Higgs boson fiducial differential cross section measurements at ATLAS

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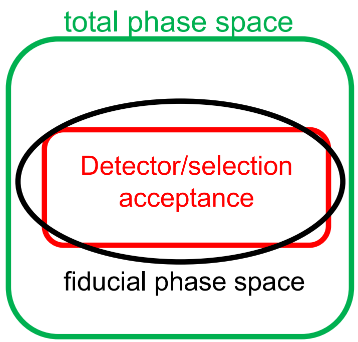
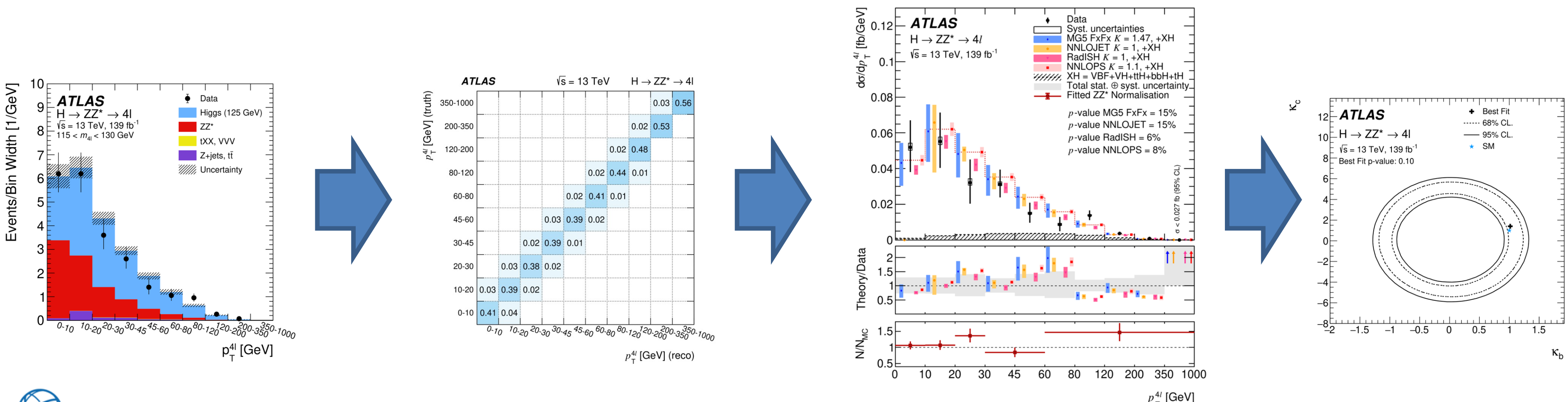
LHCP2023

22–26 May 2023. Belgrade, Serbia

Fiducial differential cross section measurements

- The fiducial phase space is defined to **minimize** the **extrapolation effects** and mimic the detector & analysis acceptance
- Most **model independent** way to study the properties of the Higgs boson
- Downside: reduced sensitivity for BSM effects compared to dedicated analyses
- Observable sensitive to: Higgs boson production kinematics, associated jet kinematics, decay kinematics e.g. to probe spin-CP of the Higgs boson

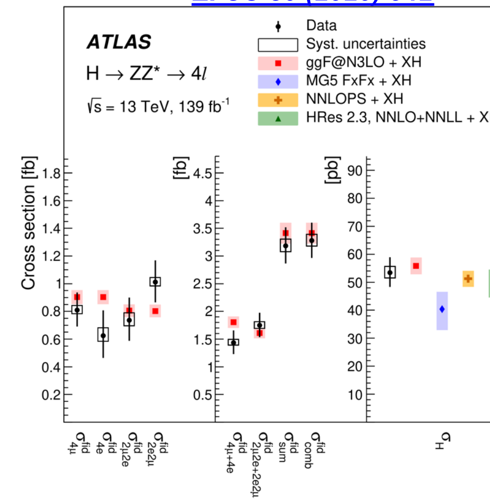




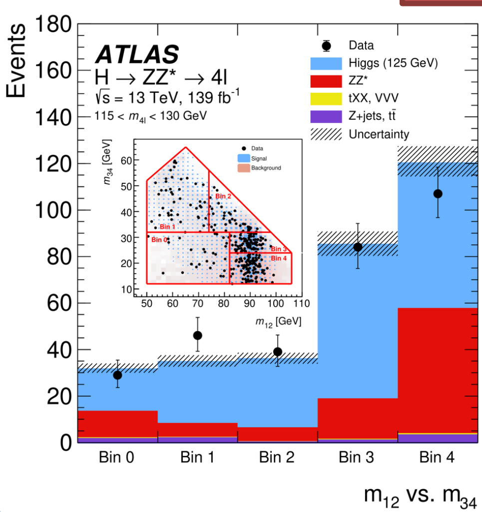
Fiducial and differential XS in H⟶ZZ⟶4l*

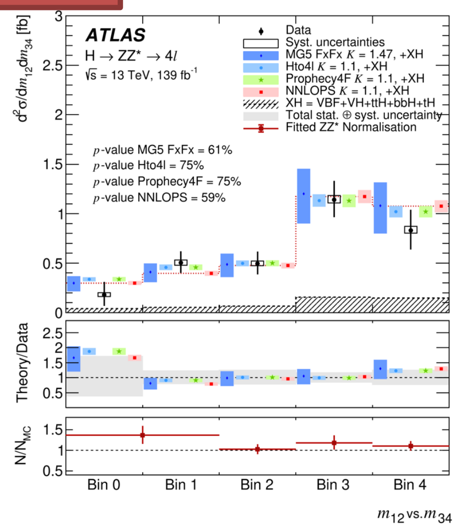
EPJC 80 (2020) 942

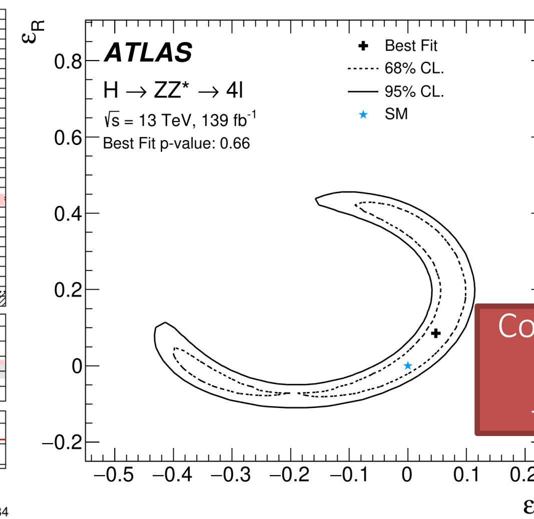
- Together with H⟶γγ perfect channel to measure differential XS for several observables sensitive to the Higgs boson production and decay
- Final state can be fully reconstructed: SF-OC lepton (e,μ) pairs
- ~1-2% mass resolution, inclusive S/B ~2
- Likelihood Unfolding via inversion of detector response matrix
- Several observables measured
  - Measurements in agreement with SM predictions
- As an example, m_{12} vs m_{34} and its interpretation within the Pseudo Observable framework



m_{12} vs m34







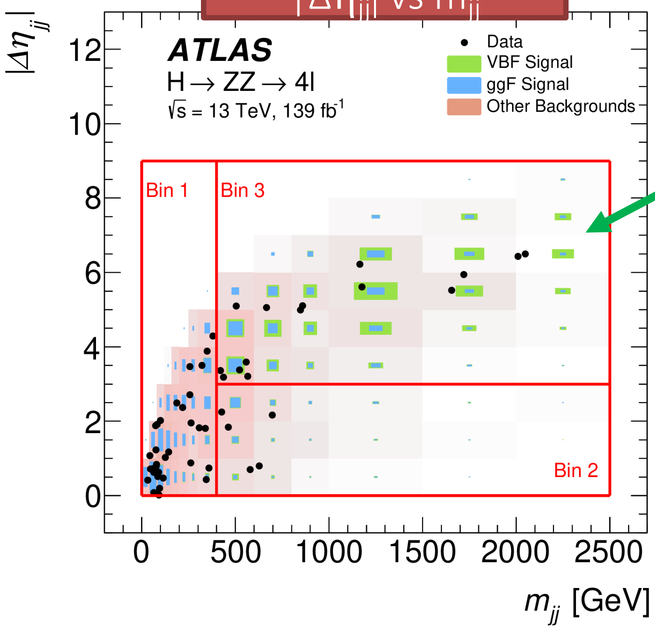
Constraints on flavour-universal contact terms interactions

Fiducial and differential XS in $H \rightarrow ZZ^* \rightarrow 4l$

- Fiducial cross section measured in a VBF enriched region

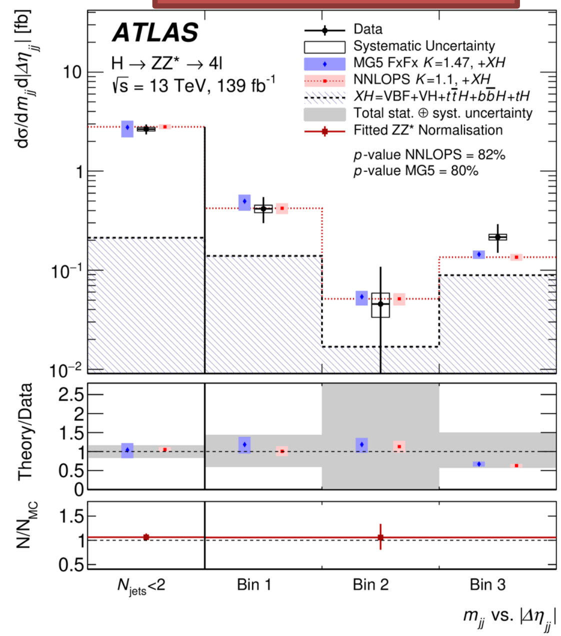
arXiv:2304.09612

$|\Delta\eta_{jj}|$ vs m_{jj}



59.3% VBF
37.5% ggF
1.7% VH
1.5% ttH

Differential XS



- Good agreement with SM predictions found
- In VBF enriched bin with $m_{jj} \geq 400$GeV and $|\Delta\eta_{jj}|>3$: (Obs) $0.215^{+0.077}_{-0.064}$ fb (exp) $0.134^{+0.065}_{-0.053}$ fb
  - ~36% uncertainty dominated by the data statistics

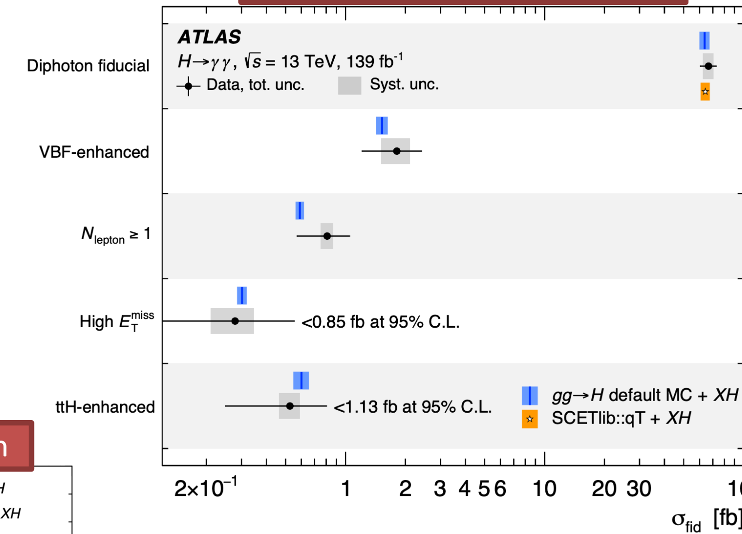
Fiducial and differential XS in H→γγ

- Very clean signature with two isolated photons
- Main background from the γγ continuum, signal extraction with a fit to $m_{\gamma\gamma}$
- Matrix unfolding implemented in the likelihood fit
- Inclusive fiducial cross section:

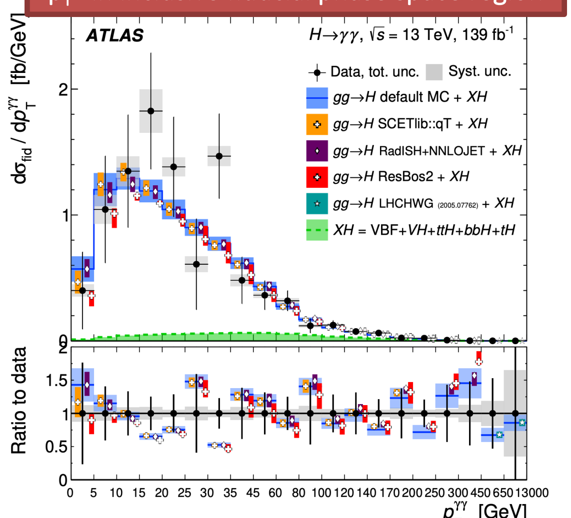
  (obs)σ_{fid}= 67±5(stat)±4 (sys) fb (SM) σ_{fid}= 64±4 fb

- Differential cross sections measured in the inclusive fiducial phase space and in a VBF-enriched fiducial region

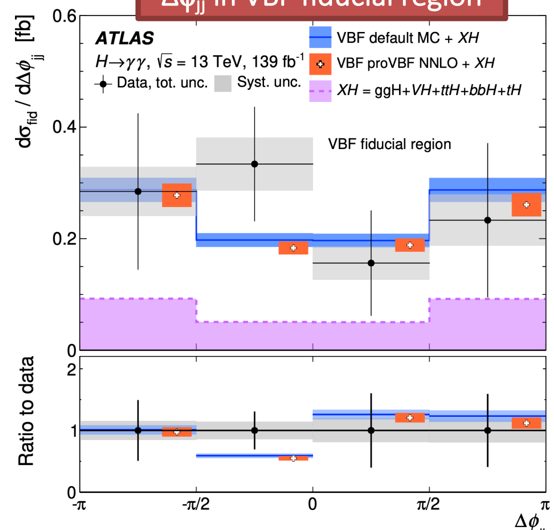
Fiducial cross sections



p_T^H in inclusive fiducial phase space region



$\Delta\phi_{jj}$ in VBF fiducial region



- χ^2 compatibility between the measured cross sections and SM predictions (default MC) ranges from 27% to 95%

[JHEP 08 (2022) 027](#)

Fiducial and differential XS in $H\rightarrow\gamma\gamma$

- Differential fiducial cross section measured for 5 observables used to constrain possible BSM effects in the Higgs boson interactions within the effective field theory framework
  - SM Lagrangian complemented with additional **CP-even** and **CP-odd** dim-6 operators in the SMEFT Warsaw basis
  - Variables: $p_T^{\gamma\gamma}$, N_j, m_{jj}, $\Delta\phi_{jj}$, p_T^{j1} with the correlation among the observables properly considered
- Limits set on SMEFT Wilson coefficients both using SM with dimension-6 operators interference-only terms and including the quadratic (dim-6) terms

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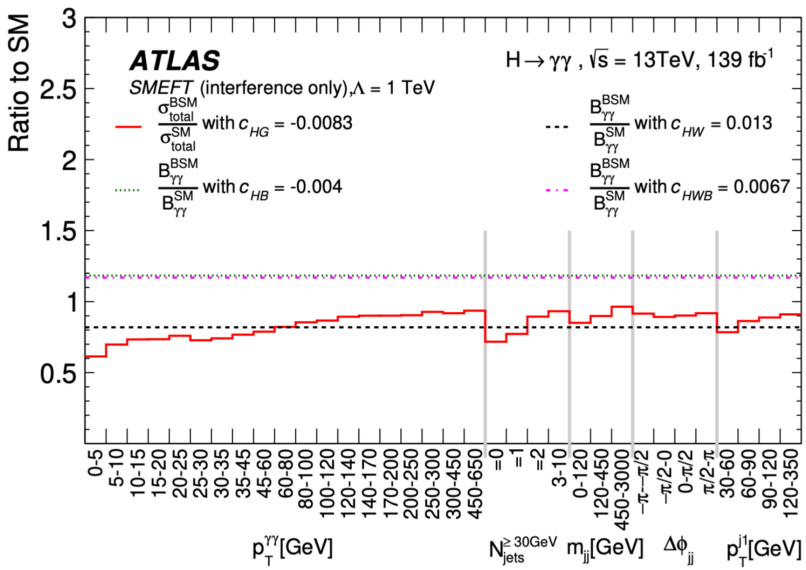
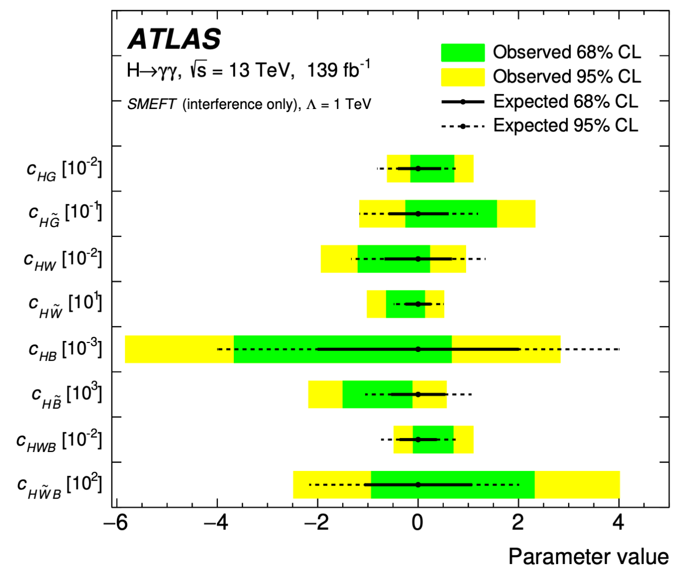
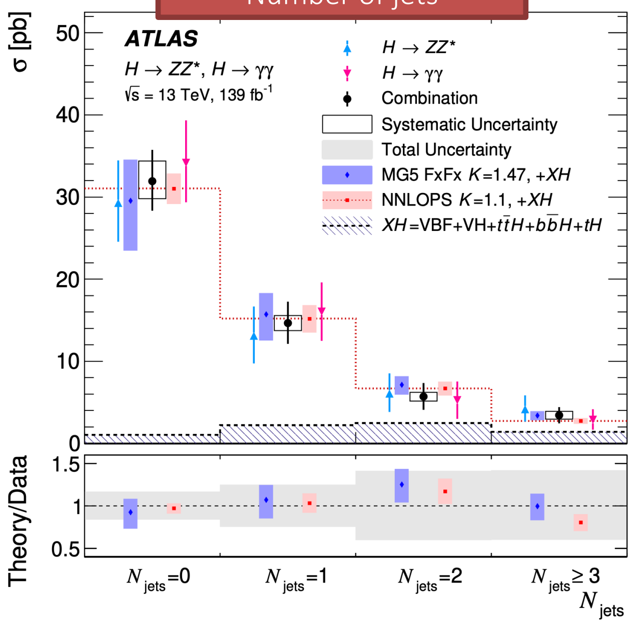




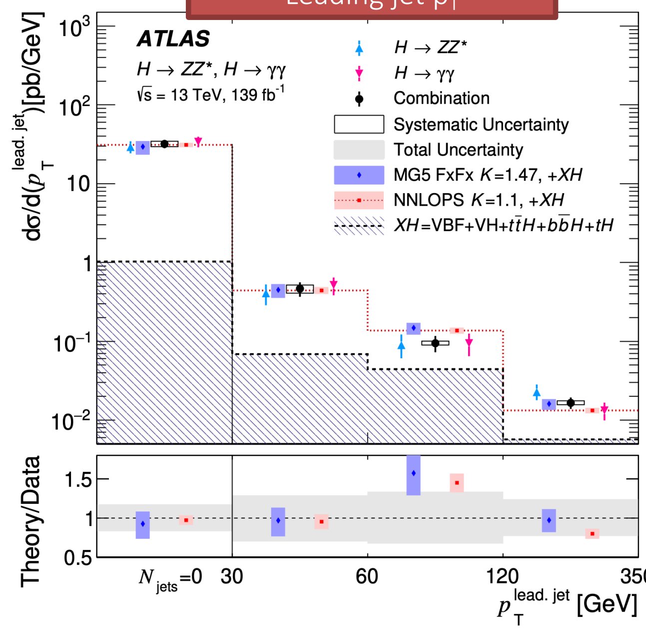
$H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ combination

- Fiducial cross section measurements at 13TeV extrapolated to the full phase-space and combined
  - Additional uncertainties + SM assumption on the BR, BUT significant reduction of stat unc.
- Total Higgs boson production cross section: $55.5^{+4.0}_{-3.8}$ pb (SM: 55.6±2.5 pb)
- Differential cross sections measured: p_T^H, $|y_H|$, N_J, $p_T^{lead.\,j}$, p_T^H vs $|y_H|$
  - Compatibility between the two channels between 20% (p_T^H) and 80% (N_{jets})
  - Compatibility with SM predictions between 23% ($p_T^{lead.\,j}$) and 98% ($|Y_H|$)

Number of jets



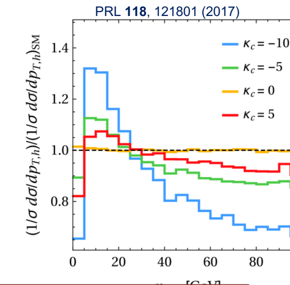
Leading jet p_T

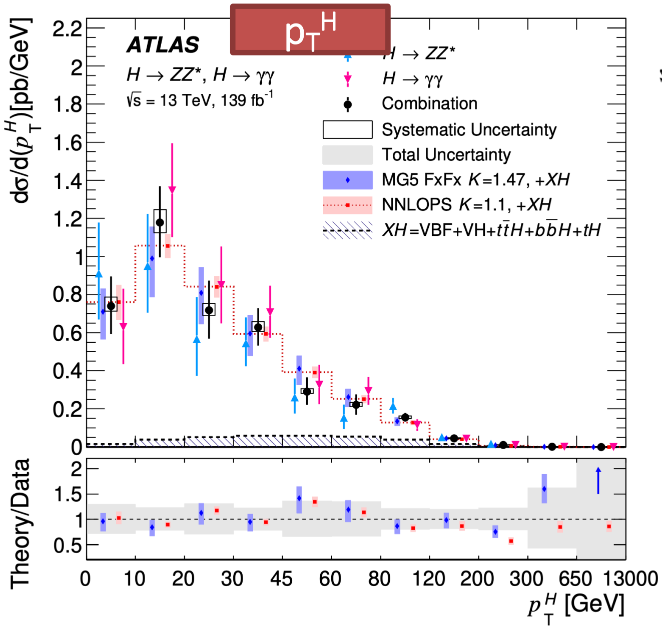


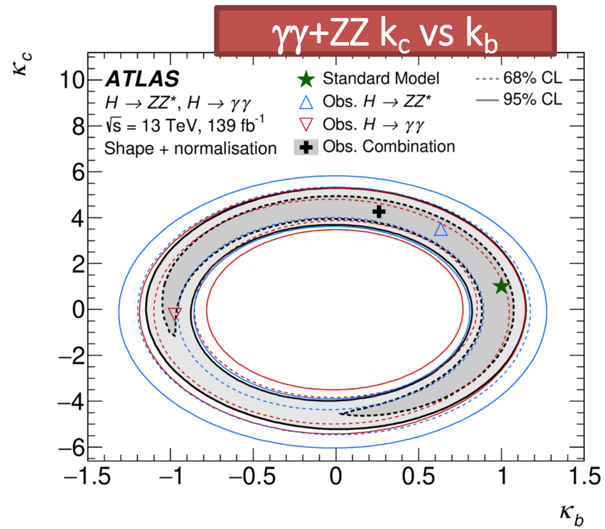
arXiv:2207.08615

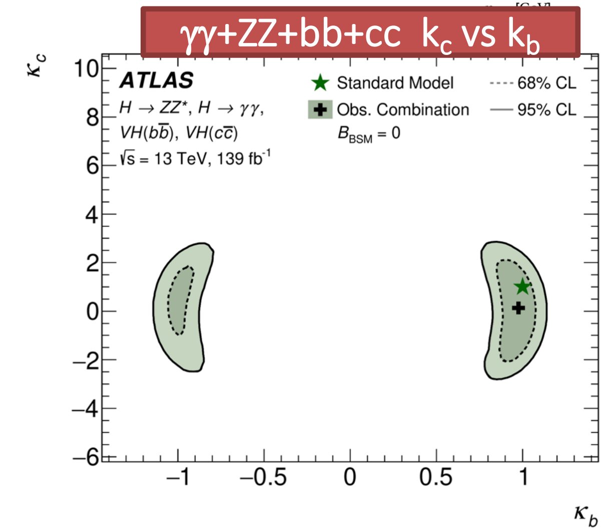
H⟶ZZ*⟶4l and H⟶γγ combination

- p_T^H measured by H⟶ZZ*⟶4l and H⟶γγ jointly interpreted in terms of **anomalous couplings** of the Higgs boson **to bottom and charm quarks (k_b, k_c)**
  - Exploited shape and normalization effects on the distribution
  - Combined also with the constraints from **VH, H⟶bb and VH, H⟶cc** analyses







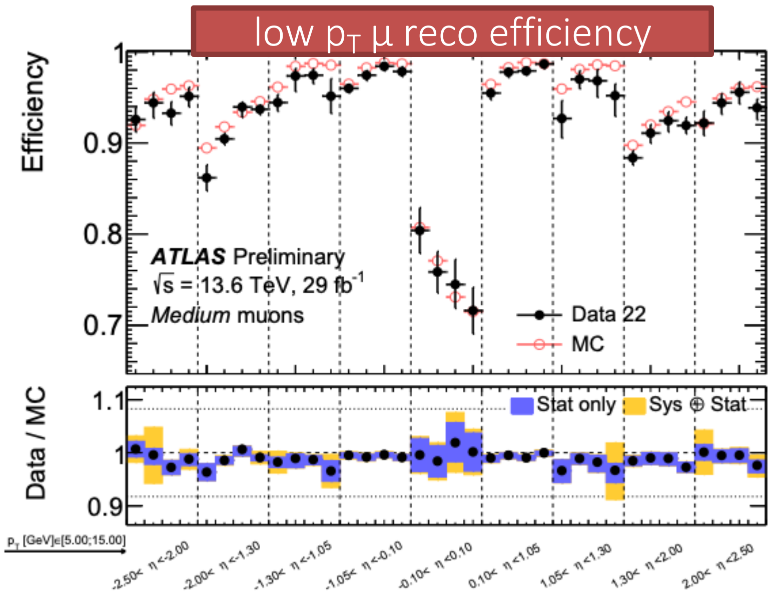


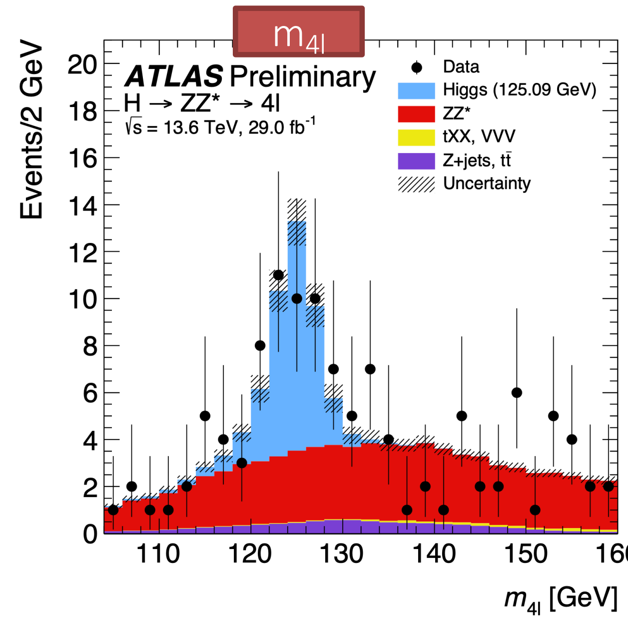
- $|k_c|<2.5$ @ 95% CL assuming $B_{BSM}=0$ and $k_i=1$ excepting for k_b

arXiv:2207.08615

New measurements at 13.6TeV

- Run3 started in 2022 with p-p collisions at $\sqrt{s}$=13.6 TeV, collected about 30fb^{-1} of collision data
  ⇒ First fiducial and total cross section in H⟶γγ and H⟶ZZ*⟶4l and their combination
- Same analysis strategy as in for the Run2, detector performances similar to Run2

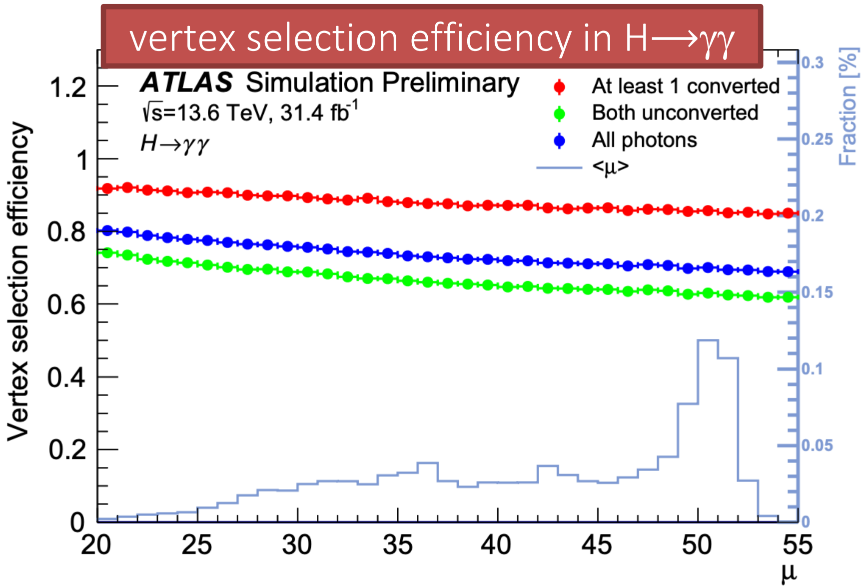


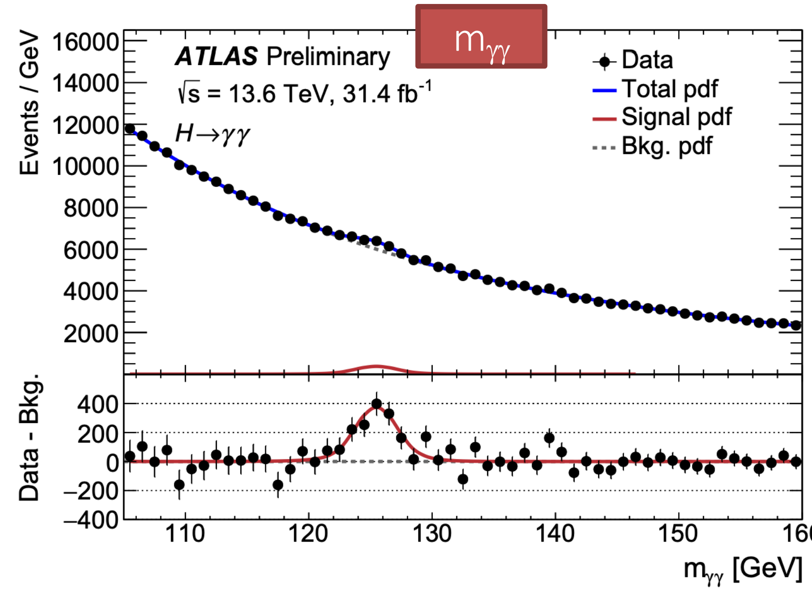


- Selection efficiency in the fiducial phase space ~50%
- (obs)σ_{fid}= 2.8±0.7(stat)±0.2 (sys) fb   (SM) σ_{fid}= 3.67±0.19 fb
- Main systematics: electron and muon syst.

New measurements at 13.6TeV

- Run3 started in 2022 with p-p collisions at $\sqrt{s}$=13.6 TeV – collected about 30/fb of collision data
  ⇒ First fiducial and total cross section in H⟶γγ and H⟶ZZ*⟶4l and their combination
- Same analysis strategy as in for the Run2, detector performances similar to Run2

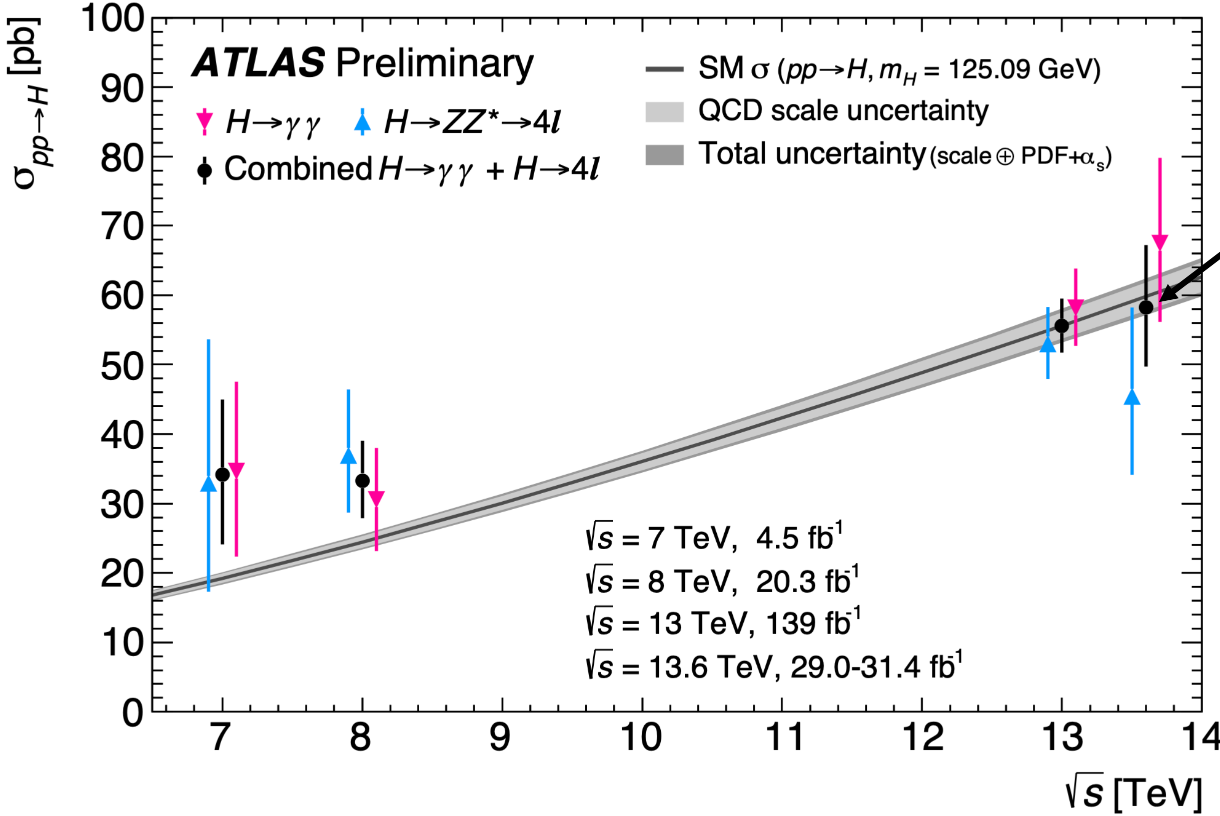




- Selection efficiency in the fiducial phase space ~72%
- (obs)σ_{fid}= 76±11(stat)±8 (sys) fb (SM) σ_{fid}= 67.7±3.7 fb
- Main systematics: bkg modelling and photon efficiency syst.

New measurements at 13.6TeV

- Fiducial cross sections extrapolated to the full phase space and combined



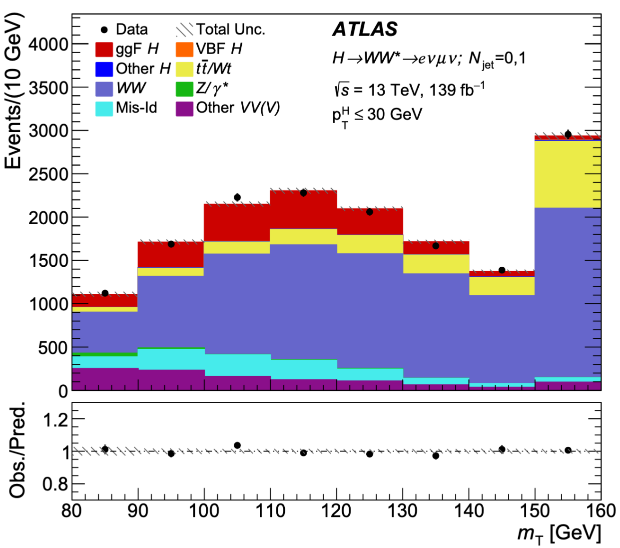
$\sigma(pp \rightarrow H)$ = 58.2 ± 8.7 pb
$\sigma(pp \rightarrow H)_{SM}$ = 59.9 ± 2.6 pb

- Compatibility with the SM prediction is 85%
- H⟶ZZ*⟶4l and H⟶γγ compatibility is 20%

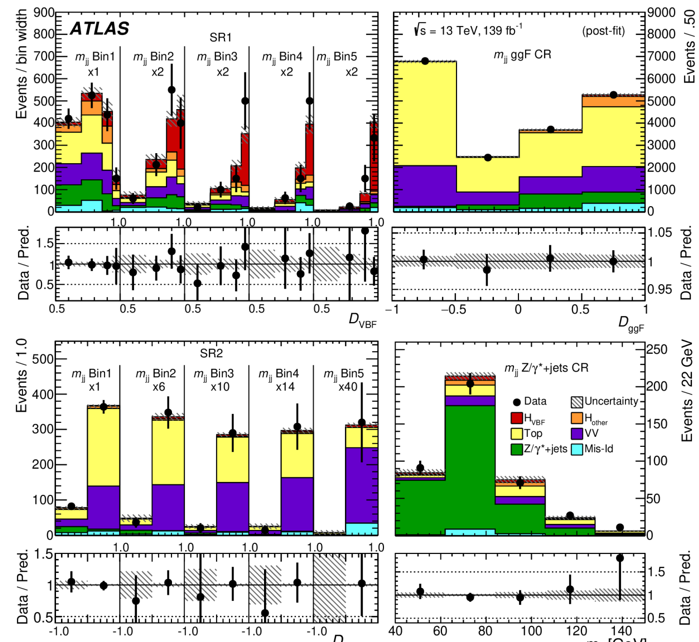
Differential XS in $H \longrightarrow WW^* \longrightarrow e\nu\mu\nu$

- Higher signal compared to $H \longrightarrow \gamma\gamma$ and $H \longrightarrow ZZ^* \longrightarrow 4l$ but lower S/B and final state not fully reconstructable.
- Measurements performed in two distinct phase space regions targeting different prod. modes
  - — ggF : =0 , =1 jet fiducial phase space
  - — VBF : ≥ 2 jets fiducial phasespace
- Observables used to extract the signal: m_T or dedicated discriminant

arXiv:2301.06822



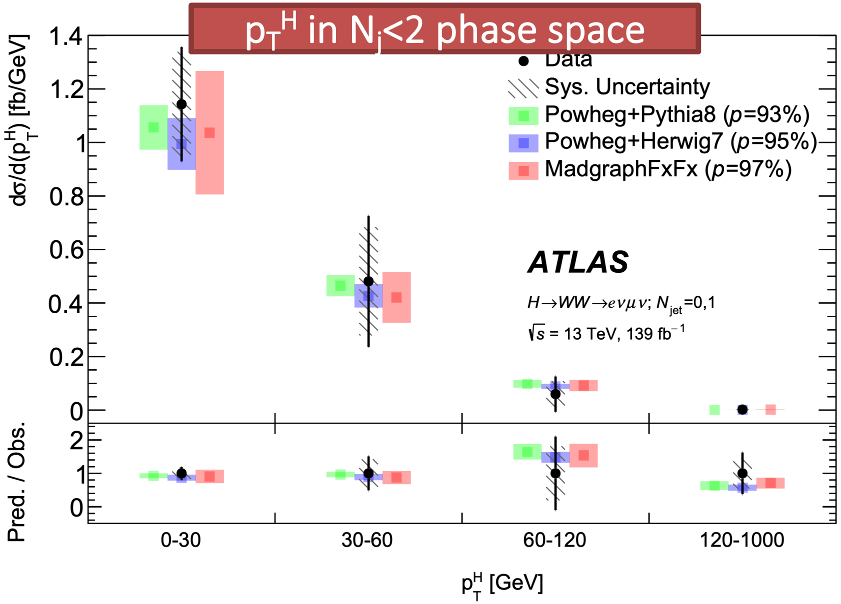
arXiv:2304.03053

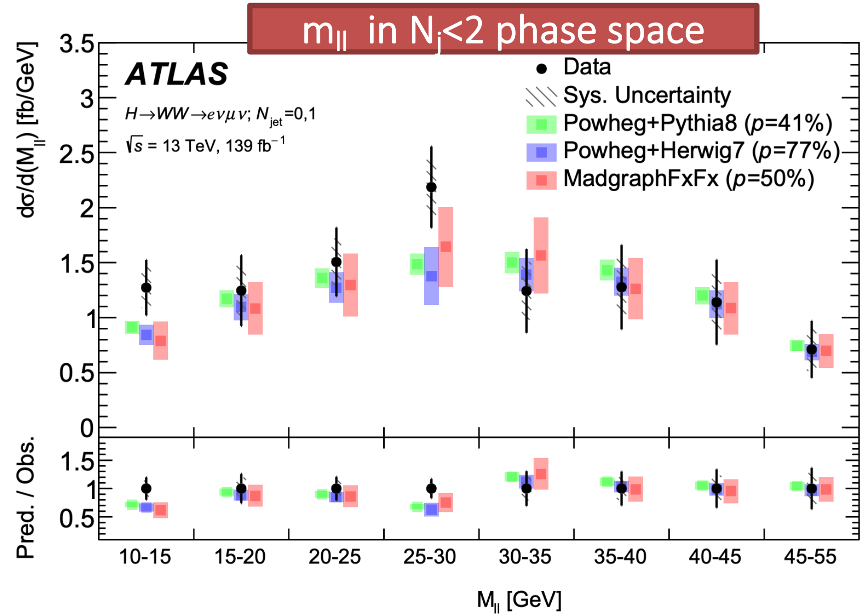


Differential XS in H⟶WW⟶eνμν: ggF phase space

arXiv:2301.06822

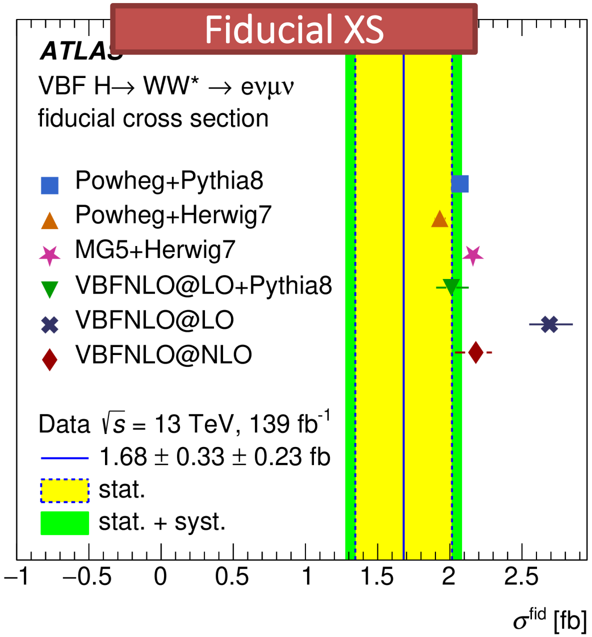
- m_T used to extract the signal in each bin of a given observable
- Compared to H⟶γγ and H⟶ZZ*⟶4l larger off diagonal terms in the response matrix
  - Tikhonov-regularized in-likelihood unfolding used

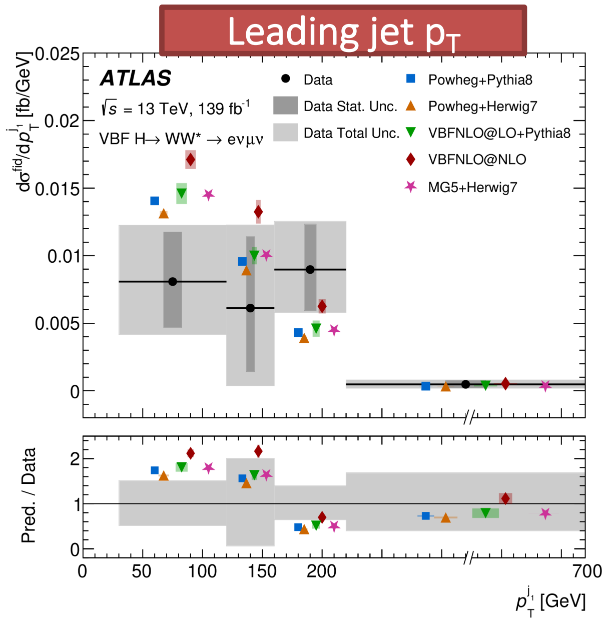


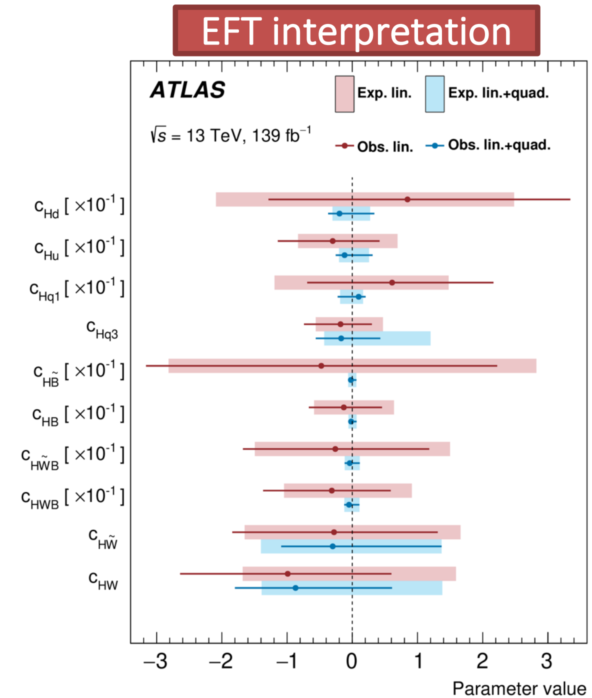


- In general, good agreement between th. predictions and measured cross sections
- At high Higgs boson transverse momentum (>120GeV) 1σ sensitivity, competitive with other channels

Differential XS in H⟶WW⟶eνμν : VBF phase space







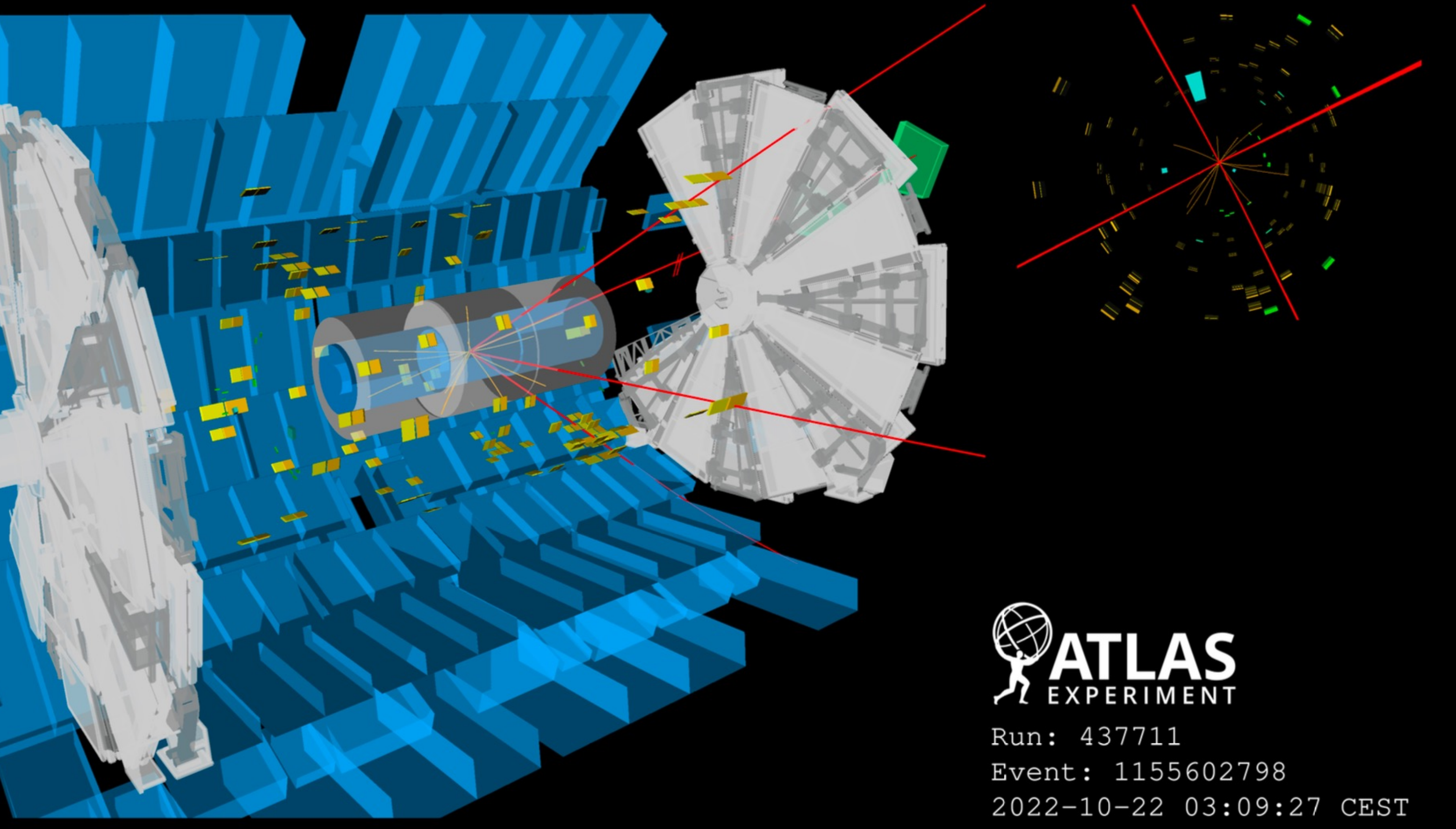
- Fiducial measurement in the VBF phase space
- 24% uncertainty , statistical still dominant
- TH predictions within 1σ excluding except for a pure LO prediction

- Differential cross sections measured for several observables
- Uncertainties driven by data statistics
- In general in agreement with SM predictions
- Differential cross sections used to constrain anomalous interactions described by a dim-6 EFT

arXiv:2304.03053

Summary

- **Run 2 data** have been already **heavily exploited** to feed the extended ATLAS Higgs boson physics program
  - A lot of measurements published using the full Run-2 available statistics
- **Fiducial differential cross sections measured in several decay modes**
  - Predictions tested against unfolded data in multiple observables sensitive to various BSM effects
    - In general, statistical uncertainty is still dominant
  - **Results compatible with the SM predictions so far**
- LHC Run3 has started in 2022 at 13.6 TeV
  - **First fiducial and inclusive cross sections measured in H⟶γγ and H⟶ZZ*⟶4l and their combination**
  - **x2 more data expected at the end of Run3 ⇒ further improve the precision and sensitivity to possible BSM effects**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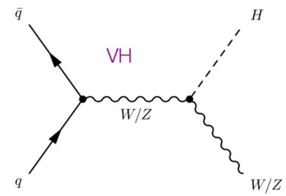
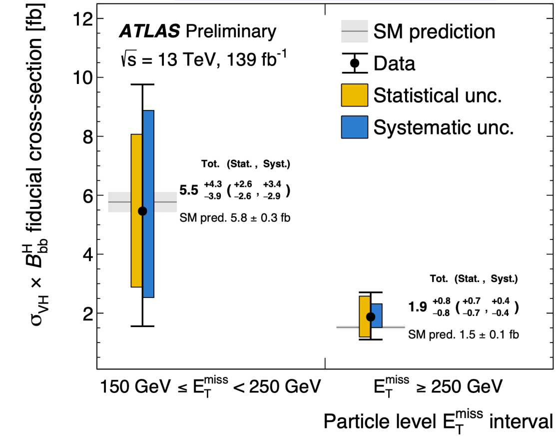
Backup

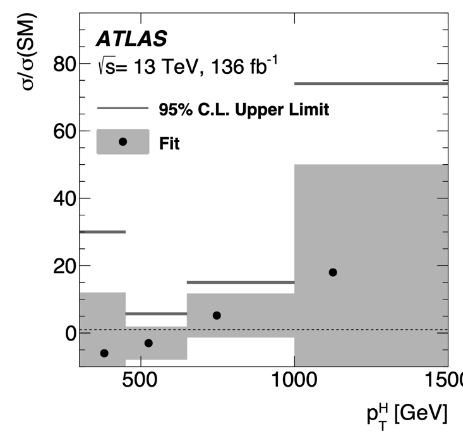
ATLAS-CONF-2022-015

- Fiducial cross section measured in VH, H ⟶ bb with 0 charged leptons associated to the V decay
  - No electron/muon required in the events
- Measured in two fiducial regions defined by the particle level E_T^{miss}





- High p_T Higgs boson production explored in H ⟶ bb events with large Lorentz boost
  - Higgs boson reconstructed from a single large-radius jet
- Upper limits set on the Higgs boson production cross section as function of p_T^H
- 95%CL on the fiducial cross section for p_T^H>450GeV is 115 fb (SM 18.4fb)



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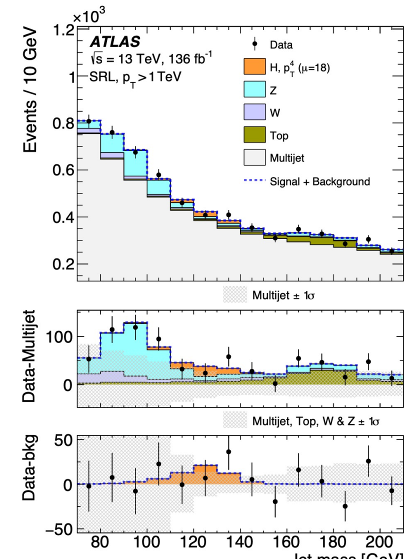


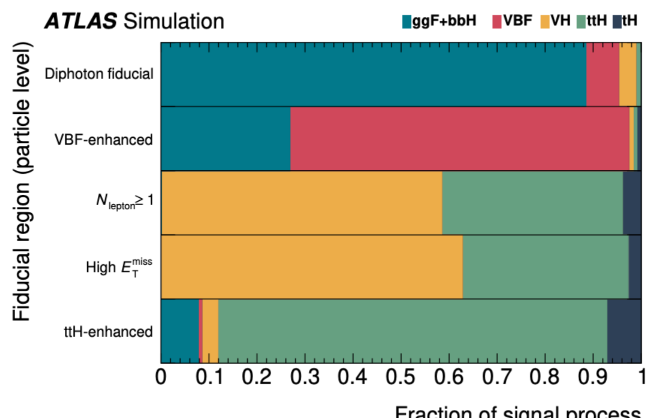
$H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ fiducial phasespace

- 4l

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element value

- $\gamma\gamma$

Photons	
Leading (sub-leading) p_T^γ	$p_T^\gamma / m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$\lvert\eta\rvert < 2.47$ and outside $1.37 < \lvert\eta\rvert < 1.52$
Isolation	$E_T^{iso} / E_T^\gamma < 0.05$
Di-photon system	
Mass window	105 GeV $< m_{\gamma\gamma} <$ 160 GeV



$H \rightarrow WW \rightarrow e\nu\mu\nu$ fiducial phase space

- ggF

Category	$N_{\text{jet},(p_T>30\text{ GeV})} = 0$	$N_{\text{jet},(p_T>30\text{ GeV})} = 1$
Pre-Selection	Exactly two isolated leptons ($\ell = e, \mu$) with opposite charge $p_T^{\text{lead}} > 22$ GeV , $p_T^{\text{sublead}} > 15$ GeV $\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.5$, $p_T^{\text{jet}} > 30$ GeV $m_{\ell\ell} > 10$ GeV $E_T^{\text{miss, track}} > 20$ GeV	
Background rejection	$N_{b\text{-jet},(p_T>20\text{ GeV})} = 0$	
	$\Delta\phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$ GeV	$\max(m_T^{\ell}) > 50$ GeV $m_{\tau\tau} < m_Z - 25$ GeV
	$m_T > 80$ GeV	
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 55$ GeV $\Delta\phi_{\ell\ell} < 1.8$	

- VBF

Selection Requirements	Signal Region	Fiducial Region
Lepton pair flavors	e-μ	
Lepton pair charge	0	
Leading (subleading) lepton p_T	> 22 GeV (> 15 GeV)	
Lepton η^ℓ	$\lvert\eta^\mu\rvert < 2.5$ $0 < \lvert\eta^e\rvert < 1.37$ or $1.52 < \lvert\eta^e\rvert < 2.47$	$\lvert\eta^\mu\rvert < 2.5$ $\lvert\eta^e\rvert < 2.5$
No. of additional leptons	0	
$\Delta R(\ell, \ell)$	overlap removal	> 0.1
$m_{\ell\ell}$	> 10 GeV	
$\Delta R(\ell, \text{jet})$	overlap removal	> 0.4
No. of jets (p_T > 30 GeV, $\lvert\eta\rvert$ < 4.5)	≥ 2	
No. of b-jets (p_T > 20 GeV, $\lvert\eta\rvert$ < 2.5)	0	
$m_{\tau\tau}$	$< m_Z - 25$ GeV	
Central jet veto (p_T > 20 GeV)	✓	
Outside lepton veto	✓	
m_{jj}	> 450 GeV	
$\lvert\Delta y_{jj}\rvert$	> 2.1	
$\lvert\Delta\phi_{\ell\ell}\rvert$	< 1.4 rad	

H→ γγ

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

H→ ZZ*→4l

Source	Uncertainty [%]
Statistical uncertainty	25.2
Systematic uncertainty	7.9
All electron uncertainties	6.6
Reducible background estimation	3.5
All muon uncertainties	3.2
Luminosity	2.2
$ZZ*$ theoretical uncertainties	2
Other uncertainties	<1
Total	26.4