Fitting nPDFs: strategies and results

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Exposing Novel Quark and Gluon Effects in Nuclei
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Outline

- Generalities: what? why? how? who?
- Fitting (n)PDFs is easy!
- What could possibly be different?
- Comparing nPDFs
- What's next?
- Summary
- To come…

- **What?**

Determine how partons behave in a proton/neutron bounded in a nucleus (in the collinear picture)

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- **Why?**

Because it is a **fact** of Nature that partons in nuclei do not behave as in the free proton

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Because it is a **fact** of Nature that partons in nuclei do not behave as in the free proton

- **How?**

Through global fits to the world data*

$$f_i^A(x, Q^2) = \frac{Zf_i^{p/A}(x, Q^2) + (A - Z)f_i^{n/A}(x, Q^2)}{A}$$

***results usually shown as the ratio of the nuclear to proton PDF. Other depictions may be used**

- **Who?**

  - HKM: Hirai, Kumano, Miyama, PRD64 (2001) 034003
  - nDS: de Florian, Sassot, PRD69 (2004) 074028
  - HKN: Hirai, Kumano, Nagai, PRC76 (2007) 065207
  - EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
  - DSSZ: de Florian, Sassot, Stratmann, PZ, PRD85 (2012) 074028
  - nCTEQ15: Kovarik et al., PRD93 (2016) no.8, 085037
  - EPPS16: Eskola, Paakkinen, Paukkunen, Salgado, EPJ C77 (2017) no.3, 163
  - KA15: Khanpour, Tehrani, PRD93 (2016) no.1, 014026

Fitting (n)PDFs is easy!

(1) Select the data

(2) Write the (n)PDFs at some initial scale (Q_0) in terms of free parameters

(3) Give values to the parameters

(4) Determine the distributions at the experimental scales (Q) using the DGLAP evolution equations

(5) Write the theoretical predictions using (4)

(6) Use (1)+(5) to construct a quantity that estimates the "goodness" of the description

(7) if (6) not "good enough" then

```
        goto (3)
    else
        print(*,*) "we have the best fit!"
    end if
```

(8) Determine how much one can move the parameters without spoiling (6)

(9) Take the parameters of (7)+(8) and generate grids for public use

What could possibly be different?

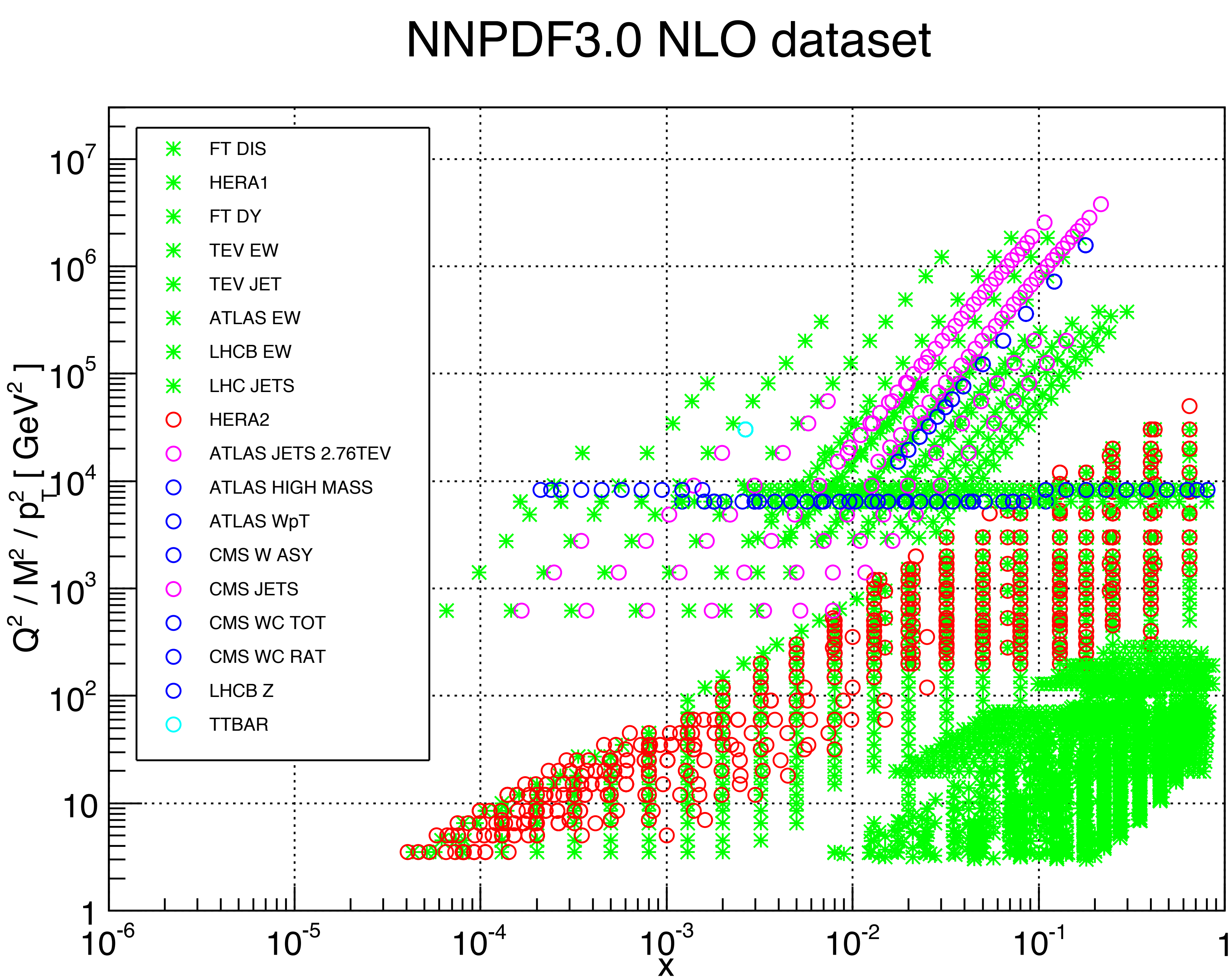
What could possibly be different?

the analyses can be affected by the **experiments**, the **theory** and the **phenomenology**

(1) the available data and how we choose it

for proton PDFs: ~3500 data points*

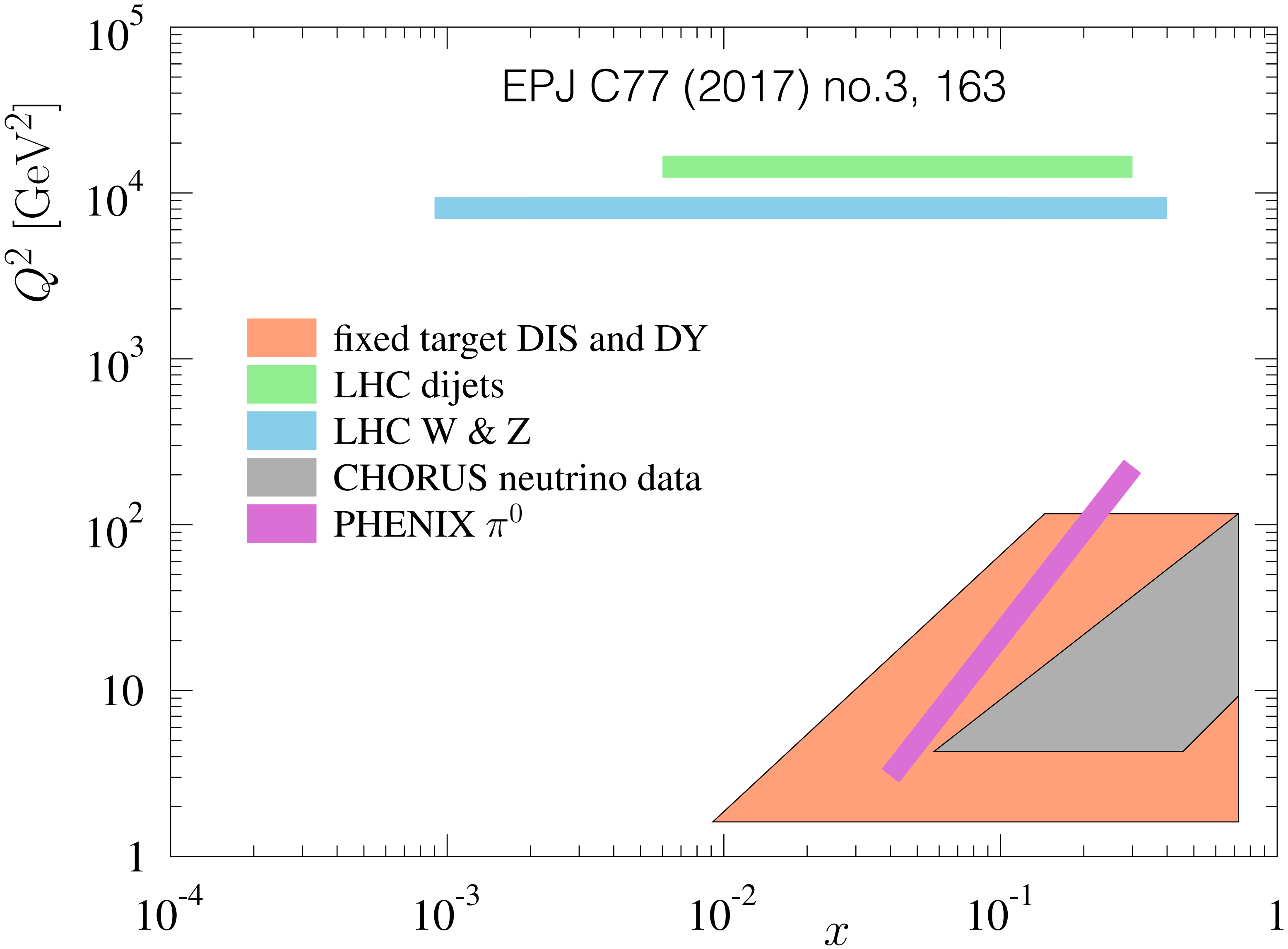
* average of all major current PDFs analyses



Ball et al., JHEP 1504 (2015) 040

e+A and p(d)+A experiments ~1400 data points*

* average of newest nPDFs analyses

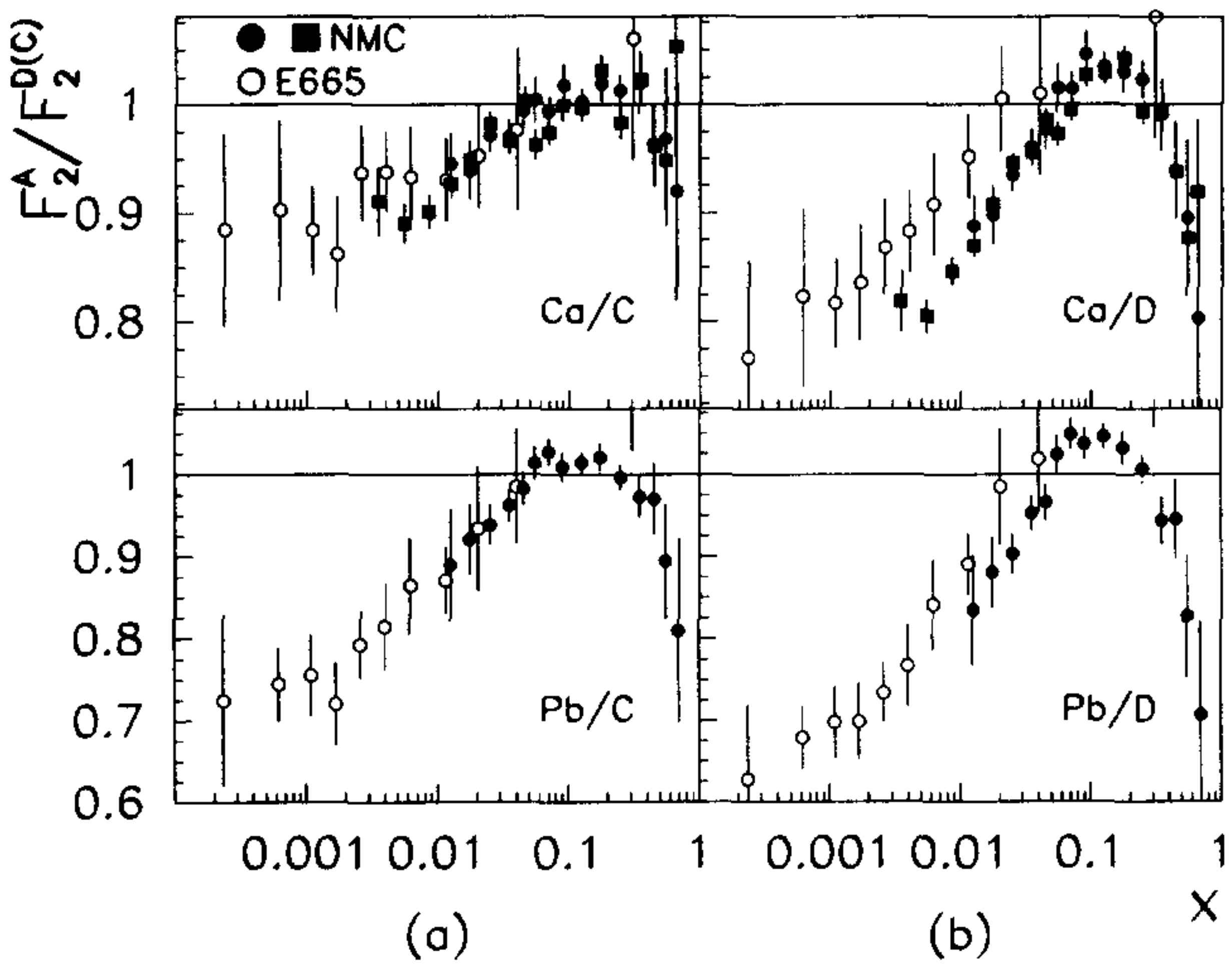


A	D	He	Li	Be	C	N	Al	Ca	Fe	Cu	Kr	Ag	Sn	Xe	W	Pt	Au	Pb
# points	82	35	93	31	148	32	34	73	141	17	26	6	151	1	33	1	39	180

- NC DIS: $\sigma^A_{red}/\sigma^D_{red}$, F^A_2/F^D_2, $f(F^A_L/F^A_2)$

$$\sigma_{red} = F_2 - \frac{y^2}{1+(1-y)^2}F_L$$

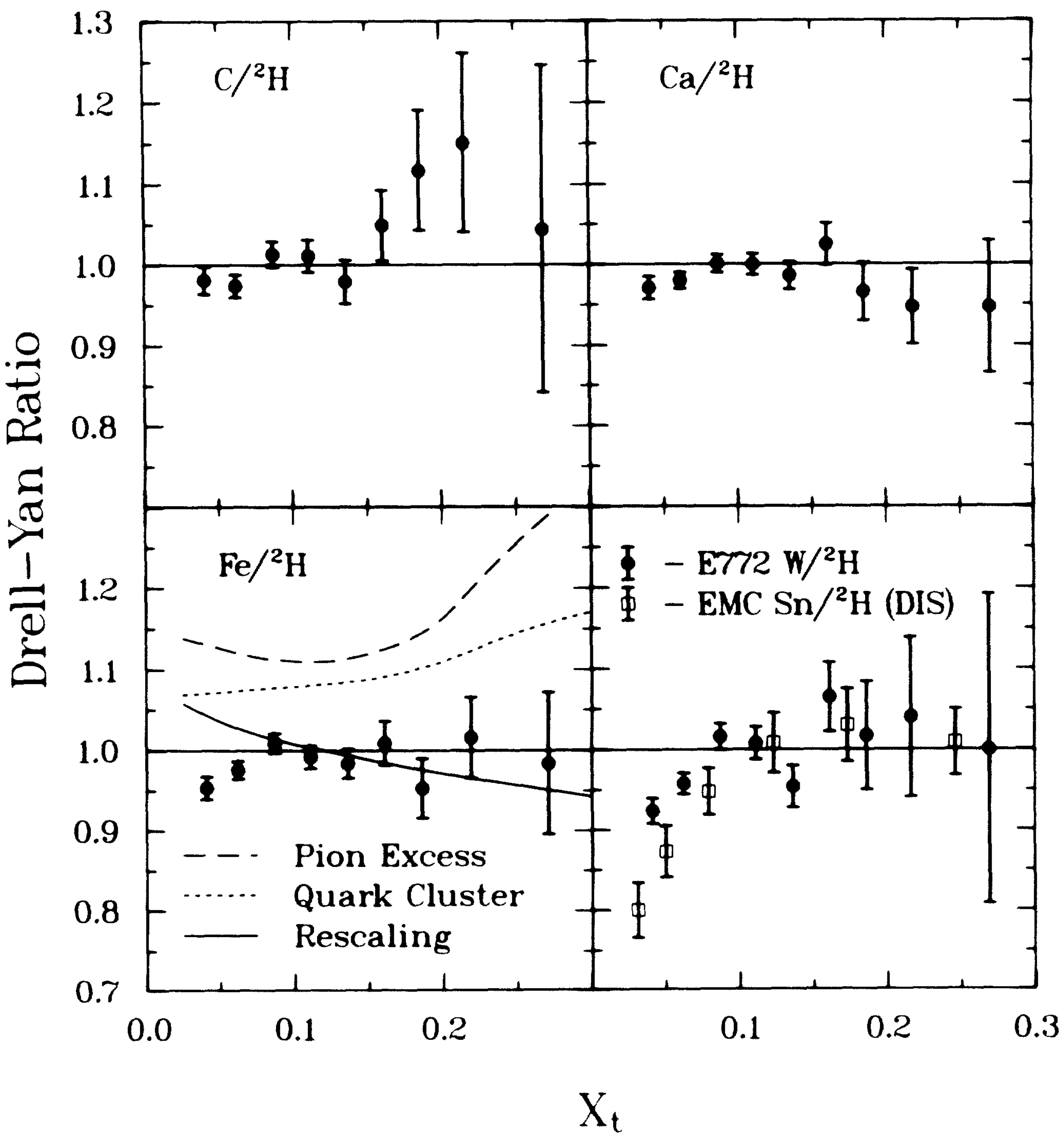
New Muon Collaboration, Nucl.Phys. B481 (1996) 3



- ✦ information lost when taking ratios
- ✦ little sensitivity to gluons
- ✦ F_2 and F_L determination based on parameterizations of their ratio
- ✦ non-isoscalarity corrections

- Drell-Yan

D.M. Alde, et al., Phys.Rev.Lett. 64 (1990) 2479

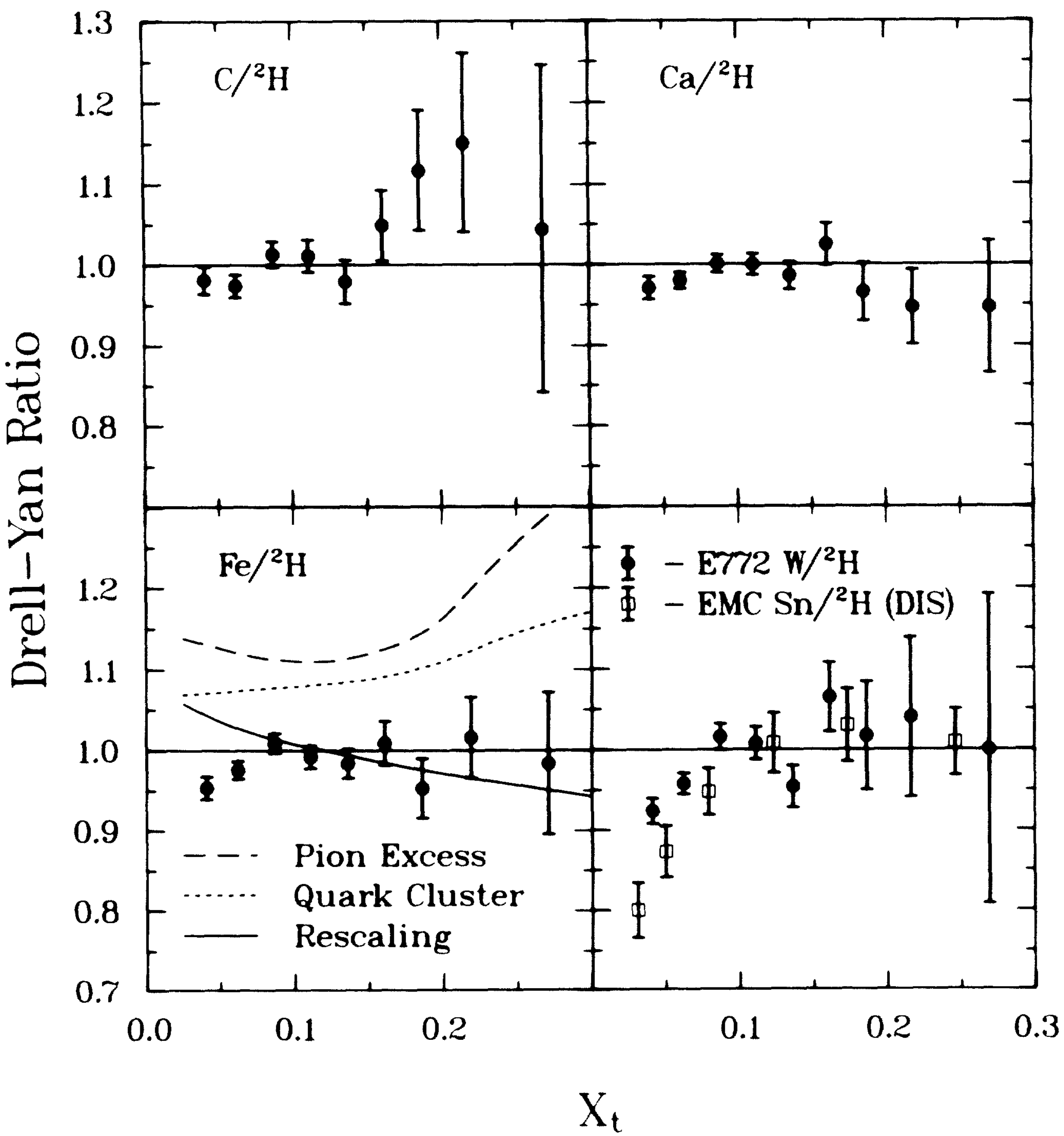


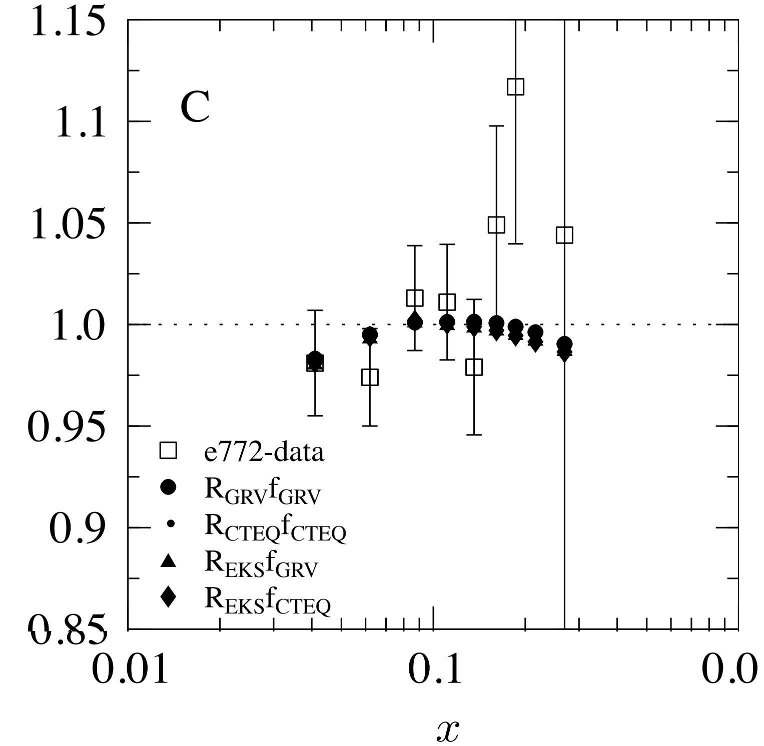
- ✦ some constraint on the sea
- ✦ LO/NLO very similar

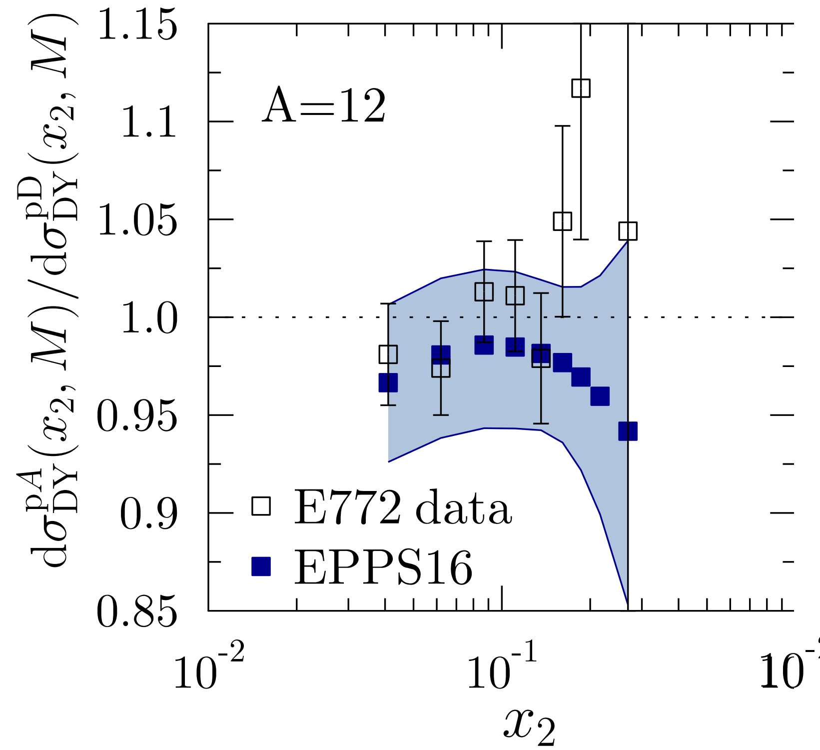
LO: Eskola, Kolhinen, Salgado, Eur.Phys.J. C9 (1999)

- Drell-Yan

D.M. Alde, et al., Phys.Rev.Lett. 64 (1990) 2479





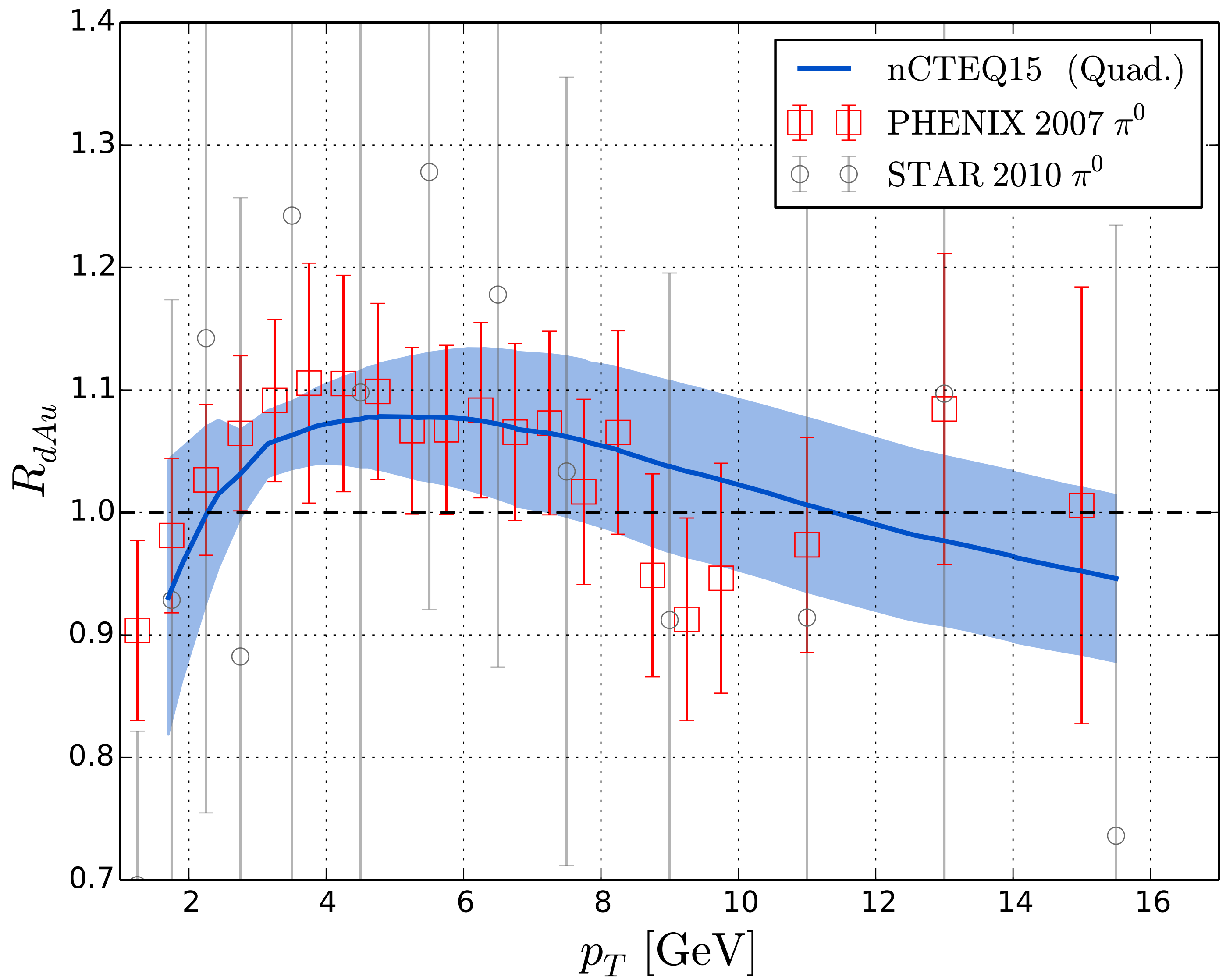


NLO: EPJ C77 (2017) no.3, 163

- ✦ some constraint on the sea
- ✦ LO/NLO very similar

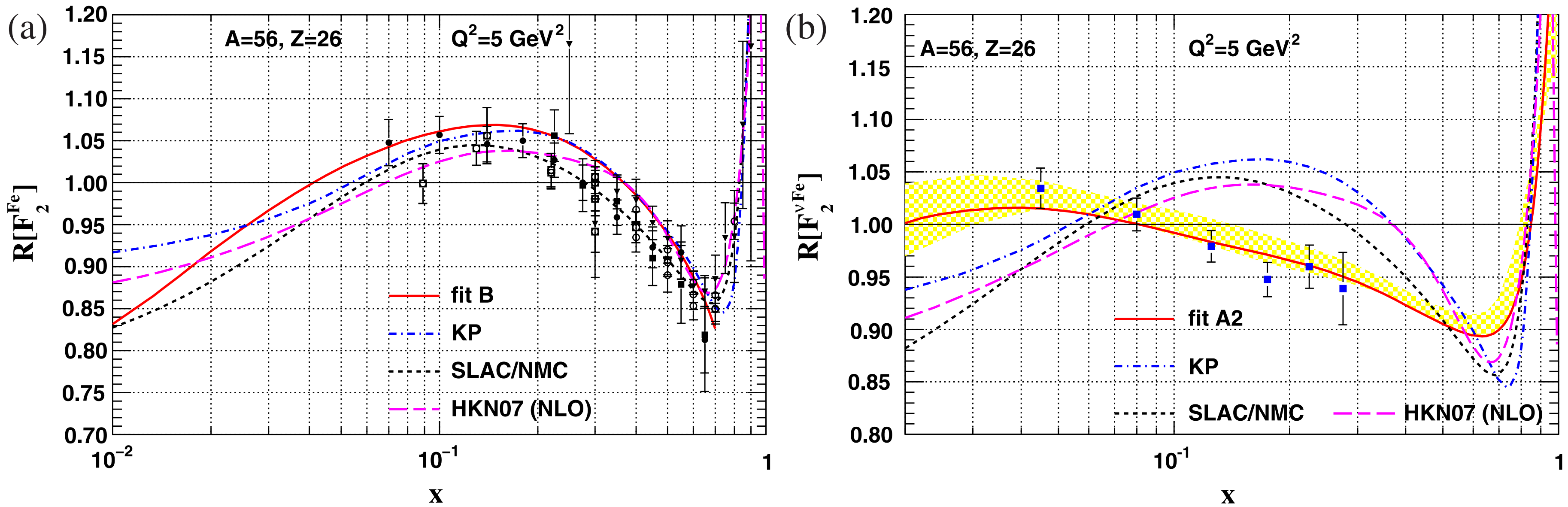
- Hadron production in dAu

PRD93 (2016) no.8, 085037



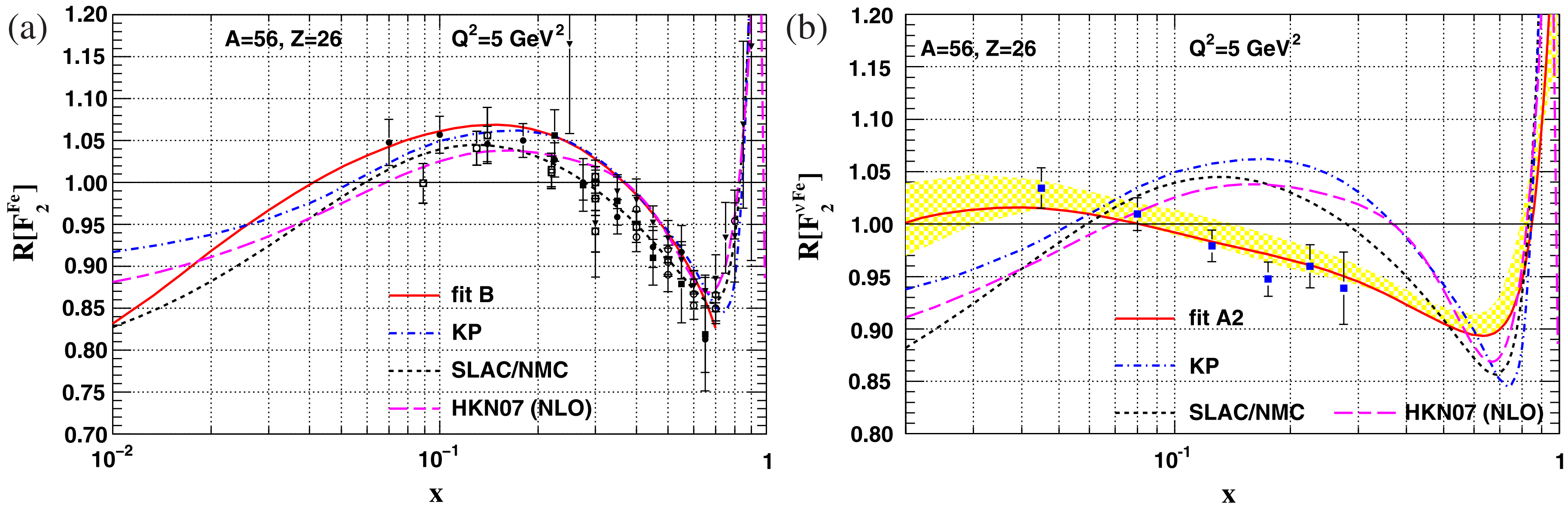
- sensitive to the gluon density
- big uncertainties
- final state effects?

- CC DIS



- ✦ no proton reference
- ✦ normalization uncertainties
- ✦ tensions between data sets

- CC DIS



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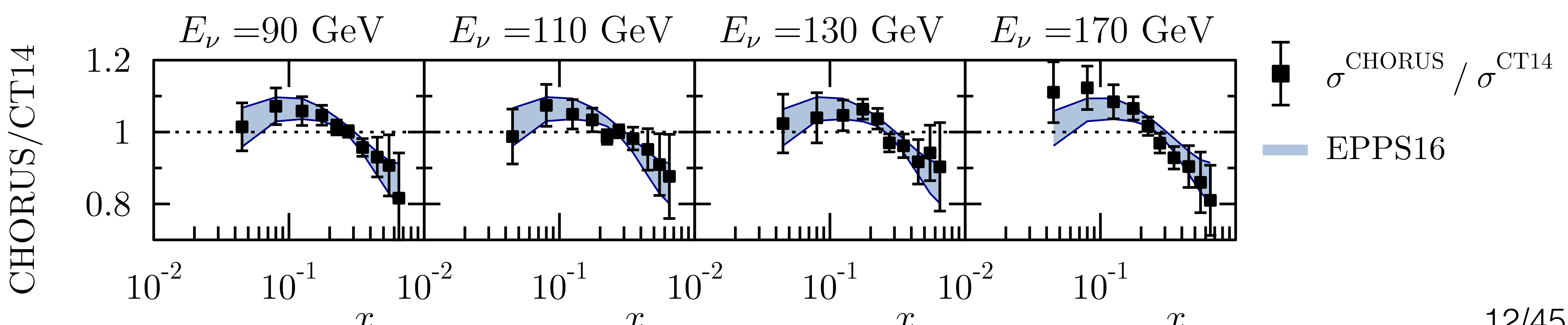
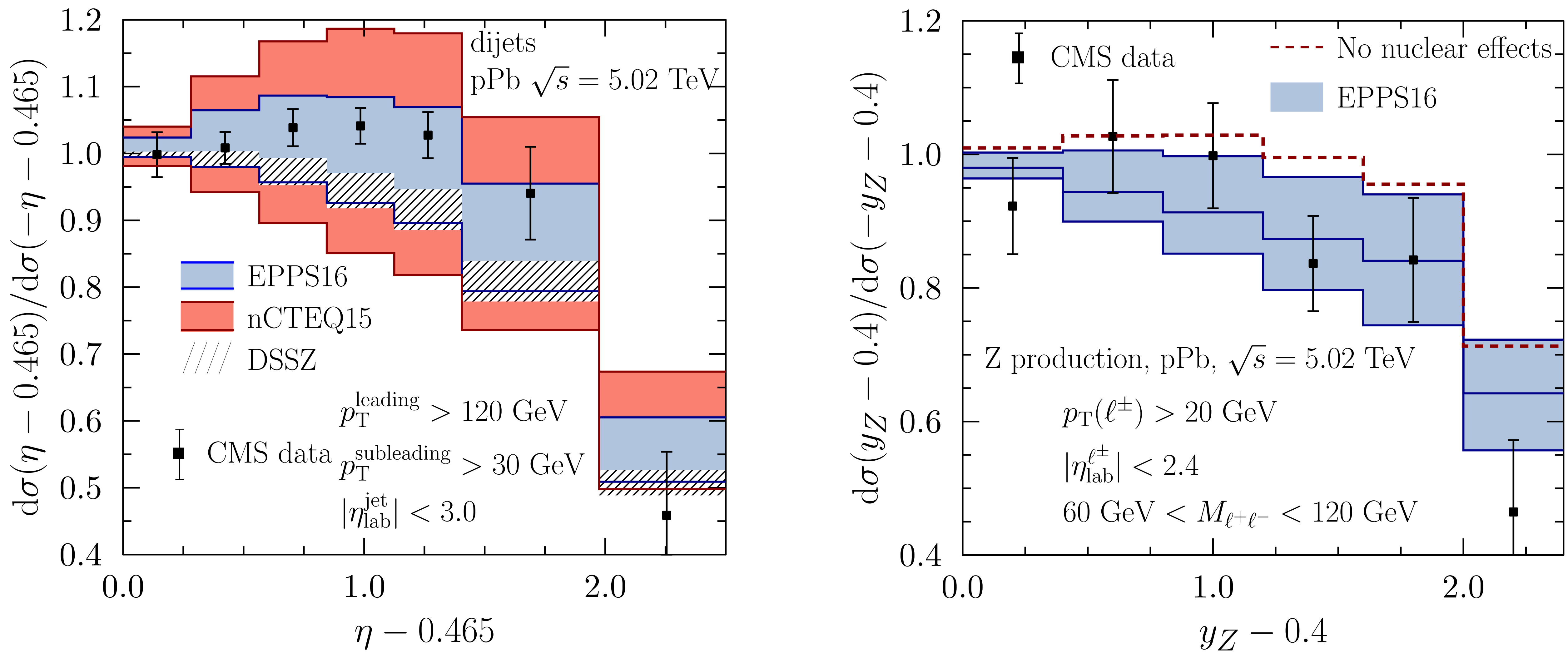


- LHC (new!): di-jets and EW bosons

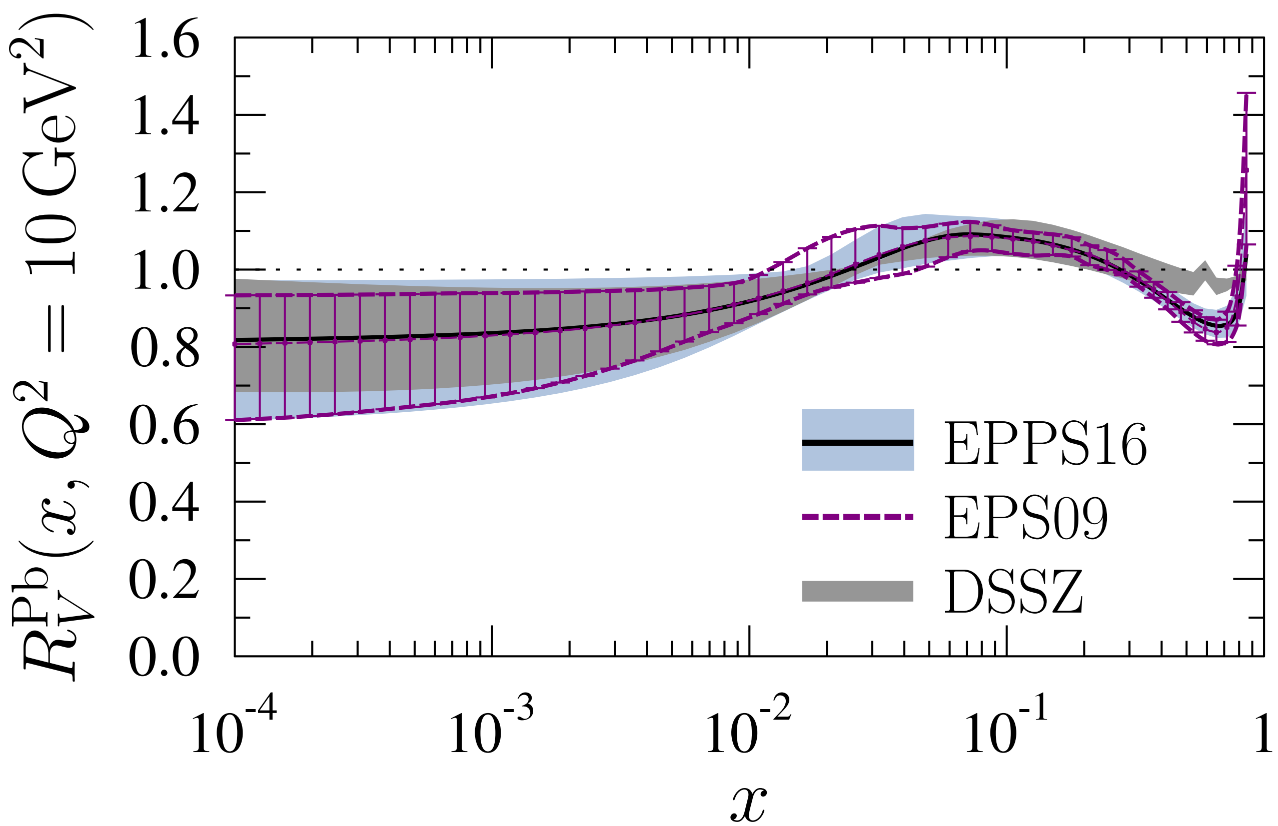


EPJ C77 (2017) no.3, 163

- little impact from EW bosons due to the high Q^2
- gluon sensitive at high x (di-jets)

We get to pick!

- ratios, structure functions, cross-sections?
- DIS, DY, jets, hadrons
- kinematical cuts
- remove or not the corrections for non-isoscalarity



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(2) the parameterization

- choose a proton PDF as reference and (try to!) be consistent
    - ✦ select Q_0 accordingly (see(4))
    - ✦ treat the heavy quarks accordingly
    - ✦ kinematical cuts not always accordingly

(2) the parameterization

- choose a proton PDF as reference and (try to!) be consistent
    - ✦ select Q_0 accordingly (see(4))
    - ✦ treat the heavy quarks accordingly
    - ✦ kinematical cuts not always accordingly

- **somehow** include the nuclear dependence (limit for A=1?)

✦ $$f_{i/A}\left(x, Q_0^2\right) \equiv f_{i/p}\left(x, Q_0^2\right) R_i^A\left(x, Q_0^2\right)$$ HKM, HKN, EPS09, EPPS16, DSSZ, KA15

✦ $$f_{i/A}\left(x, Q_0^2\right) \equiv \int_x^A \frac{dy}{y} W_i^A\left(y, Q_0^2\right) f_i^p\left(\frac{x}{y}, Q_0^2\right)$$ nDS

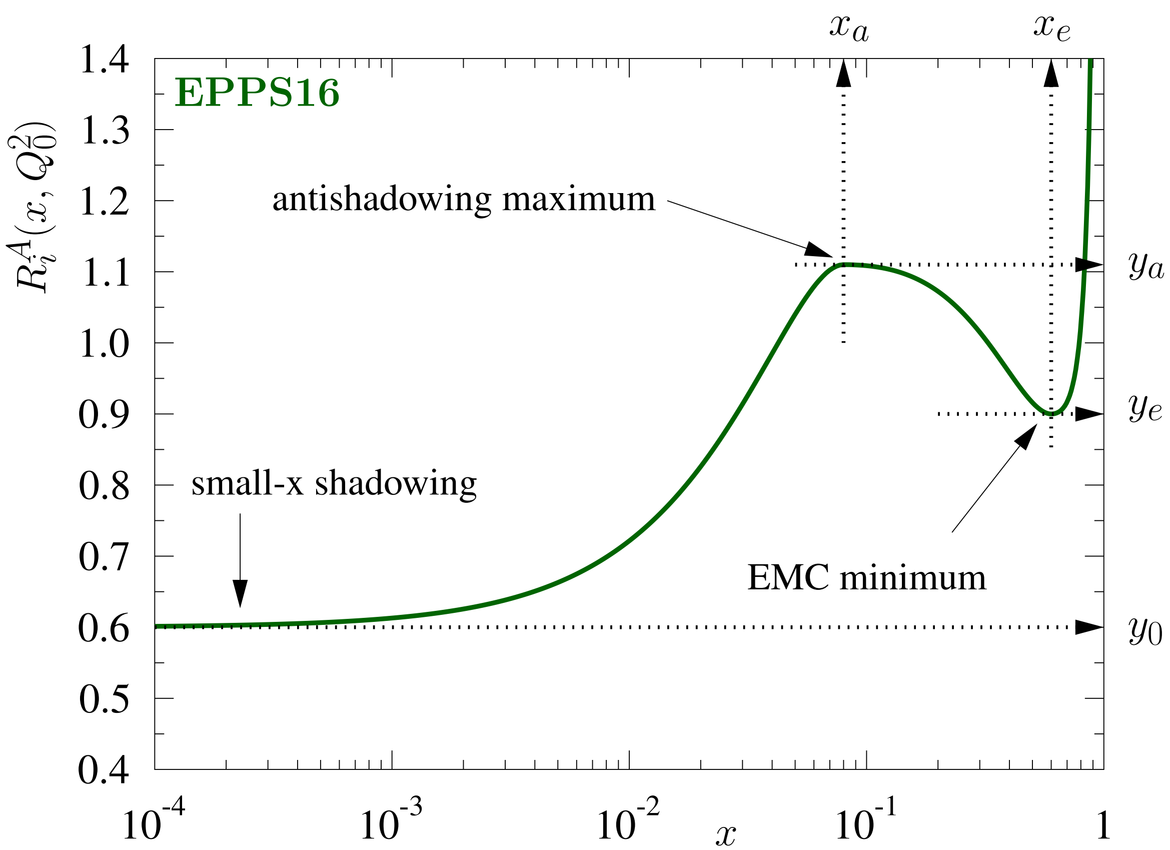
✦ directly parameterize the nPDF nCTEQ15

What could possibly be different?: the parameterization

$$f_{i/A}\left(x, Q_0^2\right) \equiv f_{i/p}\left(x, Q_0^2\right) R_i^A\left(x, Q_0^2\right)$$

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

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



EPS09	EPPS16
$R_{valence}$	R_{u_v}, R_{d_v}
R_{sea}	$R_{\bar{u}}$, $R_{\bar{d}}$, R_s
R_{gluon}	R_{gluon}

What could possibly be different?: the parameterization

$$f_{i/A}\left(x, Q_0^2\right) \equiv f_{i/p}\left(x, Q_0^2\right) R_i^A\left(x, Q_0^2\right)$$

HKM, HKN, DSSZ, KA15

$$R_i^{HKM}(x, A, Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_i(A, Z) + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

$i = u_v, d_v, \bar{q}, g$

* $$R_i^{HKN}(x, A, Z) = 1 + \left(1 - \frac{1}{A^{\alpha}}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

* also for KA15

$$R_v^{DSSZ}(x, Q_0^2) = \varepsilon_1 x^{\alpha_a} (1-x)^{\beta_1} \left[1 + \varepsilon_2 (1-x)^{\beta_2}\right] \left[1 + a_v (1-x)^{\beta_3}\right]$$

$$R_i^{DSSZ}(x, Q_0^2) = R_v^{DSSZ}(x, Q_0^2) \frac{\varepsilon_i}{\varepsilon_1} \frac{1 + a_i x^{\alpha_i}}{1 + a_i}$$

$i = sea, g$

nDS

$$f_{i/A}\left(x, Q_0^2\right) \equiv \int_x^A \frac{dy}{y} W_i^A\left(y, Q_0^2\right) f_i^p\left(\frac{x}{y}, Q_0^2\right)$$

allows to study the $1 < x < A$ region

$$W_v(y, A, Z) = A[a_v \delta(1-\varepsilon_v - y) + (1-a_v)\delta(1-\varepsilon_{v'} - y)]$$
$$+ n_v\left(\frac{y}{A}\right)^{\alpha_v}\left(1-\frac{y}{A}\right)^{\beta_v} + n_s\left(\frac{y}{A}\right)^{\alpha_s}\left(1-\frac{y}{A}\right)^{\beta_s}$$

$$W_i(y, A, Z) = A\delta(1-y) + \frac{a_i}{N_i}\left(\frac{y}{A}\right)^{\alpha_s}\left(1-\frac{y}{A}\right)^{\beta_s} \qquad i = \text{sea, gluon}$$

nCTEQ15

direct parameterization of the nPDF

$$xf_{i/A}\left(x, Q_0^2\right) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$

$$\frac{\bar{d}(x, Q_0^2)}{\bar{u}(x, Q_0^2)} = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

recovers the free proton case for A=1

(4) scale evolution using DGLAP

$$\frac{d\, q^{NS}(x,Q^2)}{d\ln(Q^2)} = \frac{\alpha_s(Q^2)}{4\pi}\int_x^1 \frac{dy}{y} P_{qq}(y)\, q^{NS}\left(\frac{x}{y},Q^2\right)$$

$$\frac{d\, q^{S}(x,Q^2)}{d\ln(Q^2)} = \frac{\alpha_s(Q^2)}{4\pi}\int_x^1 \frac{dy}{y} \left[P_{qq}(y)\, q^{S}\left(\frac{x}{y},Q^2\right) + P_{qg}(y)\, g\left(\frac{x}{y},Q^2\right)\right]$$

$$\frac{d\, g(x,Q^2)}{d\ln(Q^2)} = \frac{\alpha_s(Q^2)}{4\pi}\int_x^1 \frac{dy}{y} \left[P_{gq}(y)\, q^{S}\left(\frac{x}{y},Q^2\right) + P_{gg}(y)\, g\left(\frac{x}{y},Q^2\right)\right]$$

- No exact solution, numerical strategies implemented
- N_F dependent, so one must be careful with heavy quarks
- Initial scale to be chosen

(5) theoretical predictions

- choose perturbative order: LO, NLO, NNLO, …
- understand clearly what it means in terms of the coupling constant
- how do we treat the heavy-quarks?
  - FFNS
  - ZM-VFNS
  - GM-VFNS: TR', ACOT, SACOT, FONLL, …?
- nuclear effects in the deuteron?
- final state effects for hadrons?

(6) χ^2

$$\chi^2(\mathbf{a}) = \sum_{i,j} \left[T_i(\mathbf{a}) - E_i\right] C_{i,j}^{-1} \left[T_j(\mathbf{a}) - E_j\right]$$

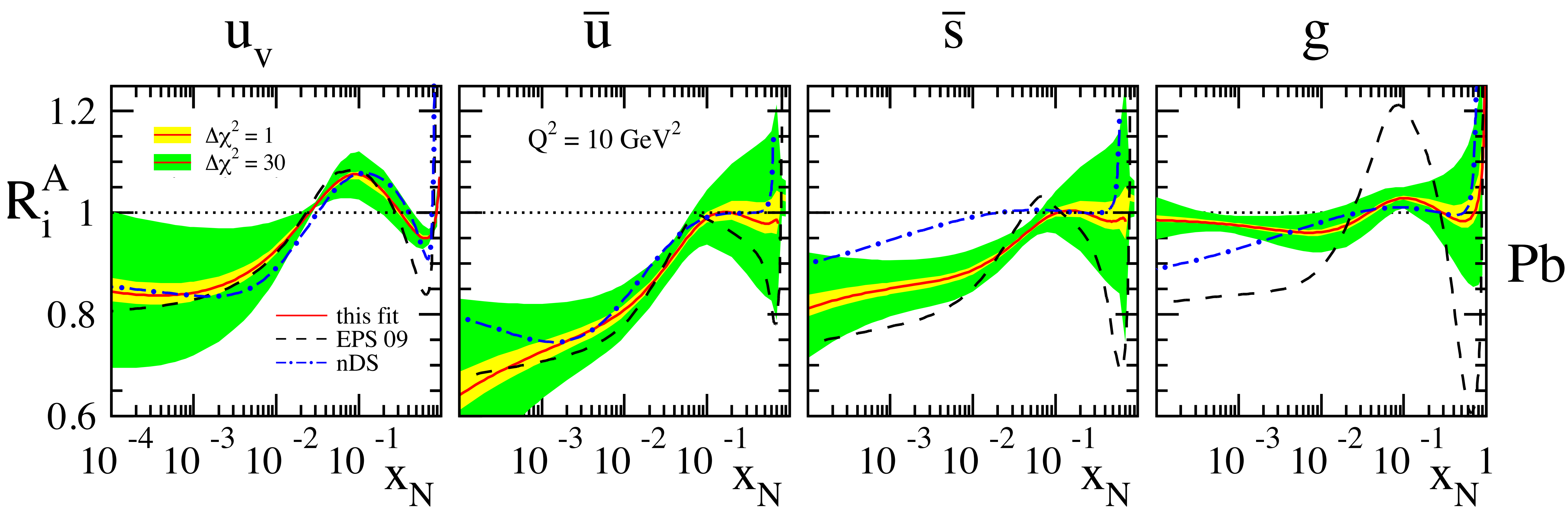
- $\mathbf{a}$: parameters
- $T_i(\mathbf{a})$: theoretical value of datapoint “i”
- E_i : experimental value of datapoint “i”
- $C_{i,j}$: **covariance matrix**

if not know ↓

$$\chi^2(\mathbf{a}) = \sum_{i} \left[\frac{T_i(\mathbf{a}) - f_N E_i}{\delta_i^{\text{uncorr.}}}\right]^2 + \left(\frac{1 - f_N}{\delta^{\text{norm}}}\right)^2$$

(7) the fit

- average number of parameters: ~ 20
- multiple local minima, very hard to find the absolute minimum
- little sensitivity of data sets to certain nPDFs
- Give relevance to some data sets using weights in the χ^2



PRD85 (2012) 074028

(8) the hessian uncertainties

We begin by expanding the around the global minimum

$$\chi^2(\mathbf{a}) \approx \chi_0^2 + \sum_{i,j} \delta a_i H_{ij} \delta a_j$$

$\delta a_i \equiv a_j - a_j^0$ deviation from best fit value of the parameter

More information in:
- J. Pumplin, D. Stump, and W. Tung, Phys.Rev. D65 (2001) 014011.
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Diagonalize the Hessian matrix: $D_{kj} \equiv \sqrt{\varepsilon_k} v_j^{(k)}$

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Diagonalize the Hessian matrix: $D_{kj} \equiv \sqrt{\varepsilon_k} v_j^{(k)}$

Define new parameters: $z_k \equiv \sum_j D_{kj} \delta a_j$

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$$\chi^2(\mathbf{a}) \approx \chi_0^2 + \sum_i z_i^2$$

Then for any PDF dependent quantity the uncertainty can be obtained by

$$\Delta\mathcal{O} = \sqrt{\sum_i (\Delta z_i)^2 \left(\frac{\partial\mathcal{O}}{\partial z_i}\right)^2} \qquad \Delta z_i = \frac{t_i^+ + t_i^-}{2}$$

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Defining the PDFs error sets $S_i^\pm$

$$z(S_i^\pm) = \pm t_i^\pm(0, \ldots, i, \ldots 0) \qquad i = 1, \ldots, N_{param}$$

$$\Delta\mathcal{O} = \frac{1}{2}\sqrt{\sum_i \left[\mathcal{O}(S_i^+) - \mathcal{O}(S_i^-)\right]^2}$$

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we get a choice!

Defining the PDFs error sets $S_i^{\pm}$

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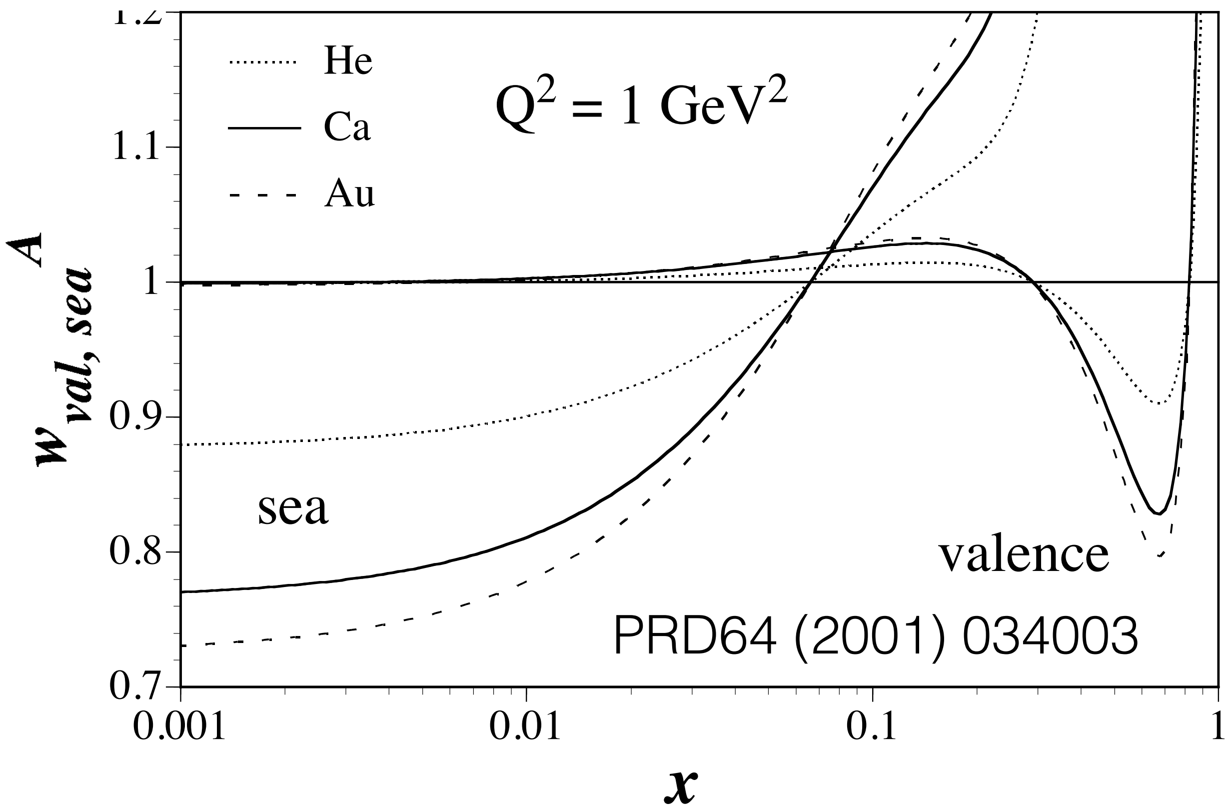
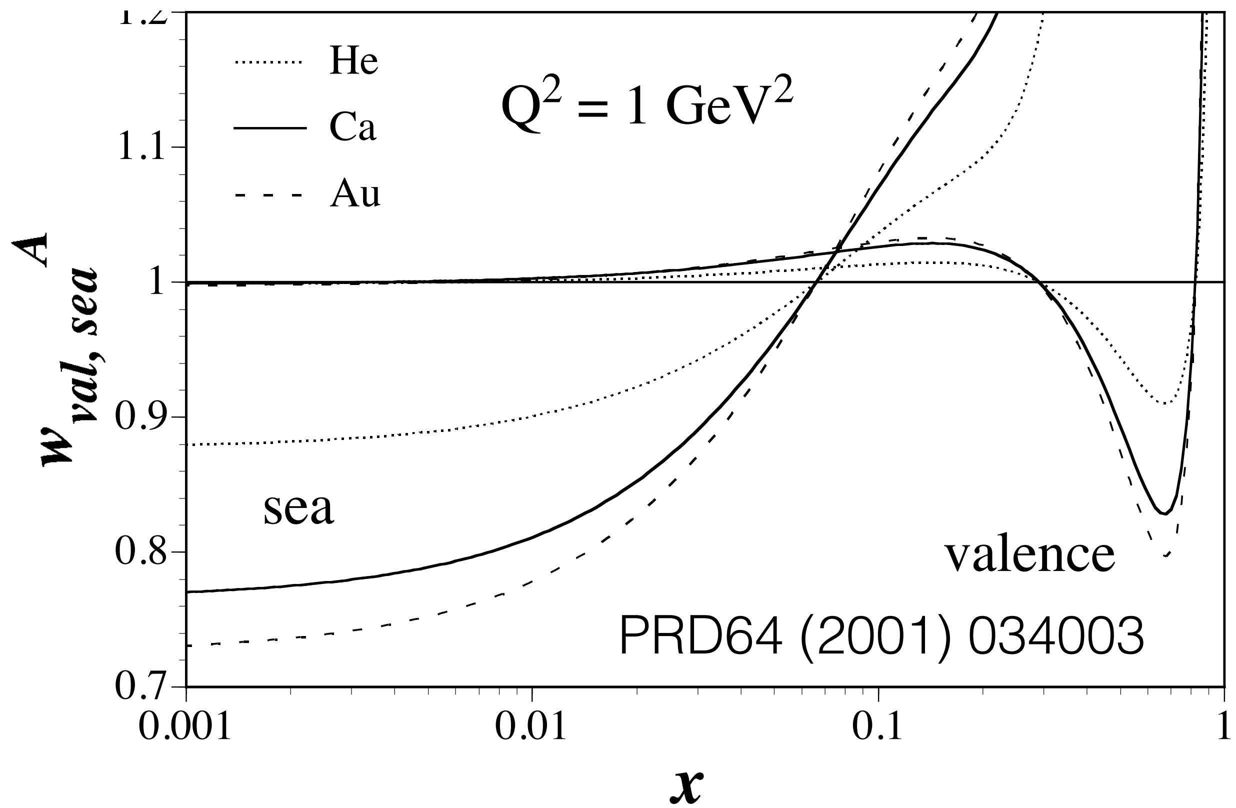
Comparing nuclear PDFs

SET		HKM	nDS	HKN	EPS09	DSSZ	nCTEQ15	KA15	EPPS16
data type	e-DIS	yes	yes	yes	yes	yes	yes	yes	yes
	D-Y	no	yes	yes	yes	yes	yes	yes	yes
	pions	no	no	no	yes	yes	yes	no	yes
	ν-DIS	no	no	no	no	yes	no	no	yes
	EW	no	no	no	no	no	no	no	yes
	jets	no	no	no	no	no	no	no	yes
# data points		309	420	1241	929	1579	740	1479	1811
χ^2		565	300	1486	731	1545	587	1696	1789
Q_0^2(GeV^2)		1	0.4	1	1.69	1	1.69	2	1.69
accuracy		LO	NLO	NLO	NLO	NLO	NLO	NNLO	NLO
proton PDF		MRST2001	GRV	MRST98	CTEQ6.1M	MSTW2008	CTEQ6.1	JR09	CT14NLO
deuteron		no/yes	no	yes	no	no	yes/no	?	no
flavour separation?		valence	no	no	no	no	valence	no	yes

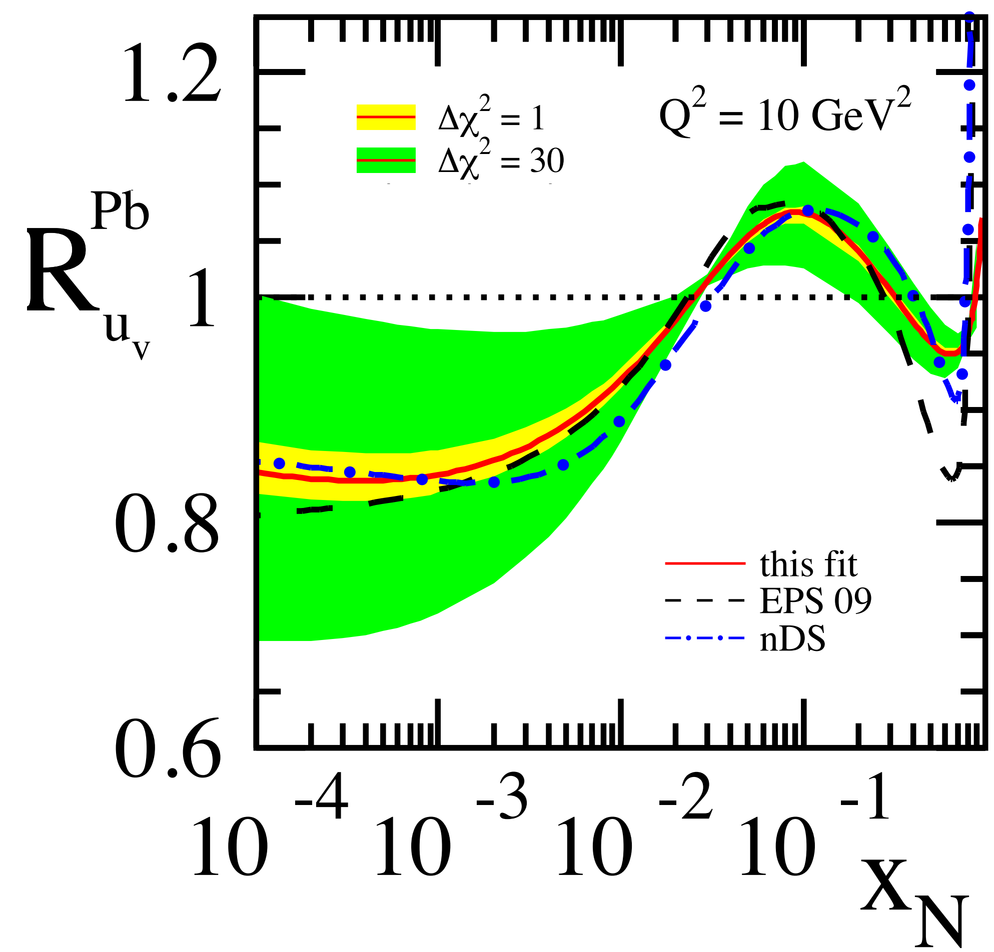


He
Ca
Au
$Q^2 = 1$ GeV^2
$w_{val, sea}^A$
sea
valence
PRD64 (2001) 034003
0.7
0.8
0.9
1
1.1
1.2
0.001
0.01
0.1
1
x

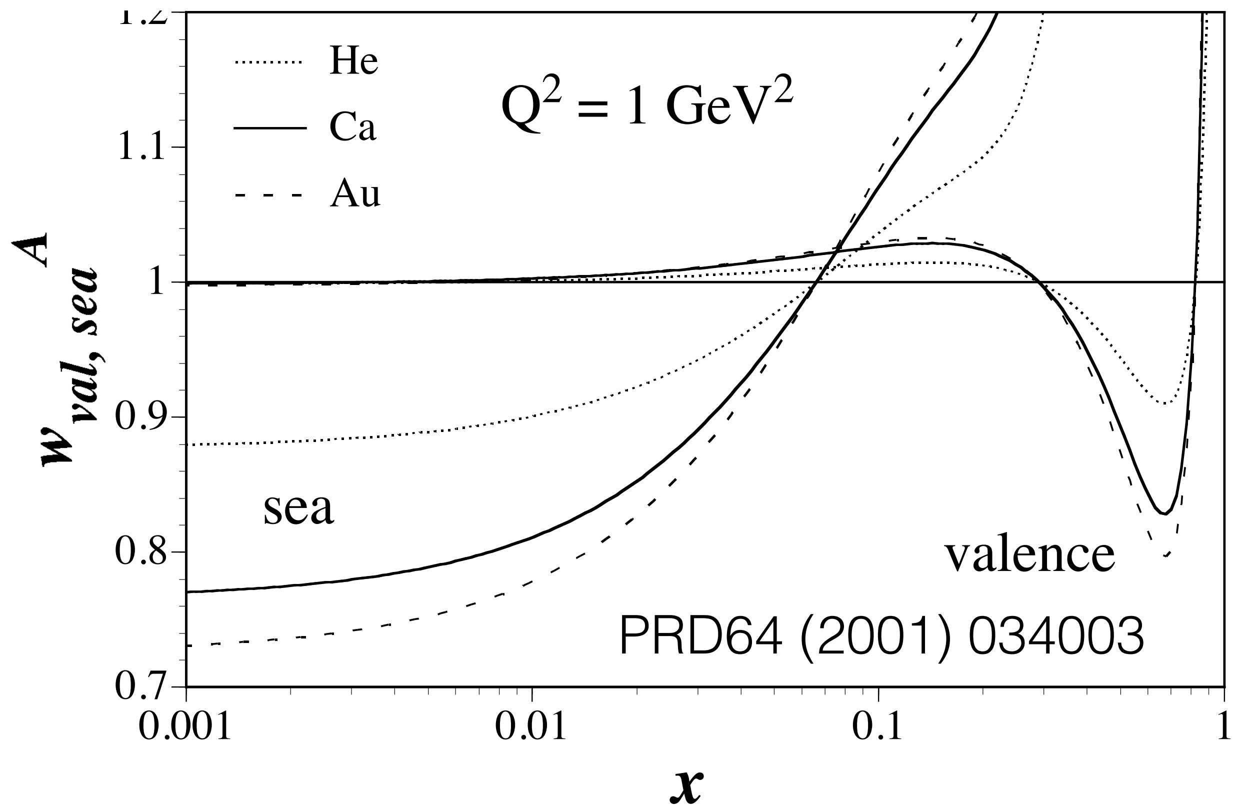
Comparing nPDFs: the valence



PRD85 (2012) 074028



Comparing nPDFs: the valence



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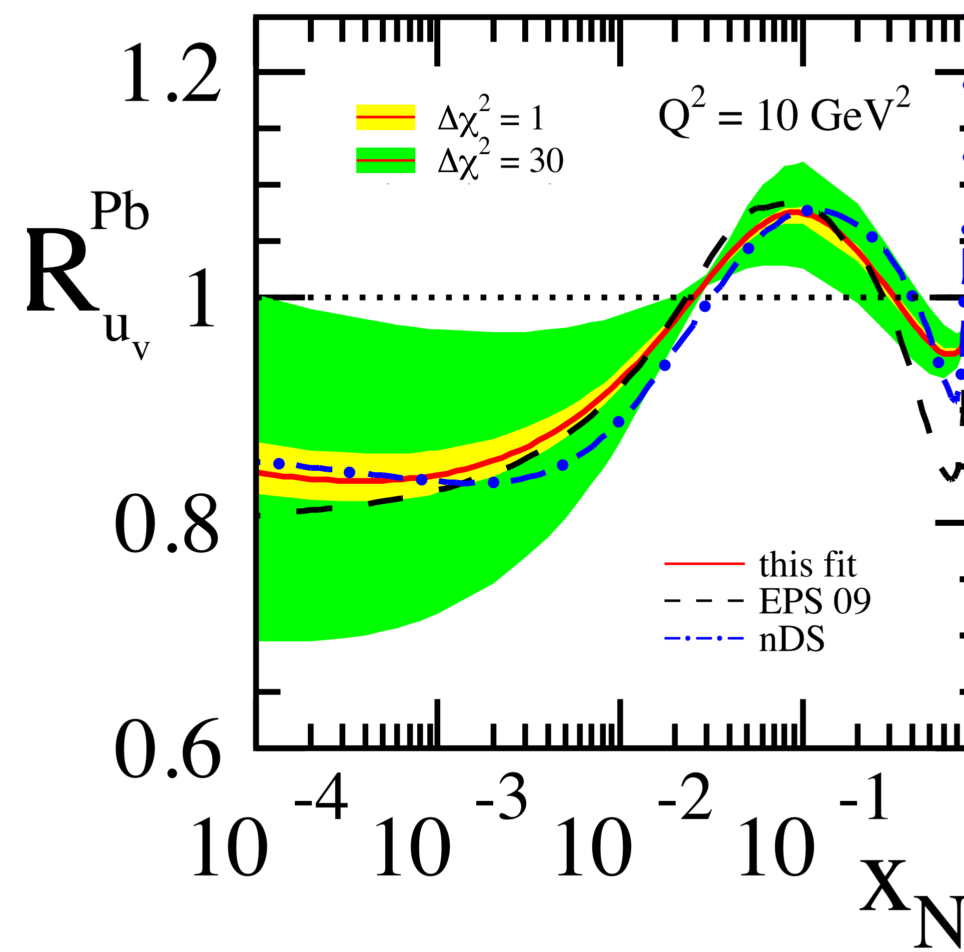
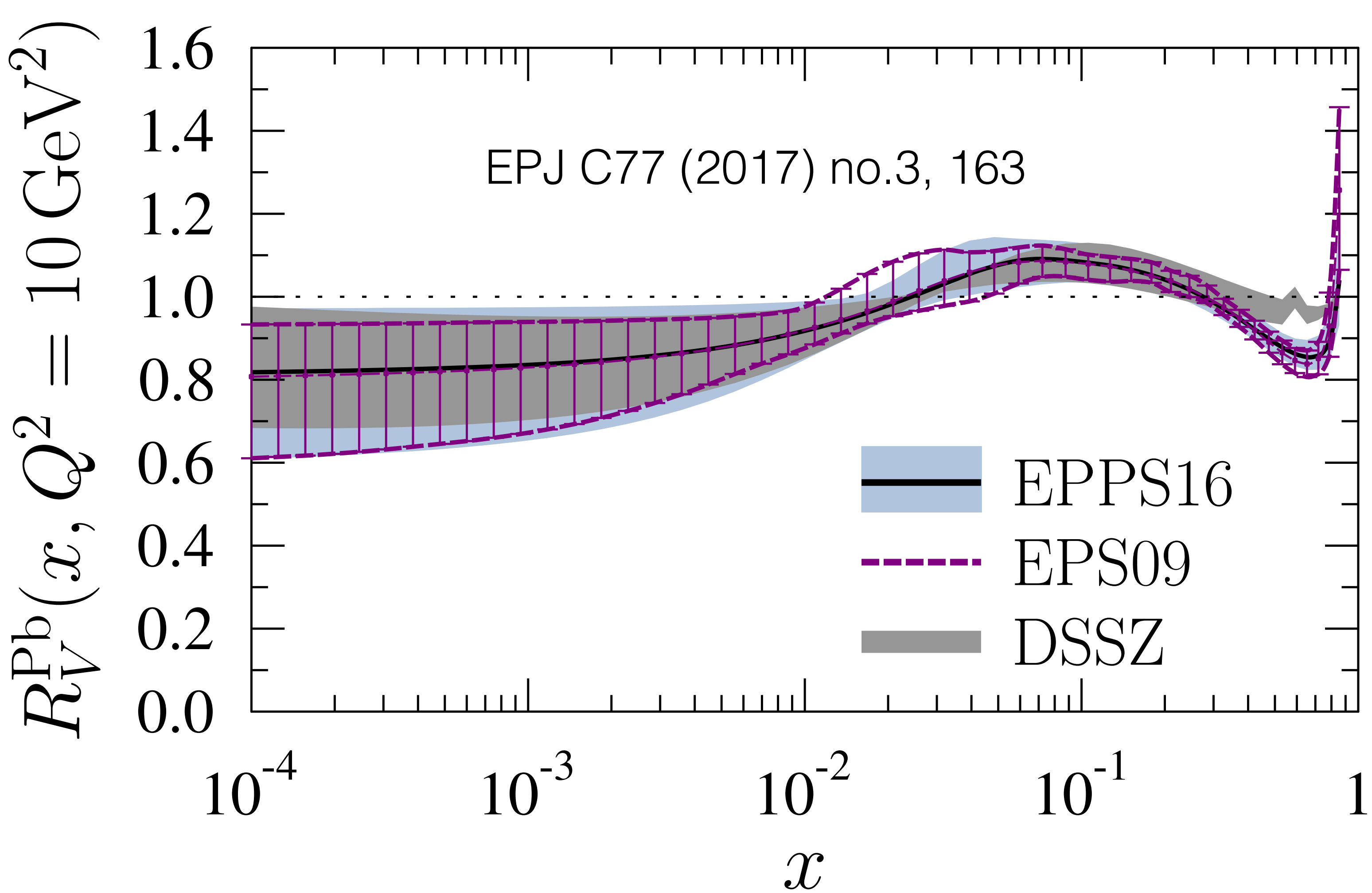
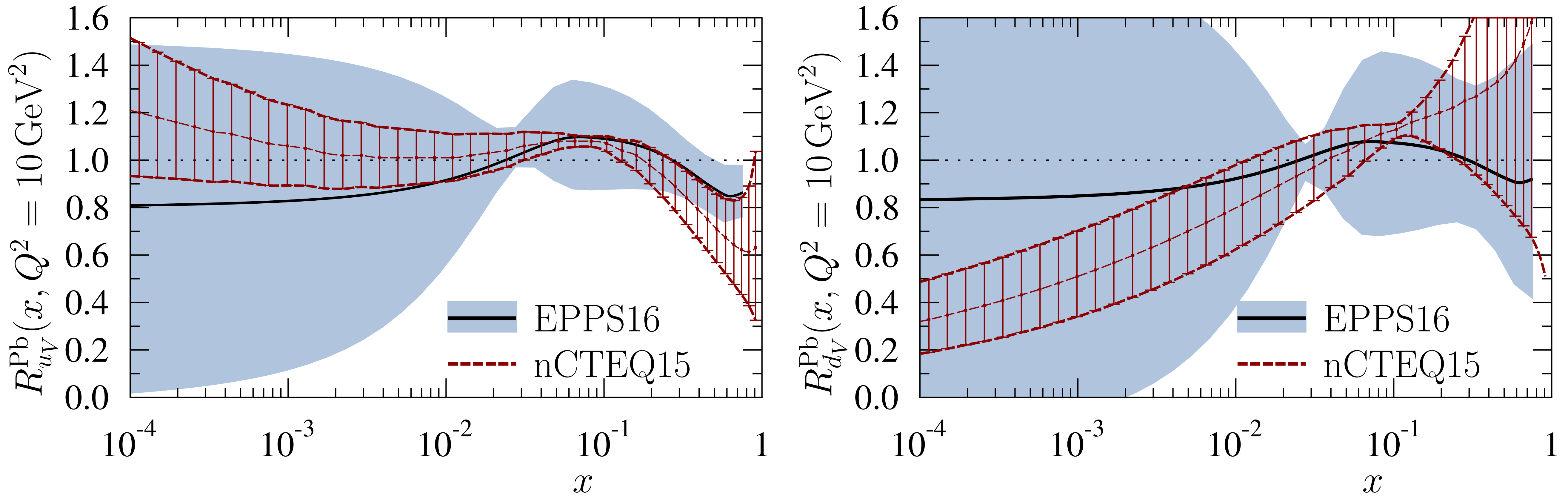




EPJ C77 (2017) no.3, 163

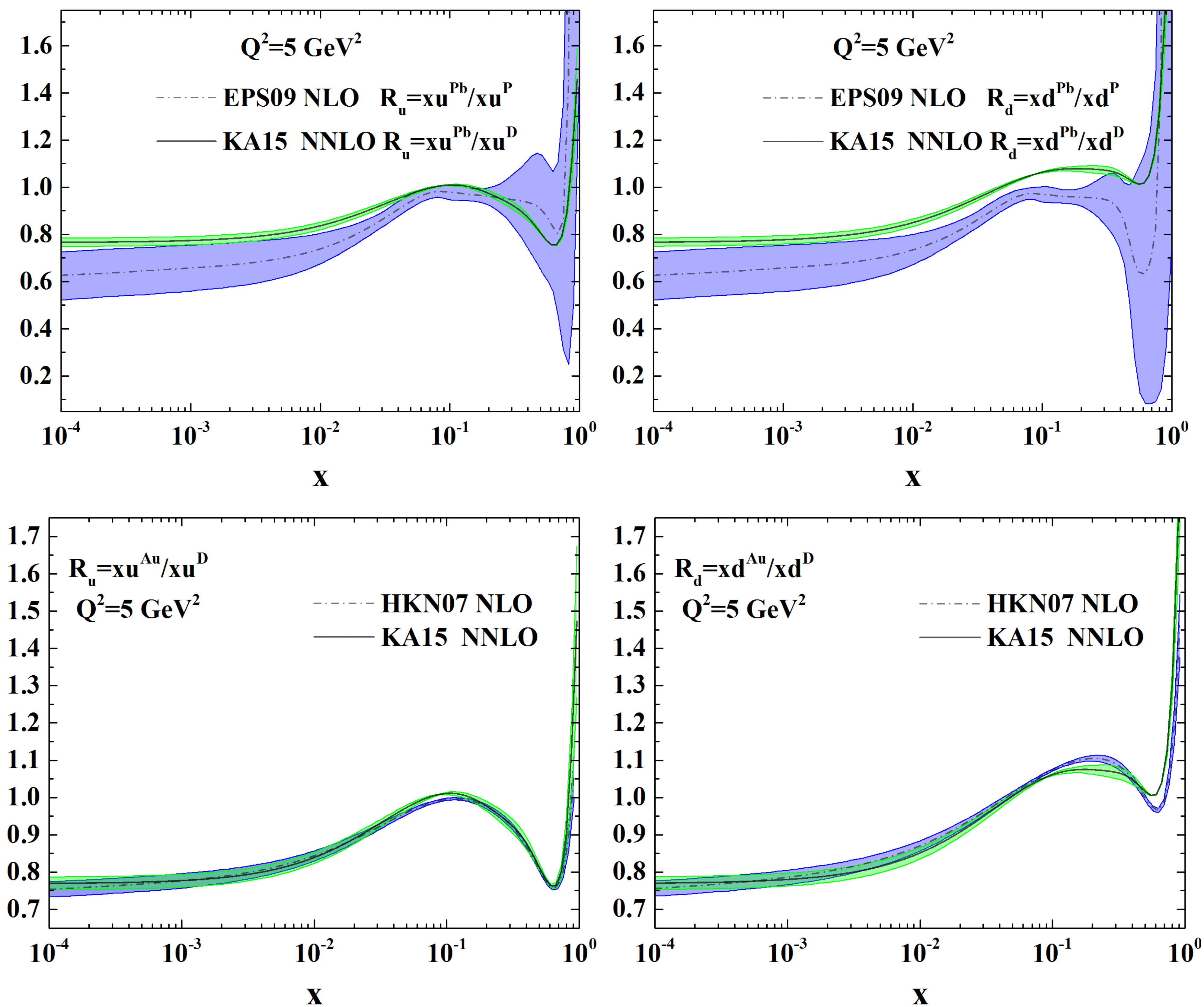


proton

nucleus

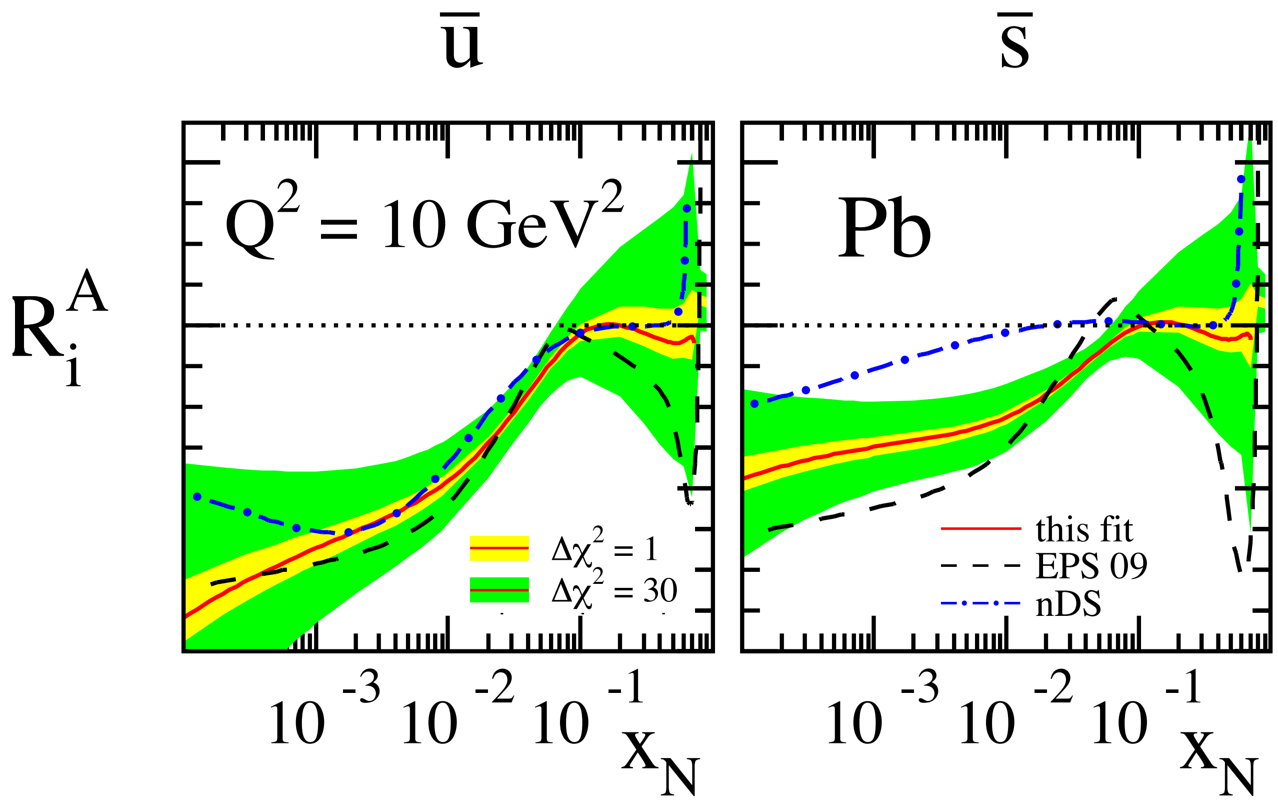
$$\frac{4}{9}u + \frac{1}{9}d \longrightarrow \left(\frac{A+3Z}{9A}\right)u + \left(\frac{4A-3Z}{9A}\right)d$$

Comparing nPDFs: the valence



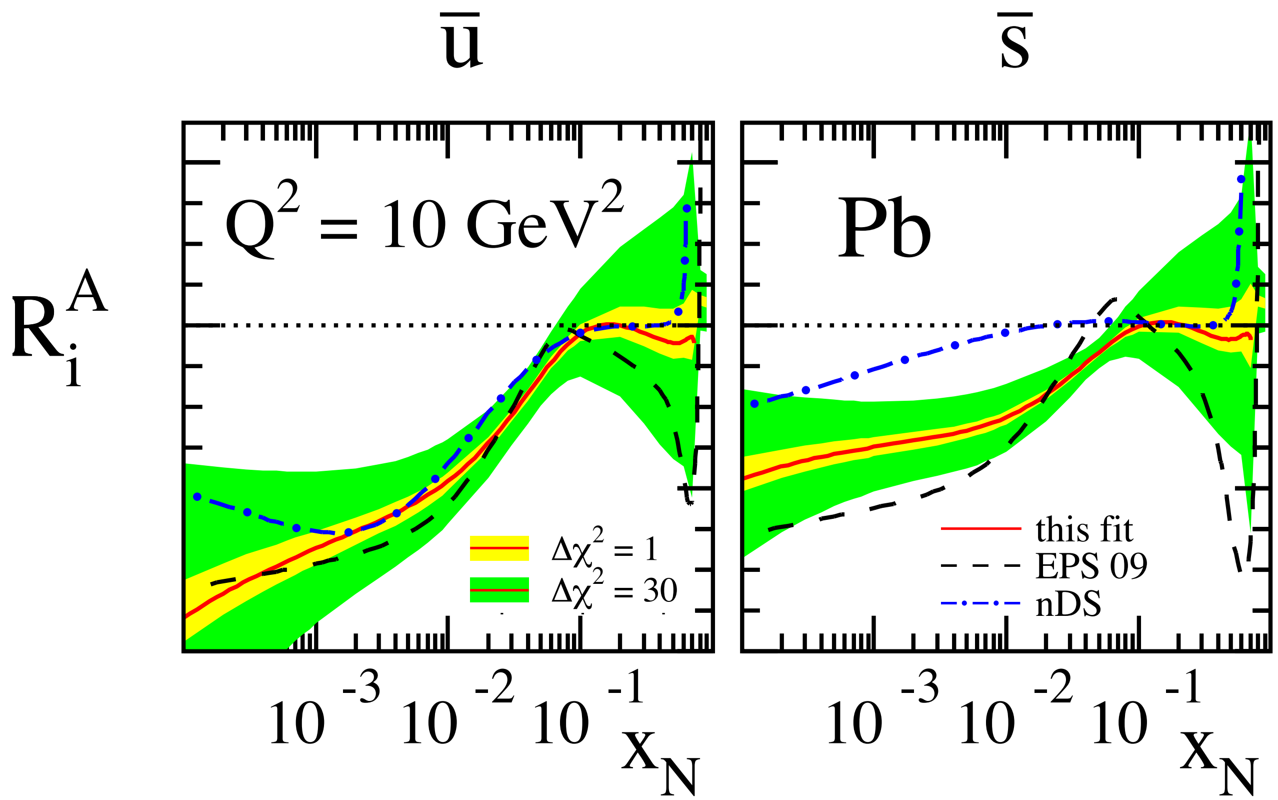
PRD93 (2016) no.1, 014026

Comparing nPDFs: the sea

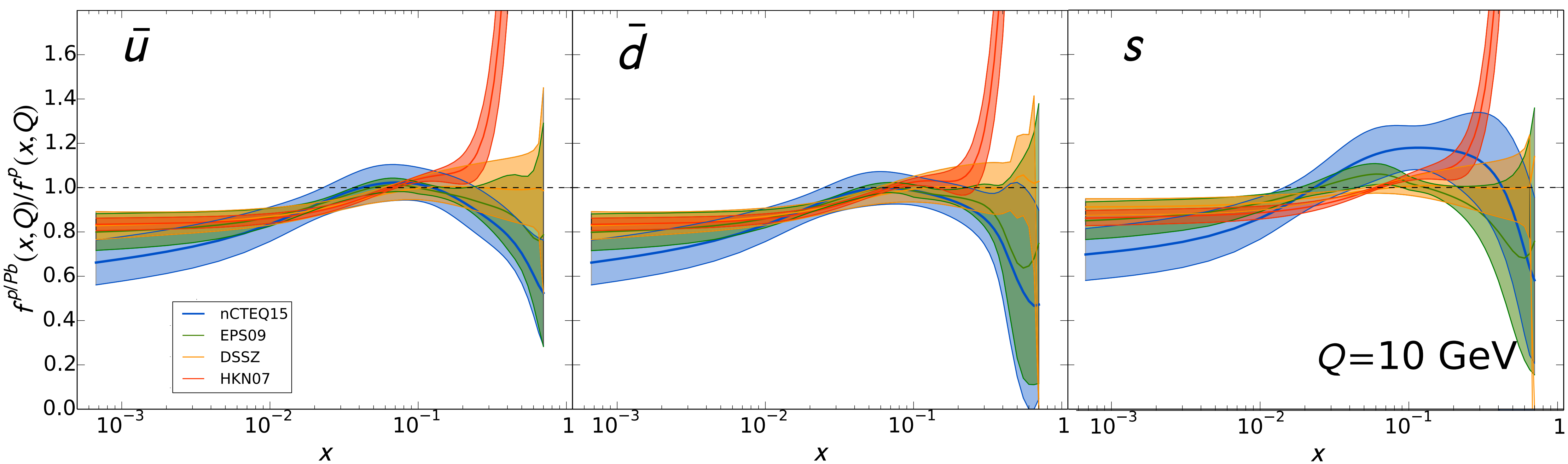


PRD85 (2012) 074028

Comparing nPDFs: the sea

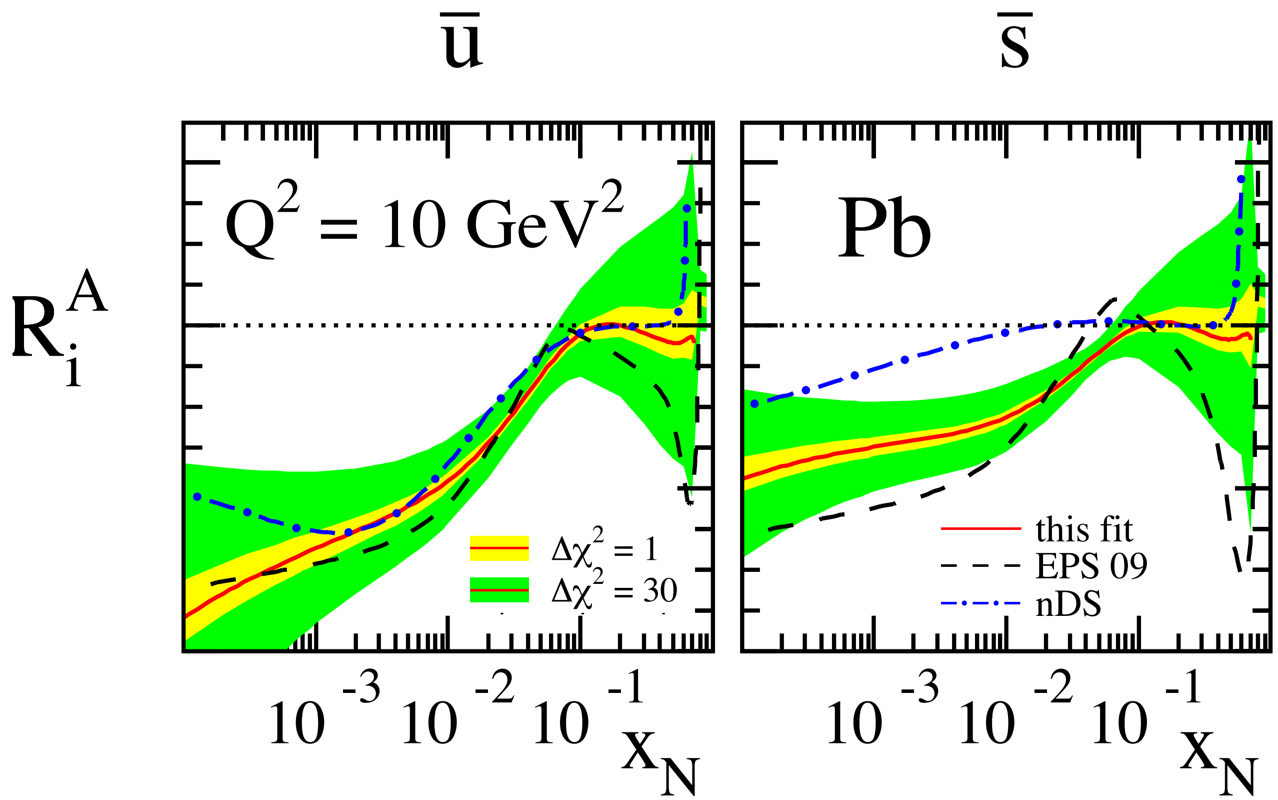


PRD85 (2012) 074028



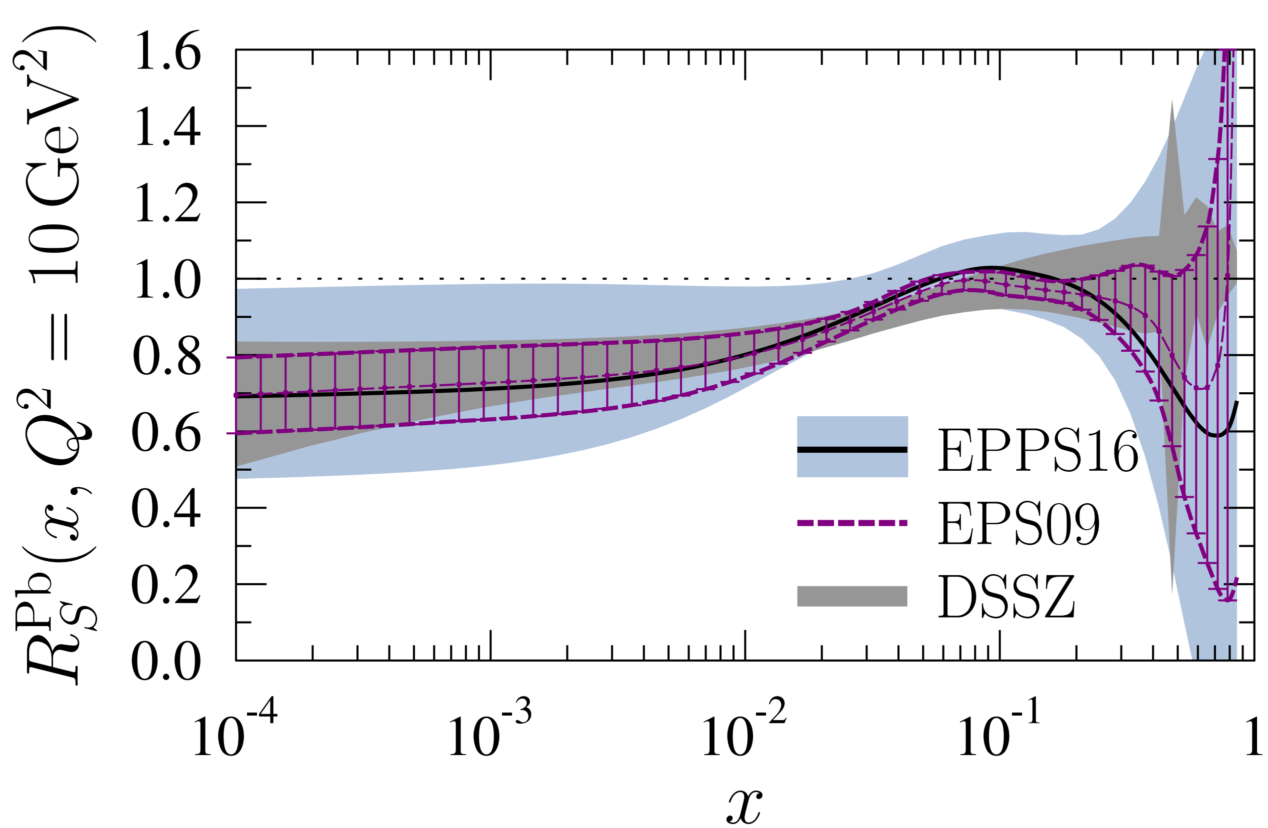
PRD93 (2016) no.8, 085037

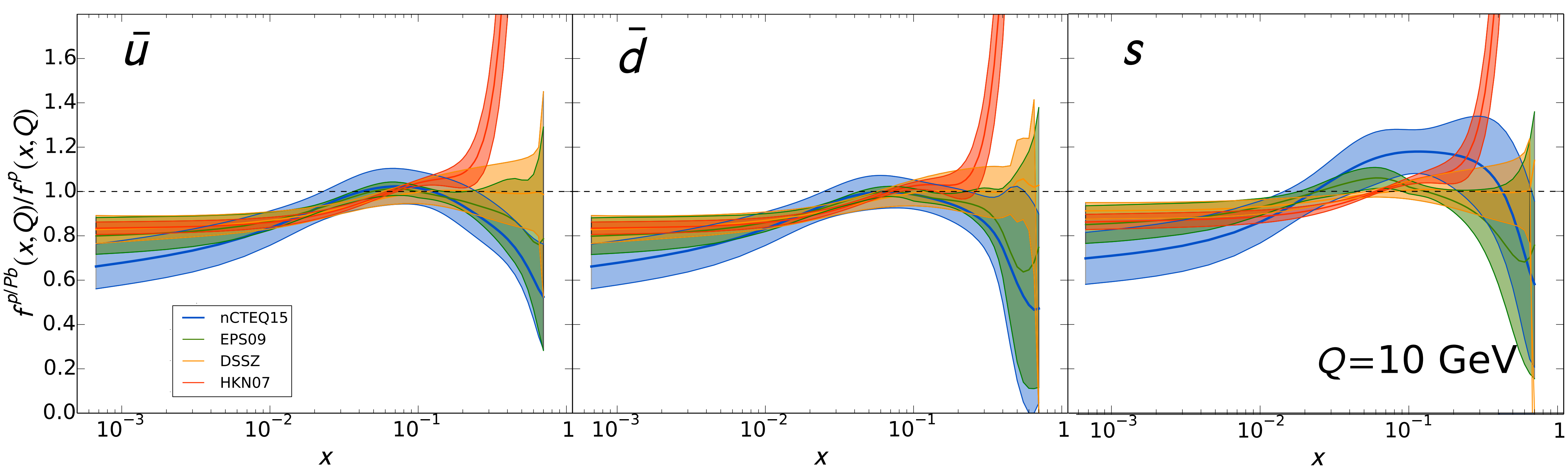
Comparing nPDFs: the sea



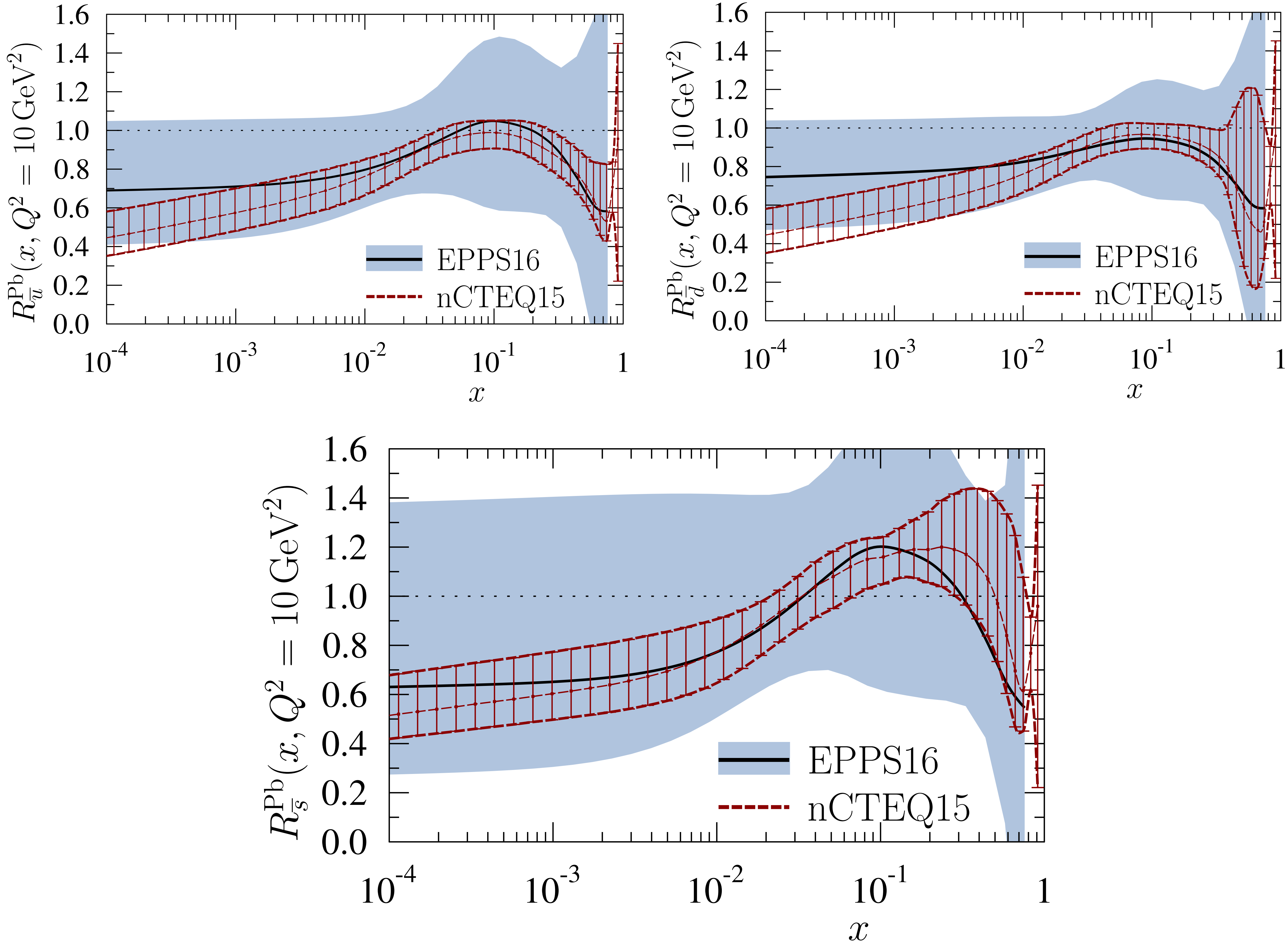
PRD85 (2012) 074028

EPJ C77 (2017) no.3, 163



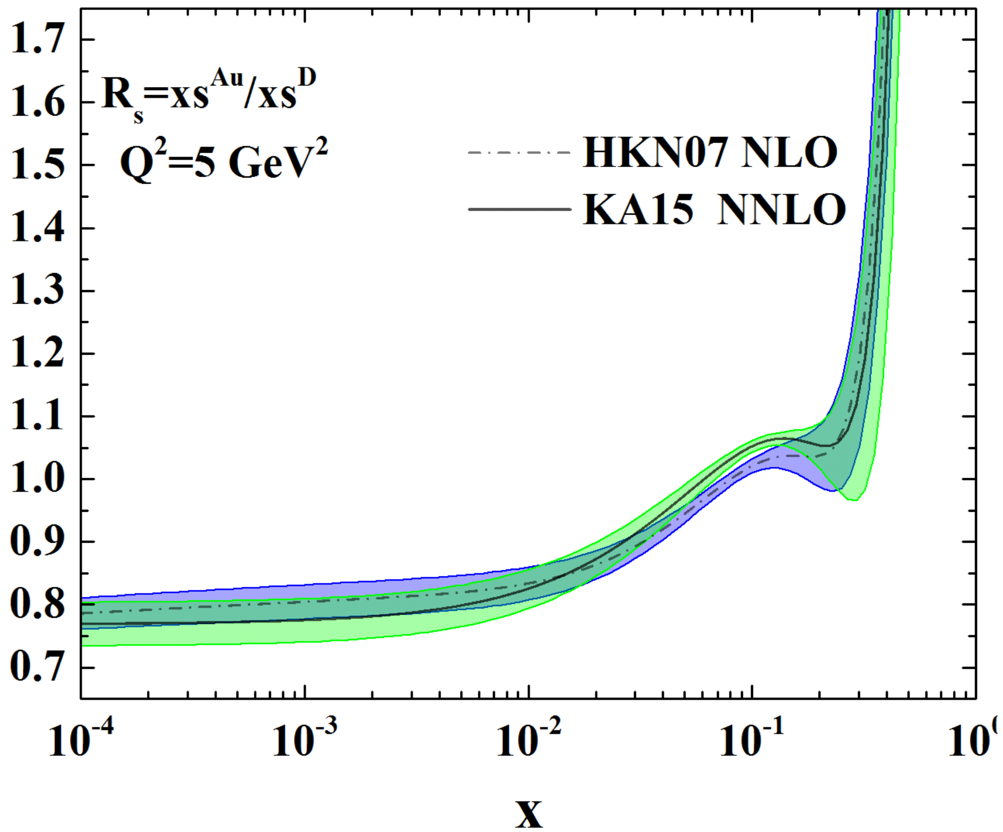


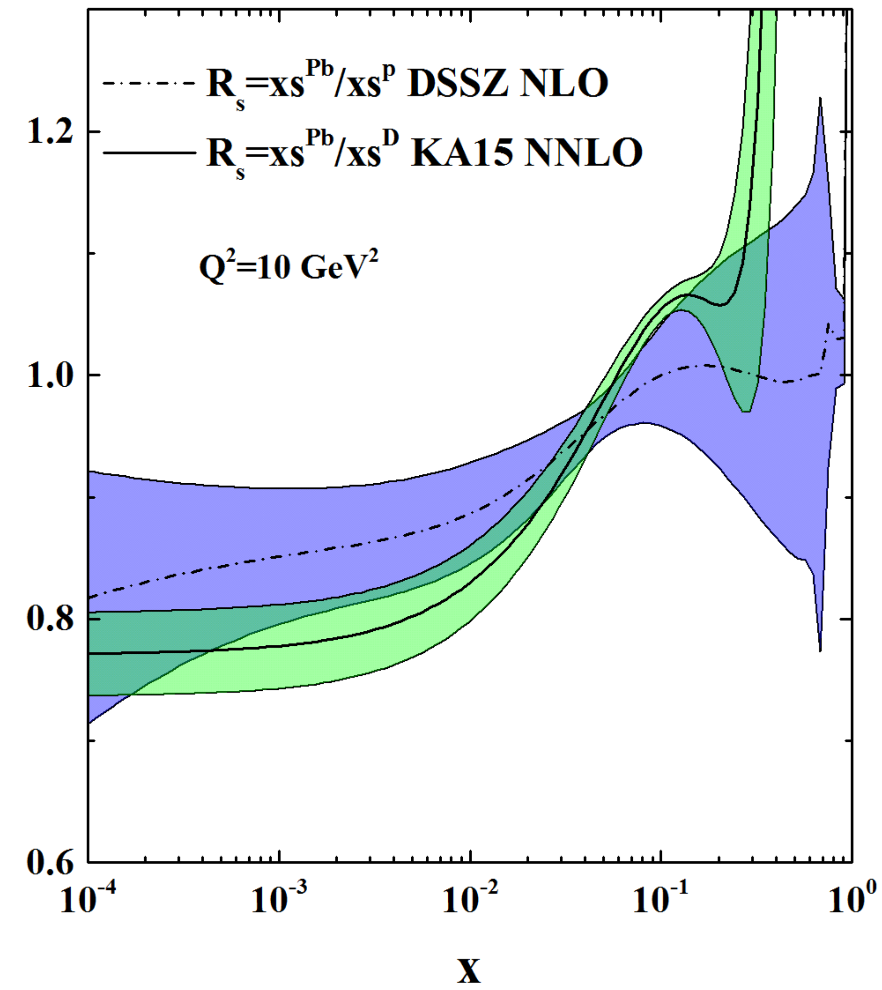
PRD93 (2016) no.8, 085037

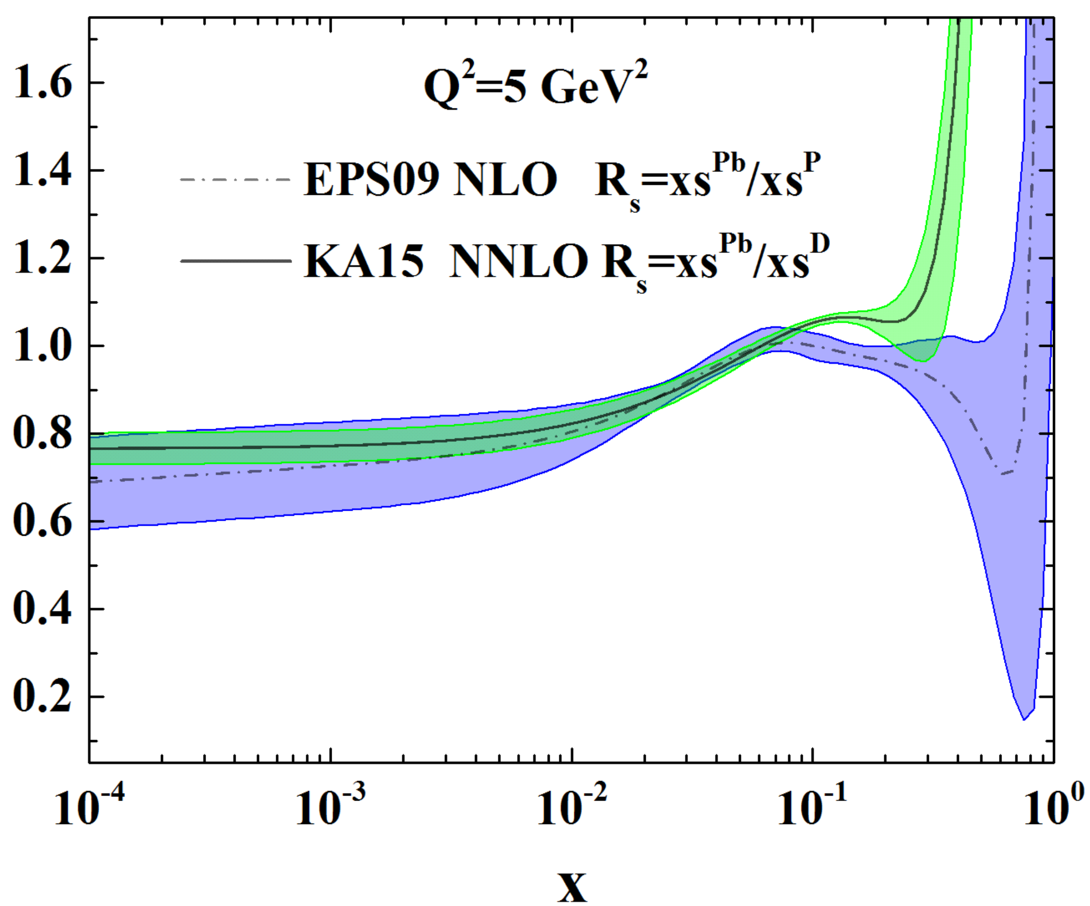


EPJ C77 (2017) no.3, 163

Comparing nPDFs: the sea

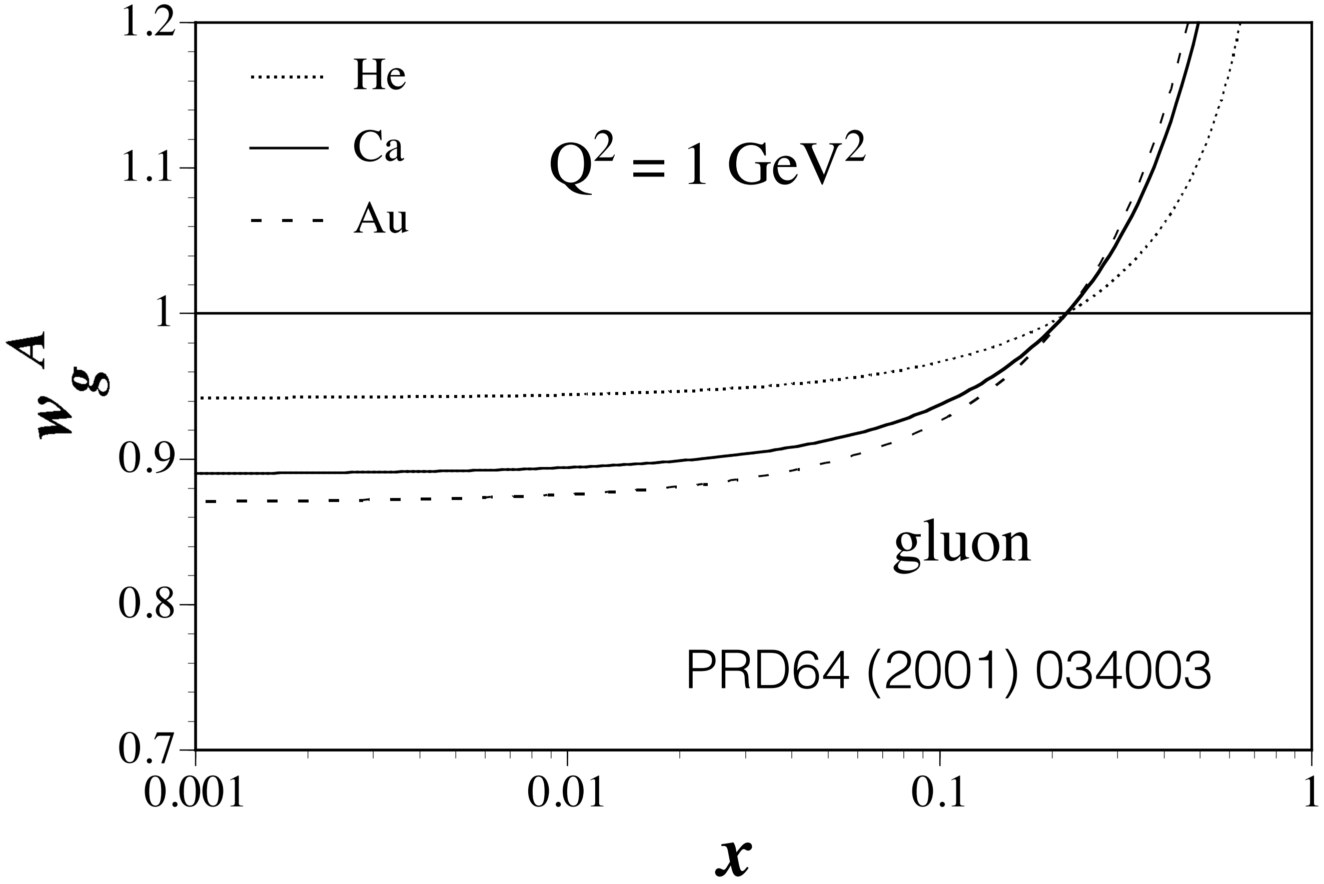




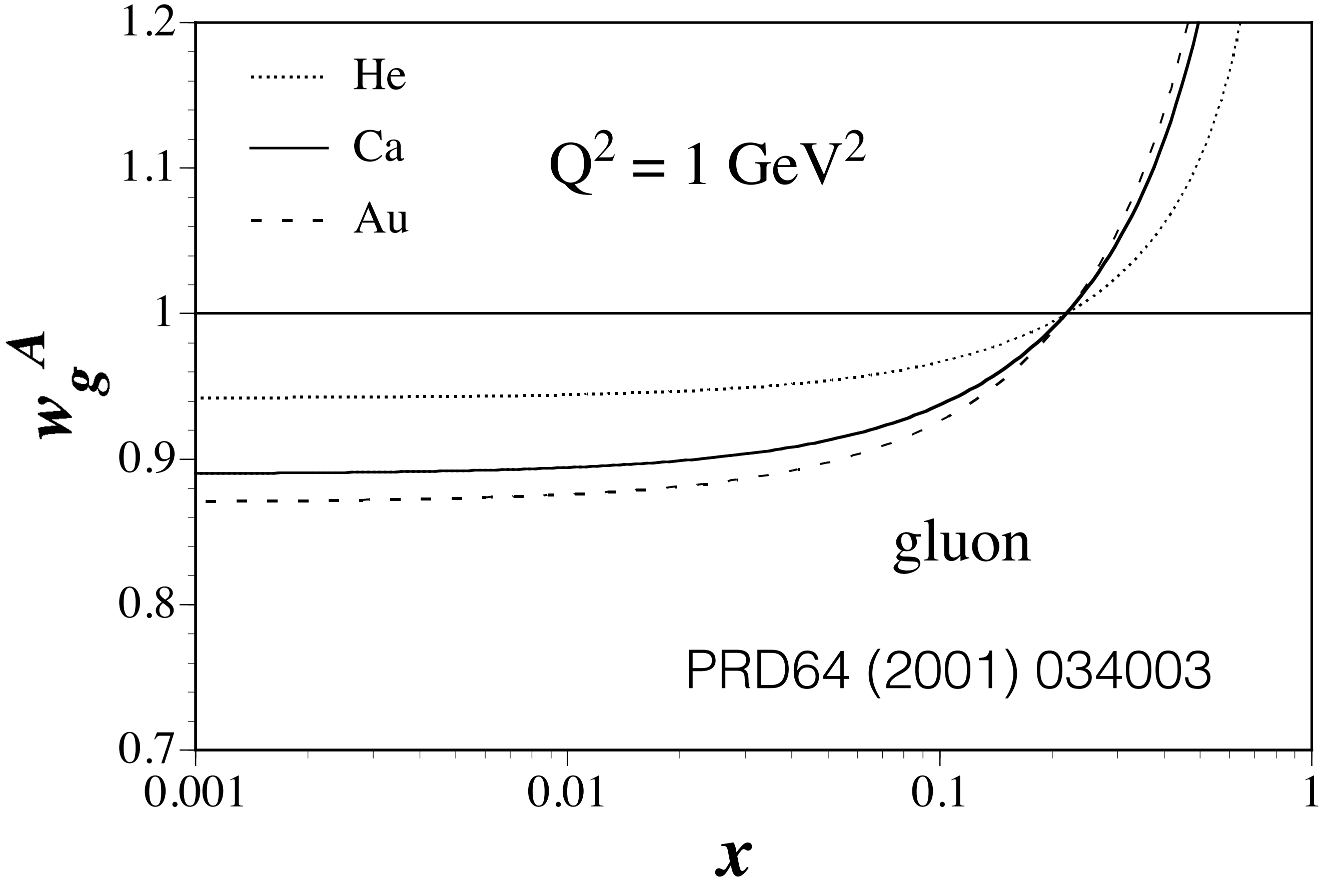


PRD93 (2016) no.1, 014026

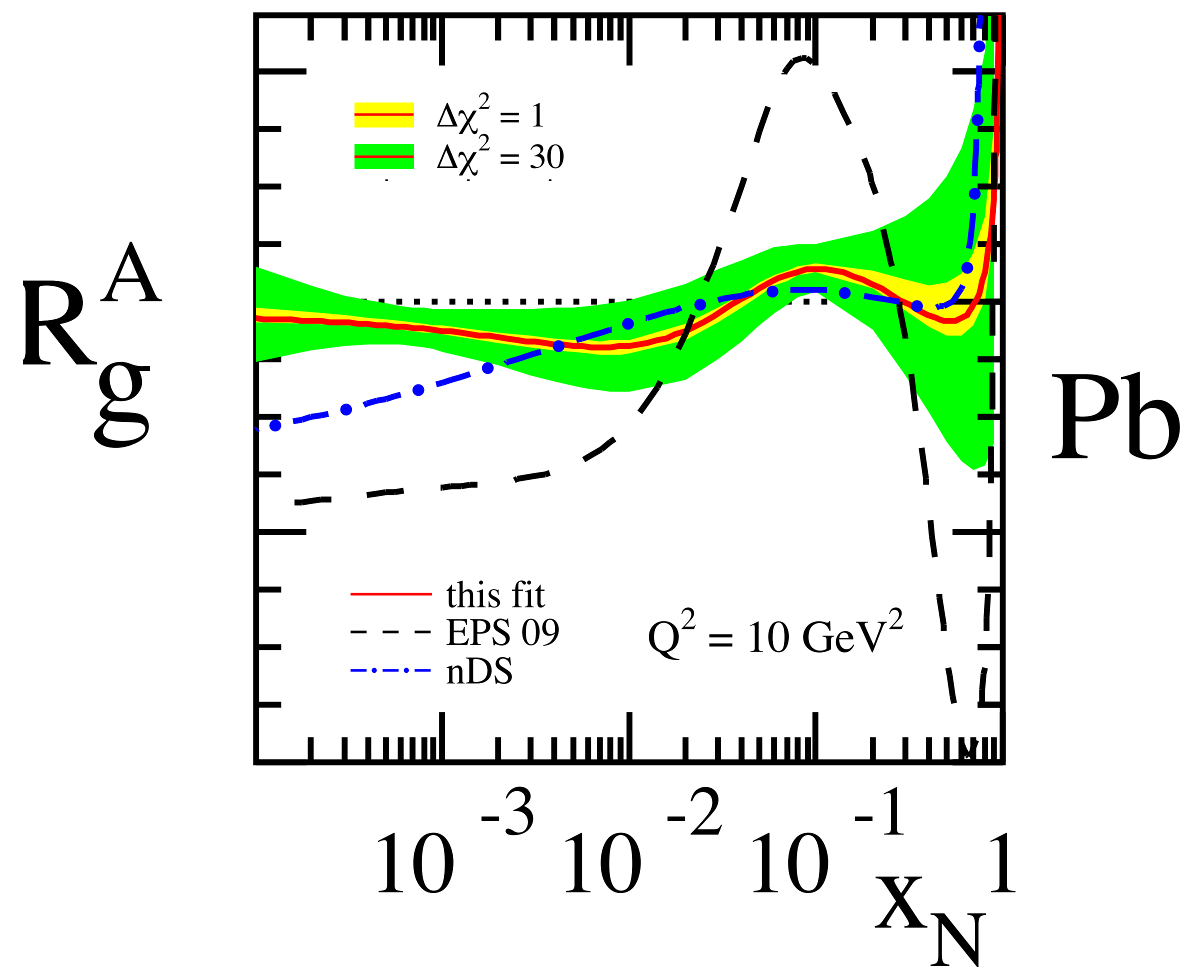
Comparing nPDFs: the gluon



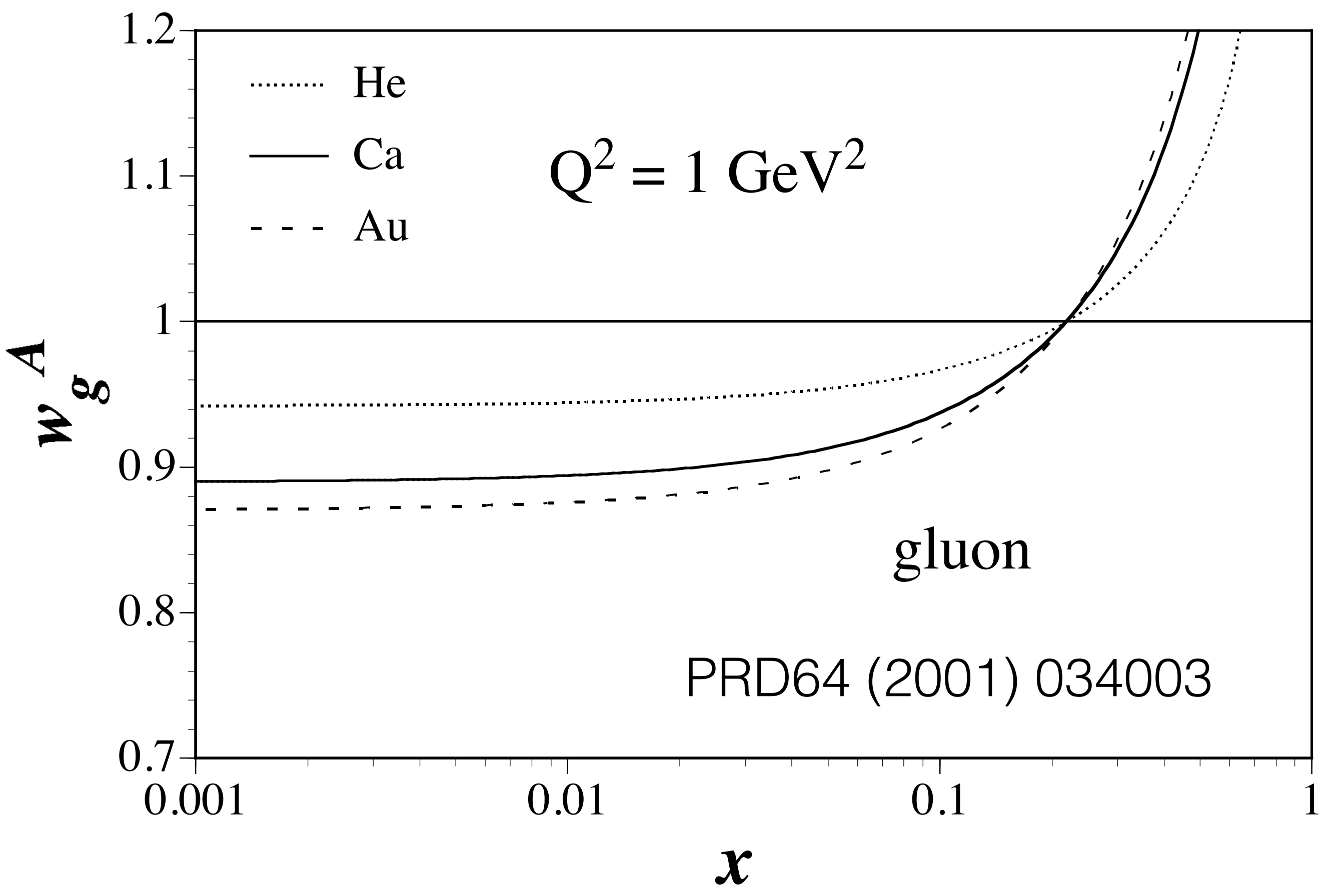
Comparing nPDFs: the gluon



PRD85 (2012) 074028



Comparing nPDFs: the gluon



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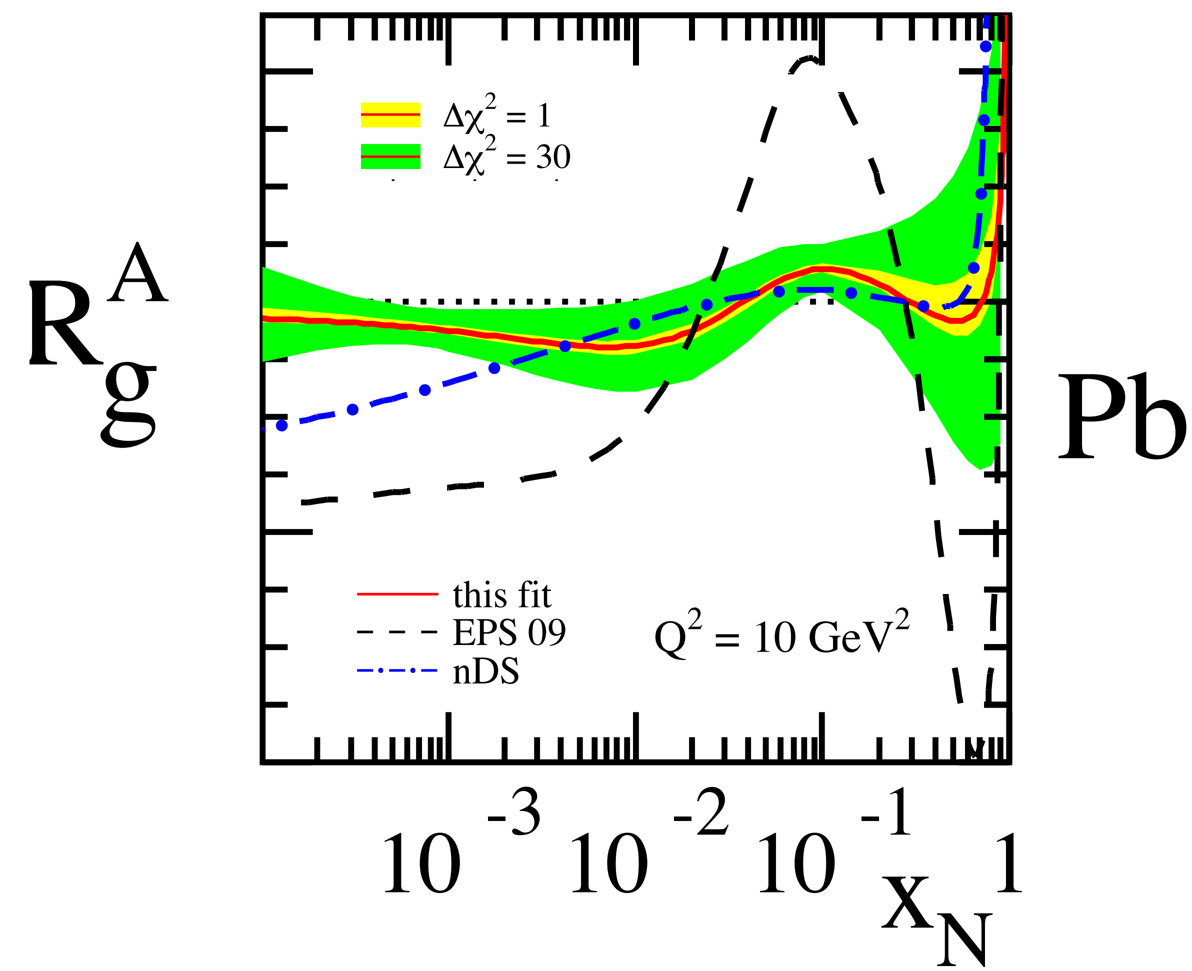
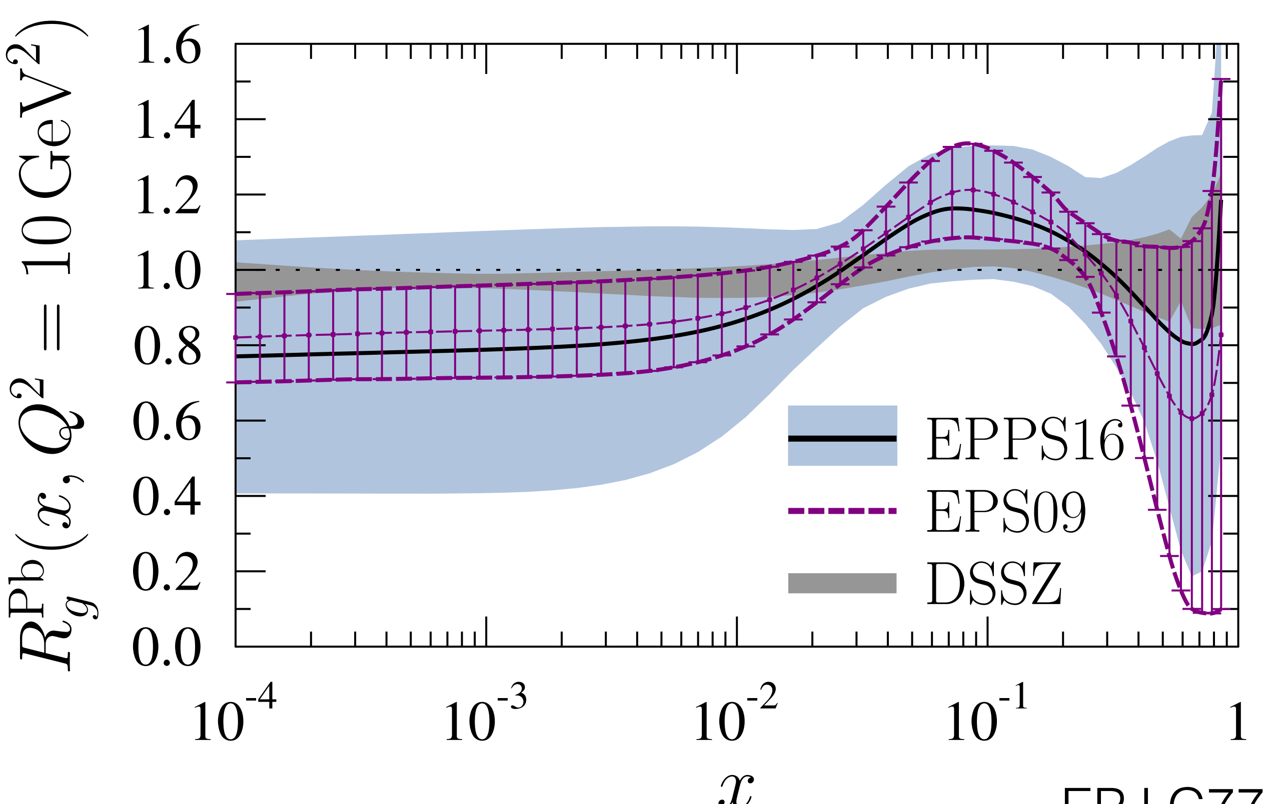
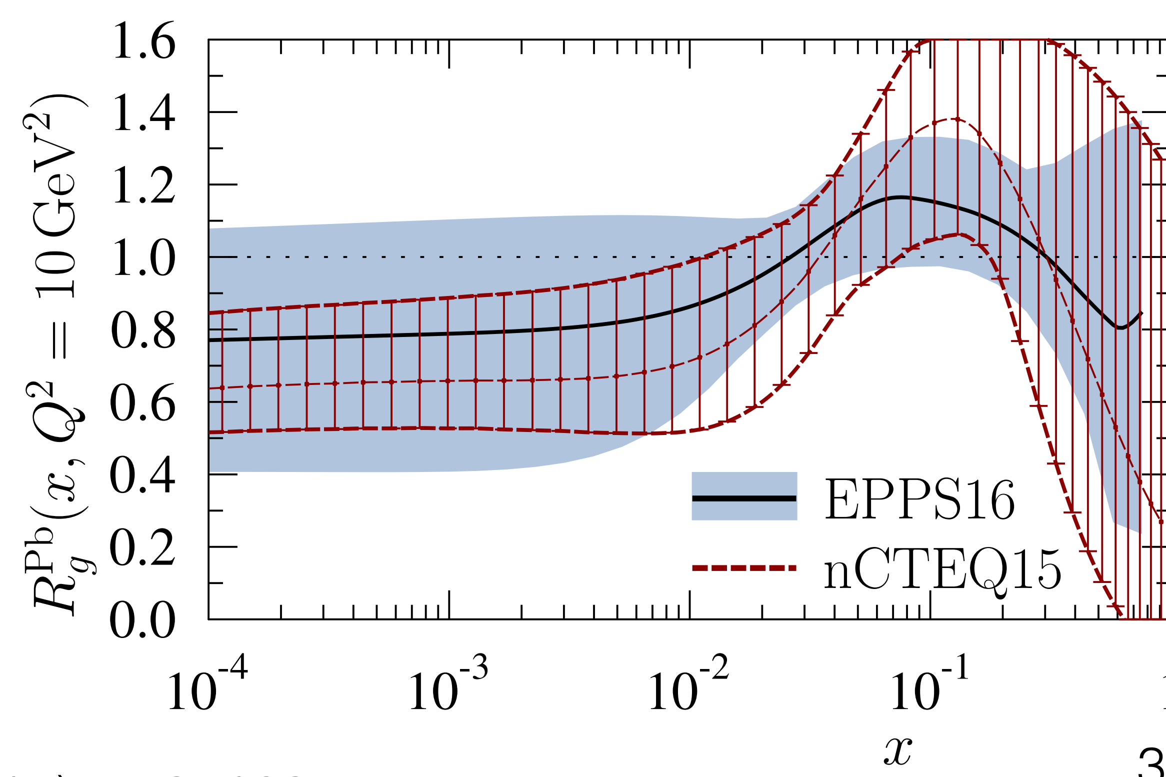
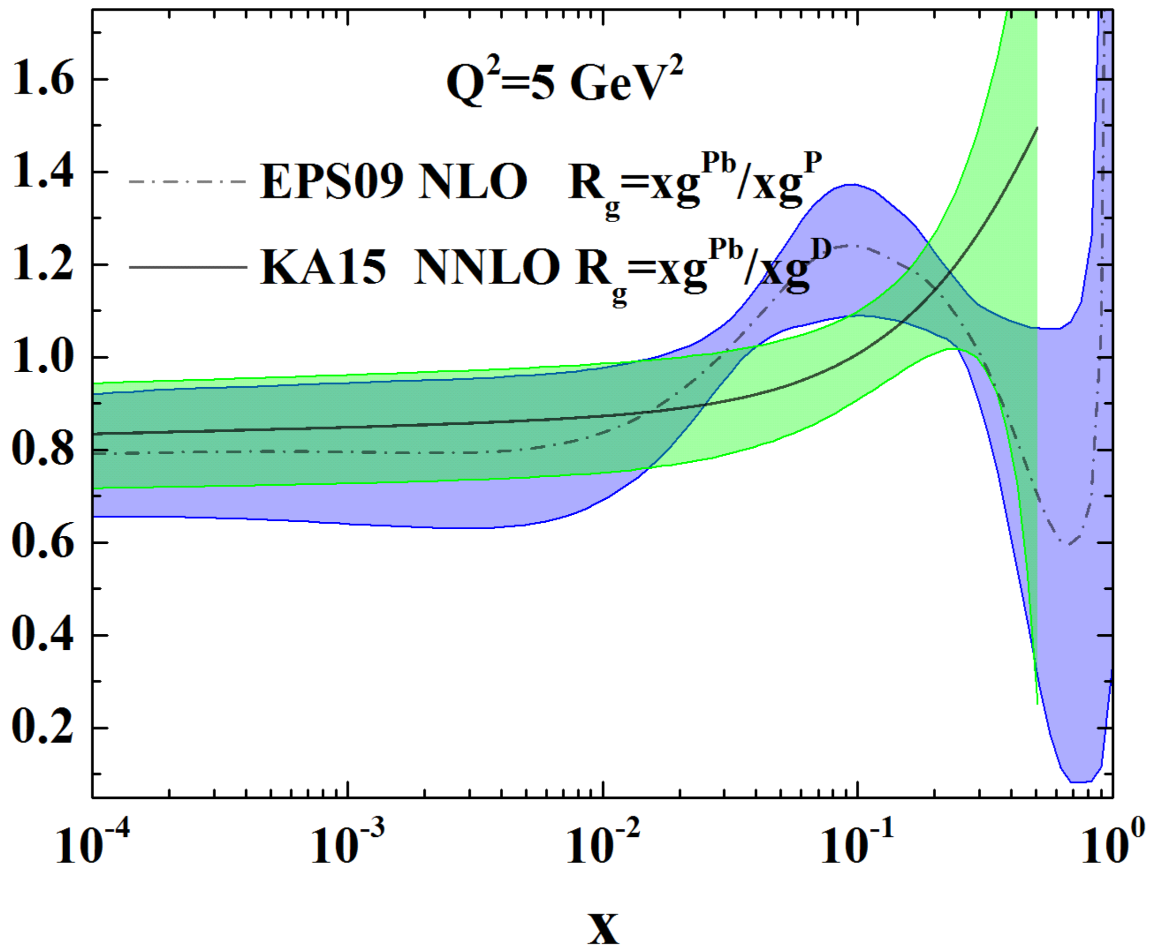




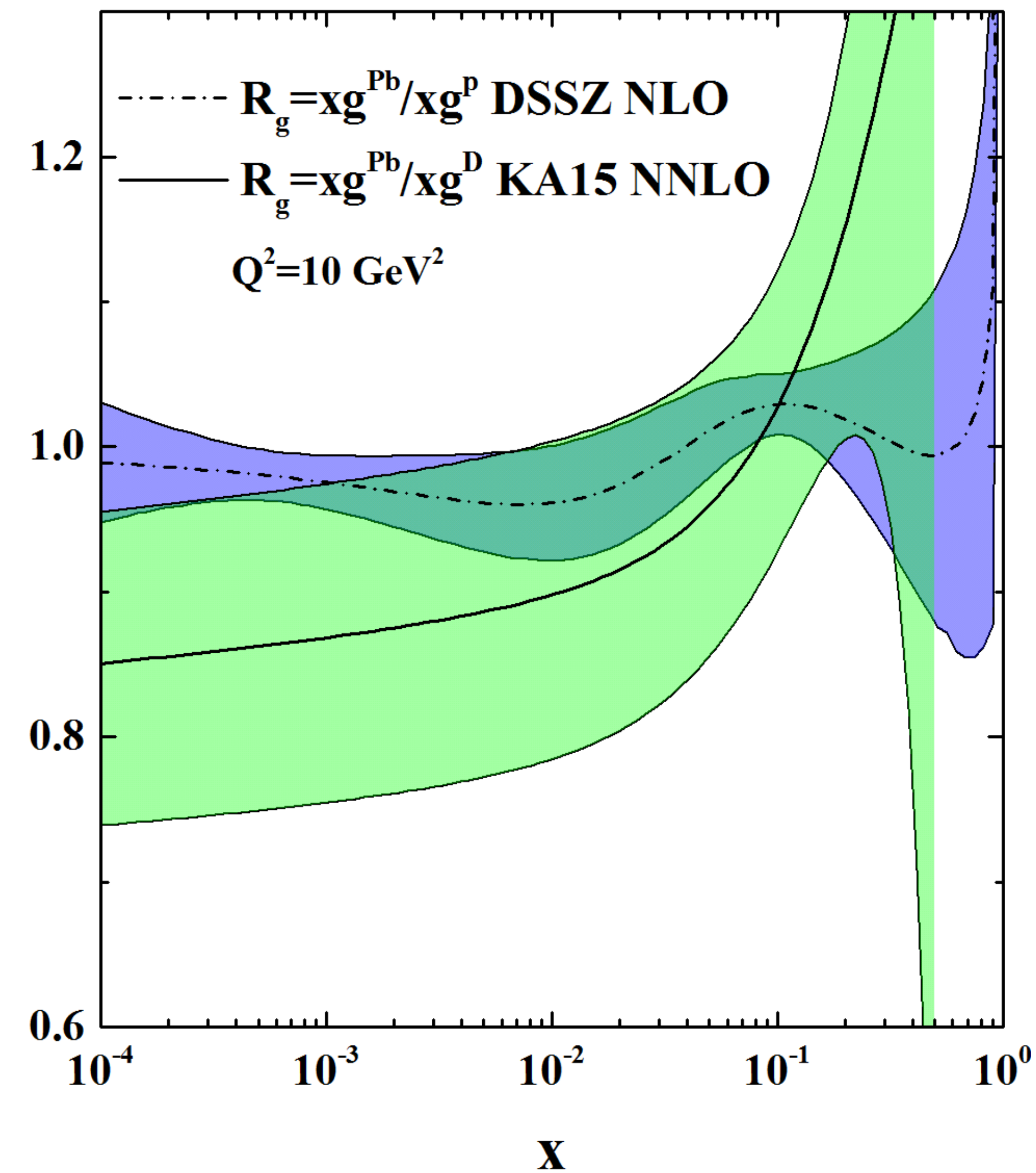


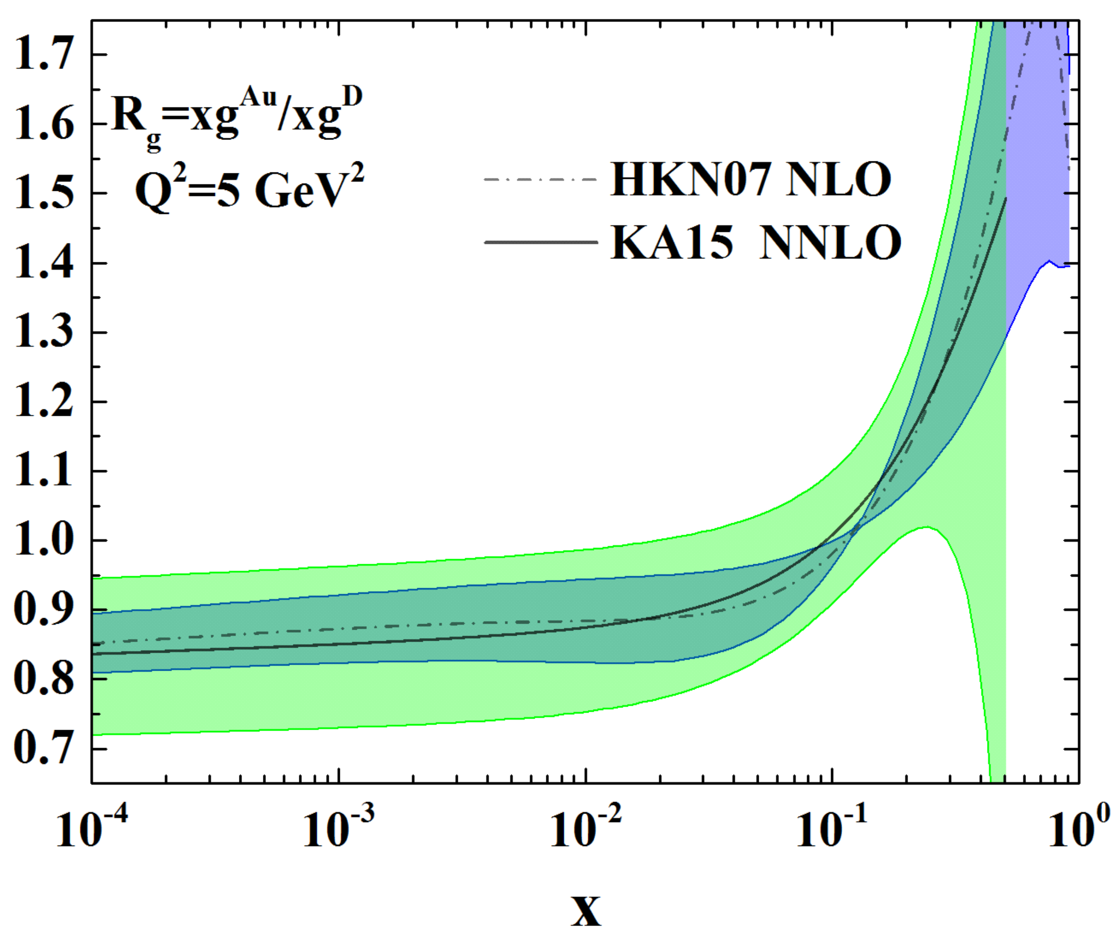
EPJ C77 (2017) no.3, 163

Comparing nPDFs: the gluon

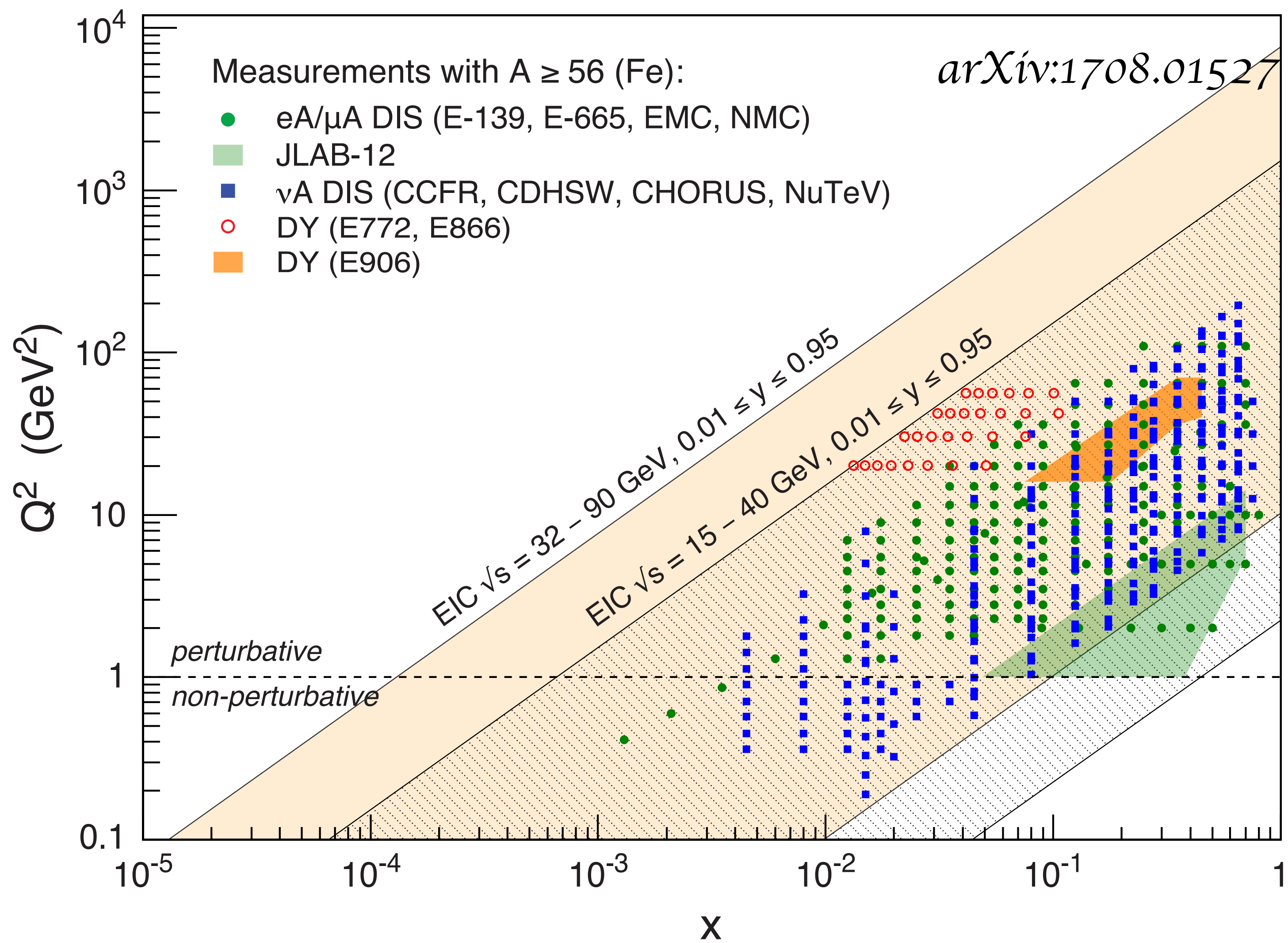


PRD93 (2016) no.1, 014026





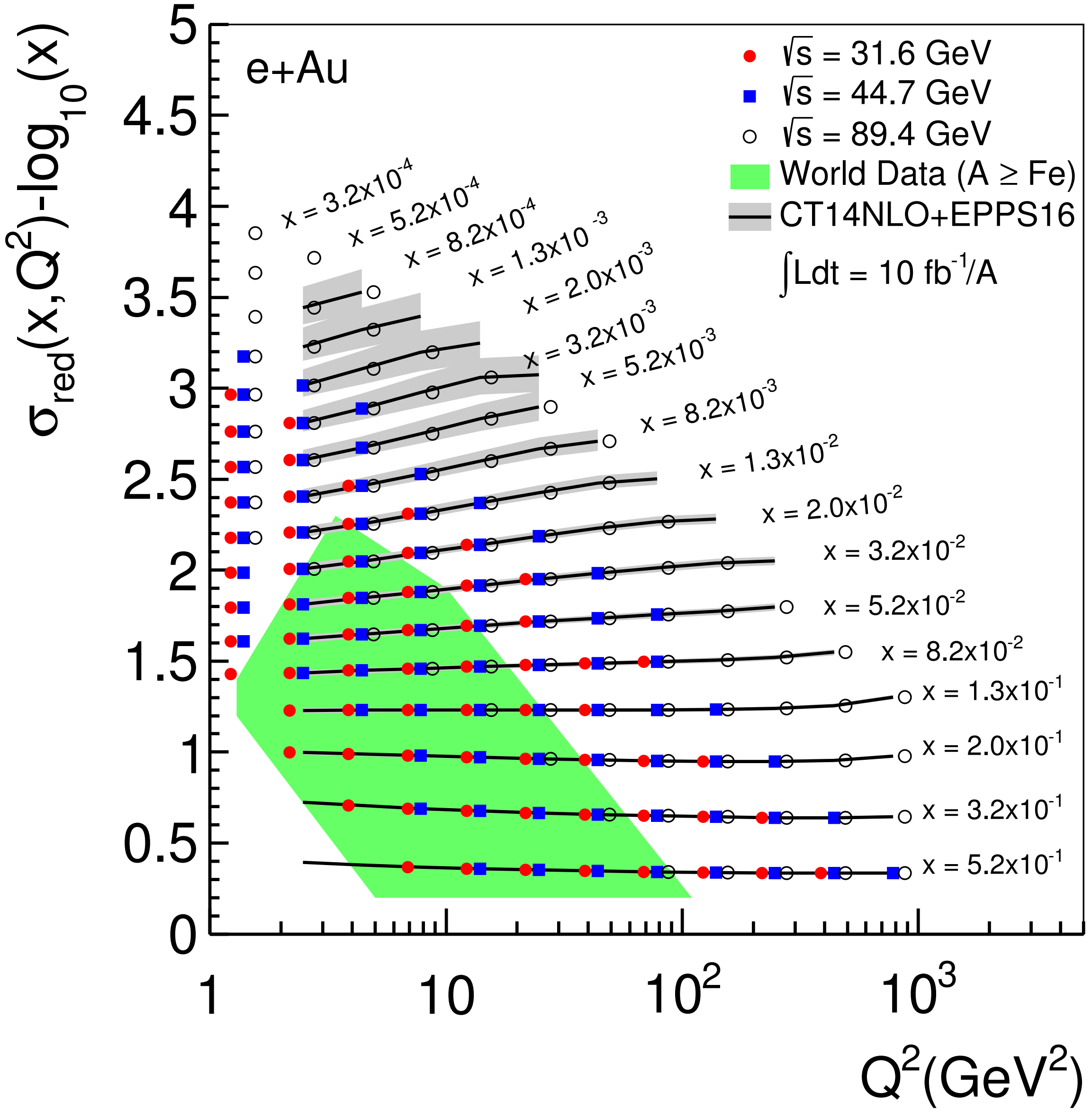
possibilities at an EIC



For energy dependent studies check:

- EPJ A52 (2016) no.9, 268
- Aschenauer, Fazio, Lee, Mantysaari, Page, Schenke, Ullrich, Venugopalan, P.Z. , arXiv:1708.01527

- observables: reduced cross-section
- pseudo-data using CT10 NLO proton PDFs + EPS09 nPDFs



Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

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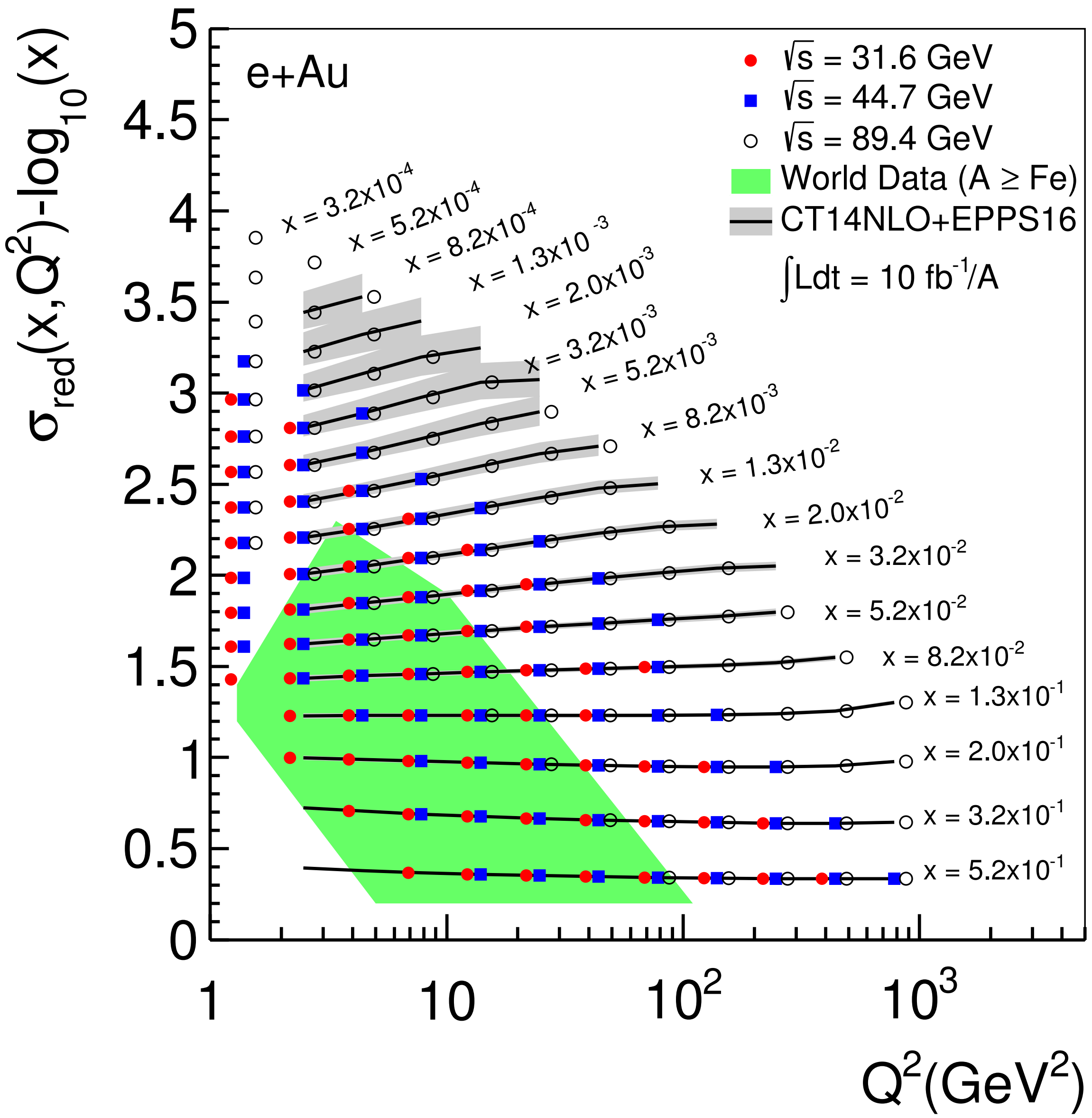
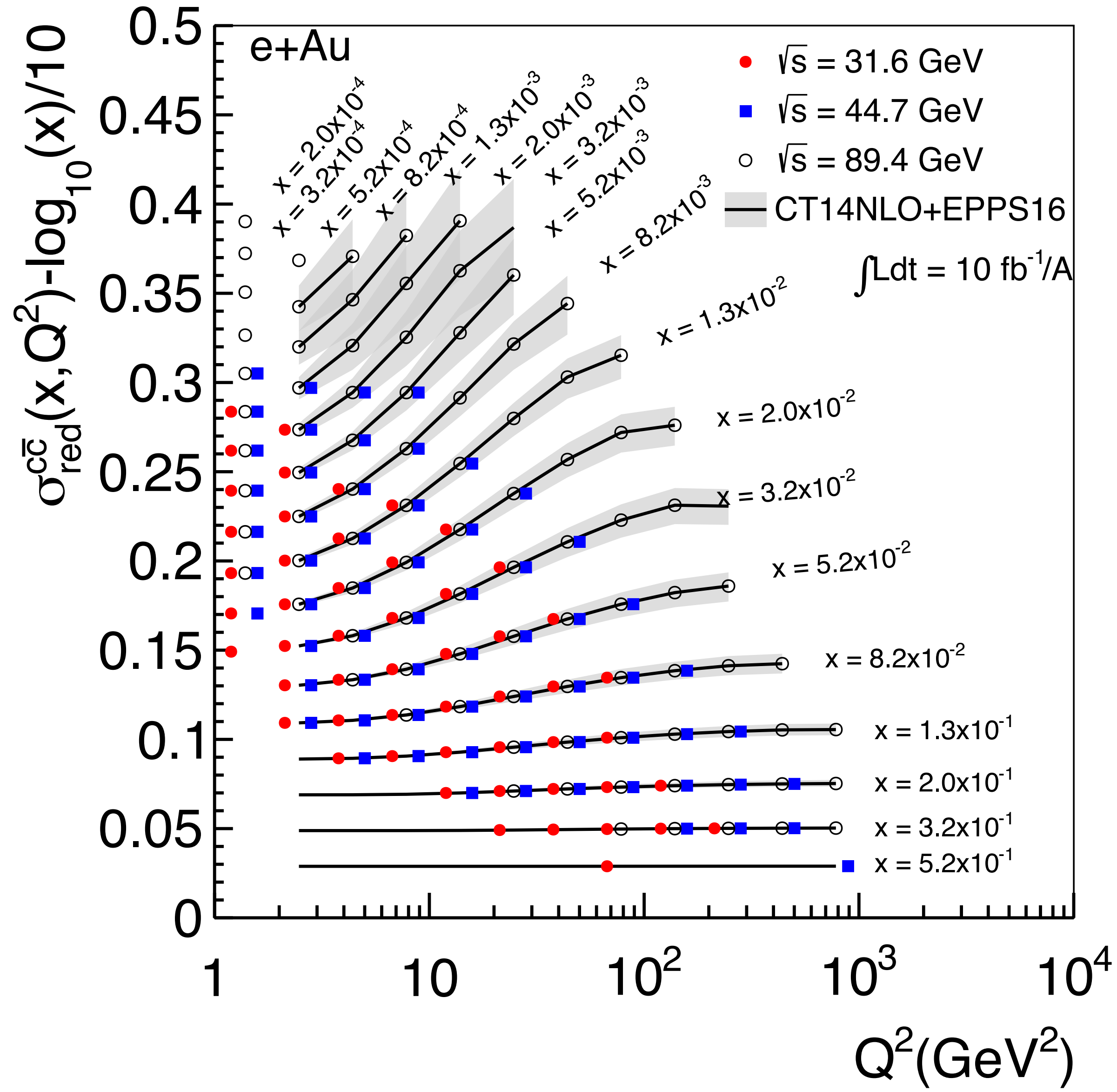
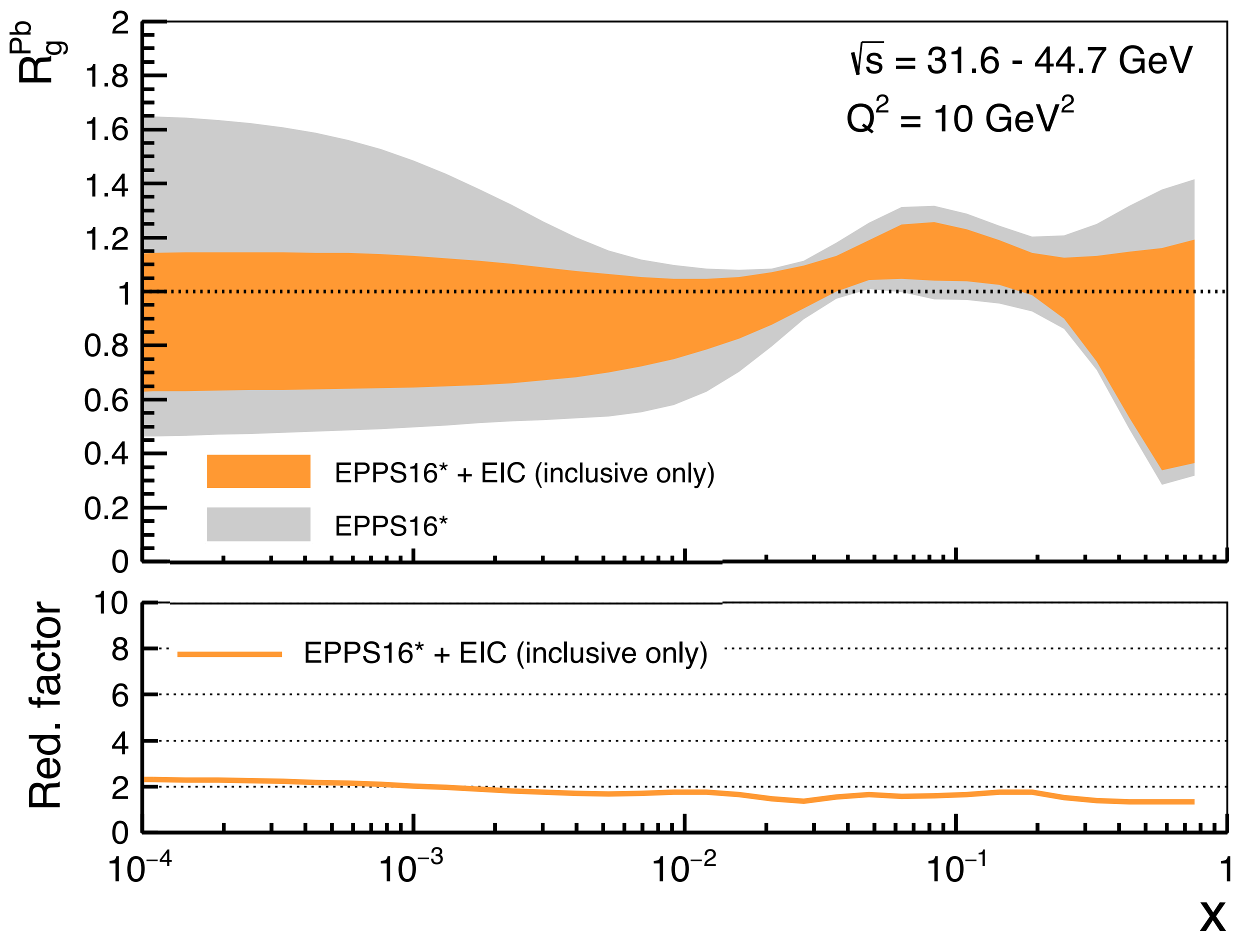




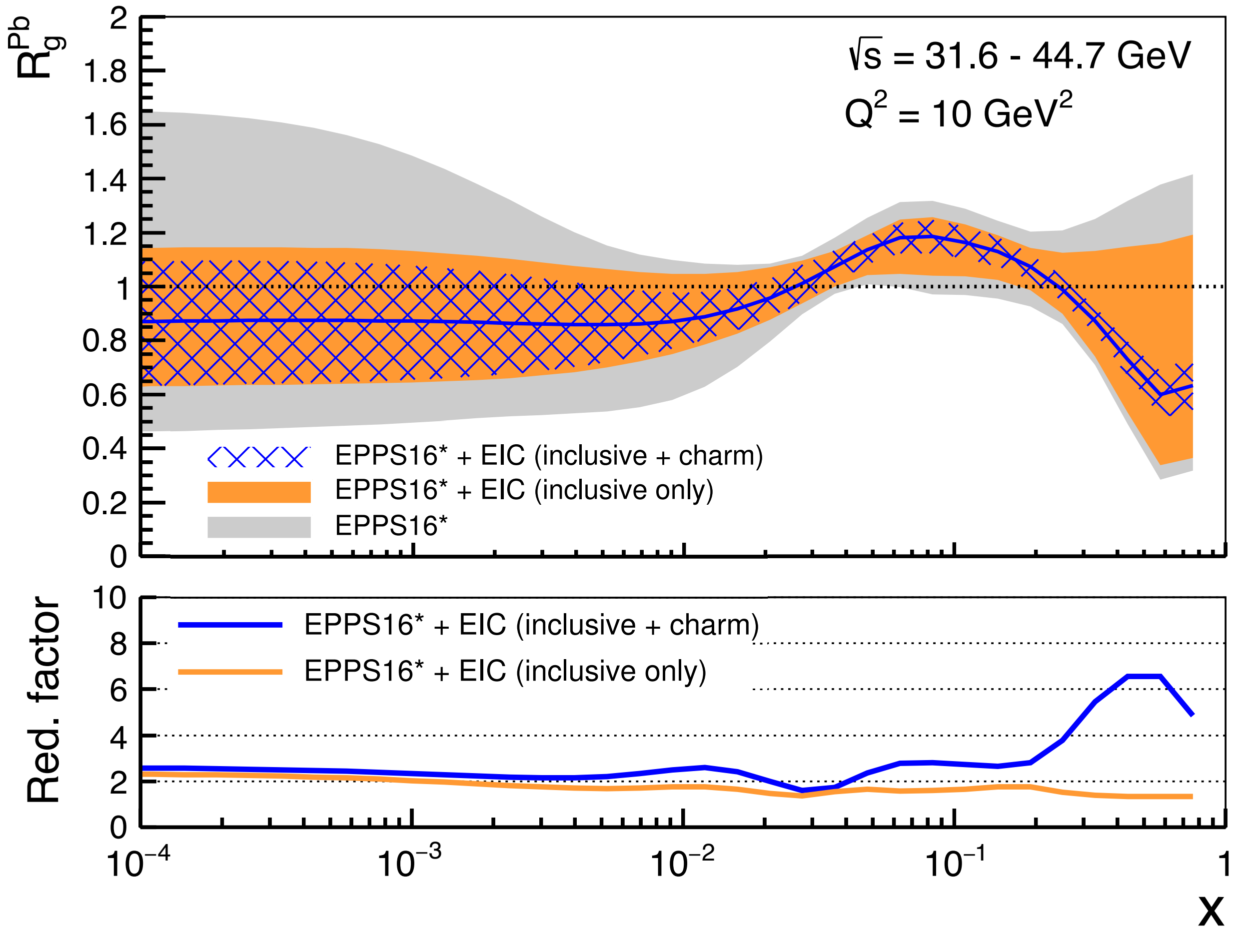
Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

- check impact on **EPPS16*** nPDFs: inclusive, low energy



PRD96 (2017) no.11, 114005

- check impact on **EPPS16*** nPDFs: charm, low energy

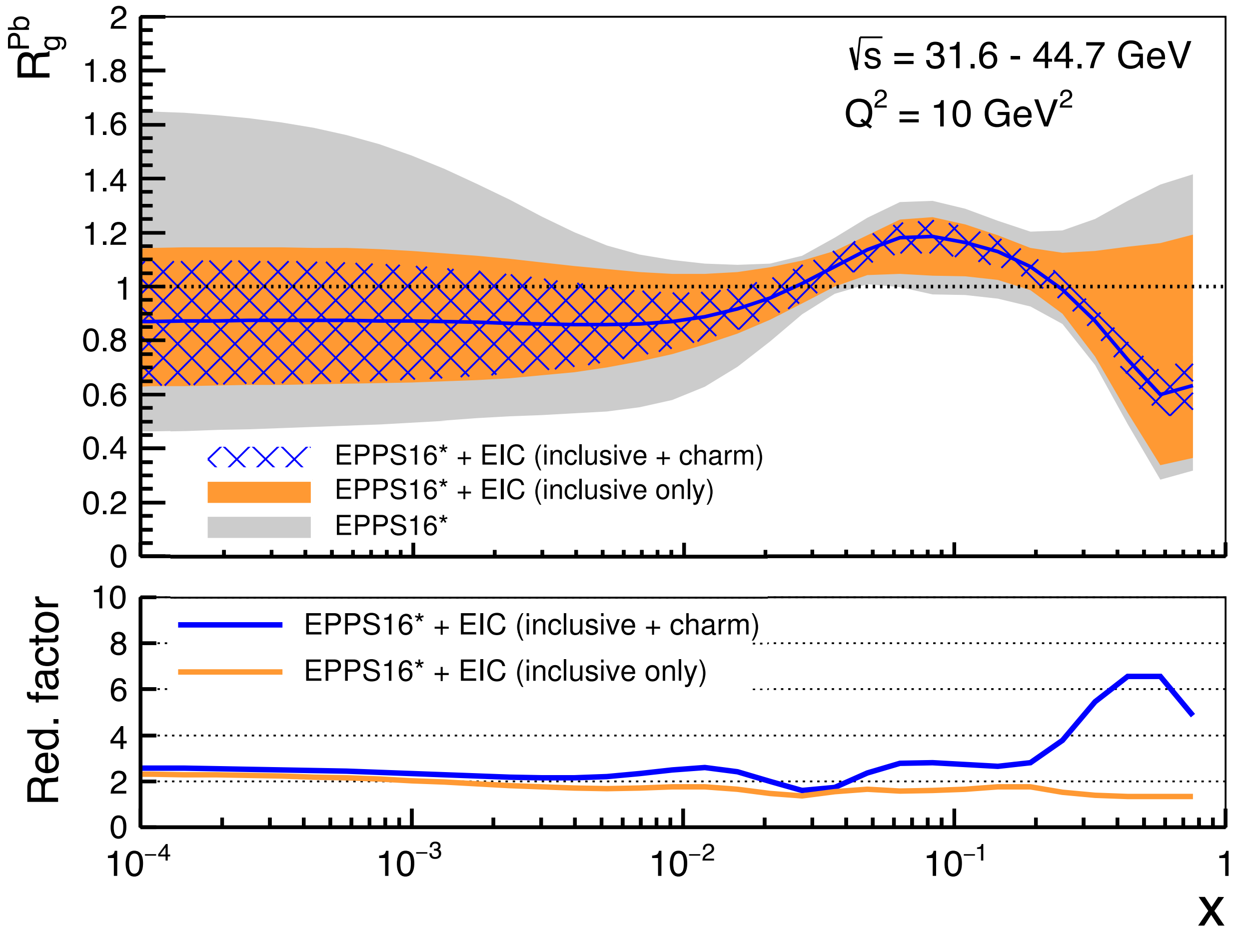


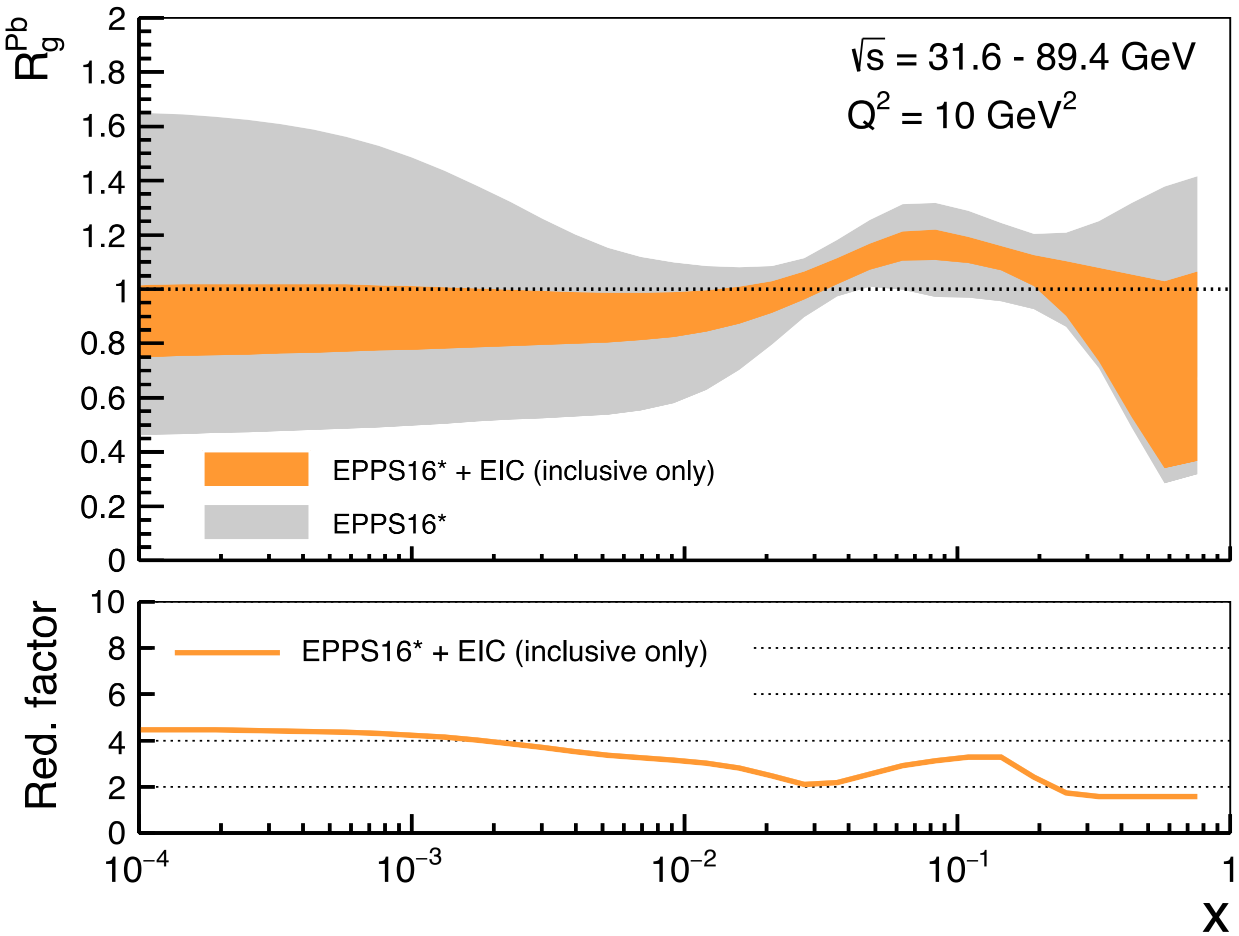
PRD96 (2017) no.11, 114005

See also C. Weiss talk at "Santa Fe Jets and Heavy Flavor Workshop, 30-Jan-18"

https://indico.fnal.gov/event/15328/session/4/contribution/15/material/slides/0.pdf

- check impact on **EPPS16*** nPDFs: inclusive, high energy





PRD96 (2017) no.11, 114005

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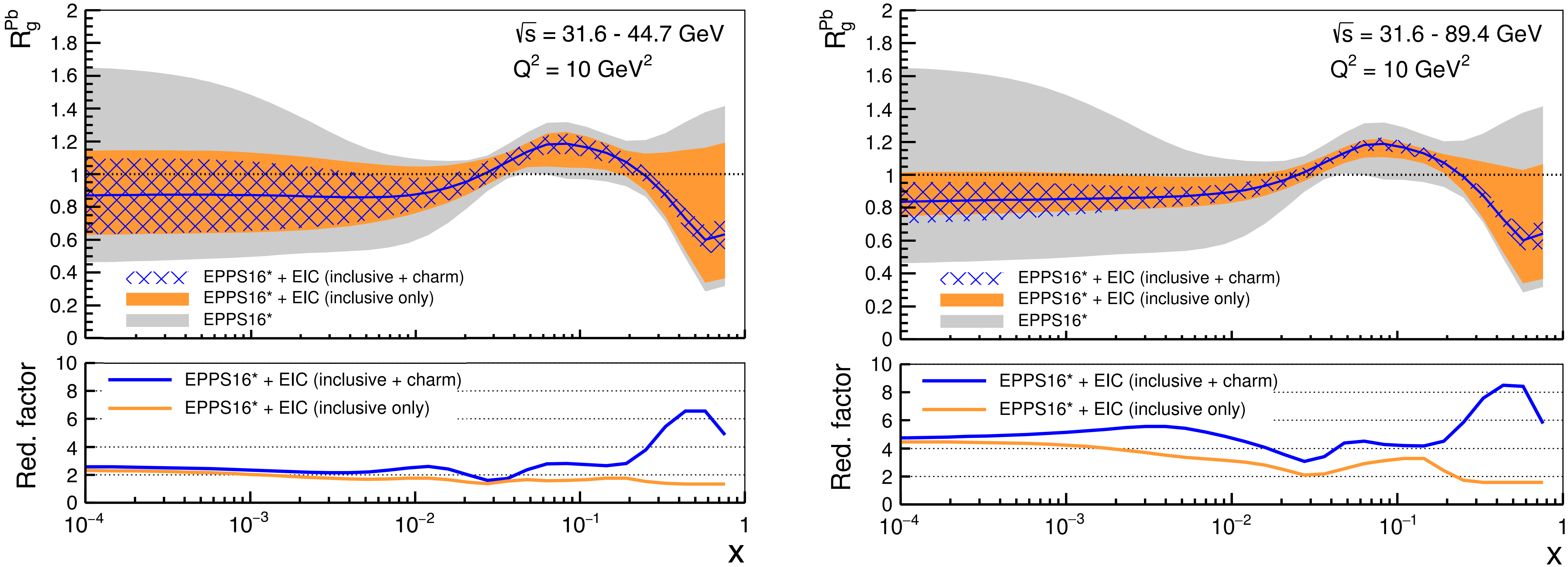

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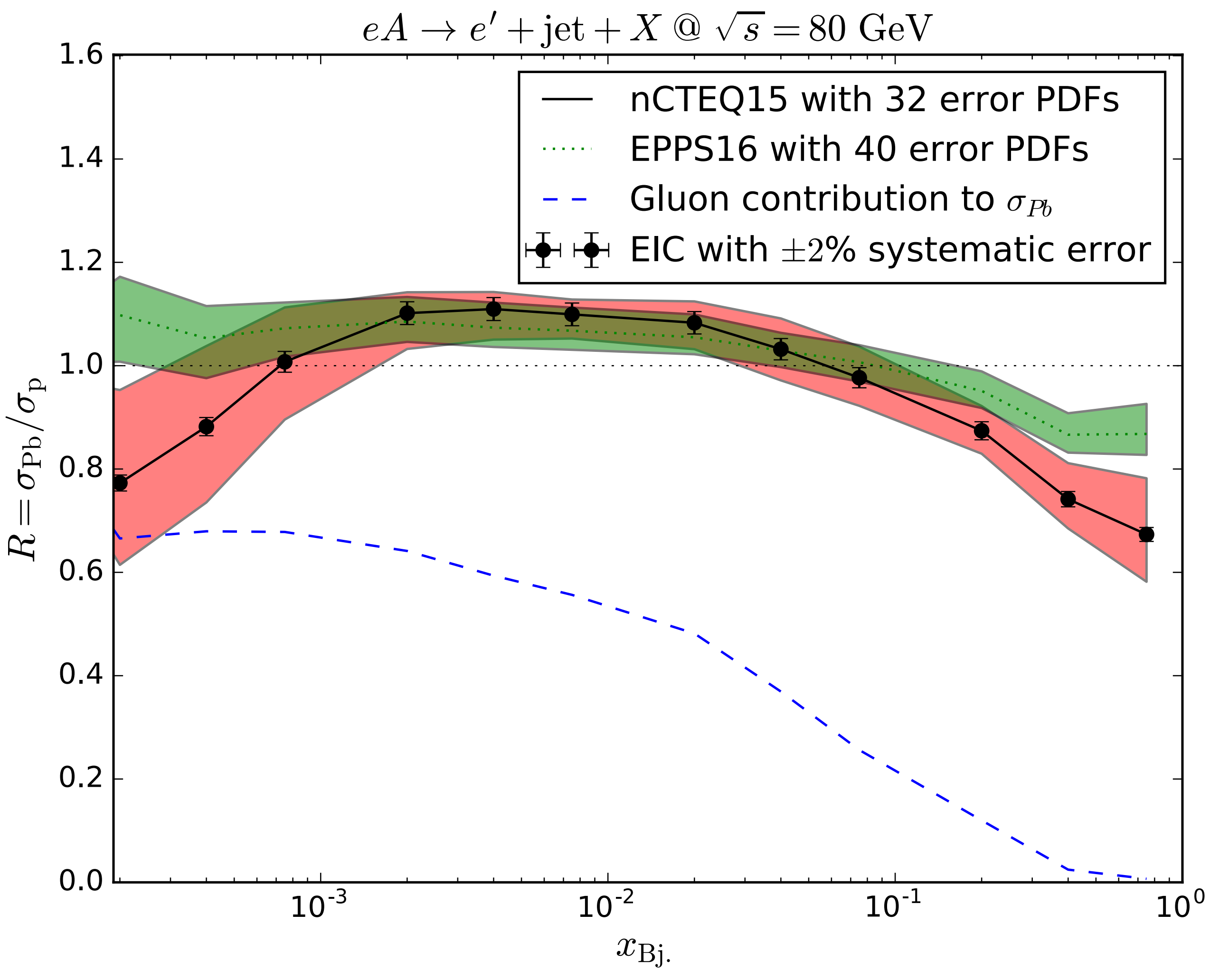
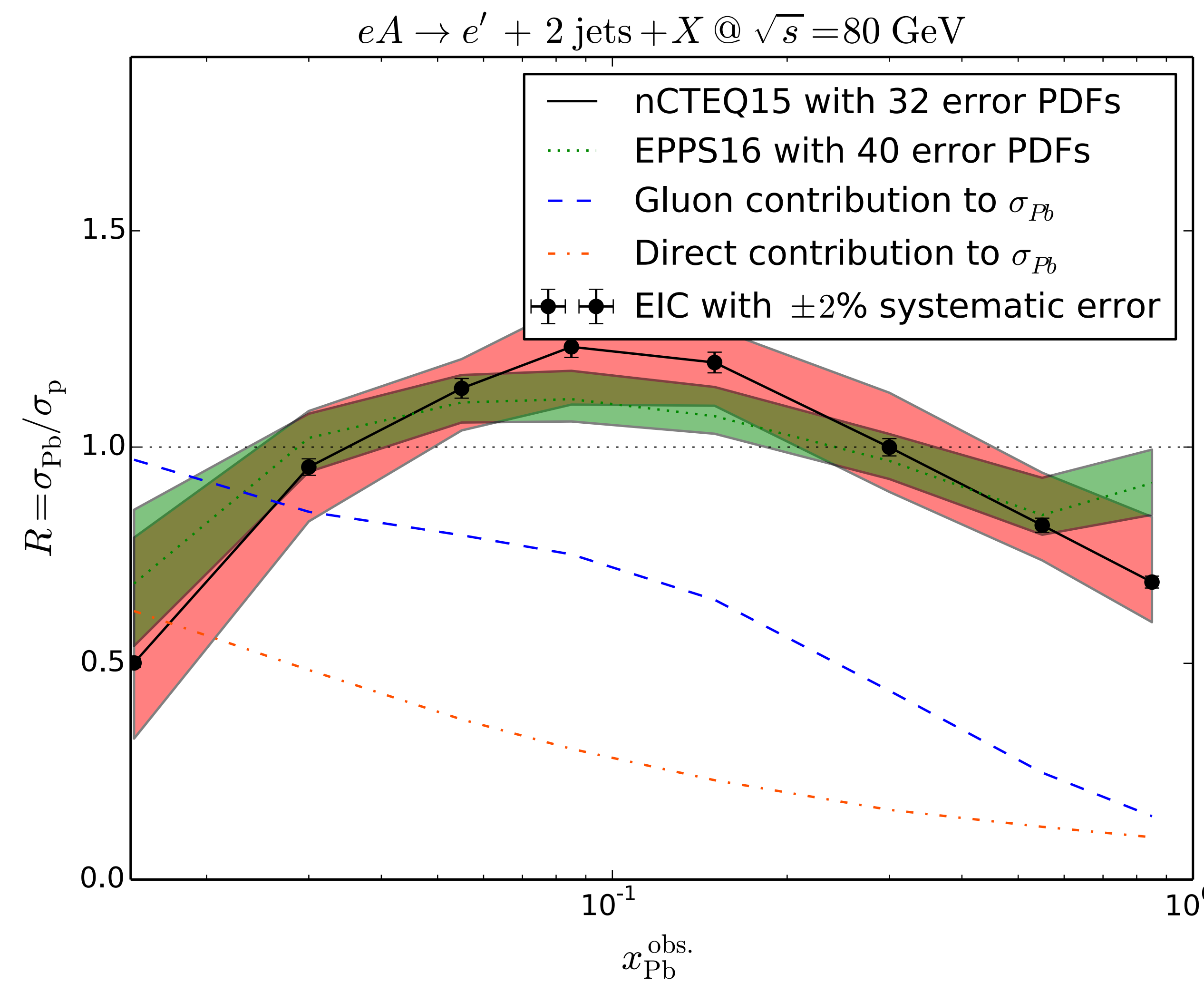
What's next?: EIC studies

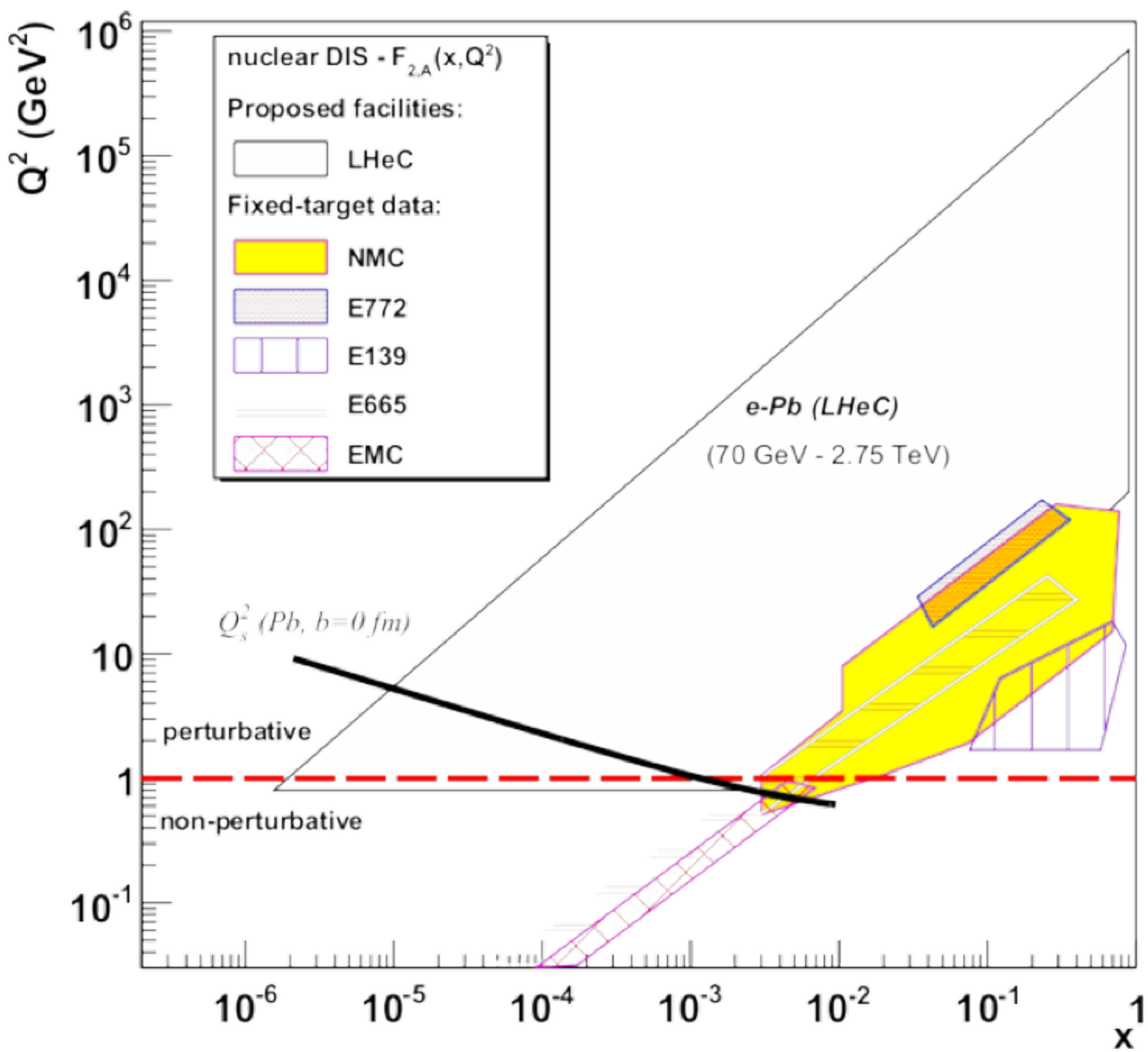
Klasen and Kovarik, arXiv:1803.10985 [hep-ph].





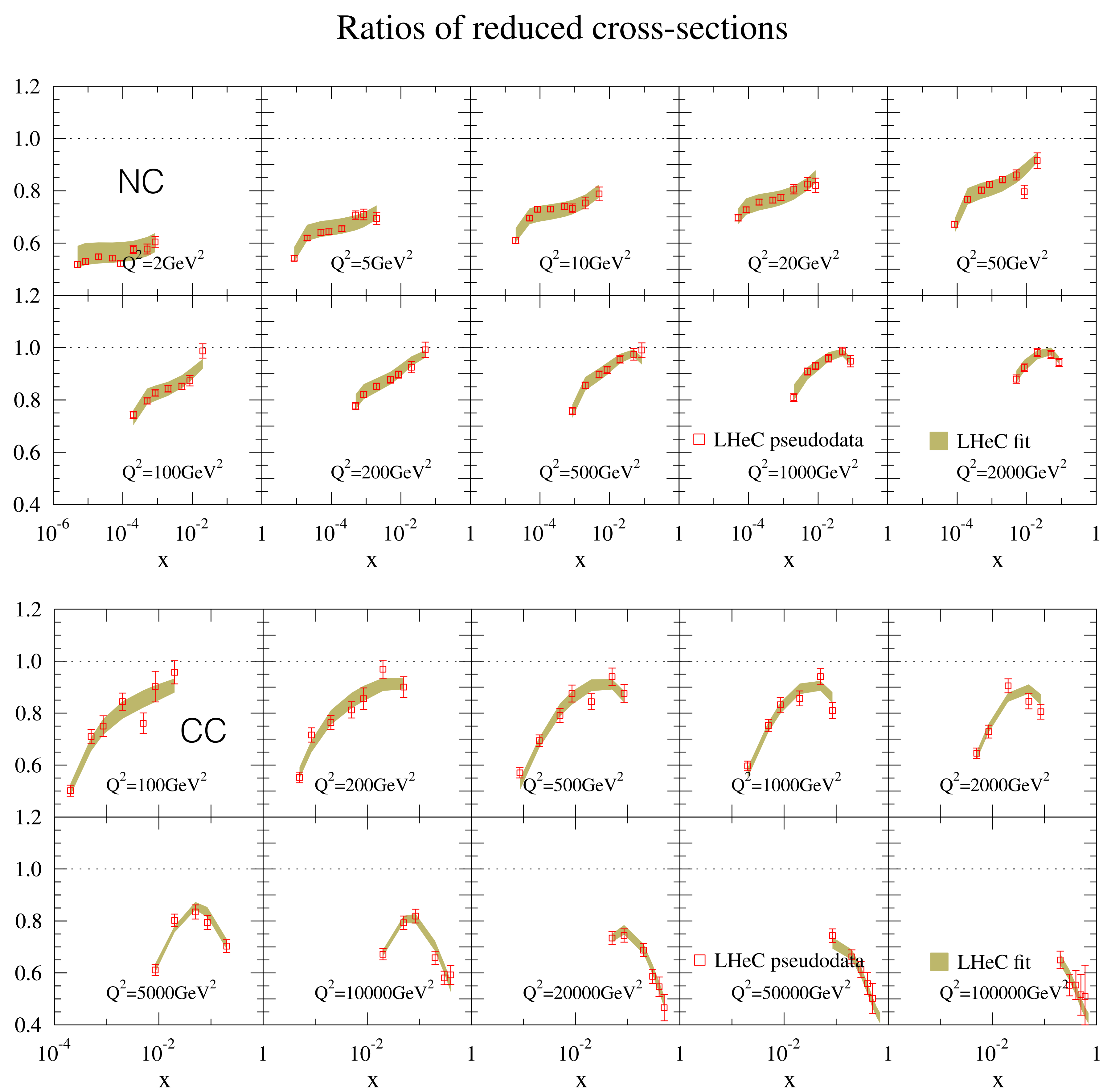
Klasen, Kovarik, Potthoff, PRD95 (2017) no.9, 094013

possibilities at the LHeC



from H. Paukkunen's talk in POETIC8

- "data" from EPS09
- NC & CC



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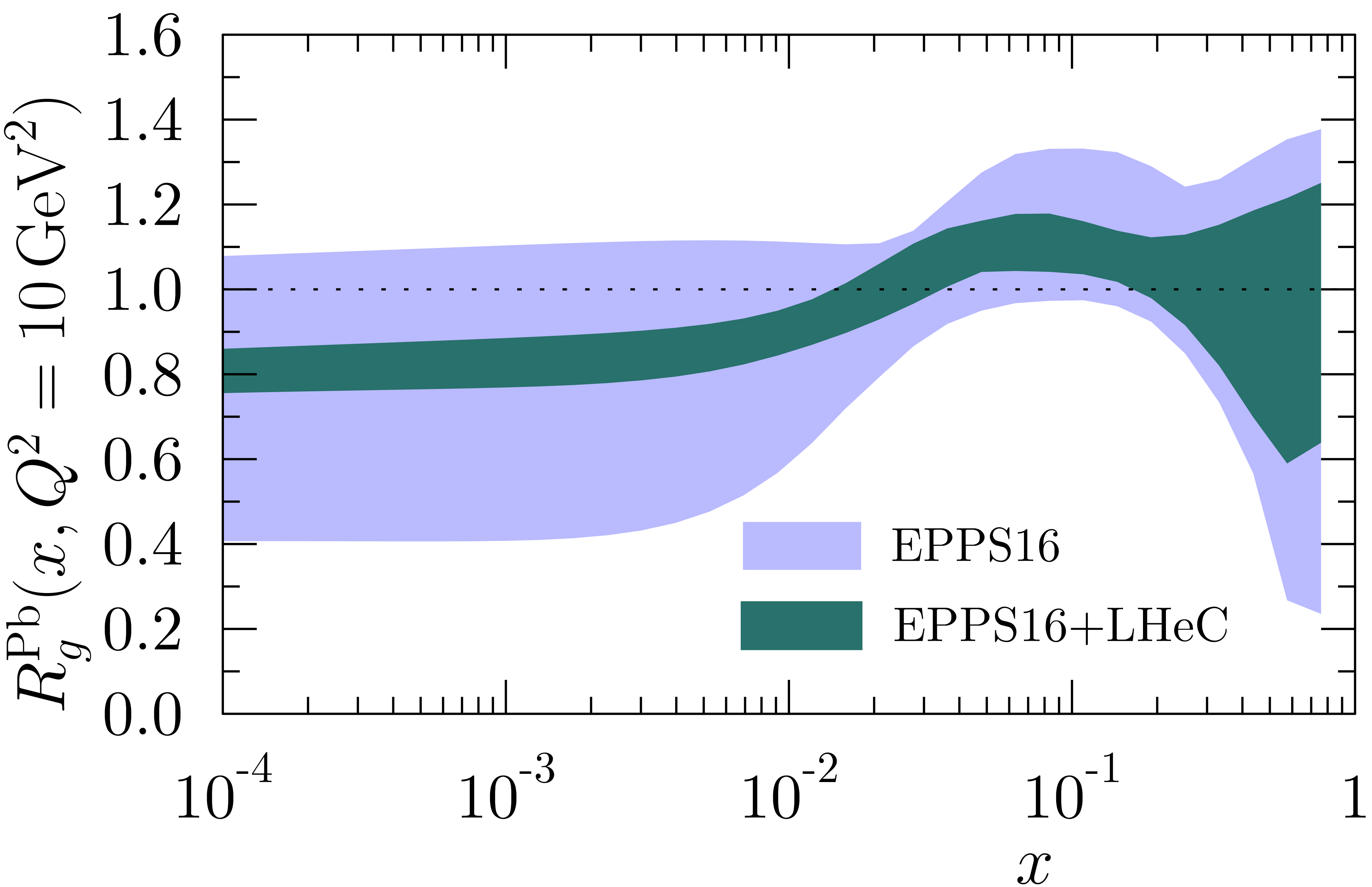


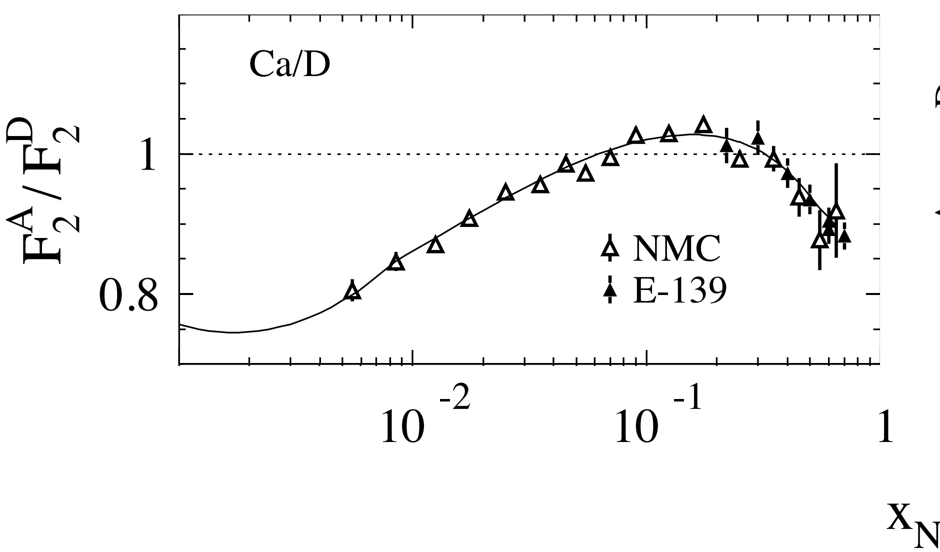
- Other proposals: fit only for one nucleus

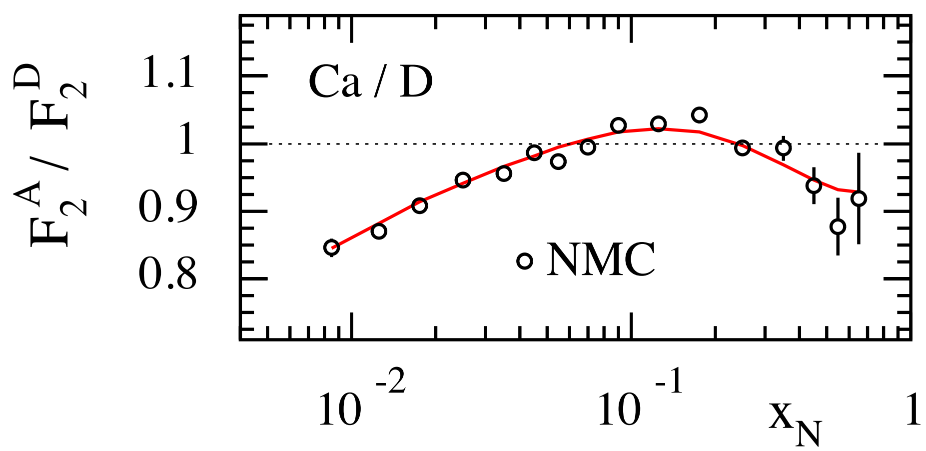
P. Agostini Infante and N. Armesto, Master Thesis, Department of Particle Physics, USC

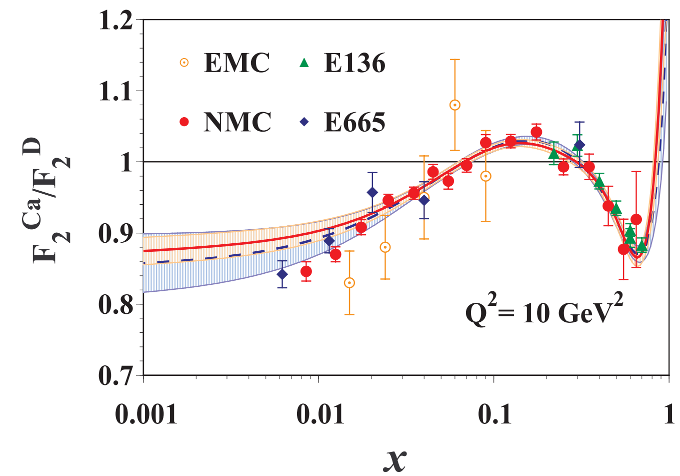
Summary

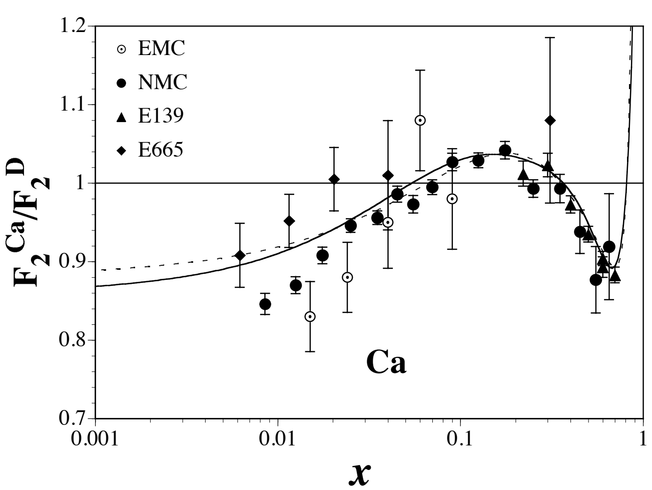
- several nPDFs sets available, comparing them is tricky

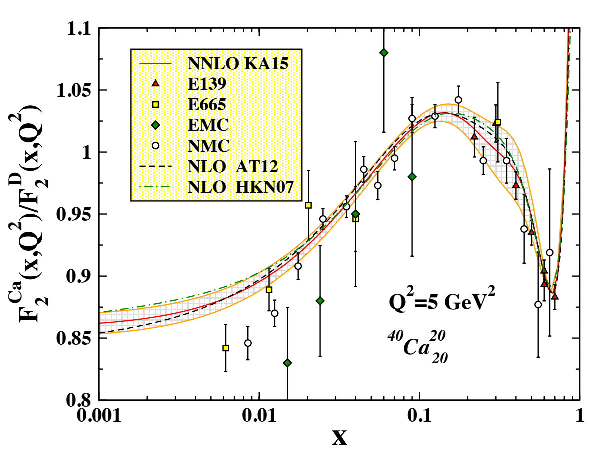
all give **NICE** descriptions of the data

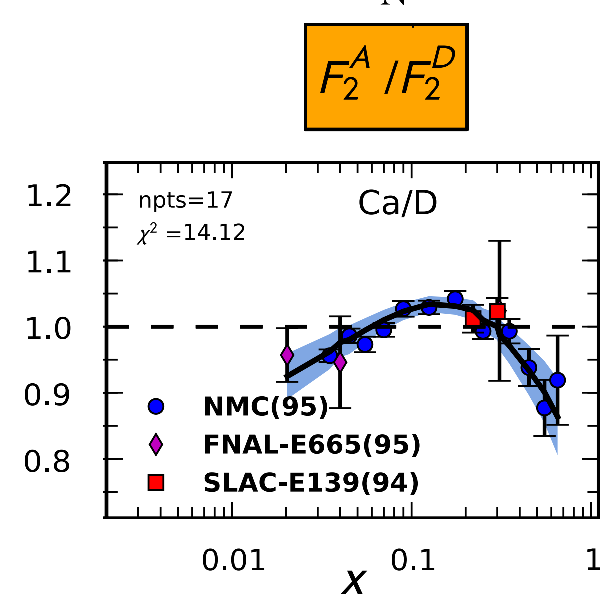


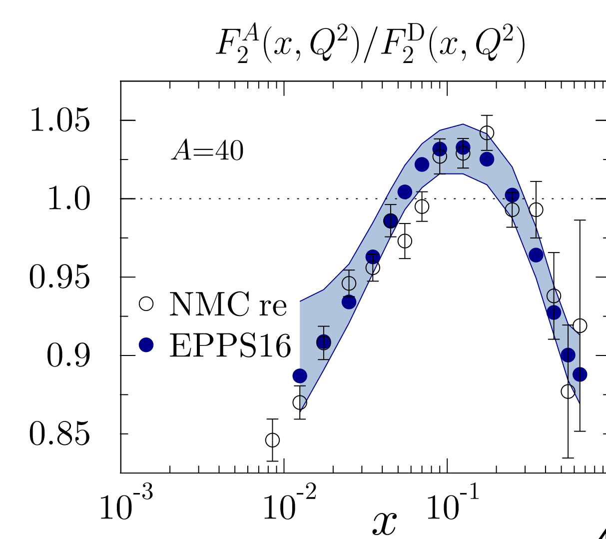












Summary

- several nPDFs sets available, comparing them is tricky
- far from the precision of proton PDFs due to the available data
- archaeological discoveries have become useful PLB 104 (1981) 335 Phys.Lett. B768 (2017) 7
- there are also a lot of data yet to be understood JHEP 1207 (2012) 073
- active work to include other data
- waiting for new results to include!

actual photo of "nPDF fitters" waiting for data (I look amazing!)

- future colliders have a huge potential to help us improve: we make impact studies!

  - for DIS at an EIC:

    - low energy: kinematical range moderately extended, high precision data
    - high energy: kinematical range extended, more chances of finding new phenomena
    - for charm: win-win situation!
    - also F_L will help determine the gluon

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    - also F_L will help determine the gluon

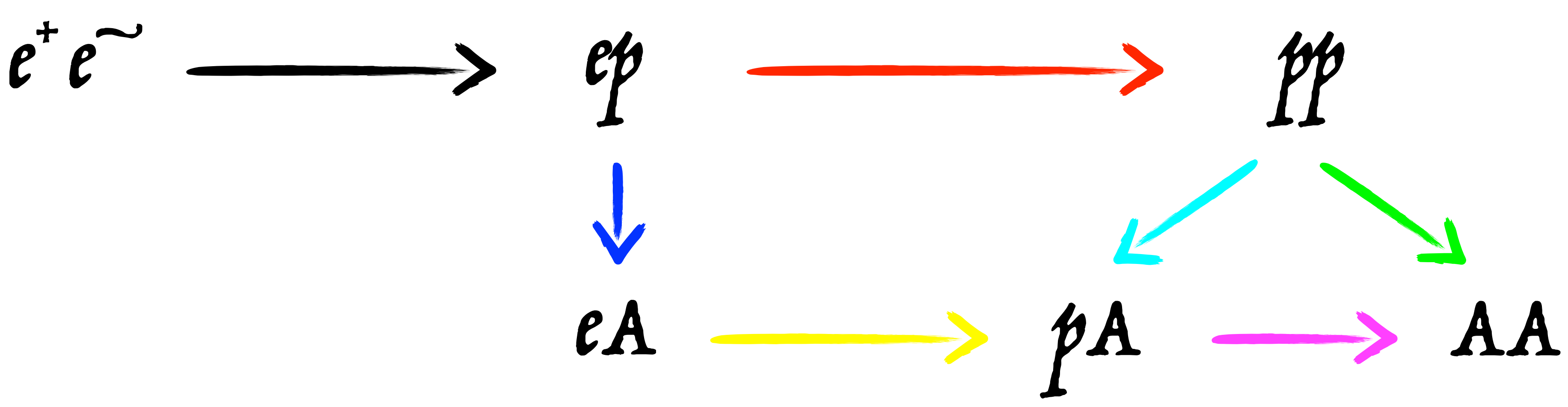
  - for jets and di-jets at an EIC:

    - relevant decrease of the gluon uncertainty
    - higher energy c.o.m. relevant

  - also great possibilities for LHeC

- Many things to do:
  - improve FFs so we can use available data
  - look for other measurements/observables (be creative!)
  - apply more refined techniques in nPDFs extractions
  - joint PDFs + nPDFs + FFs + nFFs analysis?
  - …

expectation:



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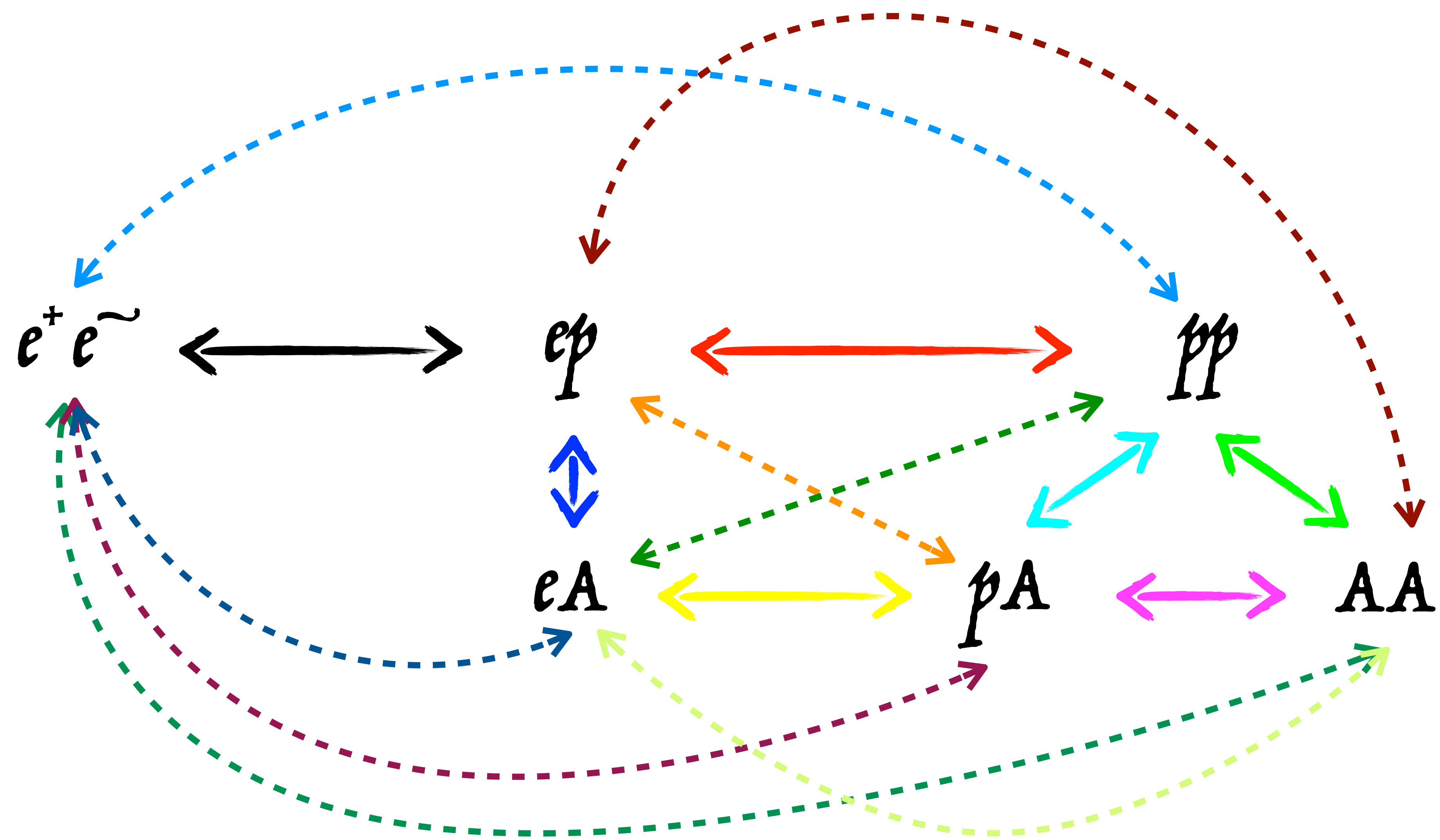
reality:



Ongoing & future work

- nPDFs NNLO in the GM-VFNS: work in progress, P.Z. and C. Andrés Casas
- nPDFs NNLO using x-Fitter: Vogelsang, Helenius et al.
- joint analysis of : Accardi et al. (see his talk at the 2017 EICUG meeting)
- nuclear PDFs from the NNPDF collaboration
- **and I'm sure, plenty more to come!**