Measuring the Higgs properties with 36.1 fb^{-1} of ATLAS data collected at $\sqrt{s} = 13$ TeV

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DESY LHC physics discussions: Higgs

September 11, 2017

ATLAS EXPERIMENT

DESY

erc

European Research Council

Established by the European Commission

Outline.

Focuses on measurement of the Higgs boson properties in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ decay channels with 36.1 fb^{-1} of 13 TeV data (2015+2016)

- ***Introduction***
- ***Higgs boson properties:***
  - Mass
  - Inclusive, fiducial and differential cross sections
  - Signal strengths, production cross sections, couplings
- ***Conclusions and outlook***

LHC and ATLAS performance.

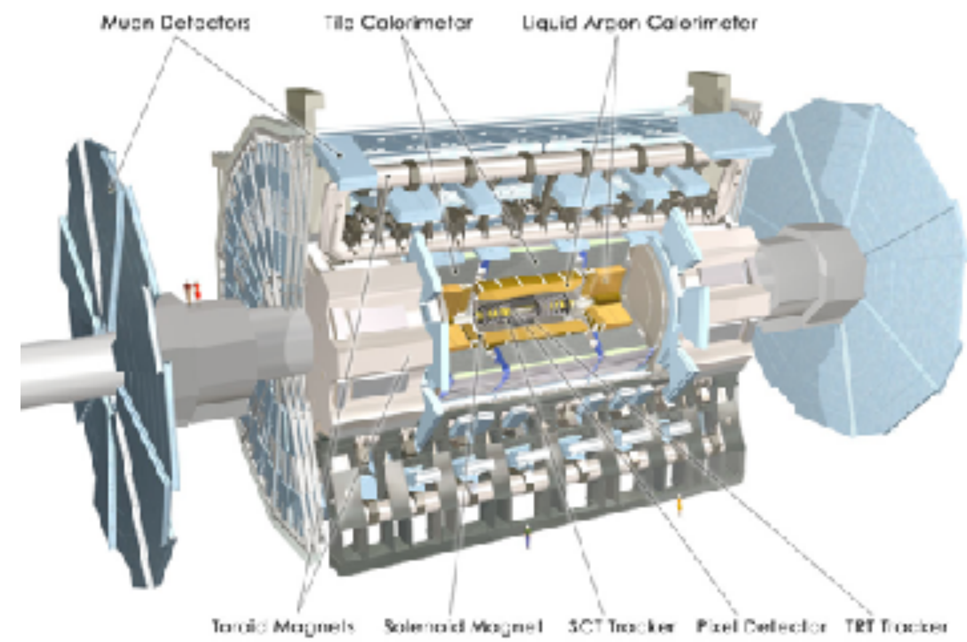
LHC performed very well during Run-1 and ***Run-2 (2015+2016)***

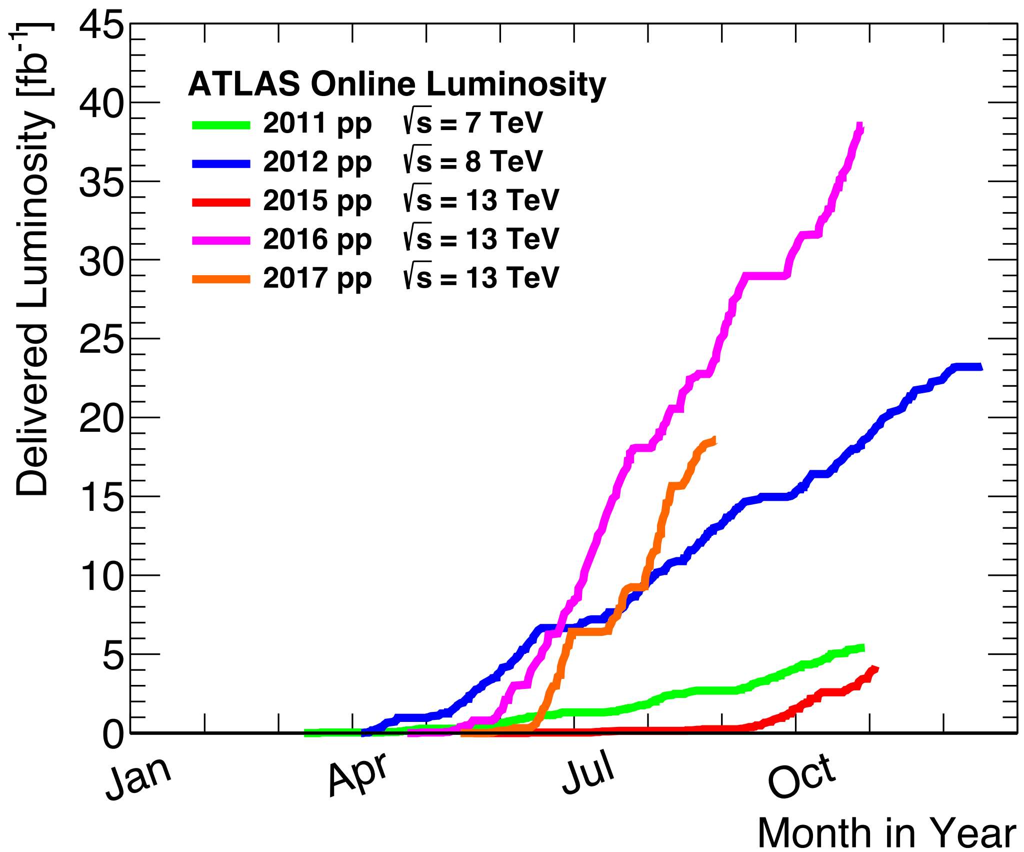
ATLAS achieved very ***high data taking efficiency***

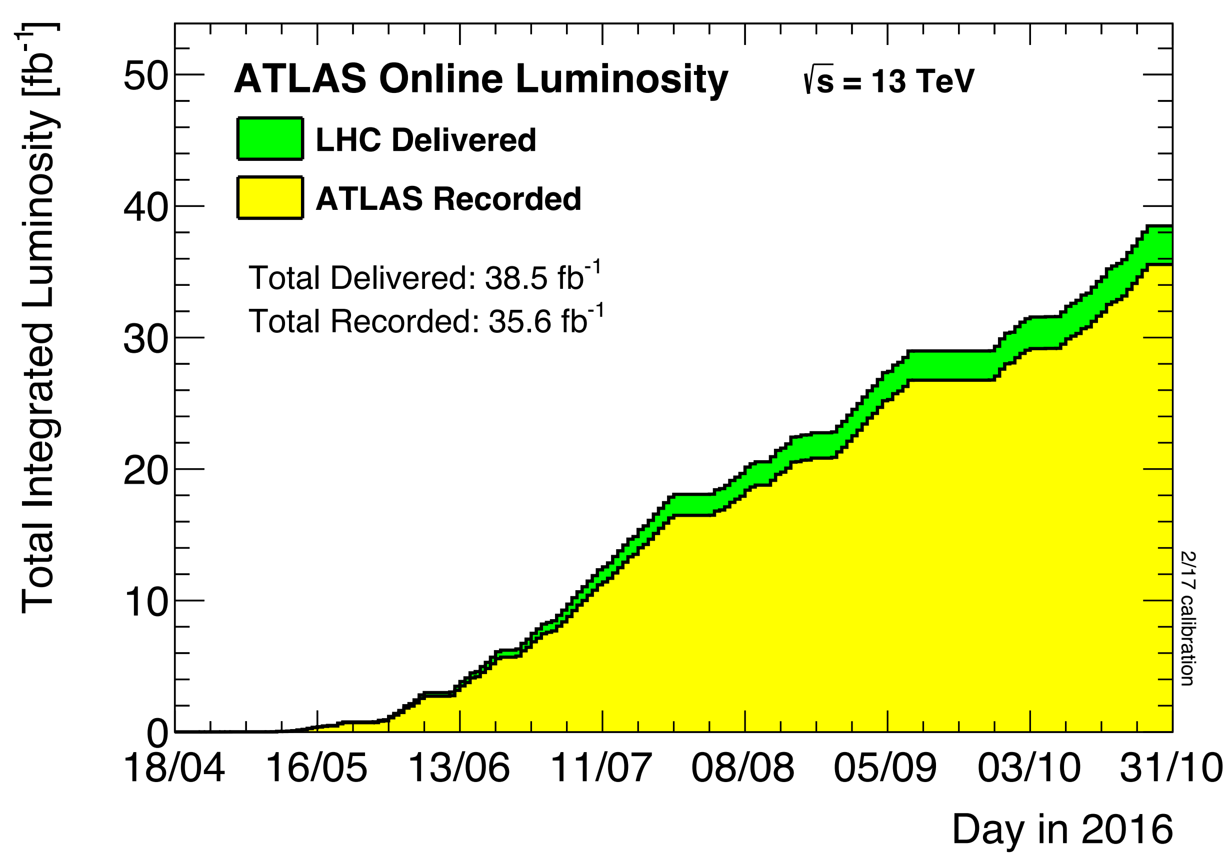
- ***~90% of data ready for physics***

Data for analysis:

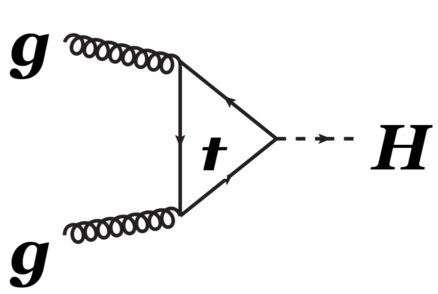
- 2011: √s=7 TeV: ~5 fb-1
- 2012: √s=8 TeV: ~20 fb-1
- ***2015 & 2016: √s=13 TeV: ~36 fb-1***



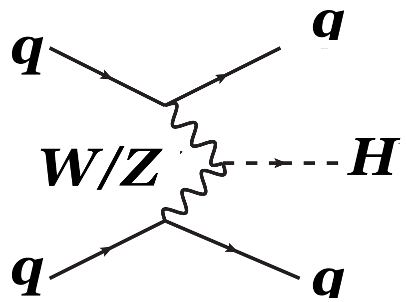




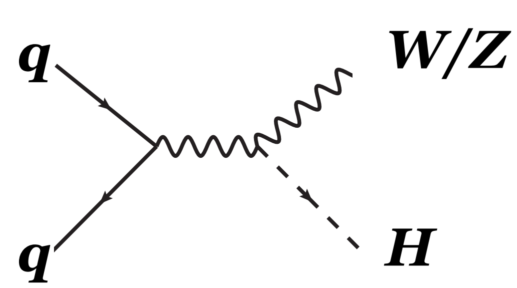
Higgs boson production & decay.



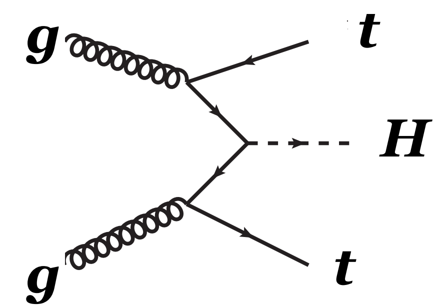
ggF: ~ 87%



VBF: ~ 7%

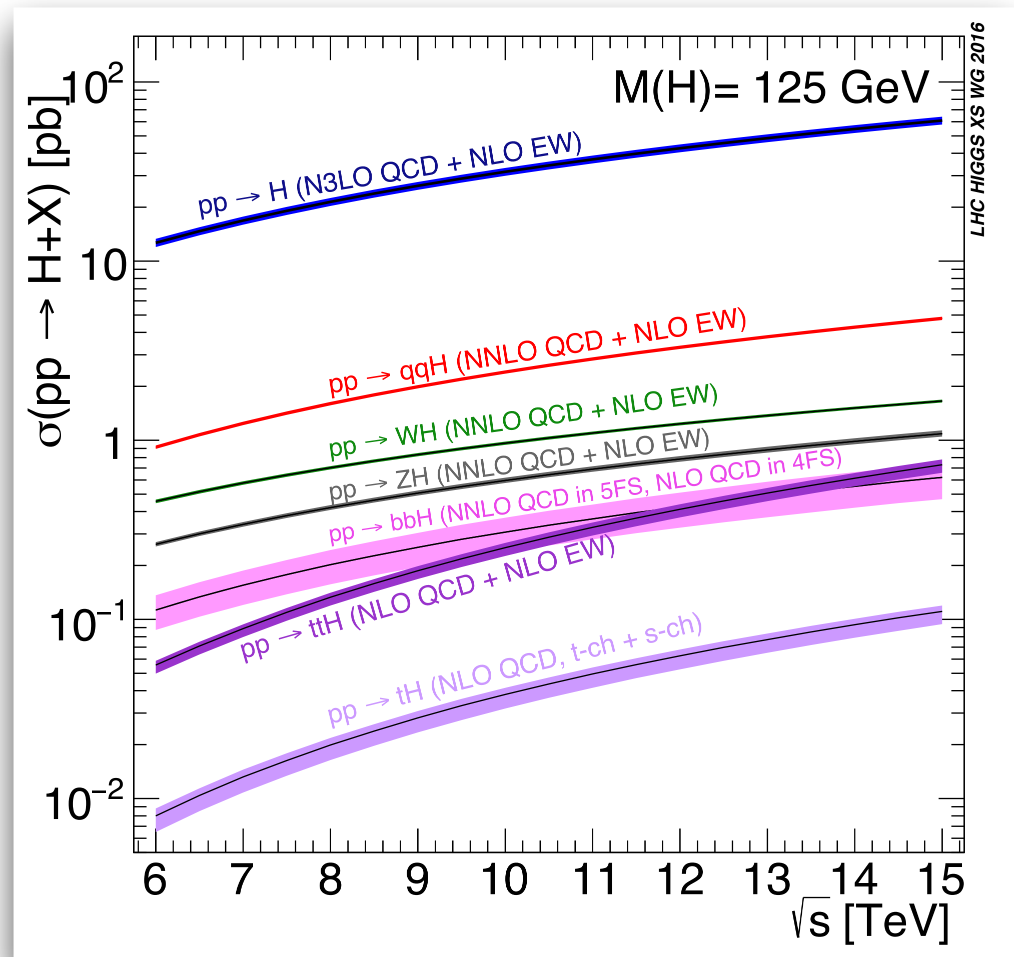


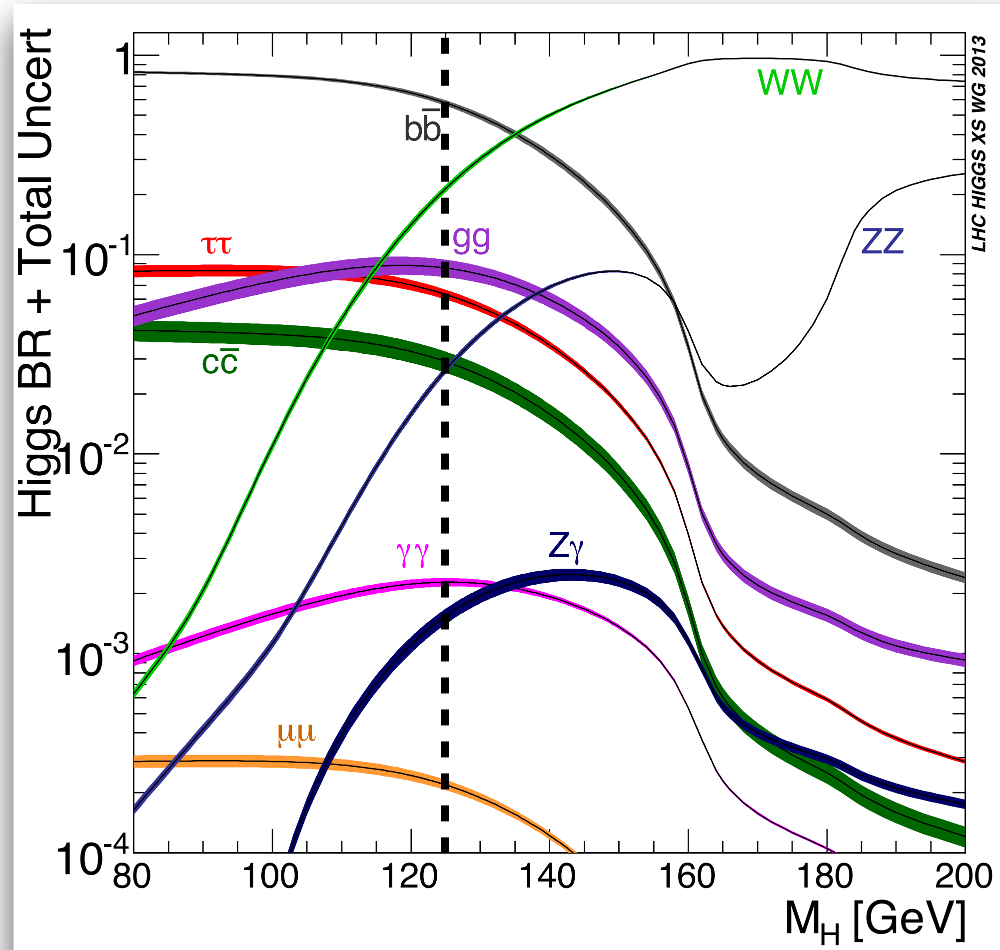
VH ≡ WH or ZH: ~4%



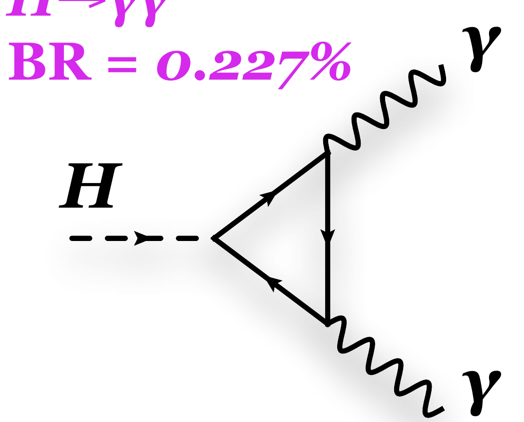
ttH: ~ 2%

bbH and gg→ZH not targeted by specific analysis categories but implemented in the fit model

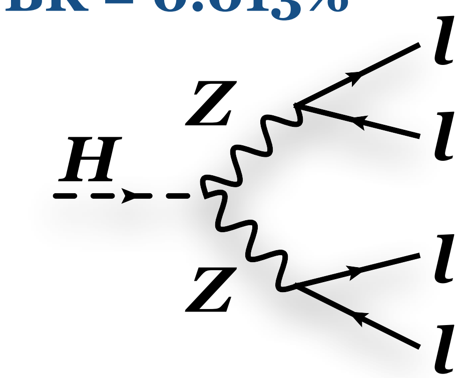




H→γγ
BR = 0.227%



H→ZZ*→4l
BR = 0.013%



Before making a statement on the SM nature of the Higgs, we first need m_H

Once m_H is determined, all other Higgs properties are calculable

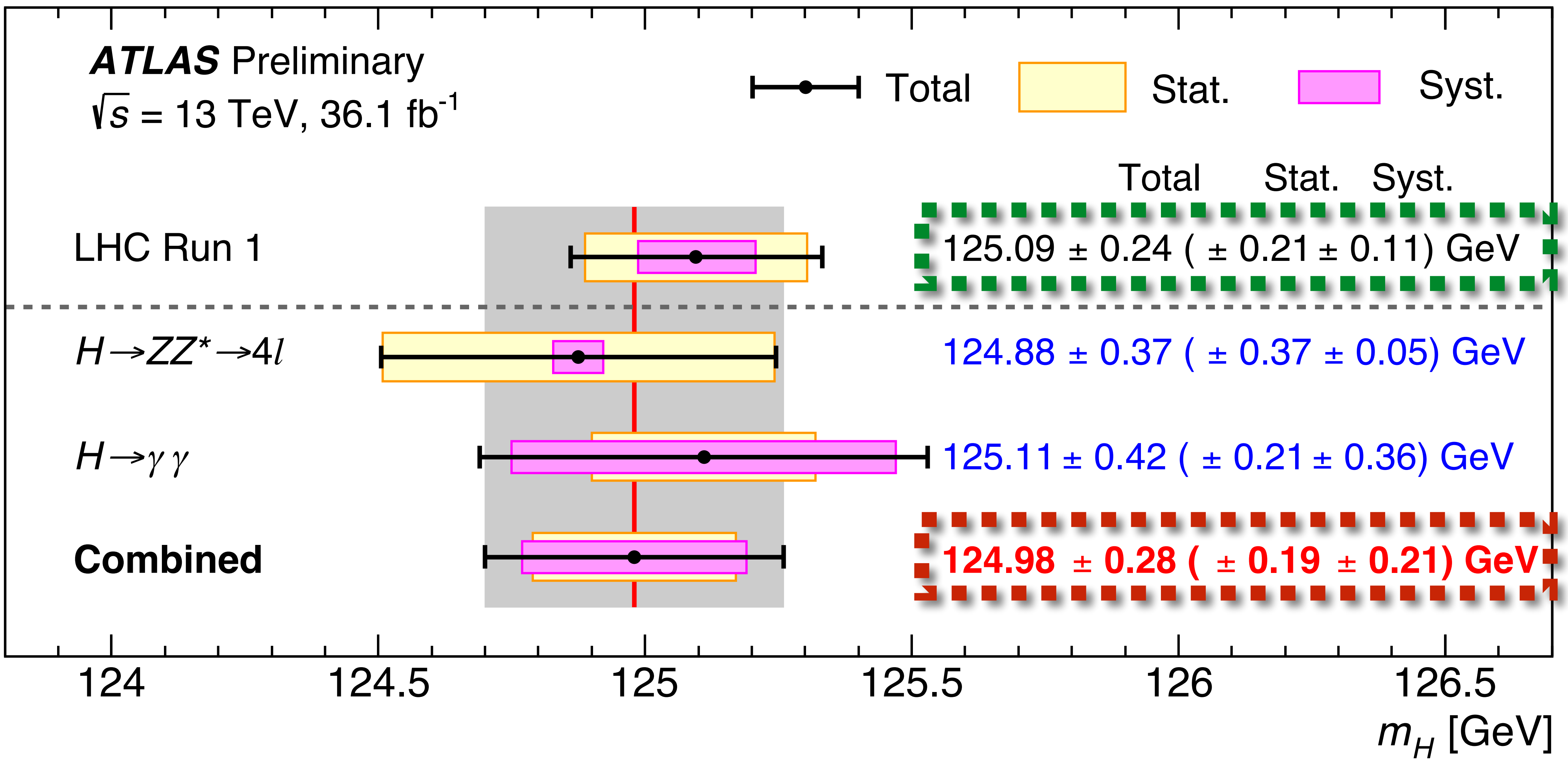
m_H well established in LHC Run-1

Higgs boson mass.

- Combining measurements in ***H→γγ*** and ***H→4l*** *decay* channels

  provides the best mass resolution
- ***Neglect interference*** between ***gg→γγ*** and ***gg→H→γγ*** :

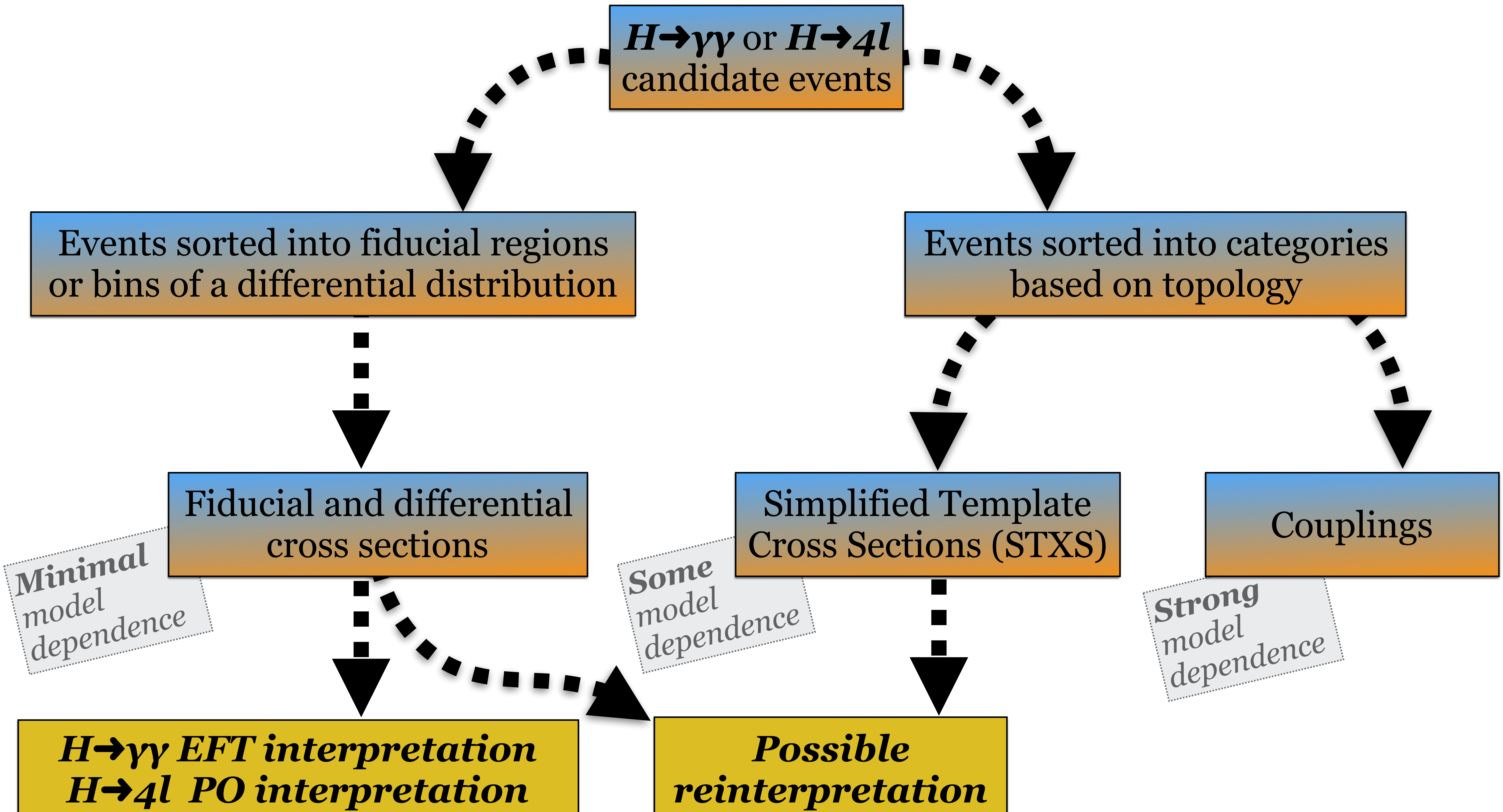
$$\Delta m_{\gamma\gamma} = -35 \pm 9 \text{ MeV (ATLAS)}$$



ATLAS combined mass in excellent agreement with the LHC Run-1 average

Overview of measurements.

Probing the Higgs sector provides a test of the SM, constrains new physics and is sensitive to new particles/processes…



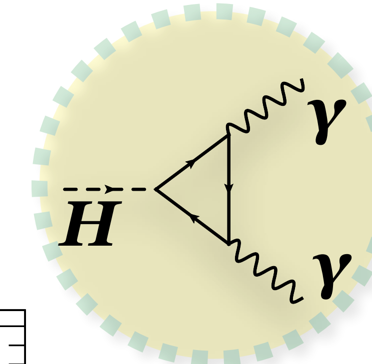
Inclusive, fiducial and differential cross sections

H*→*γγ or ***H*→*4l***
candidate events

Events sorted into fiducial regions
or bins of a differential distribution

Fiducial and differential
cross sections

$H \rightarrow \gamma\gamma$.



Two photons (tight ID and isolated):

- $|\eta| < 2.37$ (excluding: $1.37 \leq |\eta| < 1.52$)
- $p_T/m_{\gamma\gamma} > 0.35$ (0.25)
- $m_{\gamma\gamma} \in [105, 160)$ GeV

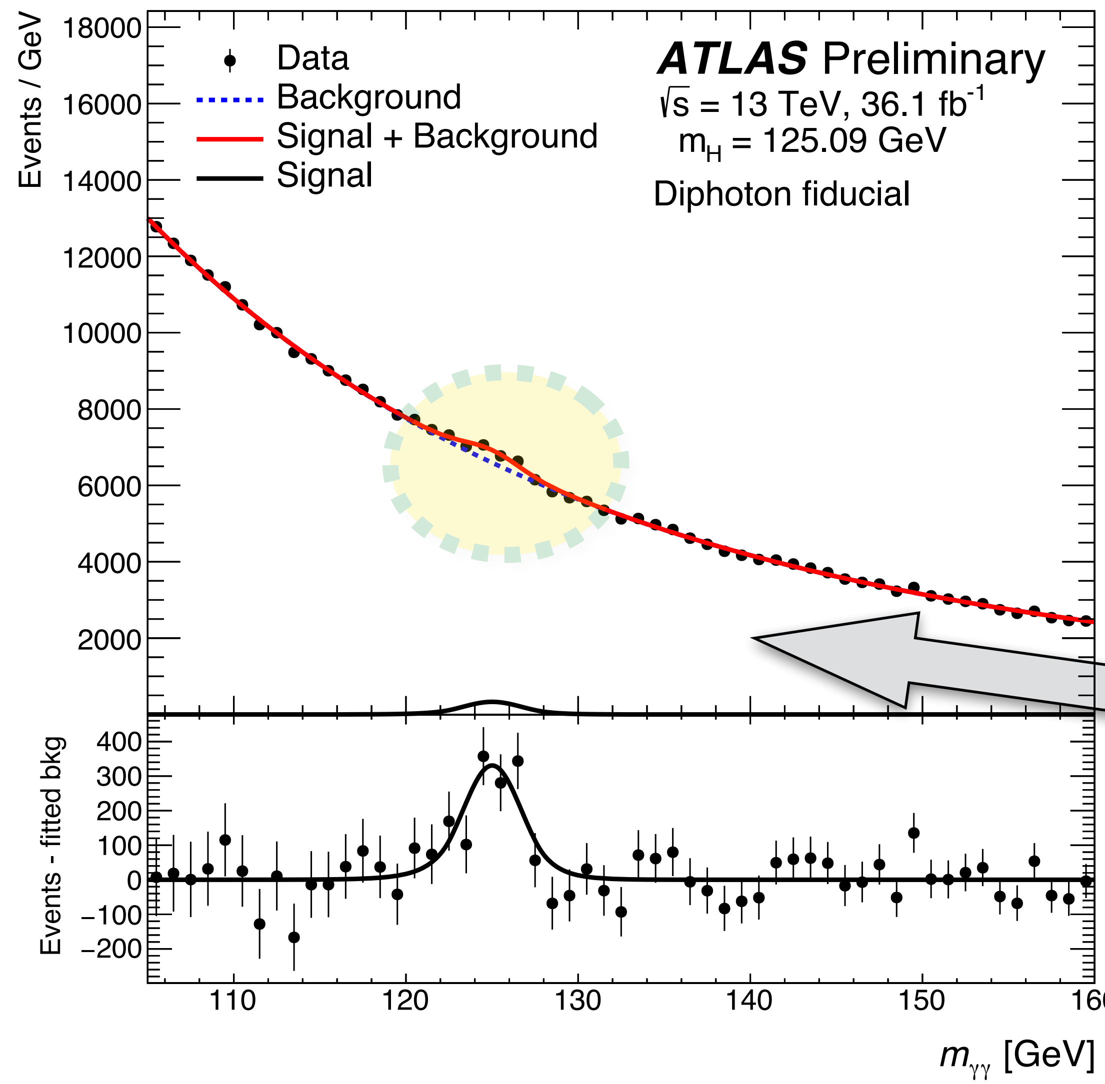
Jets (anti-k_t, R=0.4):

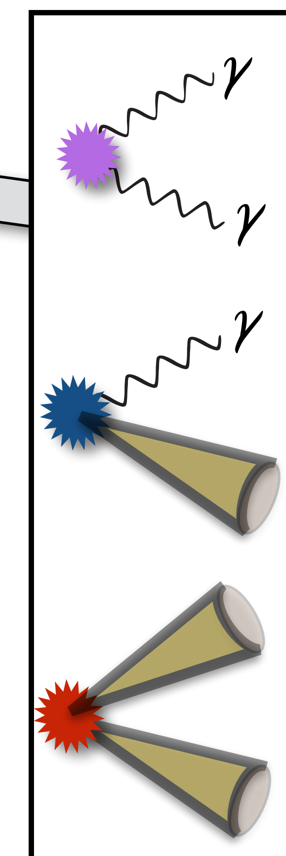
- $p_T > 30$ GeV & $|y| < 4.4$
- couplings: ($p_T > 25$ GeV for $|y| < 2.4$)

Electrons and muons:

- ***e's*** : $p_T >$ (10) 15 GeV & $|\eta| < 2.47$ (excluding: $1.37 \leq |\eta| < 1.52$)
- ***μ's*** : $p_T >$ (10) 15 GeV & $|\eta| < 2.7$

Backgrounds: *γγ, γ-jet, jet-jet*





Extract signal via a **S**+**B** ***fit to $m_{\gamma\gamma}$*** spectrum

m_H fixed to 125.09 GeV

Correct for detector effects using ***bin-by-bin correction factors***

$H \to ZZ \to 4\ell$

Leptons:

e's : $p_T > 7$ GeV & $|\eta| < 2.47$

μ's : $p_T > 5$ GeV & $|\eta| < 2.7$

Jets (anti-k_t, R=0.4):

$p_T > 30$ GeV & $|y| < 4.4$

Event selection:

- 2 opposite sign same flavour pairs

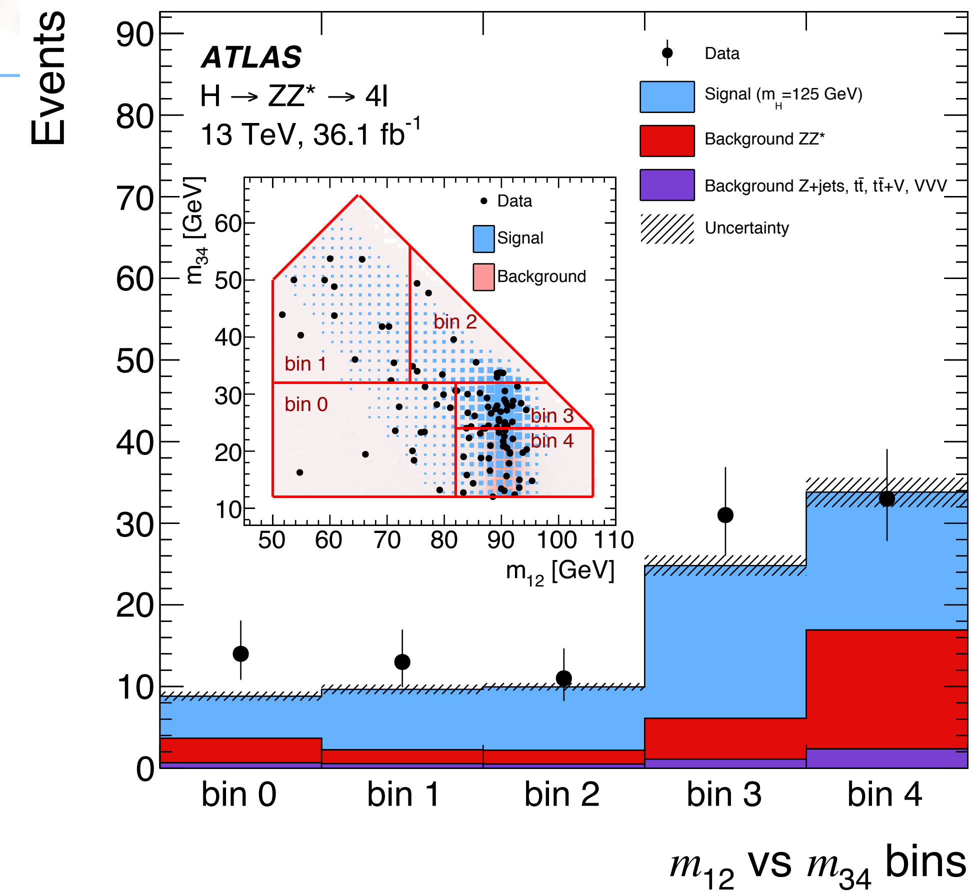
  4e, 4μ, 2e2μ, 2μ2e

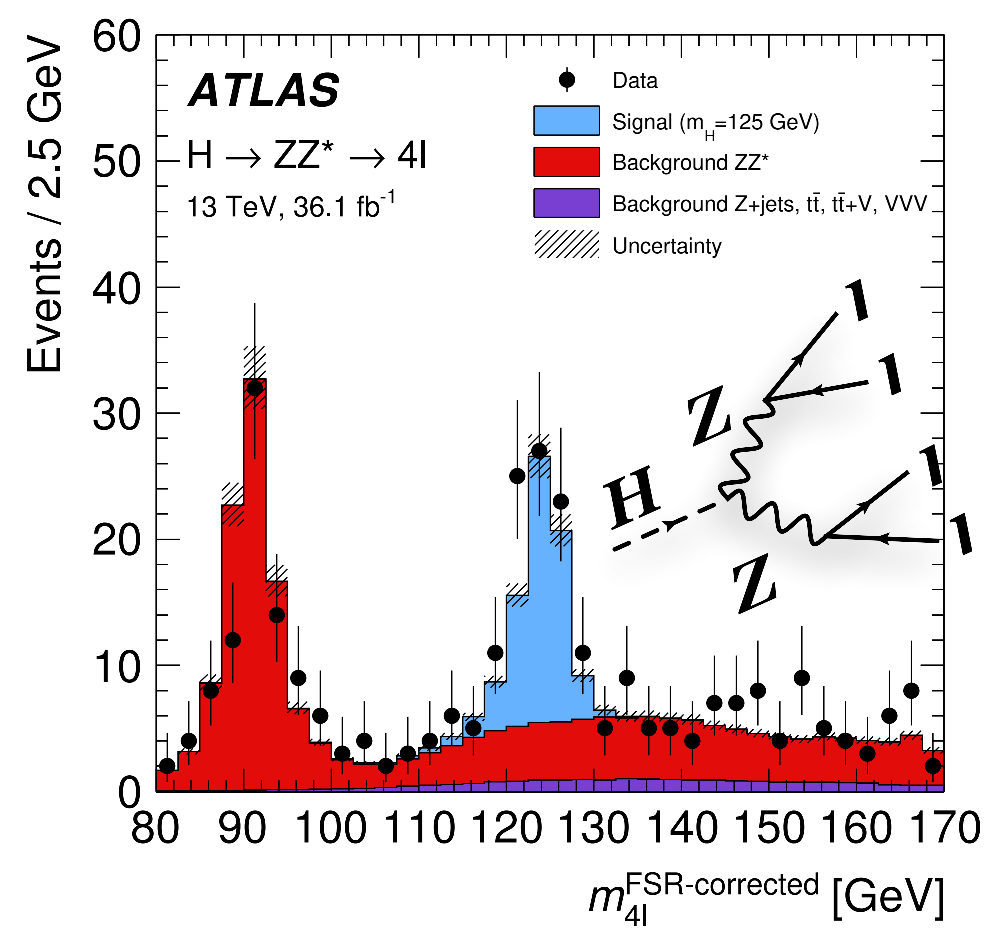
- ***m_{12}*** kinematically ***constrained to m_Z***
- select based on ***4l vertex compatibility***

Backgrounds:

ZZ: MC

Z+jets & top: data-driven

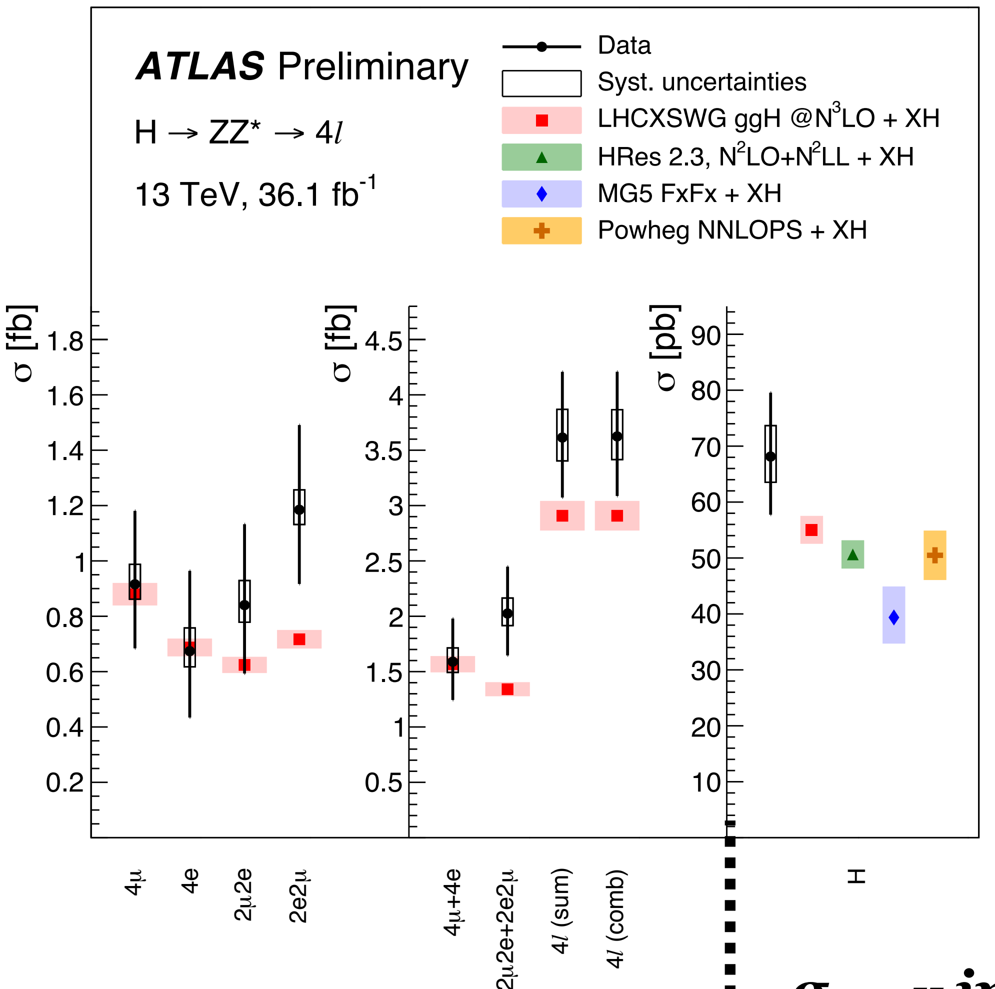




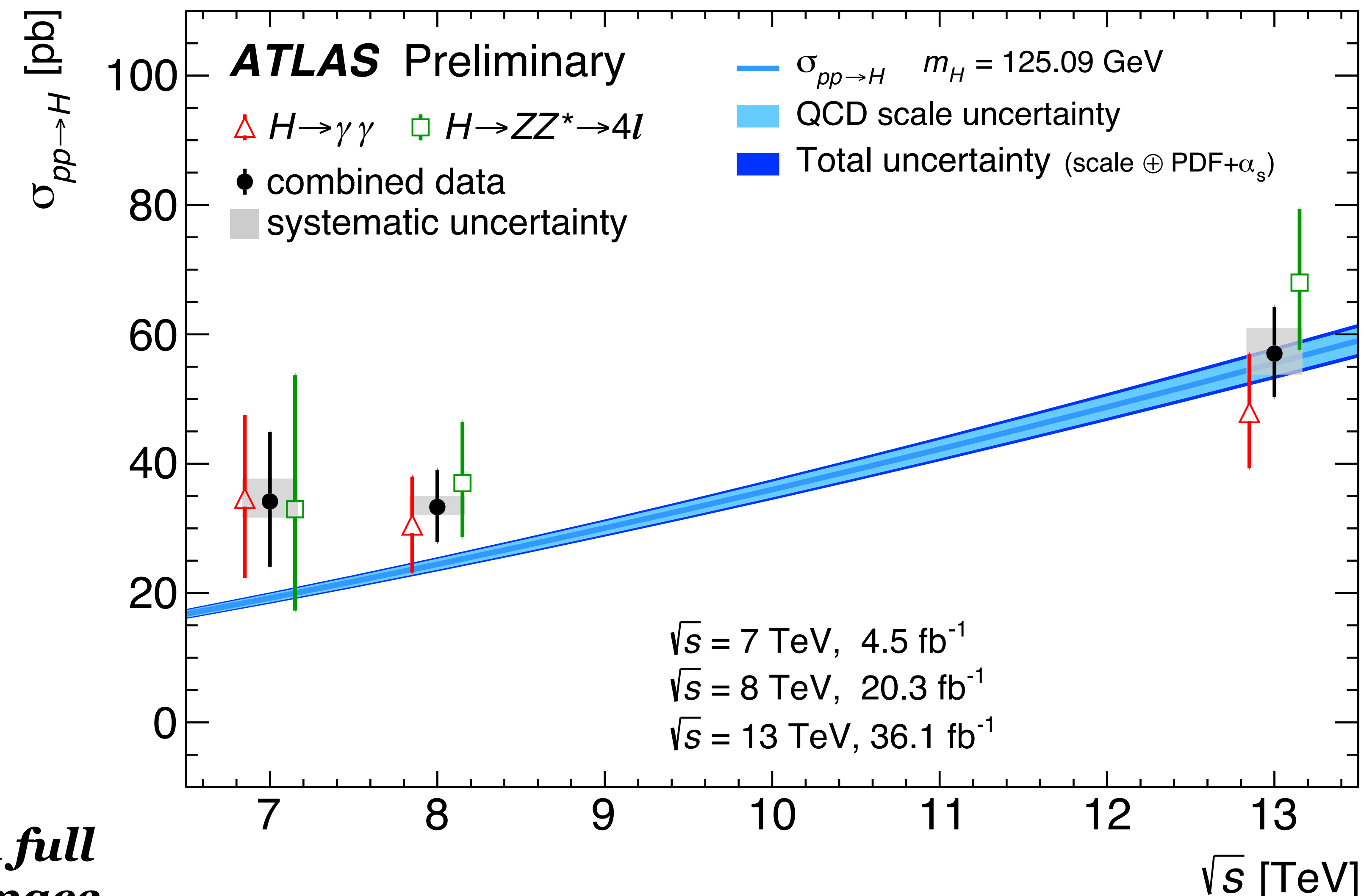
Extract signal via a ***template fit to invariant mass***

Correct for detector effects using ***bin-by-bin correction factors***

Total production & *H→4l* fiducial cross sections.



σ_{fid}



$\sigma_{pp\to H}$ in full phase-space

H→4l fiducial cross sections in terms of lepton parings

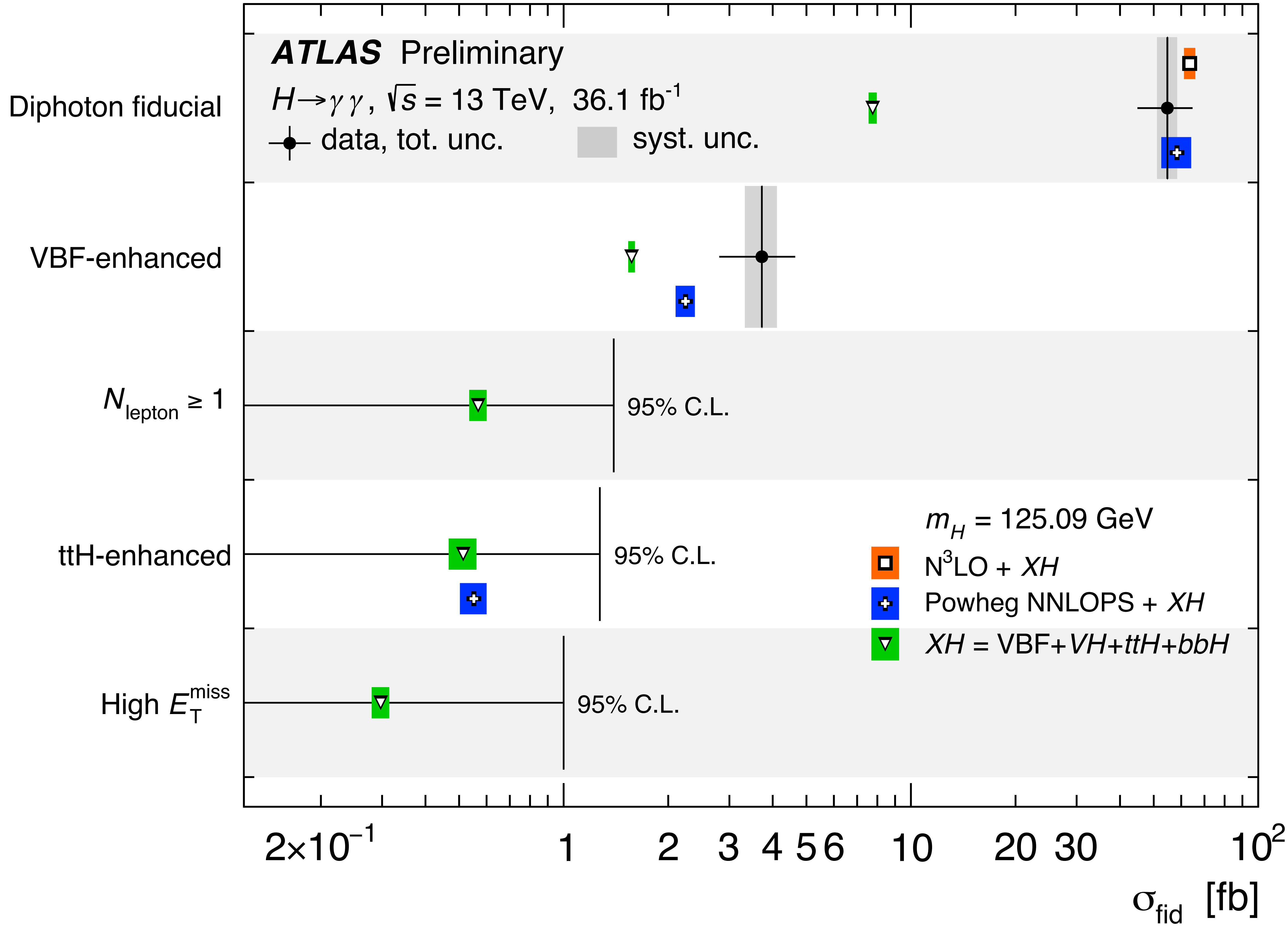
Total production cross sections obtained by extrapolating to full phase space using acceptance factors and BR

Similar statistical significance for both channels

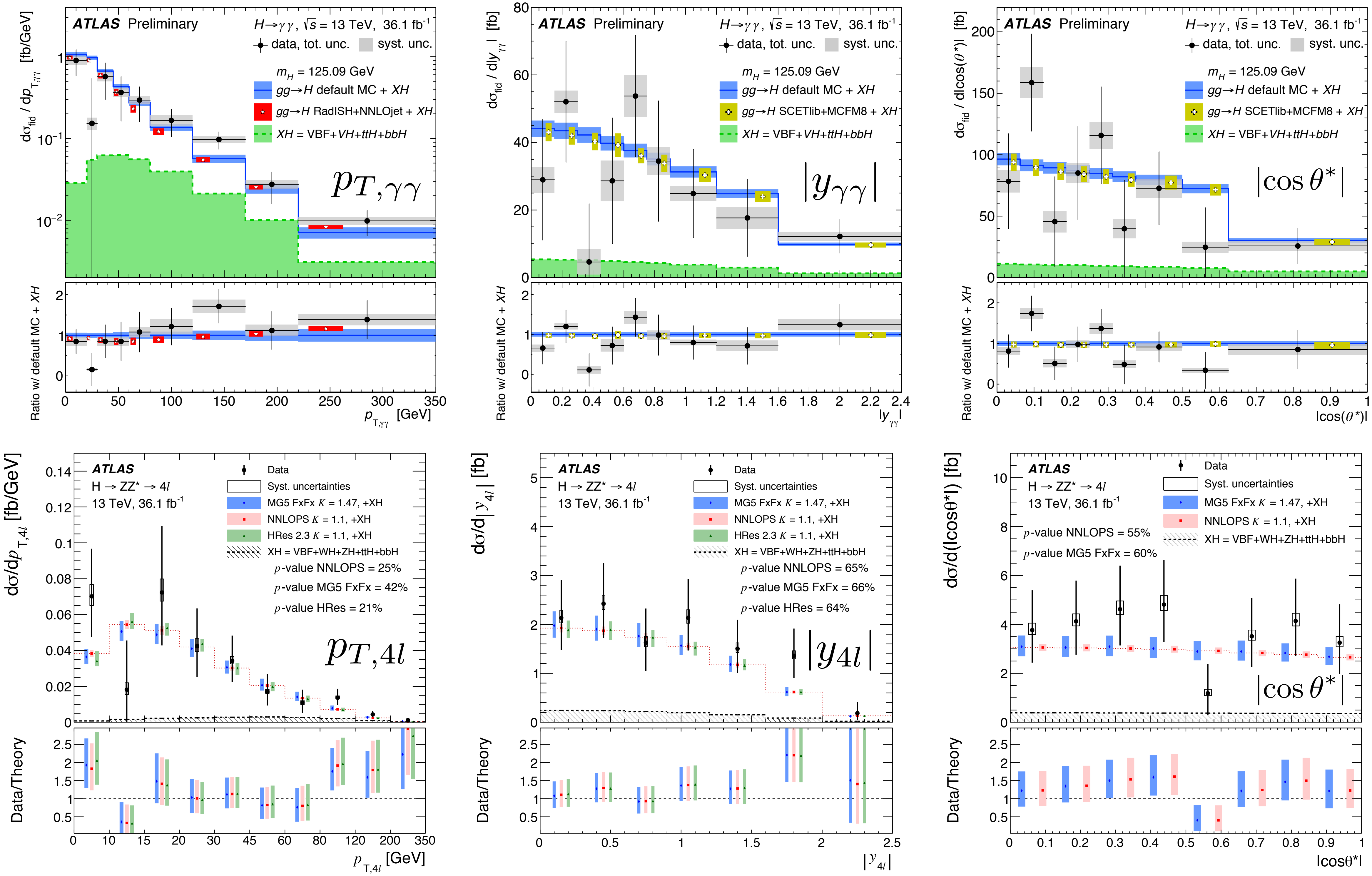
Individual channel compatibility*: *p-value = 29%

Compatibility with *SM*: *p-value = 84%*

$H \rightarrow \gamma\gamma$ fiducial cross sections.



Differential cross sections.



H→γγ: default MC = NNLOPS ggF (k-factor = 1.1) + XH, no k-factor applied to other predictions

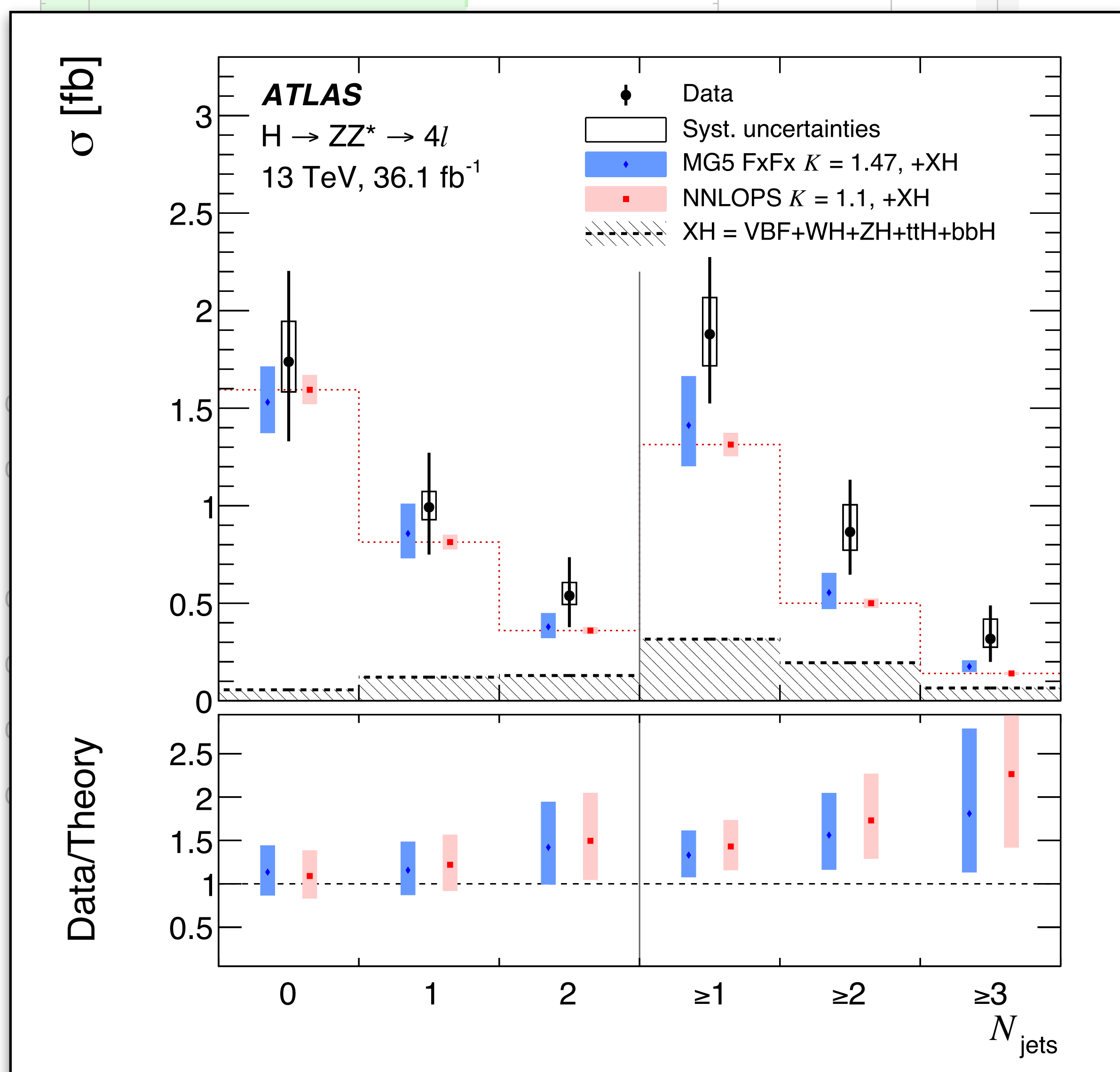
H→ZZ→4l: all predictions include k-factor

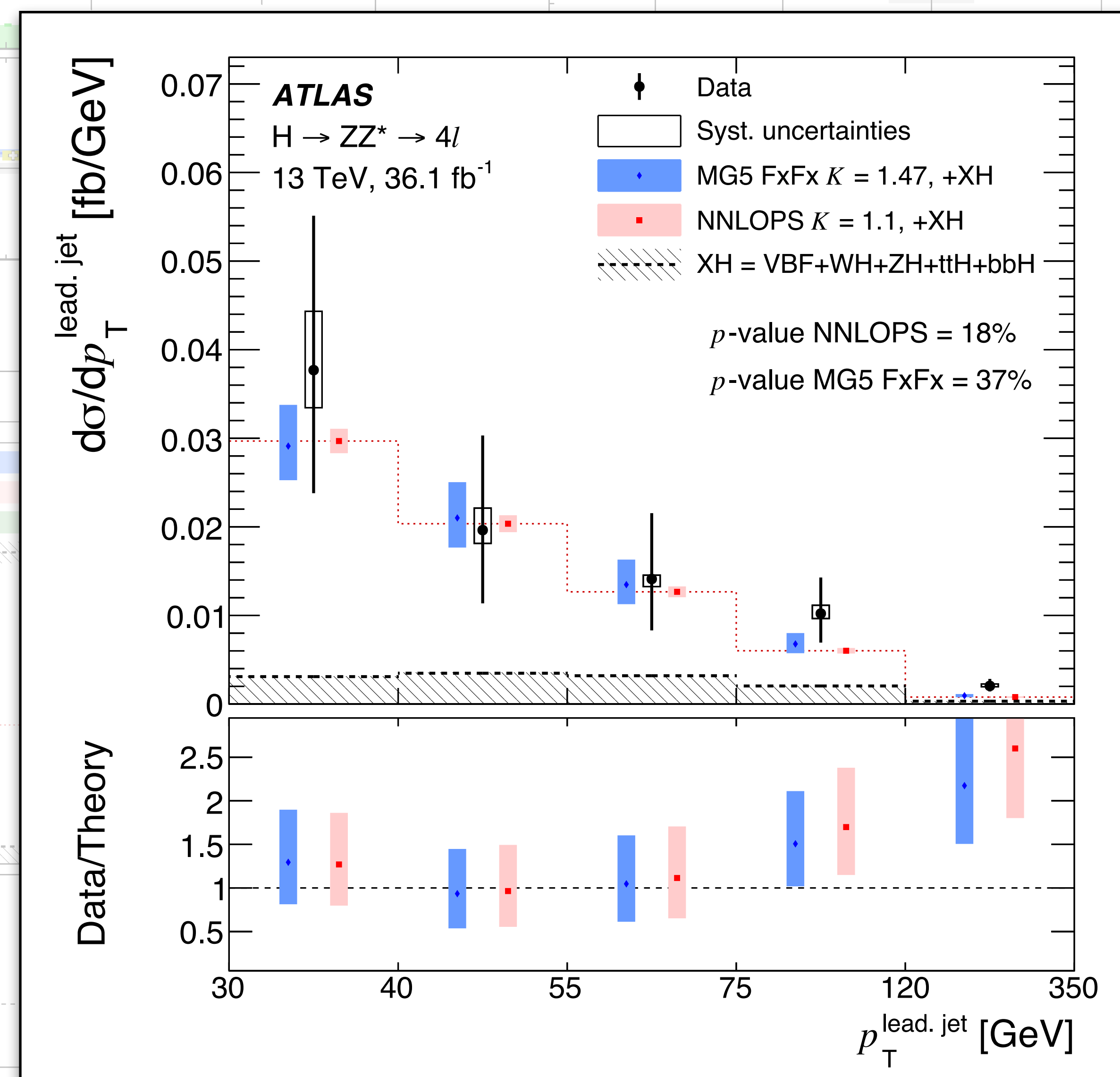
Differential cross sections.

H→4l* measures additional distributions (in backup), *including jet based observables

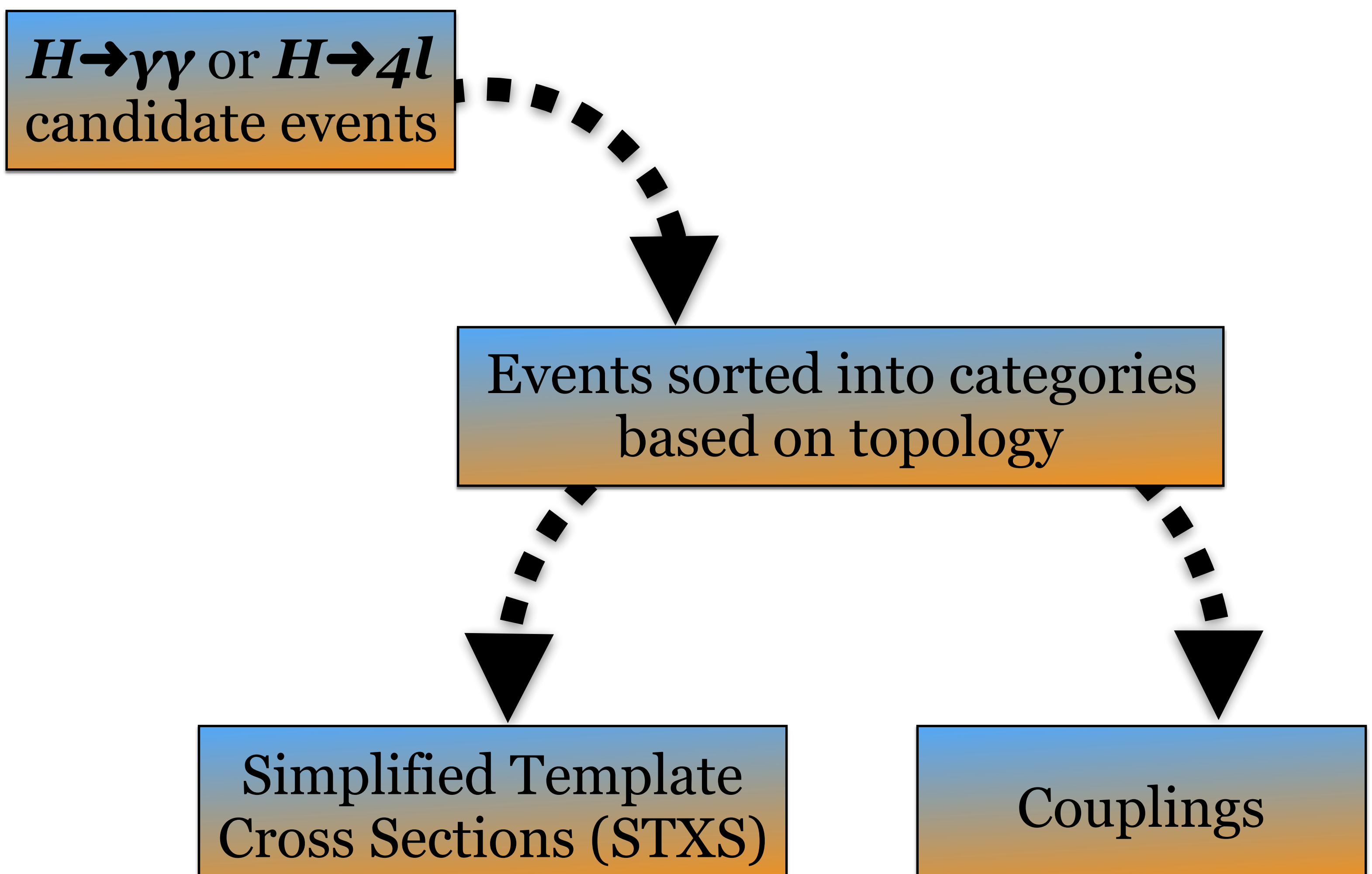
***H→γγ* measures two additional diphoton kinematic distributions (in backup)**

Results including a larger set differential variables in preparation…





Results from the $H\to ZZ\to 4\ell + H\to\gamma\gamma$ combination: Production cross sections and couplings



$H\to ZZ\to 4\ell$ + $H\to\gamma\gamma$ combination inputs.

To increase sensitivity both analyses ***categorize events***

- Categories can utilize variety of analysis techniques
- Categories have different S/B and background uncertainties
- Categories provide ***sensitivity to production modes*** and encode couplings

Categorization prioritizes processes with smallest cross sections

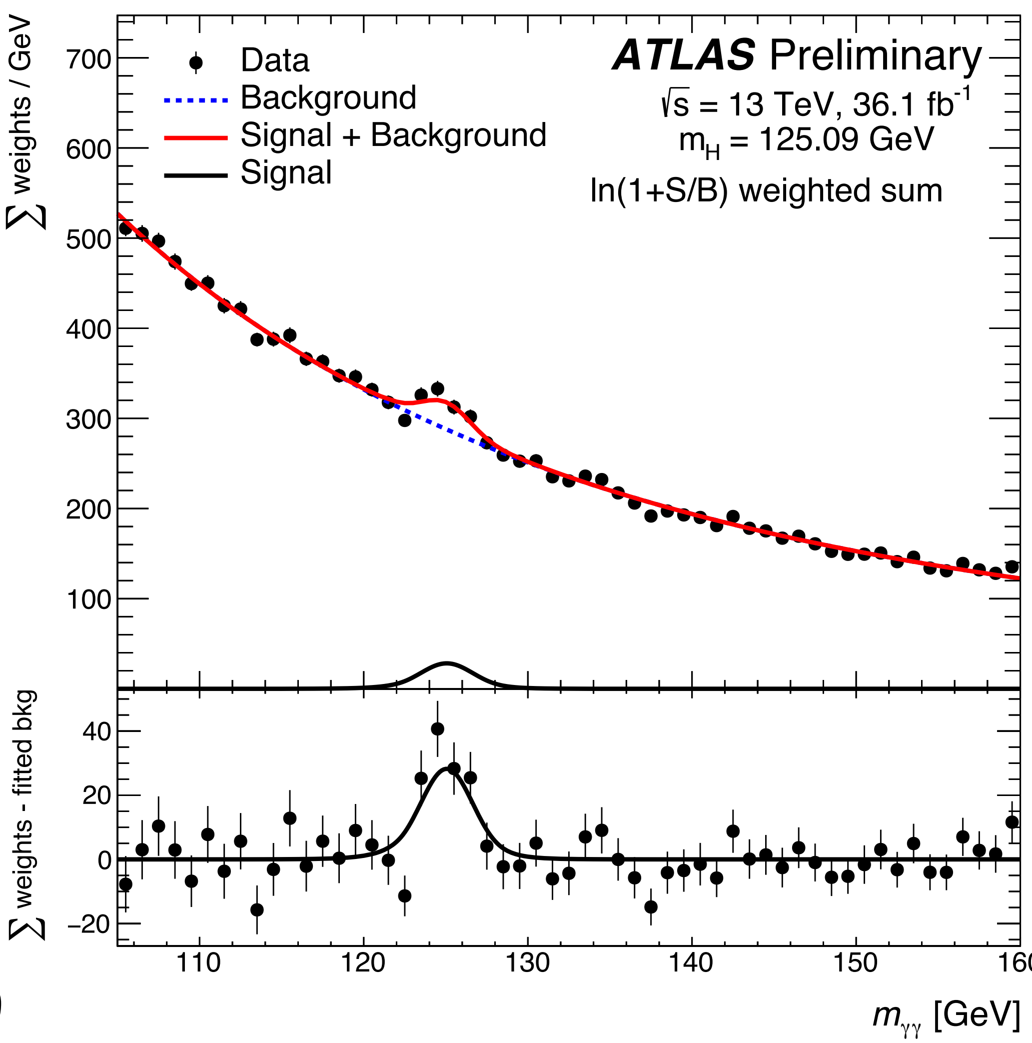
- ***ttH & tHX ➜ VH ➜ VBF ➜ ggF***

H→γγ: *31 event categories*

- Signal extraction via likelihood fit to $m_{\gamma\gamma}$

H→4l: *9 event categories*

- Signal extraction via binned fit (event counting) for BDT-based (other) categories



Assumptions:

- *Single Higgs boson, CP-even, SM kinematics*
- *Narrow Width Approximation (NWA: Γ_H ~4 MeV)*

Signal strength and production cross sections.

ATLAS+CMS Run-1: μ = 1.09 ± 0.07(*stat.*) ± 0.05(*exp.*)± 0.03(*th. B*) ± 0.07(*th. S*)

ATLAS 13 TeV: μ = 1.09 ± 0.09(*stat.*) ± 0.06(*exp.*)± 0.06(*th.*)

Signal strength measurements ***consistent with SM***

$$\mu = \frac{\sigma \cdot B}{(\sigma \cdot B)_{SM}}$$

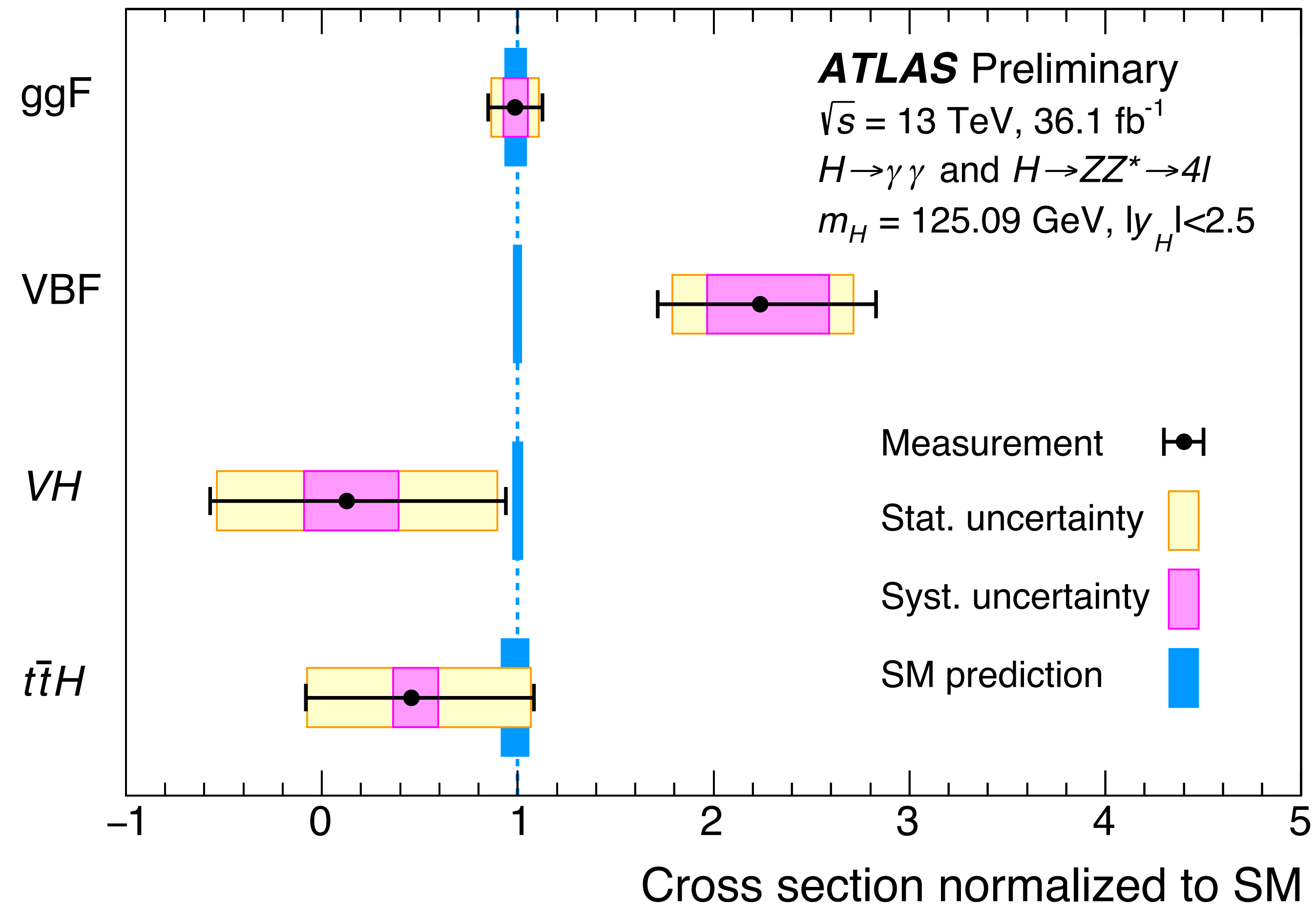
Signal strength and production cross sections.

ATLAS+CMS Run-1: $\mu = 1.09 \pm 0.07(stat.) \pm 0.05(exp.) \pm 0.03(th.\ B) \pm 0.07(th.\ S)$

ATLAS 13 TeV: $\mu = 1.09 \pm 0.09(stat.) \pm 0.06(exp.) \pm 0.06(th.)$

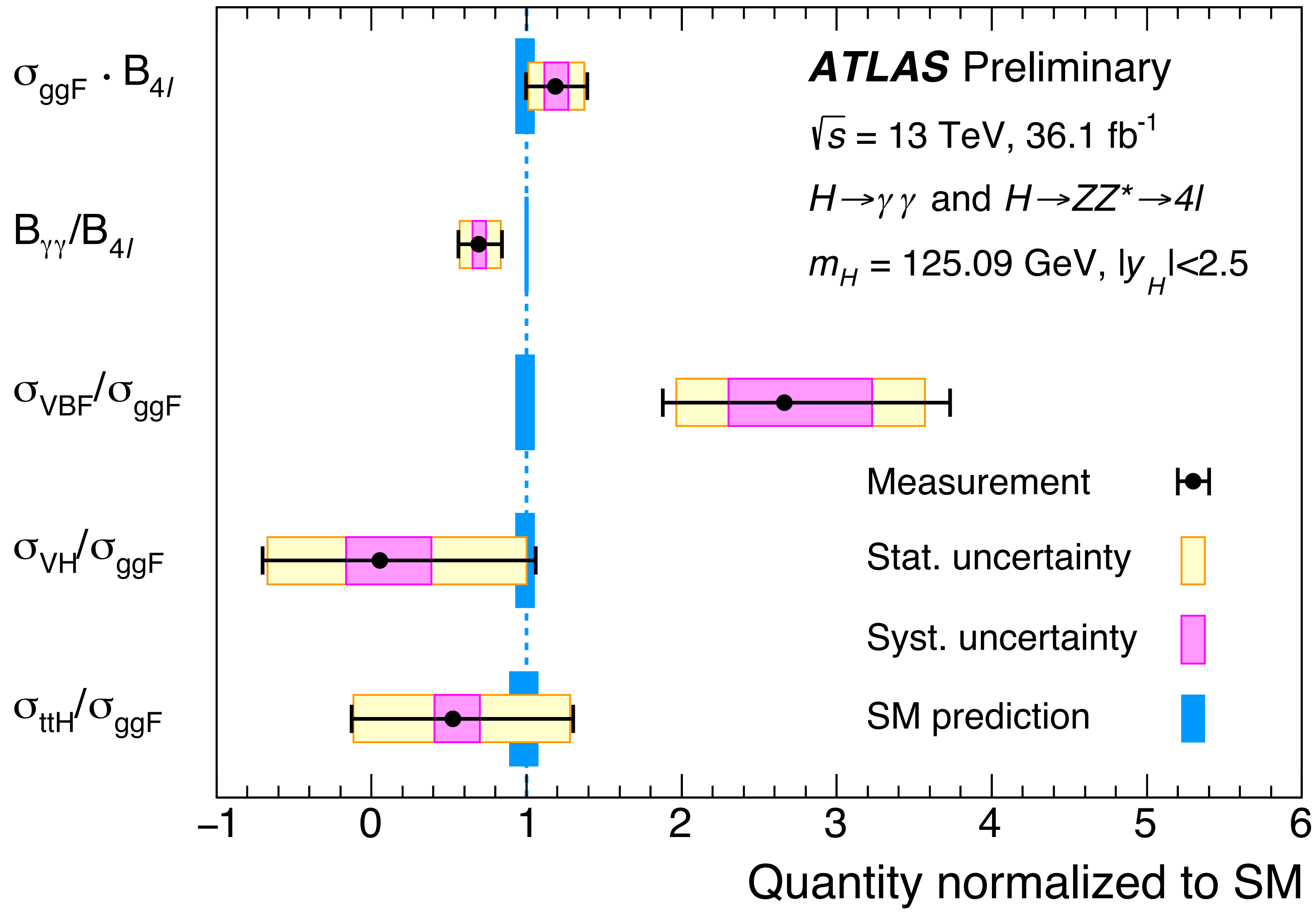
Signal strength measurements *consistent with SM*

$$\mu = \frac{\sigma \cdot B}{(\sigma \cdot B)_{SM}}$$



Higgs production is studied further by separating the production mechanisms

- ***Assuming SM branching fractions***, a combined fit is performed, to ***extract*** the ***production cross sections*** (*ggF*, VBF, *VH*, and *ttH*) for **$|y_H|<2.5$**
- Measurements of ***ggF & ttH include bbH & tH, respectively***
- Compatibility with SM predictions: ***p-value = 5%***



VBF, *VH*, and *ttH* normalized to *ggF* and $B^{\gamma\gamma}$ normalized to B^{4l}

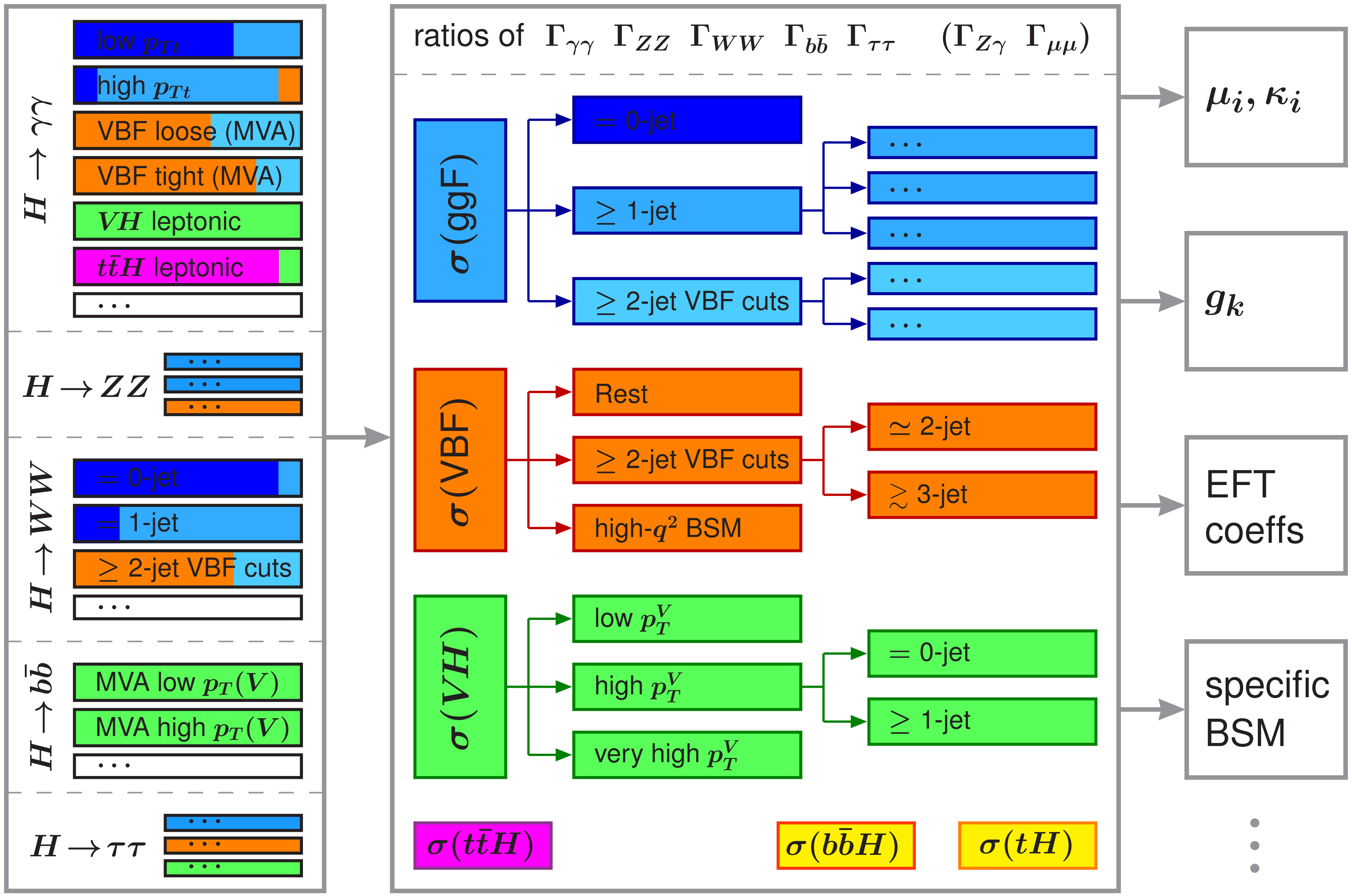
$$\sigma_i \cdot B^f = \sigma(gg \to H \to 4l) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{B^f}{B^{4l}}\right)$$

Combined fit to extract the production and decay ratios for $|y_H|$<**2.5**

Compatibility with SM predictions: ***p-value* = *3%***

STXS framework.

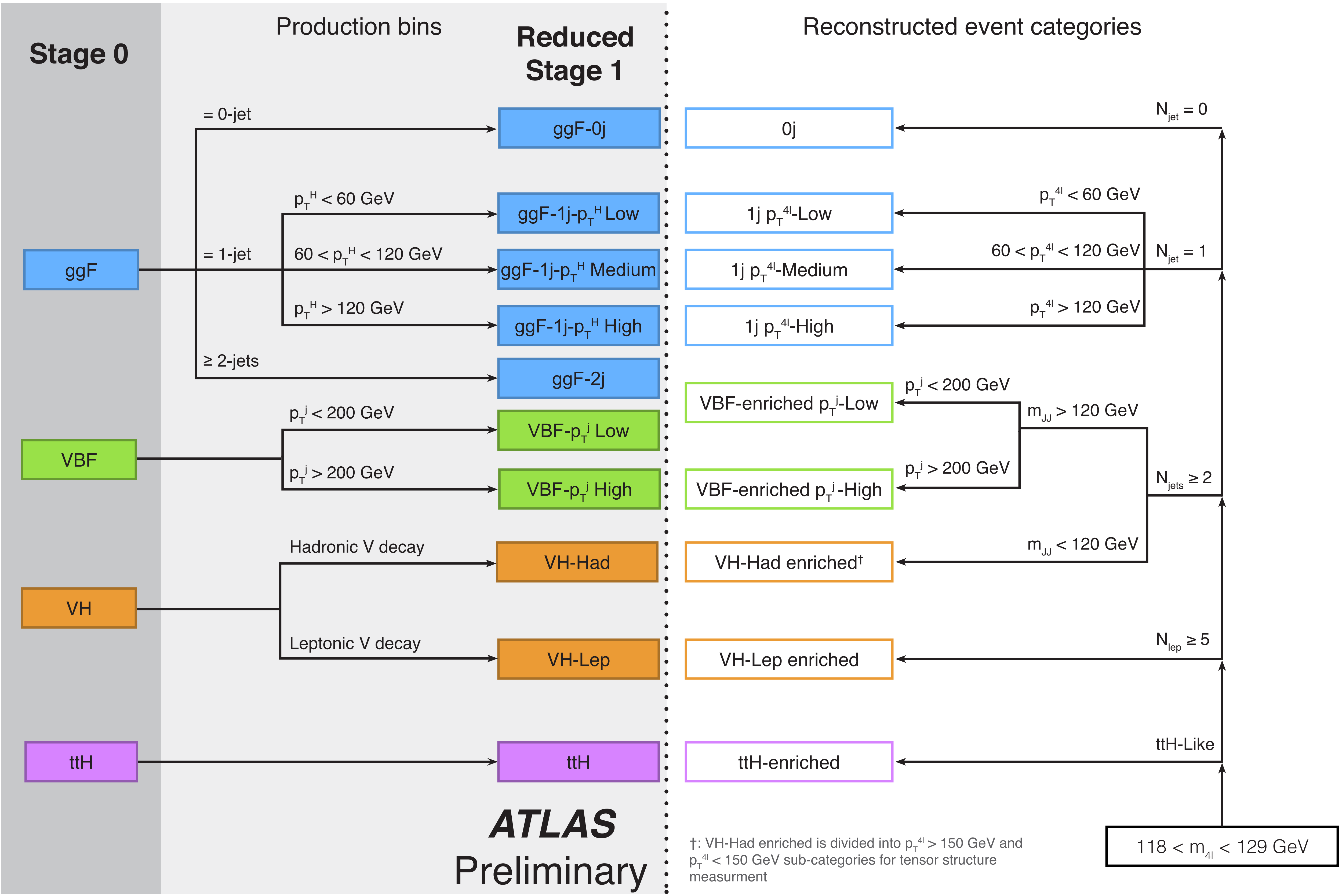
$|y_H| < 2.5$



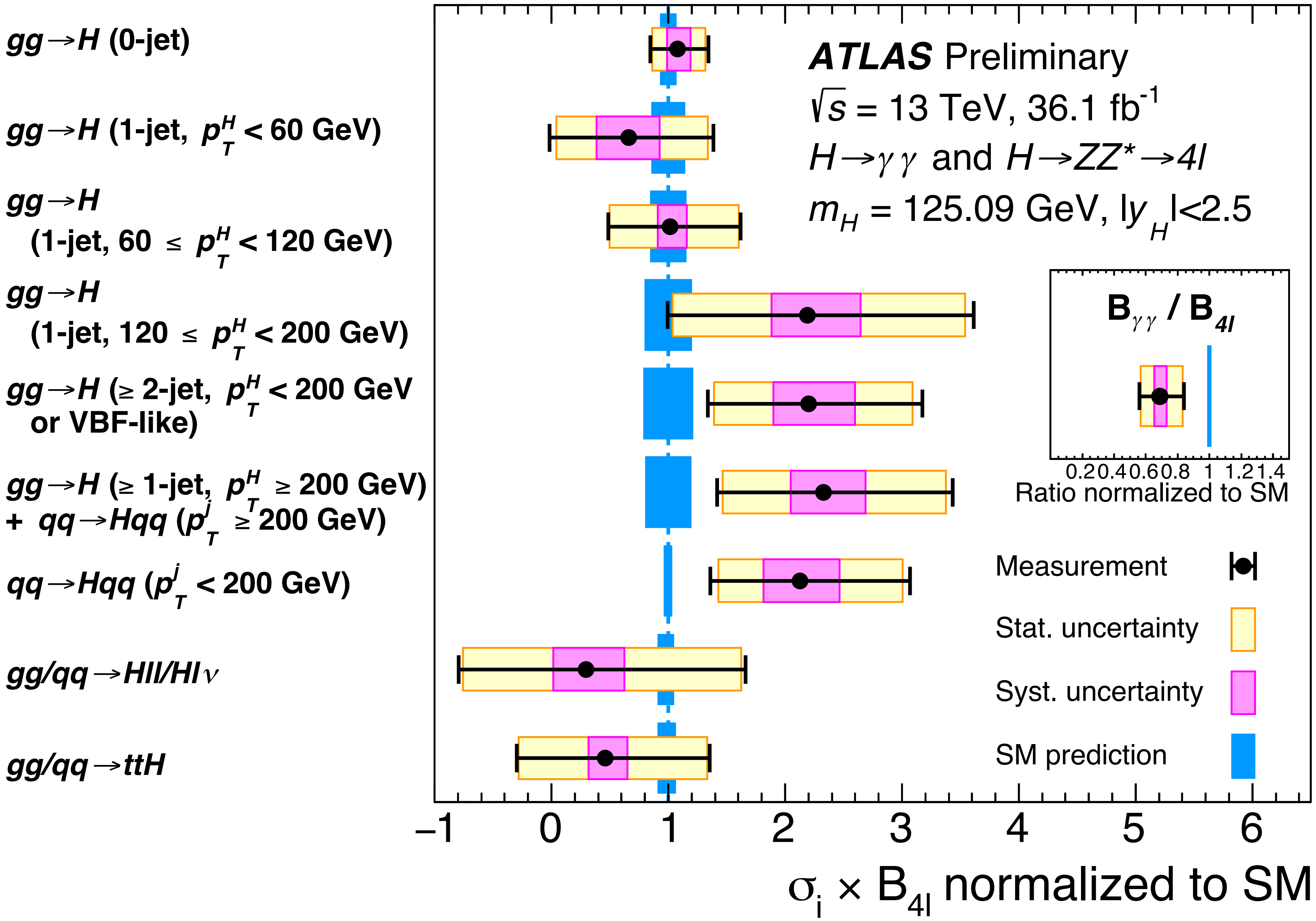
Simplified template cross sections (STXS) provide a *natural evolution of Run-1 style signal strength measurements*

Maximize sensitivity of the measurements *and* ***reduce the theory dependences*** *that get directly folded into measurements*

STXS categories ($H \to ZZ \to 4\ell$).



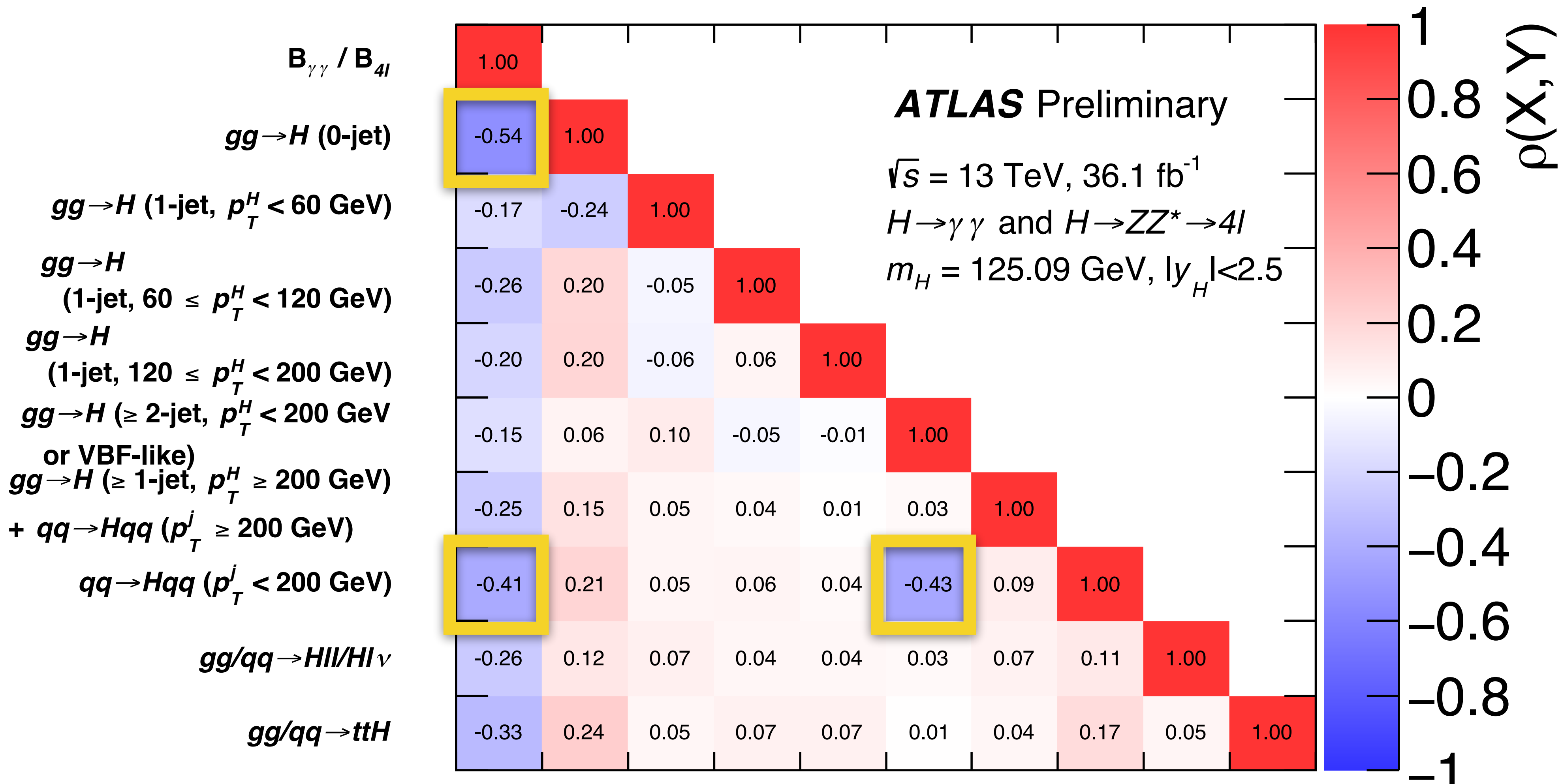
STXS stage-1 combined measurements.



Results give a ***good overall agreement with SM predictions*** in a range of kinematic regions of Higgs boson production processes

The compatibility of the measurements with the SM expectation corresponds to a ***p-value of 9%***

STXS measurement correlations.



Correlations

Largest between:

- $B_{\gamma\gamma}/B_{4l}$ & $gg \to H$ 0-jet
- $B_{\gamma\gamma}/B_{4l}$ & $qq \to Hqq$ $p_T^j < 200$GeV
  - $qq \to Hqq$ $p_T^j < 200$ GeV has greater tension between the two channels

Significant between:

- $gg \to H$ 0-jet & $gg \to H$ 1-jet $p_T^H < 60$ GeV
  - migrations between experimental jet categories

κ-framework.

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

- ***Leading-order motivated framework*** *developed by the LHC Higgs Cross Section WG to study Higgs couplings*

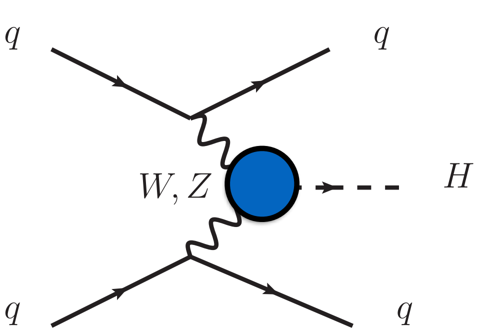
useful as long as the overall picture is SM-like

- ***Potential deviations from the SM predictions*** of the Higgs boson couplings to SM bosons and fermions ***encoded into*** a set of ***coupling modifiers***:

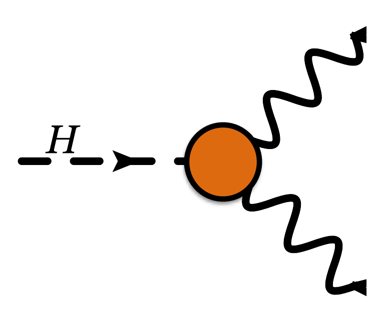
$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{B_f}{B_f^{SM}} \qquad \kappa_H^2 = \Sigma_j B_j^{SM} \kappa_j^2 \qquad \Gamma_H = \frac{\kappa_H^2 \Gamma_H^{SM}}{1 - B_{BSM}}$$

production **decay** **Total width**

- The ***same couplings*** are ***involved in production and decay modes***, hence the yield measurements need to be be projected onto the individual couplings



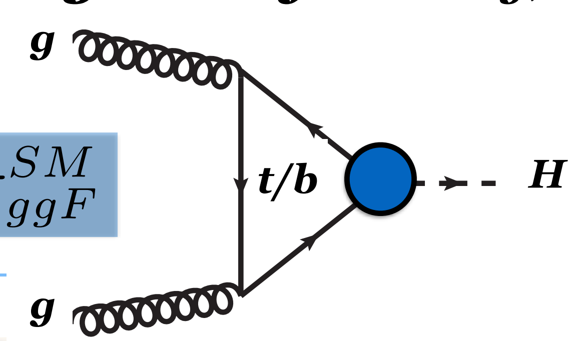
$$\sigma_{VBF} = (0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2) \cdot \sigma_{VBF}^{SM}$$

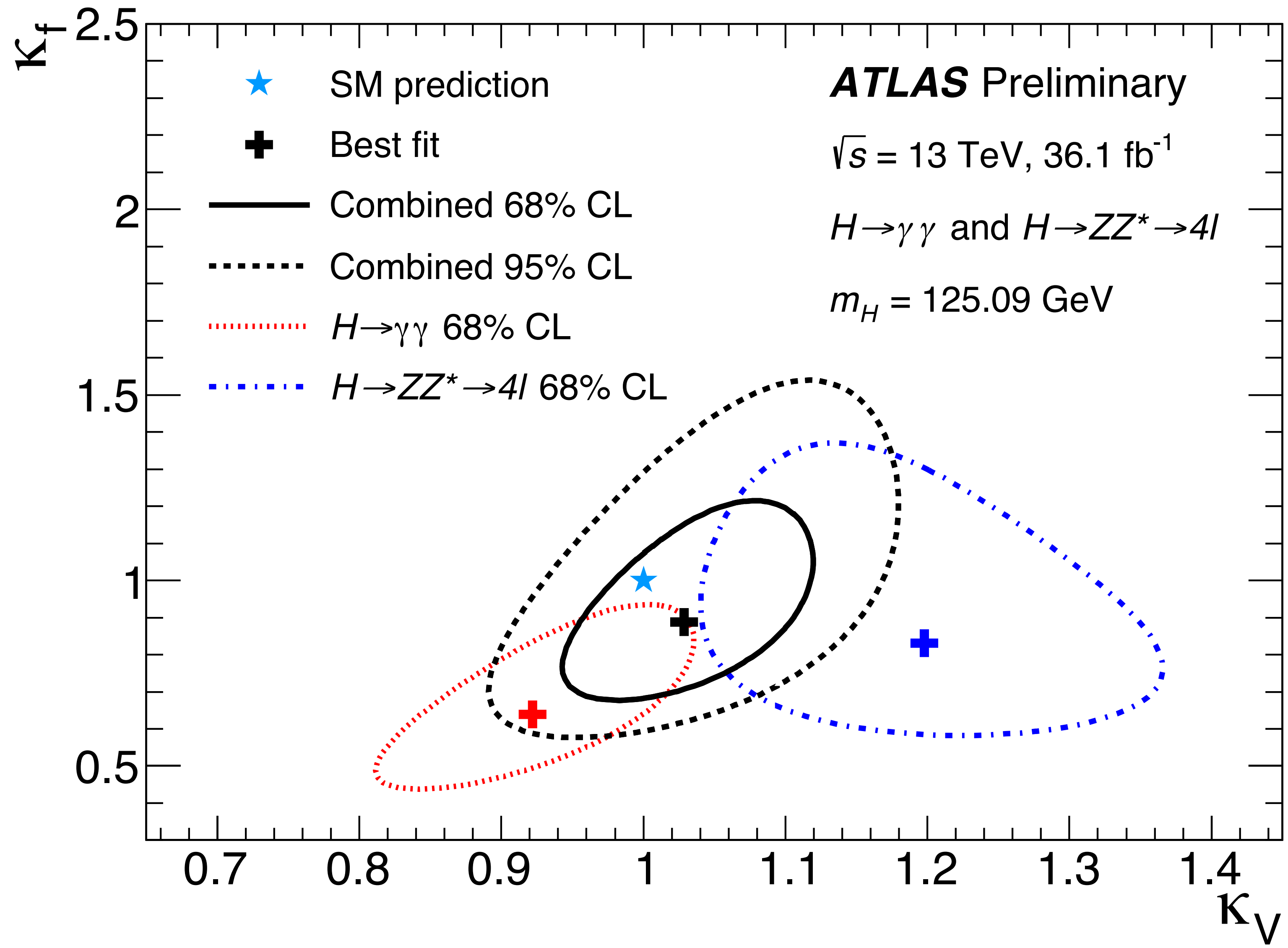


$$\kappa_{W,Z}^2 = \frac{\Gamma_{W,Z}}{\Gamma_{W,Z}^{SM}}$$

- Loops (***ggF***, ***H→γγ***) either expressed with ***effective coupling modifiers κ$_g$***, ***κ$_γ$***, or using more ***fundamental coupling modifiers κ$_x$***

$$\sigma_{ggF} = \kappa_g \cdot \sigma_{ggF}^{SM} = (1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b) \cdot \sigma_{ggF}^{SM}$$

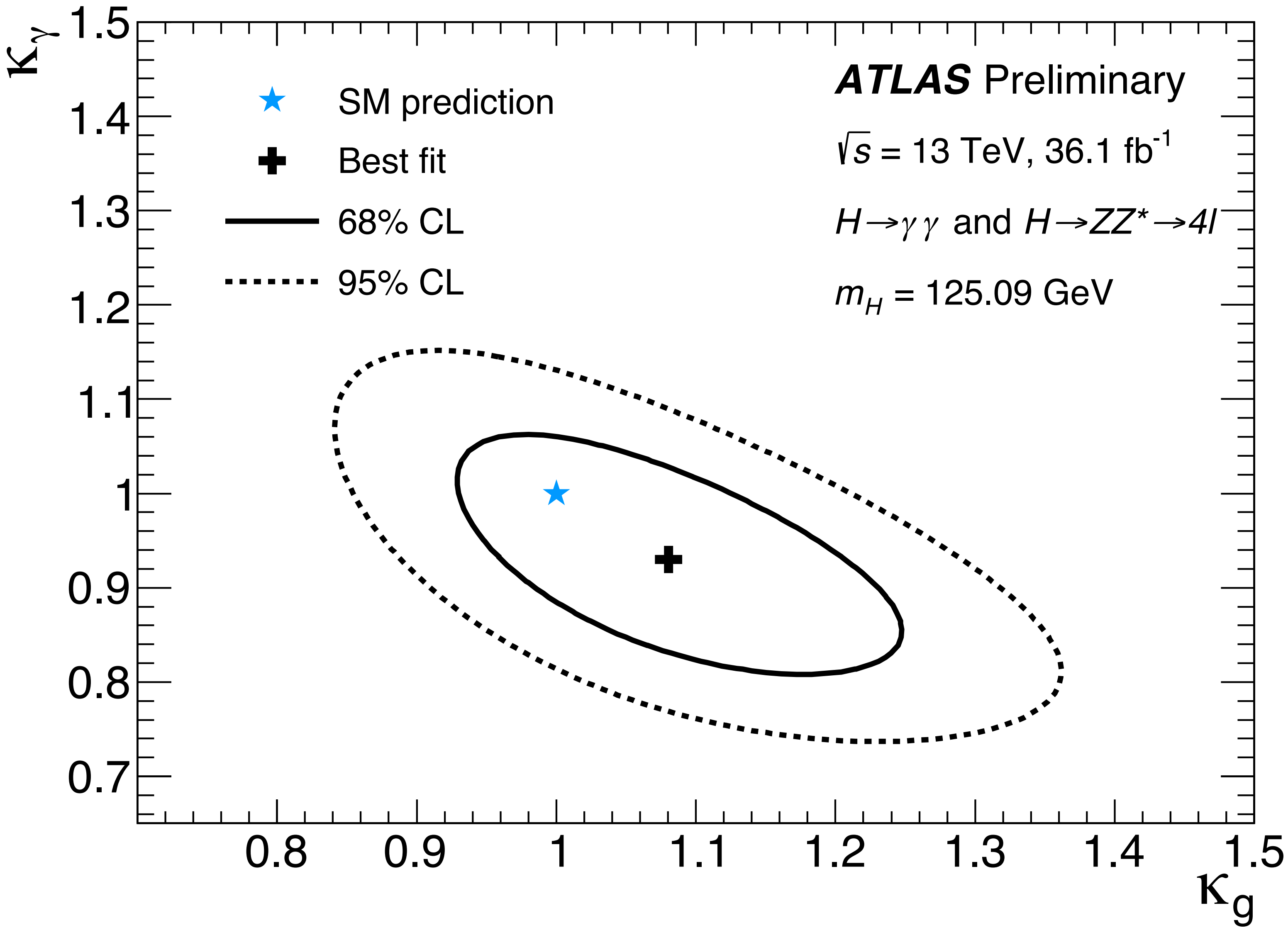




Boson vs. fermion couplings

- SM Higgs couplings to fermions and bosons very different (***Yukawa*** vs $\boldsymbol{D_\mu} \rightarrow \boldsymbol{\kappa_F}$ vs $\boldsymbol{\kappa_V}$)
- $\boldsymbol{\kappa_F}$, $\boldsymbol{\kappa_V}$ in agreement with SM
- $\boldsymbol{\kappa_F < 0}$ excluded at > 95% CL
- 2D compatibility with SM: ***p-value = 52%***

Couplings modifier results.



Effective couplings for κ_γ and κ_g

- No BSM decays (B_{BSM} = 0)
- ***ggF*** and ***Hγγ loops*** are ***allowed to be affected by contributions from additional particles***
- ***2 free parameters κ_γ, κ_g***, all other coupling modifiers fixed to their SM values
- 2D compatibility with SM: ***p-value = 68%***

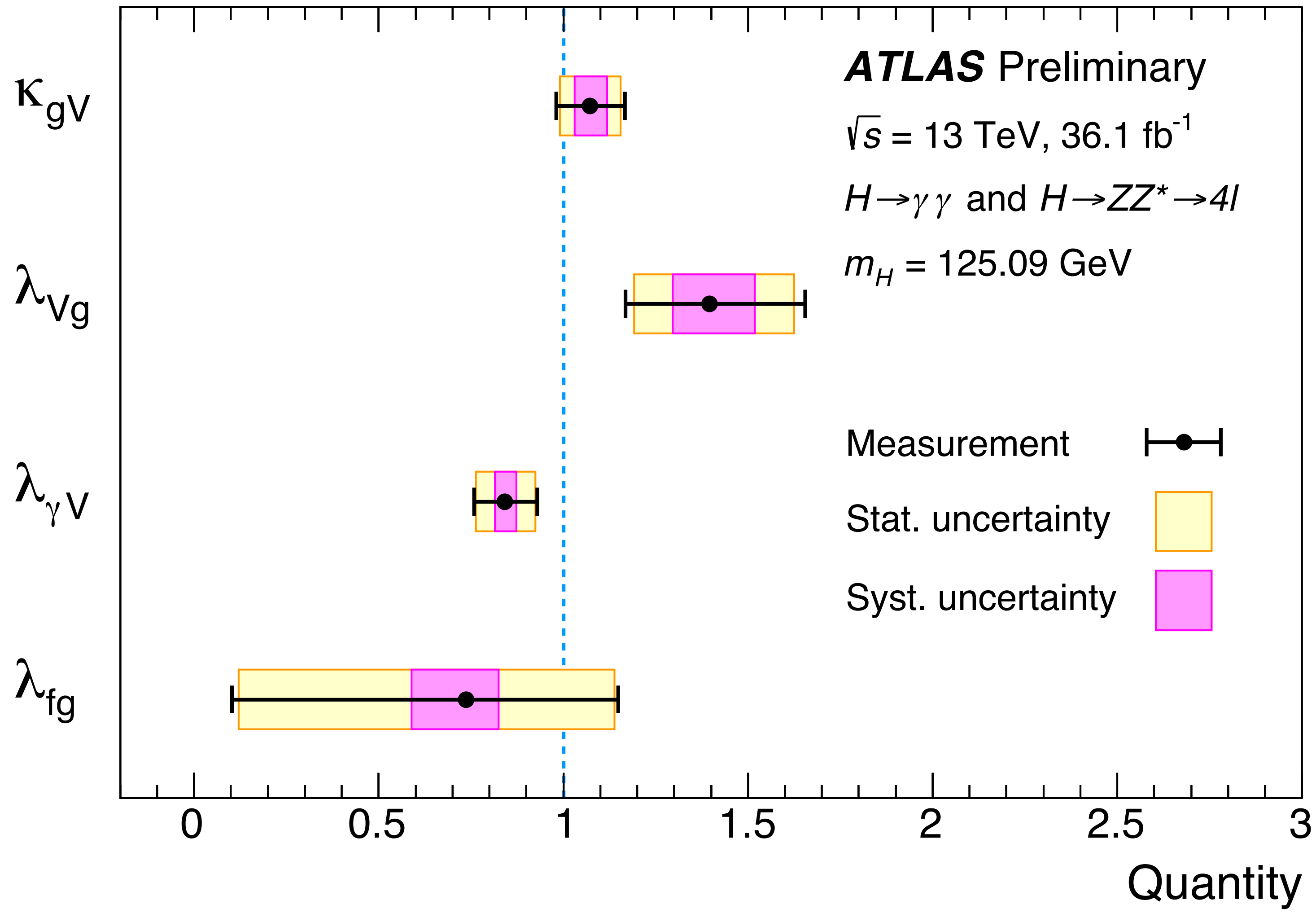
Couplings modifier ratios.

Measure ratios of coupling modifiers to remove assumptions on the total width:

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

Four ratios constructed to probe loop vertices ($\boldsymbol{\kappa_g}$, $\boldsymbol{\kappa_\gamma}$), total width $\boldsymbol{\kappa_H}$ and fermion and vector couplings ($\boldsymbol{\kappa_f}$, $\boldsymbol{\kappa_V}$)

$$\kappa_{gV} = \frac{\kappa_g \kappa_V}{\kappa_H}, \quad \lambda_{Vg} = \frac{\kappa_V}{\kappa_g}, \quad \lambda_{fg} = \frac{\kappa_f}{\kappa_g}, \quad \lambda_{\gamma V} = \frac{\kappa_\gamma}{\kappa_V}$$



$$\Gamma_H = \frac{\kappa_H^2 \Gamma_H^{SM}}{1 - B_{BSM}}$$

Negative ranges allowed for $\boldsymbol{\lambda_{fg}}$ to exploit the moderate sensitivity to the relative sign from ***tHX*** *and* ***ggZH***

- Best fit > 0, but limited sensitivity to interference terms

4D compatibility with SM:
p-value = 15%

Conclusion and outlook.

Recent results from the ATLAS Run-2 $H\rightarrow\gamma\gamma$ & $H\rightarrow 4l$ analyses presented:

- m_H = 124.98 ± 0.28 GeV, in agreement with ATLAS+CMS Run-1 result
- Inclusive, fiducial and differential cross sections
- Signal strength, coupling modifiers and production cross sections
- Improved interpretation methodologies:
  - STXS preliminary results presented
  - future considerations: EFT and PO
- Increased statistics from the Run-2 dataset and improved theory predictions are already providing a significant increase in sensitivity

All measurements consistent with SM expectations

Additionally:

- $H\rightarrow 4l$ EFT and PO interpretation (not covered here)
- $H\rightarrow\gamma\gamma$ measurements including many differential distributions and including EFT interpretation in preparation,

… stay tuned, the precision will improve over the coming years with Run3 and HL-LHC.

Links to papers and notes

13 TeV ATLAS *H→γγ* & *H→4l* combination:

- **Mass:** *ATLAS-CONF-2017-046*
- **XS & couplings:** *ATLAS-CONF-2017-047*

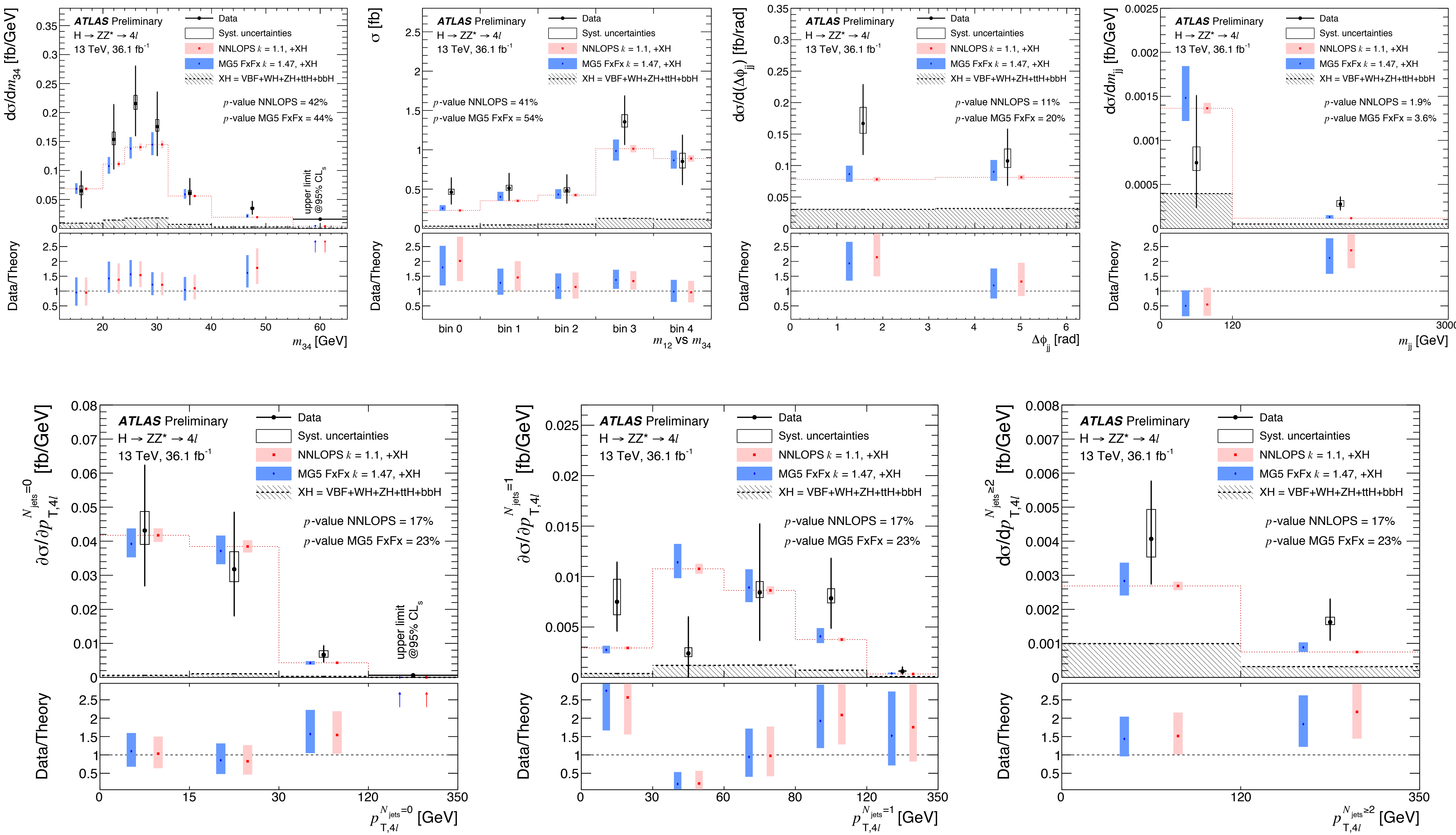
13 TeV ATLAS *H→γγ* & *H→4l analyses*:

- ***H→γγ Properties*:** *ATLAS-CONF-2017-045*
- ***H→4l Production cross sections and couplings*:** *ATLAS-CONF-2017-043*
- ***H→4l Inclusive & differential cross sections:*** *e-print arXiv:1708.02810*

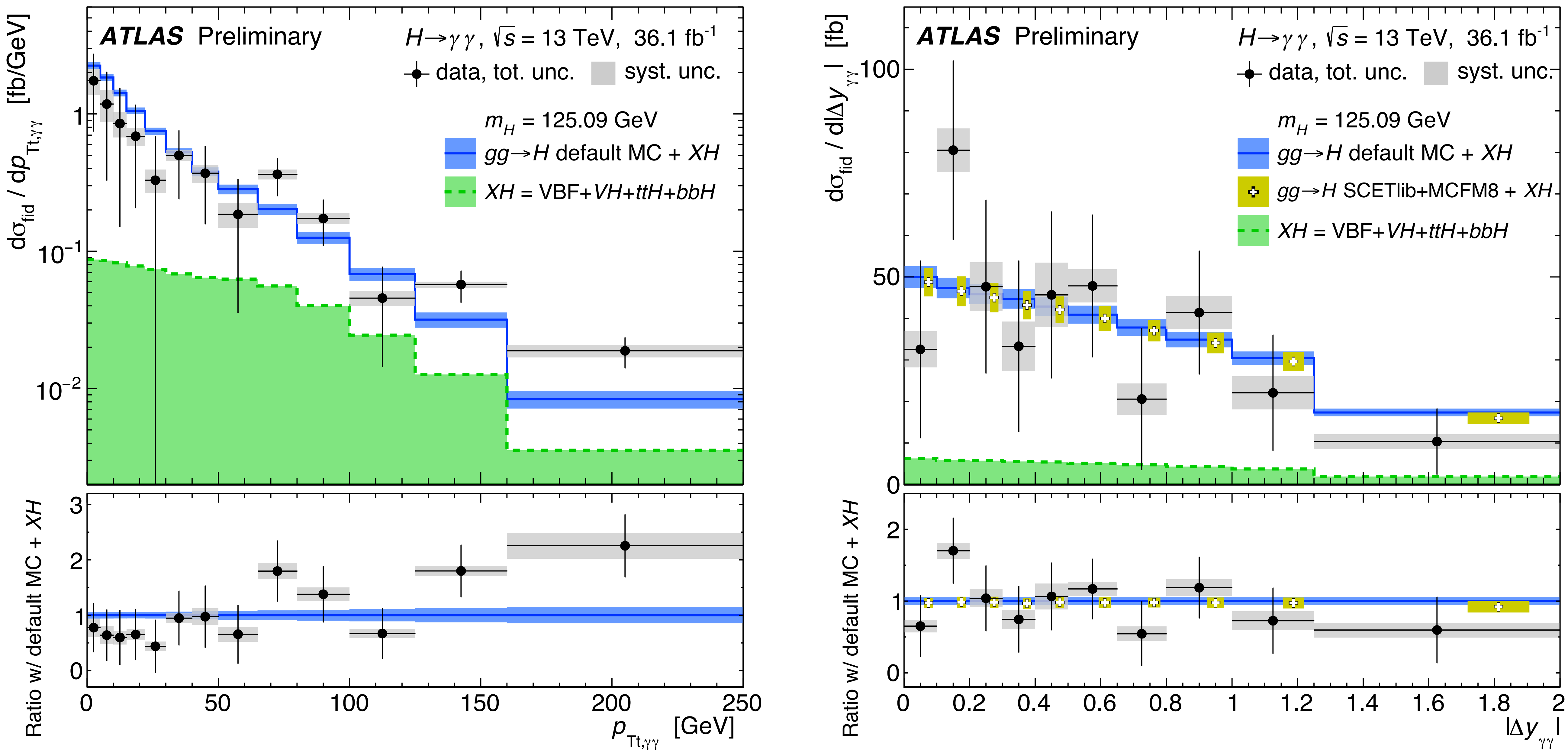
ATLAS Hγγ Mass shift through interferometry: *ATL-PHYS-PUB-2016-009*

Additional material

Additional $H \to ZZ \to 4l$ differential distributions



Additional $H \rightarrow \gamma\gamma$ differential distributions.

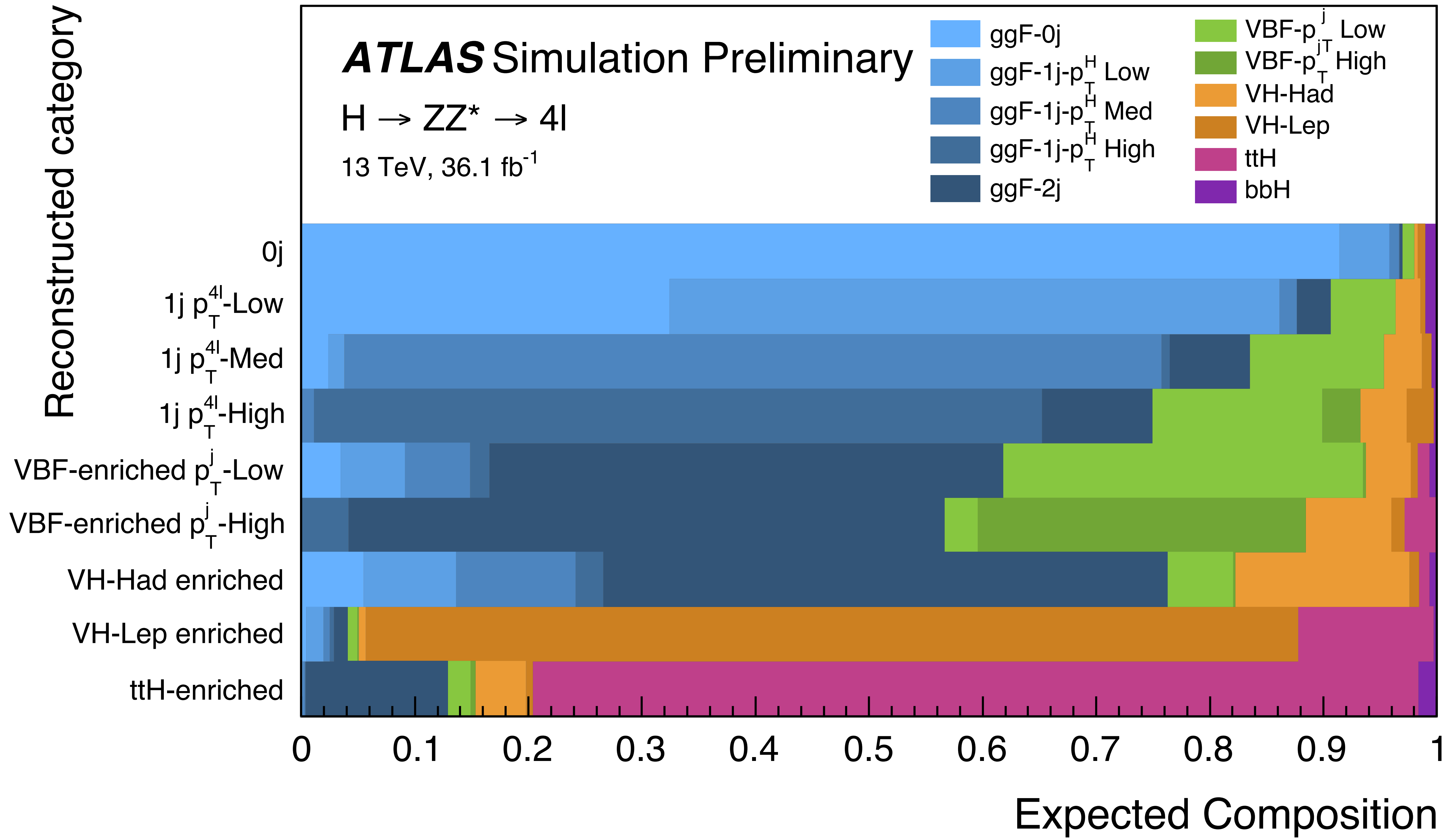


Analysis categories.

$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
$t\bar{t}H$+tH leptonic (two tHX and one $t\bar{t}H$ categories)	$t\bar{t}H$
$t\bar{t}H$+tH hadronic (two tHX and four BDT $t\bar{t}H$ categories)	VH leptonic
VH dilepton	2-jet VH
VH one-lepton, $p_{\mathrm{T}}^{\ell+\mathrm{MET}} \geq 150$ GeV	2-jet VBF, $p_{\mathrm{T}}^{j1} \geq 200$ GeV
VH one-lepton, $p_{\mathrm{T}}^{\ell+\mathrm{MET}}$¡150 GeV	2-jet VBF, p_{T}^{j1}¡200 GeV
VH $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}} \geq 150$ GeV	1-jet ggF, $p_{\mathrm{T}}^{4\ell} \geq 120$ GeV
VH $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ ¡150 GeV	1-jet ggF, 60 GeV¡$p_{\mathrm{T}}^{4\ell}$¡120 GeV
VH+VBF $p_{\mathrm{T}}^{j1} \geq 200$ GeV	1-jet ggF, $p_{\mathrm{T}}^{4\ell}$¡60 GeV
VH hadronic (BDT tight and loose categories)	0-jet ggF
VBF, $p_{\mathrm{T}}^{\gamma\gamma jj} \geq 25$ GeV (BDT tight and loose categories)	
VBF, $p_{\mathrm{T}}^{\gamma\gamma jj}$¡25 GeV (BDT tight and loose categories)	
ggF 2-jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV	
ggF 2-jet, 120 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡200 GeV	
ggF 2-jet, 60 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡120 GeV	
ggF 2-jet, $p_{\mathrm{T}}^{\gamma\gamma} < 60$ GeV	
ggF 1-jet, $p_{\mathrm{T}}^{\gamma\gamma} \geq 200$ GeV	
ggF 1-jet, 120 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡200 GeV	
ggF 1-jet, 60 GeV $\leq p_{\mathrm{T}}^{\gamma\gamma}$¡120 GeV	
ggF 1-jet, $p_{\mathrm{T}}^{\gamma\gamma}$ ¡ 60 GeV	
ggF 0-jet (central and forward categories)	

STXS category composition: $H \to ZZ \to \ell\ell\ell\ell$.

$|y_H| < 2.5$

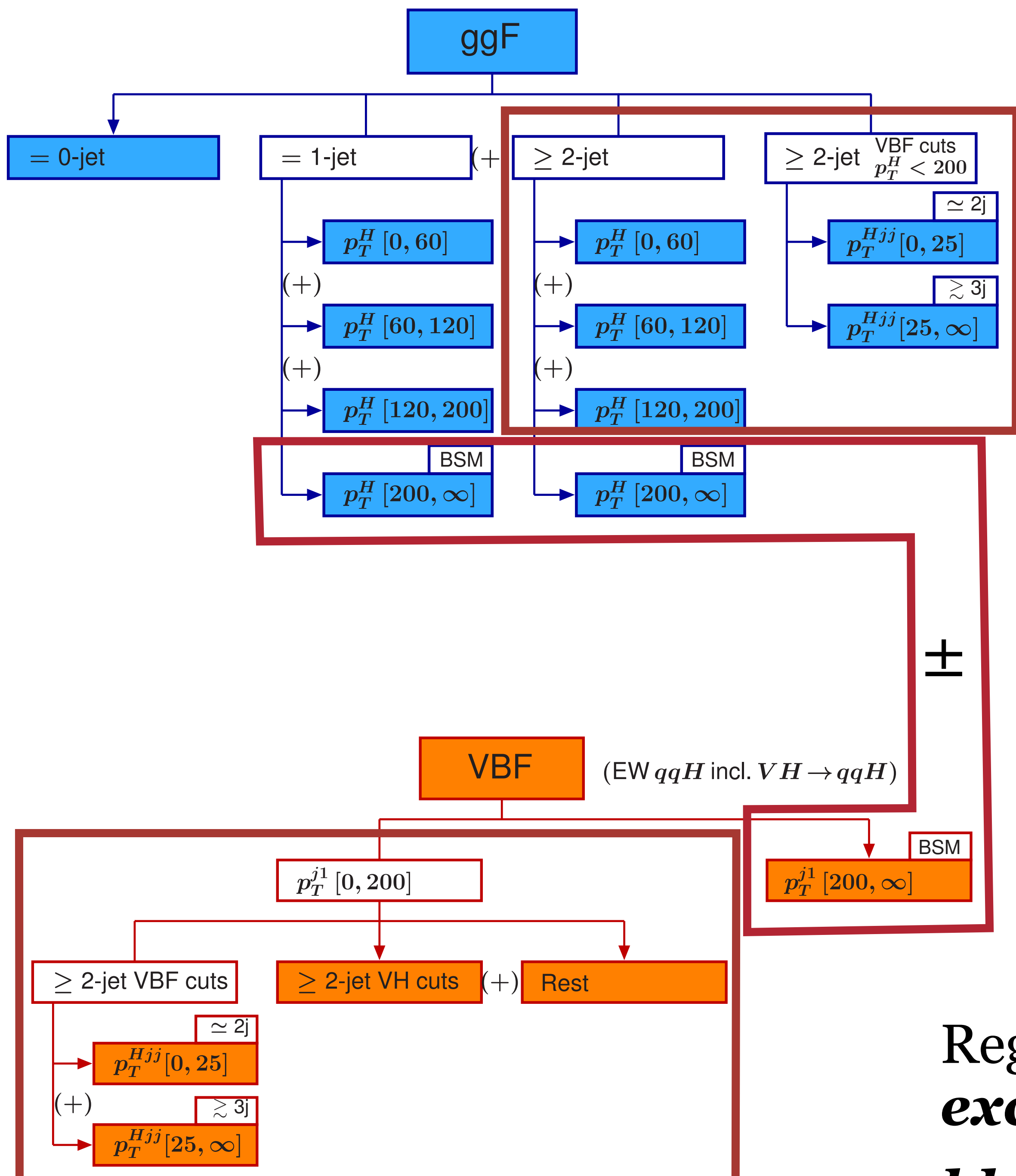


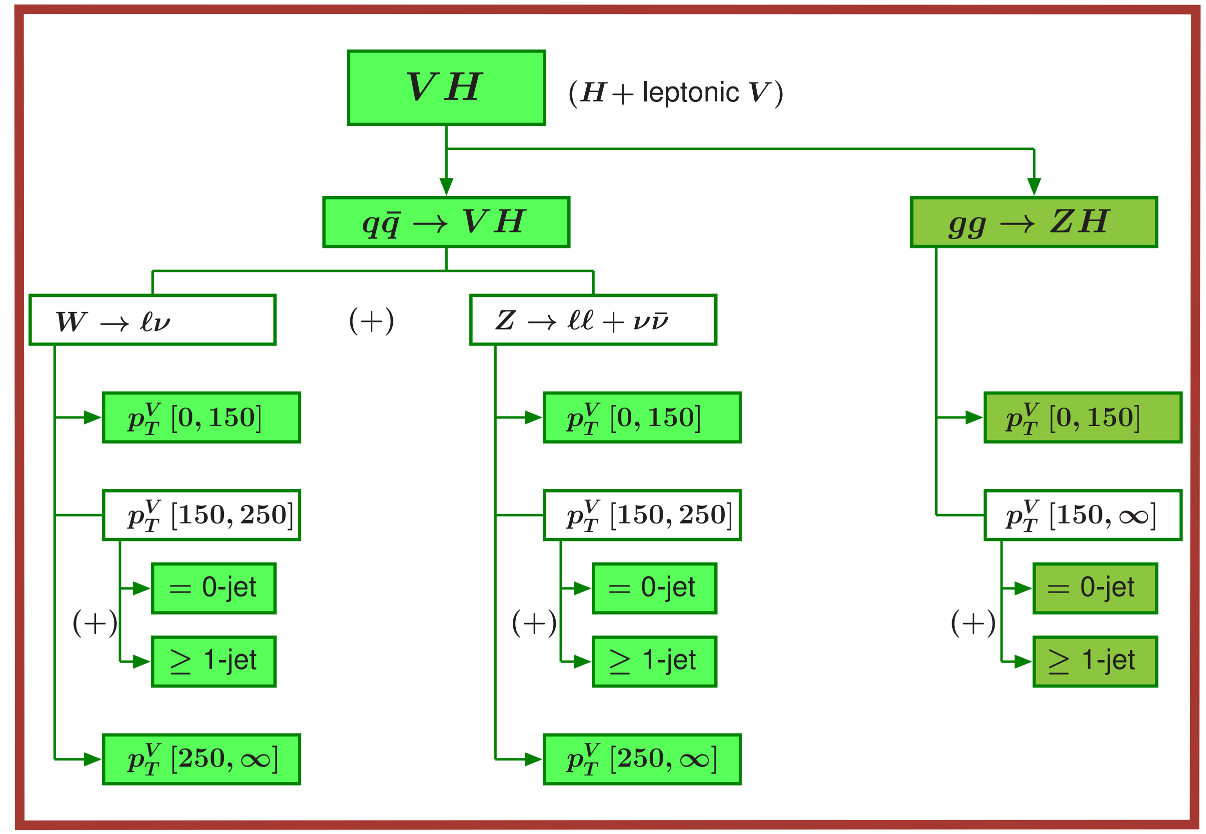
STXS stage-1 regions.

$|y_H| < 2.5$

ATLAS preliminary

$$y_i = \sum_i A_{i,j} \cdot r_i \cdot (\sigma_i \cdot B_{4l})_{SM} \cdot r_f \cdot \left(\frac{B_f}{B_{4l}}\right) \cdot \mathcal{L}$$

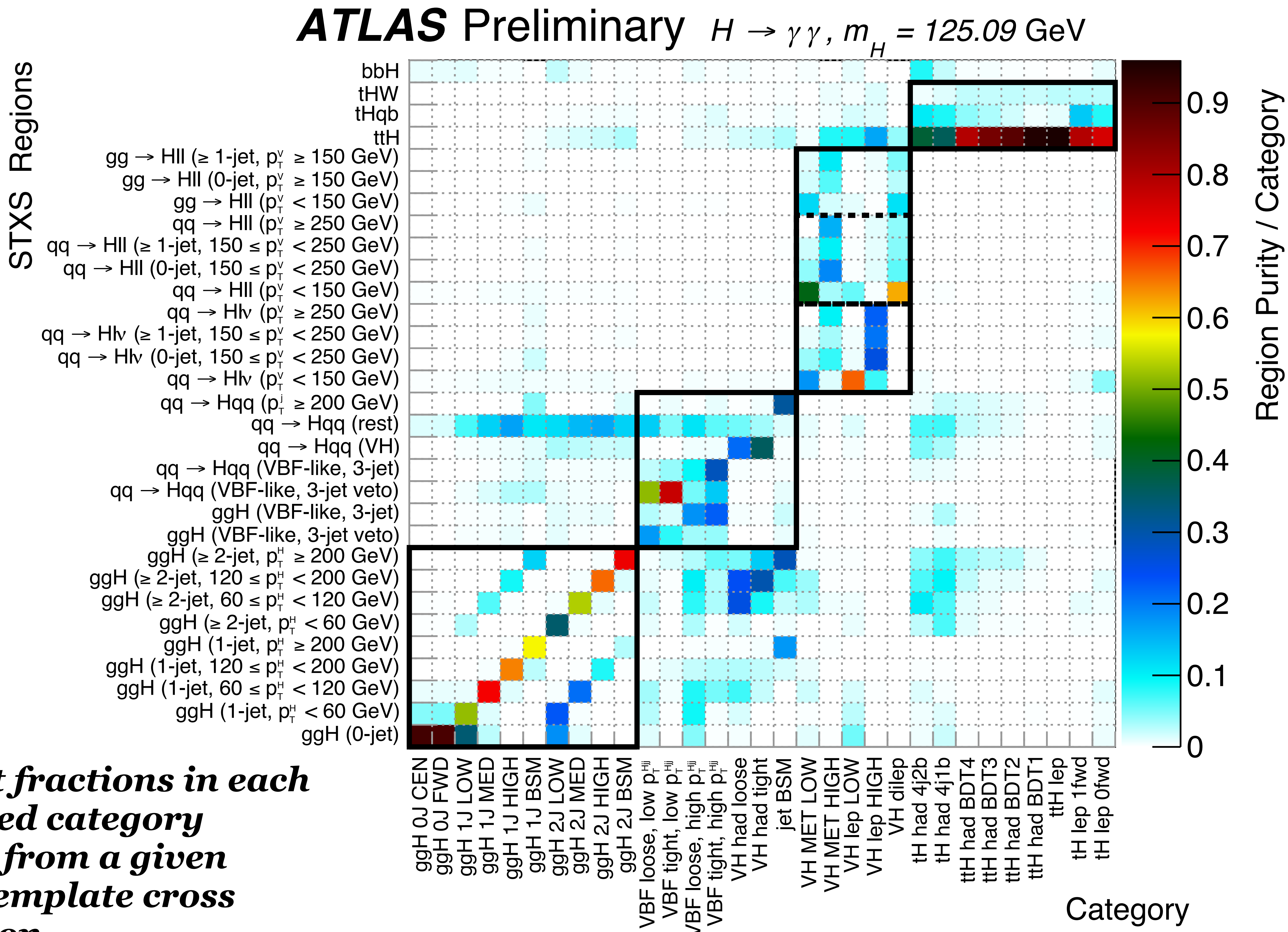




Regions enclosed by ***red boxes are merged***, ***except*** for those indicated by the "±" sign

bbH is ***merged*** with the ***ggF***

STXS signal fractions: $H \rightarrow \gamma\gamma$.

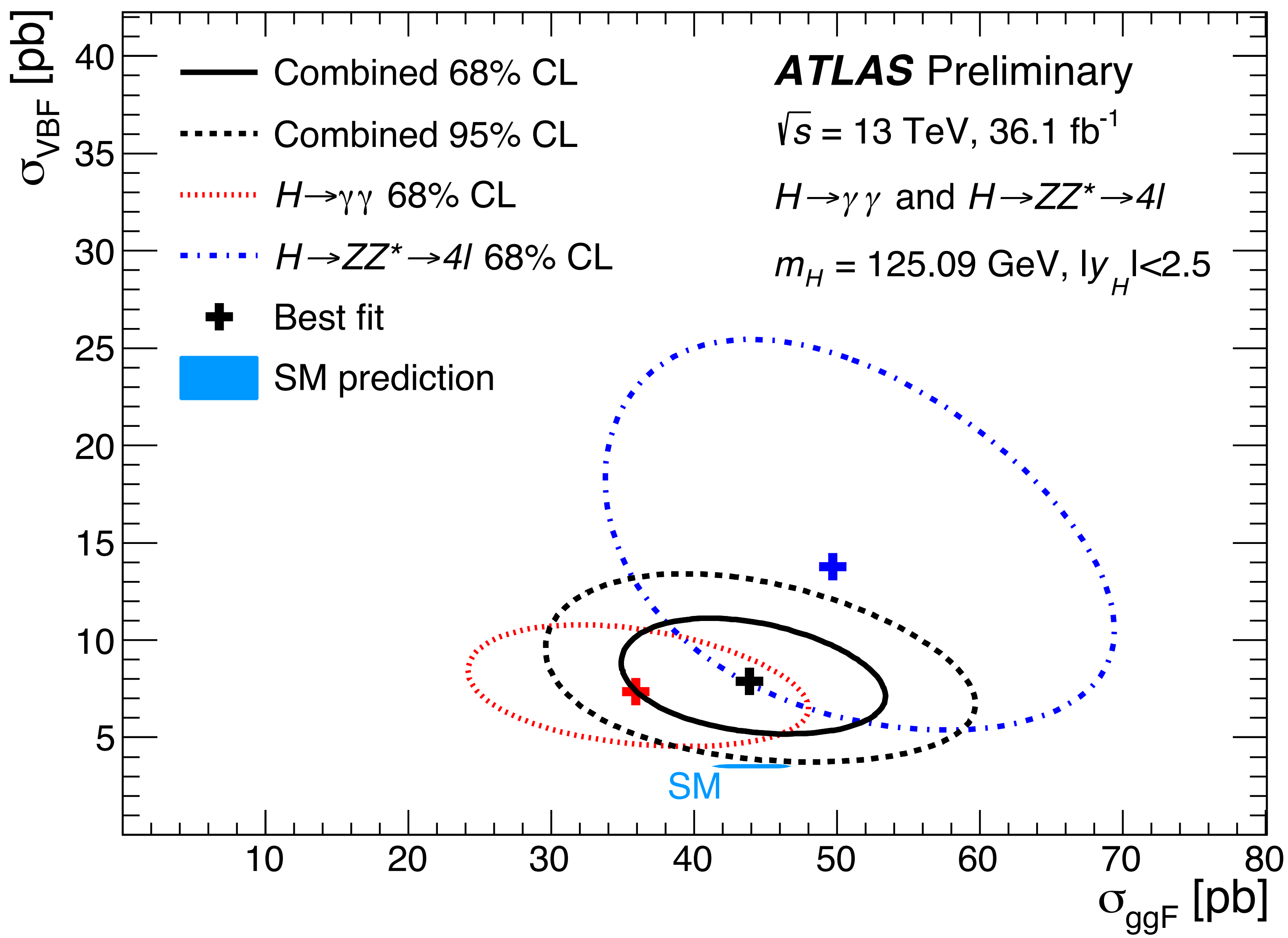


signal event fractions in each reconstructed category originating from a given simplified template cross section region

VBF *vs.* *ggF* cross sections.

ggF and **VBF** cross sections measured with the best precision

Anti-correlated since the **VBF** ***selection categories have significant contribution from ggF*** production

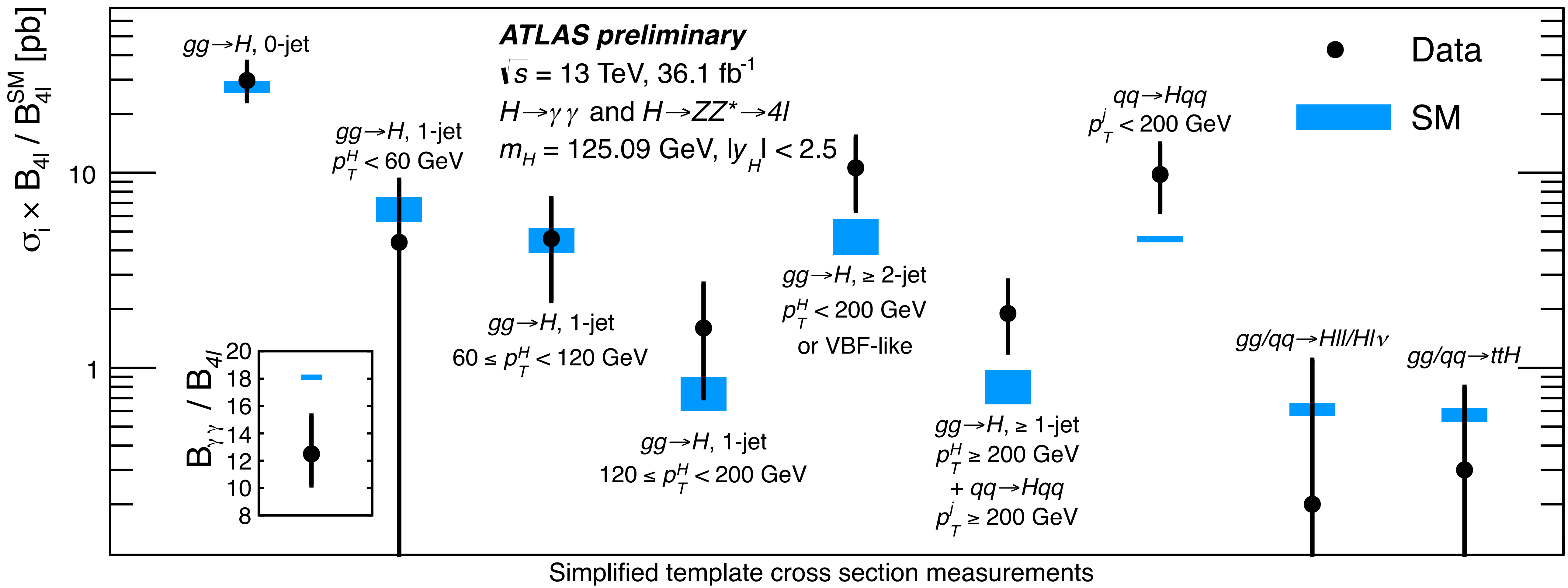


2D compatibility with SM predictions:

p-value = 3%

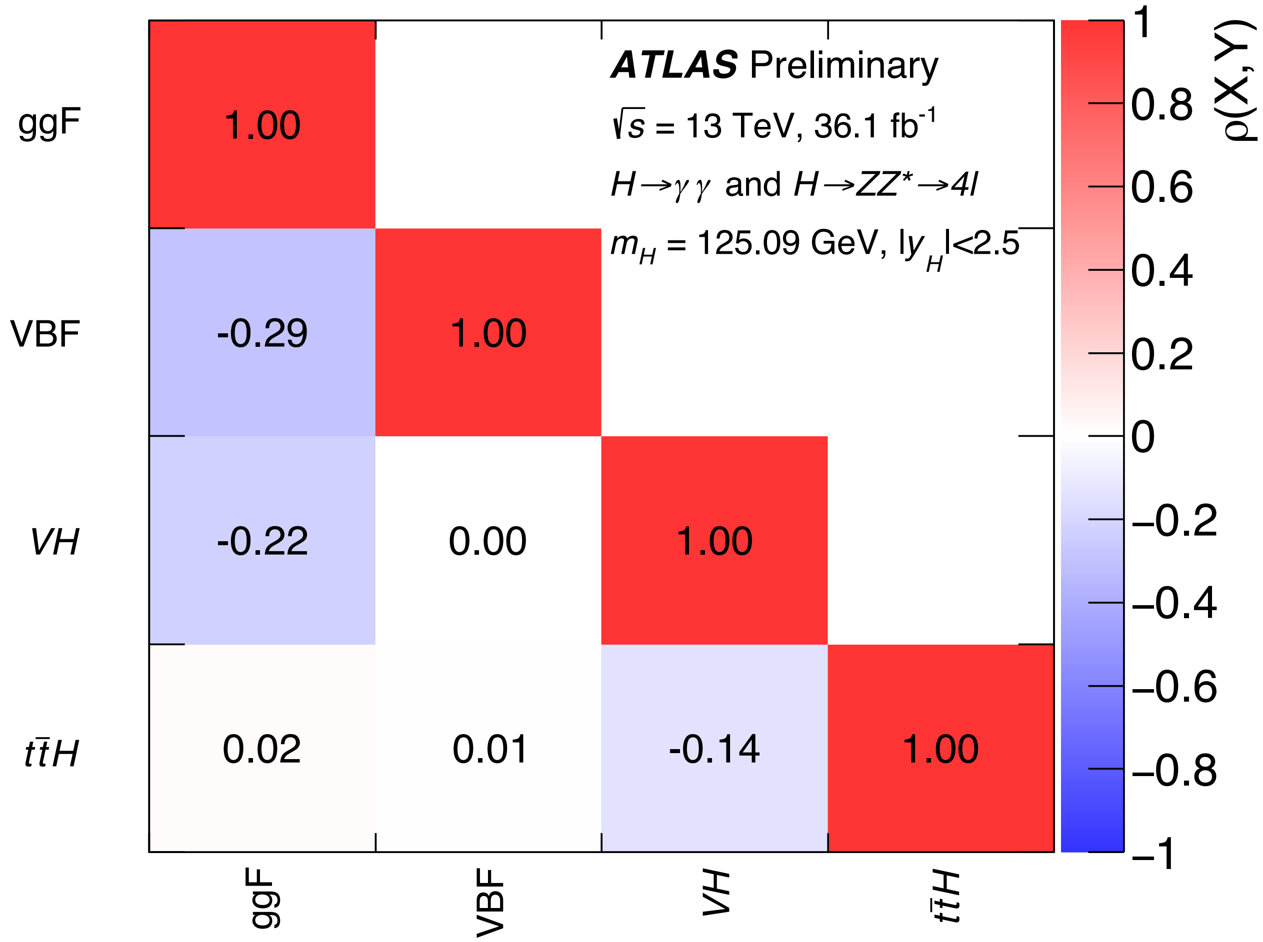
σ(VBF) vs. σ(ggF) likelihood contours for each analysis channel and their combination (***VH*** and ***ttH*** profiled with the data)

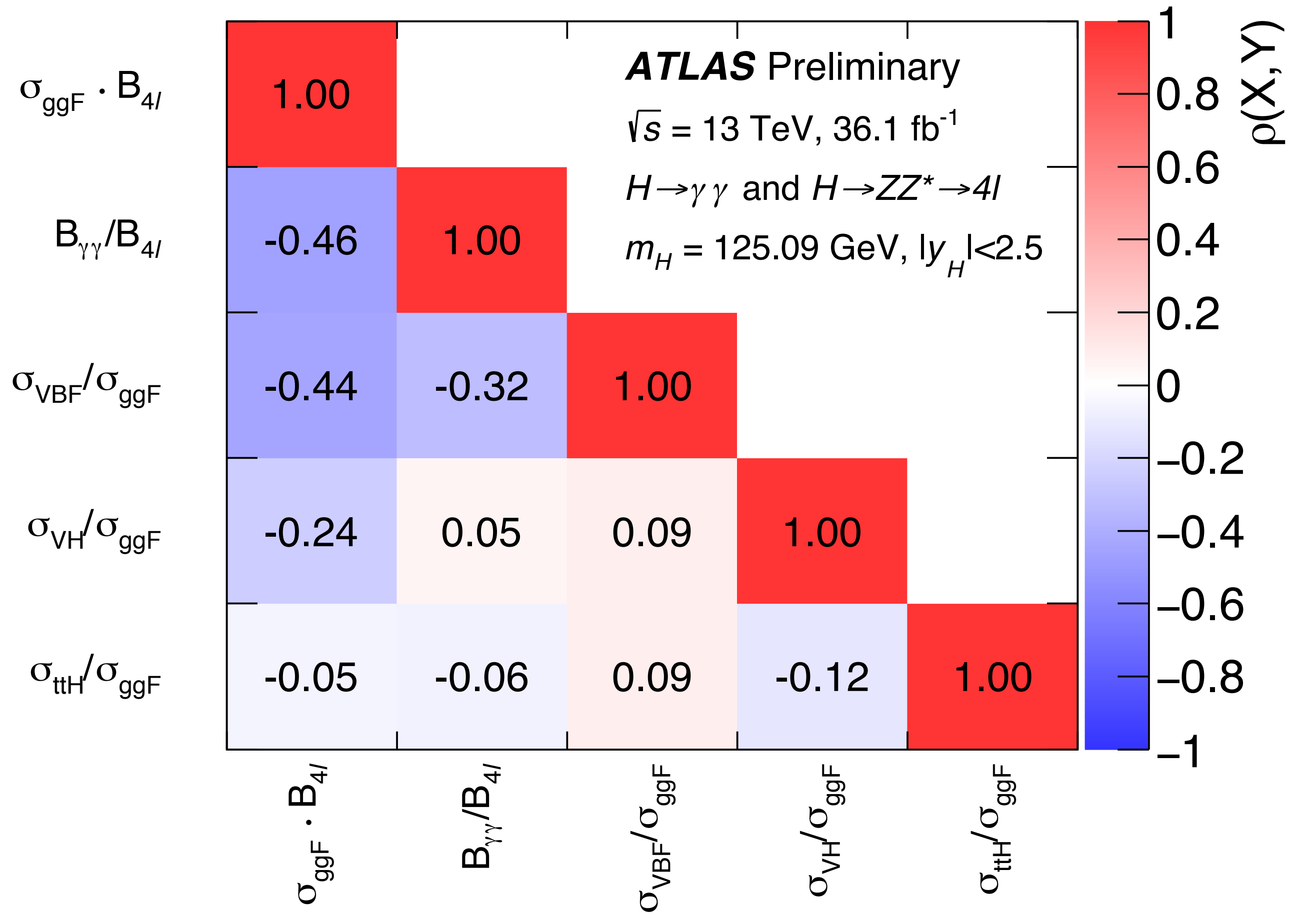
STXS stage-1.



ATLAS preliminary
√s = 13 TeV, 36.1 fb⁻¹
H→γγ and H→ZZ*→4l
m_H = 125.09 GeV, |y_H| < 2.5
Data
SM
gg→H, 0-jet
gg→H, 1-jet p_T^H < 60 GeV
gg→H, 1-jet 60 ≤ p_T^H < 120 GeV
gg→H, 1-jet 120 ≤ p_T^H < 200 GeV
gg→H, ≥ 2-jet p_T^H < 200 GeV or VBF-like
gg→H, ≥ 1-jet p_T^H ≥ 200 GeV + qq→Hqq p_T^j ≥ 200 GeV
qq→Hqq p_T^j < 200 GeV
gg/qq→Hll/Hlν
gg/qq→ttH
σ_i × B_4l / B_4l^SM [pb]
10
1
B_γγ / B_4l
20
18
16
14
12
10
8
Simplified template cross section measurements

ATLAS Run-2 cross section correlations.





Combination: statistical methodology.

Combine measurements and fit for parameters of interest (POI) using a ***profile likelihood ratio (Λ)***

$$\Lambda = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

- ***$\vec{\alpha}$: a vector of POI***
- ***$\vec{\theta}$: nuisance parameters (NP), corresponding to systematic uncertainties***
- ***$\hat{\vec{\alpha}}$, $\hat{\vec{\theta}}$ are the values of the POI and NP that maximize L***
- ***$\hat{\hat{\vec{\theta}}}(\vec{\alpha})$ is the value of the NP that maximize L for a given $\vec{\alpha}$***
- ***Assume asymptotic approximation: $f(\Lambda) = \chi^2(ndof)$***

Theory uncertainties *QCD, PDF, UE+PS, B^f*

uncorrelated between production modes (*except for VBF+VH*)

Experimental uncertainties correlated between analysis channels

Cross Sections.

Cross section

$$\sigma_i = \frac{\nu_i^{\mathrm{sig}}}{C_i \cdot A_i \cdot B \cdot \mathcal{L}_{\mathrm{int}}}$$

Number of signal events measured in data

Integrated luminosity

Correction for detector resolution and inefficiencies

Acceptance

Branching fraction

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

$$\sigma_{\mathrm{fid},i} = \frac{\nu_i^{sig}}{C_i \cdot \mathcal{L}_{\mathrm{int}}} \qquad \frac{d\sigma_i}{dX_i} = \frac{\nu_i^{\mathrm{sig}}}{\Delta X_i \cdot C_i \cdot \mathcal{L}_{\mathrm{int}}}$$

depends on event selection and decay channel

Goal: measure model independent detector-corrected event yields

Production and decay signal strengths.

Combine categories and ***fit*** for ***cross sections (σ$_i$)*** or ***signal strength of*** different ***production processes (i)*** and ***final states (f)***

$$\mu_i = \frac{\sigma_i}{\sigma_{i,SM}} \qquad \mu^f = \frac{B^f}{B^f_{SM}} \qquad \mu_i^f = \frac{\sigma_i \cdot B^f}{(\sigma_i \cdot B^f)_{SM}}$$

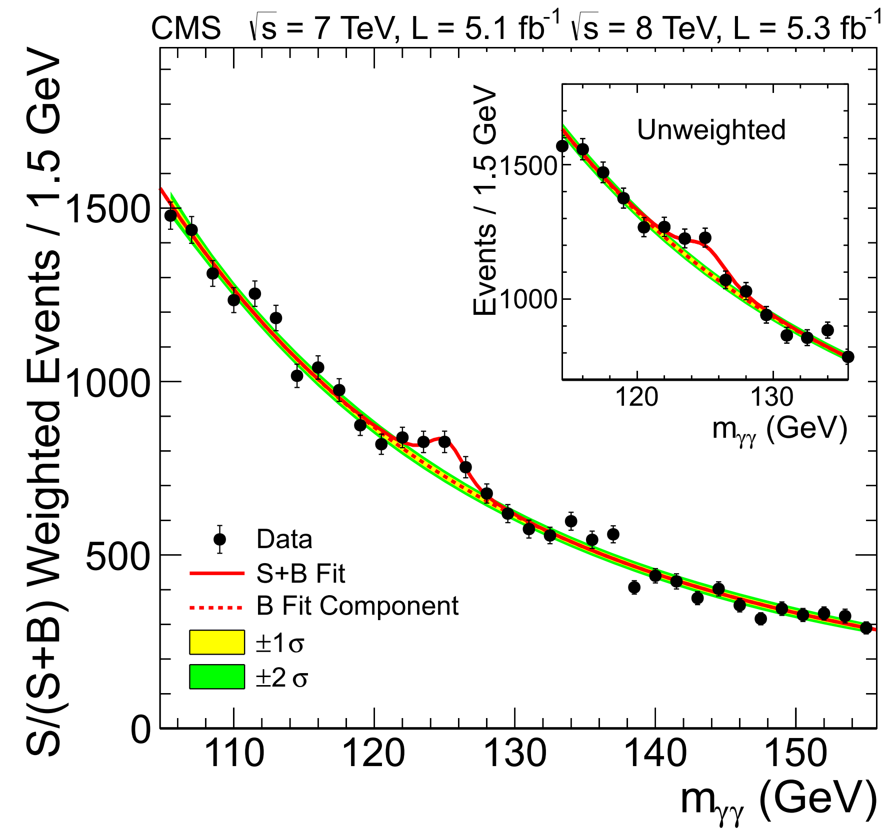
Analyses extract signal yields:

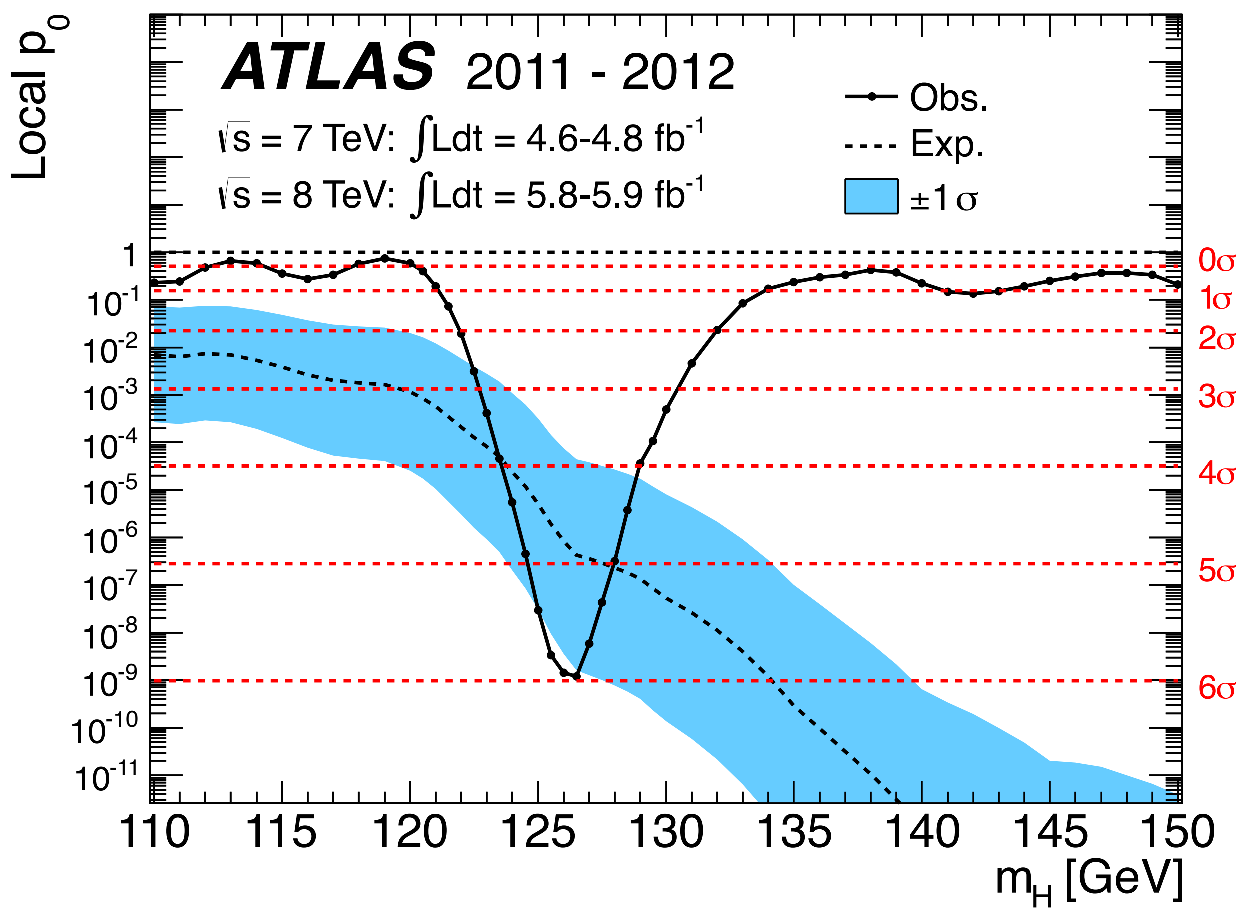
$$\begin{aligned}\nu^{\mathrm{sig}} &= \mathcal{L}\Sigma_i\Sigma_f\left(\sigma_i A^f_{i,\mathrm{SM}}\epsilon^f_{i,\mathrm{SM}}B^f\right)\\ &= \mathcal{L}\Sigma_i\Sigma_f\left(\mu_i\sigma_{i,\mathrm{SM}}A^f_{i,\mathrm{SM}}\epsilon^f_{i,\mathrm{SM}}\mu^f B^f_{\mathrm{SM}}\right)\end{aligned}$$

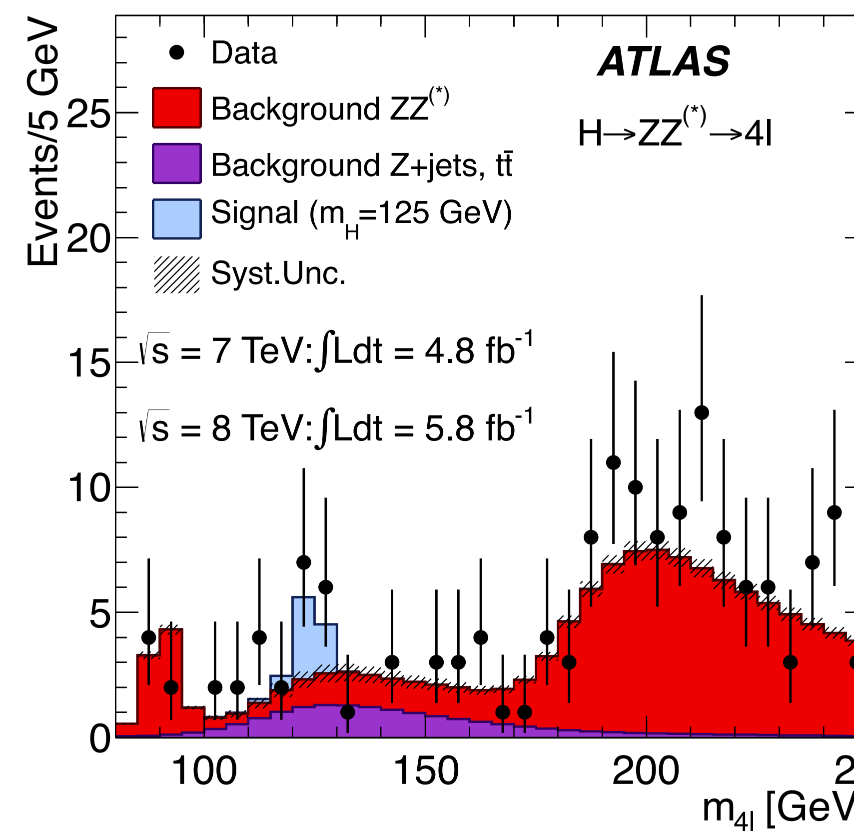
where $\mathcal{L}$ is the luminosity, $\boldsymbol{\varepsilon}$ efficiencies, $\boldsymbol{A}$ the detector acceptance and $\boldsymbol{\mu_i}$, $\boldsymbol{\mu^f}$ are production and decay signal strengths

Higgs Discovery: July 2012.

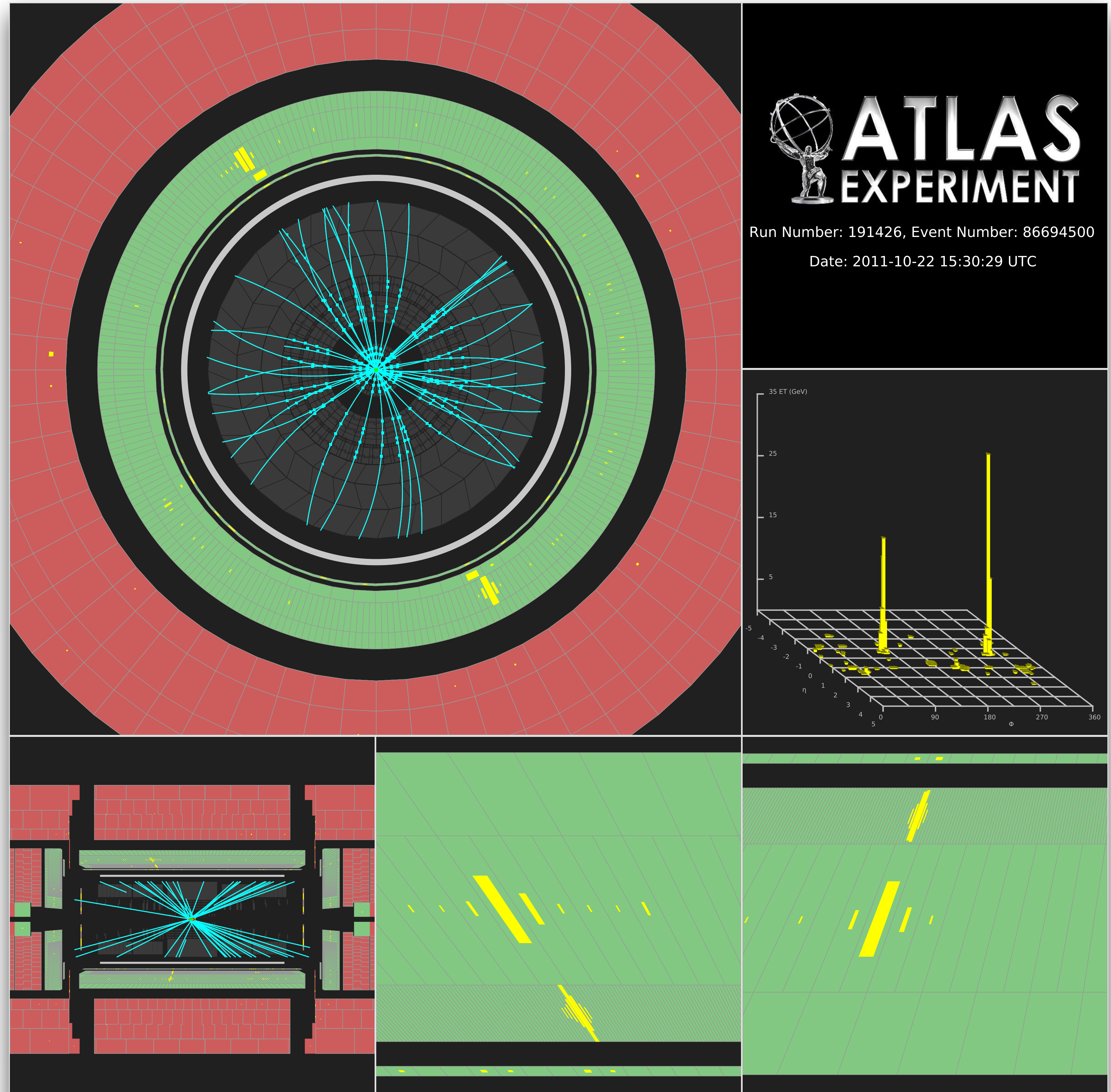
- Crowning achievement of Run 1
- To determine whether the discovered boson is ***fully compatible*** with the Standard Model Higgs, precise property measurements are required
    - ***Large effort towards studying its properties and searching for NP***



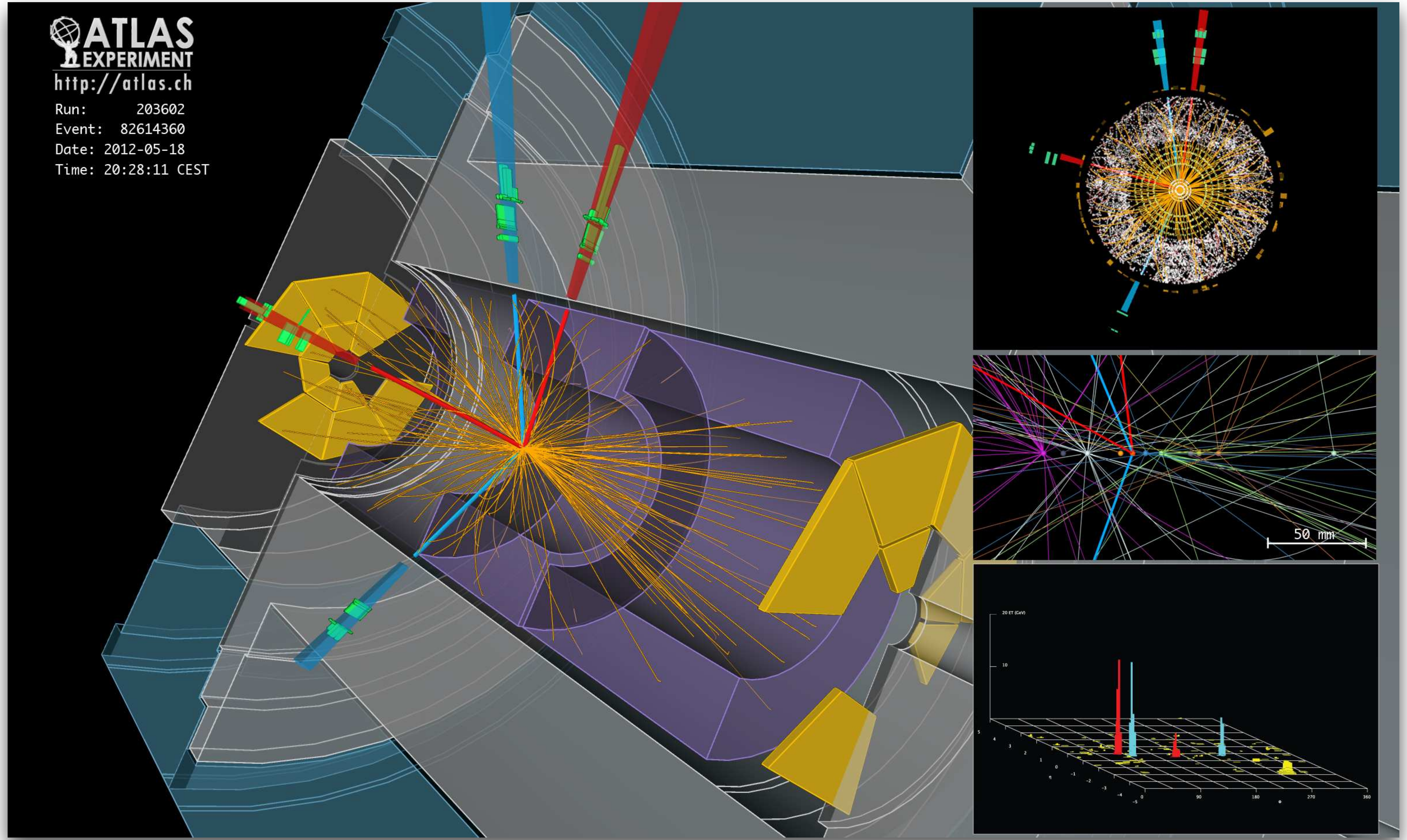




$H \to \gamma\gamma$



$H \to ZZ \to 4\ell$



Event selection.

$H \to \gamma\gamma$

Region	Definition
Inclusive	-
VBF	$m_{jj} > 400$ GeV, $\lvert\Delta\phi_{\gamma\gamma,jj}\rvert > 2.6$, $\lvert\Delta y_{jj}\rvert > 2.8$
N_{lept}	at least one lepton associated with the Higgs boson decay
High-MET	at least a missing transverse energy of 80GeV and $p_{\mathrm{T}}^{\gamma\gamma} > 80$GeV associated with the Higgs decay
ttH	at least one lepton, 3 jets (1 b-tag) OR no leptons, at least 4 jet (1 b-tag)

$H \to ZZ \to 4\ell$

Leptons and jets	
Muons:	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Jets:	$p_{\mathrm{T}} > 30$ GeV, $\lvert y\rvert < 4.4$
Jet-lepton overlap removal:	$\Delta R(\mathrm{jet}, \ell) > 0.1\,(0.2)$ for muons (electrons)
Lepton selection and pairing	
Lepton kinematics:	$p_{\mathrm{T}} > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per channel)	
Mass requirements:	$50 < m_{12} < 106$ GeV and $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1\,(0.2)$ for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115\ GeV < m_{4\ell} < 130$ GeV