EPPS16 – First nuclear PDFs to include LHC data

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Collinear factorization in nuclei

- Factorization theorem

parton distribution functions

$$\mathrm{d}\sigma^{AB\to k+X} \overset{Q\gg\Lambda_{\mathrm{QCD}}}{=} \sum_{i,j,X'} f_i^A(Q^2)\otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'}(Q^2)\otimes f_j^B(Q^2) \; + \; \mathcal{O}(1/Q^2)$$

hard-scattering coefficient

- The coefficient functions $\mathrm{d}\hat{\sigma}^{ij\to k+X'}$ are perturbatively calculable

. . . but the parton distribution functions (PDFs) contain long-range physics and cannot be obtained by perturbative means

- However, the PDFs are *universal*, process independent, and obey the DGLAP equations

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

- For a nucleus A, one has

$$f_i^A(x,Q^2) = \frac{Z}{A}f_i^{p/A}(x,Q^2) + \frac{N}{A}f_i^{n/A}(x,Q^2) \qquad \text{(per nucleon)},$$

where the neutron content is obtained via isospin symmetry

Current global nPDF analyses

	EPS09	DSSZ	nCTEQ15	KA15	**EPPS16**
Order in α_s	LO & NLO	NLO	NLO	NNLO	NLO
NC DIS lA/ld	✓	✓	✓	✓	✓
DY pA/pd	✓	✓	✓	✓	✓
RHIC pions dAu/pp	✓	✓	✓		✓
νA DIS		✓			✓
πA DY					✓
LHC pPb jets					✓
LHC pPb W, Z					✓
Q cut in DIS	1.3 GeV	1 GeV	2 GeV	1 GeV	1.3 GeV
datapoints	929	1579	708	1479	1811
free parameters	15	25	16	16	20
error analysis	Hessian	Hessian	Hessian	Hessian	Hessian
error tolerance $\Delta\chi^2$	50	30	35	?	52
Free proton PDFs	CTEQ6.1	MSTW2008	CTEQ6M-like	JR09	CT14
HQ treatment	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS
Flavour separation	no	no	valence	no	full
Weight data in χ^2	yes	no	no	no	no
Reference	JHEP 0904 065	PR D85 074028	PR D93 085037	PR D93 014026	EPJ C77 no.3, 163

EPPS16 improvements over EPS09

- **completely new data types, twice as many data points** → **more constraints**
- **general mass formalism, undo isospin corrections** → **better details**
- **more free parameters, free flavours, no data weighting** → **less biased**

EPPS16 parametrization

[EPJ C77 no.3, 163]

- Define nPDFs in terms of nuclear modifications

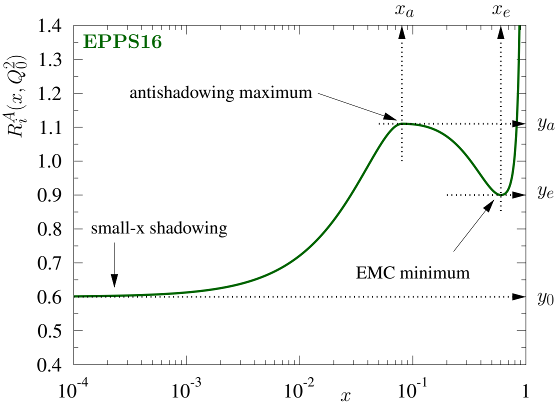
$$f_i^{\mathrm{p}/A}(x,Q^2) = R_i^A(x,Q^2) f_i^{\mathrm{p}}(x,Q^2)$$

- Parametrize the x and A dependence of $R_i^A(x,Q_0^2)$ at $Q_0^2 = m_{\mathrm{charm}}^2$

- For the first time, we allow parametric freedom for all flavours

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

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



Kinematic reach of the current data

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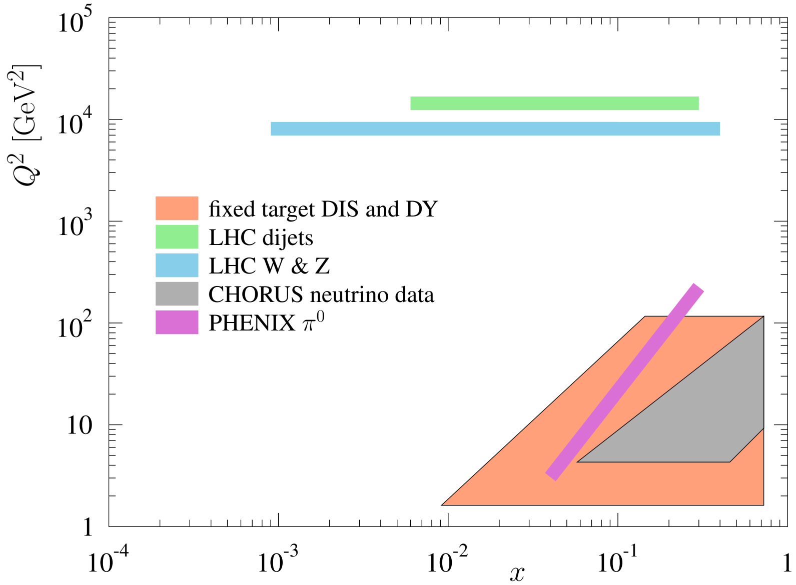
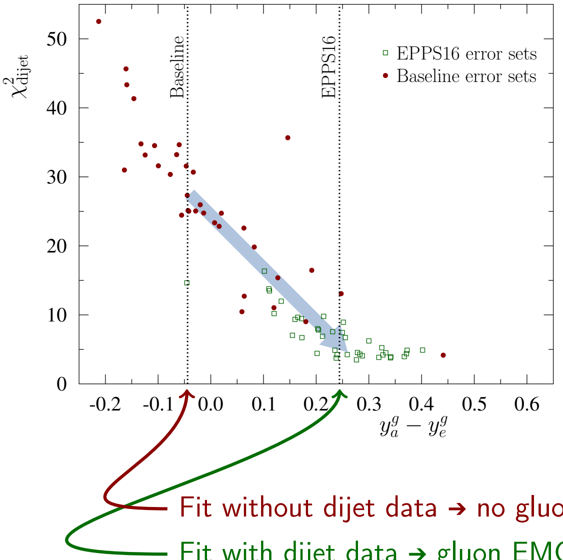
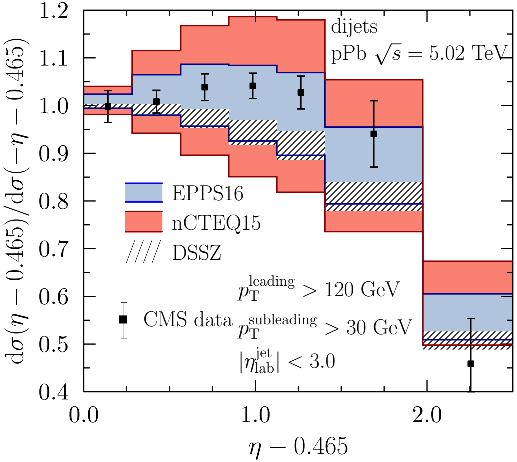


- Data much more restricted in x, Q^2 space than for proton PDFs
- The LHC data opens a new kinematic region
- The νA DIS and πA DY give complementary mid/high-x information

Impact of CMS dijet data

[EPJ C77 no.3, 163]





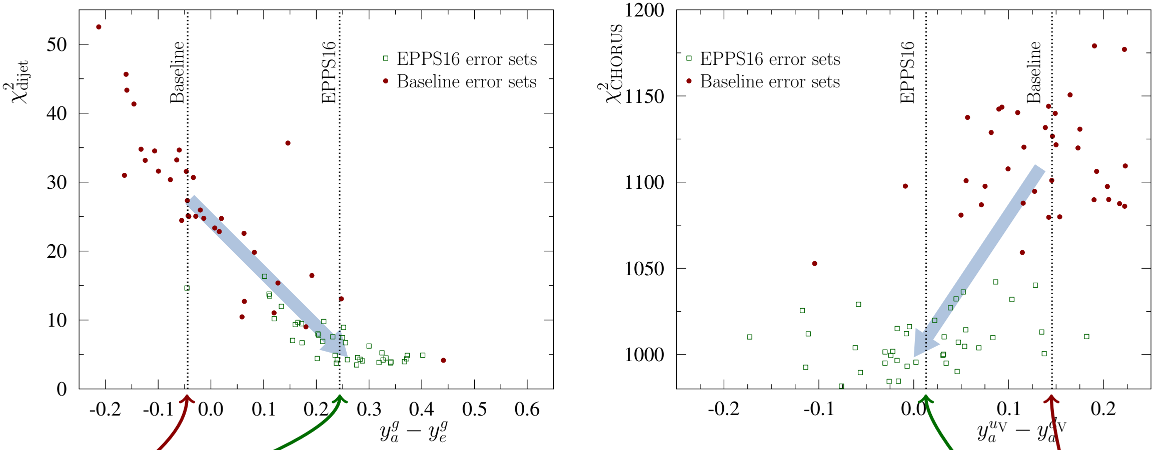
Fit without dijet data ➔ no gluon EMC effect

Fit with dijet data ➔ gluon EMC effect

- nCTEQ15 has large uncertainties due to not having these data in the fit
- DSSZ + CT14 not compatible with these data

Impact of CMS dijet and CHORUS neutrino data

[EPJ C77 no.3, 163]



Fit without dijet data → no gluon EMC effect

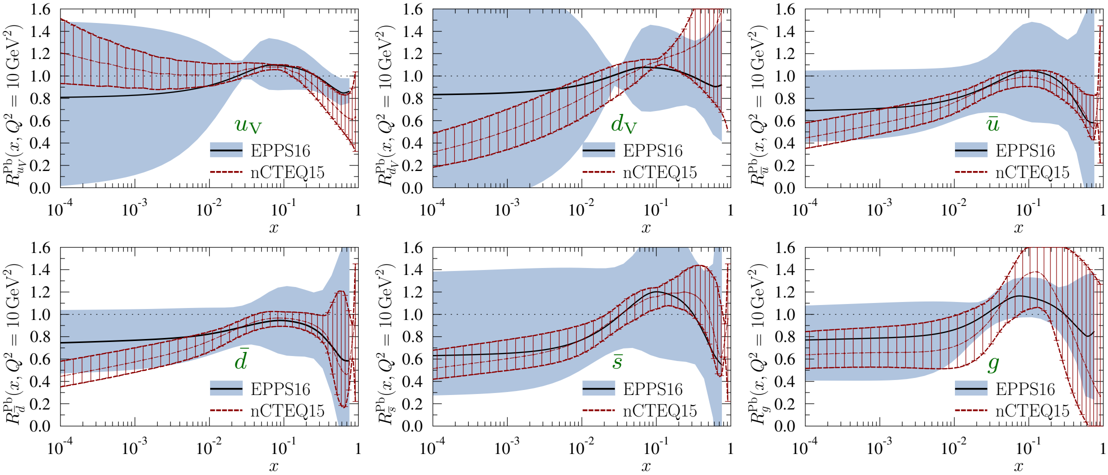
Fit with dijet data → gluon EMC effect

Fit without neutrino data → different $R^A_{u_{\rm V}}(x, Q^2_0)$ and $R^A_{d_{\rm V}}(x, Q^2_0)$

Fit with neutrino data → similar $R^A_{u_{\rm V}}(x, Q^2_0)$ and $R^A_{d_{\rm V}}(x, Q^2_0)$

Comparison between EPPS16 and nCTEQ15

[EPJ C77 no.3, 163]



- EPPS16 error bands are typically larger but less biased
- nCTEQ15 has
  - less freedom in parametrization → smaller apparent uncertainties in general
  - harder Q^2 cut and no LHC data → larger high-x gluon uncertainties
- Asymmetric valence modifications in nCTEQ15 possibly due to isospin-symmetric DIS data + no νA DIS

Comparison between EPPS16, EPS09 and DSSZ

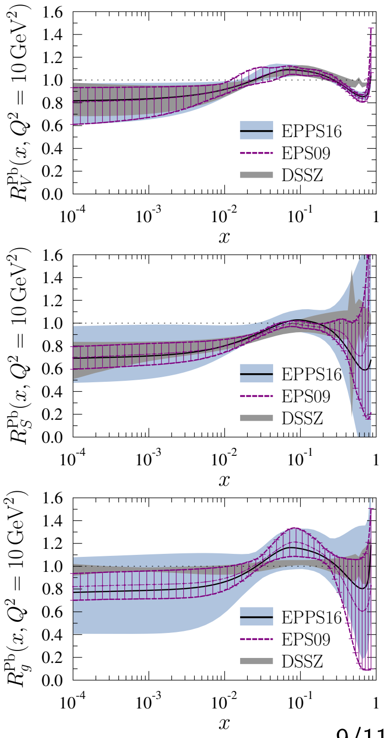
[EPJ C77 no.3, 163]

- No flavour freedom in EPS09 nor DSSZ
    - ➔ Compare the averages

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

$$R_{\mathrm{S}}^{\mathrm{Pb}} \equiv \frac{\overline{u}^{\mathrm{p/Pb}} + \overline{d}^{\mathrm{p/Pb}} + \overline{s}^{\mathrm{p/Pb}}}{\overline{u}^{\mathrm{p}} + \overline{d}^{\mathrm{p}} + \overline{s}^{\mathrm{p}}}$$

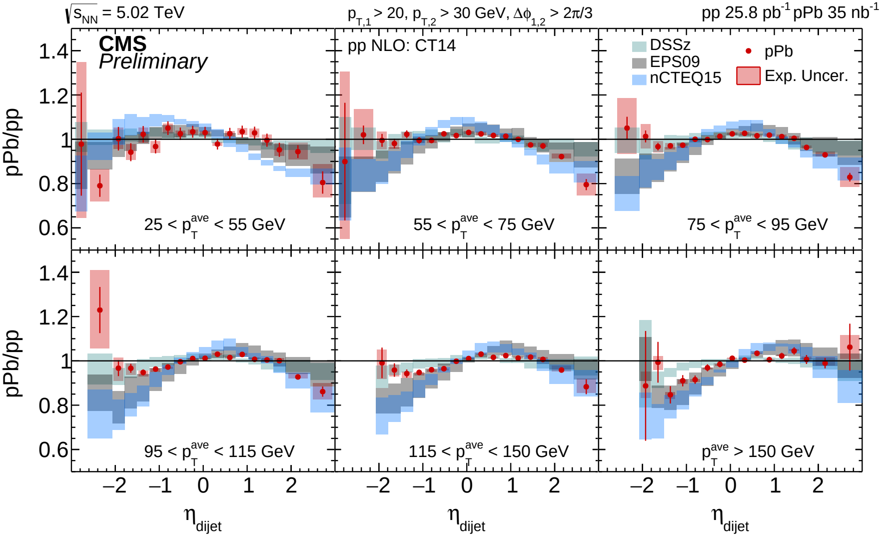
- All three appear consistent (except DSSZ large-x valence quarks)
- EPPS16 sea quark uncertainties larger due to more degrees of freedom (flavour dependence)
- EPS09 gluon uncertainties smaller due to artificial weight for PHENIX data (no gluon modifications in DSSZ due to including nuclear effects in FFs)
- EPPS16 error bands are larger but less biased



Summary

- The most important new ingredients in EPPS16:
  - CMS dijets → new constraints for mid/high-x gluons
  - Neutrino DIS data → $R^A_{u_V}(x, Q_0^2) \sim R^A_{d_V}(x, Q_0^2)$
  - Full flavour dependence → less biased but larger uncertainties
- A consistent fit for wide variety of observables and kinematic range from $Q = 1.3\ \mathrm{GeV}$ up to the EW scale can be achieved
  - → Supports collinear factorization and universality of nPDFs
- EPPS16 nPDFs with error sets available from:
  - `https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/nPDFs`
  - LHAPDF
- We look forward to more high-precision data from LHC pPb
  - Currently analyzing the impact of the more differential CMS dijet measurement

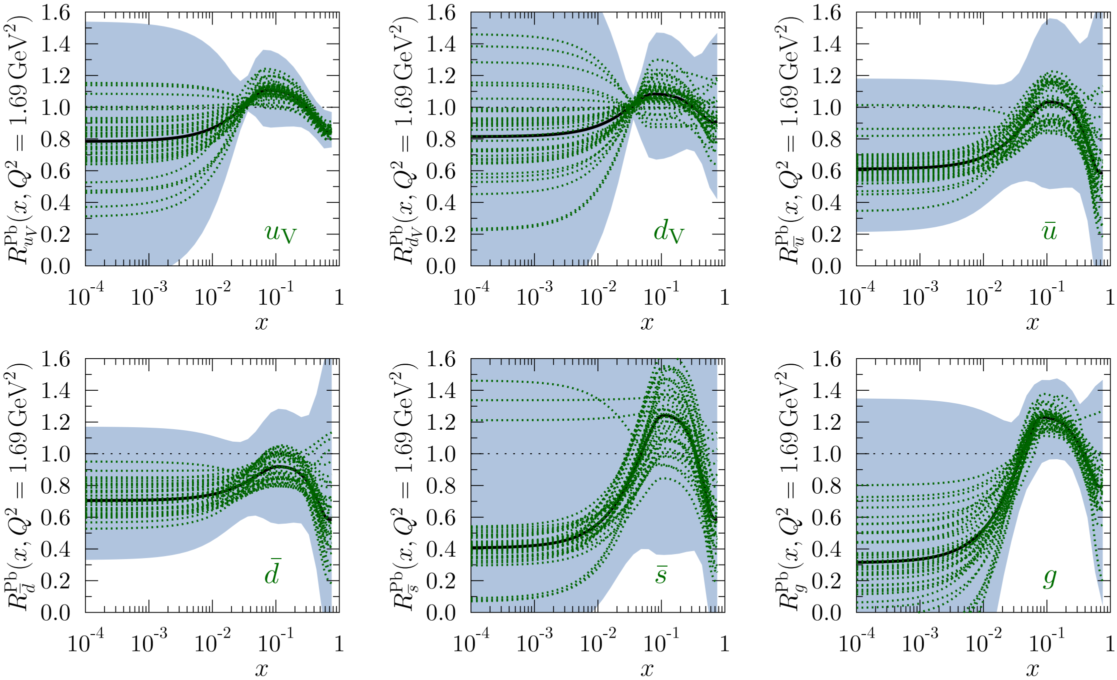
CMS dijets



- Direct dijet R_{pPb} now possible with the new pp baseline measurement
- Preliminary data [CMS-PAS-HIN-16-003]
- Sensitive to gluons in a wide x range roughly from 0.8 to 10^{-3}

EPPS16 nuclear modifications for ^{208}Pb at $Q^2 = 1.69$ GeV^2 [EPJ C77 no.3, 163]

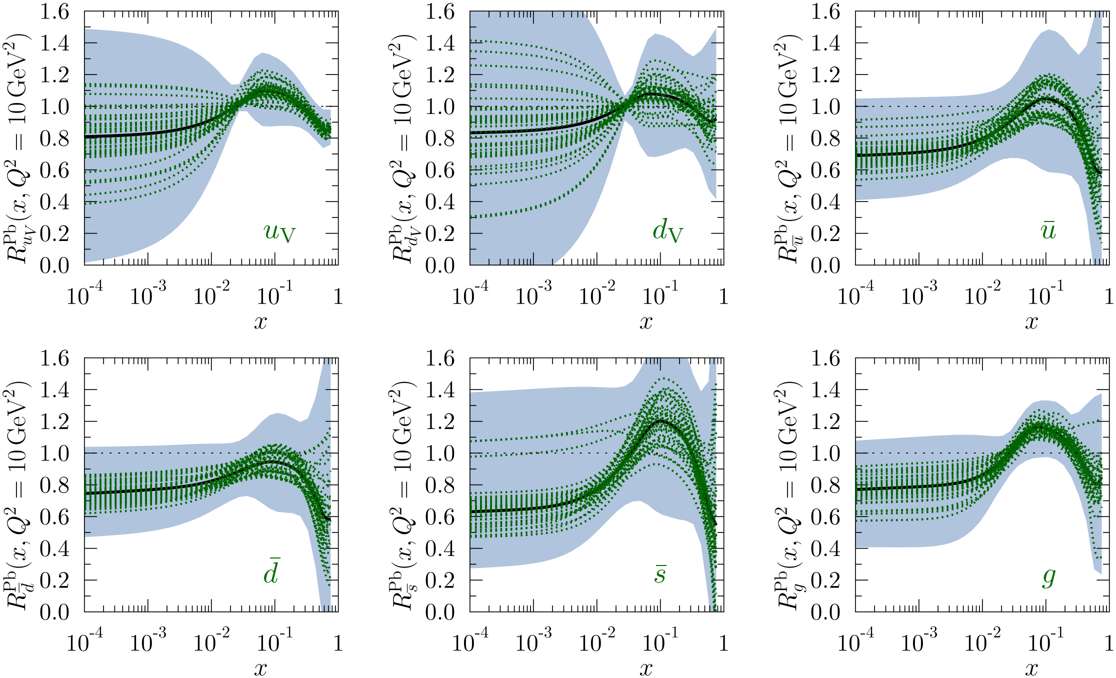
- Total uncertainties shown as blue bands, individual error sets in green



EPPS16 nuclear modifications for ^{208}Pb at $Q^2 = 10$ GeV^2

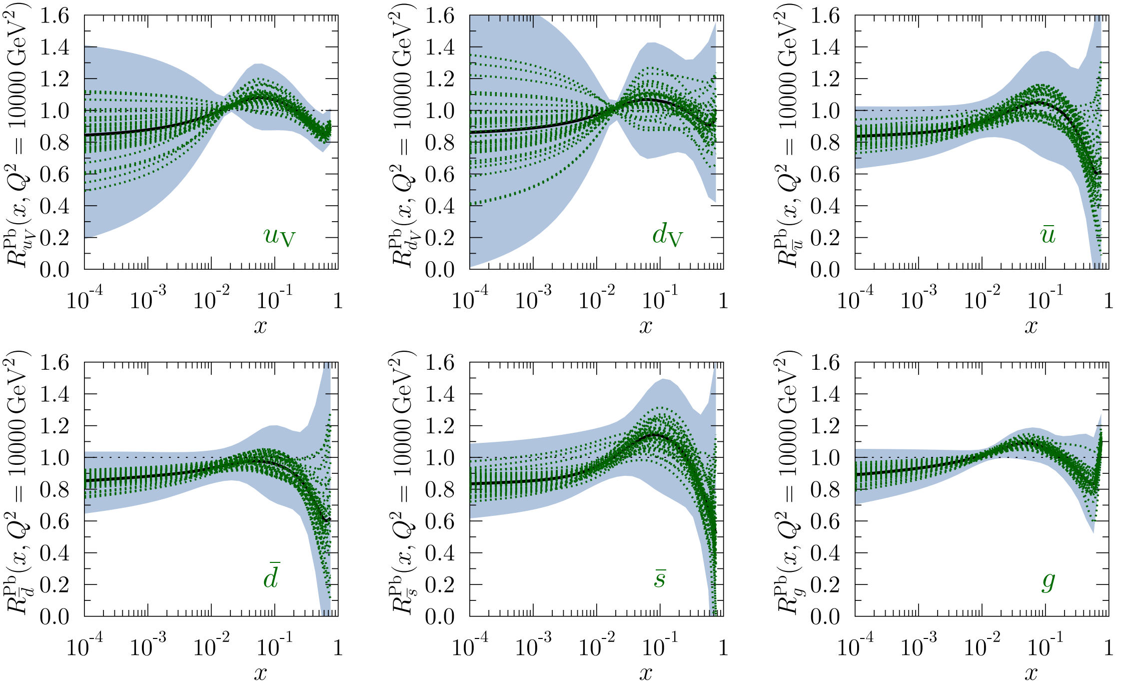
[EPJ C77 no.3, 163]

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



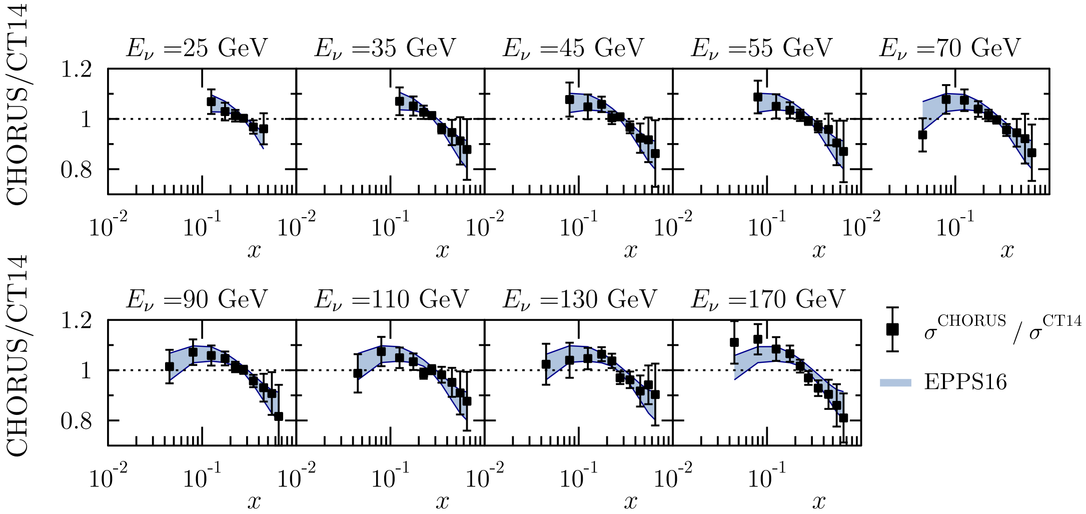
EPPS16 nuclear modifications for ^{208}Pb at $Q^2 = 10000\ \mathrm{GeV}^2$ [EPJ C77 no.3, 163]

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



νA DIS vs. EPPS16

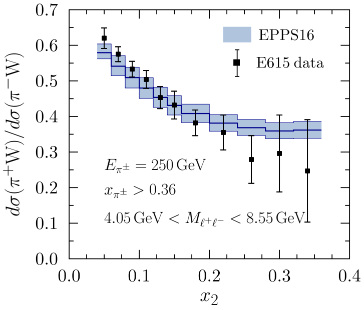
[EPJ C77 no.3, 163]

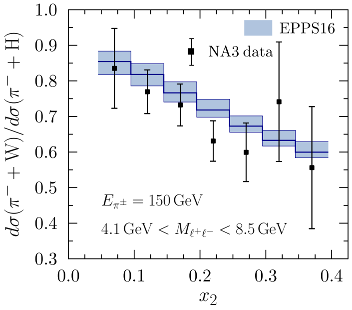


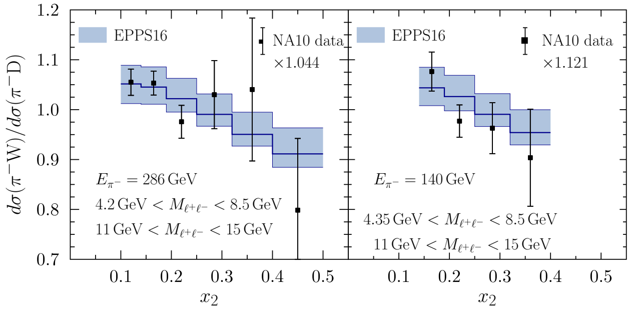
- Familiar pattern of antishadowing + EMC effect
- Important for constraining the flavour separation

πA DY vs. EPPS16

[EPJ C77 no.3, 163]



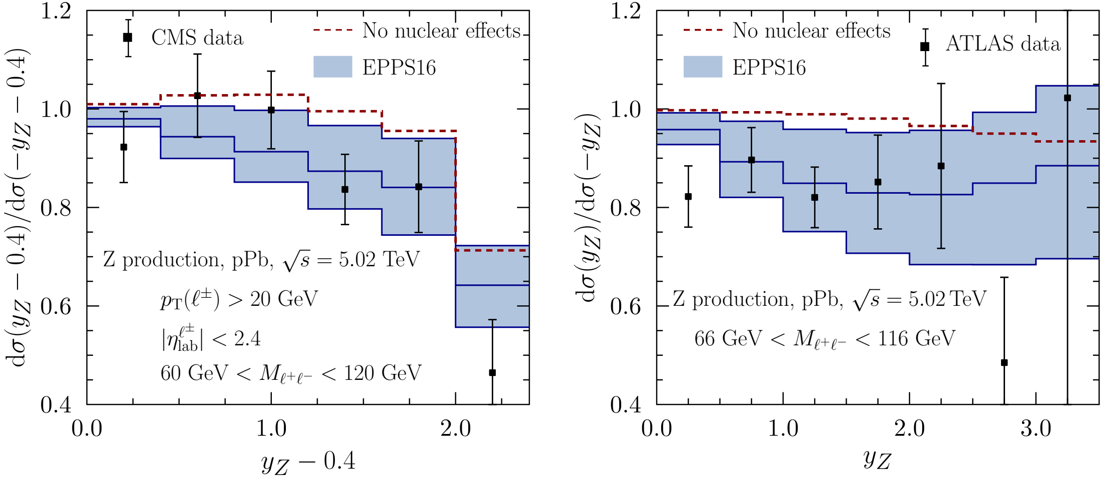




- Also sensitive to the flavour separation [Phys.Lett. B768 7-11], but has less constraining power than νA DIS

Z production vs. EPPS16

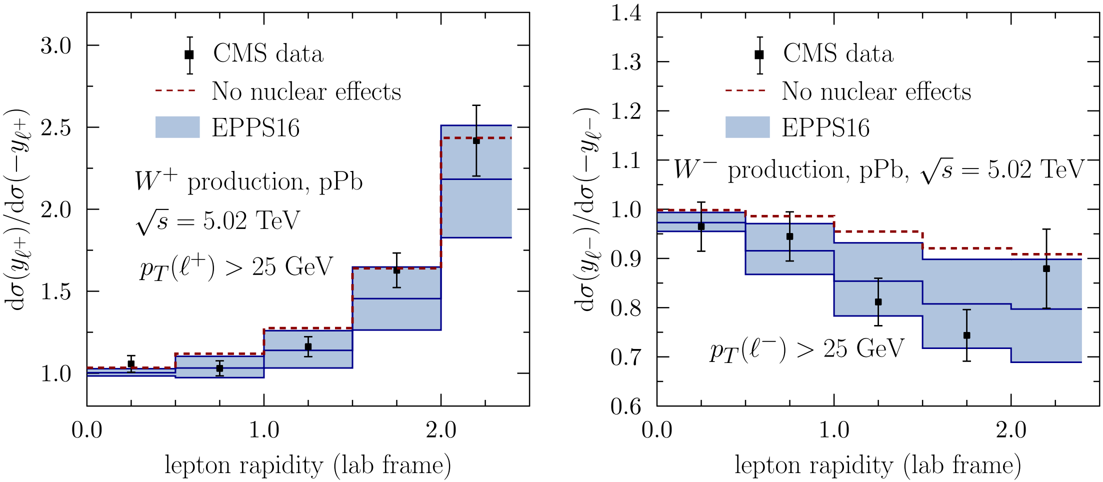
[EPJ C77 no.3, 163]



- Good agreement, data support small-x net nuclear shadowing
- Obtainable constraints limited by low statistics

W production vs. EPPS16

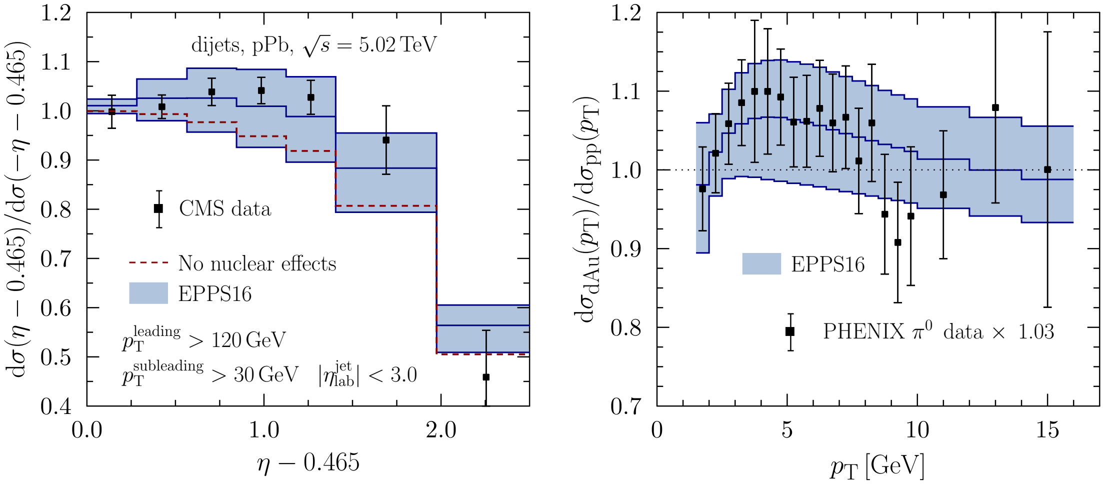
[EPJ C77 no.3, 163]



- Good agreement, data support small-x net nuclear shadowing
- More data needed for better constraints

CMS dijets + PHENIX π production vs. EPPS16

[EPJ C77 no.3, 163]



- Data support gluon antishadowing + EMC effect
- PHENIX data were included already in EPS09, but with a weight
  - EPPS16: no weights → More realistic error estimates

Why are the quark uncertainties so large?

- There is a subtle interplay with isospin
- For example, we can write

$$f^A_{u_\mathrm{V}} = \left(R^A_{u_\mathrm{V}+d_\mathrm{V}} - \frac{A-2Z}{A} R^A_{u_\mathrm{V}-d_\mathrm{V}} \right) \frac{f^p_{u_\mathrm{V}} + f^p_{d_\mathrm{V}}}{2}$$

$$f^A_{d_\mathrm{V}} = \left(R^A_{u_\mathrm{V}+d_\mathrm{V}} + \frac{A-2Z}{A} R^A_{u_\mathrm{V}-d_\mathrm{V}} \right) \frac{f^p_{u_\mathrm{V}} + f^p_{d_\mathrm{V}}}{2}$$

where

$$R^A_{u_\mathrm{V}+d_\mathrm{V}} = \frac{f^{p/A}_{u_\mathrm{V}} + f^{p/A}_{d_\mathrm{V}}}{f^p_{u_\mathrm{V}} + f^p_{d_\mathrm{V}}}$$

$$R^A_{u_\mathrm{V}-d_\mathrm{V}} = \frac{f^{p/A}_{u_\mathrm{V}} - f^{p/A}_{d_\mathrm{V}}}{f^p_{u_\mathrm{V}} + f^p_{d_\mathrm{V}}}$$

and the neutron excess $\frac{A-2Z}{A} \approx 0.2$ for Pb

➔ Need high-precision data on non-isoscalar nuclei to constrain the difference