Status of nuclear PDFs after the first LHC p-Pb run

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Outline

Introduction

Theoretical Foundations: Collinear factorization

- Factorization

Parton distribution functions (PDFs)

$$d\sigma = \sum_{i,j} f_i(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f^2) + \mathcal{O}\left(Q_f^{-2n}\right)$$

Theoretical Foundations: Collinear factorization

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Coefficient functions (calculable by perturbative methods)

Theoretical Foundations: Collinear factorization

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Coefficient functions (calculable by perturbative methods)

- PDFs obey the DGLAP equations

$$Q^2 \frac{\partial f_i(x,Q^2)}{\partial Q^2} = \sum_j P_{ij}(Q^2) \otimes f_j(x,Q^2)$$

Splitting functions (calculable by perturbative methods)

Theoretical Foundations: Collinear factorization

- Factorization

$$d\sigma = \sum_{i,j} f_i(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f^2) + \mathcal{O}\left(Q_f^{-2n}\right)$$

- Non-linear power corrections predicted to be important even at perturbative scales, particularly for large A.
- Often supplemented with external models for hadronization (e.g. PYTHIA).
- Also used in computing the initial conditions for fluid dynamical description of heavy-ion collisions [PRC93 (2016) NO.2, 024907].

Current global analyses: Situation 2 months ago

	EPS09	DSSZ12	KA15	nCTEQ15
Order in α_s	LO & NLO	NLO	NNLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓
Neutrino-nucleus DIS		✓		
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$
datapoints	929	1579	1479	708
free parameters	15	25	16	17
error analysis	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	N.N	35
Free proton baseline PDFs	CTEQ6.1	MSTW2008	JR09	CTEQ6M-like
Heavy-quark effects		✓		✓
Flavour separation	none	none	none	some
Reference	[JHEP 0904 065]	[PR D85 074028]	[PRD 93, 014026]	[PR D93 085037]

Current global analyses: Situation now

	EPPS16	DSSZ12	KA15	NCTEQ15
Order in α_s	NLO	NLO	NNLO	NLO
Neutral current DIS ℓ+A/ℓ+d	✓	✓	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓	✓	✓
RHIC pions d+Au/p+p	✓	✓		✓
Neutrino-nucleus DIS	✓	✓		
Drell-Yan dilepton $\pi+A$[1]	✓			
LHC p+Pb jet data	✓			
LHC p+Pb W, Z data	✓			
Q cut in DIS	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$
datapoints	1811	1579	1479	708
free parameters	20	25	16	17
error analysis	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	52	30	N.N	35
Free proton baseline PDFs	CT14NLO	MSTW2008	JR09	CTEQ6M-like
Heavy-quark effects	✓	✓		✓
Flavour separation	full	none	none	some
Reference	[ARXIV:1612.05741	[PR D85 074028]	[PRD 93, 014026]	[PR D93 085037]

[1] Poster by P. Paakkinen

Analysis procedures

What is actually parametrized?

- The standard definition of nuclear PDFs

Free proton baseline

$$f_i^{\mathrm{p}/A}(x,Q^2) \equiv R_i^A(x,Q^2)\, f_i^{\mathrm{p}}(x,Q^2)$$

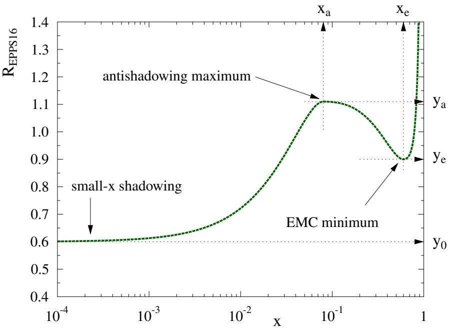
Nuclear modifications

- Why the two components?
- Much of the data are ratios of the form

$$F_2^A(x,Q^2)/F_2^p(x,Q^2)$$

$\Longrightarrow$ In a global analysis f_i^{p} must always be supplied.

$\Longrightarrow$ Nuclear PDFs are always relative to the free-proton PDFs.



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Free proton baseline

$$f_i^{\mathrm{p}/A}(x,Q^2) \equiv R_i^A(x,Q^2)\, f_i^{\mathrm{p}}(x,Q^2)$$

Nuclear modifications

- Most (EPS09, DSSZ,...) impose the flavour independence (FI) at $Q^2 = Q_0^2$:

$$R_{u_{\mathrm{V}}}(x,Q_0^2) = R_{d_{\mathrm{V}}}(x,Q_0^2)$$

$$R_{\overline{u}}(x,Q_0^2) = R_{\overline{d}}(x,Q_0^2) = R_{\overline{s}}(x,Q_0^2)$$

- The FI immediately destroyed by the DGLAP at $Q^2 > Q_0^2$

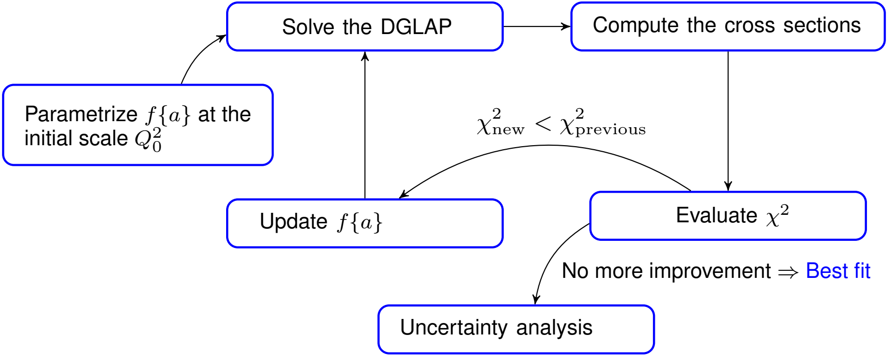
$\Longrightarrow$ No reason to assume FI in the first place.

- nCTEQ15: flavour variation for the valence quarks.
- EPPS16: flavour dependent valence & sea quarks.

The standard analysis procedure

- Based on considering χ^2 figure-of-merit function

$$\chi^2_{\text{global}} \equiv \sum_{i,j} [T_i(\vec{a}) - D_i]\, C^{-1}_{ij}\, [T_j(\vec{a}) - D_j]$$



Uncertainty analysis: the Hessian method

- Expand the global χ^2 around the minimum

Hessian matrix

$$\chi^2_{\rm global} \approx \chi^2_0 + \sum_{i,j} (a_i - a_i^0)\, H_{ij}\, (a_j - a_j^0) = \chi^2_0 + \sum_i z_i^2$$

Parameter variations

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Parameter variations

- The z_i coordinates (linear combinations of a_i) are $\sim$ uncorrelated and one can use the standard law of error propagation

$$(\delta X)^2 = \sum_i \left(\frac{\partial X}{\partial z_i} \times \delta z_i \right)^2 , \; \delta z_i = \frac{\delta z_i^+ + \delta z_i^-}{2}$$

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$$(\delta X)^2 = \sum_i \left(\frac{\partial X}{\partial z_i} \times \delta z_i \right)^2, \; \delta z_i = \frac{\delta z_i^+ + \delta z_i^-}{2}$$

- Define the PDF uncertainty sets $S_i^\pm$

$$S_1^\pm \equiv \pm \delta z_1^\pm \, (1, 0, \ldots, 0)$$

$$\vdots$$

$$S_N^\pm \equiv \pm \delta z_N^\pm \, (0, 0, \ldots, 1)$$

$$\Longrightarrow \quad (\delta X)^2 = \frac{1}{4} \sum_i \left[X(S_i^+) - X(S_i^-) \right]^2$$

Uncertainty analysis: the Hessian method

- The current fits define $\delta z_i^{\pm}$ such that they correspond to fixed $\Delta\chi^2_{\rm global}$.
- Ideally, $\Delta\chi^2_{\rm global} = 1$.
- For the parametrization bias, the global fits take $\Delta\chi^2_{\rm global} \gg 1$.

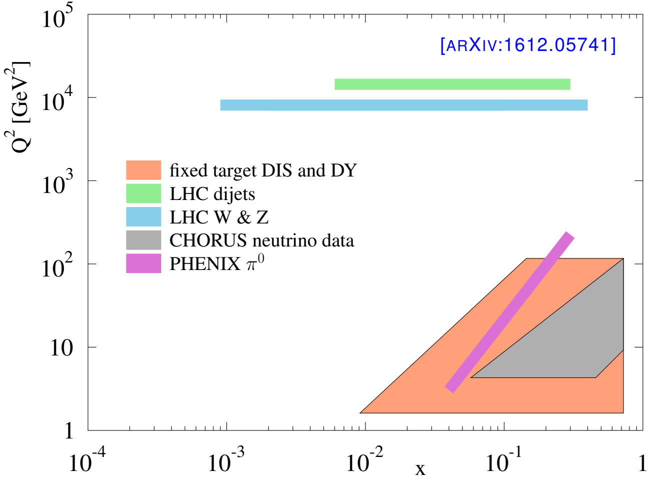
	EPPS16	DSSZ12	NCTEQ15
$\Delta\chi^2$	52	30	35

- The $\Delta\chi^2$ determination in EPS09, EPPS16, nCTEQ15:
  – Based on dynamical tolerance determination [EPJ C63 189] (90% confidence limits)
- The $\Delta\chi^2$ determination in DSSZ
  – Not exactly specified.

The use of experimental data is not unambiguous

The kinematic reach of the experimental input

- The data in global fits in a (x, Q^2) plane.
- The LHC data opens a previously unexplored kinematic region.



Experimental input: The LHC data — how should it be used?

- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A(x, Q^2)$?

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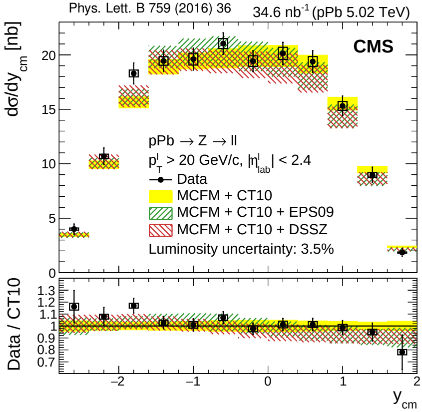
- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A(x, Q^2)$?
- Answer #1: Measured absolute distributions

$$d\sigma = \sum_{i,j} f_i^{\rm p}(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j^{\rm Pb}(Q_f^2)$$

$$f_i^{{\rm p}/A}(x, Q^2) \equiv R_i^A(x, Q^2) \; f_i^{\rm p}(x, Q^2)$$



$\Longrightarrow$ Cannot disentangle the effects of proton PDF $f_i^{\rm p}$ (~90%) and nuclear modifications $R_i^{\rm Pb}$ (~10%).

$\Longrightarrow$ Interpretation ambiguous.

- This approach was nevertheless used in a recent PDF-reweighting study by nCTEQ [arXiv:1610.02925].

Experimental input: The LHC data — how should it be used?

- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A(x, Q^2)$?
- Answer #2: Distributions normalized to the integrated one

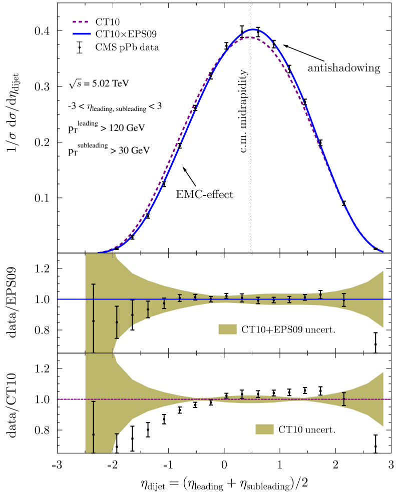
[INT.J.MOD.PHYS. E25 (2016) NO.9, 1630005]

- Part of the dependence of the proton PDF f_i^{p} cancels. How much?
- CMS dijets:

[EPJ C76 (2016) NO.4, 218]

PDF + nPDF	$\mathrm{dijets_{CMS}}$ (15)
CT10 + DSSZ	94.441
CT10 + EPS09	10.526
CT10 only	116.187
MSTW2008 + DSSZ	56.365
MSTW2008 + EPS09	5.522
MSTW2008 only	67.763

$\Longrightarrow$ Still significant dependence on the baseline $f_i^{\mathrm{p}}(x, Q^2)$.

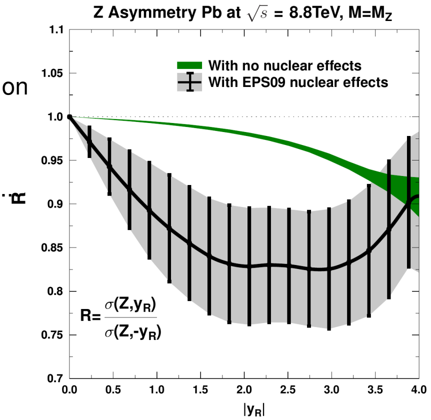


Experimental input: The LHC data — how should it be used?

- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A(x, Q^2)$?
- Answer #3: Forward-to-backward ratios $R_{\rm FB}$

$$R_{\rm FB} = \frac{d\sigma(\eta > 0)}{d\sigma(\eta < 0)}$$

[JHEP 1103 (2011) 071]



$\Longrightarrow$ As much as possible of the dependence on the proton PDF $f_i^{\rm p}$ cancels.

$\Longrightarrow$ Cancel also experimental uncertainties (especially if the correlations are known)... but lose some information also.

$\Longrightarrow$ Cannot use the Pb-Pb data in this way.

$\Longrightarrow$ $R_{\rm FB} \neq 1$ for: nuclear mods in PDFs + isospin + phase-space effects.

Experimental input: The story of neutrino-nucleus DIS

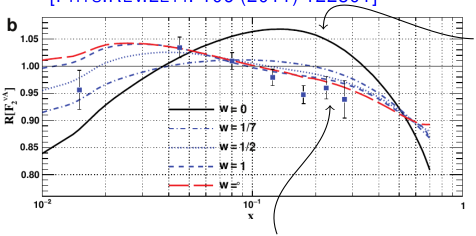
- Several measurements (NuTeV, CCFR, CHORUS, CDHSW, Minerva) on high-energy neutrino-nucleus DIS (ν-A and $\overline{\nu}$-A).
- Data available only as absolute cross sections $\dfrac{d\sigma^{\nu,\overline{\nu}}_{i,\rm exp}}{dxdy}$.

$\Longrightarrow$ Sensitive to both the free proton baseline & nuclear corrections.

- The works of nCTEQ & DSSZ use directly the extracted structure functions.

$\Longrightarrow$ nCTEQ found tension with the ℓ^--A DIS data:

[PHYS.REV.LETT. 106 (2011) 122301]



A fit with no ν-A data

Selected ν-A (NuTeV) data points with a computed baseline

Experimental input: The story of neutrino-nucleus DIS

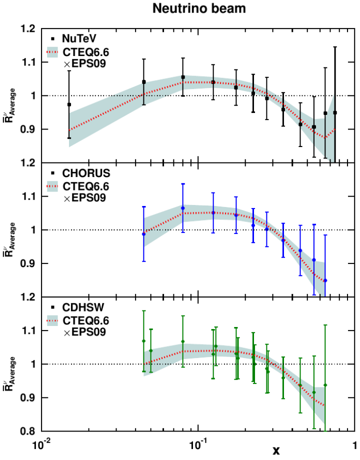
- To reduce the theoretical bias & experimental uncertainties a following observable was suggested [PRL 110 (2013) 212301]

$$\frac{d\tilde{\sigma}^{\nu,\overline{\nu}}_{i,\mathrm{exp}}}{dxdy} \equiv \frac{d\sigma^{\nu,\overline{\nu}}_{i,\mathrm{exp}}}{dxdy} / \sigma^{\nu,\overline{\nu}}_{\mathrm{exp}}(E_i),$$

$$\sigma^{\nu,\overline{\nu}}_{\mathrm{exp}}(E) = \sum_i \frac{d\sigma^{\nu,\overline{\nu}}_{i,\mathrm{exp}}}{dxdy} \Delta^{xy}_i \delta_{E,E_i}$$

$$\approx \text{integrated xsec at fixed } E$$

Size of the (x,y) bin



- A typical pattern of antishadowing + EMC effect clearly visible.

- The CHORUS ν-Pb and $\overline{\nu}$-Pb data included in the EPPS16 analysis in this way — accounting for the correlated systematics.

Experimental input: Rethink the old $\ell^- A$ DIS data

- Ambiguities in the use of old NMC, EMC, SLAC $\ell^- A$ DIS data:

  "Isoscalarized" structure functions reported by the experiments (used e.g. in EPS09, DSSZ, nCTEQ15 analyses):

$$\hat{F}_2^A = \frac{1}{2} F_2^{\mathrm{p},A} + \frac{1}{2} F_2^{\mathrm{n},A}$$

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The true structure functions (used now in EPPS16):

$$F_2^A = \frac{Z}{A} F_2^{\mathrm{p},A} + \frac{N}{A} F_2^{\mathrm{n},A}$$

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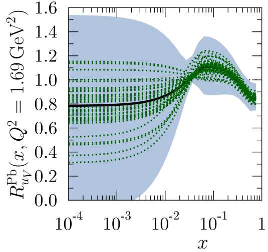
  $$F_2^A = \frac{Z}{A} F_2^{\mathrm{p},A} + \frac{N}{A} F_2^{\mathrm{n},A}$$

- Both ways have been used — the latter one less sensitive to experimental assumptions.

Comparison of the current global fits

The EPPS16 nuclear modification for ^{208}Pb at $Q^2 = m^2_{\rm charm}$

- Total uncertainties shown as blue bands, individual error sets in green



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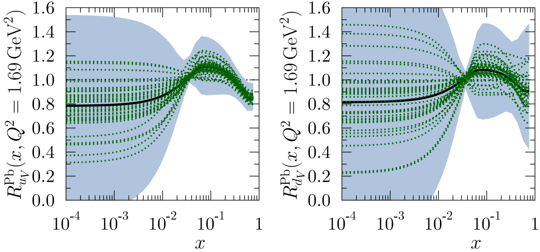

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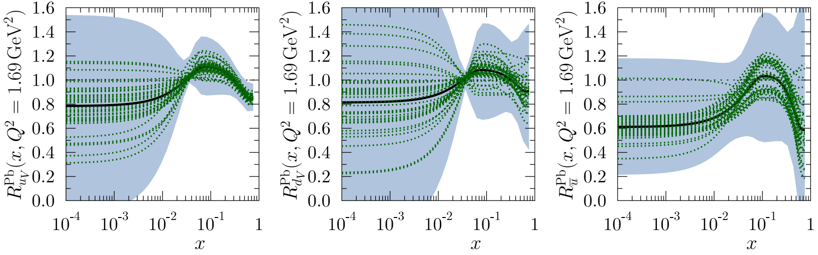

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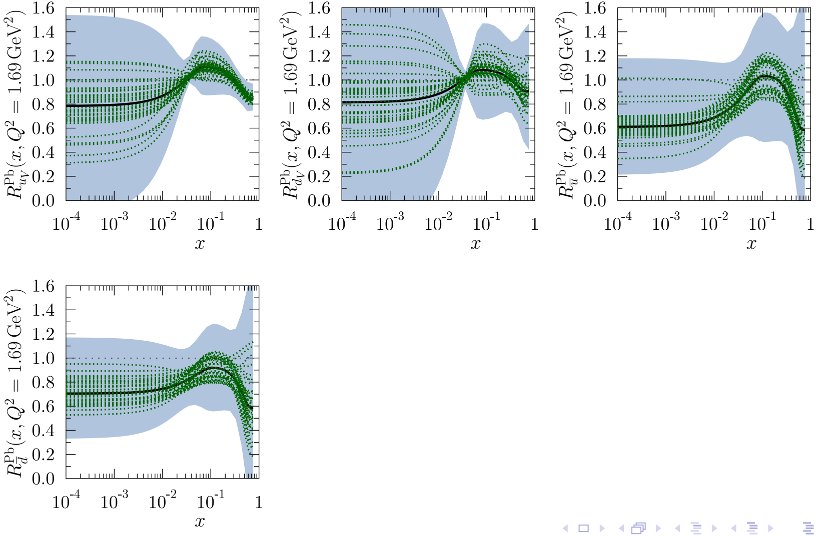

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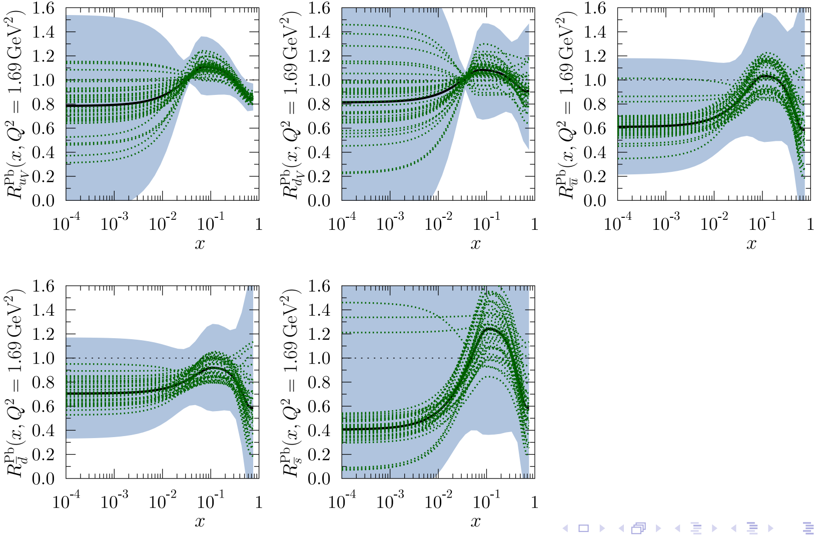

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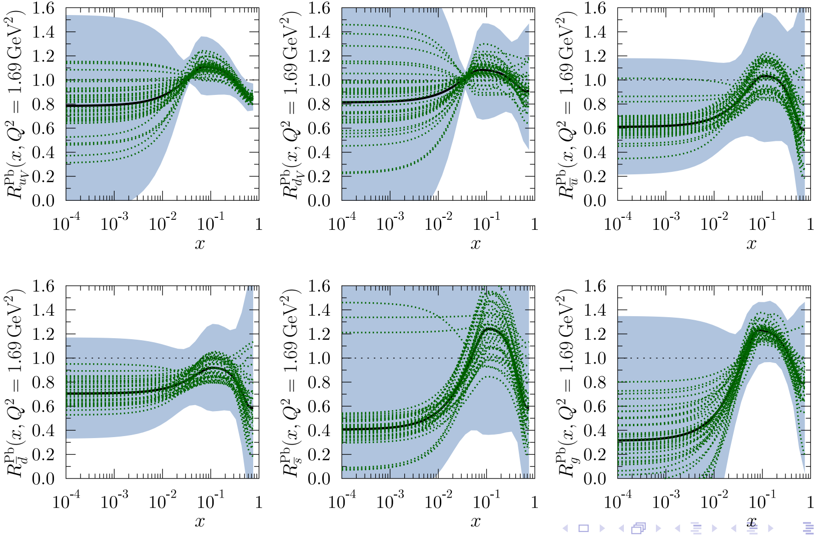
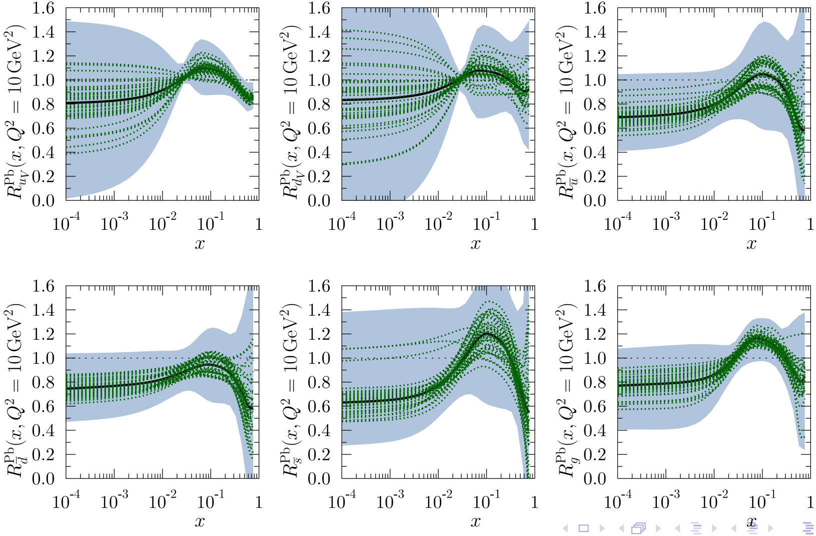


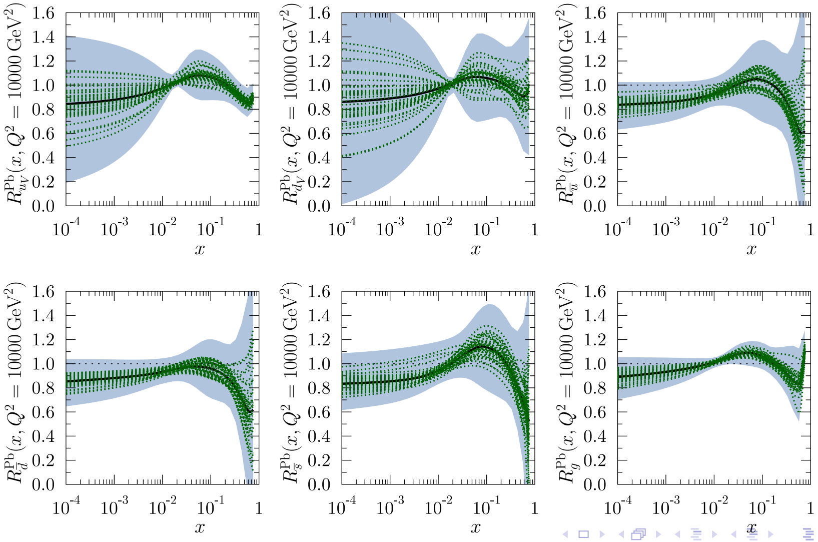
The EPPS16 nuclear modification for ^{208}Pb at $Q^2 = 10\,\mathrm{GeV}^2$

- Total uncertainties shown as blue bands, individual error sets in green



The EPPS16 nuclear modification for ^{208}Pb at $Q^2 = 10000\,\mathrm{GeV}^2$

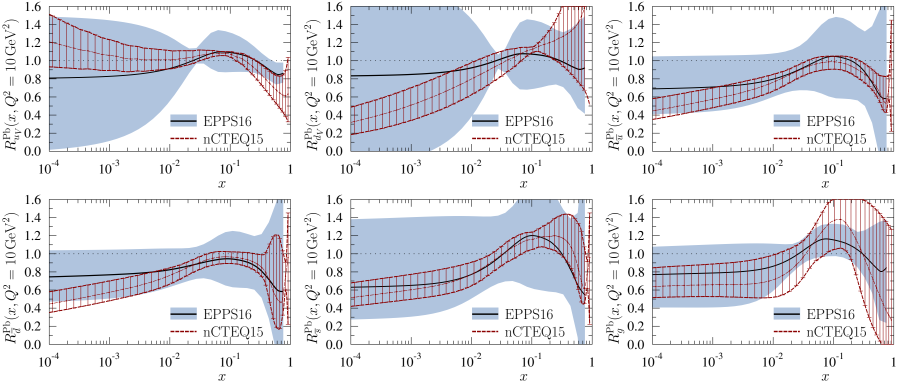
- Total uncertainties shown as blue bands, individual error sets in green



Comparison between nCTEQ15 and EPPS16, $Q^2 = 10\,\mathrm{GeV}^2$

- Typically smaller uncertainties in nCTEQ15 $\Leftarrow$ more restrictive parametrization
- Larger high-x gluon uncertainties in nCTEQ15 $\Leftarrow$ looser cuts and no LHC data
- Behaviour of the nCTEQ15 valence sector $\Leftarrow$ isospin-symmetric DIS data + no ν-A DIS

[ARXIV:1612.05741]



Comparison between EPS09, DSSZ and EPPS16

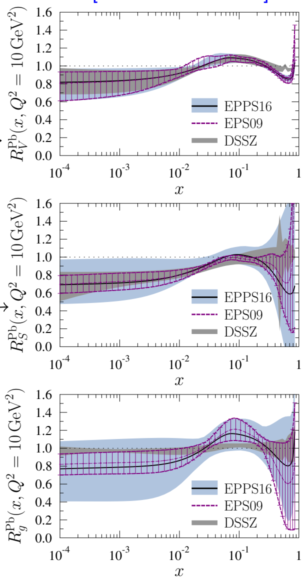
- No flavour freedom in EPS09 nor DSSZ.

  $\Longrightarrow$ compare the averages

$$R_{\rm valence} \equiv \frac{u_{\rm V}^{\rm p/Pb} + d_{\rm V}^{\rm p/Pb}}{u_{\rm V}^{\rm p} + d_{\rm V}^{\rm p}}$$

$$R_{\rm light\ sea} \equiv \frac{\overline{u}^{\rm p/Pb} + \overline{d}^{\rm p/Pb} + \overline{s}^{\rm p/Pb}}{\overline{u}^{\rm p} + \overline{d}^{\rm p} + \overline{s}^{\rm p}}$$

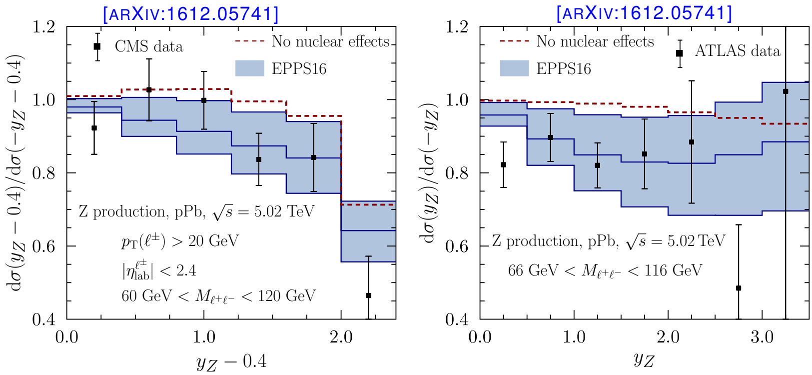
[ARXIV:1612.05741]



- All three consistent (modulo the large-x valence quarks of DSSZ).
- Typically larger uncertainties in EPPS16 (more degrees of freedom).

Effects of nuclear PDFs in LHC p-Pb observables

Effects of nuclear PDFs in the p-Pb data: Z production

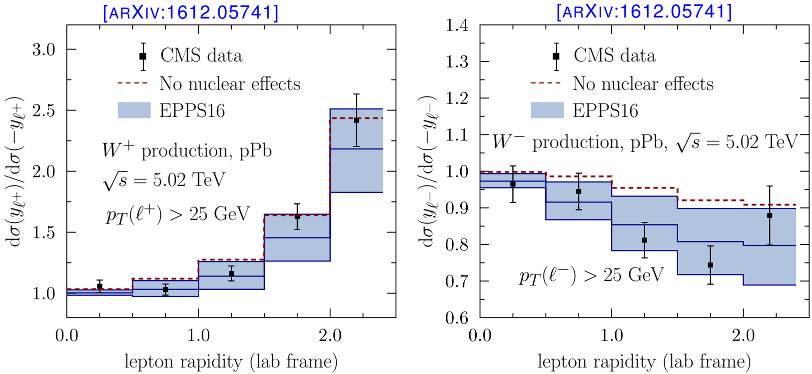


- More net shadowing for $y_Z > 0$ than for $y_Z < 0$

  $\Longrightarrow$ suppression in $R_{\rm FB}$

- The CMS data deviates significantly from unity for non-symmetric acceptance in the c.m. frame.

Effects of nuclear PDFs in the p-Pb data: W production



- More net shadowing for $y_{\ell^\pm} > 0$ than for $y_{\ell^\pm} < 0$

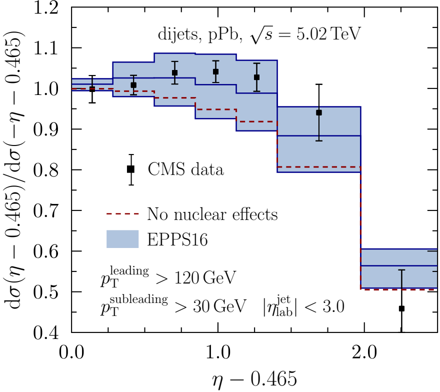
  $\Longrightarrow$ suppression in $R_{\rm FB}$

- A large isospin effect present in W production [JHEP 1103 (2011) 071]

  $\Longrightarrow$ The data deviates significantly from unity

Effects of nuclear PDFs in the p-Pb data: dijet production

[ARXIV:1612.05741]



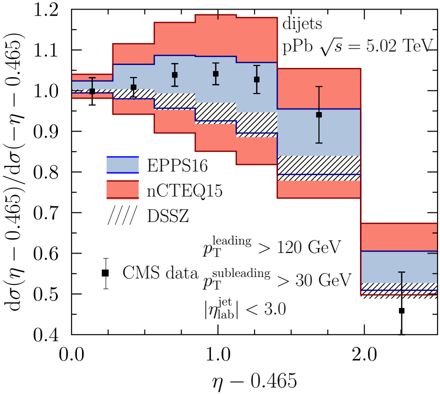
- An EMC effect for $\eta_{\rm dijet} < 0$, antishadowing for $\eta_{\rm dijet} > 0$

  $\Longrightarrow$ an enhancement in $R_{\rm FB}$

- The data deviates significantly from unity for non-symmetric acceptance [JHEP 1310 (2013) 213].

Effects of nuclear PDFs in the p-Pb data: dijet production

[ARXIV:1612.05741]



- nCTEQ15: larger high-x gluon uncertainty $\Rightarrow$ a wider uncertainty band for dijets.
- The mild nuclear effects of DSSZ gluons lead to a result similar with no effects.
- Dijets constitute currently the most stringent probe of large-x gluons.

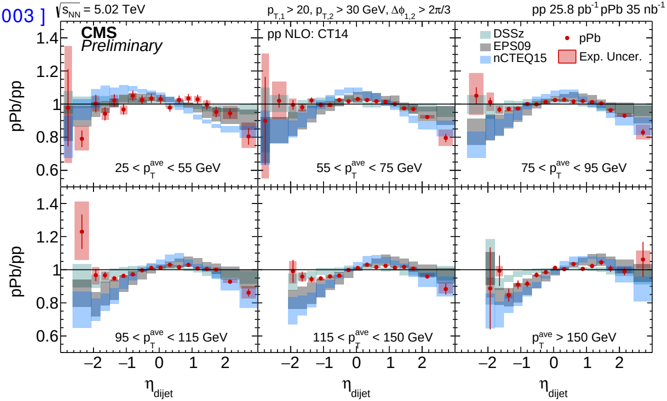
The way forward

The way forward... just a part of it

Near-future prospects

- For the new p-p baseline at $\sqrt{s} = 5\,\mathrm{TeV}$ direct measurements of nuclear modification R_{pPb} are now possible (more or less also at $\sqrt{s} = 8\,\mathrm{TeV}$).

[CMS-HIN-16-003]



- Provide theoretically a cleaner sensitivity to $R_i^A(x, Q^2)$ but....

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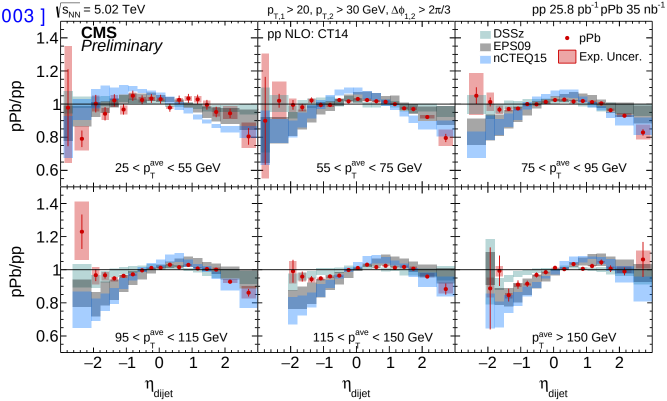
- For the new p-p baseline at $\sqrt{s} = 5\,\mathrm{TeV}$ direct measurements of nuclear modification R_{pPb} are now possible (more or less also at $\sqrt{s} = 8\,\mathrm{TeV}$).

[CMS-HIN-16-003]



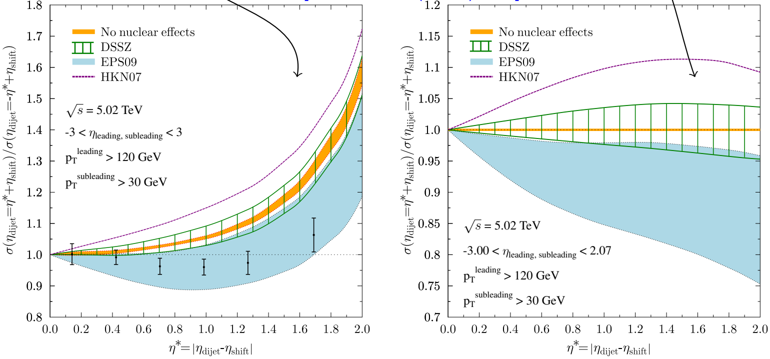
- Provide theoretically a cleaner sensitivity to $R_i^A(x, Q^2)$ but....
- It is important that in such measurements the correlated systematics between p-p and p-Pb are accounted for.
- Preferably in a common fiducial phase space.

Near-future prospects: The importance of symmetric phase space

- An example of the importance of common fiducial phase space: $R_{\rm BF}$ with a

symmetric acceptance in lab frame vs. symmetric acceptance in c.m. frame

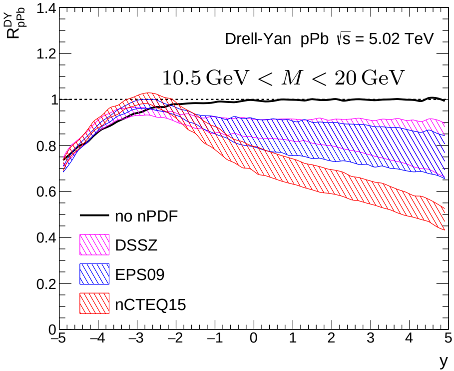
[JHEP 1310 (2013) 213]



$\Longrightarrow$ Theoretical uncertainties can be made smaller by experimental cuts.

Near-future prospects: The Drell-Yan process

- Intermediate-mass Drell-Yan process at forward direction would provide a nice probe of small-x sea quarks [ARLEO ET.AL, PHYS.REV. D95 (2017) 011502]



- Within the possibilities of e.g. LHCb with the Run-II luminosity [LHCB-PUB-2016-011].
- New low-mass Drell-Yan measurements expected from Fermilab SeaQuest experiment [FERMILAB-THESIS-2016-13].

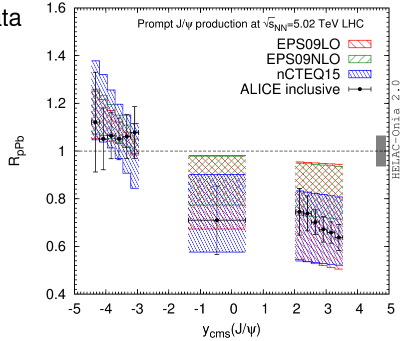
Prospects for other probes — J/ψ (+ other quarkonia)

- The theoretical description of J/ψ in p-A collisions not yet fully understood — could involve nuclear absorption etc...
- Fresh idea [Lansberg et.al, Eur.Phys.J. C77 (2017) no.1, 1]:

$$d\sigma^{J/\psi} = f_g(Q_f^2) \otimes d\sigma_{gg}^{J/\psi}(Q_f^2, Q_r^2) \otimes f_g(Q_f^2)$$

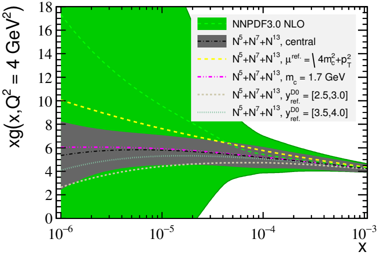
Fit the coefficient functions to p-p data

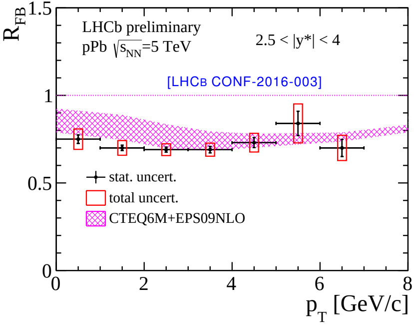
- Neglects all but the gluon-gluon channel
- A consistent description of the data with only effects from nuclear PDFs.



Prospects for other probes — open heavy flavour

- The potential of D (and B) meson production has been demonstrated in p-p [ARXIV:1610.09373 & EUR.PHYS.J. C75 (2015) NO.8, 396]:
- Different theoretical treatments e.g.
  - NLL parton-level calculation + PYTHIA
  - NLO GM-VFNS + fragmentation functions
- Can be done also in p-Pb collisions (e.g. ALICE, LHCb)



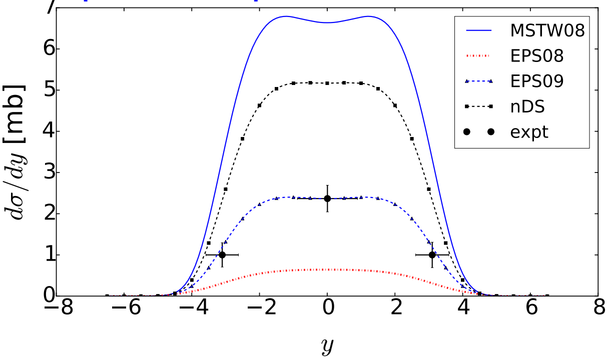


Prospects for other probes — ultra peripheral collisions (UPC)

- It has been argued that UPC vector meson (e.g. J/ψ) production in Pb-Pb collisions is particularly sensitive to nuclear gluon

$$\sigma^{\gamma A \to V} \propto \left[g^A(x, Q^2) \right]^2$$

[ARXIV:1603.01919]



- Exact relation to inclusive NLO (and beoynd) PDFs?

Summary

- Overviewed the recent progress on the global analysis of nuclear PDFs
- The most important developments new ingredients in the latest global analysis:

LHC Run I data	$\rightsquigarrow$ completely novel constraints
neutrino DIS data	$\rightsquigarrow$ $R_{u_V} \sim R_{d_V}$
full flavour dependence	$\rightsquigarrow$ significantly less bias but larger uncertainties

- The universality of nuclear PDFs now verified up to the electroweak scale.
- More (much!) data expected in the near future — e.g. the p-Pb run at $\sqrt{s} = 8\,\mathrm{TeV}$
  - The availability of correlated systematics would be advantageous.
  - Symmetric acceptance in the c.m. frame would reduce theoretical uncertainties.