Vector boson production in association with jets

Diffraction and low-x 2024 – Hotel Tonnara Trabia – 13/09/2024

G. Padovano on behalf of the ATLAS and CMS collaborations

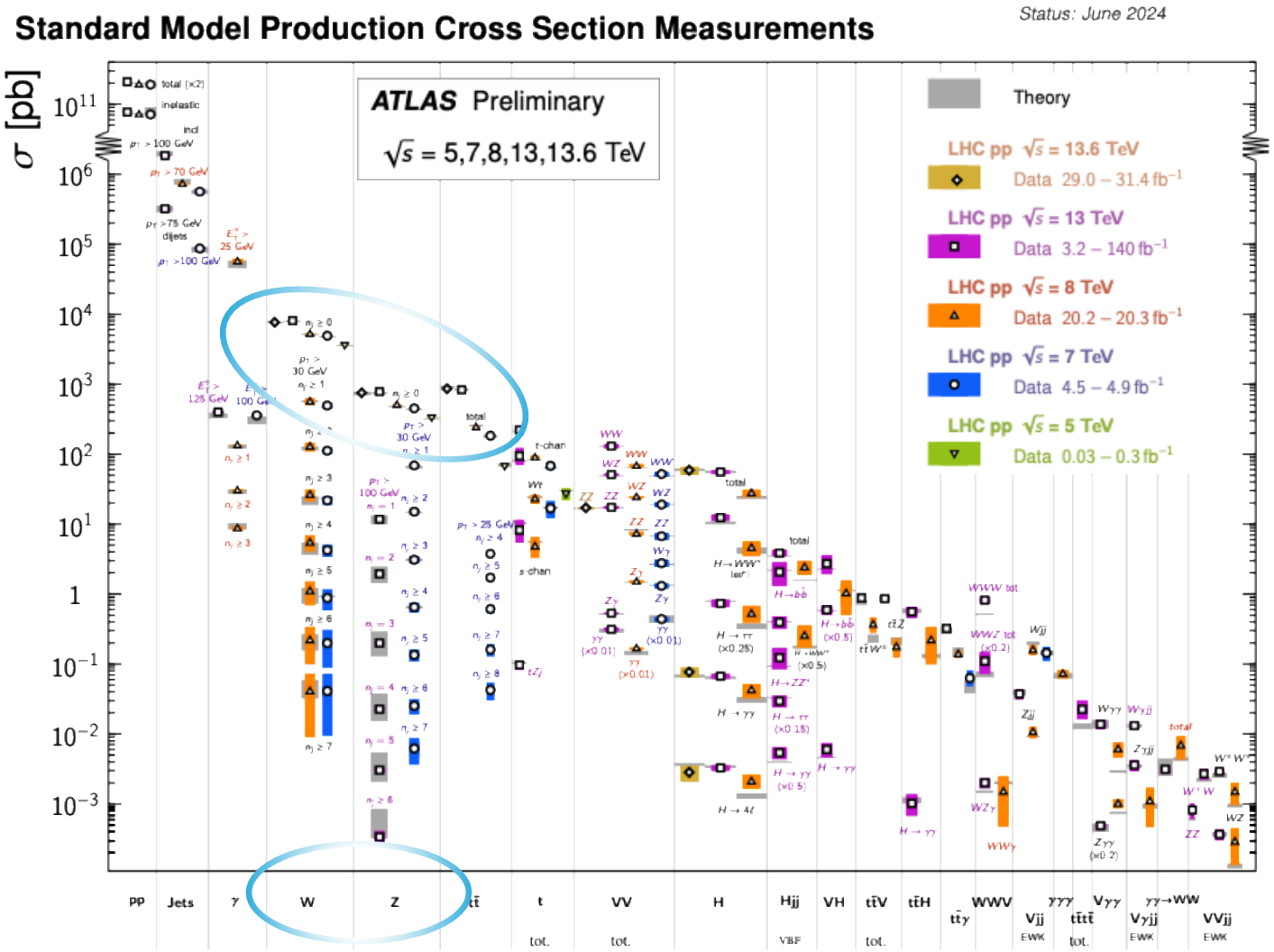
Introduction : W/Z bosons at ATLAS and CMS

- **Standard Model** cross section measurements cover a wide set of processes

- **W/Z** production **cross sections** have **high values** spanning over several orders of magnitude

⟹ a **huge dataset** for precision measurements and searches for new physics

ATL-PHYS-PUB-2024-011



Introduction : W/Z bosons at ATLAS and CMS

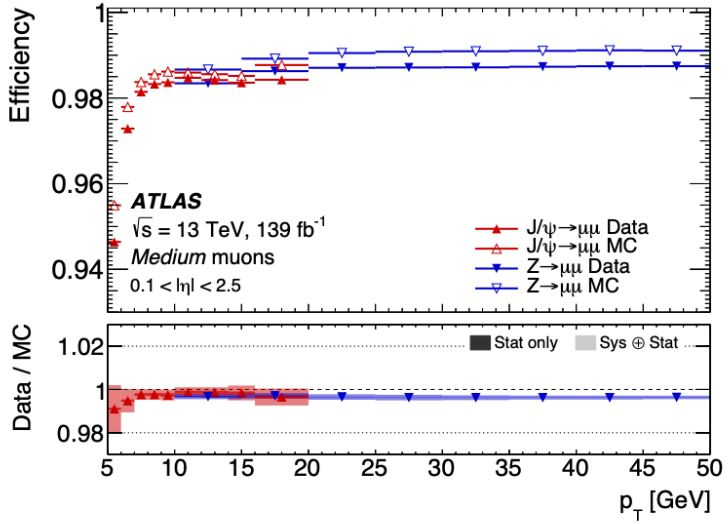
- **W and Z** decays into electrons and muons leave **clean signatures** in our detectors

  → ideal toolkit to **probe electroweak** and **QCD** models …

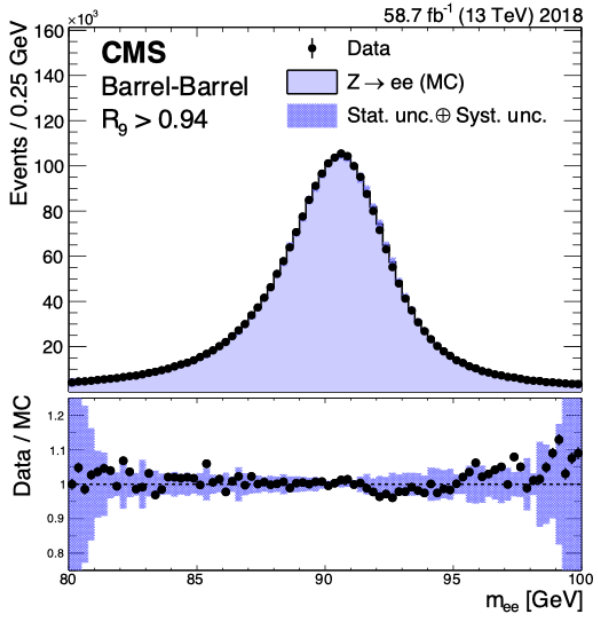
  … but also to measure our **detectors performances**

- Mainly focus on **newly published results** (in the last 6 months):
  1. W+c measurements
  2. Z+b/c measurements
  3. additional measurements

Eur. Phys. J. C 81 (2021) 578



JINST 16 (2021) P05014



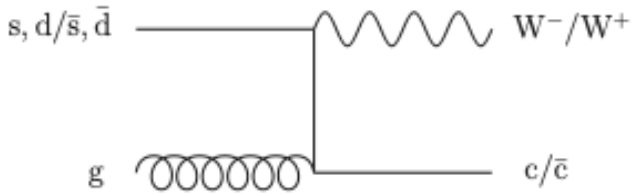
Only highlights of the main results and novelties in the papers

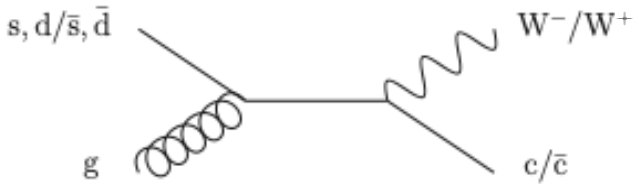
W+c measurements

W + c measurements at CMS

Eur. Phys. J. C 84 (2024) 27

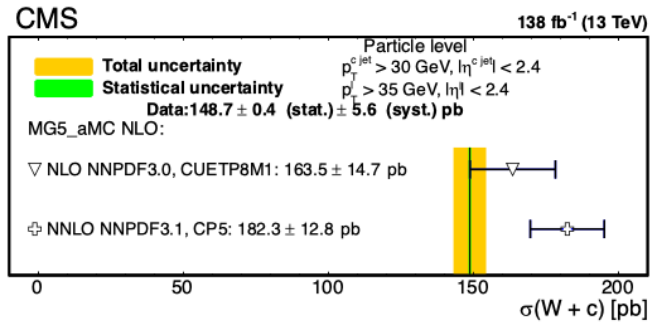
- W+c production sensible to the s-quark content of the protons





- **c-jet** tagged via its **muon decay** or the **secondary vertex**

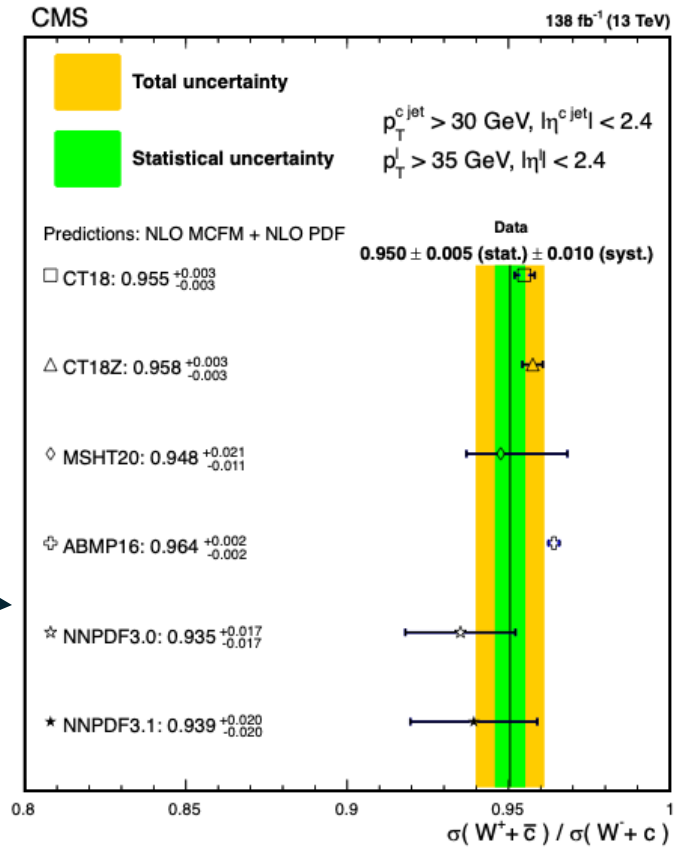
- Unfolded **total cross section** compared with MadGraph5_aMC NLO with two PDF sets



- **Cross section-ratio** compared with **different $s\bar{s}$ symmetry/asymmetry** models

  ⟹ all in agreement with data

$$R_c^{\pm} = \frac{\sigma(pp \to W^+ + \bar{c})}{\sigma(pp \to W^- + c)}$$

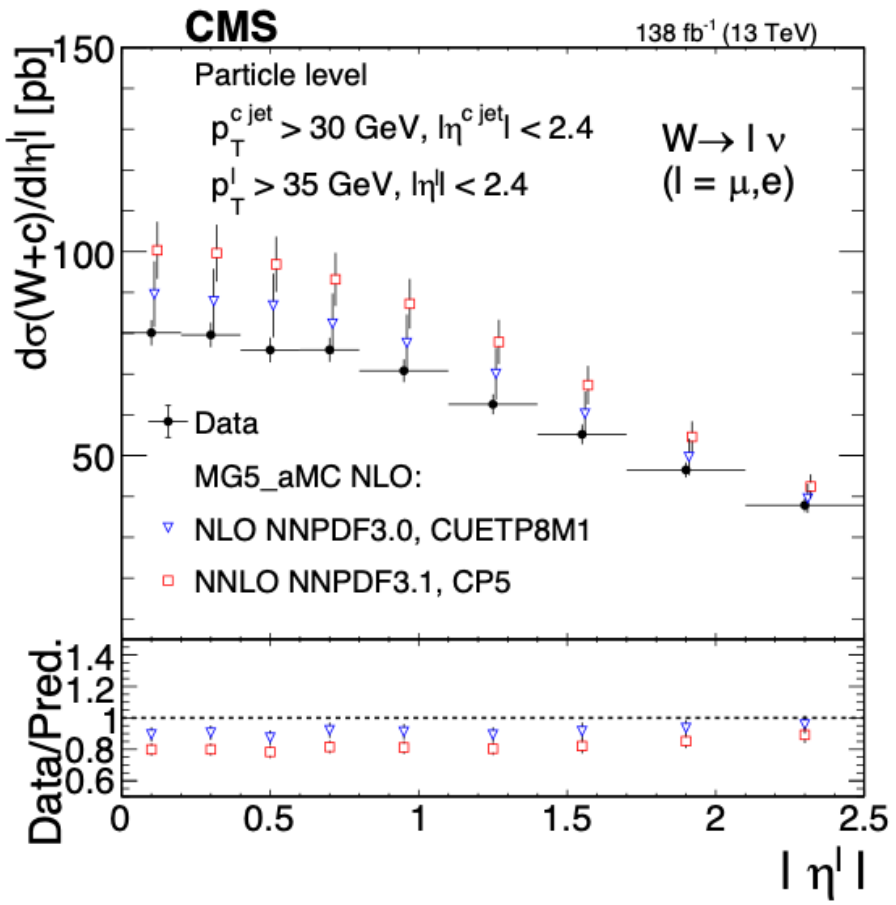


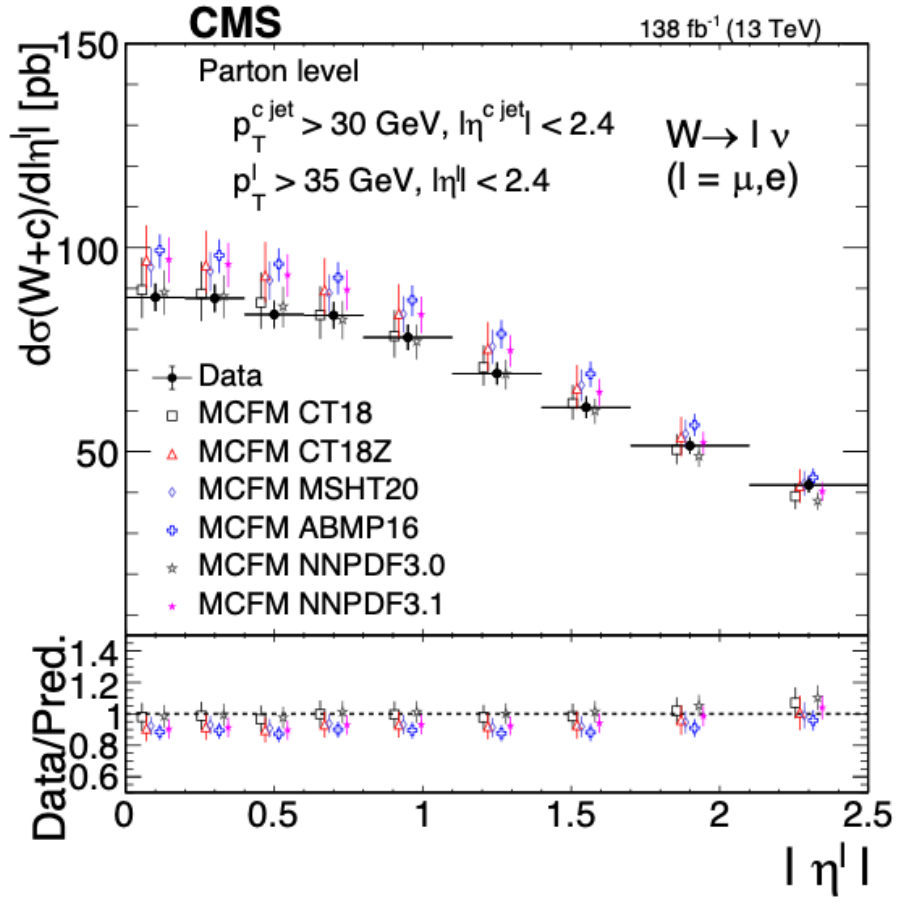
CT18 and ABMP16 assume $s\bar{s}$ symmetry while MSHT20 and NNPDF allow asymmetry

W + c measurements at CMS : parton level

Eur. Phys. J. C 84 (2024) 27

- Measured also **differential cross sections** in bins of $|\eta^{\ell}|$ and $|p_T^{\ell}|$ (with ℓ = e, μ from W decay)
- NEW : **parton level unfolding** corrects c-quark momentum smearing, which biases the cross sections towards lower values





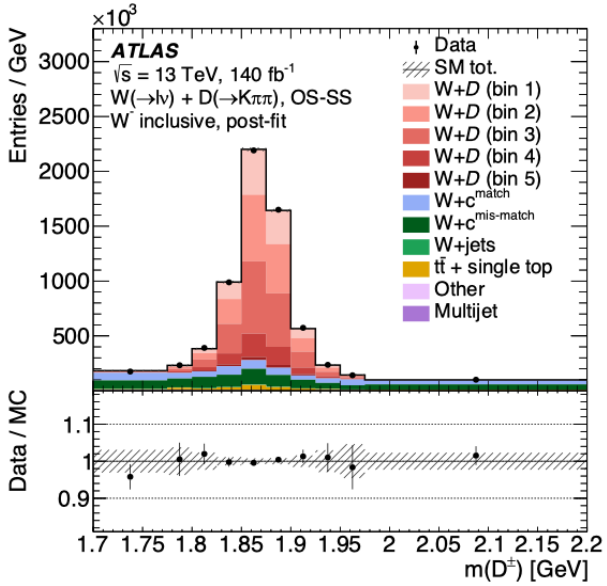
W + c measurements at ATLAS

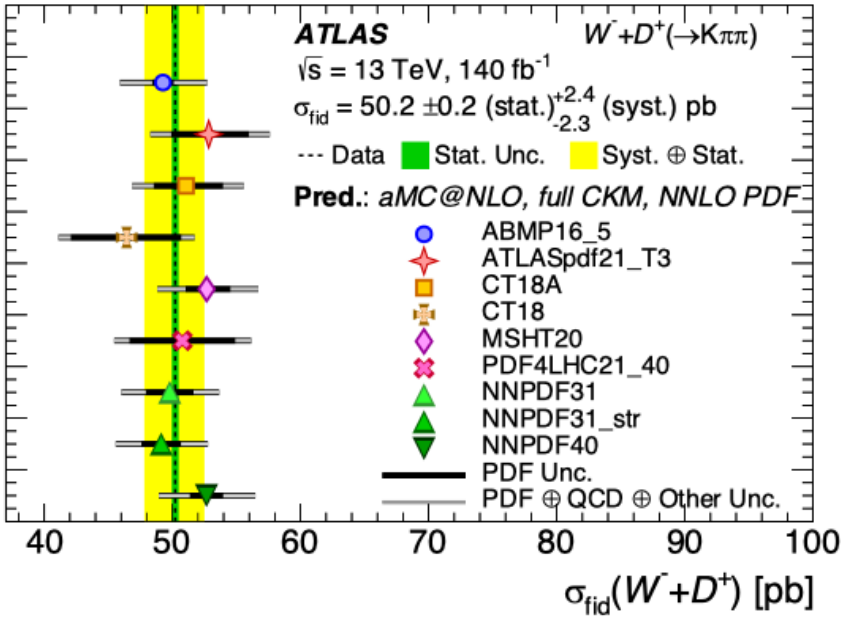
Phys. Rev. D 108 (2023) 032012

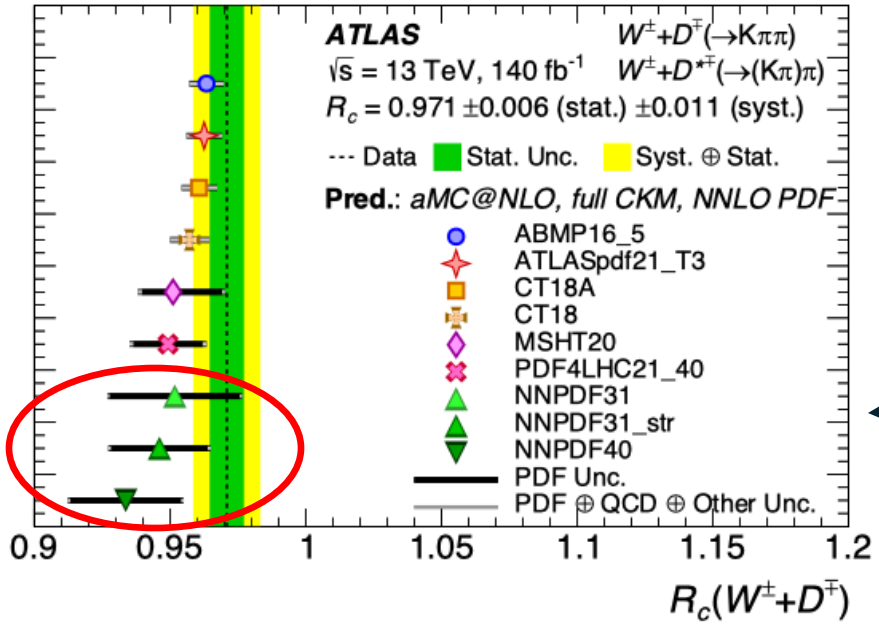
- **c-jet** tagged via the reconstruction of a **$D^{(*)\pm}$ meson**
- Background suppression via **OS - SS subtraction**

  ⟹ sgn. with opposite sign (OS) W and D, bkgs. same amount OS and same sign (SS)
- **Cross-section ratio** $R_c^{\pm}$ measurement

  ⟹ PDF allowing $s\bar{s}$ asymmetry showing tension







$$R_c^{\pm} = \frac{\sigma_{fid}^{OS-SS}(W^+D^{(*)-})}{\sigma_{fid}^{OS-SS}(W^-D^{(*)+})}$$

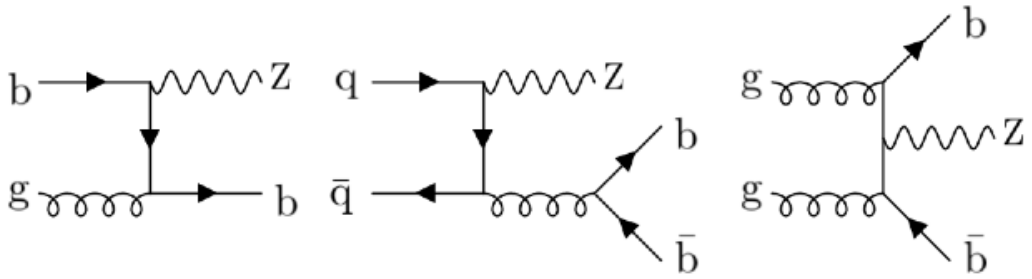
Differential cross-sections in p_T^D and $|\eta_\ell|$ available in backup

Z+b,c measurements

Z + b,c at ATLAS : integral cross sections

Submitted to Eur. Phys. J. C

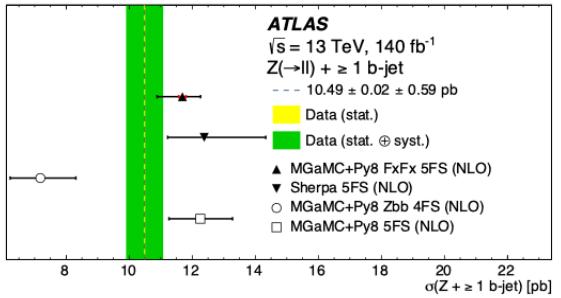
- Very relevant background, for example for H → bb analyses

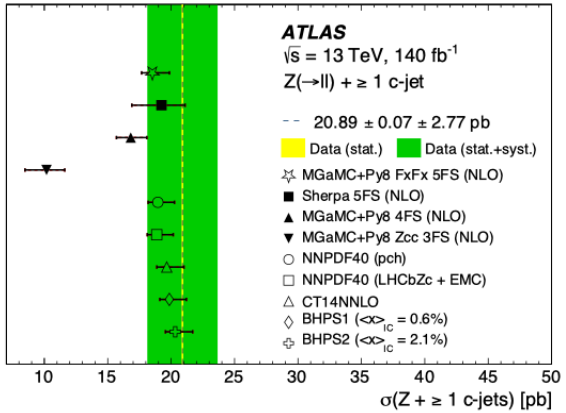


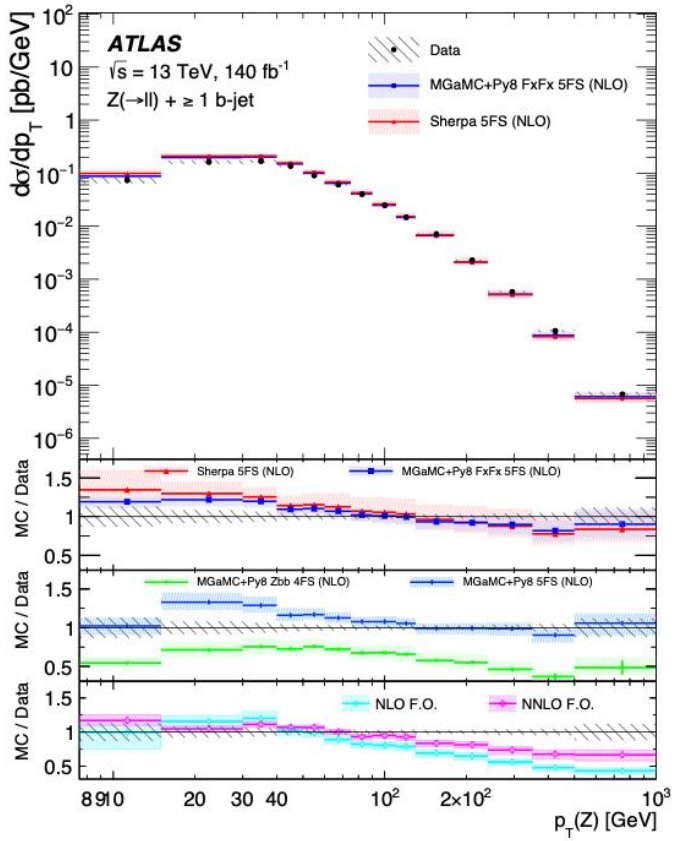
- **Events** separated in Z + ≥ 1b, Z + ≥ 2b and Z + ≥ 1c **categories**

- **Z + ≥ 1b and Z + ≥ 2b** cross sections well predicted by **5FS NLO MGaMC+Py8** and Sherpa

- **Z + ≥ 1c cross section** well predicted by **4FS NLO MGaMC+Py8** and 5FS NLO Sherpa







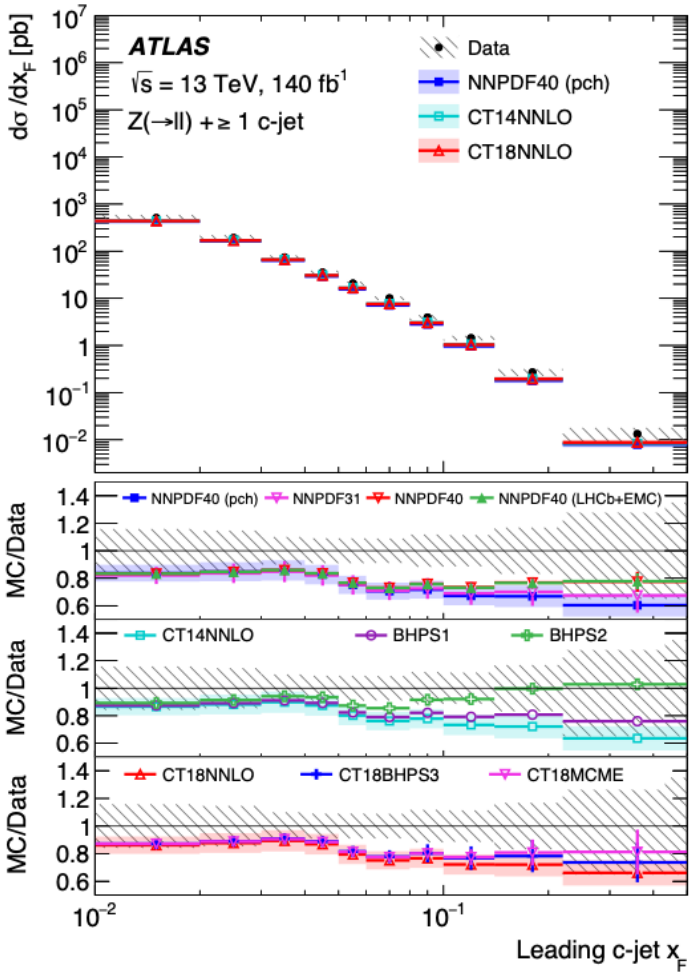
Discrepancies if flavour scheme (FS) is not chosen accurately

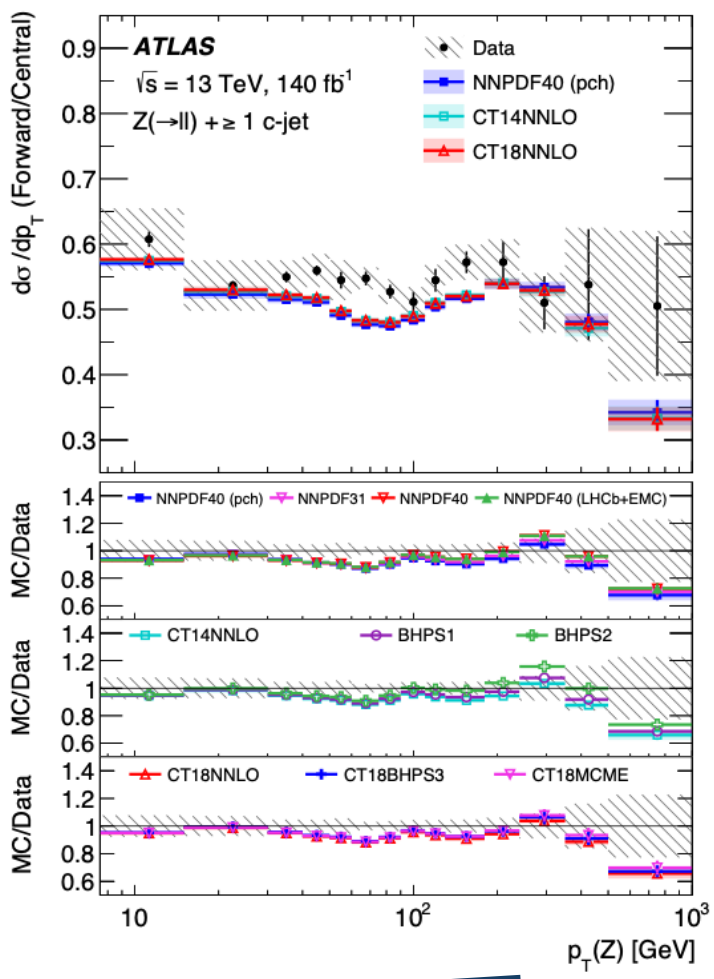
Z + b,c at ATLAS : intrinsic charm

Submitted to Eur. Phys. J. C

- **Intrinsic charm** (IC) - i.e. valence - component of the proton
- NEW : **probed several** IC **hypotheses**, measuring IC sensitive differential cross-sections
- **Agreement improves** with the BHPS2 PDF, allowing **large IC**
- **Marginal improvement** with BHPS1, NNPDF, CT18, having **small IC**

⟹ **no significant evidence** of IC





Definitions:
- $x_F = 2|p_z(c)|/\sqrt{s}$, i.e. Feynman x
- $R(p_T(Z))$: cross section ratio of $p_T(Z)$ in $|y(Z)|<1.2$ and $|y(Z)|>1.2$

Z + b measurements at CMS

Phys. Rev. D 105 (2022) 092014

- **Events** separated in Z + ≥ 1b and Z + ≥ 2b **categories**

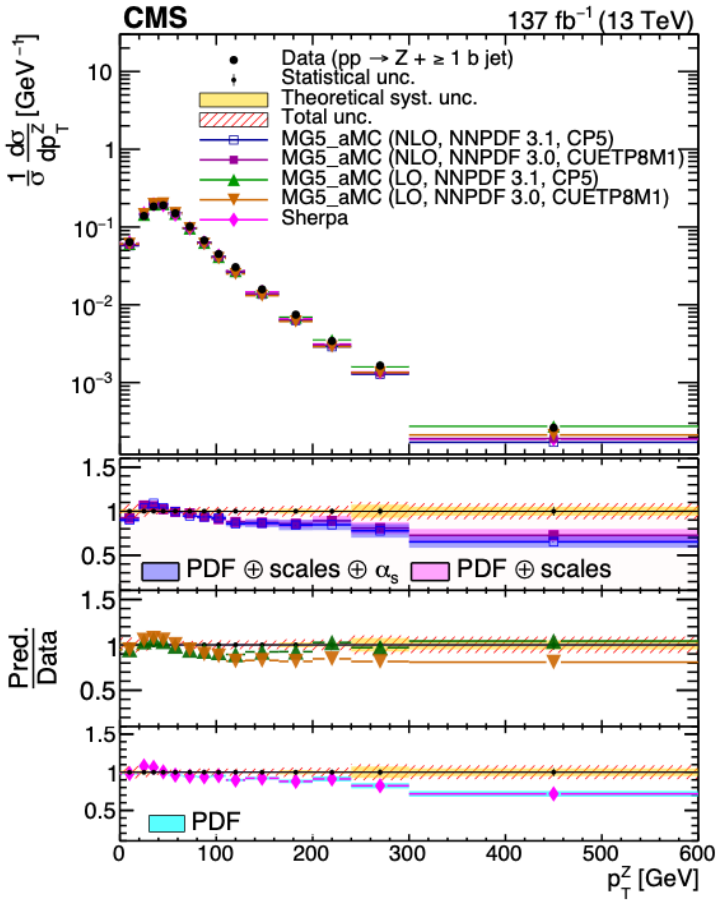
$\sigma(Z + \geq 1b) = 6.52 \pm 0.04(stat) \pm 0.40\ (syst) \pm 0.14\ (theo)$ pb

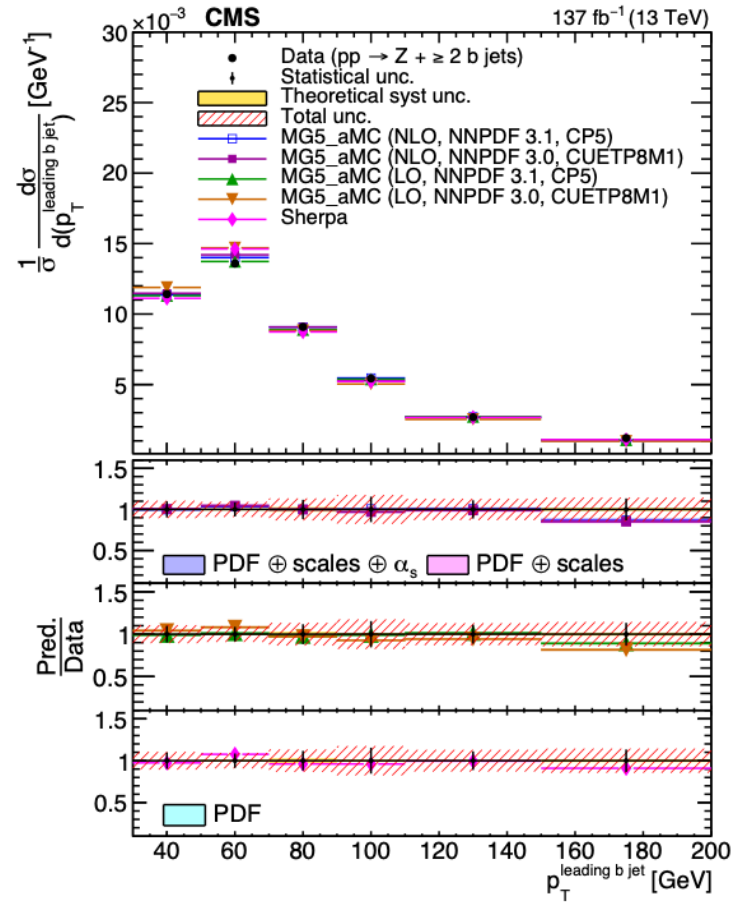
$\sigma(Z + \geq 2b) = 0.65 \pm 0.03(stat) \pm 0.07\ (syst) \pm 0.02\ (theo)$ pb

- **Integral cross-sections** best described by MG5_aMC LO generator

- **Z + ≥ 1 b differential cross** section in p_T^Z best described by MG5_aMC LO

- **Z + ≥ 2 b differential cross** section in $p_T^{b\text{-jet}}$ well described by all generators, mismodelling at high p_T





ATLAS and CMS Z+b : angular variables

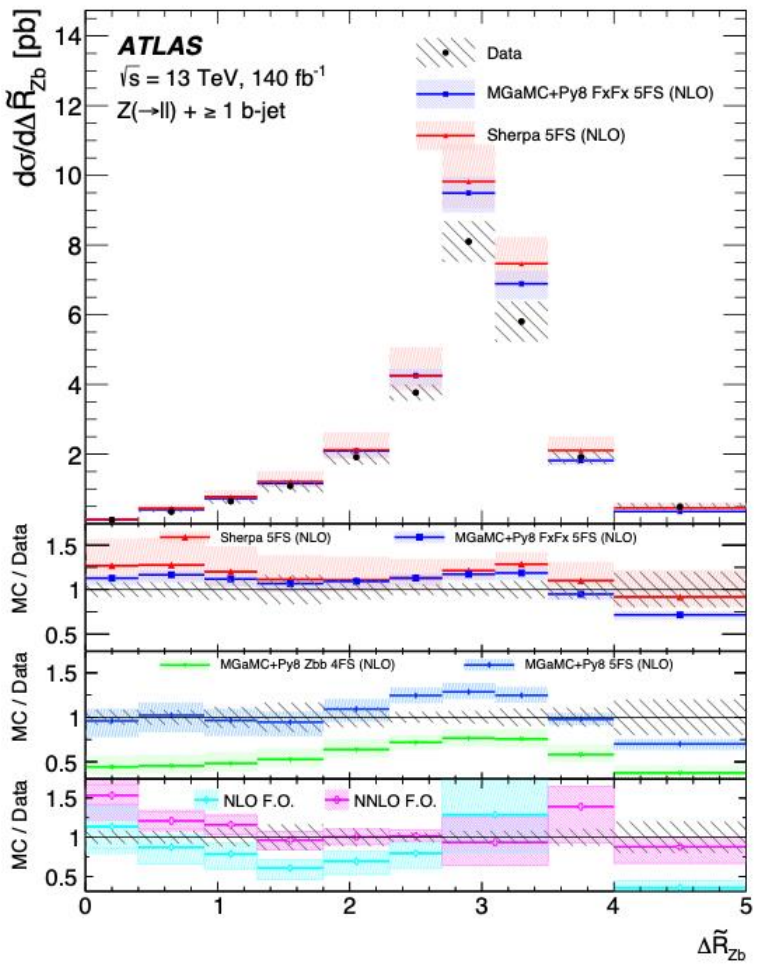
- **Non-trivial** behavior of **angular-dependent** predictions

- **ATLAS**: optimal 5FS NLO MGaMC+Py8 FxFx / Sherpa , **same generator** as integral cross sections

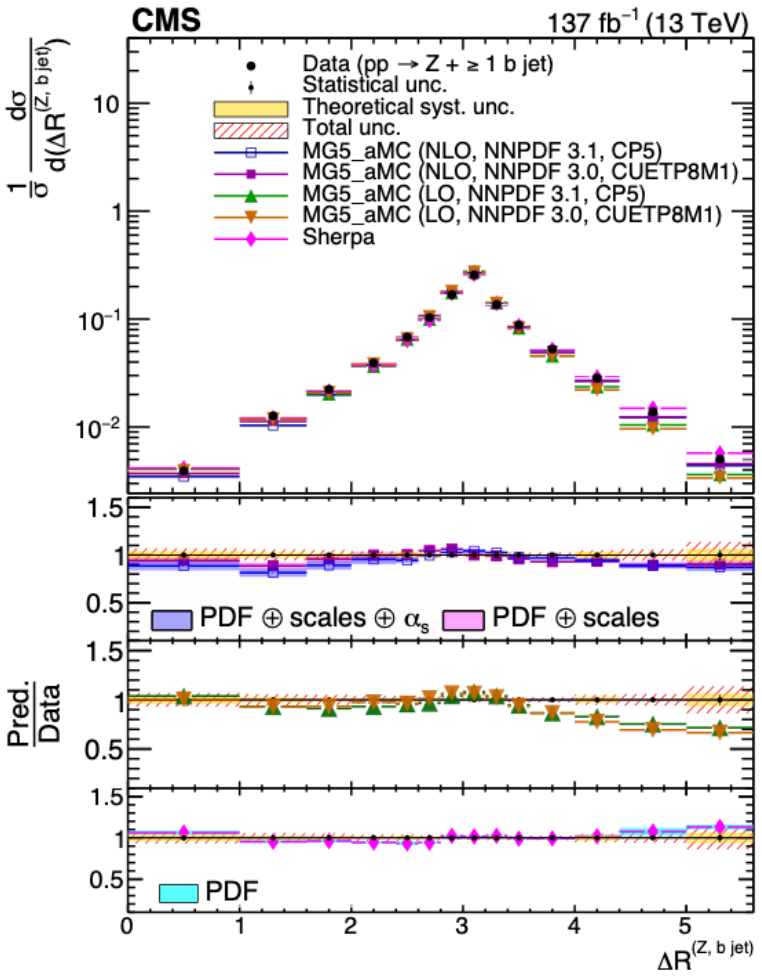
- **CMS**: optimal Sherpa / MG5_aMC NLO , **different geenrator** w.r. to integral cross sections

- Localised **discrepancies**:
  - ATLAS: $\Delta R_{Zb} \simeq \pi$ (back-to-back)
  - CMS: $\Delta R \simeq 0, 2\pi$

Submitted to Eur. Phys. J. C



Phys. Rev. D 105 (2022) 092014



Angular separation: $\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$

Additional measurements

p_T^{miss} + jets at ATLAS : cross sections

Submitted to JHEP

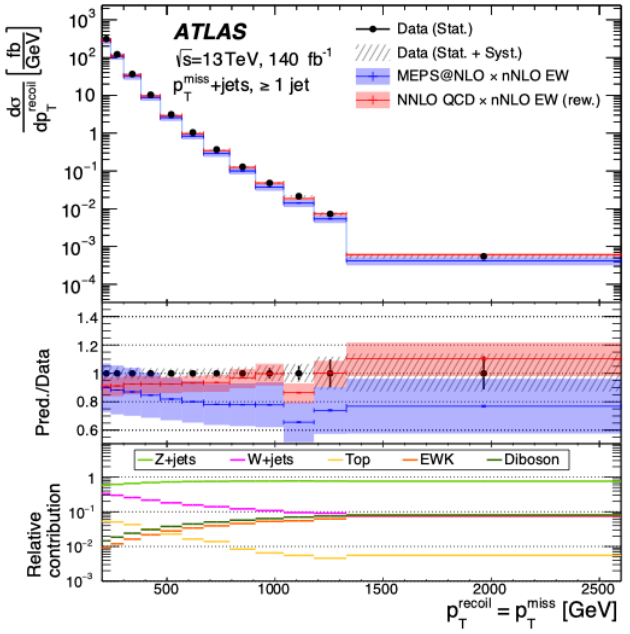
- **Cross sections** of **p_T^{miss} + jets** in signal region and in auxiliary e/μ regions ($p_T^{recoil} = p_T^{miss}$)

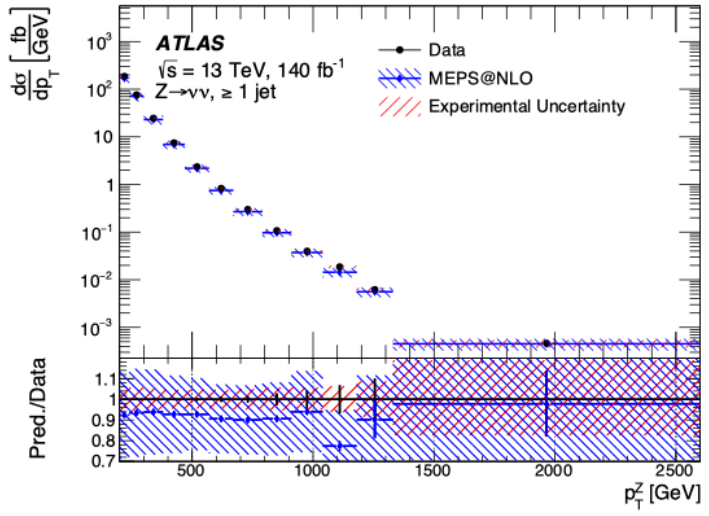
- **Cross section** measurement of the main component **$Z \rightarrow \nu\nu$ + jets**

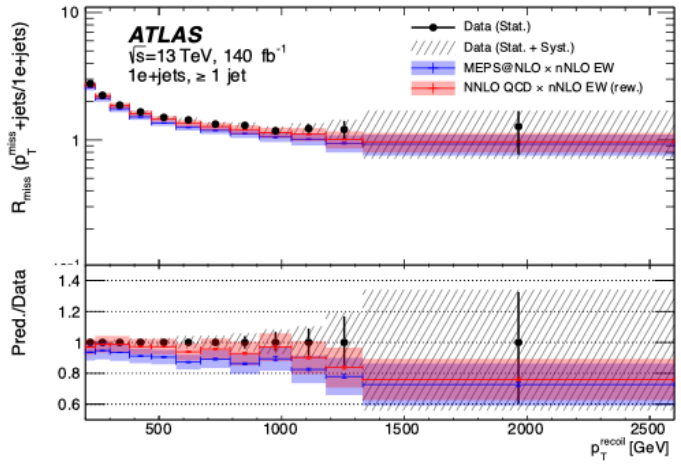
- **Measurement** of **ratio R^{miss}** of p_T^{miss} + jets over 1e/2e/2μ + jets cross sections

  $\Longrightarrow$ benefit from systematics cancellations

- Agreement between data and MEPS@NLO predictions



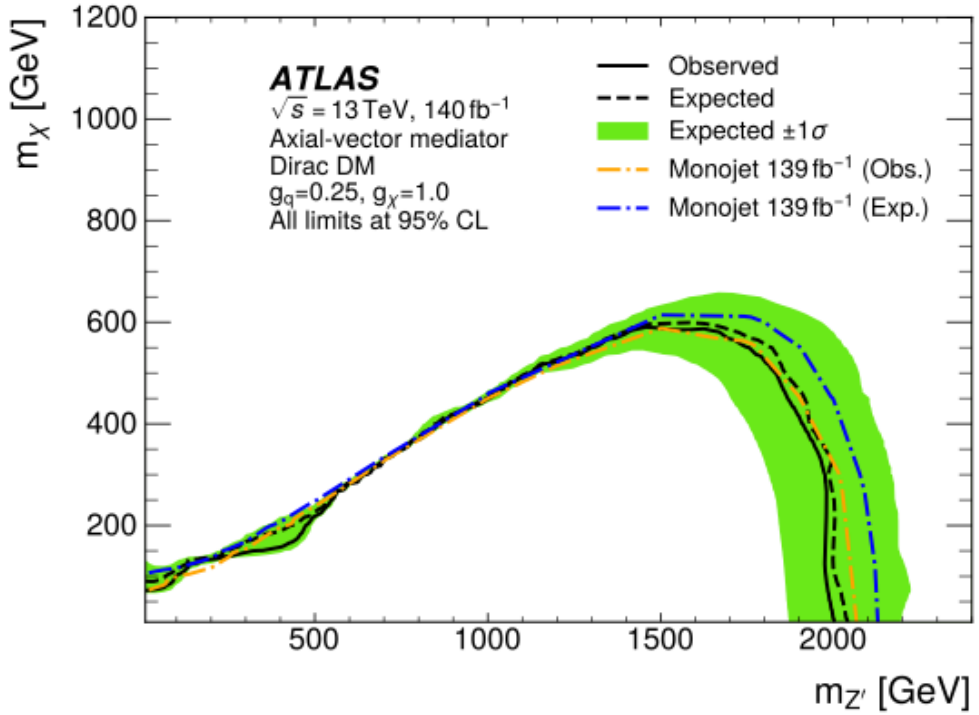


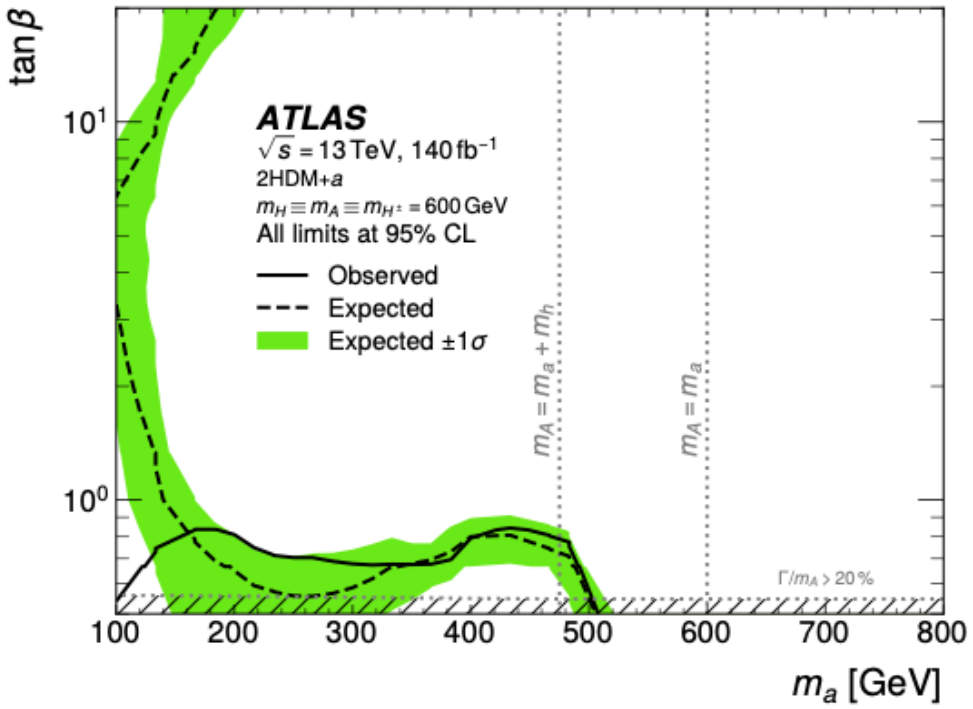


p_T^{miss} + jets at ATLAS : exotic interpretations

Submitted to JHEP

- NEW : measurements **recasted** to set **limits** on **exotics Dark Matter** models:
  - **Monojet analysis**: Dirac fermion Dark Matter candidate χ, originating from $Z' \rightarrow \chi\chi$ $\Rightarrow$ limits in $m_\chi - m_{Z'}$ space
  - **2HDM+a model:** a exotic mediator between Standard Model $\leftrightarrow$ Dark Sector $\Rightarrow$ limits in $m_a - \tan\beta$ parameters space





Exclusion contour consistent to the one obtained within the Monojet exotic search, Phys. Rev. D 103, 112006

$W \to cq$ / $W \to q\bar{q}$ at CMS : probing the CKM

CMS-PAS-SMP-24-009

- NEW : measurement of the **W hadronic branching fraction** R_c^W

- W from ttbar production, c-jets tagged via presence of a muon

- Results:

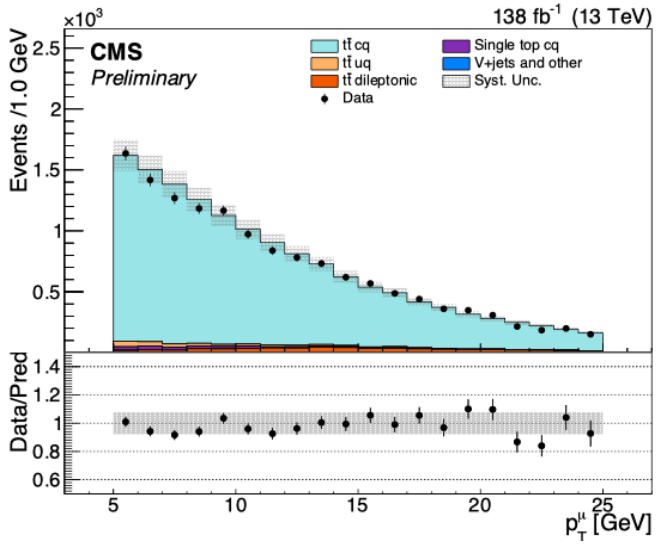
1. $\mathbf{R_c^W} = 0.489 \pm 0.020$

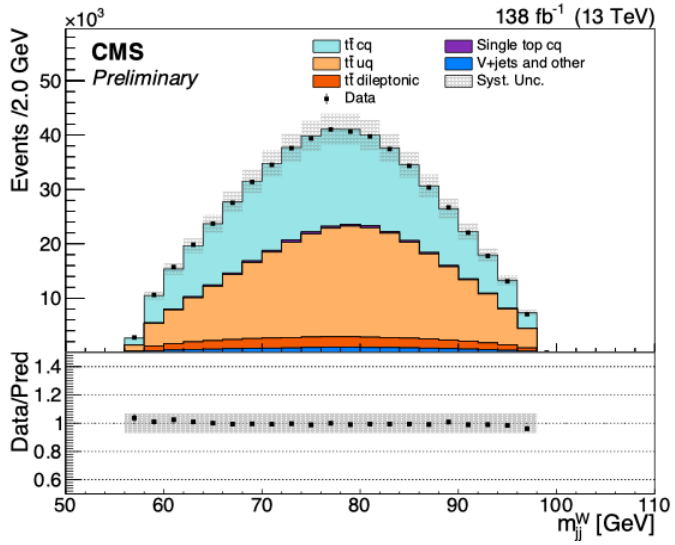
2. **Test** of CKM **unitarity**:

   $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 0.970 \pm 0.041$

3. **Measurement** of $\mathbf{|V_{cs}|}$:

   $|V_{cs}| = 0.959 \pm 0.021$





$$R_c^W = \frac{\mathcal{B}(W \to cq)}{\mathcal{B}(W \to uq) + \mathcal{B}(W \to cq)}$$

$$R_c^W = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}$$

OS-SS subtraction techniques used, as in the other ATLAS and CMS W measurements

Conclusions

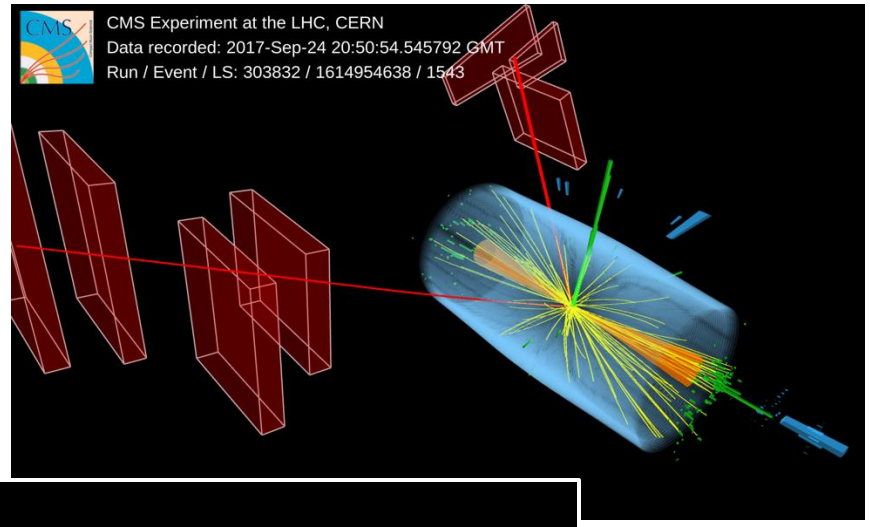
- Explored the high flexibility of **W/Z + jets measurements** in achieving different types of results

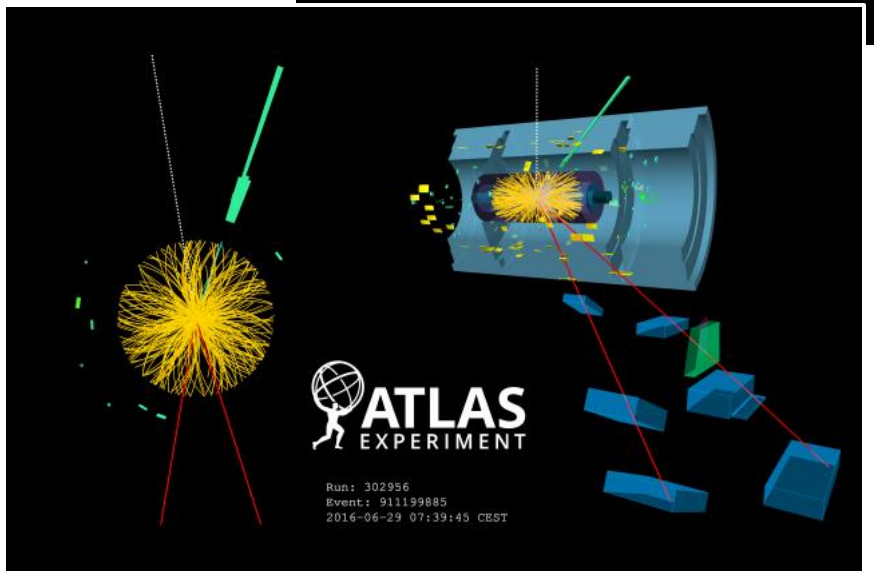
  → **precision** measurement of **electroweak** parameters

  → **probe** QCD and **PDFs** models

  → **test flavour physics** and the CKM matrix

  → **recast** into limits on **exotics models**





W/Z production events at ATLAS and CMS experiment at the LHC

An essential and powerful tool at hadron colliders

Thanks for your attention !

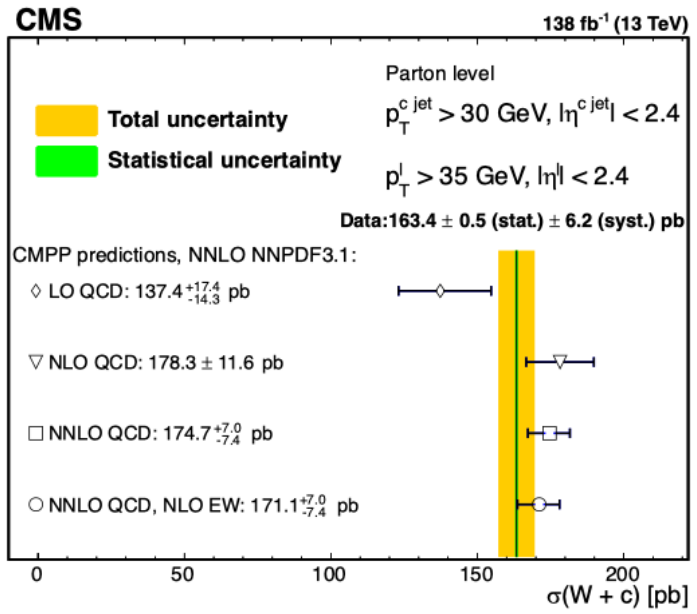
Backup

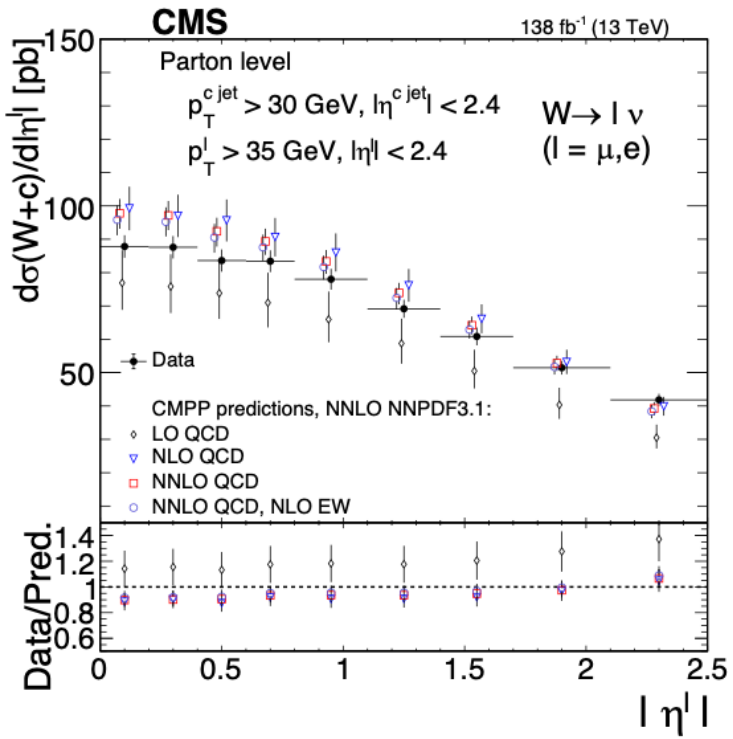
W + c measurements at CMS : NNLO predictions

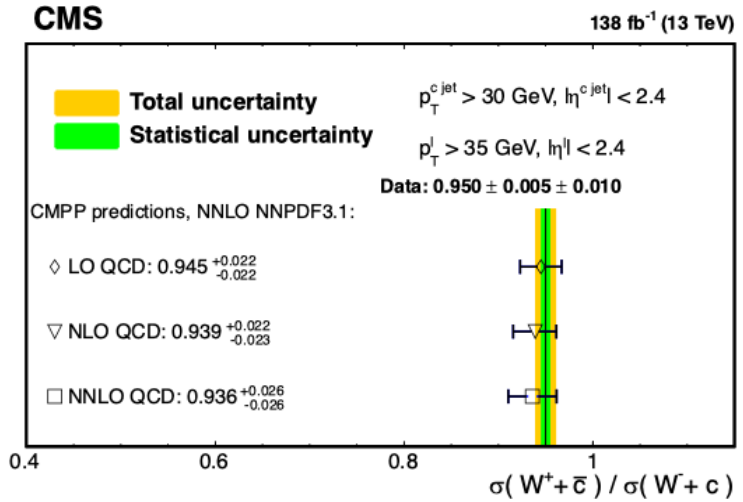
- First NNLO QCD corrections for W+c production recently released. Ad-hoc predictions evaluated for the CMS paper phase-space

Eur. Phys. J. C 84 (2024) 27

- Comparison with NNLO predictions of both integral and differential cross sections and cross section ratio





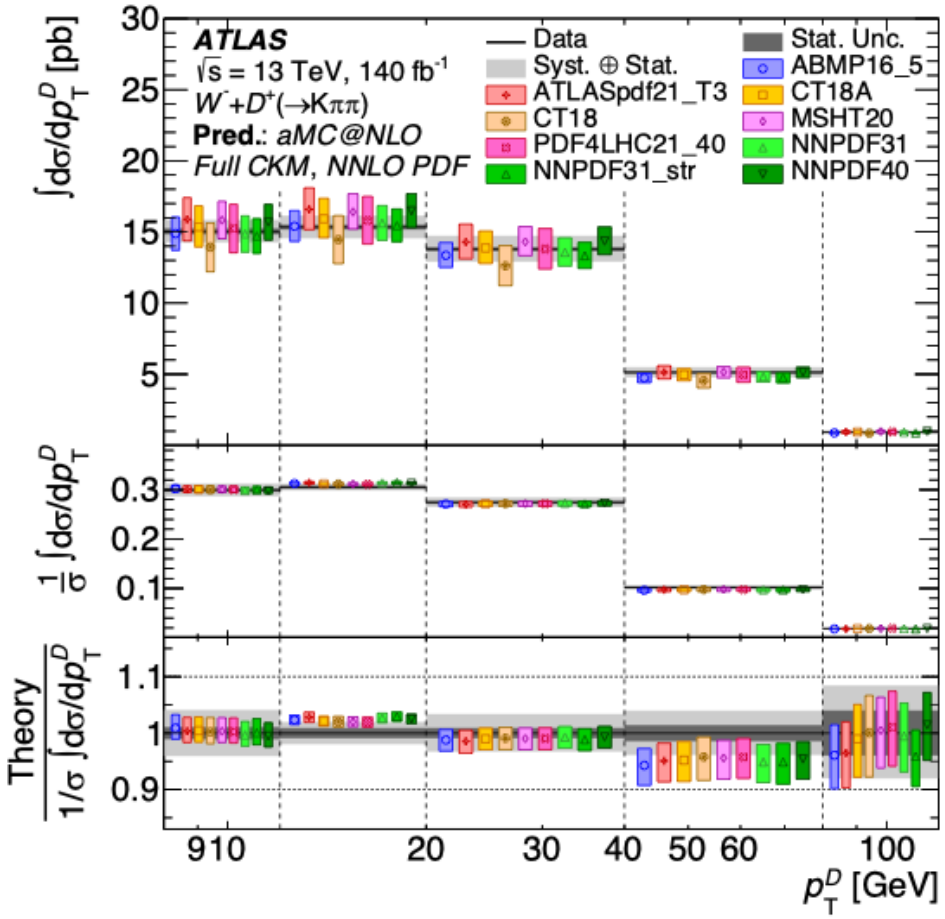


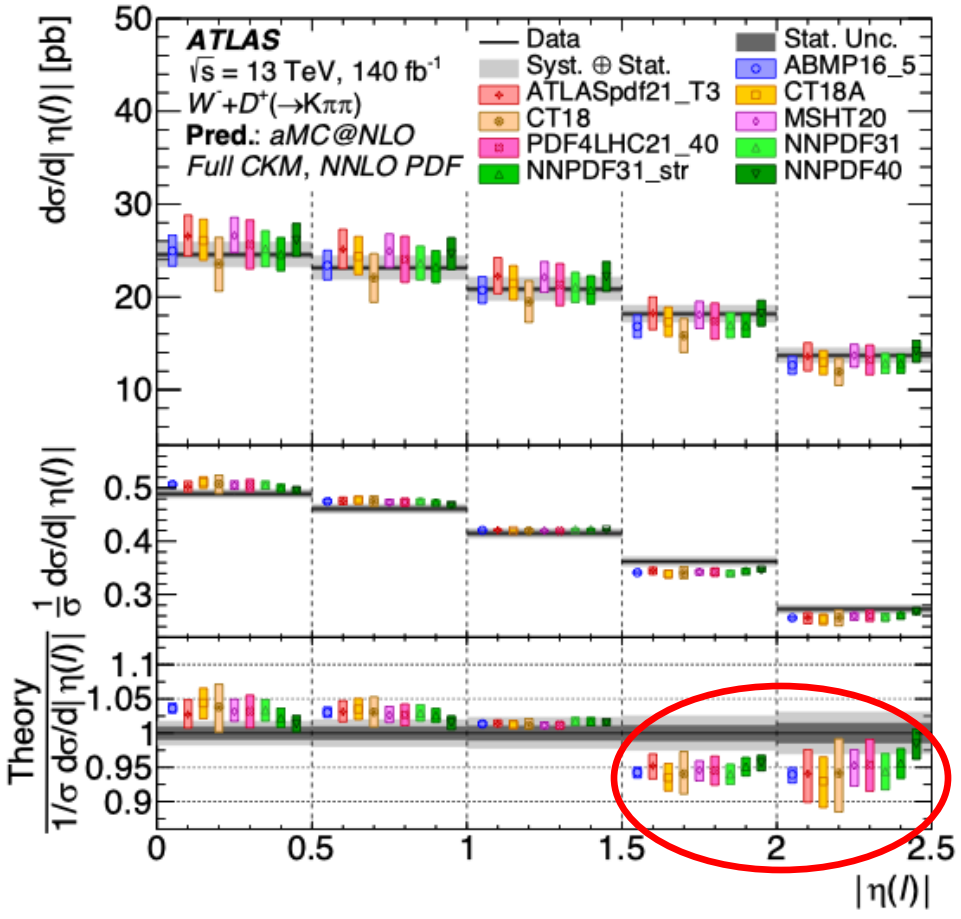
NNLO QCD correction slightly improves the already good agreement observed at NLO

W + c measurements at ATLAS

Phys. Rev. D 108 (2023) 032012

- Comments: 1) differential cross sections in p_T^D are not sensible to PDF variations; 2) slight discrepancy at high $|\eta_\ell|$, fairly covered by PDF uncertainties

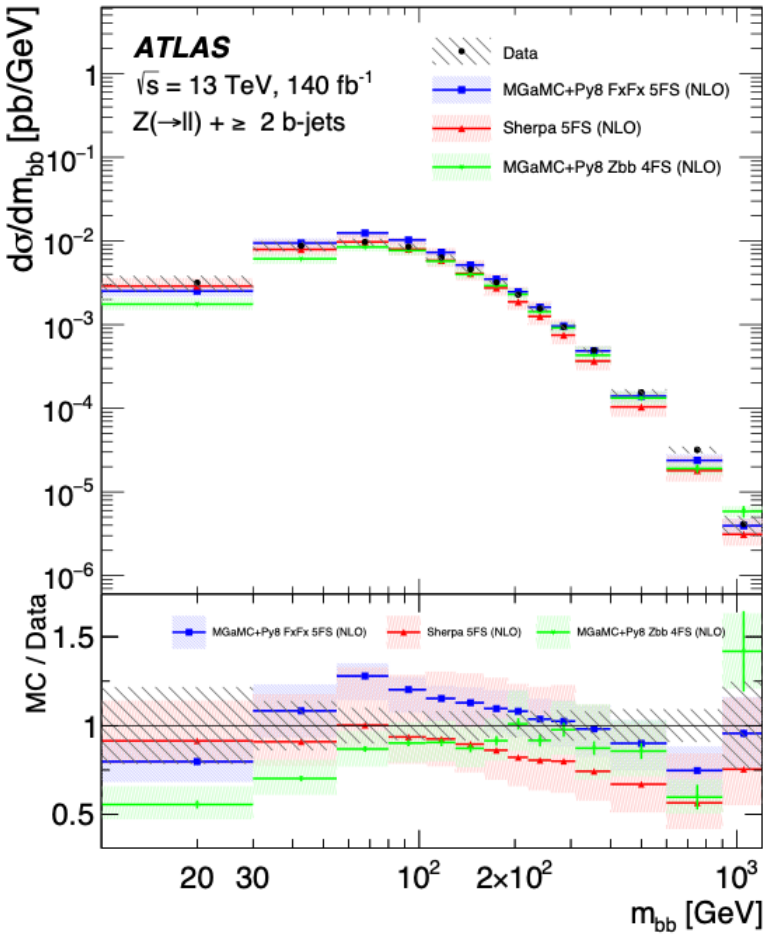


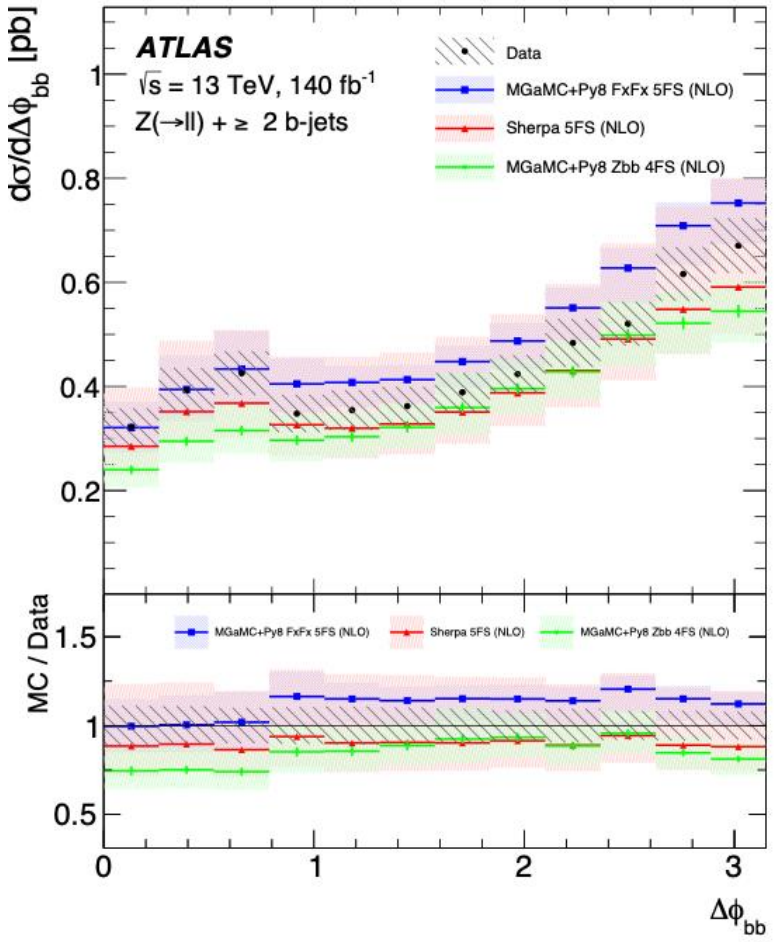


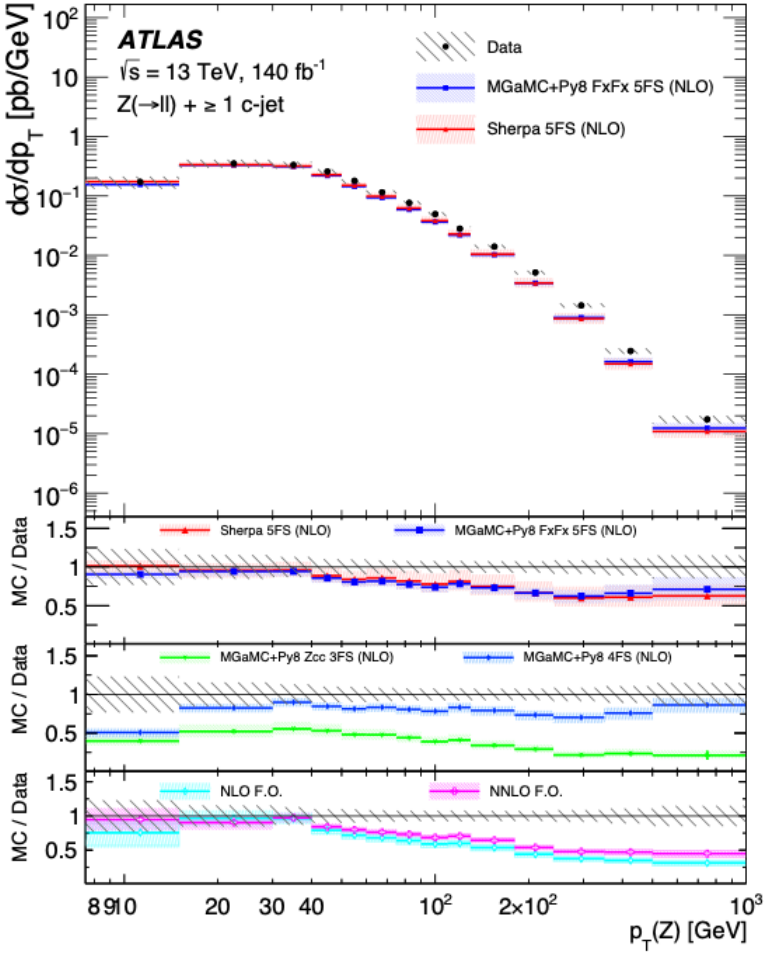
Z + b,c at ATLAS : differential cross sections

Submitted to Eur. Phys. J. C

- Additional differential distributions for Z + ≥ 2b (left, centre) and Z + ≥ 1c (right)



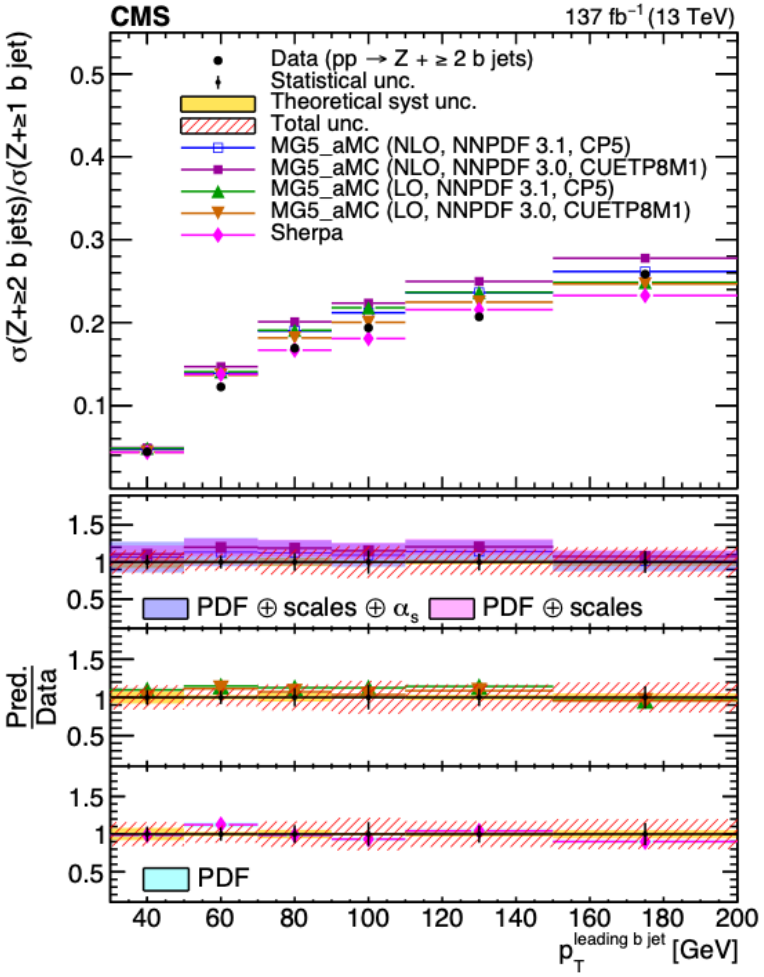


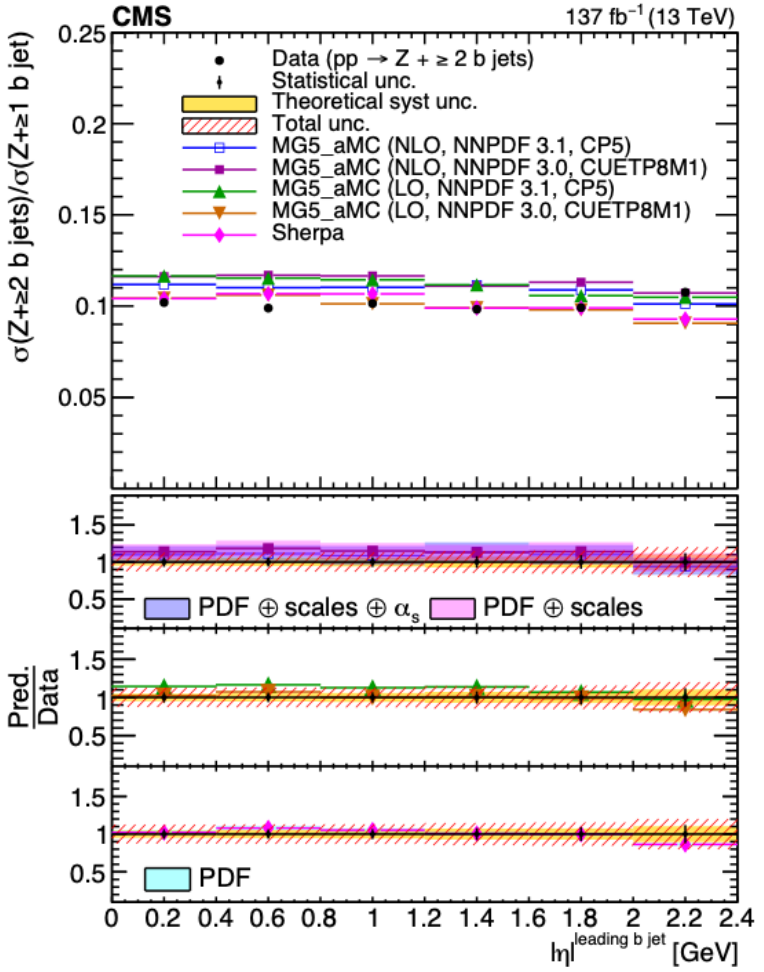


Z + b measurements at CMS

Phys. Rev. D 105 (2022) 092014

- Ratio $\sigma(Z + \geq 2\ b) / \sigma(Z + \geq 1\ b)$ well predicted by all generators, and increasing in $p_T^{b\text{-jet}}$ due to kinematics

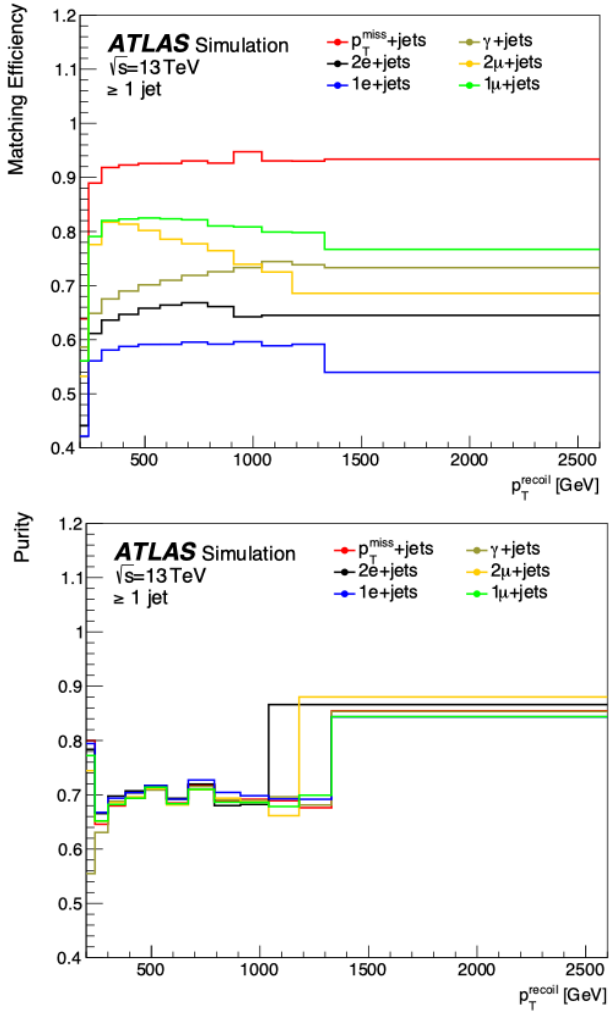


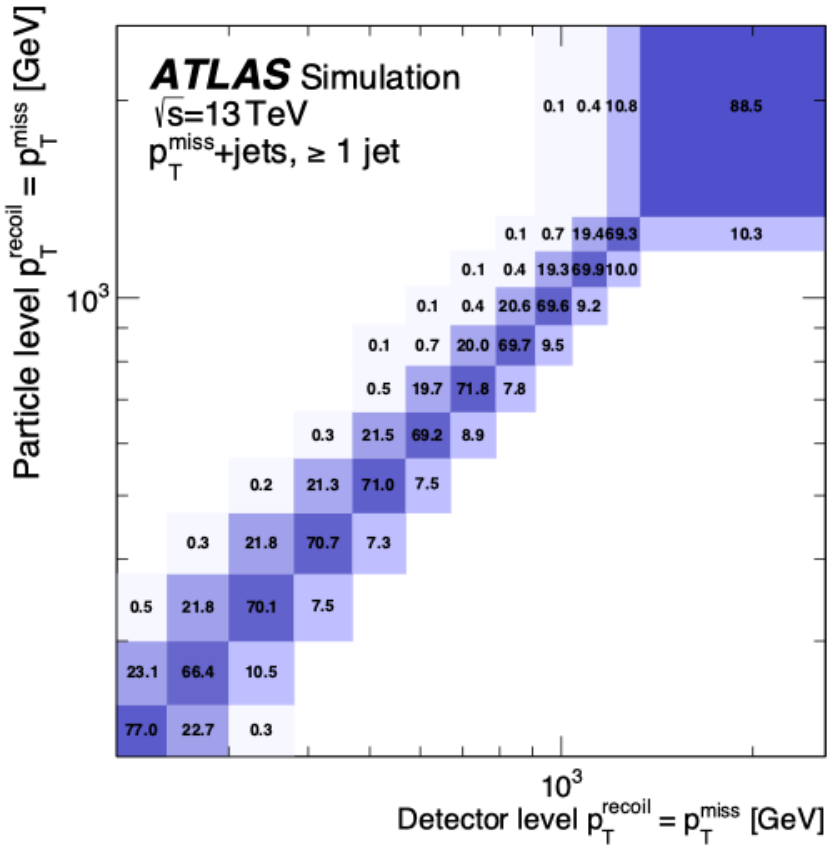


p_T^{miss} + jets at ATLAS : unfolding details

Submitted to JHEP

- Binning is optimized such that:
  - at least 20 events in each bin
  - at least purity > 60 % in each bin
- Acceptable values for efficiency, fiducial fraction, stability, migration matrix
- Hidden variables systematic uncertainties, signal injection tests





Jet energy scale measurements at ATLAS

Submitted to EPJC

ATLAS EXPERIMENT

- Z + jets events relevant for Jet energy Scale (JES) calibration
- A crucial point of the ATLAS reconstruction framework to succeed in jet-related analyses
- In situ Z → ee and Z → μμ calibrations weight at Z-peak energy scales
- Latest JES measurements recently submitted for publication (July 2024)