Higgs production with jets and with jet vetoes

A brief Overview

IPPP: Jet Vetoes and Multiplicity Observables

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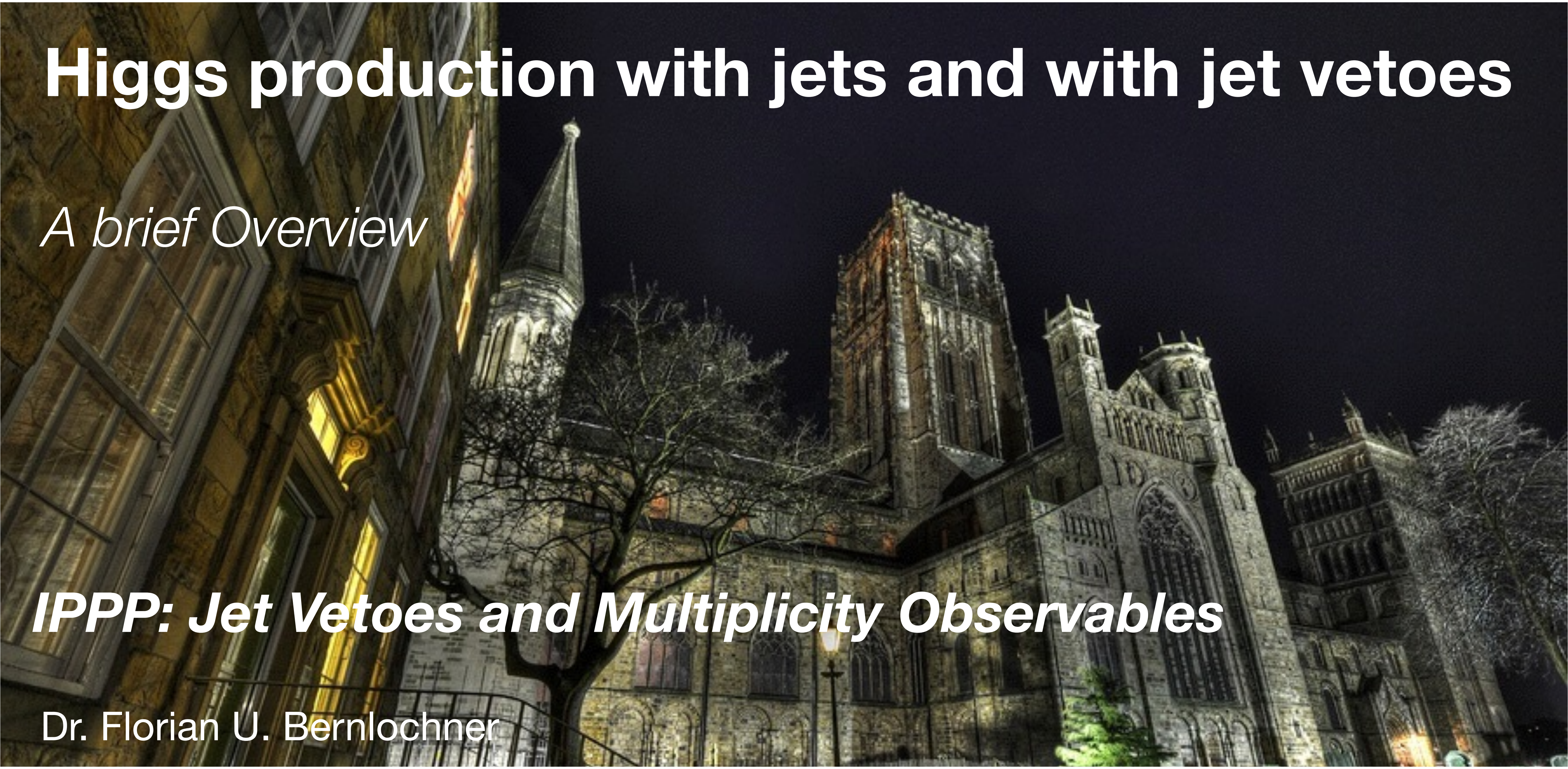
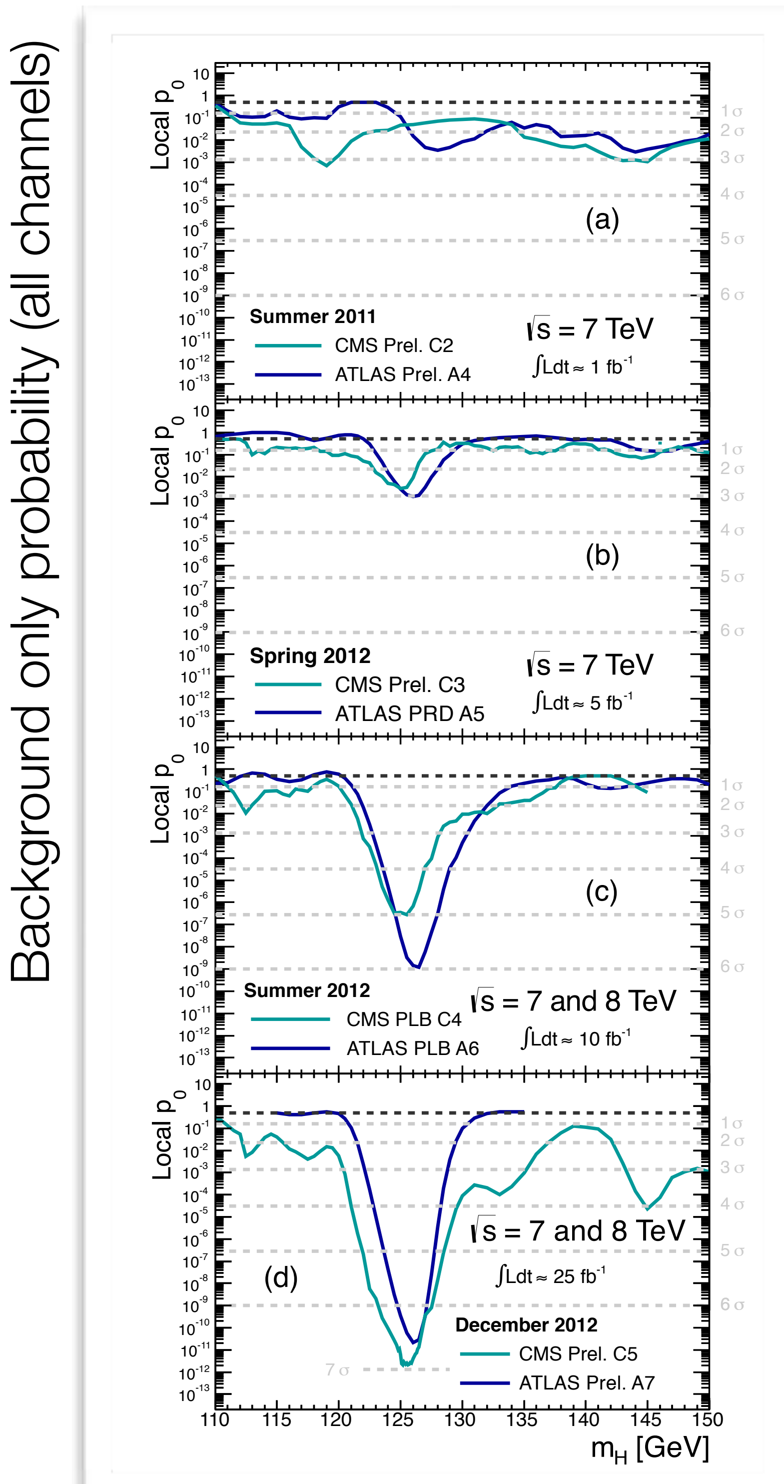


ATLAS

The (discovered) Higgs just turned two!



PDG Higgs Review, M. Carena, C. Grojean, M. Kado, V. Sharma

* A nice step-by-step discovery by **ATLAS** + **CMS**
    * **Summer 2011**: focus mainly on limits
    * **Spring 2012**: first deviations from background only hypothesis ($\sim 10^{-2}$ - 10^{-3} = >2-3 σ)
    * **Summer 2012: >5σ deviation** **Discovery!**
    * **End of 2012 & Run 1 of the LHC: >7σ**
        * **Final ATLAS & CMS analyses & combinations still in preparation**
* So far what we see is compatible with the SM Higgs Boson.
* **Jets** & **Categorizations with Jets** played an important role in gaining sensitivity.

Talk Overview

Jet Reconstruction & Simulation

Categories in **coupling measurements**

Higgs + jet cross section measurements

Run 2 Outlook

* Plan to walk you through **4** aspects of Higgs + Jet production *(sketched on the left)*

* Jets play crucial role in **enhancing sensitivity** in most Higgs analyses

* Crucial aspect: Jet reconstruction and relating **reconstructed jets** $\Longleftrightarrow$ **jet cross sections**

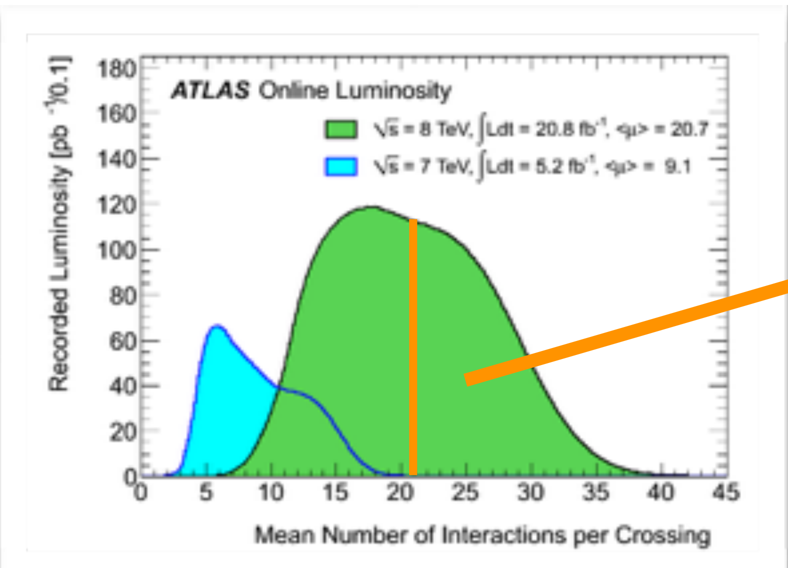
* **Uncertainties** and **correlations** to cross section predictions will be more crucial in Run 2 of LHC

Jet Reconstruction & Simulation

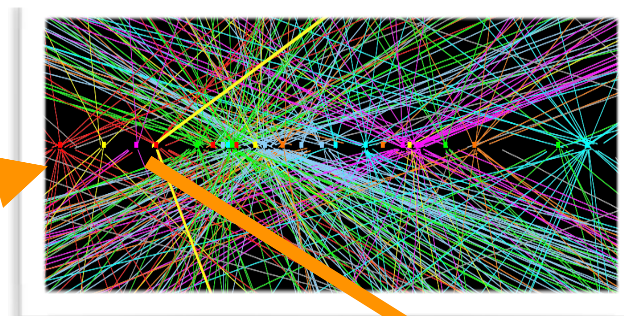
Reco. & simulation → Coupling meas. → Higgs + Jets meas. → Run 2

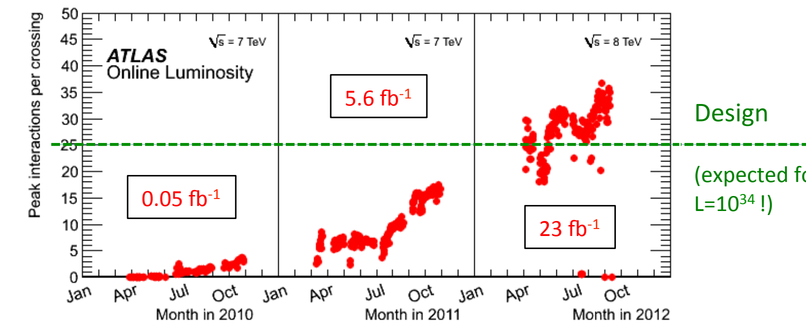
Proton-Proton collisions and Jets

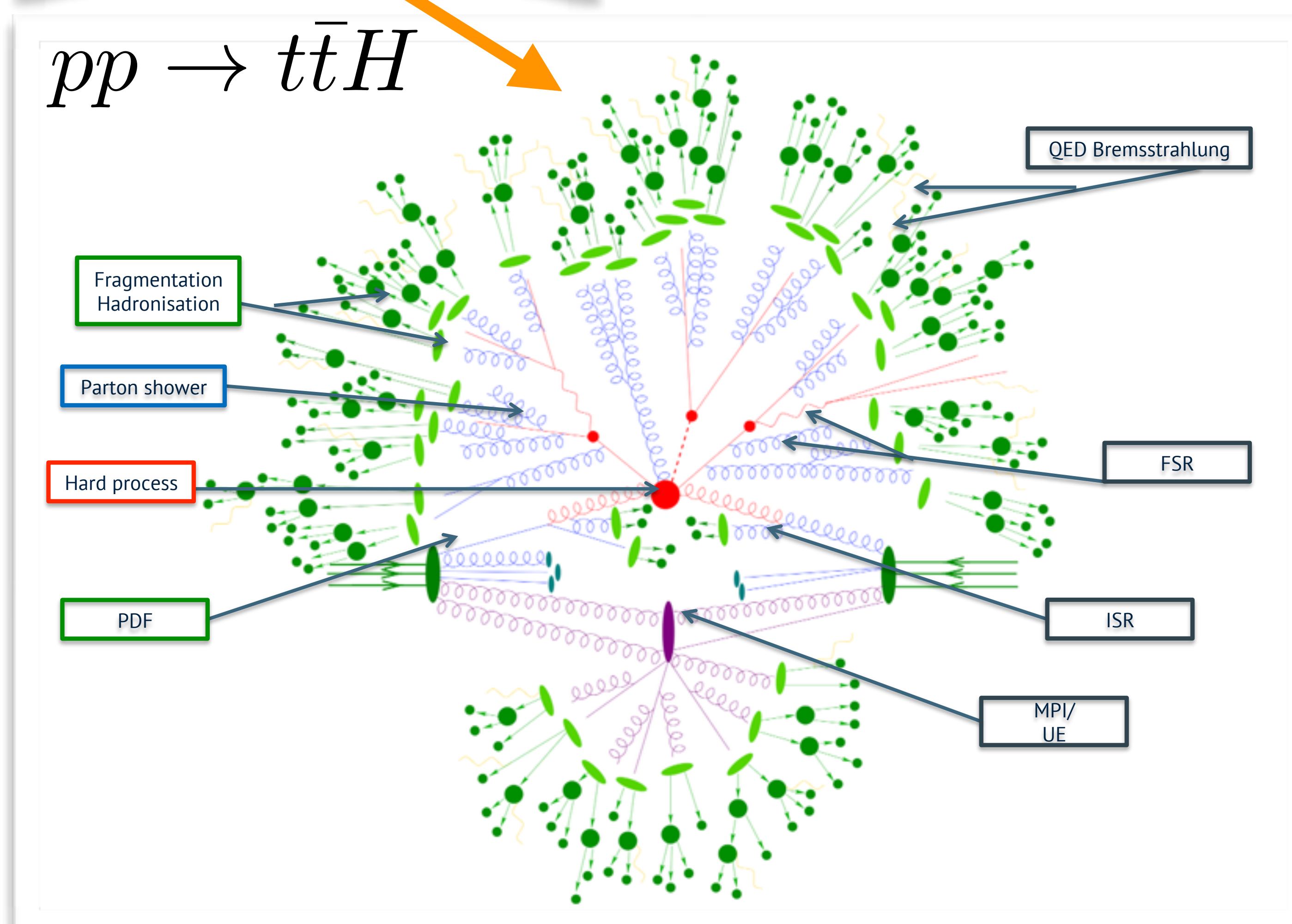
Jets in proton-proton collisions have many origins:



Peak interactions & Reconstructed vertices from a typical bunch-crossing







1. **Initial-state radiation**
2. **final-state radiation**
3. **Fragmentation**
4. **N(..)LO corrections to hard scatter + Parton-Shower**
5. **Multi-parton interaction**
6. **Pile-up**

→ Simulation & proper modelling of all of these aspects crucial

Pile-up Jets in 2012

* Most analyses use Jet-Vertex-fraction (JVF) to reject pile-up jets.

$$\mathrm{JVF} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_0) + \sum_{n\geq 1}\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_n)}$$

* Cut often used in Higgs analyses is **|JVF| > 0.25 or 0.5 for jets with |η| < 2.4**

absolute value to include jets without tracks (JVF =-1)

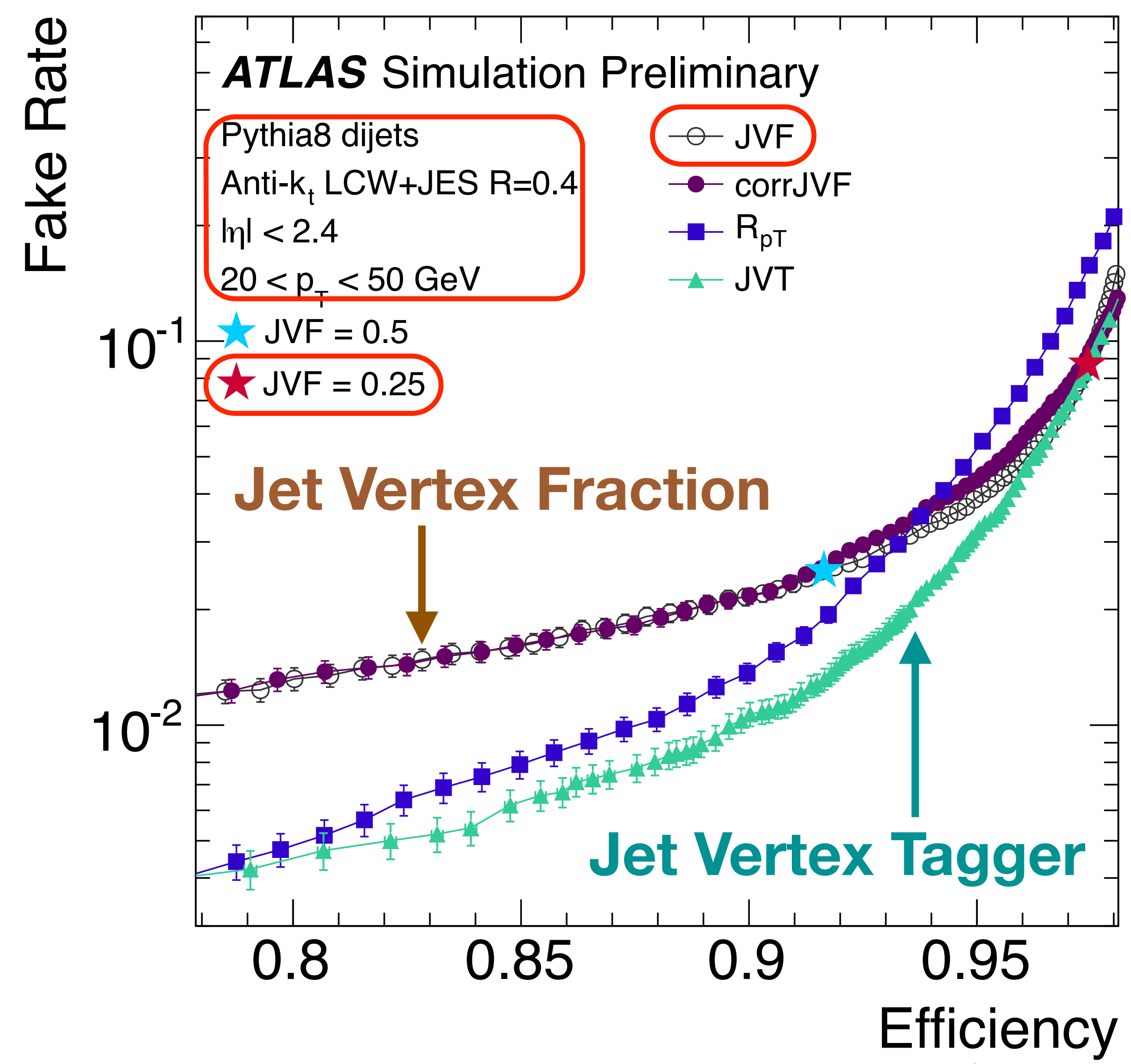
* Results in **P(pile-up jet| jet) ~ 4-6%** for typical jet selections.

selected at **p_T > 30-25** GeV

* Much work went into understanding the impact of pile-up.

* Many improvements did not make it into the final 2012 measurements.

P(selected pile-up jet | all pileup jet)

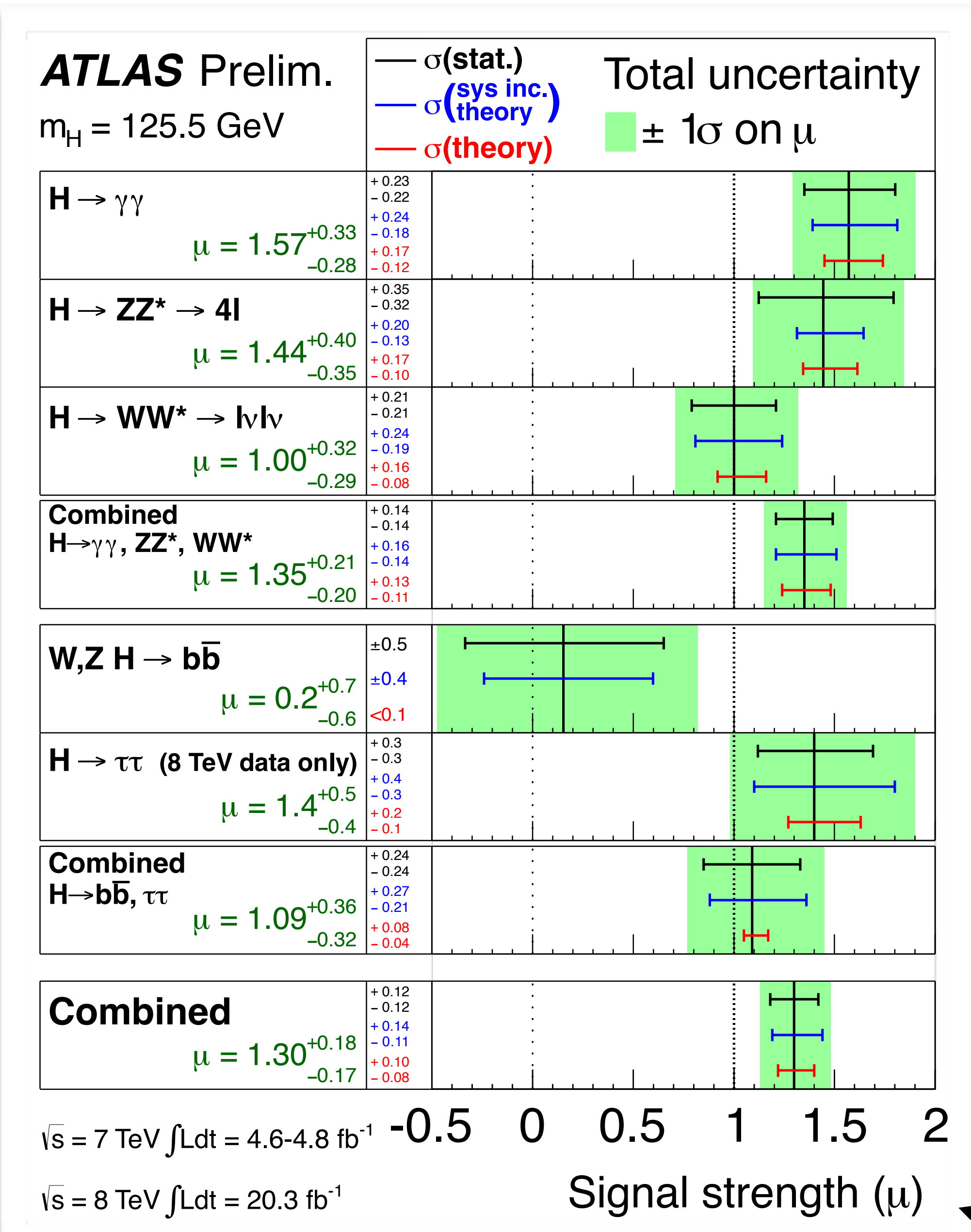


P(selected hard scatter jet | all hard scatter jet)

Coupling strength measurements using jet categories

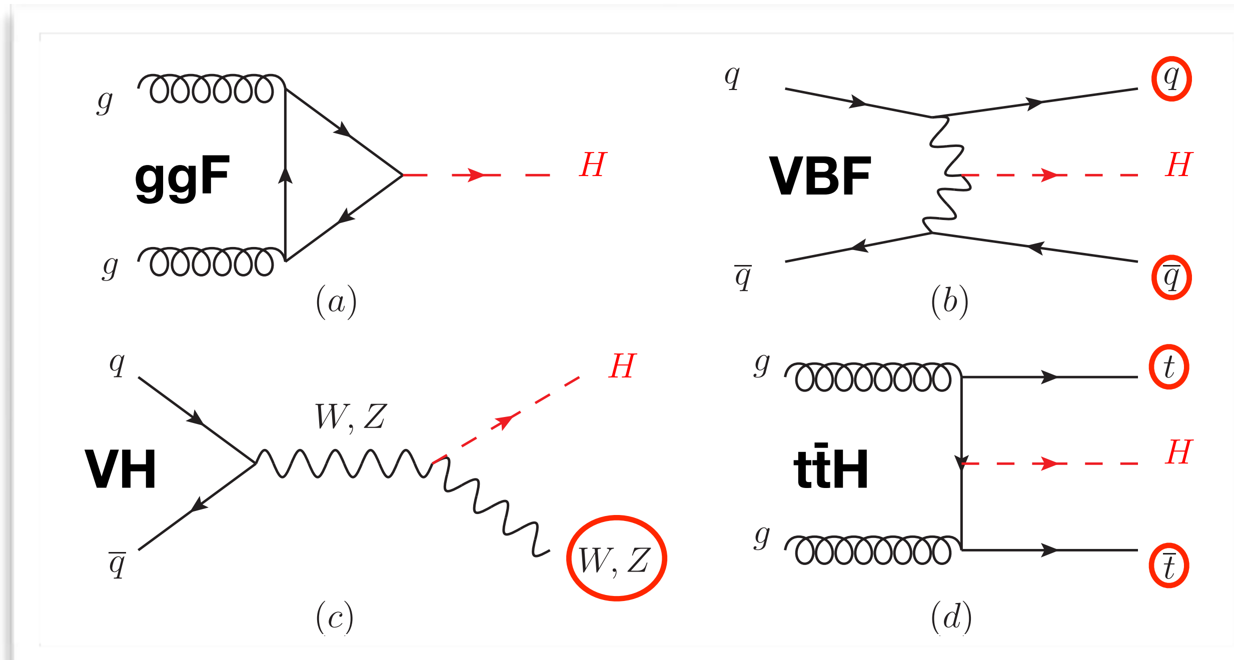
Reco. & simulation → **Coupling meas.** → Higgs + Jets meas. → Run 2

Overview of Channels



* Most Analyses don't use jets to 'Tag' a Higgs (like trigger on VBF topologies), but the Higgs decay products. ***Exception:* H →ττ (see Backup)**

* Most channels use jets to gain sensitivity to μ or to test coupling strength for certain production mechanisms



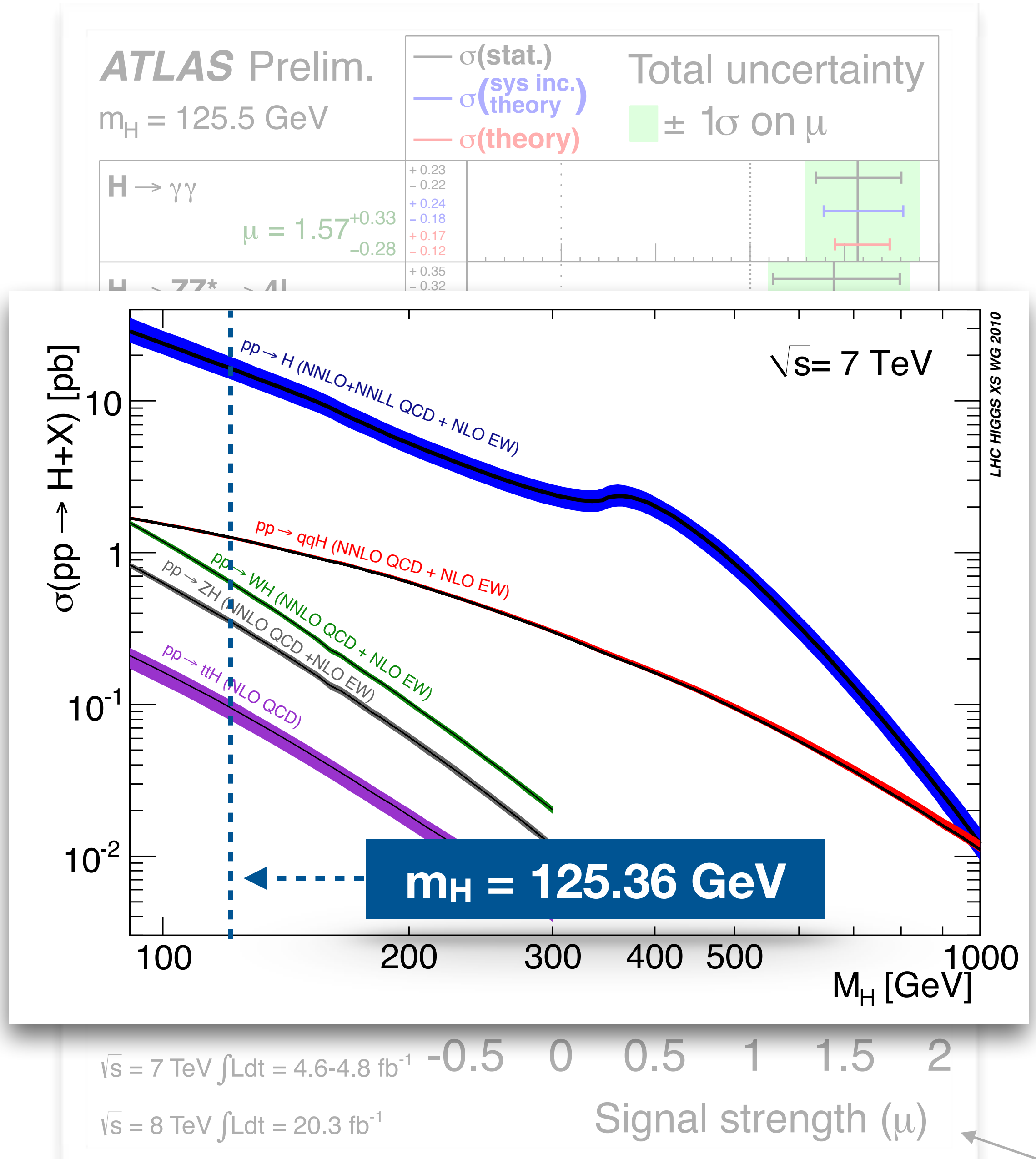
$$\mu = \frac{(\sigma \times \mathcal{BF})_{\text{obs.}}}{(\sigma \times \mathcal{BF})_{\text{SM}}}$$

Signal or Coupling strength

***other ATLAS* search channels: H → μμ, H → Zγ, H → Invisible**

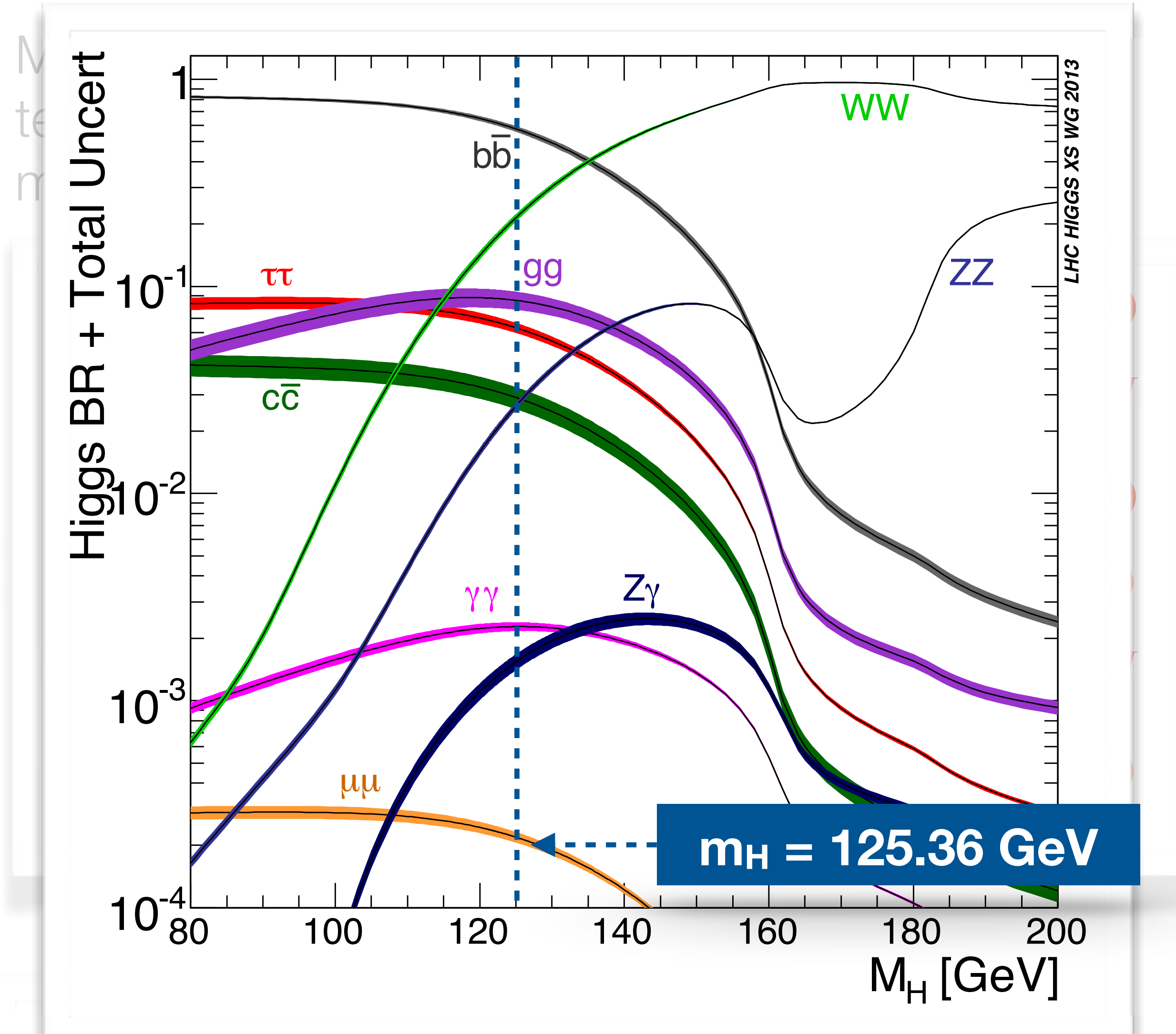
* Brief Overview of **jet categories** of H→γγ and H→WW

Overview of Channels



- Analyses don't use jets to 'Tag' a Higgs (like trigger on VBF topologies), but the Higgs decay products.

- M… te… m…



$\mu = \ldots / (\sigma \times \mathcal{BF})_{\mathrm{SM}}$

categories

H

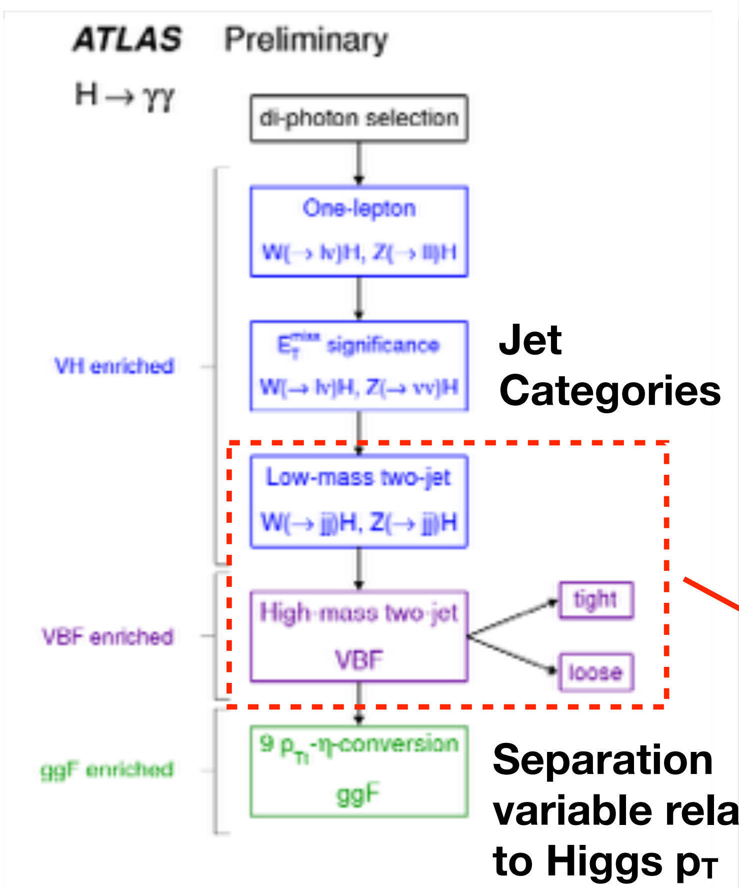
other ATLAS channels: H

Signal or Coupling strength

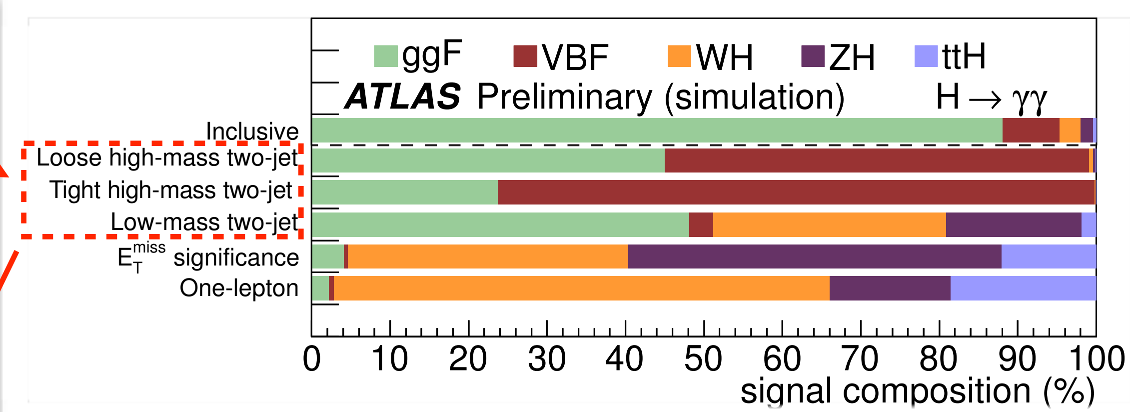
Will be updated soon!

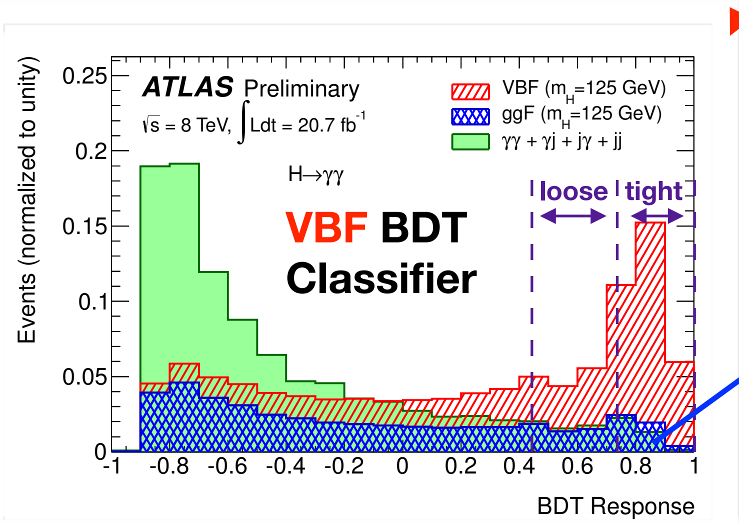
Jet categories in H→ γ γ

[ATLAS-CONF-2013-012](http://cds.cern.ch/record/1523698)
http://cds.cern.ch/record/1523698



- 3 jet categories used for **low mass VH (W→jj & Z→jj); VBF loose & tight**
  for forward jets (2.2 < |η| < 4.5)
- **at least two jets** with p_T > **25/30 GeV** and |JVF| > 0.25
- Excellent sensitivity → **VBF tight highest S/B of all categories**

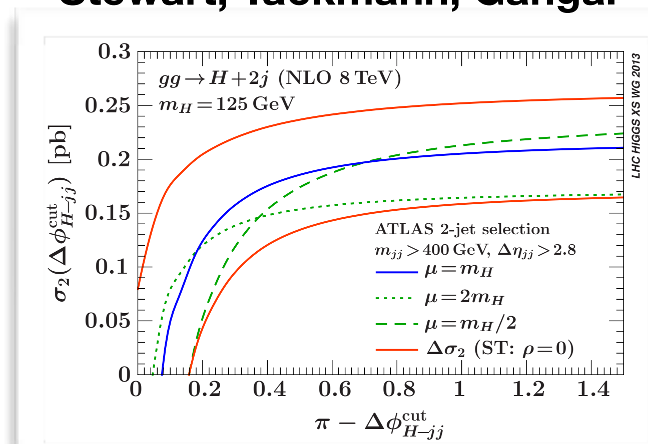




But need good control over jets

theory uncertainties from **ggF contamination important**

Stewart, Tackmann, Gangal



http://arxiv.org/pdf/1307.1347v2.pdf

Jet categories in H→ WW(lvlv)

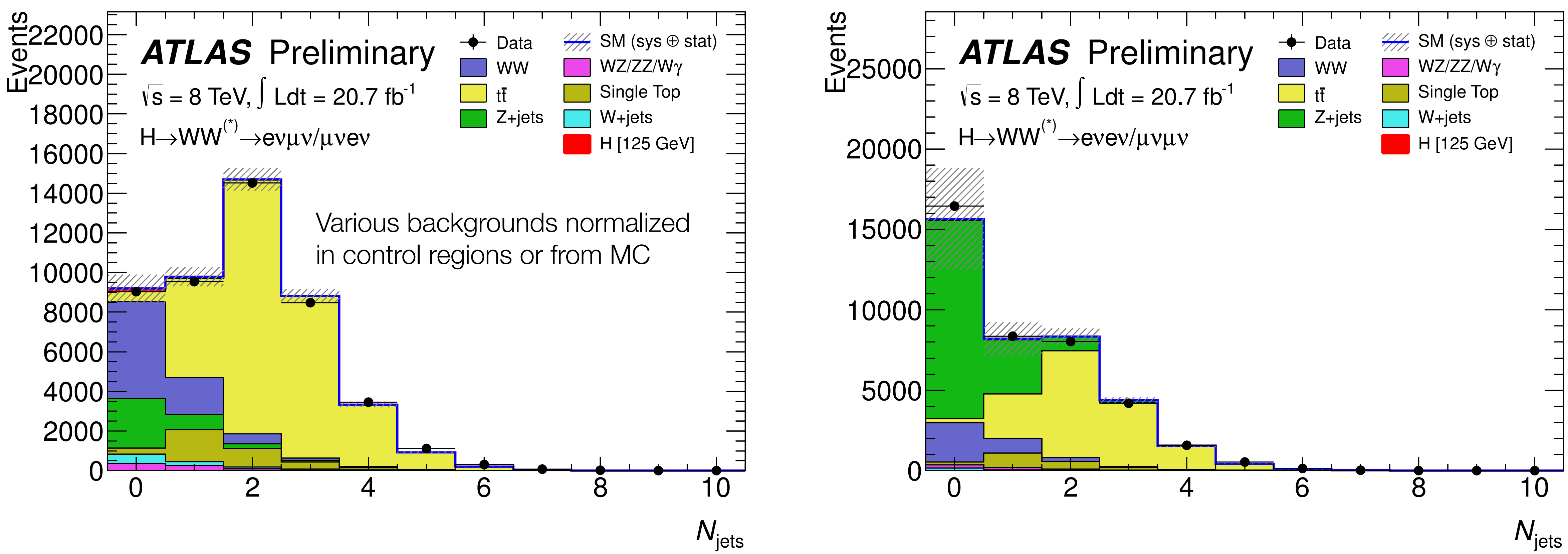
Will be updated soon!

ATLAS-CONF-2013-030

http://cds.cern.ch/record/1527126

* Although WW branching fraction sizeable, extremely challenging analysis.

Same flavour & opposite flavour H → WW(lvlv) Candidates after pre-selection



(a) $N_{\rm jet}$ distribution for $e\mu + \mu e$ (b) $N_{\rm jet}$ distribution for $ee + \mu\mu$

Very different background and signal composition as a function of jet multiplicities. One jet bin dominated by ggF + 1 jet.

Jet categories in H→ WW(lvlv)

Will be updated soon!

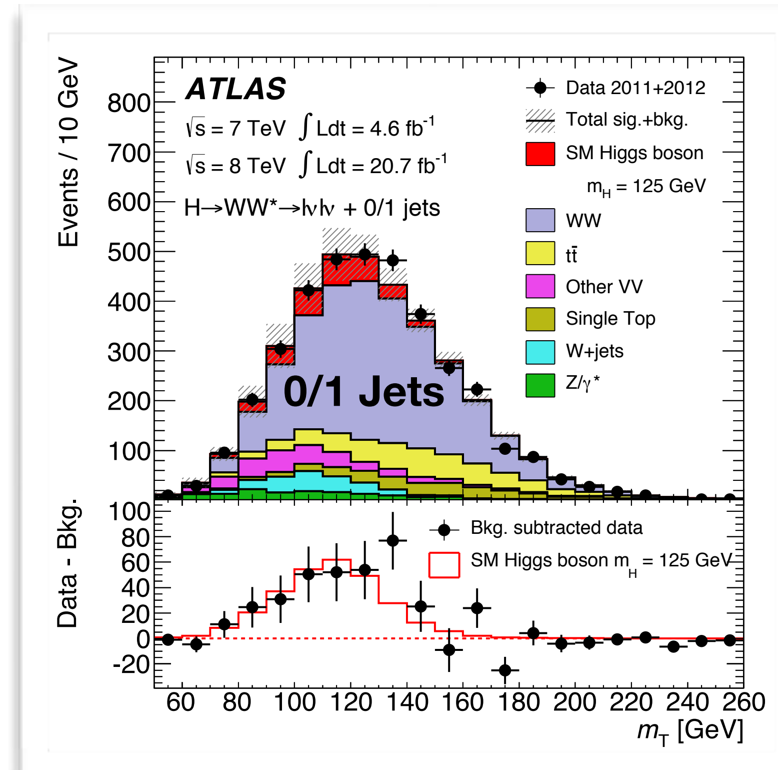
ATLAS-CONF-2013-030
http://cds.cern.ch/record/1527126

* Make use of this and split into different jet bins:

Details of Categories

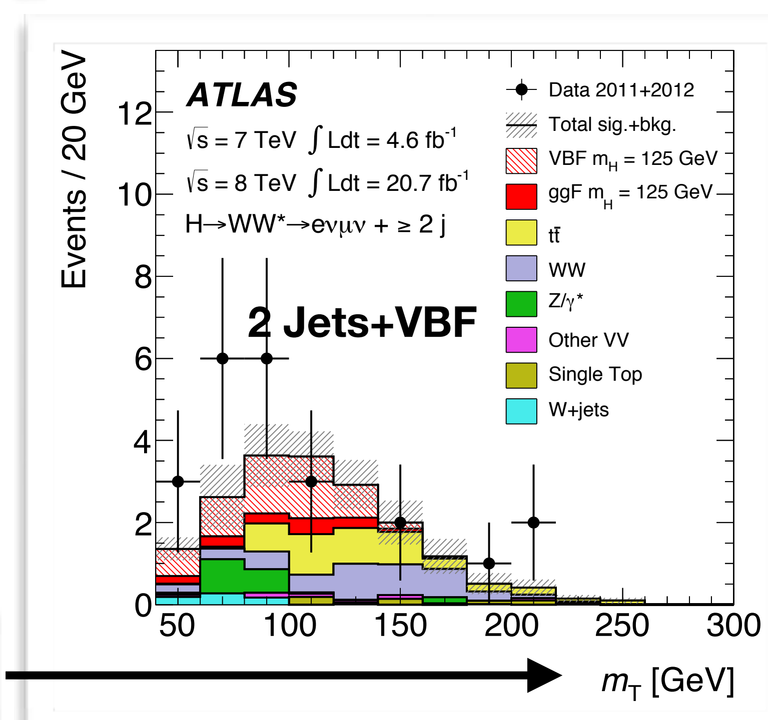
Category	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_T^{lead} > 25$ and $p_T^{sublead} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{T,rel}^{miss} > 25$ $ee + \mu\mu$: $E_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $p_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $f_{recoil} < 0.05$	$e\mu + \mu e$: $E_{T,rel}^{miss} > 25$ $ee + \mu\mu$: $E_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $p_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $f_{recoil} < 0.2$	$e\mu + \mu e$: $E_T^{miss} > 20$ $ee + \mu\mu$: $E_T^{miss} > 45$ $ee + \mu\mu$: $E_{T,STVF}^{miss} > 35$ -
General selection	- $\lvert \Delta\phi_{\ell\ell,MET} \rvert > \pi/2$ $p_T^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_T^{tot} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert \Delta y_{jj} \rvert > 2.8$ No jets ($p_T > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_T	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_T	$m_{\ell\ell} < 60$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ - Fit m_T

H→WW Categorization Overview



* Transverse mass used as discriminating variable (calculated from missing Et & dilepton system)

* Correlation between theory uncertainties from ggF between different jet bins crucial.



Transverse Mass

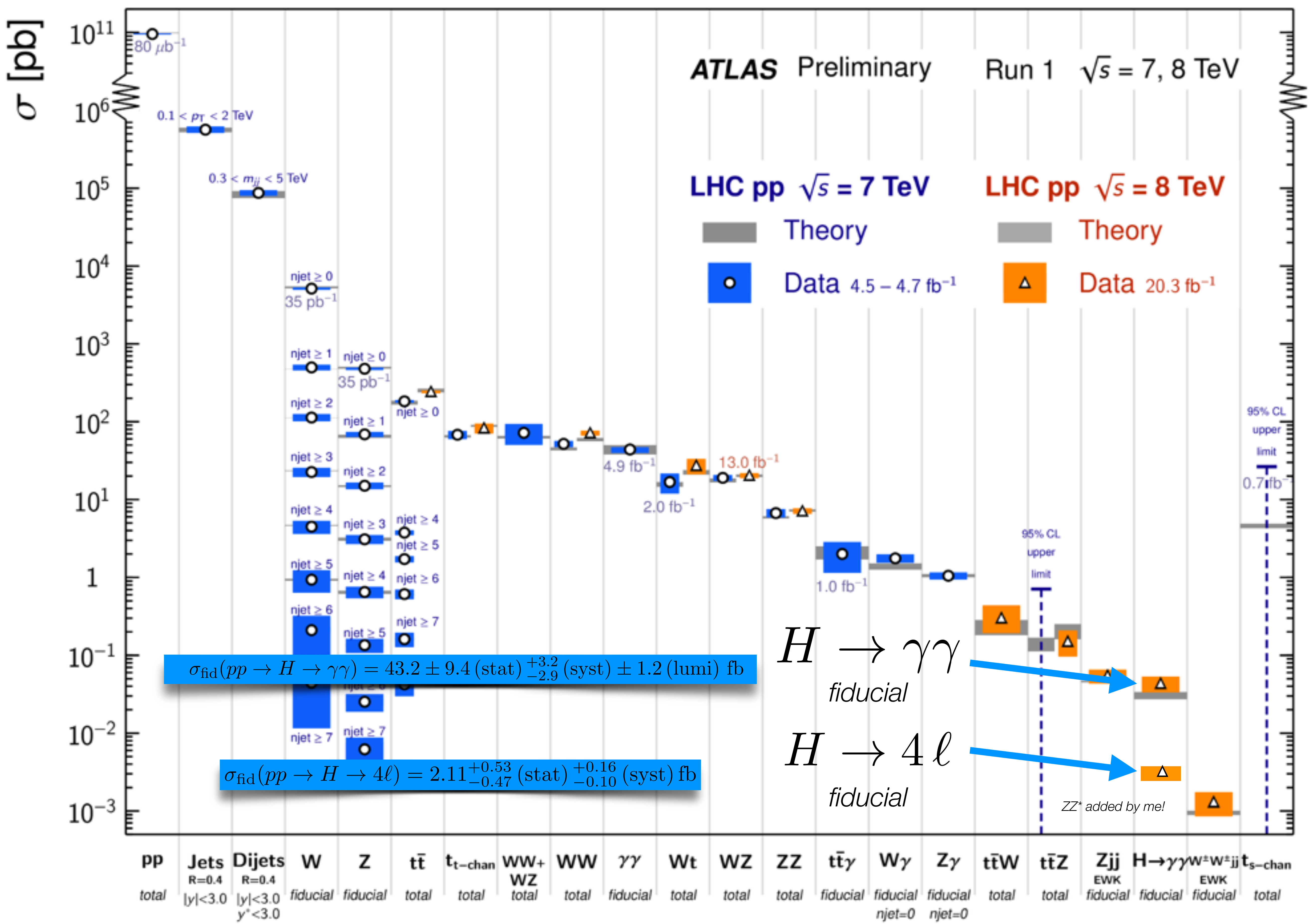
$$m_T = \left(\left(E_T^{\ell\ell} + E_T^{miss} \right)^2 - \left| \mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss} \right| \right)^{1/2}$$

Higgs + Jet cross section measurements

Reco. & simulation → Coupling meas. → Higgs + Jets meas. → Run 2

Standard Model Production Cross Section Measurements

Status: July 2014



Two new Measurements

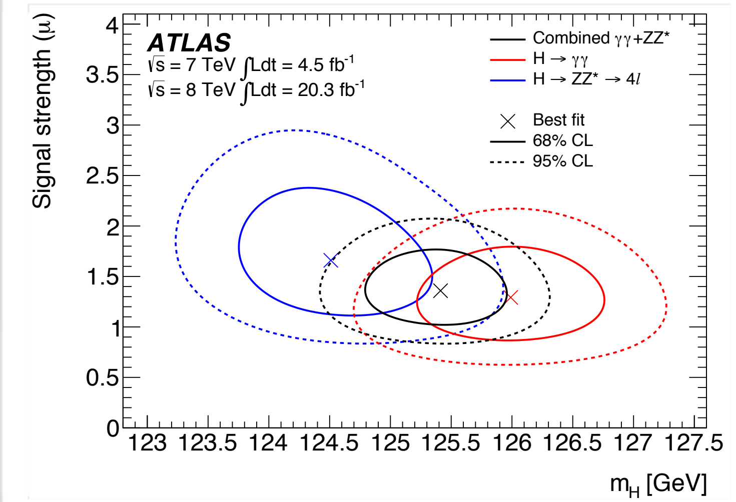
1) ***pp*** **→** ***H*** **→ γ γ** with 20 differential cross sections + 7 fiducial cross sections

Submitted Today!
arXiv:1407.4222

2) ***pp*** **→** ***H*** **→** ***Z Z**** with 6 differential cross sections

ATLAS-CONF-2014-044
http://cds.cern.ch/record/1741017

- Use **full** $\sqrt{s}$ = 8 TeV ATLAS data
- Unfolded to **particle level fiducial** definitions
- Improved photon & electron calibration with reduced uncertainties
- Measured at combined diphoton & ZZ* Higgs mass of ***m_H = 125.36 GeV***
- Data will be available on **Hep-Data** with full error covariance
- Comparisons to many state-of-the art theory predictions



http://arxiv.org/abs/1406.3827

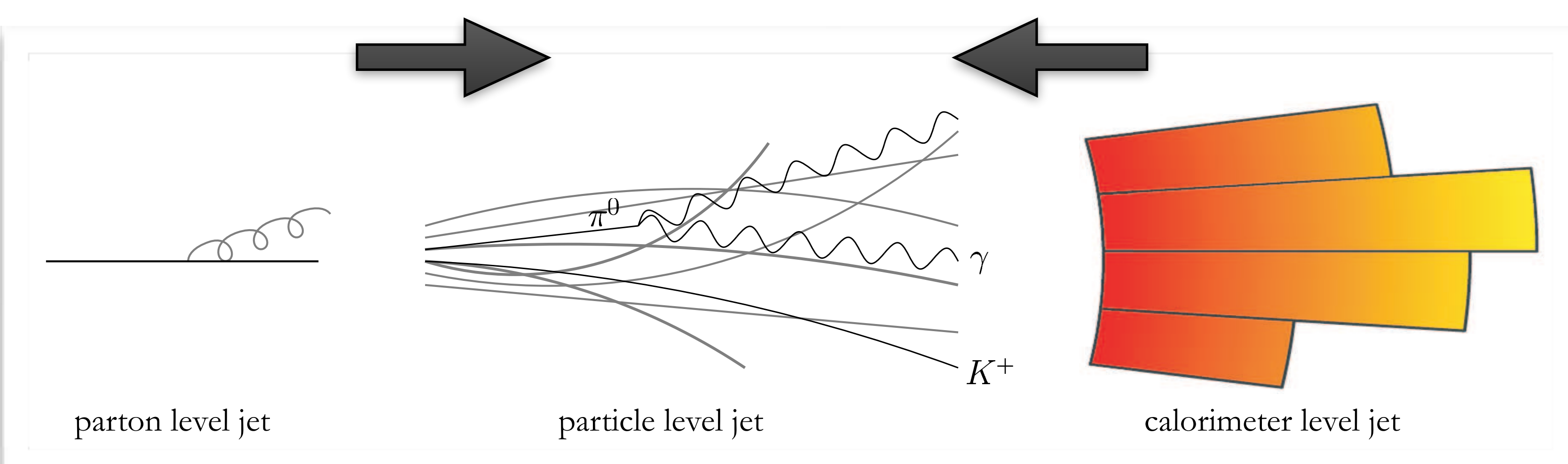
Fiducial cross sections *versus* cross sections

Fiducial cross sections:

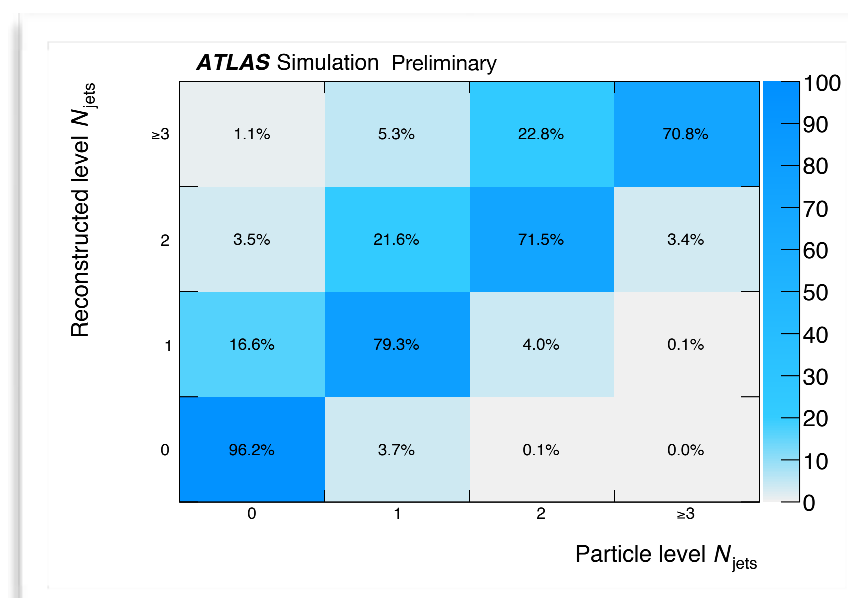
1. **Independent of detector** = allow comparisons to theory & other experimental results
2. **Minimize** theoretical uncertainty by avoiding extrapolating to full cross section.

Impact on Jets: reversing reconstructed calorimeter jets to particle (or *parton*) level jet definition

non-perturbative effects *unfolding*



Calorimeter versus Particle versus Parton level jets



Example Detector response matrix

H → γγ & H → ZZ*

Analysis Strategy in brief — Signal extraction

1. Signal extraction from fit to $m_{\gamma\gamma}$ or m_{4l} mass spectrum in bins of observable of interest

2. Unfold measured spectrum into cross section with correction factors

cross section

$$\sigma_i = \frac{\nu_i^{\mathrm{sig}}}{c_i \int \mathcal{L}\,\mathrm{d}t},$$

observed yield

integrated luminosity

correction factor

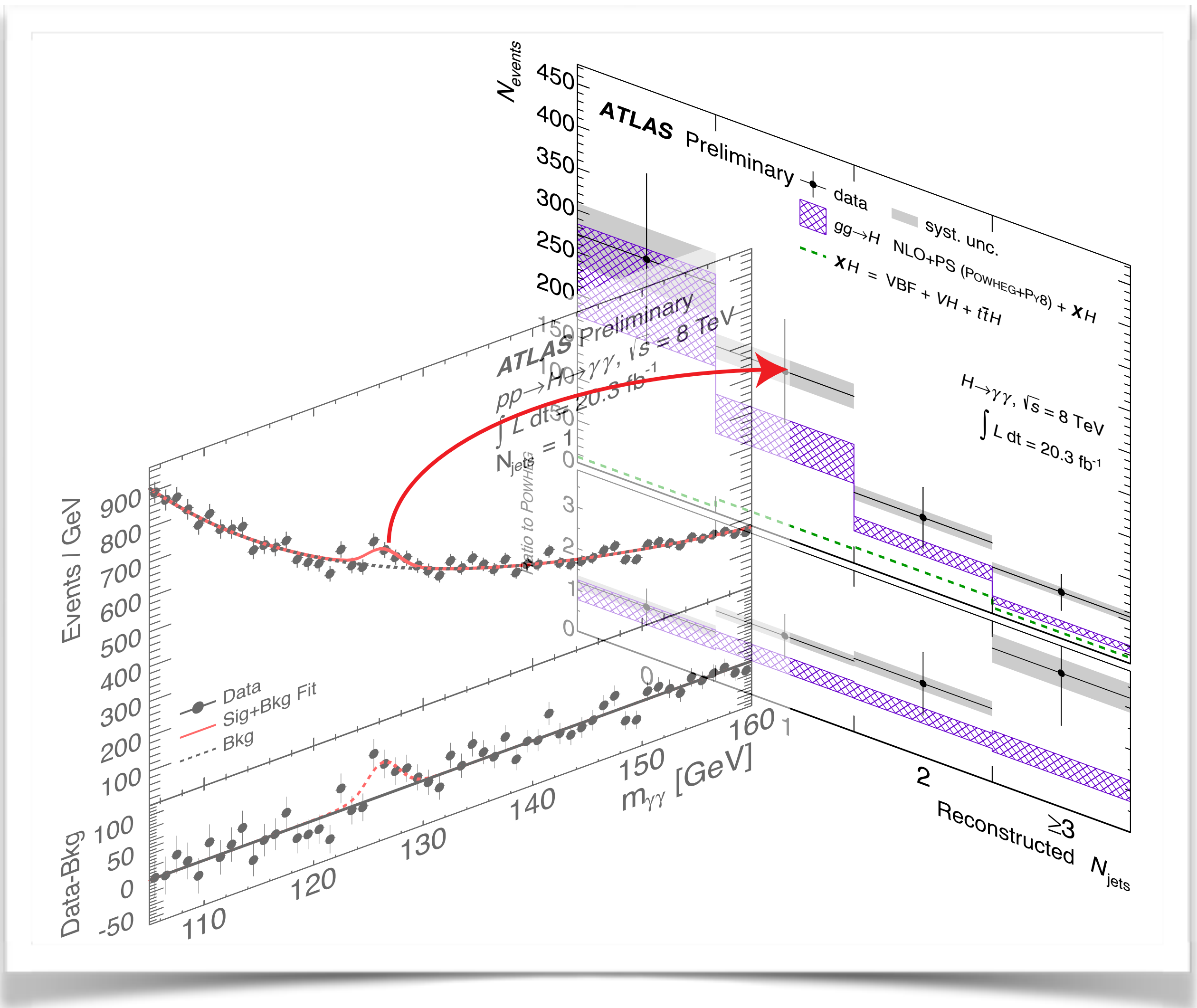
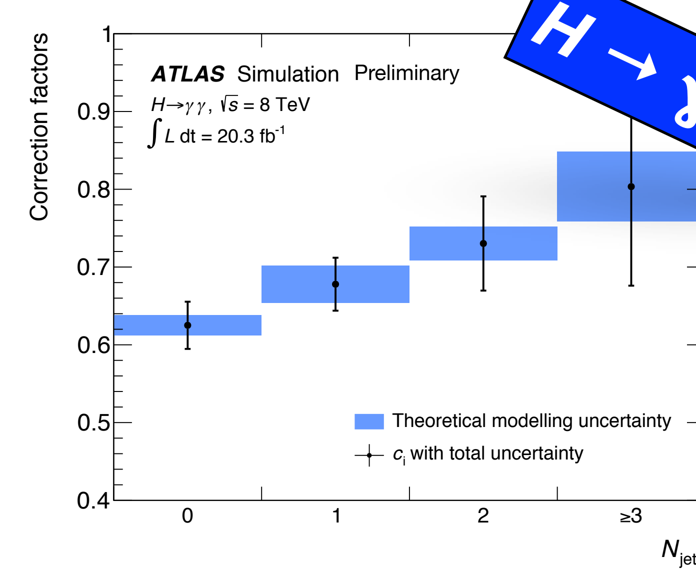


Illustration of the simultaneous fit for N_{jets} for the diphoton analysis

H → γγ



Correction factors + uncertainties for N_{jets}

H → γγ (& H → ZZ*)

Systematic Uncertainties

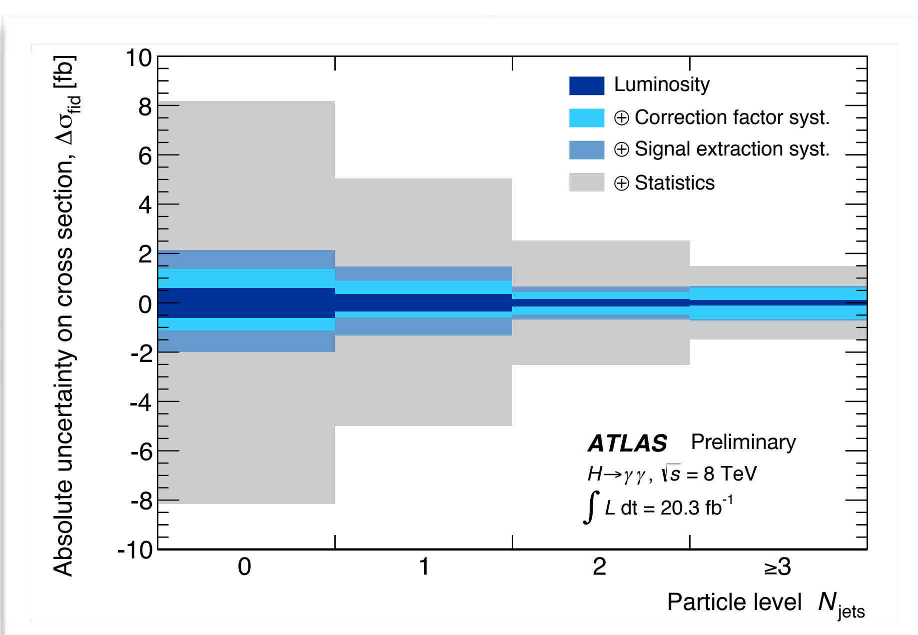
Signal Extraction Related
Photon Energy Scale
Photon Energy Resolution
Background Mass Bias
Background Yield Bias (SS)

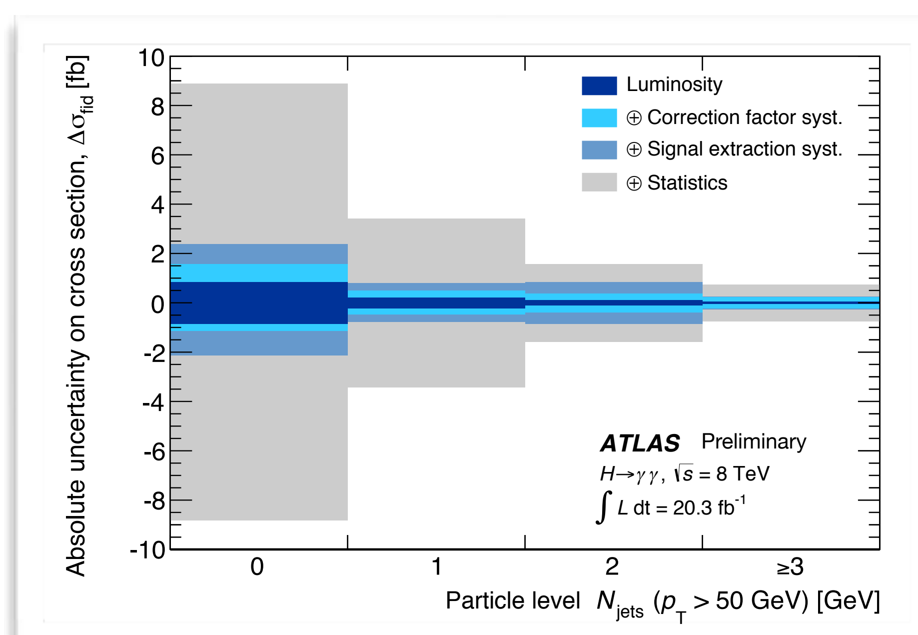
Unfolding Related
Theoretical modelling
Object reconstruction
Luminosity

Theoretical modelling → (Change generators, signal composition, MPIOff, Observation based reweighing)

Object reconstruction → JER/JES & all object uncertainties.

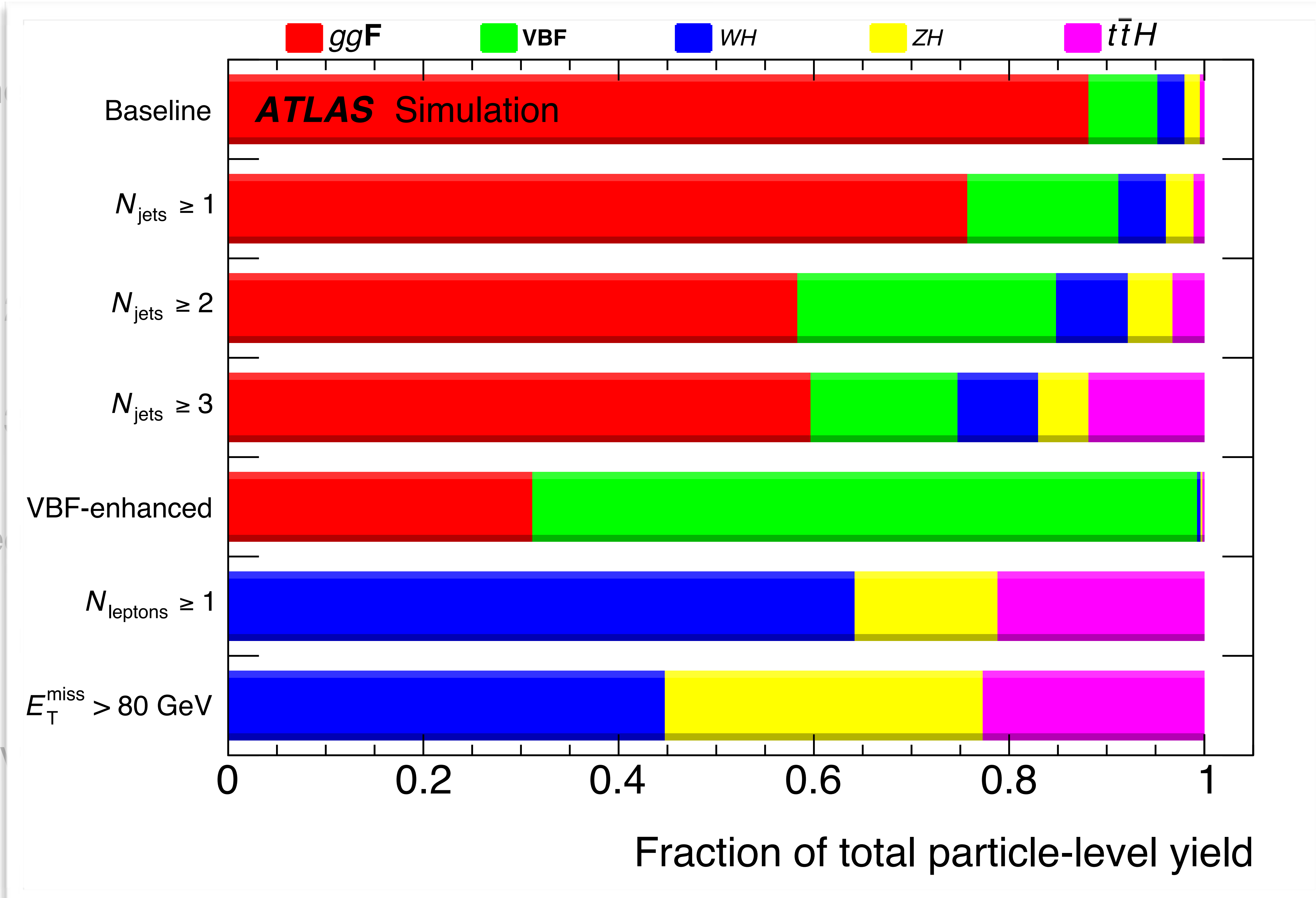
Uncertainties for N_{jets} with p_T = 30 / 50 GeV





$H \rightarrow \gamma\gamma$

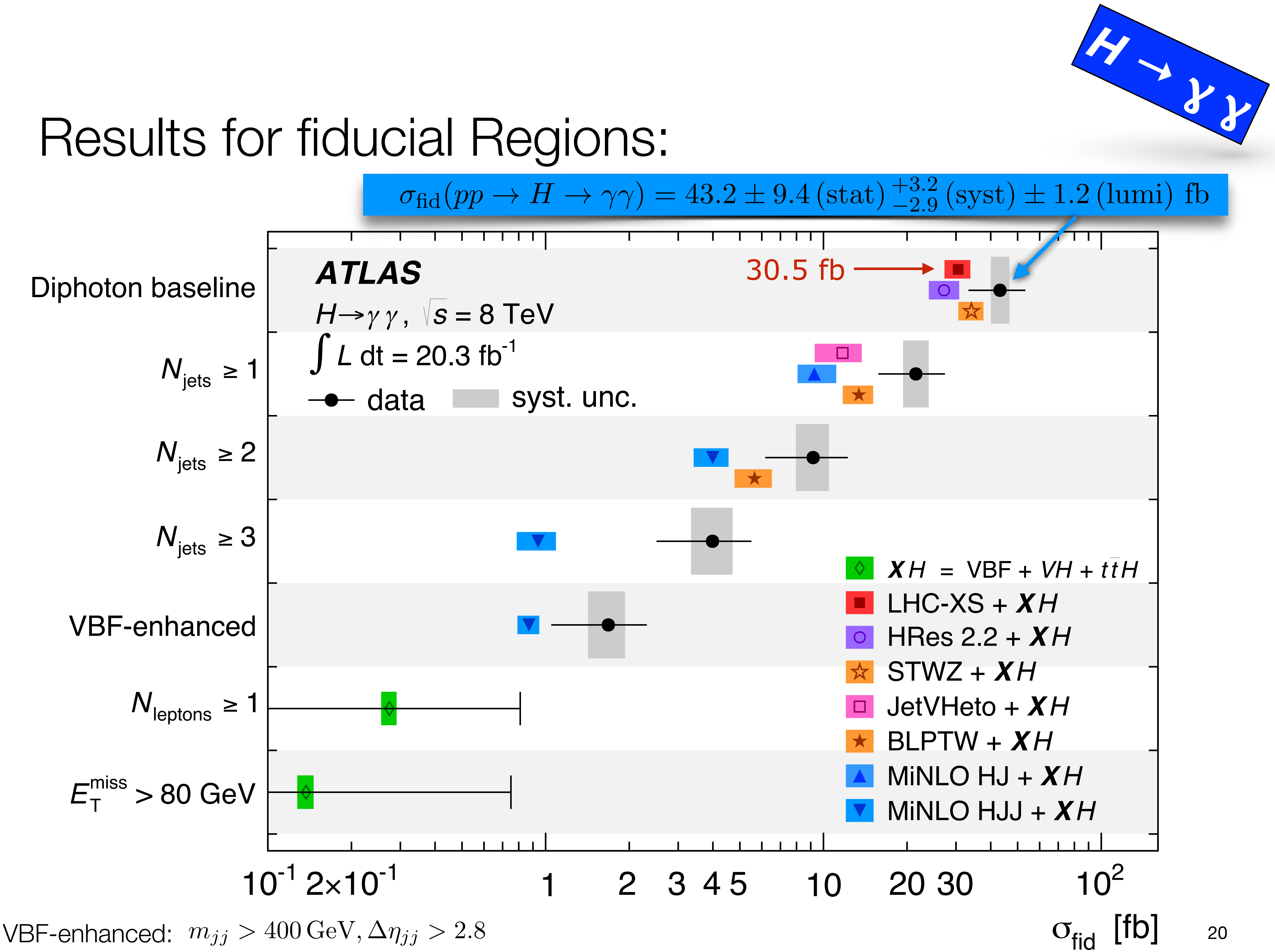
Results for fiducial Regions: Expected Composition



VBF-enhanced: $m_{jj} > 400\,\text{GeV}, \Delta\eta_{jj} > 2.8$

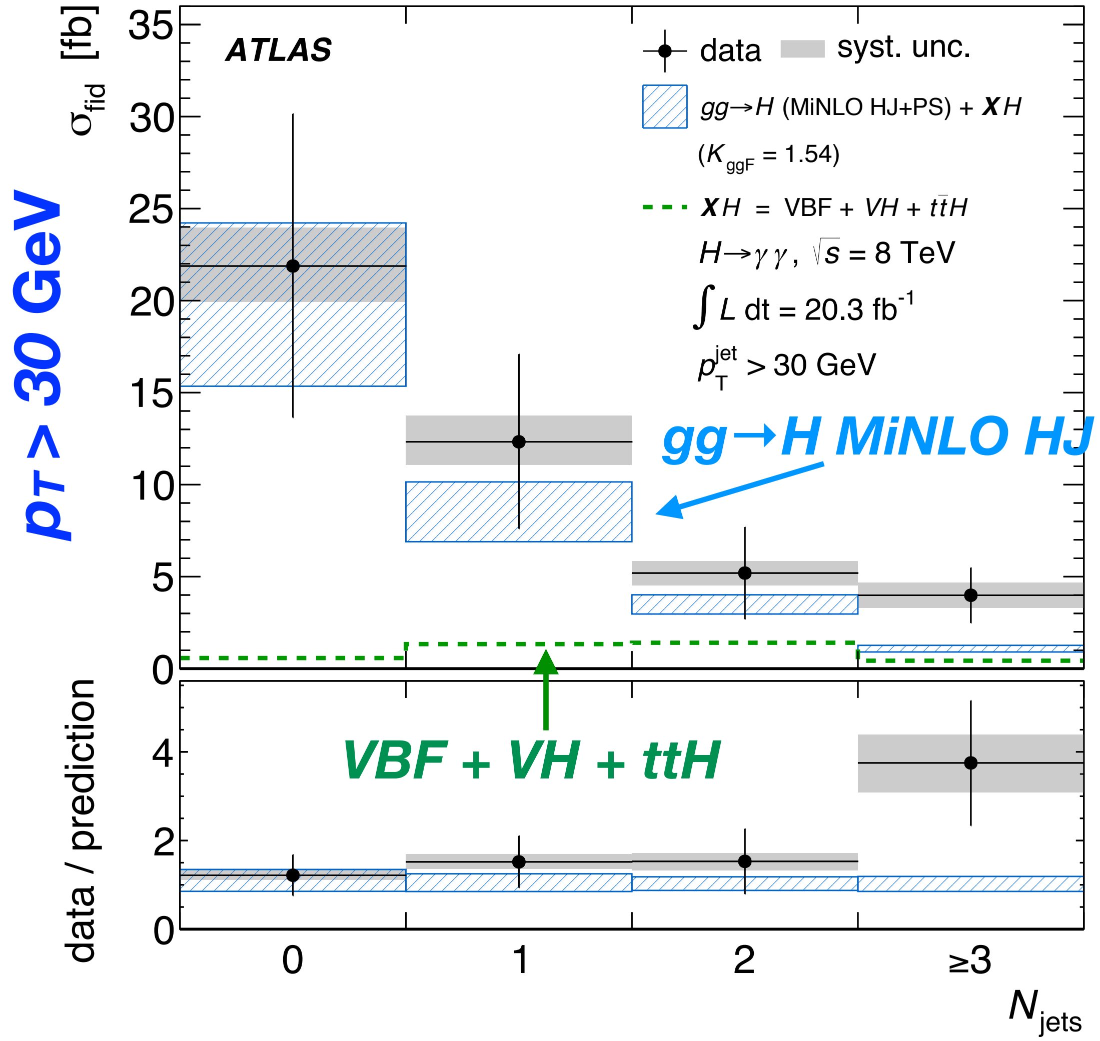
Results for fiducial Regions:

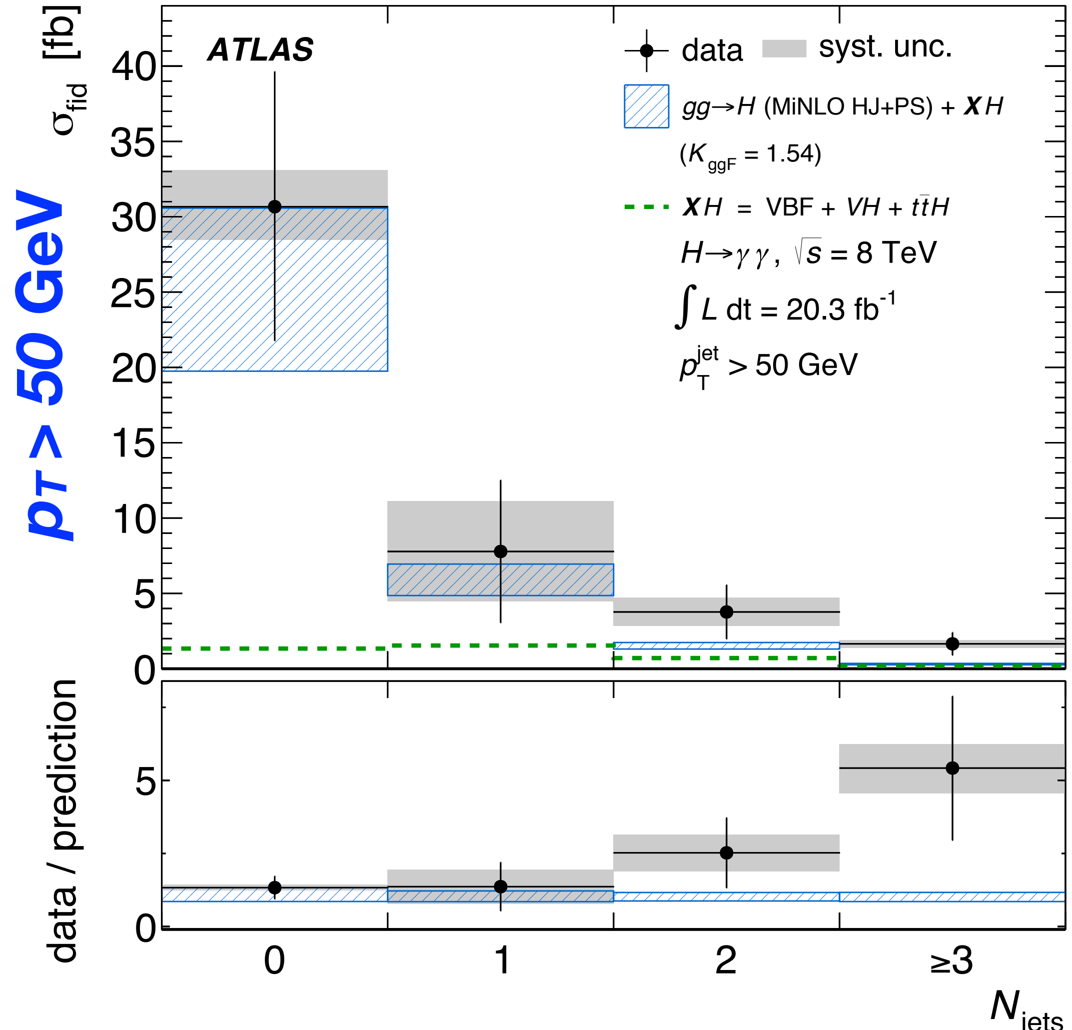
$$\sigma_{\mathrm{fid}}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4\,(\mathrm{stat})\,^{+3.2}_{-2.9}\,(\mathrm{syst}) \pm 1.2\,(\mathrm{lumi})\ \mathrm{fb}$$



VBF-enhanced: $m_{jj} > 400\,\mathrm{GeV}, \Delta\eta_{jj} > 2.8$

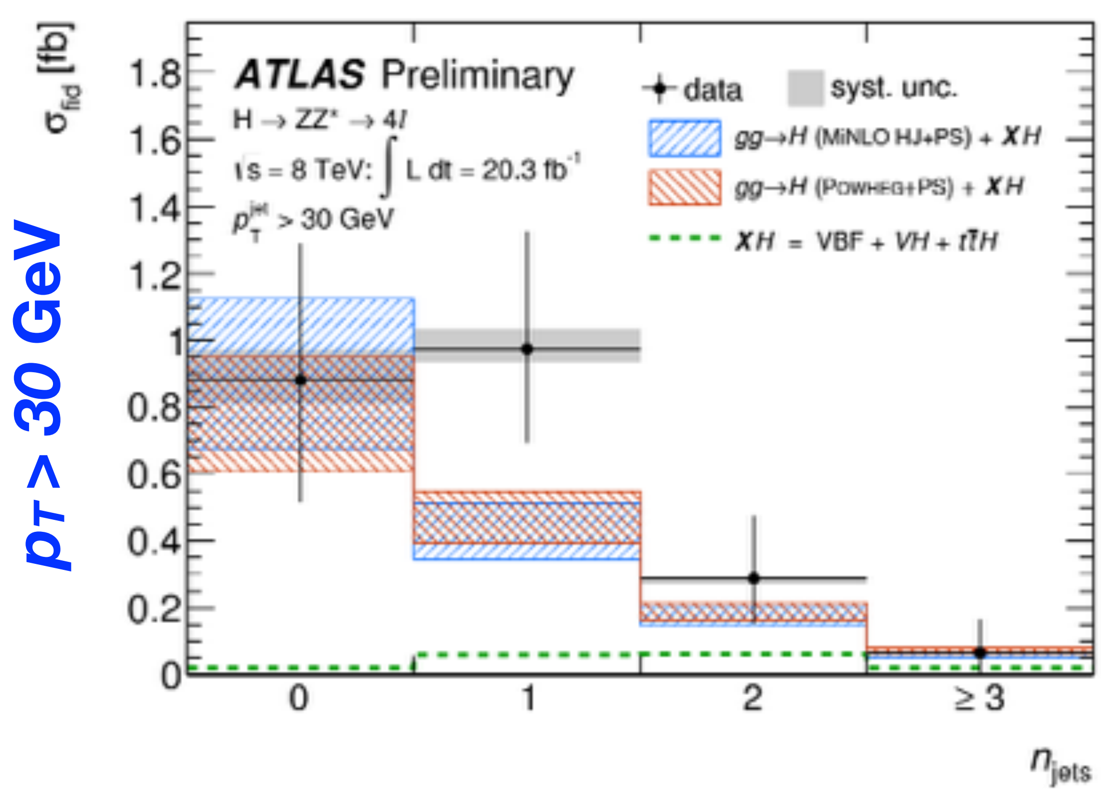
N_{jets} with 30 & 50 GeV p_T cuts on jets



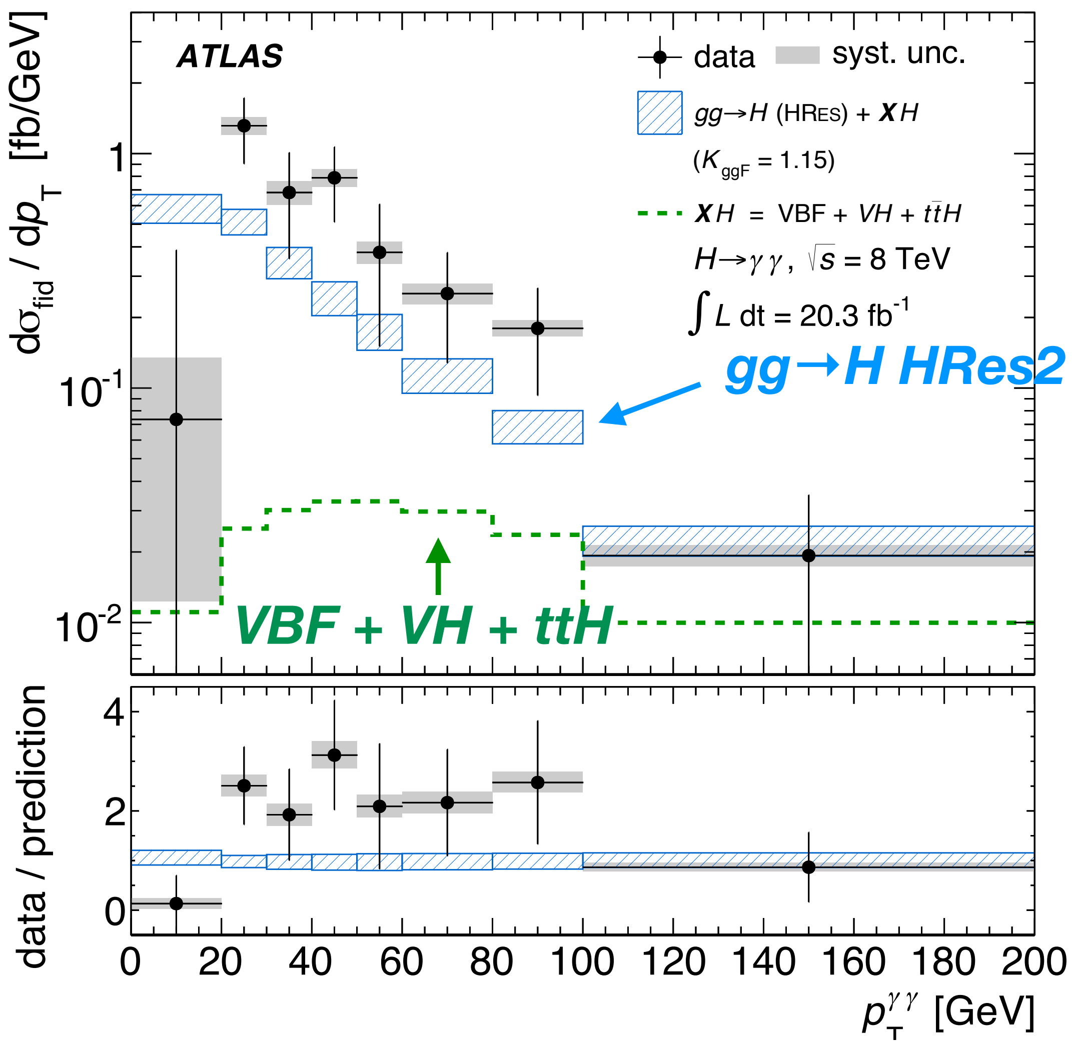


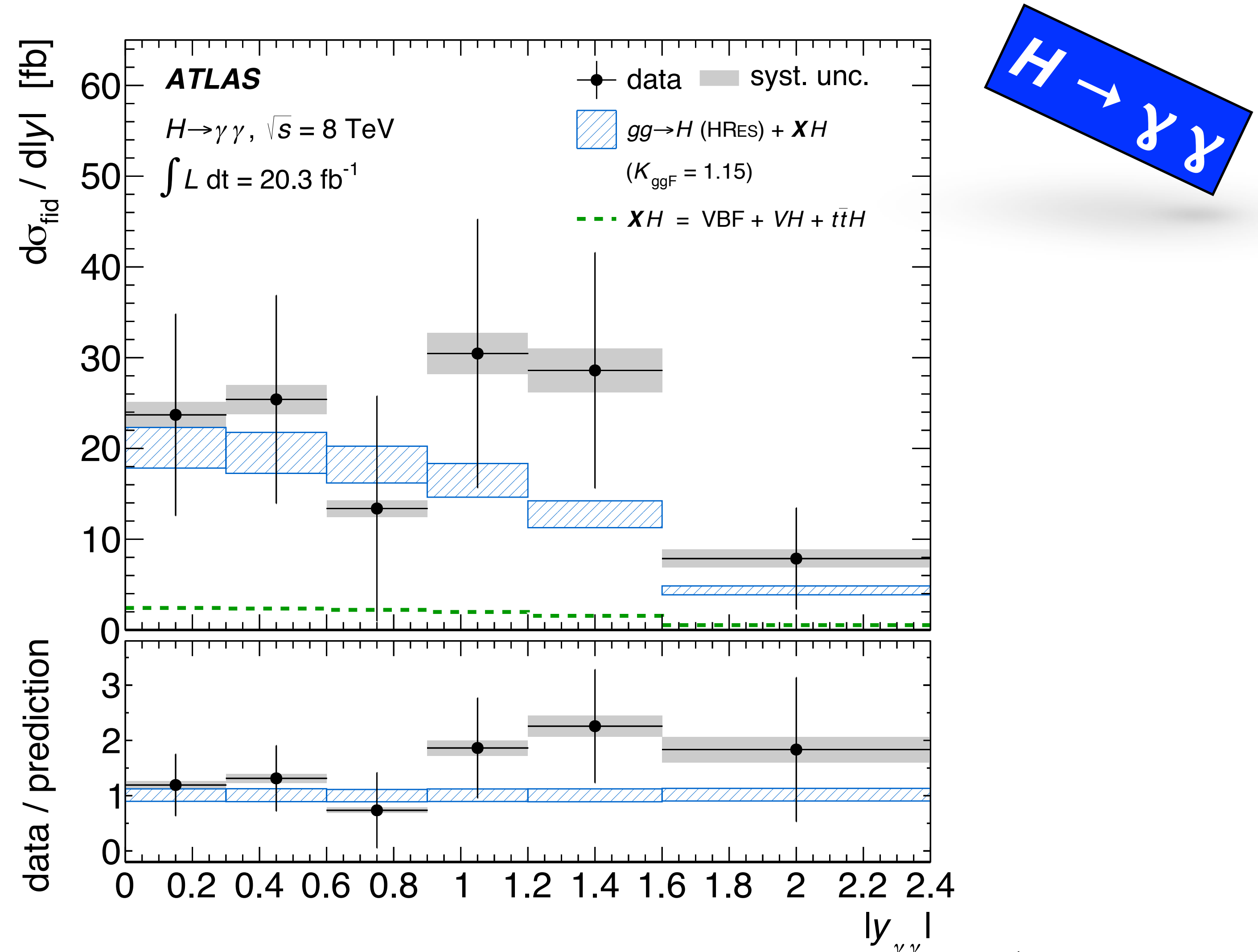
H → γ γ

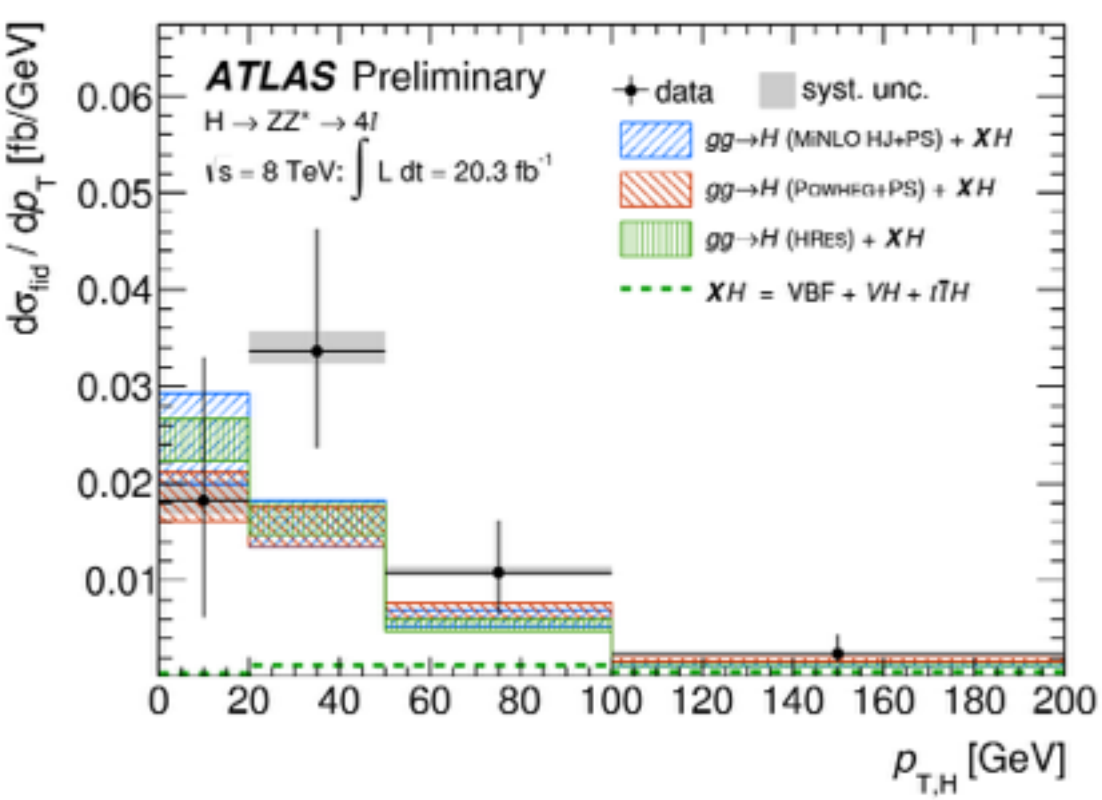
H → ZZ*

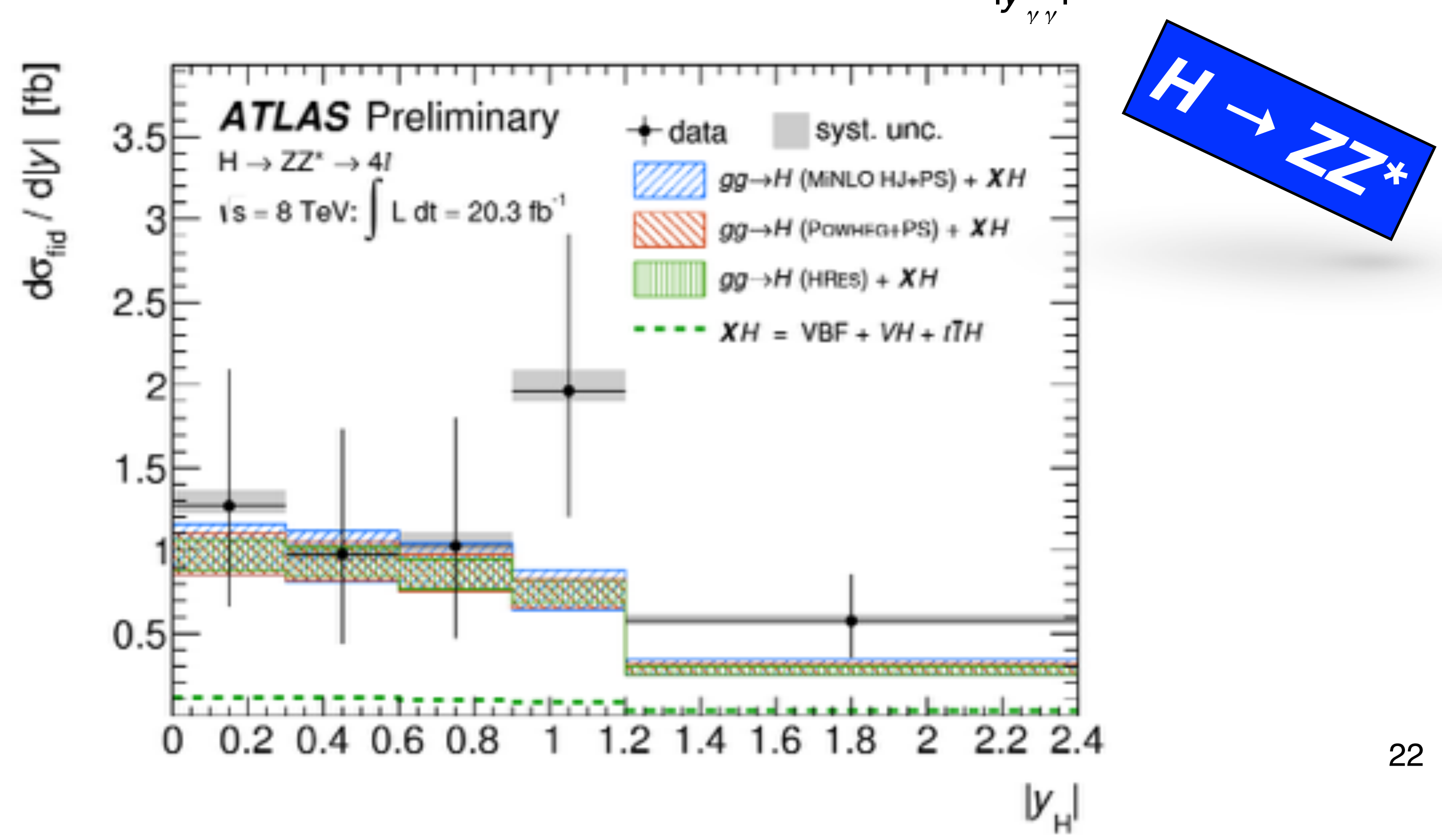


Higgs p_T and Rapidity

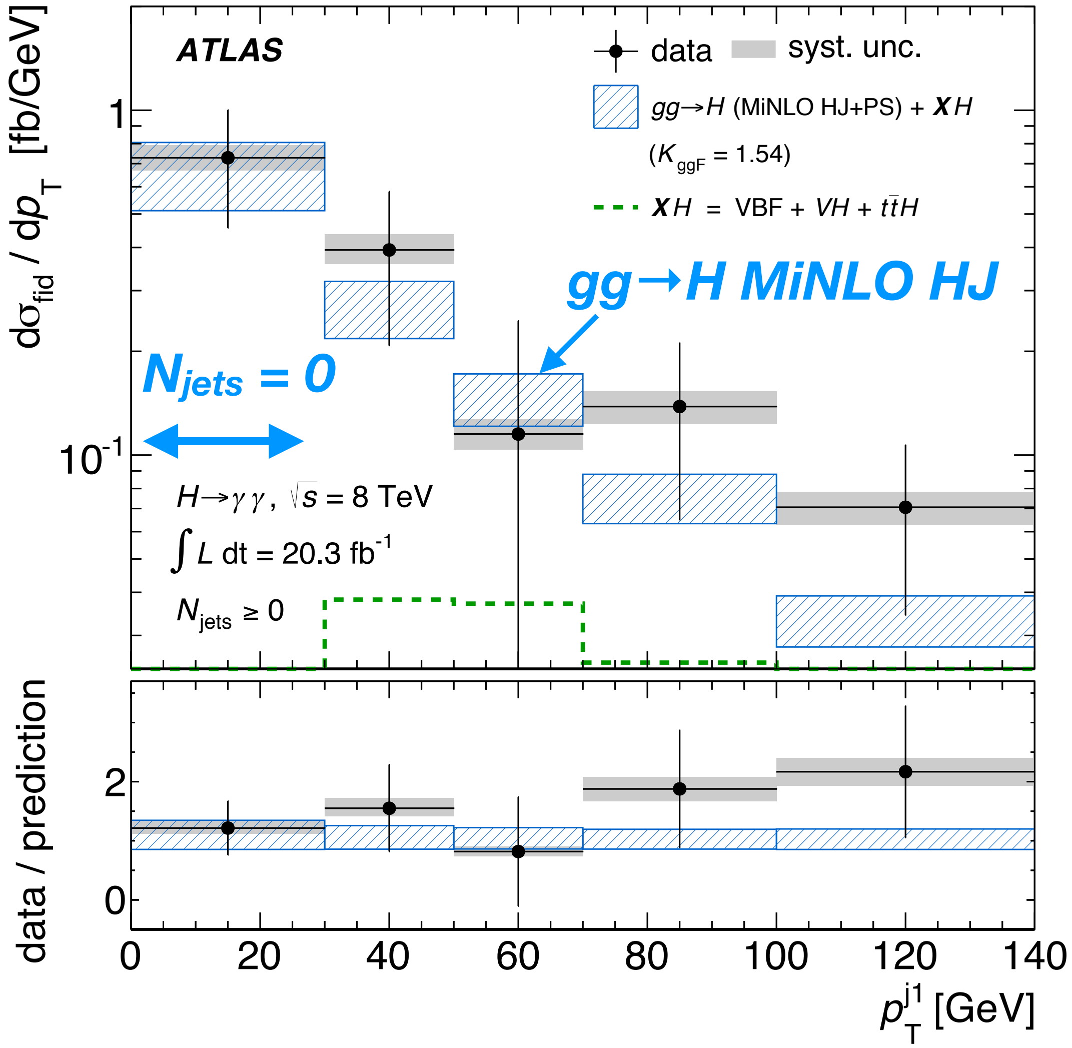


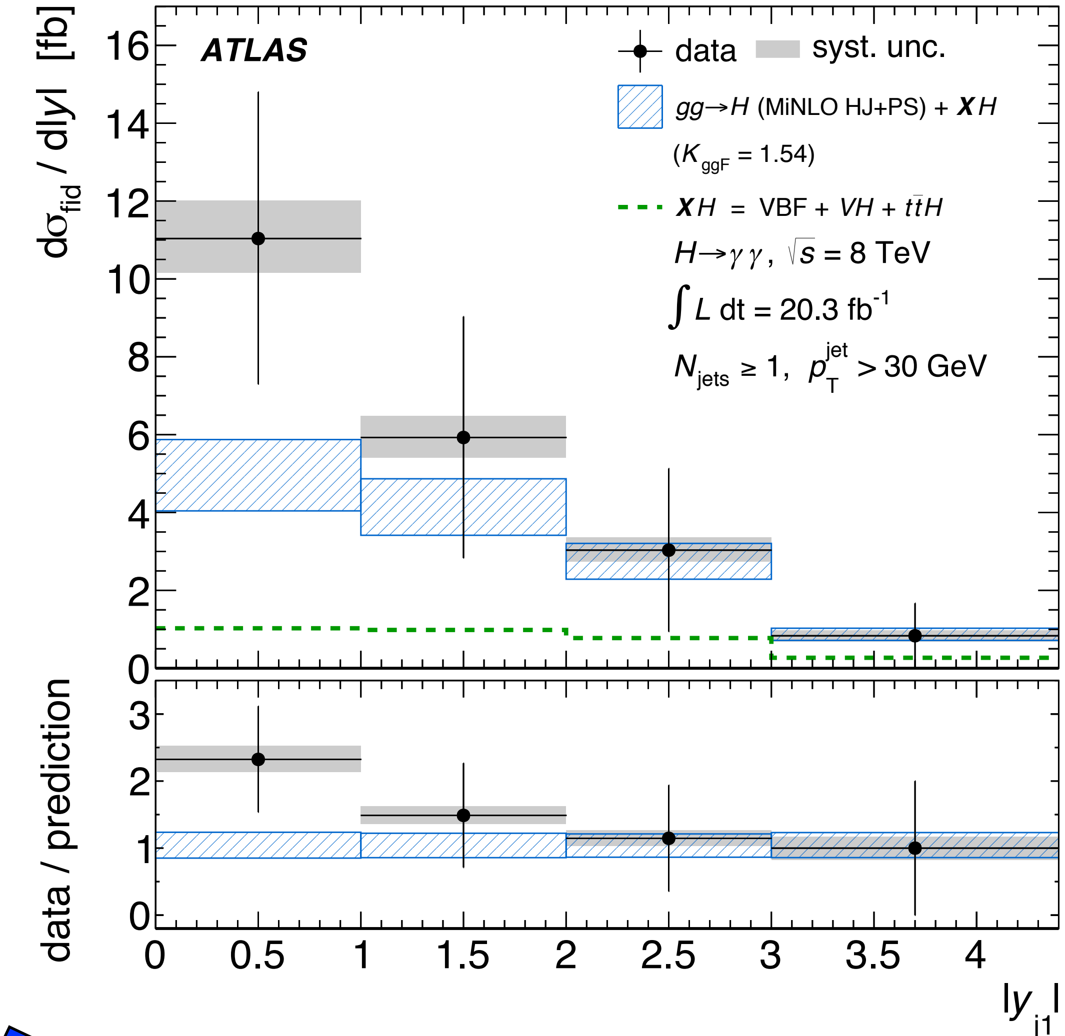




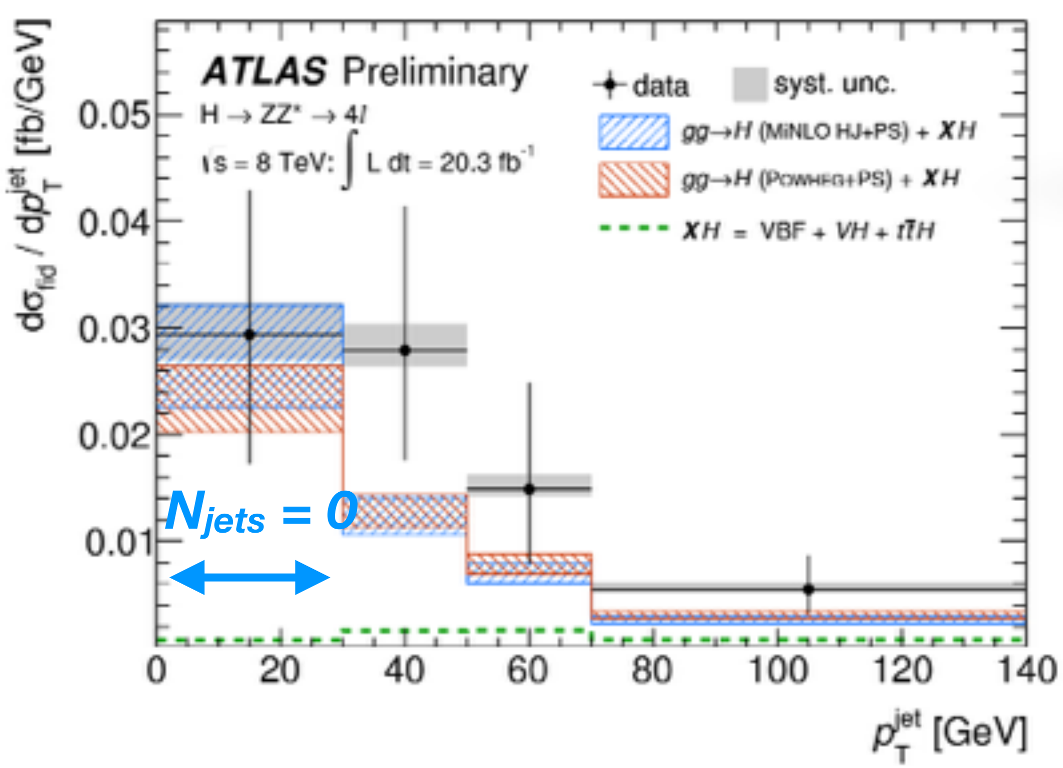


Leading jet p_T & Rapidity





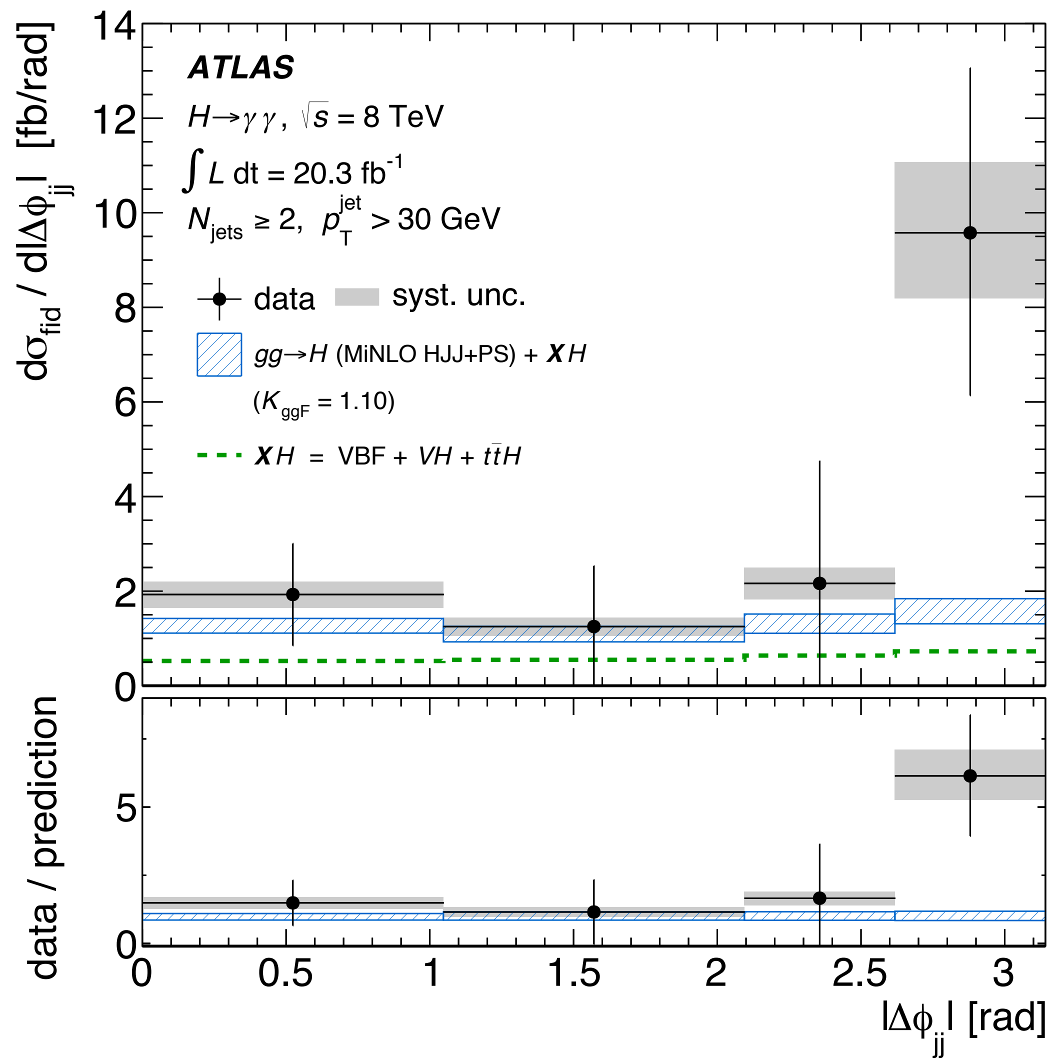
H → γγ

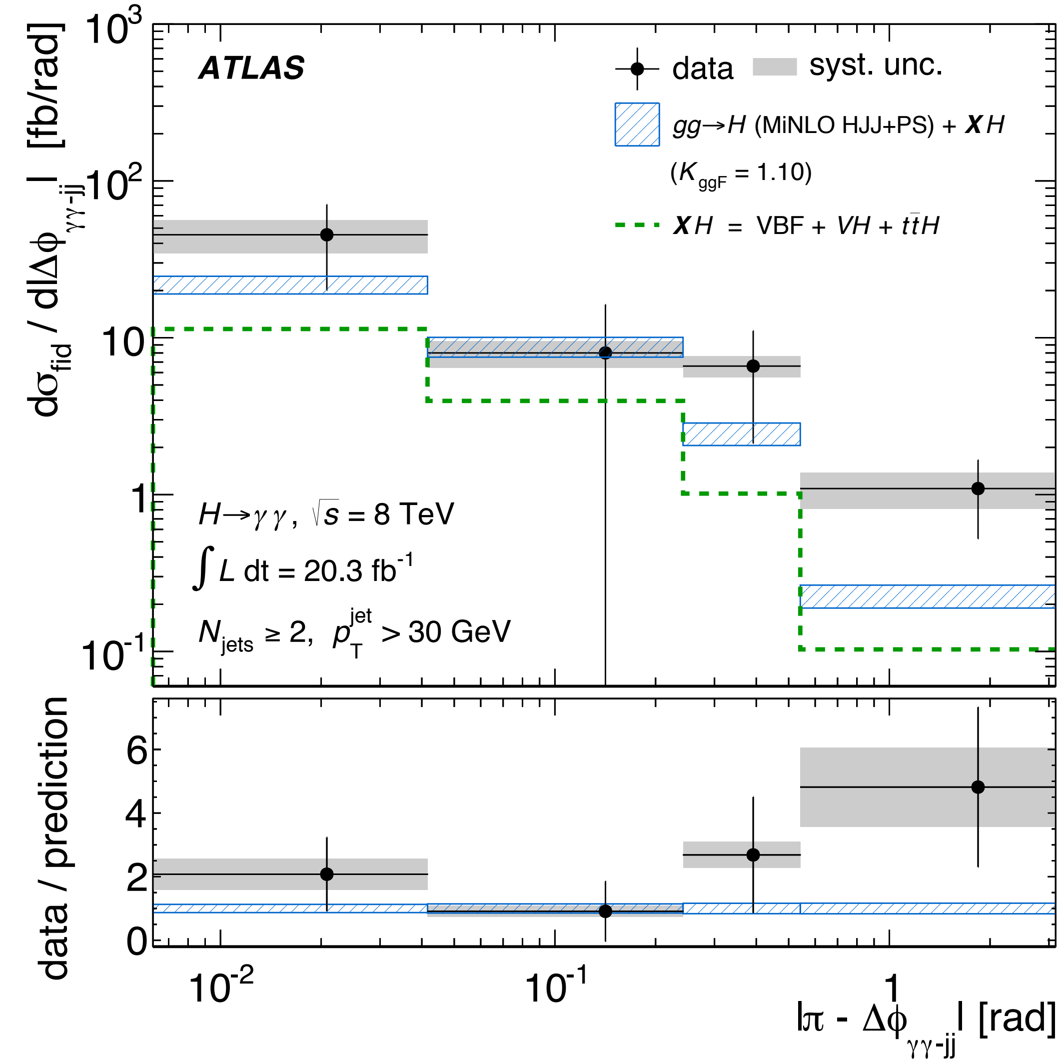


H → ZZ*

Inclusive dijet variables (1/2)

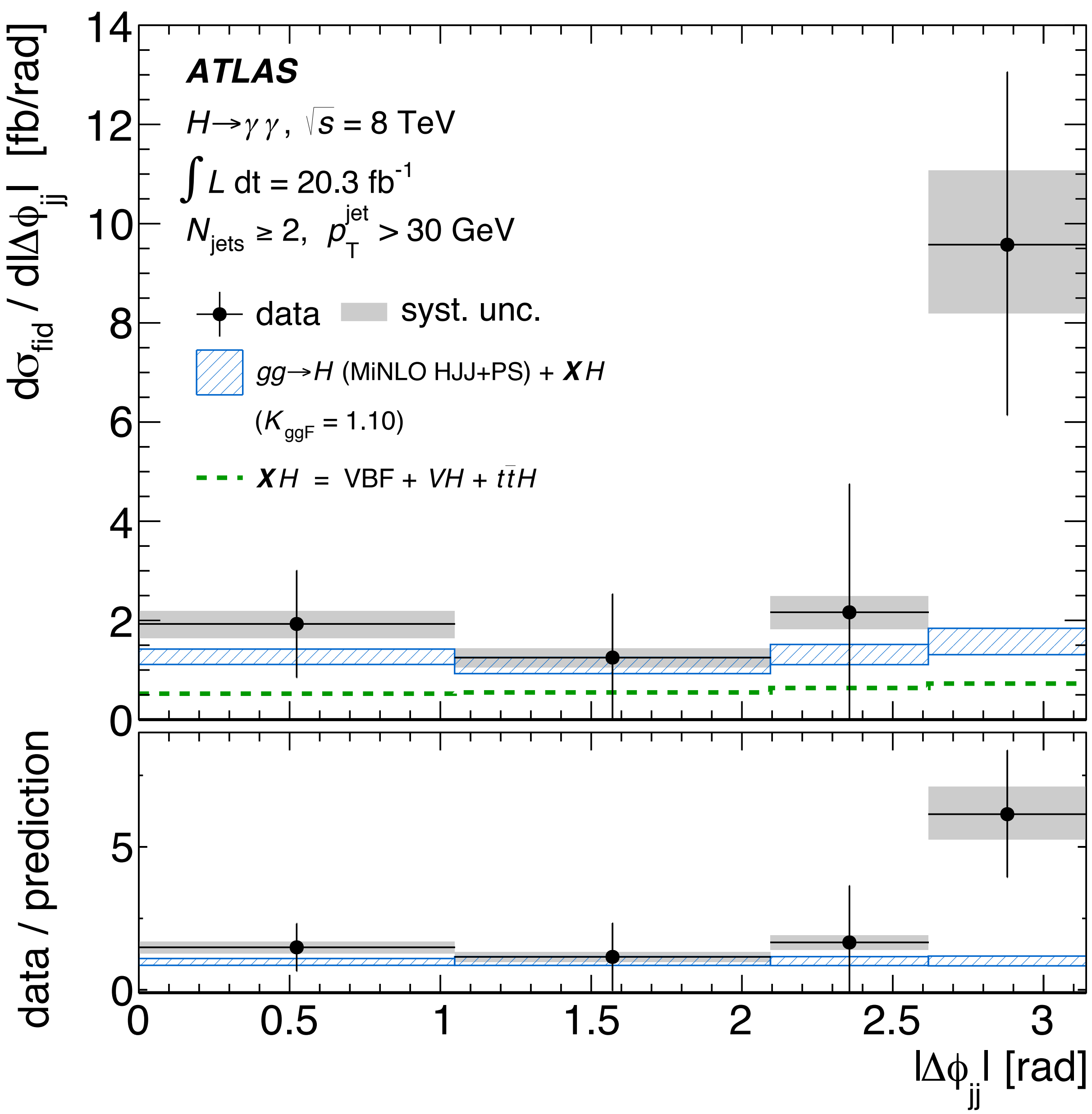
$H \rightarrow \gamma\gamma$

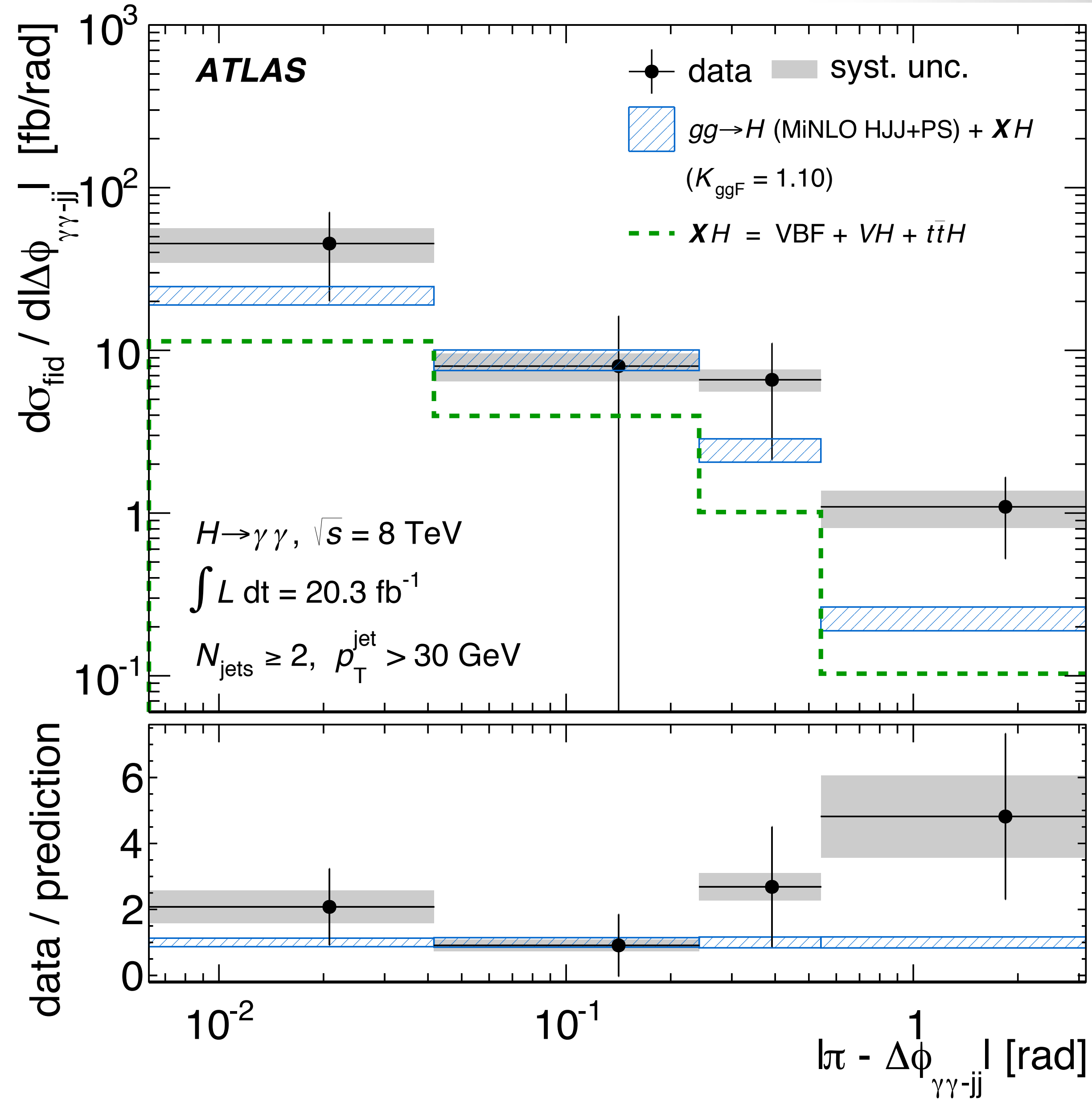




Inclusive dijet variables (1/2)

$H \rightarrow \gamma\gamma$





Asymmetry sensitive to the SM composition and tensor structure of the Higgs:

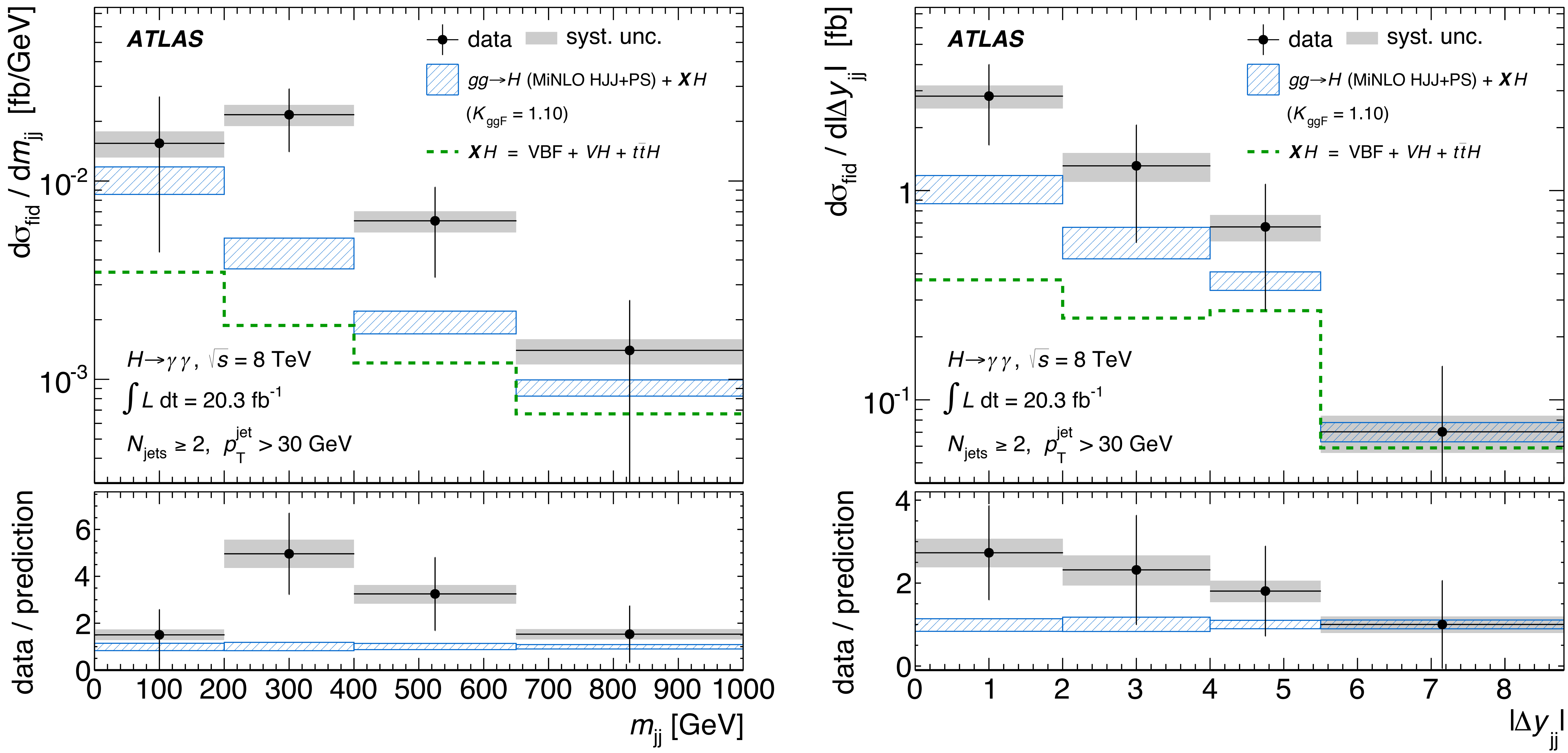
$$A_{\Delta\phi} = \frac{\sigma(|\Delta\phi| < \frac{\pi}{3}) - \sigma(\frac{\pi}{3} < |\Delta\phi| < \frac{2\pi}{3}) + \sigma(|\Delta\phi| > \frac{2\pi}{3})}{\sigma(|\Delta\phi| < \frac{\pi}{3}) + \sigma(\frac{\pi}{3} < |\Delta\phi| < \frac{2\pi}{3}) + \sigma(|\Delta\phi| > \frac{2\pi}{3})}$$

$$A_{\Delta\phi} = 0.72\,^{+0.23}_{-0.29}\,(\mathrm{stat.})^{+0.01}_{-0.02}\,(\mathrm{syst.}).$$

SM (Minlo HJJ): $A^{\mathrm{SM}}_{\Delta\phi} = 0.43 \pm 0.02,$

Inclusive dijet variables (2/2)

$H \to \gamma\gamma$



Jet veto efficiency

- The inclusive & exclusive cross sections can be used to calculate Jet veto efficiencies / fractions:

$$\sigma_i / \sigma_{\geq i}$$

- For the zero jet case (i = 0) this variable directly probes the hard quark & gluon emissions from inclusive Higgs production.

p_T > 30 GeV

Measured

$$\sigma_0/\sigma_{\geq 0} = 0.50^{+0.10}_{-0.13}\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

JetVHeto

$$\sigma_0/\sigma_{\geq 0} = 0.67 \pm 0.08$$

only for gluon-gluon fusion! taking into account the XH predictions gives roughly

$$\sigma_0/\sigma_{\geq 0} \backsim 0.61$$

Not mentioned in paper, but also easily obtained:

Calculated & errors propagated by me, so don't blame the paper if there is something wrong

p_T > 30 GeV

$$\sigma_1/\sigma_{\geq 1} = 0.57 \pm 0.12\,(\text{stat.+syst.})$$

$$\sigma_2/\sigma_{\geq 2} = 0.56 \pm 0.14\,(\text{stat.+syst.})$$

p_T > 50 GeV

$$\sigma_0/\sigma_{\geq 0} = 0.70 \pm 0.10\,(\text{stat.+syst.})$$

$$\sigma_1/\sigma_{\geq 1} = 0.59 \pm 0.14\,(\text{stat.+syst.})$$

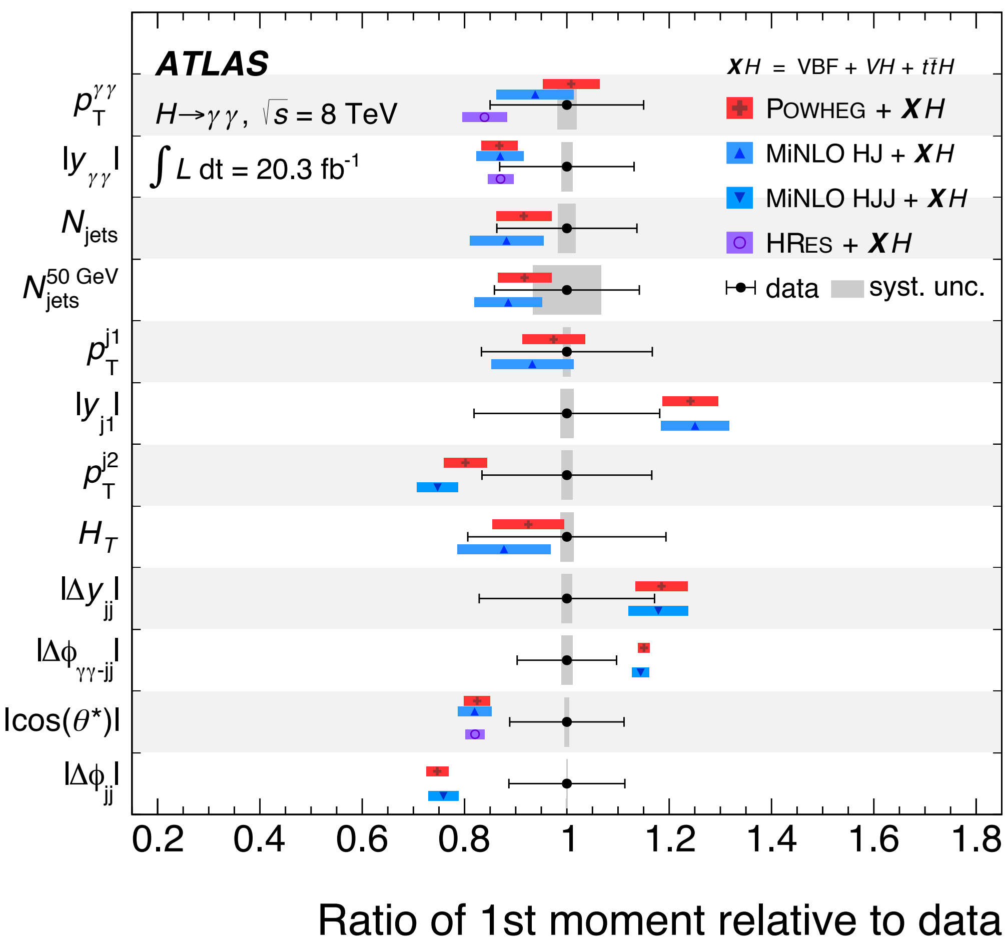
$$\sigma_2/\sigma_{\geq 2} = 0.70 \pm 0.13\,(\text{stat.+syst.})$$

Compatibility between Measurements & MC

H → ZZ*

* Tested via simple χ2 or likelihood test
* Fairly good agreement between measurements and MC predictions
* Comparison of first & second moments (H→ γ γ) :

	Compatibility (%)		
Variable	POWHEG	MINLO	HRES2
$p_{\mathrm{T},H}$	30	23	16
$\lvert y_H \rvert$	37	45	36
m_{34}	44	56	-
$\lvert \cos(\theta^*) \rvert$	35	45	-
n_{jets}	37	28	-
$p_{\mathrm{T},jet}$	33	26	-



Variable	POWHEG	MINLO HJ	MINLO HJJ	HRES 2.2
$p_{\mathrm{T}}^{\gamma\gamma}$	0.16	0.13	0.12	0.12
$\lvert y_{\gamma\gamma} \rvert$	0.81	0.83	0.83	0.82
$\lvert \cos\theta^* \rvert$	0.60	0.57	0.58	0.56
N_{jets}	0.44	0.37	0.32	-
$N_{\mathrm{jets}}^{50\ \mathrm{GeV}}$	0.36	0.33	0.30	-
H_{T}	0.43	0.39	0.34	-
p_{T}^{j1}	0.85	0.83	0.80	-
$\lvert y_{j_1} \rvert$	0.64	0.58	0.52	-
p_{T}^{j2}	0.33	0.28	0.23	-
$\lvert \Delta\phi_{jj} \rvert$	0.20	0.27	0.23	-
$\lvert \Delta y_{jj} \rvert$	0.65	0.59	0.49	-
$\lvert \Delta\phi_{\gamma\gamma,jj} \rvert$	0.45	0.47	0.42	-

Run Period 2 Challenges

Reco. & simulation → Coupling meas. → Higgs + Jets meas. → Run 2

Pile-up Suppression will be more challenging

* Base plan: Continue with the current scheme, i.e. energy density subtraction to get rid of pile-up. However decrease in performance foreseeable.

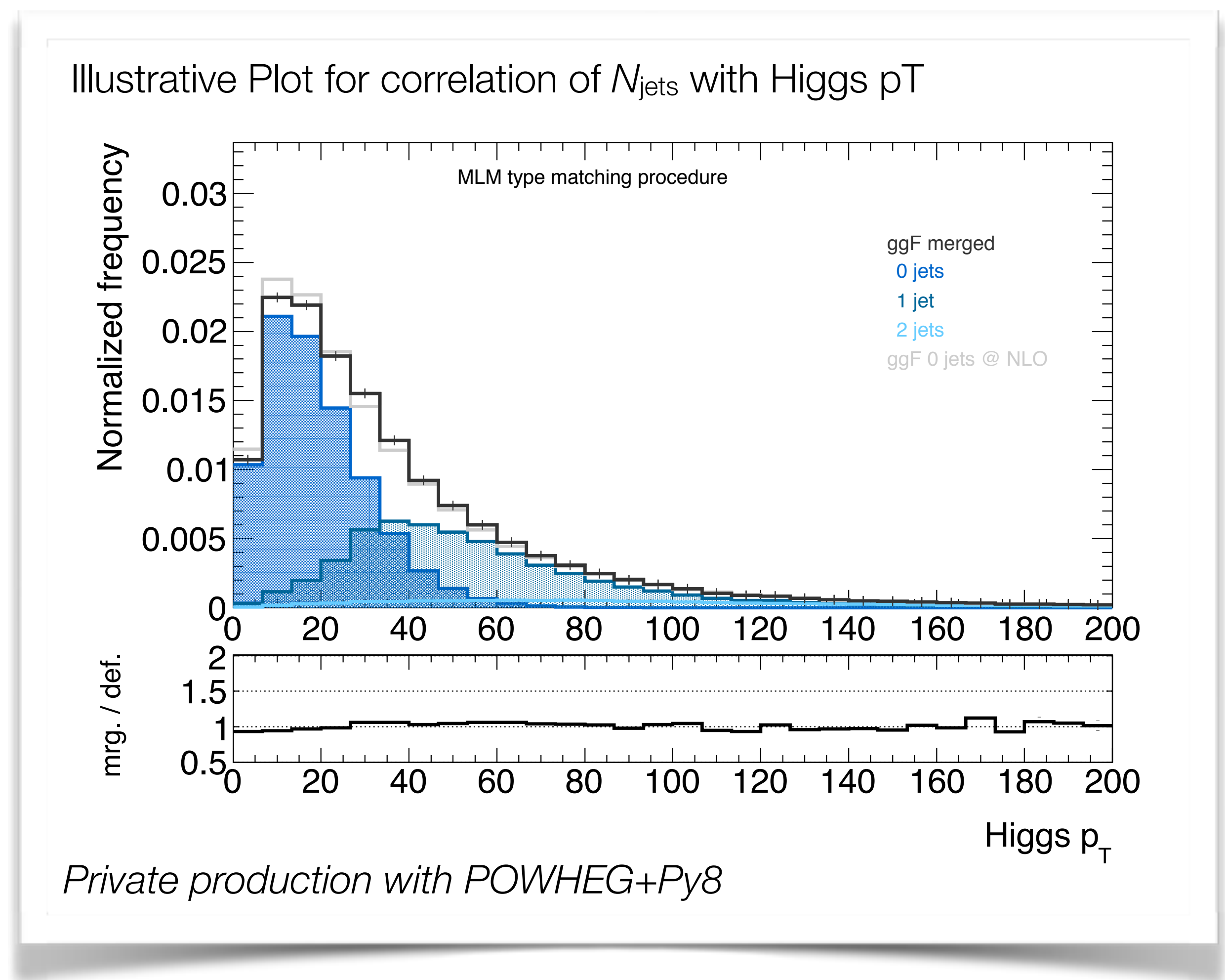
  Might need to raise p_T threshold.

* Other ideas: Particle Flow
  * *Cluster + Track association, ‘take’ out clusters not from hard collision.*
  * *Studies ongoing to see if this alternative to the current scheme is feasible.*

* Other work ongoing: Try to use other features of jets more, like quark or gluon topology to improve calibration.

Theory Uncertainties will become more important

* Although run2 will be challenging, the overall sensitivity will improve.
* This will make theory uncertainties and correlations more important than they are today.
* Right now a mix of recommendations is used to account for many sources that need improvement
    * Underlying Event uncertainty is fairly 'ad-hoc'
    * Uncertainties on Jet bins and Higgs pT would profit from a more general approach.



Summary (1/2)

* Jets play an important role in the coupling measurements to gain sensitivity and to access production mode dependent couplings strengths

* The modelling of jets is highly non-trivial and depends on many external sources, e.g.
    * Tuning of the underlying event, hadronization models
    * Precision calculation for the hard-scatter
    * Proper interleaving of hard-scatter emissions with Parton shower.
    - *All aspects which are not easy to validate*

Summary (2/2)

* Fiducial measurements of jet cross sections have started to emerge from the LHC:
  * ATLAS has two papers in preparation, you got a sneak peak.
* The (statistically limited) measurements show good agreement between measurement & predictions
  ➡ Reassuring for the coupling analyses that rely on multiplicities and shapes to calculate efficiencies!
* Unfolded distributions allow 3rd Parties to evaluate the SM nature of the Higgs boson. If new models arise, they can be tested.

Backup Slides

Reconstructing & Calibrating Jets

Jets…

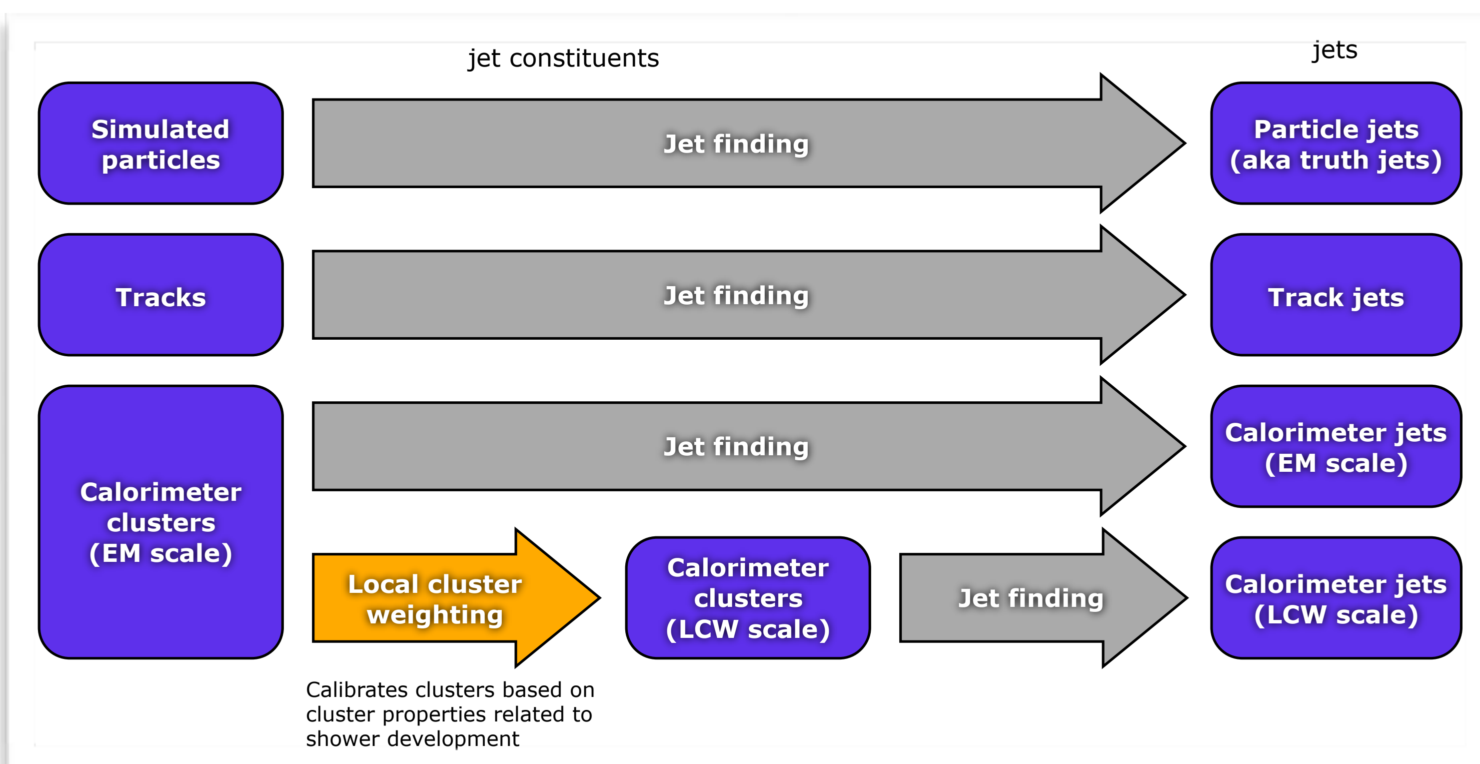
are dominant feature of *Proton-Proton* collisions at the LHC.

are observed as groups of topologically-related energy depositions in the calorimeter associated with tracks.

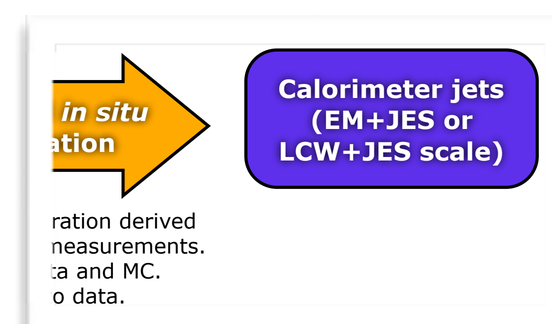
are typically reconstructed with anti-k_t jet algorithm with distance parameter of **R = 0.4** and calibrated using MC + *in situ* techniques.

do not only contain contributions from hard-scatter *Proton-Proton* interaction, but also from additional collisions, called ***Pile-up*** interactions

Simulated or Reconstructed Input

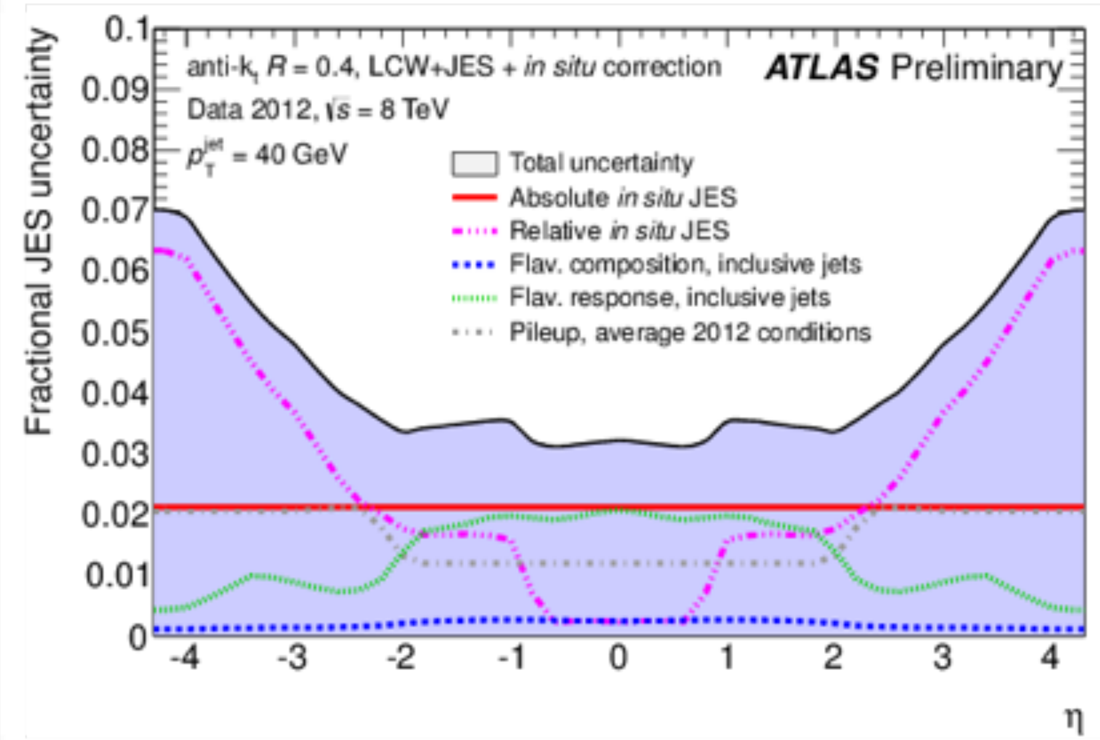


Further Calibration



Overview of *ATLAS* jet reconstruction from 2011 Performance Note

Jet Energy Scale calibration performance in 2012



Overview of H→ WW control regions

Channel	WW	Top	$Z/\gamma^* \to \tau\tau$	$Z/\gamma^* \to \ell\ell$	W+jets	VV
$N_{\text{jet}} = 0$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	Data	Data	MC + VR
$N_{\text{jet}} = 1$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	Data	Data	MC + VR
$N_{\text{jet}} \geq 2$						
$e\mu + \mu e$	MC	CR (merged)	CR	MC	Data	MC
$ee + \mu\mu$	MC	CR (merged)	CR ($e\mu + \mu e$)	Data	Data	MC

$H \to \gamma\gamma$

Signal extraction for the diphoton analysis

- **Simultaneous unbinned maximum likelihood** fit to $m_{\gamma\gamma}$ with nuisance parameters for *photon energy scale, resolution, and background bias*

Fixed at combined ZZ* & γγ value for m_H of 125.36 GeV

Background yield

$$\mathcal{L}(m_{\gamma\gamma}, \nu^{\mathrm{sig}}, \nu^{\mathrm{bkg}}, m_H) = \prod_i \left\{ \frac{e^{-\nu_i}}{n_i!} \prod_j^{n_i} \left[\nu_i^{\mathrm{sig}}\, \mathcal{S}_i(m_{\gamma\gamma}^j; m_H) + \nu_i^{\mathrm{bkg}}\, \mathcal{B}_i(m_{\gamma\gamma}^j) \right] \right\} \times \prod_k G_k$$

Constraints on Nuisance Parameters

Signal yield

Signal

$$\mathcal{S}_i(m_{\gamma\gamma}^j; m_H)$$

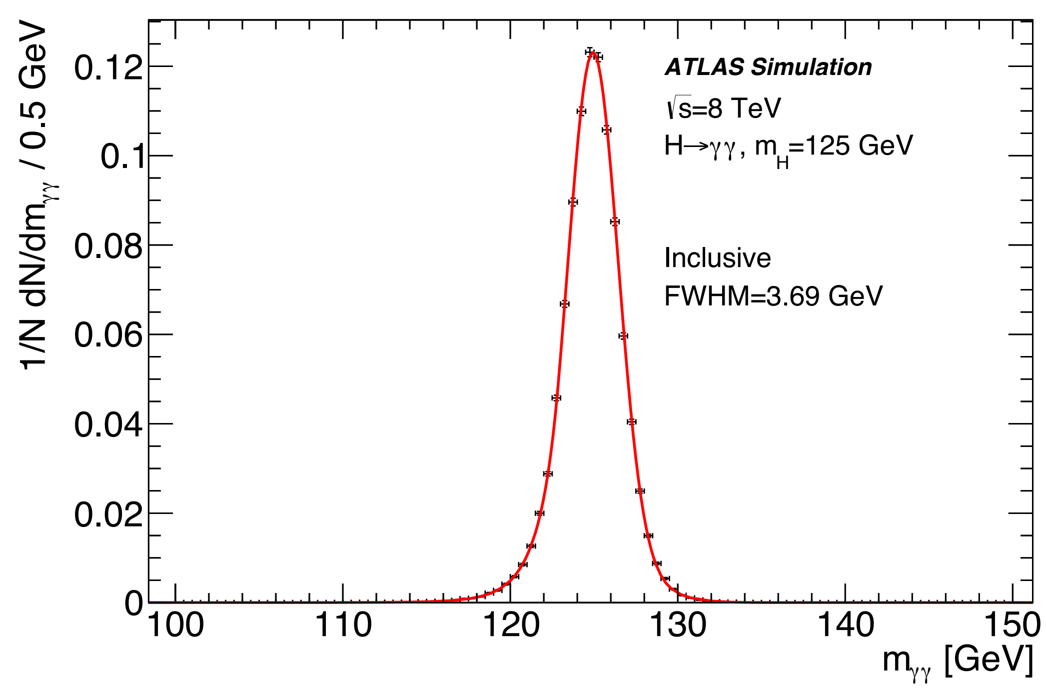
Signal shape dependence on m_H parametrized with **global resolution model** from fit to MC samples with 10 mass points

Background

$$\mathcal{B}_i(m_{\gamma\gamma}^j) = \beta_i \exp\left(-\sum_k \alpha_{ki} \left(m_{\gamma\gamma}^j\right)^k \right)$$

Background shape parametrized as a **smooth** falling function

Diphoton mass resolution



http://arxiv.org/abs/1406.3827

$H \rightarrow ZZ^*$

Signal extraction for the 4 lepton analysis

- **Inclusive cross section: fit** with shape templates for signal and background contributions.

$$N_{obs\ inclusive} = 23.7\ ^{+5.9}_{-5.3}\,(\text{stat})\ ^{+0.6}_{-0.6}\,(\text{sys})\ \ \text{Events}$$

$$\sigma_{\text{fid}}(pp \rightarrow H \rightarrow 4\ell) = 2.11^{+0.53}_{-0.47}\,(\text{stat})\,^{+0.16}_{-0.10}\,(\text{syst})\ \text{fb}$$

- **Differential cross section**: subtraction of the expected number of background events from observed number of events inside mass window (118-129 GeV) for each bin

Signal

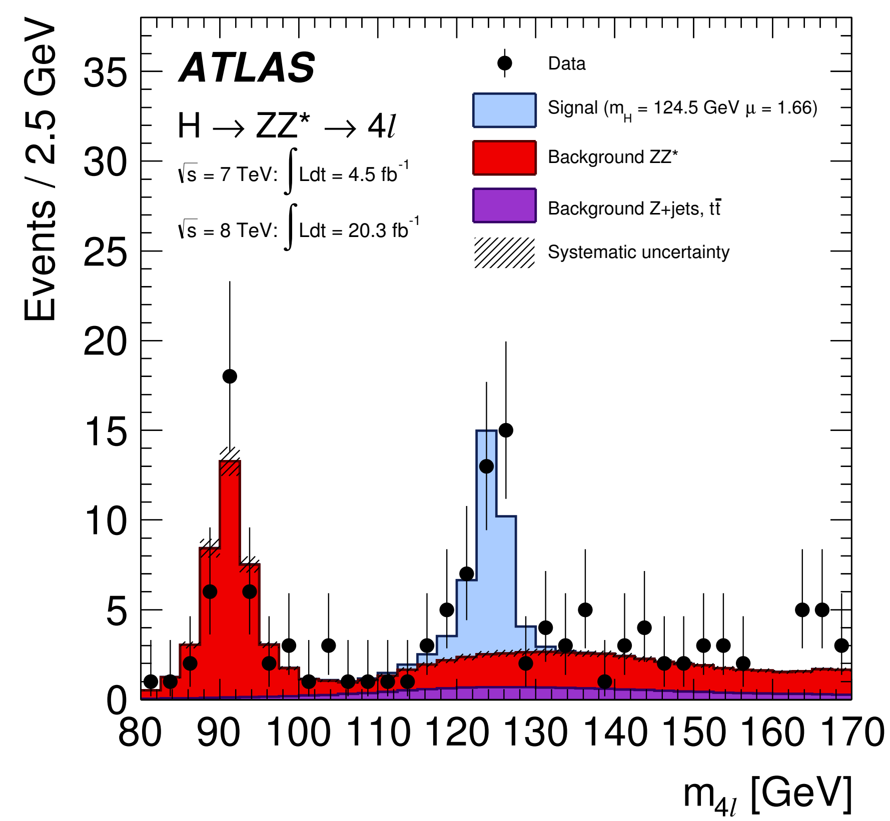
Correction for acceptance derived from signal MC.

Background

From simulated samples of ZZ & WZ at NLO in QCD

For jet related variables the predicted background is compared to the high m4l region to assign systematics.

Combined 7 & 8 TeV data (from mass paper)



http://arxiv.org/abs/1406.3827

Unfolding Procedure

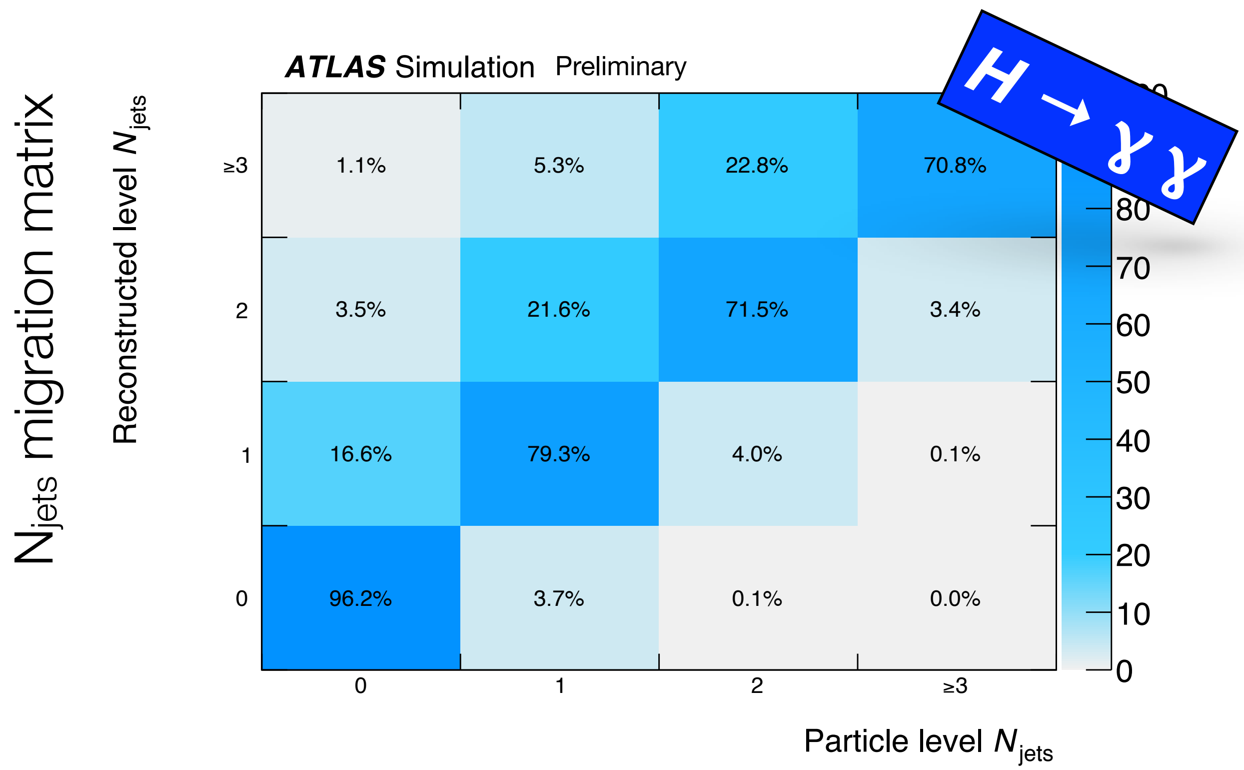
- Use **correction factor** method to unfold yields into cross sections and to revert migrations → cross checked with Bayesian unfolding

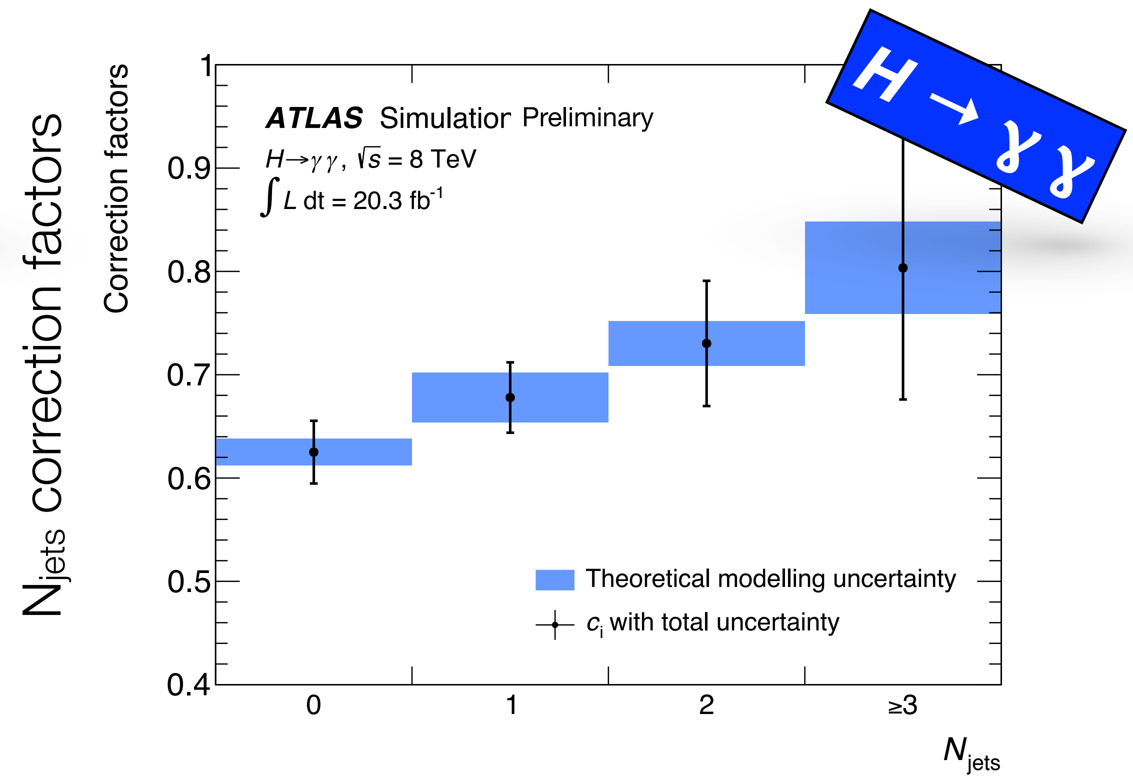
$$c_i = \frac{n_i^{\mathrm{det}}}{n_i^{\mathrm{part}}}$$

reconstruction level expected events

particle level expected events

- Only unbiased if expected & observed *(a priori unknown)* ratio are identical
→ Need to **careful evaluate** & quantify **possible bias**.





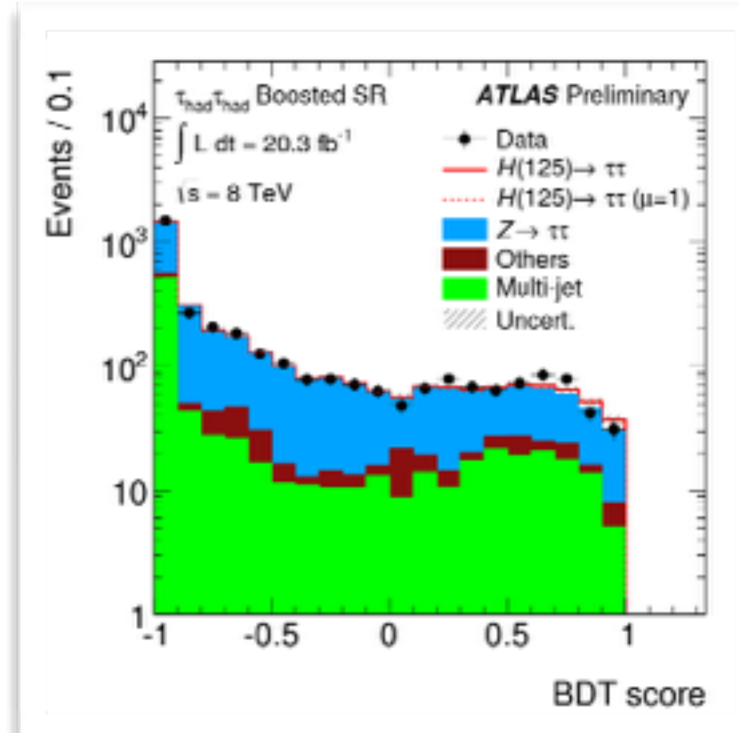
Jets in H→ $\tau\tau$

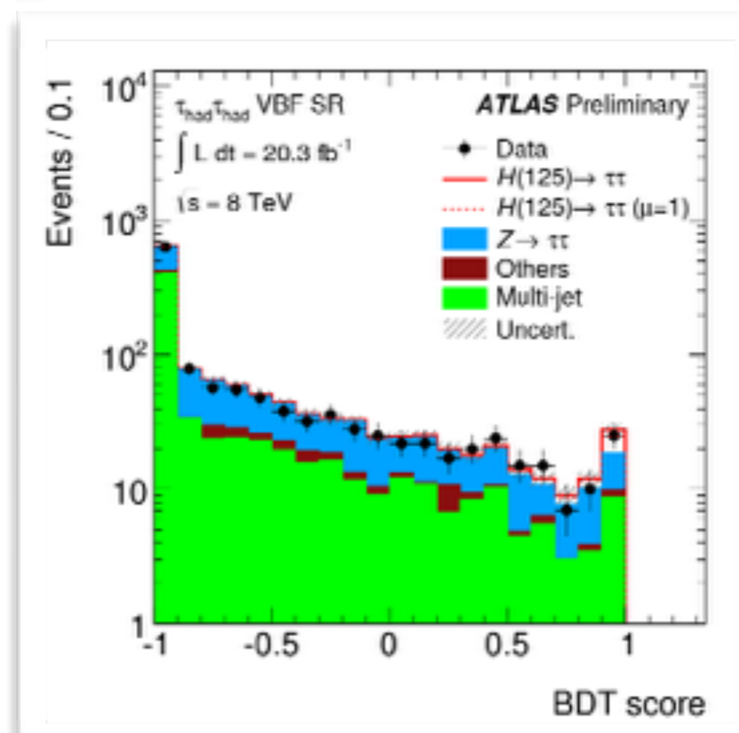
* After the τ reconstruction and pre-selection, the coupling strength is determined by fitting the shape of a multivariate classifier (a Boosted decision tree)

* Input variables for boosted and **VBF** selection:

$$p_T^{\rm total} = p_T(H - jj)$$

Variable	VBF			Boosted		
	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
$m_{\tau\tau}^{\rm MMC}$	•	•	•	•	•	•
$\Delta R(\tau,\tau)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1}\times\eta_{j_2}$		•	•			
$p_{\rm T}^{\rm Total}$		•	•			
sum $p_{\rm T}$					•	•
$p_{\rm T}(\tau_1)/p_{\rm T}(\tau_2)$					•	•
$E_{\rm T}^{\rm miss}\phi$ centrality		•	•	•	•	•
$x_{\tau 1}$ and $x_{\tau 2}$						•
$m_{\tau\tau,j_1}$				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi_{\ell_1,\ell_2}$				•		
sphericity				•		
$p_{\rm T}^{\ell_1}$				•		
$p_{\rm T}^{j_1}$				•		
$E_{\rm T}^{\rm miss}/p_{\rm T}^{\ell_2}$				•		
$m_{\rm T}$		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,{\rm jets}})$	•					
j_3 η centrality	•					
$\ell_1\times\ell_2$ η centrality	•					
ℓ η centrality		•				
$\tau_{1,2}$ η centrality			•			





* Theory uncertainties of **ggF** contribution in BDT classifier very very challenging to estimate. With increasing statistics this would be a crucial aspect in a future VBF BDT.

Monte Carlo predictions & calculations used for comparisons

$H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ^*$

Process	Fiducial Region	Name	Accuracy
$gg \rightarrow H$	*Inclusive*	LHC-XS	NNLO/NNLL+EW
		STWZ	NNLO/NNLL’
		HRes 2.2	NNLO/NNLL
	One-jet	JetVheto	NNLO/NNLL
		BLPTW	NNLO/NNLL’
		Minlo HJ	H+1 jets @ NLO
	Two-jet	Minlo HJJ	H+1 jets @ NLO
	-	MEPS@NLO	NLO multi-leg merged
VBF*	-	Powheg	NLO
VH & ttH**	-	Pythia8	LO

* = *k-Factor always applied to scale up to HXSWG cross section*

$H \rightarrow \gamma\gamma$

Fiducial Definition for Objects in diphoton analysis

Same object selection as mass & couplings analysis

Object Selection

Photons

- Diphoton trigger with 35/25 GeV
- **$p_T / m_{\gamma\gamma}$ = 0.35 (0.25)**
- **$|\eta| < 2.37$** excluding **$1.37 < |\eta| < 2.37$**
- Pass '**tight**' selection criteria
- **$m_{\gamma\gamma} \in$ [105,160] GeV**
- Isolation cut of **6 GeV**

Electrons

- Clusters matched to ID tracks
- Pass '**medium**' identification
- **p_T > 15 GeV & $|\eta| < 2.47$**
- **Cluster (Track) isolation: 20% (15%)** of p_T

Muons

- ID tracks matched to MS
- **p_T > 15 GeV & $|\eta| < 2.47$**
- Same **isolation** as for electrons

Jets

- **anti-k_t algorithm with 0.4**
- **p_T > 30** or **50 GeV & $|y| < 4.4$**
- **JVF > |0.25|**

E_T^{miss}

Calorimeter based with final calibrated photons and track information for soft contributions.

Particle level

Stable particles with **$c\tau$ = 10 mm**

Photons

- **$p_T / m_{\gamma\gamma}$ = 0.35 (0.25)** & **$|\eta| < 2.37$**
- Isolation cut of **14 GeV**

Leptons

- **p_T = 15 GeV**
- **$|\eta| < 2.37$**
- **dressed** with γ (ΔR = 0.1)

Jets

- **anti-k_t with 0.4**
- **p_T > 30 / 50 GeV** & **$|y| < 4.4$**

This particle-level isolation reproduces a mean calorimeter isolation energy of 6 GeV.

$H \rightarrow ZZ^*$

Fiducial Definition for Objects in 4 lepton analysis

Same object selection as mass & couplings analysis

Object Selection

single & double lepton trigger

Electrons
- Pass identification
- **p_T > 7 GeV & |η| < 2.47**
- **Cluster (Track) isolation**
- **…**

Muons
- ID tracks matched to MS
- **p_T > 6 GeV & |η| < 2.7**
- **Cluster (Track) isolation**
- **…**

Jets
- **anti-k_t algorithm with 0.4**
- **p_T > 30 or 50 GeV & |y| < 4.4**
- **JVF > |0.25**
- **ΔR(j,lepton) > 0.2**

Particle level

Stable particles with **cτ = 10 mm**

Muons
- **p_T = 6 GeV**
- **|η| < 2.7**
- **not dressed**

Z
- **no τ decays**

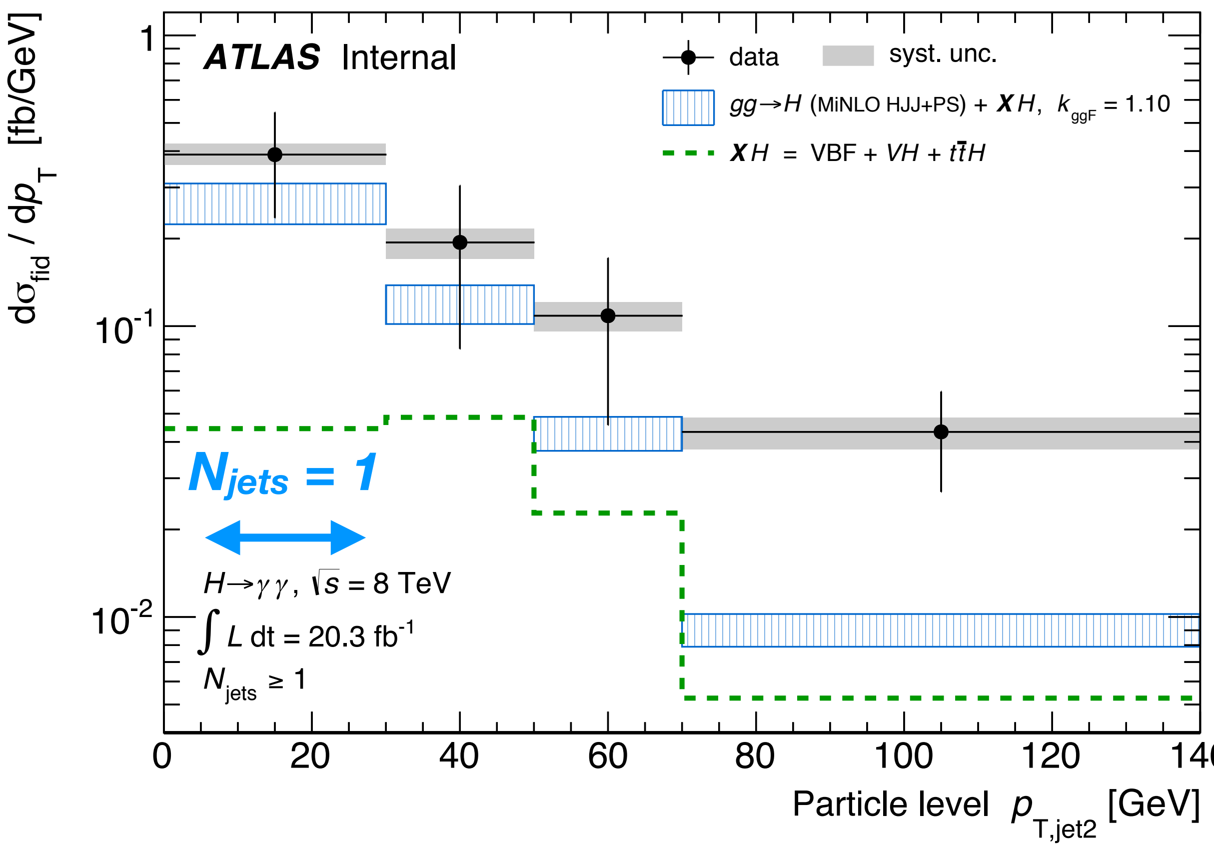
Electrons
- **p_T = 7 GeV**
- **|η| < 2.47**
- **not dressed**

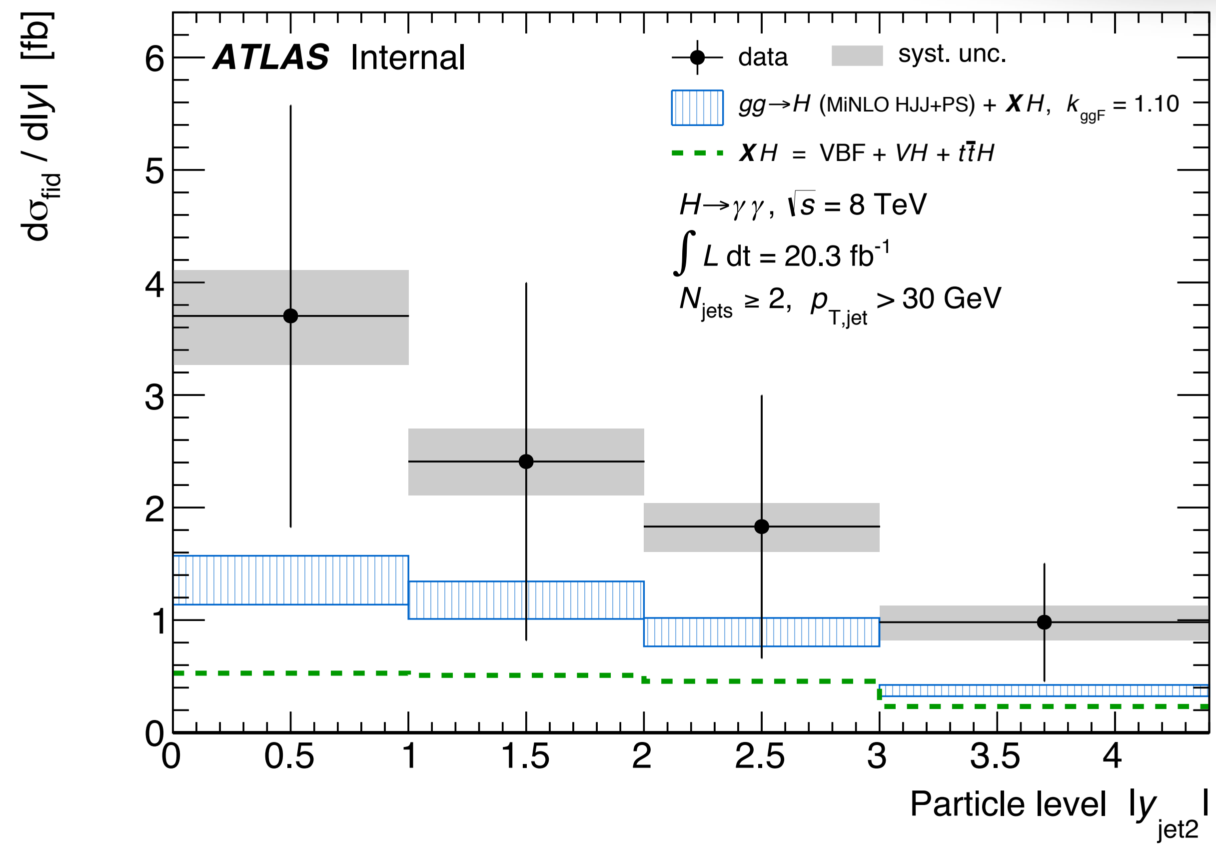
Fermions
- **50 GeV < m_{12} < 106 GeV**
- **12 GeV < m_{34} < 115 GeV**
- **mll > 5 GeV**
- **118 GeV < m4l < 129**

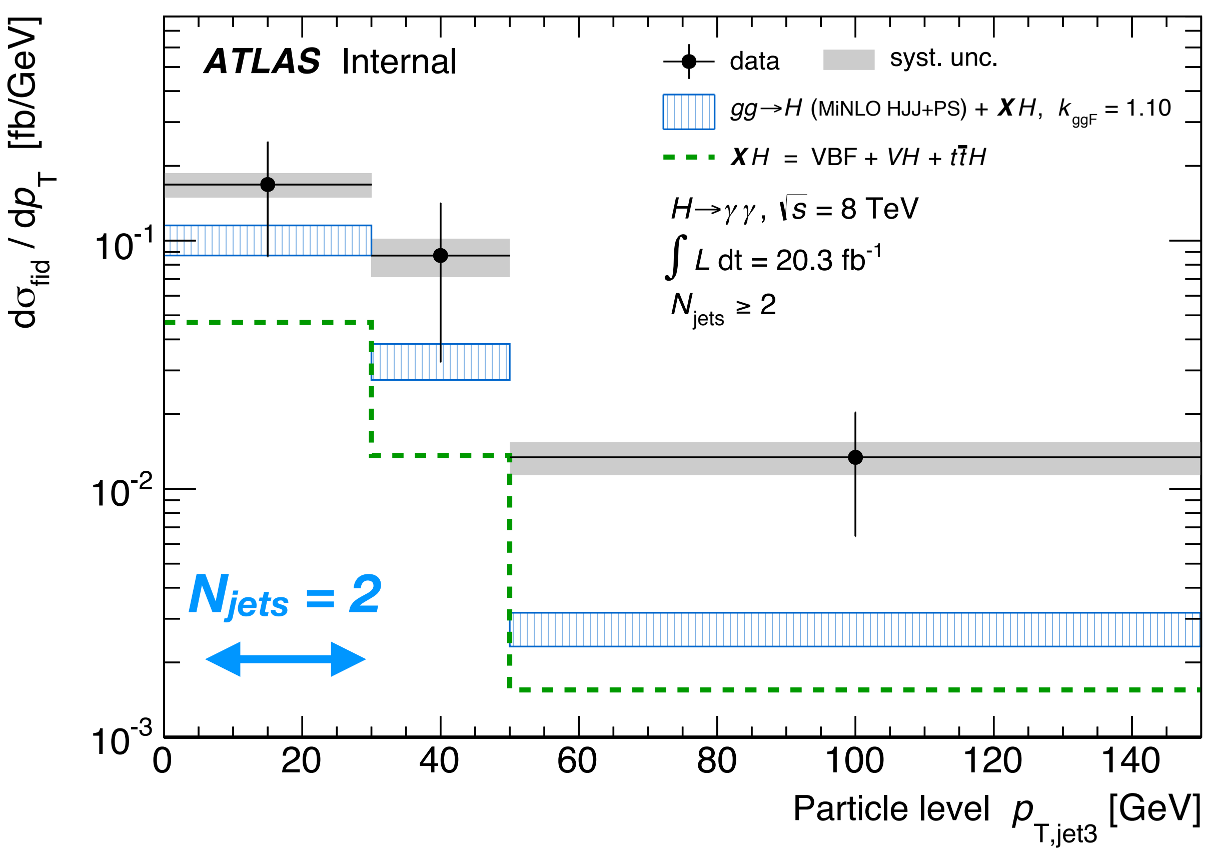
Jets
- **anti-k_t with 0.4**
- **p_T > 30 / 50 GeV & |y| < 4.4**

(sub-)sub-leading jet p_T & Rapidity

$H \rightarrow \gamma\gamma$







First & Second Moments