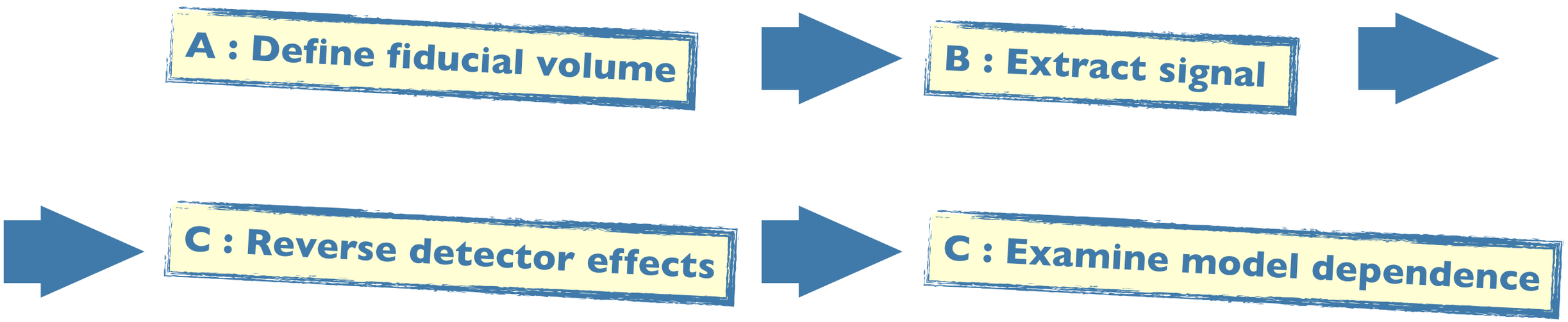
HIGGS BOSON XS MEASUREMENTS AND DIFFERENTIAL DISTRIBUTIONS AT THE LHC

P. Milenovic (University of Florida)
on behalf of the ATLAS and CMS collaborations

Preface

MOTIVATION:

- Fiducial cross sections offer a **possibility to describe data in model independent** way
  - Maximise the applicability of LHC data to explore the **QCD effects** in the SM, and capture **BSM effects** in the Higgs boson physics.



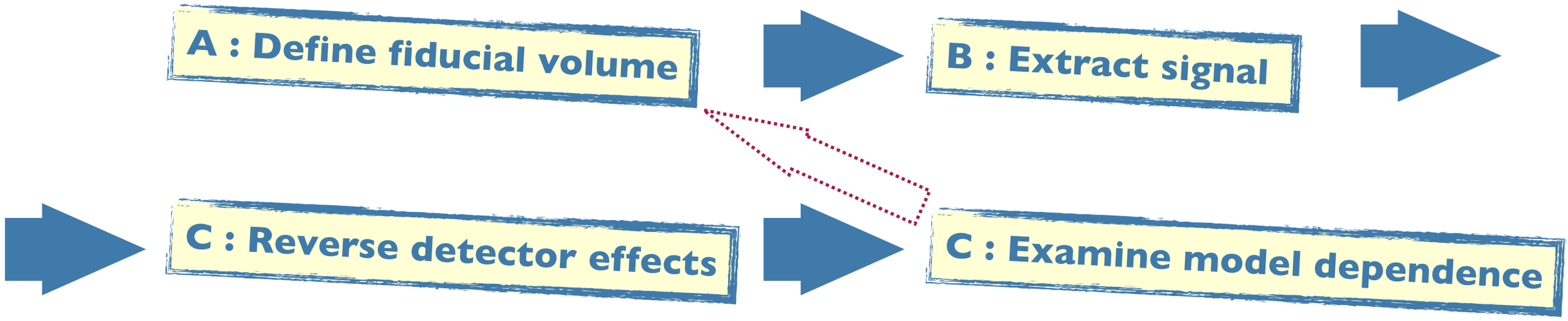
A FEW IMPORTANT ASPECTS:

- **Model independence** of the measurements
  - Factorise theory uncertainties from experimental ones (no extrapolation)
- Need for the measurements to **survive the passage of time**
  - Experiments should provide **all information** necessary for theorist **to reinterpret results.**

Preface

MOTIVATION:

- Fiducial cross sections offer a **possibility to describe data in model independent** way
  - Maximise the applicability of LHC data to explore the **QCD effects** in the SM, and capture **BSM effects** in the Higgs boson physics.



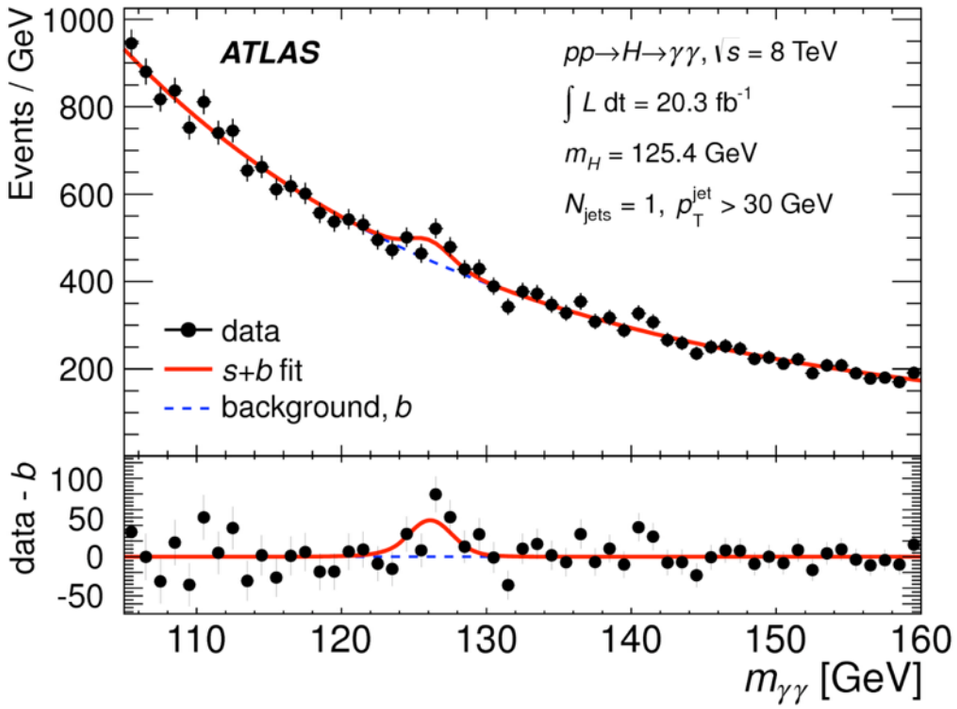
A FEW IMPORTANT ASPECTS:

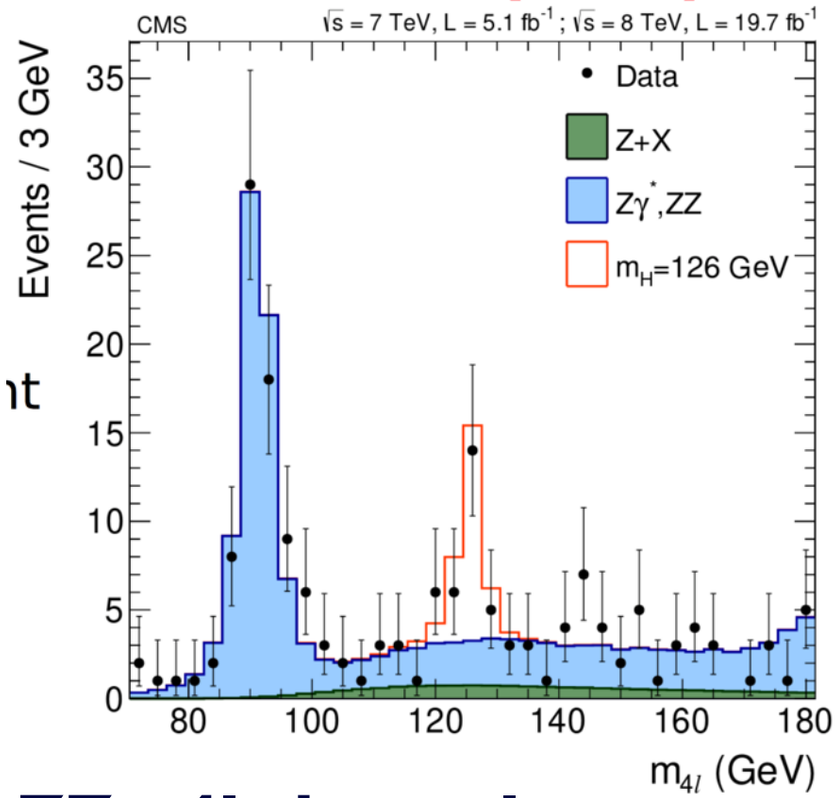
- **Model independence** of the measurements
  - Factorise theory uncertainties from experimental ones (no extrapolation)
- Need for the measurements to **survive the passage of time**
  - Experiments should provide **all information** necessary for theorist **to reinterpret results.**

APPROACHES TO THE MEASUREMENTS IN RUN I

Overview of the channels

- **Fiducial XS measured in H→γγ and H→ZZ→4l channels**
  - Fully reconstructible decays with excellent mass resolution (H→γγ : 1-2%, H→ZZ→4l: 1-3%)





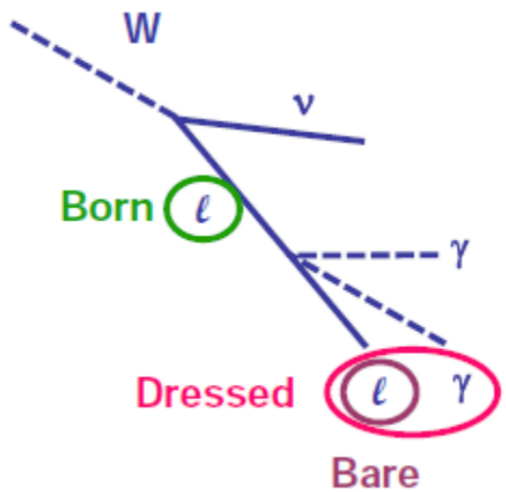
H→γγ channel:

- **Small branching fraction** (~0.2%), but allows **high selection efficiency** (~40-45%)
- **A few hundred reconstructed signal events** expected after selection (8 TeV Run I)
- **Large continuum background** from QCD γγ and γ+jet.

H→ZZ→4l channel:

- Very **small branching fraction** (~0.01%), but **very clean signature**
- About **15-20 reconstructed signal events** expected after selection (8 TeV Run I)
- **Very small background** from irreducible pp→ZZ and reducible Z+jets.

Important ingredients



FIDUCIAL DEFINITIONS:

- Definition of the **fiducial-level objects** (leptons, photons, jets)
- **Isolation requirement** plays an **important role**
- **Out-of-fiducial signal** contributions need special care
- **NOTE: Different kinematical cuts** in ATLAS/CMS (optimised to exploit detector potential).

M(H) HYPOTHESIS:

- Use **best-fit value measured by experiment(s)** for comparisons with theory (either **treat m(H) as a free parameter** and fit for it, or **fix m(H)** to best-fit value).

MODEL DEPENDENCE:

- Build response matrix and repeat the **unfolding procedure once per model**
  - **SM studies: vary production mode composition** (e.g. within experimental constraints)
  - **BSM studies:** consider a predefined **set of exotic models** (with/without exp. constraints)

Unfolding

GOAL: undo the effects of smearing due to detector resolution & efficiency

- Complex problem (and not very well defined), important for theory comparisons

APPROACHES IN RUN 1:

- Use **bin-by-bin correction factors**
  (iterative d'Agostini unfolding method used for cross-check)

$$\sigma_i = \frac{N_i^{\text{signal}}}{\mathcal{L}_{\text{int}} \cdot C_i}$$

Add systematics to cover for possible biases, cross-check the claimed coverage

- Fold detector response matrix (K) in the likelihood and
  perform background subtraction and signal unfolding simultaneously.

Function to minimize — **Response matrix** — **Gen level input distribution**

$$\mathcal{F}(\mu_i) = -2\log\mathcal{L}\left(K_{ij}\cdot\mu_i\right) N_{gen,i}|N_{reco,j})$$

L is the usual **likelihood** function of B, S+B and the nuisance parameters

Signal strength to be measured for each bin of **gen level** input distribution

Reco level signal yields in each bins and categories

Full correlation of nuisance parameters

RESULTS

Inclusive cross sections: H→γγ

JHEP 09 (2014) 112

CMS-PAS-HIG-14-016

- **Inclusive cross sections at 8TeV, measured in H→γγ channel**
  - Un-binned maximum likelihood fit to $\mathbf{m_{\gamma\gamma}}$ (primarily based on legacy analyses)
  - Compared to **theoretical estimates** with **NNLO+NNLL QCD accuracy**
  - **ATLAS:** compared also to other state-of-art predictions.

ATLAS @ 8TeV:

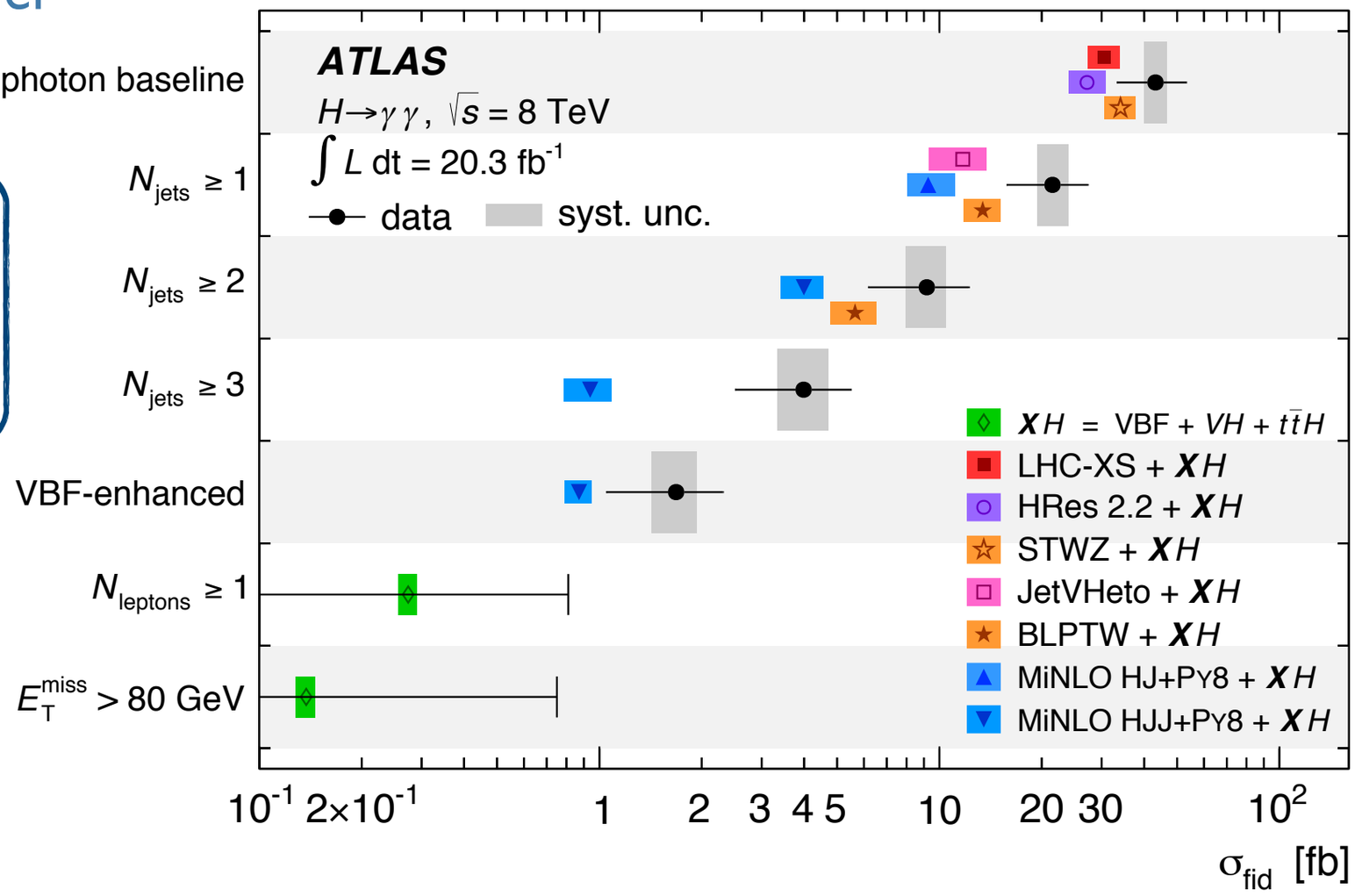
$$\sigma_{\rm fid} = 43.2 \pm 9.4({\rm stat.})^{+3.2}_{-2.9}({\rm syst.})\ {\rm fb}$$

$$\sigma^{\rm SM}_{\rm fid} = 30.5 \pm 3.3\ {\rm fb}$$

CMS @ 8TeV:

$$\sigma_{\rm fid} = 32 \pm 10({\rm stat.}) \pm 3({\rm syst.})\ {\rm fb}$$

$$\sigma^{\rm SM}_{\rm fid} = 31^{+4}_{-3}({\rm stat.})\ {\rm fb}$$



Inclusive cross sections: H→γγ

JHEP 09 (2014) 112

CMS-PAS-HIG-14-016

- **Inclusive cross sections at 8TeV, measured in H→γγ channel**
  - Un-binned maximum likelihood fit to $\mathbf{m_{\gamma\gamma}}$ (primarily based on legacy analyses)
  - Compared to **theoretical estimates** with **NNLO+NNLL QCD accuracy**
  - **ATLAS**: compared also to other state-of-art predictions.

ATLAS @ 8TeV:

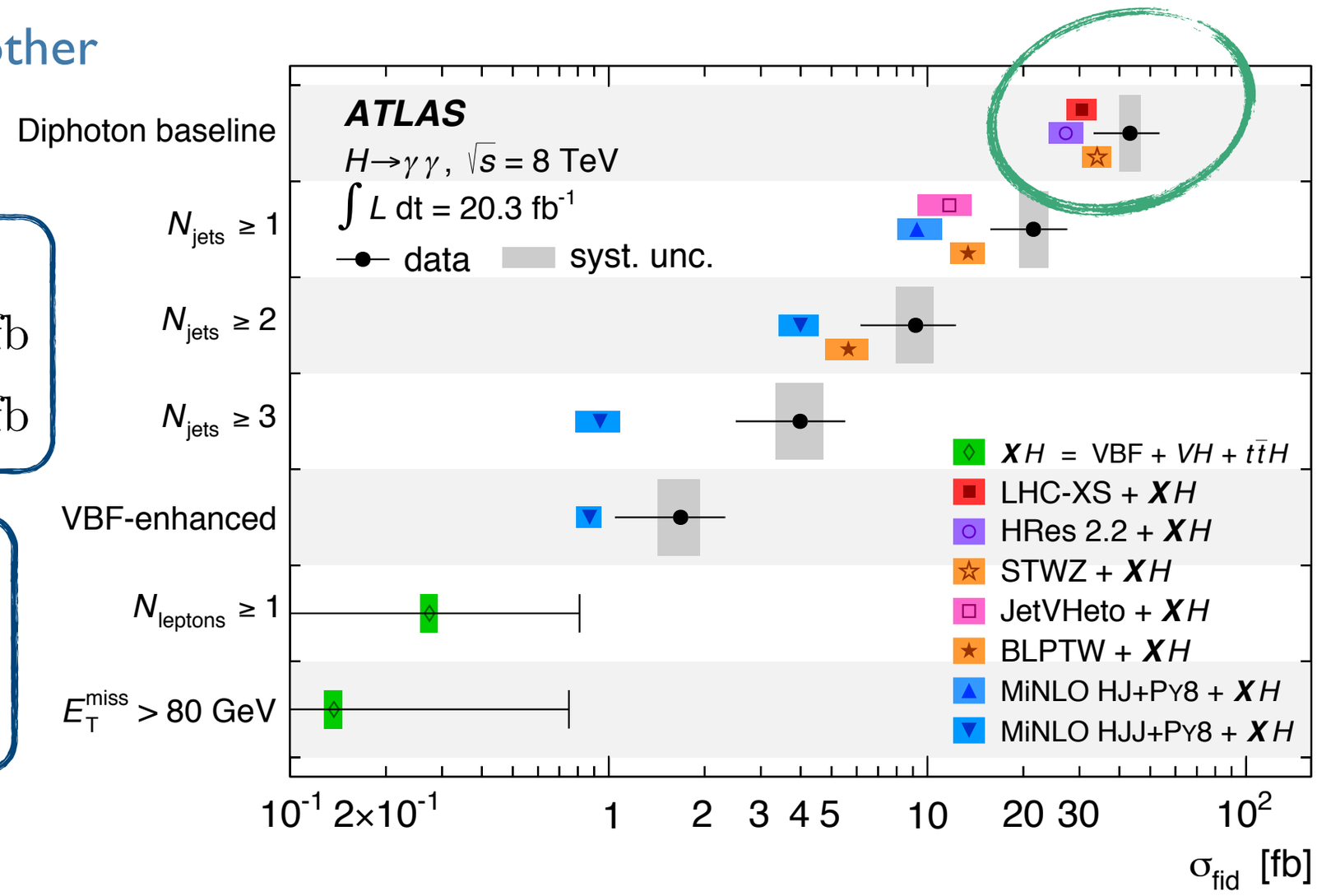
$$\sigma_{\rm fid} = 43.2 \pm 9.4({\rm stat.})^{+3.2}_{-2.9}({\rm syst.})\ {\rm fb}$$

$$\sigma^{\rm SM}_{\rm fid} = 30.5 \pm 3.3\ {\rm fb}$$

CMS @ 8TeV:

$$\sigma_{\rm fid} = 32 \pm 10({\rm stat.}) \pm 3({\rm syst.})\ {\rm fb}$$

$$\sigma^{\rm SM}_{\rm fid} = 31^{+4}_{-3}({\rm stat.})\ {\rm fb}$$



Compatible with theoretical estimates (slightly higher rates by ATLAS)

Inclusive cross sections: H→ZZ→4l

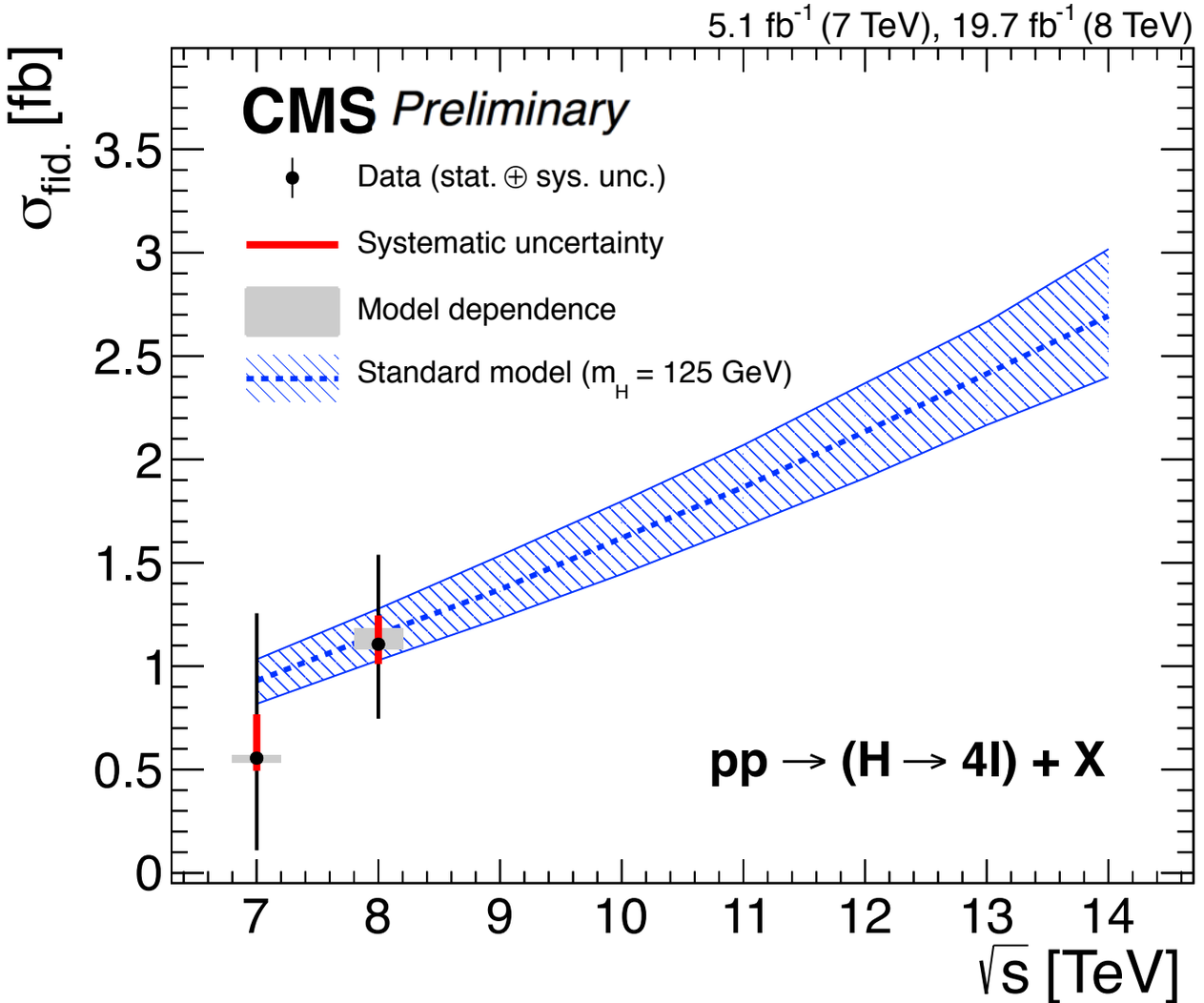
PLB 738 (2014) 234

CMS-PAS-HIG-14-028

- **Inclusive cross sections at 7 and 8TeV, measured in H→4l channel**
  - Un-binned maximum likelihood fit to m_{4l}
  - **Model dependence** estimated from range of SM and exotic Higgs models:

    <1% using experimental constraints
    ~7% without experimental constraints

  - CMS: **Z→4l resonance** used as validati
  - 7TeV measurement **statistically limited.**



ATLAS @ 8TeV:

$$\sigma_{\text{fid}} = 2.11 \pm^{+0.53}_{-0.47} (\text{stat.}) \pm 0.08(\text{syst.}) \text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 1.30 \pm 0.13 \text{ fb}$$

CMS @ 8TeV:

$$\sigma_{\text{fid}} = 1.11 \pm^{+0.41}_{-0.35} (\text{stat.})^{+0.14}_{-0.10}(\text{syst.})^{+0.08}_{-0.02}(\text{model}) \text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 1.15^{+0.12}_{-0.13}(\text{stat.}) \text{ fb}$$

CMS @ 7TeV:

$$\sigma_{\text{fid}} = 0.56 \pm^{+0.67}_{-0.44} (\text{stat.})^{+0.21}_{-0.06}(\text{syst.})^{+0.02}_{-0.02}(\text{model}) \text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 0.93^{+0.10}_{-0.11}(\text{stat.}) \text{ fb}$$

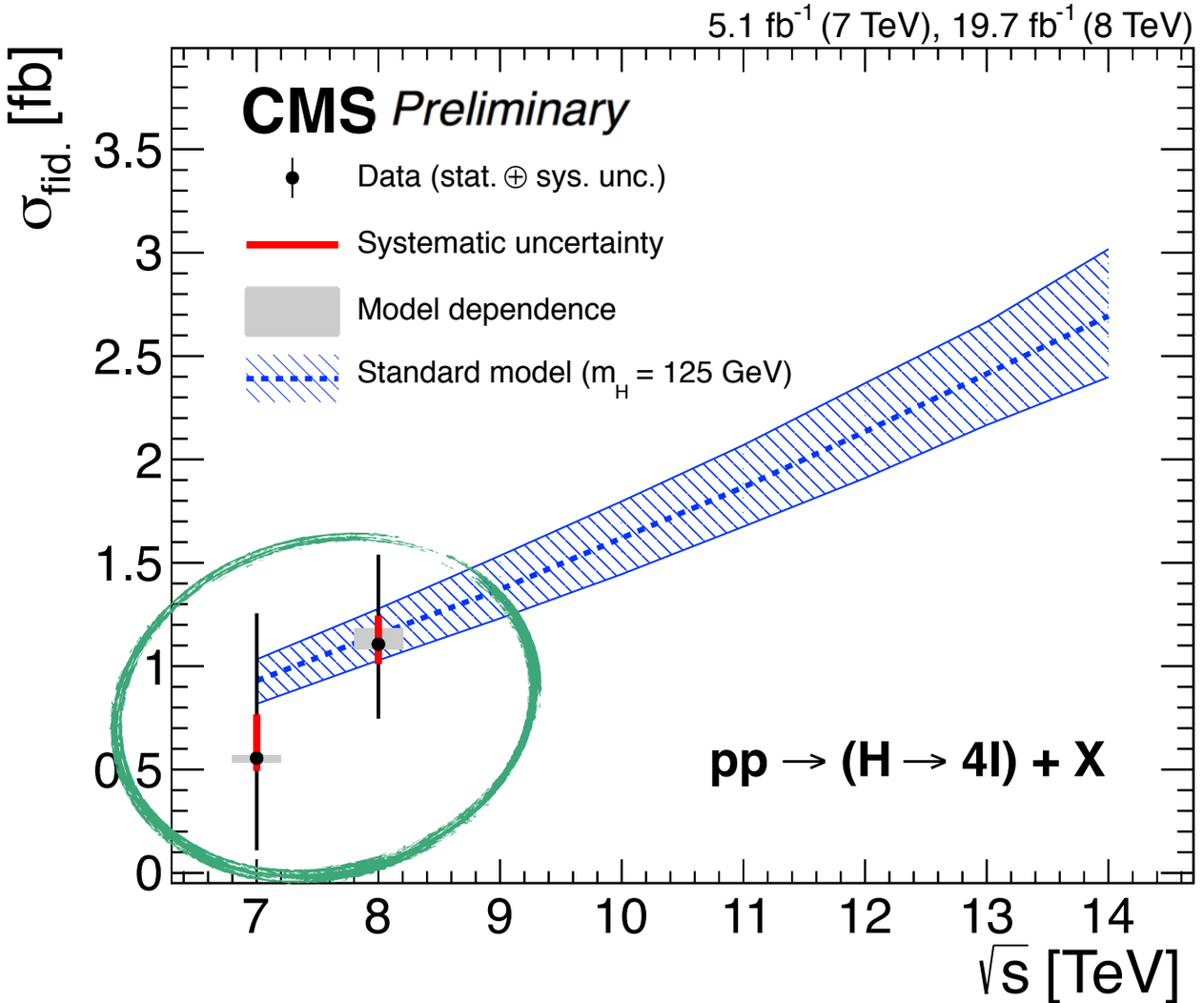
Inclusive cross sections: H→ZZ→4l

PLB 738 (2014) 234

CMS-PAS-HIG-14-028

- **Inclusive cross sections at 7 and 8TeV, measured in H→4l channel**
  - Un-binned maximum likelihood fit to m_{4l}
  - **Model dependence** estimated from range of SM and exotic Higgs models:

    <1% using experimental constraints
    ~7% without experimental constraints
  - CMS: **Z→4l resonance** used as validati
  - 7TeV measurement **statistically limited.**



ATLAS @ 8TeV:

$$\sigma_{\text{fid}} = 2.11 \pm^{+0.53}_{-0.47} (\text{stat.}) \pm 0.08(\text{syst.}) \text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 1.30 \pm 0.13 \text{ fb}$$

CMS @ 8TeV:

$$\sigma_{\text{fid}} = 1.11 \pm^{+0.41}_{-0.35} (\text{stat.})^{+0.14}_{-0.10}(\text{syst.})^{+0.08}_{-0.02}(\text{model}) \text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 1.15^{+0.12}_{-0.13}(\text{stat.}) \text{ fb}$$

CMS @ 7TeV:

$$\sigma_{\text{fid}} = 0.56 \pm^{+0.67}_{-0.44} (\text{stat.})^{+0.21}_{-0.06}(\text{syst.})^{+0.02}_{-0.02}(\text{model}) \text{ fb}$$

$$\sigma^{\text{SM}}_{\text{fid}} = 0.93^{+0.10}_{-0.11}(\text{stat.}) \text{ fb}$$

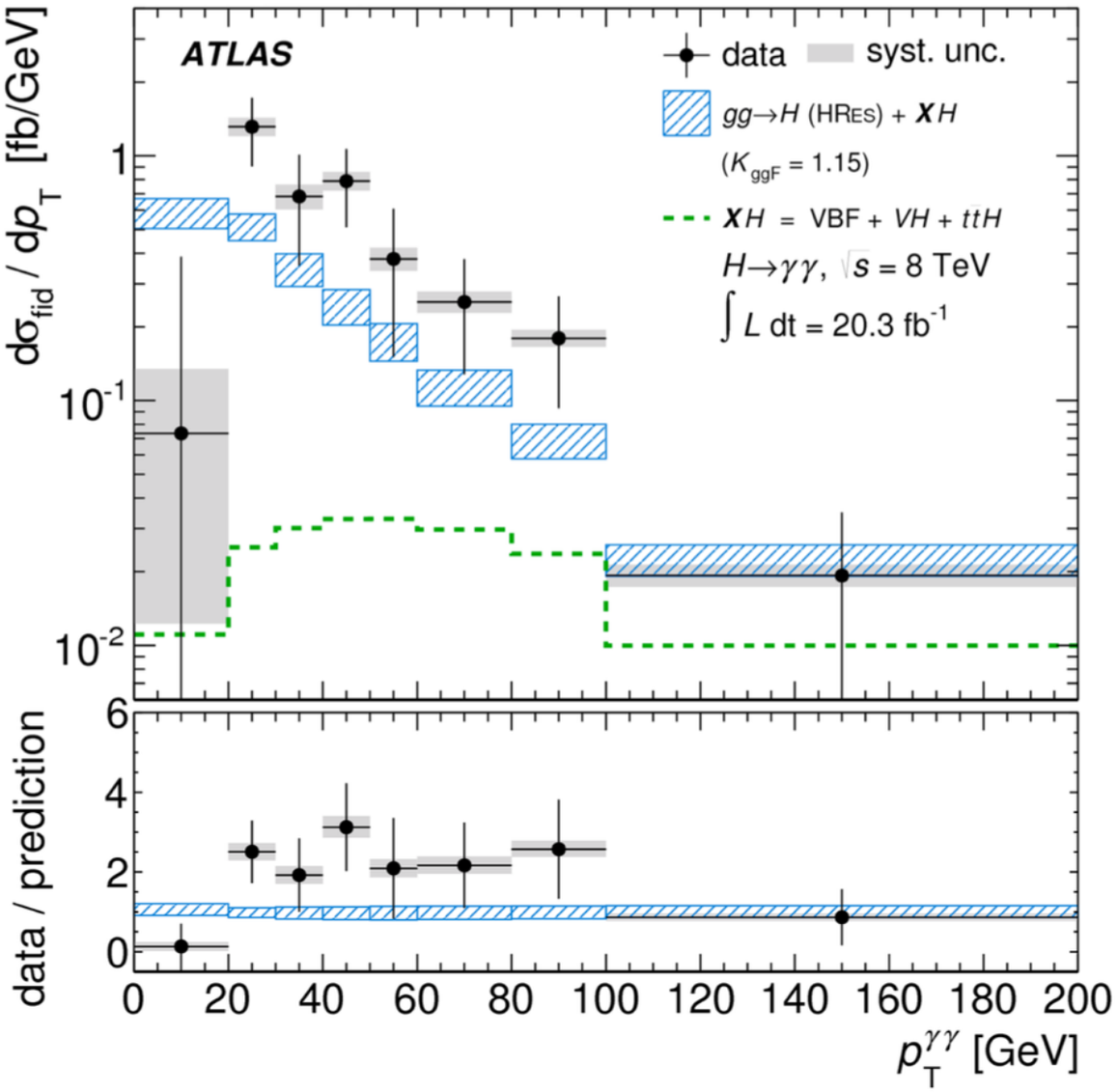
Compatible with theoretical estimates (slightly higher rates by ATLAS)

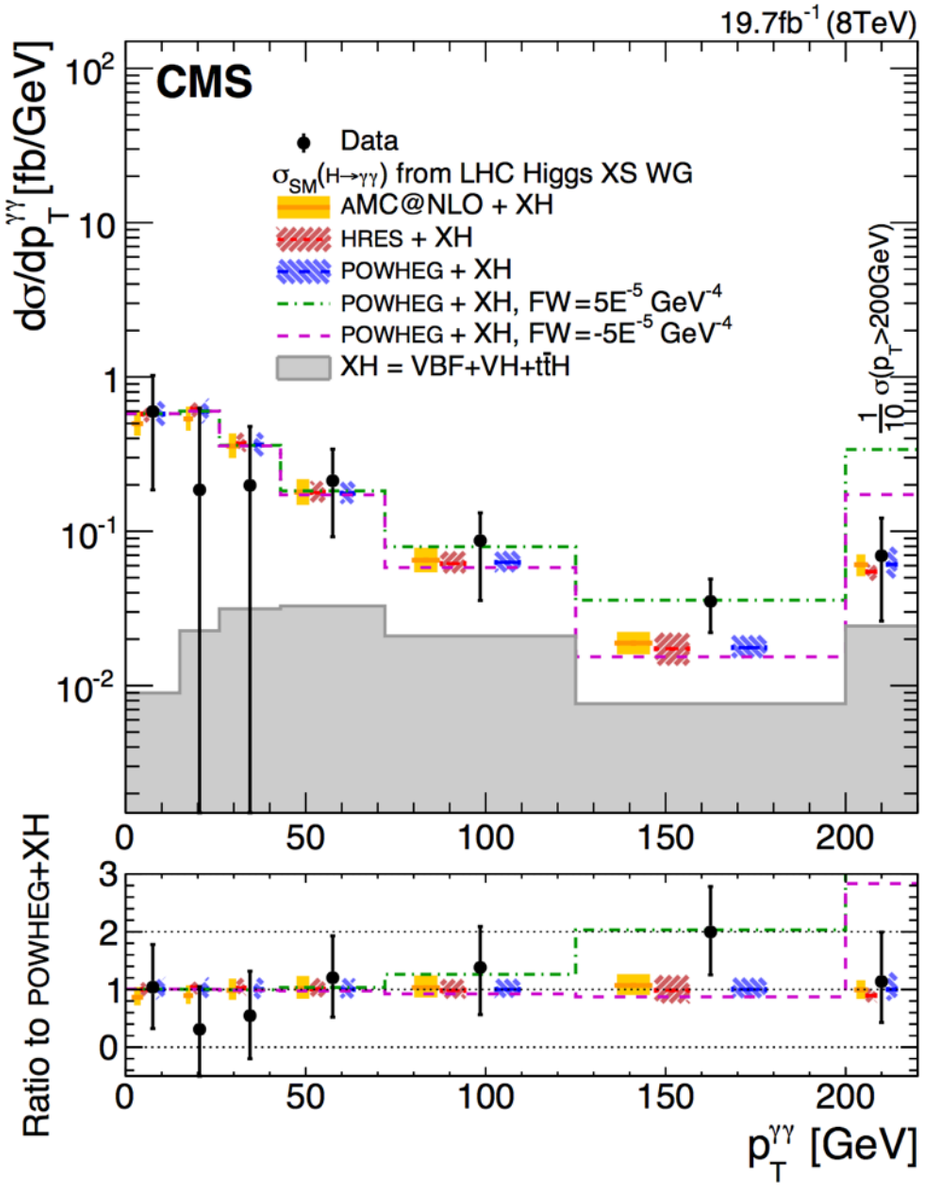
Differential XS: H→γγ

JHEP 09 (2014) 112

CMS-PAS-HIG-14-016

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).



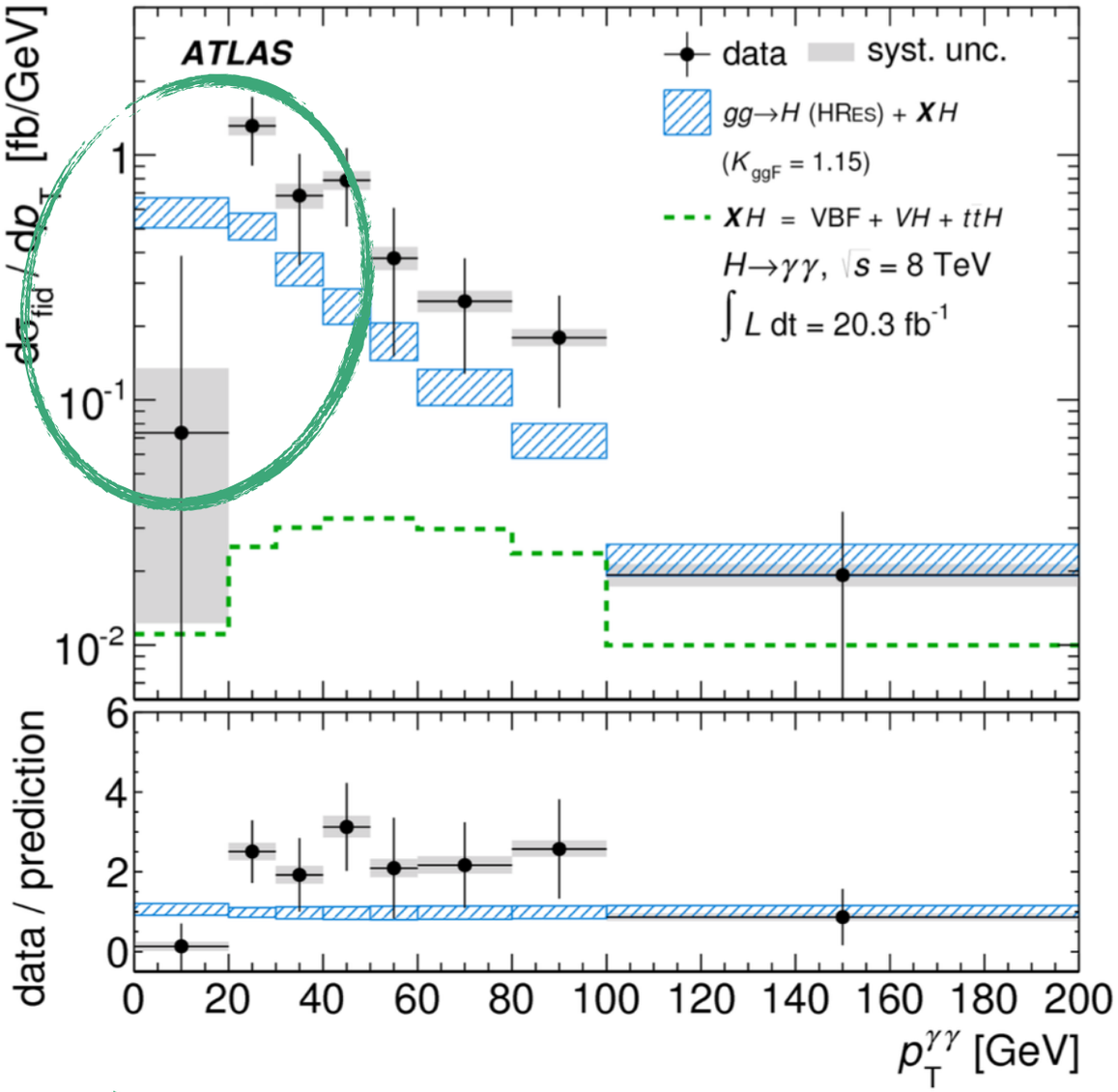


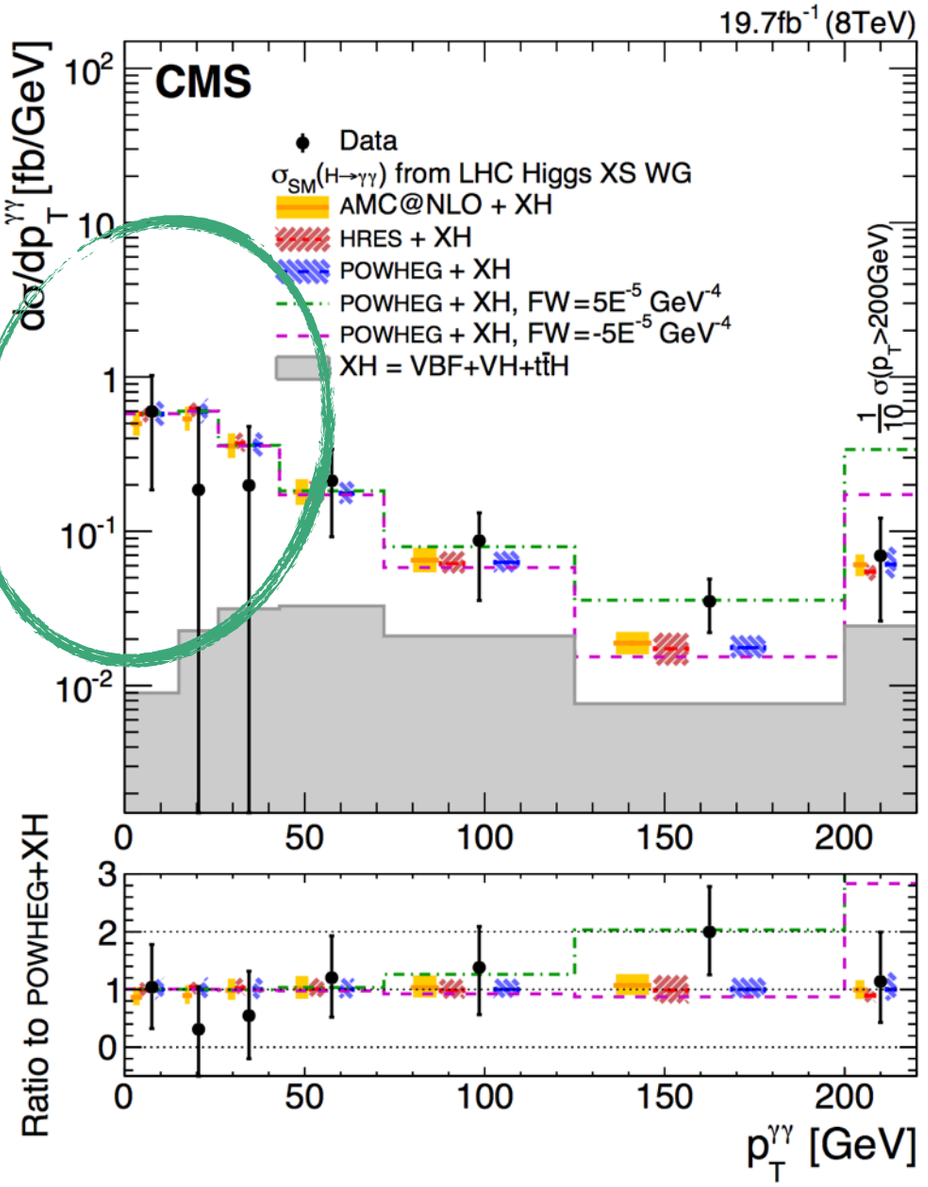
Differential XS: H→γγ

JHEP 09 (2014) 112

CMS-PAS-HIG-14-016

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).





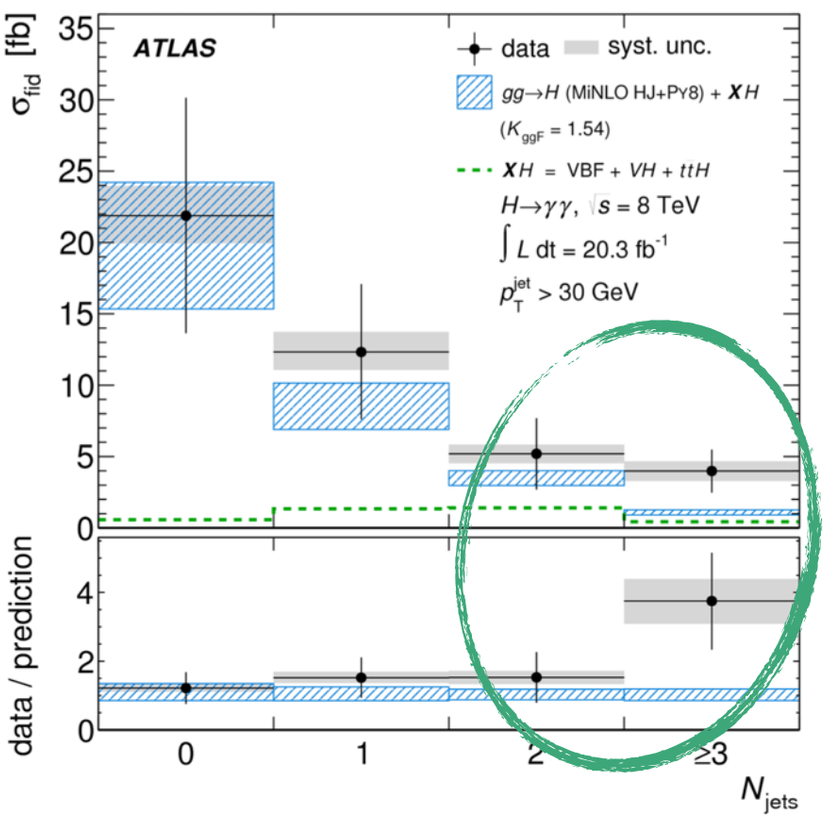
Some deficit in low-p_T range observed by ATLAS (not in CMS)

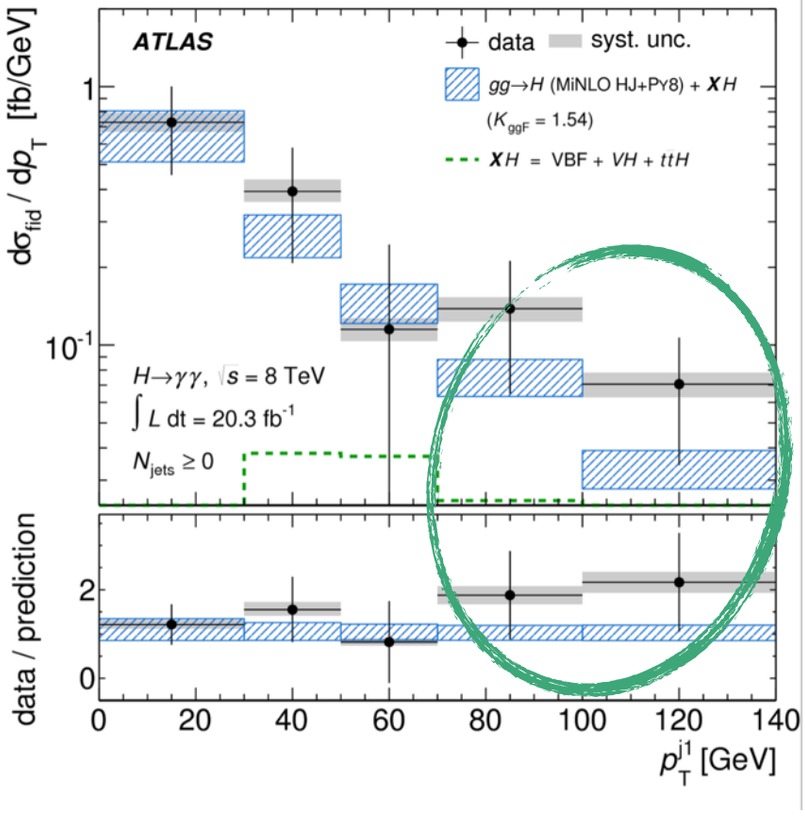
Differential XS: H→γγ

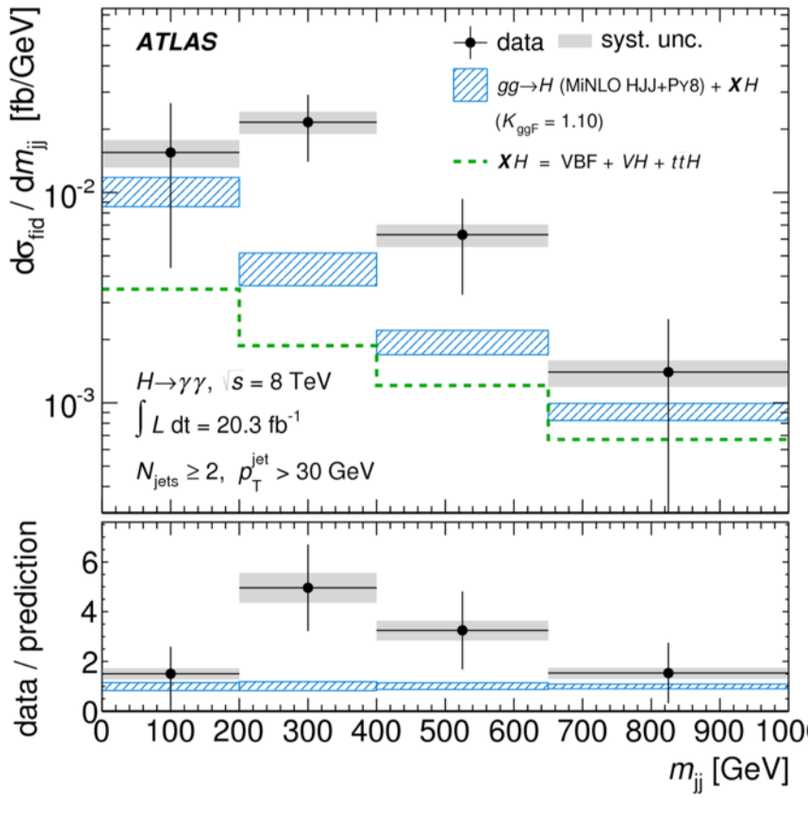
JHEP 09 (2014) 112

- Measured as a function of several **jet-related observables:**
  - **N(jet), $p_T(j_1)$, m(jj)** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

ATLAS @ 8TeV:







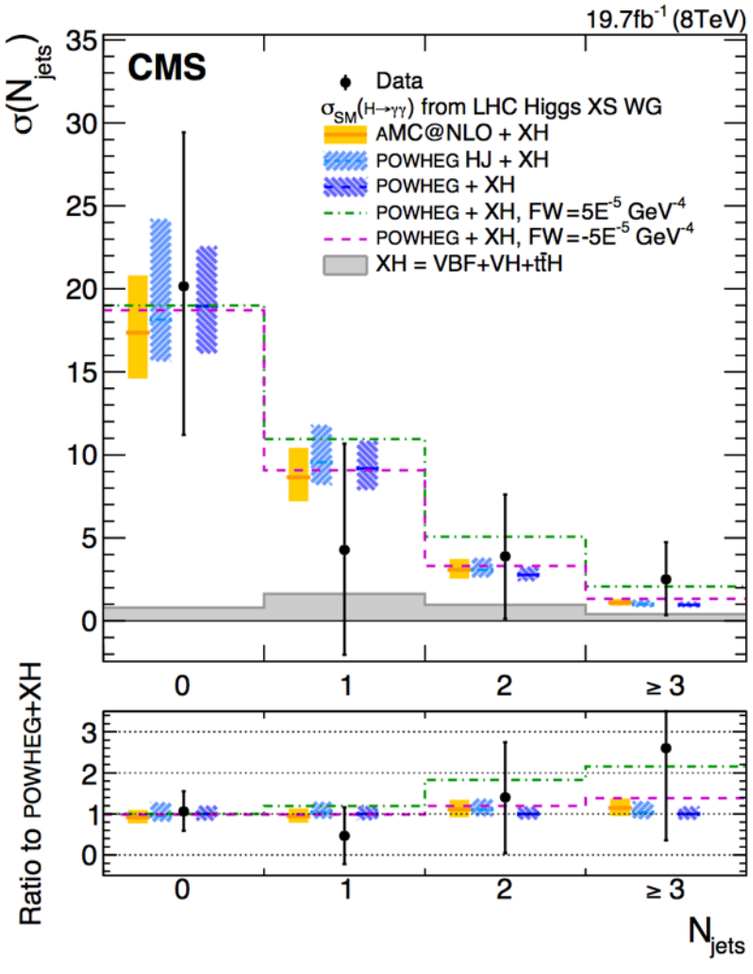
Slightly higher jet activity observed in data w.r.t theoretical estimates

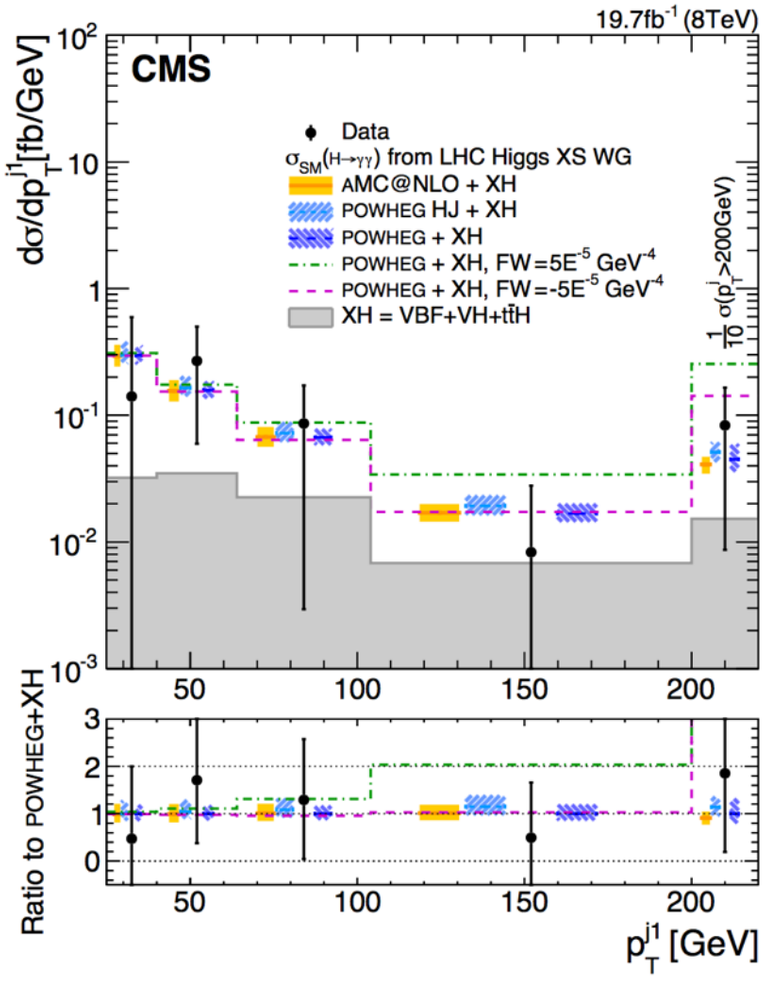
Differential XS: H→γγ

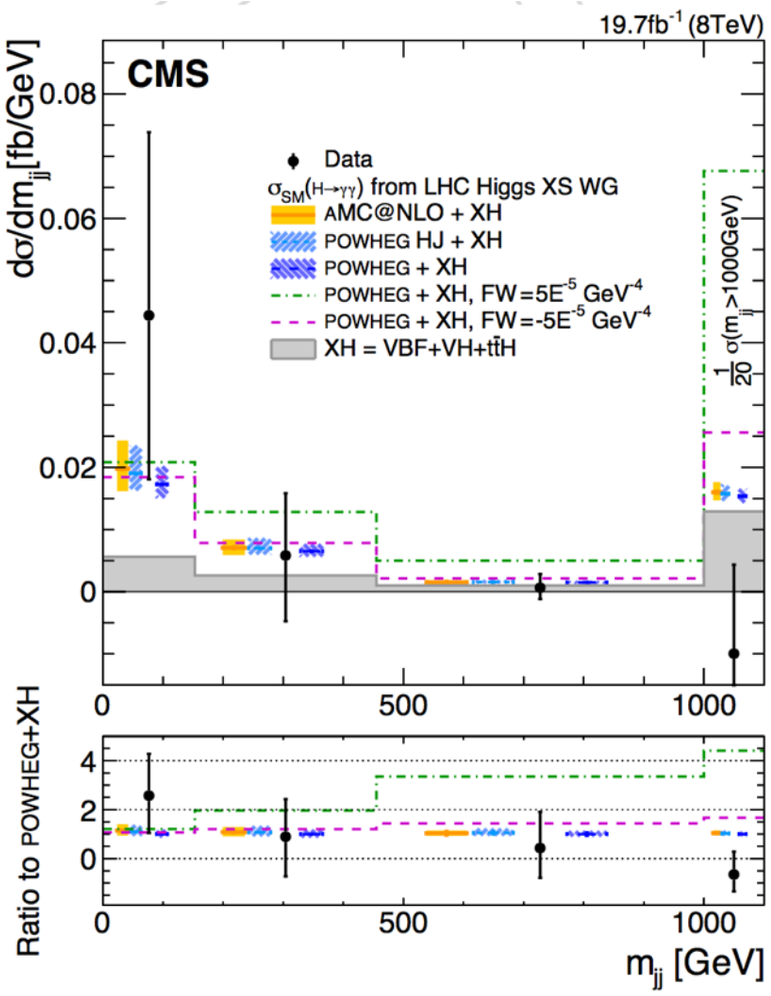
CMS-PAS-HIG-14-016

- Measured as a function of several **jet-related observables:**
  - **N(jet), $p_T(j_1)$, m(jj)** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

CMS @ 8TeV:







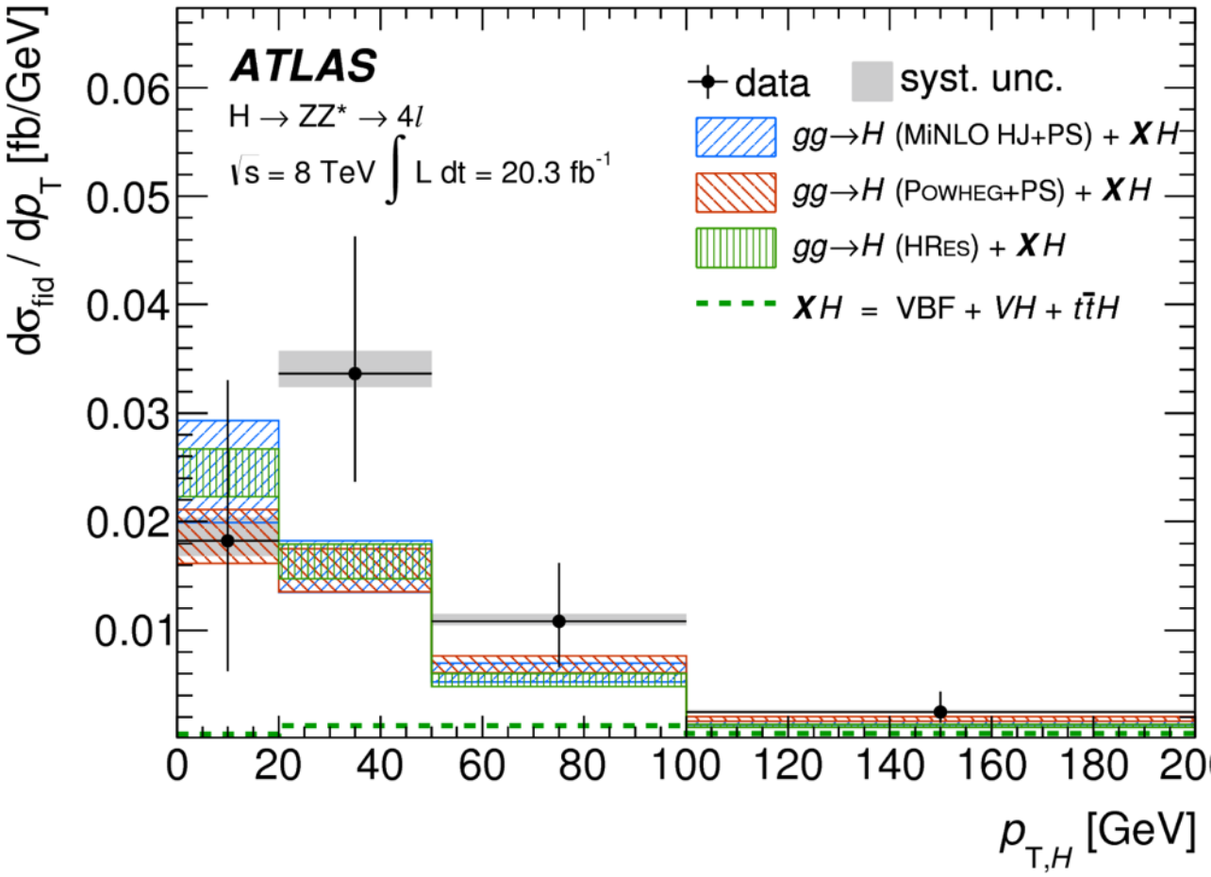
Good agreement with theoretical estimates in case of CMS

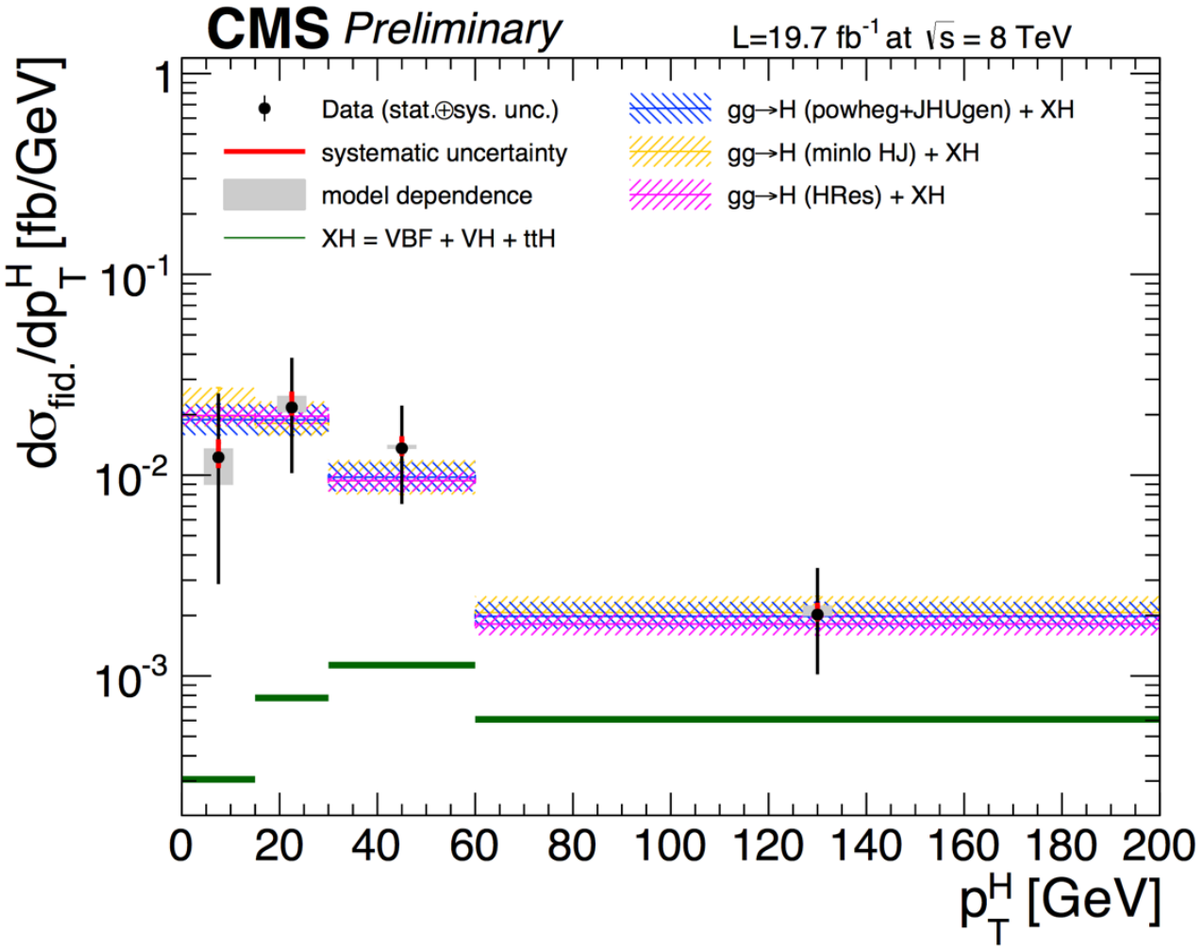
Differential XS: H→ZZ→4l

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).

PLB 738 (2014) 234

CMS-PAS-HIG-14-028



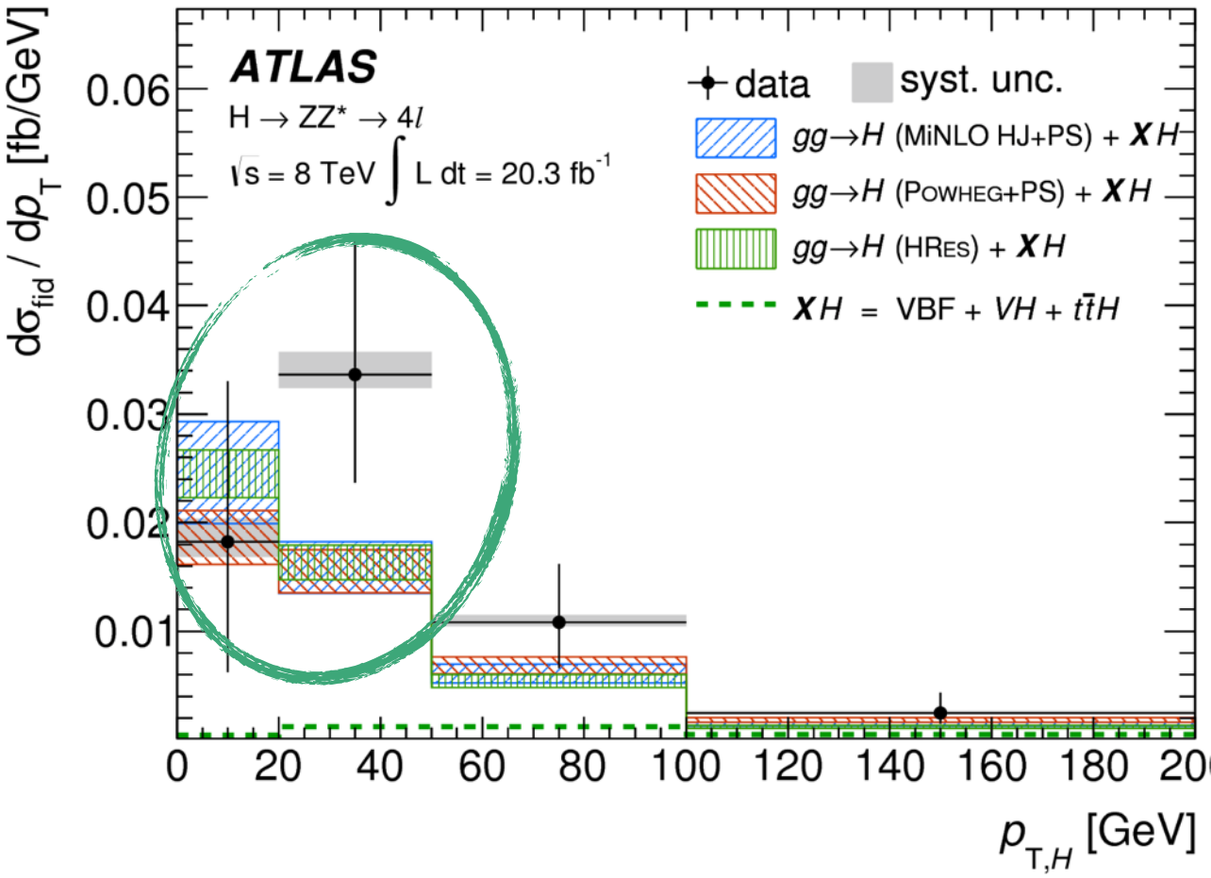


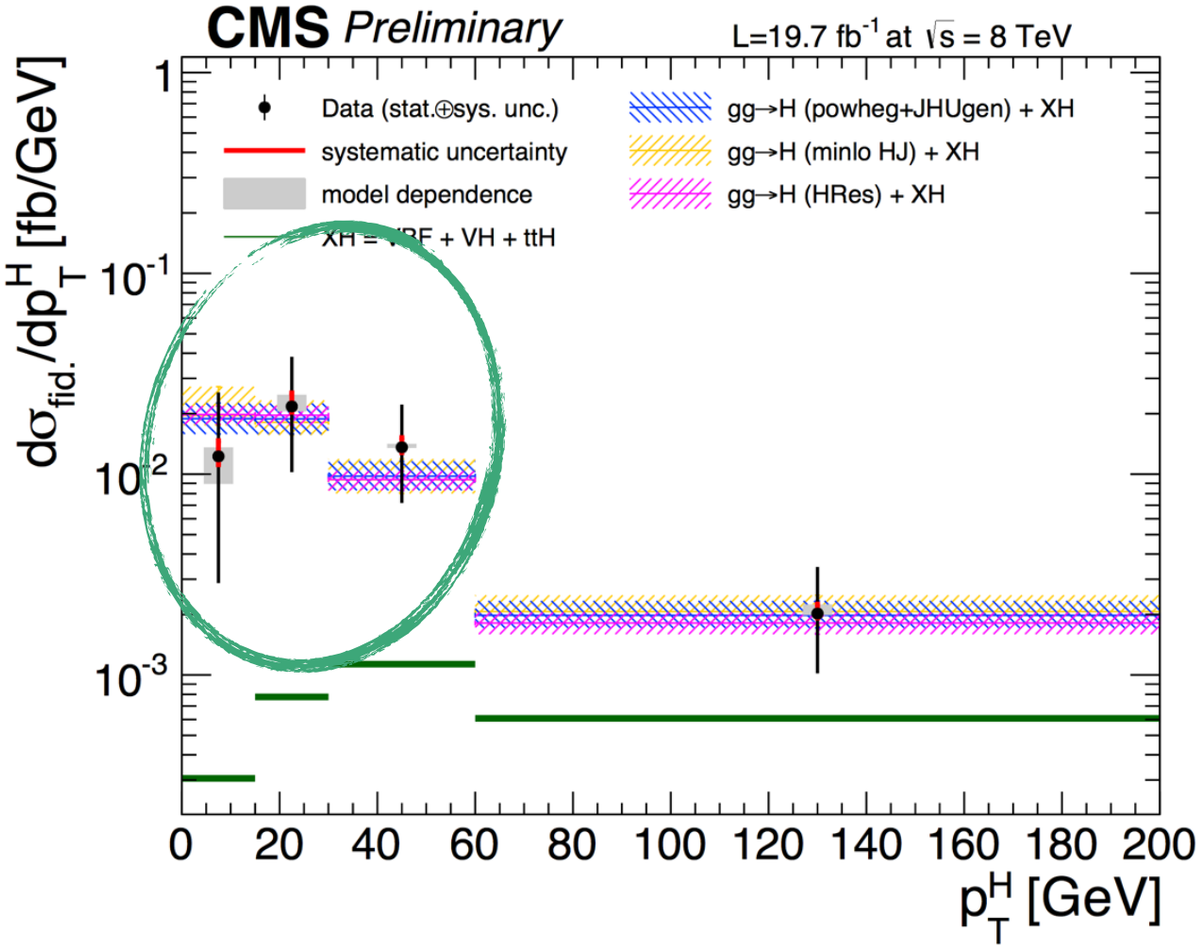
Differential XS: H→ZZ→4l

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions** (see backup).

PLB 738 (2014) 234

CMS-PAS-HIG-14-028





Somewhat harder p_T spectrum observed by ATLAS and CMS w.r.t theoretical estimates (*p*-value ~10-15%)

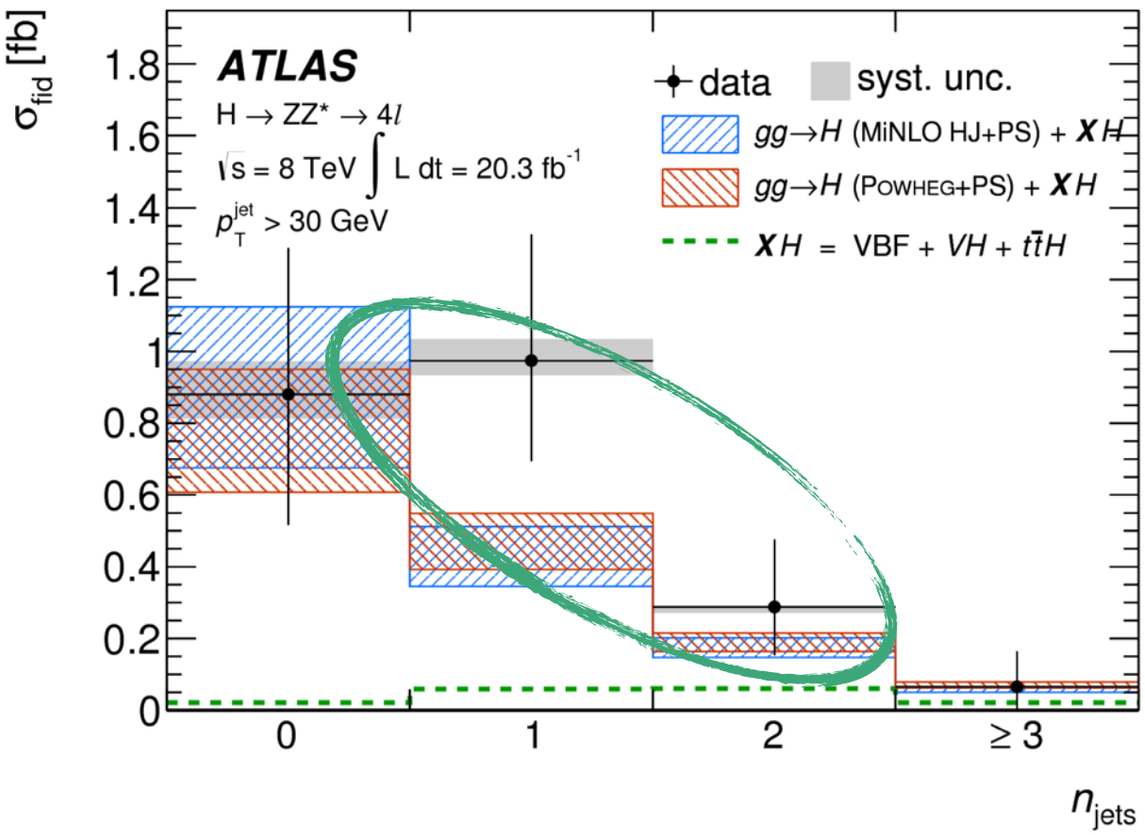
Differential XS: H→ZZ→4l

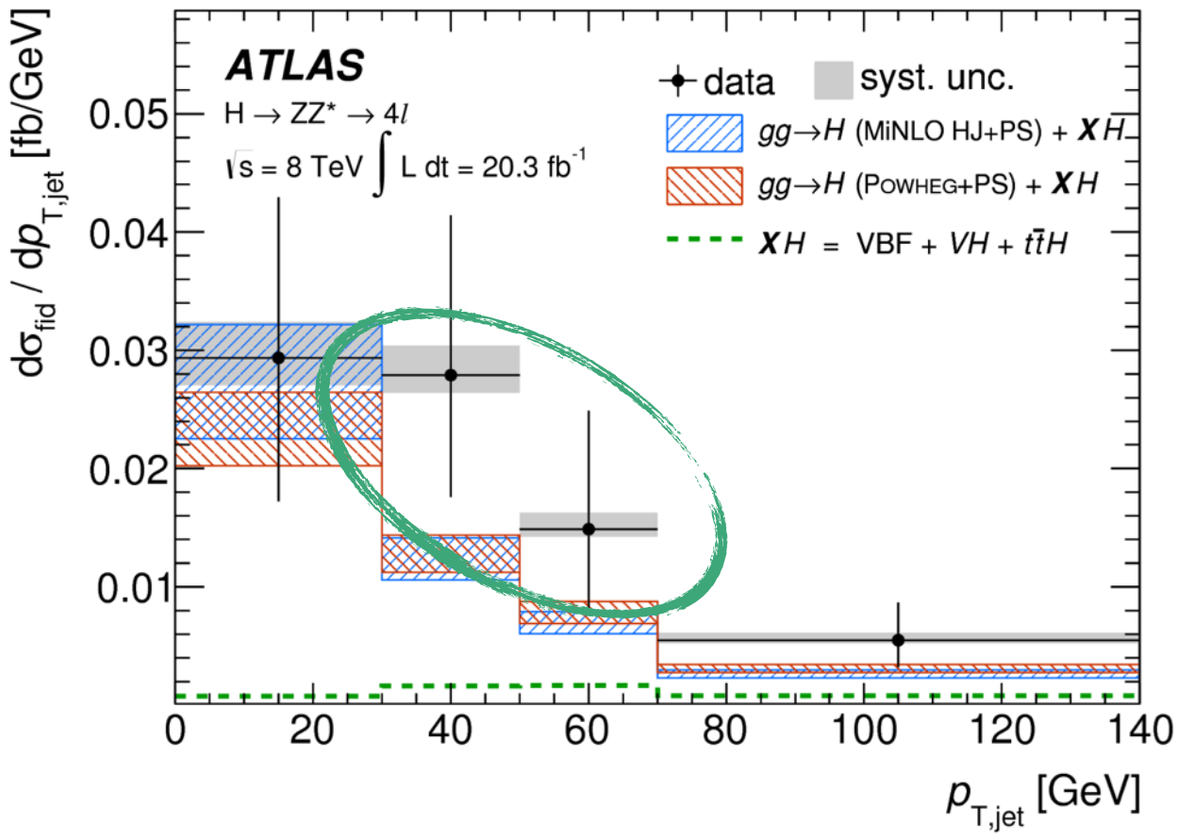
- Measured as a function of several **jet-related observables:**

PLB 738 (2014) 234

  - **N(jet), $p_T(j_1)$** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

ATLAS @ 8TeV:





Somewhat higher jet activity observed in data w.r.t theoretical estimates

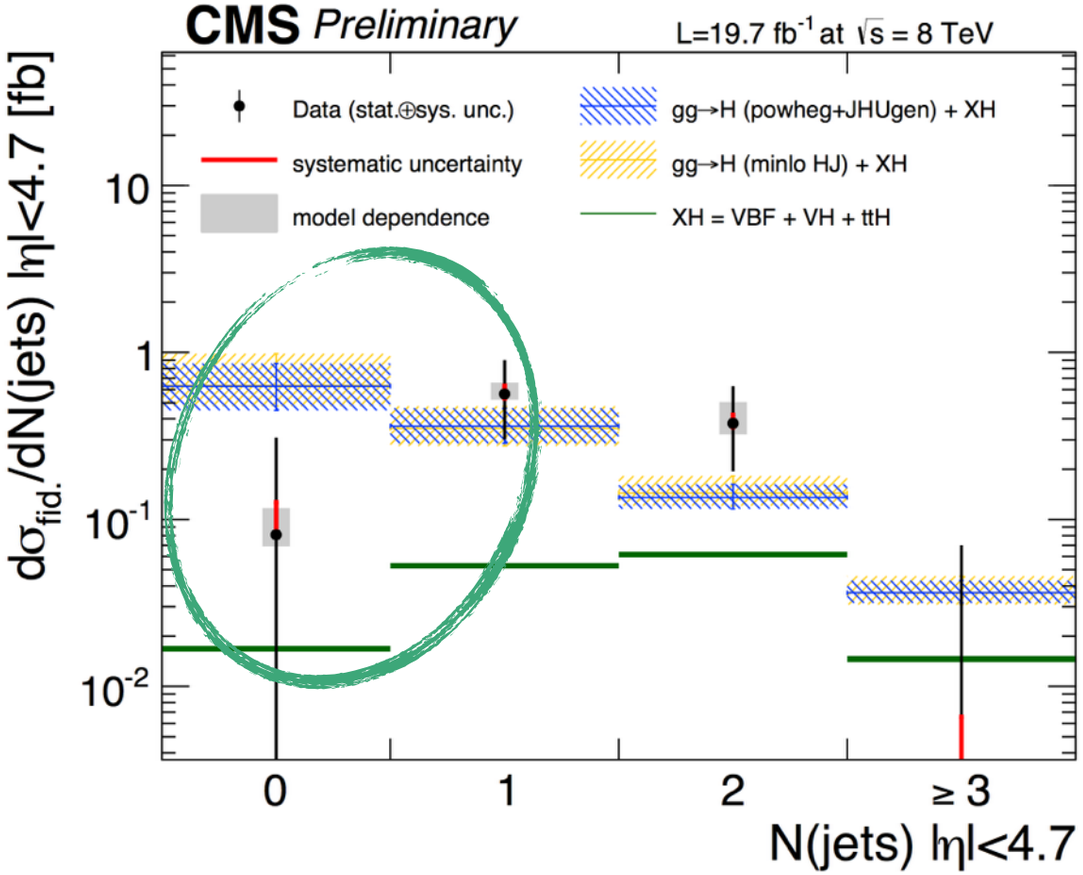
Differential XS: H→ZZ→4l

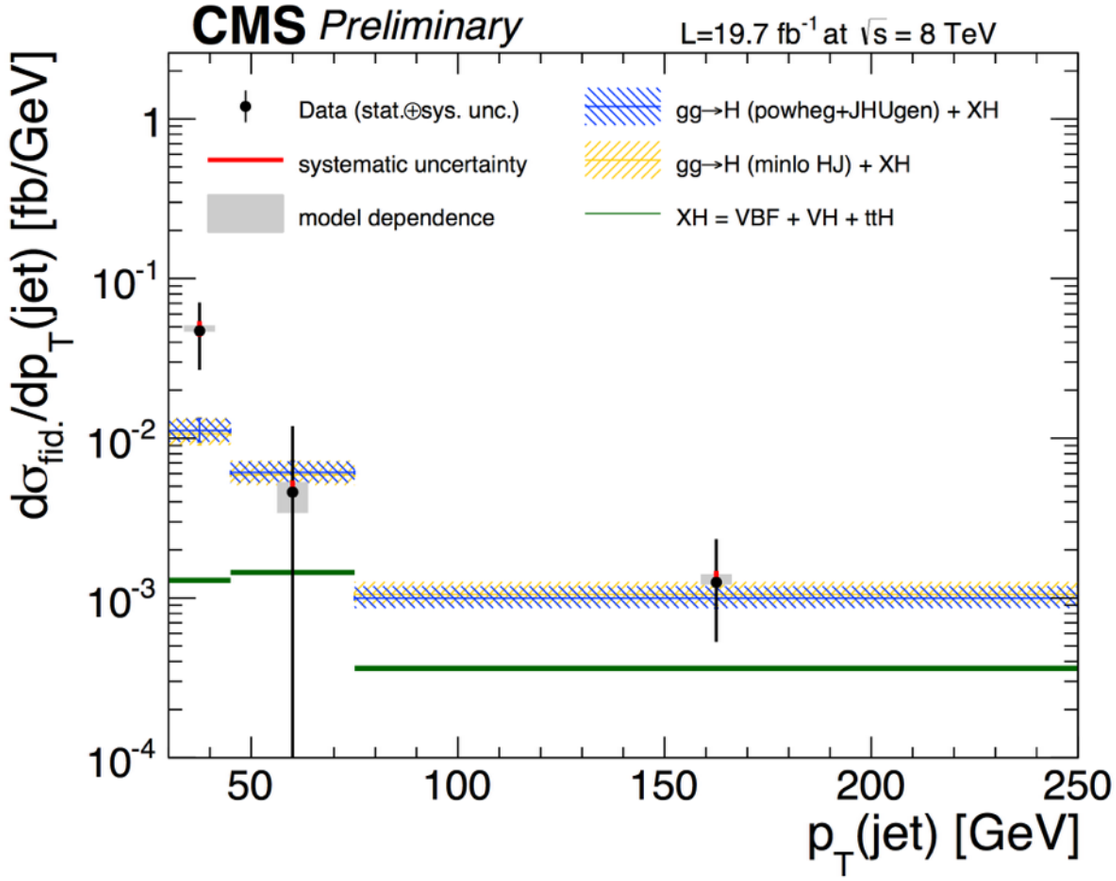
- Measured as a function of several **jet-related observables:**

CMS-PAS-HIG-14-028

  - **N(jet), $p_T(j_1)$** (many other observables, see backup)
  - Sensitive to theoretical modelling of hard quark and gluon radiation, relative contributions of different production modes, BSM effects, etc.

CMS @ 8TeV:



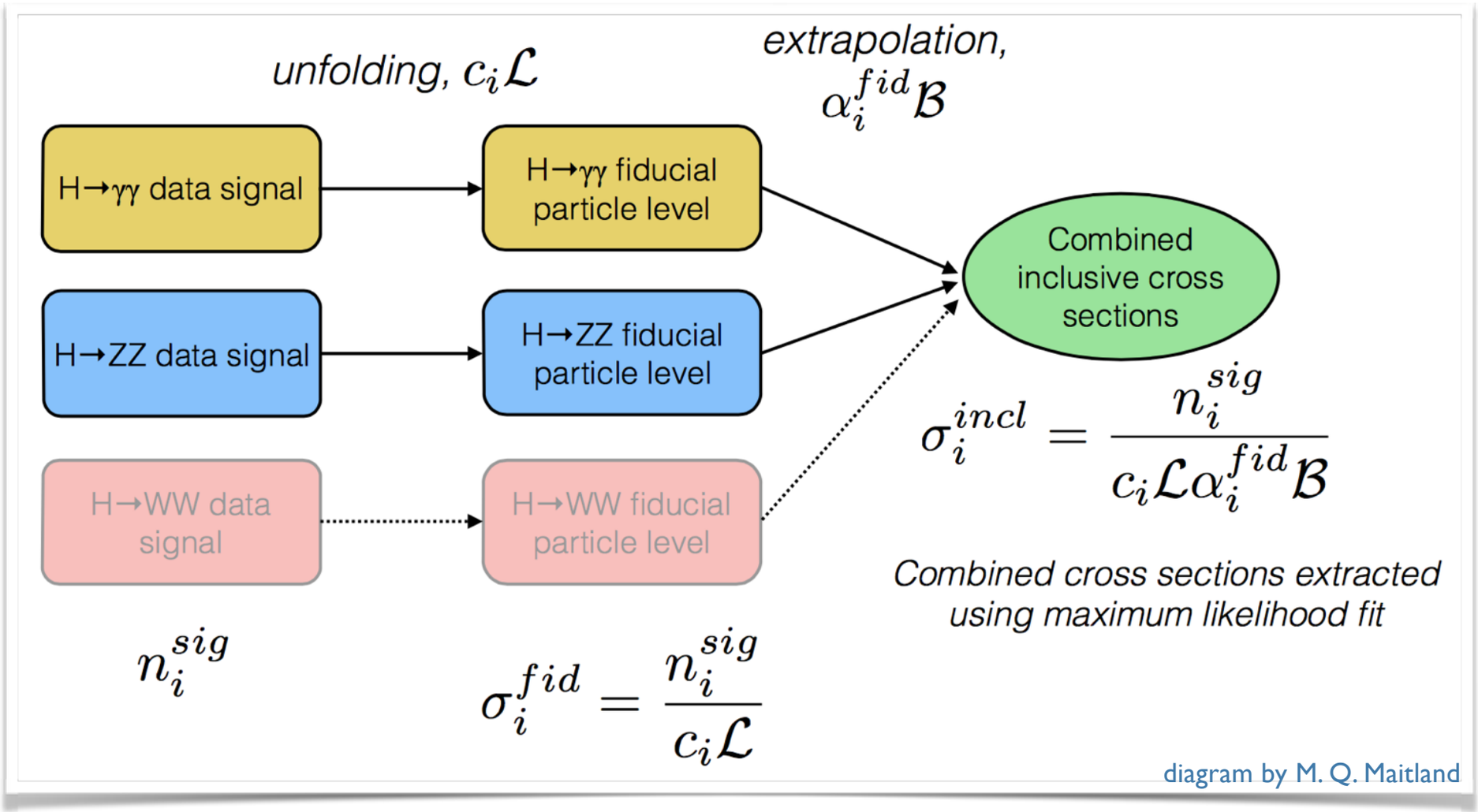


Somewhat higher jet activity observed in data w.r.t theoretical estimates also seen by CMS: *p*-value ~13%

Combination of measurements

Combination between decay channels (H→γγ, H→ZZ, H→WW, etc.):

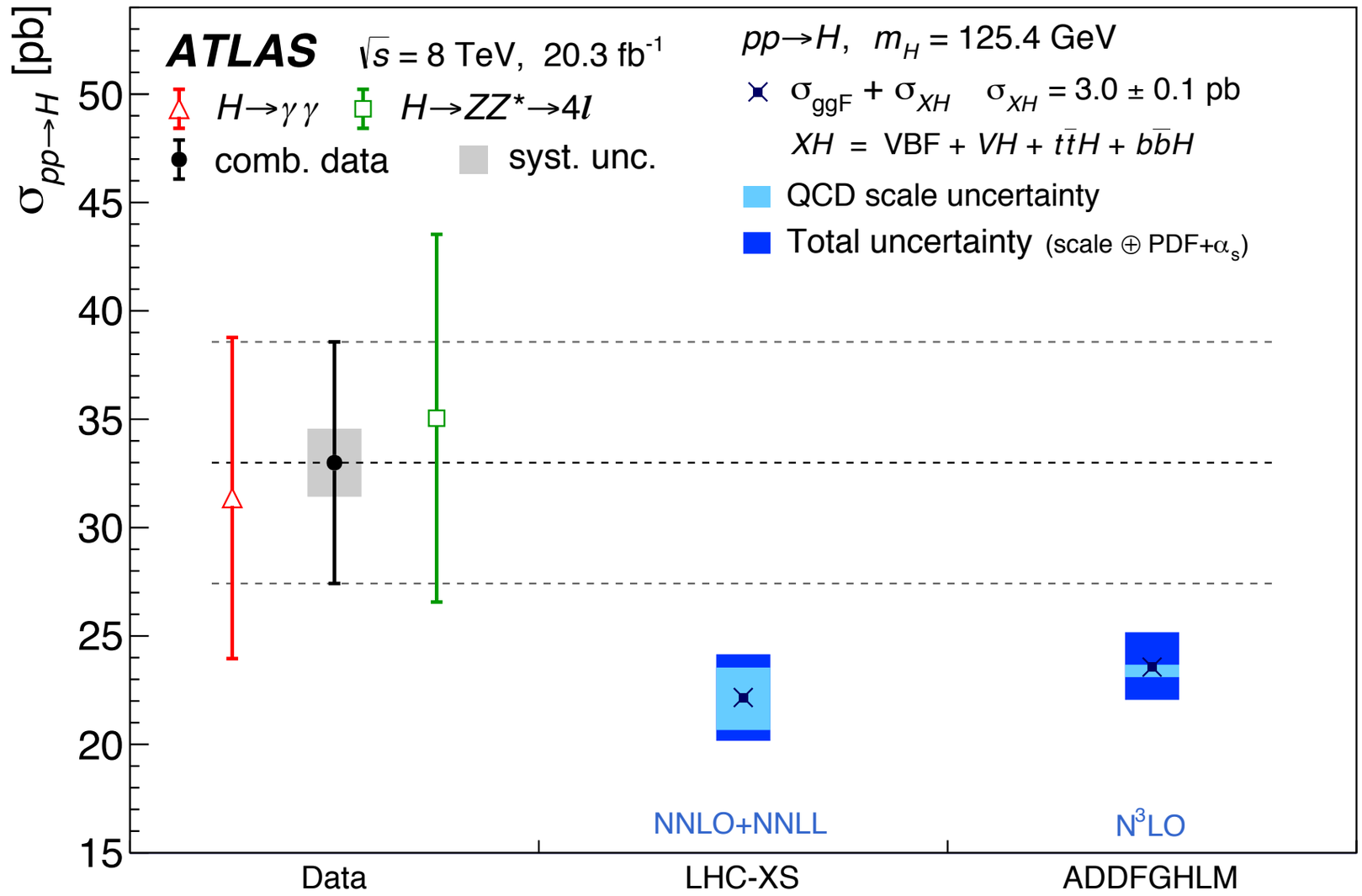
- Perform the fit to **inclusive XS in the full phase space** (inherent assumption of the same source of decays)
- **Statistical precision** at the expense of model dependance due to extrapolation (quote a total XS, check the compatibility between the measurements).



Combination: Inclusive XS (H→γγ, H→ZZ)

PRL. 115 (2015) 091801

- Inclusive XS from the combination of two channels
  - Compared to theoretical estimates with **NNLO+NNLL** and **N³LO** accuracy in **QCD.**



p-values:

LHC-XS: 5.5 %

ADDFGHLM: 9%

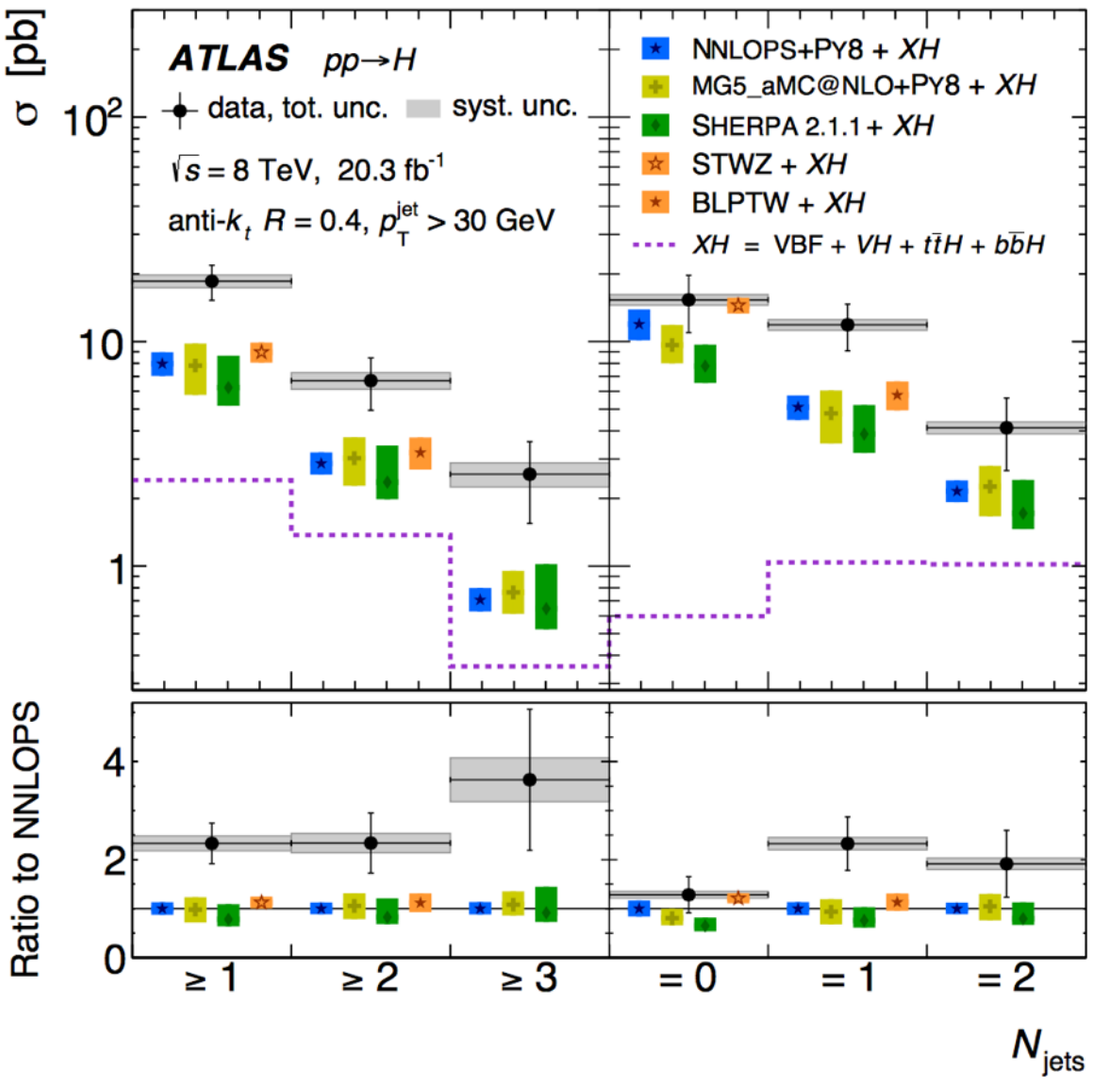
H → 4l:	**35.0 ± 8.4 (stat) ± 1.8 (sys) pb**
H → yy:	**31.4 ± 7.2 (stat) ± 1.6 (sys) pb**
Combined:	**33.0 ± 5.3 (stat) ± 1.6 (sys) pb**

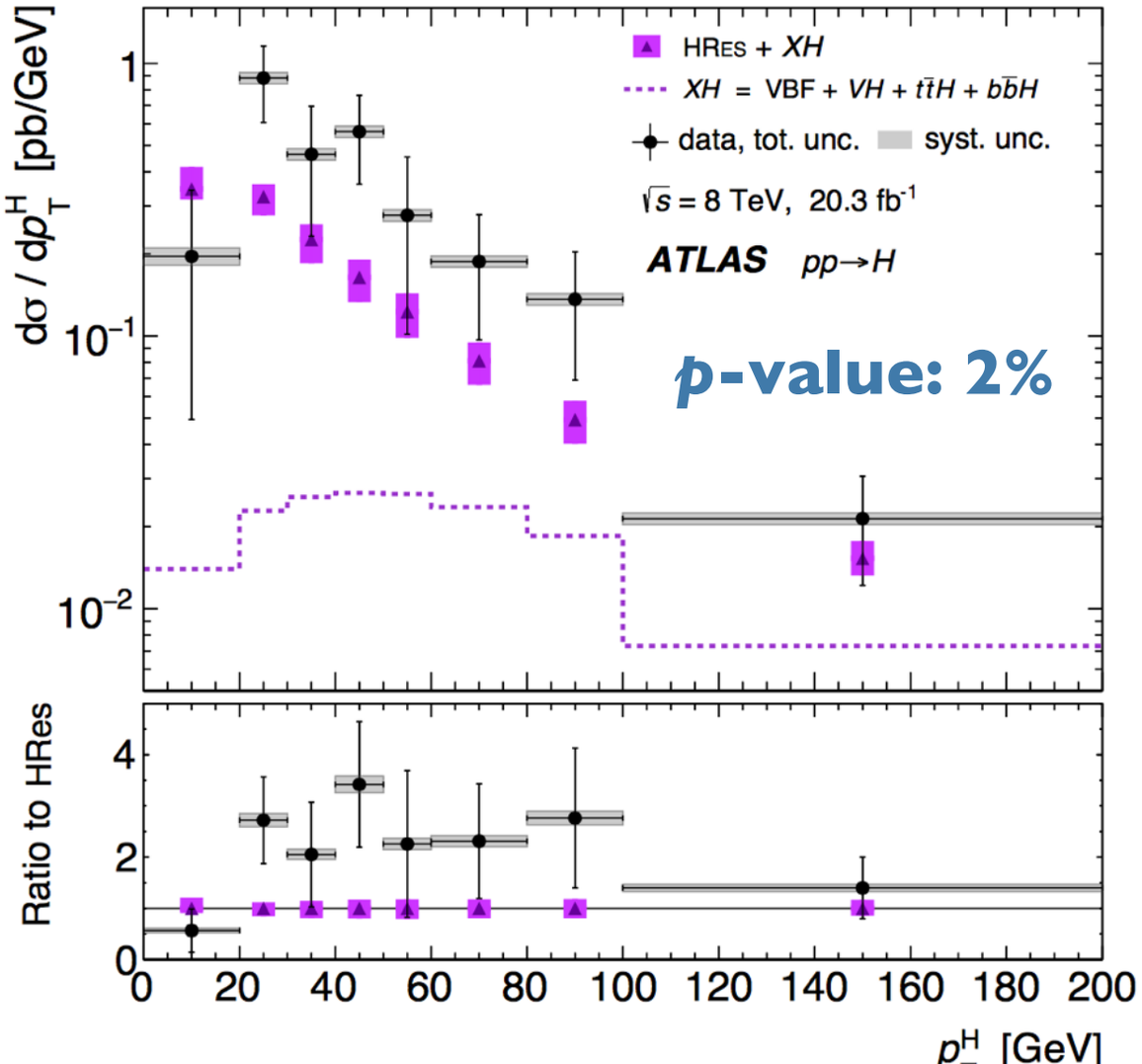
Total inclusive cross section measured by ATLAS is higher than state-of-art predictions

Combination: Differential XS (H→γγ, H→ZZ)

PRL. 115 (2015) 091801

- Differential XS from the combination of two channels
  - Compared to a range of theoretical estimates (including **HRes2**, **NNLOPS**, etc.).

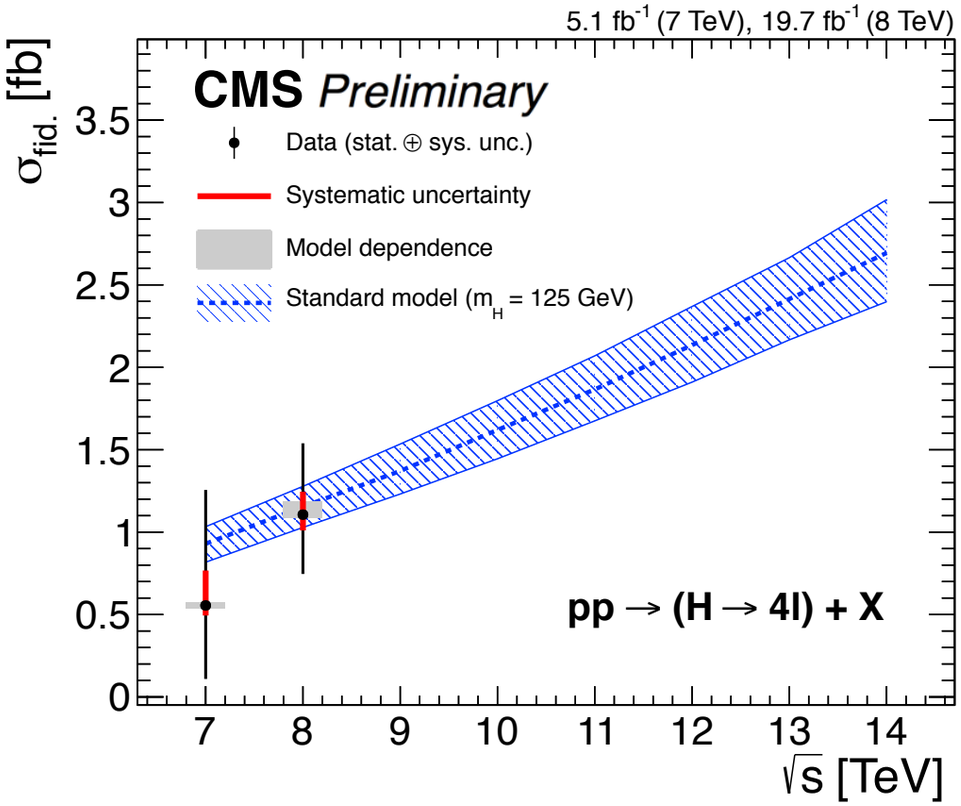


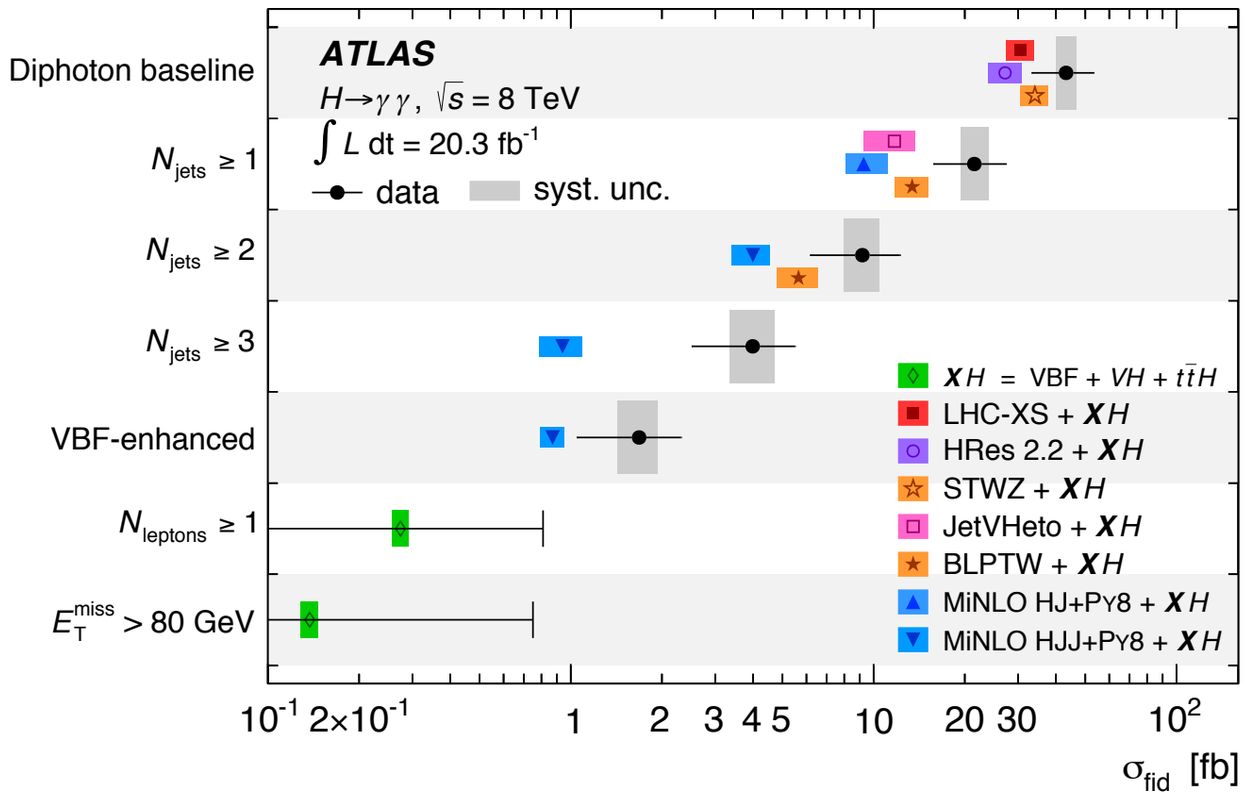


Measured cross section somewhat higher than predictions in all bins
(consequence that all ATLAS observations are higher than predicted)

Summary & towards the future

- **First measurements of inclusive and differential XS at 7 and 8 TeV**





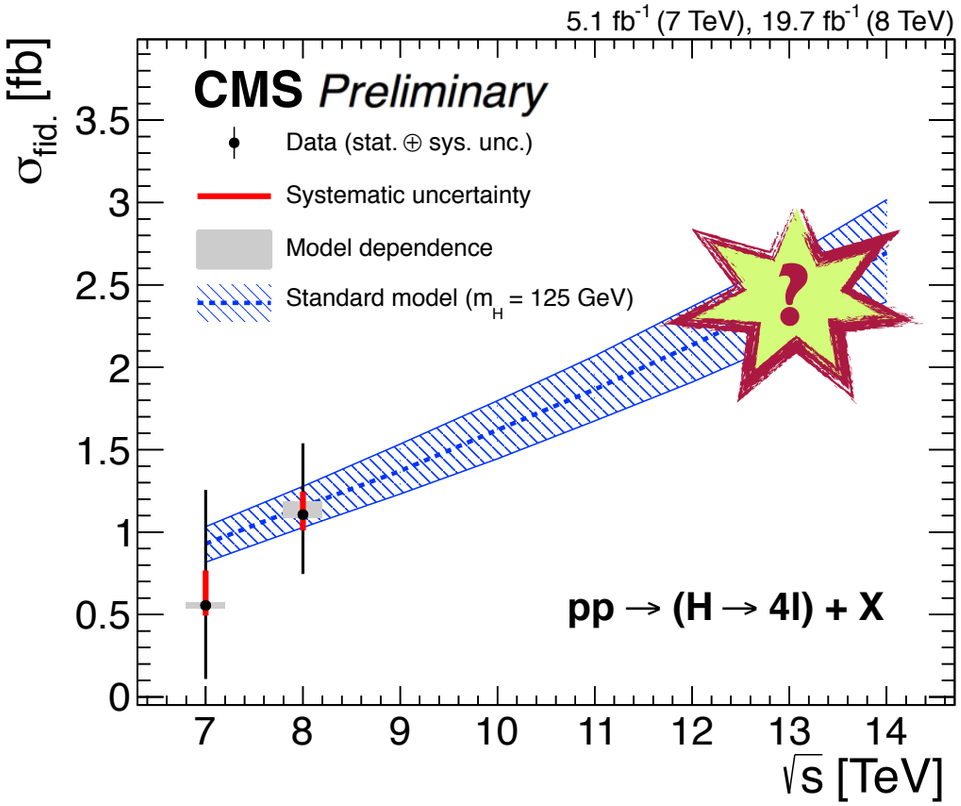
- **ATLAS & CMS**: no significant deviation from SM expectations

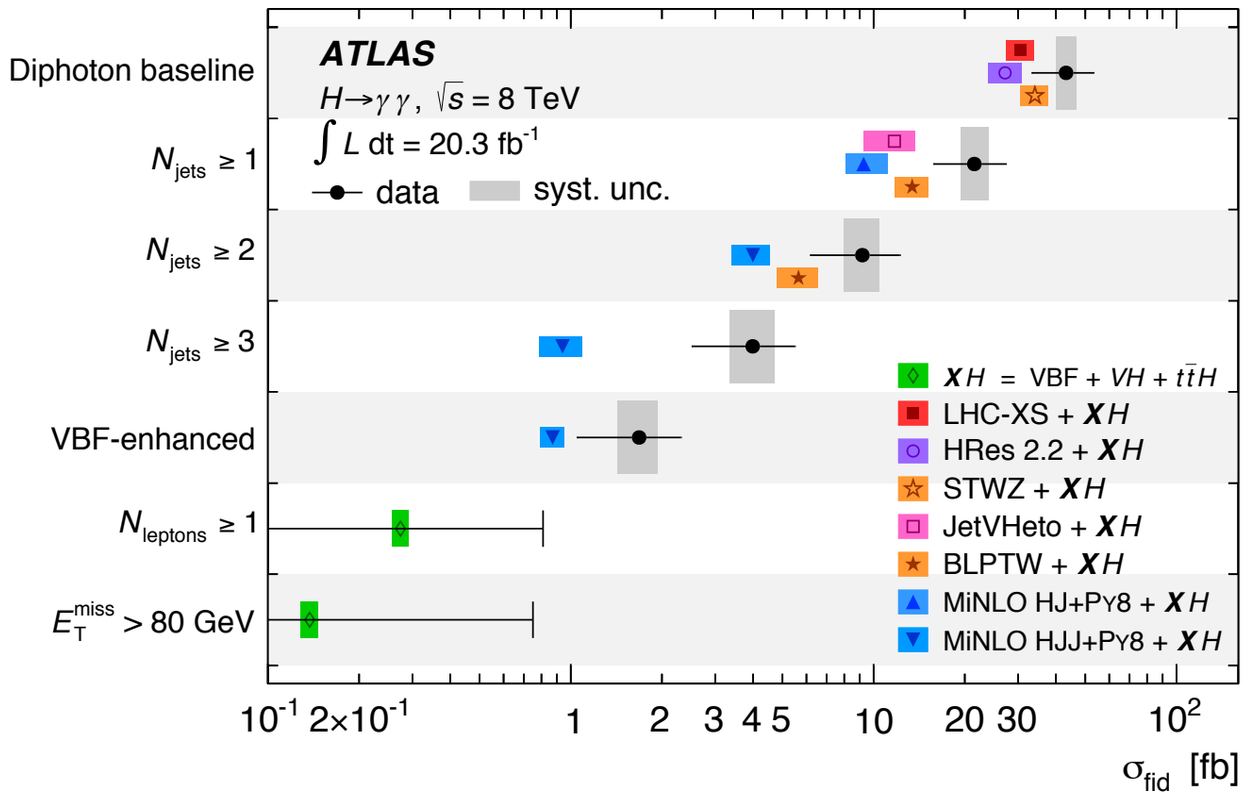
TOWARDS THE FUTURE

- **Exploit the results - example:** Constrains on non-SM Higgs boson interactions using H→γγ differential XS measurements by ATLAS (1508.02507, see plenary talk by K. Tackmann)
- **Harmonise approaches to fiducial XS measurements (within LHC HXS WG)**
  - Expect recommendation by the beginning of 2016 (YR4)
- Getting ready & looking forward to **Higgs boson measurements @ 13 TeV.**

Summary & towards the future

- **First measurements of inclusive and differential XS at 7 and 8 TeV**





- **ATLAS & CMS**: no significant deviation from SM expectations

TOWARDS THE FUTURE

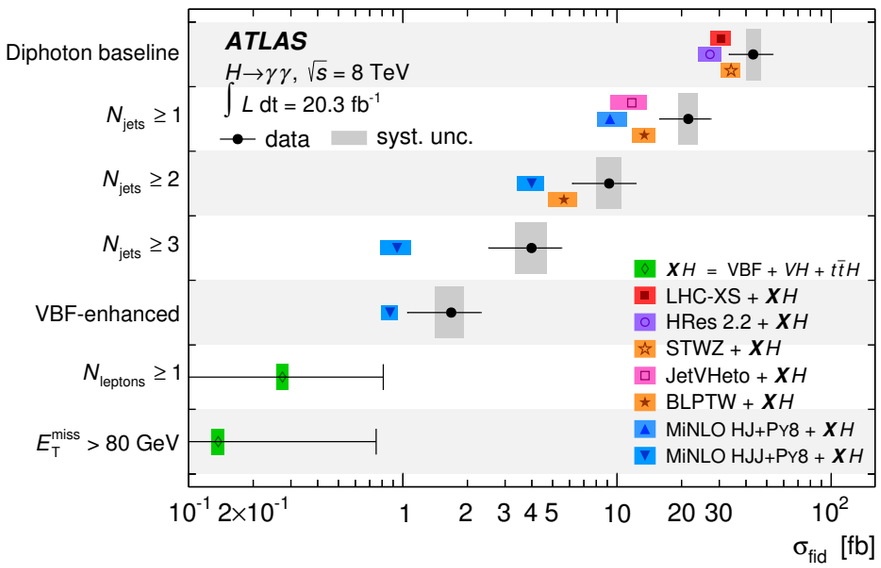
- **Exploit the results - example:** Constrains on non-SM Higgs boson interactions using H→γγ differential XS measurements by ATLAS (1508.02507, see plenary talk by K. Tackmann)
- **Harmonise approaches to fiducial XS measurements (within LHC HXS WG)**
  - Expect recommendation by the beginning of 2016 (YR4)
- Getting ready & looking forward to **Higgs boson measurements @ 13 TeV.**

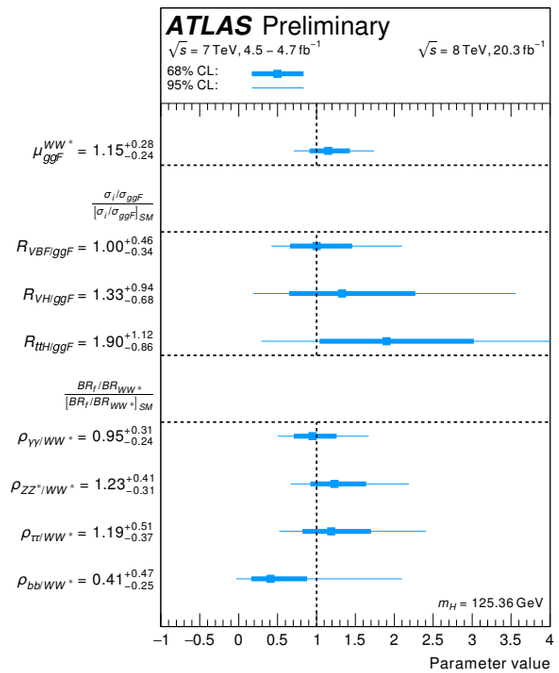
ADDITIONAL MATERIAL

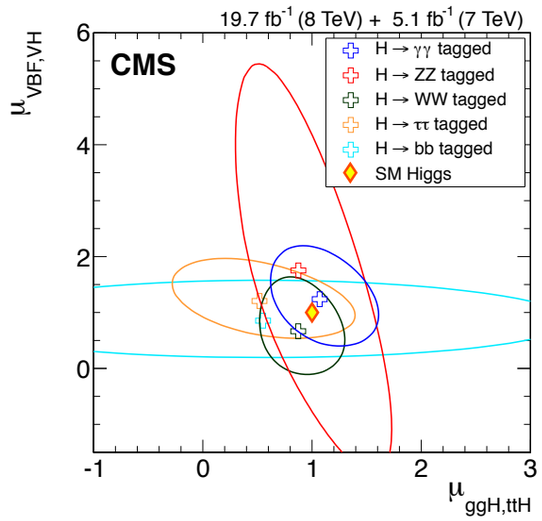
Modelling of processes @ higher orders

- **Three major improvements** in the theoretical Higgs modelling in 2015:
  - **N^{3}LO** cross section, **fully inclusive**
    [Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)]
  - **NNLO H+J** cross section, **fully exclusive**
    [Boughezal, Caola, Melnikov, Petriello, Schulze (2015)], [Boughezal, Focke, Giele, Liu, Petriello (2015)][Chen, Gerhmann, Glover, Jaquier (in progress)]
  - **NNLO VBF** cross section, **fully exclusive**
    [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)]
- **Improvements** in the theoretical modelling of VV' production:
  - **NNLO pp→VV'+X** cross section, **fully exclusive**
    [Catani, Cieri, de Florian, Ferrera, Grazzini; Grazzini, Kallweit, Rathlev (Vgamma)] [Gehrmann, Grazzini, Kallweit, Maieroefer, v. Manteuffel, Pozzorini, Rathlev, Tancredi (WW)] [Cascioli, Gehrmann, Grazzini, Kallweit, Maieroefer, v. Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs (ZZ)] [Grazzini, Kallweit, Rathlev (ZZ*, in progress)]

Simplified cross sections







Measurement

Interpretation

theory-independent

theory-dependent

Fiducial Cross sections

Coupling Fits

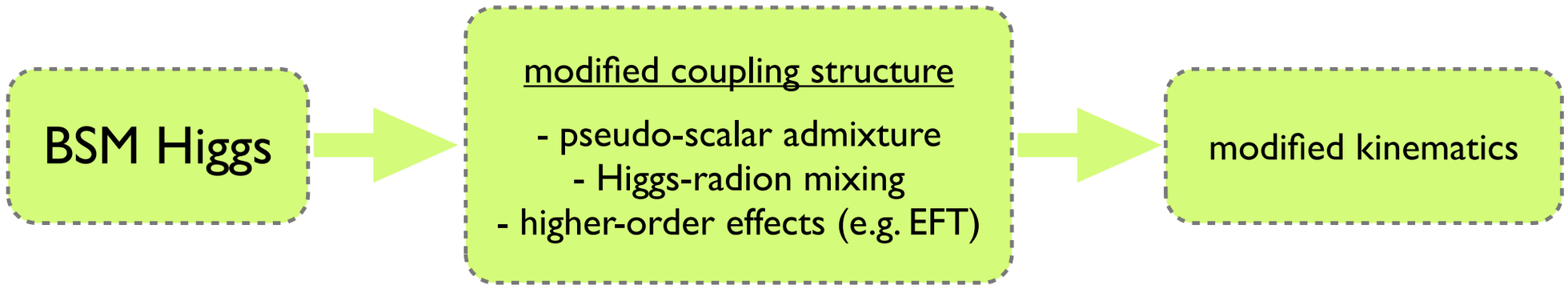
- Not everybody can measure fiducial cross sections; global analysis desirable.
- Idea: Place yourself somewhere in the middle of this picture.

e.g. $\mu_{gg\to H}$ ***old*** → $\mu_{gg\to H}^{0-jet}$ $\mu_{gg\to H}^{\geq 1-jet}$ $\mu_{gg\to H}^{\geq 2-jet+\mathrm{VBF}}$ ***new***

- Fiducial cross sections are defined for specific Higgs decay modes, whereas simplified cross sections focus on production modes; Fiducial cross sections can in principle also be used to derive simplified cross sections.

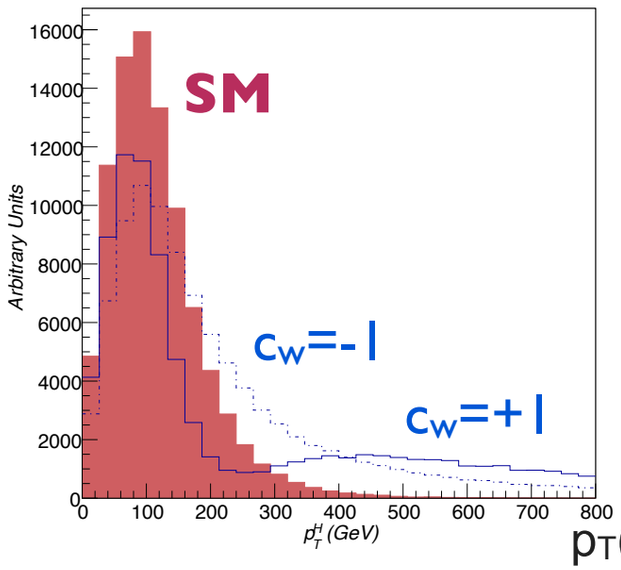
Sensitivity to BSM

- Fiducial cross sections (total or differential) offer a way to test BSM scenarios in which the kinematic distribution of the signal depends on the model parameters, leading to a change in the signal selection efficiencies w.r.t. the SM.



- Note that BSM typically affects production and decay processes
- Consider p_T, m_{jj}, η_{jj} , $\Delta\Phi$, inv. mass, etc. distributions
- Large effects may occur in extreme kinematic regions, where little or no SM signal is expected
- The same BSM may also affect the backgrounds
- Dedicated studies needed

Example of EFT effects in VBF production [V. Sanz]

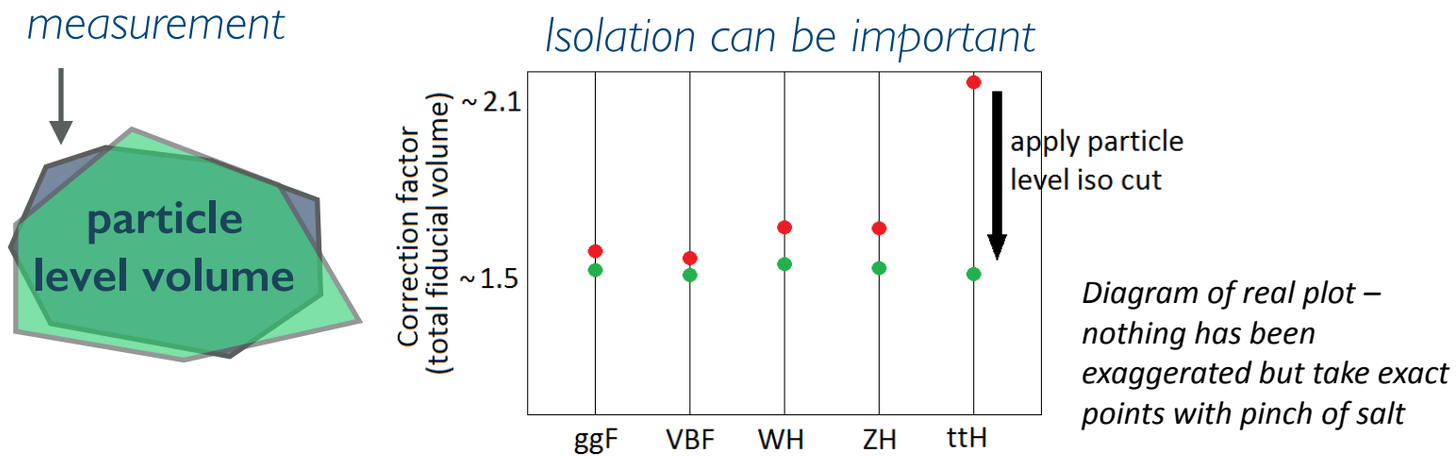


BSM review talk by Veronica Sanz at FXS kick-off meeting
https://indico.cern.ch/event/399923/session/3/contribution/14/attachments/800903/1097616/HXSWG_fiducial.pdf

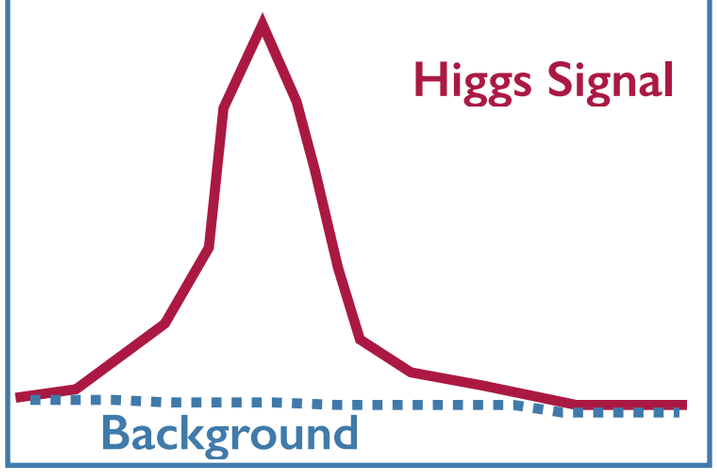
Approaches to the measurement

- **Measurements typically follow these steps**

Step A: Find/design the fiducial volume close to the reconstructed volume to minimise the model dependence



Step B: Measure signal yields by subtracting background



Step C: Reverse detector effects (migrations in and out the fiducial volume, migrations between bins of differential observables).

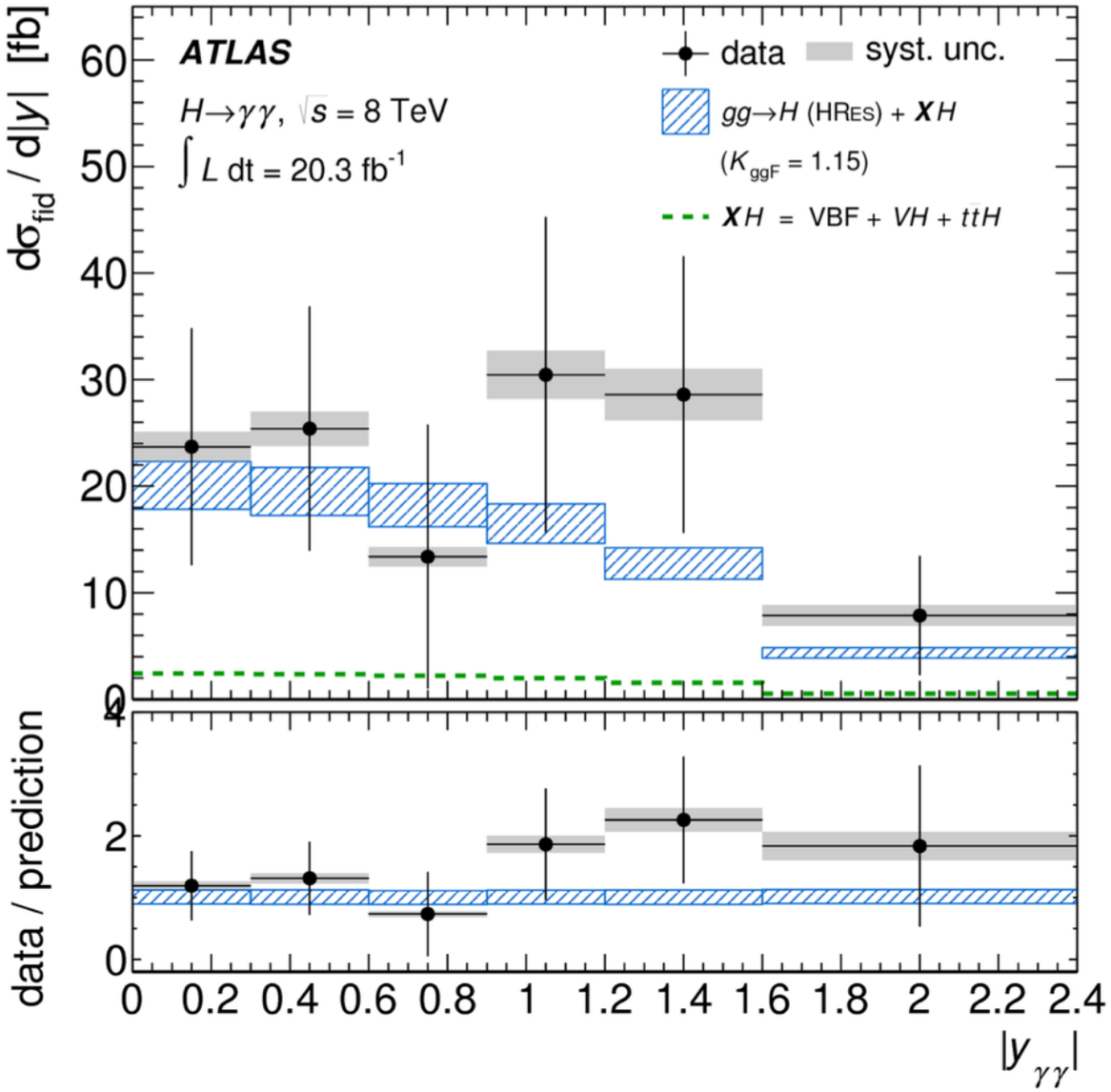
This is typically called '**unfolding**'.

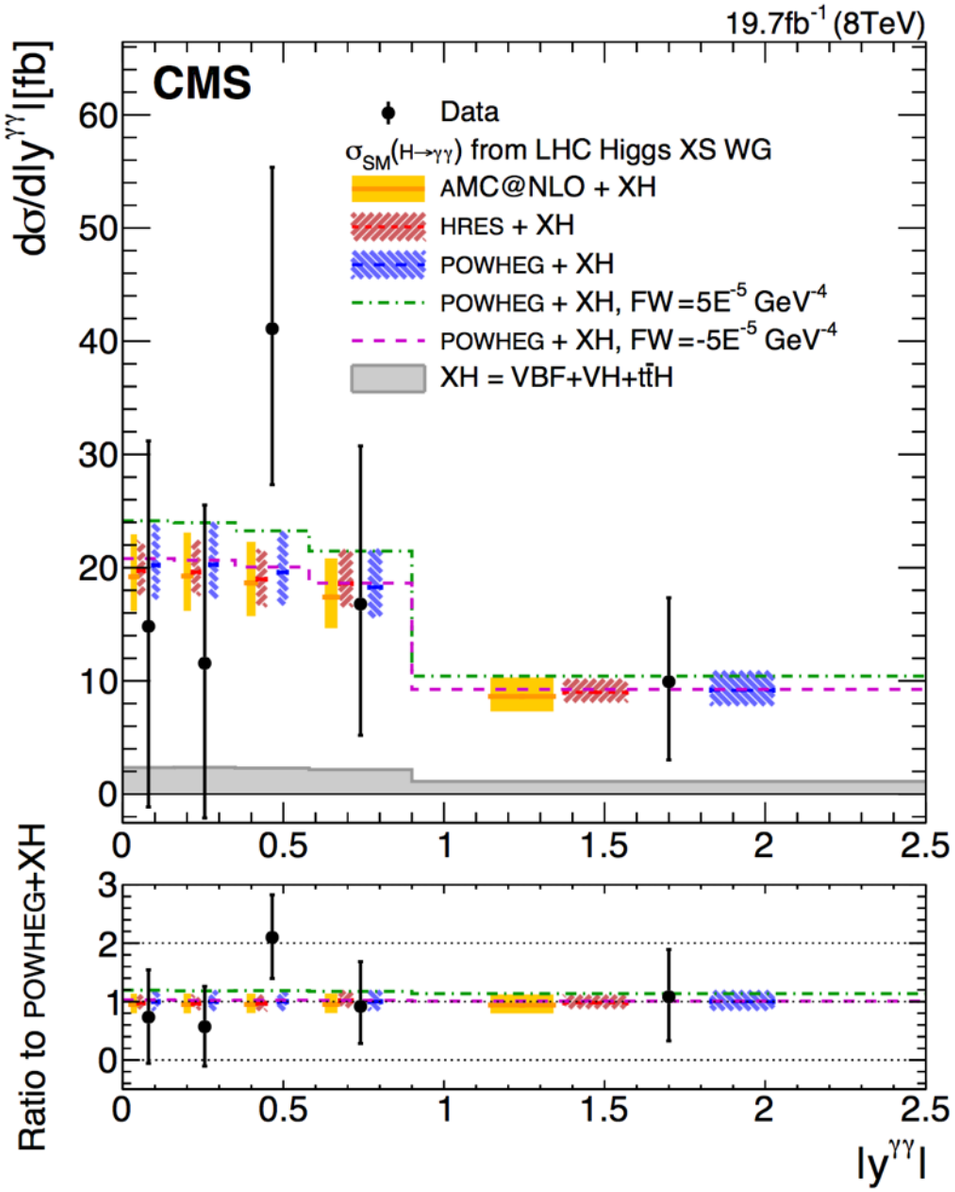
Step D: Carefully evaluate the remaining model dependence from experimental and theoretical assumptions.

- **Steps B and C sometimes performed as one step (signal fit + unfolding)**

Differential cross sections: H→γγ

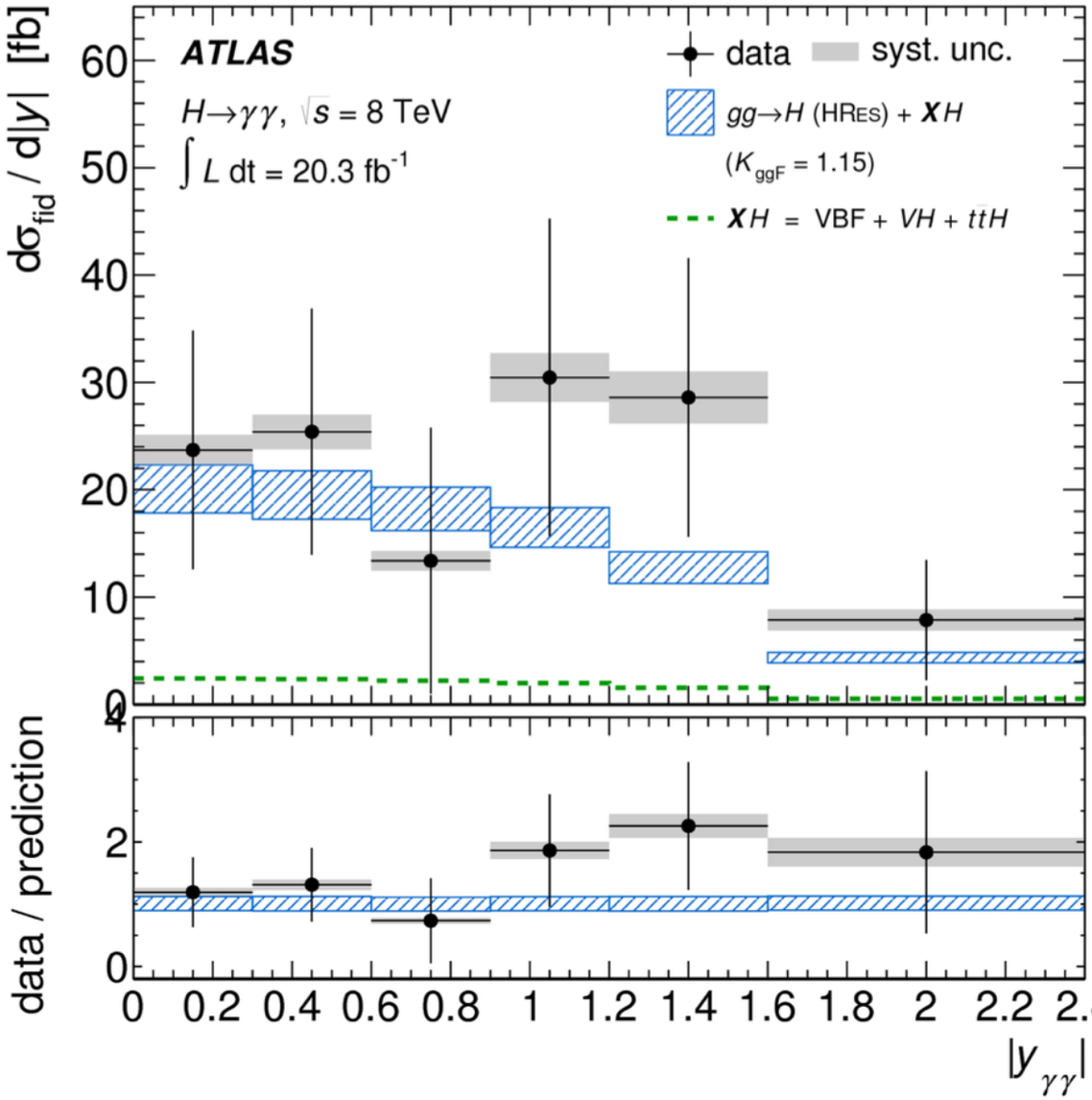
- Measured as a function of **Higgs candidate kinematic properties:**
  - **$p_T(H)$:** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions**

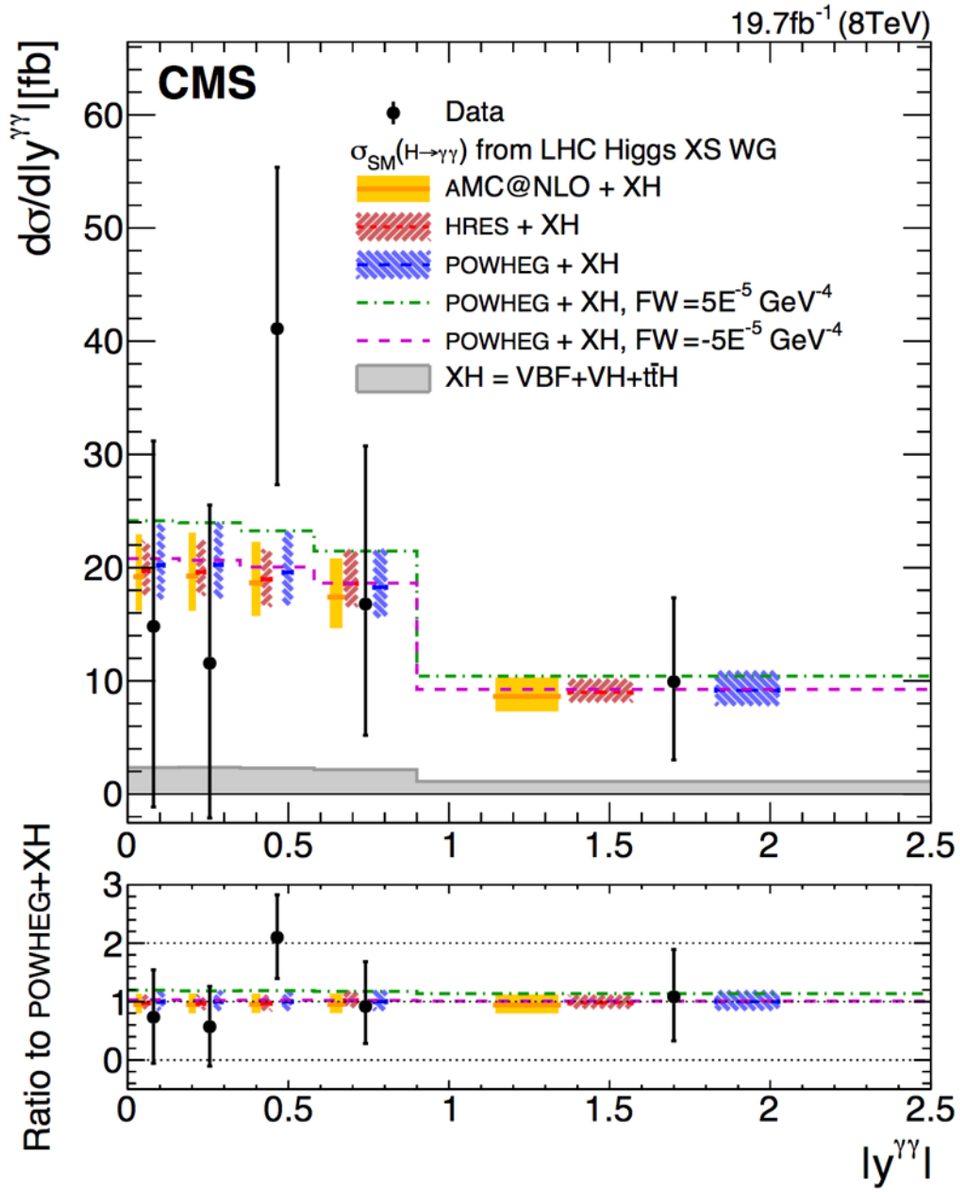




Differential cross sections: H→γγ

- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions**

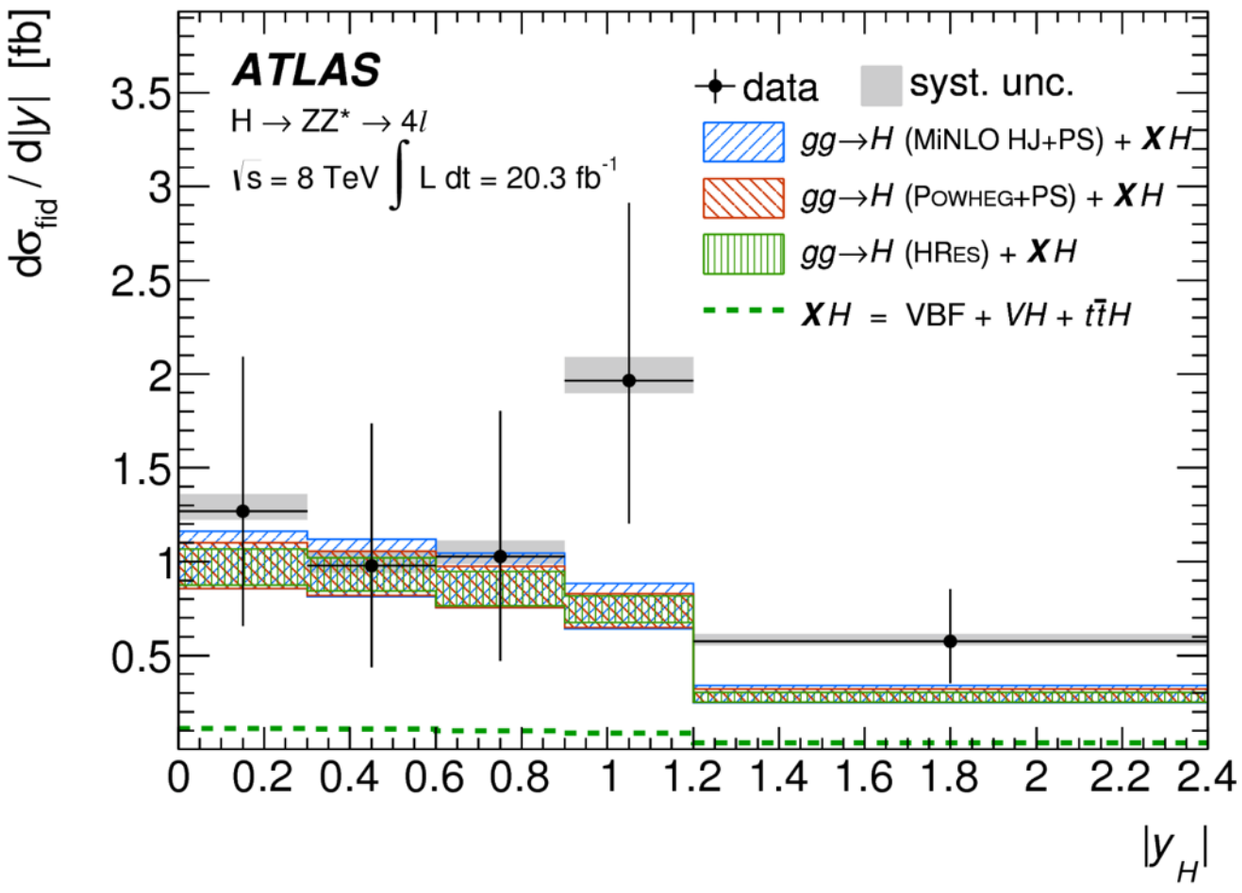


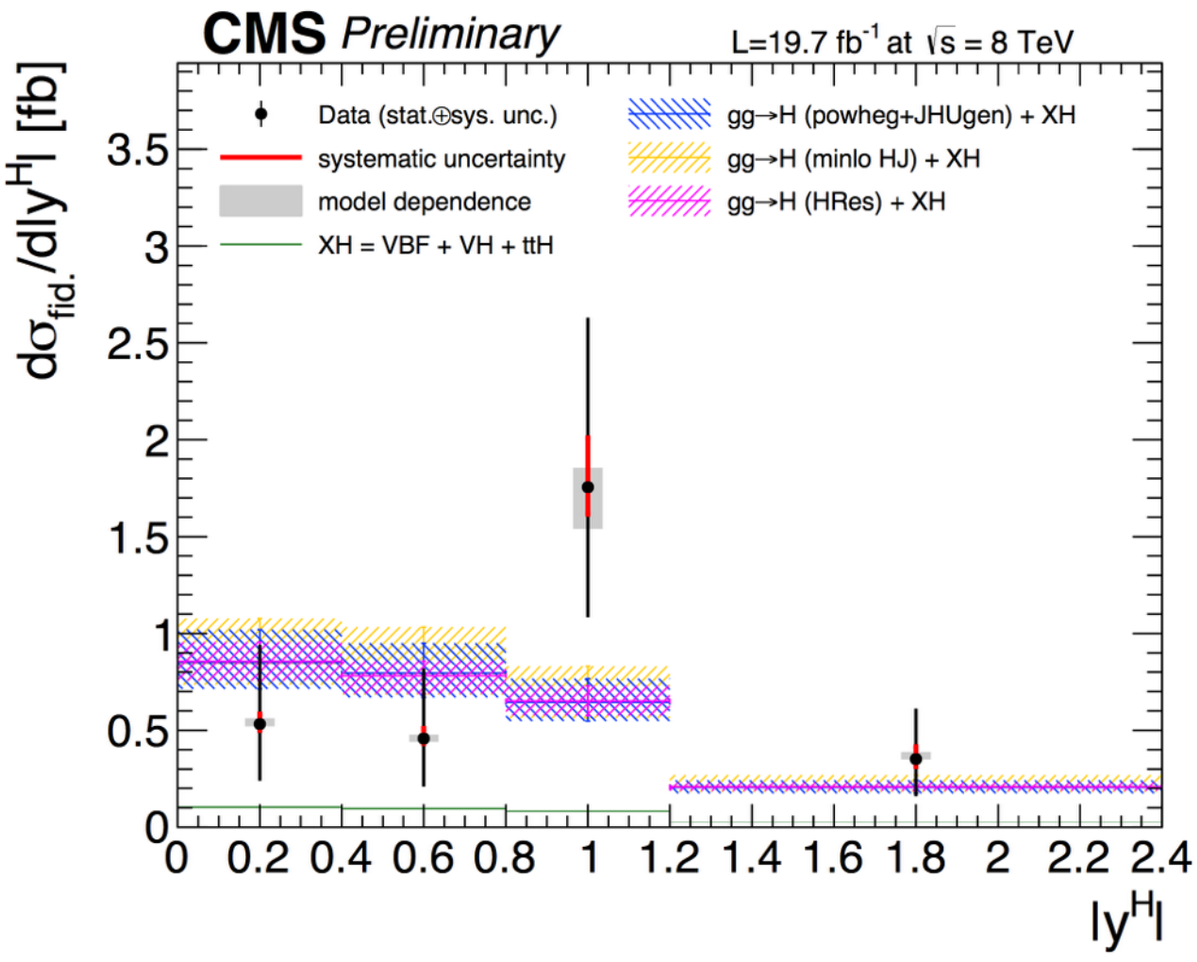


good agreement with theoretical estimates and between experiments

Differential cross sections: H→ZZ→4l

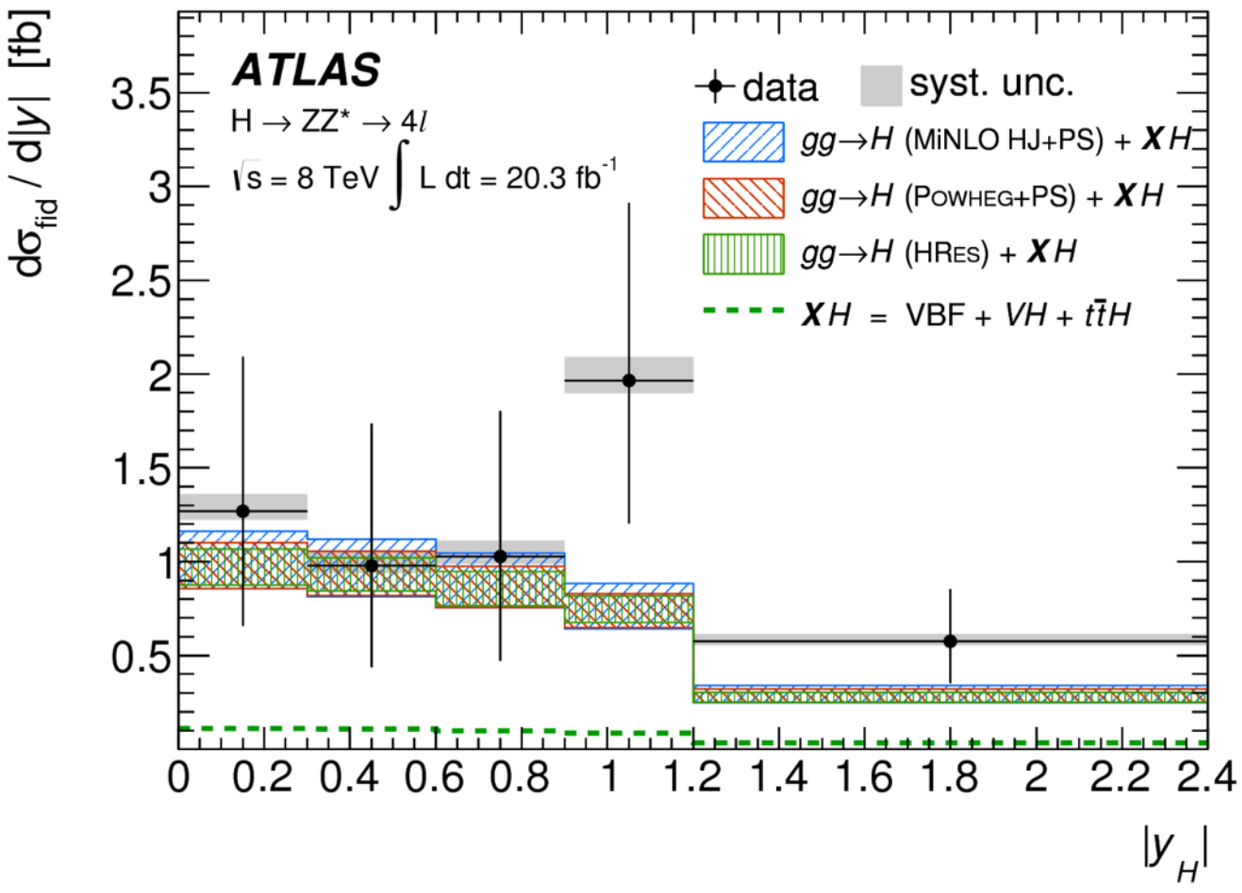
- Measured as a function of **Higgs candidate kinematic properties:**
  - **$p_T(H)$:** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions**

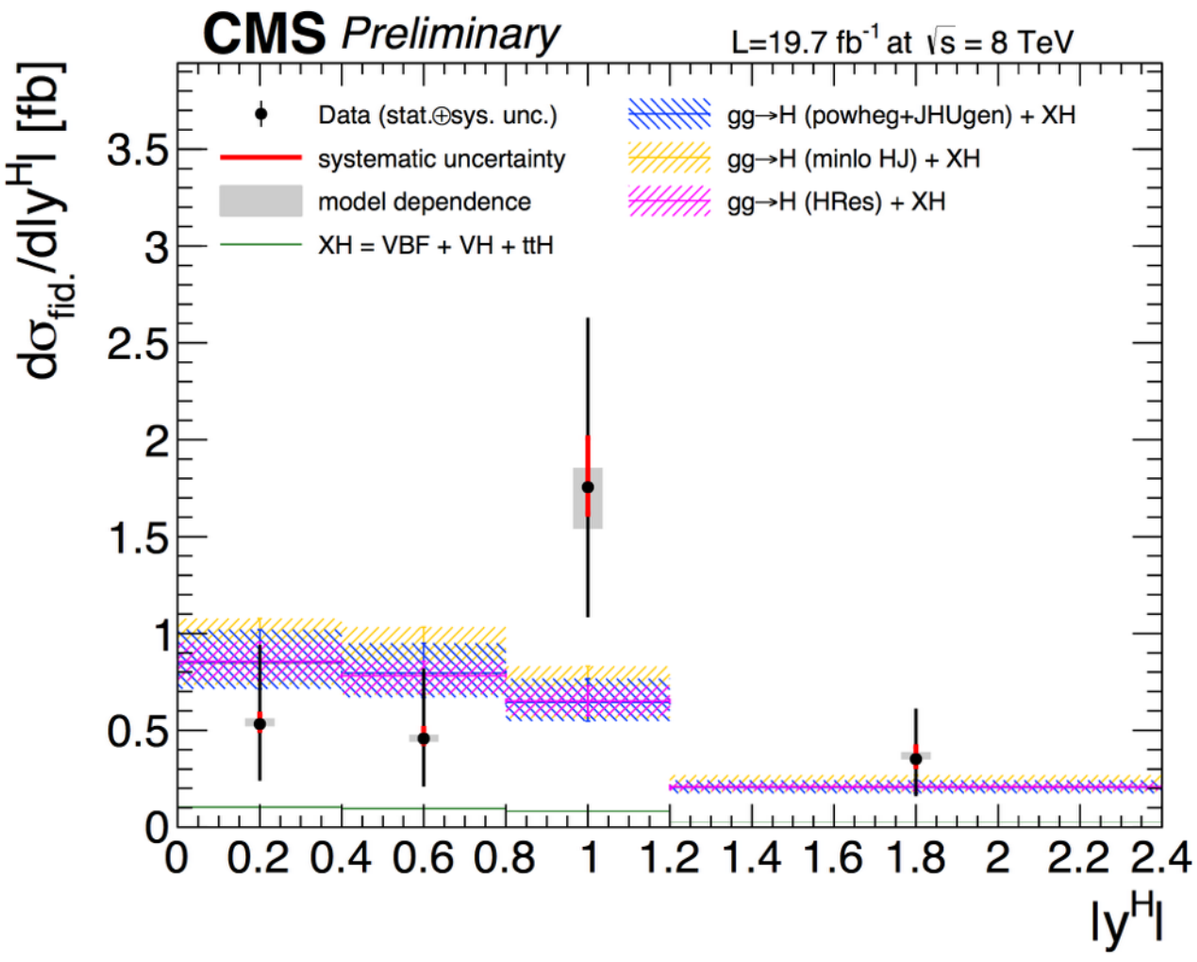




Differential cross sections: H→ZZ→4l

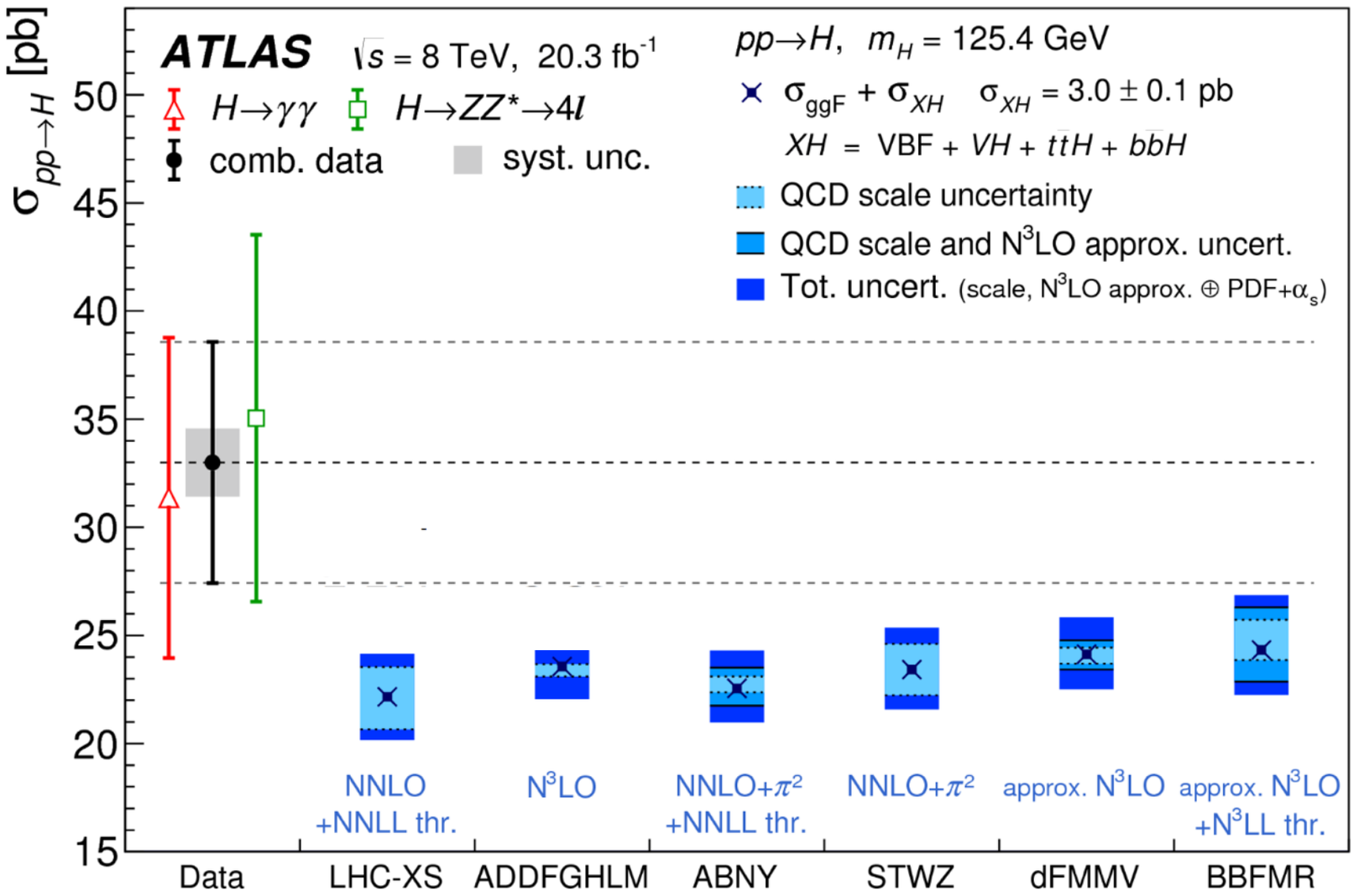
- Measured as a function of **Higgs candidate kinematic properties:**
  - **p_T(H):** sensitive to **production mode, new physics** in gg→H loop
  - **|y(H)|:** sensitive to **production mode, parton distribution functions**





good agreement with theoretical estimates and between experiments

Combination: Inclusive XS (H→γγ, H→ZZ)



Total cross section estimates:

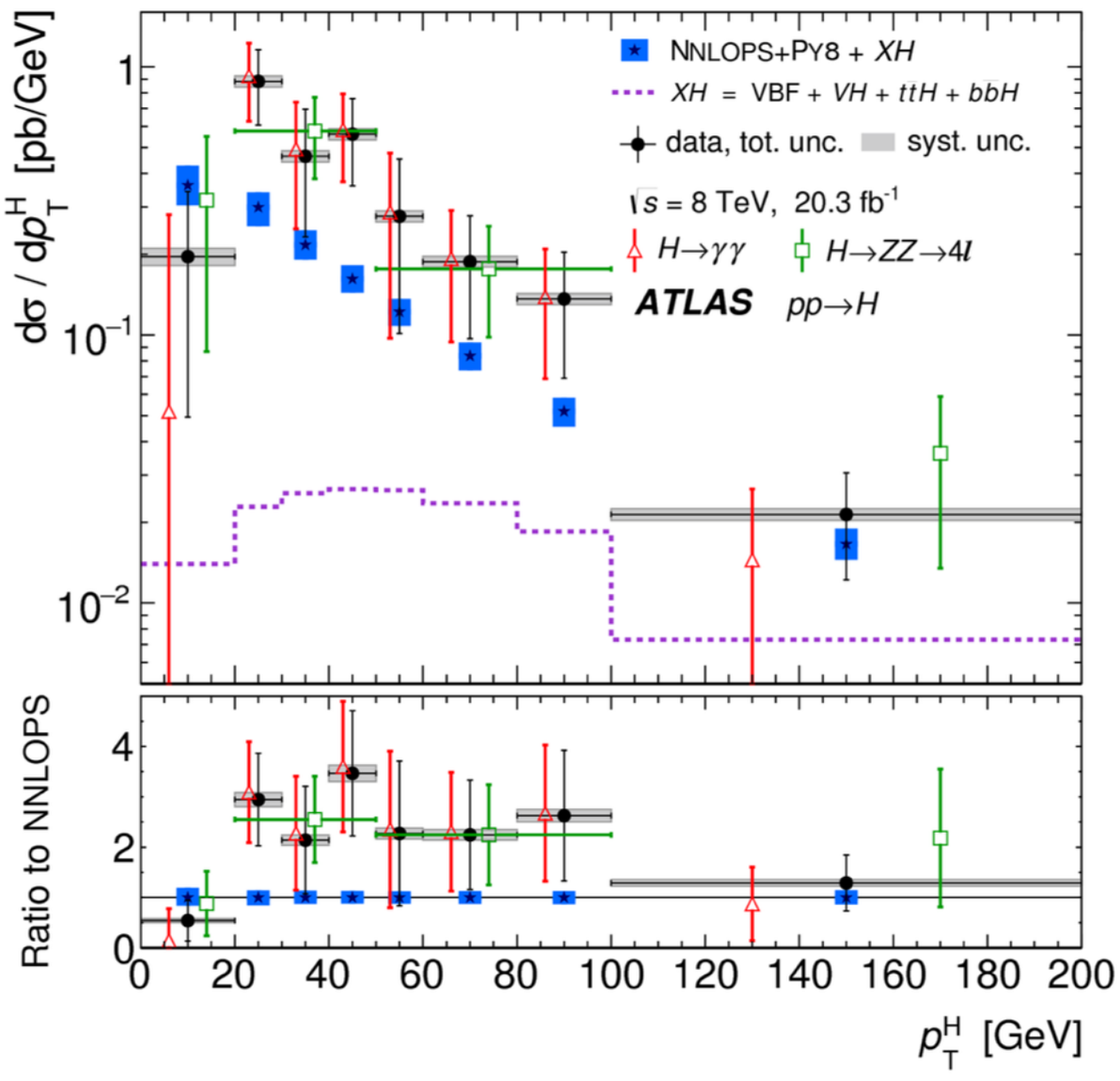
LHC-XS	NNLO+NNLL[a,b,c]
ADDFGHLM	N³LO[a,b,c]
ABNY	NNLO+NNLL[a,b,c,d,e]
STWZ	NNLO[c,d]
dFMMV	approx. N³LO[c]
BBFMR	approx. N³LO+N³LL[a,b,c]

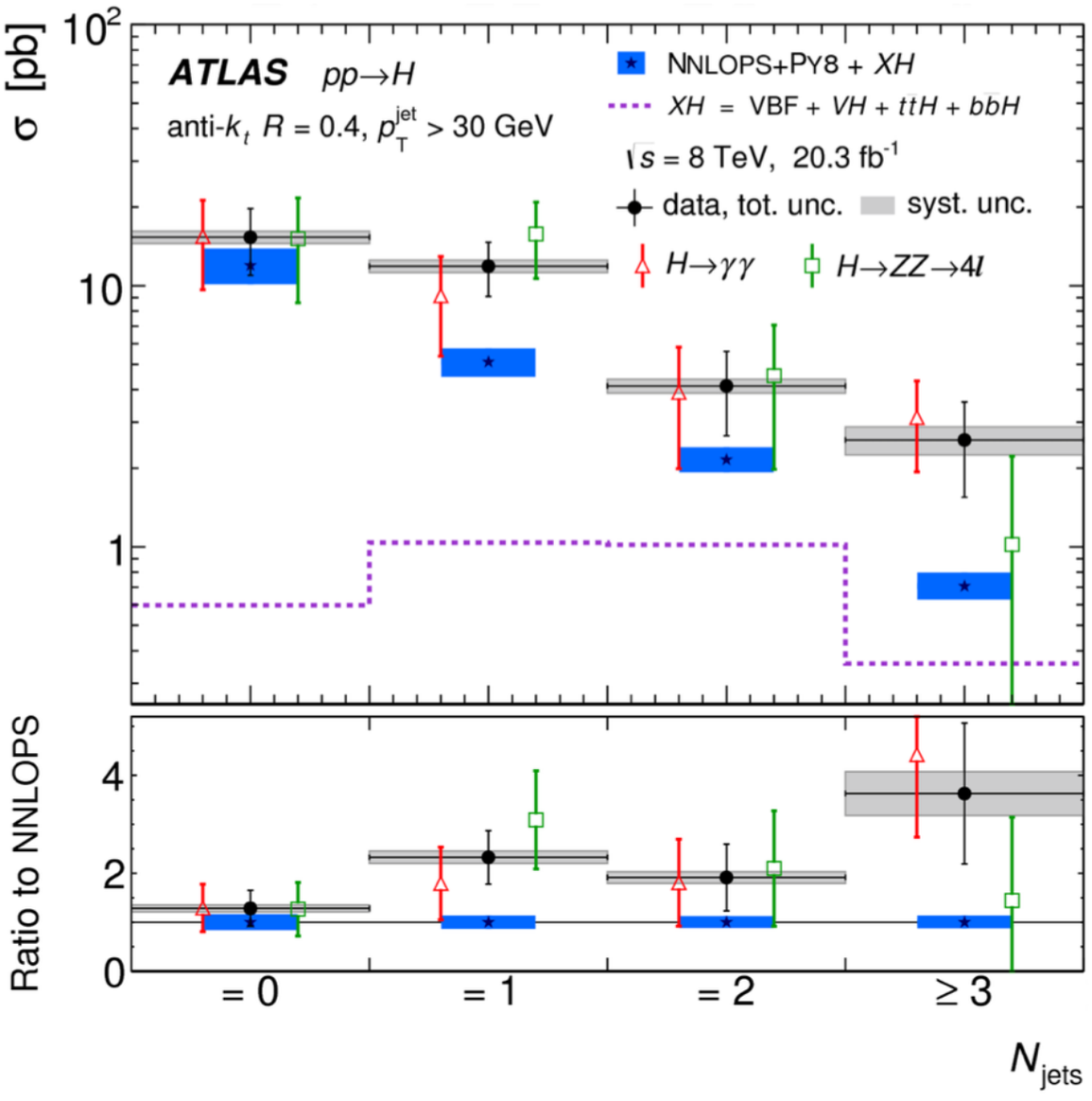
Cross section measured by ATLAS higher than all state-of-art predictions:

H → 4l:	35.0 ± 8.4 (stat) ± 1.8 (sys) pb
H → yy:	31.4 ± 7.2 (stat) ± 1.6 (sys) pb
Combined:	33.0 ± 5.3 (stat) ± 1.6 (sys) pb

Combination: Agreement between the channels

- Very good agreement between H → ZZ → 4l and H → γγ results in all variables
  - p-values higher than 56%

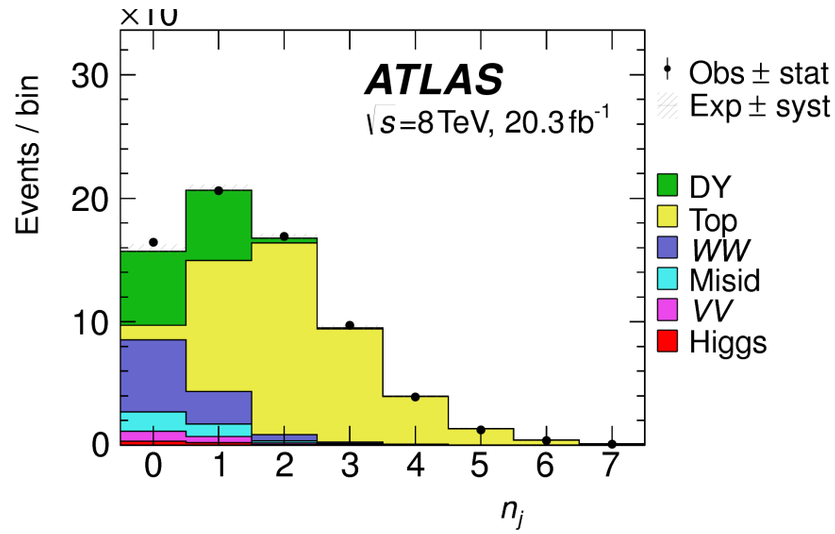


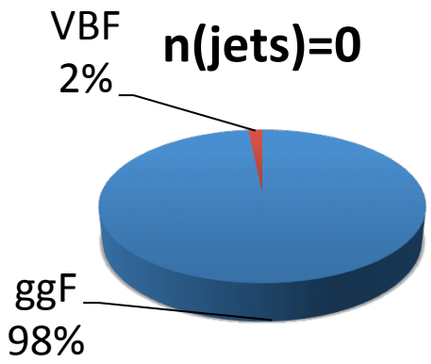


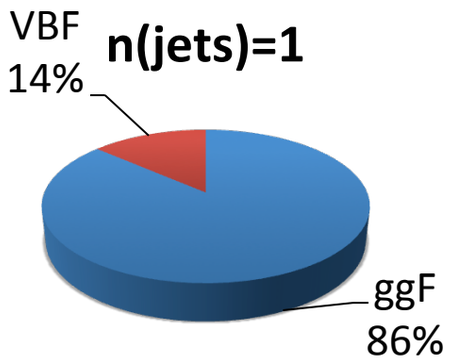
Cross sections from 2l2ν, 2 fermions?

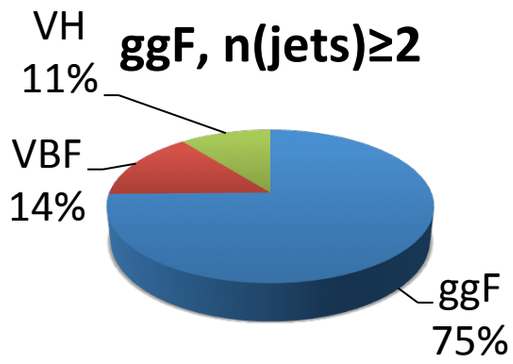
Both Experiments are considering measurement in WW

- Very challenging; jet binned analyses makes it hard to get correlations between signal regions right. Also non-trivial to define fiducial volume.
- Large amount ob background.
- Analysis is sensitive to different production mechanisms.









Combination of measurements

Combination between experiments:

- Potential to **combine inclusive and differential cross sections** (need harmonisation in fiducial objects, bin edges, unfolding, etc.)
- Choose **common fiducial** or **inclusive phase space?**
- Benefit form the HCG experience, start harmonization in time

} still to be discussed