VBS measurement in semileptonic final states with ATLAS Run-2 data

IRN Terascale @ IPHC Strasbourg - 21/5/25

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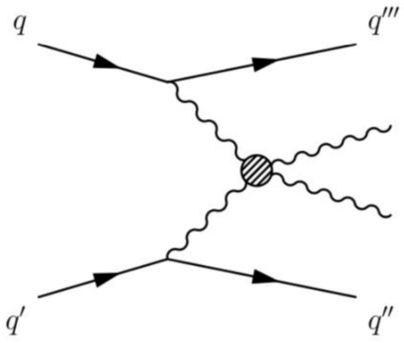
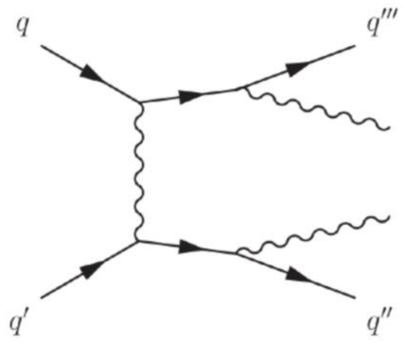
Vector Boson Scattering (VBS)

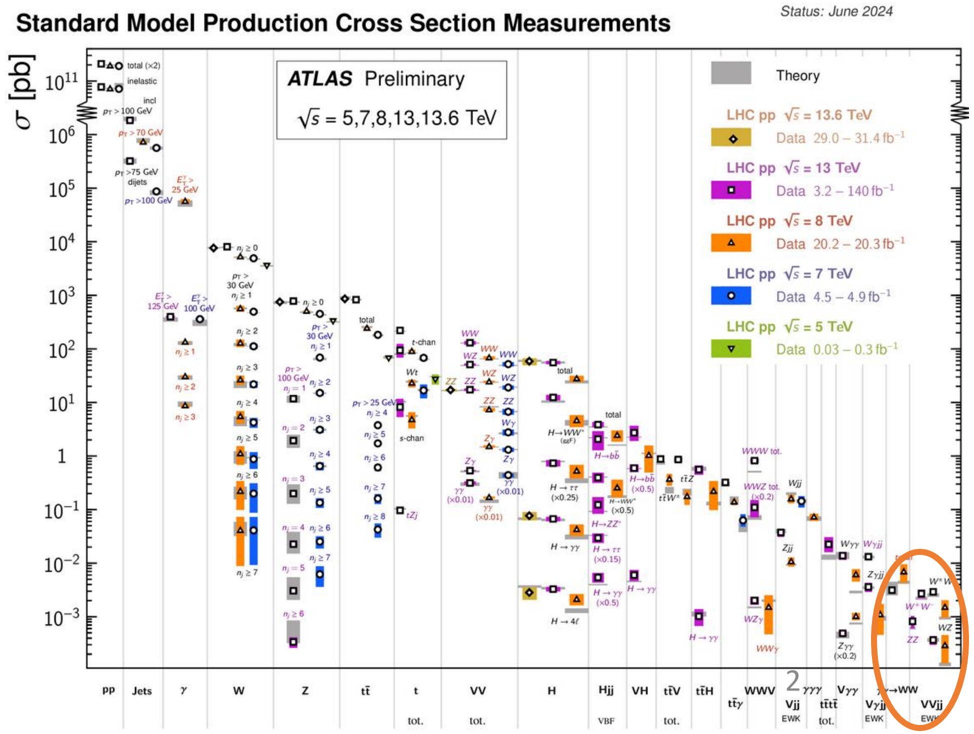
- Electroweak (EW) production of vector bosons associated with jets
- Cannot be separated from other EW diboson production
- Final states with two EW bosons and two forward jets with high invariant mass (*VVjj*)
- Very low cross sections (fb level)



VBS



Not VBS

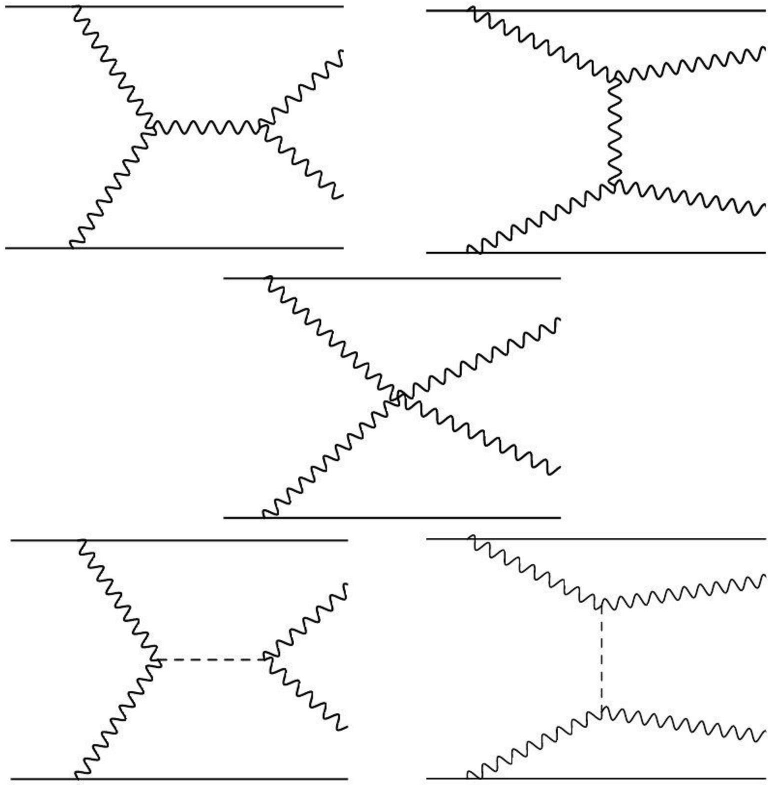


Why studying VBS ?

- Processes involving Triple Gauge Couplings (TGCs), having unique access to Quartic Gauge Couplings (QGCs)

- Couplings with the Higgs cancelling unitarity violation by longitudinally polarized EW bosons at high energy
  - Test of the EW symmetry breaking mechanism
  - Interest of polarization studies

- Effect of anomalous QGCs (aQGCs) can be studied through EFT framework



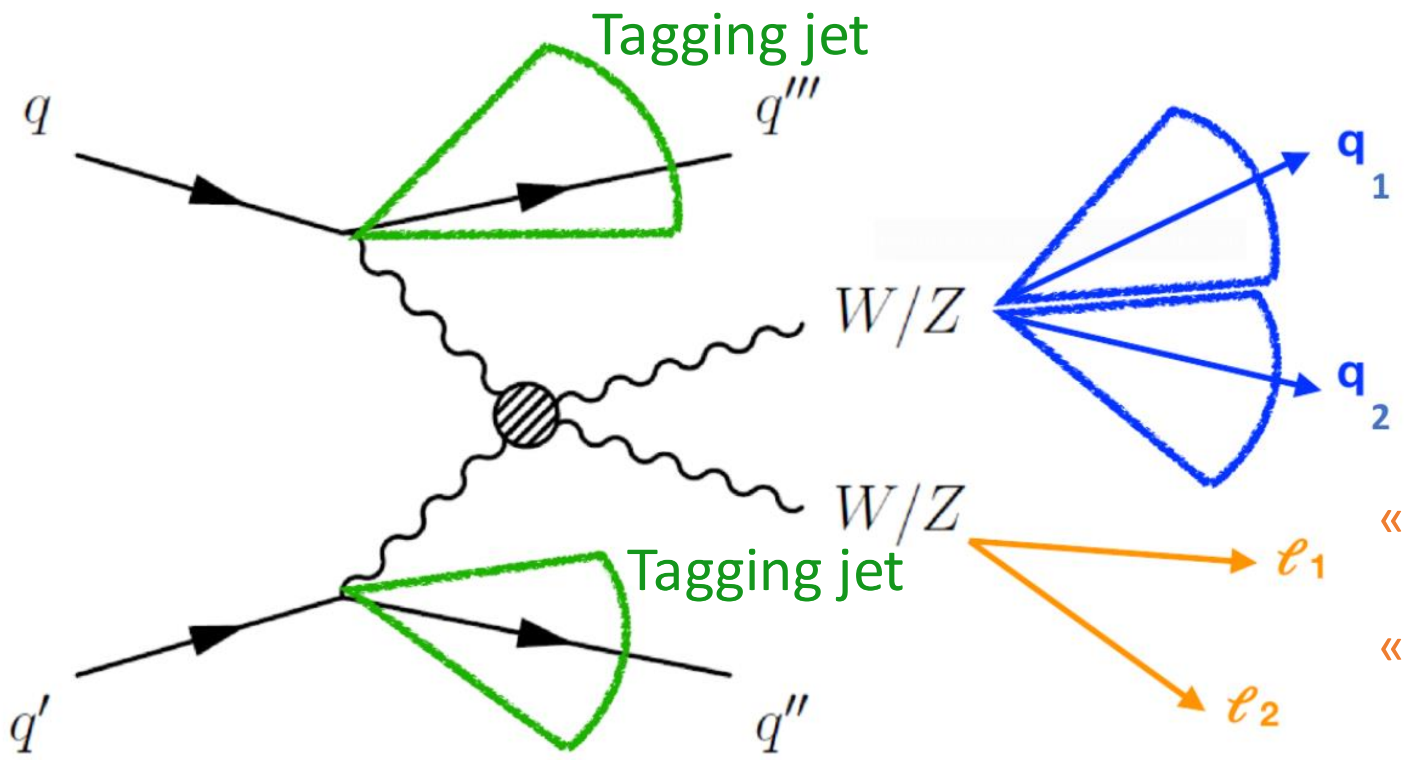
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Dimension-8 needed to introduce aQGCs without affecting TGCs

VBS in semileptonic final states

- Inclusive *VVjj* (*V*=*W*,*Z*) electroweak (EW) production
- Semileptonic final states: one gauge boson decays hadronically (quarks pair) and the other one decays leptonically (leptons pair)

Higher statistics than fully leptonic final states, but larger backgrounds...



Jets

Sub-channels defined by number of charged leptons

«0 lepton» $\mathrm{V}\to q\bar{q}',\ \mathrm{Z}\to \nu\bar{\nu}.$

«1 lepton» $\mathrm{V}\to q\bar{q}',\ \mathrm{W}\to l\nu.$

«2 leptons» $\mathrm{V}\to q\bar{q}',\ \mathrm{Z}\to l^+l^-.$

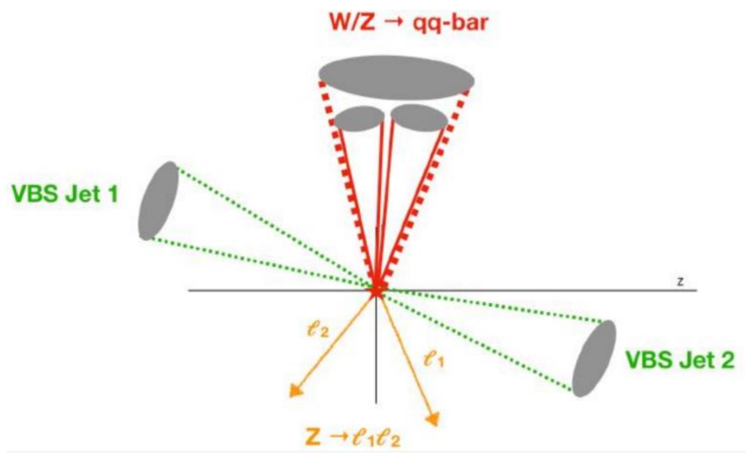
Selections (1)

- VBS jets (*tagging* jets)
  - Small-R
  - Opposite η sign
  - Pair with highest m_{jj}, $m_{jj} > 400$ GeV
  - $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV
- Leptonically decaying boson
  - 0-lep: 0 LooseLepton, $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
  - 1-lep: 0 LooseLepton, 1 TightLepton, $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV, $p_{\mathrm{T}} > 30$ GeV
  - 2-lep: 2 LooseLeptons, $p_{\mathrm{T}} > 27$ GeV, mass windows for m_{ee} and $m_{\mu\mu}$

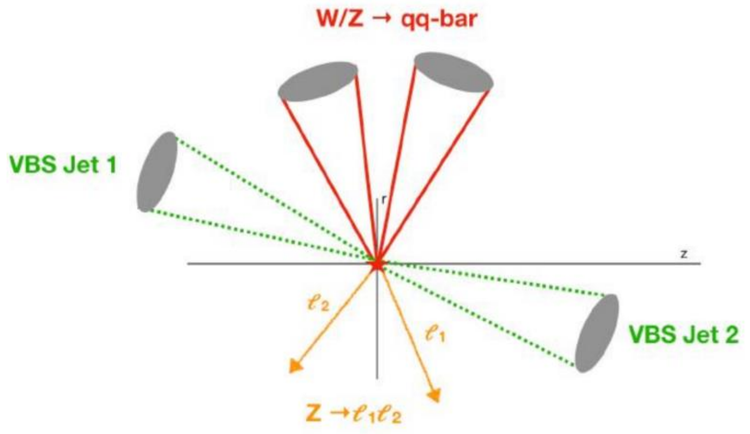
Selections (2)

- Hadonically decaying boson

  - **Merged regime** (prioritized): large-*R* jet with highest p_T, *W/Z* boson tagger, *b*-veto on additional jet in 1-lepton channel



  - **Resolved regime**: small-*R* jets with highest p_T not overlapping with tagging jets, $p_T^1 > 40$ GeV, $p_T^2 > 20$ GeV, $m_{jjj} > 220$ GeV (top veto), *b*-veto on additional jet in 1-lepton channel



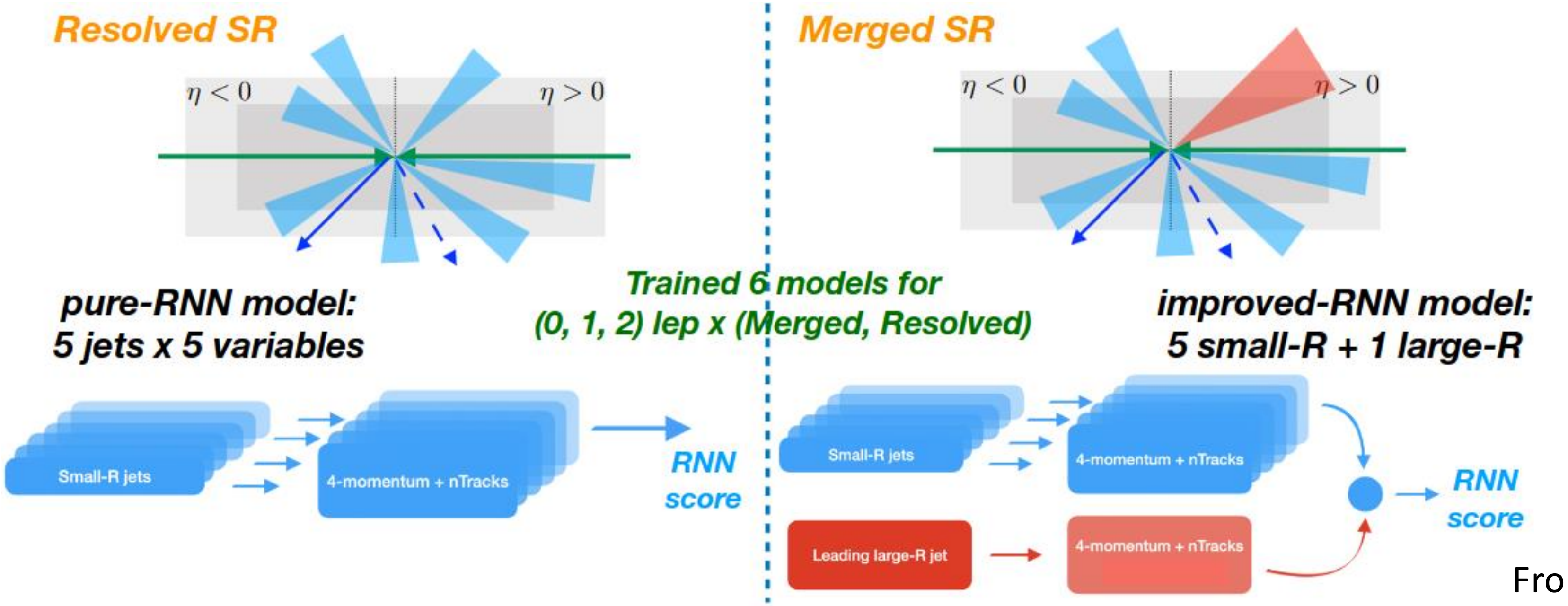
Analysis regions

- Signal regions (based on hadronically decaying boson)
  - Resolved
  - Merged with High Purity (HP): passes 50% working point of *W*/*Z* tagger
  - Merged with Low Purity (LP): fails 50%, passes 80%
- Control regions (inverting boson selection cut)
  - *V*+jets (*V*=*W* in 1-lepton, *V*=*Z* in 2-leptons)
  - Top (*b*-jet instead of *b*-veto, only in 1-lepton channel)

	0-lepton			1-lepton			2-lepton		
	Merged HP	Merged LP	Resolved	Merged HP	Merged LP	Resolved	Merged HP	Merged LP	Resolved
Signal Region	RNN	RNN	RNN	RNN	RNN	RNN	RNN	RNN	RNN
V+jets CR Inverted V_{had} Selection	M_{jj}^{tag}		M_{jj}^{tag}	M_{jj}^{tag}		M_{jj}^{tag}	M_{jj}^{tag}		M_{jj}^{tag}
Top CR b-tagged events				M_{jj}^{tag}	M_{jj}^{tag}	M_{jj}^{tag}			

RNN

- Need to discriminate between signal and backgrounds (V+jets, VV, top)
- Recurrent neural network using low-level variables (p_T, η, ϕ, E, n_{Tracks})

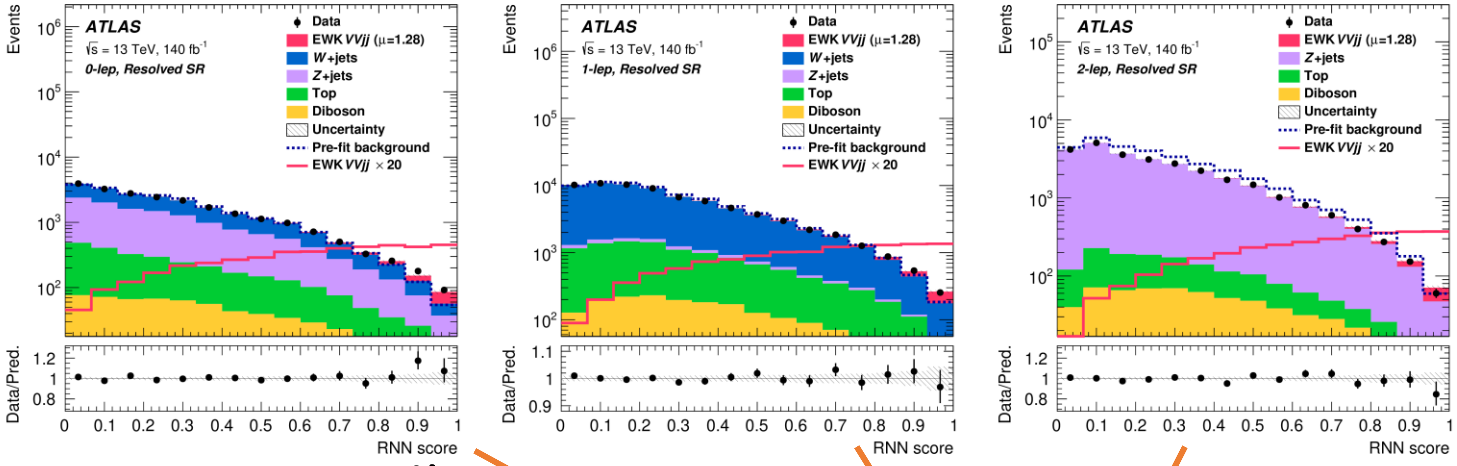


From M. Fujimoto

- Only hadronic objects to harmonize between leptons channels
- Not used for cuts but discriminant in SRs

Observation

- Signal strength μ extracted from binned likelihood fit

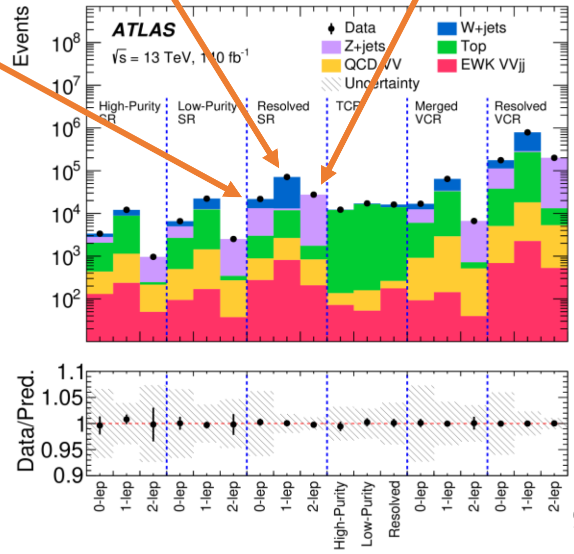


- Measured signal strength:

  $\mu_{\mathrm{EW}\ VVjj} = 1.28 \pm 0.22$

- 7.4σ observed significance (6.1σ expected)

- First observation of EW diboson production in semileptonic final states !



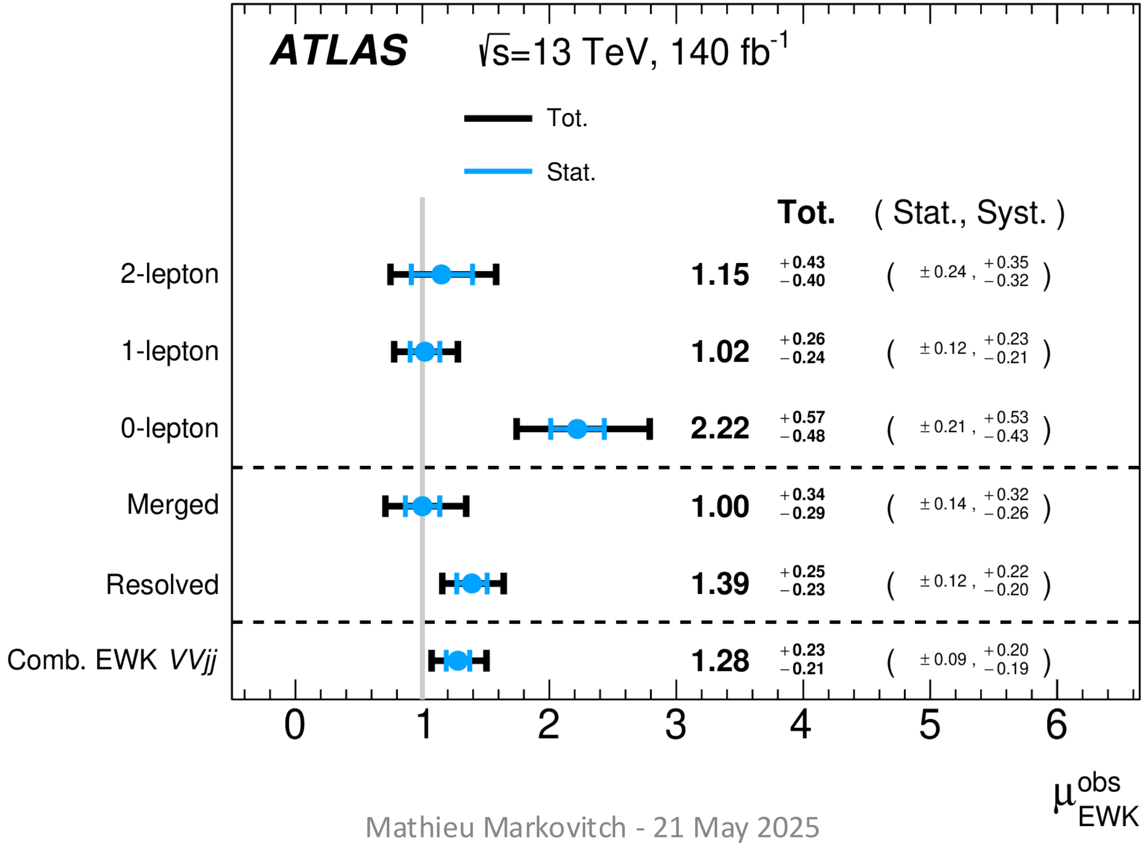
Uncertainties

Uncertainty source	σ_μ
Total	0.22
Statistical	0.09
Systematic	0.20
Theory and modelling uncertainties	
Floating normalizations	0.04
Z + jets	0.06
W + jets	0.07
$t\bar{t}$	0.02
QCD $VVjj$	0.05
Single-top	0.01
m_{jj}^{tag} reweighting	0.07
Signal modelling	0.13
MC statistics	0.07
Experimental uncertainties	
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	0.09
Tracking	0.03
Leptons	< 0.01
b-tagging	< 0.01
Luminosity	0.01

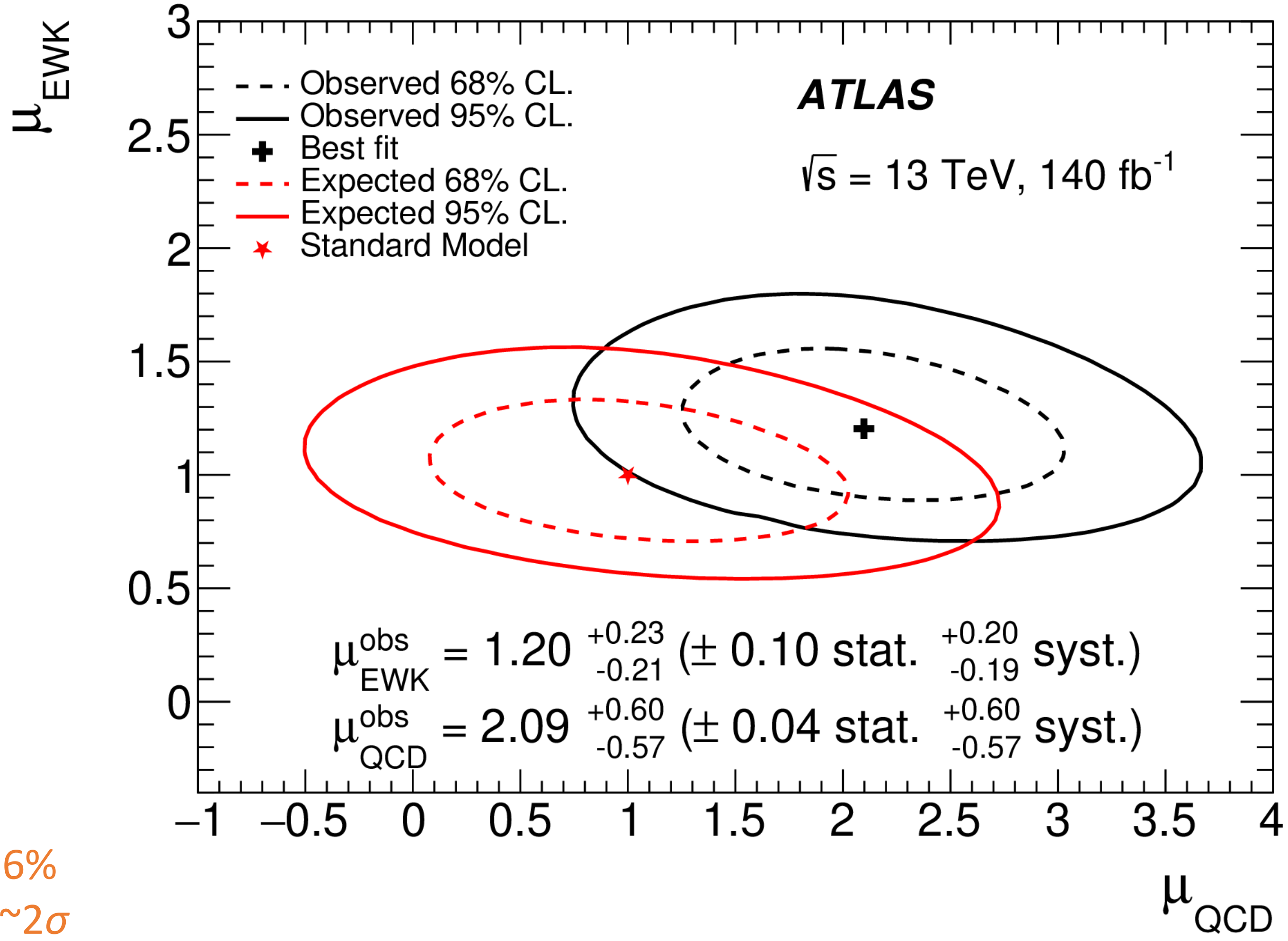
- Uncertainty dominated by systematics
- In particular theory systematics on the signal

Multi-POI fits

- Fits with multiple signal strengths
  - Good agreement with SM overall
  - Slight tension in the 0-lepton channel



2POI EW/QCD fit



EW/QCD correlation -26%
Compatibility with SM ~2σ

Fiducial cross-section measurement

- Fiducial cross-section extracted from truth yields, scaled by fitted signal strengths
  - Reparameterization of the fit because of the mixing between truth and reconstructed channels
  - Signal systematics set on shape effect only, residual normalization added to account for differences between reconstructed and truth effects

- Results compatible with Standard Model expectation

	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

EFT and aQGCs

- EFT Lagrangian

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \cancel{\frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7} + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Wilson coefficients

$$\mathcal{L}_n = \sum_i C_i^n Q_i^n$$

Dimension-n operators

- Amplitude

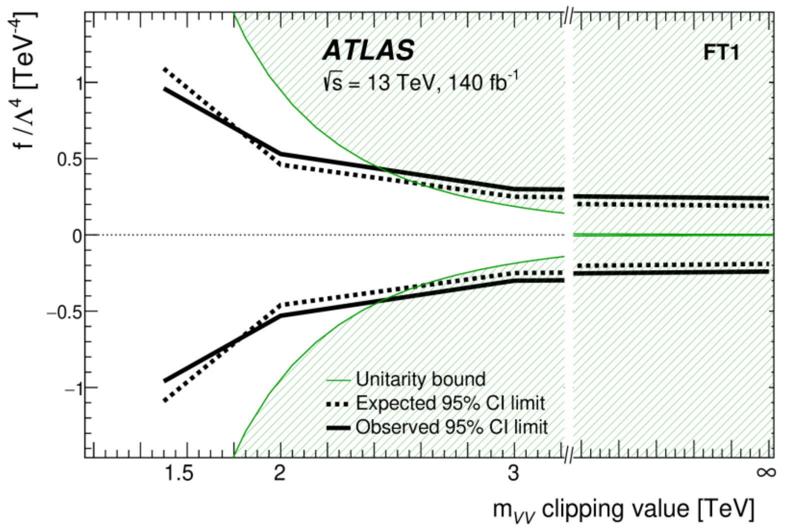
$$|A_{SM} + \frac{f_i}{\Lambda^4}A_i|^2 = \overbrace{|A_{SM}^2|}^{\text{Pure SM}} + \underbrace{\sum_i \frac{f_i^2}{\Lambda^8}|A_i^2|}_{\text{Pure EFT (quadratic)}} + \overbrace{\sum_i 2\frac{f_i}{\Lambda^4}\mathrm{Re}(A_{SM}^\star A_i)}^{\text{EFT-SM interference (linear)}} + \underbrace{\sum_{i\neq j} \frac{f_i}{\Lambda^4}\frac{f_j}{\Lambda^4}\mathrm{Re}(A_i^\star A_j)}_{\text{Interference between EFT operators « cross-terms »}}$$

- Operators (scalar/tensor/mixed) from Eboli model affecting different vertices

	SM				Not SM				
Wilson coefficients	WWWW	WWZZ	WW$\gamma\gamma$	WWγZ	ZZZZ	ZZZγ	ZZ$\gamma\gamma$	Z$\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
f_{S0}, f_{S1}, f_{S2}	✓	✓			✓				
f_{M0}, f_{M1}, f_{M7}	✓	✓	✓	✓	✓	✓	✓		
$f_{M2}, f_{M3}, f_{M4}, f_{M5}$		✓	✓	✓	✓	✓	✓		
$f_{T0}, f_{T1}, f_{T2}, f_{T3}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$f_{T4}, f_{T5}, f_{T6}, f_{T7}$		✓	✓	✓	✓	✓	✓	✓	✓
f_{T8}, f_{T9}					✓	✓	✓	✓	✓

aQGC analysis

- Dedicated aQGC signal MC samples
- All operators of the Eboli model
- SRs separated in two m_{VV} bins, RNN fitted
- Clipping method
  - aQGCs violate unitarity at high energy
  - Can be prevented by reducing theory phase space:
    introduce a cut-off scale (*clipping*) beyond which the Wilson coefficient is set to zero
  - Chosen points are 1.5, 2, 3, 5 TeV + no clipping
  - Unitarized limits: intersection between clipping scan and unitarity bounds
- Floating SM EW signal and SM background as background
- 95% CI limits extraction



Limits obtained

No unitarization | Unitarization

Wilson Coefficient	Expected limit	Observed Limit	Expected Limit Unitarized	Observed Limit Unitarized
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

[TeV^{-4}]

Amongst the best aQGC limits

No deviation from SM

Conclusion

- First observation of EW diboson production in semileptonic final states
- Measured signal strength $\mu_{\mathrm{EW}\ VVjj} = 1.28 \pm 0.22$
- Measured fiducial cross section 29.2 ± 4.2 fb
- Competitive constraints on aQGCs
- Paper available at arXiv:2503.17461 (submitted to EPJC)

Thank you !

Back-up

0-lepton event selection

Resolved

Selection		SR	V CR
$Z \to \nu\nu$	Number of Loose leptons	0	
	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV	
	p_{T}^{miss}	> 50 GeV	
anti-QCD	min($\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}$,small-R jets))	$> \pi/6$	
	$\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{miss})$	$< \pi/2$	
	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, Sig - J)$	$> \pi/9$	
VBS jets candidates	Leading Tag jet p_{T}	> 30 GeV	
	Subleading Tag jet p_{T}	> 30 GeV	
	m_{jj}	> 400GeV	
$W/Z \to jj$	Number of small-R jets	≥ 4	
	Leading signal jet p_{T}	> 40 GeV	
	Subleading signal jet p_{T}	> 20 GeV	
	$Z \to q\bar{q}$ and $W \to q\bar{q}$	$64 < m_{jj} < 106$GeV	$50 < m_{jj} < 64\,GeV$ or $m_{jj} > 106$
VBS enhancing	m_{jjj}	> 220 GeV	

Merged

Selection		SR		V CR
		HP	LP	
$Z \to \nu\nu$	Number of Loose leptons	0		
	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV		
	p_{T}^{miss}	> 50 GeV		
anti-QCD	min($\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}$,small-R jets))	$> \pi/6$		
	$\Delta\Phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{miss})$	$< \pi/2$		
	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, Sig - J)$	$> \pi/9$		
VBS jets candidates	Leading Tag jet p_{T}	> 30 GeV		
	Subleading Tag jet p_{T}	> 30 GeV		
	m_{jj}	> 400GeV		
$W/Z \to J$	Num of large-R jets	≥ 1		
	3-Var Tagger	pass50WP	pass80WP && !pass50WP	fail80WP

1-lepton event selection

Resolved

cuts		SR	W CR (WR)	$t\bar{t}$ CR (TR)
$W \to \ell\nu$	Number of Tight leptons	1		
	Number of Loose (!Tight) leptons	0		
	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 80 GeV		
	$p_{\mathrm{T}}(\ell)$	> 30 GeV		
VBS jets candidates	Leading Tag jet p_{T}	> 30 GeV		
	Subleading Tag jet p_{T}	> 30 GeV		
	m_{jj}	> 400GeV		
$W/Z \to jj$	Number of small-R jets	≥ 4		
	Leading jet p_{T}	> 40 GeV		
	Subleading jet p_{T}	> 20 GeV		
	$Z \to q\bar{q}$ and $W \to q\bar{q}$	$64 < m_{jj} < 106$GeV	$50 < m_{jj} < 64\,GeV$ or $m_{jj} > 106$	$64 < m_{jj} < 106$GeV
Top veto	Number of additional b-tagged jets	0		≥ 1
VBS enhancing	m_{jjj}	> 220 GeV		

Merged

Selection		SR		W CR (WR)	$t\bar{t}$ CR (TR)	
		HP	LP	incl	HP	LP
$W \to \ell\nu$	Num of Tight leptons	1				
	Num of Loose (!Tight) leptons	0				
	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 80 GeV				
	$p_{\mathrm{T}}(\ell)$	> 30 GeV				
VBS jets candidates	Leading Tag jet p_{T}	> 30 GeV				
	Subleading Tag jet p_{T}	> 30 GeV				
	m_{jj}	> 400GeV				
$W/Z \to J$	Num of large-R jets	≥ 1				
	3-Var Tagger	pass50WP	pass80WP && !pass50WP	fail80WP	pass50WP	pass80WP && !pass50WP
Top veto	Num of b-tagged jets outside of large-R jet	0			≥ 1	

2-leptons event selection

Resolved

Selection		SR	Z CR
$Z \to \ell\ell$	Number of Loose leptons	2	
	Same flavor	yes	
	Leading lepton p_T	> 27 GeV	
	Subleading lepton p_T	> 27 GeV	
	dilepton invariant mass	$83 < m_{ee} < 99$GeV $-0.01170 p_{T,\ell\ell} + 85.63 < m_{\mu\mu} < 0.01850 p_{T,\ell\ell} + 94.00$GeV	
	Opposite sign	For $\mu\mu$ channel only	
VBS jets candidates	Leading Tag jet p_T	> 30 GeV	
	Subleading Tag jet p_T	> 30 GeV	
	m_{jj}	> 400GeV	
$W/Z \to jj$	Number of small-R jets	≥ 4	
	Leading signal jet p_T	> 40 GeV	
	Subleading signal jet p_T	> 20 GeV	
	$Z \to q\bar{q}$ and $W \to q\bar{q}$	$64 < m_{jj} < 106$GeV	$50 < m_{jj} < 64\ GeV$ or $m_{jj} > 106$
VBS enhancing	m_{jjj}	> 220 GeV	

Merged

Selection		SR		Z CR
		HP	LP	incl
$Z \to \ell\ell$	Number of Loose leptons	2		
	Same flavor	yes		
	Leading lepton p_T	> 27 GeV		
	Subleading lepton p_T	> 27 GeV		
	dilepton invariant mass	$83 < m_{ee} < 99$GeV $-0.01170 p_{T,\ell\ell} + 85.63 < m_{\mu\mu} < 0.01850 p_{T,\ell\ell} + 94.00$GeV		
	Opposite sign	For $\mu\mu$ channel only		
VBS jets candidates	Leading Tag jet p_T	> 30 GeV		
	Subleading Tag jet p_T	> 30 GeV		
	m_{jj}	> 400GeV		
$W/Z \to J$	Num of large-R jets	≥ 1		
	3-Var Tagger	pass50WP	pass80WP && !pass50WP	fail80WP

Fiducial cross-section

$$\mu_{0\text{lep}} \rightarrow \frac{\mathrm{N}_{0,0} \times \mu_{0\text{lep truth}} + \mathrm{N}_{0,1} \times \mu_{1\text{lep truth}} + \mathrm{N}_{0,2} \times \mu_{2\text{lep truth}} + \mathrm{N}_{0,\text{none}} \times \mu_{0\text{leptruth}}}{\mathrm{N}_{0,0} + \mathrm{N}_{0,1} + \mathrm{N}_{0,2} + \mathrm{N}_{0,\text{none}}}$$

$$\mu_{0\text{lep}} \rightarrow 0.946 \cdot \mu_{0\text{leptruth}} + 0.052 \cdot \mu_{1\text{leptruth}} + 0.002 \cdot \mu_{2\text{leptruth}}$$

$$\mu_{1\text{lep}} \rightarrow \frac{\mathrm{N}_{1,0} \times \mu_{0\text{lep truth}} + \mathrm{N}_{1,1} \times \mu_{1\text{lep truth}} + \mathrm{N}_{1,2} \times \mu_{2\text{lep truth}} + \mathrm{N}_{1,\text{none}} \times \mu_{1\text{lep truth}}}{\mathrm{N}_{1,0} + \mathrm{N}_{1,1} + \mathrm{N}_{1,2} + \mathrm{N}_{1,\text{none}}}$$

$$\mu_{1\text{lep}} \rightarrow 0.979 \cdot \mu_{1\text{leptruth}} + 0.021 \cdot \mu_{2\text{leptruth}}$$

$$\mu_{2\text{lep}} \rightarrow \frac{\mathrm{N}_{2,0} \times \mu_{0\text{lep truth}} + \mathrm{N}_{2,1} \times \mu_{1\text{lep truth}} + \mathrm{N}_{2,2} \times \mu_{2\text{lep truth}} + \mathrm{N}_{2,\text{none}} \times \mu_{2\text{lep truth}}}{\mathrm{N}_{2,0} + \mathrm{N}_{2,1} + \mathrm{N}_{2,2} + \mathrm{N}_{2,\text{none}}}$$

$$\mu_{2\text{lep}} \rightarrow \mu_{2\text{leptruth}}$$

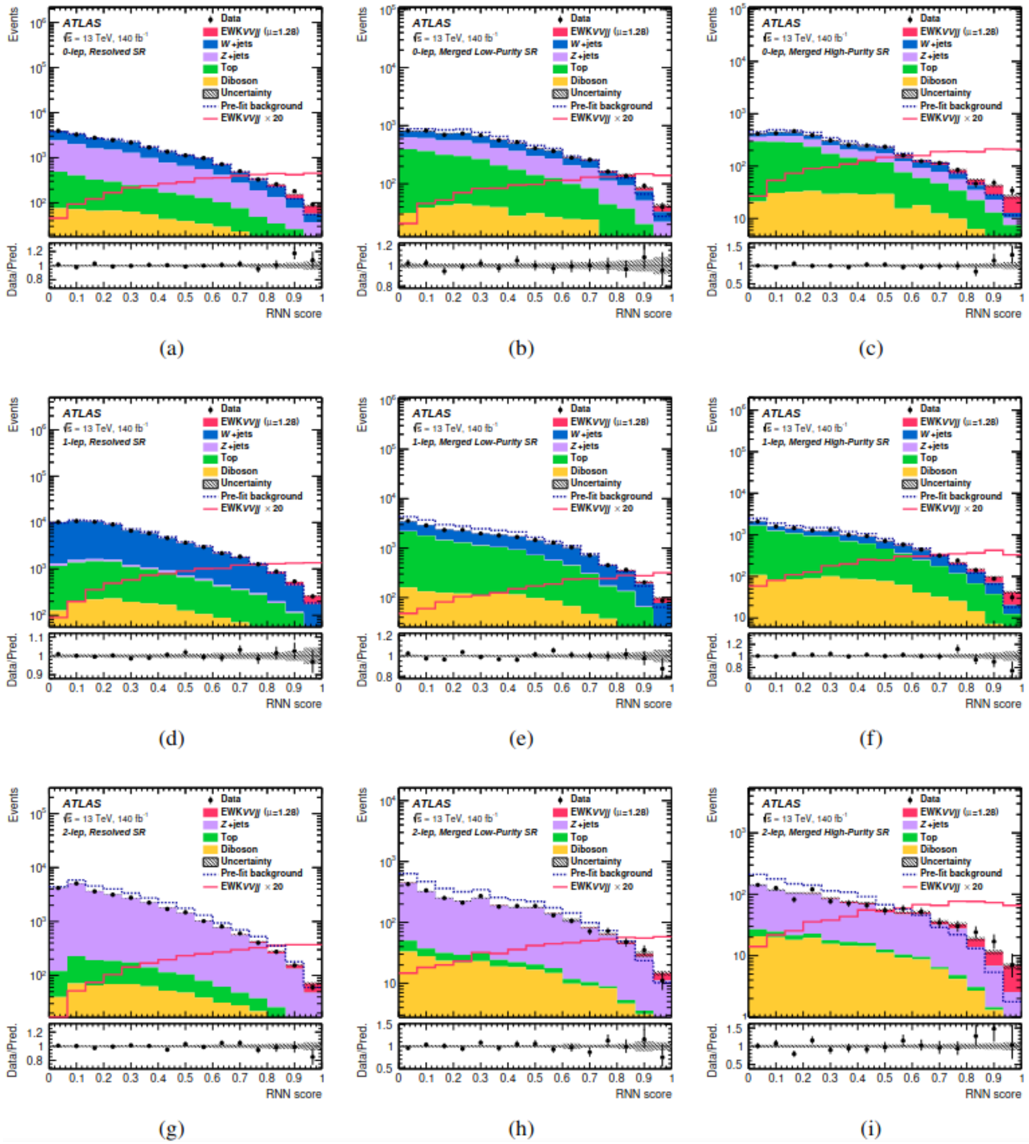
$$\mu_{\text{Res}} \rightarrow \frac{\mathrm{N}_{\text{Res,Res}} \times \mu_{\text{Res truth}} + \mathrm{N}_{\text{Res,Mer}} \times \mu_{\text{Mer truth}} + \mathrm{N}_{\text{Res,none}} \times \mu_{\text{Res truth}}}{\mathrm{N}_{\text{Res,Res}} + \mathrm{N}_{\text{Res,Mer}} + \mathrm{N}_{\text{Res,none}}}$$

$$\mu_{\text{Res}} \rightarrow 0.922 \cdot \mu_{\text{Restruth}} + 0.078 \cdot \mu_{\text{Mertruth}}$$

$$\mu_{\text{Mer}} \rightarrow \frac{\mathrm{N}_{\text{Mer,Mer}} \times \mu_{\text{Mer truth}} + \mathrm{N}_{\text{Mer,Res}} \times \mu_{\text{Res truth}} + \mathrm{N}_{\text{Mer,none}} \times \mu_{\text{Mer truth}}}{\mathrm{N}_{\text{Mer,Mer}} + \mathrm{N}_{\text{Mer,Res}} + \mathrm{N}_{\text{Mer,none}}}$$

$$\mu_{\text{Mer}} \rightarrow 0.039 \cdot \mu_{\text{Restruth}} + 0.961 \cdot \mu_{\text{Mertruth}}$$

All SRs



ATLAS
0-lep, Resolved SR
0-lep, Merged Low-Purity SR
0-lep, Merged High-Purity SR
1-lep, Resolved SR
1-lep, Merged Low-Purity SR
1-lep, Merged High-Purity SR
2-lep, Resolved SR
2-lep, Merged Low-Purity SR
2-lep, Merged High-Purity SR
Data
W+jets
Z+jets
Top
Diboson
Uncertainty
Pre-fit background
Events
Data/Pred.
RNN score
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)