Moriond EW 2025

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Triboson and VBS results at ATLAS and CMS

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Triboson and VBS results at ATLAS

- **Measurements of multiboson production at the LHC are important probes of the EW gauge structure of the Standard Model**
  - Polarised production of W/Z boson pairs via VBS processes provides a sensitive test of the EW symmetry breaking mechanism
  - Triboson and VBS processes are key to finding signs of new physics at high energies
    - Effects of anomalous quartic gauge couplings can be parameterised in the EFT framework

- **Many new ATLAS and CMS physics results!**

Presented by Max Stange today!

ATLAS EXPERIMENT Evidence for longitudinally polarised W bosons in the EW $W^{\pm}W^{\pm}$ production, arXiv:2503.11317

ATLAS EXPERIMENT EW diboson production in semileptonic final states at $13\ \mathrm{TeV}$, arXiv:2503.17461

CMS Semileptonic VBS and anomalous quartic gauge couplings at $13\ \mathrm{TeV}$, CMS-PAS-SMP-22-011

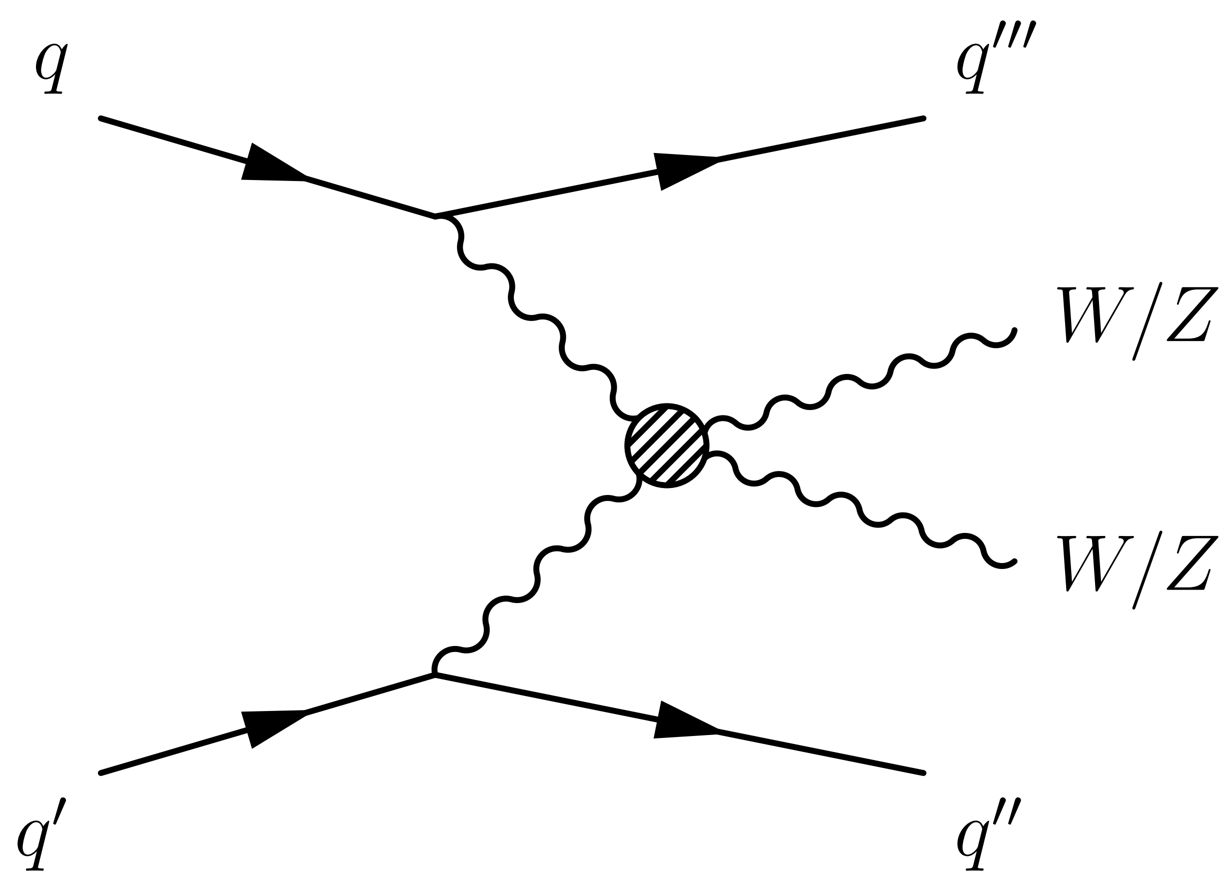
ATLAS EXPERIMENT Observation of VVZ production at $13\ \mathrm{TeV}$ with the ATLAS detector, arXiv:2412.15123

CMS Measurements of WWZ and ZH cross sections at 13 and $13.6\ \mathrm{TeV}$, CMS-PAS-SMP-24-015

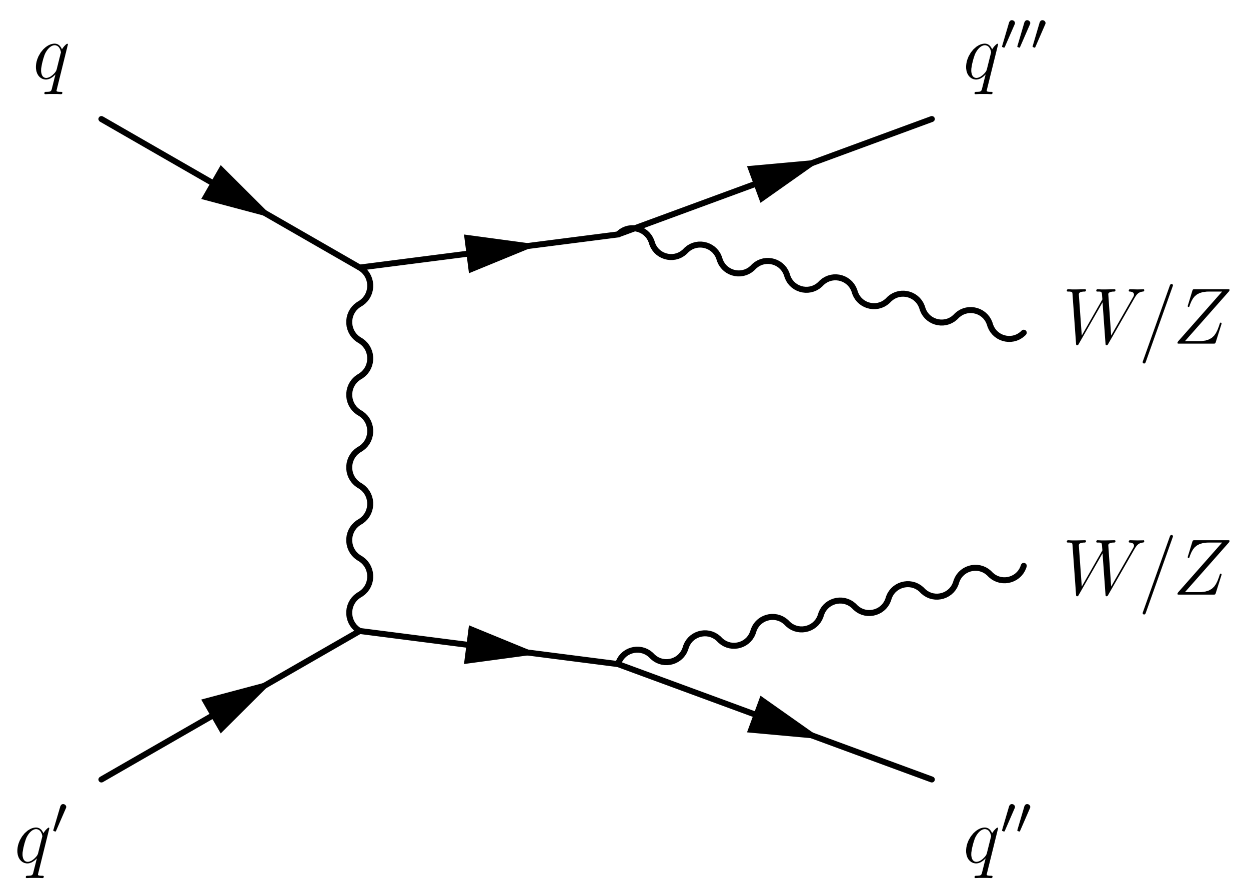
Covered by Carlos Vico Villalba today!

EW diboson production in semileptonic final states

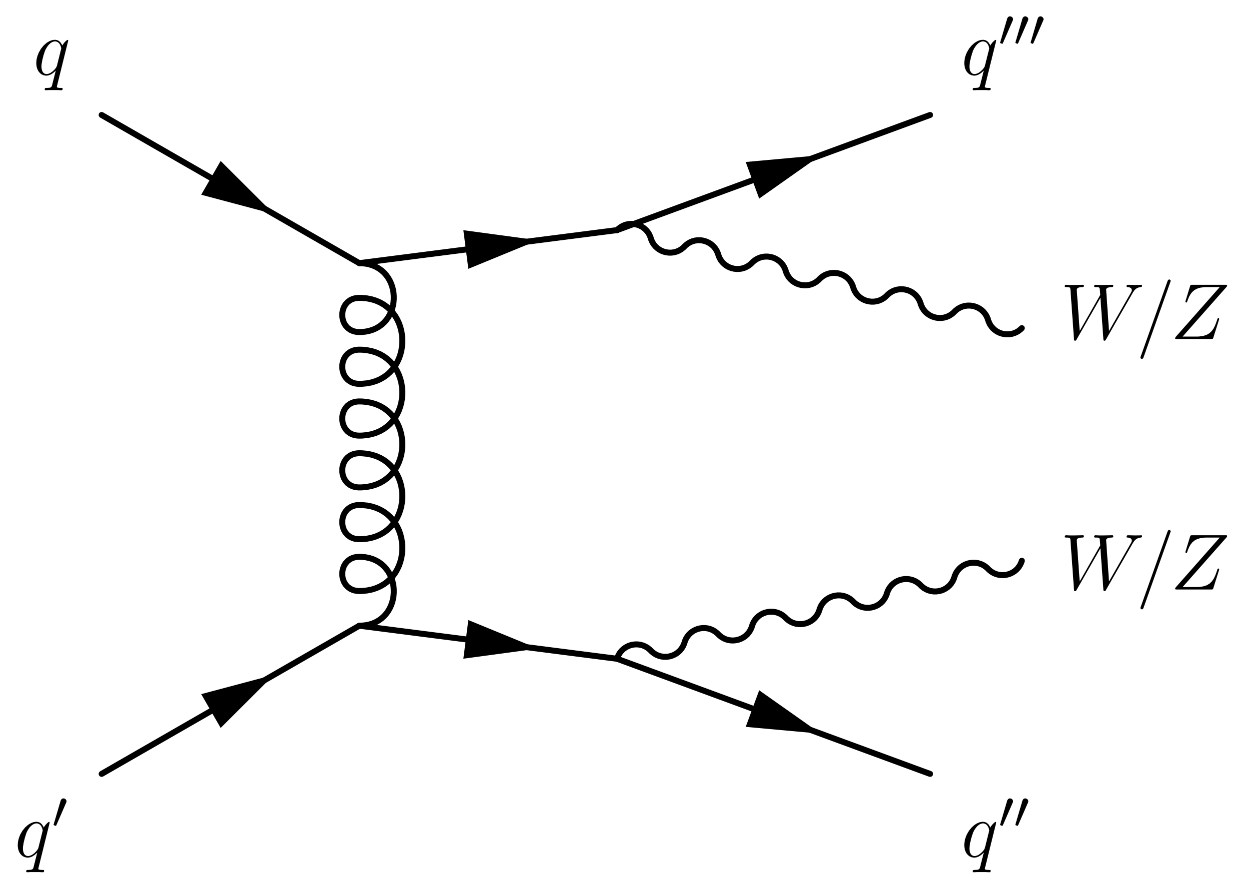
arXiv:2503.17461



EW $VVjj$ production via VBS



EW $VVjj$ production



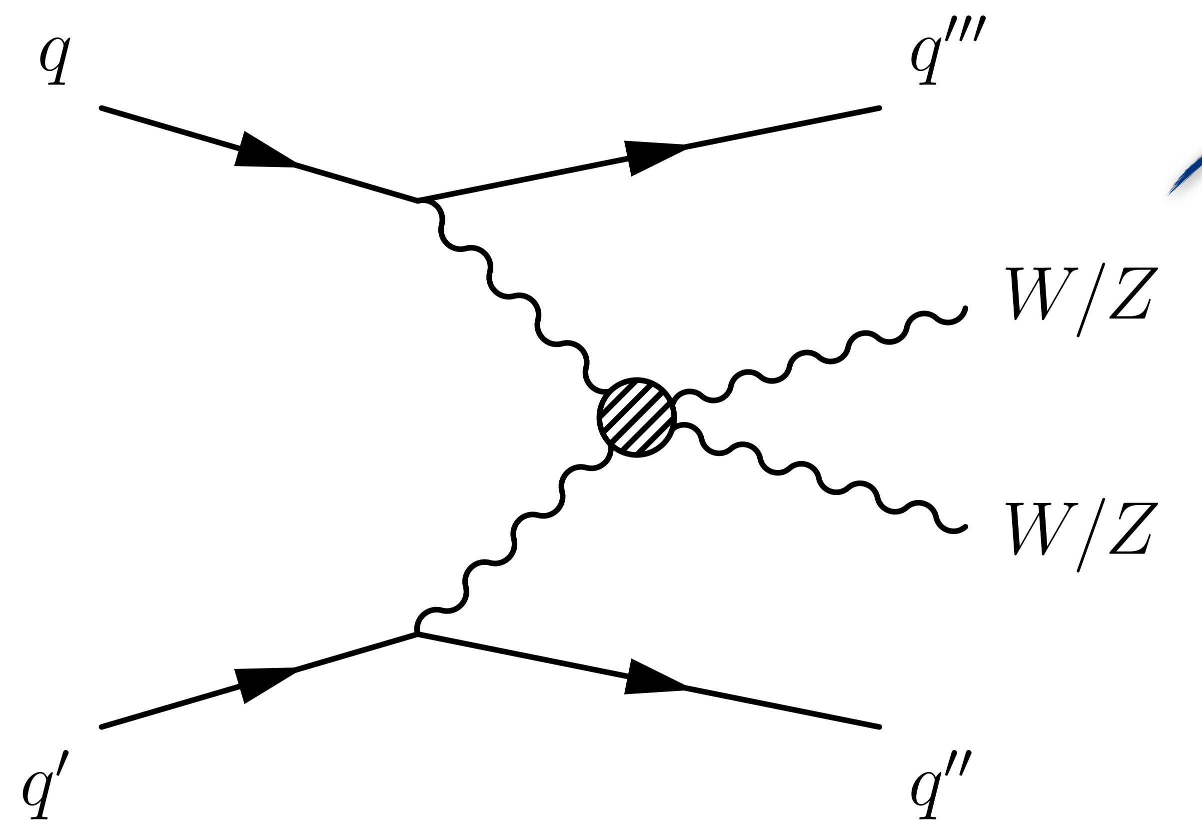
QCD $VVjj$ production

EW diboson production in semileptonic final states

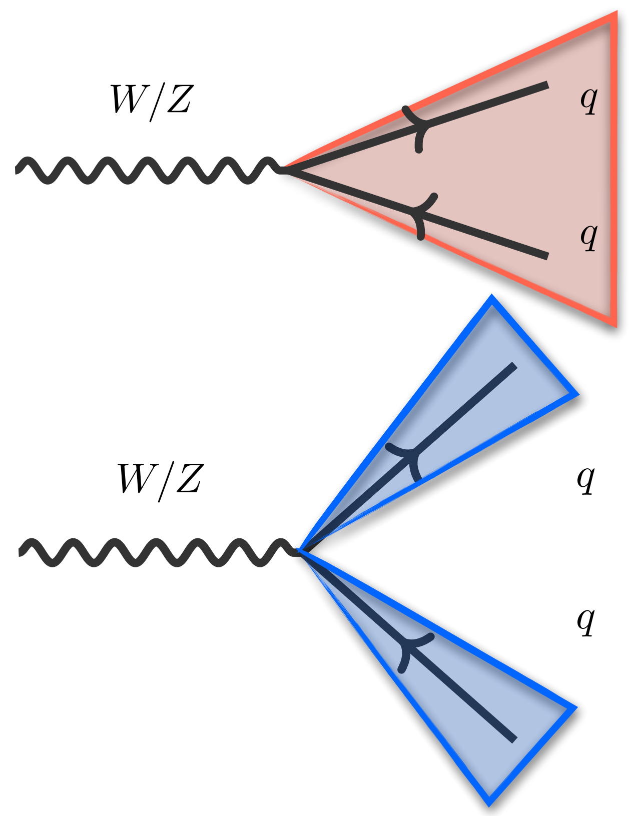
- Semileptonic VBS $VVjj$ at $13\ \mathrm{TeV}$ with $140\ \mathrm{fb}^{-1}$
  - Hadronic V decay: merged or resolved topologies
    - Select large-R tagged jet or 2 small-R jets
- **9 orthogonal SRs** plus CRs to model the $V+\mathrm{jet}$ and top backgrounds
  - (0-ℓ,1-ℓ, 2-ℓ) x (Merged HP, Merged LP, Resolved)

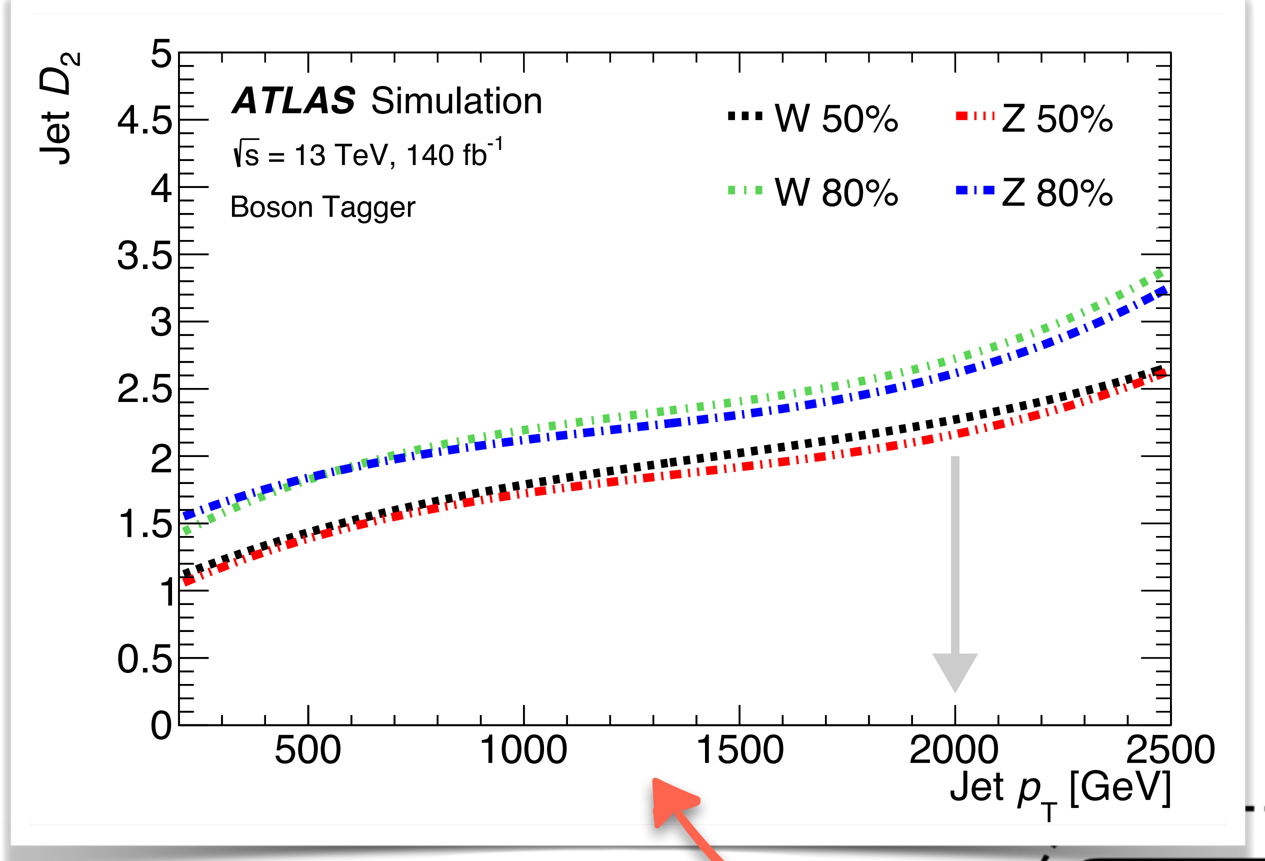
Pass $50\,\%$ tagger | **Fail** $50\,\%$ tagger
Pass $80\,\%$ tagger

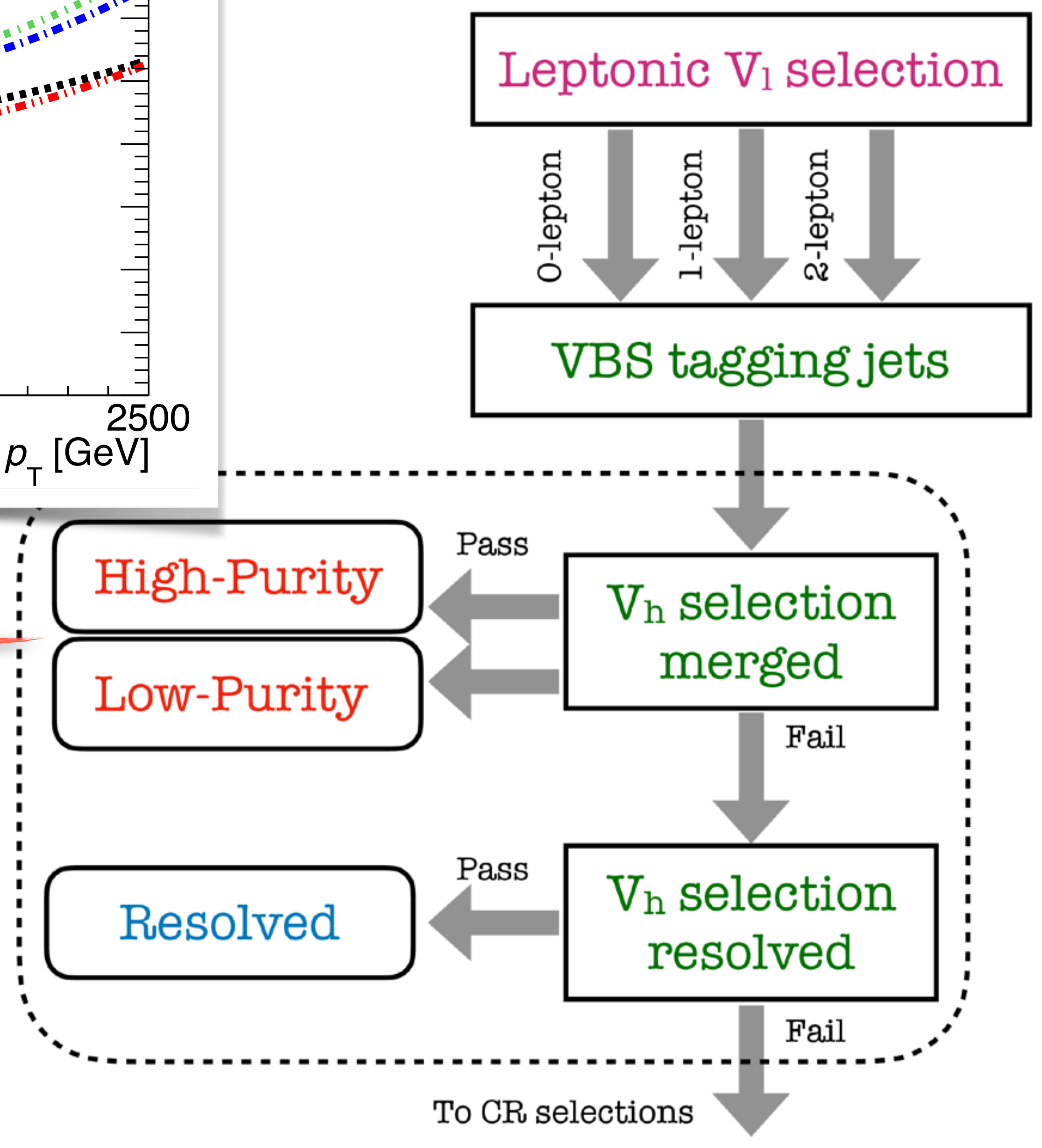
- <u>A *Recurrent Neural Network* (RNN) developed to separate VBS VV signal from backgrounds</u>
  - Dedicated training in each ℓ channel and merged/resolved regions
  - Input jet variables for training: p_T, η, ϕ, E, n_tracks
  - RNN score used as final discriminant



0-lepton: $Z\to\nu\nu$
1-lepton: $W\to\ell\nu$
2-lepton: $Z\to\ell\ell$







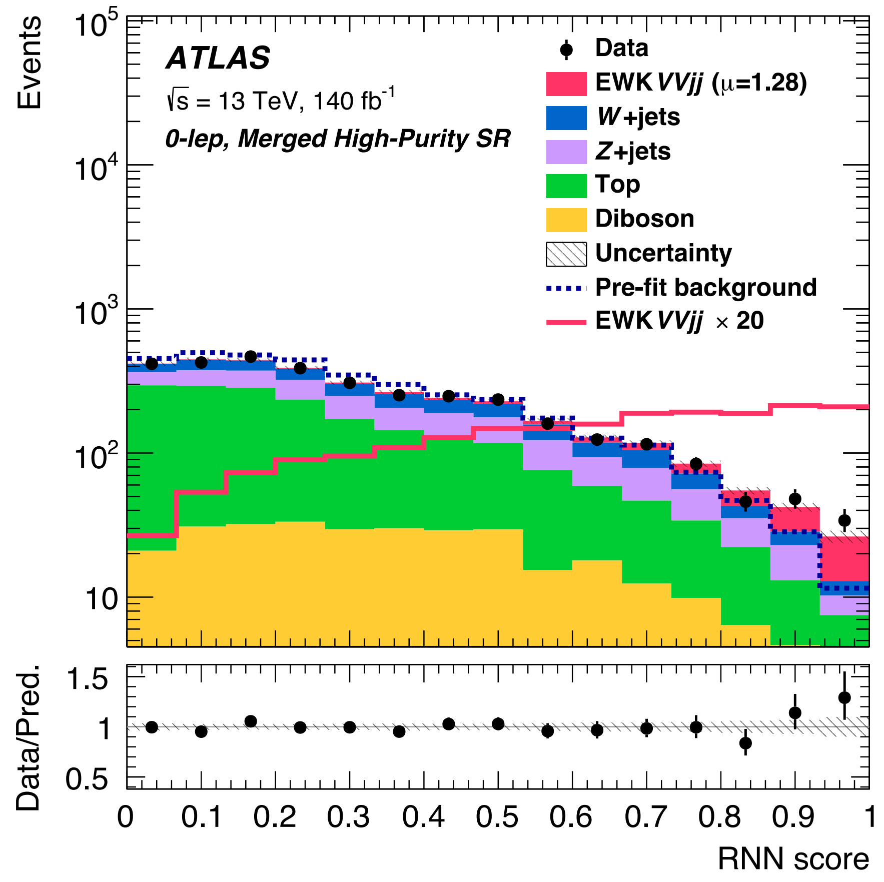
EW diboson production in semileptonic final states

- Measured EW $VVjj$ signal strength:

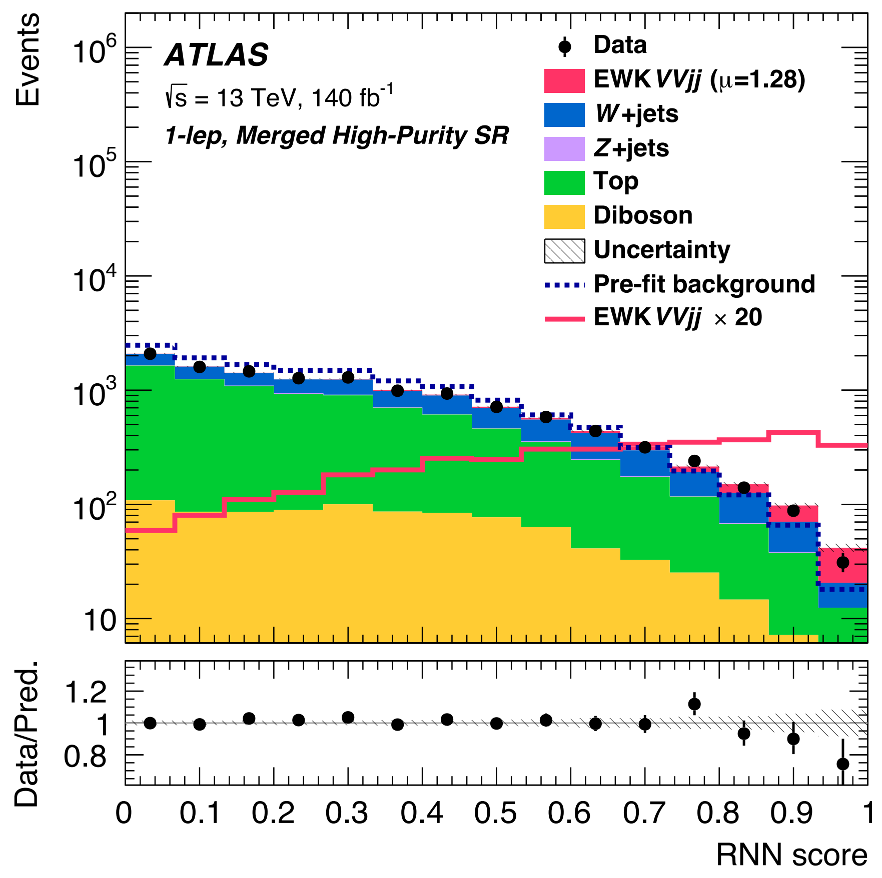
$$\mu_{\mathrm{EW}}^{\mathrm{obs}} = 1.28^{+0.23}_{-0.21} = 1.28 \pm 0.09\,(\mathrm{stat.})\,^{+0.20}_{-0.19}\,(\mathrm{syst.})$$

Dominated by signal modelling and jet reconstruction uncertainties

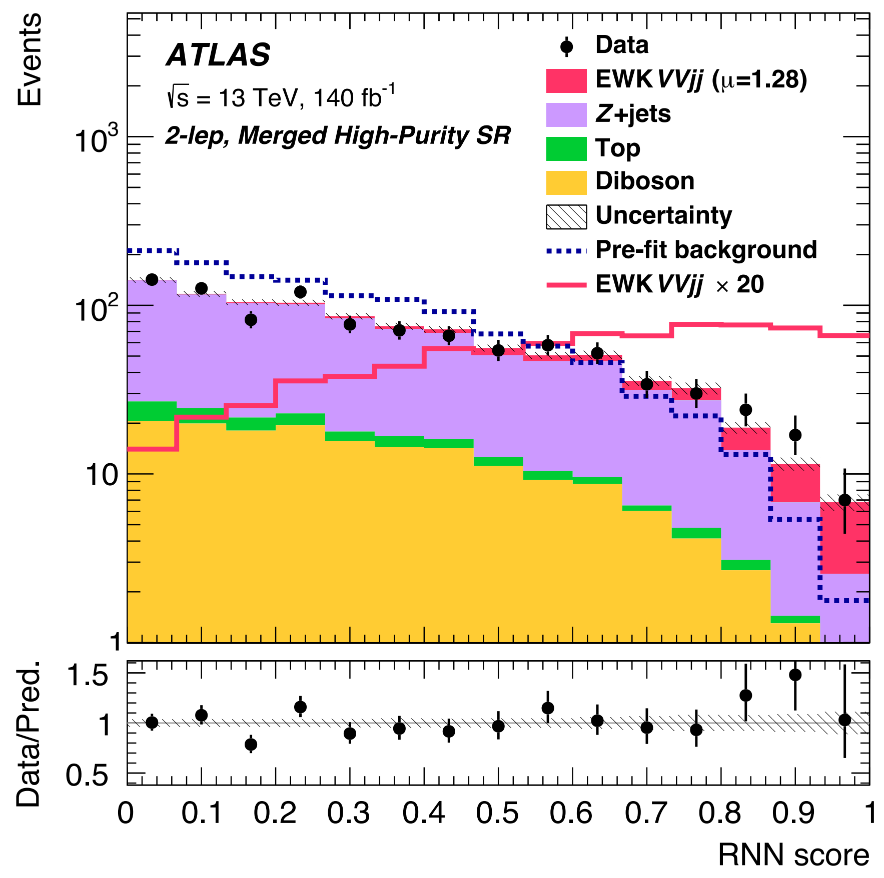
with obs. (exp.) significance of $7.4\ (6.1)\ \sigma$



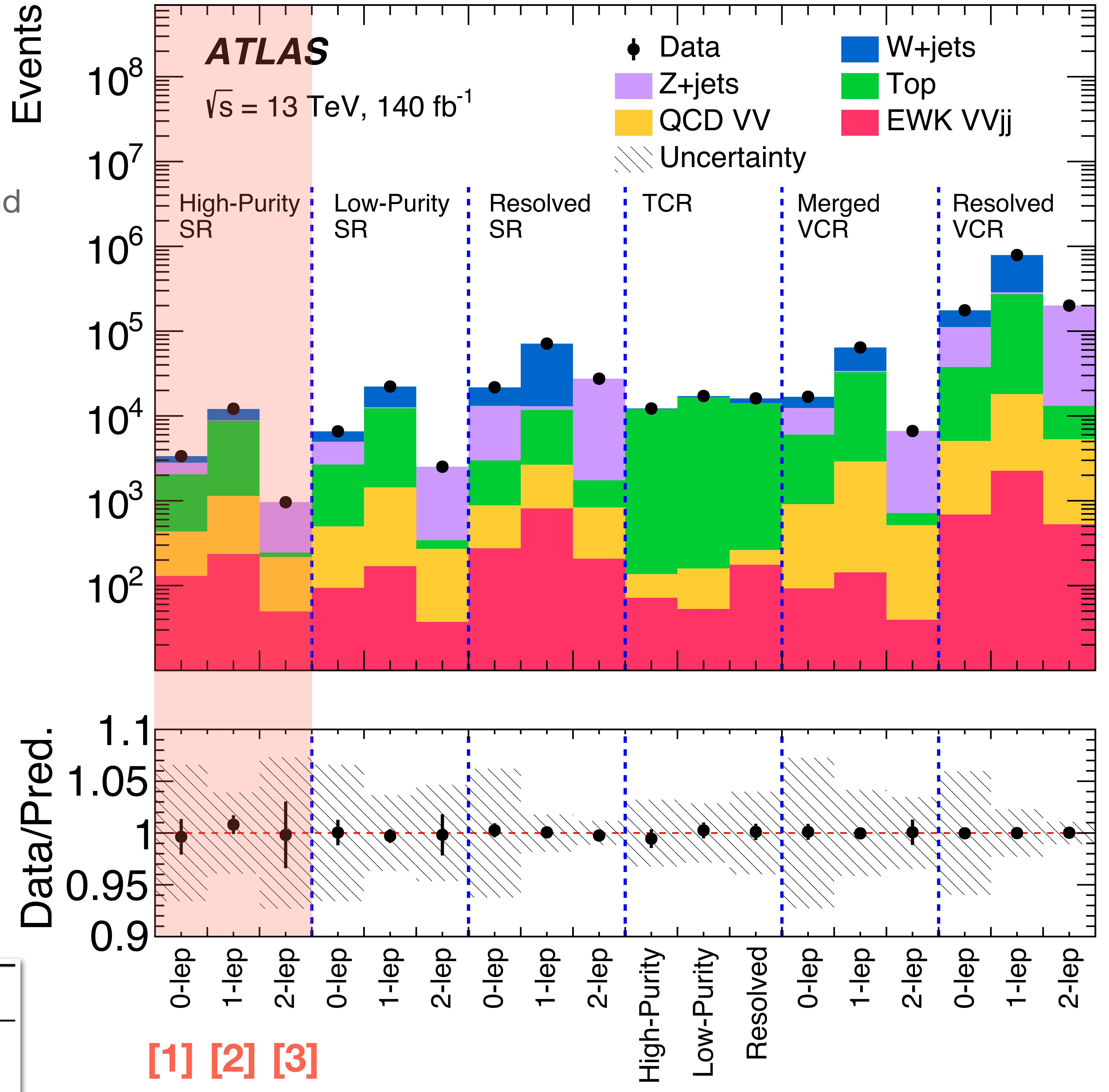
[1] High-Purity 0-ℓ



[2] High-Purity 1-ℓ



[3] High-Purity 2-ℓ



- Fiducial expected and measured cross-sections:

	Combined	0-lepton	1-lepton	2-lepton	Resolved	Merged
$\sigma_{EWK}^{\mathrm{fid,exp}}$	20.4 ± 3.5 fb	7.3 ± 2.5 fb	10.3 ± 2.5 fb	2.8 ± 1.1 fb	11.7 ± 3.4 fb	8.7 ± 2.5 fb
$\sigma_{EWK}^{\mathrm{fid,obs}}$	29.2 ± 4.9 fb	15.7 ± 2.8 fb	10.7 ± 2.8 fb	3.1 ± 1.1 fb	17.9 ± 4.3 fb	11.4 ± 3.4 fb

EW diboson production in semileptonic final states

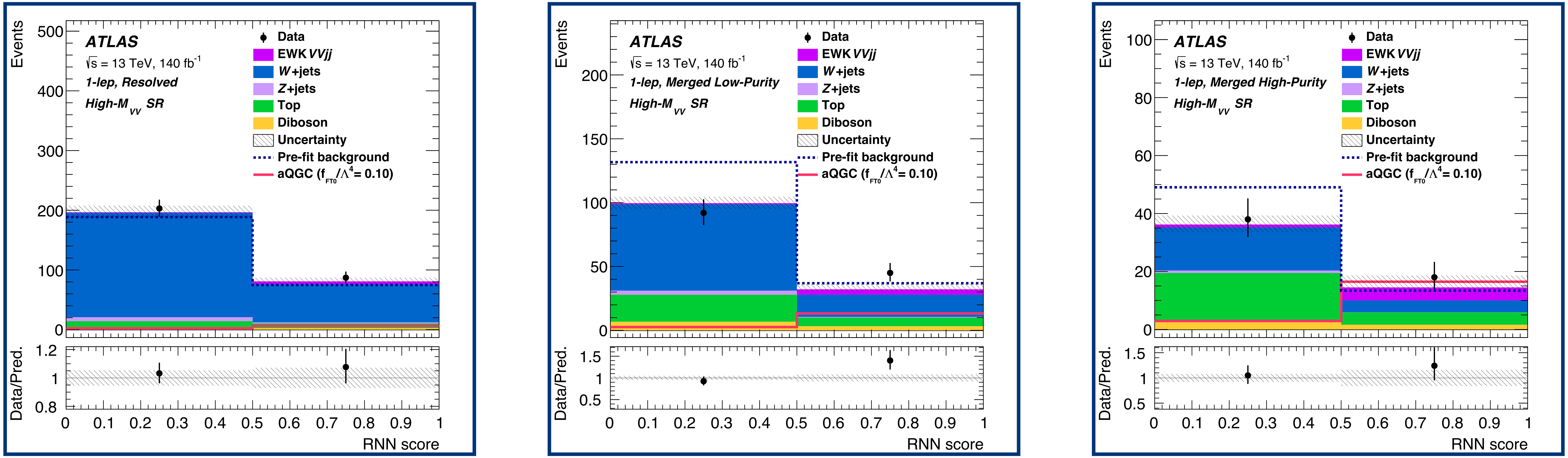
- Anomalous quartic gauge coupling (aQGC) effects can be parameterised in the EFT framework

$$\left| A_{\rm SM} + \sum_i \frac{f_i}{\Lambda^4} A_i \right|^2 = |A_{\rm SM}|^2 + \sum_i 2\frac{f_i}{\Lambda^4}{\rm Re}(A^*_{\rm SM}A_i) + \sum_i \frac{f_i^2}{\Lambda^8}|A_i|^2 + \sum_{i\neq j} 2\frac{f_i f_j}{\Lambda^8}{\rm Re}(A_i^* A_j)$$

EFT-SM interference — EFT term — EFT cross term

- New D-8 operators contributing to aQGC would enhance EW VBS prod. at high m_{VV}
  - Improvements for f_S and f_M by factor $\approx 2-3$ with respect to other ATLAS diboson measurements

Each SR is split into 2 m_{VV} bins (high/low) to improve sensitivity



EW diboson production in semileptonic final states

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EFT-SM interference | EFT term | EFT cross term

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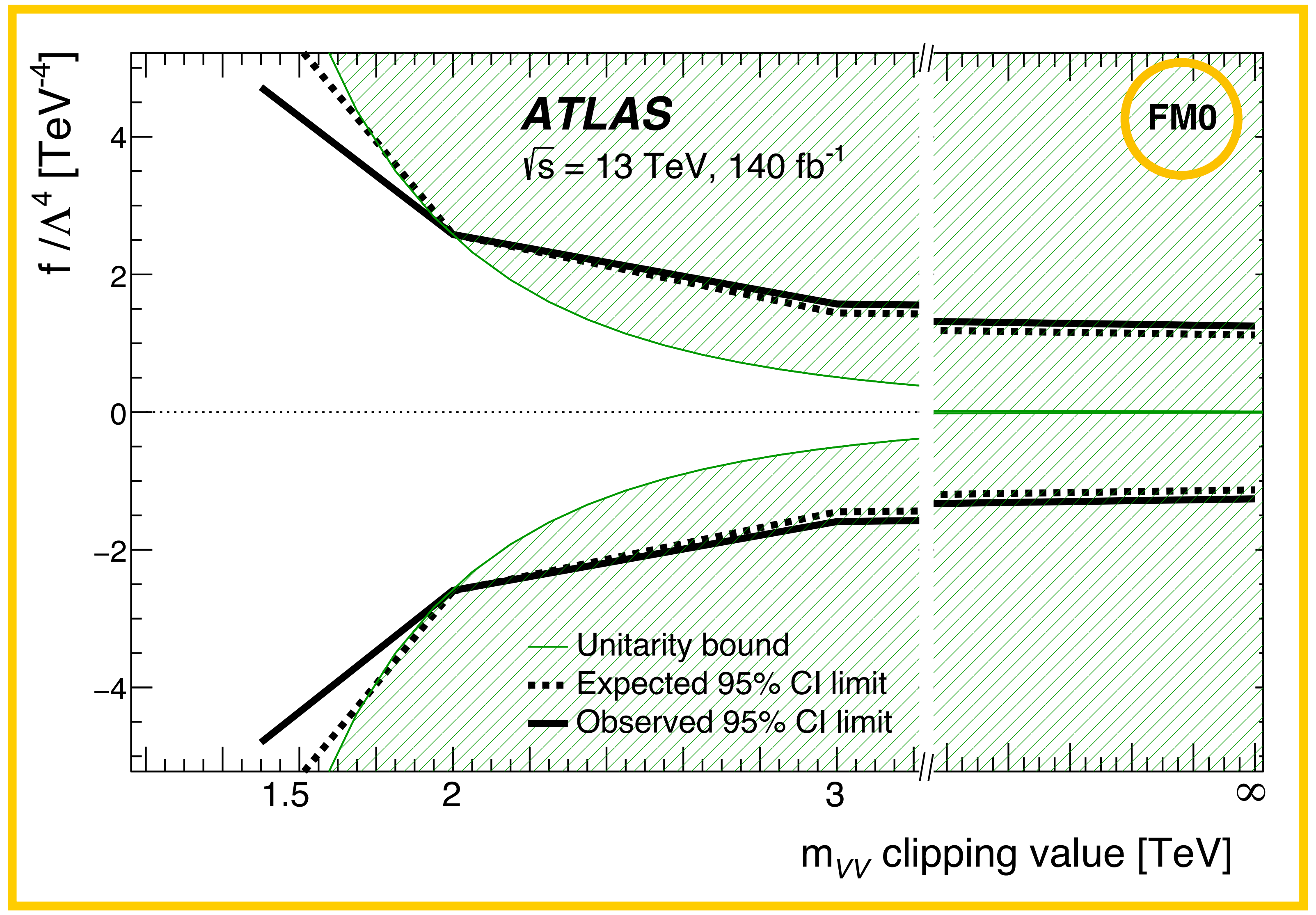
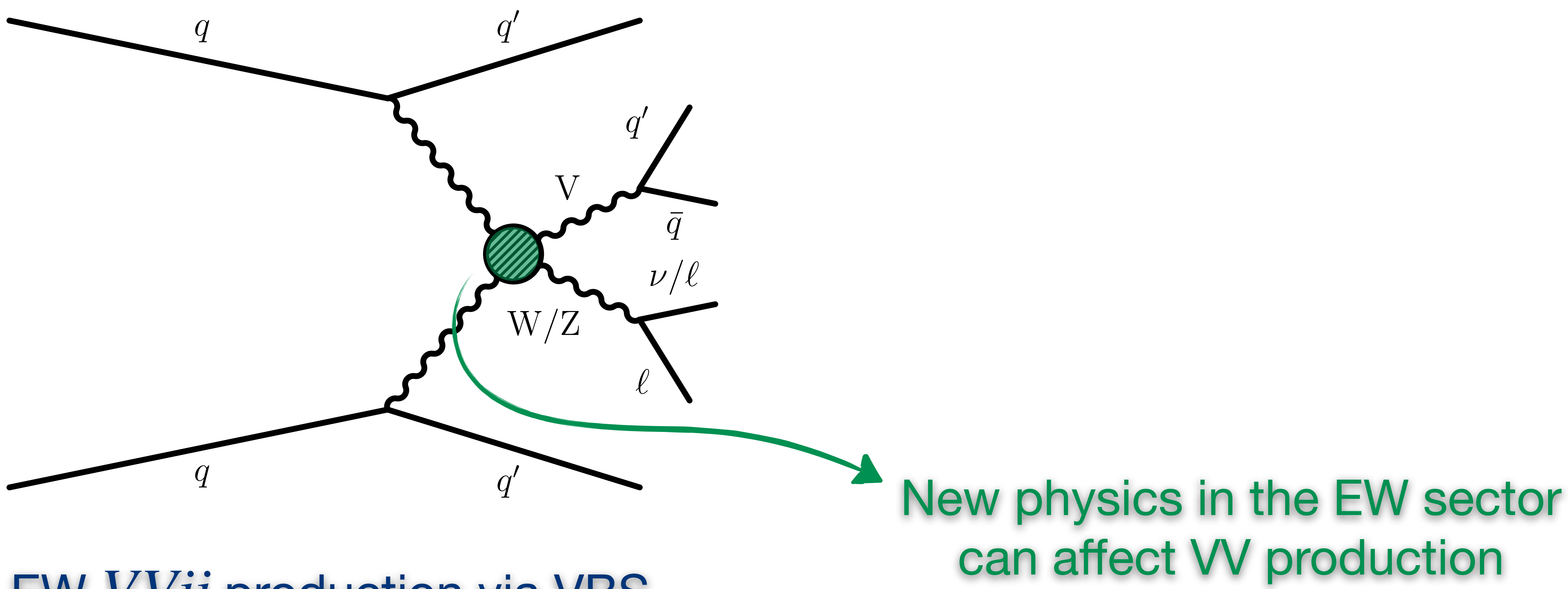
Exp. and obs. $95\,\%$ CL limits



Wilson coefficient	Expected limit [TeV^{-4}]	Observed limit [TeV^{-4}]	Expected limit unitarized [TeV^{-4}]	Observed limit unitarized [TeV^{-4}]
f_{T0}/Λ^4	[-0.20, 0.18]	[-0.25, 0.22]	[-0.79, 0.47] at [1.76, 1.96] TeV	[-0.85, 0.47] at [1.73, 2.00] TeV
f_{T1}/Λ^4	[-0.19, 0.19]	[-0.24, 0.24]	[-0.34, 0.34] at [2.59, 2.59] TeV	[-0.43, 0.43] at [2.43, 2.43] TeV
f_{T2}/Λ^4	[-0.44, 0.44]	[-0.55, 0.55]	[-0.95, 0.96] at [2.22, 2.22] TeV	[-1.16, 1.17] at [2.12, 2.11] TeV
f_{T3}/Λ^4	[-0.38, 0.38]	[-0.48, 0.48]	[-0.62, 0.62] at [2.71, 2.71] TeV	[-0.88, 0.88] at [2.49, 2.48] TeV
f_{T4}/Λ^4	[-1.46, 1.32]	[-1.51, 1.37]	[-3.03, 2.60] at [2.02, 2.09] TeV	[-3.03, 2.60] at [2.02, 2.10] TeV
f_{T5}/Λ^4	[-0.57, 0.53]	[-0.64, 0.58]	-	[-2.65, 2.57] at [1.53, 1.54] TeV
f_{T6}/Λ^4	[-0.76, 0.72]	[-0.74, 0.71]	[-2.82, 2.01] at [1.66, 1.73] TeV	[-2.98, 2.62] at [1.64, 1.69] TeV
f_{T7}/Λ^4	[-1.78, 1.52]	[-1.94, 1.70]	[-7.88, 4.29] at [1.65, 1.90] TeV	[-6.70, 4.11] at [1.72, 1.91] TeV
f_{T8}/Λ^4	[-0.59, 0.59]	[-0.48, 0.48]	-	-
f_{T9}/Λ^4	[-1.22, 1.22]	[-1.02, 1.03]	-	-
f_{S02}/Λ^4	[-3.22, 3.22]	[-3.96, 3.96]	[-5.53, 5.54] at [2.07, 2.67] TeV	[-6.16, 6.17] at [2.01, 2.01] TeV
f_{S1}/Λ^4	[-6.84, 6.86]	[-8.06, 8.06]	-	-
f_{M0}/Λ^4	[-1.13, 1.12]	[-1.26, 1.25]	[-2.61, 2.58] at [2.00, 2.00] TeV	[-2.71, 2.65] at [1.97, 1.98] TeV
f_{M1}/Λ^4	[-3.23, 3.24]	[-3.95, 3.95]	[-6.22, 6.22] at [2.27, 2.27] TeV	[-7.42, 7.43] at [2.17, 2.17] TeV
f_{M2}/Λ^4	[-1.66, 1.67]	[-1.85, 1.85]	-	-
f_{M3}/Λ^4	[-5.29, 5.29]	[-5.68, 5.71]	[-23.69, 23.39] at [1.57, 1.57] TeV	[-18.62, 19.10] at [1.66, 1.65] TeV
f_{M4}/Λ^4	[-2.62, 2.62]	[-2.96, 2.97]	-	-
f_{M5}/Λ^4	[-3.81, 3.82]	[-4.41, 4.44]	[-6.80, 6.80] at [2.33, 2.33] TeV	[-7.28, 7.30] at [2.29, 2.29] TeV
f_{M7}/Λ^4	[-5.32, 5.20]	[-6.60, 6.43]	[-9.47, 9.38] at [2.43, 2.43] TeV	[-11.91, 11.11] at [2.29, 2.33] TeV

Semileptonic VBS and anomalous quartic gauge couplings

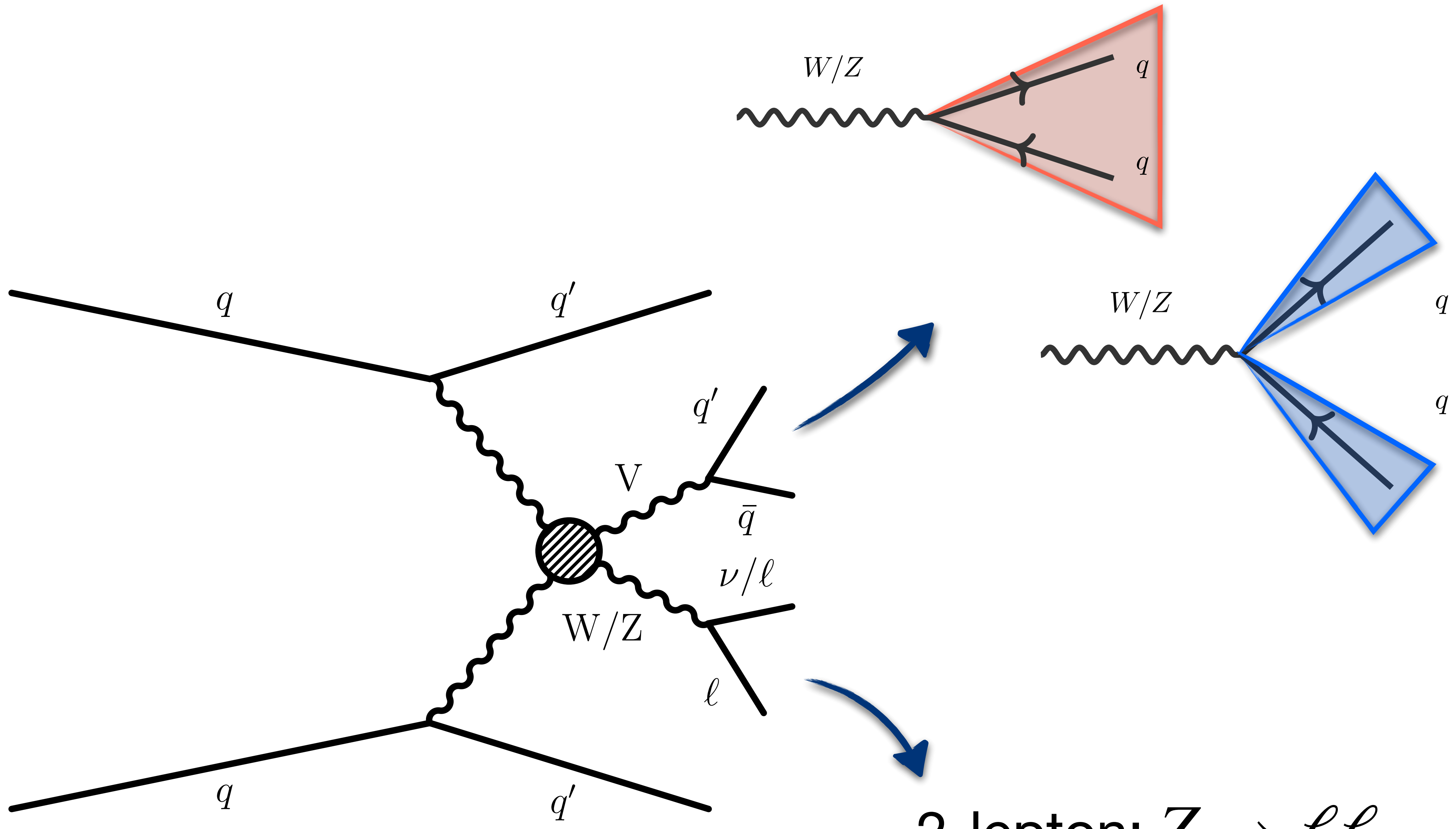
CMS-PAS-SMP-22-011



EW $VVjj$ production via VBS

Semileptonic VBS and aQGC

- EW production of $ZVjj$ at $13\ \text{TeV}$ with $138\ \text{fb}^{-1}$
  - Target final states with one $Z \to \ell\ell$ and $3 - 4$ jets
  - Hadronic V decay: boosted or resolved topologies
    - Large-R jets tagged to distinguish V from q/g jets



2-lepton: $Z \to \ell\ell$
*1-lepton: $W \to \ell\nu$

- **4 orthogonal SRs** plus CRs to model the main backgrounds (top quark and Drell-Yan)

Preselection	$n_{\text{leptons}} = 2$, $m_{\ell\ell} \in [76, 106]$ GeV, $p_T(\ell_1) > 35$ GeV, $p_T(\ell_2) > 20$ GeV, $p_T(j_{1,2}) > 30$ GeV, $m_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$		
Regions	Variables	Lepton Selection	Other Requirements
Signal Region (SR)	$65\ \text{GeV} < m_V < 105\ \text{GeV}$	Same Flavor	Split in b-tag and b-veto
DY Control Region (DY CR)	$m_V < 65\ \text{GeV}$, $m_V > 105\ \text{GeV}$	Same Flavor	Split in b-tag and b-veto
Top Control Region (Top CR)	$65\ \text{GeV} < m_V < 105\ \text{GeV}$	Opposite Flavor	-

m_V is a key discriminant!

*$\ell\nu qq$ events are used for the EFT combination

- Large background and complex topology. DNN devised to improve the VBS signal separation
  - Dedicated DNN per topology and b-tagging region (year-dependent for the resolved)
  - Up to 14 input variables used for training, e.g: m_{jj}, n_{jets} ($p_T > 30\ \text{GeV}$), ℓ Zeppenfeld, $\Delta\eta_{jj}$

Semileptonic VBS and aQGC

- The obs. (exp.) EW ZV VBS signal strength is

$$\mu_{\mathrm{EW}}^{\mathrm{obs}} = 0.63^{+0.53}_{-0.51} \ \left(1.00^{+0.61}_{-0.58}\right)$$

Corresponding to a signal significance of 1.3 (1.8) σ

- Results driven by the statistical uncertainty of the data

Impact on $\mu_{\mathrm{EW}}^{\mathrm{obs}}$

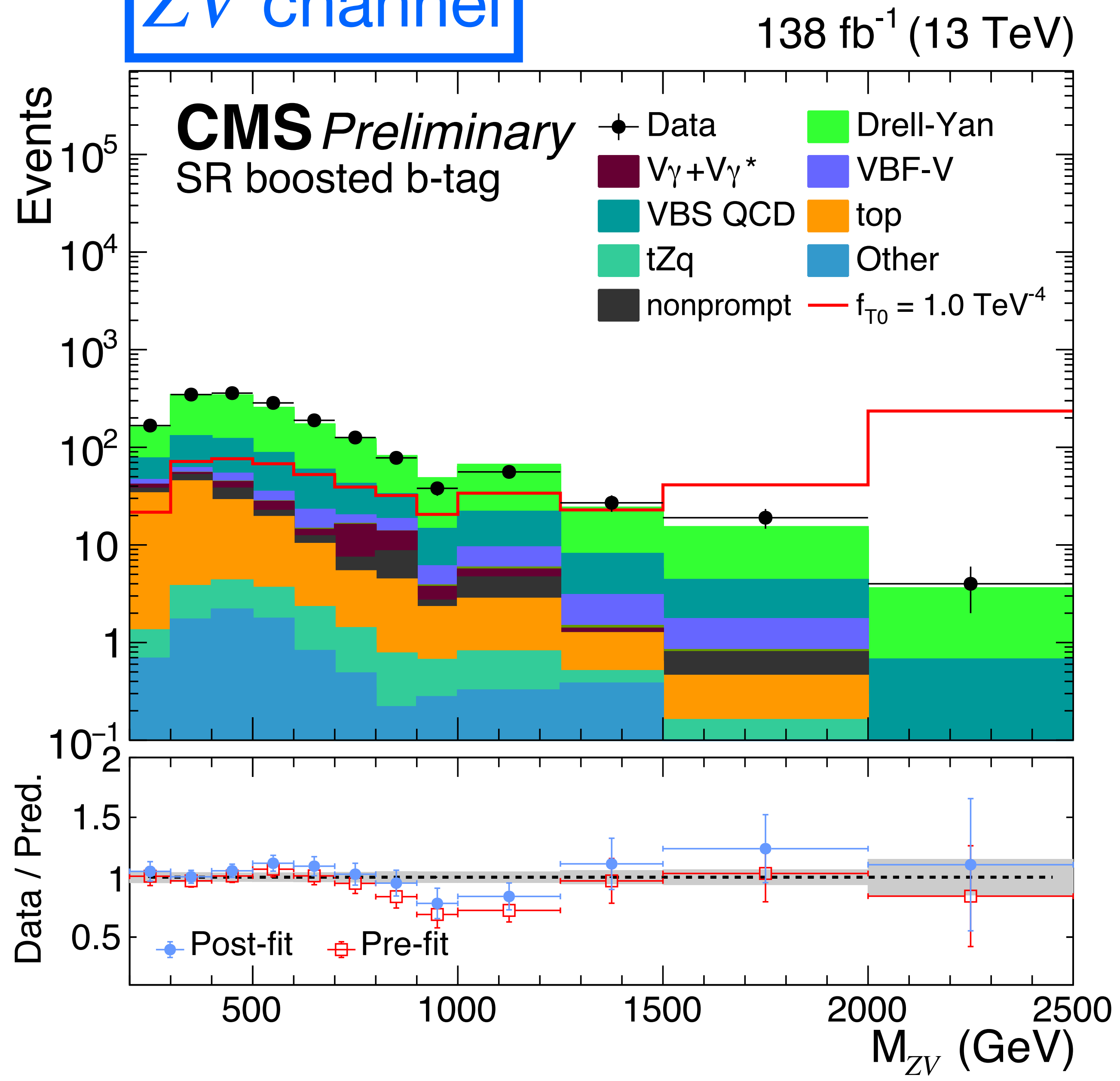
Source	$-\Delta\mu$	$+\Delta\mu$
DY and top rate parameters	−0.20	+0.20
Theory	−0.24	+0.26
MC sample size (bin-by-bin unc.)	−0.14	+0.15
Other nuisances	−0.11	+0.13
Data sample size	−0.36	+0.36
Total	−0.51	+0.53

Semileptonic VBS and aQGC

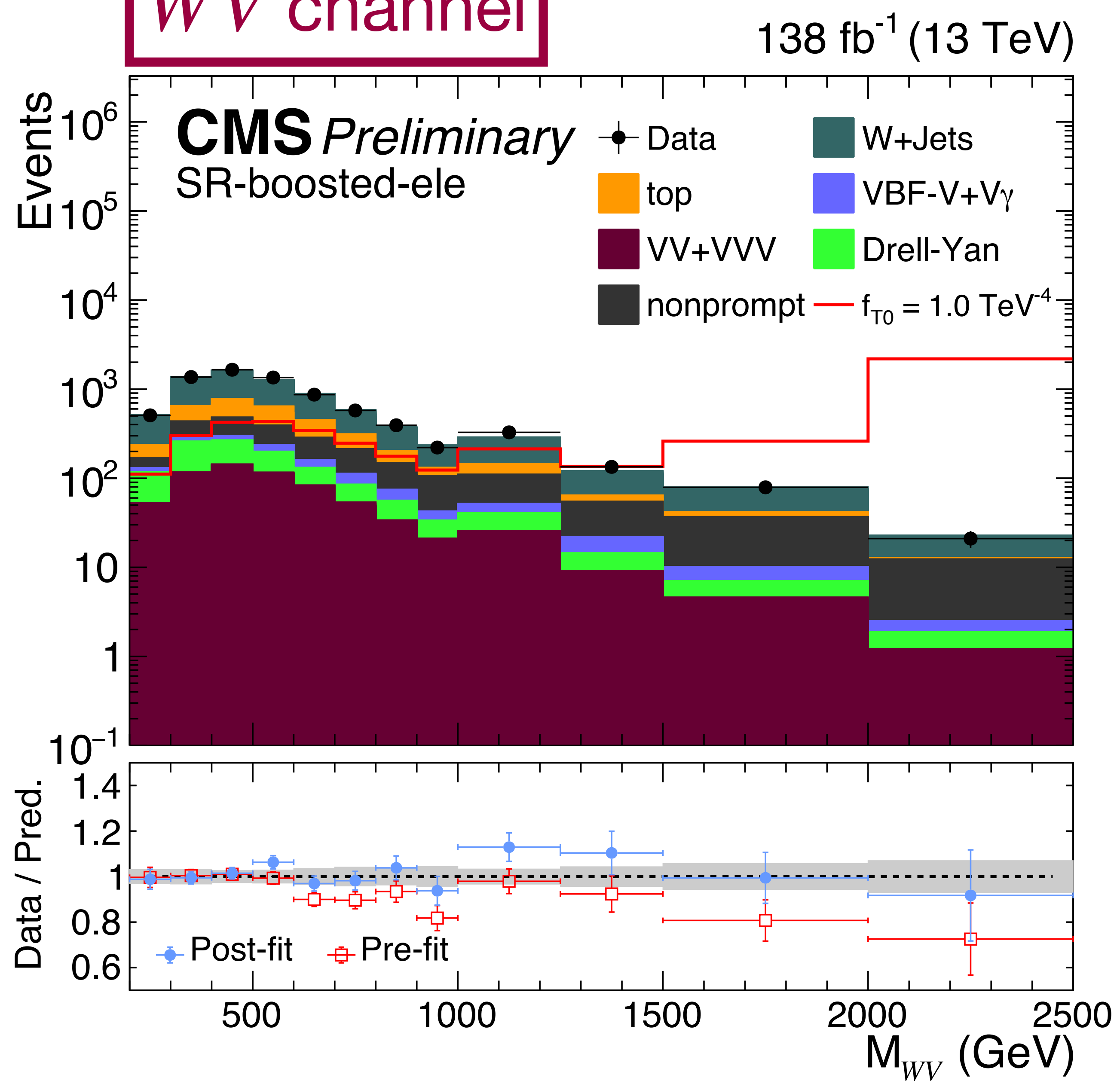
- Sensitivity to aQGC studied by performing likelihood scans varying Wilson coefficients of D-8 operators
  - Combination of ZV and WV (arXiv:2112.05259) boosted channels
  - Invariant mass of the diboson system (M_{ZV} or M_{WV}) used for fitting
- **Stringent $95\ \%$ CL limits using Run 2 data are reported**

	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	[-3.01, 3.1]	[-4.7, 4.77]	[-9.76, 9.89]	[-13.9, 14.0]	[-2.86, 2.96]	[-4.68, 4.75]
f_{S1}/Λ^4	[-4.27, 4.32]	[-6.56, 6.6]	[-10.2, 10.3]	[-13.9, 13.9]	[-3.97, 4.02]	[-6.45, 6.49]
f_{S2}/Λ^4	[-4.42, 4.48]	[-6.81, 6.86]	[-9.75, 9.89]	[-13.9, 14.0]	[-4.04, 4.11]	[-6.68, 6.73]
f_{M0}/Λ^4	[-0.568, 0.567]	[-0.844, 0.843]	[-1.38, 1.38]	[-1.74, 1.74]	[-0.539, 0.534]	[-0.828, 0.827]
f_{M1}/Λ^4	[-1.71, 1.75]	[-2.6, 2.63]	[-3.97, 4.00]	[-5.28, 5.29]	[-1.59, 1.62]	[-2.55, 2.58]
f_{M2}/Λ^4	[-0.746, 0.747]	[-1.11, 1.11]	[-1.86, 1.86]	[-2.37, 2.37]	[-0.703, 0.703]	[-1.1, 1.1]
f_{M3}/Λ^4	[-2.81, 2.81]	[-4.2, 4.2]	[-5.60, 5.59]	[-7.47, 7.47]	[-2.55, 2.55]	[-4.08, 4.07]
f_{M4}/Λ^4	[-1.74, 1.73]	[-2.6, 2.59]	[-2.70, 2.70]	[-3.61, 3.61]	[-1.48, 1.48]	[-2.42, 2.41]
f_{M5}/Λ^4	[-2.53, 2.51]	[-3.77, 3.76]	[-3.80, 3.81]	[-5.21, 5.23]	[-2.14, 2.13]	[-3.5, 3.5]
f_{M7}/Λ^4	[-2.86, 2.82]	[-4.35, 4.32]	[-6.09, 6.07]	[-8.26, 8.24]	[-2.63, 2.58]	[-4.24, 4.2]
f_{T0}/Λ^4	[-0.096, 0.083]	[-0.14, 0.128]	[-0.26, 0.25]	[-0.33, 0.32]	[-0.0921, 0.0785]	[-0.138, 0.127]
f_{T1}/Λ^4	[-0.0933, 0.1]	[-0.142, 0.149]	[-0.22, 0.24]	[-0.30, 0.31]	[-0.0863, 0.0943]	[-0.14, 0.147]
f_{T2}/Λ^4	[-0.225, 0.225]	[-0.336, 0.335]	[-0.56, 0.60]	[-0.74, 0.76]	[-0.21, 0.214]	[-0.331, 0.332]
f_{T3}/Λ^4	[-0.206, 0.206]	[-0.311, 0.31]	[-0.48, 0.51]	[-0.64, 0.66]	[-0.191, 0.194]	[-0.305, 0.305]
f_{T4}/Λ^4	[-1.09, 1.02]	[-1.58, 1.53]	[-1.44, 1.37]	[-1.84, 1.77]	[-0.895, 0.828]	[-1.4, 1.35]
f_{T5}/Λ^4	[-0.287, 0.257]	[-0.391, 0.383]	[-0.59, 0.57]	[-0.76, 0.73]	[-0.265, 0.237]	[-0.382, 0.373]
f_{T6}/Λ^4	[-0.656, 0.627]	[-0.976, 0.954]	[-0.73, 0.71]	[-0.94, 0.92]	[-0.5, 0.478]	[-0.794, 0.775]
f_{T7}/Λ^4	[-0.936, 0.899]	[-1.39, 1.36]	[-1.78, 1.67]	[-2.26, 2.16]	[-0.85, 0.8]	[-1.34, 1.29]
f_{T8}/Λ^4	–	–	[-0.53, 0.53]	[-0.67, 0.67]	[-0.53, 0.53]	[-0.67, 0.67]
f_{T9}/Λ^4	–	–	[-1.17, 1.16]	[-1.47, 1.45]	[-1.17, 1.16]	[-1.47, 1.45]

ZV channel

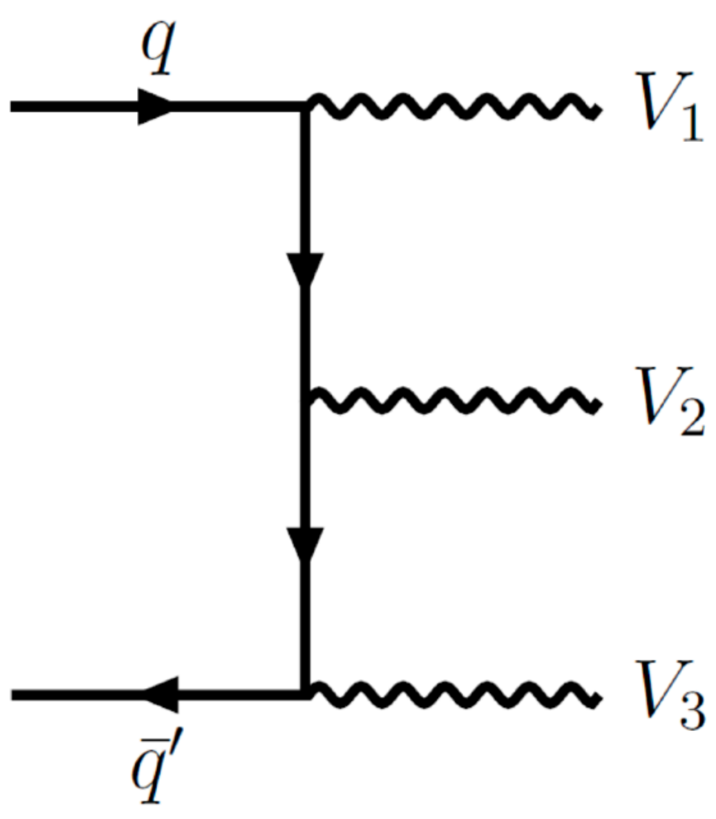


WV channel

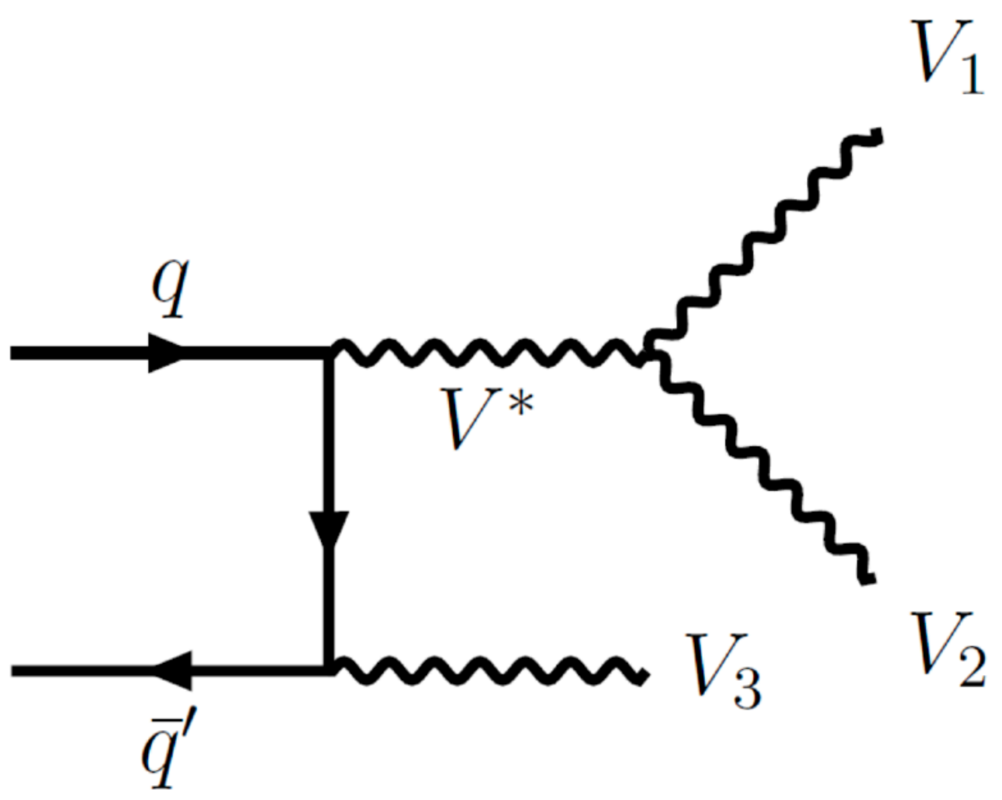


Search for *VVZ* production

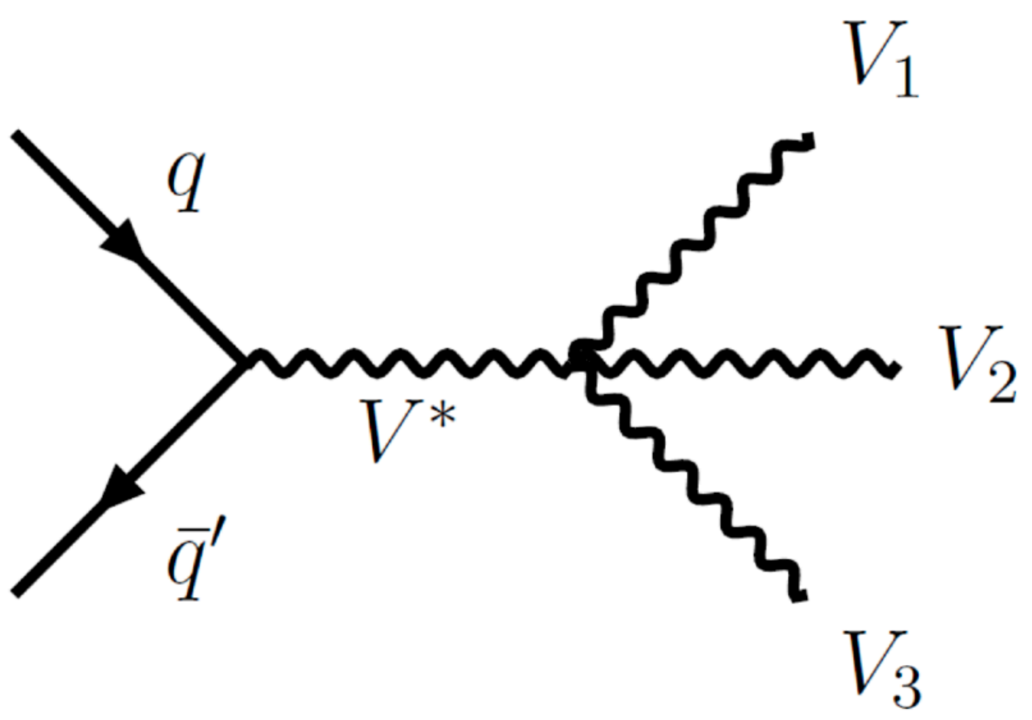
arXiv:2412.15123



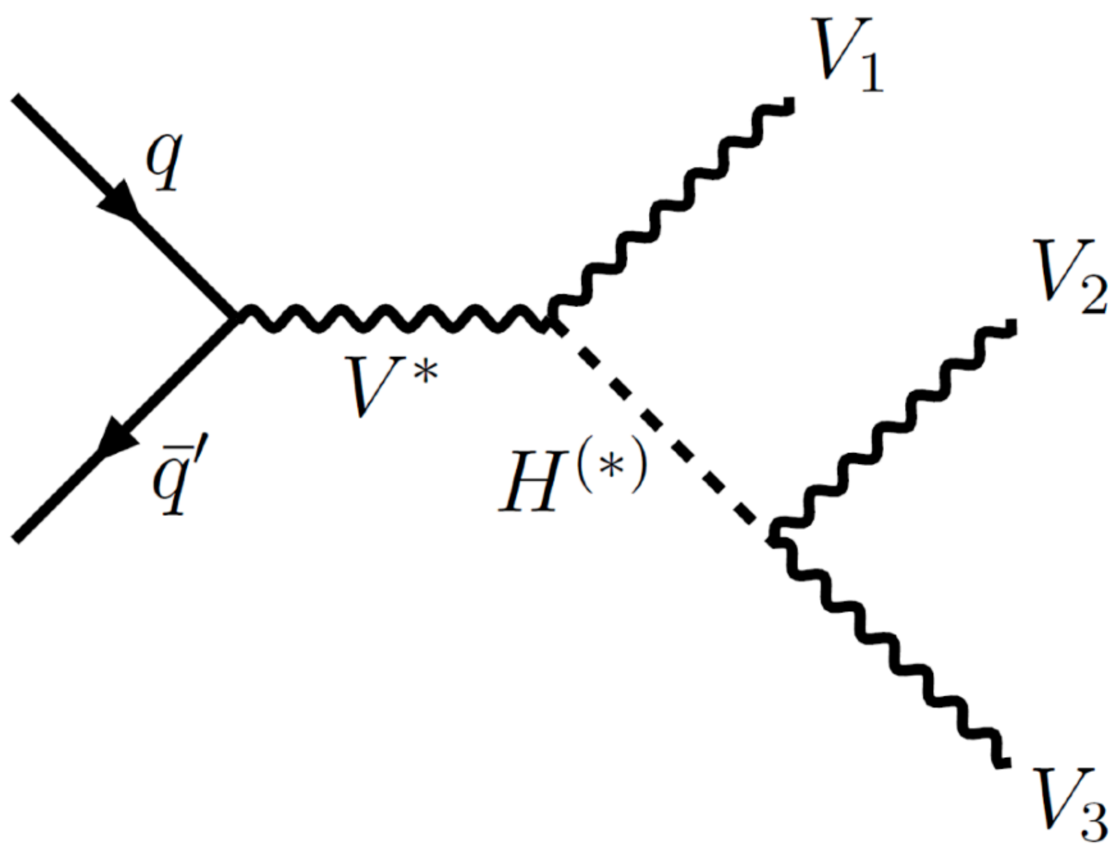
Mono-V vertices



Triple-gauge-boson vertex



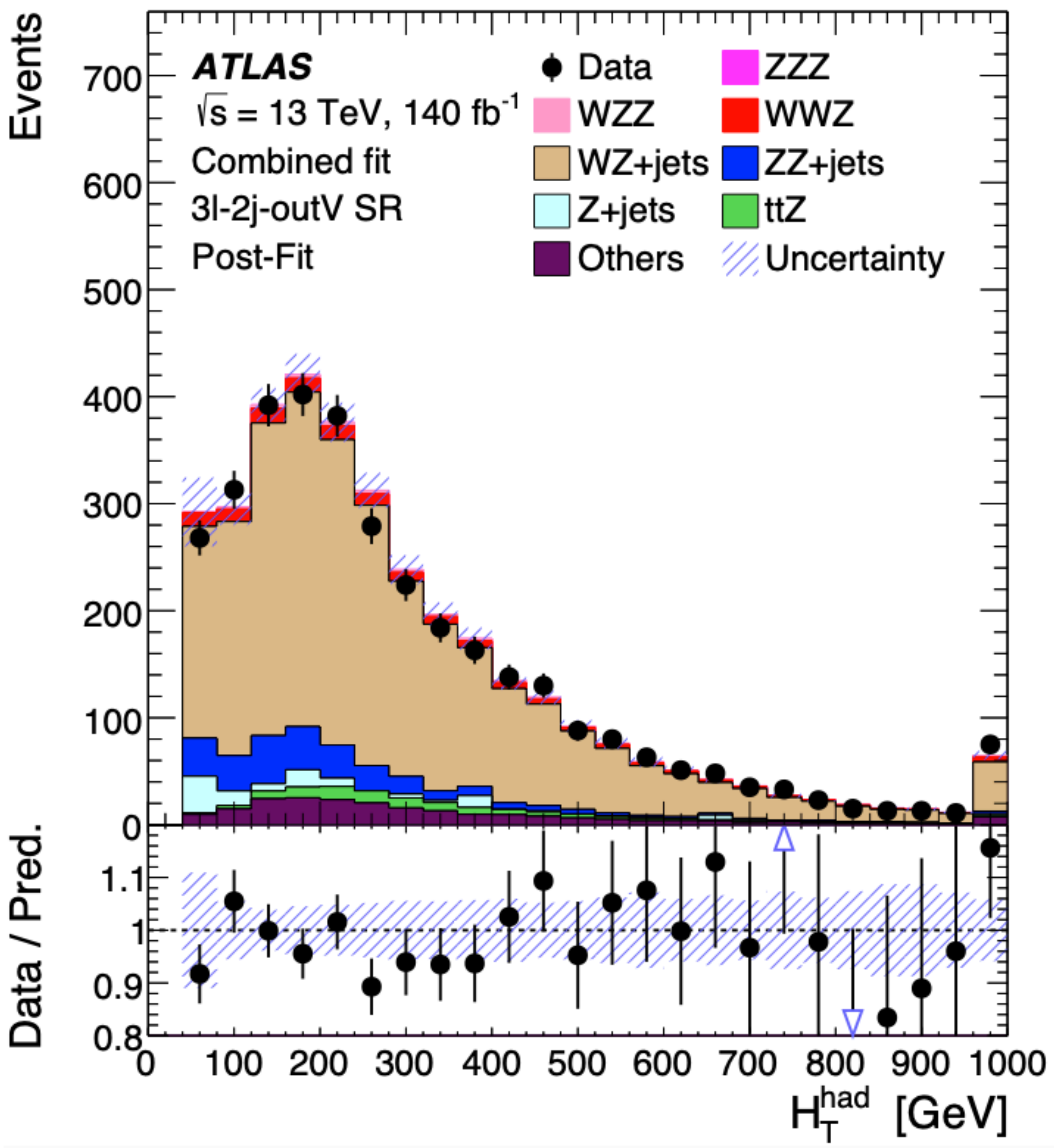
Quartic-gauge-boson vertex



Higgsstrahlung VH process

Search for VVZ production

- Search for VVZ ($WWZ + WZZ + ZZZ$) production at $13\ \text{TeV}$ using $140\ \text{fb}^{-1}$
  - Combined VVV observed by CMS (arXiv:2006.11191)
  - WWW observed by ATLAS (arXiv:2201.13045)
- Extract combined signal strength μ_{VVZ} (also μ_{WWZ} and μ_{WZZ})
- Investigate 3 different final states:



$3\ell + \text{jets}$	4ℓ	$\geq 5\ell$
$W/Z \to qq$	$W \to \ell\nu$	$W/Z \to \ell\nu/\ell\ell$
$W \to \ell\nu$	$W \to \ell\nu$	$Z \to \ell\ell$
$Z \to \ell\ell$	$Z \to \ell\ell$	$Z \to \ell\ell$
Target process	Target process	Target process
$W^{\pm}W^{\mp}Z$, $W^{\pm}ZZ$	$W^{\pm}W^{\mp}Z$	$W^{\pm}ZZ$, ZZZ
Main backgrounds	Main backgrounds	Main backgrounds
$W^{\pm}Z$	$W^{\pm}Z$ and ZZ	$W^{\pm}Z$ and ZZ

- MVA techniques utilised to enhance sensitivity to VVZ
  - BDTs optimised separately to each SR and final state
  - Most discriminant var.: H_T^{tot}, $p_T^{j_2}$, $m_{\ell\ell}^{Z_2}$, n_{jets}, MET sig., $p_T^{\ell_W}$

Search for VVZ production

- Simultaneous fit across final states and SRs/CRs

At least 3ℓ and 1 "Z candidate", with a di-ℓ pair with *same-flavour and opposite-sign* (SFOS) and $|m_{\ell\ell} - m_Z| < 20$ GeV

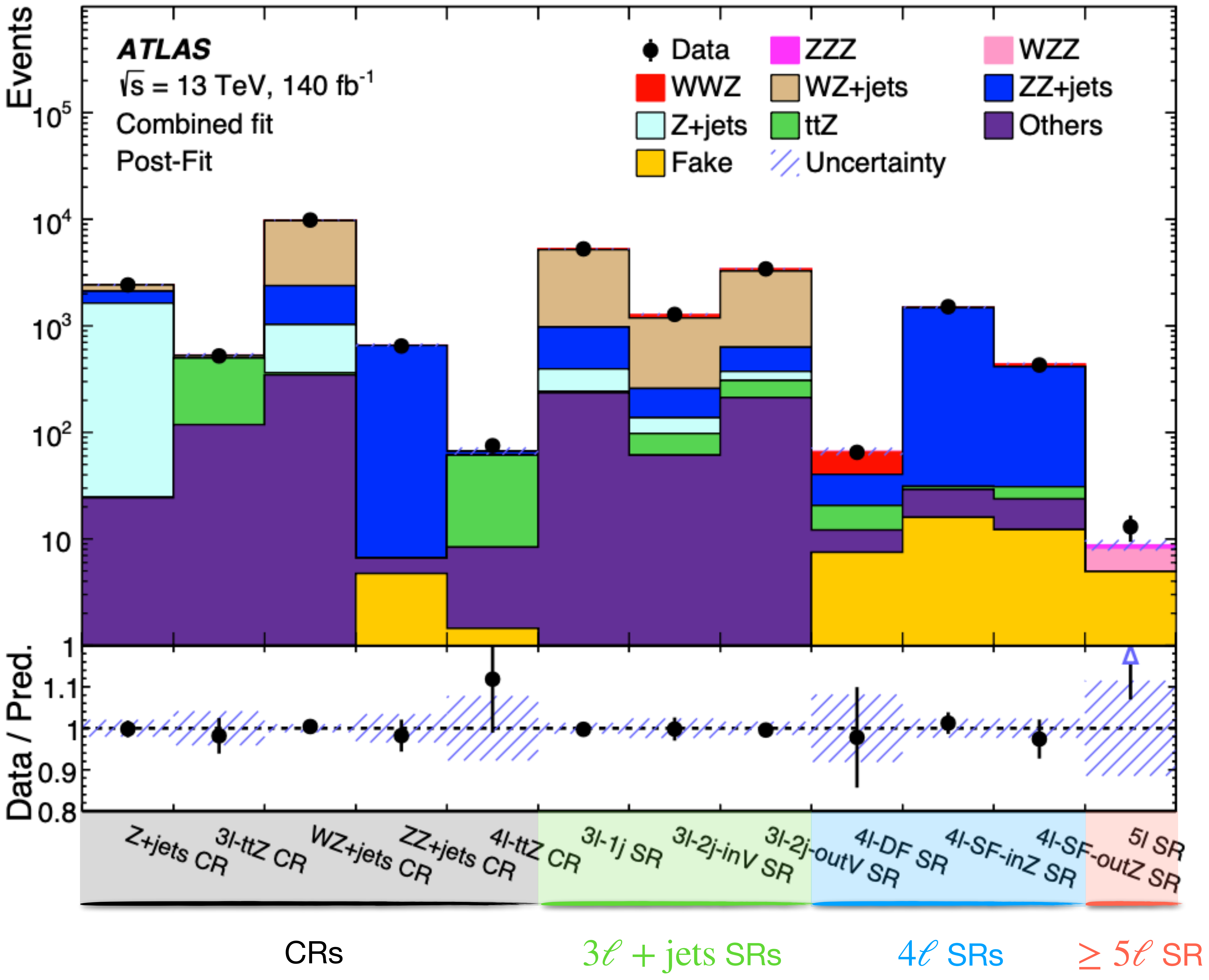
- **SR 3l-1j:** 1 jet
- **SR 3l-2j-inV:** ≥ 2 jets with $60 < m_{j_1j_2} < 110$ GeV
- **SR 3l-2j-outV:** ≥ 2 jets with $m_{j_1j_2} < 60$ or $m_{j_1j_2} > 110$ GeV
- **CRs: Z+jets**, **3l-ttZ**, and **WZ+jets** processes

At least 4ℓ and 1 SFOs di-ℓ pair with $|m_{\ell\ell} - m_Z| < 20$ GeV

Categorisation using the 2 "W-leptons" flavour:

- **SR 4l-DF:** Different Flavour ℓ
- **SR 4l-SF-inZ:** Same Flavour ℓ, $|m_{\ell_3\ell_4} - m_Z| < 20$ GeV
- **SR 4l-SF-outZ:** Same Flavour ℓ, $|m_{\ell_3\ell_4} - m_Z| \geq 20$ GeV
- **CRs: ZZ+jets** and **4l-ttZ** processes

SR 5l: at least 5ℓ and 2 SFOS with $|m_{\ell\ell} - m_Z| < 20$ GeV



Process	Signal strength	Cross section (fb)	Observed (expected) sensitivity
VVZ	$1.43 \pm 0.20(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$	$660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$	$6.4\ (4.7)\ \sigma$
WWZ	$1.33 \pm 0.28(\text{stat.})^{+0.21}_{-0.17}(\text{syst.})$	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$	$4.4\ (3.6)\ \sigma$
WZZ	$2.13^{+1.18}_{-0.96}(\text{stat.})^{+0.76}_{-0.41}(\text{syst.})$	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$	$2.8\ (1.6)\ \sigma$

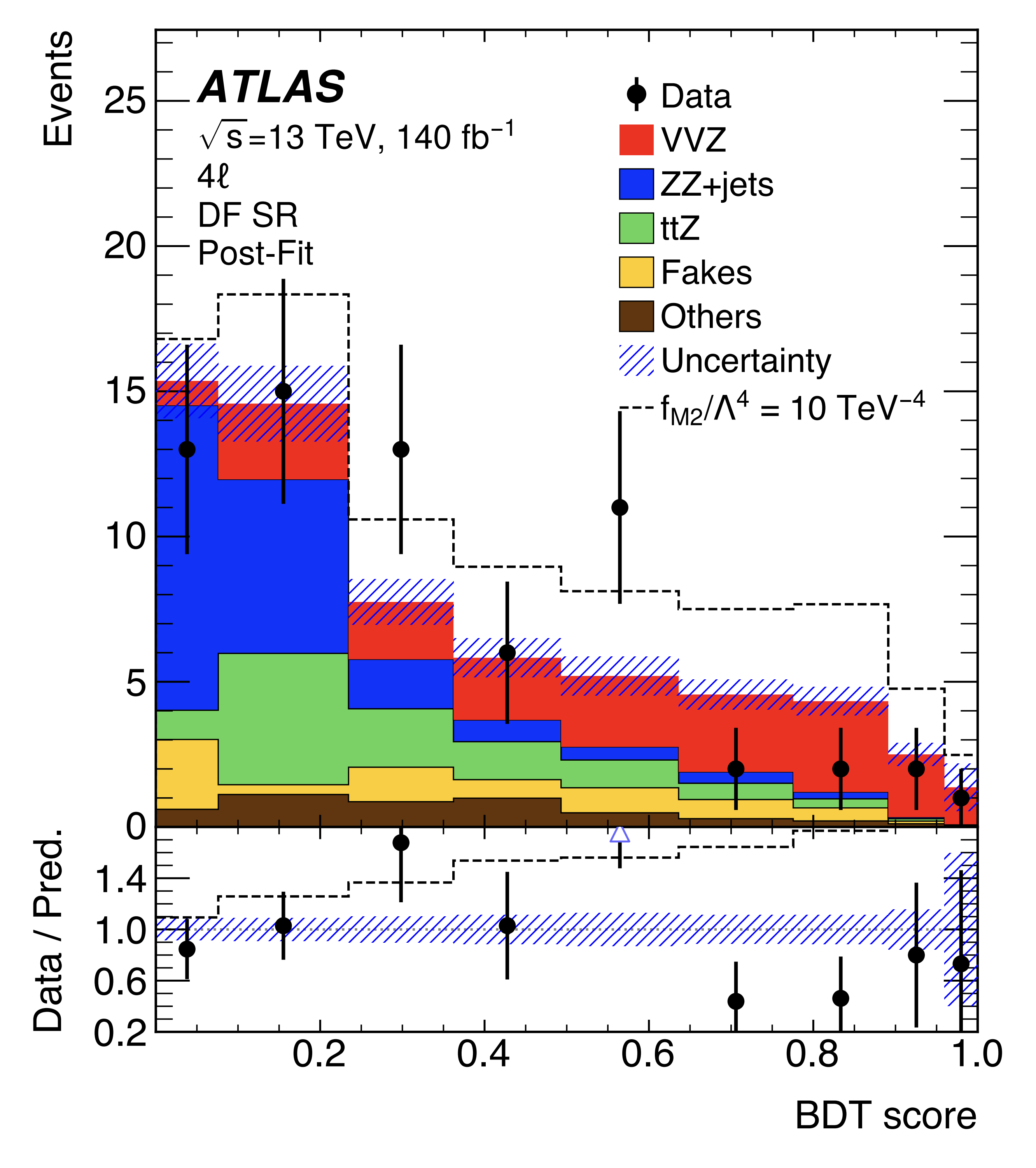
Search for VVZ production

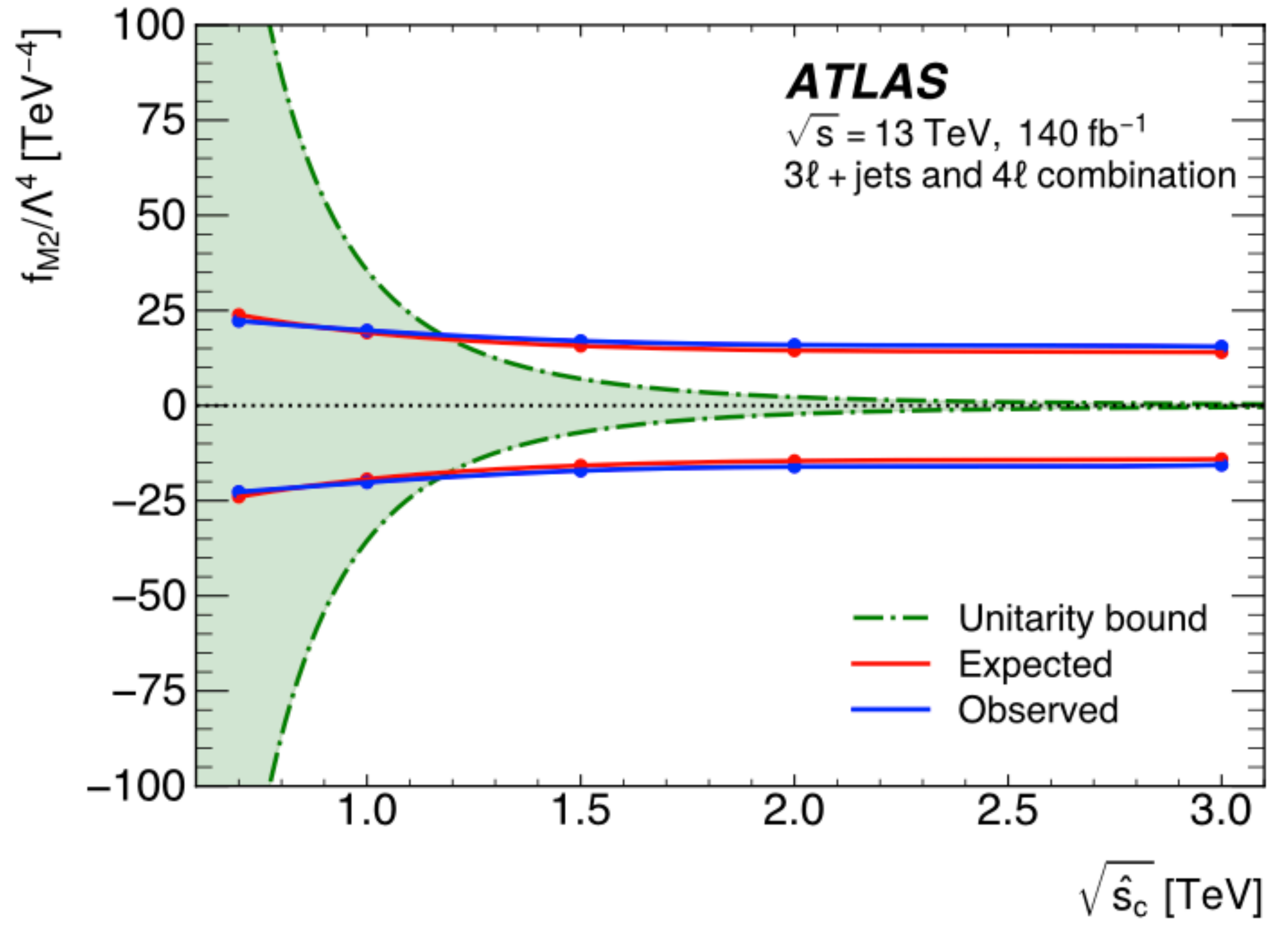
- Constraints on aQGC effects via an EFT analysis with D-8 operators
  - Wilson coefficients of most sensitive operators to VVV final states are f_{M2}, f_{M3}, f_{M4}, and f_{M5}
- BDT distributions retrained to increase sensitivity to EFT effects using events from all operators considered

Observed (expected) 95% CL limits on Wilson coefficients (TeV^{-4})			
Coefficient	3ℓ	4ℓ	Combination
f_{M2}/Λ^4	[−15, 15] ([−17, 17])	[−23, 23] ([−18, 18])	[−15, 15] ([−14, 14])
f_{M3}/Λ^4	[−25, 25] ([−29, 30])	[−39, 40] ([−31, 31])	[−26, 26] ([−25, 25])
f_{M4}/Λ^4	[−13, 14] ([−16, 16])	[−17, 17] ([−16, 16])	[−11, 11] ([−13, 13])
f_{M5}/Λ^4	[−11, 11] ([−13, 13])	[−12, 12] ([−13, 13])	[−8.5, 8.7] ([−10, 10])

- Clipping method to provide limits avoiding unitarity violation at high $\sqrt{s}$

Coefficient	Expected limit [TeV^{-4}]	Exp. $\sqrt{\hat{s}_c}$ [TeV]	Observed limit [TeV^{-4}]	Obs. $\sqrt{\hat{s}_c}$ [TeV]
f_{M2}/Λ^4	[−18, 17]	1.2	[−19, 19]	1.2
f_{M3}/Λ^4	[−28, 29]	1.5	[−28, 29]	1.5
f_{M4}/Λ^4	[−14, 14]	1.6	[−12, 12]	1.7
f_{M5}/Λ^4	[−11, 11]	2.1	[−9.1, 9.3]	2.2





Summary and conclusions

Three ATLAS / CMS measurements at $\sqrt{s} = 13\ \mathrm{TeV}$ using $140\ \mathrm{fb}^{-1}$ have been presented

Same-sign WW polarisation

- First evidence of production of polarised $W^{\pm}_{\mathrm{L}}W^{\pm}$: obs. significance $3.3\,\sigma$
- Most stringent limits to date for the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}$ cross-section: 0.45 (0.70) fb obs. (exp.)

EW diboson production in semileptonic final states

- CMS and ATLAS have reported improvements on aQGCs upper limits thanks to the extended phase space by the merged $V \to jj$ topology: especially for f_S and f_M operators

Searches for triboson production

- First observation of VVZ production by ATLAS: obs. (exp.) significance 6.4 (4.7) σ
- First evidence of WWZ production by ATLAS: obs. (exp.) significance 4.4 (3.6) σ
- CMS reports evidence of WWZ using Run 2 + 3 data: obs. (exp.) significance 4.5 (5.0) σ

Back-up

Selections

EW diboson production in semileptonic final states

arXiv:2503.17461

Selection	0-lepton	1-lepton	2-lepton
Trigger	E_T^{miss} triggers	Single-electron triggers Single-muon or E_T^{miss} triggers	Single-lepton triggers
$V \to \nu\nu/\ell\nu/\ell\ell$	0 'Loose' leptons $p_T > 7$ GeV $E_T^{miss} > 200$ GeV $p_T^{miss} > 50$ GeV $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss}) < \pi/2$ $\min[\Delta\phi(\vec{E}_T^{miss}$, small-$R$ jet$)] > \pi/6$ $\Delta\phi(\vec{E}_T^{miss}, V_{had}) > \pi/9$	1 'Tight' lepton $p_T > 27$ GeV 0 other 'Loose' leptons with $p_T > 7$ GeV $E_T^{miss} > 80$ GeV	2 'Loose' leptons $p_T > 27$ GeV $83 < m_{ee} < 99$ GeV $-0.0117 \times p_T^{\mu\mu} + 85.63$ GeV $< m_{\mu\mu}$ $0.0185 \times p_T^{\mu\mu} + 94$ GeV $> m_{\mu\mu}$
VBS topology tagging jets		Largest m_{jj} pair with $\eta_{\text{tag } j_1} \cdot \eta_{\text{tag } j_2} < 0$ $m_{jj}^{tag} > 400$ GeV, $p_T^{tag\ j_{1,2}} > 30$ GeV	
$V \to J$		Leading p_T large-R jet $p_T > 200$ GeV, $\|\eta\| < 2$ V boson tagger requirements on m_J, D_2, and $n_{\text{Tracks}}^{\text{ungroomed}}$	
$V \to jj$		Two leading p_T small-R jets $p_T > 20$ GeV if $\|\eta\| < 2.5$, and $p_T > 30$ GeV if $2.5 < \|\eta\| < 4.5$ $p_T^{j_1} > 40$ GeV $64 < m_{jj} < 106$ GeV	
Top veto		$m_{jjj} > 220$ GeV	
Additional b-jet veto	No	Yes	No

Search for VVZ production

Table 1: Summary of the object selection and event preselection criteria used in the analysis.

Object selection criteria	
Electron	Passes the "LooseAndBLayerLH" quality requirement $\|d_0\|/\sigma_{d_0} < 5$, $\|z_0 \times \sin\theta\| < 0.5$ mm $p_T > 7$ GeV, $\|\eta\| < 2.47$
Muon	Passes the "Loose" quality requirement $\|d_0\|/\sigma_{d_0} < 3$, $\|z_0 \times \sin\theta\| < 0.5$ mm $p_T > 5$ GeV ($p_T > 15$ GeV for calorimetr-tagged muons), $\|\eta\| < 2.7$
Jet	Passes the JVT requirement, $p_T > 20$ GeV, $\|\eta\| < 4.5$
Event preselection criteria	
Trigger	Single lepton, dilepton, tri-lepton, or quad-lepton triggers
Number of charged leptons	≥ 3
Z boson invariant mass	$\|m_{\ell\ell} - m_Z\| < 40$ GeV

Table 2: Overview of the criteria used to select inclusive 3ℓ events and the three 3ℓ SRs.

3ℓ + jets SRs

Inclusive 3ℓ event selection			
Satisfy preselection criteria	✓		
Lepton	$p_T > 15$ GeV and at least one lepton with $p_T > 27$ GeV		
Lepton from the Z decays	"Loose_VarRad" isolation for electrons and "PFLow_Loose_VarRad" isolation for muons		
Lepton from the W decays	"Tight" identification and "PLImprovedTight" isolation		
Invariant mass of any SFOS dilepton pairs	> 12 GeV		
Invariant mass of the Z boson	$\|m_{\ell\ell} - m_Z\| < 20$ GeV		
Number of leptons	$= 3$		
Number of b-jets	$= 0$		
3ℓ signal regions			
	3ℓ-1j	**3ℓ-2j-inV**	**3ℓ-2j-outV**
Satisfy inclusive 3ℓ selection criteria	✓	✓	✓
BDT score > 0.42	✓	✓	✓
Number of jets	$= 1$	≥ 2	≥ 2
m_{jj}	–	> 60 GeV and < 110 GeV	< 60 GeV or > 110 GeV

Table 3: Overview of the criteria used to select inclusive 4ℓ events and the three 4ℓ SRs.

4ℓ SRs

Inclusive 4ℓ event selection			
Satisfy preselection criteria	✓		
Lepton	Exactly four leptons with $p_T > 30, 15, 8, 6$ GeV		
Lepton from the Z decays	"Loose_VarRad" isolation for electrons and "PFLow_Loose_VarRad" isolation for muons		
Leptons from the W decays	"Medium" identification and "PLImprovedTight" isolation		
Invariant mass of any SFOS dilepton pairs	> 12 GeV		
Invariant mass of the Z boson	$\|m_{\ell\ell} - m_Z\| < 20$ GeV		
Minimum angular distance between any lepton pairs	> 0.1		
E_T^{miss}	> 10 GeV		
Number of b-jets	$= 0$		
4ℓ signal regions			
	4ℓ-DF	**4ℓ-SF-inZ**	**4ℓ-SF-outZ**
Satisfy inclusive 4ℓ selection criteria	✓	✓	✓
Flavour for lepton from the W decays	$e\mu$	same-flavour	same-flavour
$m_{\ell\ell}$ for the two W–leptons	–	$\|m_{\ell\ell} - m_Z\| < 20$ GeV	$\|m_{\ell\ell} - m_Z\| > 20$ GeV

Table 4: Overview of the criteria used to select inclusive 5ℓ events, which form the 5ℓ SR.

$\geq 5\ell$ SR

Inclusive 5ℓ event selection (5ℓ SR)	
Satisfy preselection criteria	✓
Leptons	At least five leptons "Loose_VarRad" isolation for electrons and "PFlow_Loose_VarRad" isolation for muons
Z boson candidates	At least two SFOS pairs with $\|m_{\ell\ell} - m_Z\| < 20$ GeV
Z boson invariant mass	$\|m_{\ell\ell} - m_Z\| < 20$ GeV
Number of b-jets	$= 0$

arXiv:2412.15123

Other

EW diboson production in semileptonic final states

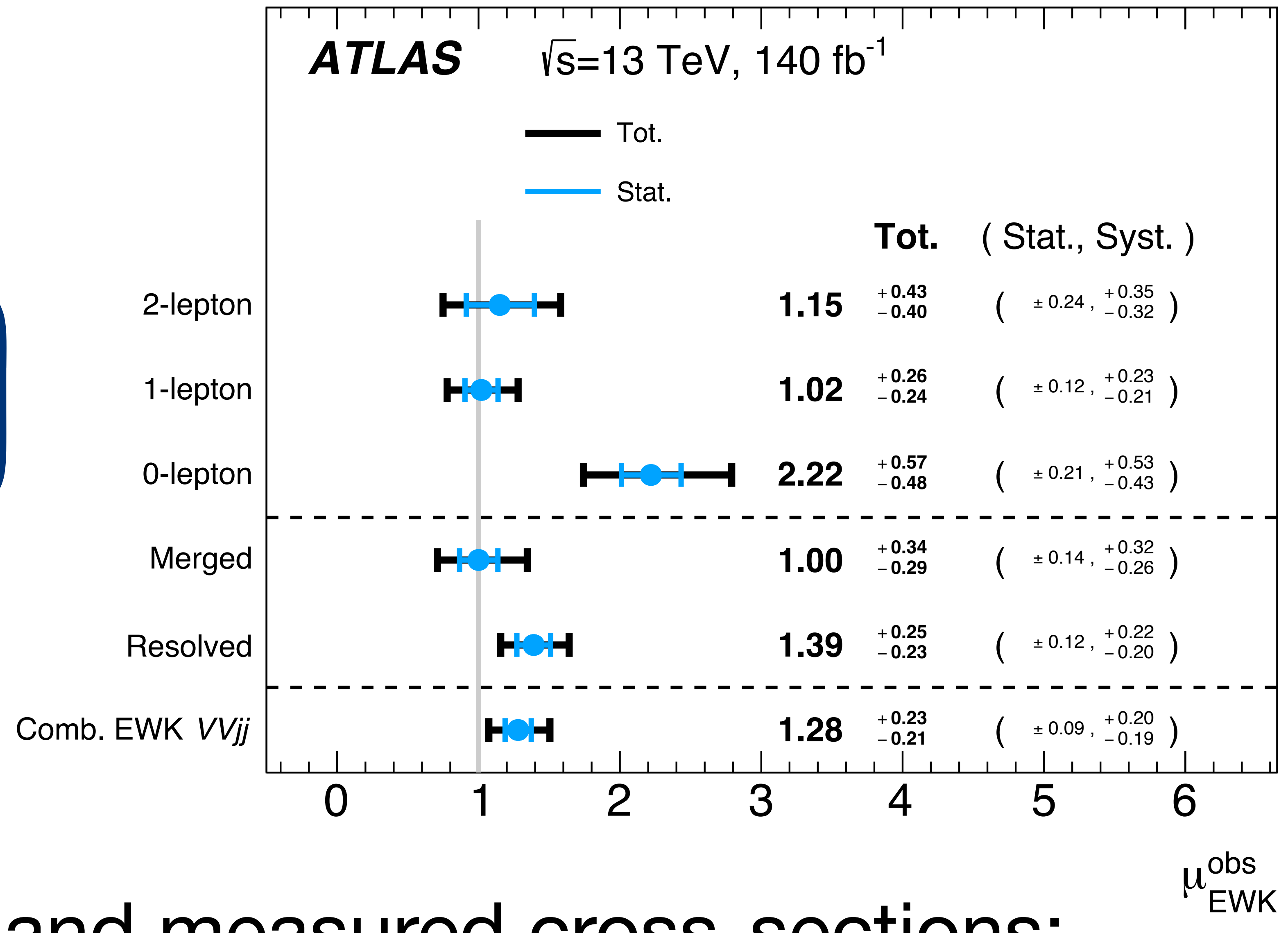
- Measured EW $VVjj$ signal strength:

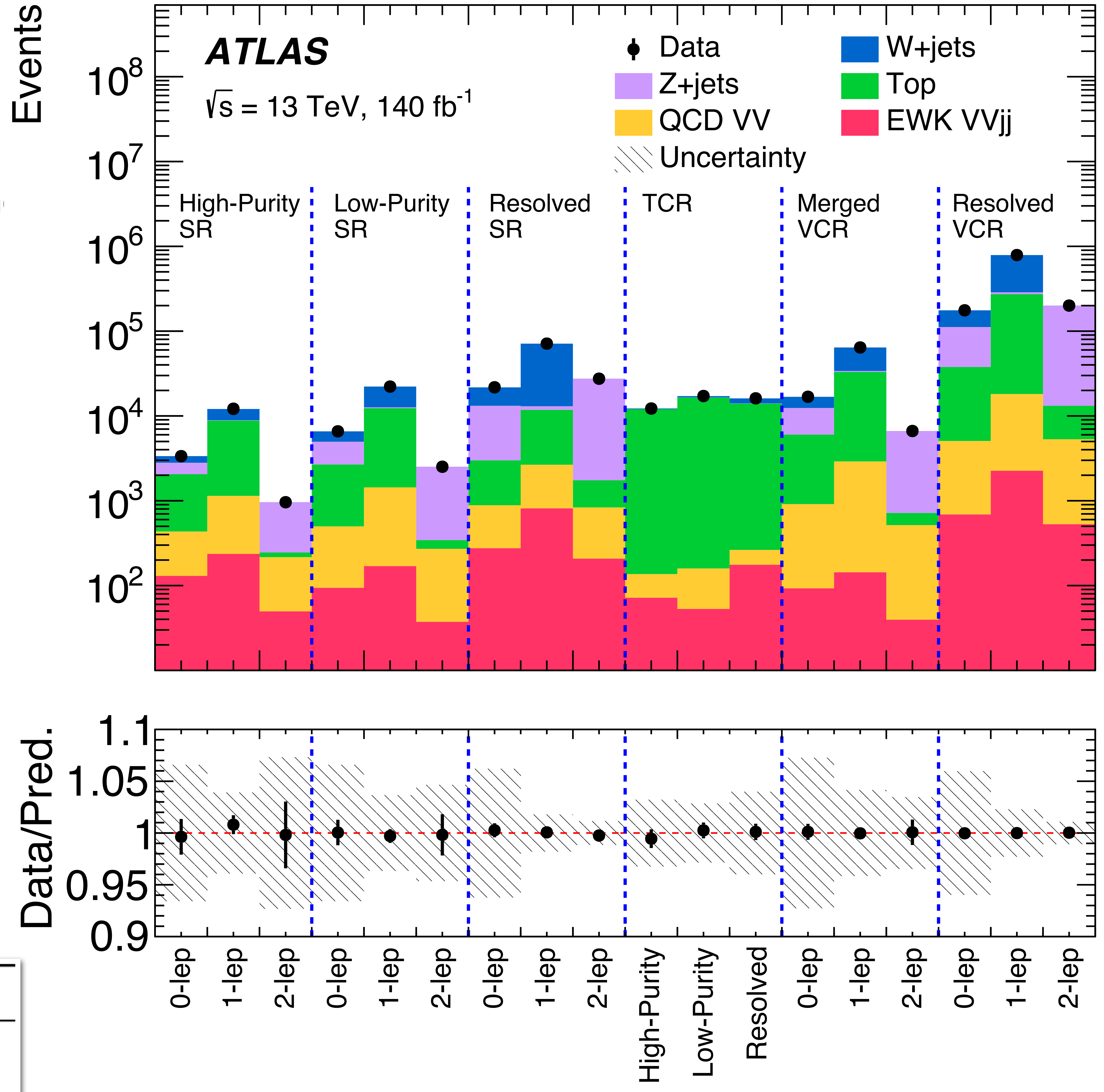
$$\mu_{EW}^{obs} = 1.28^{+0.23}_{-0.21} = 1.28 \pm 0.09\,(\text{stat.})\,^{+0.20}_{-0.19}\,(\text{syst.})$$

Dominated by signal modelling and jet reconstruction uncertainties

with obs. (exp.) significance of $7.4\ (6.1)\ \sigma$

μ_{EW}^{obs} also extracted in each region



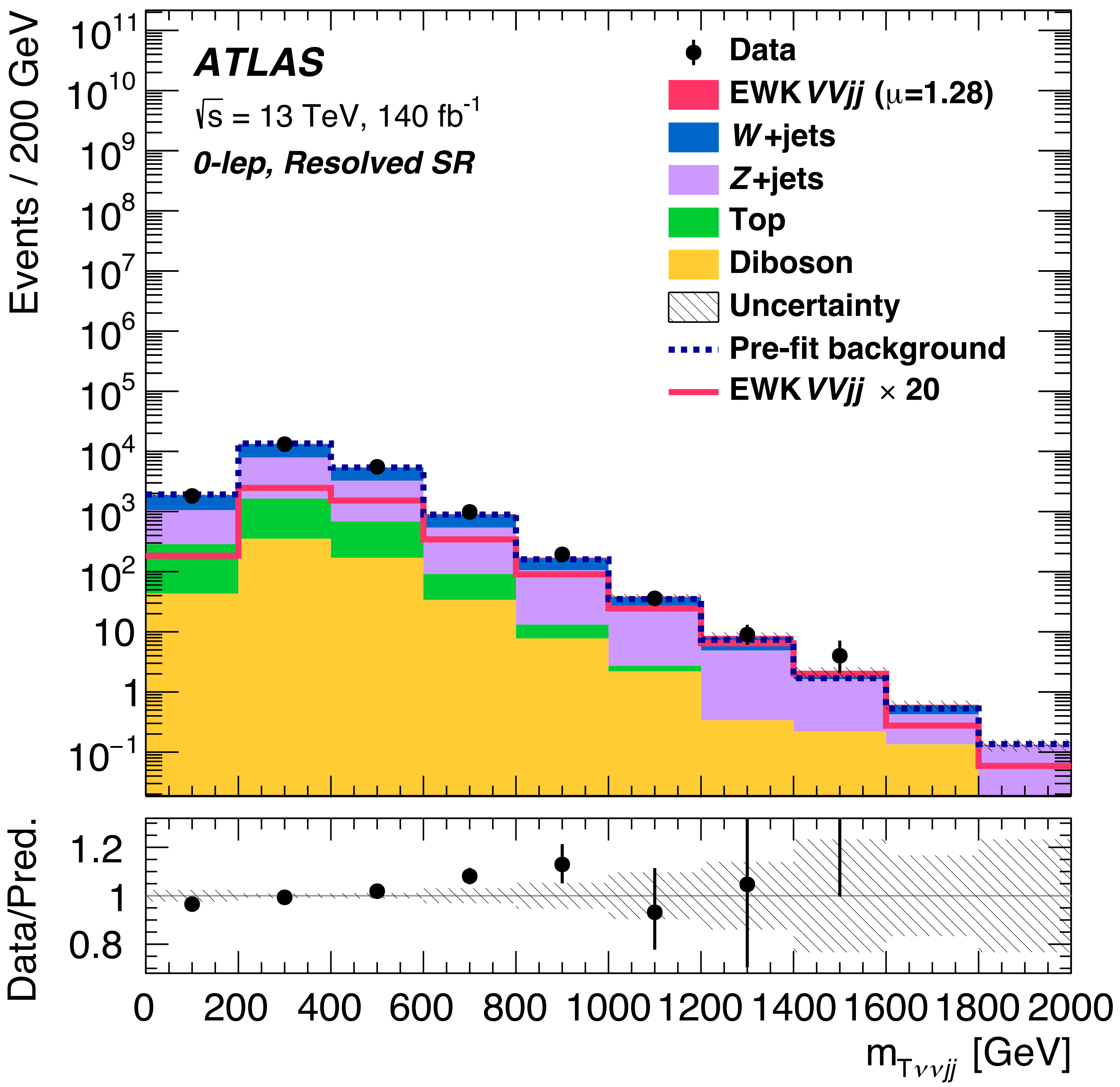


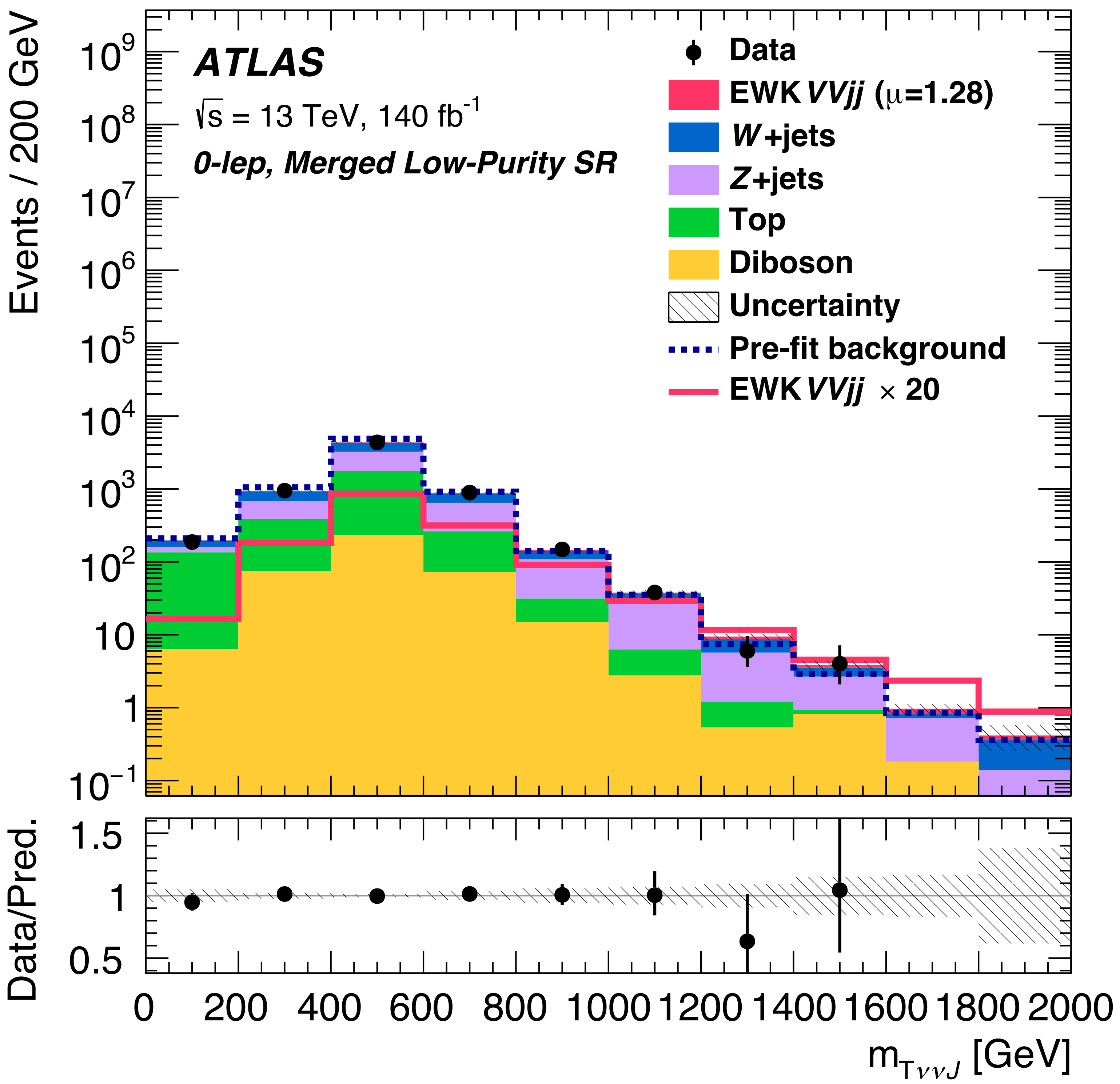
- Fiducial expected and measured cross-sections:

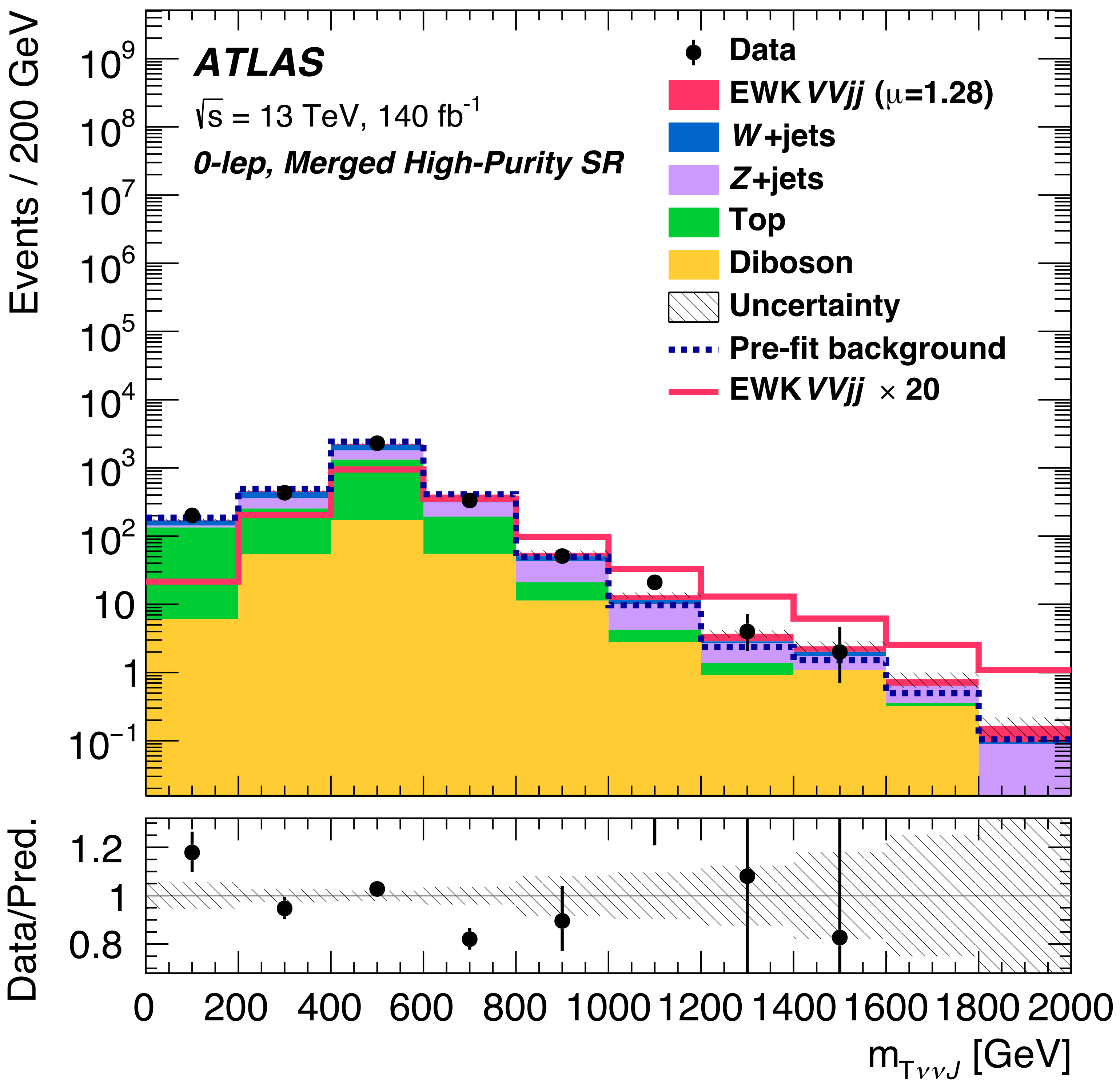
	Combined	0-lepton	1-lepton	2-lepton	Resolved	Merged
$\sigma_{EWK}^{fid,exp}$	20.4 ± 3.5 fb	7.3 ± 2.5 fb	10.3 ± 2.5 fb	2.8 ± 1.1 fb	11.7 ± 3.4 fb	8.7 ± 2.5 fb
$\sigma_{EWK}^{fid,obs}$	29.2 ± 4.9 fb	15.7 ± 2.8 fb	10.7 ± 2.8 fb	3.1 ± 1.1 fb	17.9 ± 4.3 fb	11.4 ± 3.4 fb

EW diboson production in semileptonic final states

- Diboson system mass distributions in the 0-ℓ selection



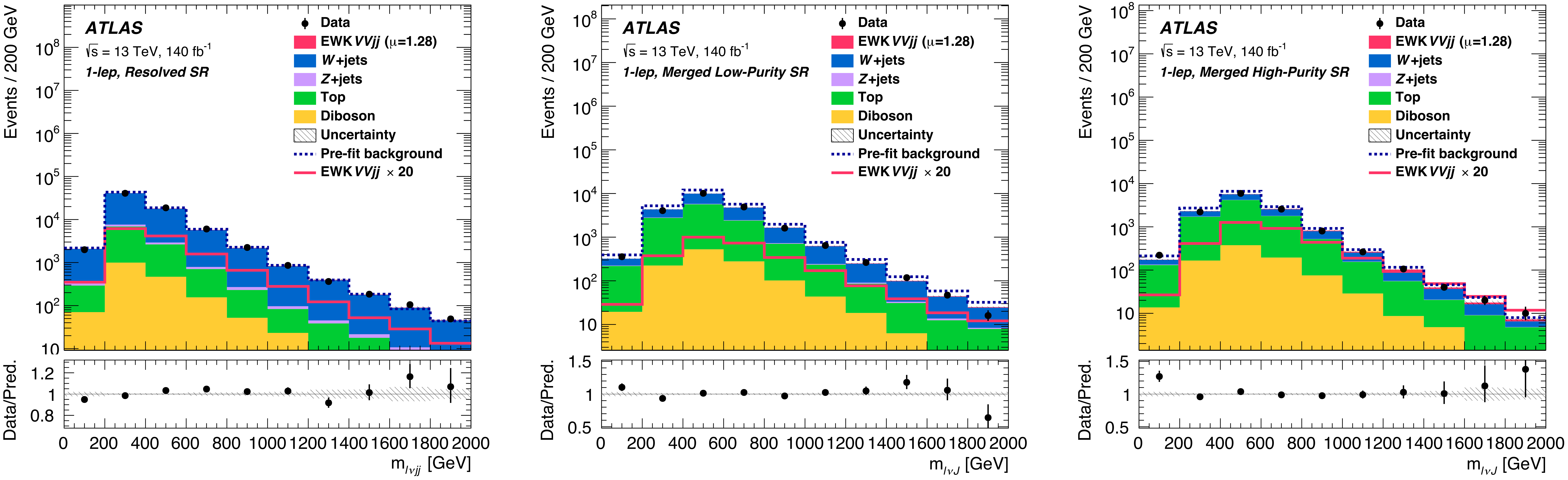




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-27/

EW diboson production in semileptonic final states

- Diboson system mass distributions in the 1-ℓ selection



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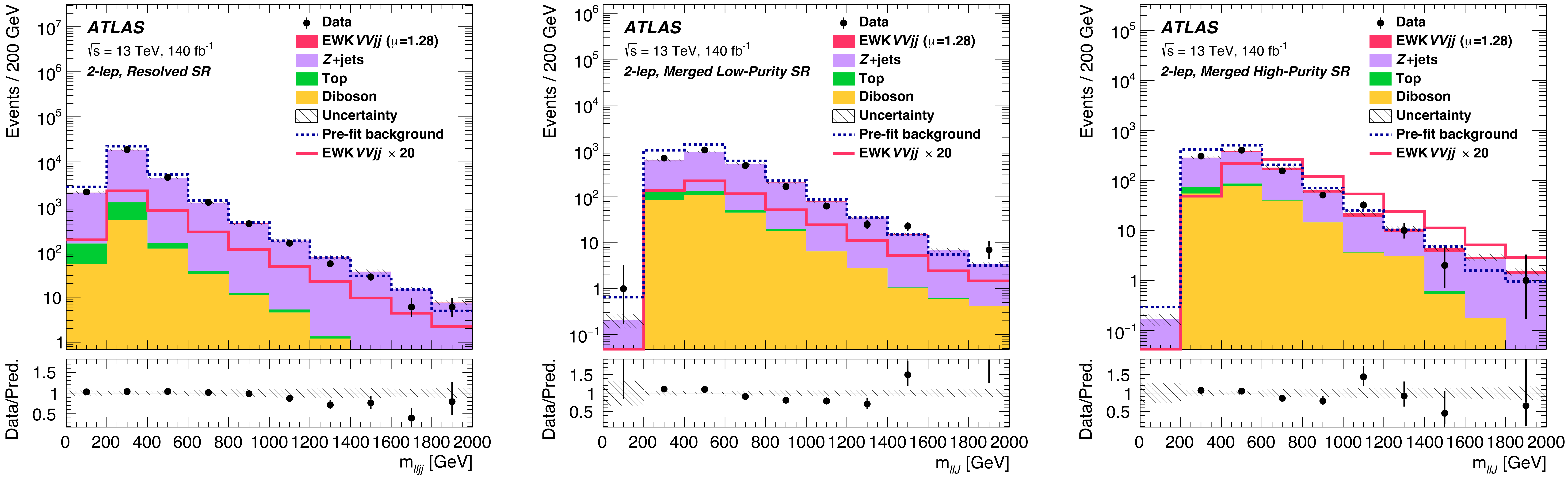
EW diboson production in semileptonic final states

- Diboson system mass distributions in the 2-ℓ selection



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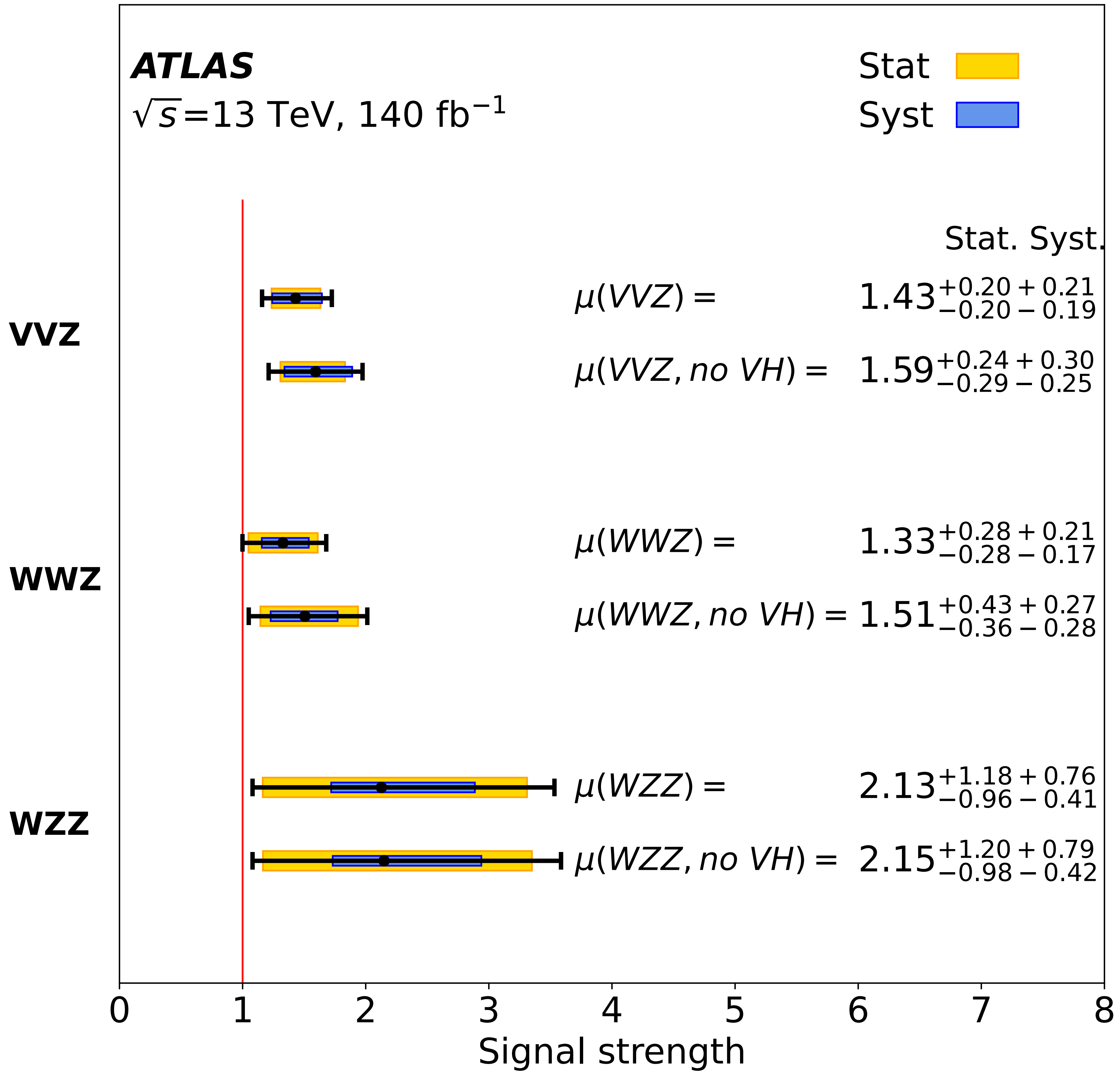
Search for VVZ production

If VH production is considered as part of the background, the combined observed cross section is found to be $\sigma(pp \to VVZ) = 382^{+65}_{-63}(\text{stat.})^{+57}_{-60}(\text{syst.})$ fb with an observed signal strength of $1.59^{+0.24}_{-0.29}$ (stat.)$^{+0.30}_{-0.25}$ (syst.). The observed (expected) significance corresponds to 5.5 (3.7) σ. The ratio of on-shell VVZ production to $VH \to VWW^*/VZZ^*$ production is determined from MC simulation and is allowed to vary within the theoretical uncertainties of the two processes.



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