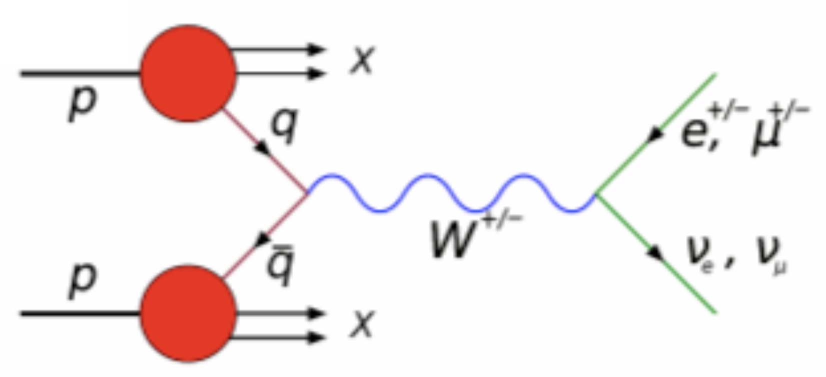
Vector boson (W, Z) Studies with CMS

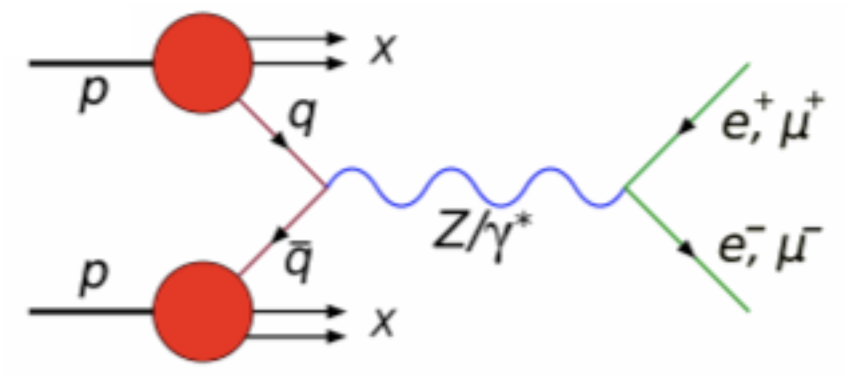
Jiyeon Han (University of Rochester)
on behalf of CMS collaboration

Apr. 13th, 2016 / DIS at DESY, Germany

Physics Motivation

- W/Z decay at LHC





$$\sigma_{pp}(Q) = \sum_{i,j} \int dx_i \int dx_j \boxed{f_i(x_i) f_j(x_j)} \boxed{\hat{\sigma}(Q/\mu, \alpha_s(\mu))}$$

- Inclusive cross section is determined by Born-cross section($\hat{\sigma}$) and PDFs
  - *It tests calculations based on higher-order perturbative QCD*
  - *It tests parton distribution functions (PDFs)*
- W/Z processes are well understood, unique signature, and have high rate
  - Good tool to calibrate the detector
  - Total cross section can be used as the luminosity candles at LHC
  - Pave the way for understanding complex final states for top or new physics

W / Z analyses at CMS

- **W or Z measurements at CMS RunII (13 TeV)**
  - Inclusive W/Z cross section — CMS-PAS-SMP-15-004
  - Differential cross section of Z boson — CMS-PAS-SMP-15-011
    - $d\sigma/dP_T$, $d\sigma/d\phi^*_\eta$, $d\sigma/dy$

- **W or Z measurements at CMS RunI (8 TeV)**
  - $d^2\sigma/dP_T dy$ of Z boson (8 TeV) — Physics Letters B 749 (2015) 187-209
  - Angular coefficients of Z boson (8 TeV) — Physics Letters B 750 (2015) 154–175
  - W charge asymmetry and $d\sigma/d\eta$ (8 TeV) — CMS-PAS-SMP-14-022, arXiv:1603.01803
  - A_{FB} of Z boson (8 TeV) — CMS-PAS-SMP-14-004, arXiv:1601.04768

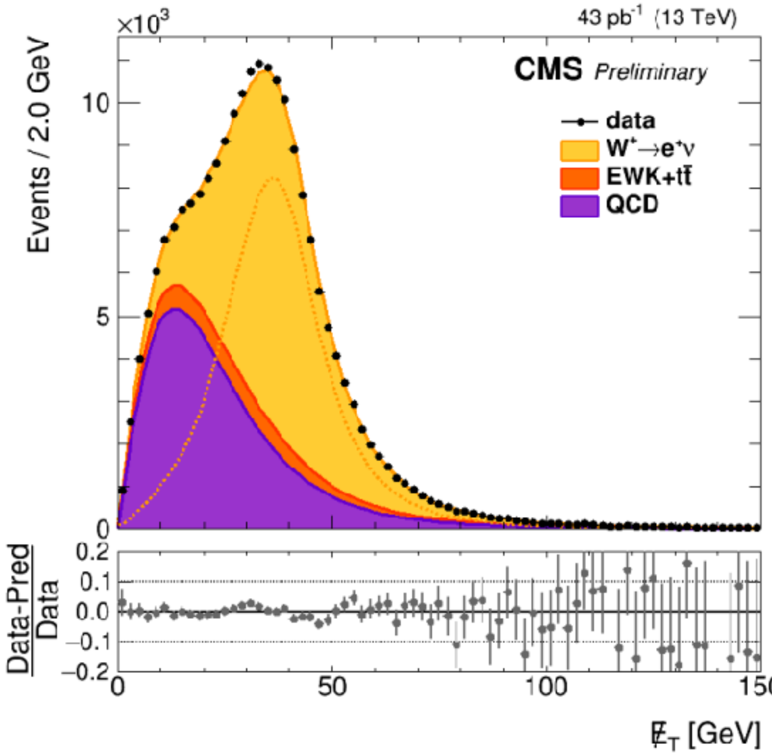
- **W-like measurement of the Z boson mass (7 TeV)** — CMS-PAS-SMP-14-007

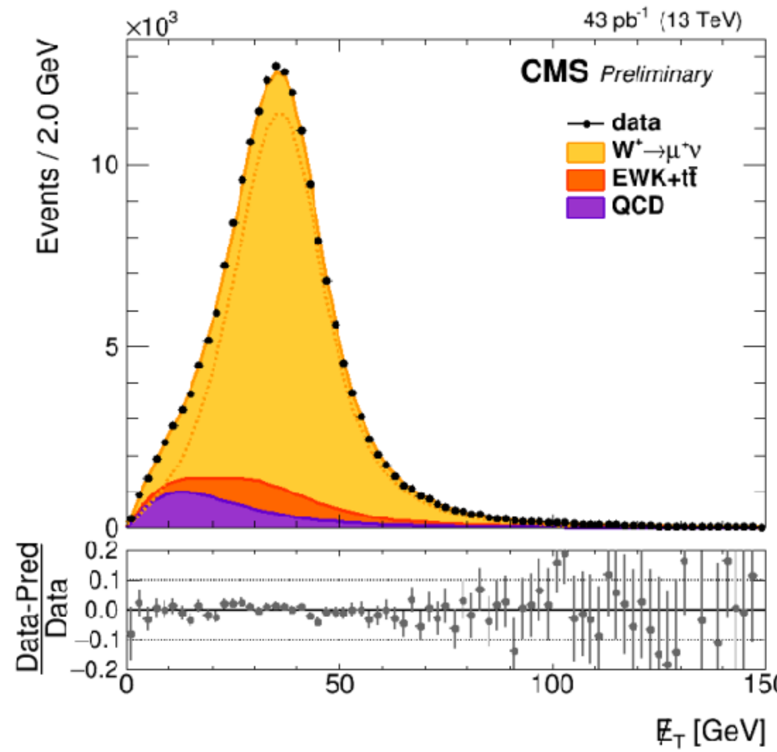
More results are available at

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Inclusive cross section of W / Z (I)

- Inclusive W/Z cross sections are measured at $\sqrt{s}$ = 13 TeV, $\int L$ = 43 pb^{-1}
  - Electron (E_T>25 GeV, |η|<2.5) and muon (p_T>25 GeV, |η|<2.4) used



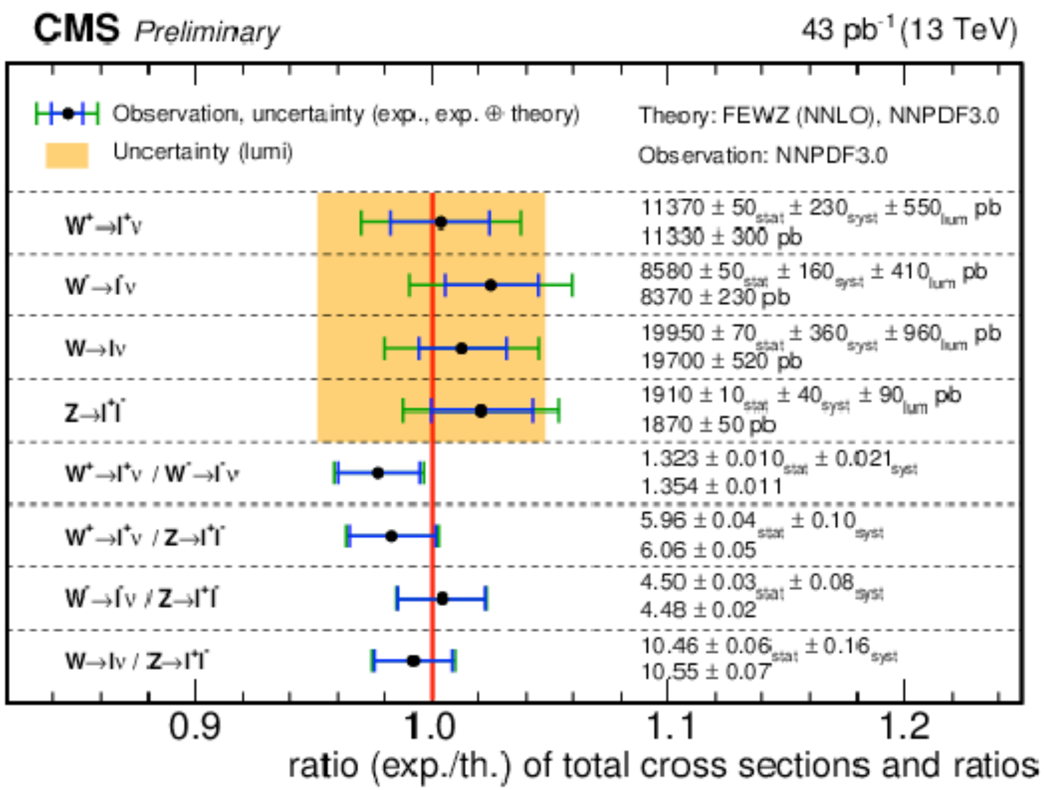


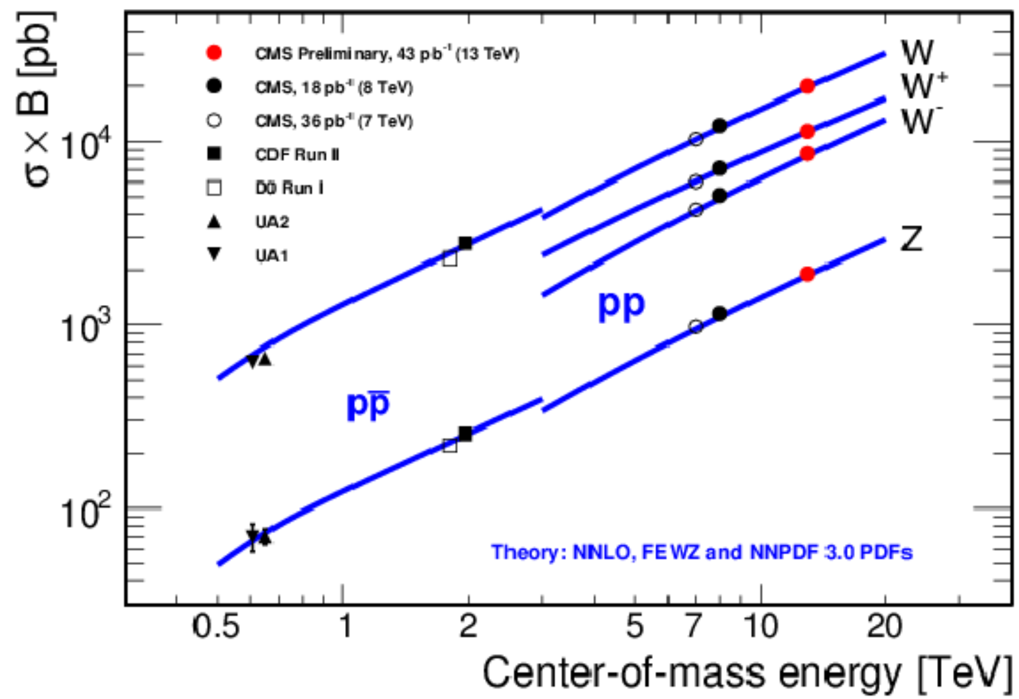
- MET fit is used for W^+ and W^- signal extraction, respectively
  - Major background is QCD
  - W→$\tau\nu$, Drell-Yan, Diboson, and top-pair production : ~10% in high MET
- Z signal extraction is estimated using counting method in 60<M(Z)<120 GeV

Inclusive cross section of W / Z (II)

- Inclusive cross section of W and Z and its ratio : acceptance is fully corrected

$$\sigma \times \mathcal{B} = N/(A \times \varepsilon \times \mathcal{L})$$

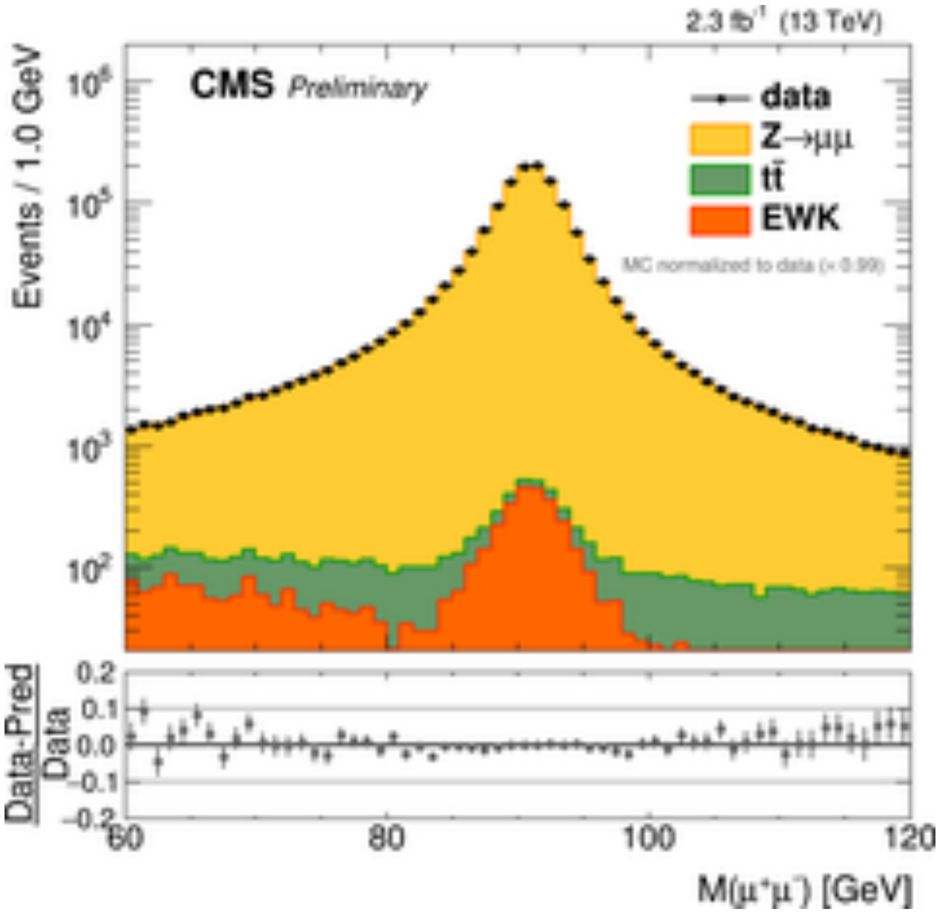




- Systematic uncertainty is ~2.5% for electron and ~2.0% for muon channel
  - 4.8% luminosity and up to 2% theoretical uncertainties are excluded
- Total cross sections are in a good agreement with FEWZ(NNLO) predictions

Z boson cross section at 13 TeV

- Differential cross sections are measured using $\int L$ = 2.3 fb^{-1} data at $\sqrt{s}$ = 13 TeV
  - Muon channel is used with $p_T(\mu)$>25 GeV and $|\eta|$<2.4
  - Events are selected in 60 < $M(\mu\mu)$ < 120 GeV : ~ 1.3M events
  - *The differential cross section is measured for Z boson P_T, φ^*_η, and y*
    - The differential cross section is *unfolded inside the fiducial volume*



Z mass comparison b/w data and MC :

muon p_T correction in data and MC

efficiency scale factor applied in MC

Background determined by MC

MC is normalized to data

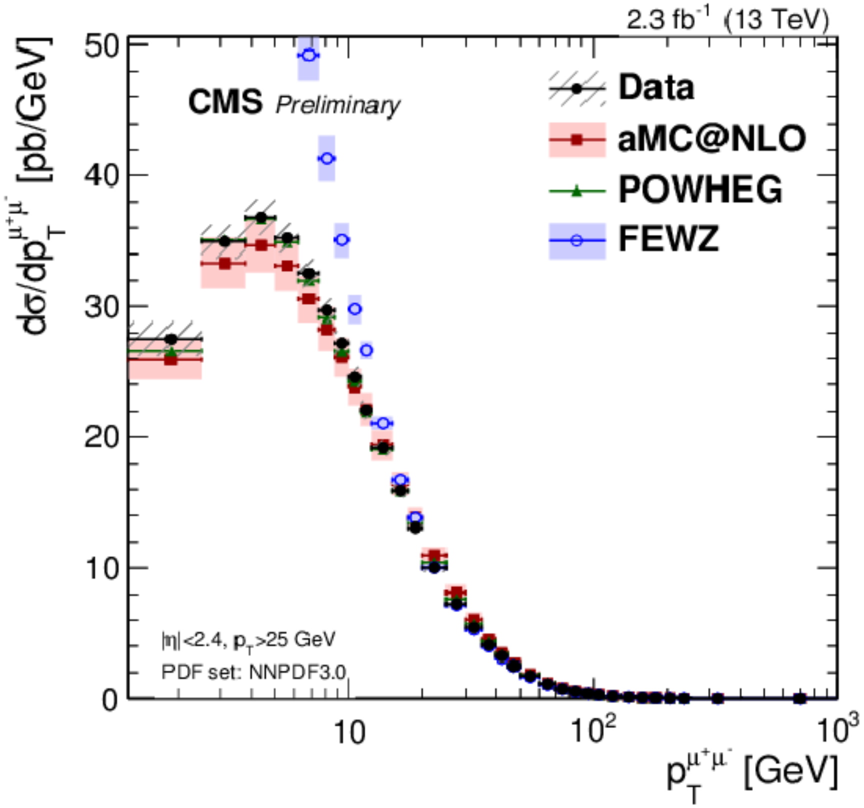
Measured inclusive σ in 60<M<120 GeV :

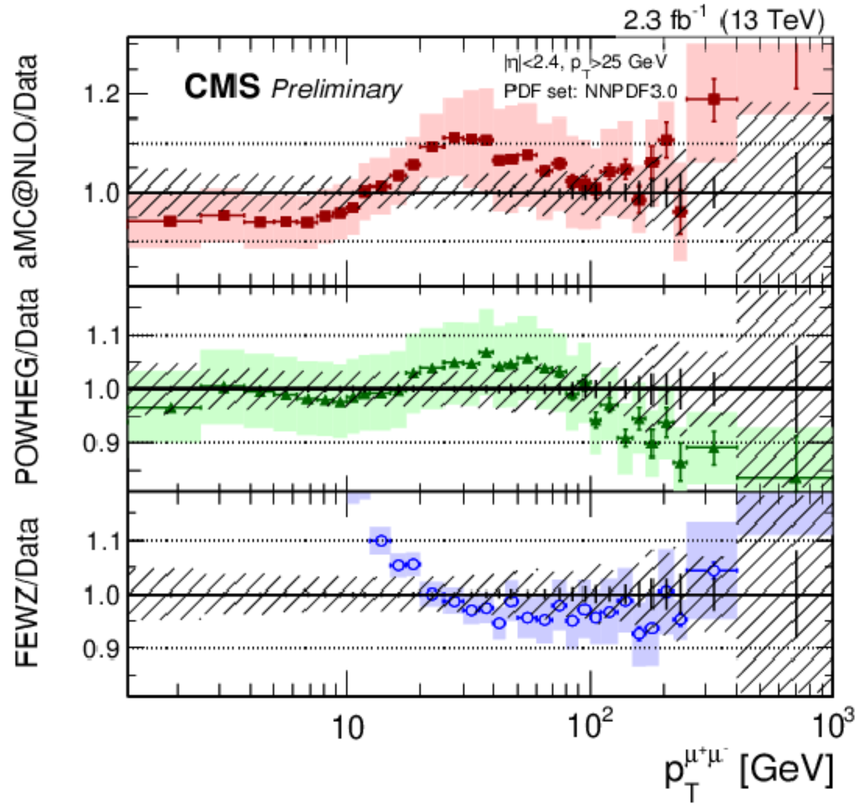
$$\sigma(pp \to ZX) \times B(Z \to \mu^+\mu^-) =$$
$$1870 \pm 2(stat) \pm 35(syst) \pm 51(lumi)pb$$

FEWZ(NNLO,NNPDF3.0) = 1870 ± 50 pb

$d\sigma / dP_T$

- Differential cross section of Z boson P_T
  - Test the soft-gluon *resummation or parton shower models in low P_T*
  - Test *perturbative QCD calculation in high P_T* where qg scattering is dominant





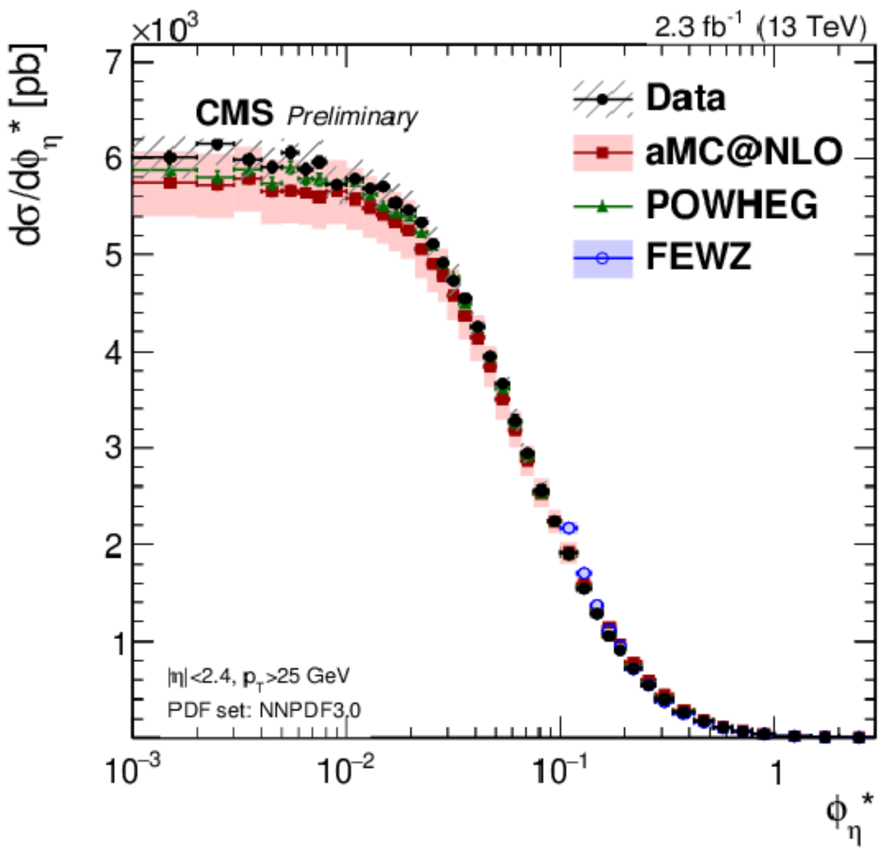
normalized to σ(NLO)

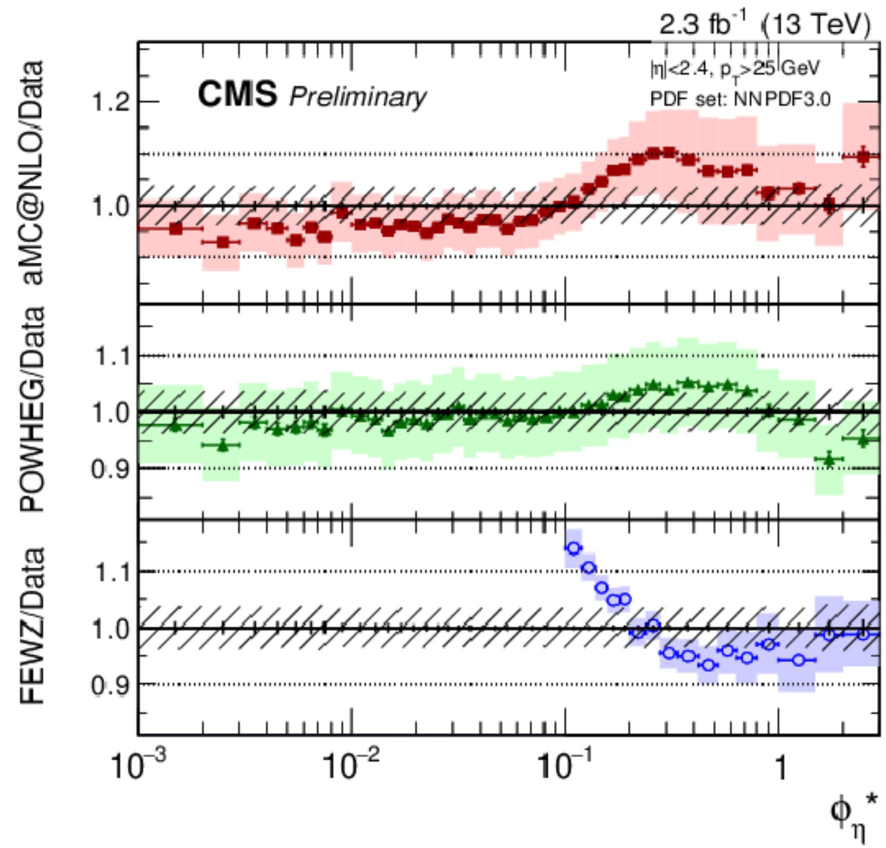
normalized to FEWZ σ(NNLO)

- FEWZ(NNLO) gives a good agreement in P_T>25 GeV
  - Deviation in low P_T is expected due to the absence of resummation
- MadGraph5_aMC@NLO and POWHEG(NLO) show a small deviations in P_T
  - Mostly covered by the theory uncertainties

$d\sigma / d\phi^*_\eta$

- ϕ^*_η probes Z boson P_T, but depends on μ's direction→ *smaller exp. error*
  - Define $\phi^*_\eta = \tan(\frac{\pi - \Delta\phi}{2}) \cdot \sin(\theta^*_\eta)$ where $\cos(\theta^*_\eta) = \tanh(\frac{\eta^- - \eta^+}{2})$

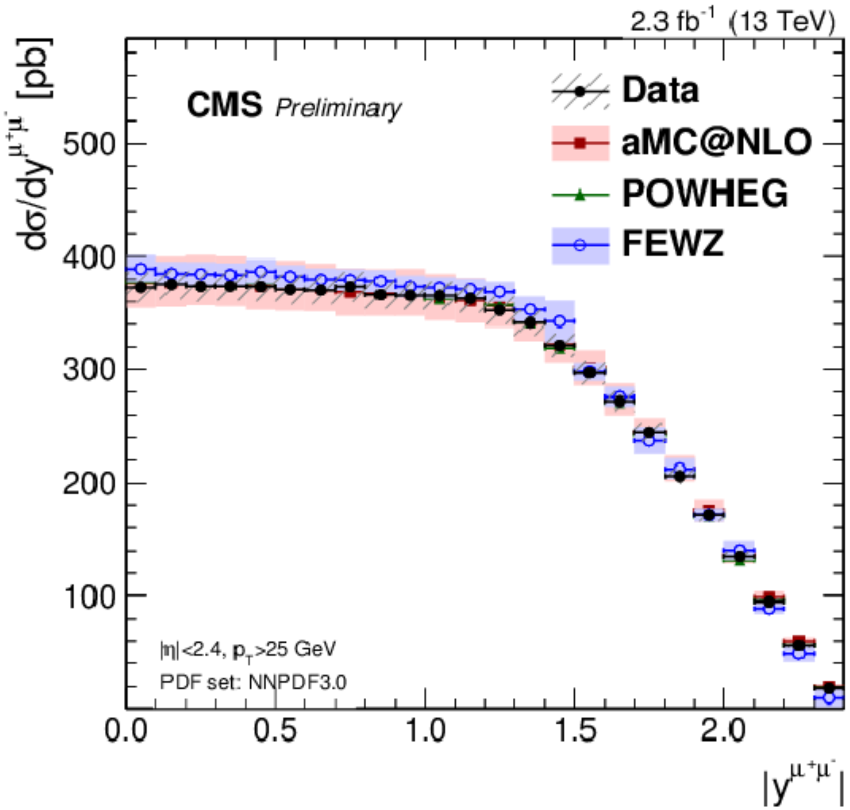


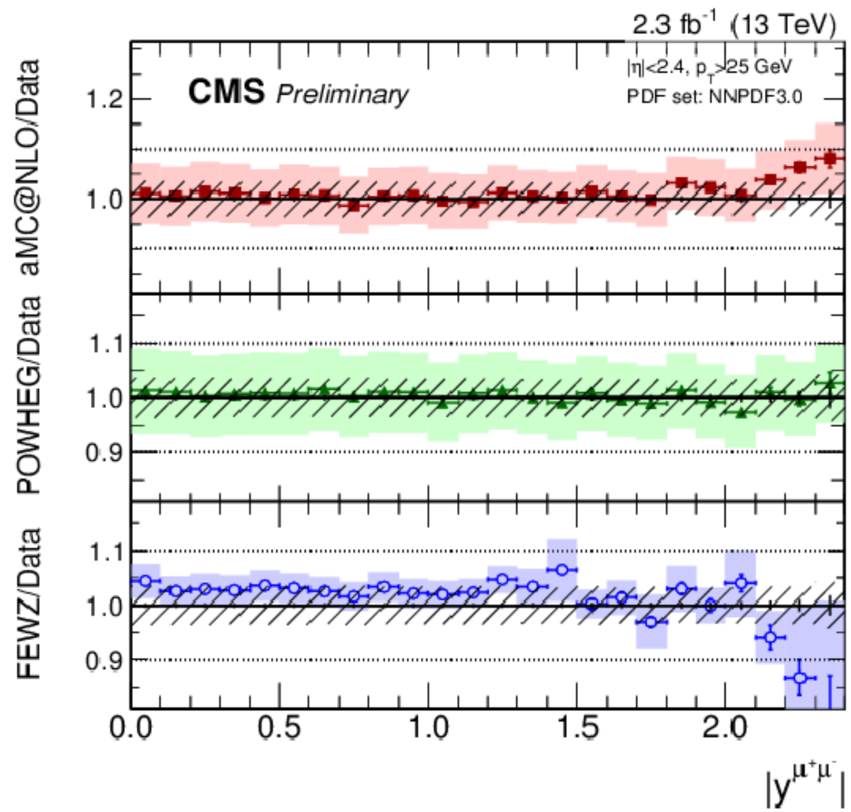


- POWHEG shows a good agreement in very low ϕ^*_η region
- FEWZ describes data well where phase-space is probed

$d\sigma / dy$

- Rapidity distribution of Z boson is used as *a good input for PDF global fit*
  - Rapidity is measured up to |y|=2.4 : high y probes lower or higher x region





  - Rapidity spectrum is well described by theory predictions up to |y|=2.0

$d^2\sigma / dP_T dy$ of Z boson at 8 TeV

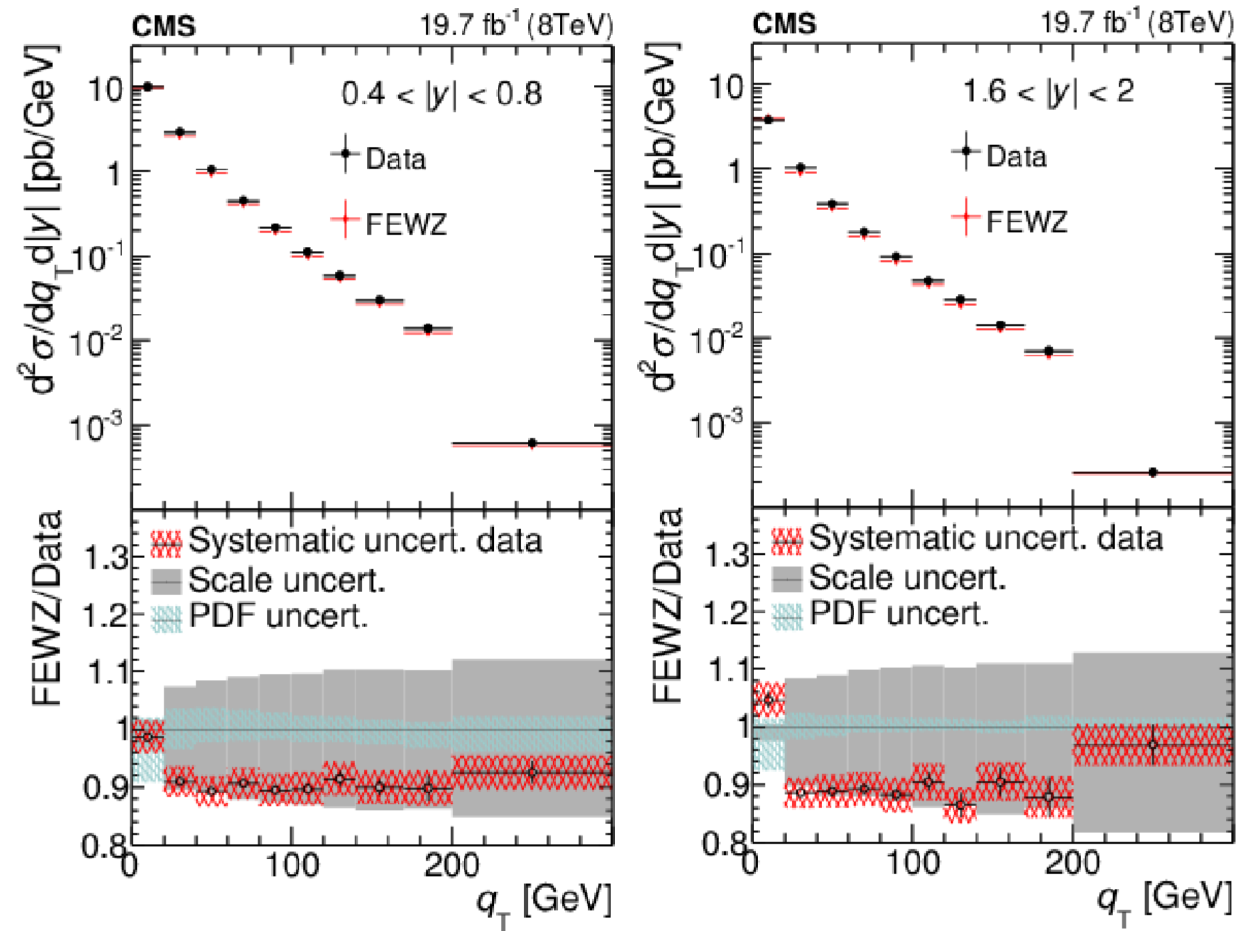
- Double differential cross section in P_T and y of Z boson at √s = 8 TeV
  - It is measured using ∫L = 19.7 fb^{-1} in muon channel
  - Leading (sub-leading) p_T muon with p_T>25(10) GeV, |η|<2.1(2.4)
  - Invariant mass 81<M(μμ)<101 GeV is required
  - *Double differential σ is unfolded to pre-FSR in lepton kinematics*
  - $d^2\sigma/dP_T dy$ and $(1/\sigma_{inc})\, d^2\sigma/dP_T dy$ are measured

PLB 749 (2015) 187-209

Measurement is compared with NNLO FEWZ (NNPDF23PDF)

FEWZ predicts the shape correctly within scale error (6~12%) in p_T>20 GeV

The absolute $d^2\sigma/dP_T dy$ in FEWZ also agrees within errors with the measurement



Angular coefficients of Z boson

- Differential cross section of $\cos\theta^*$ and ϕ^*

$$\frac{d\sigma}{dP_T^2\,dy\,d\cos\theta\,d\phi} \propto \boxed{(1+\cos^2\theta)} \longrightarrow \boxed{\textit{LO term}}$$

$$+\ \frac{1}{2}A_0(1-3\cos^2\theta) \longrightarrow \textit{$\cos^2\theta$: higher order term}$$

$$+\ A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \longrightarrow \textit{(θ, ϕ) terms}$$

$$+\ \boxed{A_4\cos\theta} \longrightarrow \boxed{\textit{LO term : determine A_{fb}}}$$

$$+\ \boxed{A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi} \longrightarrow \boxed{\textit{very small terms}}$$

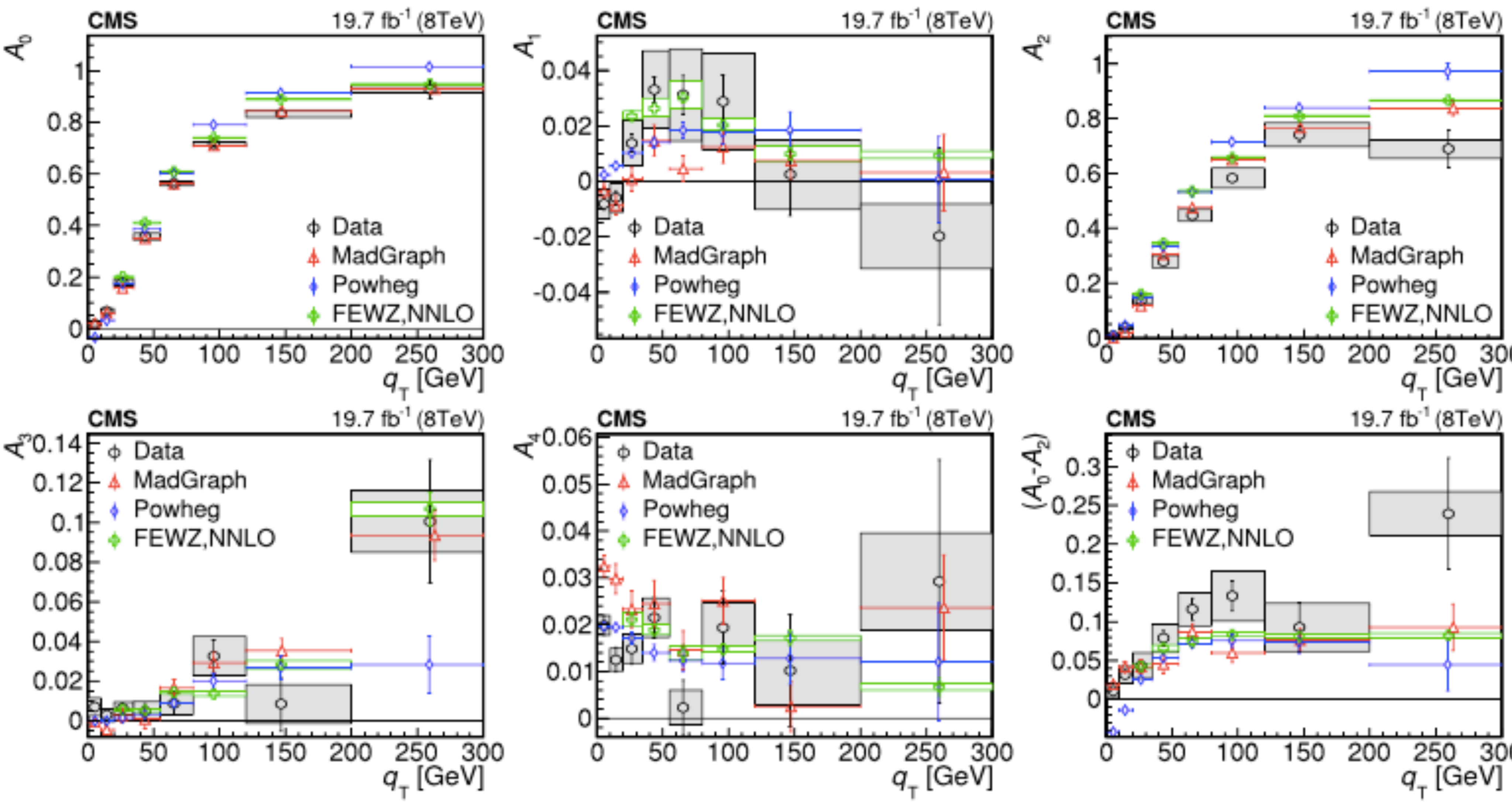
- pQCD makes definite predictions for angular coefficients
  - $A_{0,1,2}$ are related to the polarization of Z boson

    → *$A_{0,2}$ determine the fraction of qqbar and qg process*
  - $A_{3,4}$ originate from γ^*/Z interference
  - *A_4 has a direct relation with A_{FB} which is sensitive to $\sin^2\vartheta_W$*
- $A_{0,1,2,3,4}$ are measured using the template fitting method in Collin-Soper frame
  - Angular coefficients are measured as a function of Z boson P_T and $|y|$

Angular coefficients in P_T for $|y|<1$

- Angular coefficients as a function of P_T for $|y|<1$

PLB 750 (2015) 154–175



- MadGraph and FEWZ describes most of measurements well except A_4
- MadGraph has higher A_4 due to $\sin^2\theta_W$ setting (no radiative correction)

Angular coefficients in P_T for $1<|y|<2.1$

- Angular coefficients as a function of P_T for $1<|y|<2.1$

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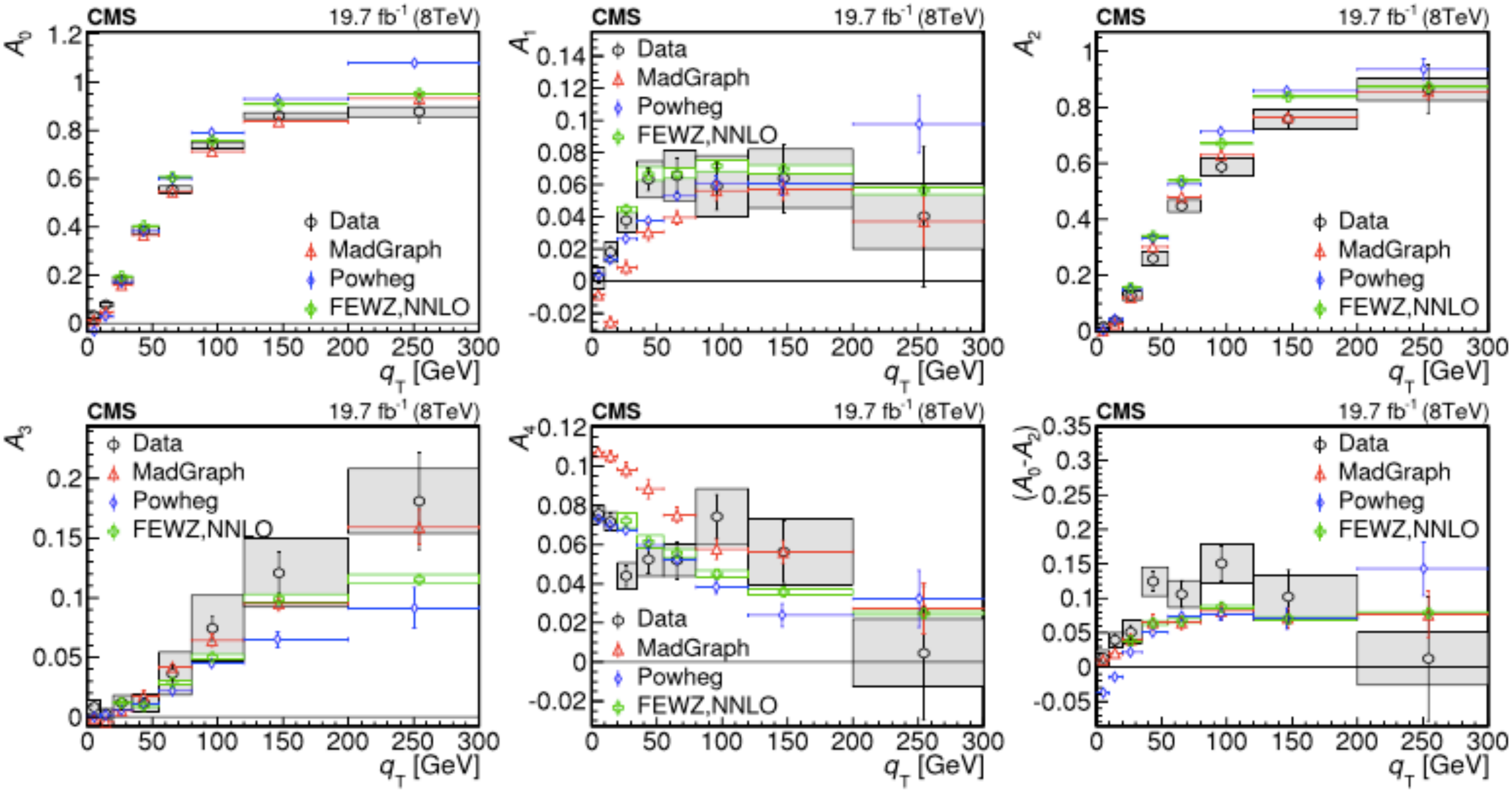


- A_4 has a large y dependence due to the dilution effect
- A_1 and A_3 also shows y dependence

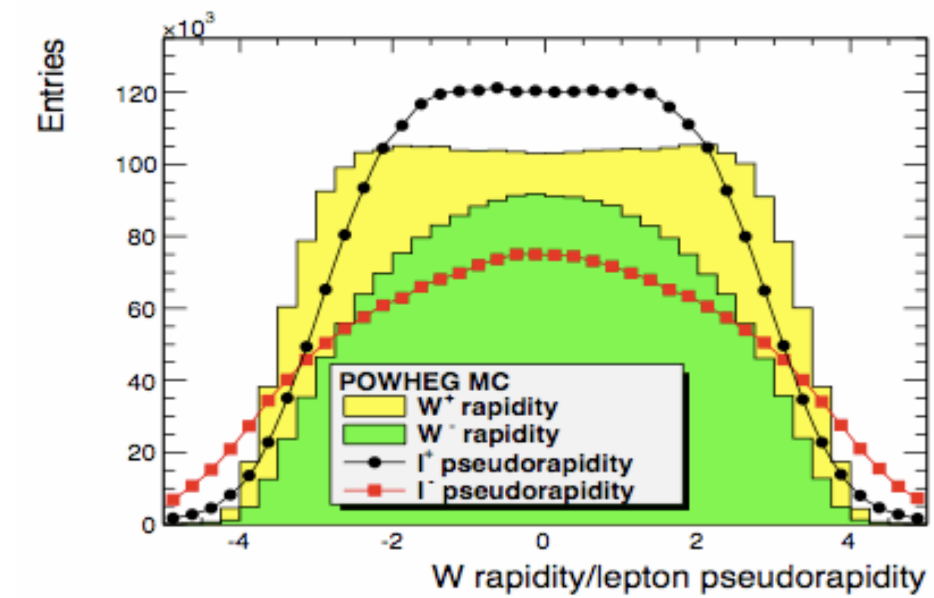
W⁺ and W⁻ asymmetry

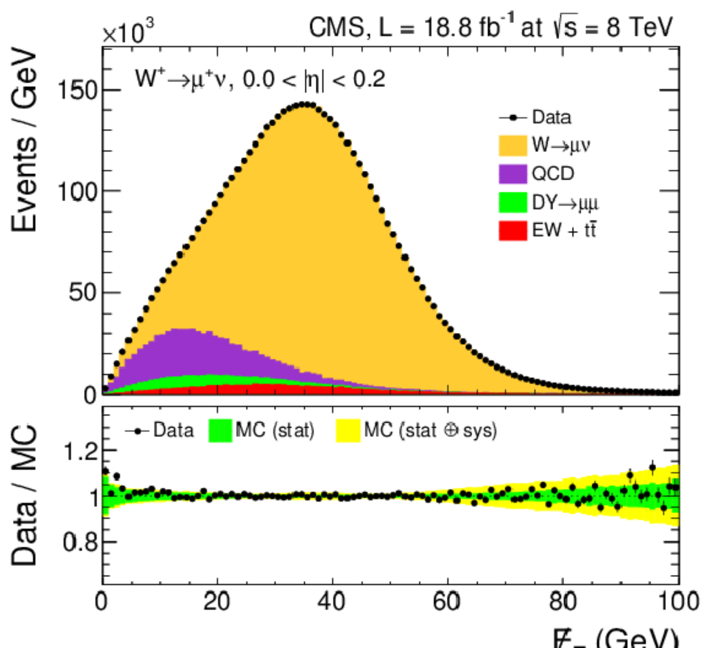
- W^+ is more produced than W^- in pp collision because proton consists of uud
- W production is polarized due to *parity violation at production*

  → *There is a strong asymmetry in the lepton decay*
- The lepton charge asymmetry of W

$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

- Constrains for PDFs :
  - *A(η) constrains for u/d quark*
  - Particularly on *sea quark* at LHC





- $d\sigma/d\eta(W^+$ or $W^-)$ and $A(\eta)$ in fiducial region
  - $\int L = 18.8\ fb^{-1}$ data at $\sqrt{s} = 8$ TeV used
  - Fiducial region : *$p_T(\mu)>25$ GeV and $|\eta|<2.4$*
  - Signal is extracted for W^+ or W^-, respectively
    - MET fit is used to extract the signal events
    - ~61M events for W^+ and ~45M events for W^-

dσ / dy for W+ and W-

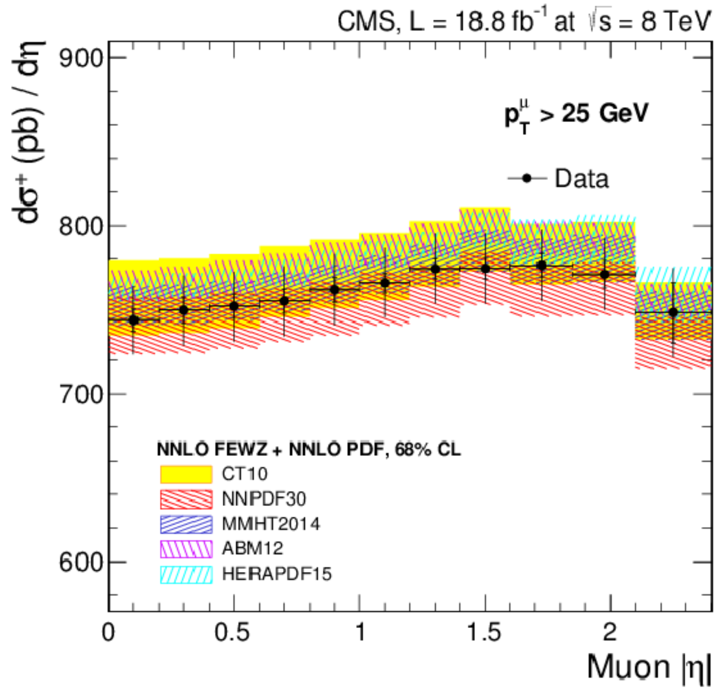
- dσ/dη for W^+, W^-

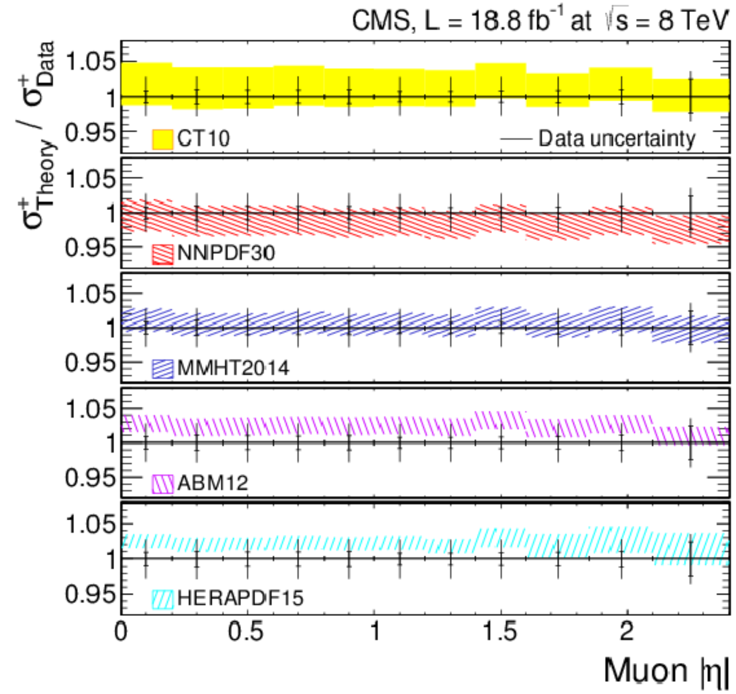
$$\sigma_\eta^\pm = \frac{1}{2\Delta\eta}\frac{N^\pm}{\epsilon^\pm \epsilon^\pm_{FSR}\mathcal{L}_{int}}$$

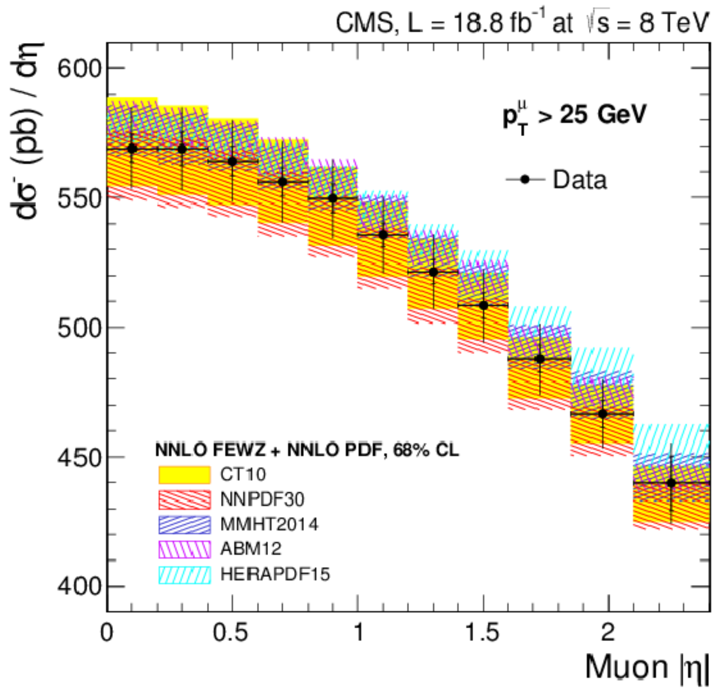
FEWZ (NNLO) with various PDFs are compared with measurement
No EWK correction is included in predictions

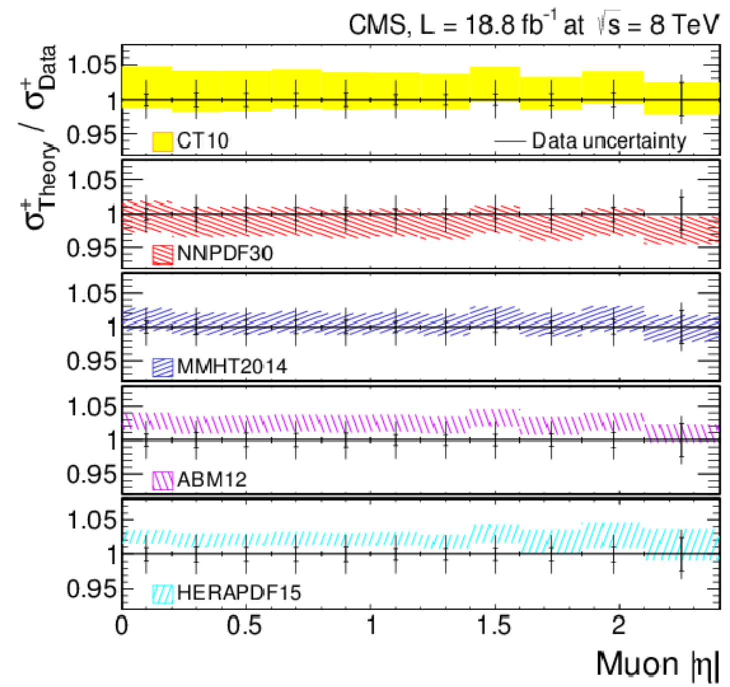
Full error bars include luminosity error (2.6%)
Otherwise, error is within 0.5 ~ 1.0% level

Measured dσ/dη are well described by all PDFs within the uncertainties







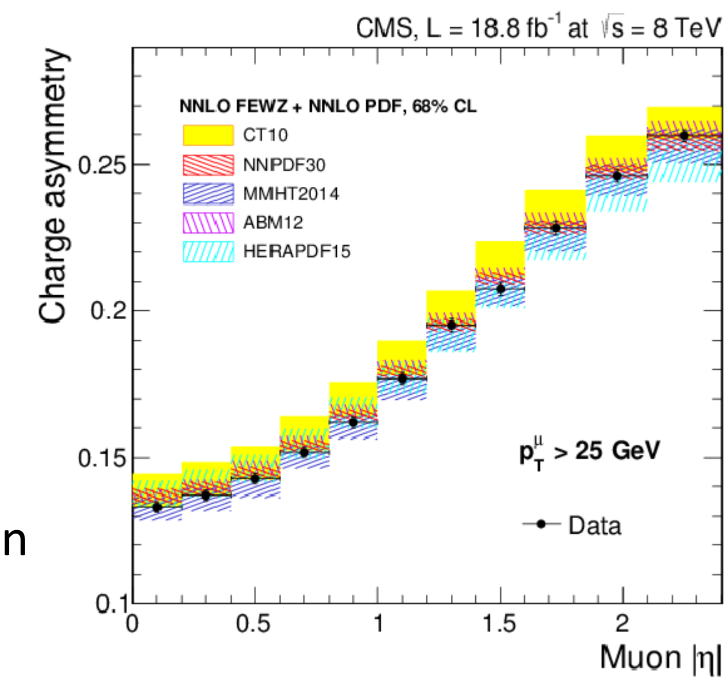


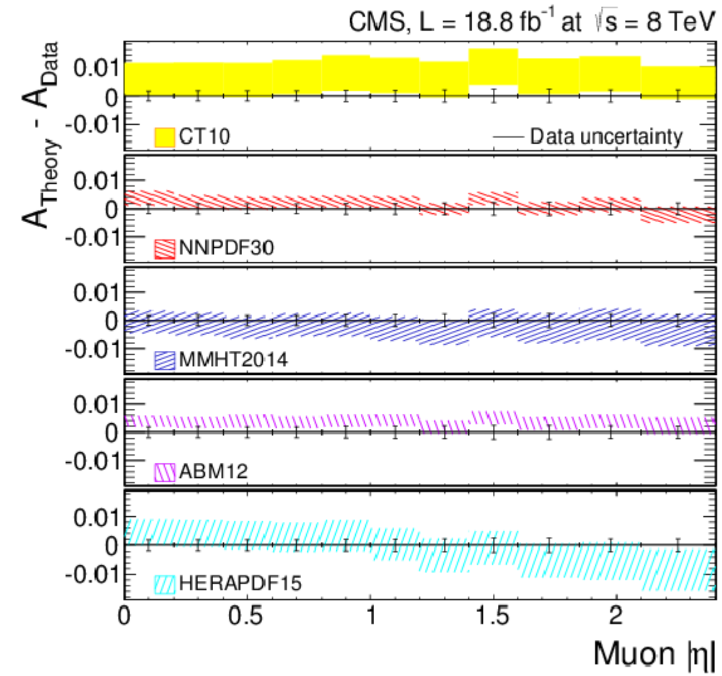
W charge asymmetry : A(η)

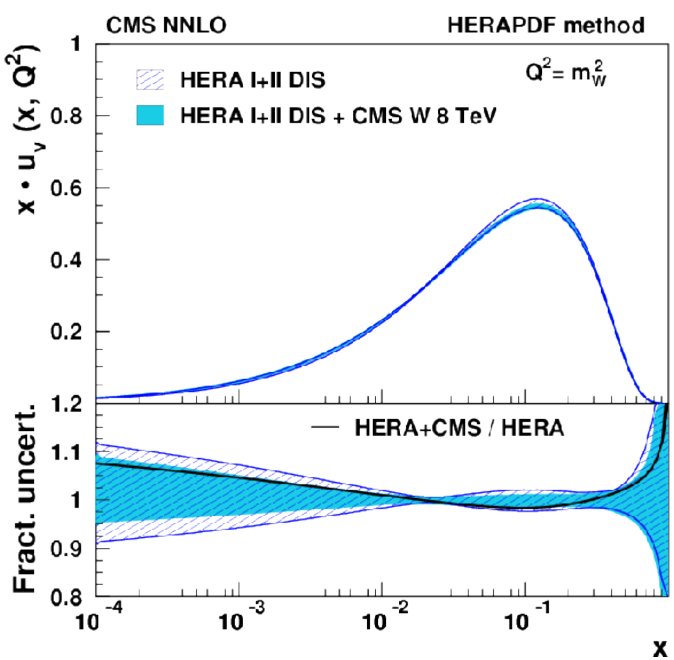
- A(η) in $p_T(\mu)>25$ GeV

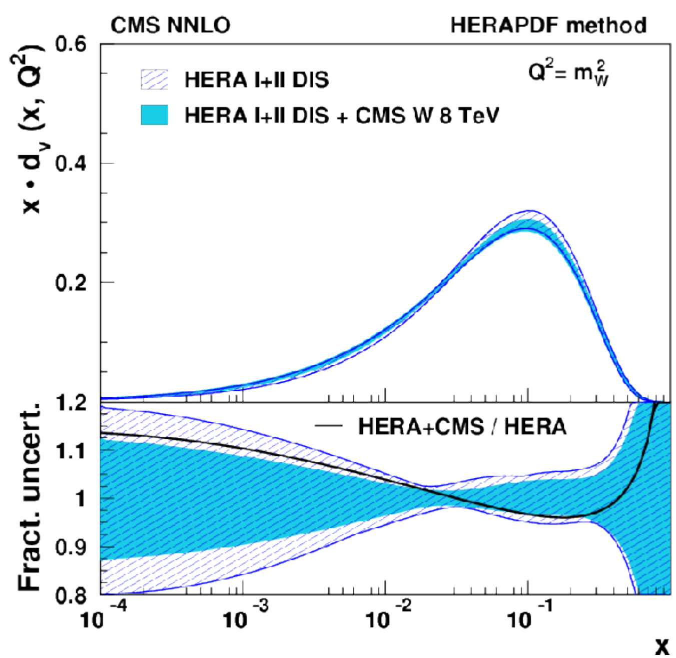
$$A(\eta) = \frac{\sigma_\eta^+ - \sigma_\eta^-}{\sigma_\eta^+ + \sigma_\eta^-}$$

Charge asymmetry is extracted by σ^+_η and σ^-_η considering the correlation









QCD analysis at NNLO : Test the impact of CMS A(η) data combining DIS data at HERA

Adding CMS A(η) significantly improves the constrains on the valence distribution

Forward-backward asymmetry of Z boson

- A_{FB} depends on Z boson mass, quark flavor, and the weak mixing angle θ_W

A_{FB} is measured by

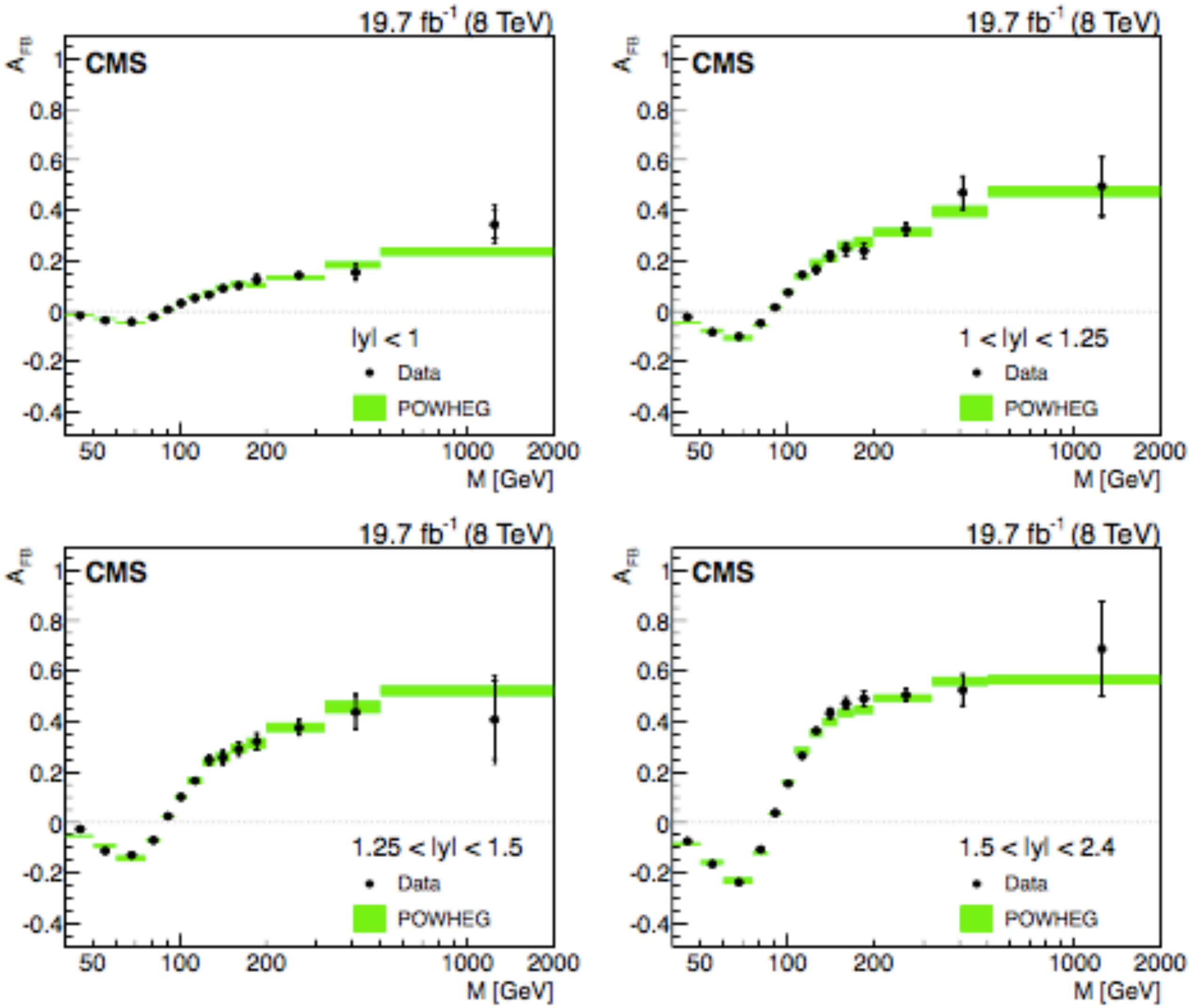
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

A_{FB} is unfolded for resolution, Acceptance x Efficiencies, and FSR effect

→ combined unfolded A_{FB} for μμ and ee up to |y|<2.4

The quark direction is not corrected, so dilution effect is large in low |y| region

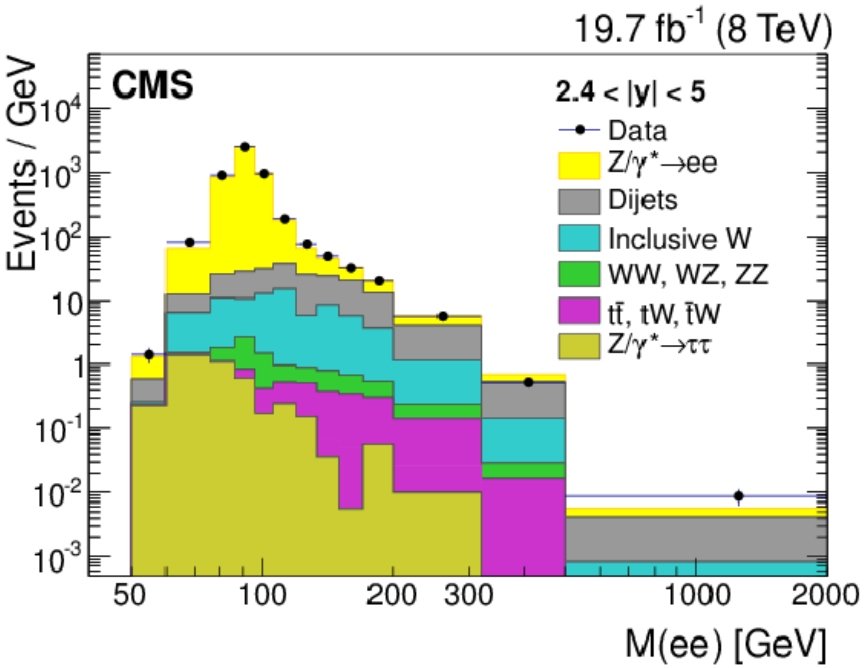
(assumed quark direction is same with the rapidity direction)



- POWHEG with $\sin^2\theta_W = 0.2312$ shows a good agreement with measurements

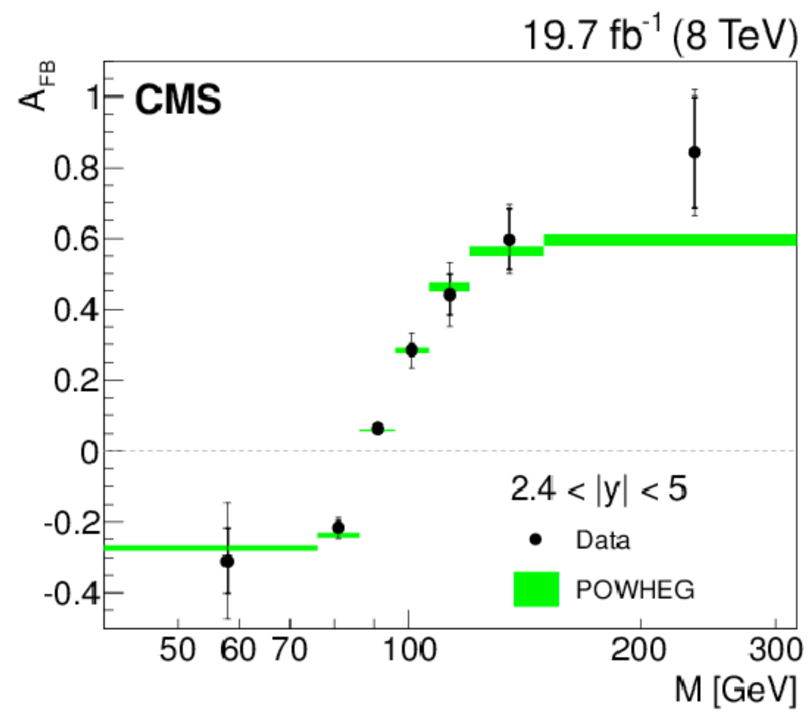
A_{FB} in forward region

- A_{FB} is extended up to |y|=5 by adding HF electron (3<|η|<5)



One central electron (p_T>30 GeV, |η|<2.4) and one forward electron (p_T>20 GeV, 3<|η|<5) are required

Dijet background is determined by data-driven method (fitting method), otherwise estimated by simulations

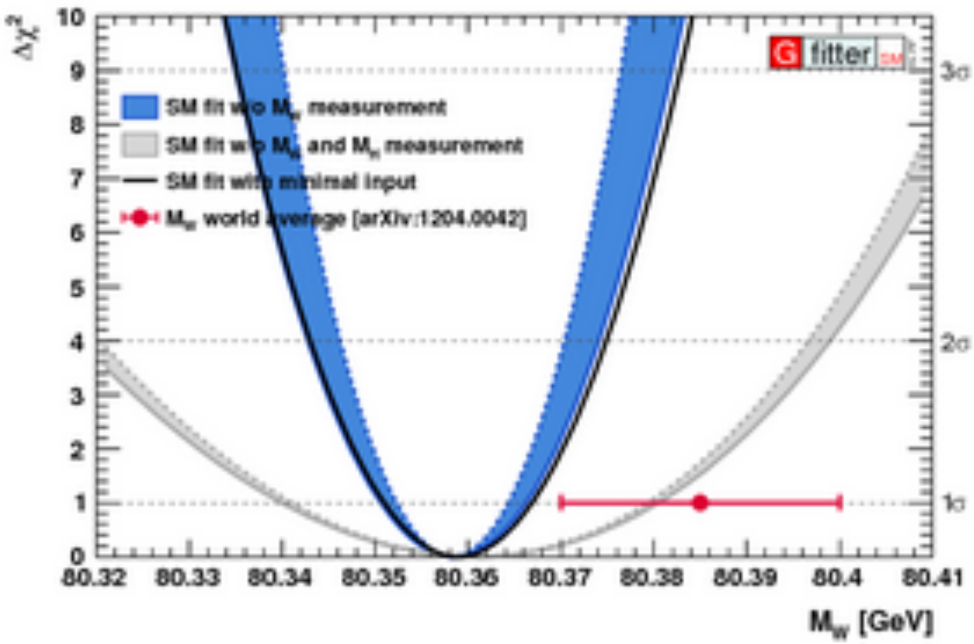


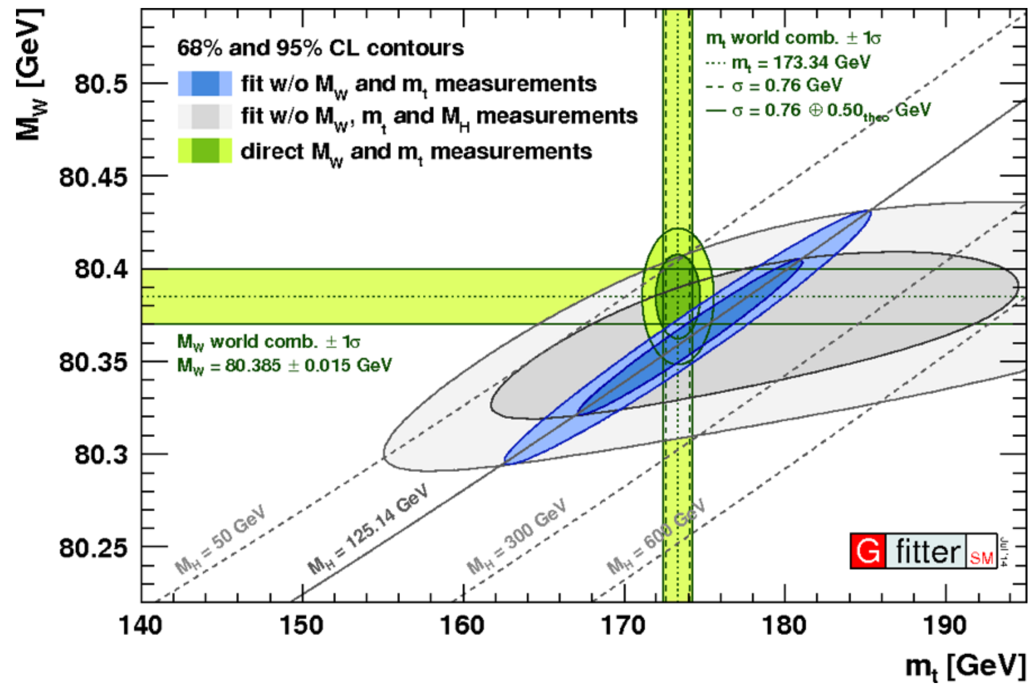
Dilution effect gets smaller in high |y|, but statistics limited, especially in high M

→ Statistical uncertainty is dominant

W mass

- *W mass provides a critical test of nature and consistency of SM along with M_t,M_H*
- M_W needs to reach a precision of 6 MeV or better to prove the consistency of SM given the presently available accuracy of M_t and M_H





World average M_W = 80.385 ± 0.015 GeV

Global EW fit prediction :

M_W = 80.358 ± 0.008 GeV

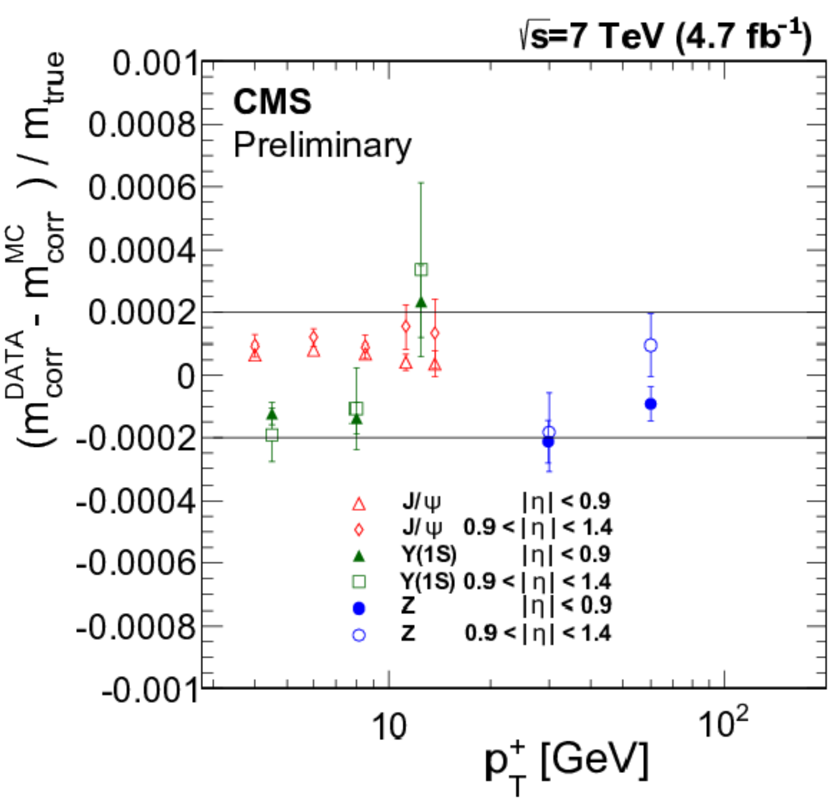
World average M_t = 174.34 ± 0.76 GeV

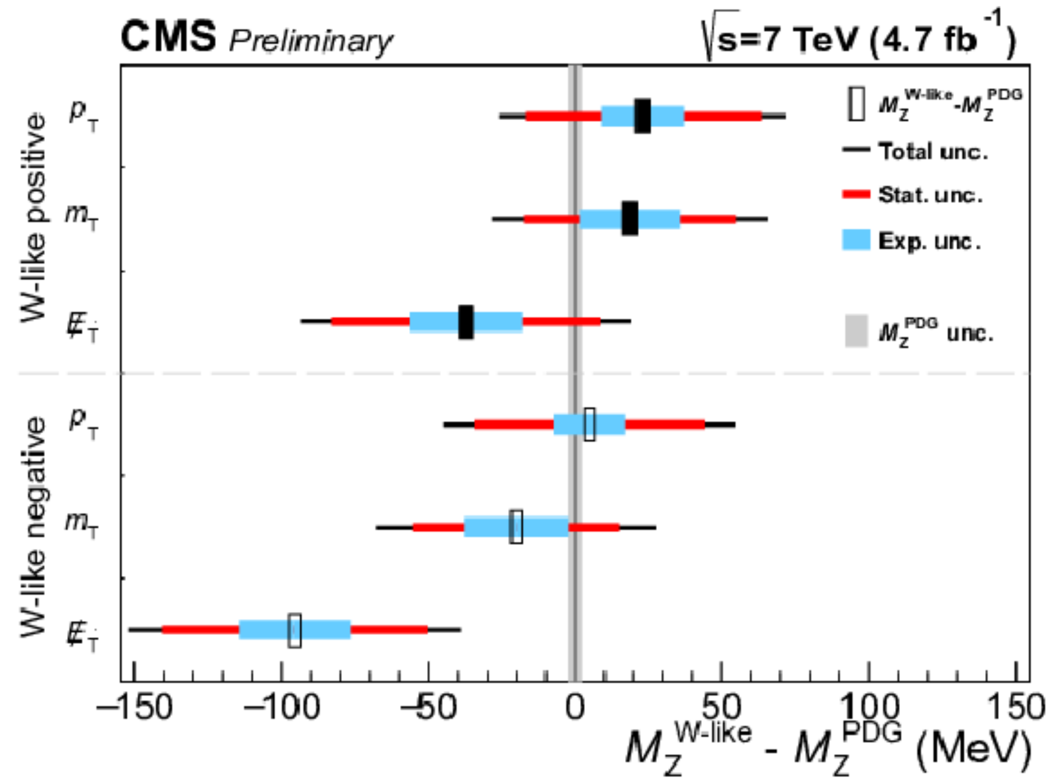
(the most precise direct M_t has error of 0.66 GeV)

- Direct W mass measurement in on-going using Run I data (7, 8 TeV)
- Z boson mass is measured removing one of two muons to form W-like candidate
  - It provides *a proof of principle and a quantitative validation of W mass analysis*

W-like measurement of Z boson mass

- W-like measurement of Z boson mass
  - The analysis is performed using ∫L = 4.7 fb^{-1} at √s = 7 TeV (2x10^5 Z→μμ events)
  - *Large improvement in muon p_T (< 15 MeV) and recoil calibration (< 14 MeV)*
  - muon p_T, m_T, MET fit are used to extract W-like mass measurement





- *Expect the most precise W mass measurement in m_T fit would differ from PDG by 18~20 MeV*, which is within the uncertainties of W-like measurements
  - *Total syst. and stat. error are 32 and 35 MeV for W^- like mass (48 MeV in total)*

Summary

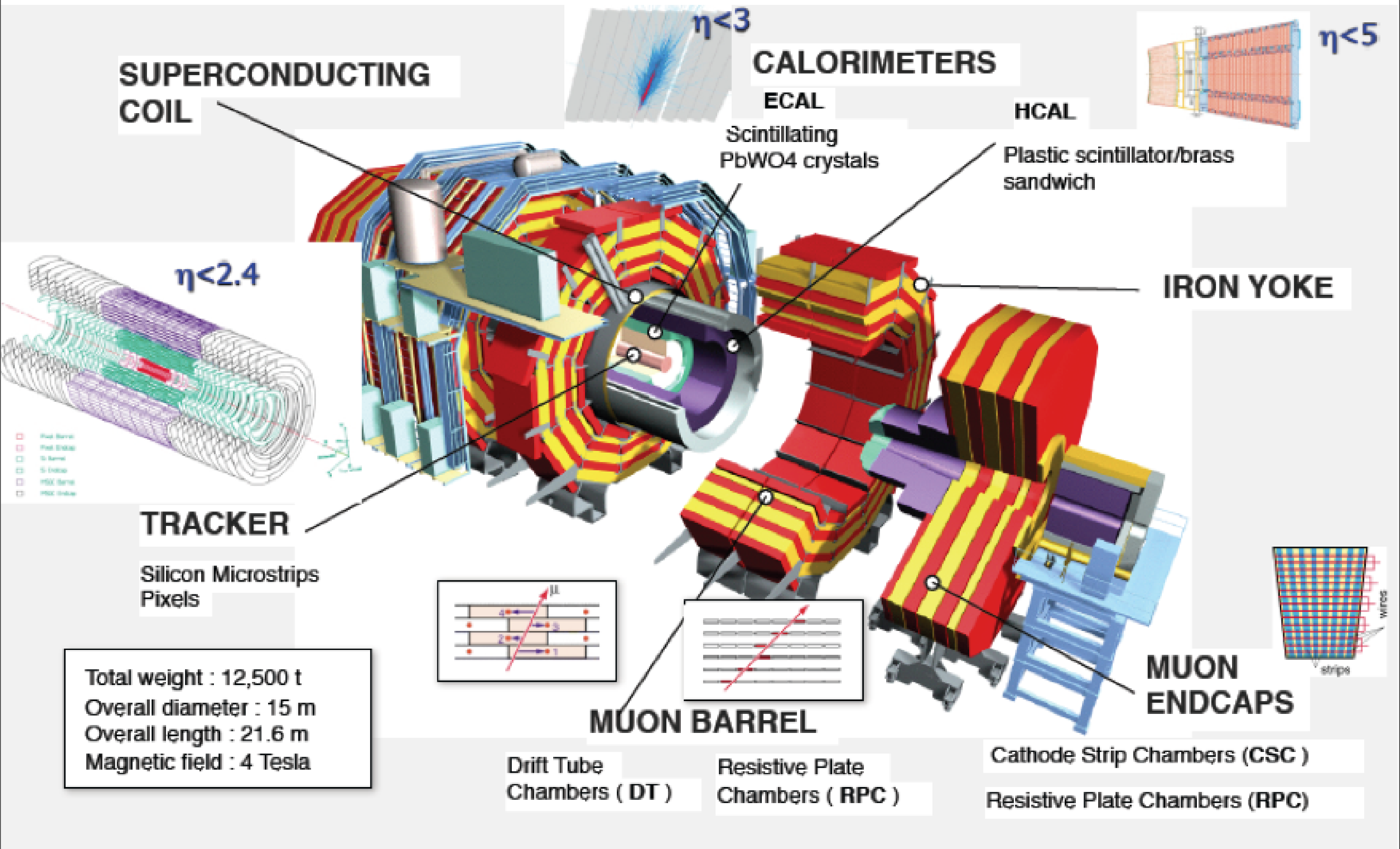
- W and Z physics at CMS
  - CMS RunI results has been used as *a good input to improve PDFs/predictions*
    - PDFs input : $d\sigma^2/dMdy$, W charge asymmetry
    - QCD calculation : Angular coefficients, $d\sigma/dP_T$
  - *New results using RunII data at √s = 13 TeV are produced or delivered soon*
    - Preliminary: inclusive σ(W/Z), differential σ in P_T, ϕ^*_η, y, η of muon for Zs
  - *High precision measurements with RunI data are on-going*
    - Preliminary : W-like mass measurement with √s = 7 data

⇒ ***Probe fundamental parameters in SM***

⇒ ***Contribute to reduce the systematic uncertainty for other physics (top,Higgs...)***

Back-up Pages

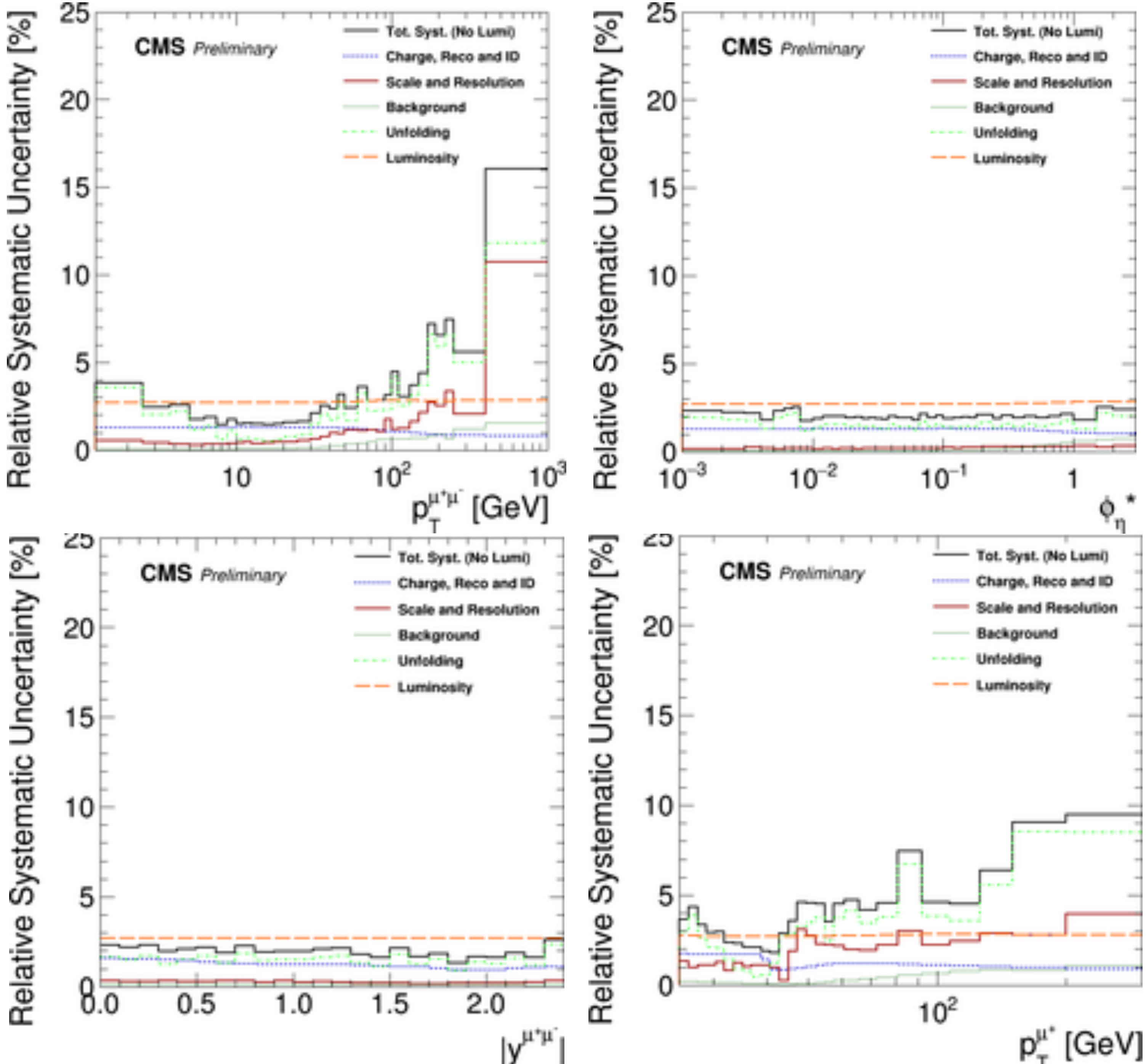
CMS Detector



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Systematic error for Z differential σ

Biggest contributions are luminosity (2.7%), Unfolding procedure, ID or scale/resolution



Systematic error for $d^2\sigma / dP_T dy$ (II)

- Systematic error for absolute fiducial cross section

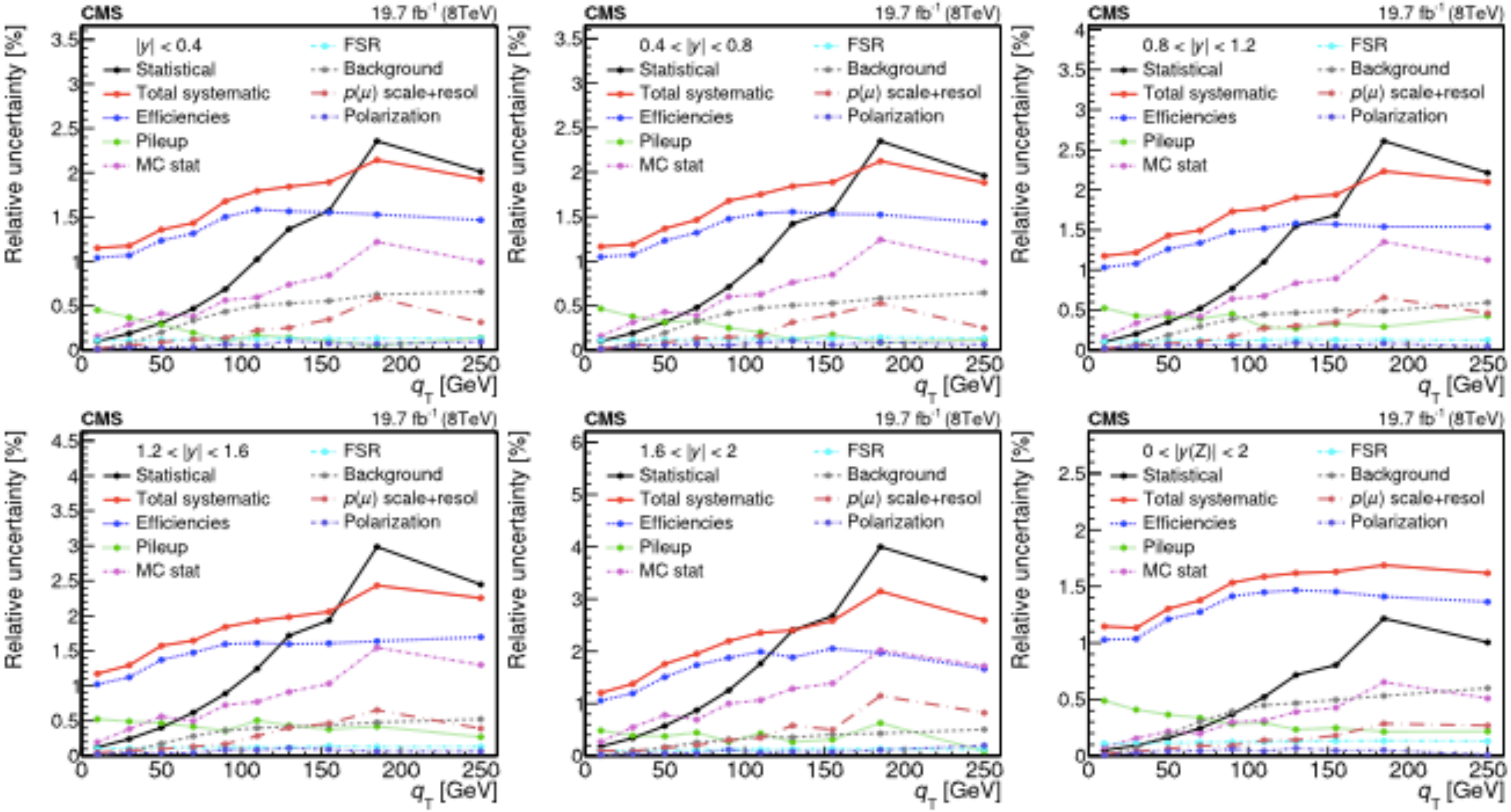


Fig. 2. Relative uncertainties in percent of the absolute fiducial cross section measurement. The 2.6% uncertainty in the luminosity is not included. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

Systematic error for $d^2\sigma / dP_T dy$ (I)

- Systematic error for normalized fiducial cross section

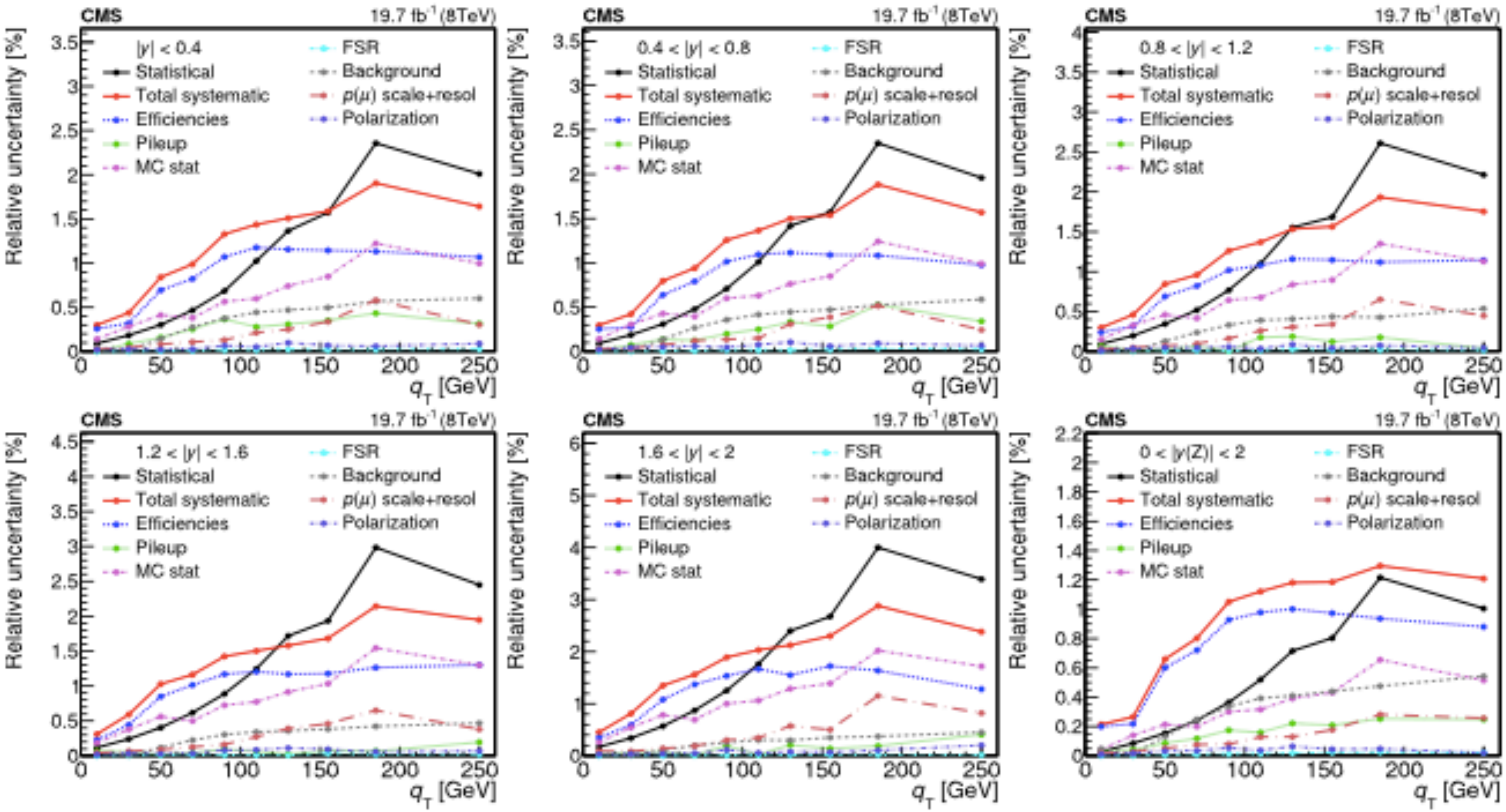


Fig. 1. Relative uncertainties in percent of the normalised fiducial cross section measurement. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

Angular coefficients : |y| dependence

- Angular coefficients between |y|<1 vs. 1<|y|<2.1

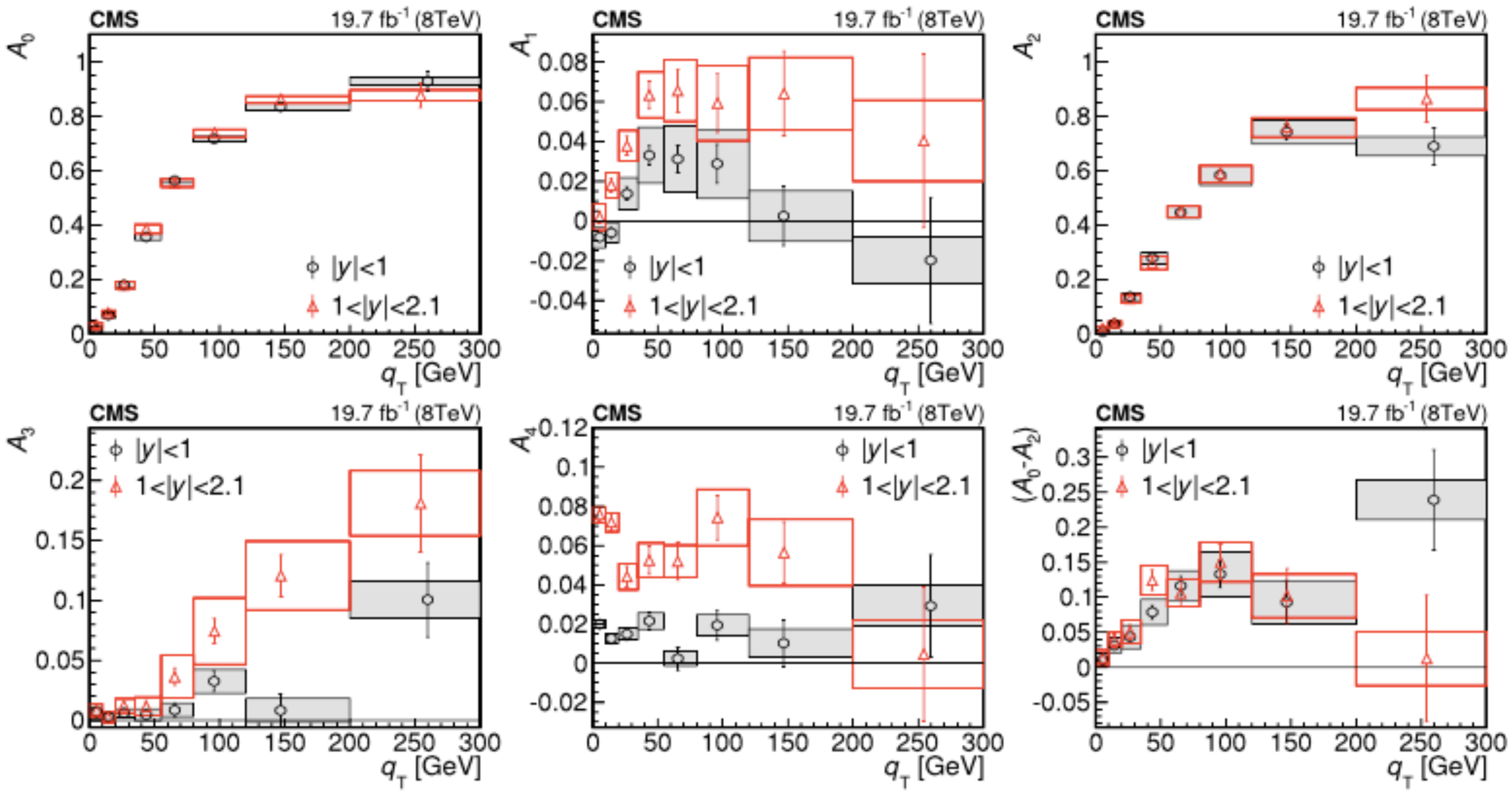
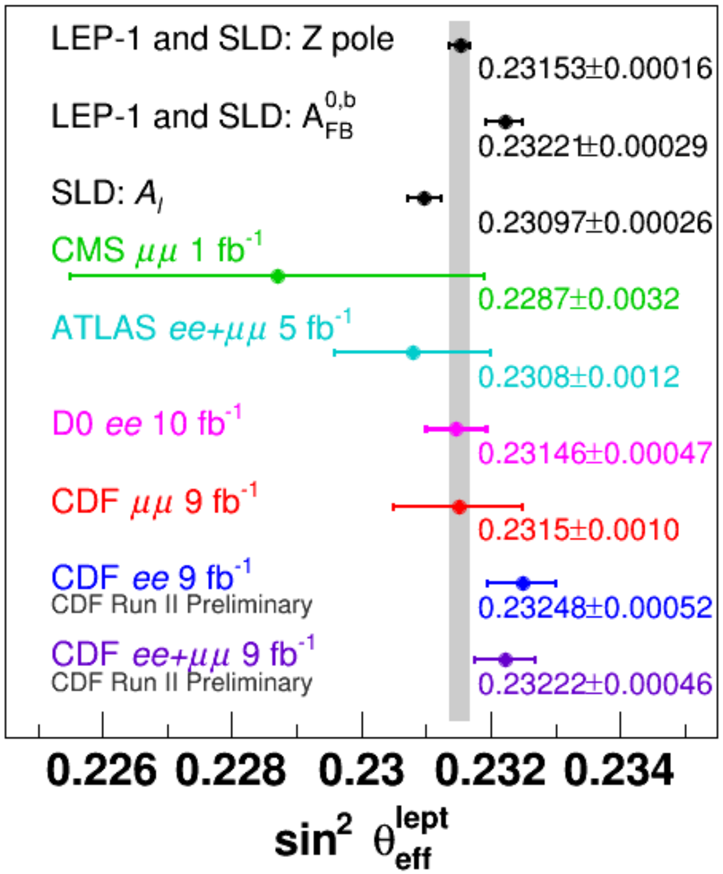


Fig. 5. Comparison of the five angular coefficients A_i and $A_0 - A_2$ measured in the Collins–Soper frame in bins of q_T between $|y| < 1$ (circles) and $1 < |y| < 2.1$ (triangles). The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement.

Weak mixing angle from Afb

- Weak mixing measurement from CMS : on-going

Weak mixing angle measurements



Extraction of $\sin^2\theta_W$ using CMS data (8 TeV) is on-going with several improvements :

A_{FB} with event weighting method,

(A. bodek et. al., Eur.Phys.J. C67 (2010))

lepton calibration, and re-optimized lepton ID

$\Rightarrow$ Expected statistical precision = ~0.0004

Systematic error for W-like mass

- Summary of systematic uncertainty

Table 2: Uncertainties on $M_Z^{\mathrm{W_{like}}}$, in MeV, obtained with the three fitting variables. Both the $M_Z^{\mathrm{W_{like}}+}$ and $M_Z^{\mathrm{W_{like}}-}$ cases are reported.

	$M_Z^{\mathrm{W_{like}}+}$			$M_Z^{\mathrm{W_{like}}-}$		
Sources of uncertainty	p_T	m_T	$\not{E}_T$	p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57