Nuclear parton distribution functions

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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

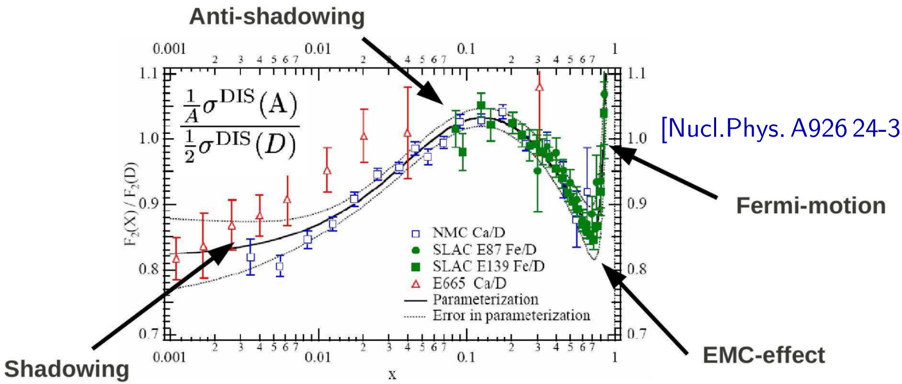
$$f_i^A(x,Q^2) = \frac{Z}{A} f_i^{p/A}(x,Q^2) + \frac{N}{A} f_i^{n/A}(x,Q^2) \qquad \text{(per nucleon)},$$

where the neutron content is obtained via isospin symmetry

Nuclear PDFs

. . . but in the nuclear environment the partonic contents of the *bound nucleons* are modified

$$\text{bound proton PDF} \sim f_i^{p/A}(x, Q^2) \neq f_i^p(x, Q^2) \sim \text{free proton PDF}$$



[Nucl.Phys. A926 24-33]

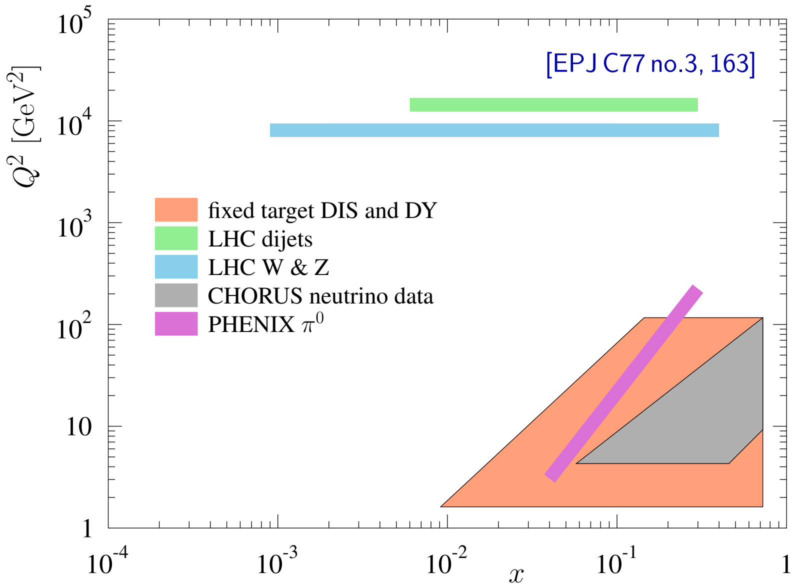
➔ Global analyses of *nuclear* parton distribution functions (nPDFs)

- First global fit: EKS98 [Nucl.Phys. B535 351-371]
- First error analysis: HKM [Phys.Rev. D64 034003]
- First NLO fit: nDS [Phys.Rev. D69 074028]

! Not enough data available to fit each nucleus separately

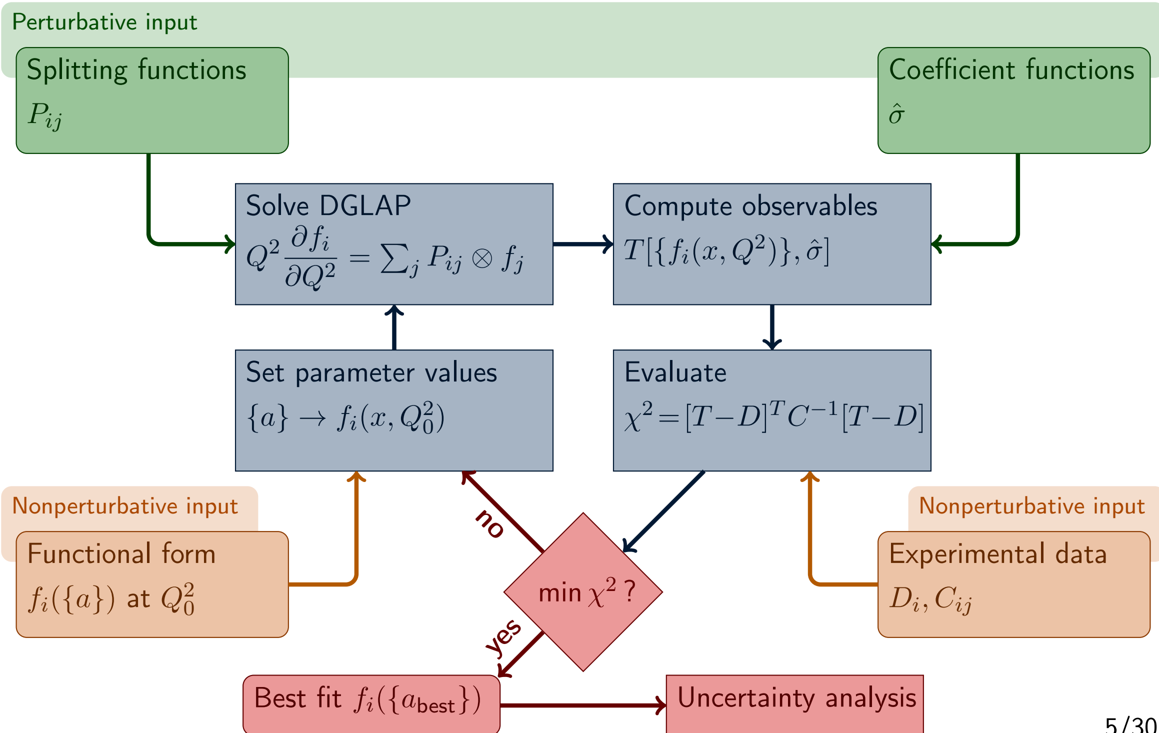
➔ Have to parametrize also the A dependence

Kinematic reach of the current data



- Data much more restricted in x, Q^2 space than for proton PDFs
- Also fewer types of data and less data points
- The LHC data opens a new kinematic region

Global analysis



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

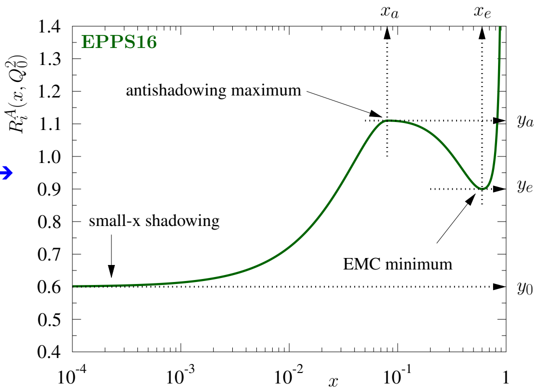
[EPJ C77 no.3, 163]

- 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 $R_i^{A_{\mathrm{ref}}=12}$ at $Q_0^2 = m_{\mathrm{charm}}^2$ as in fig. →
- Parametrize the A dependence with

$$y_i(A) = y_i(A_{\mathrm{ref}}) \left(\frac{A}{A_{\mathrm{ref}}}\right)^{\gamma_i[y_i(A_{\mathrm{ref}})-1]}, \quad \gamma_i \geq 0$$



- Parametric freedom for all flavours, in total 20 free parameters
  - Earlier analyses (EPS09, DSSZ, ...) fixed

$$R_{u_V}^A(x,Q_0^2) = R_{d_V}^A(x,Q_0^2)$$

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

  - nCTEQ15 has flavour freedom for valence quarks, but not for sea quarks

Data treatment in EPPS16

[EPJ C77 no.3, 163]

- Recover the true structure functions from the "isoscalarized" ones (charged-lepton DIS)

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

  - This is important now that we allow flavour freedom for quarks

- To reduce experimental uncertainties & sensitivity to free-proton PDFs:
  - LHC pPb data included as forward-to-backward ratios

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

  - νPb and $\bar{\nu}$Pb DIS data included as normalized cross sections

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

    We propagate correlated systematic uncertainties to the normalized cross sections

Look-up tables for LHC observables

[EPJ C77 no.3, 163]

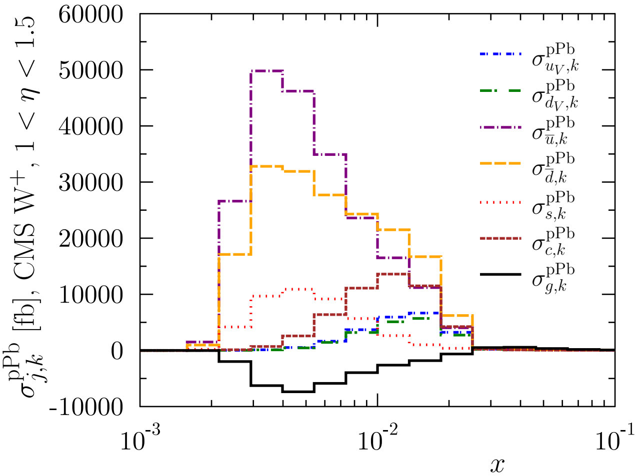
- To include the LHC observables in our fit at the NLO level, a fast method to calculate the cross sections "on the fly" is needed

  ➔ Use look-up tables in EPPS16

- Pre-calculate values $\sigma_{j,k}^{\mathrm{pPb}}$ such that during the fit the observable values are obtained with

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

  ➔ No K-factors needed!



Uncertainty analysis in EPPS16

[EPJ C77 no.3, 163]

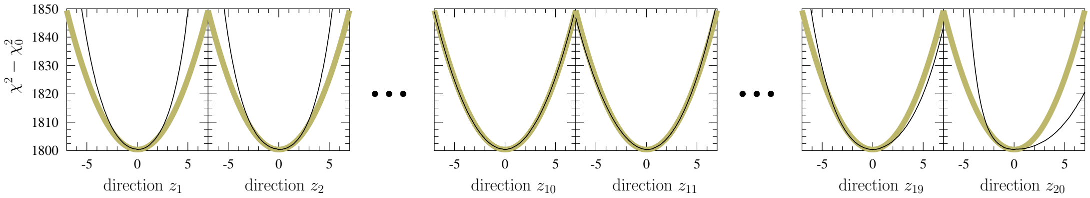
- We use the standard Hessian method

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

original parameters

value at minimum

- Quadratic approximation typically very good

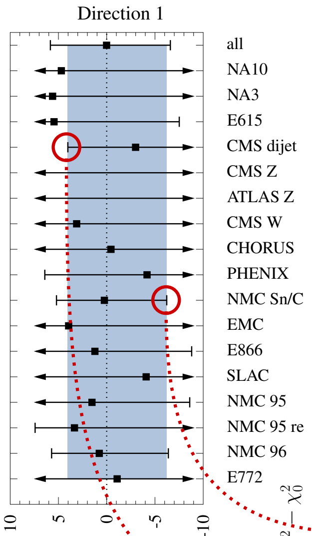


... but due to presence of some non-quadratic components, the uncertainties are computed separately for the upward and downward directions

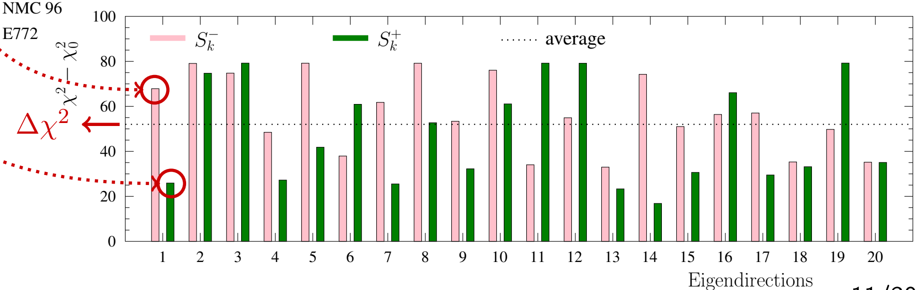
$$\left(\delta X^{\pm}\right)^2 = \sum_i \left[{}^{\max}_{\min} \left\{ X\left(\delta z_i^+\right) - X_0, X\left(\delta z_i^-\right) - X_0, 0 \right\} \right]^2$$

- $\delta z_i^{\pm}$ are defined such that they correspond to fixed increase $\Delta\chi^2$ in the $\chi^2_{\rm global}$ function

How to obtain $\Delta\chi^2$ and EPPS16 error sets? [EPJ C77 no.3, 163]

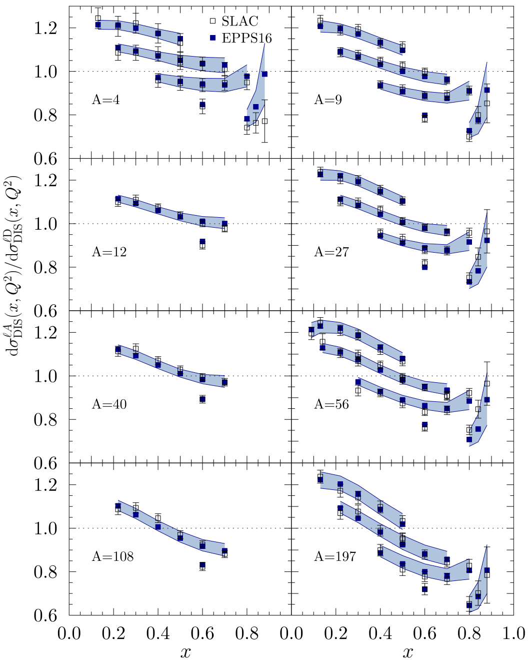


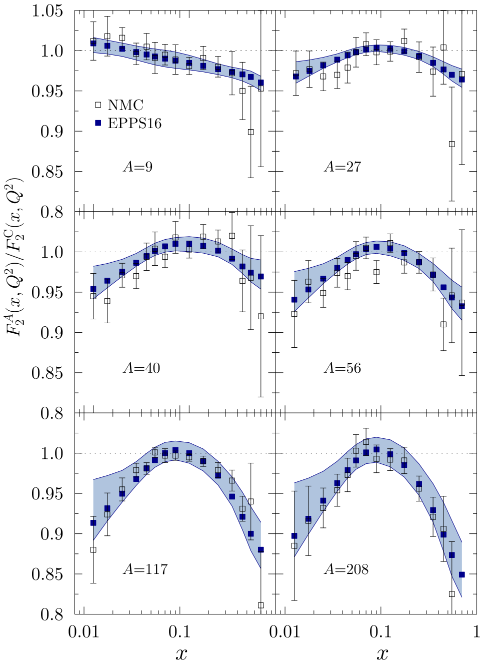
- For each eigendirection, find $z_{i,\max/\min}$ such that all data sets remain within their 90% confidence ranges
- For each $z_{i,\max/\min}$, find the corresponding change in χ^2
- Take the average ➔ global tolerance $\Delta\chi^2 = 52$
  - ➔ allowed parameter variations $\delta z_i^{\pm}$
  - ➔ EPPS16 error sets



lA DIS vs. EPPS16 (sample plots)

[EPJ C77 no.3, 163]

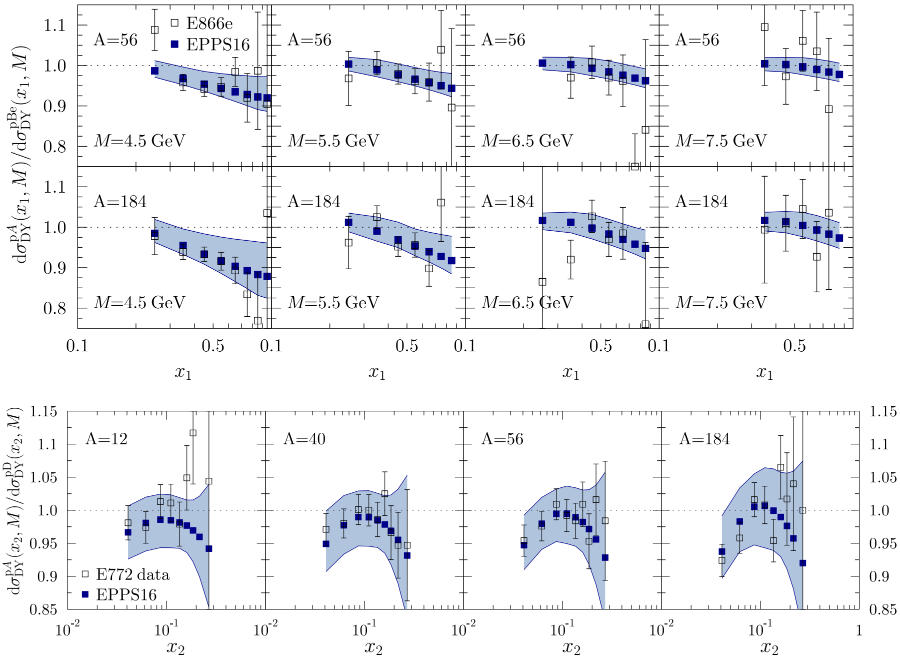




- Bulk of the data, good fit obtained

pA DY vs. EPPS16

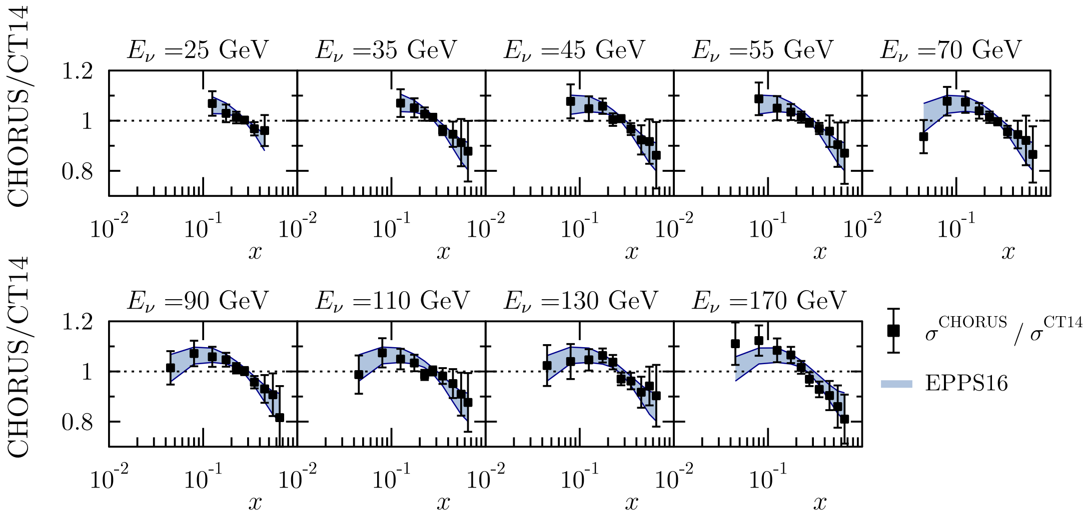
[EPJ C77 no.3, 163]



- Bulk of the data, good fit obtained

νA DIS vs. EPPS16

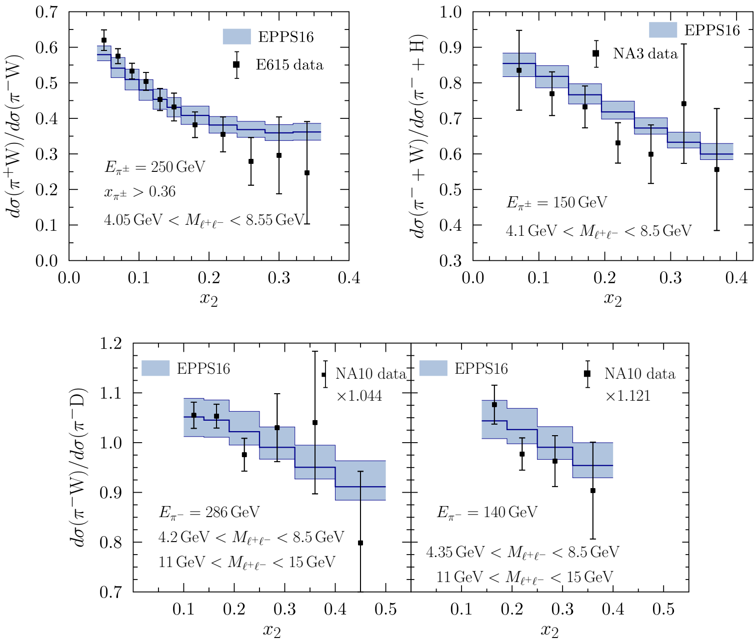
[EPJ C77 no.3, 163]



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

πA DY vs. EPPS16

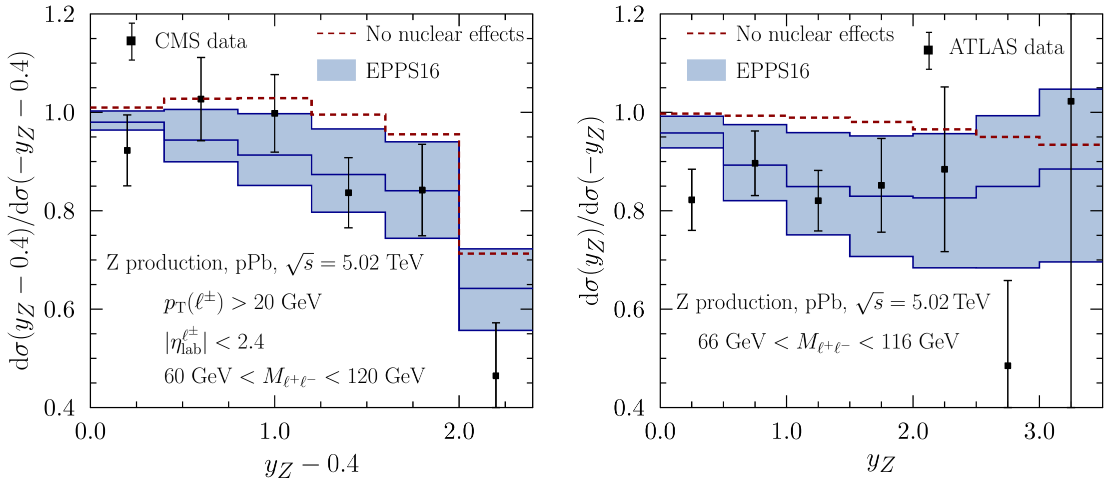
[EPJ C77 no.3, 163]



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

Z production vs. EPPS16

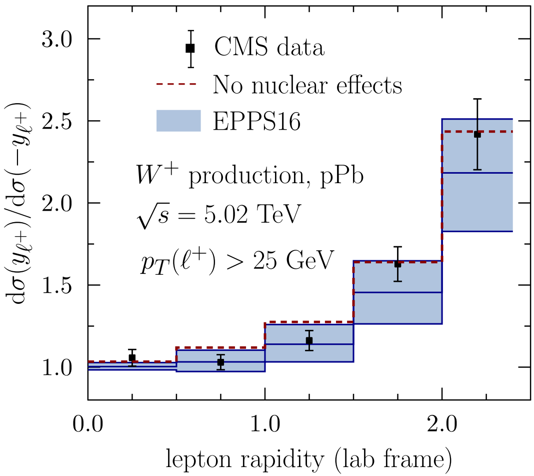
[EPJ C77 no.3, 163]

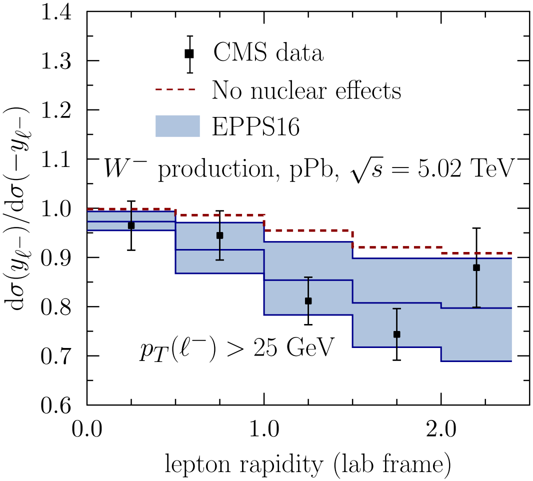


- Good agreement, data support small-x net nuclear shadowing
- Obtainable constraints limited by low statistics

W production vs. EPPS16

[EPJ C77 no.3, 163]

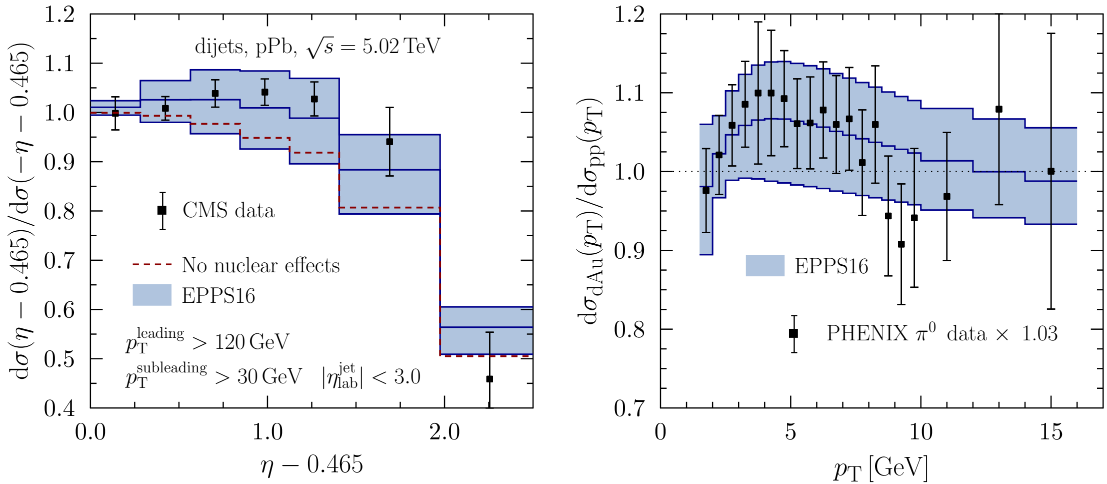




- Good agreement, data support small-x net nuclear shadowing
- More data needed for better constraints

CMS dijets + PHENIX π production vs. EPPS16

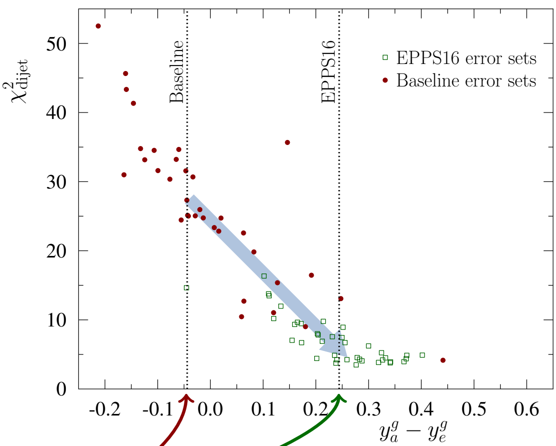
[EPJ C77 no.3, 163]

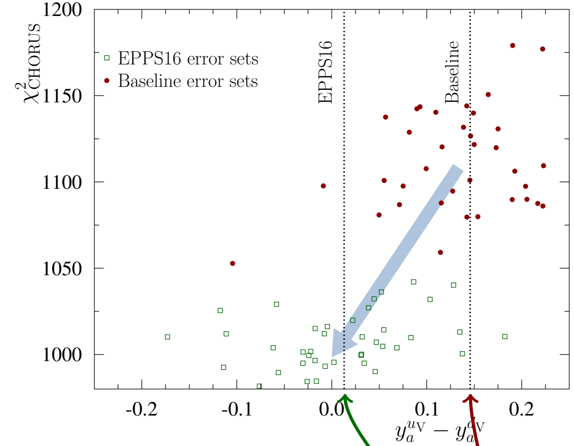


- Data support gluon antishadowing + EMC effect
- PHENIX data were included already in EPS09, but with a weight
  - EPPS16: no weights ➔ More realistic error estimates

The effect of including dijet and neutrino data

[EPJ C77 no.3, 163]





Fit without dijet data ➔ no gluon EMC effect

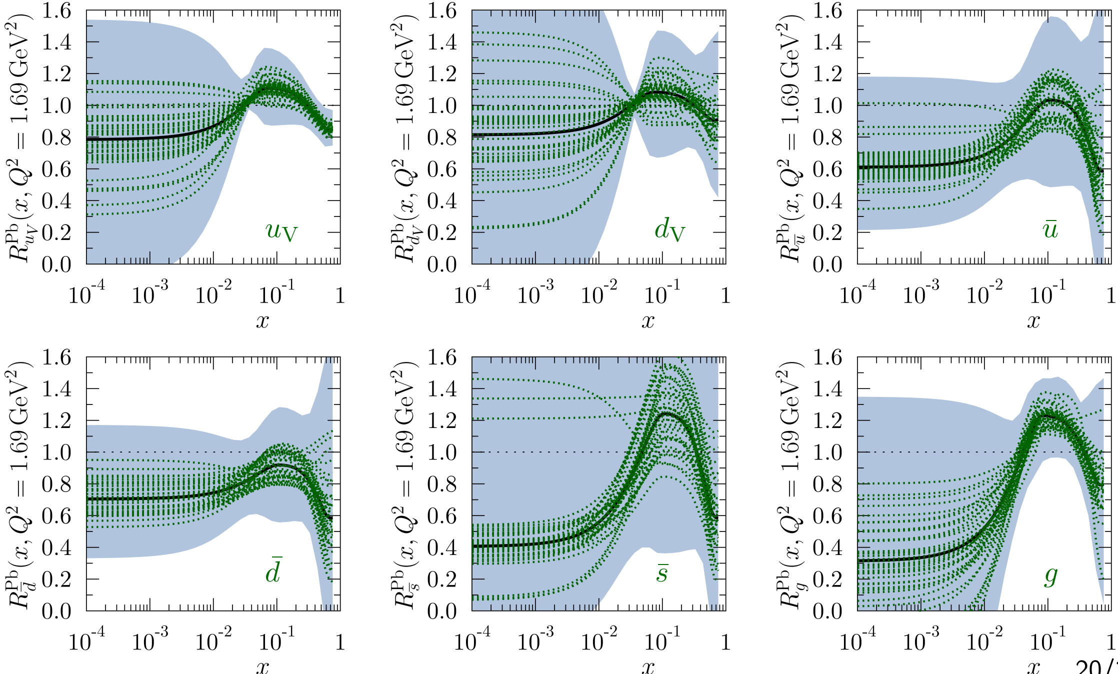
Fit with dijet data ➔ gluon EMC effect

Fit without neutrino data ➔ different $R^A_{u_V}(x, Q^2_0)$ and $R^A_{d_V}(x, Q^2_0)$

Fit with neutrino data ➔ similar $R^A_{u_V}(x, Q^2_0)$ and $R^A_{d_V}(x, Q^2_0)$

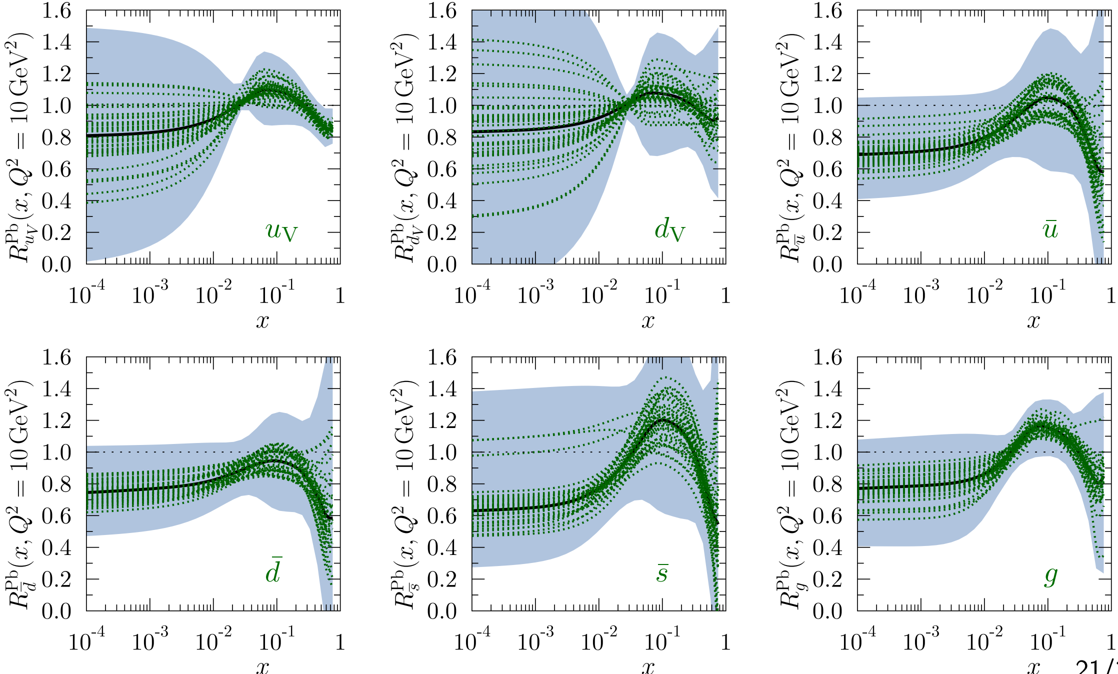
EPPS16 nuclear modifications for ^{208}Pb at $Q^2 = 1.69$ GeV^2 [EPJ C77 no.3, 163]

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



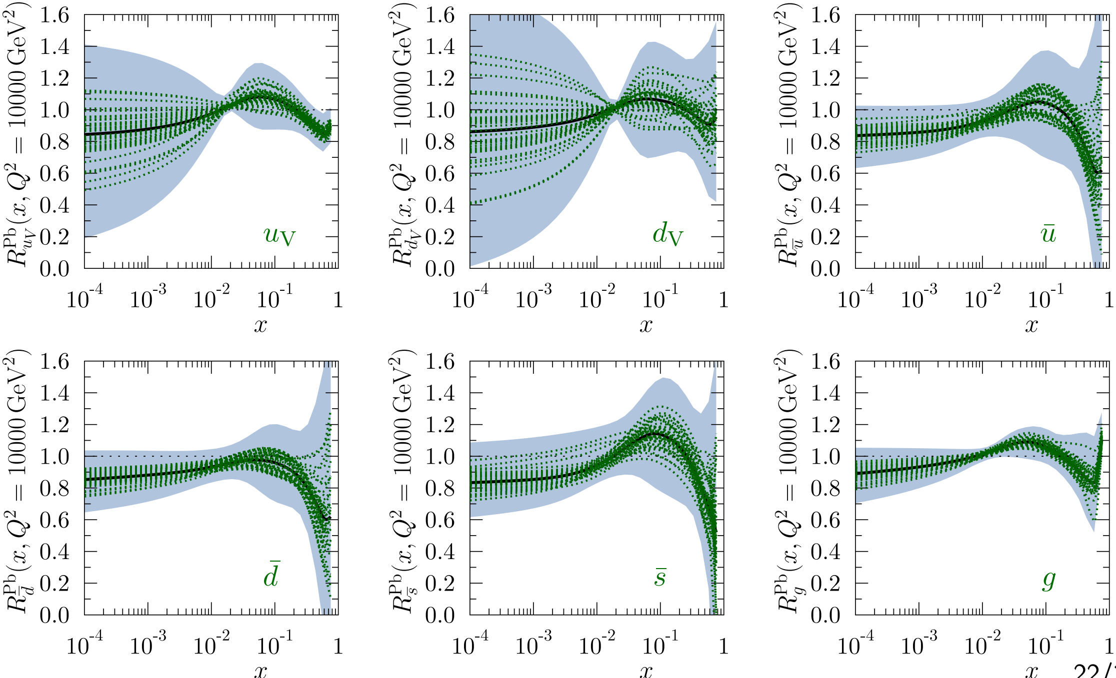
EPPS16 nuclear modifications for ^{208}Pb at $Q^2 = 10$ GeV^2 [EPJ C77 no.3, 163]

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



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

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



Why are the quark uncertainties so large?

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

$$f^A_{u_V} = \left(R^A_{u_V+d_V} - \frac{A-2Z}{A} R^A_{u_V-d_V} \right) \frac{f^p_{u_V} + f^p_{d_V}}{2}$$

$$f^A_{d_V} = \left(R^A_{u_V+d_V} + \frac{A-2Z}{A} R^A_{u_V-d_V} \right) \frac{f^p_{u_V} + f^p_{d_V}}{2}$$

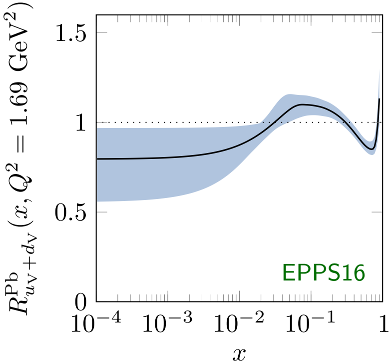
where

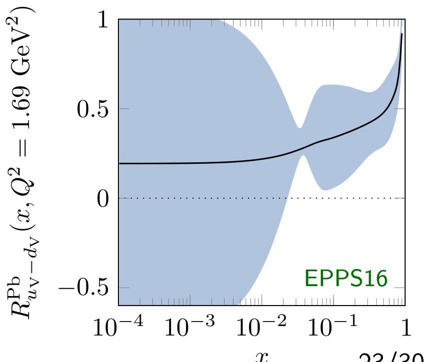
$$R^A_{u_V+d_V} = \frac{f^{p/A}_{u_V} + f^{p/A}_{d_V}}{f^p_{u_V} + f^p_{d_V}}$$

$$R^A_{u_V-d_V} = \frac{f^{p/A}_{u_V} - f^{p/A}_{d_V}}{f^p_{u_V} + f^p_{d_V}}$$

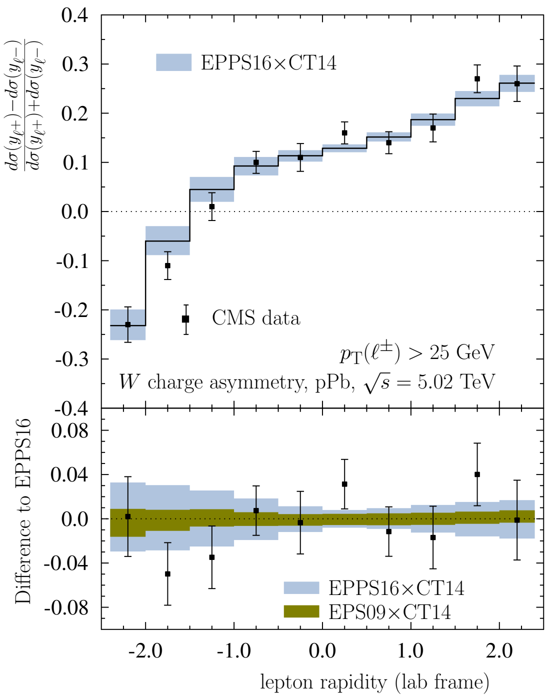
and the neutron excess $\frac{A-2Z}{A} \approx 0.2$ for Pb

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





Comparison between EPS09 and EPPS16: W asymmetry [EPJ C77 no.3, 163]



- Example of an observable where the flavour dependence plays a role
- CMS measurement suggested some deviation from EPS09 prediction in the backward direction
- This deviation is now accommodated by the larger uncertainties (flavour freedom) of EPPS16
- These data are not included in the EPPS16 analysis since they are predominantly sensitive to free proton PDFs

Comparison between EPS09, DSSZ and EPPS16

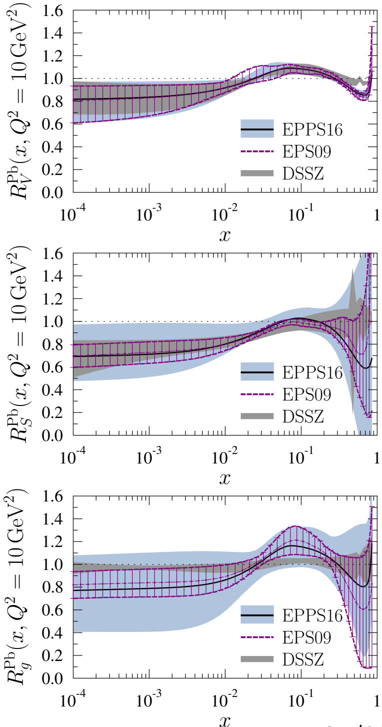
[EPJ C77 no.3, 163]

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

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

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

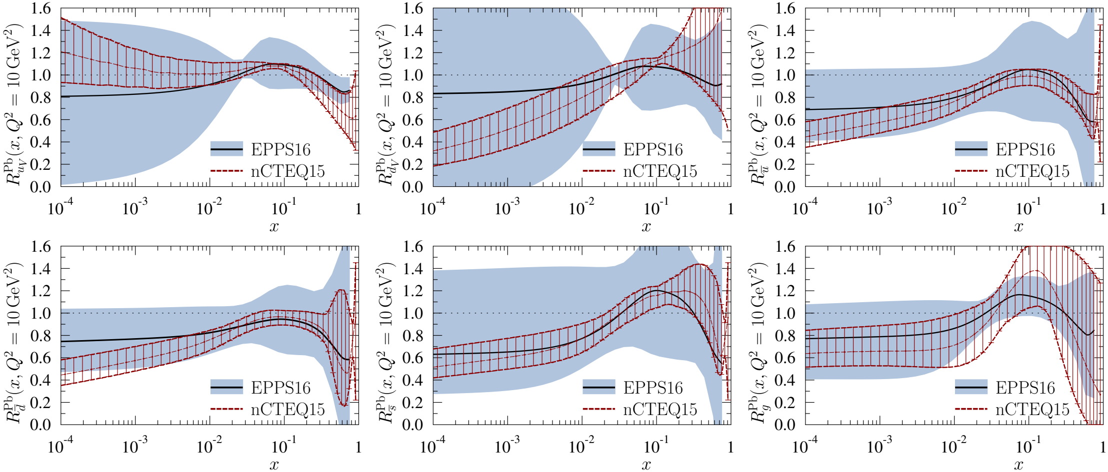
- All three appear consistent (except DSSZ large-x valence quarks)
- EPPS16 sea quark uncertainties larger due to more degrees of freedom (flavour dependence)
- EPS09 gluon uncertainties smaller due to artificial weight for PHENIX data (no gluon modifications in DSSZ due to including nuclear effects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



Comparison between nCTEQ15 and EPPS16

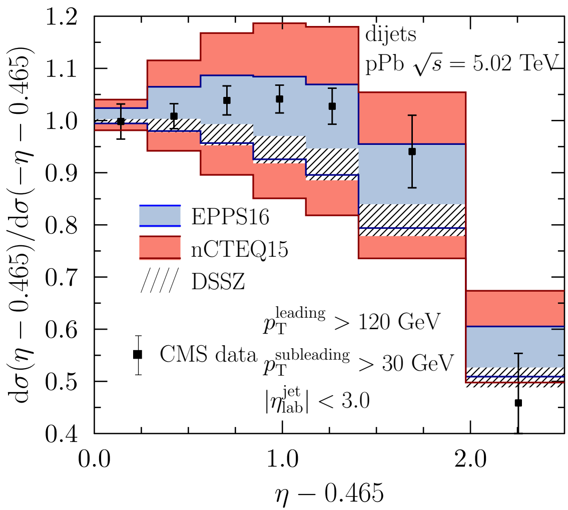
[EPJ C77 no.3, 163]

- 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
- EPPS16 error bands are typically larger but less biased

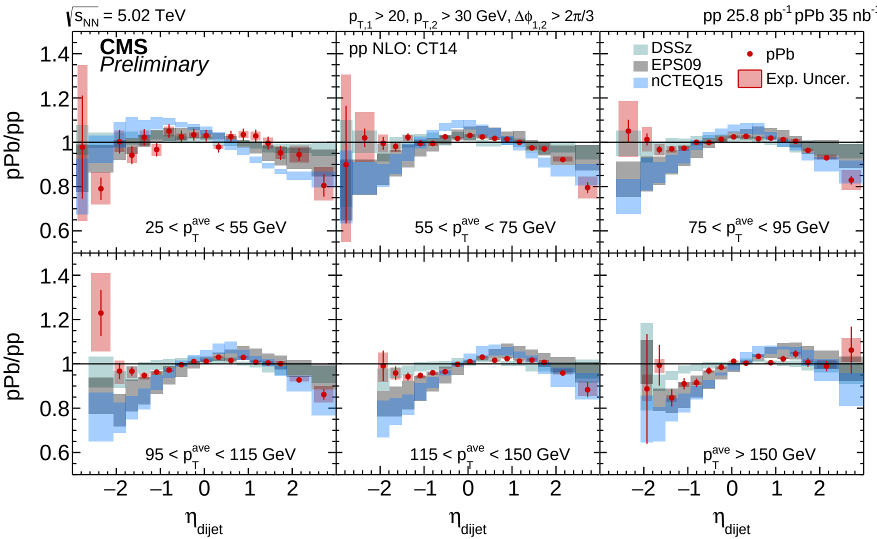
Comparison between nCTEQ15, DSSZ and EPPS16: CMS dijets



[EPJ C77 no.3, 163]

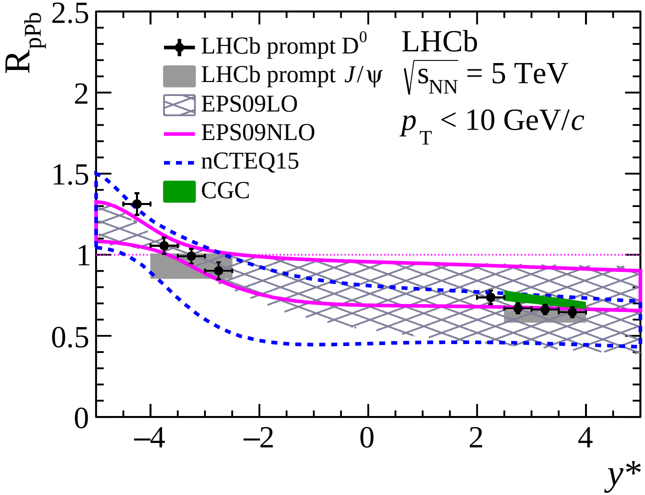
- These data were used as input in EPPS16
- nCTEQ15 has large uncertainties due to not having these data in the fit
- DSSZ + CT14 not compatible with these data

CMS dijets



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

Open heavy flavour production



- Finalized D^0 data recently published by LHCb [LHCB-PAPER-2017-015]
- PDF uncertainties significantly larger than the experimental uncertainties
- Forward rapidities sensitive to gluons at *very* small x down to $\sim 10^{-5}$

Summary

- I have given an introduction to nuclear PDFs
- Most important recent developments (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 $Q = 1.3$ GeV up to the EW scale can be achieved
  → Supports collinear factorization and universality of nPDFs
- We look forward to more high-precision data from LHC pPb (and from the future colliders)