Measurement of Higgs boson properties via the $H \to \tau\tau$ decay channel

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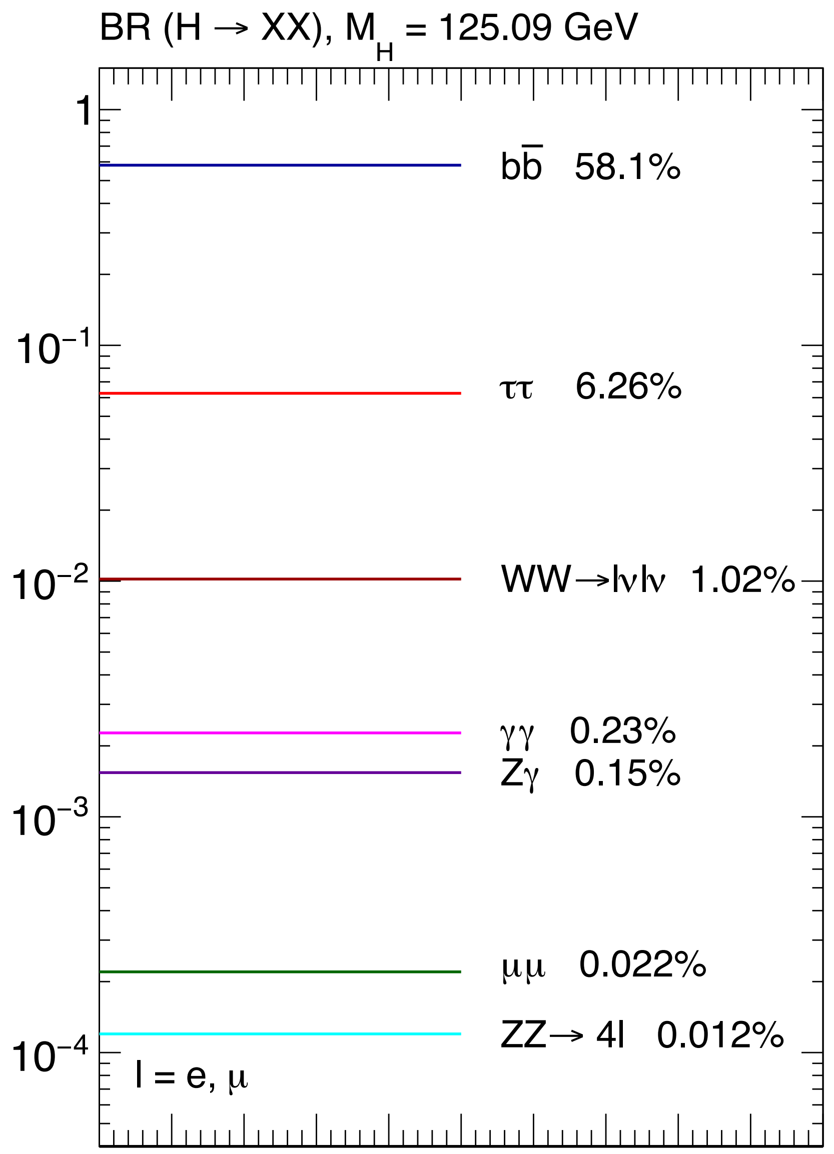
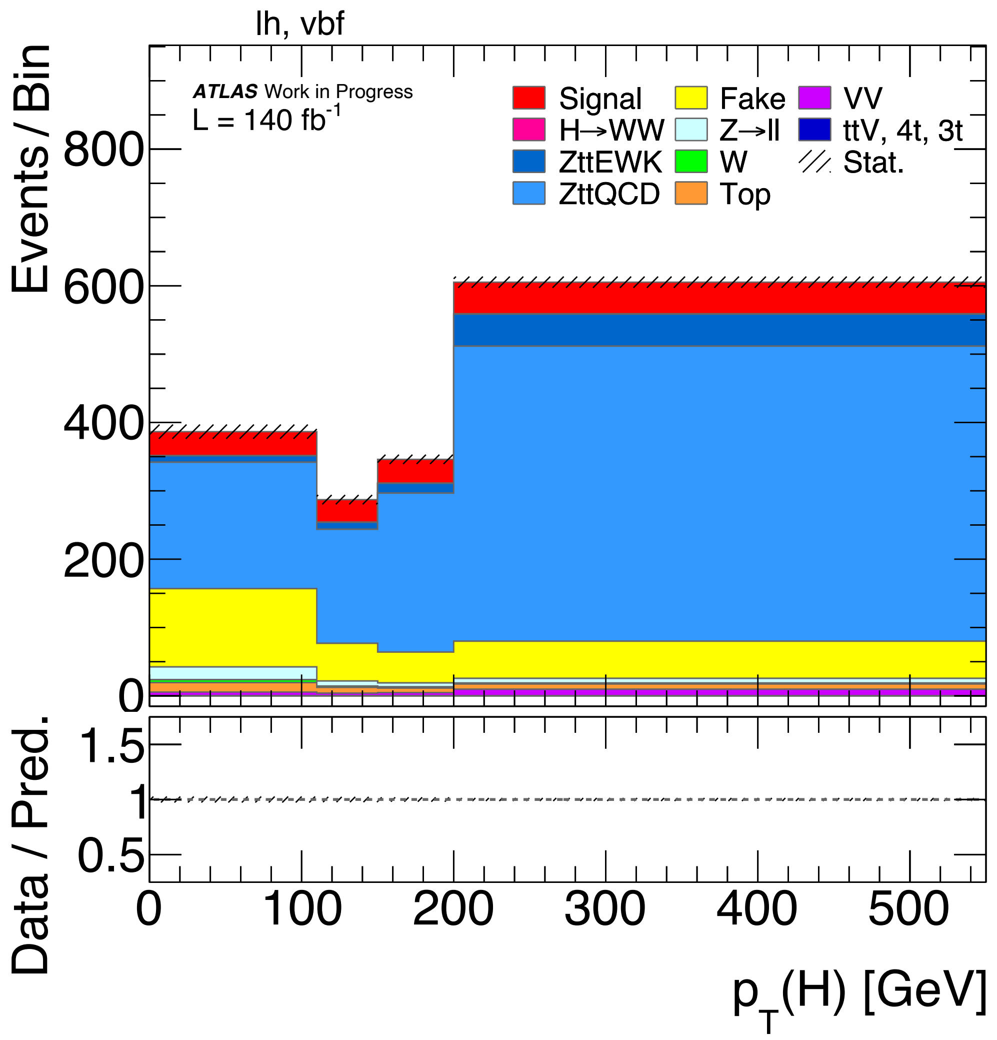
Why use the $H \to \tau\tau$ decay channel?

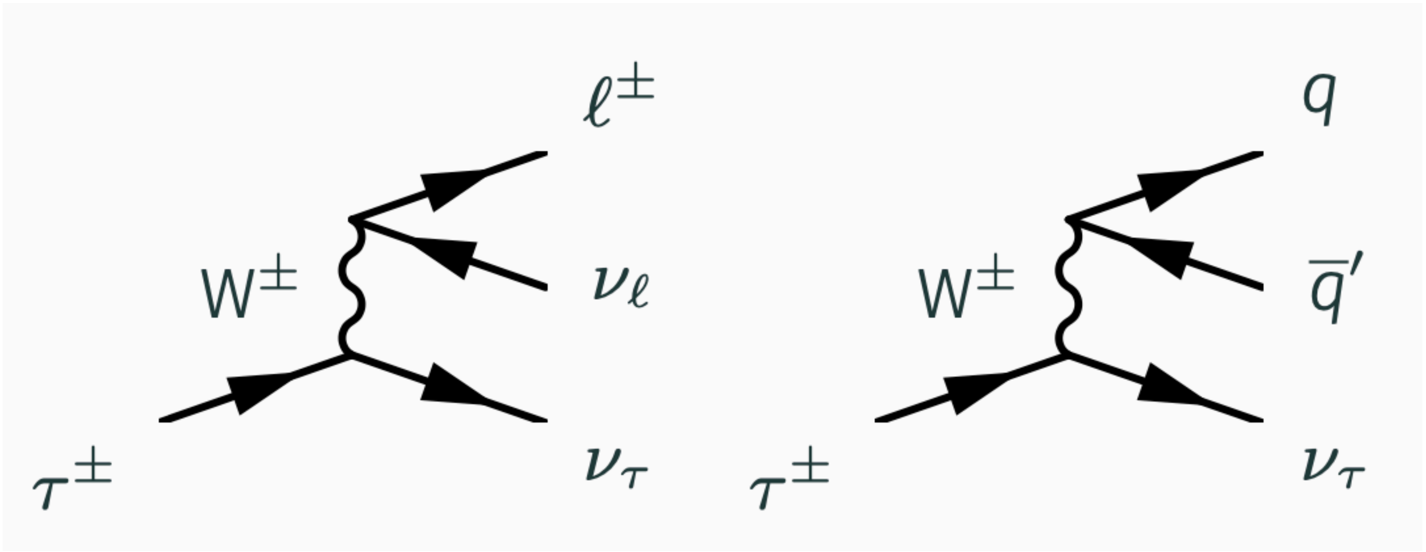


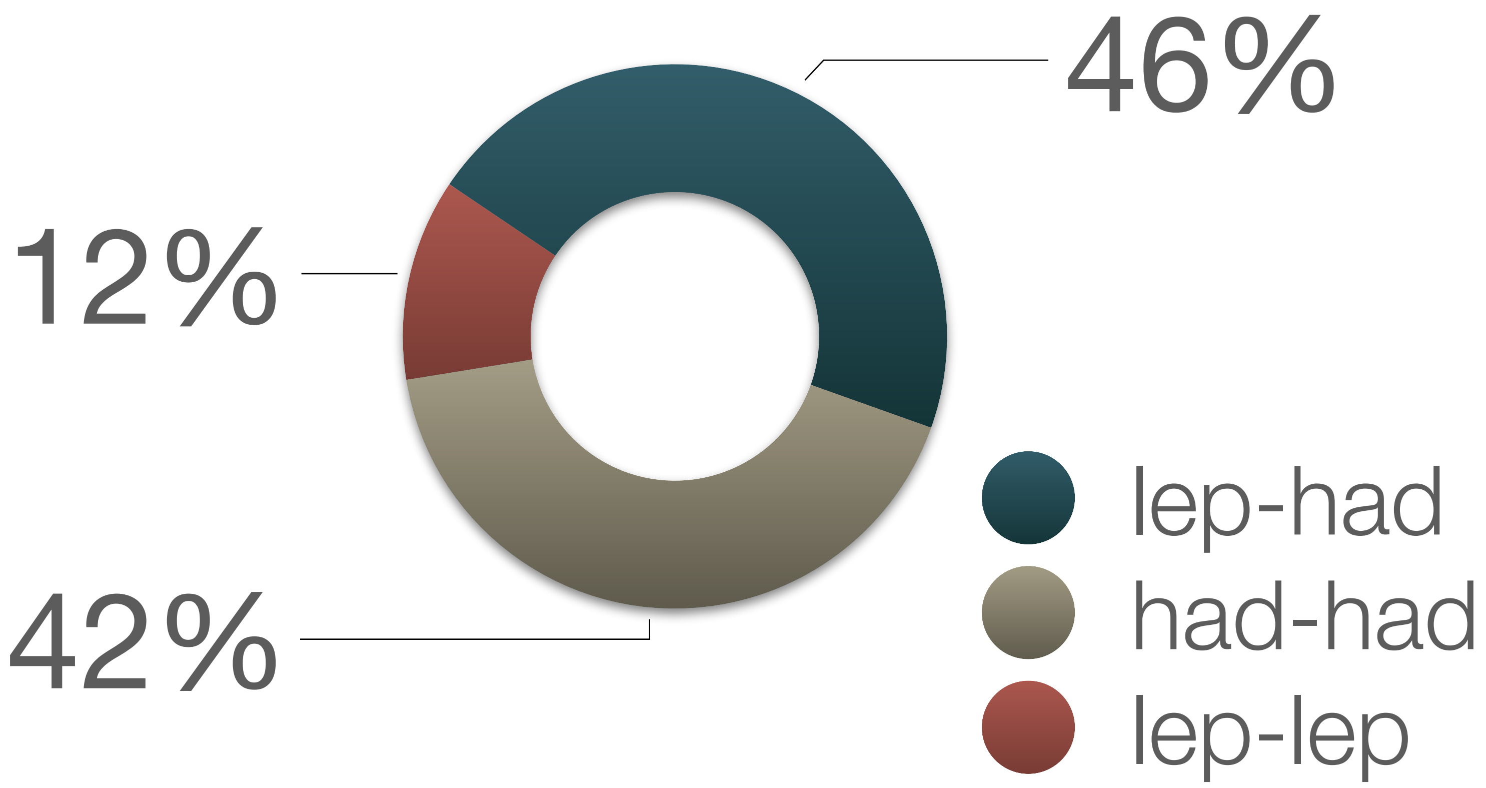
[1] Branching Ratios



- The $H \to \tau\tau$ has the highest branching ratio to leptons, $\mathscr{B}r(H \to \tau\tau) \approx 6.3\,\%$ for a Higgs mass of 125.09GeV

- Fermionic decay modes provide direct measurements of the Yukawa coupling



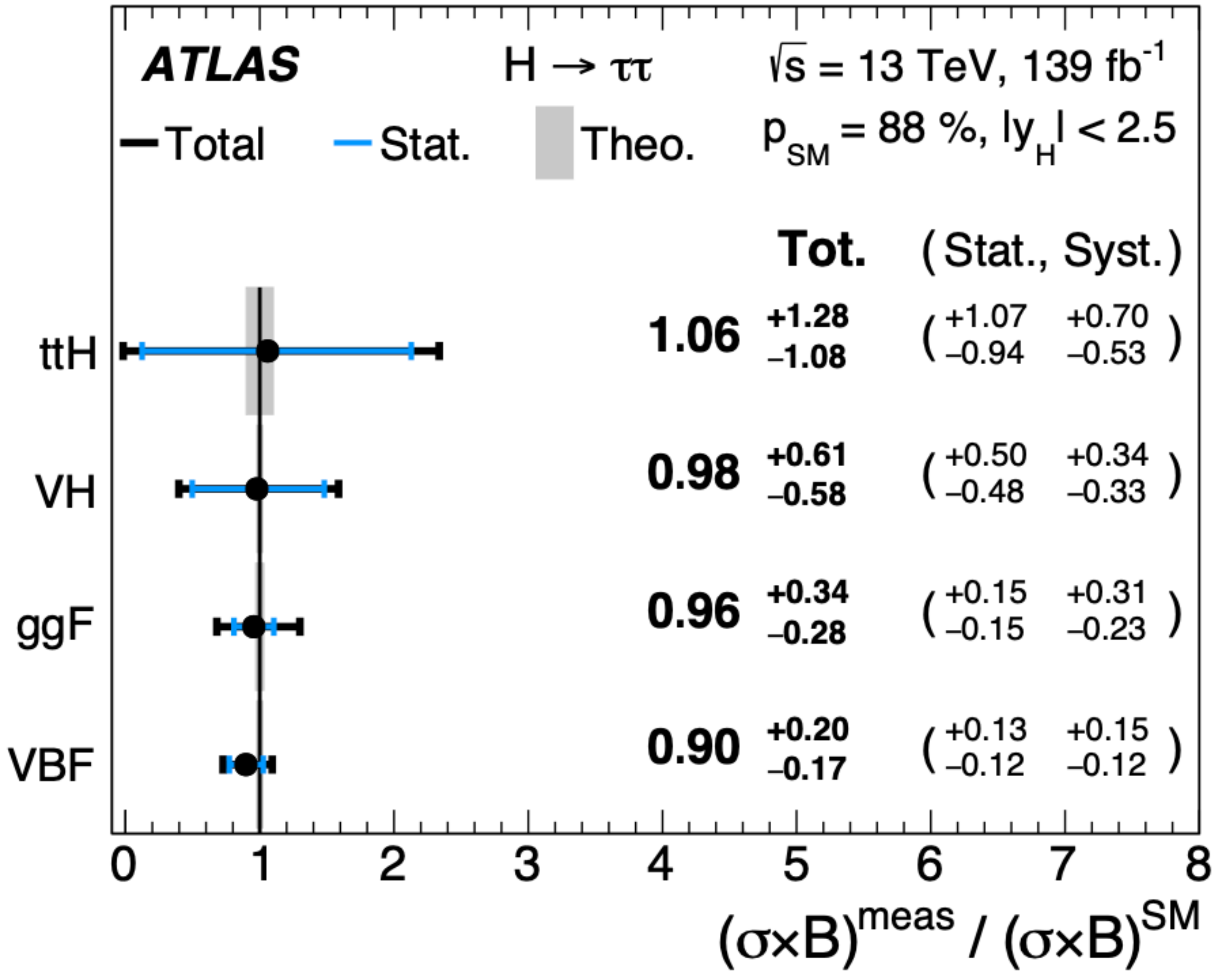


At the same time:

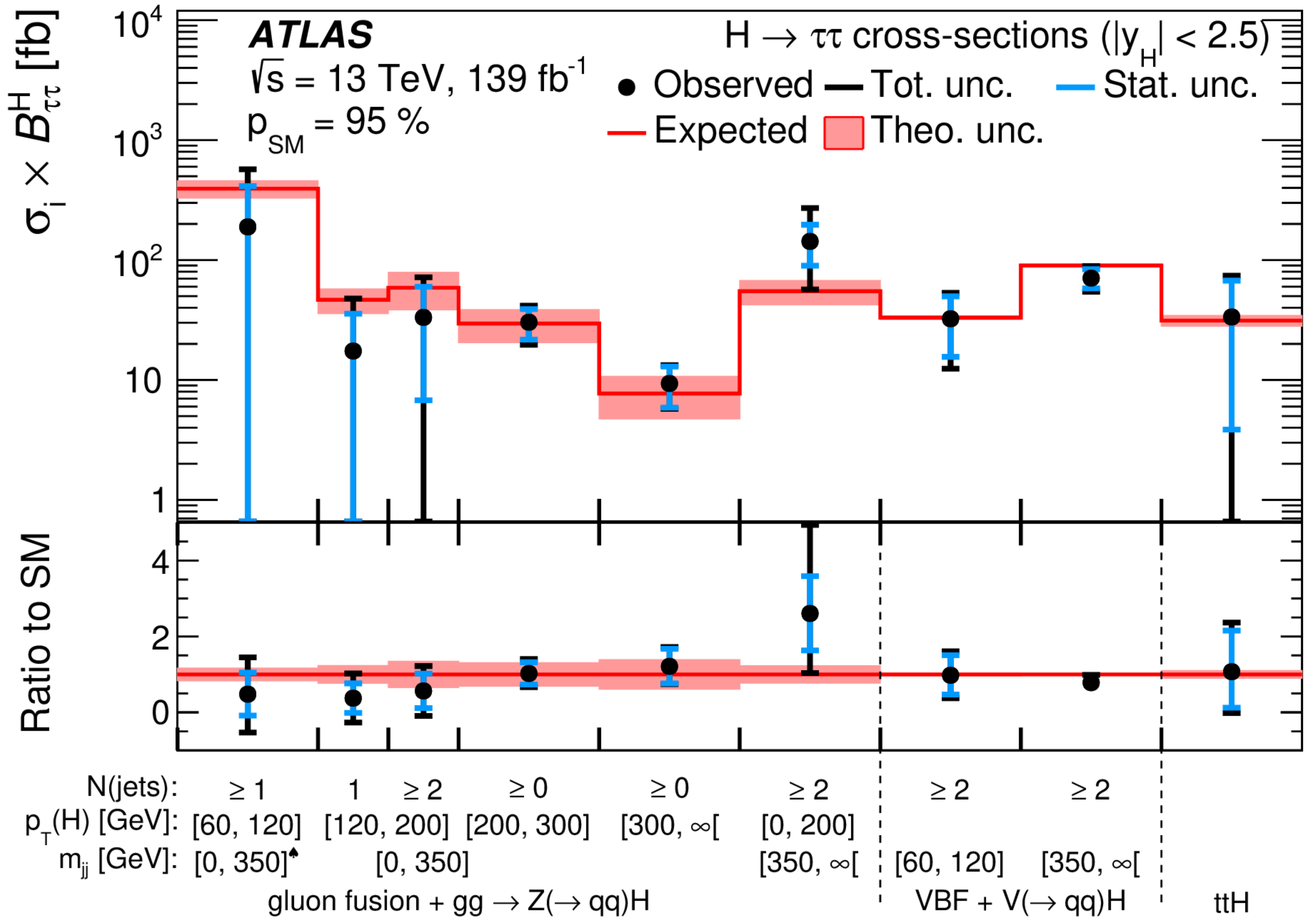
- τ lepton is the only lepton heavy enough to allow hadronic decays (65%)
- However, in both leptonic and hadronic τ decays, neutrinos are present in the final state. Their presence poses an additional challenge to the tau reconstruction.
- $H \to \tau\tau$ has a relatively low background contribution. Dominant background process $Z \to \tau\tau$, followed by misidentified τ leptons (Fake)

Why looking at the VBF Production Mode?

I am currently engaged in improving and extending JHEP 08 (2022) 175 to look at unfolded CP sensitive variables



[2] Measured Signal strength

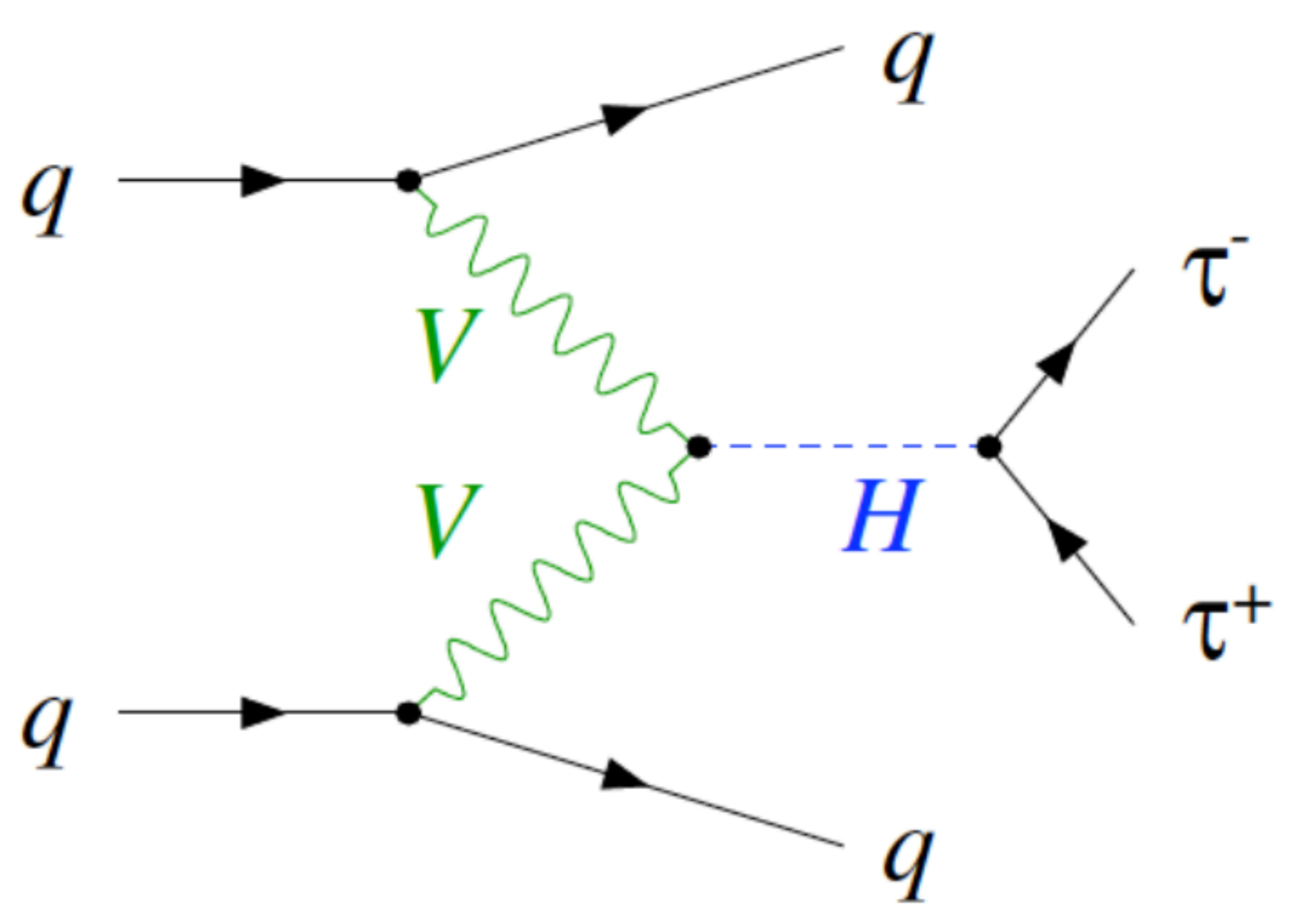


[3] $\sigma_H \times B(H \to \tau\tau)$ relative to the SM expectations in the 9 fiducial volumes defined in the STXS measurement.

- From Higgs combination has been seen that the $H \to \tau\tau$ can have very good sensitivity to the VBF production mode

One of the goals of the 2nd round analysis: $H \to \tau\tau$ fully differential measurement in ATLAS in the VBF phase space

VBF Production Mode



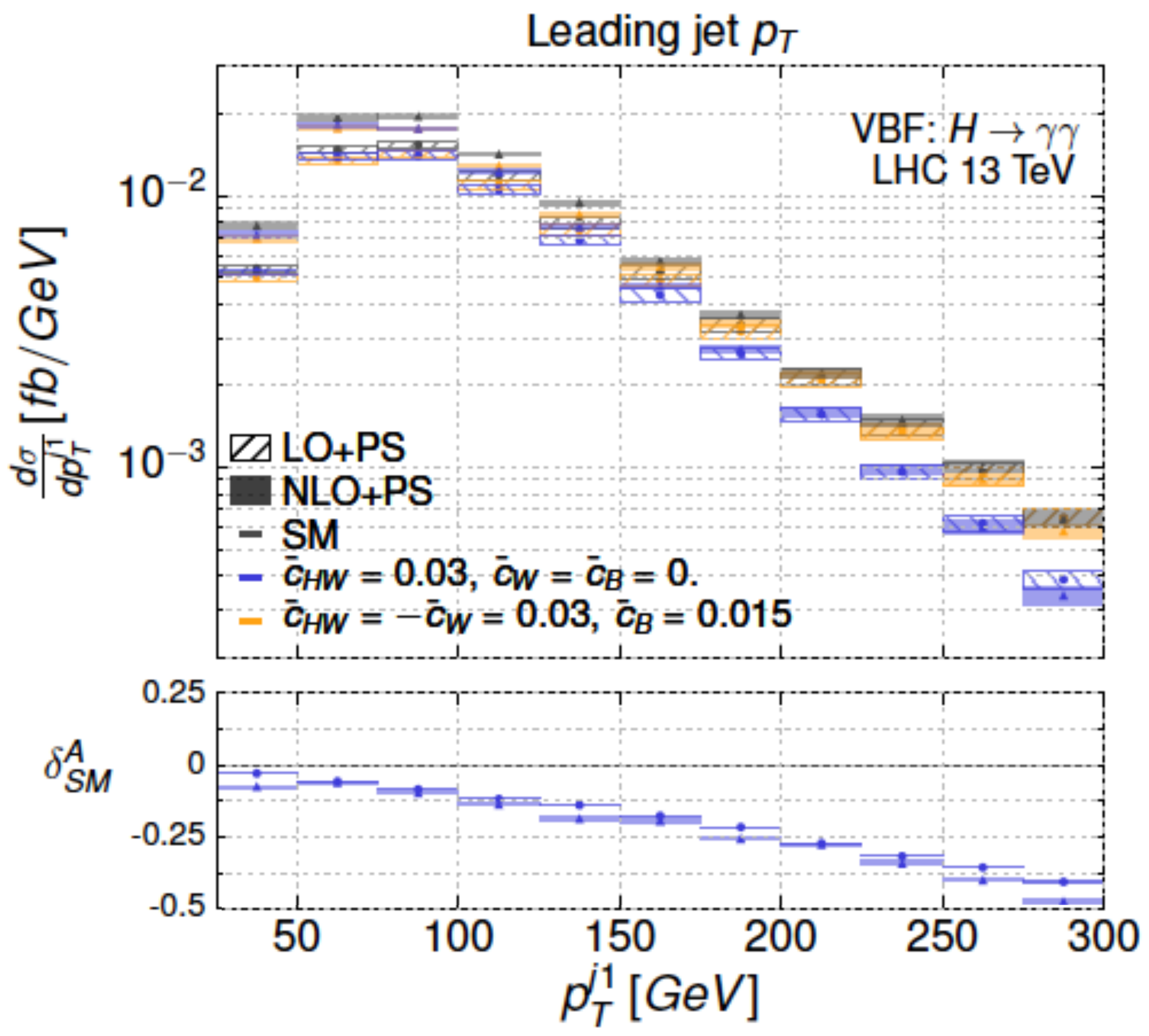
Use the VBF production mode

- Studying the kinematics of the Higgs boson and the two tagging jets
- Studying the CP properties of the Higgs boson
- Probing for new physics with Effective Field Theory (EFT)

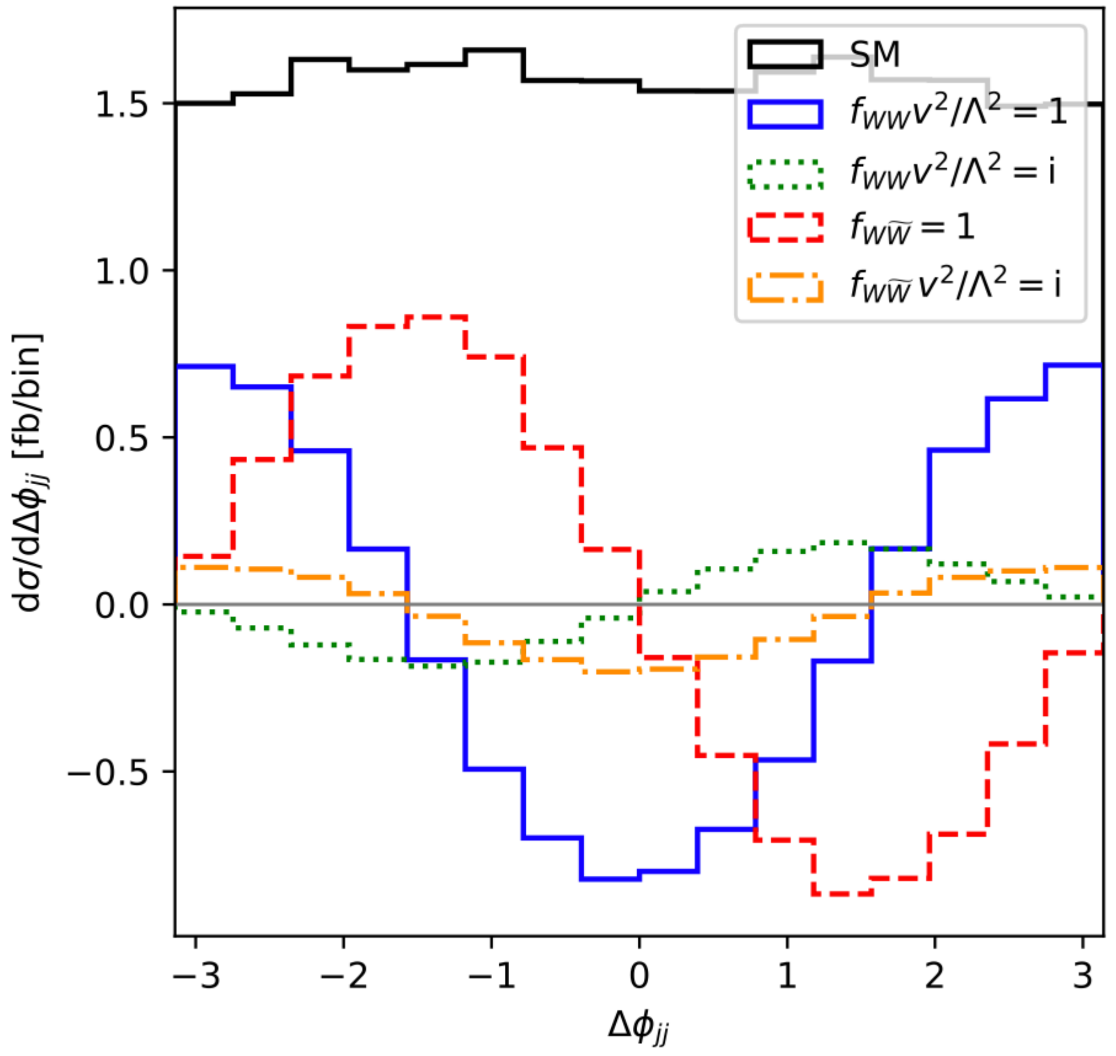
VBF related — SMEFT related

Variables to unfold: $\Delta\phi_{jj}^{signed}$, $p_T^{j_0}$, p_T^H, $\Delta\phi_{jj}^{signed}$ vs p_T^H

$\Delta\phi_{jj}^{signed}$ is defined as the azimuthal angle between the two jets, sorted by the jet rapidity



[3] Different EFT scenarios



[4] $\Delta\phi^{signed}$ in different EFT scenarios

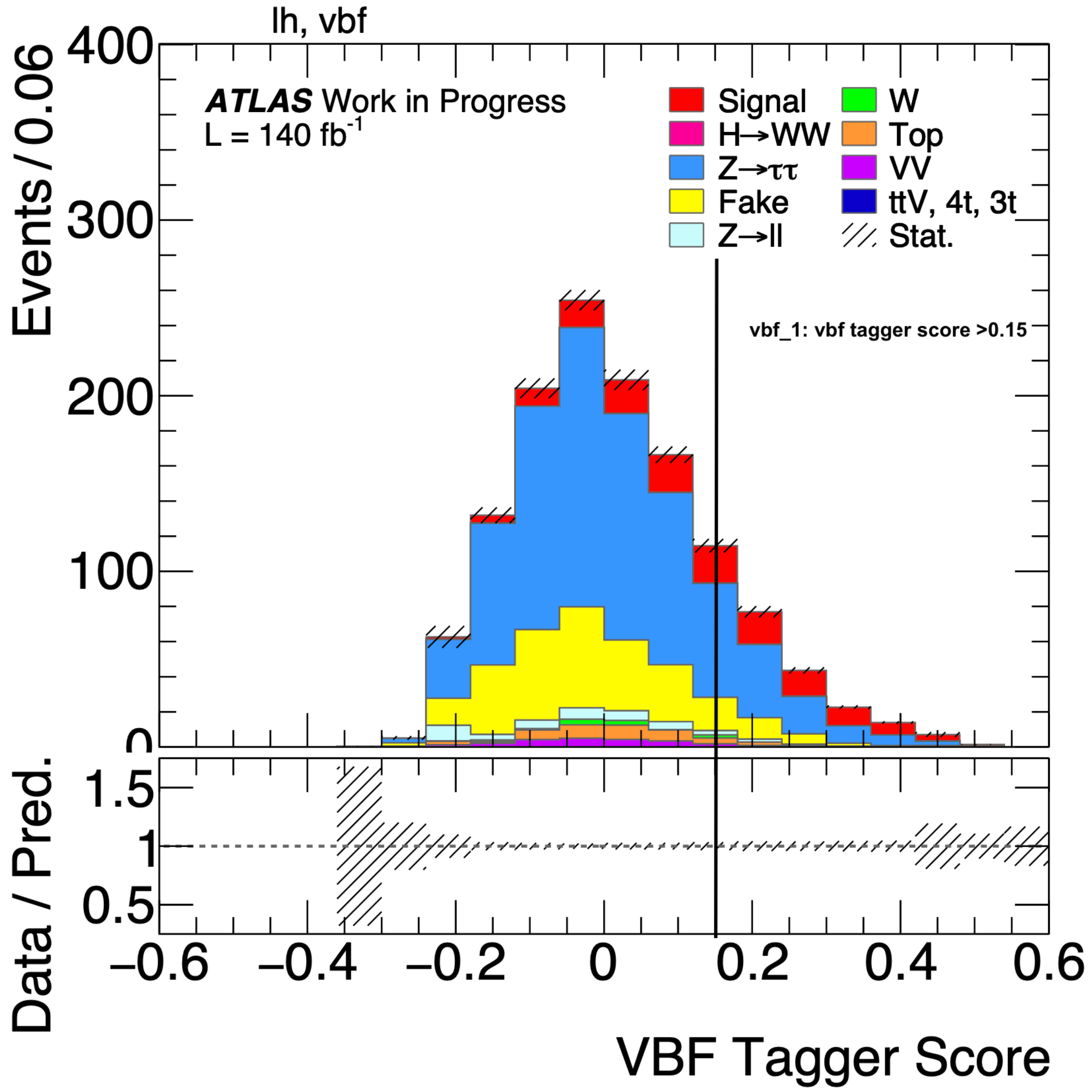
- In the VBF production mode , the $\Delta\phi_{jj}^{signed}$ distribution, a CP odd observable and can be used as a probe for the Higgs CP properties

- $\Delta\phi_{jj}^{signed}$ sensitive to the Higgs Gauge coupling, both CP conserving and CPV new physics
- Good sensitivity to possible BSM effects for $\Delta\phi_{jj}^{signed}$ at high-p_T^H

Differential Analysis Strategy: Selection Cuts

- Followed the previous analysis closely:
  - Select VBF Higgs using VBF selection cuts and MVA Tagger
  - Since we target only on VBF events: Tightened VBF cuts to decrease the ggF contamination
  - VBF splits in two regions:
    - VBF_1 is much richer in Signal,
    - VBF_0 has a larger ggF fraction

Old VBF cuts	New VBF cuts
$\eta^{j_0} \times \eta^{j_1} < 0$	
$\lvert\Delta\eta_{jj}\rvert > 3$	$\lvert\Delta\eta_{jj}\rvert > 3.4$
$C = 1$	
$m_{jj} > 350GeV$	$m_{jj} > 600GeV$
$p_T^{j_1} > 30GeV$	
—	$p_T^{jj} > 30GeV$
—	$p_T^{tot} < 50GeV$



VBF Cuts	Region	ggF fraction (%)
Old	VBF	26.5
	VBF 0	35.6
	VBF 1	6.1
New	VBF	17.0
	VBF 0	26.1
	VBF 1	6.1

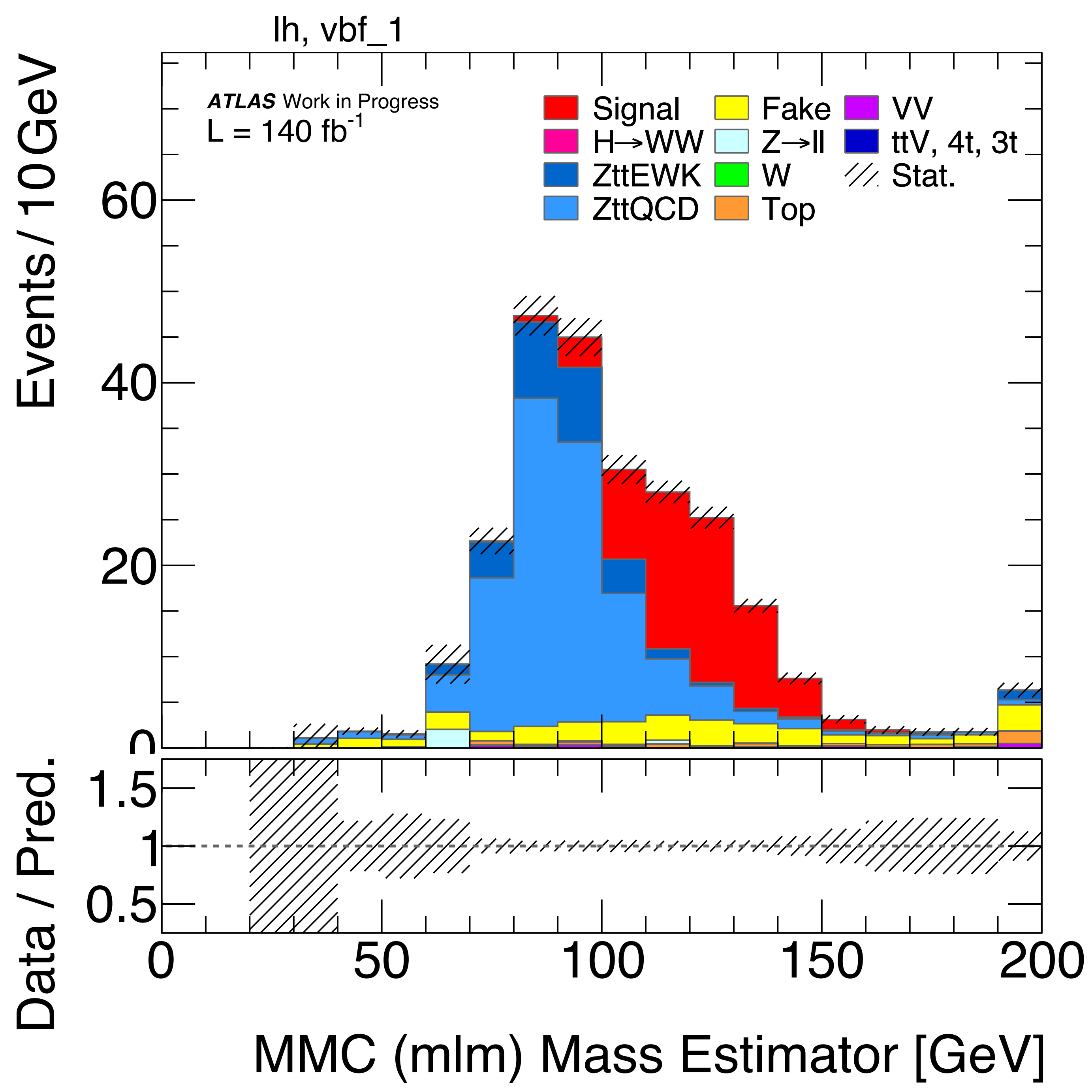
ggF contamination in $\tau_{lep}\tau_{had}$ channel

- The new cuts are chosen to keep vbf_1 region the same and vbf_0 is reduced

Differential Analysis Strategy: Mass Reconstruction

- Fit the $m_{\tau\tau}$ in each bin of the unfolded distributions to distinguish Signal from the dominant $Z \to \tau\tau$ background contribution
- To reconstruct the invariant mass of the ditau system $m_{\tau\tau}$, 2 tools were used
  - The missing Mass Calculator (MMC)
  - The Collinear Mass Approximation (CLMA) -only for a tiny fraction of events where MMC fails

→ expect to recover 0.7% of Signal events



MMC

- Advanced likelihood-based technique
- Relies on the variance of energy and position of neutrinos due to the limited resolution, and aims at estimating their energy and direction

CLMA

- Two assumption are considered:
  - The invisible decay products of the t-lepton decays fly in the same direction as the visible decay products
  - The missing transverse energy can only correspond to neutrinos

Unfolding & Differential Cross-section Measurement

- The differential cross-section measurement is obtained by:

$$\sigma^{diff} = \frac{N_i^{truth}}{L} = \frac{1}{L}\frac{1}{\varepsilon_i} \cdot \sum_j M_{ij}^{-1} \cdot f_j^{reco} \cdot (N_j^{reco} - N_j^{bkg})$$

Migration Matrix

Efficiency

Correction Factor

$$\varepsilon_i = \frac{N_i^{truth+reco}}{N_i^{truth}}$$

$$f_j = \frac{N_j^{truth+reco}}{N_j^{reco}}$$

VBF Cuts	Region	ε_i	f_j
Lep-Had	VBF	0.33	0.77
	VBF 0	0.16	0.64
	VBF 1	0.17	0.88

Our goal is to increase ε_i, while keeping f_j at high values

VBF Cuts	Region	Reco	Truth	Reco & Truth
Old	vbf	161.70	389.72	134.54
	vbf_0	97.74		77.03
	vbf_1	63.96		57.51
New	vbf	123.74	395.86	98.51
	vbf_0	61.65		42.85
	vbf_1	62.10		54.68

Yield Table of $\tau_{lep}\tau_{had}$

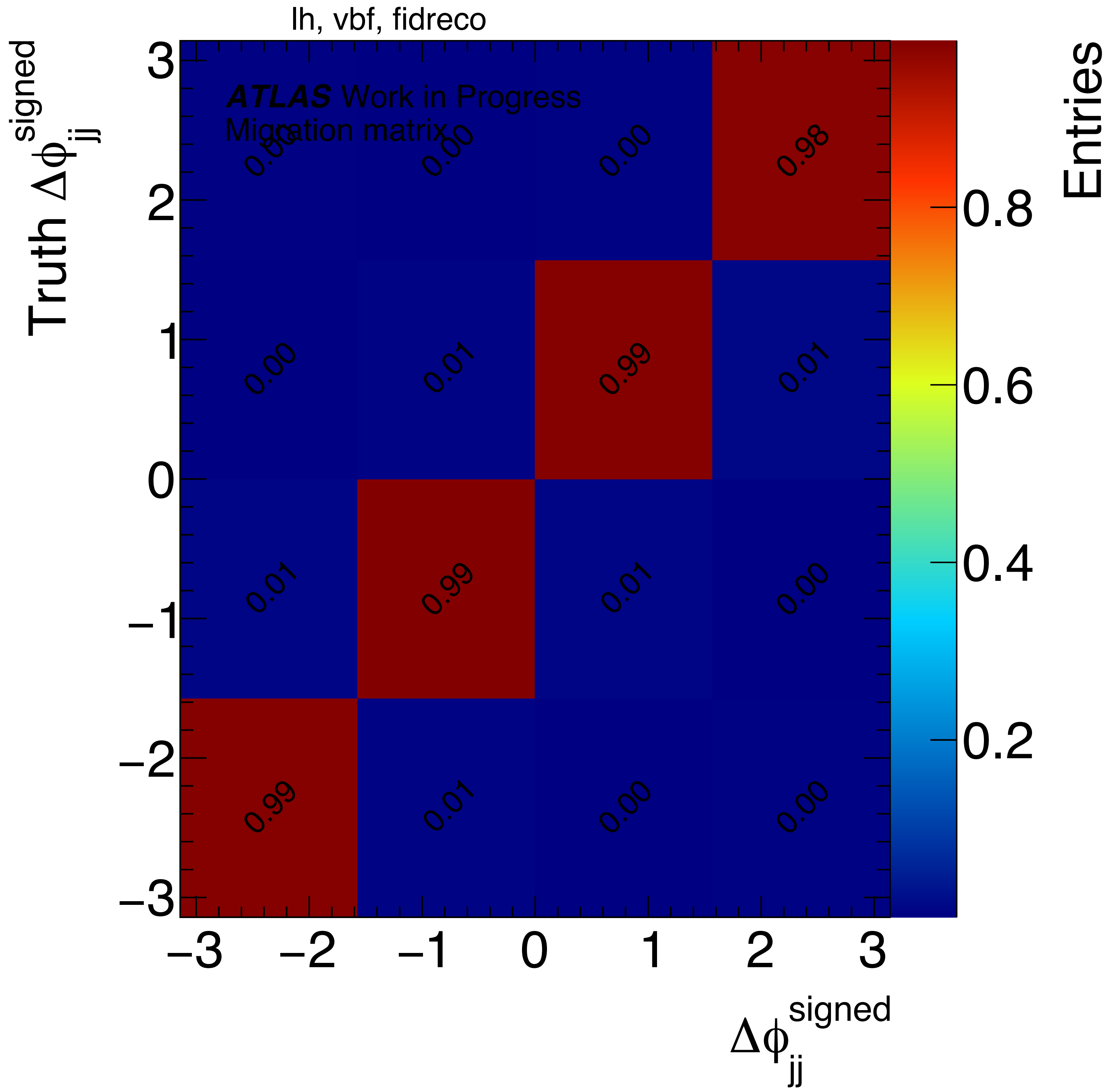
- Fiducial cross section = cross section in fiducial volume (Cuts applied to particle-level events to reproduce the phase space of the measurement)
- The Unfolding method is used to invert the migration matrix and extract the particle-level spectrum of a variable from the reconstructed.
- A Profiled Likelihood Unfolding is employed in this analysis

→ **The Unfolding problem boils down to a matrix inversion problem**

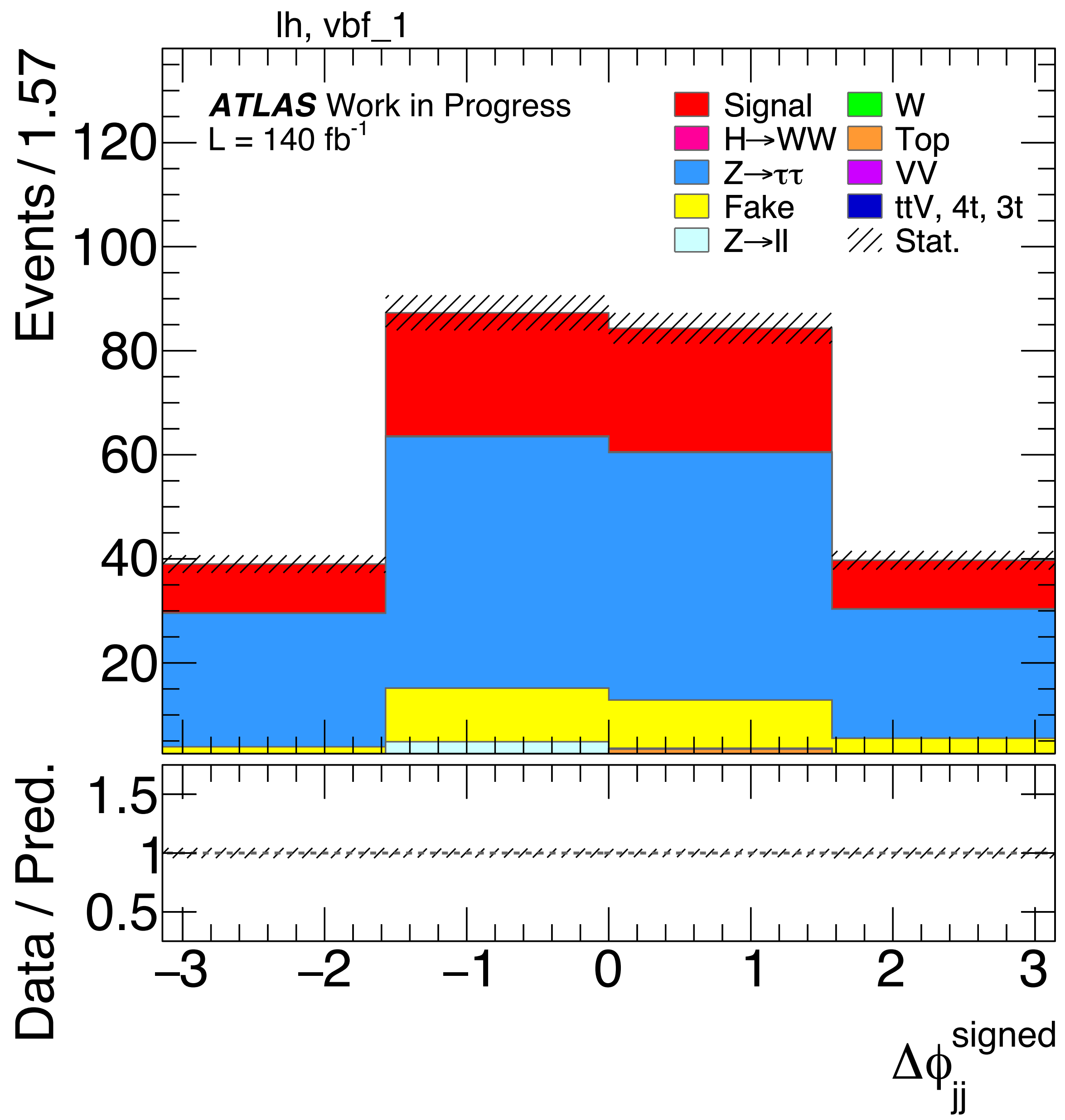
Unfolding: Binning of the unfolding variables

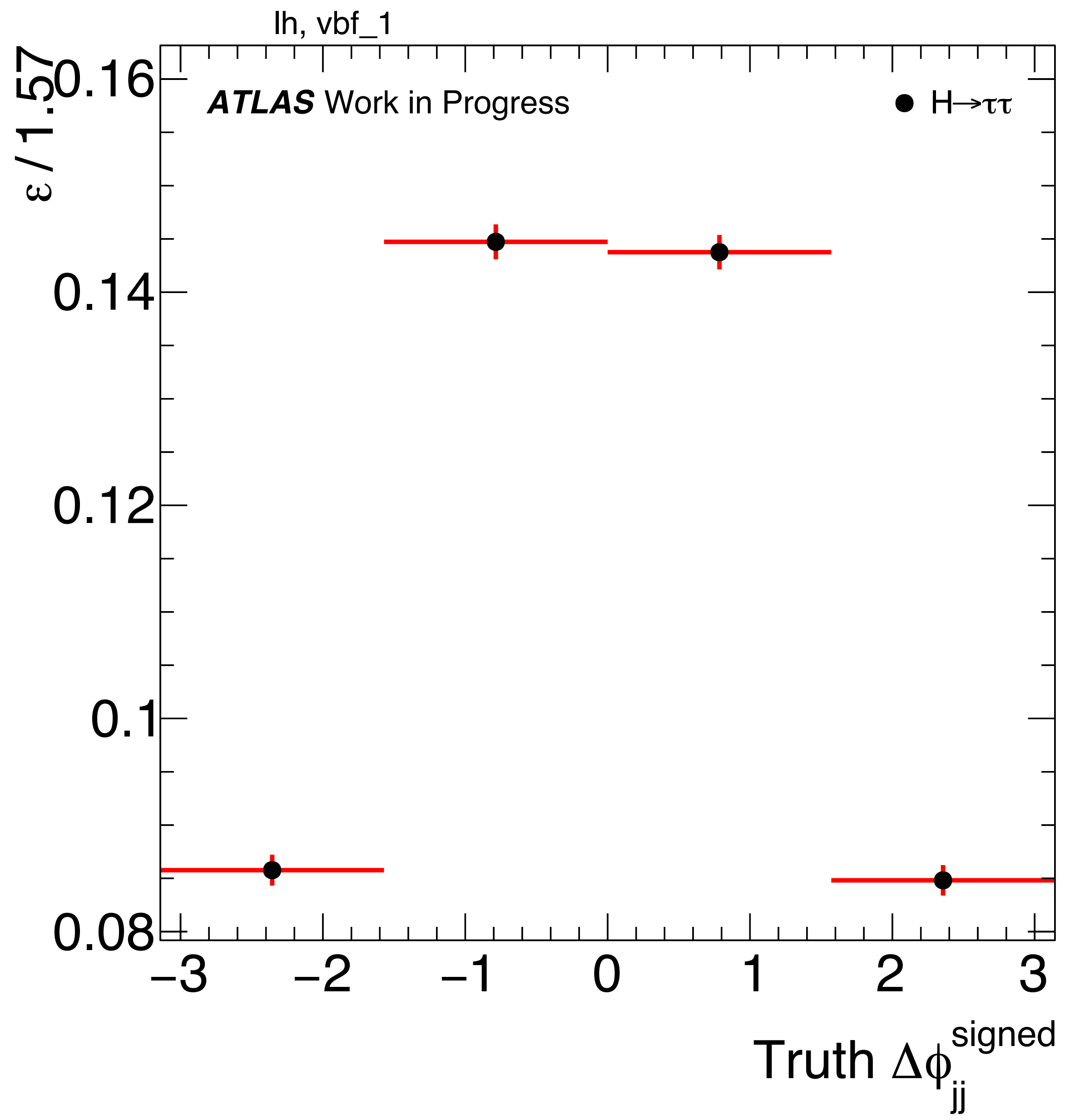
- Large off-diagonal elements lead to instabilities/large uncertanties → Choose binning in a way that the migration matrix is diagonal, and consequently easy to invert.
  - Due to limited statistics, decided to make 4 bins for each one of the unfolding variables
    - For $\Delta\phi_{jj}^{signed}$, same binning as in the $H \rightarrow \gamma\gamma$ was used
    - For $p_T^{j_0}$ and p_T^H, a yield significance approach was employed

$p_T^{j_0}$	p_T^H	$\Delta\phi_{jj}^{signed}$	$\Delta\phi_{jj}^{signed}$ vs p_T^H
[40,95]	[0,110]	$[-\pi,-\pi/2]$	$p_T^H < 200$ & $\Delta\phi_{jj} < 0$
[95,130]	[110,150]	$[-\pi/2,0]$	$p_T^H < 200$ & $\Delta\phi_{jj} > 0$
[130,180]	[150,200]	$[0,\pi/2]$	$p_T^H > 200$ & $\Delta\phi_{jj} < 0$
[180,500]	[200,550]	$[\pi/2,\pi]$	$p_T^H > 200$ & $\Delta\phi_{jj} > 0$



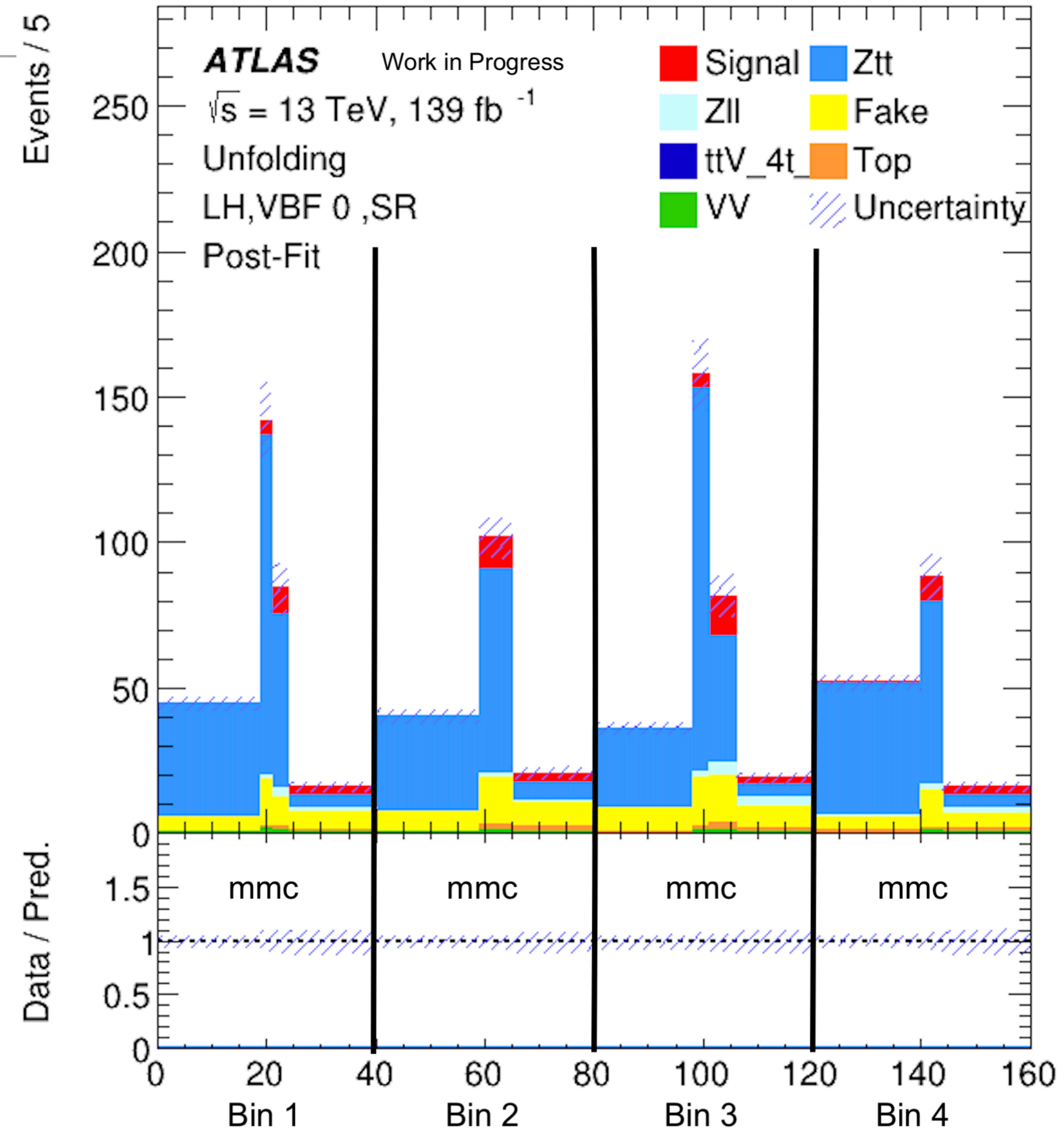
The migration matrices for all variables are very diagonal (see back up)





Fit Setup and Results

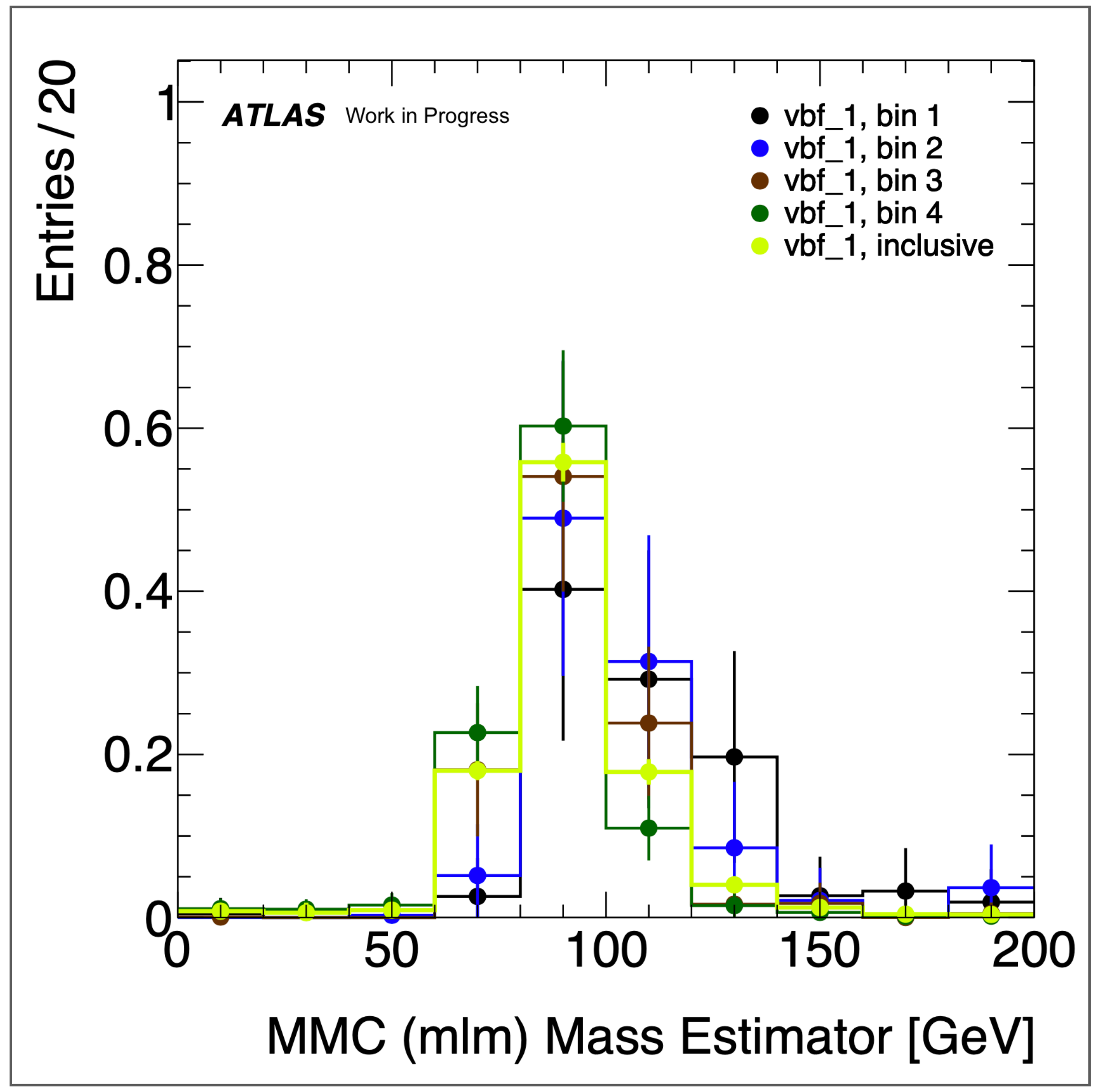
- Fit the $m_{\tau\tau}^{mmc}$ in each one of the unfolded bins
- MMC range [0,200]GeV
- For the mmc binning an algorithm is employed that requires every bin to have $\alpha^{MC\ stat} < 20\,\%$
- In the fit, 2 SR regions VBF_0 and VBF_1, and a Top control region are considered.



	syst + stat.	MC+data stat.	data stat.
$\Delta\mu_1$	± 0.65	± 0.58	± 0.47
$\Delta\mu_2$	± 0.66	± 0.65	± 0.47
$\Delta\mu_3$	± 0.62	± 0.60	± 0.43
$\Delta\mu_4$	± 0.45	± 0.44	± 0.32

- Results are dominated by Data stat. followed by MC stat. (Background Templates) which includes statistical uncertainty of Fake estimate and $Z \to \tau\tau$

$Z \to \tau\tau$ (QCD) background template



- Need to improve background templates; this will enable us to bin more finely, but also reduce the MC stat uncertainty in the fit.
- Observed similar behaviour in all unfolding variables

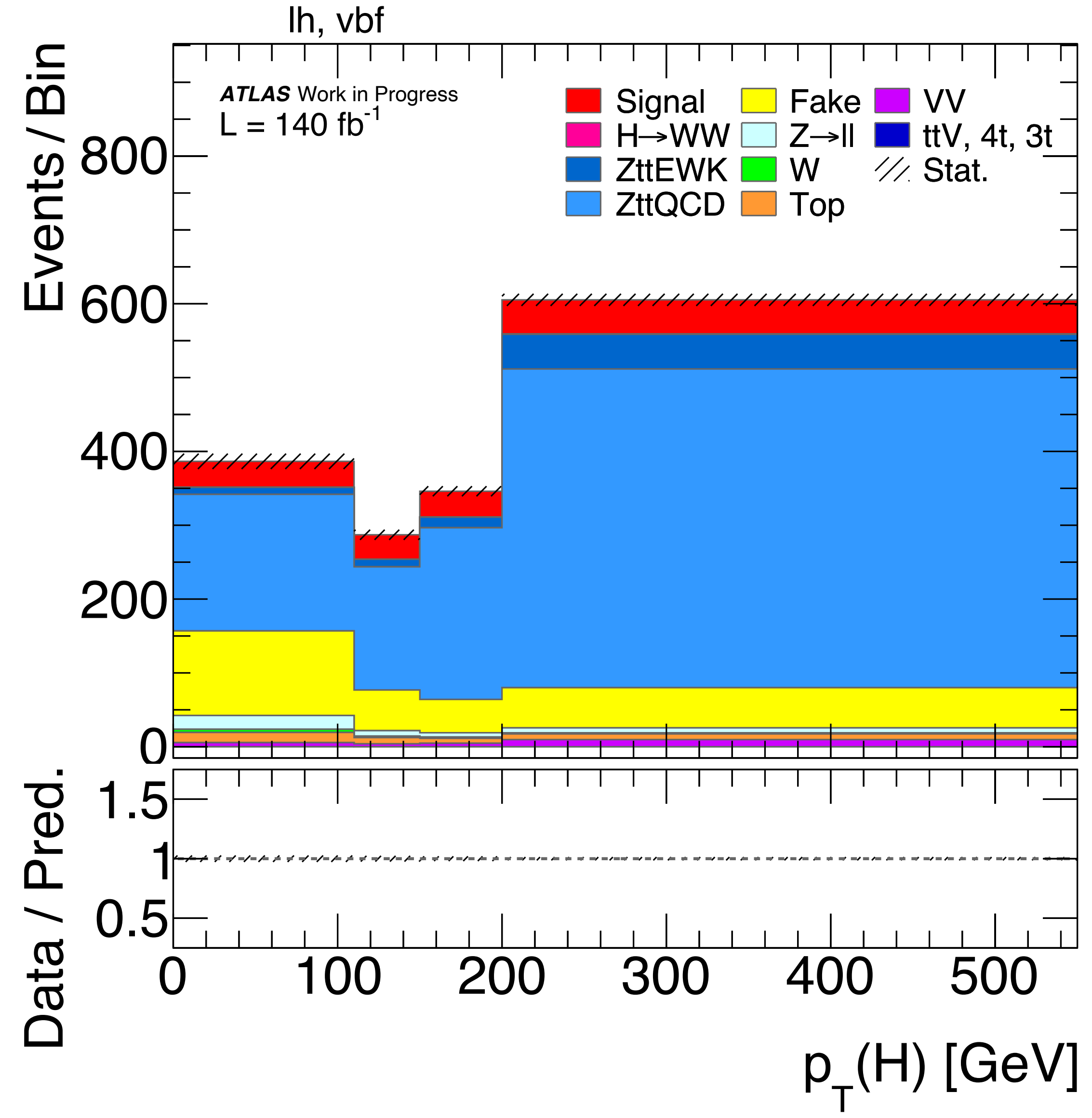
- For Fake templates, more inclusive templates were used

ZttQCD: Go with the flow

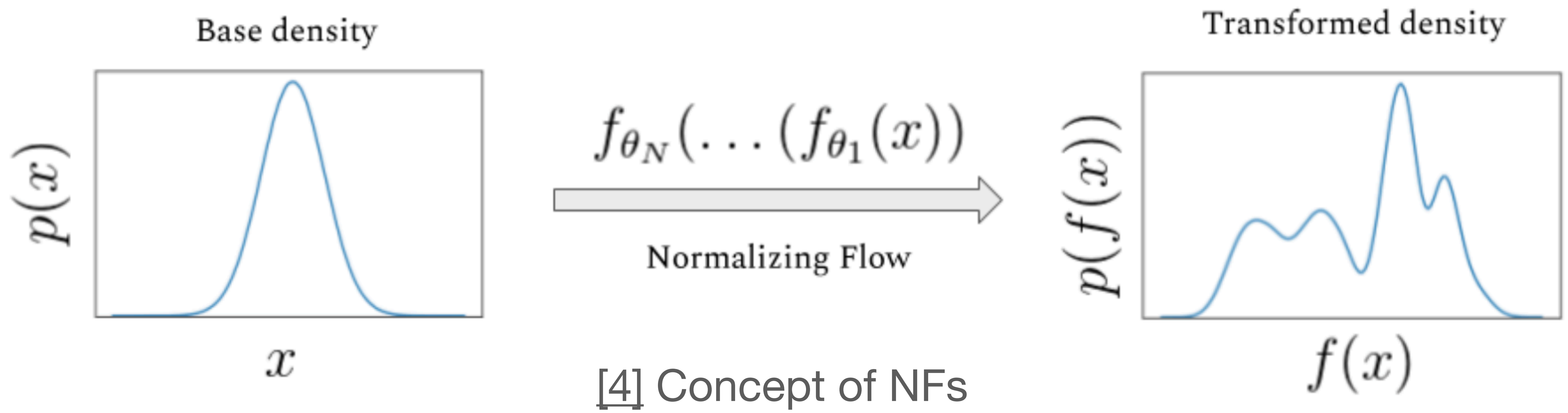
- The limited statistics of the Fake template and the ZttQCD template have the largest effect next to data stats on the results
- Generating more MC stats for $Z \rightarrow \tau\tau$ (QCD) is highly inefficient due to pile-up jets in the selection

Normalising Flows: Make the best out of the MC statistics

- Neural network to learn the correlation between the understudy variables under the assumption that distributions are smooth.
- Expert in Warwick group (Chris Pollard)



ZttQCD has the largest contribution in the $Z \rightarrow \tau\tau$ background



[4] Concept of NFs

- Normalizing Flows (NFs) learn an invertible mapping f: X →f(x), where X: Data and f is a chosen latent-distribution
- The invertible functions are constructed in a way so that we can easily sample from f(x) and calculate its density function $p(f(x))$
- Once we learn the mapping f, we generate data and apply the inverse transformation $f^{-1}(x)$

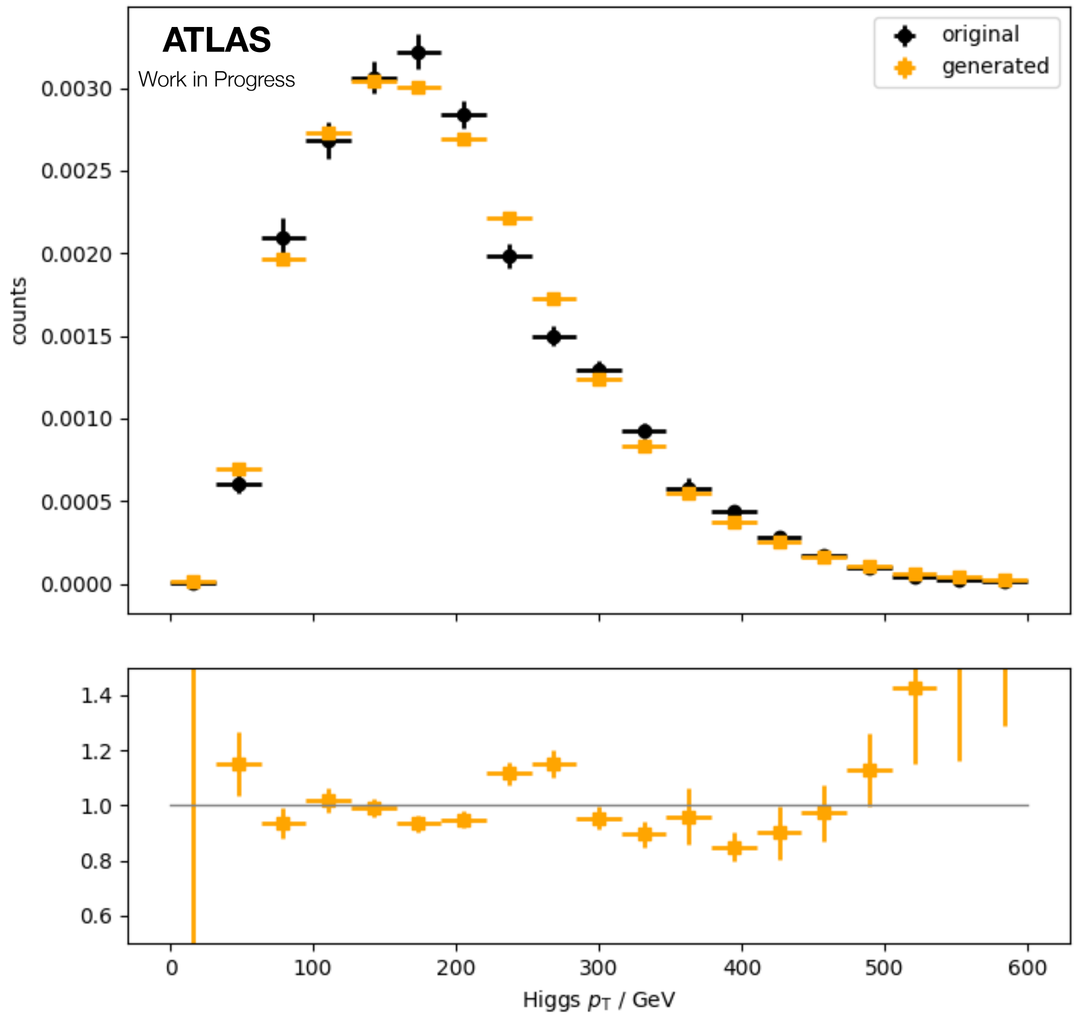
Normalising Flows Implementation

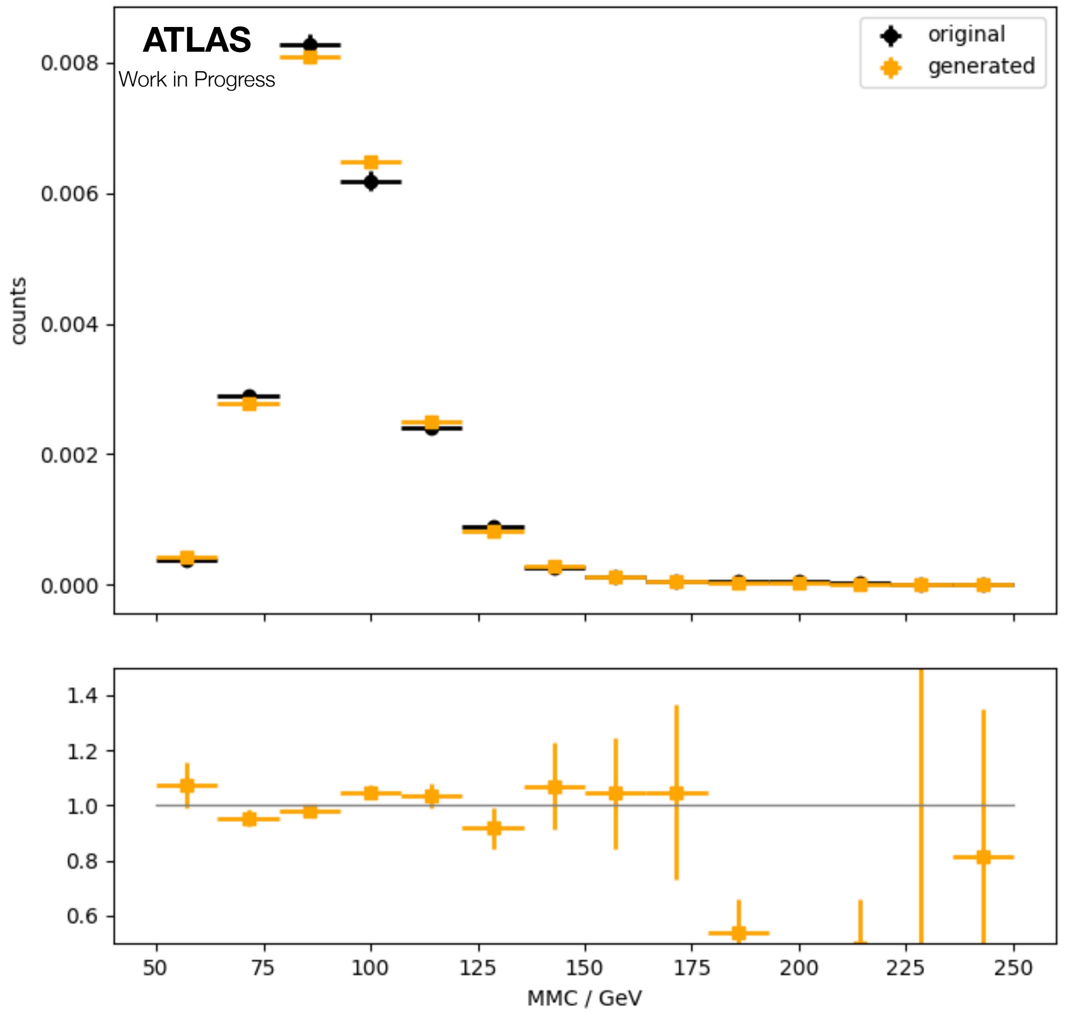
- Normalising Flows (NFs) is morphing strategy that transforms simulated event by employing a deep learning based Machine Learning (ML) method to estimate the probability density function to to better match the data.
- Several different neural network architectures were studied, the NN takes 11 variables as inputs:

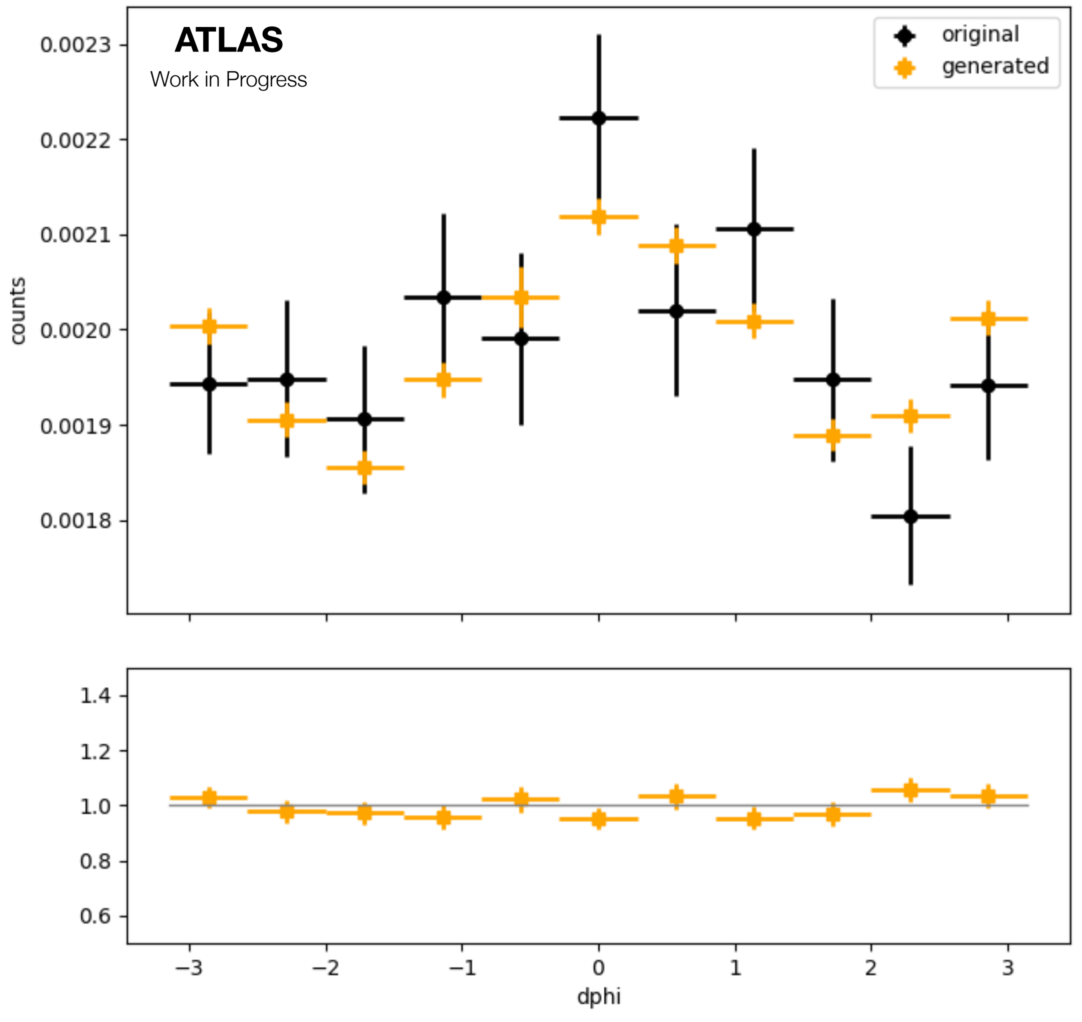
p_T^H	$p_T^{j_0}$	mmc	vbf tagger	weights	p_x^0	p_y^0	p_x^1	p_x^1	y_0	y_1

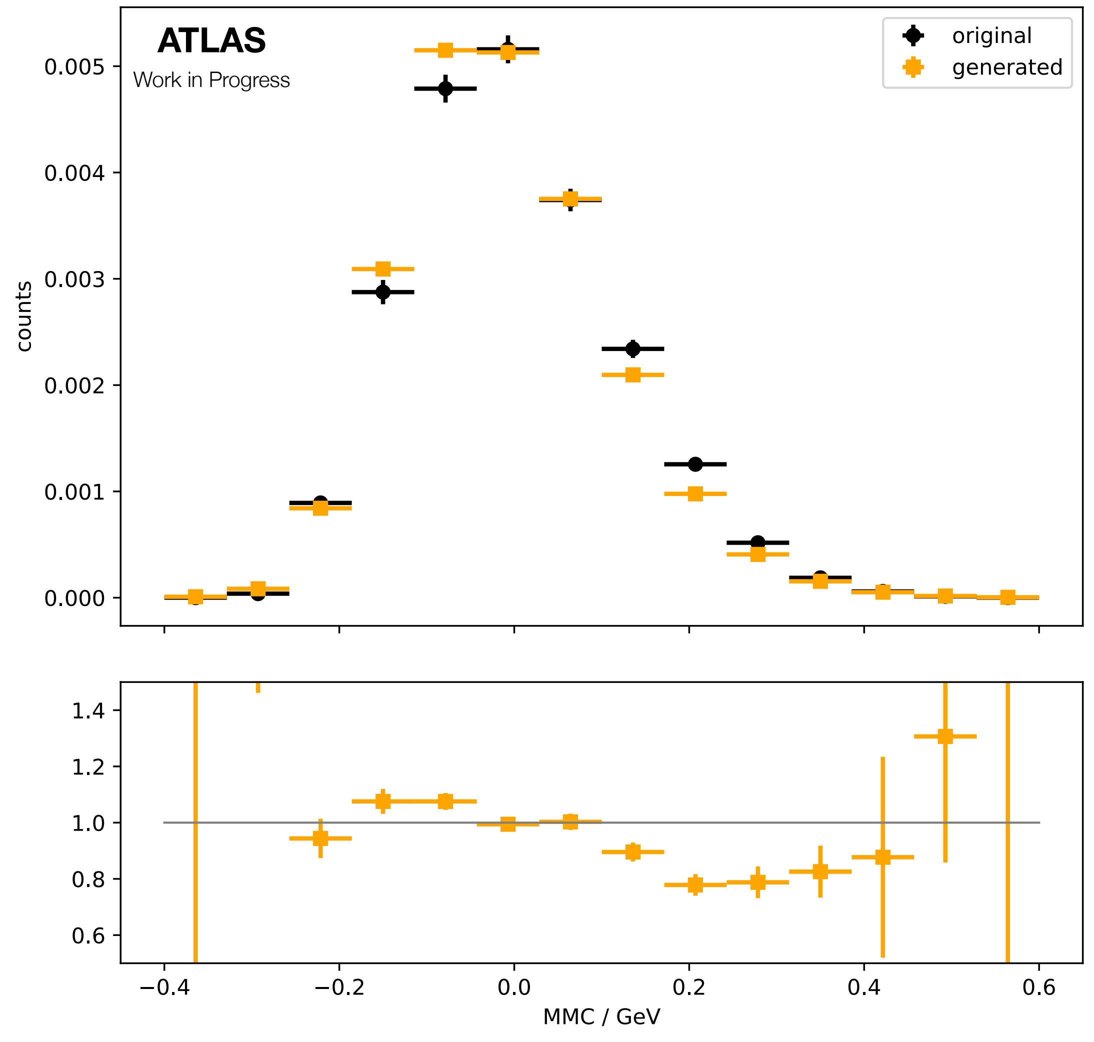
$\Delta\phi_{jj}^{signed}$

Issue with Periodic quantities such as ϕ or Δϕ. That's because really π and −π are equivalent in Δϕ space.





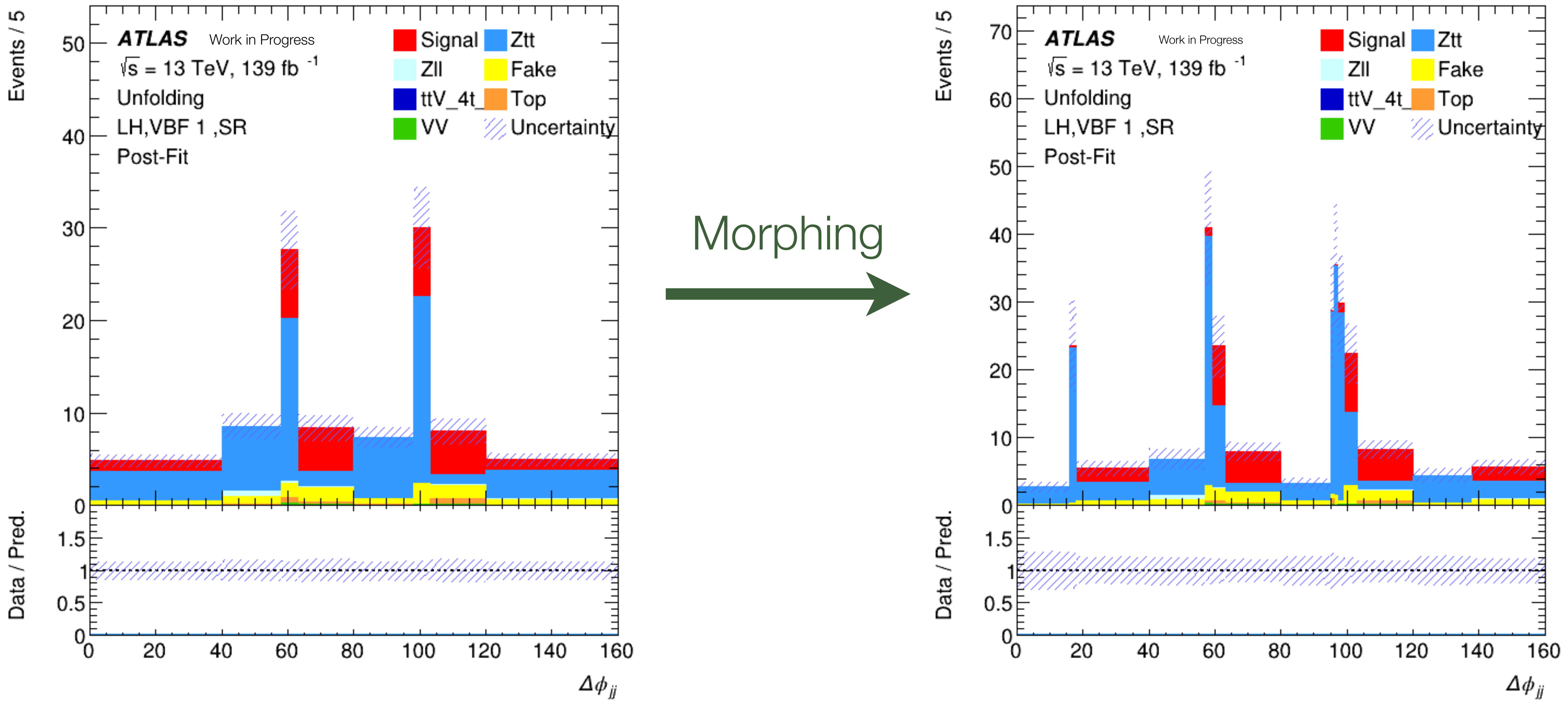




The current hyper parameter tuning shows good agreement between original and generated events

First Attempt with Normalising Flows

- At this point NFs are only applied to the nominal histograms
- An additional uncertainty related to the NFs needs to be considered (work in progress)



	syst + stat	MC + data stat.	Data stat.
$\Delta\mu_1$	±0.60	±0.54	±0.46
$\Delta\mu_2$	±0.38	±0.35	±0.27
$\Delta\mu_3$	±0.38	±0.35	±0.28
$\Delta\mu_4$	±0.59	±0.54	±0.44

(See back-up for other variables in $\tau_{lep}\tau_{had}$ channel)

So far, Morphing has been applied in the $\tau_{lep}\tau_{had}$ channel

- When Morphing is applied, able to bin more finely
- Additionally, Bin μ uncertainties were decreased for all variables

Status of the analysis

- The first differential measurement cross-section $H \rightarrow \tau\tau$ measurement in the VBF phase space and 4 distributions were unfolded $\Delta\phi_{jj}$ $p_T^{j_0}, p_T^H, \Delta\phi_{jj}$ vs p_T^H.
- A brief overview of the analysis was presented here
- In this presentation, only the Asimov unfolding results for the $\tau_{lep}\tau_{had}$ channel were presented.
- Due to time constraints, Normalising flows were not applied to the other channels. Thus, morphed histograms are not used for the combined fit.

Status of the analysis

✓ The analysis is complete and in the approval process to be unblinded

Unblinding Results coming soon!

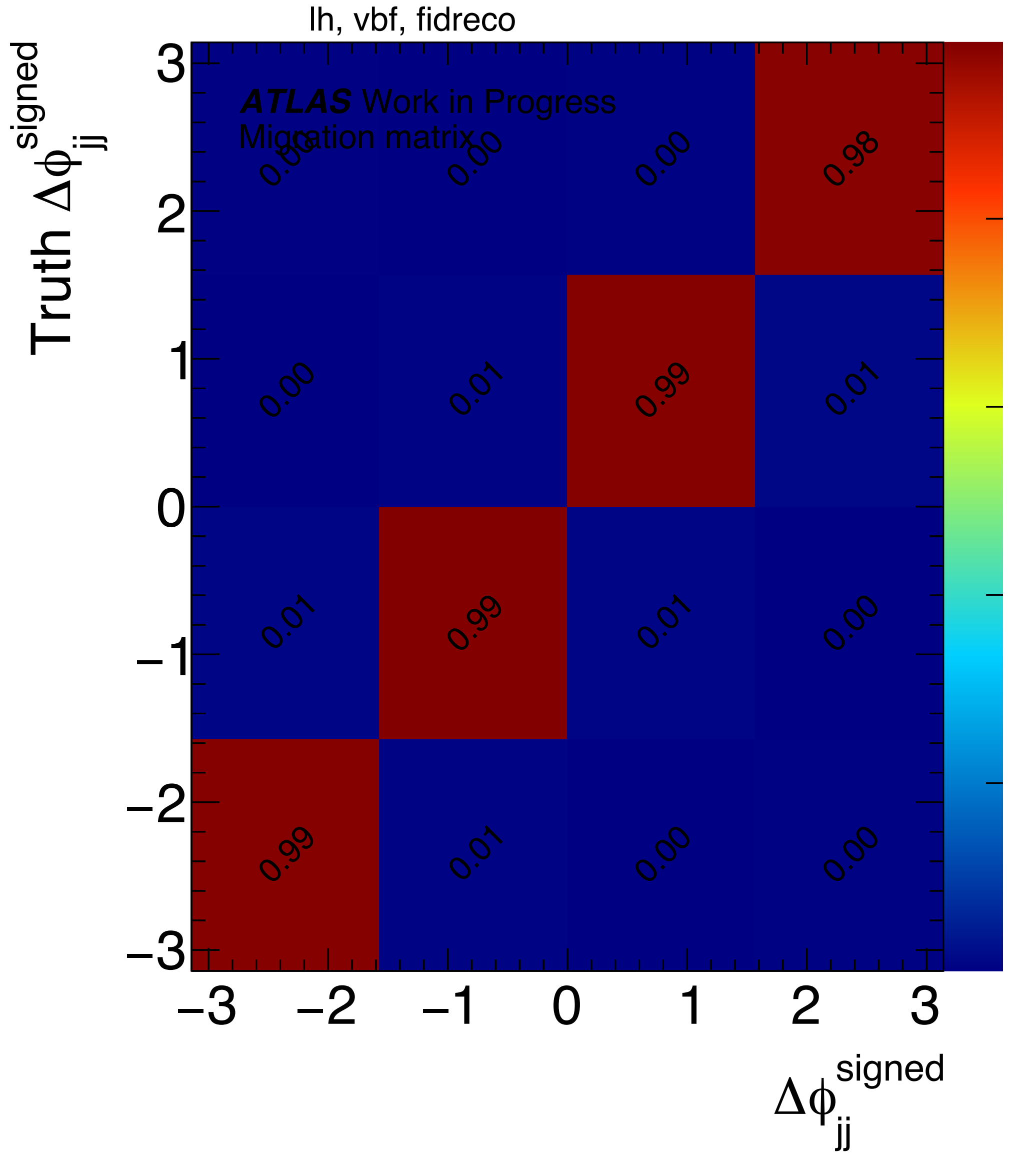
Thank you!

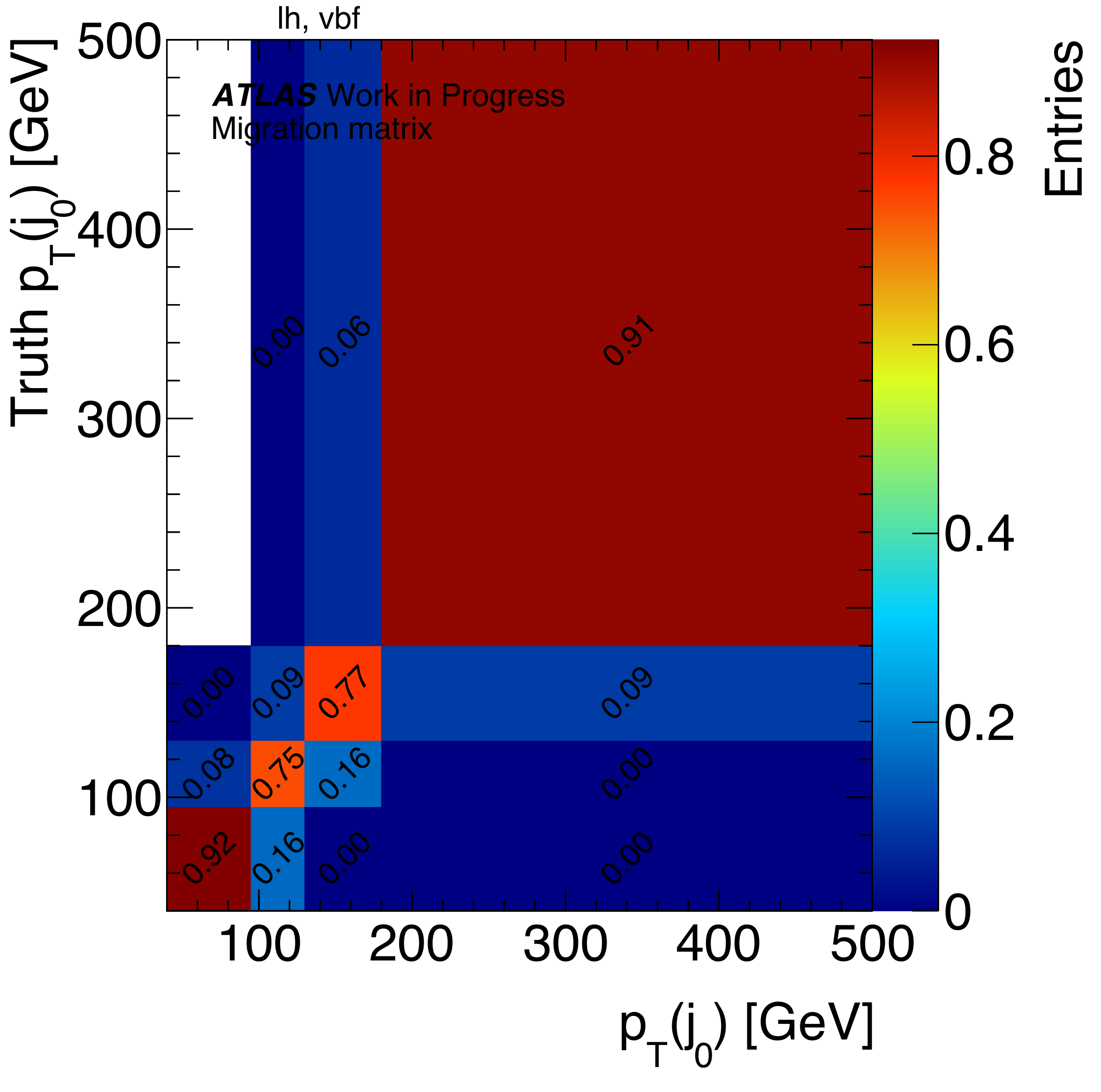
References

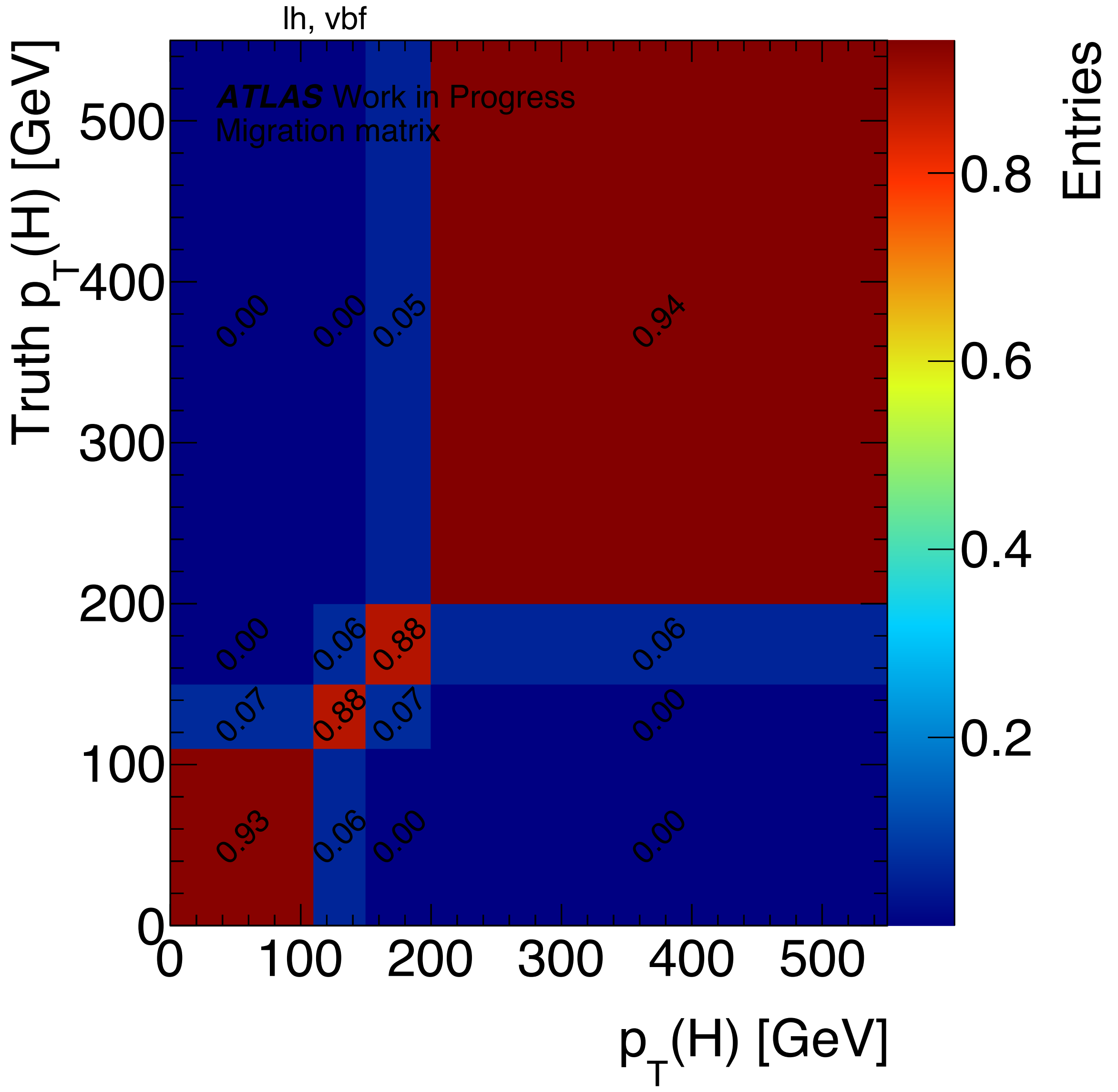
- [1] LHC Higgs Cross Section Working Group, Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, CERN-2017-002, CERN, 2017.
- [2,3] ATLAS Collaboration, Measurements of Higgs boson production cross-sections in the $H \to \tau^+ \tau^-$ decay channel in pp collisions at $\sqrt{13}$ TeV with the ATLAS detector, JHEP 08 (2022) 175, arXiv: 2201.08269 [hep-ex].
- [4] https://gebob19.github.io/normalizing-flows/
- [5] Title page background: ATLAS Collaboration, Cross-section measurements of the Higgs boson decaying into a pair of τ -leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, Phys. Rev. D 99 (2019) 072001.

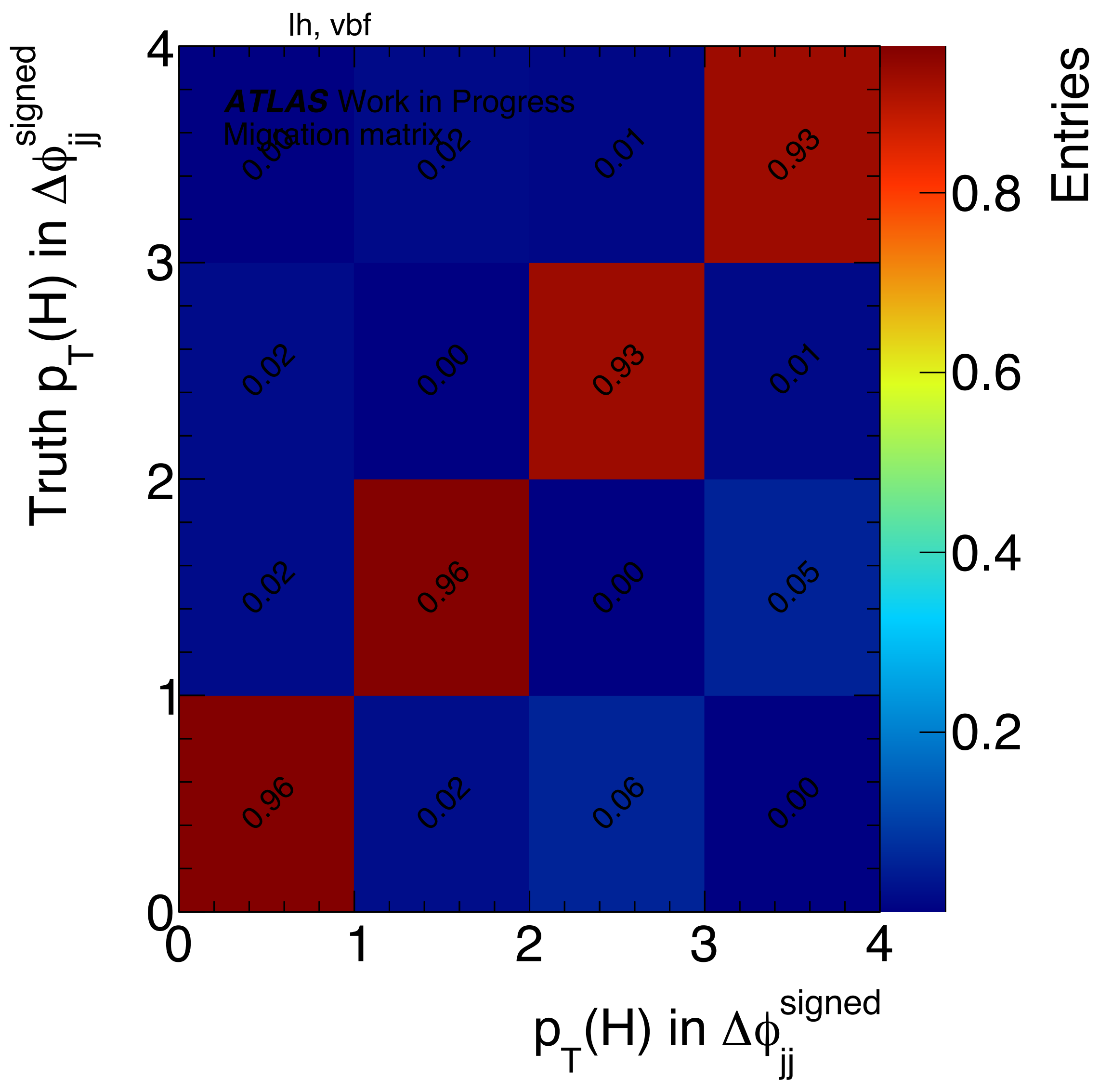
Backup

Migration Matrices in vbf region









First Attempt with Normalising Flows

	syst + stat	MC + data stat.	Data stat.
$\Delta\mu_1$	± 0.57	± 0.54	± 0.42
$\Delta\mu_2$	± 0.63	± 0.58	± 0.46
$\Delta\mu_3$	± 0.57	± 0.55	± 0.41
$\Delta\mu_4$	± 0.59	± 0.40	± 0.31

$p_T^{j_0}$

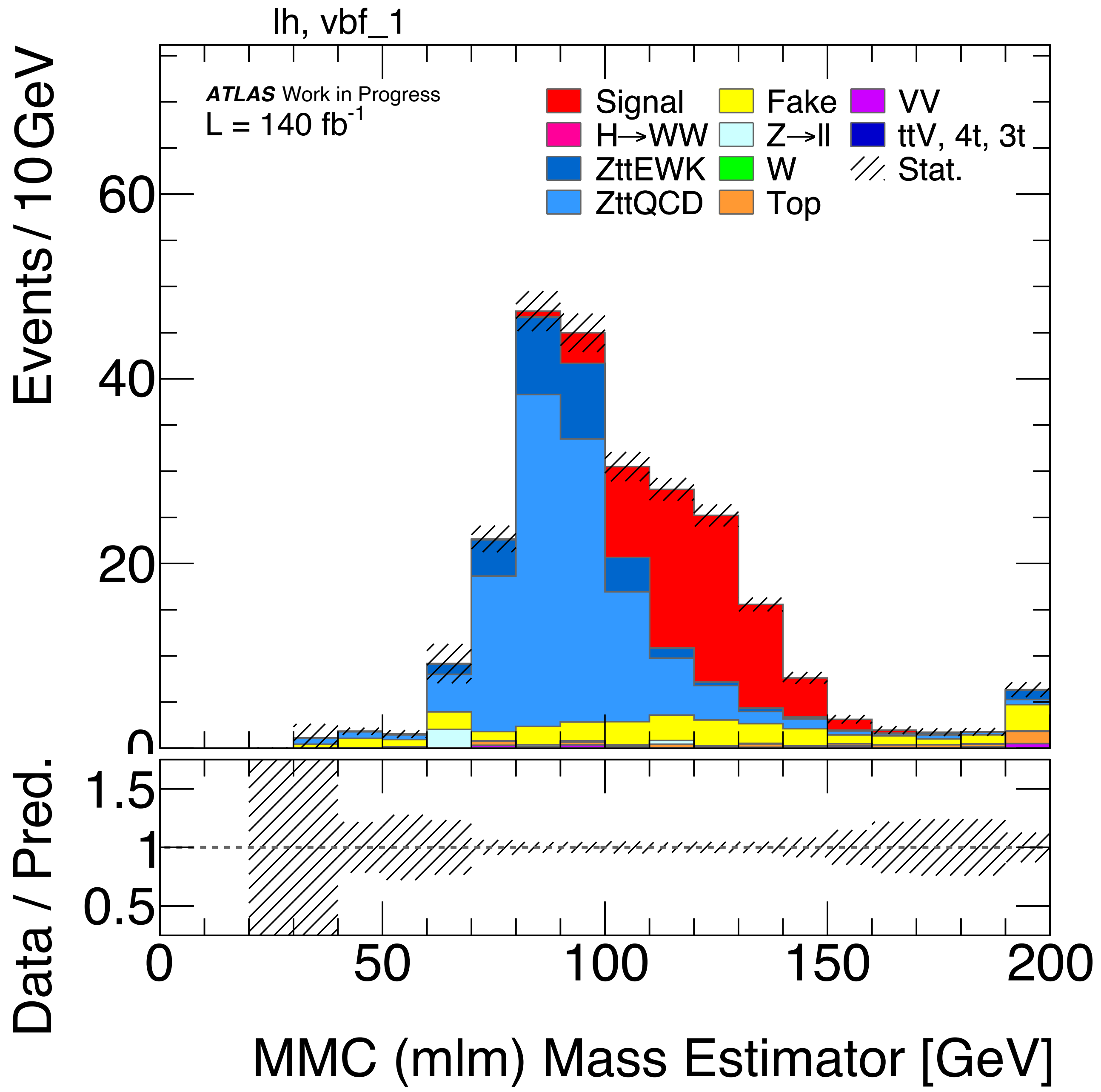
	syst + stat	MC + data stat.	Data stat.
$\Delta\mu_1$	± 0.80	± 0.62	± 0.62
$\Delta\mu_2$	± 0.58	± 0.52	± 0.43
$\Delta\mu_3$	± 0.43	± 0.42	± 0.32
$\Delta\mu_4$	± 0.33	± 0.32	± 0.24

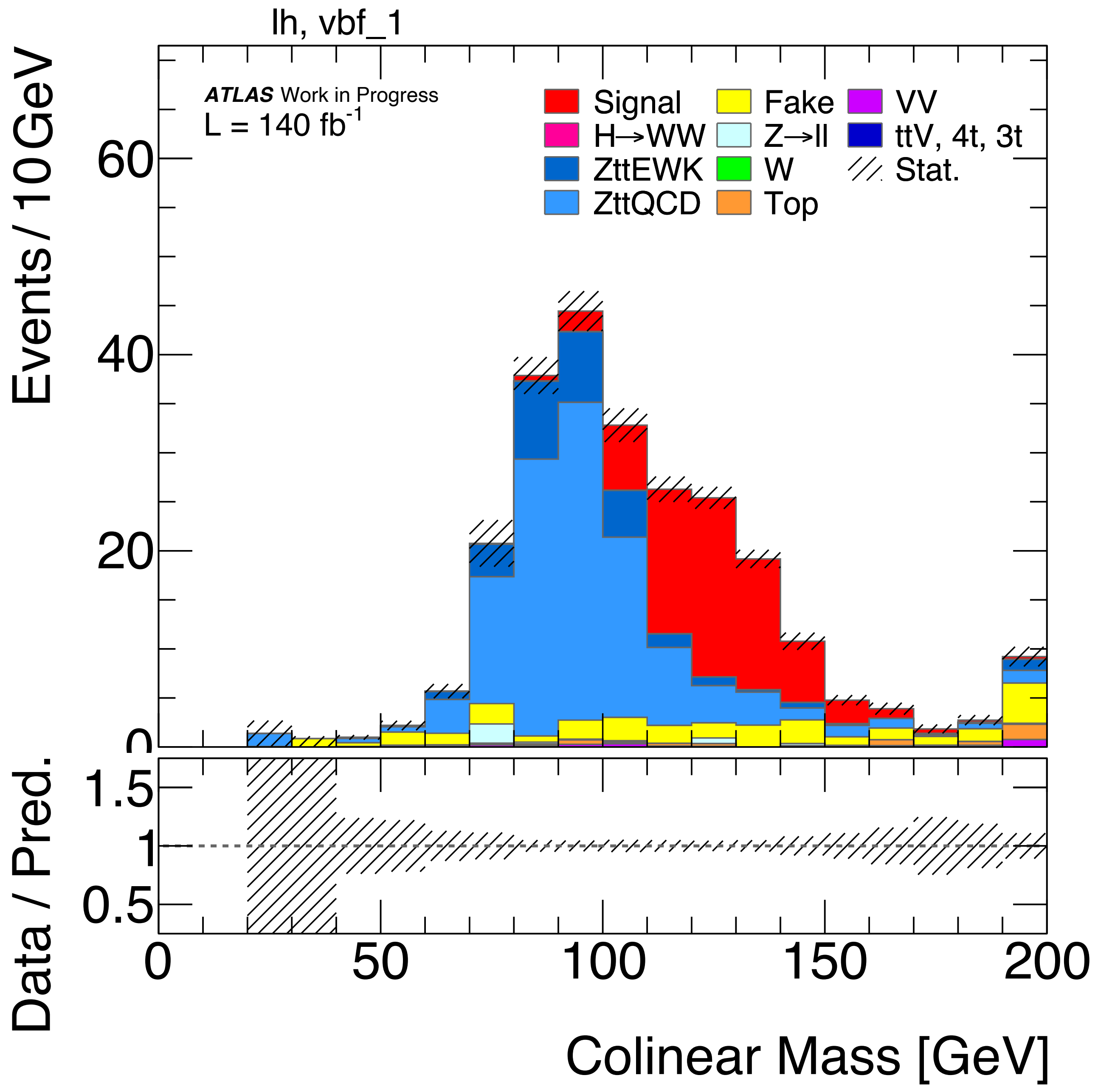
p_T^H

	syst + stat	MC + data stat.	Data stat.
$\Delta\mu_1$	± 0.44	± 0.37	± 0.32
$\Delta\mu_2$	± 0.44	± 0.38	± 0.33
$\Delta\mu_3$	± 0.52	± 0.49	± 0.40
$\Delta\mu_4$	± 0.50	± 0.48	± 0.38

$\Delta\phi_{jj}^{signed}$ vs p_T^H

MMC vs CLMA


lh, vbf_1
ATLAS Work in Progress
L = 140 fb-1
Signal
H→WW
ZttEWK
ZttQCD
Fake
Z→ll
W
Top
VV
ttV, 4t, 3t
Stat.
Events / 10 GeV
Data / Pred.
MMC (mlm) Mass Estimator [GeV]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