

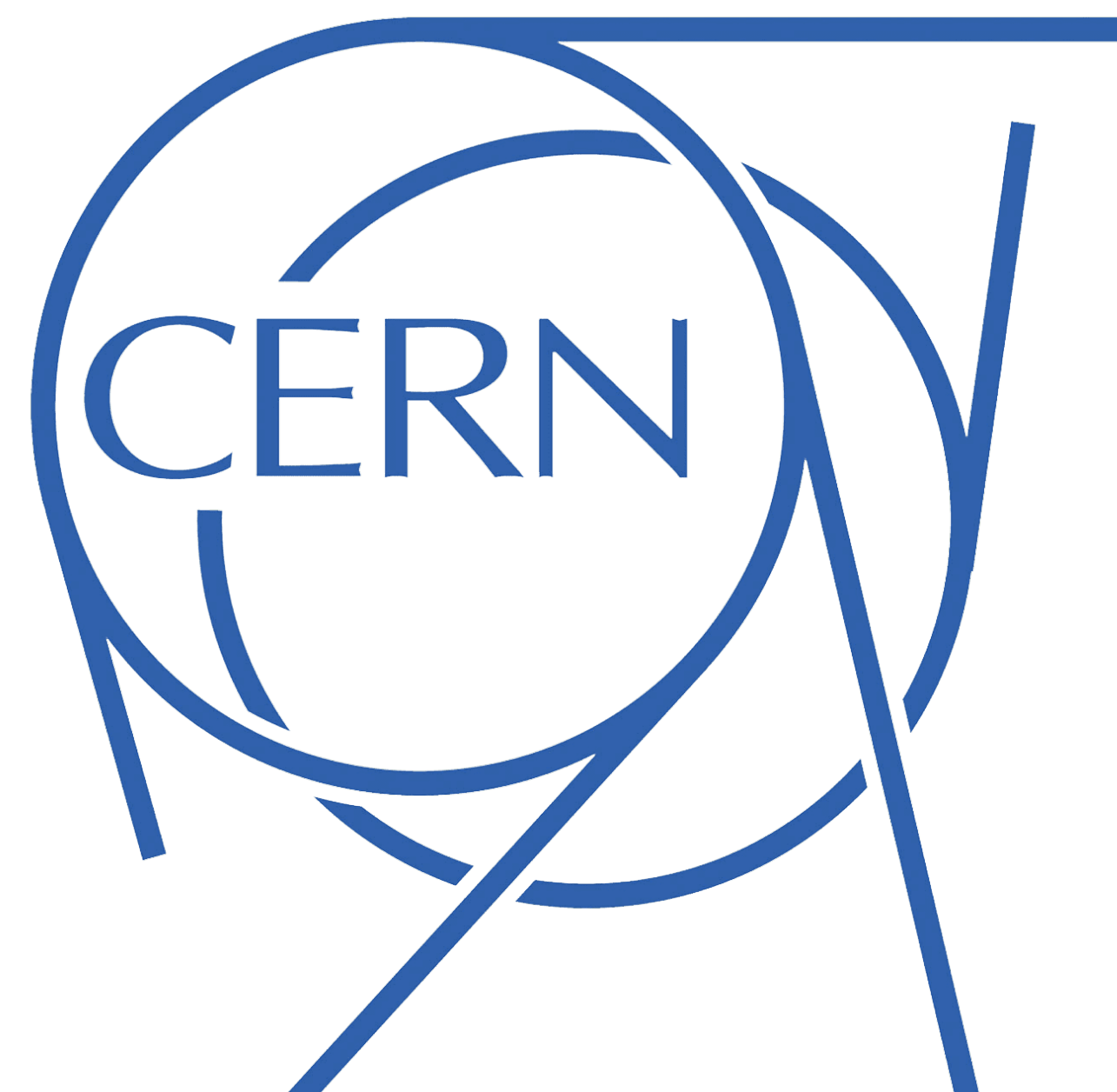
Vector boson fusion and scattering measurements in ATLAS

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on behalf of
ATLAS collaboration

IFIC (UV-CSIC)

QCD@LHC

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RYC2022-038164-I

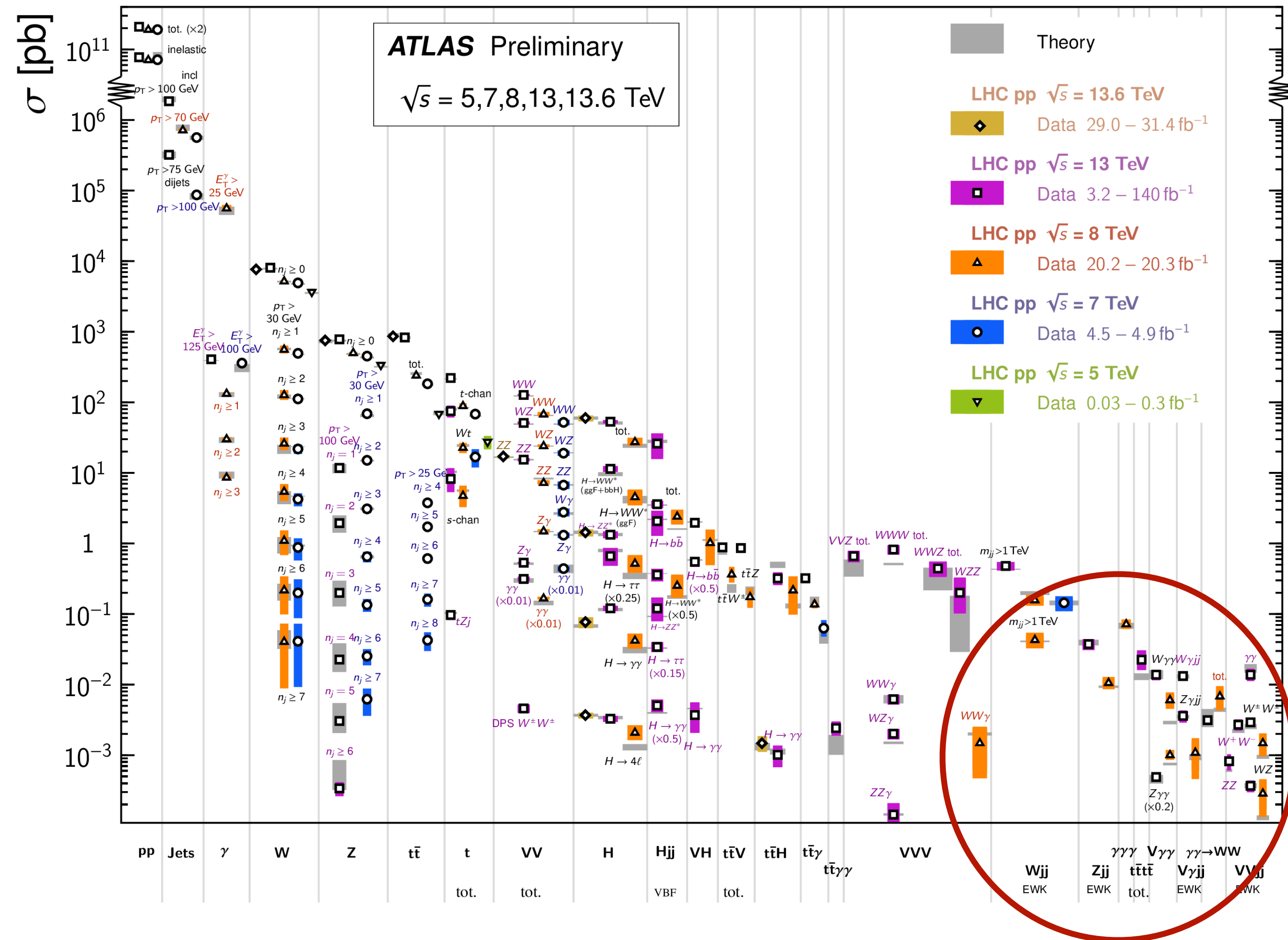


Introduction

- ▶ VBF and VBS measurements only accessible with large datasets.
 - ▶ Low cross-section due to small α_W .
- ▶ They allow to probe the EWK sector:
 - ▶ Stringent test of the SM.
 - ▶ Probes TGC and QGC self interactions and the Higgs role in maintaining unitarity.
 - ▶ Deviations from SM predictions can be interpreted through EFT.
- ▶ All measurements shown today with full Run 2 statistics $\sim 140 \text{ fb}^{-1}$:
 - ▶ VBF W production.
 - ▶ VBS VV production in semileptonic channel
 - ▶ Observation of EWK $\gamma\gamma$ production.
 - ▶ Polarisation in VBS $W^\pm W^\pm$ production.
 - ▶ Global EFT fits.
 - ▶ Combine EFT interpretation for anomalous Quartic Gauge Coupling (aQGC).

Standard Model Production Cross Section Measurements

Status: July 2026



EWK $W^\pm jj$ production

- Sensitivity to $WW\gamma$ and WWZ couplings.

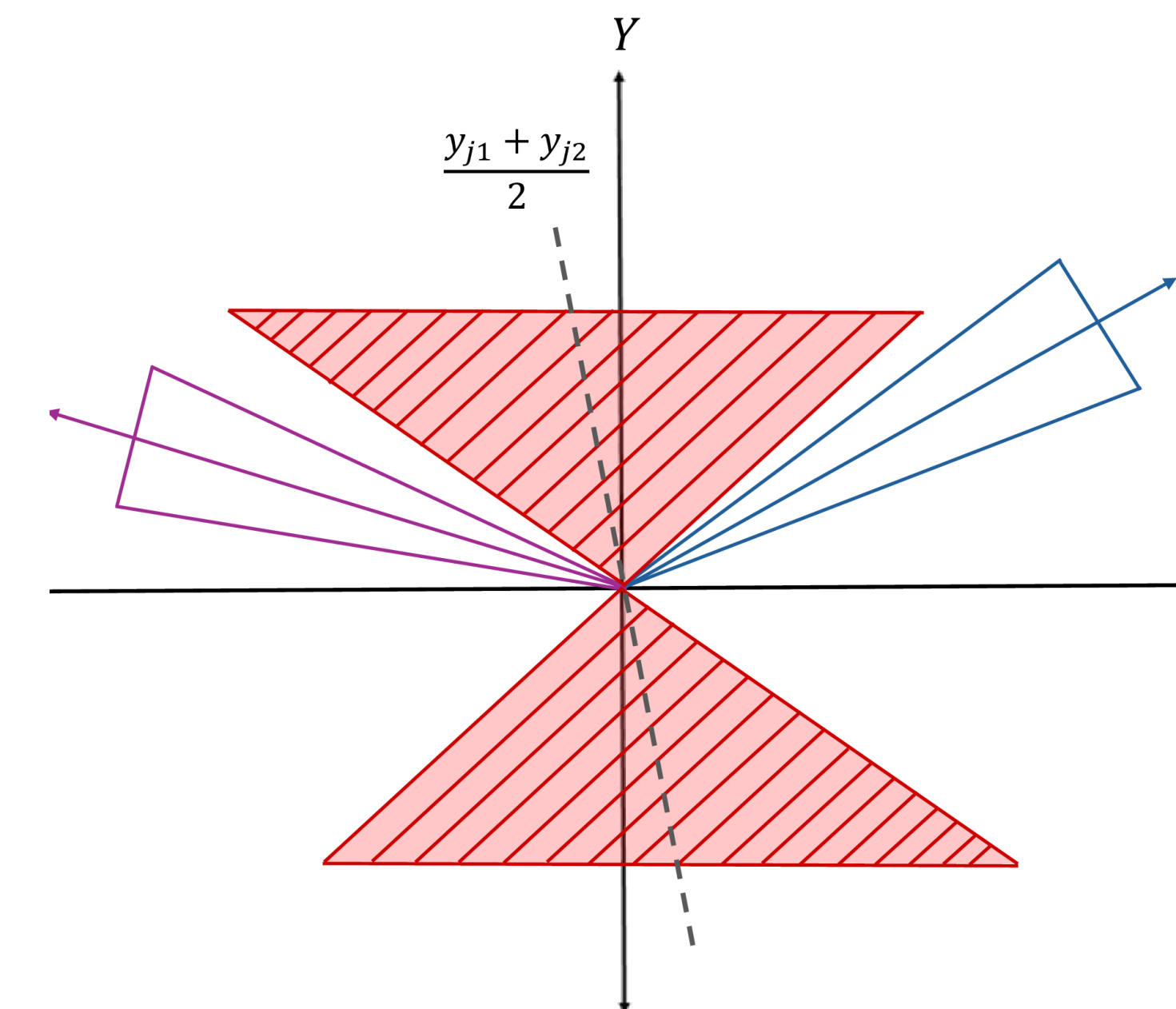
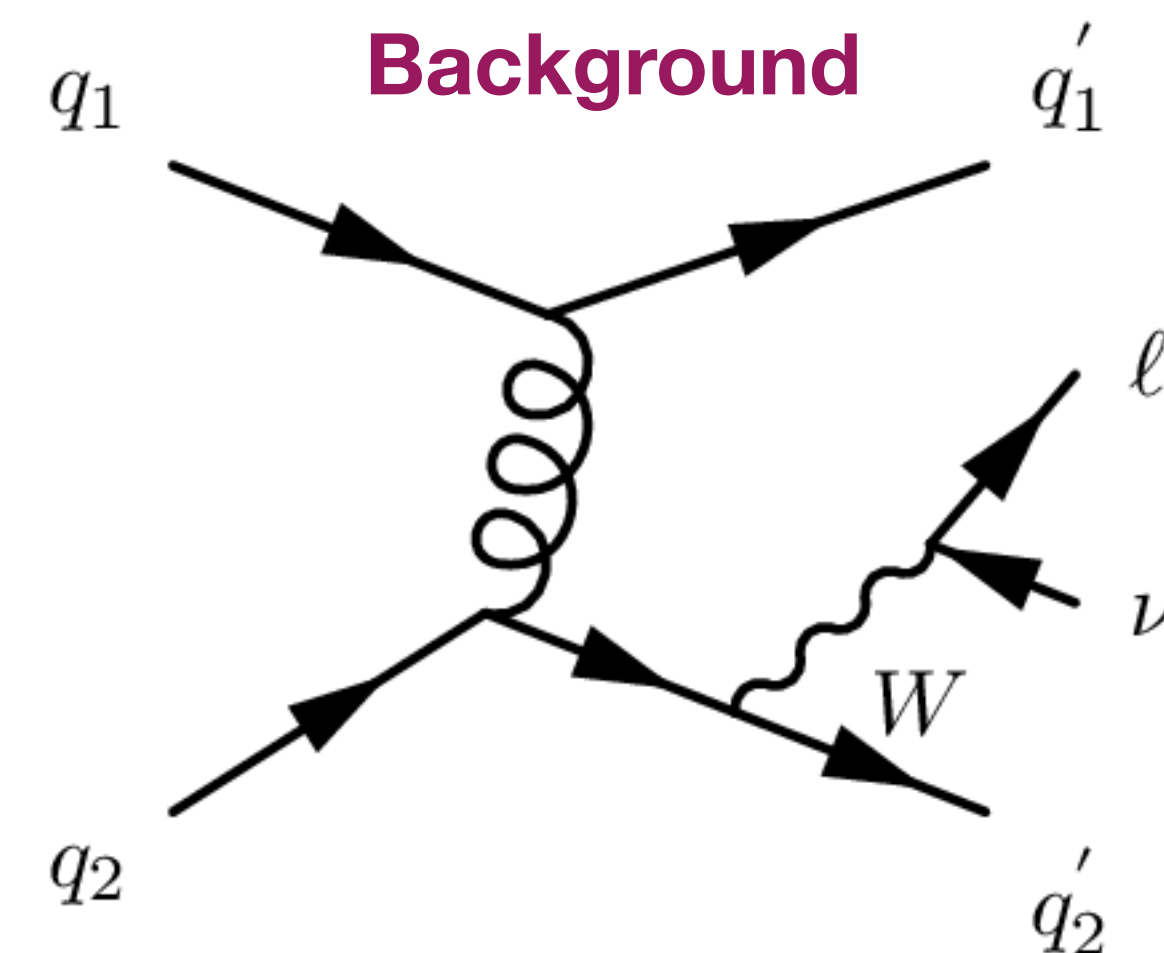
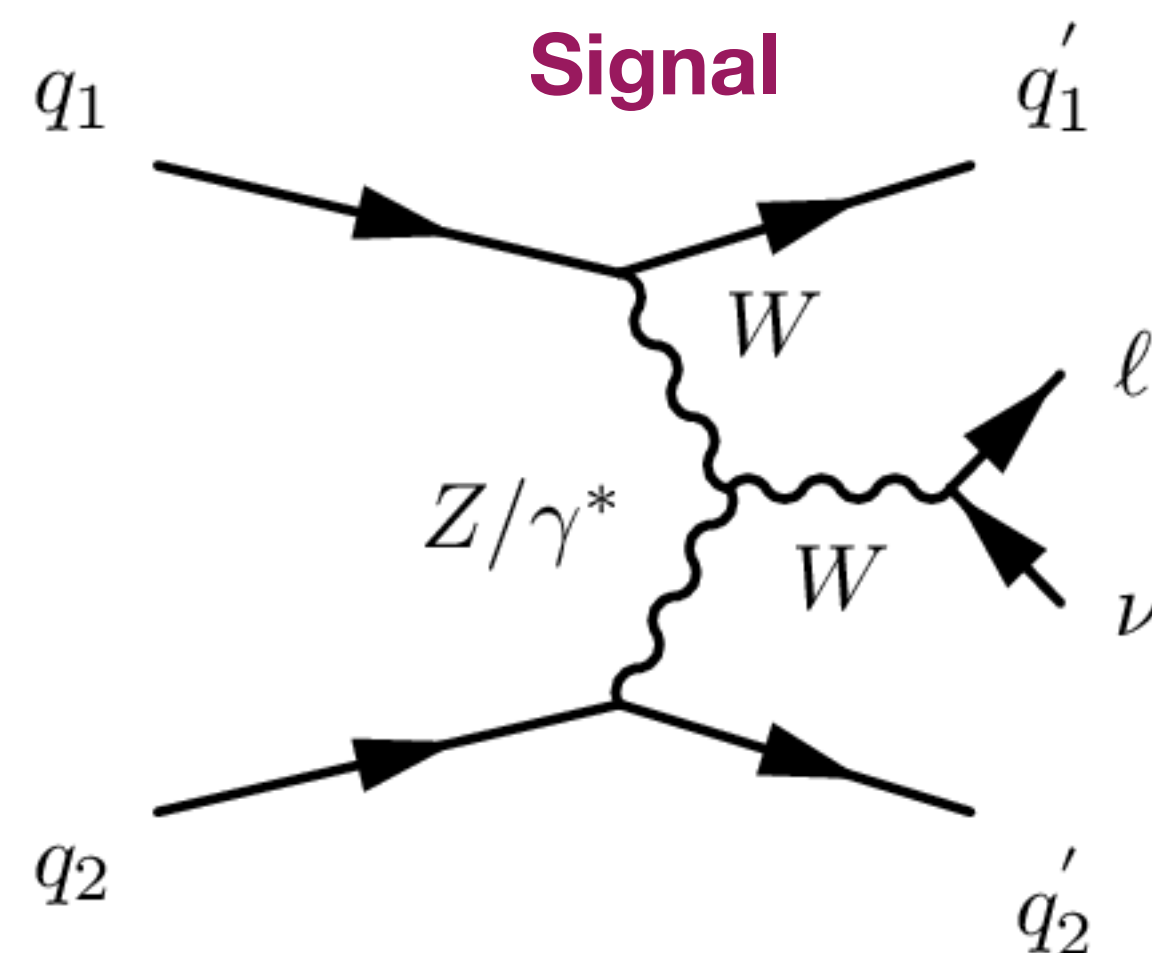
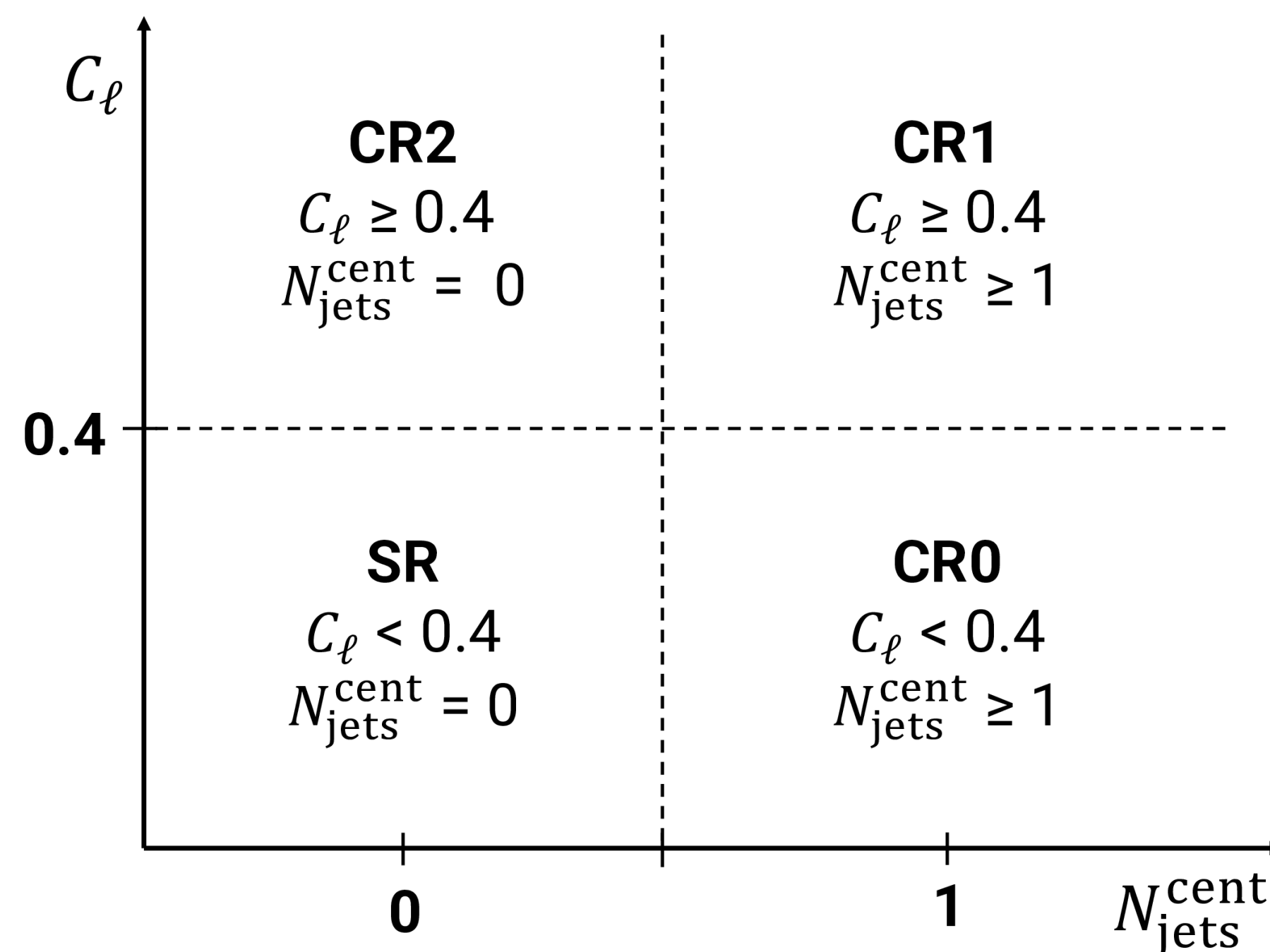
Event selection

- Exactly 1 lepton (e or μ), $E_T^{\text{miss}} > 30$ GeV and $m_T^W > 50$ GeV.
- 2 well separated jets with $|\Delta y_{jj}| > 2.0$ and $m_{jj} > 1$ TeV.

Backgrounds

- Dominant background is QCD $W^\pm jj$ production.
- Data-driven estimation using ABCD method on C_ℓ and $N_{\text{jets}}^{\text{gap}}$ plane.

$$C_{\ell(j)} = \left| \frac{y_{\ell(j)} - \frac{y_{j1} + y_{j2}}{2}}{y_{j1} - y_{j2}} \right|$$



arXiv:2607.21531

EWK $W^\pm jj$ production

- Combined PPL fit in SR and CRs to extract signal EWK.
- Iterative bayesian unfolding to obtain differential cross-sections.
- Uncertainties dominated by jet related unc. and jet vertex taggers.

Cross-section

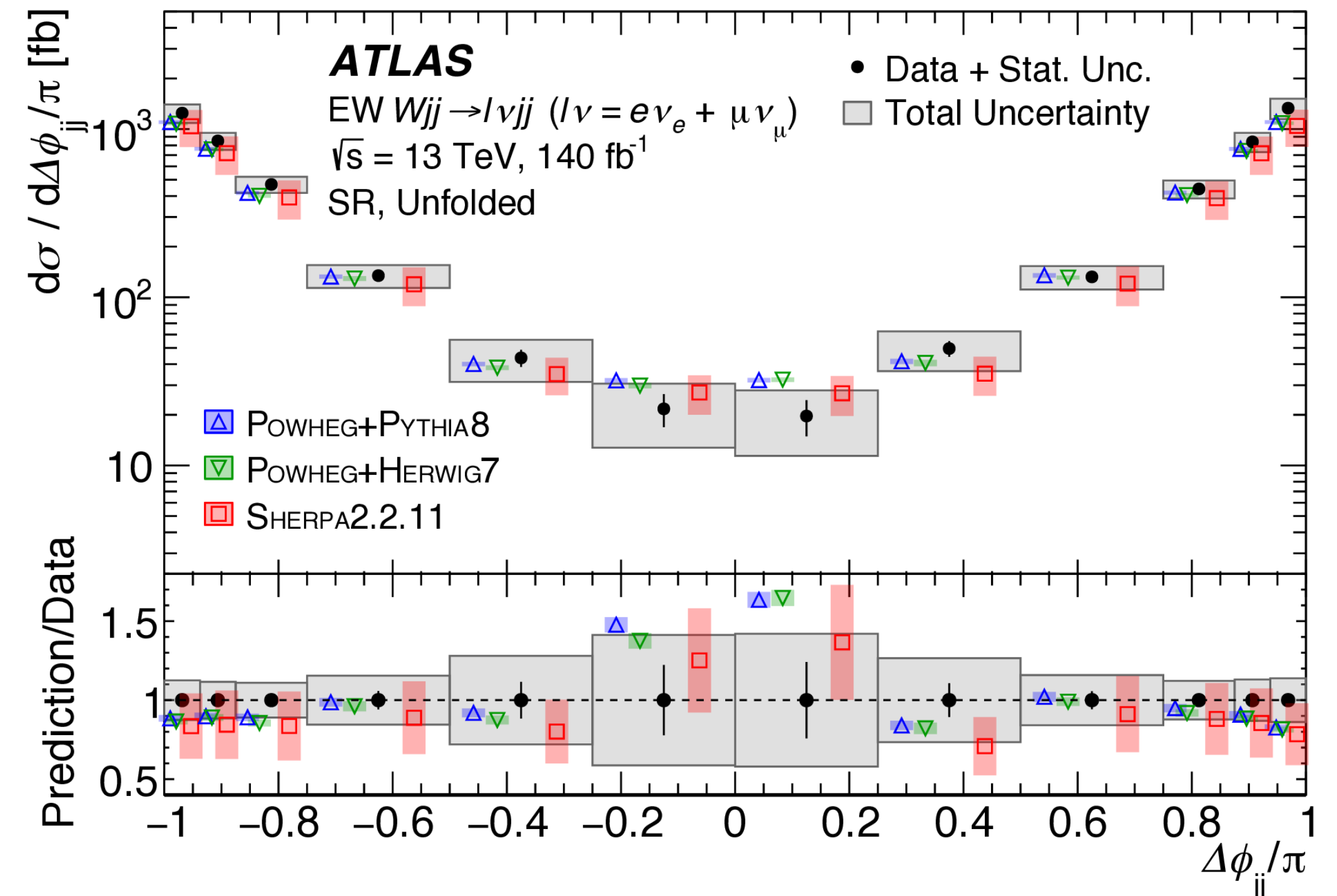
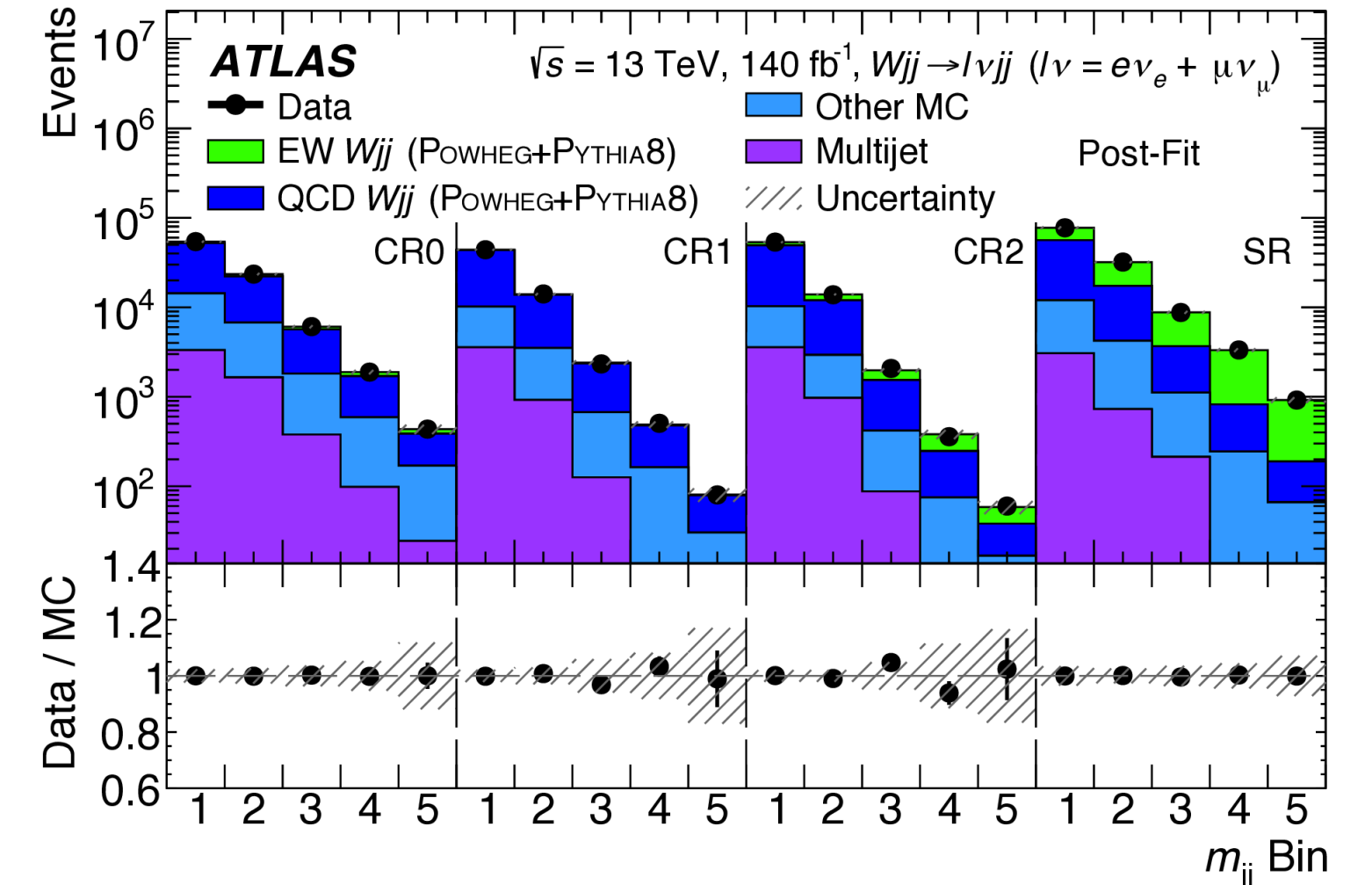
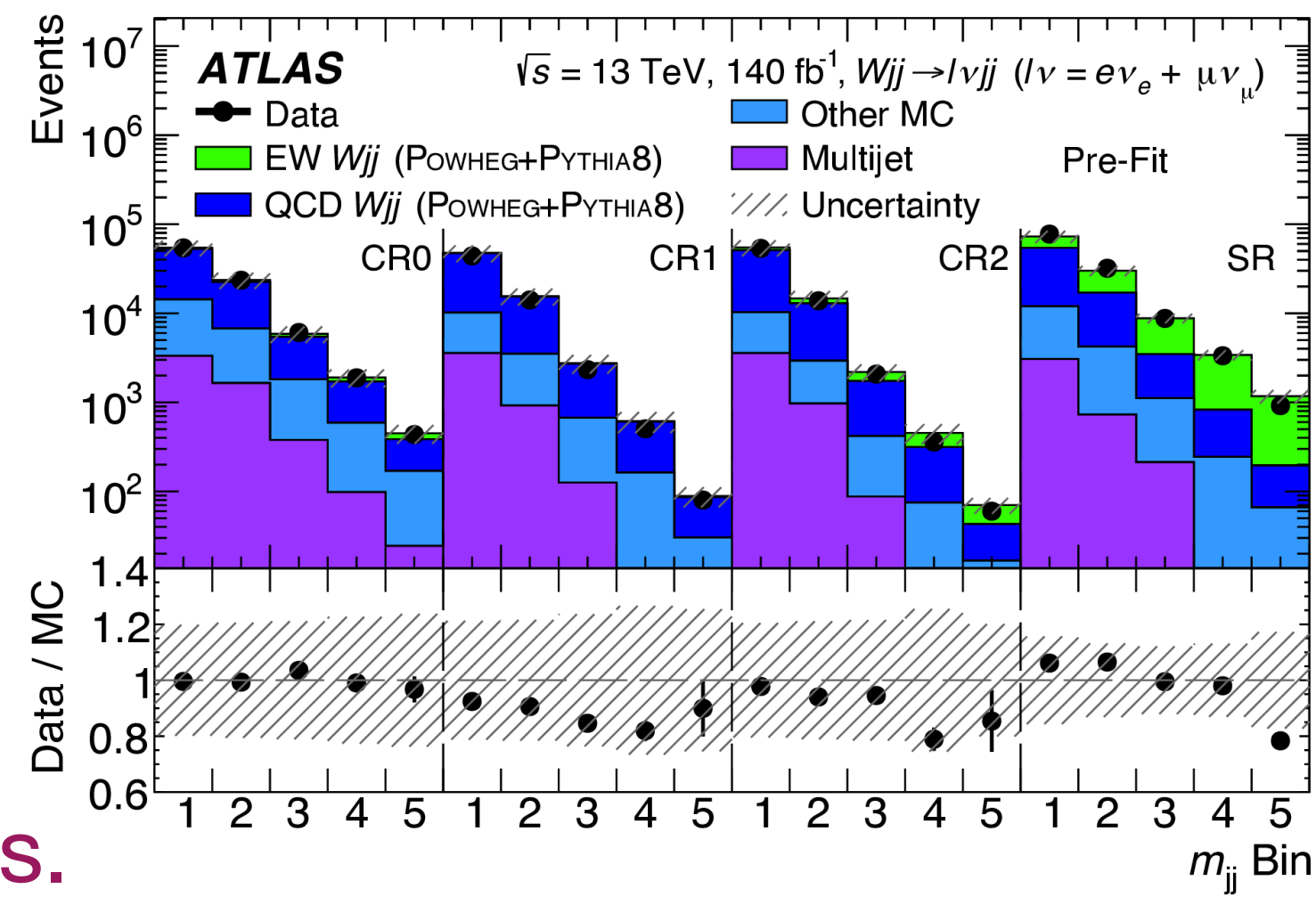
$$\sigma_{EW} = 480 \pm 12 \text{ (stat.)} \pm 39 \text{ (exp.)} \pm 53 \text{ (theory)}$$

$$\sigma_{\text{NLO}} = 431 \pm 7 \text{ fb (Powheg+Pythia)}$$

EFT interpretation

- Competitive limits with other ATLAS/CMS results.

Wilson coefficient	Expected interval [TeV^{-2}]		Observed interval [TeV^{-2}]	
	Linear-only	Linear+quadratic	Linear-only	Linear+quadratic
c_W/Λ^2	$[-0.17, 0.17]$	$[-0.17, 0.16]$	$[-0.17, 0.12]$	$[-0.15, 0.10]$
$\tilde{c}_W/\Lambda^2$	$[-0.19, 0.19]$	$[-0.18, 0.19]$	$[-0.083, 0.25]$	$[-0.079, 0.18]$
c_{HWB}/Λ^2	$[-5.6, 4.3]$	$[-3.4, 5.4]$	$[-4.1, 4.4]$	$[-2.2, 2.9]$
$\tilde{c}_{HWB}/\Lambda^2$	$[-10, 10]$	$[-4.1, 4.1]$	$[-11, 7.3]$	$[-2.8, 2.5]$



Semileptonic EWK VVjj

- Larger branching fraction and access to high- p_T regime compared to fully leptonic final states.

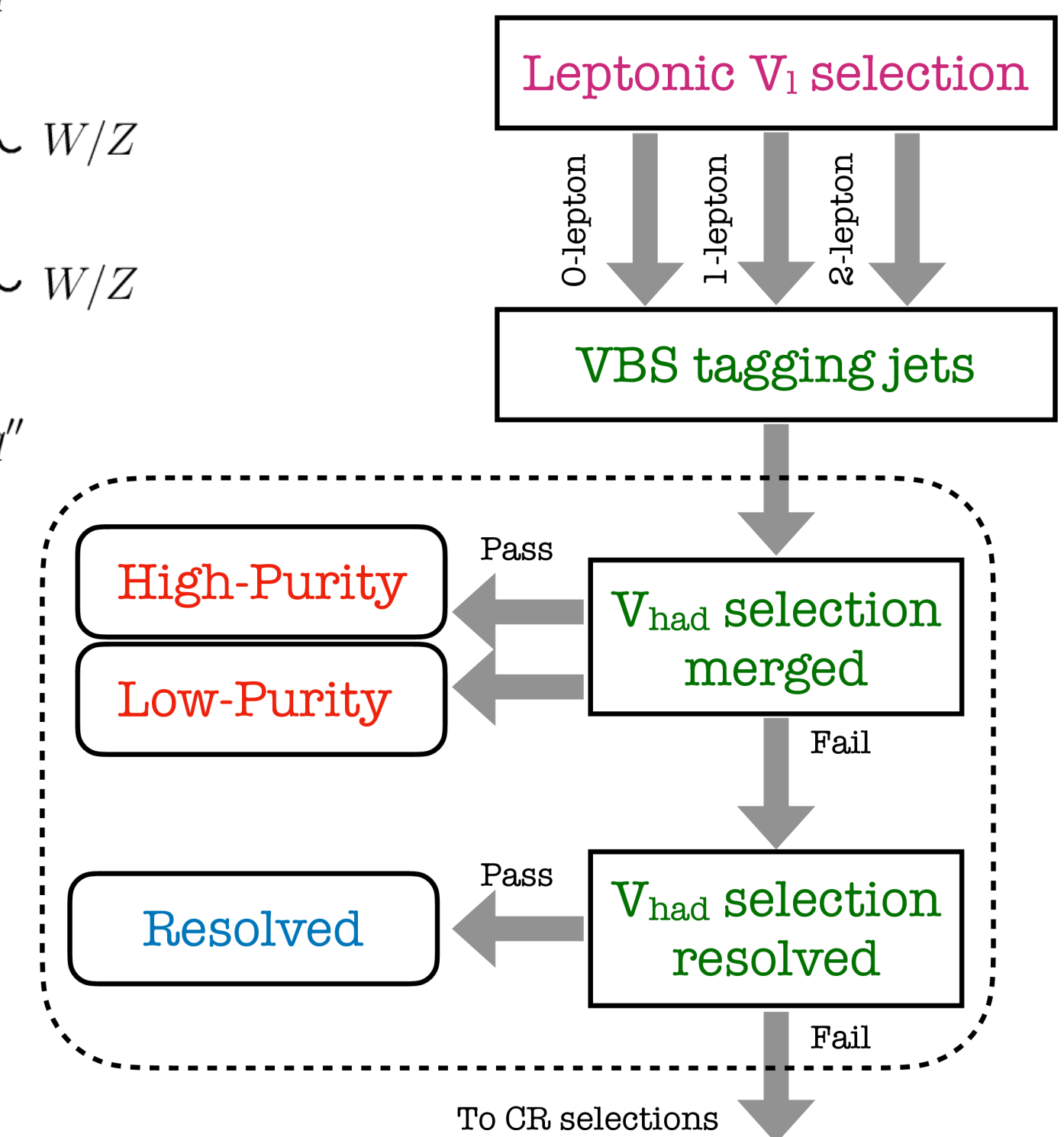
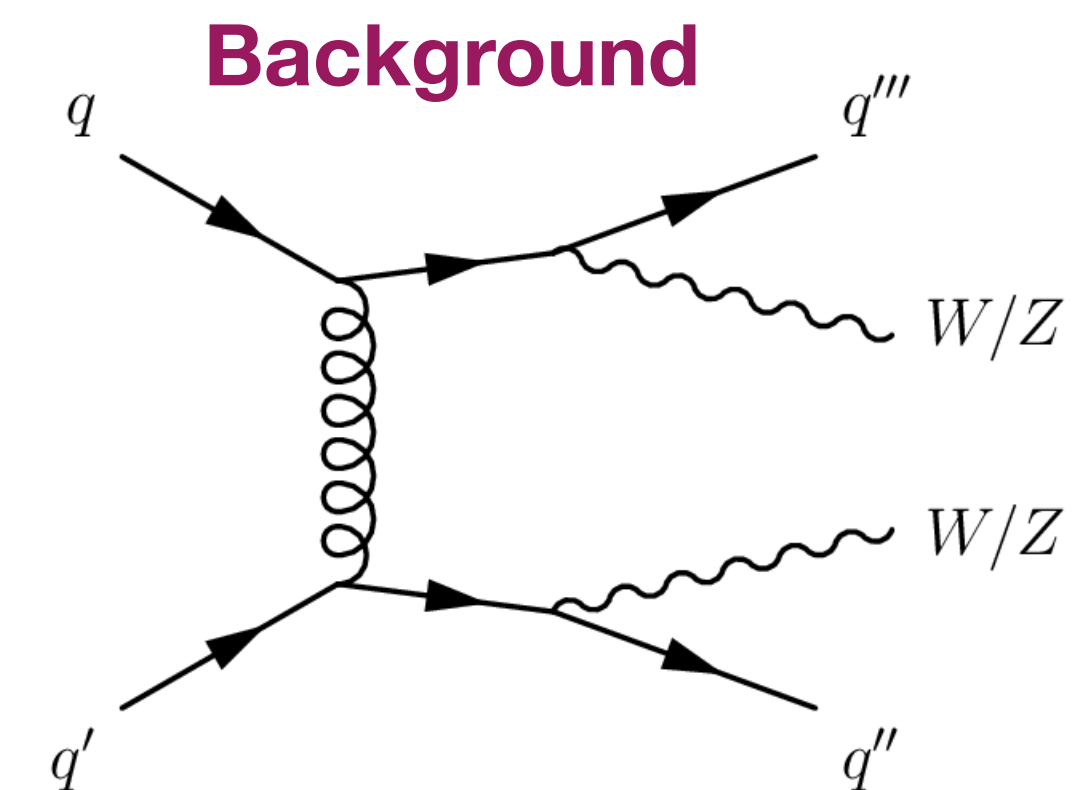
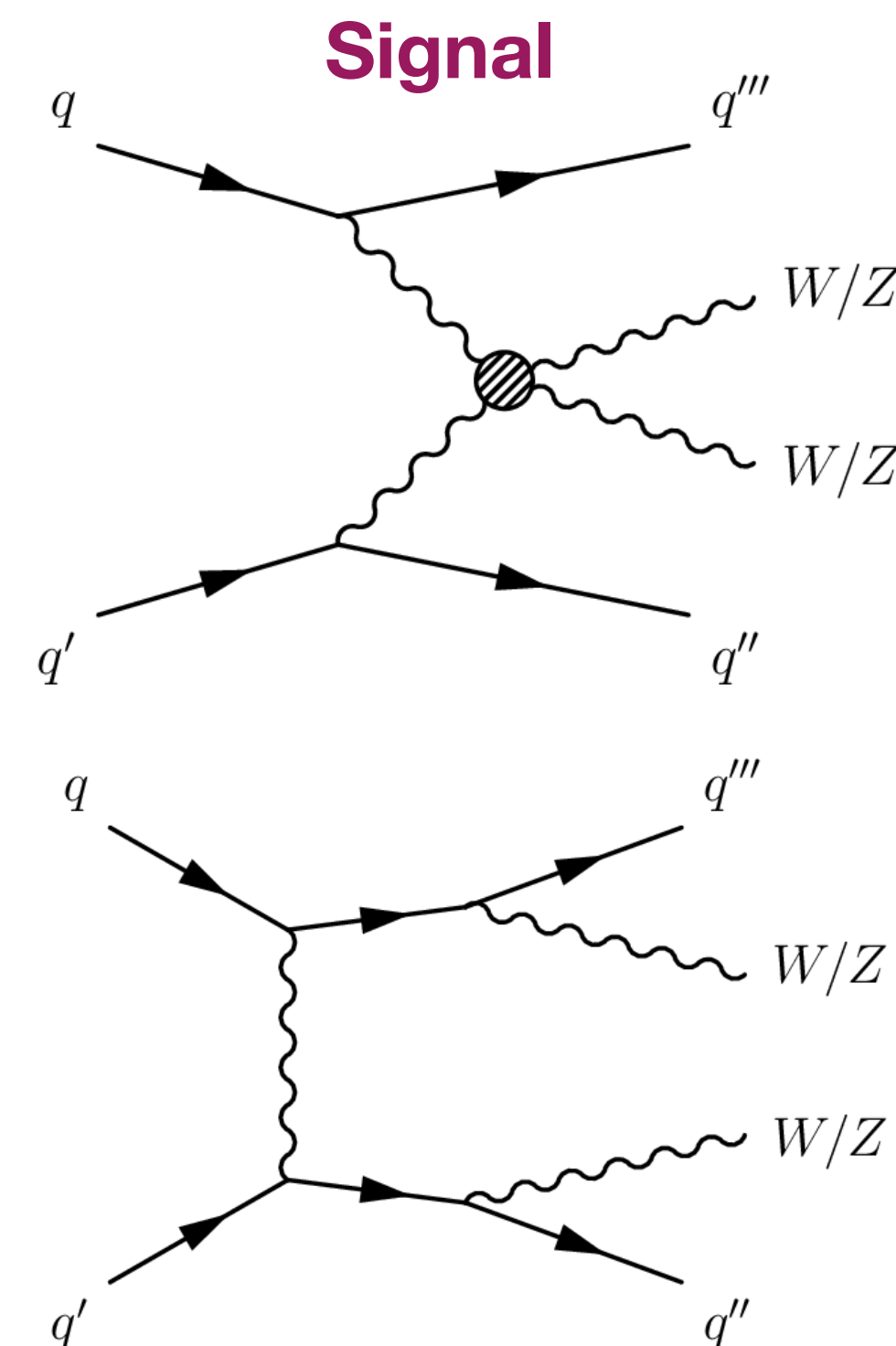
Eur. Phys. J. C 86 (2026) 433

Signature:

- Three channels defined by lepton multiplicity:
 - 0-, 1- and 2-leptons: $VV \rightarrow (l\nu, ll, \nu\nu)(qq)$.
- 2 forward jets with large m_{jj} and $\eta_{j_1} \cdot \eta_{j_2} < 0$.
- $p_T > 30$ GeV and $m_{jj} > 400$ GeV.

Hadronic V reconstruction:

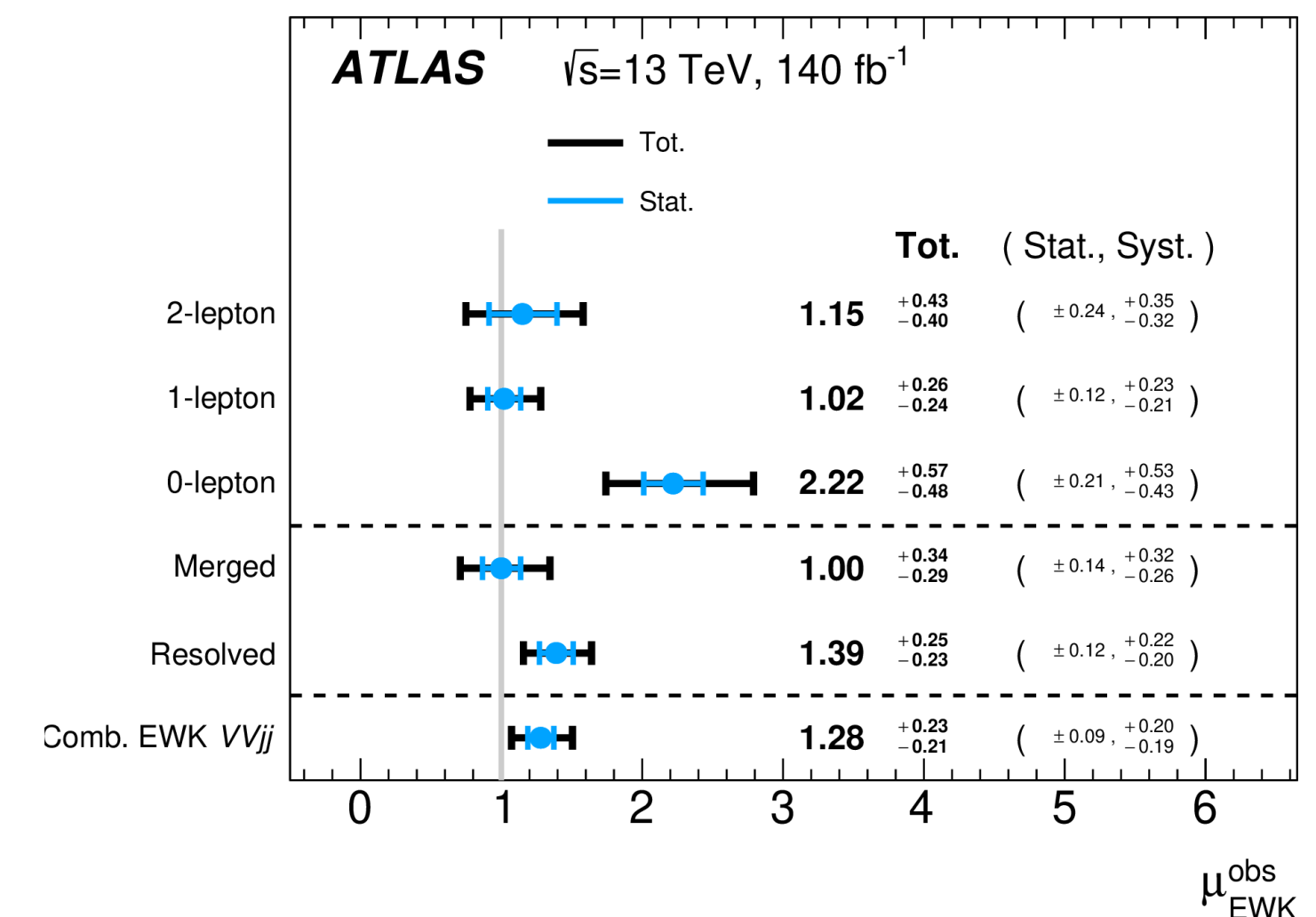
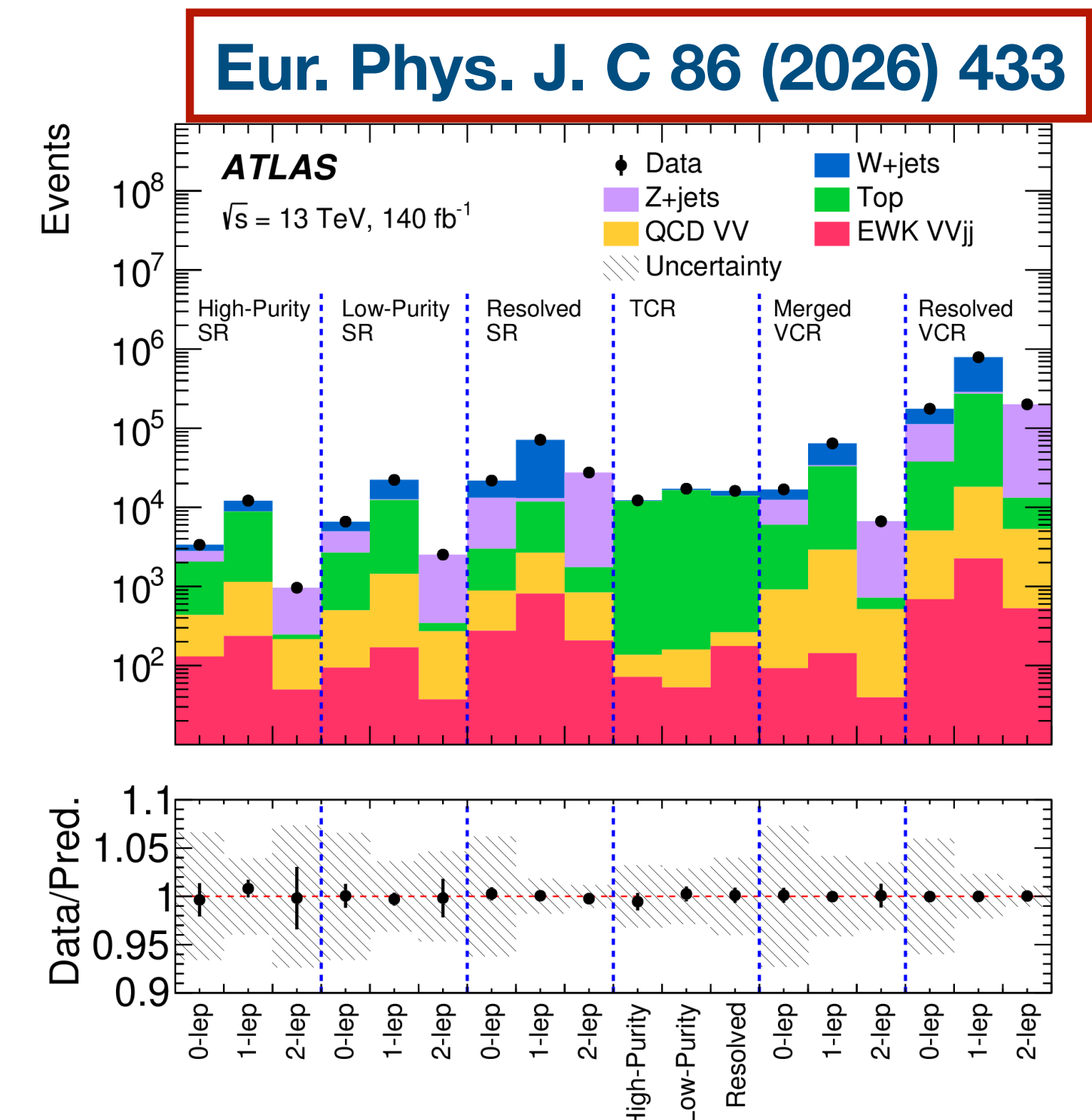
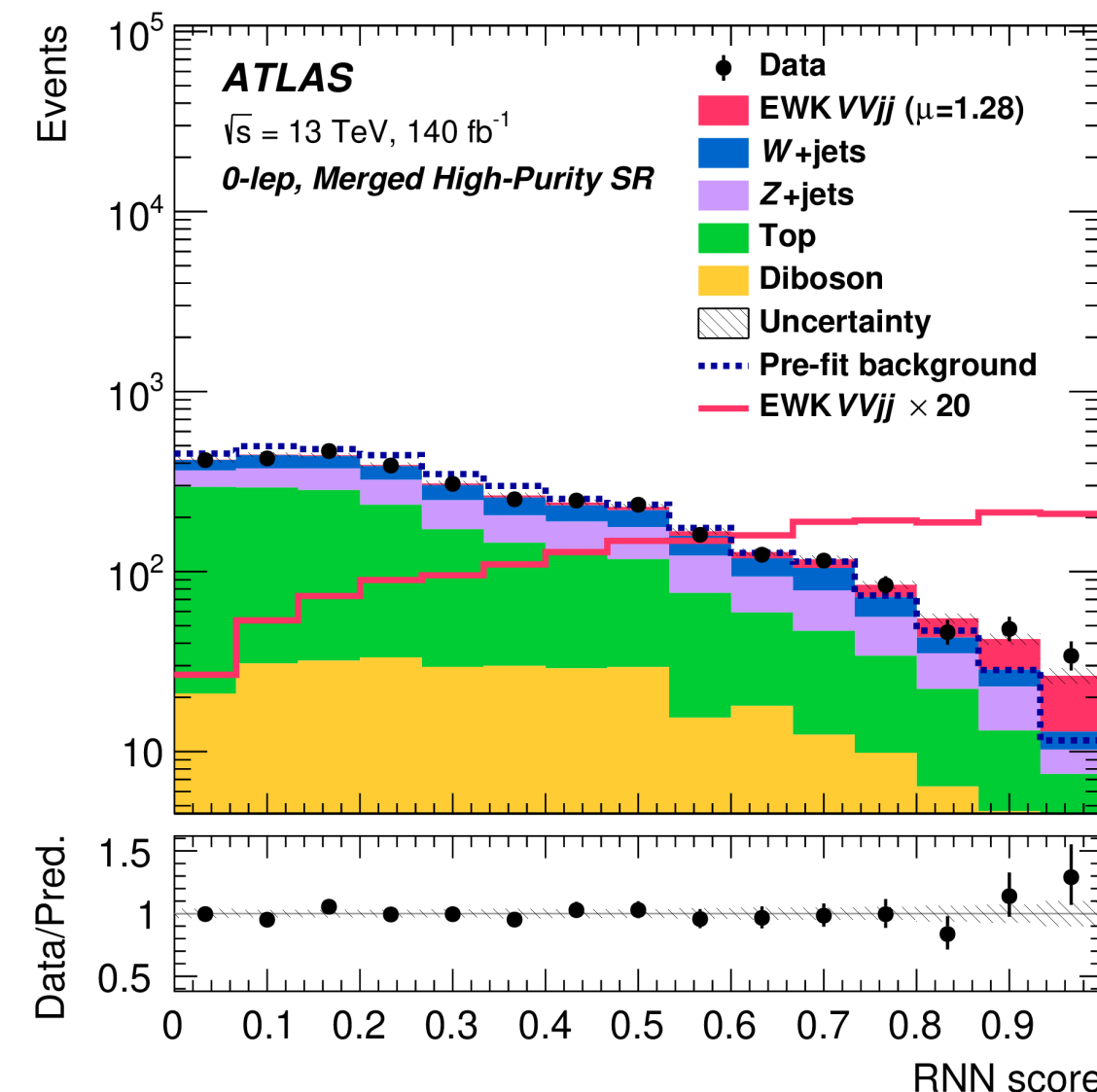
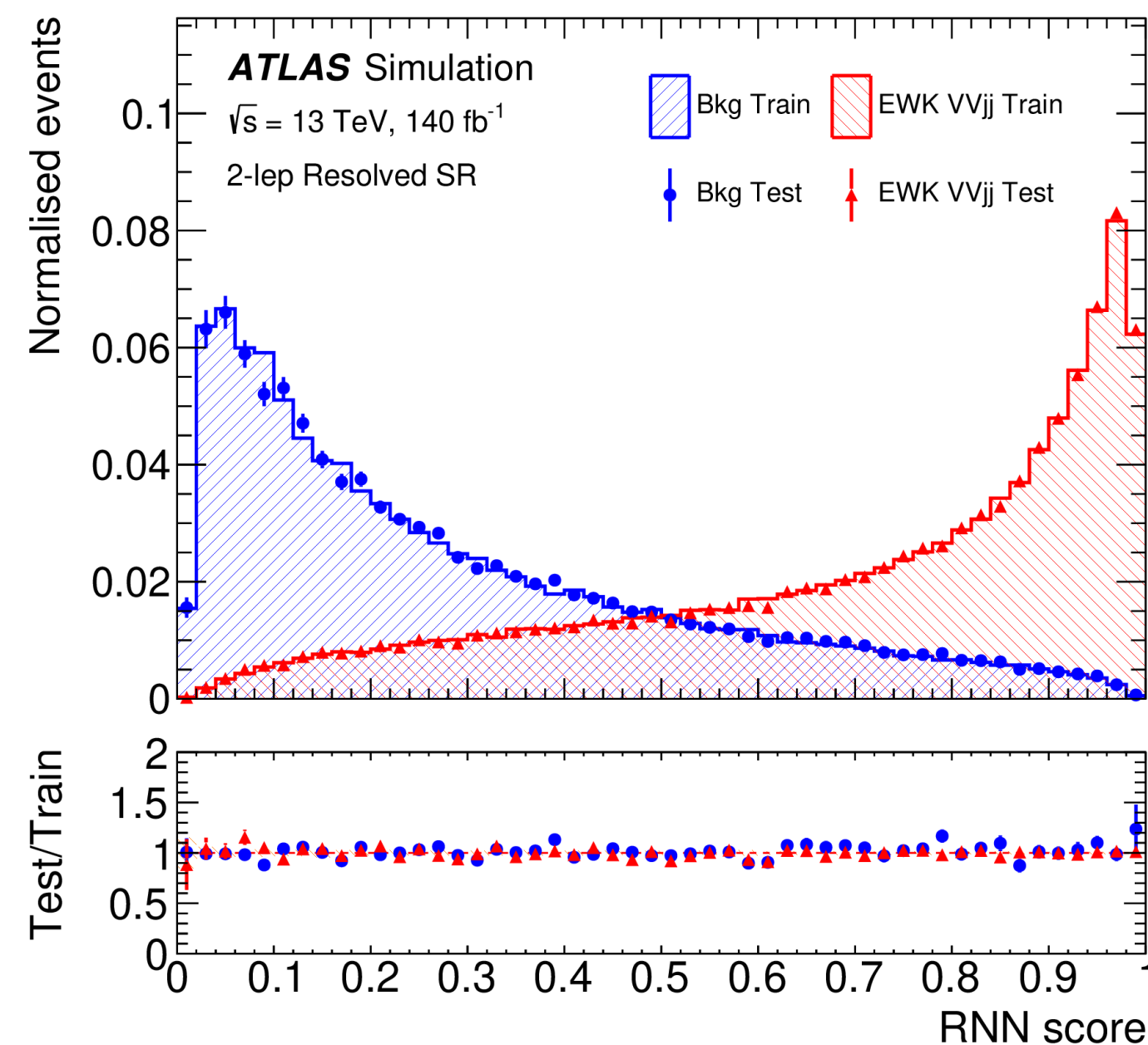
- **Merged** (boosted V_{had}):
 - 1 large-R jet ($R = 1.0$) with $p_T^V > 200$ GeV.
 - Boson tagging using jet mass, D_2 and N_{track} .
 - High- and low-purity categories.
- **Resolved** ($V \rightarrow jj$):
 - 2 small-R jets
 - $64 < m_{jj} < 106$ GeV



Semileptonic EWK $VVjj$

► Signal extraction:

- RNN using jet kinematics and track multiplicity to separate EWK $VVjj$ from V +jets and top-quark bkg.
- Simultaneous likelihood fit across SRs and CRs.
- First observation: 7.4σ (6.1σ expected).
- Consistent with the SM:
 - Measured fiducial cross-section:
 - $\sigma_{\text{fid.}}^{\text{EWK}} = 29.2 \pm 4.9 \text{ fb}$
 - Systematics dominated by signal modelling, jets and E_T^{miss} .
 - $\sigma_{\text{fid.}}^{\text{SM}} = 20.2 \pm 3.5 \text{ fb}$
- First ATLAS semileptonic $VVjj$ EFT limits
 - Up to x3 stronger constraints for selected dim-8 operators.



EWK $\gamma\gamma jj$ production

► Event selection:

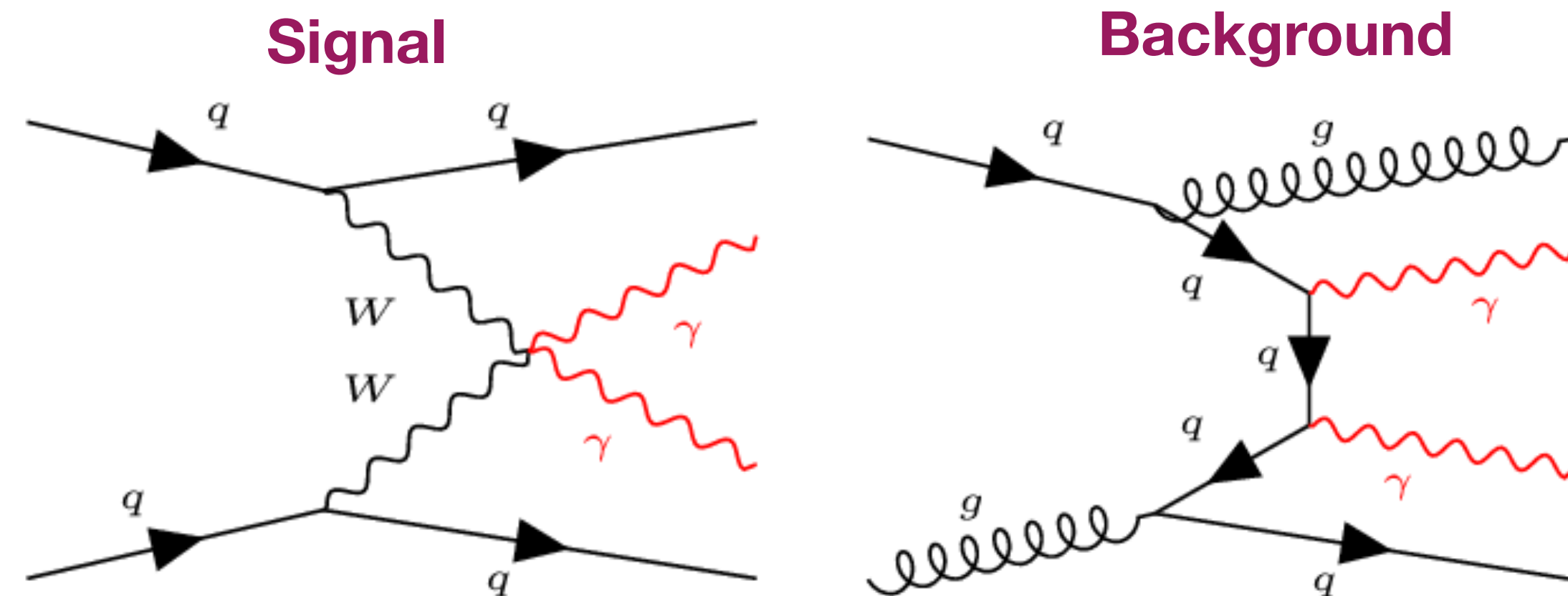
- 2 isolated photons: $p_T^{\gamma_1, \gamma_2} > 40, 30$ GeV.
- 2 leading jets: $p_T^{j_1, j_2} > 60$ GeV and $|y_j| < 4.4$
- VBS-enriched topology:
 - $m_{jj} > 500$ GeV, $|\Delta\eta(j_1, j_2)| > 2.0$ and $y_{j_1} \cdot y_{j_2} < 0$

► Background Strategy:

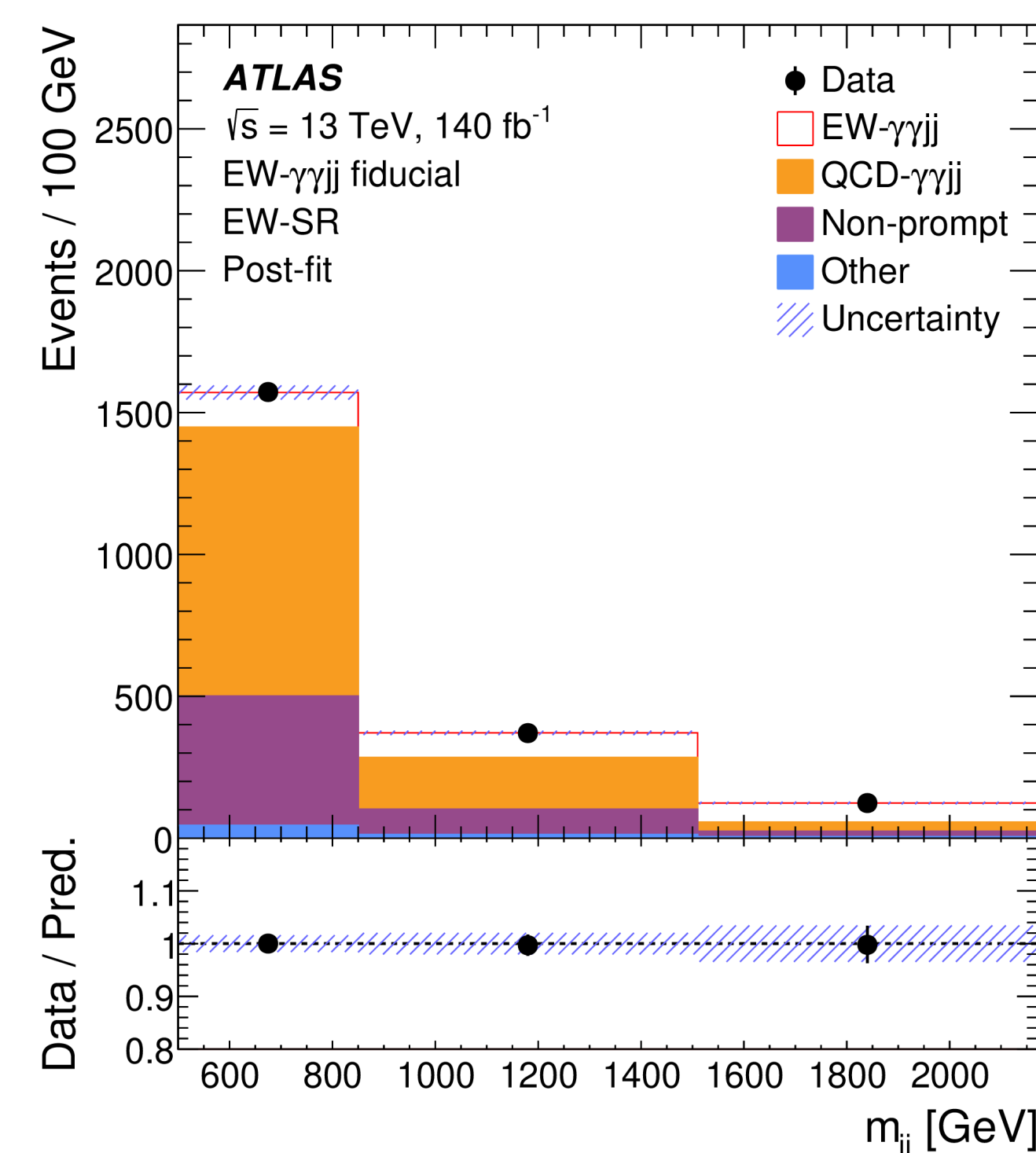
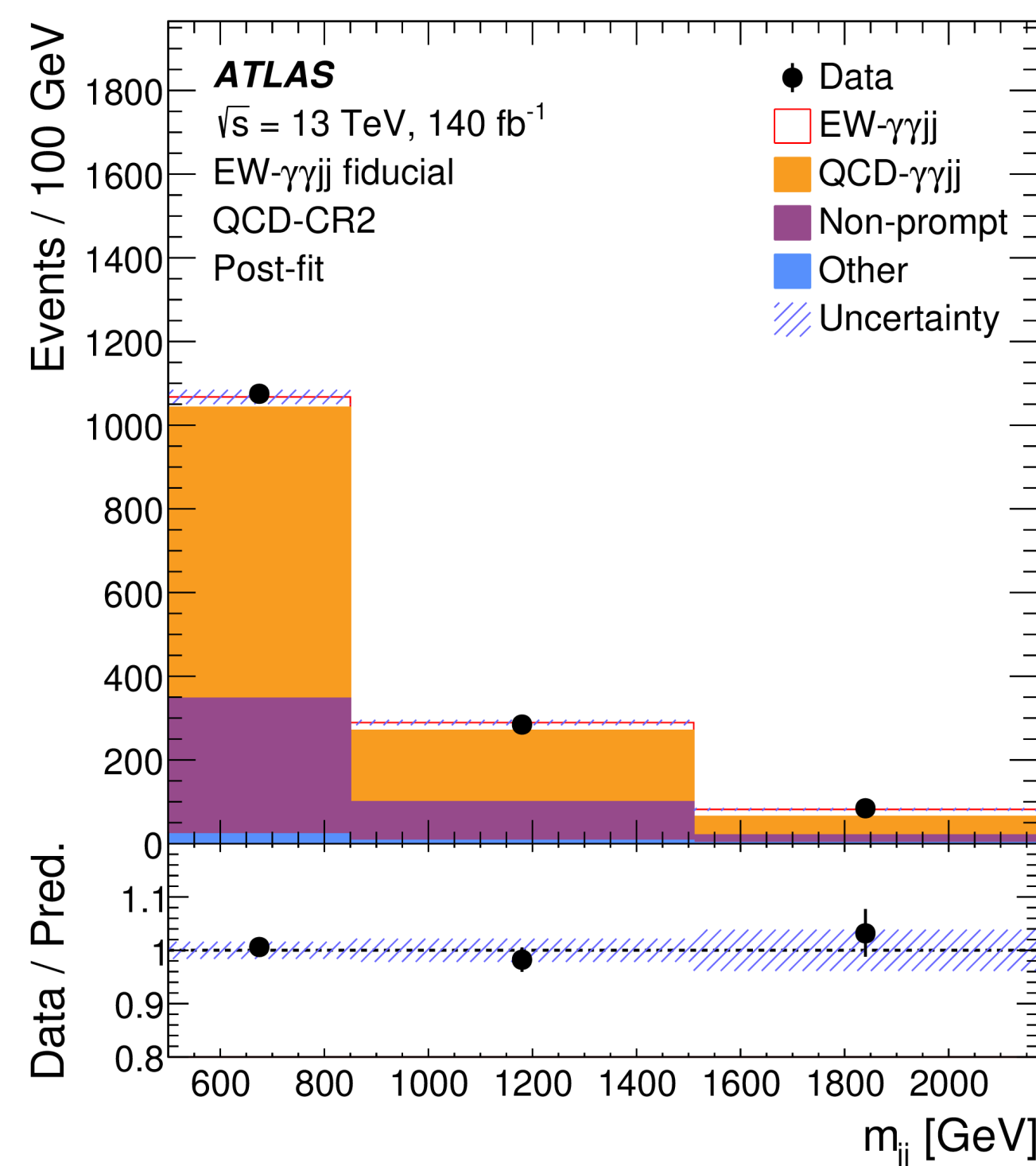
- Dominant QCD $\gamma\gamma jj$ background estimated using 3 CRs.
 - They are based on $\gamma\gamma$ centrality and $N_{\text{jet}}^{\text{gap}}$.
 - ABCD method to estimate QCD in SR.
- Non-prompt γ background estimated using data from γ ID and isolation sidebands.

► Signal extraction:

- Signal is extracted from a combined PLL fit to SR and CRs.



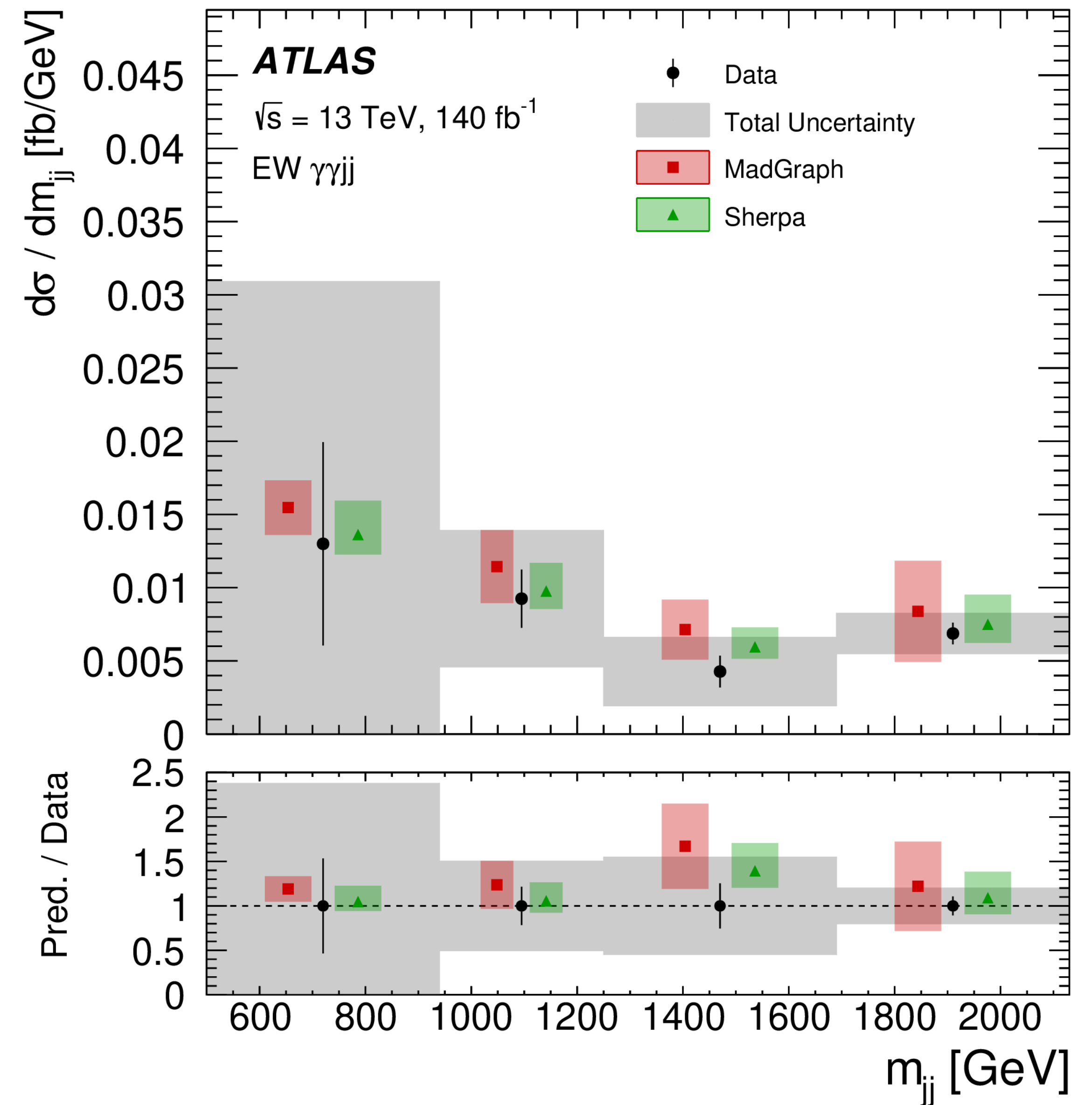
arXiv:2607.25869



EWK $\gamma\gamma jj$ production

- ▶ First observation: 6.2σ (7.2σ expected).
 - ▶ Consistent with the SM
 - ▶ Measured fiducial cross-section:
- $$\sigma_{\text{obs}}^{\text{EW}} = 13.8_{-2.6}^{+3.0} \text{ fb} \quad (\sigma_{\text{exp}}^{\text{EW}} = 17.1 \pm 2.4 \text{ fb})$$
- ▶ Uncertainties dominated by signal modelling (13%) and non-prompt background estimation (9%).
 - ▶ Differential cross-section measurements as a function of 6 observables:
 - ▶ $m_{\gamma\gamma}, m_{jj}, p_T^{\gamma_1}, p_T^{j_1}, p_T^{j_2}, |\Delta\phi_{jj}|$
 - ▶ Measurements of QCD+EWK differential cross-sections also performed.
 - ▶ EFT interpretation to set limits on dim-8 operators.
 - ▶ Largest sensitivity to f_{T5}/Λ^4 : $[-0.4, 0.372] \text{ TeV}^{-4}$ and f_{T8}/Λ^4 : $[-0.220, 0.219] \text{ TeV}^{-4}$

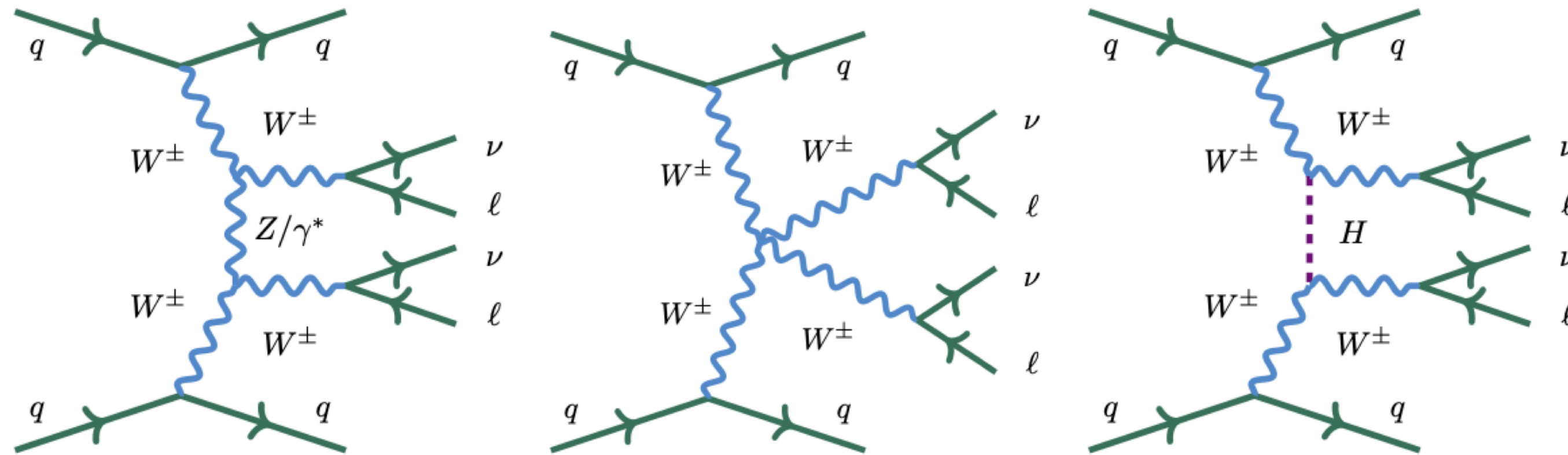
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W polarisation in EWK $W^\pm W^\pm jj$ production

Motivation

- ▶ Longitudinal W bosons originate from Goldstone modes.
- ▶ $W_L W_L$ scattering is a direct probe of EWK symmetry breaking.



- ▶ $W^\pm W^\pm jj$ is a sensitive channel due to small background.

Event selection and topology

- ▶ Two same-sign leptons (e or μ).
- ▶ $E_T^{\text{miss}} > 30$ GeV.
- ▶ At least two jets with $m_{jj} > 500$ GeV and $|y_{jj}| > 2.0$.

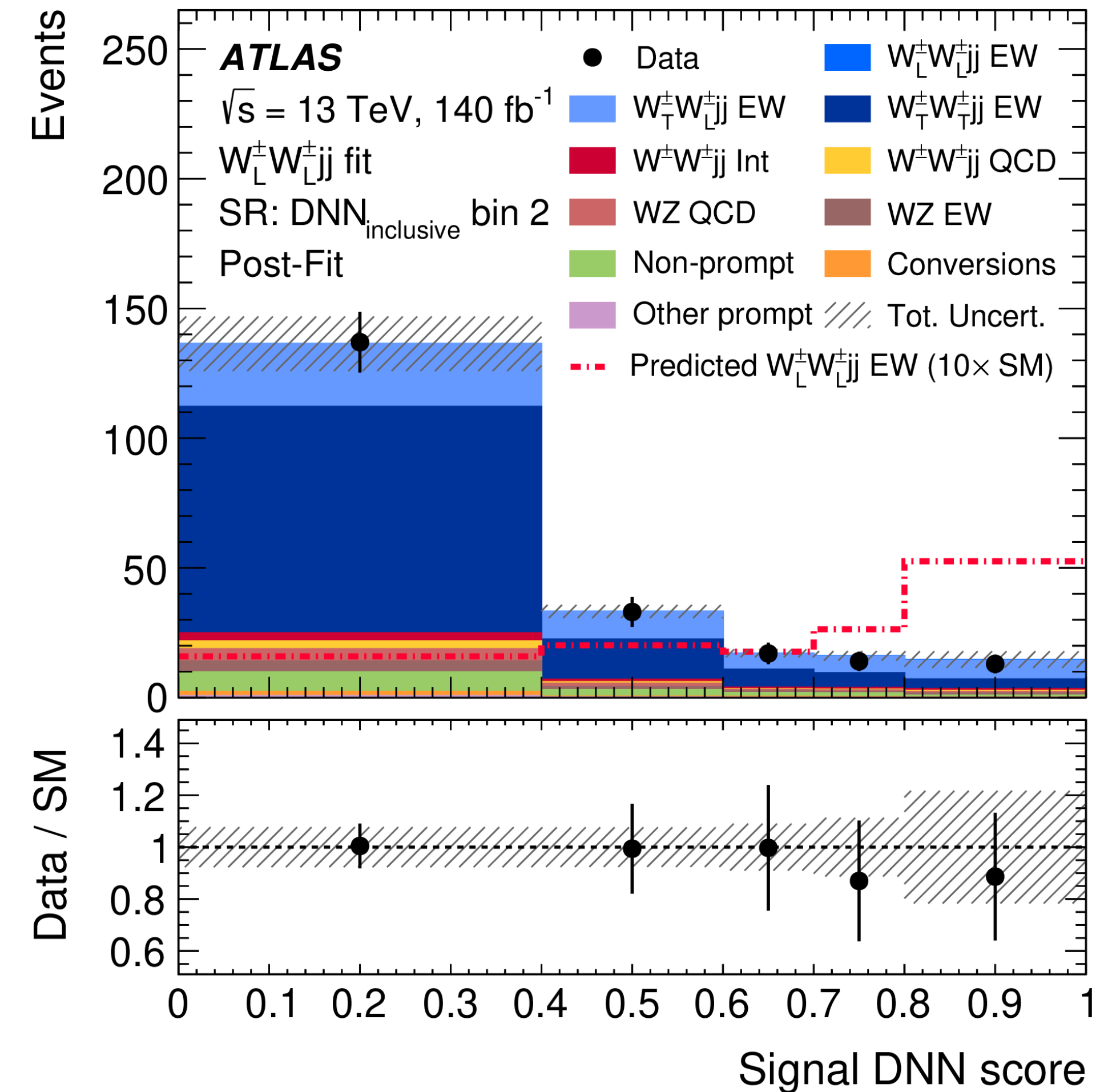
Analysis Strategy

- ▶ Use a DNN to separate EWK $W^\pm W^\pm jj$ from background processes.
- ▶ Use DNNs to separate longitudinal and transverse contributions.
- ▶ Polarisation vectors defined in $W^\pm W^\pm$ centre-of-mass energy frame.
 - Observables also measured in lab frame.
- ▶ Binned maximum likelihood fits of DNN.
- ▶ Distributions used to extract $W_L^\pm W_L^\pm jj$ and $W_L^\pm W_T^\pm jj$.

Phys. Rev. Lett. 135 (2025) 111802

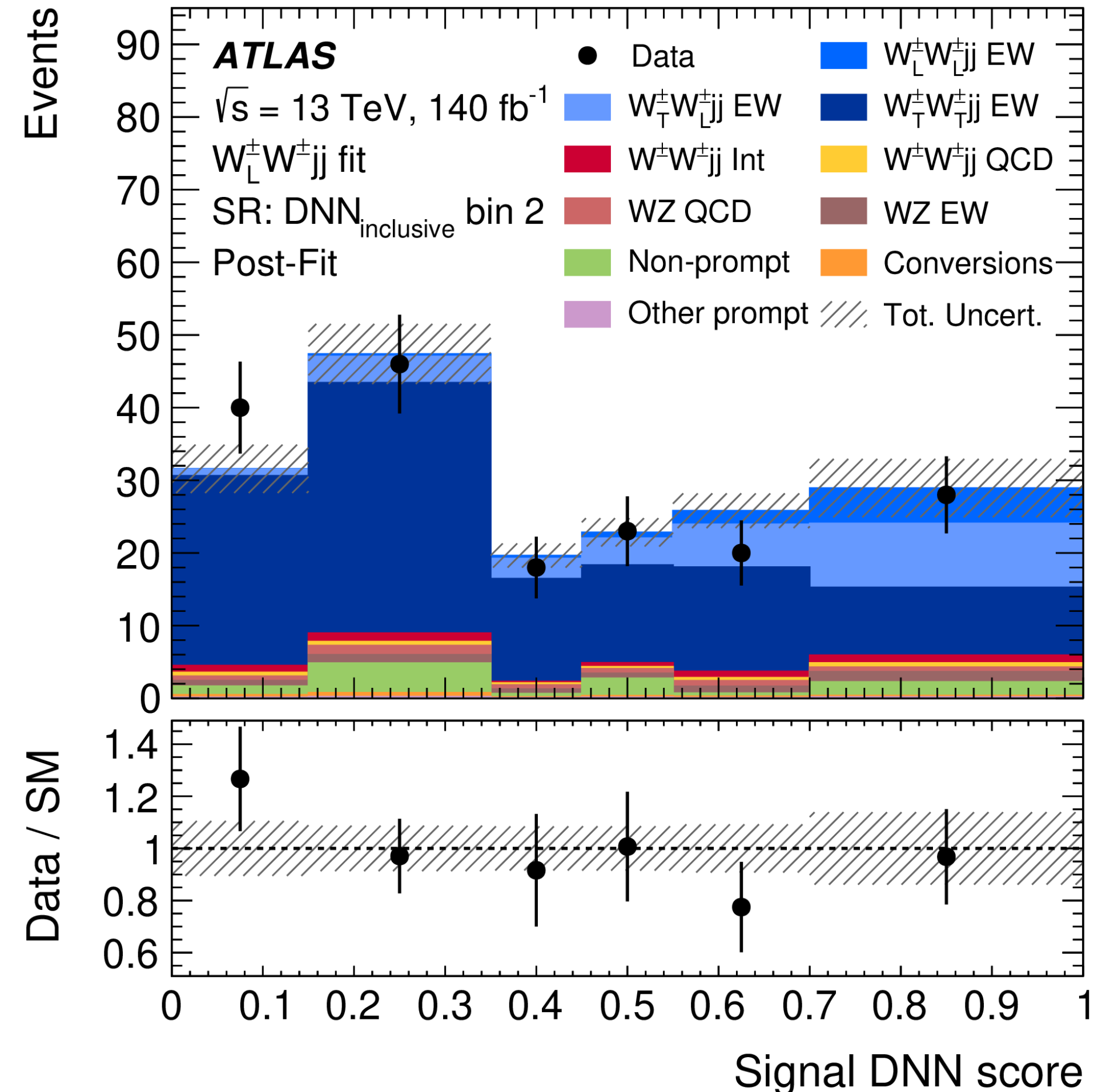
W polarisation in EWK $W^\pm W^\pm jj$ production

DNN score for $W_L^\pm W_L^\pm jj$ measurement



- ▶ No significant $W_L^\pm W_L^\pm$ signal is observed.
- ▶ 95% CL upper limit on $\sigma \cdot B(W_L^\pm W_L^\pm jj)$ is 0.45 fb (0.70 is expected)

DNN score for $W^\pm W_L^\pm jj$ analysis



- ▶ Observed significance of 3.3σ (4.0σ expected).
- ▶ It corresponds to measured $\sigma \cdot B(W^\pm W_L^\pm jj) = 0.88 \pm 0.3 \text{ fb}$ (SM: $1.18 \pm 0.29 \text{ fb}$)

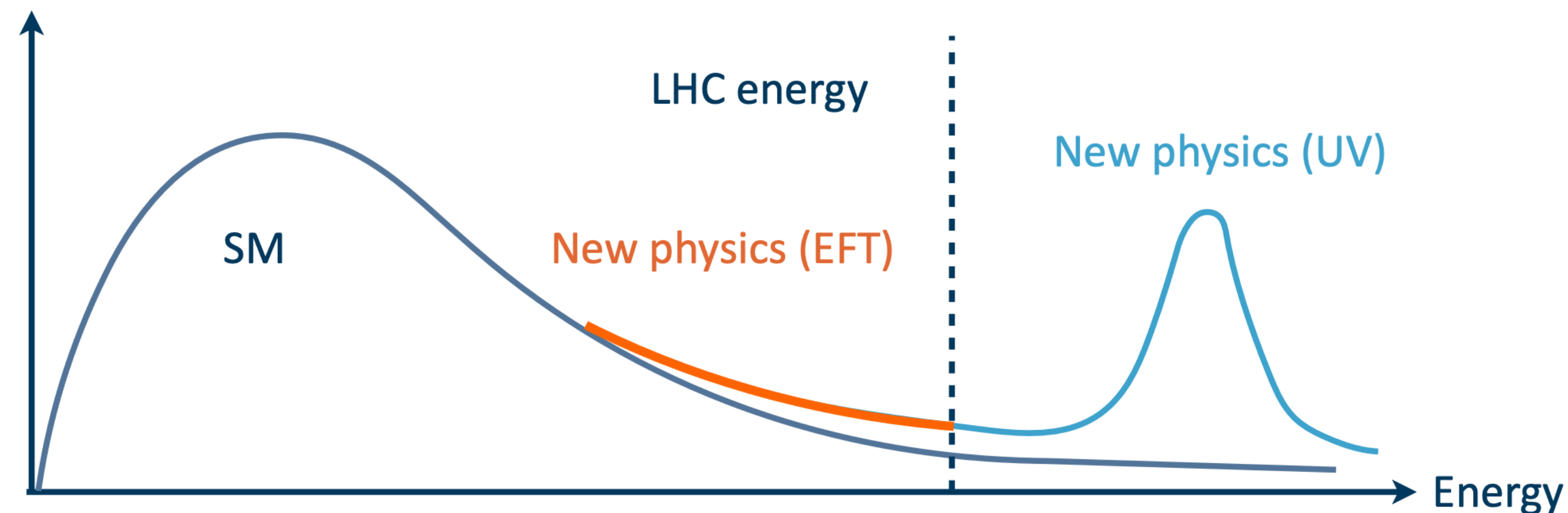
- ▶ Effective field theory: a model agnostic framework for possible higher scale new physics beyond direct search.

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- ▶ Many experimental measurements have been interpreted in the EFT framework.

- ▶ Expansion of the SM Lagrangian into local operators with mass dimension > 4 .

- Λ is the scale of new physics.
- $O_i^{(n)}$ operators introduce new interaction vertices.
- $c_i^{(n)}$ are Wilson coefficients that indicate the strength of the coupling.



- ▶ Warsaw basis:

- ▶ It provides a complete and non-redundant parametrization of dim-6 operators respecting SM gauge symmetries.

Violating Lepton and Baryon numbers

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}}_{\text{Dimension-6}} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \underbrace{\sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)}}_{\text{Dimension-8}} + \dots$$

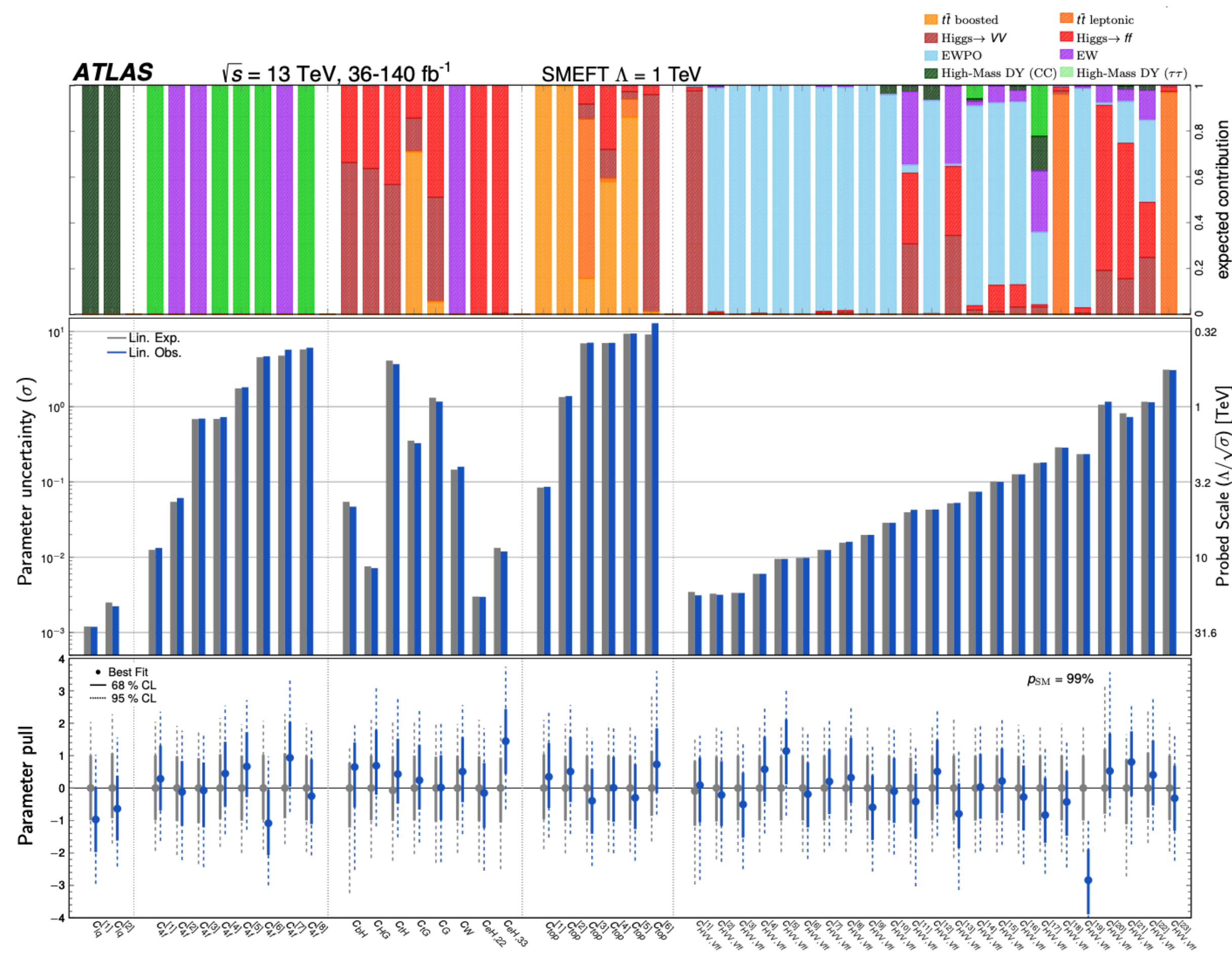
ATLAS Global EFT fit

- Several measurements included.
 - SM prediction is varied according to the EFT expectation.
 - Global EFT fit is performed to constrain dim-6 Wilson coefficients.

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Process	Dataset [fb ⁻¹]	SMEFT sensitivity
Higgs boson measurements [10–19]		
$pp \rightarrow H \rightarrow \gamma\gamma, ZZ^* \rightarrow 4\ell, WW^* \rightarrow \ell\nu\ell\nu$	140	Higgs boson operators
$pp \rightarrow H \rightarrow Z\gamma, \mu^+\mu^-$	140	Higgs boson operators
$pp \rightarrow H \rightarrow b\bar{b}, \tau^+\tau^-$	126–140	Higgs boson operators
Electroweak measurements [22–24]		
$pp \rightarrow W^+W^- \rightarrow e^\pm\nu\mu^\mp\nu$	36	Four-fermion operators and triple gauge couplings
$pp \rightarrow W^\pm Z \rightarrow \ell^\pm\nu\ell^+\ell^-$	36	Four-fermion operators and triple gauge couplings
$pp \rightarrow Zjj \rightarrow \ell^+\ell^-jj$	140	Four-fermion operators and triple gauge couplings
HMDY measurements [25, 26]		
$pp \rightarrow Z/\gamma^* \rightarrow \tau^+\tau^-$	140	Four-fermion operators involving leptons
$pp \rightarrow W^\pm \rightarrow \ell^\pm\nu$	140	Four-fermion operators involving leptons
Top-quark measurements [27, 28]		
$pp \rightarrow t\bar{t} \rightarrow WbWb \rightarrow e^\pm\mu^\mp\nu b\bar{b}$	140	Four-fermion (heavy-flavour) operators
$pp \rightarrow t\bar{t} \rightarrow WbWb \rightarrow qq'b\ell\nu b$	140	Four-fermion (heavy-flavour) operators
Di-Higgs measurements [20, 21]		
$pp \rightarrow HH \rightarrow b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-$	140	Trilinear Higgs boson self-coupling
Electroweak precision observables [29–33]		
LEP, SLD, ATLAS EWPO	–	Weak boson–fermion couplings

$$\mu_{SMEFT} = \mu_{SM} \left(1 + \underbrace{\sum_i A_i \frac{c_i^{(6)}}{\Lambda^2}}_{\text{Linear component}} + \underbrace{\sum_i B_i \frac{(c_i^{(6)})^2}{\Lambda^4} + \sum_{i,j} C_{ij} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4}}_{\text{Quadratic component}} \right)$$



Combined EFT interpretation sensitive to aQGC

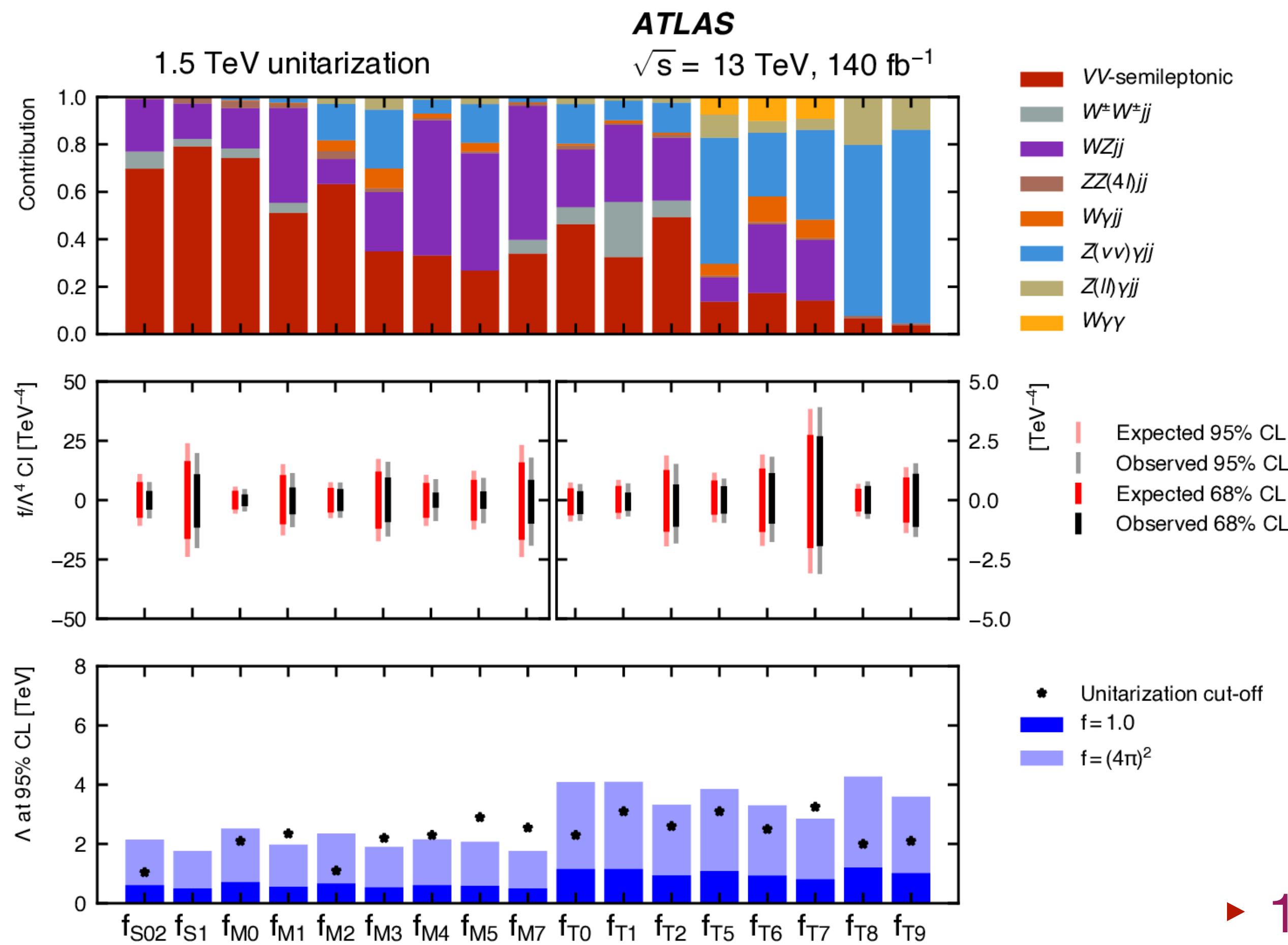
- ▶ 7 VBS + 1 triboson Run 2 measurements are combined to put limits on dim-8 Wilson coefficients.
 - 17 Eboli basis operators allow to probe all gauge boson vertices.
 - Eboli basis includes dim-8 operators (S, T and M) designed to probe aQGC.
 - S operators includes derivative of Higgs field.
 - T operators include only gauge fields.
 - M operators mixed Higgs and Gauge fields.

Phys. Lett. B 879 (2026) 140683

Analysis	Input type	Éboli operator results	Luminosity [fb ⁻¹]	Reference
$VVjj \rightarrow (\ell\ell jj/\ell\nu jj/\nu\nu jj)jj$	Reco-level Differential	Full	140	
$WZjj \rightarrow l^+l^-l^\pm\nu jj$	Reco-level Differential	Partial	140	
$W^\pm W^\pm jj \rightarrow l^\pm\nu l^\pm\nu jj$	Reco-level Differential	Full	139	
$ZZjj \rightarrow l^+l^-l^+l^-jj$	Unfolded Differential	None	140	
$W\gamma jj \rightarrow l^\pm\nu\gamma jj$	Unfolded Differential	Full	140	
$Z\gamma jj \rightarrow \nu\bar{\nu}\gamma jj$	Reco-level Inclusive	Partial	139	
$Z\gamma jj \rightarrow l^+l^-\gamma jj$	Unfolded Differential	None	140	
$W\gamma\gamma \rightarrow l^\pm\nu\gamma\gamma$	Reco-level Differential	None	140	

Combined EFT interpretation sensitive to aQGC

- ▶ Combination of results respecting unitarity and positivity bounds.
 - ▶ UV theories assumed to obey unitarity, locality and causality.
- ▶ Clipping scan to report unitarized limits.
 - ▶ Remove EFT effects for energy scales above a certain threshold.



Phys. Lett. B 879 (2026) 140683

Coefficient	Profiled expected confidence intervals [TeV^{-4}]	Profiled observed confidence intervals [TeV^{-4}]
f_{S02}/Λ^4	[-4.06, 4.08]	[-4.87, 4.88]
f_{S1}/Λ^4	[-8.72, 8.73]	[-9.82, 9.82]
f_{M0}/Λ^4	[-1.67, 1.68]	[-1.68, 1.65]
f_{M1}/Λ^4	[-8.13, 7.52]	[-9.05, 8.58]
f_{M2}/Λ^4	[-1.91, 1.91]	[-1.97, 1.99]
f_{M3}/Λ^4	[-4.16, 4.16]	[-3.89, 3.92]
f_{M4}/Λ^4	[-3.15, 3.15]	[-2.55, 2.56]
f_{M5}/Λ^4	[-3.48, 3.49]	[-2.77, 2.77]
f_{M7}/Λ^4	[-16.6, 15.7]	[-12.4, 12.9]
f_{T0}/Λ^4	[-0.33, 0.24]	[-0.34, 0.22]
f_{T1}/Λ^4	[-0.199, 0.211]	[-0.254, 0.283]
f_{T2}/Λ^4	[-0.578, 0.639]	[-0.665, 0.599]
f_{T5}/Λ^4	[-0.405, 0.384]	[-0.319, 0.289]
f_{T6}/Λ^4	[-0.658, 0.642]	[-0.490, 0.370]
f_{T7}/Λ^4	[-1.51, 1.58]	[-1.17, 1.13]
f_{T8}/Λ^4	[-0.196, 0.181]	[-0.163, 0.147]
f_{T9}/Λ^4	[-0.360, 0.384]	[-0.281, 0.280]

▶ 17-96% improvements over published ATLAS results.

Conclusions

- ▶ The study of VBF and VBS processes are essential for understanding of the EWK sector of the SM.
 - ▶ These processes provide direct access to the triple and quartic gauge couplings predicted by the SM.
 - ▶ Several BSM scenarios predict deviations from these couplings.
- ▶ Full Run 2 data have enabled the first observations of $\text{EWK } VVjj$ and $\gamma\gamma jj$ production, together with differential measurements that test SM predictions.
 - ▶ New channels to probe quartic gauge interactions and constraining aQGC at high energies.
- ▶ Evidence for at least one longitudinally polarised W boson in same-sign WW scattering marks an important step towards measuring the fully longitudinal component where Higgs mechanism plays a central role in preserving unitarity.
- ▶ Run 3 data together with improved theoretical modelling and better control of systematic uncertainties, will allow more precise measurements of rare EWK processes.
 - ▶ EFT fits provide a model-independent framework to constrain possible extension of the SM.
 - ▶ Stay tuned for new results!

Backup

EWK $\gamma\gamma jj$ production

- First observation: 6.2σ (7.2σ expected).
- Consistent with the SM

- Measured fiducial cross-section:

$$\sigma_{\text{obs}}^{\text{EW}} = 13.8_{-2.6}^{+3.0} \text{ fb}$$

- Uncertainties dominate by signal modelling and non-prompt background estimation.

Source	Relative uncertainty [%]
EW- $\gamma\gamma jj$ modelling	13
QCD- $\gamma\gamma jj$ modelling	4.0
Other backgrounds modelling	2.4
Non-prompt stat. uncertainty	8.7
Jet	5.0
Photon	2.5
Pile-up modelling	1.9
Luminosity	0.9
MC statistical uncertainty	3.8
Total systematic uncertainty	18
Statistical uncertainty	9.6

- Differential cross-section measurements as a function of 6 observables performed for first time.
 - $m_{\gamma\gamma}, m_{jj}, p_{\text{T}}^{\gamma_1}, p_{\text{T}}^{j_1}, p_{\text{T}}^{j_2}, |\Delta\phi_{jj}|$
 - Measurements of QCD+EWK differential xsecs also performed.

	EW-only fit			EW+QCD fit	
	QCD-CR1	QCD-CR2	QCD-CR3	EW-SR	EW-SR
EW $\gamma\gamma jj$	46 ± 12	330 ± 70	10 ± 5	1450 ± 280	6010 ± 250
QCD $\gamma\gamma jj$	1640 ± 100	3850 ± 220	1230 ± 70	4740 ± 340	
$\gamma j + j\gamma + jj$	610 ± 90	1870 ± 190	400 ± 60	2310 ± 220	2470 ± 230
electrons	18.3 ± 2.3	25 ± 7	13 ± 8	61 ± 15	61 ± 15
pile-up	30 ± 10	100 ± 30	36 ± 6	150 ± 26	150 ± 26
$H \rightarrow \gamma\gamma$	2.6 ± 0.04	16.90 ± 0.15	1.45 ± 0.03	55.0 ± 0.5	55 ± 0.5
Total	2350 ± 50	6190 ± 80	1690 ± 40	8760 ± 110	8750 ± 100
Data	2348	6192	1686	8754	8754

Coefficient	Expected Limits [TeV^{-4}]	Observed Limits [TeV^{-4}]
f_{T0}/Λ^4	$[-1.29, 1.22]$	$[-1.16, 1.09]$
f_{T1}/Λ^4	$[-1.61, 1.59]$	$[-1.45, 1.43]$
f_{T2}/Λ^4	$[-3.29, 3.15]$	$[-2.97, 2.82]$
f_{T3}/Λ^4	$[-3.42, 3.26]$	$[-3.08, 2.92]$
f_{T4}/Λ^4	$[-1.73, 1.61]$	$[-1.57, 1.44]$
f_{T5}/Λ^4	$[-0.443, 0.416]$	$[-0.400, 0.372]$
f_{T6}/Λ^4	$[-0.987, 0.972]$	$[-0.890, 0.872]$
f_{T7}/Λ^4	$[-1.48, 1.39]$	$[-1.34, 1.24]$
f_{T8}/Λ^4	$[-0.244, 0.244]$	$[-0.220, 0.219]$
f_{T9}/Λ^4	$[-0.524, 0.524]$	$[-0.471, 0.471]$

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- ▶ Consistent with the SM
 - ▶ Measured fiducial cross-section:
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- ▶ Uncertainties dominate by signal modelling and non-prompt background estimation.
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 - ▶ Measurements of QCD+EWK differential xsecs also performed.
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Pile-up modelling	1.9
Luminosity	0.9
MC statistical uncertainty	3.8
Total systematic uncertainty	18
Statistical uncertainty	9.6

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