Differential Inclusive Single W/Z Measurements Sensitive to PDFs and EFT in ATLAS and CMS

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Introduction

W / Z : Weak force carriers discovered 40 years ago → key tools in precision tests of the Standard Model (SM)

- LHC: high energy + high luminosity → "W and Z factory"

$O(10^9)$ $W \to l\nu$, $O(10^8)$ $Z \to ll$ for each $l = e, \mu, \tau$ in Run 2 at 13 TeV

- negligible statistical uncertainty: differential cross-sections

SM precisely predicts production/decay rates and properties

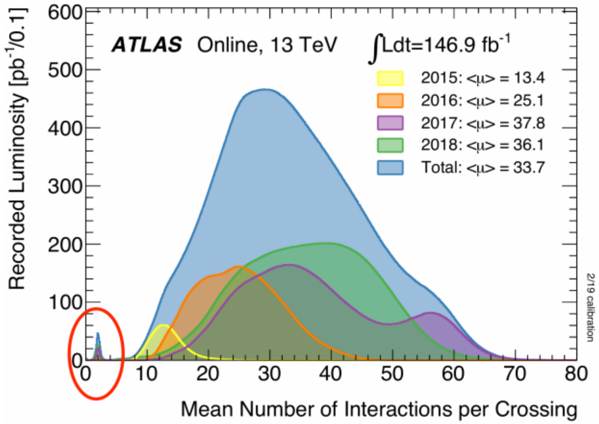
- Stringent tests of QCD and electroweak (EW) calculations
- Sensitivity on Effective Field Theory (**EFT**)
- Constraint on Parton Distribution Functions (**PDFs**): a large number of inclusive and differential cross sections measured by the ATLAS, CMS, and LHCb experiments have already been used by different PDF groups to improve the precision on the PDFs

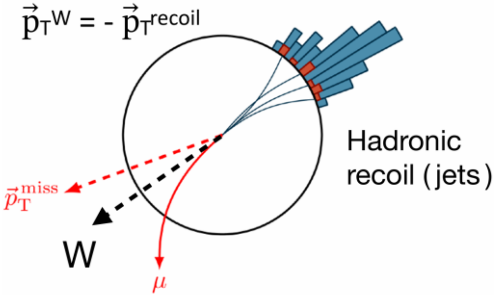
Precision W differentials @ 5.02 TeV & 13 TeV

arXiv: 2502.09403

$W \to l\nu$ key challenge: the missing transverse momentum, p_T^{miss}

- Dedicated low pileup ($<\mu>\sim 2$) data: 255 pb^{-1} (5.02 TeV), 338 pb^{-1} (13 TeV)
- Excellent experimental conditions for a clean hadronic recoil energy measurement.





- Phase space: $p_T^{l/\nu} > 25$ GeV, $|\eta^l| < 2.5$, $m_T^W > 50$ GeV ($m_T^W = \sqrt{2p_T^l p_T^\nu(1-\cos(\Delta\phi))}$)
- Signal process: $pp \to W^{\pm} \to e\nu/\mu\nu$
- Use $Z \to ll$ for the recoil response calibration

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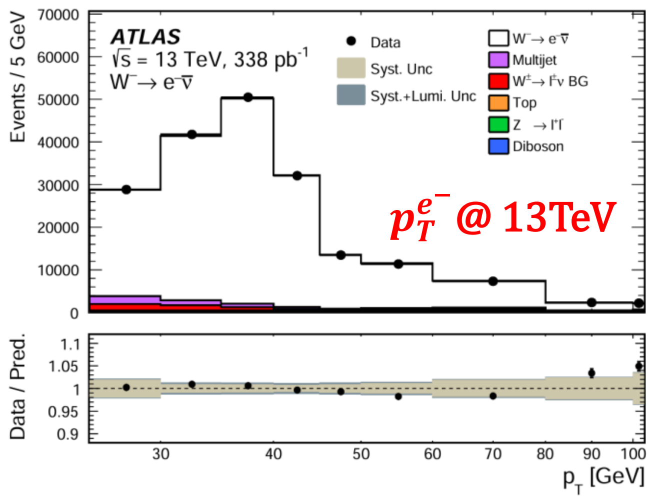
- For each energy, $d\sigma/d|\eta|$, $d\sigma/dp_T$, and $d^2\sigma/d|\eta|dp_T$ are measured for W^+, W^- and in e and μ final states.
- **Backgrounds**: MC simulation (EW and top), data-driven (multijet)
- **Good data-prediction agreement** at detector-level.
- **Unfolding**: Iterative Bayesian
- The e-channel and μ-channel are compared and then **combined** (the BLUE method).



Channel	Observed	Expected	Signal [%]	$W \to \ell\nu$ BG [%]	$Z \to \ell\ell$ [%]	Top [%]	Diboson [%]	Multijet [%]
$\sqrt{s}$ = 5.02 TeV $W \to \ell\nu$								
$W^- \to e^-\bar{\nu}$	274375	276000 ± 1000	95.8	2.6	0.4	0.3	0.1	0.8 ± 0.4
$W^+ \to e^+\nu$	430662	431000 ± 1000	96.8	2.1	0.3	0.2	0.1	0.5 ± 0.2
$W^- \to \mu^-\bar{\nu}$	288026	289000 ± 1000	94.8	1.8	2.9	0.3	0.1	0.1 ± 0.3
$W^+ \to \mu^+\nu$	457223	457000 ± 1000	95.8	1.7	2.1	0.2	0.1	0.1 ± 0.2
$\sqrt{s}$ = 13 TeV $W \to \ell\nu$								
$W^- \to e^-\bar{\nu}$	949297	947000 ± 6000	92.6	2.4	0.7	1.3	0.2	2.9 ± 0.6
$W^+ \to e^+\nu$	1207652	1192000 ± 7000	93.7	2.1	0.6	1.1	0.1	2.4 ± 0.6
$W^- \to \mu^-\bar{\nu}$	964514	966000 ± 4000	92.9	1.5	3.5	1.2	0.2	0.6 ± 0.4
$W^+ \to \mu^+\nu$	1245755	1230000 ± 4000	93.8	1.5	3.1	1.0	0.1	0.5 ± 0.3

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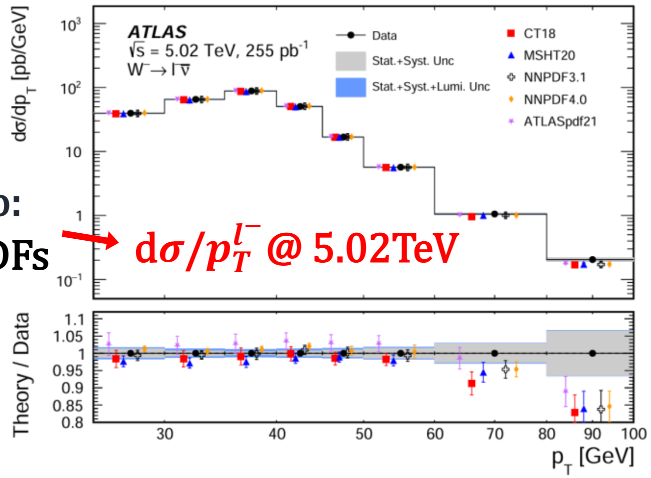
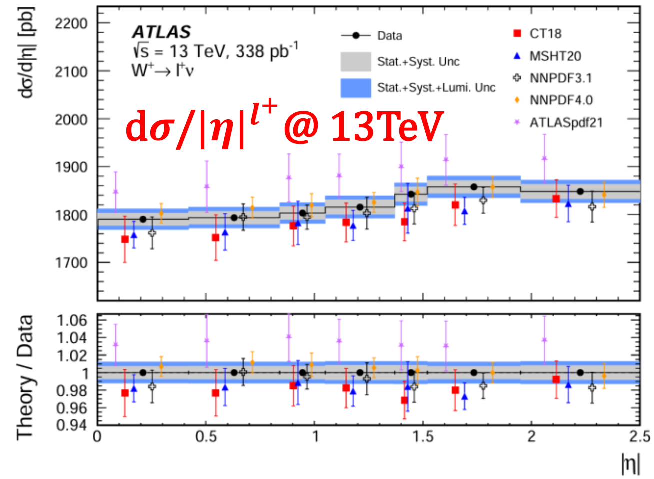
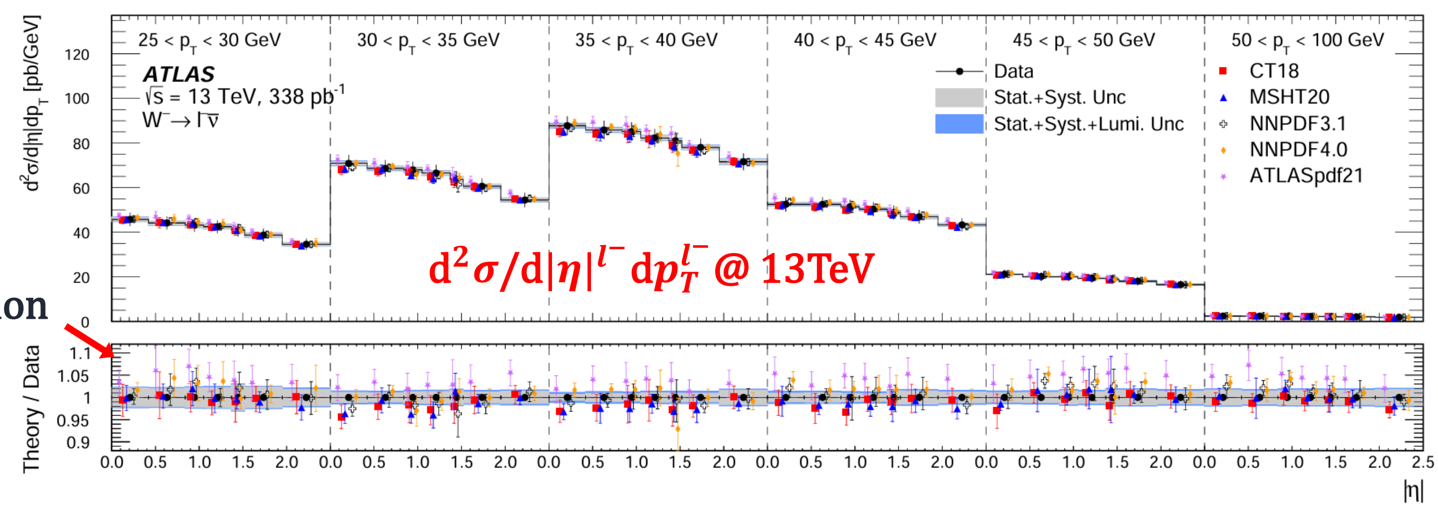
For each energy, $\mathrm{d}\sigma/\mathrm{d}|\eta|$, $\mathrm{d}\sigma/\mathrm{d}p_T$, and $\mathrm{d}^2\sigma/\mathrm{d}|\eta|\mathrm{d}p_T$ are measured for W^+, W^-.

Sensitive to:
m_W, m_T^W, PDFs





High precision



Precision W differentials @ 5.02 TeV & 13 TeV

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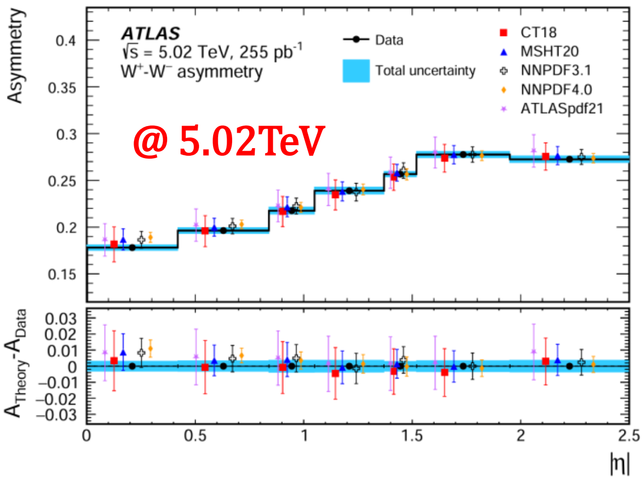
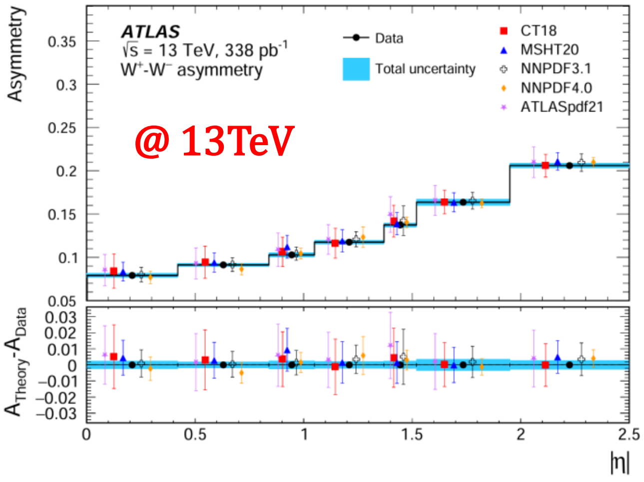
W-boson charge asymmetries are measured at both energies using the measured $d\sigma/d|\eta|$.

- experimental uncertainties cancel out
- more precise than the predictions (<1.8% @5.02 TeV, < 3% @13TeV)
- good potential to constrain the PDFs (for u and d quarks)

$$A_l(|\eta|) = \frac{\frac{d\sigma_{W^+}}{d|\eta|} - \frac{d\sigma_{W^-}}{d|\eta|}}{\frac{d\sigma_{W^+}}{d|\eta|} + \frac{d\sigma_{W^-}}{d|\eta|}}$$





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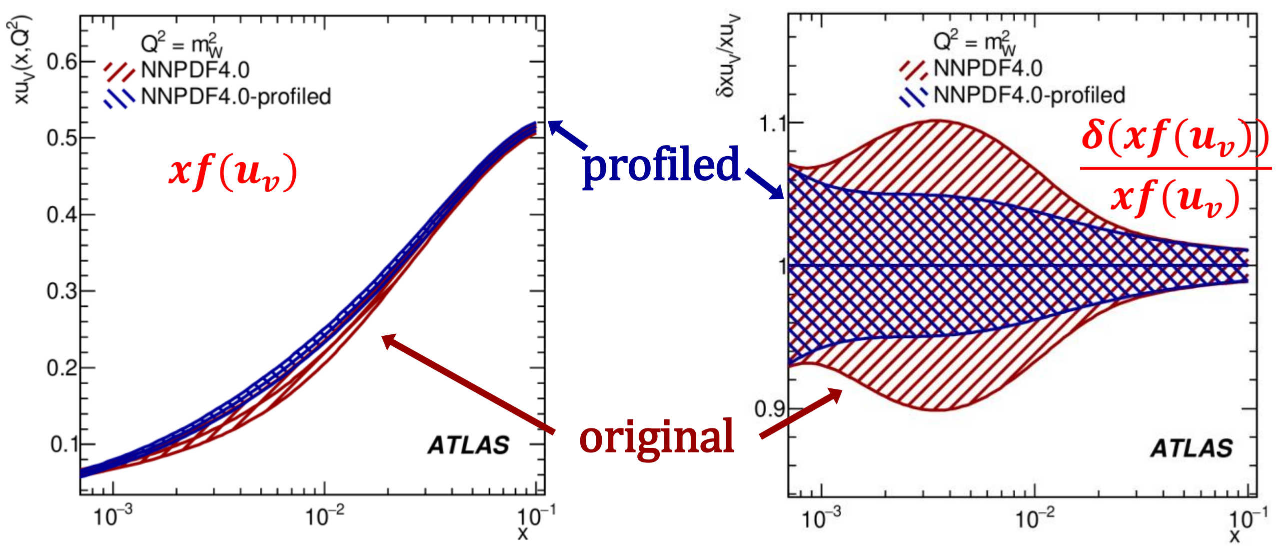
PDF impact profiling

- Performed in the xFitter framework, minimizing:

$$\chi^2(\vec{\beta}^{\mathrm{exp}}, \vec{\beta}^{\mathrm{th}}) = \sum_{i}^{N_{\mathrm{data}}} \left(\frac{\sigma_i^{\mathrm{exp}} - \sigma_i^{\mathrm{th}} \left(1 - \sum_j \beta_j^{\mathrm{exp}} \gamma_{ij}^{\mathrm{exp}} - \sum_k \beta_k^{\mathrm{th}} \gamma_{ik}^{\mathrm{th}}\right)}{\Delta_i} \right)^2 + \sum_{j}^{N_{\mathrm{exp,sys}}} \left(\beta_j^{\mathrm{exp}}\right)^2 + \sum_{k}^{N_{\mathrm{th,sys}}} \left(\beta_k^{\mathrm{th}}\right)^2$$

- Uncertainty reduced ($\sim$50% around $x = 0.004$)
- NNPDF4.0 (similar improvement is also observed for CT18, MSHT20 and ATLASpdf21)



First measurement of W differentials @ High-m_T^W

[arXiv: 2502.21088]

High m_T^W : 200 GeV ~ 5000 GeV

- Full Run2 data: 140 fb^{-1} @13 TeV

Bjorken variable x: the fraction of the parton momentum to the energy of the proton,

$$x = \frac{\sqrt{Q_T^2 + M^2}}{\sqrt{s}} \cdot e^{\pm Y}$$

Motivation for high mass:

- High-x region of the proton structure, where PDFs are less well constrained

$$x \sim 10^{-2} \text{ up to } x \sim 1$$

- Sensitive to new physics beyond the SM, which can be described in terms of EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \mathcal{L}^{(d)} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

First measurement of the cross-section for the process $pp \rightarrow l\nu + X$ above the W resonance production region.

First measurement of W differentials @ High-m_T^W

arXiv: 2502.21088

Phase space: $p_T^l > 65$ GeV, p_T^ν (E_T^{miss})> 85 GeV, $|\eta^l| < 2.4$, 200 GeV $< m_T^W < 5000$ GeV

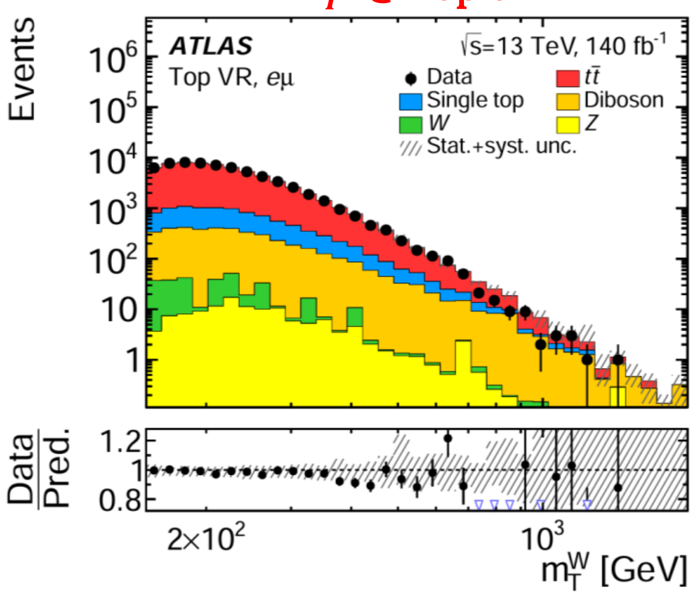
Signal process: $pp \rightarrow W^\pm \rightarrow e\nu/\mu\nu$

Background:

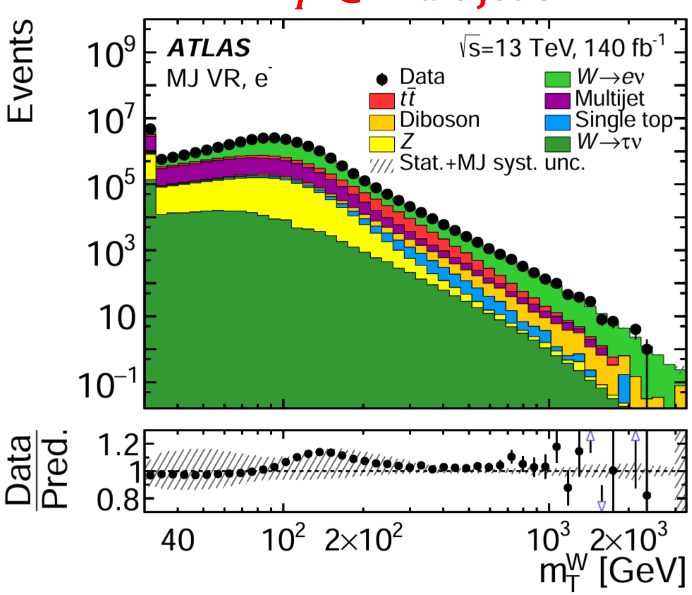
- MC simulation: $Z \rightarrow ll$, $W \rightarrow \tau\nu$, diboson, top (validated in $e\mu$ region with 94% Top events)
- data-driven: multijet (matrix method)

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_r & \epsilon_f \\ 1-\epsilon_r & 1-\epsilon_f \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix} \rightarrow N^{\text{multijet}} = \epsilon_f N_F = \frac{\epsilon_f}{\epsilon_r - \epsilon_f}\left[\epsilon_r (N_L + N_T) - N_T\right]$$

m_T^W @ Top VR



m_T^W @ multijet VR



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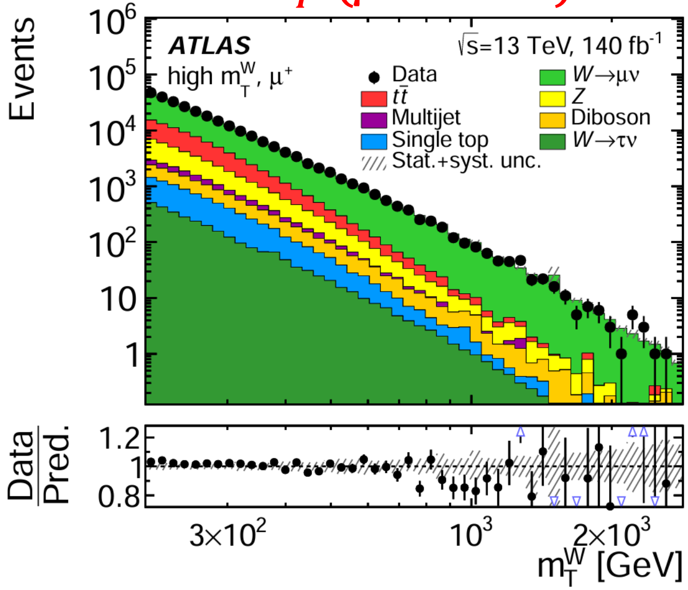
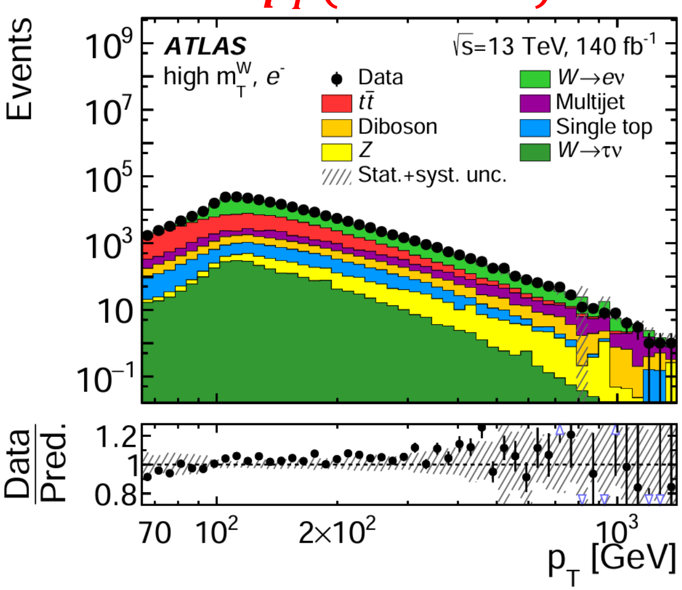
Control plots: data yields and spectra are well described by the simulation

m_T^W (μ^+ channel)



p_T^l (e^- channel)



First measurement of W differentials @ High-m_T^W

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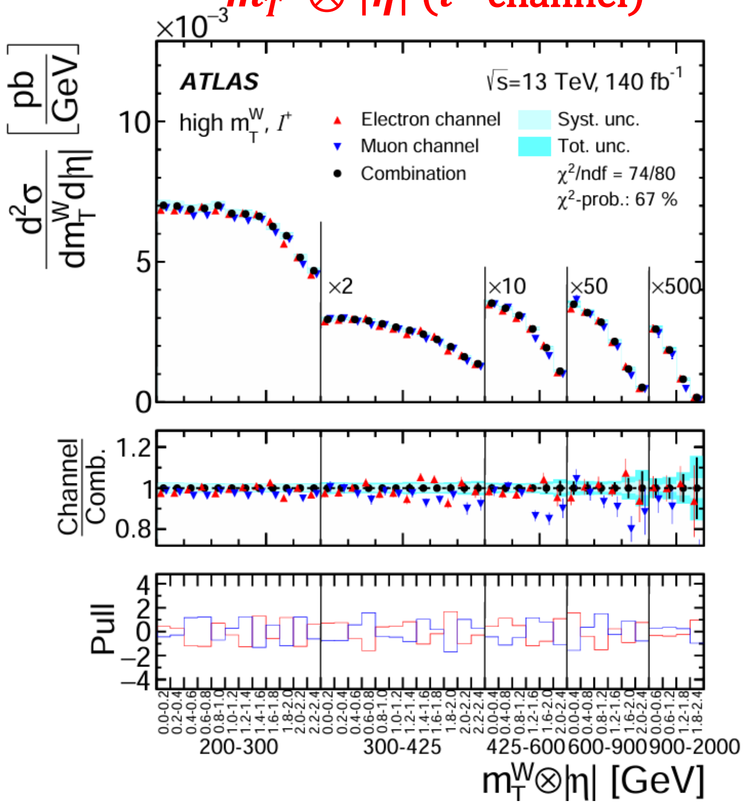
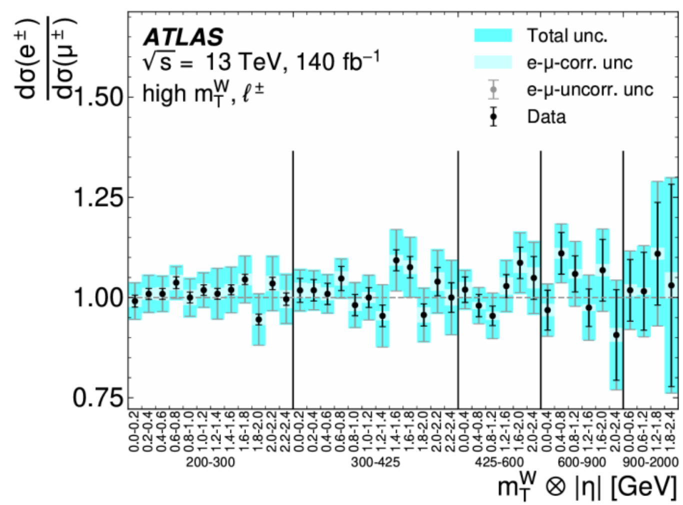
$\mathrm{d}\sigma/\mathrm{d}m_T^W$ and $\mathrm{d}^2\sigma/\mathrm{d}|\eta|\mathrm{d}m_T^W$ are measured for W^+ and W^-

- for e-channel and μ-channel, and then combined (improving the statistical & systematic precision)
- no sign of lepton flavor universality deviation beyond SM

$m_T^W \otimes |\eta|$ (l^+ channel)



$d\sigma(e^{\pm})/\,d\sigma(\mu^{\pm})$



First measurement of W differentials @ High-m_T^W

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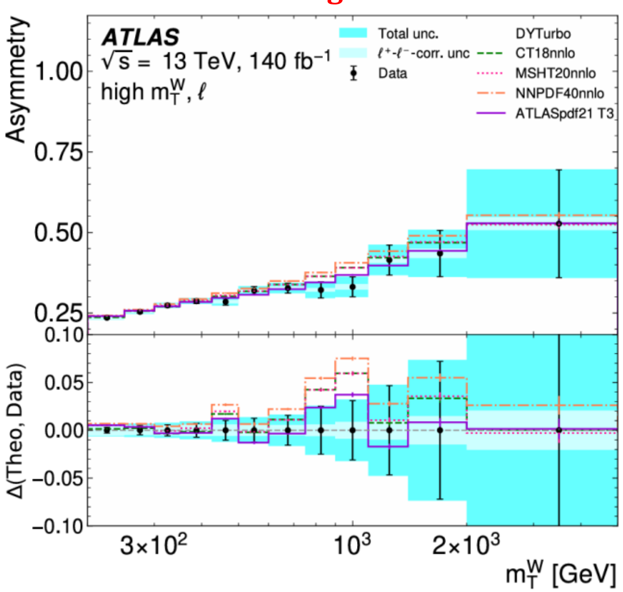
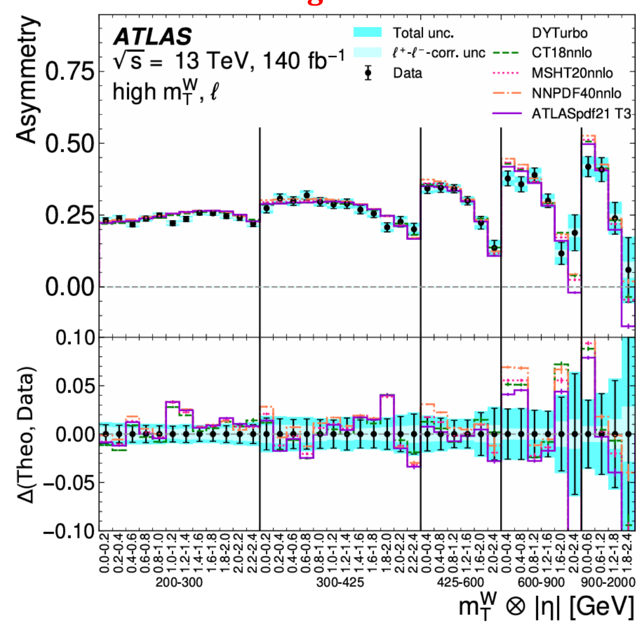
$A^l_{\text{charge}}(m_T^W)$ and $A^l_{\text{charge}}(|\eta|, m_T^W)$ are measured

- as a function of m_T^W for the first time
- grows with transverse mass: $m_T^W \uparrow \implies x \uparrow \implies \frac{u_v(x)}{d_v(x)} \uparrow$
- sensitive to the differences in u_v and d_v PDFs (PDF unc. < experimental unc. for most bins)

$A^l_{\text{charge}}(m_T^W)$



$A^l_{\text{charge}}(|\eta|, m_T^W)$



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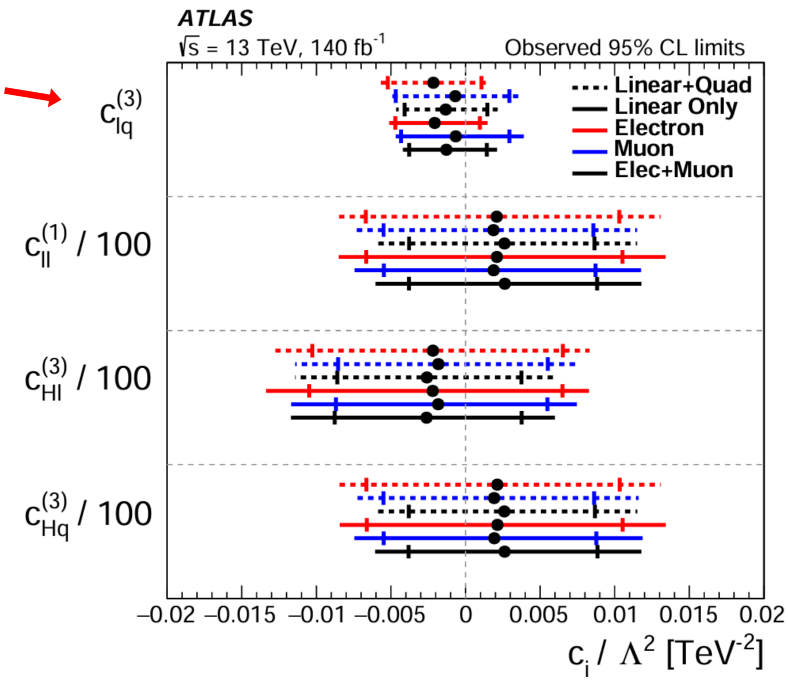
New physics: dimension-6 SMEFT operators grow with energy

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

- only one coefficient to be non-zero at a time

$$|\mathcal{A}^2| = |\mathcal{A}_{\text{SM}}|^2 + \underbrace{\sum_i \frac{c_i}{\Lambda^2} \mathcal{A}_{SM}^\dagger \mathcal{A}_i}_{\text{Linear}} + \underbrace{\sum_i \frac{|c_i|^2}{\Lambda^4} |\mathcal{A}_i|^2}_{\text{Quadratic}}$$

- world-leading constraints on the Wilson coefficient $c_{lq}^{(3)}$
- new physics beyond the direct energy reach of the LHC



Conclusion and Outlook

Two precision measurements:

- Low-pileup W differentials @ 5.02 TeV & 13 TeV
- First measurement of W differentials @ High-m_T^W

W/Z Differential cross-sections:

- Sensitivity to new physics via EFT
- Constraint on PDFs

Many other results with single W/Z at the LHC (Run2, Run3):

- Unprecedented precision (excellent performance, large statistics)
- various valuable inputs for tests and new physics