Fiducial and differential measurements of Higgs boson production cross sections at the LHC

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References:

ATLAS $\gamma\gamma$:	JHEP 1409 (2014) 112
ATLAS 4l:	Phys. Lett. B738 (2014) 234-253
ATLAS combination:	Phys. Rev. Lett. 115, 091801 (2015)
CMS $\gamma\gamma$:	arXiv:1508.07819 (submitted to EPJC)
CMS 4l:	CMS-PAS-HIG-14-028

The Higgs boson as a probe for new physics

The Standard Model of particle physics is not complete,

among other things it cannot explain many cosmological observations

Examples:

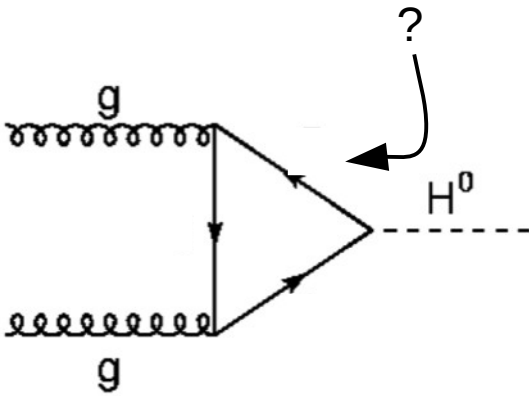
- **gravity**
- **matter-antimatter asymmetry in the universe**
- **existence of dark matter**

The discovery of the Higgs boson in 2012

opened a new sector of investigations

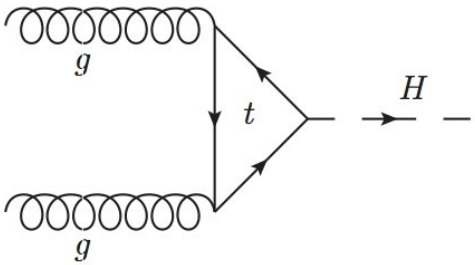
Examples:

- **search for new particles interacting with the Higgs, like dark matter**
  - **in the ggF production loop**
  - **in association with the Higgs boson**
  - **in Higgs boson decays**
- **search for additional Higgs bosons (SUSY predicts at least 5)**

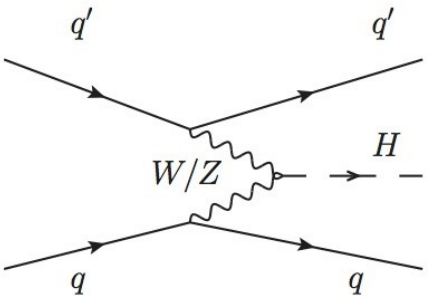


Higgs boson production and decay

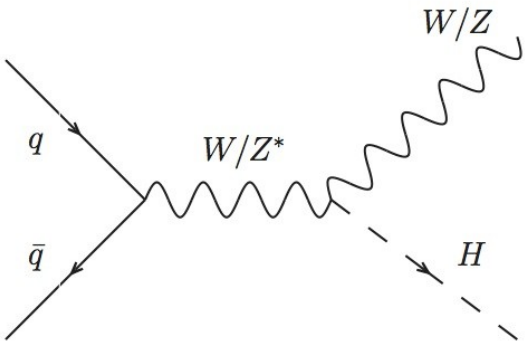
SM production modes (fractions at 8 TeV)



ggF (86.1%)

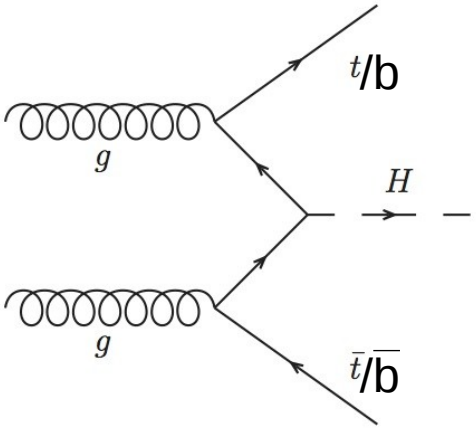


VBF (6.9%)



c)

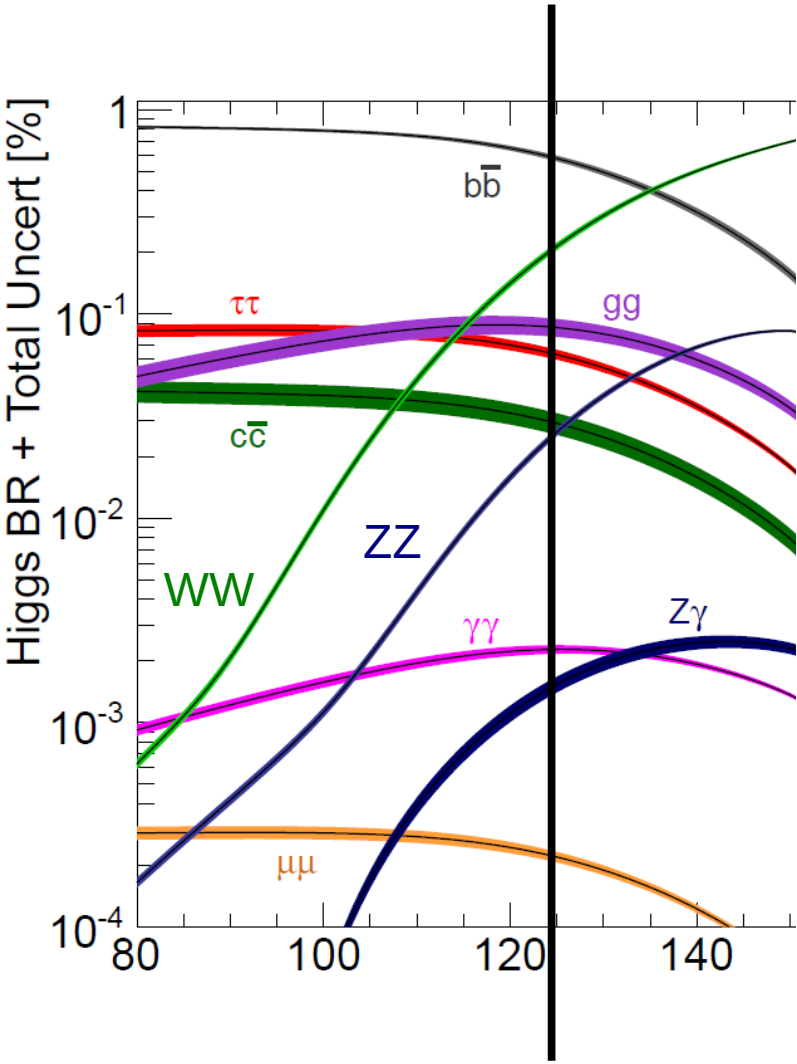
VH (4.9%)



d)

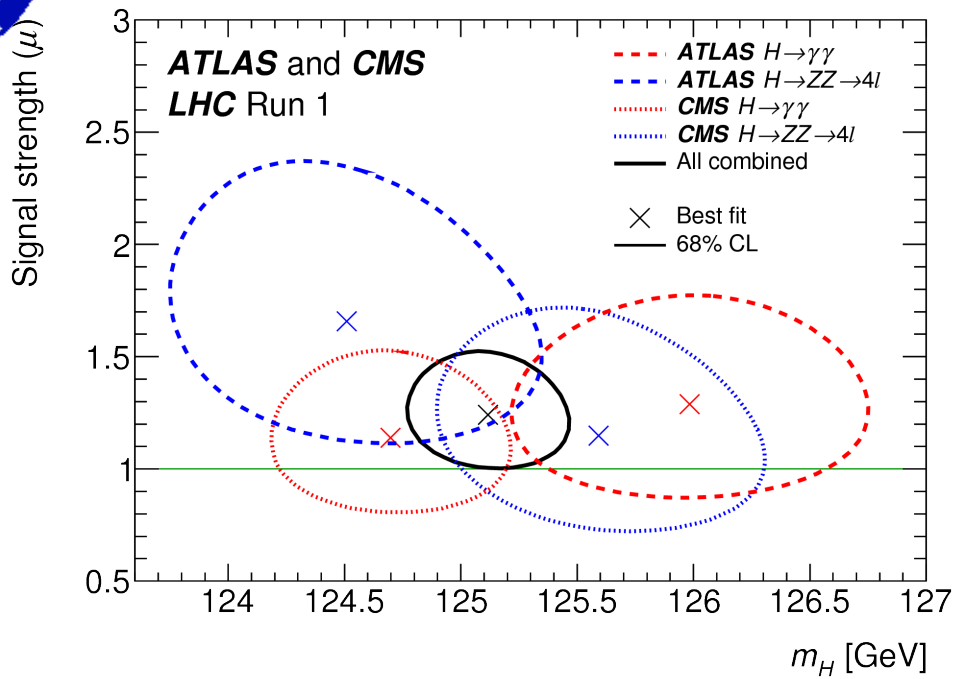
ttH, bbH (2.2%)

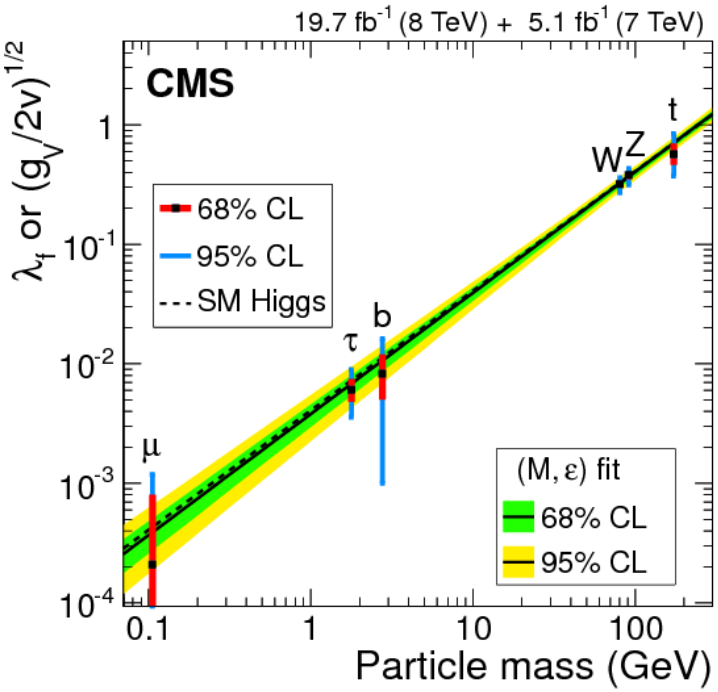
Decay branching fractions



125 GeV

The Higgs boson – property measurements at the LHC





Measured properties

- mass 125.09 GeV (125.4/125.0 for shown measurements)
- spin/CP = 0+
- couplings: agreement with SM predictions
- differential cross sections

Cross section definitions

Number of measured signal events

Cross section

$$\sigma_i = \frac{N_{reco,i}}{c_i * A_i * L * B}$$

bin i

Branching fraction

Integrated luminosity

Correction for detector efficiency

Acceptance

Fiducial cross section
=
cross section in fiducial volume
(cuts applied to generated events)

$$\sigma_{fid,i} * B = \frac{N_{reco,i}}{c_i * L}$$

Fiducial volumes depend on event selection/decay channel

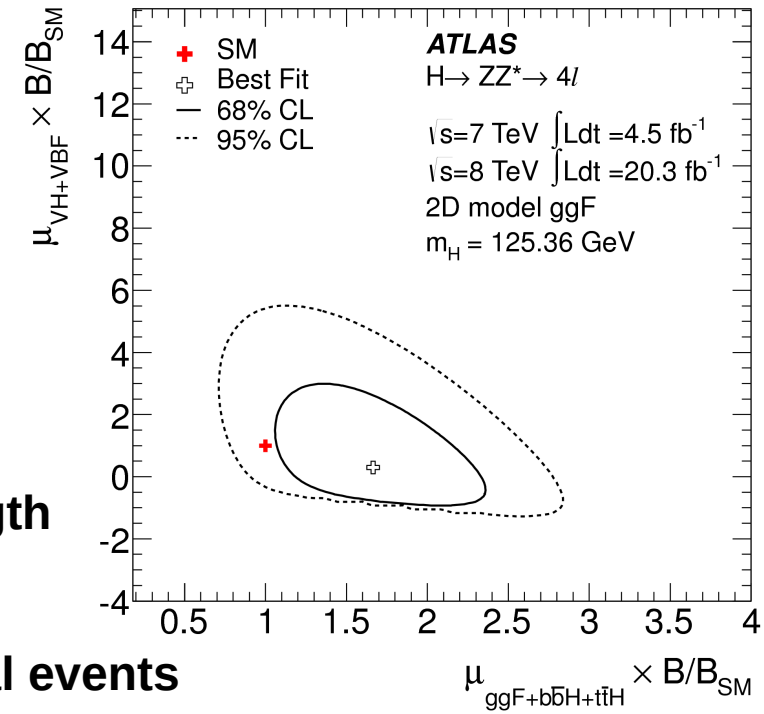
Why fiducial cross sections?

Correction for detector effects

- **easy interpretation for theorists**
- **preserve measurements for posterity**

No acceptance correction

- **less model dependence**



Compared to measurements of signal strength

- **signal strength is a ratio:**

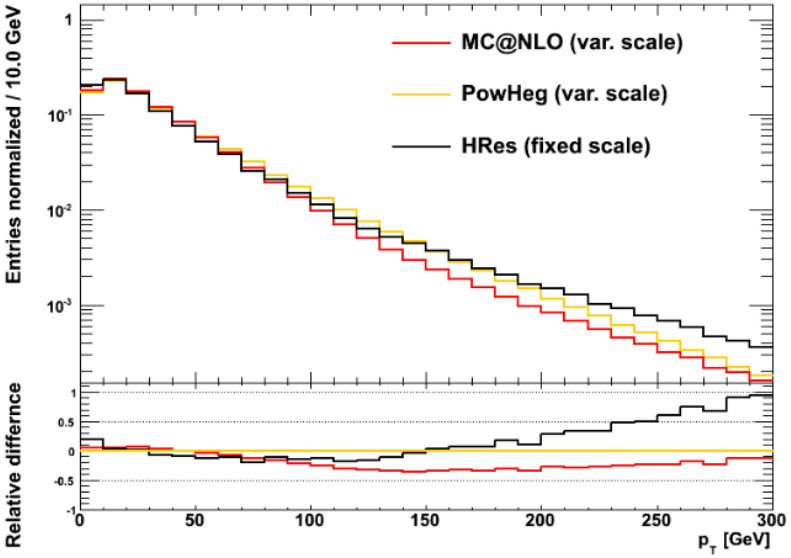
  observed signal events/expected signal events
- **legacy from the search phase**
- **entangles experimental with theoretical uncertainties**
- **often split into categories with SM assumptions**

Why differential cross sections?

Properties of the Higgs boson

1. check of SM calculations,
and MC generators used in the analyses
feedback to theory groups

2. deviations from the Standard Model
predictions could be due to new physics



Example Higgs p_T:

- **modification of the spectrum due to production in association with dark matter**
- **low p_T sensitive to quark couplings**
- **high p_T tail sensitive to modified couplings at high energies**

Pick variables

- fiducial cross section

- Higgs kinematics
    - Higgs p_T, rapidity

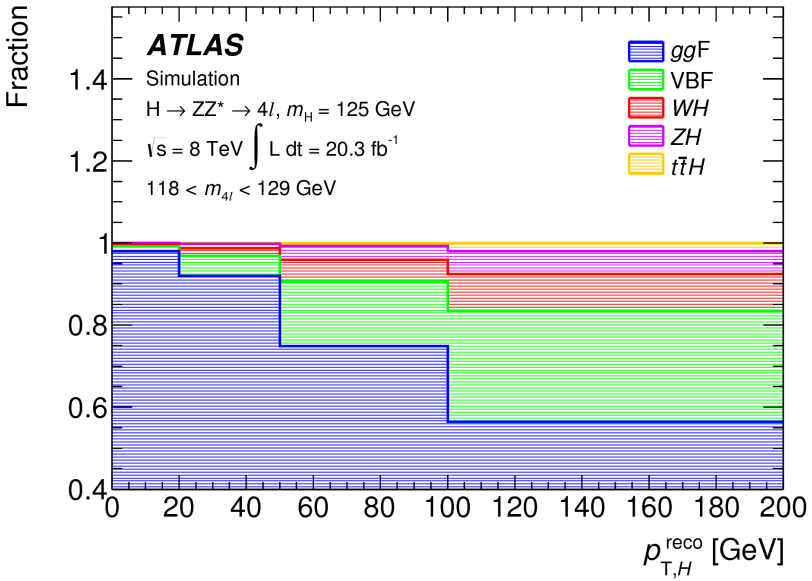
→ sensitive to production modes, QCD modeling, PDF

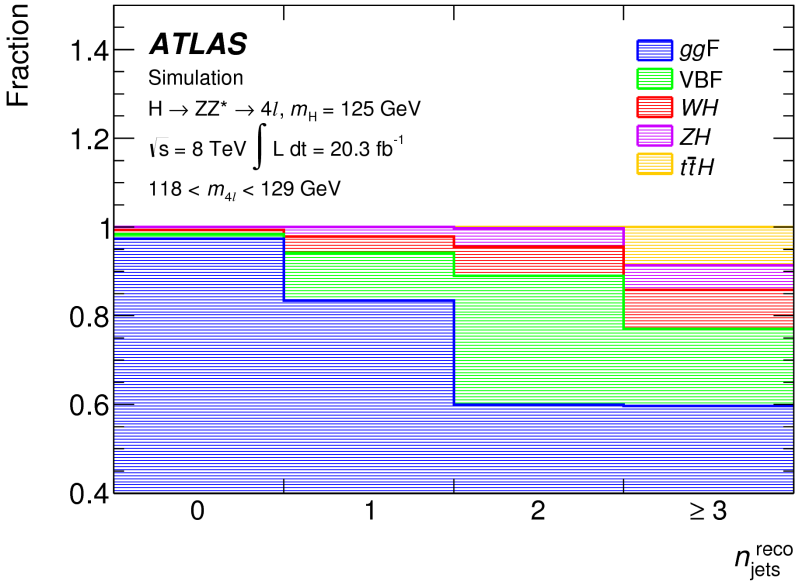
- Jet properties
    - njets, leading jet p_T,
    - VBF sensitive variables

→ sensitive to production modes, QCD modeling

- Decay variables
    - like $|\cos\theta^*|$ (angle between Z/γ and incoming quark)

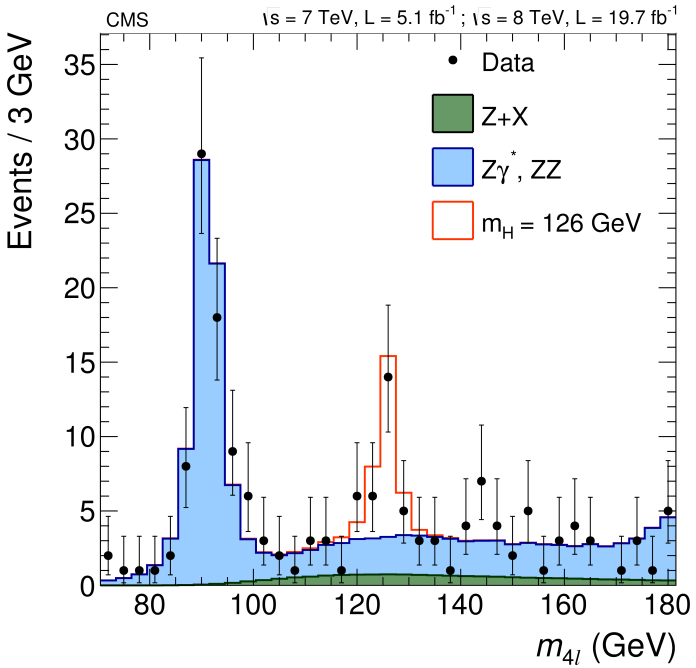
→ sensitive to spin/CP of Higgs boson

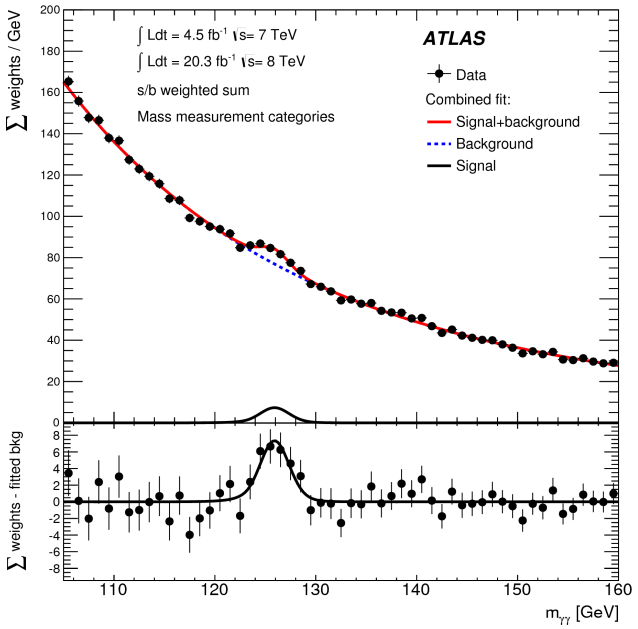




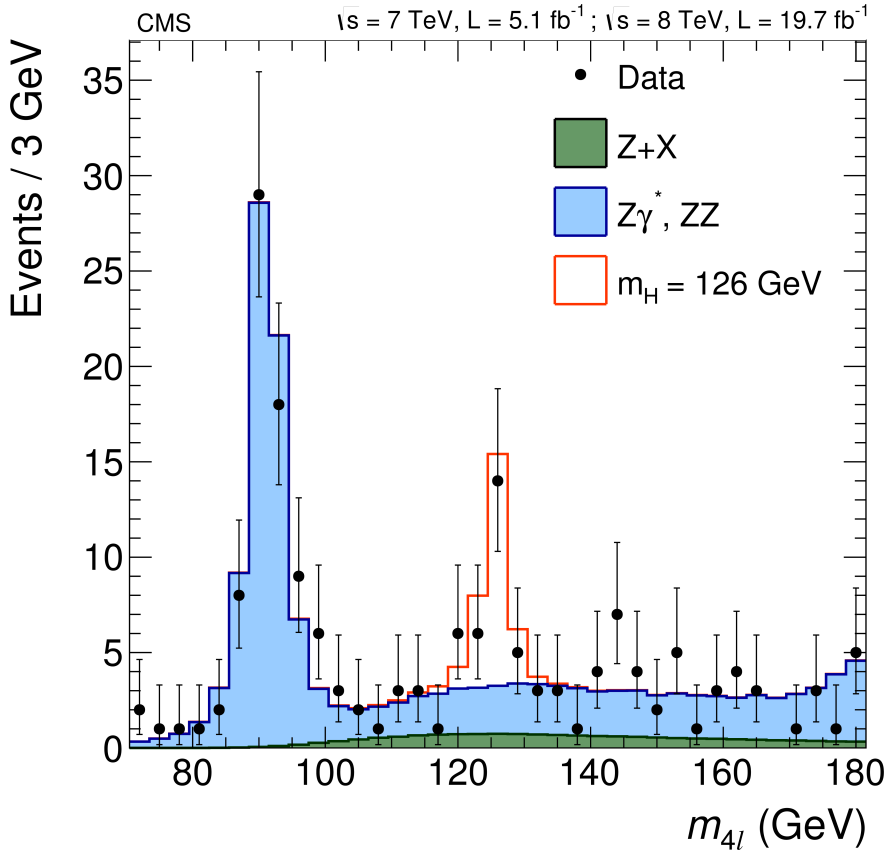
Part 1: H → 4l and H → γγ analyses

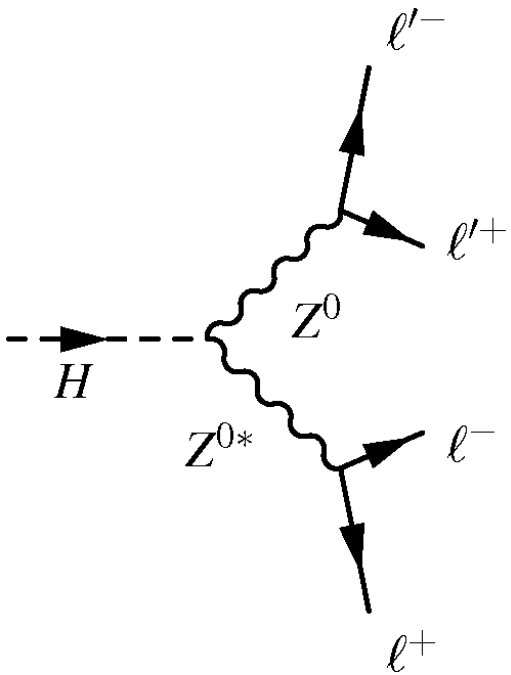
ATLAS & CMS





The H → 4l channel





- 4 leptons in the final state, full reconstruction of Higgs kinematic variables
- small backgrounds due to requirement of 4 isolated leptons
  - ZZ, WZ, Z+jets, top pairs (leptons from heavy flavor decays, faked by hadron jets)
  - S/B around 125 GeV: 2-3
- statistically limited in run 1 due to small branching fraction:

  ATLAS had 15.6 expected signal events after event selection for 8 TeV data

Signal extraction in the H → 4l channel

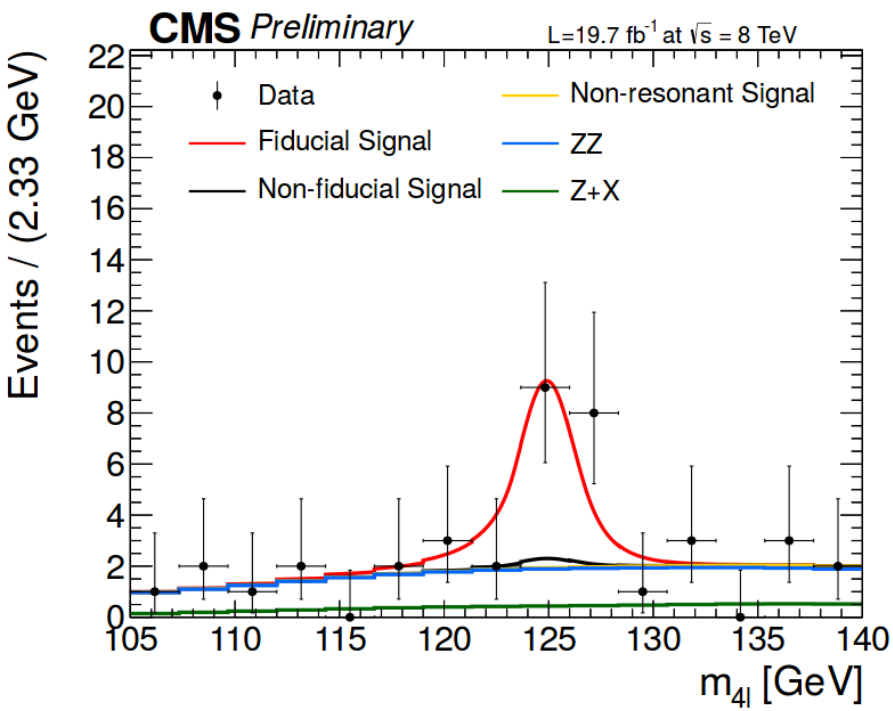
In inclusive fiducial measurement and CMS differential:

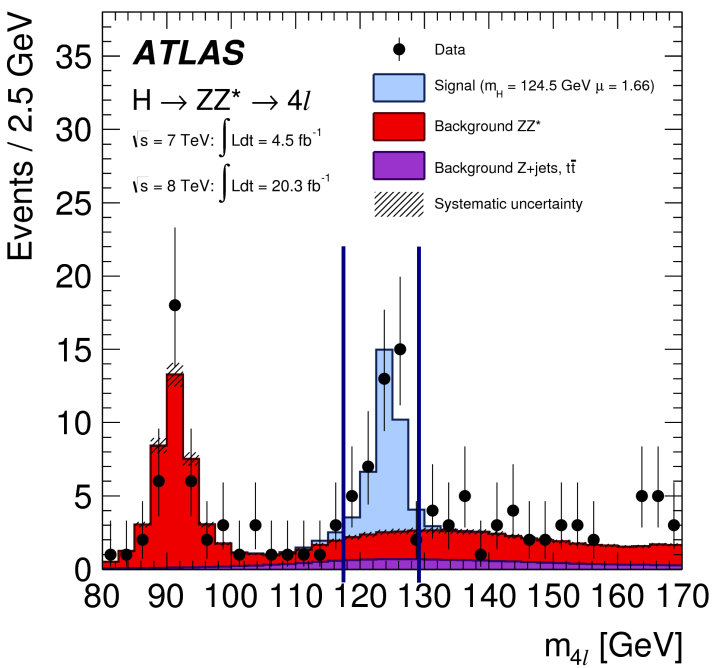
- fit performed to the m_{4l} distribution

In ATLAS differential measurement,

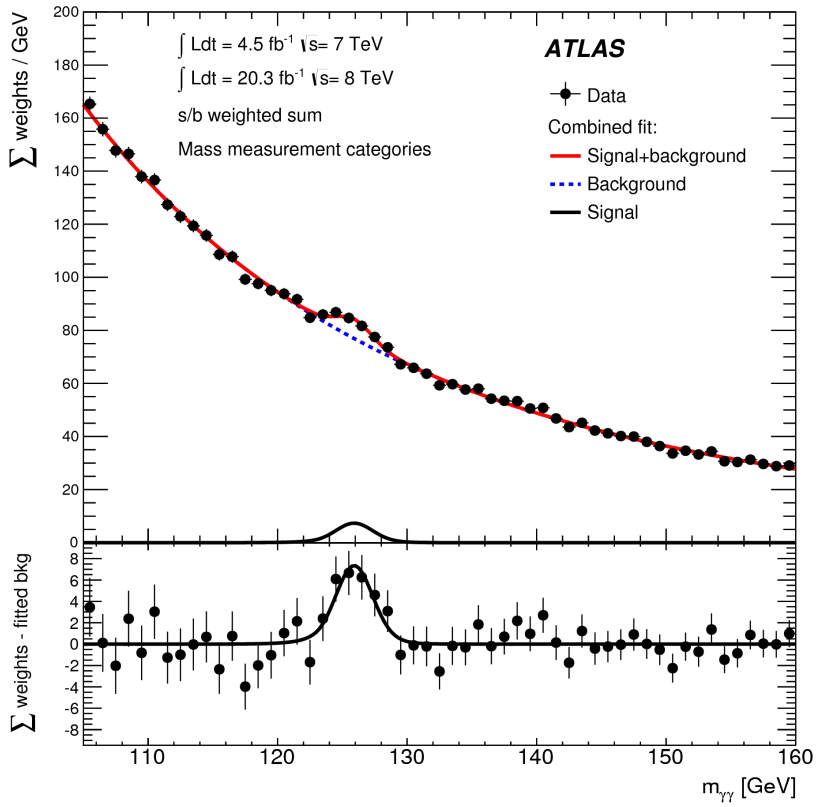
- background estimate subtracted

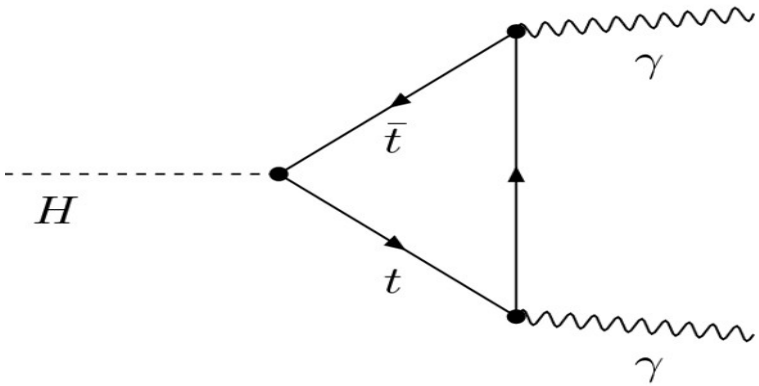
in a mass window around the Higgs peak (118-129 GeV)





The H → γγ channel

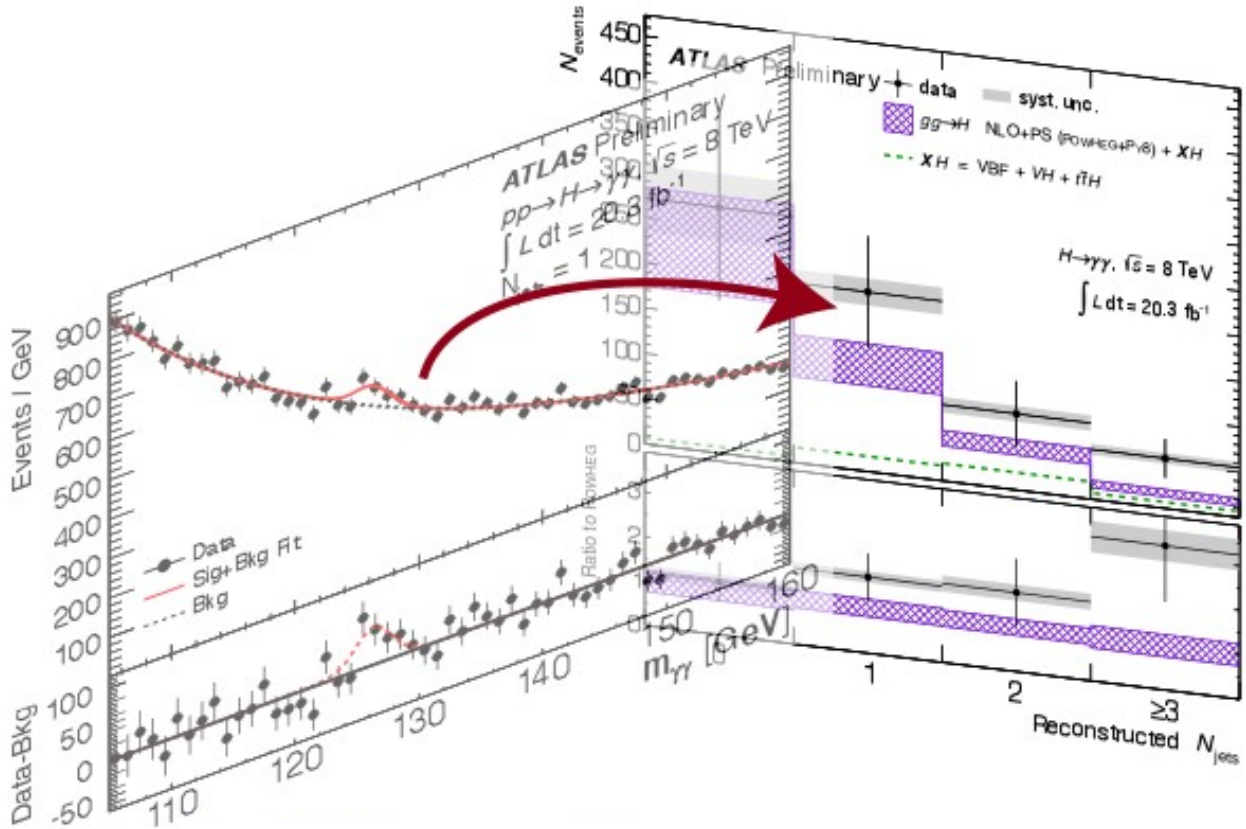




- 2 photons in the final state, full reconstruction of Higgs kinematics
- sensitive to new particles in the decay loop
- more expected signal events, more background than H → 4l channel:

  ATLAS 2012: ~400 signal events expected, S/B ~ 0.03 (at 125 GeV)

Signal extraction in the H → γγ channel



Unbinned likelihood fit to $m_{\gamma\gamma}$ spectrum in each bin

- **signal model: Crystal-Ball + Gaussian or Gaussian**

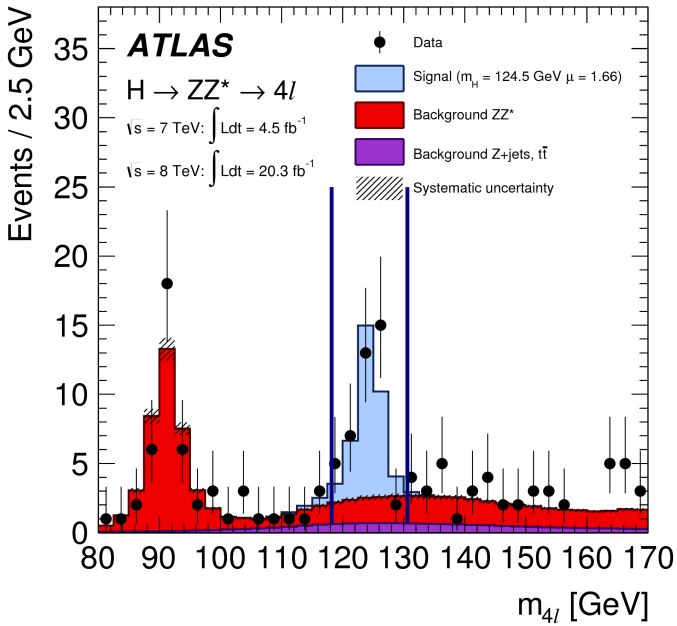
  (mass fixed for ATLAS, floated for every observable for CMS)

- **background model: exponential of polynomial and other functions**

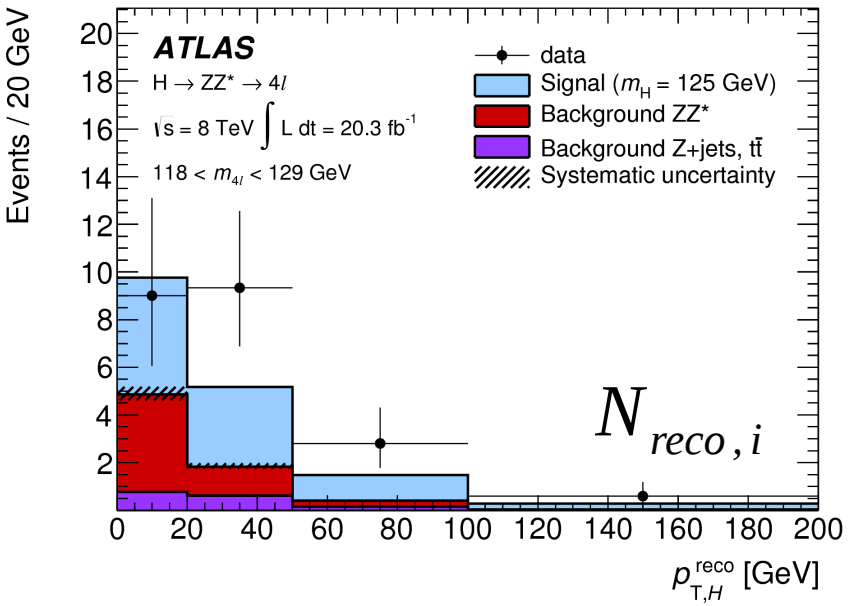
Functional form chosen by minimizing fake signal
in background-only simulation (ATLAS), and by quality of fit (CMS)

Overview diff XS analysis strategy ATLAS (γγ and 4l)

1. Select events

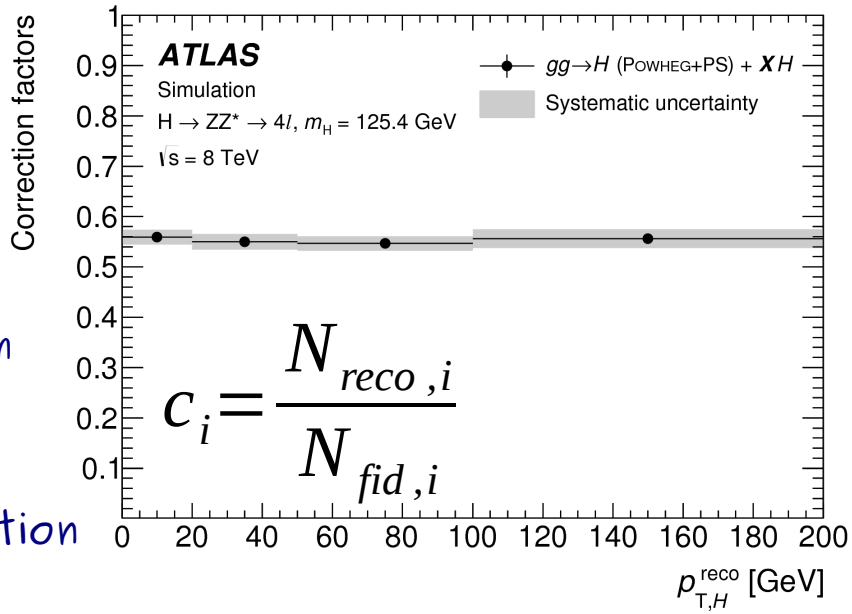


2. Bin in variable of interest, extract signal



$$N_{reco,i}$$

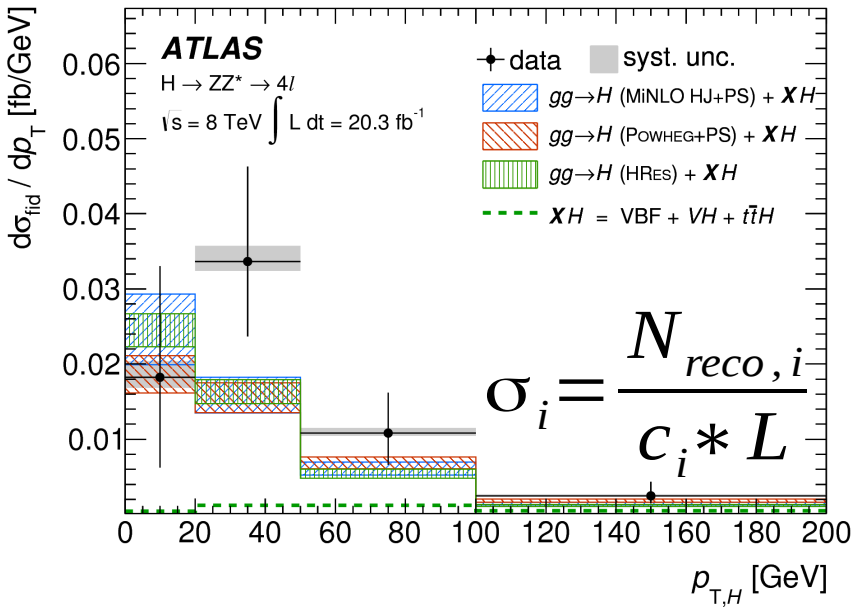
3. Correct for detector effects



$$c_i = \frac{N_{reco,i}}{N_{fid,i}}$$

go from reco to truth information

4. Calculate fiducial cross sections

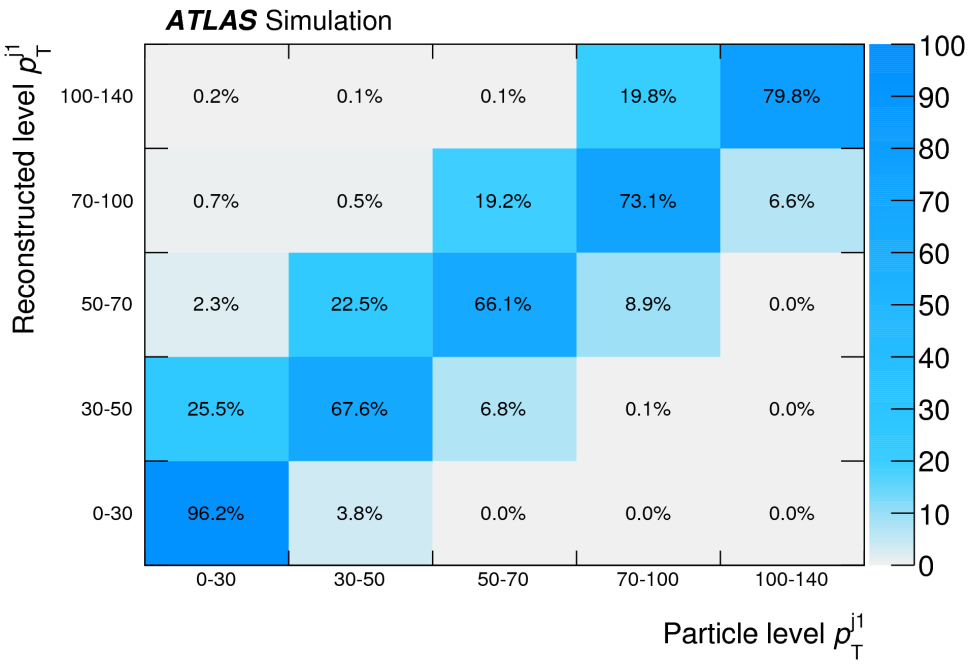


$$\sigma_i = \frac{N_{reco,i}}{c_i * L}$$

Correction for detector effects (unfolding)

Go from reconstructed to truth information, for example $p_T(\gamma\gamma) \rightarrow$ Higgs p_T

- corrects for detector efficiency and resolution



Simulation, based on SM

To really only correct for the detector efficiencies and keep model dependence low

- select truth events in fiducial region close to data event selection

(cuts on the kinematics of the truth lepton/photons, etc.)

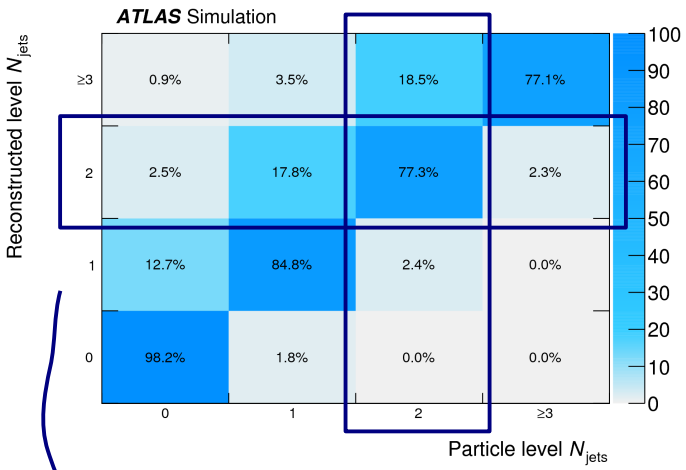
$\rightarrow$ no acceptance correction

- fiducial cuts depend on decay channel

- small differences between ATLAS and CMS

Different unfolding strategies

- ATLAS used bin-by-bin unfolding factors
- CMS used response matrix in the signal extraction fit
    - allows full correlation of nuisance parameters
    - less model dependence



$$c_i = \frac{N_{reco,i}}{N_{fid,i}}$$

Issues

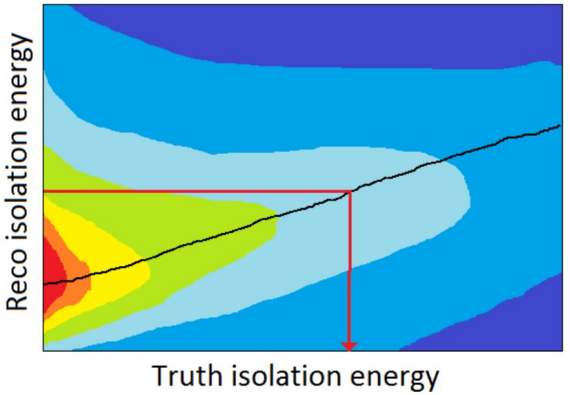
- biases are introduced if true distribution is different from used simulation
- uncertainties to cover the model dependence

Alternative: iterative Bayesian unfolding (d'Agostini)

- several iterations: feed in unfolded distribution as new truth distribution
- minimizes dependence on the true underlying distribution
- BUT: can be affected by statistical fluctuations in the data distributions

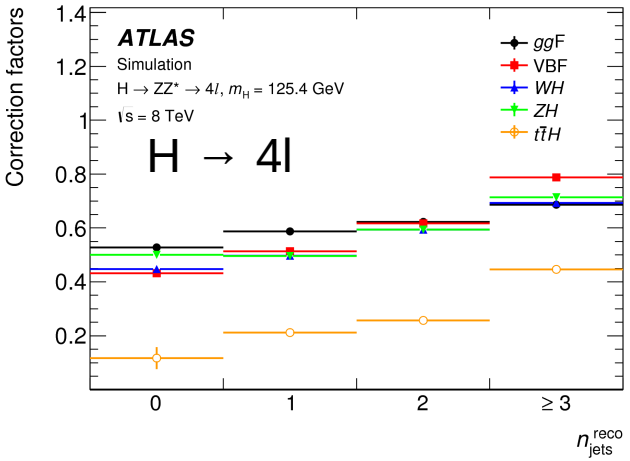
Truth isolation – 2 strategies

Isolation is applied at reco level in all analyses



H → γγ, H → 4l CMS: apply truth isolation in fiducial volume

- **defined as the 4-vector sum of the E_T of particles within a cone of R < 0.4 excluding μ, ν**
- **find truth isolation cut that corresponds to reco isolation energy**
- **keeps correction factor similar for different production modes**

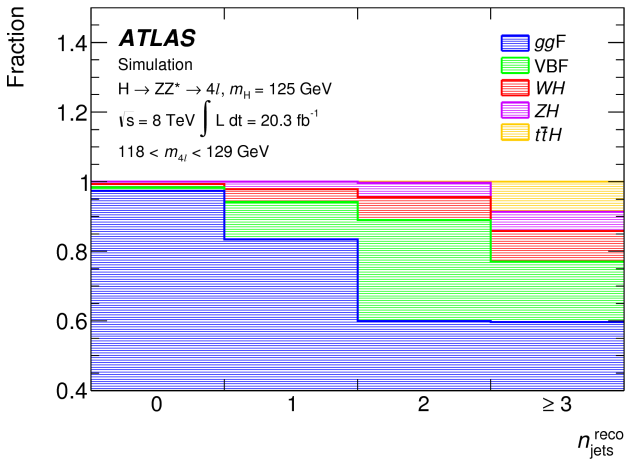


H → 4l ATLAS: no truth isolation applied

- **for simplicity of fiducial selection**
- **correction factor varies for ttH**

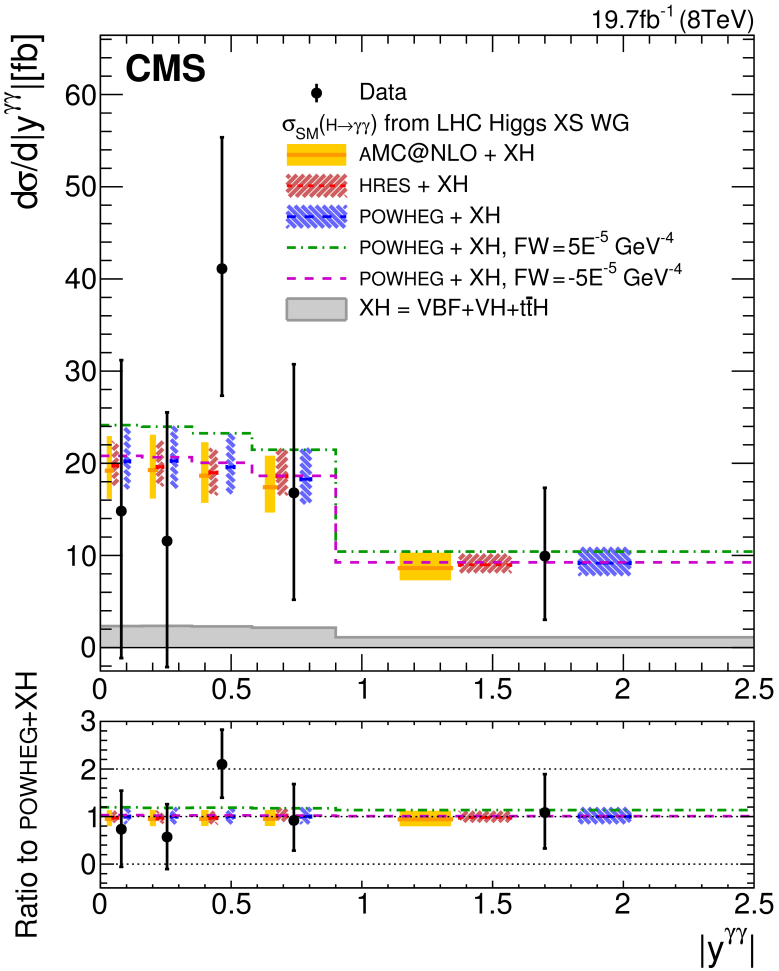
→ varying production modes will increase uncertainties

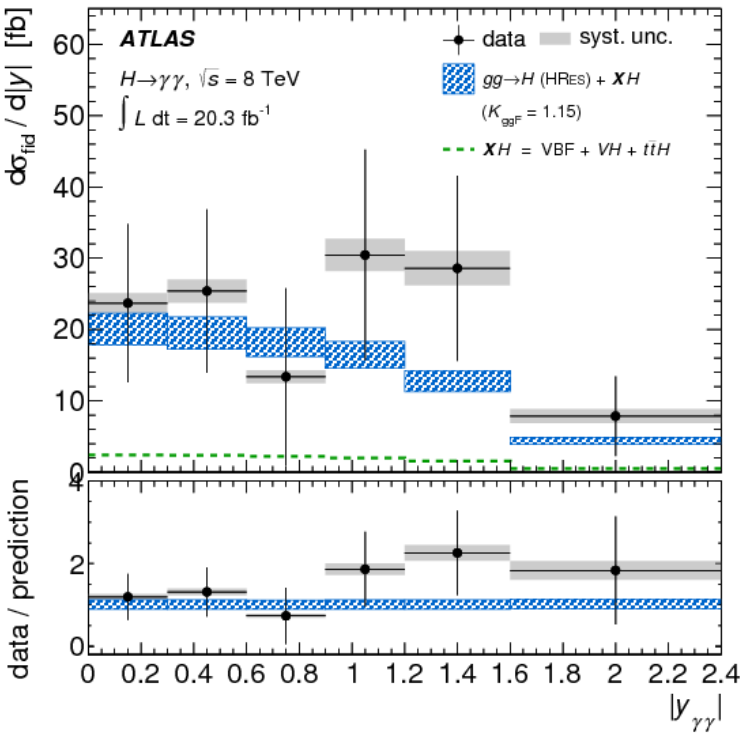
- **small effect, as ttH is tiny everywhere except for highest njet bin**



Results H → 4l and H → γγ analyses

ATLAS & CMS





Comparison to state-of-the-art ggF theory predictions

Best calculation to date, N3LO!

Used for LHC run 1 publications

Total cross-section calculations	
LHC-XS	NNLO+NNLL [a,b,c]
ADDFGHLM	N^3LO [a,b,c]
Analytical differential cross-section predictions	
HRes 2.2	NNLO+NNLL [a,e,f]
STWZ, BLPTW	NNLO+NNLL [c,d,e,g,h]
JetVHeto 2.0	NNLO+NNLL [a,c,e]
Monte Carlo event generators	
SHERPA 2.1.1	$H + 0, 1, 2$ jets @NLO [i,j]
MG5_aMC@NLO	$H + 0, 1, 2$ jets @NLO [i,k,l]
Powheg Nnlops	$\mathrm{NNLO}_{\geq 0j}$, $\mathrm{NLO}_{\geq 1j}$ [e,l,m]

Latest and greatest MC generators, to be used more and more in run 2

These predictions will be added to the non-ggF predictions for the comparisons to data.

(for footnotes, see backup)

Results in the individual channels: Fiducial XS

$\gamma\gamma$

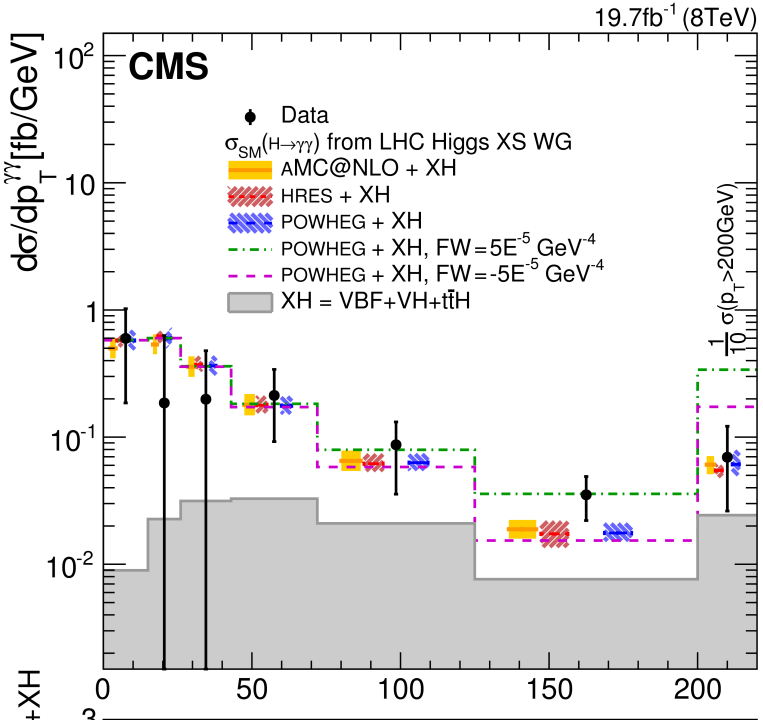
[fb]	obs	exp	
ATLAS	$43.2\,^{9.9}_{9.8}$	30.5 ± 3.3	LHC-XS
CMS	32 ± 10	$32\,^{+6}_{-5}$	NLO

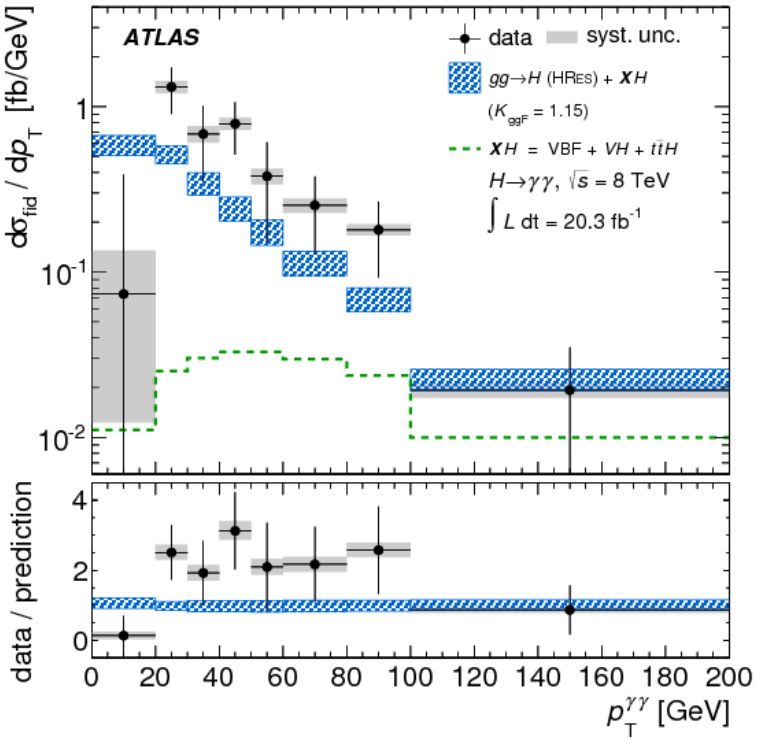
Different fiducial volumes between ATLAS and CMS

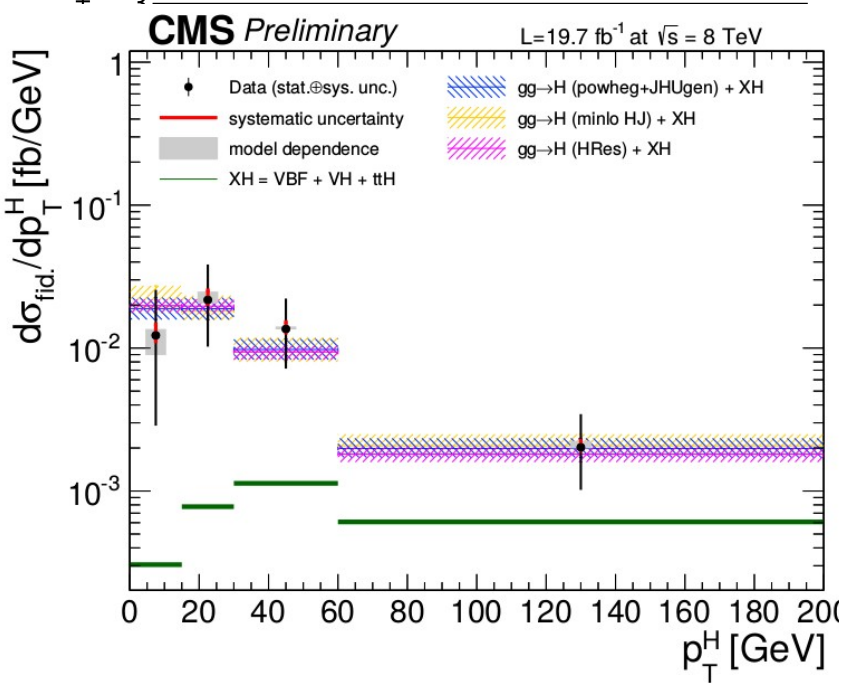
4l

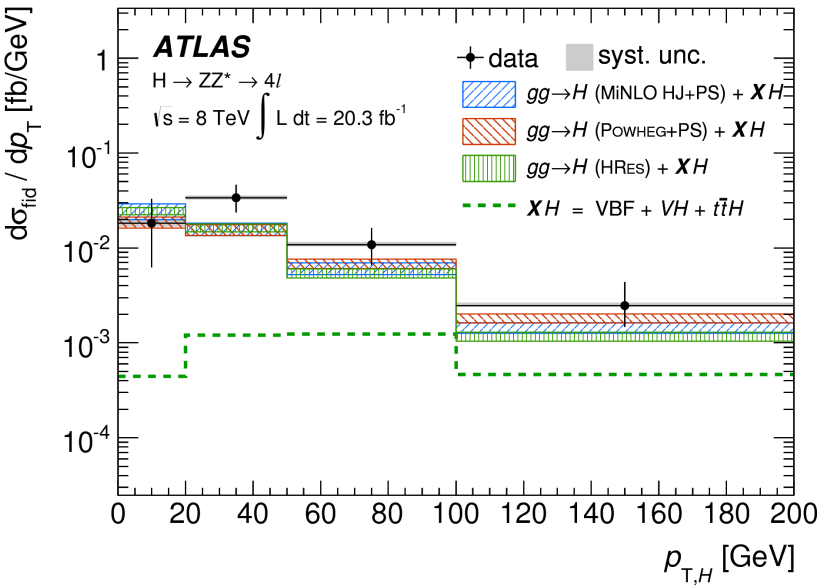
[fb]	obs	exp	
ATLAS	$2.11^{+0.54}_{-0.48}$	1.30 ± 0.13	LHC - XS
CMS	$1.11\,^{+0.44}_{-0.36}$	$1.15\,^{+0.12}_{-0.13}$	LHC - XS

Results in individual channels: Higgs p_T

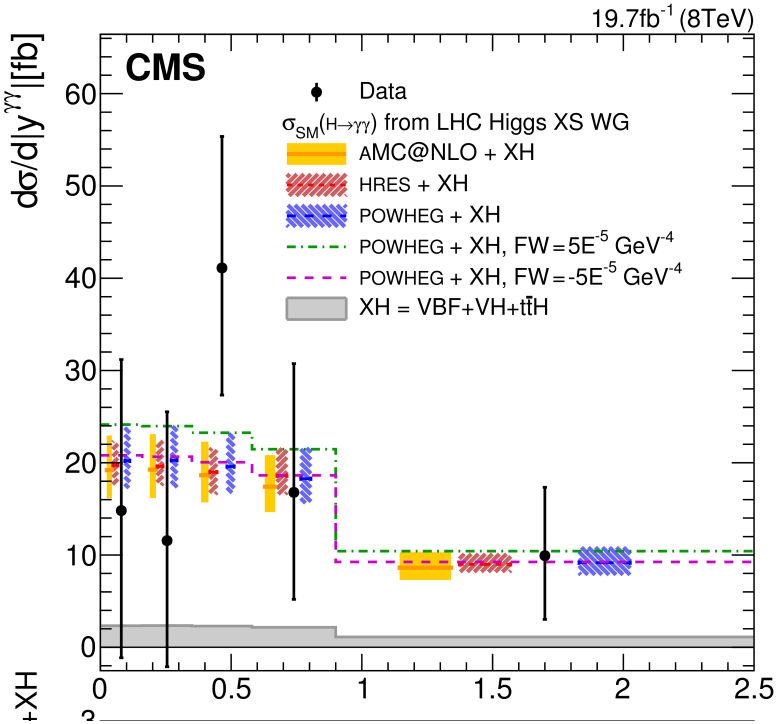


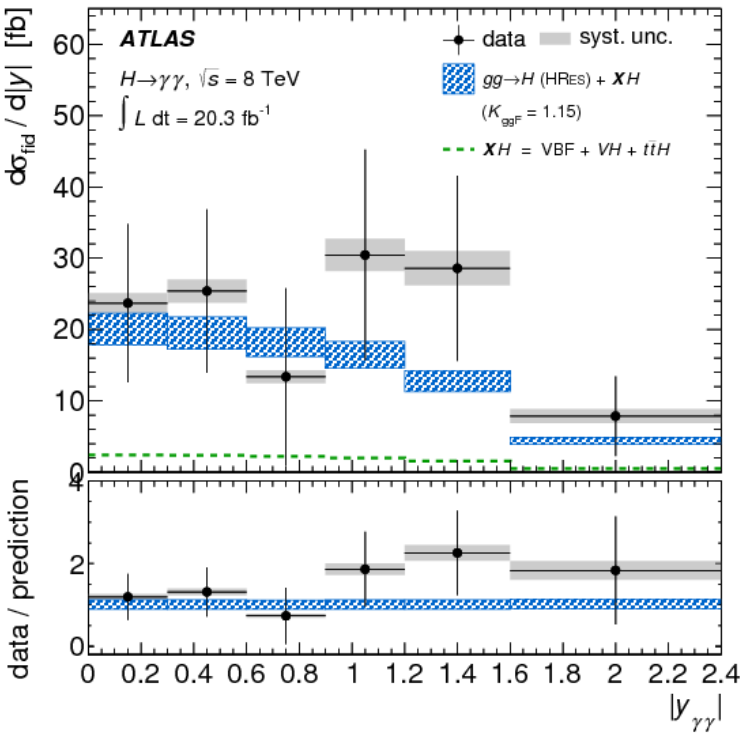


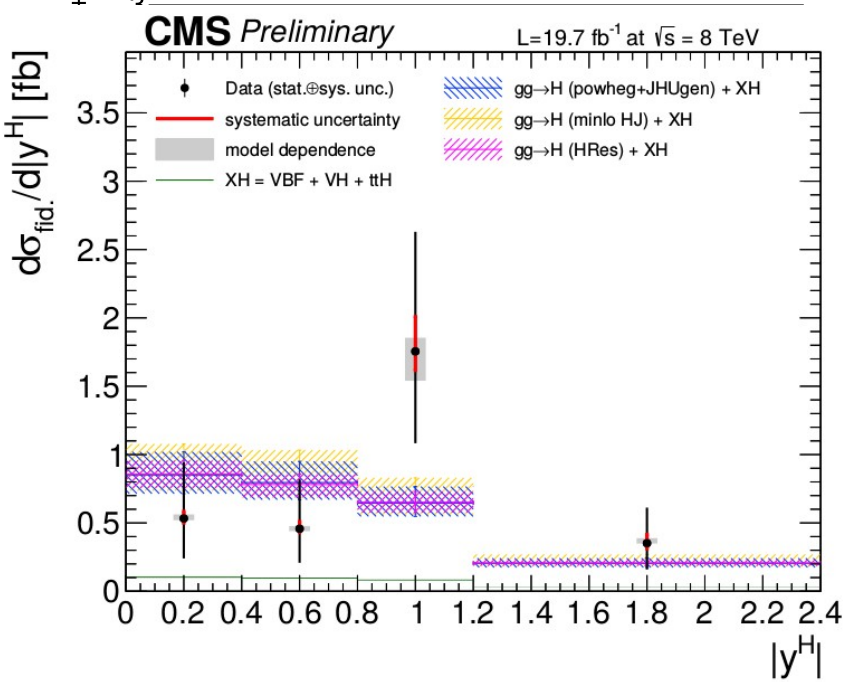


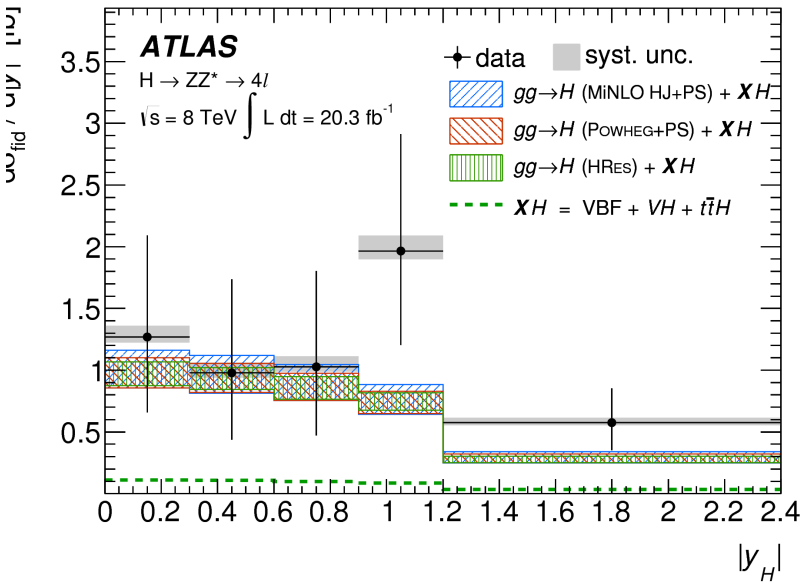


Results in individual channels: Higgs rapidity

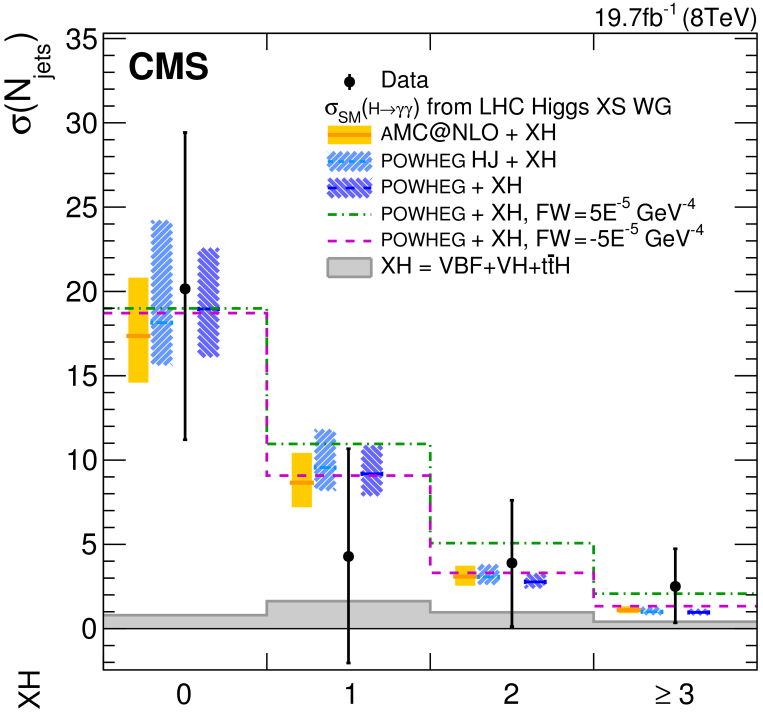


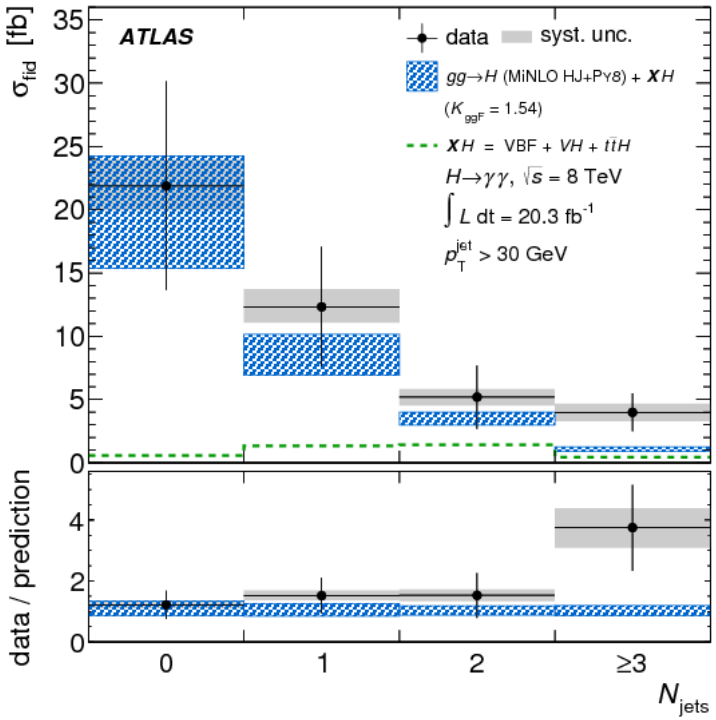


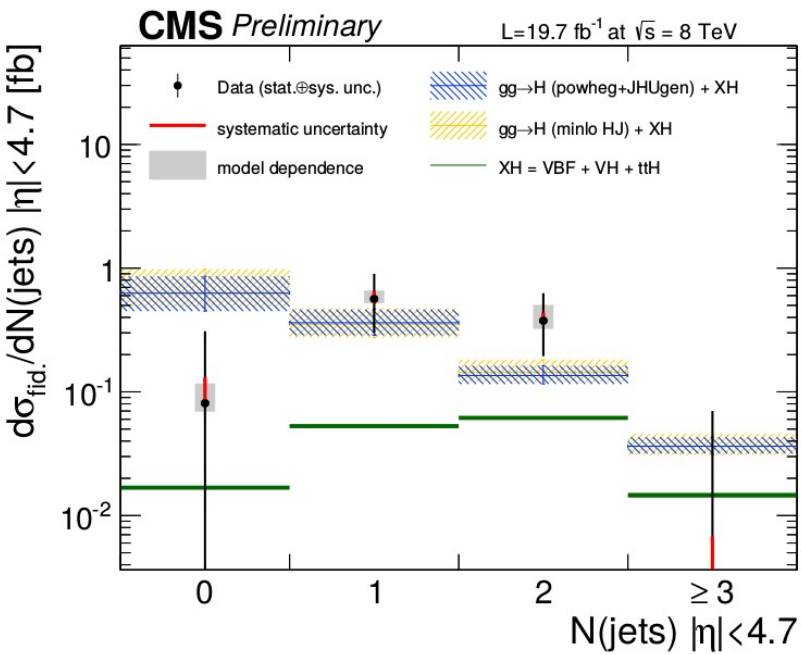


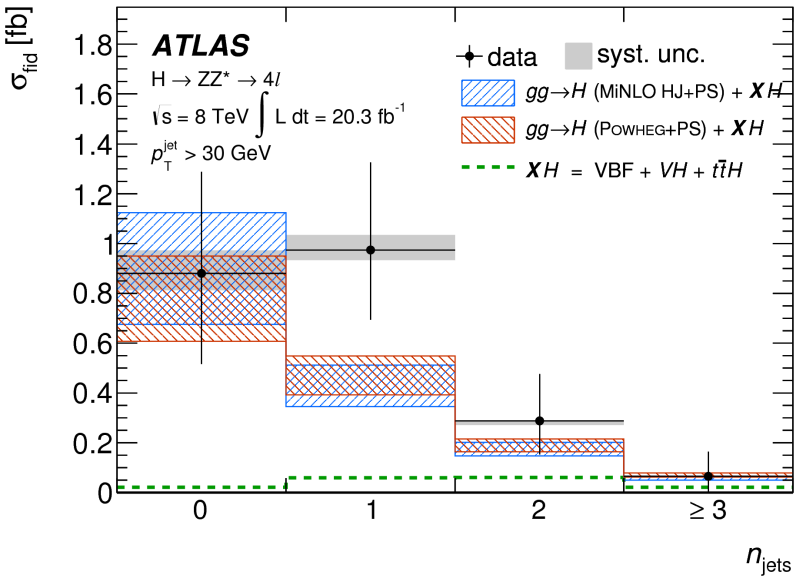


Results in individual channels: Number of jets



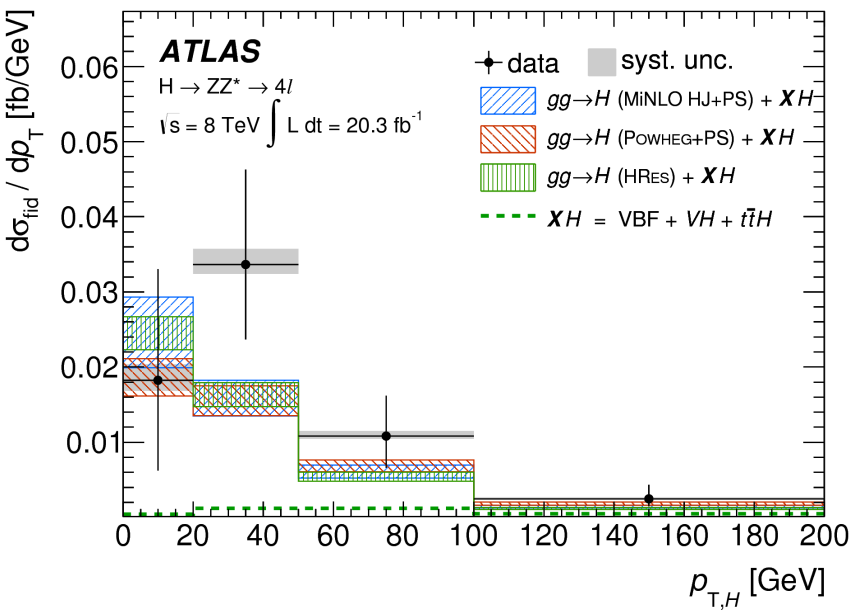






Part 2: The combination of ATLAS

H → 4l and H → γγ



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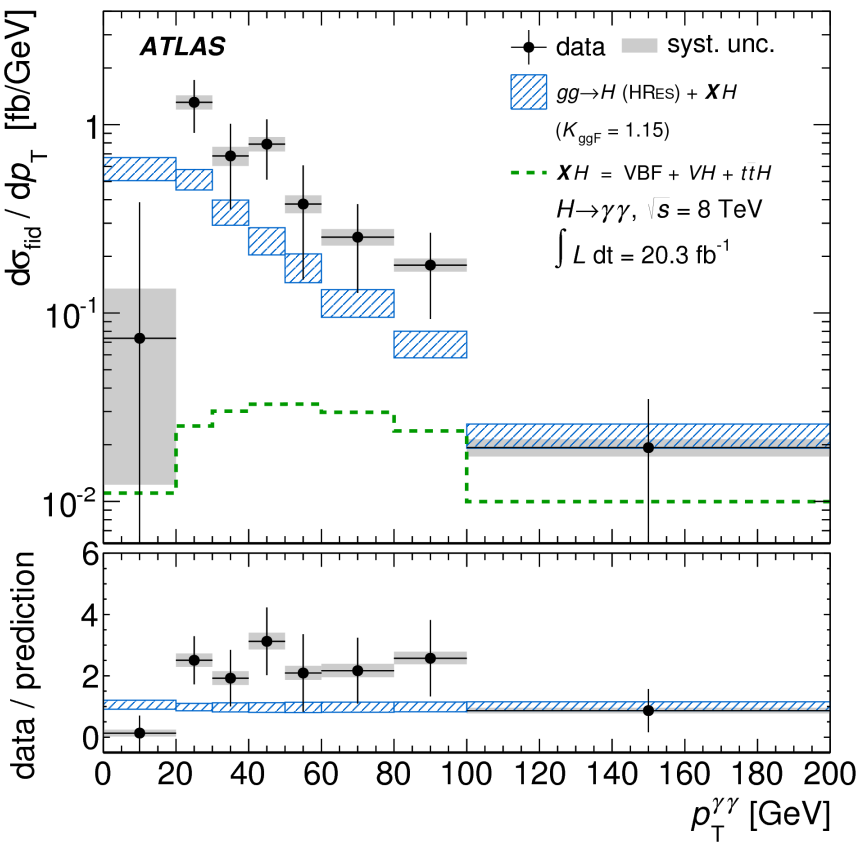


Why a combination and what did we include?

Why?

- check agreement between $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ measurements
- combine to reduce statistical uncertainties

Have to give up some model independence here

What do we have to do for it?

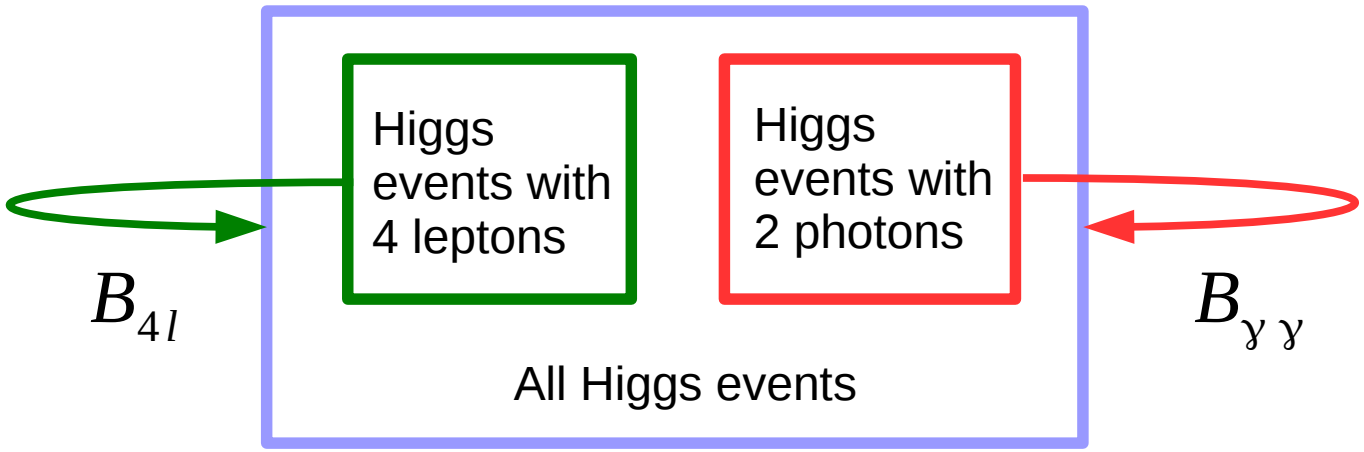
- Extrapolate both $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ cross sections to total phase space
  → necessary for combination to have common fiducial volume
- correct for branching fractions
- deal with different bin widths (shared bin boundaries)
- combination actually done starting from the measured event numbers to take uncertainty correlations properly into account

Extrapolation from fiducial to total phase space

Correct for acceptance and branching fraction

→ combined cross sections valid for "stable" Higgs (before decay)

$$A_i^{4l} = \frac{N_{fid,i}^{4l}}{N_{tot,i}}$$



$$A_i^{\gamma\gamma} = \frac{N_{fid,i}^{\gamma\gamma}}{N_{tot,i}}$$

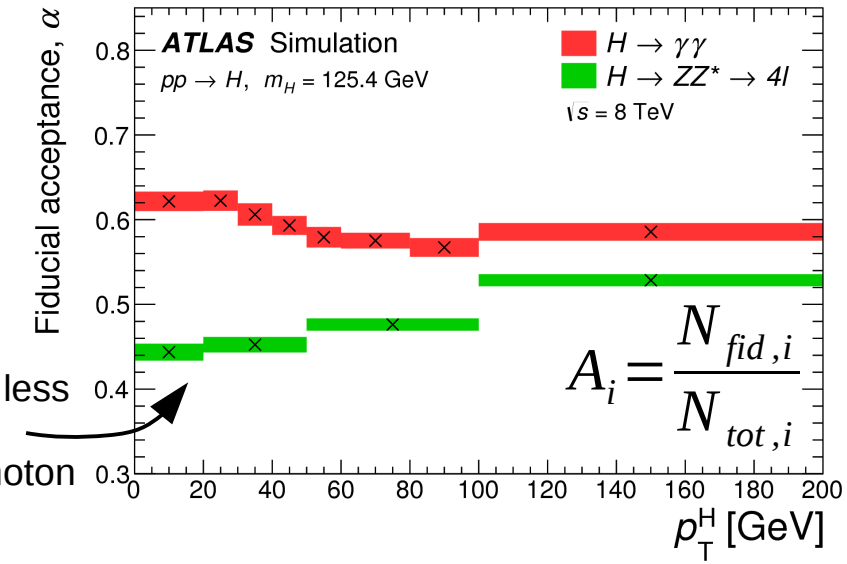
Details on acceptance correction factors

- **calculated assuming SM, m_H = 125.4 GeV**
- **truth jets are defined excluding decay products of the Higgs (to deal with different decay topologies)**
- **uncertainties: Higgs mass and production mode variations, PDF and scale variation, reweight p_T to most precise prediction (HRes), isolation in H → γγ**

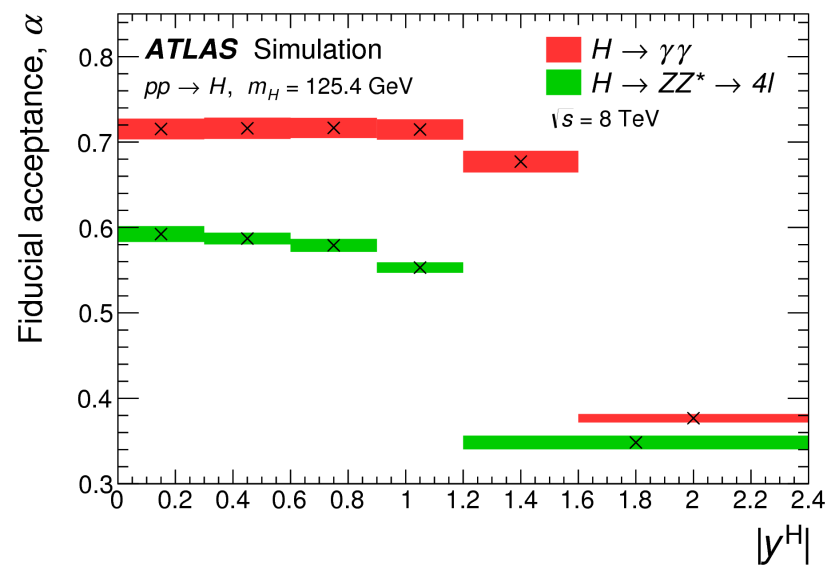
Acceptance factors from fiducial to total phase space

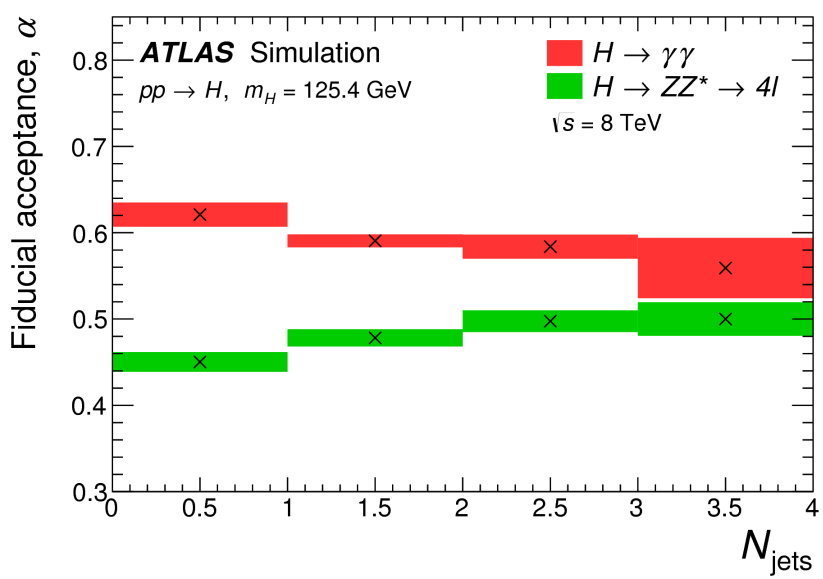
- correcting for soft and forward Higgs decay products
- bin migrations due to different jet definitions

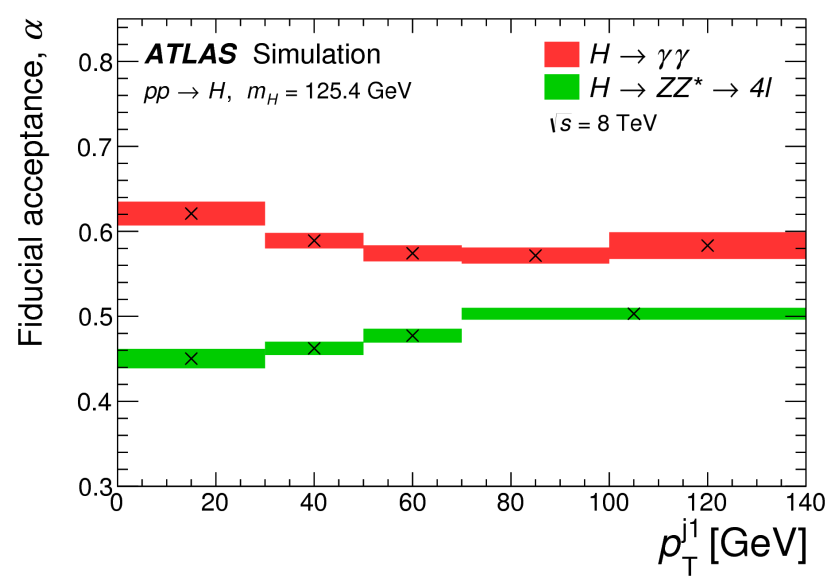
4-lepton selection less efficient than 2-photon selection



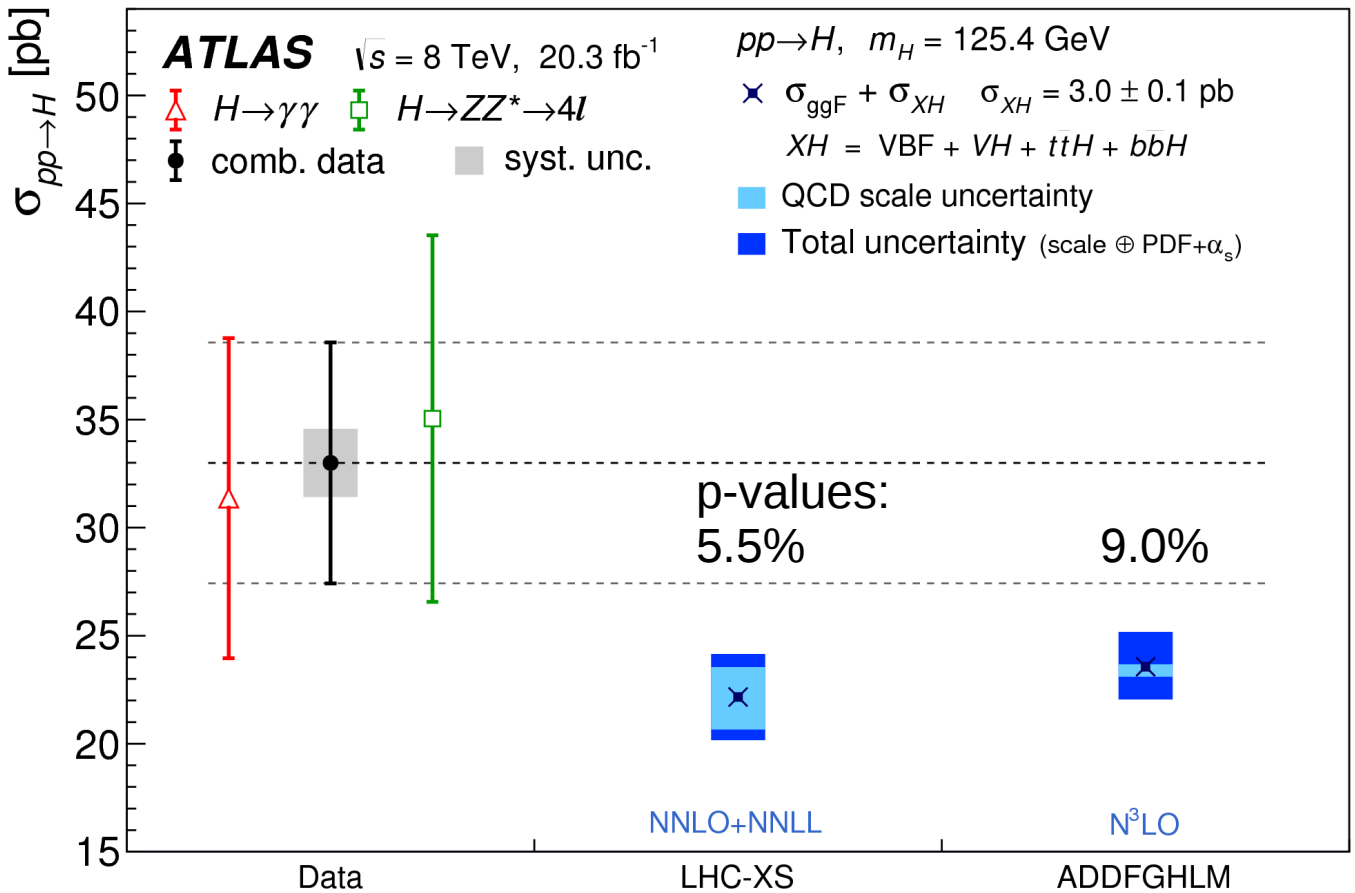
$$A_i = \frac{N_{fid,i}}{N_{tot,i}}$$







Results total cross section



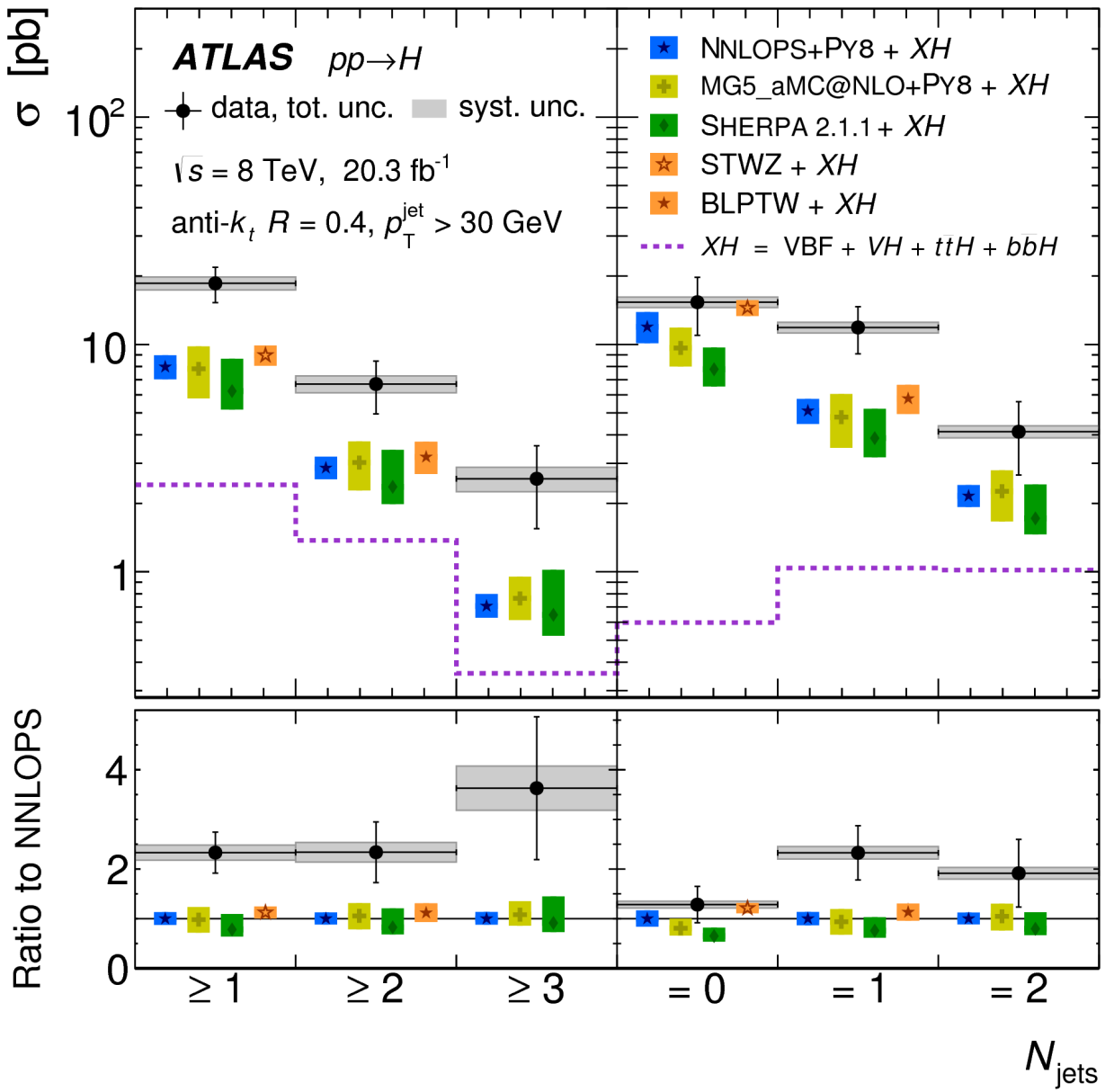
Measured cross section higher than all predictions

H → 4l: 35.0 ± 8.4 (stat) ± 1.8 (sys) pb

H → γγ: 31.4 ± 7.2 (stat) ± 1.6 (sys) pb

Combined: 33.0 ± 5.3 (stat) ± 1.6 (sys) pb

Results in jet bins



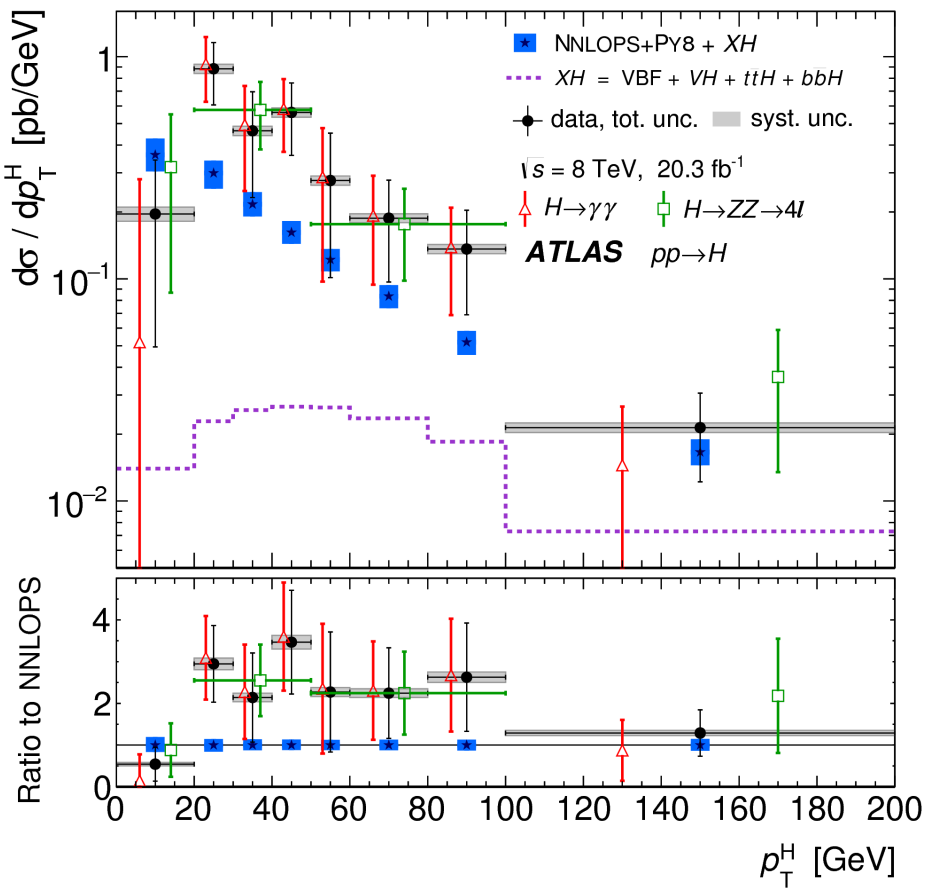
Cross section higher than predictions in all bins (except for STWZ, Njets=0).

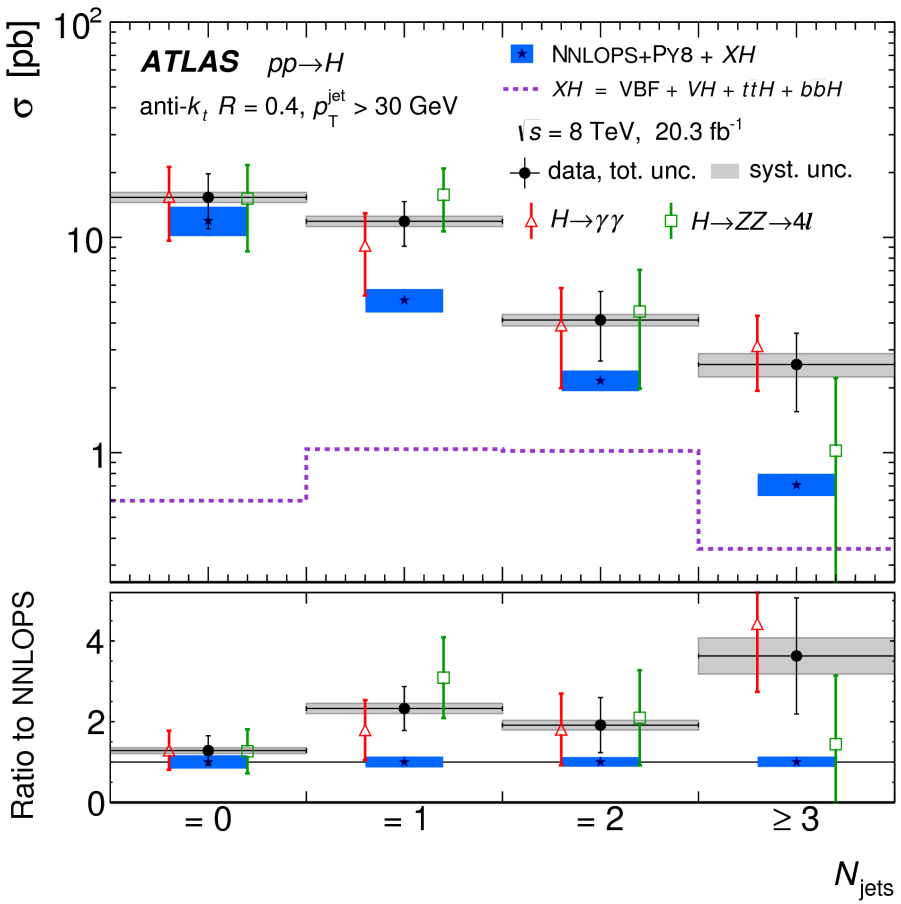
Worst agreements in 1-jet bins.

Compatibility between H → 4l and H → γγ results

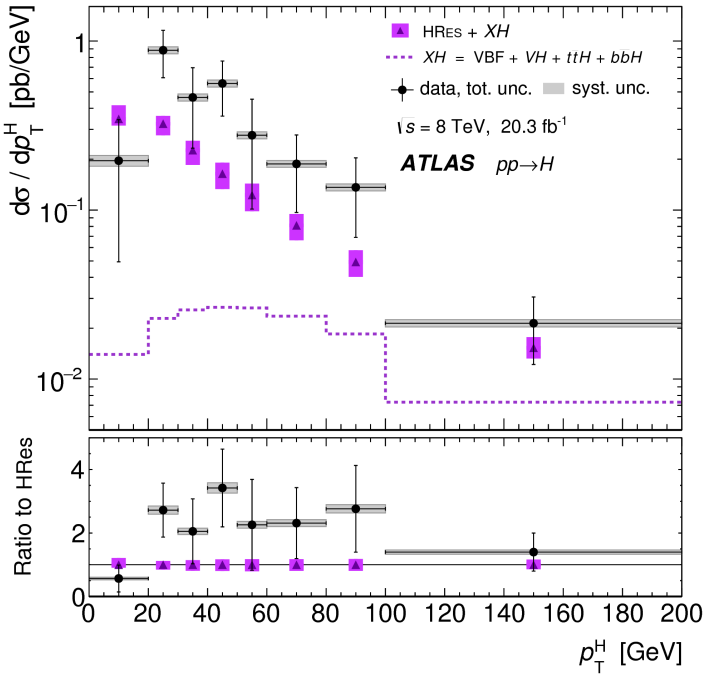
Very good agreement between H → 4l and H → γγ results in all variables:

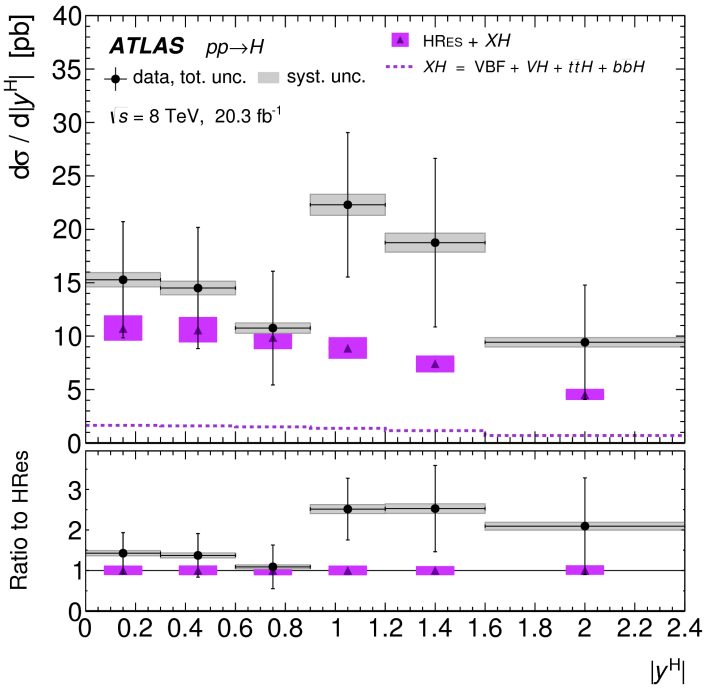
p-values higher than 56%

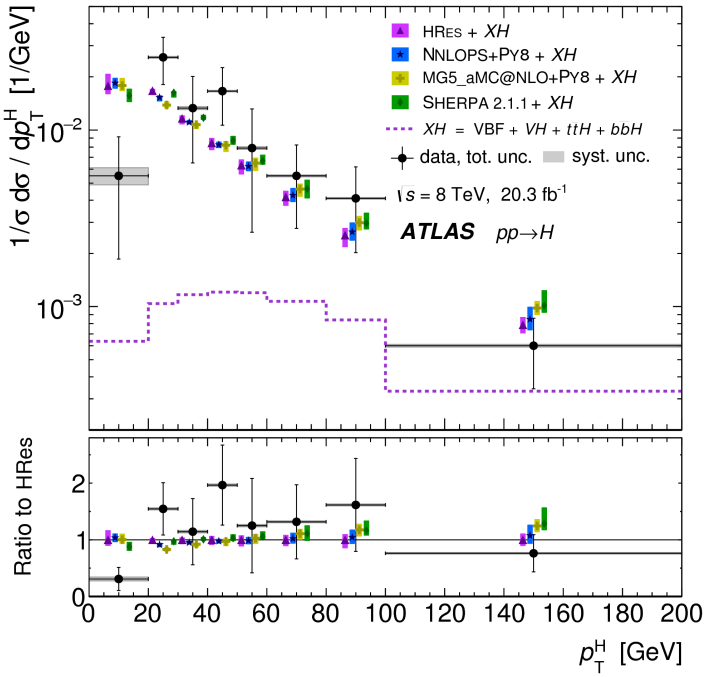


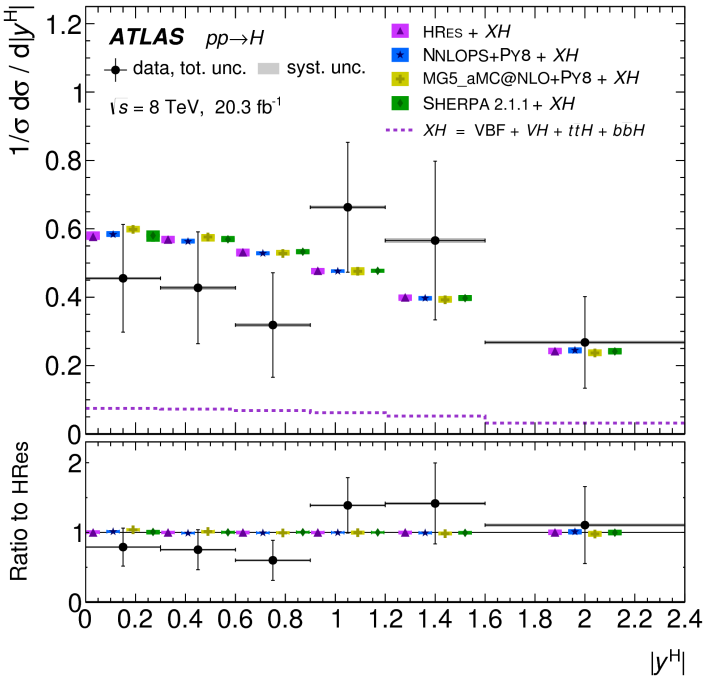


Results differential cross sections and shapes









Example: How to use differential cross sections

Constraints on non-Standard Model Higgs boson interactions in an effective field theory using differential cross sections measured in the $H \to \gamma\gamma$ decay channel at $\sqrt{s}$ = 8 TeV with the ATLAS detector

The ATLAS Collaboration

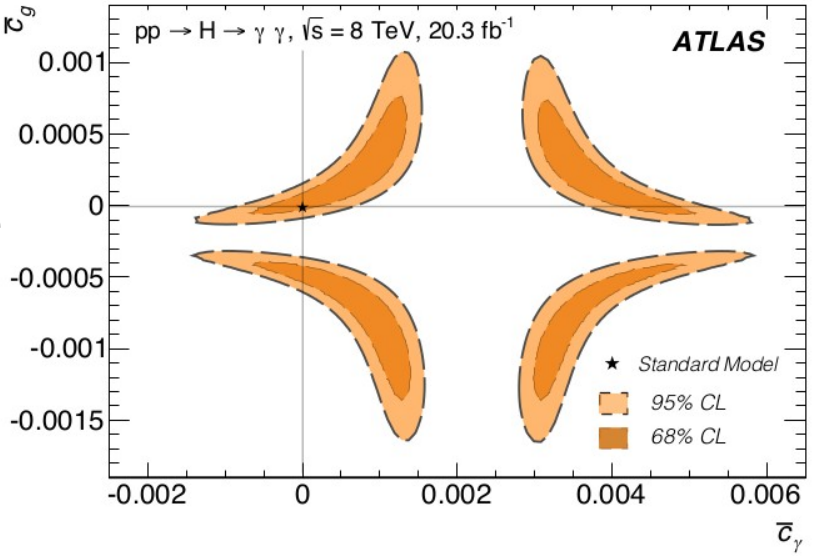
Submitted to PLB

- **Test the Higgs interactions with an effective field theory framework**
  - **allow new CP-even/odd interactions**
- **Use unfolded distributions for EFT**
  - **5 $\gamma\gamma$ distributions: Higgs p_T, jet properties**

Difficulty:

statistical correlations between distributions

→ re-evaluated and made publicly available

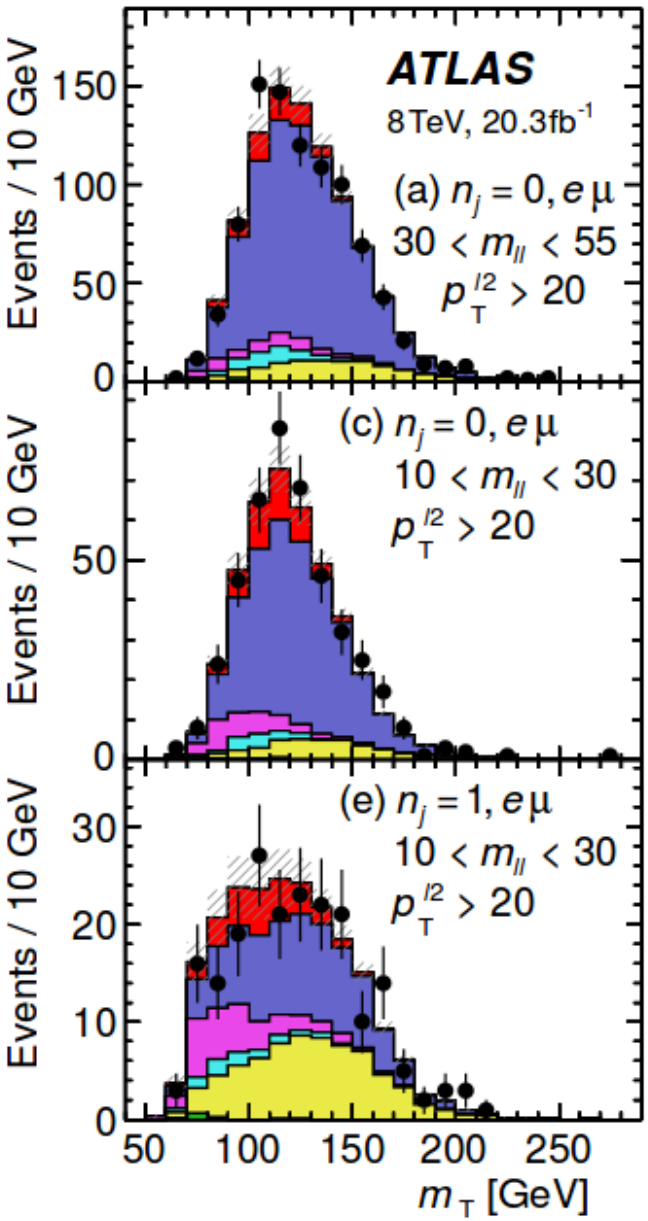


Result: No significant deviation from SM predictions observed

What about other decay channels?

WW differential cross section measurement ongoing at ATLAS

- challenging: broad signal distribution, analysis binned in jet multiplicity
- strong involvement of Oxford ATLAS group



Channels like WW, bb, ττ, other ZZ decays

- some of them have very low S/B
- large model dependence of unfolding factors
- it is hard to incorporate MVA techniques in the fiducial volume

Possible solution to extract most information from these channels:

- instead of one signal strength measurement, measure cross sections binned to be BSM sensitive, minimize theory dependence, less dependent on SM kinematics
  - low Higgs p_T, high p_T
  - number of jets

→ **simplified/templated cross sections**

Conclusions

ATLAS and CMS measured fiducial, differential and total cross sections in the H → 4l and H → γγ channels

Measurements limited by large statistical uncertainties

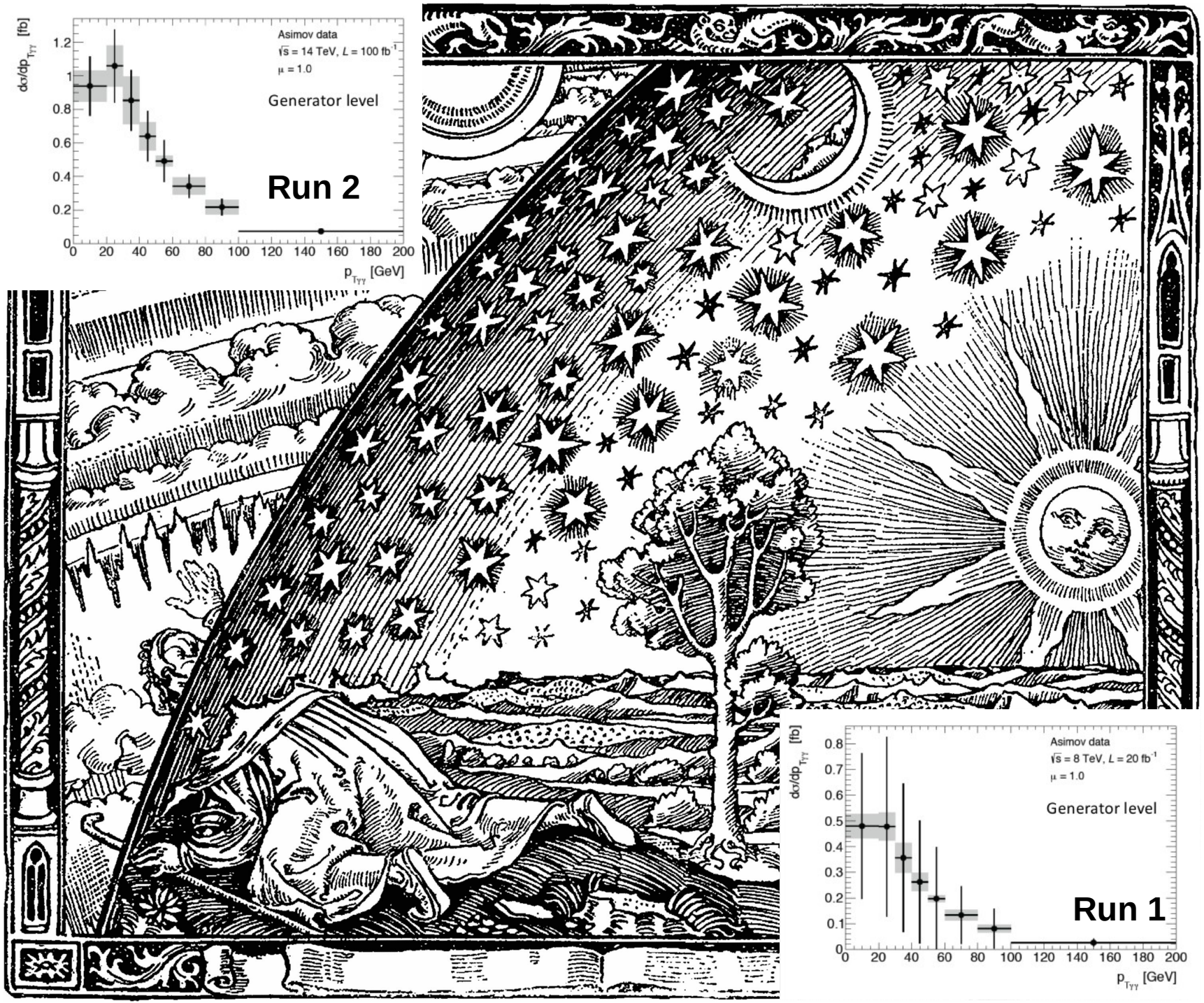
- **not possible yet to make definite statements on deviations from predictions**
- **ATLAS excesses and p_T deviations not confirmed by CMS**

Looking forward to more collisions!

- **100 fb^{-1} by 2018**
- **300 fb^{-1} by 2023**

10 times more data than used for results in this presentation

On to Run 2!


Asimov data
√s = 14 TeV, L = 100 fb⁻¹
μ = 1.0
Generator level
Run 2
dσ/dp_Tγγ [fb]
p_Tγγ [GeV]
Asimov data
√s = 8 TeV, L = 20 fb⁻¹
μ = 1.0
Generator level
Run 1
dσ/dp_Tγγ [fb]
p_Tγγ [GeV]

BACKUP

BACKUP: Likelihood combination

1. Ingredients (per channel and bin)

Reco selection: N_{reco}

Unfold the reco numbers to fiducial: $c = N_{fid}/N_{reco}$

Extrapolation factor A from fiducial to total phase space

Luminosity L, branching fractions B to determine cross sections

$$\sigma_i^{incl} = \frac{n_i^{sig}}{c_i \mathcal{L} \mathcal{A}_i^{fid} \mathcal{B}}$$

2. Likelihood

$$\mathcal{L} = \prod_i \mathcal{P}_i \prod_j \mathcal{G}_j \times \prod_k \mathcal{G}_k(0; \theta_k, 1)$$

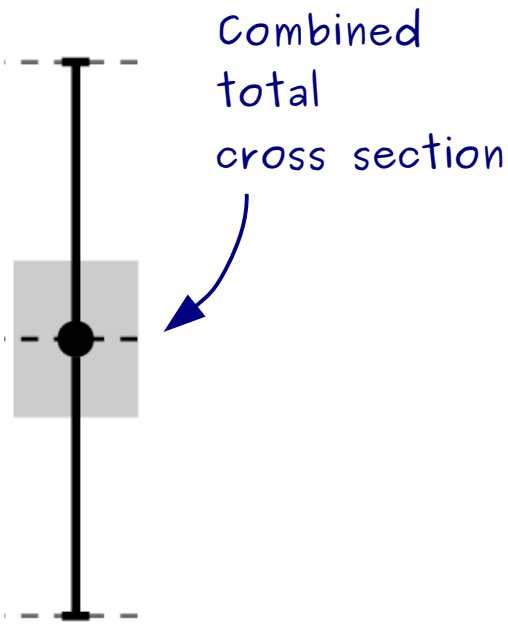
Gaussian for H → γγ
(background subtracted with fit)

Poisson for H → 4l
(includes simple background subtraction)

- possible to include different bin granularities

- small modification for shape combination

BACKUP: Uncertainties



Dominated by statistical uncertainties

Common uncertainties correlated between bins and channels through likelihood

Dominant uncertainties on cross sections

- **kinematic variables:**
  - **luminosity**
  - **background estimates in both channels**
- **jet variables:**
  - **jet energy scale**
  - **resolution**
- **for shapes, normalization uncertainties like luminosity, branching fractions, efficiencies do not apply**

BACKUP: Theory prediction details

Total cross-section calculations	
LHC-XS	NNLO+NNLL [a,b,c]
ADDFGHLM	N^3LO [a,b,c]
Analytical differential cross-section predictions	
HRes 2.2	NNLO+NNLL [a,e,f]
STWZ, BLPTW	NNLO+NNLL [c,d,e,g,h]
JetVHeto 2.0	NNLO+NNLL [a,c,e]
Monte Carlo event generators	
SHERPA 2.1.1	$H + 0, 1, 2$ jets @NLO [i,j]
MG5_aMC@NLO	$H + 0, 1, 2$ jets @NLO [i,k,l]
Powheg Nnlops	$\mathrm{NNLO}_{\geq 0j}$, $\mathrm{NLO}_{\geq 1j}$ [e,l,m]

[a] Considers b- (and c-) quark masses in the $gg \to H$ loop
[b] Includes electroweak corrections
[c] Based on MSTW2008nnlo (α_s from PDF set)
[d] Uses π^2-resummed $gg \to H$ form factor
[e] NNLO refers to the total cross section
[f] Based on the CT10nnlo PDF set
[g] This corresponds to NNLL$'$
[h] Includes 1-jet resummation included at NLL$'$+NLO
[i] Based on the CT10nlo PDF set
[j] Uses MEPS@NLO method and CKKW merging scheme
[k] Software version 2.2.1, NLO merged using FxFx scheme
[l] Interfaced with Pythia8 for parton showering
[m] Uses Minlo method & y^H reweighting to HNNLO.

Please see arxiv:1504.05833 for references

BACKUP: More theory

TABLE XXI. Central values and uncertainties for the different ggF predictions and the data.

Name	$\sigma_{gg\to H}$ [pb]		
Data$-XH$[a]	30.0 ± 5.3 (stat)	± 1.6 (sys)	
LHC-XS	19.15 $^{+1.38}_{-1.49}$ (scale)	$^{+1.44}_{-1.32}$ (pdf)	
ADDFGHLM	20.55 $^{+0.04}_{-0.45}$ (scale)	$^{+1.60}_{-1.44}$ (pdf)	
ABNY	19.54 $^{+0.55}_{-0.14}$ (scale)	$^{+1.47}_{-1.35}$ (pdf)	± 0.78 (appr.)
STWZ	20.41 ± 1.18 (scale)	$^{+1.53}_{-1.41}$ (pdf)	
dFMMV	21.12 $^{+0.29}_{-0.42}$ (scale)	$^{+1.58}_{-1.46}$ (pdf)	± 0.56 (appr.)
BBFMR	21.32 $^{+1.39}_{-0.45}$ (scale)	$^{+1.60}_{-1.47}$ (pdf)	± 1.39 (appr.)

[a] Non-ggF cross section $\sigma_{XH} = 3.01^{+0.05}_{-0.06}$ (scale) ± 0.09 (pdf) pb, subtracted from the measured inclusive cross section: 33.0 ± 5.3 (stat) ± 1.6 (sys) pb.

BACKUP: Signal strength measurement, ATLAS

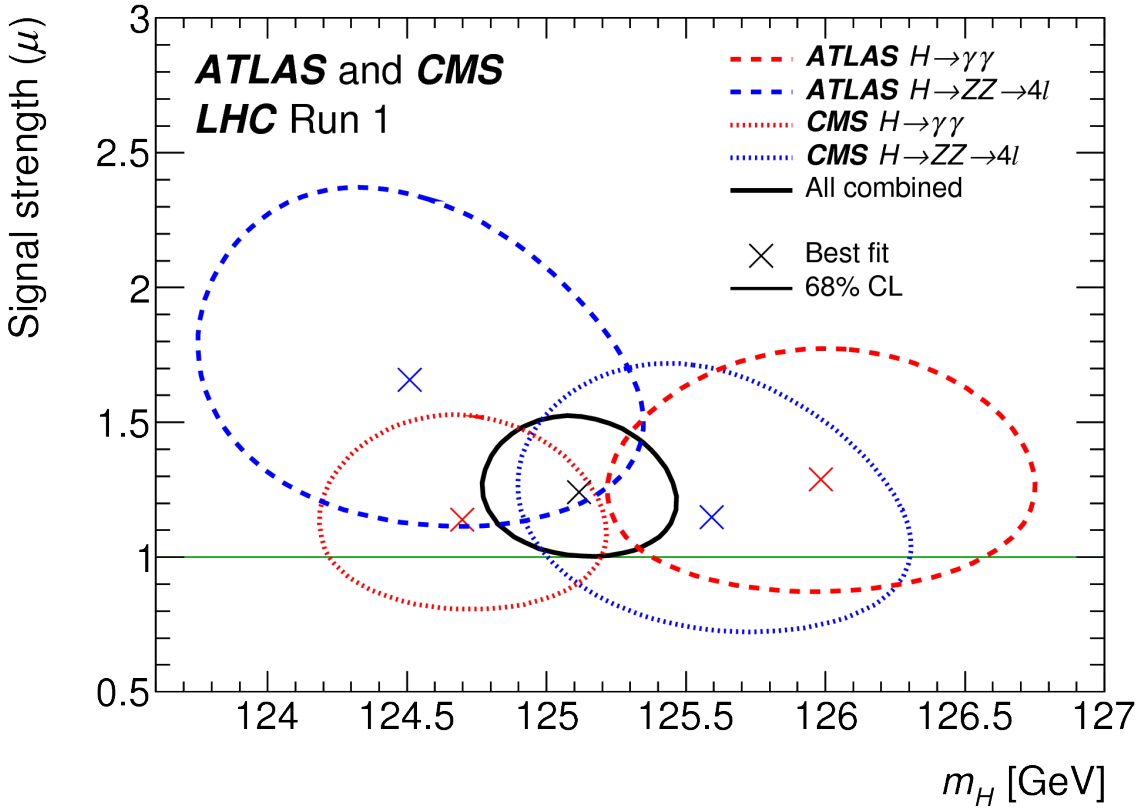
ATLAS H → 4l channel: 1.44 +0.40/-0.33
(1.7 +0.5/-0.4 for ggF, ttH only)
- Phys Rev D 91

ATLAS H → yy channel: 1.17 +/- 0.27
(1.32 +/- 0.28 for ggF only)

- Phys Rev D 90

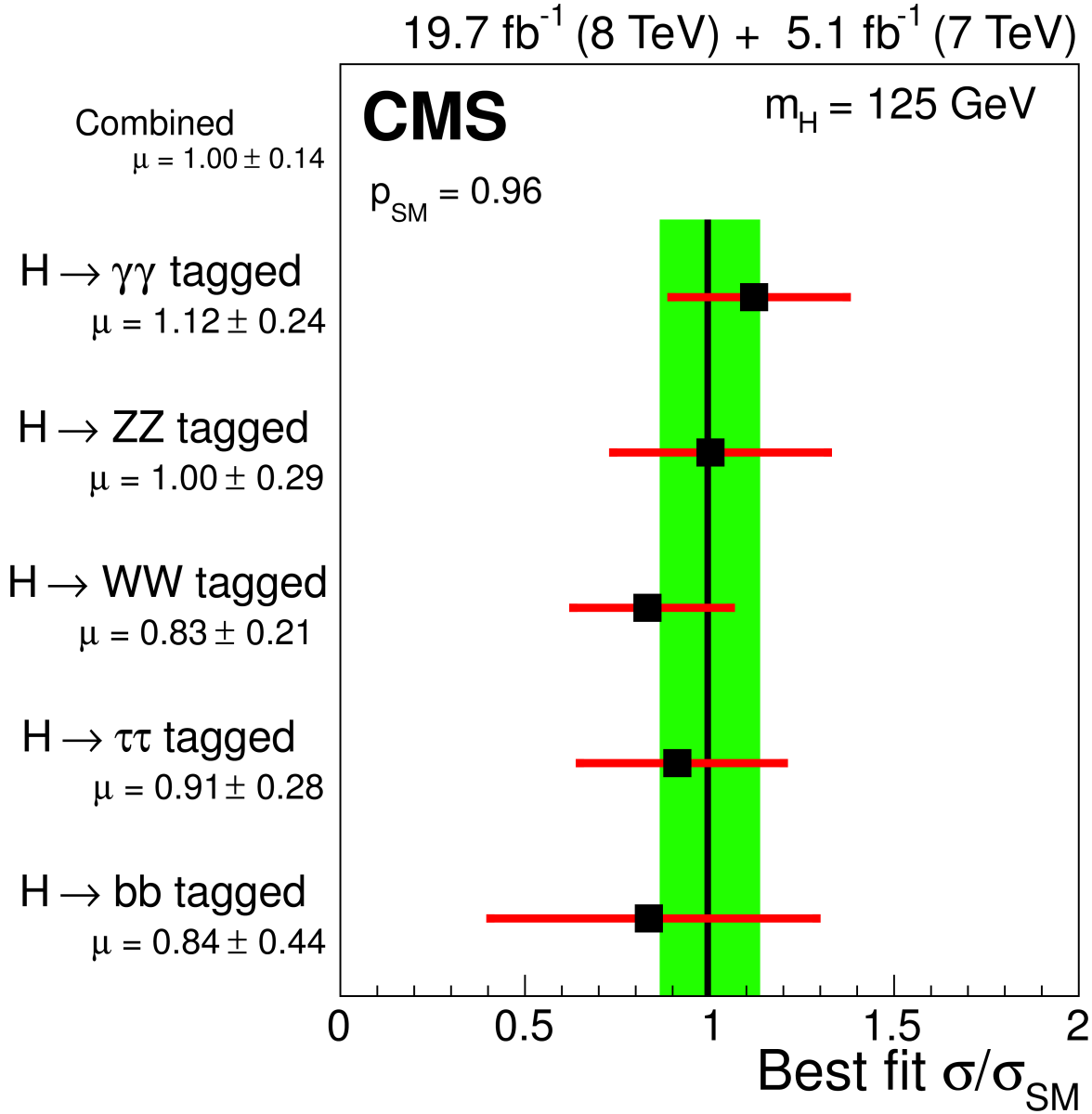
Combination all channels: 1.18 ± 0.10 ± 0.07±0.08
- ATLAS-CONF-2015-007

BACKUP: CMS results - mass



mH=125.09±0.21(stat.)±0.11(syst.) GeV

BACKUP: CMS results – signal strength



BACKUP: How to use differential cross sections

ArXiv: 1506.00612 – version 1

Explaining the Higgs boson p_T distributions with a new heavy scalar boson and a dark matter candidate

Stefan von Buddenbrock,[1,*] Nabarun Chakrabarty,[2,†] Alan S. Cornell,[3,‡] Deepak Kar,[1,§] Mukesh Kumar,[3,¶] Tanumoy Mandal,[2,**] Bruce Mellado,[1,††] Biswarup Mukhopadhyaya,[2,‡‡] and Robert G. Reed[1,§§]

ArXiv: 1506.00612 – version 2

The compatibility of LHC Run 1 data with a heavy scalar of mass around 270 GeV

Stefan von Buddenbrock[a], Nabarun Chakrabarty[b], Alan S. Cornell[c], Deepak Kar[a], Mukesh Kumar[c], Tanumoy Mandal[b], Bruce Mellado[a], Biswarup Mukhopadhyaya[b], Robert G. Reed[a]