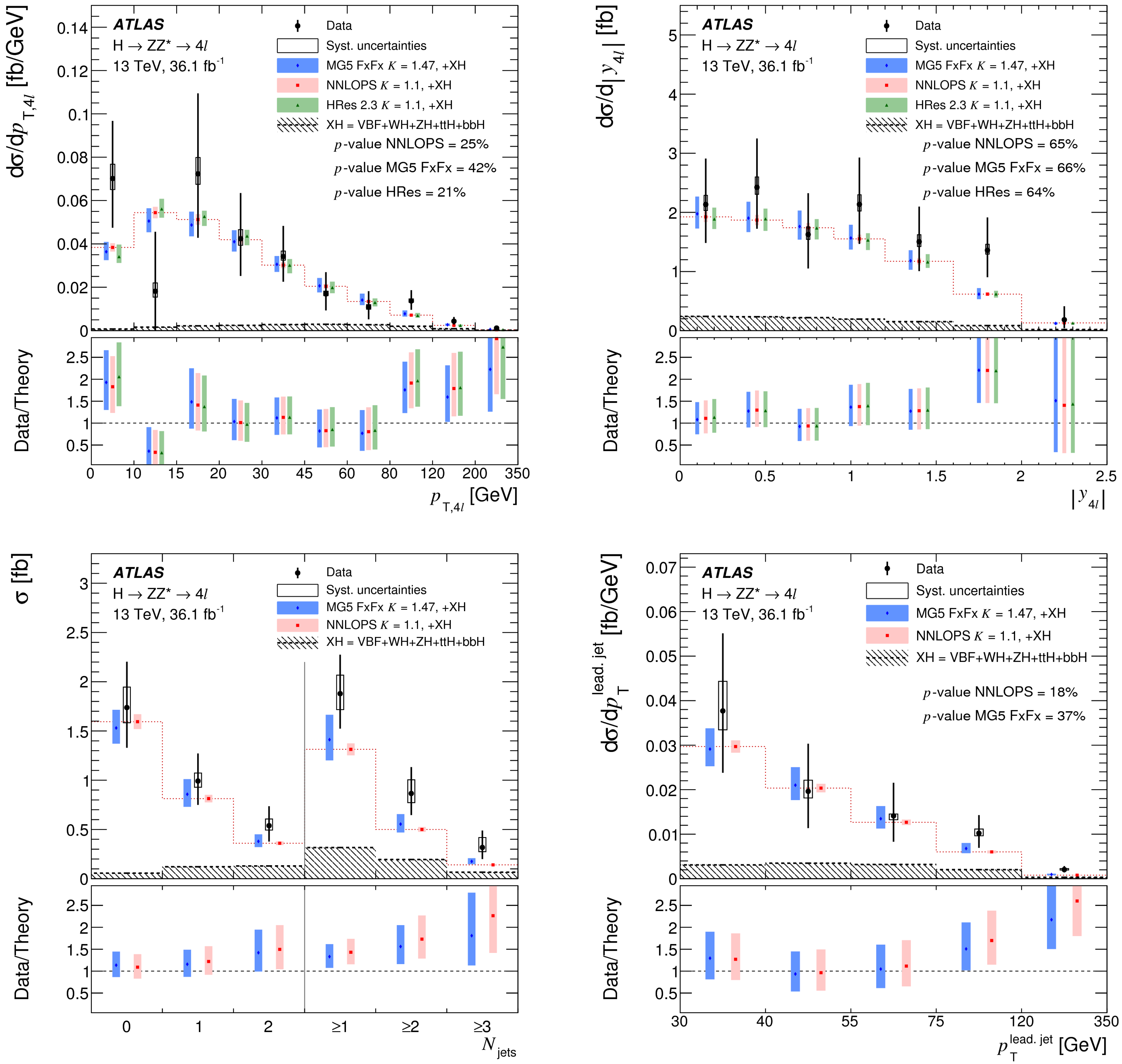
Unfolded Distribution



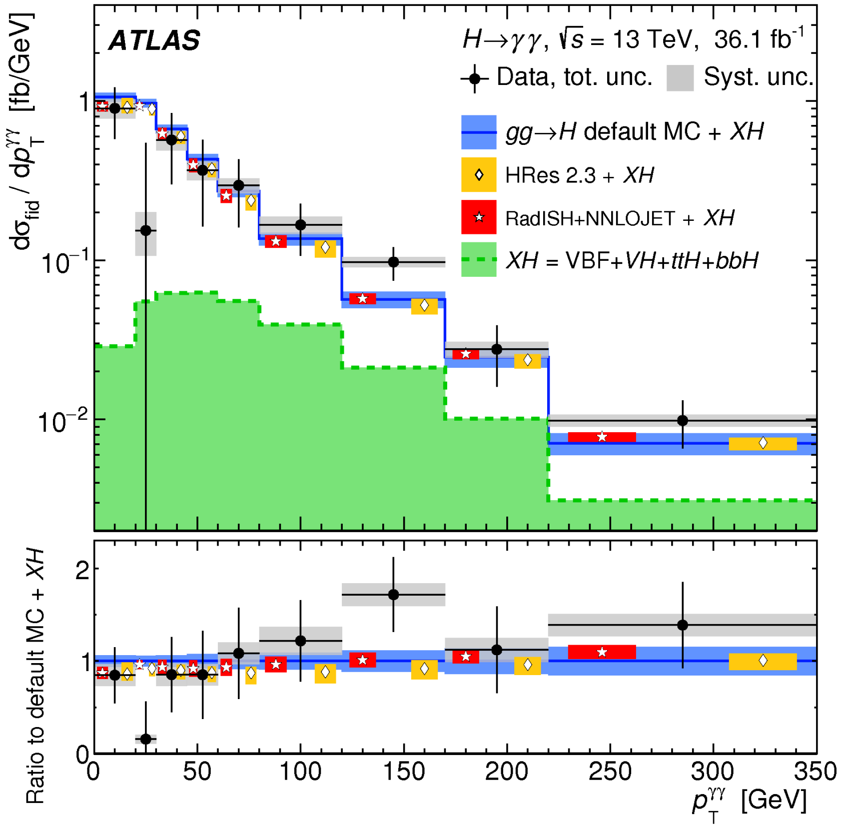
Unfold by maximizing the profile likelihood ratio:

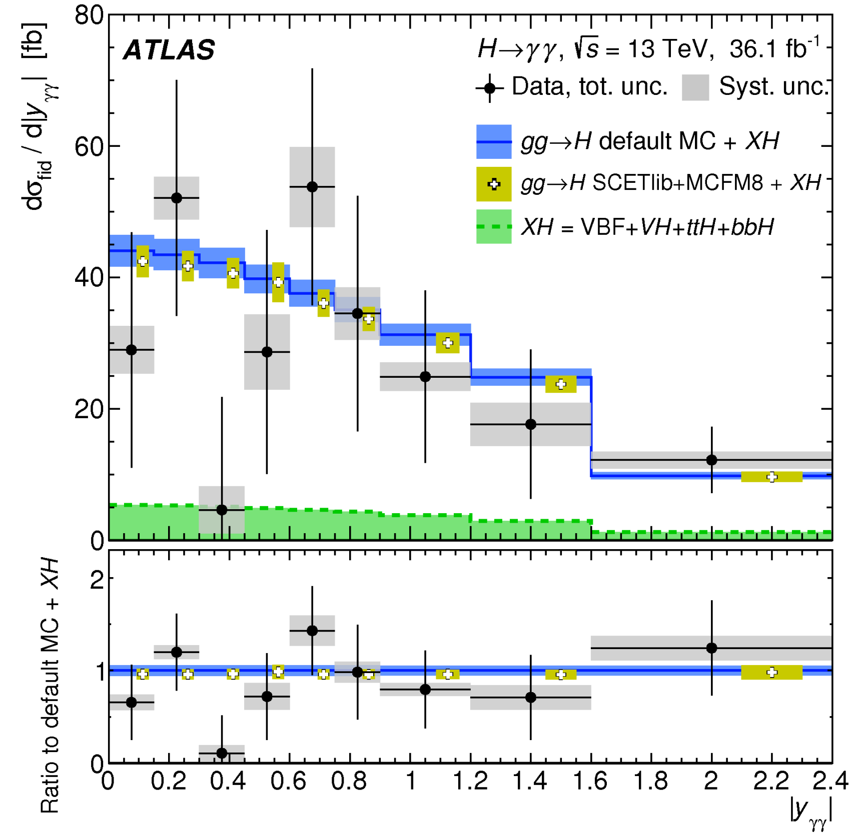
$$\Lambda(\sigma) = \frac{\mathcal{L}(\sigma, \hat{\hat{\theta}}(\sigma))}{\mathcal{L}(\hat{\sigma}, \hat{\theta})}$$

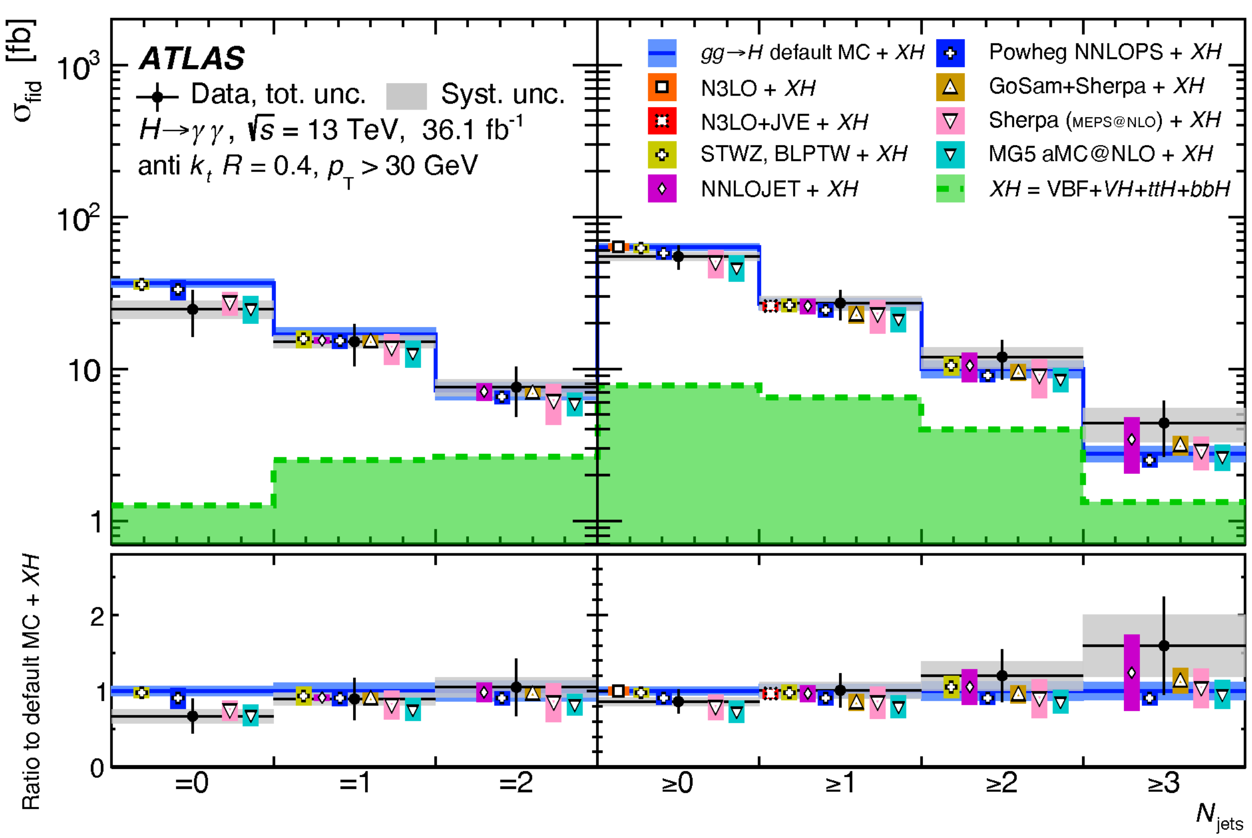
H→ZZ*→4ℓ Differential Results

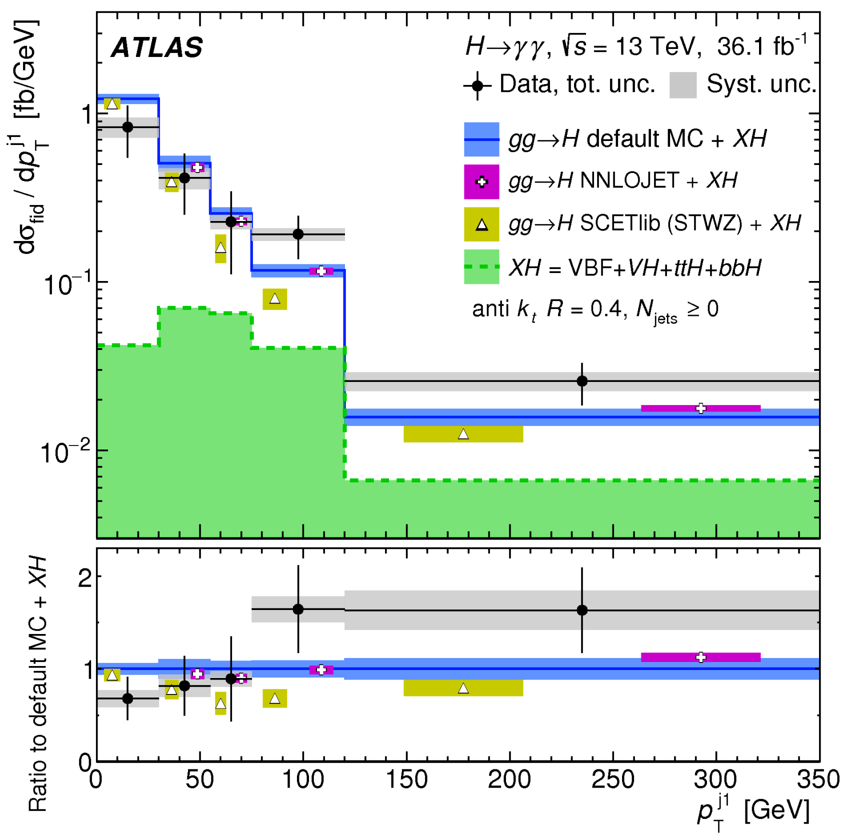


$H\rightarrow\gamma\gamma$ Differential Results



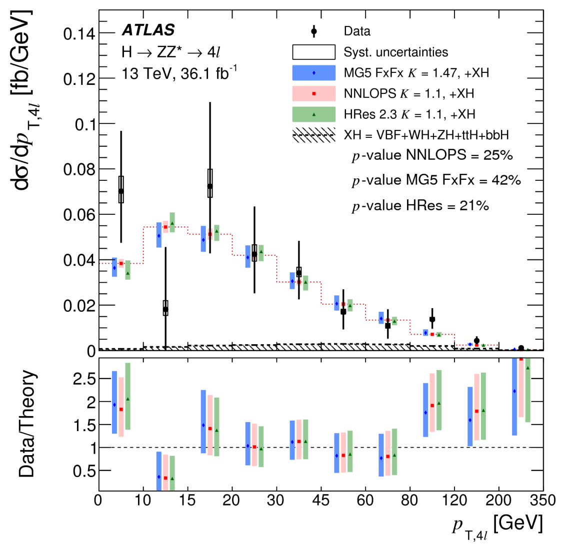




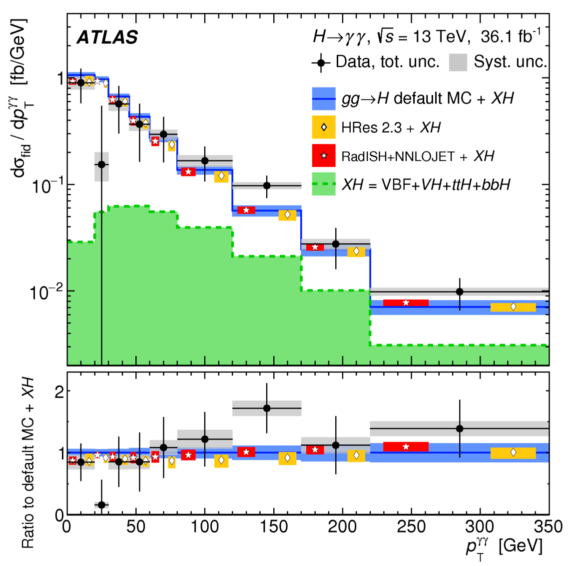


Combination of ZZ* and γγ Channels

ZZ



γγ



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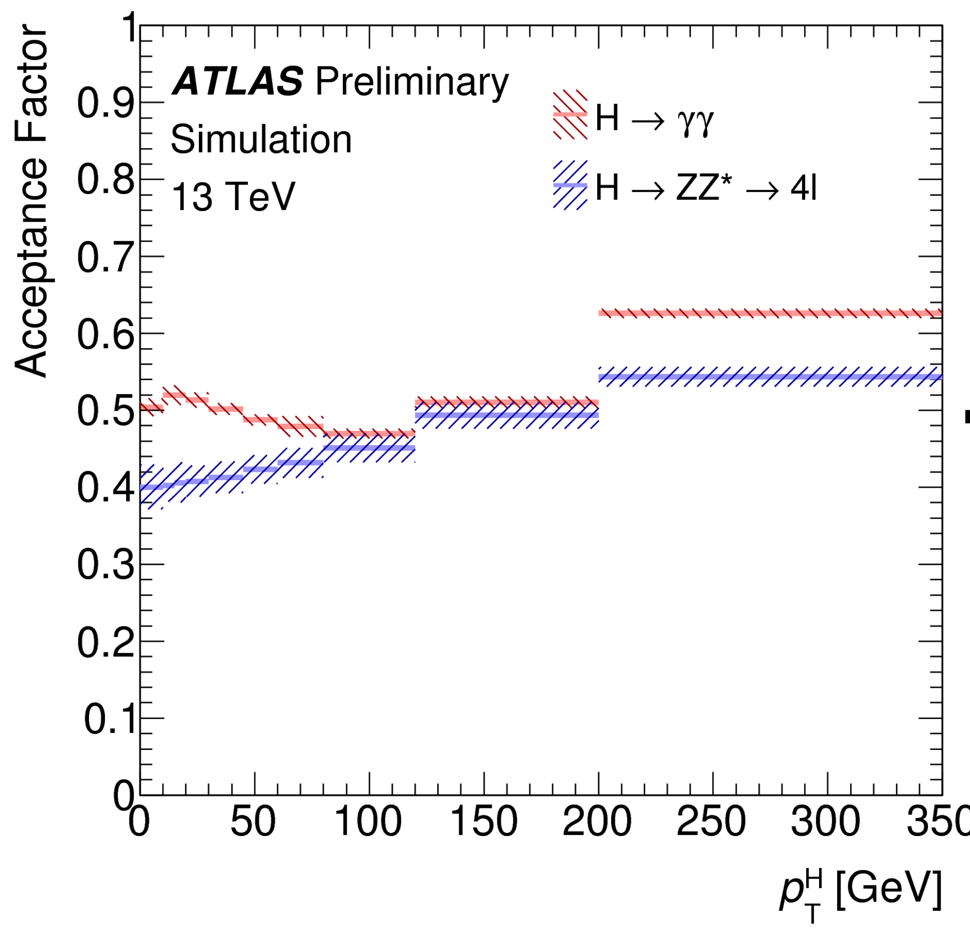
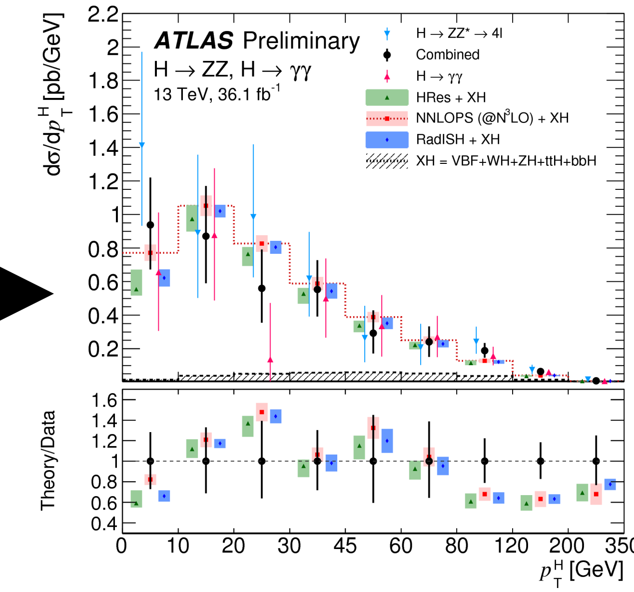
Correction Factors for γγ and ZZ



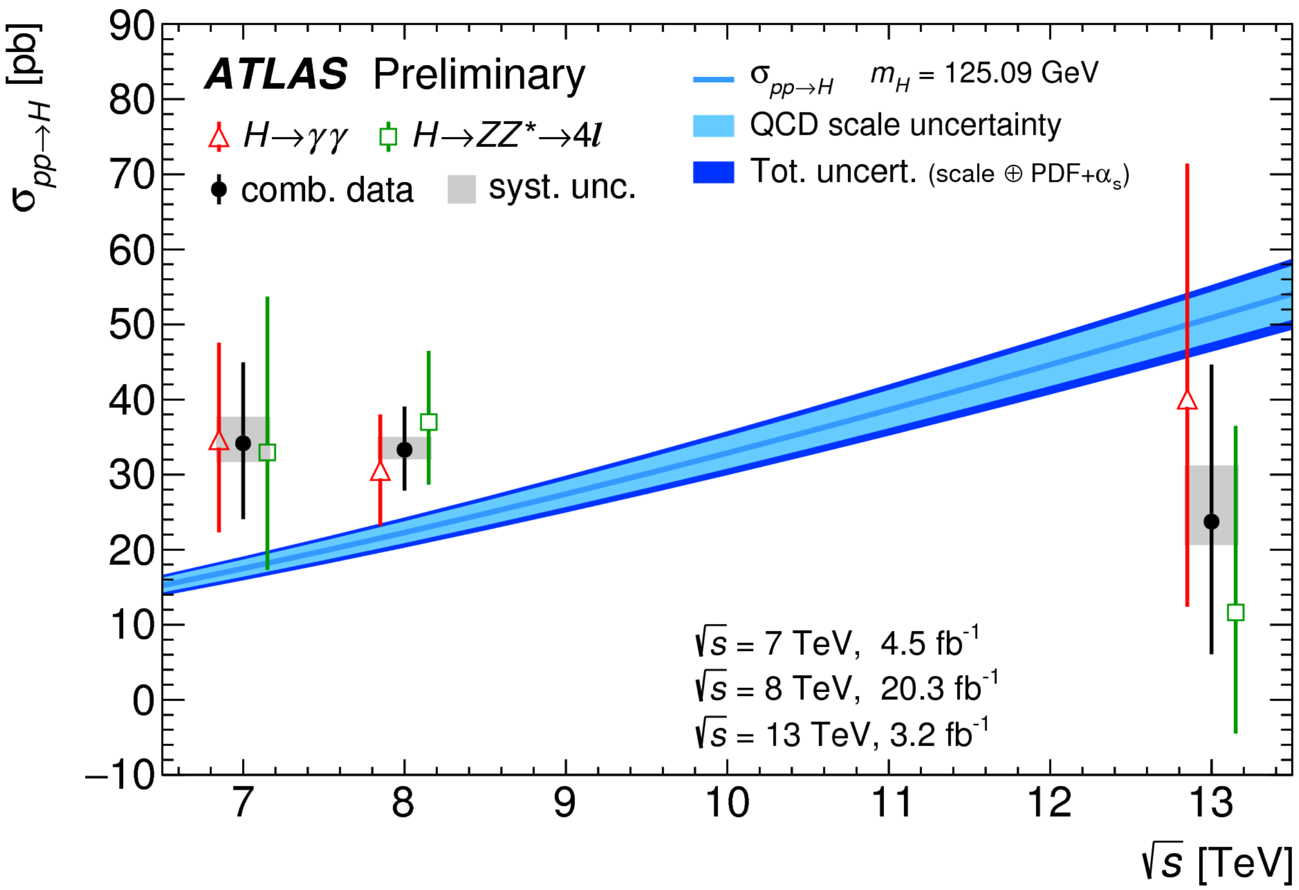


- Channels are individually corrected to full phase space using an additional correction factor
- Unfolding combination performed by maximizing the profile likelihood ratio:

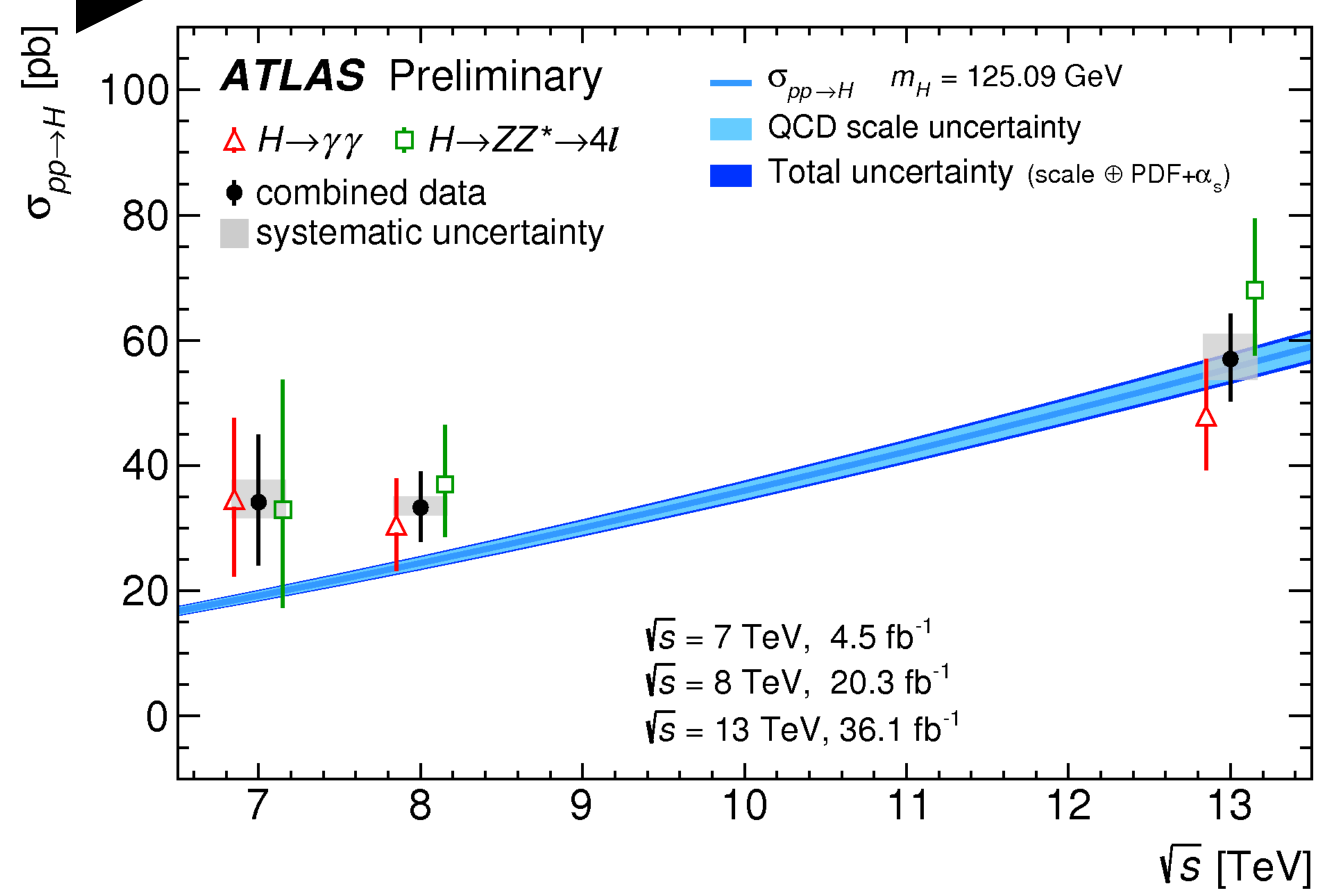
$$\Lambda(\sigma) = \frac{\mathcal{L}(\sigma, \hat{\hat{\theta}}(\sigma))}{\mathcal{L}(\hat{\sigma}, \hat{\theta})}$$

- Calculate a p-value between data and theory based on the profile likelihood ratio test statistic

ATLAS-CONF-2015-069



ATLAS-CONF-2017-047



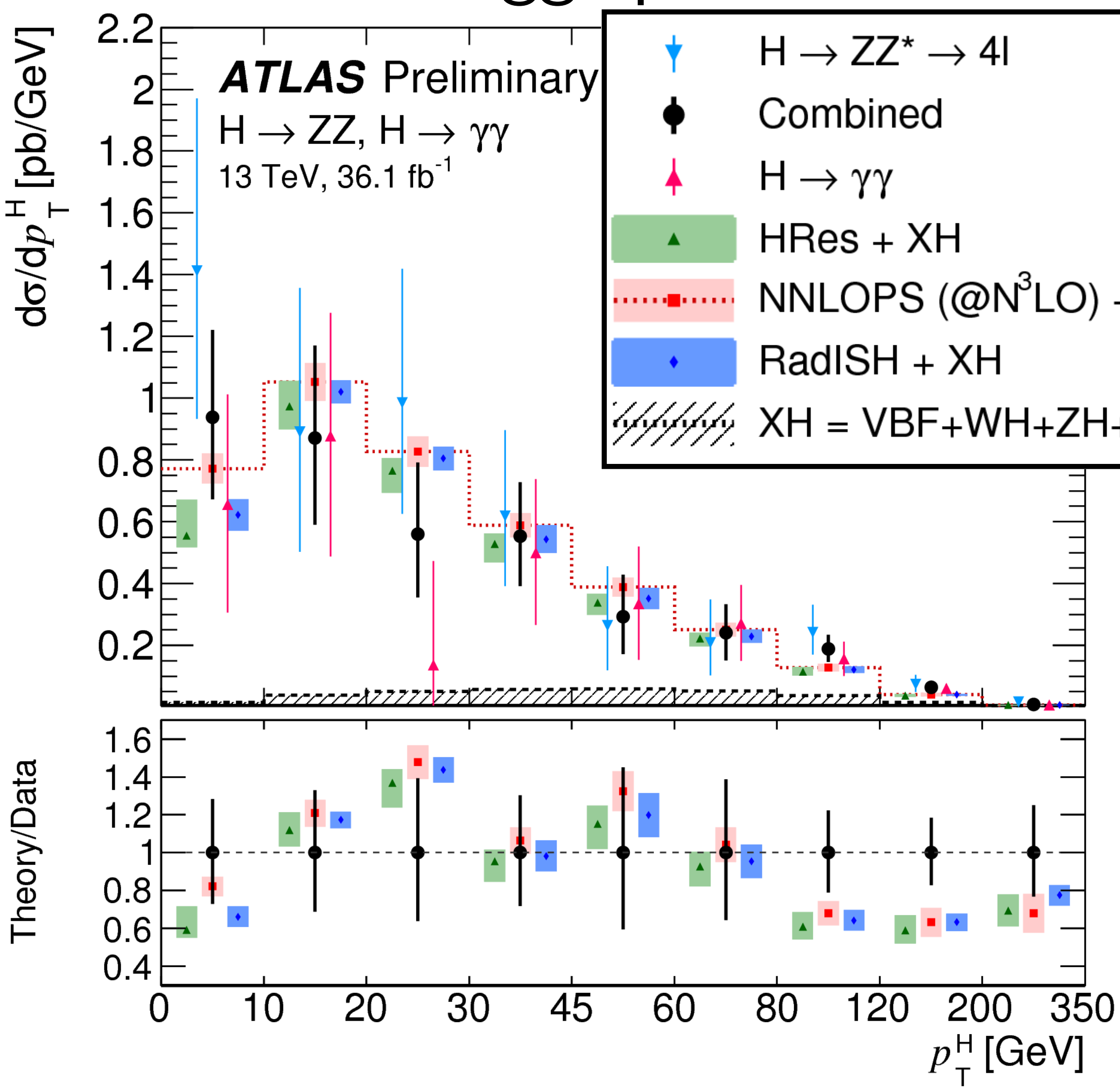
New Results:

Measured total $\sigma = 57.0^{+6.0}_{-5.9}$ (stat.) $^{+4.0}_{-3.3}$ (syst.) pb

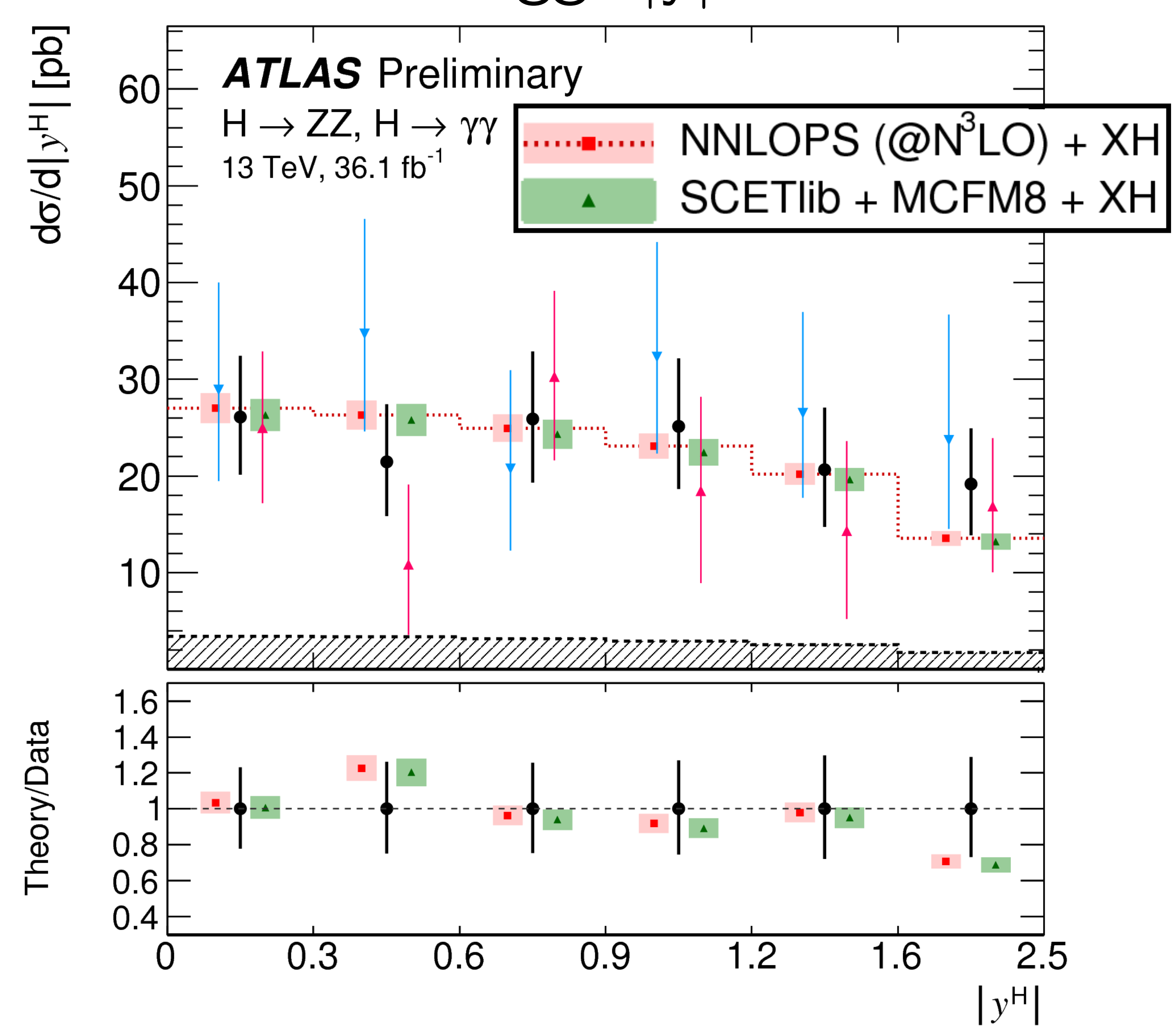
(prediction = 55.6±2.5 pb)

Results - Differential Cross Section Combination

Higgs p_T



Higgs $|y|$

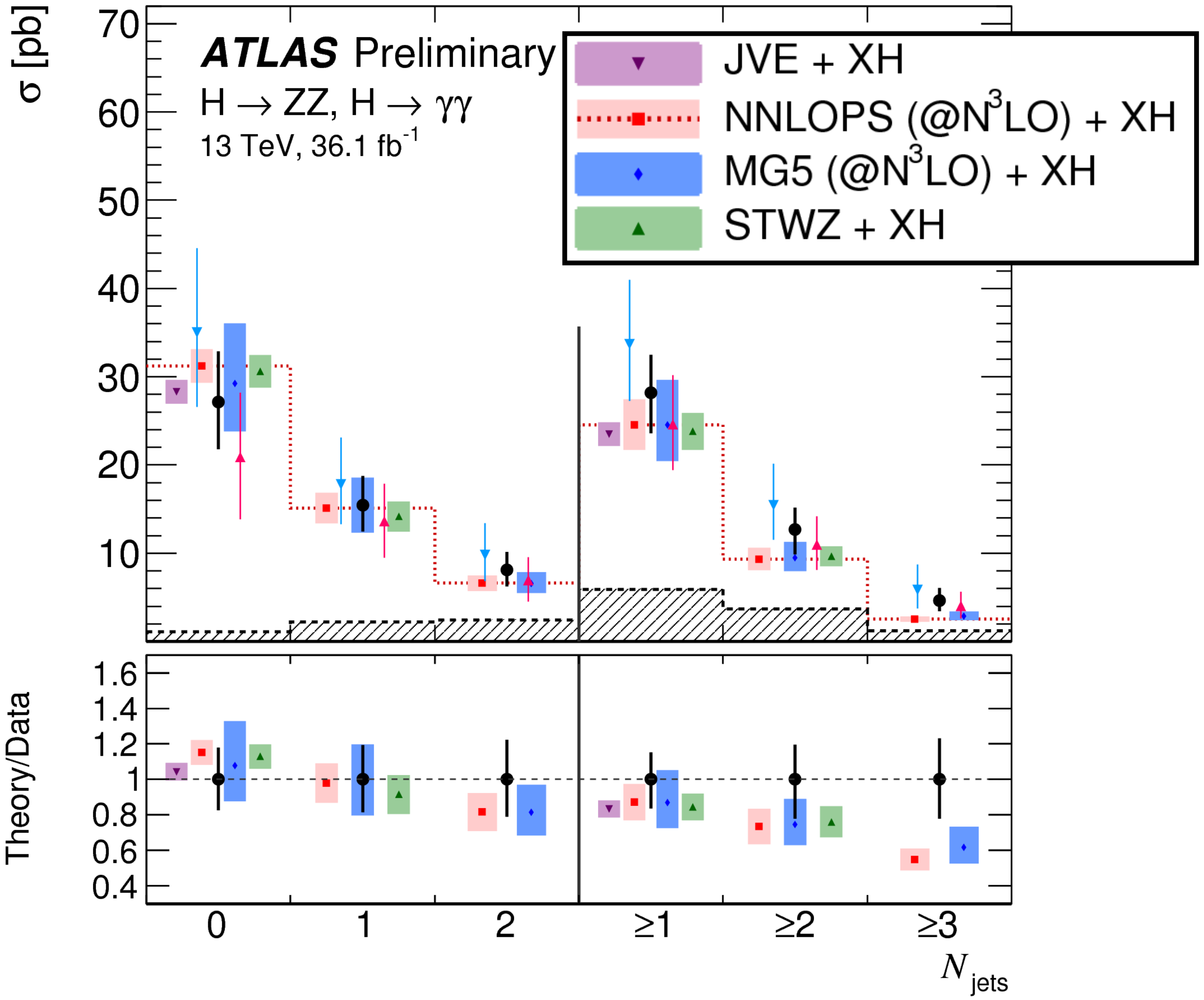


- Results compatible with Standard Model
- HRes more discrepant - has a lower predicted cross section (NNLO+NNLL accuracy)

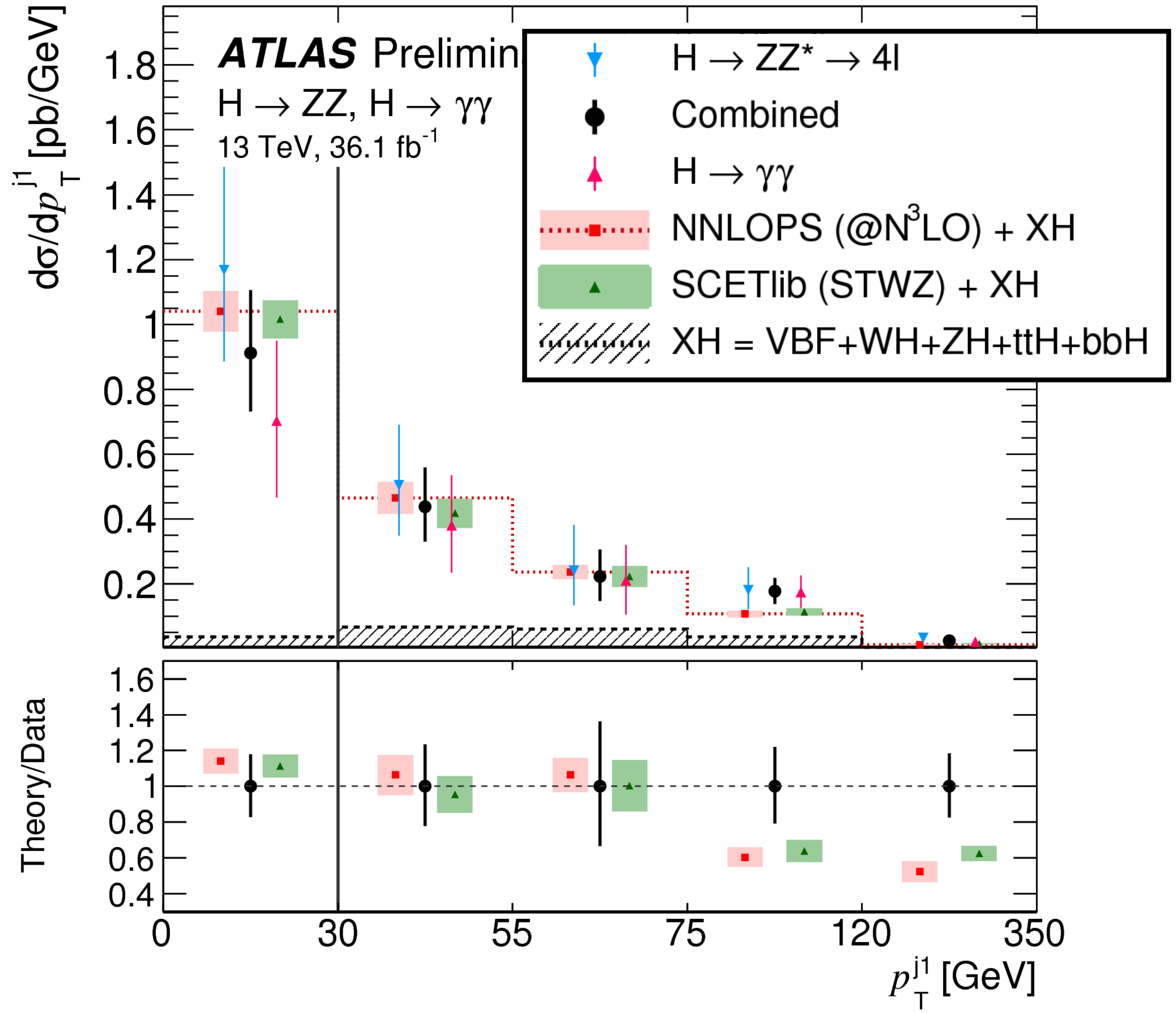
p-values [%]	p_T^H	$\lvert y^H \rvert$
NNLOPS (@N^{3}LO)	29	92
HRes	5	–
RaDISH + NNLOJET	29	–
SCETlib	–	91

Results - Differential Cross Section Combination

N_{jets}



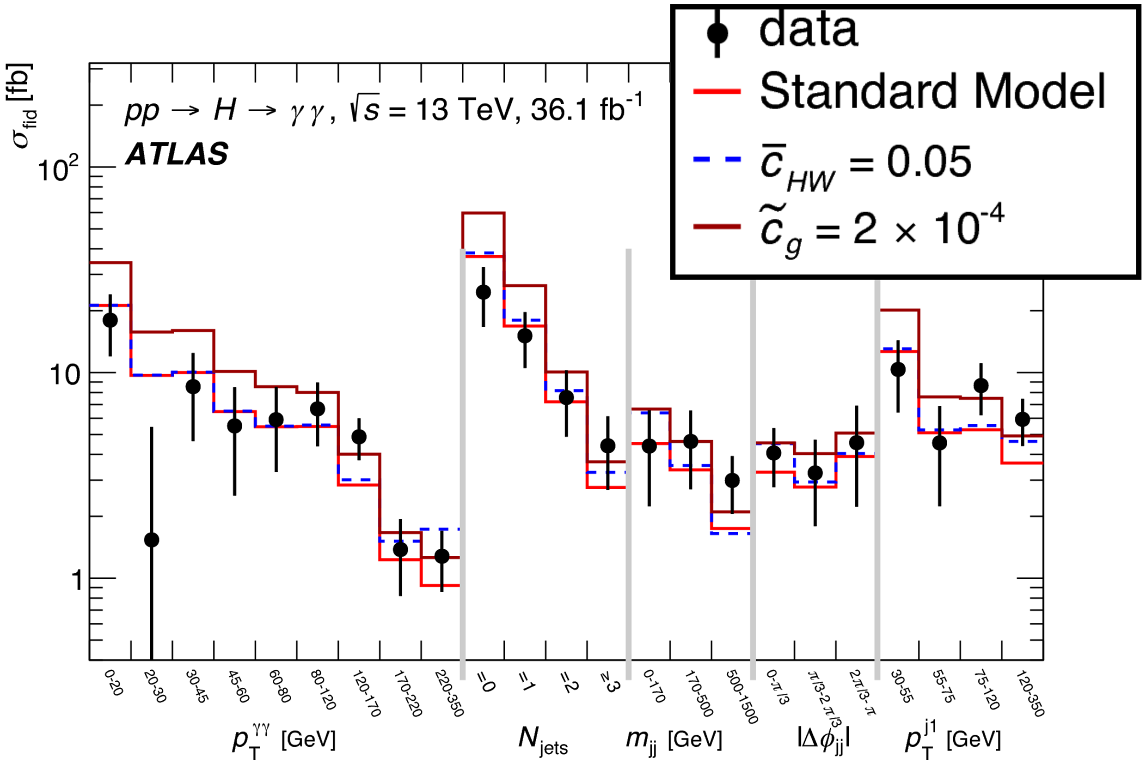
Leading jet p_T



p-values [%]	N_{jets}	p_{T}^{j1}
NNLOPS (@N^{3}LO)	45	5
SCETLIB	–	21
MADGRAPH5_AMC@NLO (@N^{3}LO)	57	–

Additional H$\to\gamma\gamma$ Results

- Using differential cross sections to constrain effective Lagrangians
- Couplings using Simplified Template Cross Sections



- Unfolded differential measurements can be used to constrain effective Lagrangian operators
  - Provide differential measurements of several variables,
  - plus covariance matrices of statistical, experimental and theoretical uncertainties to theorists
  - With these two ingredients, can constrain parameter space of effective Lagrangians

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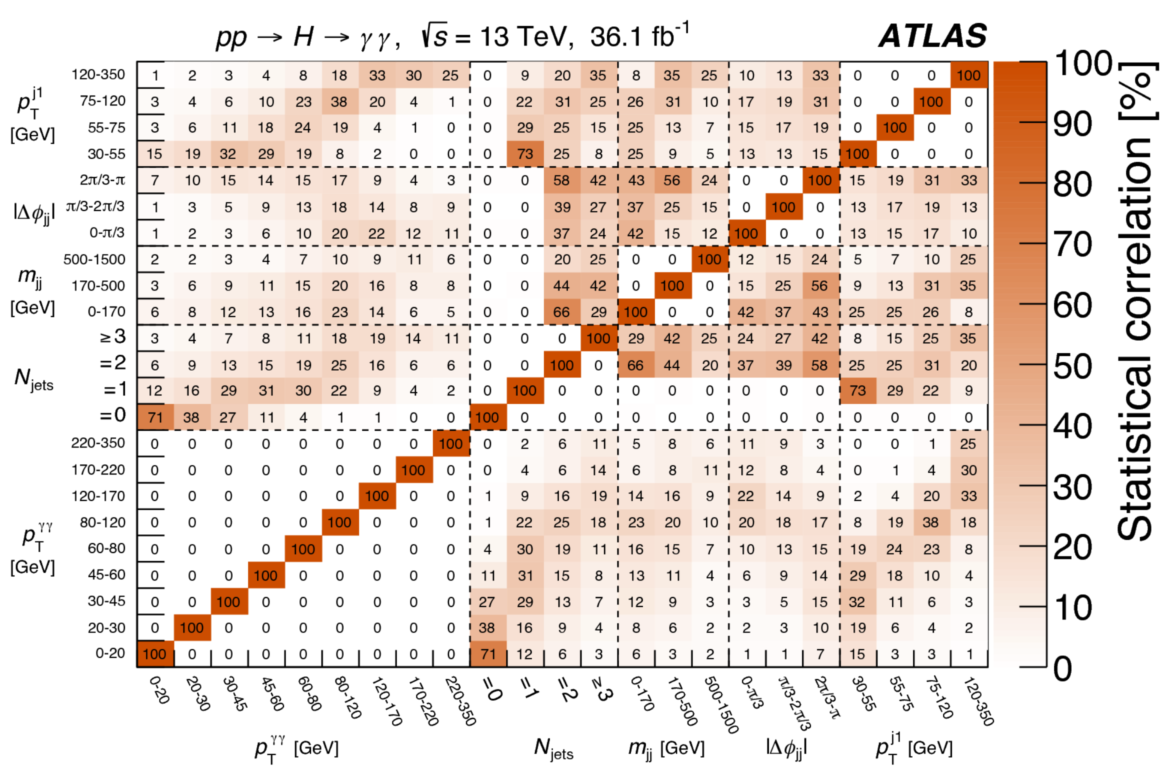
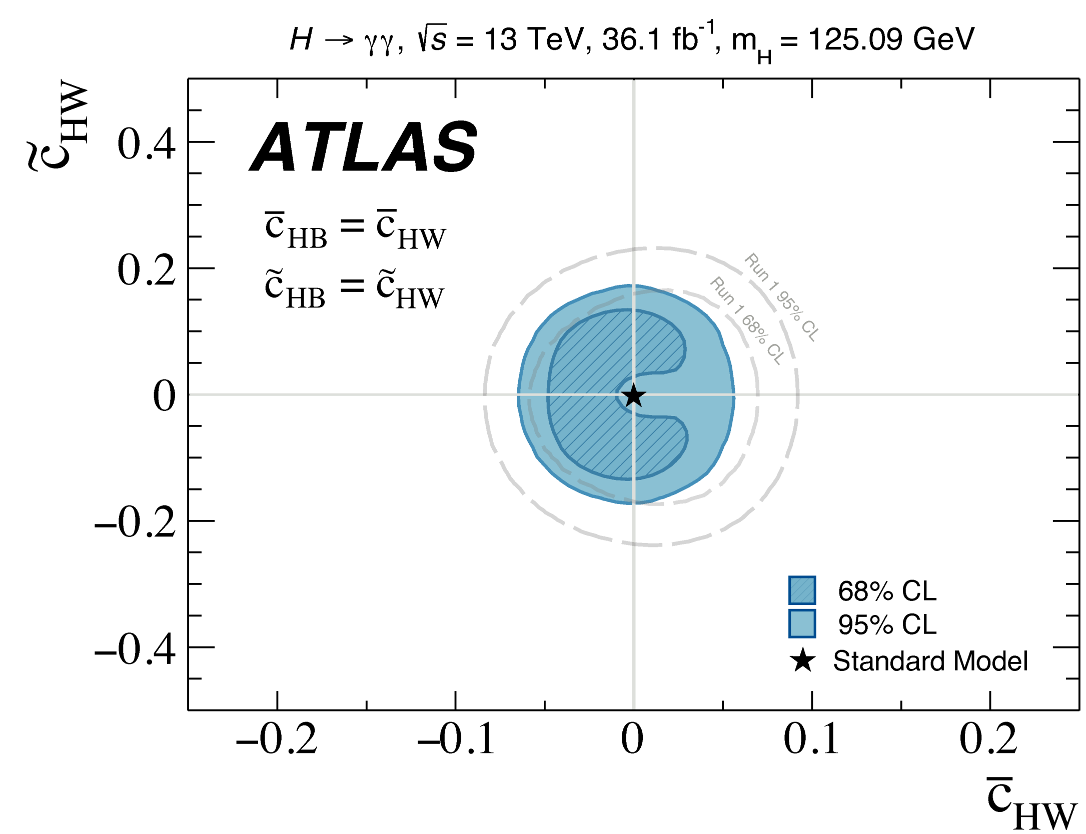
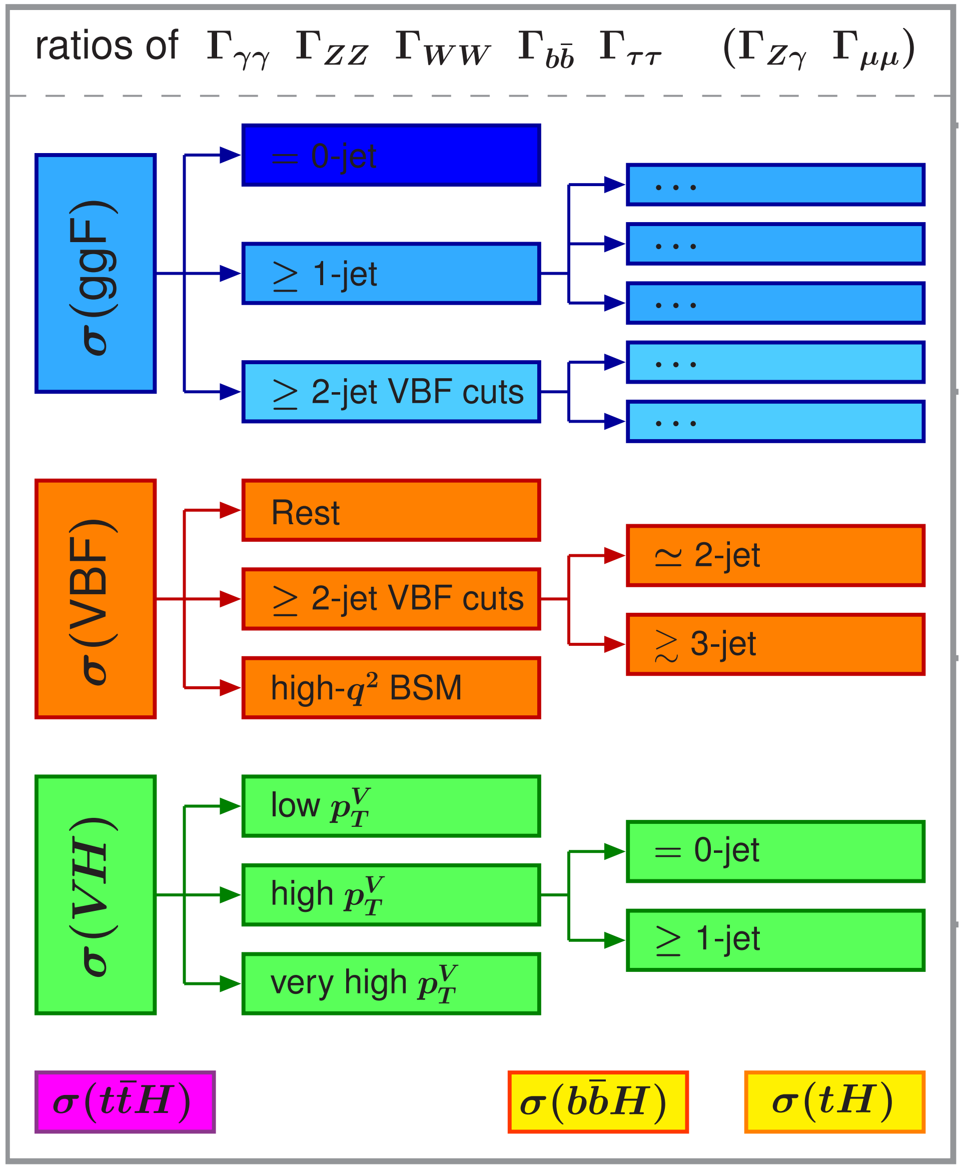


Constraints on Wilson Coefficients



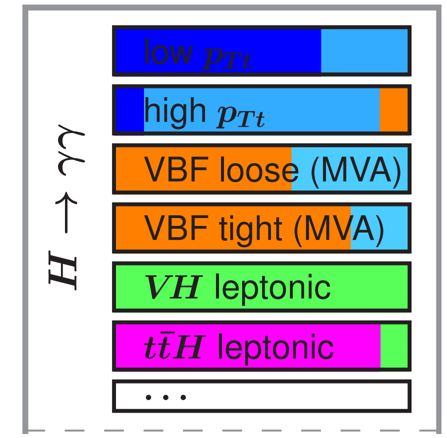
Couplings using Simplified Template Cross Sections

(1)



Particle-level (truth) categories

(2)

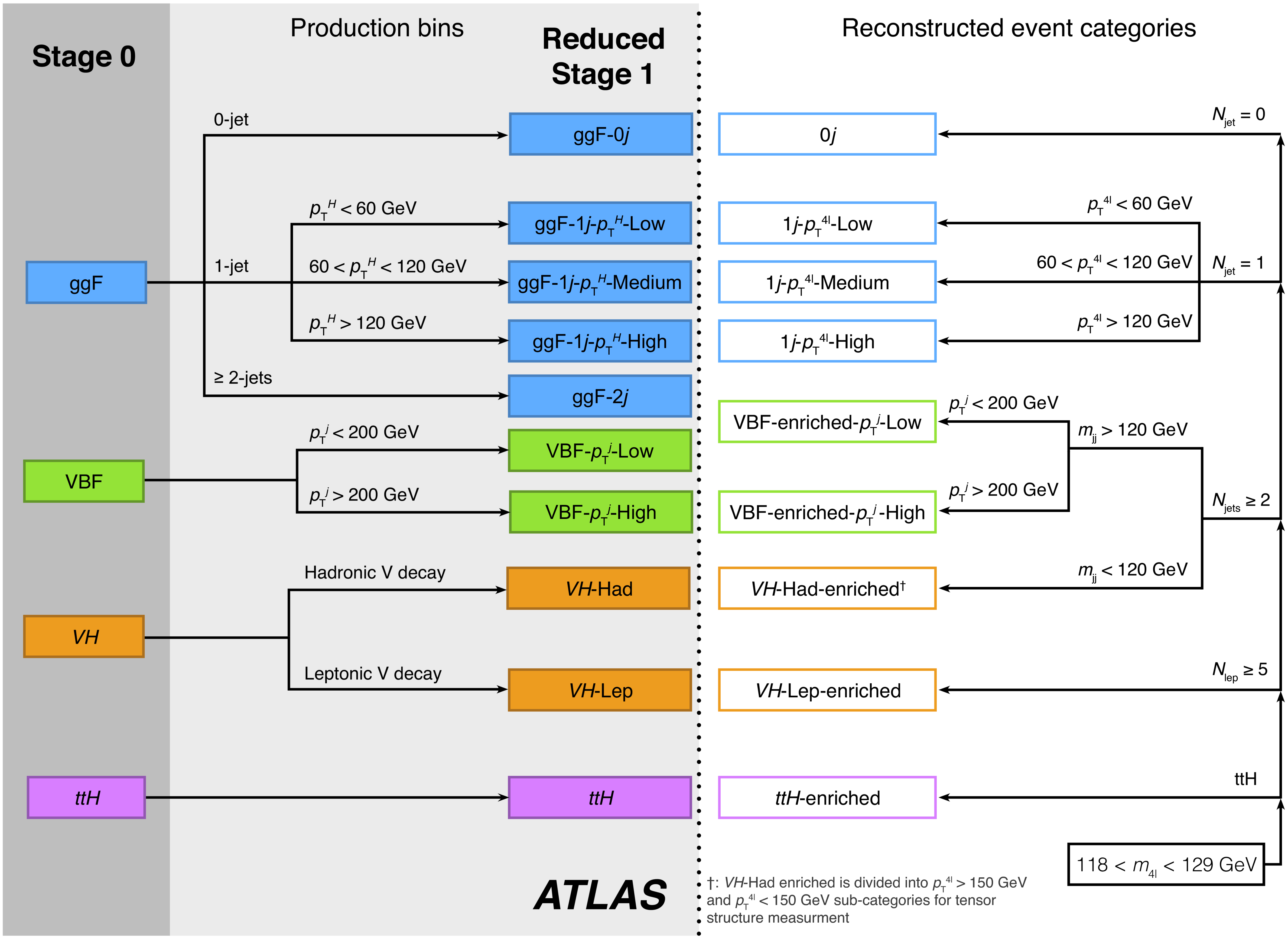


Reco categories to be measured individually

- (1) Split your Higgs particle phase space into "truth categories" (based on production modes, kinematics)
- (2) Construct reco categories to ~match truth categories
- (3) Measure cross section in each category

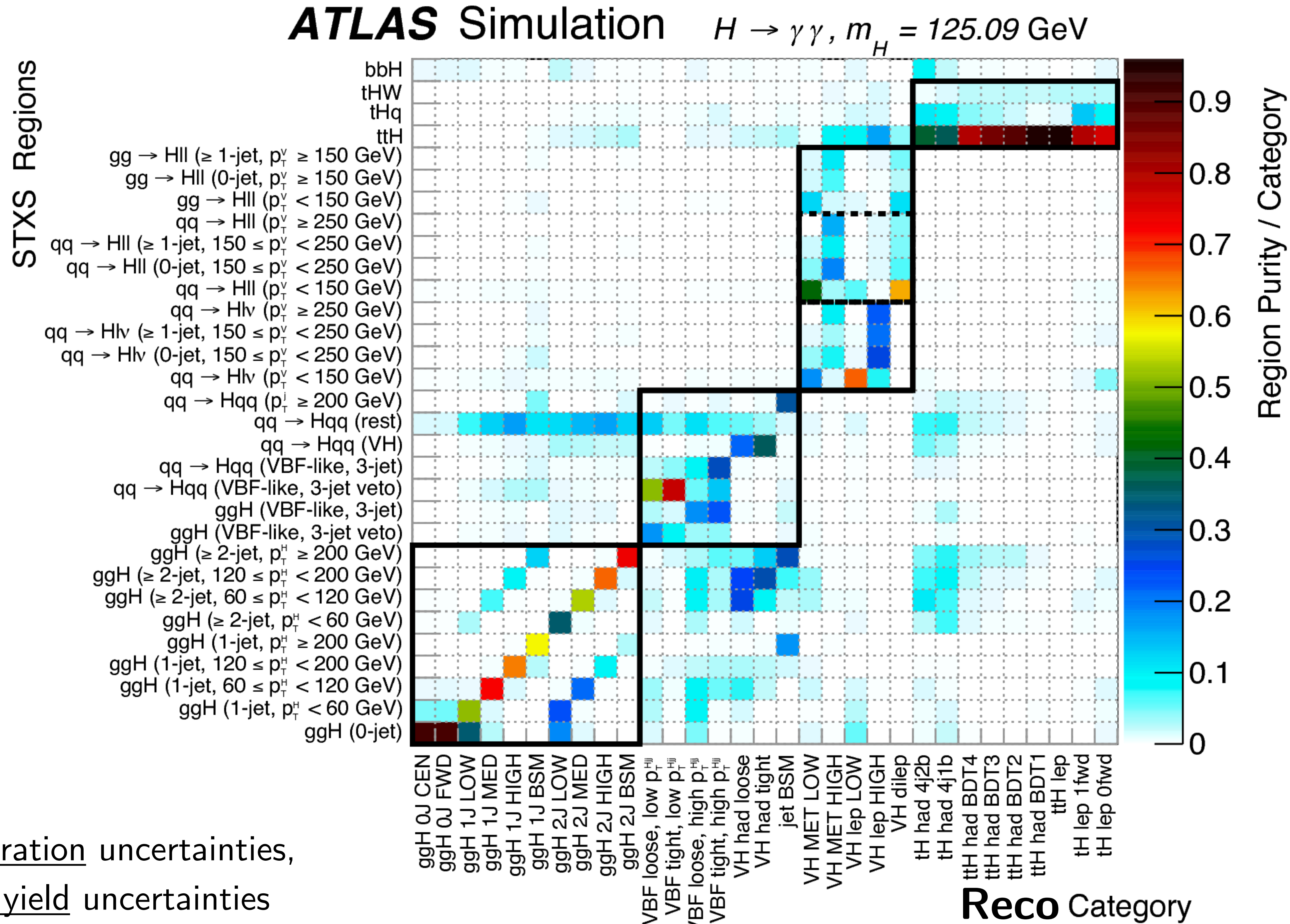
- More model-independent than measuring signal strengths μ
- Maximize sensitivity of measurements, while
- reducing theory dependencies folded into measurement

Simplified template cross sections: $H \to ZZ^* \to 4\ell$



STXS Reco-Truth Matrix

"Migration Matrix"

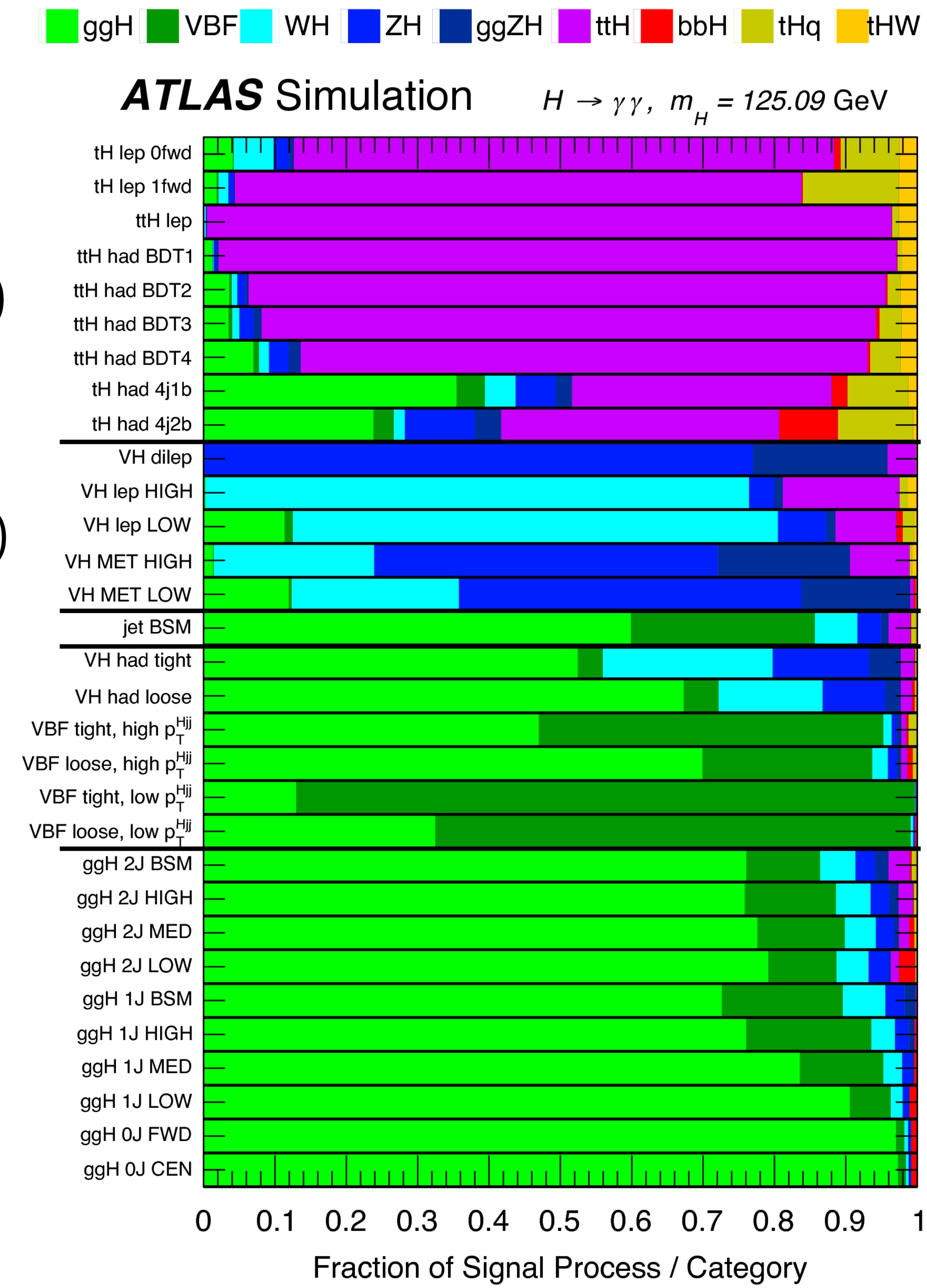


Truth

***Theory migration uncertainties,
but not theory yield uncertainties

Reco Category Purity (focusing on prod. mode)

Truth processes:



Reco Category

ttH (ideally all purple)

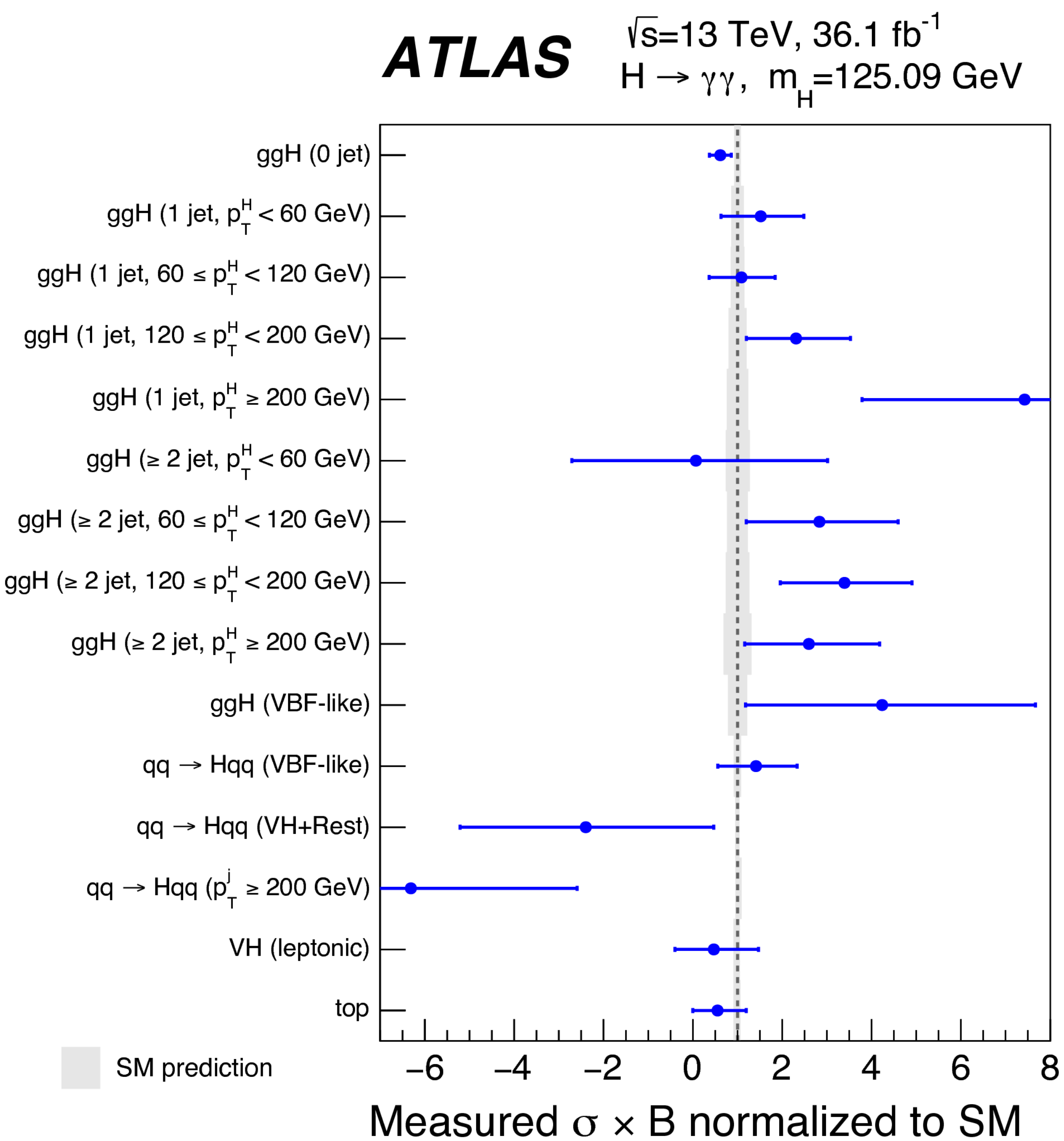
VH leptonic (ideally all light/dark blue)

VBF + VH hadronic (ideally all dark green)

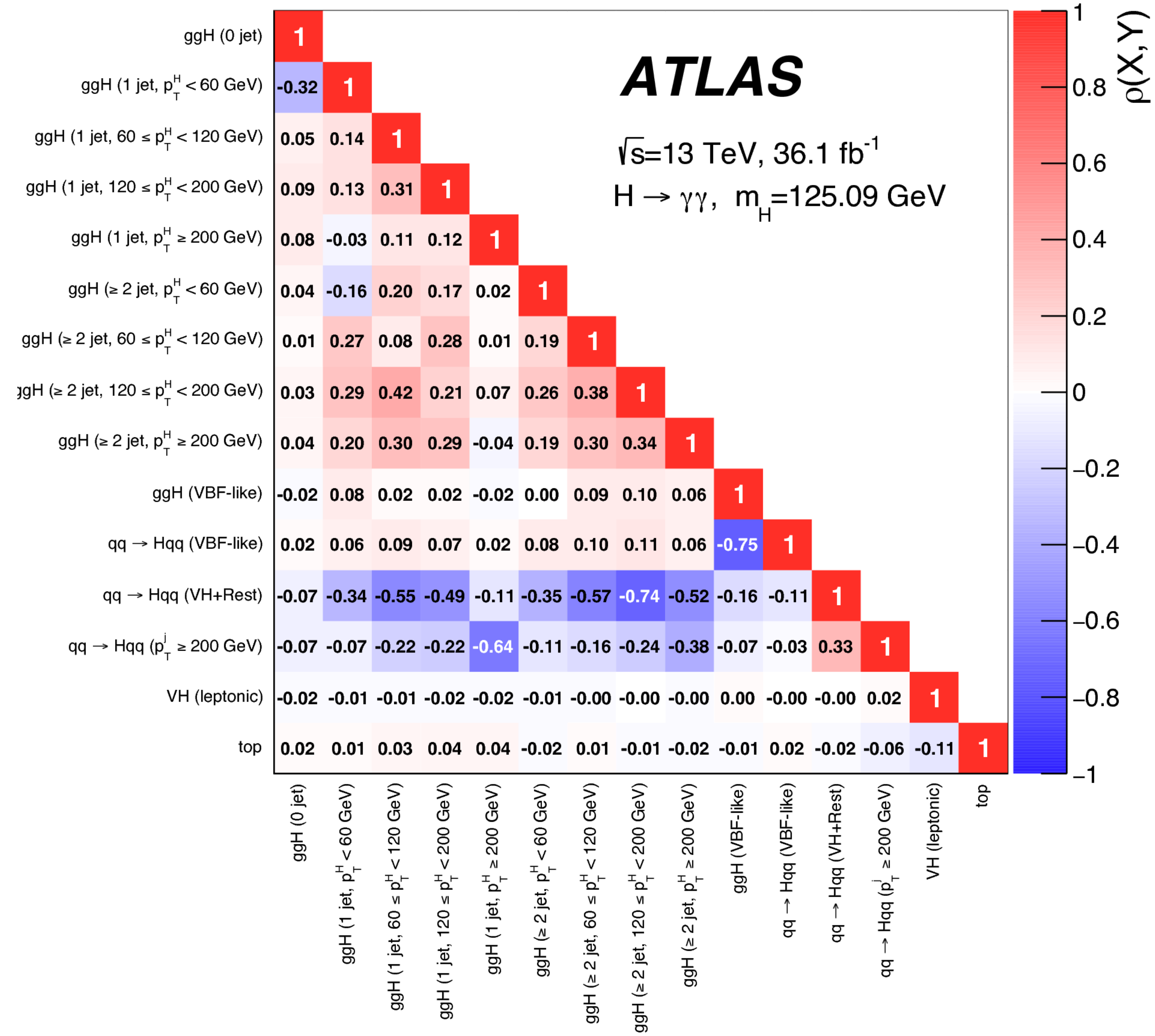
ggH + gg→Z(→qq)H

*** Measured cross sections will be correlated, so we must provide a correlation matrix alongside our final results for proper interpretation

H→ γγ STXS Results

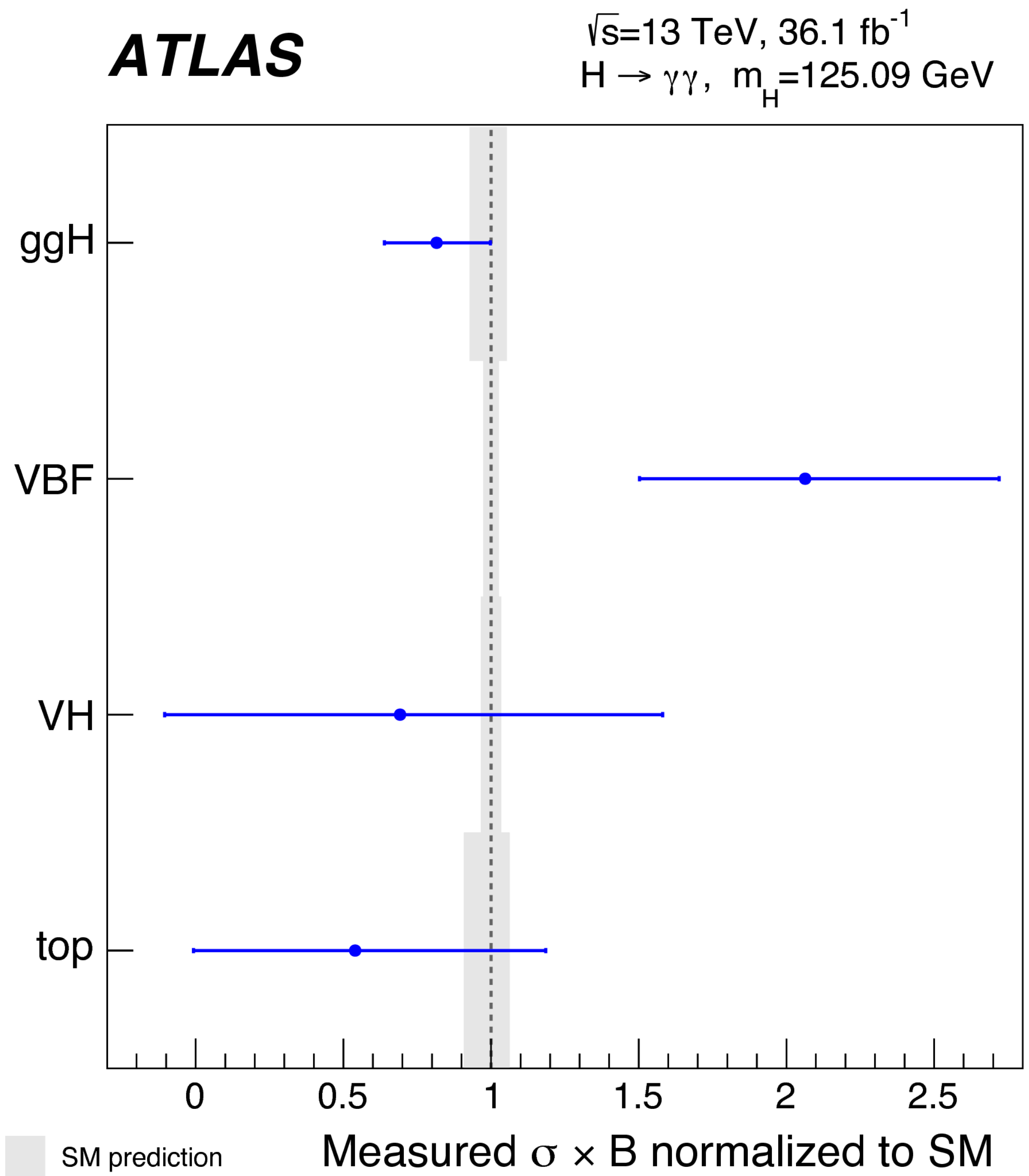


Correlation among measured σ

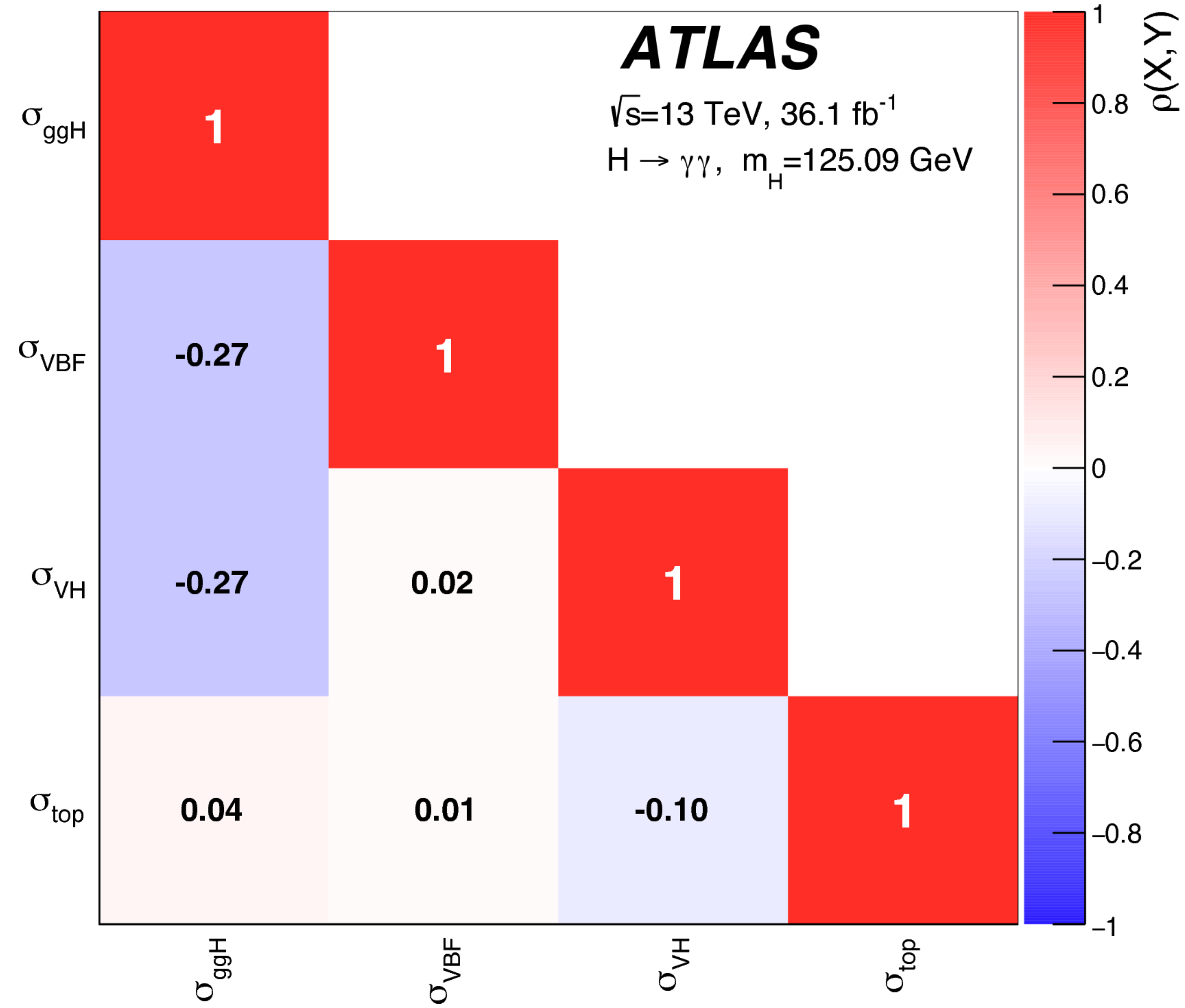


- Note that some truth categories have been “merged away” due to lack of sensitivity.
- A theorist could take the above and plug in his favorite BSM model to see how it compares to data

Measured σ for each production mode



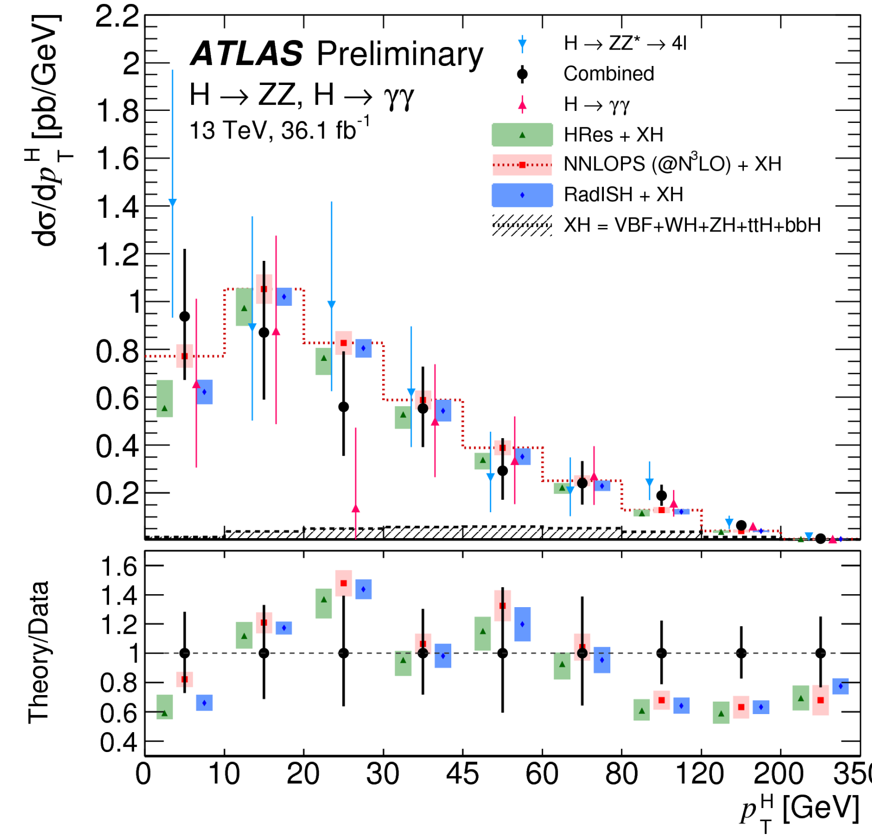
Correlation among measured σ

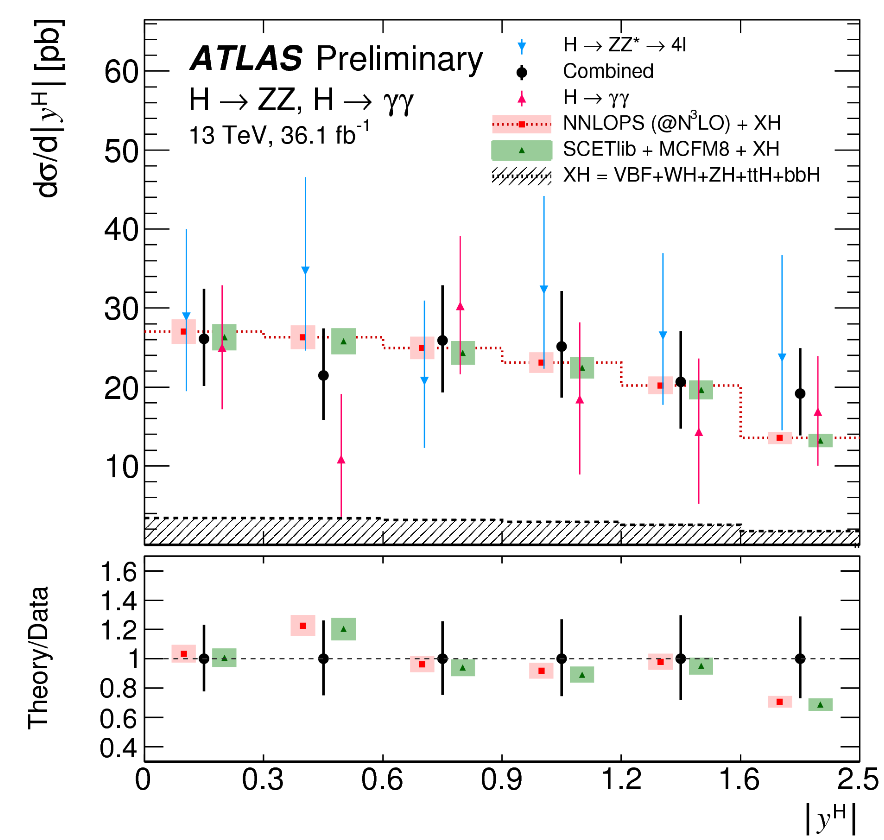


Process ($\lvert y_H \rvert < 2.5$)	Result [fb]	Uncertainty [fb] Total	Stat.	Exp.	Theo.	SM prediction [fb]
ggH	82	$^{+19}_{-18}$	± 16	$^{+7}_{-6}$	$^{+5}_{-4}$	102^{+5}_{-7}
VBF	16	$^{+5}_{-4}$	± 4	± 2	$^{+3}_{-2}$	8.0 ± 0.2
VH	3	± 4	$^{+4}_{-3}$	± 1	$^{+1}_{-0}$	4.5 ± 0.2
Top	0.7	$^{+0.9}_{-0.7}$	$^{+0.8}_{-0.7}$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

Conclusions

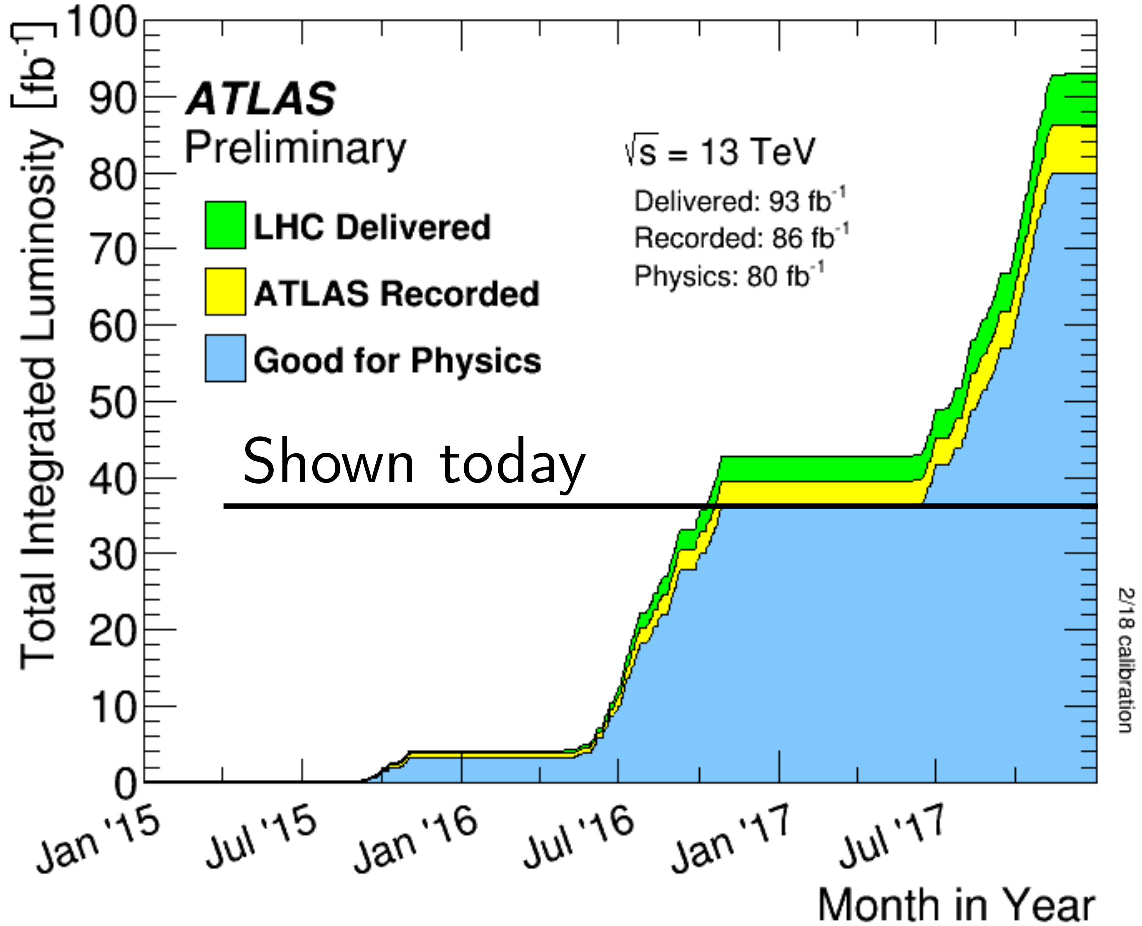
- Fiducial and differential cross section measurements in $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$ channels
- Combination of differential measurements
- Constraints on Effective Lagrangians using differential results
- $H\rightarrow\gamma\gamma$ Couplings using Simplified Template Cross Sections





Outlook – Run 2 Physics at 150 fb^{-1}

Run II so far... 2018...



- LHC has delivered 93 fb–1 of data so far in Run 2
- $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$ results using the first 36 fb^{-1} of this data
  - Adding 2017 data will double the dataset for these measurements
- 2018 data-taking period began again on April 28
  - Already reached a peak luminosity of 20×10^{33} cm^{-2}s^{-1}
  - Looking forward to Physics with 150 fb^{-1}!

Latest ATLAS 13 TeV Results

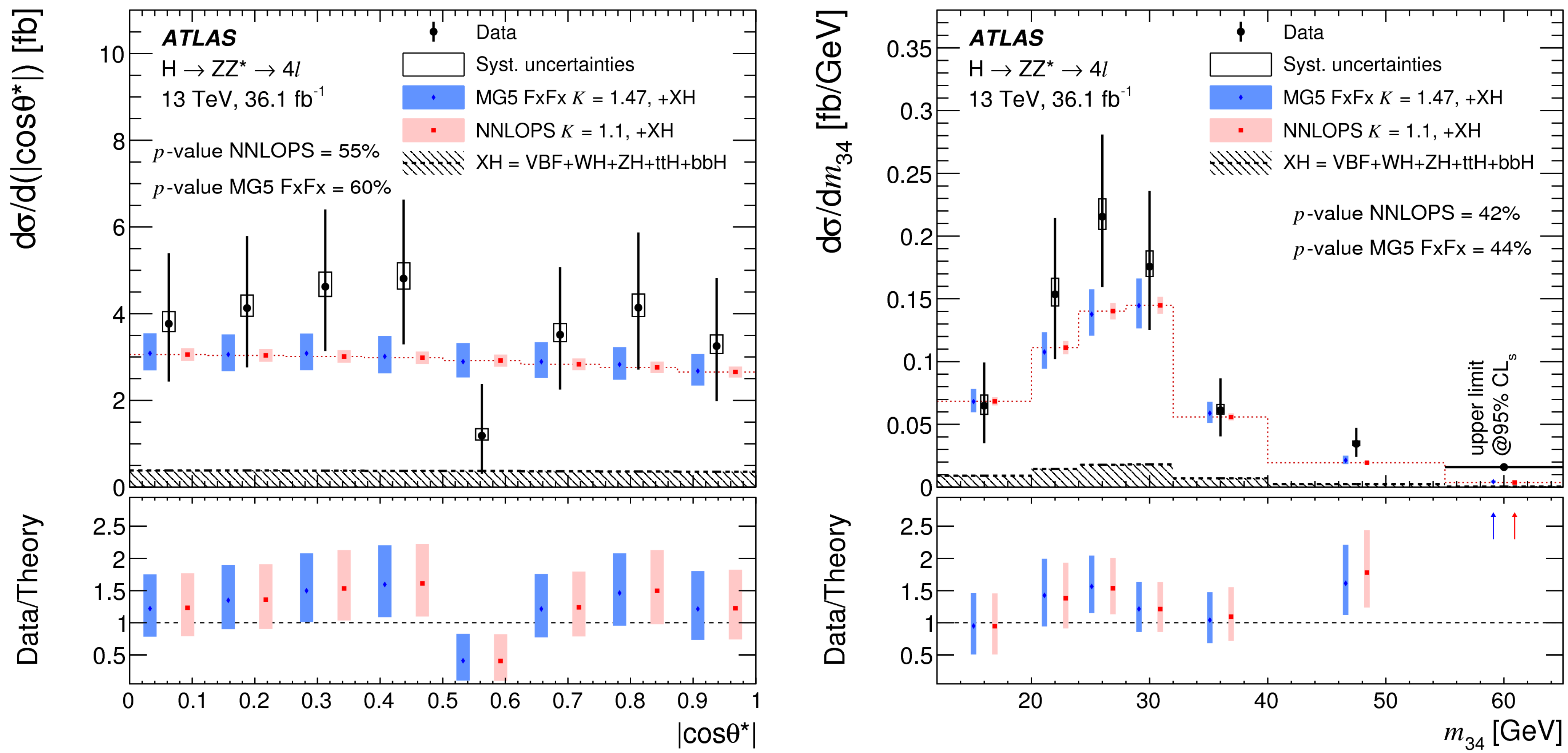
- Measurements of Higgs boson properties in the $\gamma\gamma$ decay channel (36 fb^{-1})
  - arXiv:1802.04146 (Feb 12, 2018 – Submitted to PRD)
  - Adds to previous conference note (ATLAS-CONF-2017-045 – July 2017)

- Combination of Fiducial and Differential Cross Sections ($\gamma\gamma$ and 4ℓ) (36.1 fb–1)
  - Conference note: http://cdsweb.cern.ch/record/2308390 (Mar 12, 2018)
  - Paper in final stages of preparation
  - Last differential combination of $\gamma\gamma$ and ZZ results was in December 2015 (3.2 fb^{-1})

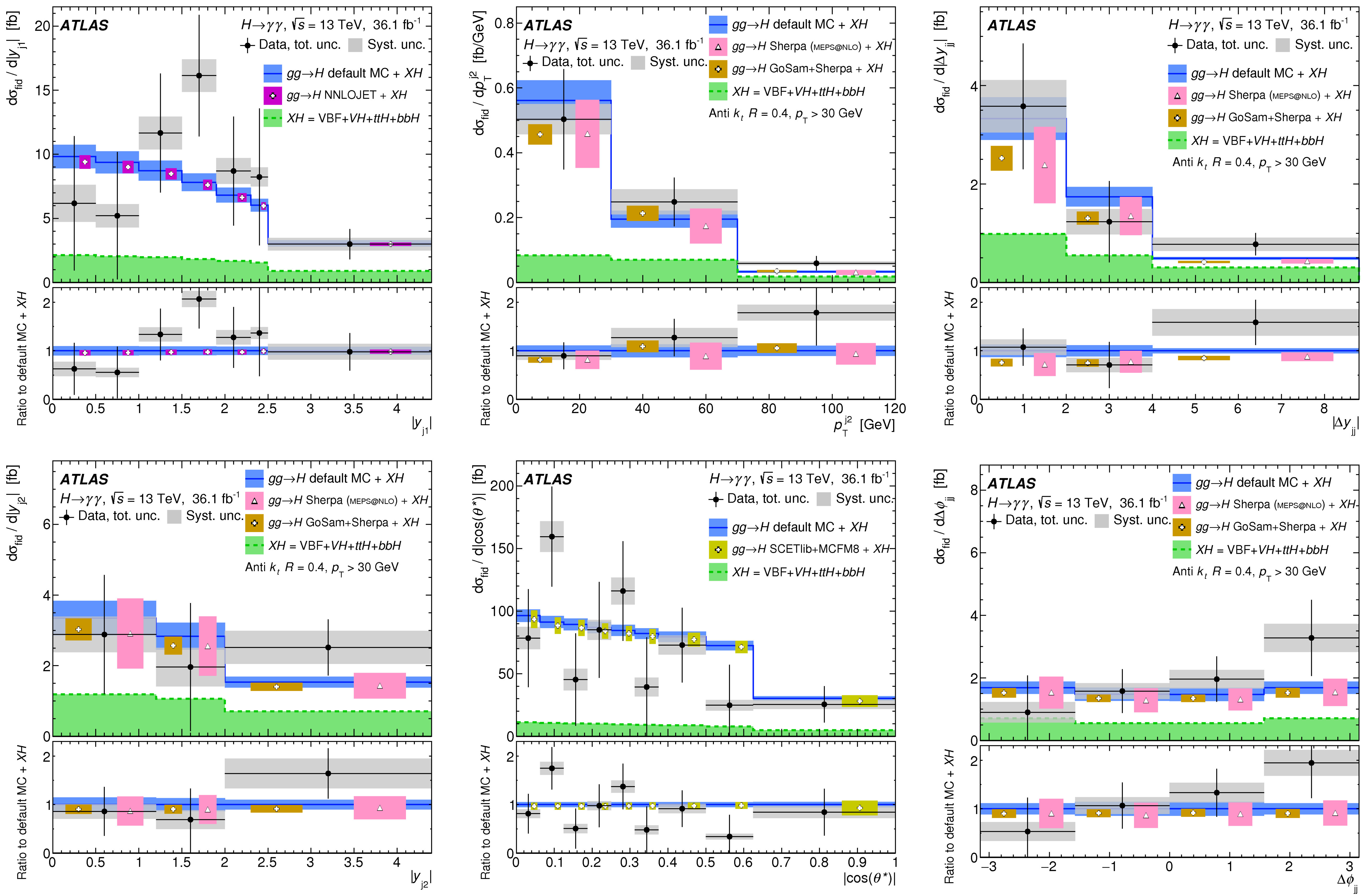
- Other recent results:
  - Couplings combination of $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$ (ATLAS-CONF-2017-047) – July 2017
  - Mass combination (ATLAS-CONF-2017-046) – July 2017
  - $H\rightarrow ZZ^*\rightarrow 4\ell$ Differential (JHEP 10 (2017) 132) – Aug 2017
  - $H\rightarrow ZZ^*\rightarrow 4\ell$ Couplings (JHEP 03 (2018) 095) – Dec 2017

BACKUP

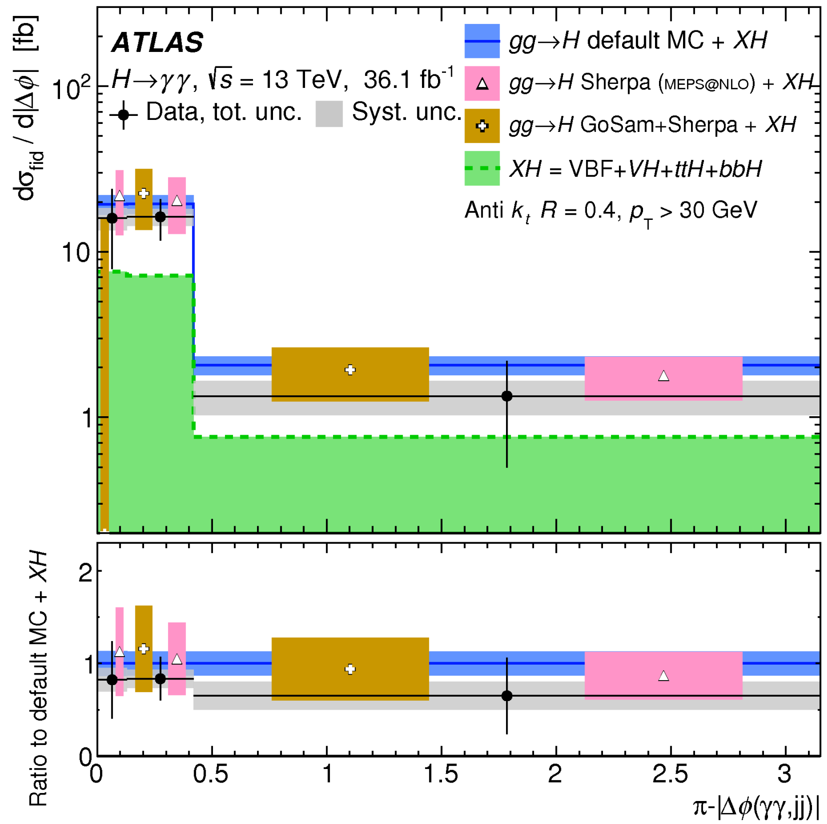
Additional H→ZZ*→4ℓ Variables

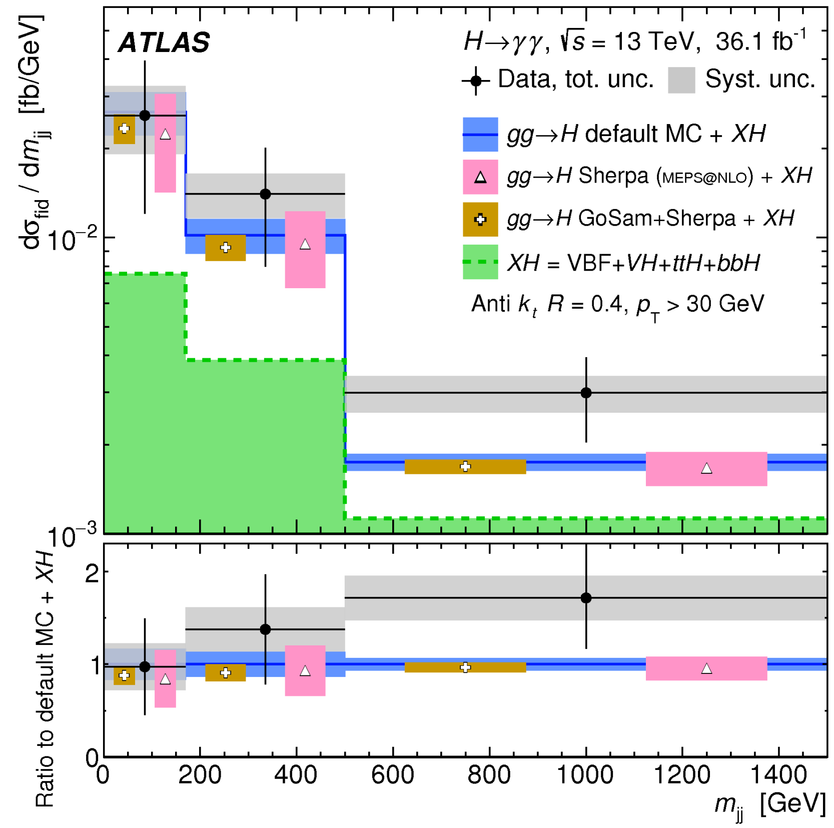


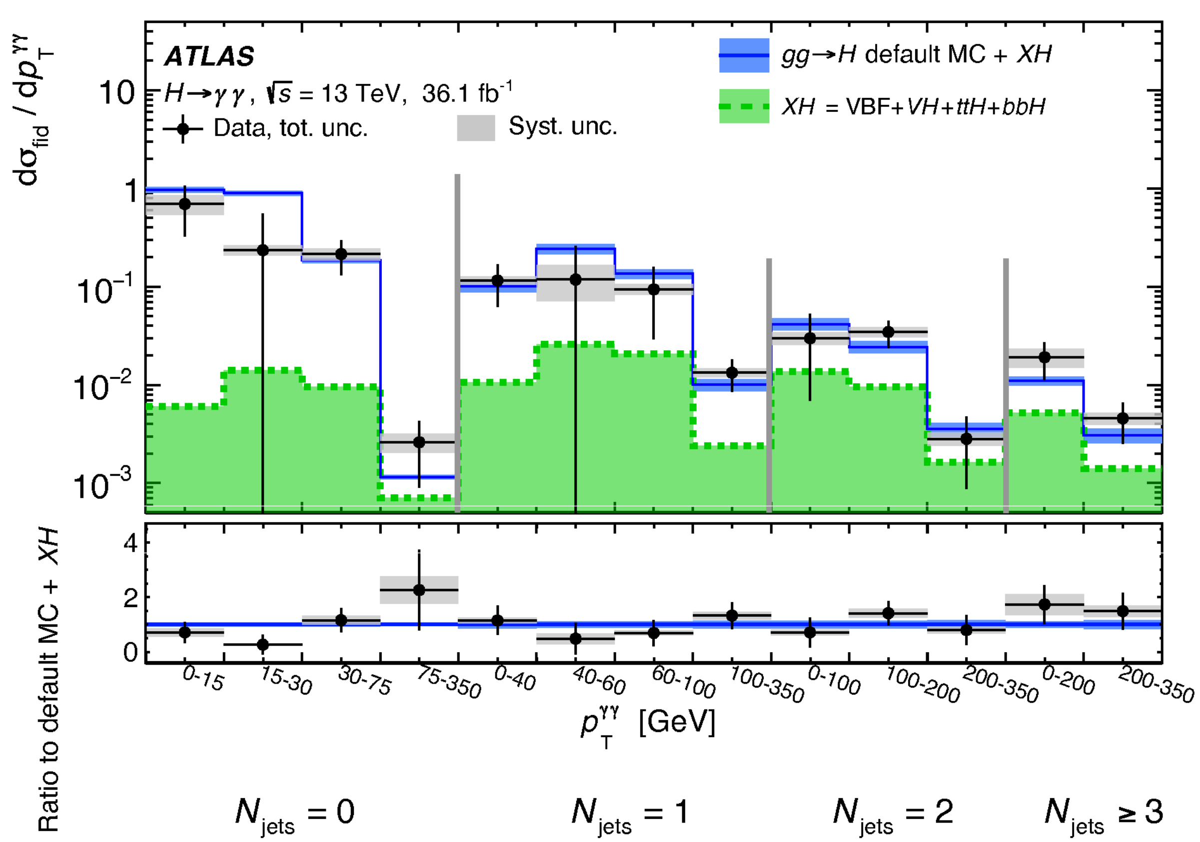
H→γγ Differential Variables

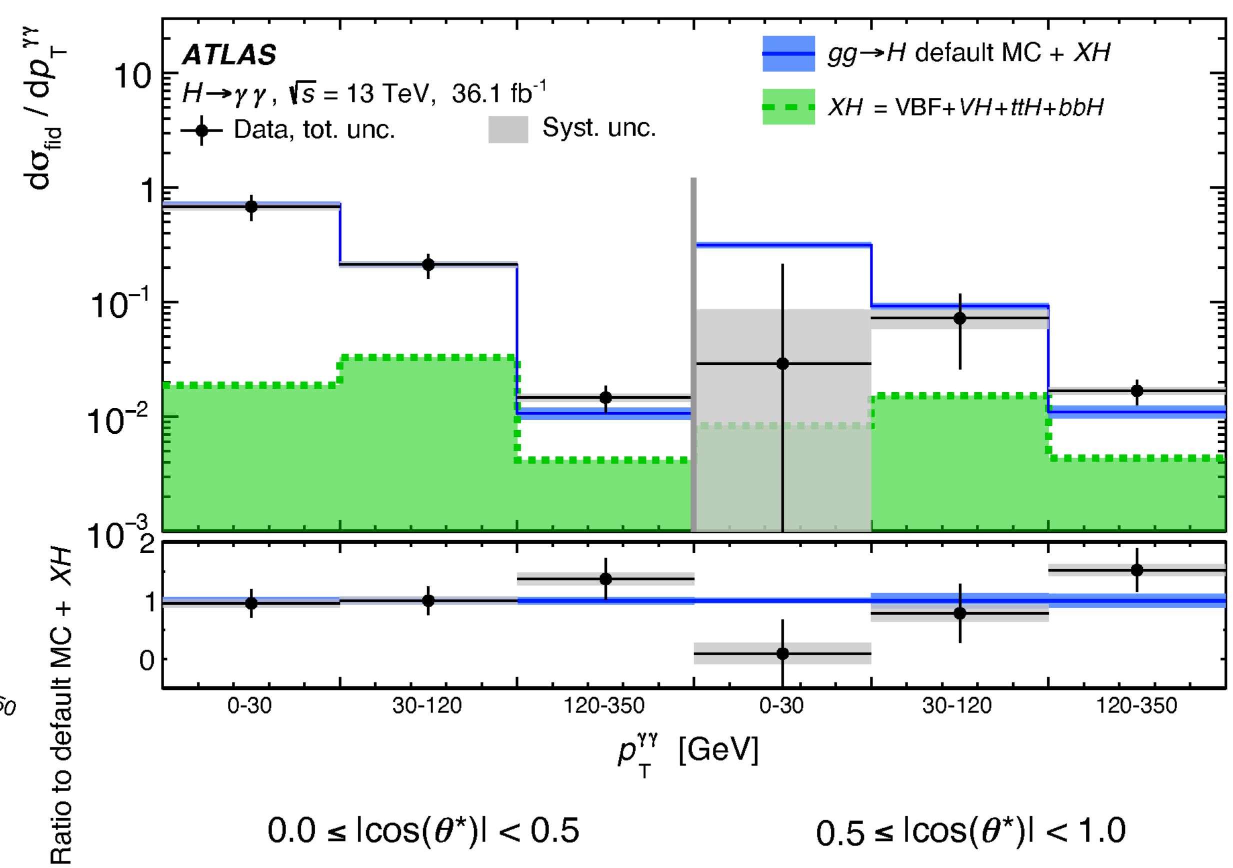


H→γγ Differential Variables

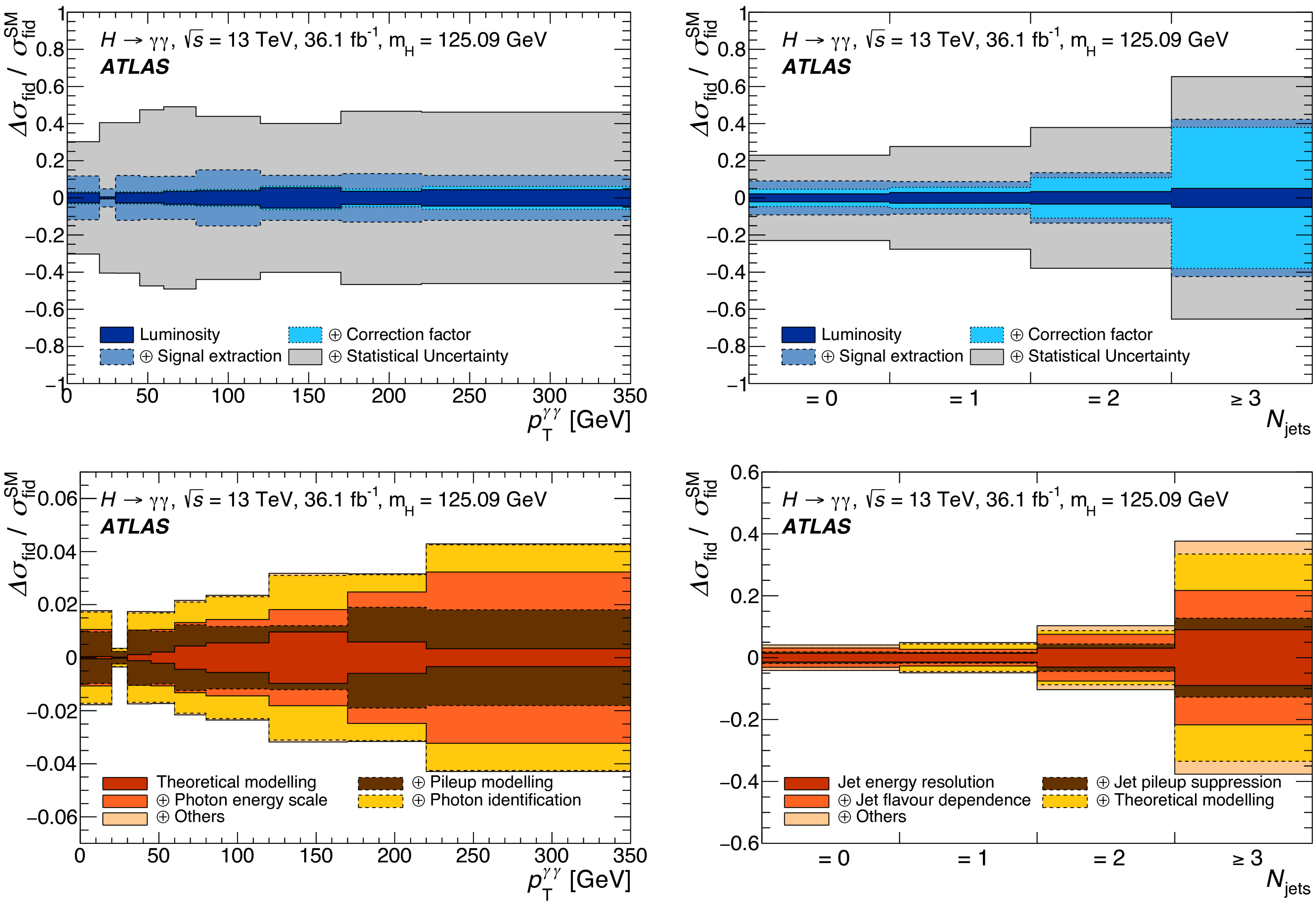








$H\rightarrow\gamma\gamma$ p_T and N_{jet} Systematic uncertainties



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- Monte Carlo used:

Process	Generator	Accuracy in QCD	PDF set
ggF	Powheg-Box v2 (NNLOPS) [19–22]	NNLO in $\|y^{H}\|$ [23], p_{T}^{H} consistent with HqT (NNLO+NNLL) [25, 26]	PDF4LHC [24]
VBF	Powheg-Box v2 [19–21, 27]	NLO	PDF4LHC
VH	Powheg-Box v2 (MiNLO) [19–21, 28]	NLO	PDF4LHC
$t\bar{t}H$	MadGraph5_aMC@NLO (v.2.2.3) [29]	NLO	CT10nlo [30]
$b\bar{b}H$	MadGraph5_aMC@NLO (v.2.3.3) [29, 31]	NLO	NNPDF23 [32]

- Cross section predictions used to normalize MC:

Process	Accuracy	Fraction [%]
ggF	N^{3}LO, NLO EW corrections [36–49]	87.4
VBF	NLO, NLO EW corrections [50–52] with approximate NNLO QCD corrections [53]	6.8
VH	NNLO [54, 55], NLO EW corrections [56]	4.1
$t\bar{t}H$	NLO [57–60]	0.9
$b\bar{b}H$	five-flavour: NNLO, four-flavour: NLO [61]	0.9

Reconstruction-level Categorization

Filled first (smallest σ)

	Category	Selection	
tH, ttH	tH lep 0fwd	$N_{\mathrm{lep}} = 1, N^{\mathrm{cen}}_{\mathrm{jets}} \leq 3, N_{\mathrm{b-tag}} \geq 1, N^{\mathrm{fwd}}_{\mathrm{jets}} = 0$ ($p^{\mathrm{jet}}_{\mathrm{T}} > 25$ GeV)	
	tH lep 1fwd	$N_{\mathrm{lep}} = 1, N^{\mathrm{cen}}_{\mathrm{jets}} \leq 4, N_{\mathrm{b-tag}} \geq 1, N^{\mathrm{fwd}}_{\mathrm{jets}} \geq 1$ ($p^{\mathrm{jet}}_{\mathrm{T}} > 25$ GeV)	
	ttH lep	$N_{\mathrm{lep}} \geq 1, N^{\mathrm{cen}}_{\mathrm{jets}} \geq 2, N_{\mathrm{b-tag}} \geq 1, Z_{\ell\ell}$ veto ($p^{\mathrm{jet}}_{\mathrm{T}} > 25$ GeV)	
	ttH had BDT1	$N_{\mathrm{lep}} = 0, N_{\mathrm{jets}} \geq 3, N_{\mathrm{b-tag}} \geq 1, \mathrm{BDT}_{\mathrm{ttH}} > 0.92$	**BDT**
	ttH had BDT2	$N_{\mathrm{lep}} = 0, N_{\mathrm{jets}} \geq 3, N_{\mathrm{b-tag}} \geq 1, 0.83 < \mathrm{BDT}_{\mathrm{ttH}} < 0.92$	
	ttH had BDT3	$N_{\mathrm{lep}} = 0, N_{\mathrm{jets}} \geq 3, N_{\mathrm{b-tag}} \geq 1, 0.79 < \mathrm{BDT}_{\mathrm{ttH}} < 0.83$	
	ttH had BDT4	$N_{\mathrm{lep}} = 0, N_{\mathrm{jets}} \geq 3, N_{\mathrm{b-tag}} \geq 1, 0.52 < \mathrm{BDT}_{\mathrm{ttH}} < 0.79$	
	tH had 4j1b	$N_{\mathrm{lep}} = 0, N^{\mathrm{cen}}_{\mathrm{jets}} = 4, N_{\mathrm{b-tag}} = 1$ ($p^{\mathrm{jet}}_{\mathrm{T}} > 25$ GeV)	
	tH had 4j2b	$N_{\mathrm{lep}} = 0, N^{\mathrm{cen}}_{\mathrm{jets}} = 4, N_{\mathrm{b-tag}} \geq 2$ ($p^{\mathrm{jet}}_{\mathrm{T}} > 25$ GeV)	
VH Lep	VH dilep	$N_{\mathrm{lep}} \geq 2$, 70 GeV $\leq m_{\ell\ell} \leq$ 110 GeV	
	VH lep HIGH	$N_{\mathrm{lep}} = 1$, $\lvert m_{e\gamma} - 89\,\mathrm{GeV}\rvert > 5$ GeV, $p_{\mathrm{T}}^{l+E_{\mathrm{T}}^{\mathrm{miss}}} > 150$ GeV	
	VH lep LOW	$N_{\mathrm{lep}} = 1$, $\lvert m_{e\gamma} - 89\,\mathrm{GeV}\rvert > 5$ GeV, $p_{\mathrm{T}}^{l+E_{\mathrm{T}}^{\mathrm{miss}}} < 150$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 1	
	VH MET HIGH	150 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 250 GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 9 or $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV	
	VH MET LOW	80 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 150 GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 8	
	jet BSM	$p_{\mathrm{T,j1}} > 200$ GeV	
VH Had	VH had tight	60 GeV $< m_{\mathrm{jj}} <$ 120 GeV, $\mathrm{BDT}_{\mathrm{VH}} > 0.78$	**BDT**
	VH had loose	60 GeV $< m_{\mathrm{jj}} <$ 120 GeV, $0.35 < \mathrm{BDT}_{\mathrm{VH}} < 0.78$	
VBF	VBF tight, high p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2, \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5, p_T^{Hjj} > 25$ GeV, $\mathrm{BDT}_{\mathrm{VBF}} > 0.47$	**BDT**
	VBF loose, high p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2, \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5, p_T^{Hjj} > 25$ GeV, $-0.32 < \mathrm{BDT}_{\mathrm{VBF}} < 0.47$	
	VBF tight, low p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2, \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5, p_T^{Hjj} < 25$ GeV, $\mathrm{BDT}_{\mathrm{VBF}} > 0.87$	**BDT**
	VBF loose, low p_T^{Hjj}	$\Delta\eta_{\mathrm{jj}} > 2, \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\mathrm{j1}} + \eta_{\mathrm{j2}})\rvert < 5, p_T^{Hjj} < 25$ GeV, $0.26 < \mathrm{BDT}_{\mathrm{VBF}} < 0.87$	
ggH	ggH 2J BSM	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV	
	ggH 2J HIGH	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \in [120, 200]$ GeV	
	ggH 2J MED	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \in [60, 120]$ GeV	
	ggH 2J LOW	≥ 2 jets, $p_{\mathrm{T}}^{\gamma\gamma} \in [0, 60]$ GeV	
	ggH 1J BSM	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV	
	ggH 1J HIGH	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \in [120, 200]$ GeV	
	ggH 1J MED	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \in [60, 120]$ GeV	
	ggH 1J LOW	$= 1$ jet, $p_{\mathrm{T}}^{\gamma\gamma} \in [0, 60]$ GeV	
	ggH 0J FWD	$= 0$ jets, one photon with $\lvert\eta\rvert > 0.95$	
	ggH 0J CEN	$= 0$ jets, two photons with $\lvert\eta\rvert \leq 0.95$	

Filled last (largest σ)

Relationship between truth bins and reco categories

- The number of signal in a given reconstruction **c**ategory s_c is the sum of the contributions from each truth bin:

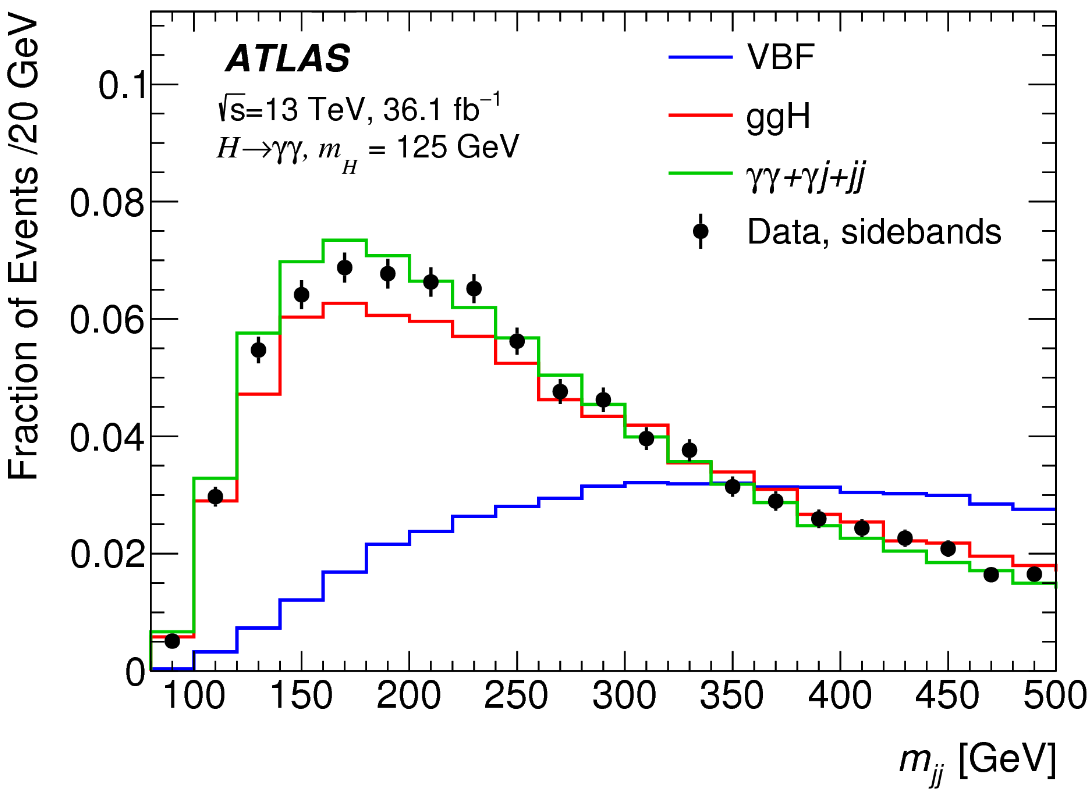
$$s_c = \mathcal{L} \cdot \sum_t \sigma_t^{\gamma\gamma} \epsilon_{tc}$$

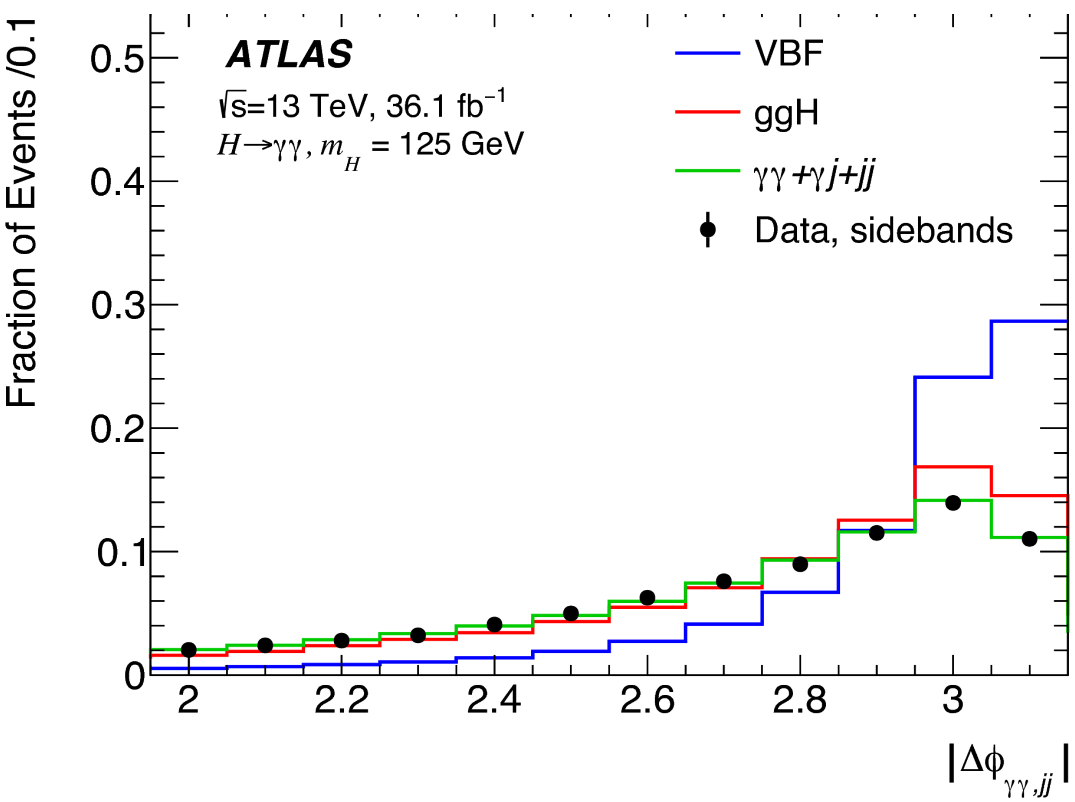
acceptance factor

- L is luminosity
- $\sigma_t^{\gamma\gamma}$ is the cross section $\times$ BR of a given truth category **t**
  - **These are the parameters we want to find**
- Acceptance factor for a given truth bin t to fall into reco category c: $\varepsilon_{tc} = n_{tc}/n_t$, estimated using MC
  - (introduces small migration theory uncertainty)
- Similarities with differential cross sections: $\sigma_i^{\text{fid}} = \dfrac{N_{\text{data},i} - N_{\text{bkg},i}}{\mathcal{L}_{\text{int}} \cdot C_i}$
- Want our reconstruction categories to be as pure as possible in a single truth category $\rightarrow$ analogy to bin-to-bin migrations in differential XS

Using BDTs in the reconstruction categories

2 of the 6 input variables





- 4 BDTs are used to enhance certain production processes (ttH, VH Hadronic, VBF (x2)
- Can significantly improve significance
- We try to avoid introducing large uncertainties by avoiding variables that are poorly described by theory

BDT Score (VBF high-$P_{T,Hjj}$)