

# The EPPS16 nuclear PDFs

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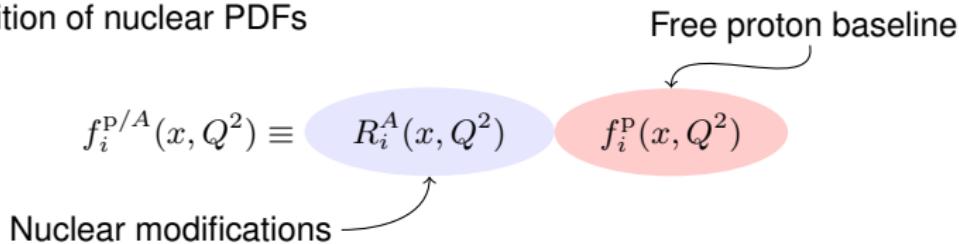
Reference: Eur.Phys.J. C77 (2017) no.3, 163

# EPPS16 in a nutshell

	EPS09	NCTEQ15	EPPS16
Order in $\alpha_s$	NLO	NLO	NLO
Neutral current DIS $\ell+A/\ell+d$	✓	✓	✓
Drell-Yan dilepton $p+A/p+d$	✓	✓	✓
RHIC pions $d+Au/p+p$	✓	✓	✓
Neutrino-nucleus DIS			✓
LHC $p+Pb$ jet data			✓
LHC $p+Pb$ W, Z data			✓
Drell-Yan dilepton $\pi+A$			✓
$Q^2$ cut in DIS	1.3 GeV	2 GeV	1.3 GeV
datapoints	929	708	1811
free parameters	15	17	20
error analysis	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	35	52
Free proton baseline PDFs	CTEQ6.1	CTEQ6M-LIKE	CT14NLO
Heavy quark treatment	ZM-VFNS	GM-VFNS	GM-VFNS
Flavour separation	none	some	✓
Weight data in $\chi^2$	yes	no	no
Reference	[JHEP 0904 065]	[PR D93 085037]	[EPJ C77, 163]

## EPPS16 framework: Parametrization

- Our definition of nuclear PDFs



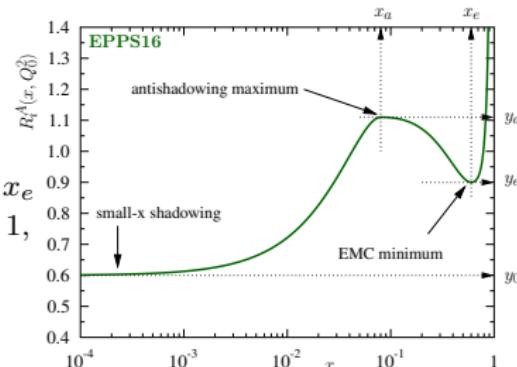
- Fit function  $x$  dependence at  $Q_0^2 = m_{\text{charm}}^2$

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

- The  $A$  dependence parametrized at  $x \rightarrow 0$ ,  $x_a$ , and  $x_e$

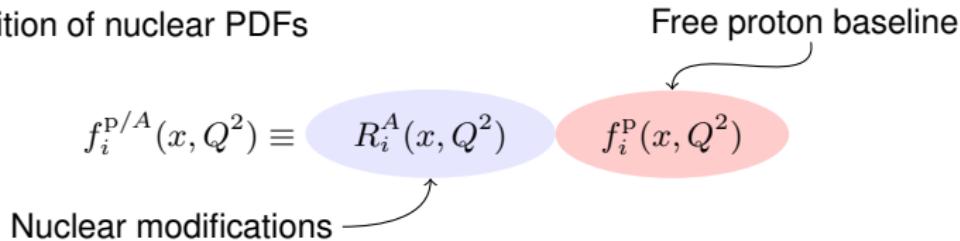
$$y_i^A = y_i^{A=12} \left( \frac{A}{12} \right)^{\gamma_i [y_i^{A=12} - 1]}, \gamma_i > 0$$

⇒ Stronger nuclear effects for a larger nucleus



## EPPS16 framework: Parametrization

- Our definition of nuclear PDFs



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

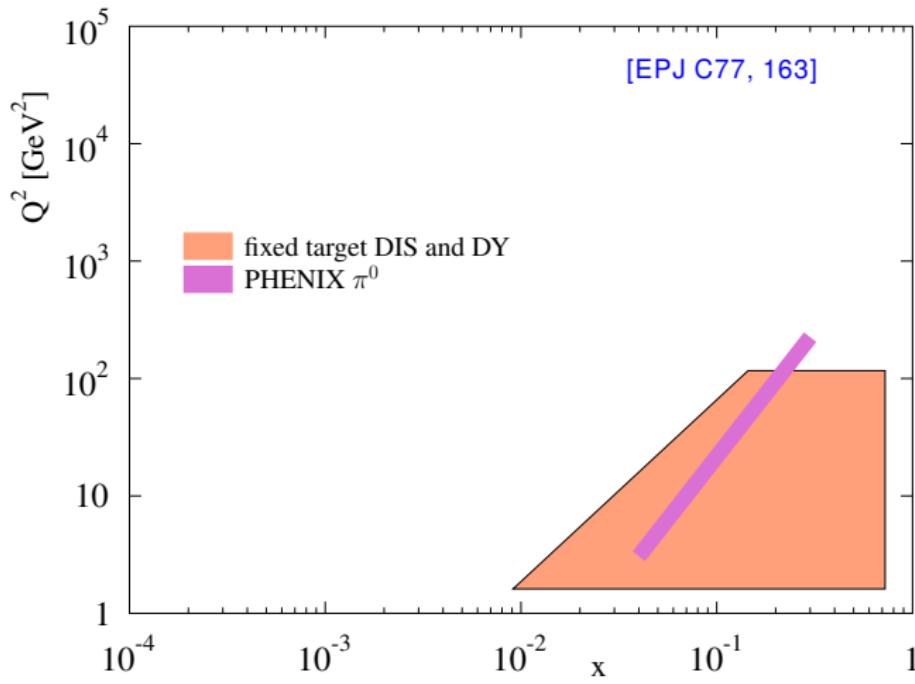
$$R_{uV}(x, Q_0^2) = R_{dV}(x, Q_0^2)$$

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

- The FI immediately destroyed by the DGLAP at  $Q^2 > Q_0^2$   
⇒ No reason to assume FI in the first place.
- nCTEQ15: flavour variation for the valence quarks.
- EPPS16: flavour dependent valence & sea quarks (small + intermediate  $x$ ).

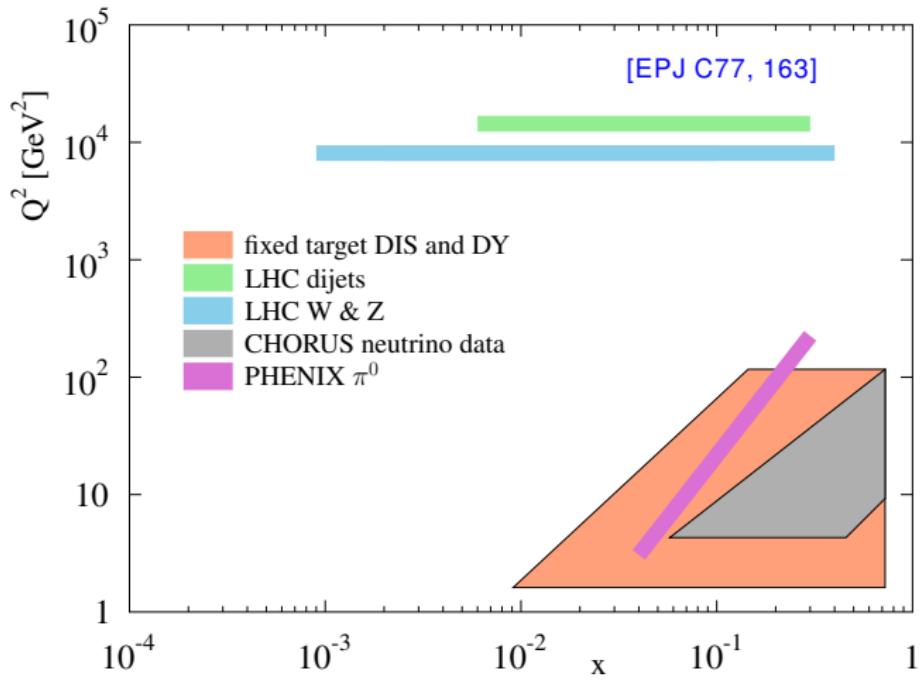
## The kinematic reach of the experimental input: EPS09

- The data in EPS09 global fit in the  $(x, Q^2)$  plane.



## The kinematic reach of the experimental input: EPPS16

- The data in EPPS16 global fit in the  $(x, Q^2)$  plane.
- The LHC data opens a previously unexplored kinematic region.



## Experimental input: Corrections for fixed-target $\ell^- A$ 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):

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

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Relation between the two:  $\hat{F}_2^A = \left[ \frac{A}{2} \left( 1 + \frac{F_2^{\text{n},A}}{F_2^{\text{p},A}} \right) / \left( Z + N \frac{F_2^{\text{n},A}}{F_2^{\text{p},A}} \right) \right] F_2^A,$

- Less sensitivity to the experimental assumptions on  $F_2^{\text{n},A}/F_2^{\text{p},A}$  when using the non-corrected  $F_2^A$

## Experimental input: CHORUS Neutrino DIS data

- The  $\nu$ -Pb and  $\bar{\nu}$ -Pb DIS data available as absolute cross sections  $\frac{d\sigma_{i,\text{exp}}^{\nu,\bar{\nu}}}{dxdy}$   
⇒ Sensitive to both the free proton baseline & nuclear modifications

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⇒ Sensitive to both the free proton baseline & nuclear modifications
- To reduce the sensitivity to the free proton PDF we use normalized cross sections instead [PRL 110 (2013) 212301]:

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

$$\sigma_{\text{exp}}^{\nu,\bar{\nu}}(E) = \sum_i \frac{d\sigma_{i,\text{exp}}^{\nu,\bar{\nu}}}{dxdy} \Delta_i^{xy} \delta_{E,E_i} \approx \text{integrated xsec at fixed } E$$

Δ<sub>i</sub><sup>xy</sup>

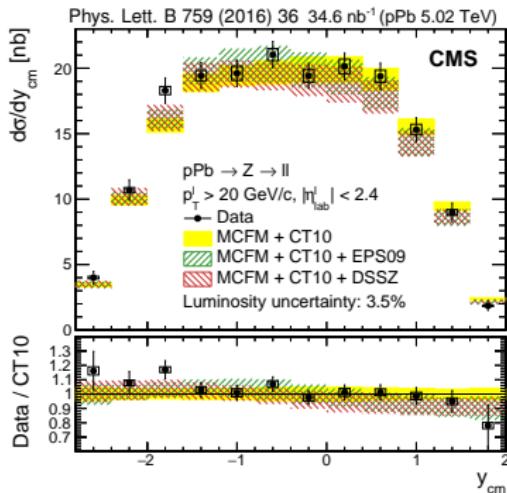
Size of the (x,y) bin (rectangle)

- Correlated systematic uncertainties propagated to the normalized cross sections

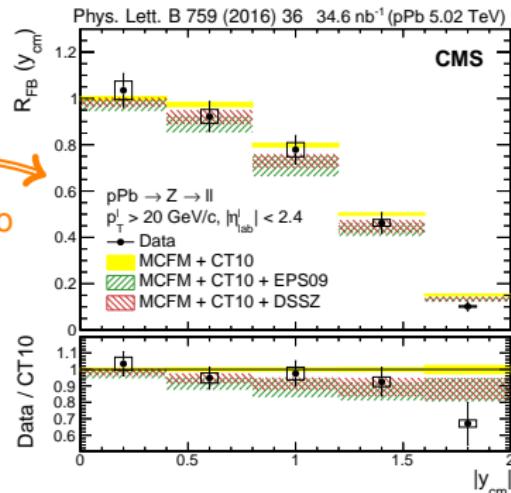
## Experimental input: The LHC p-Pb data

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

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



Take the ratio



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

## Look-up tables for the LHC cross sections

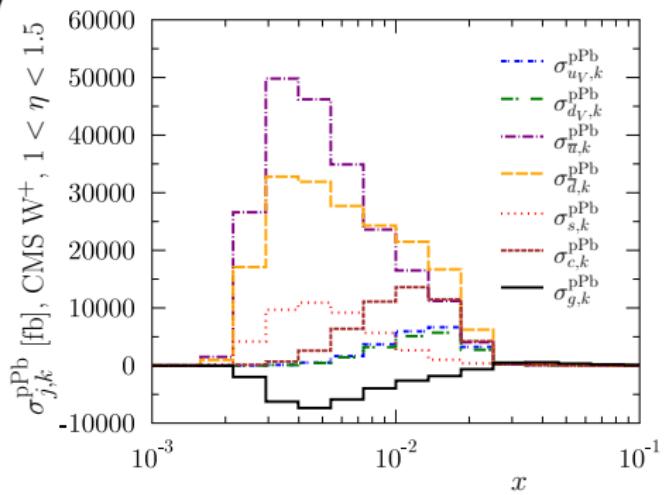
- Precompute the p-Pb cross sections in specific  $x$  bins for each  $R_i(x, Q^2)$

$$\sigma_{j,k}^{\text{pPb}} = \sum_i f_i^{\text{p}} \otimes \hat{\sigma}_{ij} \otimes f_{j,k}^{\text{Pb}}$$
$$f_{j,k}^{\text{Pb}}(x) \equiv \sum_{\ell} \left[ Z f_{\ell}^{\text{p,Pb}}(x) + N f_{\ell}^{\text{n,Pb}}(x) \right] \Big|_{R_j^{\text{Pb}}=1, R_{i \neq j}^{\text{Pb}}=0} \theta(x - x_{k-1}) \theta(x_k - x).$$

- The p-Pb cross sections obtained by weighting the nuclear modifications  $R_i(x, Q^2)$  with  $\sigma_{j,k}^{\text{pPb}}$ :

$$\sigma^{\text{pPb}} = \sum_{j,k} \sigma_{j,k}^{\text{pPb}} R_j^{\text{Pb}}(x_{k-1} < x < x_k).$$

- Works well since  $R_i(x, Q^2)$  are smooth functions.



## Uncertainty analysis

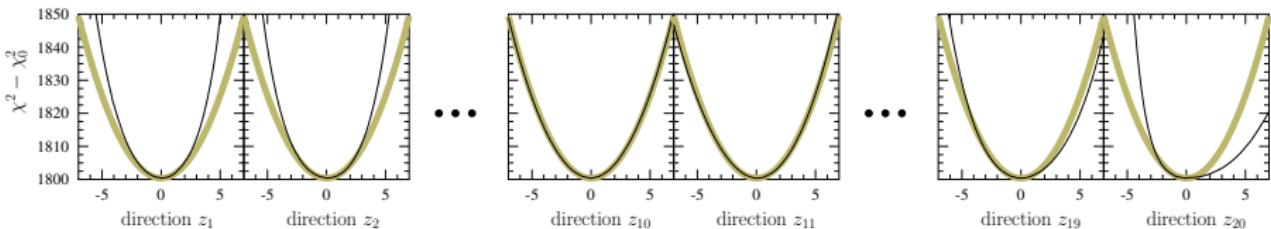
- We use the standard Hessian method

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

Parameter variations

Hessian matrix

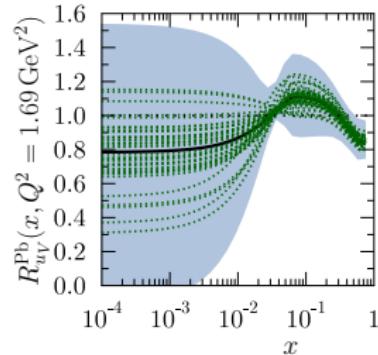
- Quadratic approximation typically very good



- The 90% confidence level defined by global tolerance  $\Delta\chi^2 = 52$  (essentially equivalent to dynamical tolerance determination [EPJ C63 189])

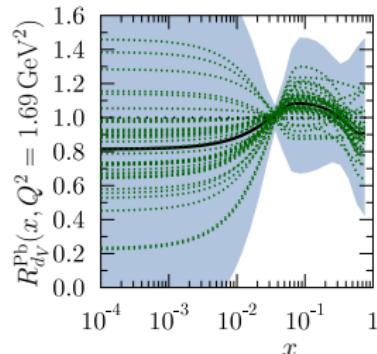
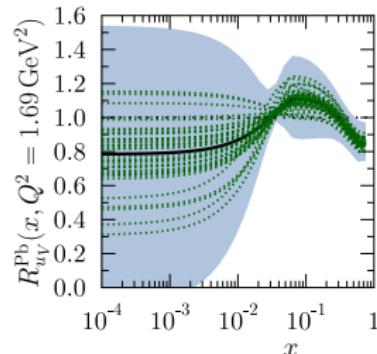
## Results: Nuclear modification for $^{208}\text{Pb}$ at $Q^2 = m_{\text{charm}}^2$

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



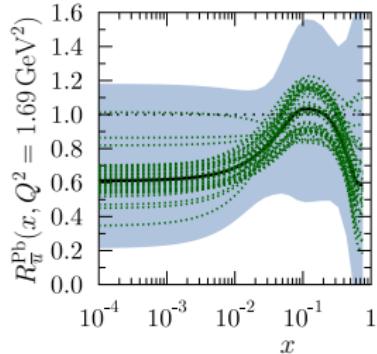
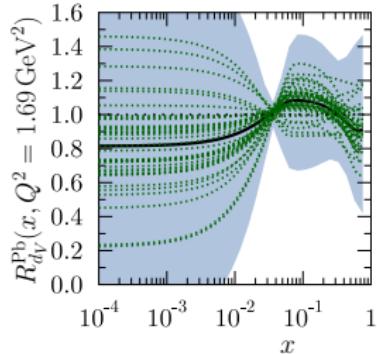
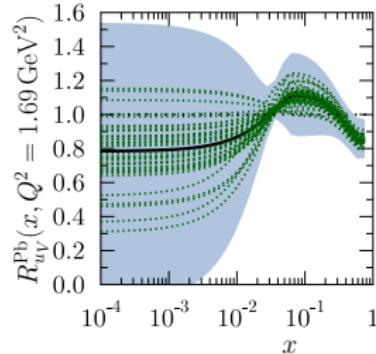
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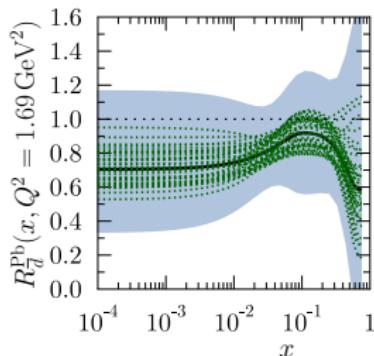
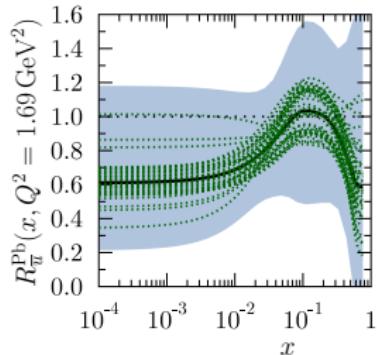
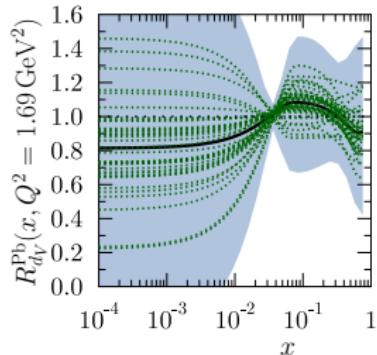
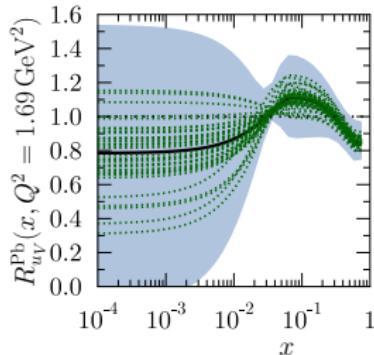
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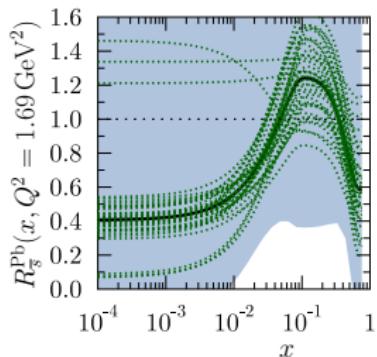
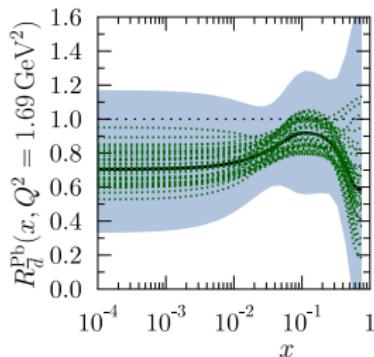
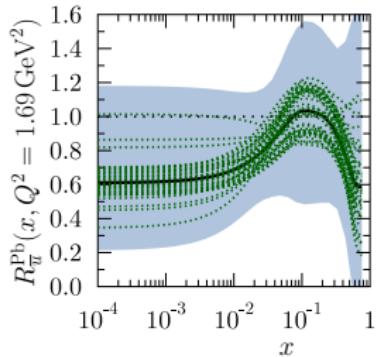
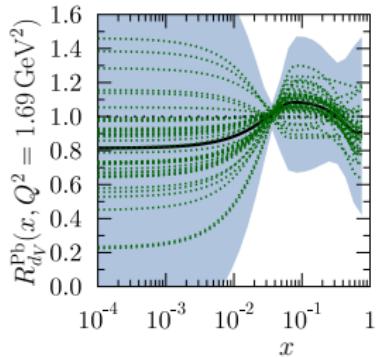
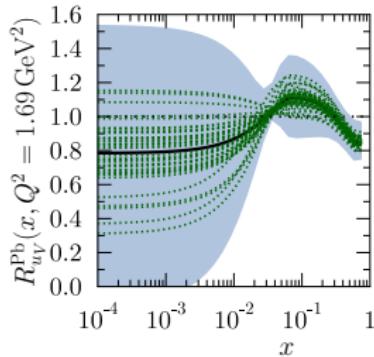
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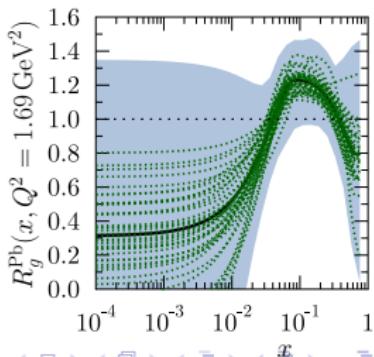
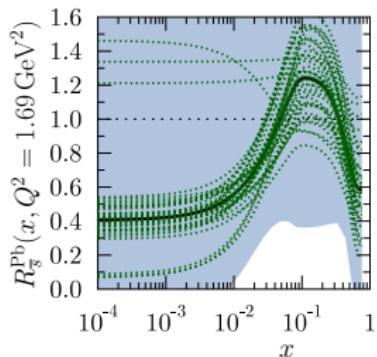
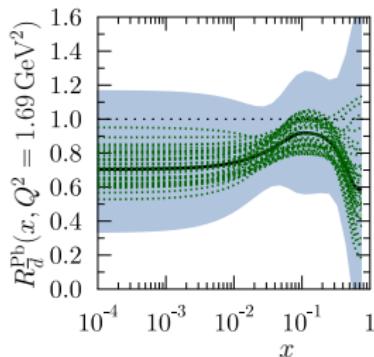
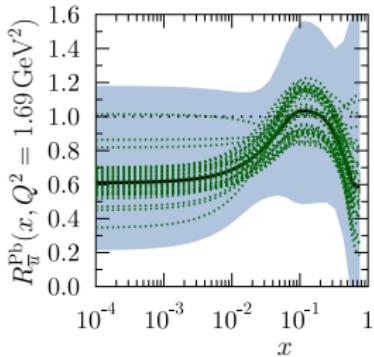
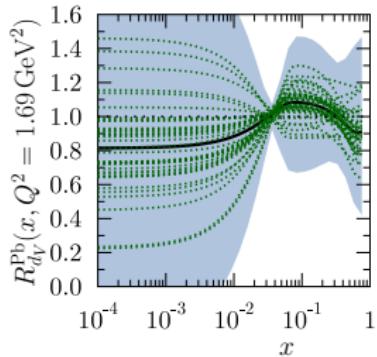
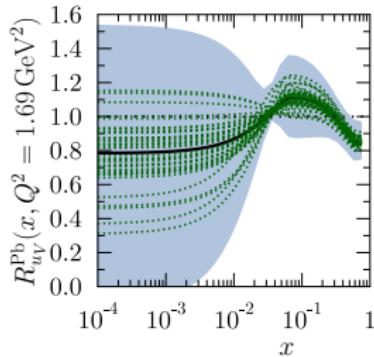
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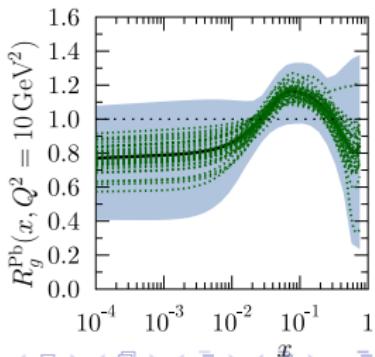
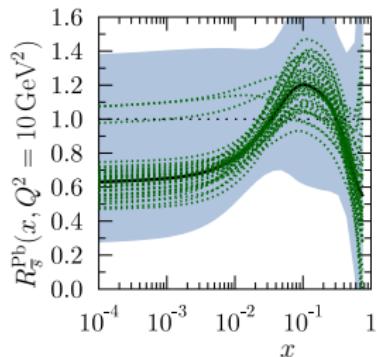
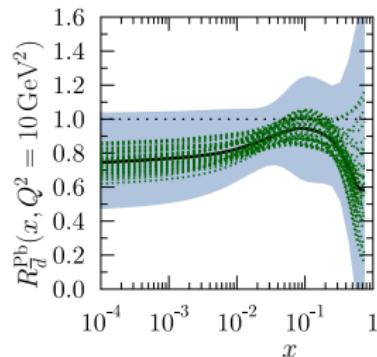
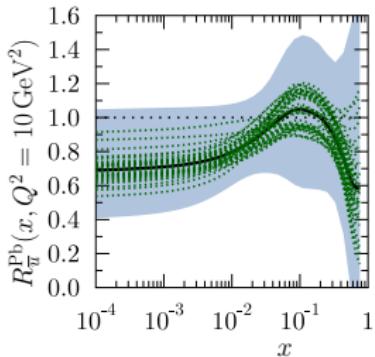
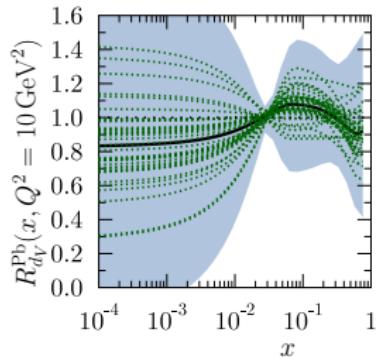
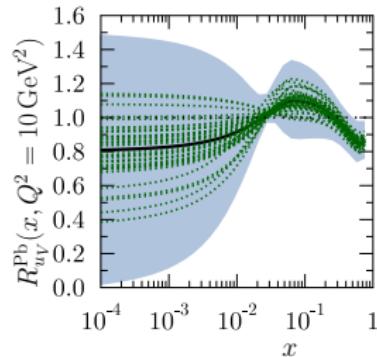
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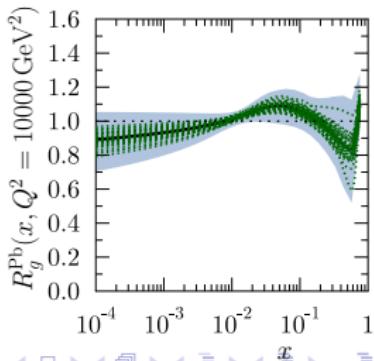
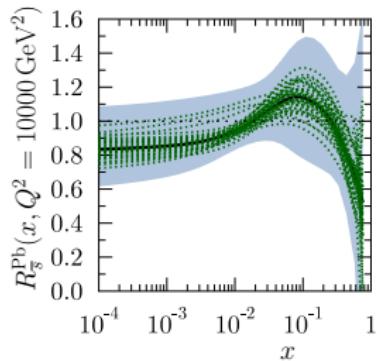
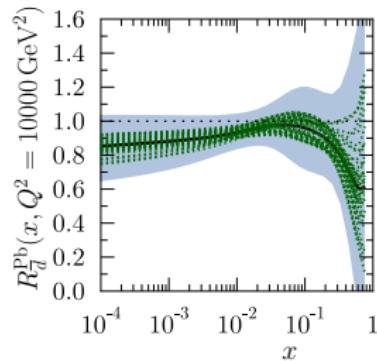
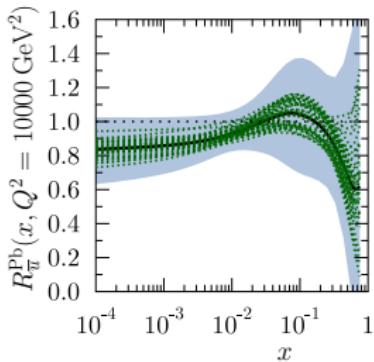
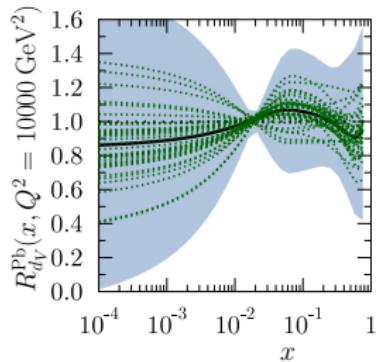
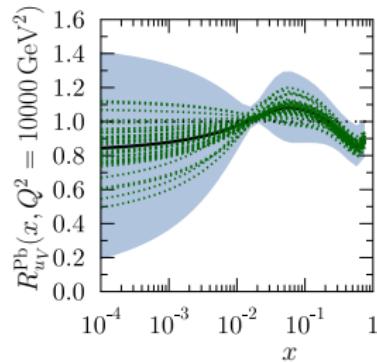
## Results: Nuclear modification for $^{208}\text{Pb}$ at $Q^2 = 10 \text{ GeV}^2$

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



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

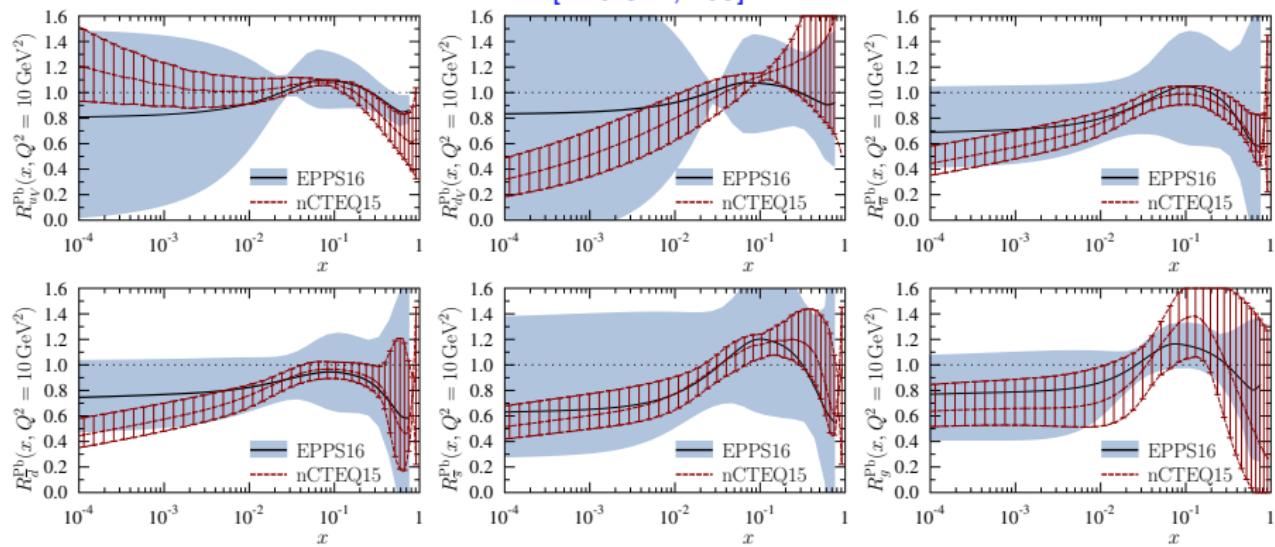
- Total uncertainties shown as blue bands, individual error sets in green



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

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

[EPJ C77, 163]



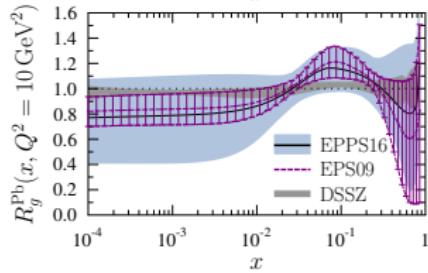
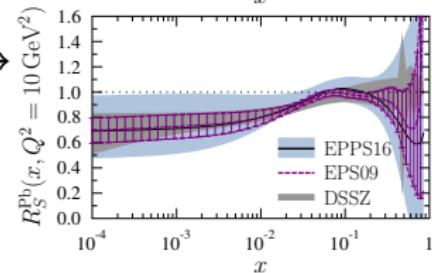
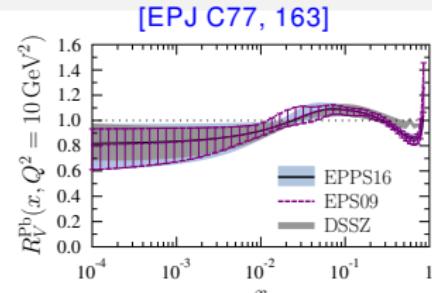
# Comparison between EPS09, DSSZ and EPPS16

- No flavour freedom in EPS09 nor DSSZ.

⇒ compare the averages

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

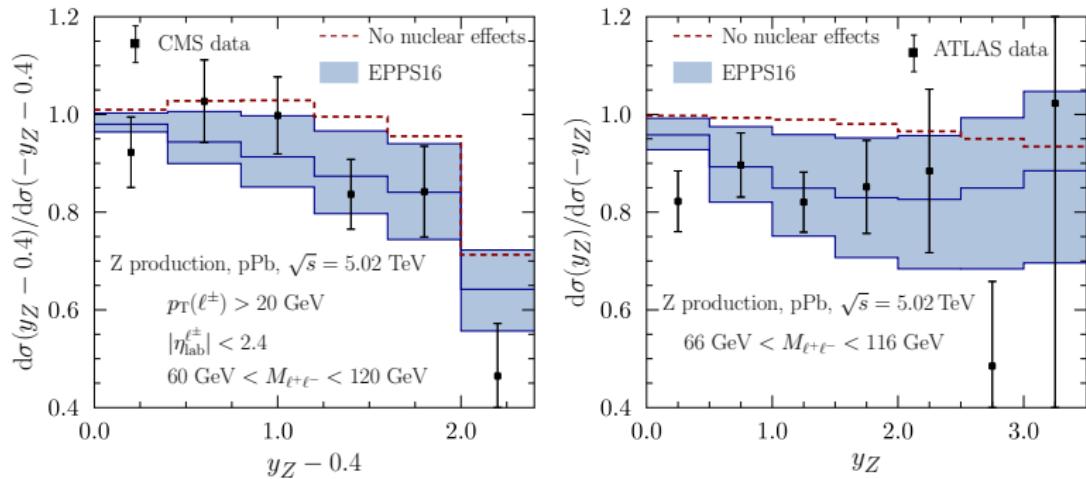
$$R_{\text{light sea}} \equiv \frac{\bar{u}^{\text{p}/\text{Pb}} + \bar{d}^{\text{p}/\text{Pb}} + \bar{s}^{\text{p}/\text{Pb}}}{\bar{u}^{\text{p}} + \bar{d}^{\text{p}} + \bar{s}^{\text{p}}}$$



- All three appear consistent (but note the large- $x$  valence quarks of DSSZ).
- Typically larger uncertainties in EPPS16 (for having more degrees of freedom — even more data constraints).

# Comparison with the LHC p-Pb data: Z production

- Good agreement — obtainable constraints limited by low statistics

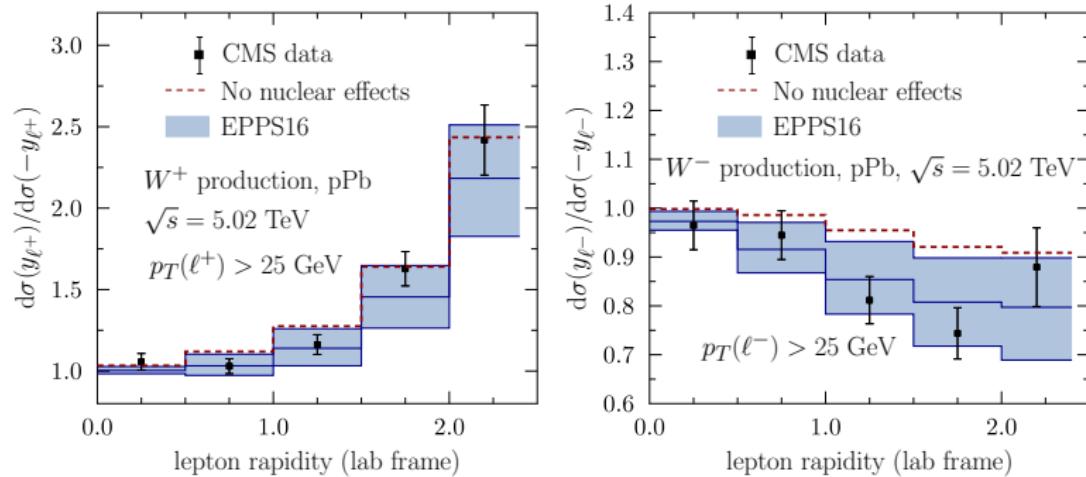


- More net shadowing for  $y_Z > 0$  than for  $y_Z < 0$

⇒ suppression in  $R_{FB}$

## Comparison with the LHC p-Pb data: W production

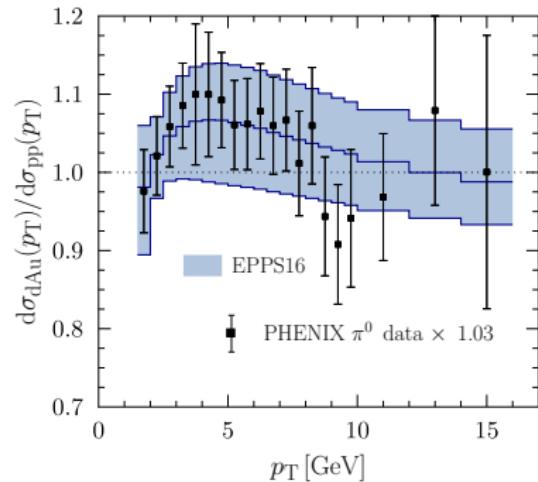
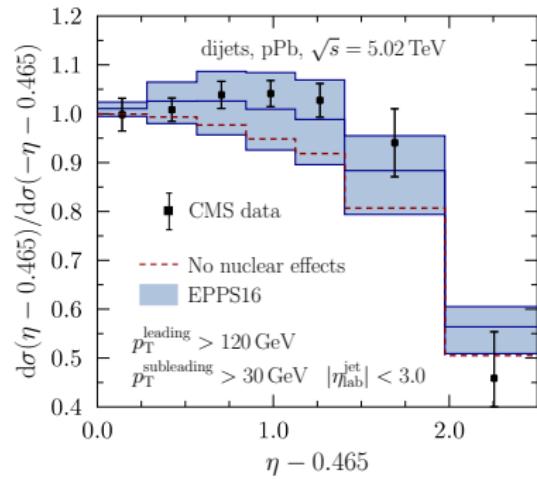
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- More net shadowing for  $y_{\ell^{\pm}} > 0$  than for  $y_{\ell^{\pm}} < 0$   
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# Comparison with the LHC p-Pb dijet and RHIC d-Au pion data

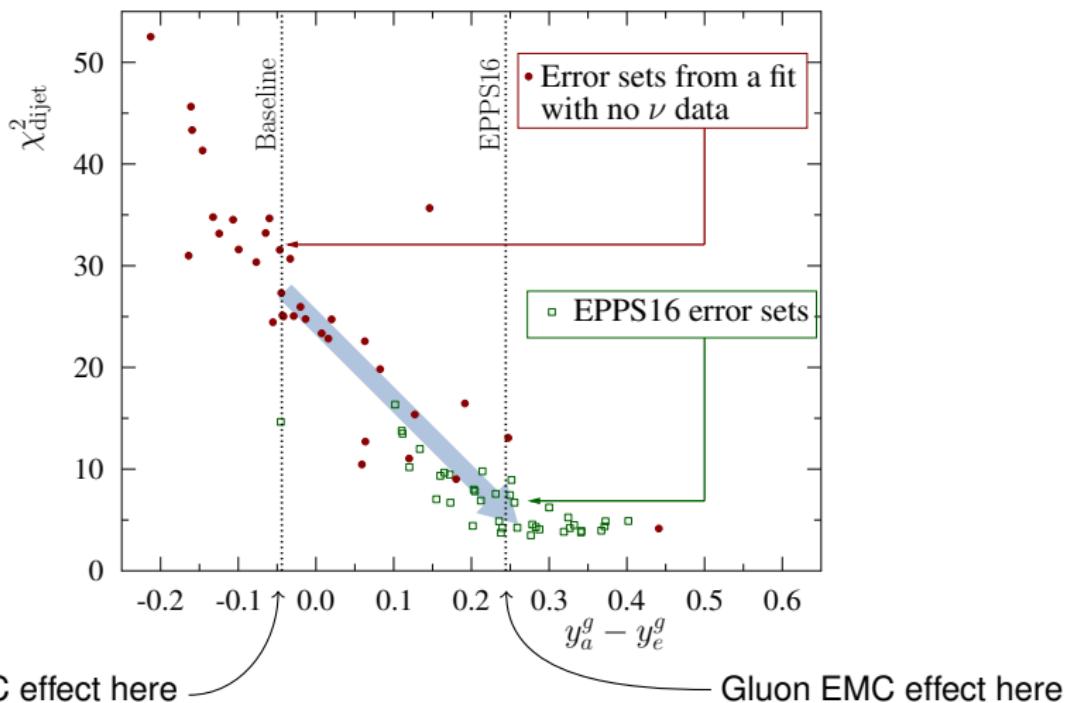
- Both data sensitive to the large- $x$  gluons — mutually compatible



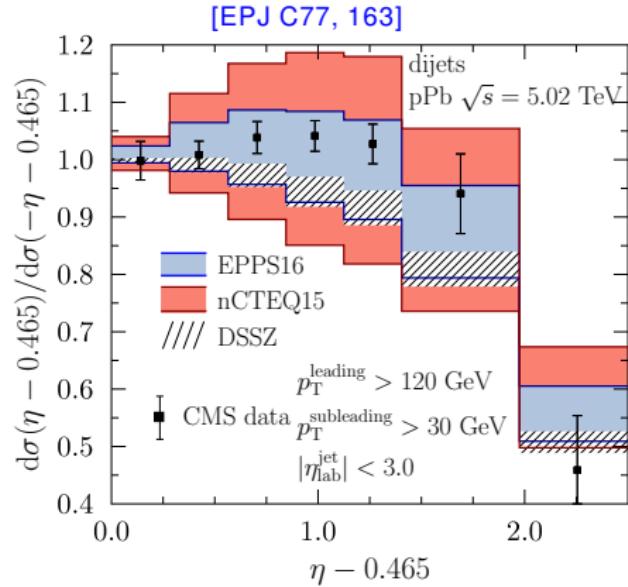
- An EMC effect for  $\eta_{\text{dijet}} < 0$ , antishadowing for  $\eta_{\text{dijet}} > 0$   
⇒ an enhancement in  $R_{FB}$

## Comparison with the LHC p-Pb dijet data

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



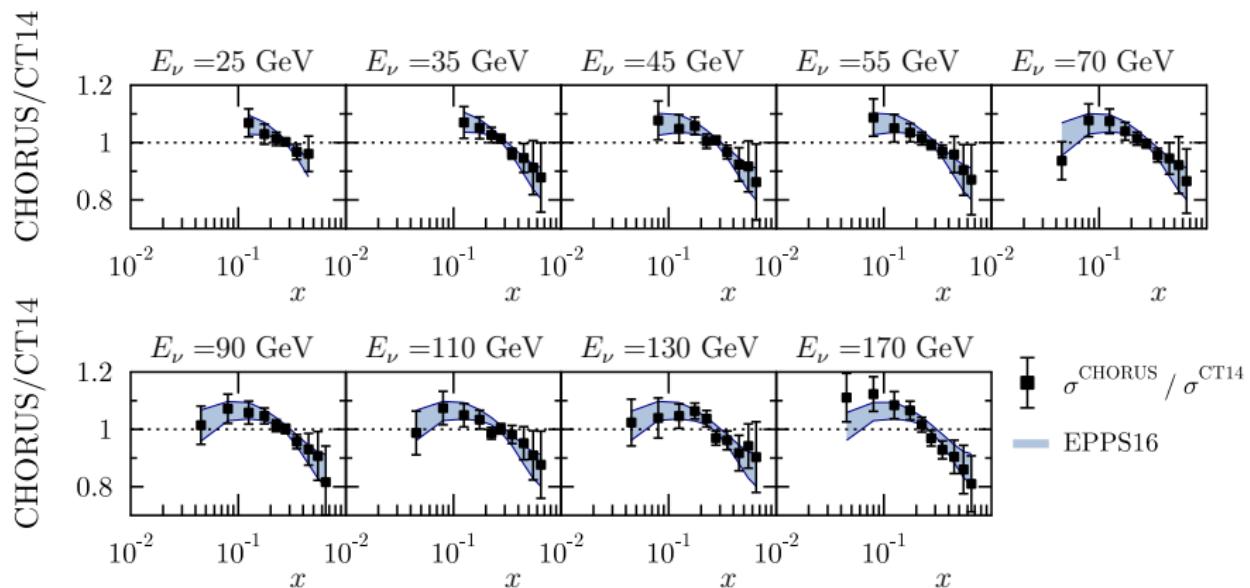
## p-Pb dijets vs. nCTEQ15 & DSSZ & EPPS16



- nCTEQ15: larger high- $x$  gluon uncertainty  $\Rightarrow$  wider uncertainty band for dijets
- The mild nuclear effects of DSSZ gluons  $\Rightarrow$  result similar to no effects at all

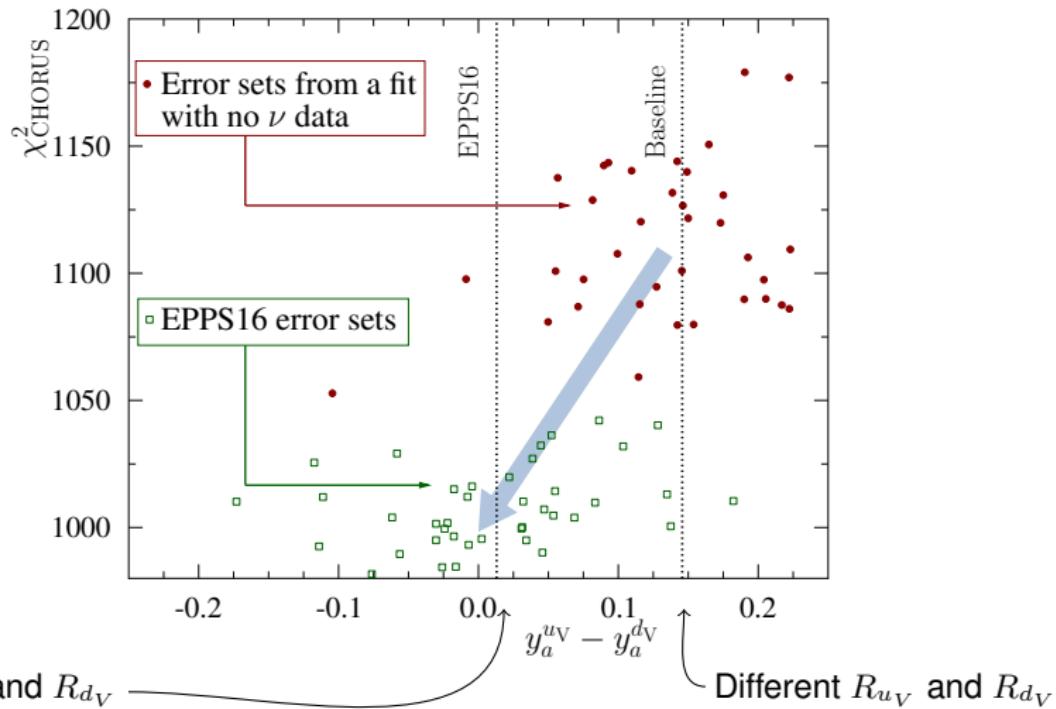
## Comparison with the neutrino data

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



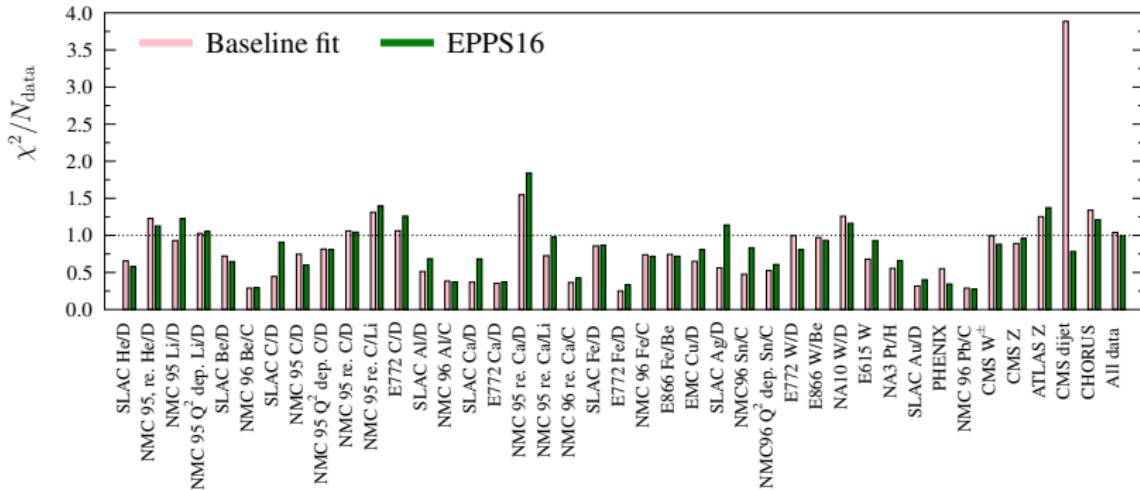
## Comparison with the neutrino data

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



## Mutual compatibility of the data

- The mutual compatibility of the data assessed by looking the  $\chi^2/N_{\text{data}}$  data set by data set



- No abnormally large values in the final EPPS16 result

⇒ The data input is self-consistent

## Summary & Outlook

- Introduced EPPS16 NLO nuclear PDFs
  - supersedes EPS09
- The most essential new ingredients:
  - LHC Run I data  $\rightsquigarrow$  novel constraints, especially dijets
  - neutrino DIS data  $\rightsquigarrow R_{u_V} \sim R_{d_V}$
  - full flavour dependence  $\rightsquigarrow$  less bias but larger uncertainties
- Excellent agreement with the data
  - supports the validity of collinear factorization in nuclear collisions up to the electroweak scale
- Available from
  - <https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/nPDFs>
  - LHAPDF