# Higgs differential distributions at the LHC

fiducial cross sections in ZZ/γγ decay modes

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**on behalf of ATLAS and CMS**

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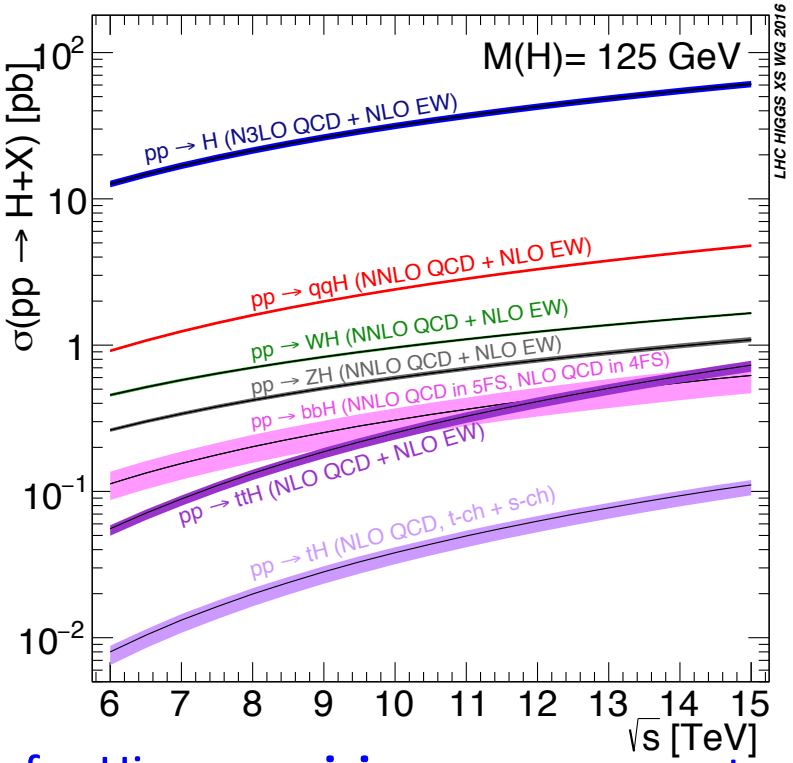
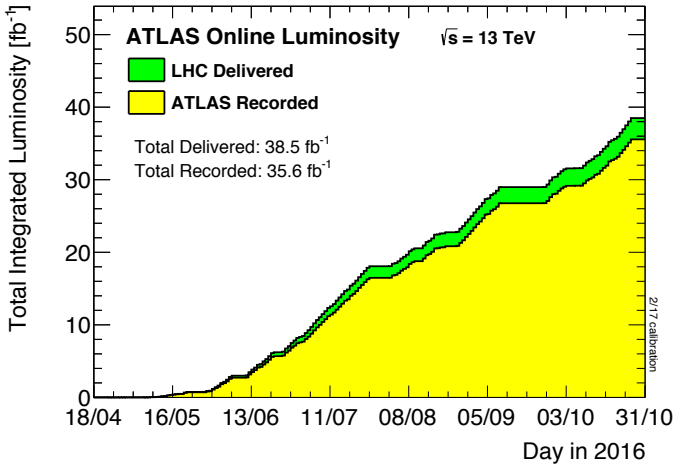
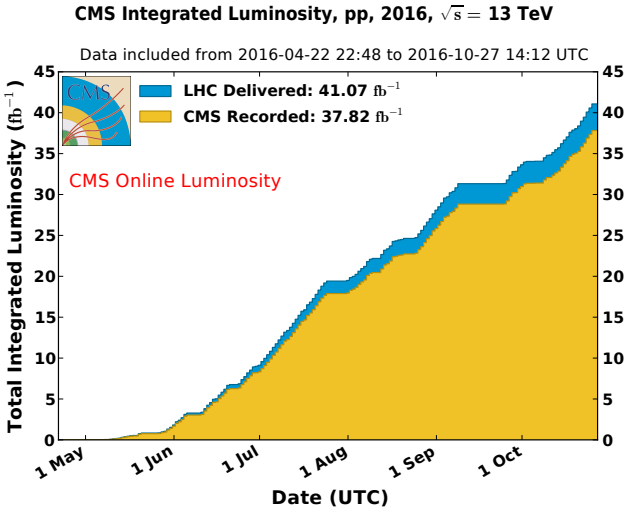
# Higgs at the 13TeV LHC




Era for Higgs **precision** measurements:

- statistical unc. approaches theoretical unc.

- **Larger cross section** at 13TeV :
  **especially for some rare production modes**
- ATLAS and CMS are taking data with full power:
  **> 100 fb$^{-1}$ data** for Run-II for each experiment
  (x4 data w.r.t. 2016 )

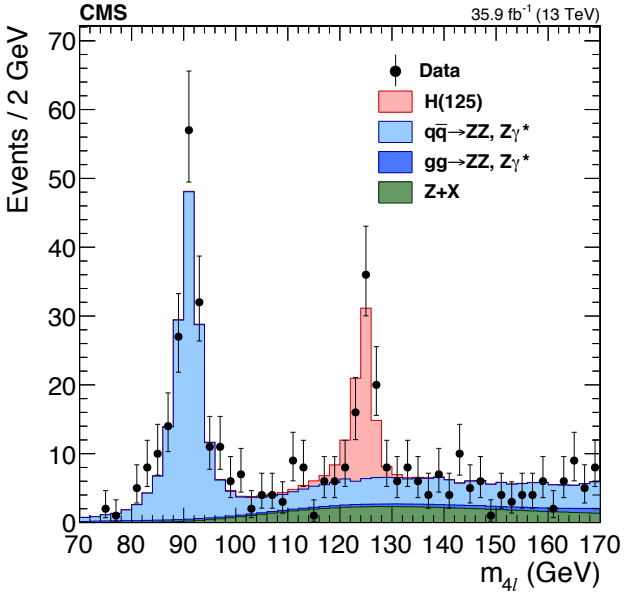
# Reference publications for the two sensitive channels

| H->ZZ*->4l | Publication | Dataset |
|---|---|---|
| ATLAS | ATLAS-CONF-2018-018 | 2015-2017 79.8 $fb^{-1}$ |
| ATLAS | JHEP 10 (2017) 132 | 2015+2016 36.1$fb^{-1}$ |
| CMS | JHEP 11 (2017) 047 | 2016 35.9 $fb^{-1}$ |

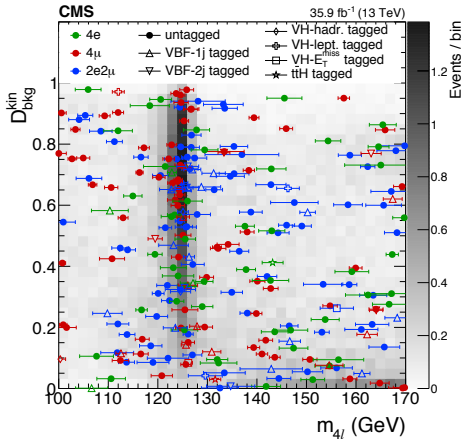
| H->γγ | Publication | Dataset |
|---|---|---|
| ATLAS | arXiv:1802.04146 (submitted to PRD) | 2015+2016 36.1$fb^{-1}$ |
| CMS | HIG-17-015 | 2016 35.9 $fb^{-1}$ |

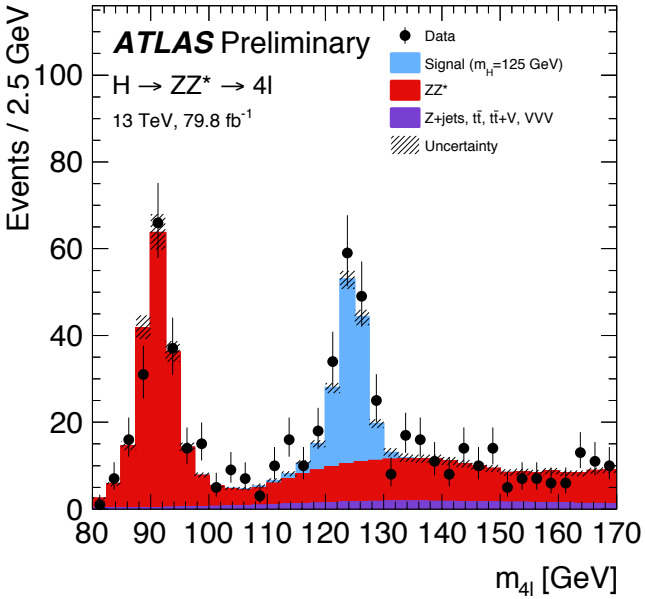
| H->γγ + H->ZZ*->4l | Publication | Dataset |
|---|---|---|
| ATLAS | ATLAS-CONF-2018-002 | 2015+2016 36.1$fb^{-1}$ |
| CMS | Under preparation | 2016 35.9 $fb^{-1}$ |

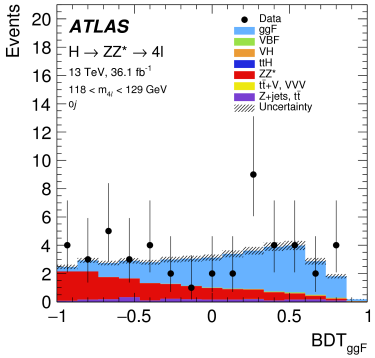
# Sensitive channels : H→ZZ*→4l




- Signal is fully reconstructed using four lepton with good momentum resolution
- Majority part of the backgrounds are from **SM ZZ**
- Large signal V.S. bkg ratio : > 2:1 under the **Higgs peak**
- **Kinematic information** for further S/B separation
  in terms of BDT (ATLAS)
  or Matrix-Element Kinematic Discriminant (CMS)
- **Z->4l** can be used as standard candle



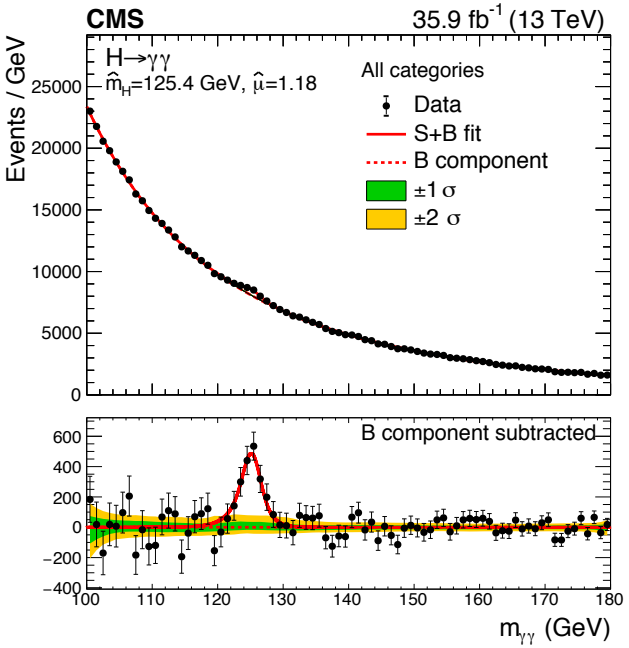



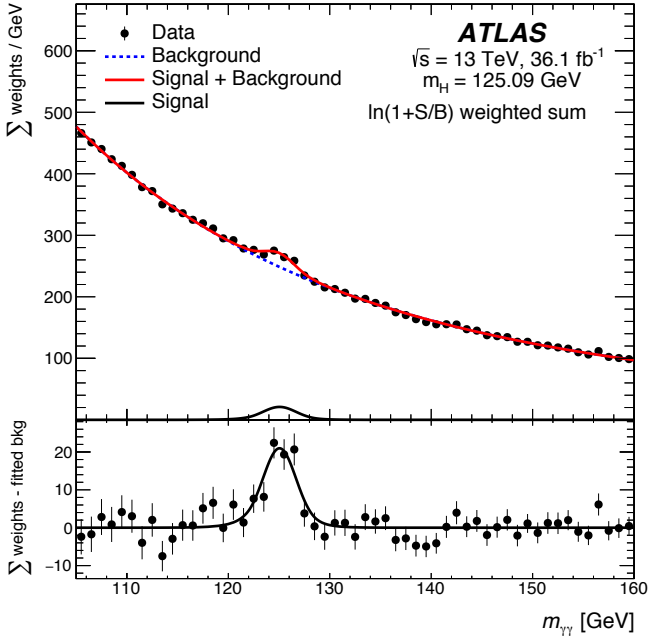
# Sensitive channels : H→γγ

- Signal is reconstructed by two energetic photons
- Majority of the backgrounds are from **SM γγ** and **γ+jets**
- Vertex assignment

  ATLAS : neural network(vertex/track, calorimeter pointing)

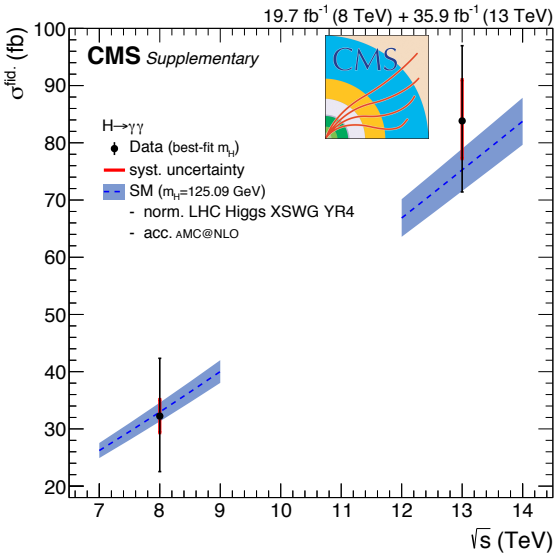
  CMS: BDT combines tracking and calorimeter information
- Good mass resolution : about 1-2% for a 125 GeV Higgs
- Signal is extracted by fitting the di-photon mass spectrum

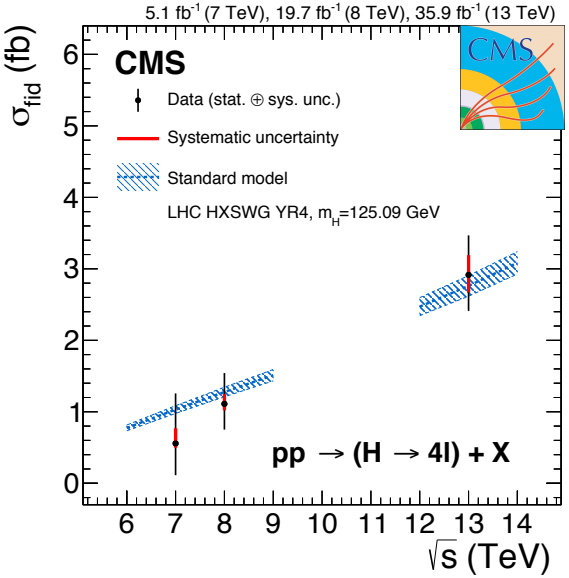


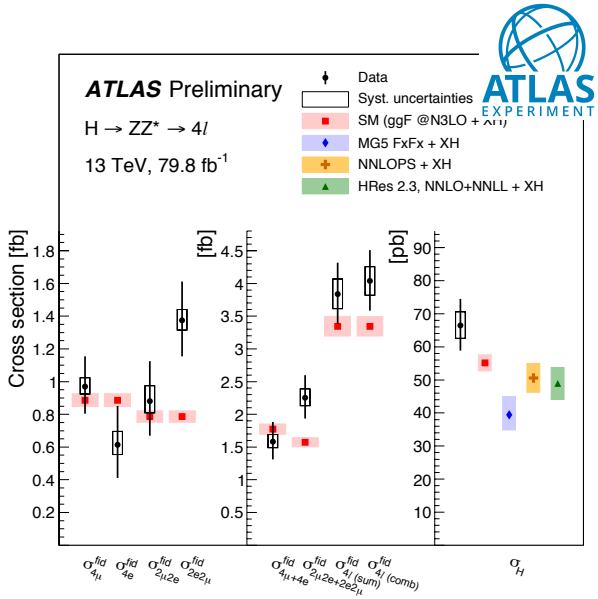



# Fiducial and differential fiducial cross sections

- **Fiducial** phase space is defined to match closely experimental acceptance
  - **minimize extrapolation** into experimentally invisible phase space
  - allows an **easier comparison** of measurements **with the theoretical estimations**



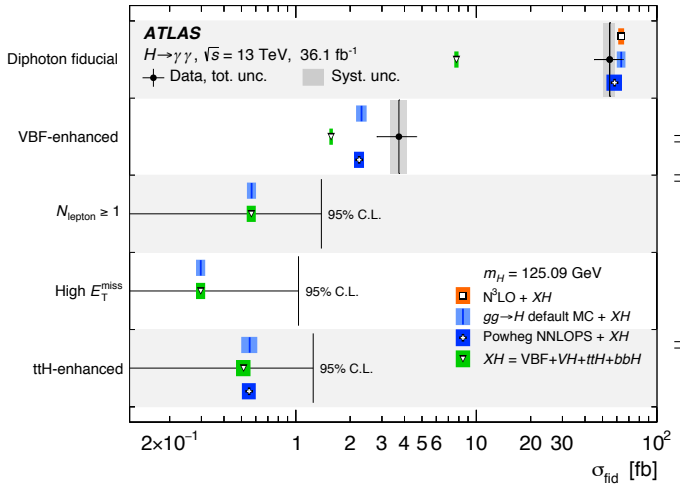



# **Fiducial** and differential fiducial cross sections

- **Fiducial** phase space is defined to match closely experimental acceptance
  - can be defined such that they are **enriched in a given production mode**

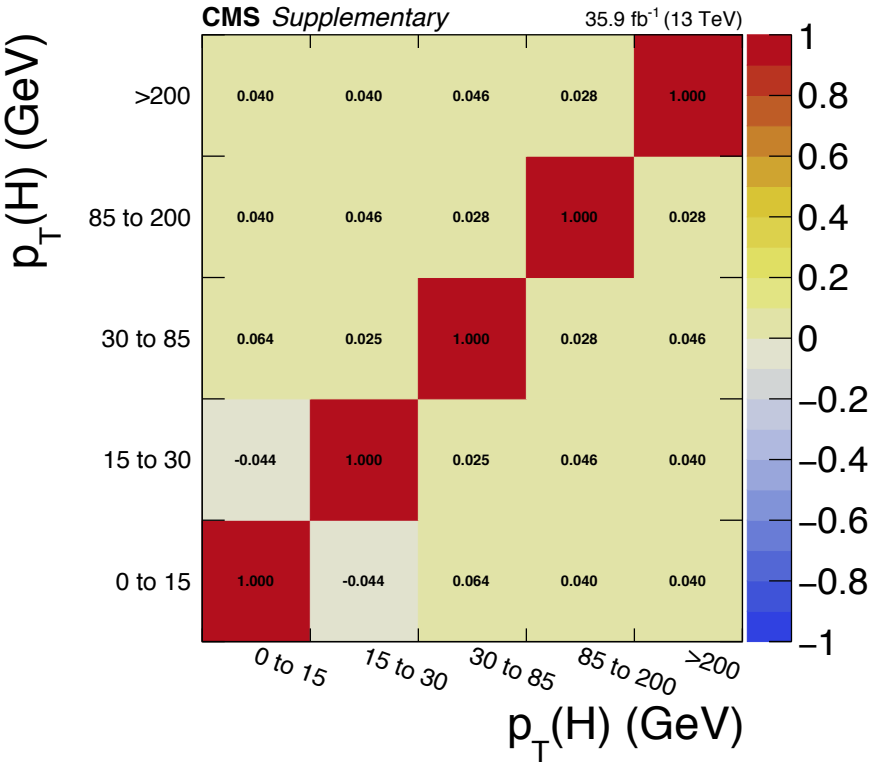
| Objects | Definition |
|---|---|
| Photons | $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$, $p_{\mathrm{T}}^{\mathrm{iso},0.2}/p_{\mathrm{T}}^{\gamma} < 0.05$ |
| Jets | anti-$k_t$, $R = 0.4$, $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert y\rvert < 4.4$ |
| Leptons, $\ell$ | $e$ or $\mu$, $p_{\mathrm{T}} > 15\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.47$ for $e$ (excluding $1.37 < \lvert\eta\rvert < 1.52$) and $\lvert\eta\rvert < 2.7$ for $\mu$ |
| **Fiducial region** | **Definition** |
| Diphoton fiducial | $N_\gamma \geq 2$, $p_{\mathrm{T}}^{\gamma 1} > 0.35\, m_{\gamma\gamma} = 43.8$ GeV, $p_{\mathrm{T}}^{\gamma 2} > 0.25\, m_{\gamma\gamma} = 31.3$ GeV |
| VBF-enhanced | Diphoton fiducial, $N_j \geq 2$ with $p_{\mathrm{T}}^{\mathrm{jet}} > 25$ GeV, $m_{jj} > 400$ GeV, $\lvert\Delta y_{jj}\rvert > 2.8$, $\lvert\Delta\phi_{\gamma\gamma,jj}\rvert > 2.6$ |
| $N_{\mathrm{lepton}} \geq 1$ | Diphoton fiducial, $N_\ell \geq 1$ |
| High $E_{\mathrm{T}}^{\mathrm{miss}}$ | Diphoton fiducial, $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV, $p_{\mathrm{T}}^{\gamma\gamma} > 80$ GeV |
| $t\bar{t}H$-enhanced | Diphoton fiducial, $(N_j \geq 4, N_{b\text{-jets}} \geq 1)$ or $(N_j \geq 3, N_{b\text{-jets}} \geq 1, N_\ell \geq 1)$ |




| Fiducial region | Measured cross section | SM prediction | |
|---|---|---|---|
| Diphoton fiducial | $55 \pm 9\,(\mathrm{stat.}) \pm 4\,(\mathrm{exp.}) \pm 0.1\,(\mathrm{theo.})$ fb | $64 \pm 2$ fb | [N$^3$LO + $XH$] |
| VBF-enhanced | $3.7 \pm 0.8\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{exp.}) \pm 0.2\,(\mathrm{theo.})$ fb | $2.3 \pm 0.1$ fb | [default MC + $XH$] |
| $N_{\mathrm{lepton}} \geq 1$ | $\leq 1.39$ fb 95% CL | $0.57 \pm 0.03$ fb | [default MC + $XH$] |
| High $E_{\mathrm{T}}^{\mathrm{miss}}$ | $\leq 1.00$ fb 95% CL | $0.30 \pm 0.02$ fb | [default MC + $XH$] |
| $t\bar{t}H$-enhanced | $\leq 1.27$ fb 95% CL | $0.55 \pm 0.06$ fb | [default MC + $XH$] |

# Fiducial and **differential fiducial** cross sections

- In (double) differential fiducial cross section measurements, the signal is extracted from the bins defined by the reconstructed observables using bin-by-bin correction (ATLAS)
  unfolding matrix including correlation between by the reconstructed observable and differential fiducial volume



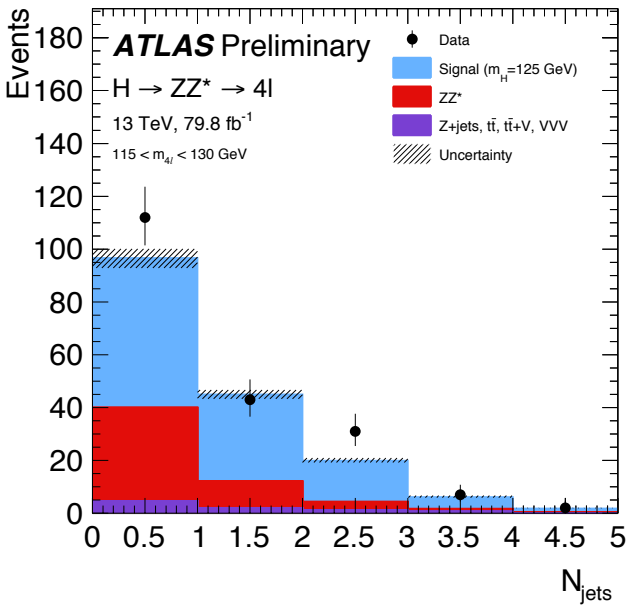
# Fiducial and **differential fiducial** cross sections

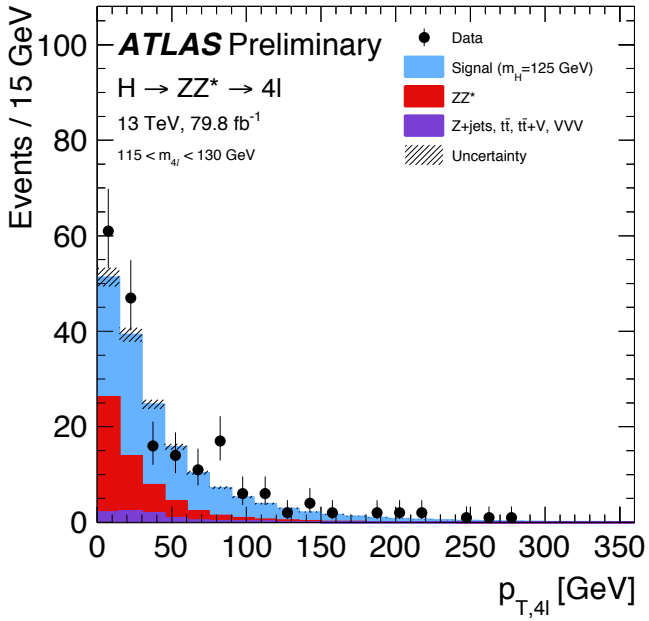
- Results contain more rich information

  - cross sections in a series of fiducial volume form a certain pattern

  - can characterize the Higgs boson production mode(s), spin/parity

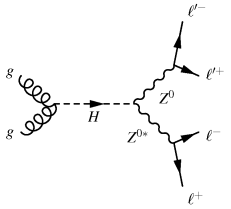
  - can be interpreted in the context of beyond SM search

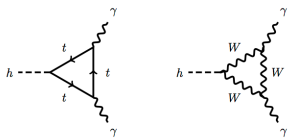


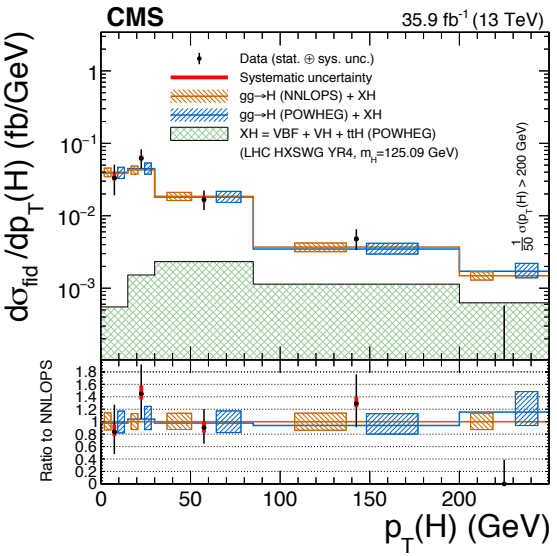



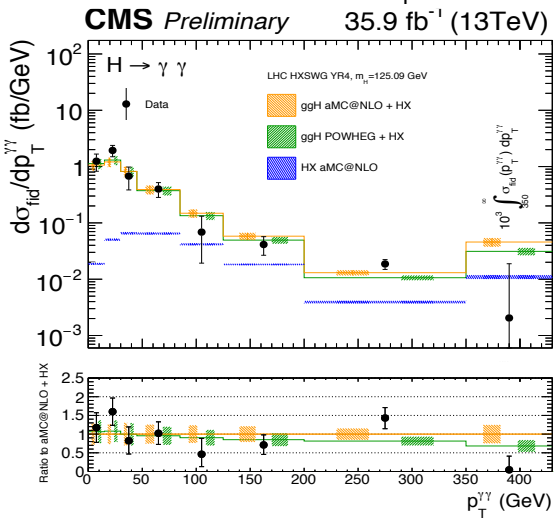

**Number of events for each bin defined by reconstructed observables**

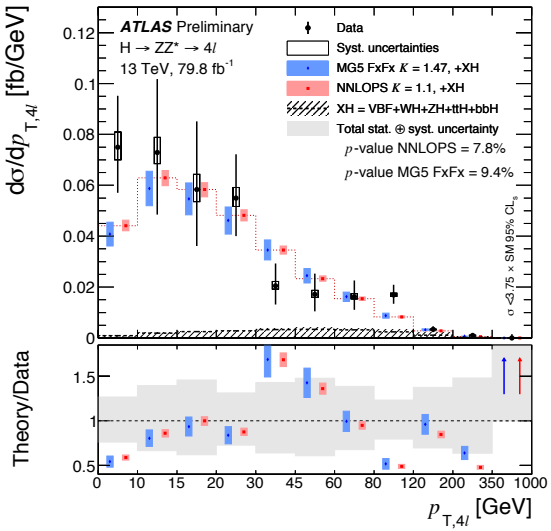
# Differential distributions
## – Higgs's $p_T$ and rapidity

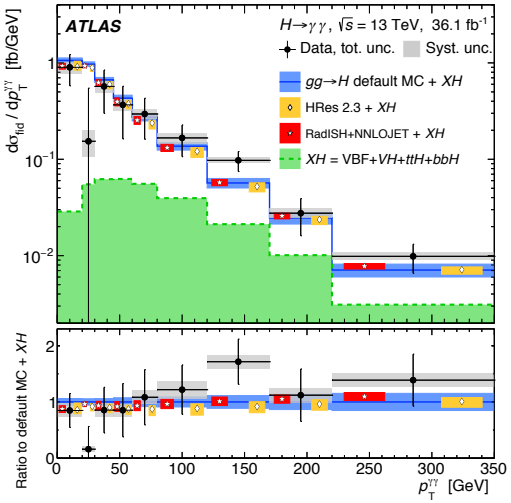


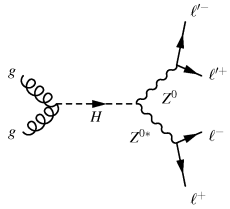



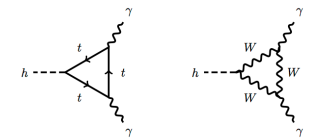


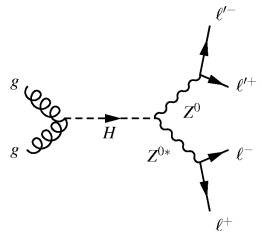



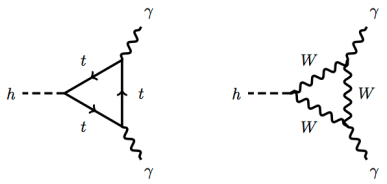



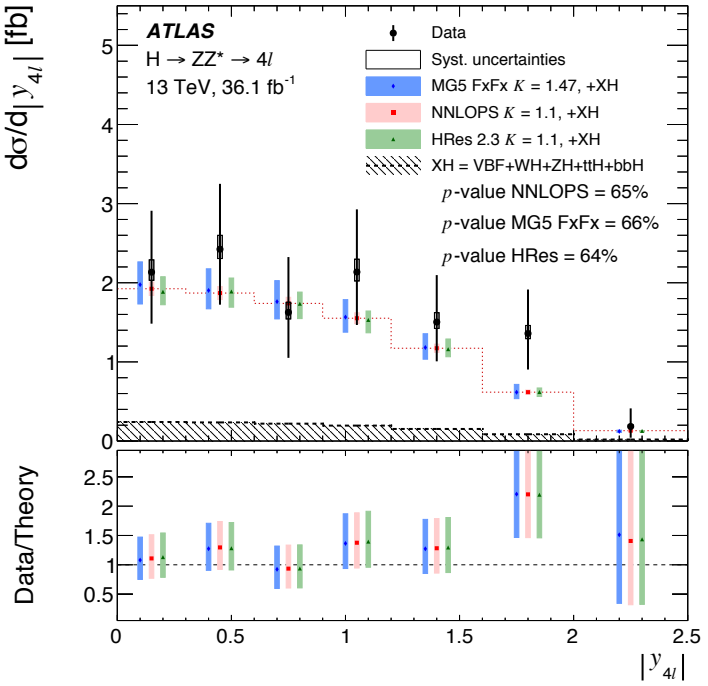


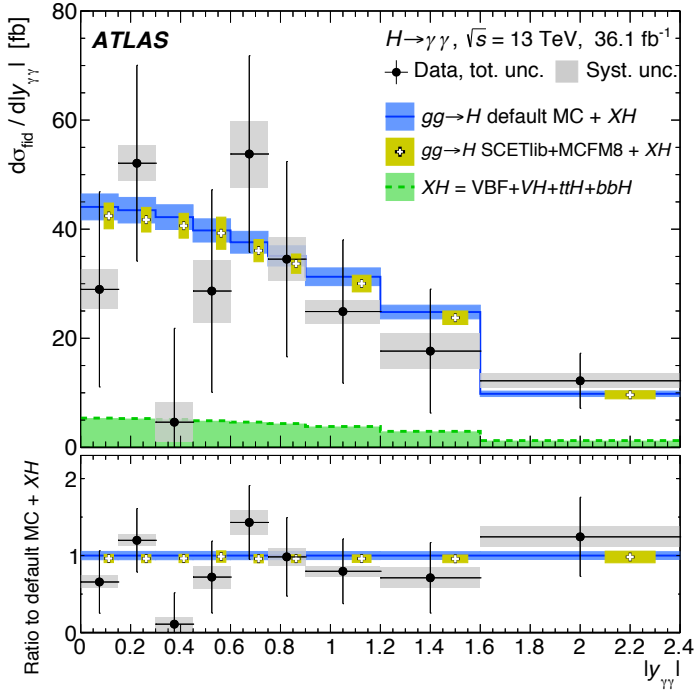
➢ $p_T$ (tranverse momentum) probes the perturbative QCD modeling of Higgs production

# Differential distributions
## – Higgs's $p_T$ and **rapidity**



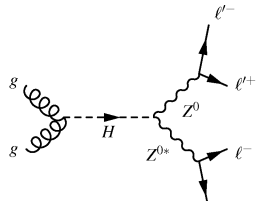



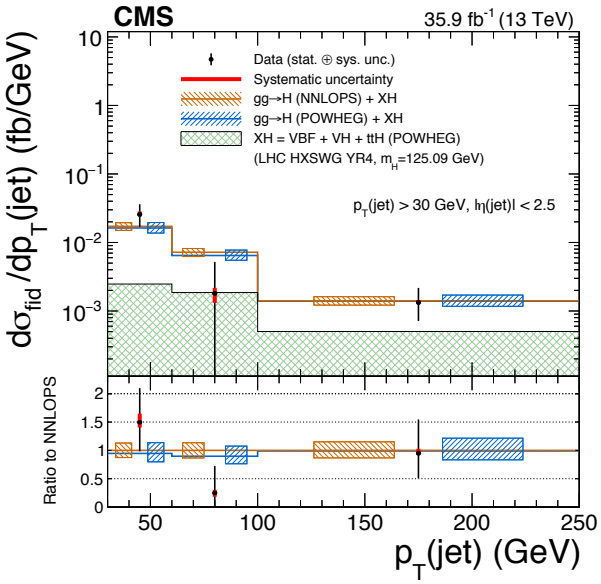



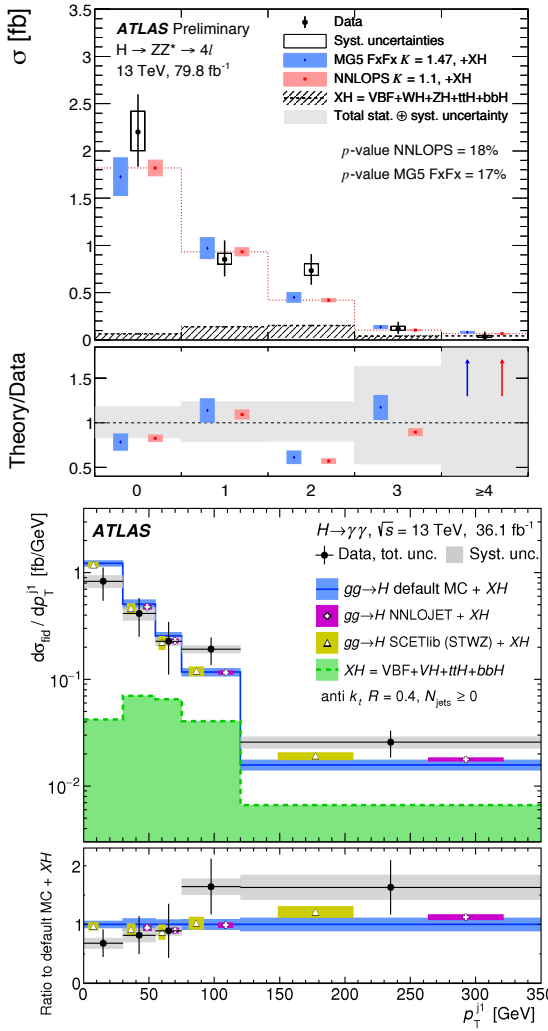



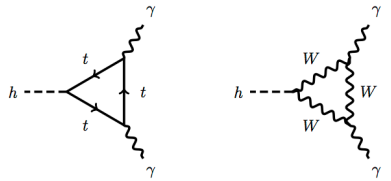

- **Rapidity (longitudinal momentum) is also sensitive to the Higgs production mode**

# Differential distributions – jet kinematics



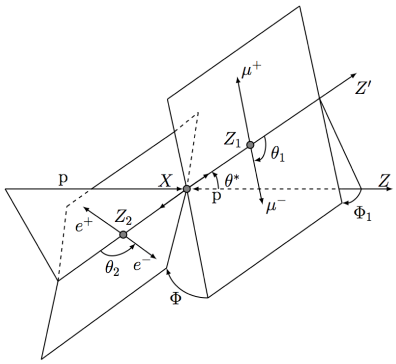



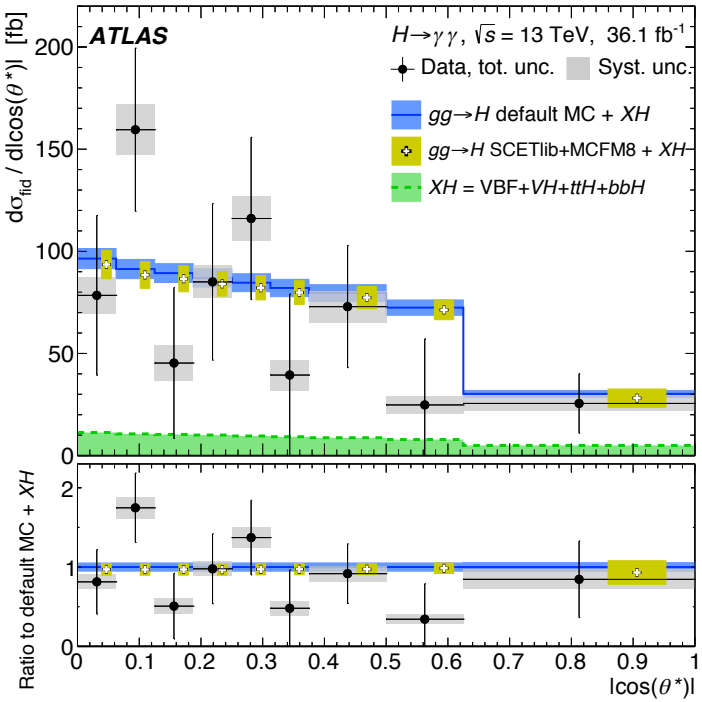



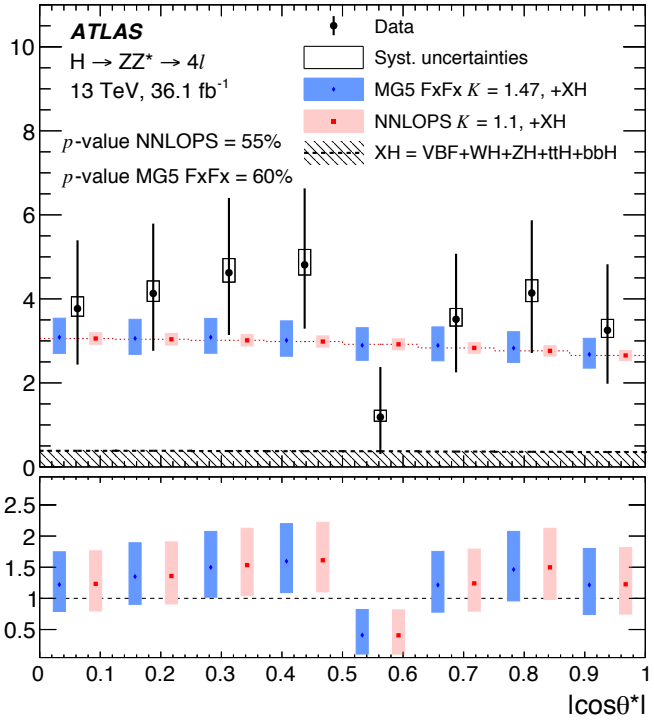




**Jet kinematics are sensitive to the relative contributions of Higgs production modes.**

# Differential distributions – probing spin/parity

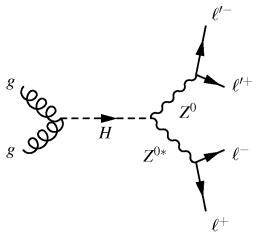


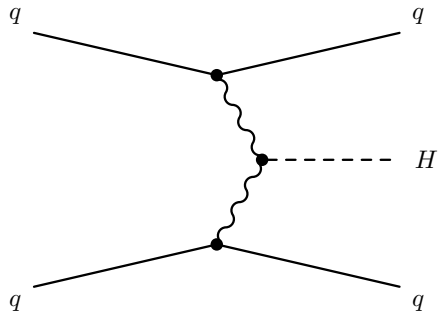



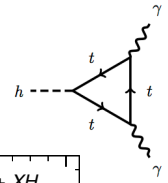



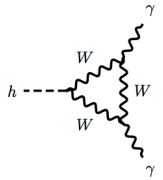

- **Angular observables can be sensitive to the spin/parity of the particle.**
- **Differential distributions of production angle θ* show compatibility with a scalar**

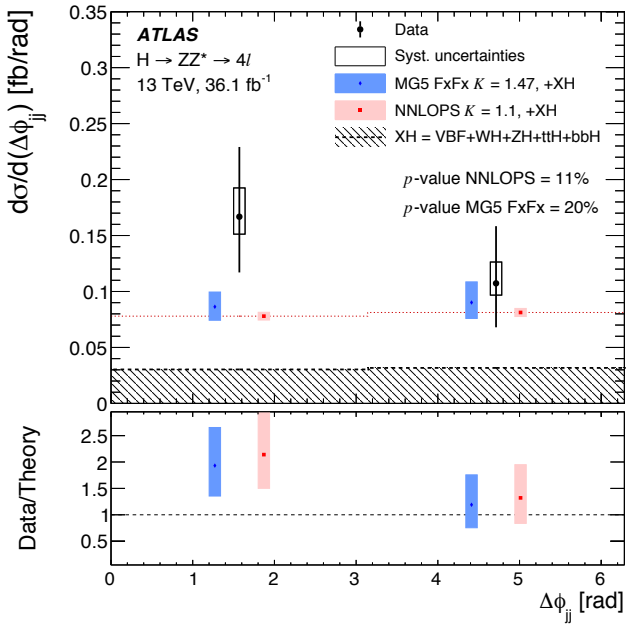
# Differential distributions – probing VBF

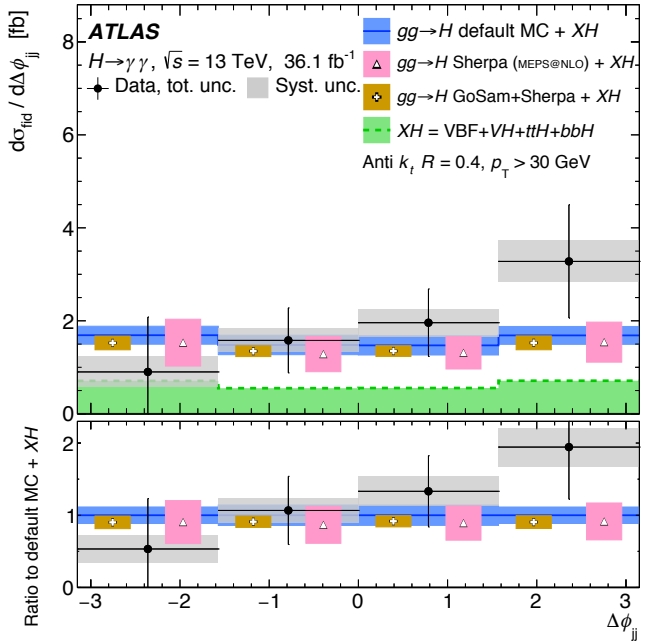


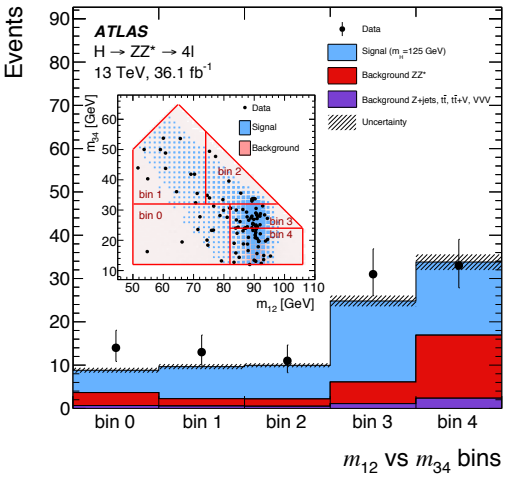



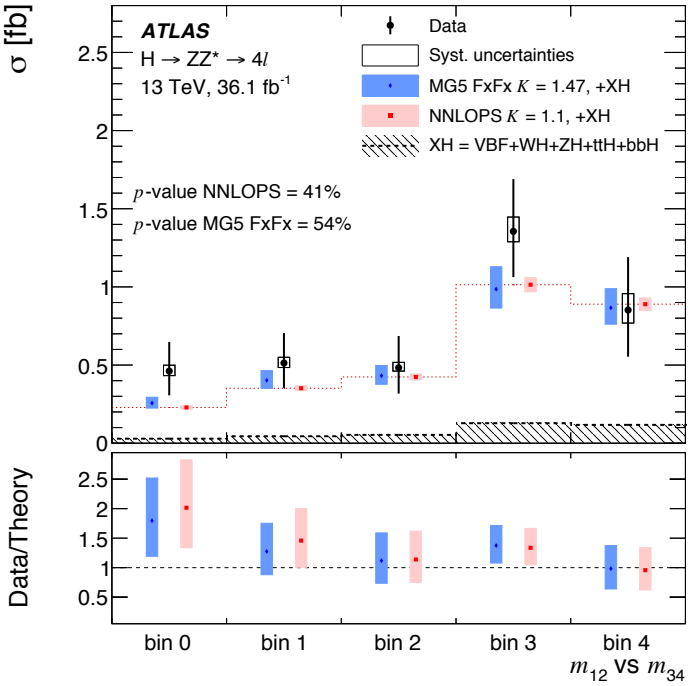



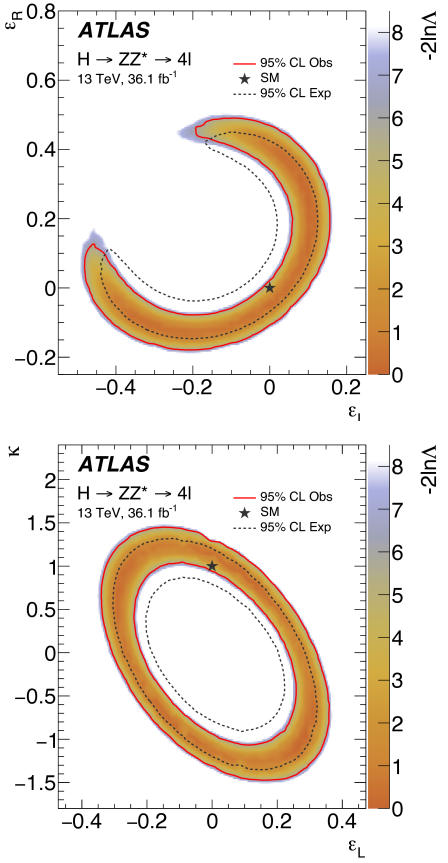




- **SM VBF, $\Delta\phi_{jj}$ is approximately flat with a slight tendency towards ±π.**
- **Any additional anomalous contribution would manifest itself as an additional oscillatory component.**

# Differential distributions – di-lepton mass in PO framework




Electroweak bounds on Higgs pseudo-observables and h→4l decays
Eur. Phys. J. C 75 (2015) 341

**$\varepsilon_{L/R}$ modifies the contact terms between the Higgs and left- and right-handed leptons.**
**$\kappa$ is the strength of coupling between Higgs and Z boson.**

**Double differential distribution of di-lepton invariant mass shows compatibility with SM.**
**Limits are set on the contact-interaction coupling strengths under PO framework.**

# Simultaneous fit of differential observables

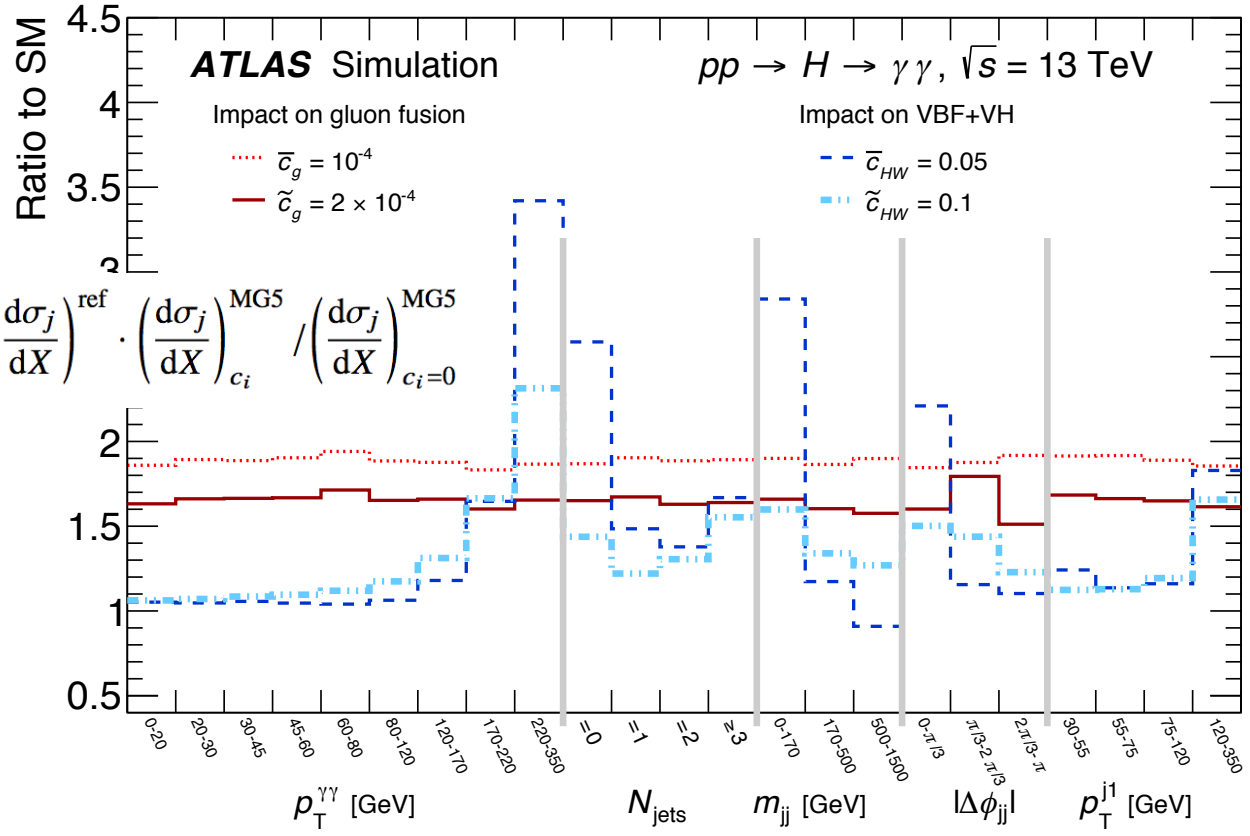
## Search for anomalous interactions using EFT approach

$$\mathcal{L}_{\text{eff}} = \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$

**Effective Lagrangian for a light Higgs-like scalar, JHEP 07 (2013) 035**

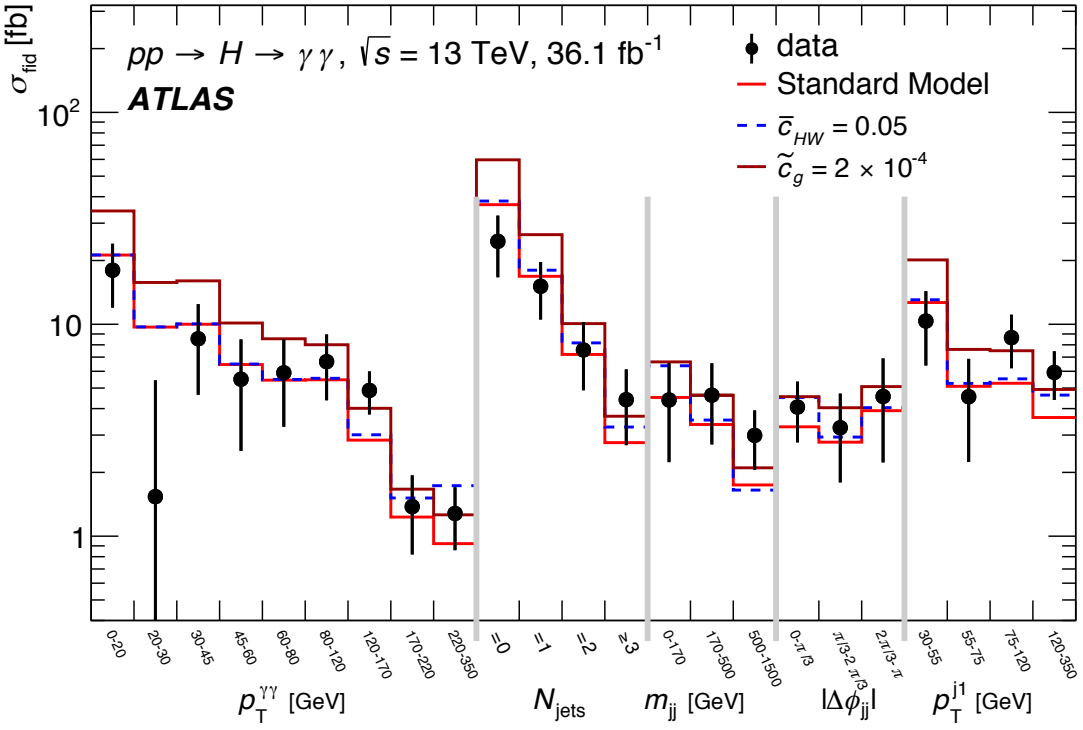
**Phenomenology of the Higgs Effective Lagrangian via FEYNRULES, JHEP 04 (2014) 110**

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



# Simultaneous fit of differential observables

Differential distributions from **simultaneous fit** are compatible with SM.




| Distribution | Default MC Prediction |
|---|---|
| $p_{\mathrm{T}}^{\gamma\gamma}$ | 51% |
| $\lvert y_{\gamma\gamma}\rvert$ | 57% |
| $p_{\mathrm{T}}^{j_1}$ | 32% |
| $\lvert y_{j_1}\rvert$ | 66% |
| $p_{\mathrm{T}}^{j_2}$ | 61% |
| $\lvert y_{j_2}\rvert$ | 56% |
| $\lvert\cos\theta^*\rvert$ | 47% |
| $\Delta\phi_{jj}$ | 64% |
| $\lvert\Delta y_{jj}\rvert$ | 53% |
| $\lvert\Delta\phi_{\gamma\gamma,jj}\rvert$ | 43% |
| $m_{jj}$ | 54% |
| $N_{\mathrm{jets}}$ ($p_{\mathrm{T}} > 30$ GeV) | 56% |
| $N_{\mathrm{jets}}$ ($p_{\mathrm{T}} > 50$ GeV) | 19% |

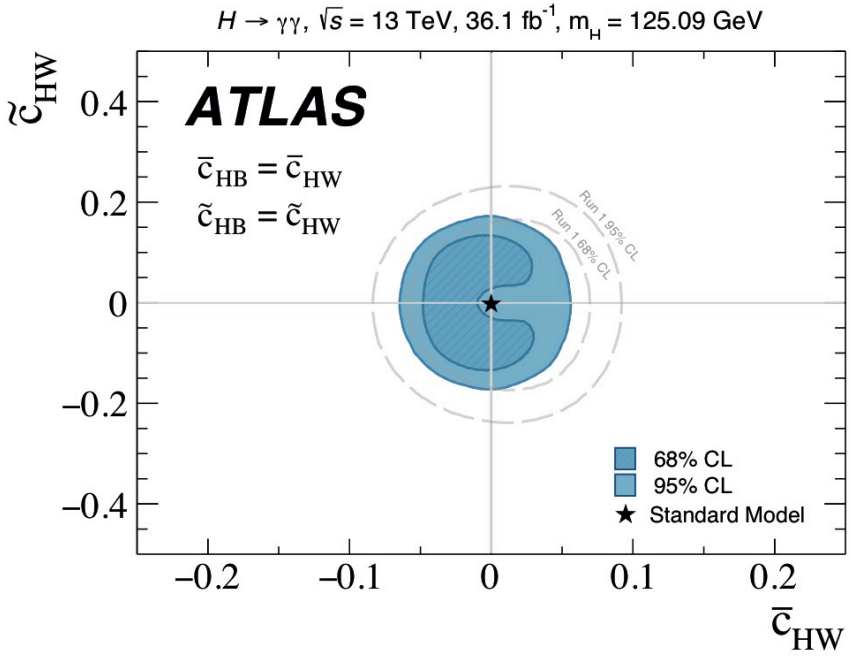
**P-values for the comparison between data and the default SM prediction**

# Simultaneous fit of differential observables

Differential distributions from simultaneous fit are compatible with SM.

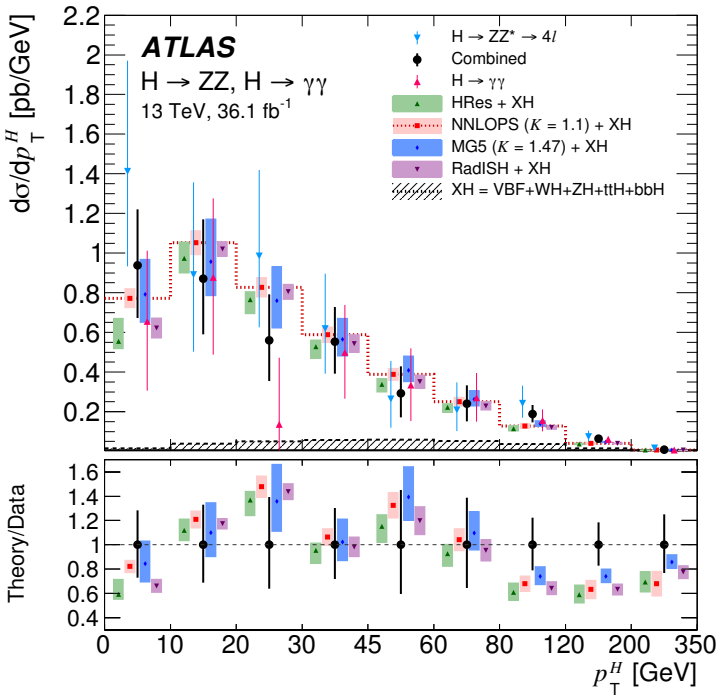
**Limits are set on the parameters of BSM interactions.**

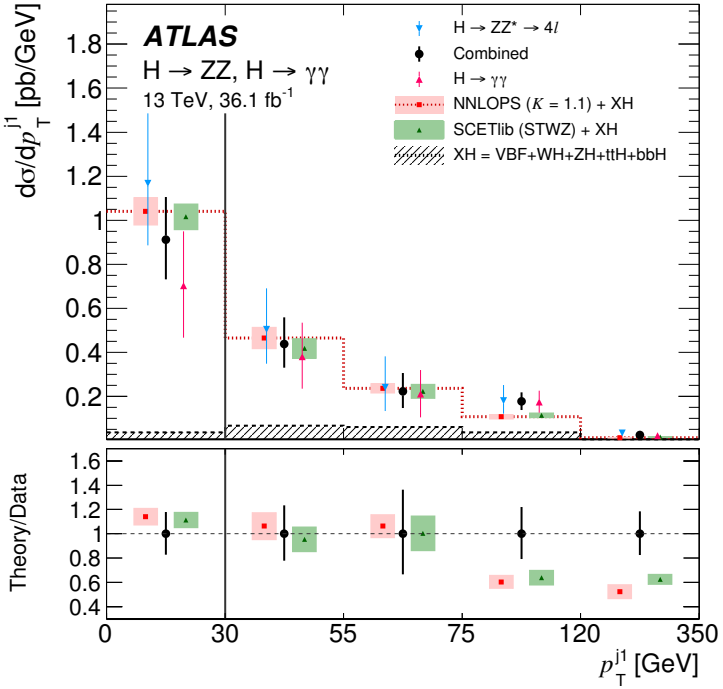
| Coefficient | Observed 95% CL limit | Expected 95% CL limit |
|---|---|---|
| $\bar{c}_g$ | $[-0.8, 0.1] \times 10^{-4} \cup [-4.6, -3.8] \times 10^{-4}$ | $[-0.4, 0.5] \times 10^{-4} \cup [-4.9, -4.1] \times 10^{-4}$ |
| $\tilde{c}_g$ | $[-1.0, 0.9] \times 10^{-4}$ | $[-1.4, 1.3] \times 10^{-4}$ |
| $\bar{c}_{HW}$ | $[-5.7, 5.1] \times 10^{-2}$ | $[-5.0, 5.0] \times 10^{-2}$ |
| $\tilde{c}_{HW}$ | $[-0.16, 0.16]$ | $[-0.14, 0.14]$ |



# Combination of ZZ*->4l and H->γγ

- Combination is performed in **total phase space**
  - **Increasing model dependence** is compensated by **significant** reduction of **statistical uncertainty**
  - Both **combined** and **individual** channel results show compatibility with SM



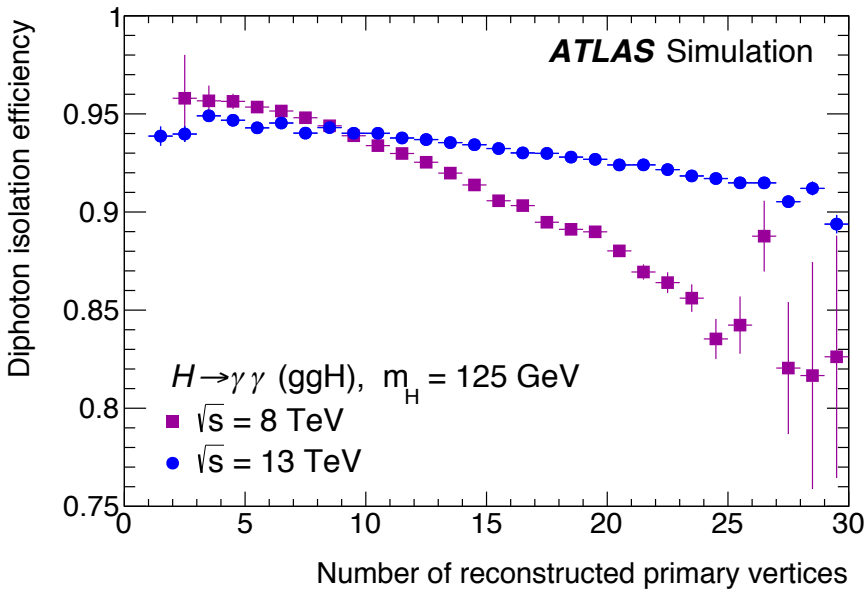



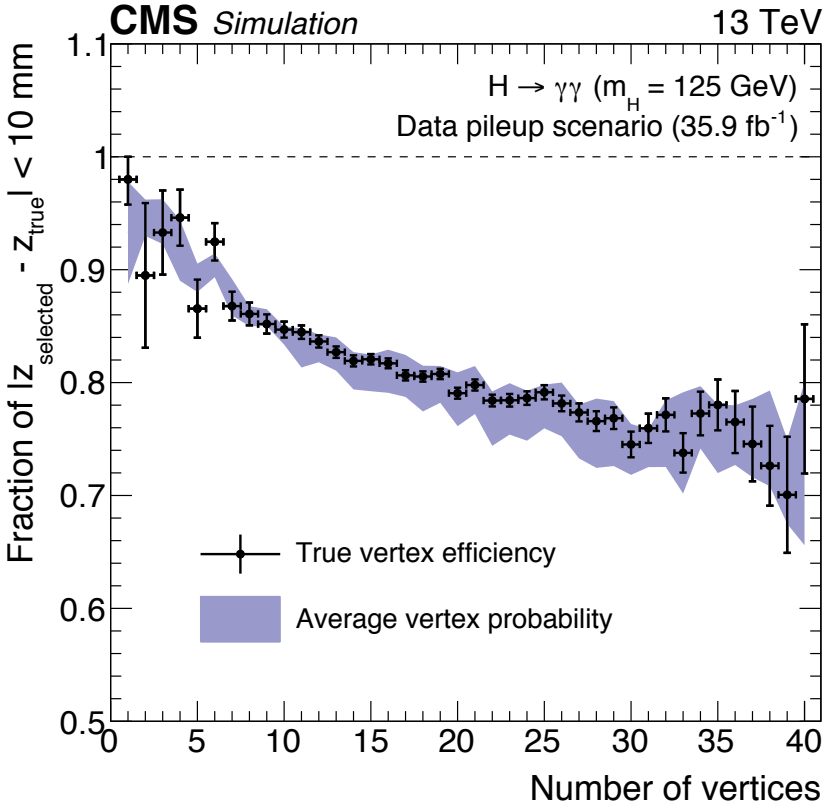
# Summary

- Higgs differential distributions are studied with the 13TeV collision data collected in 2016 at the LHC
  - (Differential) fiducial cross sections are consistent with a SM Higgs
  - results are used to probe BSM couplings in PO or EFT framework. No significant deviation with SM is observed, limits are set on the parameters for BSM interactions
- With data accretion, more than 100 $fb^{-1}$ data will be available for both experiments by the end of 2018 (Run-II)
  - More results will come with much better precision
    - statistical uncertainty to be reduced by a factor of 2
- New ideas are more than welcomed to fully exploit the results of precision measurements of Higgs properties

# Backup slides

# H→γγ : vertex assignment



# H→γγ : systematic uncertainties

| Uncertainty Group | $\sigma_{\mu}^{\text{syst.}}$ |
|---|---|
| Theory (QCD) | 0.041 |
| Theory ($B(H \to \gamma\gamma)$) | 0.028 |
| Theory (PDF+$\alpha_S$) | 0.021 |
| Theory (UE/PS) | 0.026 |
| Luminosity | 0.031 |
| Experimental (yield) | 0.017 |
| Experimental (migrations) | 0.015 |
| Mass resolution | 0.029 |
| Mass scale | 0.006 |
| Background shape | 0.027 |

# H->γγ : simultaneous fit of all observables