Electroweak bosons in Heavy Ion Collisions

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Heavy Ion Meeting

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Outline

- Introduction
- Z boson results in pPb collisions at 5.02 TeV
- W boson results in pPb collisions at 5.02 TeV
- W boson results in pPb collisions at 8.16 TeV

Introduction

What are electroweak bosons?

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

They are force carriers of the electroweak force:

- **Electromagnetism** → Photons
- **Weak force** → W and Z bosons

How do weak bosons interact?

W boson decays

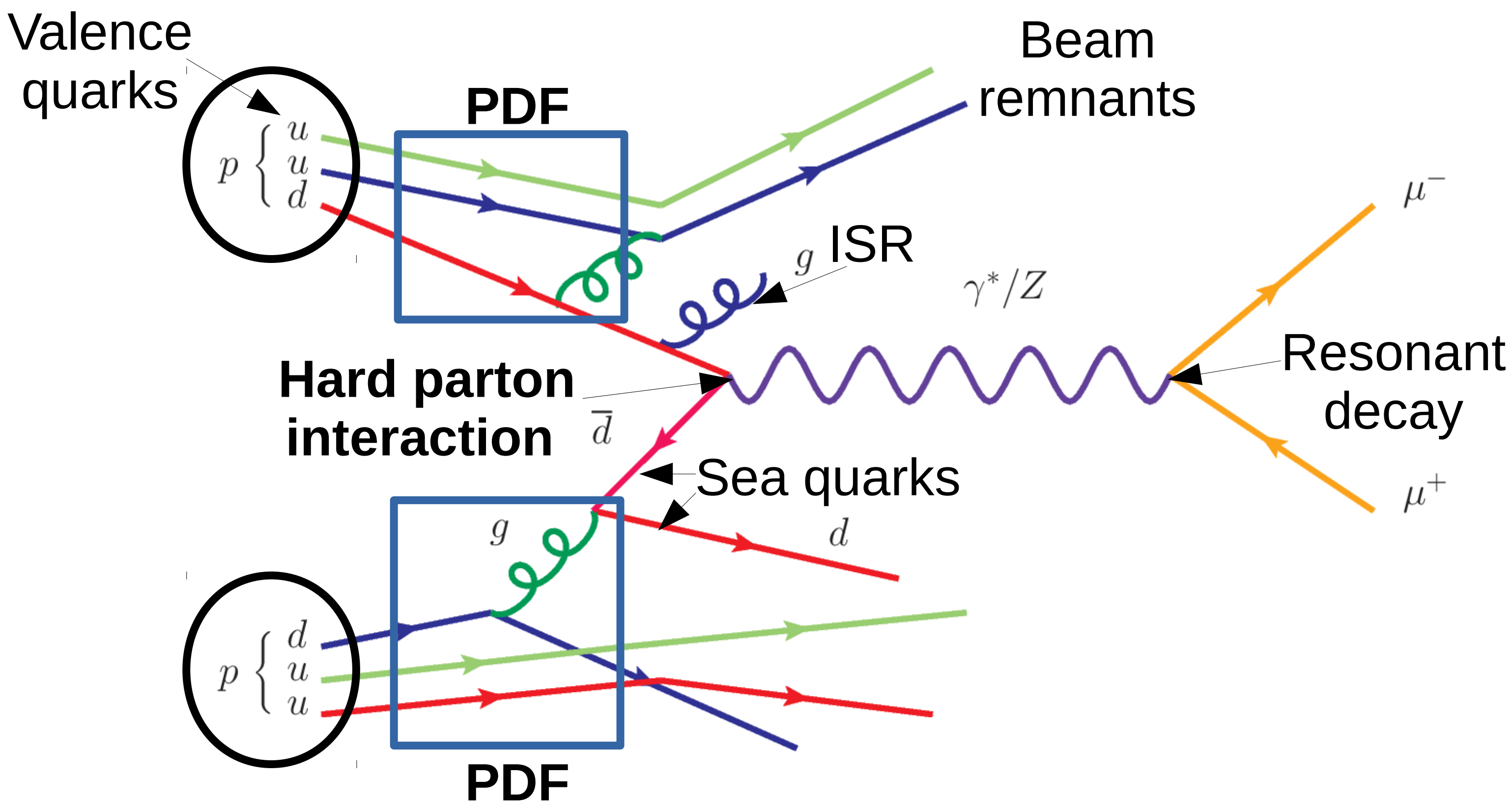
leptonic	hadronic
$W^+ \to l^+ \nu$	$W^+ \to q\bar{q}$
$W^- \to l^- \bar{\nu}$	$W^- \to q\bar{q}$

Z boson decays

hadronic	leptonic: visible	leptonic: invisible
$Z^\circ \to q\bar{q}$	$Z^\circ \to e^+ e^-$	$Z^\circ \to \nu\bar{\nu}$
	$Z^\circ \to \mu^+ \mu^-$	
	$Z^\circ \to \tau^+ \tau^-$	

- Weak bosons only interact with leptons and quarks. They don't couple to gluons (QCD).
- Weak bosons **don't interact strongly** with the nuclear medium produced in heavy ions

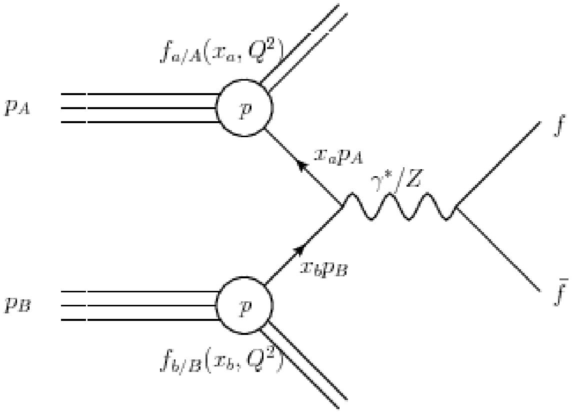
How are weak bosons produced in pp?



- Protons are made of three valence quarks (2 up and 1 down).
- Sea quarks are produced from gluon into virtual q-qbar pairs.
- Weak bosons are produced from a valence quark and sea antiquark in the initial hard parton scattering
- Production of weak bosons is sensitive to quark PDFs

QCD Factorization

QCD Factorization Theorem: separate the hadronic cross section into a perturbative partonic cross section depending on the process, and non-perturbative Parton Distribution Functions.



$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^{1} dx_1\, dx_2\, f_{a/h_1}(x_1, M_X^2) f_{b/h_2}(x_2, M_X^2) \hat{\sigma}_{ab\to X}\,(x_1 x_2 s, M_X^2)$$

Hadron-level cross section | **Parton Distributions** | **Parton-level cross-section**

- **x**: Fraction of hadron's momentum carried by the parton (gluon or quark)
- $\mathbf{M_X}$: Scale at which the process is probed (mass of hard probes or p_T of jets)
- The **PDFs** are **universal** (doesn't depend on the hard scattering process). Thus can be used to provide predictions for hadronic collisions.
- **Good precision** of PDFs is vital for understanding LHC collisions.

Parton Distribution Functions

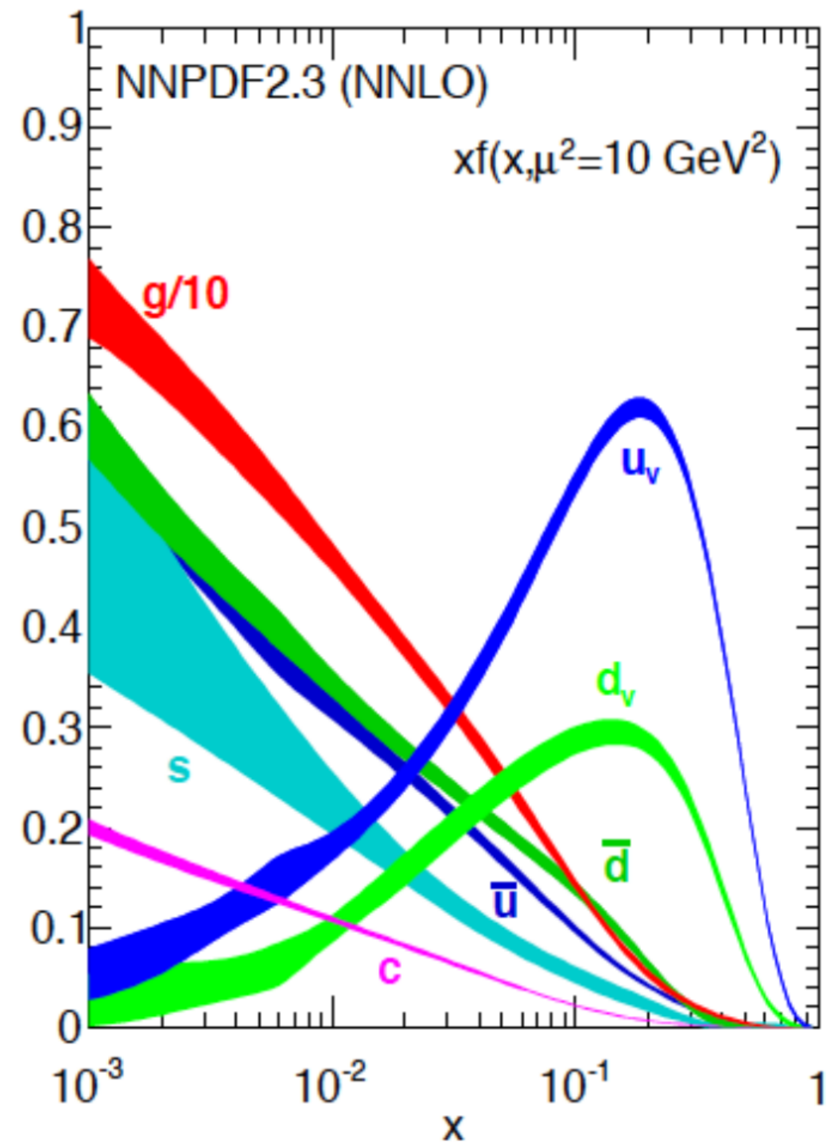
- One **PDF** for **each parton** in the hadron: u(x,Q²), d(x,Q²), g(x,Q²), ...
- At LO, PDFs **represent** the **probability** of **finding** a **parton** carrying a **fraction x** of the hadron's momentum.
- Shape of each PDF changes depending on the flavour.
- **QCD** imposes **constrains** based on valence and momentum **sum rules**

Momentum sum rule

$$\int_0^1 dx\ x\,[\Sigma(x) + g(x)] = 1$$

Valence sum rule (proton)

$$\int_0^1 dx\ (u(x) - \bar{u}(x)) = 2\ , \qquad \int_0^1 dx\ (d(x) - \bar{d}(x)) = 1$$

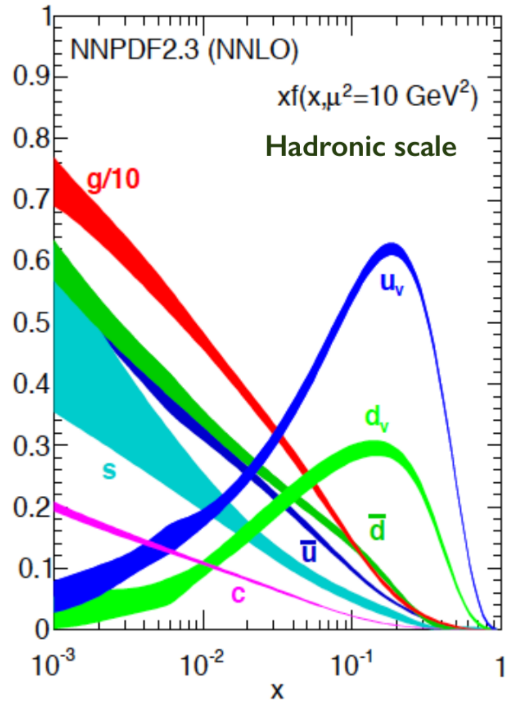


Parton evolution equations (DGLAP)

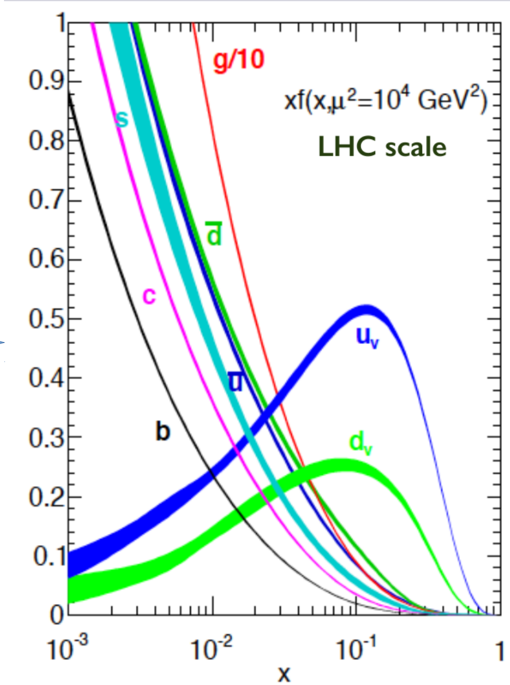
- The **dependence** of **PDFs** on the **energy scale Q** can be derived using **perturbative QCD** (**DGLAP** evolution equations).

$$\frac{\partial q_i(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s\left(Q^2\right)}{2\pi} \int_x^1 \frac{dz}{z} P_{ij}\left(z, \alpha_s\left(Q^2\right)\right) q_j\left(\frac{x}{z}, Q^2\right)$$

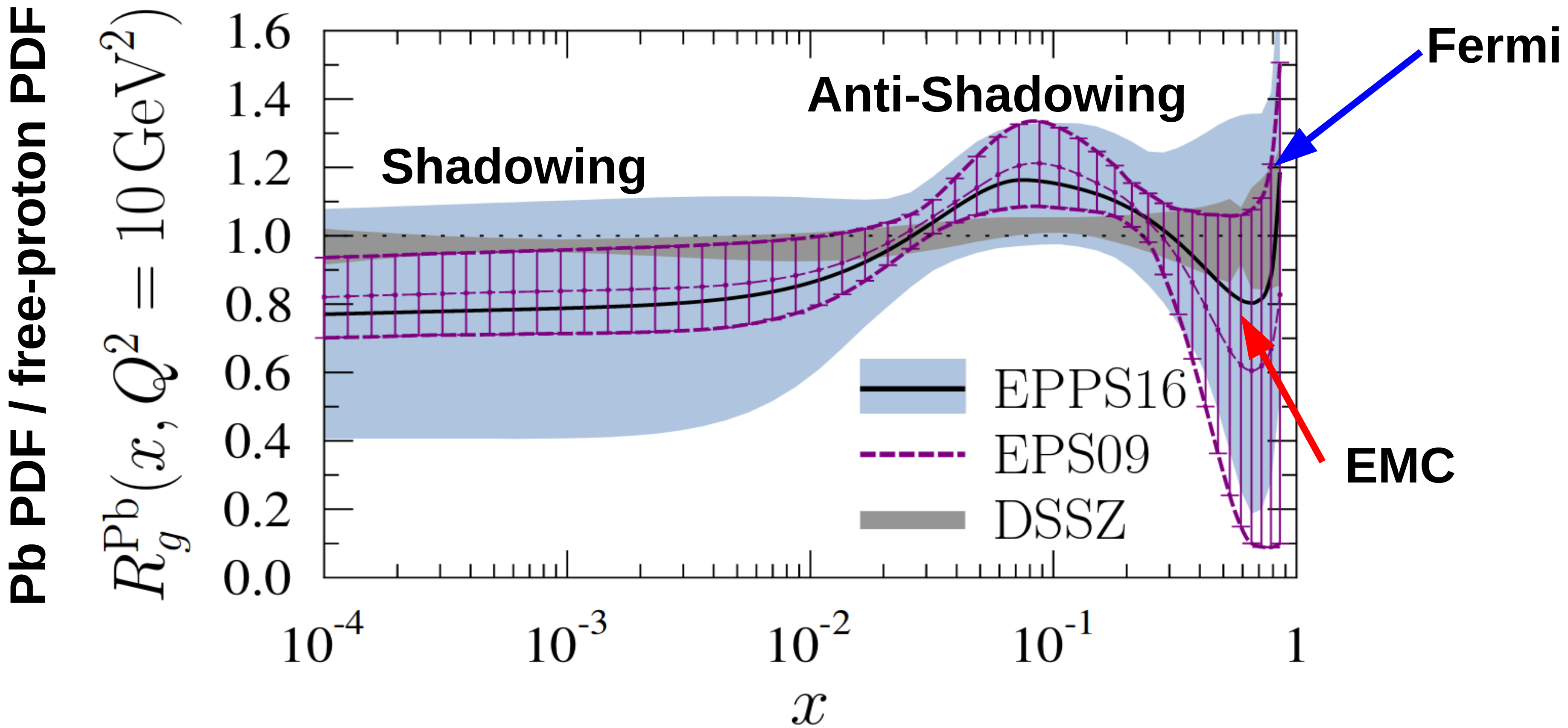
- The **x-dependenc**e of the **PDFs** is **non-perturbative** and can only be **derived** by **fitting data** (global analysis). Once constrained at a given **scale Q_0**, DGLAP determines the PDFs at other scales Q.



Parton evolution



What happens in HI collisions?



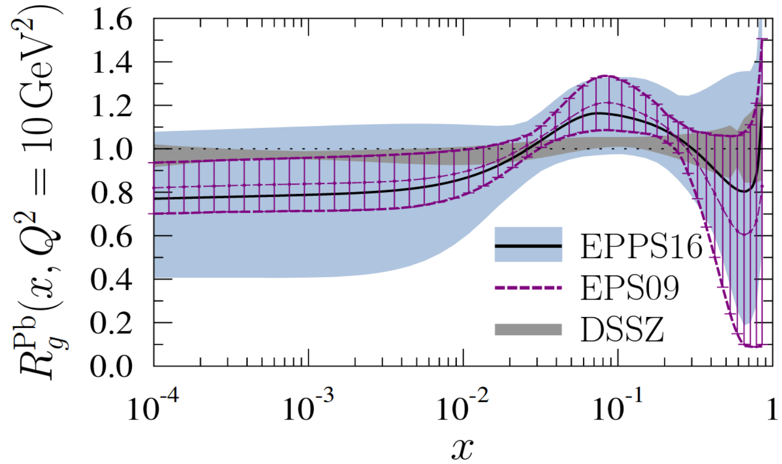
- **PDFs** of **nucleons** inside **nuclei** are **modified** compare to free proton PDFs
- Knowledge of **nuclear PDF** (nPDF) in Pb is **important** to understand the **initial state** of **pPb** and **PbPb** collisions at LHC

Nuclear PDFs

1) Multiplicative nuclear correction factors (EPS, EPPS, DSSZ)

$$f_i^{p/A}(x_N, Q_0) = R_i(x_N, Q_0, A)\; f_i^{free\ proton}(x_N, Q_0)$$

$$R_i(x, Q_0, A) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$



2) Generalized A-parametrization (nCTEQ)

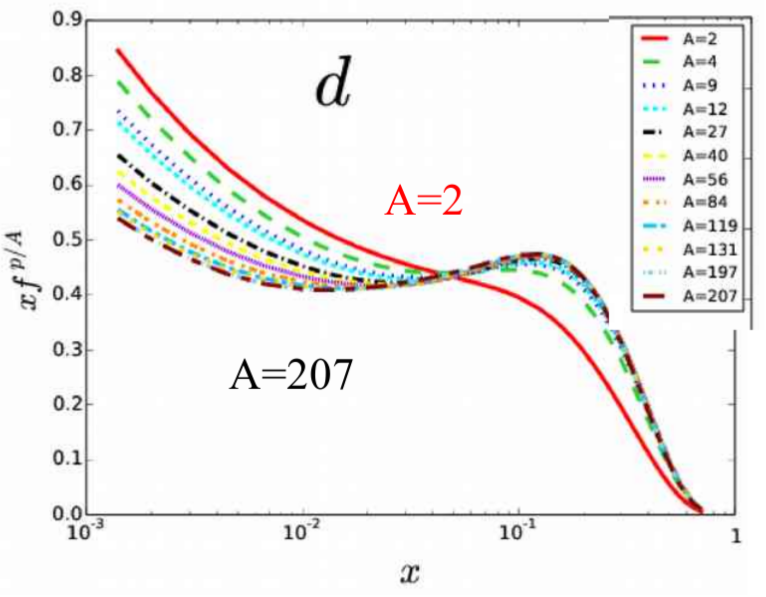
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f \sim ...x^{c_1(A)}(1-x)^{c_2(A)}...$$

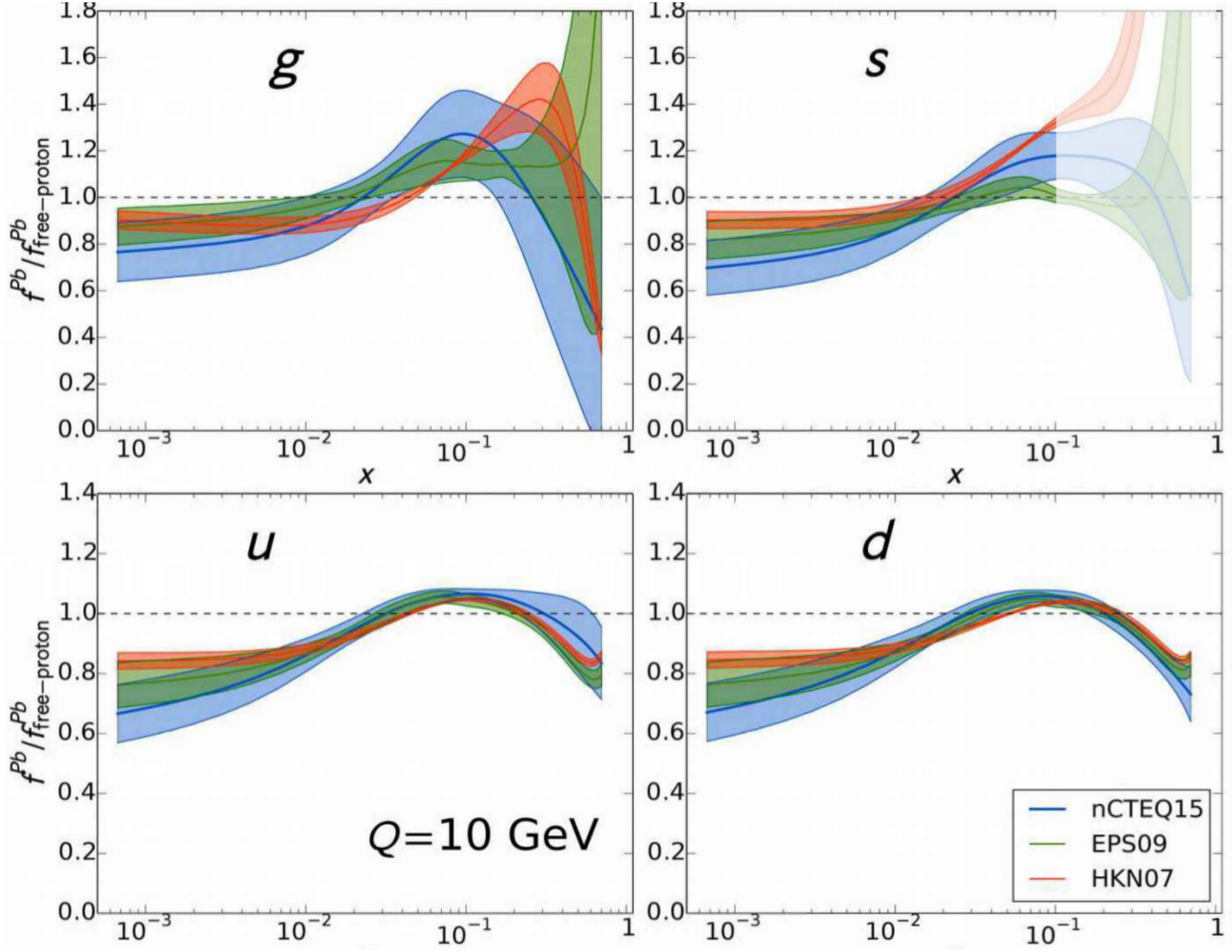
$$c_k \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

Proton

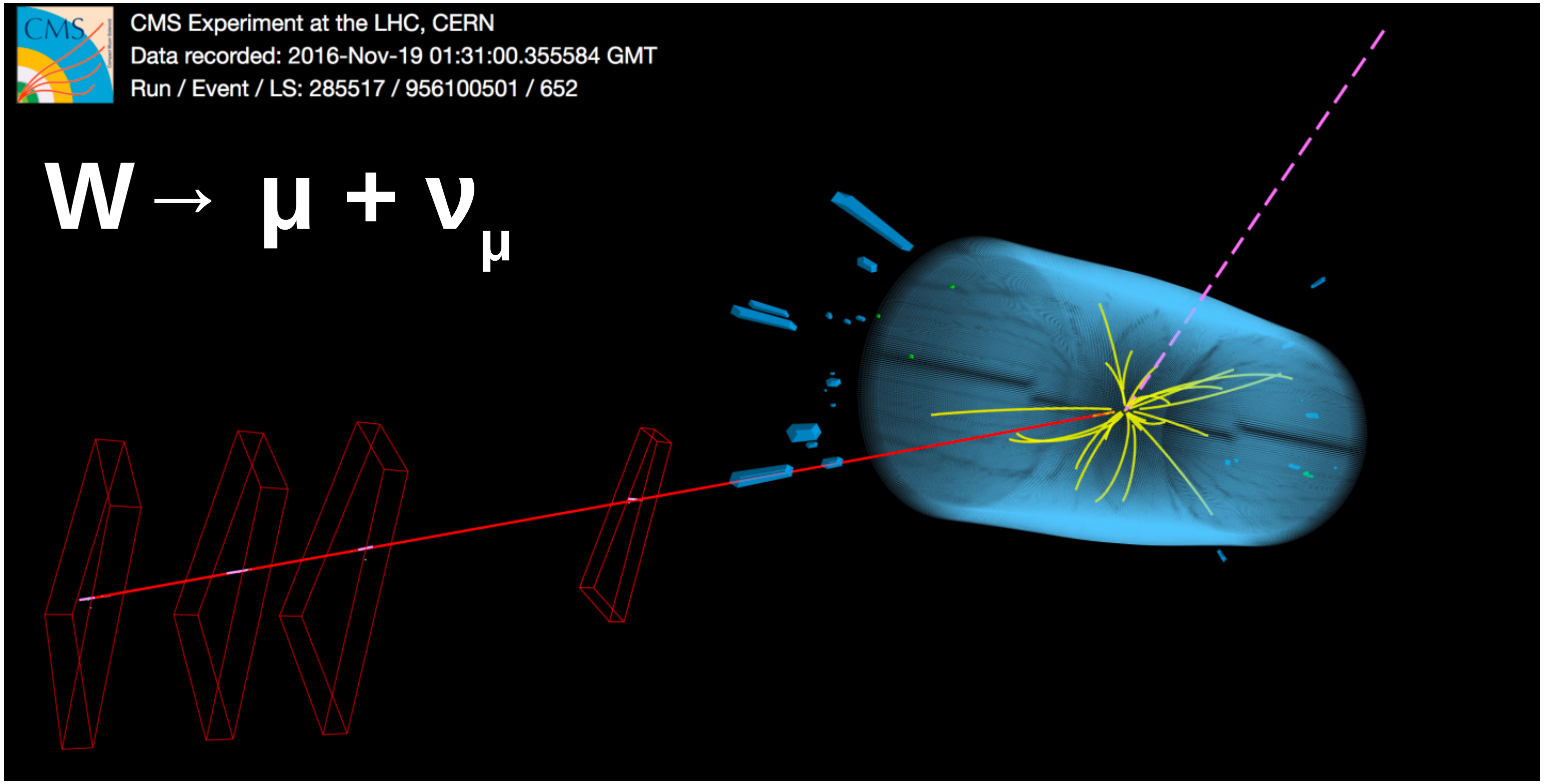
Nuclear



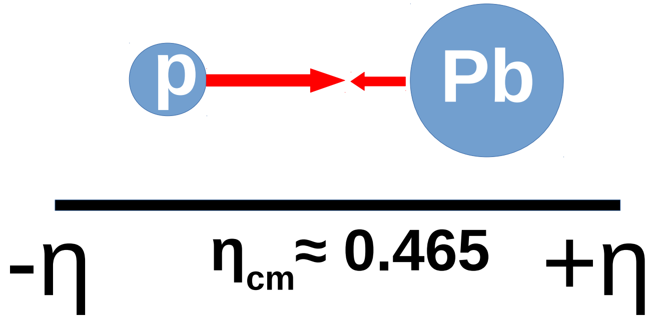
Nuclear PDF factors



Proton-lead collisions



- Proton-lead asymmetric collisions
- Center-of-mass frame rapidity boost ≈ 0.465
- Define forward-backward ratios:
  - $R_{FB} = \frac{N(\eta_{CM}>0)}{N(\eta_{CM}<0)} = \frac{N(p-going)}{N(Pb-going)}$

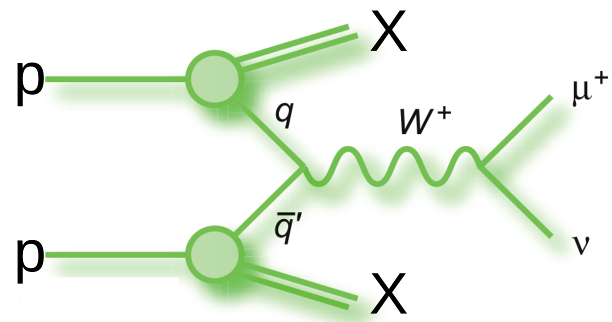


Weak bosons in pPb collisions

Dominant production modes:

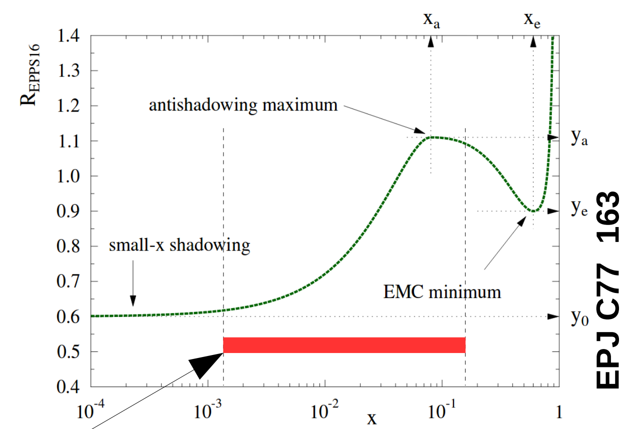
$u\bar{d} \rightarrow W^{+}$, $d\bar{u} \rightarrow W^{-}$

$u\bar{u} \rightarrow Z$, $d\bar{d} \rightarrow Z$

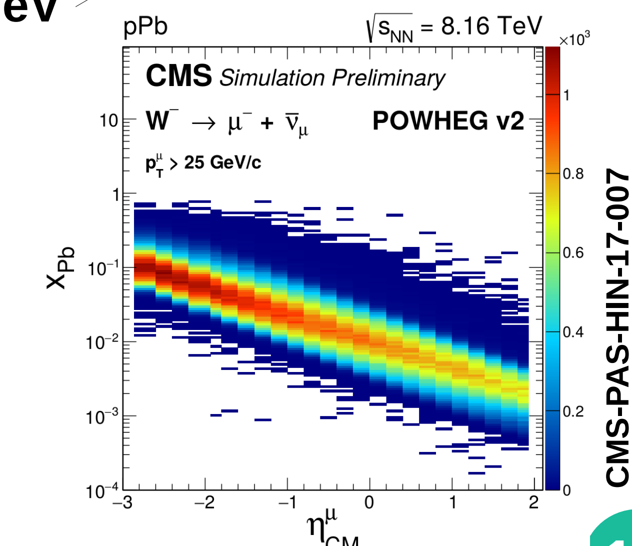


- Sensitive to PDFs of **valence and sea quarks**

- Quarks behave differently inside bound nucleons compared to free-nucleons → **nuclear PDF effects.**



W in pPb @ 8.16 TeV

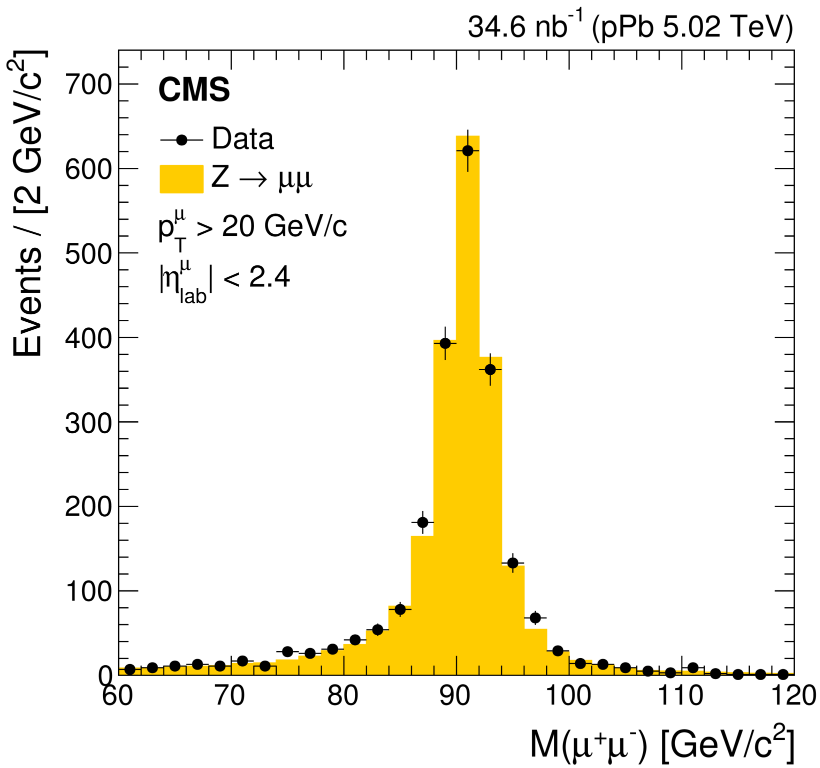


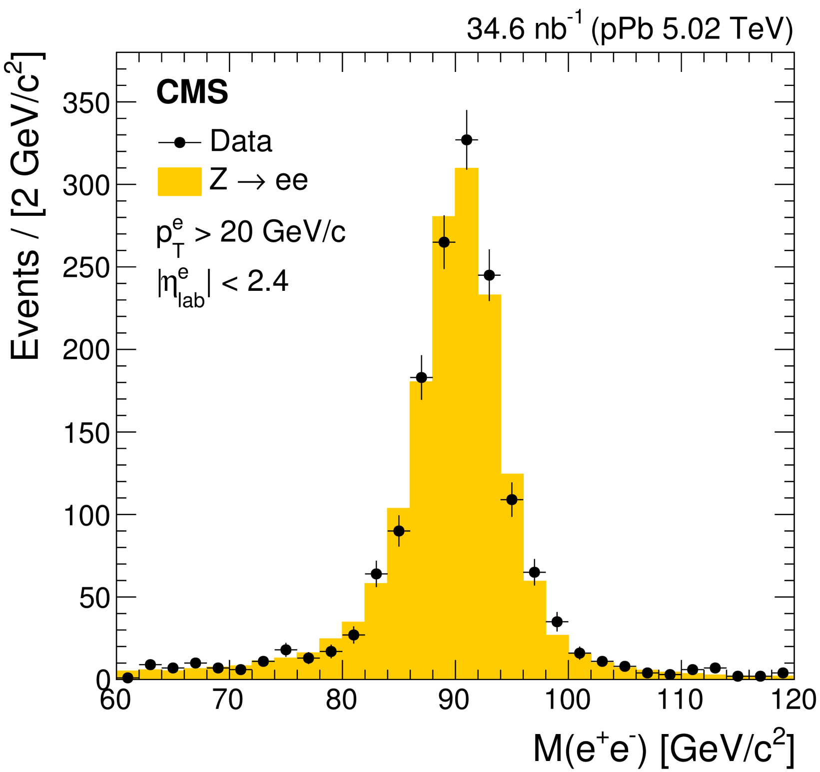
- Weak boson production in pPb @ CMS probe the quark nPDFs in **$10^{-3} < x < 10^{-1}$ @ high Q^2**

$$x_{Pb} = \frac{M}{\sqrt{s}} e^{-y}$$

Z boson in pPb at 5.02 TeV

Z in pPb at 5.02 TeV: CMS

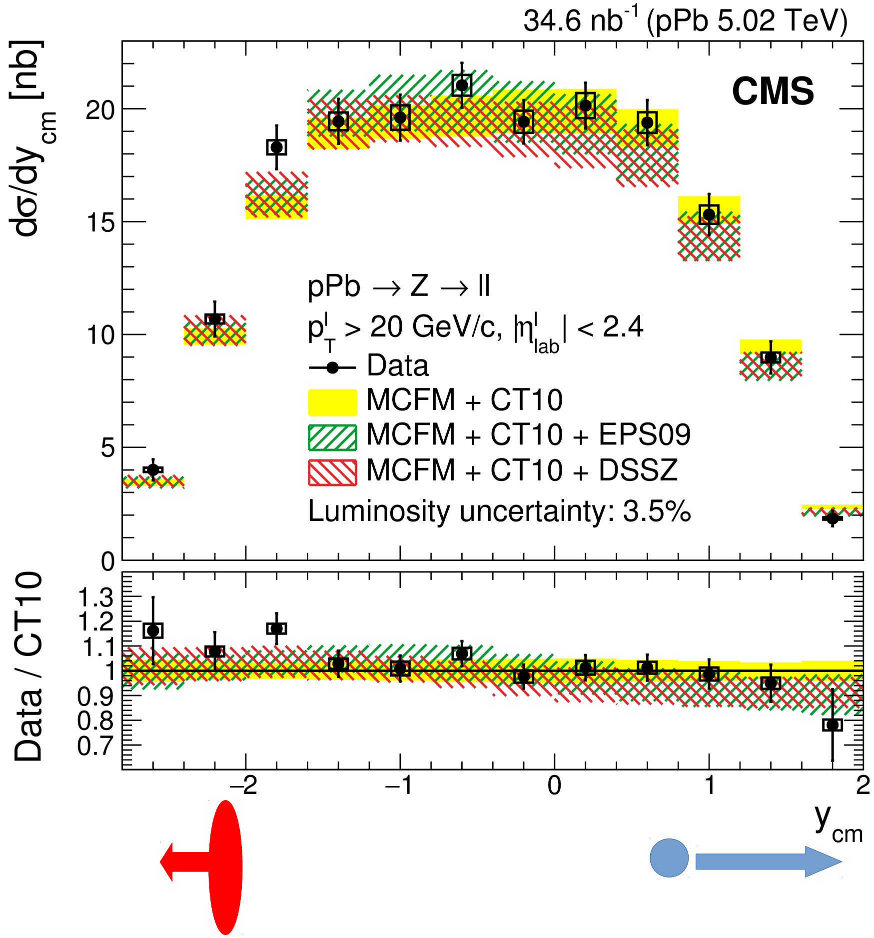




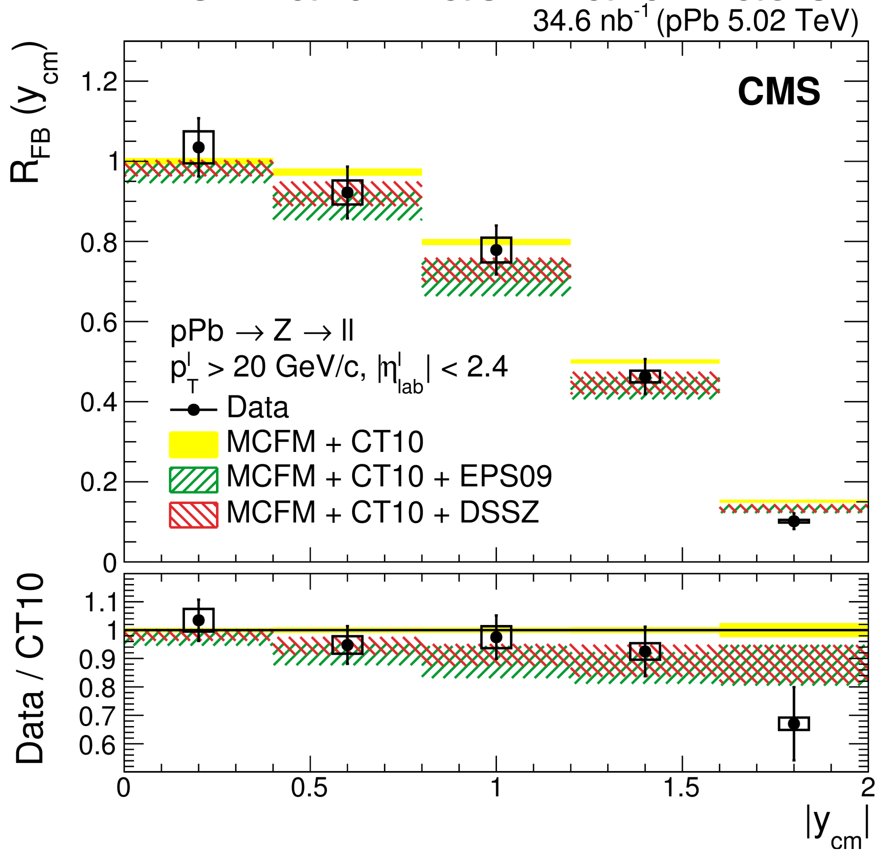
- **Lepton kinematic cuts**: p_T > 20 GeV/c and |η| < 2.4
- Z boson yield **extracted** by **counting** $\mu^+ \mu^-$ and $e^+ e^-$ **pairs** within invariant mass 60 < M < 120 GeV/c^2

Z in pPb at 5.02 TeV: CMS

Cross Section



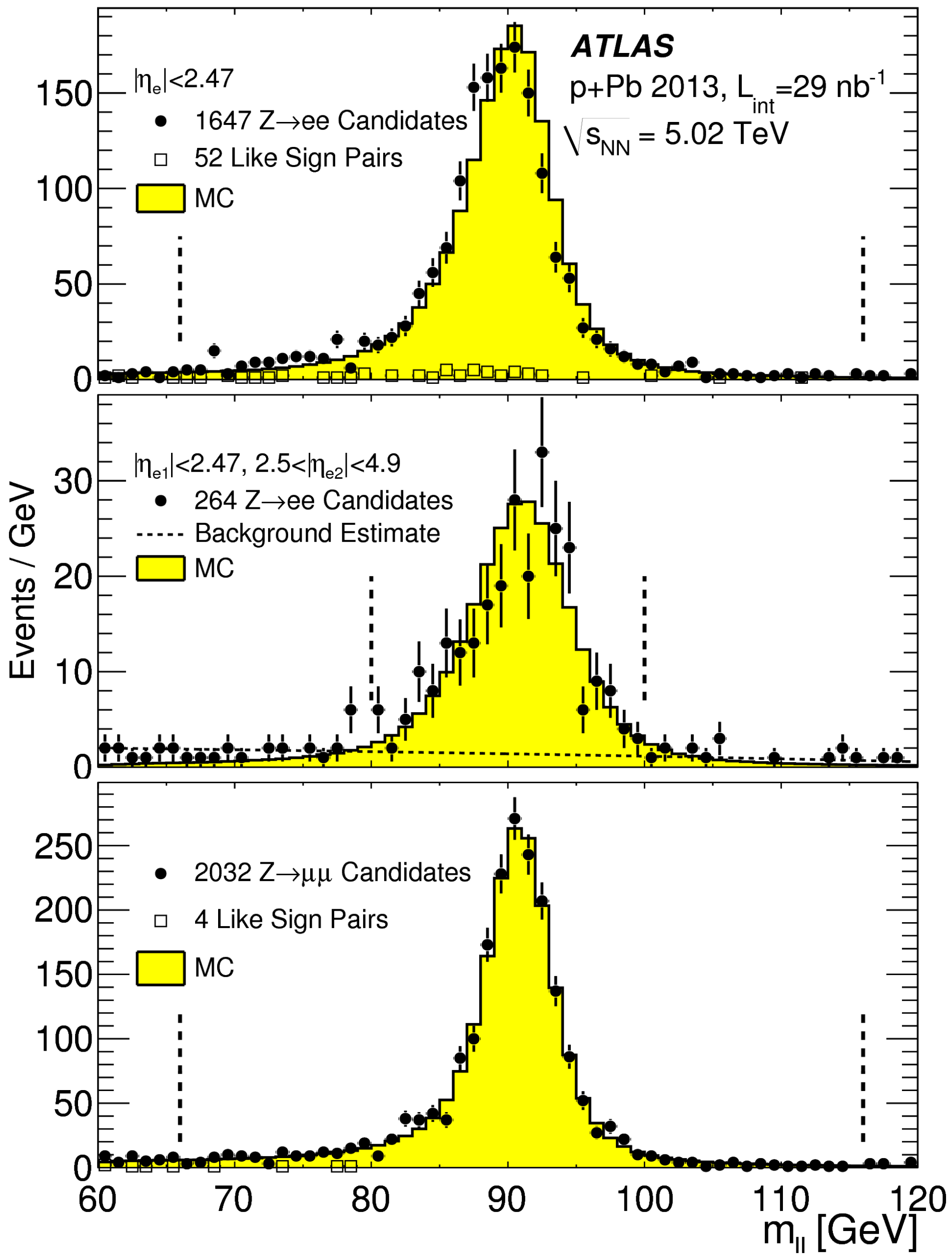
Forward-Backward Ratio



- PDF calculations with and without nuclear corrections in agreement with measured pPb cross section
- Forward-backward results slightly favors nPDFs but large unc.

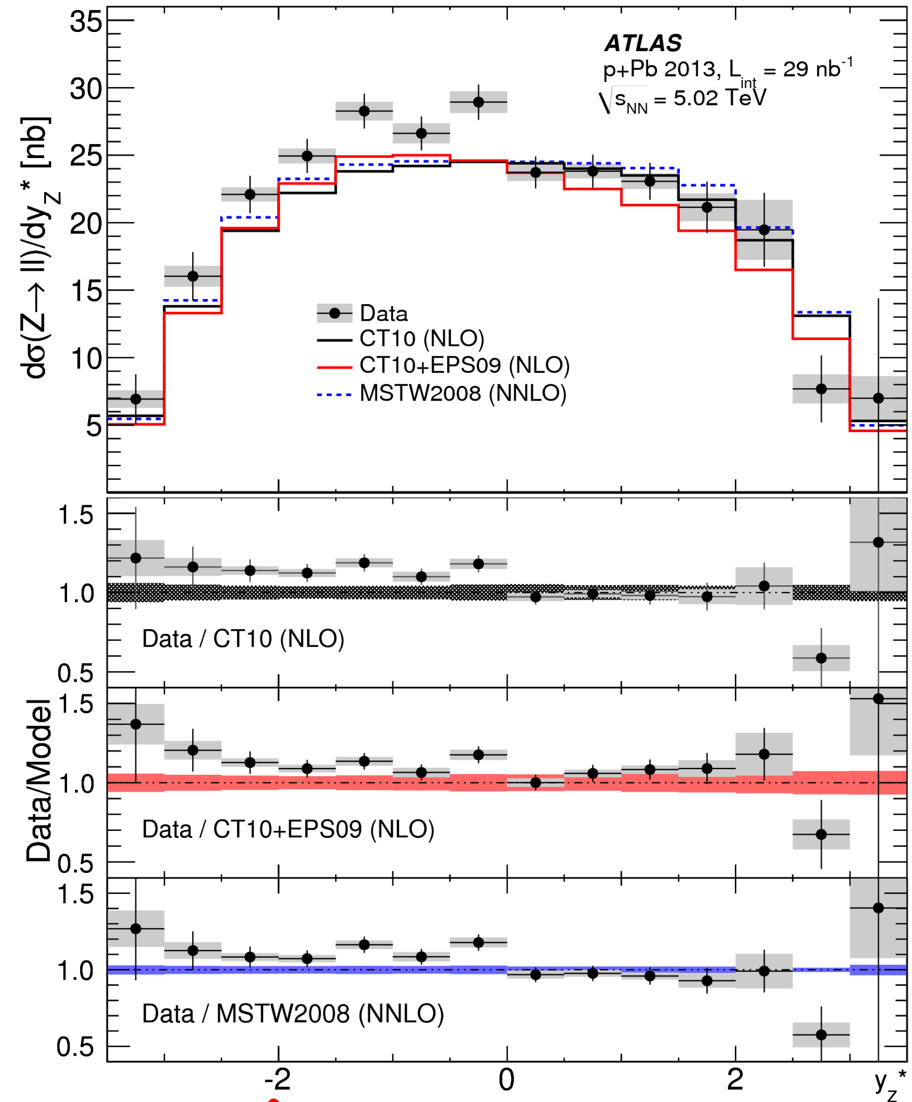
Z in pPb at 5.02 TeV: ATLAS

- Lepton kinematic cuts: $p_T^1 > 20$ GeV/c and $p_T^2 > 10$ GeV/c
- Z boson yield extracted by performing a fit of the $\mu^+ \mu^-$ and $e^+ e^-$ invariant mass within $60 < M < 120$ GeV/c^2
- Signal given by MC template while background parameterized from like same-sign lepton pairs in data.

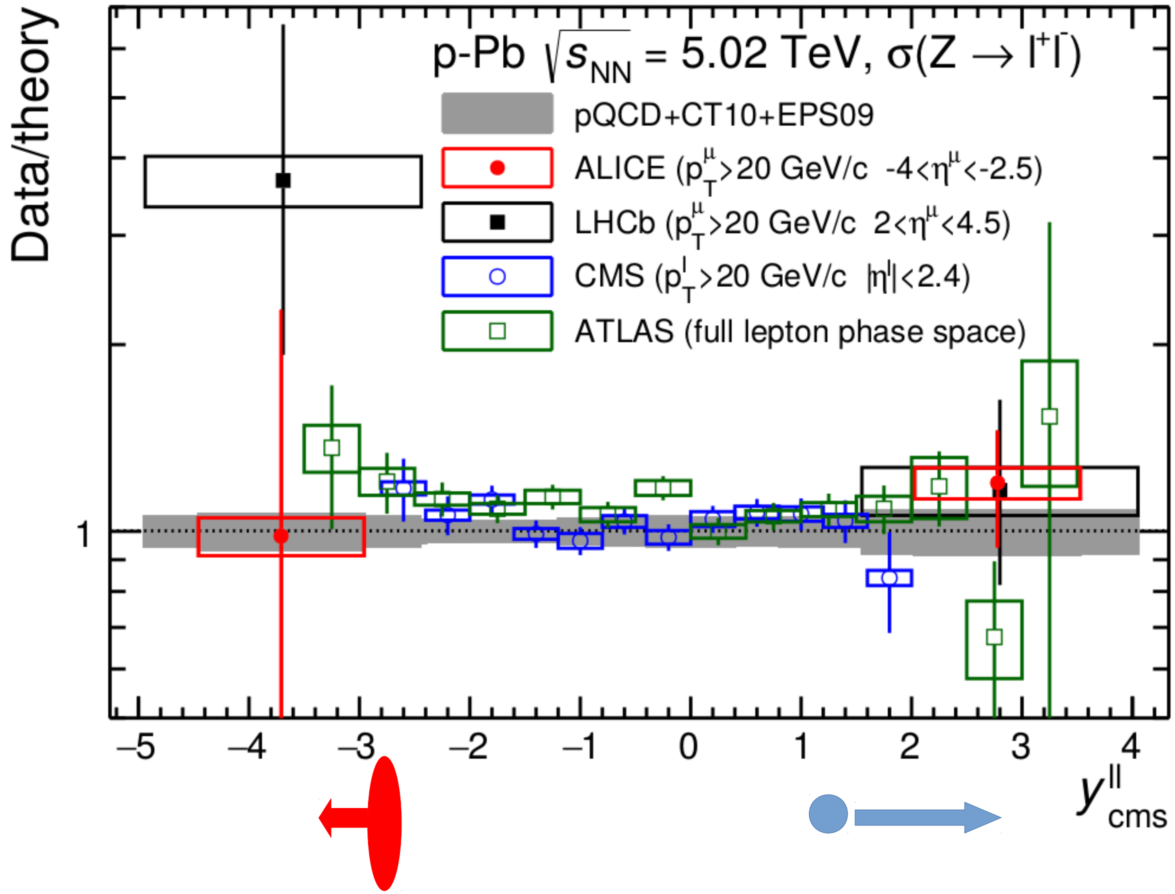


Z in pPb at 5.02 TeV: ATLAS

- A slight increase of the cross sections seen in the backward region (large x).
- Results can’t exclude the PDF without nuclear corrections.



Z in pPb at 5.02 TeV

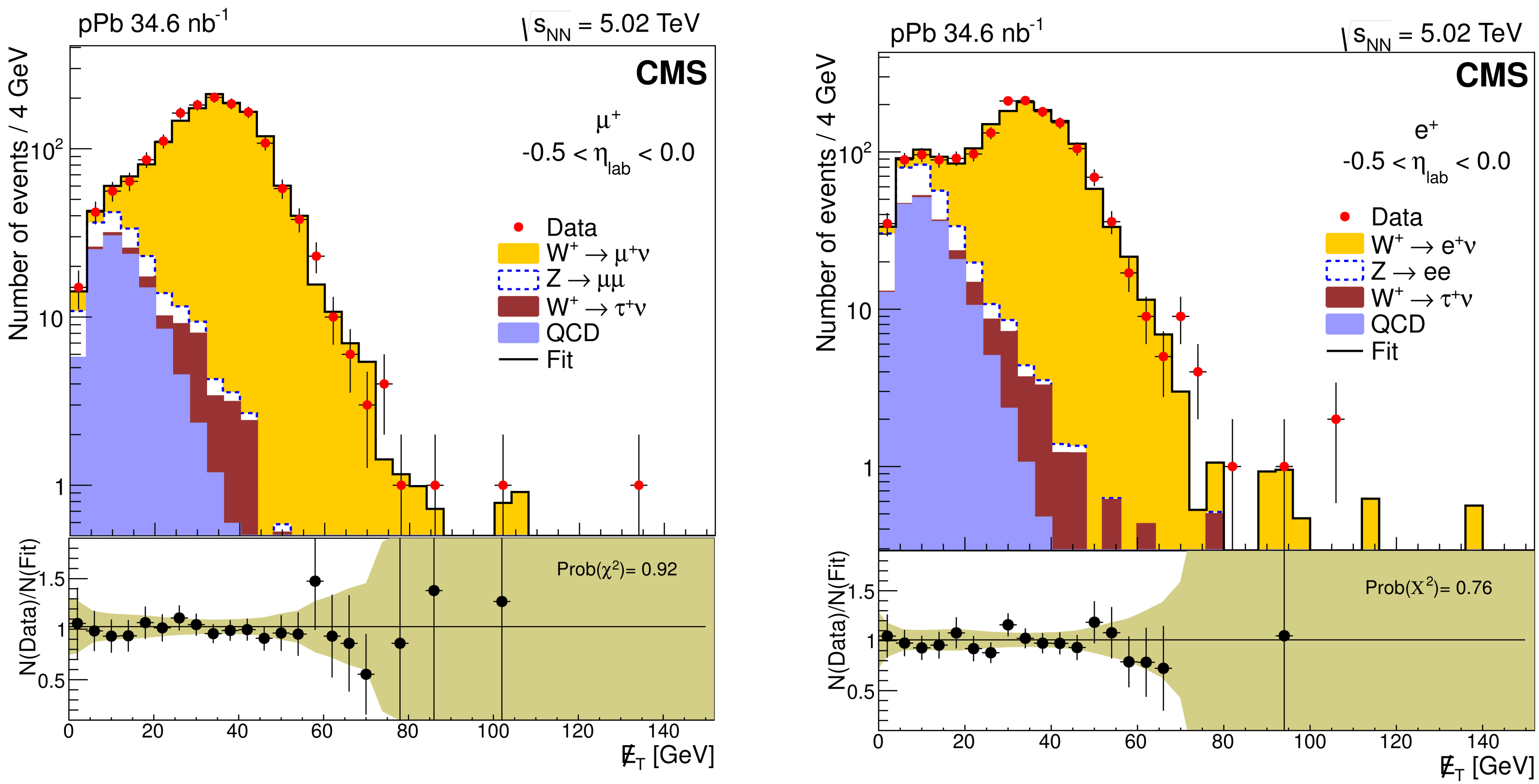


- ALICE and LHCb used same strategy as CMS for Z bosons. But suffered from statistics (< 100 Z bosons)

- In overall, the run1 Z boson data is in good agreement with EPS09 nPDF calculations but can not exclude PDF without nuclear corrections

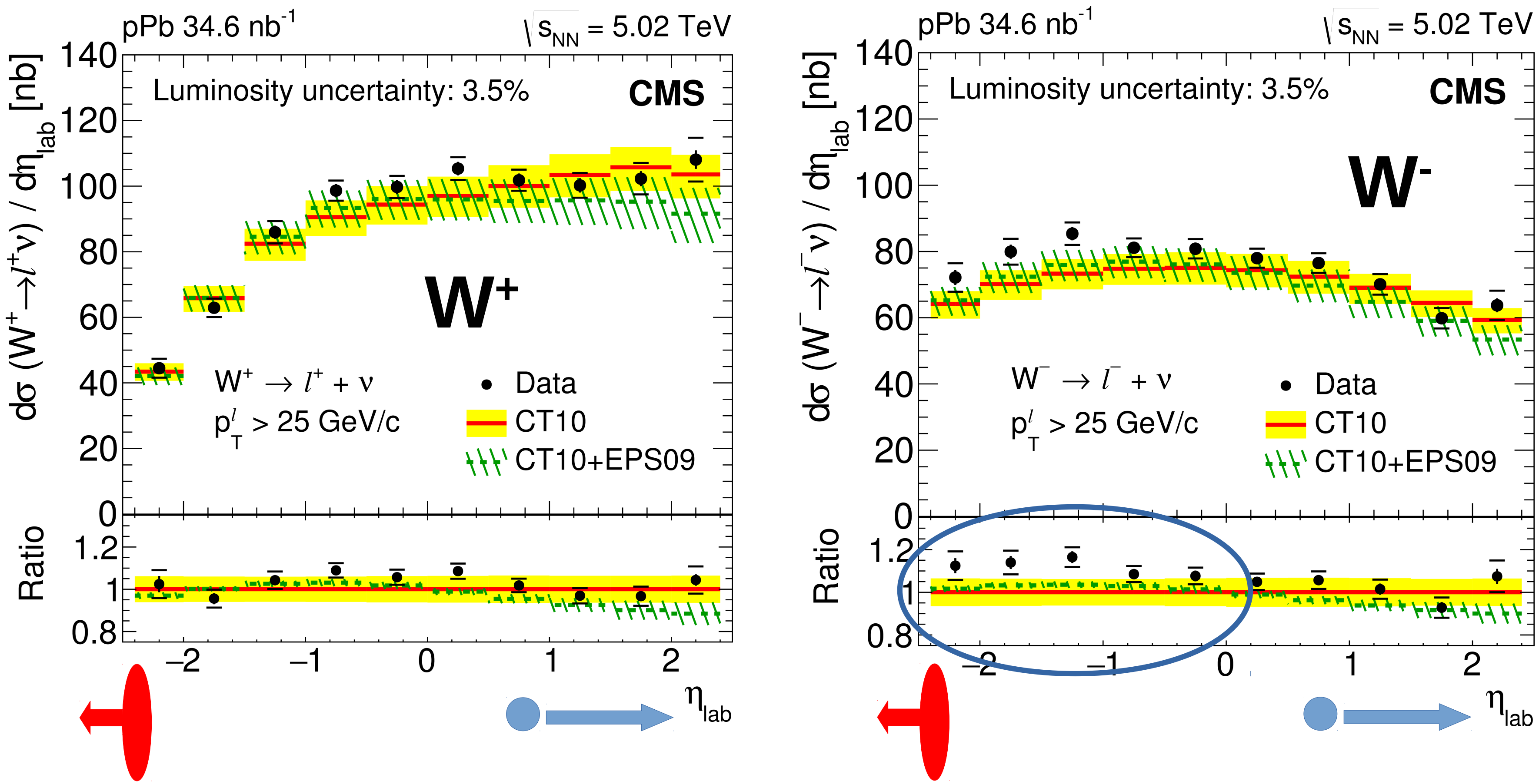
W boson in pPb at 5.02 TeV

W in pPb at 5.02 TeV: CMS



- Lepton kinematic selection: p_T > 25 GeV/c and $|\eta| < 2.4$
- W boson yield extracted by fitting the missing transverse energy (MET) in different bins of lepton pseudorapidity.

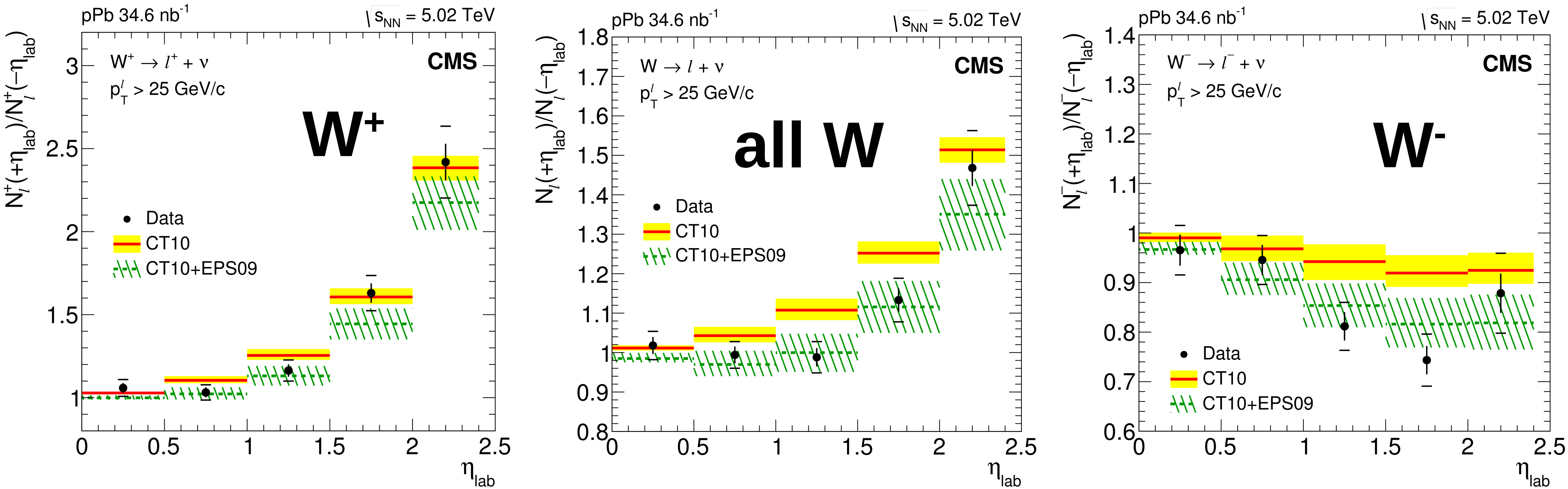
W in pPb at 5.02 TeV: CMS



- Good agreement with PDF calculations with and without nuclear corrections within uncertainties.
- Slight increase for W^- in the backward region (large x_{Pb}) compared to PDF calculations

W in pPb at 5.02 TeV: CMS

Forward-Backward Ratios

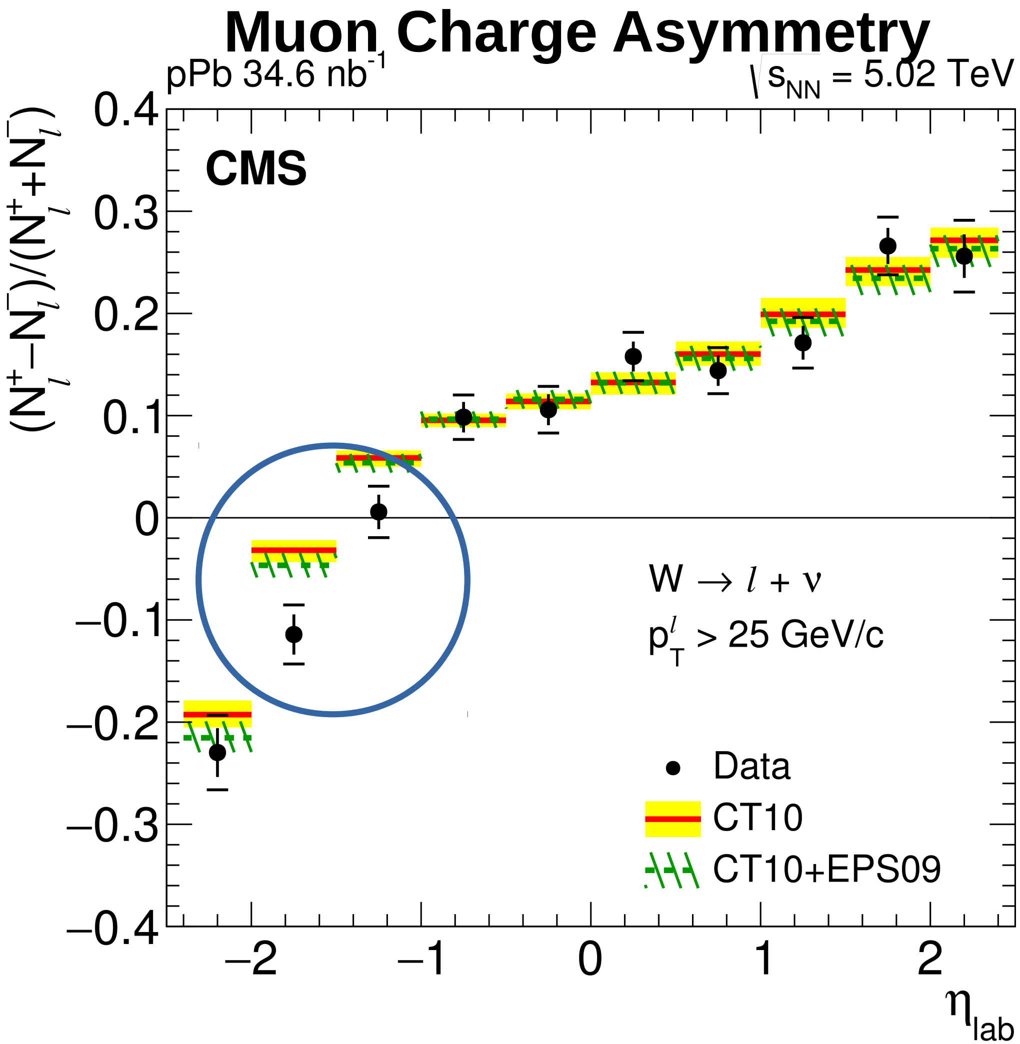


- Measured forward-backward ratios tend to favor the nuclear PDF calculations but uncertainties too large to exclude the free-proton PDF

W in pPb at 5.02 TeV: CMS

Charge asymmetry

$$\frac{N_{\mu^+ \leftarrow W^+} - N_{\mu^- \leftarrow W^-}}{N_{\mu^+ \leftarrow W^+} + N_{\mu^- \leftarrow W^-}}$$

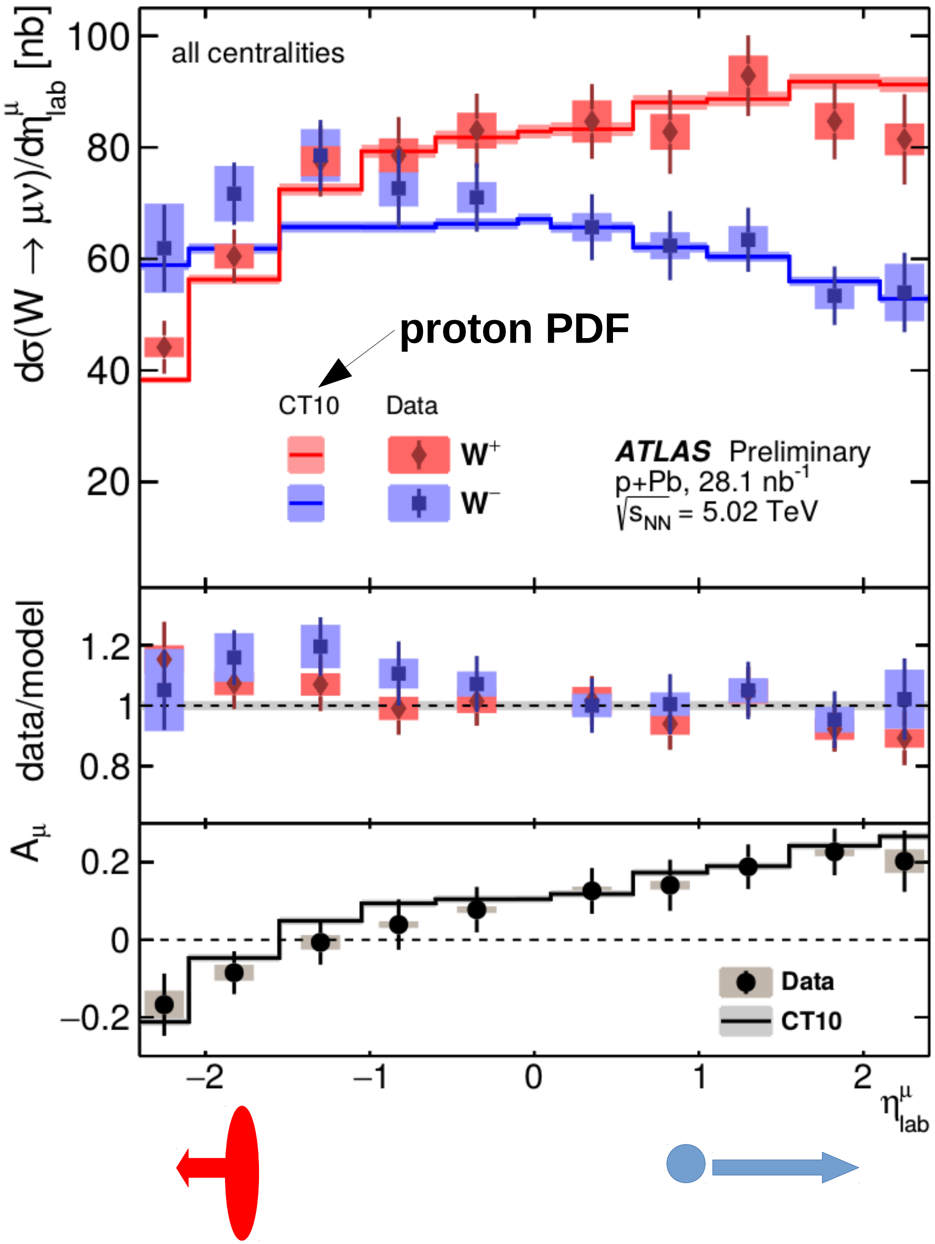


- Muon charge asymmetry insensitive to nuclear corrections. Deviations in data in the backward region might suggest differences between up and down PDFs but more statistics is needed.

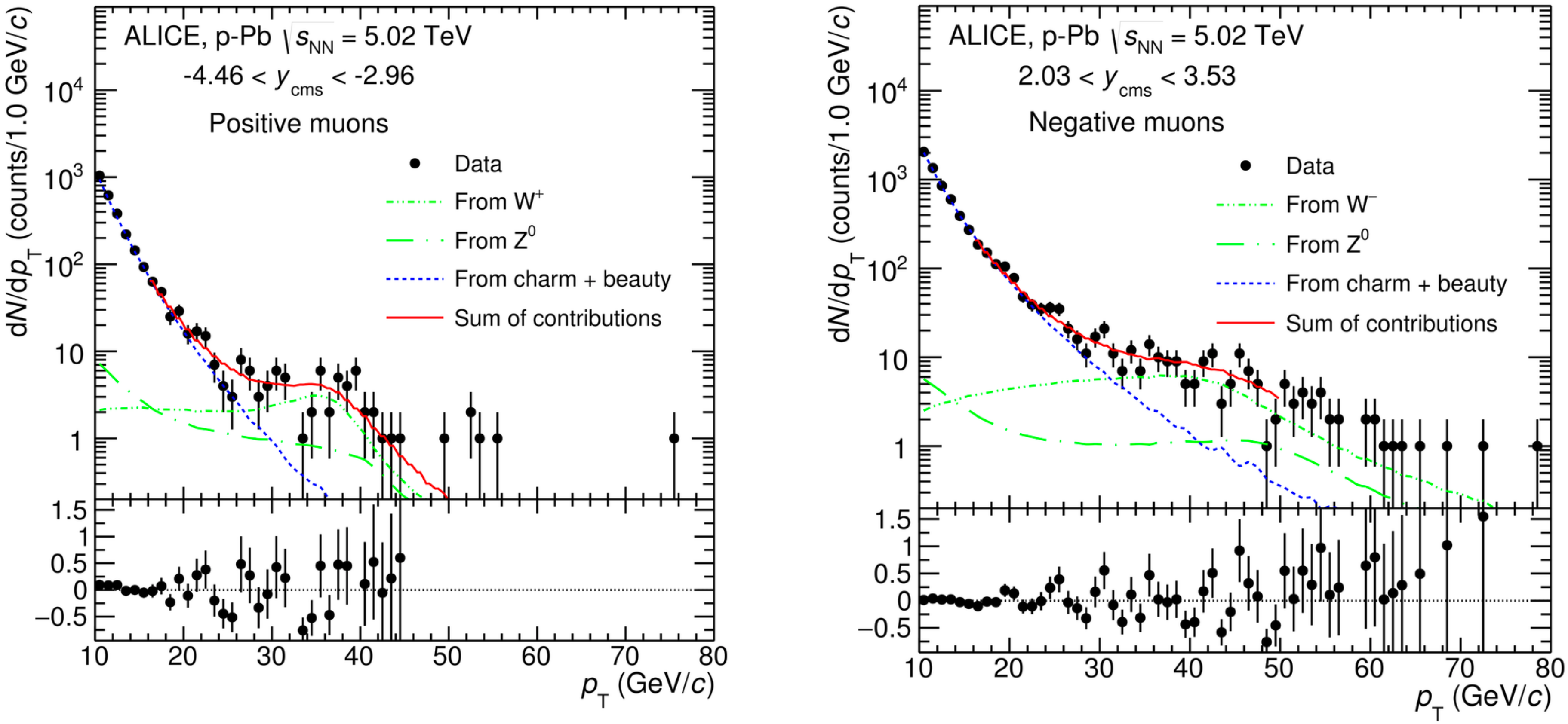
W in pPb at 5.02 TeV: ATLAS

- A small enhancement in data for W^- at backward η compared to proton PDF (similar to CMS).

- Results agree with PDF calculations within uncertainties

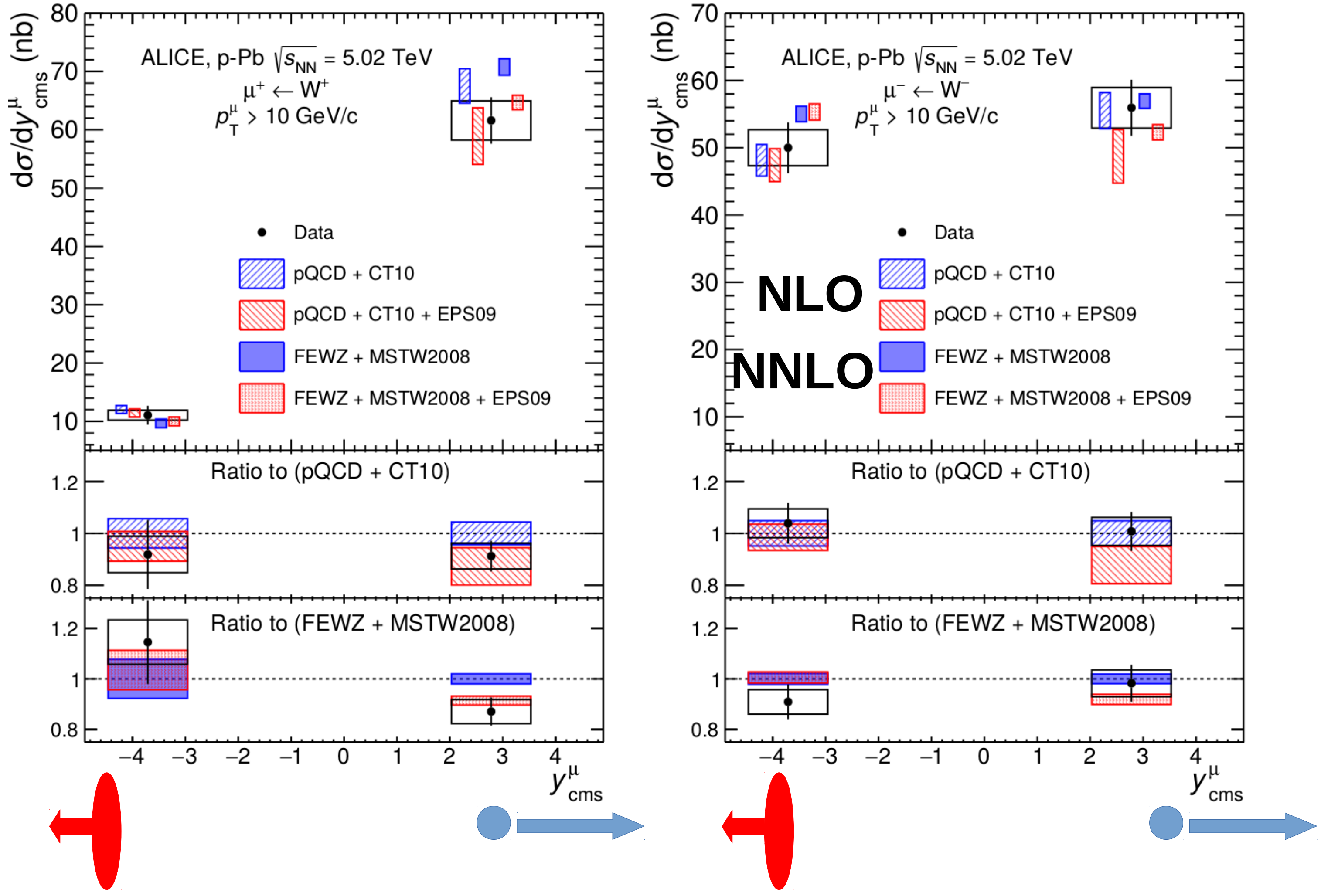


W in pPb at 5.02 TeV: ALICE



- Muon kinematic selection: p_T > 10 GeV/c
- W boson yield extracted by fitting the muon p_T in two forward η bins

W in pPb at 5.02 TeV: ALICE



- Good agreement between proton and nPDF calculations. Not enough statistics to discriminate between the results

W bosons in pPb at 8.16 TeV

W in pPb at 8.16 TeV

Year	$\sqrt{s_{NN}}$	Luminosity (CMS)
2013	5.02 TeV	35 nb^{-1}
2016	8.16 TeV	174 nb^{-1}

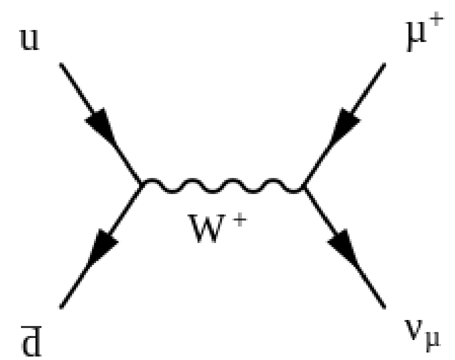
- **W boson** yield **increased** by **~10x** in **2016** data w.r.t. 2013, due to increase of **~2x** in **xsec** and **~5x** in **lumi**

W bosons in pPb

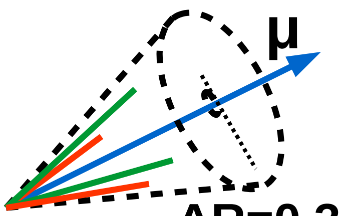
CMS-PAS-HIN-17-007

NEW RESULT CMS

- **Decay channel:** muon + missing momentum



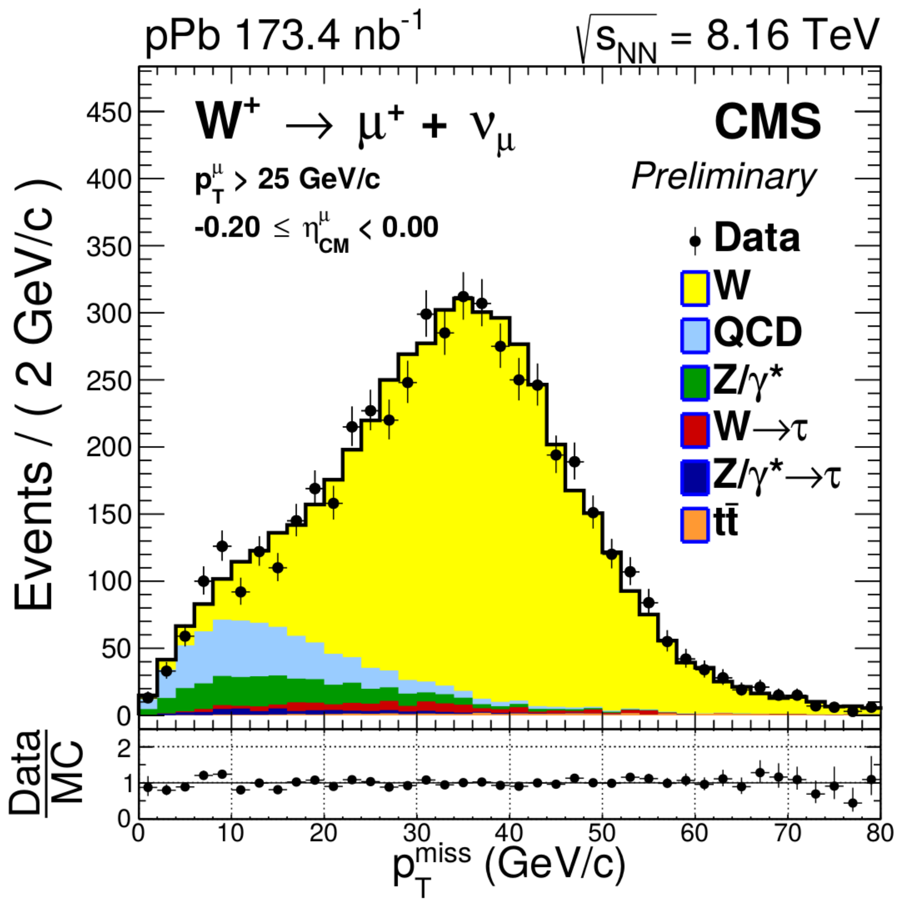
- Objects reconstructed with the **Particle Flow (PF) algorithm**
- **Muon selection:** Leading isolated muon with p_T > 25 GeV/c and $|\eta|<2.4$
- **Muon isolation:** Sum of p_T of PF particles (γ , $h^{\pm}$ & h^0) around the muon < 15% of muon p_T (**suppress multi-jet bkg**)



- **Event selection:**
  - **Veto $Z\rightarrow\mu^-\mu^+$:** Reject events with $\mu^-\mu^+$ pairs, $p^{\mu-}_T$ > 15 & $p^{\mu+}_T$ > 15 GeV/c
- **Dominant backgrounds:** QCD jet→muon passing isolation, and Z→muon + (missing muon)

W bosons in pPb

CMS-PAS-HIN-17-007

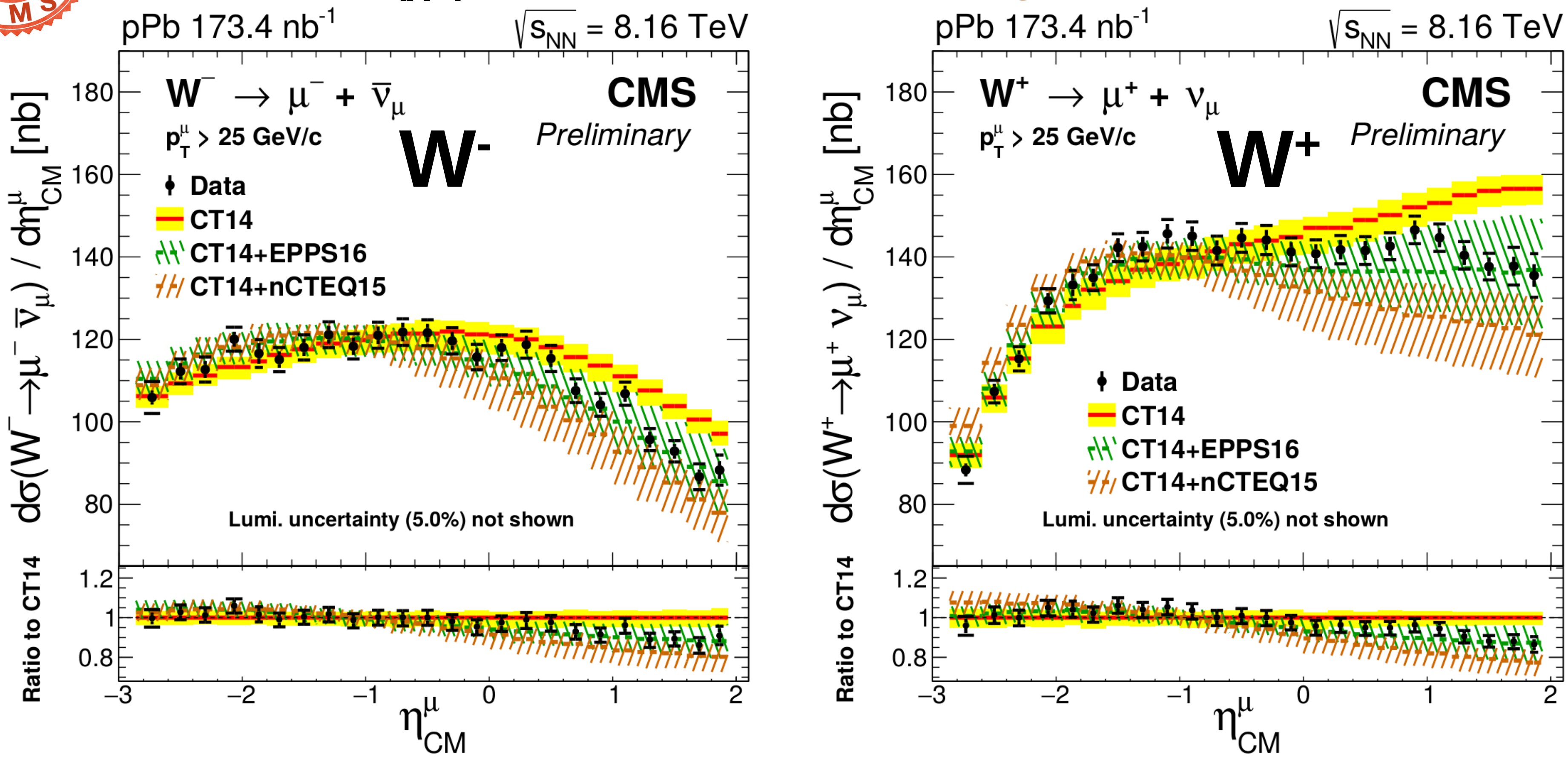


- **Simulation:** pPb NLO POWHEG v2 including CT14+EPPS16 nPDF
- **Signal and electroweak background:** Template from **simulation**
- **QCD multi-jet background:** **Data-driven** functional form
- **Extraction:** Fits of the **missing p_T** distribution in 24 bins of muon η_{CM}

W boson: cross section

CMS-PAS-HIN-17-007

$P(\chi^2)$ = <0.01% CT14 , 79% nCTEQ15 , 96% EPPS16

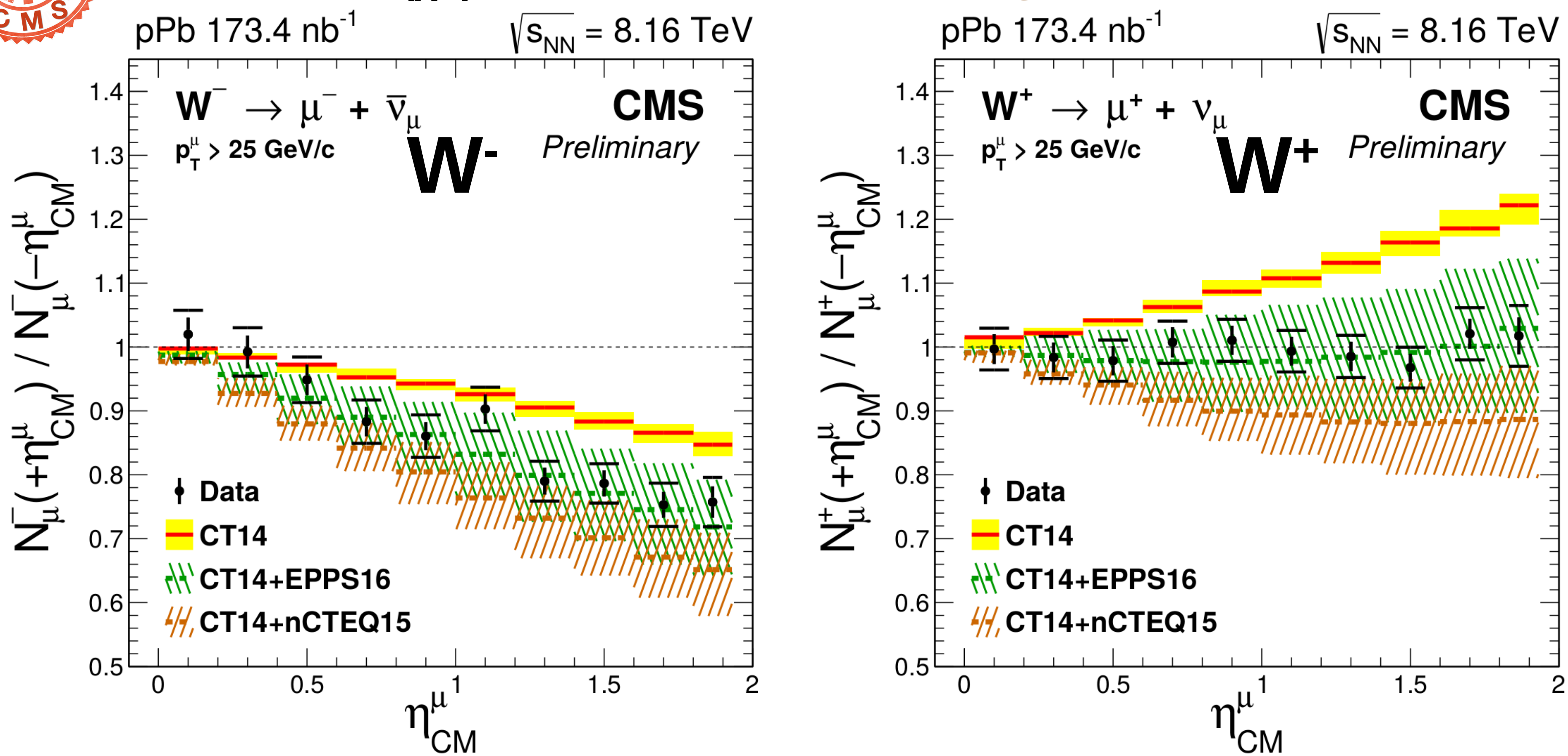


- **η_{CM} < 0 (large x_{Pb})**: Results **agree** with **PDF** and **nPDF** calculations
- **η_{CM} > 0 (small x_{Pb})**: Results **favor** the **nuclear PDF** calculations

W boson: forward-backward ratio

CMS-PAS-HIN-17-007

P(χ^2) = <0.01% CT14 , 83% nCTEQ15 , 95% EPPS16



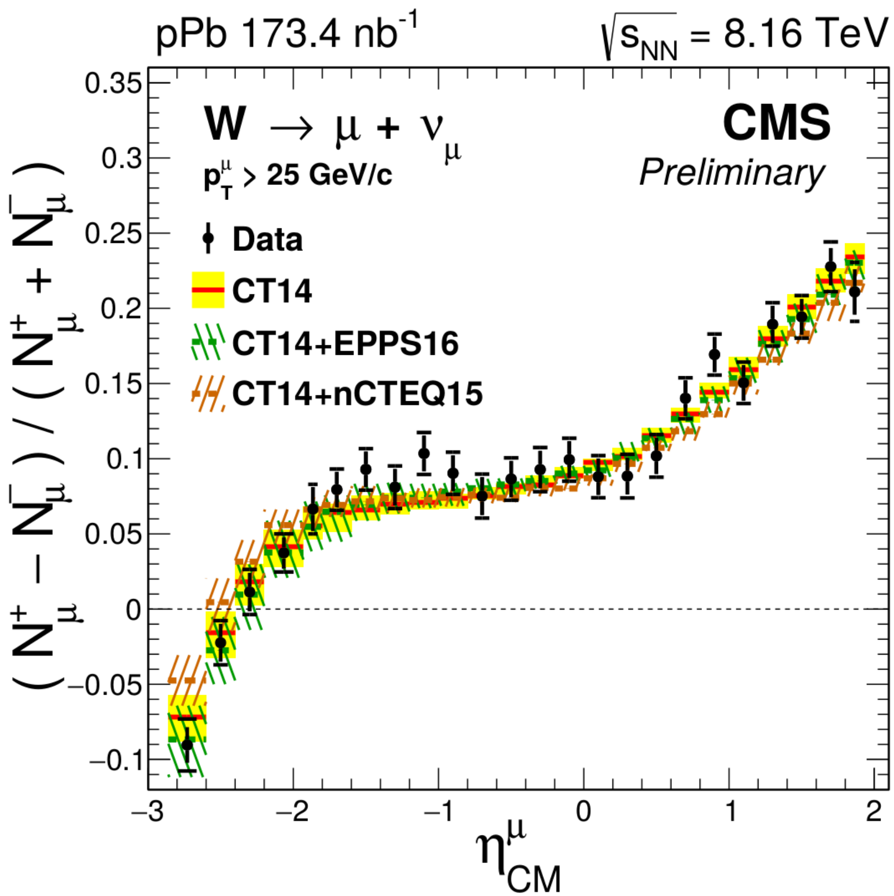
- Uncertainties fully correlated in η_{CM} cancels (correlations included)
- **Exclude** (>7σ) **free-nucleon PDF** calculations
- Experimental uncertainties smaller than nPDF uncertainties

W boson: charge asymmetry

CMS NEW RESULT

CMS-PAS-HIN-17-007

P(χ^2) = 54% CT14 , 23% nCTEQ15 , 80% EPPS16



- nPDF effects cancel, except for different up / down quark modification
- **All (n)PDF** calculations **reproduce** the **measurements**

SUMMARY

SUMMARY

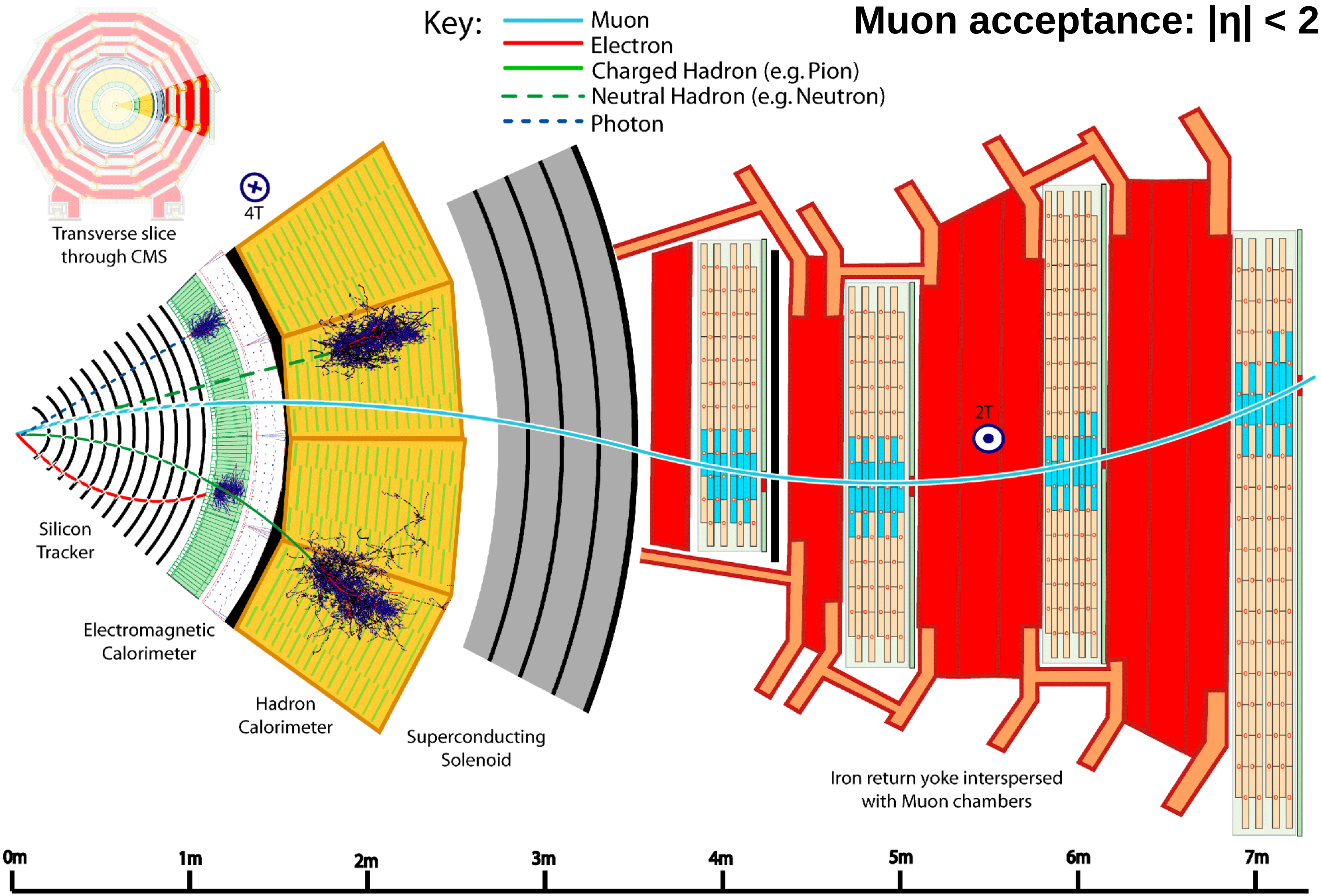
- The study of weak boson production in pPb provides a powerful tool to constrain the nuclear modifications of the quark PDFs.
- Z and W boson production measured in pPb at 5.02 TeV are in good agreement with PDF calculations with and without nuclear corrections.
- The results of the W boson production at 8.16 TeV presents the **observation** of **nuclear modifications** of the **(anti) quark** PDFs by excluding the free-proton PDF.
- W boson production at 8.16 TeV measurements are in good agreement with EPPS16 nPDF calculations and its experimental uncertainties are smaller than the PDF uncertainties.

Thank you for your attention!

BACKUP

CMS detector

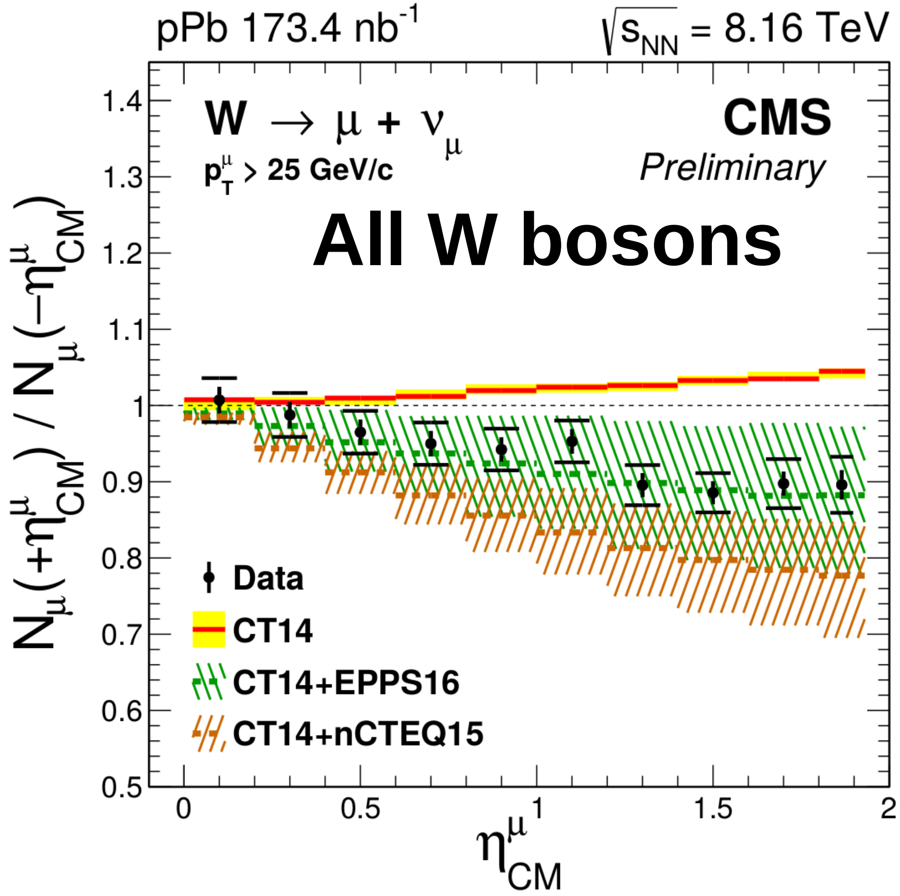
Muon acceptance: |η| < 2.4



W boson: forward-backward ratio

CMS-PAS-HIN-17-007

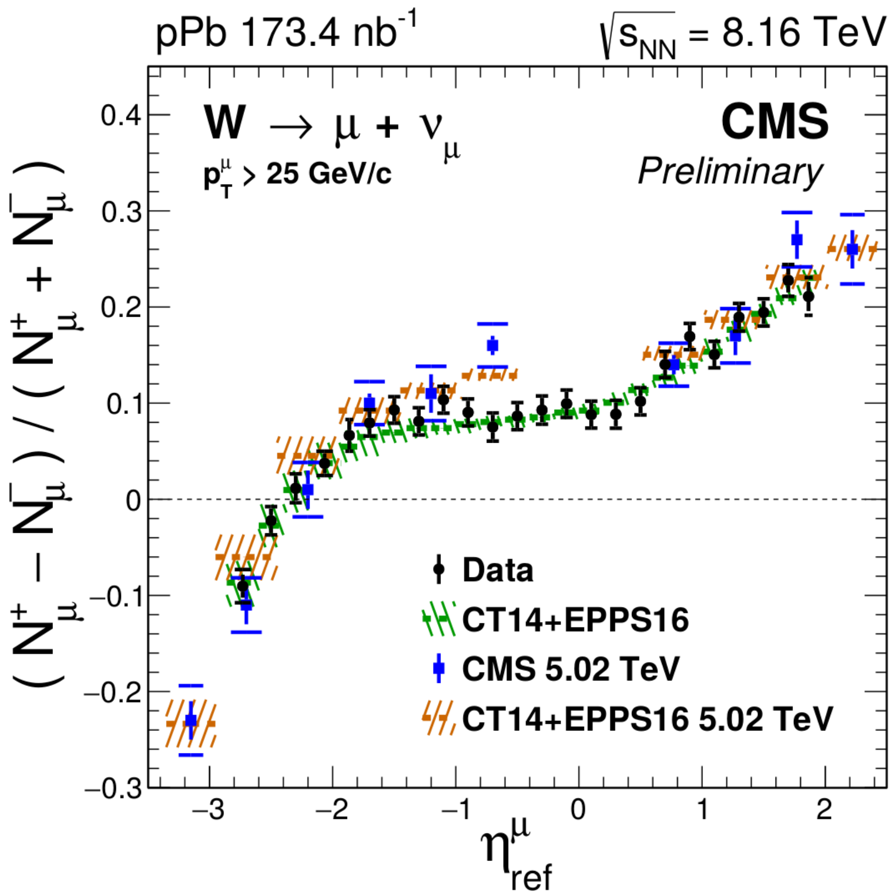
P(χ^2) = <0.01% CT14 , 90% nCTEQ15 , 99% EPPS16



- **Strongly deviate from CT14** calculations **favoring EPPS16**
- Experimental uncertainties significantly smaller than nPDF uncertainties

W boson: charge asymmetry

CMS-PAS-HIN-17-007



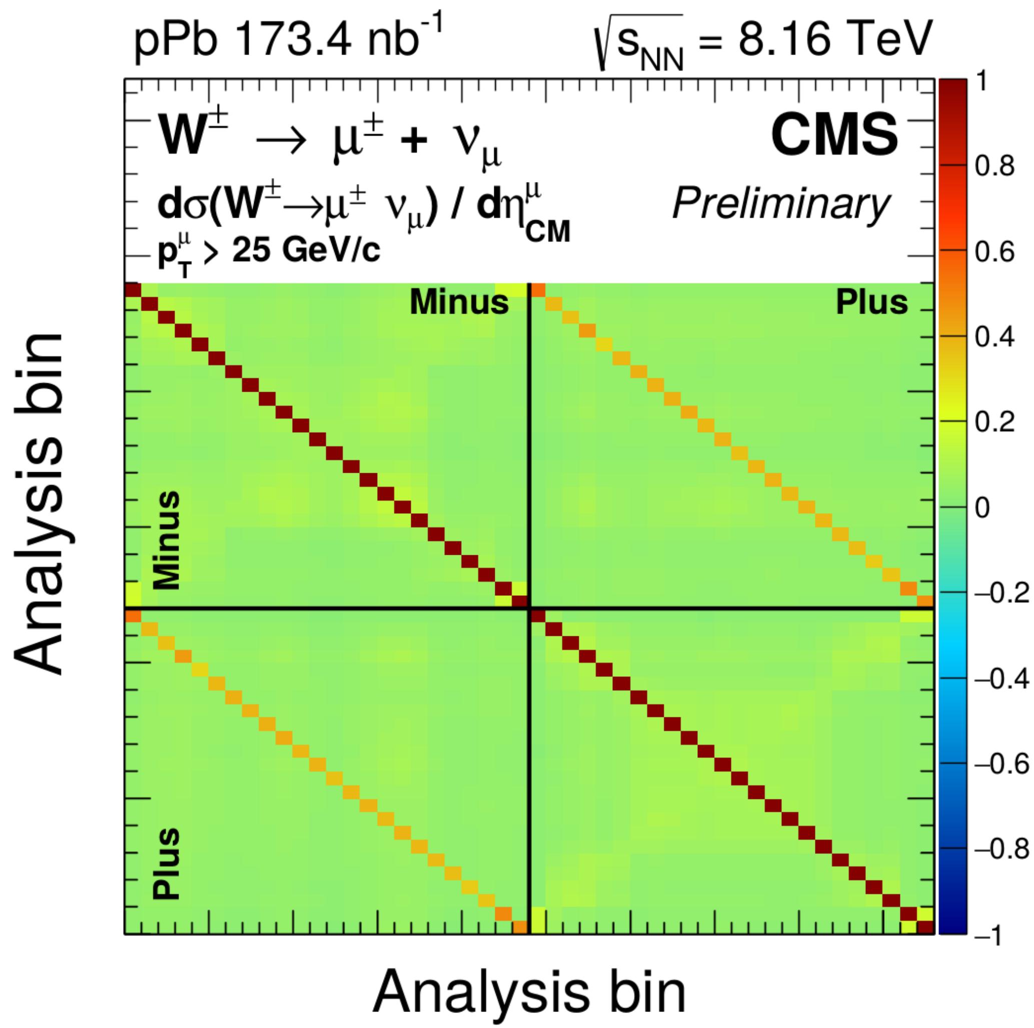
$$\eta^{\mu}_{\mathrm{ref}} = \eta^{\mu}_{\mathrm{CM}} \pm \ln\left(\frac{8.16\ \mathrm{TeV}}{\sqrt{s_{\mathrm{NN}}}}\right), \eta^{\mu}_{\mathrm{CM}} \gtrless 0$$

- Good agreement between measurement at 8.16 TeV and 5.02 TeV after shifting the η_{CM} taking into account the difference in energy

W boson: correlation matrix

CMS NEW RESULT QM18

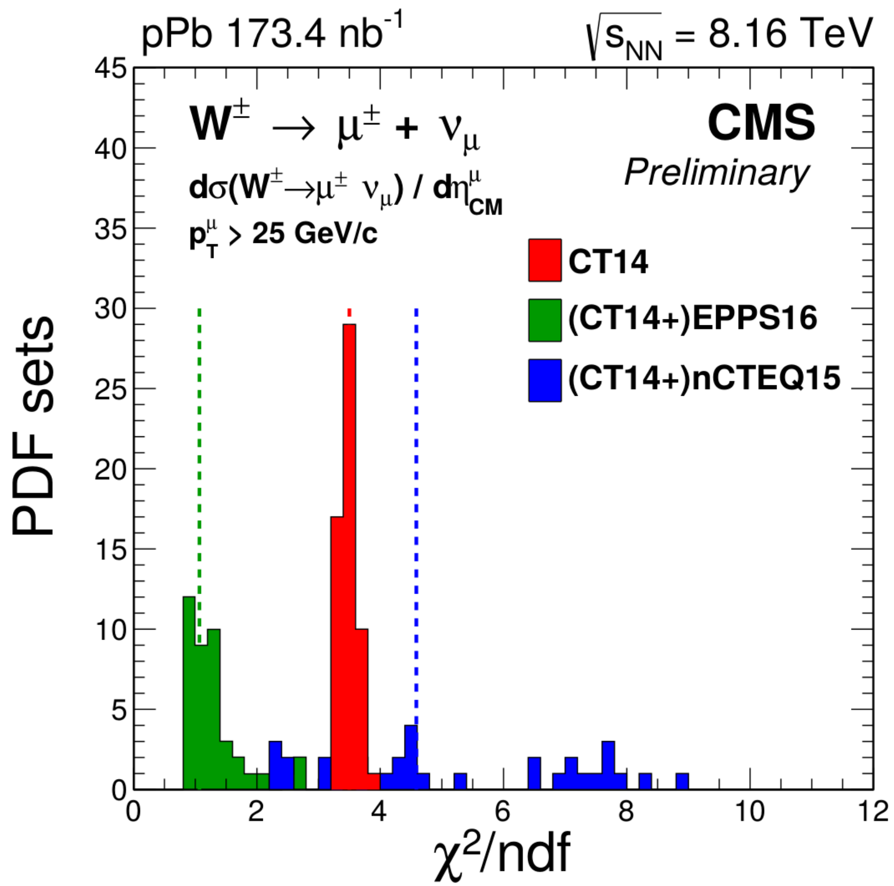
CMS-PAS-HIN-17-007



- W boson cross section measurement almost uncorrelated in muon pseudorapidity, while a bit correlated in muon charge

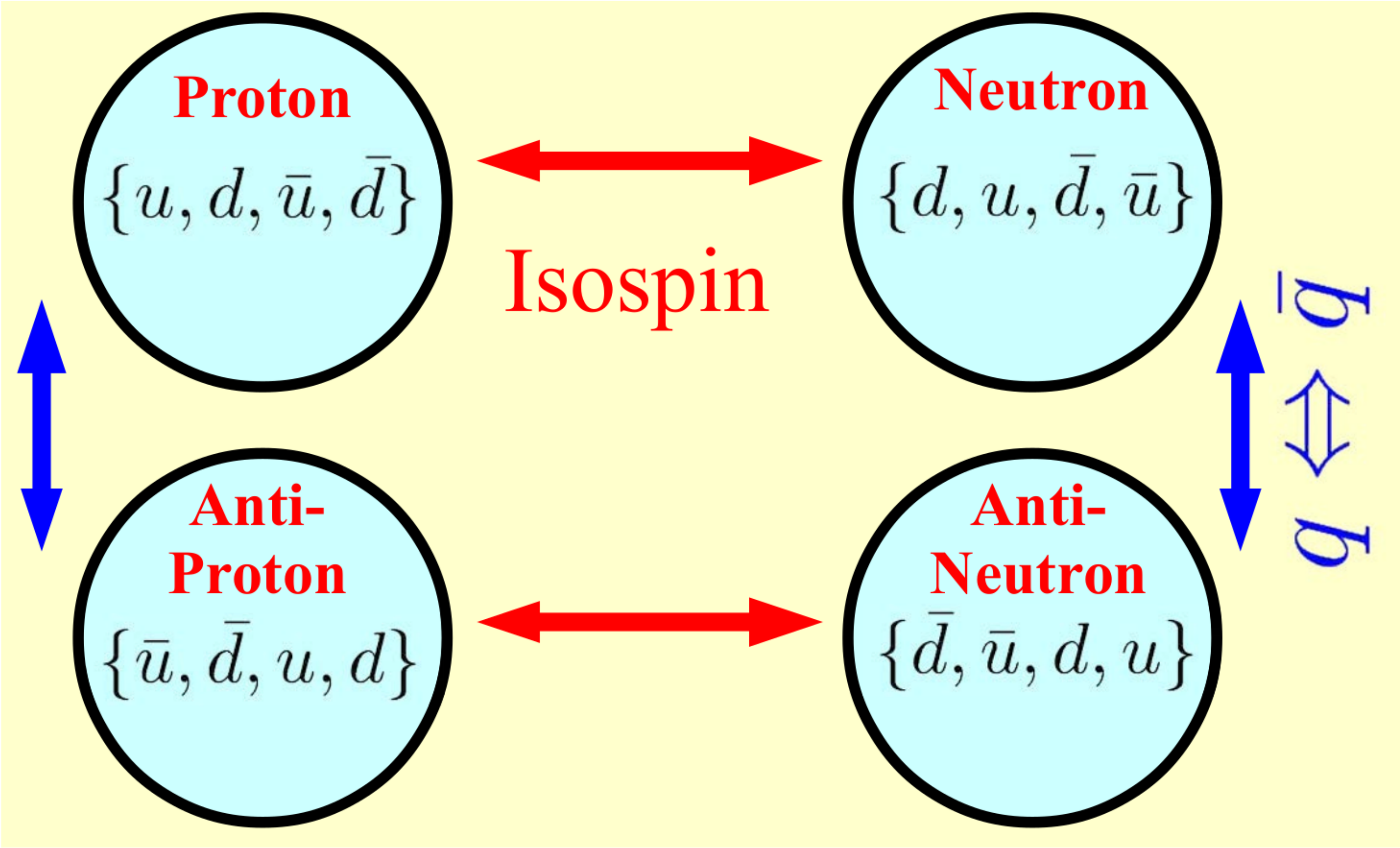
W boson: PDF comparison

CMS-PAS-HIN-17-007



- Compute χ^2 test between the measurements and each individual PDF set
- Good agreement between data and EPPS16 nPDF

Neutron nPDF

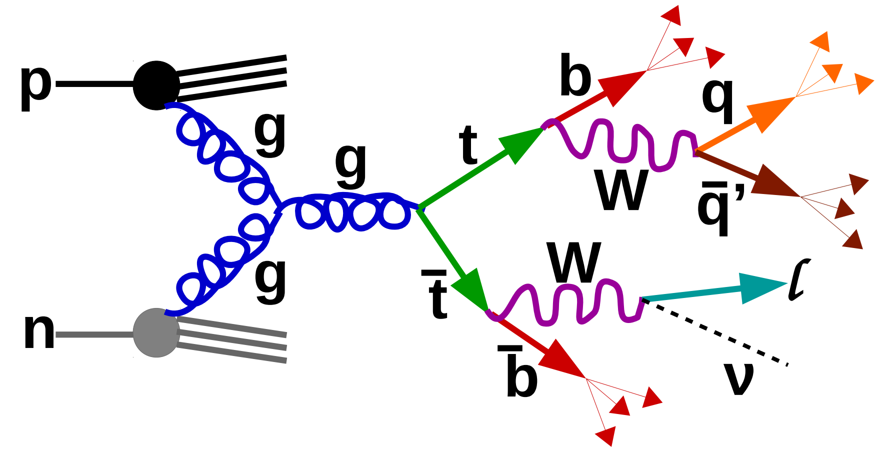


- Use isospin symmetry to correlate the proton PDF with the neutron PDF in the Pb ion, taking into account the right proportions of each: 82 protons and 126 neutrons

Top quarks in pPb collisions

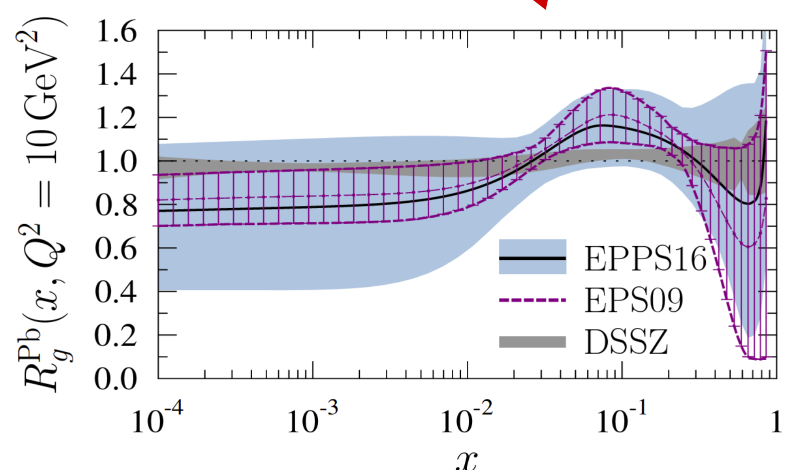
Dominant production modes:

gluon → $t\bar{t}$



- Top quarks decay before interacting with the medium

- Measurement of top quark and dijet production probe modifications to gluon PDF



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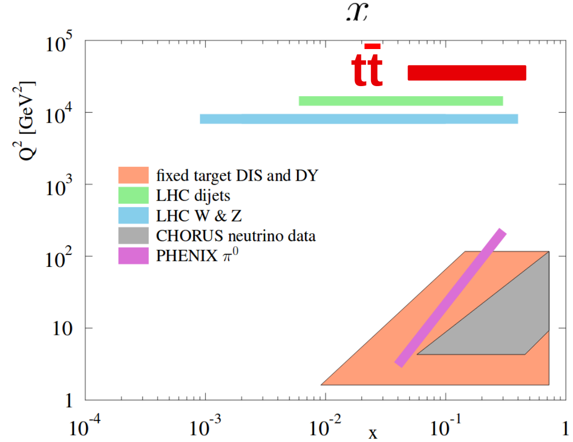
- Top quarks constrain the high x (**x>0.05**) and high Q (**$Q^2 \sim m^2_{top}$**) region



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Top quarks in pPb

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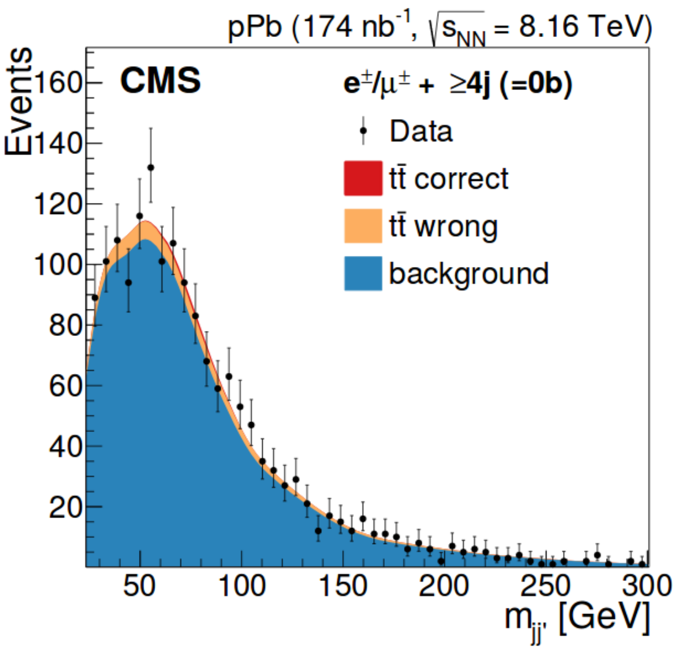
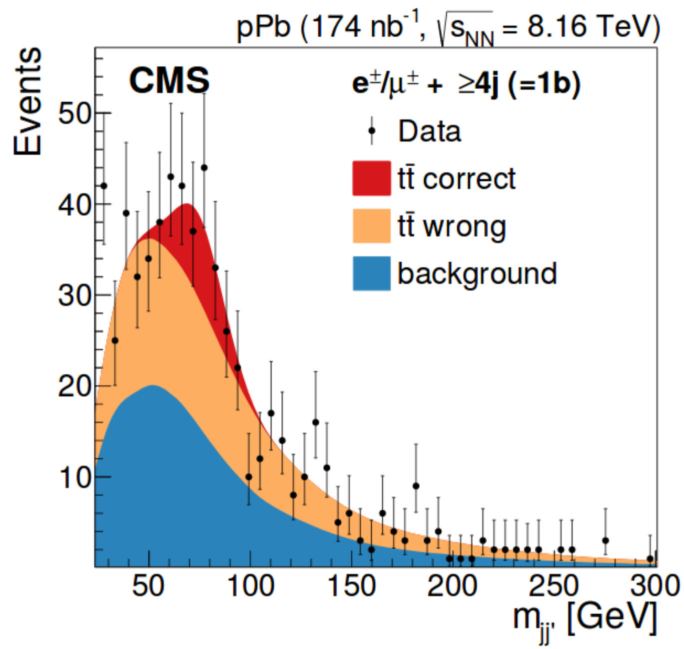
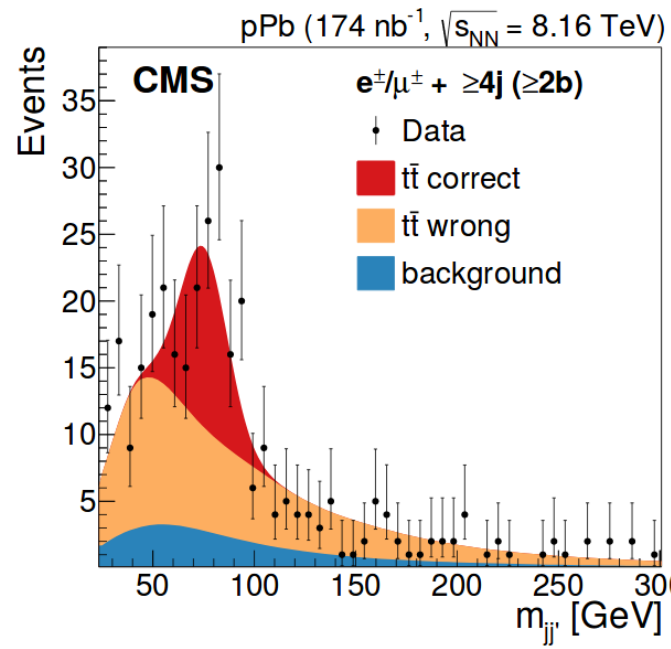
0 b-tagged jets



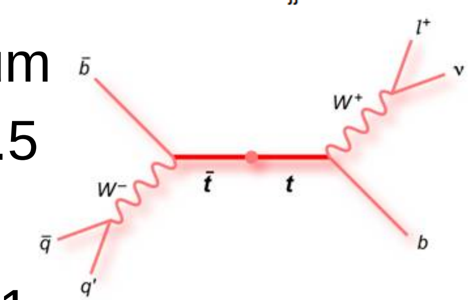
1 b-tagged jet



>=2 b-tagged jets



- **Decay channel:** >=4 jets + lepton (μ or e) + missing momentum
- **Jet Selection:** Anti-k_T (ΔR=0.4) jet with p_T > 25 GeV/c & $|\eta|$<2.5
- **B-quark tagger:** Based on combined secondary vertex
- **Lepton Selection:** Isolated lepton with p_T > 30 GeV/c & $|\eta|$<2.1
- **Extraction:** Fits of the **W→jj'** mass using functional forms in different b-jet and lepton flavor categories, **without relying on simulation**



Top quarks: cross section

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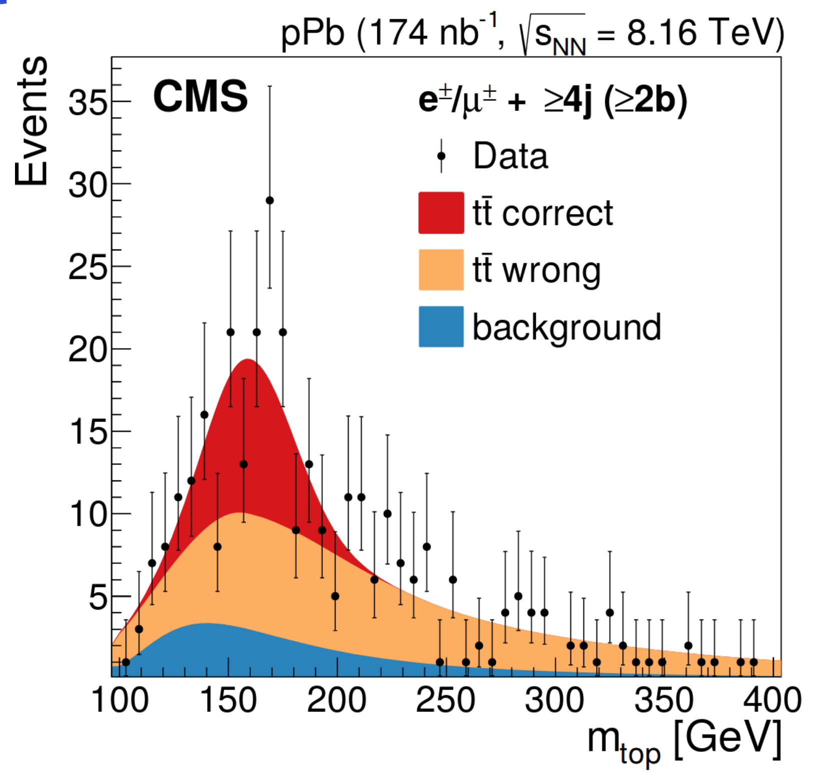
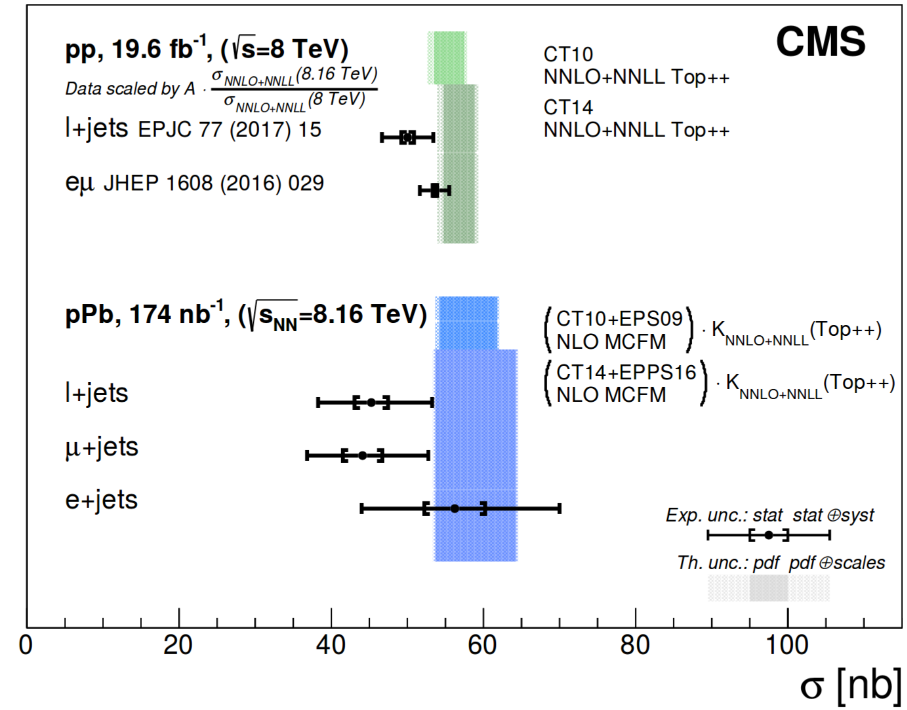
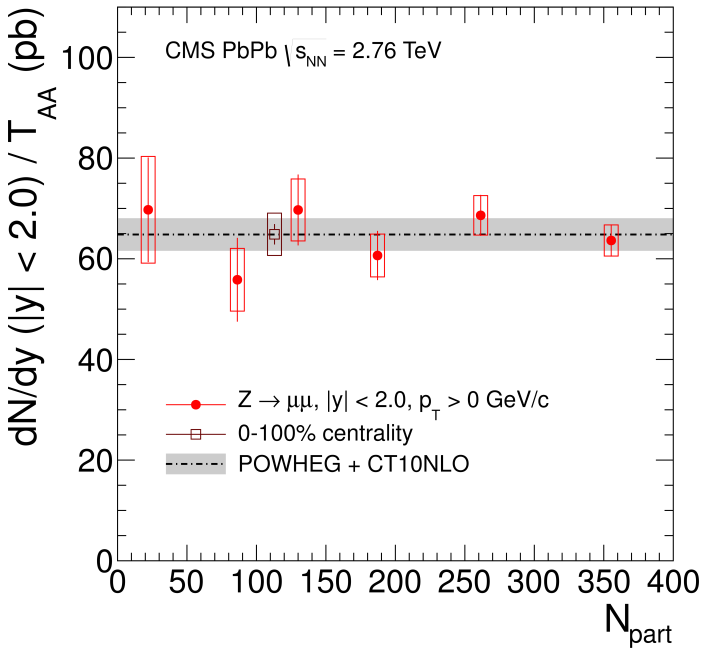
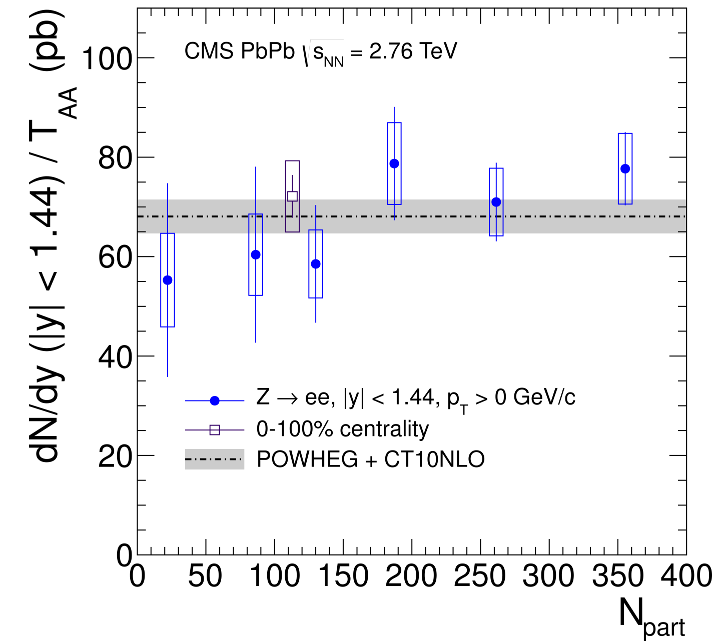


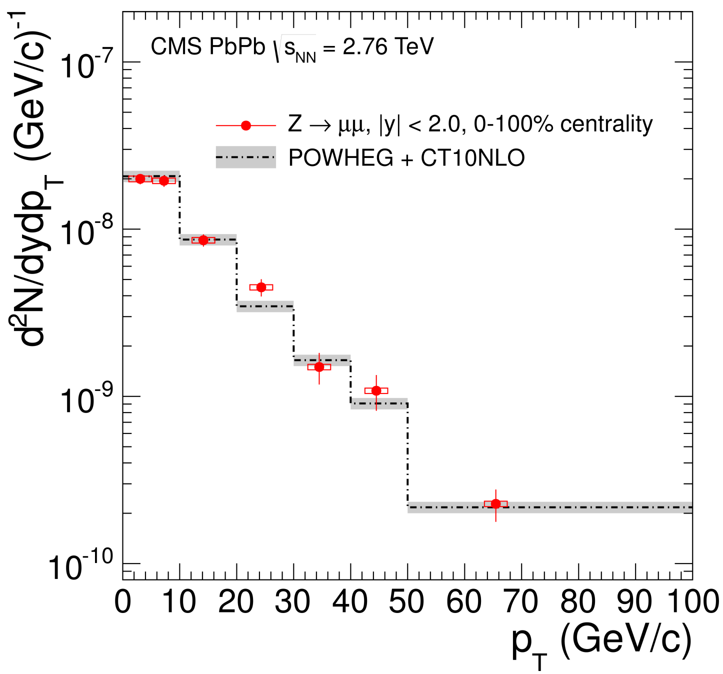


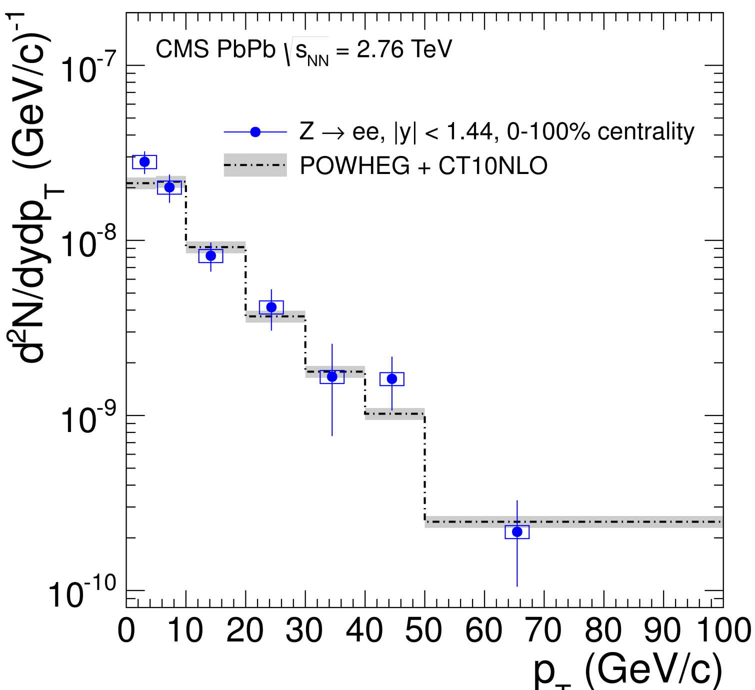
- **First observation** (**>5σ**) of **top quark** production in **pPb** collisions!
- Inclusive cross section (45±8 nb) in agreement with NNLO+NNLL pQCD interfaced to NLO proton/nuclear PDF calculations

Z in PbPb at 2.56 TeV: CMS

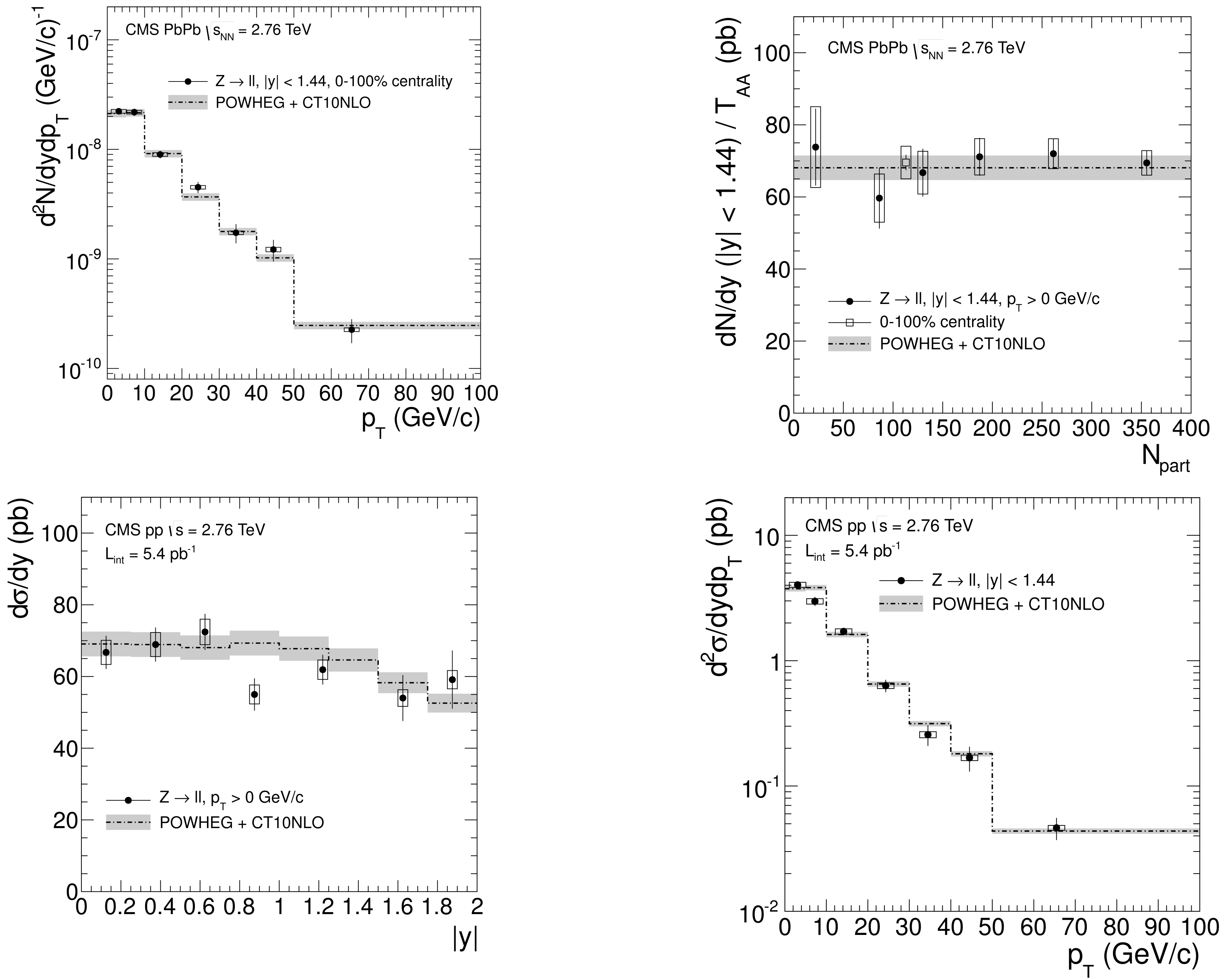




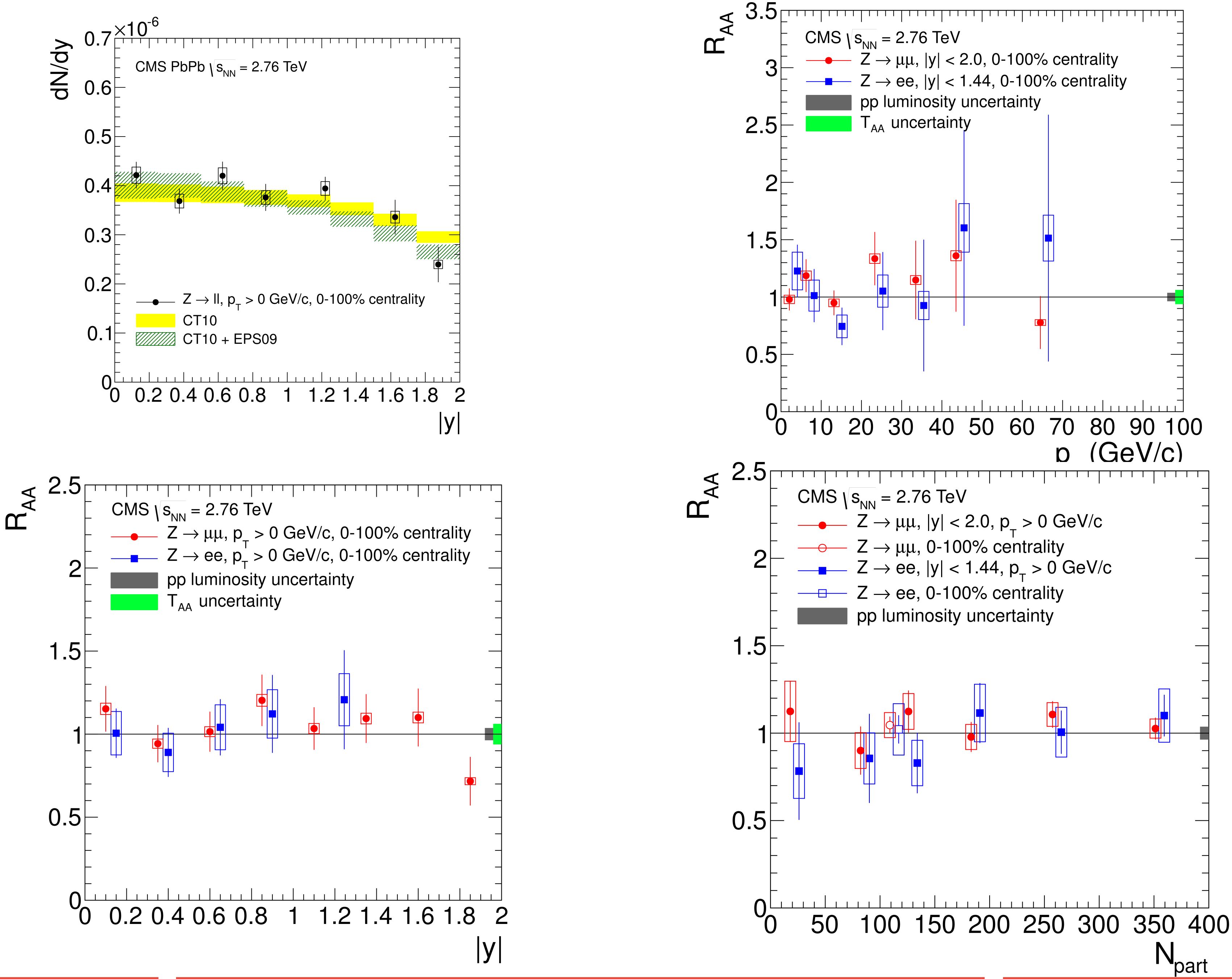




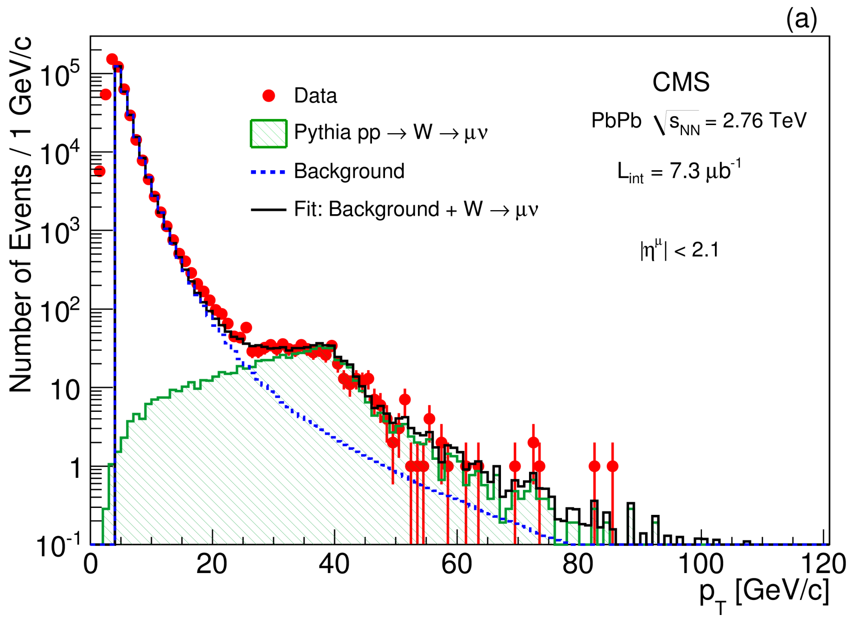
Z in PbPb at 2.56 TeV: CMS

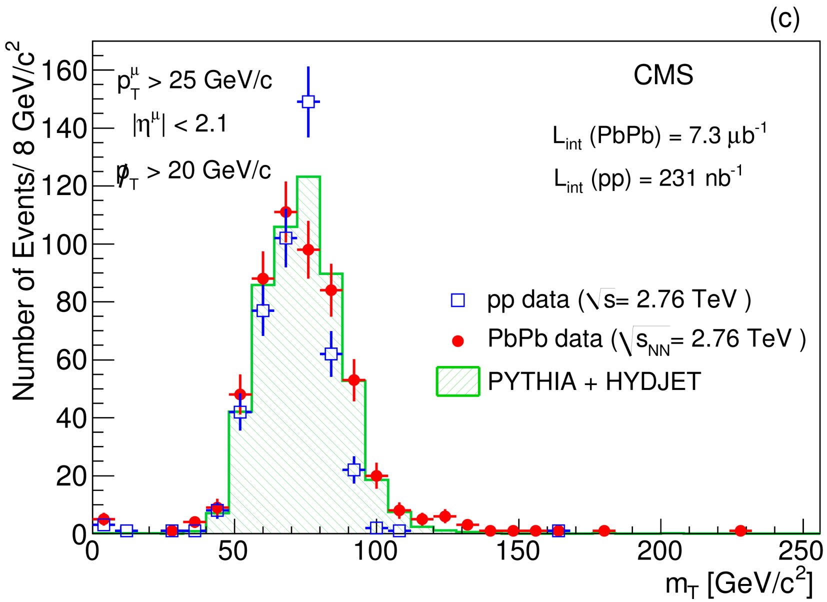


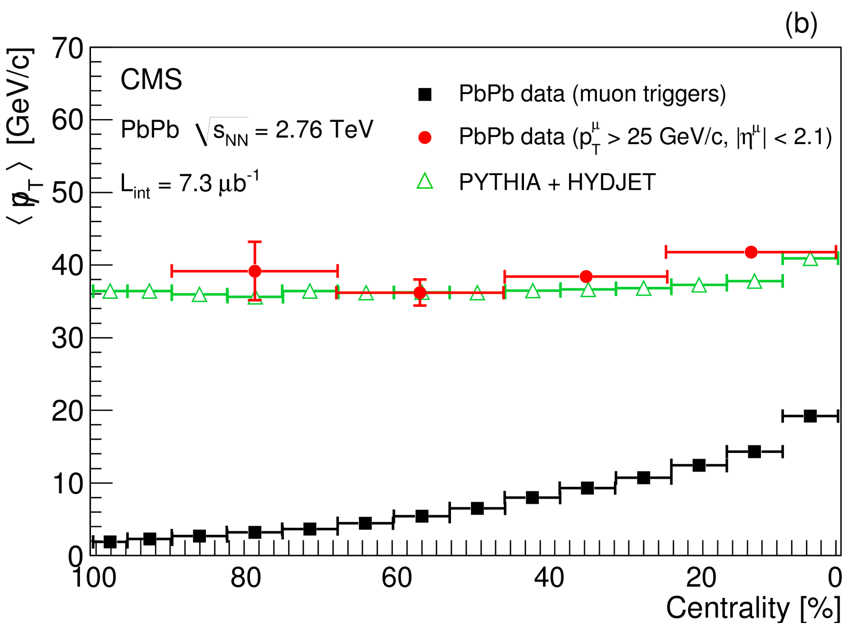
Z in PbPb at 2.56 TeV: CMS

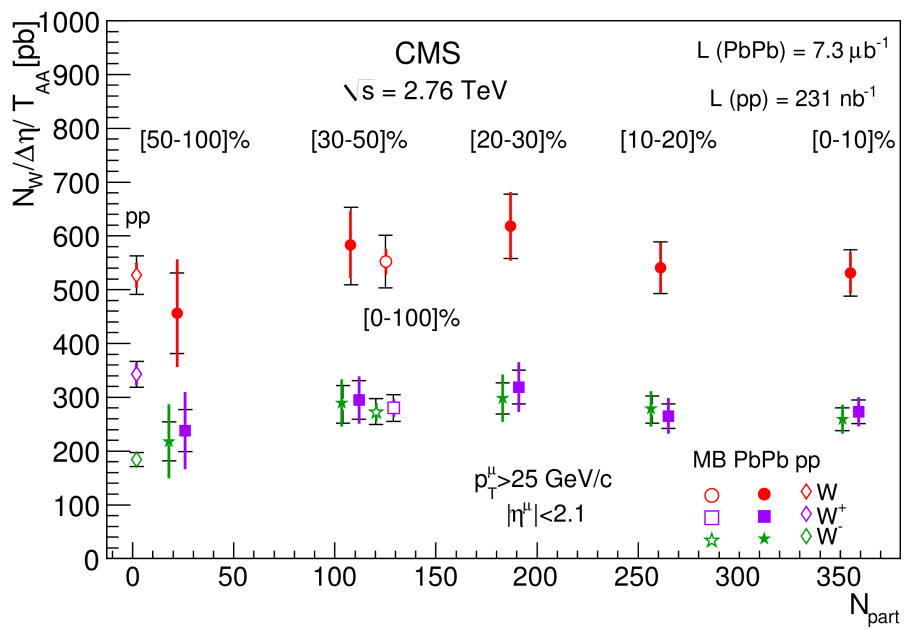


W in PbPb at 2.56 TeV: CMS









W in PbPb at 2.56 TeV: CMS