Analysis

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The Higgs boson Width and Off-shell production

- SM Higgs width Γ_H=4.1 MeV $\rightarrow$ experimental resolution O(1-2 GeV) are too small to allow direct measurements

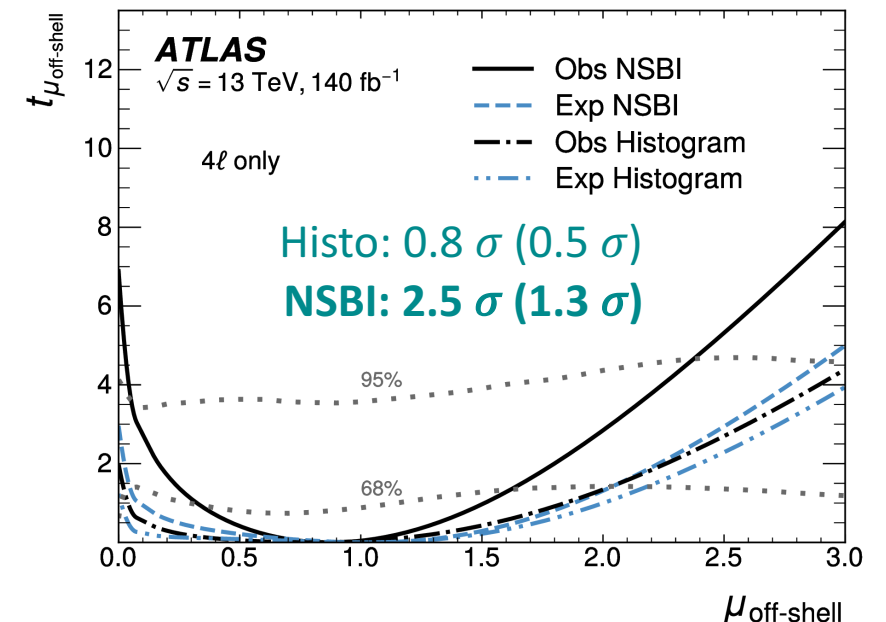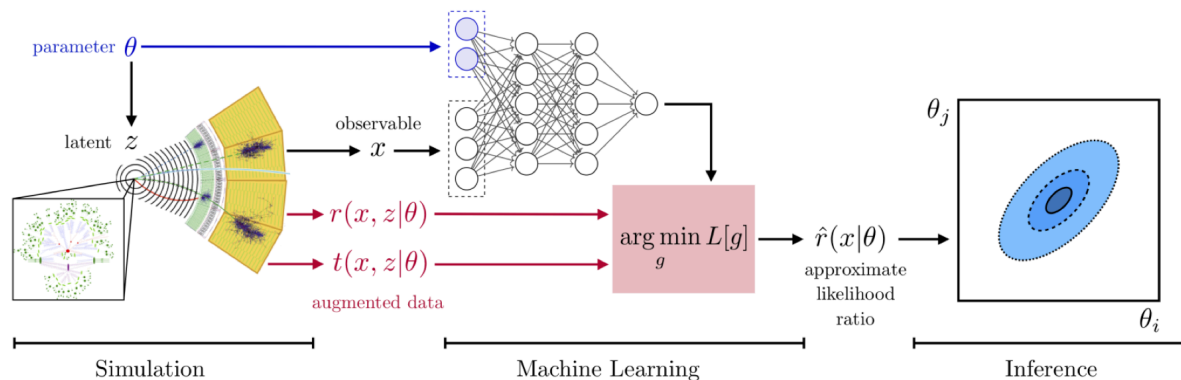- Indirect measurement from the ratio of the on-shell/off-shell Higgs boson production

$$\sigma_{gg \to H \to ZZ}^{\text{on-shell}} \sim \frac{g_{\text{ggH}}^2 g_{\text{HZZ}}^2}{m_H \Gamma_H} \qquad \sigma_{gg \to H \to ZZ}^{\text{off-shell}} \sim \frac{g_{\text{ggH}}^2 g_{\text{HZZ}}^2}{m_{ZZ}^2} \qquad \Longrightarrow \qquad \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

2nd wave of the analysis used the Simulation-based Inference (SBI) method

- SBI provides powerful method for increased sensitivity
- directly approximating relevant likelihood ratios with neural networks
- O(1000) NNs to describe the LL requires lots of GPUs

H$\rightarrow$ZZ*$\rightarrow$ 4l and 2l2ν channels performed this measurements with full Run 2 dataset: Γ_H = 4.3$^{+2.7}_{-1.9}$ MeV @68% C. L.

Evidence of **off-shell** Higgs boson production: $\mu_{\text{off-shell}}$ = 1.06$^{+0.62}_{-0.45}$ (3.7 σ)

Histo: 0.8 σ (0.5 σ)

NSBI: 2.5 σ (1.3 σ)

ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
4ℓ only

Obs NSBI
Exp NSBI
Obs Histogram
Exp Histogram

95%
68%

$t_{\mu_{\text{off-shell}}}$
$\mu_{\text{off-shell}}$

parameter θ
latent z
observable x
$r(x, z|\theta)$
$t(x, z|\theta)$
augmented data
$\arg\min_g L[g]$
$\hat{r}(x|\theta)$
approximate likelihood ratio
θ_j
θ_i

Simulation
Machine Learning
Inference

H→ZZ*→4l differential XS and STXS

First results with partial Run 3 dataset (2022+2023) in this channel for Moriond → Paper planned to include also 2024 data

CONF NOTE results

- Differential observables p_T^H, y_H, N_{jets}, m_{34} → EFT interpretation
- STXS: Stage 0 → κ-framework
- **R&D to include in the paper**
  - *Fake-Factor* method to estimate the reducible background
  - κ_λ interpretation of p_T^H
  - Use of GNN for STXS and decay STXS
  - Additional differential CP-odd sensitive variables for EFT interpretation
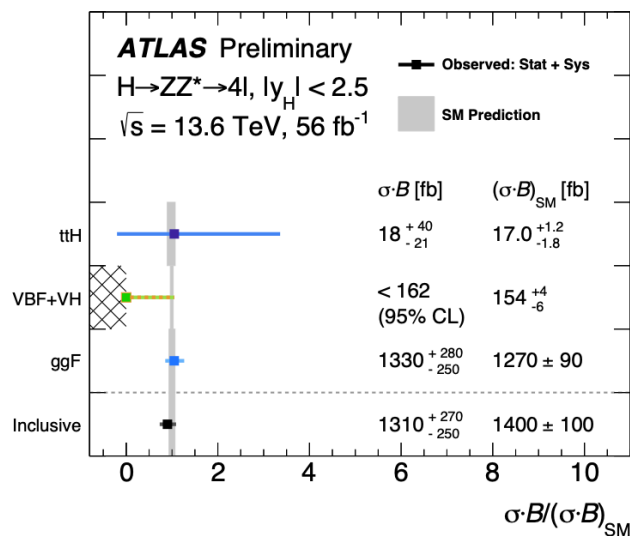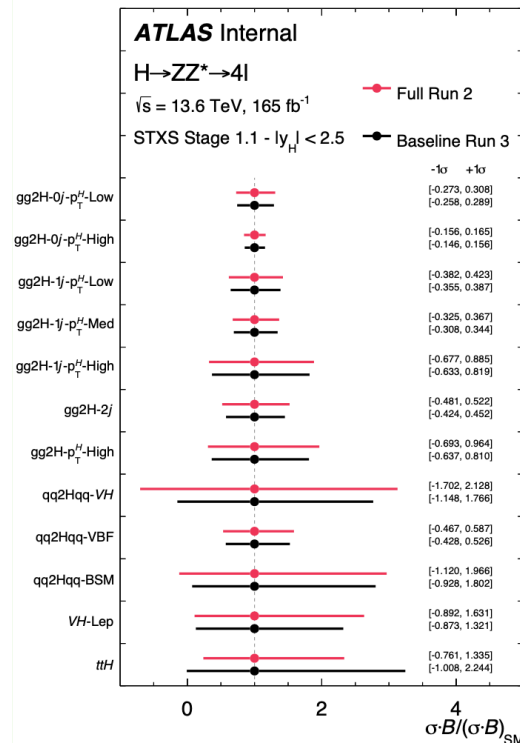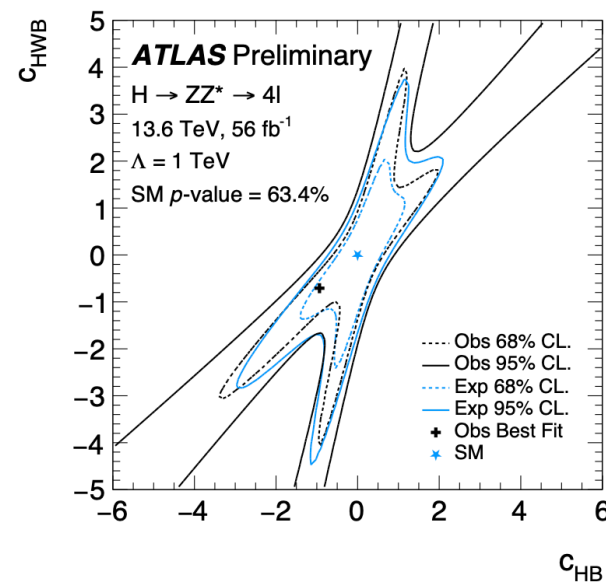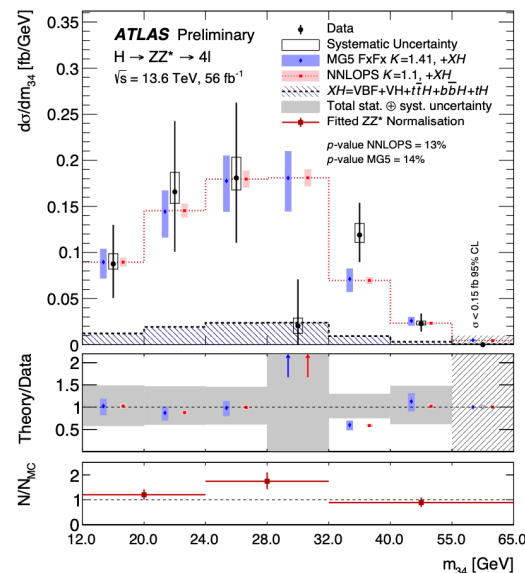
First Run2+Run3 combined result!
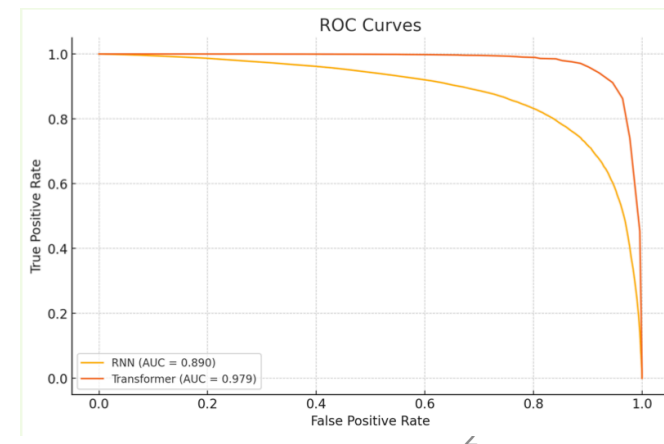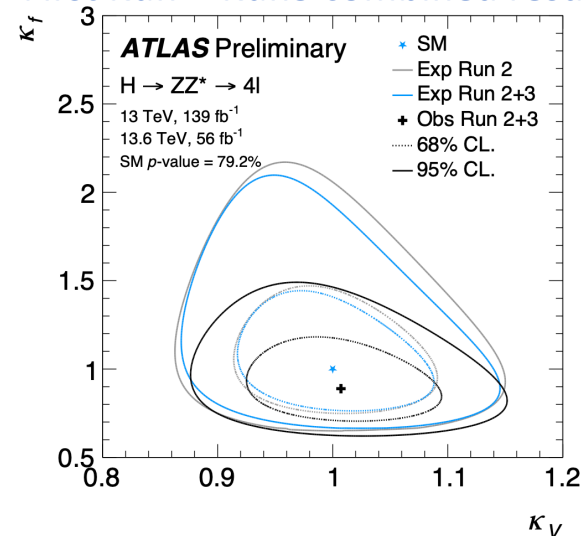
Quantum Entanglement in Higgs

Test the Quantum Entanglement and Bell theorem with Di-boson pairs

- Instead of traditional 'qubits' (0, 1) system test, the VV system provides '*qutrits*' (-1, 0, 1) test!
- (Scalar) Higgs system provides pure state!

What are we going to measure?

H→ZZ* and H→WW* optimizing the analyses on different observables based on the final state

- **H→ZZ*→4l** final state fully reconstructed → **spin density matrix**

  - Peres-Horodecki criterion provides a necessary condition for entanglement (in the ggH system) which, given the form of spin density matrix, translates into: $C_{2,1,2,-1} \neq 0$ or $C_{2,2,2,-2} \neq 0$

  - Hypothesis test longitudinal (non-entangled) vs SM mixture (non-entangled) → **Preliminary sensitivity estimation up to 4.1 σ**

  - Study the impact of EW NLO correction

  - Under EB review
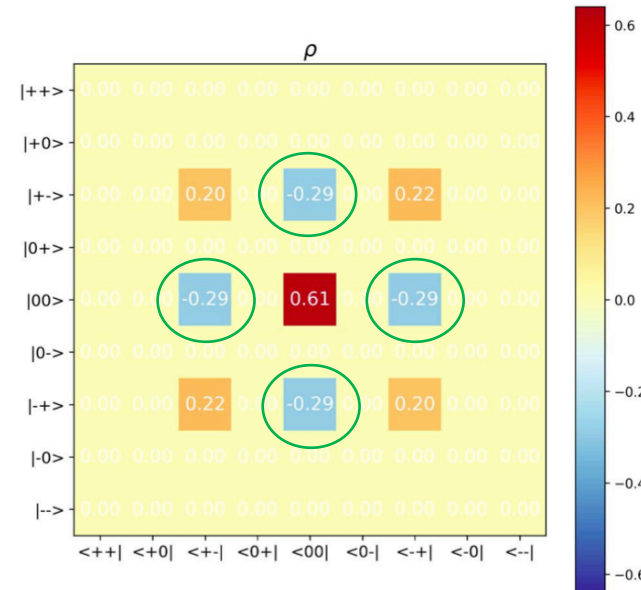
Non-separable state
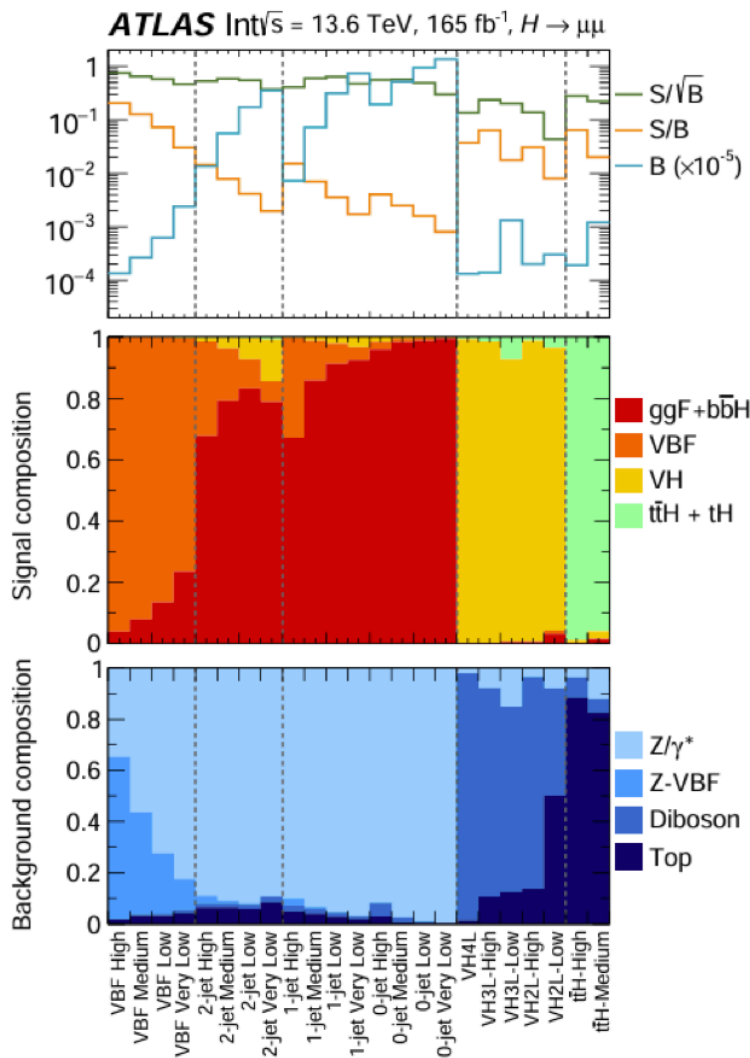
$$\rho_{tot} \neq \sum_n p_n \rho_n^A \otimes \rho_n^B$$

H→μ⁺ μ⁻
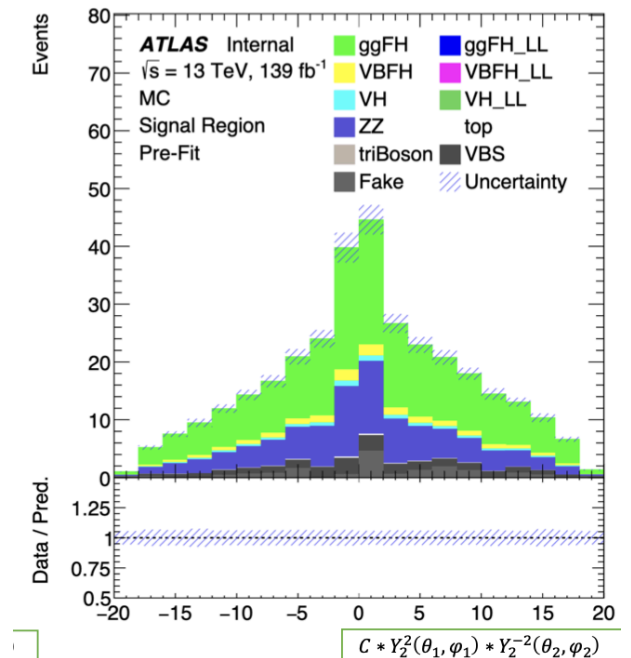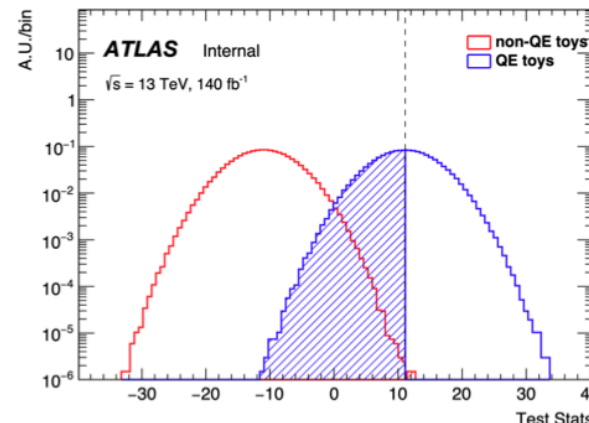
Direct probe of the muon Yukawa coupling

- **First look at $H \to \mu\mu$ in Run 3 data (2022-2024 ~ 165 fb^{-1})** + combination with Run2 (140 fb^{-1})

Analysis Strategy (wrt Run2)

- Require 2 muons: refitting H→μμ primary vertex improved 1.8% mass resolution
- Improved Bkg modelling: include cc and bb contribution and use of FullSim instead of FastSim
- Fit over 23 categories
  - Improved VH categories (+ new VH2l category)
  - Use of NN classifier for ttH category
- Main systematics from bkg modelling (spurious signal)
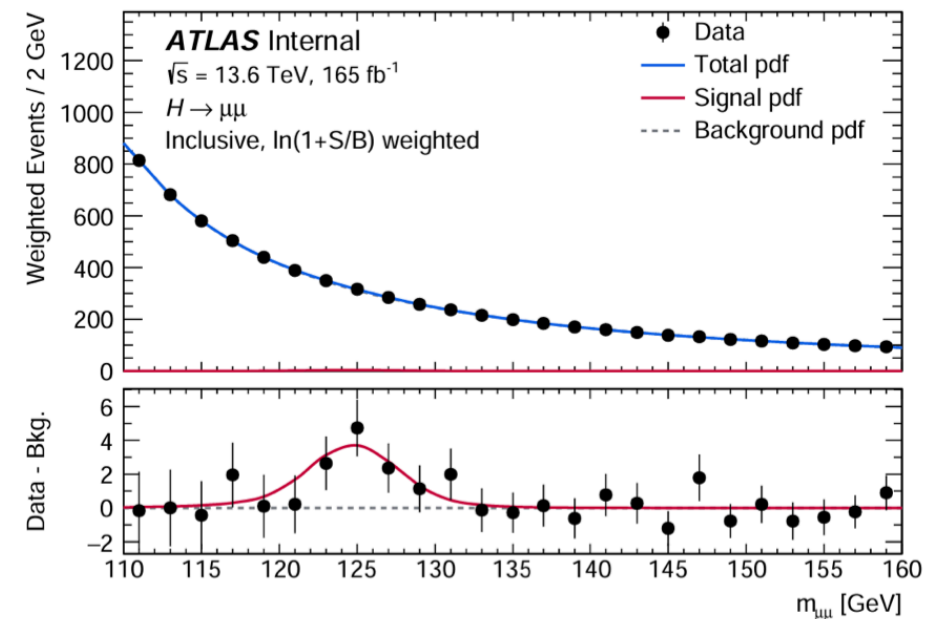
ATLAS first standalone evidence for $H \to \mu\mu$

Observed significance: 3.4σ (exp. 2.5σ)

Best-fit value for the signal strength Run 2+3 combined **μ=1.4±0.4(stat.)±0.1(syst.)**

4

Plans

- On-going analysis with partial Run 3 is differential XS and STXS
  - No real game changer in the strategy, but few ideas that could be tested in view of a final Run 3 publication
  - Timescale super tight (Higgs 2025), no real margin for real innovation

- Coming analyses most probably with full Run 3 dataset
  - Exception for the mass measurement that could be a partial Run 3 one, but not kicked-off yet, so timescale not defined → will be probably a "fast" publication, so *the basic the better*
  - Other analyses that will probably start soon is Offshell measurement using again NSBI method, and ZH->invisible search (just started, no real discussion on doing something new)

- RML (HZZ) is going a bit around with analyses
  - The statistical limit always justify the improvement without a real need of changing the strategies
  - Few ideas of making new measurements (see QE)
  - ML techniques will drive all the future analyses, so need to stay on spot: NSBI raised lots of interest in the community. Interesting idea to study is ML for unfolding → maximise information and much better sensitivity, but what about combination? Are we still interested in doing it?
  - Could be interesting studying new final states? H→WW is going a bit forward in this direction (lvqq, lvcs), but is it worth it for HZZ? Taus inclusion is already under investigation in High-mass search