Multi-boson Production in ATLAS

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on behalf of the ATLAS collaboration

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Multi-boson Production in ATLAS

- ★ Precision measurements
- ★ Probe beyond the Standard Model physics

I. Measurements of differential cross-sections in **four-lepton events** in 13 TeV proton-proton collisions with the ATLAS detector arxiv:2103.01918 [submitted to JHEP]

II. Measurements of **W^+W^- + ≥ 1 jet** production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector arxiv:2103.10319 [submitted to JHEP]

III. Observation of photon-induced **W^+W^-** production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector *Phys. Lett. B* 816 (2021) 136190

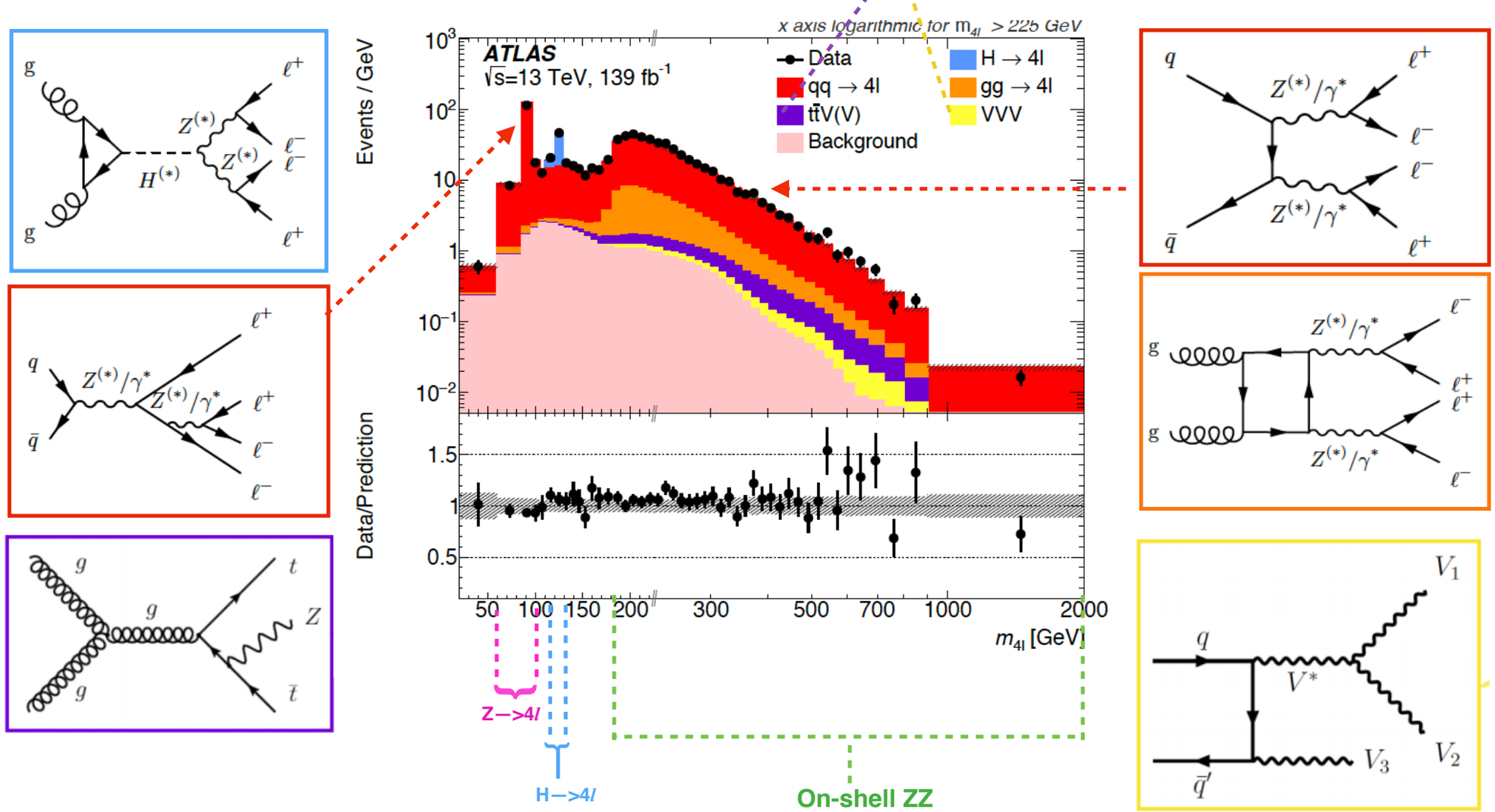
IV. Differential cross-section measurements for the **electroweak production of dijets in association with a Z boson** in a proton-proton collisions at ATLAS arXiv:2006.15458

Differential 4l: Introduction

Motivation:

- ★ Contribution from several interesting physics processes, fully reconstructed final state with clean detector signature & low background
  - ✦ **Excellent opportunity for precision SM measurements!**
- ★ Possible contribution from different BSM processes

Signal includes leptons from ttV + VVV processes for maximum reinterpretability



arxiv:2103.01918

Differential 4l: Results

Analysis Strategy:

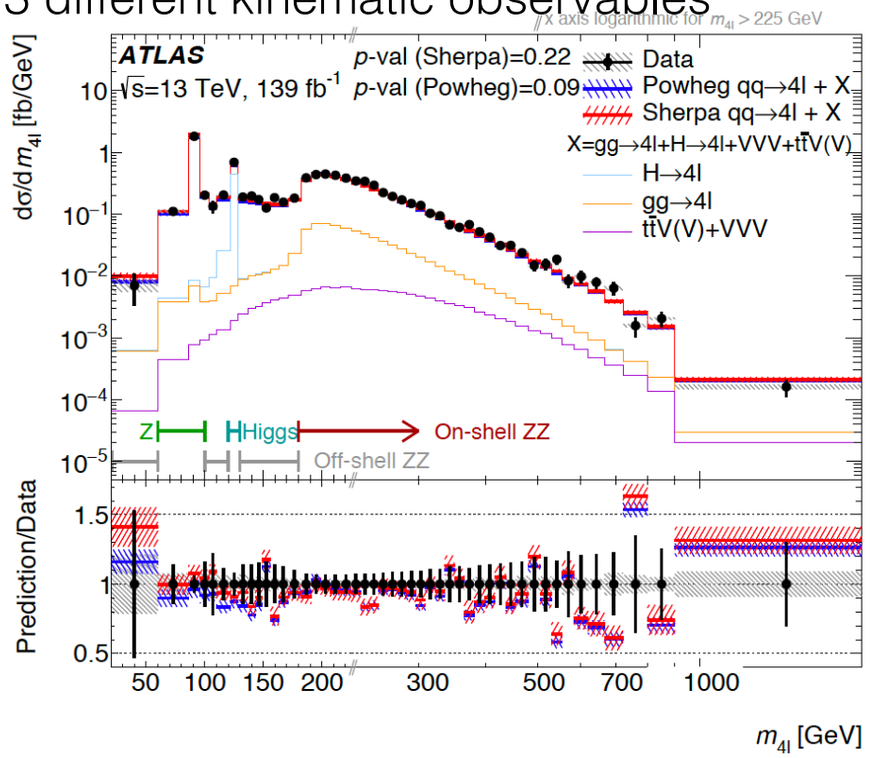
- ★ Background from non-prompt leptons estimated using data driven fake factor estimation
- ★ Iterative Bayesian unfolding (2-3 iterations) to correct for the remaining detector effects
  - ★ Novel technique of using per lepton pre-unfolding correction to minimize the SM lepton kinematics dependent inefficiencies

Integrated fiducial Cross-sections:

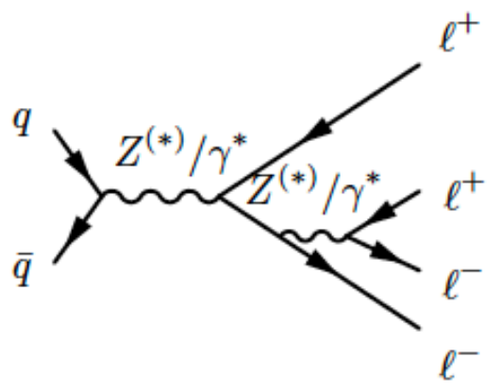
	Region				
	Full	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured fiducial cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
SHERPA	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
POWHEG + PYTHIA8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

Particle Level Differential Measurements:

- ✦ Single/double differential measurements of 13 different kinematic observables



All results in HepData



Predicted (Powheg):
$B_{Z\to 4l} = (4.50 \pm 0.01) * 10^{-6}$

Branching Fraction of Z—>4l

$$B_{Z\to 4l} = (\,4.41 \pm 0.13\,[stat] \pm 0.23\,[syst] \pm 0.09\,[theory] \pm 0.12\,[lumi]\,) * 10^{-6} = (4.41 \pm 0.30) * 10^{-6}$$

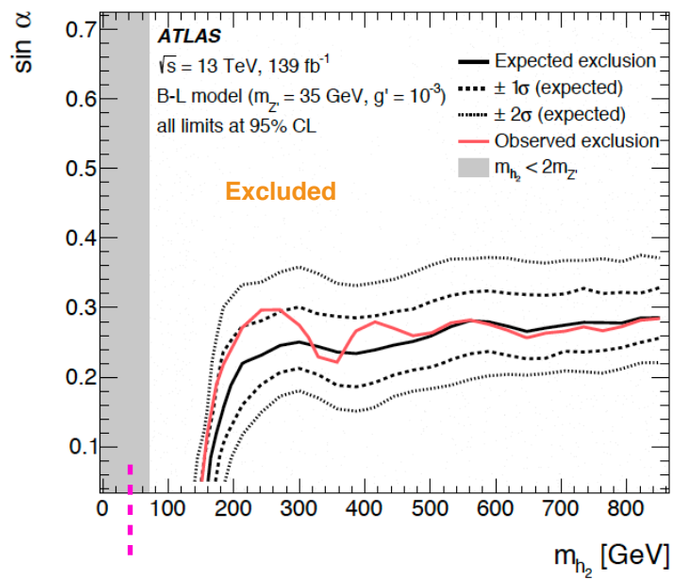
Most precise measurement to date! **In agreement with SM!**

arxiv:2103.01918

Differential 4l: BSM Interpretations

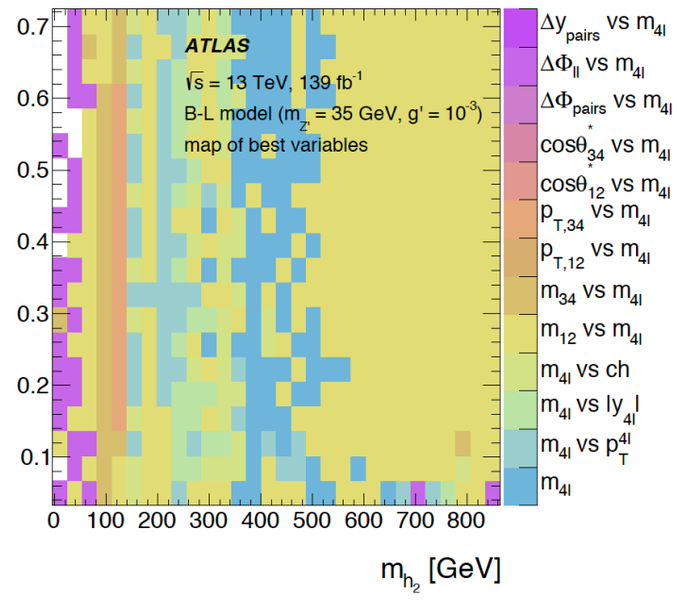
B-L [Baryon-minus-lepton-number] Gauge Model

- ★ BSM model where B-L local gauge symmetry is spontaneously broken
- ★ Model predicts Z' and exotic Higgs bosons h_2
  - ✳ Possible decay to ZZ or Z'Z'
  - ✳ Mixing with SM Higgs with mixing angle α



$m_{h2} < 2m_{Z'}$

No sensitivity in 4l final state

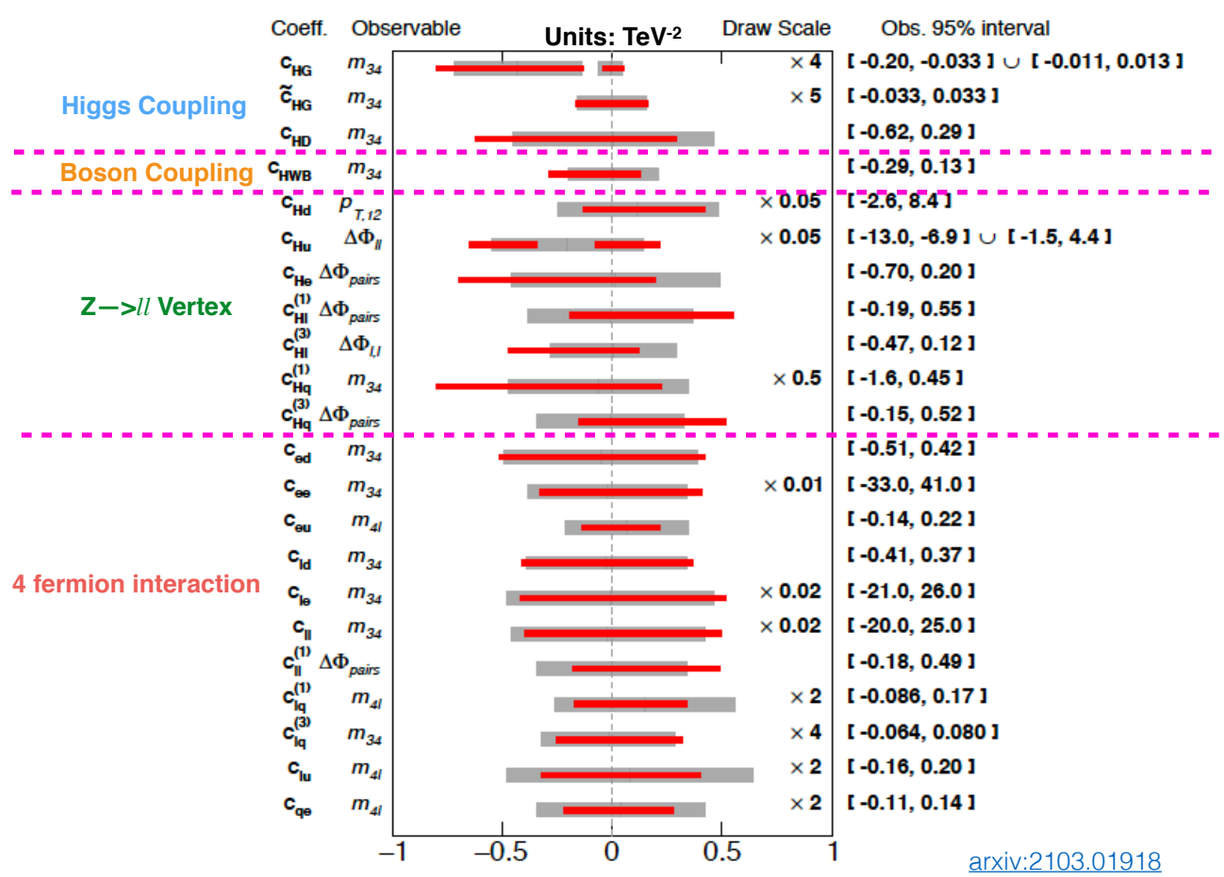


EFT Interpretation:

$$L_{SMEFT} = L_{SM} + \sum_{\forall_i} \frac{C_i O^{(d)}}{\Lambda^{(d-4)}}$$

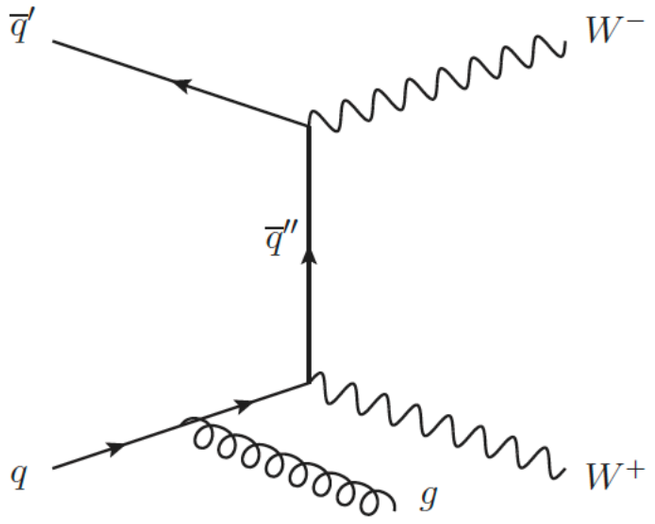
- ★ Constrain on 22 Wilson coefficients of dim6 operators
- ★ Limits on both linear only and full model

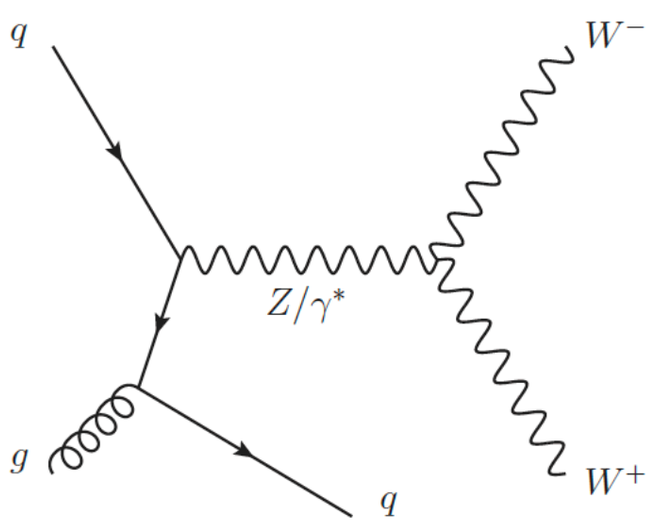
$$\sigma_{Prediction} = \sigma_{SM} + c_i \sigma_{Interference} + c_i^2 \sigma_{BSM}$$

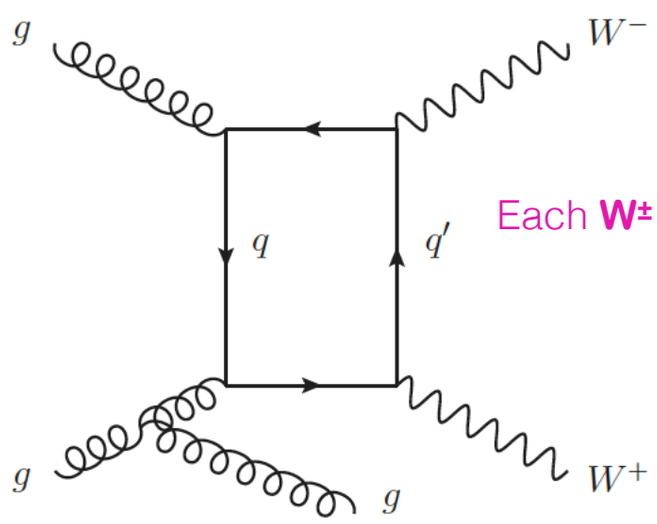


arxiv:2103.01918

W^+W^- + jets Production: Introduction







Each **W± decays to e±ν[μ± ν]**

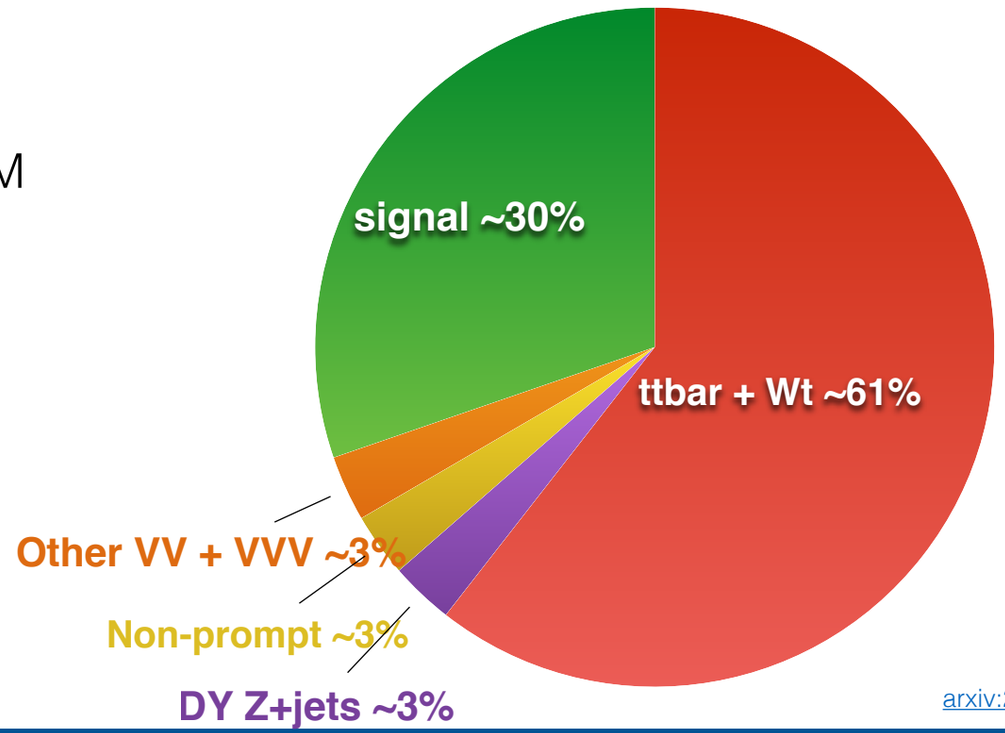
Main Challenge:

★ Final state dominated by background processes

Motivation:

★ First measurement of jet inclusive topology
  - ✳ Test of perturbative QCD and SM EWk sector

★ Sensitive to electroweak boson self interactions & to BSM anomalous triple gauge couplings (aTGC)
  - ✳ Jet inclusive topology increases sensitivity to aTGC by allowing different helicity configurations



arxiv:2103.10319

W^+W^- + jets Production: Background Estimation

ttbar estimation:

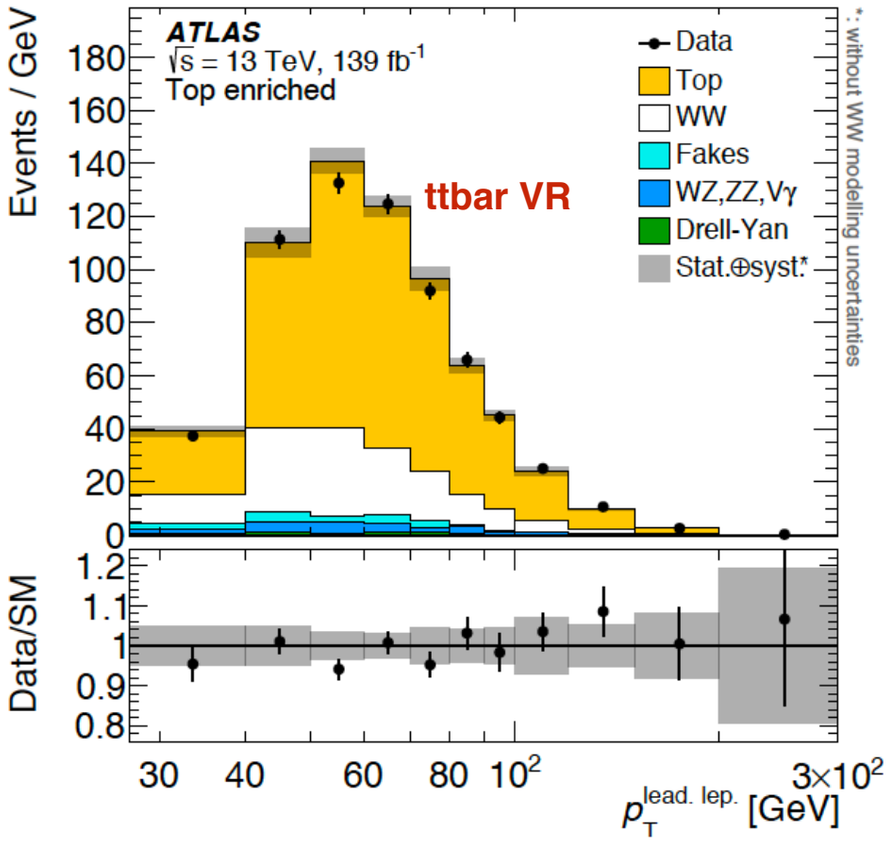
★ Data-driven estimation based on 2 control regions [1b-jet/2b-jets]

$$N_{0b}^{t\bar{t}} = \frac{C_b (N_{1b}^{t\bar{t}} + 2N_{2b}^{t\bar{t}})^2}{4\, N_{2b}^{t\bar{t}}} - N_{1b}^{t\bar{t}} - N_{2b}^{t\bar{t}}$$

- $N_{0b}^{t\bar{t}}$: Yield in SR
- C_b: Correction factor ~1
  - Only component from **MC**
  - **Correlation** effects between **selecting 1 and 2 b-jets**
- $N_{1b}^{t\bar{t}}$: Yield in 1 b-jet CR
- $N_{2b}^{t\bar{t}}$: Yield in 2 b-jets CR
- $N_{1b}^{t\bar{t}} + N_{2b}^{t\bar{t}}$: Data

★ Based on observed yield from data resulting in smaller experimental & theoretical uncertainties

- Total Uncertainty of on bkg yield **2.8%**



Non-prompt Lepton:

★ Estimated by data driven approach in a CR [similarly to Inclusive 4l]

All estimated backgrounds are validated in separate validation regions

W+t , DY Z+jets & other VV + VVV: estimated from MC

arxiv:2103.10319

W^+W^- + jets Production: Results & EFT Interpretation

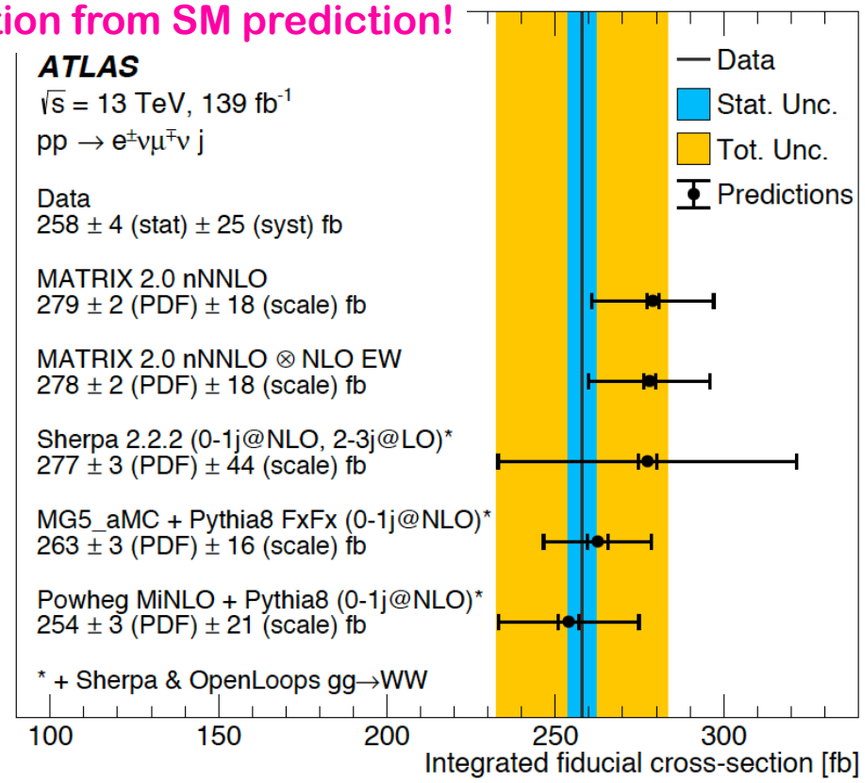
Fiducial Cross-section:

$$\sigma_{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times L} = 258 \pm 4(\text{stat}) \pm 25(\text{syst}) \text{ fb}$$

Correction factor [detector effects] [0.747±0.061]

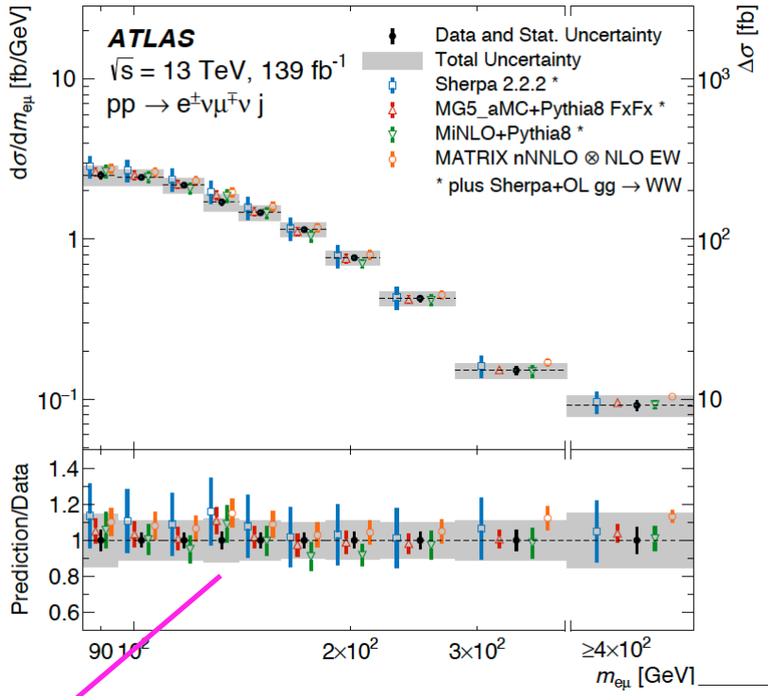
Jet Calibration ~6.3%
Top Modeling ~4.5%
Fake Bkg ~4.3%

No deviation from SM prediction!



Differential Measurement:

★ Particle level differential measurement using Iterative Bayesian unfolding



Differential Measurements:

- Lepton Observables: $p_{T\text{leadlep}}$, $p_{T\text{subleadlep}}$, s_T
- Di-lepton Observables: $m_{e\mu}$, $m_{T e\mu}$, $p_{T e\mu}$, $\Delta\phi_{e\mu}$, $y_{e\mu}$
- Jet Observables: $p_{T\text{leadjet}}$, n_{jets} ,H_T
- Polarisation Observable: $\cos\theta^*_{e\mu}$

All results in HepData

EFT Interpretation:

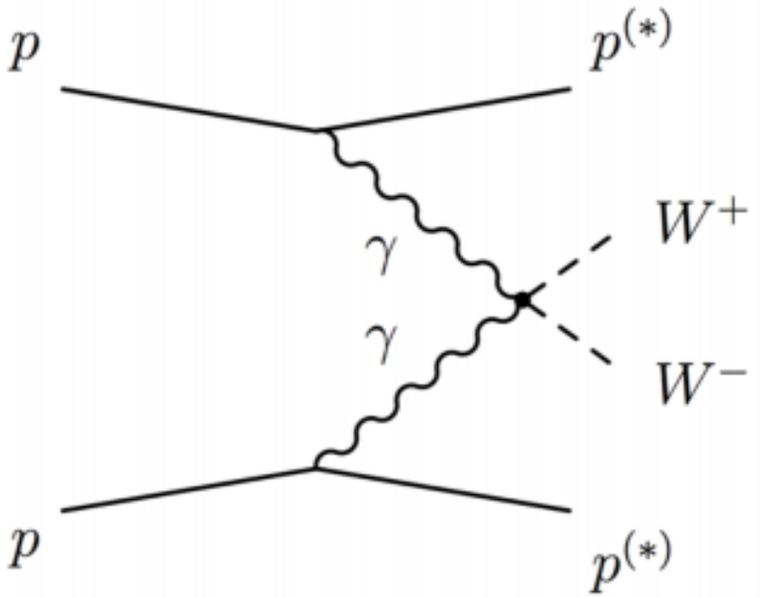
★ Wilson coefficient c_W [Dim-6 aTGC operator Q_W] constrained

Linear limit improved compared to W^+W^- [jet vetoed] 36 fb^{-1} measurement

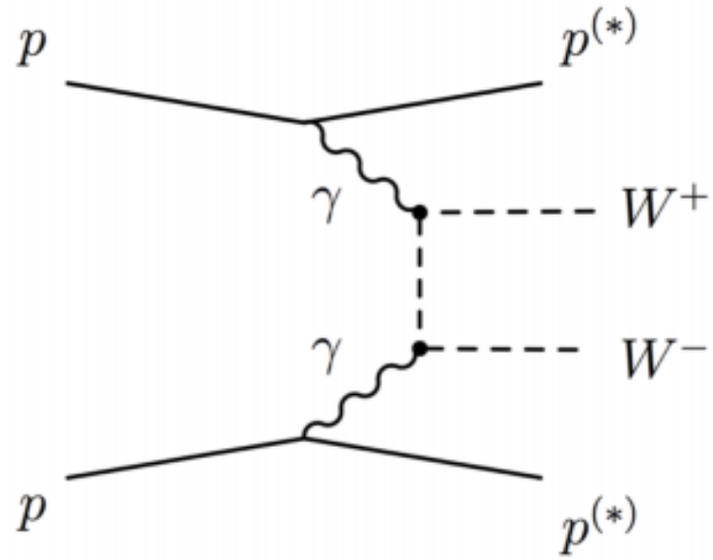
Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[–1.64, 2.86]	[–3.85, 4.97]	[–2.30, 2.27]	[–4.53, 4.41]
> 30 GeV	no	[–0.20, 0.20]	[–0.33, 0.33]	[–0.28, 0.27]	[–0.39, 0.38]
> 200 GeV	yes	[–0.29, 1.84]	[–1.37, 2.81]	[–1.12, 1.09]	[–2.24, 2.10]
> 200 GeV	no	[–0.43, 0.46]	[–0.60, 0.58]	[–0.38, 0.33]	[–0.53, 0.48]

arxiv:2103.10319

Photon induced W^+W^- Production: Introduction



Each **W± decays to e±ν[μ± ν]**



Motivation:

- ★ Rare and interesting measurement to probe SU(2) ⨉ U(1) gauge structure of SM
- ★ Electroweak boson self interactions sensitive to anomalous quartic electroweak boson coupling

Measurement Topology:

- ★ Initial state protons could stay intact or fragment outside detector acceptance
  - ✦ Unique signature: **completely isolated di-lepton vertex with no additional tracks**

Background:

- ★ QCD-induced **WW (main)**, **Drell Yan , $\gamma\gamma$—>ll, non prompt leptons**

Main Challenge:

- ★ Physics modeling of events with low charged particle activity around hard scatter

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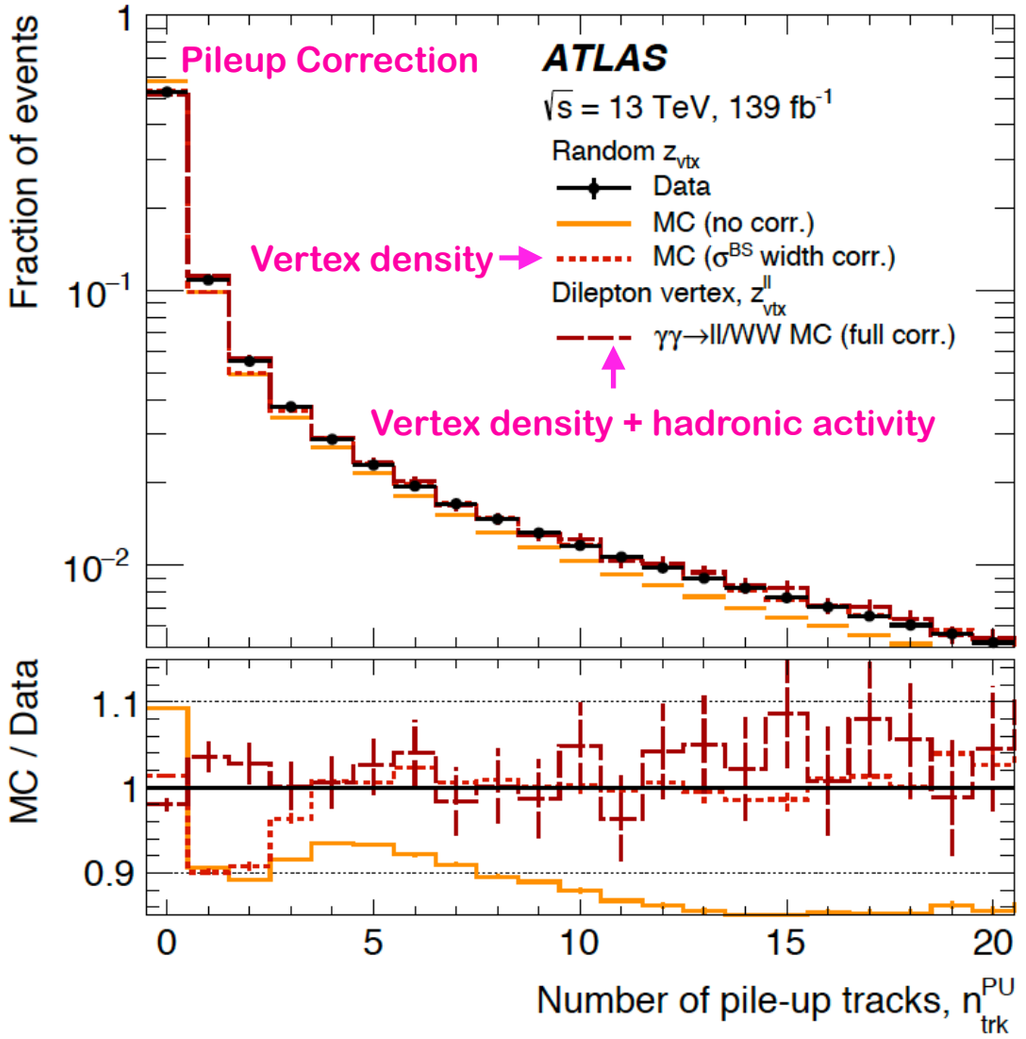
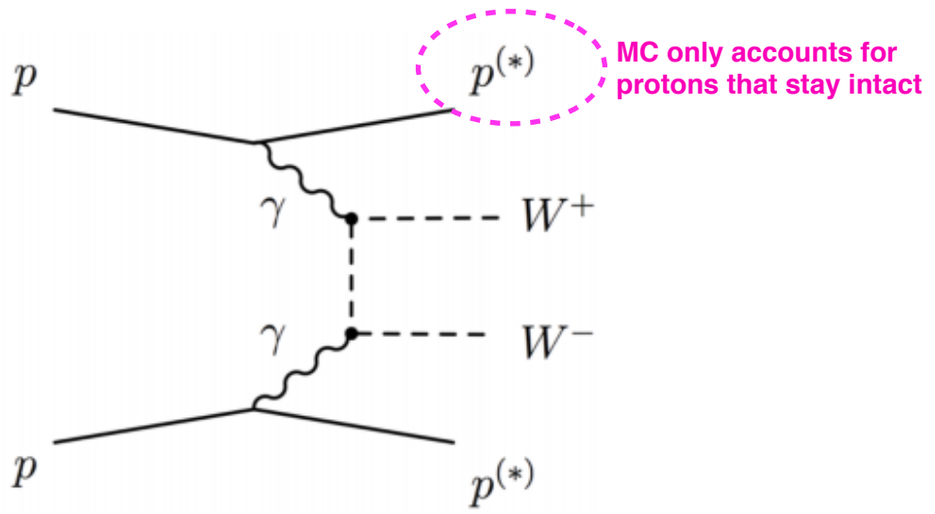
Photon induced W^+W^- Production: Analysis Strategy

- Number of tracks **(n_{trk})** within **1mm of di-lepton vertex** and used in classifying CRs and SR events
  - Accurate modeling of **n_{trk} crucial**

- 3 sets of data driven corrections applied to MC prediction
  - **Pileup**: signal efficiency, **biggest challenge**
    - Corrects for mis-modeling in pileup tracks based on z_0 sampling technique
  - **Underlying Event:** background prediction
    - Reweight **WW [$\gamma\gamma$ + QCD] & DY$\tau\tau$** to correct track multiplicity
  - **Signal**:
    - Account for any **additional re-scatterings** after initial elastic collision & **dissociative components** [MC elastic only]





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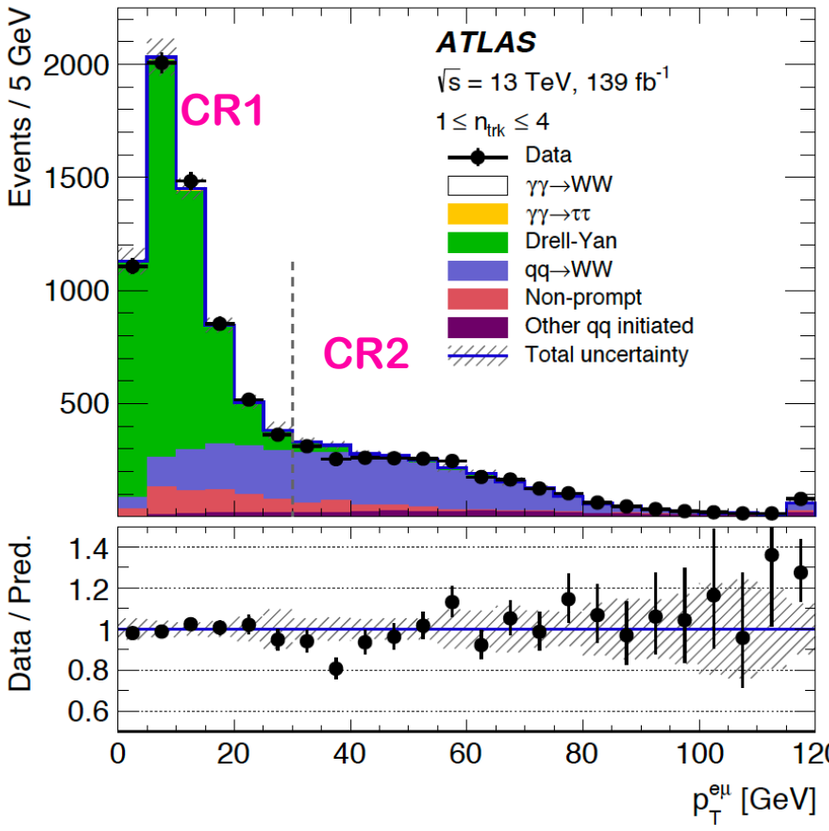
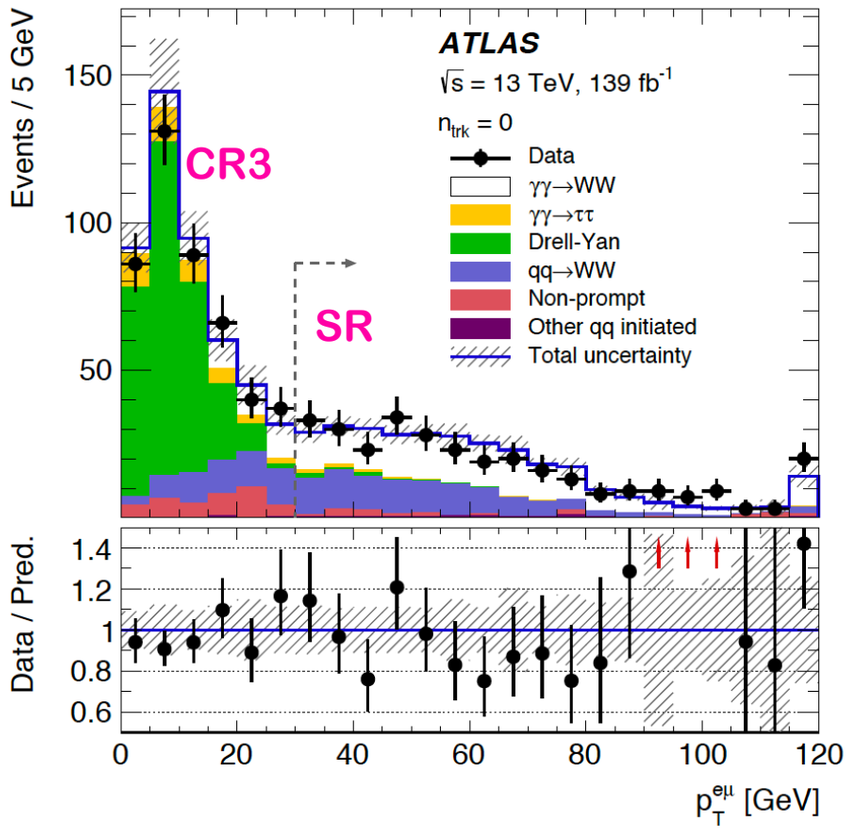
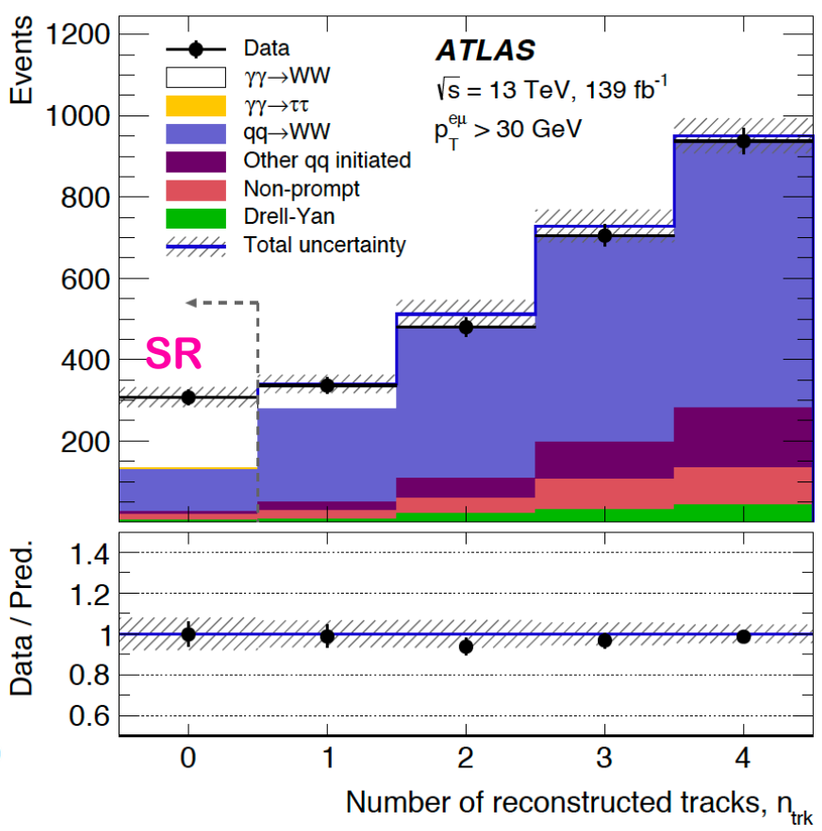
Photon induced W^+W^- Production: Results

SR	CR1	CR2	CR3
$p_T^{e\mu} > 30$ GeV & $n_{trk} = 0$ Expected purity ~ 57% **QCD WW** ~ 33%	$p_T^{e\mu} < 30$ GeV & $1 \le n_{trk} \le 4$ ~75 % $\gamma\gamma \rightarrow \tau\tau$ **DY normalisation**	$p_T^{e\mu} > 30$ GeV & $1 \le n_{trk} \le 4$ ~70% **QCD WW** **WW** normalisation	$p_T^{e\mu} < 30$ GeV & $n_{trk} = 0$ Constrain additional bkg with no tracks **[10% sig]**

Non prompt leptons Bkg [W+jets] production estimated from data in different CR [same sign $e\mu$ $1 \le n_{trk} \le 4$]







★ Simultaneous fit of SR & 3 CR to **reject background only hypothesis by 8.4σ** to extract the **signal strength 1.33**

★ Measured fiducial cross section **(3.13 ± 0.31 [stat] ± 0.28 [syst]) fb**

- **Experimental [dominant non prompt bkg stat]**
- **Modeling [dominant WW & signal modeling]**

In agreement with SM prediction!

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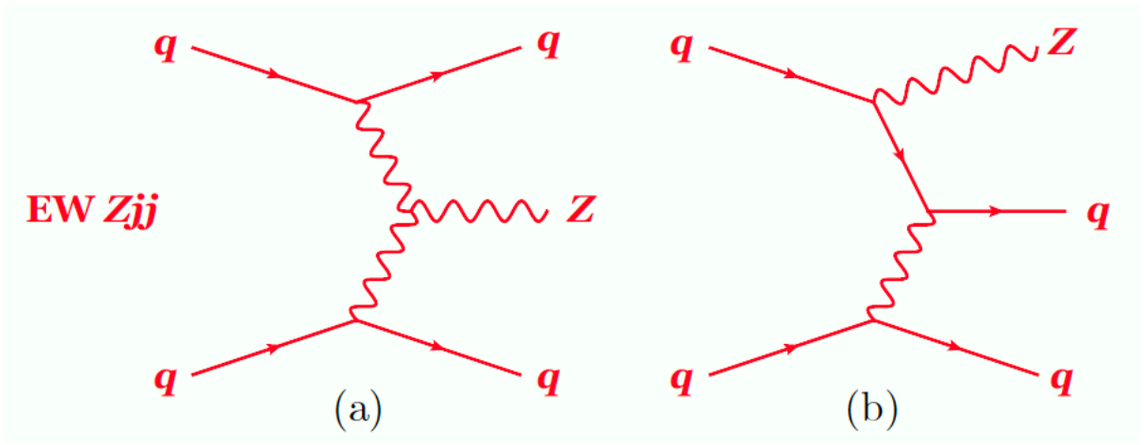
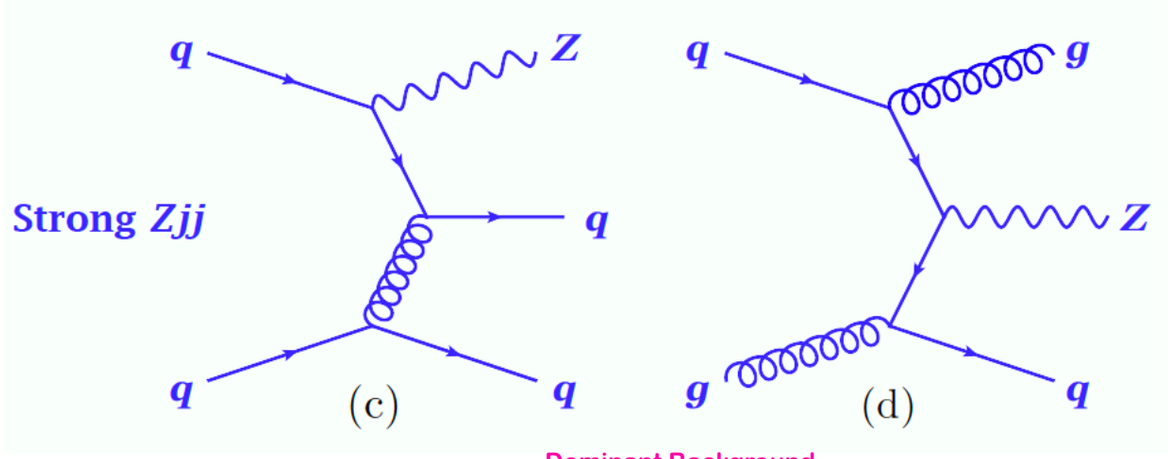
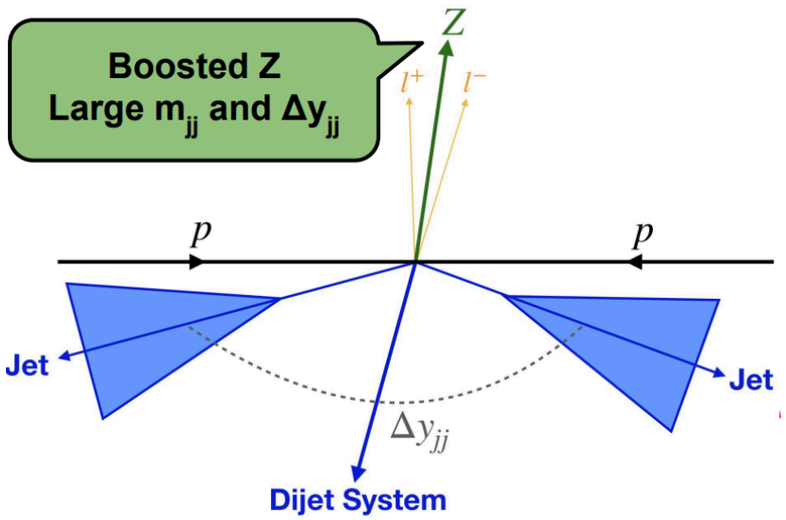
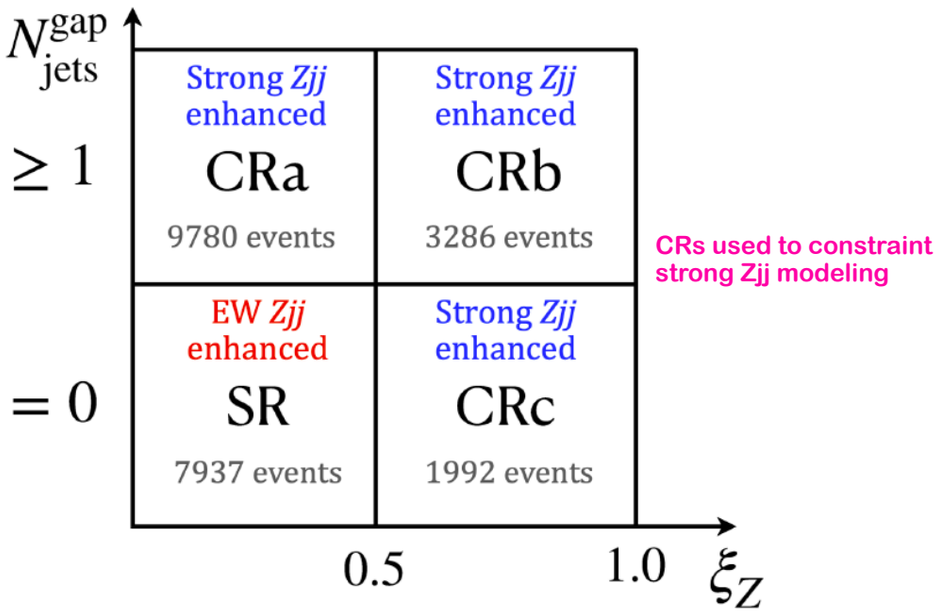
Differential EWk Zjj: Introduction





Dominant Background
Biggest challenge → modeling strong Zjj





CRs used to constraint strong Zjj modeling

Motivation:

- ★ Sensitive to VBF
  - ✦ Test of the SU(2) ⨉ U(1) gauge structure of SM and sensitive to anomalous weak-boson self-interactions
- ★ Could provide crucial input for theoretical predictions for future VBF/VBS sensitive multi-boson measurements

Background:

- ★ **ZV(V—>jj), ttbar, other VV**

Analysis Strategy:

- ★ Profile likelihood fit of 3 CRs and **EWk Zjj** enhanced SR to extract the signal events

arXiv:2006.15458

Differential EWk Zjj: Results & BSM Interpretation

Fiducial Cross-section:

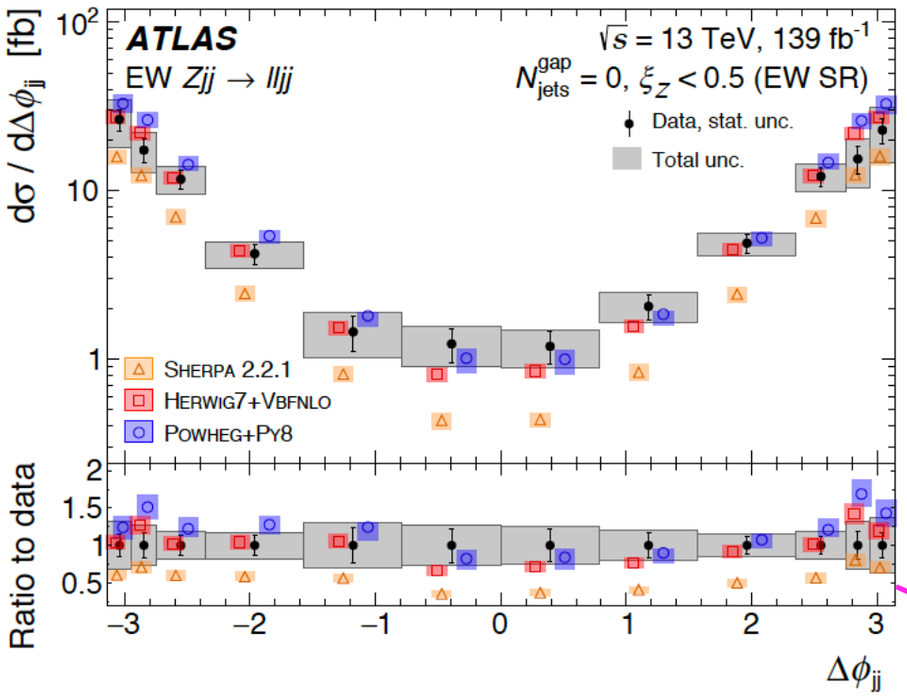
$$\sigma_{EWk} = (37.4 \pm 3.5[stat] \pm 5.5[syst])\, fb$$

Dominant: jet energy scale and energy resolution

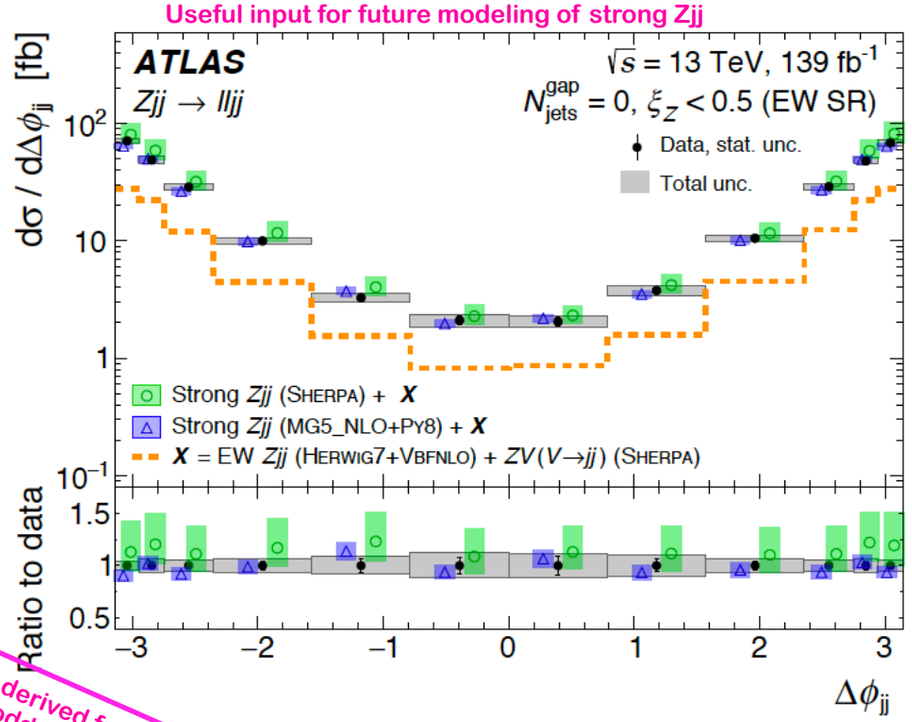
In agreement with SM!

Particle Level Differential Measurements:

★ Particle level differential measurements in **inclusive** and **EWk Zjj** region $[m_{jj}, p_{T_{ll}}, \Delta\phi_{jj}, |\Delta y_{jj}|]$ All results in HepData



Useful input for future modeling of strong Zjj



Limits derived from parity-odd observable

EFT Interpretation:

★ Dim-6 Wilson coefficients c_W, $\tilde{c}_W$, c_{HWB}, $\tilde{c}_{HWB}$ constrained using fits to EWk Zjj differential cross-section as a function of $\Delta\phi_{jj}$

Sensitive to SM & CP-odd EFT interference amplitudes → Direct test of CP invariance in weak-boson self-interactions

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

arXiv:2006.15458

Summary

- ★ Presented 3 recent and exciting multi boson measurements with ATLAS
- ★ Precision measurements of the integrated and differential cross-sections along with
  - ✳ Development of novel pre-unfolding techniques in **Differential 4l**
  - ✳ Excellent precision achieved for background estimation with data driven approach in **W^+W^- + jets**
  - ✳ Interesting analysis technique for $\gamma\gamma$ —> **W^+W^-** technique to distinguish signal events using track counting
  - ✳ Differential measurement of inclusive **[QCD +EWk] Zjj** —> input for future Zjj modeling
- ★ Constraints on new physics with particle level measurements
- ★ Important ground-work in measurements for Run 3 and beyond

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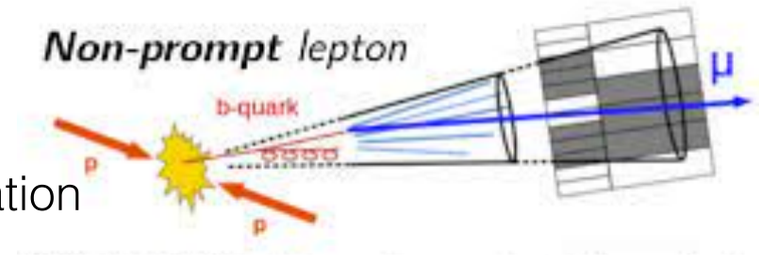
BACK UP

Differential 4l: Analysis Strategy & Results

Background Estimation:

- ★ Non prompt leptons not from hard scatter
- ★ Data driven fake factor background estimation

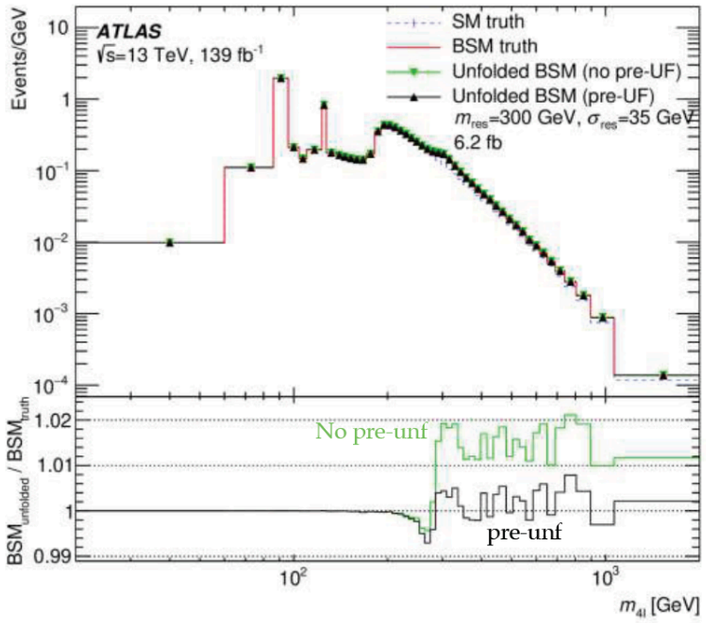


- Measured from data in fake enriched Z—>ll control region
- Ratio of fake leptons passing vs failing **signal requirement [TTVA +isolation]**

$$F = \frac{f}{1-f}$$

f: how likely a fake lepton is to be reconstructed as signal

To estimate final background yield apply F to each **baseline-not-signal leptons**



Unfolding:

- ★ Unfold (Data - Background)
- ★ Iterative Bayesian unfolding (2-3 iterations) to correct for the remaining detector effects
- ★ single/double differential measurements of 13 different kinematic observables

$$w = \frac{}{\prod_{i=1}^{4} \epsilon_i[p_T^i, \eta^i]}$$

- ★ Novel technique of using per lepton pre-unfolding correction to minimize the SM lepton kinematics dependent inefficiencies

m4l (inc., pT4l, y4l, flavour), Δy_{pairs}, $\Delta\phi_{pairs}$, $\Delta\phi_{ll}$, m_{z1}, m_{z2}, p_{Tz1}, p_{Tz2}, pol. variables

arxiv:2103.01918

Differential 4l: Systematics & BR [Z—>4l]

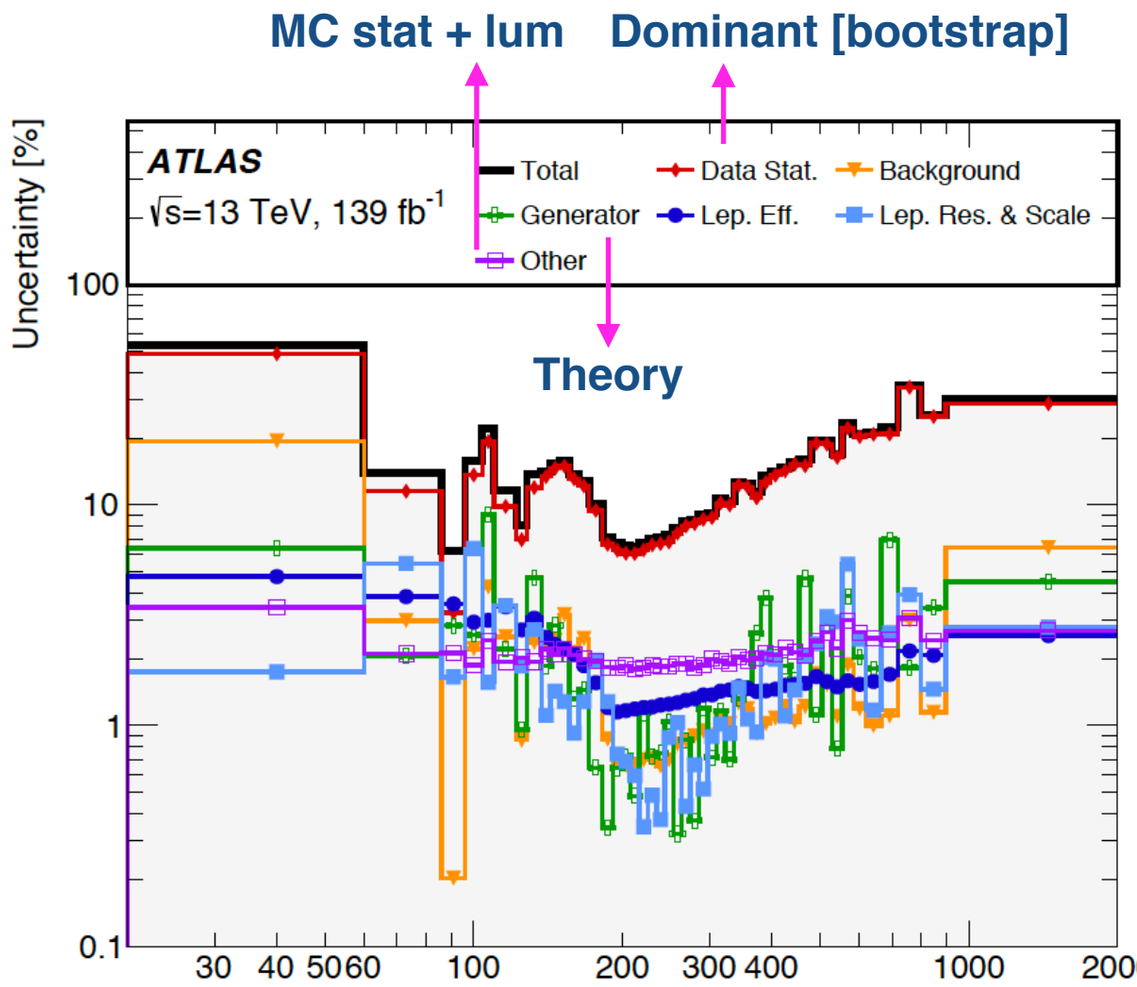
Previous precision:

$BR(Z \to 4l) = 8.7\,\%$

Current Precision: 2.5 gain in statistical precision

$BR(Z \to 4l) = 6.9\,\%$

	Full	$Z \to 4\ell$
Measured	88.9	22.1
fiducial	±1.1 (stat.)	±0.7 (stat.)
cross-section	±2.3 (syst.)	±1.1 (syst.)
[fb]	±1.5 (lumi.)	±0.4 (lumi.)
	±3.0 (total)	±1.3 (total)
SHERPA	86±5	23.6±1.5
POWHEG + PYTHIA8	83±5	21.2±1.3



Fraction of single Z production rather than t channel ZZ

$$\mathcal{B}_{Z\to 4\ell} = \frac{\left(\sigma^{\text{meas}} - \sigma^{\text{pred}}_{\text{non-}q\bar{q}\to 4\ell}\right) \times f_Z \times f_{\text{non-}\tau}}{\sigma_Z \times A_{\text{fid}}}$$

Fraction of leptons Not originating from taus

Factor to extend phase space
80 < m4l < 100, mll > 4, no kin. req on leptons

Total cross-section of single Z production

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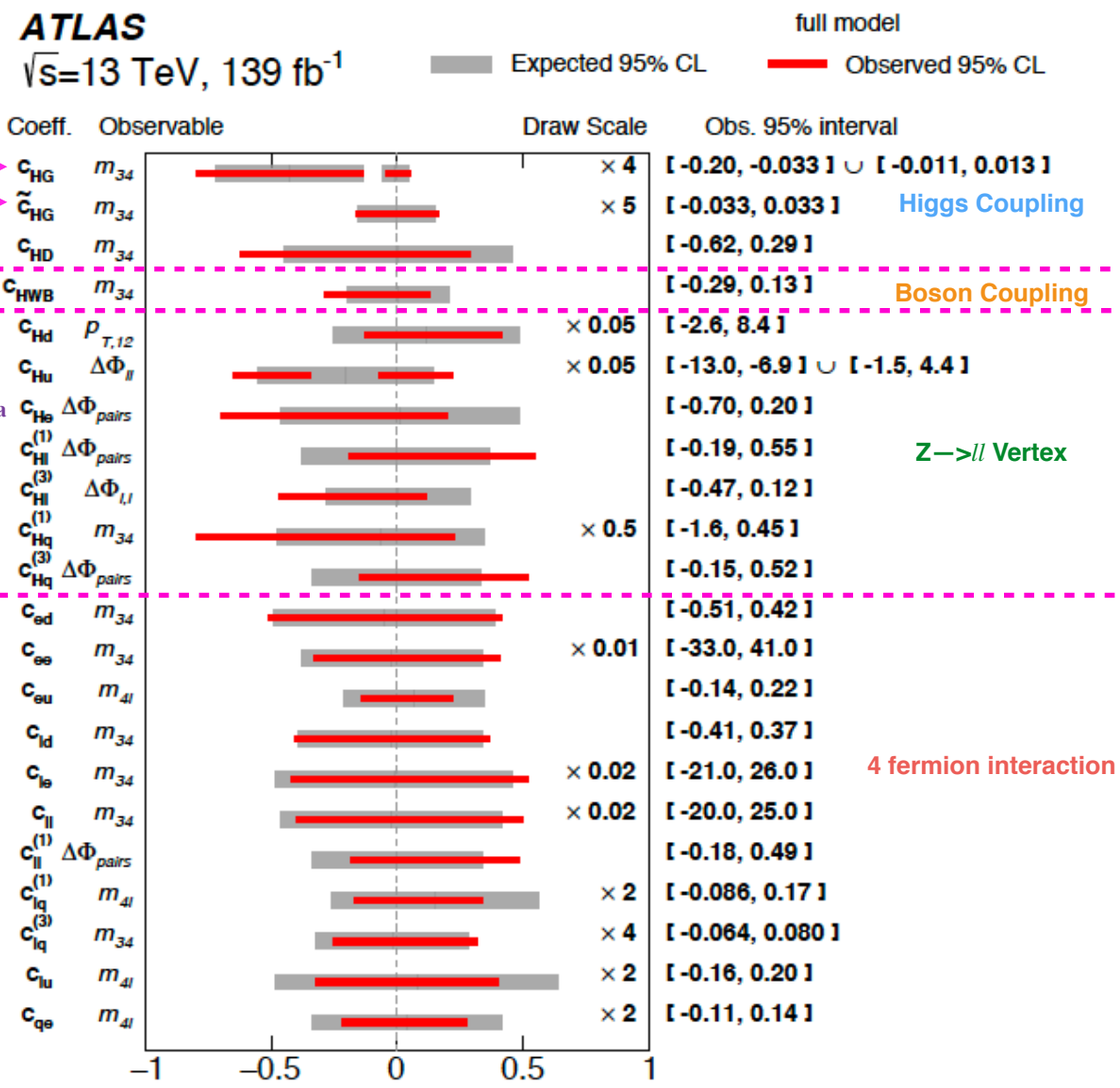
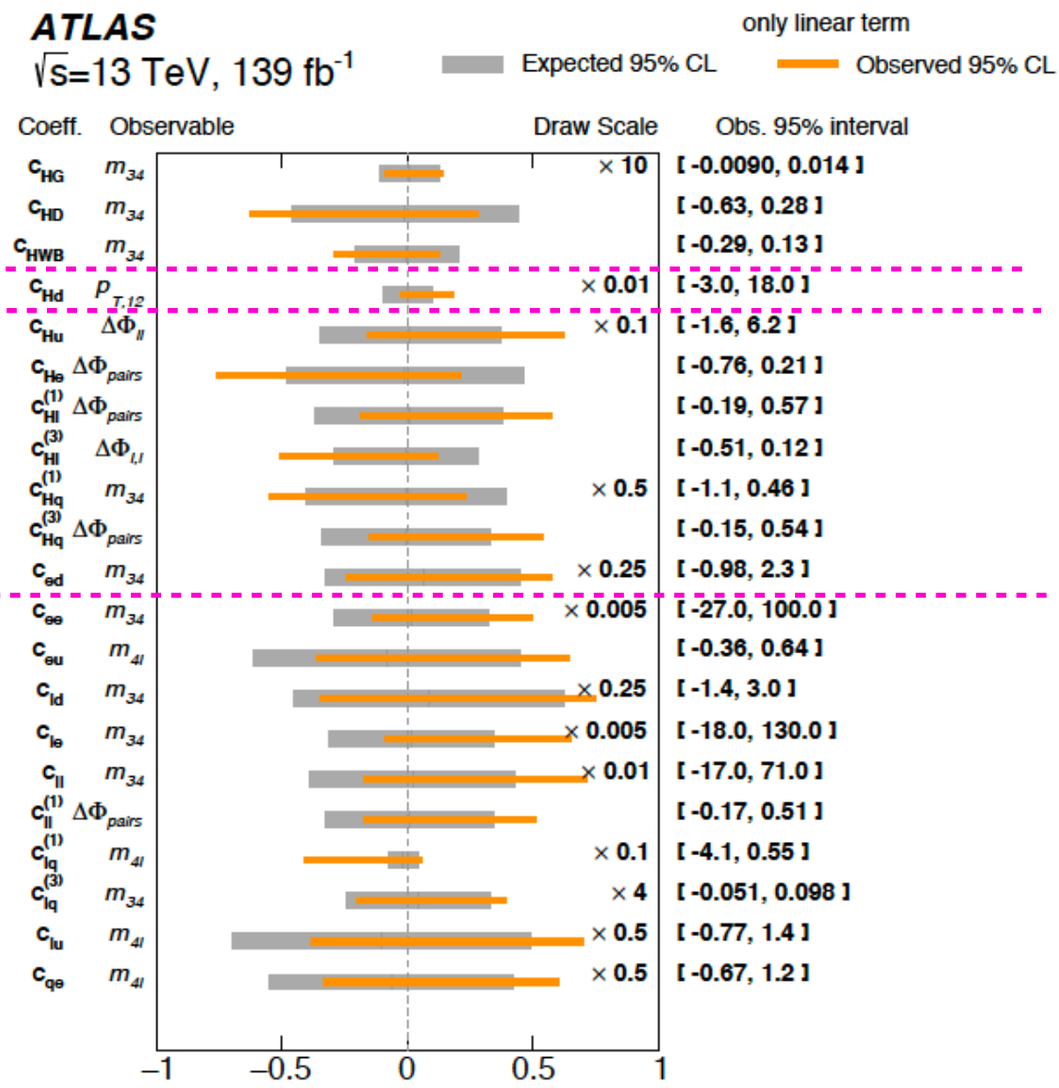
Uncertainty on $\sigma^{meas}_{Z\to 4l}$ & σ_Z

$$B_{Z\to 4l} = (\,4.41 \pm 0.13\,[stat] \pm 0.23\,[syst] \pm 0.09\,[theory] \pm 0.12\,[lumi]\,) * 10^{-6}$$

arxiv:2103.01918

Differential 4l: EFT Limits





Negligible contribution from quadratic term: c_{HD}, c_{HWB}, c_{He}, $c^{(1)}{}_{Hl}$, $c^{(3)}{}_{Hq}$, $c^{(3)}{}_{Hl}$ and $c^{(1)}{}_{ll}$

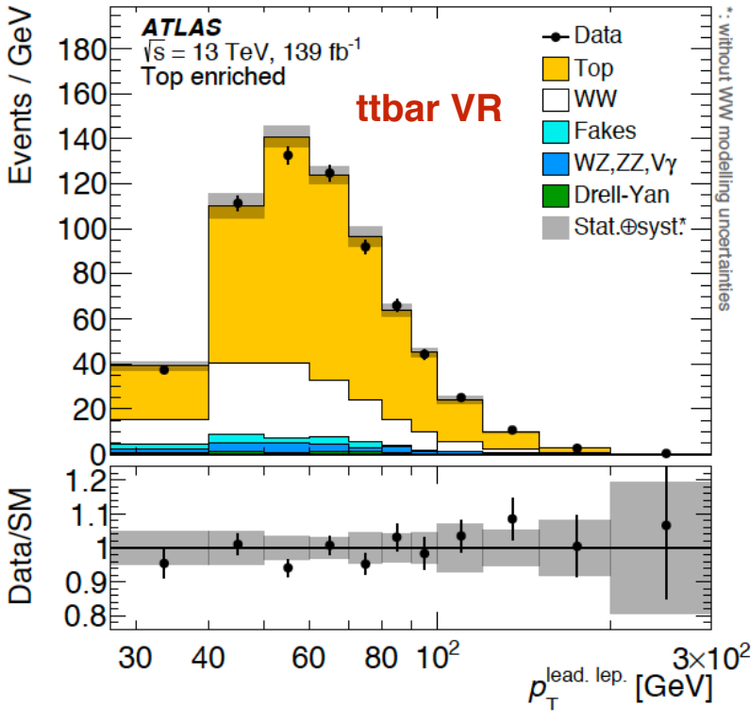
Small positive contribution from quadratic terms: $c^{(1)}{}_{Hq}$, $c^{(3)}{}_{lq}$

Tighter limits with linear only terms: c_{HG}, c_{Hu}

All other have tighter limit with full EFT

arxiv:2103.01918

W^+W^- + jets Production: Validation Region Background Estimation

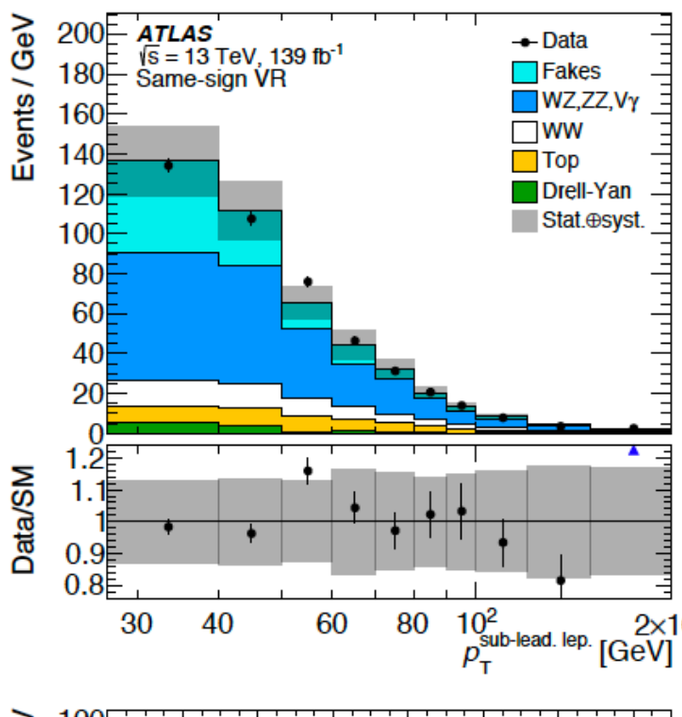


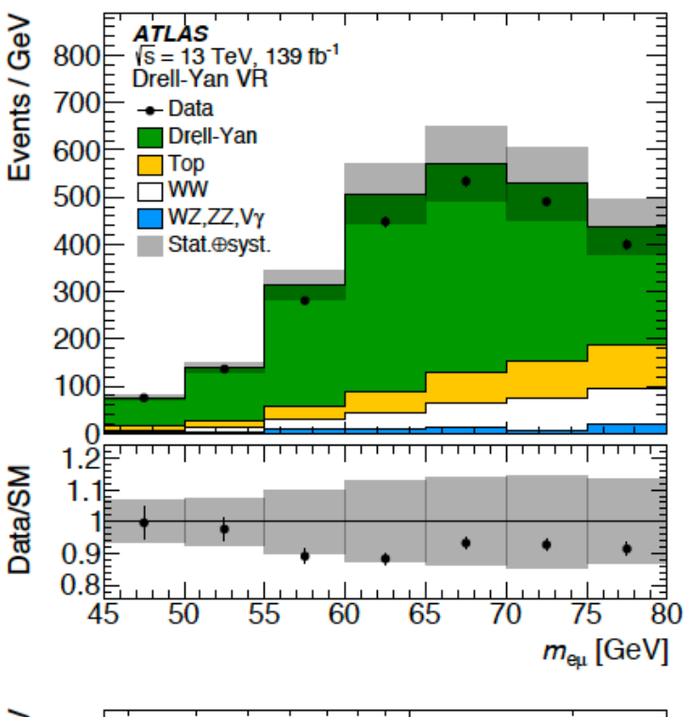
Non ttbar events estimated from MC

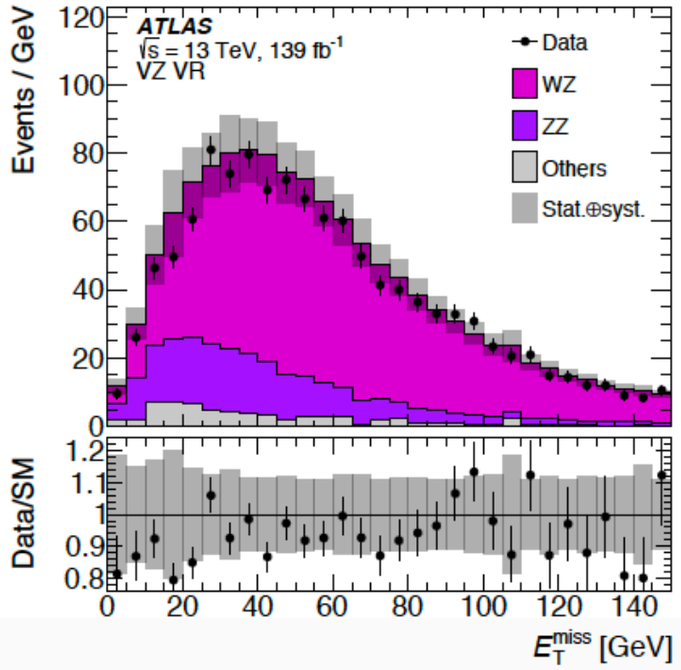
$$N_{1b}^{t\bar{t}} = N_{1b} - N_{1b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot 2\varepsilon_b \left(1 - C_b\varepsilon_b\right) ,$$
$$N_{2b}^{t\bar{t}} = N_{2b} - N_{2b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot C_b\varepsilon_b^2 ,$$
$$N_{0b}^{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot \left(1 - 2\varepsilon_b + C_b\varepsilon_b^2\right) ,$$

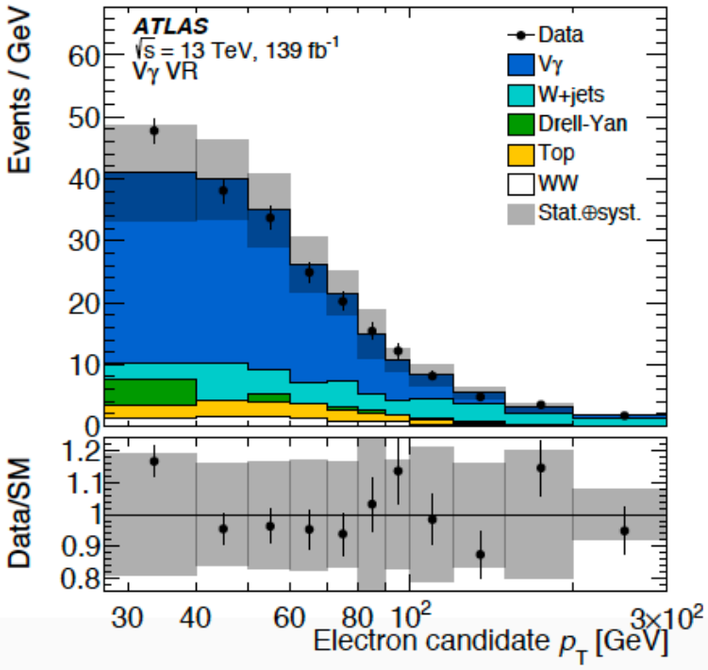
$$N_{0b}^{t\bar{t}} = \frac{C_b \left(N_{1b}^{t\bar{t}} + 2N_{2b}^{t\bar{t}}\right)^2}{4\, N_{2b}^{t\bar{t}}} - N_{1b}^{t\bar{t}} - N_{2b}^{t\bar{t}}$$

$$C_b = \frac{4.N_{MC}^{t\bar{t}} N_{2b,MC}^{t\bar{t}}}{N_{1b,MC}^{t\bar{t}} + 2.N_{2b,MC}^{t\bar{t}}}$$





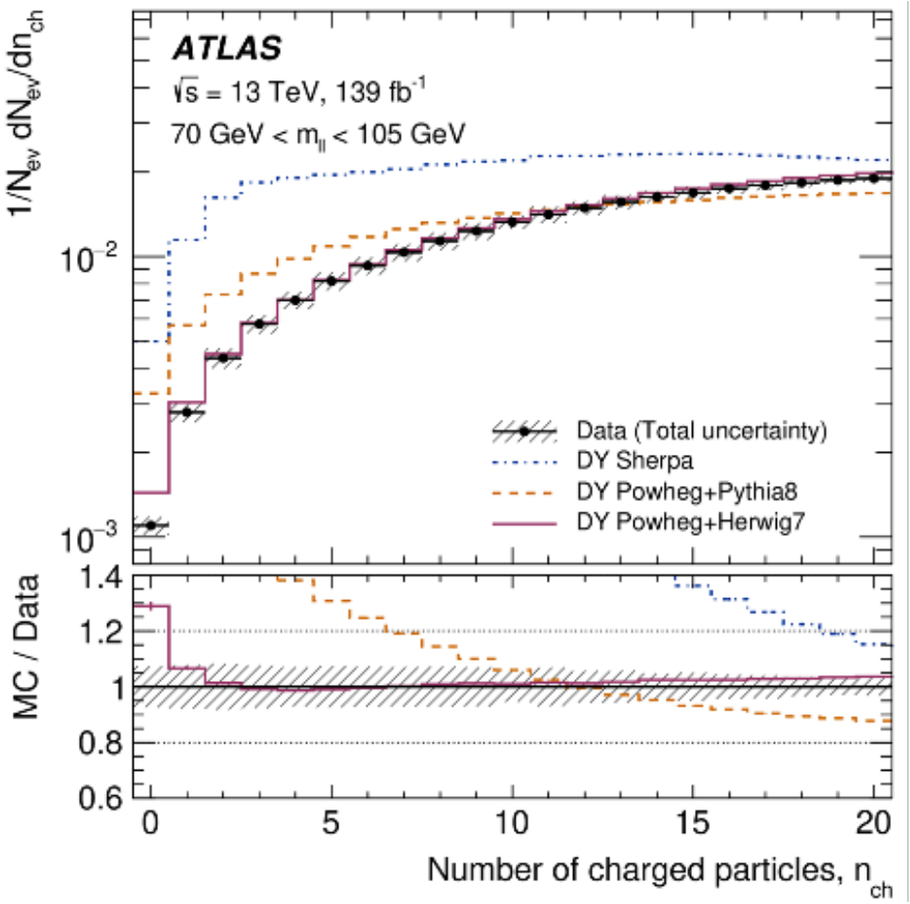




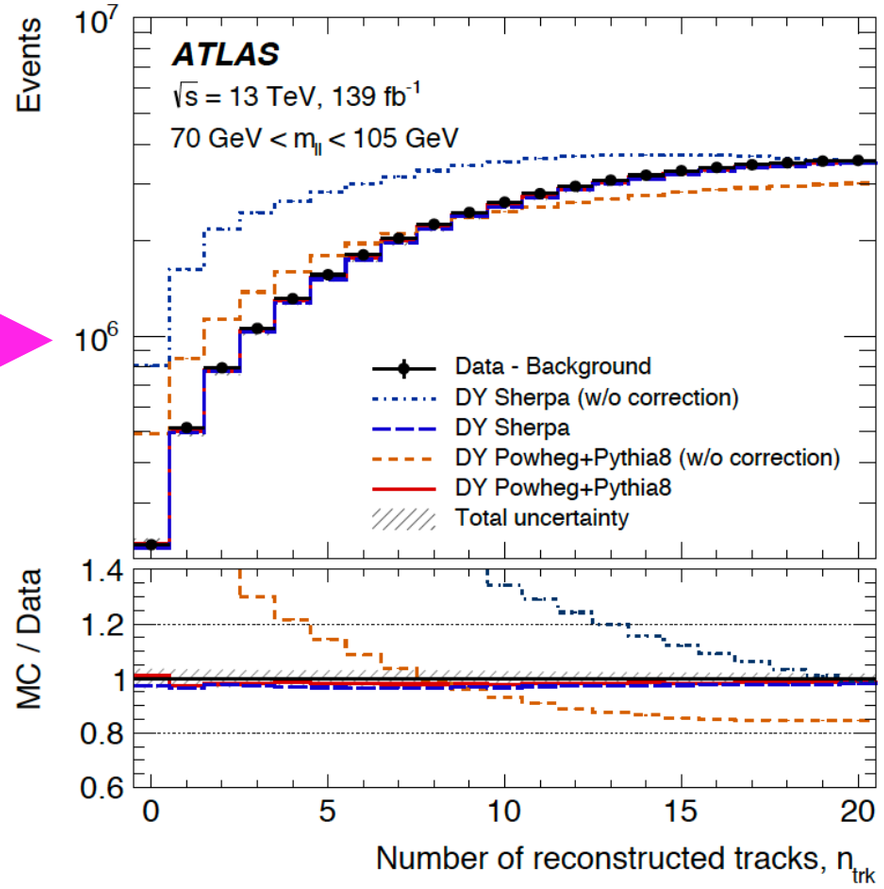
arxiv:2103.10319

Photon induced W^+W^- Production: Additional Details

- ★ Pileup Correction: Additional pile up tracks around di-lepton vertex affects the signal selection efficiency
  - ✳ MC/Data reweighing to match average number of pp collisions per bunch
  - ✳ Correction to account for different beam-spot width during different runs in data
  - ✳ Track density around random z location in $Z \text{—>} ll$ events in data/MC
- ★ Underlying Event Correction: Modeling inaccurate could affect the accepted background events
  - ✳ Correct factor obtained using particle level n_{ch} distribution measured in $Z \text{—>} ll$
  - ✳ Bayesian unfolding with 4 iterations to unfold the data, after subtracting $\gamma\gamma \text{—>} ll$ events and pile-up tracks
  - ✳ Reweight simulation using the measured data/MC ratio of particle-level n_{ch} as function of $p_{T,\text{final state}}$



Great closure data/MC after reweighing



Phys. Lett. B 816 (2021) 136190

Differential EWk Zjj: Strong Zjj modeling correction & Signal Extraction

$$\frac{d\sigma_i^{EW}}{dx} = \mathcal{U}\frac{N_{SR,i}^{data} - \nu_{SR,i}^{strong} - \nu_{SR,i}^{other,MC}}{\Delta x_i \mathcal{L}}$$

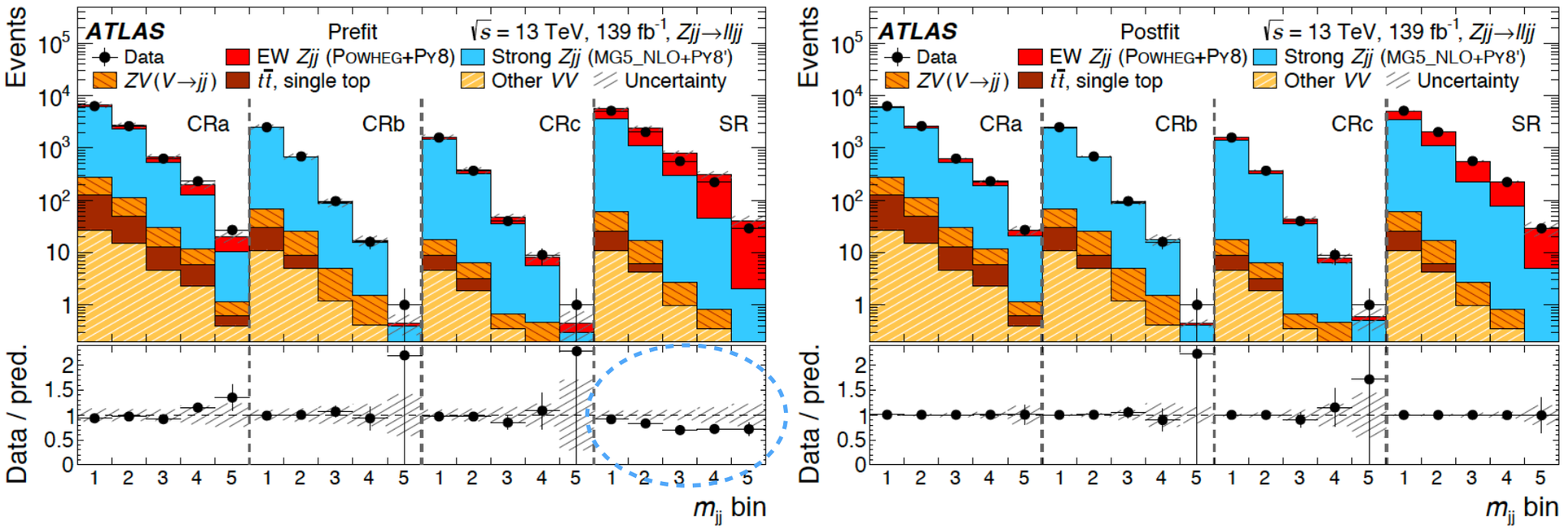
Bayesian Unfolding

$$\nu_{ri} = \mu_i \nu_{ri}^{EW,\,MC} + \nu_{ri}^{strong} + \nu_{ri}^{other,\,MC}$$

Measured EW Zjj

Strong Zjj Yield —> CR data driven constraint

$$ln\, L = -\sum_{r,i} \nu_{ri}(\theta) + \sum_{r,i} ln\, \nu_{ri}(\theta) - \sum_{s} \frac{\theta_s^2}{2}$$



Strong scale factors 0.93 for low m_{jj} rising to 2.2 at high m_{jj}

arXiv:2006.15458

Differential EWk Zjj: BSM Interpretation

- Dim-6 Wilson coefficients c_W, $\tilde{c}_W$, c_{HWB}, $\tilde{c}_{HWB}$ constrained using fits to EWk Zjj differential cross-section as a function of $\Delta\phi_{jj}$
- Limits weaker than obtained from 36^{-1} fb
  - **W$^+$W$^-$** production at ATLAS
  - **WZ** production at CMS
  - **EWk Zjj** with CMS
- However these measurement only includes linear term and more sensitive to impact of missing higher-dimensional operators
- Also the limits are on $\Delta\phi_{jj}$ more sensitive observable to CP violation

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

arXiv:2006.15458