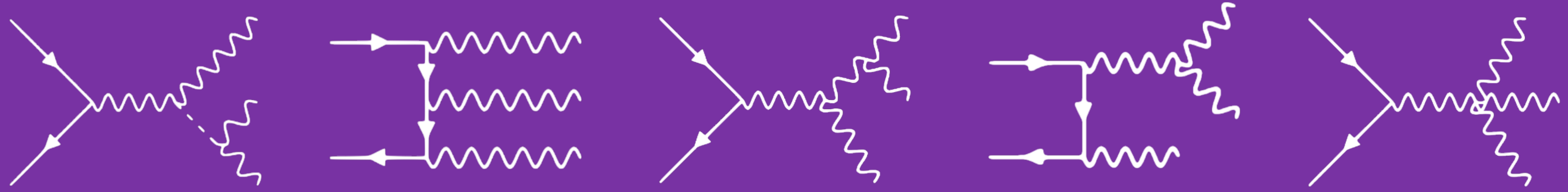


Massive Triboson Production

Constraining Anomalous Quartic Gauge Couplings in Production of Three Massive Vector Bosons with the ATLAS detector

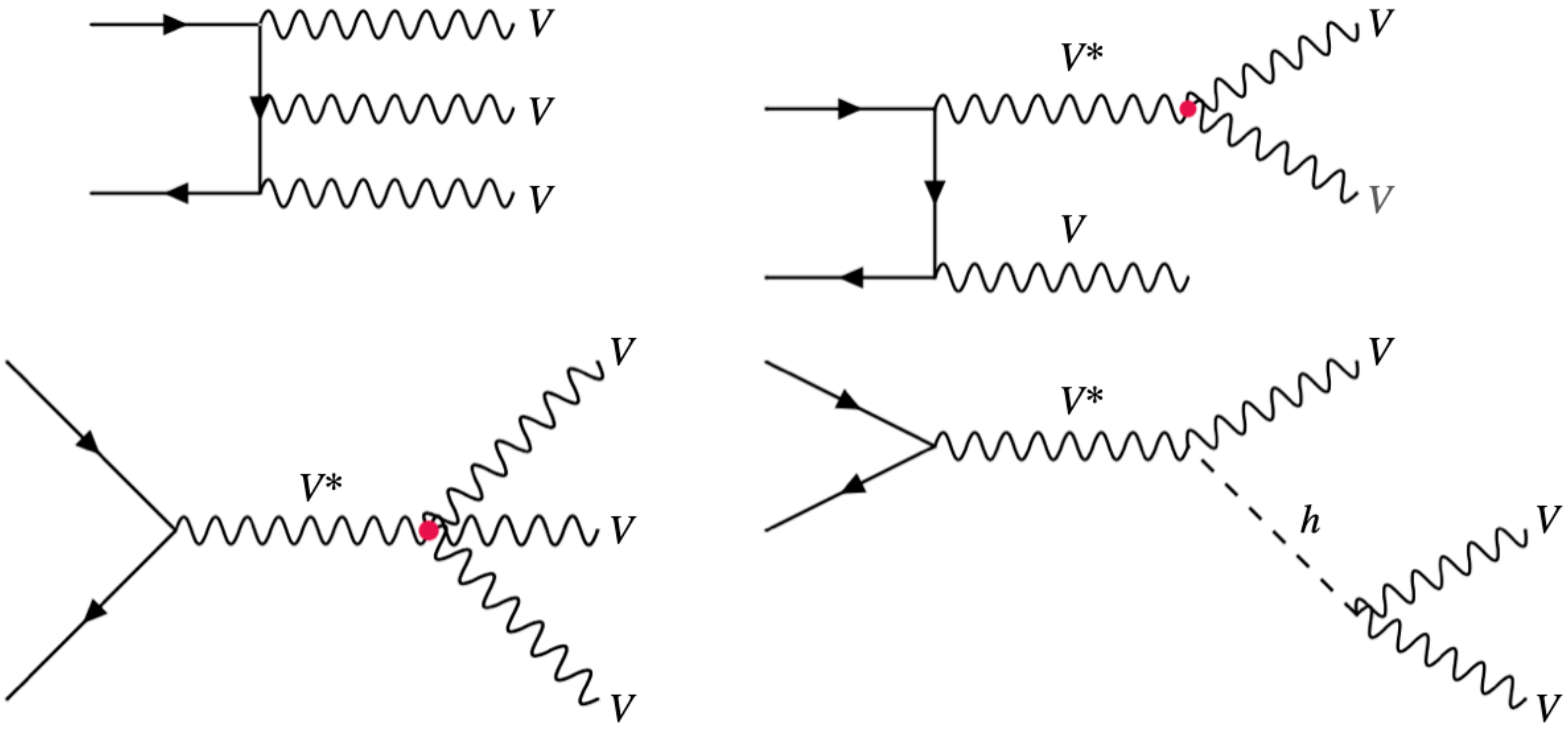
MANCHESTER
1824
The University of Manchester

Patrick Dougan
On behalf of the analysis team

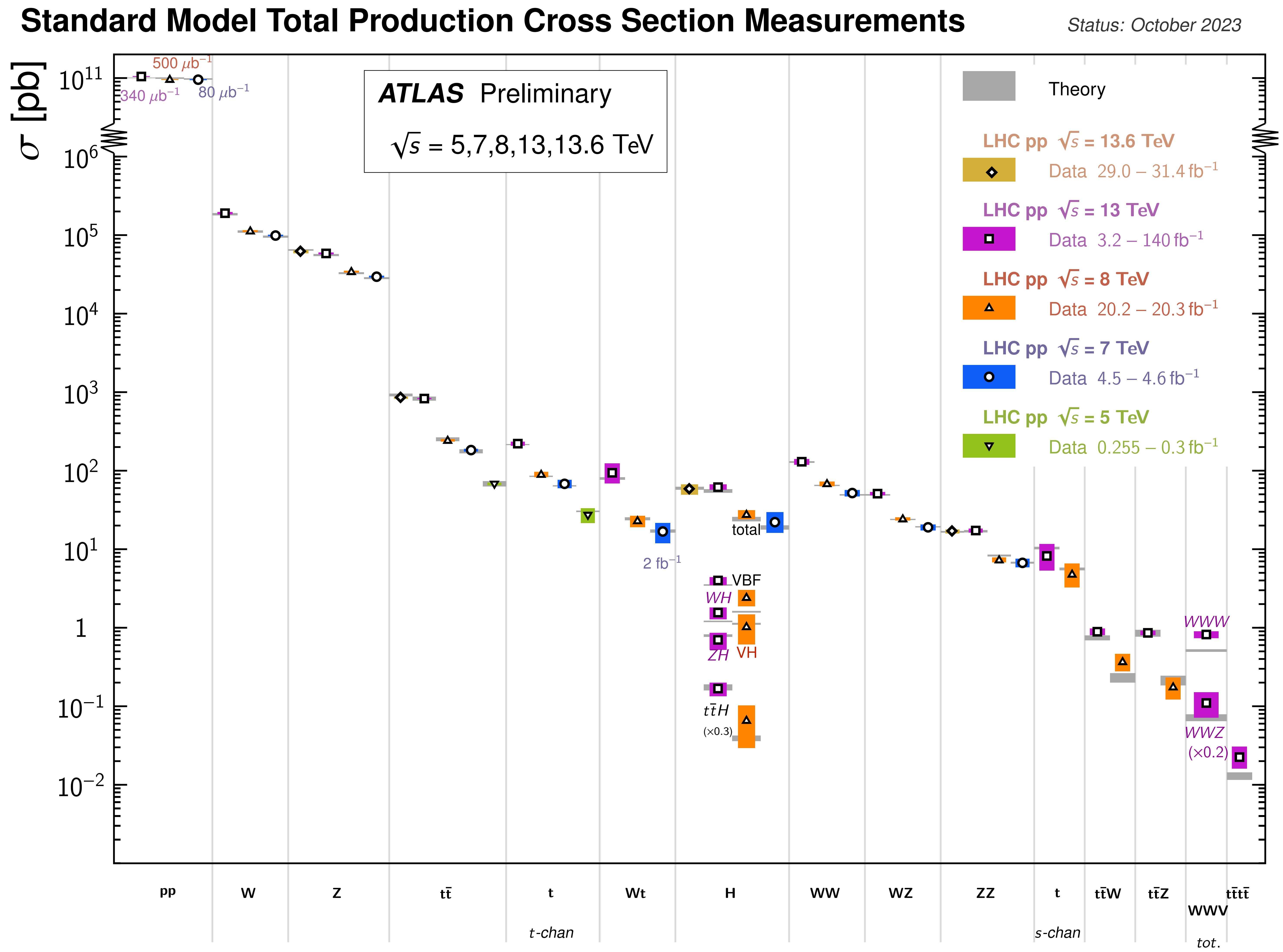
IoP APP, HEPP & NP
University of Liverpool
10th April 2024

ATLAS
EXPERIMENT

Massive VVV



Rare Standard Model Process



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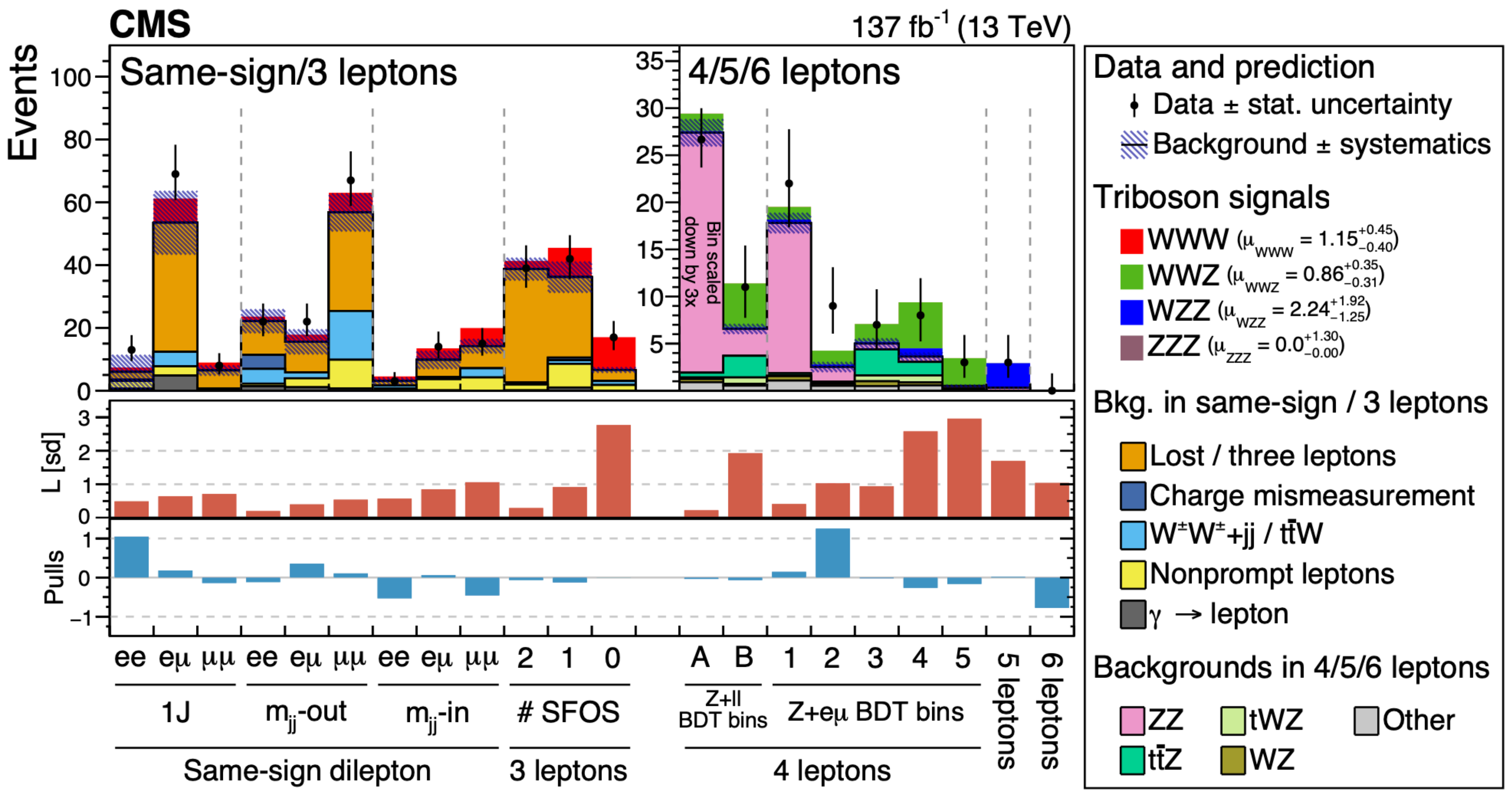
Observation

CMS VVV

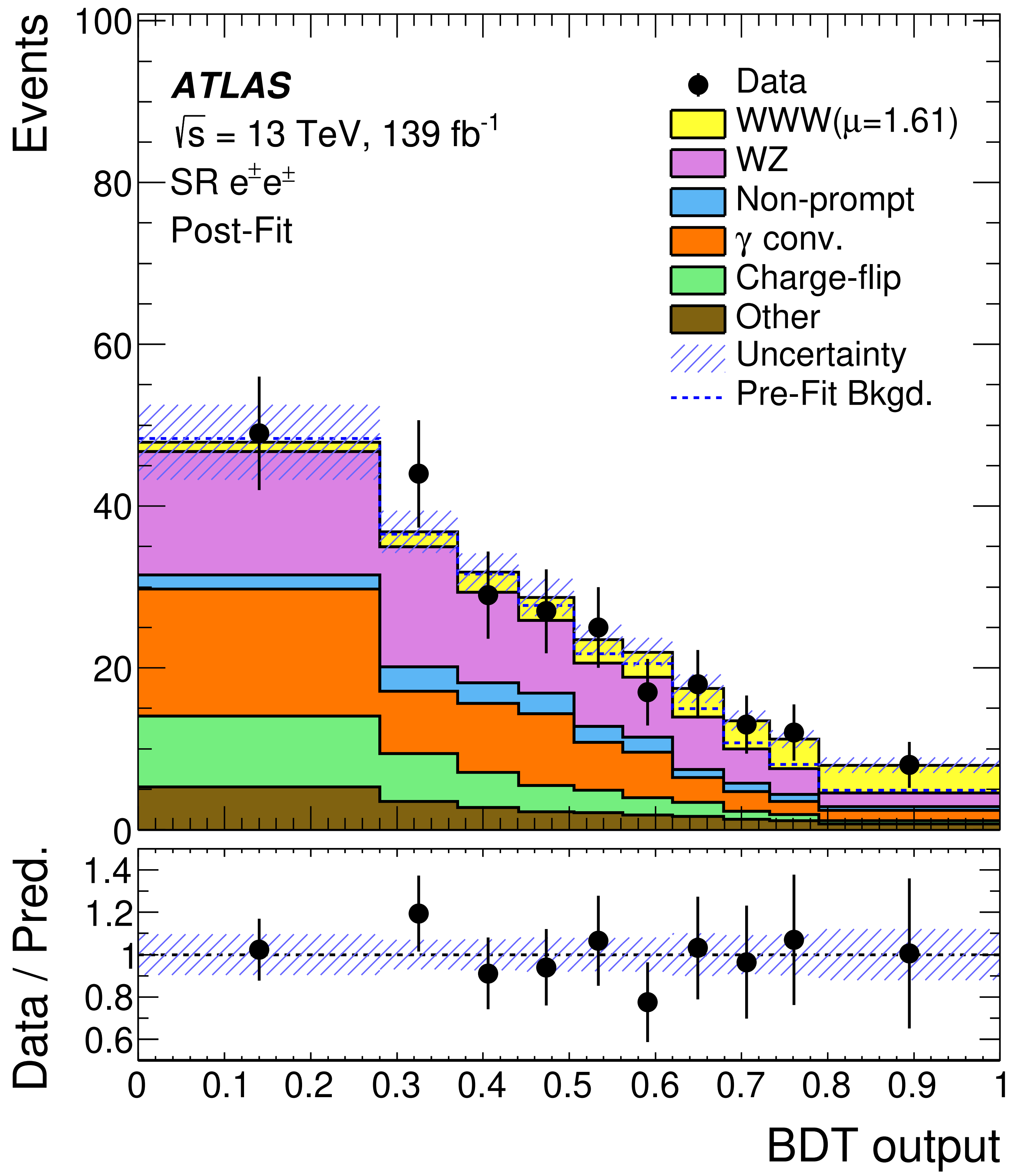
2006.11191
2020

Significance of the observation is 5.7 standard deviations (sd) with 5.9 sd expected

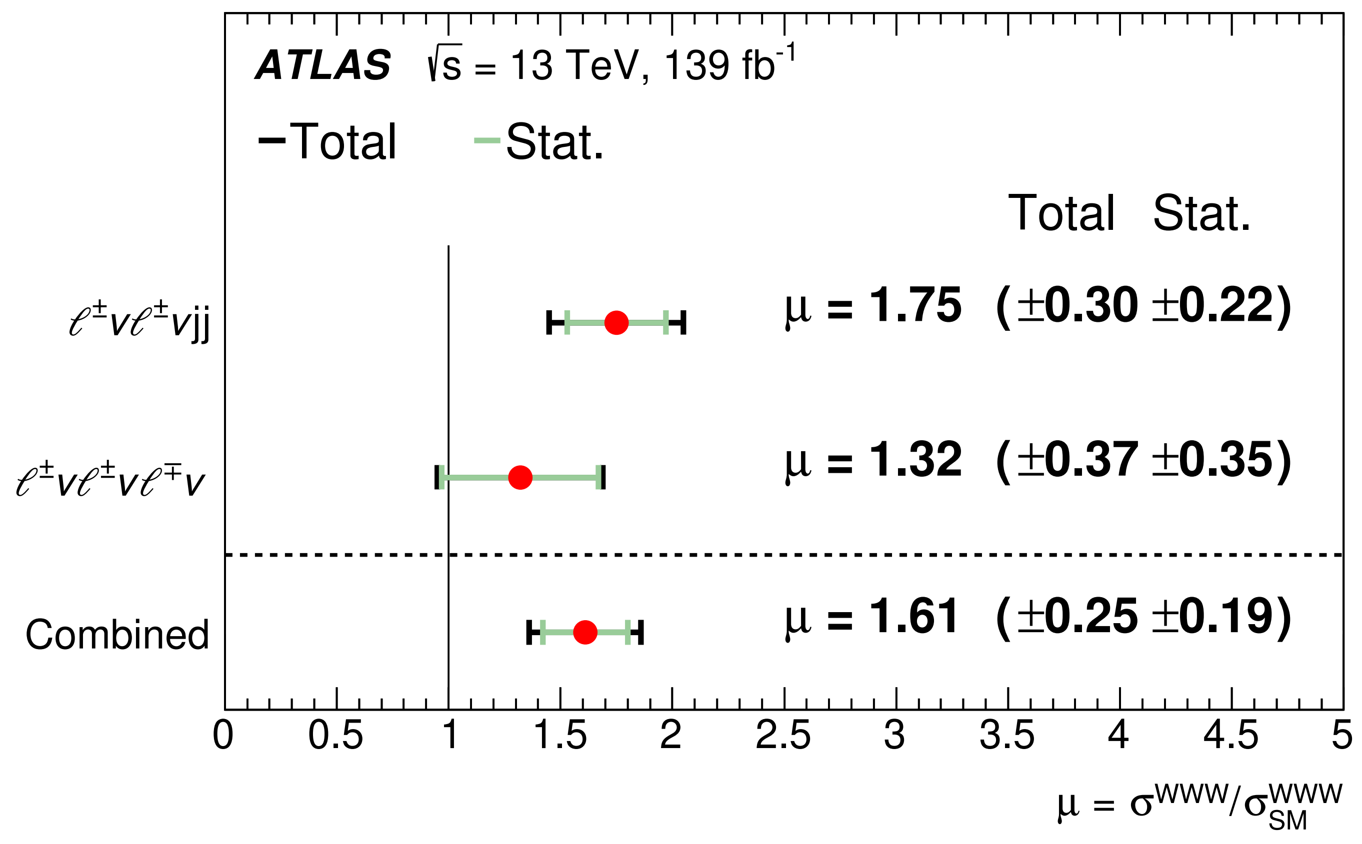


ATLAS WWW

2201.13045
2022



Inclusive cross section is measured to be 820 ± 100 (stat) ± 80 (syst) fb, approximately 2.6 standard deviations from the predicted cross section of 511 ± 18 fb



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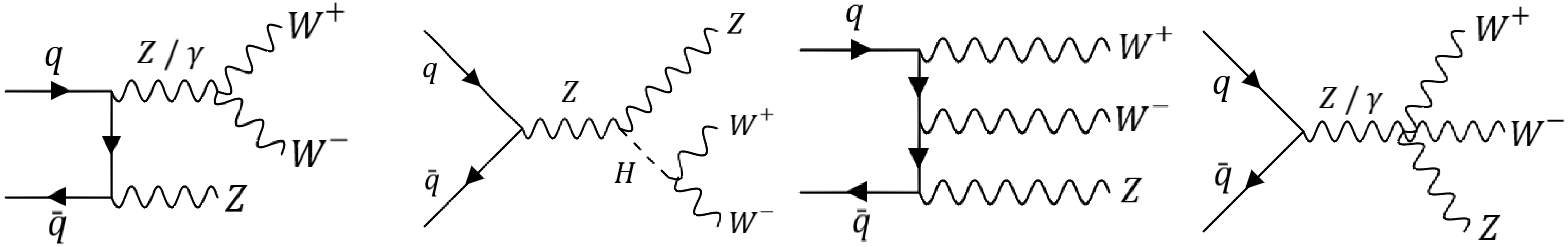
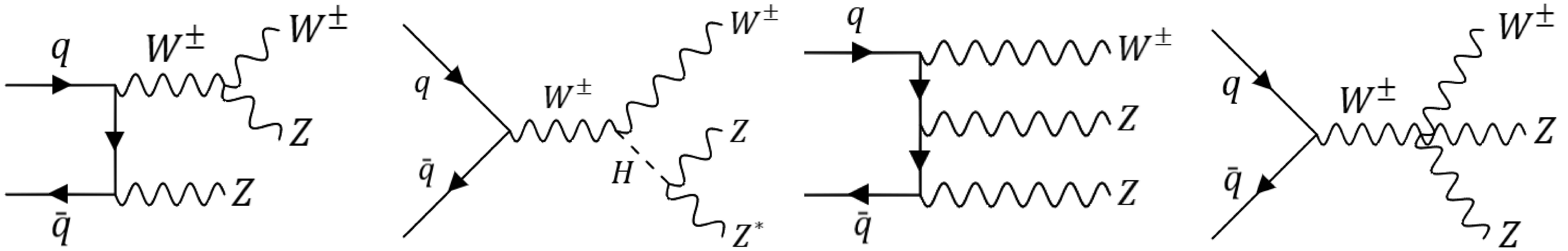
VVZ

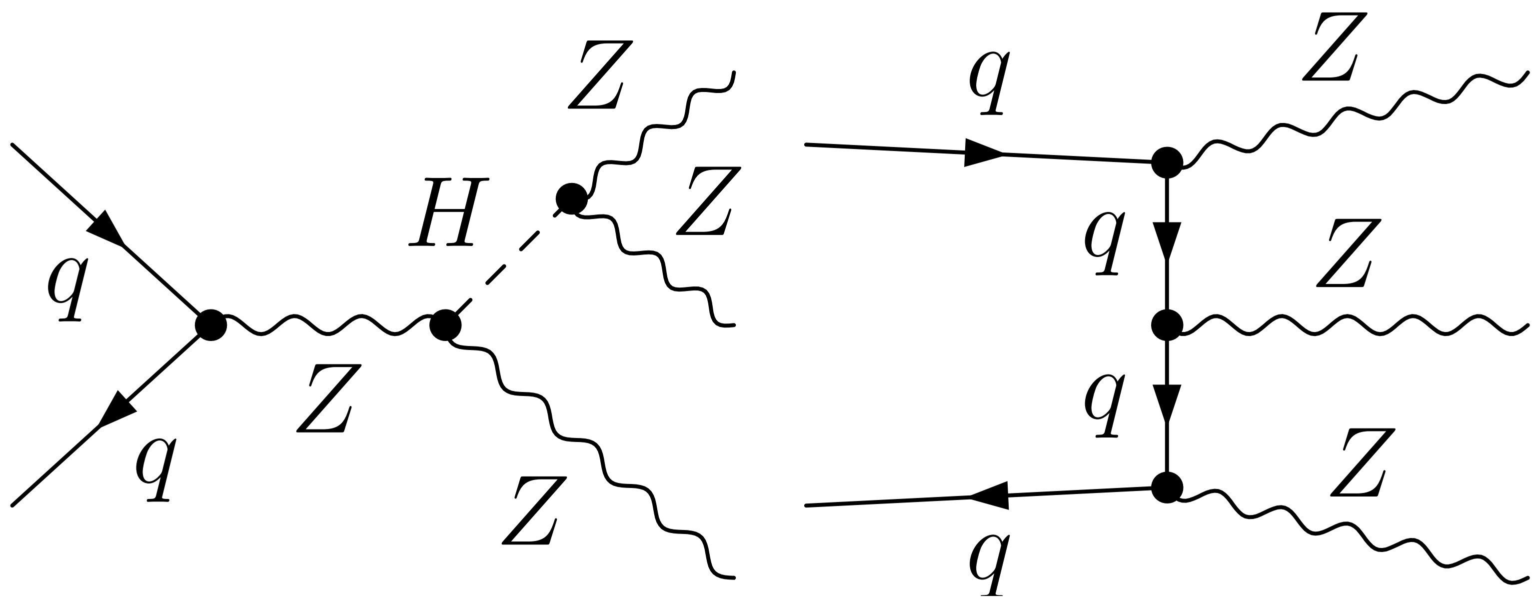
$W^{\pm}W^{\pm}Z^{0}$
~0.172 pb



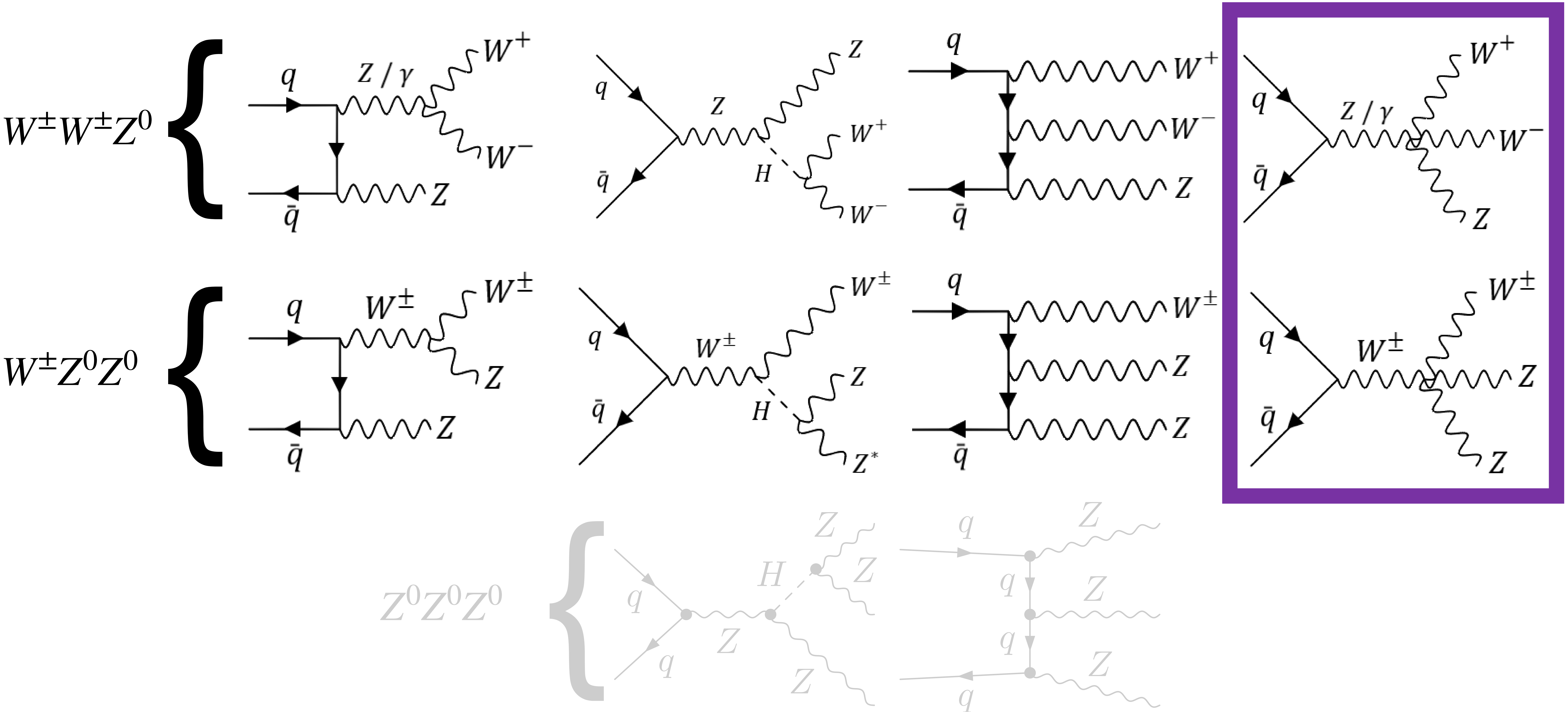
$W^{\pm}Z^{0}Z^{0}$
~0.055 pb



$Z^{0}Z^{0}Z^{0}$
~0.0135 pb



WVZ



Full Run2 VVZ Search

Analysis Strategy

Utilise the entire ATLAS Run 2 dataset, 140 fb^{-1} in continuation of previous ATLAS search (1903.10415)

Target different event topologies for each final state with multiple signal regions (3, 3, 1)

Enhance signal sensitivity with dedicated MVAs for all SRs

Constrain uncertainties in primary background modelling with Control Regions

$3\ell 1\nu 2j$

$W/Z \rightarrow qq$

$W \rightarrow \ell\nu$

$Z \rightarrow \ell\ell$

$\Gamma_i/\Gamma_{total}(WWZ) = 1.01\,\%$

$\Gamma_i/\Gamma_{total}(WZZ) = 1.05\,\%$

$4\ell 2\nu$

$W \rightarrow \ell\nu$

$W \rightarrow \ell\nu$

$Z \rightarrow \ell\ell$

$\Gamma_i/\Gamma_{total} = 0.32\,\%$

$5\ell 1\nu$ & 6ℓ+

$W/Z \rightarrow \ell\nu/\ell\ell$

$Z \rightarrow \ell\ell$

$Z \rightarrow \ell\ell$

$\Gamma_i/\Gamma_{total}(WZZ) = 0.32\,\%$

$\Gamma_i/\Gamma_{total}(ZZZ) = 0.11\,\%$

Full Run2 VVZ Search

Analysis Strategy

Utilise the entire ATLAS Run 2 dataset, 140 fb^{-1} in continuation of previous ATLAS search (1903.10415)

Target different event topologies for each final state with multiple signal regions (3, 3, 1)

Enhance signal sensitivity with dedicated MVAs for all SRs

Constrain uncertainties in primary background modelling with Control Regions

$3\ell 1\nu 2j$

Target Process

$W^{\pm}W^{\mp}Z$ & $W^{\pm}ZZ$

Main Backgrounds

$W^{\pm}Z$, ZZ, Z+jets, $t\bar{t}Z$

$4\ell 2\nu$

Target Process

$W^{\pm}W^{\mp}Z$

Main Backgrounds

ZZ, Z+jets, $t\bar{t}Z$, Fakes

$5\ell 1\nu$ & 6ℓ+

Target Process

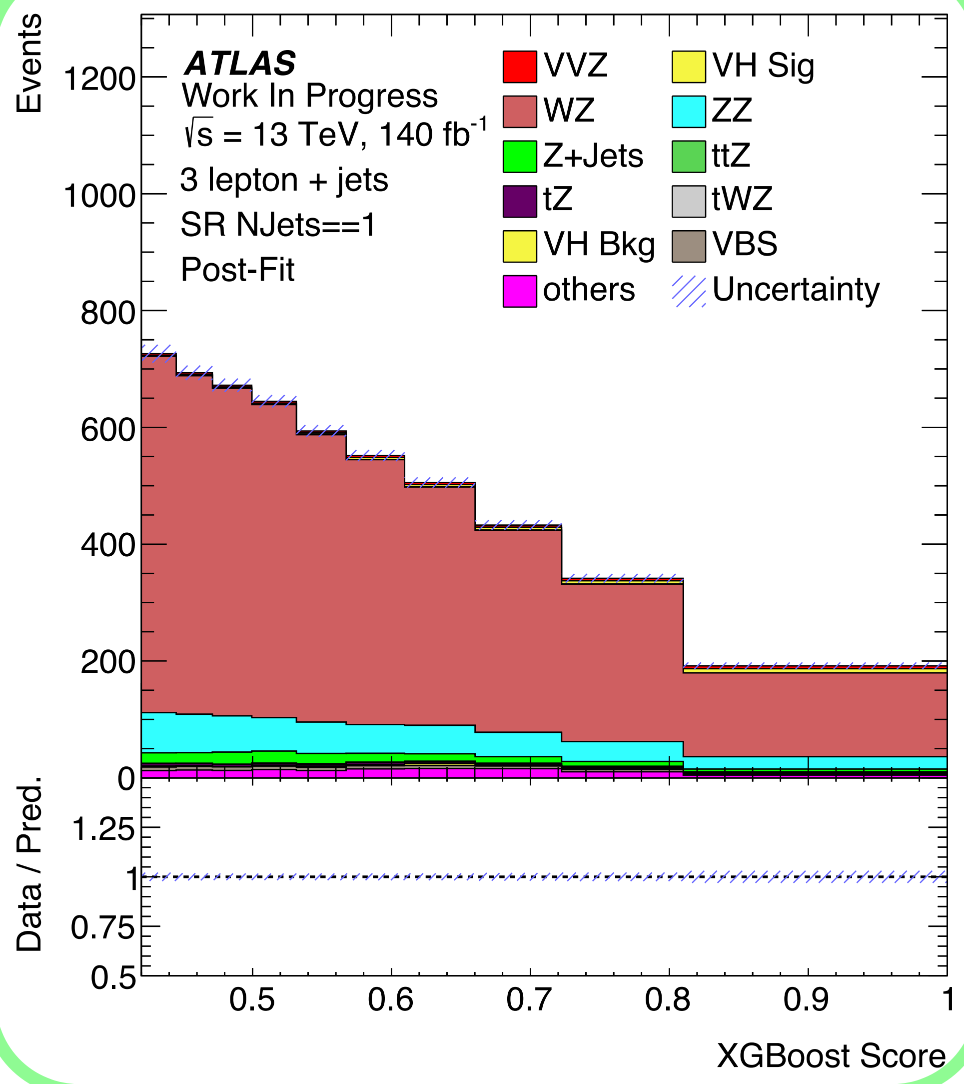
$W^{\pm}ZZ$ & ZZZ

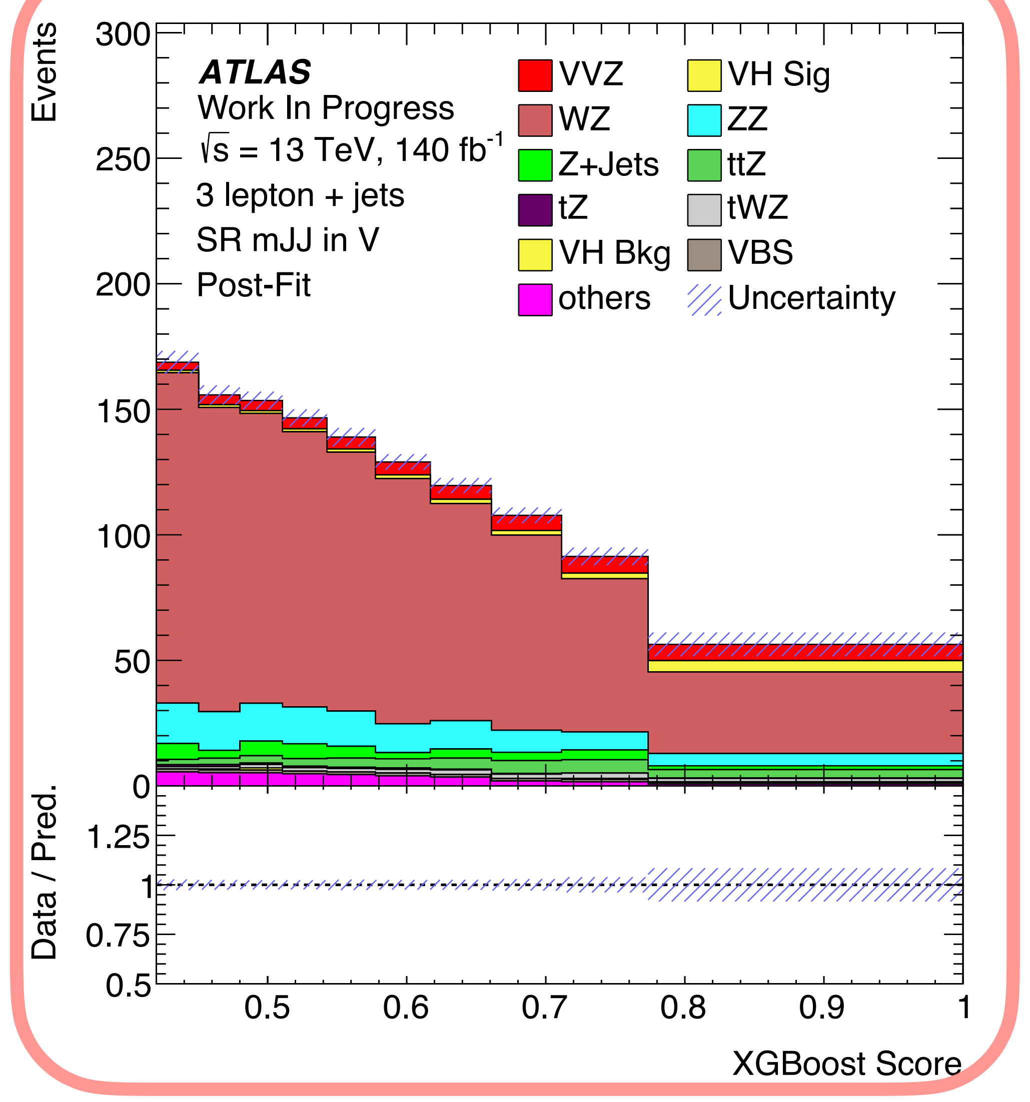
Main Backgrounds

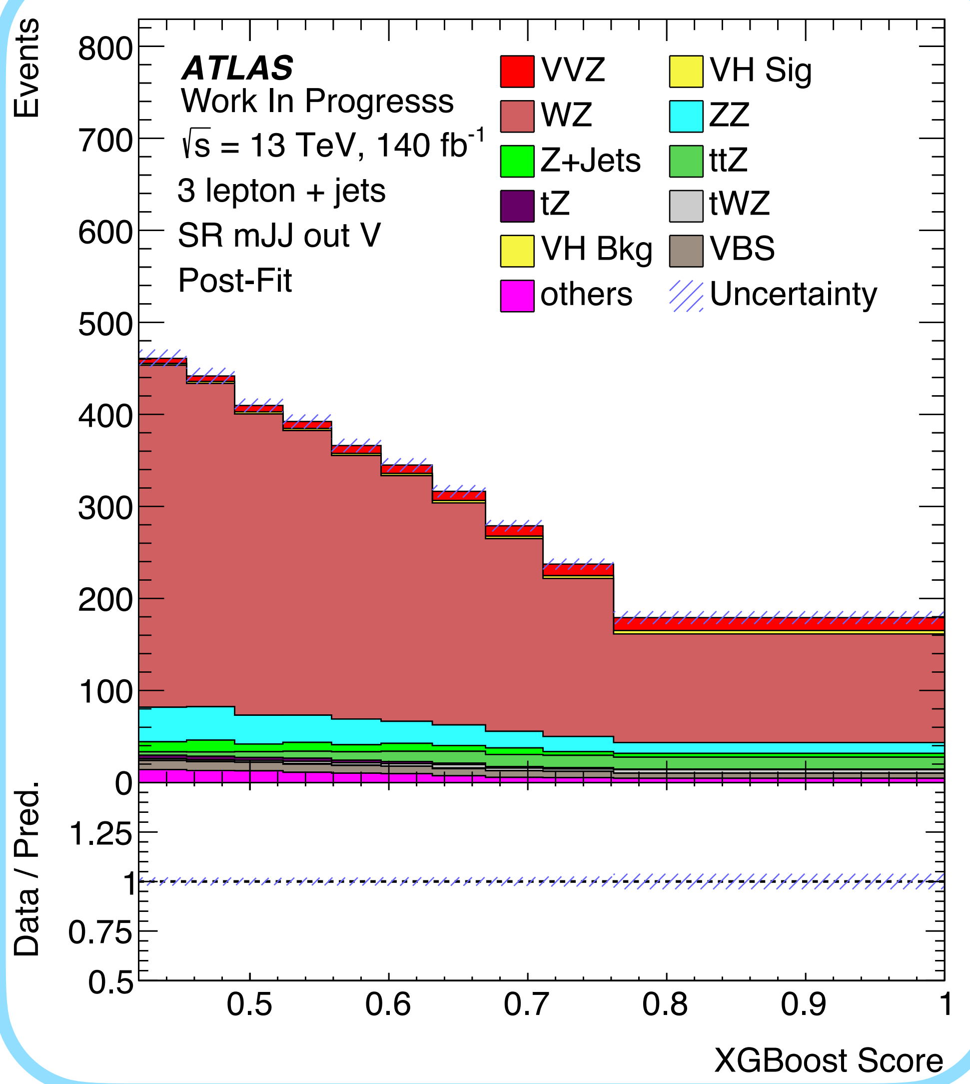
$t\bar{t}X$, ZZ + Fakes

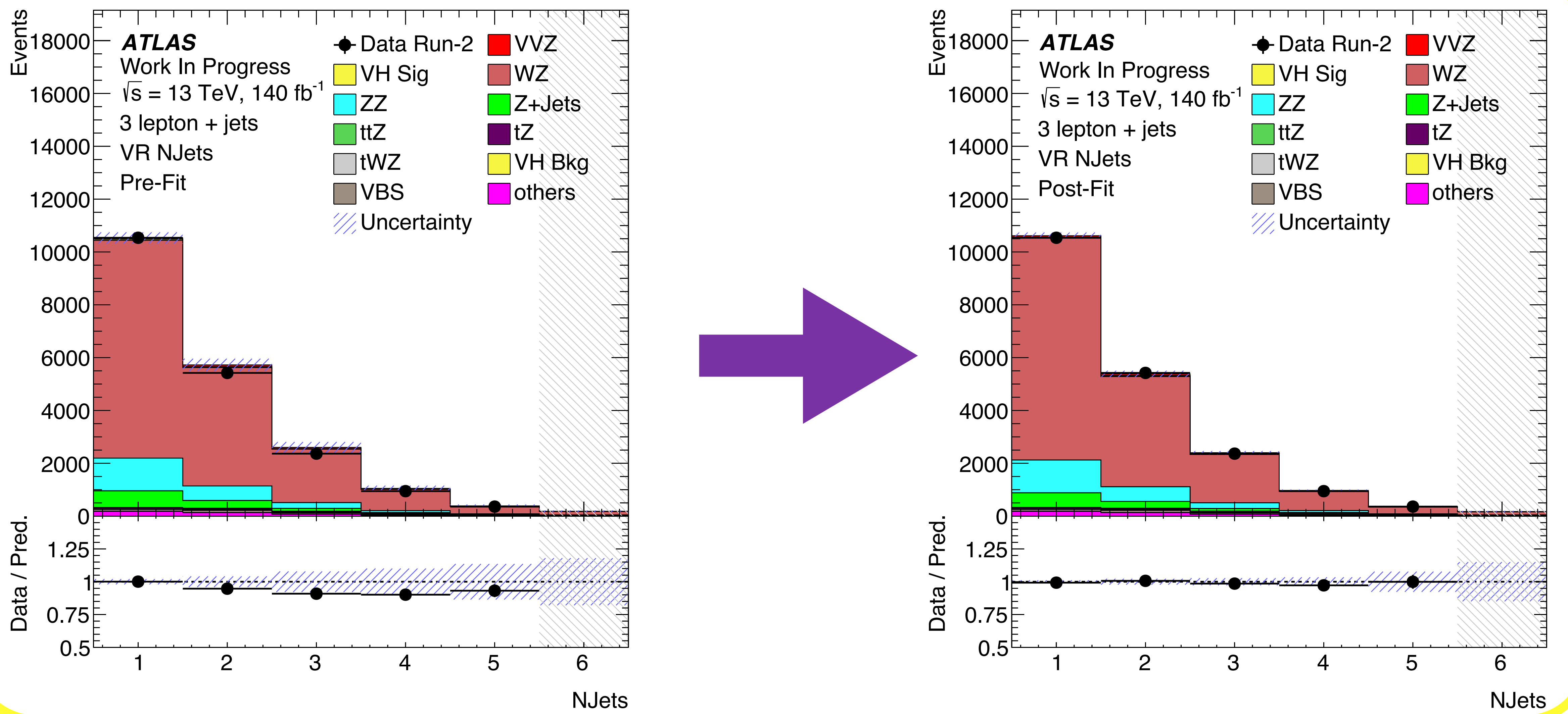
$3\ell 1\nu 2j$ Channel

- Signal Regions defined for post selection cuts:
  - 1 jet
  - $\geq$ 2 jets inside m_{jj} window [60, 110] GeV
  - $\geq$ 2 jets outside m_{jj} window [60, 110] GeV
- BDTs are trained for each SR using kinematic & angular variables
- WZ CR created with cut on SR BDT Outputs has μs for NJet bins 1-3 to improve modelling of high Jet Multiplicity
- Z+jets & $t\bar{t}Z$ CRs are defined to normalise backgrounds to data
- Fit to Asimov dataset in SRs and data in CRs before unblinding



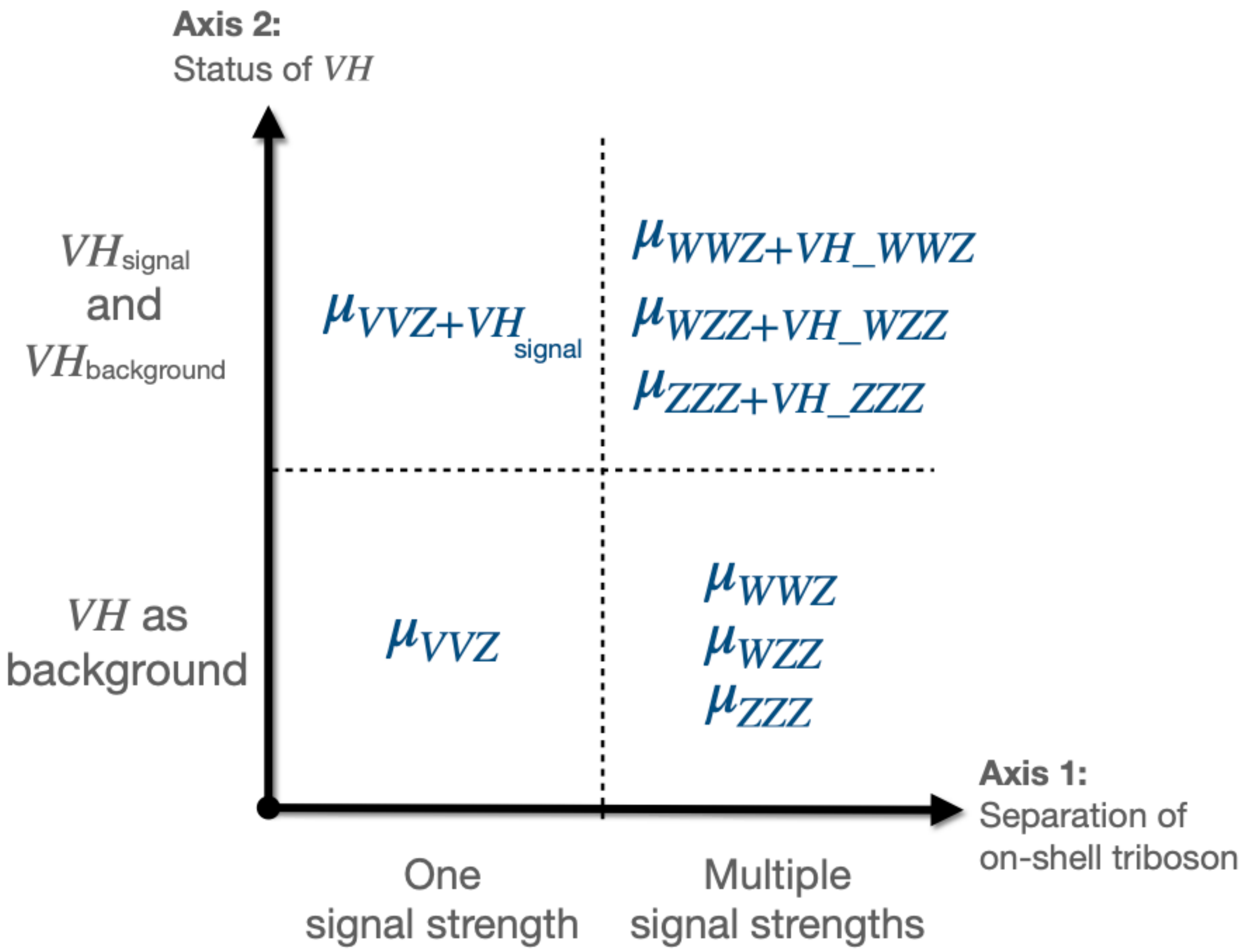


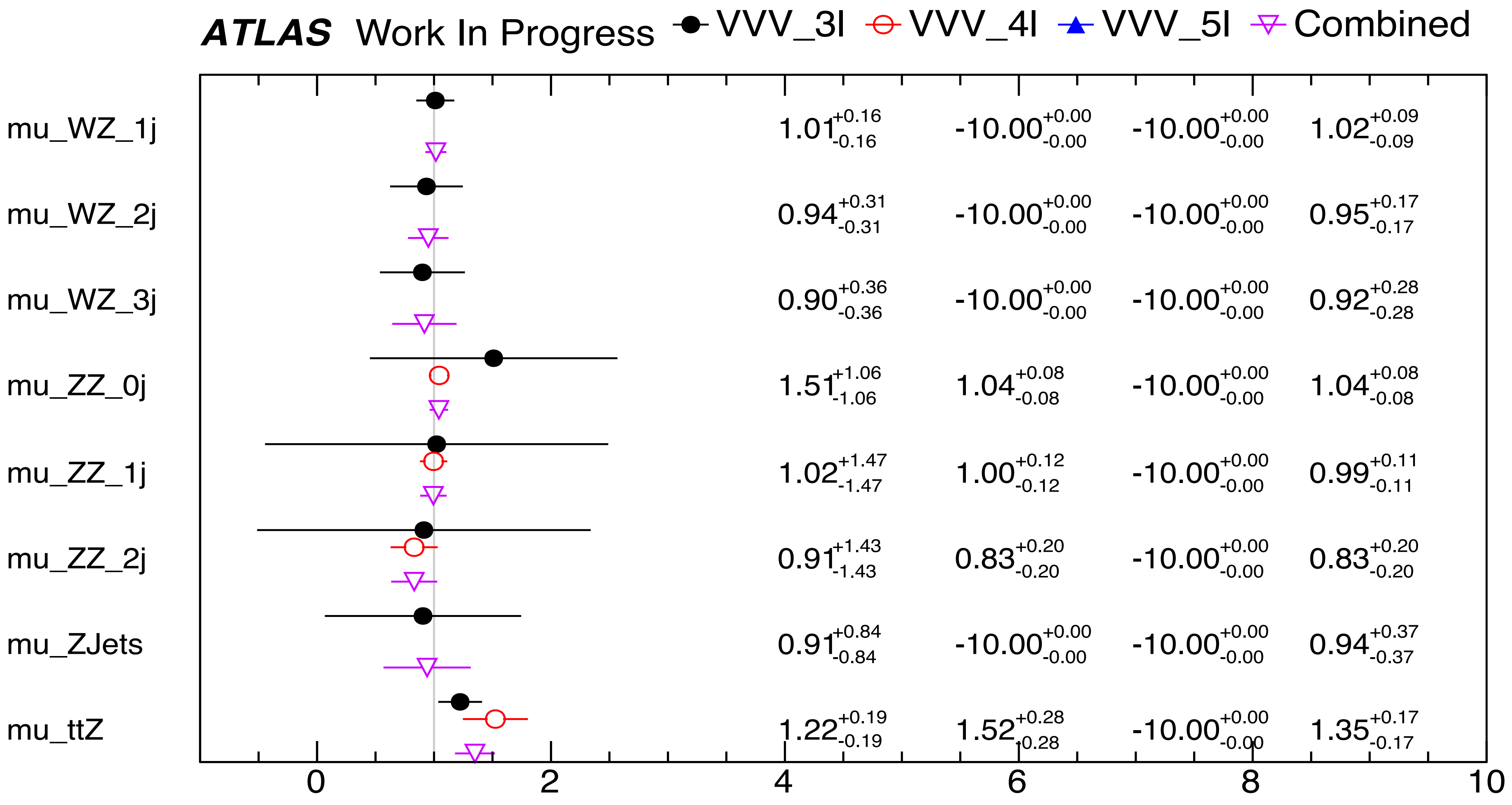




Blinded Combined Results

- 3ℓ+jets, 4ℓ and 5ℓ+ channels used in combined fit
- Results produced with VH as background process & with a truth-cut in MC to extract VH mediated signal processes
- 3ℓ+jets and 4ℓ channels sees ~50% & ~45% improvements in expected significance respectively compared to previous ATLAS analysis (1903.10415)



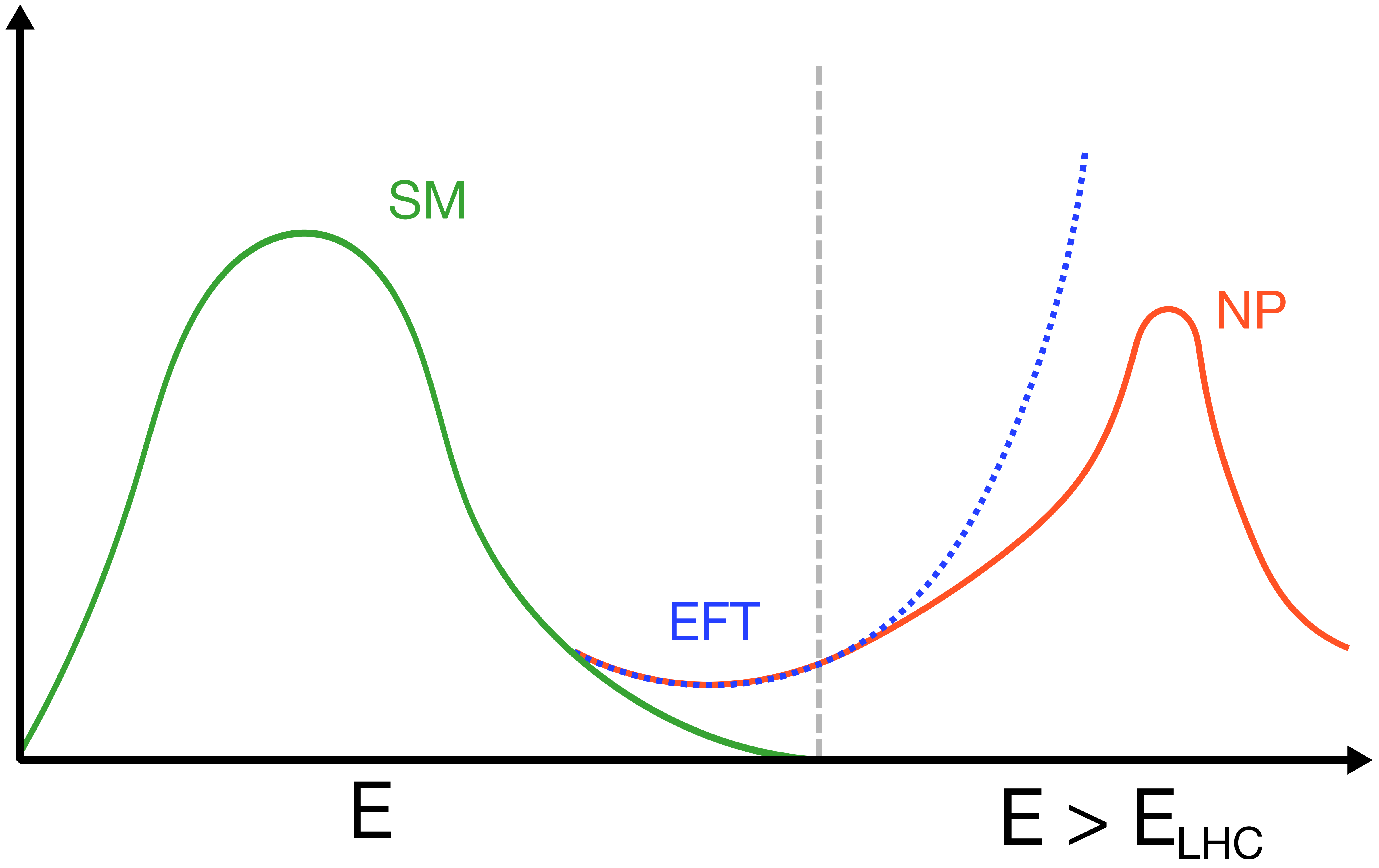


Median Expected Significance σ, VH as Signal (Background), ATLAS Work In Progress			
Fit	VVZ	WWZ	WZZ + ZZZ
3 leptons + jets	2.08 (1.40)	0.75 (0.35)	0.14 (0.10)
4 leptons	3.97 (2.97)	2.98 (2.31)	0.47 (0.46)
5+ leptons	2.42 (2.20)	0.00 (0.00)	2.33 (2.13)
Combined	**4.93 (3.85)**	**3.72 (2.70)**	**2.46 (2.25)**

Effective Field Theory

We want to probe the effects of New Physics beyond the energy frontier of the LHC in a model independent way

Using gauge invariant extensions to the Standard Model Lagrangian, we can add operators which describe specific extensions from BSM physics



Effective Field Theory

We want to probe the effects of New Physics beyond the energy frontier of the LHC in a model independent way

Using gauge invariant extensions to the Standard Model Lagrangian, we can add operators which describe specific extensions from BSM physics

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \mathscr{L}^{(5)} + \mathscr{L}^{(6)} + \mathscr{L}^{(7)} + \dots, \quad \mathscr{L}^{(d)} = \sum_{i=1}^{n_d} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathscr{O}_i^{(d)} \quad \text{for } d > 4$$

The strength of these NP effects are determined by Wilson coefficients c_i for a NP energy scale Λ

Genuine Anomalous Quartic Gauge couplings enter at dimension $d = 8$, and these bosons operators are described in the Eboli parametrisation

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{f_i^{(8)}}{\Lambda^4} \mathscr{O}_i^{(8)}$$

Anomalous Quartic Gauge Couplings

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓		
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓	✓	✓
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓	✓	✓
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓	✓	✓
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓	✓	✓
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$				

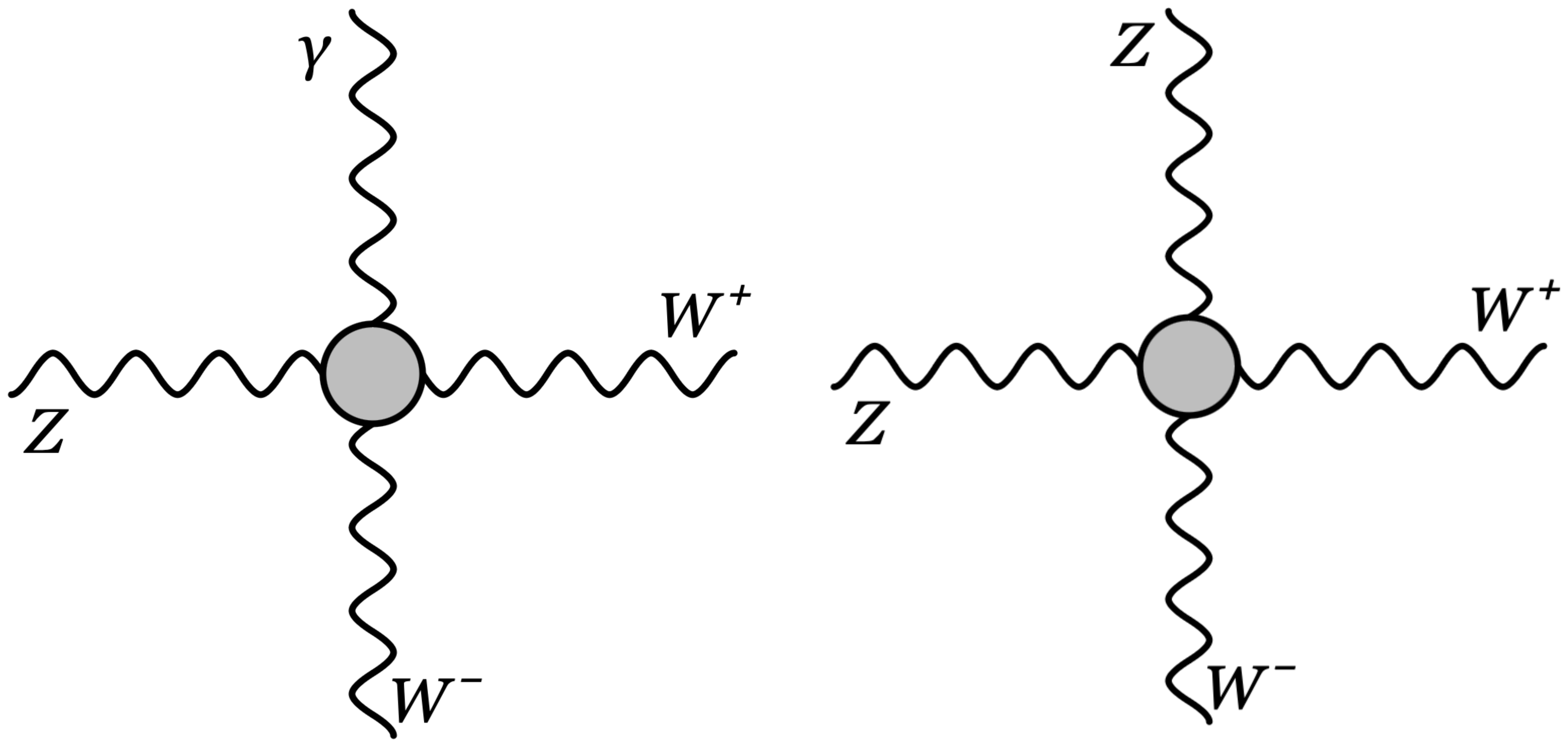
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right]$$

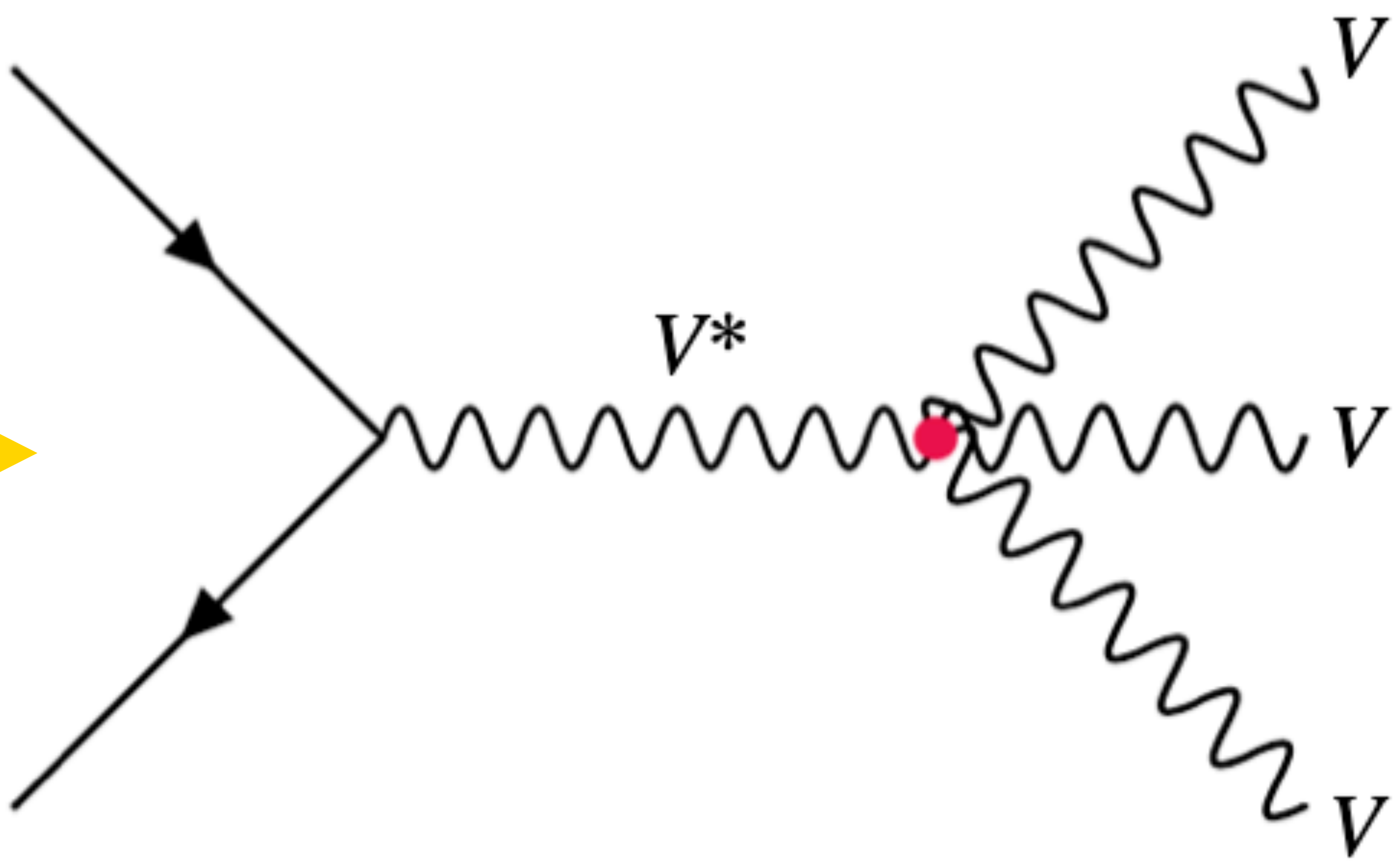
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[\left(D_\mu\Phi\right)^\dagger \widehat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[\left(D_\mu\Phi\right)^\dagger \widehat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} + \text{h.c.}$$

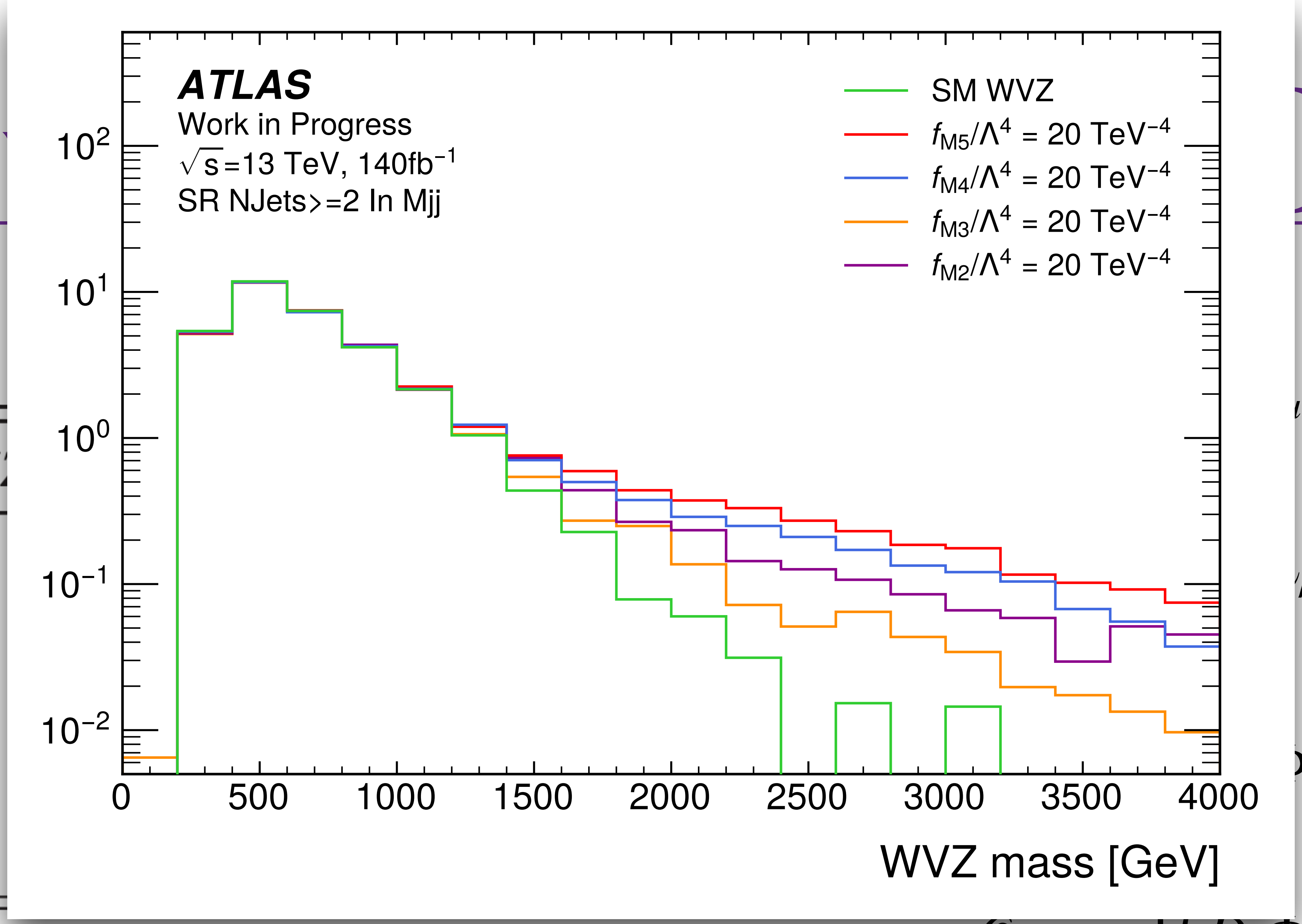
1604.03555





Anomalo… Couplings

	WWWW	WWZ…
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$		



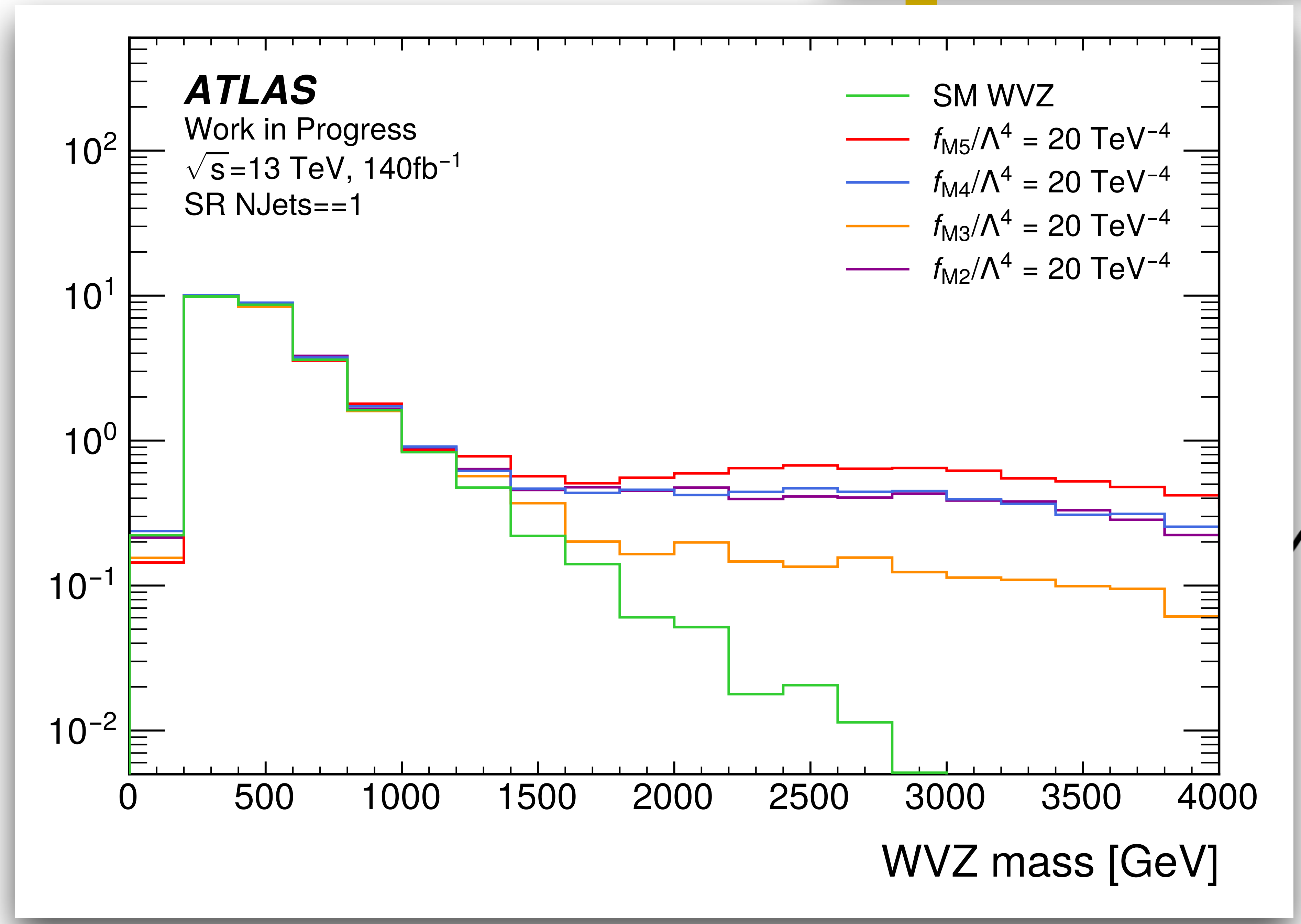
$$\ldots\Big] \times \Big[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\Big]$$

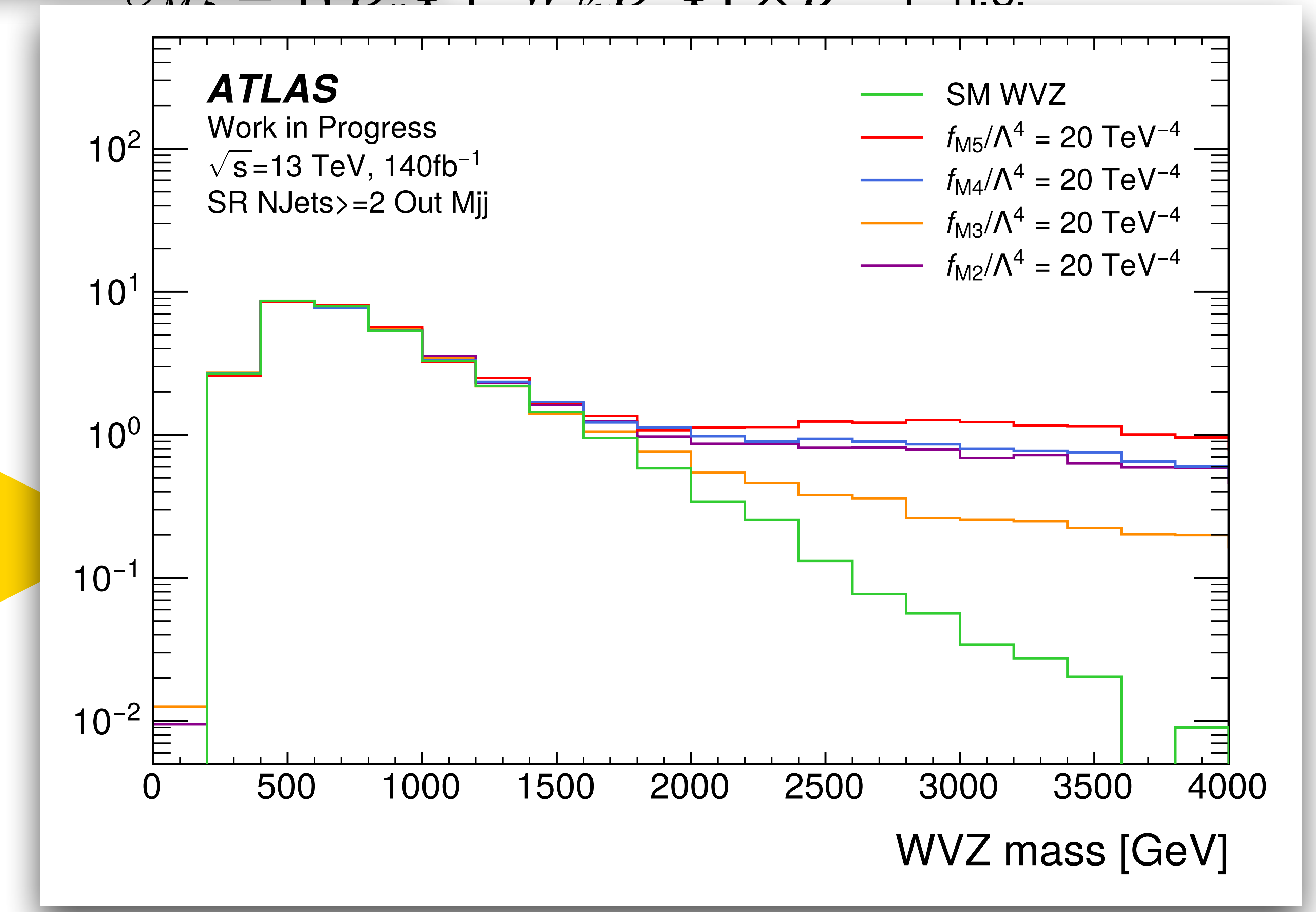
$$\ldots\Big] \times \Big[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\Big]$$

$$\ldots\Big)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\Big] \times B^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \Big[\left(D_\mu\Phi\right)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\Big] \times B^{\beta\mu} + \text{h.c.}$$

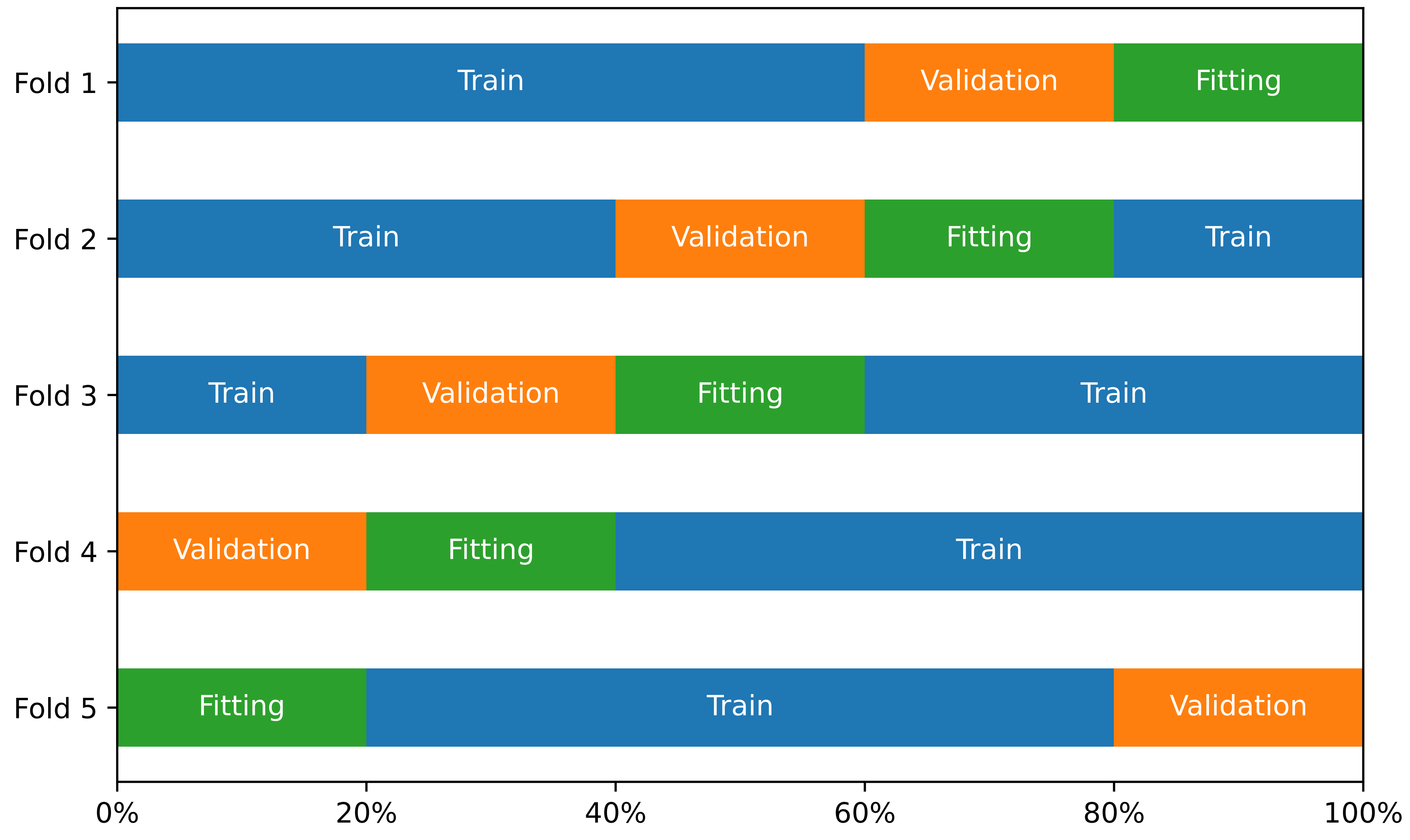
1604.03555

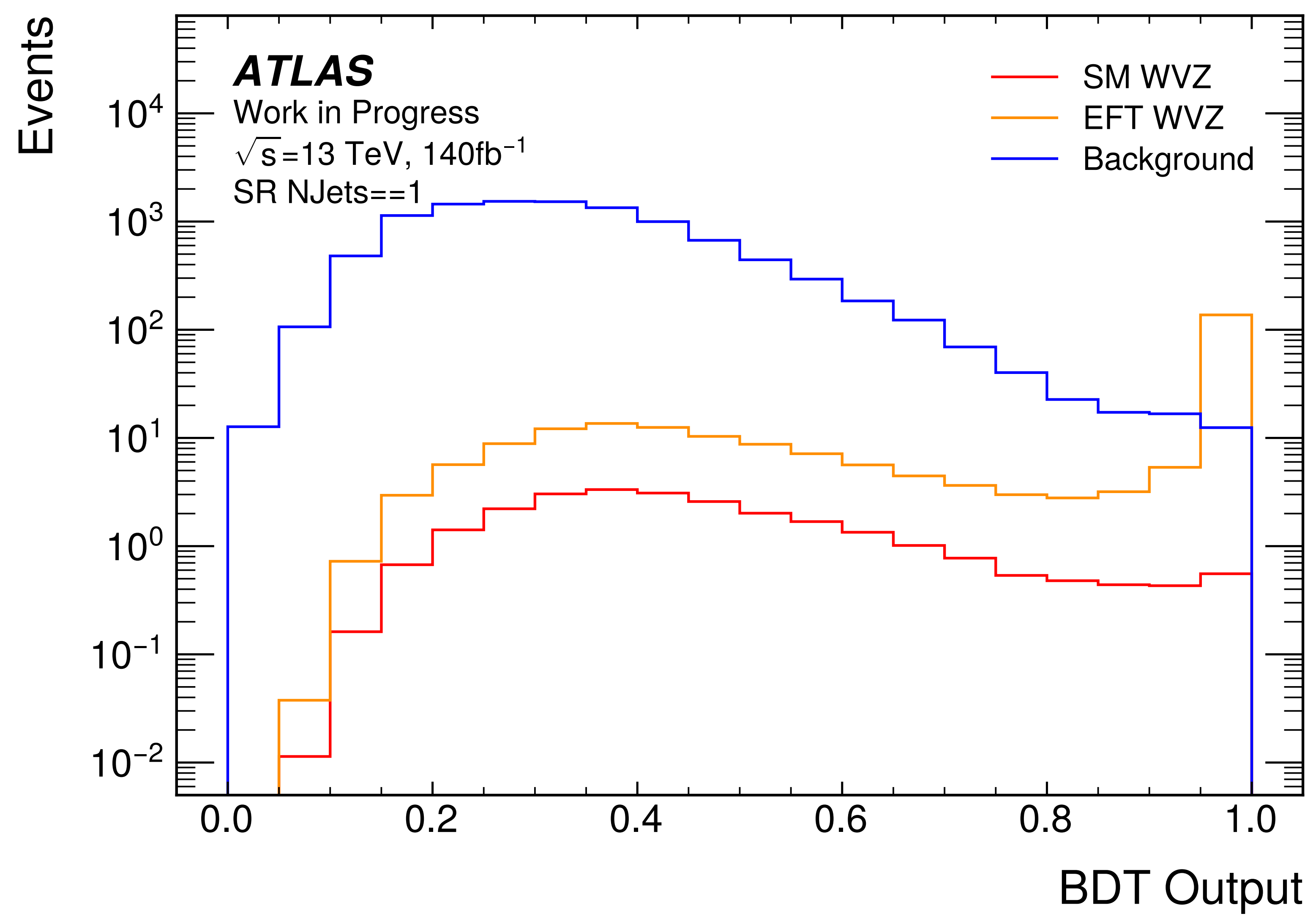


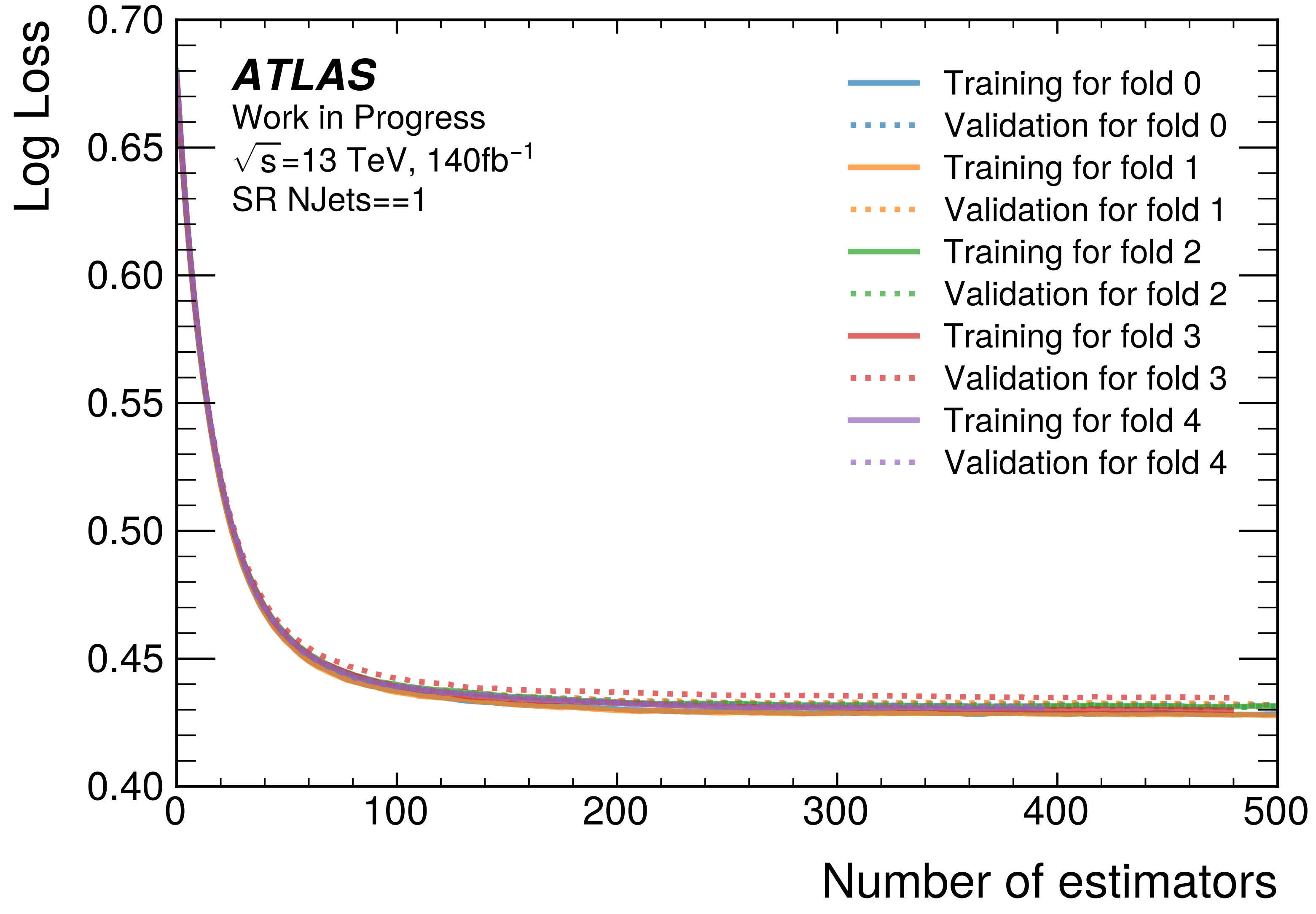


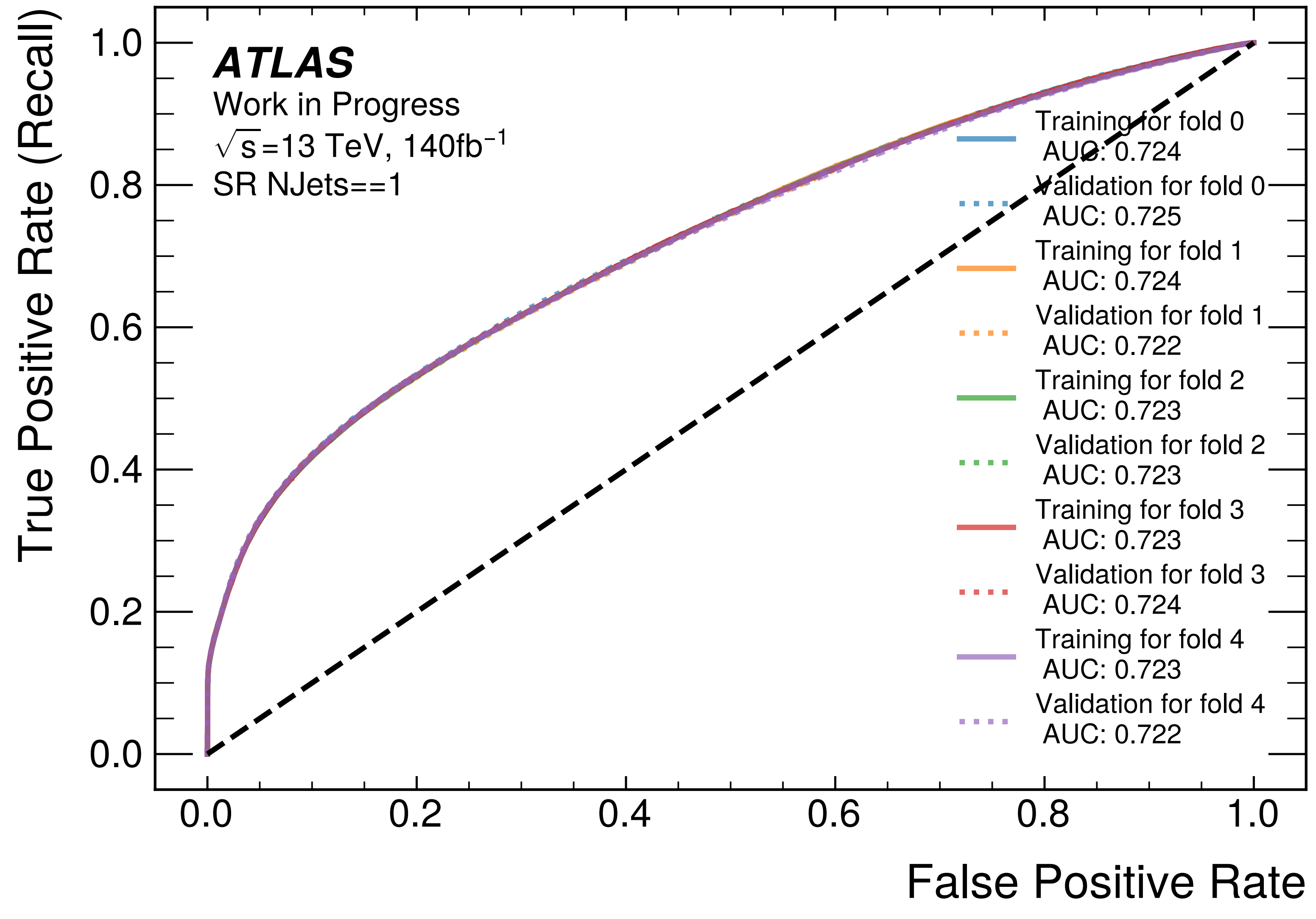
EFT BDTs

- Retrain BDTs used in SM analysis with expanded definitions of ‘Signal” now including a range of EFT signal strengths, across f_{M2-5} operators
- Use k-folding to maximise power gained from available MC statistics
- Recursive feature elimination utilised to minimise length of BDT feature list, to prevent overfitting of model and optimise performance to simplest model





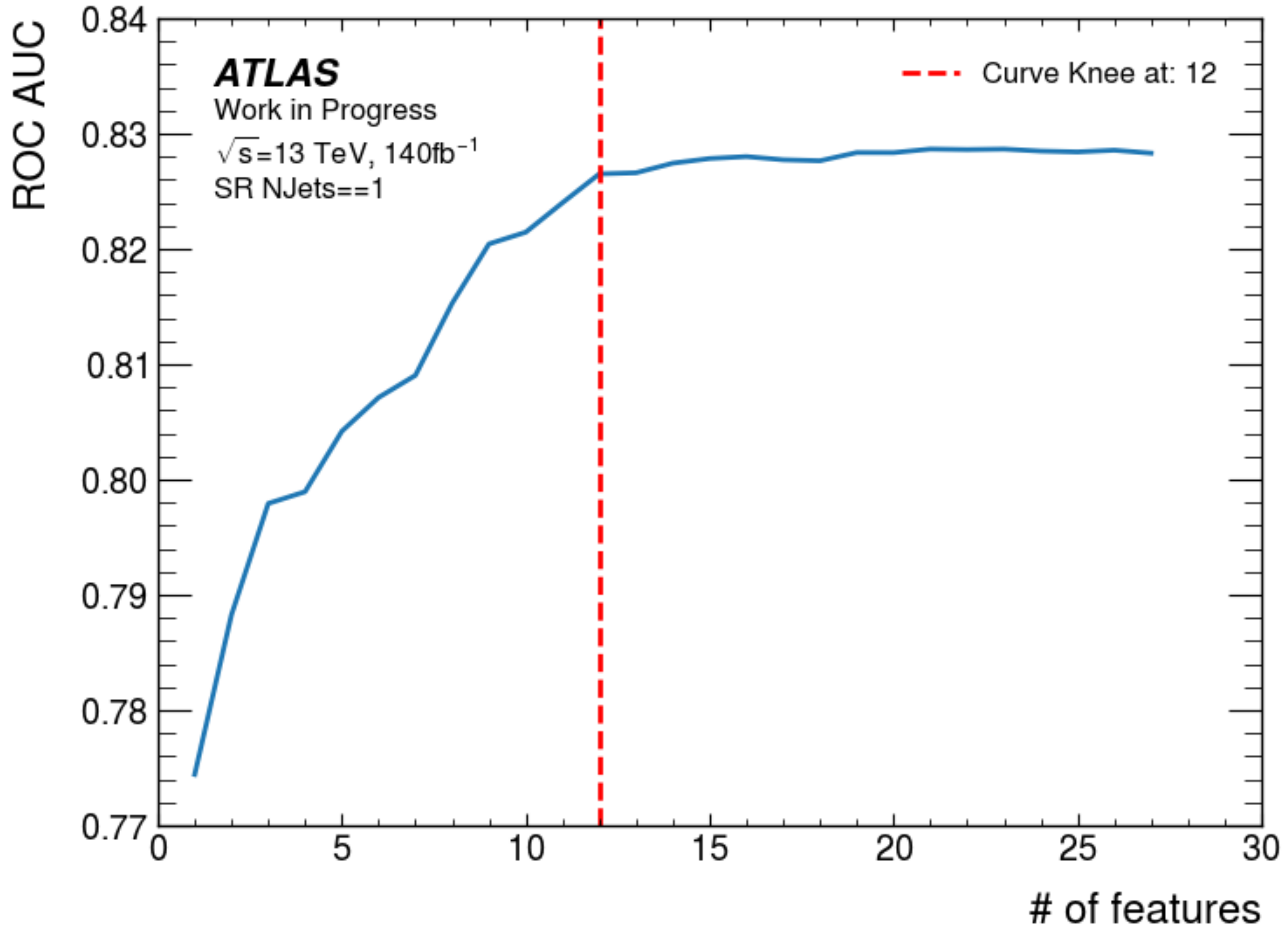


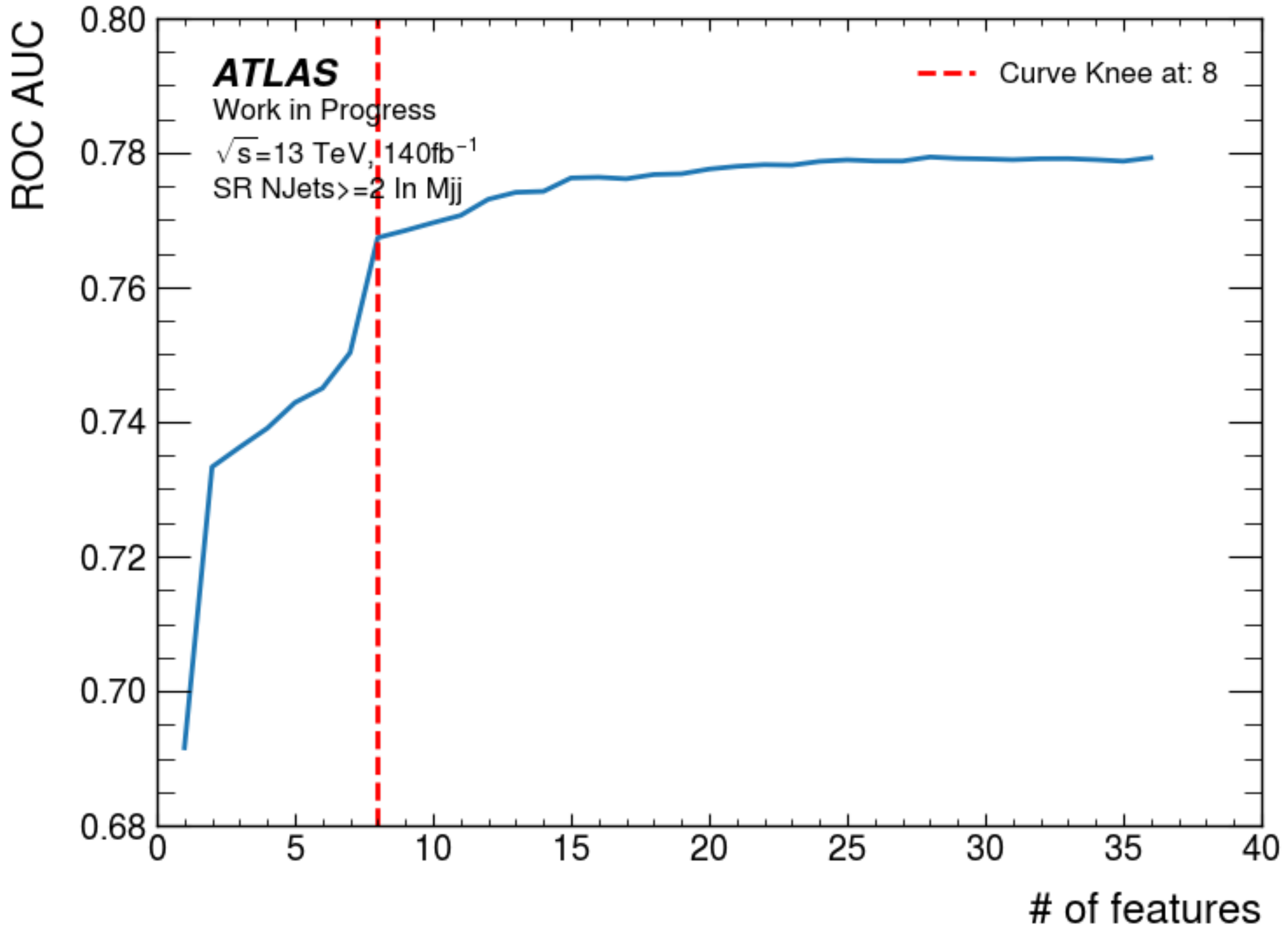


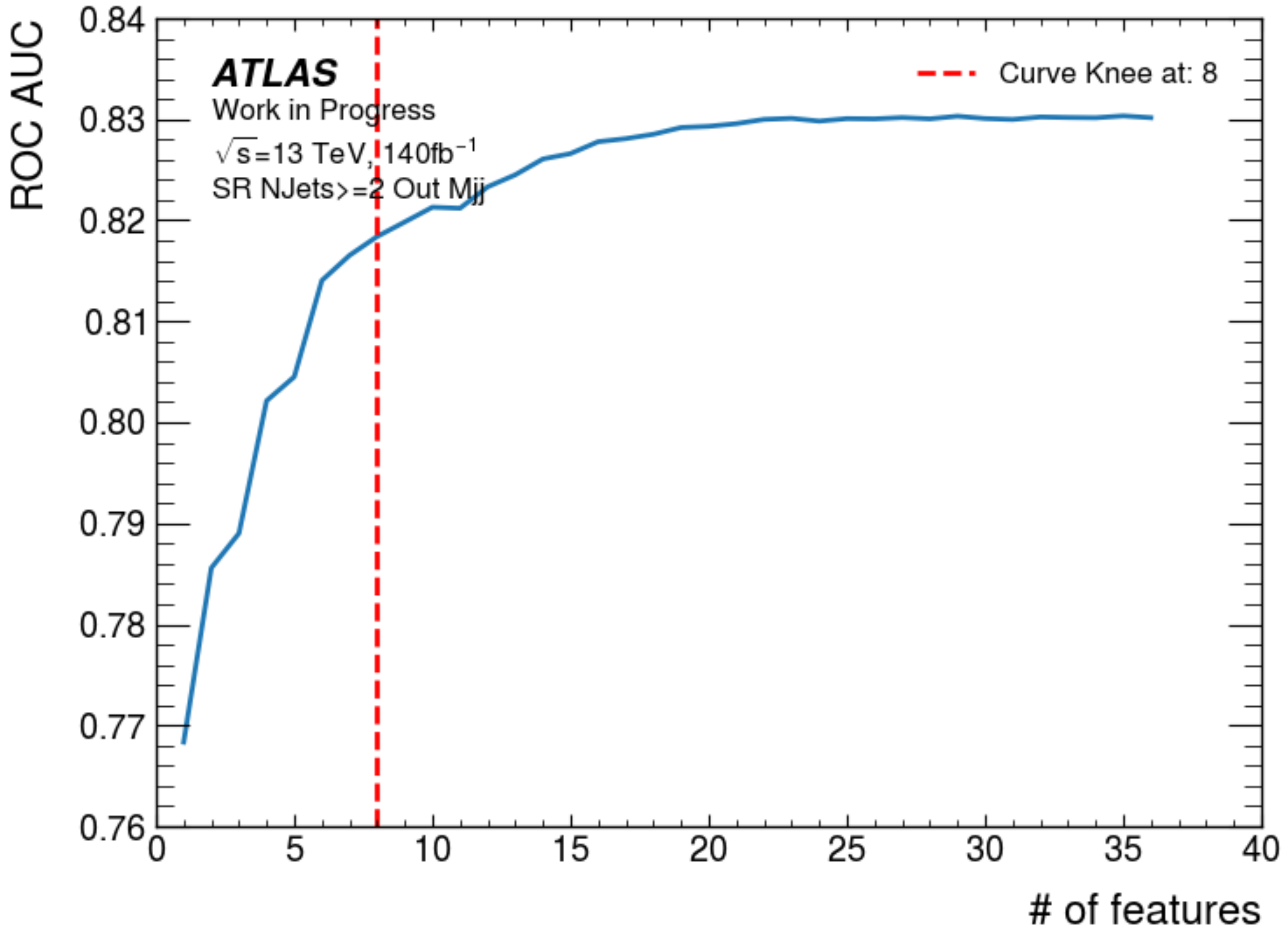
EFT BDTs

- Recursive feature elimination utilised to minimise length of BDT feature list, to prevent overfitting of model and optimise performance to simplest model
- Feature removal of highly correlated observables (>75%) in order of important
- Maximum point of curvature in RFE curve used to cut feature list to minimal length using the Kneedle algorithm

NJets == 1	NJets $\geq$ 2 in $V_{m_{jj}}$	NJets $\geq$ 2 out $V_{m_{jj}}$
WWZ_M	m^{01}_{jj}	p_T^{j1}
E_T^{miss}	p_T^{j2}	H_T^{lep}
$\Delta M(Z_{\ell\ell}, V_{qq})$	$m^{012}_{\ell\ell\ell\ell}$	E_T^{miss}
$M^W_{T,\ell}$	p_T^{j1}	$M^W_{T,had}$
$\Delta p_T(Z_{\ell\ell}, V_{qq})$	$\Delta p_T(Z_{\ell\ell}, V_{qq})$	$M^{12}_{\ell\ell}$
$p_T^{\ell_3}$	HT	p_T^{j2}
$\Delta p_T(Z_{ll}, V_{qq})$	E_T^{miss}	$p_T^{W,lep}$
$\Delta R(\ell_3, Z)$	$\Delta R(\ell_1 2)$	$\Delta R(\ell_1 2)$
$\Delta R(\ell_3, V_{qq})$		
E_{j1}		
$\Delta R(\ell_1 2)$		
$\Delta R(\ell_1 23)$		







EFT BDTs


ATLAS
Work in Progress
√s=13 TeV, 140 fb⁻¹
3ljets
SR NJets==1
Post-Fit
VVZ
WZ
ZZ
Z+Jets
ttZ
tZ
tWZ
VH
VBS
others
Uncertainty
f_{M5}/Λ^4 = 40 TeV^{-4}
SR NJets>=2 In Mjj
SR NJets>=2 Out Mjj
Events
EFT/SM
BDT Output

Limit Setting

- As EFT MC model is only currently available at LO, a k-factor must be applied to EFT signal samples to account for large NLO enhancements to triboson production

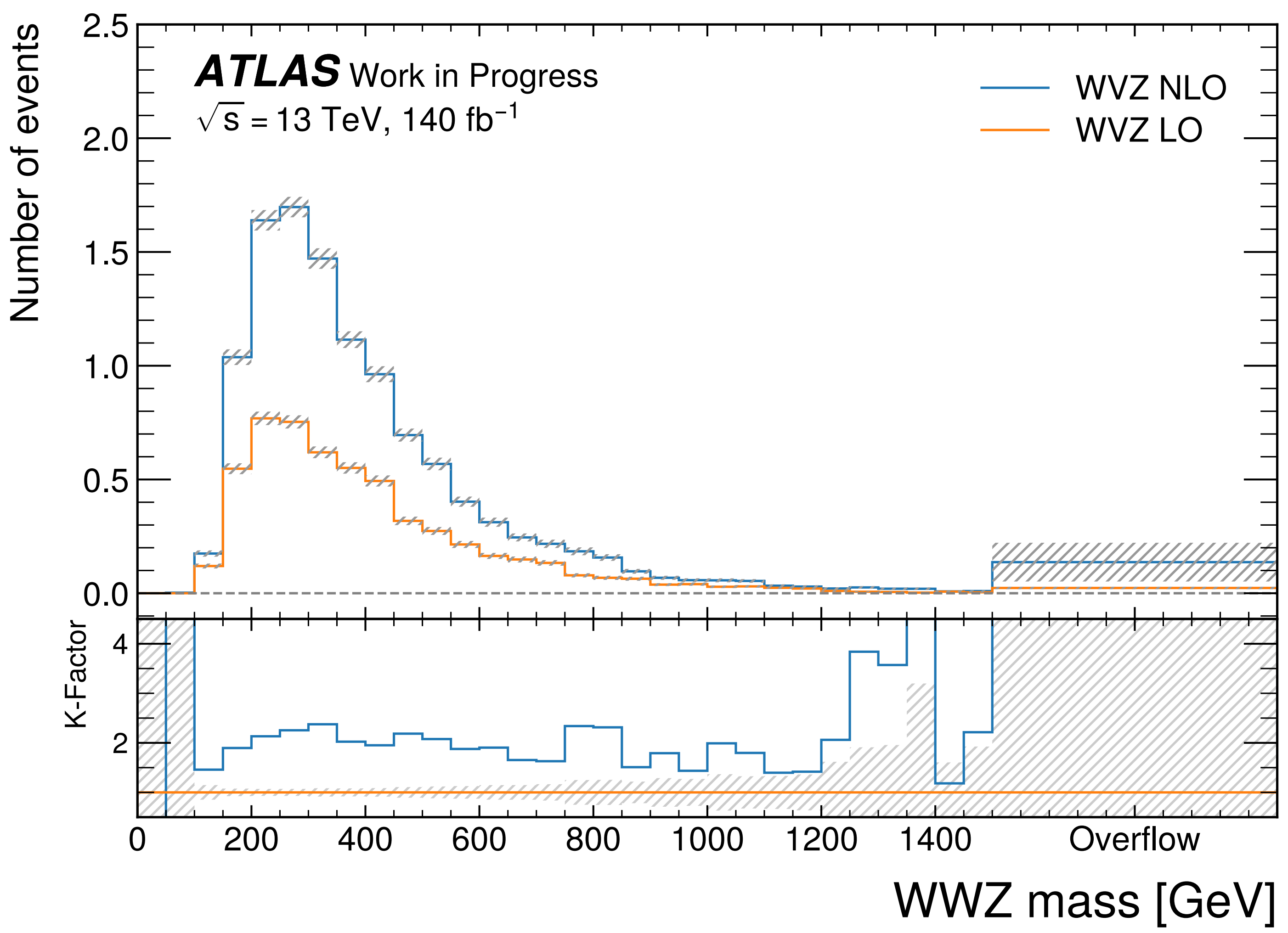
- Binned likelihood constructed from product of Poisson distributions, used to form a Profile Likelihood ratio

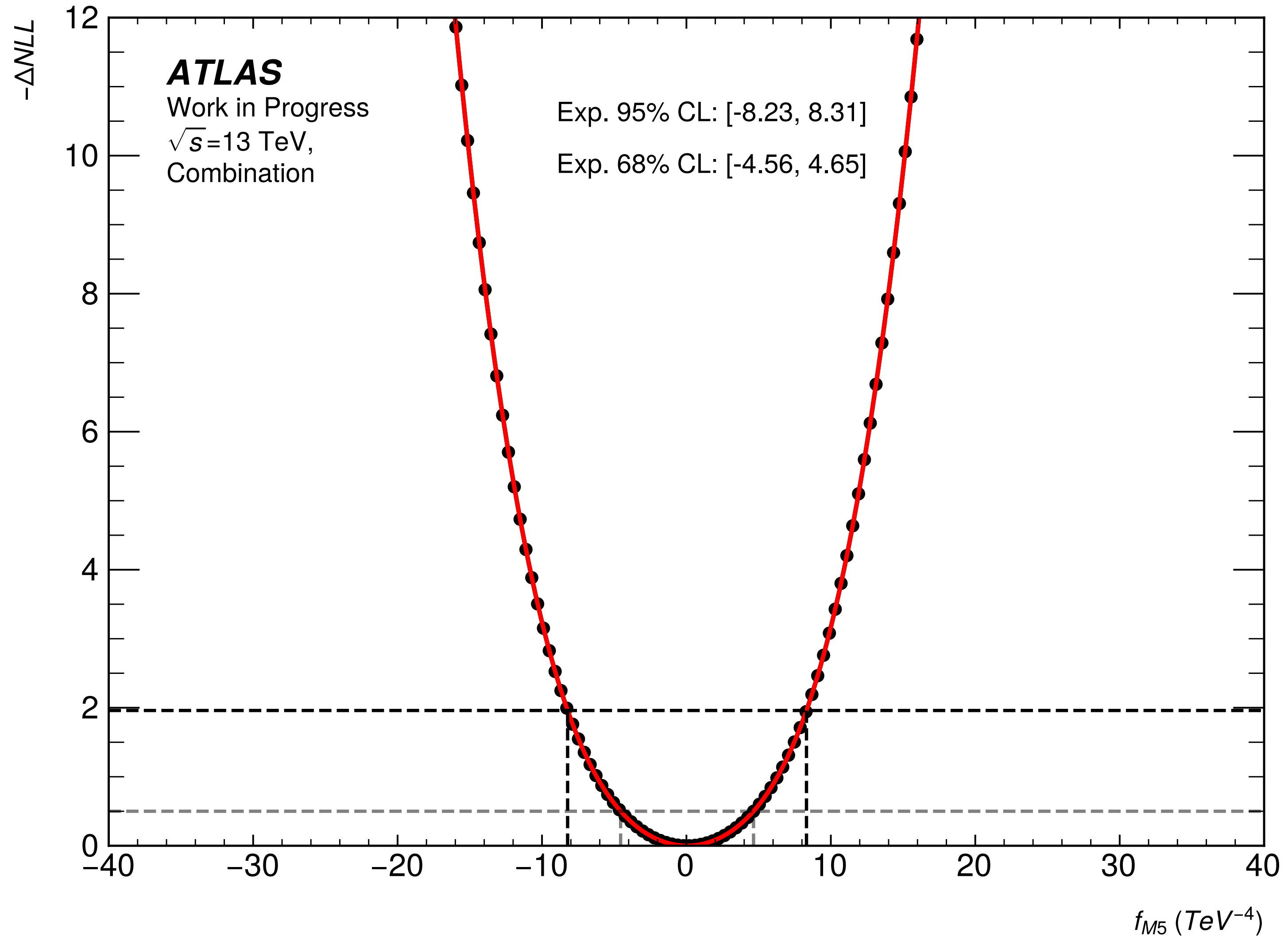
$$L(\boldsymbol{N} \mid \boldsymbol{c}, \boldsymbol{\theta}) = \prod_{b}^{n_{bins}} Poisson\left(N_b \mid N_b^{pred}(\boldsymbol{c}, \boldsymbol{\theta})\right) \times \prod_{i}^{n_{syst}} f_i\left(\theta_i\right), \quad q\left(c_i\right) = -2\log\frac{L\left(\boldsymbol{x} \mid c_i, \hat{\hat{\theta}}\right)}{L\left(\boldsymbol{x} \mid \hat{c}_i, \hat{\boldsymbol{\theta}}\right)}$$

- Log likelihood scan performed for each WC, setting 95% confidence level limits

- 3ℓ+jets and 4ℓ channels display similar containing power, combined results are first ever aQGC limits from fully massive triboson final state measurement at the LHC

- M2-5 = f_{M2-5}/Λ^4





Expected Wilson Coeffeicent 95% CL Limits (TeV^-4), ATLAS Work In Progress		
3l + Jets	4l	Combined
-18.1 < M2 < 18.0	-18 < M2 < 18	-8.7 < M2 < 8.6
-30.3 < M3 < 30.3	-30 < M3 < 30	-15.9 < M3 < 16.0
-16.4 < M4 < 16.6	-16 < M4 < 16	-8.6 < M4 < 8.8
-13.0 < M5 < 13.1	-12 < M5 < 12	-8.2 < M5 < 8.3

Clipping scan still to be completed

Summary

Search for remaining massive triboson production modes improves on previous run 2 efforts

- Search targets all VVZ final states across leptonic and semi-leptonic final states, with close to 5σ sensitivity to VVZ expected

- First limits on aQGCs from a massive triboson production measurement at the LHC

- BDTs used across SM and EFT sections of analysis to enhance sensitivity to rare SM process

- Next: Complete internal review and unblind data in SRs!

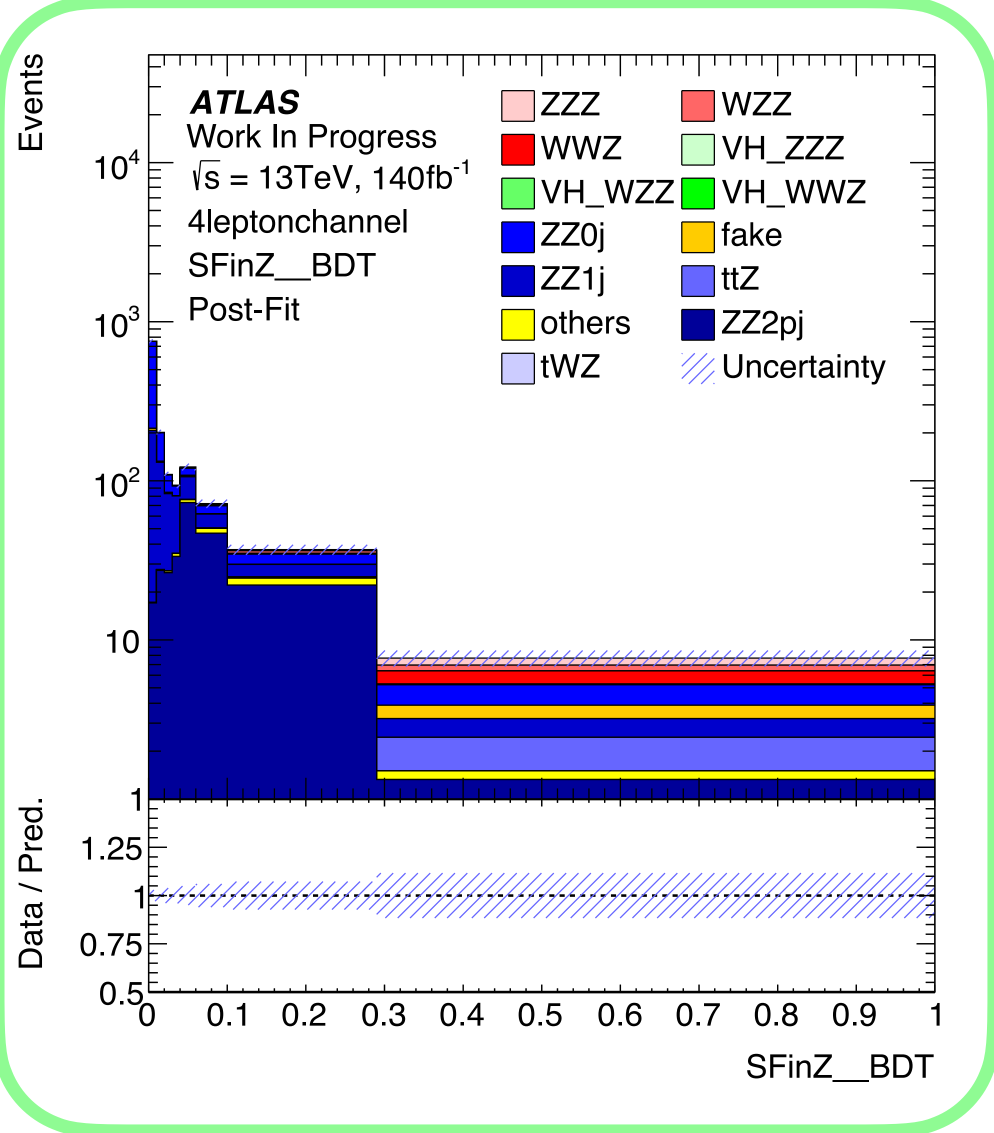
Backup

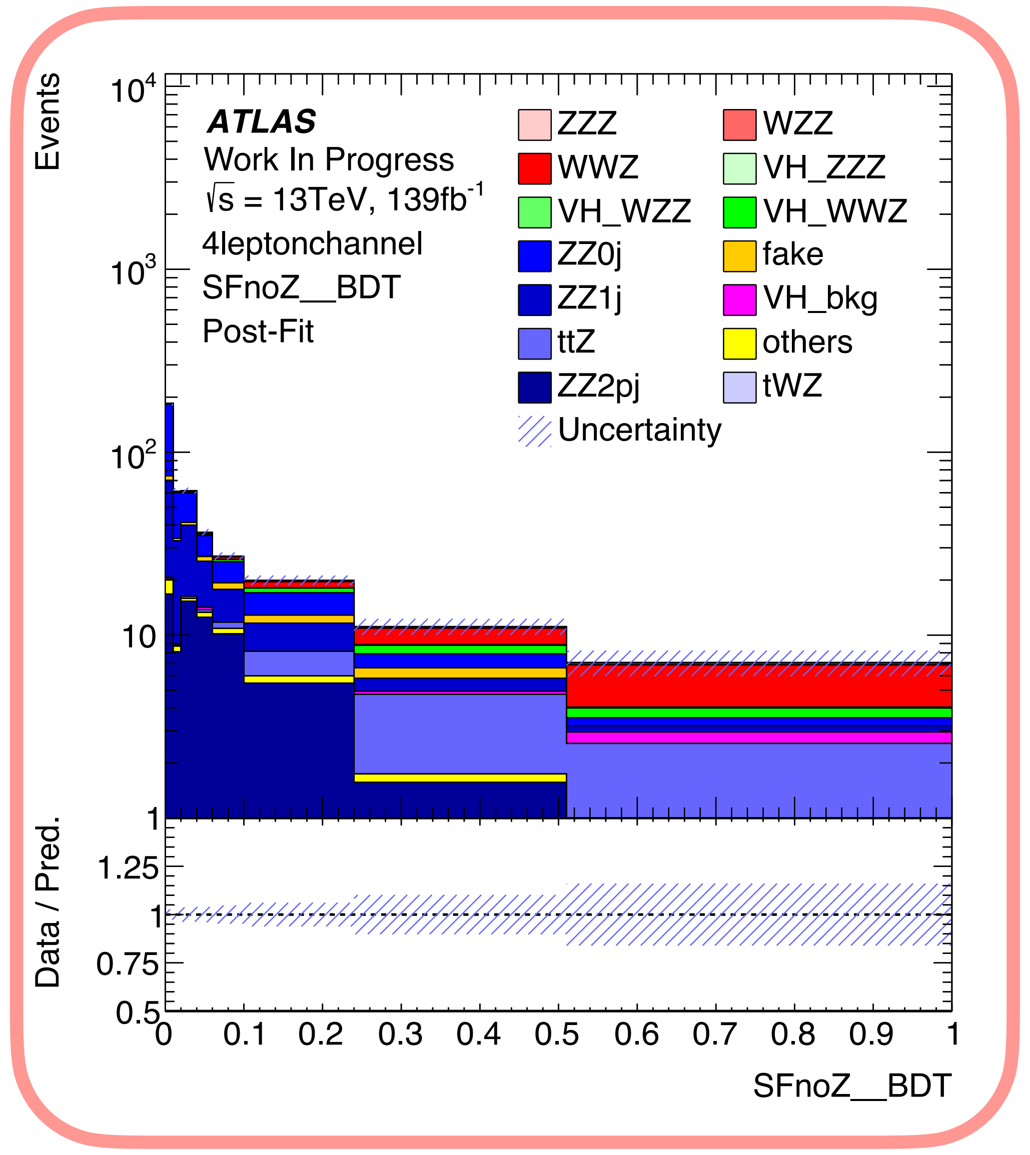
$4\ell 2\nu$ Channel

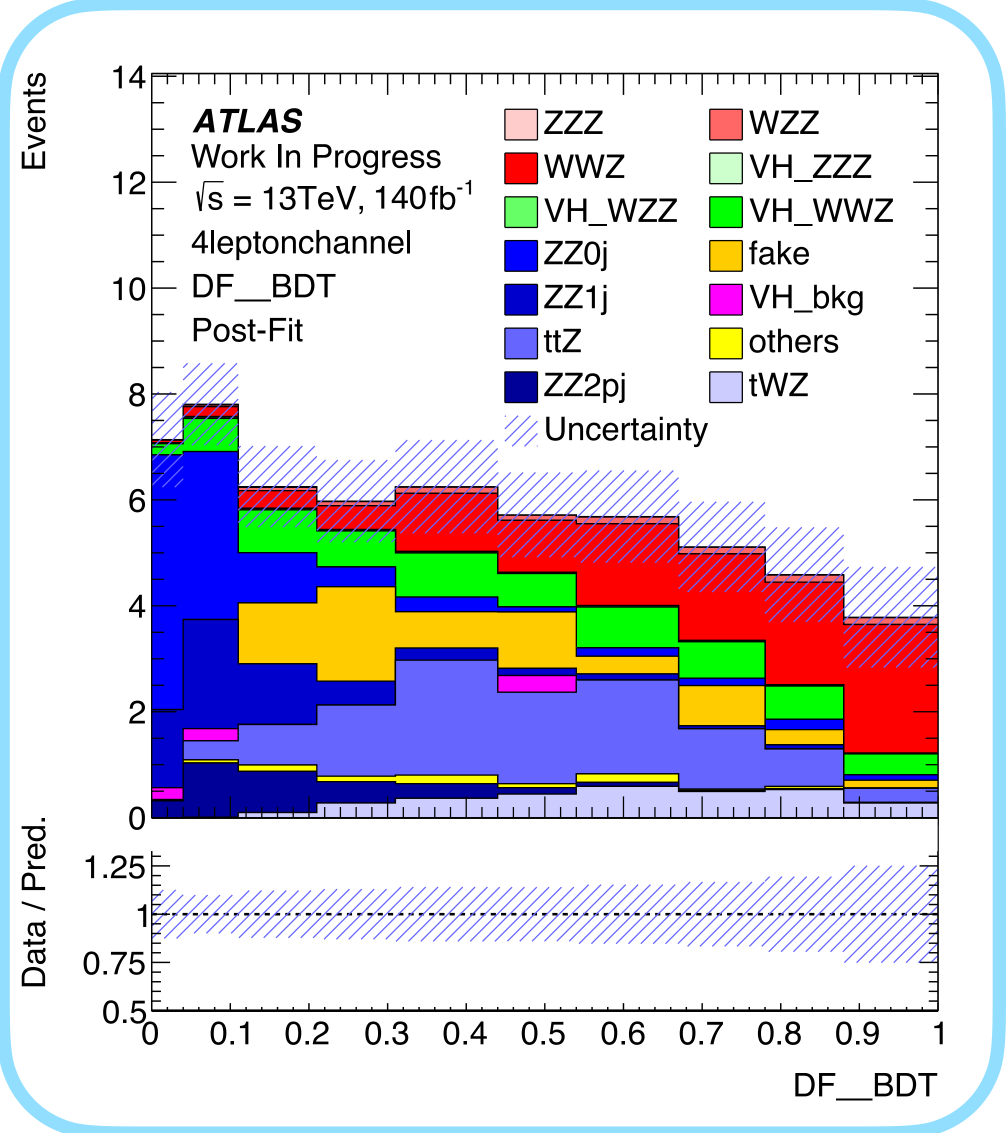
- Same Flavour Opposite Sign di-leptons with a mass closest to the Z mass is selected as the Z candidate, then other leptons used to define SRs:
  - SFinZ - Same-flavor leptons inside of 20 GeV Z mass window region
  - SFoutZ - Same-flavor leptons outside of 20 GeV Z mass window region
  - DF - Different-flavor leptons
- BDTs are trained for each SR using kinematic & angular variables
- ZZ & $t\bar{t}Z$ CRs are defined to normalise backgrounds to data
- Fake estimate derived from data in Z+jets & $t\bar{t}$ Fakes regions

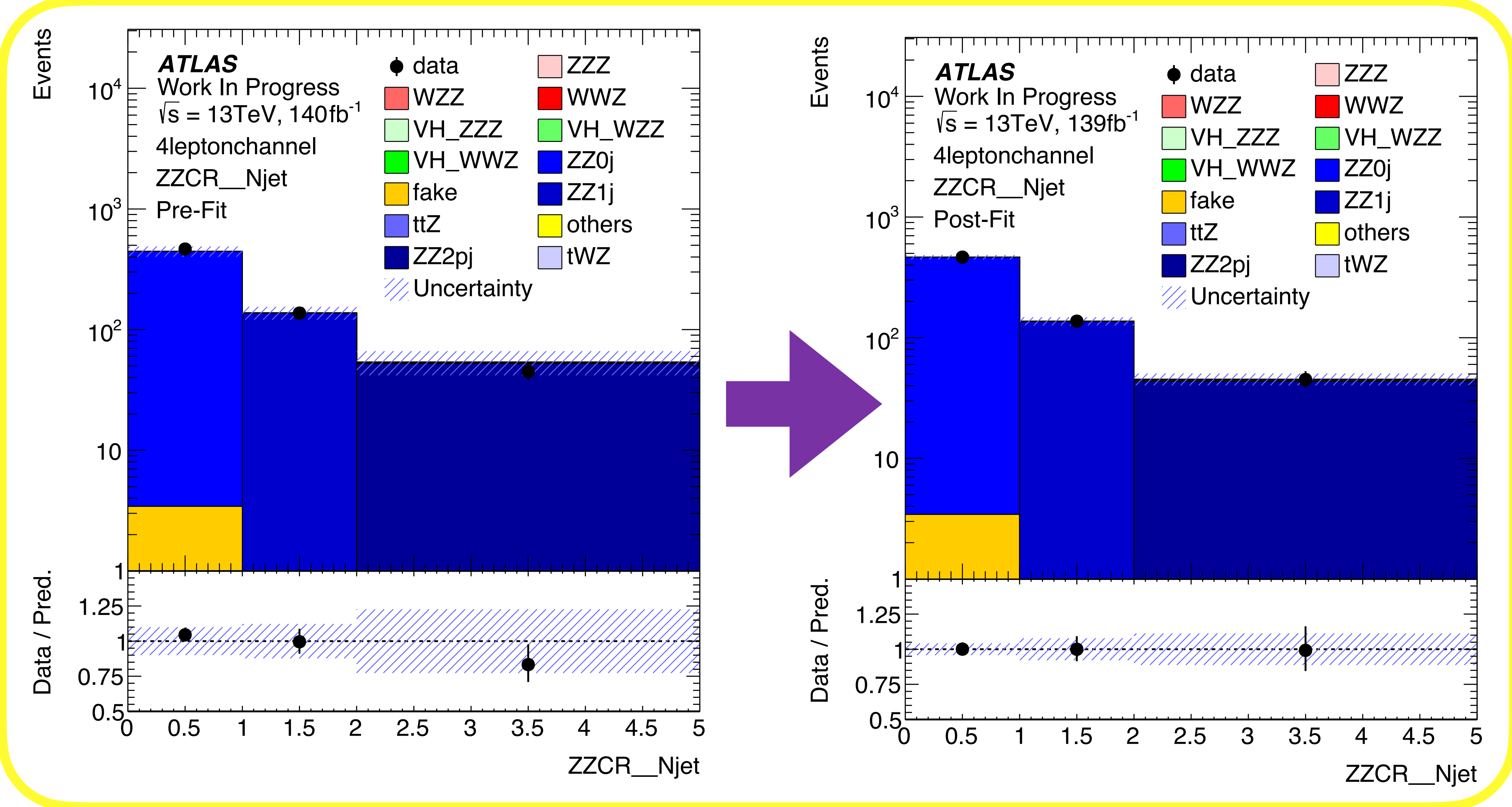
$$FF_{4l,fakeCR} = \frac{d_{ata_{good}} - MC_{good,prompt}}{data_{bad} - MC_{bad,prompt}}$$

- Fit to Asimov dataset in SRs and data in CRs before unblinding

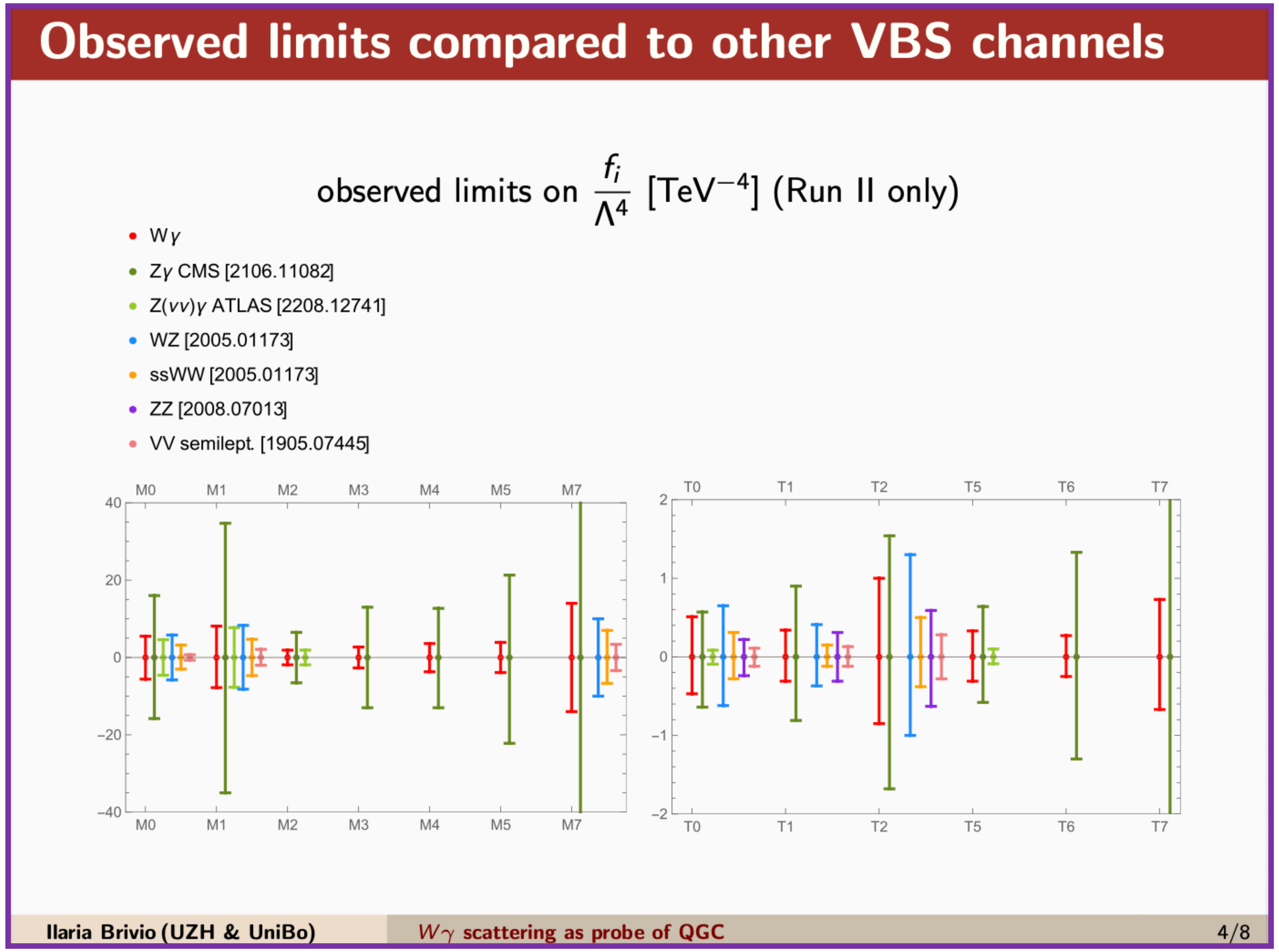








World Leading Limits?



- Current best limits on operators from CMS paper can be found here.
- Limits do not have clipping scan or unitarity bounds
- Slides credit to I. Brivio

Table 2: Exclusion limits at the 95% CL for each aQGC coefficient, derived from the $m_{W\gamma}$ distribution, assuming all other coefficients are set to zero. Unitarity bounds corresponding to each operator are also listed. All coupling parameter limits are in TeV^{-4}, while U_{bound} values are in TeV.

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1