$H \rightarrow 4l$
Higgs properties and BSM searches

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ATLAS EXPERIMENT

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Exclusive Higgs

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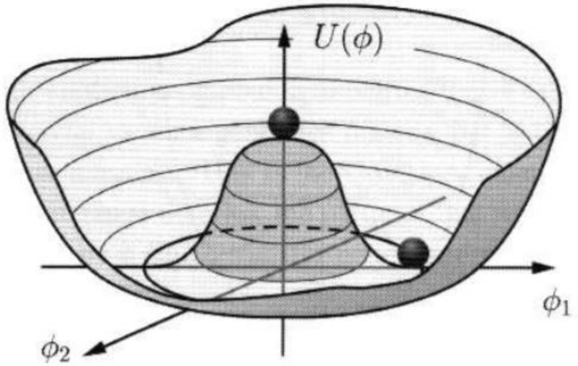
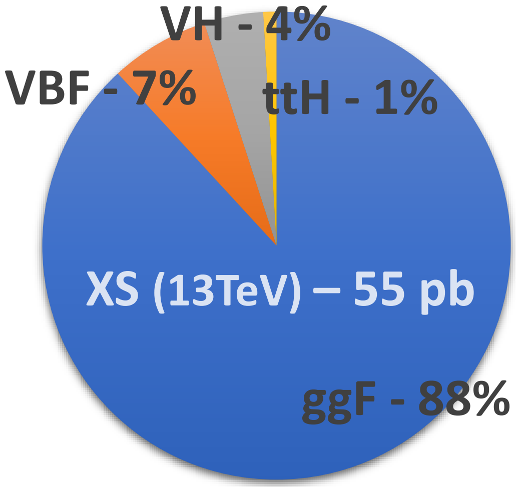
10/3/2021

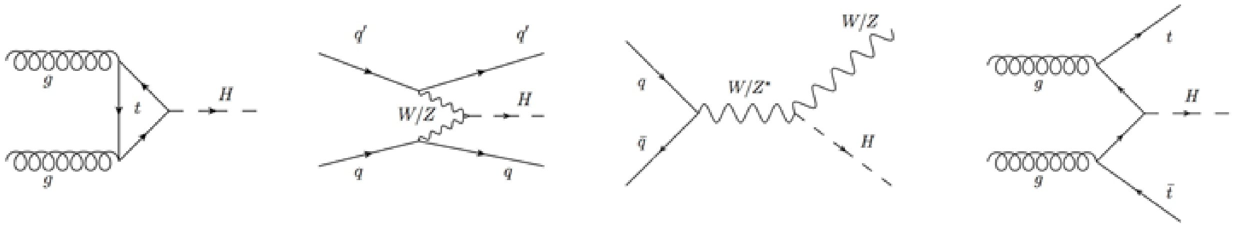
Higgs Production and Decay

- **Higgs boson is a way to introduce massive bosons retaining local gauge invariance**
- **It is a spinless particle coupling to all massive particles**

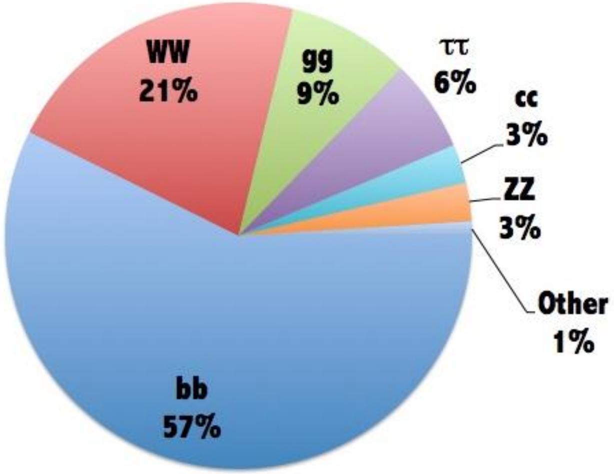


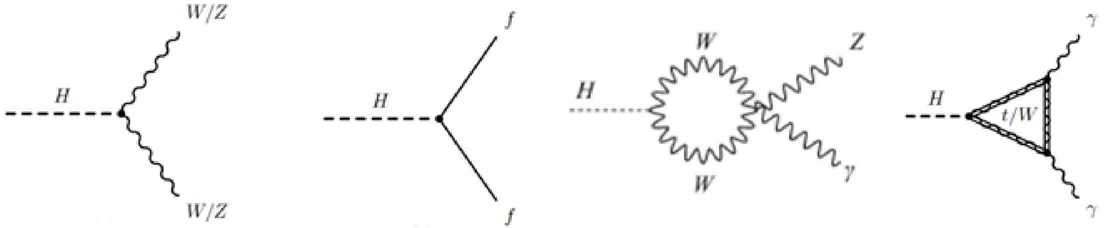
4 production processes





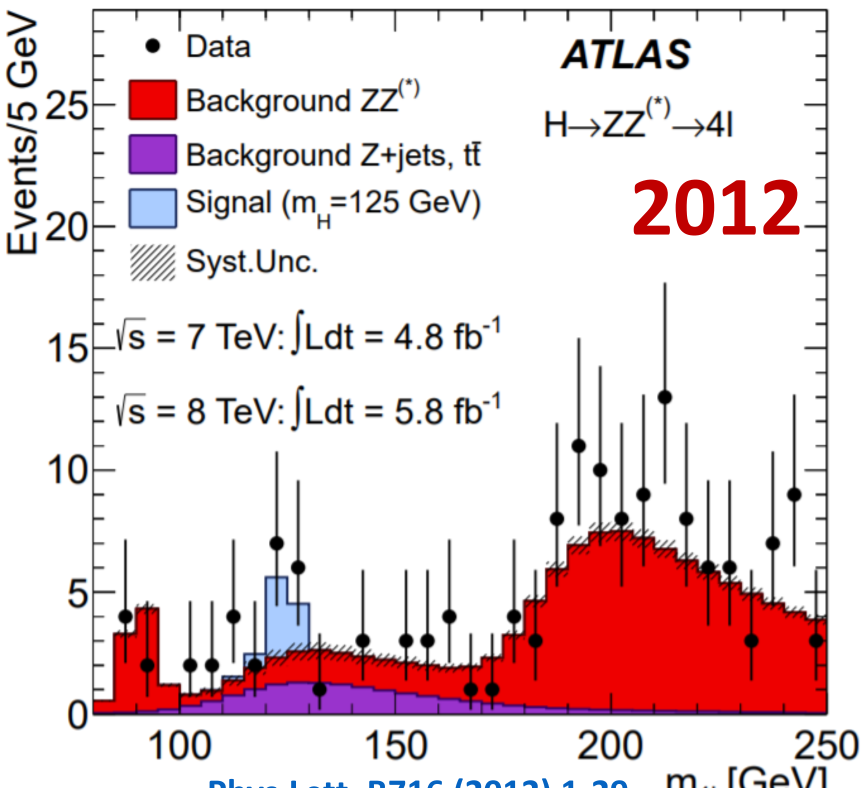
Several decay modes





4l Channel

- **Higgs discovery (2012) in 4l and γγ channels**
- $H \rightarrow ZZ^* \rightarrow 4\ell$ (ℓ: e or μ) channel has
  - High signal-to-background ratio
  - Ability to completely reconstruct the final state
- **Clear signature of Higgs boson – "Golden channel" for studies**



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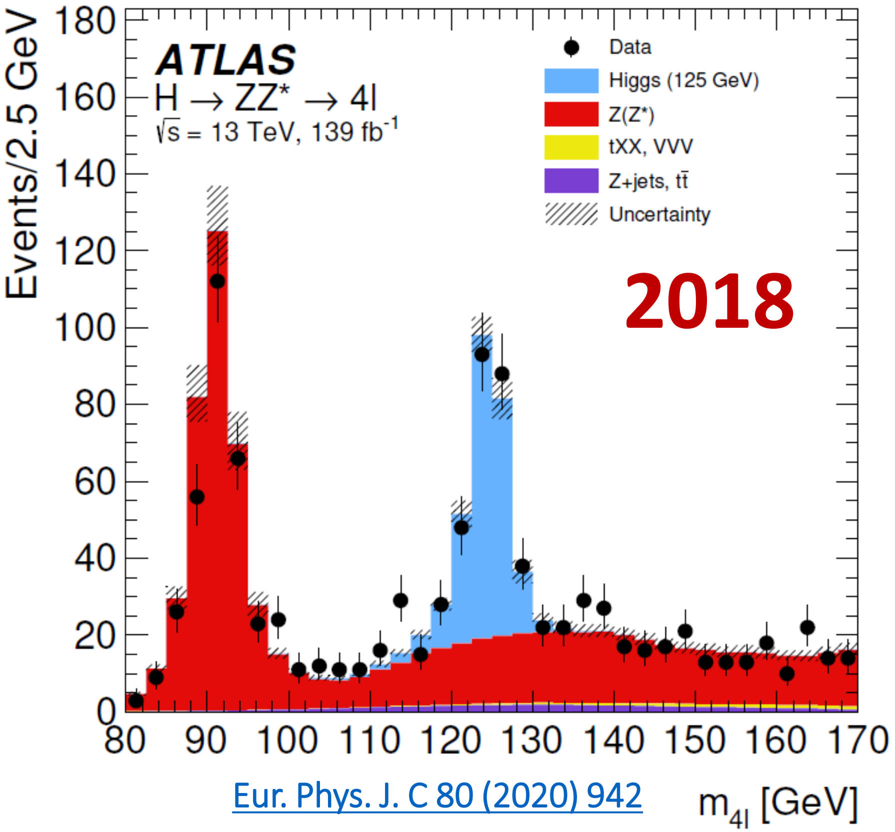

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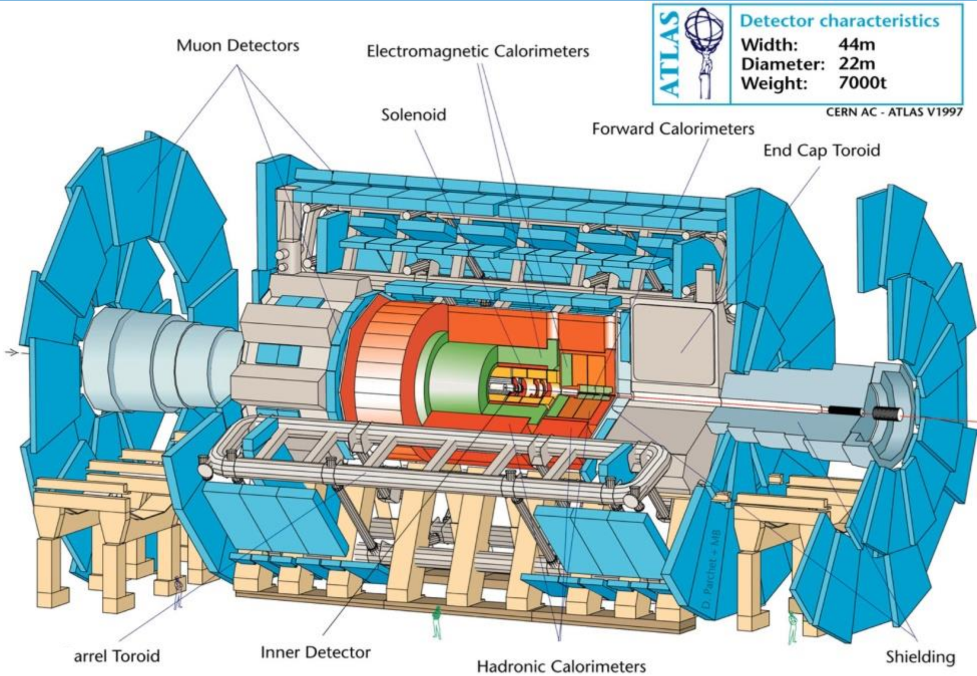
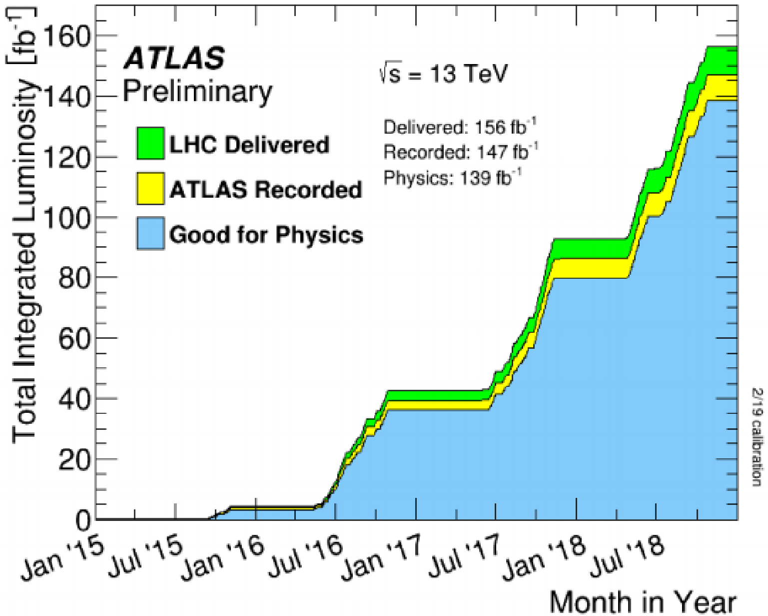
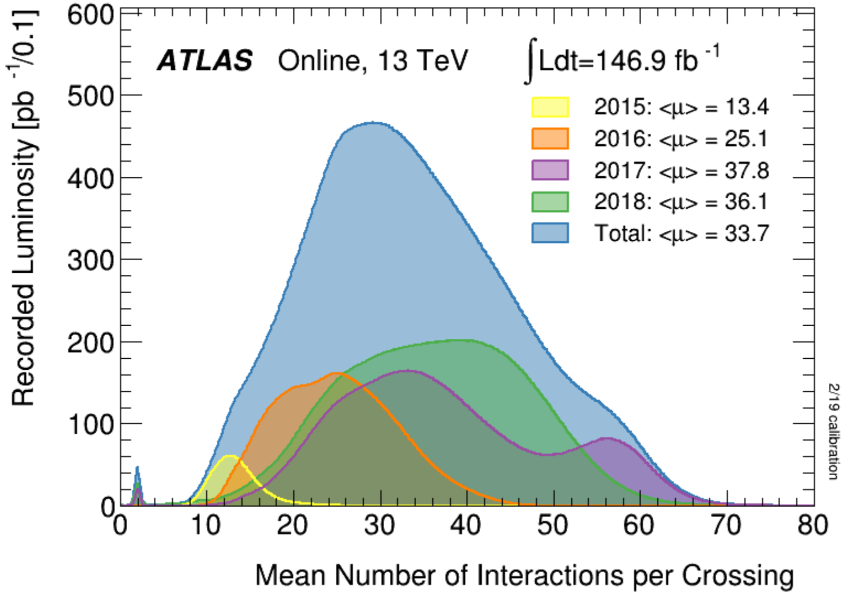
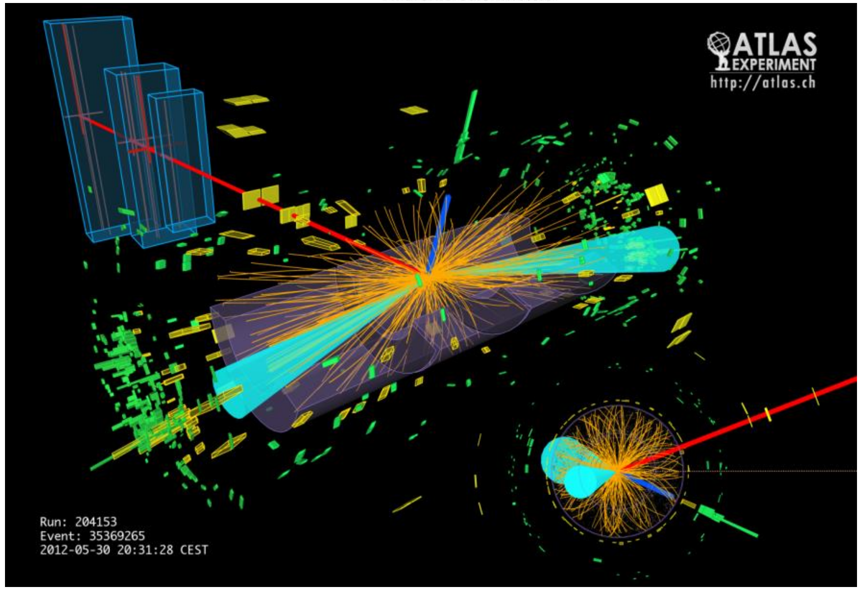
ATLAS Experiment

- **Run II – 2015-2018**
- **Integrated Luminosity 140 fb^{-1}**
- **$\langle \mu \rangle$ > 35**
- **> 7M Higgs bosons**



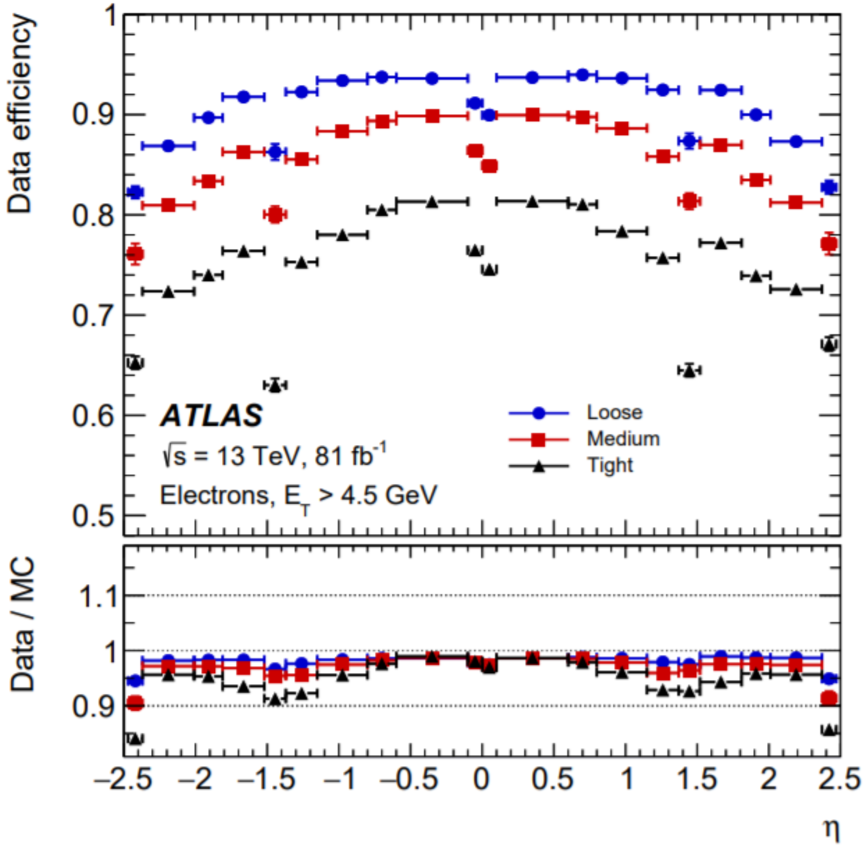






4l event reconstruction

- **Events with at least 4 leptons**
- **Loose identification criteria for both e (~ 90%) and μ (~ 99%) efficiencies**



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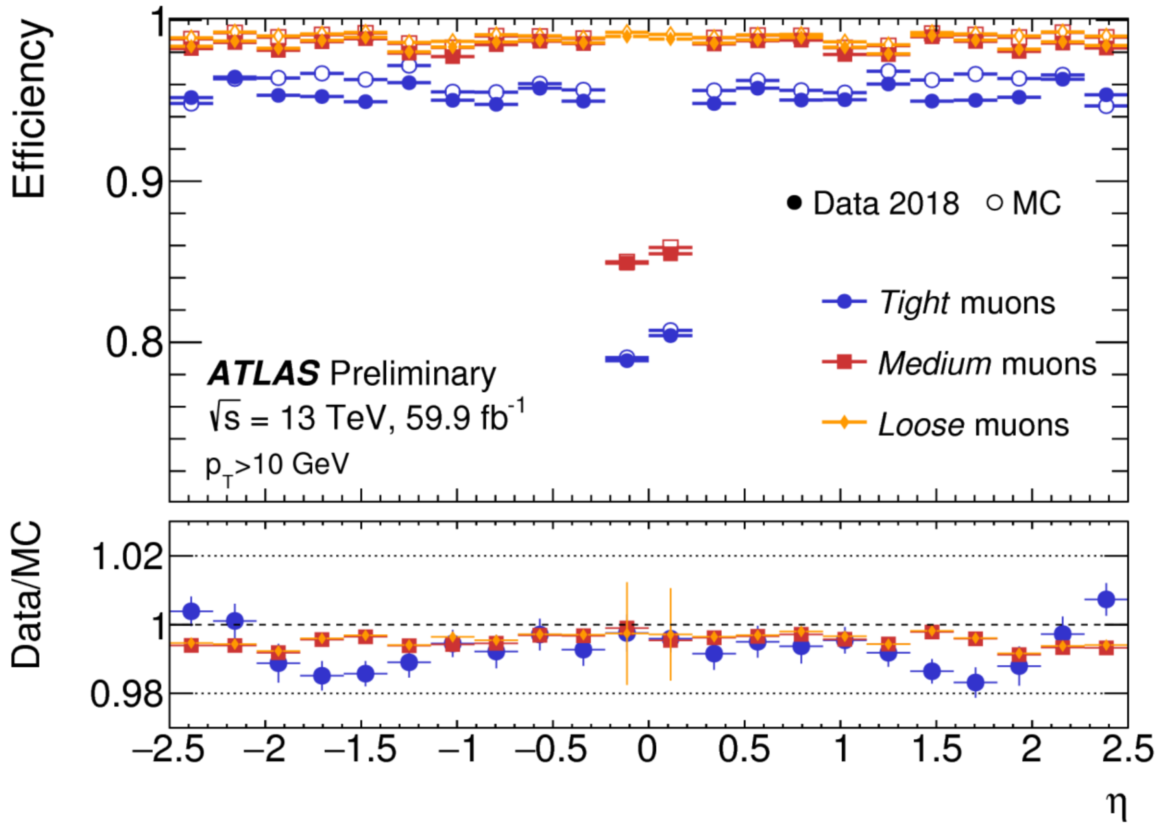
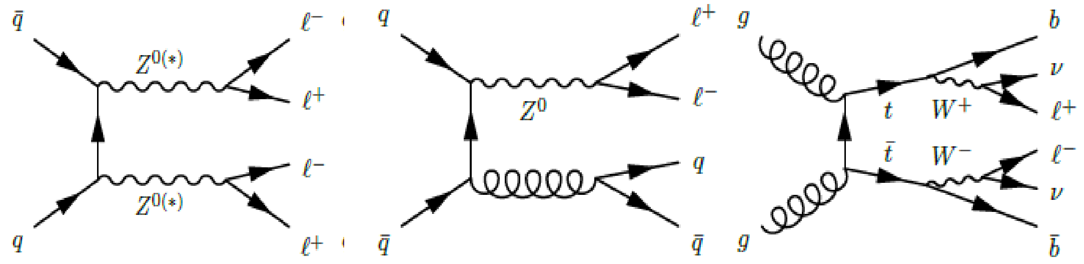


ATL-COM-PHYS-2018-1624

4l Event Selection

- <u>ZZ bkgs</u>
  - qq → ZZ(EW)
  - gg → ZZ
- <u>Reducible bkgs</u>
  - Z+jets Heavy (b,c) or Light (u,d,s) Flavor jets
  - $t\bar{t}$
  - Smaller contribution from WZ and VVV, ttV



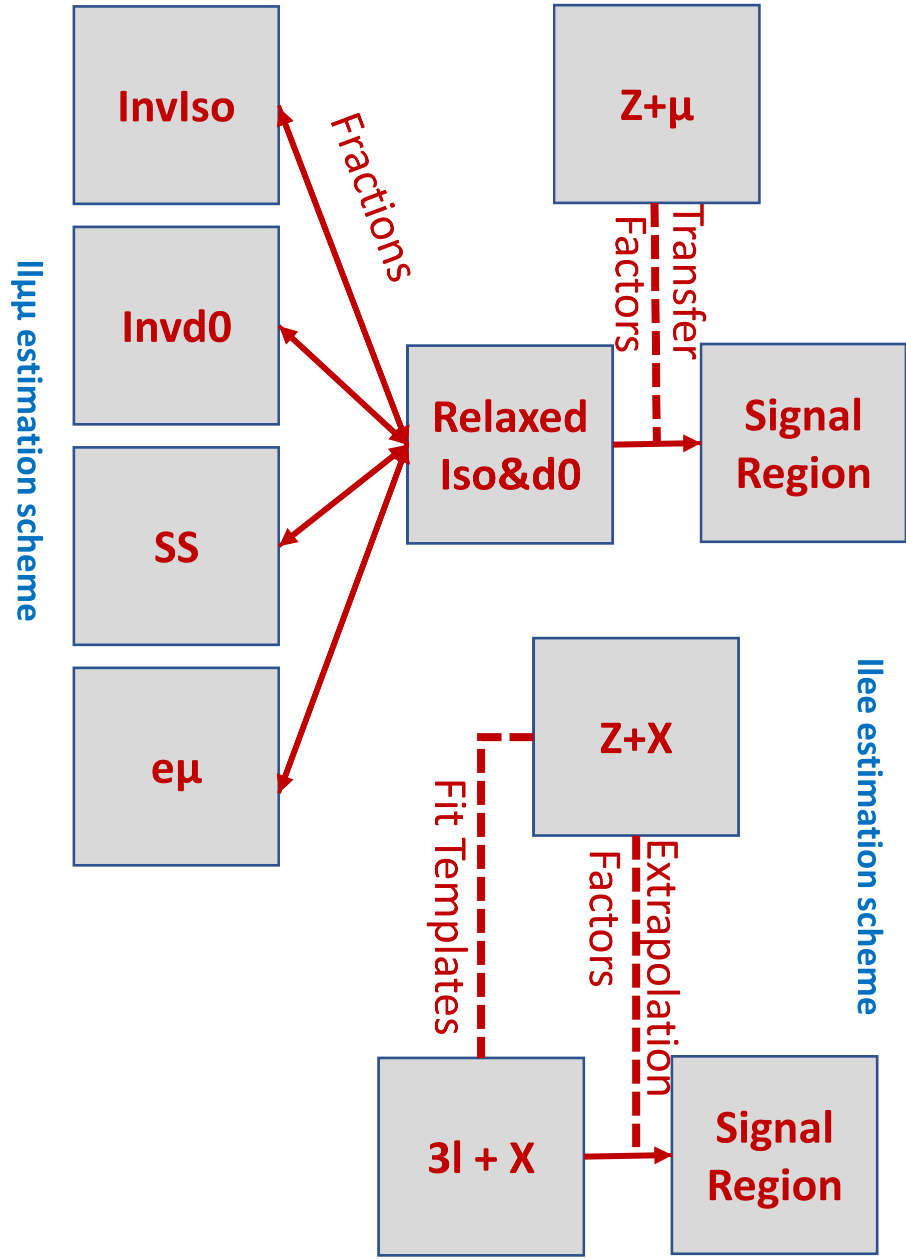
- 4 leptons
  - Isolated
  - Small impact parameter significance
  - Originating from the same vertex
- 2 lepton pairs compatible with the ZZ* hypothesis
  - Invariant masses [50-106 GeV] and [m_{th} – 115 GeV]
  - Same flavor
  - Opposite charge
- Best quadruplet according to the Matrix Element

Event selection heavily suppresses the reducible bkg

Final state	Signal full mass range	Signal	ZZ^*	Z + jets, $t\bar{t}$ WZ, ttV, VVV	Expected	S/B	Observed
Total	217.5 ± 13.0	206.1 ± 13.0	96.7 ± 6.0	12.1 ± 0.6	314.9 ± 14.0	1.9	316

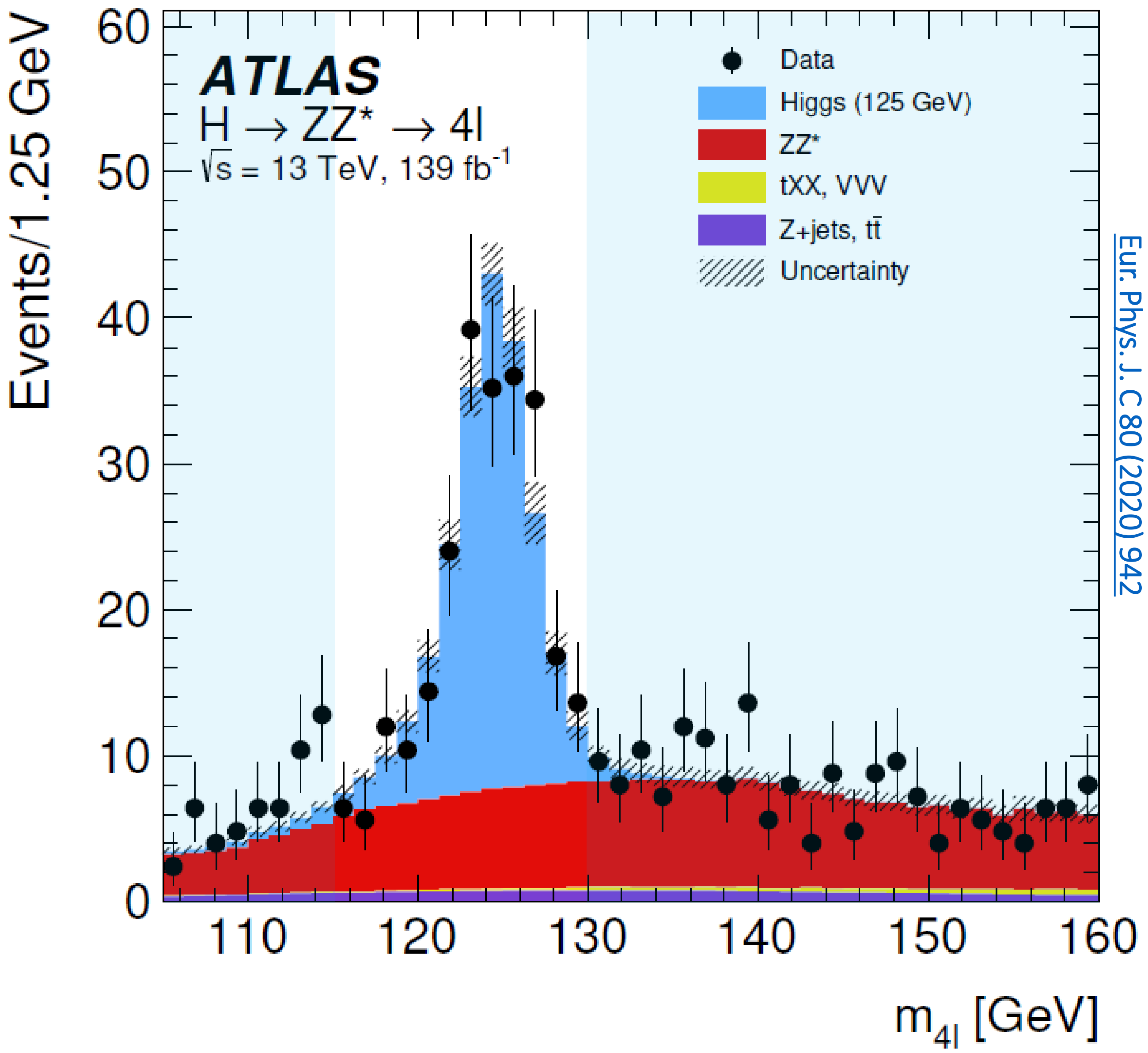
Reducible bkg estimation

- **Data Driven estimation of reducible bkg**
- **Properties are determined by the subleading dilepton**
- **2 methods for**
  - **<u>*ll μμ*</u> : Mainly Z + HF jets and $t\bar{t}$ - minor Z + LF jets**
  - **<u>*ll ee*</u> : Mainly Z+LF jets and fake electrons - minor Z+HF jets and $t\bar{t}$**
- **Changed selection criteria -> Control Regions (CRs) with high bkg purity**
- **CRs are fitted to the data and the yields are extrapolated to the signal region**



ZZ bkg estimation

- **ZZ is the largest background after event selection**
- **The ZZ normalization is a free parameter decided by signal region Sidebands**



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Mass measurement

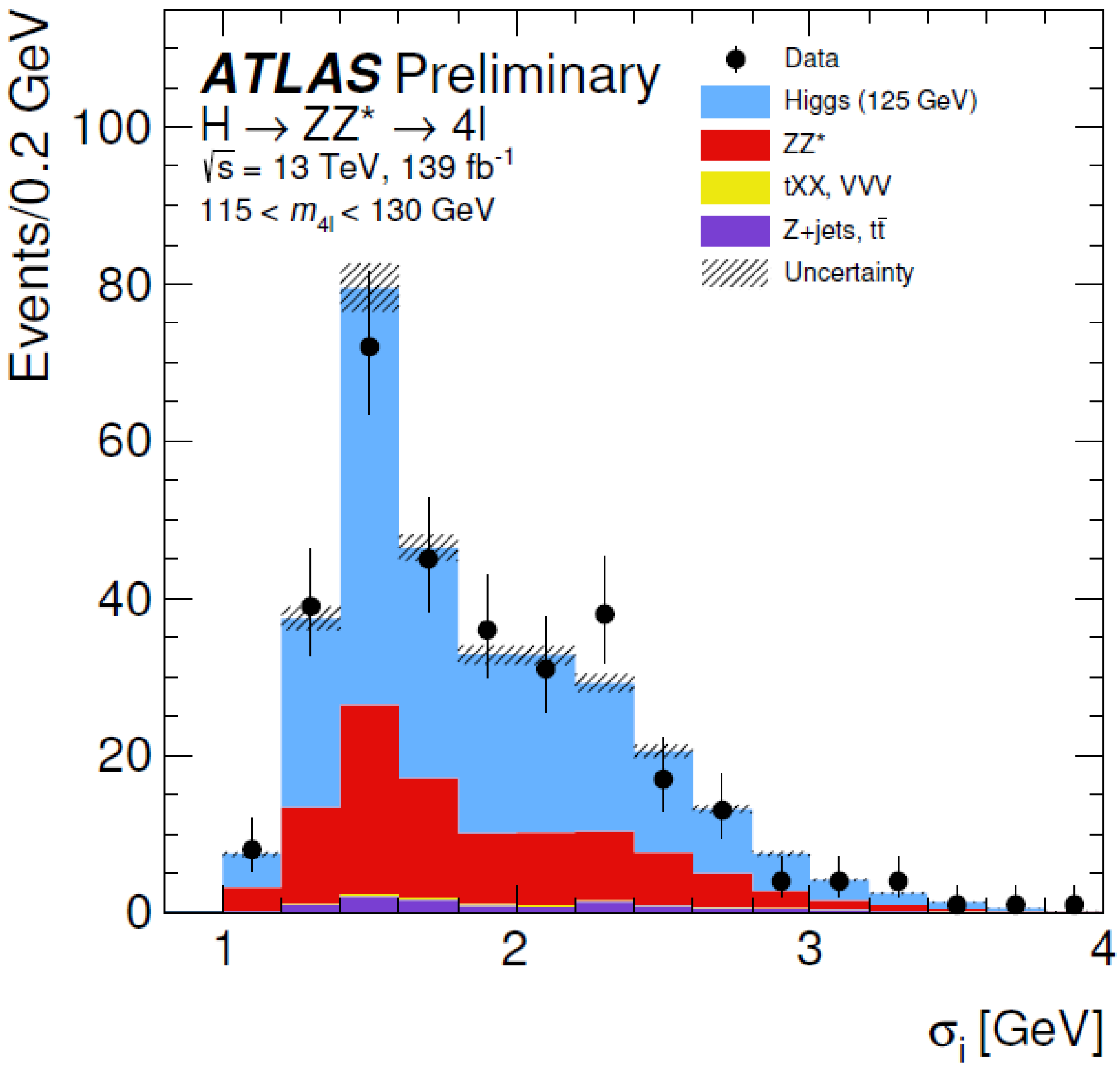
Resolution

- **Signal m_{4l} model**
  - Relativistic Breit–Wigner (BW) convoluted with
  - Double-sided Crystal Ball (DCB)

- **Shape is completely dominated by detector resolution**
  - Higgs Width - 4 MeV
  - Detector energy resolution - O (GeV)

- **Estimation of per-event resolution, a NN is trained with**
  - Lepton p_T, η, ϕ
  - p_{T4l} , Δp_{T4l}

- **Per event resolution included in DCB**



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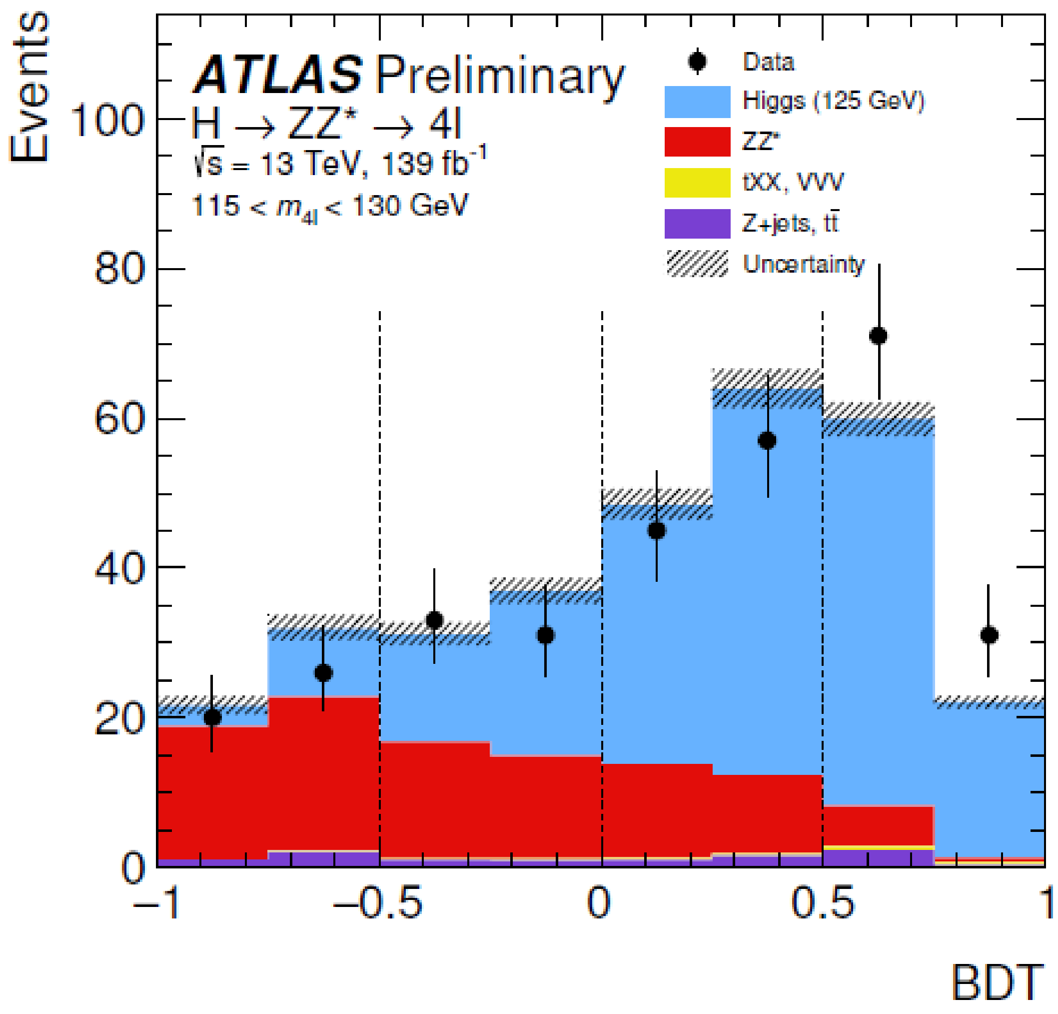
Signal/bkg separation

- **Boosted decision tree (BDT) for signal / ZZ separation trained on**
  - **- p_{T4l}**
  - **- η_{4l}**
  - **- Matrix element based kinematic discriminant**
- **4 BDT bins**
- **4 4lepton final states (4μ, 2μ2e, 2e2μ, 4e).**
- **Bkgs from MC and smoothed**
- **Simultaneous profile likelihood fit to the16 categories**



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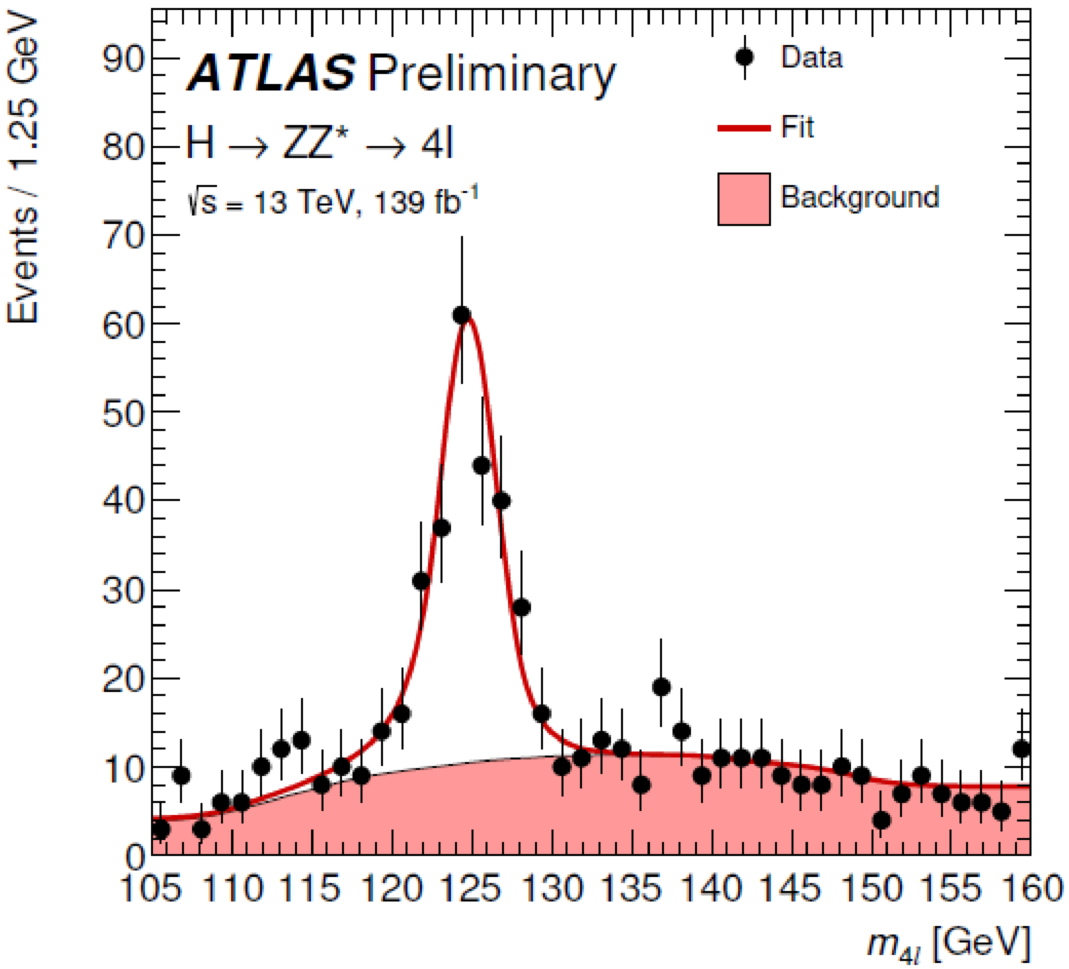
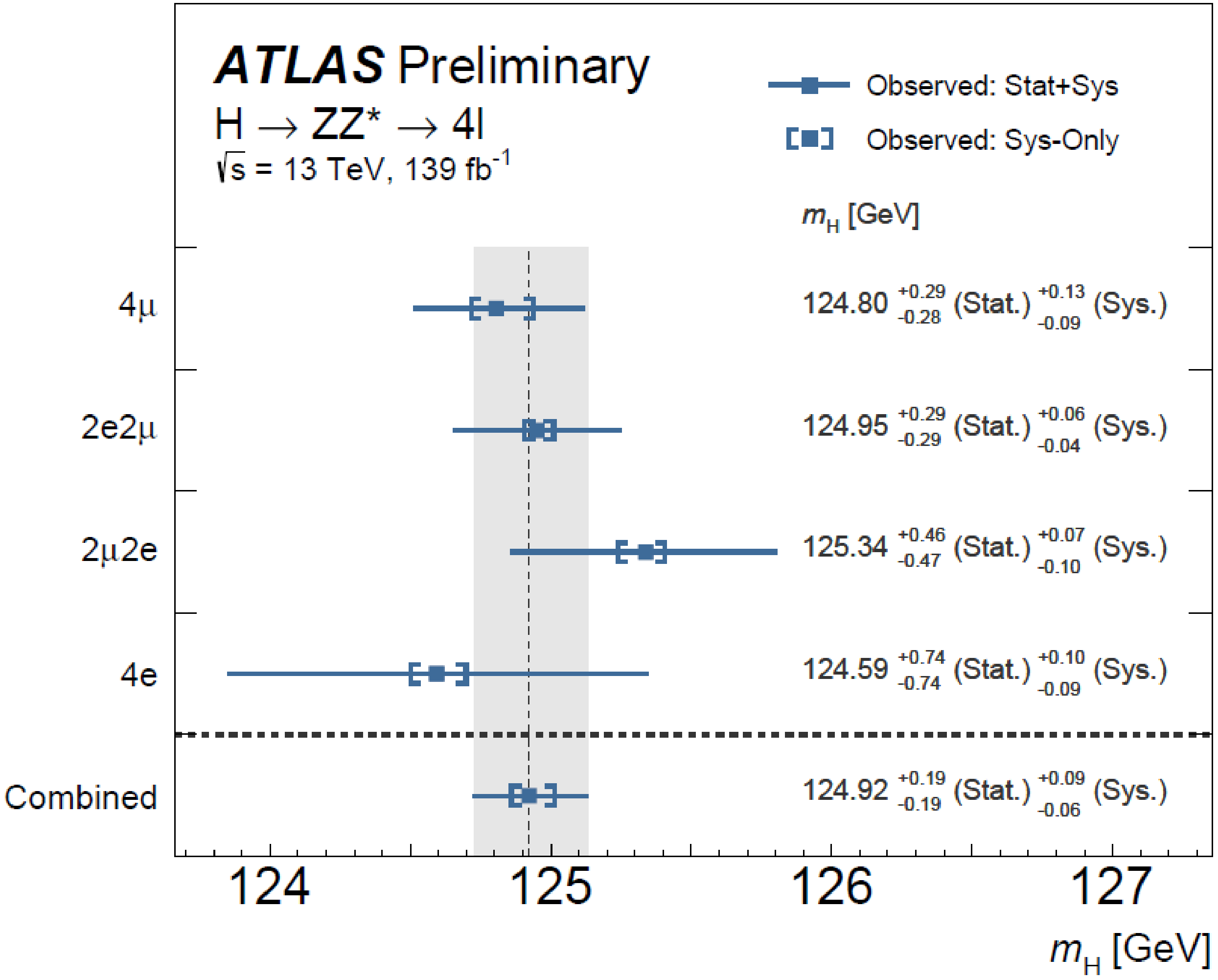
Results





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$$m_H = 124.92^{+0.19}_{-0.19}\,(\text{Stat.})^{+0.09}_{-0.06}\,(\text{Sys.})$$

Cross section measurement

Inclusive cross section

- **Fiducial phase space defined by selection criteria**
- **Fit on 4l invariant mass**

$$\sigma^{fid} = \sigma \cdot A \cdot BR(H \to 4l) = \frac{N_s}{C \cdot L_{int}}$$

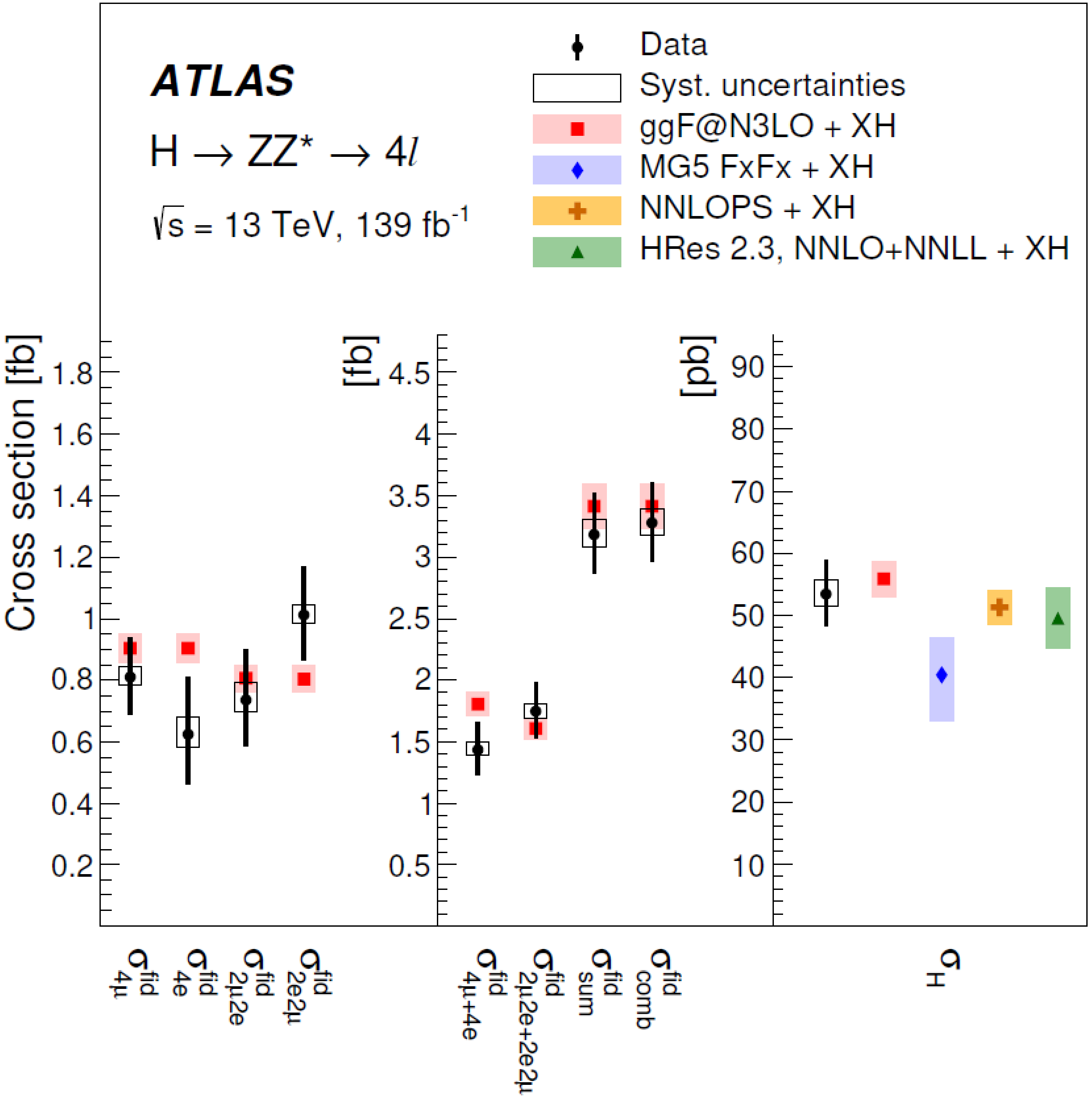
N_s : *number of signal events*

$A = \frac{N_{fid}}{N_{truth}}$: *Acceptance*

$C = \frac{N_{rec}}{N_{fid}}$: *Detector Efficiency*

BR : *Branching Ratio*

L_{int} : *Integrated Luminosity*



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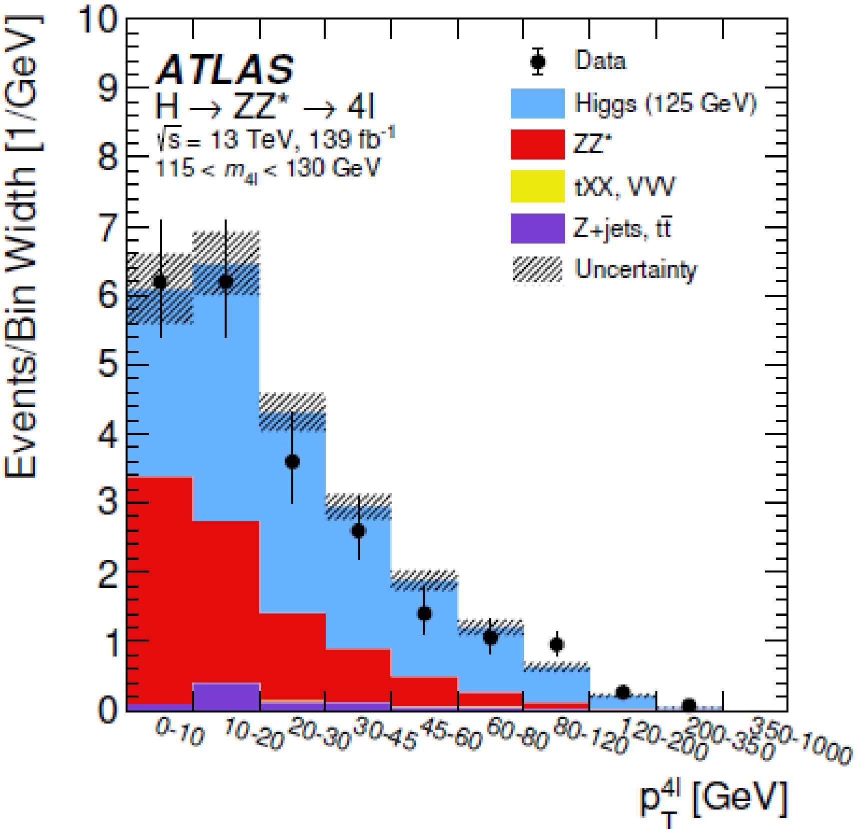
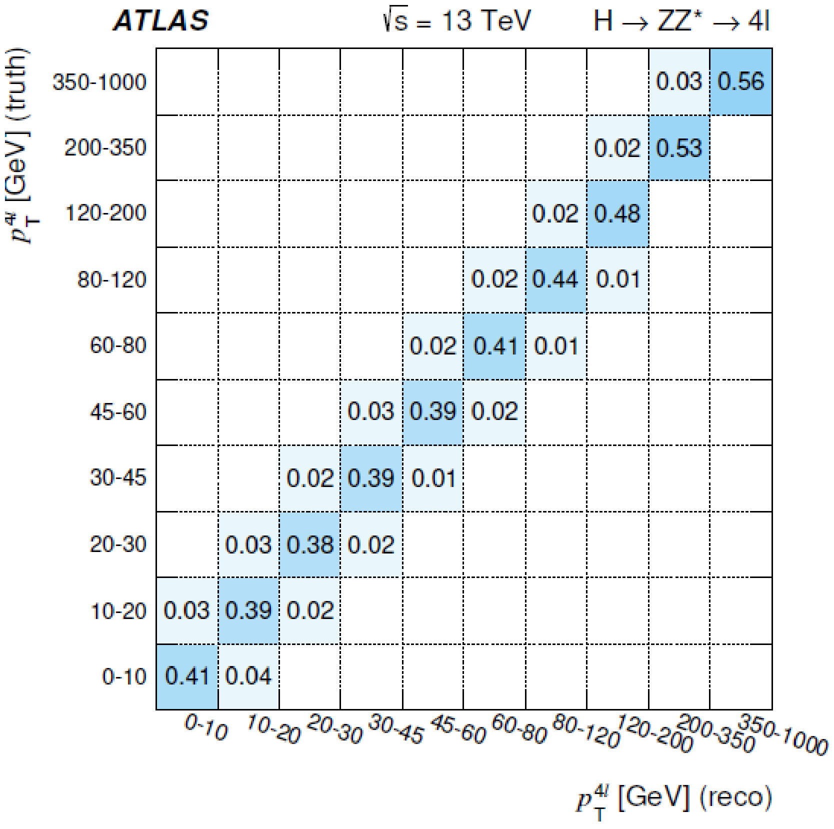
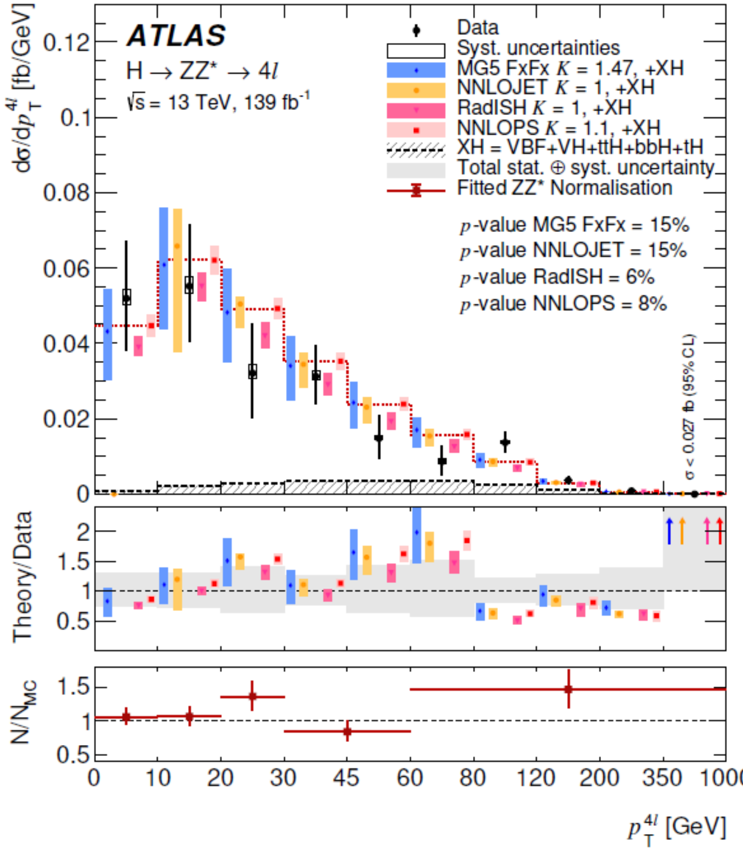
Unfolding

- **Differential cross sections are affected by migrations**
- **Unfolding extracts the information at truth level using the detector response matrix**
- **Fit on m_{4l} in each bin**







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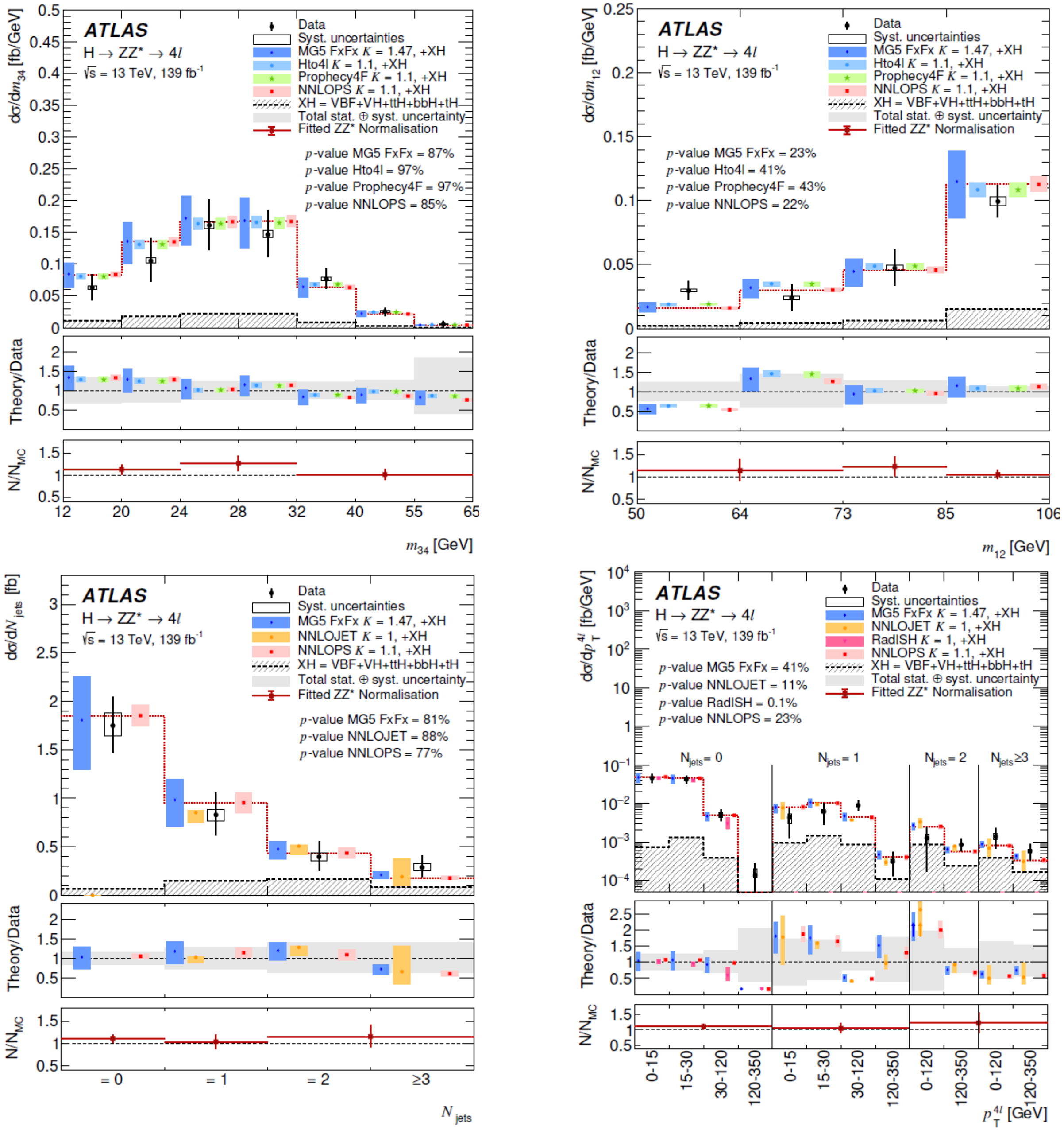
Differential cross sections

- **Measured cross sections are related to**
  - **- Higgs Boson kinematics**
  - **- Jets produced along with the Higgs boson**
  - **- Higgs boson and jets**

Higgs Boson kinematic-related variables
$p_T^{4l}, \|y_{4l}\|$
m_{12}, m_{34}
$\|cos\theta^*\|$, $cos\theta_1, cos\theta_2$
ϕ_1, phi_2
Jet-related variables
N_{jets}, N_{b-jets}
$p_T^{leadjet}, p_T^{subleadjet}$
$m_{jj}, \|\Delta\eta_{jj}\|, \Delta\phi_{jj}$
Higs boson and jet-related variables
$p_{T4lj}, m4lj$
p_{T4ljj}, m_{4ljj}
Double differential observables
m_{12} vs. m_{34} , p_T^{4l} vs. N_{jets}
p_T^{4l} vs. $p_T^{leadjet}$, p_T^{4l} vs. $\|y_{4l}\|$
p_T^{4lj} vs. $m4lj$, $p_T^{leadjet}$ vs. $p_T^{subleadjet}$
$p_T^{leadjet}$ vs. $\|y\|^{leadjet}$



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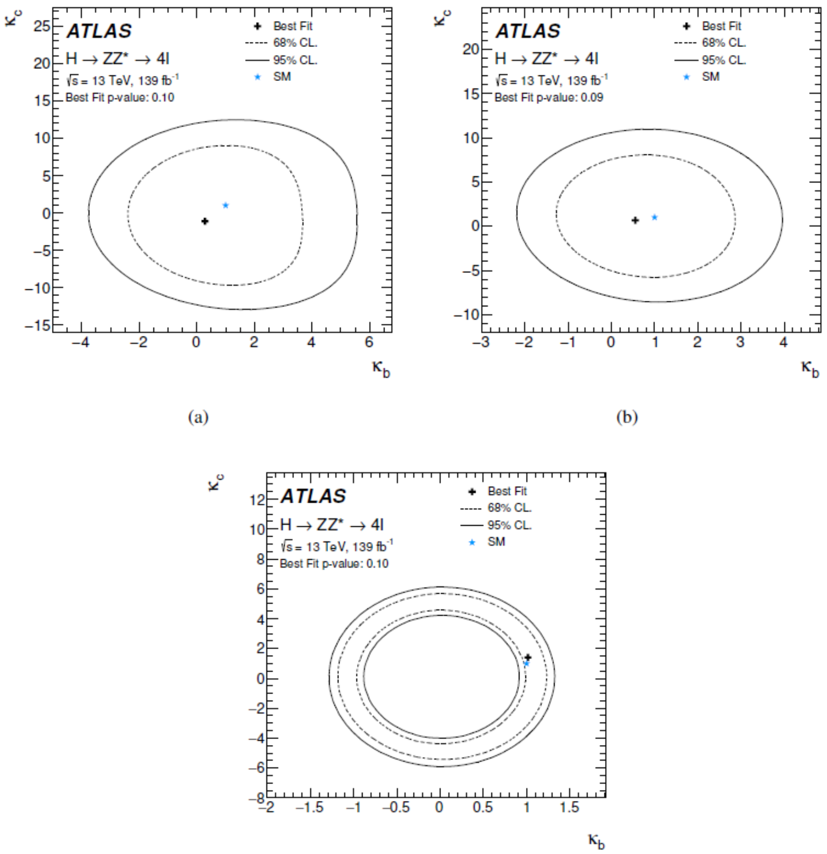
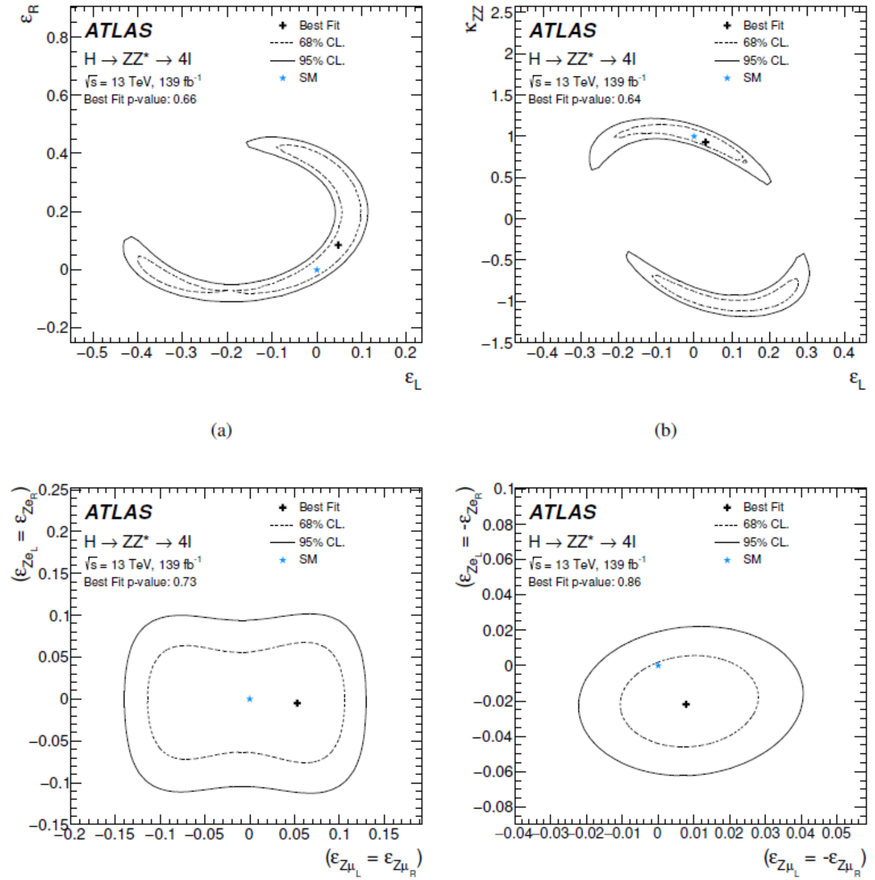
Interpretations

- **Yukawa couplings can be constrained by p_{TH} spectrum**
- **3 scenarios under different assumptions are investigated for κ_b and κ_c**



(a) (b)

- **In pseudo-observables framework contact terms between Higgs, Z and the L- or R-handed leptons are predicted**
- **The m_{12} vs. m_{34} double differential cross section can be used to probe several scenarios**



(a) (b)

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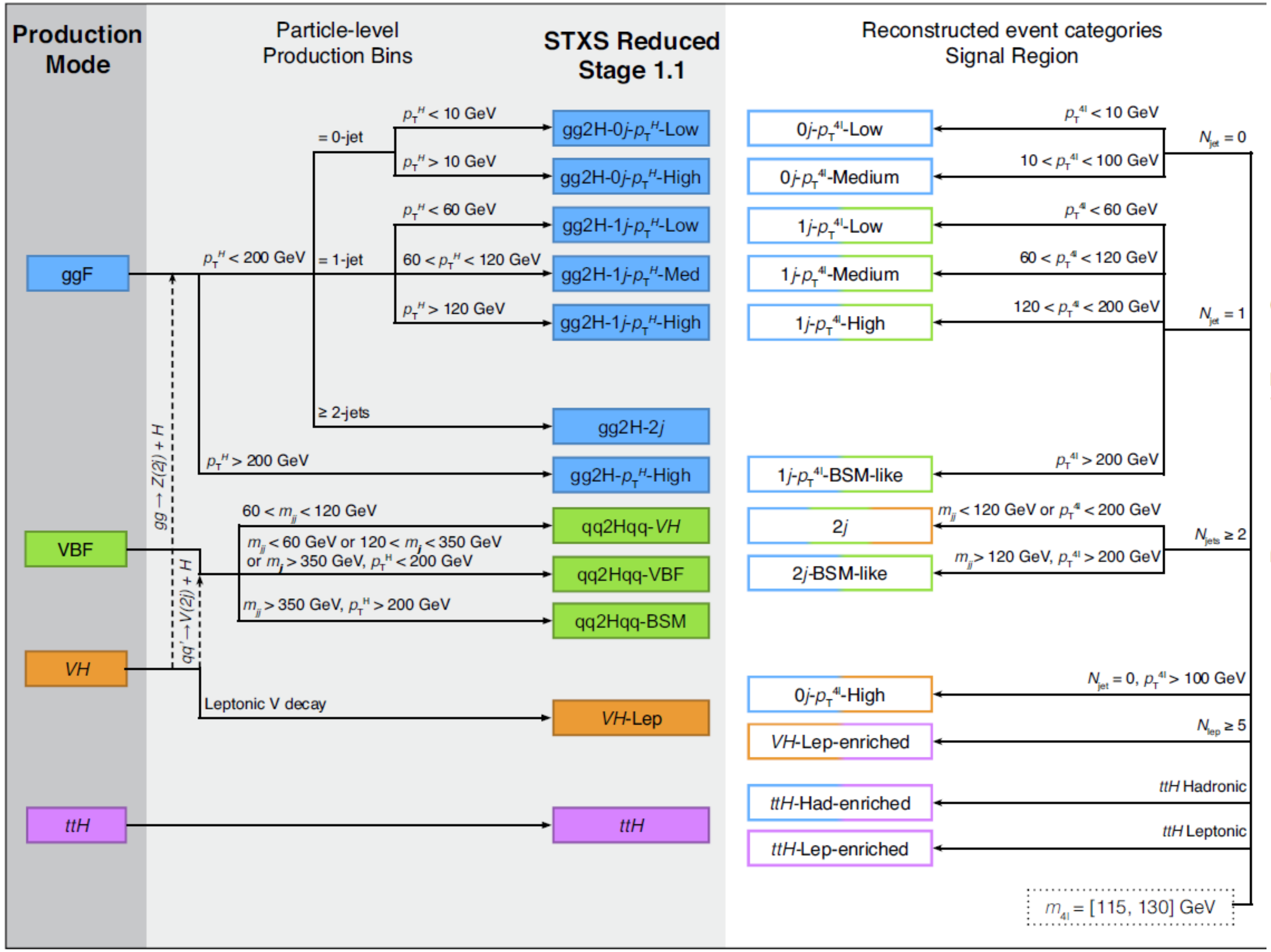
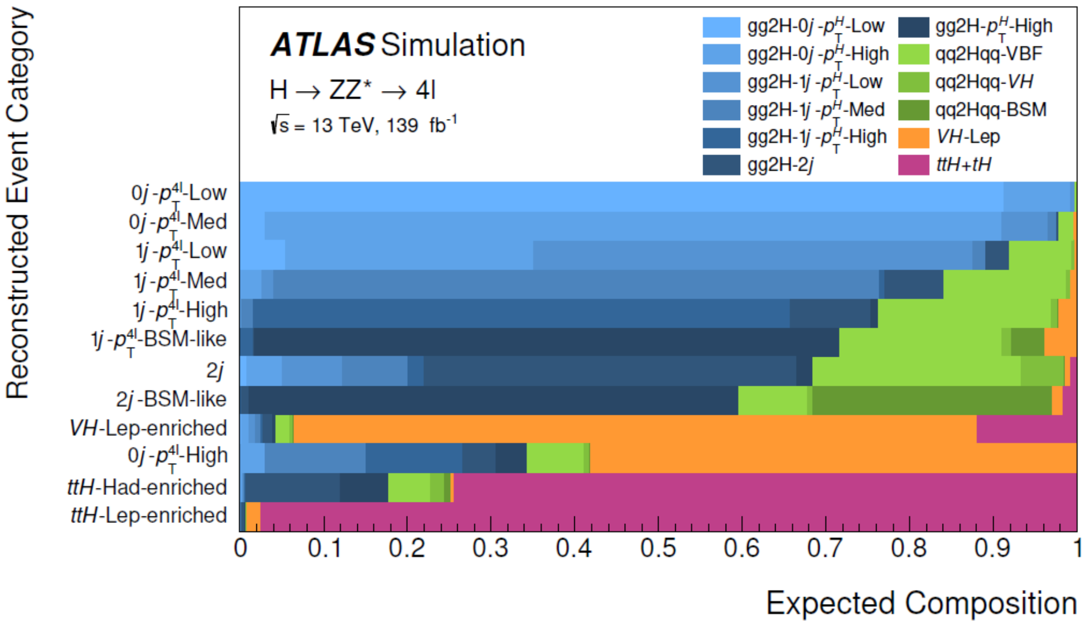
Measuring production mechanisms

Production mode categories

- **Events are classified into 12 categories sensitive to different production mechanisms**



- **The categories are chosen to**
  - **- Maximize measurement precision**
  - **- Probe possible Beyond Standard Model contributions**



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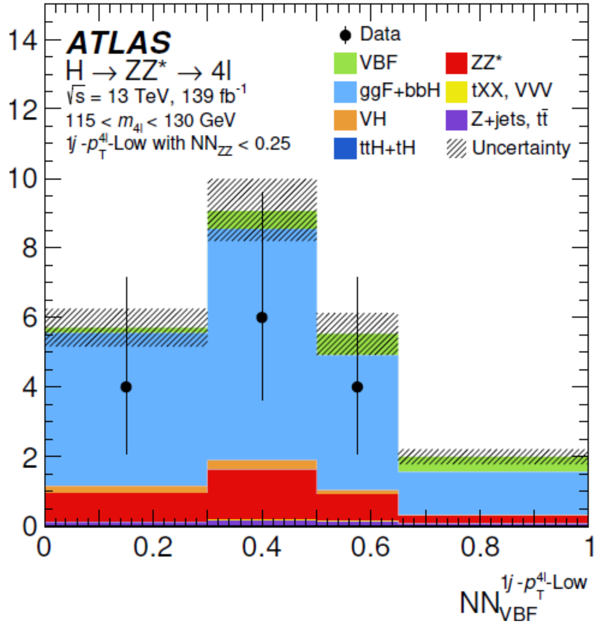
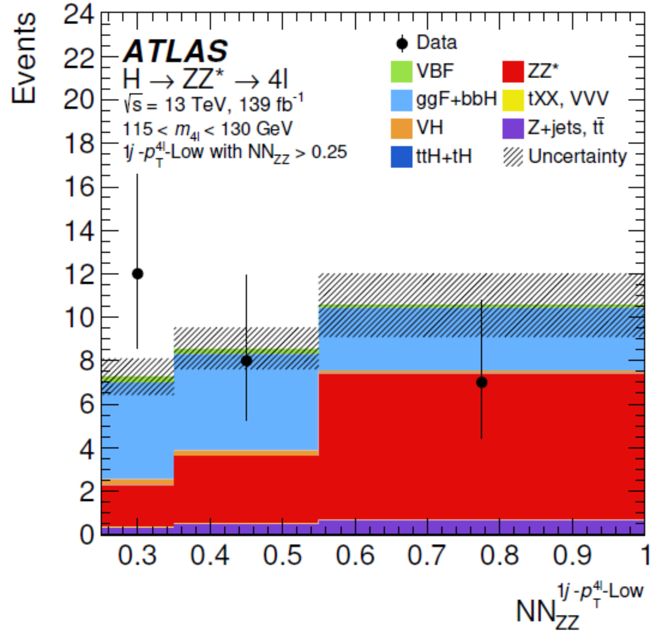
Neural Networks

- **8 Neural Networks - increase sensitivity**
- **Discriminate among production mechanism and against bkg**
- **NN discriminants are fitted**

Category	Processes	MLP	Lep rNN	Jet rNN
$0j$	ggF,ZZ	$p_T^{4\ell}$, D_{ZZ^*}, m_{12}, m_{34}, $\cos\theta^*$, $\cos\theta_1$, ϕ_{ZZ}	$p_{T,\ell}$, η_ℓ	n/a
$1j$-$p_T^{4\ell}$-Low	ggF,VBF,ZZ	$p_T^{4\ell}$, $p_{T,j}$, η_j, $\Delta R_{4\ell j}$, D_{ZZ^*}	$p_{T,\ell}$, η_ℓ	n/a
$1j$-$p_T^{4\ell}$-Med	ggF, VBF, ZZ	$p_T^{4\ell}$, $p_{T,j}$, η_j, E_T^{miss} $\Delta R_{4\ell j}$, D_{ZZ^*}, $\eta_{4\ell}$	-	n/a
$1j$-$p_T^{4\ell}$-High	ggF, VBF	$p_T^{4\ell}$, $p_{T,j}$, η_j, $\Delta R_{4\ell j}$, $\eta_{4\ell}$, E_T^{miss}	$p_{T,\ell}$	n/a
$2j$	ggF, VBF, VH	m_{jj}, $\Delta\eta_{jj}$, $p_{T,4\ell jj}$	$p_{T,\ell}$, η_ℓ	$p_{T,j}$, η_j
$2j$-BSM-like	ggF, VBF	$\Delta\eta_{jj}$, $\Delta\eta_{4\ell jj}$, $p_{T,4\ell jj}$	$p_{T,\ell}$, η_ℓ	$p_{T,j}$, η_j
VH-Lep-enriched	ttH, VH	N_{jets}, N_{b-jets}, E_T^{miss}, HT, $\ln(\lvert\mathcal{M}_{sig}\rvert^2)$	$p_{T,\ell}$	n/a
ttH-Had-enriched	ttH, tXX, ggF	$p_T^{4\ell}$, m_{jj}, $\Delta\eta_{jj}$, $p_{T,jj}$, $\min(\Delta R_{Zj})$, $\Delta\eta_{4\ell jj}$, N_{jets}, N_{b-jets}, E_T^{miss}, $\min(\Delta R_{4\ell j})$, HT, $\ln(\lvert\mathcal{M}_{sig}\rvert^2)$	$p_{T,\ell}$, η_ℓ	$p_{T,j}$, η_j





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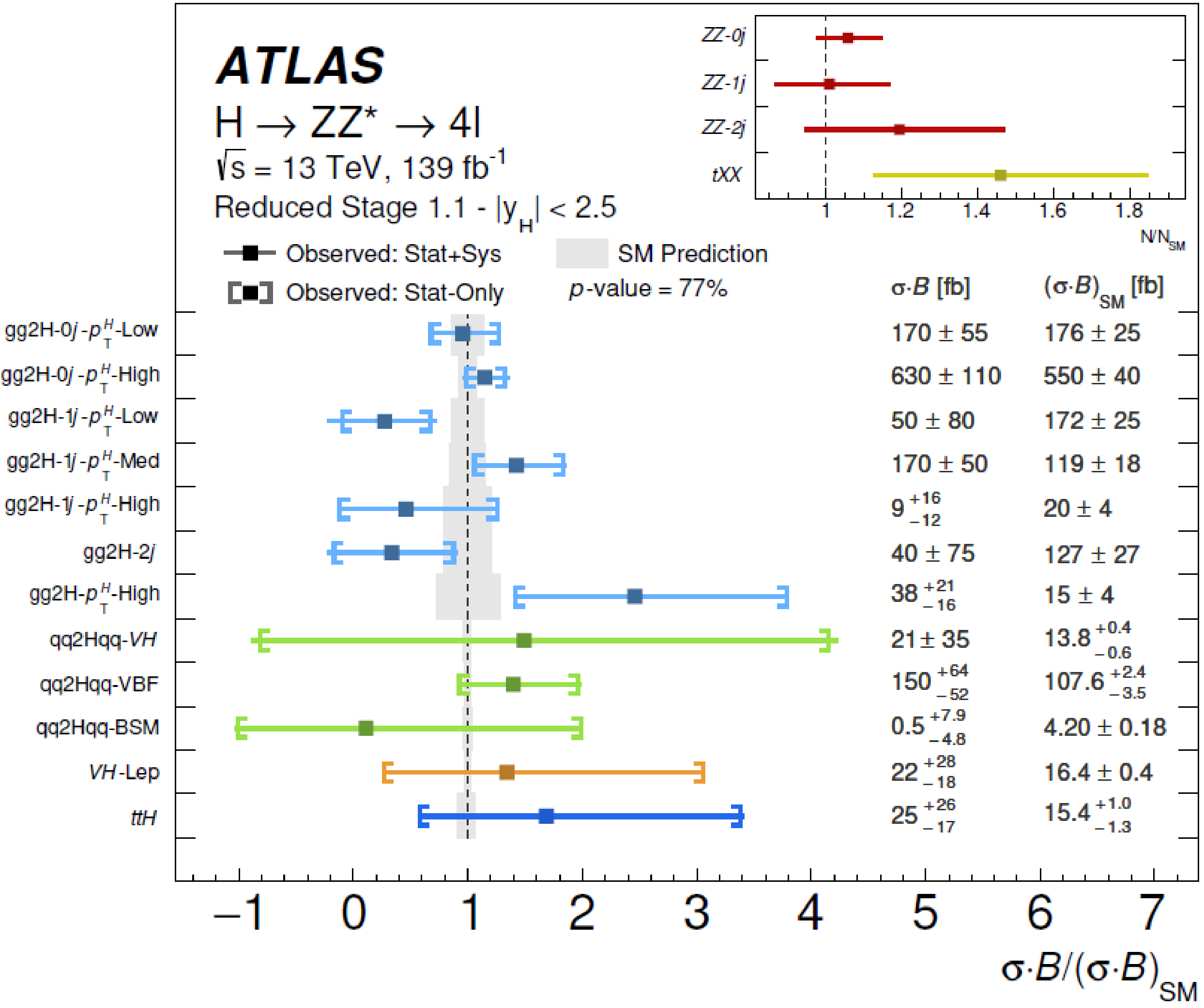
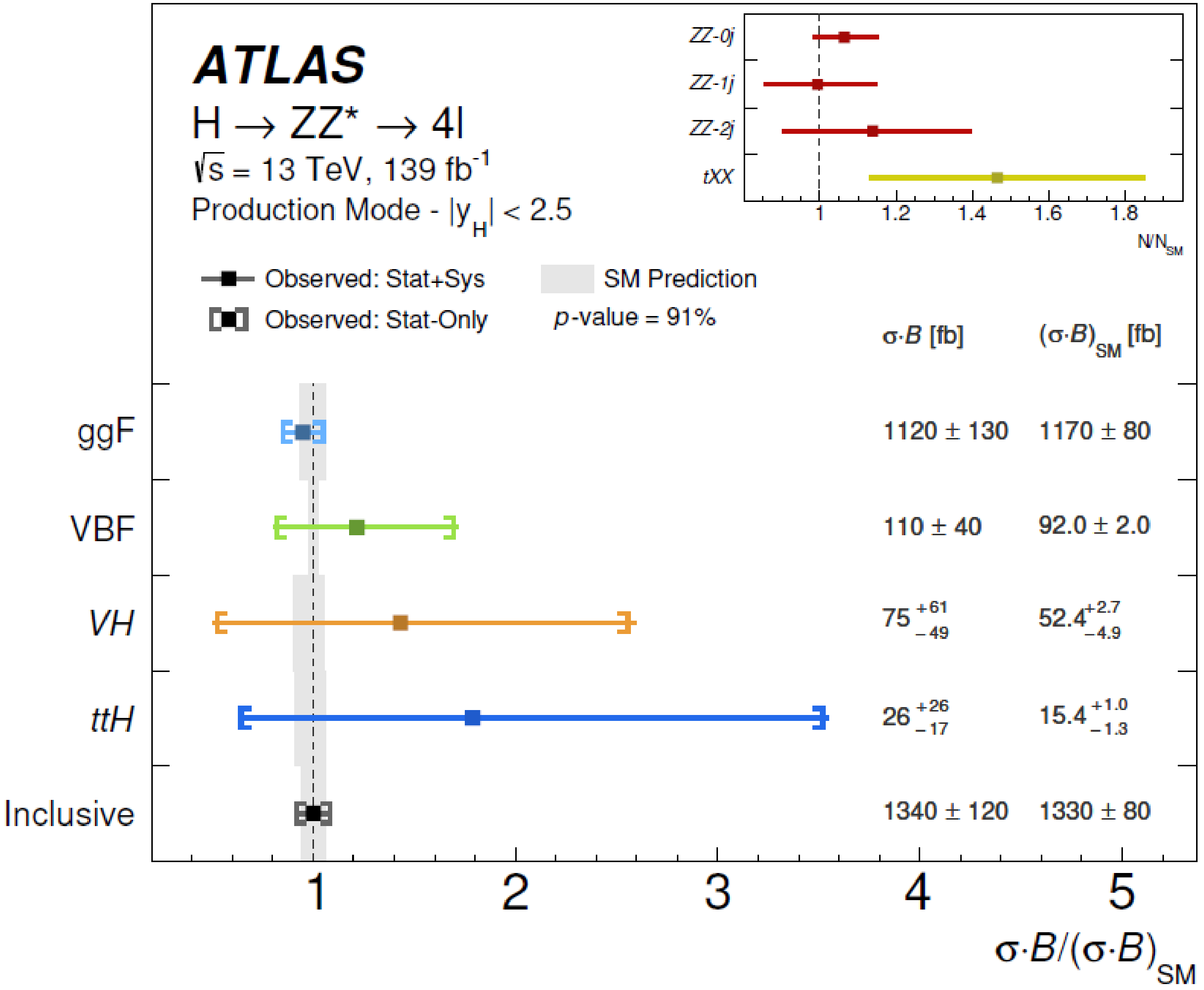
Production modes cross sections





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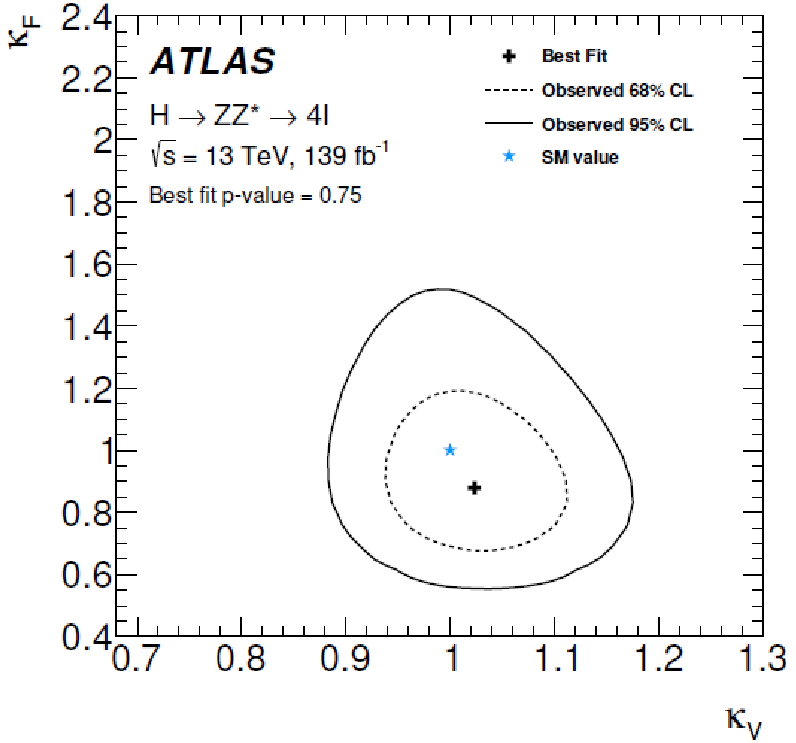
Interpretations

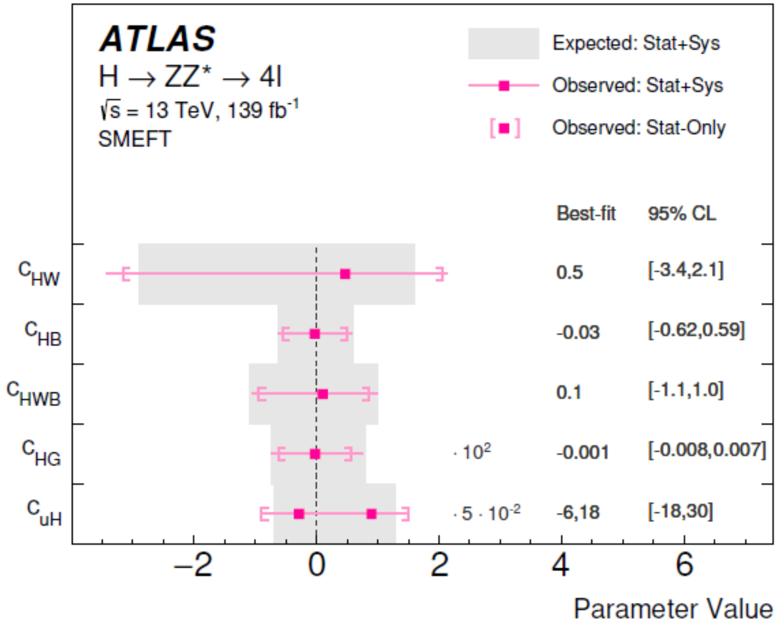
- **The universal coupling-strength modifiers κ_F for fermions and κ_V for vector bosons are defined as**
  - $\kappa_V = \kappa_W = \kappa_Z$
  - $\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_\mu$

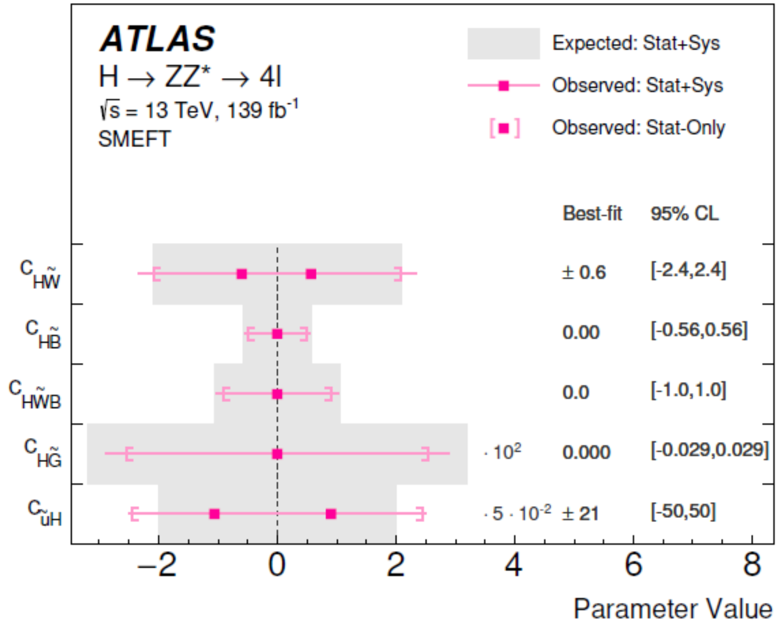
- **In EFT BSM interactions are introduced via additional operators in the Lagrangian**

- **Parameters $C_i^{(d)}$ specify the strength of new interactions**

- **A minimal flavor-violating scenario consisted of five CP-even and five CP-odd operators is tested**







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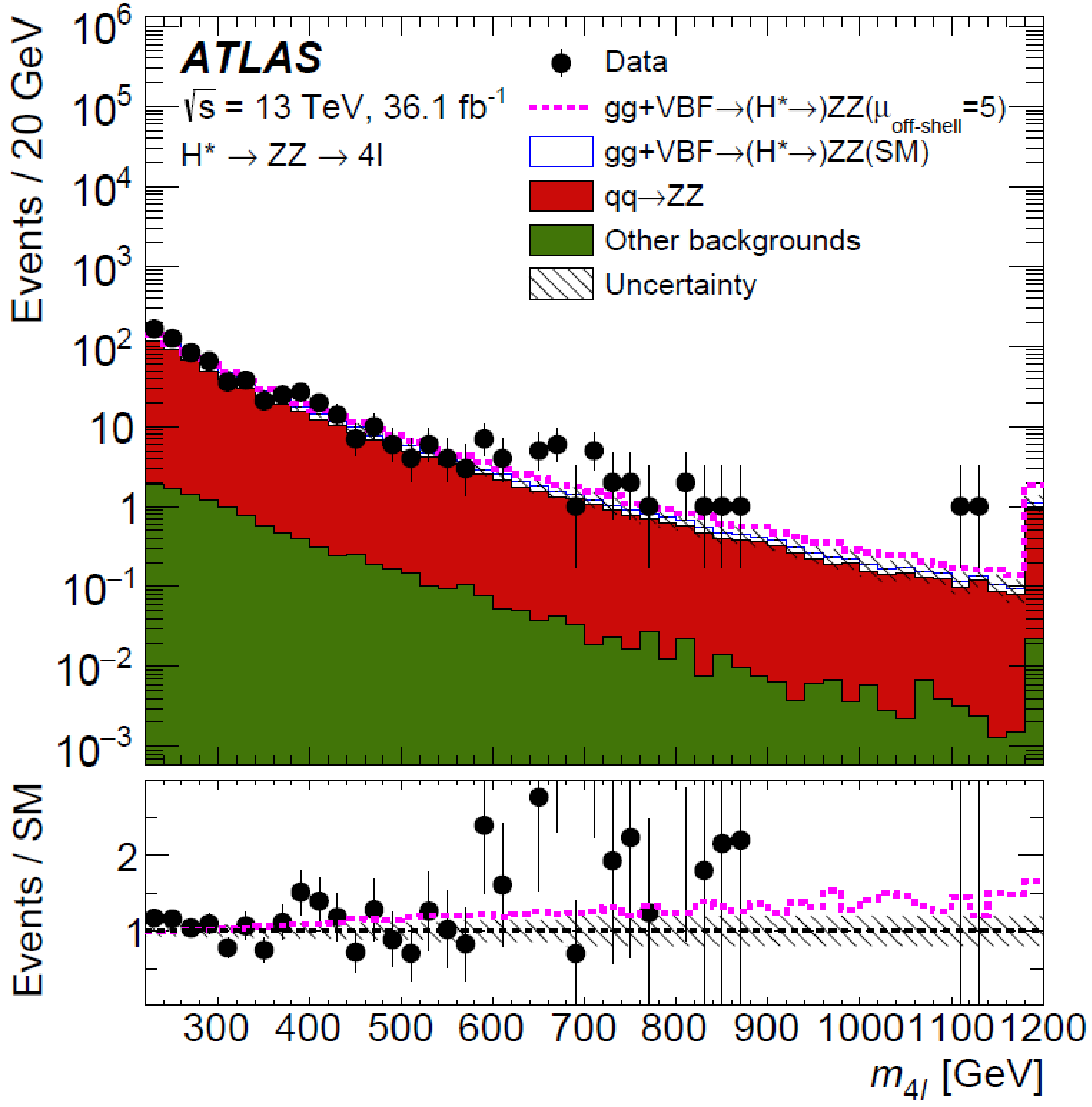
Width measurement

Methodology

- **Higgs Decay Width - 4 MeV**
- **The ATLAS detector energy resolution - O (GeV)**
- **Direct measurement is not possible**
- **Higgs boson off-shell production –> higher mass**
- **On-shell/off-shell XS ratio is depended on the width**

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$



Phys. Lett. B 786 (2018) 223

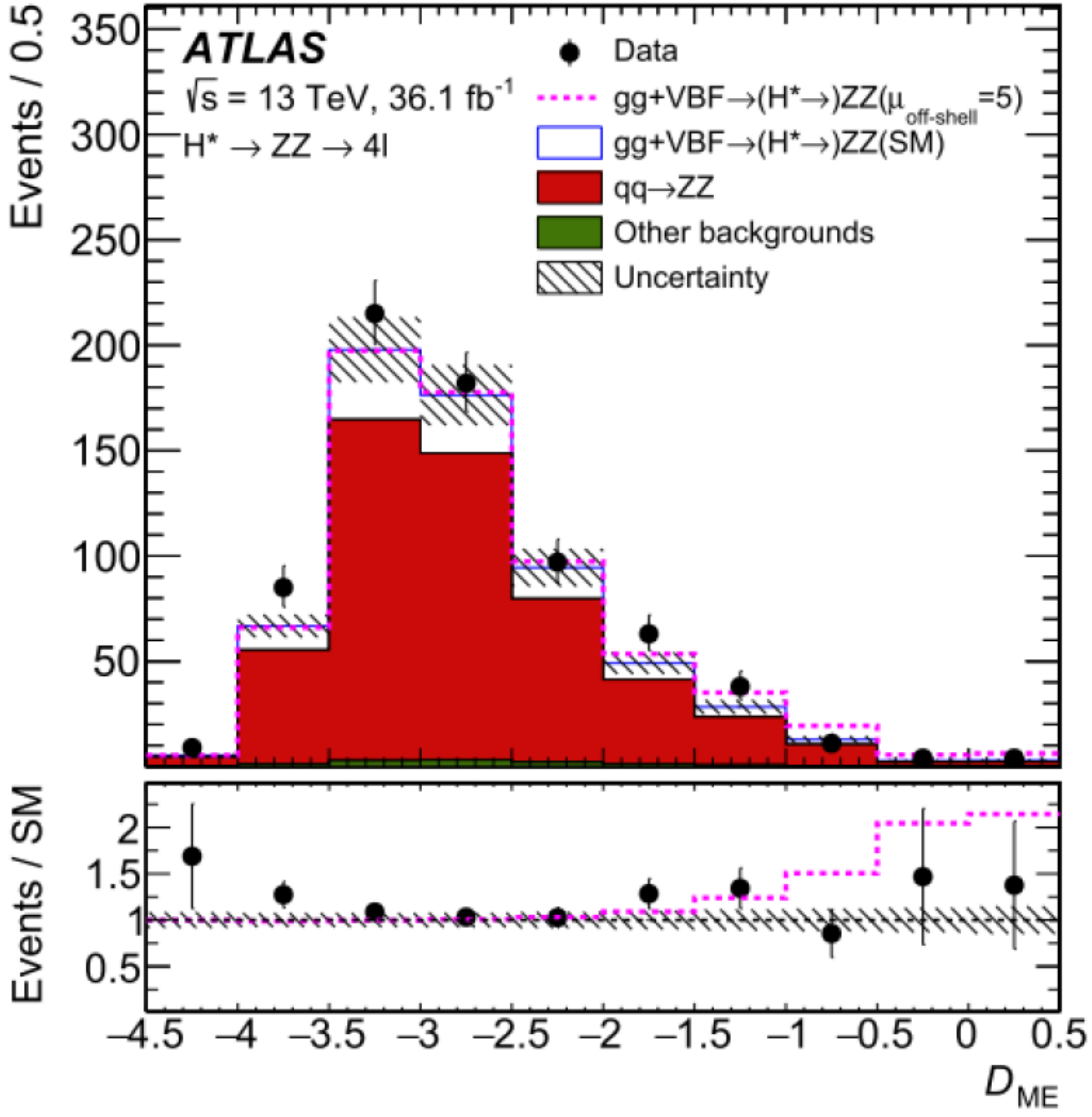
Matrix Element Discriminant

- **Matrix elements**
  - **- qq → ZZ → 4l (P_{qq})**
  - **- gg->(H* →)ZZ → 4l (P_{gg})**
  - **- gg → H* → ZZ → 4l (P_H)**

- **The discriminant is defined by**

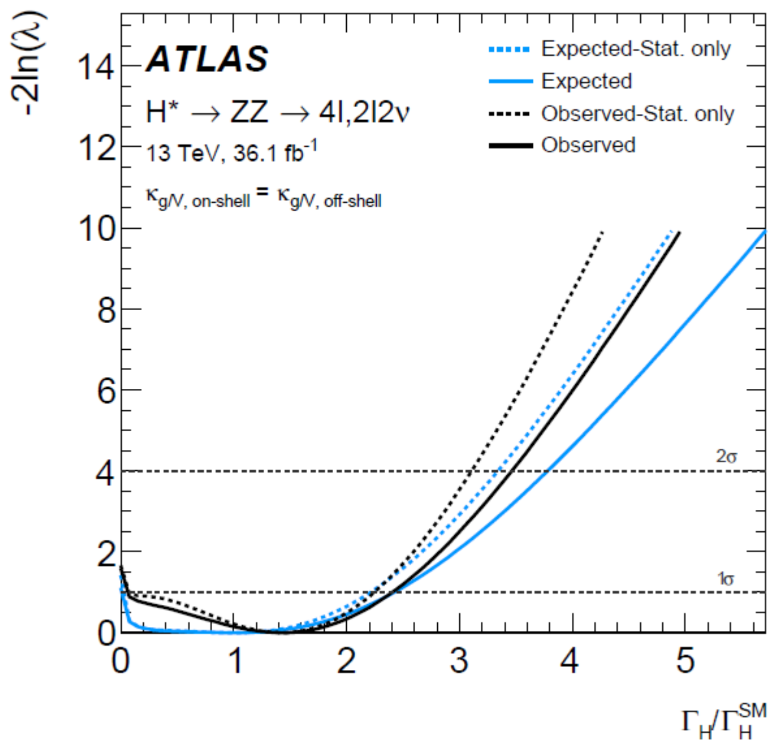
$$D_{\mathrm{ME}} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

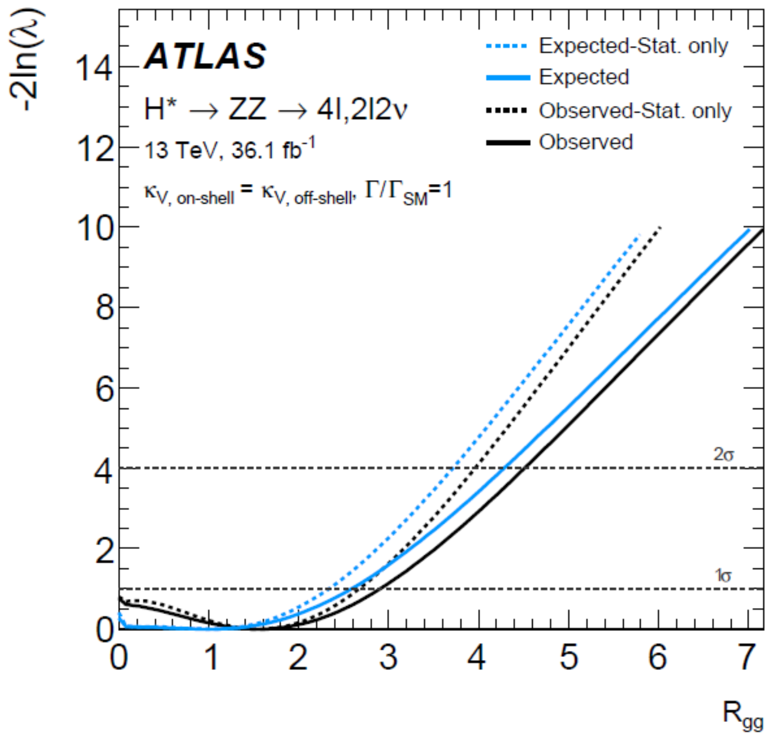
- **The D_{ME} distribution is fitted**



Phys. Lett. B 786 (2018) 223

- **4l – llνν combination**
- **Off-shell – on-shell combination to extract the decay width**
- **Data from the first period (2015-2016) of Run II - 36.1 fb^{-1}**
- **Upper limit of Higgs boson decay width is 3.8·SM @ 95% CL**





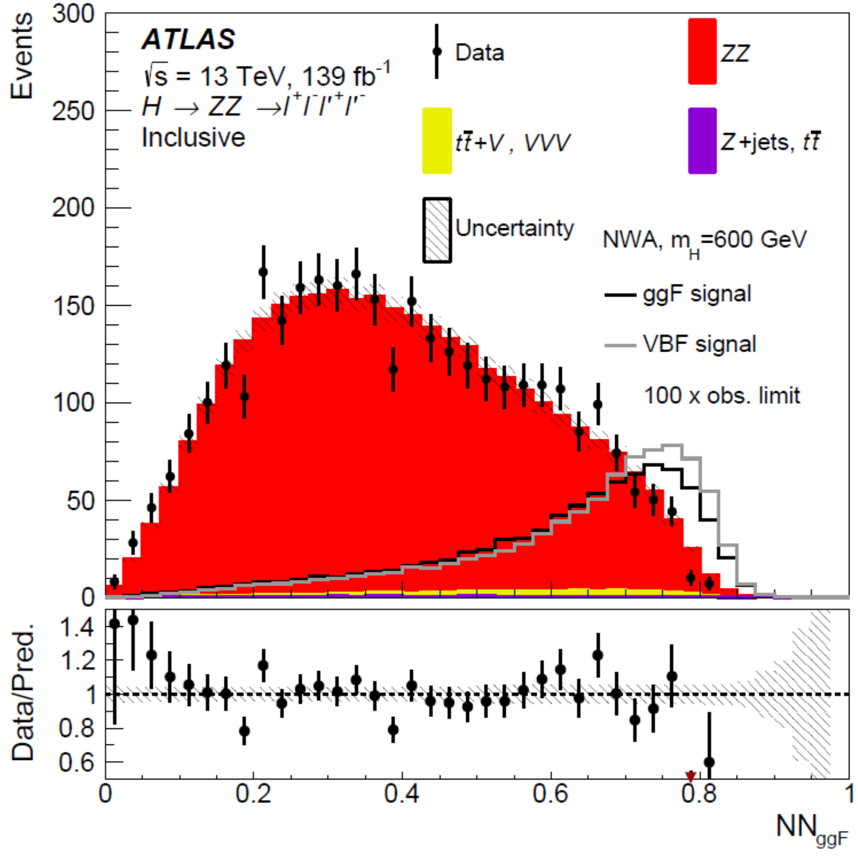
		Observed	Expected Median	Expected ±1 σ	Expected ±2 σ
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \to 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
$\Gamma_H/\Gamma_H^{\text{SM}}$	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]
R_{gg}	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]

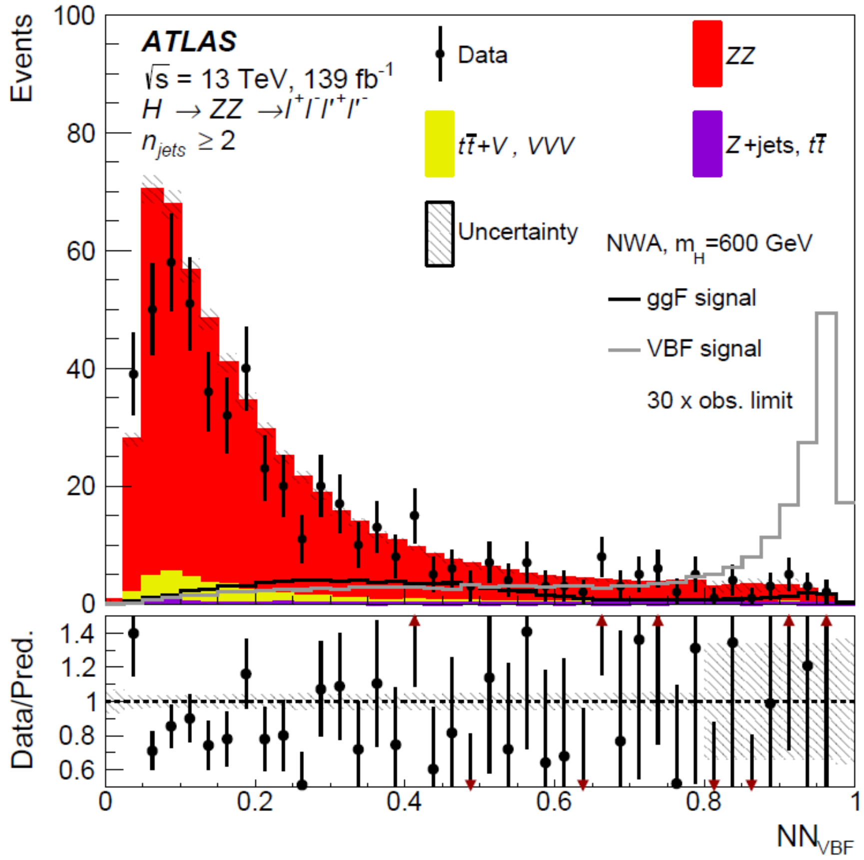
Phys. Lett. B 786 (2018) 223

High mass resonances search

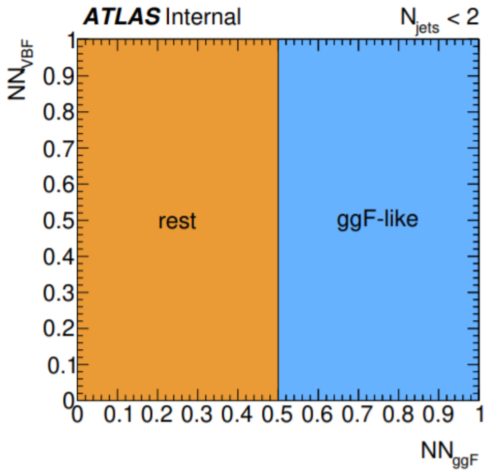
Neural Networks

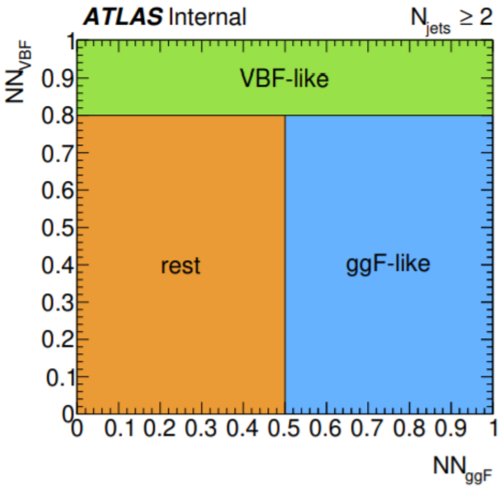
- **High mass Higgs-like bosons predicted by several BSM models**
- **2 NNs probe the ggF/VBF produced signal against ZZ bkg**
- **Trained on event kinematic variables for 11 mass points**





- **5 Categories**
  - ggF-like (4μ, 2μ2e, 4e)
  -VBF-like
  -Rest

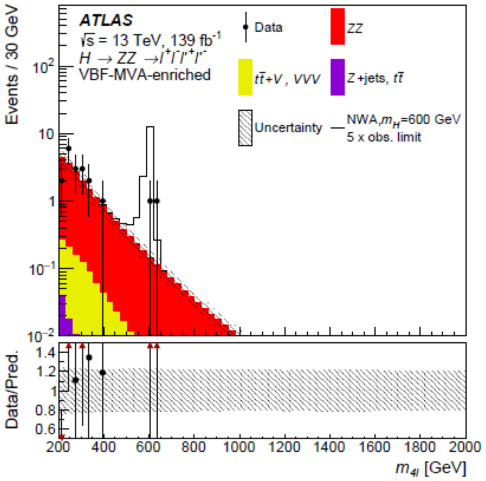


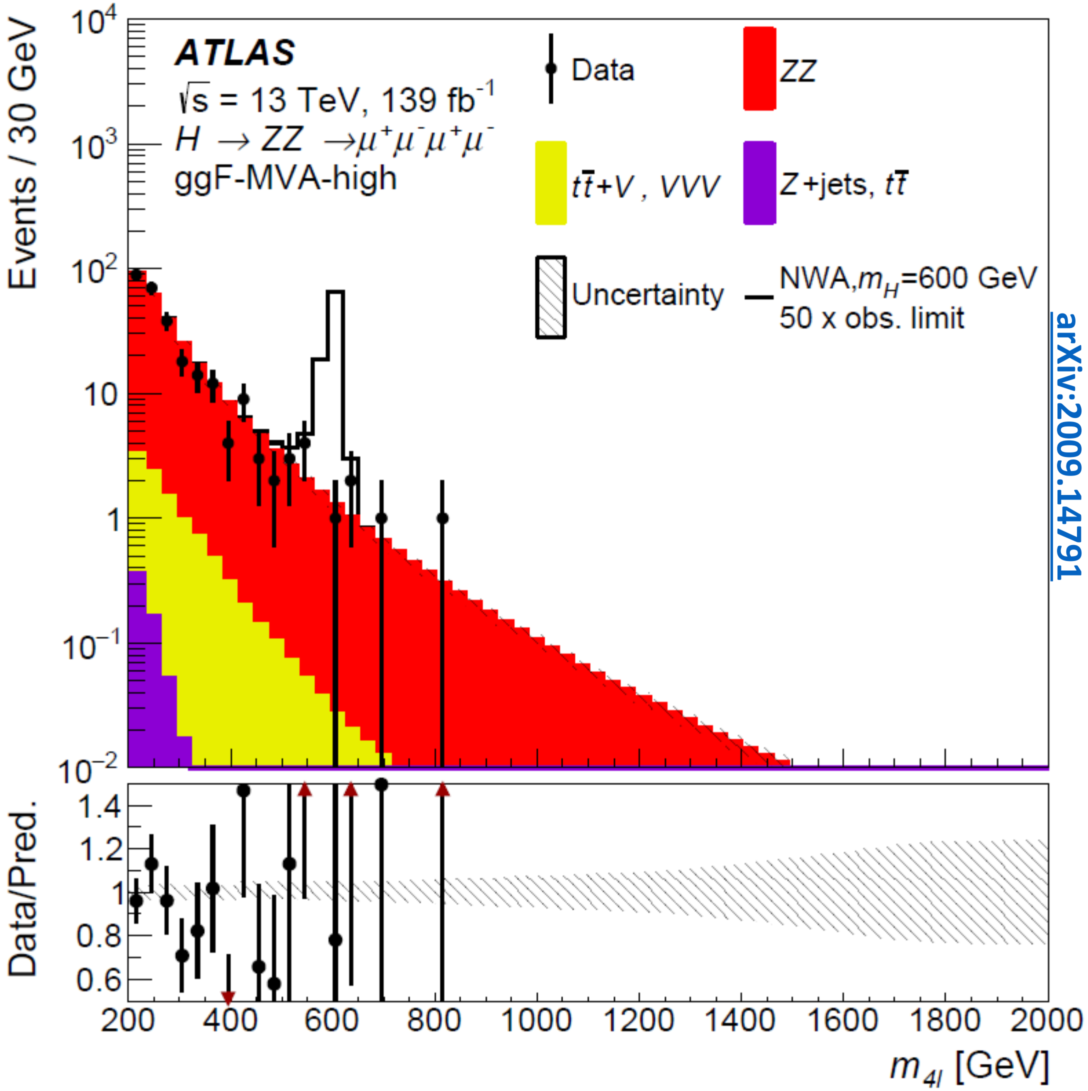


arXiv:2009.14791

Signal and background modelling

- **NWA signal model**
  - **Gaussian + Crystal Ball**
- **LWA & graviton signal model**
  - **Relativistic Breit-Wigner convoluted with**
  - **Gaussian + Crystal Ball**
- **ZZ bkg model**
  - **Empirical functions**





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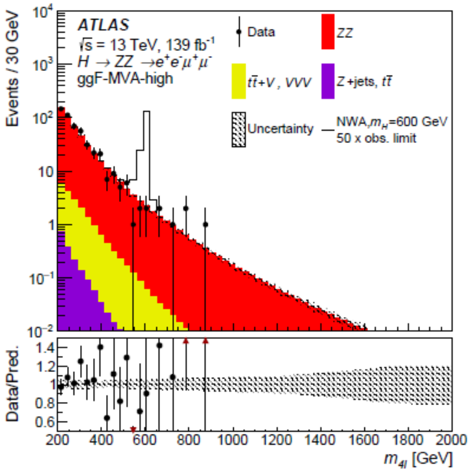
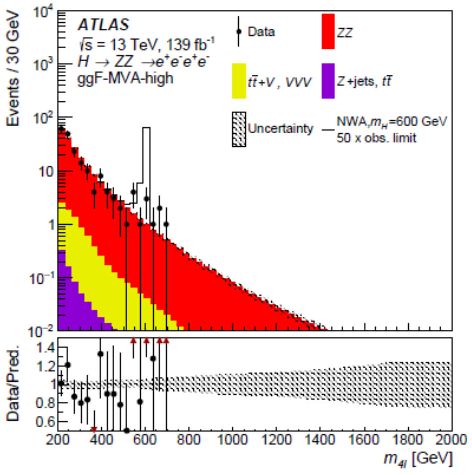
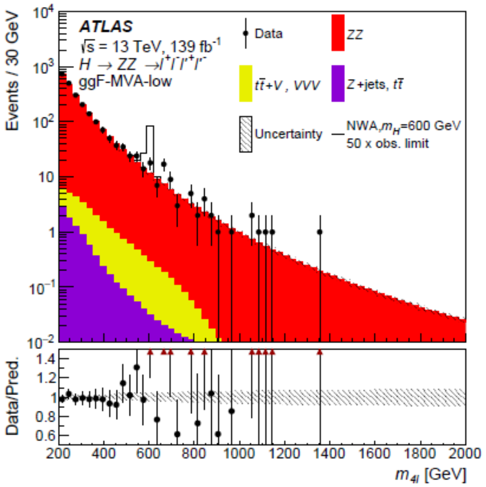
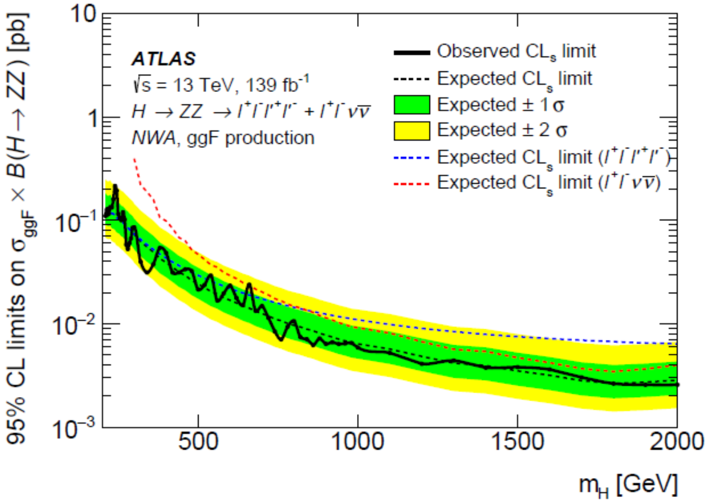


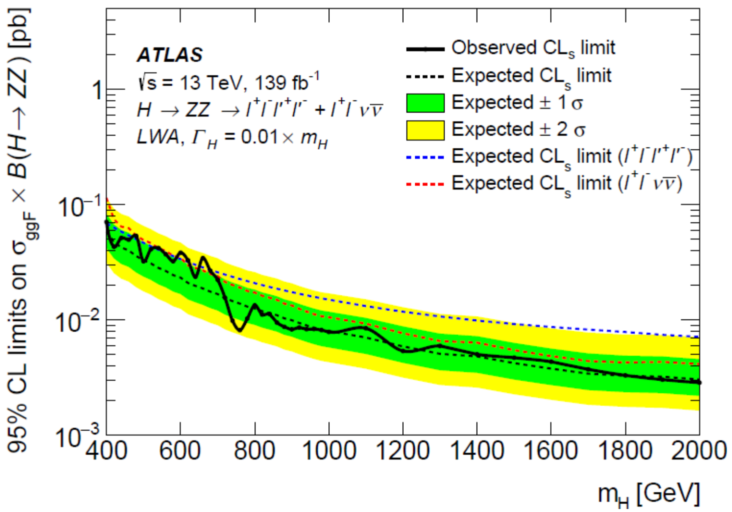


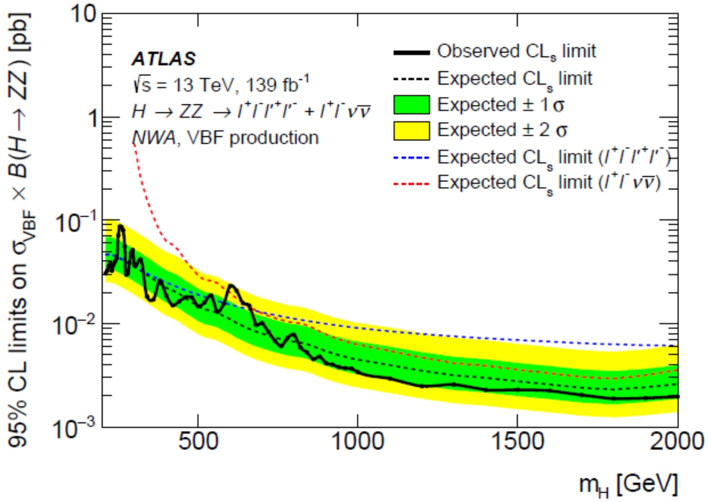


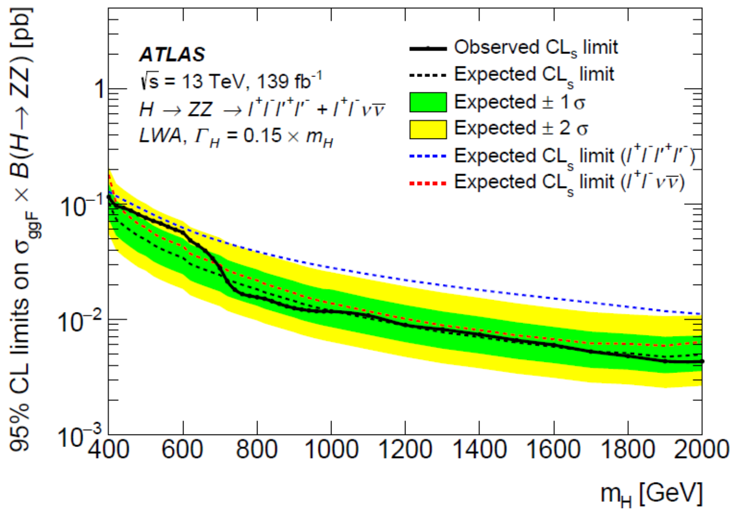
Exclusion limits

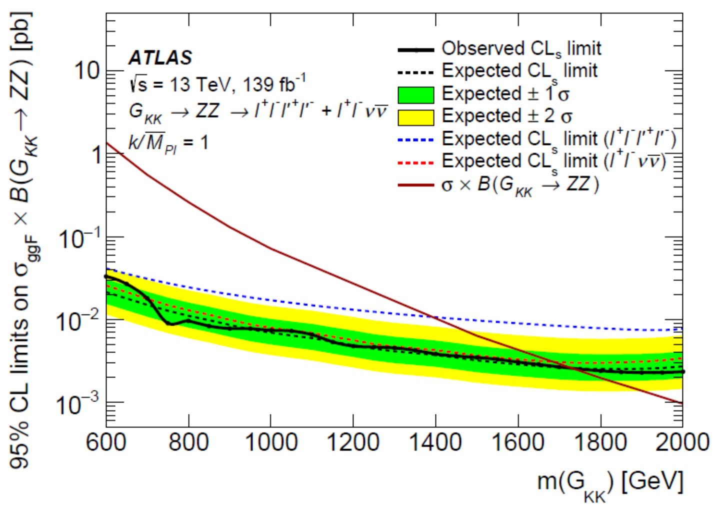
- **4l combined with 2l2ν to increase sensitivity**
- **Narrow width Higgs-like – Large width Higgs-like – Graviton**











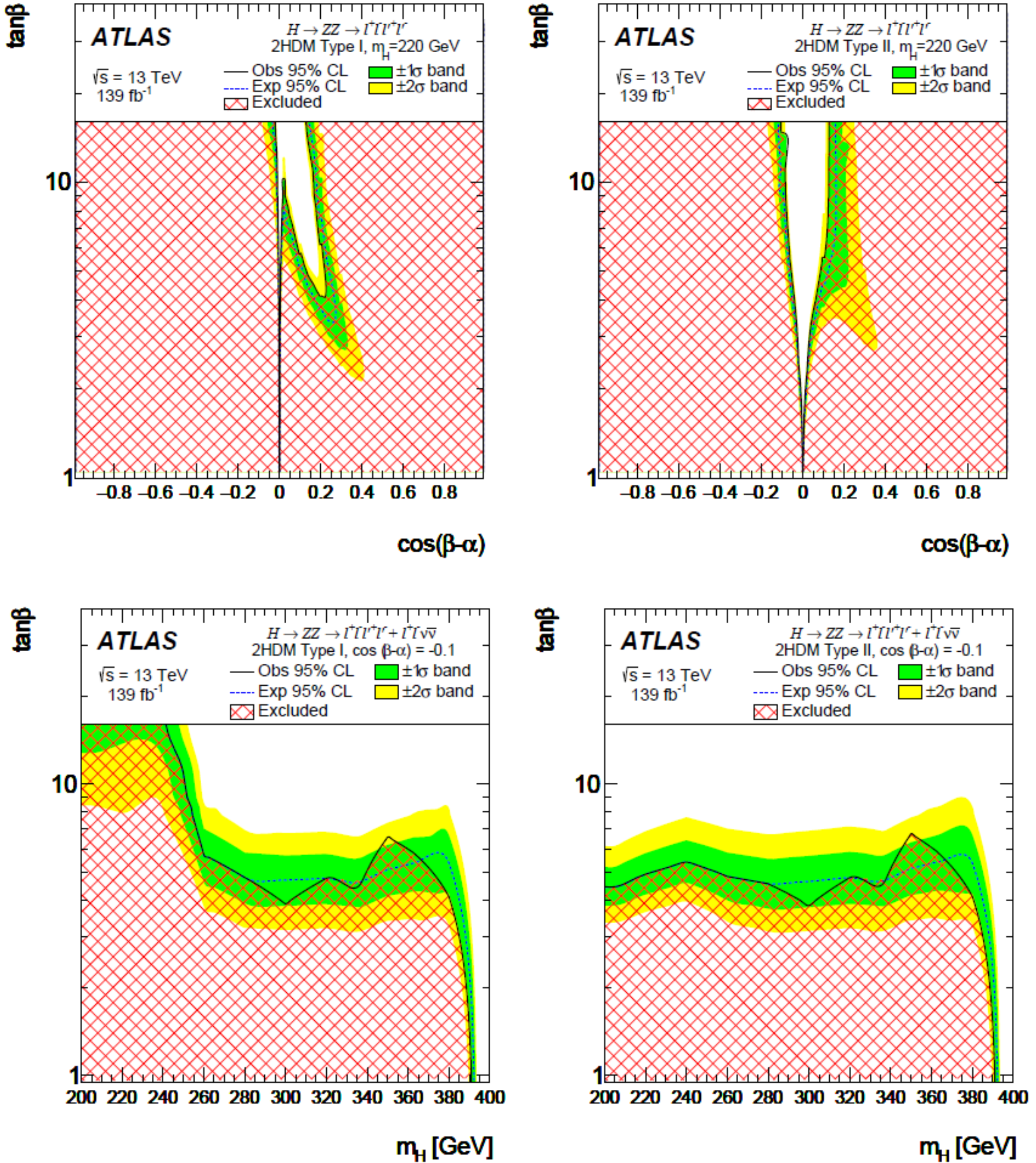
arXiv:2009.14791

Interpretations

- **A CP-conserving 2HDM predicts 5 Higgs bosons**

- **Some of the model free parameters can be constrained**
  - The ratio of the vacuum expectation values of the 2 Higgs doublets (tanβ)
  - The mixing angle between the CP-even Higgs bosons (α)

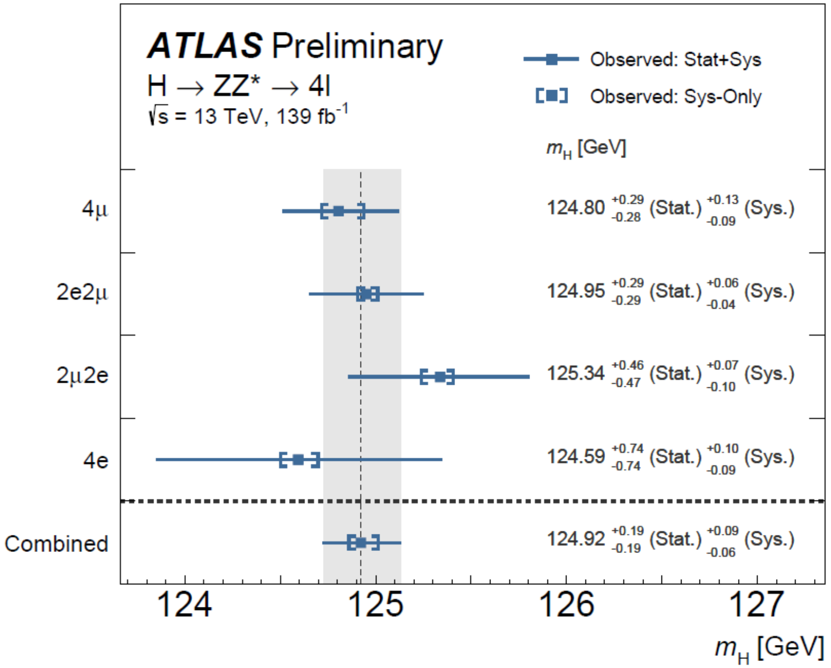
- **2 different Types (I, II) exist depending on Higgs doublets coupling to leptons and quarks**



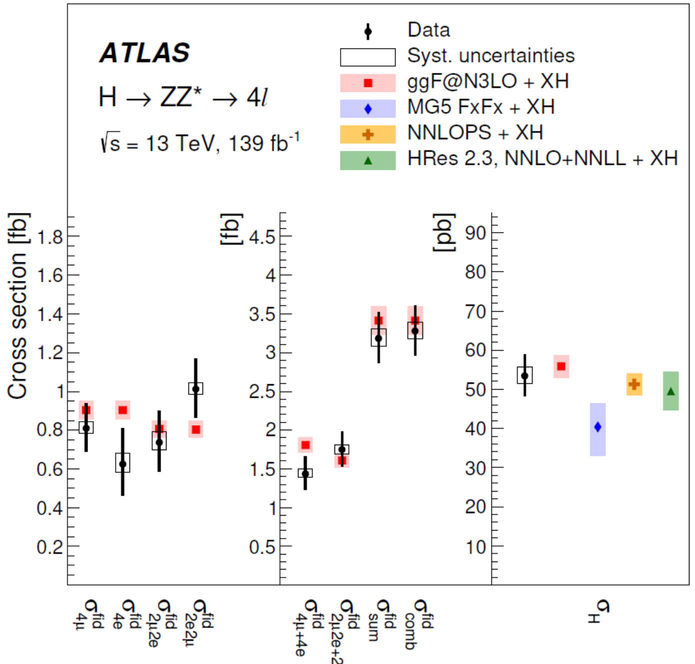
arXiv:2009.14791

Future prospects

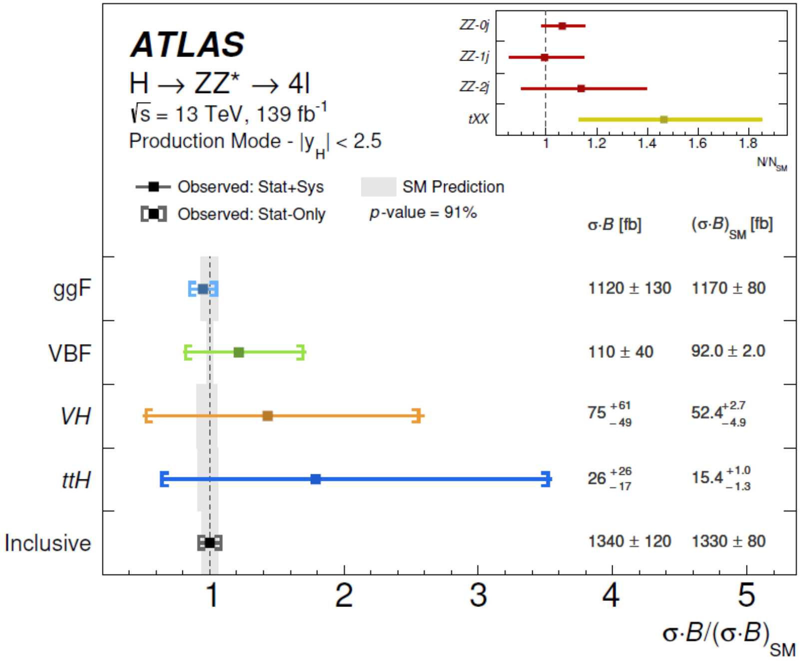
- **Statistical uncertainties still dominant**
- **After run III (300\fb) and run IV (3000/fb) are going to be reduced by a factor of √2 and √20 wrt run I (150 /fb)**
- **Reducing the systematic uncertainties needs better modeling of physics processes (theoretical) and particles-detector interaction (experimental)**



ATLAS-CONF-2020-005



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



Eur. Phys. J. C 80 (2020) 957

Summary

- H4l is a major Higgs channel performing a lot of studies
- All measurements agree with the SM predictions
- More analyses are ongoing
- Our ability for making even more precise measurements is going to improve by
  - Reducing uncertainties
  - Improving analysis techniques
- Run 3 is expected to begin next year and it will lead to more exciting results