Measurements of single and double vector boson production with jets in the final state in ATLAS

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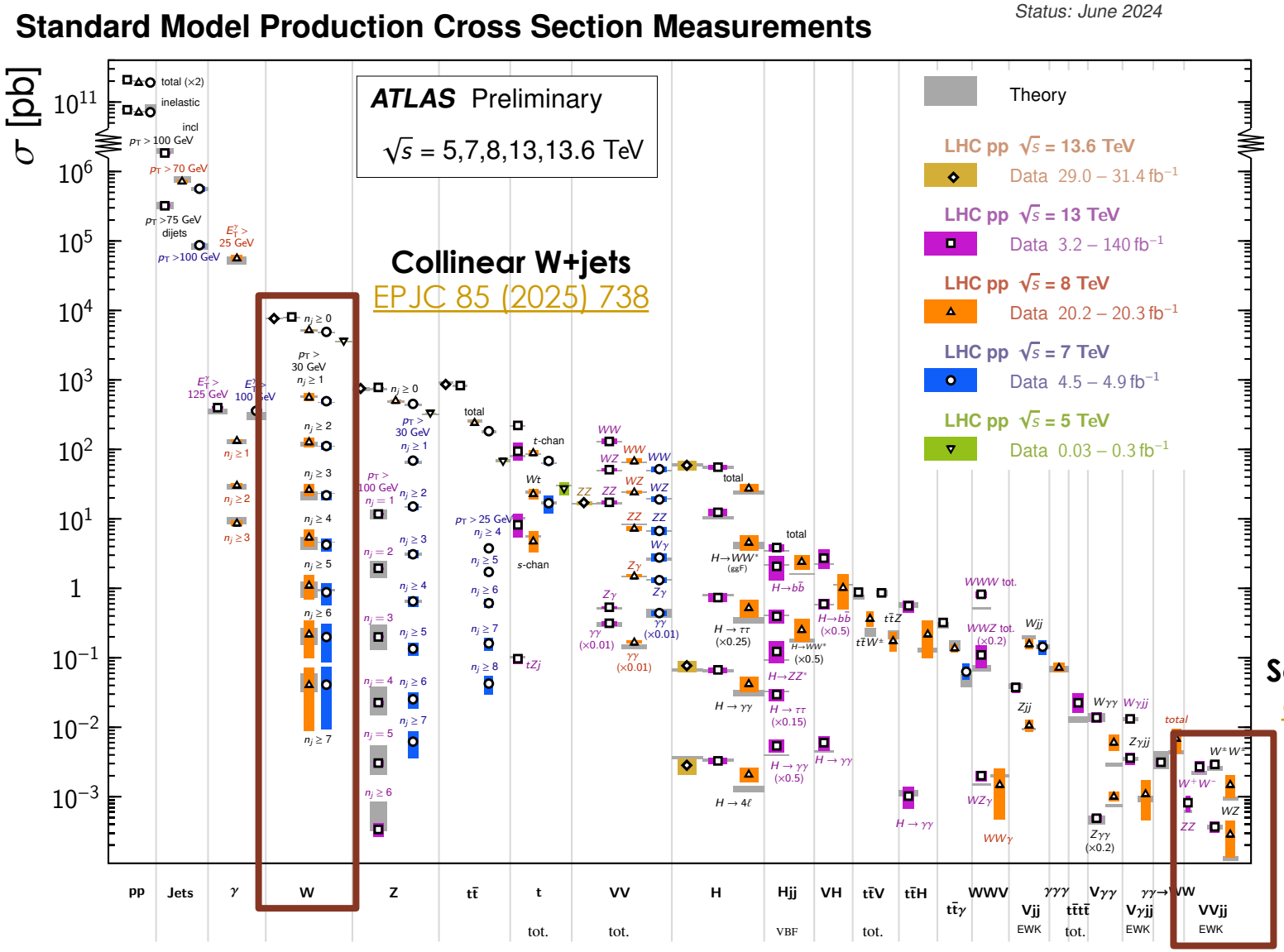
Motivation

- **QCD** governs strong interactions in proton-proton collisions at LHC
- **Jets** stem from the **emission of a quark or gluon + parton shower** (quark/gluon radiation) **+ hadronisation**
- Involves **perturbative** (calculable from first principles) and **non-perturbative** (from phenomenological models) regimes
- Jet studies i.e. cross-sections, substructures probe QCD across both regimes
- V(V)+jets measurements:
  - Sensitive to QCD and EW corrections
  - Provide critical input to tune MC generators
  - Represents an important background to SM precision measurements and BSM searches
  - Sensitive to anomalous gauge couplings
  - Serves as a testing ground for EWK-QCD interference

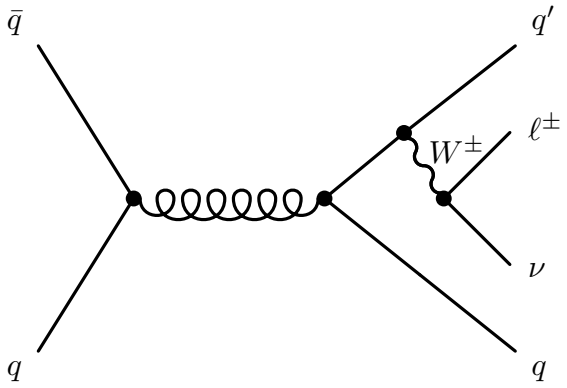
Outline

ATLAS SM results

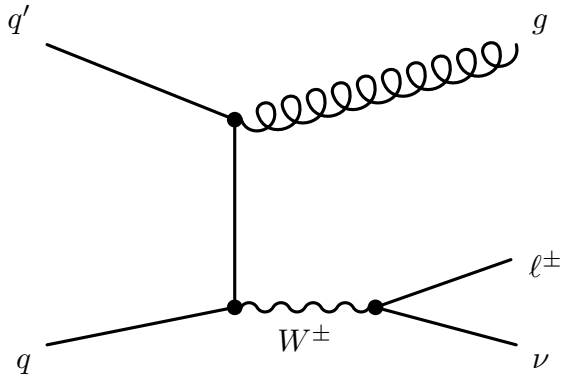


Collinear W+jets

- Measurement of collinear W boson emission from high energy jets at $\sqrt{s}$ = 13 TeV with the full Run 2 dataset (140 fb^{-1})
- **Goal:** test EW and pQCD in advantageous final state (clean signature, large cross-section)
- Inclusive and differentially in $\boldsymbol{\Delta R_{min}(l, jet_i^{100})}$ (sensitive to collinear enhancement in the production rate) and $\boldsymbol{p_T^{lv}}$
- Comparing unfolded results with:
  - **NLO-merged** predictions w/wo NLO EW corrections (Sherpa, MG5_aMC@NLO)
  - Fixed-order W + 1 jet **NNLO predictions** (MCFM)



Collinear topology

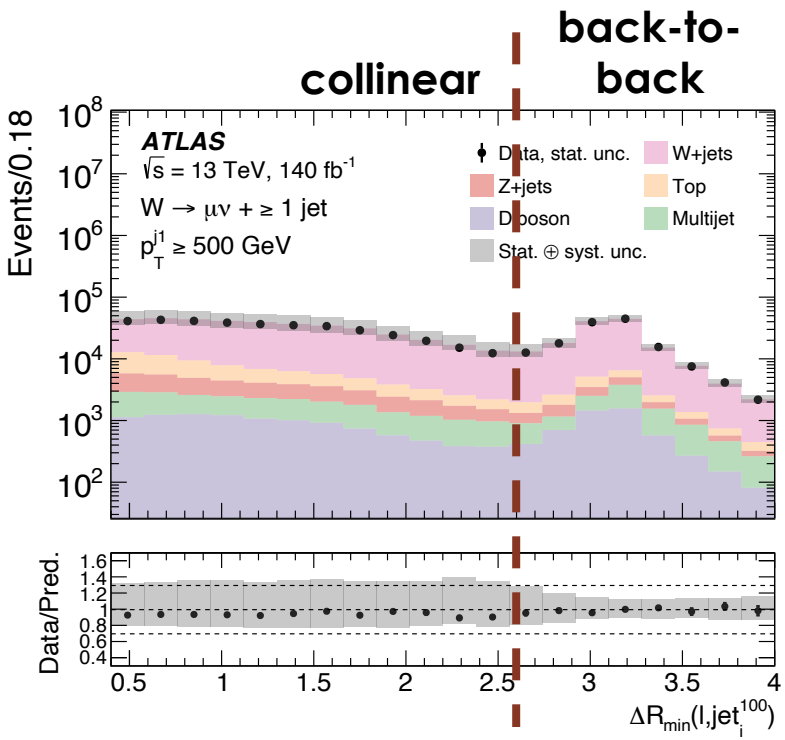


Back-to-back topology

Collinear W+jets

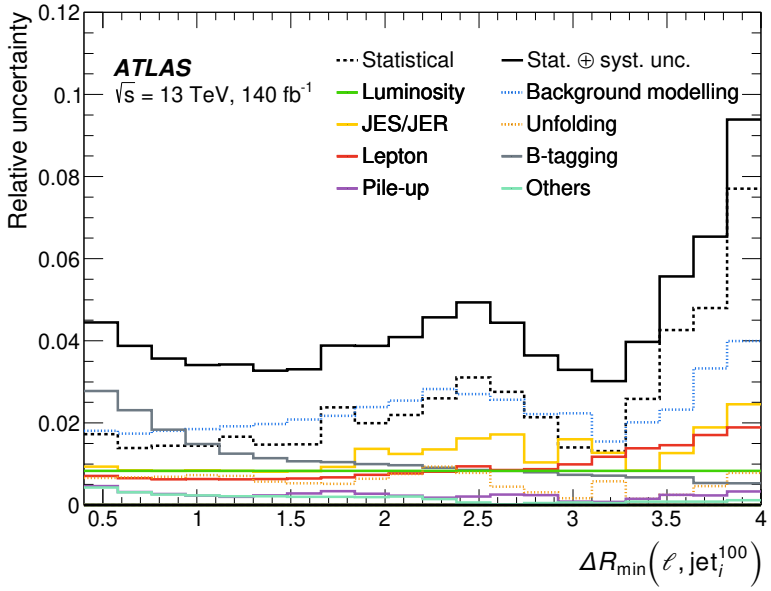
- Collinear/back-to-back region defined wrt $\Delta R_{min}(l, jet_i^{100})$

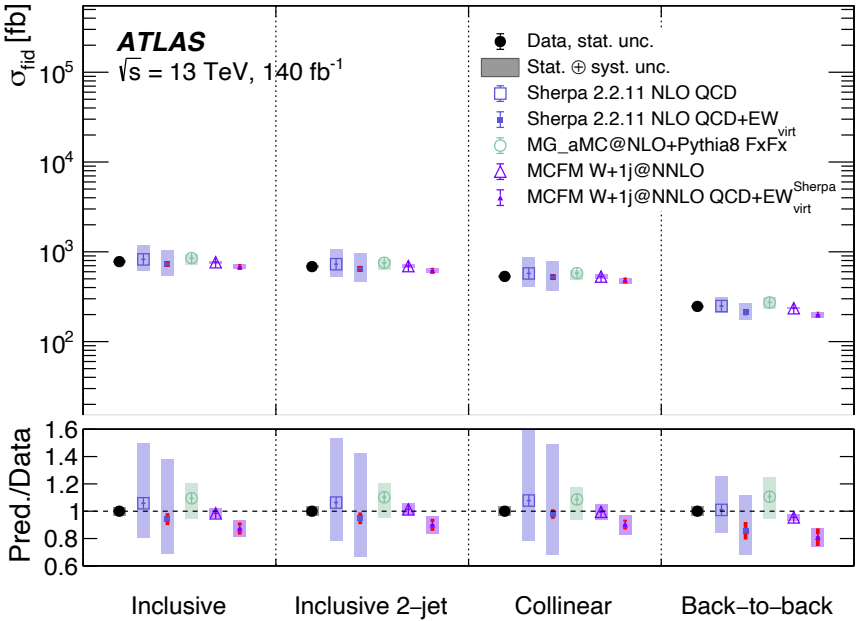
Object selection	
Lepton momentum	$p_{\mathrm{T}}^{\ell} > 10$ GeV
Electron pseudorapidity	$\lvert\eta\rvert < 1.37,\ 1.52 < \lvert\eta\rvert < 2.47$
Muon pseudorapidity	$\lvert\eta\rvert < 2.4$
Jet transverse momentum	$p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV
Jet rapidity	$\lvert y\rvert < 2.5$
Event selection	
Leading lepton	$p_{\mathrm{T}}^{\ell} > 30$ GeV, trigger matched
Number of leptons	$n_{\ell} = 1$
Angular separation of leptons and jets	$\Delta R(\ell, \mathrm{jet}) > 0.4$
Number of jets	$n_{\mathrm{jet}} \geq 1$
Leading jet transverse momentum	$p_{\mathrm{T}}^{\mathrm{jet}} > 500$ GeV
b-jet veto	$n_{b\text{-jet}} = 0$
Signal regions	
Inclusive	All requirements above
Inclusive 2-jet	Inclusive plus $n_{\mathrm{jet}} \geq 2$
Collinear	Inclusive plus $\Delta R_{\mathrm{min}}(\ell, \mathrm{jet}_i^{100}) < 2.6$
Back-to-back	Inclusive plus $\Delta R_{\mathrm{min}}(\ell, \mathrm{jet}_i^{100}) > 2.6$



Collinear W+jets

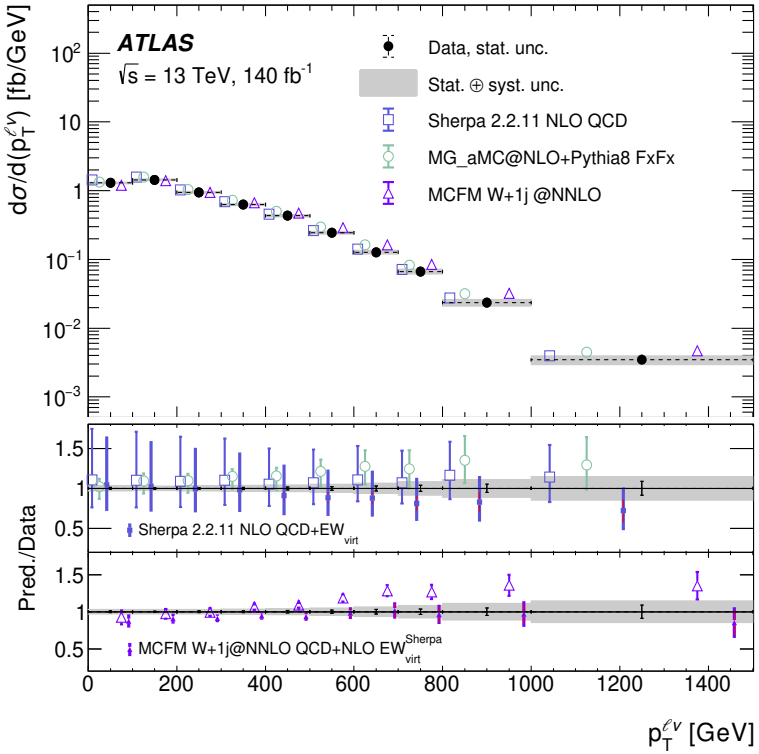
- **Total cross-section** for each region:
  - **Experimental uncertainties ~3-4%**, dominated by JES, JER, b-tagging, background modelling
  - **Sherpa, MG5_aMC@NLO** uncertainties larger, dominated by QCD scale uncertainties
  - **Good data/theory agreement** for all regions
  - **NLO EW corrections** improve agreement for **Sherpa** but leads to underestimation of data by **MCFM**

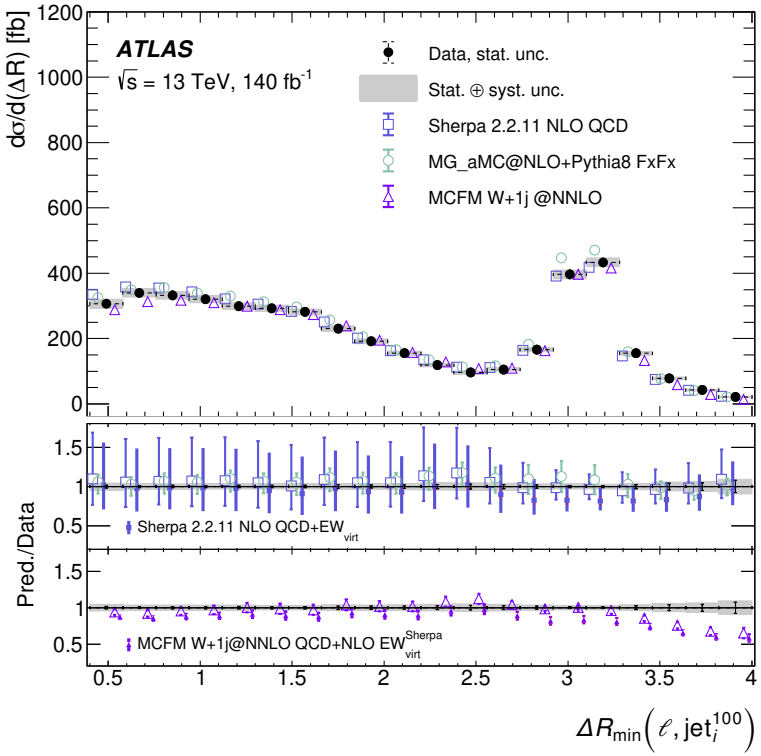




Collinear W+jets

- **Differential cross-sections**
- **~5-15%** experimental uncertainties
- Inclusion of **NLO EW** corrections in **Sherpa** improve **agreement** with data in the **collinear region**

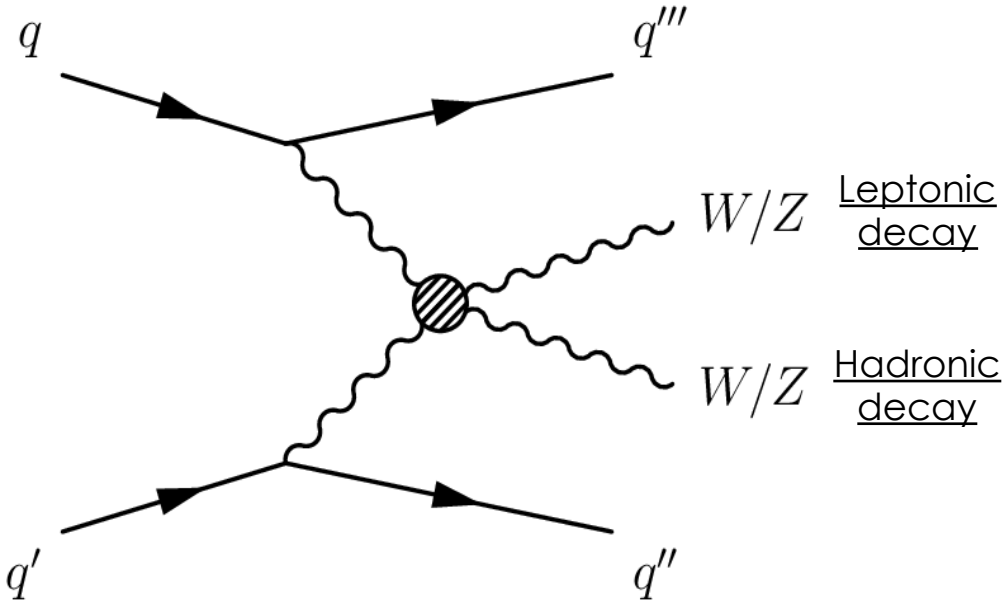




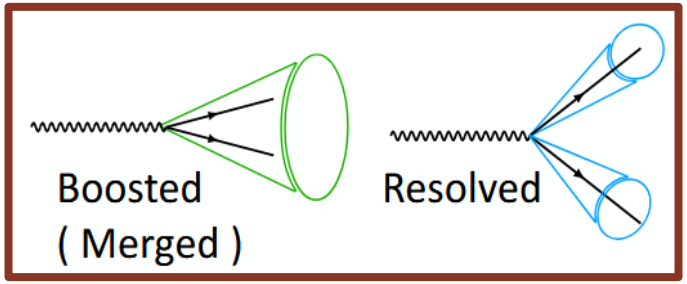
- **MCFM underestimates** data for $\Delta R_{min} > \pi$
- Inclusion of **NLO EW** corrections in **MCFM** significantly improve **agreement** with data for large values of p_T^{lv}

Semi-leptonic VVjj

- **Semileptonic mode** – one boson decays to leptons, the other one to hadrons
- Bigger number of events due to **higher branching ratio** → allows to reach higher momentum space as compared to leptonic mode
- Bigger sensitivity to **anomalous Quartic Gauge Coupling** search ☺
- Bigger background due to other SM processes ☹



0-lepton: $Z \to \nu\nu$
1-lepton: $W \to l\nu$
2-leptons: $Z \to ll$

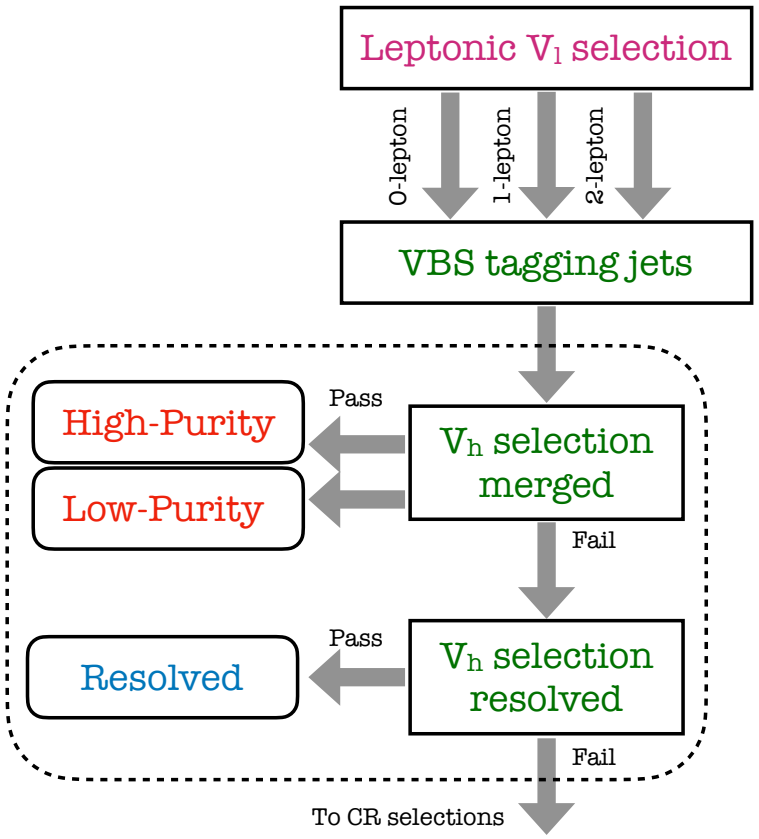


Semi-leptonic VVjj

Object selection			
Leptons	$p_{\mathrm{T}} > 27$ GeV, $\lvert\eta\rvert < 2.5$		
Small-R jets	$p_{\mathrm{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$ and $p_{\mathrm{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$		
Large-R jets	$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2.0$		
Event selection			
Selection	0-lepton	1-lepton	2-lepton
$V \to \nu\nu/\ell\nu/\ell\ell$	$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV	1 lepton $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV	2 leptons
VBS topology tagging jets	Largest m_{jj} pair with $\eta_{\mathrm{tag}\ j_1} \cdot \eta_{\mathrm{tag}\ j_2} < 0$, $p_{\mathrm{T}}^{tag\ j_{1,2}} > 30$ GeV, $m_{jj}^{tag} > 400$ GeV		
$V \to J$ **Boosted V decay**	Leading p_{T} large-R jet $64 < m_J < 106$ GeV		
$V \to jj$ **Resolved V decay**	Two leading p_{T} small-R jets $p_{\mathrm{T}}^{j_1} > 40$ GeV, $p_{\mathrm{T}}^{j_2} > 20$ GeV $64 < m_{jj} < 106$ GeV $m_{jjj} > 220$ GeV		
Additional b-jet veto	No	Yes	No

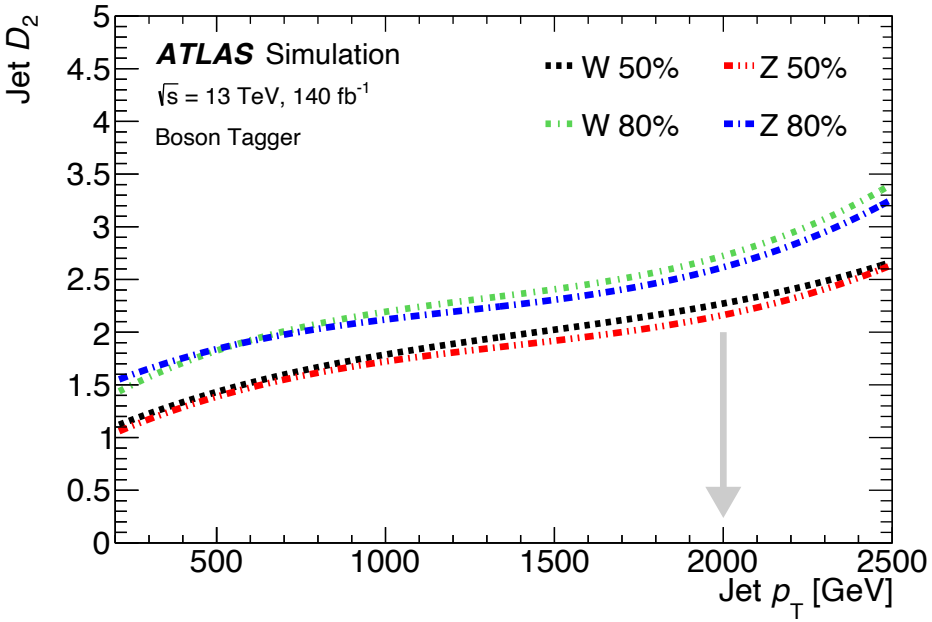
Semi-leptonic VVjj

- Event selection procedure does not provide unique event classification → **additional categorisation needed**!



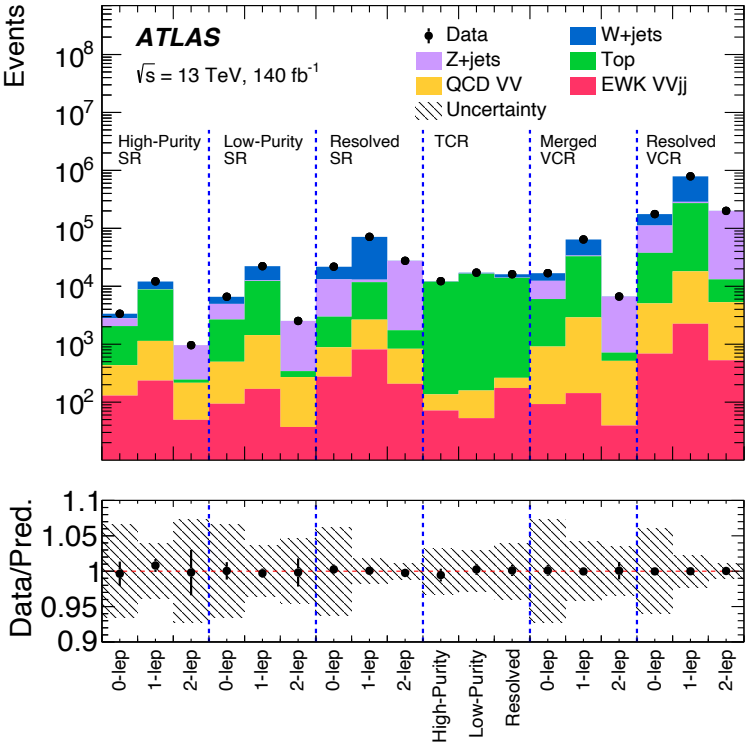
D_2 – reconstructed from energy correlation functions based on energies and pair-wise angles

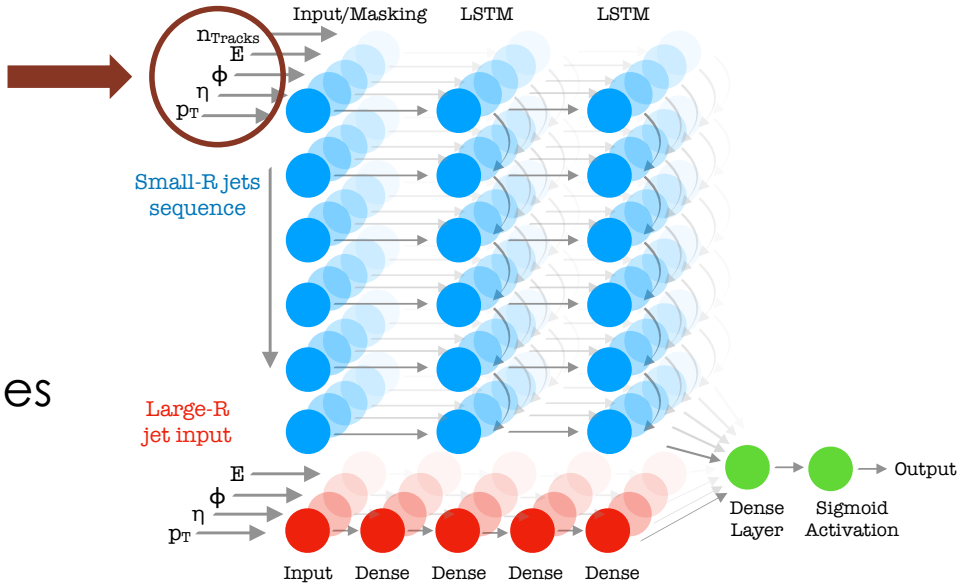
- **Large-R jet vector tagging**
- Simultaneous p_T-dependent cuts in 3 variables (m_{jet}, D_2, N_{tracks}) to define WPs
  - High-purity WP → 50% efficiency
  - Low-purity WP → 80% efficiency, but fail 50% WP cuts

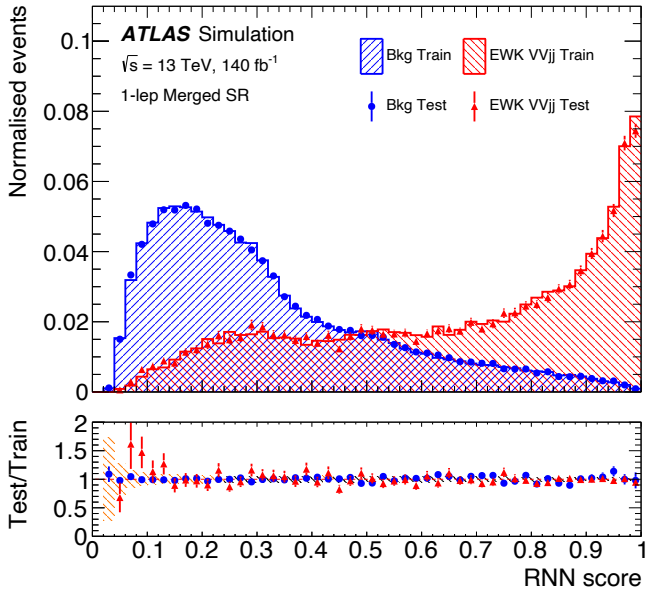


Semi-leptonic VVjj

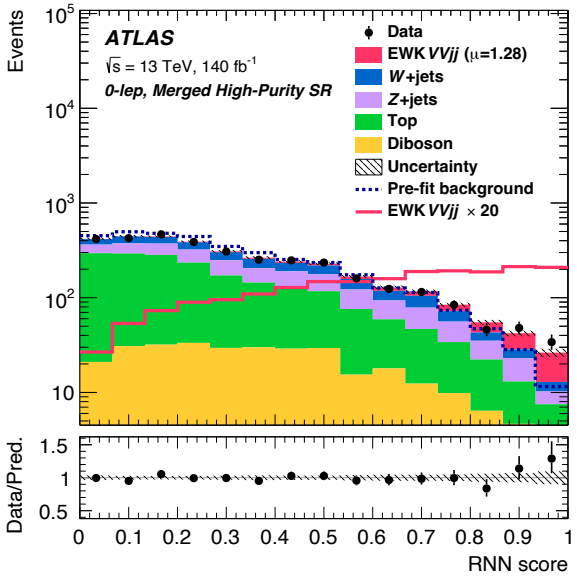
- **9 SRs + 9 CRs** for $t\bar{t}$ and V + jets backgrounds
- Linear m_{jj} shape reweighting from data for V + jets backgrounds
- **RNN** trained on low-level jet variables

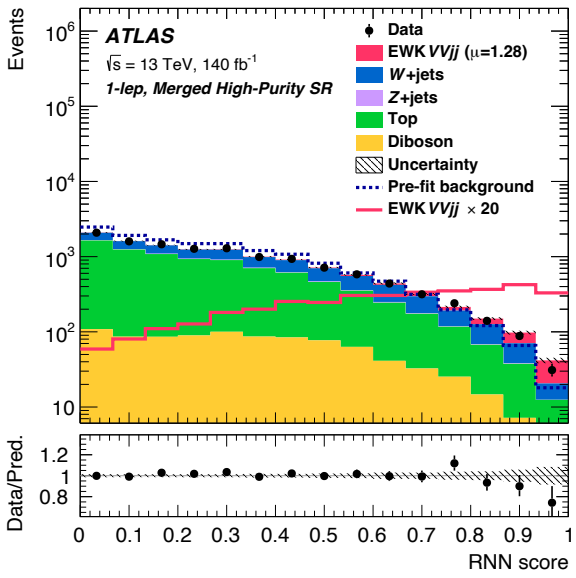


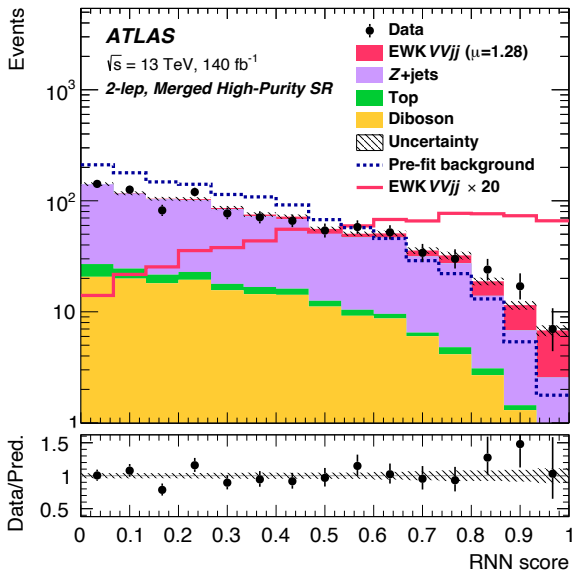




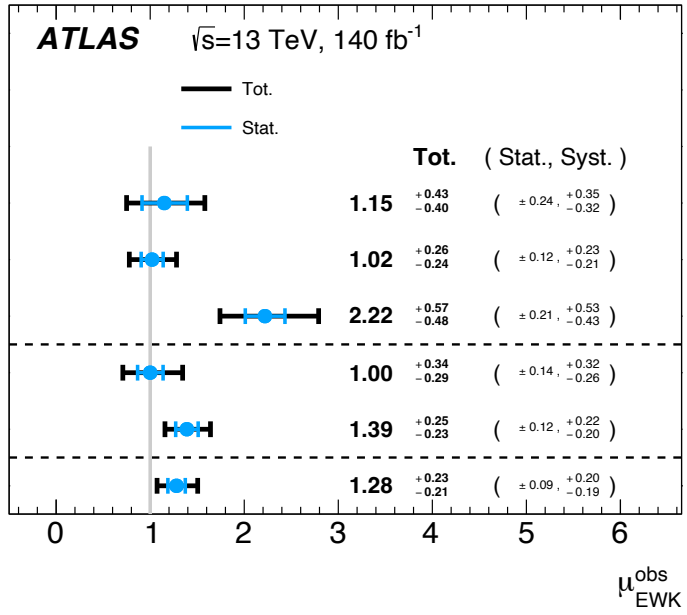
Semi-leptonic VVjj







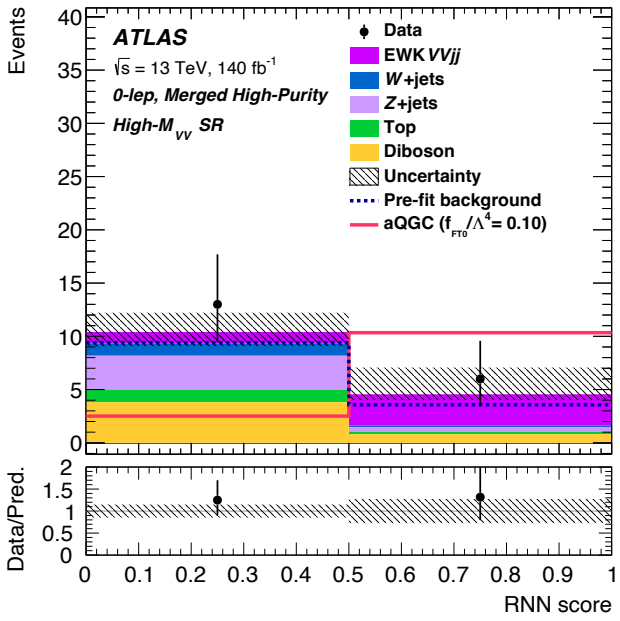
	Combined	0-lepton	1-lepton	2-lepton	Resolved	Merged
$\sigma_{EWK}^{\text{fid,exp}}$	20.4 ± 3.5 fb	7.3 ± 2.5 fb	10.3 ± 2.5 fb	2.8 ± 1.1 fb	11.7 ± 3.4 fb	8.7 ± 2.5 fb
$\sigma_{EWK}^{\text{fid,obs}}$	29.2 ± 4.9 fb	15.7 ± 2.8 fb	10.7 ± 2.8 fb	3.1 ± 1.1 fb	17.9 ± 4.3 fb	11.4 ± 3.4 fb



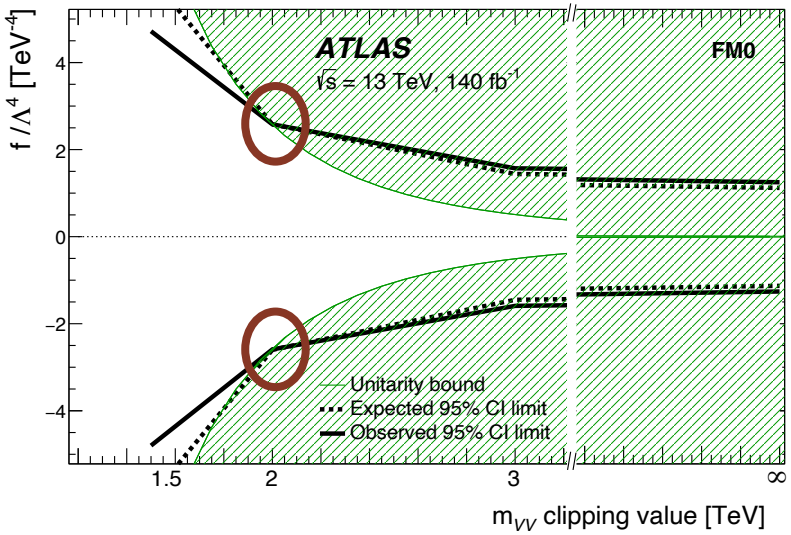
- **Simultaneous constraints** on both EWK and QCD VVjj
- EWK VVjj decaying semileptonically **observed with 7.4 (6.1)σ**

Semi-leptonic VVjj

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



- To increase aQGC sensitivity all SRs were split into low- and high-m_{VV} parts
- Expected and observed limits on the Wilson coefficients f_N/Λ^4 of dimension-8 operators
- Last 2 columns: limits at unitarity bounds
- Observed limits with unitarity bounds on aQGCs from PRD 101 (2020) 113003



Summary

- Recent results from ATLAS measure a variety of observables, enabling precise study of QCD in various regimes (and more)
- Measurement of collinear **W boson emission from high energy jets**, sensitive to EW and pQCD
- **Observation** of the **EW di-boson scattering in the semileptonic mode** with **7.4 (6.1)σ significance**
- **First ATLAS EFT limits from this final state**
- ATLAS is analysing Run 3 data - physics analyses ramping up!
- **Run 3** should be seen as a **marathon race**, not a sprint race
  - Run 2 + Run 3 data samples will be larger or comparable to Run 4!
  - It will be our **main dataset until ~2032**
- Interesting time ahead - stay tuned! ☺