W and Z bosons with CMS

and other fun facts about the W boson

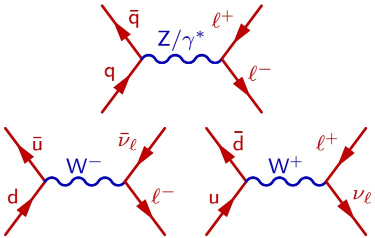
Émilien Chapon

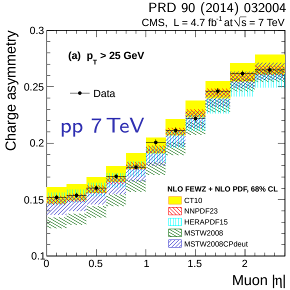
Laboratoire Leprince-Ringuet, École polytechnique, Palaiseau

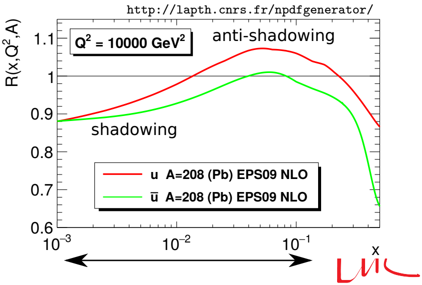
QGP France 2015, Étretat

European Research Council
Established by the European Commission

- Not affected by final state effects in the medium (early produced in collisions)
- Sensitive to initial state effects:
  - isospin effect (different between pp, pn and nn binary collisions, mostly W): well-known.
  - nuclear modifications of the PDFs (in particular quark PDFs).







Electroweak bosons in heavy ion collisions

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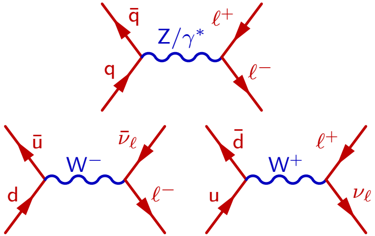
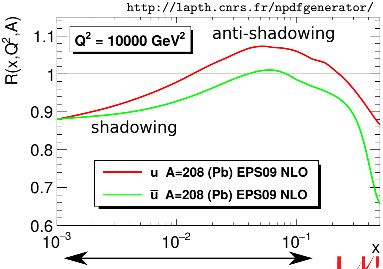
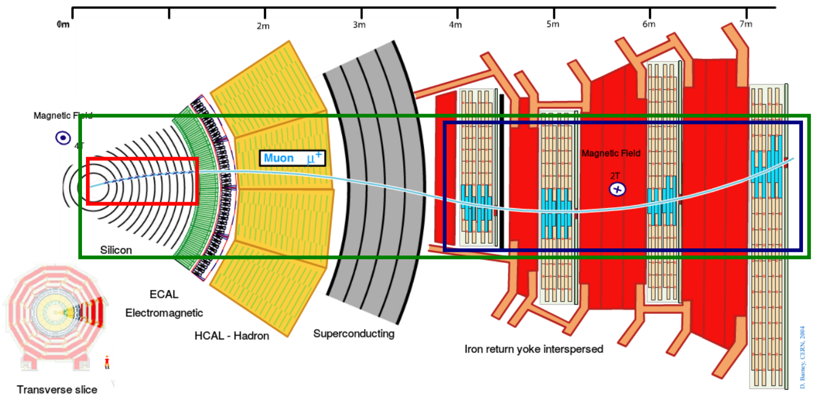


Outline

1. W and Z bosons in CMS
   - The CMS experiment
   - W and Z bosons in PbPb and pp
   - Z boson in pPb
   - W boson in pPb
2. Scaling of W boson production

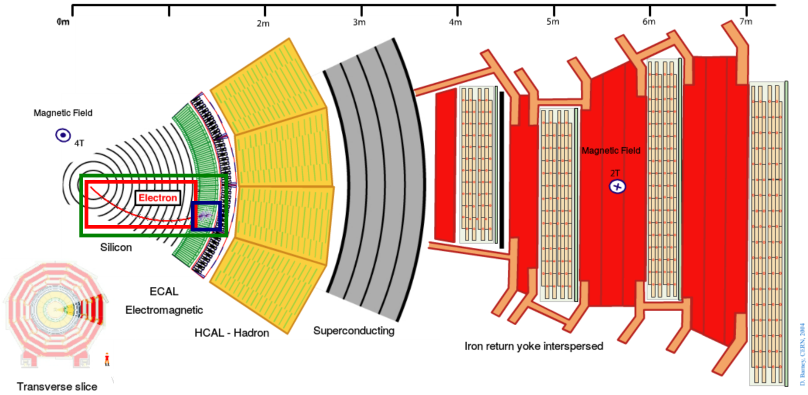


Electrons and muons in the CMS experiment



- *Muon reconstruction*: silicon tracker + muon sub-detectors
- *Electron reconstruction*: tracks associated with an ECAL cluster
- $\not\!\!E_T$ *reconstruction* thanks to the hermetic detector
  - using silicon tracks (PbPb) or particle flow (pPb)

Electrons and muons in the CMS experiment



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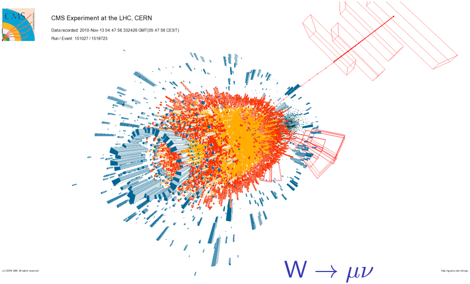
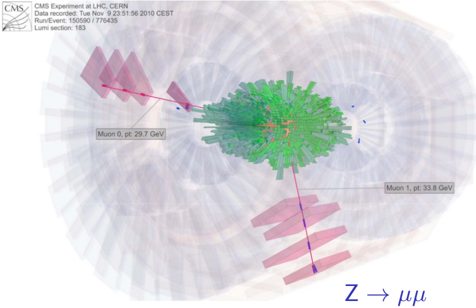
W and Z bosons in PbPb ($\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$)

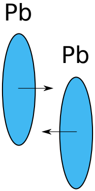
PLB 715 (2012) 66, JHEP 03 (2015) 237



W $\rightarrow \mu\nu$

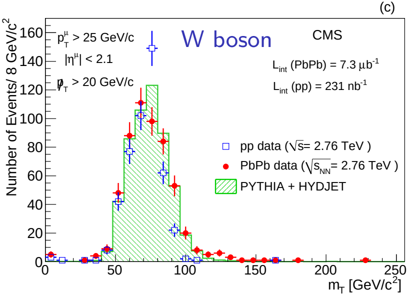


Z $\rightarrow \mu\mu$



W and Z bosons in PbPb and pp: event kinematics

PLB 715 (2012) 66, JHEP 03 (2015) 237



$$m_T = \sqrt{2 p_T^\mu \not{p}_T (1 - \cos\phi)}$$

- Data: 2010 (PbPb), 2011 (pp)
- Muon channel only
- $|\eta^\mu| < 2.1$,
  $p_T^\mu > 25\,\mathrm{GeV}/c$,
  $\not{p}_T > 20\,\mathrm{GeV}/c$
- $\not{p}_T$ reconstructed using silicon tracks.

W and Z bosons in PbPb and pp: event kinematics

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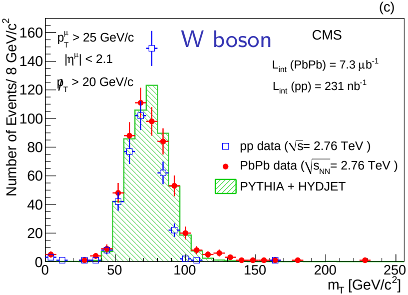

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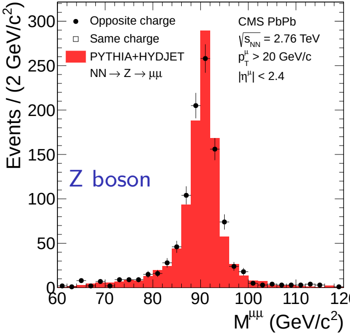

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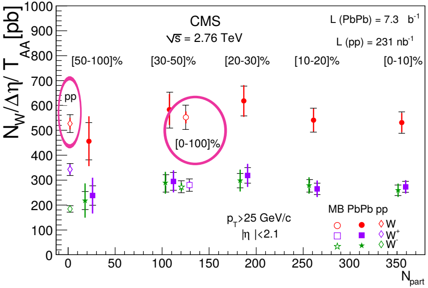
- $\not{p}_T$ reconstructed using silicon tracks.

- Data: 2011 (PbPb), 2013 (pp)
- Muon and electron channels
- $|\eta^{\mu(e)}| < 2.4\,(1.44)$,
  $p_T^\ell > 20\,\mathrm{GeV}/c$,
  $M_{\ell\ell} \in [60, 120]\,\mathrm{GeV}/c^2$

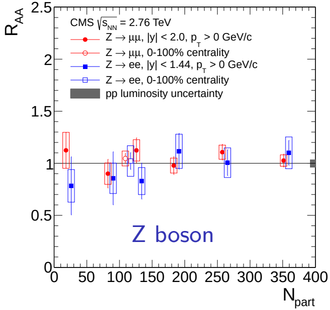
W and Z bosons in PbPb and pp: nuclear modification factor

PLB 715 (2012) 66, JHEP 03 (2015) 237

W boson



$$\left(\frac{1}{T_{AA}}\right)\frac{N_W}{\Delta\eta}$$



$$R_{AA} = \frac{N_{AA}}{N_{coll} N_{pp}}$$

$$R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$$

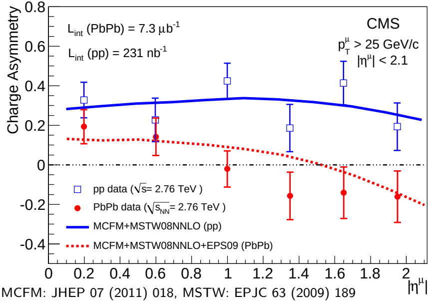
$$R_{AA}(Z \to \mu\mu) = 1.05 \pm 0.05 \pm 0.08$$
$$R_{AA}(Z \to ee) = 1.02 \pm 0.08 \pm 0.15$$

- Nuclear modification factor consistent with 1
- No dependence on centrality

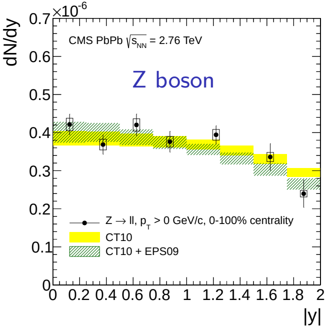
W and Z bosons in PbPb and pp: nuclear effects?

PLB 715 (2012) 66, JHEP 03 (2015) 237

W boson



MCFM: JHEP 07 (2011) 018, MSTW: EPJC 63 (2009) 189



CT10: PRD 82 (2010) 074024, EPS09: JHEP 0904 (2009) 065

$$\text{Charge asymmetry} = \frac{dN(W^+) - dN(W^-)}{dN(W^+) + dN(W^-)}$$

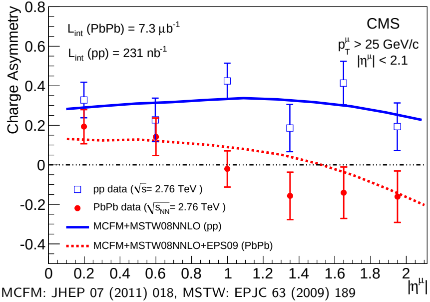
- Large isospin effect
- No sensitivity to nPDF

- Some nPDF sensitivity but limited statistics

W and Z bosons in PbPb and pp: nuclear effects?

PLB 715 (2012) 66, JHEP 03 (2015) 237

W boson



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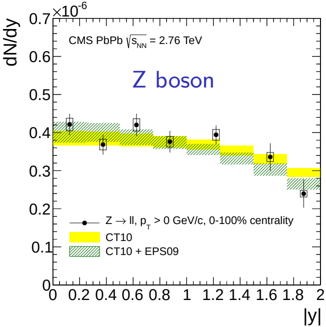

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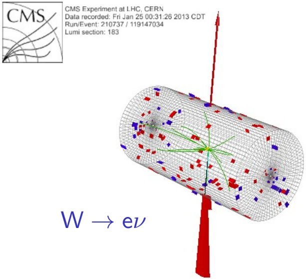
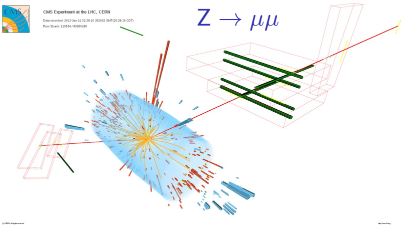
What about proton-lead collisions?

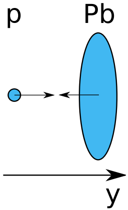
Electroweak bosons in pPb collisions





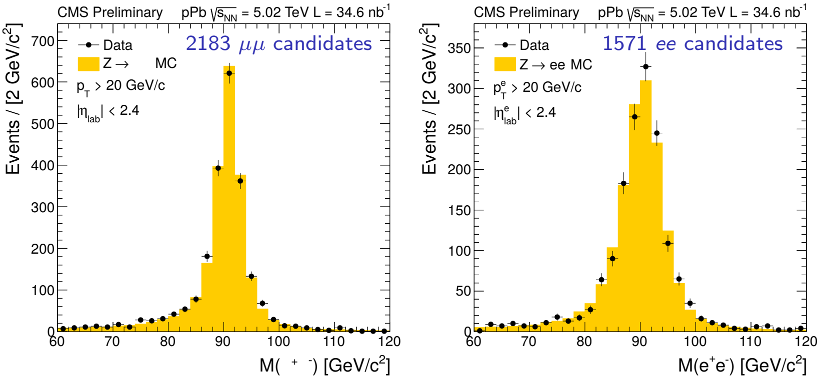
Asymmetric collisions:

- forward / backward asymmetries
  $R_{FB} = N(+y)/N(-y) = N(\text{p-going})/N(\text{Pb-going})$
- Better sensitivity to nPDF (probing a single x_{Pb} at a given rapidity)
- $|\Delta y| = 0.465$ rapidity boost between c.m. and lab frames



Z boson: event kinematics

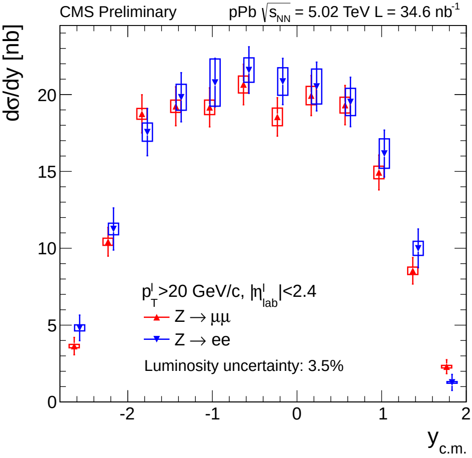
CMS-PAS-HIN-15-002



- Electron and muon channels
- $|\eta^\ell| < 2.4$, $p_T^\ell > 20\,\mathrm{GeV}/c$ (fiducial region)
- $M_{\ell\ell} \in [60, 120]\,\mathrm{GeV}/c^2$

Z boson: fiducial cross subsection vs. rapidity

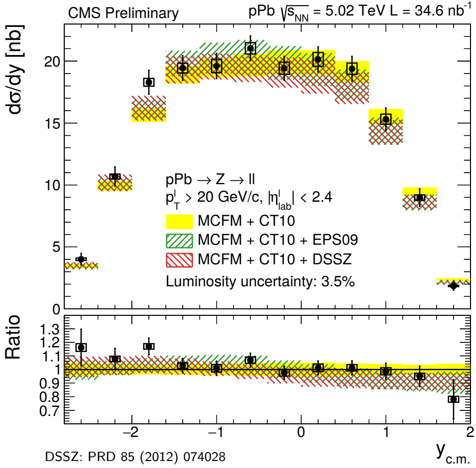
CMS-PAS-HIN-15-002



- Good agreement between electron and muon: combine the measurements

Z boson: fiducial cross section vs. rapidity

CMS-PAS-HIN-15-002



DSSZ: PRD 85 (2012) 074028

$\sigma_{pPb\to Z\to\ell\ell}$ (data) =
$71.3\pm1.2(\mathrm{stat})\pm1.5(\mathrm{syst})\pm2.5(\mathrm{lumi})$ nb

$\sigma_{pPb\to Z\to\ell\ell}$ (POWHEG+PYTHIA) =
70.4 ± 3.5 nb

- Also available: acceptance-corrected results
- Comparison with MCFM with and without nPDFs (DSSZ, EPS09)

Z boson: fiducial cross section vs. rapidity

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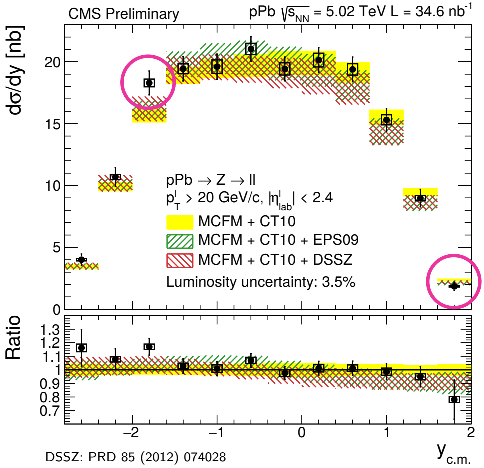

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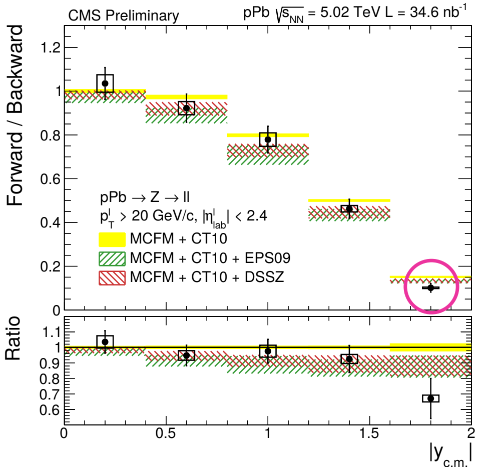
- Also available: acceptance-corrected results
- Comparison with MCFM with and without nPDFs (DSSZ, EPS09)
- Nuclear effects most prominent in the forward and backward regions (different x regions)

Z boson: foward-backward asymmetry

CMS-PAS-HIN-15-002



$$R_{FB} = \frac{\frac{d\sigma}{dy}(+y_{c.m.})}{\frac{d\sigma}{dy}(-y_{c.m.})}$$

- Improved sensitivity to nPDFs
- Favoring the presence of nuclear effects

Z boson: foward-backward asymmetry

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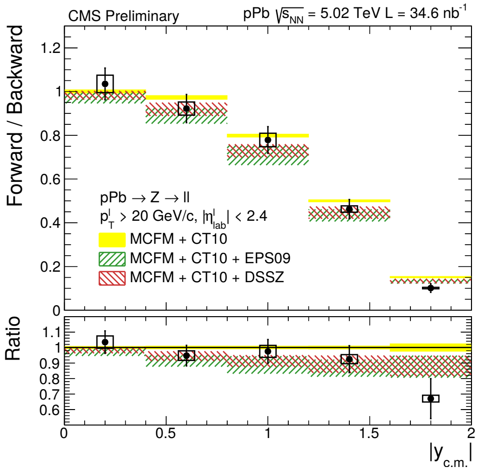

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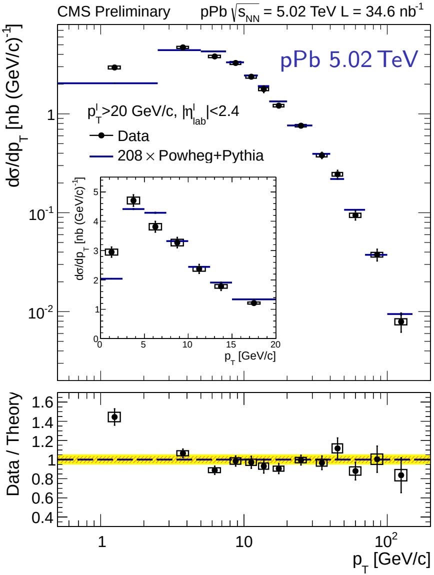
Z boson: fiducial cross section vs. p_T

CMS-PAS-HIN-15-002



- Modification of the p_T spectrum from nPDF expected to be small

Z boson: fiducial cross section vs. p_T

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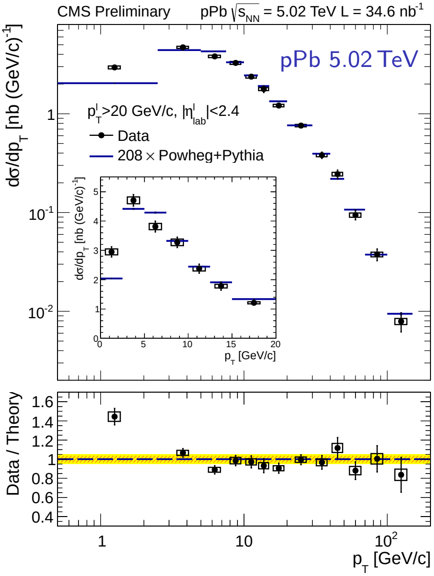
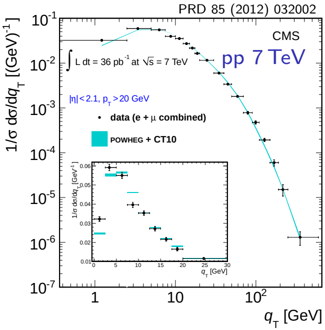
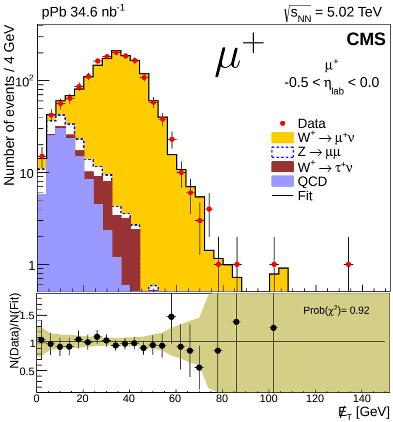


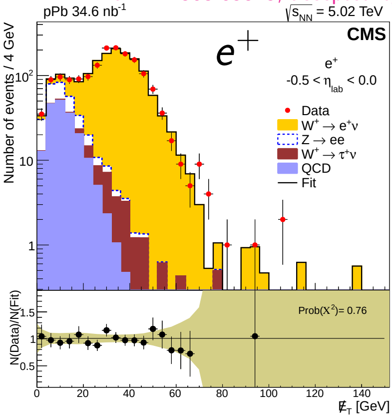
- Modification of the p_T spectrum from nPDF expected to be small
- Deviations at low p_T consistent with 7 TeV and 8 TeV pp results



W boson: event kinematics

arXiv:1503.05825, accepted by PLB

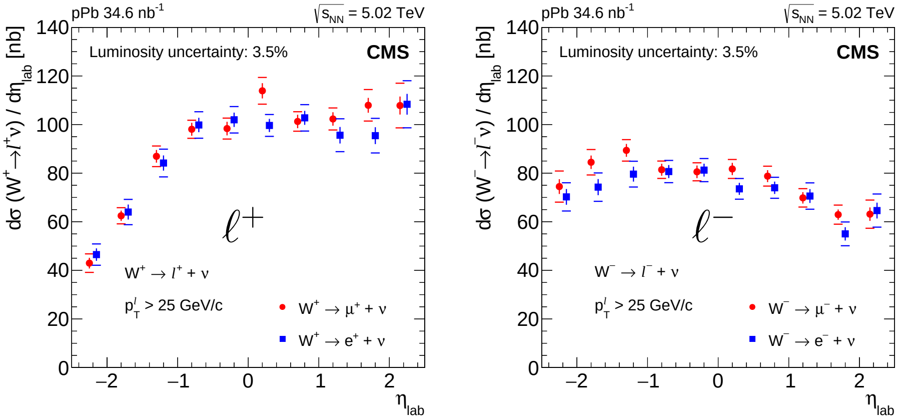




- Electron and muon channels ($p_T > 25$ GeV, $|\eta^\ell| < 2.4$)
- $\not{E}_T$ reconstructed using particle flow
- No $\not{E}_T$ cut: extract signal through a $\not{E}_T$ fit
- Requiring isolated lepton (to reject the HF and jet backgrounds)

W boson: cross section

arXiv:1503.05825 (PLB)



- Good agreement between the electron and muon channels
- Combine the two channels for a better precision

W boson: cross section

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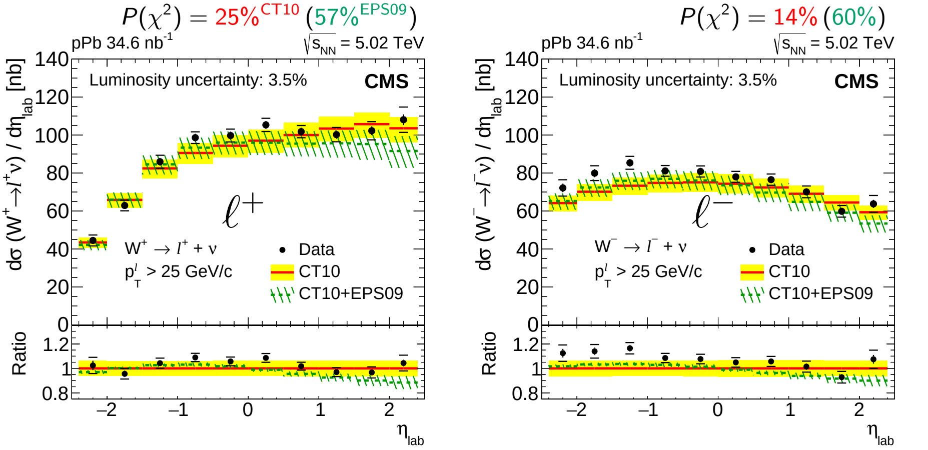
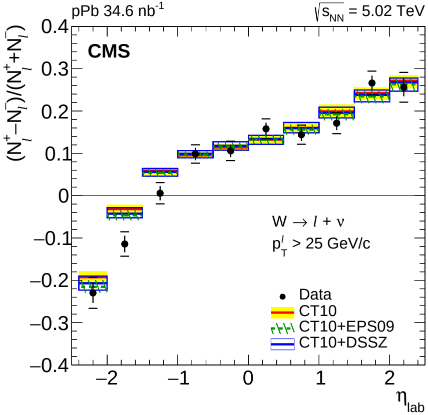


- Poor discrimination between CT10 and CT10+EPS09: build asymmetries

W boson: charge asymmetry $(N^+ - N^-)/(N^+ + N^-)$

arXiv:1503.05825 (PLB)

$P(\chi^2) = 12\%^{CT10}$ $(35\%^{EPS09})$



Comparing with different nPDFs

- Deviation at large negative η: different u vs. d quark modification?

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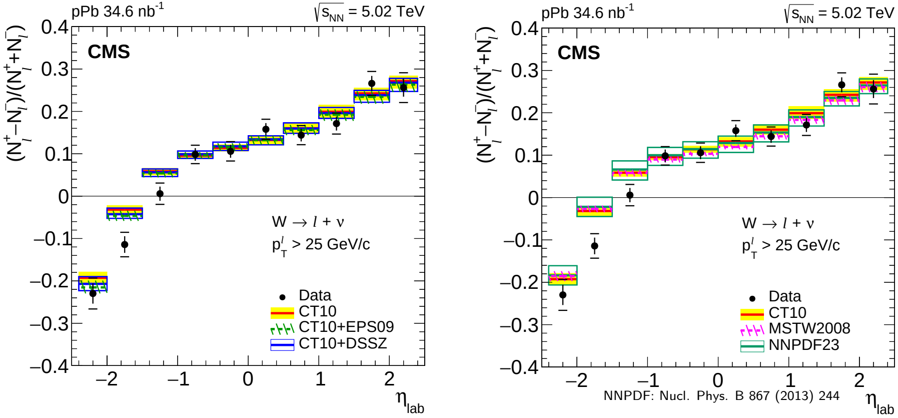

Comparing with different nPDFs

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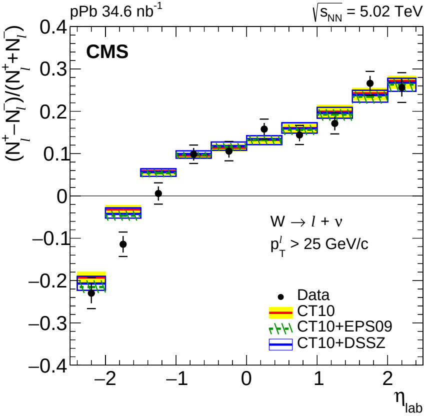
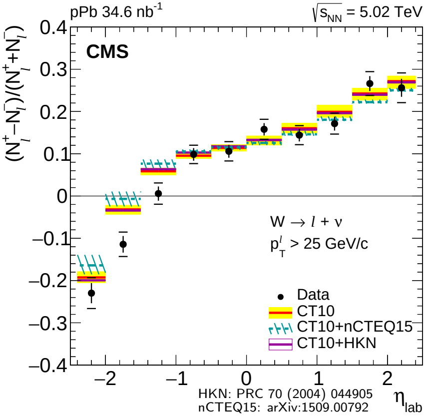




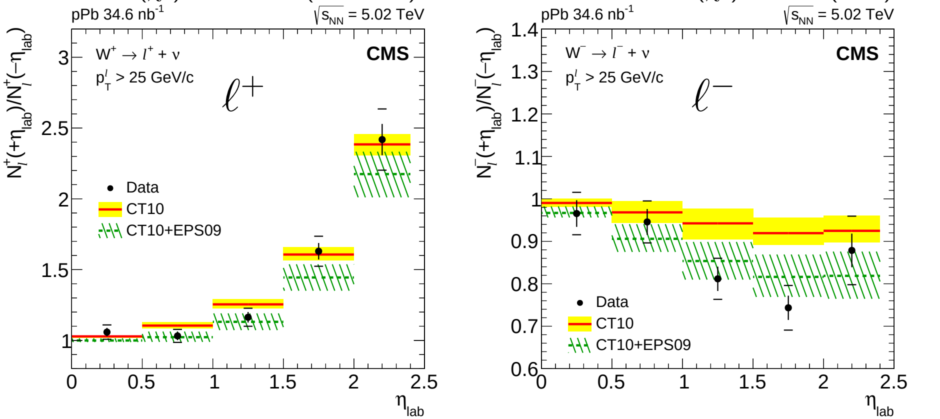
Comparing with different nPDFs

- Deviation at large negative η: different u vs. d quark modification?
  - Not a free proton PDF effect
  - Not included in EPS09 / DSSZ / HKN
  - Included in nCTEQ15 (but wrong direction)

W boson: forward-backward asymmetry $N^{\pm}(+\eta_{\text{lab}})/N^{\pm}(-\eta_{\text{lab}})$

arXiv:1503.05825 (PLB)

$P(\chi^2) = 68\%^{\text{CT10}}$ $(68\%^{\text{EPS09}})$ | $P(\chi^2) = 8.4\%$ (63%)

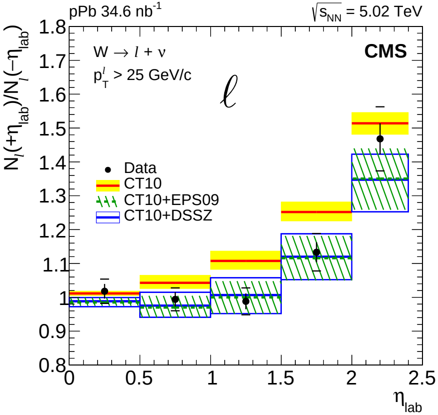


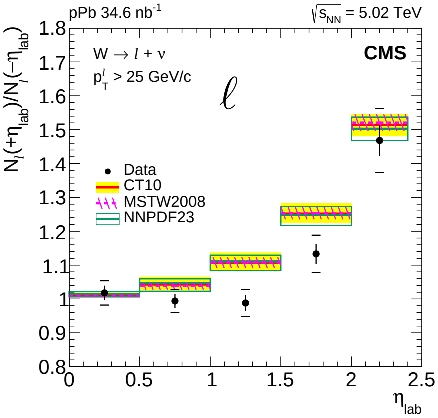
- F/B asymmetries are more sensitive to nuclear modifications.
- Negative leptons favor EPS09
- Unclear conclusion for positive leptons

W boson: forward-backward asymmetry $N(+\eta_{\mathrm{lab}})/N(-\eta_{\mathrm{lab}})$

arXiv:1503.05825 (PLB)

$P(\chi^2) = 29\%^{\mathrm{CT10}}$ $(83\%^{\mathrm{EPS09}})$





- Favoring the presence of nuclear modifications of PDFs

W boson: forward-backward asymmetry $N(+\eta_{\text{lab}})/N(-\eta_{\text{lab}})$

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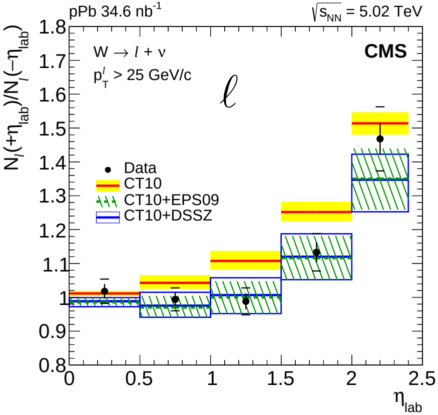
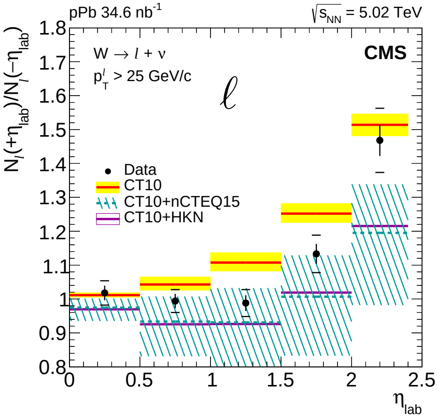




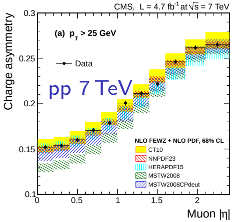
- Favoring the presence of nuclear modifications of PDFs

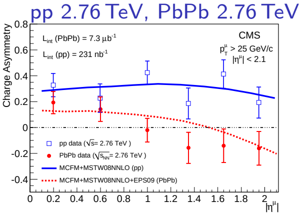
Outline

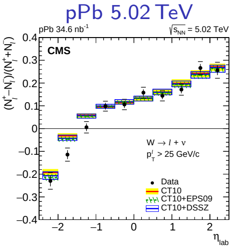
Scaling properties of inclusive W boson production in hadronic collisions

F. Arleo, EC and H. Paukkunen, arXiv:1509.03993

Measurements of the W boson lepton charge asymmetry have been shown in different systems:







Q: can we directly check the consistency of these different measurements?

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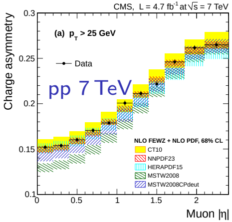
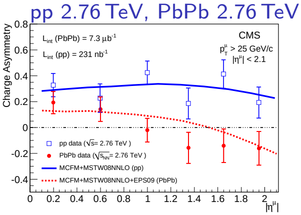
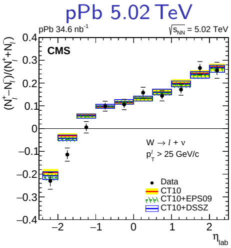
F. Arleo, EC and H. Paukkunen, arXiv:1509.03993

Measurements of the W boson lepton charge asymmetry have been shown in different systems:







Q: can we directly check the consistency of these different measurements?

A: yes, we can!

Scaling of the cross section $d\sigma^{W^\pm \to \ell^\pm}/dy$

arXiv:1509.03993

Inclusive W production in hadronic collisions

$$\mathrm{H}_1 + \mathrm{H}_2 \to \mathrm{W}^- + \mathrm{X} \to \ell^- + \bar{\nu} + \mathrm{X},$$
$$\mathrm{H}_1 + \mathrm{H}_2 \to \mathrm{W}^+ + \mathrm{X} \to \ell^+ + \nu + \mathrm{X}.$$

We find the scaling law[1]

$$\frac{d\sigma^{\ell^\pm}(s,\xi_1)}{d\xi_1} \approx s^\alpha \times F^\pm(\xi_1, \mathrm{H}_1, \mathrm{H}_2), \quad y \gg 0, \tag{1}$$

with $\sqrt{s}$ the center-of-mass energy, and

$$\xi_1 \equiv \frac{M_\mathrm{W}}{\sqrt{s}} e^y. \tag{2}$$

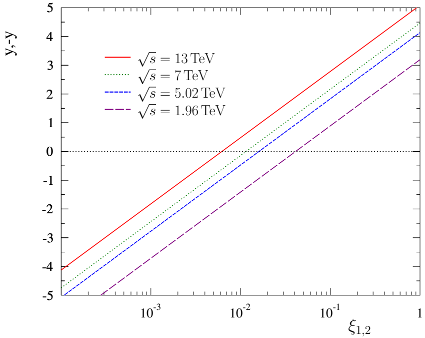
$F^\pm(\xi_1, \mathrm{H}_1, \mathrm{H}_2)$ is a function that does not depend explicitly on s or y, and α is the effective exponent for the sea-quark PDF at low x:

$$x\overline{q}_i(x,Q^2) \approx xq_i(x,Q^2) \approx N_i\ x^{-\alpha} \qquad (\alpha > 0).$$

[1] Similar scaling for $y \ll 0$, with $\xi_2 \equiv \frac{M_\mathrm{W}}{\sqrt{s}} e^{-y}$.

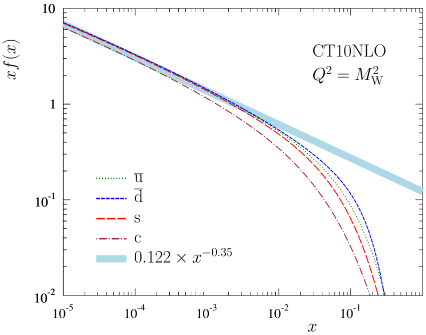
Scaling exponent α

arXiv:1509.03993



Relation of rapidity y and $\xi_{1,2}$ for a few values of $\sqrt{s}$.

$$\xi_1 \equiv \frac{M_W}{\sqrt{s}} e^y, \quad \xi_2 \equiv \frac{M_W}{\sqrt{s}} e^{-y}$$



Scaling exponent extracted from NLO calculations compared to CT10NLO PDFs.

$$x\bar{q}_i(x, Q^2) \approx xq_i(x, Q^2) \approx N_i\ x^{-\alpha}$$

Scaling of the lepton charge asymmetry $\mathcal{C}_\ell$

arXiv:1509.03993

The $\sqrt{s}$ dependence in Eq. (1) cancels out in the lepton charge asymmetry[2]:

$$\mathcal{C}_\ell^{\mathrm{H}_1,\mathrm{H}_2}(s,\xi_1) \quad \approx \quad F(\xi_1,\mathrm{H}_1,\mathrm{H}_2) \quad y \gg 0$$

The approximate flavor independence of the sea quarks at small x even implies

$$\mathcal{C}_\ell^{\mathrm{H}_1,\mathrm{H}_2}(s,\xi_1) \quad \approx \quad F(\xi_1,\mathrm{H}_1), \quad y \gg 0,$$

independently of the nature of hadron H_2 (nucleon, anti-nucleon, nucleus) probed at small x.

Note

At the LHC, scaling holds even at $y \sim 0$, because the probed x in H_2 is already small.

[2] Similar scaling again for $y \ll 0$ (with ξ_2).

Heavy ions at the LHC

arXiv:1509.03993

What does this scaling mean in practice in the case of heavy ion collisions?

$y > 0$: scaling between pp, pPb collisions:

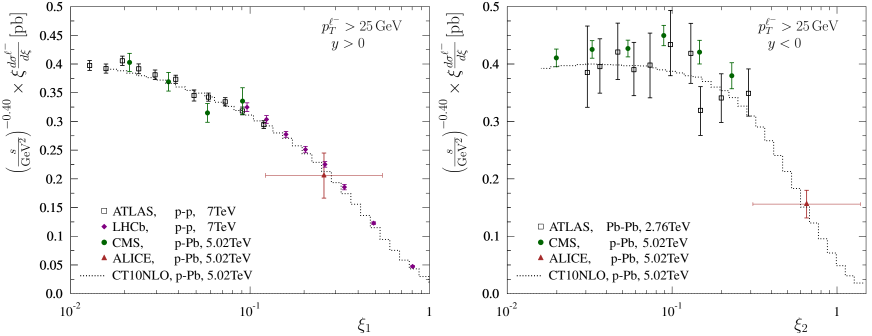
$$\mathcal{C}_\ell^{\mathrm{pp}}(s, \xi_1) \quad \approx \quad \mathcal{C}_\ell^{\mathrm{pPb}}(s', \xi_1), \quad y > 0.$$

$y < 0$: scaling between pPb, PbPb collisions:

$$\mathcal{C}_\ell^{\mathrm{pPb}}(s, \xi_2) \quad \approx \quad \mathcal{C}_\ell^{\mathrm{PbPb}}(s', \xi_2), \quad y < 0.$$

Comparison with data: $d\sigma^{W^\pm \to \ell^\pm}/dy$

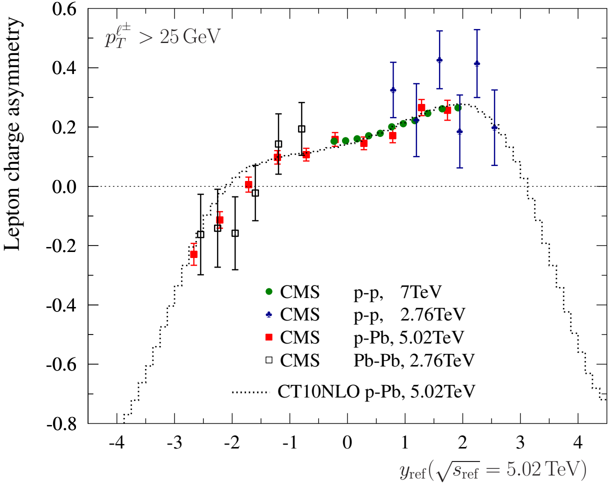
arXiv:1509.03993



Absolute spectra for ℓ^- in different collision systems, scaled by $(s/\mathrm{GeV}^2)^{-0.40}$.

Comparison with data: $\mathcal{C}_\ell$

arXiv:1509.03993

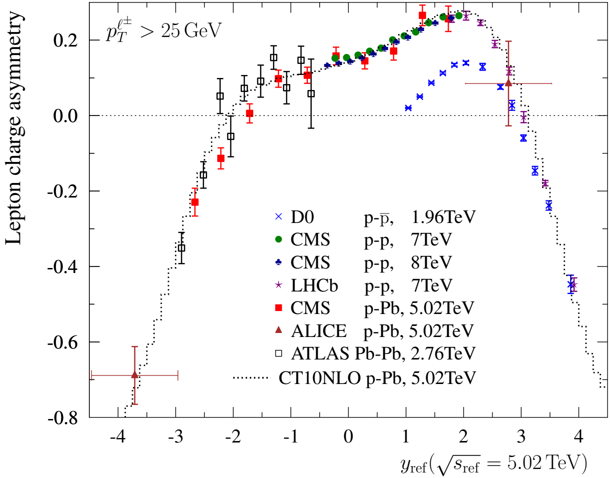


The CMS data on lepton charge asymmetry as a function of y_{ref}[3] taking $\sqrt{s_{\mathrm{ref}}} = 5.02\,\mathrm{TeV}$.

[3] $y_{\mathrm{ref}} \equiv y \pm \frac{1}{2}\log\frac{s_{\mathrm{ref}}}{s}$, such that e.g. $\xi_1(y, \sqrt{s}) = \xi_1(y_{\mathrm{ref}}, \sqrt{s_{\mathrm{ref}}})$ for $y > 0$.

Comparison with data: $\mathcal{C}_\ell$

arXiv:1509.03993

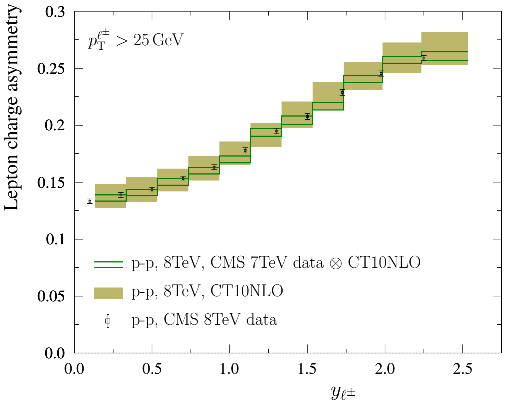


The world data on lepton charge asymmetry as a function of $y_{\rm ref}$[3] taking $\sqrt{s_{\rm ref}} = 5.02\,{\rm TeV}$.

[3] $y_{\rm ref} \equiv y \pm \frac{1}{2} \log \frac{s_{\rm ref}}{s}$, such that e.g. $\xi_1(y, \sqrt{s}) = \xi_1(y_{\rm ref}, \sqrt{s_{\rm ref}})$ for $y > 0$.

Predictions

arXiv:1509.03993



Predictions for the lepton charge asymmetries in 8 TeV pp, based on the 7 TeV CMS data.

Summary

W and Z bosons in PbPb

- R_{AA} compatible with 1: reference process
- Large isospin effect for W boson production

W and Z bosons in pPb

- Sensitivity to nuclear modifications of the PDFs
- Hints of nuclear effects in the data: important input for future nPDF fits
- Some tension between data and theory in the leptonic charge asymmetry (different u and d PDF modifications?)

Scaling properties of inclusive W boson production in hadronic collisions

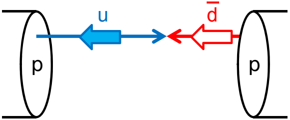
- The inclusive W boson production at a fixed value of $\xi_{1,2}$ obeys a one-parameter law in $\sqrt{s}$
- $\mathcal{C}_\ell(\xi_{1,2})$ is approximately independent of $\sqrt{s}$.
- $\mathcal{C}_\ell(\xi_{1,2})$ is also independent of the nucleus probed at small x.

Additional material

W production

Leading order

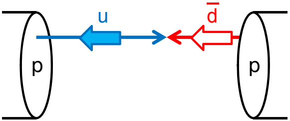
$$u\bar{d} \to W^+, \quad d\bar{u} \to W^-$$



W production

Leading order

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

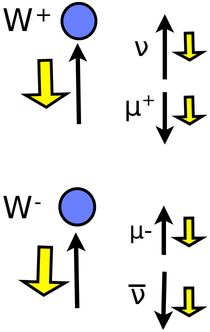


Yields

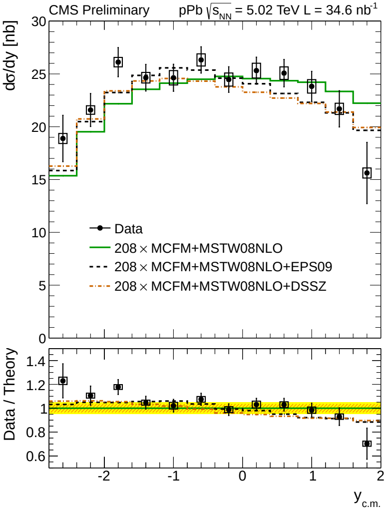
- Expect 2× more W^+ than W^- in pp.
- Expect more W^- than W^+ in PbPb.

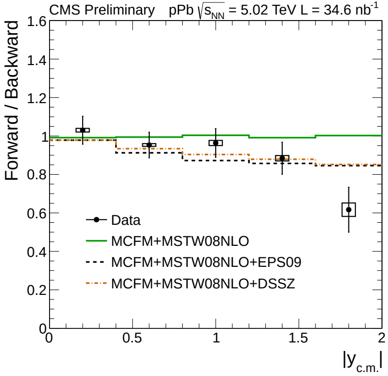
Rapidity

- W boosted towards the valence quark.
- Spin conservation + parity violation: μ^+ (μ^-) boosted back to (away from) midrapidity.
  - ⇒ different rapidity distributions between μ^+ and μ^-.



Z in pPb: acceptance-corrected resutls





nPDF (arXiv:1509.00792)