Wuhan HP2016

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Probing Cold Nuclear Medium Effects with W/Z Production in Heavy-ion Collisions

Peng Ru

Dalian University of Technology

Central China Normal University

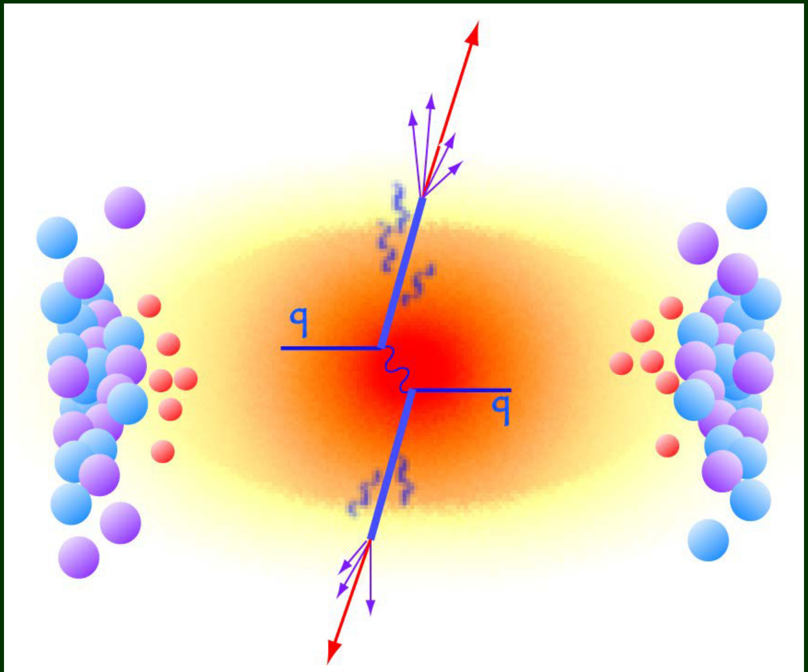
Collaborators :

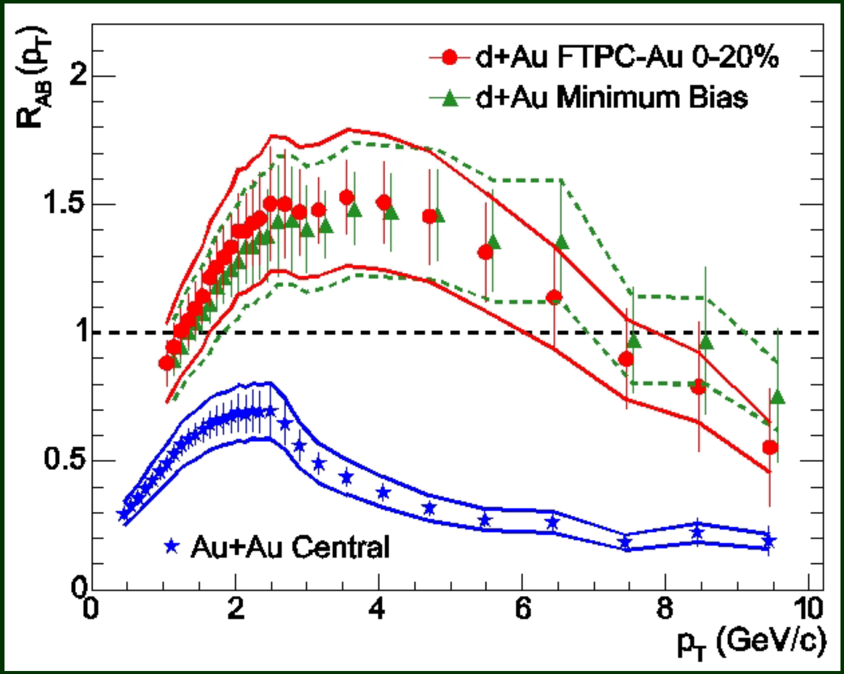
Ben-Wei Zhang, Enke Wang, Wei-Ning Zhang,

Luan Cheng, S. A. Kulagin, R. Petti

Publications: 1412.2930 [nucl-th], 1505.08106 [nucl-th], 1608.06835 [nucl-th]

CNM effect or NPDFs: baseline of the study on jet quenching





Gyulassy, Vitev, X.N.Wang, B.W.Zhang, 《QGP3》p123-191 (2004); nucl-th/0302077.

Outline

I. **Framework** of the study

II. Vector boson production in HIC **at the LHC**

III. W/Z production in p+Pb collisions with **KP NPDFs**

IV. W/Z production in **future** heavy-ion collisions

V. Summary

I. Framework of the study

Vector boson as a probe of Cold Nuclear Medium effect

Features of W/Z production:

- **Drell-Yan process**
- **High-invariant mass**

$$m_{\mathrm{W/Z}} \sim 80-90\ \mathrm{GeV}$$

- **Produced in early stage**

$$\sim 1/m_{\mathrm{W/Z}} \sim 10^{-3}\ \mathrm{fm/c}$$

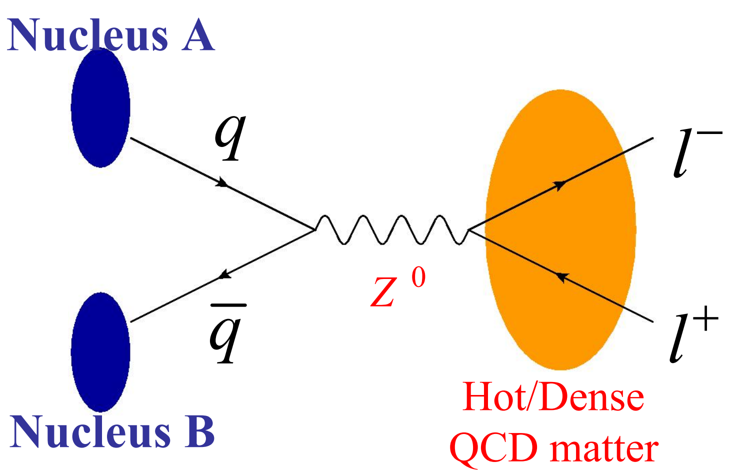
- **Decay later**

$$\sim 0.08-0.09\ \mathrm{fm/c}$$

- **Colorless lepton pair in final state**

Clean signal of initial state of the collision, e.g. parton distributions (**PDFs**), and cold nuclear medium effects or **NPDFs.**

In nucleus-nucleus collisions at LHC:



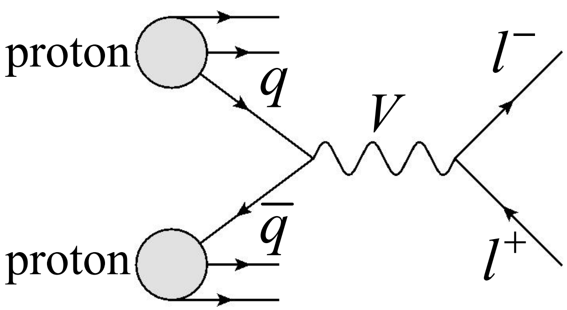
$$\lambda_{\mathrm{mfp}} > l_{\mathrm{QGP}} \sim 10\ \mathrm{fm}$$

The created hot/dense nuclear environment (after ~1fm/c) can hardly pollute the signal of initial CNM effect.

I. Framework of the study

Factorization in pQCD

Drell-Yan in hadronic collision



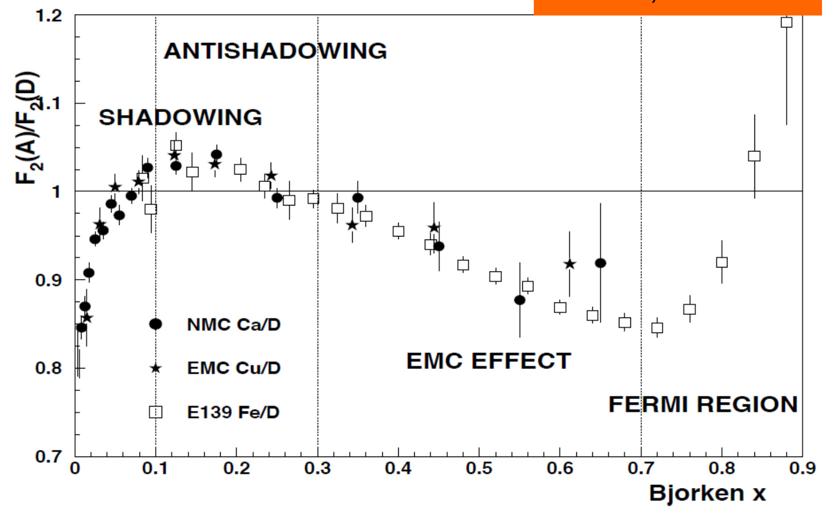
$$\sigma^{DY}_{AB\to VX\to llX} = \sum_{a,b}\int dx_a dx_b f_a^A(x_a,Q^2) f_b^B(x_b,Q^2)\hat{\sigma}_{ab\to VX\to llX}$$

PDFs

Partonic cross section

In nuclear collisions:

R.Petti, DIS2016



- Factorization theorem holds
- Parton distributions is altered in the cold nuclear medium

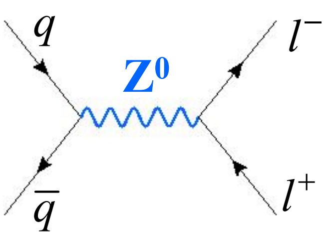
QCD Factorization theorem

PDFs → NPDFs (EPS09, DSSZ, ...)

I. Framework of the study

Partonic sub-process in pQCD

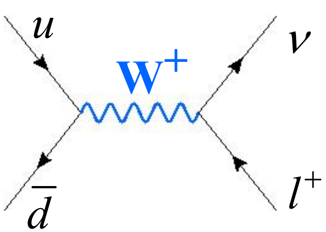
Leading order (LO)



$u\bar{u} \to Z^0$

$d\bar{d} \to Z^0$

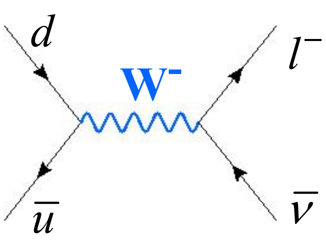
$s\bar{s} \to Z^0$ . . .



$u\bar{d} \to W^+$

$c\bar{s} \to W^+$

$u\bar{s} \to W^+$ . . .



$d\bar{u} \to W^-$

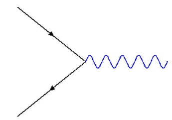
$s\bar{c} \to W^-$

$s\bar{u} \to W^-$ . . .

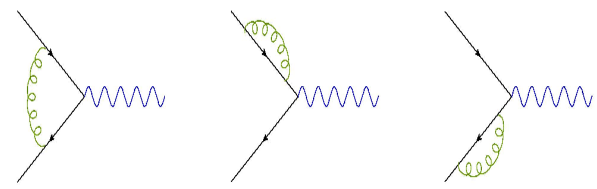
Weak interaction at LO

Next-to-leading order (NLO)

LO

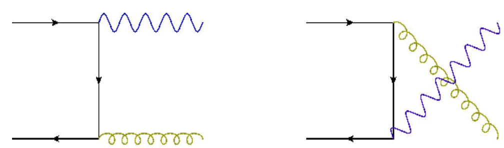


Virtual correction



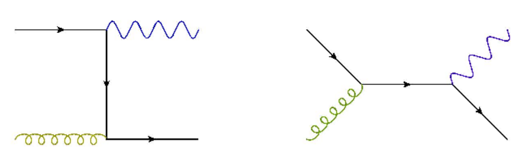
$p_T^V = 0$

Real emission



$q\bar{q} \to Vg$

Quark-gluon scattering



$qg \to Vq$

$\bar{q}g \to V\bar{q}$

Numerical simulation in pp collision

Program :DYNNLO

Code :Drell-Yan Next-to-Next-to Leading Order (DYNNLO)

S. Catani, *et al* , **PRL**(2009) , **PRL**(2007)

- High-order QCD correction:

  NLO[$O(\alpha_S)$], NNLO[$O(\alpha_S^2)$]

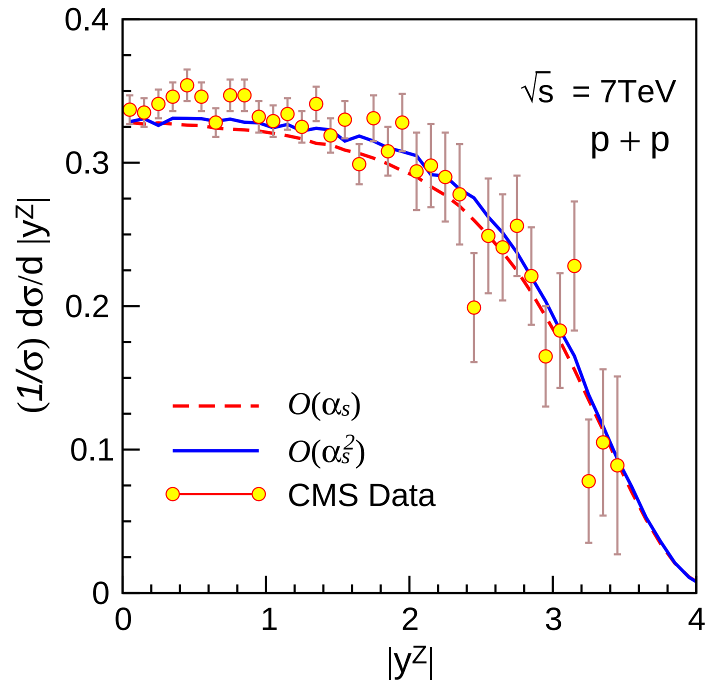
- Renormalization and factorization scales

  $$\mu_R = \mu_F = m_{W/Z}$$

- PDFs: MSTW08, CT10, ABMP15

Comparison with the LHC data

PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104



Both NLO and NNLO agree with data.

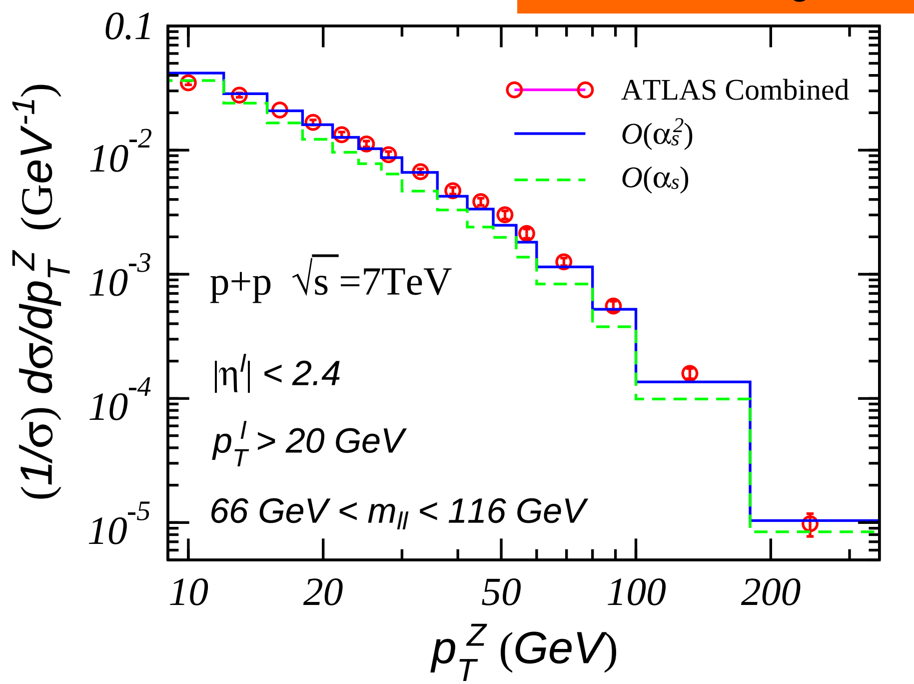
NNLO corrections are small.

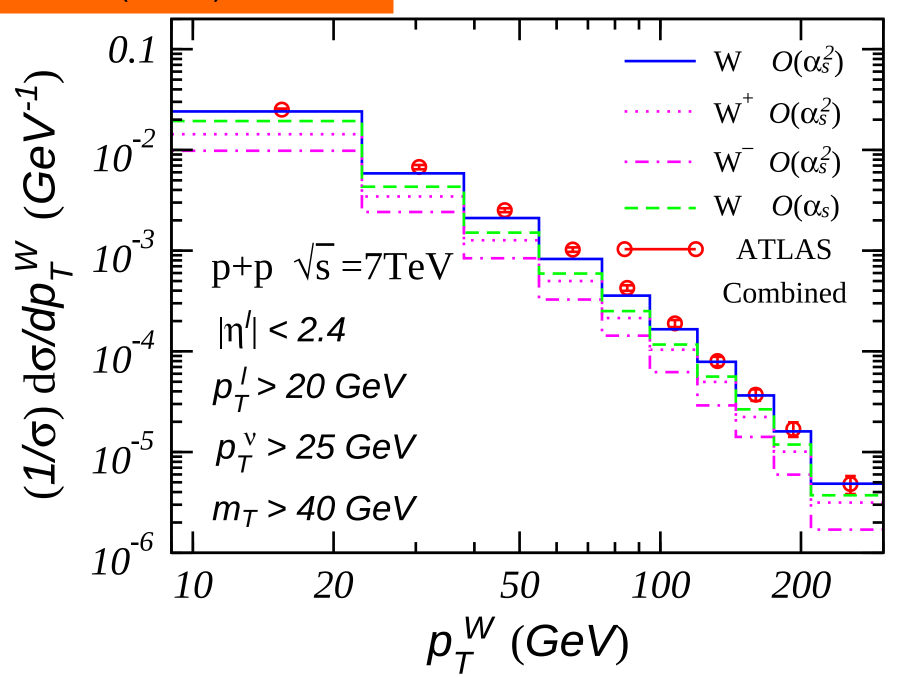
I. Framework of the study

Numerical simulation in pp collision: pT spectra

Z Boson | **W Boson**

PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104



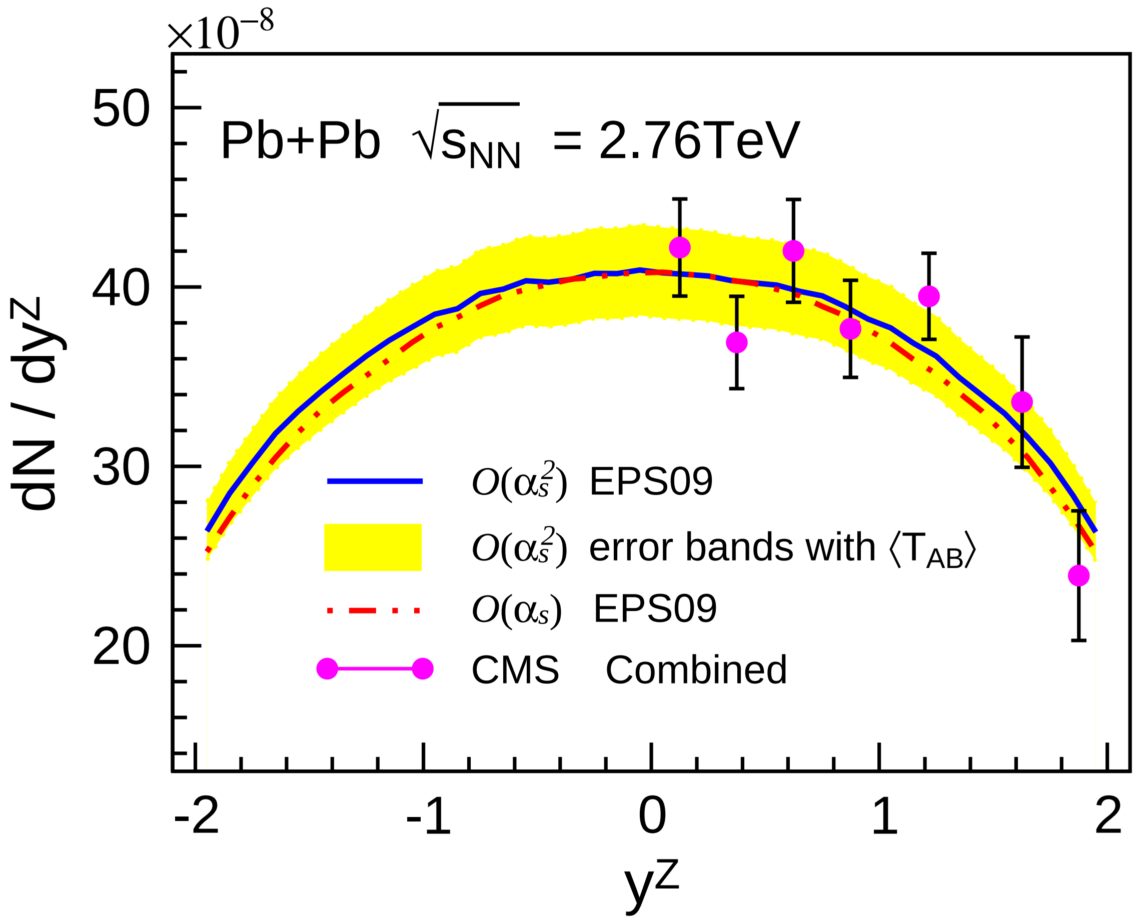


- **Different process from the rapidity distribution**
- **NLO calculation agree well with the high-pT data**

I. Framework of the study

- Sensitive to the initial-stage cold nuclear medium effect or NPDFs in nuclear collisions
- Well understood process in pQCD (Drell-Yan)
- Numerical results agree well with the LHC proton-proton data

Rapidity distribution in Pb+Pb collisions



Results with EPS09 NPDFs show a good agreement with the data.

NNLO correction is small.

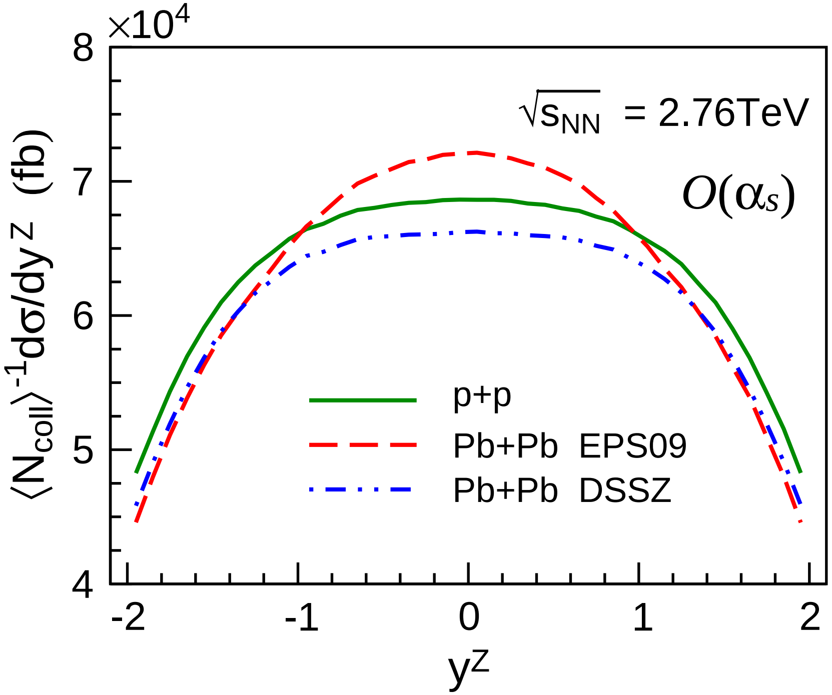
PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104

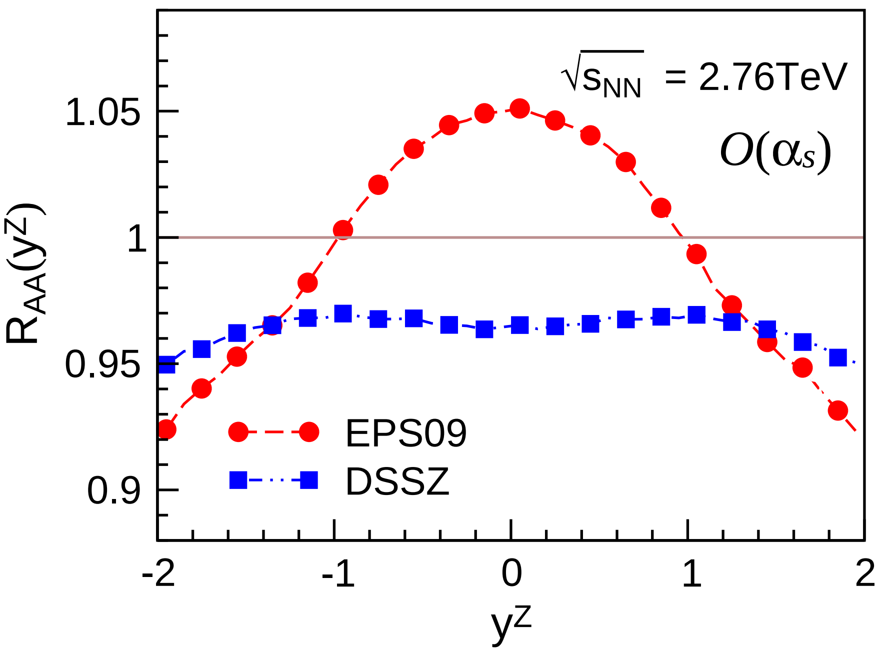
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in Pb+Pb collisions

Nuclear corrections	R_AA

PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104



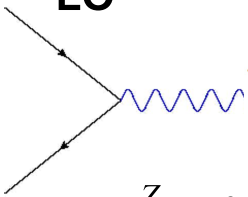


- Different nuclear corrections from EPS09 and DSSZ
- A good probe of the NPDFs

Rapidity distribution in Pb+Pb collisions: Parton Level

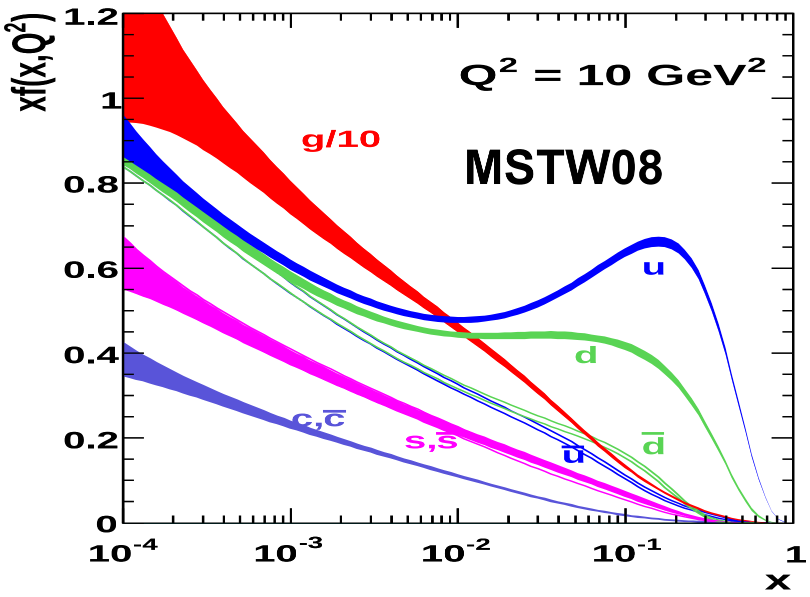
Momentum fraction at LO

LO



$$x_1 = \frac{m_Z}{\sqrt{s_{NN}}} e^{y^Z},\ x_2 = \frac{m_Z}{\sqrt{s_{NN}}} e^{-y^Z}$$

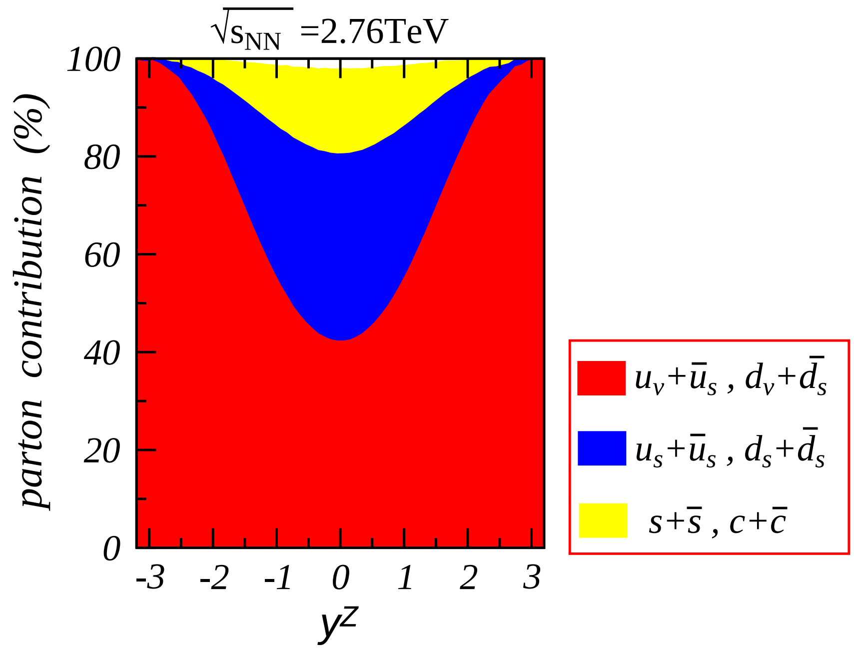
$$y^Z \sim 0: \quad x_1 \sim x_2 \sim m_Z / \sqrt{s_{NN}} \sim 0.033$$



Parton contributions

Initial partons are mainly quarks and anti-quarks.

Gluon give small high-order contribution.



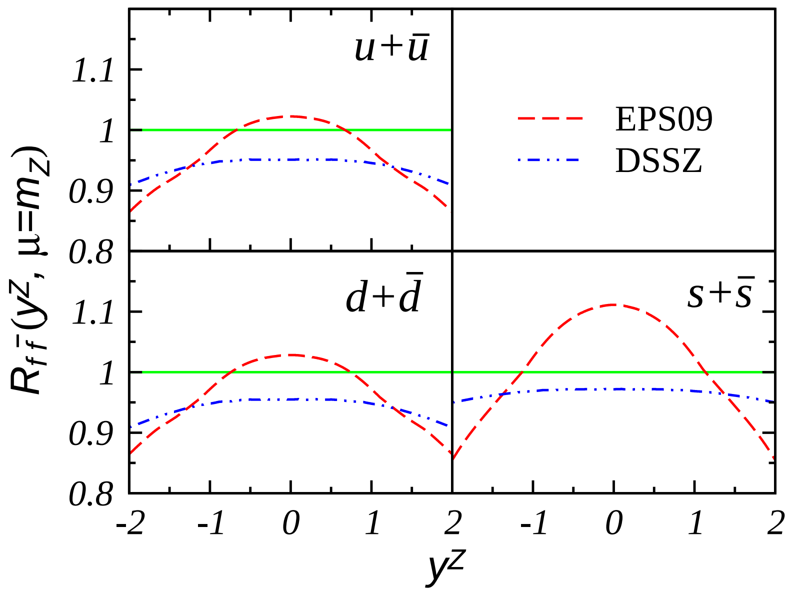
Rapidity distribution in Pb+Pb collisions: Parton Level

$$R_f(x,Q^2) = f^{Pb}(x,Q^2)/f^p(x,Q^2) \quad \text{and} \quad x_1 = \frac{m_Z}{\sqrt{s_{NN}}}e^{y^Z},\ x_2 = \frac{m_Z}{\sqrt{s_{NN}}}e^{-y^Z}$$

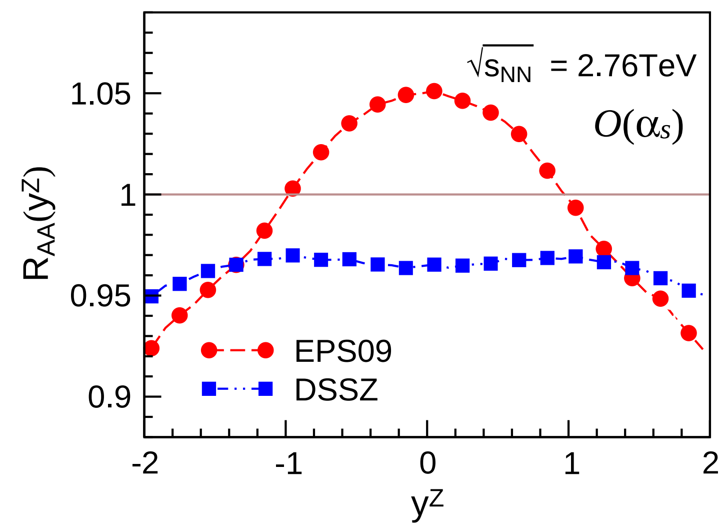
Define : $R_{f\bar{f}}(y^Z) = \alpha(y^Z)R_f(x_1)R_{\bar{f}}(x_2) + \beta(y^Z)R_f(x_2)R_{\bar{f}}(x_1)$

PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104

A naïve choice: $\alpha(y^Z) = \beta(y^Z) = 1/2$



Probe of the nuclear corrections on **quark PDFs**



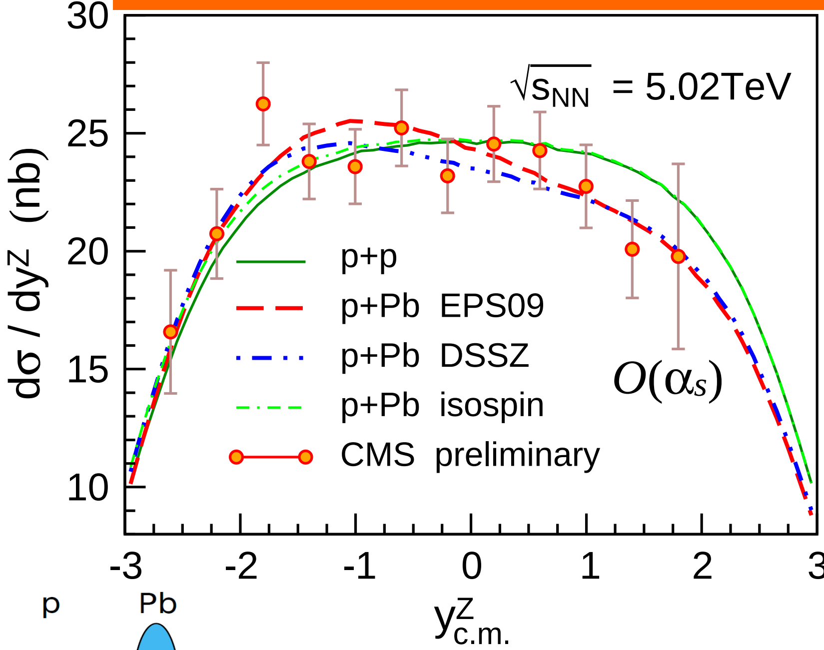
II. Vector boson production in heavy-ion collisions at the LHC

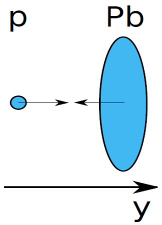
Rapidity distribution in p+Pb collisions

Differential cross section at NLO

PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104

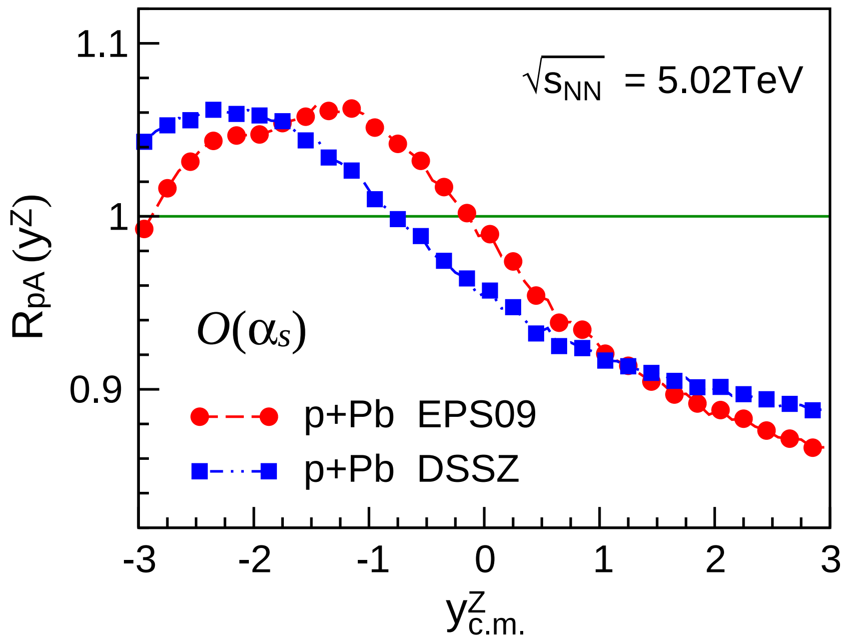
J. Albacete *et al.* 1605.09479 [hep-ph]





Nuclear corrections result in a asymmetric distribution

R_pA



Differences between EPS09 and DSSZ are observed

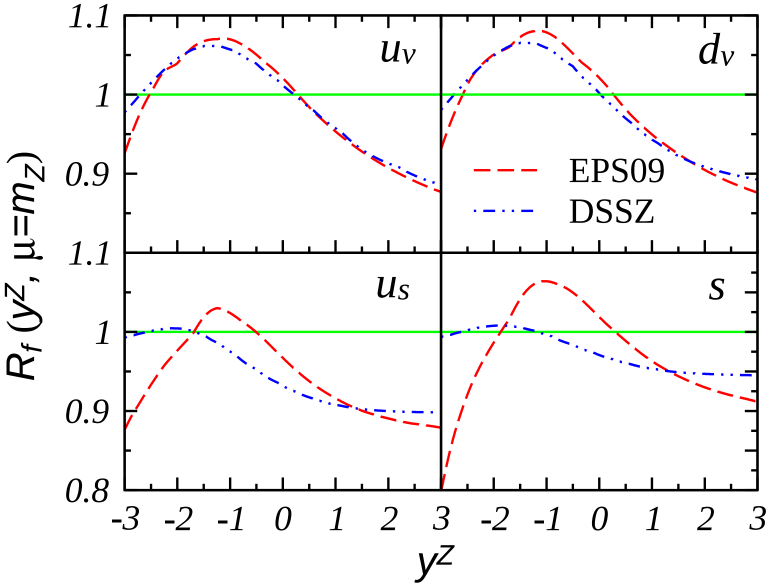
II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in p+Pb collisions: Parton Level

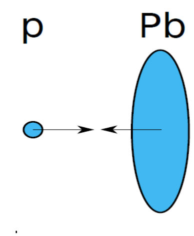
Nuclear correction at parton level

$$x_{Pb} = x_2 = \frac{m_Z}{\sqrt{s_{NN}}} e^{-y^Z}$$

$$R_f(x_{Pb}) \rightarrow R_f(y^Z)$$

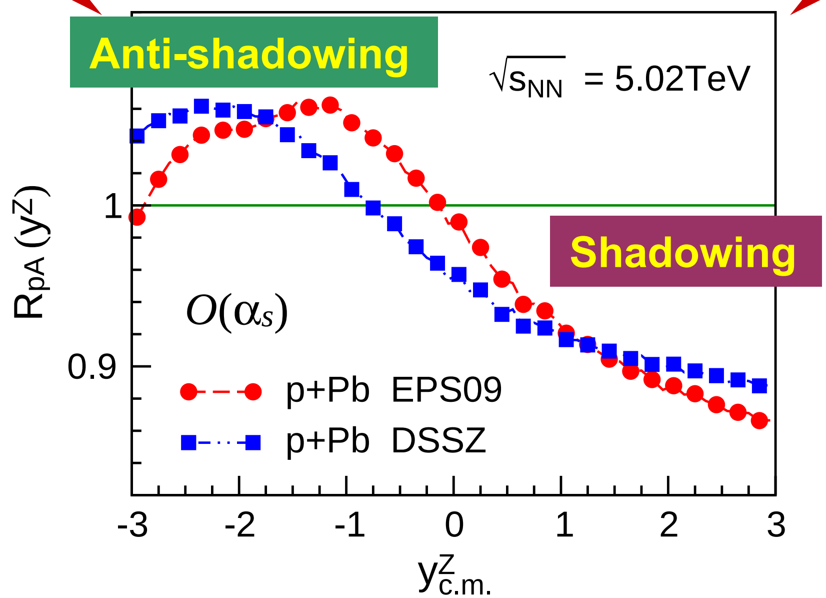


R_pA provides an image of the nuclear corrections on quark PDFs.

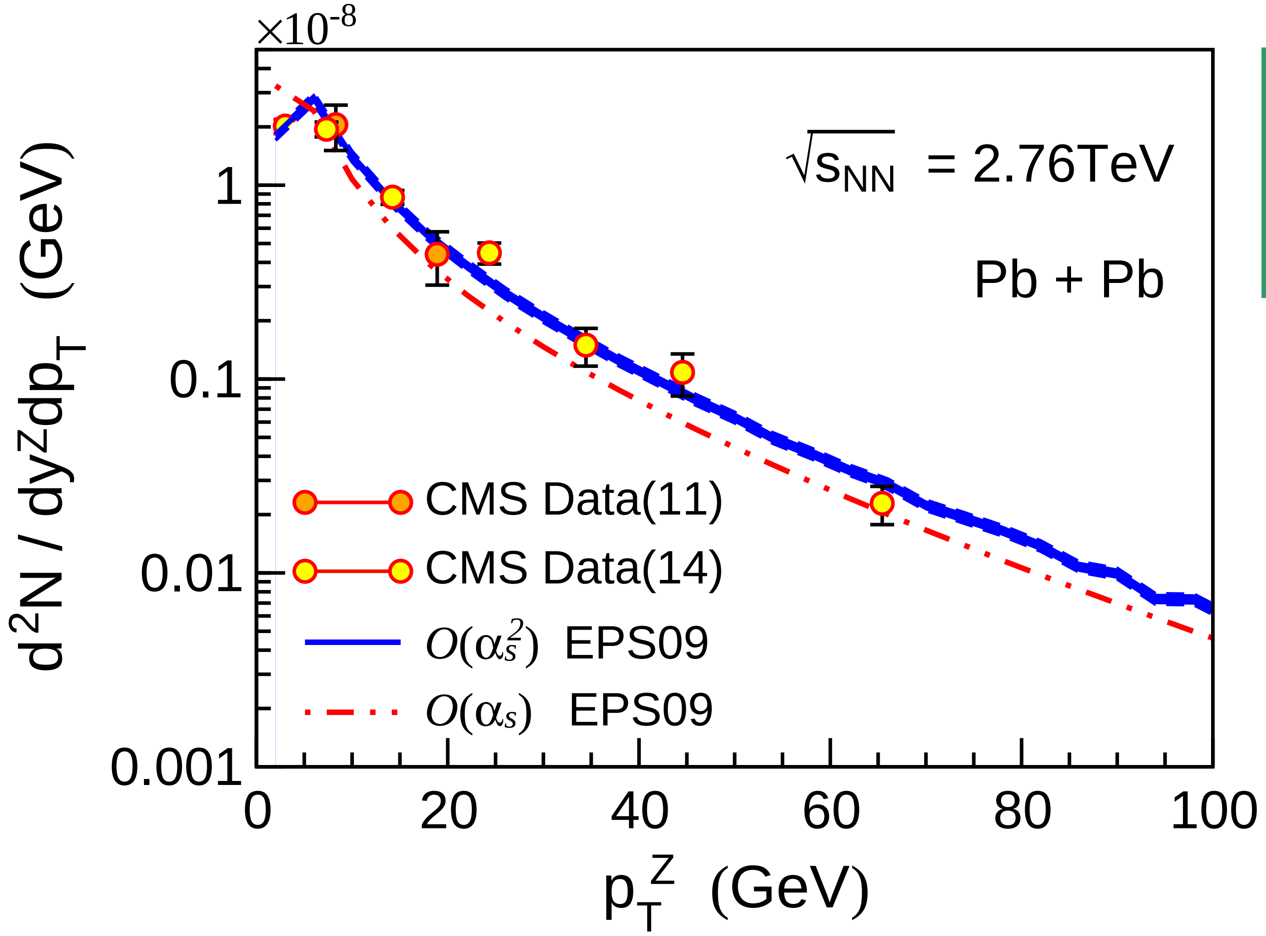


Large-x, valence dominated

small-x, sea quark dominated



Transverse momentum (pT) spectra



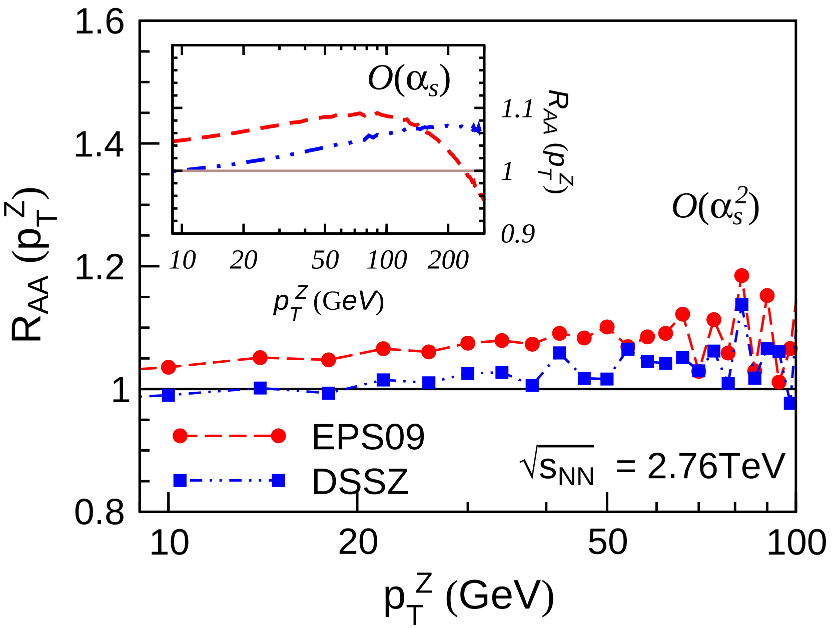
NLO results with EPS09 NPDFs show good agreement with the data.

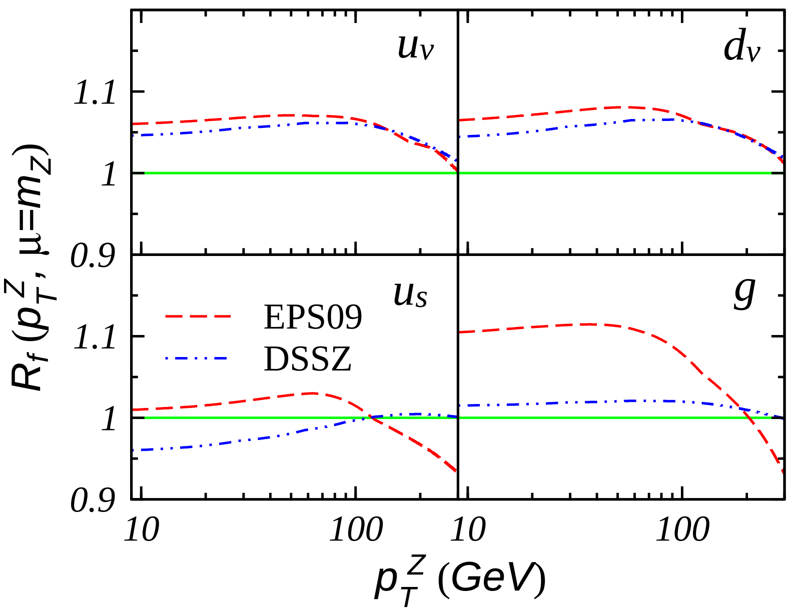
PR, B.W.Zhang, *et al*,

JPG **42** (2015) 085104

Nuclear corrections on pT spectra: Parton Level

$$y^Z \sim 0: \qquad x \sim \frac{p_T + \sqrt{p_T^2 + m_{Z/W}^2}}{\sqrt{s_{NN}}} \qquad\qquad R_f(x_{Pb}) \to R_f(p_T)$$

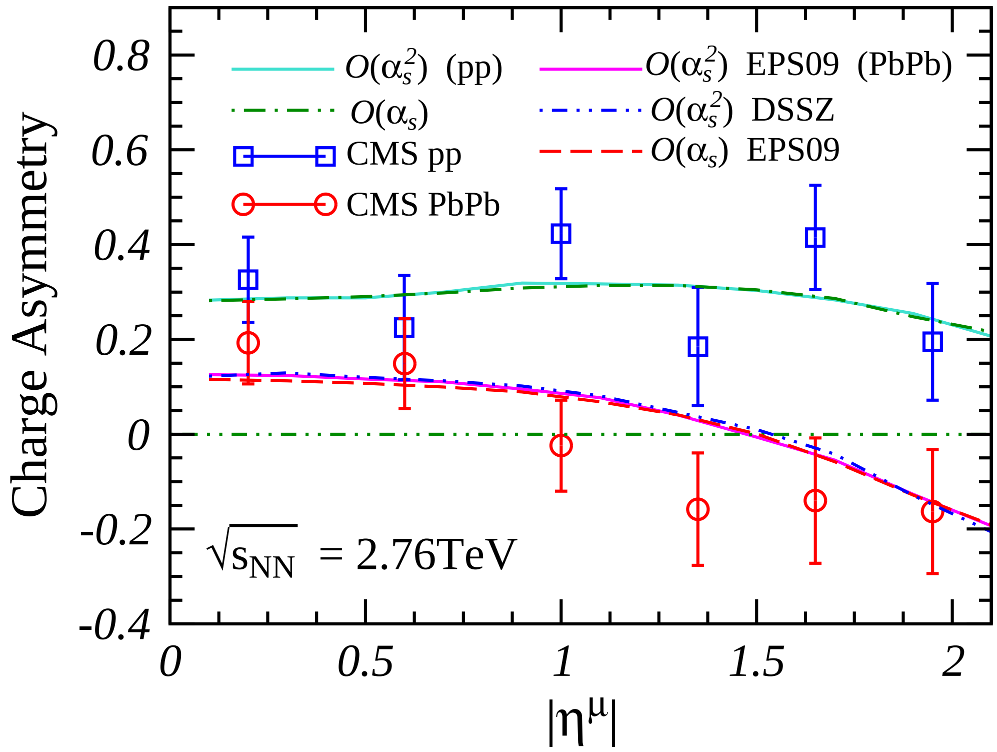




pT spectrum provides more knowledge of nuclear correction on gluon PDFs

W Boson: Charge Asymmetry

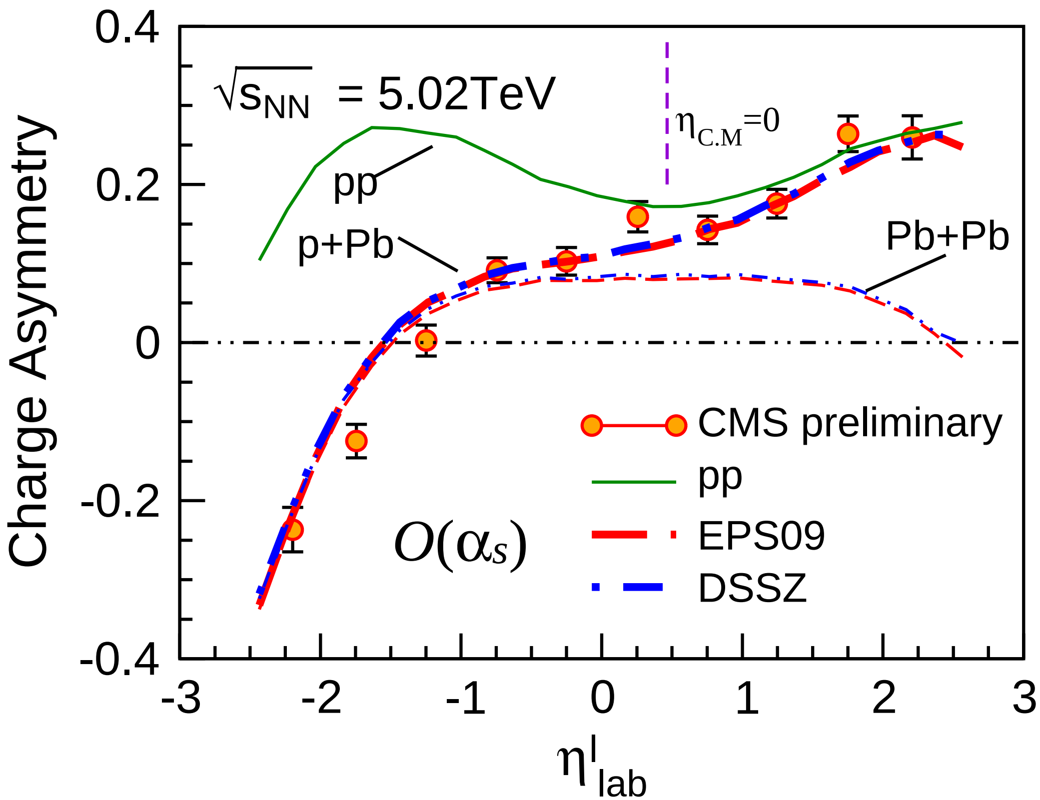
$$A = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}} \Rightarrow \frac{u(x)}{d(x)} \qquad \frac{u^{Pb}(x)}{d^{Pb}(x)} = \frac{R_u(x)}{R_d(x)} \cdot \frac{u^p(x)}{d^p(x)}$$



In p+p and Pb+Pb

- Not sensitive to the order.
- Not sensitive to the choice of NPDF.

W Boson: Charge Asymmetry



In p+Pb

- Not sensitive to the choice of NPDF.
- Somewhat deviation from the data in negative rapidity.
- **At the same colliding energy(5.02TeV)**

  P+Pb →p+p in forward region

  P+Pb →Pb+Pb in backward region

  At small-x(sea-quark dominated), isospin effect is small

III. W/Z production in p+Pb collisions with KP NPDFs

KP nuclear parton distribution

- Predicted from the semi-microscopic model developed by S. A. Kulagin and R. Petti.

  NPA 756 (2006) 126; **PRC** 90 (2014) 045204

- Not a fit, unlike conventional approaches.
- Offer insights on the underlying nuclear physics mechanisms.
- The KP nuclear PDFs have been validated with data from a wide range of processes including lepton-nucleus DIS, Drell-Yan production in pA collisions, Z,W production in heavy ion collisions at colliders.

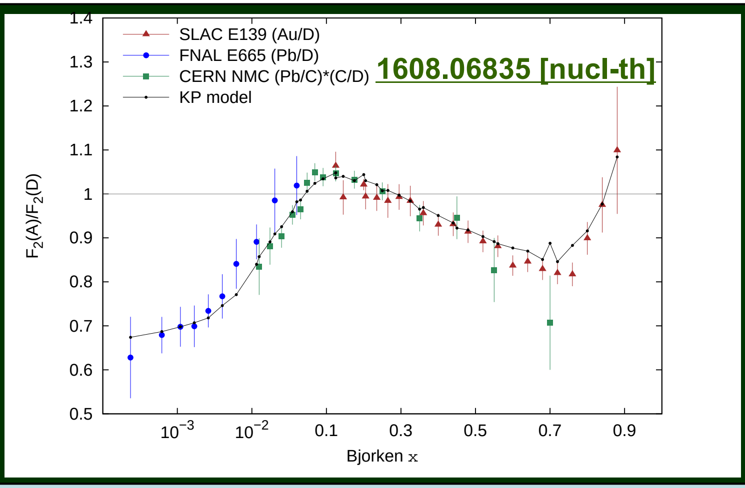
III. W/Z production in p+Pb collisions with KP NPDFs

KP nuclear parton distribution

Different nuclear effects on parton distributions (PDF) are taken into account:

$$q_{a/A} = q_a^{p/A} + q_a^{n/A} + \delta q_a^{MEC} + \delta q_a^{coh}$$

- $q_a^{p(n)/A}$: PDF in bound p(n) with Fermi Motion, Binding (**FMB**), and Off-Shell effect (**OS**)
- δq_a^{MEC} : nuclear Meson Exchange Current (**MEC**) correction
- δq_a^{coh} : Contribution from coherent nuclear interactions: Nuclear Shadowing (**NS**)



KP model prediction

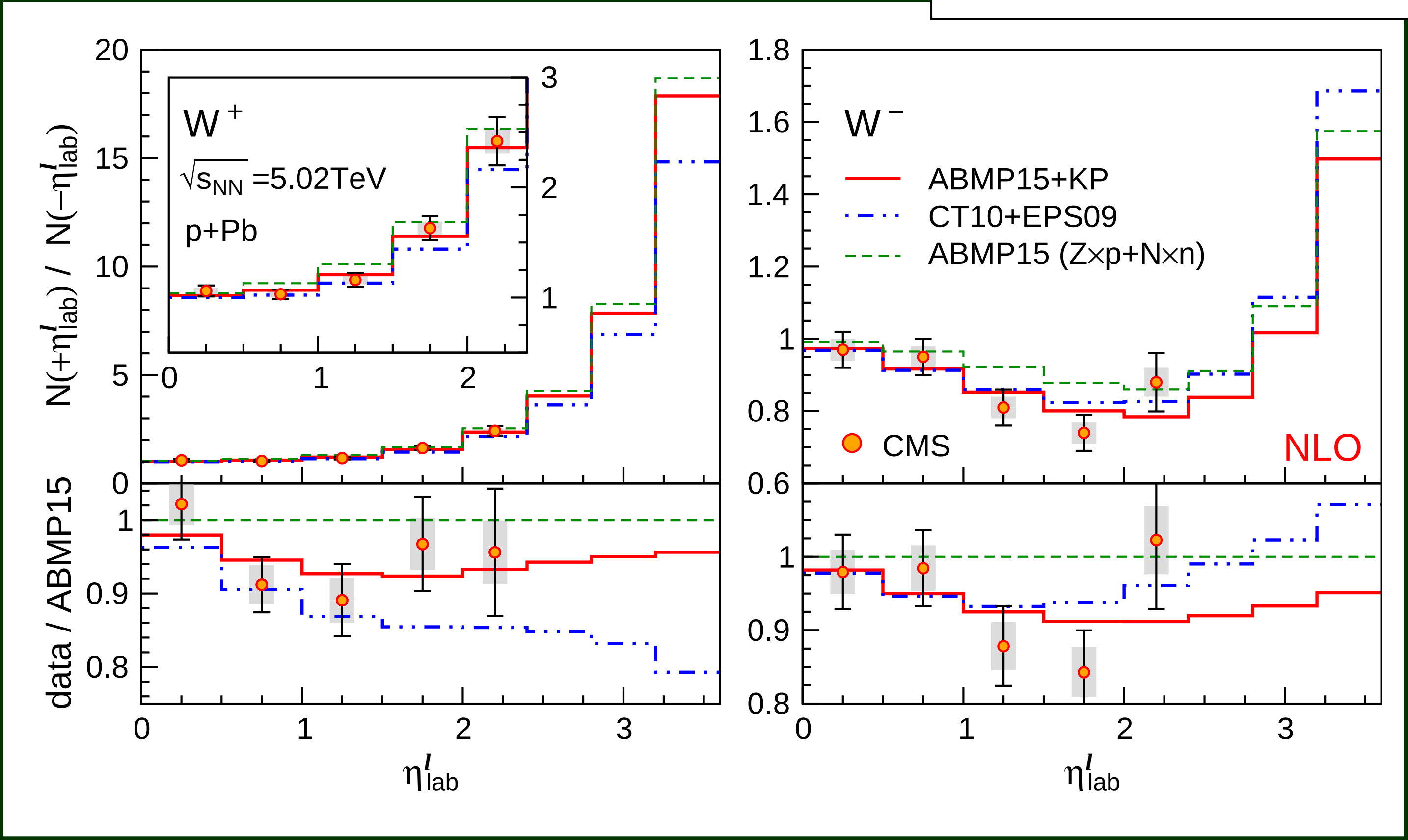
vs

DIS data

Results on p+Pb at the LHC

Forward-backward asymmetry of W boson

$$R_{FB}(y) = N(+y)/N(-y)$$

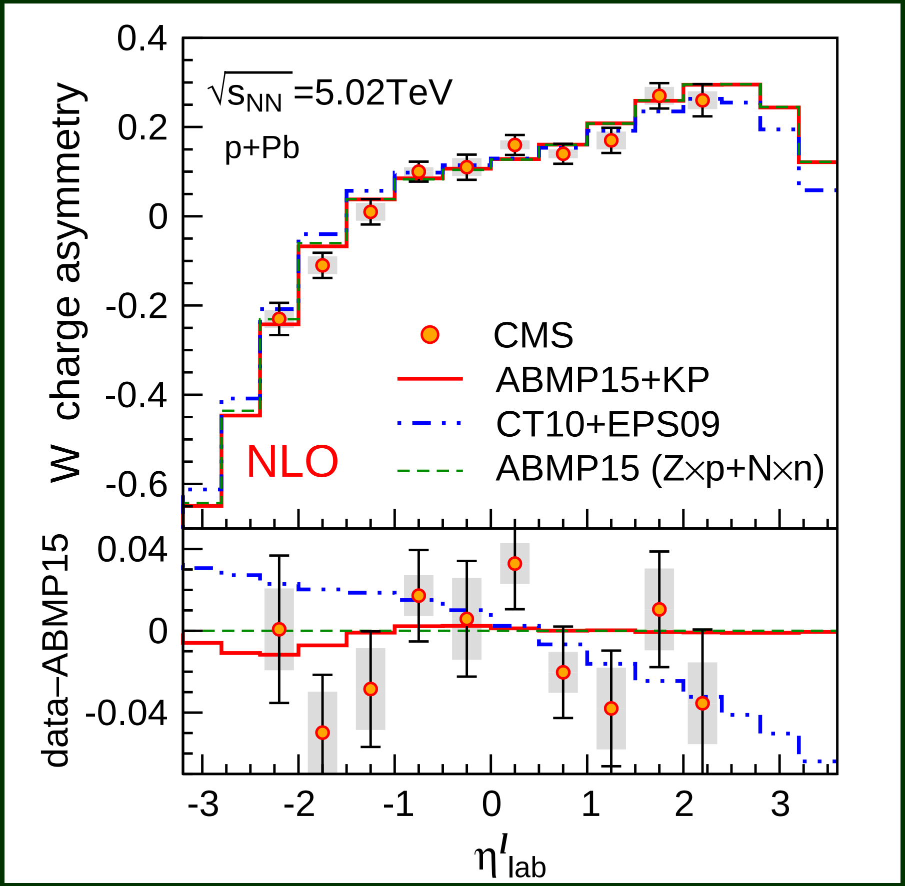


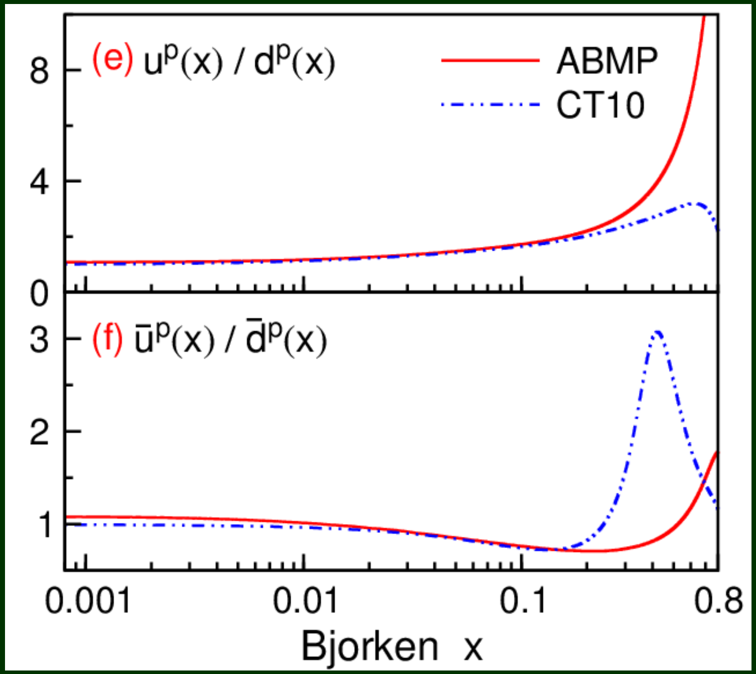
PR, Kulagin, Petti, B.W.Zhang, [1608.06835 [nucl-th]]

Results on p+Pb at the LHC

Charge asymmetry of W boson

PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

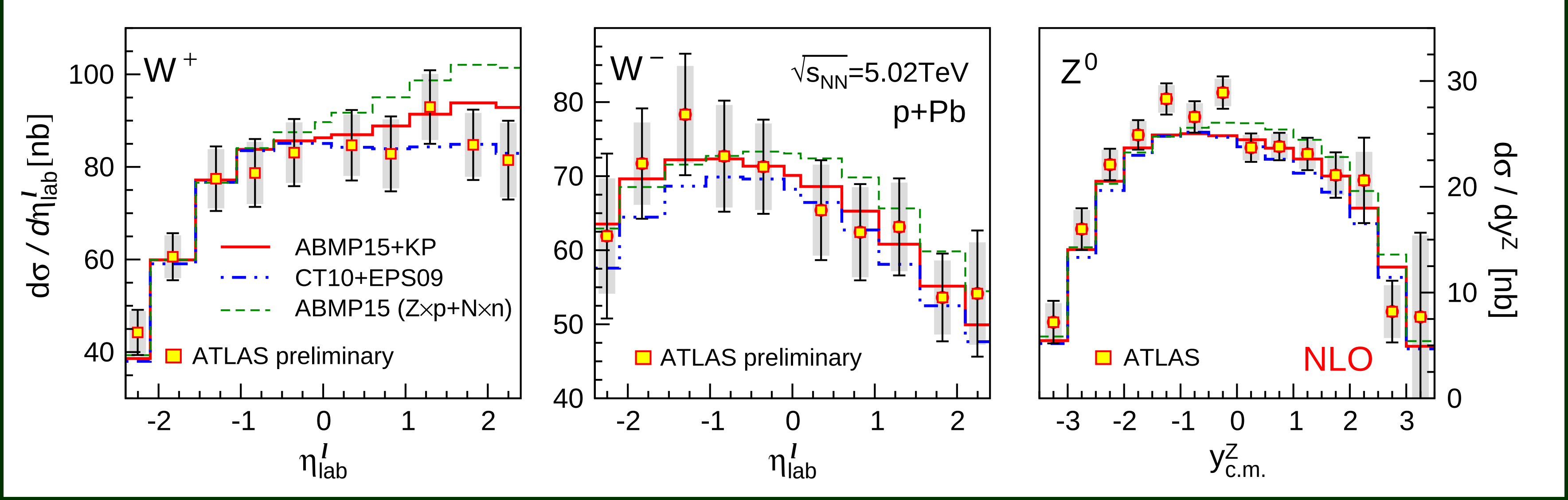




III. W/Z production in p+Pb collisions with KP NPDFs

Results on p+Pb at the LHC

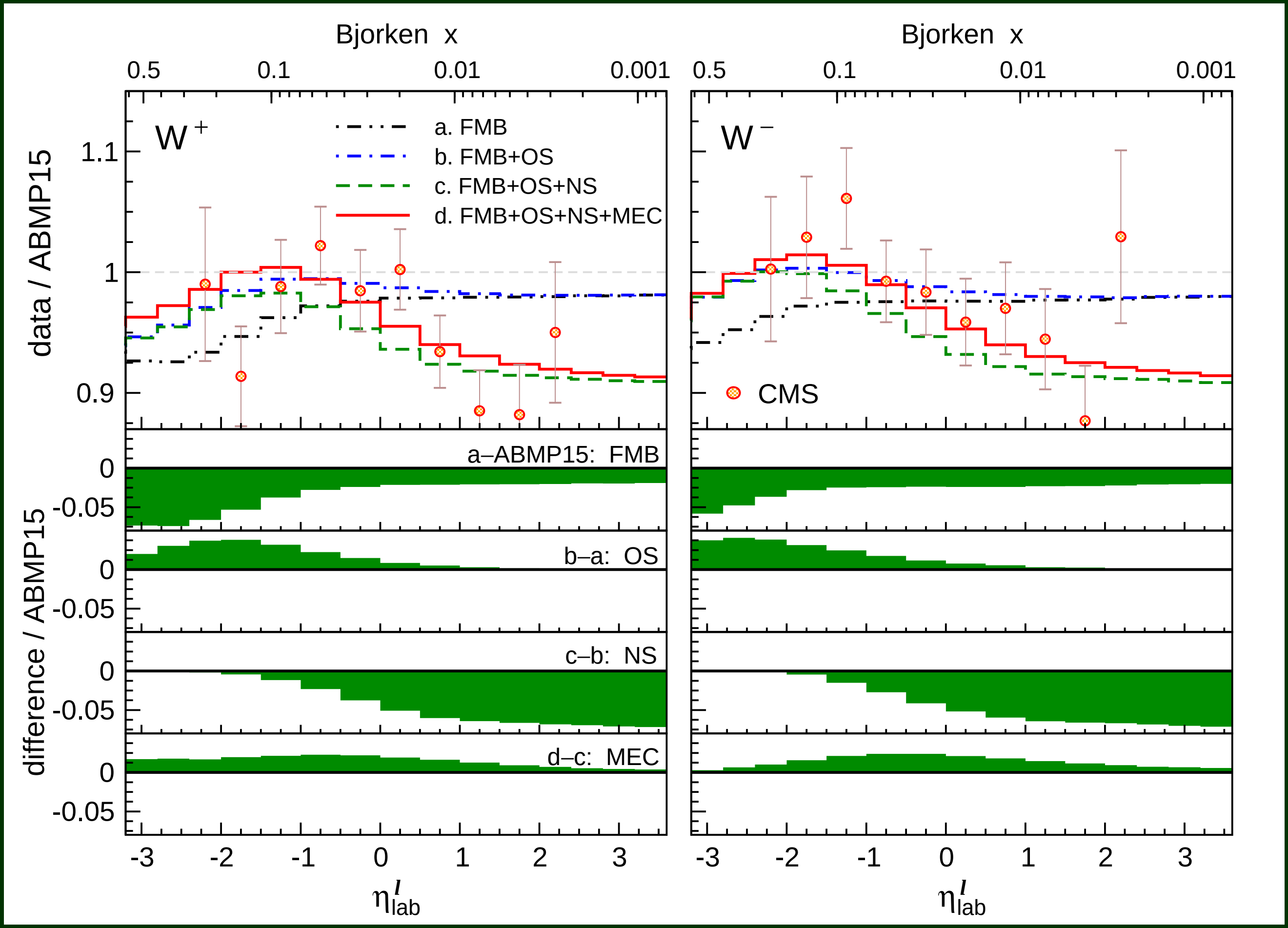
Comparison with the ATLAS data



PR, Kulagin, Petti, B.W.Zhang,
1608.06835 [nucl-th]

III. W/Z production in p+Pb collisions with KP NPDFs

Nuclear corrections with different effects



W diffenential cross section

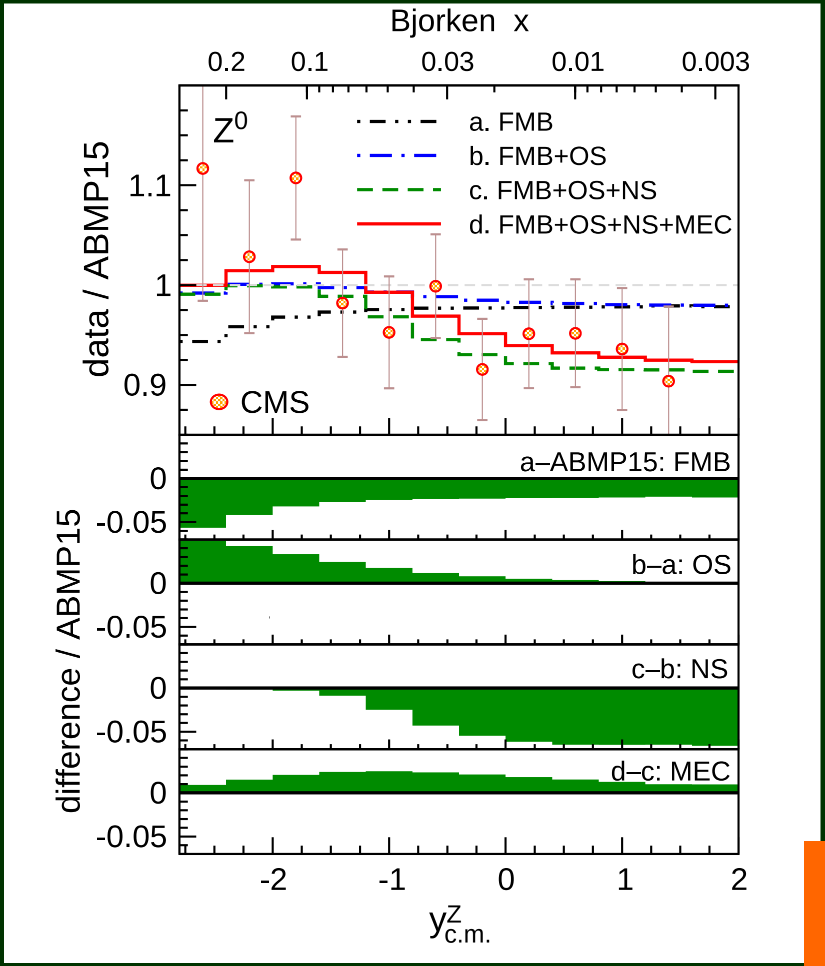
4 nuclear effects (FMB, OS, NS, MEC) play roles at the LHC.

PR, Kulagin, Petti, B.W.Zhang,
1608.06835 [nucl-th]

III. W/Z production in p+Pb collisions with KP NPDFs

Nuclear corrections with different effects

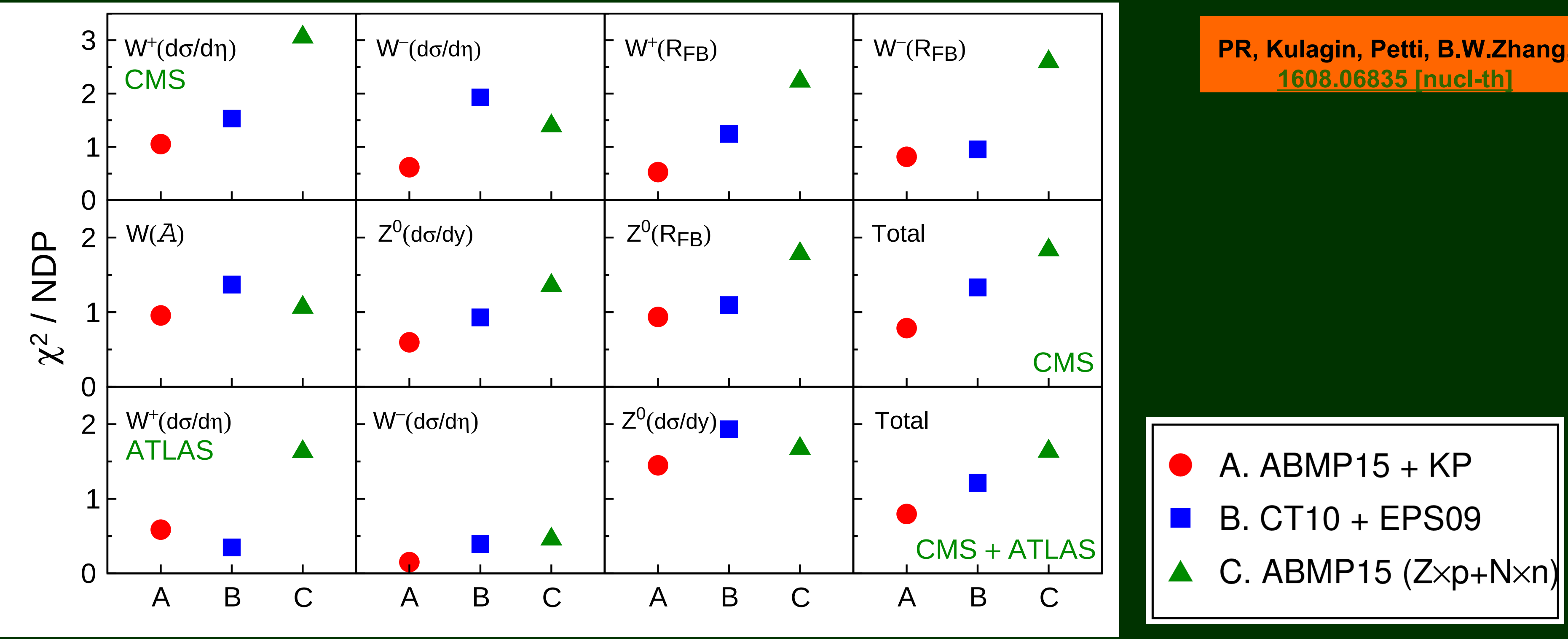
Z boson



PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

III. W/Z production in p+Pb collisions with KP NPDFs

χ^2/N_{Data} between model and measurement



PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

$$\chi^2/N_{Data} = \frac{1}{N_{Data}} \sum_{i=1}^{N_{Data}} \left[\frac{(O_{th} - O_{exp})^2}{\varepsilon^2_{stat} + \varepsilon^2_{syst}} \right]_i$$

- Good agreement between KP model predictions and the latest LHC data.
- Evidence of nuclear modification.

IV. W/Z production in future heavy-ion collisions

Pb+Pb at 39TeV
p+Pb at 63TeV

$$x \sim \frac{m_{Z,W}}{\sqrt{s_{NN}}}$$

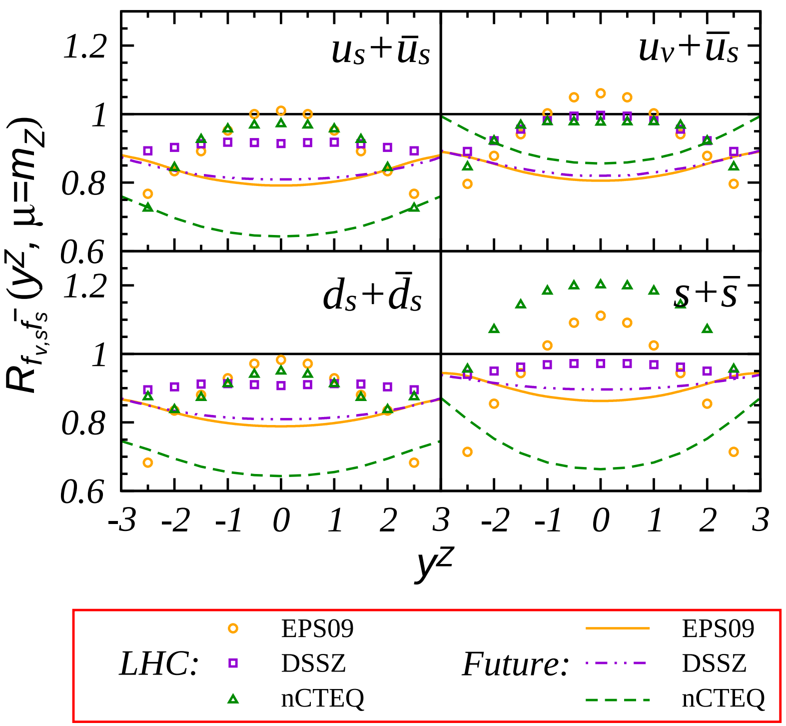
- Vector boson will be produced by smaller-x initial partons.
- The shadowing effect of the sea quark and gluon would be significant.
- Valence quark contribution and isospin effect would be small.

IV. W/Z production in future heavy-ion collisions

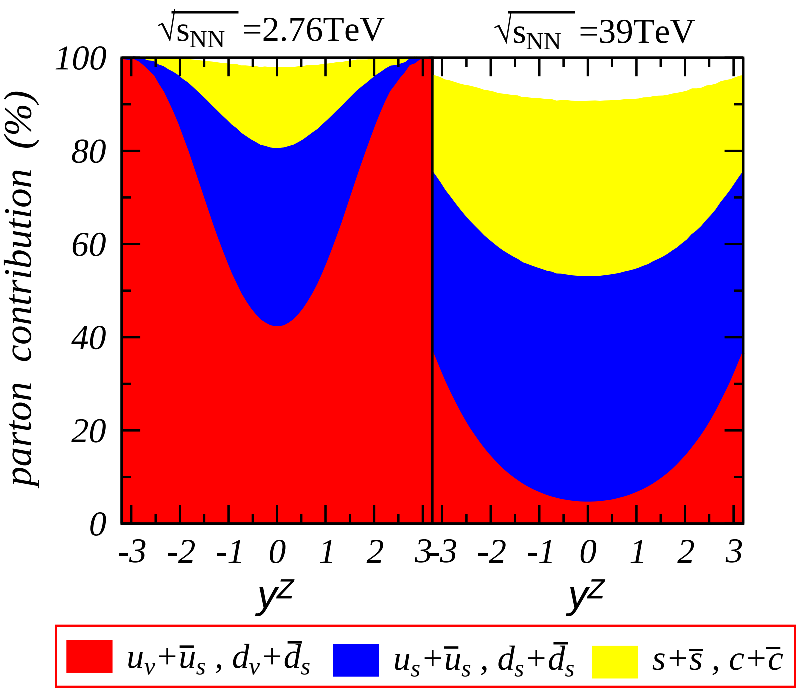
Pb+Pb: Z boson rapidity distribution

Nuclear correction at parton level

$$R_{f\bar{f}}(y^Z) = 1/2\left[R_f(x_1)R_{\bar{f}}(x_2) + R_f(x_2)R_{\bar{f}}(x_1)\right]$$



Parton contributions at LO

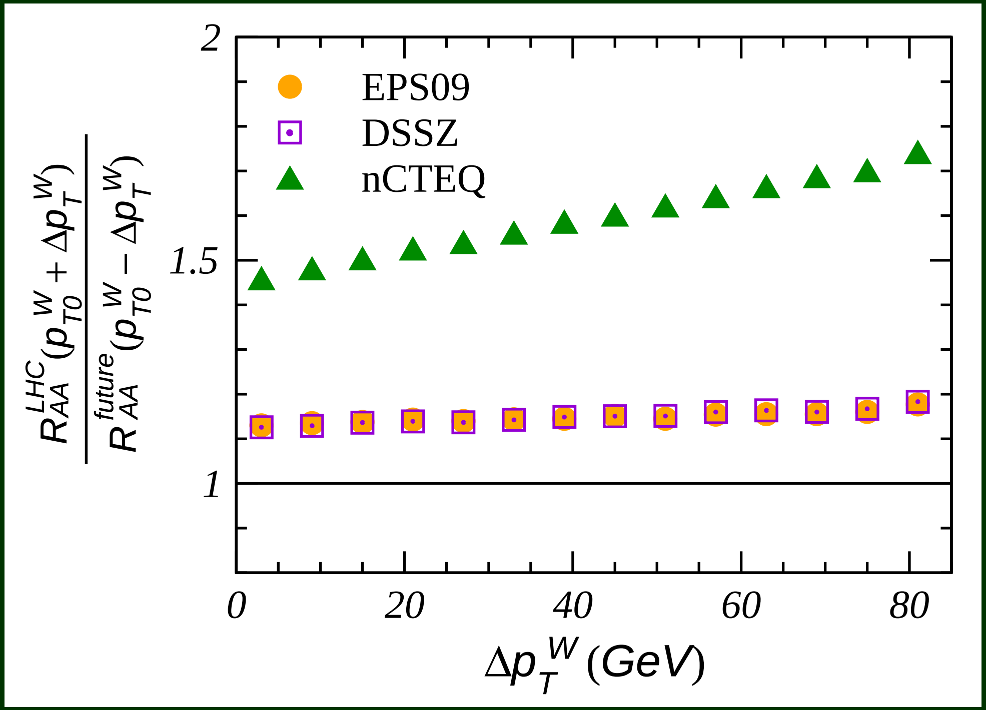


PR, B.W.Zhang, *et al.*
EPJC 75 (2015) 426

Differences between LHC and future

IV. W/Z production in future heavy-ion collisions

LHC + Future



PR, B.W.Zhang, *et al.*
EPJC 75 (2015) 426

$$\mathscr{R}(\Delta p_T^W) = \frac{R_{AA}^{LHC}(p_{T0}^W + \Delta p_T^W)}{R_{AA}^{Futu}(p_{T0}^W - \Delta p_T^W)}$$

- Valuable constraints on NPDFs

V. Summary

- **Nuclear corrections** on W/Z boson **rapidity** and **transverse momentum** distribution at the LHC are studied at **partonic level**. EPS09 and DSSZ predict different rapidity dependences.

- With the **KP model**, the nuclear corrections on W/Z production with different **underlying physical mechanisms** are shown for the first time.

- The predictions with **KP nuclear effect show a better agreement** with the latest LHC p+Pb data, than those without nuclear correction. The KP NPDFs well describe the W charge asymmetry.

- A further **improvement** of the accuracy of future **LHC data** may allow to **disentangle the effects** of different underlying mechanisms.

- The W/Z production in **future** heavy-ion collisions may provide more **powerful constraints on the NPDFs**.

Thank you !

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- The W/Z production in **future** heavy-ion collisions may provide more **powerful constraints on the NPDFs**.

Thank you !

I. Framework of the study

Numerical simulation in pp collision

Program :DYNNLO

Code :Drell-Yan Next-to-Next-to Leading Order (DYNNLO)

S. Catani, *et al* , PRL(2009) , PRL(2007)

- High-order QCD correction:

  NLO[$O(\alpha_S)$], NNLO[$O(\alpha_S^2)$]

- Renormalization and factorization scales

$$\mu_R = \mu_F = m_{W/Z}$$

- PDFs: MSTW08, CT10, ABMP15

Comparison with the LHC data

Total cross section

Vector boson	Cross-section(nb) at $\mathcal{O}(\alpha_s)$	Cross-section(nb) at $\mathcal{O}(\alpha_s^2)$
Z^0	0.45 ± 0.0002	0.458 ± 0.0008
W^+	3.000 ± 0.0016	3.062 ± 0.0092
W^-	2.025 ± 0.001	2.045 ± 0.0048

PR, B.W.Zhang, *et al*, JPG **42** (2015) 085104

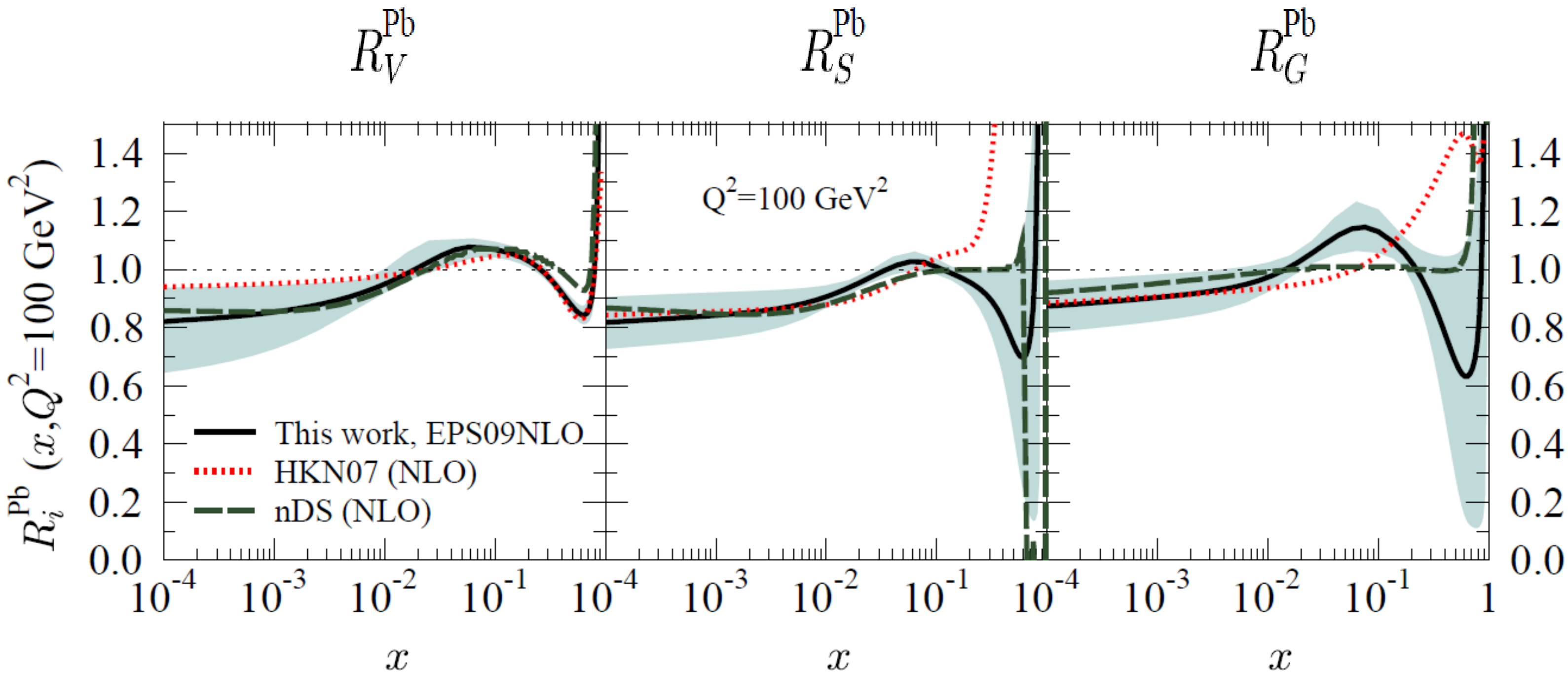
NNLO corrections are quite small

~1-2%

II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on PDFs

$$R_f(x,Q^2) = f^{Pb}(x,Q^2) / f^p(x,Q^2)$$

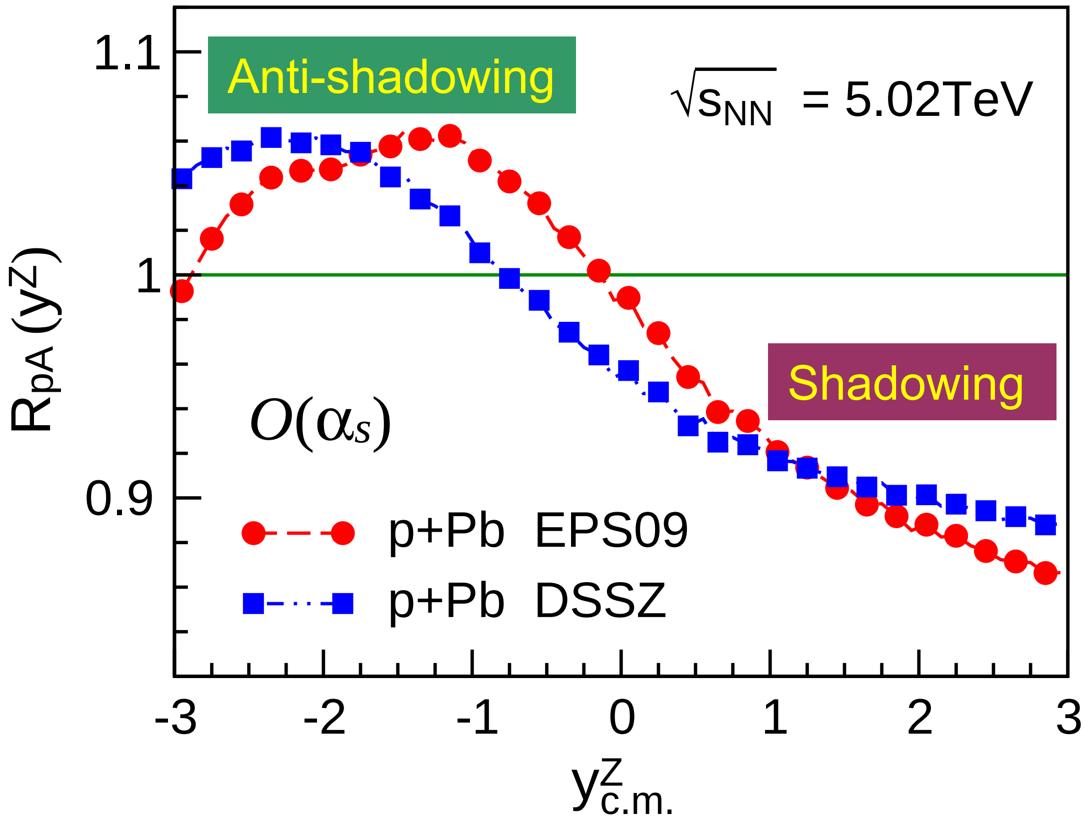


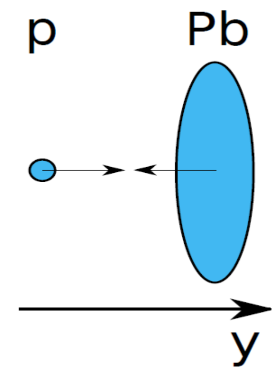
K. J. Eskola, *et al* JHEP **0904** 065 (2009)

Nuclear corrections on rapidity distribution in p+Pb collisions

Large-x, valence dominated

small-x, sea quark dominated



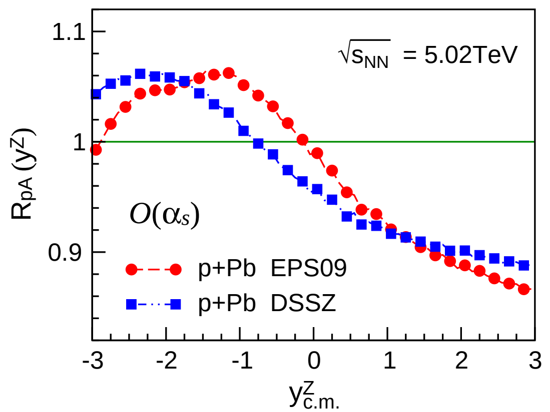


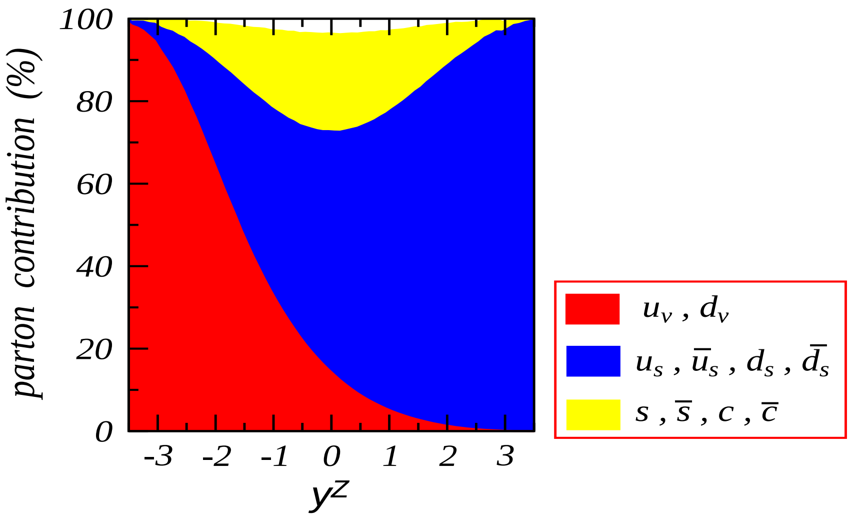
R_pA(y) provides an image of the nuclear corrections on quark **PDFs**.

II. Vector boson production in heavy-ion collisions at the LHC

Rapidity distribution in p+Pb collisions: Parton Level

Parton contributions at LO

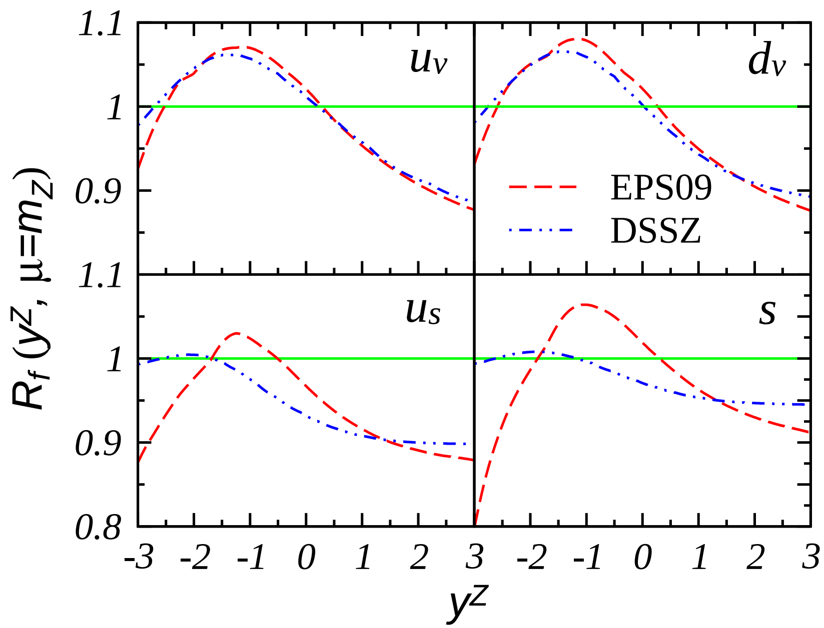




Nuclear correction at parton level

$$x_{Pb} = x_2 = \frac{m_Z}{\sqrt{s_{NN}}} e^{-y^Z}$$

$$R_f(x_{Pb}) \rightarrow R_f(y^Z)$$

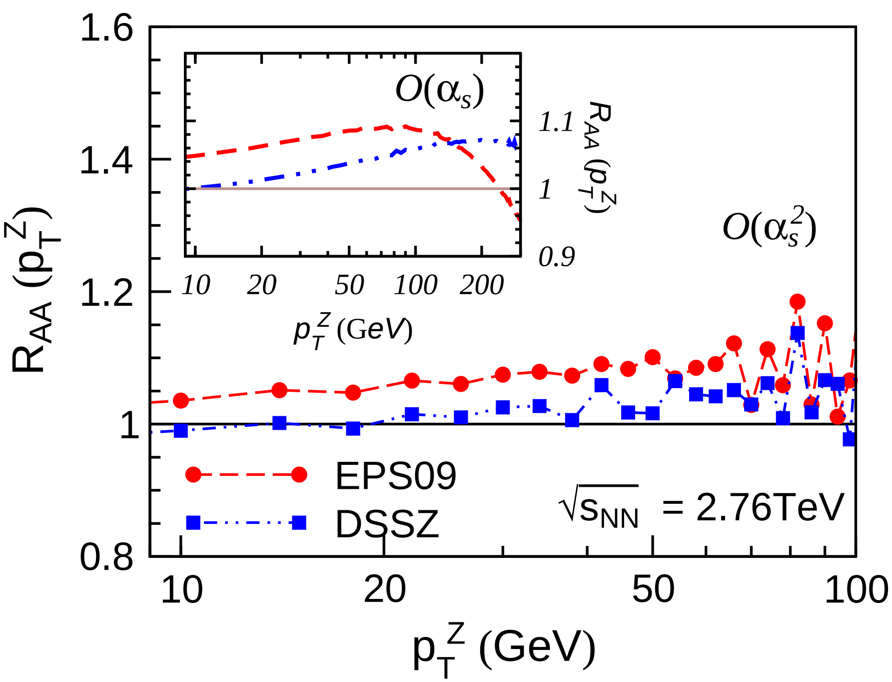


II. Vector boson production in heavy-ion collisions at the LHC

Nuclear corrections on Transverse momentum (pT) spectra: Pb+Pb

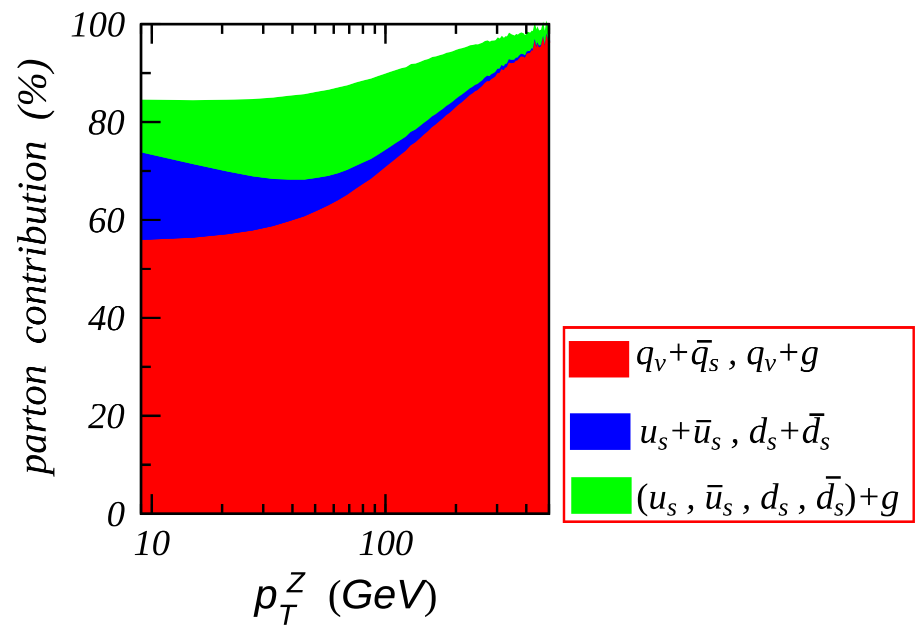
R_AA

Difference between EPS09 and DSSZ are observed.



Parton contributions at LO

Gluon gives LO contributions.



II. Vector boson production in heavy-ion collisions at the LHC

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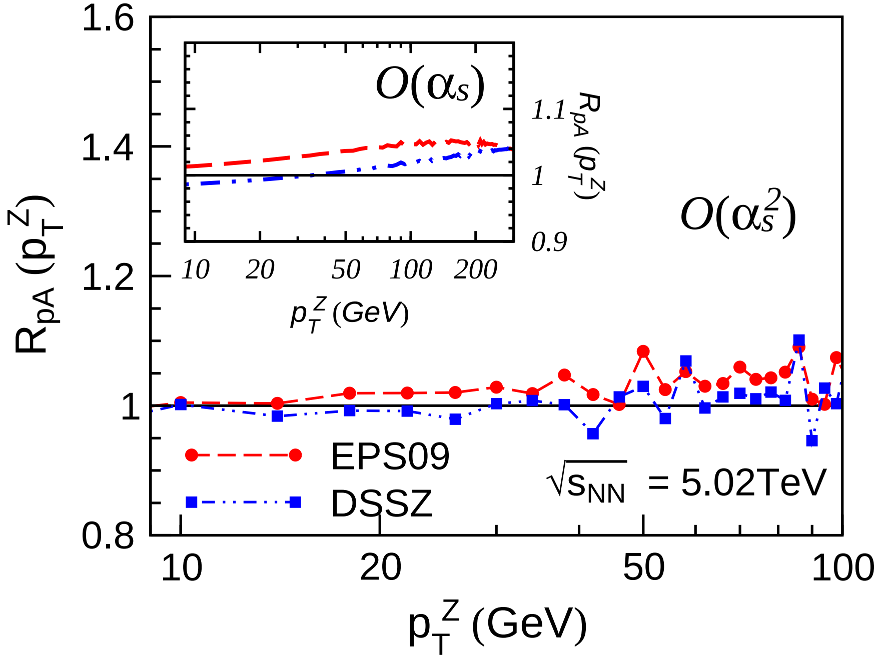

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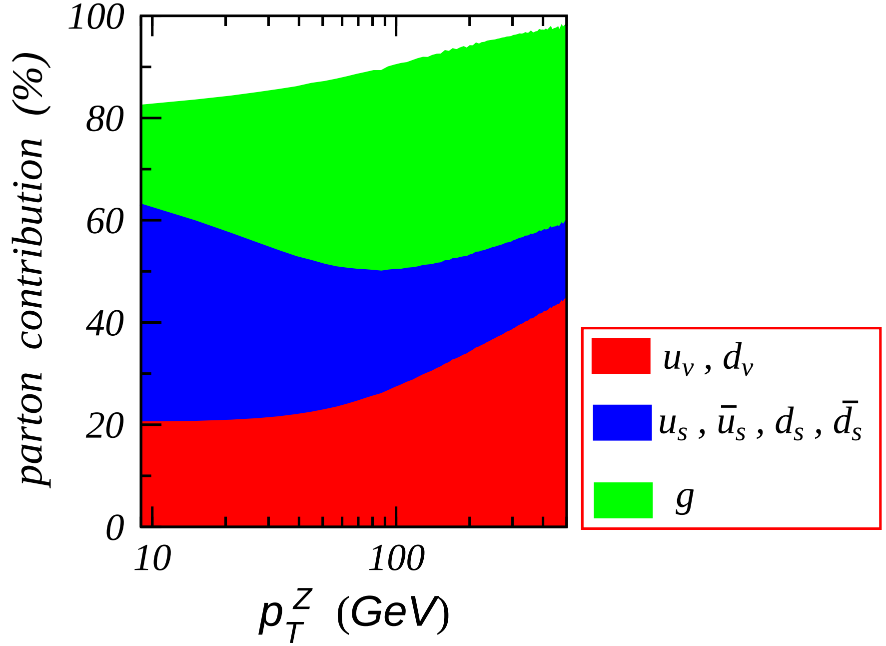


II. Vector boson production in heavy-ion collisions at the LHC

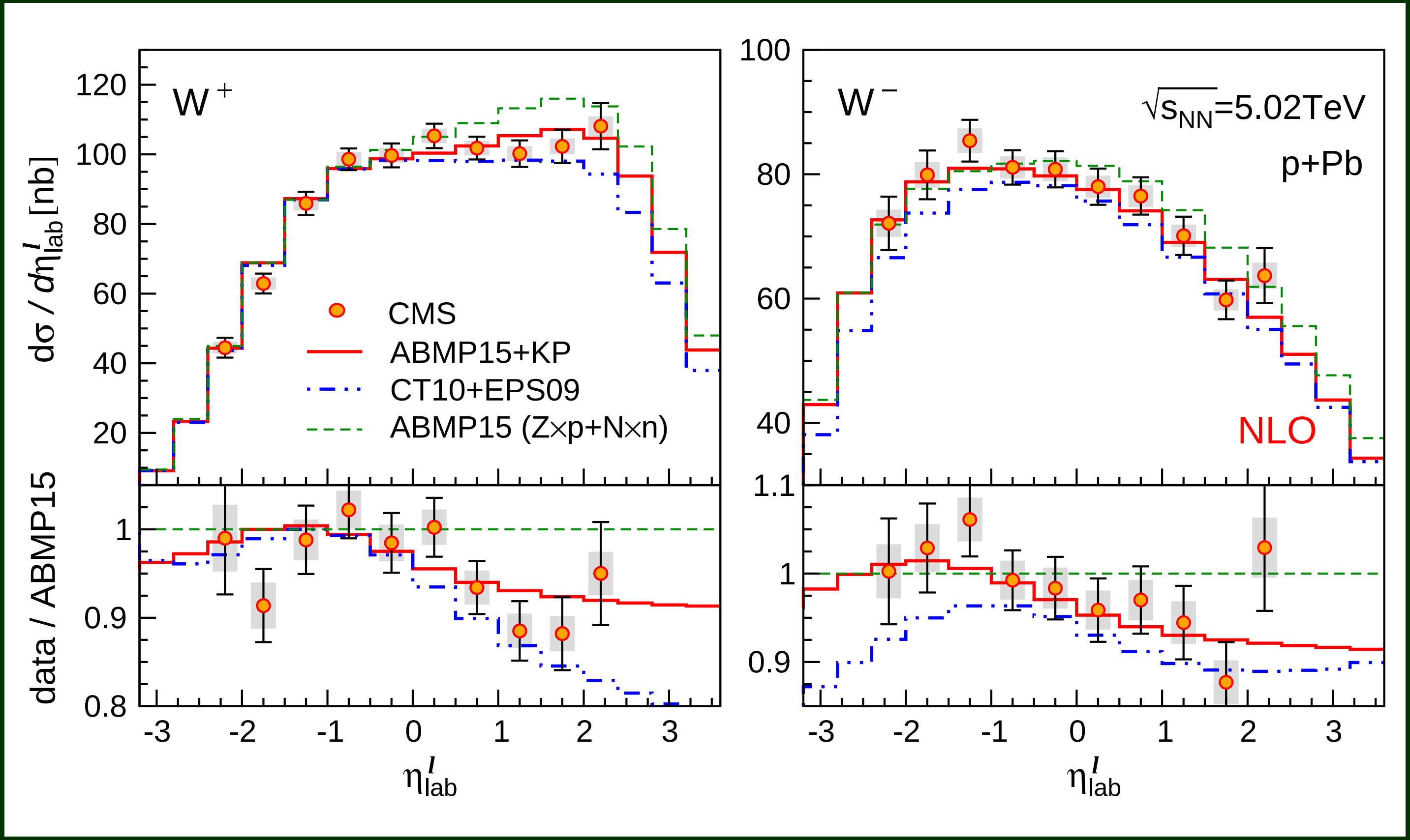
- **Rapidity distribution:** Sensitive to the CNM effect (shadowing and anti-shadowing) on quark distribution (both valence and sea).
- **pT spectrum:** Valuable probe of nuclear gluon distribution.
- **Differences** between predictions with different NPDF are observed.
- **W boson asymmetry:** Sensitive to the isospin effect.

  A good probe of flavor dependent nuclear corrections on PDFs.

III. W/Z production in p+Pb collisions with KP NPDFs

Results on p+Pb at the LHC

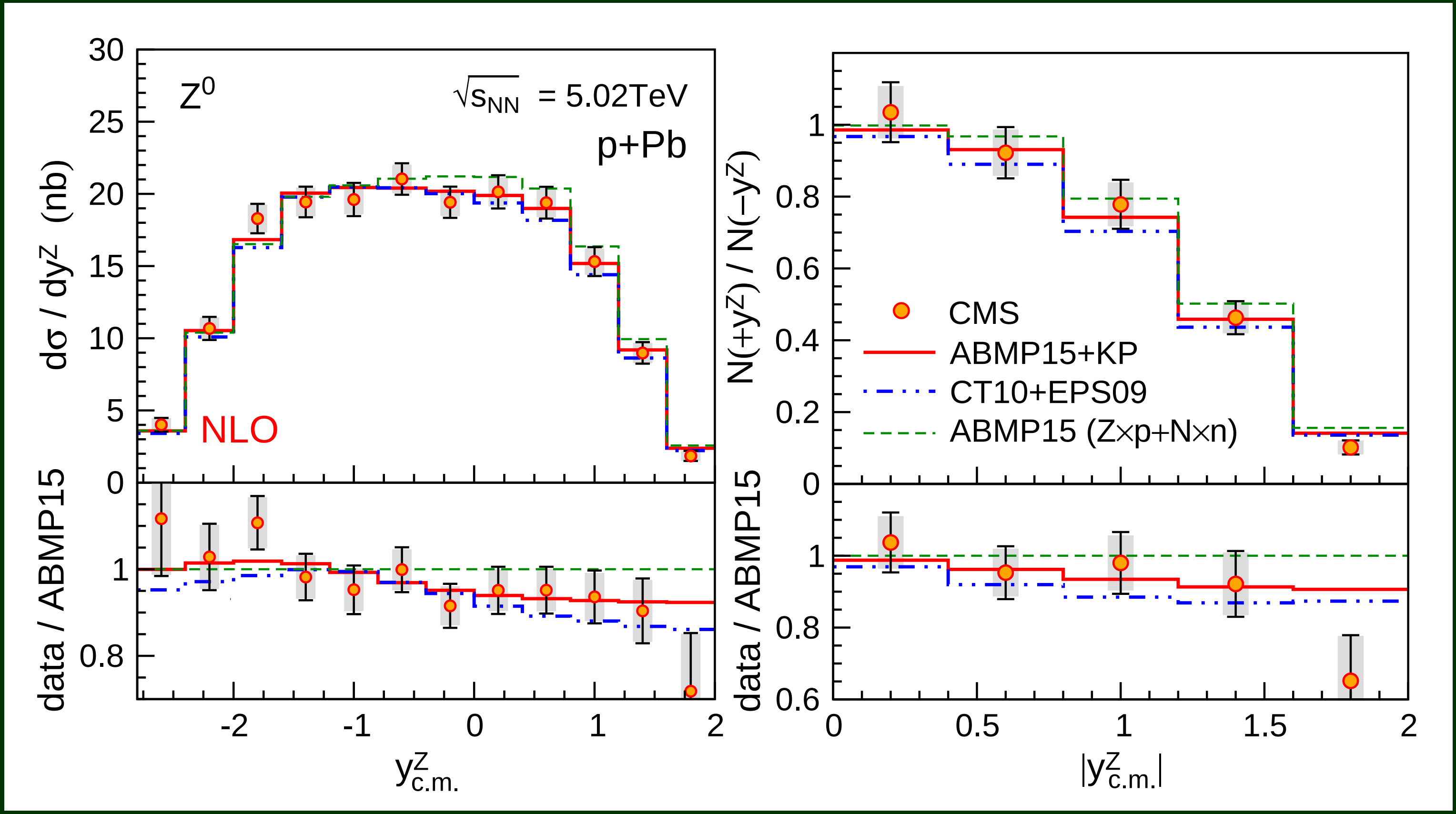
Differential cross section of W boson



PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

Results on p+Pb at the LHC

Z boson



PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

III. W/Z production in p+Pb collisions with KP NPDFs

χ^2/N_{Data} between model and measurement

TABLE I. Normalized χ^2 (per degree of freedom) for the various observables (rows) shown in the plots listed in the first column, calculated between each data set and three different model predictions: ABMP15+KP, CT10+EPS09, and ABMP15 without nuclear modifications (last column).

Observable	N_{Data}	ABMP15 + KP	CT10 + EPS09	ABMP15 (Zp + Nn)
		CMS experiment:		
$d\sigma^+/d\eta^l$	10	1.052	1.532	3.057
$d\sigma^-/d\eta^l$	10	0.617	1.928	1.393
$N^+(+\eta^l)/N^+(-\eta^l)$	5	0.528	1.243	2.231
$N^-(+\eta^l)/N^-(-\eta^l)$	5	0.813	0.953	2.595
$(N^+ - N^-)/(N^+ + N^-)$	10	0.956	1.370	1.064
$d\sigma/dy^Z$	12	0.596	0.930	1.357
$N(+y^Z)/N(-y^Z)$	5	0.936	1.096	1.785
CMS combined	57	0.786	1.332	1.833
		ATLAS experiment:		
$d\sigma^+/d\eta^l$	10	0.586	0.348	1.631
$d\sigma^-/d\eta^l$	10	0.151	0.394	0.459
$d\sigma/dy^Z$	14	1.449	1.933	1.674
CMS+ATLAS combined	91	0.796	1.213	1.635

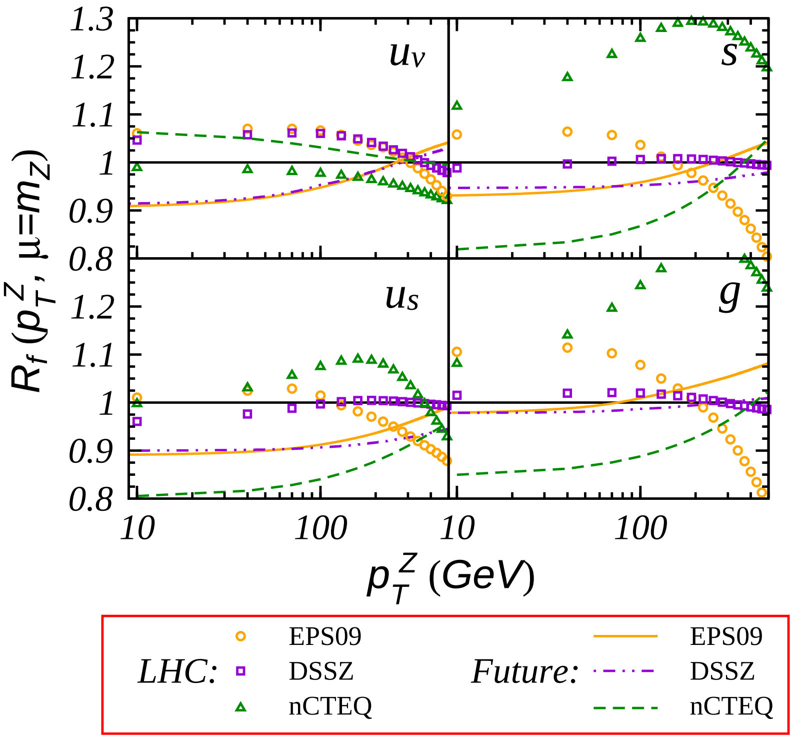
PR, Kulagin, Petti, B.W.Zhang, 1608.06835 [nucl-th]

IV. W/Z production in future heavy-ion collisions

Pb+Pb: Z boson pT spectra

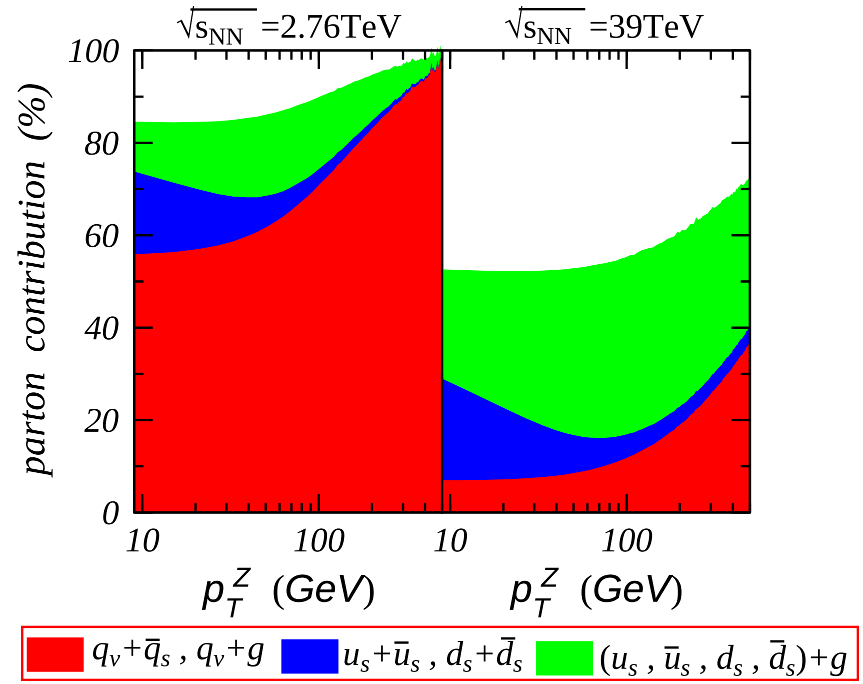
Nuclear correction at parton level

$$R_f(x_{Pb}) \rightarrow R_f(p_T)$$



Differences between LHC and future

Parton contributions at LO



PR, B.W.Zhang, *et al.* **EPJC** 75 (2015) 426

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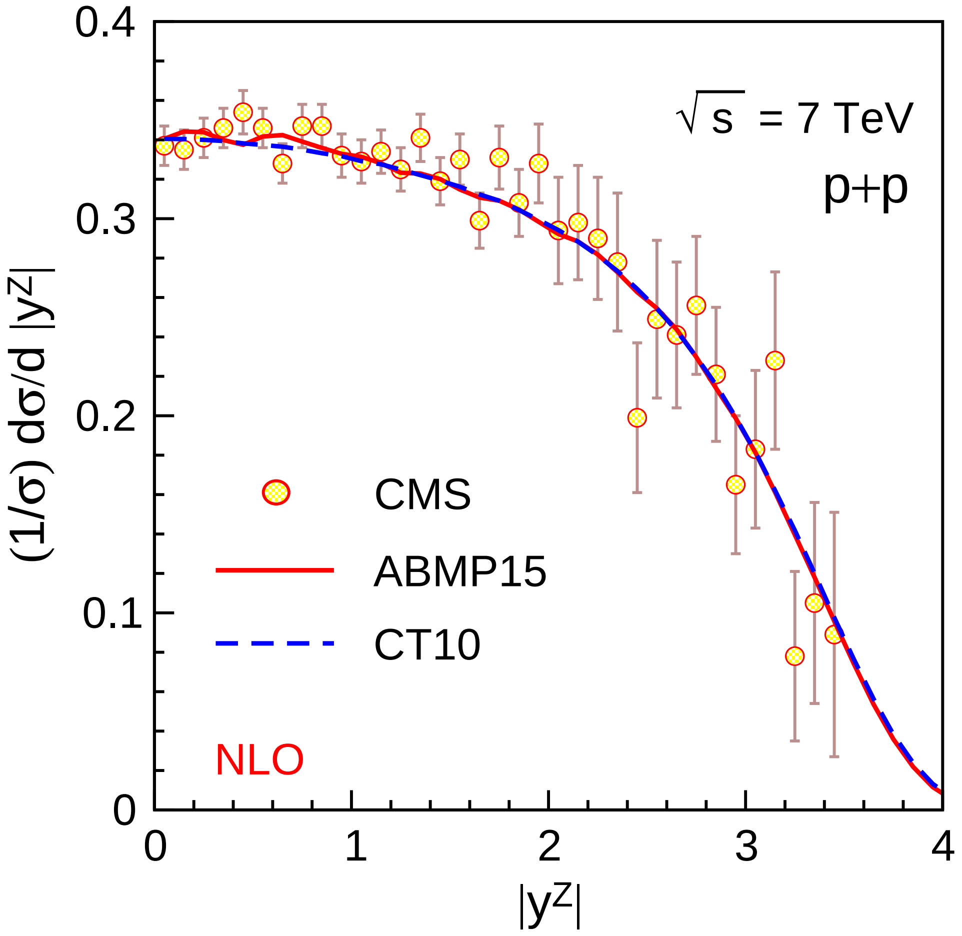
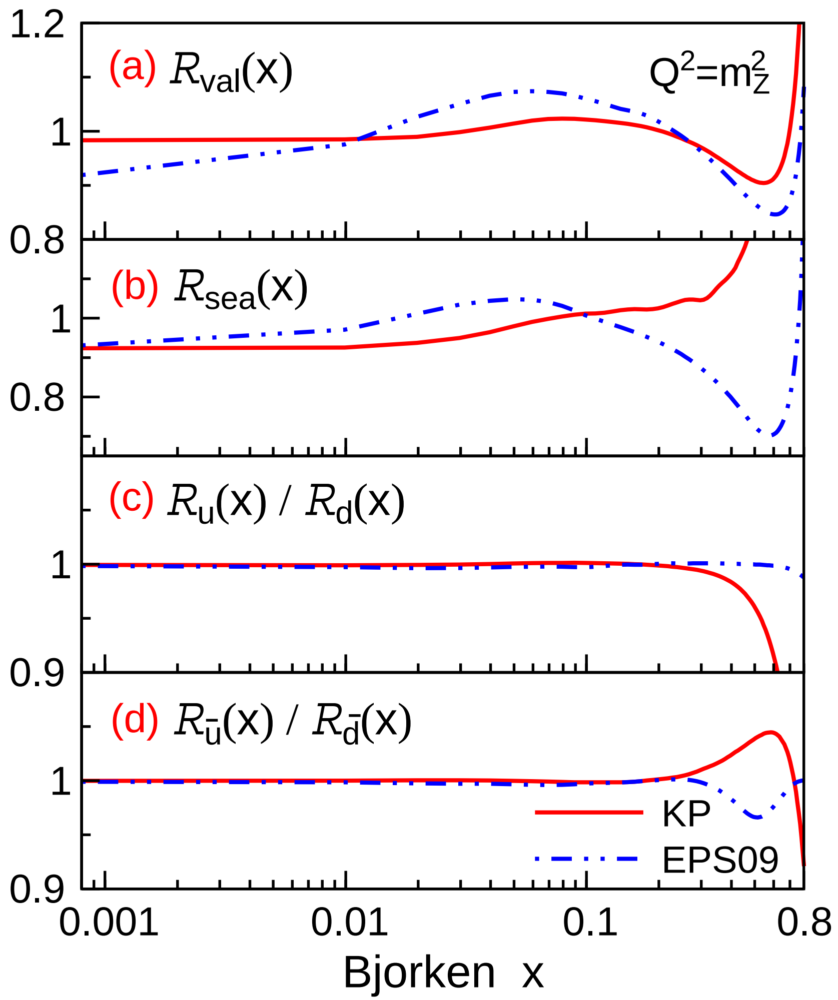


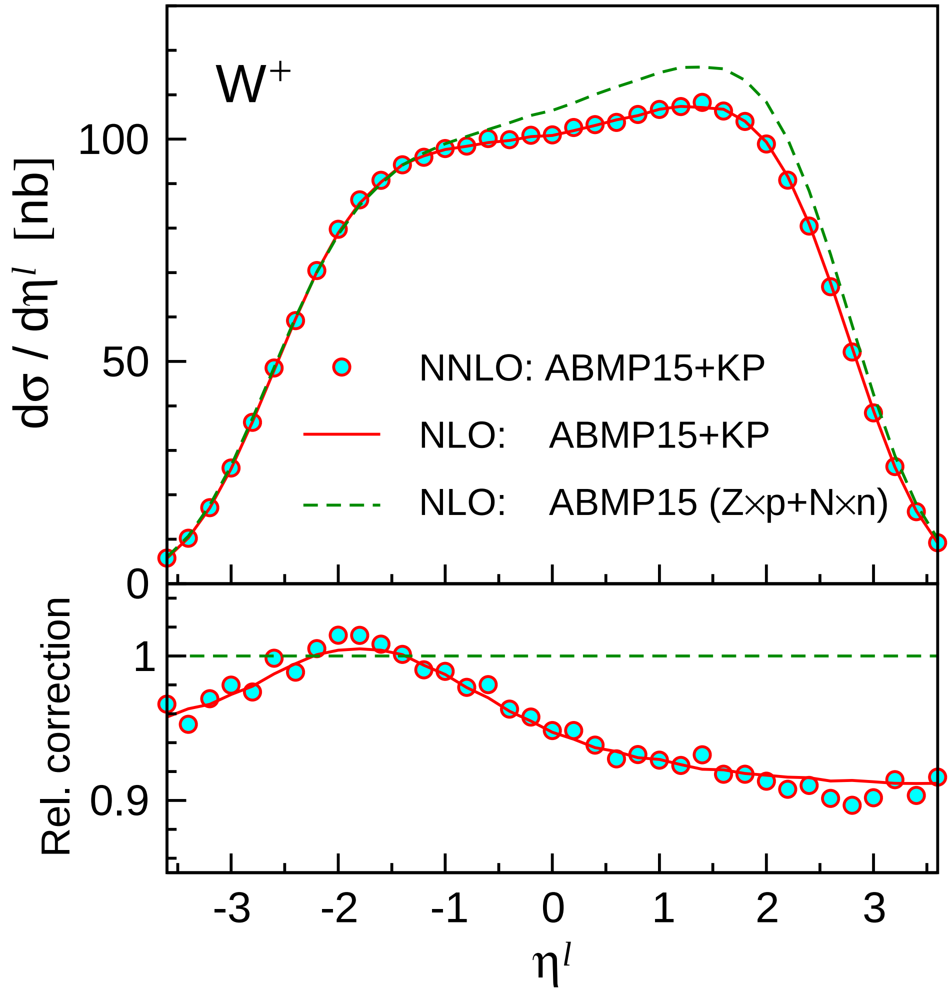
0.4
0.3
0.2
0.1
0
0
1
2
3
4
$|y^Z|$
$(1/\sigma)\ d\sigma/d\ |y^Z|$
$\sqrt{s}$ = 7 TeV
p+p
CMS
ABMP15
CT10
NLO

Backup

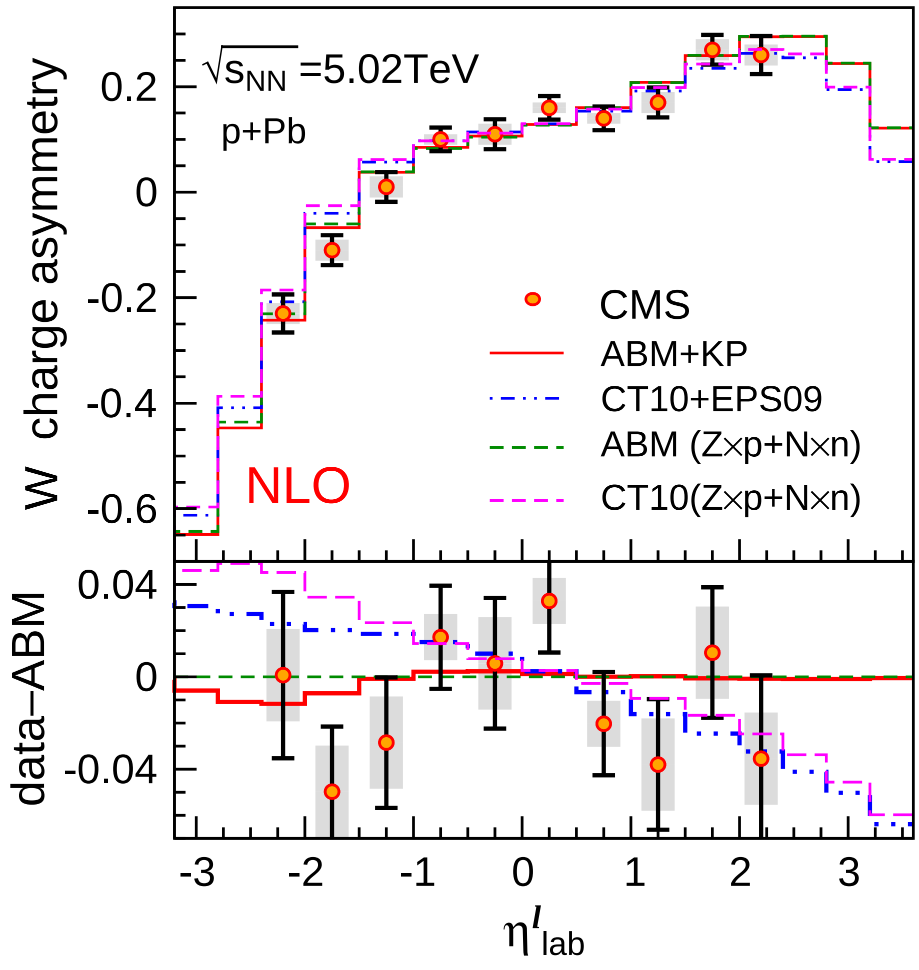


1.2
1
0.8
(a) R_{val}(x)
$Q^2=m_Z^2$
1
0.8
(b) R_{sea}(x)
(c) R_u(x) / R_d(x)
1
0.9
(d) $R_{\bar{u}}$(x) / $R_{\bar{d}}$(x)
1
0.9
KP
EPS09
0.001
0.01
0.1
0.8
Bjorken x

Backup

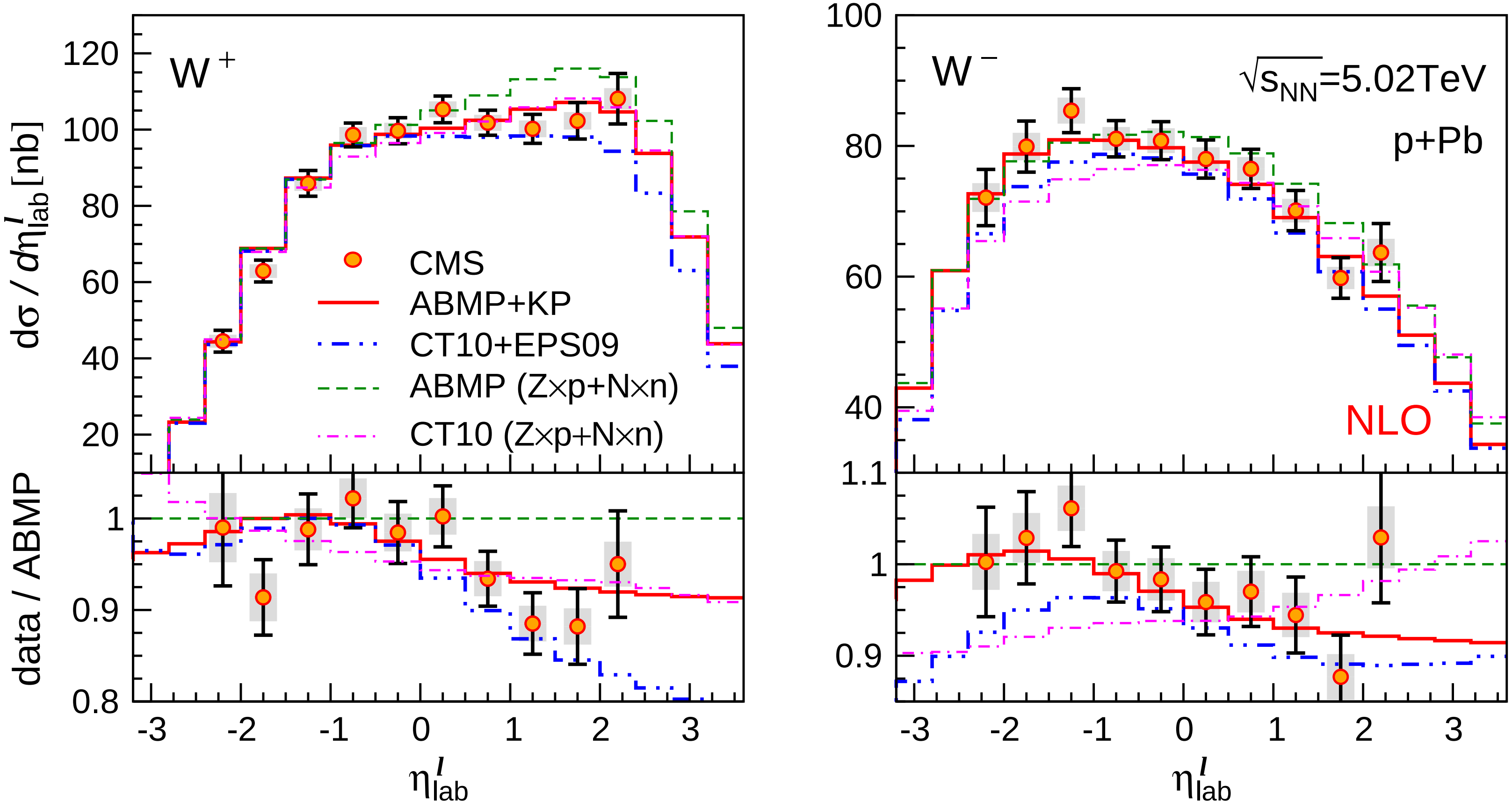

W+
dσ / dη^l [nb]
100
50
0
NNLO: ABMP15+KP
NLO: ABMP15+KP
NLO: ABMP15 (Z×p+N×n)
Rel. correction
1
0.9
-3
-2
-1
0
1
2
3
η^l

Backup



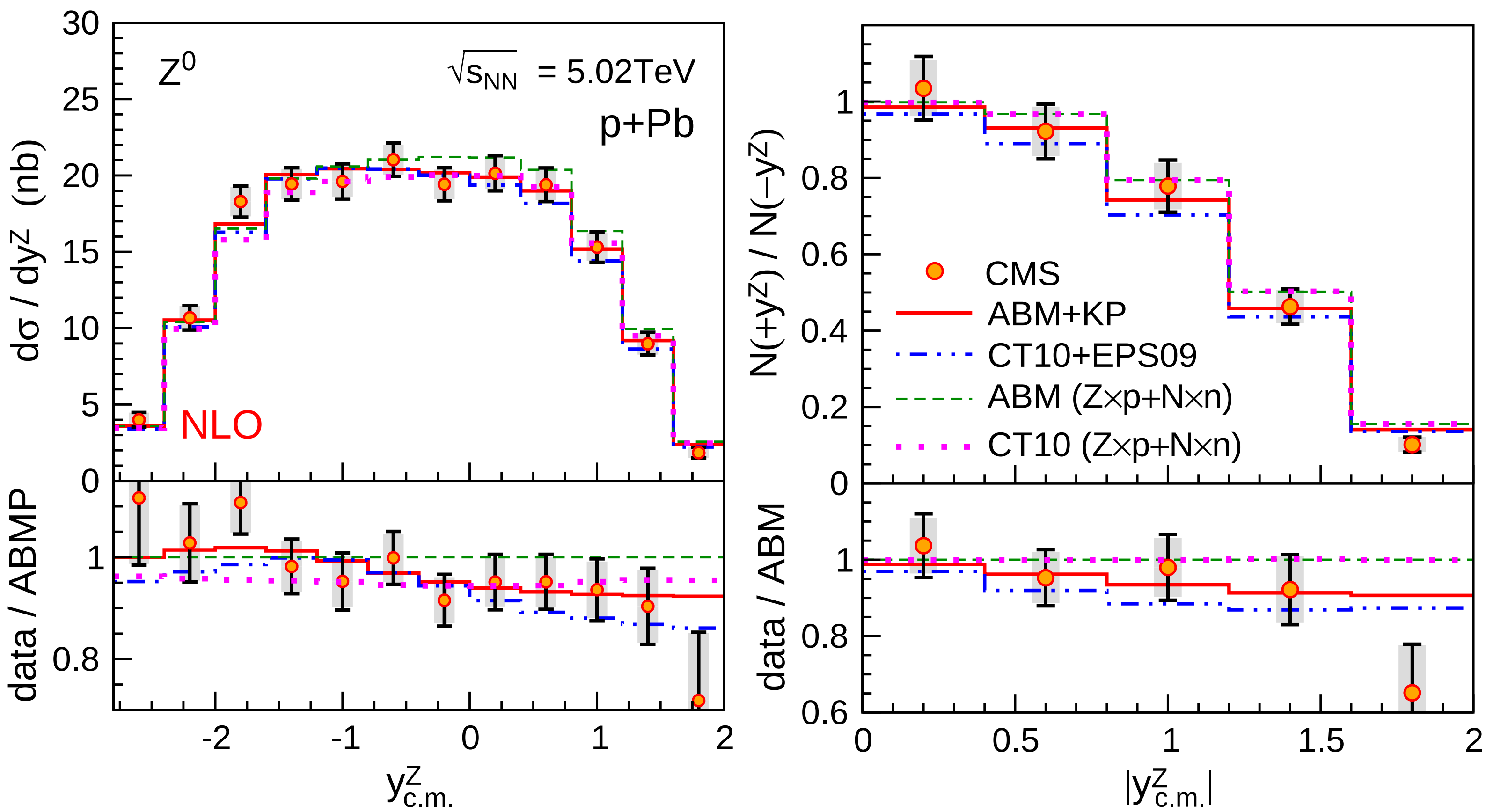
$\sqrt{s_{NN}}$ =5.02TeV
p+Pb
W charge asymmetry
0.2
0
-0.2
-0.4
-0.6
CMS
ABM+KP
CT10+EPS09
ABM (Z×p+N×n)
CT10(Z×p+N×n)
NLO
data–ABM
0.04
0
-0.04
-3
-2
-1
0
1
2
3
η^{l}_{lab}

Backup



W +
W −
$\sqrt{s_{NN}}$=5.02TeV
p+Pb
NLO
CMS
ABMP+KP
CT10+EPS09
ABMP (Z×p+N×n)
CT10 (Z×p+N×n)
dσ / dη$^l_{lab}$ [nb]
data / ABMP
η$^l_{lab}$
120
100
80
60
40
20
1.1
1
0.9
0.8
-3
-2
-1
0
1
2
3

Backup



Z^0
$\sqrt{s_{NN}}$ = 5.02TeV
p+Pb
NLO
dσ / dy^Z (nb)
data / ABMP
$y^Z_{c.m.}$
N(+y^Z) / N(−y^Z)
data / ABM
$|y^Z_{c.m.}|$
CMS
ABM+KP
CT10+EPS09
ABM (Z×p+N×n)
CT10 (Z×p+N×n)

Backup

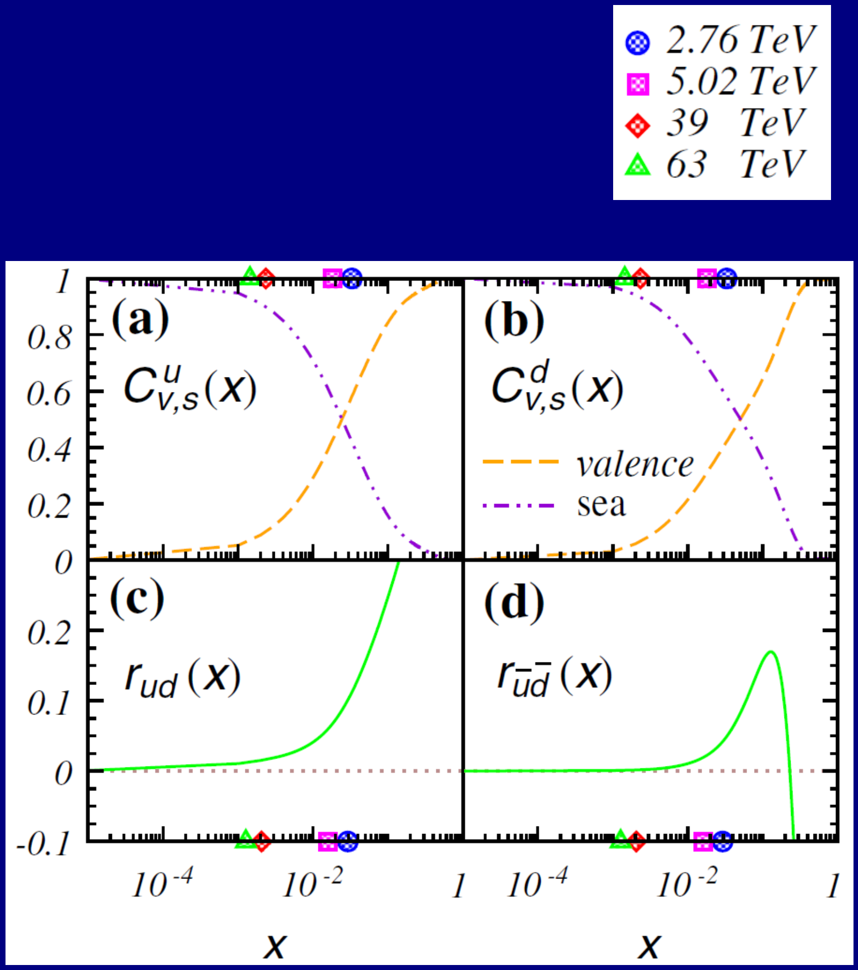
In future heavy-ion collisions

$$C_v^f(x) = \frac{f_v(x)}{f_v(x) + f_s(x)}$$

$$C_s^f(x) = \frac{f_s(x)}{f_v(x) + f_s(x)}$$

$$r_{ud}(x) = \frac{u(x) - d(x)}{u(x) + d(x)},$$

$$r_{\bar{u}\bar{d}}(x) = -\frac{\bar{u}(x) - \bar{d}(x)}{\bar{u}(x) + \bar{d}(x)}$$



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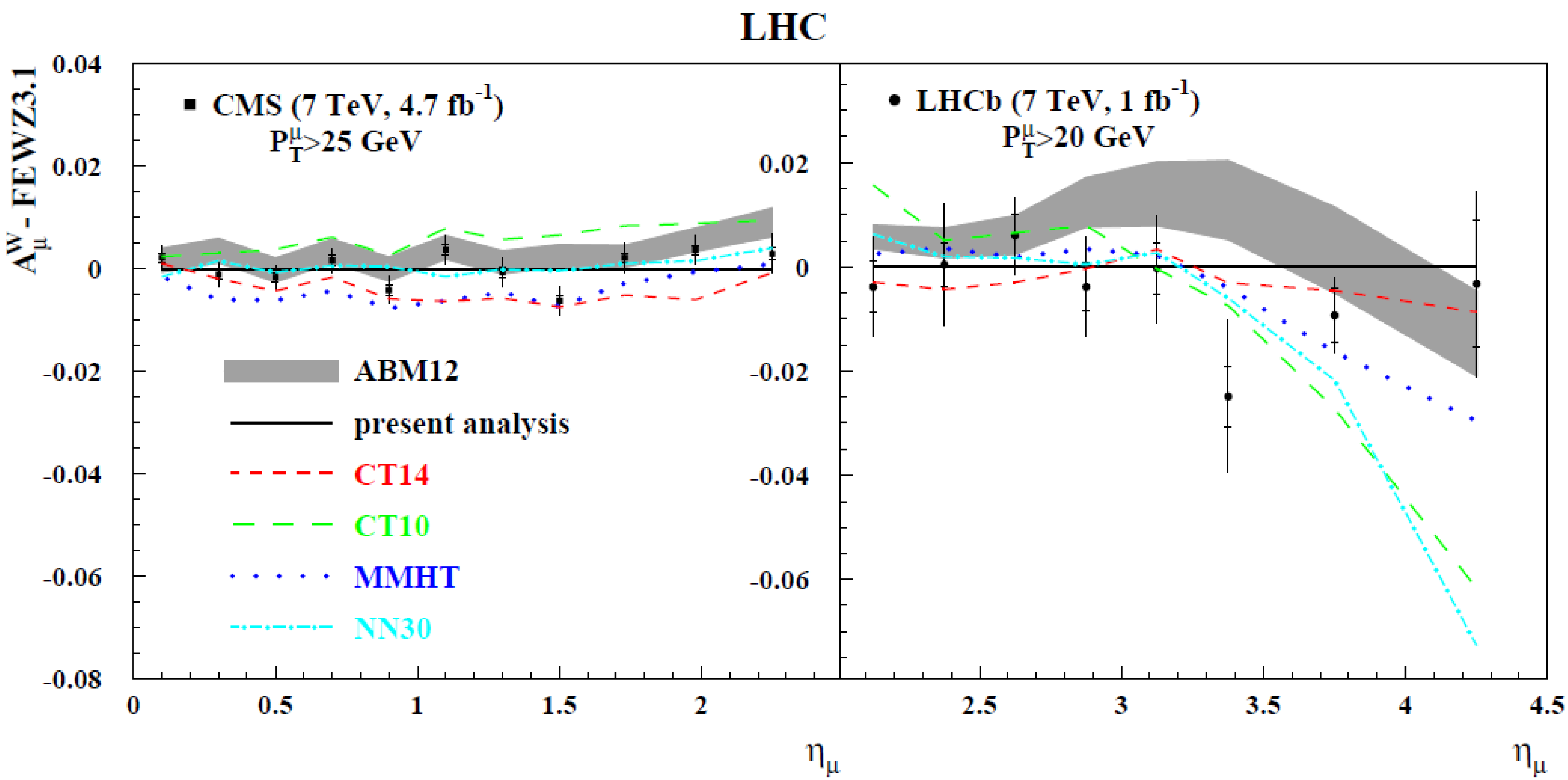

S.Alekhin et al,
1508.07923[hep-ph]

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