QCD aspects in W and Z production, with focus on high-pT W/Z

QCD@LHC - Freiburg
7 of October 2024
Florencia Castillo on behalf of the ATLAS and CMS Collaborations

CMS
Compact Muon Solenoid

anr
agence nationale
de la recherche

LAPP
Laboratoire d'Annecy de Physique des Particules

ATRAPP

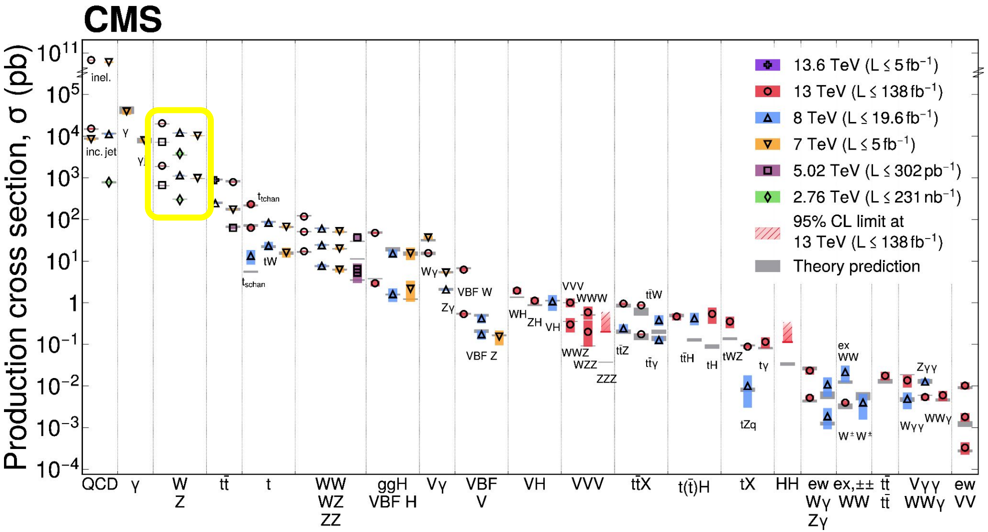
cnrs

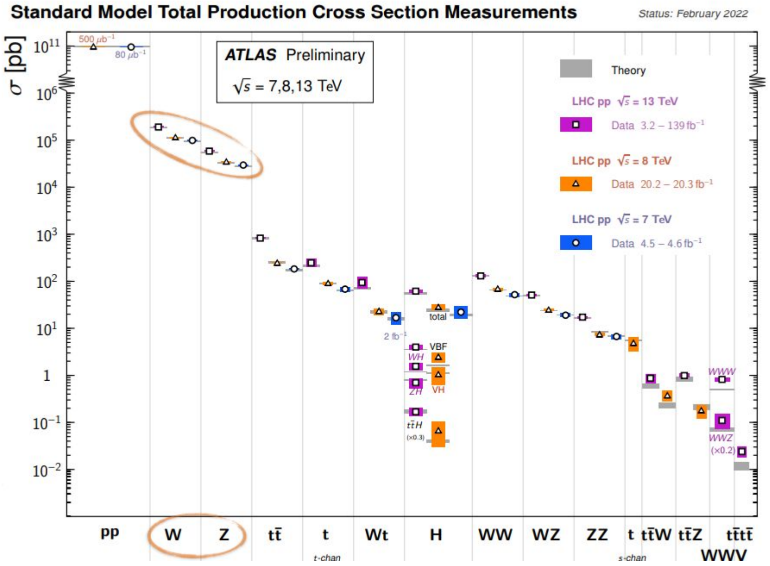
ATLAS
EXPERIMENT

Motivation

ATL-PHYS-PUB-2022-009
CMS-SMP-23-004

- ➔ We have a high sensitivity to a wide dynamic range of cross sections at the LHC.
- ➔ The production of W and Z particles has relatively high cross sections.

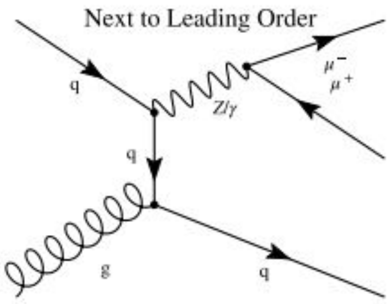


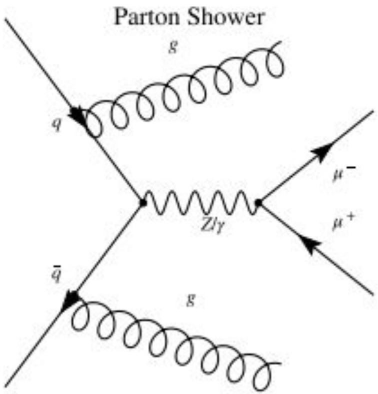


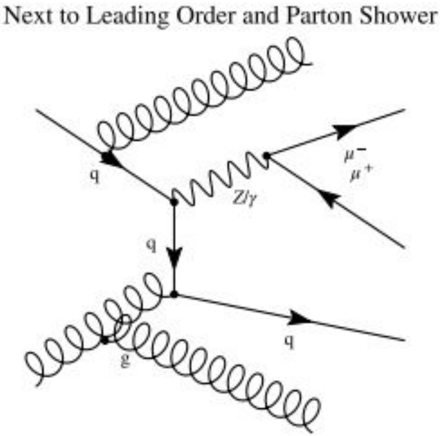
- ➔ A large dataset enabling us to investigate a broad spectrum of physical processes.

Still a lot of to learn

- **W and Z Bosons**: crucial for understanding electroweak interactions
- **Precision Tests of QCD**: To accurately and precisely characterize W and Z processes at the LHC, all aspects of QCD must be thoroughly understood across a wide range of scales
    - PDF, Higher-order Matrix Element calculation, parton shower, matching or merging, factorization/renormalization, hadronization.


Next to Leading Order


Parton Shower


Next to Leading Order and Parton Shower

QCD aspects in W and Z physics

- Many analyses from ATLAS and CMS! We can't showcase everything here, but you can check them out!
  - CMS SM results
  - ATLAS SM results

* Talk on Friday by Max

This talk contains:

ATLAS → * Z pT and rapidity at 8 TeV (Eur. Phys. J. C 84 (2024) 315), * Precise W and Z pT measurements at 5.02 and 13 TeV(arXiv:2404.06204), Z+jet unbinned unfolding (arXiv:2405.20041) and MET+jets differential x-section at 13 TeV (JHEP 08 (2024) 223)

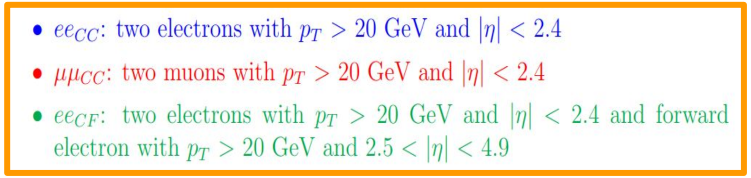
CMS → Drell-Yan FB asymmetry and the weak mixing angle (arXiv:2408.07622), Precise W and Z pT measurements 5.02, 13 TeV and 13.6TeV (arXiv:2408.03744, CMS-PAS-SMP-22-017) and Z decaying to four leptons at 8 and 13 TeV (CMS-PAS-SMP-19-007)

Z pT and rapidity at 8 TeV

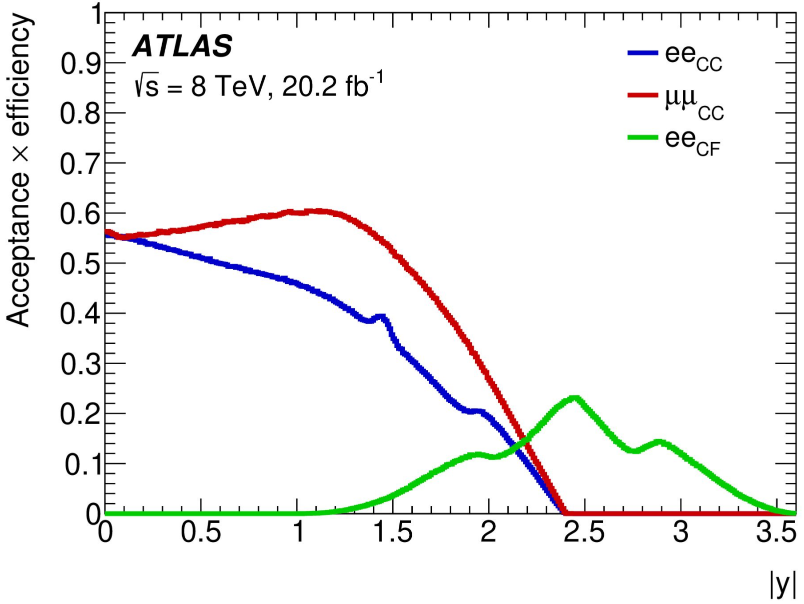
Eur. Phys. J. C 84 (2024) 315

- Measuring **leptonic decay** in the **full phase** space enhances the effects, while leading to **higher experimental and theoretical precision**
- Measurement performed on 20 fb^{-1} of 8 TeV ATLAS

- Very high experimental precision (Δ< 1%)
  - First comparison with N3LO QCD predictions (MSHT20).
  - Comparison to other NNLO PDFs are also provided.
- Rapidity-dependence of differential cross-section yields high sensitivity to PDF



- ee_{CC}: two electrons with $p_T > 20$ GeV and $|\eta| < 2.4$
- $\mu\mu_{CC}$: two muons with $p_T > 20$ GeV and $|\eta| < 2.4$
- ee_{CF}: two electrons with $p_T > 20$ GeV and $|\eta| < 2.4$ and forward electron with $p_T > 20$ GeV and $2.5 < |\eta| < 4.9$



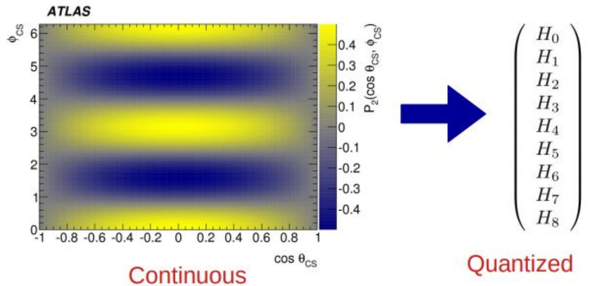
Eur. Phys. J. C 84 (2024) 315

Z pT and rapidity at 8 TeV: Methodology

- Measure θ and ϕ distributions defined in the Collin-Soper frame and **extract the free parameters** (A_i,σ^{U+L}) from a fit in , p_T -y bins
  - $d\sigma/dp_T$: transverse dynamics
  - $d\sigma/dy$: longitudinal dynamics (PDFs)

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T\,dydm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

- Measuring $A_i \rightarrow$ a “quantized” representation of ($cos(\theta)$, ϕ) from the construction of a synthetic model
  - allow to control uncertainties while accounting for correlations
  - provide analytic extrapolation of lepton cuts and enables a richer interpretation programme



Continuous

Quantized

Parameters of interests are the 8 A_i + 1 cross section in(p_T-y)bins: **9 parameters in 352 bins**

Expected Yield

Reco (p_T^Z,y^Z,m^Z, cosθ, ϕ) bin

Cross section

Background template

$$N^n_{\mathrm{exp}}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{\mathrm{bins}}}\mathcal{L}\sigma_j\left[t^n_{8j}(\beta)+\sum_{i=0}^{7}A_{ij}t^n_{ij}(\beta)\right]\right\}\gamma^n+\sum_{B}^{\mathrm{bkgs}}T^n_B(\beta)$$

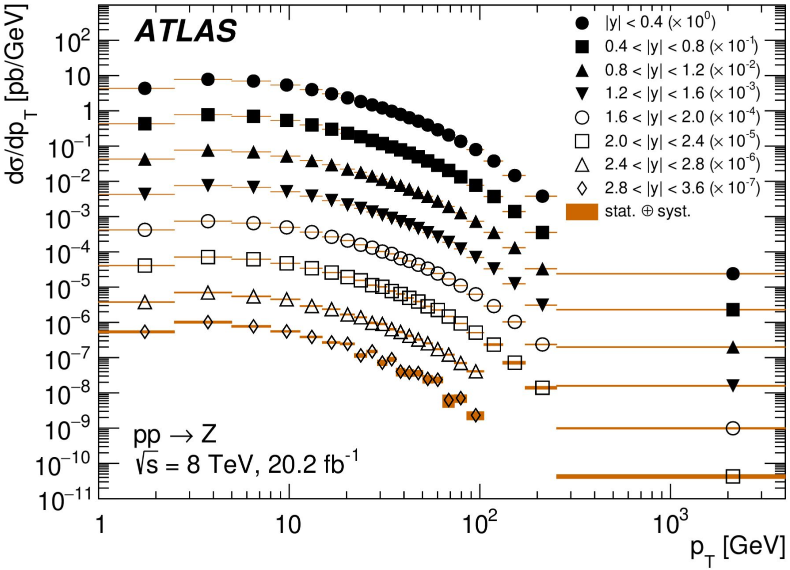
Truth (p_T^Z,y^Z,m^Z) bin

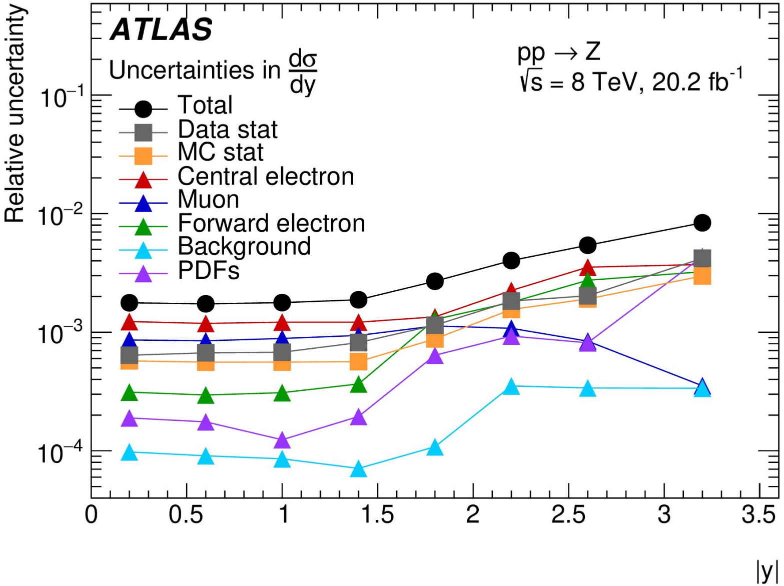
Angular coefficient

Templated polynomial

Z pT and rapidity at 8 TeV: Differential cross section

Eur. Phys. J. C 84 (2024) 315



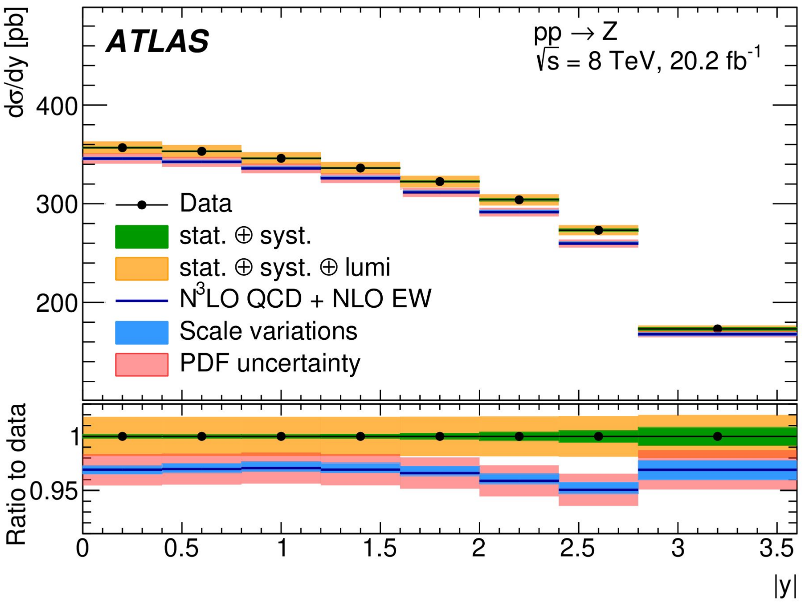


- Statistically dominated measurement
- Achieved precision at the 0.1% level in the central region.
- Less than 1% uncertainties for |y| < 3.6, thanks by dedicated forward electron calibration

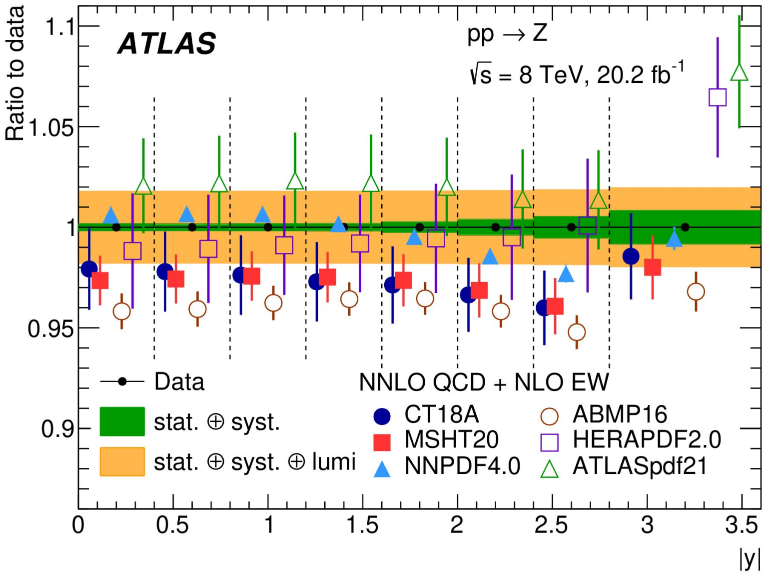
Z pT and rapidity at 8 TeV: Differential cross section

[Eur. Phys. J. C 84 (2024) 315]()

aN3LO MSHT PDF



NNLO PDFs



- First comparison to aN3LO PDF sets. Comparison to other NNLO PDFs are also provided (DYTurbo)
    - Only the **aN3LO MSHT, NNLO CT18A and NNLO MSHT PDF** sets show reasonable agreement with the data

Drell-Yan FB asymmetry and the weak mixing angle

arXiv:2408.07622

- $Z \to \ell\ell$ used full Run 2
- A_{FB} is sensitive to near Z peak

Collin-Soper frame

$$\frac{d\sigma}{d\cos\theta_{CS}} \propto 1+\cos^2\theta_{CS}+A_4\cos\theta_{CS} \; +0.5A_0*(1-3\cos^2\theta_{CS}) \qquad A_{FB}=\frac{3}{8}A_4=\frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B}$$

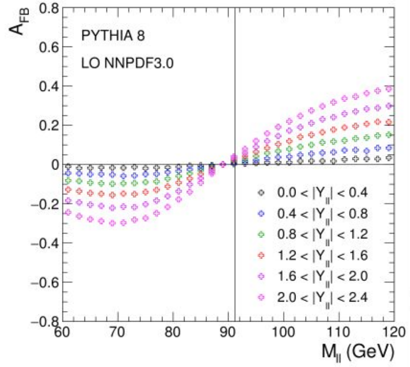
$$\sigma_F(cos(\theta_{CS})>0) \qquad \sigma_B(cos(\theta_{CS})<0)$$

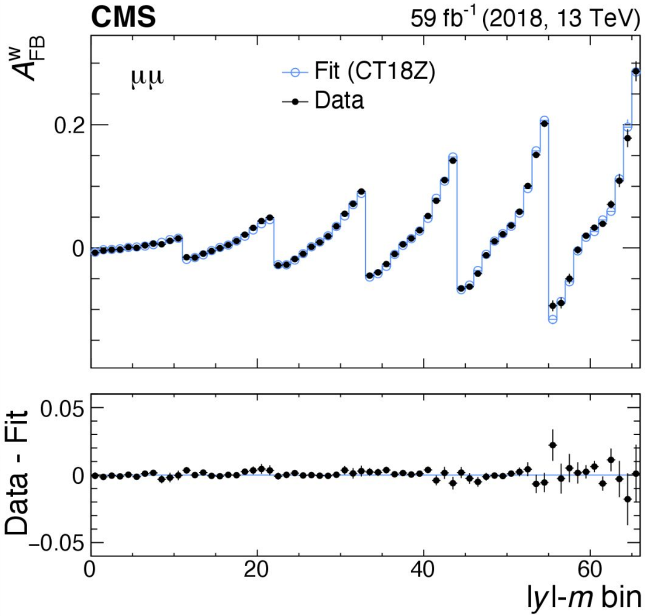
- Three $sin^2\theta^{\ell}_{eff}$ measurements:
  - Directly from the reco-level A_{FB}
    - small systematic uncertainty
  - Unfolded angular coefficient A_4 and $sin\theta_{CS}$ distribution
    - allows for reinterpretations in future

Backgrounds

- QCD multijet – data-driven
- W/EW/top – from simulation (validated in CR)

Forward-backward Asymmetry

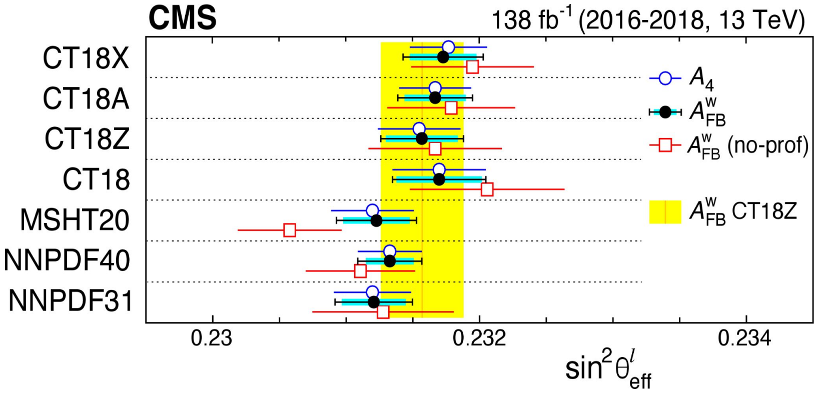


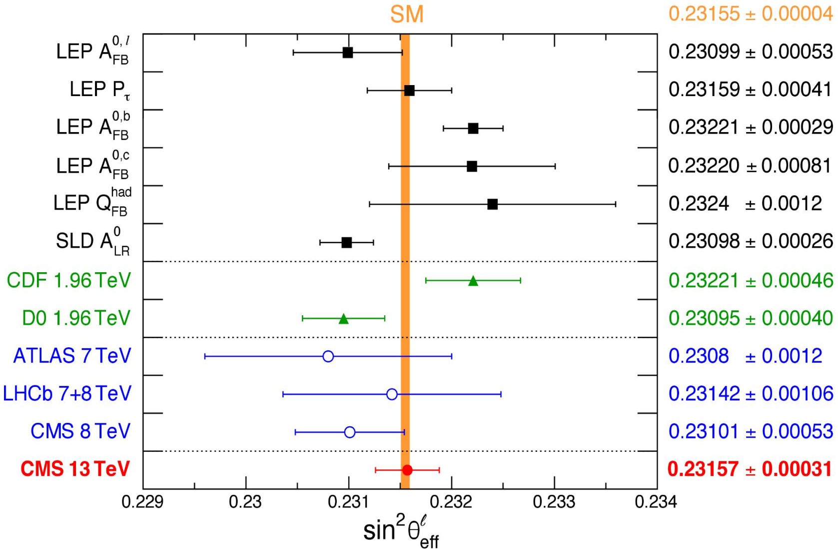


Drell-Yan FB asymmetry and the weak mixing angle

arXiv:2408.07622

- ➔ all PDF sets lead to good quality fits





- Three fit results are shown
  - A_{FB} detector-level
  - A_4 unfolded
  - $cos\theta_{CS}$ distribution

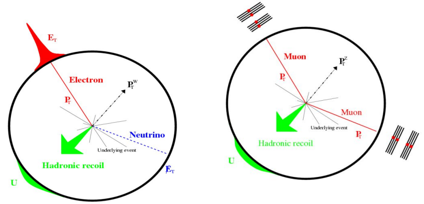
- ➔ Comparable with e^+e^- results precision, dominated by the PDF uncertainty
- ➔ Differential A_4 coefficient measurement can be used in combination with other experiments to improve further precision $sin^2\theta^\ell_{eff}$

arXiv:2404.06204

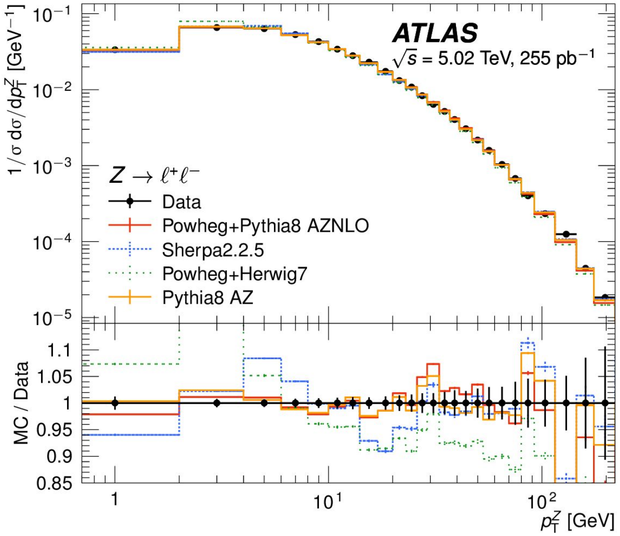
Precise W and Z pT measurements

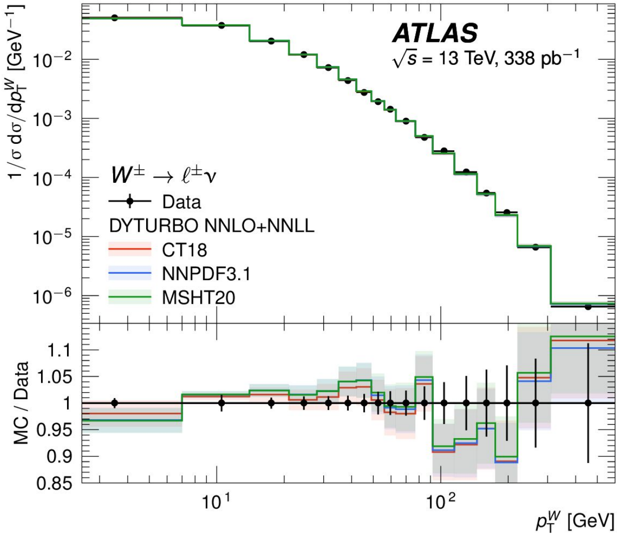
- The hadronic recoil (u_T) is the primary factor limiting of p_T^W measurements:
  - Recoil resolution worsens with increased pileup.
    - add energy to the recoil

- 2 runs: 13 and 5.02 TeV low-pileup runs with an average ⟨μ⟩ ~ 2.
  - L= 255 pb^{-1} at √ s = 5.02 TeV
    L=338 pb^{-1} at √ s = 13 TeV



- p_T^W : unfolded from the hadronic recoil u_T
- p_T^Z : unfolded from $p_T^{\ell,\ell}$ and checked to be consistent with u_T
- Reasonable agreement from the tune from ATLAS 7 TeV (AZNLO) data in $p_T^{W/Z}$< 40 GeV region
- DYTURBO: the best agreement across the spectrum

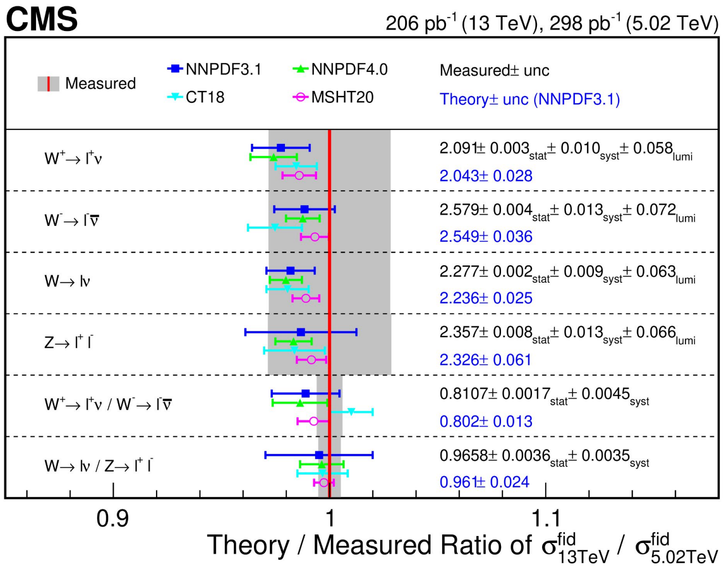


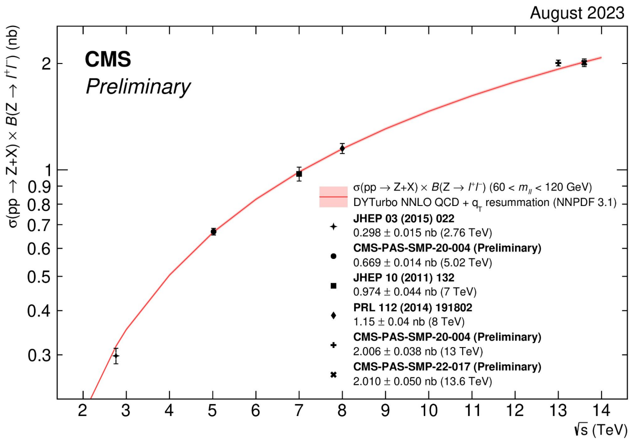


Precise W and Z pT measurements

arXiv:2408.03744 CMS-PAS-SMP-22-017

- W signal distribution $m_T = \sqrt{2p_T^{\ell}p_T^{\nu}[1-\cos(\Delta\phi)]}$
  - p_T^{ν} estimated by p_T^{miss}
- Z signal distribution $m_{\ell^+\ell^-}$
- 3 low pile-up runs:
  - L= 298 pb^{-1} at √s=5.02 TeV
  - L=201 pb^{-1} at √s=13 TeV
  - L=5.04 fb^{-1} √s=13.6 TeV

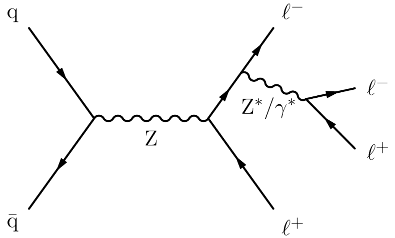




- Cross sections, ratios and double ratios measured
  - Dominated by the lumi uncertainty
  - ATLAS and CMS in agreement
- CMS compared with DYTURBO
  - Very good agreement across runs at low pileup

CMS-PAS-SMP-19-007

Z decaying to four leptons at 8 and 13 TeV



- L= 19.7 fb^{-1}at √ s = 8 TeV
- L=138 fb^{-1} at √ s = 13 TeV

- Motivation
  - Study rare decays
  - Calculate branching ratios, test SM
  - Fit of data using templates from POWHEG
  - Search for new physics

$$\mathcal{B}(Z \to 4\ell) = \mathcal{B}(Z \to \ell^+\ell^-)(1 - f_{\mathrm{nr}})\frac{(A \times \epsilon)_{\ell^+\ell^-}}{(A \times \epsilon)_{4\ell}}\frac{(N^{\mathrm{obs}} - N^{\mathrm{bkg}})_{4\ell}}{(N^{\mathrm{obs}} - N^{\mathrm{bkg}})_{\ell^+\ell^-}}.$$

	$\mathcal{B}(Z \to 4\ell)$ $[\times 10^{-6}]$	
Channel	Expected	Observed
4μ	1.20 ± 0.01	1.25 ± 0.04 (stat) ± 0.03 (syst)
$2\mu 2e$	2.31 ± 0.01	2.17 ± 0.08 (stat) ± 0.06 (syst)
4e	1.20 ± 0.01	1.16 ± 0.09 (stat) ± 0.06 (syst)
4ℓ	4.70 ± 0.02	4.67 ± 0.11 (stat) ± 0.10 (syst)

➔ The signal purity for each of the four final states is above 97%.

➔ The most significant sources of systematic uncertainty are the lepton identification and reconstruction efficiencies

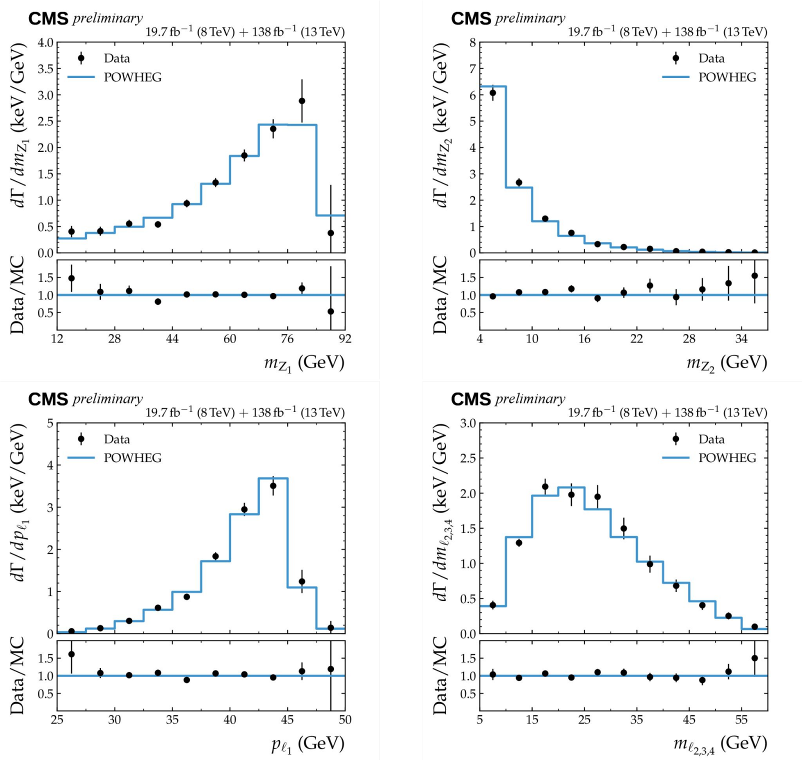
➔ $B(Z \to 4\ell)$ more precise than the combined value reported

➔ All measured branching fractions are consistent with the SM expectations.

CMS-PAS-SMP-19-007

Z decaying to four leptons at 8 and 13 TeV

Differential decay rates

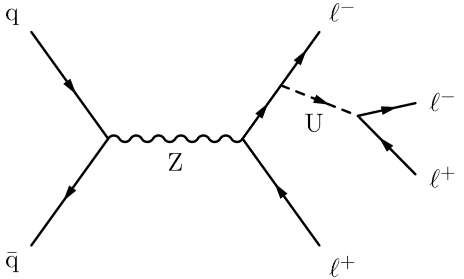


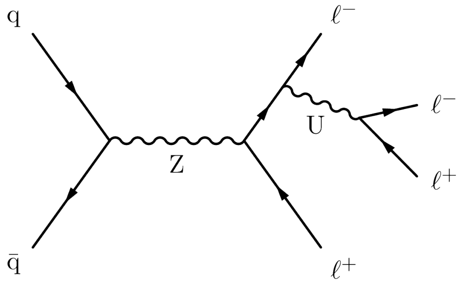
- Backgrounds are subtracted bin-by-bin
- The shape of the nonprompt-lepton background is taken from the loose control region
- Shapes of other backgrounds are taken from simulations
- The unfolded distributions are corrected to the full phase space and normalised to the measured width
- Overall, the agreement of the simulation is good

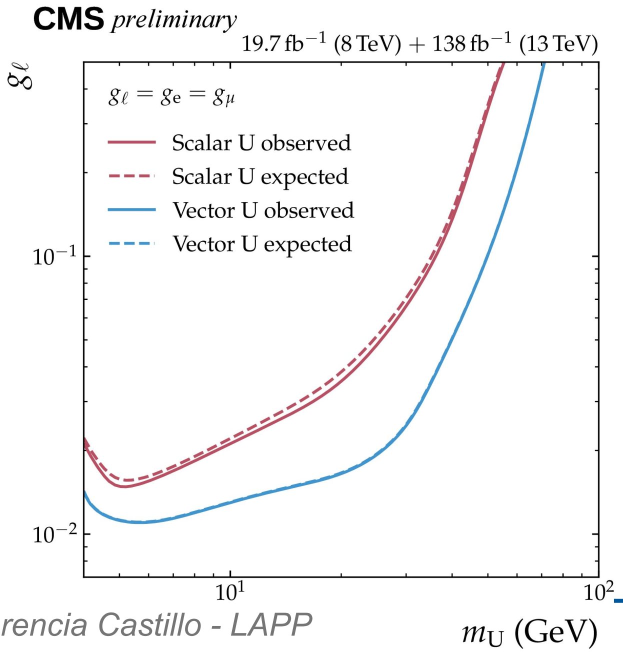
CMS-PAS-SMP-19-007

Z decaying to four leptons at 8 and 13 TeV

- ➔ Search for Physics beyond the SM
  - ◆ A light gauge boson may be produced on shell in Z boson decays.
  - ◆ Looking for a scalar or vector boson U with a significant coupling to leptons
  - ◆ Insensitive to assumptions about the U boson total width







upper limits branching fractions

	95% CL UL [$\times 10^{-6}$]	
Channel	Expected	Observed
4μ	1.28	1.34
$2\mu 2e$	2.48	2.33
4e	1.37	1.32
4ℓ	4.95	4.91

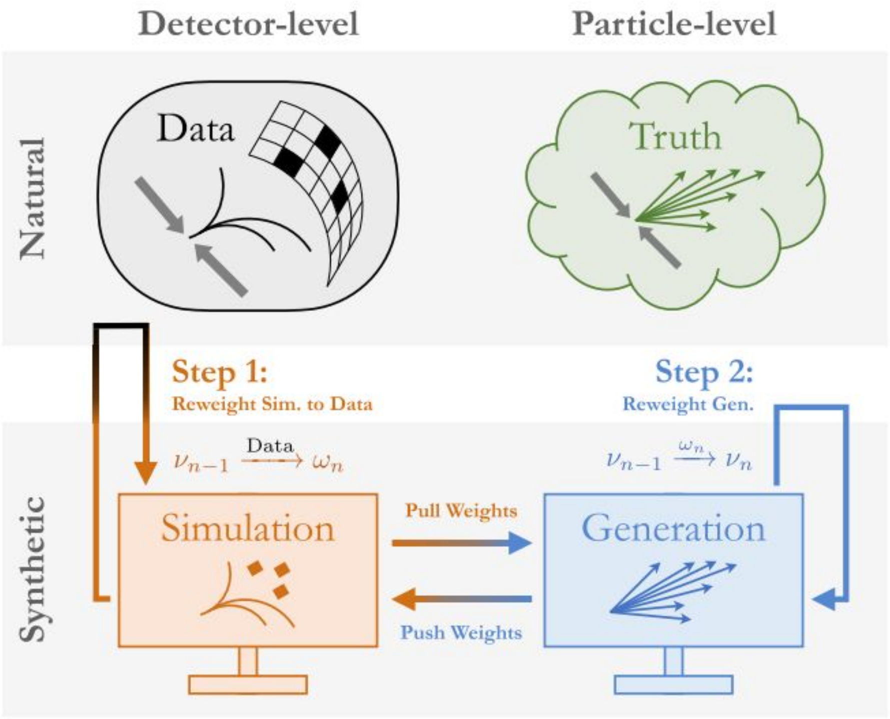
- ➔ The region above and to the left of the curve is excluded
- ➔ These limits are more stringent than those set using previous measurements

Z+jets processes

arXiv:2405.20041

Omnifold Z+jets

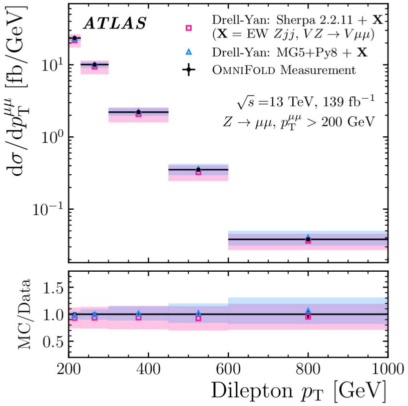
Schema from Phys. Rev. Lett. 124, 182001 (2020)

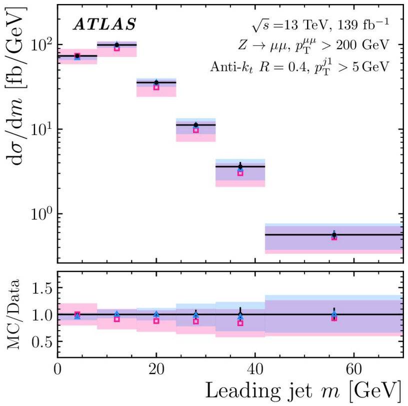


- OmniFold weights particle-level Gen to be consistent with Data once passed through the detector
  - This technique bypass the current unfolding (fixed binned data, not feasible for unfolding multiples dimensions)
- Advantages of Omnifold
  - Can capture all detector effects
  - Unbinned: final result is a list of events with a weight, user can construct any binning and any possible variable
- *The output of OmniFold is an **event-by-event reweighting function** that adjusts the Generation to match the Truth.*

arXiv:2405.20041

Z+jet unbinned unfolding





- $Z \to \mu\mu + jets$

  Sherpa 2.2.1.1

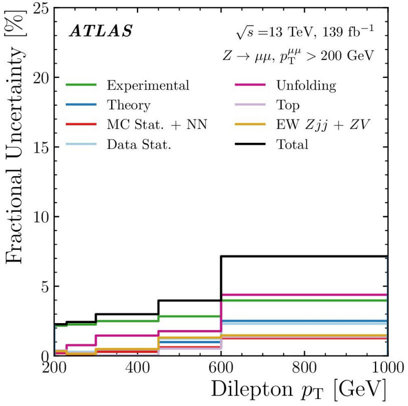
  Madgraph 5 interfaced to Pythia 8.240

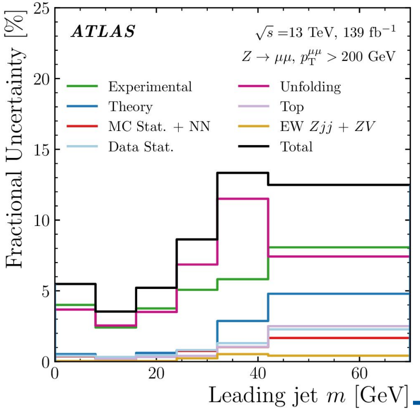
- Detector Simulation

  ATLAS detector -> Geant4

- Jets

  Anti-kT=0.4 $p_T^{\mu\mu}$ > 200 GeV





➔ The results align with the predictions

➔ Unfolded 24 observables simultaneously

➔ Omnifold total uncertainties similar, but slightly larger than those found with Bayesian comparison (3.0% average bin uncertainty vs. 3.9% for Omnifold)

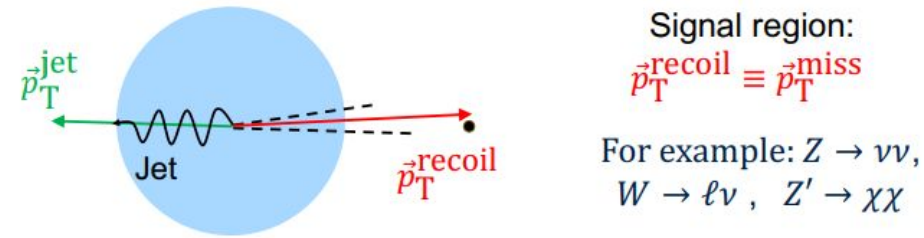
  ◆ primarily due to the NN initialization uncertainty

MET+jets differential x-section at 13 TeV

JHEP 08 (2024) 223

Schema from link

Signal region: missing transverse momentum + jets

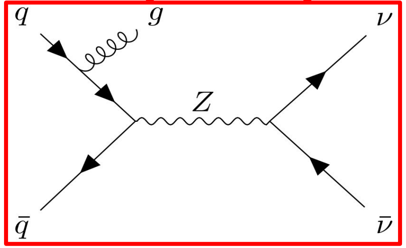


Signal region: $\vec{p}_T^{\,recoil} \equiv \vec{p}_T^{\,miss}$

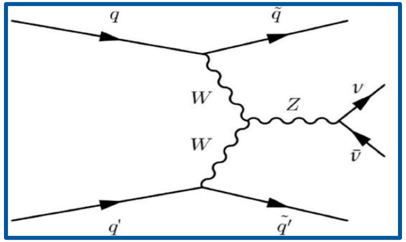
For example: $Z \to \nu\nu$, $W \to \ell\nu$, $Z' \to \chi\chi$

- Unfolded differential measurements of pT miss produced in association with jets
  - Process-specific (Z → vv)
    - Dominant in “mono-jet” region
    - After subtraction of all sub-dominant processes
  - Important background for BSM processes
    - Simplified DM models
    - 2HDM+a models

Monojet >=1 jet



VBF >=2 jet



- Measurement made in 6 phase-space regions and their ratios
  - Allow cancellation of systematics and modelling effects

SR: $p_T^{miss} + jets$	Aux: $\mu + jets$
Aux: $e + jets$	Aux: $2\mu + jets$
Aux: $2e + jets$	Aux: $\gamma + jets$

MET+jets differential x-section at 13 TeV

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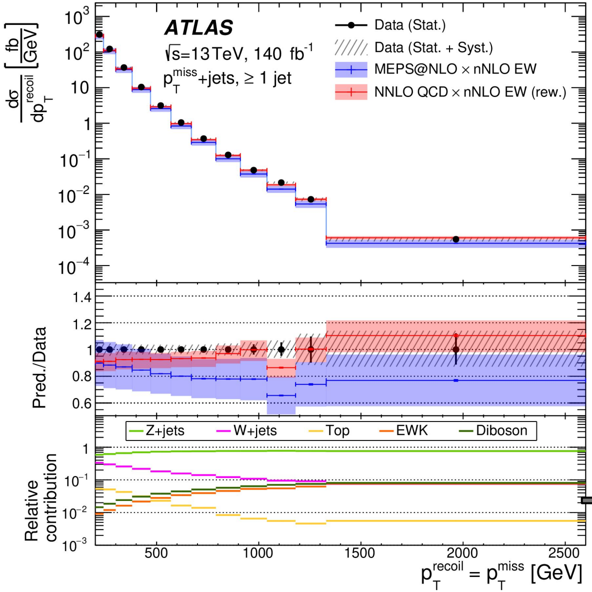
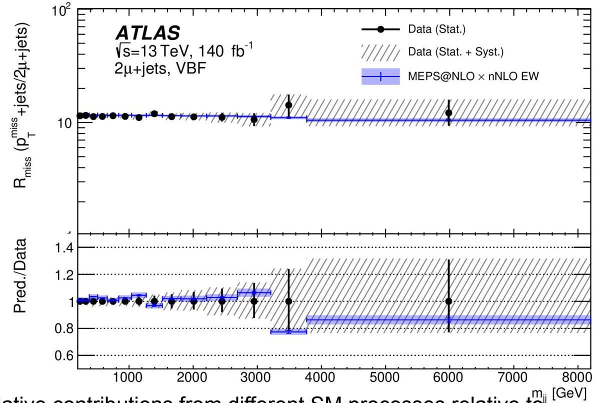
Inclusive >= 1jet



Inclusive VBF

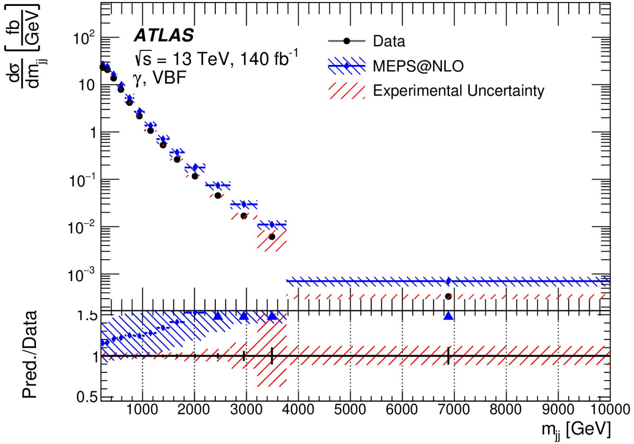
$R_{miss} = \sigma(p_T^{miss} + jets)/\sigma(2\mu + jets)$



relative contributions from different SM processes relative to the total MEPS@NLO prediction.

- Experimental systematics from detector calibrations, identification and resolution

m_{jj}



Observables measured
All regions: p_T^{recoil}
VBF: $m_{jj}, \Delta\phi_{jj}$ and p_T^{recoil}

- There is generally good agreement with SM predictions
  - except for m_{jj} (mismodelling).
  - the prediction-to-data ratio for is flat $R_{miss} = \sigma(p_T^{miss} + jets)/\sigma(AR)$

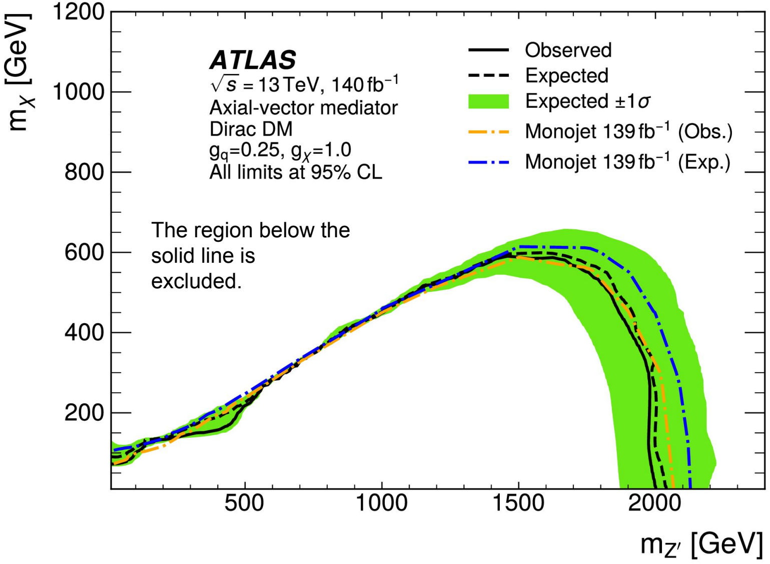
MET+jets differential x-section at 13 TeV

JHEP 08 (2024) 223

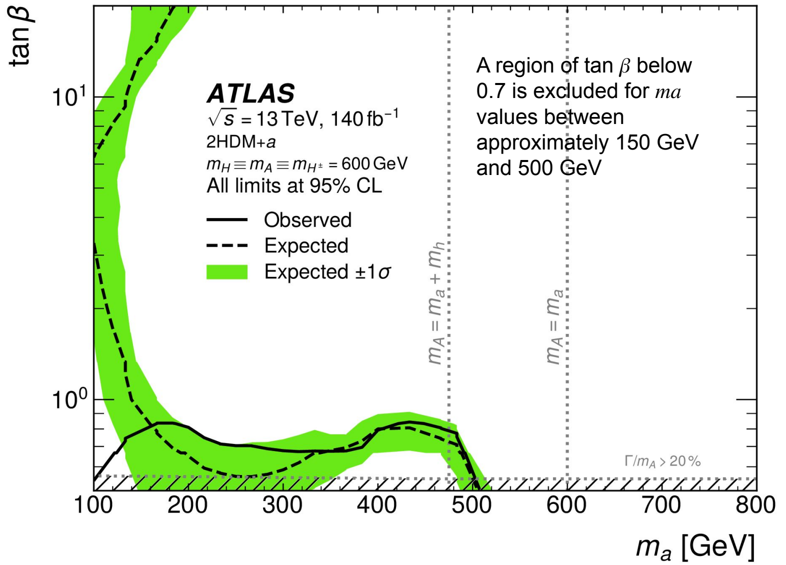
- Measurement compatible with SM
  - Use to set limits on contribution from BSM particles
    - Can be reinterpreted for different models.

- Sensitivity is similar to that of dedicated ATLAS searches
  - Phys. Rev. D 103, 112006
  - arXiv:2306.00641

Axial-vector DM: benchmarked to dedicated DM search



2HDM+a model: Higgs doublet and scalar couple to DM



Outlook

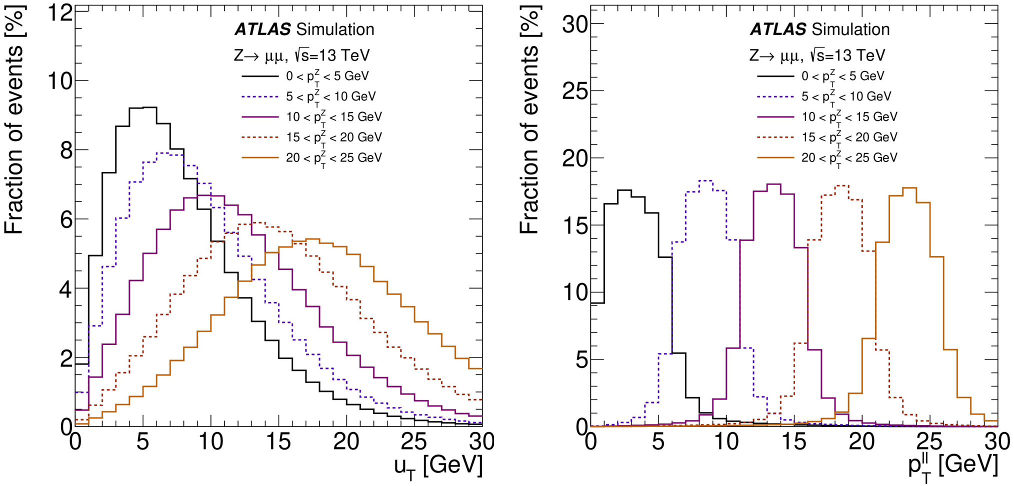
- W/Z+ jets processes are abundant in the LHC, offering valuable opportunities for precision testing of Standard Model predictions.
- Recent ATLAS and CMS results highlight the wide variety of tests that can be performed, achieving higher levels of precision.
- Innovative unfolding techniques will facilitate easier reuse of data for future analyses.
- Inclusive particle-level measurement offers good sensitivity to BSM physics and can be reinterpreted for different models.
- Run 3 will bring numerous opportunities for exciting new discoveries! Stay Tune!

Thank you!

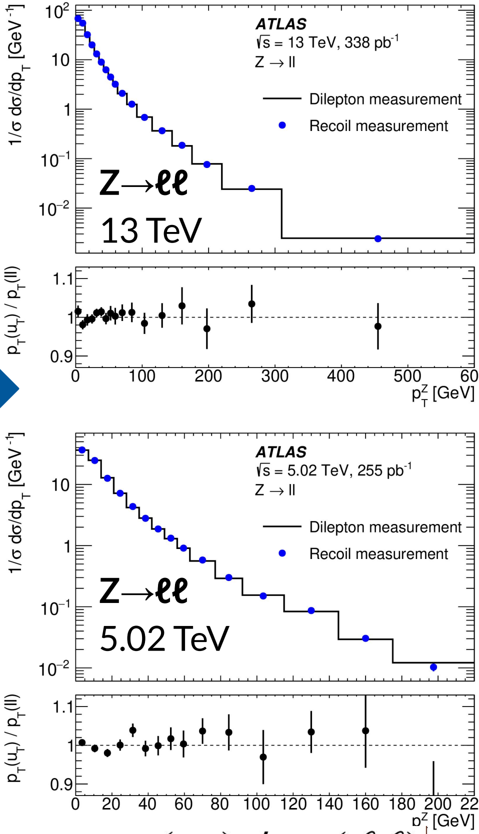
BACKUP

arXiv:2404.06204

Precise W and Z pT measurements at 5.02 and 13 TeV



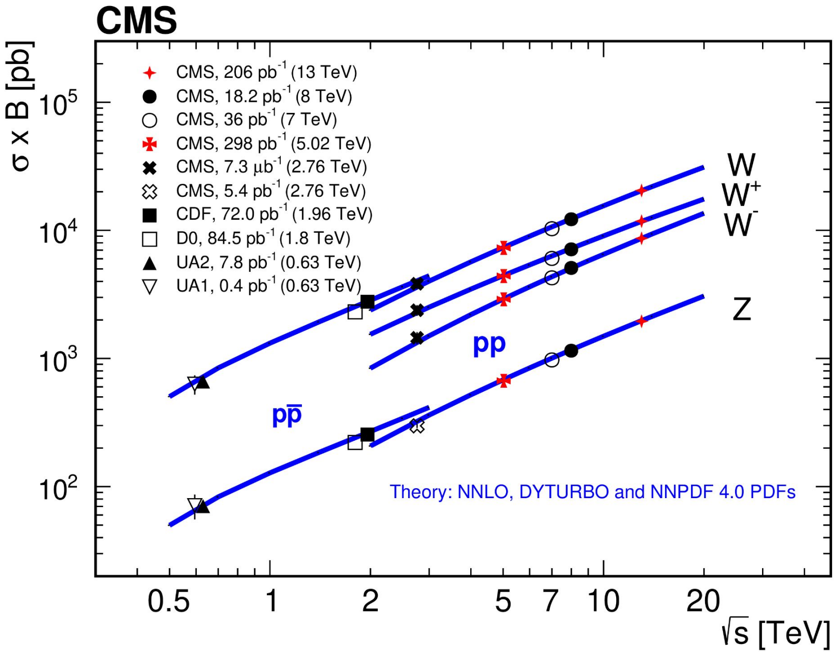
Validate the u_T reconstruction with Z→ℓℓ distribution using u_T and $p_T^{\ell,\ell}$



$p_T(u_T)$ / $p_T(\ell\ell)$

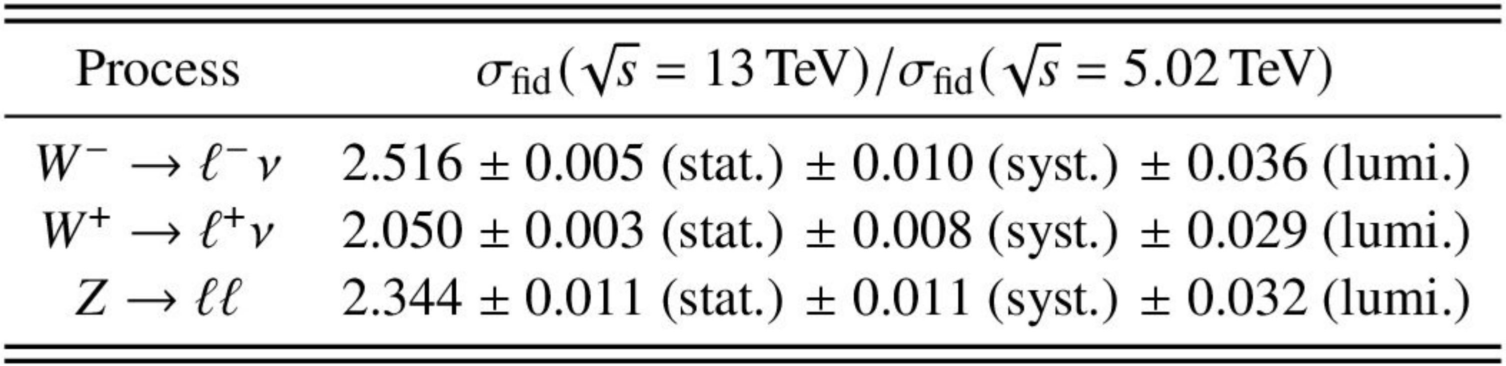
- Recoil calibration is performed using Z events
  - modeling of underlying activity
  - response and resolution corrections
- p_T^W: unfolded from the hadronic recoil, u_T
- p_T^Z: unfolded from $p_T^{\ell,\ell}$ and checked to be consistent with u_T

Precise W and Z pT measurements



excellent agreement data-MC from 0.63 TeV up to 13.6 TeV using DYTURBO@NNLO

Precise W and Z pT measurements



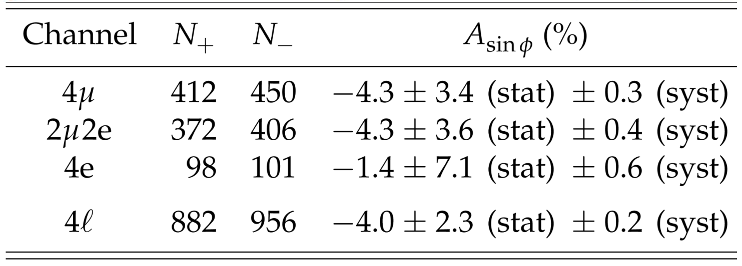
Process	$\sigma_{\text{fid}}(\sqrt{s} = 13\,\text{TeV})/\sigma_{\text{fid}}(\sqrt{s} = 5.02\,\text{TeV})$
$W^- \rightarrow \ell^- \nu$	2.516 ± 0.005 (stat.) ± 0.010 (syst.) ± 0.036 (lumi.)
$W^+ \rightarrow \ell^+ \nu$	2.050 ± 0.003 (stat.) ± 0.008 (syst.) ± 0.029 (lumi.)
$Z \rightarrow \ell\ell$	2.344 ± 0.011 (stat.) ± 0.011 (syst.) ± 0.032 (lumi.)

CMS-PAS-SMP-19-007

Z decaying to four leptons at 8 and 13 TeV

$$A_{\sin\phi} = \frac{N_+ - N_-}{N_+ + N_-}$$

signal Z → 4ℓ events N_+ (N_-) in which $\sin\phi > 0$ (< 0).



Channel	N_+	N_-	$A_{\sin\phi}$ (%)
4μ	412	450	-4.3 ± 3.4 (stat) ± 0.3 (syst)
$2\mu 2e$	372	406	-4.3 ± 3.6 (stat) ± 0.4 (syst)
4e	98	101	-1.4 ± 7.1 (stat) ± 0.6 (syst)
4ℓ	882	956	-4.0 ± 2.3 (stat) ± 0.2 (syst)

ϕ :the angle between the decay planes of Z1 and Z2 in the Z boson rest frame.

no evidence of CP invariance violation (no* difference between amplitudes*)

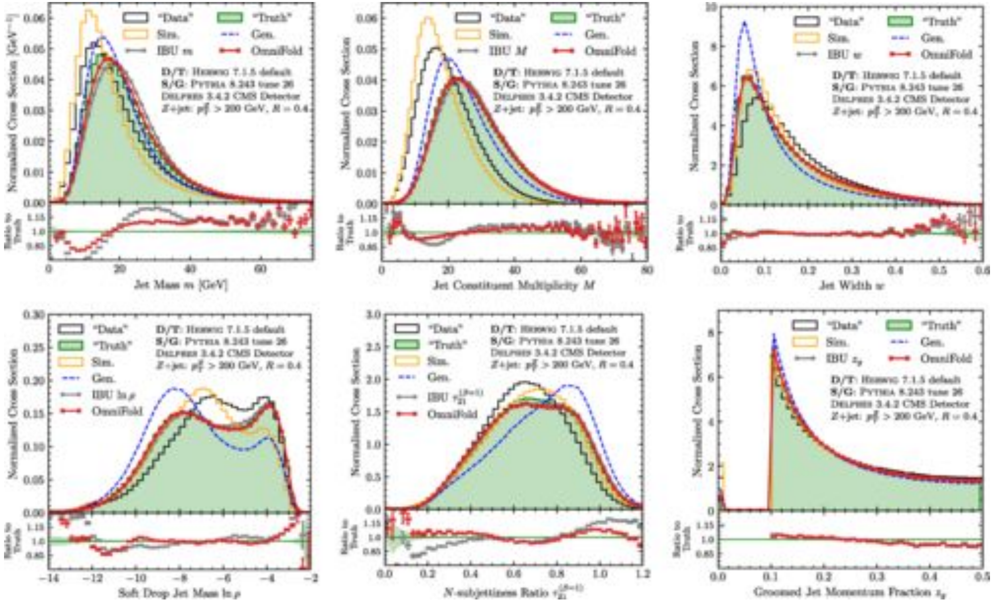
Omnifold + CMS geometry

[Phys. Rev. Lett. 124, 182001 (2020). Anders Andreassen, Patrick T. Komiske, Eric M. Metodiev, Benjamin Nachman, and Jesse Thaler]

- $Z \to \mu\mu + jets$
  "Data"- HERWIG 7.1.5
  MC- PYTHIA 8.243

- Detector Simulation
  CMS-> DELPHES 3.4.2

- Jets
  Anti-kT=0.4 $p_T^{\mu\mu}$ > 200 GeV ,
  Assumed excellent muon detector resolution



➔ six widely used jet substructure observable

➔ OmniFold equals or outperforms OmniFold equals or outperforms Iterated Bayesian Unfolding (IBU)