Measurements of differential Z boson production cross sections in pp collisions with CMS at $\sqrt{s} = 13$ TeV (SMP-17-010)

Guillelmo Gómez-Ceballos (MIT)

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Introduction

- Purpose of the talk is to show a short summary on the differential Z boson cross section measurements using dilepton events
- Making use of full 2016 dataset at $\sqrt{s} = 13\ \mathrm{TeV}$
- Selecting two dimuons or dielectrons compatible with a Z boson decay
  - simple selection
  - very low background level
- Fiducial region emulates selection at the reconstruction level
- Measurements: differential and normalized cross sections
  - $p_{\mathrm{T}}^{\mathrm{Z}}$
  - $|y^{\mathrm{Z}}|$
  - $\phi^{\star}$
  - $p_{\mathrm{T}}^{\mathrm{Z}}$ in $|y^{\mathrm{Z}}|$ regions
- Analysis went from a simple 2017 Summer student project to a huge R&D enterprise
  - simple experimental analysis, but requiring an unprecedented precision in CMS

Selection Strategy

- Reconstruction level (RECO):
  - two opposite-sign same-flavor leptons (electrons or muons)
  - "medium" identification & isolation lepton requirements
  - $p_{\mathrm{T}}^{\ell_1,\ell_2} > 25$ GeV, $|\eta^{\ell_1,\ell_2}| < 2.4$
  - $|m_{\ell\ell} - m_{\mathrm{Z}}| < 15$ GeV
- Fiducial definition at generation level (GEN):
  - making use of so-called dressed leptons
    - accounting for photons in $\Delta R_{\ell,\gamma} < 0.1$
  - two opposite-sign same-flavor leptons (electrons or muons)
  - $p_{\mathrm{T}}^{\ell_1,\ell_2} > 25$ GeV, $|\eta^{\ell_1,\ell_2}| < 2.4$
  - $|m_{\ell\ell} - m_{\mathrm{Z}}| < 15$ GeV
  - tested that muon and electron cross sections agree better than the sample statistical precision with this definition

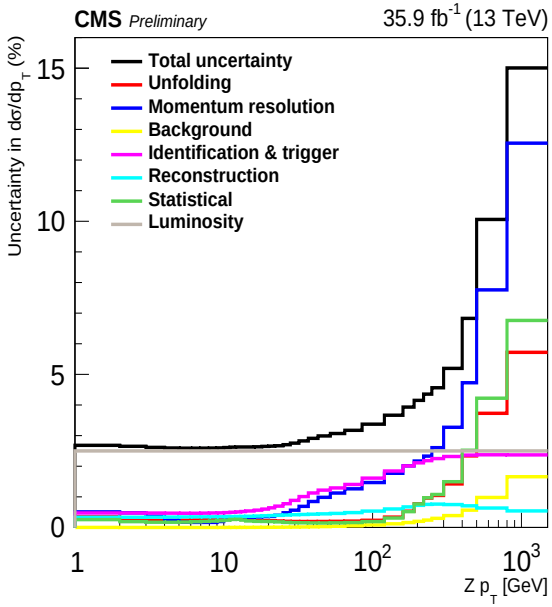
Final state	Data	$\mathrm{Z} \to \ell\ell$	Resonant bkg.	Nonresonant bkg.
$\mu\mu$	$\sim 20.4 \times 10^6$	$\sim 20.7 \times 10^6$	$\sim 30 \times 10^3$	$\sim 41 \times 10^3$
ee	$\sim 12.1 \times 10^6$	$\sim 12.0 \times 10^6$	$\sim 19 \times 10^3$	$\sim 26 \times 10^3$

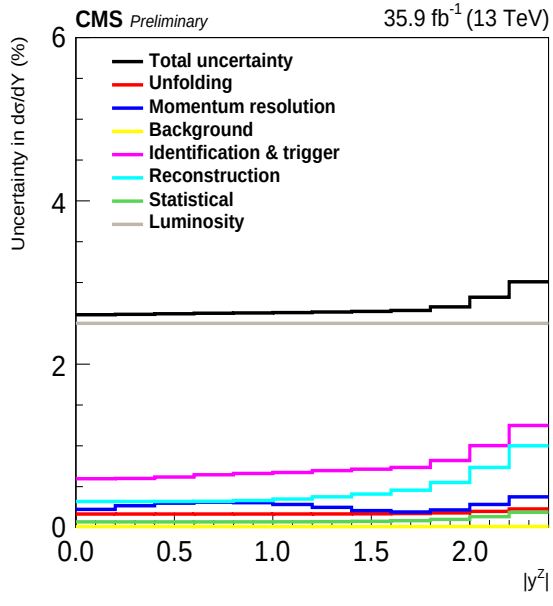
Systematic Uncertainties

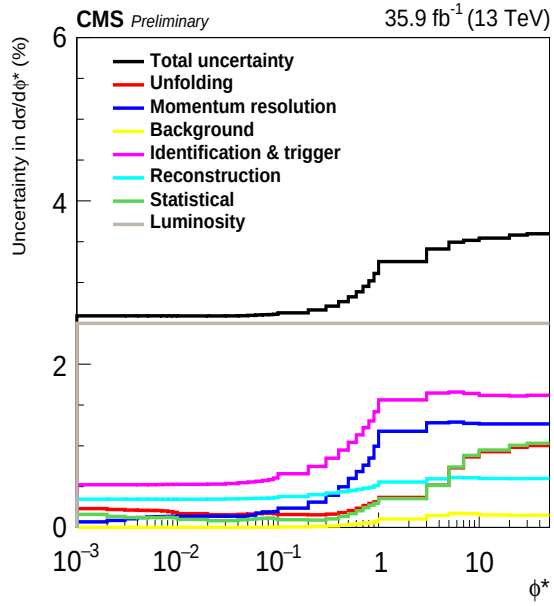
- Luminosity:
  - using current recommended 2.5%
- Lepton trigger, reconstruction & identification:
  - computed "in-house" due to the required precision
  - effects due to the signal and background components taken into account
- Momentum scale:
  - relevant on differential measurements
- Background:
  - VV resonant bkg. from simulation
  - nonresonant bkg. from data
- Data and simulated sample size

Summary of Systematic Uncertainties (Differential)

$\mu\mu$







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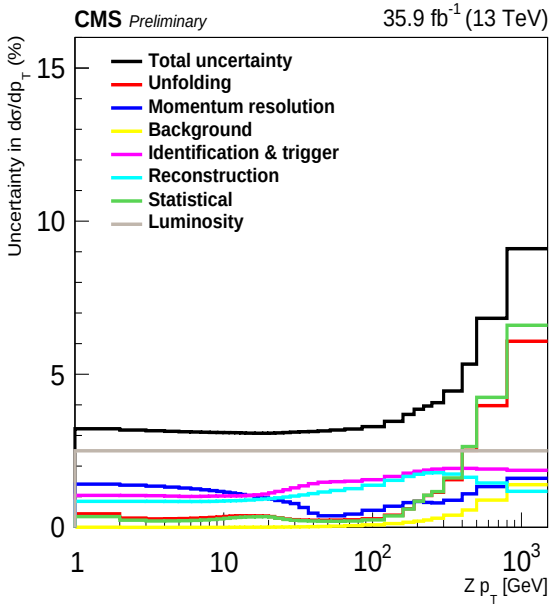
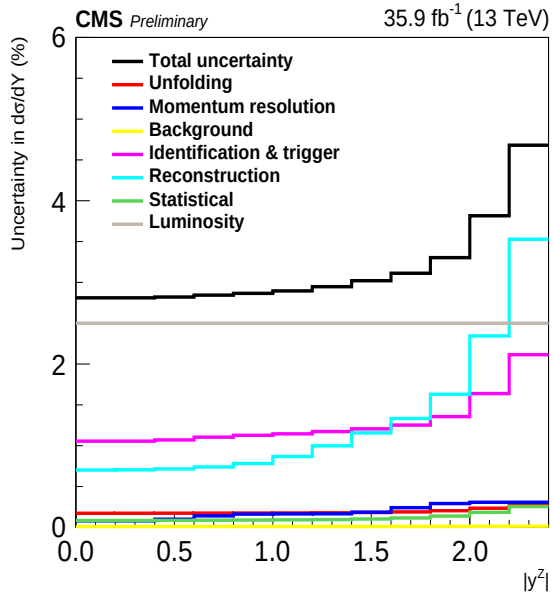
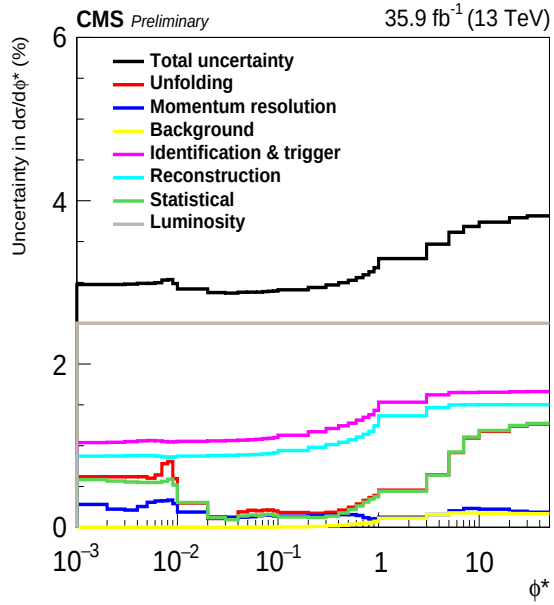
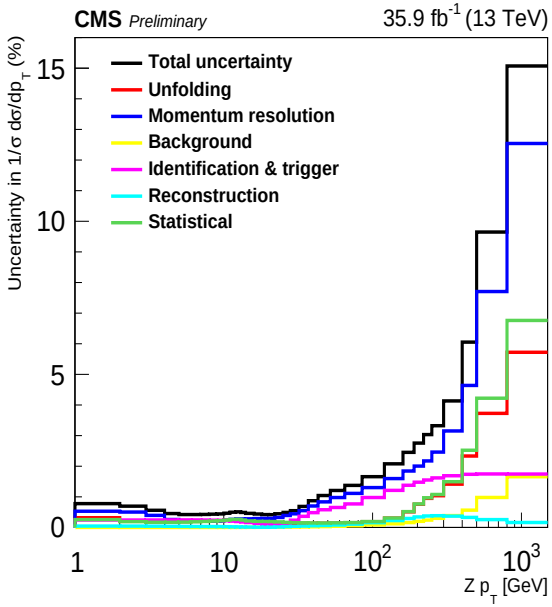


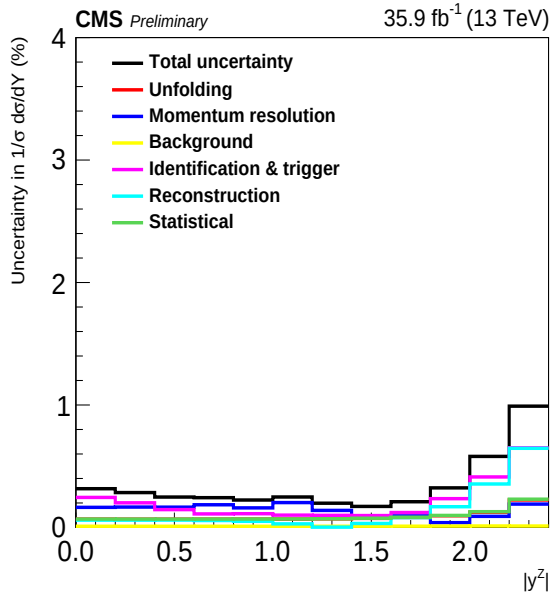


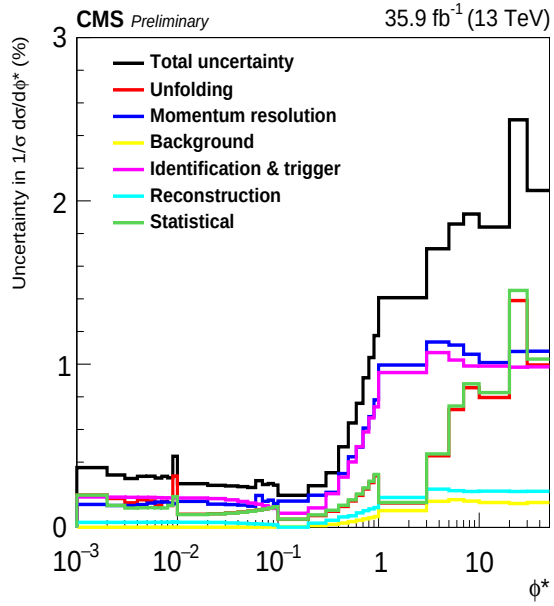


Summary of Systematic Uncertainties (Normalized)

$\mu\mu$







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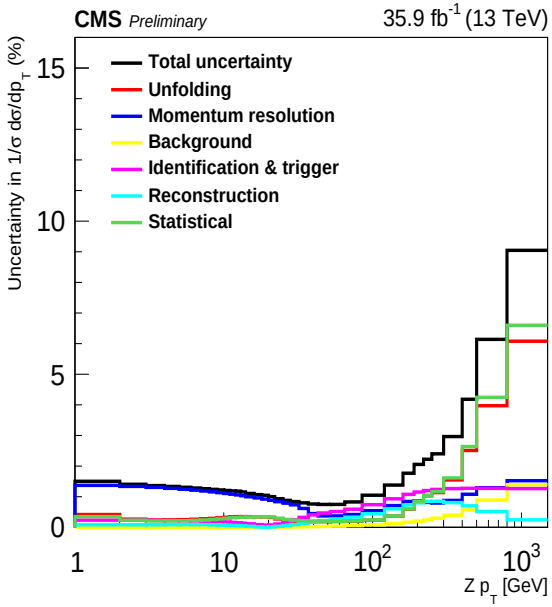
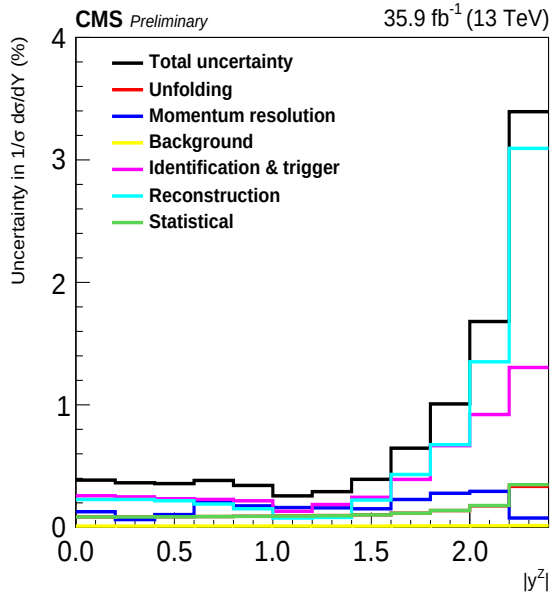
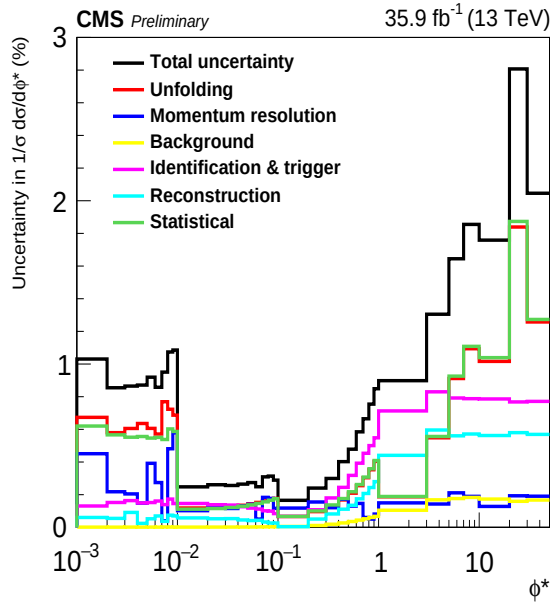






Inclusive Fiducial Uncertainties

Source	$Z \to \mu\mu$ (%)	$Z \to ee$ (%)
Luminosity	2.5	2.5
Muon reconstruction efficiency	0.4	-
Muon selection efficiency	0.7	-
Muon momentum scale	0.1	-
Electron reconstruction efficiency	-	0.9
Electron selection efficiency	-	1.0
Electron momentum scale	-	0.2
Background estimation	< 0.1	< 0.1
Total (excluding luminosity)	0.8	1.4

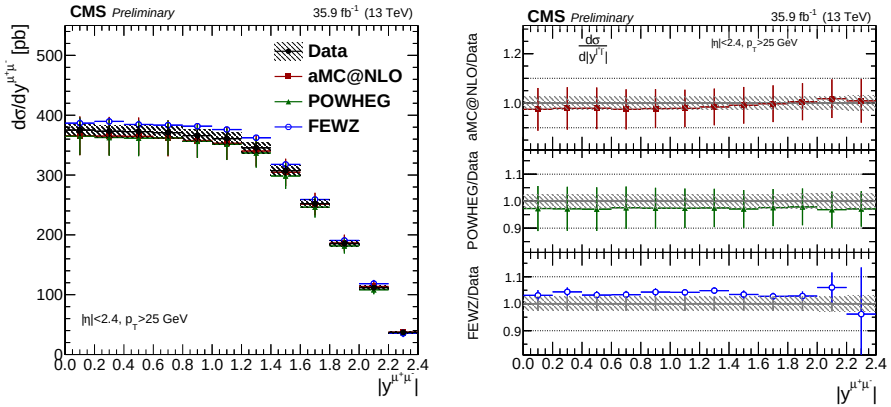
Cross section	$\sigma\,\mathcal{B}$ [pb]
$\sigma_{Z\to\mu\mu}$	694 ± 6 (*syst.*) ± 17 (*lum.*)
$\sigma_{Z\to ee}$	712 ± 10 (*syst.*) ± 18 (*lum.*)
$\sigma_{Z\to\ell\ell}$	699 ± 5 (*syst.*) ± 17 (*lum.*)

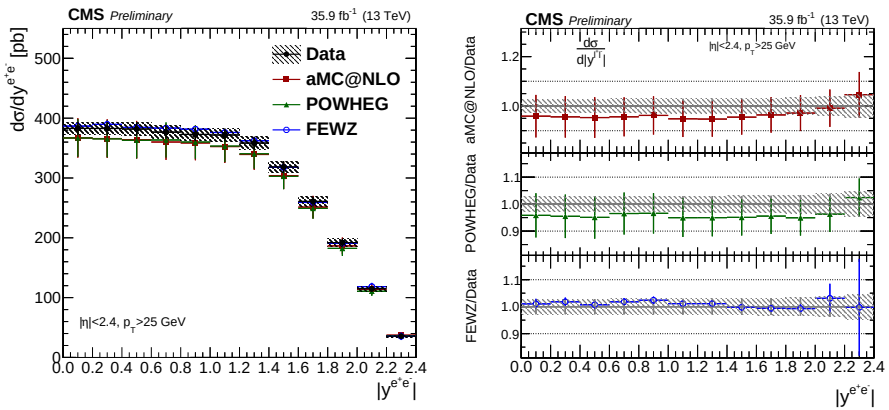
$\sigma_{Z\to\ell\ell} = 682 \pm 55$ pb (MadGraph5_aMC@NLO, NNPDF 3.0)

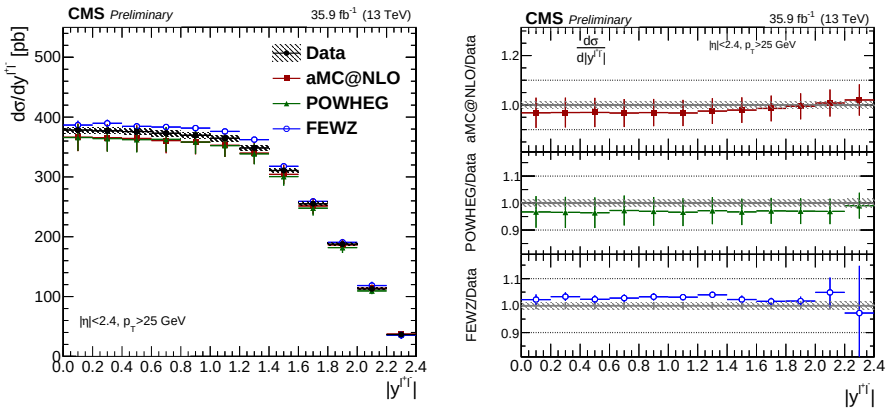
Data vs. Predictions

- In principle, we could just report our results, but we tried to be pretty generic
- Experimental distributions compared with several theoretical predictions (and more to come):
  - MadGraph5_aMC@NLO
  - POWWEG
  - FEWZ ($p_{\mathrm{T}}^{Z} > 30$), NNLO inclusive
  - Z + 1 jet at NNLO
  - MINLO
  - RESBOS
  - GENEVA
- Data unfolded uncertainties include all experimental effects
- Theory uncertainties include QCD scales and PDF uncertainties
- MINLO:
  - before you ask, aware of large theory uncertainties
  - not a mistake, long discussions about it, will use another prescription for the paper

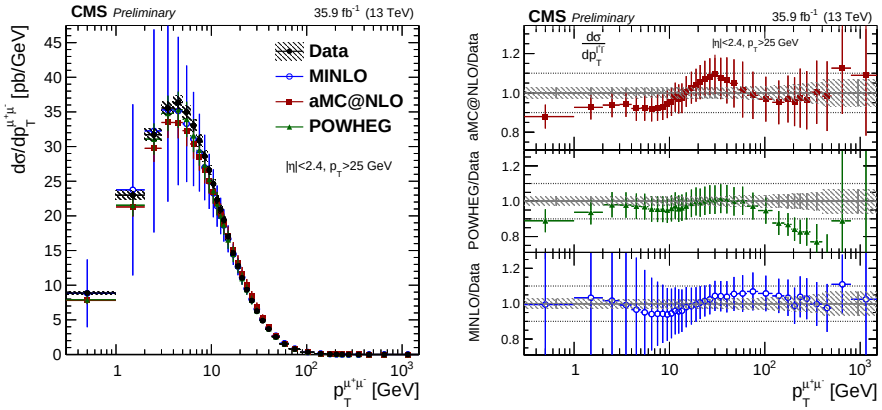
$|y^Z|$ Measurements

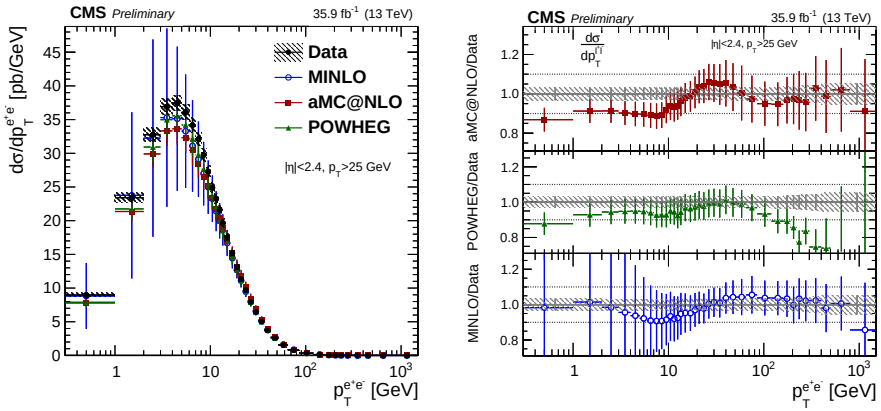


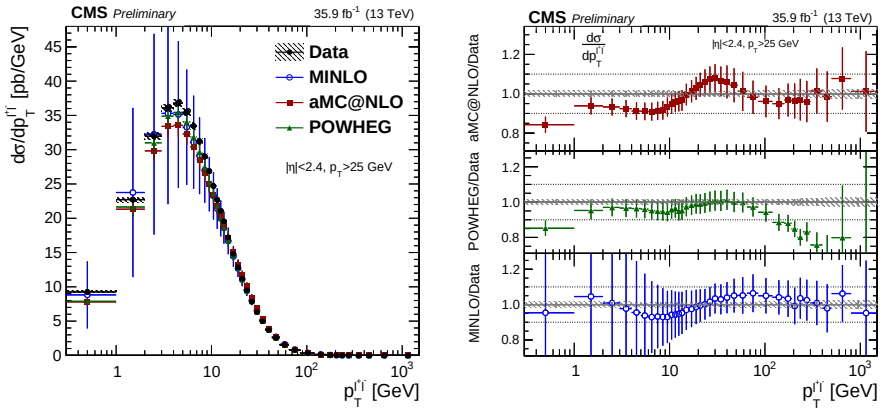




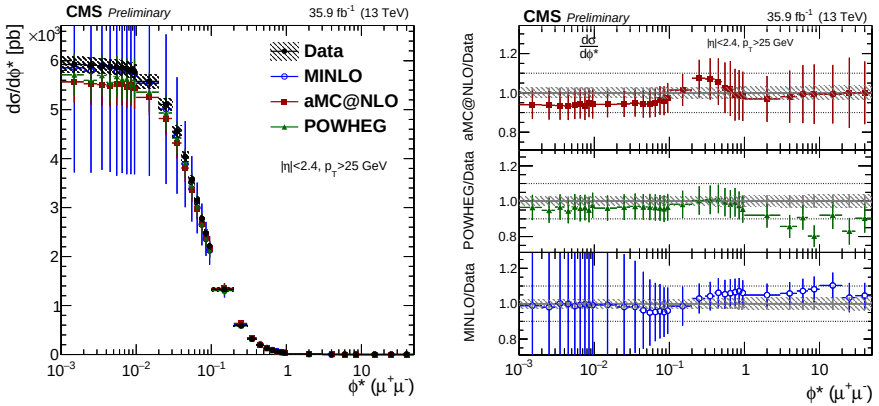
p_{T}^{Z} Measurements

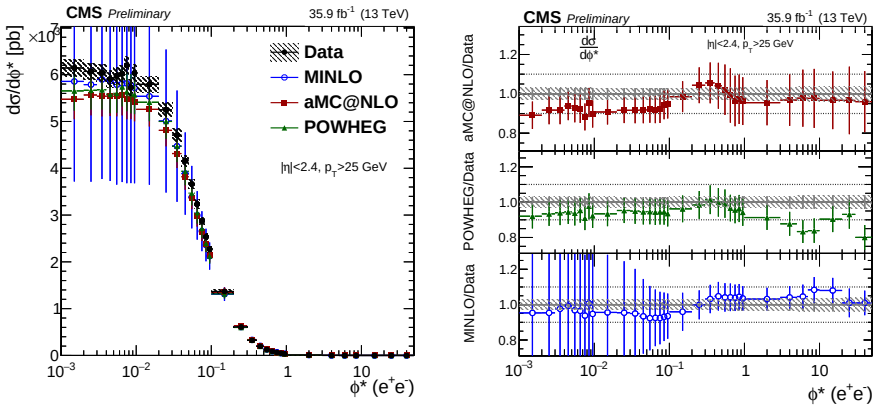


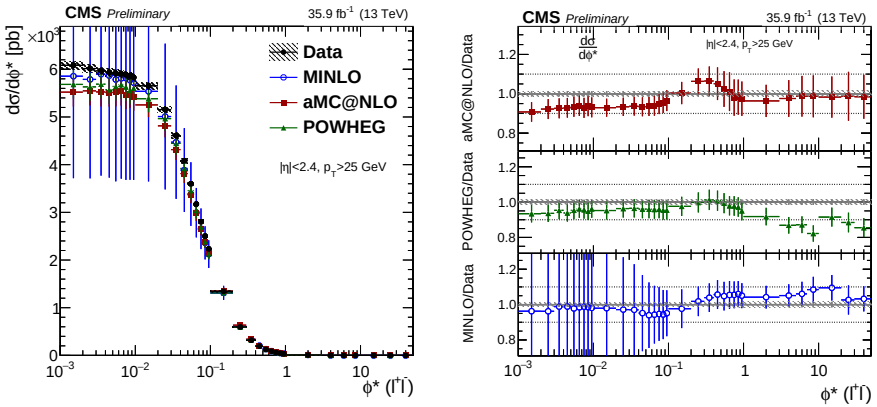




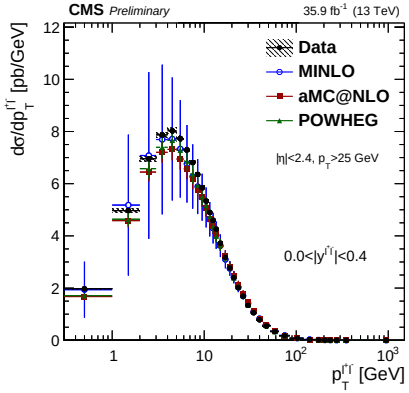
$\phi^\star$ Measurements

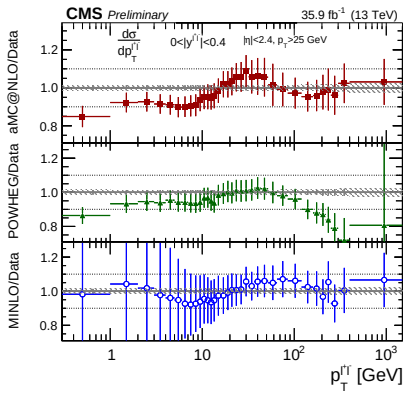


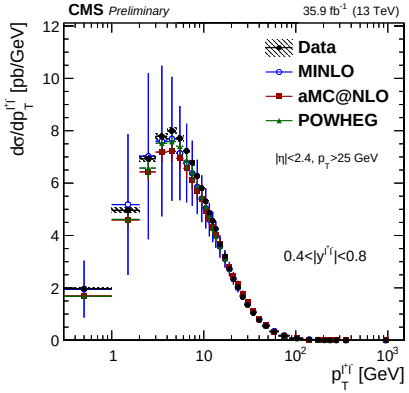


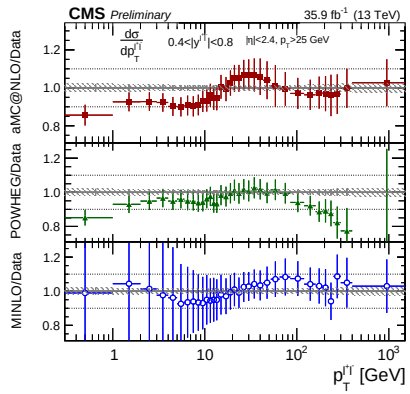


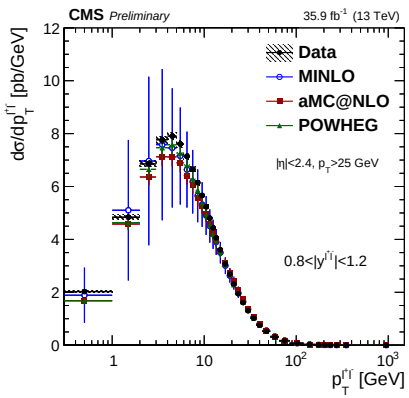
$p_{\mathrm{T}}^{\mathrm{Z}}$ vs. $|y^{\mathrm{Z}}|$ Measurements

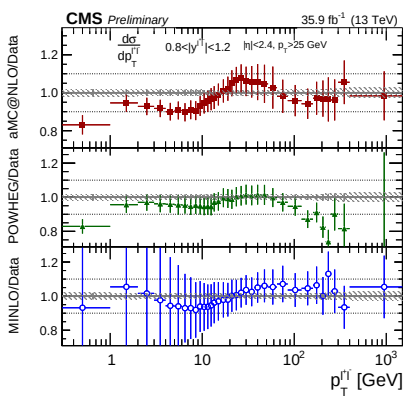


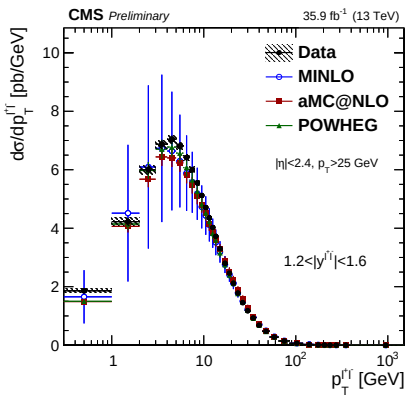


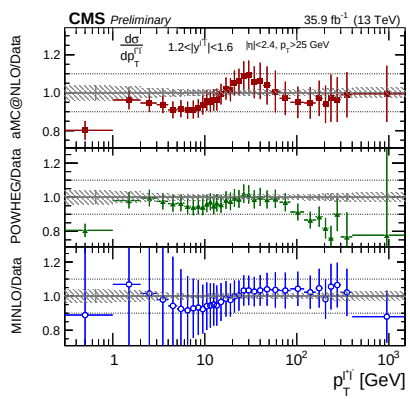


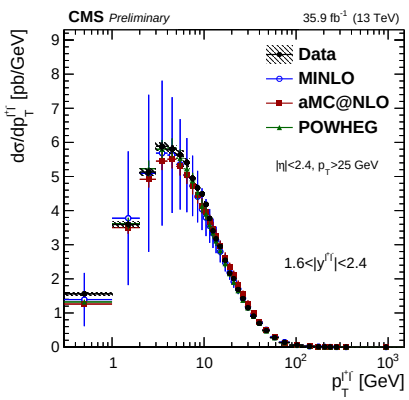


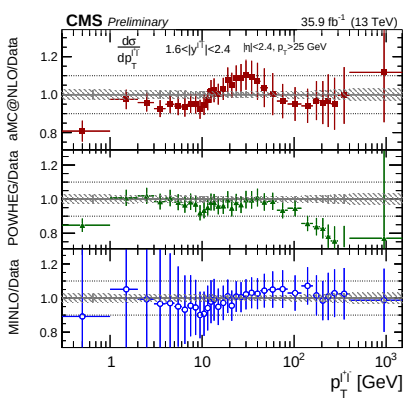




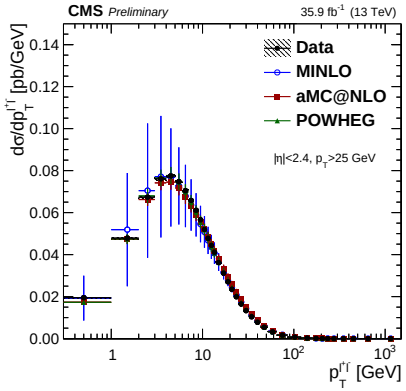


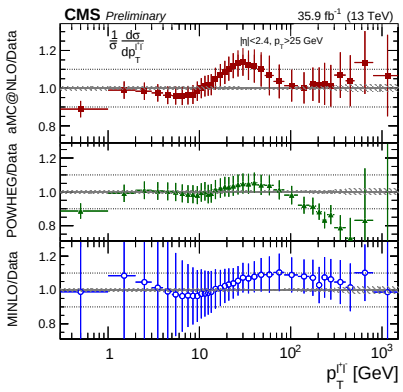


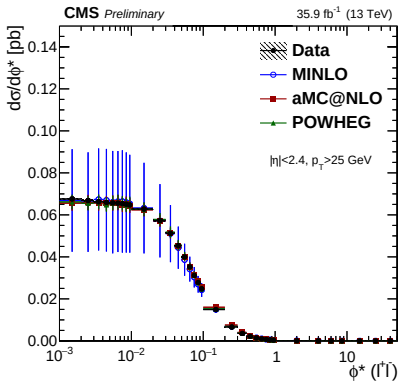


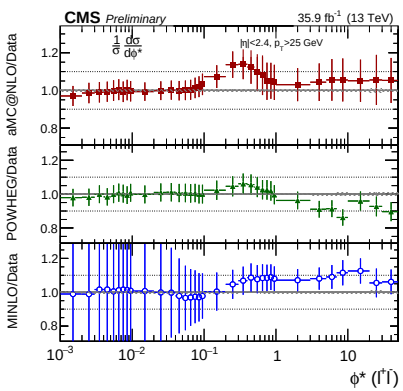


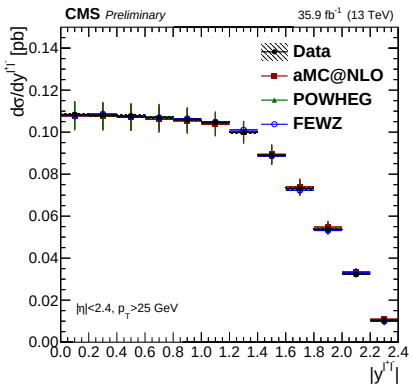
Normalized Measurements

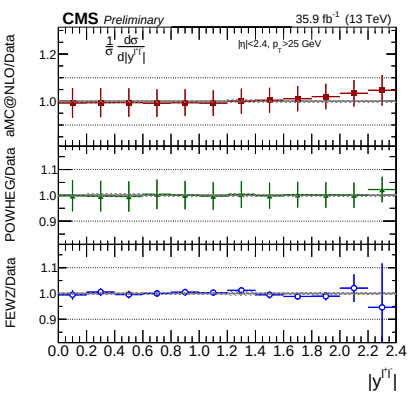












Summary

- Reported results on the differential Z boson production cross section measurements using dilepton events
- large effort to improve lepton efficiency uncertainties
- Paper publication in progress
- Read details on https://cds.cern.ch/record/2675022

Back-Up Slides

Unfolding & Binning

Using TUnfold method to perform the unfolding, as officially suggested

- $p_{\mathrm{T}}^{\mathrm{Z}}$ (in GeV): {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 18, 20, 22, 25, 28, 32, 37, 43, 52, 65, 85, 120, 160, 190, 220, 250, 300, 400, 500, 800, 1500}
- $|y^{\mathrm{Z}}|$: {0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4}
- $\phi^{\star}$: $\{1 \cdot 10^{-3}, 2 \cdot 10^{-3}, 3 \cdot 10^{-3}, 4 \cdot 10^{-3}, 5 \cdot 10^{-3}, 6 \cdot 10^{-3}, 7 \cdot 10^{-3}, 8 \cdot 10^{-3}, 9 \cdot 10^{-3}, 1 \cdot 10^{-2}, 2 \cdot 10^{-2}, 3 \cdot 10^{-2}, 4 \cdot 10^{-2}, 5 \cdot 10^{-2}, 6 \cdot 10^{-2}, 7 \cdot 10^{-2}, 8 \cdot 10^{-2}, 9 \cdot 10^{-2}, 1 \cdot 10^{-1}, 2 \cdot 10^{-1}, 3 \cdot 10^{-1}, 4 \cdot 10^{-1}, 5 \cdot 10^{-1}, 6 \cdot 10^{-1}, 7 \cdot 10^{-1}, 8 \cdot 10^{-1}, 9 \cdot 10^{-1}, 1, 3, 5, 7, 10, 20, 30, 50\}$
- $p_{\mathrm{T}}^{\mathrm{Z}}$ in $|y^{\mathrm{Z}}|$ regions (in GeV): {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 18, 20, 22, 25, 28, 32, 37, 43, 52, 65, 85, 120, 160, 190, 220, 250, 300, 400, 1500}

QED Uncertainty

- Making use of dressed leptons instead of born level leptons
- Easier way to compare with theory predictions
- Cross sections for electrons and muons agree better than statistical precision of the samples
- Experimental uncertainty due to FSR effects taken into account
- Neglected theoretical uncertainty in the prediction