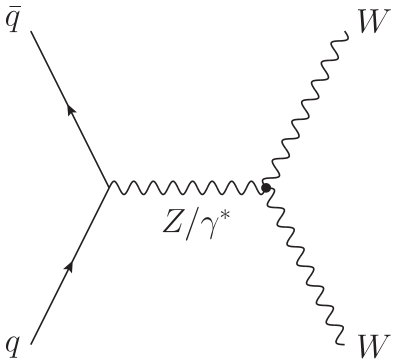
@julian.macdonald.photography

Measurements of W^+W^- production cross sections at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Jack C. MacDonald

IOP Joint APP, HEPP and NP Conference
12-15th April 2021, Online

Introduction



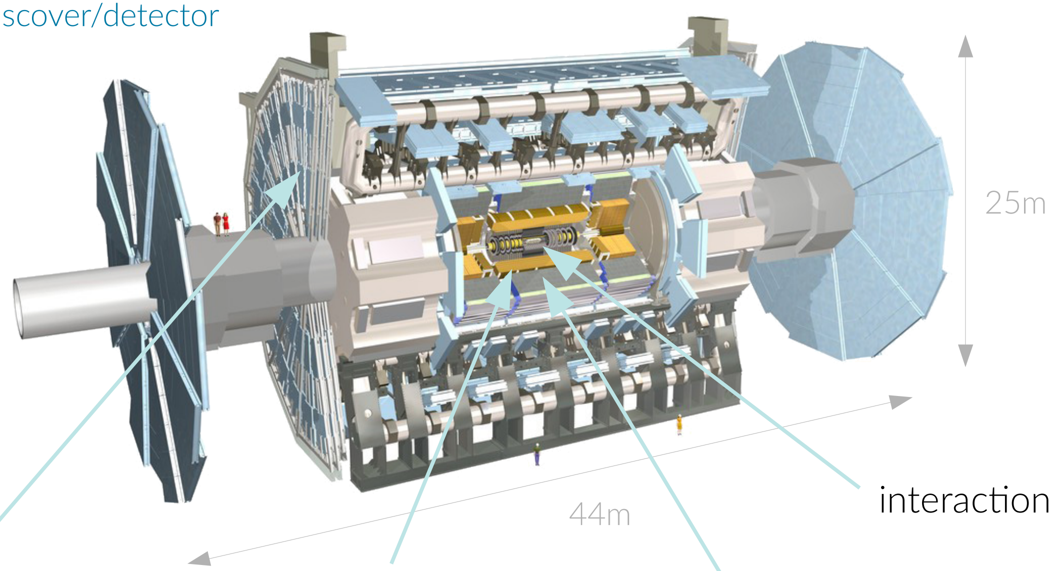
- **WW measurements provide precision tests of Standard Model (SM)**
  - Sensitive to properties of gauge boson self-interactions
  - Test of perturbative quantum chromodynamics (pQCD) and electroweak (EW) theory
- **Important background for $H \rightarrow WW$ measurements and BSM searches**
- **Previous WW measurements at the LHC:**
  - $\sqrt{s}$ = 7 TeV arXiv:1210.2979 arXiv:1306.1126 2013
    $\sqrt{s}$ = 8 TeV arXiv:1603.01702 arXiv:1507.03268 arXiv:1608.03086 ↓
    $\sqrt{s}$ = 13 TeV arXiv:1702.04519 arXiv:1905.04242 arXiv:2009.00119 2020
  - All limit number of hadronic jets to reduce backgrounds

Most recent ATLAS measurement inclusive over jets → focus of this talk 2021

→ shown at Moriond in March 2021

ATLAS detector and reconstruction

https://atlas.cern/discover/detector



Muon spectrometer **Tracker (ID)** **EM** and **hadronic calorimeters**

Muons = tracks in tracker and muon spectrometer
$|\eta| < 2.5$

Electrons = calorimeter deposits and tracks
$|\eta| < 2.47$ (excl. $1.37 < |\eta| < 1.52$)

arXiv:1703.10485
arXiv:0802.1189 ← *Jets* = (anti-k_T) clustered calorimeter deposits and tracks
$|\eta| < 4.5$

ATL-PHYS-PUB-2017-013
arXiv:1907.05120 ← Secondary vertices from *b*-hadron decays allow for *b*-jet identification (DL1r)

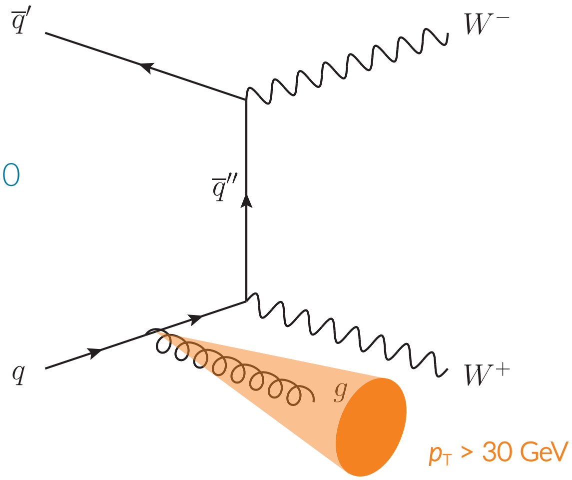
$WW + \geq 1$ jet analysis in a nutshell

Paper: arXiv:2103.10319

Motivation

- **Jet-inclusive differential measurements made for first time at LHC**
- **Improved precision in fully inclusive measurement** (when combined with jet veto measurement)
- **Improved sensitivity to BSM physics**
  - Effective field theory (EFT) interference term less helicity suppressed than in jet veto case

→ arXiv:1707.08060



Analysis strategy

- **Count $pp \to e\nu\mu\nu$ (+ jets) events**
  - Data binned in 12 observables*
- **Estimate backgrounds**
  - Dominant contribution from $t\bar{t}$ events → estimate with data-driven method
  - Fakes (data-driven), Z+jets, diboson, $V\gamma$
- **Unfolded result = detector $^{-1}$ (data – backgrounds)**

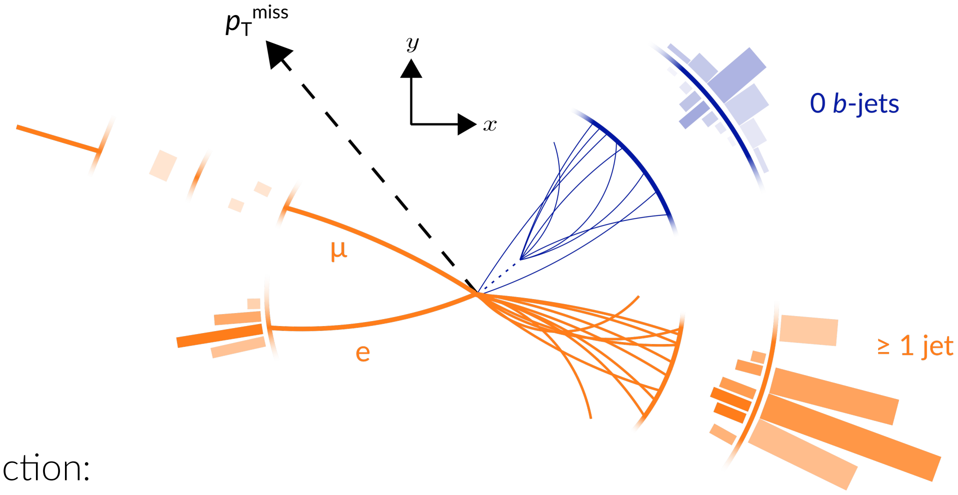
* $p_T^{\text{lead.lep.}}$, $p_T^{\text{sublead.lep.}}$, $p_T^{\text{lead.jet.}}$, n jets, $m_{e\mu}$, $p_{T,e\mu}$, H_T, S_T, $m_{T,e\mu}$, $\Delta\varphi_{e\mu}$, $\cos\theta^*$

Event selection

- Lepton and jet cuts:

p_T^e, p_T^μ > 27 GeV

≥ 1 jet
p_T > 30 GeV



- Selections for background rejection:

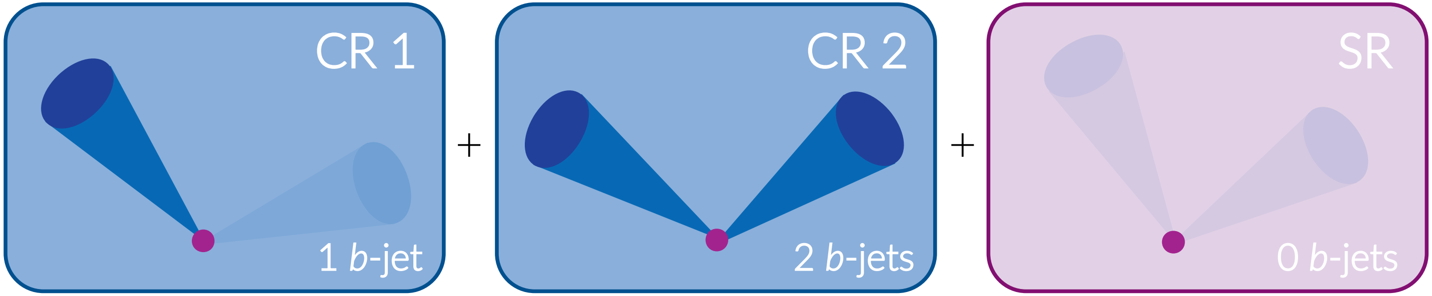
opposite flavour leptons → *Rejects:* $Z/\gamma^* \to ee/\mu\mu$

$m_{e\mu}$ > 85 GeV → *Rejects:* $Z/\gamma^* \to \tau\bar{\tau}$ where $\tau \to e/\mu$ $(+\nu\nu)$

b-jet veto
p_T > 20 GeV → *Rejects:* $t\bar{t}$ and Wt

Top estimate ($t\bar{t}$ + Wt)

- **Top events account for ~61% of events in signal region (SR)**
  - Use data-driven '*b*-tag counting' method inspired by $t\bar{t}$ cross-section measurement → arXiv:1910.08819
  - Two control regions (CRs) with different numbers of *tagged* b-jets



$$\underbrace{\underset{\mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}}{N_{t\bar{t}}}}_{t\bar{t}\text{ count}} = \underbrace{\underset{\mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}\cdot 2\epsilon_b\,(1-C_b\epsilon_b)}{N^{1b}_{t\bar{t}}} + \underset{\mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}\cdot C_b\epsilon_b^2}{N^{2b}_{t\bar{t}}}} + \underbrace{\underset{\mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}\cdot\left(1-2\epsilon_b+C_b\epsilon_b^2\right)}{N^{\mathrm{SR}}_{t\bar{t}}}}$$

$t\bar{t}$ enhanced CRs → count events in **data**
(subtract small backgrounds from MC)

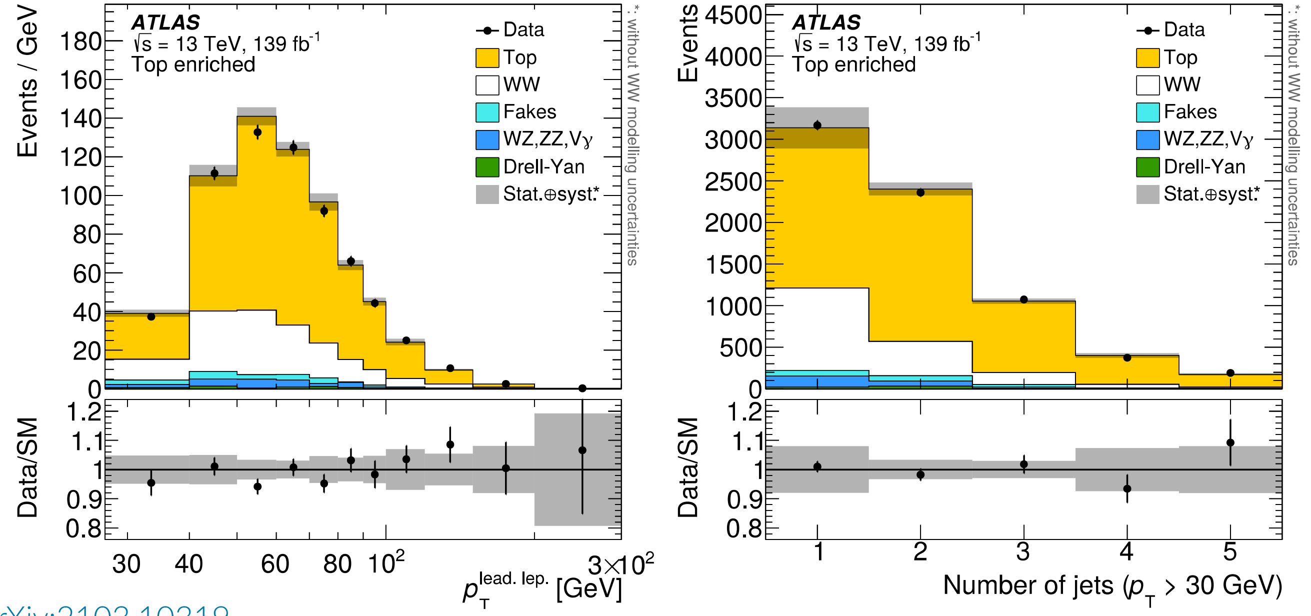
what we want
(solve simultaneous equations)

- ***$t\bar{t}$* modelling only enters in C_b**
- **Single top (*Wt*) contribution from MC**

ϵ_b = *b*-jet selection efficiency
C_b = correlation factor (MC)

Top estimate ($t\bar{t}$ + Wt) validation

- **Estimate strongly reduces systematic uncertainties:** 15% (pure MC) → 2.8%
  - Anti-correlation between some $t\bar{t}$ and Wt systematics reduces total uncertainty
- **Extensive closure tests performed**
- **Check estimate in top enriched validation region (VR):** $m_{lj} < 140$ GeV, $\Delta\varphi_{e\mu} < \pi/2$ (+ SR)



arXiv:2103.10319

Fake estimate

- **Fake = jet misidentified as lepton / lepton from heavy flavour (HF) decay**, e.g. *W*+jets (3%)
- **Poorly modelled** → estimate contribution with data-driven fake factor (FF) method
  - Use two auxiliary regions: *dijet* and *ID+anti-ID*

e/*μ* selection in SR = ID
orthogonal selection = anti-ID

Dijet region (dominated by two-jet events)

Extract **fake factors** here

$$\mathrm{FF} = \frac{N_{\mathrm{ID}} - N^{\mathrm{prompt}}_{\mathrm{ID,MC}}}{N_{\text{anti-ID}} - N^{\mathrm{prompt}}_{\text{anti-ID,MC}}} = \frac{\text{ID}}{\text{anti-ID}}$$

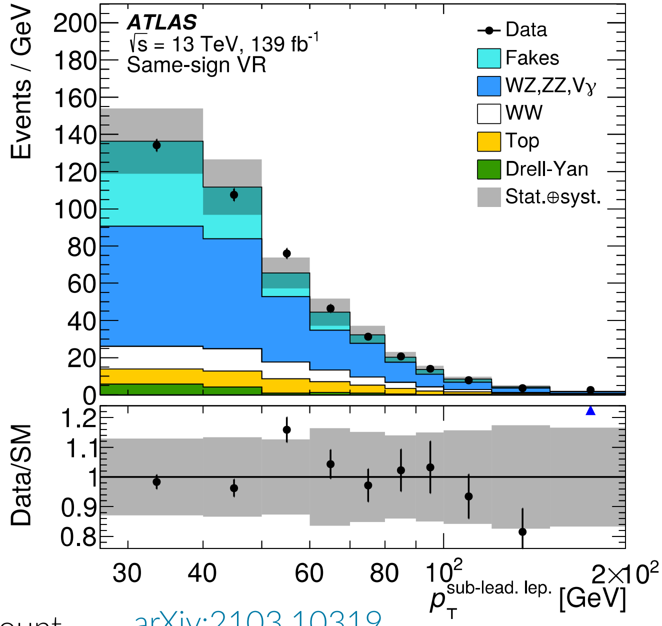
ID+anti-ID region (SR with one ID → anti-ID)

Apply fake factors here

$$N^{\text{non-prompt}}_{\mathrm{ID+ID}} = \mathrm{FF} \times \left(N_{\text{ID+anti-ID}} - N^{\mathrm{prompt}}_{\text{ID+anti-ID,MC}}\right)$$

$$= \frac{\text{ID}}{\text{anti-ID}} \times (\text{ID+anti-ID}) = (\text{ID+ID})$$

fake count in SR

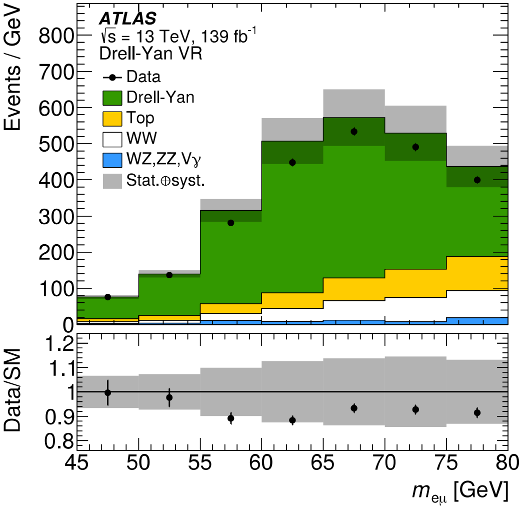


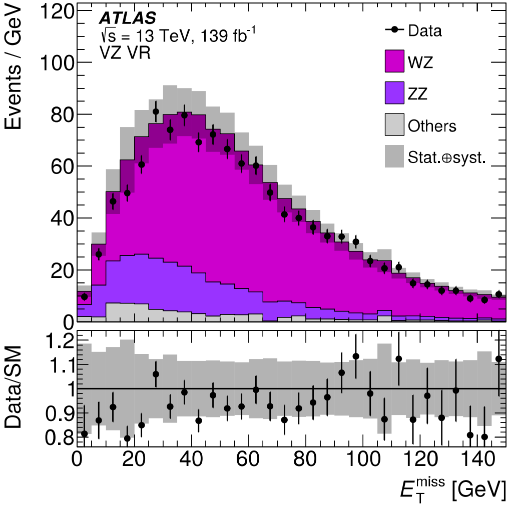
arXiv:2103.10319

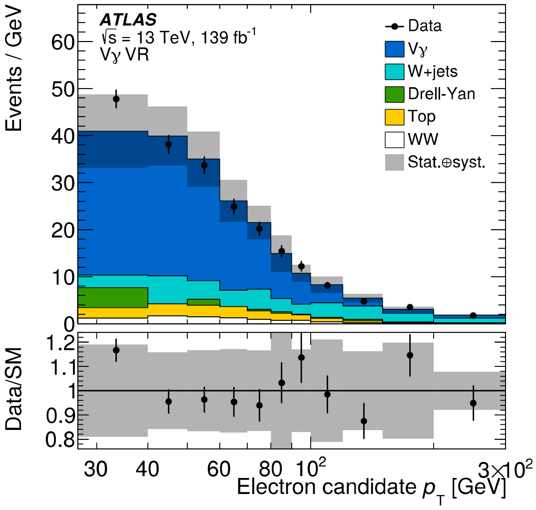
- **FF estimate validated in same sign region**

Other backgrounds

- **All remaining backgrounds estimated from simulation and validated in dedicated VRs**
  - Account for ~3% of events in SR
  - *Z*+jets (Drell-Yan), *VZ*, *Vγ*
  - Triboson negligible (< 0.1% of selected events)



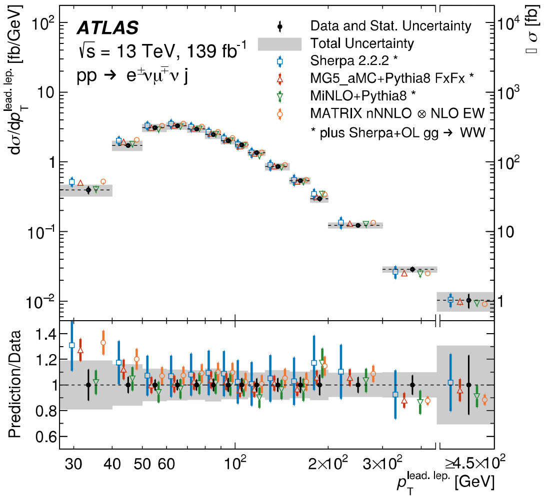


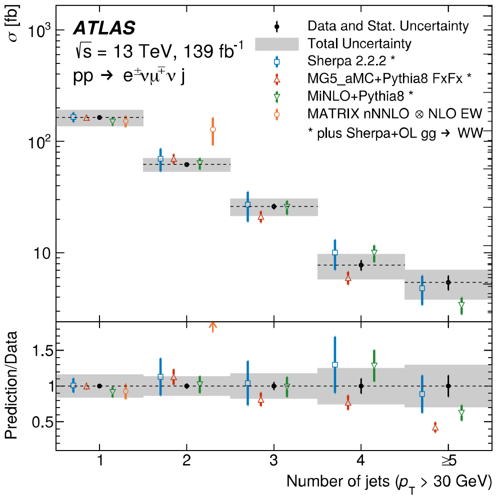


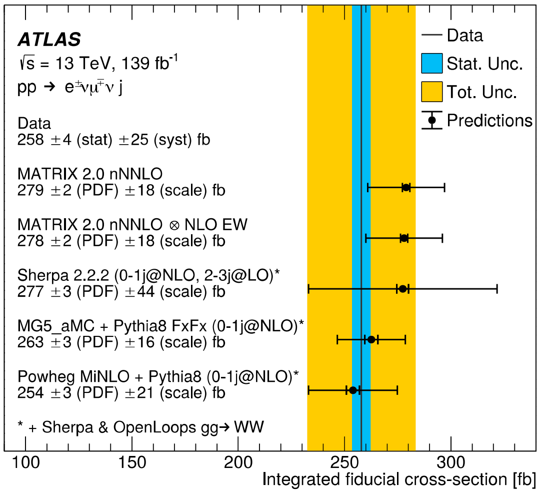
arXiv:2103.10319

Results

- **Correct for detector effects** using iterative Bayesian unfolding method ⟶ D'Agostini, 95 arXiv:1010.0632
- **Unfolded results obtained for fiducial and differential cross sections**
  - σ_{fid} = 258 ± 4 (stat.) ± 25 (syst.) fb
  - Total uncertainty of ~10% driven by jet calibration, top and fake contributions
- **Excellent agreement seen with theoretical predictions**







arXiv:2103.10319

Conclusions

- **First *WW* jet-inclusive differential measurements performed at LHC**
- **Reduction of uncertainties in dominant top background** using powerful data-driven $t\bar{t}$ estimate
- **Fiducial and differential cross sections agree with theoretical predictions** up to highest measured p_{T} and for up to 5 jets

Analysis team proceeding to look at *WW* + 0 jets

In near future combine results for high precision fully inclusive measurement

Backup

Top estimate ($t\bar{t}$) calculation details

- **Number of $t\bar{t}$ events passing $e\mu$ selection:**

$$N_{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}$$

$e\mu$ selection efficiency

$t\bar{t}$ (+jets) cross-section

- **Number of $t\bar{t}$ events in CRs obtained from data** (backgrounds estimated with MC)

$$N^{2b}_{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu} \cdot C_b\epsilon_b^2$$
$$N^{1b}_{t\bar{t}} = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu} \cdot 2\epsilon_b\left(1 - C_b\epsilon_b\right)$$

ϵ_b = efficiency to find and tag a *b*-jet
ϵ_{bb} = efficiency to find and tag two *b*-jets
$C_b = \epsilon_{bb}/\epsilon_b^2$ = correlation factor

- **Solve for** $\epsilon_b = \dfrac{2N^{2b}_{t\bar{t}}}{C_b\left(N^{1b}_{t\bar{t}} + 2N^{2b}_{t\bar{t}}\right)}$ $\quad \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu} = \dfrac{C_b}{4}\dfrac{\left(N^{1b}_{t\bar{t}} + 2N^{2b}_{t\bar{t}}\right)^2}{N^{2b}_{t\bar{t}}}$

- **Obtain estimate in SR**

$$\begin{aligned} N^{SR}_{t\bar{t}} &= N_{t\bar{t}} - N^{1b}_{t\bar{t}} - N^{2b}_{t\bar{t}} \\ &= \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu} \cdot \left(1 - 2\epsilon_b + C_b\epsilon_b^2\right) \end{aligned}$$

$$\boxed{N^{SR}_{t\bar{t}} = \frac{C_b}{4}\frac{\left(N^{1b}_{t\bar{t}} + 2N^{2b}_{t\bar{t}}\right)^2}{N^{2b}_{t\bar{t}}} - N^{1b}_{t\bar{t}} - N^{2b}_{t\bar{t}}}$$

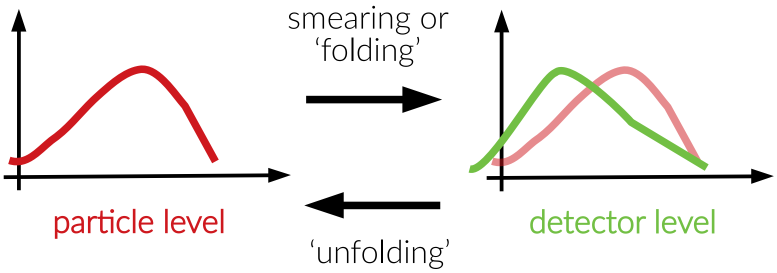
$$N^{ib}_{t\bar{t}} = N^{ib}_{\text{data}} - N^{ib}_{\text{bkg,MC}}$$

$$C_b = \frac{4N^{0+1+2b}_{t\bar{t},\text{MC}}N^{2b}_{t\bar{t},\text{MC}}}{\left(N^{1b}_{t\bar{t},\text{MC}} + 2N^{2b}_{t\bar{t},\text{MC}}\right)^2}$$

only use of $t\bar{t}$ modelling
$C_b^{fid.}$ = 0.991 ± 0.002

Unfolding details

- **Want fiducial-level cross sections** → need to 'undo' detector effects



D'Agostini, 95
arXiv:1010.0632

- **Use iterative Bayesian unfolding method**
  - Events can move from one truth-level bin to a different detector-level bin → describe by *migration matrix*
  - Match truth and detector level selections as closely as possible
  - Additional corrections applied for reconstruction inefficiencies/inaccuracies

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

iterate

contains prior from signal model

$$N^j_{\text{unf}} = \underbrace{\frac{1}{\epsilon^j_{\text{reco}}}}_{\text{reco. efficiency}} \sum_{i=1}^{n_{\text{reco bins}}} \left(N^i_{\text{data}} - N^i_{\text{bkg}}\right) \cdot \underbrace{f^i_{\text{fid}}}_{\text{fid. correction}} \cdot \underbrace{P(N^j_{\text{true}}|N^i_{\text{reco}})}_{\text{calculated from migration matrix via Bayes' theorem}}$$

- **Optimise number of iterations** to reduce prior bias and stat. fluctuations

Extra: EFT interpretation

- **SM can be considered as EFT** with additional dim. > 4 operators suppressed by some UV scale Λ

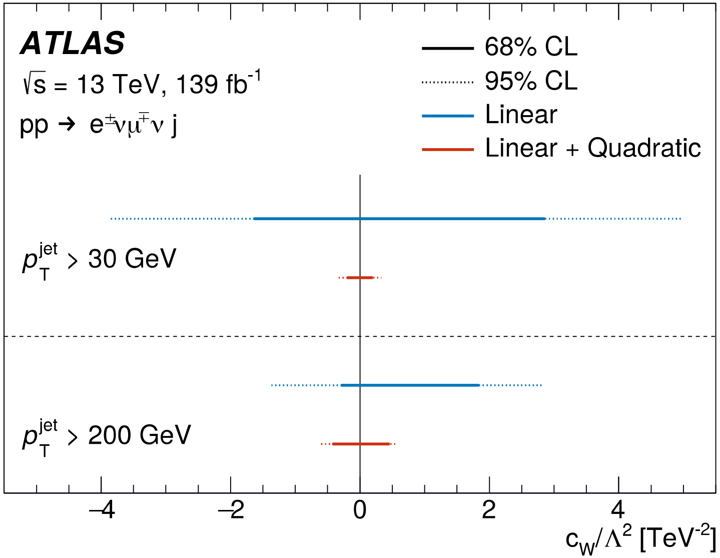
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i,d>4} \frac{c_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}$$

- **Small scale EFT study**: focus on dim. 6
  - Analysis sensitive to Q_W affecting gauge boson self-couplings ⟶ arXiv:1008.4884
  - Importance of SM+BSM interference term in cross section expected to increase with jet p_T

$$\sigma = \underbrace{\sigma_{\text{SM}}}_{\text{purely SM}} + \underbrace{\frac{c_W}{\Lambda^2}\sigma_{\text{int}}}_{\text{SM+BSM}} + \underbrace{\frac{c_W^2}{\Lambda^4}\sigma_{\text{BSM}}}_{\text{purely BSM}}$$

Fitting and results

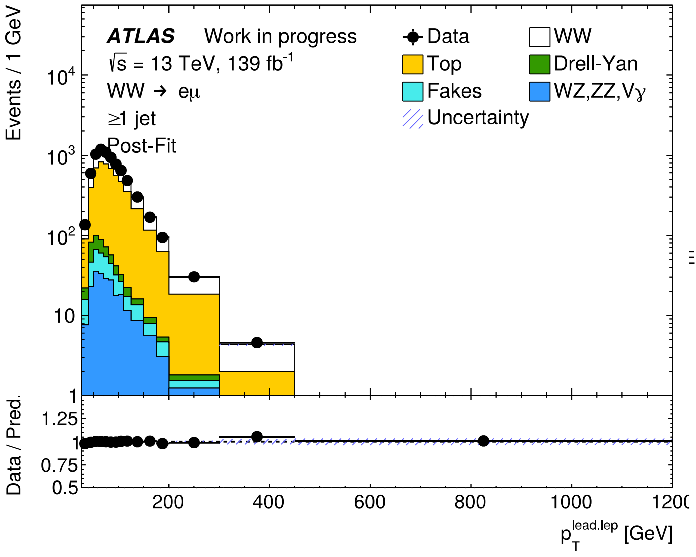
- **Perform likelihood fits in dedicated $p_T^{\text{lead.jet}}$ > 200 GeV region** using (unfolded) $m_{e\mu}$ distribution
- **Impact of quadratic term seen to reduce** compared to $p_T^{\text{lead.jet}}$ > 30 GeV (nominal SR) fit

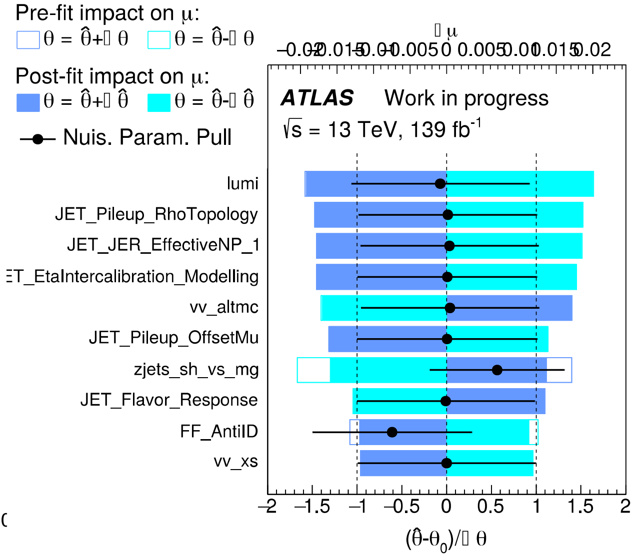


arXiv:2103.10319

Looking to the future: fitting

- **Performing profile likelihood fits to data in SR** → alternative strategy to “cut-and-count” approach shown here
    - Use simulated signal and backgrounds on reconstruction-level, including effects of modelling and experimental systematic uncertainties
    - Extract signal (and background) normalisation as POI
- e.g. **validation of top estimate** (shown here) in $p_T^{\text{lead.lep.}}$ fit with μ_{WW} and μ_{Top} as POIs





$\hat{\mu}_{WW} = 0.96 \pm 0.09$

$\hat{\mu}_{Top} = 1.00 \pm 0.05$