The EPPS16 NLO nuclear PDFs

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Theoretical Foundations on collinear factorization

- Factorization formula

Parton distribution functions (PDFs)

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

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Coefficient functions (calculable by perturbative methods)

- PDFs obey the DGLAP equations

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

Splitting functions(calculable by perturbative methods)

Previous analyses

	HKN07	EPS09	DSSZ	NCTEQ15
Order in α_s	LO & NLO	LO & NLO	NLO	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^2 cut in DIS	$1\,\mathrm{GeV}$	$1.3\,\mathrm{GeV}$	$1\,\mathrm{GeV}$	$2\,\mathrm{GeV}$
datapoints	1241	929	1579	708
free parameters	12	15	25	17
error analysis	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	13.7	50	30	35
Free proton baseline PDFs	MRST98	CTEQ6.1	MSTW2008	CTEQ6M-like
Heavy quark treatment	ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS
Cites	272	674	129	43

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RHIC pions d+Au/p+p		✓	✓	✓
Neutrino-nucleus DIS		✓	✓	
LHC p+Pb jet data		✓		
LHC p+Pb W, Z data		✓		
Drell-Yan dilepton π+A		✓		
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Framework: Parametrization

Free proton baseline
(CT14NLO)

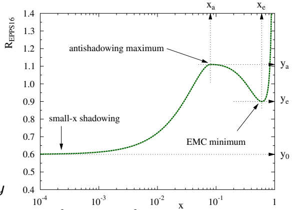
- Our definition of nuclear PDFs

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

Nuclear modifications

- Fit function x dependence at $Q_0^2 = m_{\mathrm{charm}}^2$

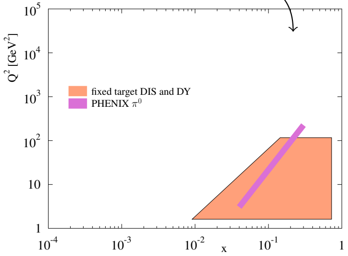
$$R(x,Q_0^2) = \begin{cases} a_0 + a_1 (x - x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1, \end{cases}$$



- The A dependence parametrized at $x \to 0$, x_a, and x_y
- Freedom allowed for all quark flavours separately — we no longer impose flavour-independent nuclear effects for valence and sea quarks (as e.g. in EPS09).
- 20 free parameters (15 in EPS09)

Experimental input

- EPS09:
  - – fixed-target deep-inelastic scattering (DIS) ($\ell^{\pm}$-A)
  - – low-mass Drell-Yan dilepton data (p-A)
  - – inclusive pion production (d-Au)



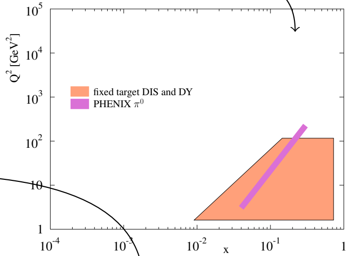
Experimental input

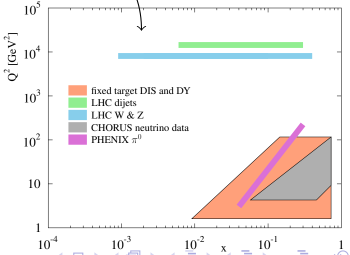
- EPS09:
  - – fixed-target deep-inelastic scattering (DIS) ($\ell^{\pm}$-A)
  - – low-mass Drell-Yan dilepton data (p-A)
  - – inclusive pion production (d-Au)
- Additional data in EPPS16:
  - – low-mass Drell-Yan dilepton data ($\pi^{\pm}$-A)
  - – Neutrino DIS data (ν-Pb, $\overline{\nu}$-Pb)
  - – LHC data for dijets, W$^{\pm}$ and Z (p-Pb)

$\Longrightarrow$ Completely new region open in (x, Q^2) plane!

$\Longrightarrow$ Larger variety of data than in any other contemporary analysis!

$\Longrightarrow$ First true test of nuclear PDF universality!





Experimental input: Corrections for old $\ell^- A$ DIS data

- Recover the true structure functions from the “isoscalarized” ones ($\ell^- A$ DIS):

“Isoscalarized” structure functions reported by the experiments (used e.g. in EPS09 analysis):

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

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Relation between the two:

$$\hat{F}_2^A = \left[\frac{A}{2} \left(1 + \frac{F_2^{\mathrm{n}}}{F_2^{\mathrm{p}}} \right) / \left(Z + N \frac{F_2^{\mathrm{n}}}{F_2^{\mathrm{p}}} \right) \right] F_2^A,$$

Can find these from the literature

$\Longrightarrow$ Better sensitivity for flavour separation

Experimental input: CHORUS Neutrino DIS data

- The ν-Pb and $\overline{\nu}$-Pb DIS data available as absolute cross sections $\dfrac{d\sigma^{\nu,\overline{\nu}}_{i,\mathrm{exp}}}{dxdy}$

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

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

- To be less sensitive to the free proton PDF use normalized cross sections instead:

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

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

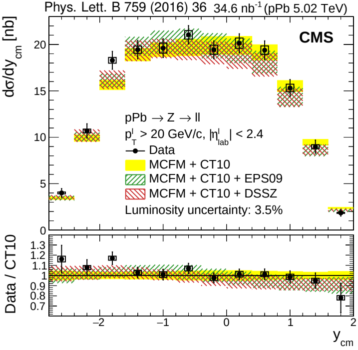
Size of the (x,y) bin (rectangle)

- Correlated systematic uncertainties propagated to the normalized cross sections

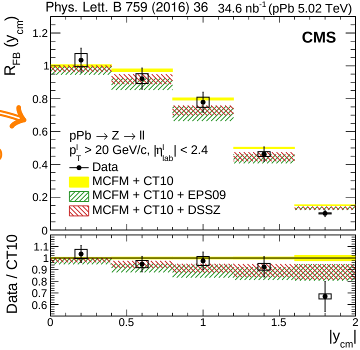
Experimental input: The LHC p-Pb data

- The LHC p-Pb data included as forward-to-backward ratios

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



Take the ratio



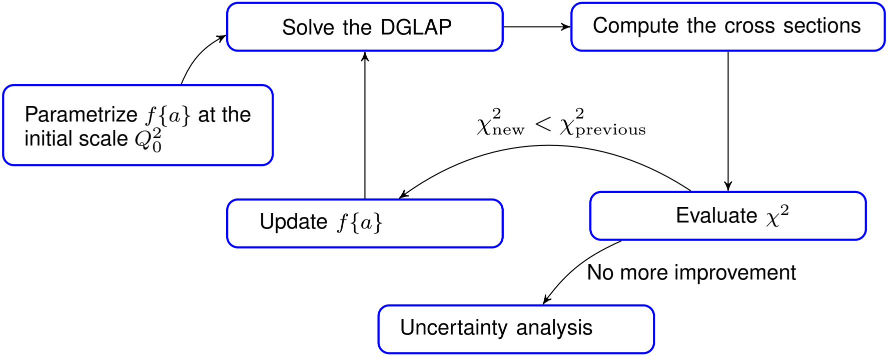
- Cancel experimental & theory uncertainties...but lose some information also
- $R_{\rm FB} \neq 1$ for: nuclear mods in PDFs + isospin and phase-space effects

Analysis procedure

- We consider χ^2 figure-of-merit function

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

- Minimize χ^2 by built-in Levenberg-Marquardt algorithm



Uncertainty analysis by Hessian method

- Expand the global χ^2 around the minimum

Hessian matrix

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

Parameter variations

Uncertainty analysis by Hessian method

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Hessian matrix

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

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

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

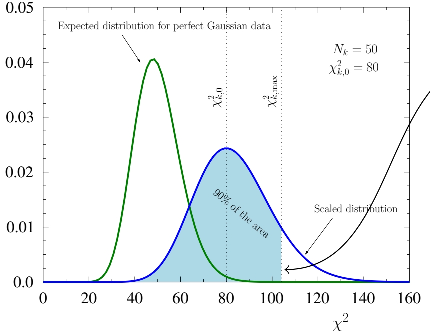
$$\vdots$$

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

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

Uncertainty analysis by Hessian method

- The deviations $\delta z_i^{\pm}$ are determined by "hypothesis testing" finding "90% confidence limits" from scaled χ^2 distributions



1. Find $\chi^2_{k,\max}$ for each data set k

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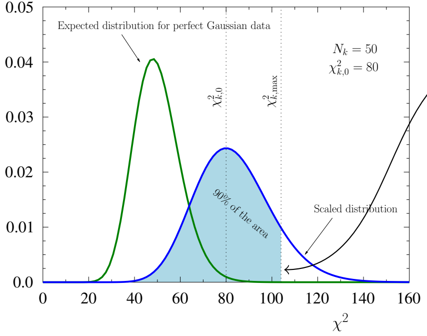

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2. Find the corresponding variations $\delta z^{\pm}_{i,k}$ for all directions i

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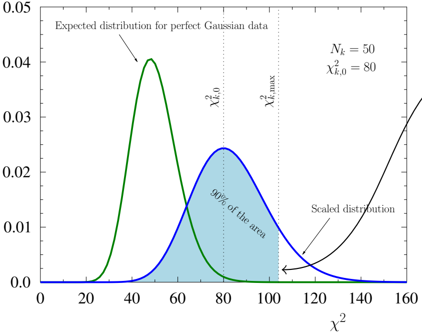

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3. Find the most limiting of all $\delta z^{\pm}_{i,k} \Rightarrow \delta z^{\pm}_i$

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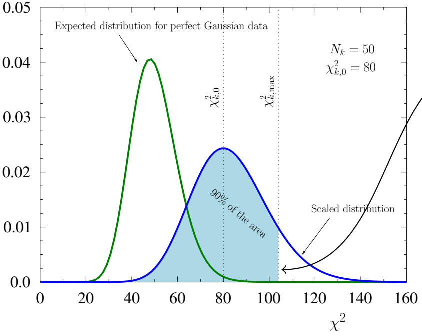

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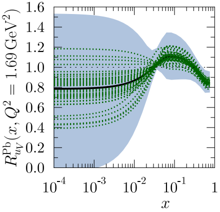
- Uncertainty sets $S_i^{\pm}$ are limiting cases that still reproduce all the data within "90% confidence limit"
- Procedure is *ad hoc* but used by several PDF fitters

Results: Nuclear modification for ^{208}Pb at $Q^2 = m^2_{\rm charm}$

- Total uncertainties shown as blue bands, individual errorsets in green



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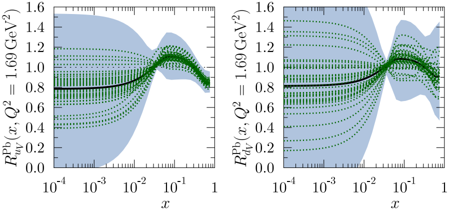

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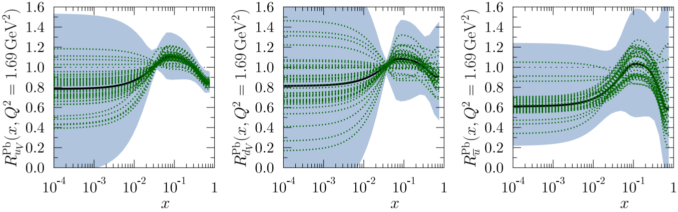

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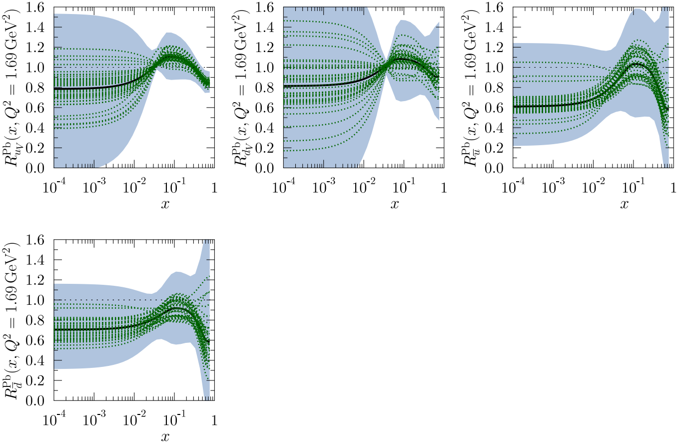

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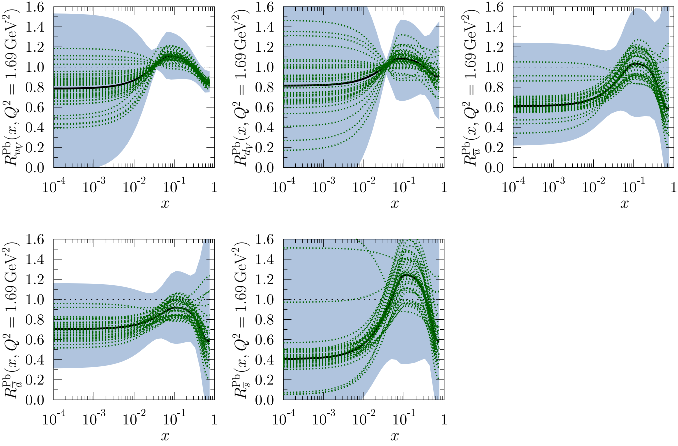

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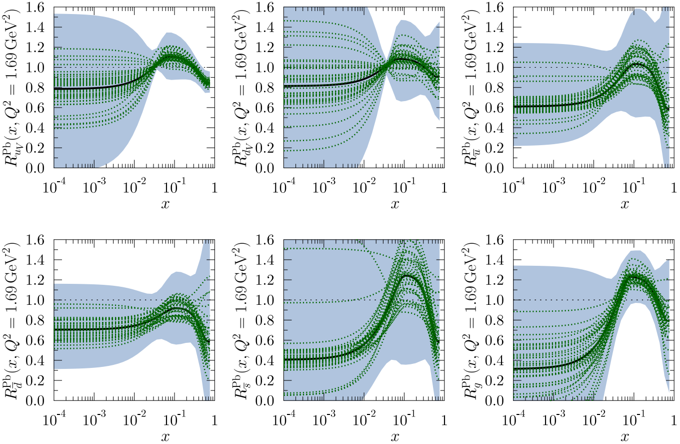

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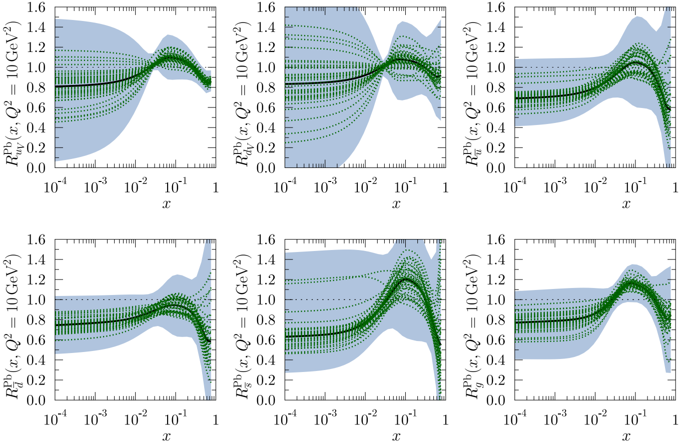
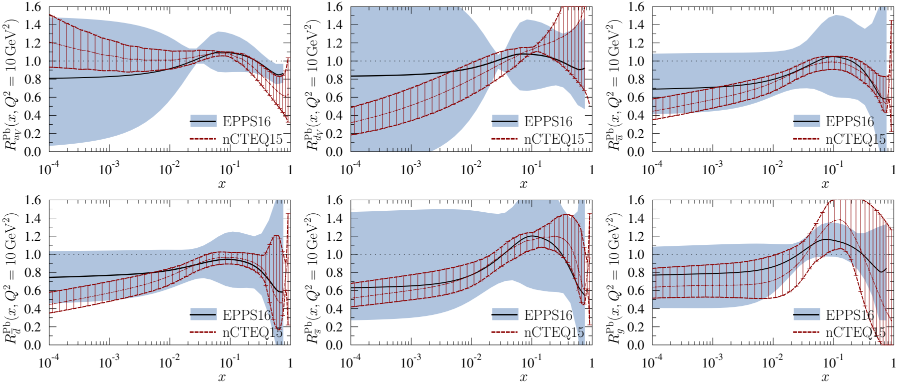


- EPPS16 consistent with nCTEQ15
- Typically smaller uncertainties in nCTEQ15 $\Leftarrow$ less freedom in the parametrization
- Larger high-x gluon uncertainties in nCTEQ15 $\Leftarrow$ looser cuts and no LHC data

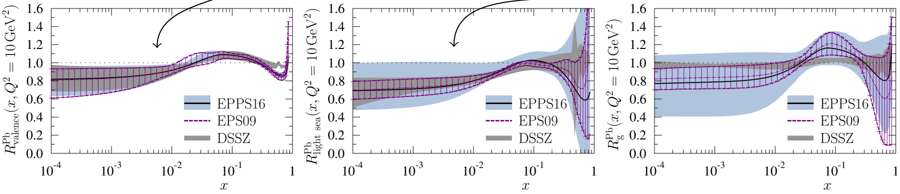


Results: Comparison with EPS09 and DSSZ

- No flavour freedom in EPS09 nor DSSZ — compare the averages

$$R_{\text{valence}} \equiv \frac{u_V^{p/Pb} + d_V^{p/Pb}}{u_V^p + d_V^p}$$

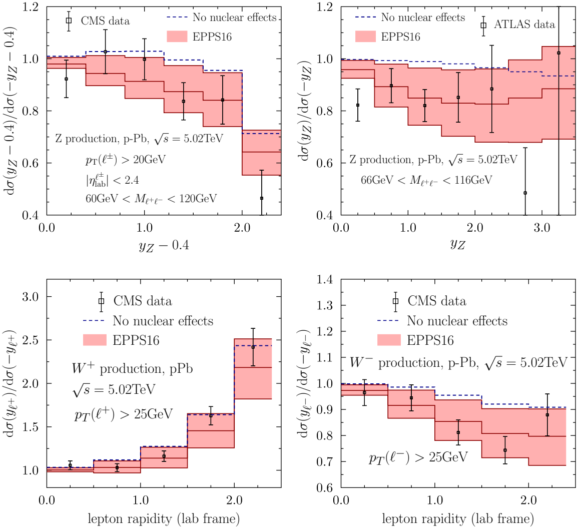
$$R_{\text{light sea}} \equiv \frac{\overline{u}^{p/Pb} + \overline{d}^{p/Pb} + \overline{s}^{p/Pb}}{\overline{u}^p + \overline{d}^p + \overline{s}^p}$$



- EPPS16 consistent with these earlier analyses
- Typically larger uncertainties in EPPS16 (for having more degrees of freedom)

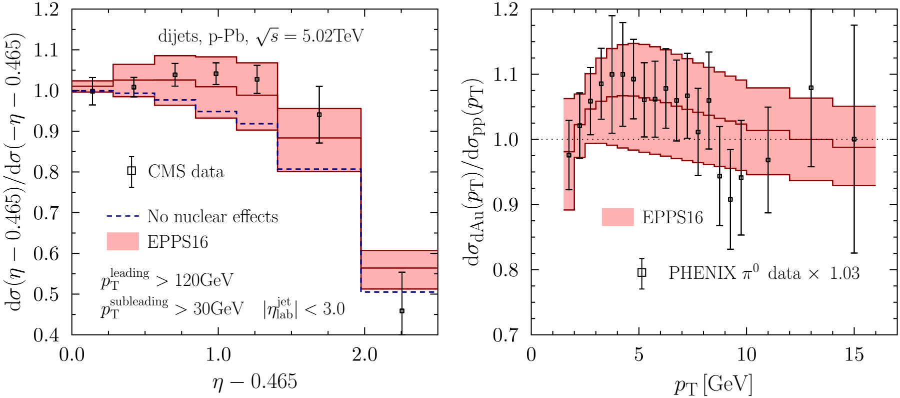
Comparison with the LHC p-Pb electroweak data

- Good agreement — lowish statistics limits the obtainable constraints



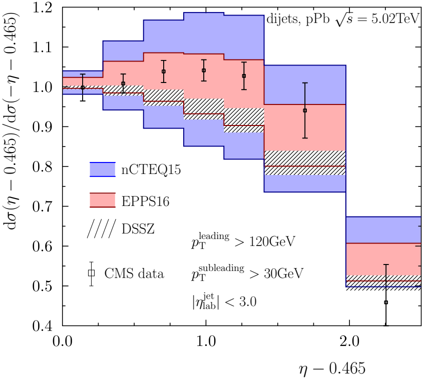
Comparison with the LHC p-Pb dijet and RHIC d-Au pion data

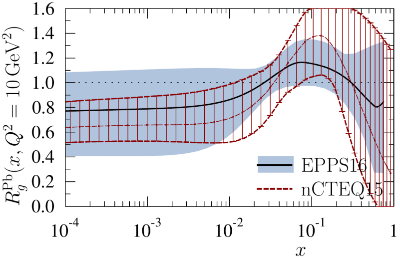
- Both data sensitive to the large-x gluons — mutually compatible



Comparison with the LHC p-Pb dijet and RHIC d-Au pion data

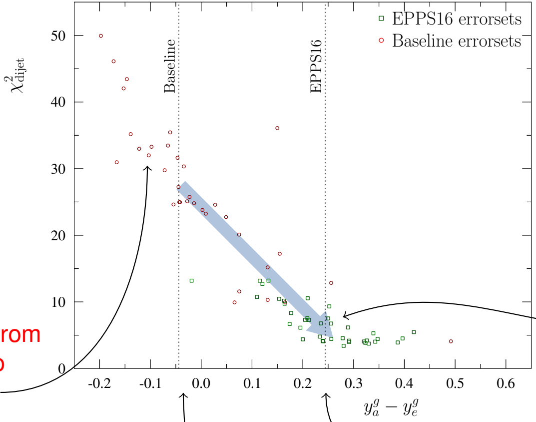
- Larger gluon uncertainties of nCTEQ15 clearly reflected in the dijets

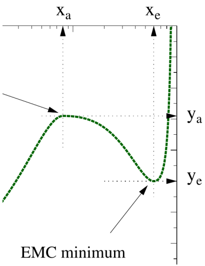




Comparison with the LHC p-Pb dijet data

- For us the dijet data are essential in establishing a gluon EMC effect





Error sets from a fit with no LHC data

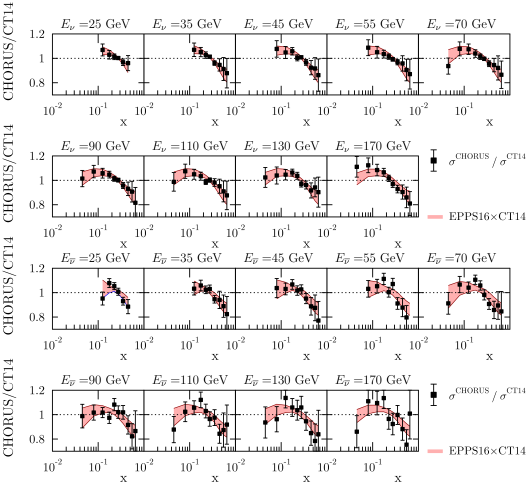
EPPS16 error sets

No gluon EMC effect here

Gluon EMC effect

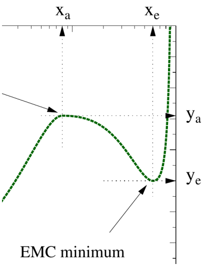
Comparison with the neutrino data

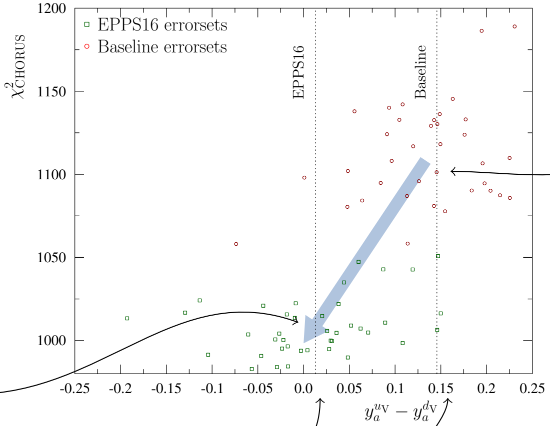
- The neutrino DIS data from CHORUS collaboration show a typical pattern of antishadowing + EMC effect (unity without nuclear mods)



Comparison with the neutrino data

- The neutrino data are essential in establishing mutually similar R_{u_V} and R_{d_V}





Error sets from a fit with no $\nu, \overline{\nu}$ data

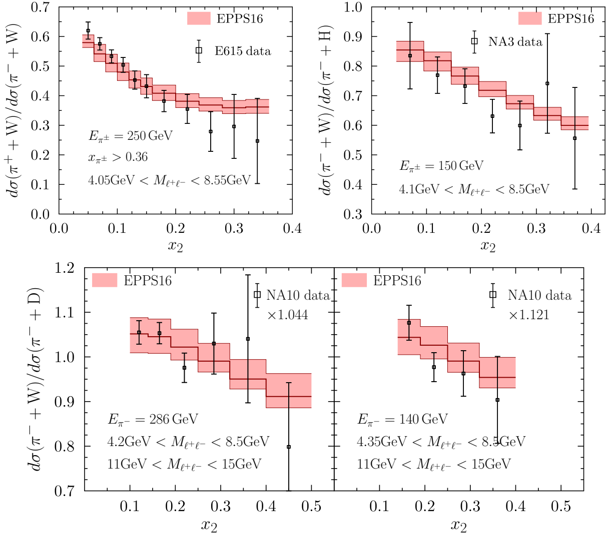
EPPS16 error sets

Similar R_{u_V} and R_{d_V}

Different R_{u_V} and R_{d_V}

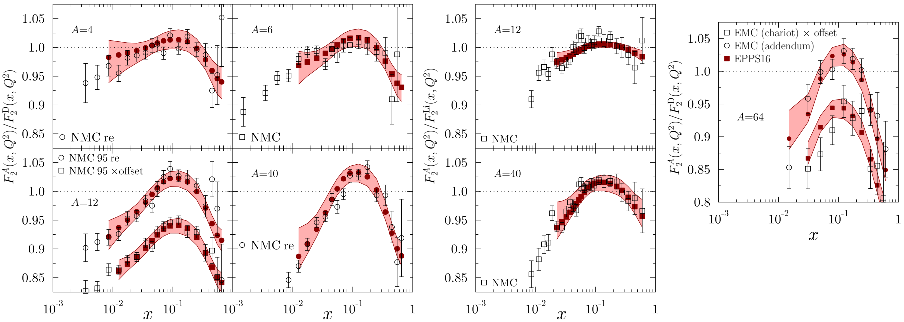
Comparison with fixed-target $\pi^{\pm}$-A Drell-Yan data

- Also the $\pi^{\pm}$-A Drell-Yan data well consistent with EPPS16

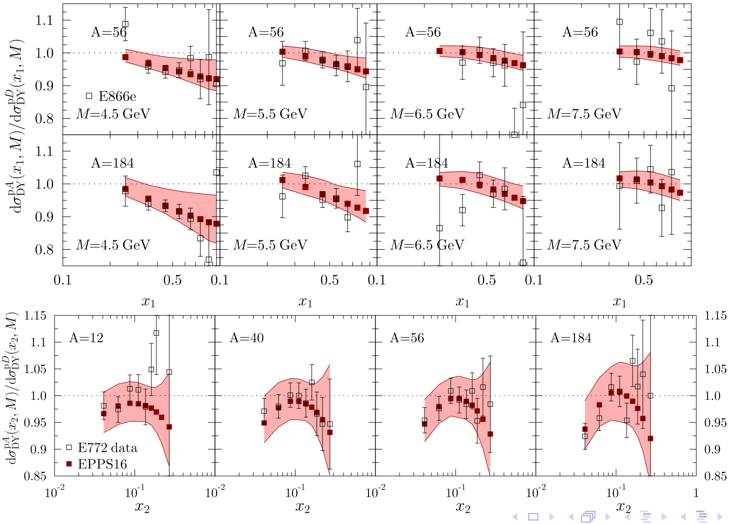


Comparison with charged-lepton DIS data

- No significant differences in the fit quality for older DIS measurements (included already in EPS09)



- No large differences in the fit quality for older Drell-Yan measurements neither (included already in EPS09)



Summary & Outlook

- Presented EPPS16 NLO nuclear PDFs
  — supersedes EPS09
- More variety of data input than in other available fits
  — the most essential additions are the CMS dijet and CHORUS neutrino DIS data
- More fit-function freedom flavour-by-flavour than in other available fits
  — less "biased" result
  — reveals large uncertainties flavour-wise
- Excellent agreement with the data
  — supports the validity of collinear factorization in a largest region of (x, Q^2) plane examined examined to date

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- More (much!) data expected in the near future
  — e.g. the second p-Pb run at $\sqrt{s} = 8\,\mathrm{TeV}$
- Ample room for theoretical/procedural improvements
  — NNLO, electroweak corrections (photon PDF), more flexible fit functions, including free proton data (no need for a separate baseline PDF), etc...