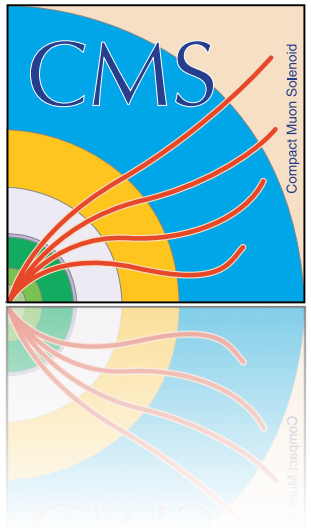


Vector Boson studies with CMS

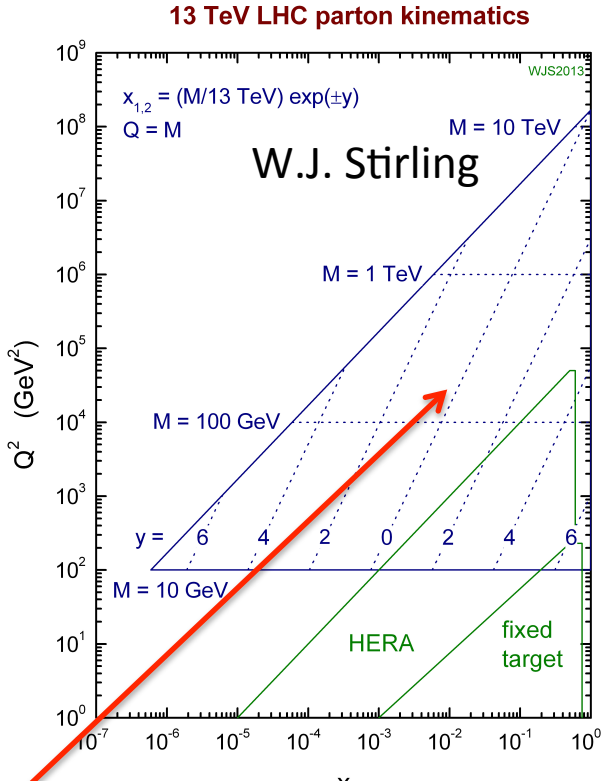
LHCP, 2016

Aram Apyan

On behalf of CMS collaboration

Standard candles

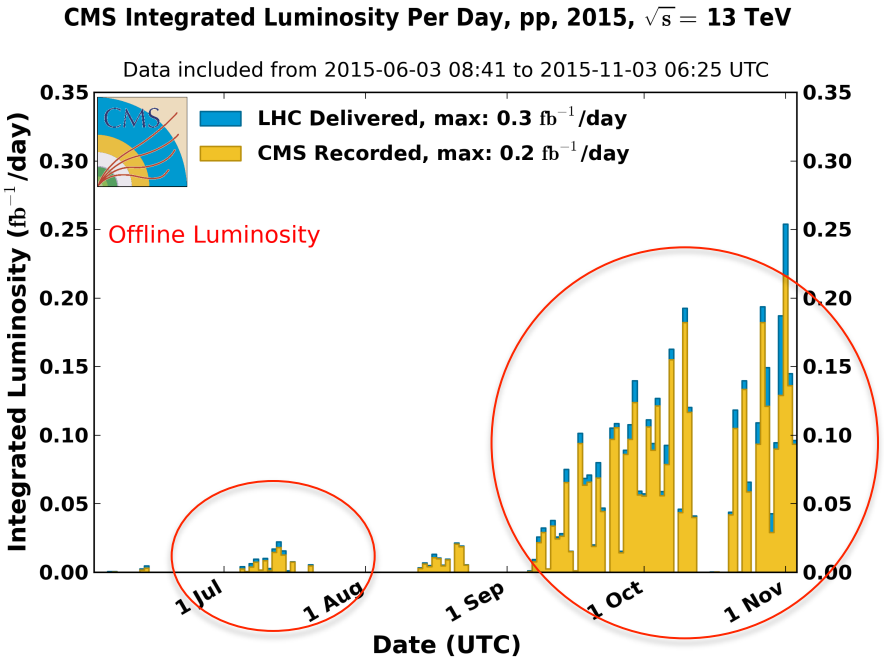
- Started the new run with the W, Z cross sections and ratio measurements
  - Via leptonic final states
  - Clean experimental signature
  - Large dataset
- Detector and physics commissioning
  - Luminosity calibration
  - Lepton efficiencies, missing energy, etc.
- Precision tests of the SM
  - Perturbative QCD calculations
  - Constraints on PDF
  - Electroweak sector



$$\sigma(pp \to O + X) = \sum_{a,b} \int dx_1\, dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \hat{\sigma}_{ab \to O}(s, \mu_F, \mu_R)$$

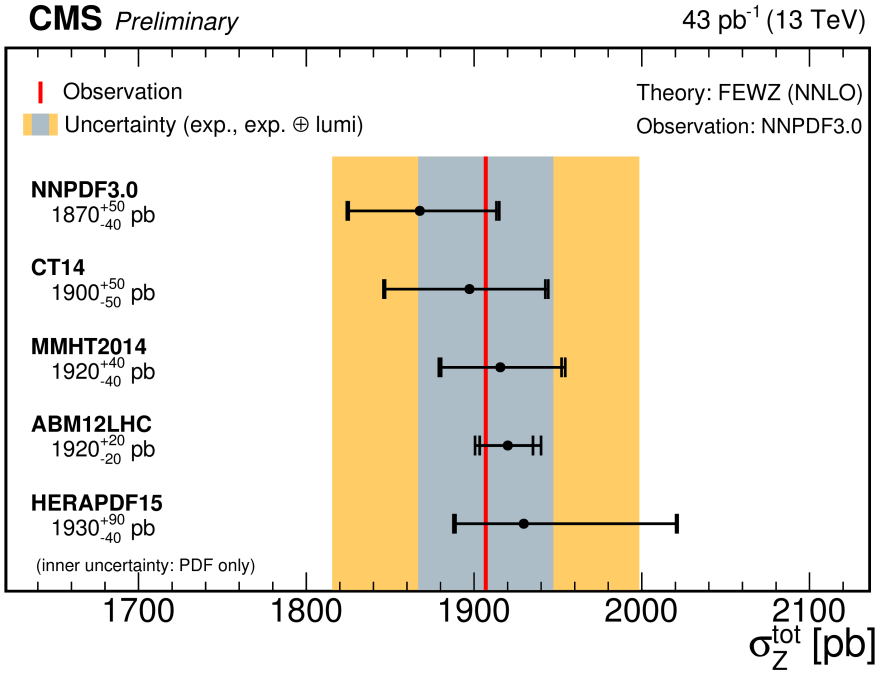
Experimental setup

- 50ns collisions in July -> 43 pb^{-1} integrated luminosity, total cross section measurements
  - 4.8% uncertainty in the luminosity
    - 2.6% uncertainty from VDM scan
    - 4.0% uncertainty due to the luminometer linearity and stability
- 25 ns collisions -> Include the differential measurements
  - 2.7% uncertainty in the luminosity



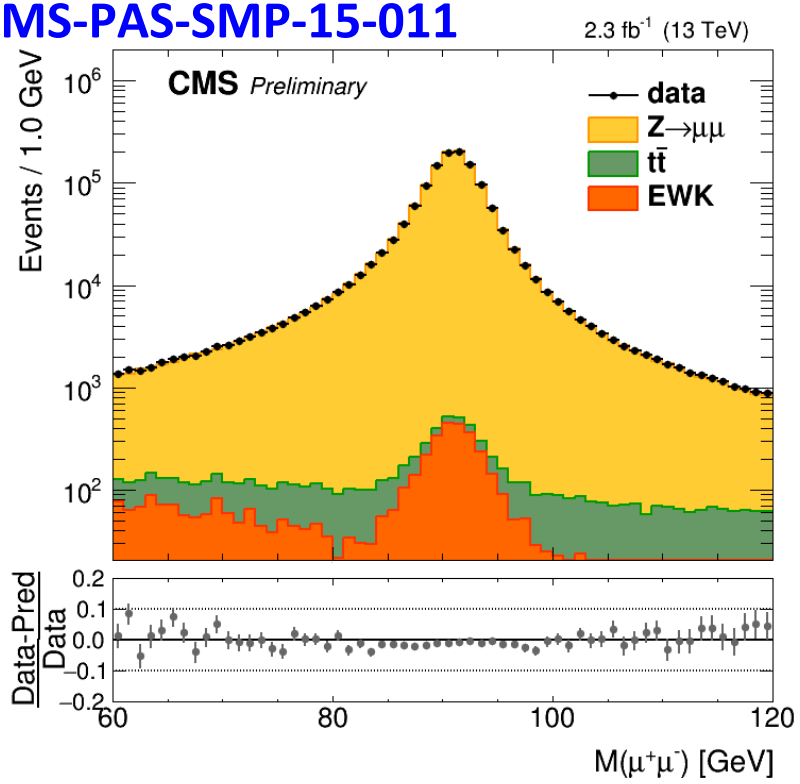
Inclusive Z cross section at √s = 13 TeV

- Electron and muon results combined assuming lepton universality
- Good agreement with SM NNLO [QCD] prediction [FEWZ]
- Z->μμ update with 2015 dataset: 1870 ± 2 (stat) ± 35 (syst) ± 51 (lumi) pb



60 GeV < M_Z < 120 GeV

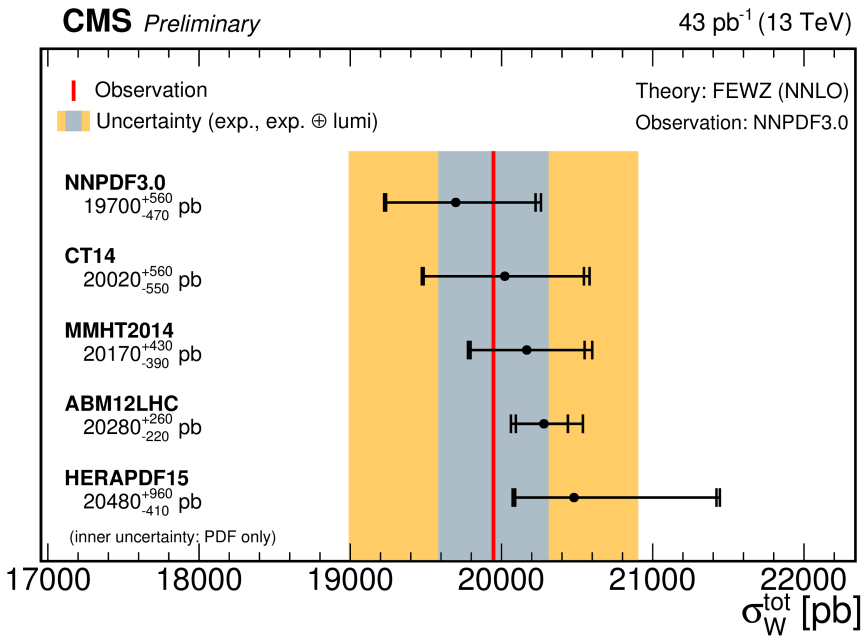
CMS-PAS-SMP-15-011

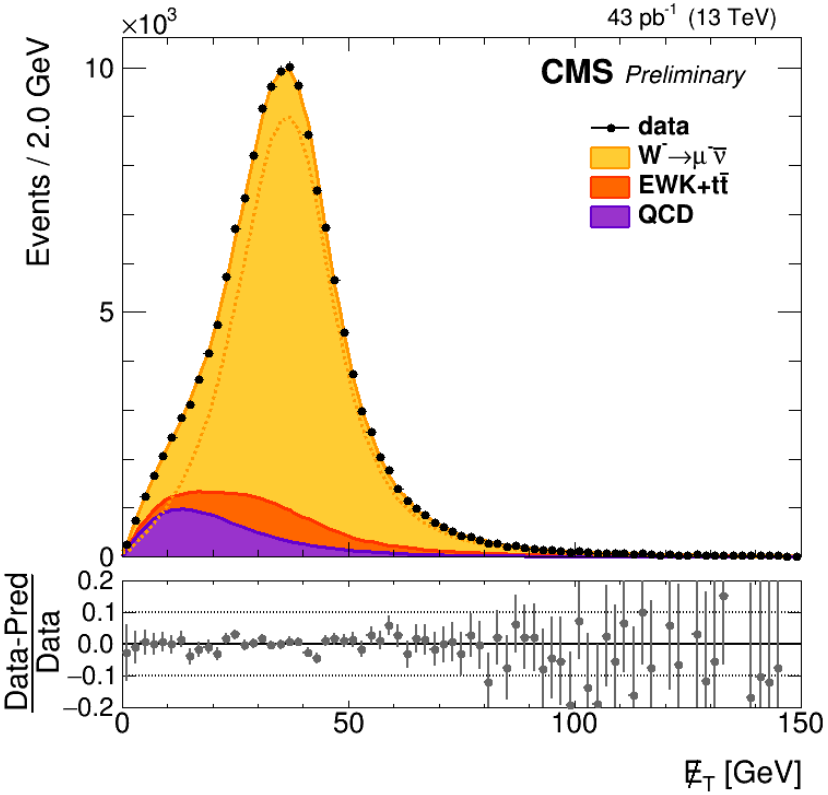


CMS-PAS-SMP-15-004

Inclusive W cross section at √s = 13 TeV

- Fit to the missing energy distribution to extract the signal
- Missing energy resolution is crucial
  - Pileup mitigation
- Fiducial cross sections in backup

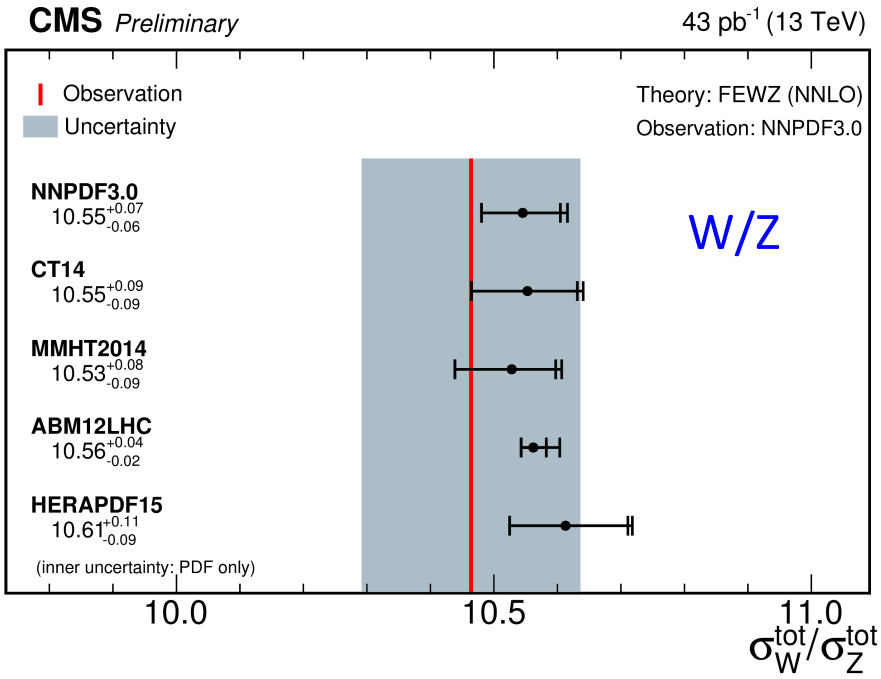


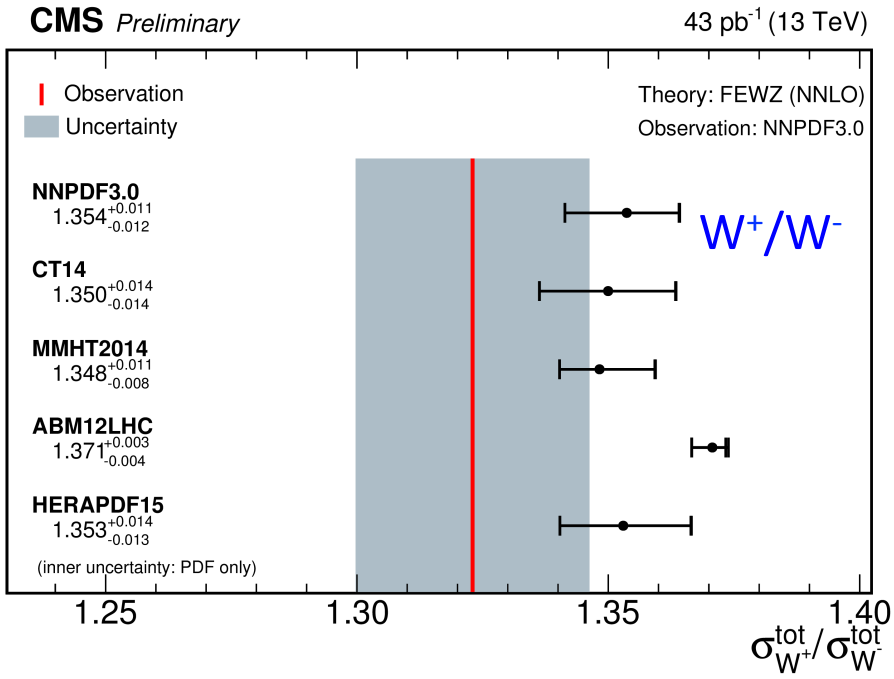


CMS-PAS-SMP-15-004

Cross section ratios

- "Cancellation" of the systematic uncertainties
  - No luminosity uncertainty
  - Partial cancelation of theory and experimental uncertainties
- Constraints on PFDs



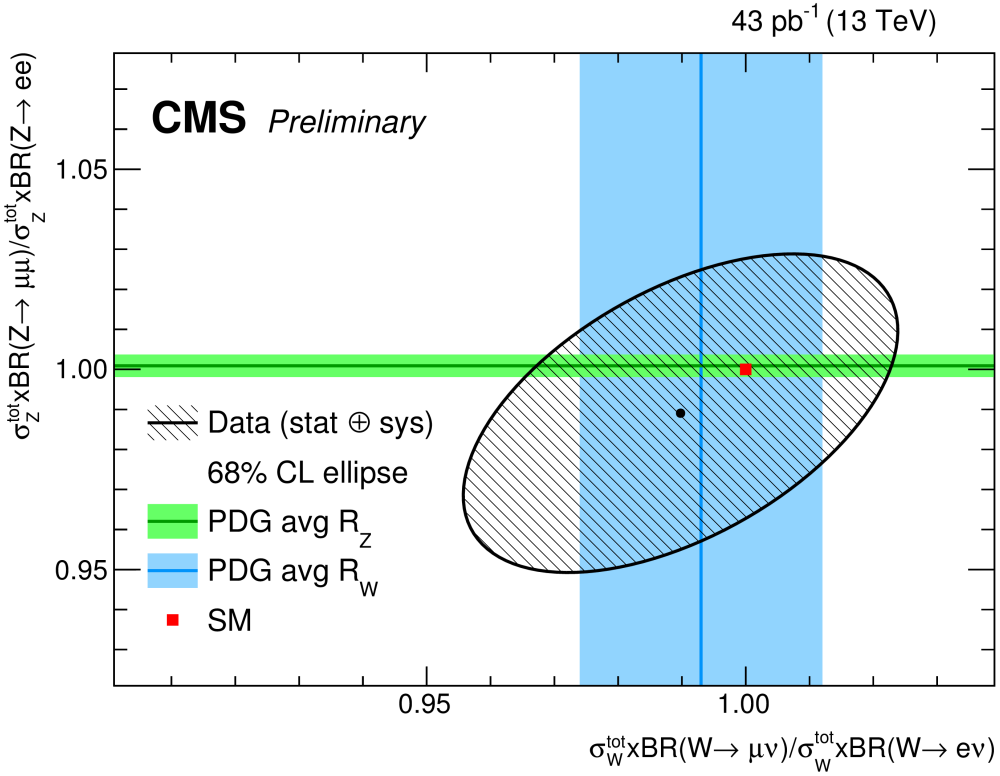


CMS-PAS-SMP-15-004

Lepton universality

- Ratios of the W and Z total inclusive cross sections in electron and muon channels
  - Check of the lepton universality
  - Results compatible with SM prediction

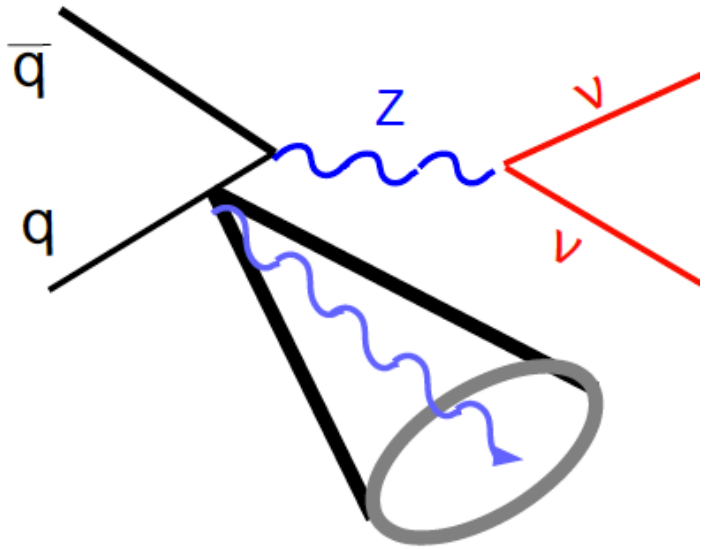
CMS-PAS-SMP-15-004

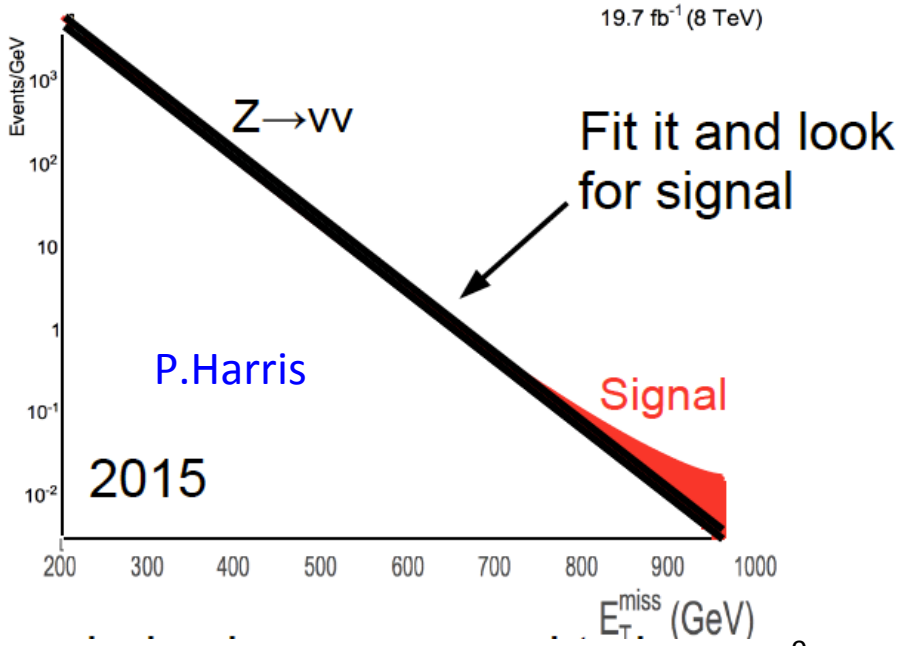


DIFFERENTIAL RESULTS

Z boson p_T modeling

- Transverse momentum distribution of Z boson
  - BSM searches rely on understanding of the Z background
- Dark matter searches
  - Find signal on the MET tails
  - We have to deal with Z->νν background

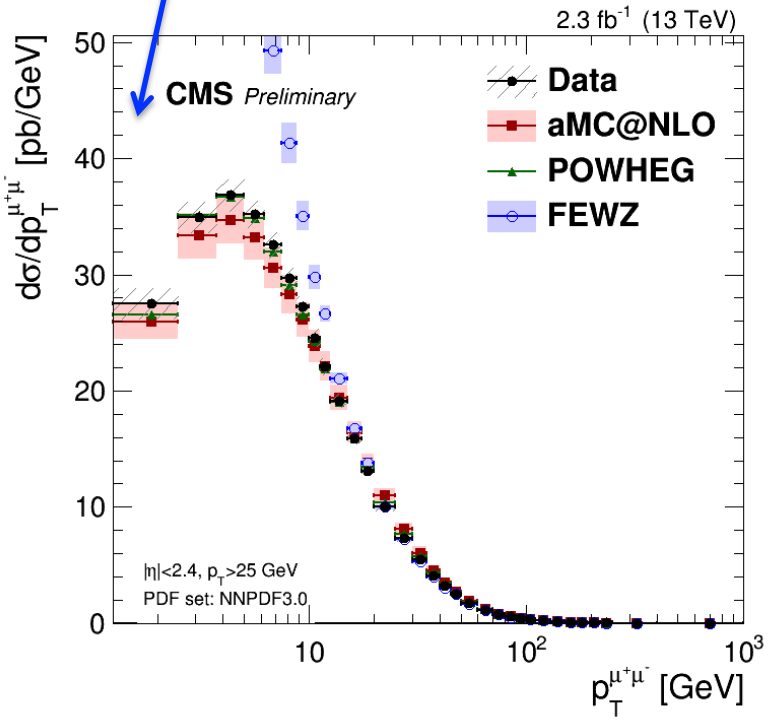


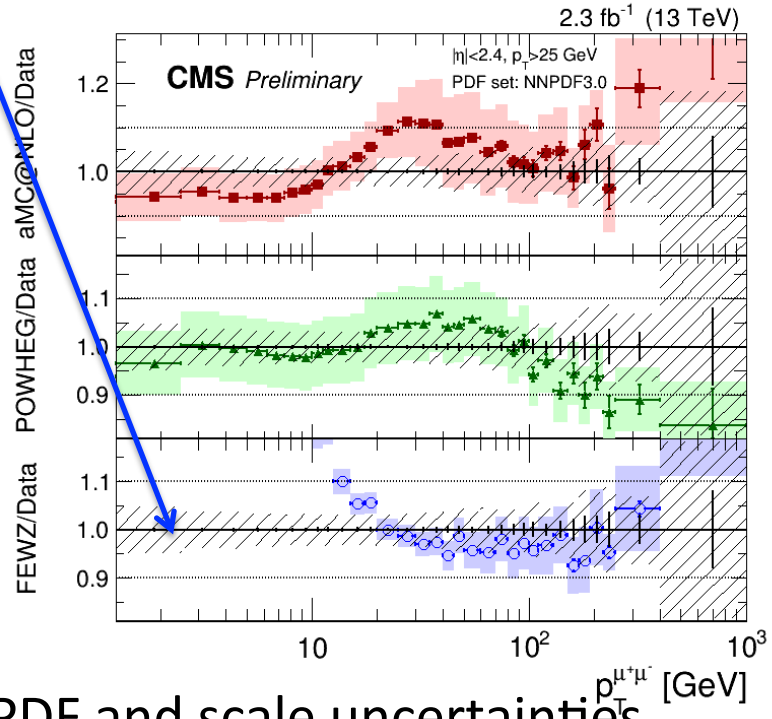


Differential cross sections at √s = 13 TeV

- Transverse momentum distribution of Z boson in di-muon channel
  - Compared to AMC@NLO, POWHEG, and FEWZ predictions
  - Missing NLO electroweak corrections for AMC@NLO and POWHEG
  - FEWZ calculations are not resummed (soft gluon resummation)

$$\left(\alpha_s \ln^2 \frac{M_Z}{p_{T,Z}}\right)^n$$



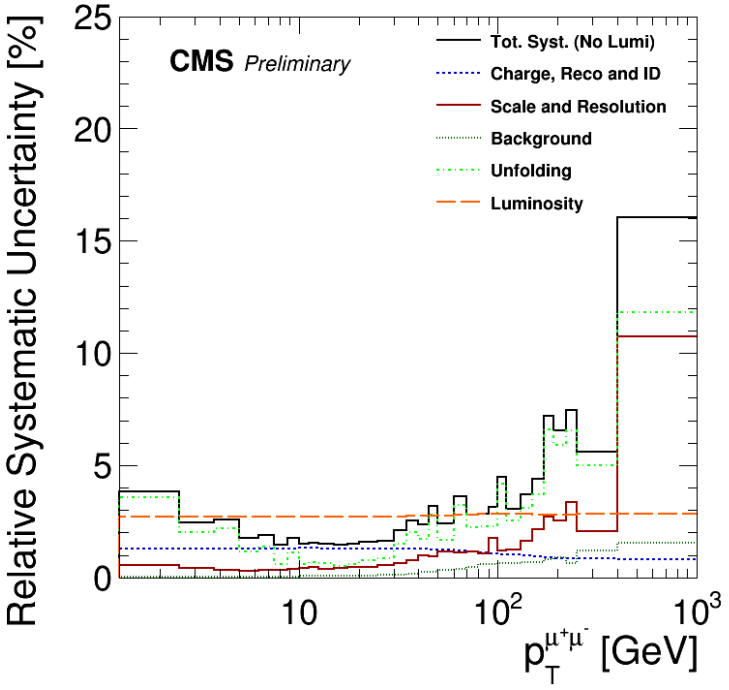


PDF and scale uncertainties

CMS-PAS-SMP-15-011

Systematic uncertainties

- Summary of systematic uncertainties for differential cross section
  - Sensitivity not good enough yet to separate the effects of EWK corrections



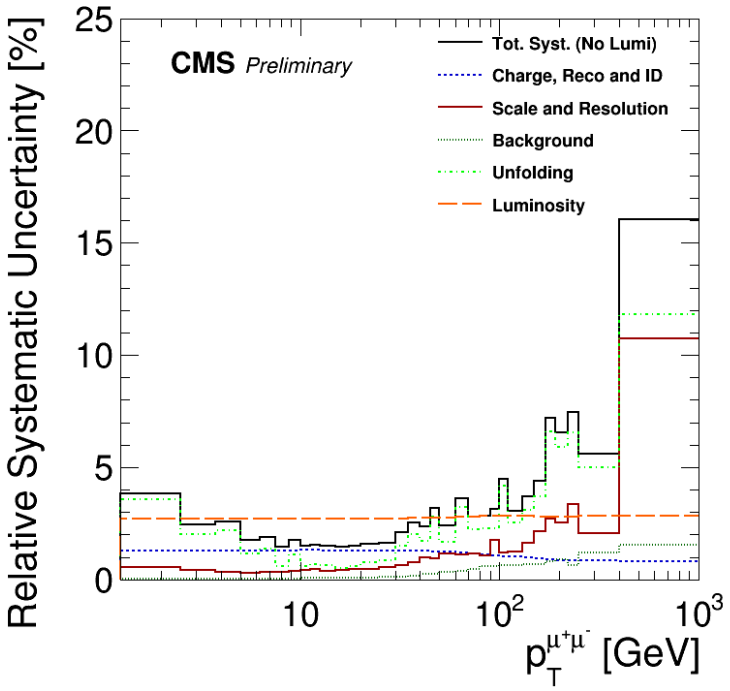
- Unfolding uncertainty (model dependence) dominant in some regions of phase space

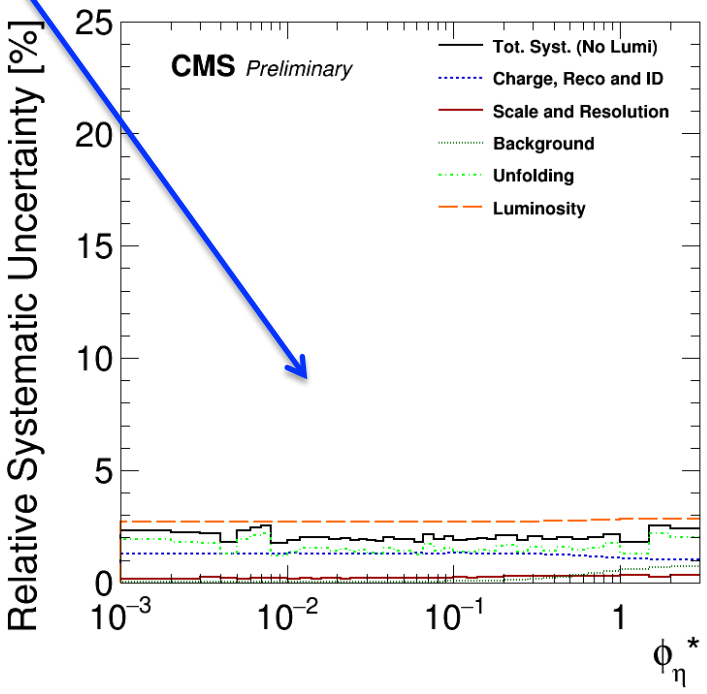
Phi Star (ϕ^*) at $\sqrt{s}$ = 13 TeV

- ϕ^* defined exclusively by the lepton directions
  - Less susceptible to the resolution effects
  - Sensitive to the same effects as Q_T
  - Reduced systematic uncertainties

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta^*_\eta)$$

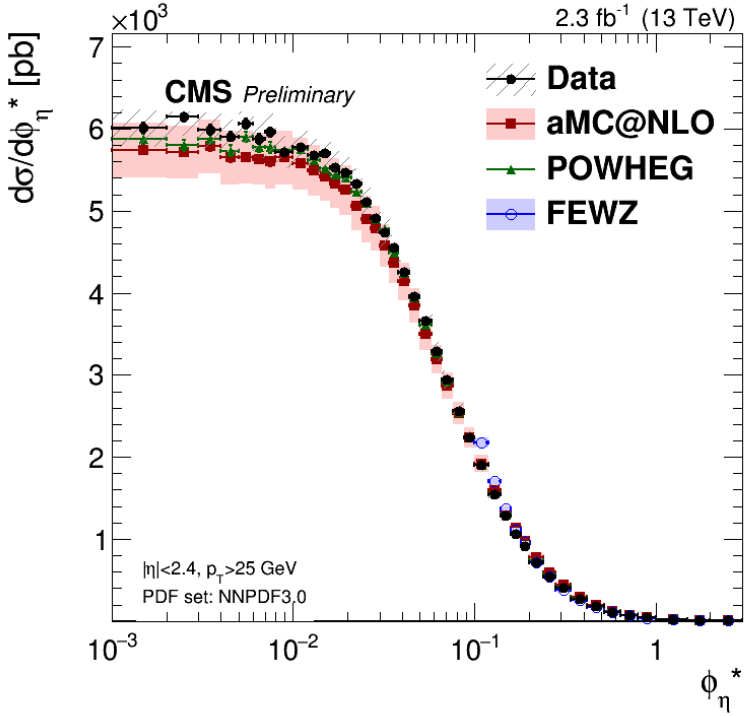
$$\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),$$

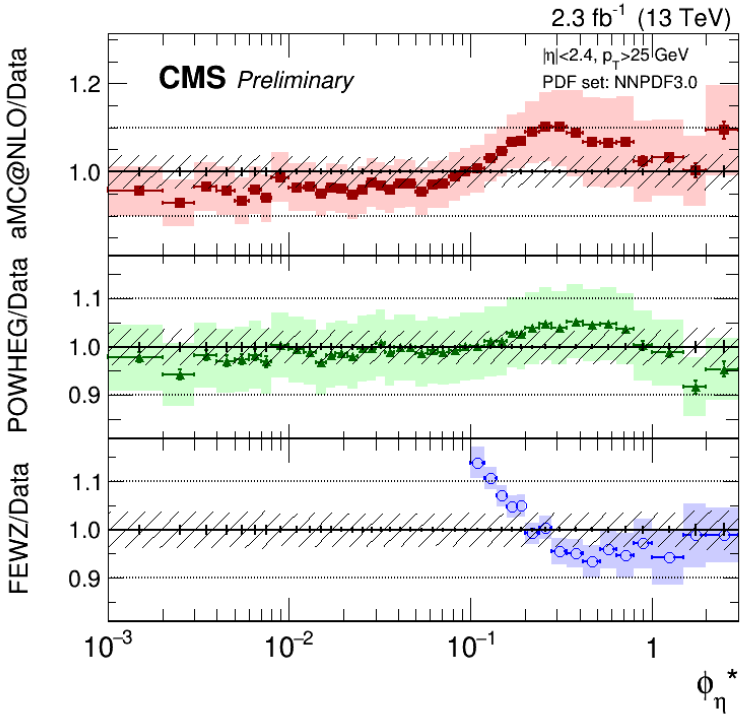




Phi Star (ϕ^*) at $\sqrt{s}$ = 13 TeV

- ϕ^* distribution of Z boson
- AMC@NLO and Powheg predictions are normalized to NLO cross section
- PDF and scale uncertainties are shown for the predictions

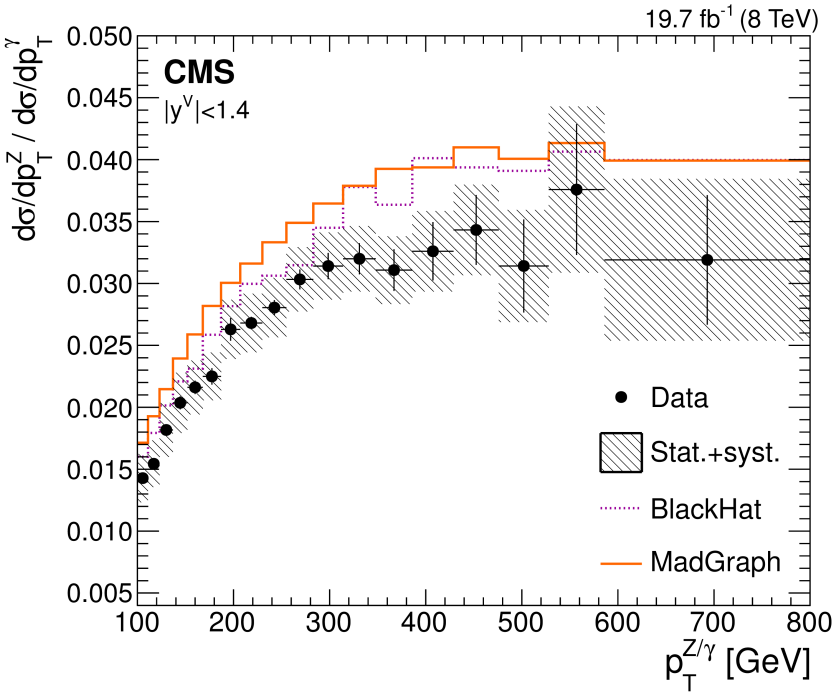


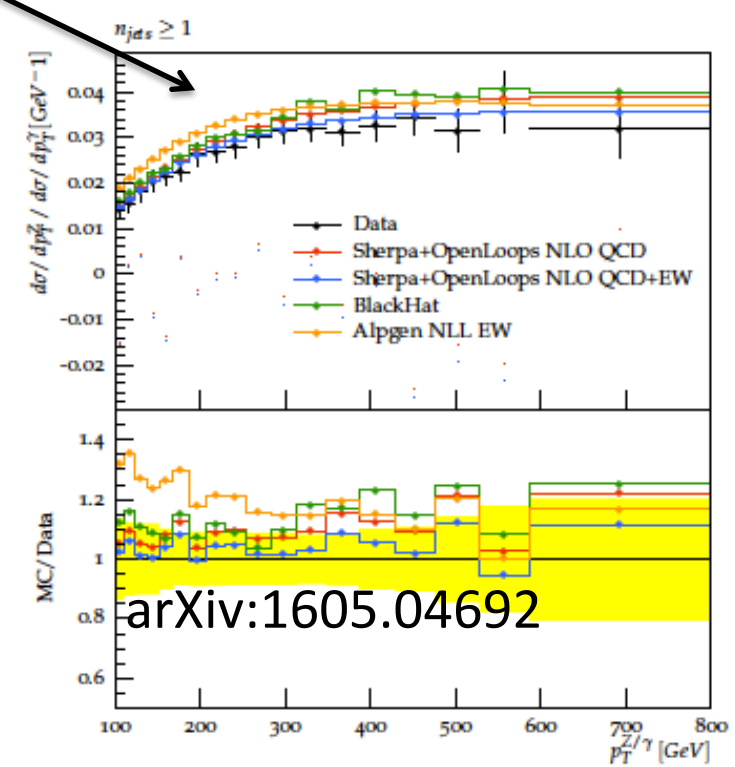


CMS-PAS-SMP-15-011

Z/γ^*+jet and γ+jet ratio at √s = 8 TeV

- Differential cross section ratio as a function of boson p_T
  - Compared to Madgraph and BLACKHAT (QCD-NLO) calculation
- Inclusion of EW corrections results in better agreement

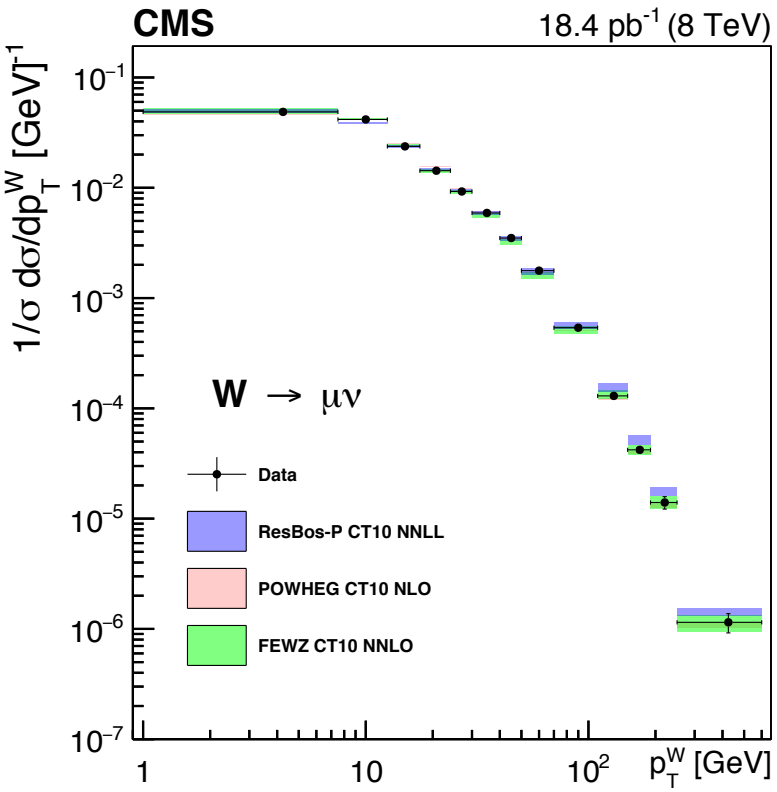


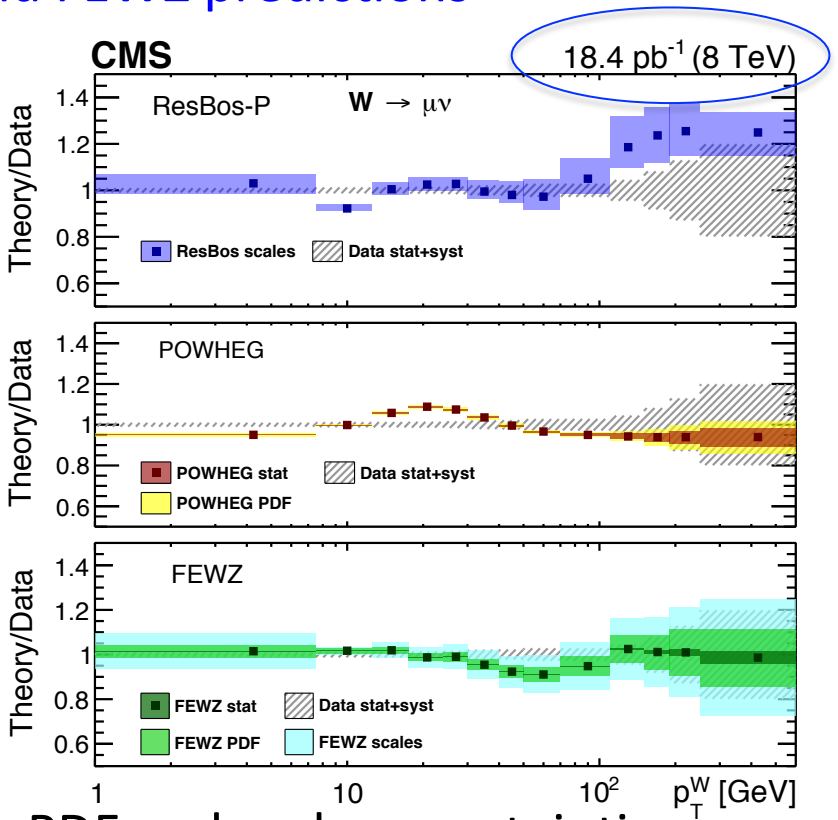


CMS-PAS-SMP-14-005 71 GeV < M_Z < 111 GeV

Differential cross sections at √s = 8 TeV

- Transverse momentum distribution of W boson for muon channel
  - Special low pileup run at √s = 8 TeV
  - Compared to ResBos, POWHEG, and FEWZ predictions



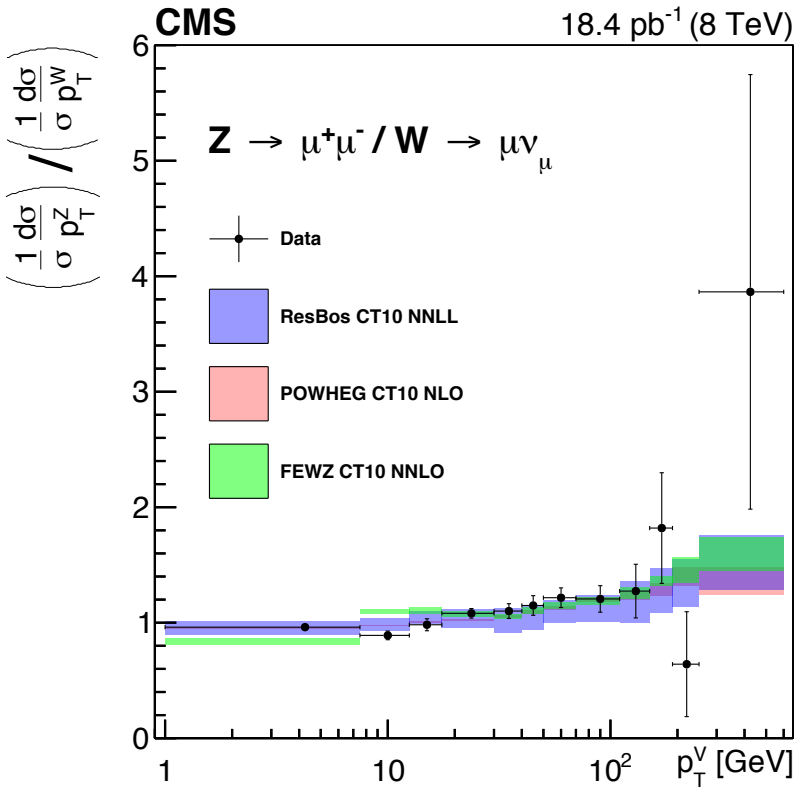


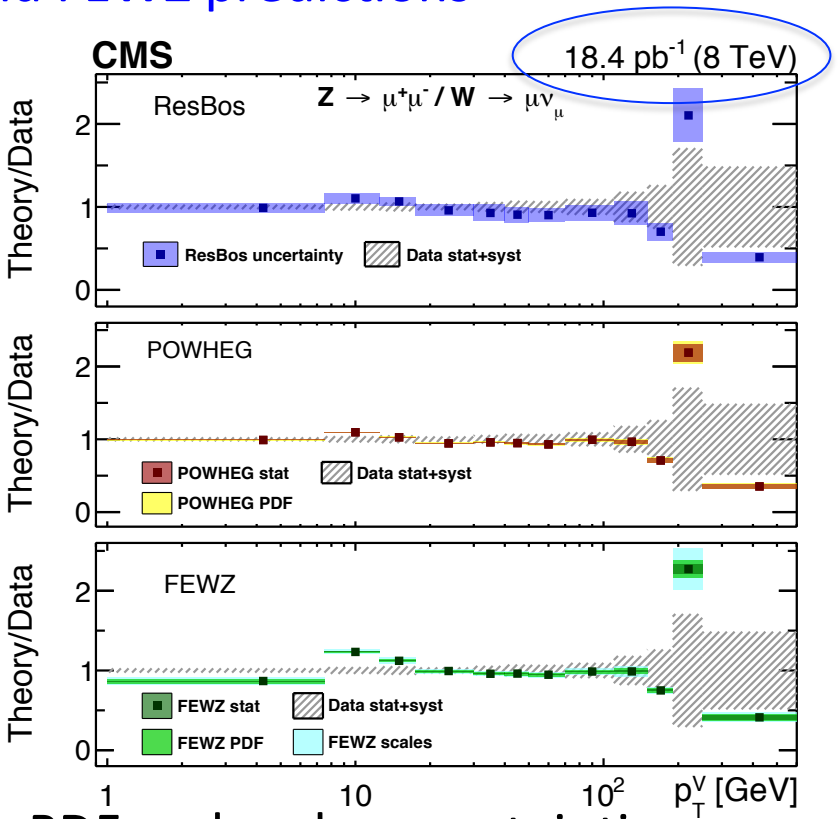
PDF and scale uncertainties

CMS-PAS-SMP-14-012

Differential ratios at √s = 8 TeV

- Z/W differential cross section ratio for muon channel
  - W^-/W^+ ratio in backup
  - Compared to ResBos, POWHEG, and FEWZ predictions



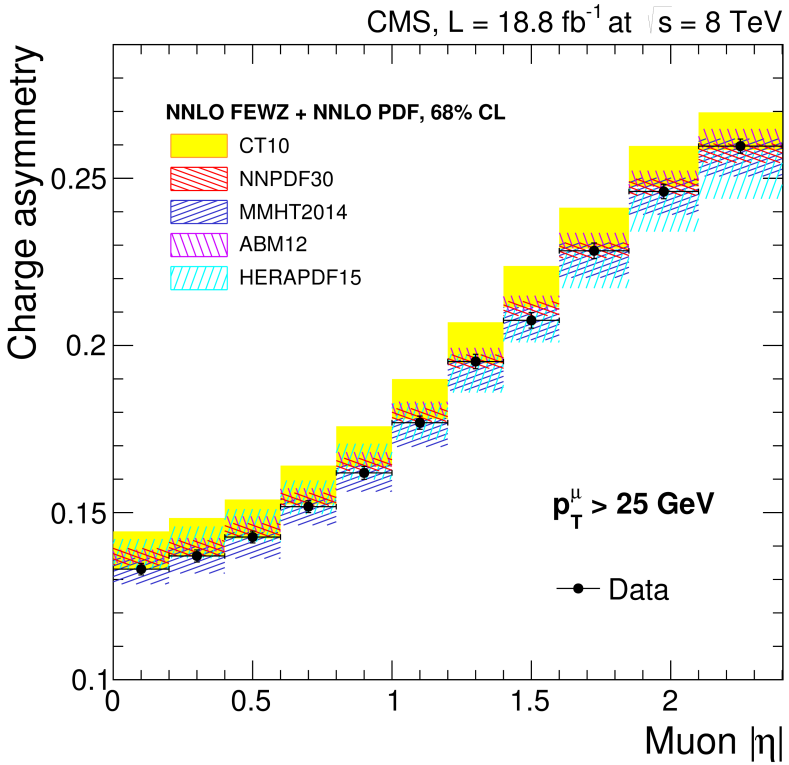


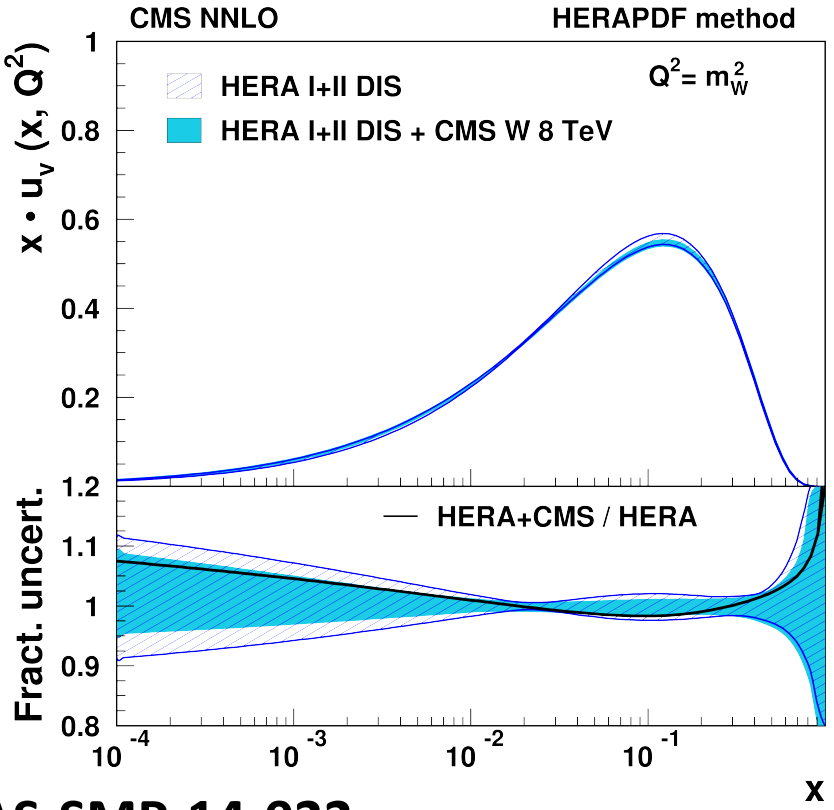
PDF and scale uncertainties

CMS-PAS-SMP-14-012

W charge asymmetry at √s = 8 TeV

- Differential cross section and muon charge asymmetry
- Constraints on the valence and sea quark distributions

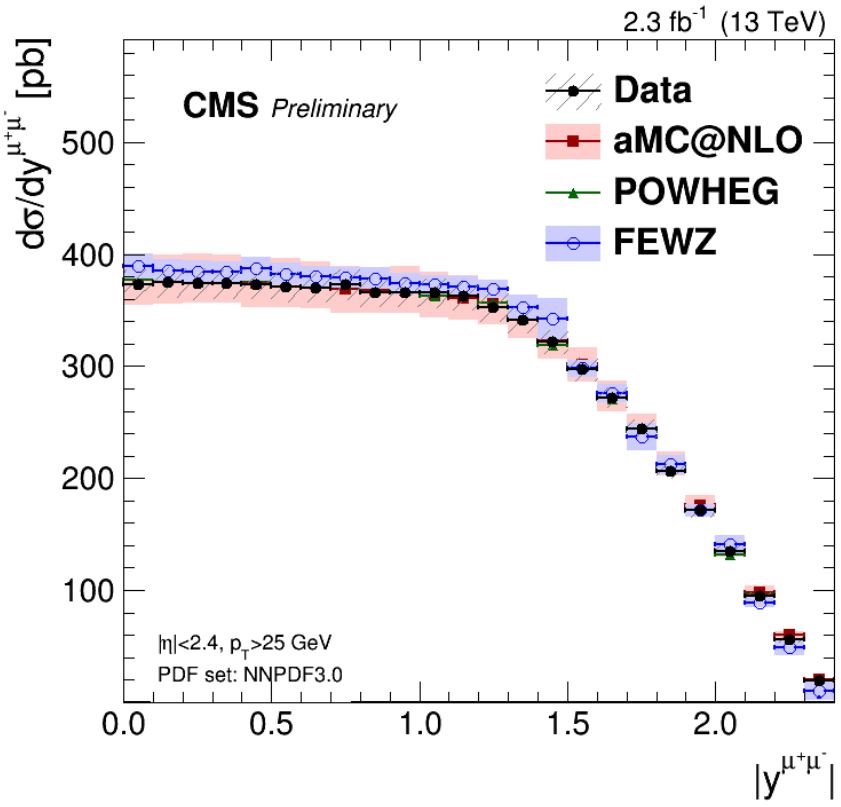


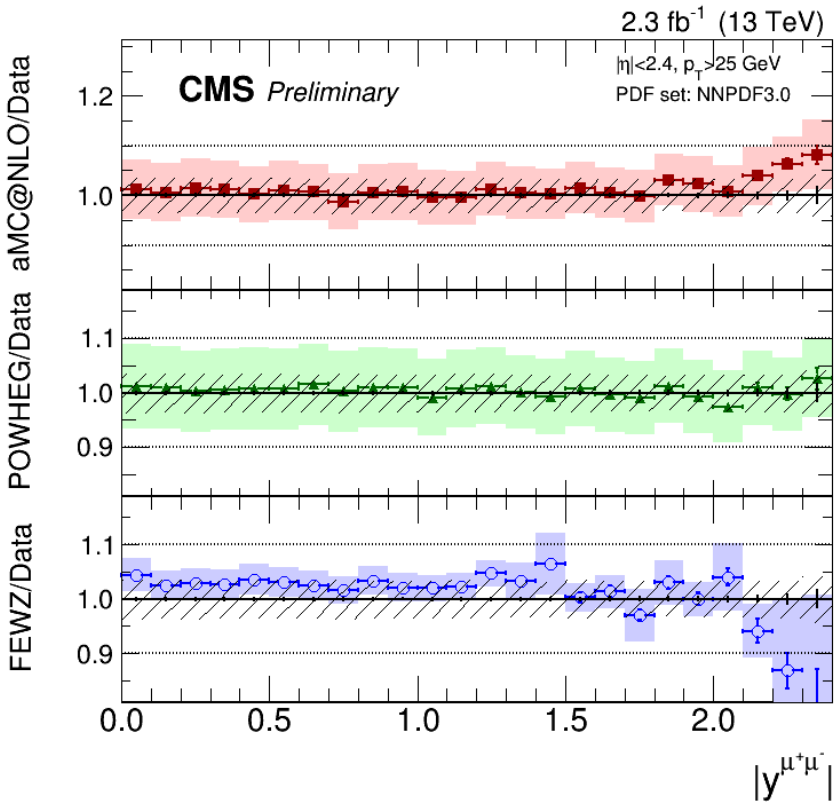


CMS-PAS-SMP-14-022

Rapidity of Z boson at √s = 13 TeV

- Rapidity distribution of Z boson





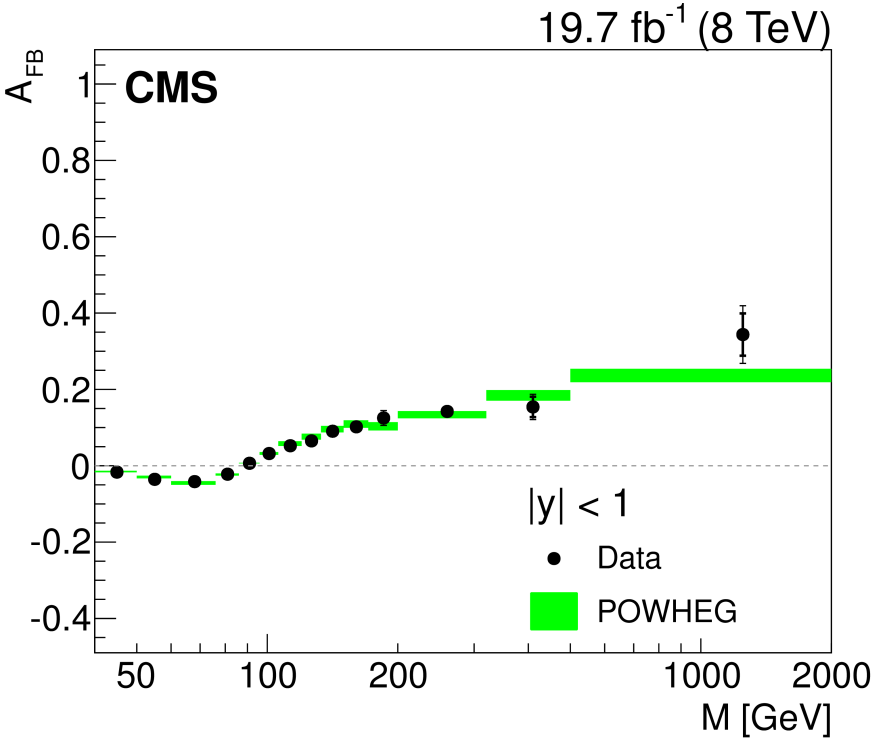
CMS-PAS-SMP-15-011

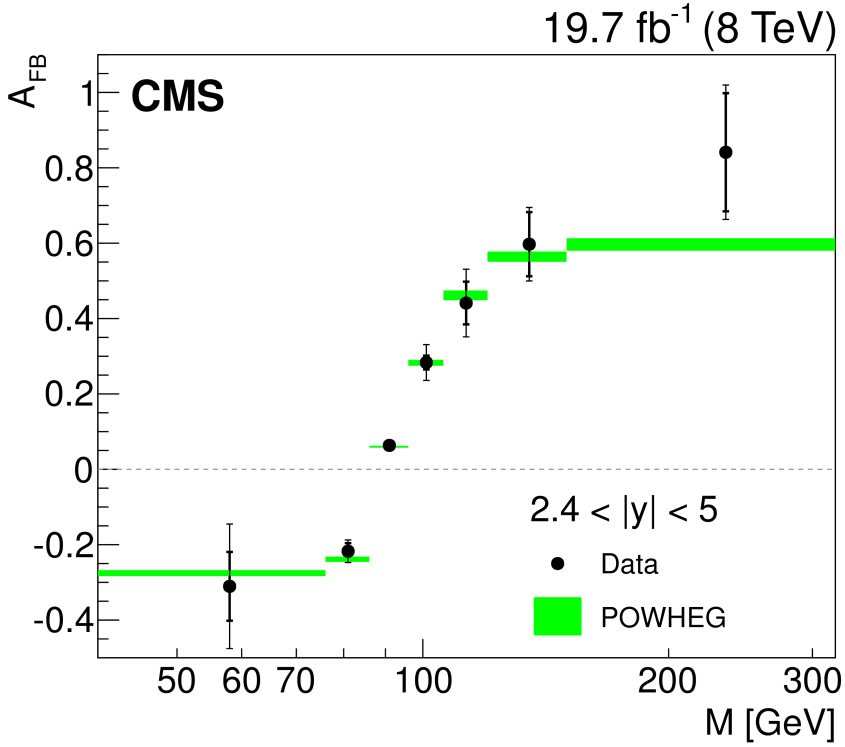
A_{FB} at √s = 8 TeV

- Vector and axial-vector couplings
- Extract the effective weak mixing angle $\sin^2\theta^{eff}(m_Z)$
- Measurement extended to larger rapidity (|y|=5)
  - Electrons in forward calorimeter

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Collins-Soper frame

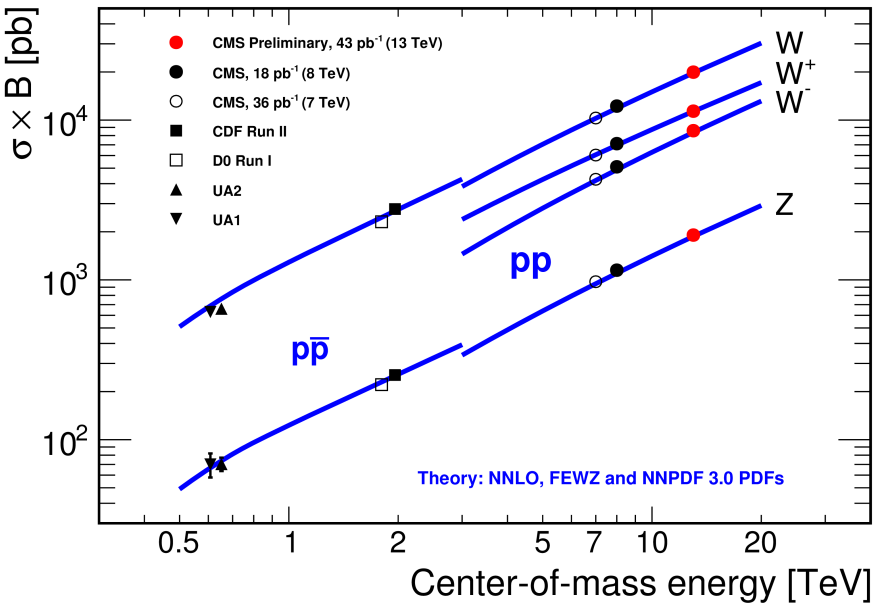




CMS-PAS-SMP-14-004

Summary

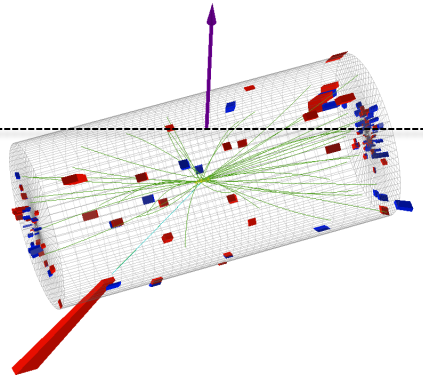
- Large and successful program at LHC Run 1 completed and being finalized
- New opportunities with CMS at at √s= 13 TeV
- Preliminary measurements of inclusive and fiducial W and Z cross sections and ratios
  - Already achieved excellent accuracy
  - Precise tests with ratios
- Z p_T spectra measurements at 13 TeV
- Many more results in the pipeline

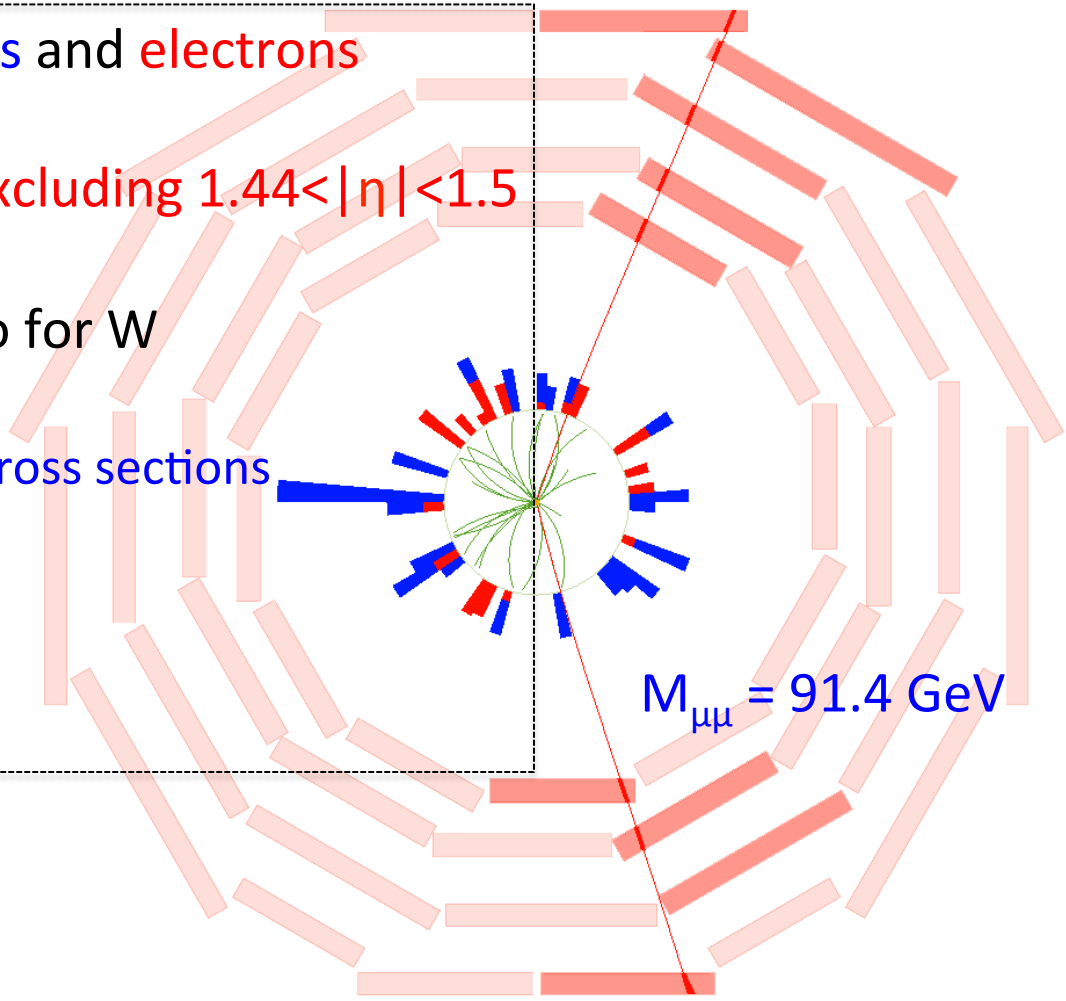


BACKUP

Fiducial region

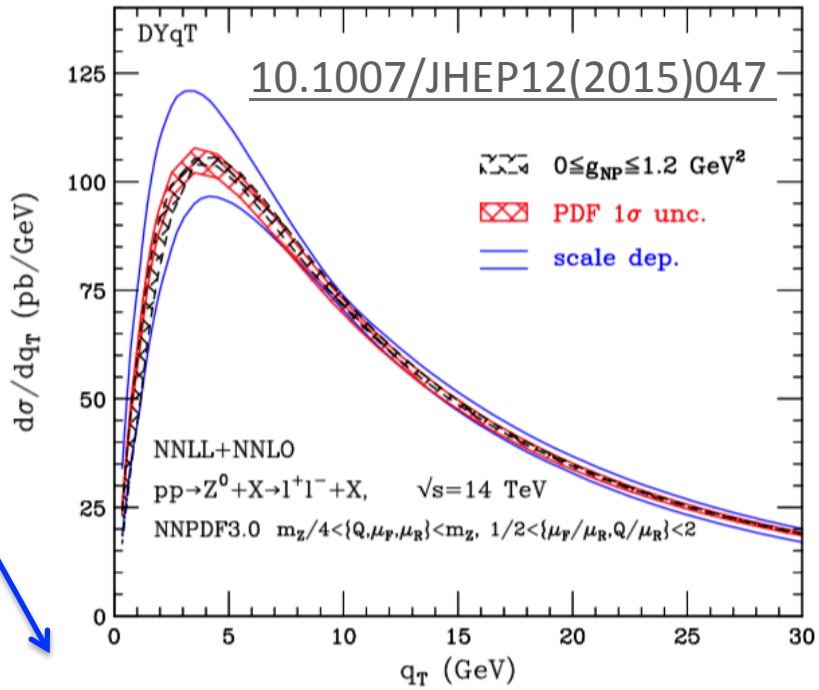
- Fiducial region definition: muons and electrons
  - p_T > 25 GeV and $|\eta|$ < 2.4
  - E_T > 25 GeV and $|\eta|$ < 2.5 excluding 1.44<$|\eta|$<1.5
- 60 GeV < $M_{\mu\mu}$ < 120 GeV
- No requirement on the neutrino for W
- Dressed level: (ΔR =0.1)
  - Fiducial total and differential cross sections
- Naked level: (post-fsr)
  - Fiducial total cross section





QCD and EWK calculations

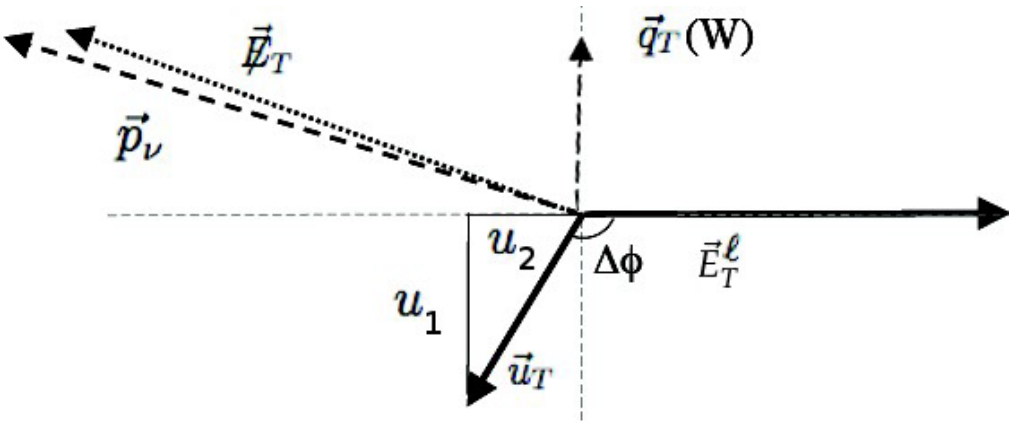
- State of the art tools
- NLO calculations matched to parton showers
  - AMC@NLO, POWHEG, SHERPA
- NNLO fixed order calculations
  - FEWZ, DYNNLO
  - Partonic differential cross section
- NNLL analytic ressumation at low p_T
  - RESBOS, DYqT
  - Matched with NNLO calculations
- EWK corrections
  - Horace, FEWZ

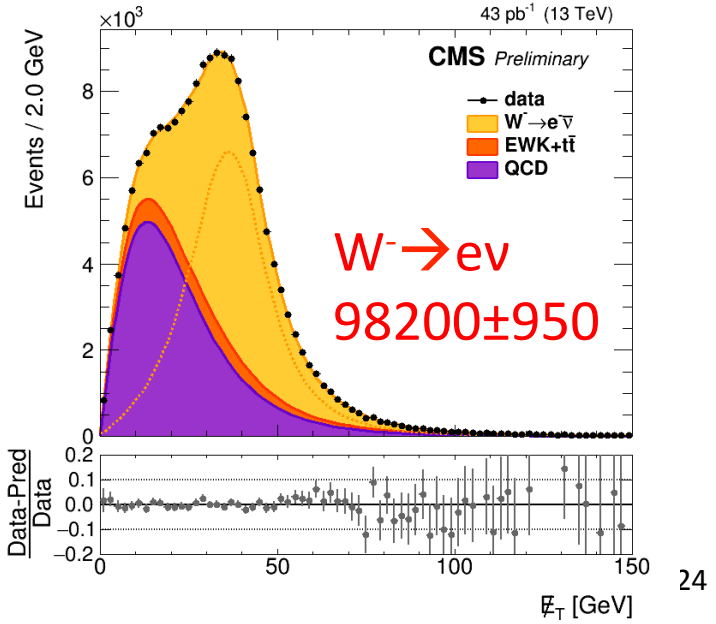


$$\left(\alpha_s \ln^2 \frac{M_Z}{p_{T,Z}}\right)^n$$

MET modeling

- Recoil calibrated MET
  - Measure response and resolution of the hadronic recoil against W boson using Z events
  - Parameterize parallel (u_1) and perpendicular (u_2) components of the recoil as function of boson p_T
  - Use the data driven recoil model to correct W simulation

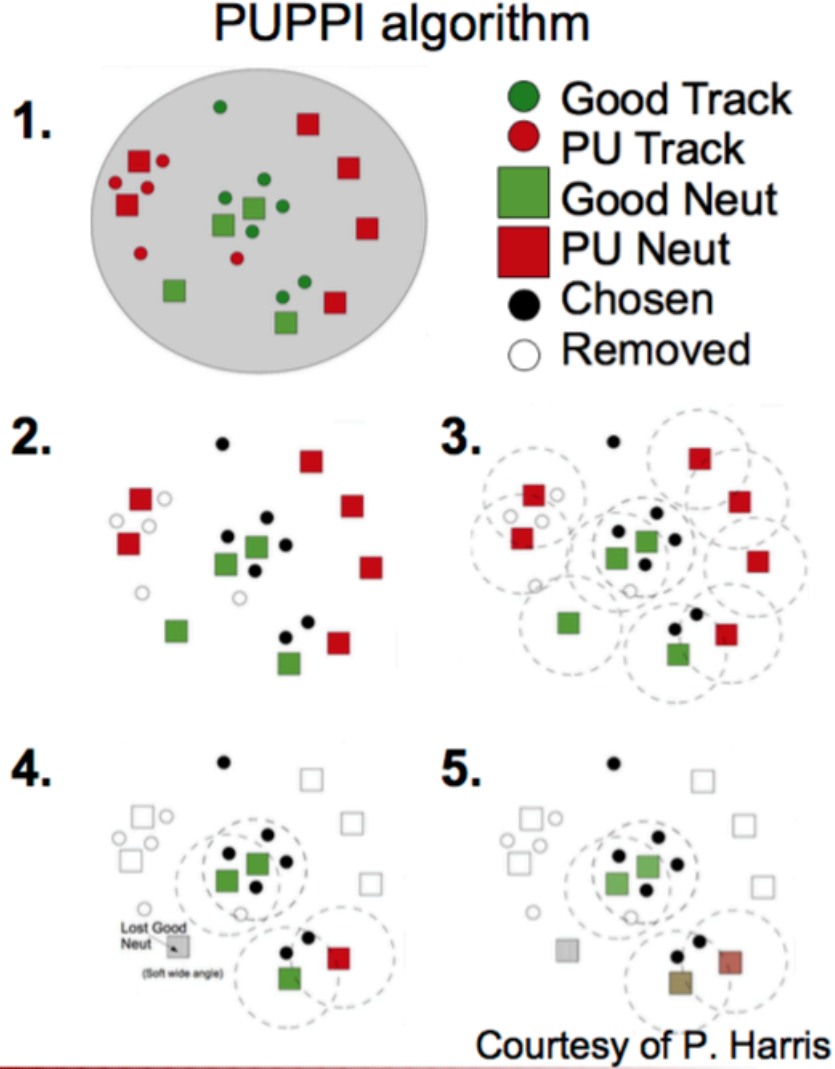




PUPPI Algorithm

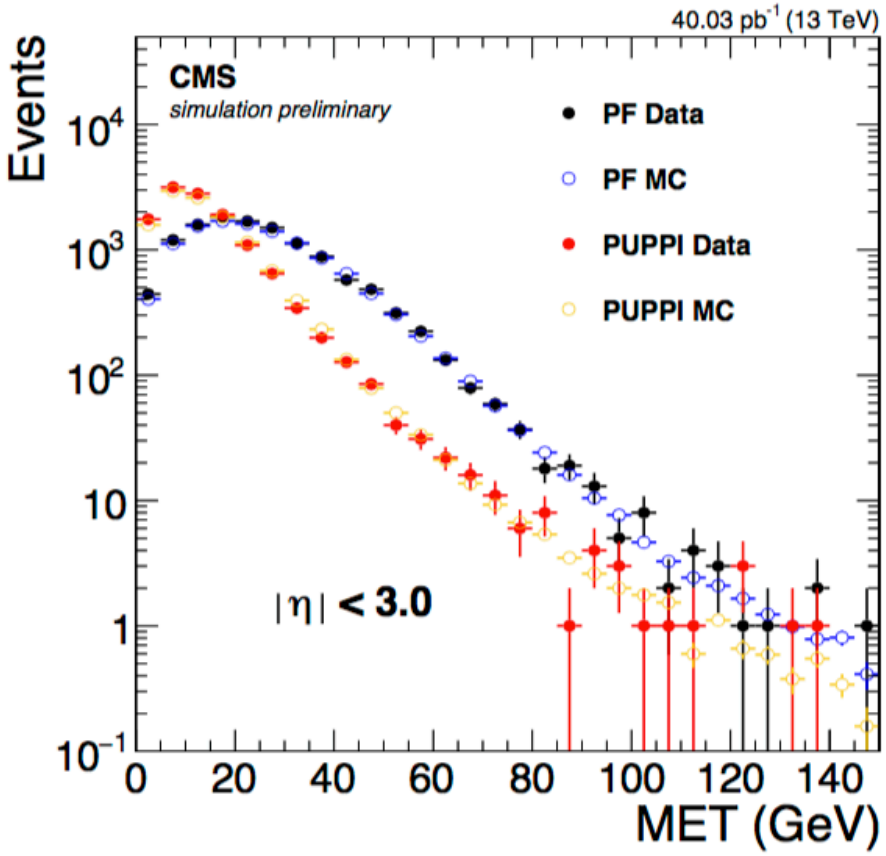
- Missing energy resolution is crucial for the W signal extraction

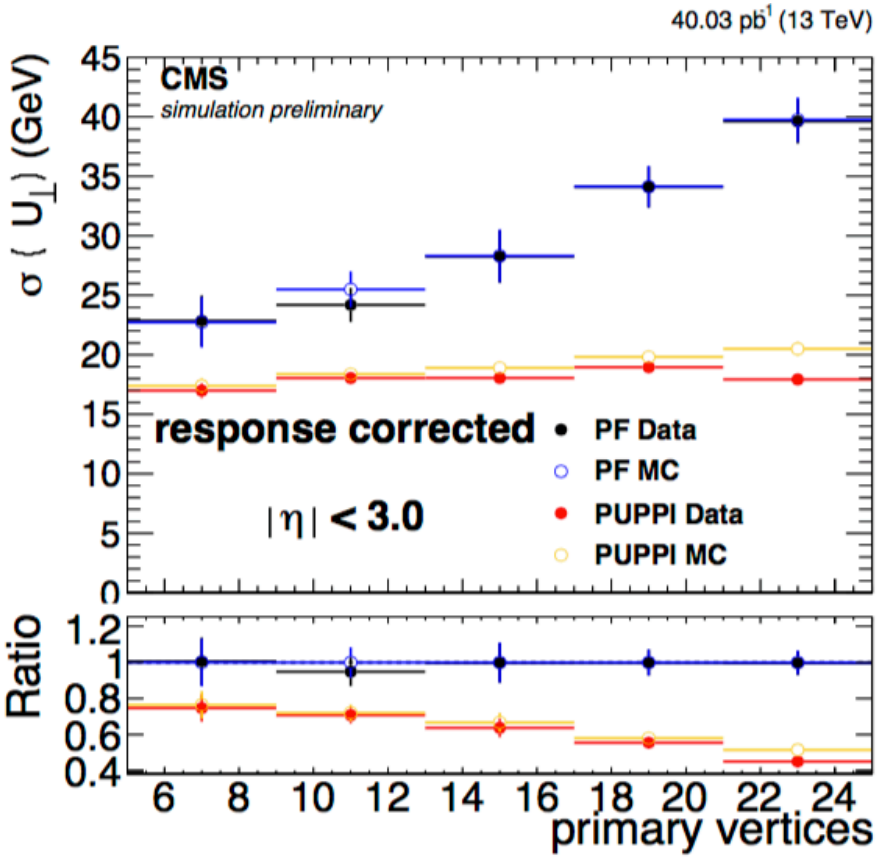
- Pileup mitigation
- Single particle level
- Compute weight per particle
- Discard small-weight particles
- Calculate MET as the negative weighted sum of particles



PUPPI MET performance

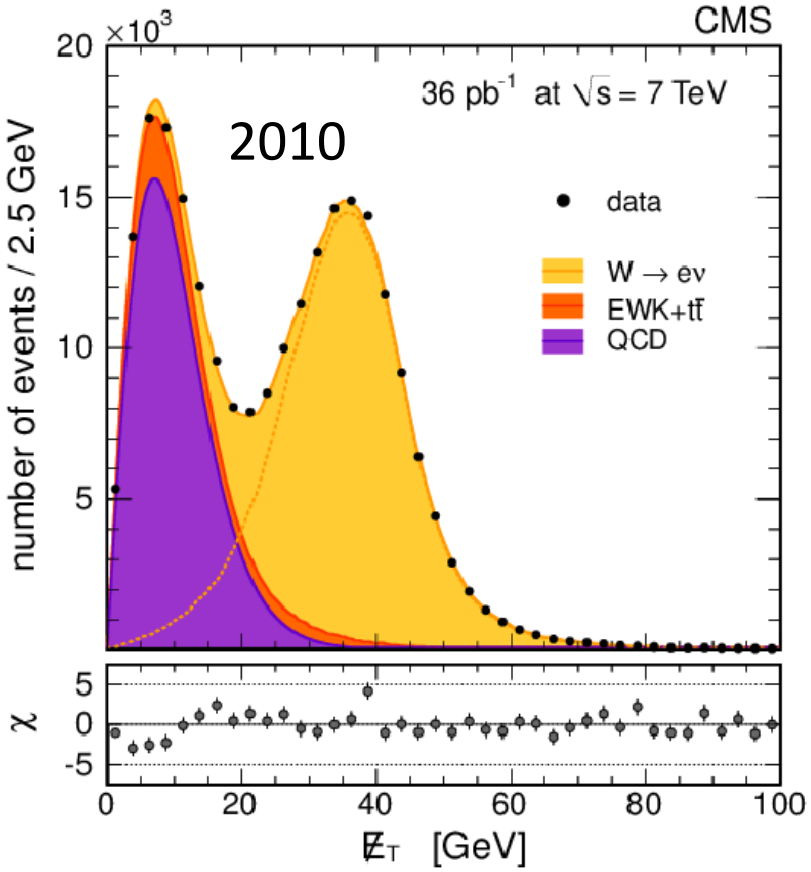
- New method with respect to Run 1 for pileup mitigation
  - Weight per particle to discriminate PU

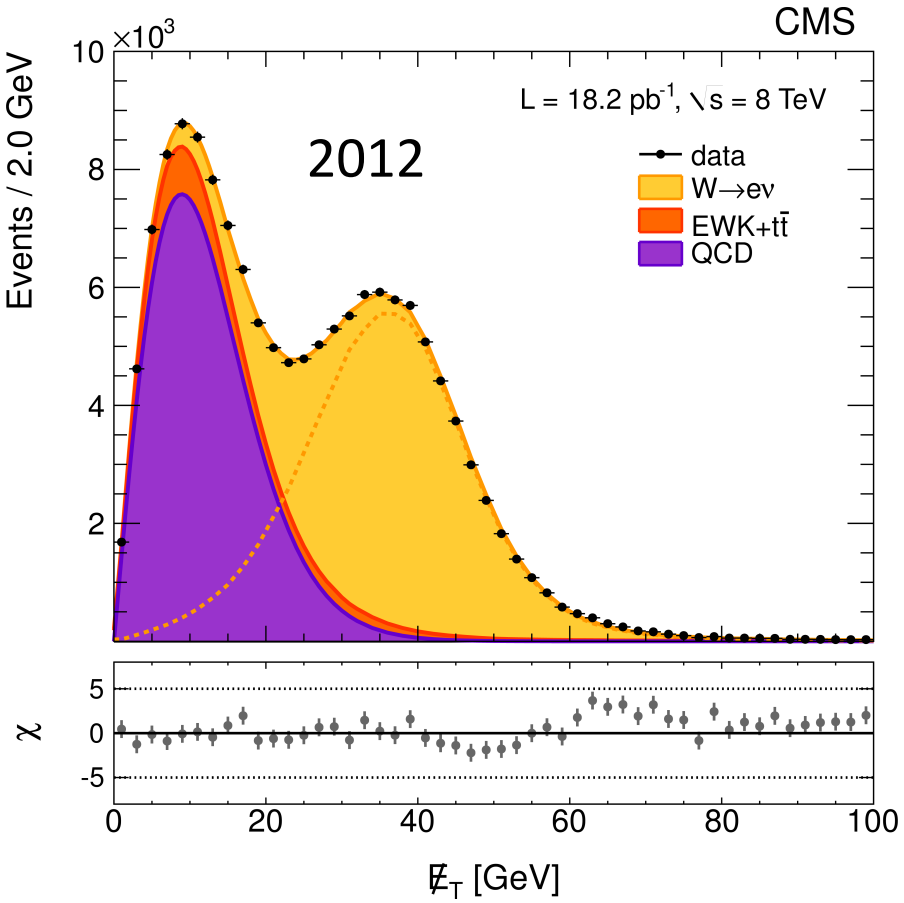




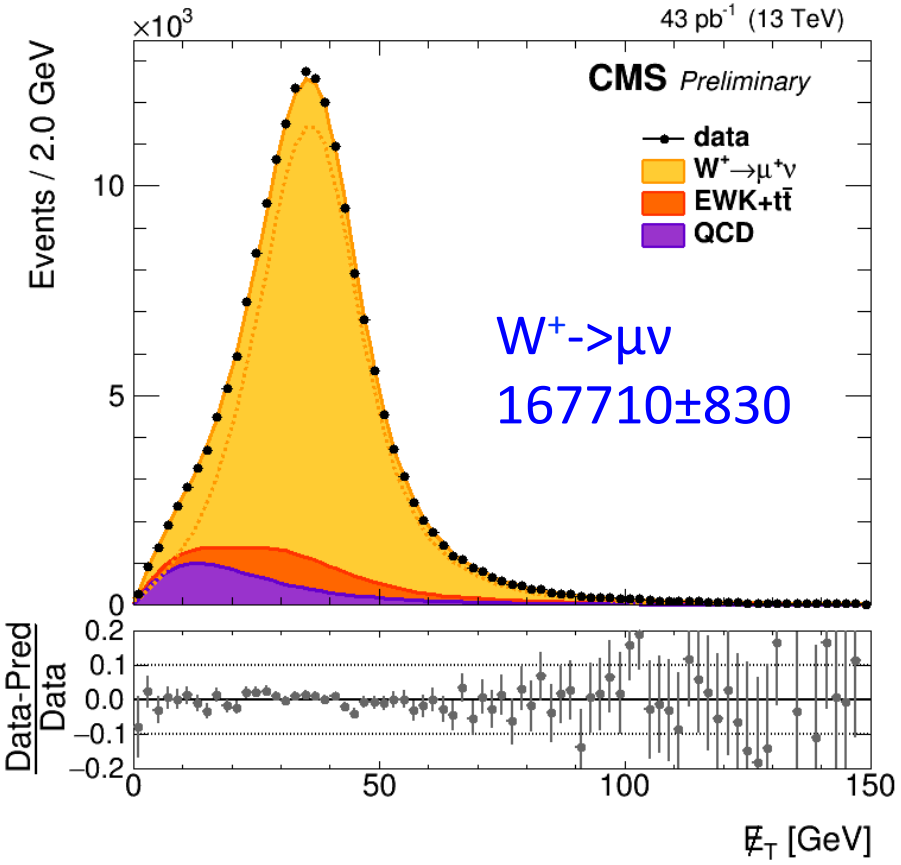
Missing Energy

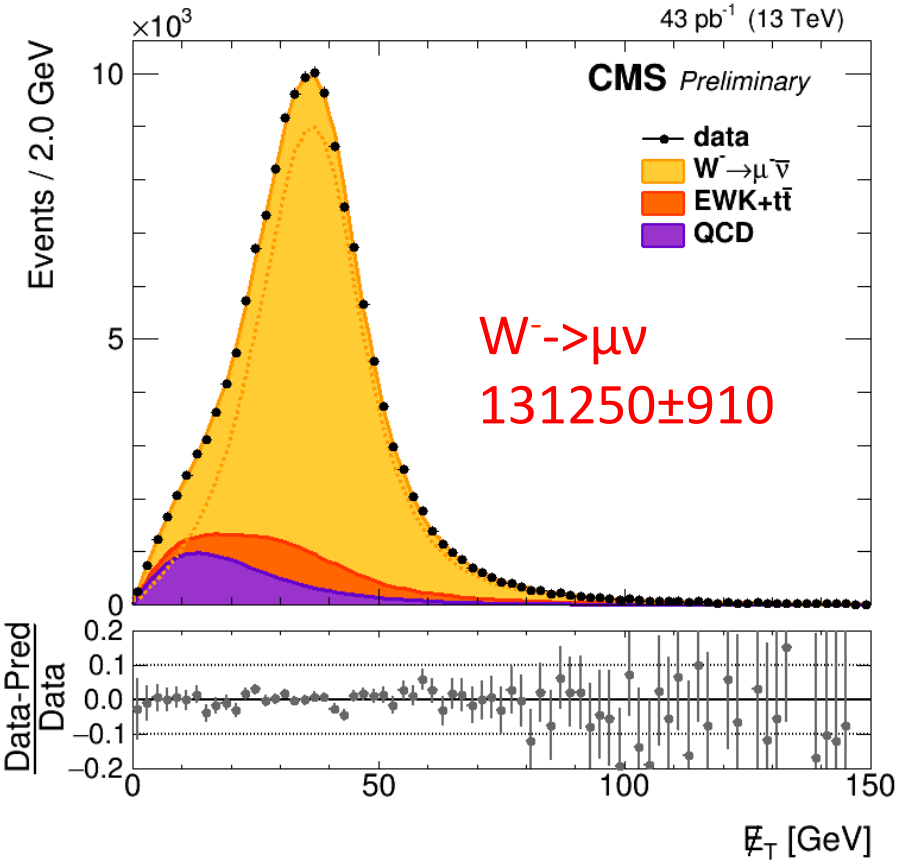
- Missing energy resolution is crucial for the W signal extraction



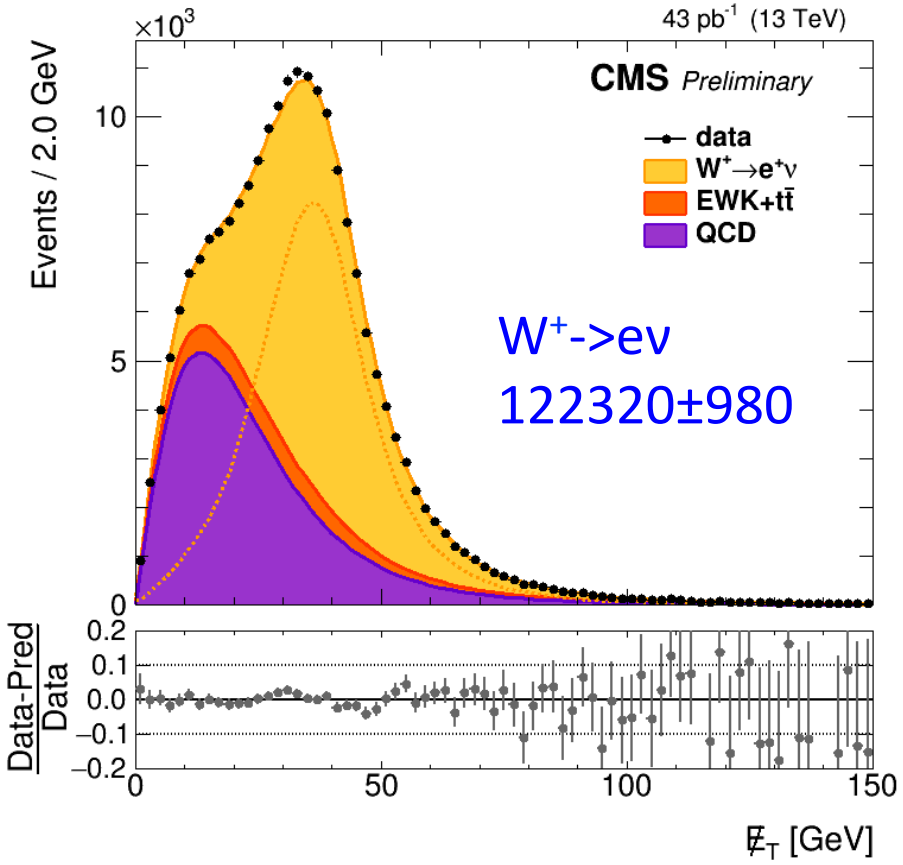


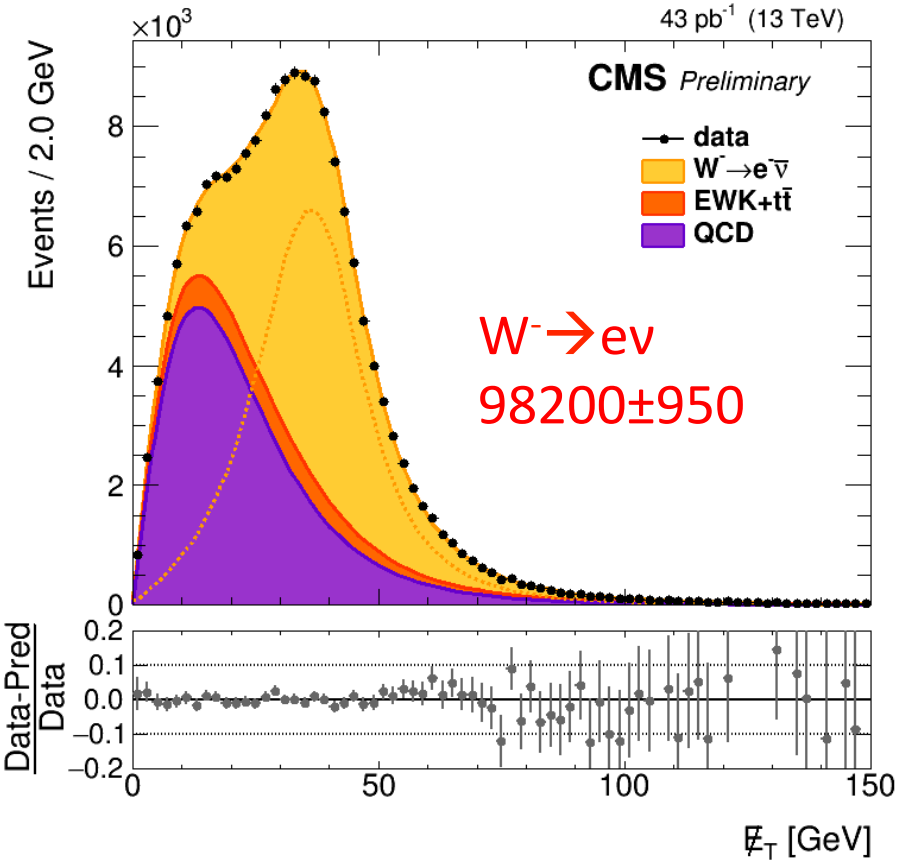
W->μν yields


×10^3
43 pb^-1 (13 TeV)
CMS Preliminary
data
W+→μ+ν
EWK+tt̄
QCD
Events / 2.0 GeV
W+->μν
167710±830
Data-Pred / Data
E_T [GeV]

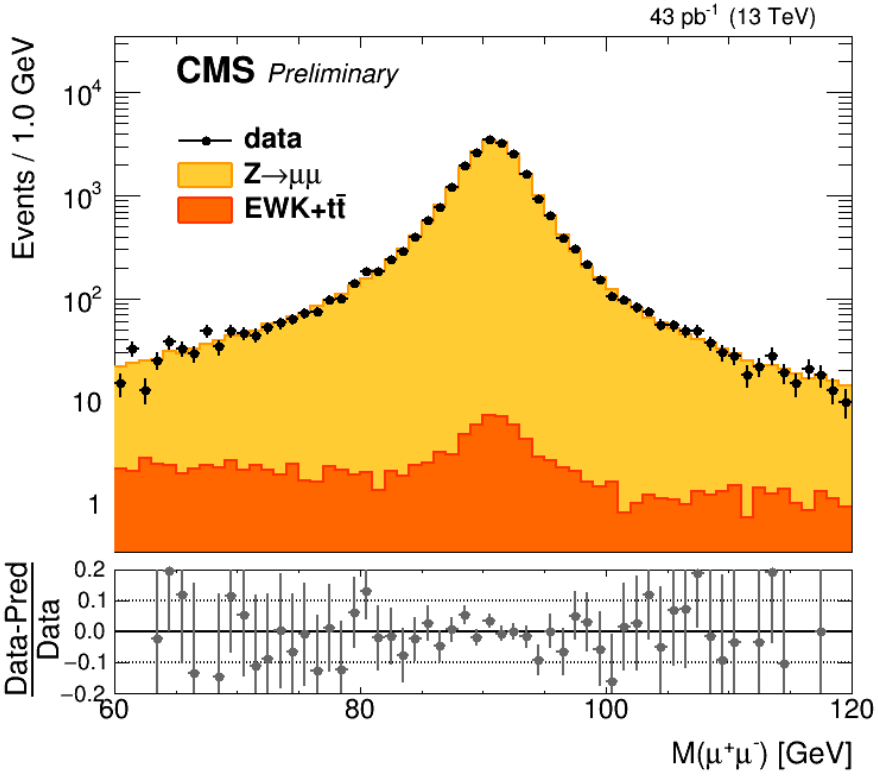

×10^3
43 pb^-1 (13 TeV)
CMS Preliminary
data
W-→μ-ν̄
EWK+tt̄
QCD
Events / 2.0 GeV
W-->μν
131250±910
Data-Pred / Data
E_T [GeV]

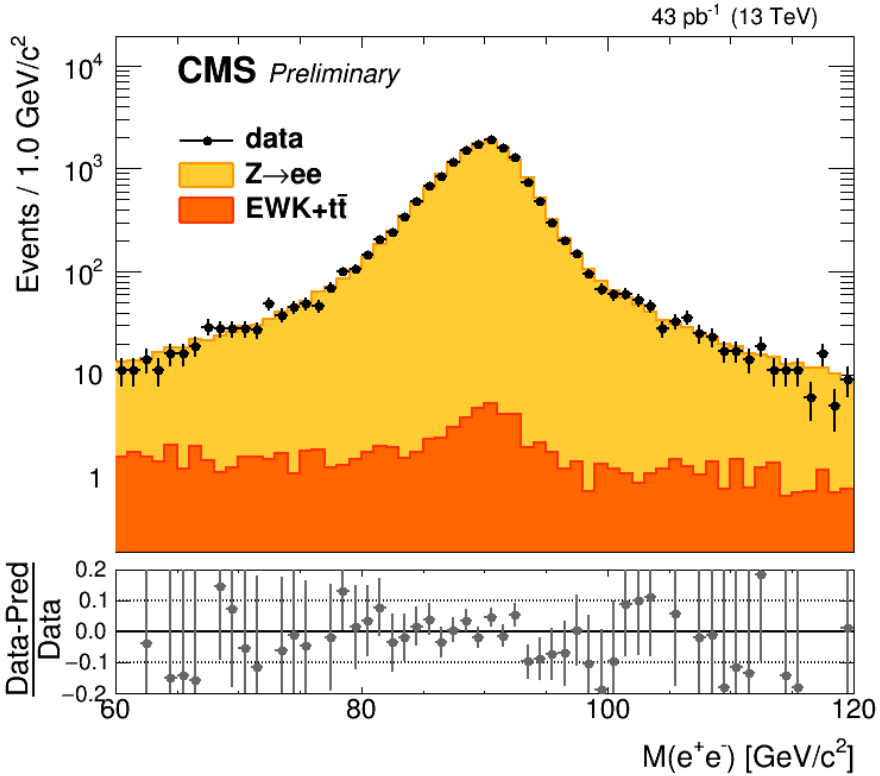
W->ev yields


×10³
43 pb⁻¹ (13 TeV)
CMS Preliminary
data
W⁺→e⁺ν
EWK+tt̄
QCD
Events / 2.0 GeV
W⁺->ev
122320±980
Data-Pred / Data
E_T [GeV]


×10³
43 pb⁻¹ (13 TeV)
CMS Preliminary
data
W⁻→e⁻ν̄
EWK+tt̄
QCD
Events / 2.0 GeV
W⁻→ev
98200±950
Data-Pred / Data
E_T [GeV]

Z yields





Z->μμ
23670±150

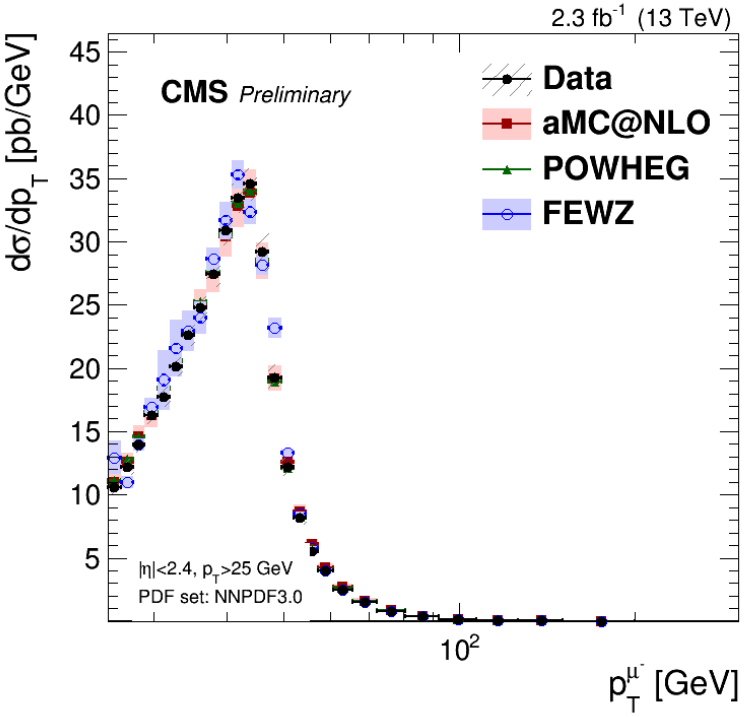
Z->ee
15290±120

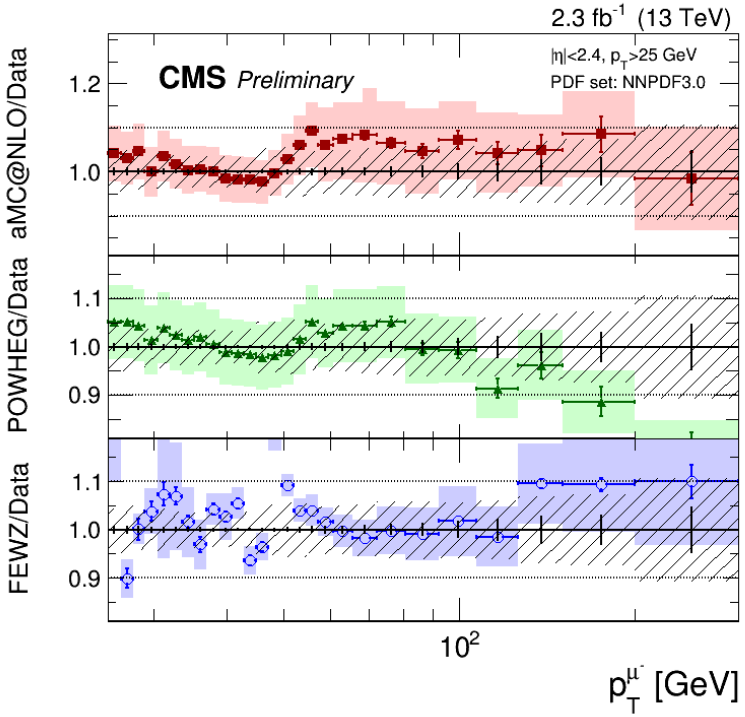
Total cross sections summary

Channel		$\sigma \times \mathcal{B}$ [pb] (total)	NNLO [pb]
W^+	$e^+\nu$	$11390 \pm 90\,(\text{stat}) \pm 340\,(\text{syst}) \pm 550\,(\text{lumi})$	11330^{+320}_{-270}
	$\mu^+\nu$	$11350 \pm 60\,(\text{stat}) \pm 320\,(\text{syst}) \pm 550\,(\text{lumi})$	
	$\ell^+\nu$	$11370 \pm 50\,(\text{stat}) \pm 230\,(\text{syst}) \pm 550\,(\text{lumi})$	
W^-	$e^-\nu$	$8680 \pm 80\,(\text{stat}) \pm 250\,(\text{syst}) \pm 420\,(\text{lumi})$	8370^{+240}_{-210}
	$\mu^-\nu$	$8510 \pm 60\,(\text{stat}) \pm 210\,(\text{syst}) \pm 410\,(\text{lumi})$	
	$\ell^-\nu$	$8580 \pm 50\,(\text{stat}) \pm 160\,(\text{syst}) \pm 410\,(\text{lumi})$	
W	$e\nu$	$20070 \pm 120\,(\text{stat}) \pm 570\,(\text{syst}) \pm 960\,(\text{lumi})$	19700^{+560}_{-470}
	$\mu\nu$	$19870 \pm 80\,(\text{stat}) \pm 460\,(\text{syst}) \pm 950\,(\text{lumi})$	
	$\ell\nu$	$19950 \pm 70\,(\text{stat}) \pm 360\,(\text{syst}) \pm 960\,(\text{lumi})$	
Z	e^+e^-	$1920 \pm 20\,(\text{stat}) \pm 60\,(\text{syst}) \pm 90\,(\text{lumi})$	1870^{+50}_{-40}
	$\mu^+\mu^-$	$1900 \pm 10\,(\text{stat}) \pm 50\,(\text{syst}) \pm 90\,(\text{lumi})$	
	$\ell^+\ell^-$	$1910 \pm 10\,(\text{stat}) \pm 40\,(\text{syst}) \pm 90\,(\text{lumi})$	
Quantity		Ratio (total)	NNLO
R_{W^+/W^-}	e	$1.313 \pm 0.016\,(\text{stat}) \pm 0.028\,(\text{syst})$	$1.354^{+0.011}_{-0.012}$
	μ	$1.334 \pm 0.011\,(\text{stat}) \pm 0.031\,(\text{syst})$	
	ℓ	$1.323 \pm 0.010\,(\text{stat}) \pm 0.021\,(\text{syst})$	
$R_{W^+/Z}$	e	$5.94 \pm 0.07\,(\text{stat}) \pm 0.16\,(\text{syst})$	$6.06^{+0.04}_{-0.05}$
	μ	$5.98 \pm 0.05\,(\text{stat}) \pm 0.14\,(\text{syst})$	
	ℓ	$5.96 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst})$	
$R_{W^-/Z}$	e	$4.52 \pm 0.06\,(\text{stat}) \pm 0.12\,(\text{syst})$	$4.48^{+0.03}_{-0.02}$
	μ	$4.49 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst})$	
	ℓ	$4.50 \pm 0.03\,(\text{stat}) \pm 0.08\,(\text{syst})$	
$R_{W/Z}$	e	$10.46 \pm 0.11\,(\text{stat}) \pm 0.26\,(\text{syst})$	$10.55^{+0.07}_{-0.06}$
	μ	$10.47 \pm 0.08\,(\text{stat}) \pm 0.20\,(\text{syst})$	
	ℓ	$10.46 \pm 0.06\,(\text{stat}) \pm 0.16\,(\text{syst})$	

Differential cross sections

- Transverse momentum of the negatively charged muon
- AMC@NLO and Powheg predictions are normalized to NLO cross section
- PDF and scale uncertainties are shown for the predictions

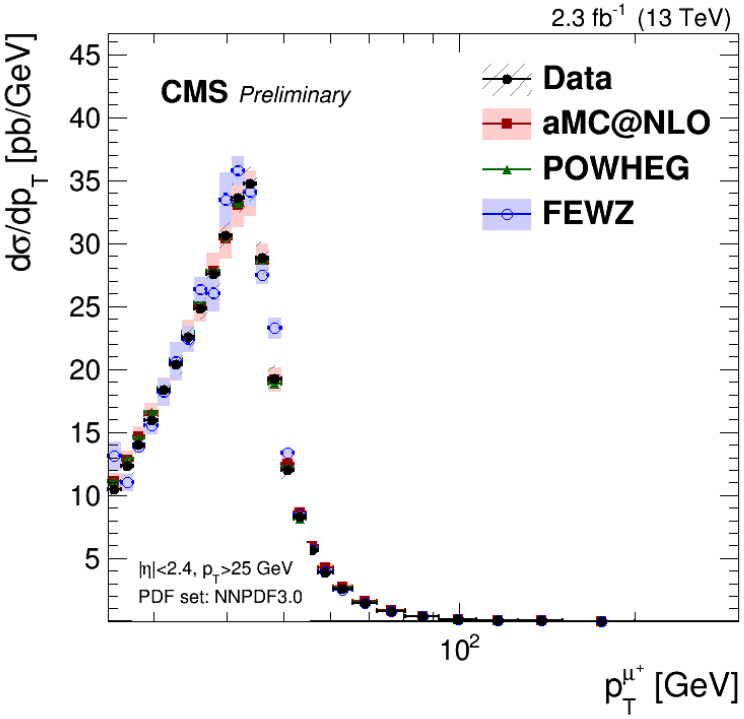


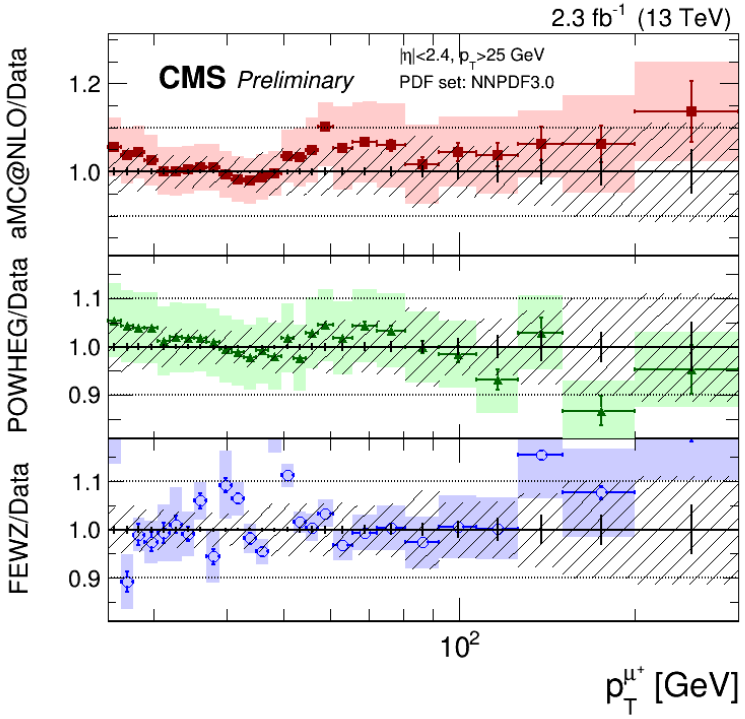


CMS-PAS-SMP-15-011

Differential cross sections

- Transverse momentum of the positively charged muon
- AMC@NLO and Powheg predictions are normalized to NLO cross section
- PDF and scale uncertainties are shown for the predictions

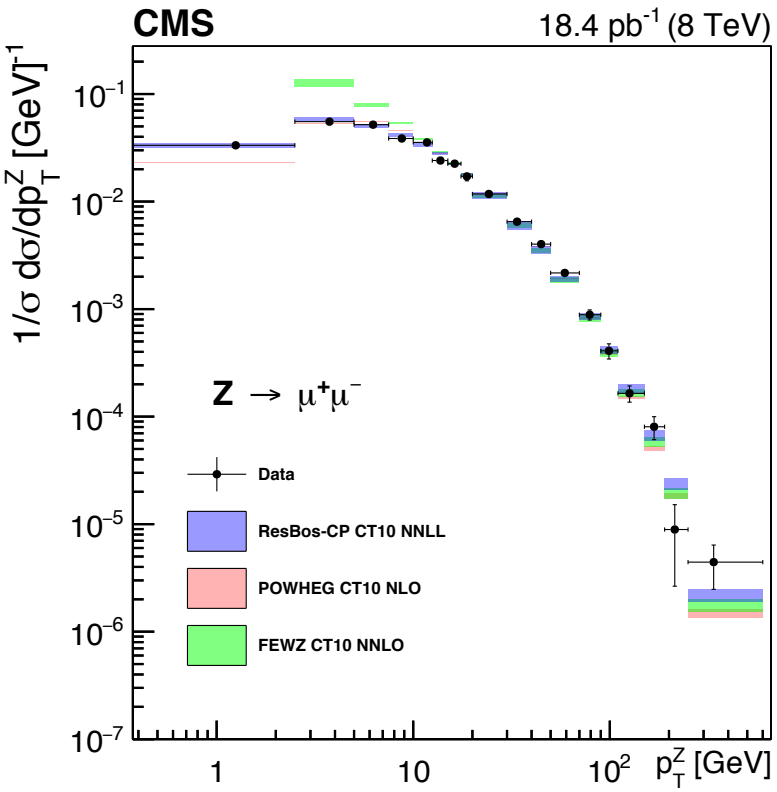


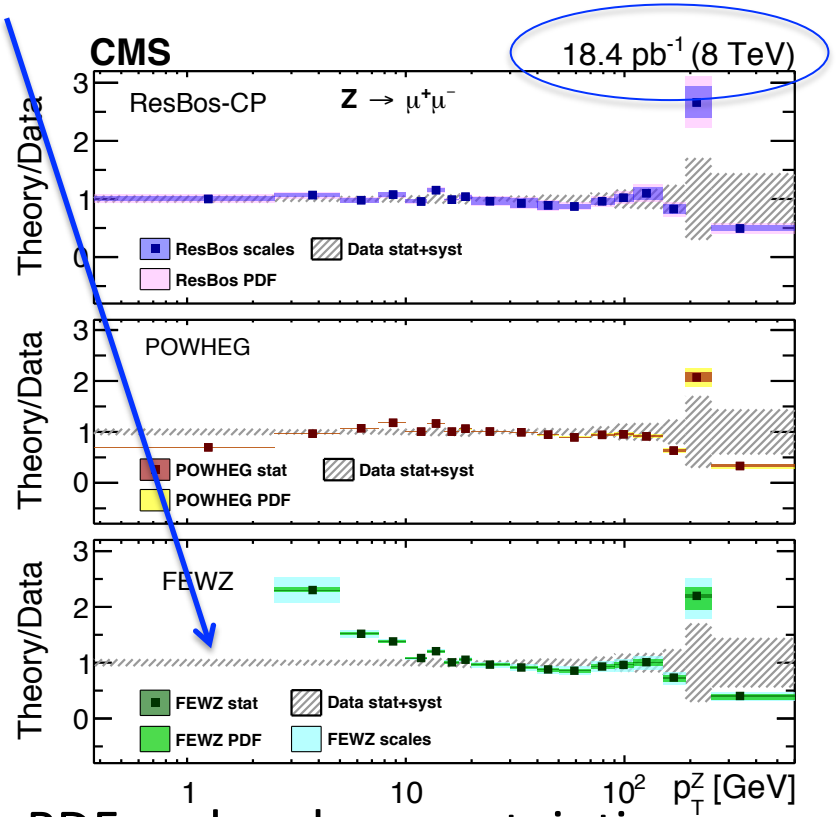


CMS-PAS-SMP-15-011

Differential cross sections at √s = 8 TeV

- Transverse momentum distribution of Z boson in di-muon channel
  - Compared to ResBos, POWHEG, and FEWZ predictions
  - FEWZ calculations are not resummed (soft gluon resummation)



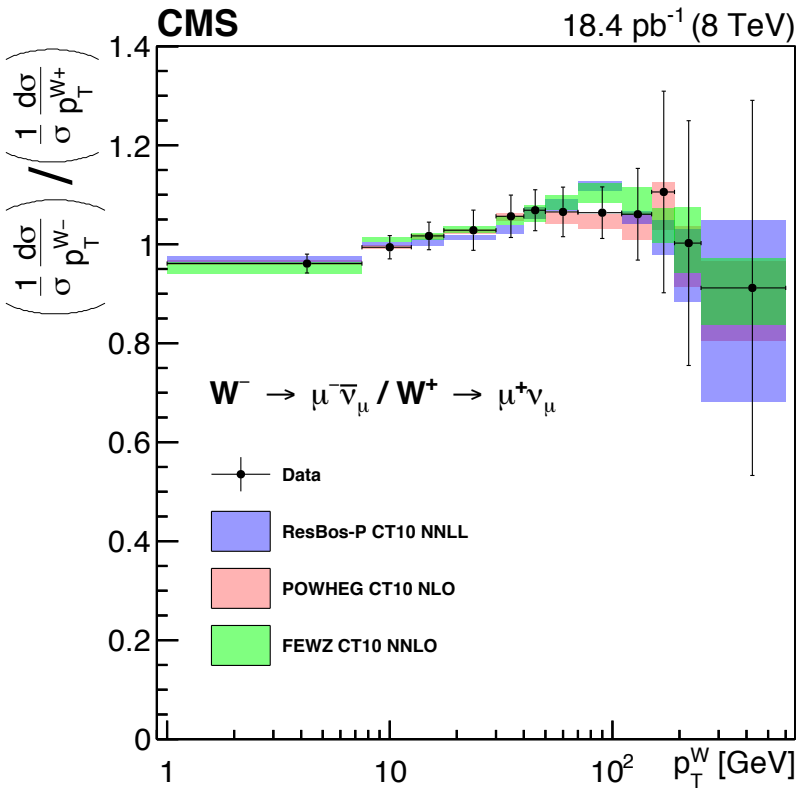


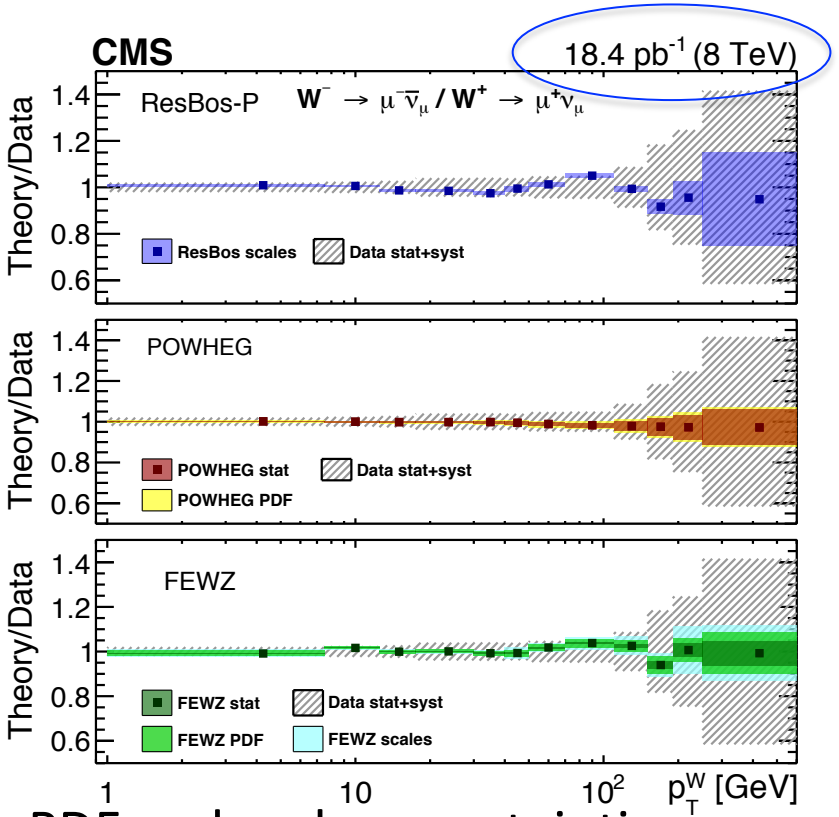
PDF and scale uncertainties

CMS-PAS-SMP-14-012

Differential ratios at √s = 8 TeV

- W^-/W^+ differential cross section ratio for muon channel
  - Compared to ResBos, POWHEG, and FEWZ predictions



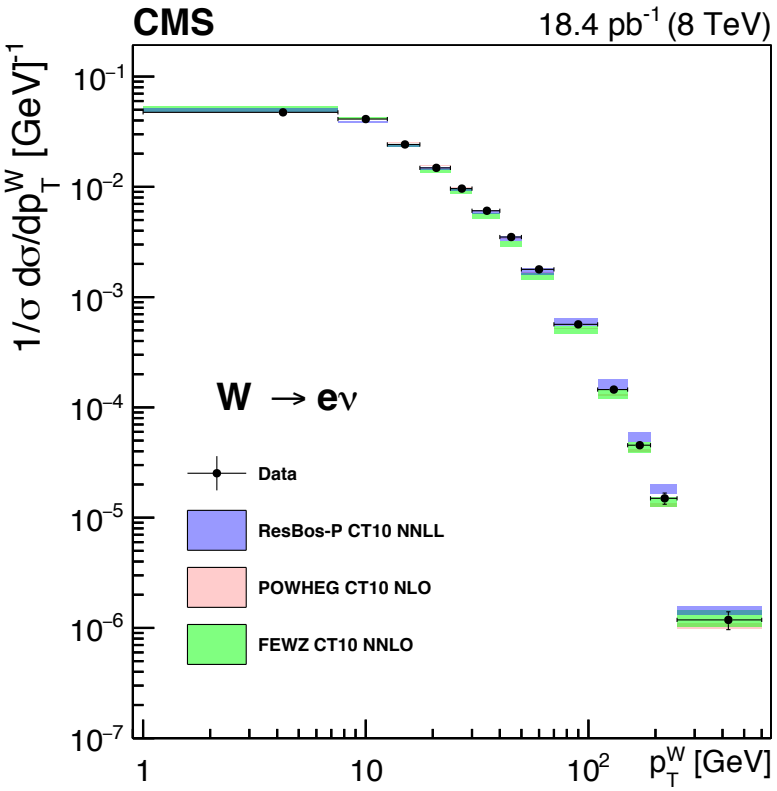


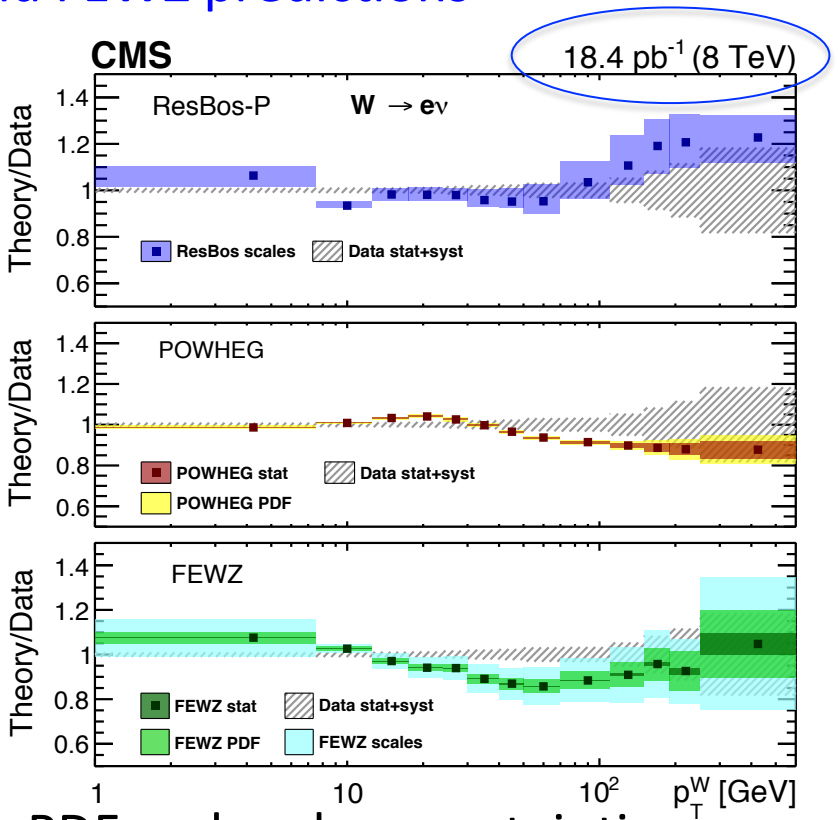
PDF and scale uncertainties

CMS-PAS-SMP-14-012

Differential cross sections at √s = 8 TeV

- Transverse momentum distribution of W boson for electron channel
  - Special low pileup run at √s = 8 TeV
  - Compared to ResBos, POWHEG, and FEWZ predictions



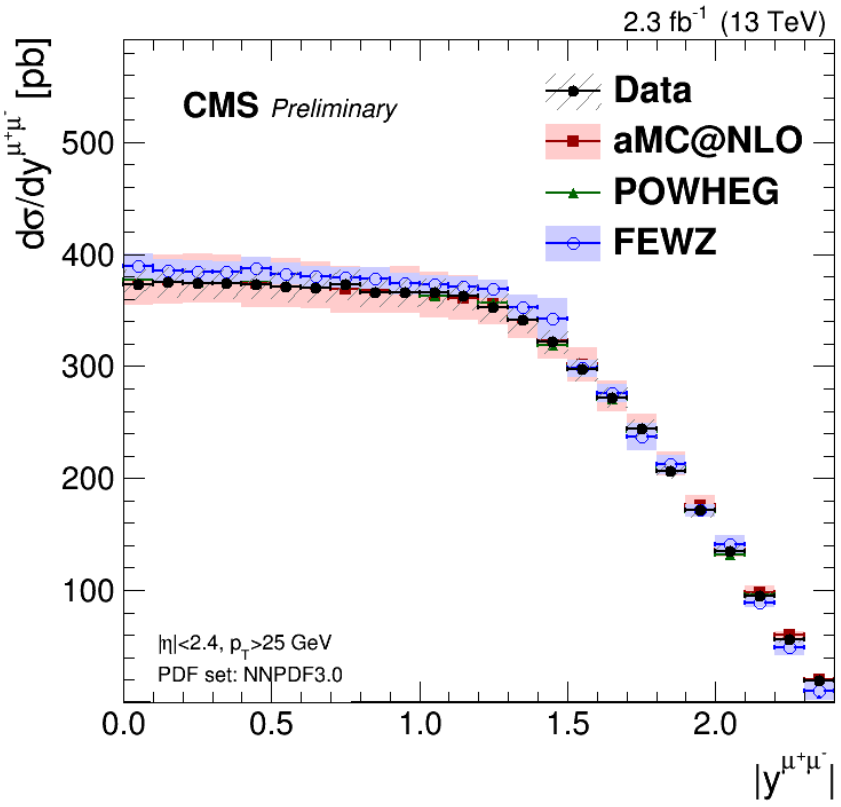


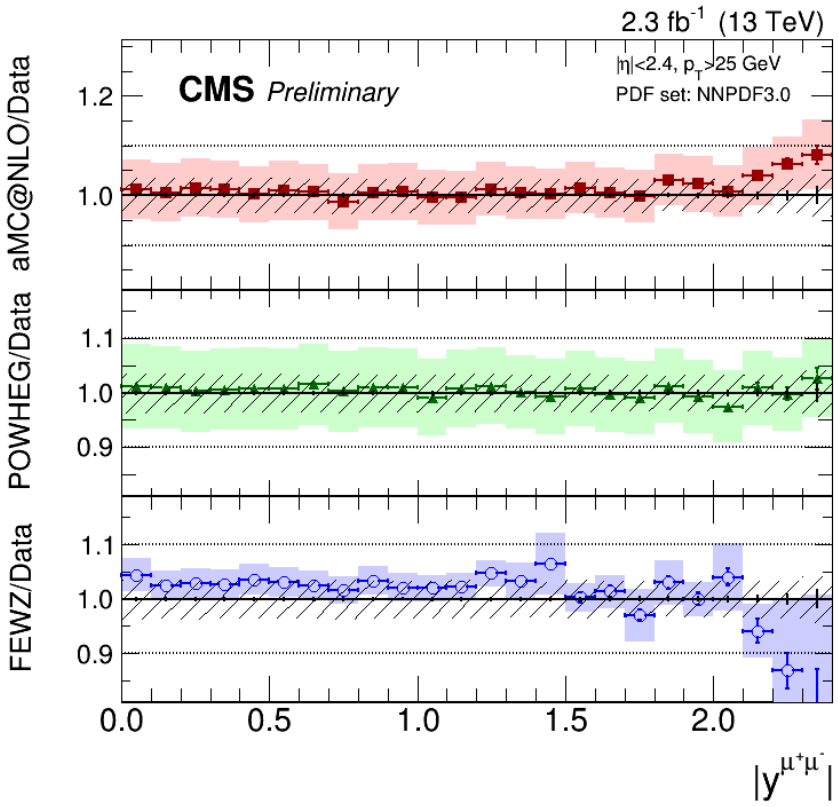
PDF and scale uncertainties

CMS-PAS-SMP-14-012

Rapidity of Z boson at √s = 13 TeV

- Rapidity distribution of Z boson

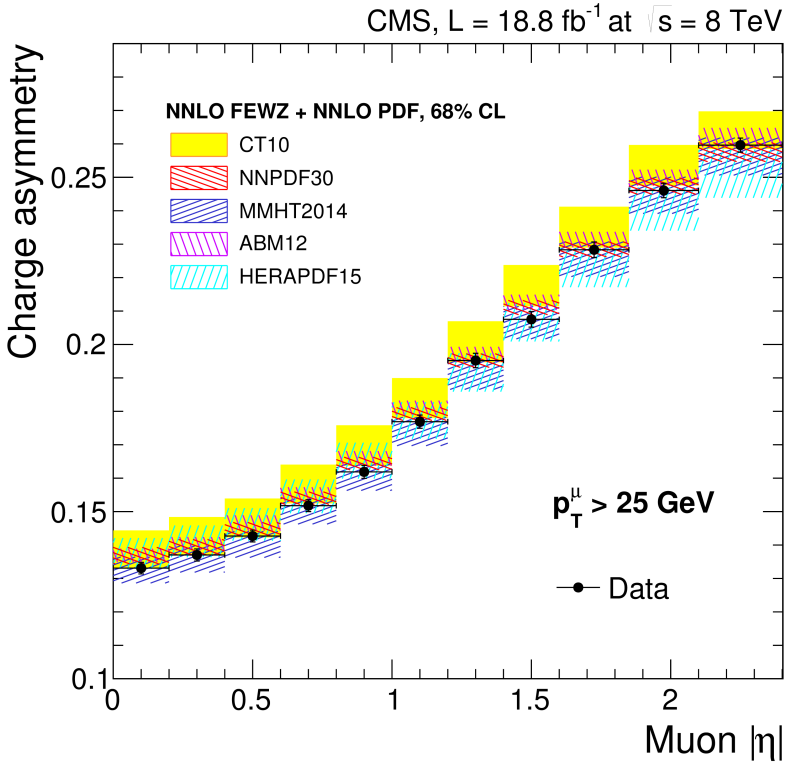


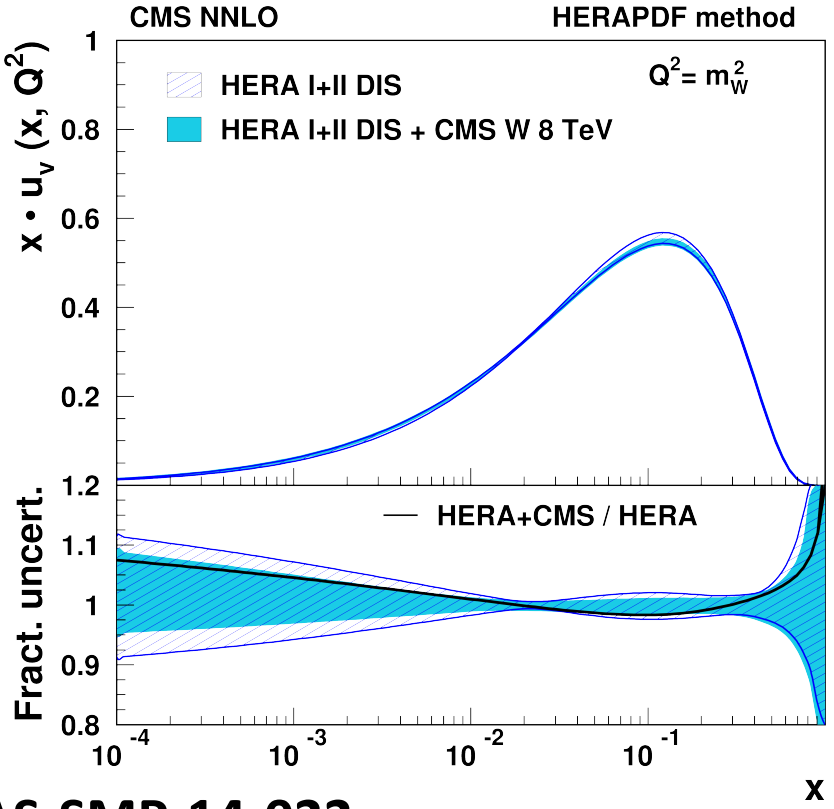


CMS-PAS-SMP-15-011

W charge asymmetry at √s = 8 TeV

- Differential cross section and muon charge asymmetry
- Constraints on the valence and sea quark distributions





CMS-PAS-SMP-14-022

Systematic uncertainties (muons)

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	1.9	1.7	1.8	0.3	2.2	0.6	0.6	0.6
Bkg. subtraction / modeling [%]	0.6	0.6	0.6	0.4	0.6	0.8	0.8	0.8
E_T^{miss} scale and resolution			shape		NA		shape	
Muon scale and resolution			shape		NA		shape	
Total experimental [%]	2.0	1.8	1.9	0.5	2.3	1.1	1.1	1.1
Theoretical Uncertainty [%]	2.0	1.7	1.3	2.3	1.5	2.0	1.9	1.6
Lumi [%]	4.8	4.8	4.8	NA	4.8	NA	NA	NA
Total [%]	5.6	5.4	5.3	2.3	5.5	2.3	2.2	1.9

- 50 ns results
- Dominated by the current luminosity uncertainty
  - Cancels in the ratios
- Experimental and theoretical uncertainties are comparable

CMS-PAS-SMP-15-004

Systematic uncertainties (muons)

Lepton reco. & id. [%]	1.3
Bkg. subtraction / modeling [%]	0.1
Total experimental [%]	1.3
PDF [%]	0.7
QCD corrections [%]	1.1
EW corrections [%]	0.4
Theoretical Uncertainty [%]	1.4
Lumi [%]	2.7
Total [%]	3.3

Total data yield	1343017 ± 1160
Background yield	7050 ± 1330
Dressed acceptance	0.372 ± 0.005
Naked acceptance	0.366 ± 0.005
Efficiency	0.85 ± 0.01

- 25ns Z->μμ results
  - Full dataset, 2.3 fb^{-1}
  - SMP-15-011
- Reduced experimental and luminosity uncertainties

CMS-PAS-SMP-15-011

Systematic uncertainties (electrons)

Source	W^+	W^-	W	W^+/W^-	Z	W^+/Z	W^-/Z	W/Z
Lepton charge, reco. & id. [%]	2.1	2.0	2.1	0.6	2.5	1.2	1.0	1.0
Bkg. subtraction / modeling [%]	1.4	1.4	1.4	0.9	0.6	1.5	1.5	1.5
E_T^{miss} scale and resolution			shape		NA		shape	
Electron scale and resolution			shape		NA		shape	
Total experimental [%]	2.5	2.5	2.5	1.1	2.6	1.9	1.8	1.8
Theoretical uncertainty [%]	1.6	1.4	1.4	1.9	1.6	1.9	1.9	1.7
Lumi [%]	4.8	4.8	4.8	NA	4.8	NA	NA	NA
Total [%]	5.6	5.6	5.6	2.1	5.7	2.7	2.6	2.5

- Dominated by the current luminosity uncertainty
  - Cancels in the ratios
- Experimental and theoretical uncertainties are comparable

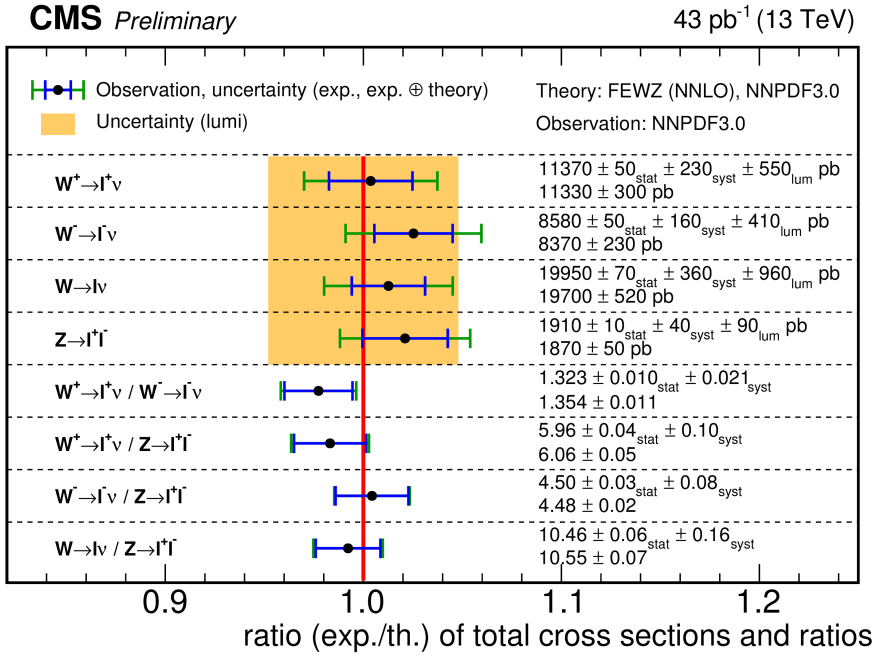
CMS-PAS-SMP-15-004

Theory uncertainties

- Higher order QCD corrections [NNLO] and resummation
  - Compare ResBos/DYRES [NNLO and NNLL] with the baseline acceptance
- PDF uncertainties
  - Uncertainties due to error PDF sets and α_s
- Missing QCD corrections beyond NNLO
  - Use FEWZ 3.1 to estimate the uncertainty by varying the factorization and renormalization scales: $\mu_R=\mu_F=\{M,2M,M/2\}$
- FSR modeling and higher order EWK corrections
  - Use Horace for FSR modeling and compare to Pythia 8 FSR modeling
  - Compare Horace with full NLO EWK corrections to Horace with just FSR correction

Total inclusive cross sections

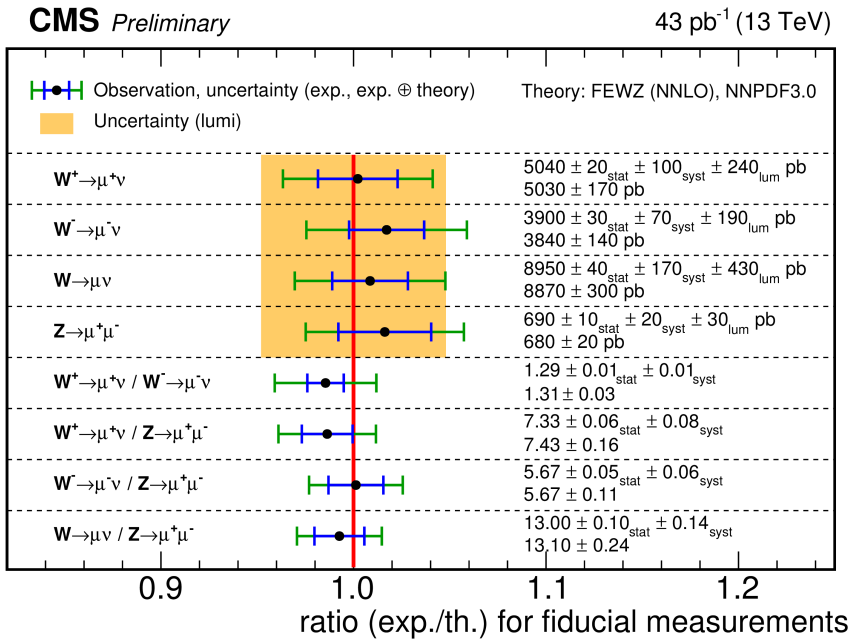
- Electron and muon results combined assuming lepton universality
- Good agreement with SM NNLO prediction
- Theoretical predictions at NNLO from FEWZ using NNPDF3.0 PDF set
  - Scale and PDF uncertainties are included
- Z->μμ update with full dataset: 1870 ± 2 (stat) ± 35 (syst) ± 51 (lumi) pb



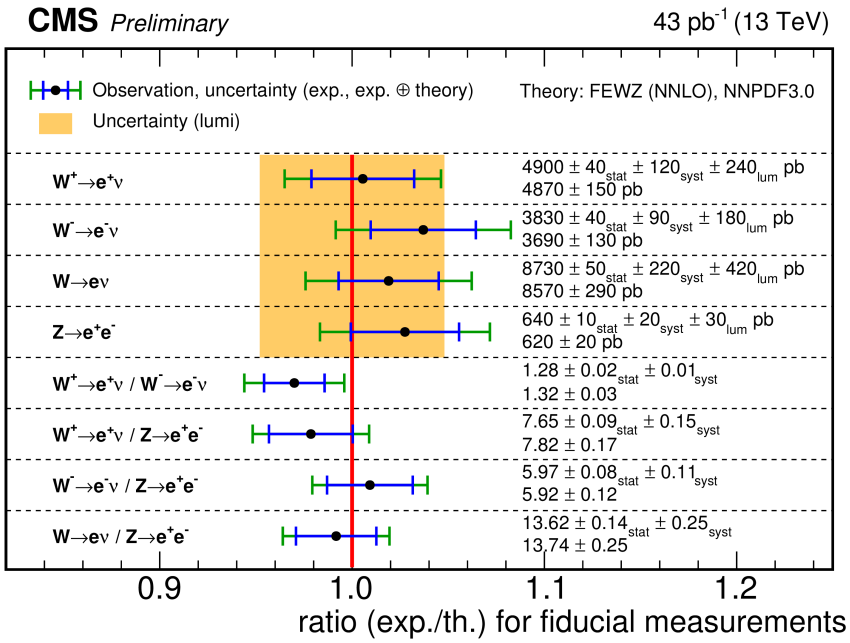
Fiducial inclusive cross sections

- No theoretical uncertainties on the measurement
- Good agreement with SM predictions

Muons



Electrons

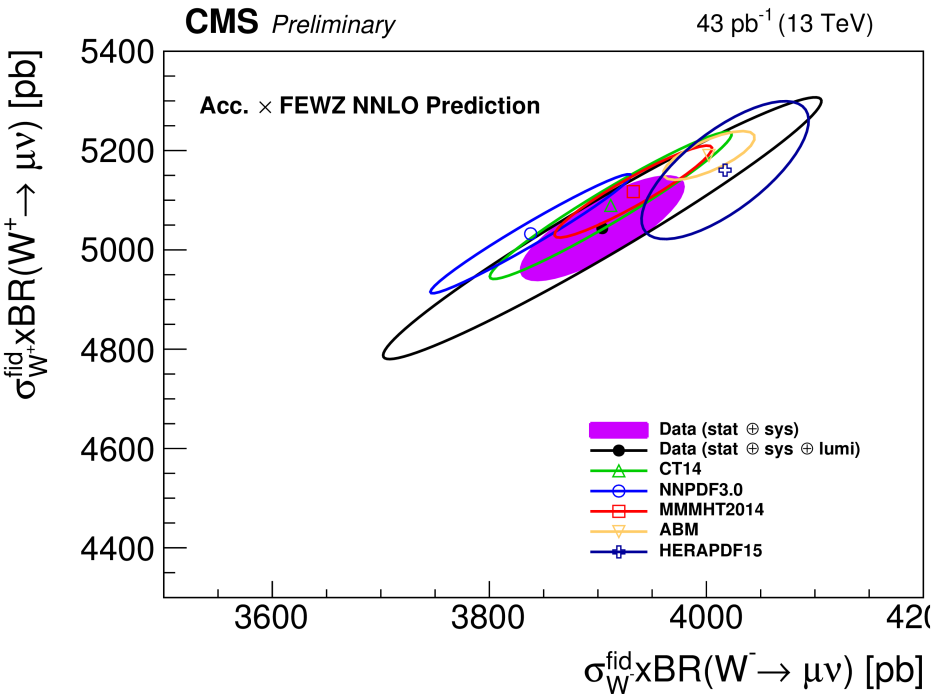


CMS-PAS-SMP-15-004

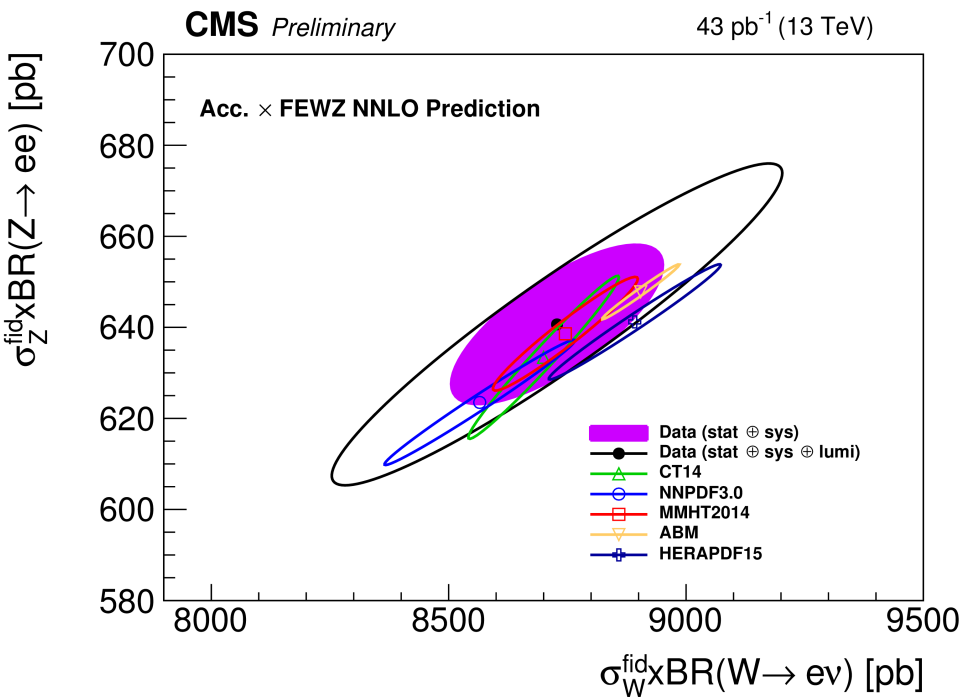
Fiducial inclusive cross sections

- Good agreement with SM predictions with different PDF predictions

Muons



Electrons



CMS-PAS-SMP-15-004

Total fiducial cross sections

- Measured fiducial cross sections:
  - Dressed: 695 ± 1 (stat) ± 9 (syst) ± 19 (lumi) ± 2 (FSR) pb
  - Naked: 684 ± 1 (stat) ± 9 (syst) ± 19 (lumi) pb
- Fiducial cross section prediction: σ x A
  - σ: inclusive total cross section from FEWZ
  - A: acceptance from AMC@NLO
  - Dressed: 695 ± 23 pb
  - Naked: 684 ± 23 pb
- FEWZ fiducial cross section
  - Dressed: 712 ± 16 (PDF) pb
  - Naked: 700 ± 16 (PDF) pb

CMS-PAS-SMP-15-011