Searching for the Dimuon Decay of the Higgs through VH using the ATLAS Experiment

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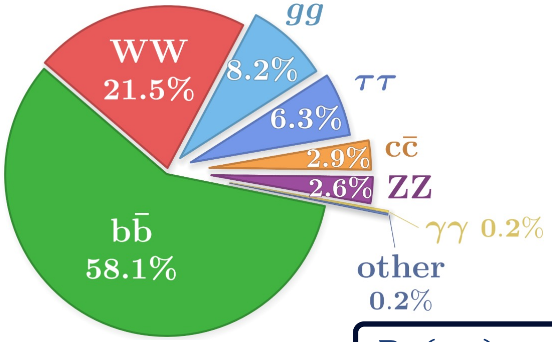
Why Probe $\mathrm{H} \rightarrow \mu\mu$?

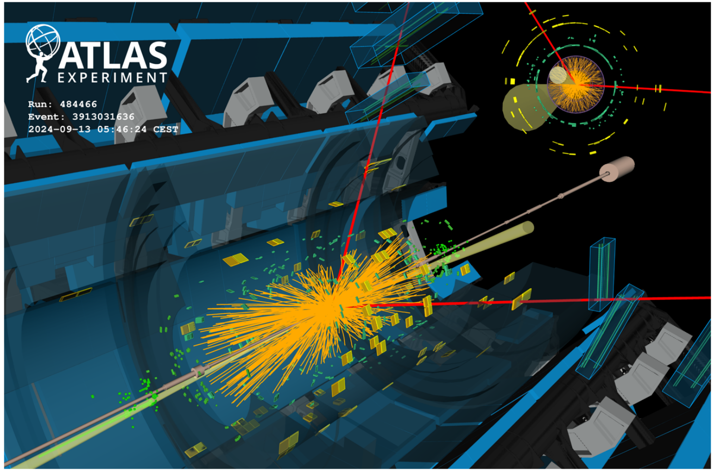
- Higgs discovery by ATLAS and CMS in 2012
- Natural next step to probe properties of Higgs boson e.g. Yukawa couplings (to fermions), self-interaction couplings (di-Higgs)
- Want to probe Higgs couplings to second generation fermions

Muons vs Charm Quarks
Muons provide cleaner signature
Much better p_T resolution

Tiny branching ratio makes for a challenging search 🫣 (Higgs couples to mass)



$Br(\mu\mu) = 0.000217\%$



Likely $\mathrm{H} \rightarrow \mu\mu$ event in pp collision data in ATLAS from 2024

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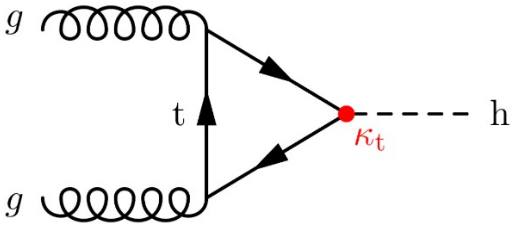
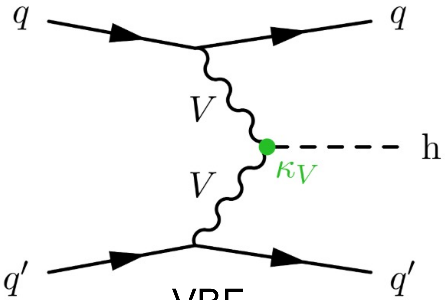
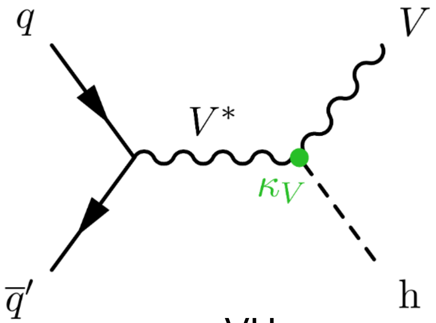
Higgs Productions Modes



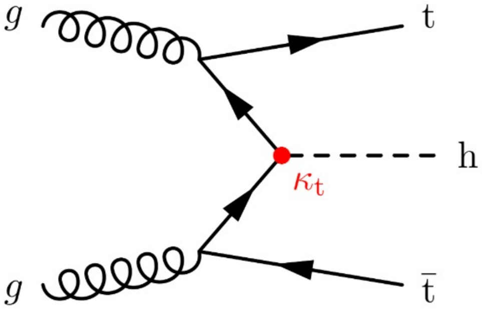
ggF



VBF



VH



ttH

Why focus on VH Higgs production?

- **Significant Production Mode:** ~3% of total Higgs production
- **Background rejection**: VH channel reduces Drell-Yan leaving clean Diboson background
- **Everything Counts**: Push for 3σ result
- **Interesting Mode:** studies shown excess in signal strength

- Splitting by lepton multiplicity allows for independent channels which maximise sensitivity

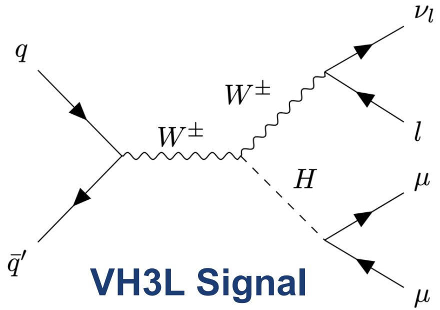
Preselection

This is what allows VH3L category to not overlap with any other defined categories

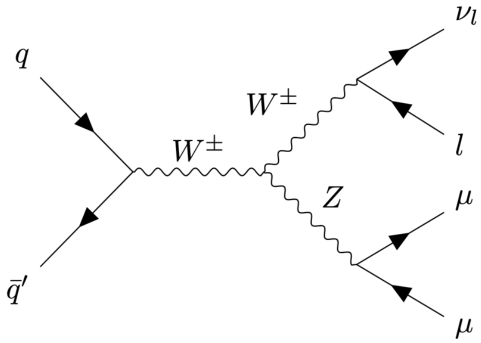
Require 3 leptons as this is what we expect from VH3L

Disallow any b-jets

Fitting Region: $m_{\mu\mu} \in [110, 160]$ GeV
Signal Region: $m_{\mu\mu} \in [120, 130]$ GeV



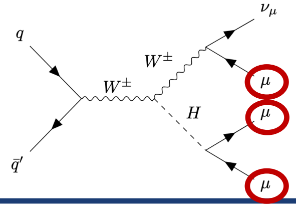
VH3L Signal



WZ Diboson Irreducible Background

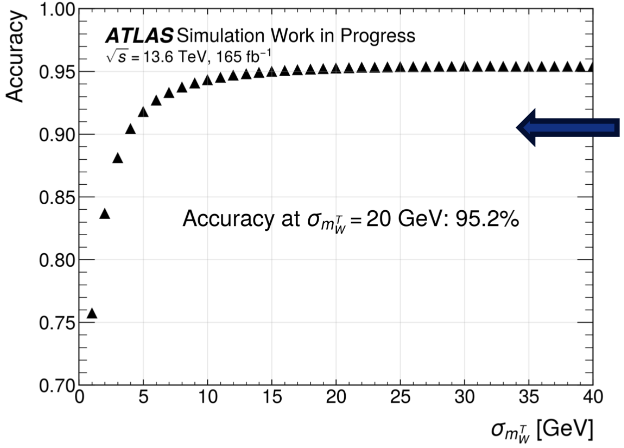
Muon Assignment

How do we assign which muon originates from which boson?



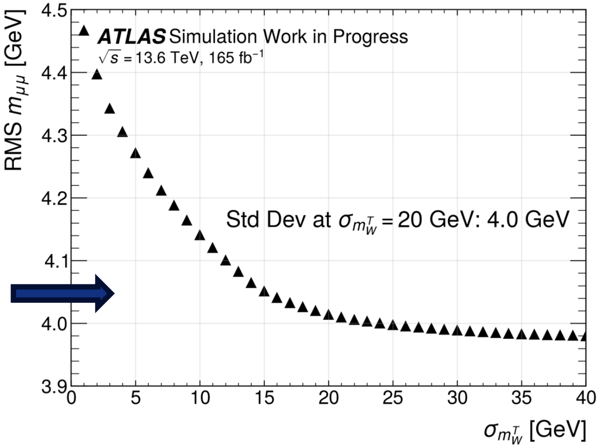
$$\chi^2 = \frac{\left(m_H^{\text{cand}} - m_H\right)^2}{\sigma_{m_H}^2} + \frac{\left(m_W^{T,\text{cand}} - m_W^T\right)^2}{\sigma_{m_W^T}^2}$$

The resolutions are derived from the reconstructed object resolutions



$$\text{Accuracy} = \frac{\text{Correct Assigned Event}}{\text{All Events}}$$

Resolution of VH3L signal



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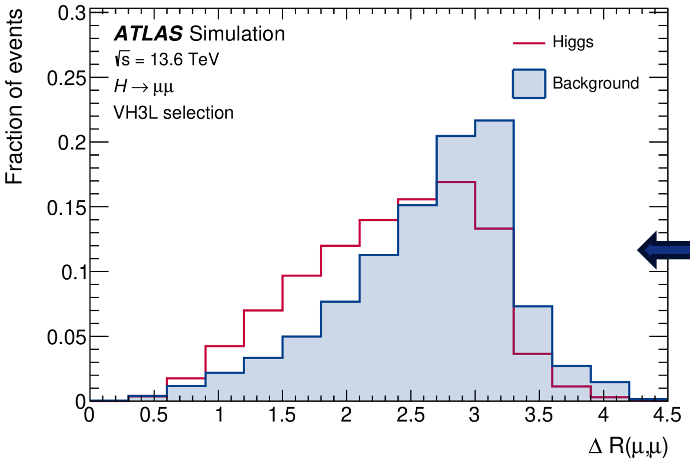
VH3L BDT Training

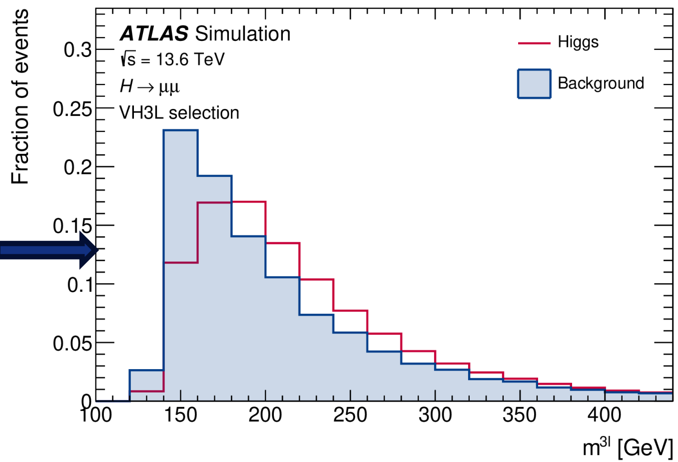
In data from the ATLAS detector, this region has a mixture of signal and backgrounds which need to be distinguished

Train on similar signal region

Used 4 fold cross validation



2 of the highest ranking features



Dimuon angular separation

Three lepton invariant mass

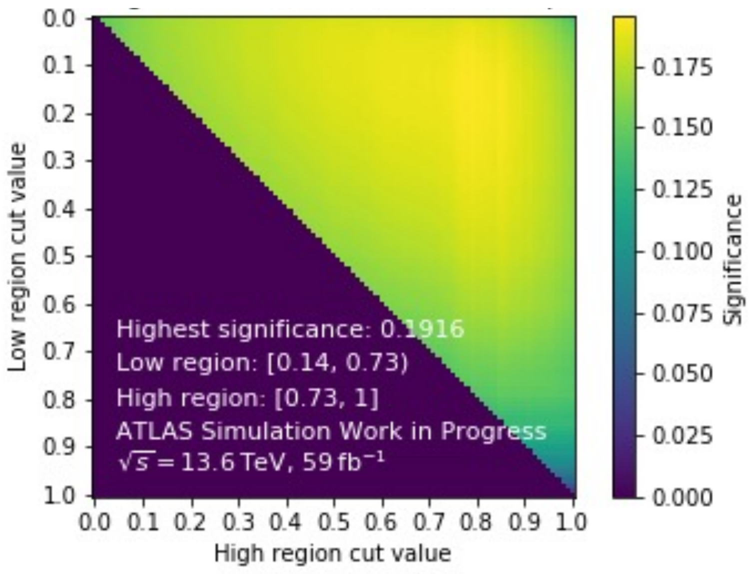
Event Categorisation Result

BDT was only trained and optimized using 2022-23 simulation

Scanned through all possible BDT boundaries selections to choose boundaries which give highest counting significance ($S/\sqrt{B}$)

We require enough weighted events to help with modelling the background

- Low purity: 0.14 – 0.73
- High purity: 0.73 – 1.00



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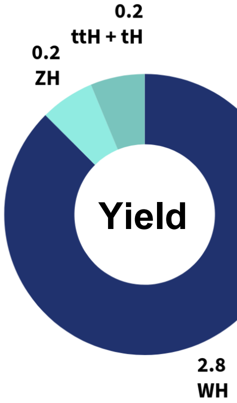
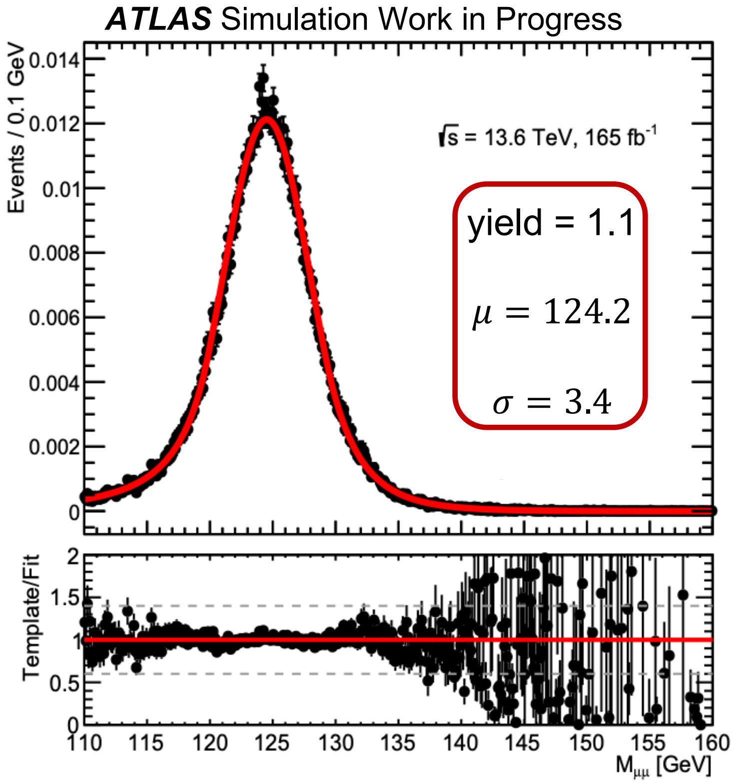
Signal Modelling

After combining both categories:



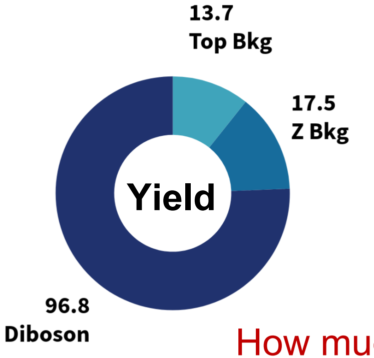
The signal is modeled using a double-sided Crystal Ball function (Gaussian core with power-law tails).

We fit this to Higgs signal MC



VH3L High Purity

Background Modelling



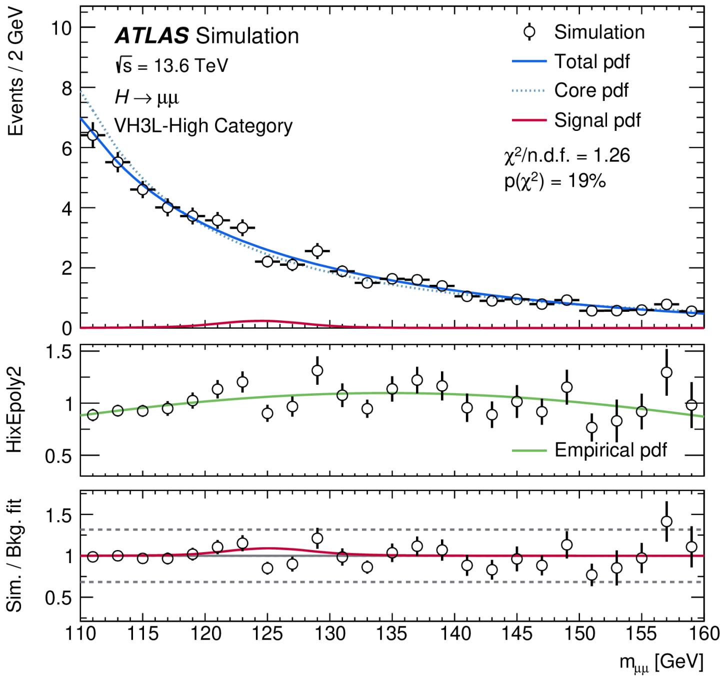
Background model is combination of DY core and functional component

How much can the background imitate the signal?

Perform signal + background fits on the background-only template

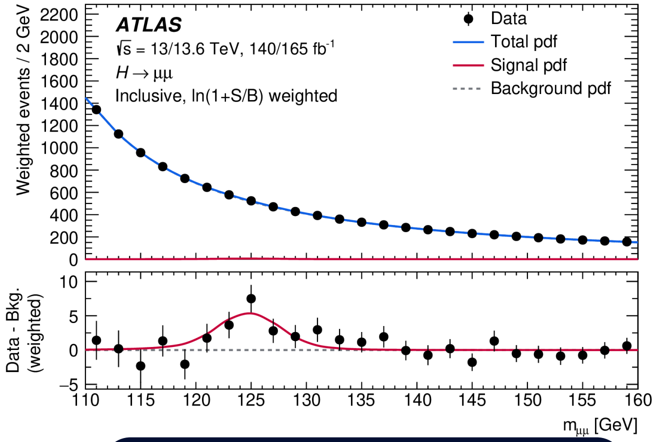
Vary the signal model mean across the scan

Extract the spurious signal, defined as the largest fitted signal yield



VH3L High Purity

Unblinded Results



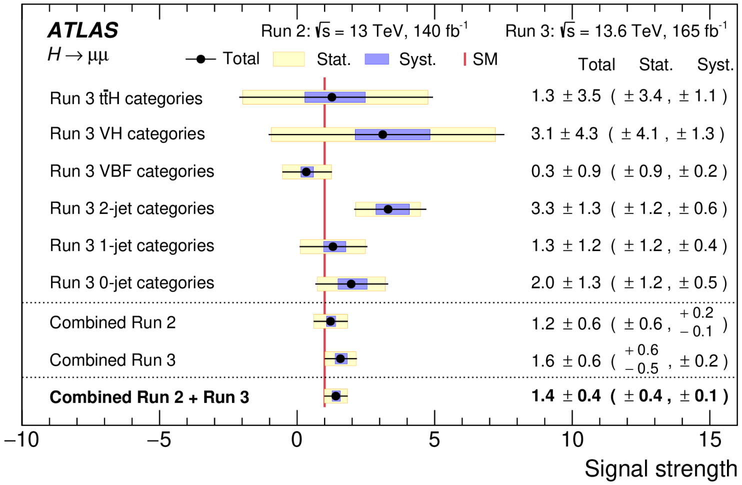
Combined run 2 + 3 signal strength falls within the standard model prediction.

Largest uncertainty contributions:

- Statistics (analysis is stat limited)
- Spurious signal (bias due to bkg model)

Simultaneous fit using all the defined categories led to 3.42σ (2.46σ) observed (expected) significance

VH3L contributed 1.47σ (0.18σ) for observed (expected) significance



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Summary

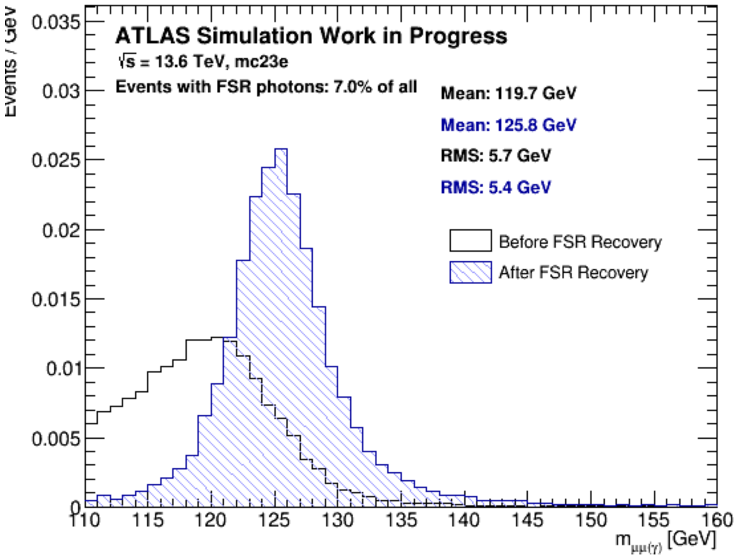
Analysis highlights:
- BDT categorisation → improved signal/background separation
- Events split into low/high purity → maximised sensitivity
- Robust signal & background modelling (spurious signal tests)

Limiting factors: statistics & background modelling systematics

Strong evidence for H → μμ: 3.42σ observed (2.46σ expected)

Next steps: Things like more data, FSR recovery, vertex refitting, BDT re-optimisation

Further Study Sneak Peak



Colinear FSR is recovered in the VH3L signal back into the muon which we assume it radiates from

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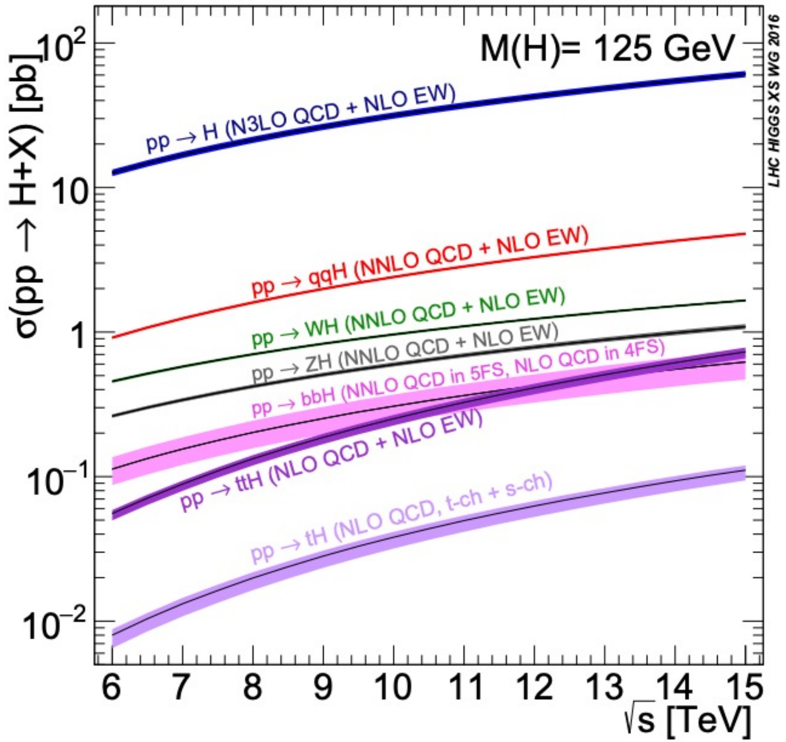
Backup

XS vs COM Higgs Production Modes



arXiv:1610.07922

Preselection

This is what allows VH3L category to not overlap with any other defined categories

	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\|\eta\| < 2.5$, $p_T^{lead} > 27$ GeV, $p_T^{sublead} > 15$ GeV
Fit region	$m_{\mu\mu} = 110 - 160$ GeV
Jets	$p_T > 25$ GeV and $\|\eta\| < 2.4$ or with $p_T > 30$ GeV and $2.4 < \|\eta\| < 4.5$
b-tagged jets	$p_T > 25$ GeV and $\|\eta\| < 2.4$ or with $p_T > 30$ GeV and $2.4 < \|\eta\| < 2.5$ Tagging efficiency working point of 85%
$t\bar{t}H$ categories	At least one b-jet
VH 4-lepton category	Exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b-jets
VH 3-lepton categories	Exactly one additional e or μ with $p_T > 15$ GeV, no b-jets
VH 2-lepton categories	No additional lepton, no b-jets, $E_T^{miss} > 120$ GeV
VBF and ggF categories	No additional lepton, no b-jets, $E_T^{miss} < 120$ GeV

Require 3 leptons as this is what we expect from VH3L

Disallow any b-jets

Lepton from W boson is required to be “tight” isolated from hadronic activity

Backgrounds from Z decays are removed by not allowing any opposite charged muon pair [80, 105] GeV

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BDT Features

Variable	Description
$p_T^{\ell_W}$	Transverse momentum of the W-boson lepton
E_T^{miss}	Missing transverse energy
m_T^W	Transverse mass of the W boson
N_j	Number of jets
N_μ	Number of muons
$\Delta R(\mu, \mu)$	ΔR between the Higgs-boson candidate muons
$\cos\theta^*$	μ^- decay angle in the Collins–Soper frame
$m^{3\ell}$	Invariant mass of the three leptons
$p_T^{j_1}$	Transverse momenta of the leading jet
$\Delta\phi(\ell\ell, \ell_W)$	Azimuthal angle between the muon pair and the W-boson lepton
$\Delta\eta(\ell\ell, \ell_W)$	Pseudorapidity separation between muon pair and W-boson lepton
$\Delta\phi(\ell\ell, E_T^{miss})$	Azimuthal angle between the muon pair and the missing transverse momentum

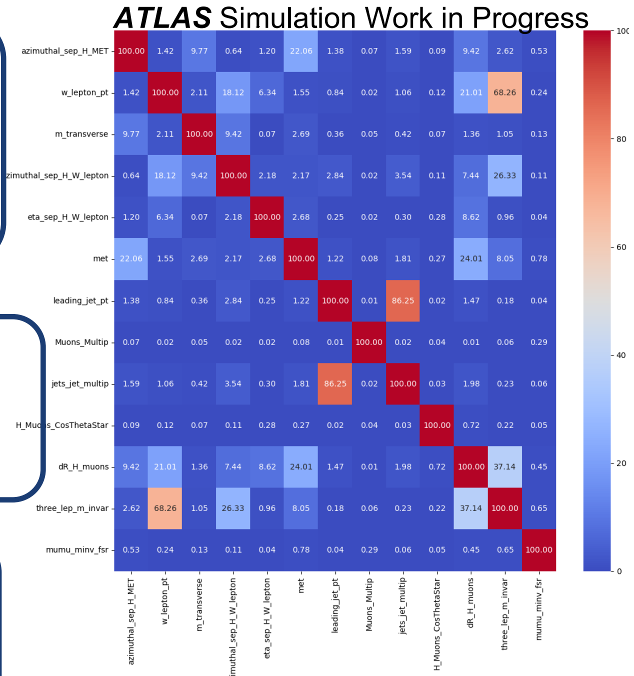
Distance Correlation Between BDT Features

Distance correlation used to capture both linear and non-linear correlations between BDT variables and our fitting variable $m_{\mu\mu}$

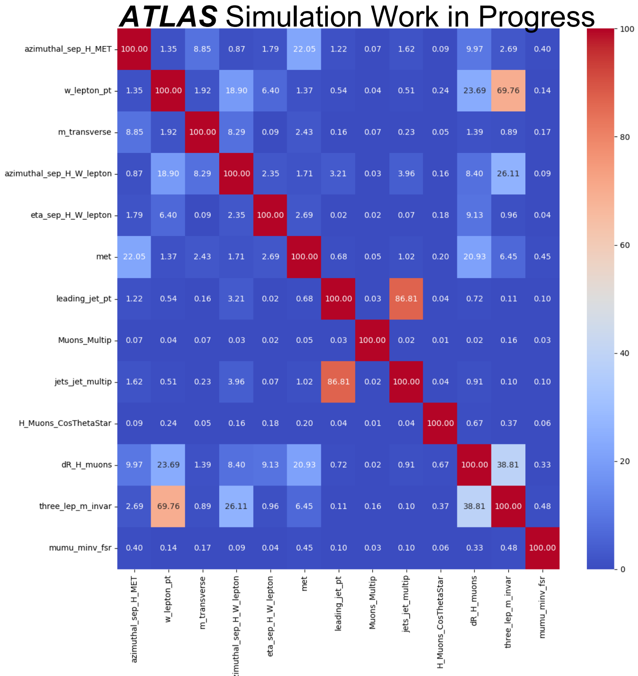
How much bias can the BDT have?

All correlations against $m_{\mu\mu}$ < 1%

Large correlation between number of jets and leading jet p_T expected (if there are no jets there is no jet p_T)



Background



Signal

Event Categorisation Result

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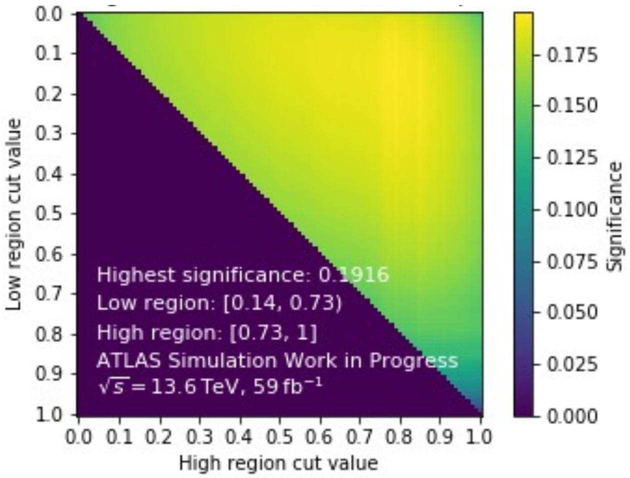

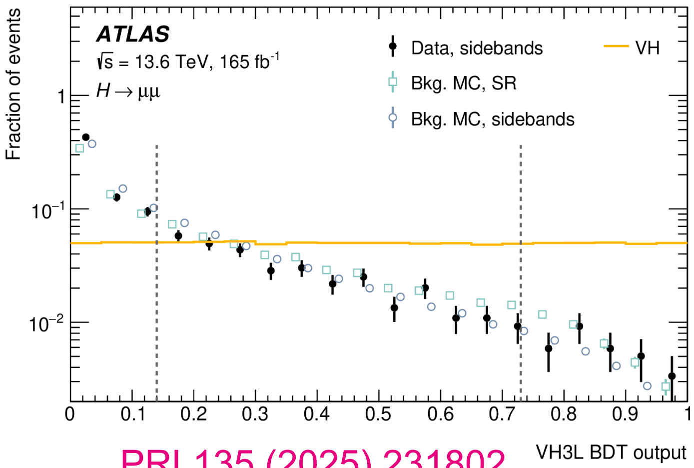

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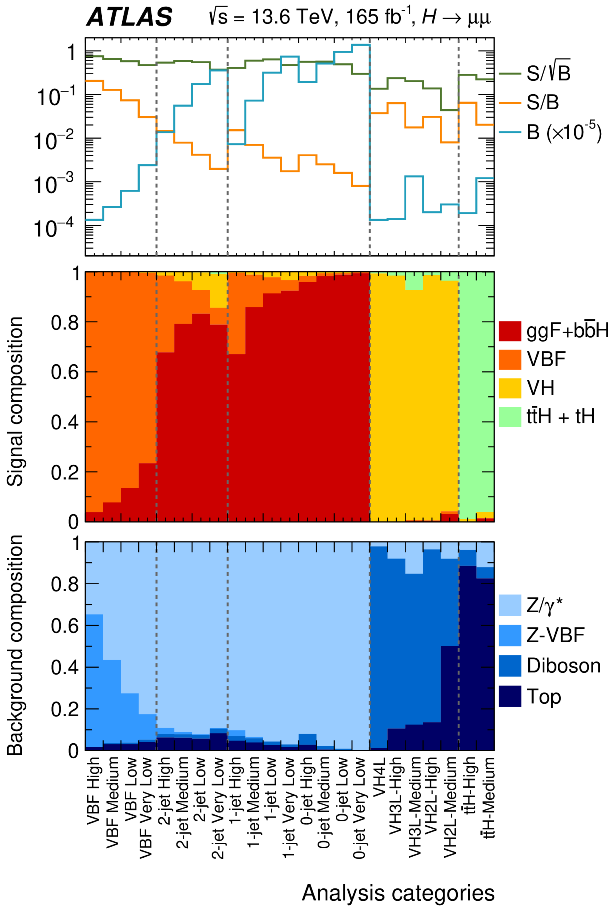
Scanned through all possible BDT boundaries selections to choose boundaries which give highest counting significance ($S/\sqrt{B}$)

We require at least 5 weighted event to help with modelling the background

- Low purity: 0.14 – 0.73
- High purity: 0.73 – 1.00

Event Categorisation Result

By the end of event categorisation, we end up with different contributions of signal and background in each category



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For VH3L:

- Background is mostly Diboson
- Signal is mostly VH

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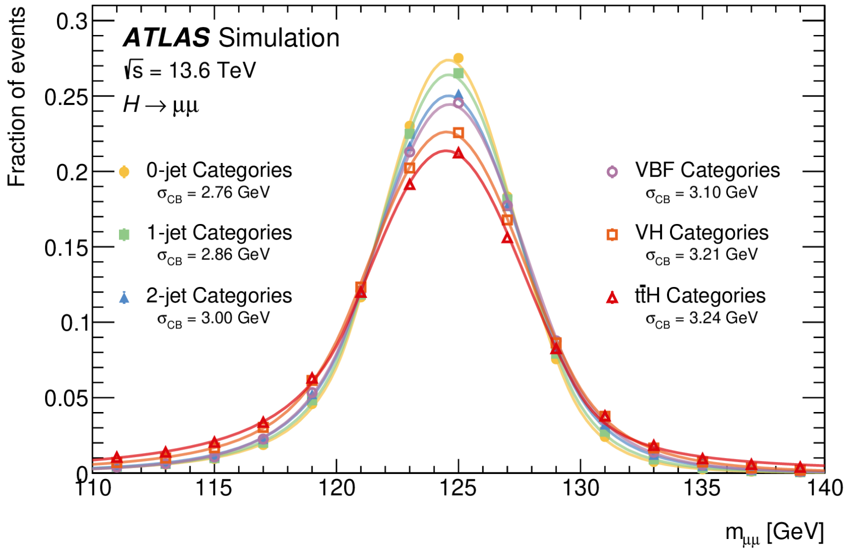
Dimuon Invariant Mass Resolutions per Category



Background Modelling Details

	VH3L High	VH3L Low
PDF	HixEpoly2	HixEpoly4
$\max(\mathrm{SS}/dS)$ [%]	24.7	27.3
$\max(\mathrm{SS}_{+1\sigma}/dS)$ [%]	11.7	13.7
$\max(\mathrm{SS})$	1.59	5.74
$S_{\mathrm{SM}}(125)$	1.14	2.81
n_{Pars}	2	4
$P(\chi^2)_{\mathrm{Full\ Simulation}}$ [%]	18.7	18.6

Requirements:
1. Max spurious signal / stat error < 20%
2. $\mathrm{prob}(\chi^2) > 1\%$

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Unblinded Results

Category	Expected Significance [σ]	Observed Significance [σ]
Stat. only		
VBF	1.13	0.38
Higgs-2Jet	0.85	2.86
Higgs-1Jet	0.85	1.12
Higgs-0Jet	0.82	1.61
VH-4L	0.12	0.00
VH-3L	0.19	1.51
VH-2L	0.11	0.00
ttH	0.31	0.38
Combined	1.88	2.92
Stat. + Syst.		
VBF	1.11	0.38
Higgs-2Jet	0.83	2.77
Higgs-1Jet	0.82	1.08
Higgs-0Jet	0.77	1.51
VH-4L	0.12	0.00
VH-3L	0.18	1.47
VH-2L	0.11	0.00
ttH	0.29	0.37
Combined	1.82	2.81
Run2	1.65	2.01
Run2 + Run3	2.46	3.42

3σ Evidence!!!

Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.55	+0.55
Systematic uncertainty	-0.18	+0.24
Spurious signal	-0.14	+0.15
Theory	-0.08	+0.13
Luminosity	-0.04	+0.08
Muon	-0.03	+0.07
Jets, flavor tagging	-0.02	+0.03
Other	-0.04	+0.07
Total	-0.57	+0.60

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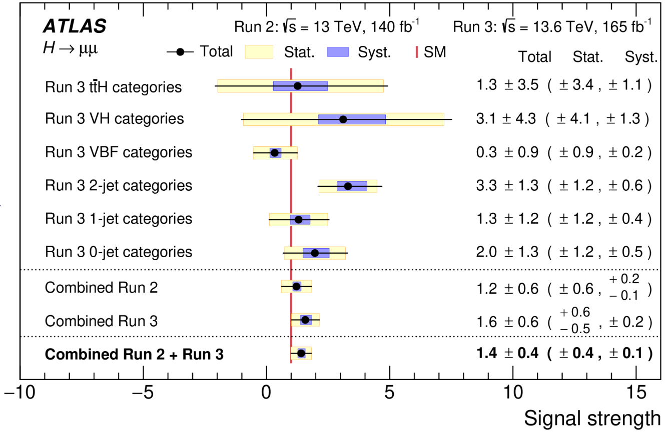
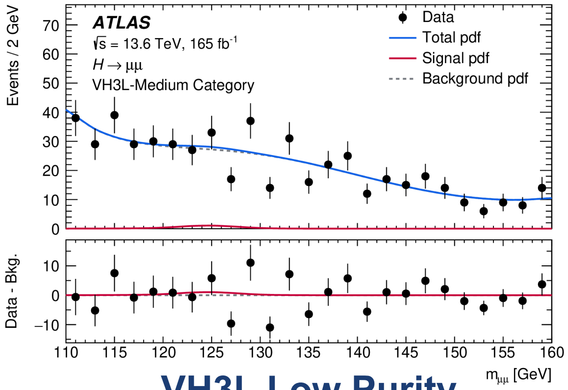
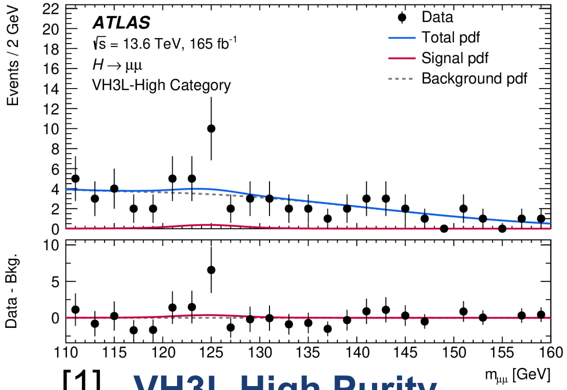
Unblinded Results

Combined run 2 + 3 signal strength falls within the standard model prediction.





VH3L Low Purity



[1] **VH3L High Purity**

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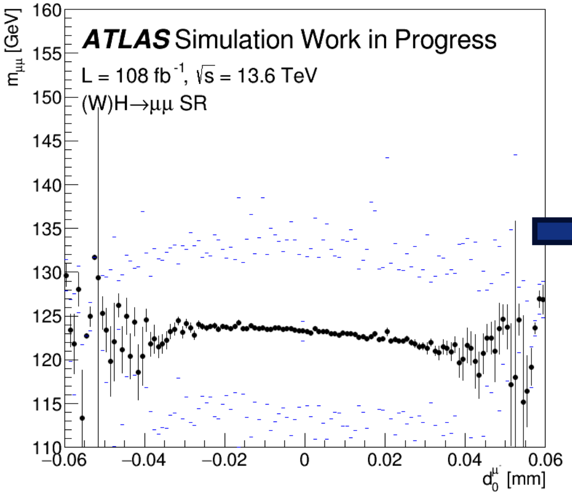
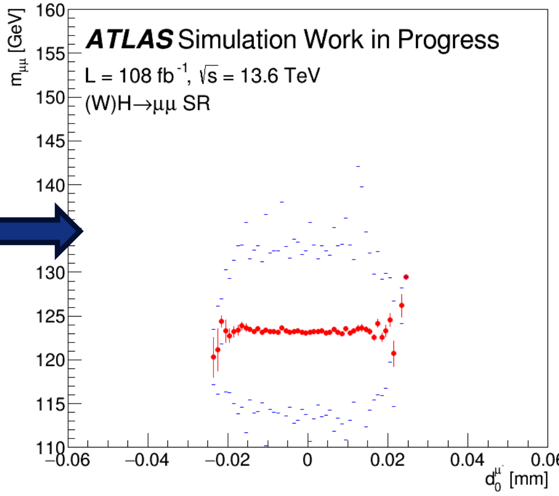
Further Studies: FSR Recovery and Vertex Refitting

- Tracks from a decay are fitted to a common vertex using their measured parameters and covariances
- A χ^2 fit is minimized to find the vertex position best matching the tracks
- Refitting updates track parameters - improves invariant mass resolution

Before vertex refitting - larger spread in $m_{\mu\mu}$ due to track vertex misalignment



After vertex refitting — mass distribution tightens, showing improved mass resolution



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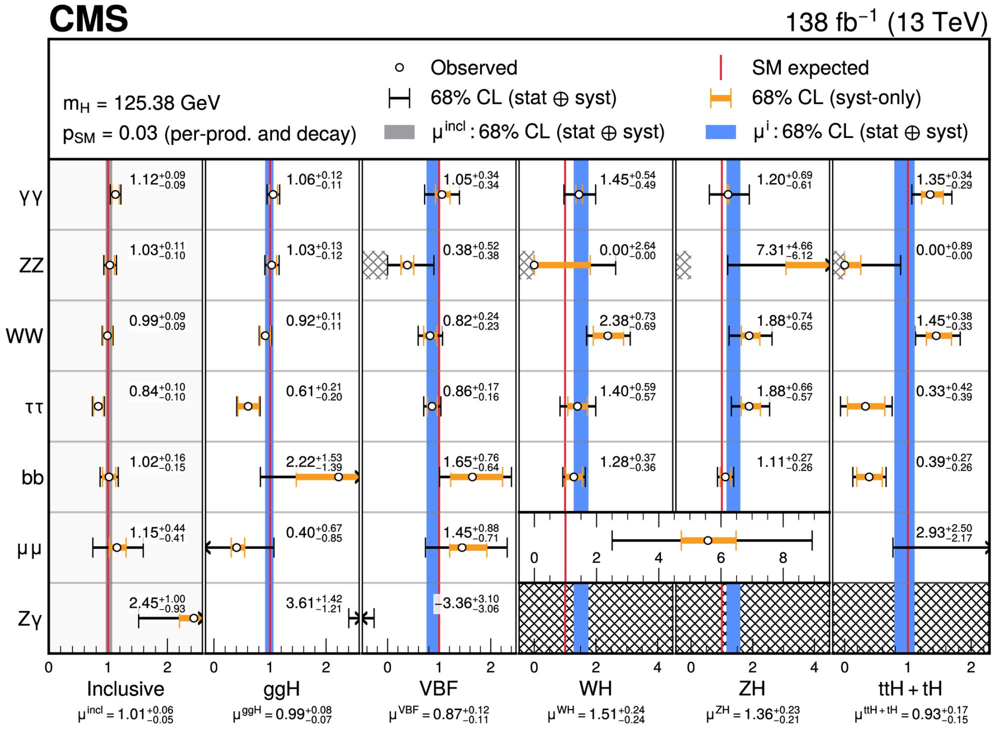
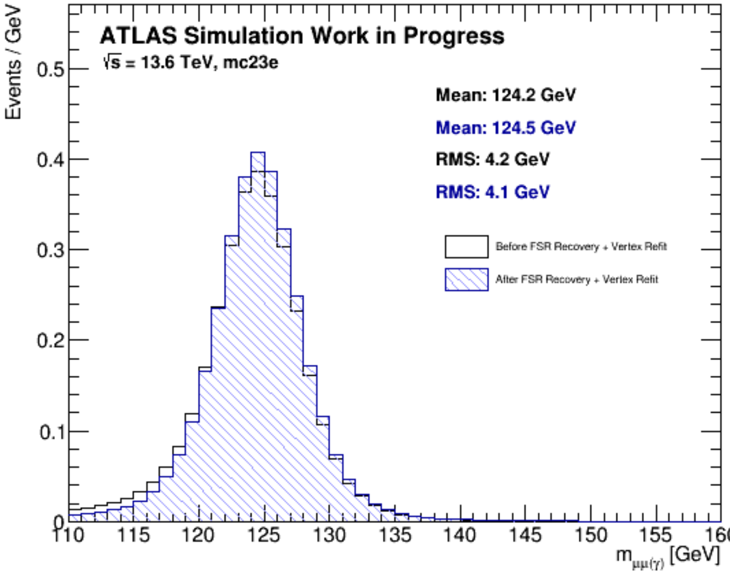
arXiv:2602.18611

CMS Signal Strength Plots

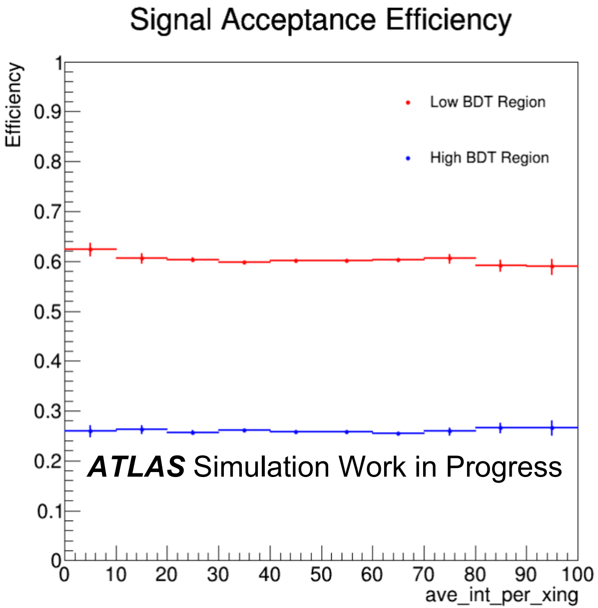


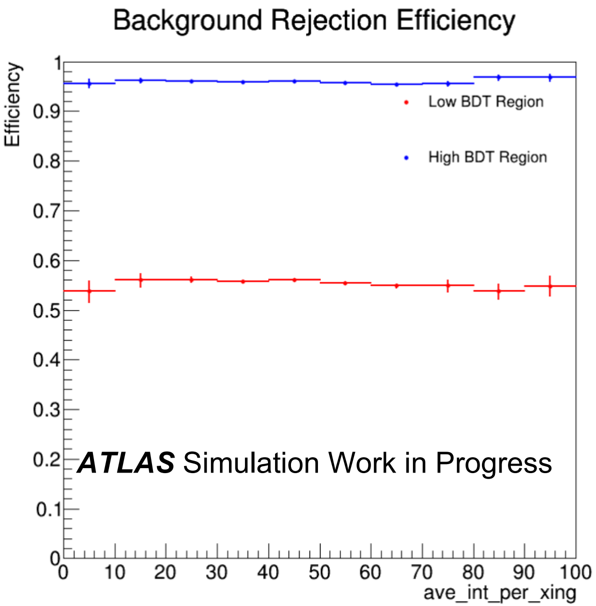
Further Studies: FSR Recovery and Vertex Refitting



Comparison of before and after applying FSR recovery and Vertex refitting

VH3L Category Efficiency vs. Pileup





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