ATLAS measurements of Drell Yan processes

Mingzhe Xie

On behalf of ATLAS collaboration

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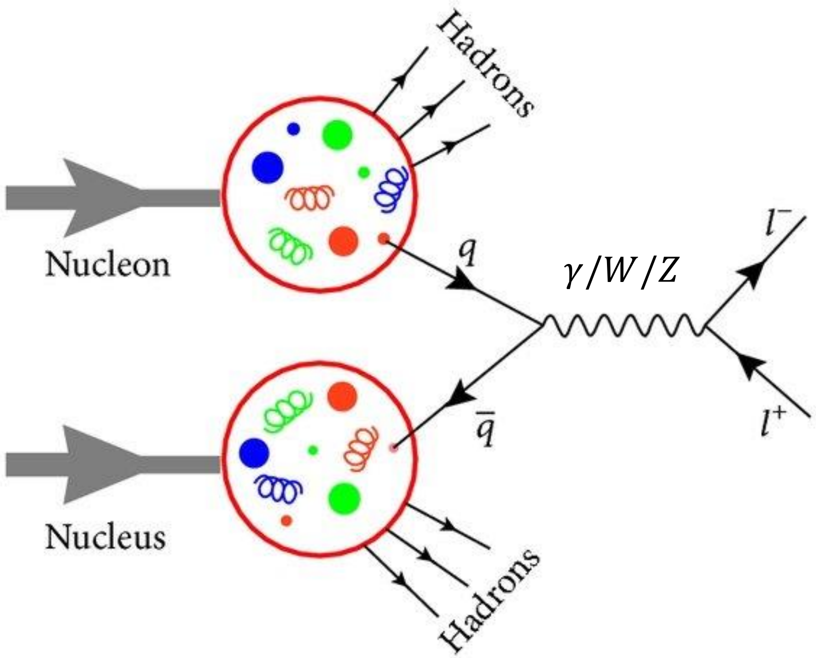
Drell-Yan process

- Proposed in 1970s, play an important role in both electroweak, PDF and QCD



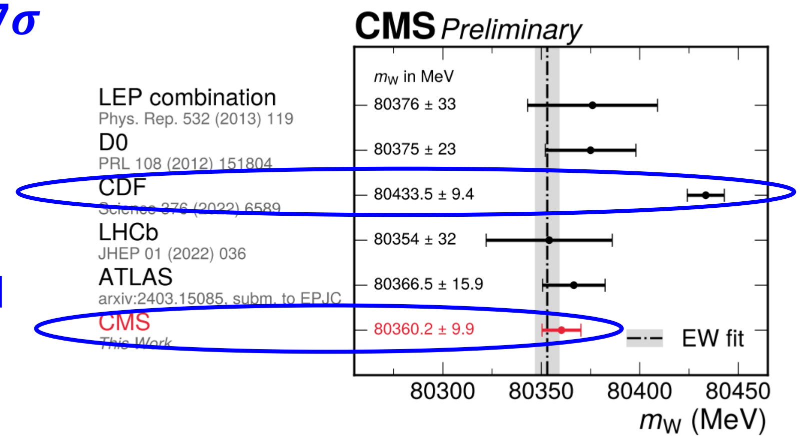
- **Electroweak precision measurement**
  - **W mass and width at 7TeV**
- **QCD and Proton inner structure (PDF)**
  - **W, Z cross sections and their ratio at 13.6 TeV**
  - **Z+b/c jets cross sections**
  - **W, Z pT distribution**
- **New physics search**
  - **Missing transverse momentum +jets cross sections**

W boson mass and width at $\sqrt{S} = 7$ TeV

- **W boson mass**
  - As a fundamental parameter of standard model (SM), crucial to both validation of standard model and probe for potential new physics.
  - Two most precise measurements:
    - **CDF: differ from SM prediction around 7σ**
    - **CMS: agree well with SM.**

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r),$$

Δr represents the radiative corrections within SM and the extensions of it.



Latest measurement of W mass from CMS group

- **W decay width Γ^W**
  - Comparison between measured value and SM prediction probe for new particles
  - Current world average 2085 ± 42 MeV from LEP-2 and Tevatron, **NO** LHC measurements

W mass reanalysis using 7 TeV data

- **Previous result**
  - χ^2 offset method

$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11 (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV} = 80370 \pm 19\ \text{MeV},$$

- **Major updates**
  - Profile likelihood

$$\mathcal{L}(\vec{n}|\mu,\vec{\theta}) = \prod_j \prod_i \text{Poisson}\left(n_{ji}|\nu_{ji}(\mu,\vec{\theta})\right) \cdot \text{Gauss}\left(\vec{\theta}\right),$$

Simultaneous fit of mw and nuisance parameters representing experimental and modelling uncertainties

- **Fitting strategy**

	Nuisanse parameters	Fitting Range
p_T^l	214	30-50GeV
m_T	223	60-100GeV

p_T^W modelling validated with the latest measurement

- Combined by BLUE method with the correlation estimated from fluctuated toys

$$\rho \sim 50.4\% \rightarrow w(p_T^l) \sim 86\% \quad (\text{for CT18NNLO})$$

- Final result dominated by p_T^l fit

New W mass result at $\sqrt{S} = 7$ TeV

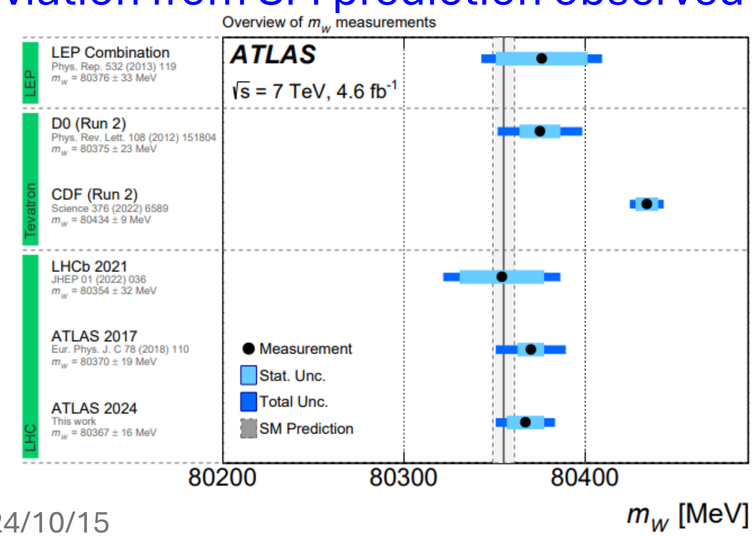
- **A dependence on the PDF choice is tested**

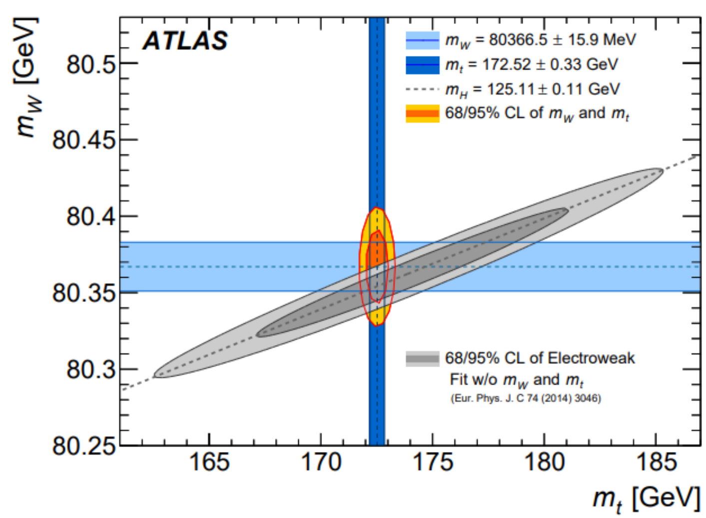
	CT14	CT18	CT18A	MMHT2014	MSHT20	NNPDF3.1	NNPDF4.0	ATLASpdf21
Central value	80363.6	80366.5	80357.2	80366.2	80359.3	80349.6	80345.6	80367.6
Total unc.	15.9	15.9	15.6	15.8	14.6	15.3	14.9	16.6

- **CT18 is chosen as the baseline**

$$m_W = 80366.5 \pm 9.8 \text{ (stat.)} \pm 12.5 \text{ (syst.) MeV} = 80366.5 \pm 15.9 \text{ MeV},$$

- Central value decreased by 3 MeV, total uncertainty reduced by 3 MeV (16%)
- No deviation from SM prediction observed





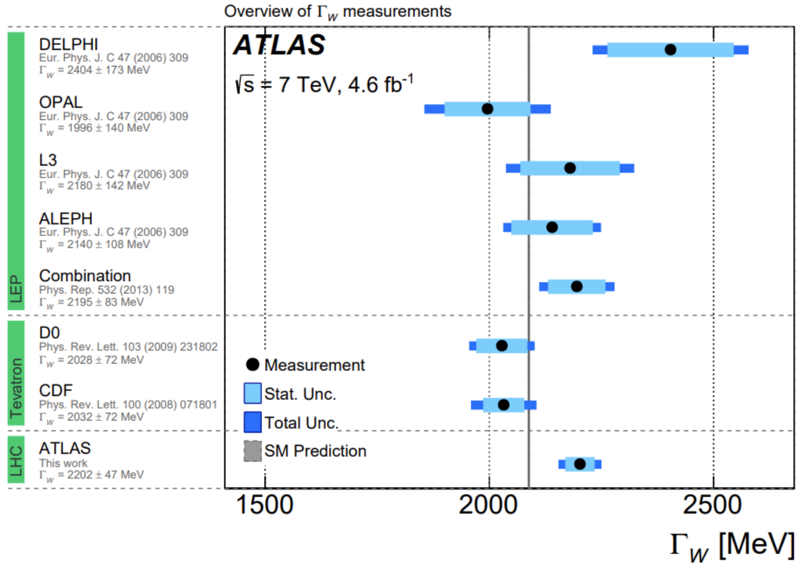
W width measurement at $\sqrt{S} = 7$ TeV

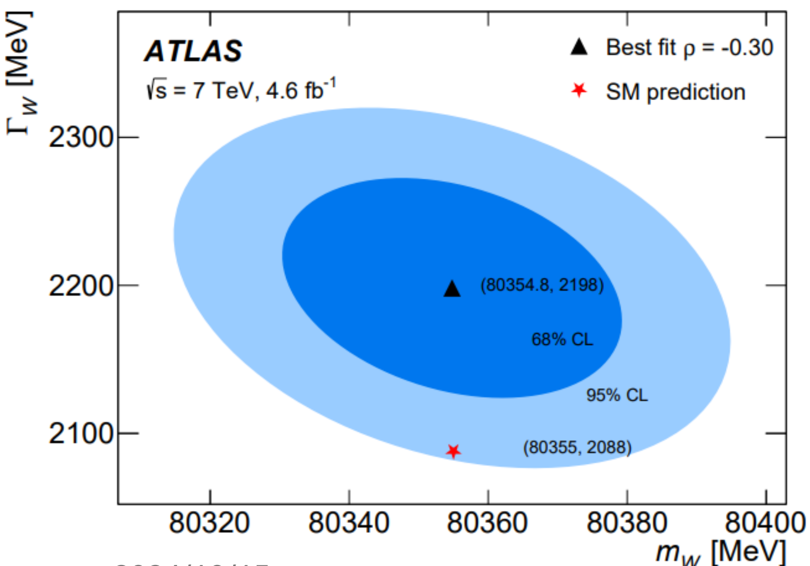
- **Same strategy used as m_W measurement**

$$\Gamma_W = 2202 \pm 32\ (\text{stat.}) \pm 34\ (\text{syst.})\ \text{MeV} = 2202 \pm 47\ \text{MeV},$$

$w(m_T)$~87%, dominated by m_T fit

- First measurement at LHC, most precise experimental results at present





Simulaneously determination of m_W and Γ_W, yield

$$m_W = 80354.8 \pm 16.1\ \text{MeV}$$

$$\Gamma_W = 2198 \pm 49\ \text{MeV},$$

p_T^W and p_T^Z at $\sqrt{S} = 5.02/13$ TeV

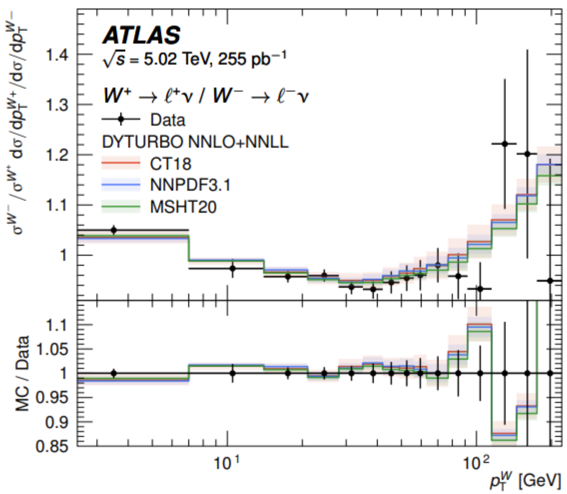
- **A sensitive test of QCD**
  - higher order corrections
  - non-perturbative effects such as the primordial k_T of the incoming partons
- **$p_T^V \leq 30$ GeV are particularly important for the measurement of W mass**
  - can be used to tune QCD model which affects the p_T^l and m_T distributions

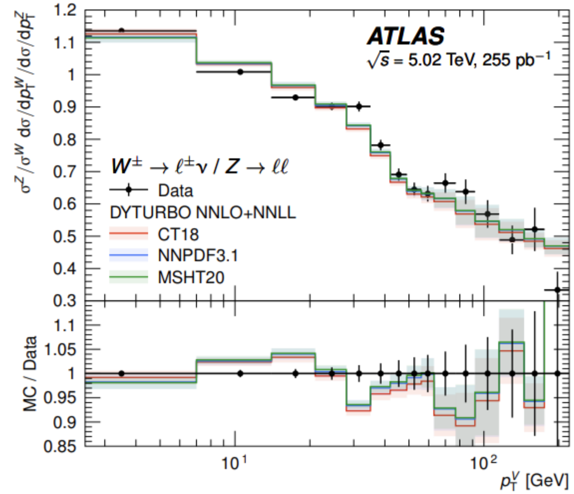
- **Strategy**
- To reduce pile-up, low $< \mu >$ data was used, 255 pb^{-1} at 5.02 TeV, 338 pb^{-1} at 13 TeV
- Both electron and muon final states used
- p_T^W unfolded from hadronic recoil $\vec{u}_T$
- p_T^Z measured through the dilepton system p_T^{ll}
- Hadronic recoil calibration
  - $\vec{u}_T = -\vec{p}_T^V$ is valid for both W and Z
  - Well-measured dilepton system can thus be used to calibrate the hadronic recoil response, and the unfolded p_T^{ll} distribution provides a cross-check of the p_T^Z spectrum measured from u_T

p_T^W and p_T^Z at $\sqrt{S} = 5.02$ TeV

Data vs various PDF predictions

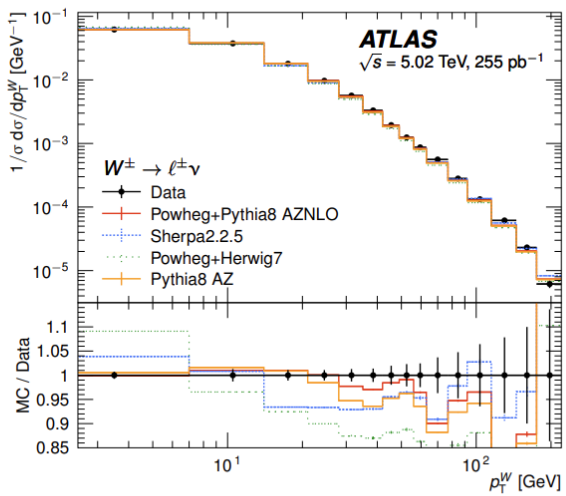
- DYTURBO generally agrees well with data
- PDF predictions have only small difference

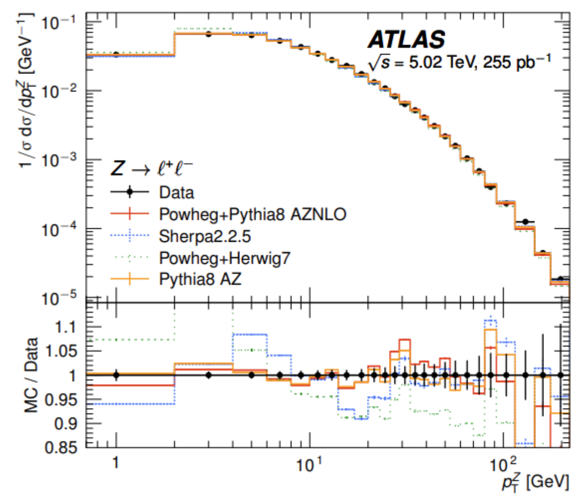




Data vs various MC predictions

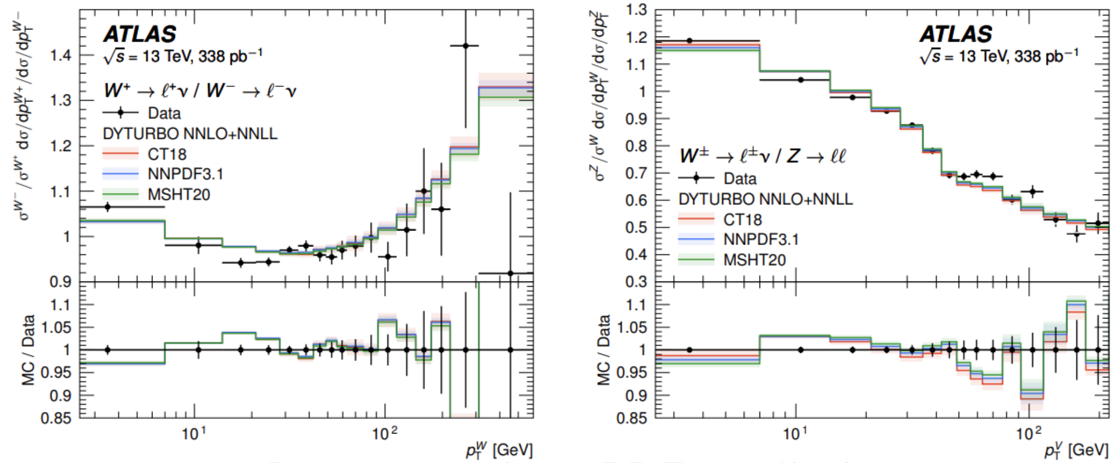
- MC predictions tuned to 7 TeV data (Powheg+Pythia8 AZNLO, Pythia8 AZ) agrees well with data in low p_T
- Sherpa2.2.5 matches data best at high p_T
- Powheg+Herwig7 does not perform well





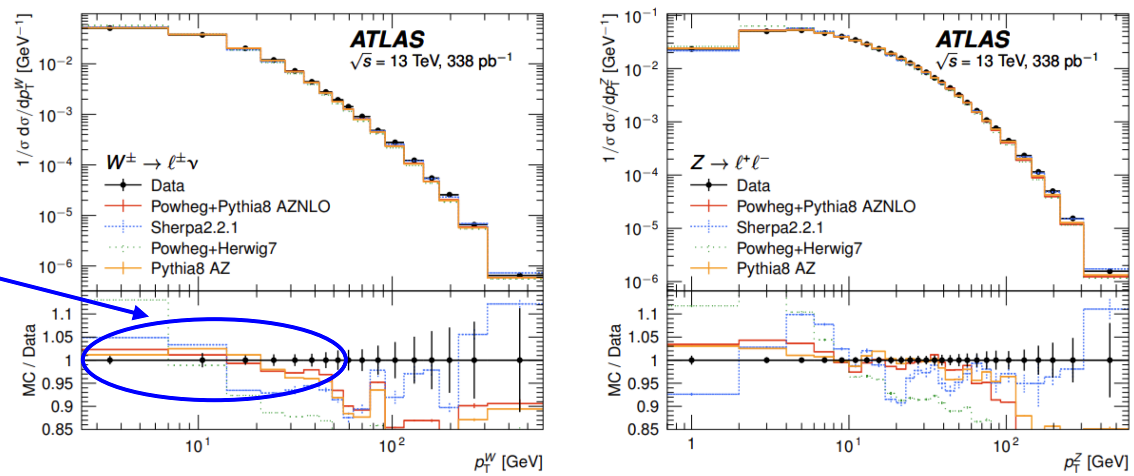
p_T^W and p_T^Z at $\sqrt{S} = 13$ TeV

- Same conclusion as in 5.02 TeV



Data vs various PDF predictions

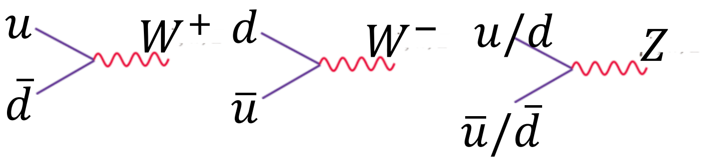
- Nice validation of the AZNLO Pythia8 tune, developed for m_W determination at 7 TeV

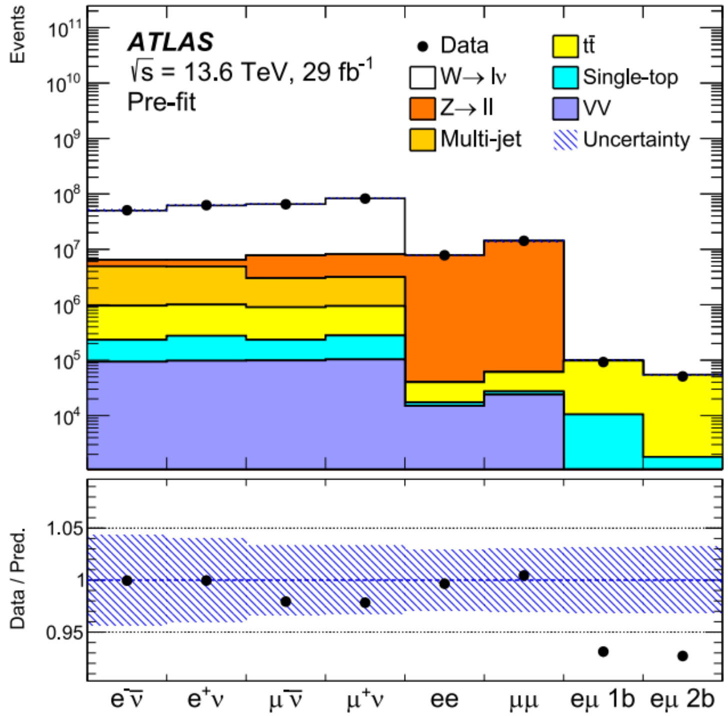


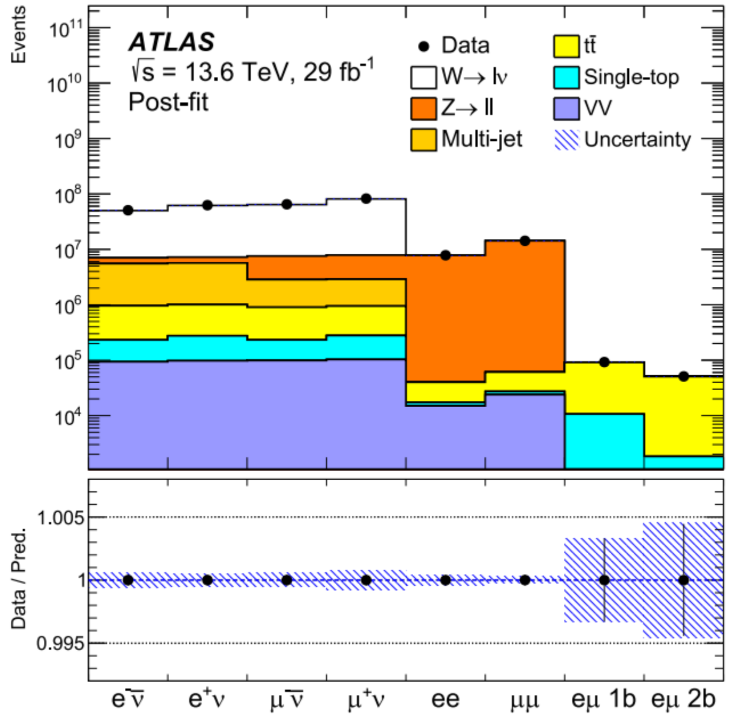
Data vs various MC predictions

W, Z cross sections and their ratio at $\sqrt{S} = 13.6$ TeV

- **An excellent probe of QCD and of the proton structure**
- **Fit from profile likelihood (PLH) method**



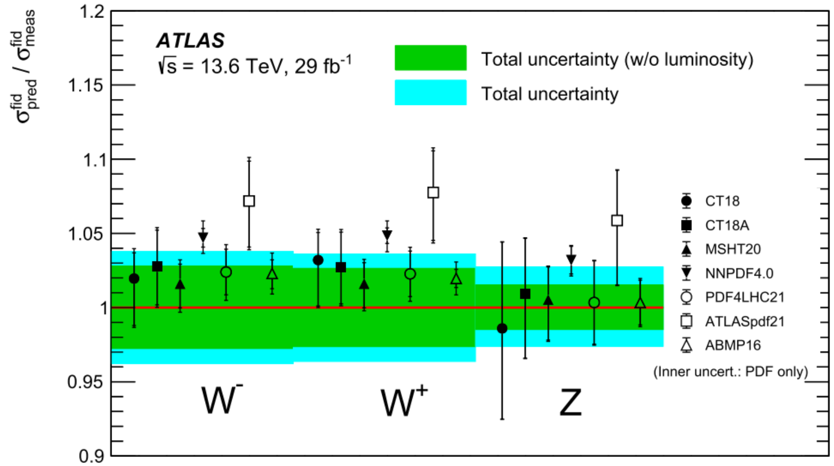


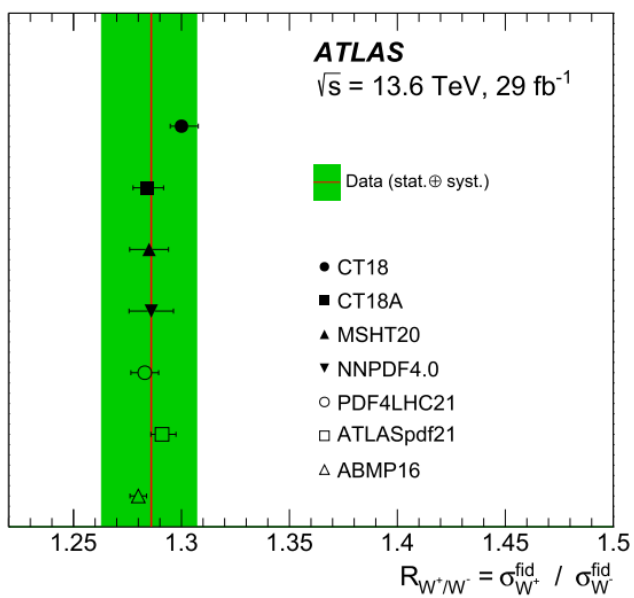


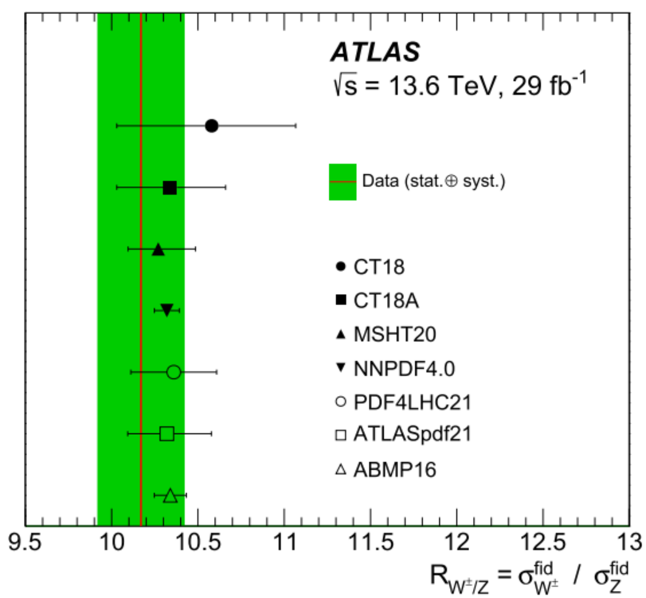
W, Z cross sections and their ratio at $\sqrt{S} = 13.6$ TeV

- Measured results for W^+, W^-, Z cross sections and their ratios

- generally in good agreement with SM predictions with different PDF sets.

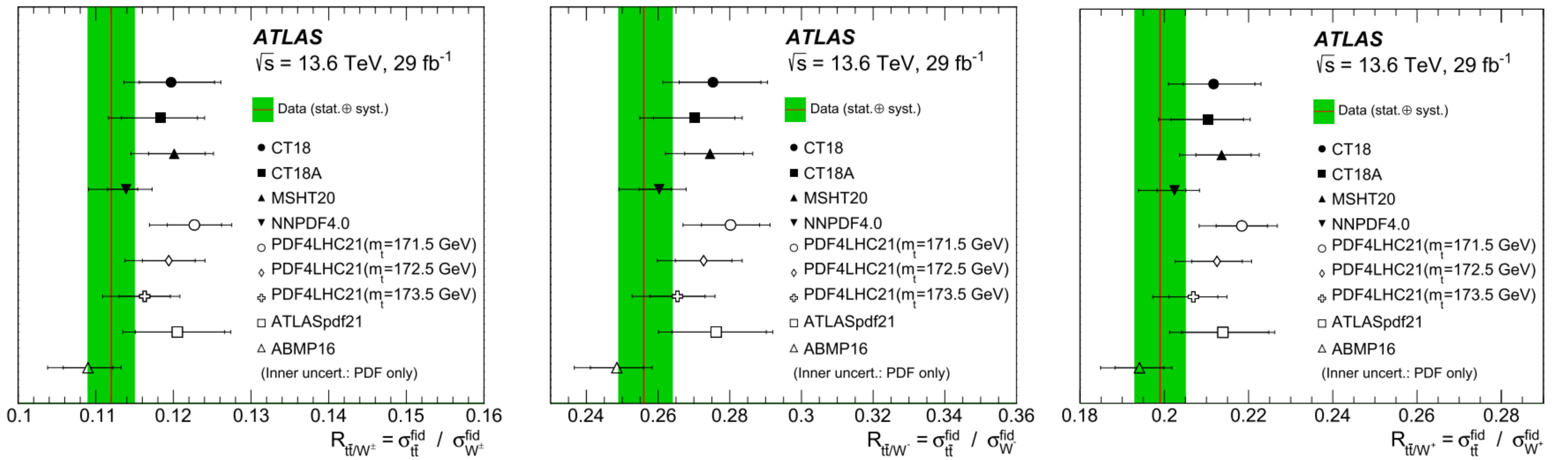






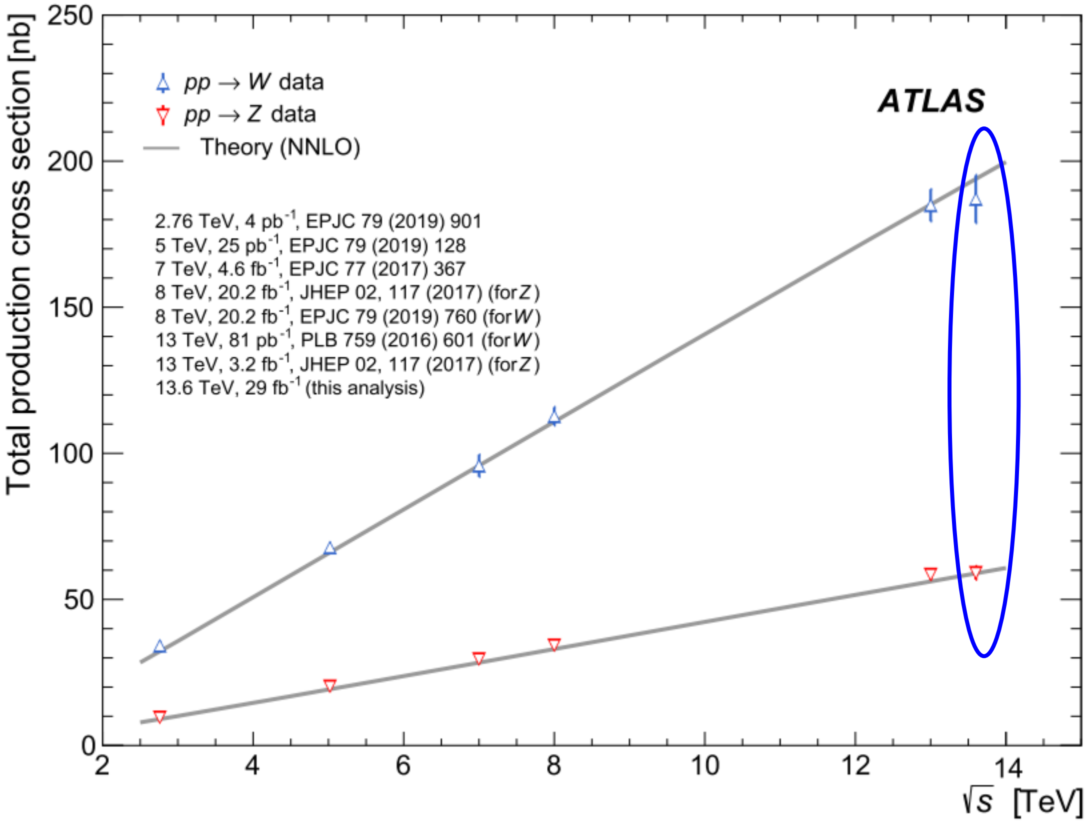
W, Z cross sections and their ratio at $\sqrt{S} = 13.6$ TeV

- **$t\bar{t}/W$ cross section ratio given here for the first time at 13.6 TeV**
- Lower than the theory predictions of most PDFs, mainly due to the measured $t\bar{t}$ cross section at 13.6TeV is lower as shown in PLB 848(2024)138376



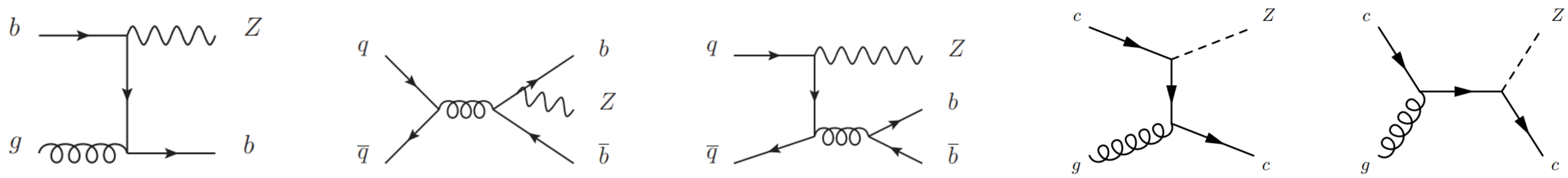
W, Z cross sections and their ratio at $\sqrt{S} = 13.6$ TeV

- **Dependence of cross sections on the center-of-mass energy**
- Good agreement with theory prediction



Z + heavy flavor at $\sqrt{S} = 13$ TeV

- **Test of perturbative QCD and heavy-flavor quarks inside proton**
- **Important background of Higgs boson measurements or search for new physics**



- **Measured observables**

Table 1: List of observables used to perform differential cross-section measurements.

Final state	Observable	Notation
$Z + \geq 1$ b-jet	p_{T} of the leading b-jet	$p^0_{\mathrm{T},b}$
	p_{T} of the Z boson	$p_{\mathrm{T}}(Z)$
	$\Delta\tilde{R} = \sqrt{(\Delta\phi)^2 + (\Delta y)^2}$ between the Z boson and leading b-jet, where $\Delta\phi$ (Δy) is the azimuthal angle (rapidity) difference	$\Delta\tilde{R}_{Zb}$
$Z + \geq 1$ c-jet	p_{T} of the leading c-jet	$p^0_{\mathrm{T},c}$
	p_{T} of the Z boson	$p_{\mathrm{T}}(Z)$
	Feynman-x variable $x_F = 2\lvert p_z(c)\rvert/\sqrt{s}$ [25]	$x_F(c)$
	Cross-section ratio of $p_{\mathrm{T}}(Z)$ in $\lvert y(Z)\rvert < 1.2$ and $\lvert y(Z)\rvert > 1.2$	$\mathrm{R}(p_{\mathrm{T}}(Z))$
$Z + \geq 2$ b-jets	Invariant mass of the two leading b-jets	m_{bb}
	Azimuthal angle difference between the two leading b-jets	$\Delta\phi_{bb}$

pQCD and MC modelling ($p^0_{\mathrm{T},b}$, $p_{\mathrm{T}}(Z)$; $p^0_{\mathrm{T},c}$, $p_{\mathrm{T}}(Z)$)

PDF model: 4FS vs 5FS ($\Delta\tilde{R}_{Zb}$)

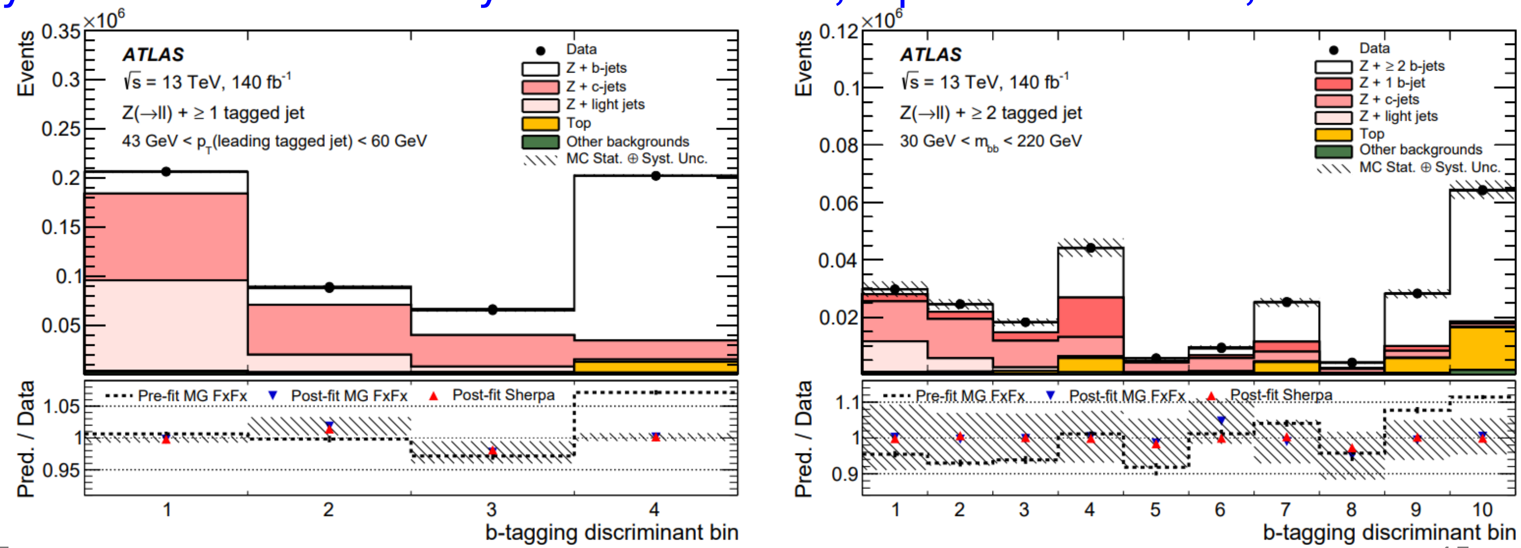
Intrinsic charm ($x_F(c)$, $\mathrm{R}(p_{\mathrm{T}}(Z))$)

$g \to b\bar{b}$ modelling Background to ZH (m_{bb}, $\Delta\phi_{bb}$)

Z + heavy flavor at $\sqrt{S} = 13$ TeV

Measurement strategy

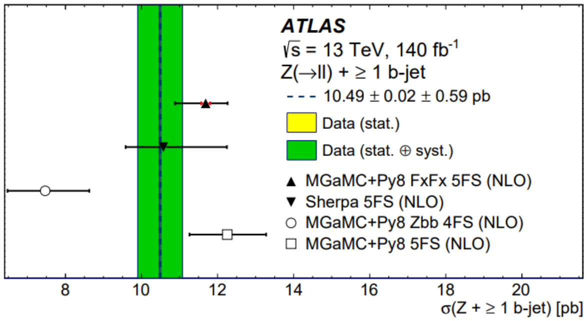
- Background estimation
  - Z+jets background: A likelihood fit on a flavor-sensitive observable ("flavor-fit") to decide the shape and normalization of Z+b-jets, Z+c-jets and Z+light jets, done separately in >=1 flavor-tagged jet and >=2 flavor-tagged jets
  - $t\bar{t}$ and MJ estimated vis data-driven method
  - Other non-Z+jets background estimated via MC simulations
- Bayesian unfolding
- Uncertainty estimation: for each systematic source, repeat the flavor fit, then unfold

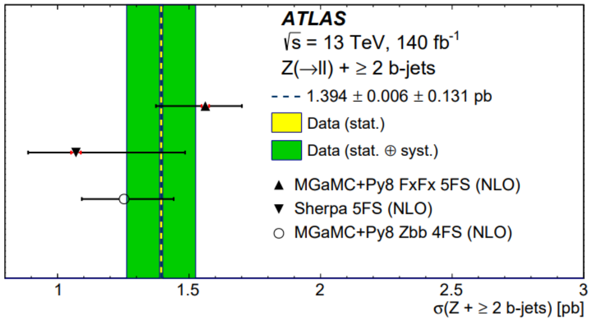


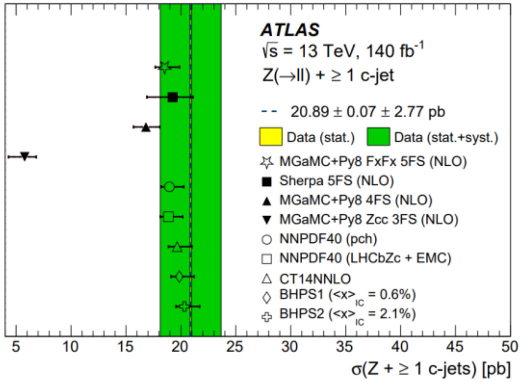
Z + heavy flavor at $\sqrt{S} = 13$ TeV

Inclusive cross-sections in the fiducial phase space

5FS: massless b-quark
4FS: b quark generated by $g \to b\bar{b}$
3FS: c quark generated by $g \to c\bar{c}$



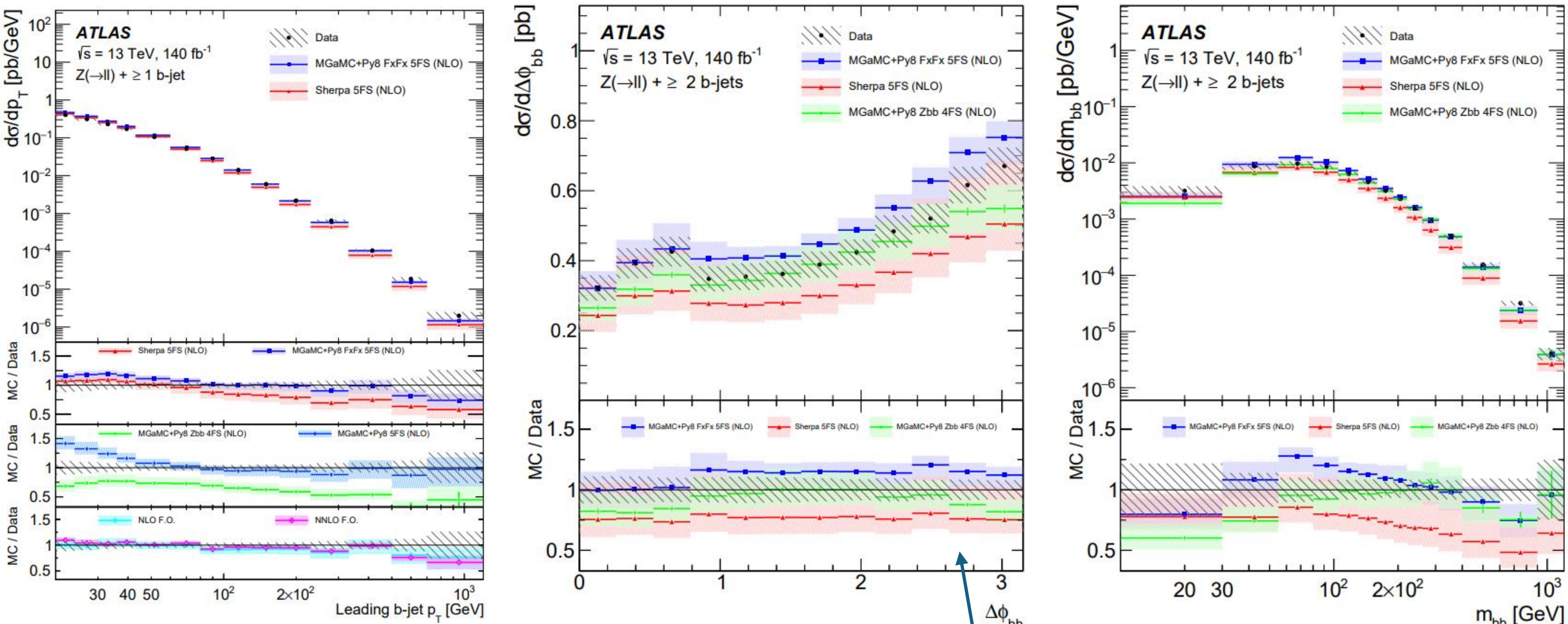




- 5FS predict the inclusive cross-sections for both Z+>=1b-jet and Z+>=2b-jets well
- 4FS only works for Z+>=2 b-jets

3FS underestimate the measurement by about 3σ, due to lack of resummation of $\ln(Q^2/m_c^2)$ in the collinear PDF evolution.

Z + b-jet at $\sqrt{S} = 13$ TeV



transverse momentum of the most energetic b-jet in the event

Predictions treating b-quarks as massless provide the best agreement with measurements.

Angular observables well-predicted

Invariant mass not well-modelled.

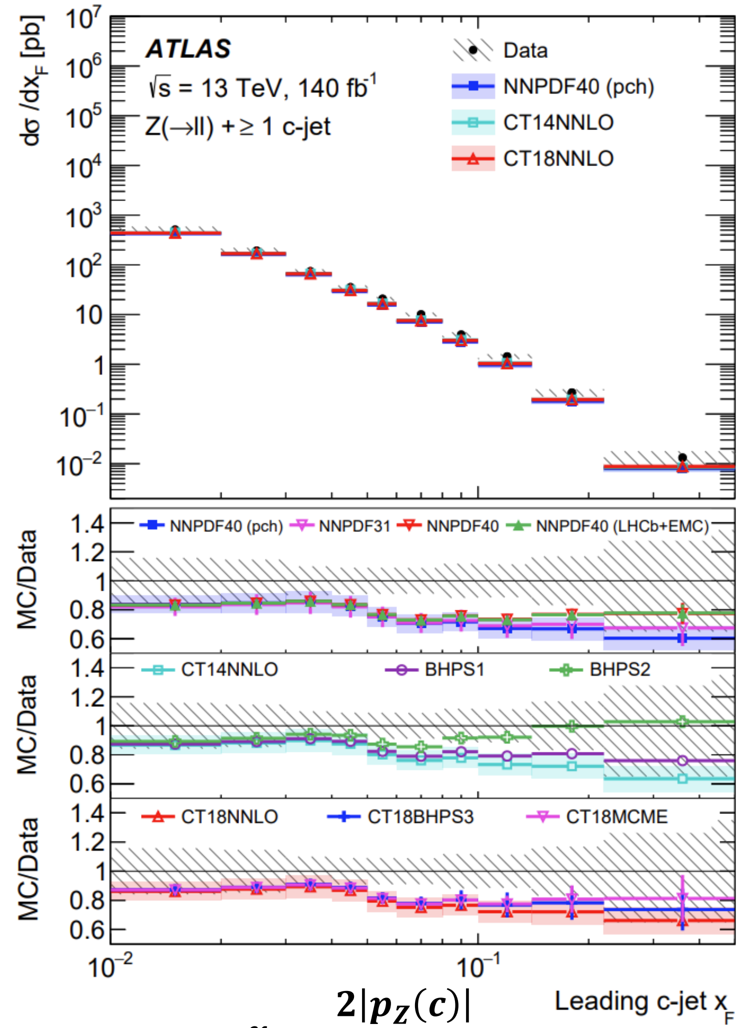
Z + c-jet at $\sqrt{S} = 13$ TeV

Investigate the hypothesis of intrinsic charm

- Comparison with various IC models show no strong evidence for intrinsic charm component in proton.
- Can be used as new inputs to the future QCD global analysis.

No-IC
- **NNPDF40(pch)**
- **CT14NNLO**
- **CT18NNLO**

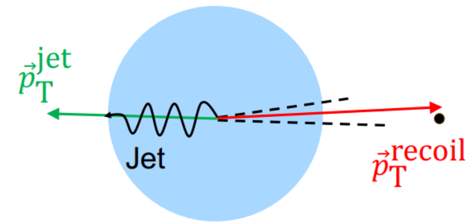
The rest are IC models



$$x_F = \frac{2|p_Z(c)|}{\sqrt{S}}$$

p_T^{miss} plus jets cross sections at $\sqrt{S} = 13$ TeV

- Precise measurement of standard model (SM)
- **search and constraint beyond the SM (BSM) physics**

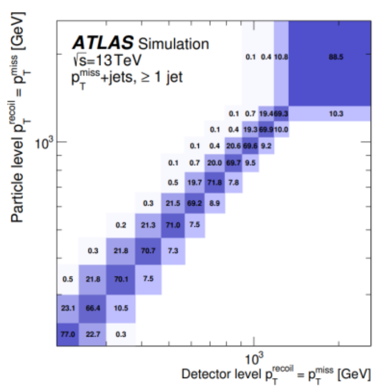


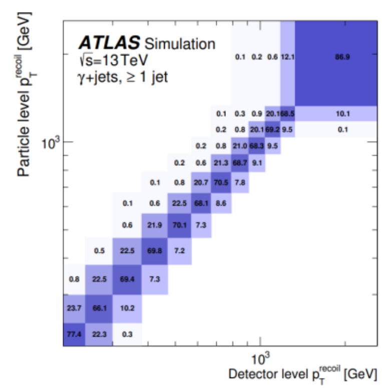
- Signal region: p_T^{miss} + jets $\qquad \boldsymbol{p_T^{miss} = p_T^{recoil}}$
- Control regions: lepton/photon + jets
- R_{miss}=σ(Signal region) / σ(Control region), uncertainties cancels out in the ratio

- **Two different jet topologies, enhance the sensitivity to BSM physics**
- ≥ 1 jet ($p_T^{jet} > 120$ GeV)
- VBF region ($|\Delta y_{jj}| > 1, m_{jj} > 200$ GeV)

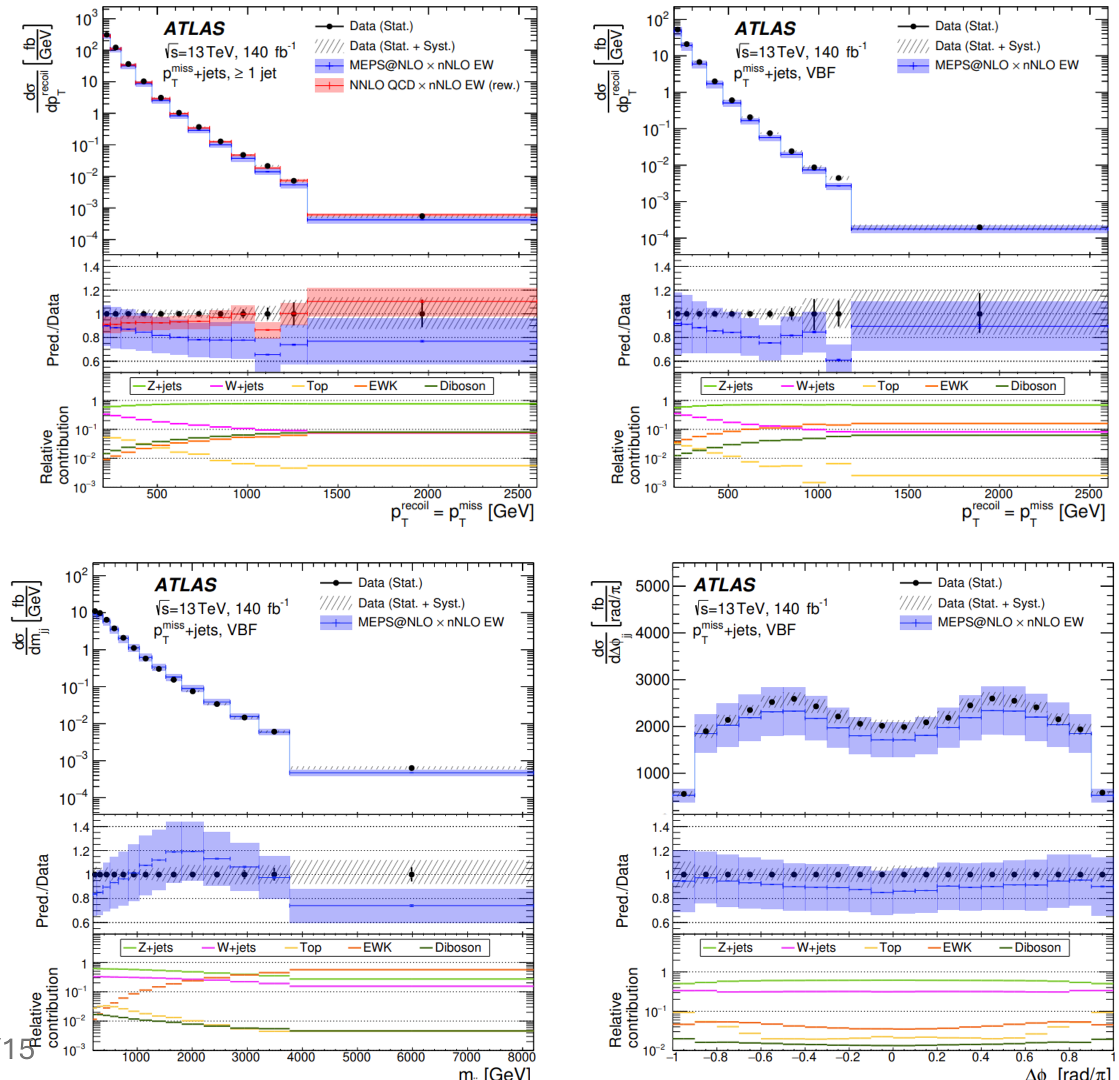
- **Three BSM-sensitive observables**
- Transverse momentum of hadronic system P_T^{recoil}
- Invariant dijet mass m_{jj}
- Jet angular separation $\Delta\phi_{jj}$

- Unfolding: corrected for detector effects and fiducial phase space
- **designed for reinterpretation, no need to repeat detector-simulations**





p_T^{miss} plus jets cross sections at $\sqrt{S} = 13$ TeV

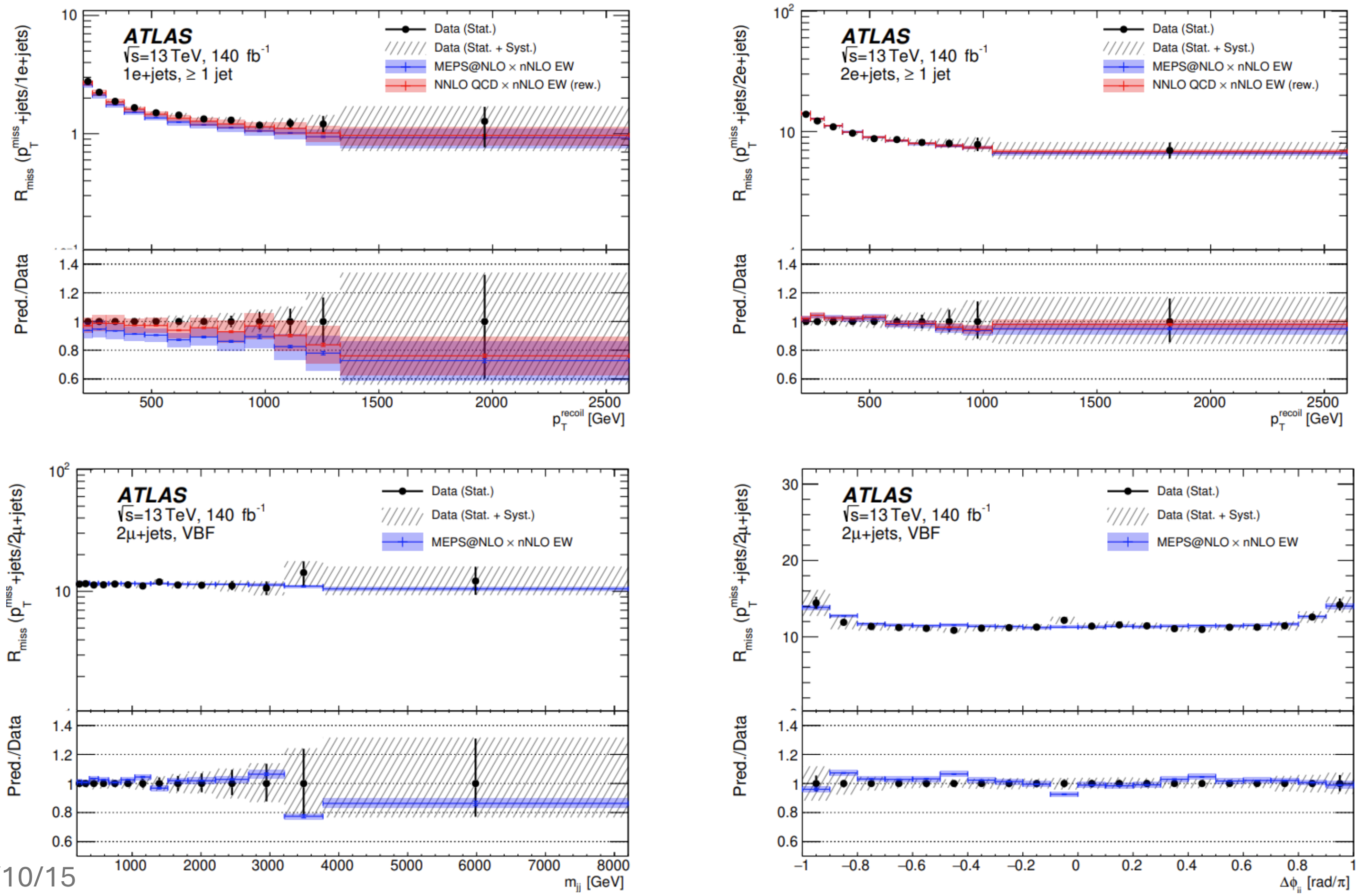


Differential cross sections compared to state-of-art SM predictions

Good agreement except for the m_{jj} distribution.

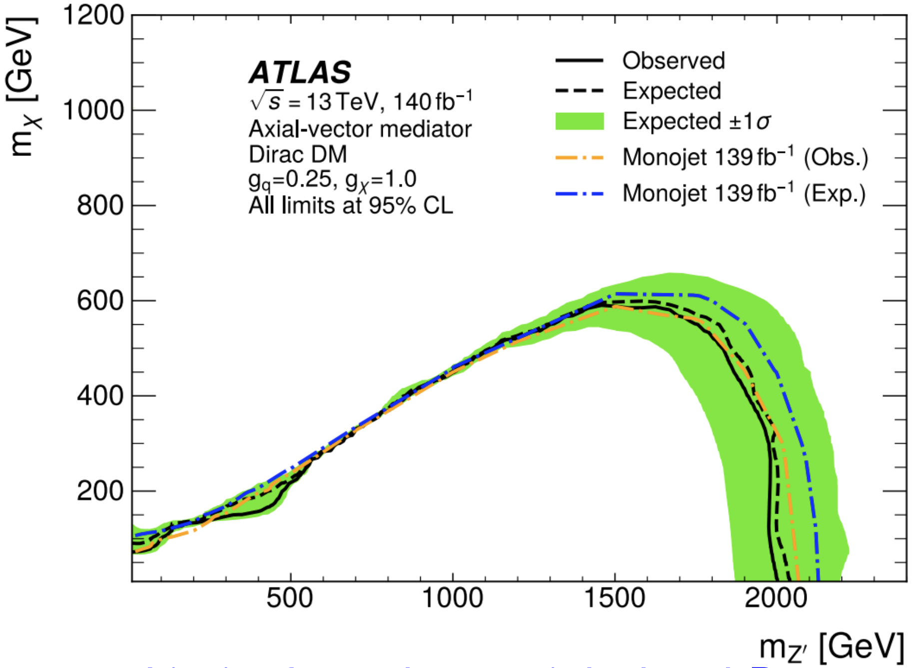
p_T^{miss} plus jets cross sections at $\sqrt{S} = 13$ TeV

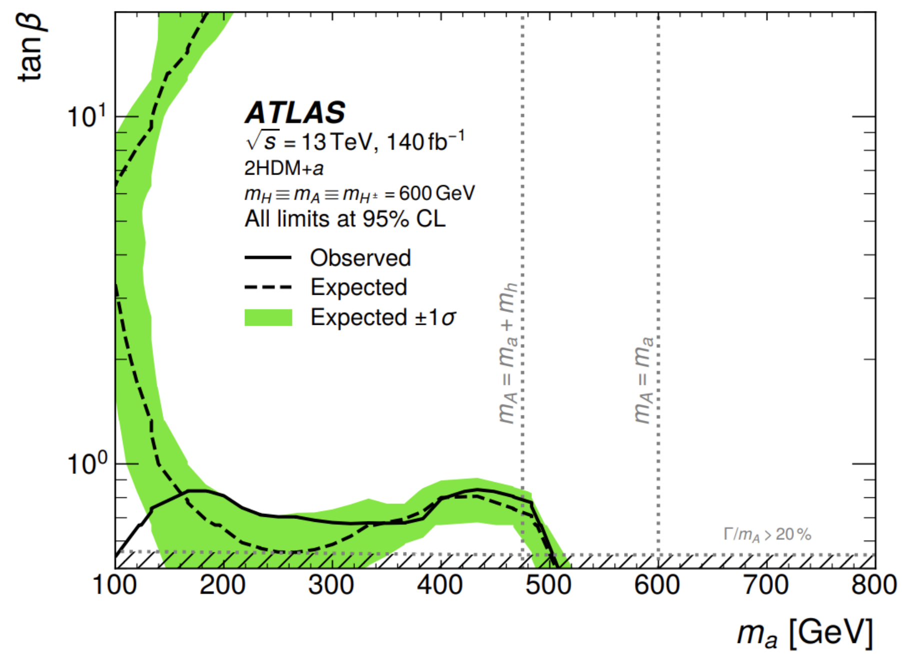
- Discrepancy in modelling and some systematic uncertainties cancels in the ratio R_{miss}
- Better agreement than cross-sections, especially in m_{jj}



p_T^{miss} plus jets cross sections at $\sqrt{S} = 13$ TeV

- **Implications for physics beyond the Standard Model**





- Limits from the particle-level R_{miss} measurements are competitive to that from detector-level ATLAS monojets search
- Also similar sensitivity on 2HDM+a model to the p_T^{miss}-based direct search

Particle-level measurements provides as good sensitivity to BSM physics as detector-level searches, amenable to reinterpretation in terms of different models.

Conclusions

- Measurement of Drell-Yan process provide important test on several aspects
  - Electroweak
    - W mass and width measurement by reanalysis of 7 TeV data
    - Consistent with the SM fit result
  - QCD
    - W and Z transverse momentum at 5.02 TeV and 13 TeV
    - Especially important for future W mass measurement
  - Proton structure
    - W, Z cross section at 13.6 TeV
    - Z+b/c jets at 13 TeV
    - Provide constraint on both light quark and heavy quark inside proton
  - BSM constraints
    - Missing transverse momentum + jets at 13 TeV
    - Prove the particle-level measurement show same sensitivity to BSM physics