Differential cross section measurements of $WW+\geq 1$ jets with ATLAS.

Jan Küchler on behalf of the ATLAS collaboration
Standard Model at the LHC, 29.04.2021

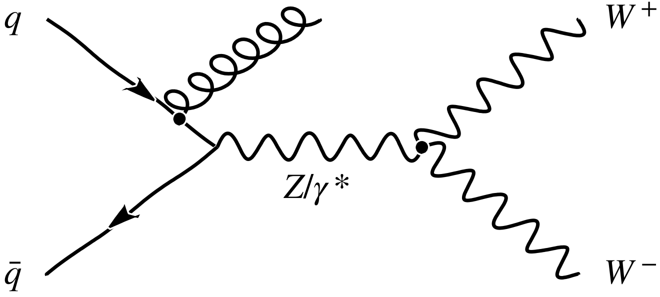
[arXiv:2103.10319]

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

DESY.

Introduction



[arXiv:2103.10319]

WW production

…is interesting

- pQCD and NLO EWK
- sensitive to aTGC operators

…is well measured

- Jet veto (large $t\bar{t}$ background)

$\Rightarrow$ Study WW+jet production

- Inclusive: ≥ 1 jet
- Increased sensitivity to linear aTGC effects

Analysis strategy

Event selection

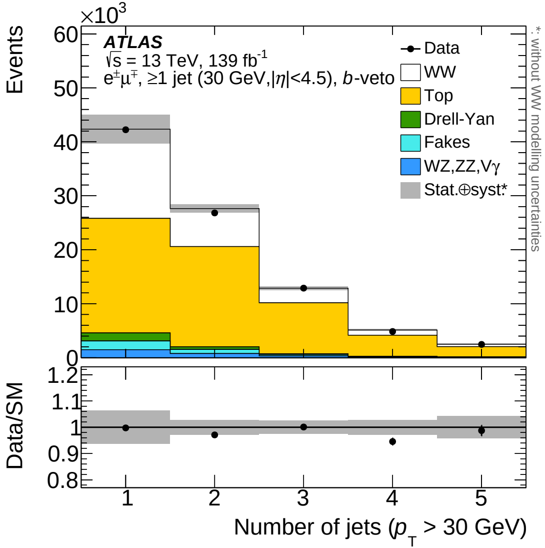
- $e^{\pm}\mu^{\mp}$, $m(e\mu) > 85$ GeV DY, $H \to WW$
- b-jet veto (20 GeV) Top bkg.
- ≥ 1 jet (35 GeV)

Background estimate

- Top and fakes data-driven
- Drell-Yan and other diboson from MC, validated in data

Correct for detector effects

- Iterative Bayesian unfolding



Top background

- Top background $> 60\%$ of selected events

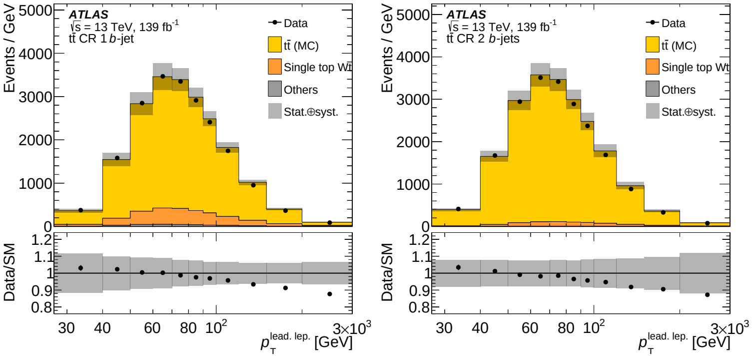
$\Rightarrow$ Data-driven estimate

- Two clean control regions with $= 1$ and $= 2$ b-jets

  Data:
  $\mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu}$: total $t\bar{t}$ events
  ε_b: b-jet finding and tagging efficiency

  MC: b-jet correlation
  $C_b = \varepsilon_{bb}/\varepsilon_b^2 \simeq 1$

- $t\bar{t}$ estimated in each bin



$$N_{1b}^{t\bar{t}} = N_{1b}^{\text{data}} - \underbrace{N_{1b}^{\text{others}}}_{\text{from MC}, \lesssim 10\%} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot 2\varepsilon_b\left(1 - C_b\varepsilon_b\right)$$

$$N_{2b}^{t\bar{t}} = N_{2b}^{\text{data}} - N_{2b}^{\text{others}} = \mathcal{L}\sigma_{t\bar{t}}\varepsilon_{e\mu} \cdot C_b\varepsilon_b^2$$

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

Top background: validation and uncertainties

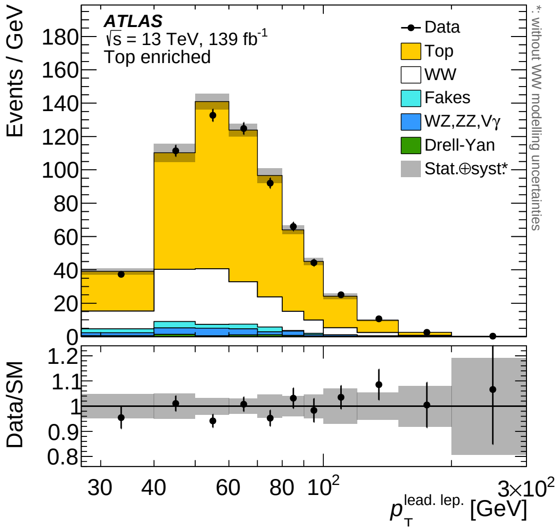
Uncertainties

- Modelling uncertainties affect C_b: QCD scale, radiation, generator, parton shower
- Strong reduction of experimental (jet, flavour tagging) and theory uncertainties

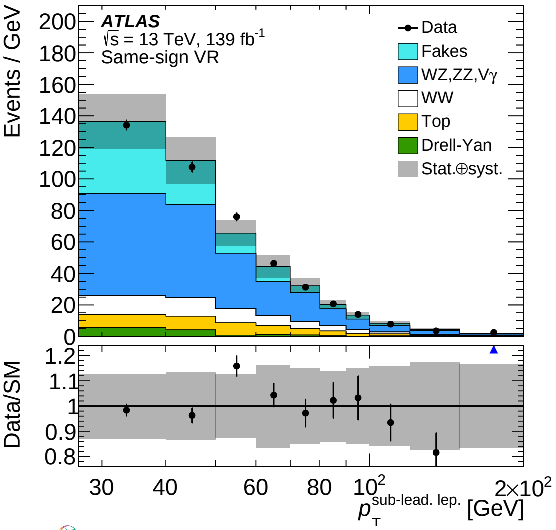
$\Rightarrow$ 2.8% total uncertainty

Validation

- Validation with b-jet veto: subset of SR
- $m_{\ell j} < 140$ GeV and $\Delta\phi_{e\mu} < \pi/2$
- Good agreement



Fake lepton background



> Background from fake leptons: $\sim 3\%$
  - Dominated by W+jets

Data driven estimate

> Control region with one 'anti-ID' lepton

> Extrapolation factor F from di-jet events

Uncertainties

> F: di-jet selection (b-jets), prompt sub.

> CR: subtraction of prompt leptons (MC)

→ $\sim 40\%$ total uncertainty

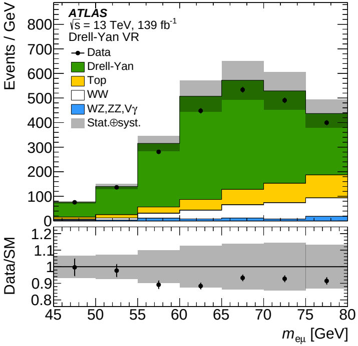
Validation

> Requiring same-sign leptons

Minor backgrounds from simulation

Drell-Yan: $\sim 2\%$

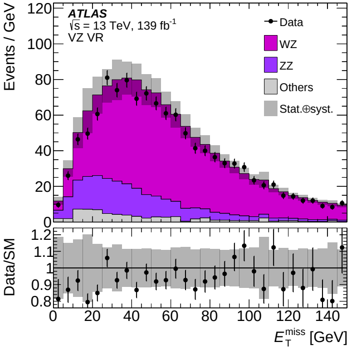
$Z \to \tau\tau \to e\mu + X$



VR: low $m(e\mu)$

Diboson WZ, ZZ $\} \sim 3\% \{$ **Diboson** $W\gamma, Z\gamma$

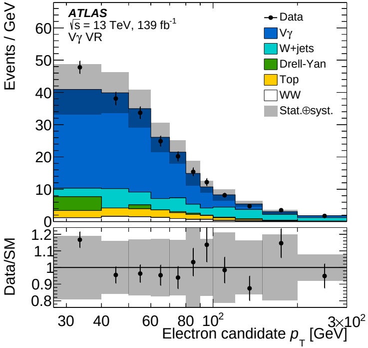
missed lepton(s)



VR: 3rd lepton req.,

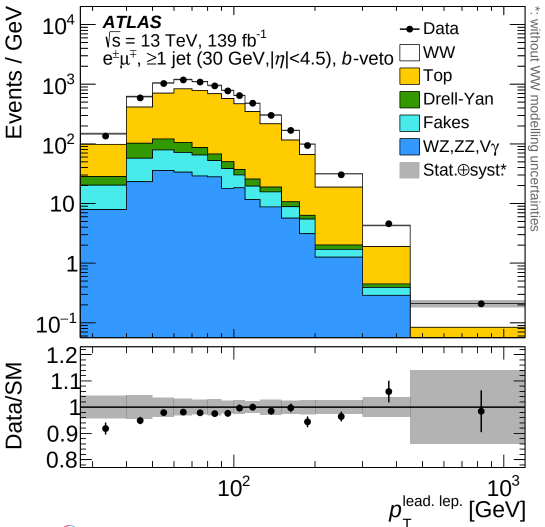
$m(\ell\ell) \simeq m_Z$

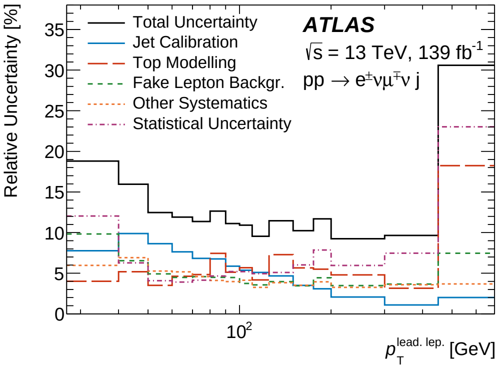
γ mis-reconstructed as e



VR: γ-like e-candidate

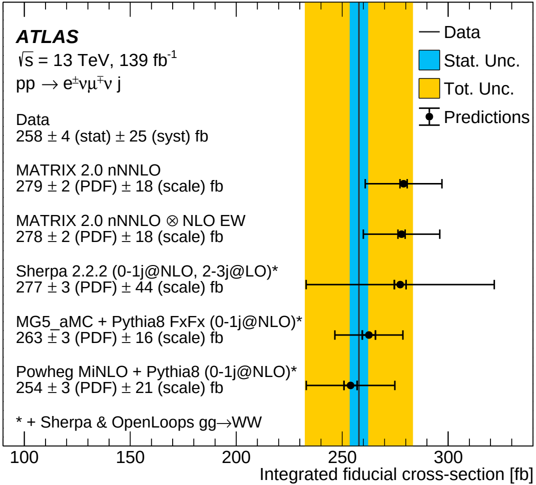
Detector-level results and uncertainties





- Data well described by signal and background estimates
- Dominant uncertainties: jets, top modelling and fakes

Results: fiducial cross-section

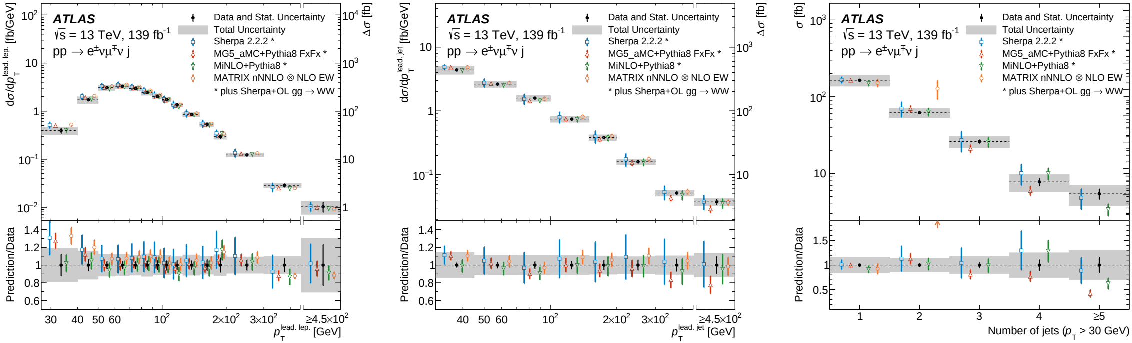


Fiducial selection requirements		
p_T^ℓ	$>$	27 GeV
$\lvert\eta^\ell\rvert$	$<$	2.5
$m_{e\mu}$	$>$	85 GeV
p_T^j	$>$	30 GeV
$\lvert y^j\rvert$	$<$	4.5

Results with a fiducial b-veto available on [HEPData]

- Using iterative Bayesian unfolding
- **Good agreement** with fixed order (MATRIX 2.0) and MC+PS (Sherpa, MG5_aMC@NLO and Powheg MiNLO)

Results: differential measurements



- Excellent agreement in differential measurements up to high p_T and many jets
- Also: measurements at high jet or lepton p_T $\rightarrow$ in good agreement

Summary and conclusions

[arXiv:2103.10319] [HEPData]

- First jet inclusive measurement of WW: ≥ 1 jet
  - Fiducial and differential cross sections
- Robust background estimate $\rightarrow$ small uncertainties
  - Data-driven estimate of dominant $t\bar{t}$ background: b-tag counting
  - Data-driven estimate of fake and non-prompt lepton backgrounds
  - Minor backgrounds from simulation, validated with data
- Unfolded measurement compared to state-of-the-art predictions
- Excellent agreement of fiducial and differential results
  - Up to high p_{T} and large number of jets

EFT interpretation (reduced helicity suppression) $\rightarrow$ Talk by [Thomas Calvet] tomorrow

Backup.

EFT interpretation

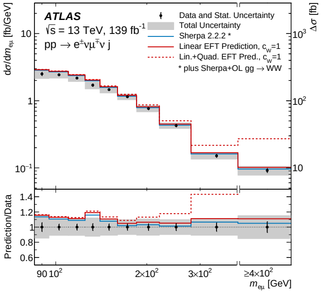
- SM EFT operator expansion in new physics scale Λ:

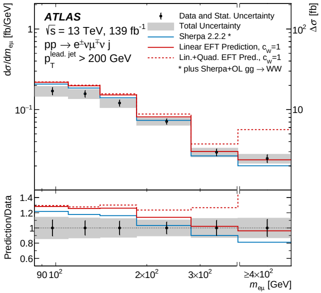
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^2}\mathcal{O}_j^{(8)} + \dots$$

- Contribution to observables:

$$|\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \sum_i \frac{c_i}{\Lambda^2} 2\Re(\mathcal{M}_i \mathcal{M}_{\text{SM}}) + O\left(\frac{1}{\Lambda^4}\right)$$

- Not all Λ^{-4} contributions known $\rightarrow$ sensitivity to interference important
- Interference with aTGC operators suppressed in diboson production (different dominant helicities for SM and BSM)
- Requirement of hard jet allows for additional helicity configurations, reduced suppression

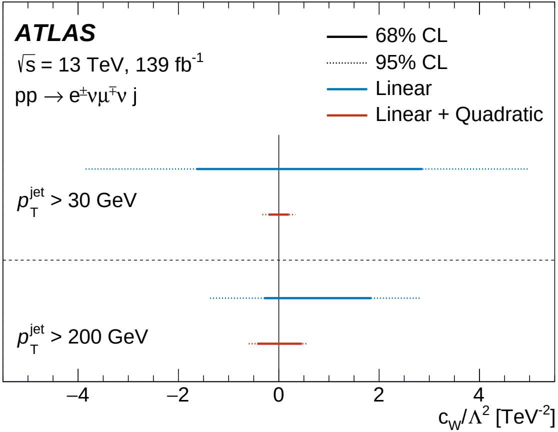




EFT interpretation

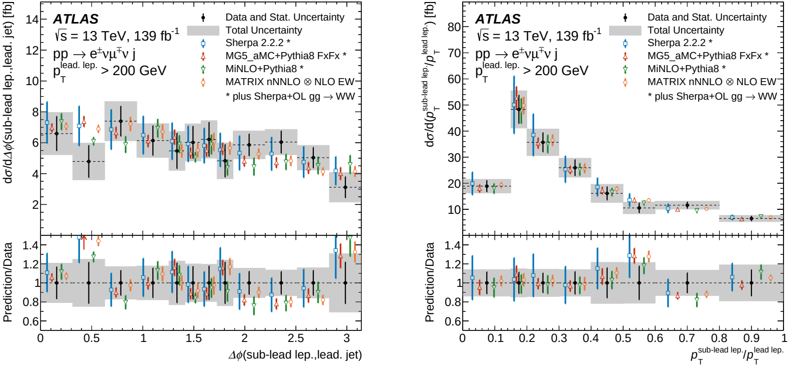
- EFT fit to unfolded cross sections
- Full covariance of measurement + nuisance parameters for signal theory uncertainties

⇒ Results compatible with SM



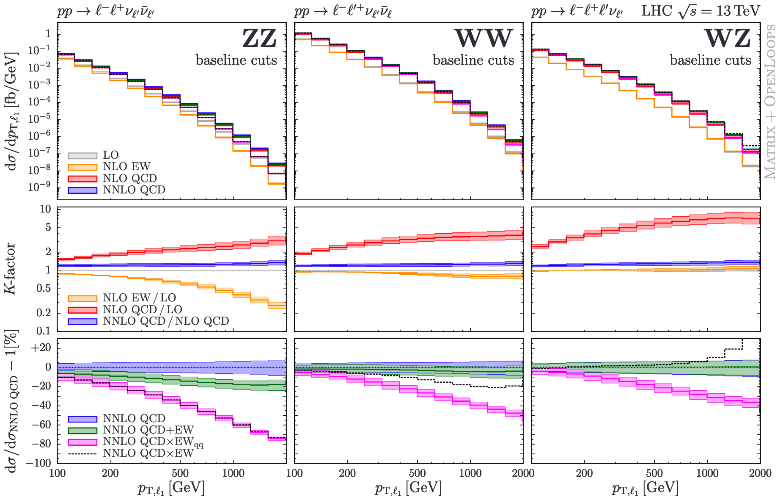
- Increased sensitivity to linear terms with 200 GeV jet requirement, but quadratic term dominant

Measurement at high leading lepton p_T



- > 'Giant K-factors' at high p_T in inclusive WW production
- > W+jets like with extra W emission
- > Measure in region with $p_T^{\text{lead. lep.}} > 200$ GeV
- > Good description even for sub-leading lepton close to a jet, and imbalanced leptons
- > Sensitivity to giant K-factors requires fully inclusive selection (≥ 0 jets)

Giant K-factors



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Object and event selection

Selection	Criteria
Lepton p_{T}	$> 27\,\mathrm{GeV}$
Lepton η	$\lvert\eta\rvert < 2.47$ and not $1.37 < \lvert\eta\rvert < 1.52$ (electron) $\lvert\eta\rvert < 2.5$ (muon)
Lepton identification	`TightLH` (electron), `Medium` (muon)
Lepton isolation	`Gradient` (electron), `Tight_FixedRad` (muon)
Lepton impact parameter	$\lvert d_0/\sigma_{d_0}\rvert < 5, 3$ (electron, muon) $\lvert z_0 \cdot \sin\theta\rvert < 0.5\,\mathrm{mm}$
Jet selection	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.5$
b-jet selection	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$, DL1r (85% eff. WP)
Lepton selection	1 electron and 1 muon of opposite charge, no additional lepton with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
Number of jets	≥ 1
Number of b-jets	0
$m_{e\mu}$	$> 85\,\mathrm{GeV}$
High $p_{\mathrm{T}}^{\text{lead. jet}}$ selection	$p_{\mathrm{T}}^{\text{lead. jet}} > 200\,\mathrm{GeV}$

Simulated samples

Process	Generator	Parton shower	Matrix element $\mathcal{O}(\alpha_S)$	Normalization
$q\bar{q} \to WW$	Sherpa 2.2.2	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†
$gg \to WW$	Sherpa 2.2.2	Sherpa	LO (0–1 jet)	Generator
$t\bar{t}$	Powheg-Box v2	Pythia 8	NLO	NNLO+NNLL
Wt	Powheg-Box v2	Pythia 8	NLO	NLO+NNLL
Z+jets	Sherpa 2.2.1	Sherpa	NLO (0–2 jets), LO (3–4 jets)	NNLO
WZ, ZZ	Sherpa 2.2.2	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†
$W\gamma$, $Z\gamma$	Sherpa 2.2.8	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†
VVV	Sherpa 2.2.2	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†

†: The cross-section calculated by Sherpa is found to be in good agreement with the NNLO result .

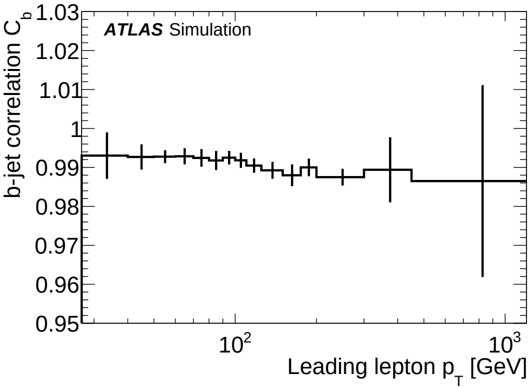
Breakdown of uncertainties

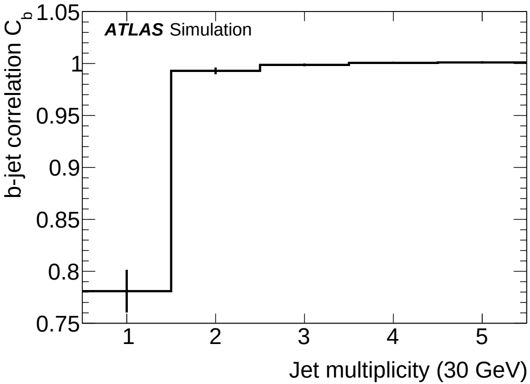
Uncertainty source	Relative effect
Total uncertainty	10%
Signal region statistical uncertainty	1.1%
Data-driven background and MC statistics	1.2%
Jet calibration	6.3%
Top modelling	4.5%
Fake-lepton background	4.3%
Signal modelling	2.7%
Other background	2.3%
Flavour tagging	2.3%
Luminosity	1.9%
Other systematic uncertainties	0.6%

Breakdown of selected events

	Signal region		$p_T^{\text{lead. jet}} > 200$ GeV	
Data	89 239		5825	
Total SM	91 600 ± 2500		5980 ± 150	
WW	28 100 ± 1200	31%	2480 ± 60	42%
Total bkg.	63 500 ± 1800	69%	3500 ± 140	58%
Top	55 800 ± 1500	61%	3030 ± 110	51%
Drell–Yan	2200 ± 700	2%	66 ± 9	1%
Fake leptons	2700 ± 1100	3%	140 ± 70	2%
$WZ, ZZ, V\gamma$	2800 ± 500	3%	270 ± 70	4%

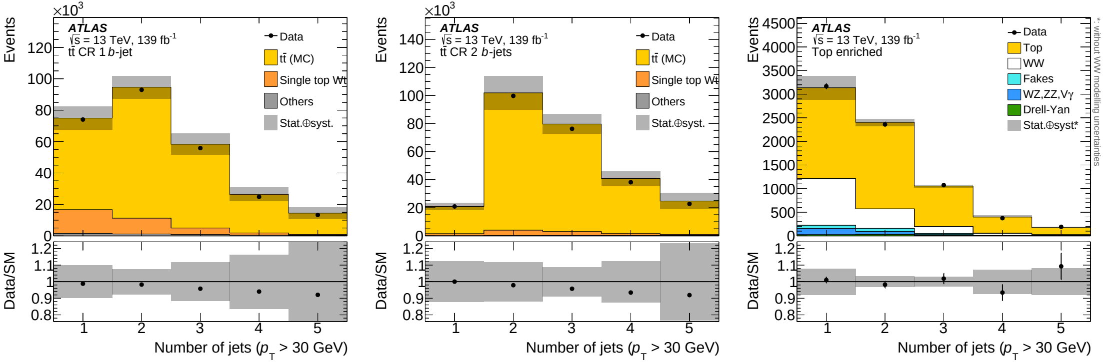
Top estimate: b-jet correlation



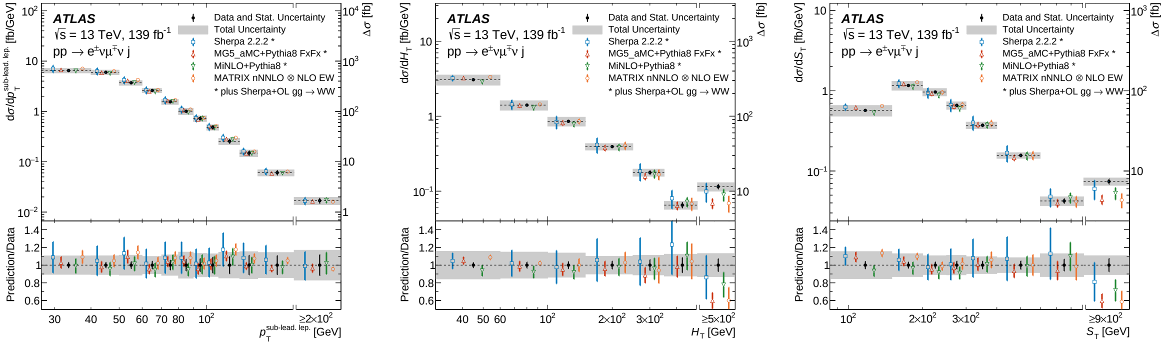


$$C_b = \frac{\varepsilon_{bb}}{\varepsilon_b^2} = \frac{4 N^{t\bar{t}}_{\text{MC}} N^{t\bar{t}}_{2b,\text{MC}}}{\left(N^{t\bar{t}}_{1b,\text{MC}} + 2 \cdot N^{t\bar{t}}_{2b,\text{MC}}\right)^2}$$

Top estimate: jet multiplicity



Results: differential measurements



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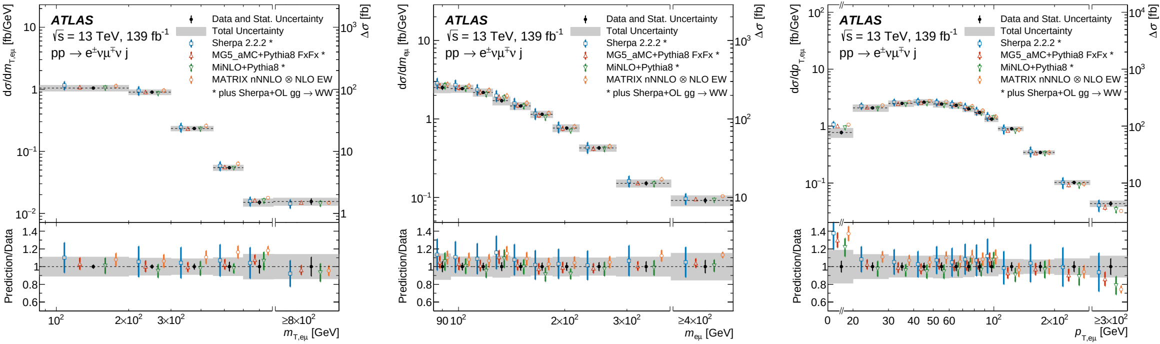

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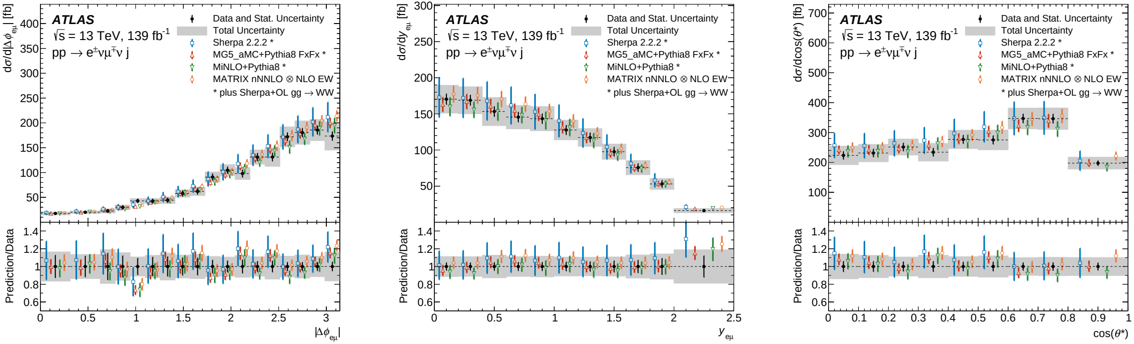

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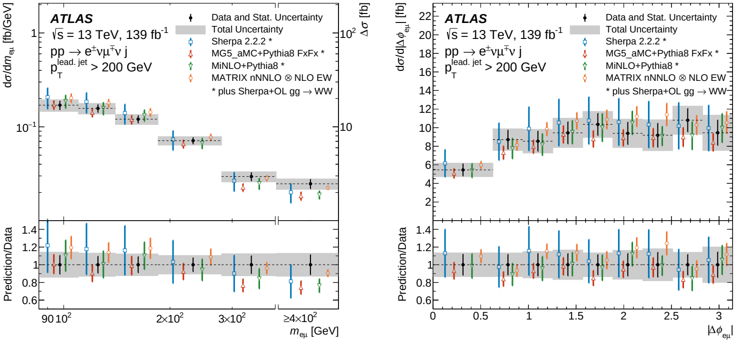

Results: differential measurements