



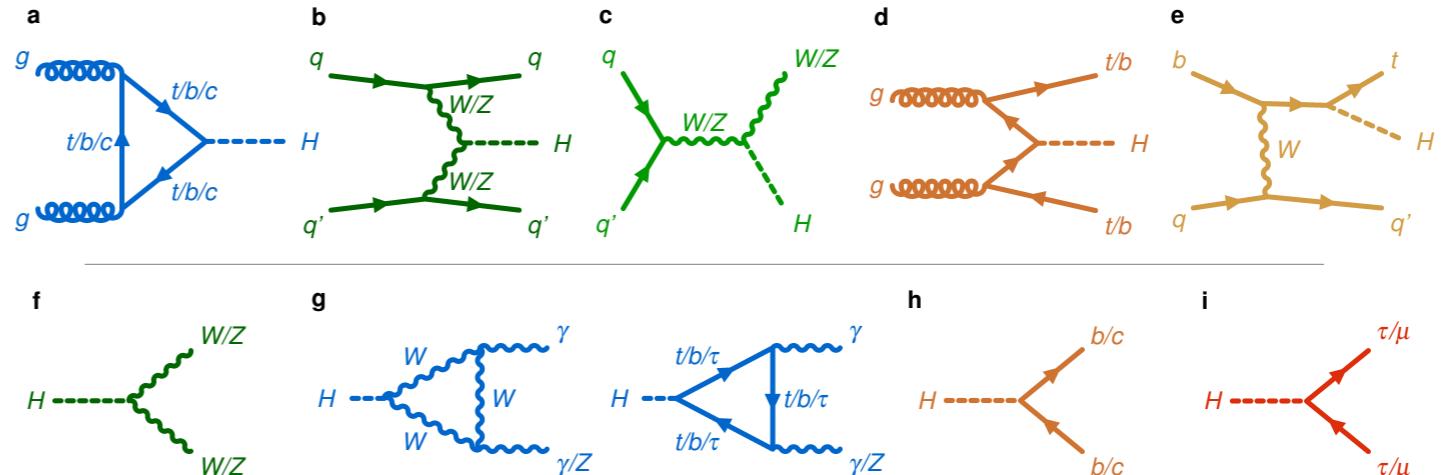
Measurements of the Higgs boson fiducial and differential cross sections with the ATLAS detector

Weitao Wang
on behalf of the ATLAS collaboration

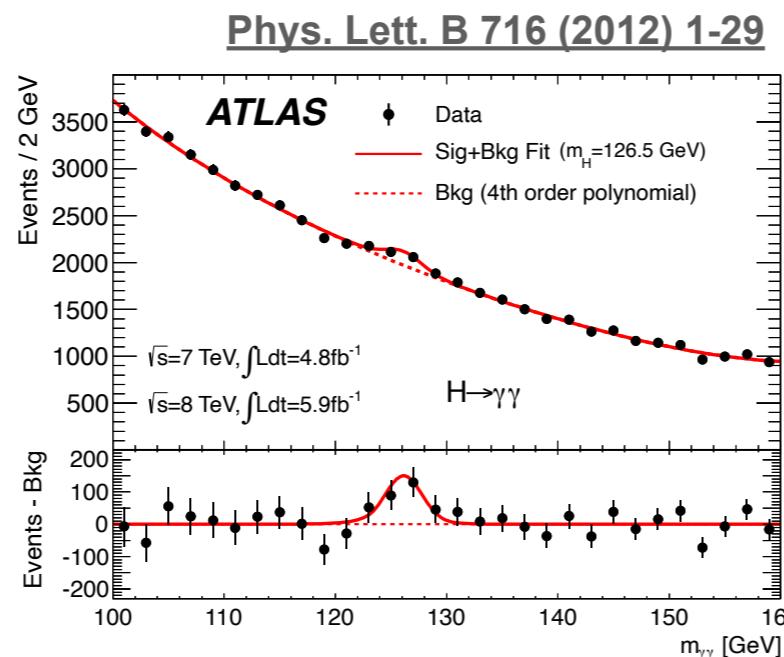
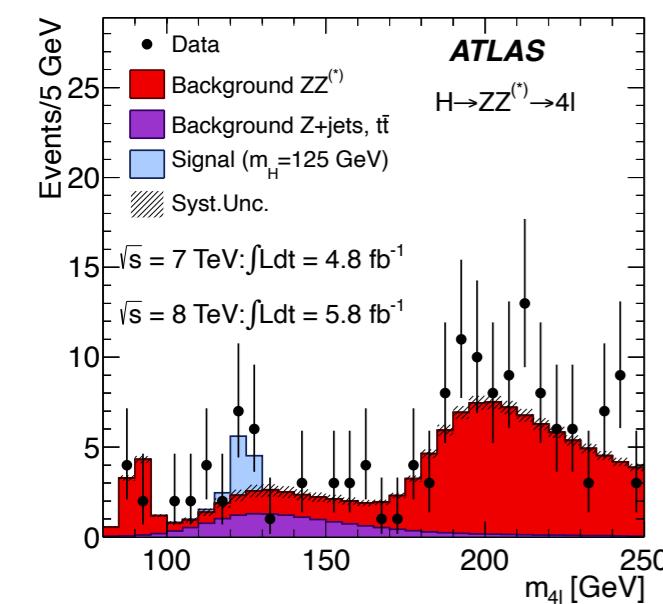
SUSY 2022
UNIVERSITY OF IOANNINA
27.06.2022

10 years since Higgs Boson discovery

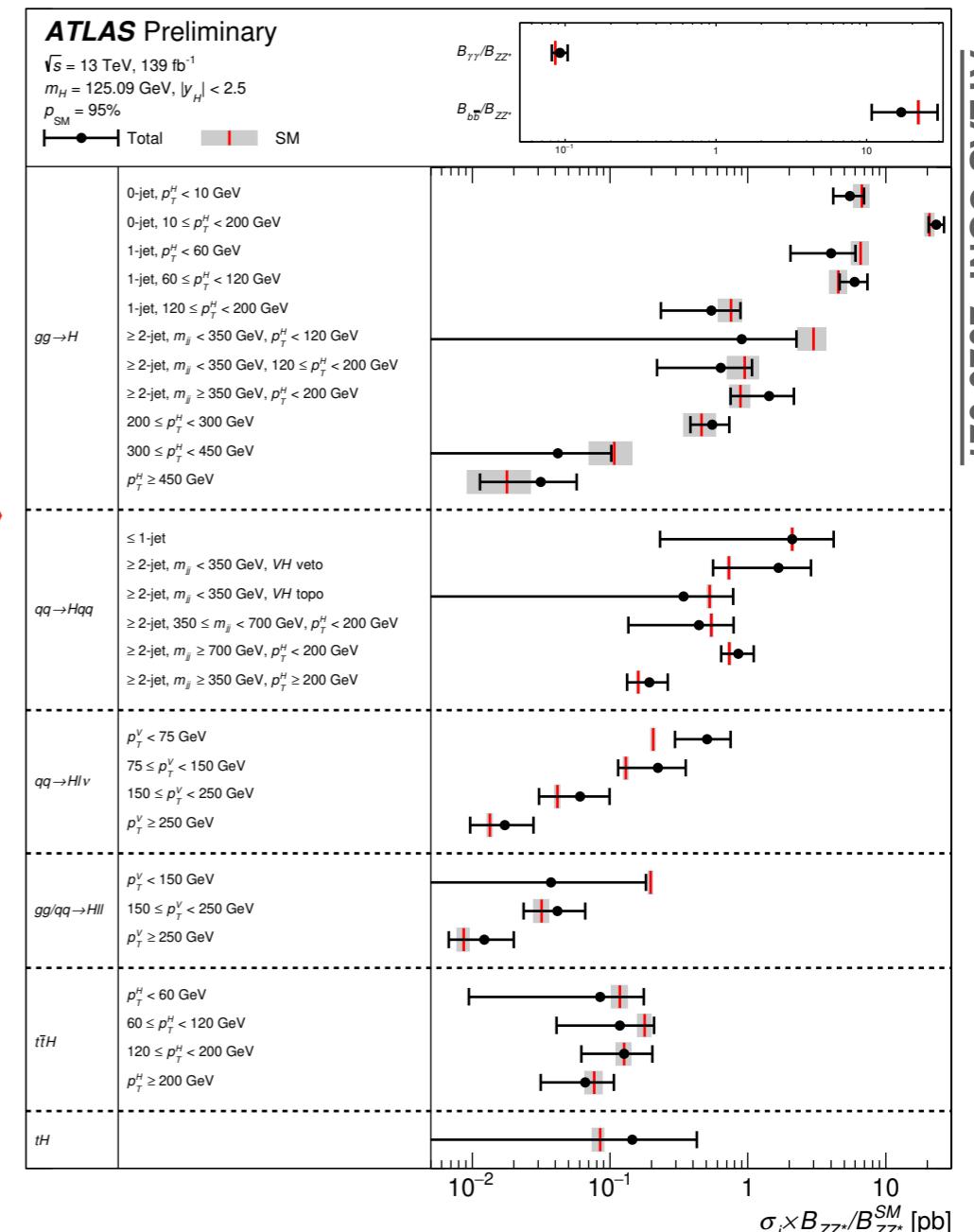
- All the main Higgs boson production modes observed with $> 5\sigma$
- All the main decay modes are also observed



From searching for a new particle to precision measurements!



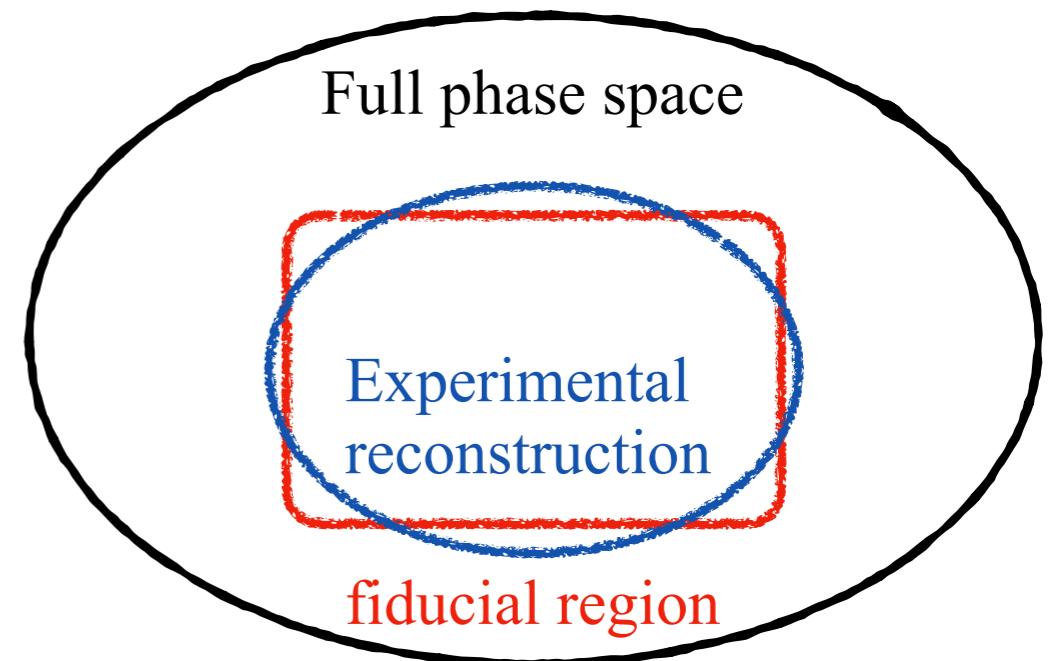
Cross section spans different orders of magnitude due to the nature of the Yukawa coupling



Fiducial and differential cross sections

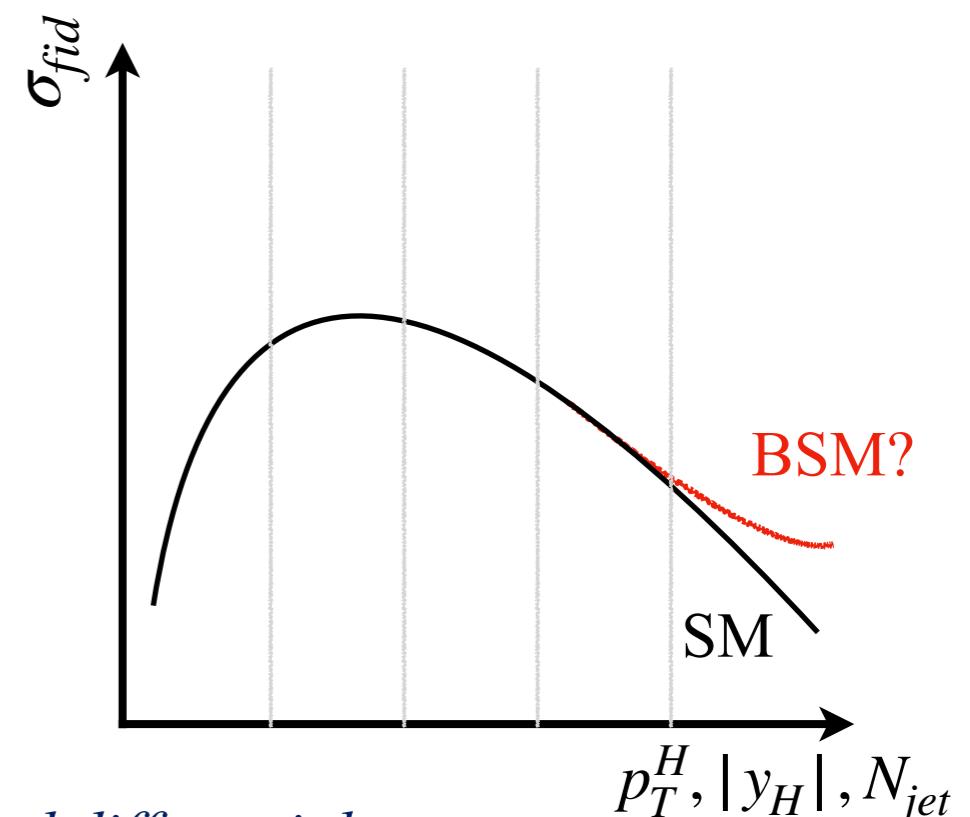
Fiducial cross section measurements

- Fiducial region: defined to closely match to experimental acceptance
- Reduce model dependence by avoiding the extrapolation to the full phase space



Differential cross section measurements

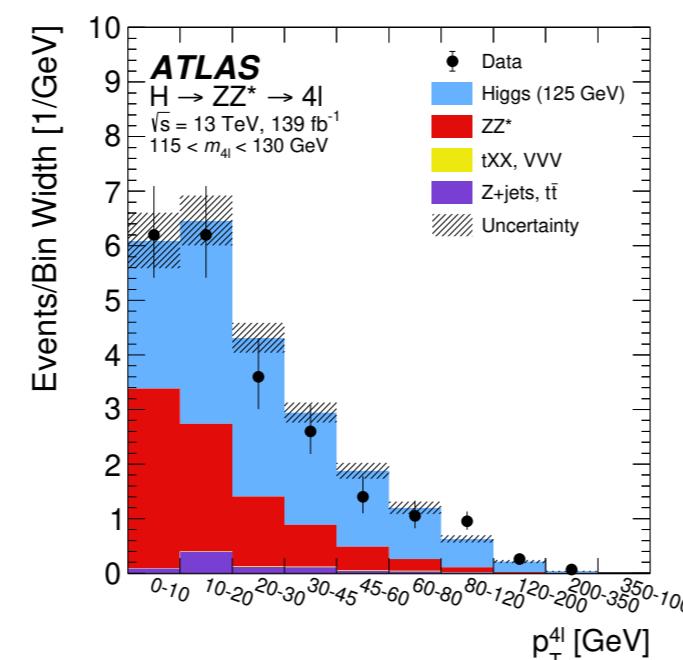
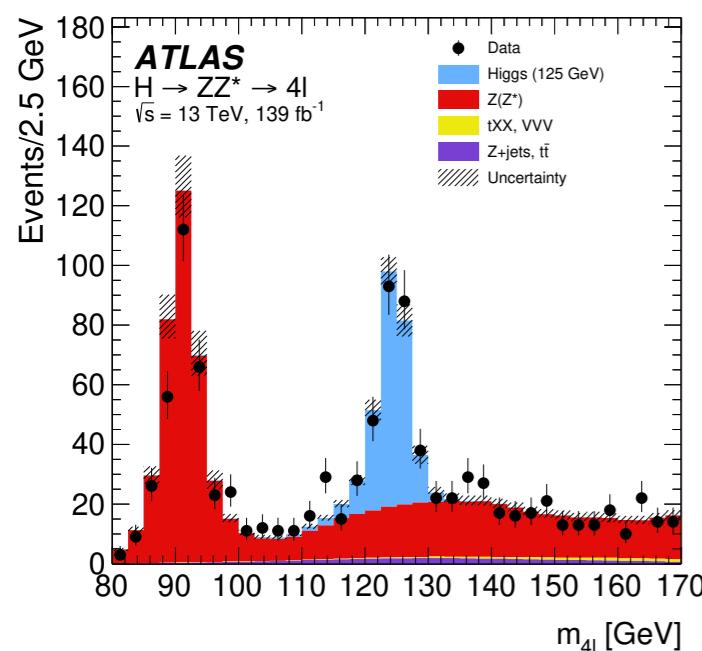
- Measure cross section in bins of some observables:
 $p_T^H, |y_H|, N_{jet} \dots$
- The shape information provided by differential cross sections can be exploited for a range of further interpretations



Many additional interpretations of the measured fiducial and differential cross sections that can be performed — Francesco's talk on Friday

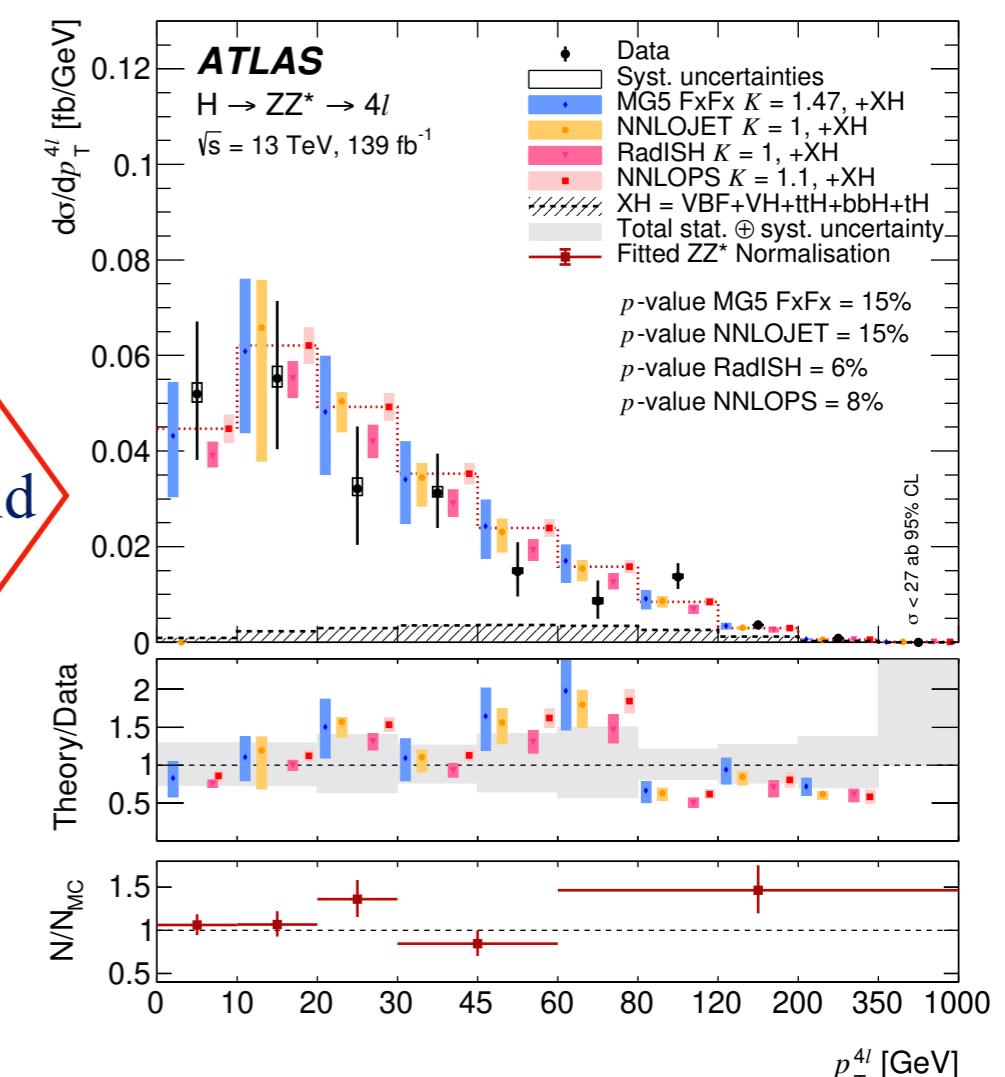
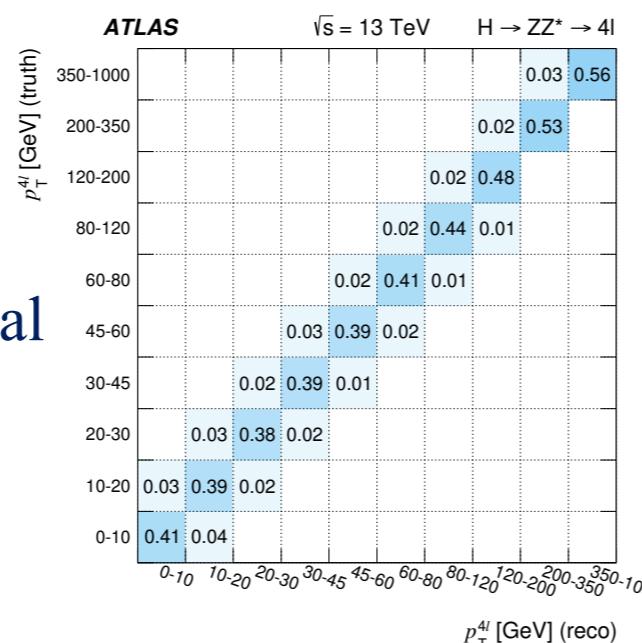
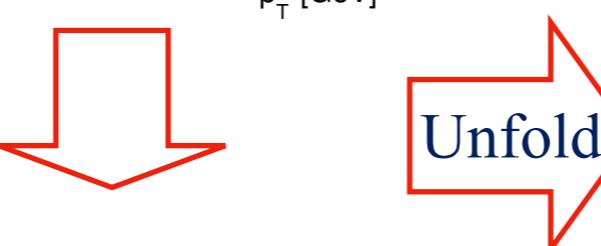
Fiducial differential cross sections measurement

Perform analysis in each experimental bin



Can be performed for any measure variable

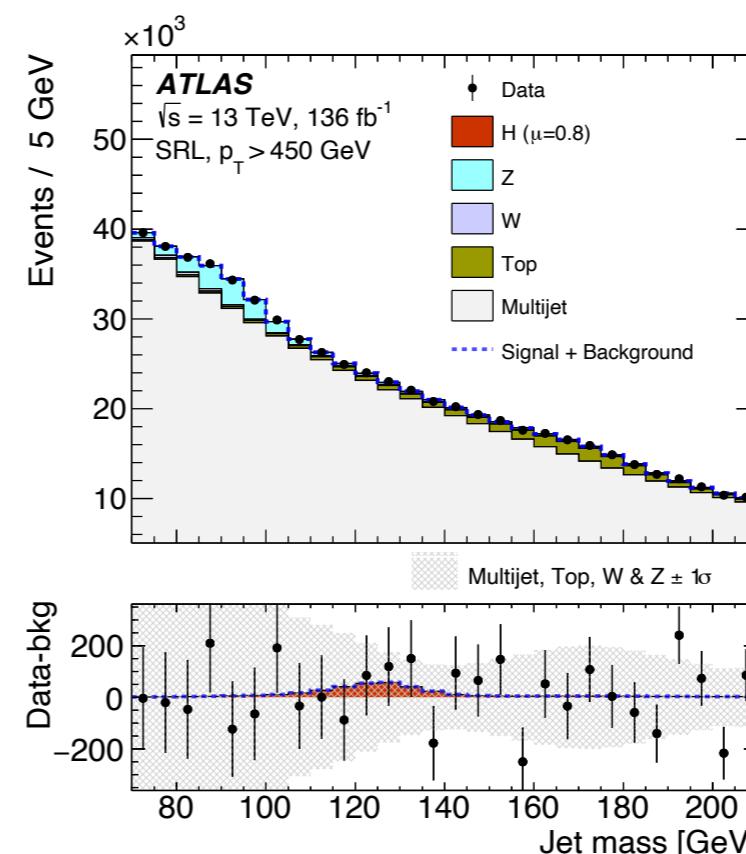
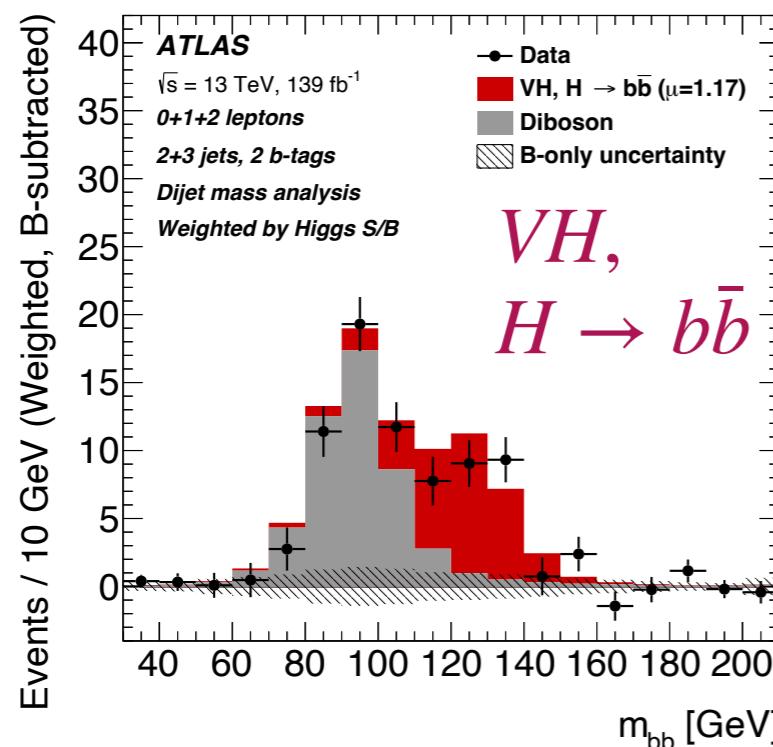
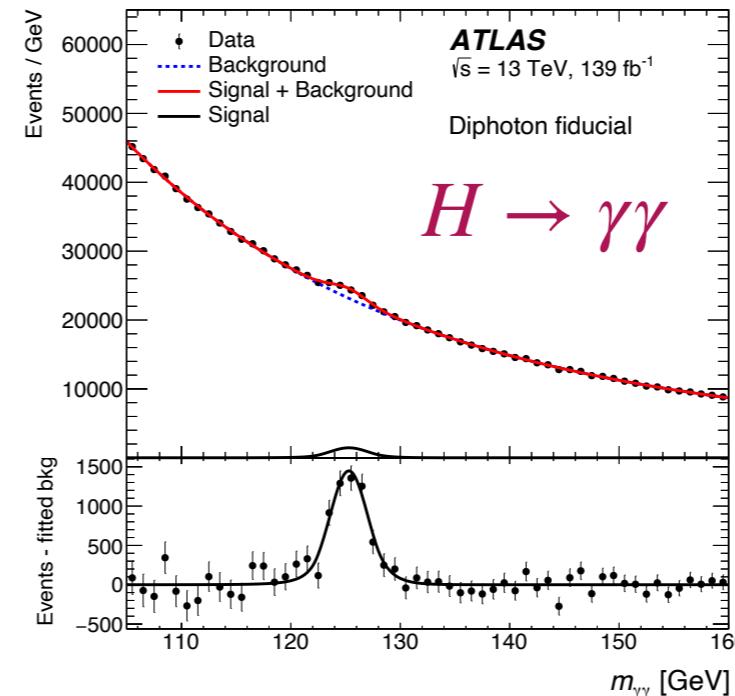
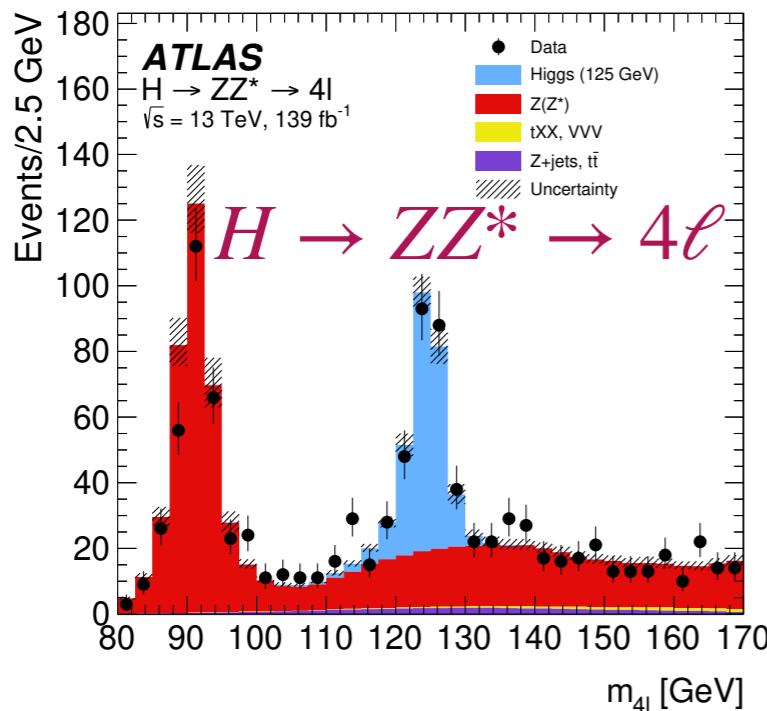
Define a fiducial region + binning, matching experimental selections



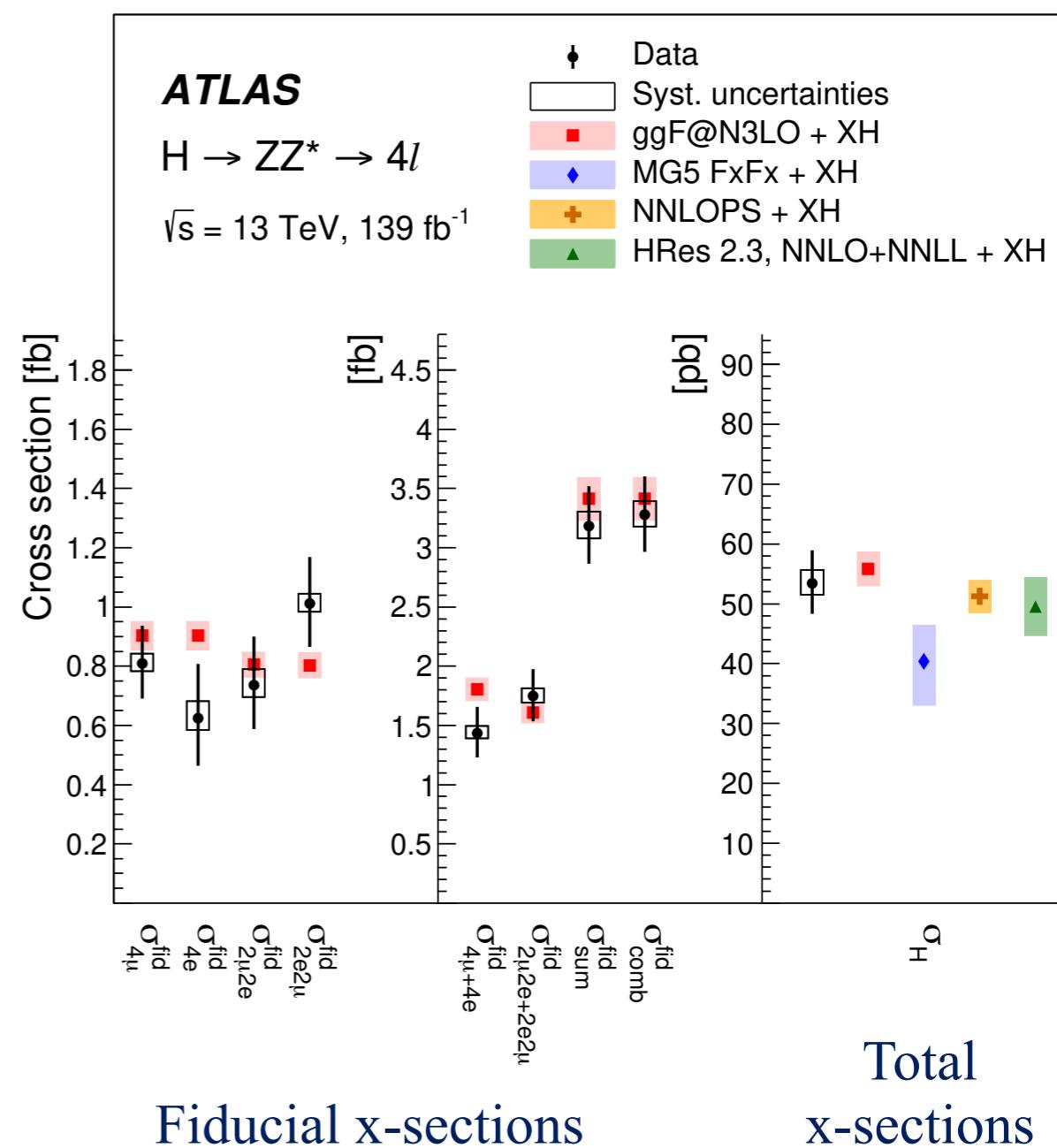
Unfold signal based on the migrations between experimental and fiducial bins

ATLAS Run-2 results

- Focus on the full Run2 available fiducial and differential cross sections measurement results



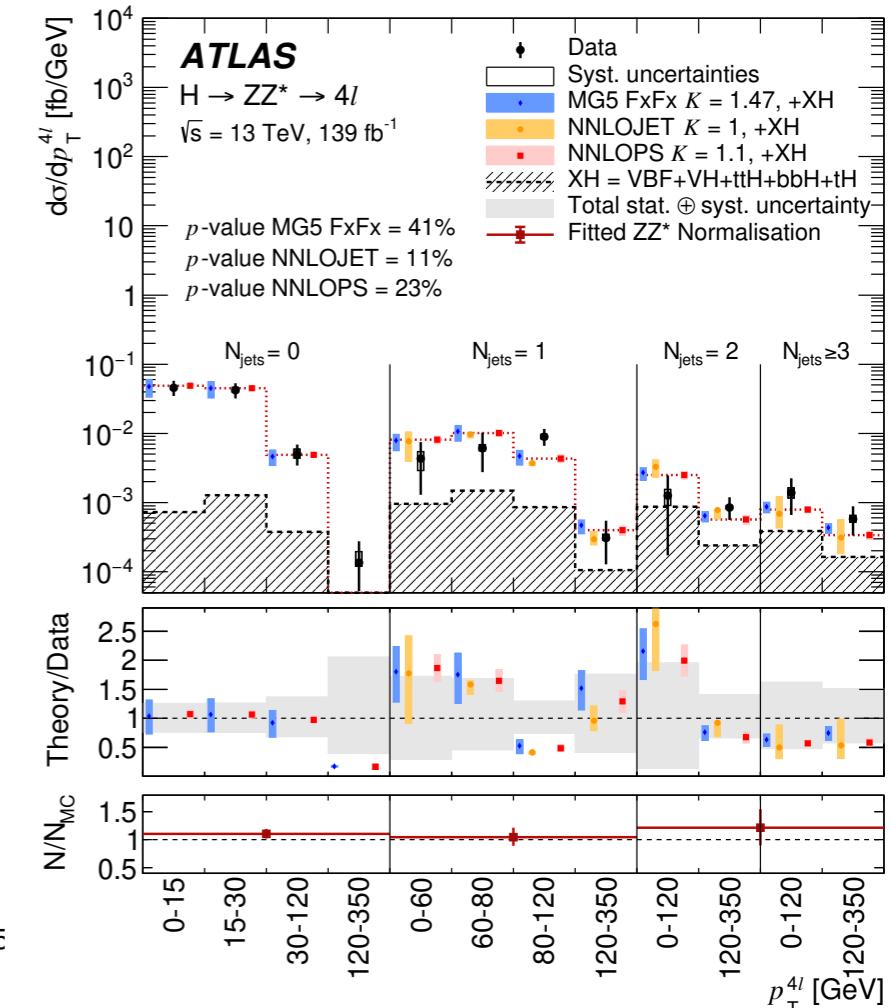
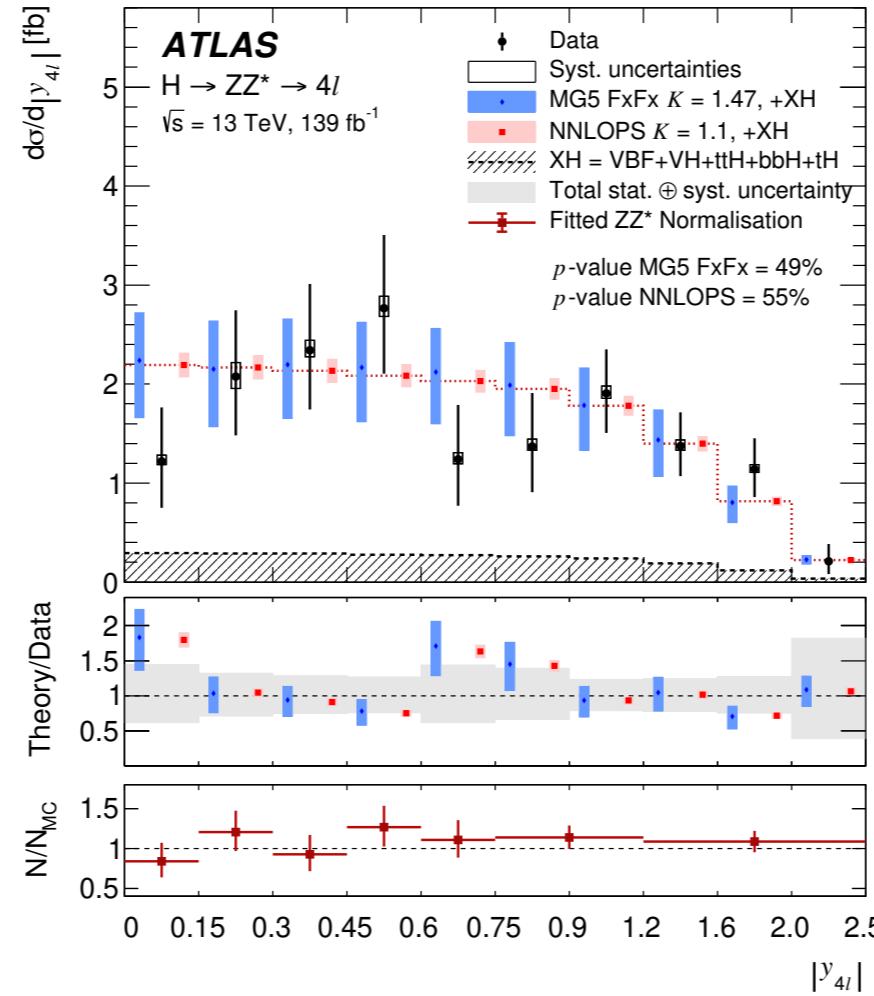
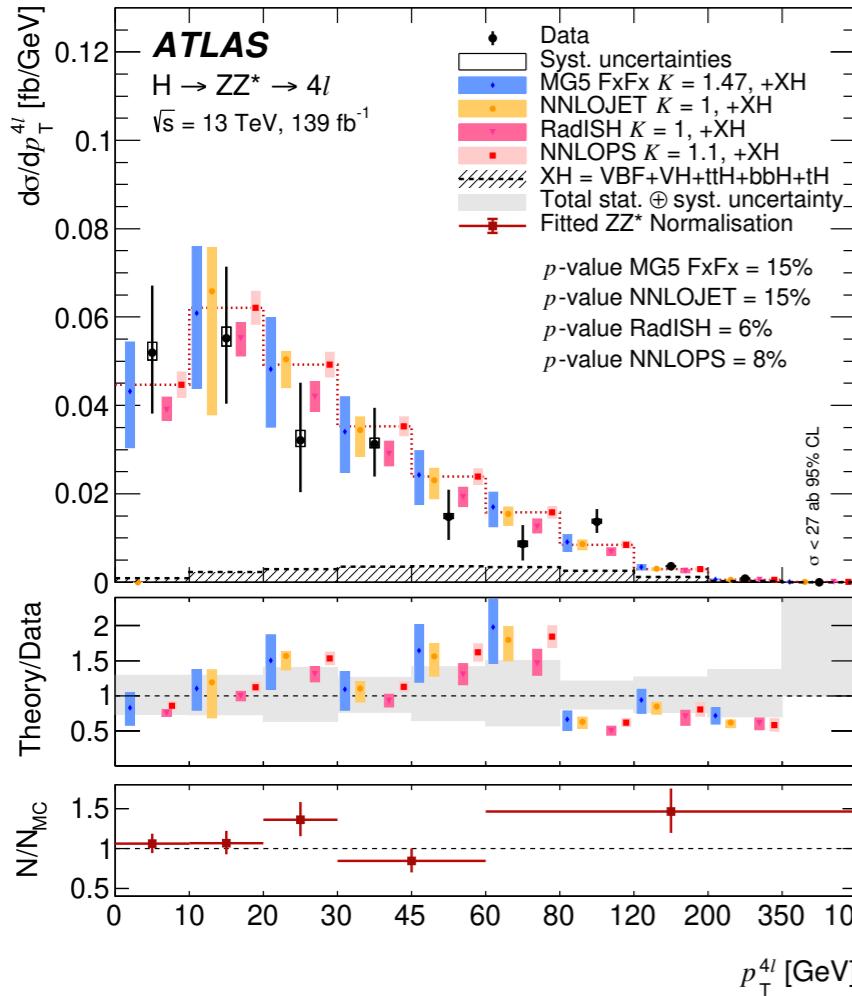
- 4 isolated leptons (muons or electrons) \rightarrow 2 lepton pairs, same flavour opposite sign \rightarrow 2 Z boson
- Signal extracted from a binned likelihood fit to the four-lepton invariant mass
- Dominant background: Non-resonant ZZ^* estimated directly from data sideband
- $Z+jets$ and $t\bar{t}$ constrained from control regions
- Acceptance of the fiducial selection $\sim 49\%$
- **Inclusive fiducial cross-section:**
 - $\sigma_{fid} = 3.28 \pm 0.30(stat.) \pm 0.11(sys.) \text{ fb}$,
 - $\sigma_{fid}^{SM} = 3.41 \pm 0.18 \text{ fb}$
- 10% level precision, and good agreement with SM predication
- Fiducial cross-sections in different lepton flavour are presented



$H \rightarrow ZZ^* \rightarrow 4\ell$ differential cross-section

Eur. Phys. J. C 80 (2020) 942

- 20 1-dimension differential cross-section measurements presented
- 8 double differential observables



p_T^H

y_H

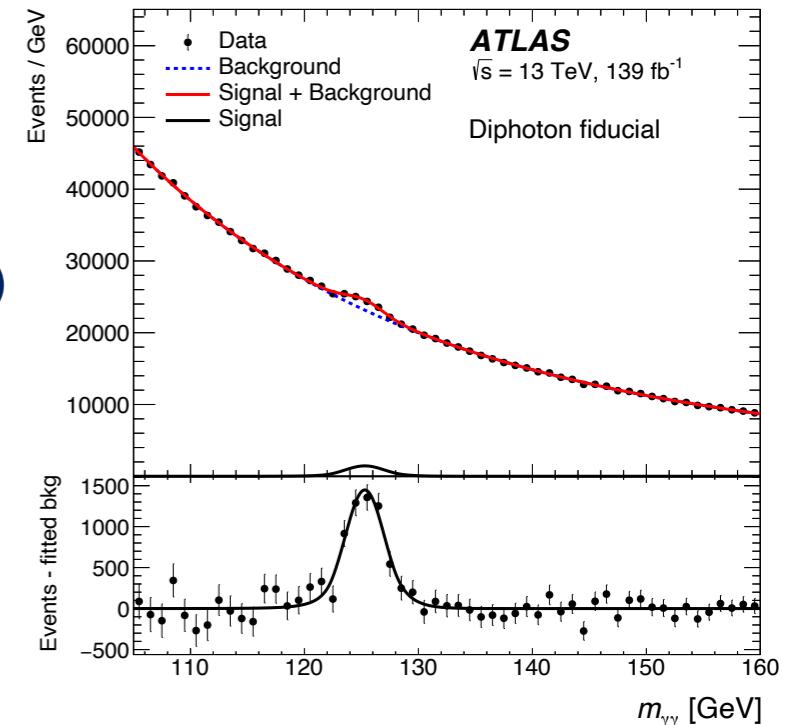
p_T^H and N_{jet}
 double differential

Jet: $p_T > 30 \text{ GeV}$, $|y| < 4.4$

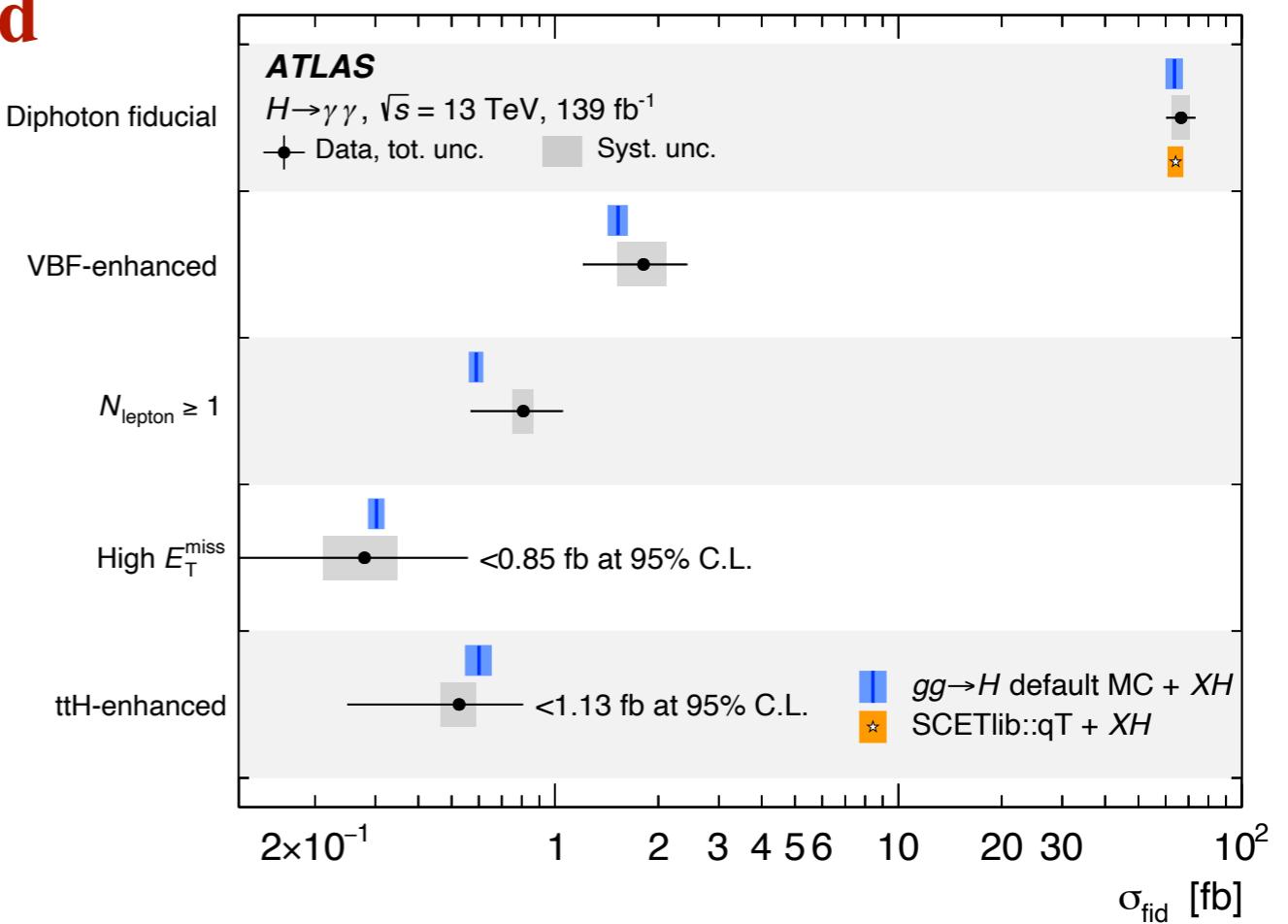
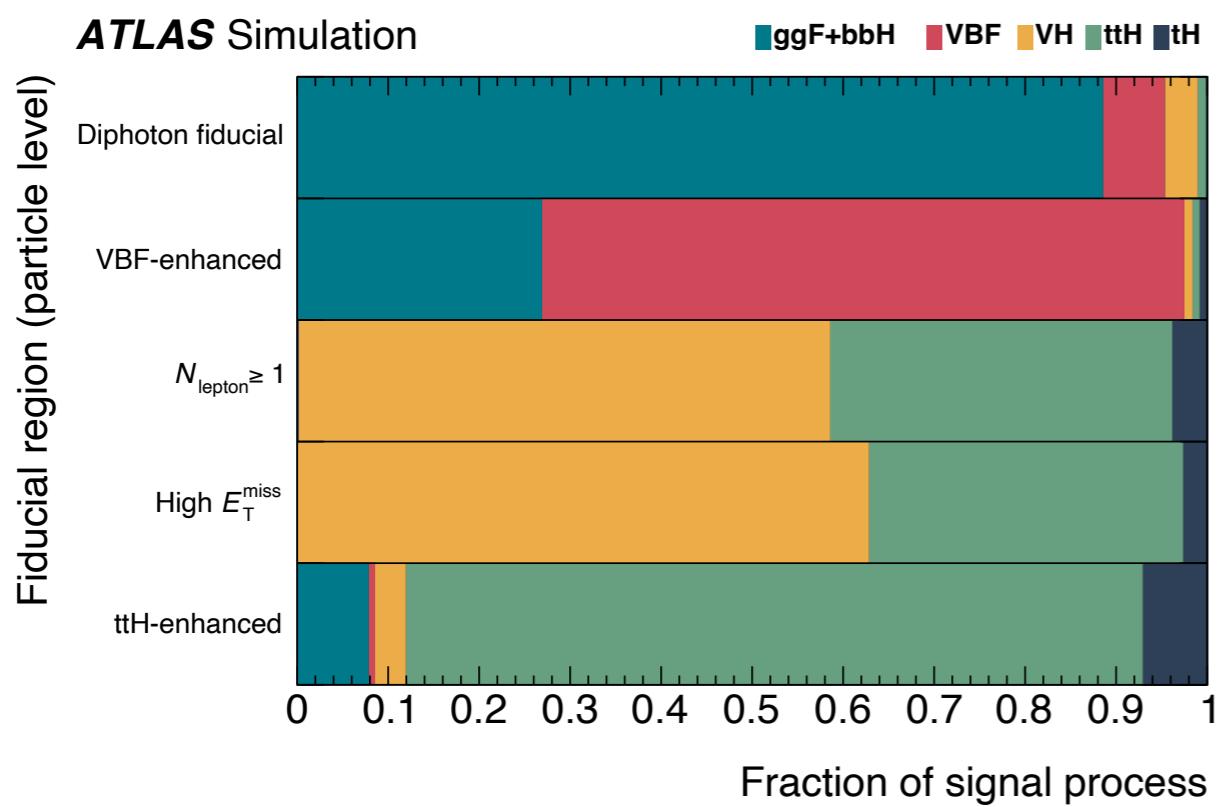
$H \rightarrow \gamma\gamma$ fiducial cross-section

arXiv:2202.00487

- Diphoton channel: small branching ratio but high selection efficiency
 - Clean final state and precise reconstructed diphoton invariant mass
 - Main background:
 - continuum $\gamma\gamma$ production (irreducible), γ -jet and jet-jet (reducible)
 - Diphoton fiducial cross-section:**
- $\sigma_{fid} = 67 \pm 5(stat.) \pm 4(sys.) \text{ fb}$, $\sigma_{fid}^{SM} = 64 \pm 4 \text{ fb}$
- 10% level precision, and good agreement with SM predication
 - Main systematics from spurious signal and photon energy resolution

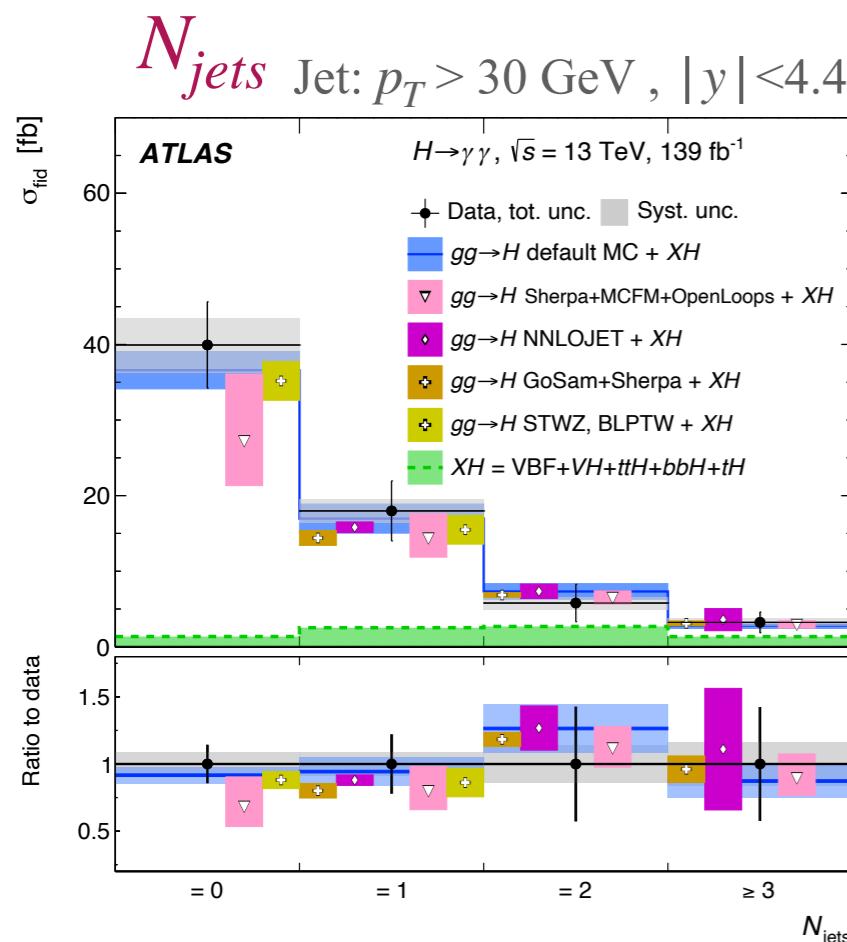
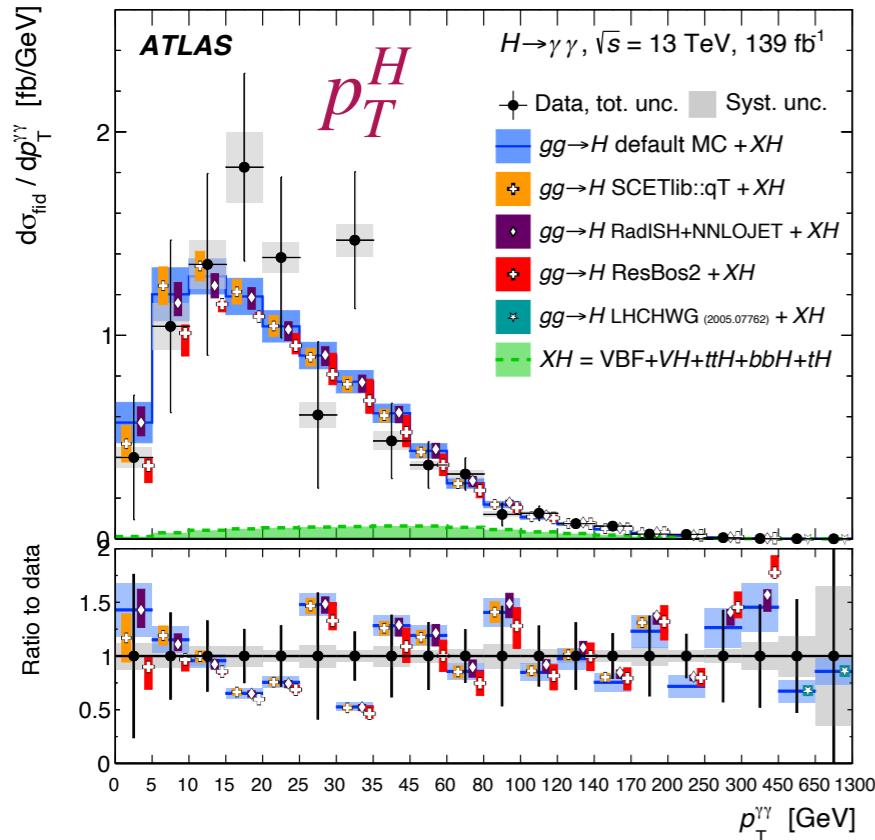


5 different fiducial regions are presented



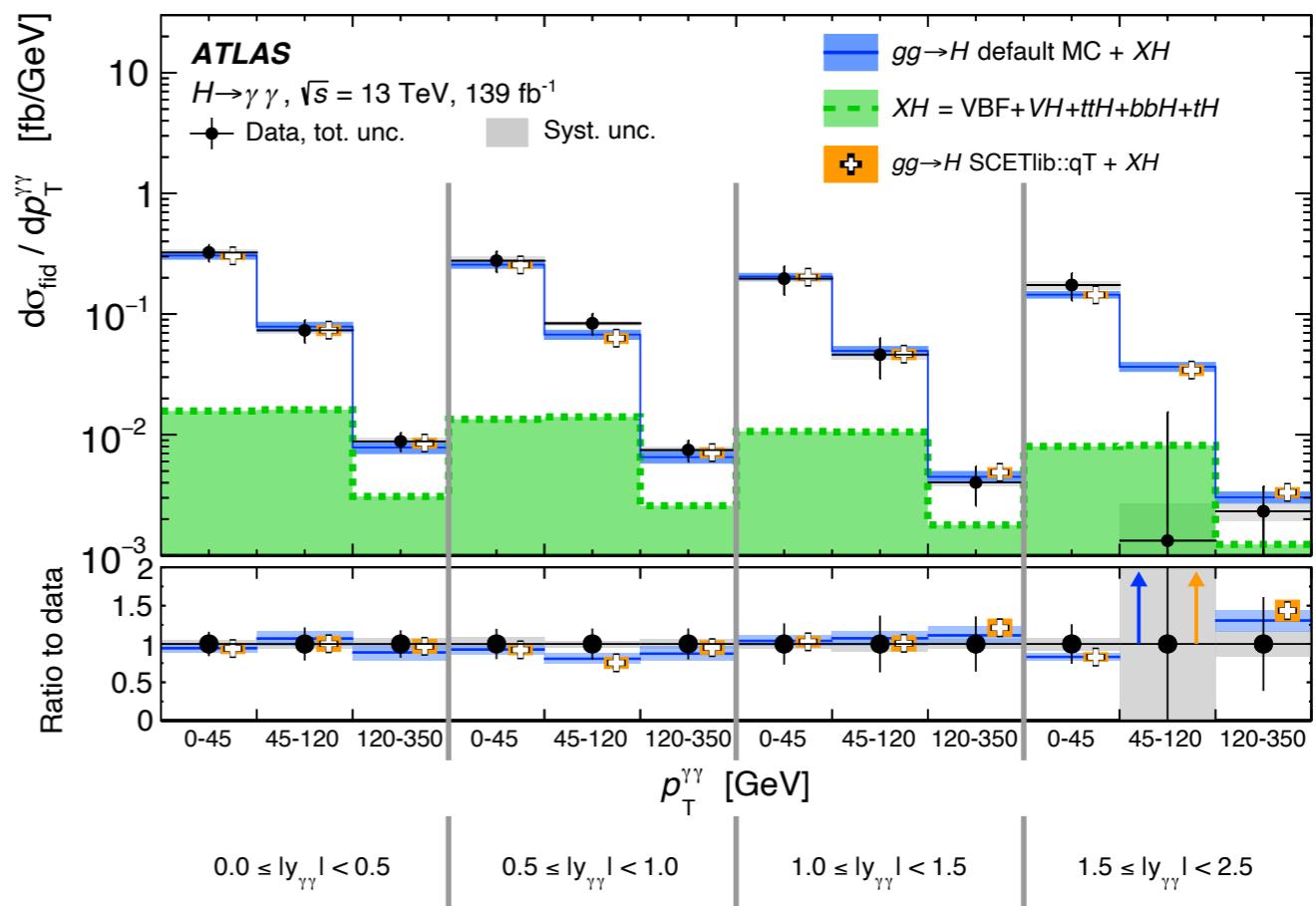
$H \rightarrow \gamma\gamma$ differential cross-section

arXiv:2202.00487



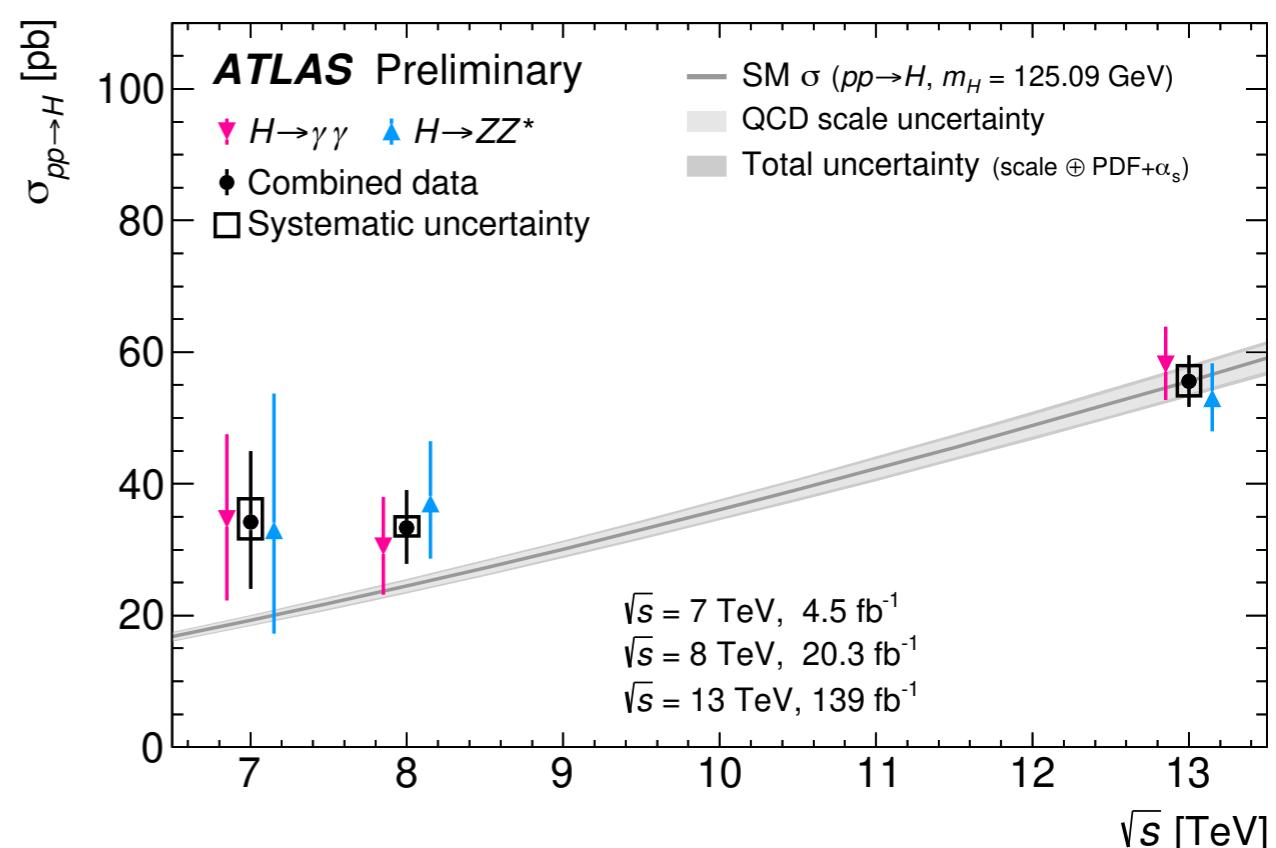
- Large set of kinematical observables probing different Higgs boson properties
- Including various 1D and 2D cross-section measurements

p_T^H and $|y_H|$ double differential

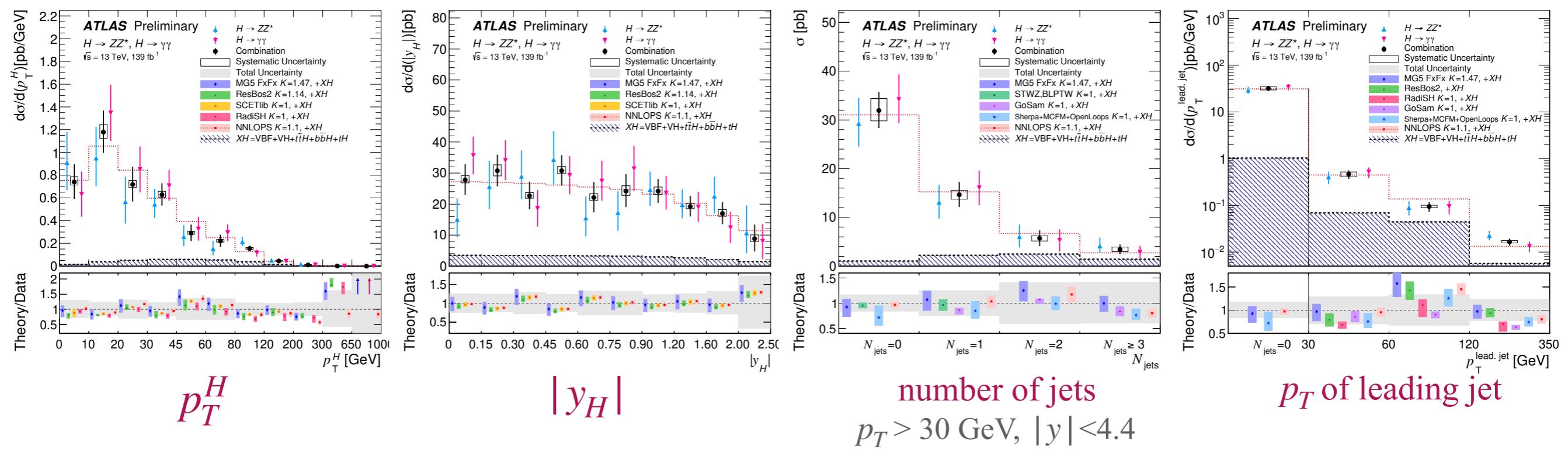


Total cross section

- Based on individual channel measurements
- Extrapolated to the full phase space to perform the combination
- Inclusive in production modes
- Uncertainties affected both channels are correlated
- Overall uncertainty reduced
- Observed: $55.5^{+4.0}_{-3.8}$ pb vs. SM: 55.6 ± 2.5 pb



Differential cross section

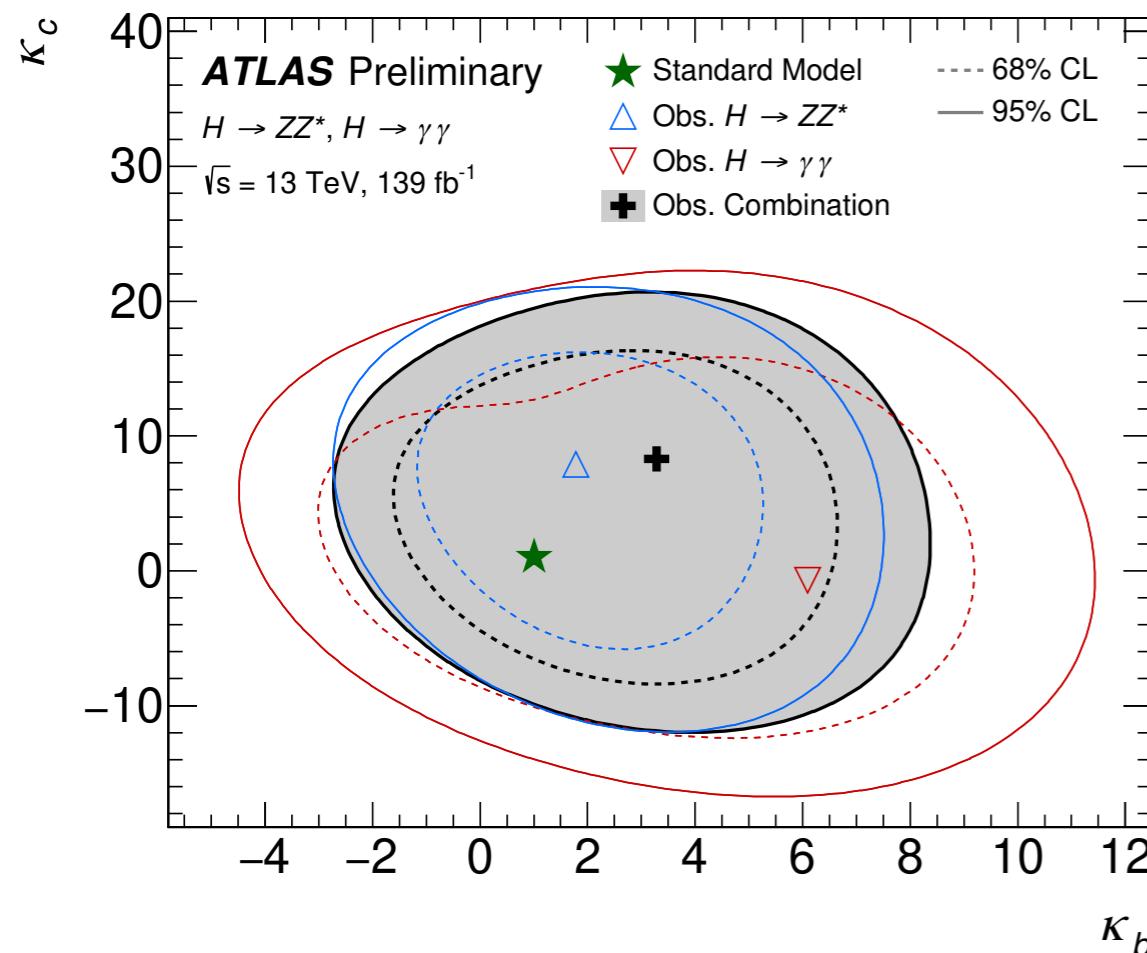


Yukawa coupling interpretation

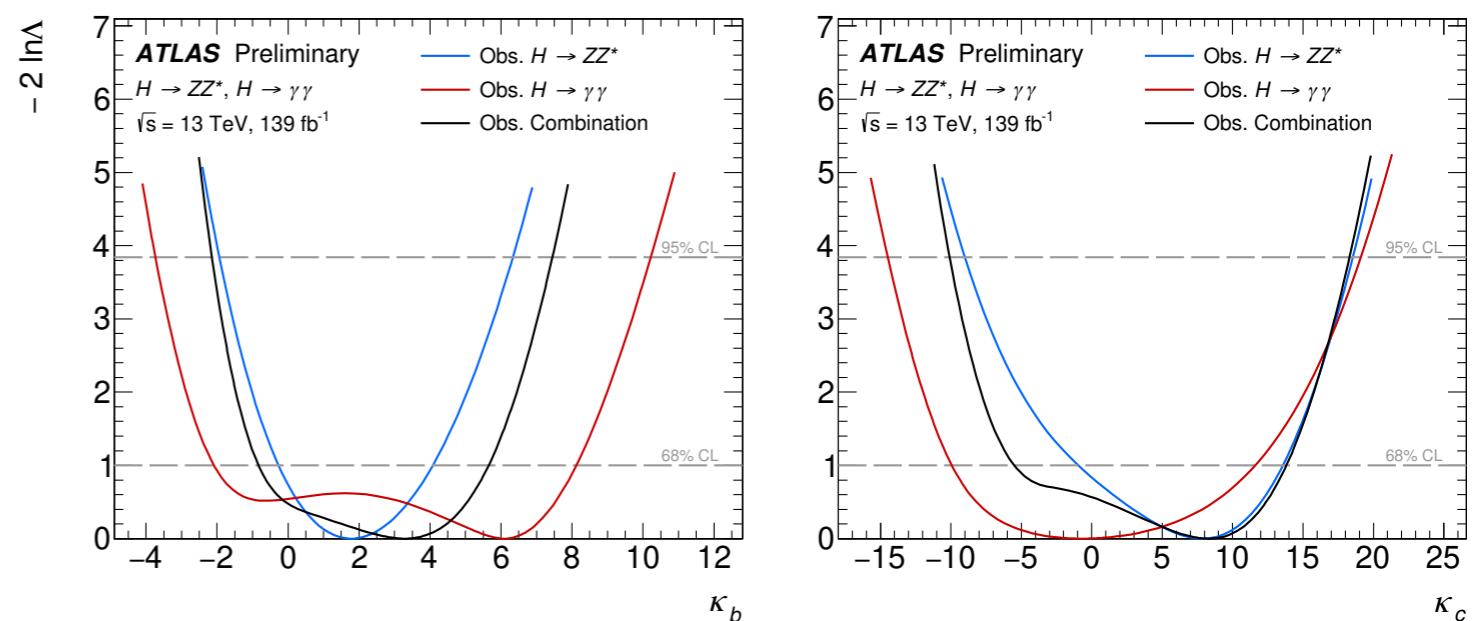
ATLAS-CONF-2022-002

- Indirectly constrain the Yukawa coupling using observed p_T distribution
- The interpretations are based on p_T shape only, normalisation is not used in constraints
- ggF and $b\bar{b} \rightarrow H + c\bar{c} \rightarrow H$ production modes are parameterised as a function of κ_b and κ_c

2D contours of κ_b and κ_c



1D contours of κ_b and κ_c



- κ_b : combined limit is less stringent than ZZ^* :
- Cross-section depends quadratically on κ_b
 - Second minimum on NLL scan for large κ_b
 - Observed κ_b from $H \rightarrow \gamma\gamma$ is farther SM predication

κ_c : combined limit is similar to ZZ^*

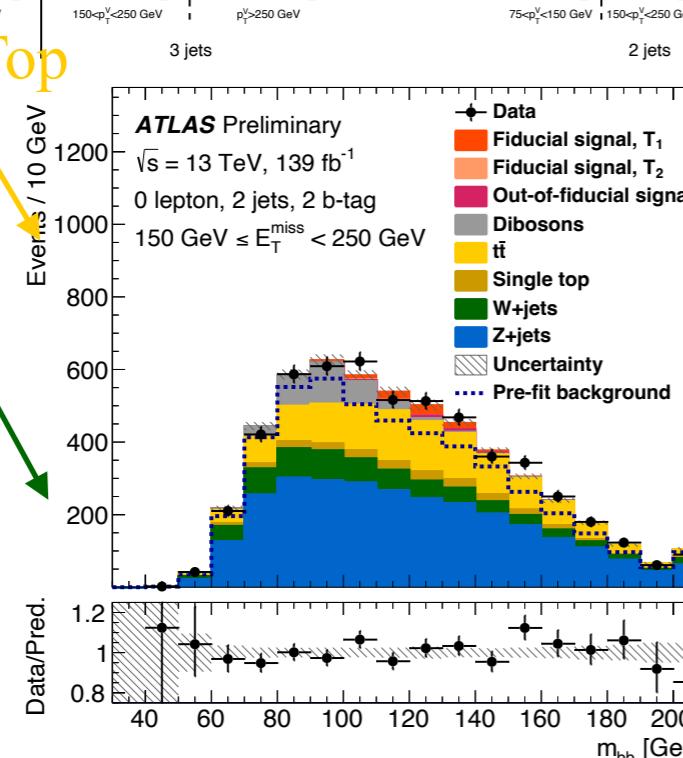
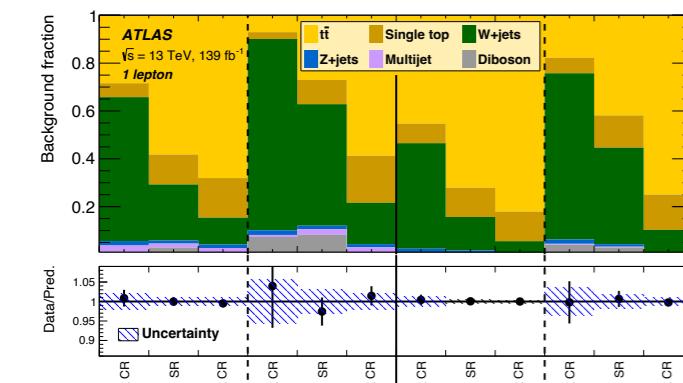
$VH(H \rightarrow b\bar{b})$ 0 lepton fiducial cross section

ATLAS-CONF-2022-015

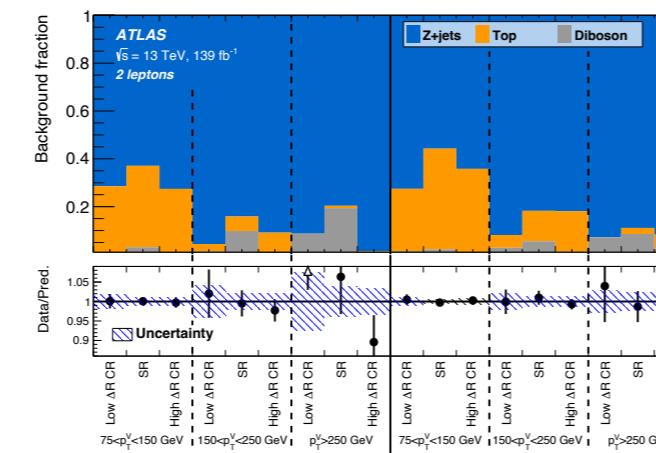
- $H \rightarrow b\bar{b}$: largest branch ratio but complex background
- First fully fiducial measurement in $H \rightarrow b\bar{b} + E_T^{miss}$ final state
- Based on Run-2 resolved $VH(H \rightarrow b\bar{b})$ analysis [Eur. Phys. J. C 81 \(2021\) 178](#)

Background constraint

1L channel constrains
top and W background

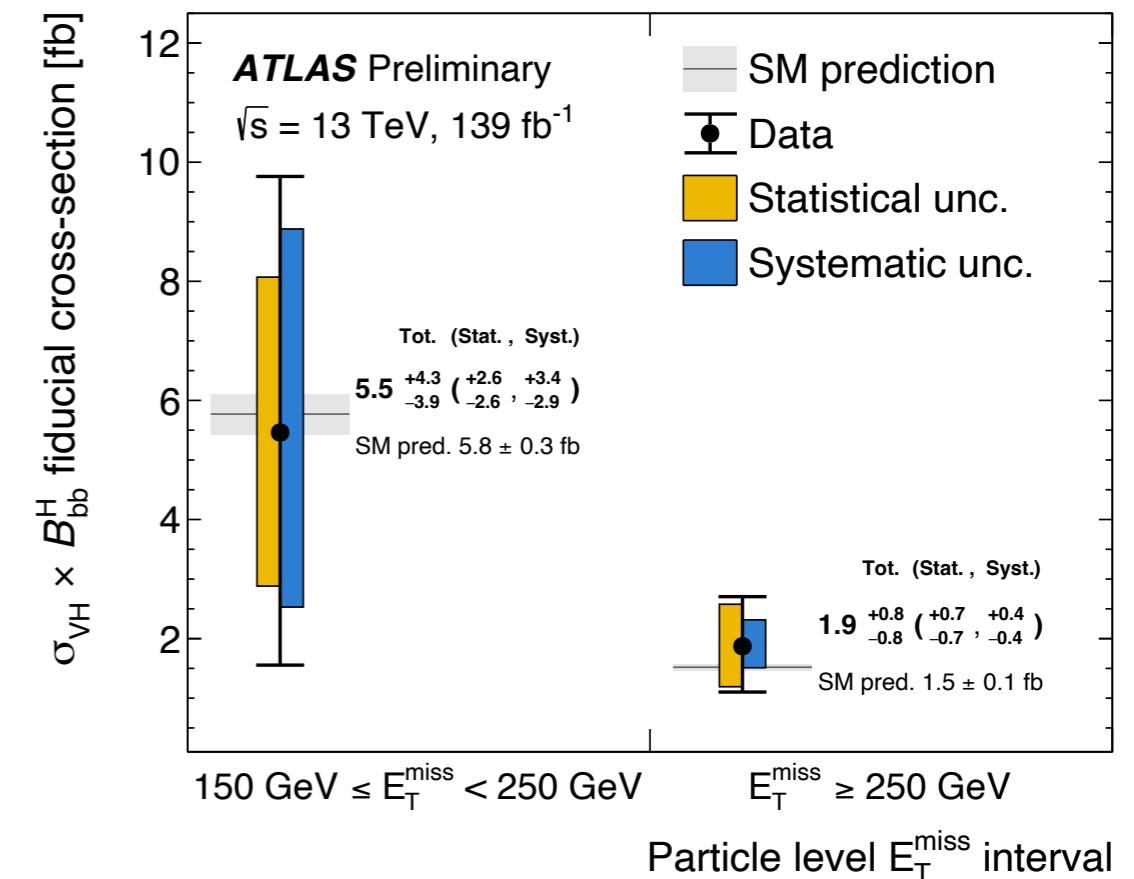


2L channel constrains
Z background



Z+jets

2 fiducial region presented

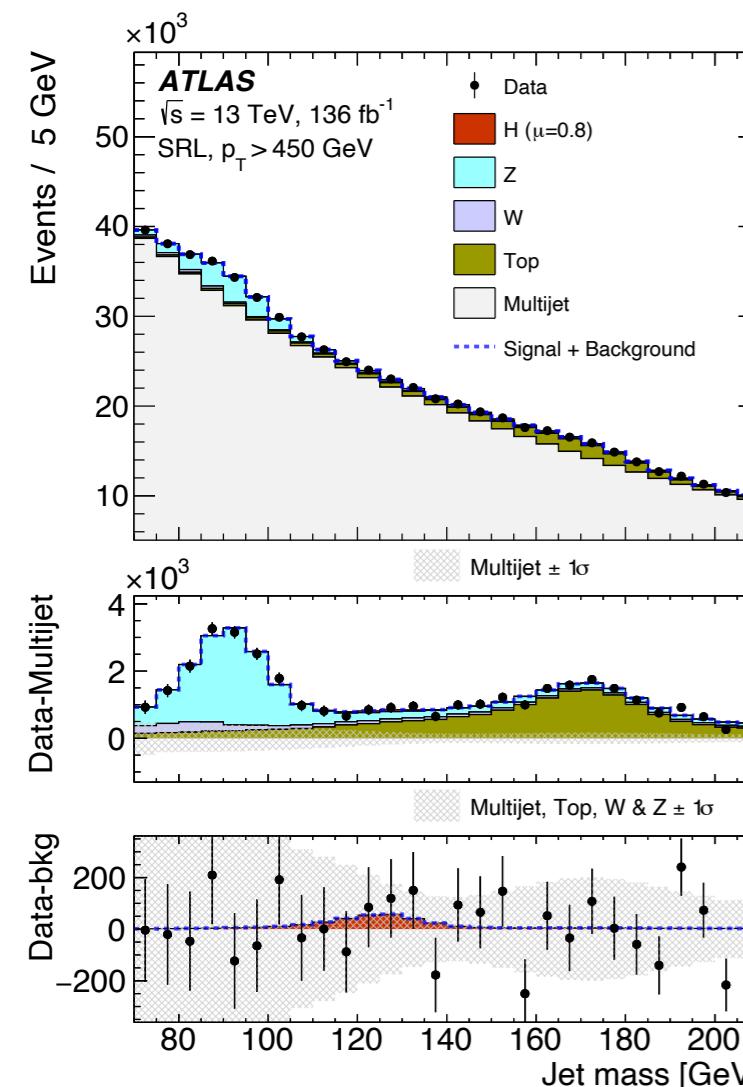


- Good agreement with SM predication
- Useful exercise in view of possible future fiducial measurements in all VH channels

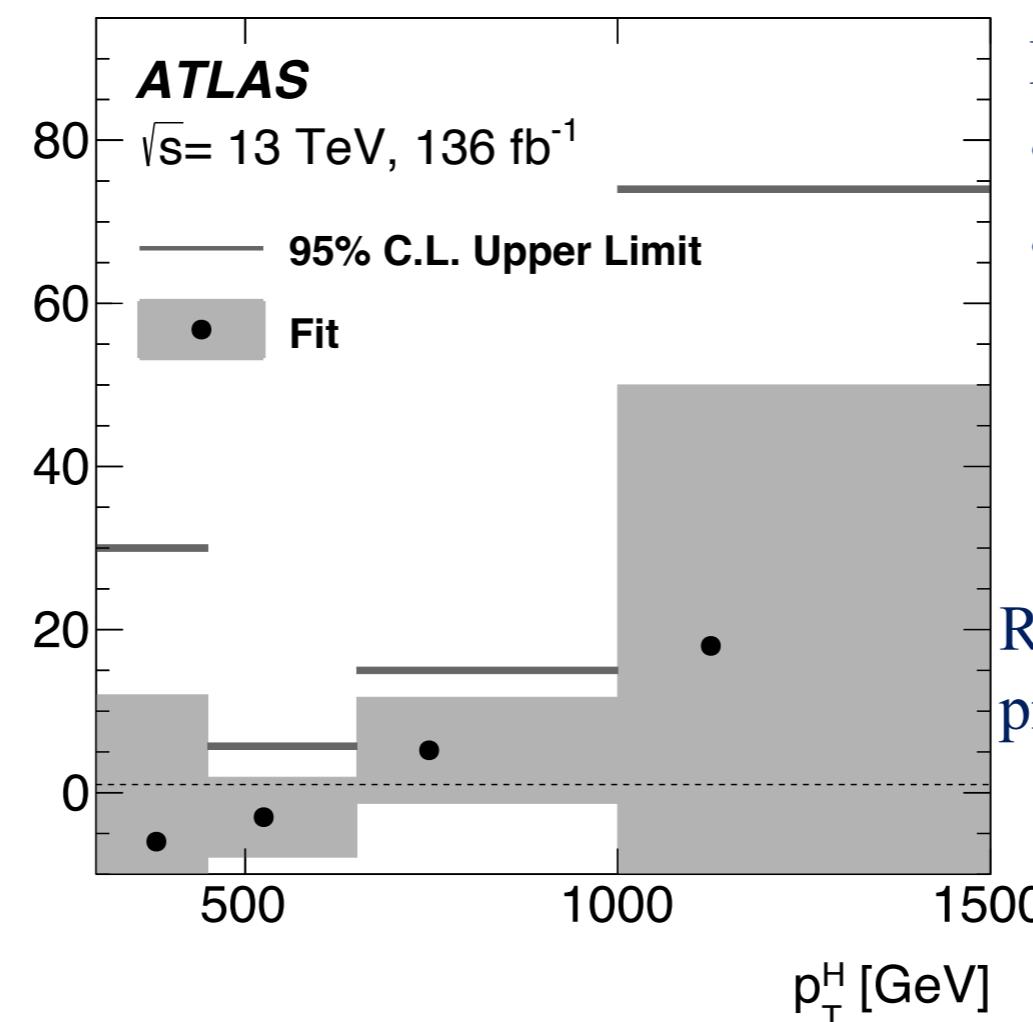
Boosted $H \rightarrow b\bar{b}$ channel

[Phys. Rev. D 105 \(2022\) 092003](#)

- Challenging channel but uniquely able to measure the highly boosted regime
⇒ Reach p_T^H to 1 TeV
- Reconstructed Higgs bosons with large Lorentz boost from single large-radius jets
- Mass of the large-radius jets \sim Higgs boson mass, used as final discriminant
- Main background: QCD Multijet



Cross-section limit



Fiducial region:

- $p_T^H > 450 \text{ GeV}, |y_H| < 2.0$
- $\sigma_{fid} < 115 \text{ fb}$ @ 95% CL

SM 18.4 fb

← Provide 4 p_T^H volumes

Results are compatible with SM predictions within the uncertainty

Conclusion

- Plenty of knowledge has been acquired in the 10 years since the Higgs boson discovery
- The measurements of the fiducial and differential cross-section in several Higgs boson decays modes with good precision

ZZ	$\gamma\gamma$	$\tau\tau$	WW	bb
✓	✓			✓

- Good agreement between the measurements and SM predictions
 - Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ improves precision of individual measurements
 - Interpretation of c- and b-quarks coupling modifiers using p_T^H shape information
 - $H \rightarrow b\bar{b}$ allows exploration of high p_T^H region
- Statistical uncertainty is still the dominant uncertainty source
- Several Run-2 results will come out soon
- Run3 has just started with much more to come

Back up

$H \rightarrow ZZ^* \rightarrow 4\ell$ selection and fiducial region

Event selection

Leptons and jets	
Muons	$p_T > 5 \text{ GeV}, \eta < 2.7$
Electrons	$E_T > 7 \text{ GeV}, \eta < 2.47$
Jets	$p_T > 30 \text{ GeV}, \eta < 4.5$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10 \text{ GeV}$
Leading pair (m_{12})	SFOC lepton pair with smallest $ m_Z - m_{\ell\ell} $
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $ m_Z - m_{\ell\ell} $
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	$50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ and $m_{\text{threshold}} < m_{34} < 115 \text{ GeV}$
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\mu_i(e_i), \text{jet}) > 0.1(0.2)$
J/ψ veto	$m(\ell_i, \ell_j) > 5 \text{ GeV}$ for all SFOC lepton pairs
Impact parameter	$ d_0 /\sigma(d_0) \geq 5 (3)$ for electrons (muons)
Mass window	$105 \text{ GeV} < m_{4\ell} < 160 \text{ GeV}$
Vertex selection:	$\chi^2/N_{\text{dof}} \leq 6 (9)$ for 4μ (other channels)
If extra lepton with $p_T > 12 \text{ GeV}$	Quadruplet with largest matrix element (ME) value

Fiducial region

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

$H \rightarrow ZZ^* \rightarrow 4\ell$ cross-section

Cross section [fb]	Data (\pm (stat.) \pm (syst.))	Standard Model prediction	p -value [%]
$\sigma_{4\mu}$	0.81 \pm 0.12 \pm 0.03	0.90(5)	46
σ_{4e}	0.62 \pm 0.17 \pm 0.05	0.90(5)	14
$\sigma_{2\mu 2e}$	0.74 \pm 0.15 \pm 0.05	0.80(4)	67
$\sigma_{2e 2\mu}$	1.01 \pm 0.15 \pm 0.03	0.80(4)	15
$\sigma_{4\mu+4e}$	1.43 \pm 0.21 \pm 0.05	1.81(10)	10
$\sigma_{2\mu 2e+2e 2\mu}$	1.75 \pm 0.21 \pm 0.06	1.61(9)	51
σ_{sum}	3.18 \pm 0.31 \pm 0.11	3.41(18)	49
σ_{comb}	3.28 \pm 0.30 \pm 0.11	3.41(18)	67
$\sigma_{\text{tot}} [\text{pb}]$	53.5 \pm 4.9 \pm 2.1	55.7(28)	66

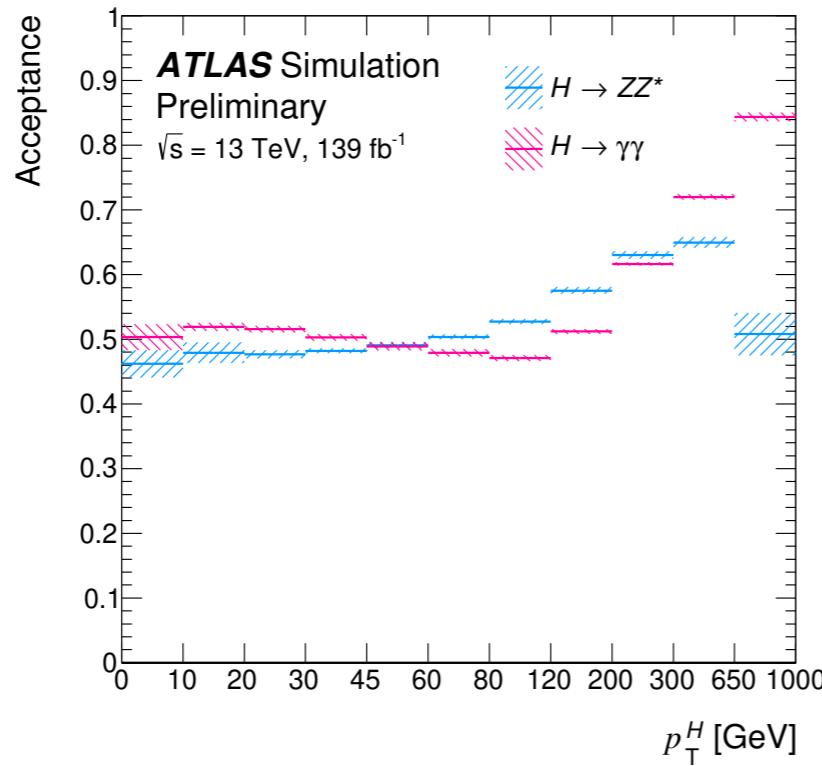
$H \rightarrow \gamma\gamma$ selection and fiducial region

Object	particle-level	detector-level
Photons	$E_T > 0.35/0.25 \times m_{\gamma\gamma}$ $ \eta \in [0, 1.37] \cup [1.52, 2.37]$ $E_T^{\text{iso}}(\Delta R < 0.2, p_T > 1 \text{ GeV, charged}) < 0.05E_T$	\leftarrow same \leftarrow same <i>tight identification (shower shapes)</i> $E_T^{\text{iso, track}}(\Delta R < 0.2, p_T > 1 \text{ GeV}) < 0.05E_T$ $E_T^{\text{iso, calo}}(\Delta R < 0.2) < 0.065E_T$
Leptons	dressed with photons in $\Delta R < 0.1$ $p_T > 15 \text{ GeV}$ $e: \eta \in [0, 1.37] \cup [1.52, 2.47]$ $\mu: \eta \in [0, 2.7]$	$ z_0 \sin \theta < 0.5 \text{ mm} \wedge d_0/\sigma(d_0) < 5(e)/3(\mu)$ \leftarrow same \leftarrow same \leftarrow same <i>medium identification requirements</i> calorimeter and track-based isolation
Jets	anti- k_t $R = 0.4$ (excluding $\nu, \ell, X \leftarrow H$) $p_T > 30 \text{ GeV}$ $ y < 4.4$	anti- k_t $R = 0.4$ particle-flow \leftarrow same \leftarrow same tight-JVT for jets with $ \eta < 2.5$ and $p_T < 60 \text{ GeV}$
b -jets	jets with $ \eta < 2.5$ and b -hadron of $p_T > 5 \text{ GeV}$ within $\Delta R < 0.4$	jets passing the DL1r b -tagging at 70% efficiency
E_T^{miss}	$\sum p_T$ of neutrinos not from hadrons	$-\sum p_T$ of selected $\gamma, \ell, \text{jets}$ + soft tracks from primary vertex

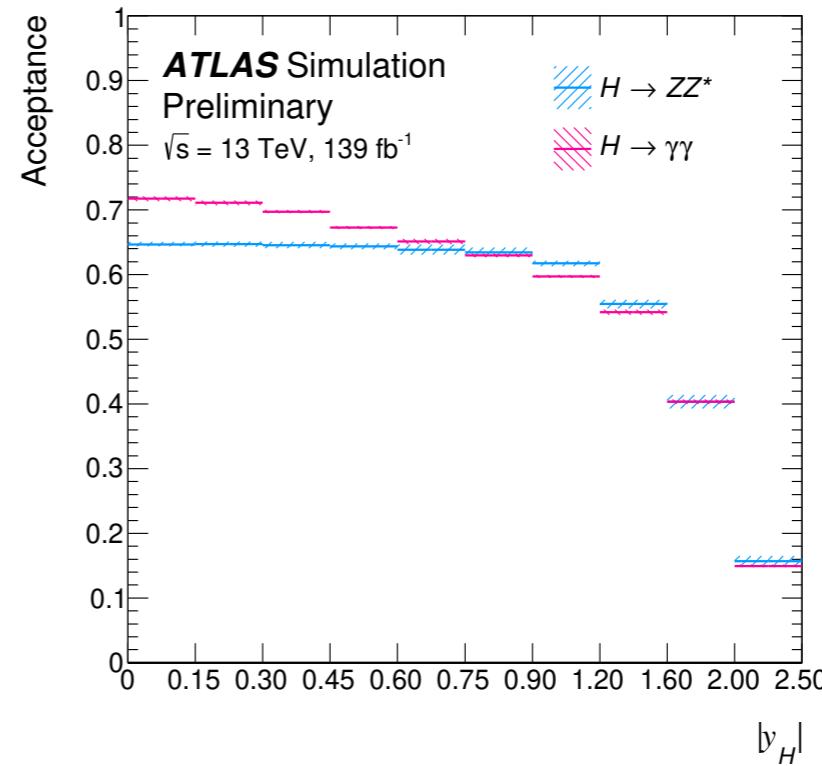
$H \rightarrow \gamma\gamma$ cross-section

Fiducial region	Measured [fb]				SM prediction [fb]	95% CL _s upper limit [fb]	<i>p</i> -value			
	\pm	stat	\pm	sys						
Diphoton	67	\pm	5	\pm	4	64	\pm	4	-	69%
VBF-enhanced	1.8	\pm	0.5	\pm	0.3	1.53	\pm	0.10	-	64%
$N_{\text{lepton}} \geq 1$	0.81	\pm	0.23	\pm	0.06	0.59	\pm	0.03	-	36%
High E_T^{miss}	0.28	\pm	0.27	\pm	0.07	0.302	\pm	0.017	0.85	93%
$t\bar{t}H$ -enhanced	0.53	\pm	0.27	\pm	0.06	0.60	\pm	0.05	1.13	79%
Total	132	\pm	10	\pm	8	126	\pm	7	-	69%

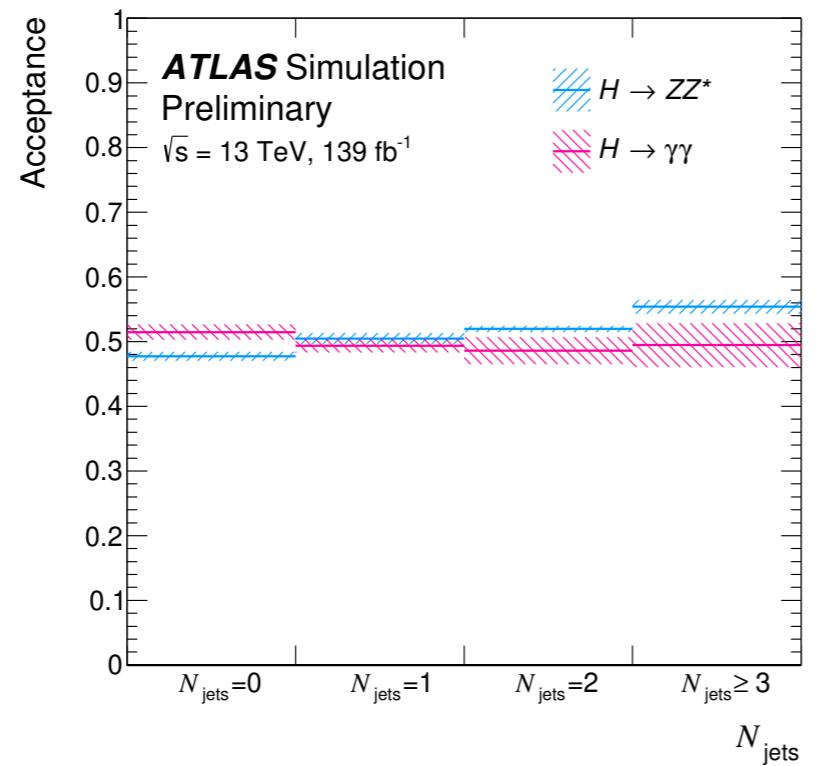
$H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ acceptance



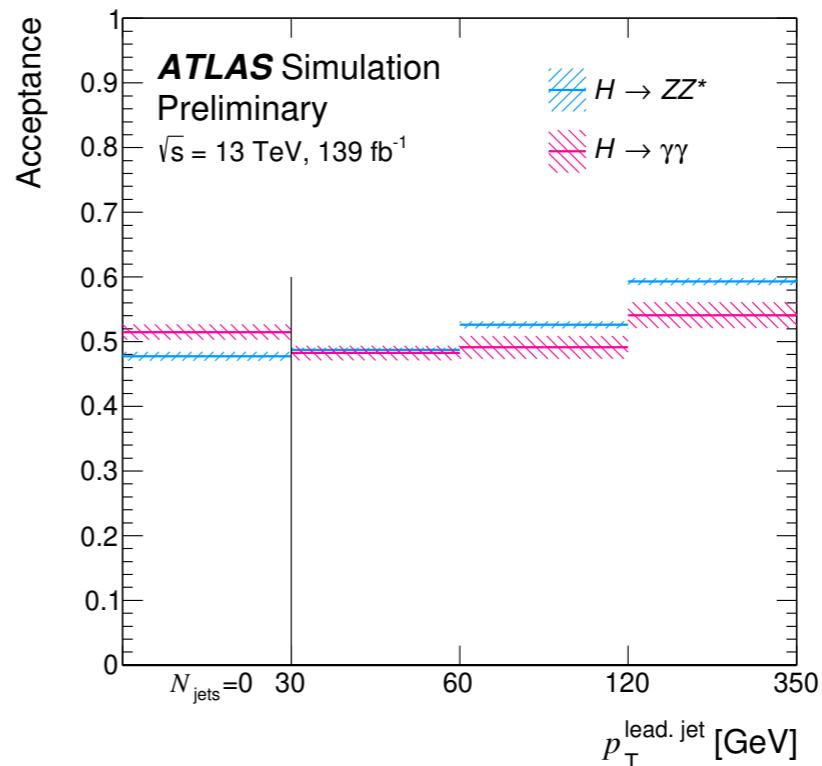
(a)



(b)



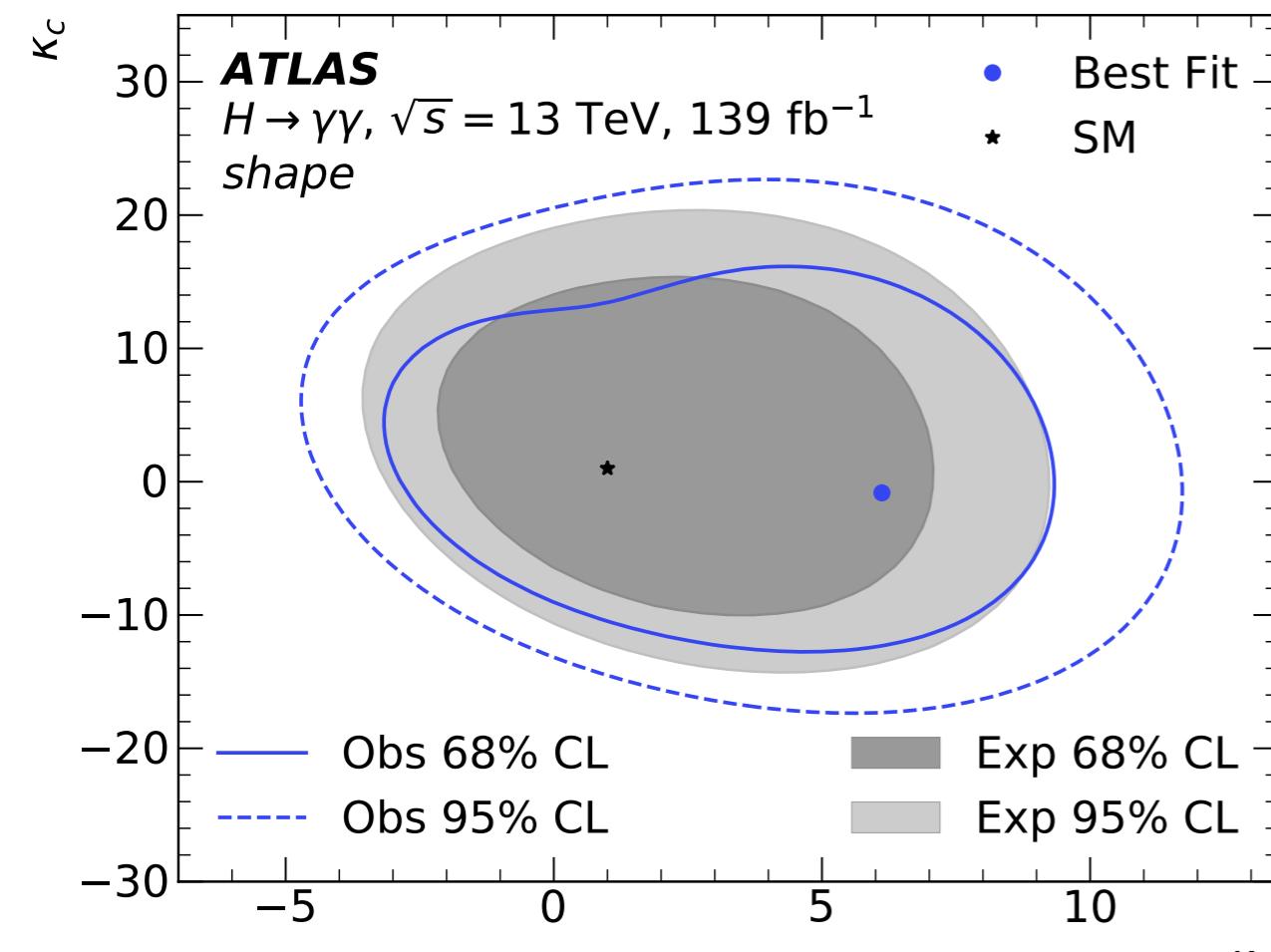
(c)



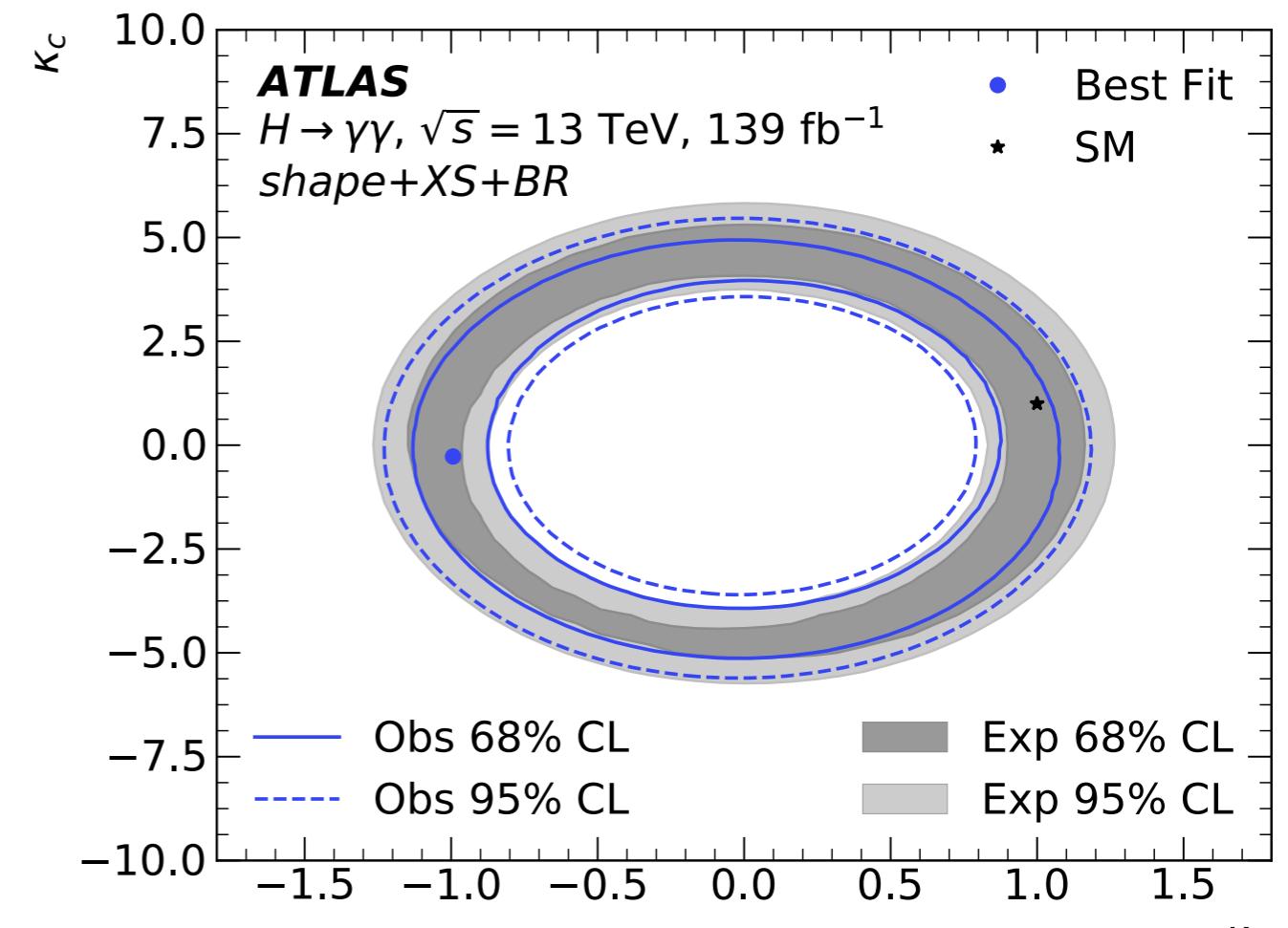
(d)

Interpretations with shape and normalisation

- Interpretation of κ_b and κ_c with shape only and shape + normalisation



shape only



shape + normalisation

$VH(H \rightarrow b\bar{b})$ selection and fiducial region

Selection	Detector-level		Particle-level
	No electrons or muons $p_T > 7 \text{ GeV}$		
	Electrons	Muons	No electrons or muons $p_T > 7 \text{ GeV}$
Leptons	$ \eta < 2.47$ LooseLH $ d_0/\sigma_{d_0} < 5$ $ z_0 \sin \theta < 0.5 \text{ mm}$	$ \eta < 2.7$ Loose $ d_0/\sigma_{d_0} < 3$ $ z_0 \sin \theta < 0.5 \text{ mm}$	Electrons $ \eta < 2.47$
	Loose track-isolation		Muons $ \eta < 2.7$
Hadronic τ	$p_T > 20 \text{ GeV}$ $ \eta < 1.37$ or $1.52 < \eta < 2.5$ Medium		τ -labelled central jets
Anti- k_t $R = 0.4$ Jets	From topological clusters ≥ 2 central jets Central Forward		From collider-stable particles ≥ 2 central jets Central Forward
	$p_T > 20 \text{ GeV}$ $ \eta < 2.5$		$p_T > 20 \text{ GeV}$ $ \eta < 2.5$
	$p_T > 30 \text{ GeV}$ $2.5 < \eta < 4.5$		$p_T > 30 \text{ GeV}$ $2.5 < \eta < 4.5$
b -jets	2 b -tagged central jets, MV2 (70% efficiency) At least one b -jet with $p_T > 45 \text{ GeV}$		2 b -labelled central jets At least one b -labelled jet with $p_T > 45 \text{ GeV}$
Jet categories	Two, with exactly 2 and 3 jets		One, with 2 or 3 jets
Overlap removal	Between e, μ, τ and jets		Remove e/μ within $\Delta R = 0.4$ of a jet, remove τ -labelled jets
E_T^{miss}	Negative vectorial sum of p_T of jets, leptons, taus and photons plus a track-based soft term $> 150 \text{ GeV}$		Negative vectorial sum of p_T of all stable interacting particles with $ \eta < 5$, including muons with $p_T > 6 \text{ GeV}$ $> 150 \text{ GeV}$
H_T	$> 120 \text{ GeV}$ (2 jets), $> 150 \text{ GeV}$ (3 jets)		$> 120 \text{ GeV}$ (2 jets), $> 150 \text{ GeV}$ (3 jets)
$\min \Delta\phi(\vec{E}_T^{\text{miss}}, \vec{j})$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)		$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{b}_1 + \vec{b}_2)$	$> 120^\circ$		$> 120^\circ$
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$		$< 140^\circ$
$\Delta\phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$	$< 90^\circ$		—
E_T^{miss} regions	$150 \text{ GeV} \leq E_T^{\text{miss}} < 250 \text{ GeV}$ $E_T^{\text{miss}} \geq 250 \text{ GeV}$		$150 \text{ GeV} \leq E_T^{\text{miss}} < 250 \text{ GeV}$ $E_T^{\text{miss}} \geq 250 \text{ GeV}$