

Measurements of the Higgs boson width with the ATLAS detector

H+HH Conference at IHEP

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Introduction

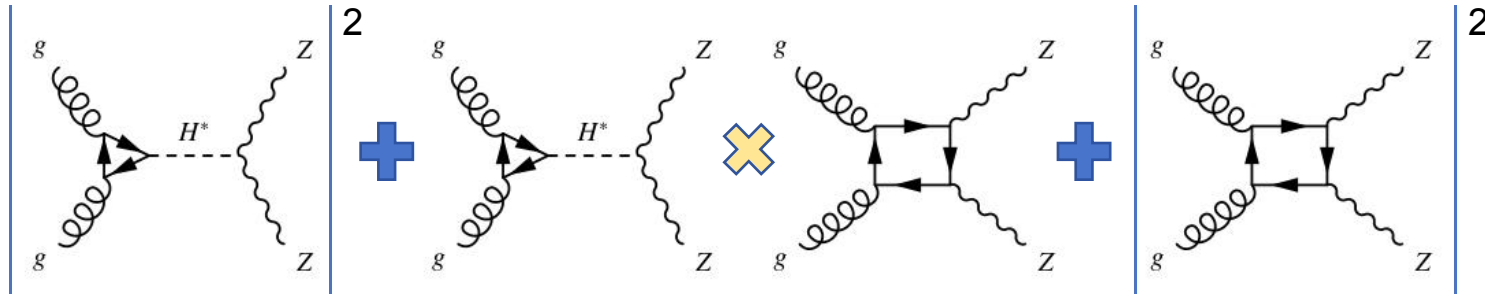
- Higgs width Γ_H : a fundamental parameter that quantifies the intrinsic instability of the Higgs boson.
- **SM prediction**: $\Gamma_{H,SM} = 4.1 \text{ MeV } (\pm 1\%)$;
 - Higgs boson mass $\sim 125 \text{ GeV}$;
 - Including all the **known** decay processes.
- **Why** measure Γ_H ?
 - **SM consistency**: one of the most stringent tests of the theoretical consistency of the Standard Model.
 - **New physics window**: any deviation from the SM prediction could reveal new BSM decays or new interactions modifying Higgs couplings.

Introduction

- **Challenge:** detector resolution $> 1 \text{ GeV} \gg \Gamma_{H,SM} \rightarrow$ an incredibly narrow width.
- Solution: indirect measurement strategy.
 - On-shell Higgs: $\mu_{on-shell} = K_{prod} K_{decay} / (\Gamma_H / \Gamma_{H,SM})$;
 - Off-shell Higgs: $\mu_{off-shell} = K'_{prod} K'_{decay}$;
 - Assumption: $K_{on-shell} = K'_{off-shell}$;
$$\Rightarrow \frac{\mu_{on-shell}}{\mu_{off-shell}} = \frac{\Gamma_{H,SM}}{\Gamma_H}$$

Off-shell process: $gg \rightarrow ZZ$

- $\sigma_{gg \rightarrow (H^* \rightarrow) ZZ}^{SM} = \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{SM} + \sigma_{gg, interference}^{SM} + \sigma_{gg \rightarrow ZZ}^{SM}$



- $\sigma_{gg \rightarrow (H^* \rightarrow) ZZ}^{offshell} = \mu_{offshell} \cdot \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{SM} + \sqrt{\mu_{offshell}} \cdot \sigma_{gg, interference}^{SM} + \sigma_{gg \rightarrow ZZ}^{SM}$

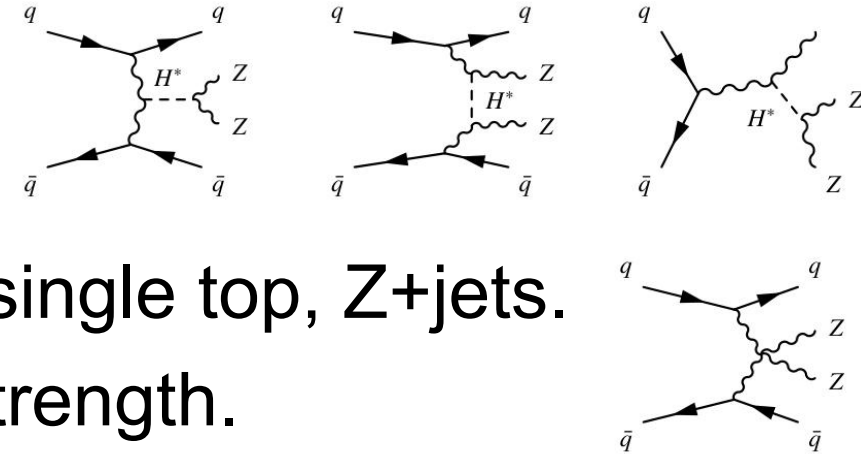
- Rewrite $\sigma_{gg, interference}^{SM} = \sigma_{gg \rightarrow (H^* \rightarrow) ZZ}^{SM} - \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{SM} - \sigma_{gg \rightarrow ZZ}^{SM}$

- $\sigma_{gg \rightarrow (H^* \rightarrow) ZZ}^{offshell} = (\mu_{offshell} - \sqrt{\mu_{offshell}}) \cdot \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{SM}$
 $+ \sqrt{\mu_{offshell}} \cdot \sigma_{gg \rightarrow (H^* \rightarrow) ZZ}^{SM}$
 $+ (1 - \sqrt{\mu_{offshell}}) \cdot \sigma_{gg \rightarrow ZZ}^{SM}$

Difficult to generate MC samples

Off-shell process: EW

- Signal: VBF + VH.
- Background: qqZZ (major), WW/WZ, ttbar, single top, Z+jets.
- EW interference: parameterized by signal strength.



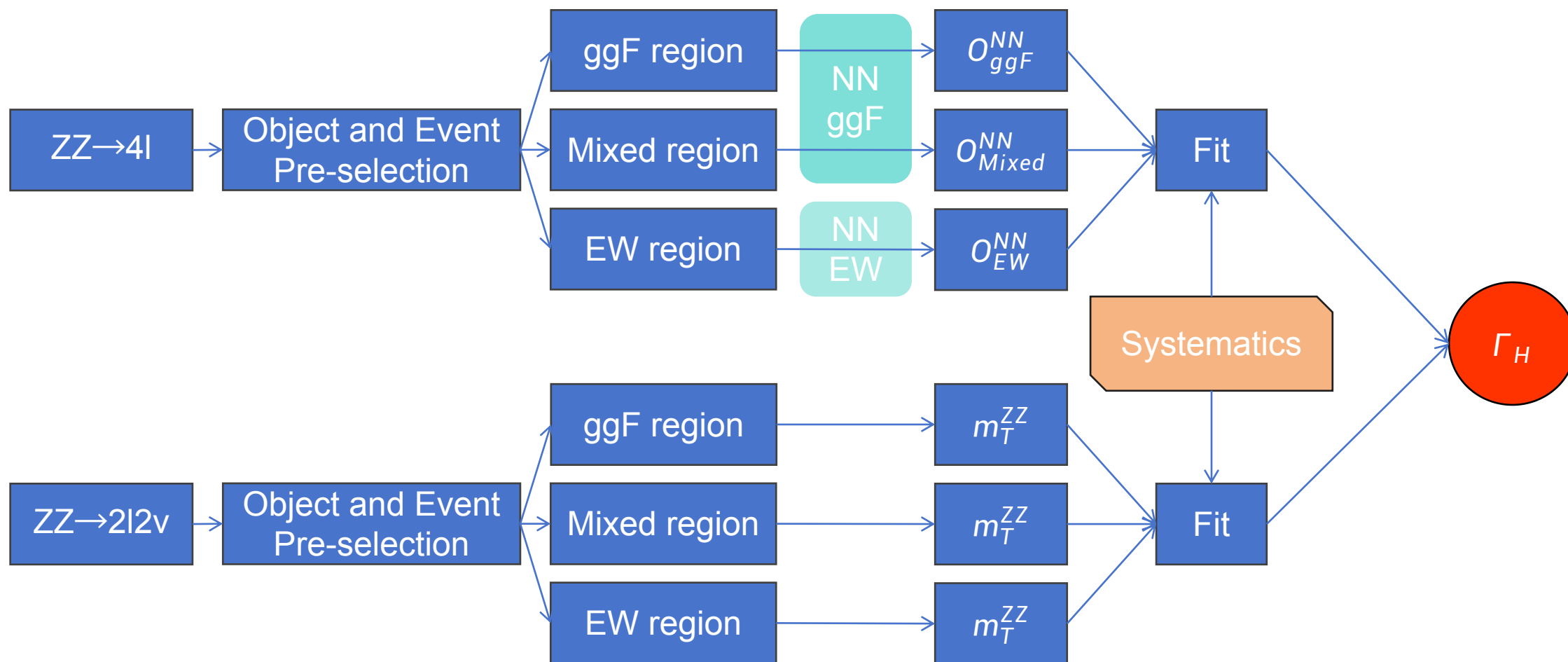
$$\begin{aligned}
 - \sigma_{EW}^{offshell} &= \mu_{offshell} \cdot \sigma_{ppHZZ2j}^{SM} + \sqrt{\mu_{offshell}} \cdot \sigma_{EW,interference}^{SM} + \sigma_{ppZZ2j}^{SM} \\
 \Rightarrow \begin{pmatrix} \sigma_{EW}^{offshell}(\mu_{offshell} = 1) \\ \sigma_{EW}^{offshell}(\mu_{offshell} = 10) \\ \sigma_{EW}^{offshell}(\mu_{offshell} = 0) \end{pmatrix} &= \begin{pmatrix} 1 & 1 & 1 \\ 10 & \sqrt{10} & 1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_{ppHZZ2j}^{SM} \\ \sigma_{EW,interference}^{SM} \\ \sigma_{ppZZ2j}^{SM} \end{pmatrix}
 \end{aligned}$$

- To overcome the difficulty of separating u-channel VBF off-shell production from the VBS background.

Method of histogram (binned likelihood)

arxiv:2304.01532v3

Analysis Strategy Overview

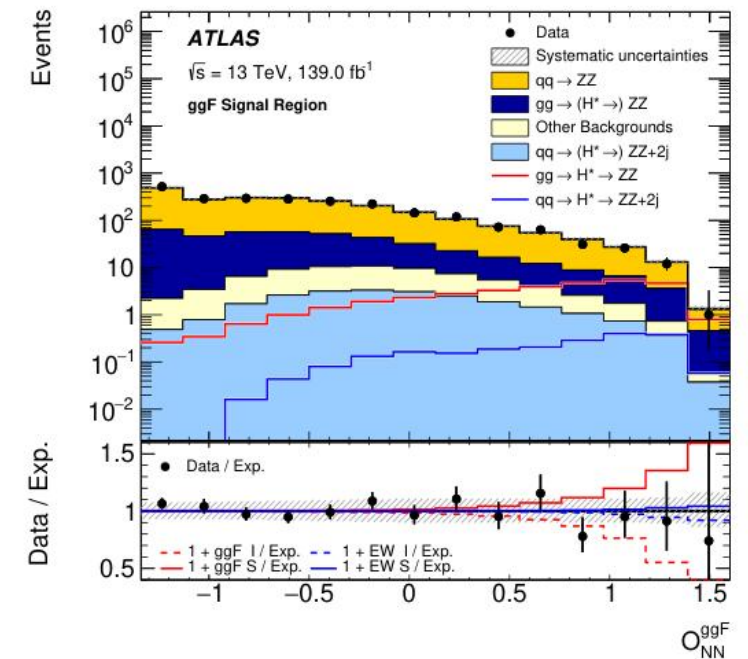
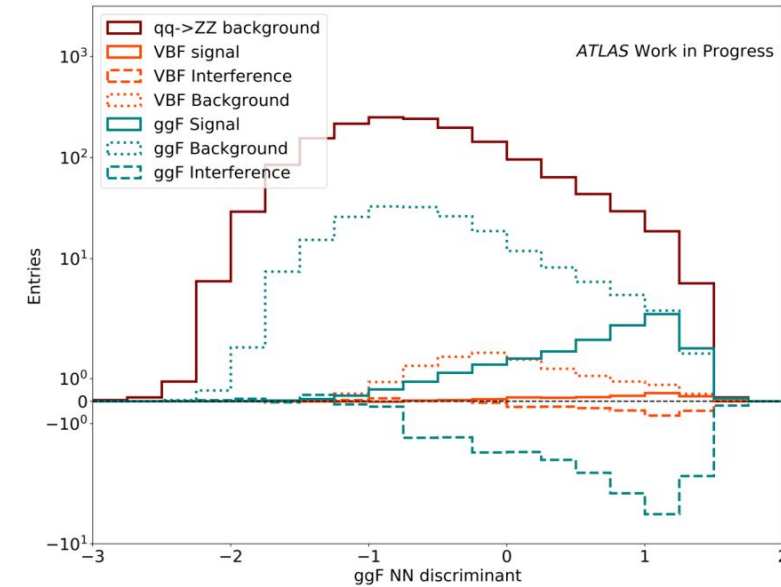


$ZZ \rightarrow 4l$

- Signal region (SR): $220 < m_{4l} < 2000$ GeV;
 - **ggF region**: 0 jet or (1 jet and $|\Delta\eta_{jj}| < 2.2$) or (≥ 2 jets and $|\Delta\eta_{jj}| < 4$);
 - **Mixed region**: 1 jet and $|\Delta\eta_{jj}| > 2.2$;
 - **EW region**: ≥ 2 jets and $|\Delta\eta_{jj}| > 4$.
- Control region (CR): $180 < m_{4l} < 220$ GeV;
 - **CR-I**: 0 jet;
 - **CR-II**: 1 jet;
 - **CR-III**: ≥ 2 jets.

ZZ→4l: NN Training

- NN ggF
 - Trained in 0-jet SR; applied to both **ggF** and **mixed** region.
 - 3 classes and outputs: $P_{ggHZZ}, P_{ggZZ}, P_{q\bar{q}}$.
 - Observable: $O_{ggF(Mixed)}^{NN} = \log_{10} \frac{P_{ggHZZ}}{P_{ggZZ} + P_{q\bar{q}}}$.
- NN EW
 - Trained in ≥ 2 jets SR; applied only to **EW** region.
 - 3 classes and outputs: $P_{VBFH}, P_{q\bar{q}EW}, P_{q\bar{q}QCD}$.
 - Observable: $O_{EW}^{NN} = \log_{10} \frac{P_{VBFH}}{P_{q\bar{q}EW} + P_{q\bar{q}QCD}}$.



ZZ→2l2ν

- Signal region (SR)

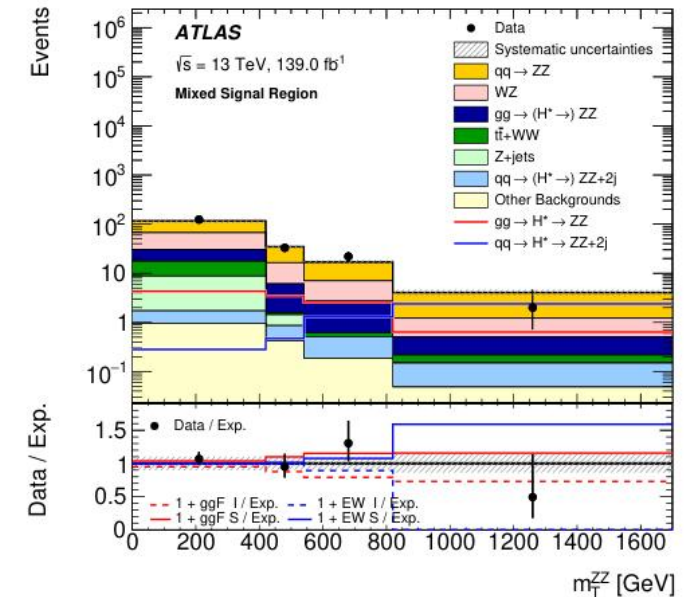
Signal Region	Selection Criteria
ggF	Common selection + excluding events assigned to the EW and Mixed SRs
Mixed	Common selection + 1 jet + $ \Delta\eta_{jj} > 2.2$
EW	Common selection + ≥ 2 jets + $ \Delta\eta_{jj} > 4$

- Control region (CR)

- **WZ CR** 0 jet / 1 jet / ≥ 2 jets;
- **Non-resonant-dilepton CR**;
- **Z+jets CR**.

- Observable: transverse mass of ZZ.

$$(m_T^{ZZ})^2 = \left(\sqrt{m_Z^2 + |\vec{p}_T^{ll}|^2} + \sqrt{m_Z^2 + |\vec{E}_T^{miss}|^2} \right)^2 - (\vec{p}_T^{ll} + \vec{E}_T^{miss})^2$$



Systematic uncertainties

Process	Uncertainty	Final State	Value (%)
ggF Signal Region			
$q\bar{q} \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	4–40
$q\bar{q} \rightarrow ZZ$	QCD Scale	4ℓ	21–28
$q\bar{q} \rightarrow ZZ$	HOEW	4ℓ	1–7
$q\bar{q} \rightarrow ZZ$	HOEW	$2\ell 2\nu$	2–20
$q\bar{q} \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	1–67
$q\bar{q} \rightarrow ZZ + 2j$	Parton Shower	$2\ell 2\nu$	1–33
$q\bar{q} \rightarrow ZZ + 2j$	Parton Shower	4ℓ	2–10
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	8–45
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	6–43
$WZ + 0j$	QCD Scale	$2\ell 2\nu$	1–54
1-jet Signal Region			
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	13–18
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$q\bar{q} \rightarrow ZZ + 2j$	QCD Scale	$2\ell 2\nu$	7–18
$q\bar{q} \rightarrow ZZ + 2j$	QCD Scale	4ℓ	3–10

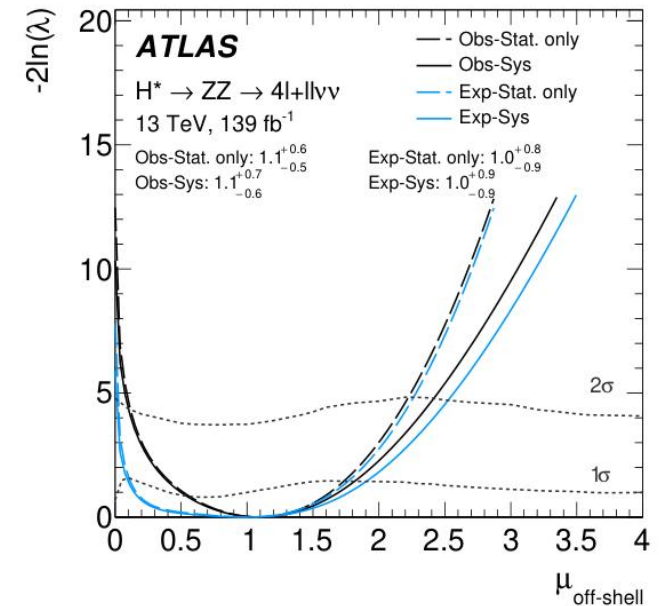
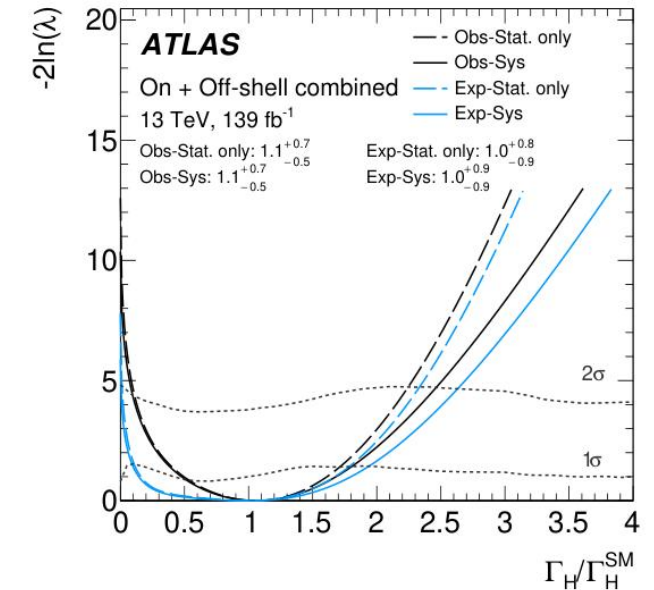
Parton Shower and QCD Scale
dominant the systematic uncertainties!

2-jet Signal Region			
$q\bar{q} \rightarrow ZZ$	QCD Scale	4ℓ	18–26
$q\bar{q} \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	8–32
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	14–18
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	20–22
$q\bar{q} \rightarrow ZZ + 2j$	QCD Scale	4ℓ	8–14
$q\bar{q} \rightarrow ZZ + 2j$	QCD Scale	$2\ell 2\nu$	8–16
$qq \rightarrow ZZ$ Control Regions			
$q\bar{q} \rightarrow ZZ$	QCD Scale	4ℓ	26
Three-lepton Control Regions			
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	28

Results

- Fitting: $\mu_{off-shell} = 1.1^{+0.7}_{-0.6}$, upper limit = 2.4 at 95% CL;
- Observed significance: 3.3σ ;
- Combined with on-shell results $\mu_{on-shell} = 1.01 \pm 0.11$, the width ratio is

$$\Gamma_H/\Gamma_{H,SM} = 1.1^{+0.7}_{-0.5} \Rightarrow \Gamma_H = 4.4^{+3.0}_{-2.2} \text{ MeV}.$$



Method of NSBI (unbinned likelihood)

arxiv:22.01548v2

Neural Simulation-Based Inference (NSBI)

- Traditional ML outputs, e.g. O_{ggF}^{NN} , compresses the info from multi-dimensions to 1 dimension.
- NSBI aims to learn the **per-event density ratio** directly.

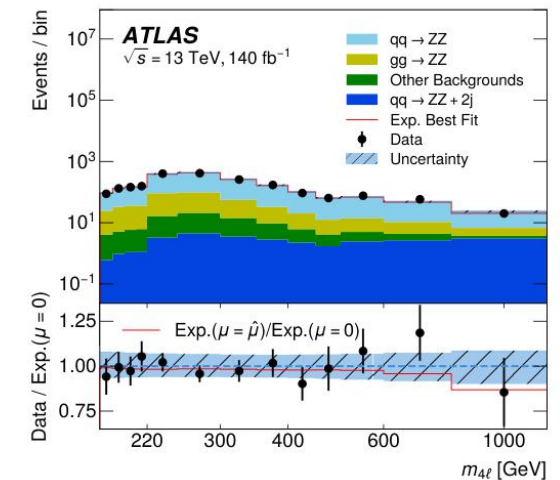
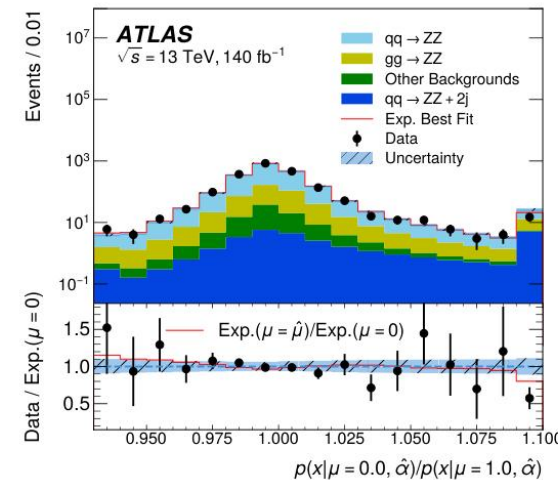
- Using neural network with binary cross entropy,

$$r_X(x) = \frac{p_X(x)}{p_{ref}(x)} = \frac{s_X(x)}{1 - s_X(x)}$$

- Density ratio estimator.
- Perform an unbinned fit.

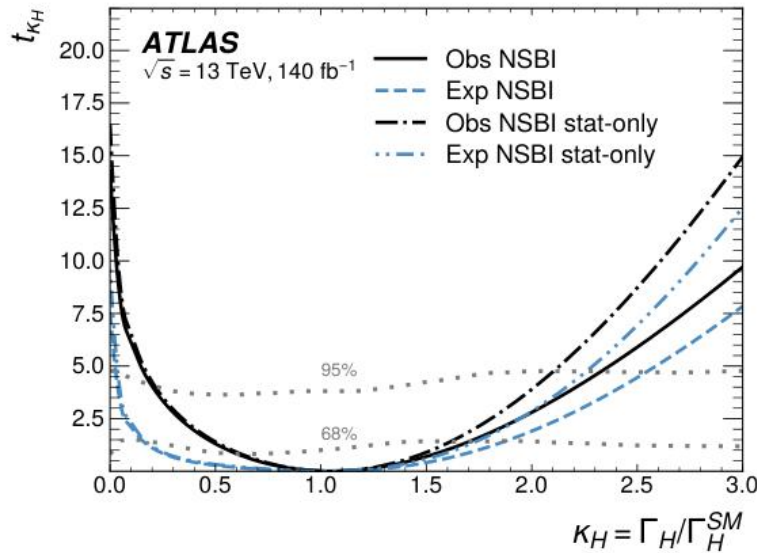
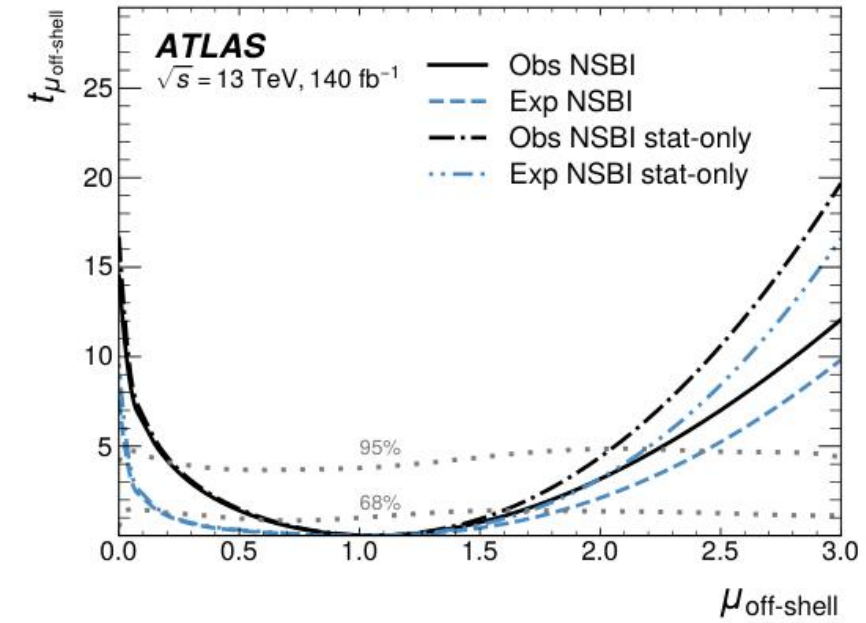
NSBI in Γ_H measurement

- Focus on 4-lepton final state, i.e., $ZZ \rightarrow 4l$.
- SR/CR are given by a 5-class NN observable.
 - 14 input variables; 5 hidden layers; 1000 neurons per layer.
 - 1 SR for ggF and EW, 3 CRs for backgrounds.
- In SR, train NN for each process with different reference.
 - Provide density ratio.
- Construct likelihood function.
- Fit & results.



Results

- Fitting (combined with $ZZ \rightarrow 2l2\nu$):
 - $\mu_{off-shell} = 1.06^{+0.62}_{-0.45}$,
 - upper limit = 2.24 at 95% CL;
- Observed significance: 3.7σ ;



$$\Gamma_H = 4.3^{+2.7}_{-1.9} \text{ MeV.}$$

Method of histogram: $\Gamma_H = 4.4^{+3.0}_{-2.2} \text{ MeV.}$

Summary

Summary

- Higgs width is too small to measure directly using the ATLAS detector.
- Measurement is done indirectly by using off-shell processes.
- Two methods are performed:
 - Both methods show evidence of off-shell Higgs decay to ZZ process;
 - Histogram: Higgs width = $4.4 (+3.0-2.2)$ MeV;
 - NSBI: Higgs width = $4.3 (+2.7-1.9)$ MeV.
- NSBI has a better accuracy, but needs more computing resources.

Future Plan

- Run 3 Higgs width measurement is on-going.
 - NSBI: MPI, U. Mass Amherst, U. Michigan.
 - Histogram: MPI, SDU, USTC.
 - MPI had progress in reproducing the Run 2 results.
- SDU's plan:
 - Push the histogram based result to match the project timeline;
 - Open to contribute to the NSBI studies.

Thank you!

Backup

Object selection

Physics object	Selection / requirement		
Collision vertex	At least one collision vertex associated with at least two tracks, each with $p_T > 0.5$ GeV. The primary vertex (PV) is defined as the vertex with the largest $\sum p_T^2$ of its associated tracks.	Jets	Jets are reconstructed from particle-flow objects using the anti- k_t algorithm with radius parameter $R = 0.4$. Candidate jets are required to have $p_T > 30$ GeV and $ \eta < 4.5$.
Muon	Standard muons: $p_T > 5$ GeV and $ \eta < 2.7$. Standalone muons are allowed in the region $2.5 < \eta < 2.7$. Calorimeter-tagged muons are allowed for $ \eta < 0.1$, with a higher requirement of $p_T > 15$ GeV.	Central pile-up suppression	A jet-vertex tagger is applied to jets with $p_T < 60$ GeV and $ \eta < 2.4$ to suppress pile-up jets.
Muon ID (4ℓ)	“loose” muon identification criterion; at most one standalone or calorimeter-tagged muon is allowed per Higgs boson candidate.	Forward pile-up suppression	A jet-shape and topological-correlation based tagger is applied to jets with $p_T < 50$ GeV and $2.5 < \eta < 4.5$.
Muon ID ($2\ell 2\nu$)	“medium” identification criterion; $ \eta < 2.5$.	b -jet veto	b -jets are identified using a multivariate b -tagging algorithm, and events containing b -jets are rejected. The algorithm has an efficiency of 85% for b -jets and a rejection factor of 33 against light-flavour jets.
Electron	Electrons are reconstructed from energy deposits in the electromagnetic calorimeter matched to an inner-detector track. They are required to have $p_T > 7$ GeV and $ \eta < 2.47$.	Missing transverse momentum	The missing transverse momentum is computed as the negative vector sum of the transverse momenta of all leptons and jets, together with tracks originating from the primary vertex that are not associated with any lepton or jet.
Electron ID (4ℓ)	The “loose” electron identification criterion is required.		
Electron ID ($2\ell 2\nu$)	The “medium” electron identification criterion is required.	Fake E_T^{miss} suppression	The statistical significance $S(E_T^{\text{miss}})$, calculated using the resolution information of the physics objects entering the E_T^{miss} reconstruction, is used to suppress events with fake missing transverse momentum.
Lepton isolation	All electrons and muons must satisfy the FixedCutPFlowLoose isolation criterion.		
Electron impact parameter	$ d_0/\sigma_{d_0} < 5$ and $ z_0 \sin \theta < 0.5$ mm.		
Muon impact parameter	$ d_0/\sigma_{d_0} < 3$ and $ z_0 \sin \theta < 0.5$ mm.		
Lepton separation	Events are rejected if the minimum angular separation between two leptons satisfies $\Delta R_{\ell\ell} < 0.1$, where $\Delta R_{\ell\ell} = \sqrt{(\Delta\phi_{\ell\ell})^2 + (\Delta\eta_{\ell\ell})^2}$.		

Event Pre-selection

Selection	4ℓ	$2\ell 2\nu$
Lepton multiplicity	Four leptons forming two OSSF pairs	Exactly two opposite-sign leptons
Lepton p_T	$p_T^{1,2,3} > 20, 15, 10$ GeV	$p_T^{1,2} > 30, 20$ GeV
Dilepton mass	$50 < m_{12} < 106$ GeV; m_{34} requirement as a function of $m_{4\ell}$	$76 < m_{\ell\ell} < 106$ GeV
Mass requirement	$m_{4\ell} > 180$ GeV	—
Missing transverse momentum	—	$E_T^{\text{miss}} > 120$ GeV
E_T^{miss} significance	—	$S(E_T^{\text{miss}}) > 10$
Lepton topology	$\Delta R_{\ell\ell} > 0.1$	$\Delta R_{\ell\ell} < 1.8$
Dilepton- E_T^{miss} topology	—	$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{\text{miss}}) > 2.5$
Jet- E_T^{miss} topology	—	$\Delta\phi(\vec{p}_T^j, \vec{E}_T^{\text{miss}}) > 0.4$ for $p_T^j > 100$ GeV
b -jet veto	Yes	Yes
SR requirement	$m_{4\ell} > 220$ GeV	Full event selection
SR categorisation	EW / mixed / ggF	EW / mixed / ggF

ZZ4l NN Input Variables: ggF

Input Variable	Motivation
Matrix elements: $\text{ME}_{\text{ggHZZ}}, \text{ME}_{\text{ggZZ}}, \text{ME}_{q\bar{q}}$	Hard scatter information in the centre-of-mass frame of the 4l system
Higgs system: m_{4l}, pT_{4l}	Additional kinematic information from parton shower and hadronization effects
MELA variables: $\cos\theta^*, \cos\theta_1, \cos\theta_2, \phi_1, \phi, m_{Z1}, \text{ and } m_{Z2}$	Hard-scatter information and detector effects

ZZ4l NN Input Variables: EW

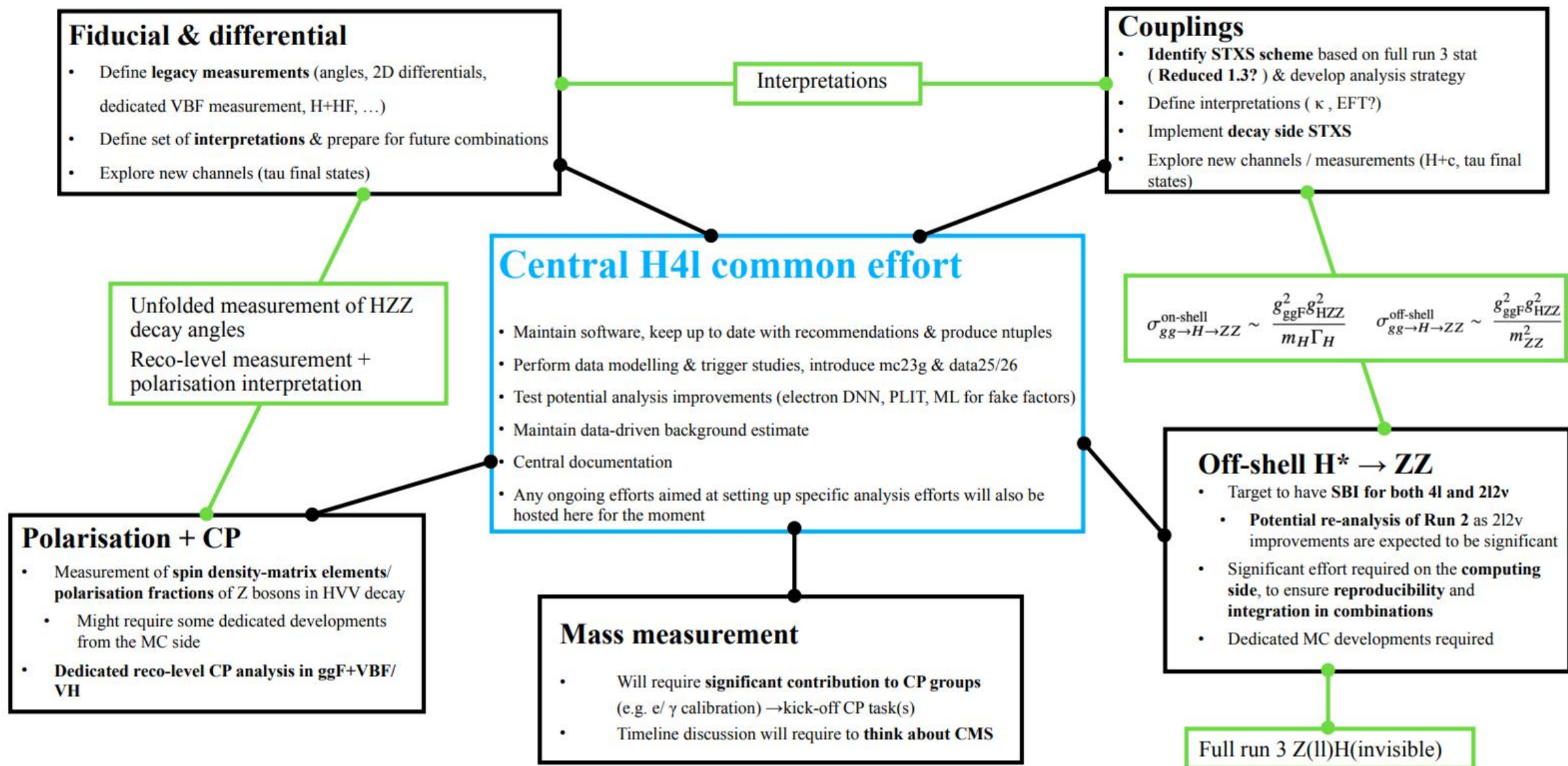
Input Variable	Motivation
Matrix elements: $\text{ME}_{\text{VBFH}}, \text{ME}_{q\bar{q}\text{EW}}, \text{ME}_{q\bar{q}\text{QCD}}$	Hard-scatter information in the centre-of-mass frame of the 4l system
Higgs system: m_{4l}, pT_{4l}	Additional kinematic information from parton shower and hadronization effects
MELA variables: $\cos\theta^*, \cos\theta_1, \cos\theta_2, \phi_1, \phi, m_{Z1}, \text{ and } m_{Z2}$	Hard-scatter information as well as detector effects
Jet variables: $m_{jj}, \phi_{jj},$ $\eta_{\text{Zeppenfeld } 1}, \text{ and } \eta_{\text{Zeppenfeld } 2}$	Additional information about the di-jet system using specifically engineered variables

NSBI likelihood

- For process X , $p_X(x) = r_X(x)p_{ref}(x)$,

$$\Rightarrow p(x|\mu) = \frac{\sum_X v_X(\mu)r_X(\mu)}{v(\mu)}.$$

Therefore, for two processes, μ_1 and μ_0 , the p_{ref} is canceled out in the likelihood ratio, $p(x|\mu_1)/p(x|\mu_0)$.



https://indico.cern.ch/event/1653701/contributions/7174041/attachments/3307187/5917472/26_06_29_RML_H4lPlan_HIGP.pdf