Higgs boson differential cross sections

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on behalf of the CMS and ATLAS collaborations

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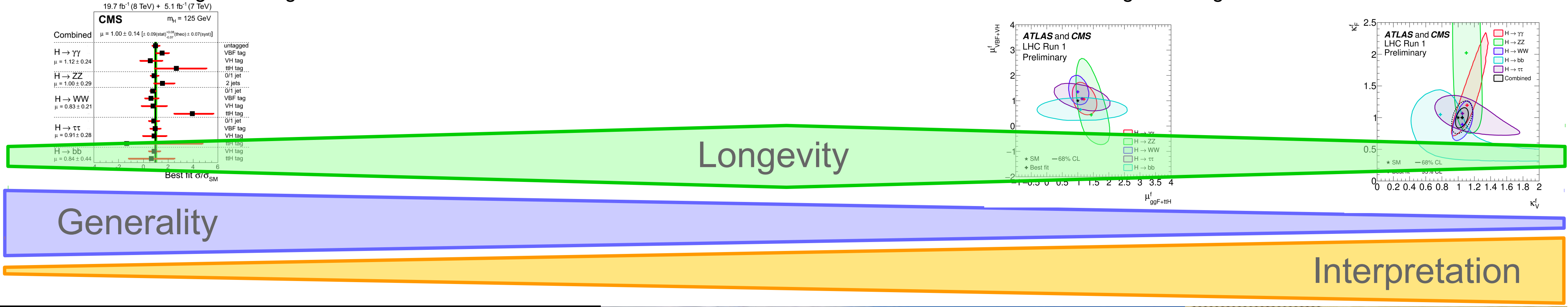
Why fiducial cross sections?

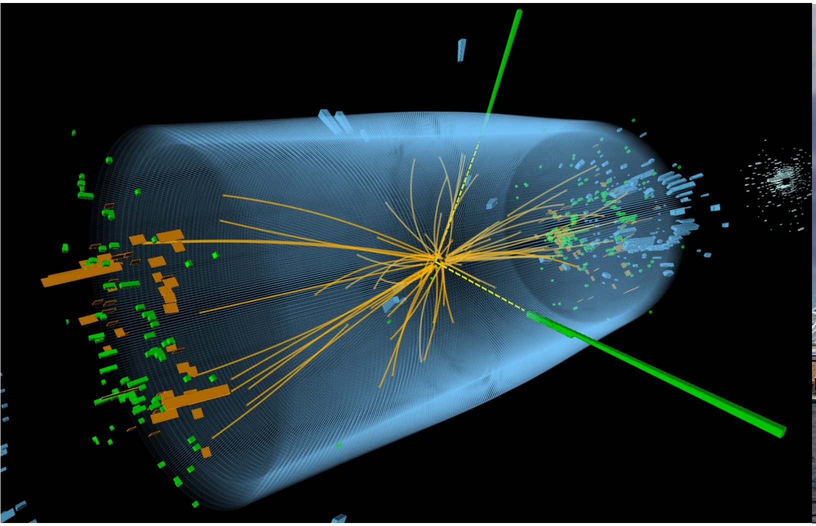
- **Experimental data** can be presented in many possible ways.
  - Presentations can be classified according to different metrics: generality, power of the interpretation, longevity...

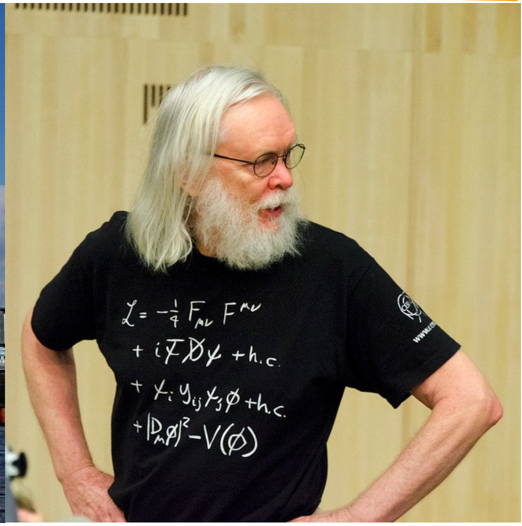
Per-channel signal strengths

“Unfolded” signal strengths

Coupling modifiers

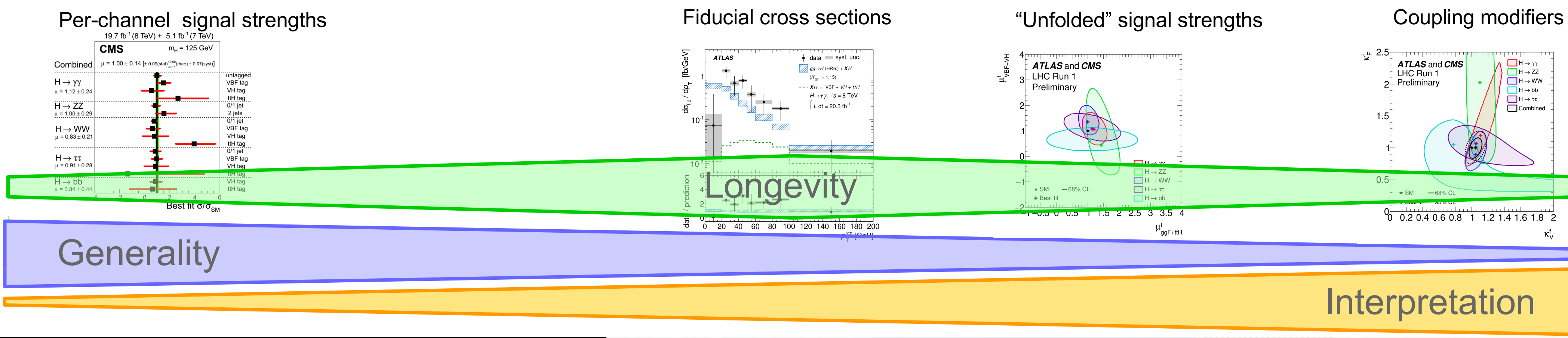


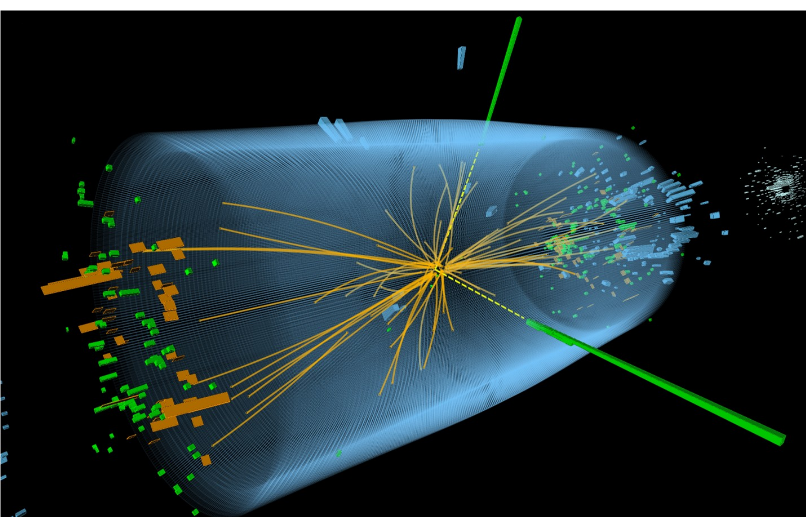


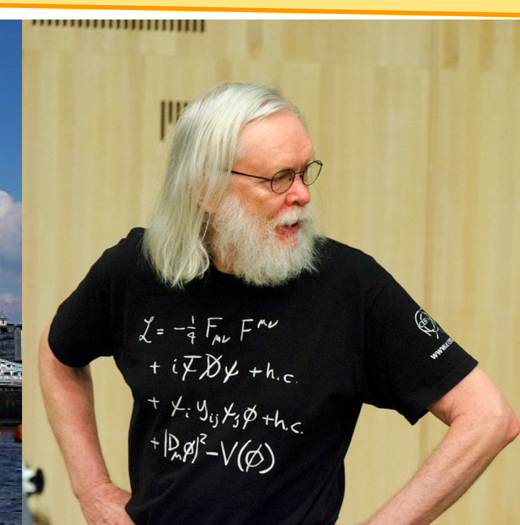


Why fiducial cross sections?

- **Experimental data** can be presented in many possible ways.
  - Presentations can be classified according to different metrics: generality, power of the interpretation, longevity...
  - **Differential cross sections** help maximizing **longevity** while preserving most of the power of the data.







Higgs differential cross sections: run 1 results

JHEP09(2014)112	Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at sqrt(s) = 8 TeV with ATLAS	$\gamma\gamma$
PLB 738 (2014) 234-253	Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector	**ZZ**
PRL 115 (2015) 091801	Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$ Decay Channels at s√=8 TeV with the ATLAS Detector	$\gamma\gamma$,**ZZ**
PLB 753 (2016) 69-85	Constraints on non-Standard Model Higgs boson interactions in an effective Lagrangian using differential cross sections measured in the $H\to\gamma\gamma$ decay channel at s√=8 TeV with the ATLAS detector	$\gamma\gamma$
arXiv:1508.07819 (accepted by EPJC)	Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at s√= 8 TeV	$\gamma\gamma$
arXiv:1512.08377	Measurement of differential and integrated fiducial cross sections for Higgs boson production in the four-lepton decay channel in pp collisions at s√= 7 and 8 TeV	**ZZ**
CMS-PAS-HIG-15-010	Measurement of the transverse momentum spectrum of the Higgs boson produced in pp collisions at s√= 8 TeV using the $H\to WW$ decays	**WW** NEW

Disclaimer

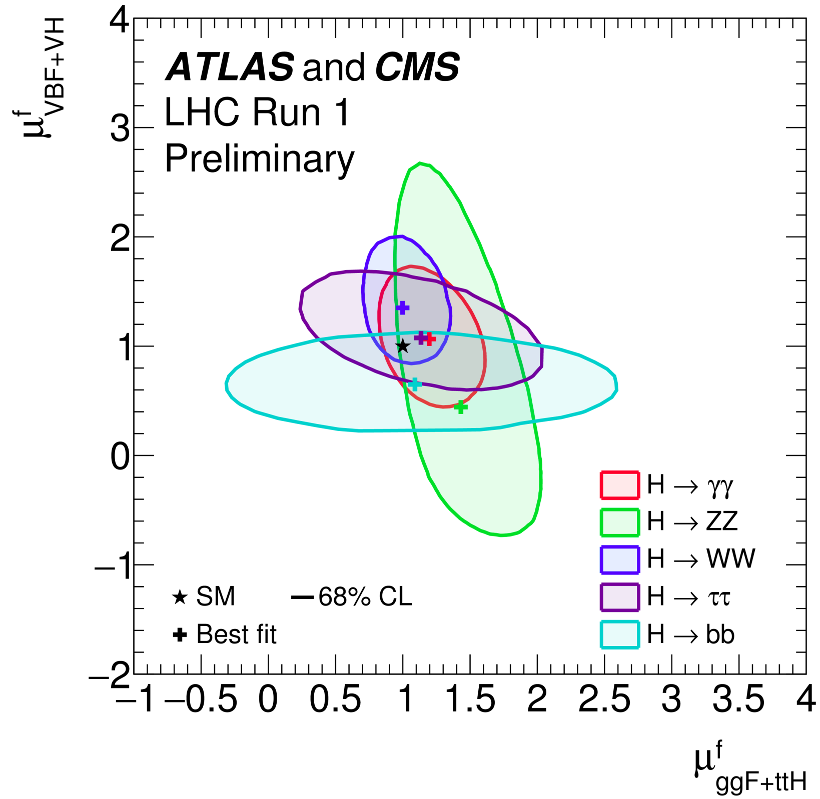
- Will show a personally biased selection of the available material.
  - Will put some more focus on how the results are obtained, rather than on the results themselves.

- Restrict presentation to total fiducial cross sections and Higgs pT spectrum.
  - This does not exhaust the available measurements.
  - Few more distributions are in the extra material section, but please refer to the documentation above for more details.

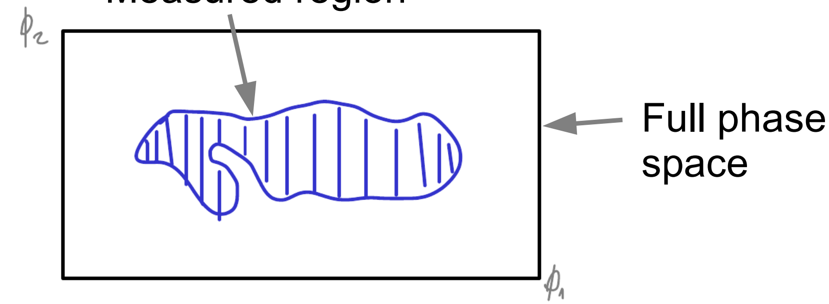
Aren't signal strengths good enough?

- Signal strengths are one of the most powerful summary of Higgs data from LHC Run 1.
  - They are also fairly general, especially within the Run 1 uncertainties.
  - Generally defined as the ratio between the expected and observed signal cross sections.
    A more explicit definition is:

$$\mu = \frac{A \cdot \sigma}{A_{SM} \cdot \sigma_{SM}}$$



  - Precision maximized by exploiting knowledge of signal characteristics.
  - However, interpreting the signal strengths as cross sections requires a number of assumptions.
    - Acceptance can have non trivial dependence on phase space variables.



(Fiducial) differential cross sections

Detector level observable

Particle level observable

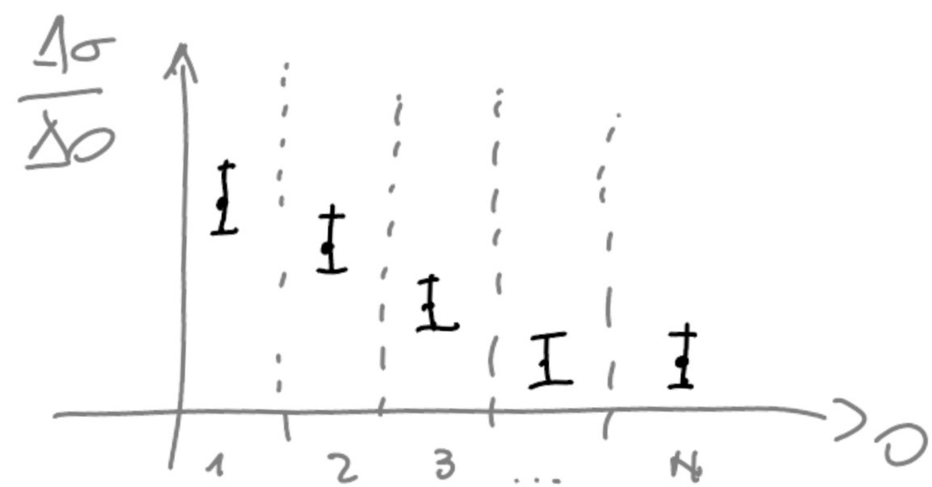
$$\Delta N(O_j) = \sum_i \left[\Delta\sigma(O_i^{*}) \cdot R_{ij} \cdot L\right] + \Delta Bkg(O_j)$$

Fiducial cross-section
Includes acceptance definition

Detector response matrix
Accounts for efficiency and resolution effects

$$\Delta\sigma_i = \Delta\sigma_i(\lambda_1, \lambda_2, \ldots, \lambda_N)$$

Theory degrees of freedom
Can be inferred from the fiducial cross sections



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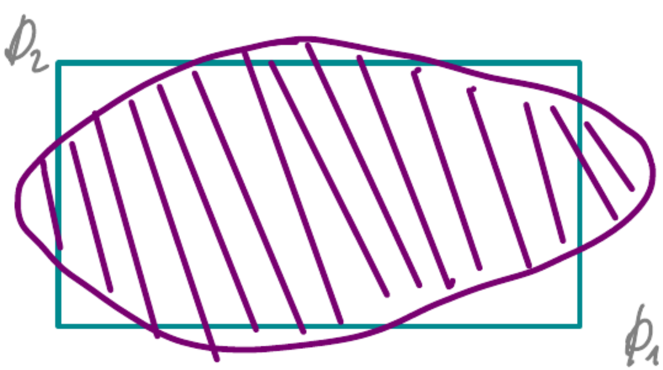

- Fiducial cross sections measured in well defined phase space.

Theory degrees of freedom

  - Detector level selection brought as close as possible to particle level.

(Fiducial) differential cross sections

Detector level observable

Particle level observable

$$\Delta N(O_j) = \sum_i \left[\Delta\sigma(O_i^{*}) \cdot R_{ij} \cdot L \right] + \Delta Bkg(O_j)$$

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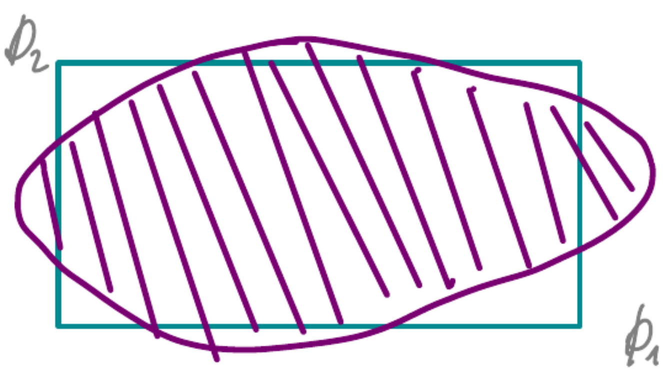


- Fiducial cross sections measured in well defined phase space.

Theory degrees of freedom

  - Detector level selection brought as close as possible to particle level.
  - Can tune selection to make measured cross sections as theory independent as possible.

$$\Delta\sigma^{SM} \sim \Delta\sigma(\lambda_{1,\ldots}, \lambda_N)$$

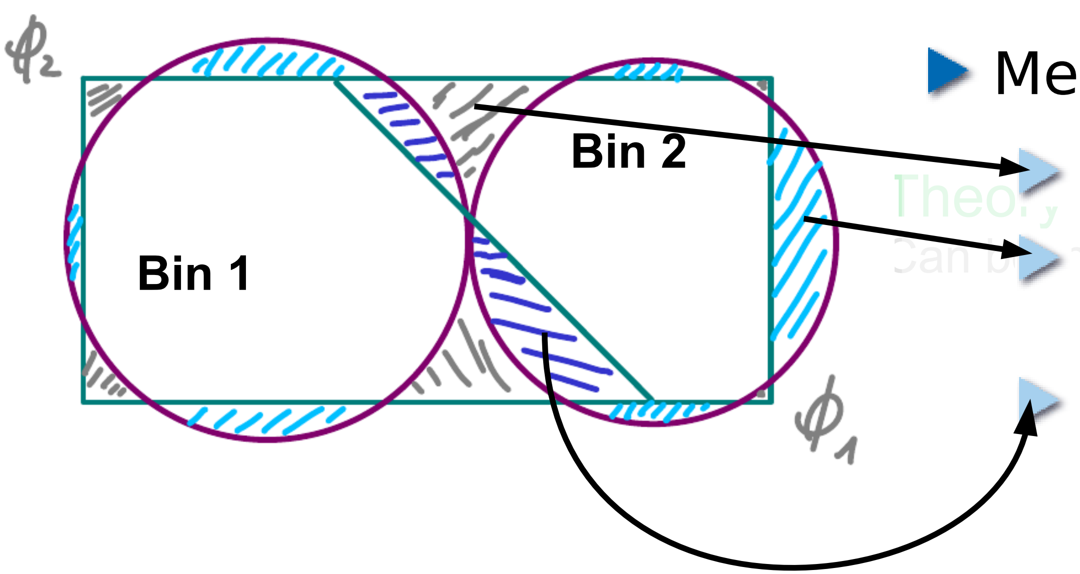
Detector level observable

Particle level observable

$$\Delta N(O_j) = \sum_i \left[\Delta\sigma(O_i^{*})\cdot R_{ij}\cdot L\right] + \Delta Bkg(O_j)$$

Fiducial cross-section
Includes acceptance definition

Detector response matrix
Accounts for efficiency and resolution effects



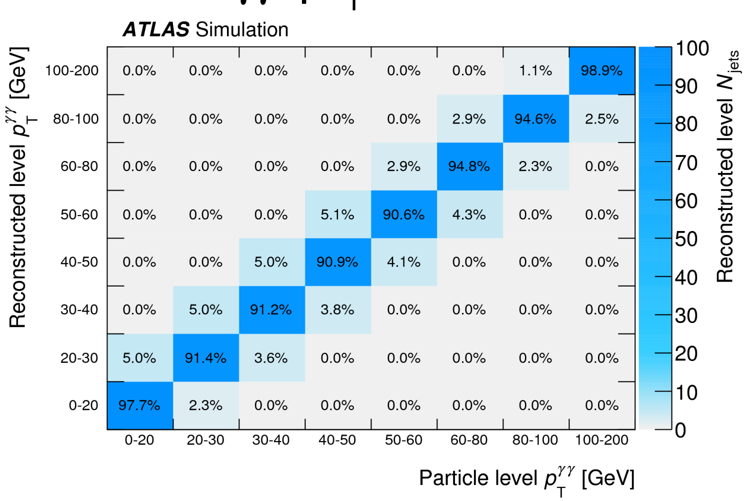
- Measurement ↔ response matrix.
  - **Efficiency**.
  - Contamination from **out-of-acceptance signal**.
  - Bin-to-bin **migration**.

Theory degrees of freedom

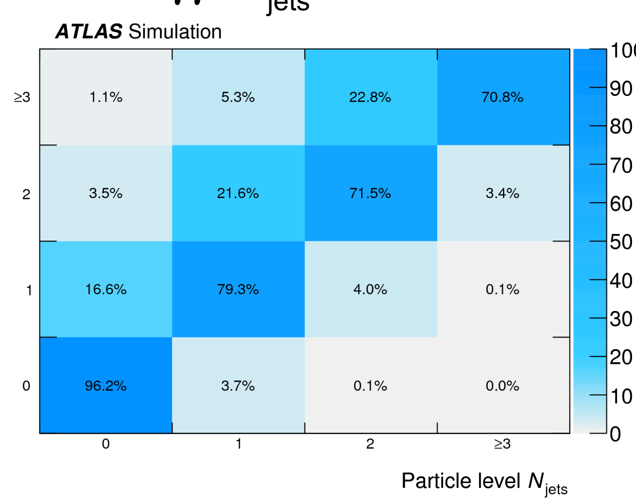
Example of detector response matrixes

- For variables involving only high resolution objects (i.e. leptons and photons) response matrixes are almost diagonal.
- If low-resolution quantities (e.g. jets and missing energies) large non diagonal terms are present.

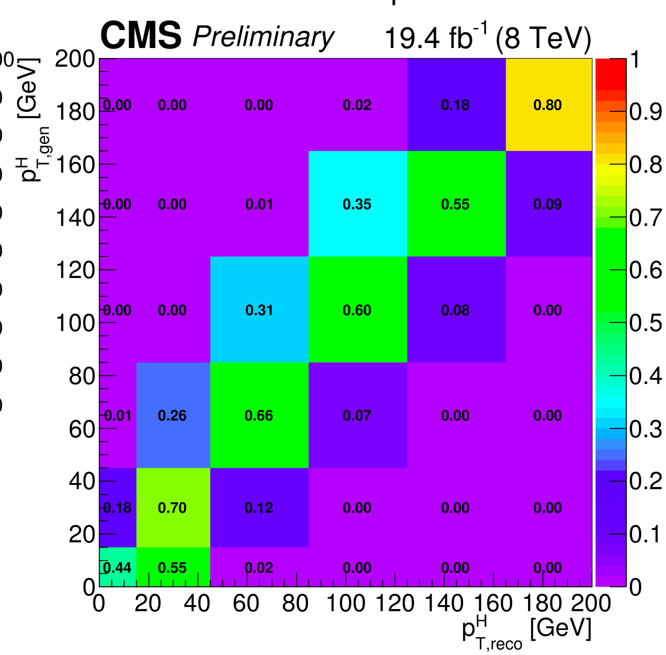
$H \rightarrow \gamma\gamma$: p^H_T



$H \rightarrow \gamma\gamma$: N_{jets}



$H \rightarrow WW$: p^H_T



Unfolding

- Techniques used to correct the measured cross sections to particle levels go under the name of unfolding.
  - Problem is not completely well defined as some assumptions on the underlying distributions are needed in the procedure.
- Several methods on the market.
  - Problem can be phrased in terms of minimizing the following quantity.

Measured event yields

$$\chi^2\left(\Delta\sigma(O_1^{*})\ldots\Delta\sigma(O_m^{*})\middle|\Delta\sigma(O_0)\right)=\sum_{j=1}^{m}\frac{\left(\sum_{i=0}^{m}L\,R_{ij}\,\Delta\sigma(O_i^{*})-\Delta N(O_j)\right)^2}{\sigma_j^2}+ \\ +\tau\sum_{i=1}^{m}\sum_{j=1}^{m}\Delta\sigma(O_i^{*})\,K_{ij}\,\Delta\sigma(O_j^{*})$$

Out-of-acceptance signal.
Not measurable from data.

Regularization term.
Dumps fluctuations in measured cross sections, at the biasing the measurement.

Unfolding (2)

- Different choices taken by different analyses.
  - ATLAS H → γγ and H → ZZ: bin-by-bin correction.
    Known to be pathological for very non diagonal response matrixes.

$$R_{ij} \rightarrow c_{ij} = \delta_{ij} \cdot \sum_k R_{ik} \Delta\sigma_{MC}(O_k^*)$$
$$\tau = 0$$

  - CMS H → γγ and H → ZZ: un-regularized unfolding using likelihood function instead of χ^2.
    Unbiased result, regularization can be applied a-posteriori.

$$\chi^2(\Delta\sigma) \rightarrow -2\log L(\Delta\sigma)$$
$$\tau = 0$$

  - CMS H → WW: regularized SVD unfolding.
    Regularization term needed due to large non diagonal elements in response matrix.

- **Simple** final state, kinematics can be measured with **high resolution**.
  - Good precision can be achieved.
- Fiducial phase space definition very similar between ATLAS and CMS.

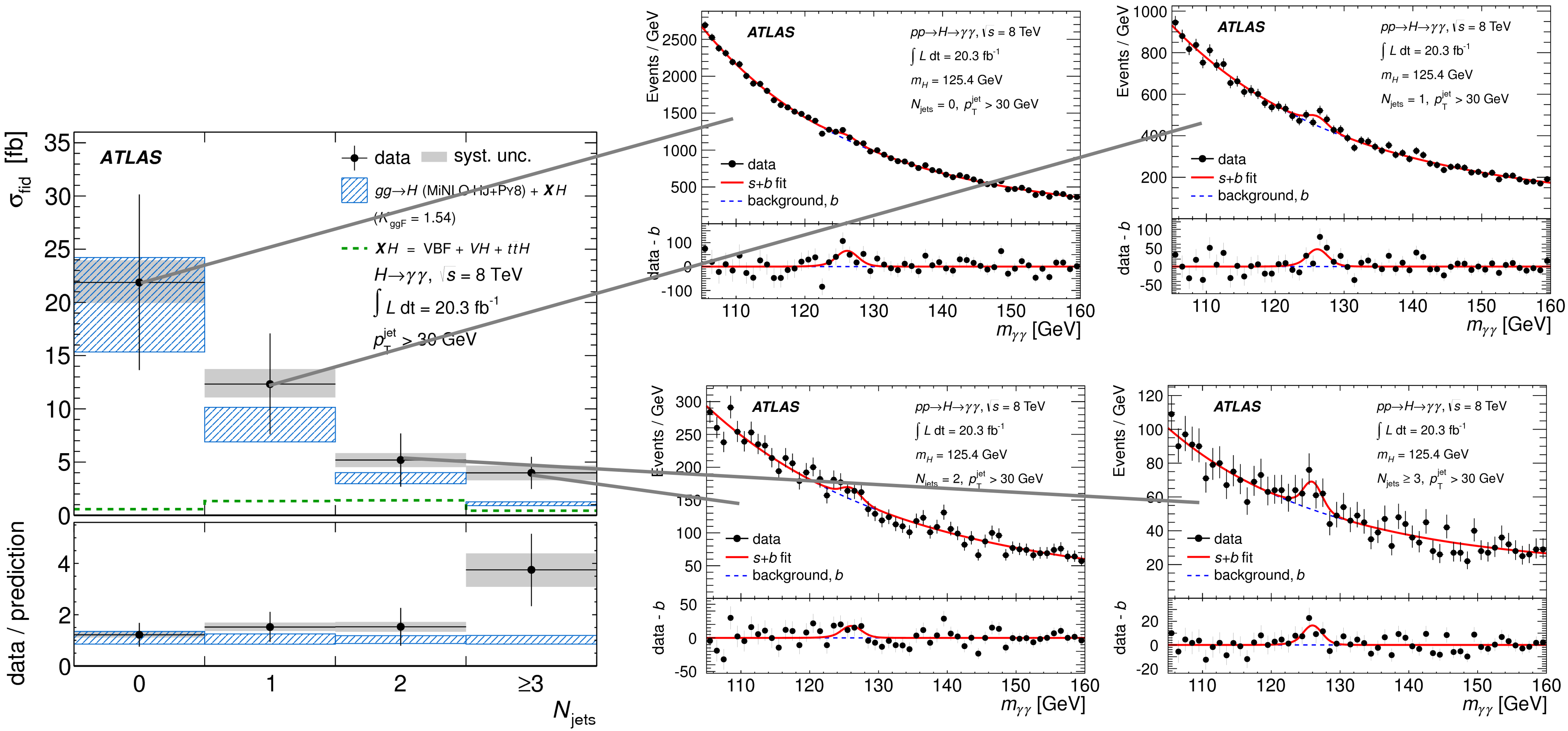
	ATLAS	CMS
$\|\eta\|$	<2.37	<2.5
p_T^1/m	<0.35	<1/3
p_T^2/m	<0.25	<1/4
$\Sigma_{\Delta R<0.3} E^{had}_T$	14GeV	10GeV

In the case of CMS, events are categorized according to resolution.

- Measured **many observables** at $\sqrt{s}$=8TeV.
  - Diphoton kinematics as well as to additional activity.
- **Systematic** uncertainties **negligible** wrt statistical ones.
  - It will still be the case in Run 2.

H → γγ: signal extraction

- Signal extracted from **fit** to the diphoton **invariant mass** spectrum.
  - Different unfolding techniques used by CMS and ATLAS.



$H \rightarrow \gamma\gamma$: Fiducial cross sections

- Fiducial cross sections measured with an **uncertainty** of roughly **1/3 of the SM prediction**.
  - Uncertainties are 10-15% larger than those on the (8TeV) signal strengths.

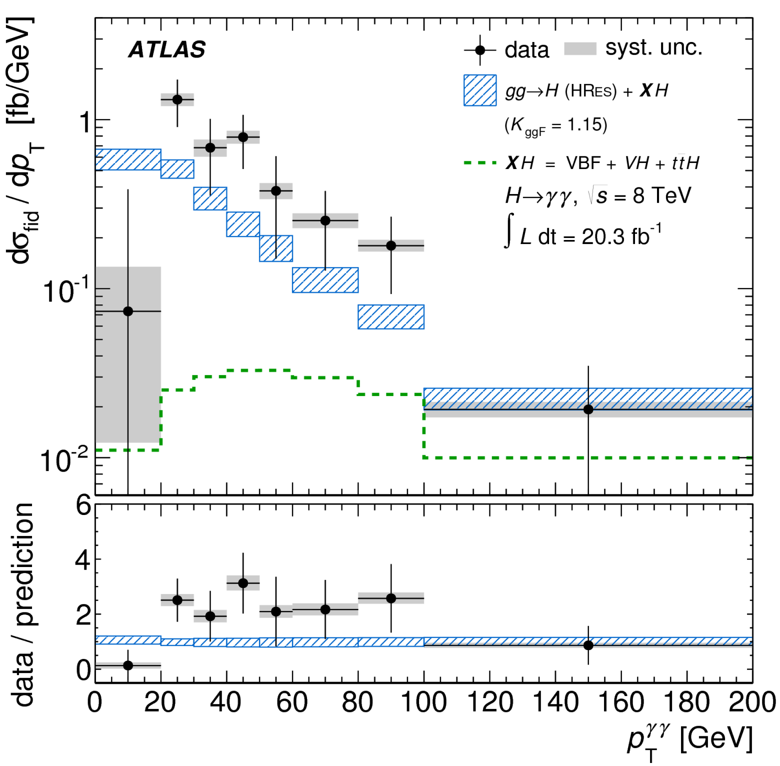
$\sigma_{fid}(pp \rightarrow H \rightarrow \gamma\gamma)$ [fb]	Data	Theory (LHCHXSWG+ HRes,POWHEG,PYTHIA)
ATLAS (8TeV)	43.2 +- 9.4(stat) $^{+3.2}_{-2.9}$(syst) +- 1.2(lumi)	30.5 +- 3.3
CMS (8TeV)	32 +- 10(stat) +- 3(syst)	31^{+3}_{-4}

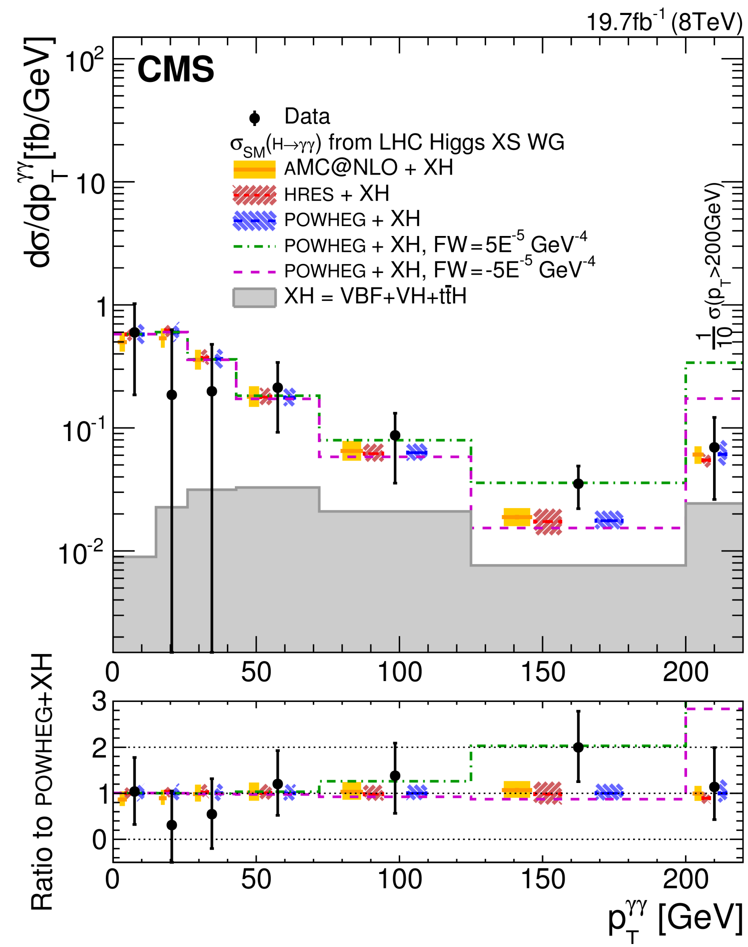
  - Measurements well in agreement with SM predictions.

$H \to \gamma\gamma$: Measured p_T spectra

- Uncertainties on single bins scale as total uncertainties.
  - ATLAS: 8 bins → unc. on average ∼85% of SM prediction.
  - CMS: 6bins (plus overflow) → unc. ∼75% of SM prediction.
- Spectra in agreement with SM expectations.

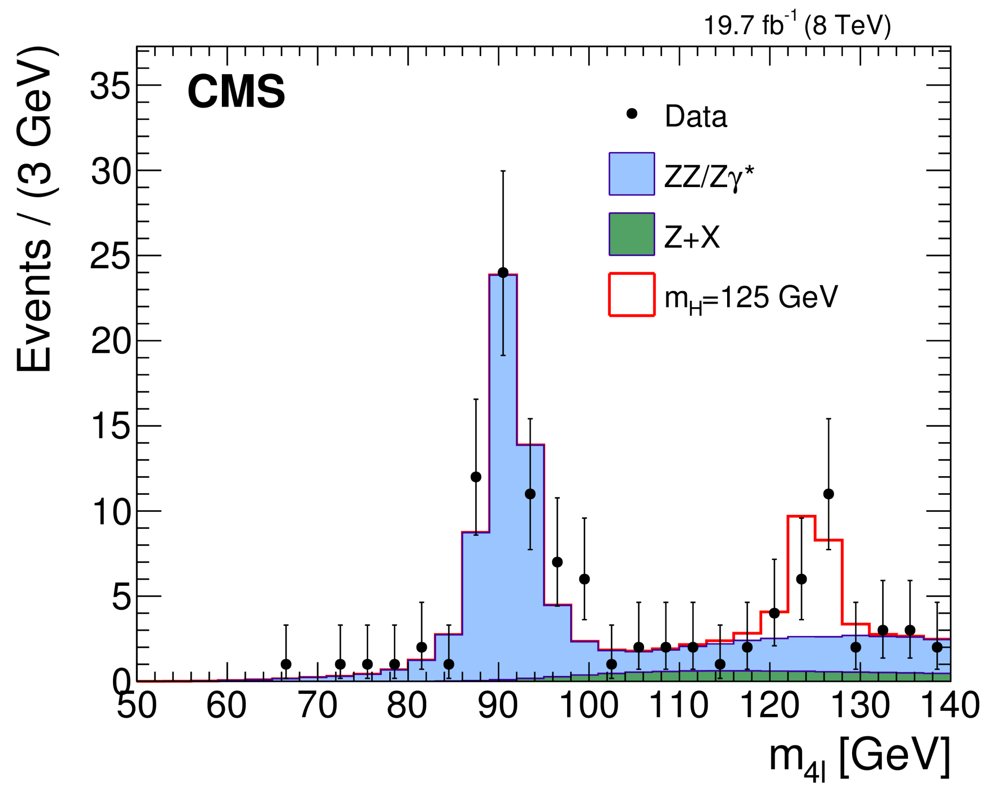
ATLAS p(χ2) ∼ 0.10





$H \rightarrow ZZ(4l)$

- Extremely **clean** final state.
  - Low event yield.
  - Very low background.
- Definition of fiducial phase space more complicated than $H \rightarrow \gamma\gamma$ (see next slide).



- Signal extraction:
  - ATLAS: Event counting in m4l window (after background substraction)
  - CMS: S+B fit to m_{4l}.
- Worse precision than $H \rightarrow \gamma\gamma$.
  - **Many observables** measured, but using **wider binning**.

$H \to 4l$: fiducial phase space definition

- Similar definitions for both experiments.
  - In the case of CMS, lepton isolation required as part of phase space definition. Minimizes model dependence.
  - Leptons taken before FSR in both cases. ATLAS checked that differences wrt dressed leptons are negligible.

CMS

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7$ (5) GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 p_T$
Event topology	
Existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m(Z_1) < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m(Z_2) < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$
Inv. mass of any opposite-sign lepton pair	$m(\ell_i^+ \ell_j^-) > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

ATLAS

Lepton selection	
Muons:	$p_T > 6$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.47$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV, $12 < m_{34} < 115$ 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:	$118 < m_{4\ell} < 129$ GeV

$H \rightarrow 4l$: Fiducial cross sections

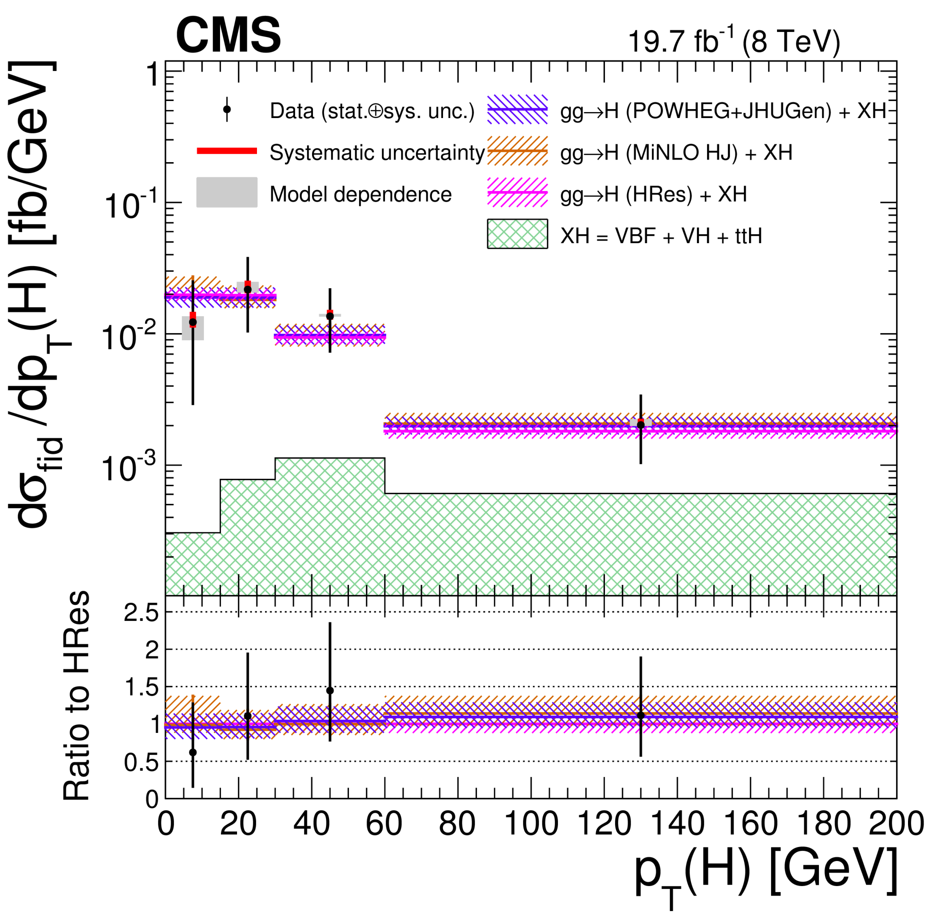
- Fiducial cross sections measured with an **uncertainty** of roughly **35-40% of the SM prediction**.

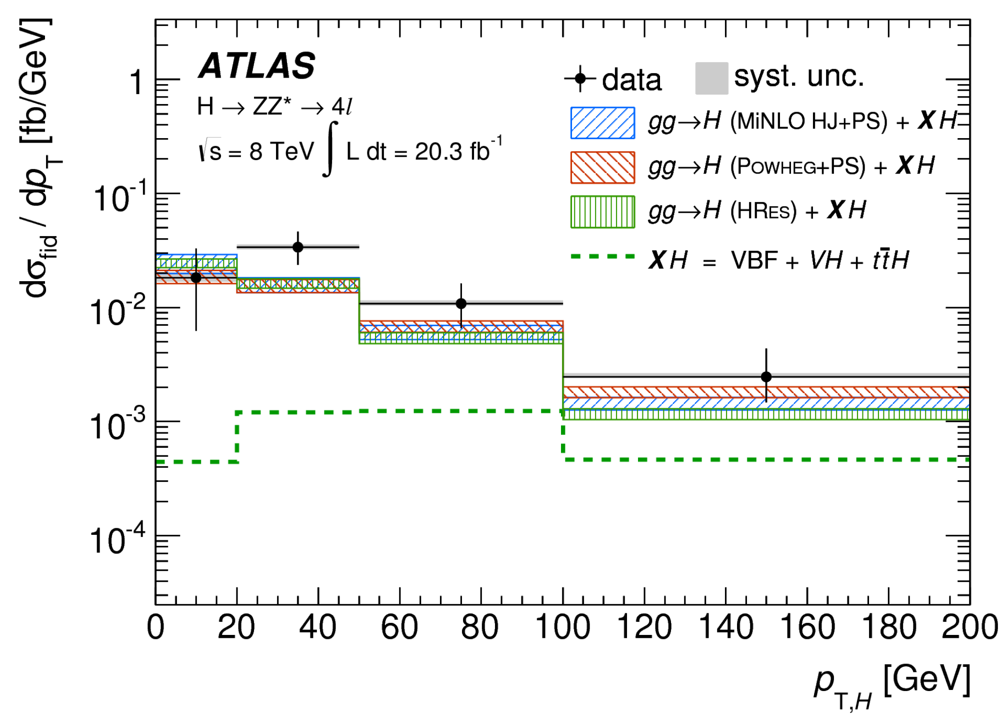
$\sigma_{fid}(pp \rightarrow H \rightarrow 4l)$ [fb]	Data	Theory (LHCHXSWG+ HRes,POWHEG,PYTHIA)
ATLAS (8TeV)	$2.11\ ^{+0.53}_{-0.47}$(stat) +- 0.08(syst)	1.3 +- 0.13
CMS (8TeV)	$1.11\ ^{+0.41}_{-0.35}$(stat) $^{+0.14}_{-0.10}$(syst)	1.15 +- 0.12
CMS (7TeV)	$0.54\ ^{+0.67}_{-0.44}$(stat) $^{+0.21}_{-0.06}$(syst)	0.93 +- 0.10

- Measurements in agreement with SM predictions.

H → 4l: Measured p_T spectra

- Only four bins measured.
  - No significant deviations observed.





$H \rightarrow WW\ (2l2\nu)$

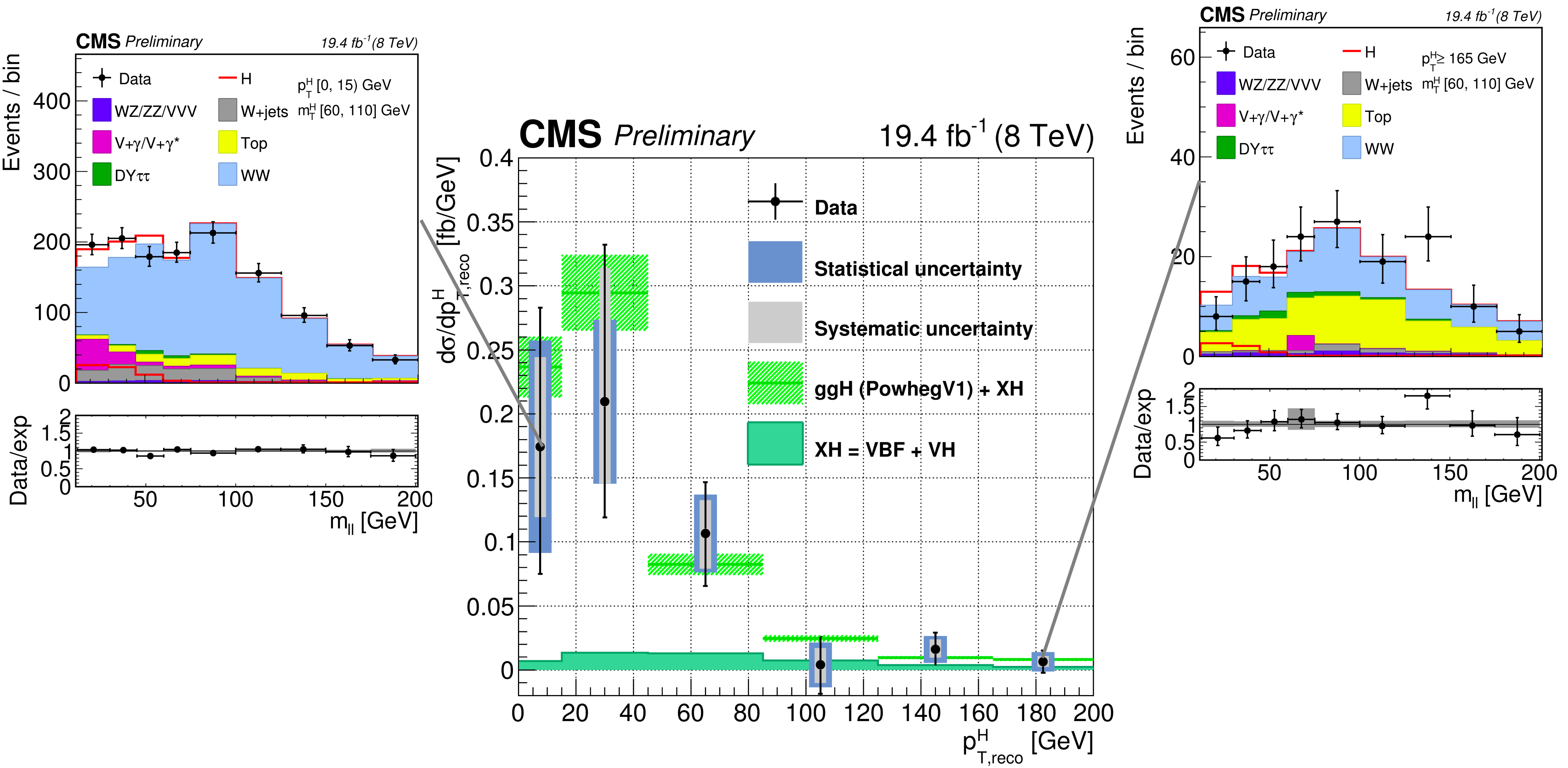
- Analysis limited to the measurement of the Higgs candidate p_T and of the fiducial cross section.
  - Significant re-optimization of the analysis compared to the search.
    - Replace jet veto with a much looser b-jet veto.
    - Loosened selection cuts to reduce gap between reconstruction and generation level.
  - Fiducial phase space defined as:

Kinematic requirements for the $H \rightarrow W^+W^-$ fiducial phase space	
Leading lepton p_T	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 10$ GeV
Pseudorapidity of electrons and muons	$\|\eta\| < 2.5$
Invariant mass of the two leptons	$m_{\ell\ell} > 12$ GeV
Transverse momentum of the lepton pair	$p_T^{\ell\ell} > 30$ GeV
Invariant mass of the leptonic system in the transverse plane	$m_T^{\ell\ell E_T^{miss}} > 50$ GeV
No E_T^{miss} cut applied	

  - Higgs candidate p_T reconstructed as: $\vec{p}_T^{\,H} = \vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}$
  - Use of missing energy has large impact on resolution.
    - Measurement crucially depends on unfolding (and regularization).
  - Systematic uncertainties are comparable to statistical uncertainties.

H → WW (2l2ν)

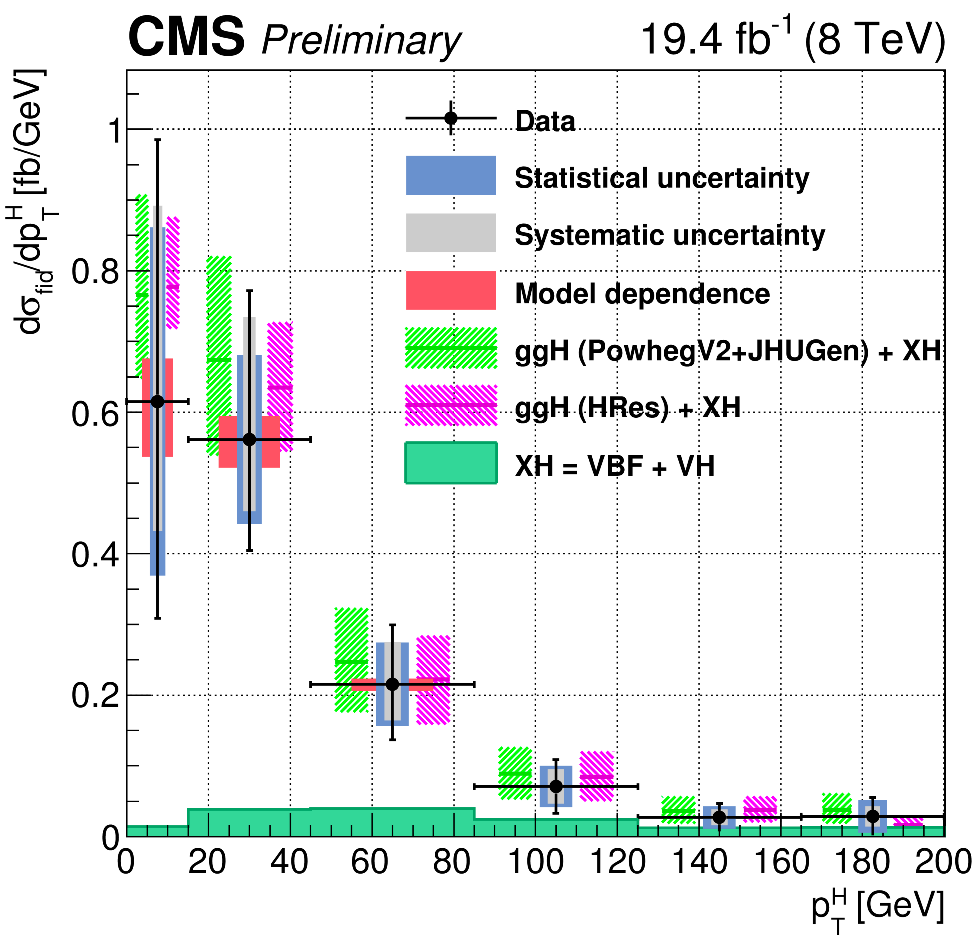
- Signal extracted from template fit in 2D (m^{ll},$m_T^{ll,MET}$).
  - Background shapes obtained from MC
  - Normalizations constrained using data.



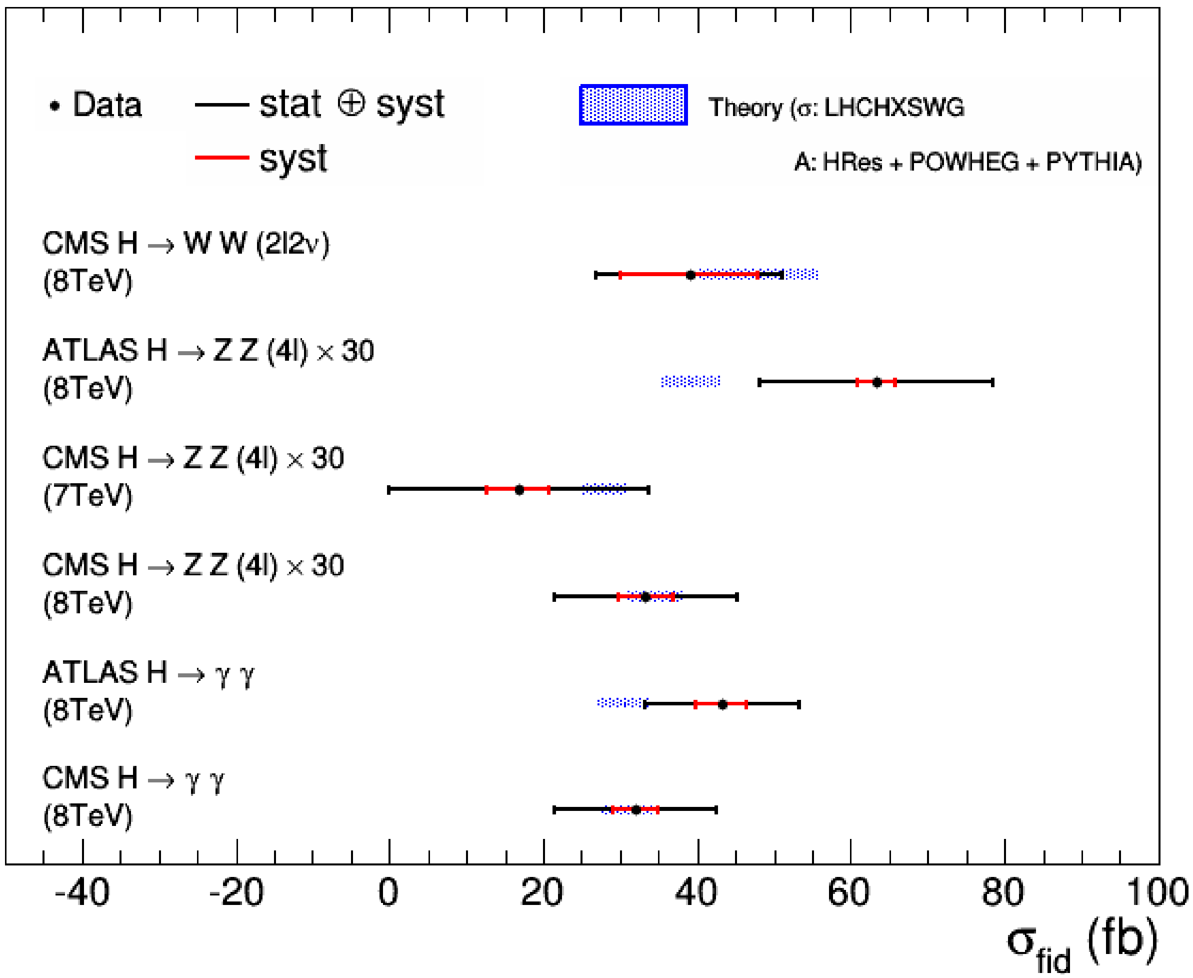
- Fiducial cross section.
  - **Uncertainty ~25% of SM prediction**. Systematic uncertainty of the same order of the statistical one.

Data	Theory (LHCHXSWG+POWHEG,PYTHIA)
39 +- 8(stat) +- 9(syst) fb	48 +- 8 fb

- Measured p_T spectrum in agreement with expectations.
  - Note: large bin-to-bin correlations.

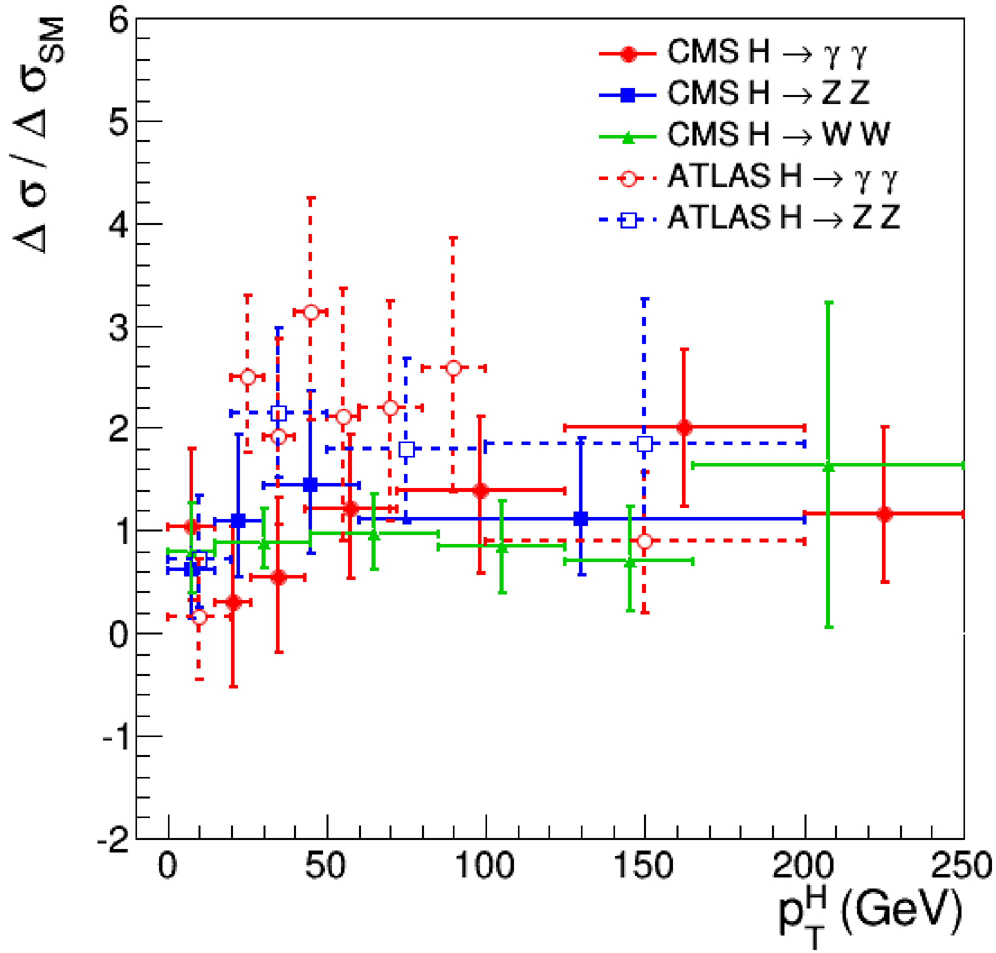


Fiiducial cross sections: summary



p_T spectrum: summary

- To compare all the available measurement, divide measured cross sections by common reference.
  - This is very close to a differential signal strength.
- Taking into account all measurements and using 6-7 bins could constrain shape to ~35%.
  - By the end of Run 2 expect to have measurement at the level of 10%.



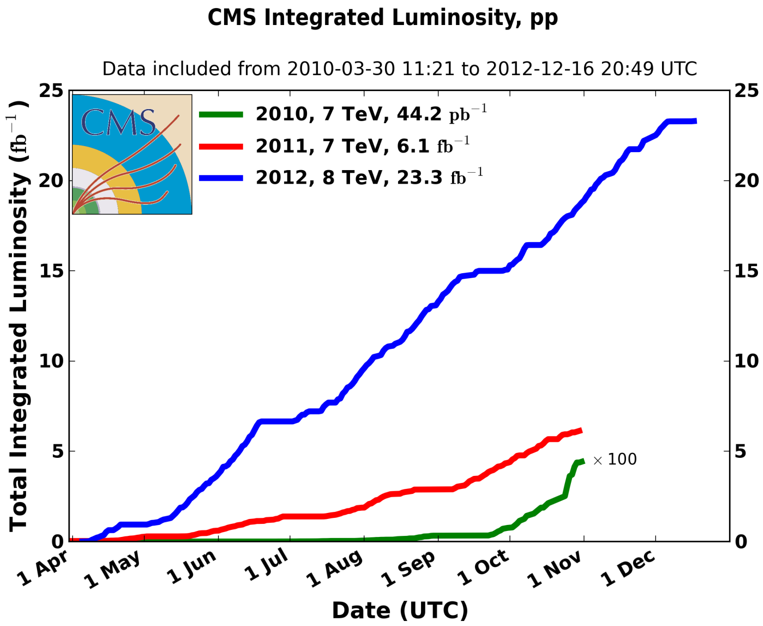
Summary

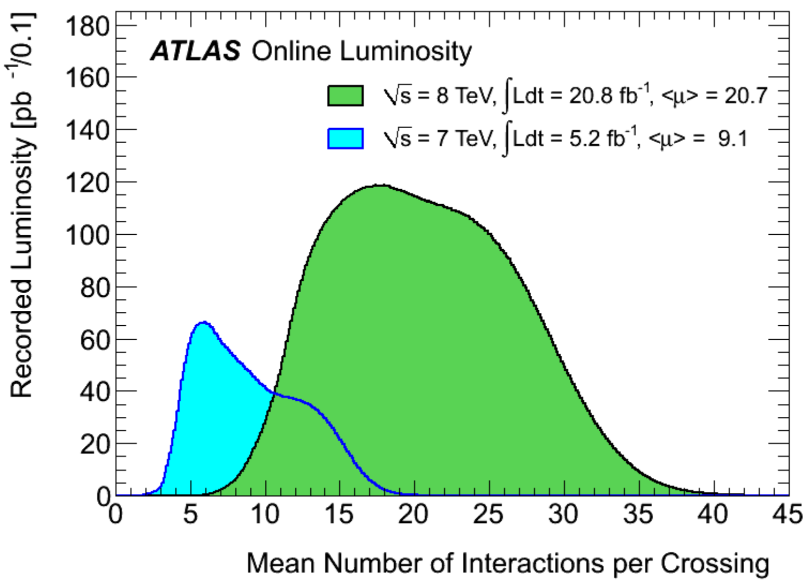
- Measuring fiducial and differential cross sections for Higgs production is of great importance.
  - Test Standard Model predictions in well defined phase space.
  - Ensure long term usability of LHC data.
- First measurement of fiducial cross sections performed by CMS and ATLAS using LHC Run 1 data.
  - Using bosonic decay channels.
  - Measurements are in most cases statistically-limited.
  - No significant deviations from expectations observed so far.
- Importance of such measurements will grow as the LHC delivers more data in Run 2.

Additional material

LHC Run 1 dataset

- Excellent performance of the LHC machine throughout the Run 1.
- Also excellent performance of the CMS and ATLAS detectors
  - ~90% of the delivered data available for offline analysis.
- Available dataset:
  - ~5fb^{-1} $\sqrt{s}$=7TeV + ~20fb^{-1} $\sqrt{s}$=8TeV
- Challenging pile-up conditions.
  - Up to 30 average interactions per bunch-crossing.
  - Ingenious ideas needed to keep detector performances.





Signal strenghts

"Per-category signal strength"

Measured

$$N^{cat} = \mu^{cat} \cdot \sum_{p,d} \left[\left(\varepsilon \cdot A^{SM} \right)^{cat}_{pd} \cdot \sigma^{SM}_{p} \cdot BR^{SM}_{d} \cdot L \right] + Bkg^{cat}$$

Theory prediction

$$\mu^{cat} = \mu^{cat}\left(\lambda_{1}, \lambda_{2}, \ldots, \lambda_{N} \right)$$

Theory degrees of freedom

Statistical model

Inference

$$q(\mu) = -\ln \left[\frac{\mathcal{L}(data|\mu;\hat{\theta}_{\mu})}{\mathcal{L}(data|\hat{\mu};\hat{\theta})} \right]$$

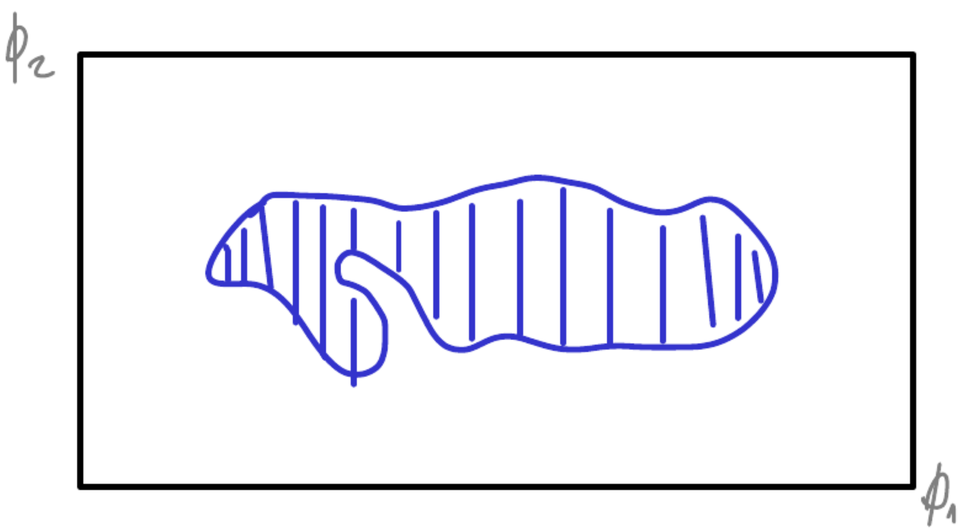
Signal strenghts – limitations

"Per-category signal strength"

Measured

$$N^{cat} = \mu^{cat} \cdot \sum_{p,d} \left[\left(\varepsilon \cdot A^{SM} \right)^{cat}_{pd} \cdot \sigma^{SM}_{p} \cdot BR^{SM}_{d} \cdot L \right] + Bkg^{cat}$$

Theory prediction



- Acceptance can have complicated shape.
  - Meaning of the signal strength not immediate.
  - Relies on state-of-the-art theoretical predictions.

Statistical model

$$q(\mu) = -\ln \left[\frac{\mathcal{L}(data|\mu;\hat{\theta}_{\mu})}{\mathcal{L}(data|\hat{\mu};\hat{\theta})} \right]$$

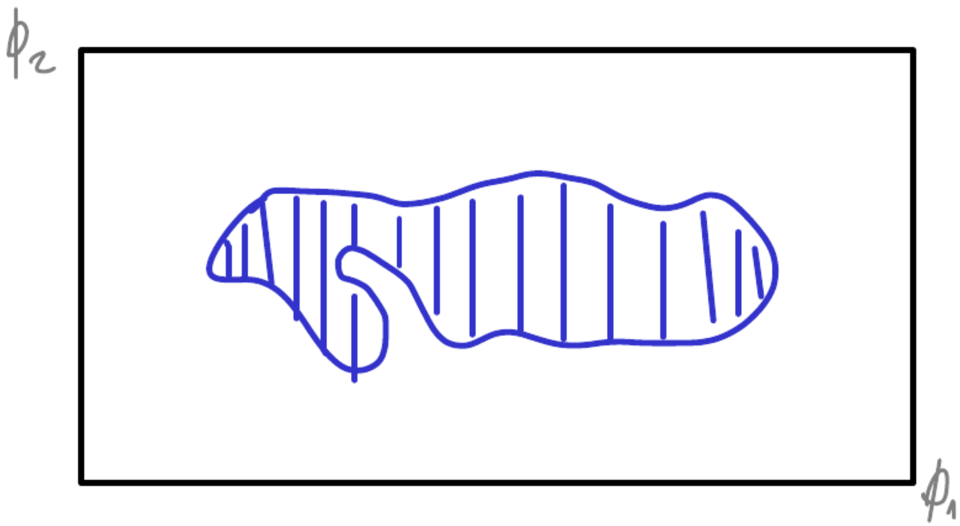
Signal strenghts – limitations

"Per-category signal strength"

Measured

$$N^{cat} = \mu^{cat} \cdot \sum_{p,d} \left[\left(\varepsilon \cdot A^{SM} \right)^{cat}_{pd} \cdot \sigma^{SM}_{p} \cdot BR^{SM}_{d} \cdot L \right] + Bkg^{cat}$$

Theory prediction



- Kinematics can be modified by BSM interactions.

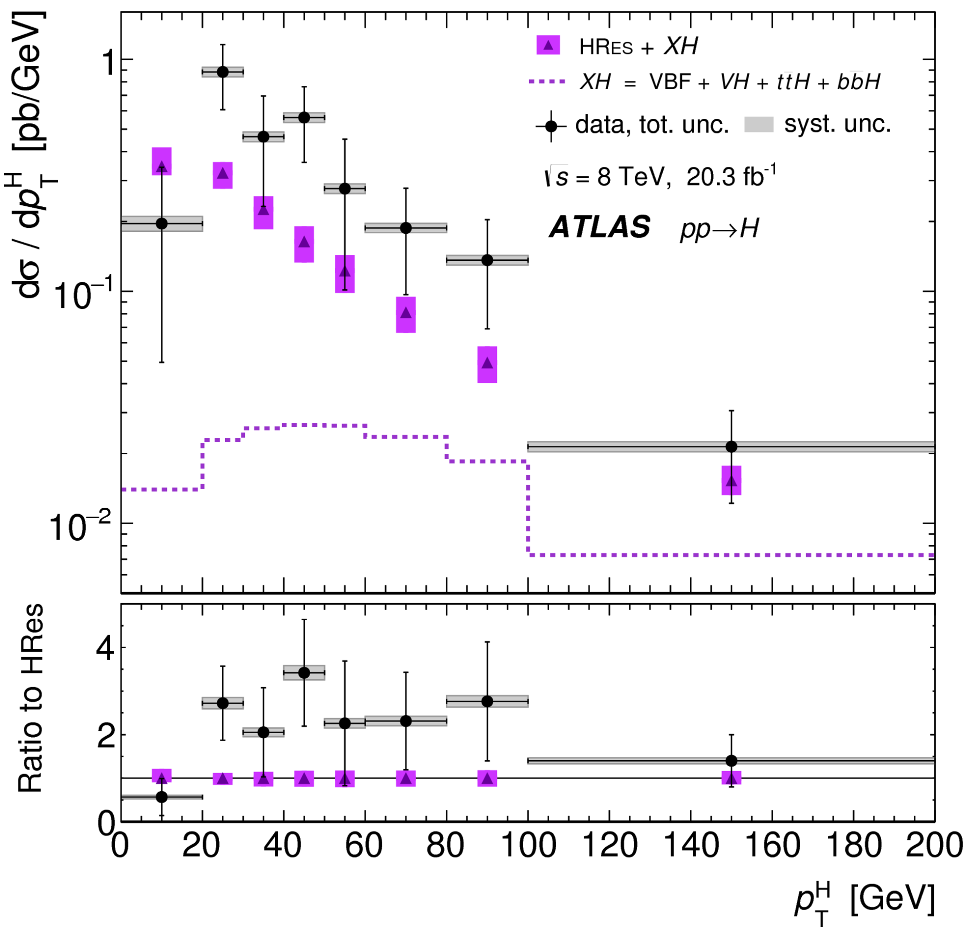
$$A^{SM} \neq A\left(\lambda_{1,\dots},\lambda_{N}\right)$$

y degrees of freedom

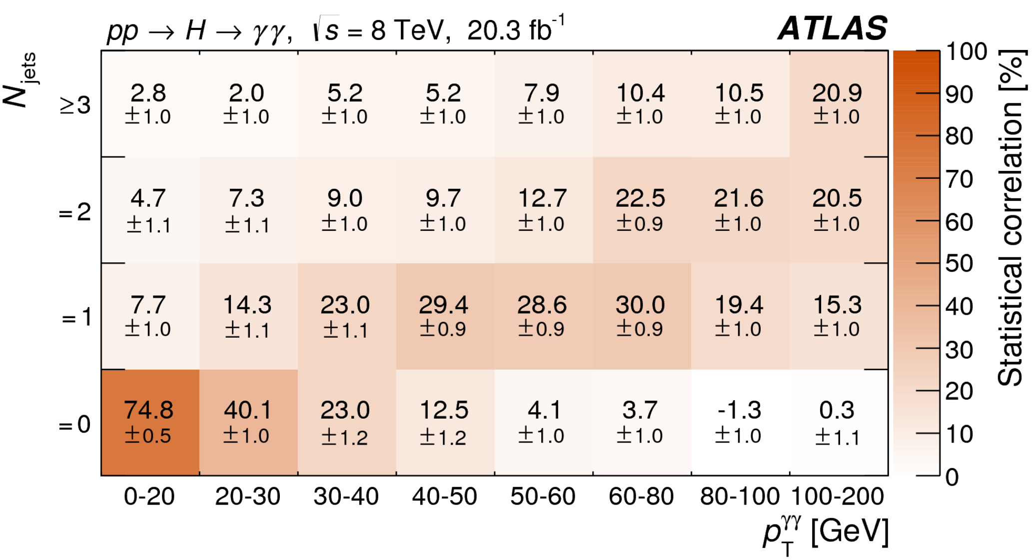
Statistical model

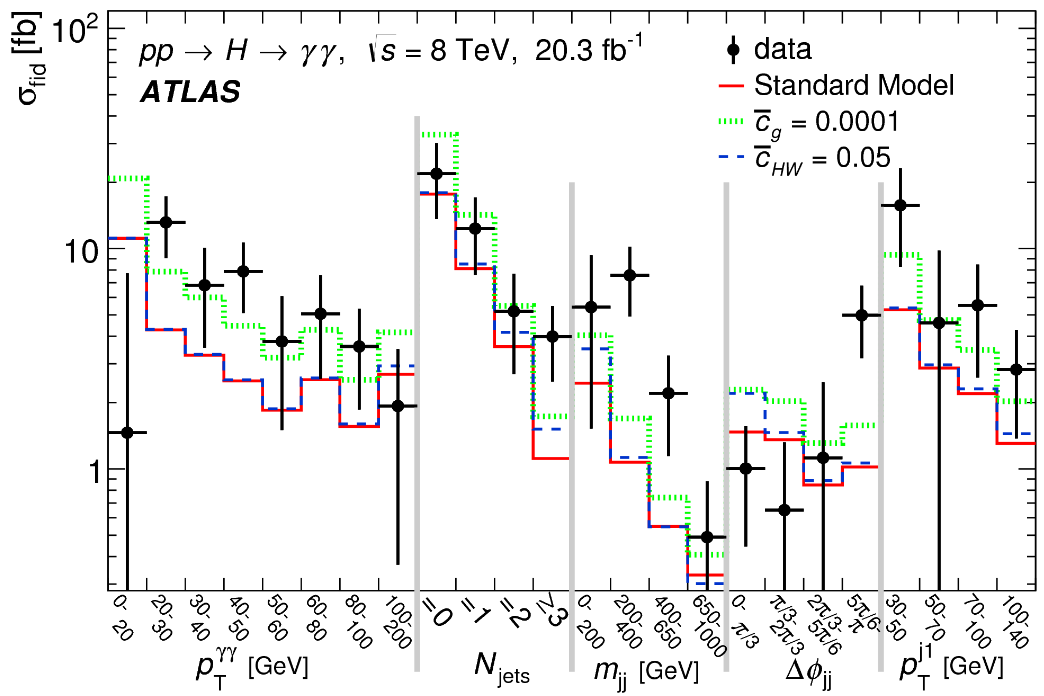
$$q(\mu) = -\ln\left[\frac{\mathcal{L}(data|\mu;\hat{\theta}_{\mu})}{\mathcal{L}(data|\hat{\mu};\hat{\theta})}\right]$$

ATLAS: combined p_T spectrum

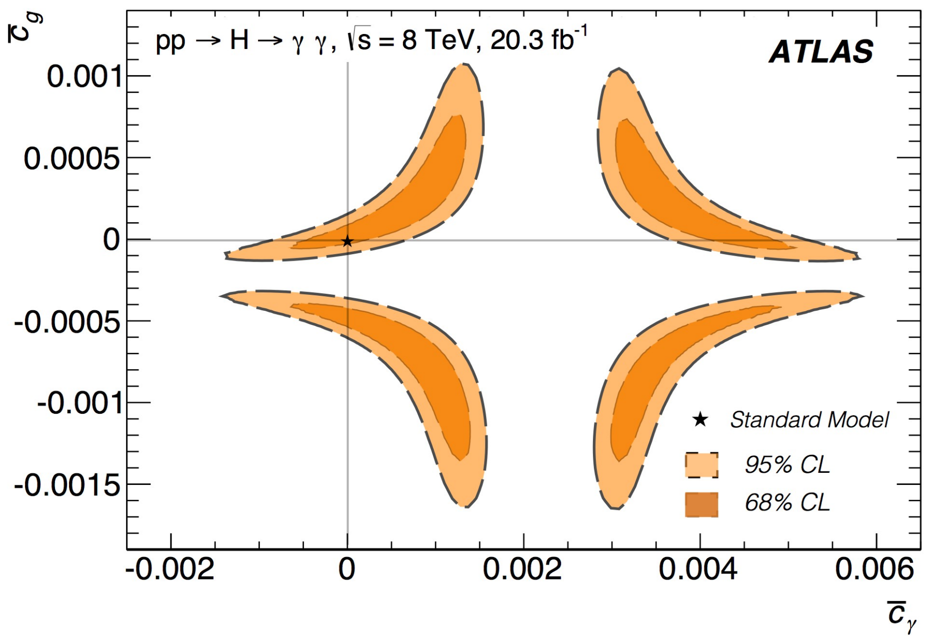


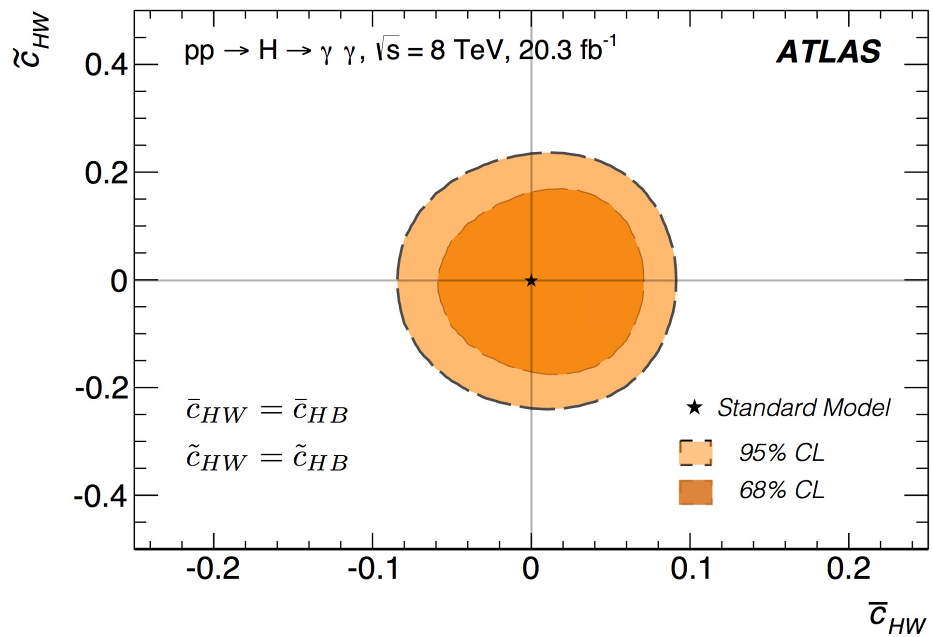
ATLAS: constraints on EFT using differential cross sections.



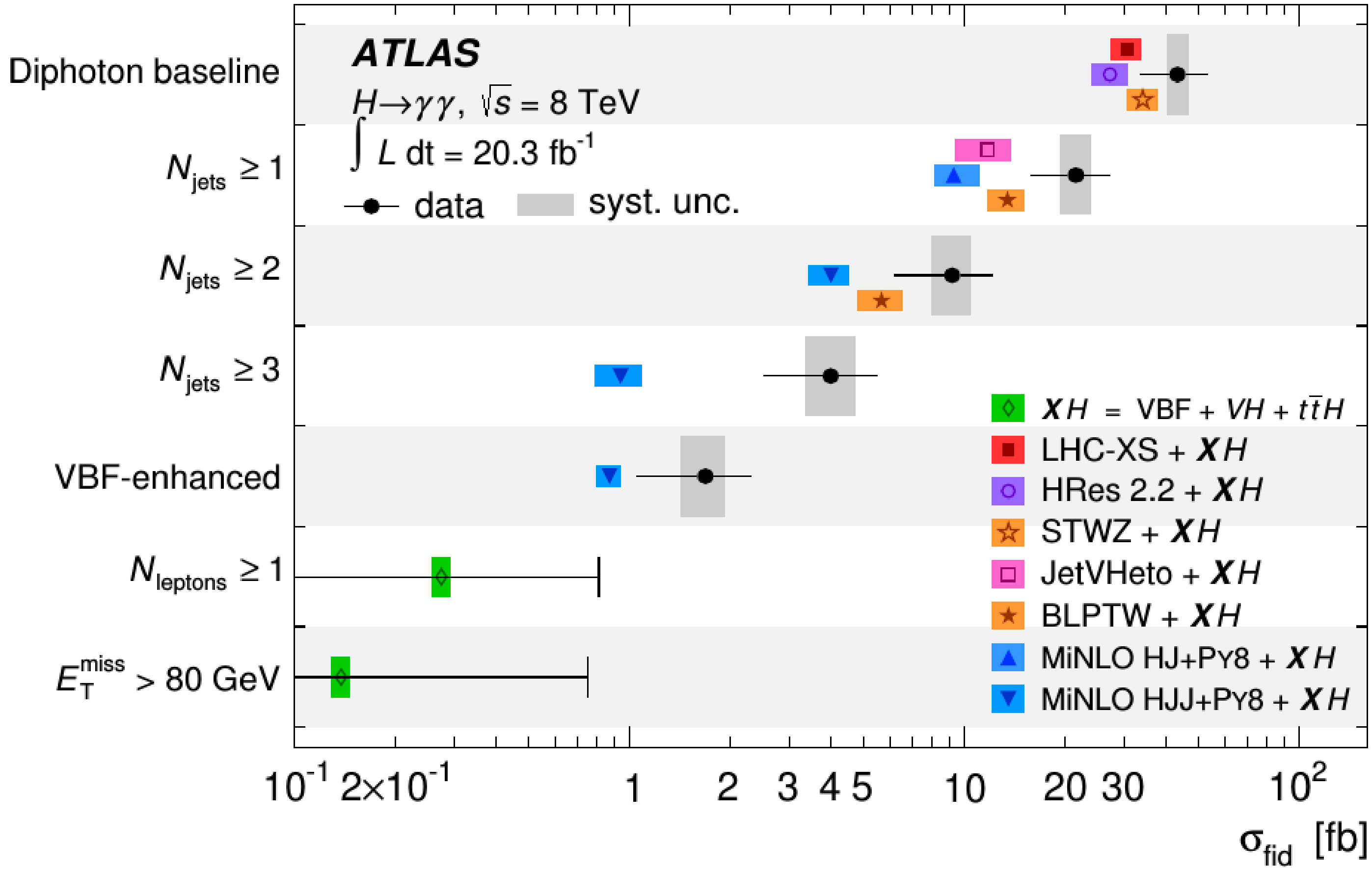


ATLAS: constraints on EFT using differential cross sections.

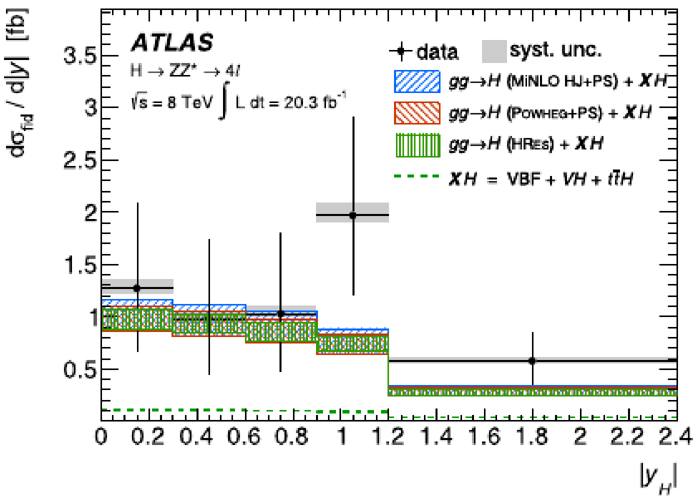


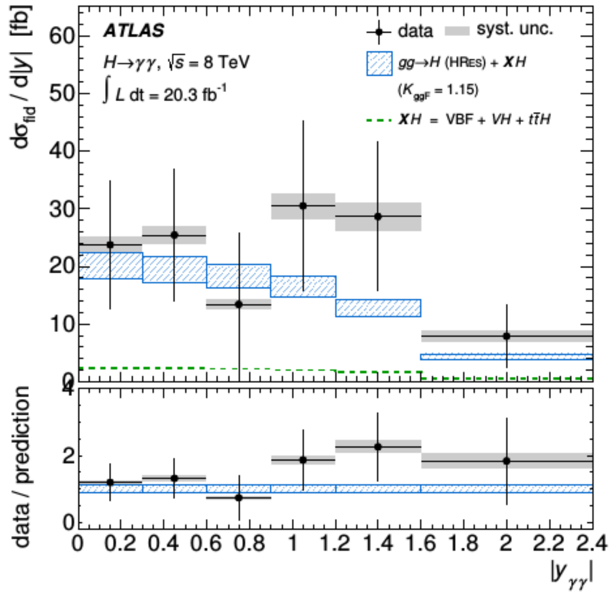


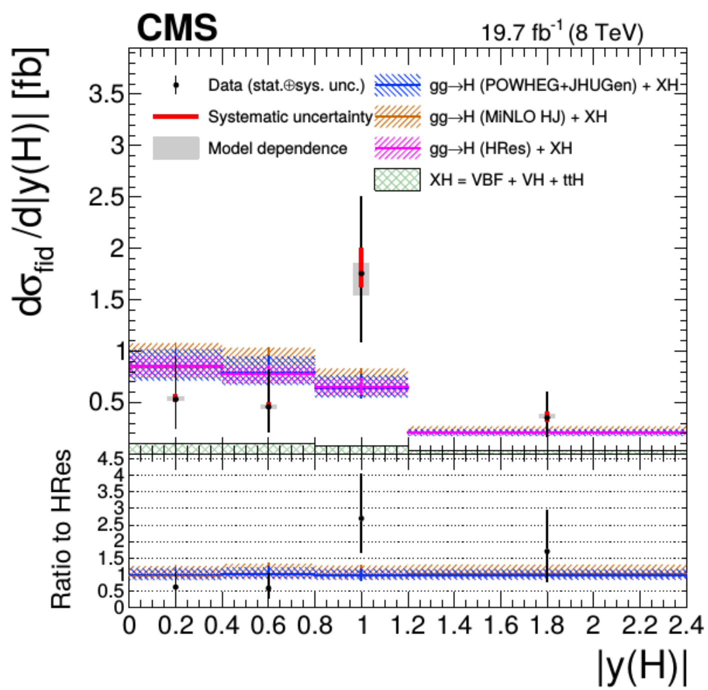
ATLAS: more H → fiducial cross sections

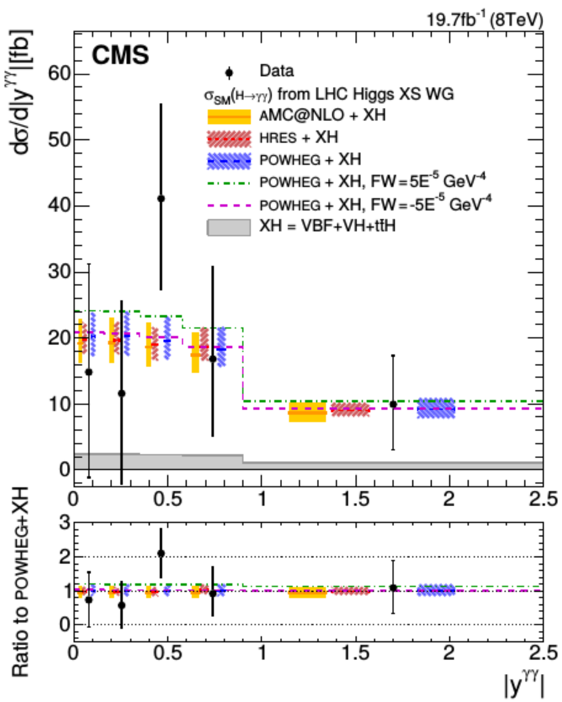


Higgs rapidity distribution

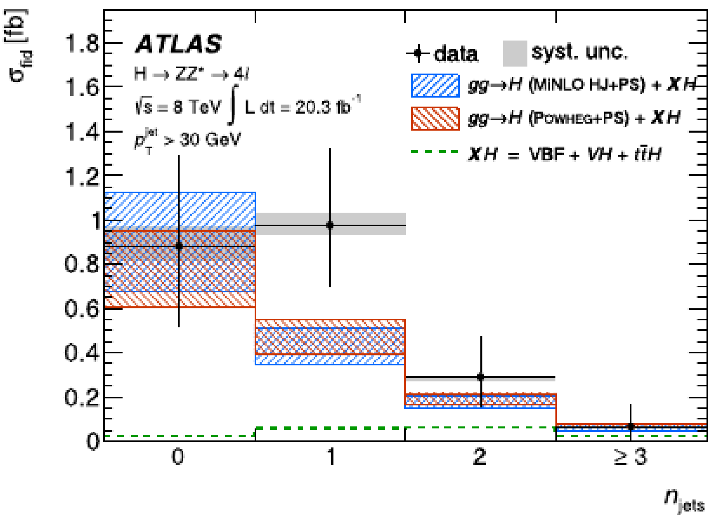




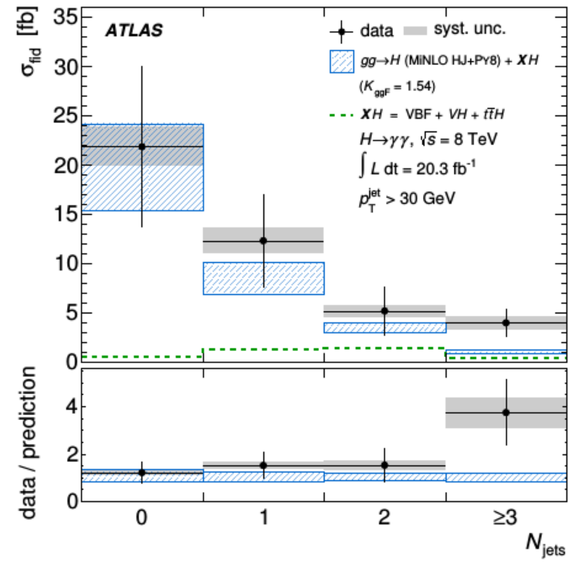




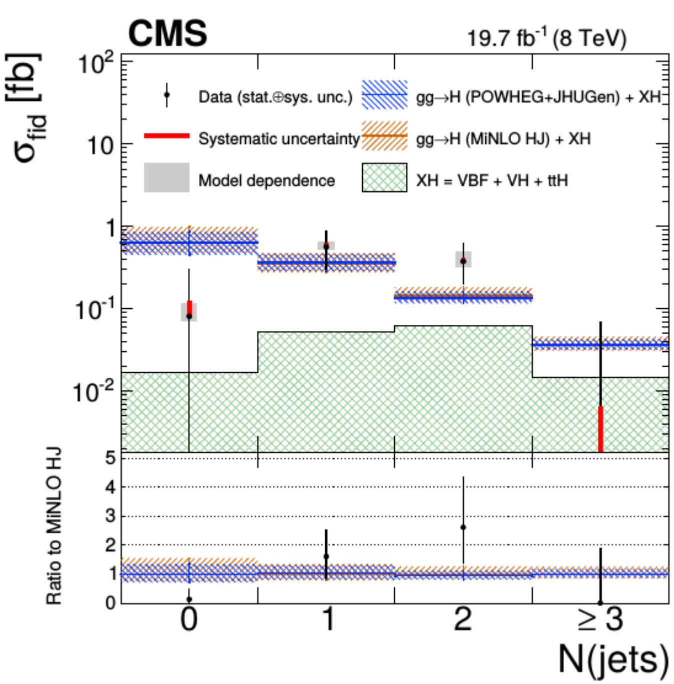
Njets



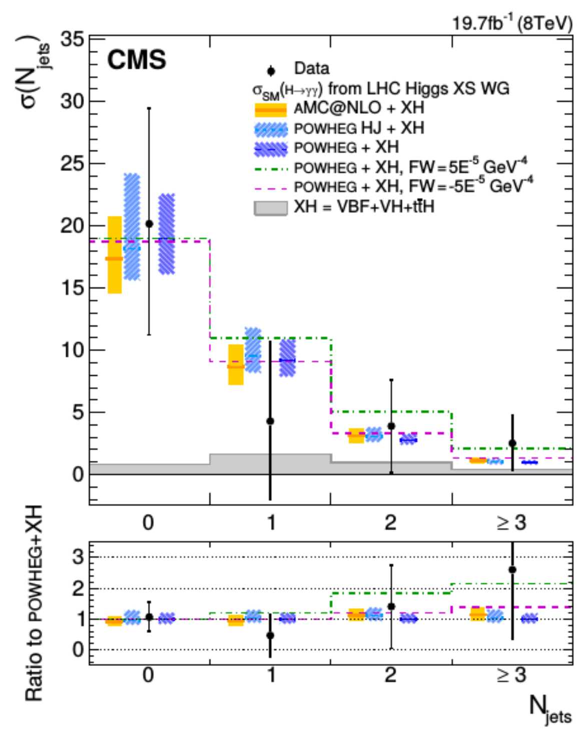
ATLAS
H → ZZ* → 4l
√s = 8 TeV ∫ L dt = 20.3 fb⁻¹
p_T^jet > 30 GeV
data
syst. unc.
gg→H (MiNLO HJ+PS) + XH
gg→H (POWHEG+PS) + XH
XH = VBF + VH + tt̄H
σ_fid [fb]
n_jets
0
1
2
≥ 3



ATLAS
data
syst. unc.
gg→H (MiNLO HJ+Py8) + XH
(K_ggF = 1.54)
XH = VBF + VH + tt̄H
H→γγ, √s = 8 TeV
∫ L dt = 20.3 fb⁻¹
p_T^jet > 30 GeV
σ_fid [fb]
data / prediction
N_jets
0
1
2
≥3

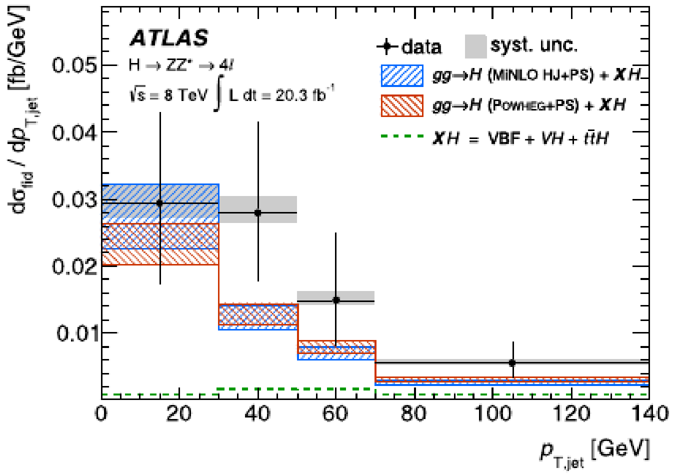


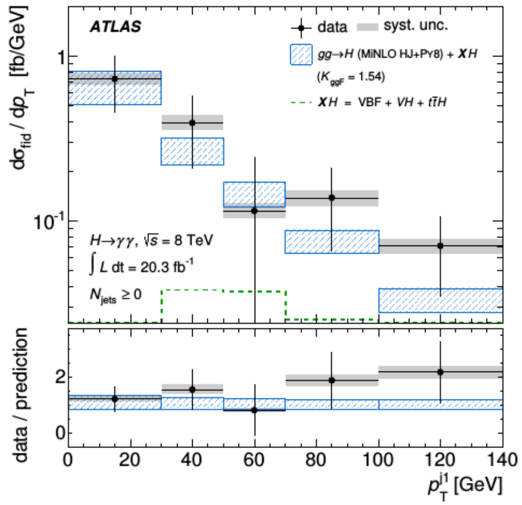
CMS
19.7 fb⁻¹ (8 TeV)
Data (stat.⊕sys. unc.)
gg→H (POWHEG+JHUGen) + XH
Systematic uncertainty
gg→H (MiNLO HJ) + XH
Model dependence
XH = VBF + VH + ttH
σ_fid [fb]
Ratio to MiNLO HJ
N(jets)
0
1
2
≥ 3

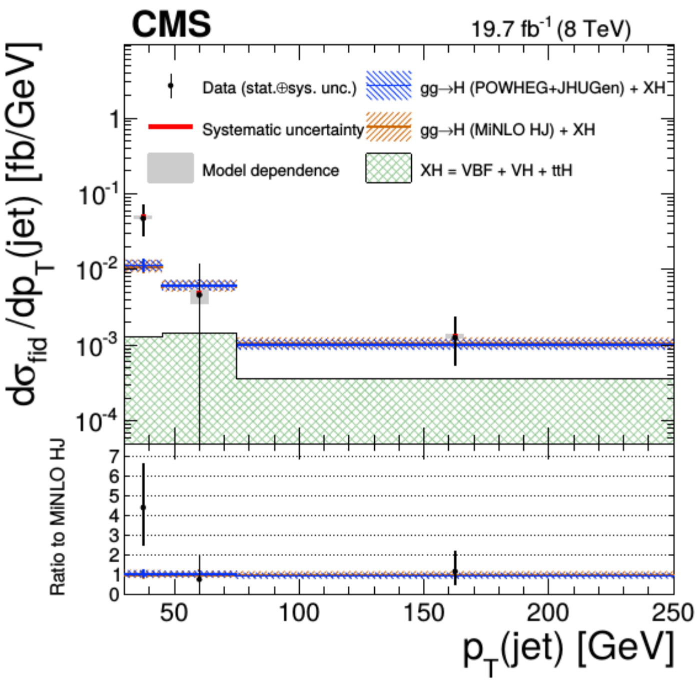


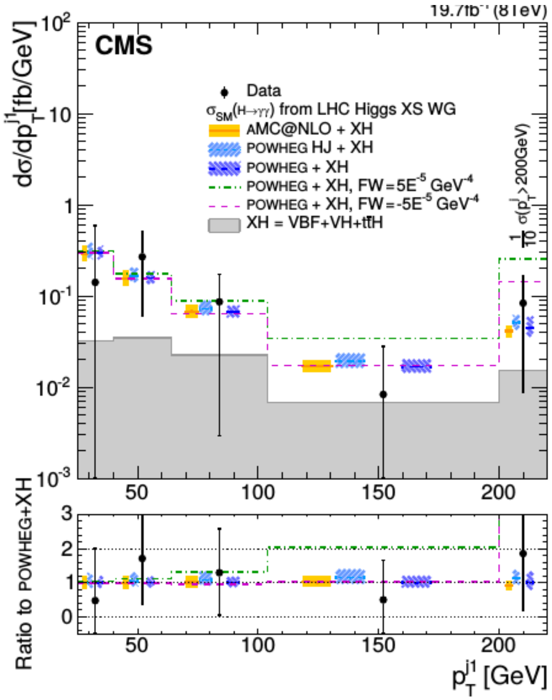
19.7fb⁻¹ (8TeV)
CMS
Data
σ_SM(H→γγ) from LHC Higgs XS WG
AMC@NLO + XH
POWHEG HJ + XH
POWHEG + XH
POWHEG + XH, FW=5E⁻⁵ GeV⁻⁴
POWHEG + XH, FW=-5E⁻⁵ GeV⁻⁴
XH = VBF+VH+tt̄H
σ(N_jets)
Ratio to POWHEG+XH
N_jets
0
1
2
≥ 3

Leading jet p_T









Two-jets azimutal decorrelation