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NNV section for (astro)particle physics fall meeting - 03/11/23

Probing the Width of the Higgs Boson Through Offshell Decays

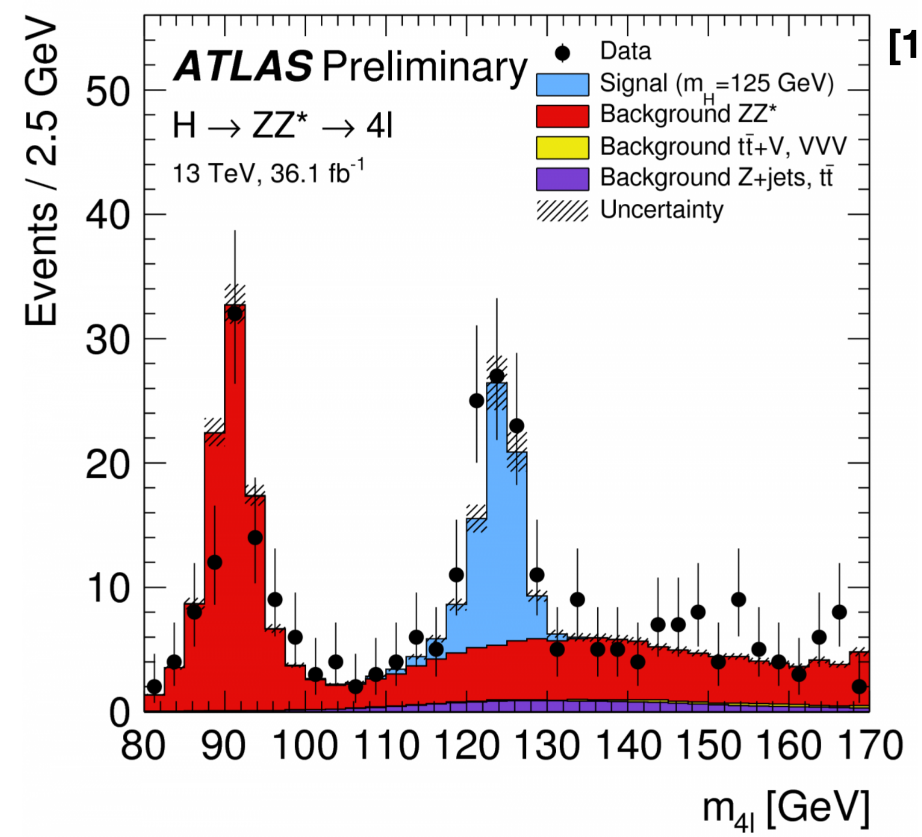
Zef Wolffs

On behalf of the analysis team, including: Bryan Kortman, Matouš Vozák, Ivo van Vulpen, Hella Snoek, Pamela Ferrari, Bob van Eijk

ATLAS EXPERIMENT

General Introduction

- At the LHC, and in particular ATLAS and CMS, we **study the Higgs Boson by colliding protons** at energies high enough to produce the Higgs momentarily



- Just over 10 years ago we managed to find it, both in the ATLAS and CMS experiments, but **large questions about its properties** still remain
  - In this analysis, we aim to answer one such question, namely: **"Can we measure the decay width of this elusive particle?"**
  - Trailer: Yes! Through "offshell" Higgs decays, but it is not trivial

[1] https://atlas.cern/updates/briefing/exploring-higgs-discovery-channels

General Introduction

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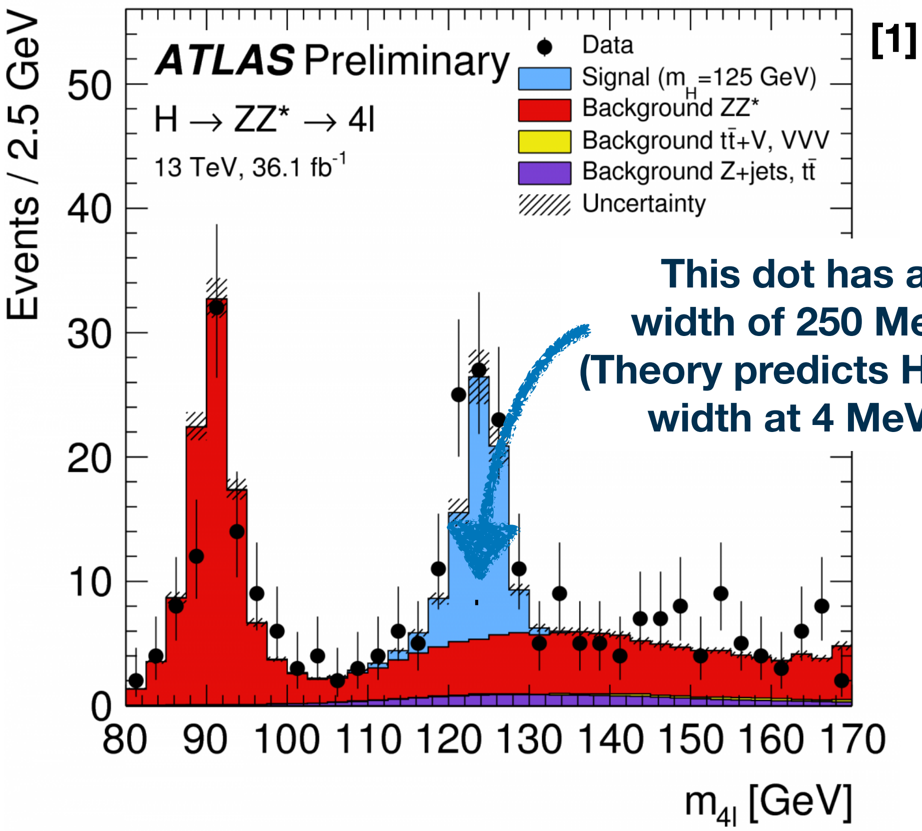

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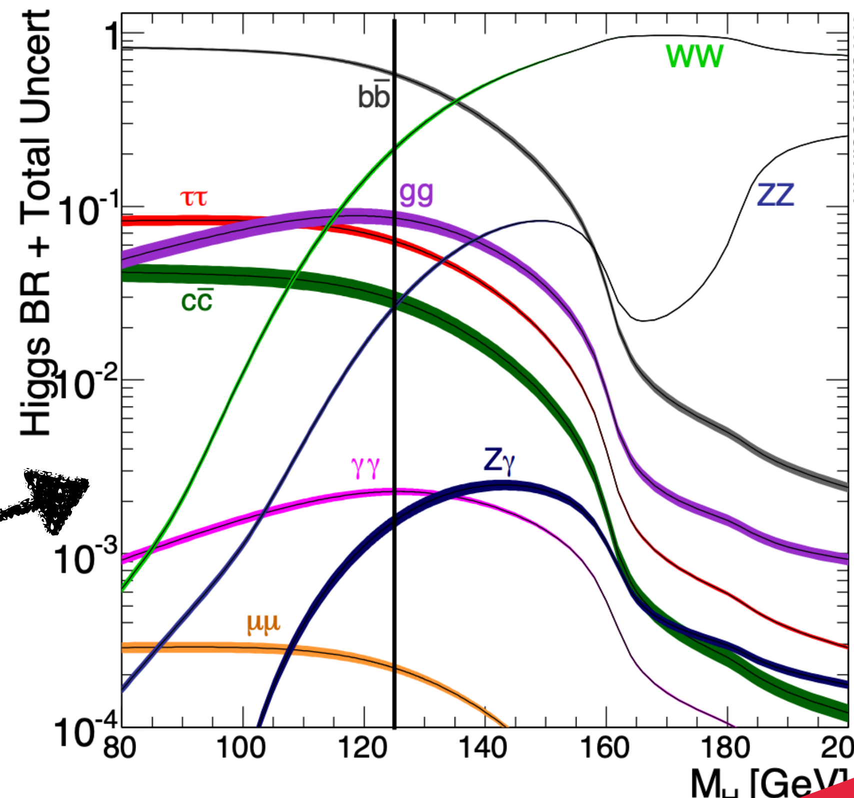
Probing new Physics Through the Width

- While the width of the Higgs is an interesting property to measure in and of itself, this analysis **might also hint towards, or constrain, new physics phenomena**
  - As the only known mechanism to give particles mass, the Higgs should decay into all massive particles, so **new massive particles should affect its total decay width**

$$\Gamma_H^{tot} = \sum_{W,Z}^{V} \Gamma^{H\to VV} + \sum_{u,d,c,s,t,b}^{q} \Gamma^{H\to q\bar{q}} + \sum_{e,\mu,\tau}^{l} \Gamma^{H\to l\bar{l}} + \ldots \Gamma^{H\to NP}?$$

Currently known Higgs decay modes at different energies, could there be more?

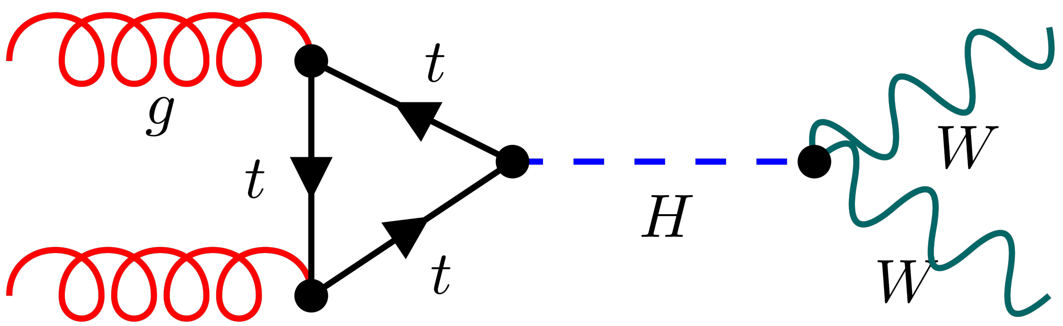


[2]

[2] http://opendata.atlas.cern/books/current/get-started/_book/the-higgs-boson.html

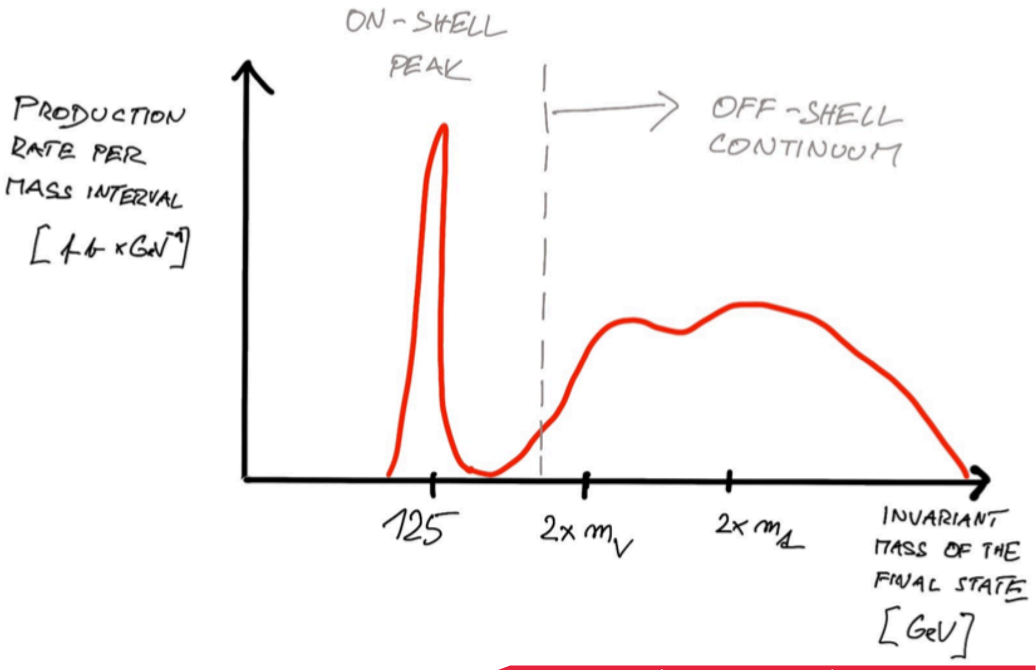
Introduction - Offshell Decays?

- With the collisions of these protons (which consist of gluons for a large part) we **create the Higgs through the following process**, among others



- Due to it being **virtual**, the Higgs does not have to obey the **energy-momentum relation**, and can decay at a higher energy than its pole mass ("offshell")
  - Intuitively, the **Heisenberg uncertainty relation** allows for this brief violation $\Delta t \Delta E \geq \hbar/2$

- The **Breit-Wigner shape of the Higgs** is very narrow
  - The $t\bar{t}$ and WW intermediate states enhance offshell Higgs decay at $2m_t$ and $2m_W$
  - Offshell accounts for $\mathcal{O}(10\%)$ of all $gg \to H$ decays!



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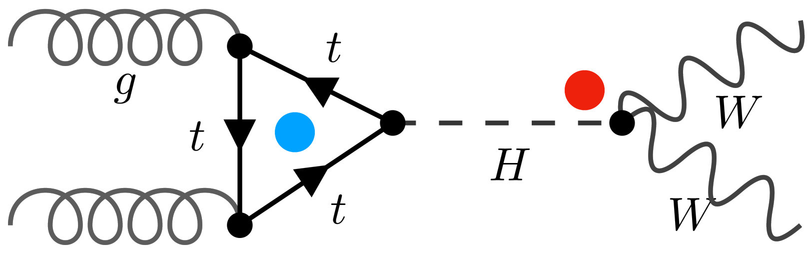
Introduction - Width from Offshell Higgs?

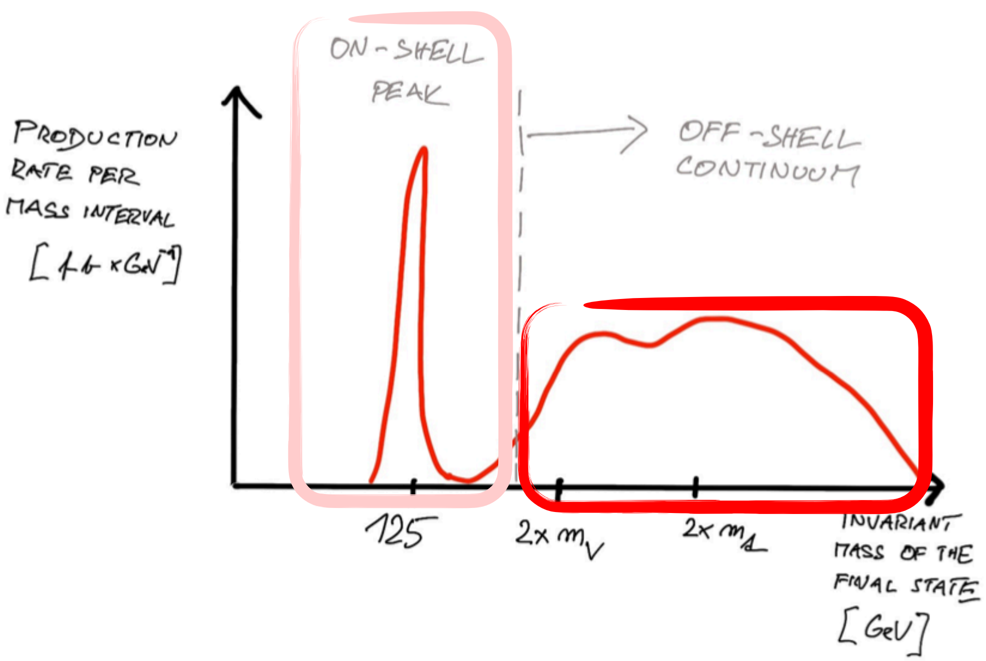
- Now **how do we get the width** from this? Consider cross section of $gg \to H \to WW$



$$\sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{(m_f^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

In the onshell regime ($m_f \approx m_H$) $\quad \sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{m_H^2 \Gamma_H^2}$

In the offshell regime ($m_f \gg m_H$) $\quad \sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{(m_f^2 - m_H^2)^2}$

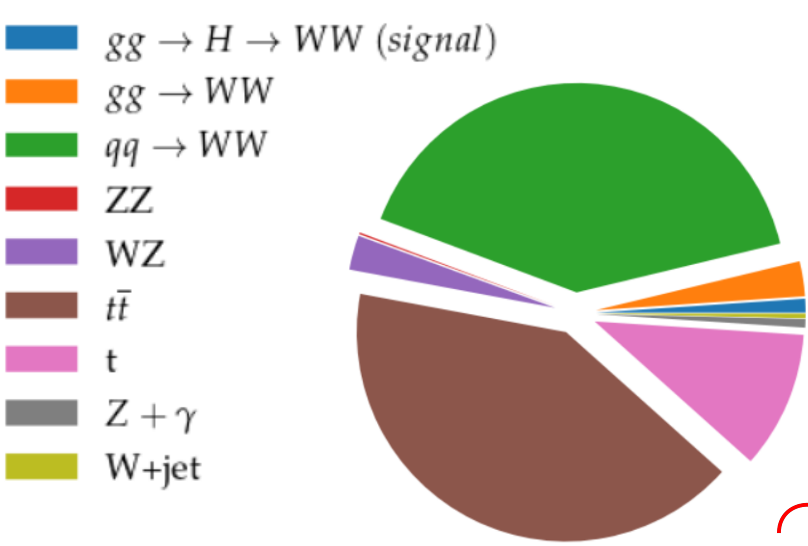


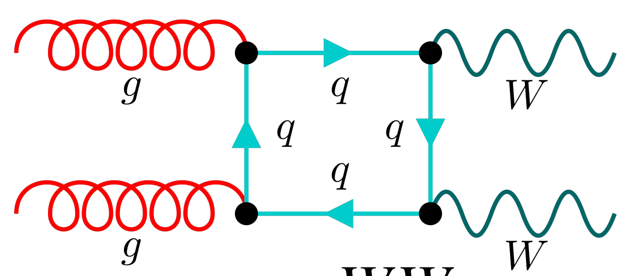
$$\frac{\sigma^{offshell}_{i \to H \to f}}{\sigma^{onshell}_{i \to H \to f}} \propto \Gamma_H$$

Introduction - Quantum Interference

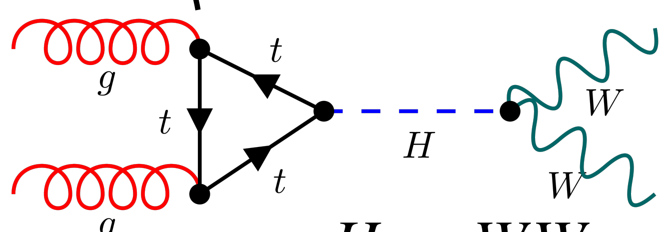
- **One of the major "backgrounds" in this analysis** is $gg \rightarrow WW$ without the Higgs intermediate state
  - **Processes with the same initial and final states exhibit quantum interference** effects
  - In the cross section, i.e. "probability for an interaction to occur", we get

$$\sigma_{gg\to(H\to)WW} \propto |M_{gg\to(H\to)WW}|^2 = |M_{gg\to H\to WW}|^2 + |M_{gg\to WW}|^2 + M_{gg\to H\to WW}M_{gg\to WW}$$

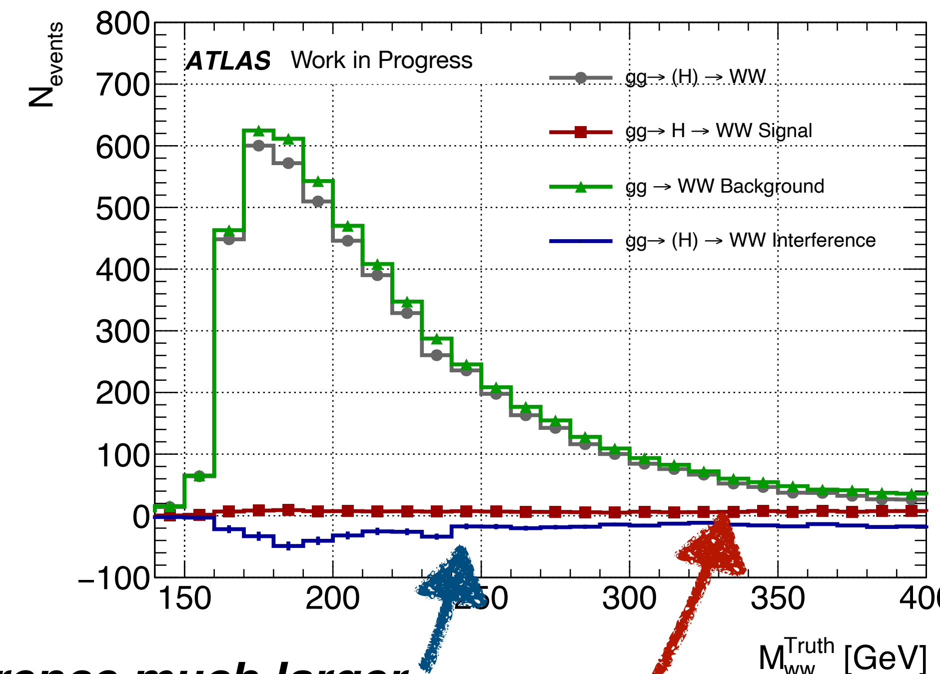




$gg \rightarrow WW$



$gg \rightarrow H \rightarrow WW$



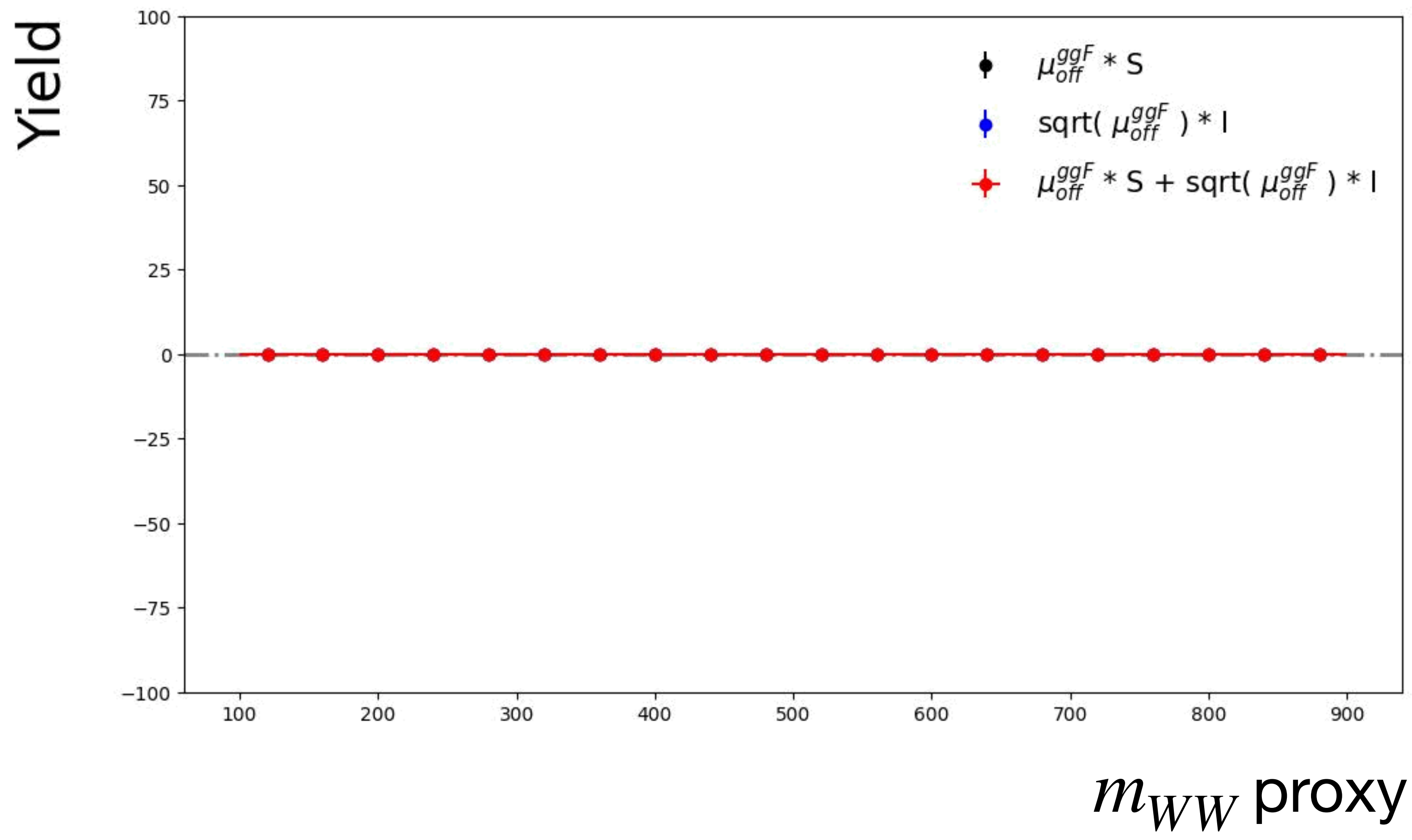
Interference much larger

Actual Higgs signal small

Introduction - Quantum Interference

- We parametrize our analysis using the **offshell signal strength** $\mu_{off} \propto \Gamma_H^{tot}$
- Which tells us our signal strength as a function of **the different contributions**

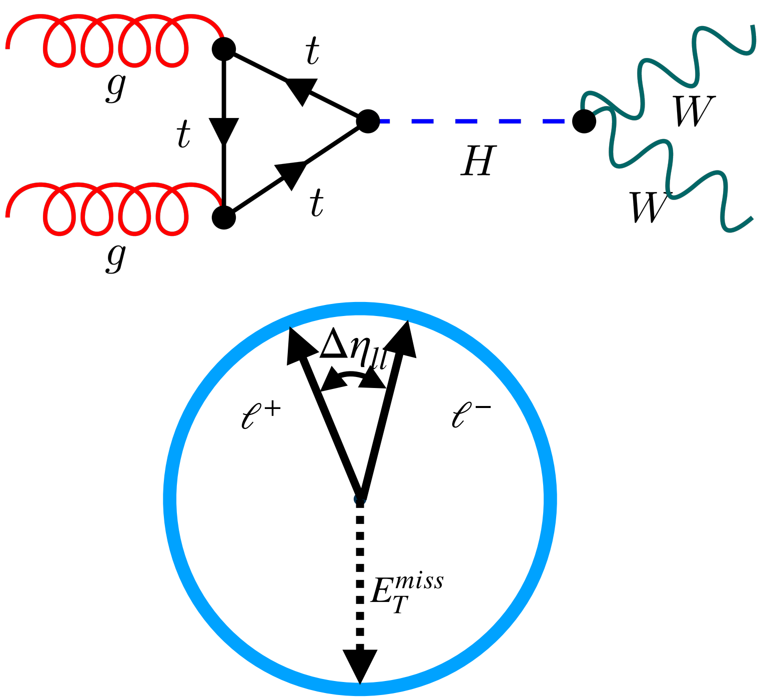
$$\sigma_{gg\to(H\to)WW} = \mu_{offshell}\sigma_S + \sigma_B + \sqrt{\mu_{offshell}}\sigma_I$$



Analysis Strategy

Analysis Topologies

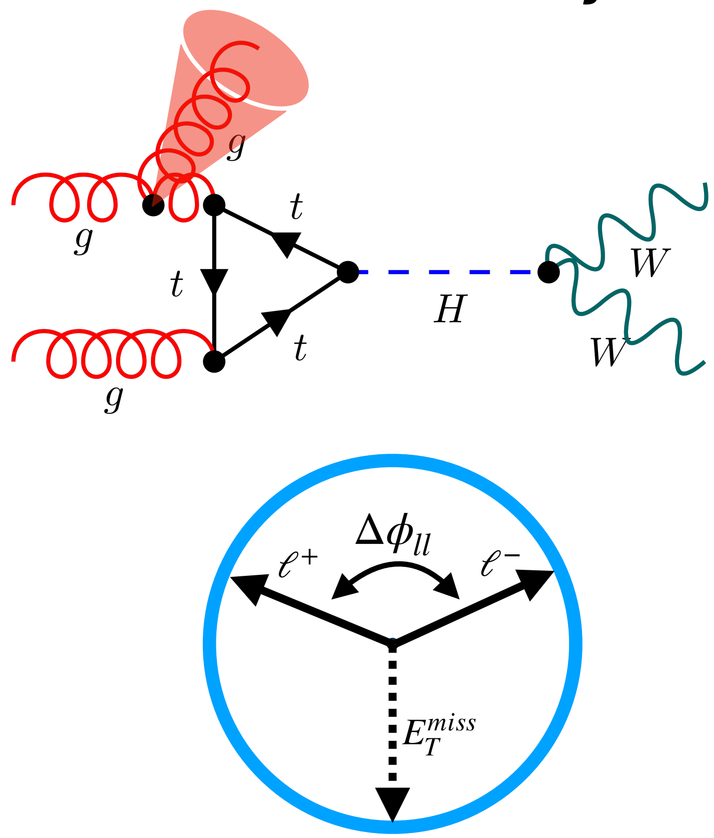
Gluon fusion



$\Delta\eta_{ll} < 1.8$

$n_{jets} = 0$

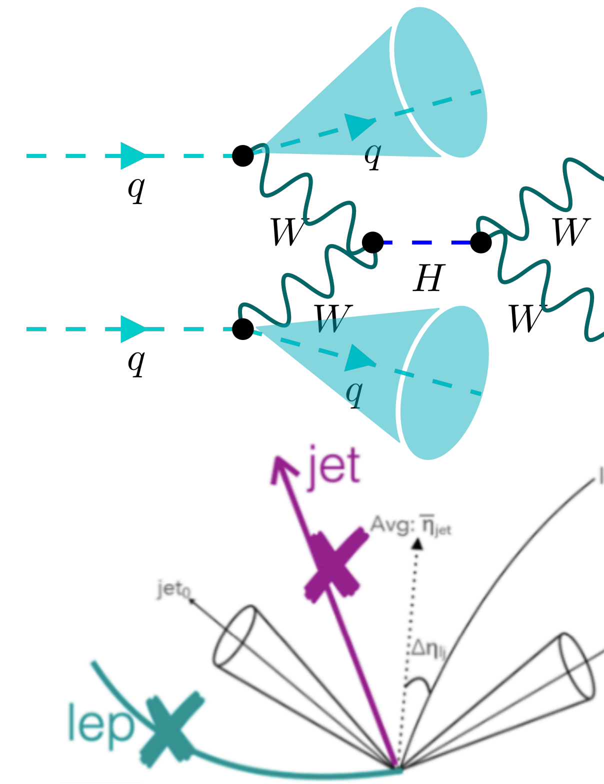
Gluon fusion + 1 jet



$\Delta\phi_{ll} > 1.8$

$n_{jets} = 1$

Vector boson fusion



CJV (Central-jet-veto)

OLV (outside-lepton-veto)

$n_{jets} \geq 2$

- We consider the different flavour ($WW \rightarrow e\nu\mu\nu$) and same flavour ($WW \rightarrow e\nu e\nu/\mu\nu\mu\nu$) decay modes
- This separation helps us isolate specific processes and backgrounds

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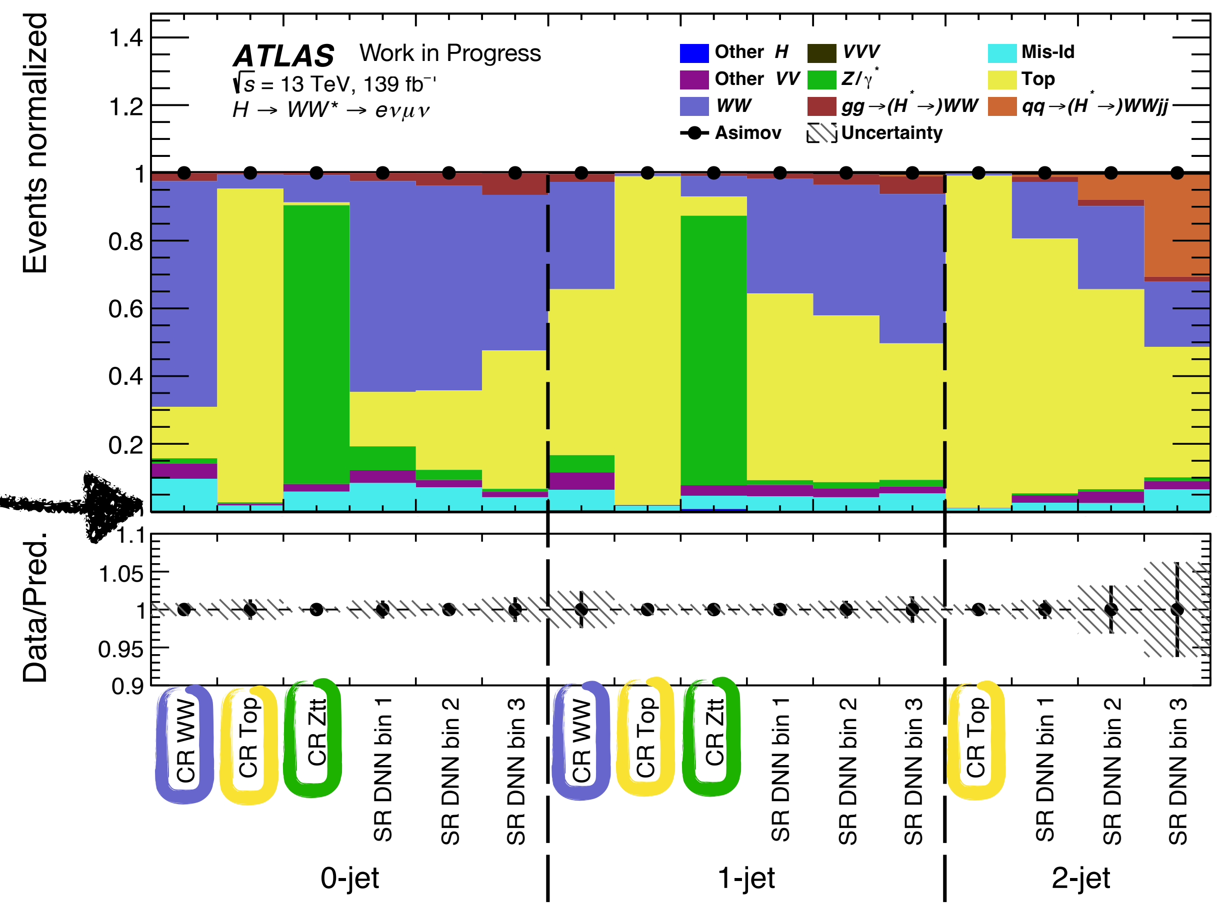
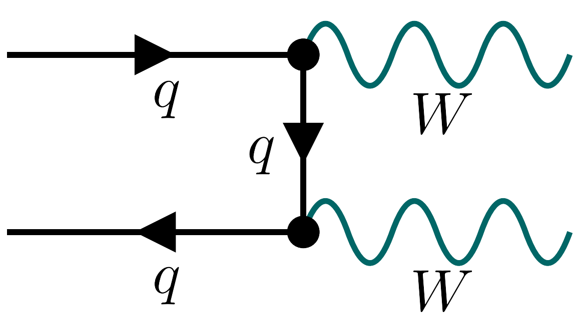
Analysis Composition

We use a data-driven technique for estimating non-prompt leptons



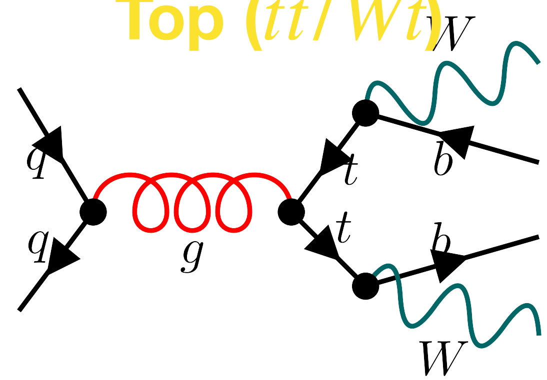
Signal is relatively small even in SR

$qq \to WW$



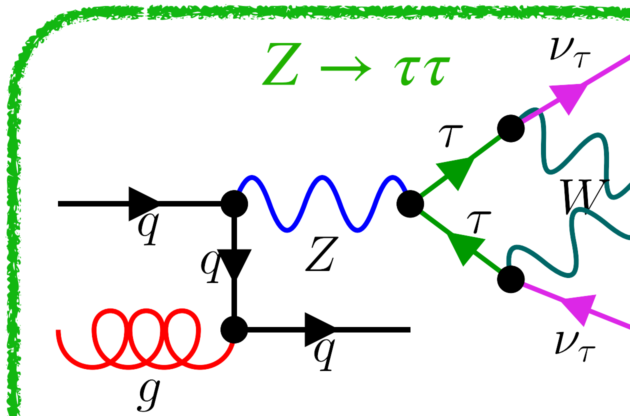
Selected for in CR with $\Delta\eta_{\ell\ell} > 1.8$

Top ($t\bar{t}/Wt$)



Selected for in CR with b-tag

$Z \to \tau\tau$



Selected for in CR with $m_{\ell\ell} < 80$ GeV

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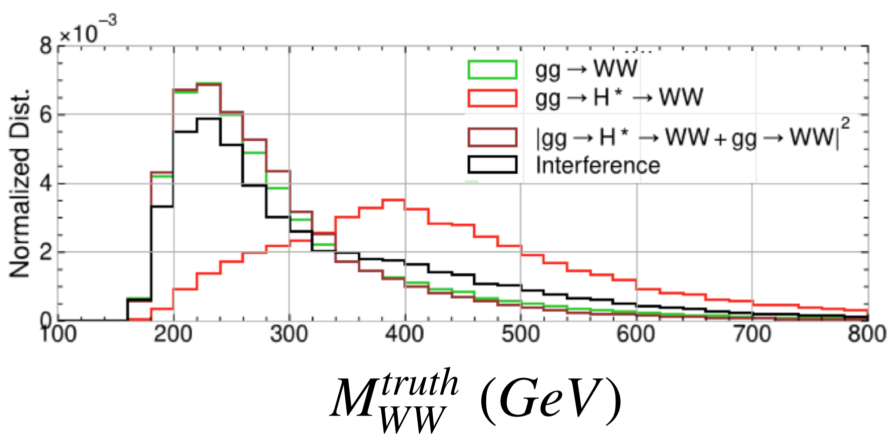
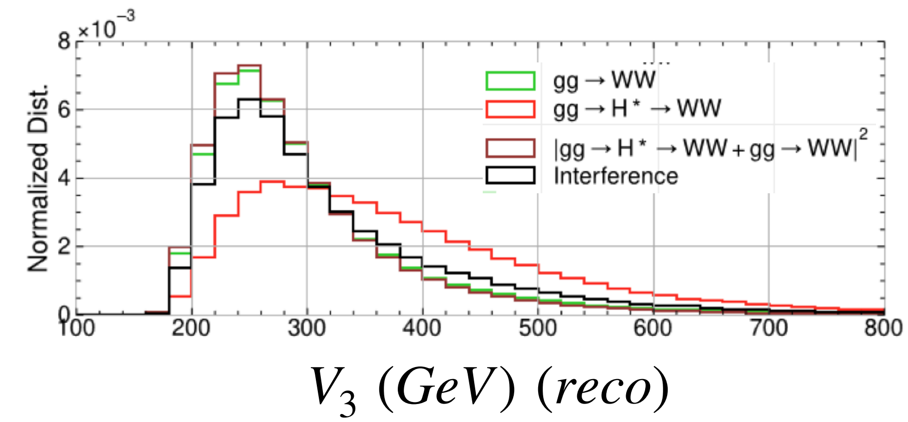
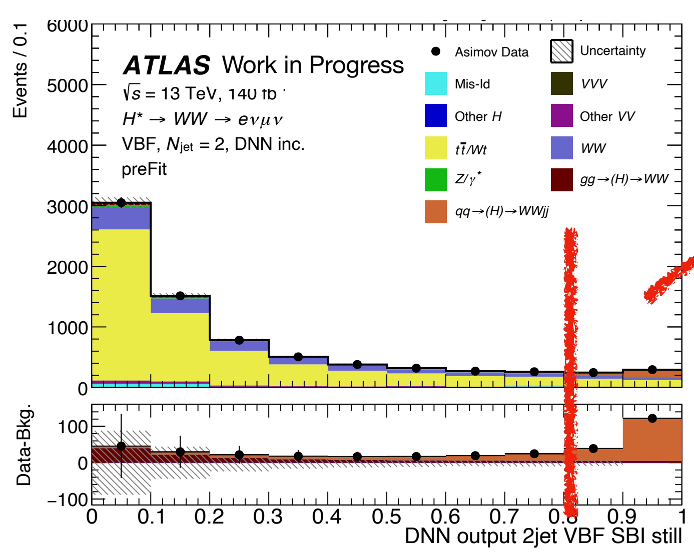
Analysis Optimisation

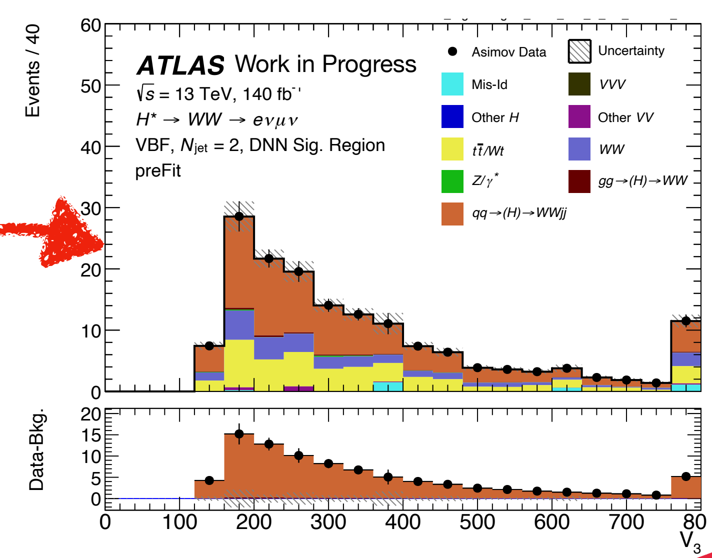
- Cancellation of destructive interference with signal **reduces sensitivity**
  - We need a fitting variable that **discriminates between signal and interference**
- **Mass of WW system** provides this naturally, but since neutrino's cannot be measured in detector, we **cannot fully reconstruct WW mass**
  - Instead, we construct V_3 (=$0.x \times M_{ll} + M_T$), as a proxy to M_{WW}





- We also **train and cut on a DNN** to reduce all other (non-interfering) backgrounds

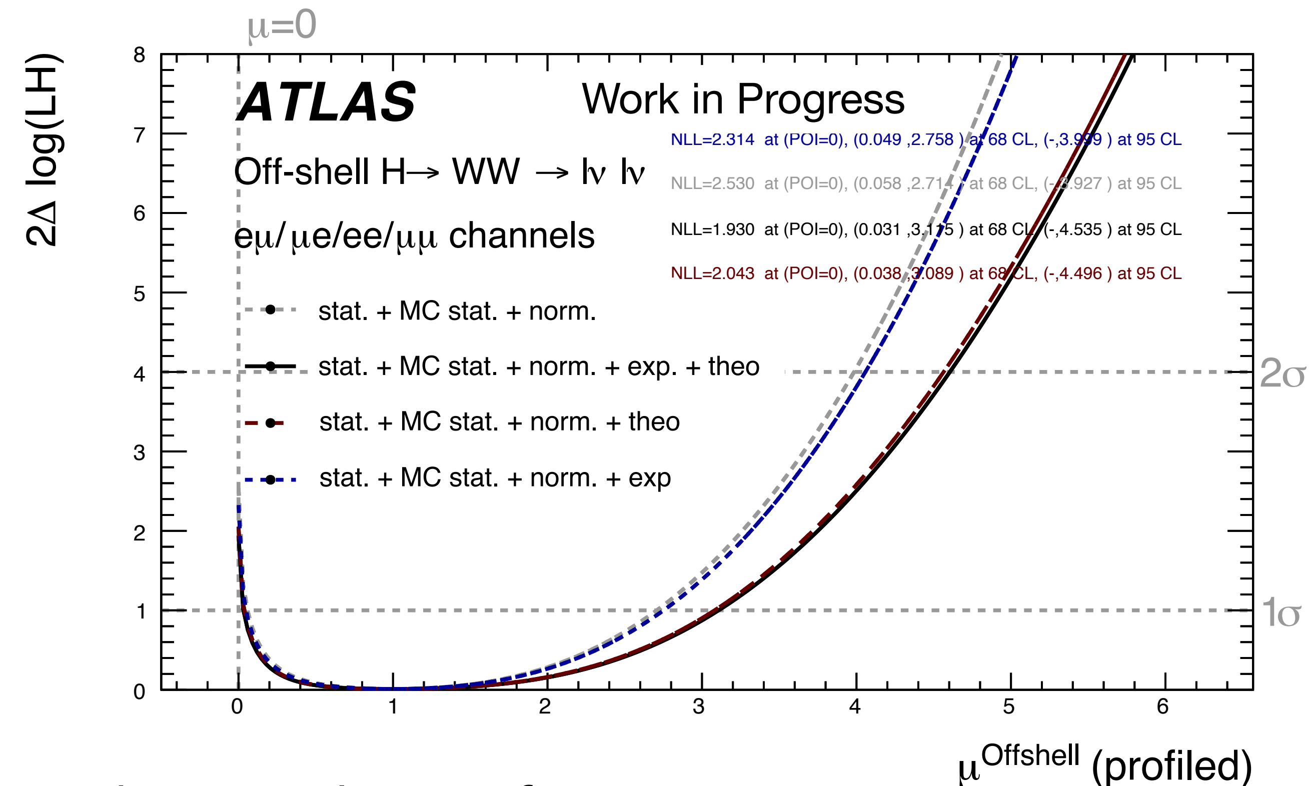




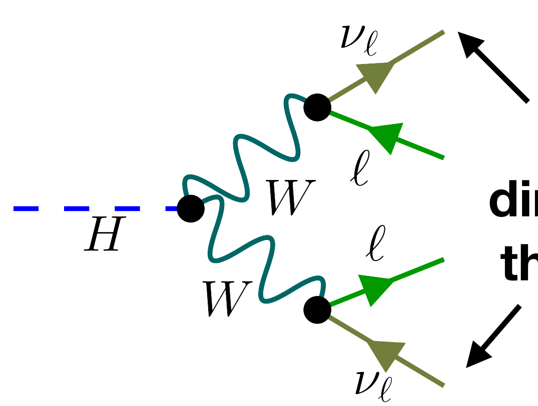
Results

Higgs Offshell Measurement

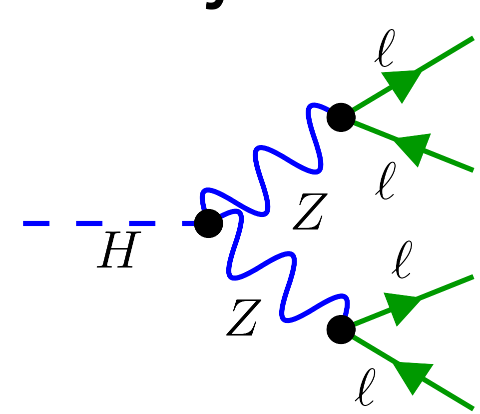
- **We reject the hypothesis that the Higgs does not decay offshell** with an expected significance of 1.4σ
- The **expected upper limit** of μ_{off} is 4.5 at the 95% confidence interval level
  - ATLAS run 1 $H \rightarrow WW$: 20.3



- The $H \rightarrow ZZ$ [3] analysis achieved an expected upper limit of 2.4
  - While the $H \rightarrow WW$ decay mode has a 7 times larger cross section, $H \rightarrow ZZ$ is more sensitive due to having **fully reconstructable final states**
  - This in turn **increases resolution** and **decreases systematic uncertainties**



We cannot directly measure these in ATLAS!



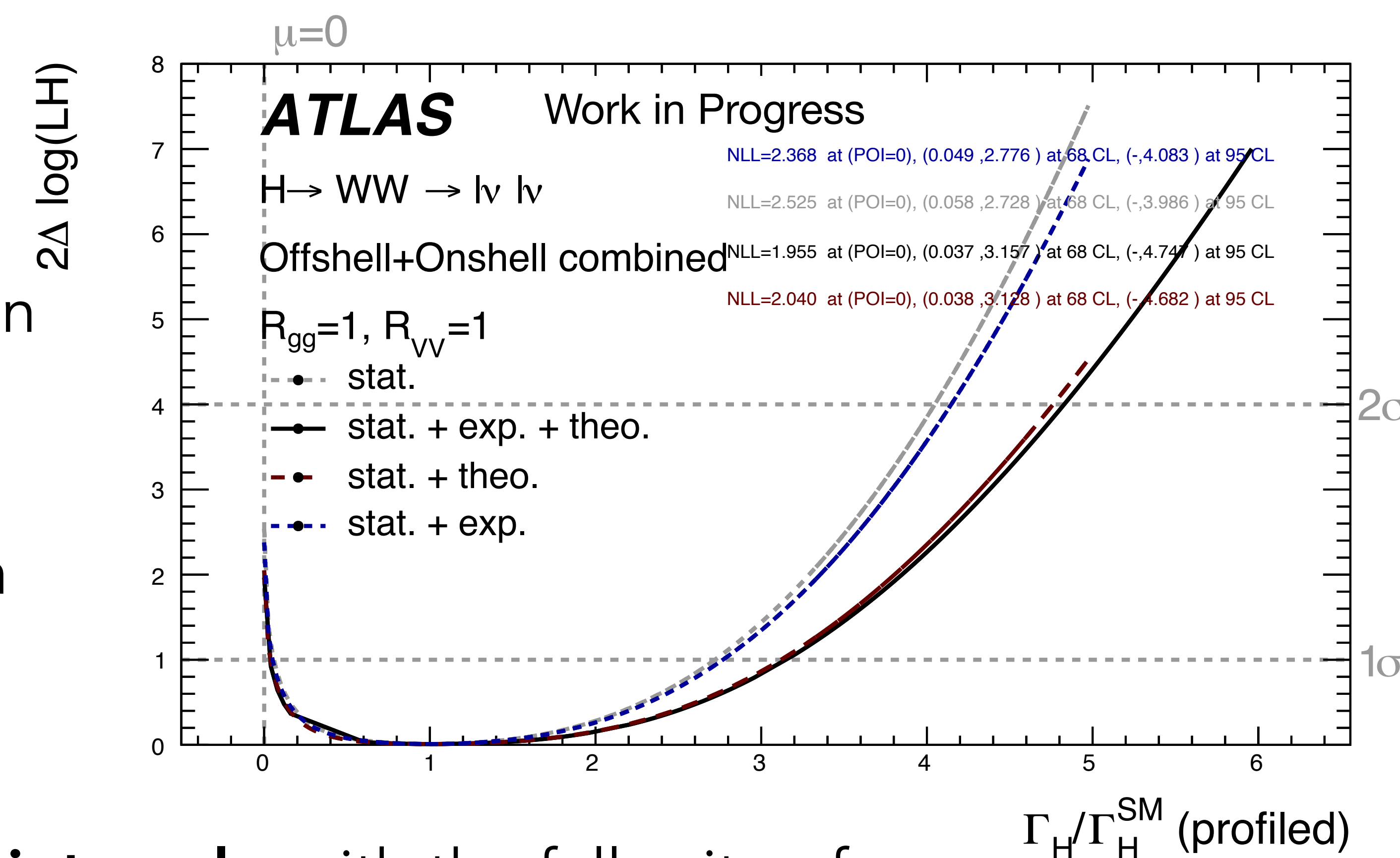
[3] Aad, Georges, et al. Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector. No. arXiv: 2304.01532. ATLAS-HIGG-2018-32-003, 2023.

Onshell Combination and Width

- By **combining with the onshell measurement** we can calculate $\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{offshell}}{\mu_{onshell}}$

- This **assumes cancellation of on- and offshell** couplings
  - This is **expected from the standard model**, but does add one assumption to the interpretation

- **Onshell measurement** is **proceeding in parallel** with combination in mind



- **The expected result at 1σ confidence intervals**, with the full suite of experimental and theoretical uncertainties, is $\Gamma_H = 4.1^{+8.86}_{-3.94}$
  - $H \rightarrow ZZ$ expected measurement was $\Gamma_H = 4.1^{+3.85}_{-3.77}$
    - Improved μ_{off} result translates directly to improved Γ_H

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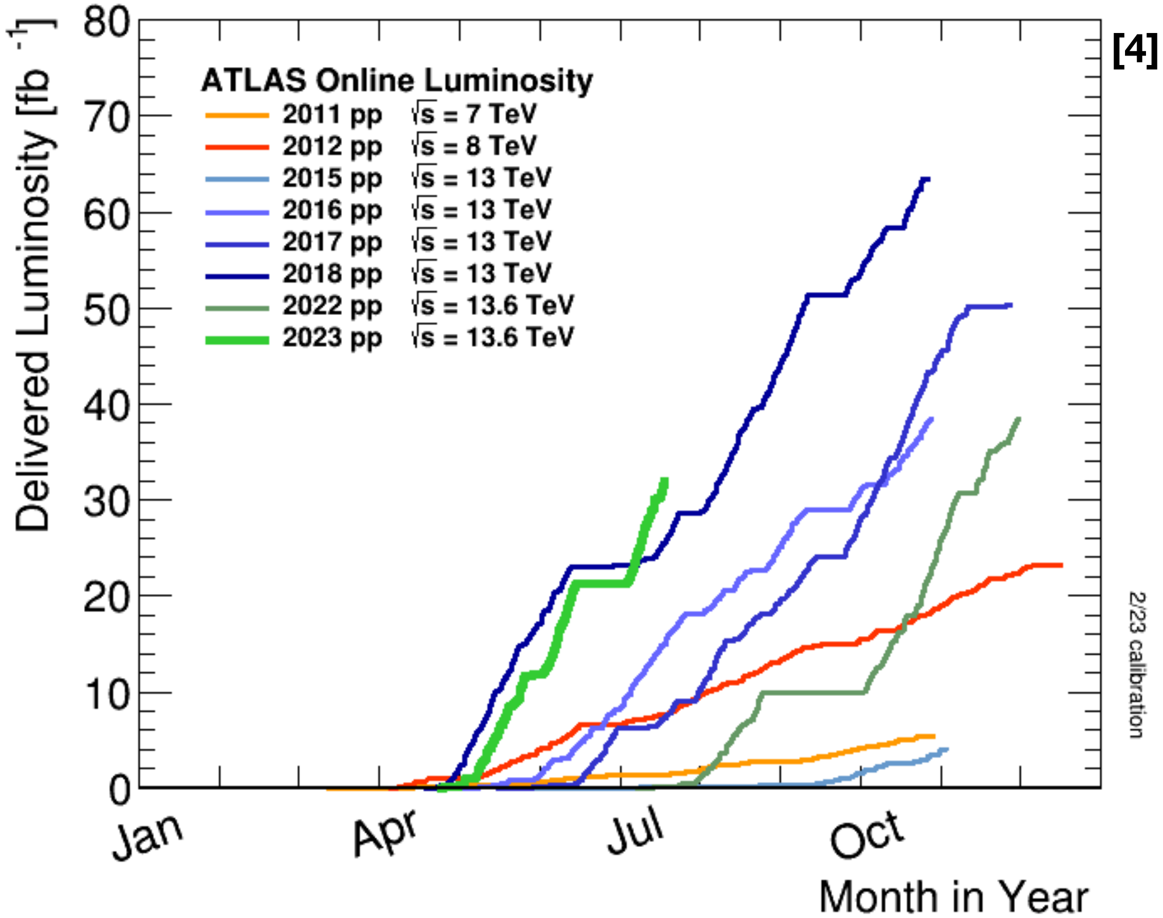
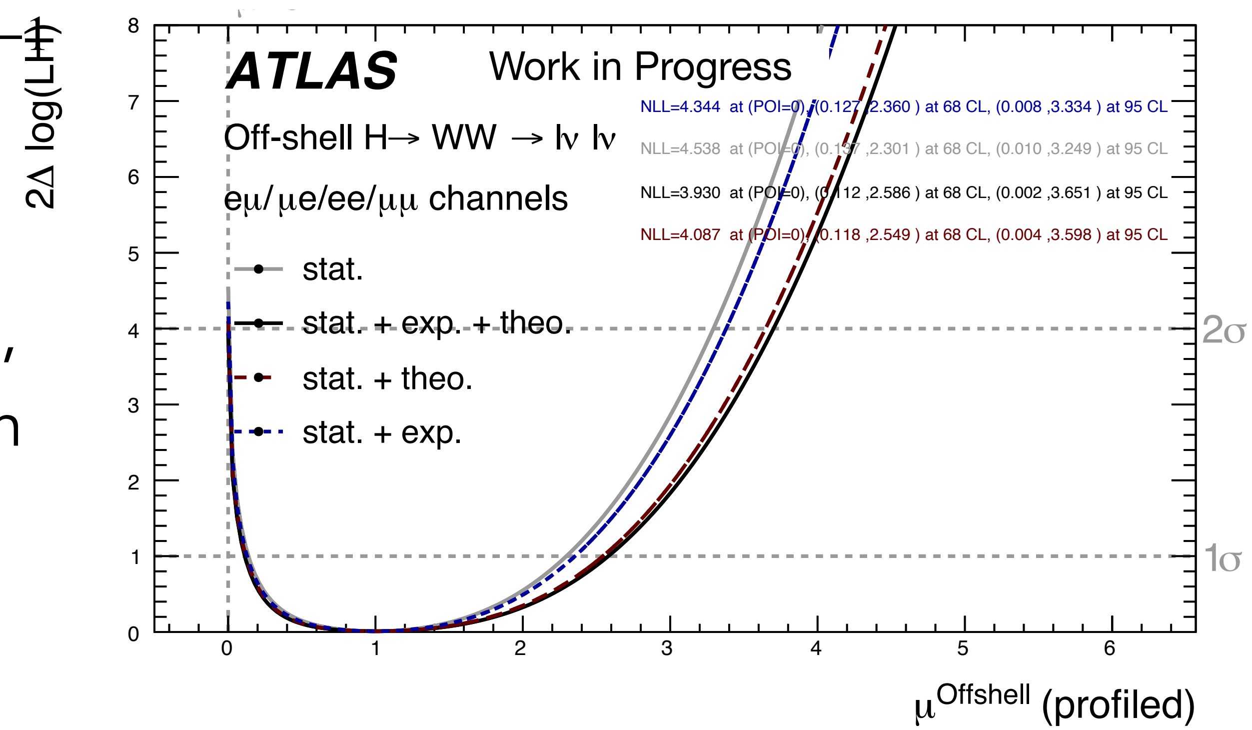
Conclusions and Prospects

Run 3 Prospects

- Currently the LHC is in run 3, which is planned until end of 2025
  - The **goal was to collect 300 fb^{-1}**, but due to a difficult year at the LHC we are now approximately 30 fb^{-1} behind schedule
  - In run 2 we collected 140 fb^{-1}



- **Assuming an identical analysis, with 280 fb^{-1}** of collected data and 50% reduced theory systematic uncertainties
  - Improvement of μ_{off} limits by approx. 20%, similar improvement expected in the width
  - Potential **advanced analysis techniques** might improve this further

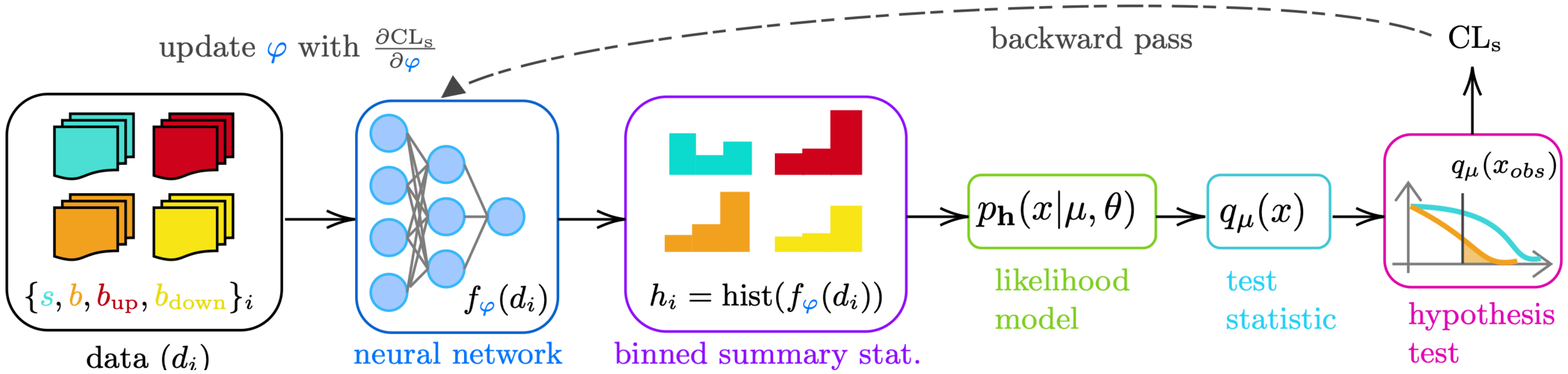


[4] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

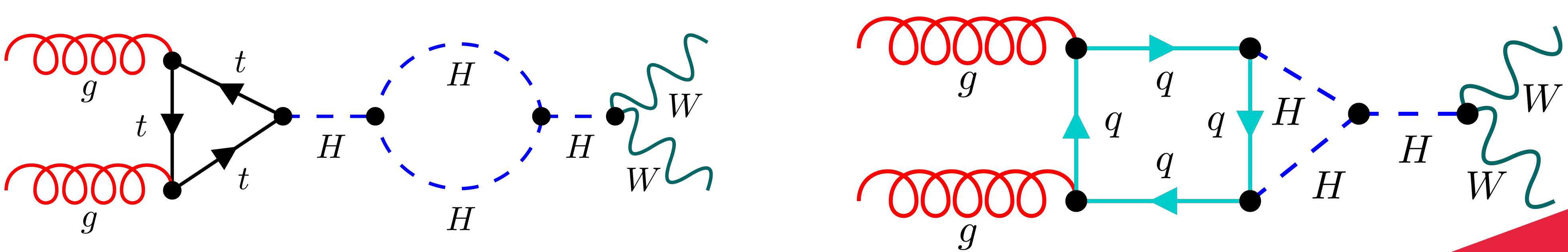
Future Developments

- Combination with $H \rightarrow ZZ$ offshell analysis expected in near future for **best limit possible with current data** on Γ_H
  - Potential for 3σ exclusion of the "no offshell Higgs decays" hypothesis!

- Developing analysis techniques for run 3, in particular in the context of advanced machine learning techniques such as **inference-aware learning**



- Effective field theory interpretation of this analysis started recently, promising first developments and potential **sensitivity to Higgs self-coupling operators**



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Backup

Results Split by Channel

- In terms of **decay modes** the different flavour channels are relatively sensitive
  - Higher signal yields and purities
  - Reduced systematic uncertainties in different flavour region compared to same flavour region

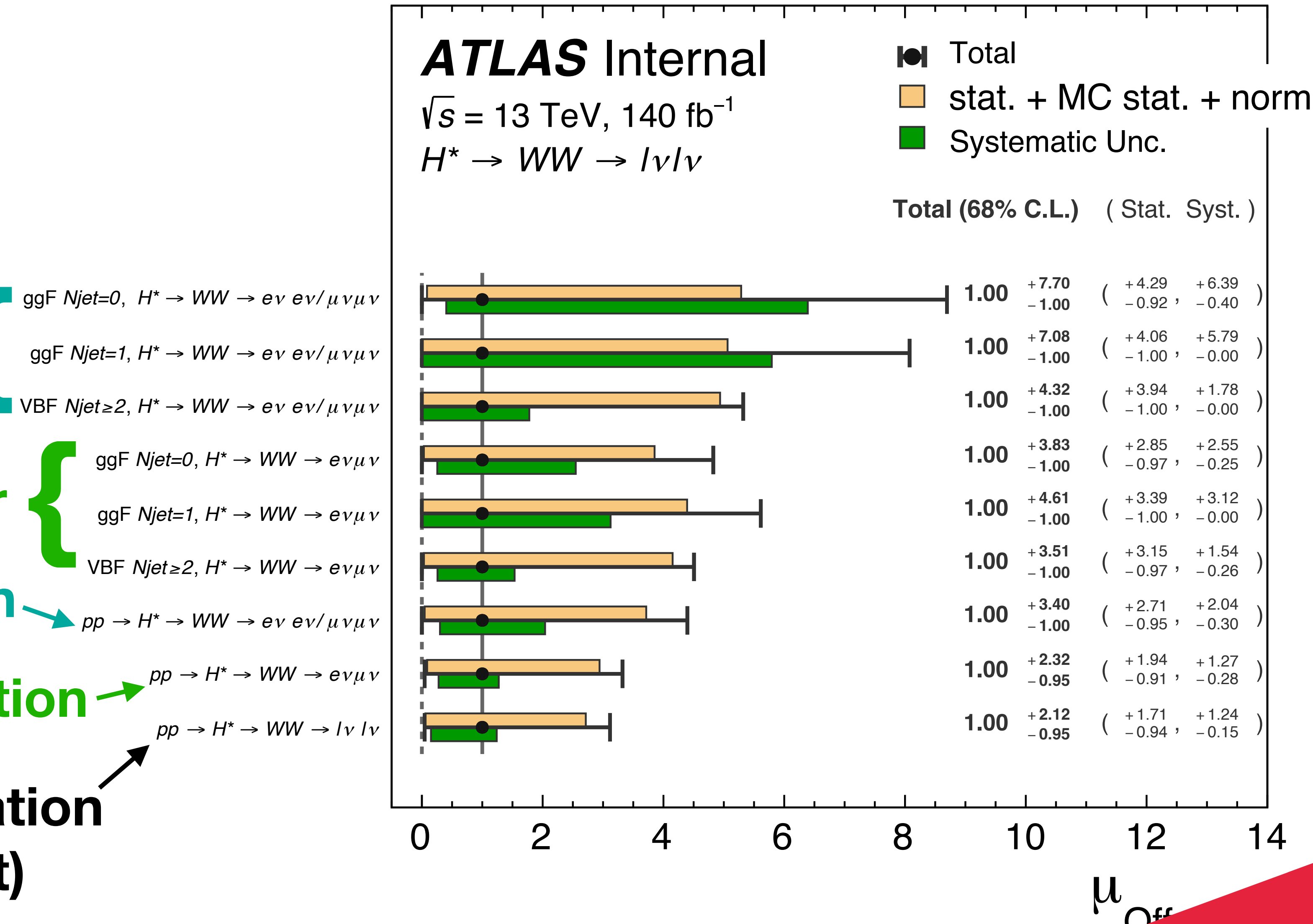
Same Flavour

Different Flavour

Same flavour combination

Different flavour combination

Total combination (final result)



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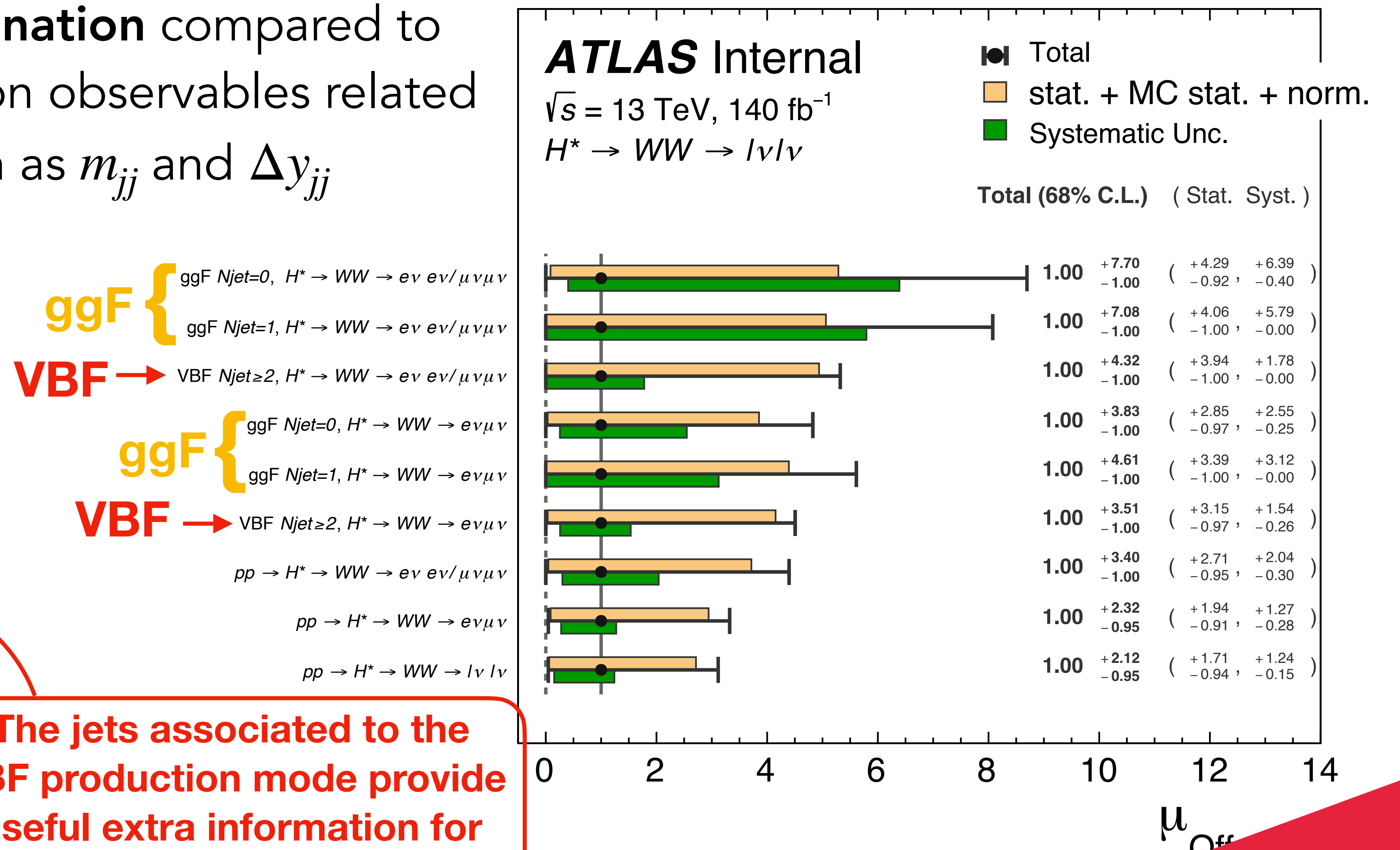
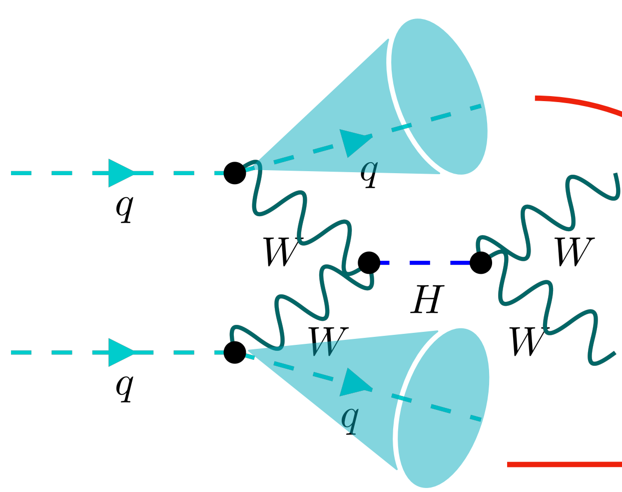
Results Split by Channel

- In terms of **production modes** the VBF channels are relatively sensitive
  - **Theory uncertainties** in VBF are **reduced** compared to ggF

- **Better DNN discrimination** compared to ggF as model relies on observables related to jet kinematics such as m_{jj} and Δy_{jj}





The jets associated to the VBF production mode provide useful extra information for the DNN

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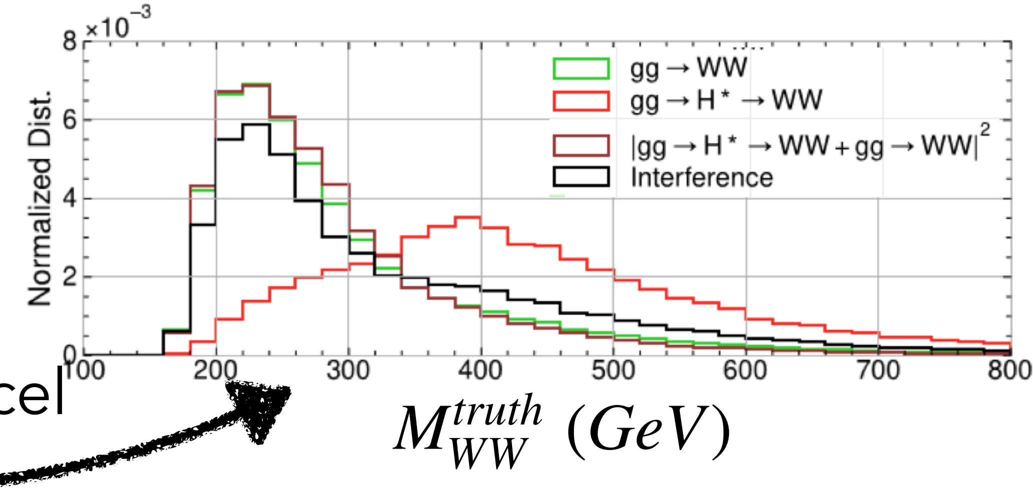
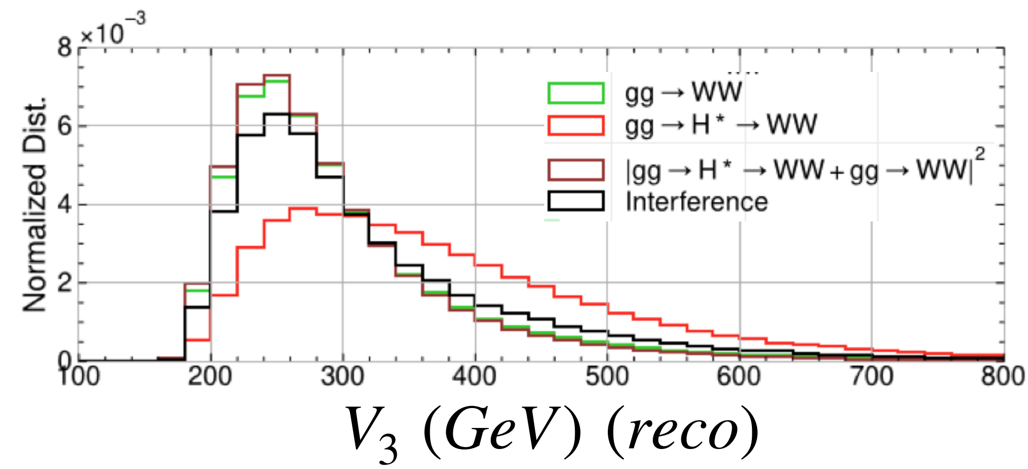
Fitting Variable

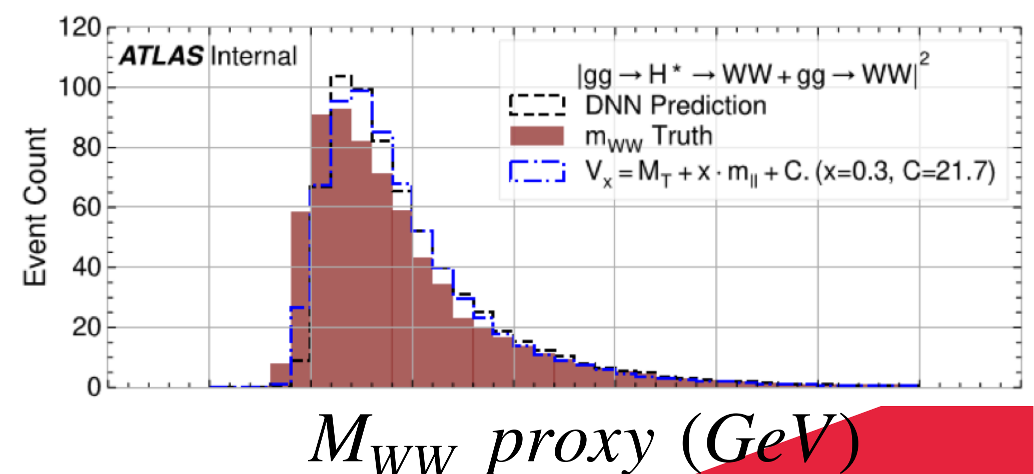
- Cancellation of destructive interference with signal **reduces sensitivity**
  - We need a variable that **discriminates between signal and interference**, such that they don't cancel
  - **Mass of WW system** provides this naturally



- However, since neutrino's cannot be measured in detector, we **cannot fully reconstruct WW mass**
  - Instead, we construct V_3 $(=0.x \times M_{ll} + M_T)$, as a proxy to M_{WW}

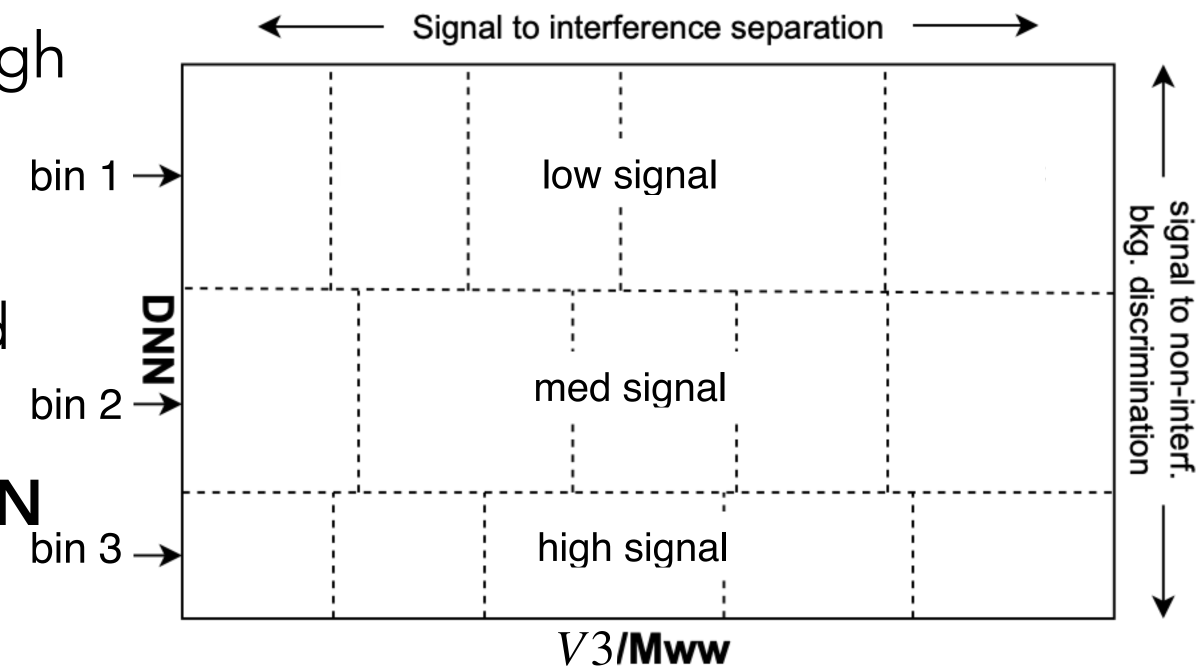


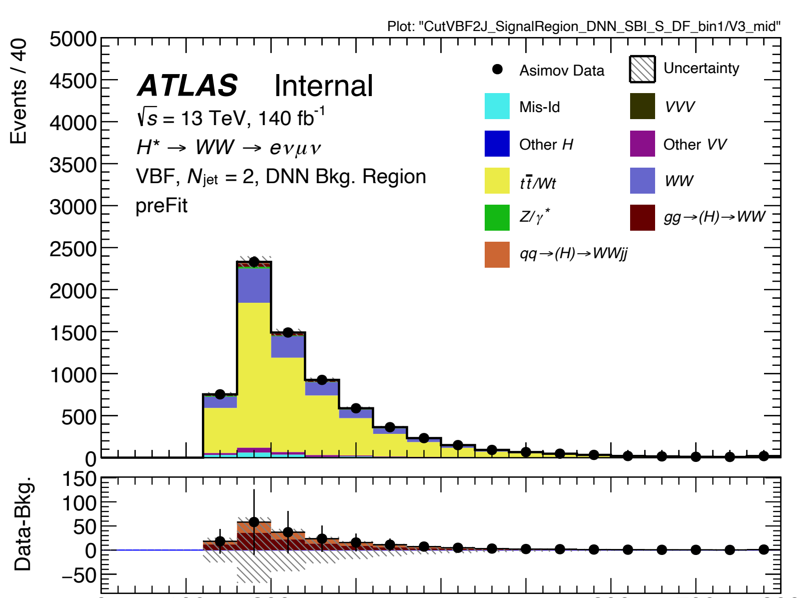
- Alternative attempted approach was to **train a DNN to regress** M_{WW}, but this did not outperform simply V_3 in its accuracy to M_{WW}



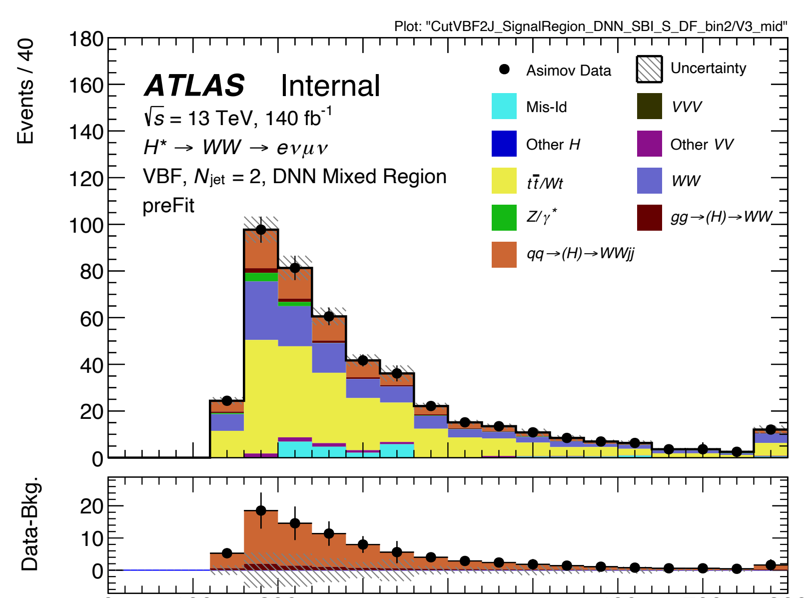
DNN Strategy

- **DNN split up** into three bins: low, med, and high signal purity
  - In each, M_{WW} proxy used in fit to **capture unique shape effects** from interference and signal interplay
  - Essentially this comprises **unrolling the DNN**
- **Low signal DNN bin included** effectively as a control region

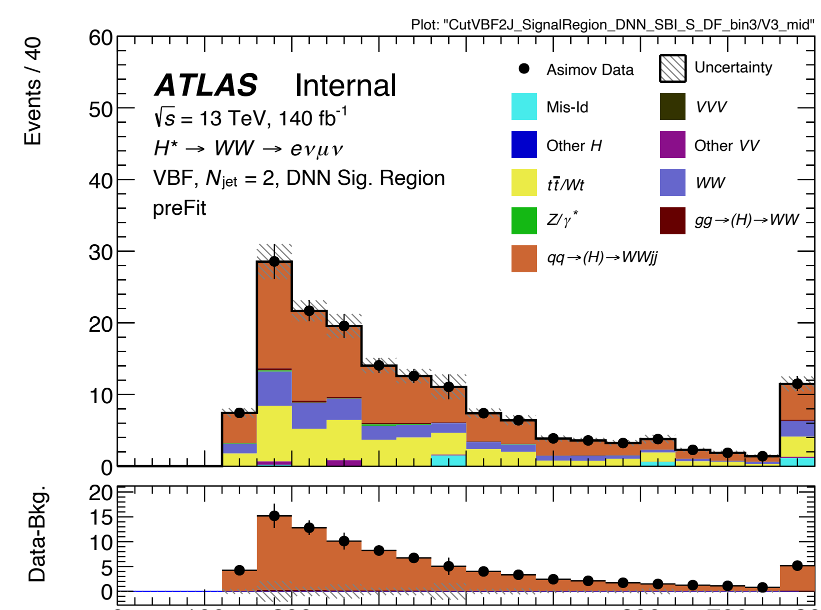




DNN bin 1

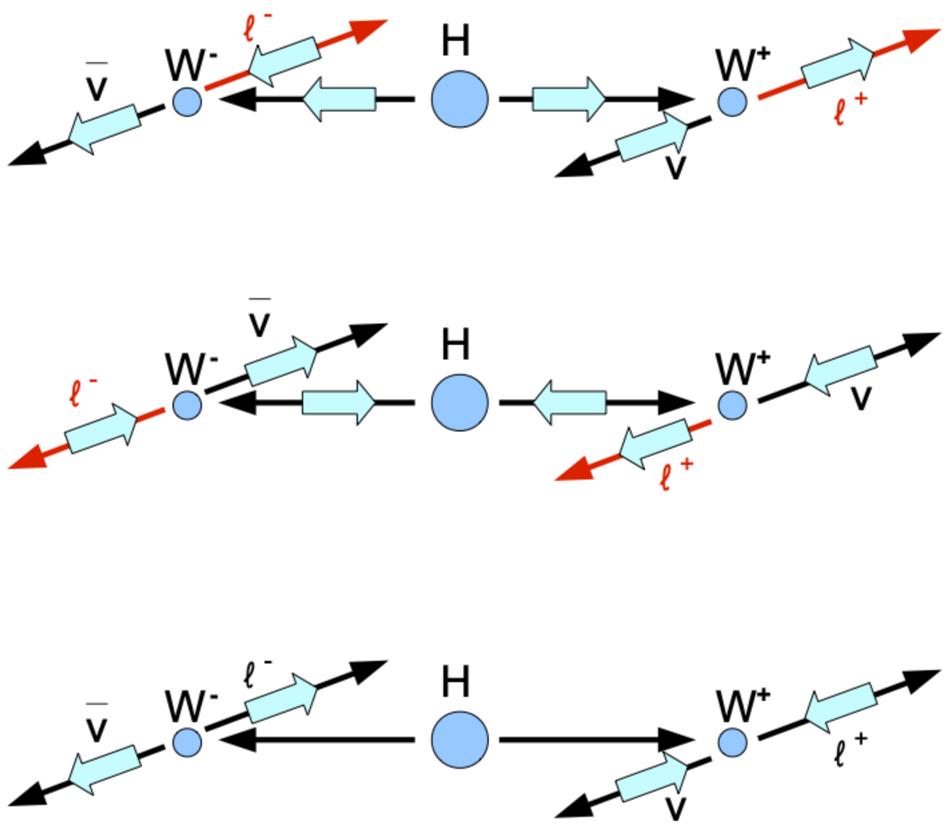


DNN bin 2

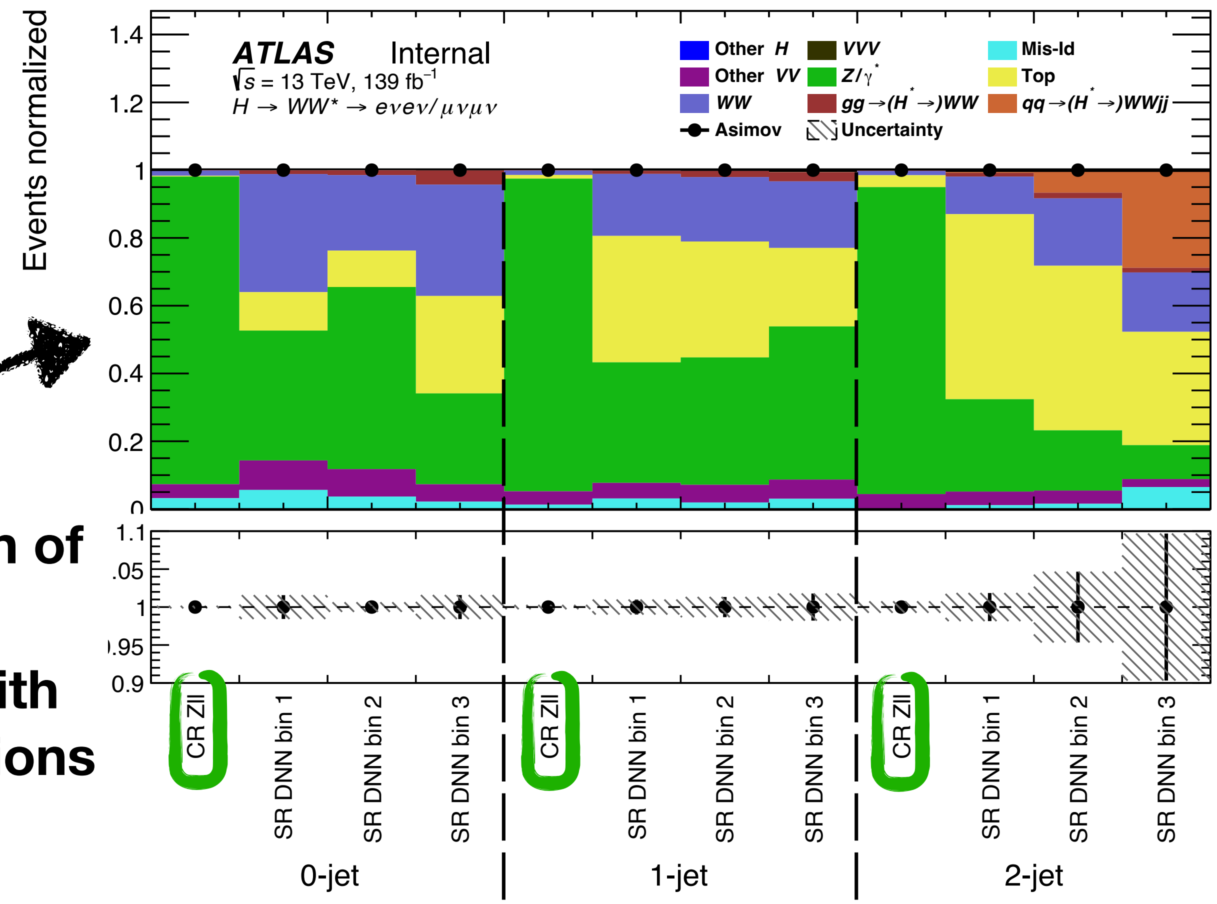


DNN bin 3

Spin and Helicity of decaying WW bosons

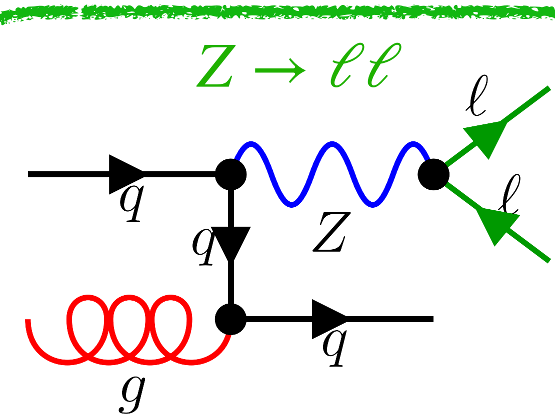


Same Flavour Analysis

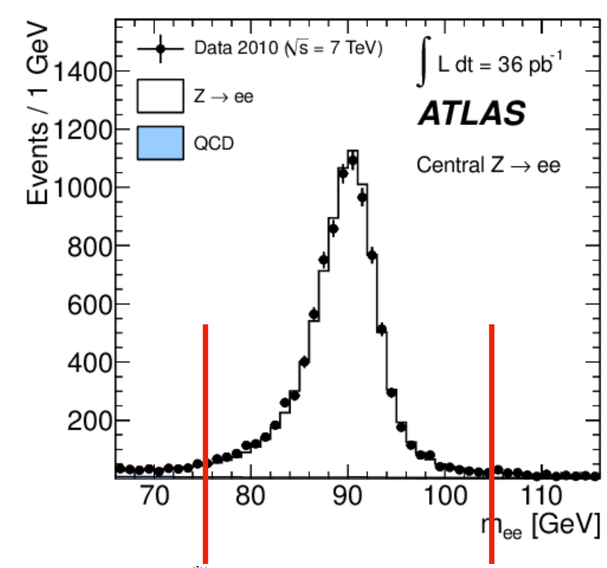


Relatively large contribution of $Z\ell\ell$ background, other backgrounds controlled with different flavour control regions

Notoriously bad modelling of $Z \to \ell\ell$ sample generated with Sherpa hampers this regions' sensitivity



Selected for in CR with $|m_{\ell\ell} - m_Z| < 15$ GeV



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Likelihood Scan Shape