Nuclear PDFs and electron-ion colliders

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Probing Nucleons and Nuclei in High Energy Collisions
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Why do nPDFs matter?

PDFs

$$e + p$$
$$p + p$$

$$e^+ + e^-$$

FFs

PDFs

$e + p$

$p + p$

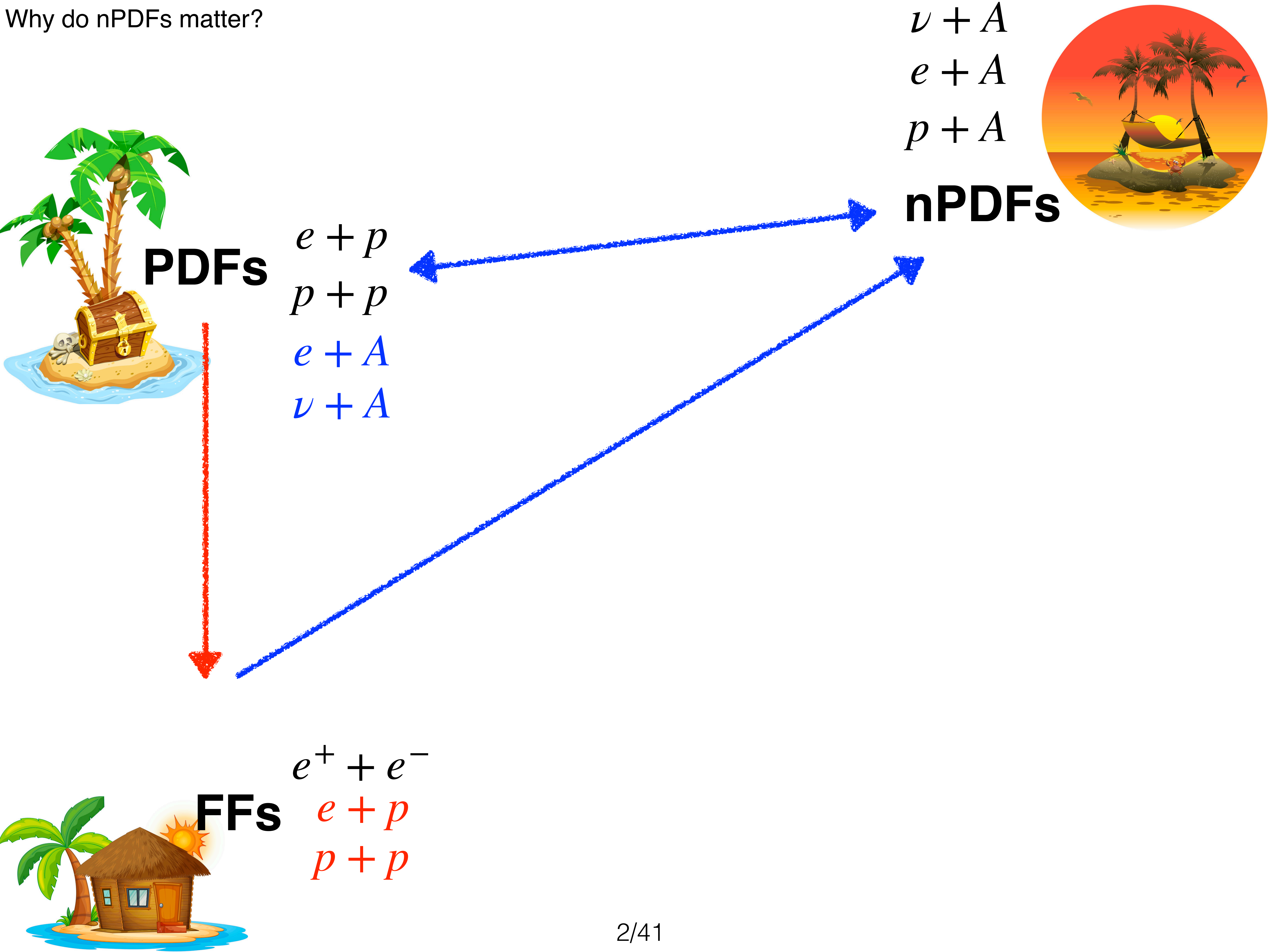
FFs

$e^+ + e^-$

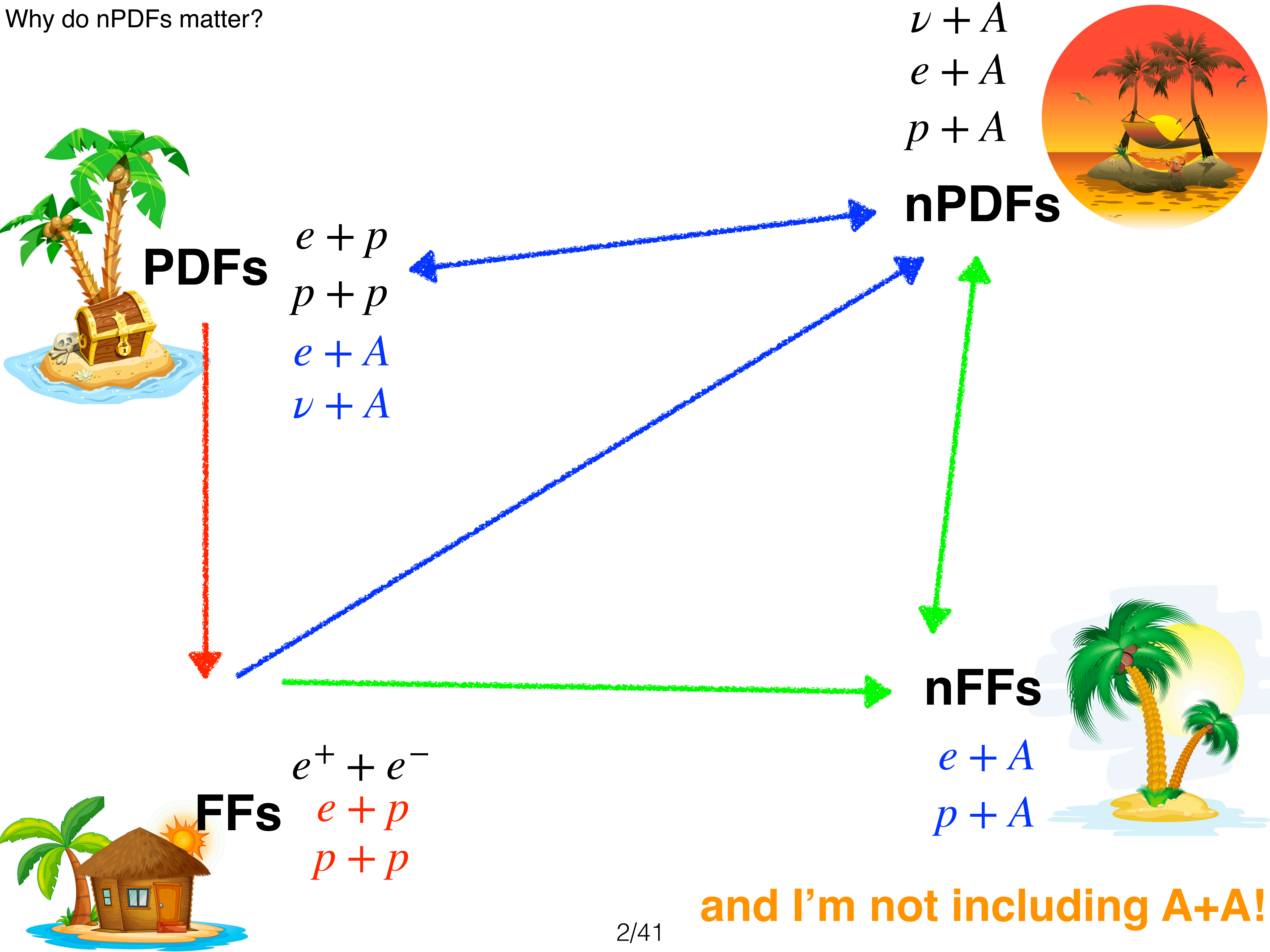
$e + p$

$p + p$

Why do nPDFs matter?



Why do nPDFs matter?



Outline

- The things we all know
- What's up with the data?
- I'm free!
- Comparing nPDFs
- What can we do with an EIC?

The things

we all know

The things we all know

"Measurement of the Ratio of Longitudinal and Transverse Structure Functions in Neutrino Interactions Between 30 GeV and 200 GeV", Phys.Lett. 107B (**1981**) 141.

"Experimental Study of the Nucleon Structure Functions and of the Gluon Distribution from Charged Current Neutrino and anti-neutrinos Interactions", Phys.Lett. 123B (**1983**) 269.

"Electron Scattering from Nuclear Targets and Quark Distributions in Nuclei", Phys.Rev.Lett. 50 (**1983**) 1431.

"*A Comparison of the Deep Inelastic Structure Functions of Deuterium and Aluminum Nuclei*", Phys.Rev.Lett. 51 (**1983**) 534.

if we maintain the partonic description

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

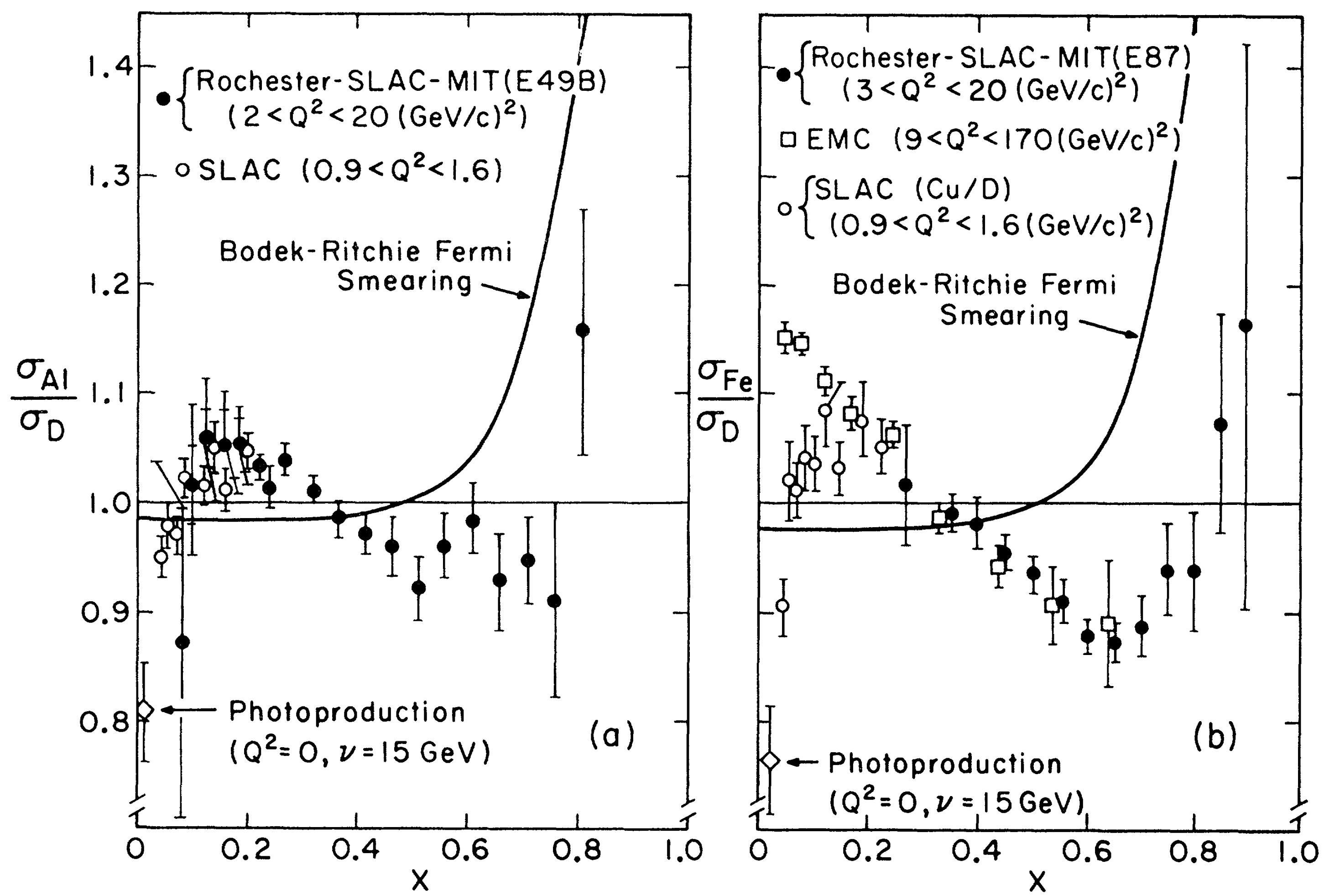


FIG. 1. (a) σ_{Al}/σ_D and (b) σ_{Fe}/σ_D vs x. Only random errors are shown. Point-to-point systematic errors have been added linearly (outer bars) where applicable. The normalization errors of ±2.3% and ±1.1% for σ_{Al}/σ_D (E49B) and σ_{Fe}/σ_D (E87), respectively, are not included. All data for $W \geq 1.8$ GeV are included. The data have been corrected for the small neutron excess and have *not* been corrected for Fermi-motion effects. The curve indicates the expected ratio if Fermi-motion effects were the only effects present (Ref. 11). High-Q^2 σ_{Fe}/σ_D data from EMC (Ref. 2), low-Q^2 σ_{Al}/σ_D and σ_{Cu}/σ_D data from Ref. 9, and photoproduction σ_{Al}/σ_D and σ_{Fe}/σ_D data from Ref. 13 are shown for comparison. The systematic error in the EMC data is ±1.5% at $x = 0.35$ and increases to ±6% for the points at $x = 0.05$ and $x = 0.65$.

Phys.Rev.Lett. 51 (1983) 534

we have the factorisation theorems

+

we know about proton PDFs

so we use the same ideas

and perform global fits to the world data

$$f_i^A(x, Q_0^2) = \frac{Z f_i^{p/A}(x, Q_0^2) + (A - Z) f_i^{n/A}(x, Q_0^2)}{A}$$

we have the factorisation theorems

+

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$$f_i^A(x, Q_0^2) = \frac{Z f_i^{p/A}(x, Q_0^2) + (A - Z) f_i^{n/A}(x, Q_0^2)}{A}$$

Are nuclear PDFs a done deal?

we have the factorisation theorems

+

we know about proton PDFs

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$$f_i^A(x, Q_0^2) = \frac{Z f_i^{p/A}(x, Q_0^2) + (A - Z) f_i^{n/A}(x, Q_0^2)}{A}$$

Are nuclear PDFs a done deal?

ABSOLUTELY NOT!

Steps for a global fit:

(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 theoretical predictions using (4)

(6) Use (1)+(5) to estimate the "goodness" of the description

(7) Repeat (6) until the description is "good enough"

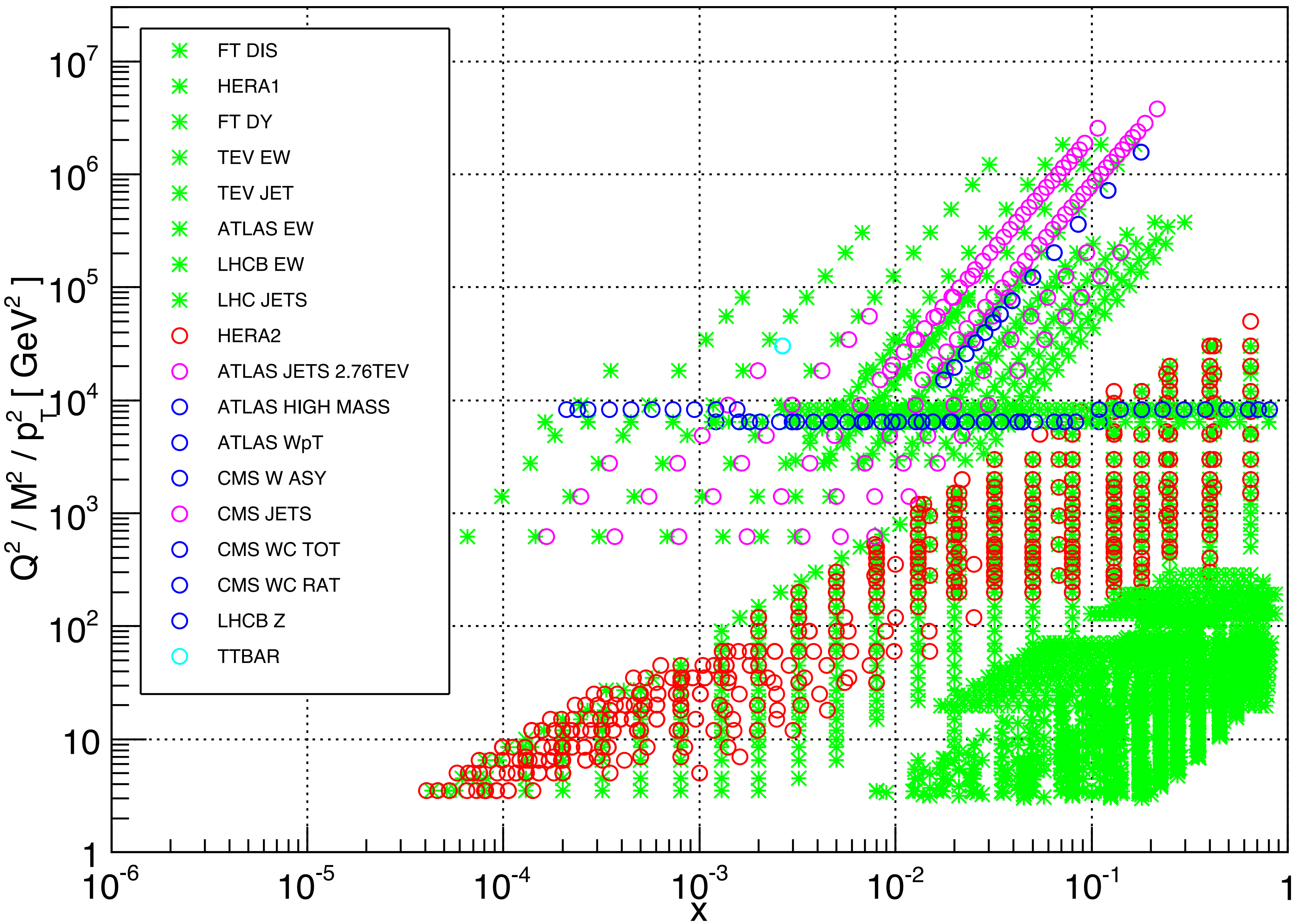
(8) Determine how much one can move the parameters without spoiling (6)

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

What's up with the data?

What's up with the data?

NNPDF3.0 NLO dataset



Ball et al., JHEP 1504 (2015) 040

for the proton

Points	**4276**
NC DIS **proton and deuteron**	51.8 %
CC DIS	4.6 %
CC DIS neutrino	22 %
DY & EW	15 %
Jets	6.6 %

What's up with the data?

for nuclei

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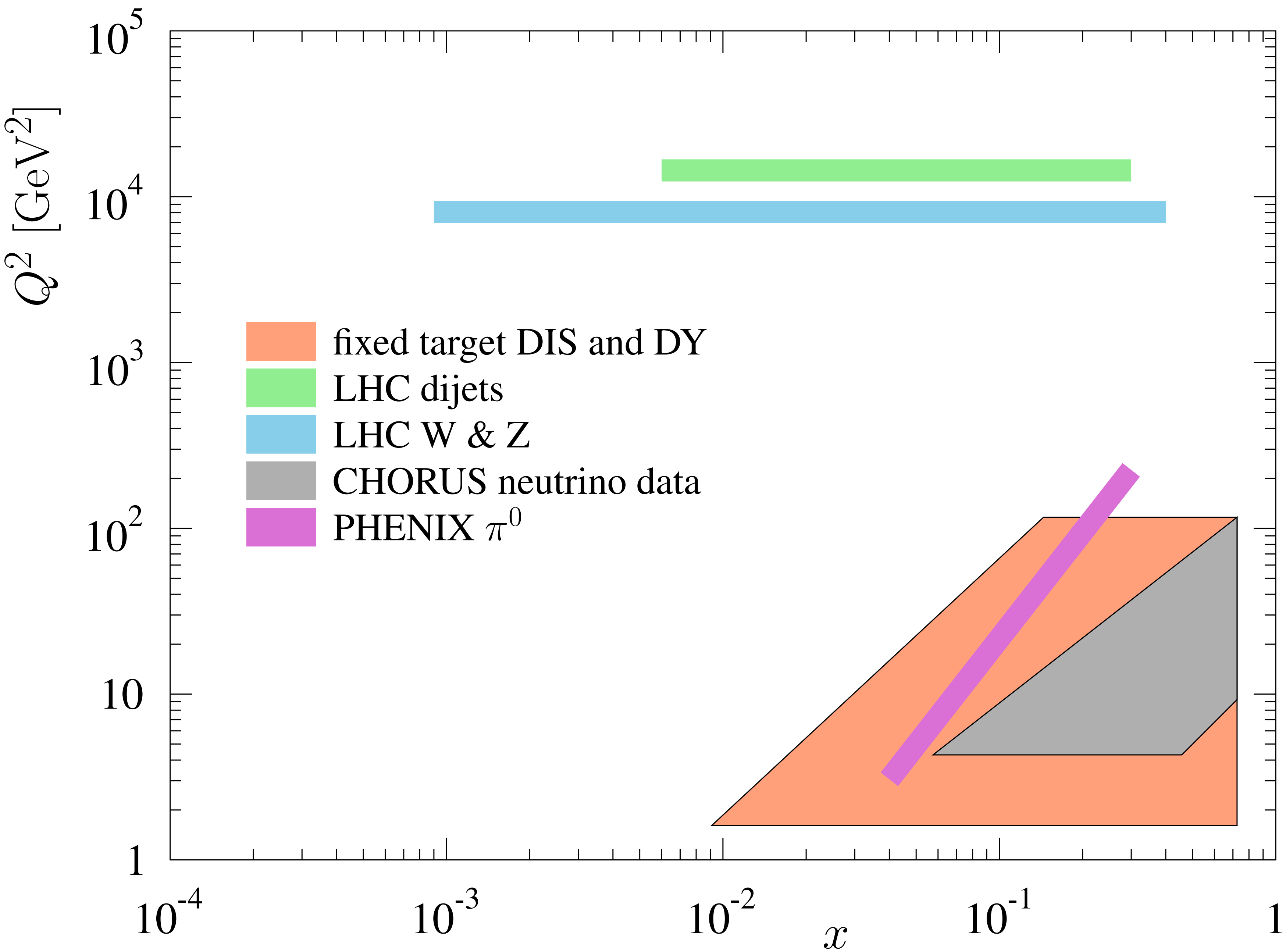

Points	**1811**
NC DIS	45.11 %
CC DIS	45.5 %
DY & EW	7.89 %
di-Jets	0.4 %
pion production	1.1 %

A	He	Li	Be	C	Al	Ca	Fe	Cu	Ag	Sn	W	Pt	Au	Pb
# points	37	168	35	232	35	66	78	19	7	159	58	7	41	869

What's up with the data?

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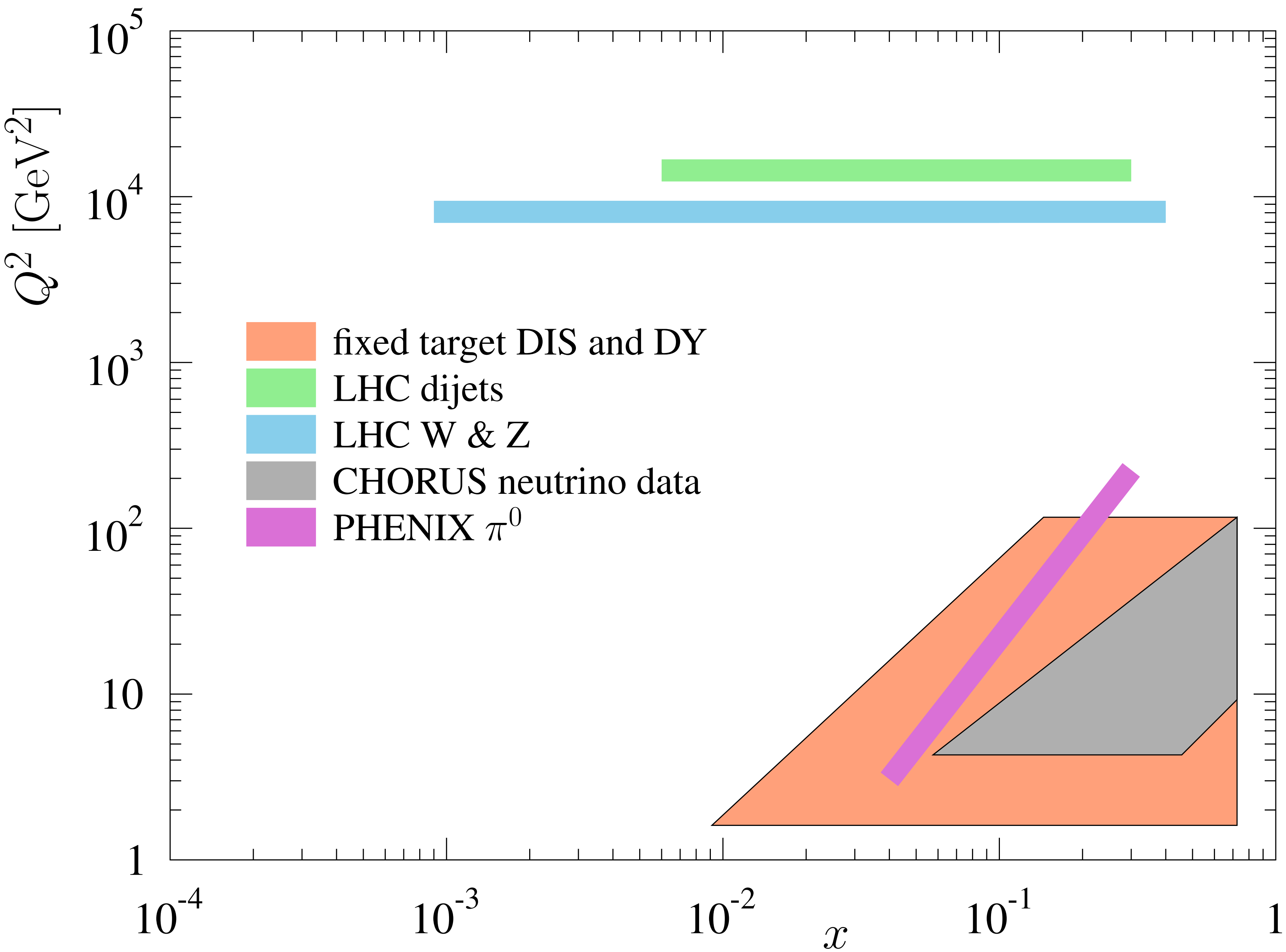

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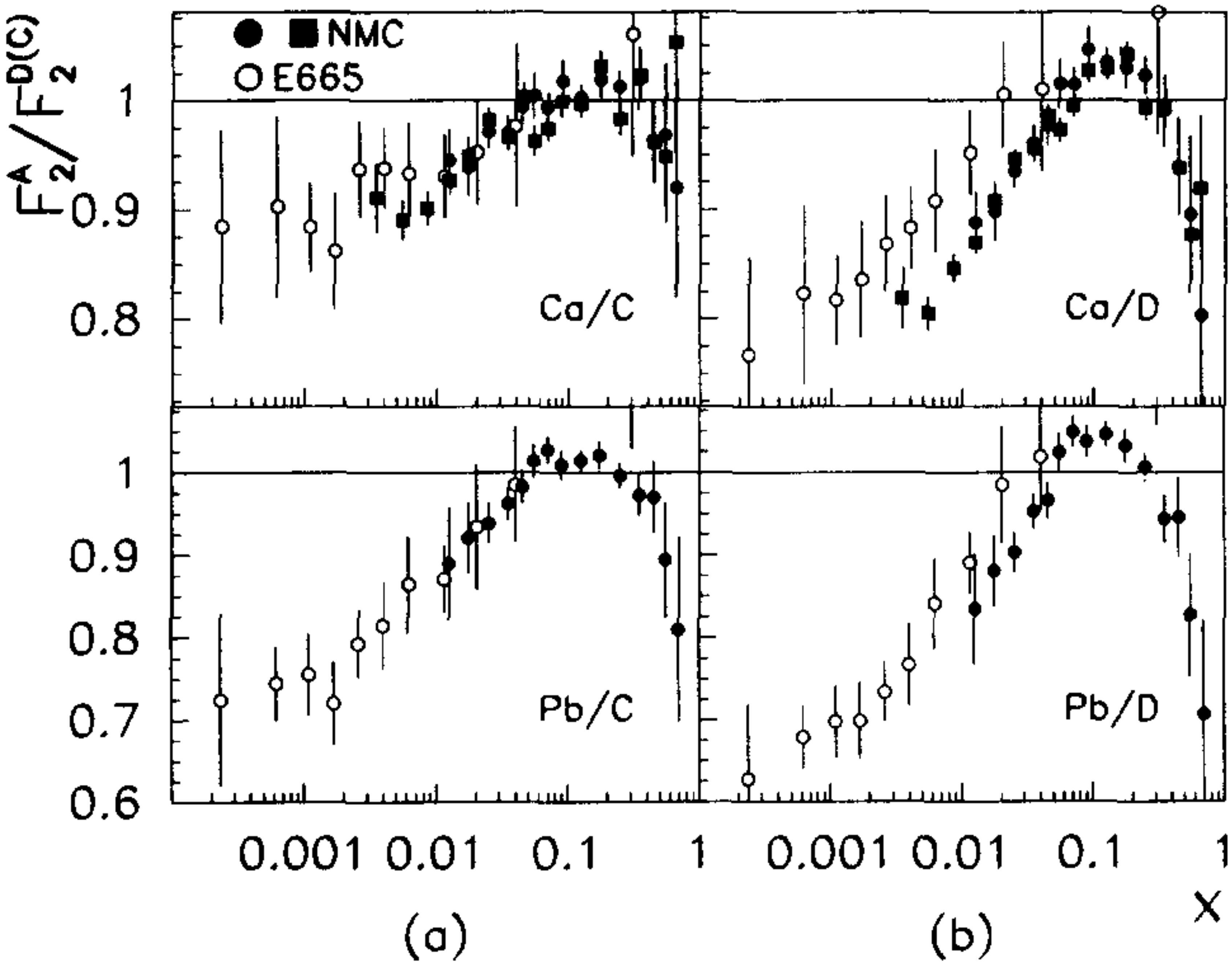
not only issues with the amount of data and the coverage

$$F_2^A / F_2^{A'}$$

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



- little sensitivity to gluons
- F_2 extraction based on parameterisations of $R = \sigma_L/\sigma_T$
- some are actually $\sigma^A/\sigma^{A'}$
- are there any ***R*** data? **YES!**
- are there any ***non-ratio*** data? **YES!**

doing some archeology, for $Q^2 > 1$ GeV^2

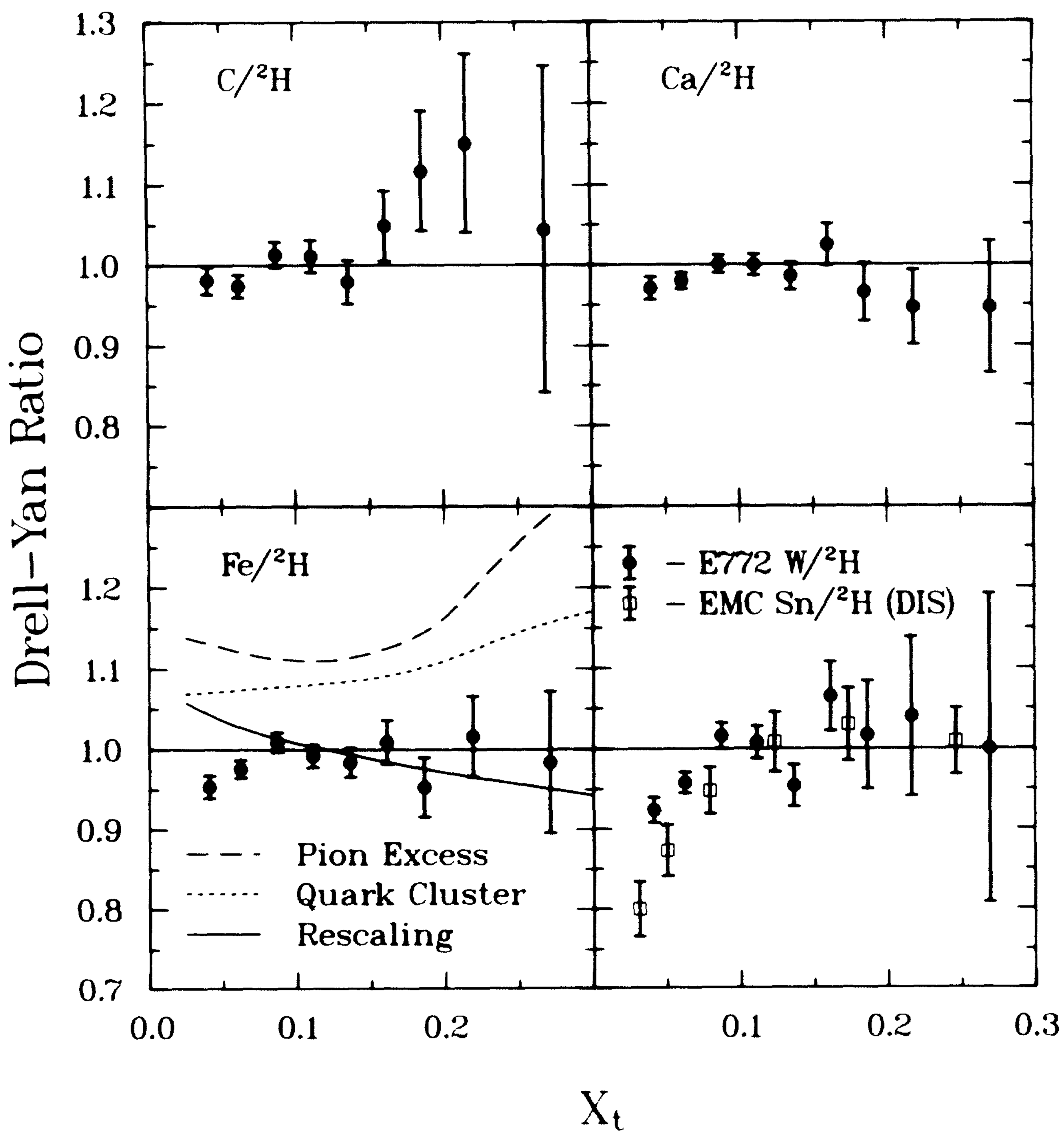
	# points
F_2 ratio	1061
σ ratio	730
F_2	927
R	79

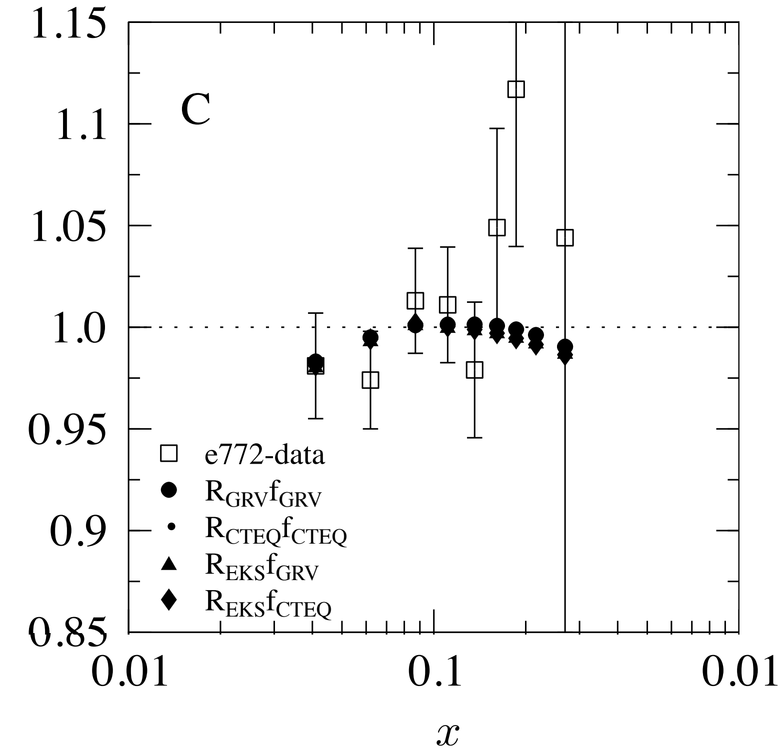
- corrections for non-isoscalarity

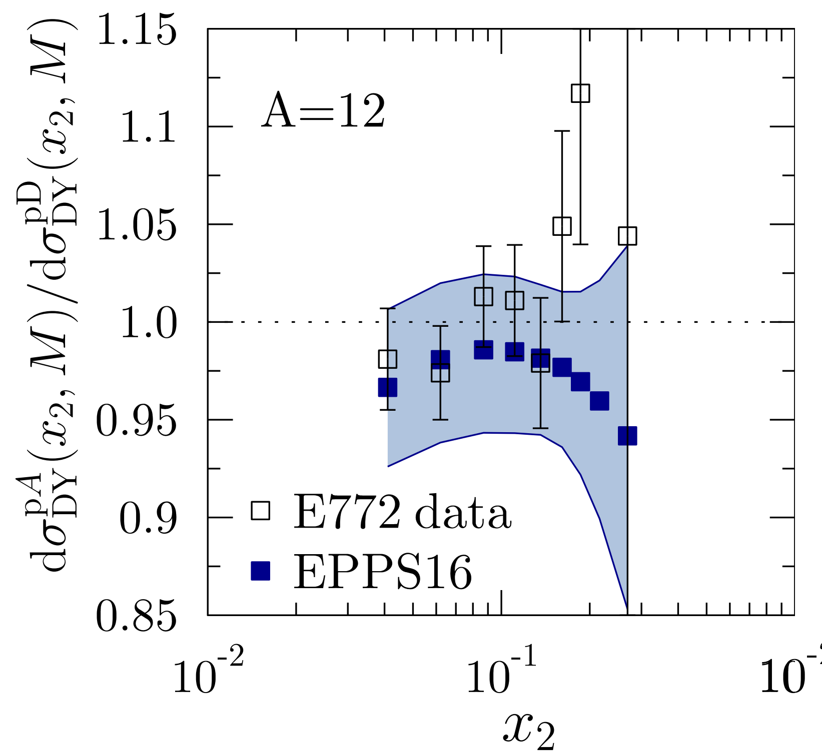
What's up with the data? Drell-Yan

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

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



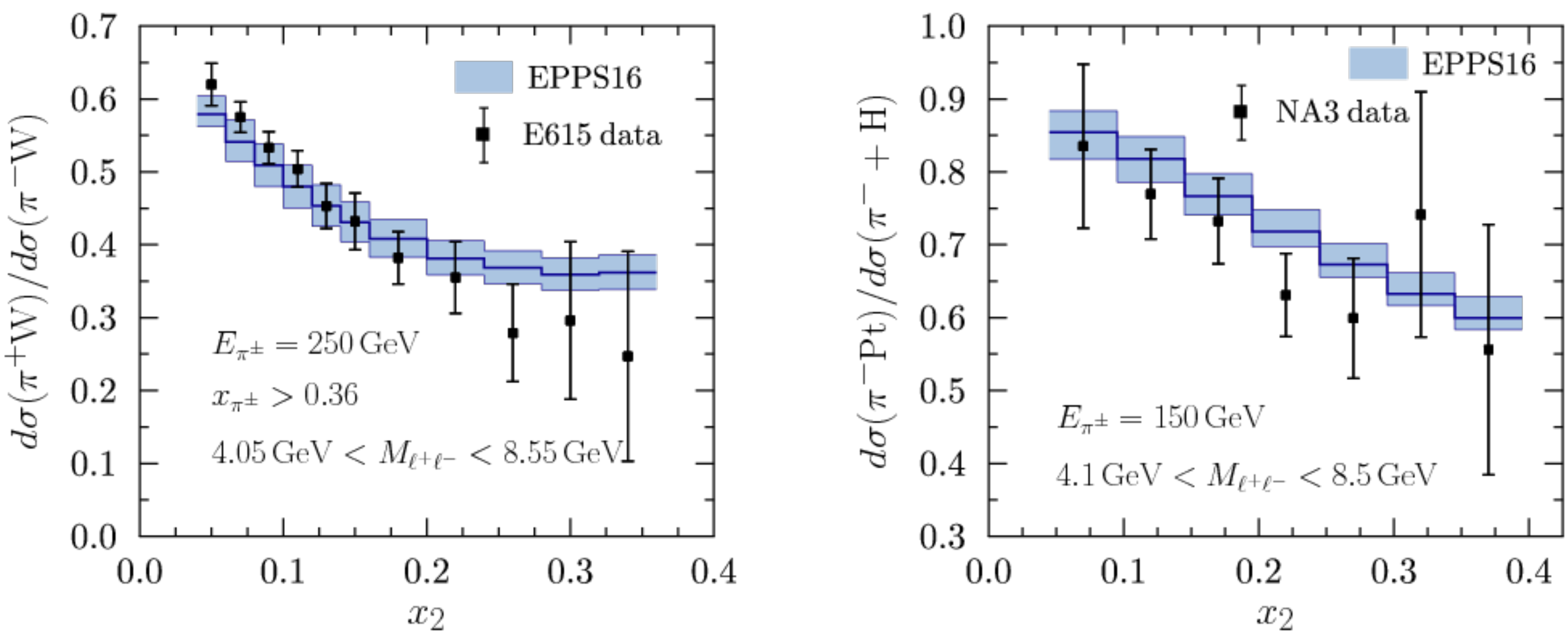




NLO: EPJ C77 (2017) no.3, 163

- some constraint on the sea
- 92-120 points
- LO/NLO very similar

- Badier, J. *et al.*, Phys.Lett. 104B (1981) 335.
- Bordalo, P. *et al.,* Phys.Lett. B193 (1987) 368.
- Heinrich, J.G. *et al.,* Phys.Rev.Lett. 63 (1989) 356.



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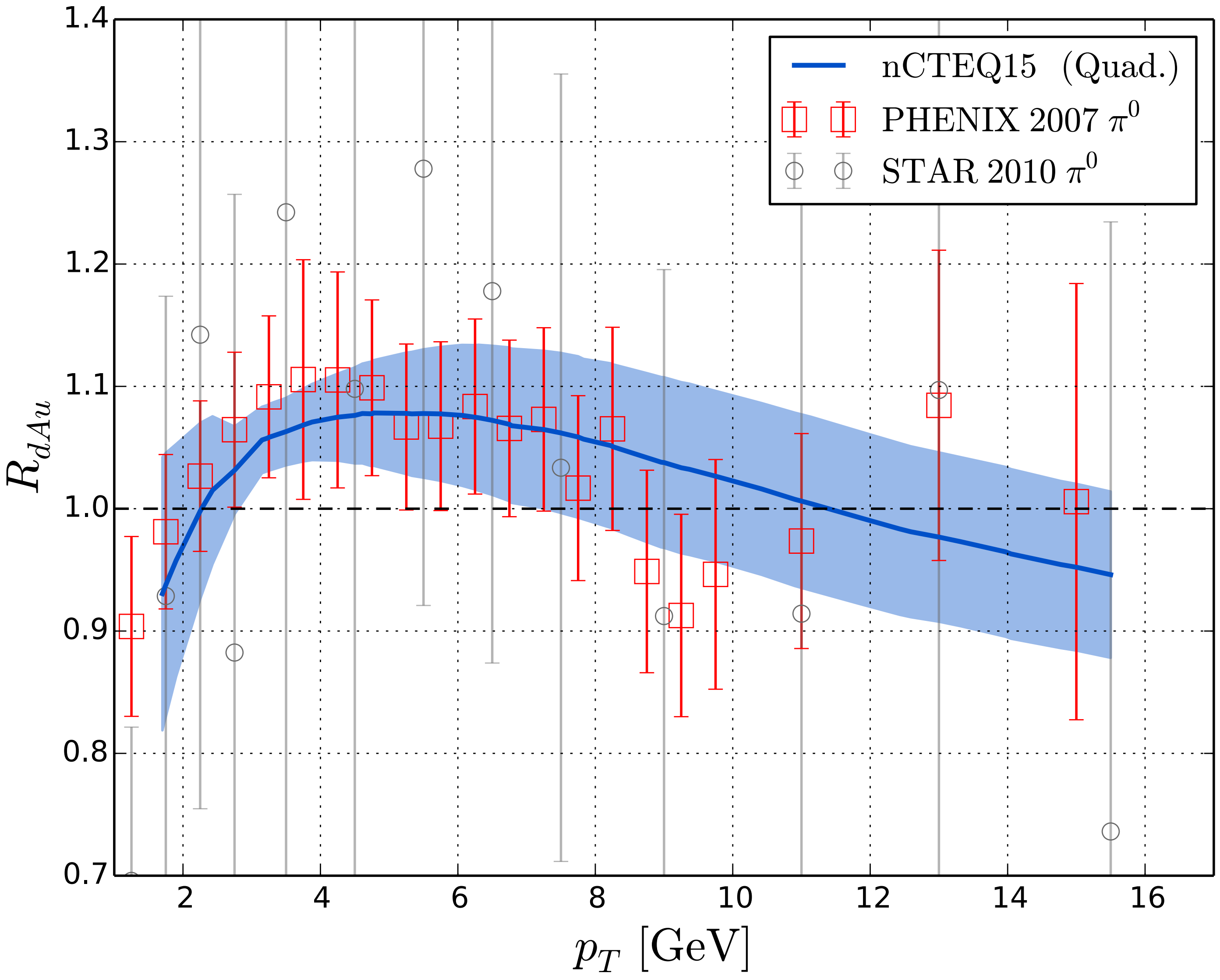
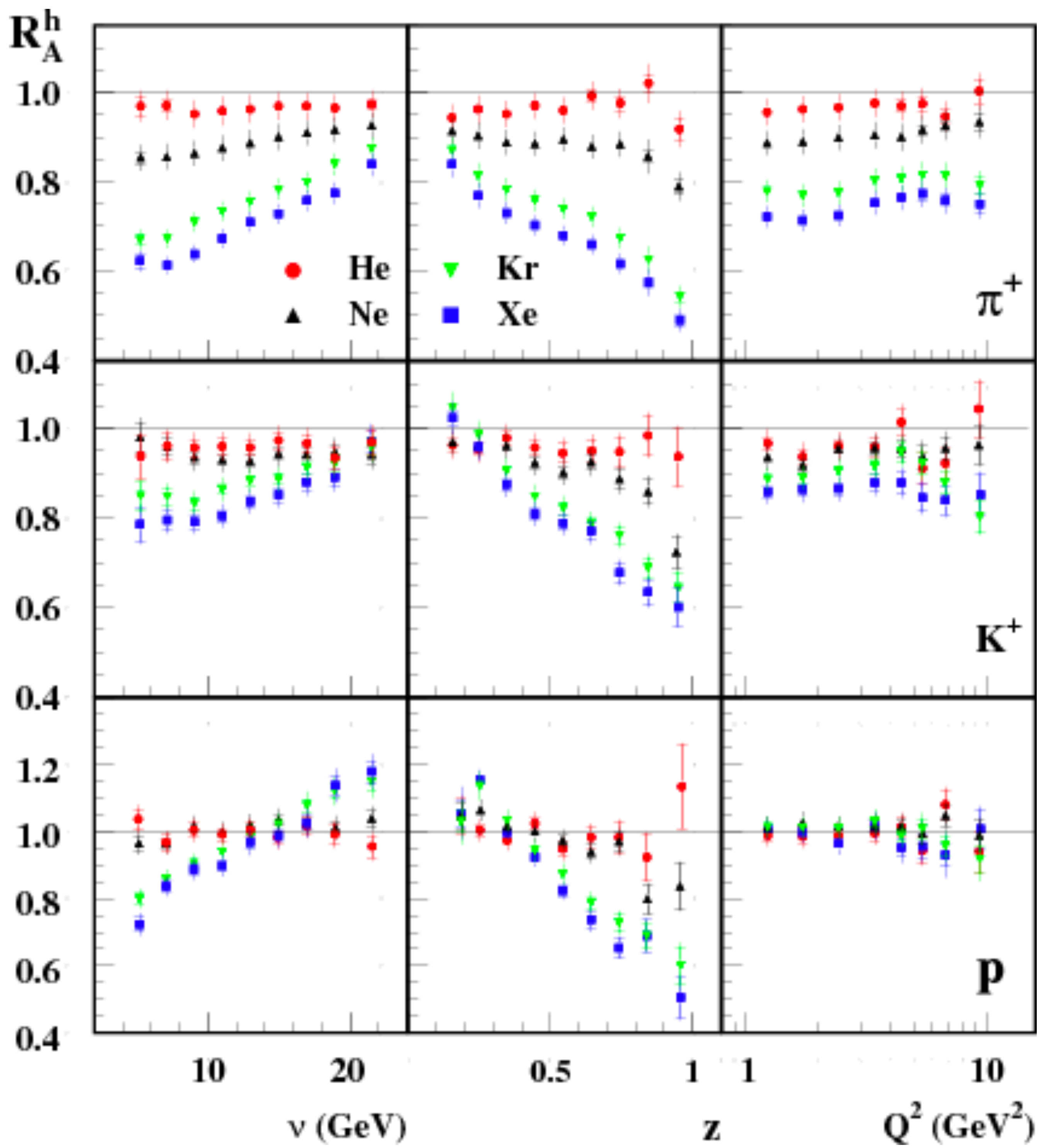
What's up with the data? π production at RHIC

PRD93 (2016) no.8, 085037



- sensitive to the gluon density
- large uncertainties
- depends on the fragmentation functions

- final state effects?



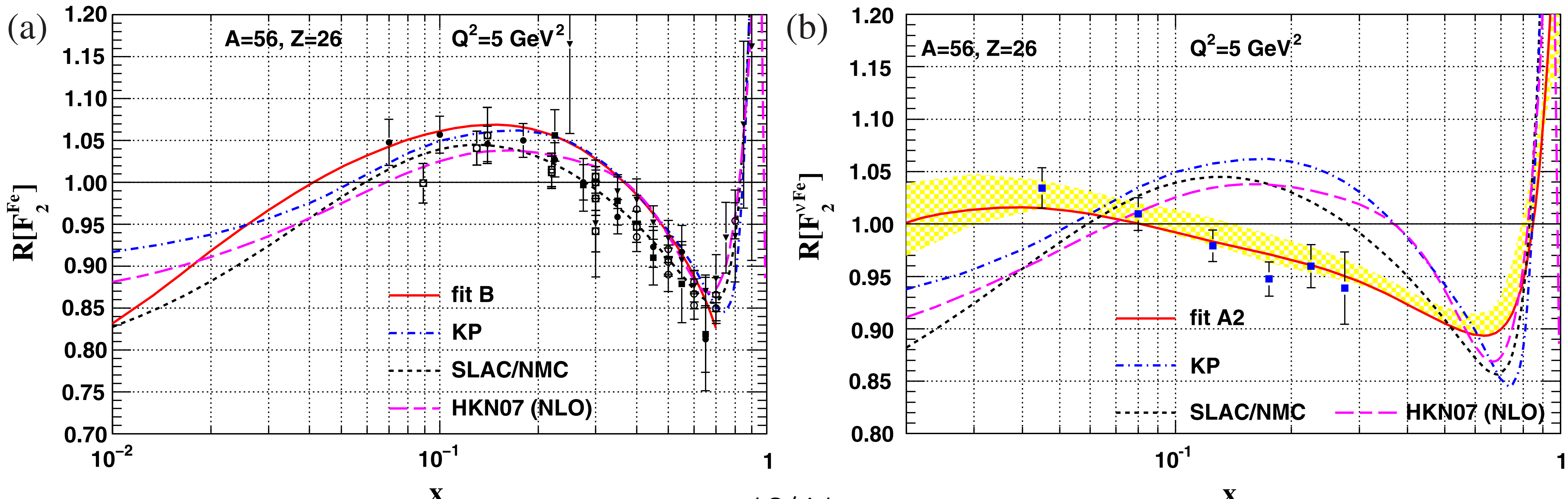
$$R_A^h(\nu, Q^2, z, p_T^2) = \frac{\left(\frac{N^h(\nu, Q^2, z, p_T^2)}{N^e(\nu, Q^2)}\right)_A}{\left(\frac{N^h(\nu, Q^2, z, p_T^2)}{N^e(\nu, Q^2)}\right)_D}$$

Airapetian et al.,
Nucl. Phys. B780 (2007) 1

What's up with the data? CC DIS

Exp.	Ref.	A	Comments
CDHSW	Z.Phys. C49 (1991) 187	Fe	structure functions in DSSZ
NuTeV	Phys.Rev. D74 (2006) 012008	Fe	structure functions in DSSZ
CHORUS	Phys.Lett. B632 (2006) 65	Pb	structure functions in DSSZ cross-sections in EPPS16

Also: CCFR, IHEP-JINR, CHARM, Gargamelle, NOMAD, Minerva



- the ratio **is** different
- no proton reference for these experiments
- the problem seems to be NuTev data, only for the σ
  - normalisation uncertainties in some energy bins
  - only when considering the covariance matrix

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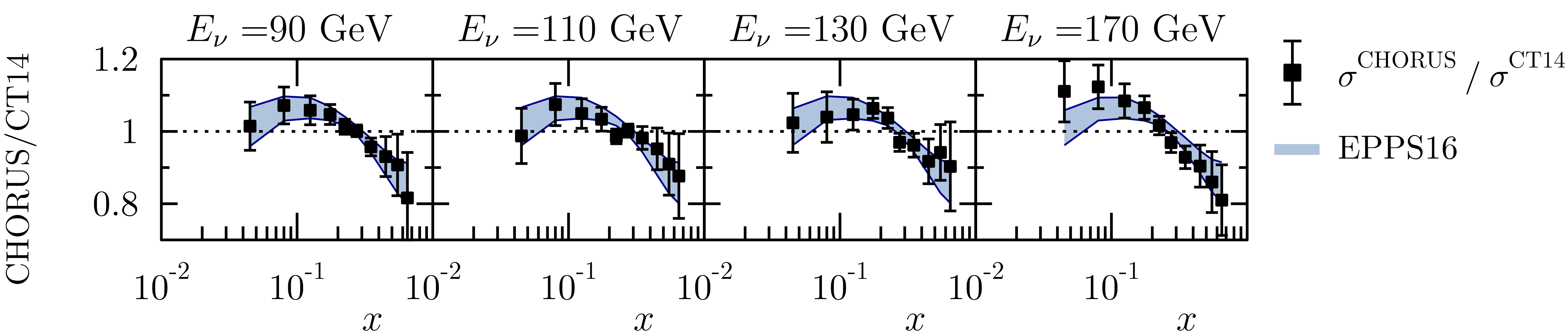


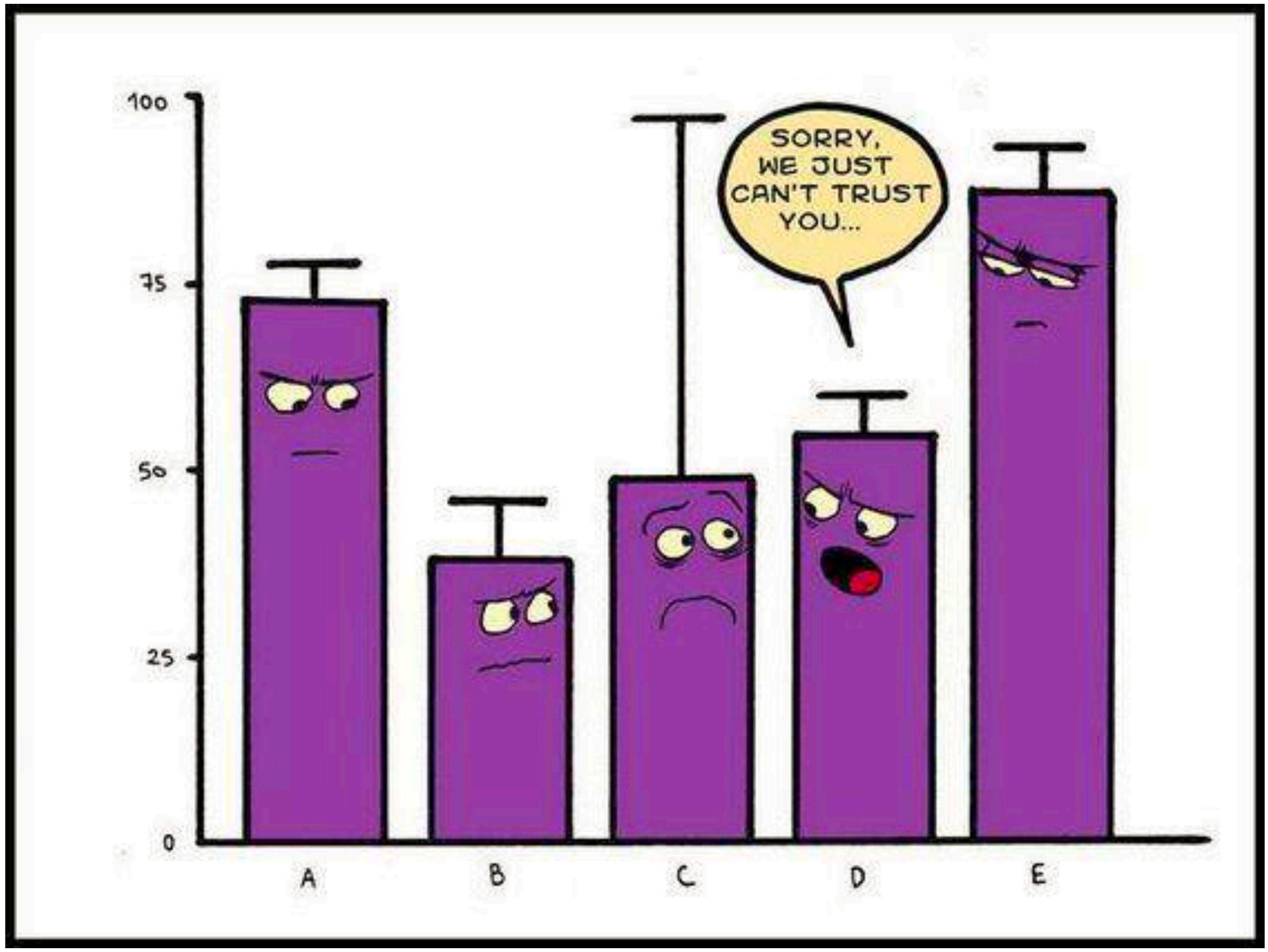
OPEN ISSUE

I'm free!

(all I can do and how it impacts the results)

I get to pick!

- the data
  - ratios, F_2, cross-sections?
  - DIS, DY, jets, hadrons?
  - non-isoscalar corrections?
  - kinematical cuts
  - etc.



- the theory
  - FFs, final state effects?
  - scales?
  - nuclear effects for deuteron?
  - proton PDF reference?
  - etc.

(2) the parameterisation

- 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

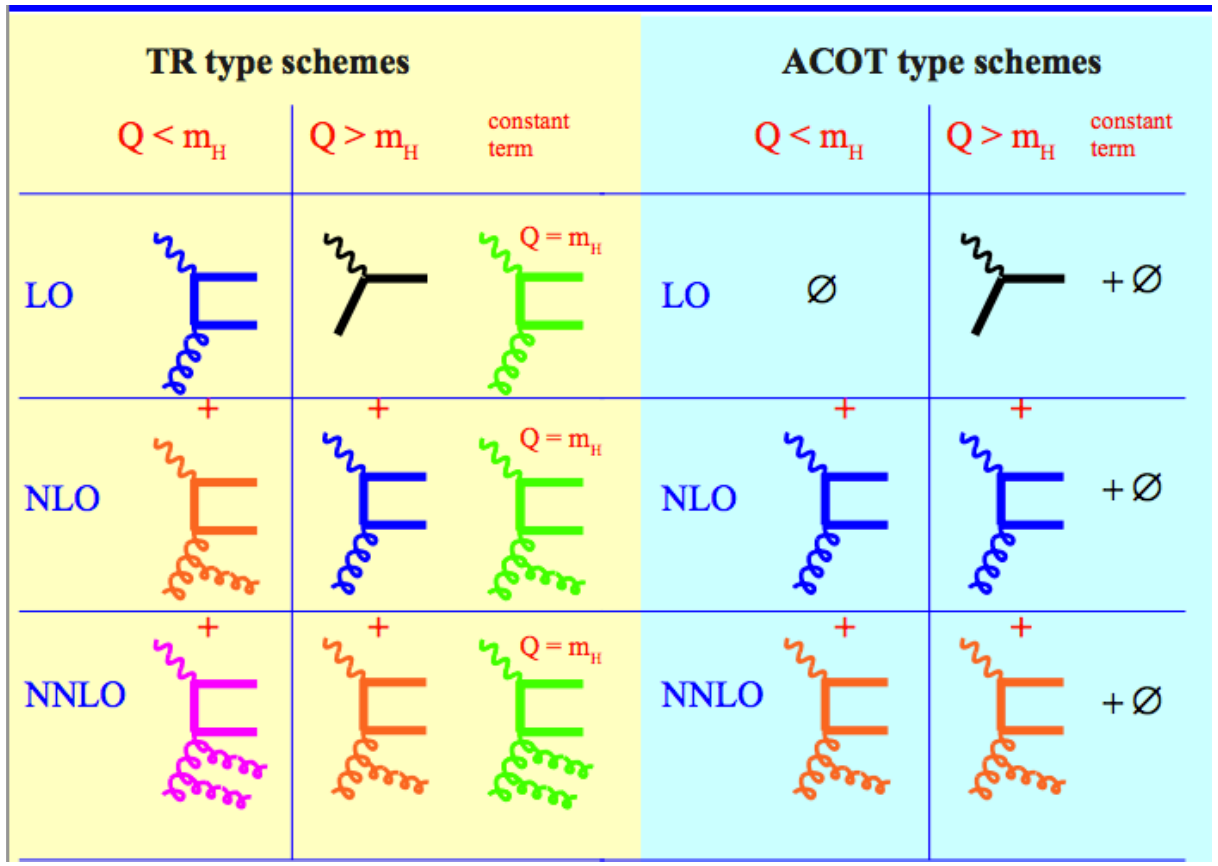
- somehow include the nuclear dependence (limit for A=1?)
  - HKM, HKN, EPS09, DSSZ, KA15, EPPS16 $$f_{i/A}\left(x, Q_0^2\right) \equiv f_{i/p}\left(x, Q_0^2\right) R_i^A\left(x, Q_0^2\right)$$
  - nDS $$f_{i/A}\left(x, Q_0^2\right) \equiv \int_x^A \frac{dy}{y} W_i^A\left(y, Q_0^2\right) f_i^p\left(\frac{x}{y}, Q_0^2\right)$$
  - nCTEQ: directly parameterise the nPDF

(5) theoretical predictions

- choose perturbative order: LO, NLO, NNLO, …
- understand clearly what it means in terms of α_s
- how do we treat the heavy-quarks?

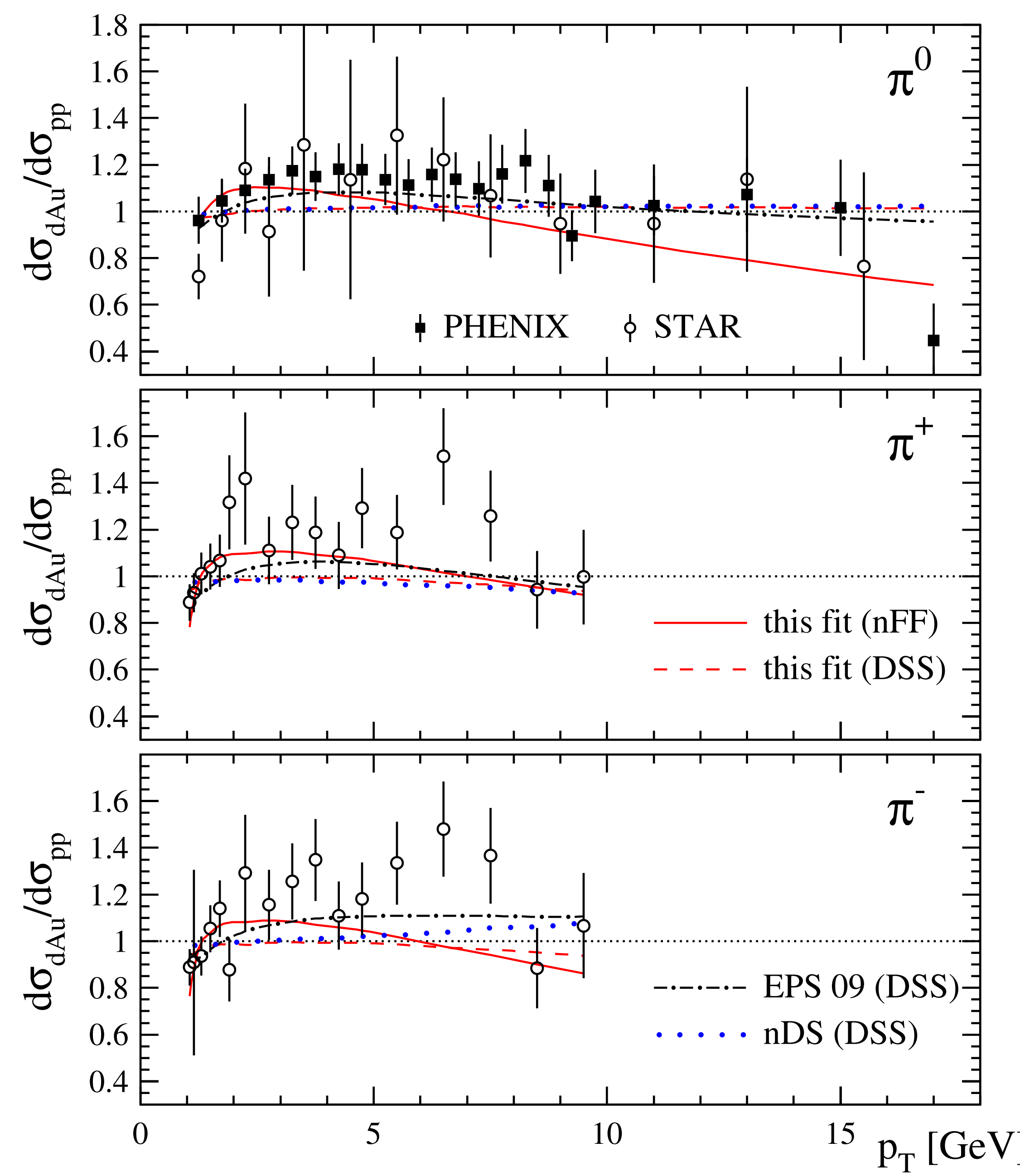
xFitter manual: https://www.xfitter.org/

- GM-VFNS: TR', ACOT, SACOT, FONLL, …?
- FFNS
- ZM-VFNS



- nuclear effects in the deuteron?
    - in HKN07 (and CTEQ15?)
- final state effects for hadrons?
    - only in DSSZ
    - 25% variation in RHIC χ^2
    - < 2% variation on the fit χ^2

PRD85 (2012) 074028



(6) χ^2

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

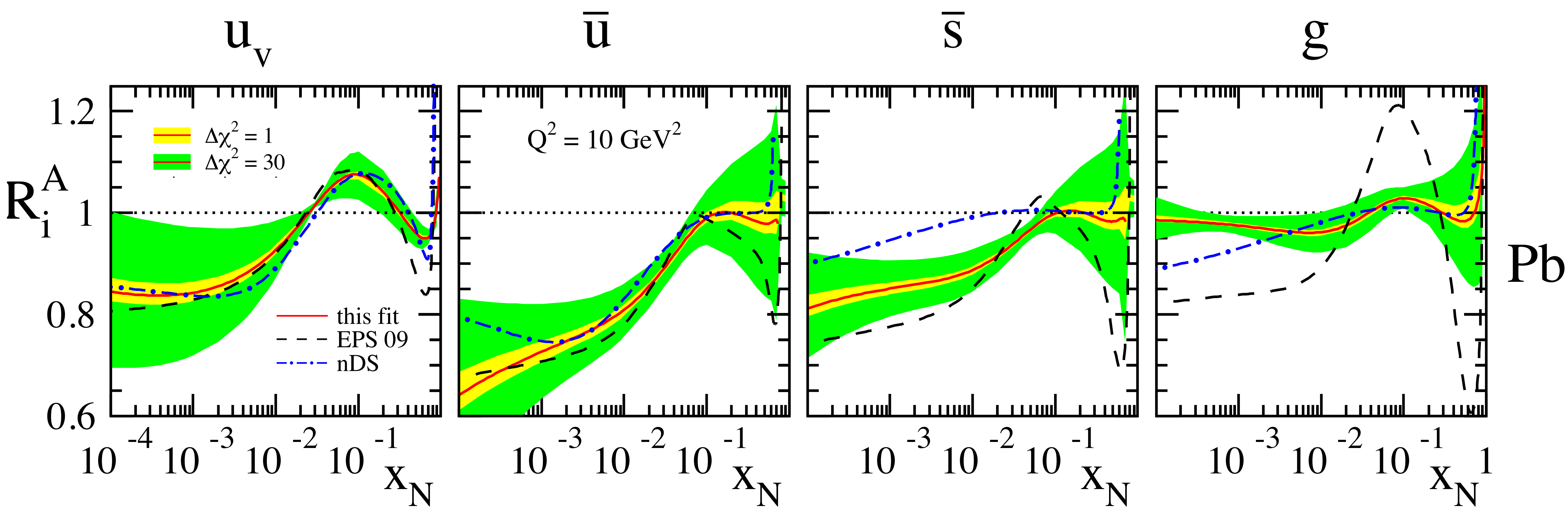
$\mathbf{a}$: parameters
$T_i(\mathbf{a})$: theoretical value of datapoint "i"
E_i : experimental value of datapoint "i"
$C_{i,j}$: **covariance matrix**

if not know ↓

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

(7) the fit

- average number of parameters: ~ 20
- multiple local minima, very hard to find the absolute minimum
- poor sensitivity to some flavours
- can give relevance to some data sets by adding weights



PRD85 (2012) 074028

(8) the hessian uncertainties

- quadratic expansion the around the global minimum

not always enough!

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

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

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

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

More information in:
- J. Pumplin, D. Stump, and W. Tung, Phys.Rev. D65 (2001) 014011.
- J. Pumplin, D. Stump, R. Brock, D. Casey, J. Huston, Phys.Rev. D65 (2001).

- in the new parameter space

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

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

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

$$\Delta z_i = \frac{t_i^+ + t_i^-}{2}$$

we get a choice!

- defining the PDFs error sets $S_i^\pm$

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

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

More information in:
- J. Pumplin, D. Stump, and W. Tung, Phys.Rev. D65 (2001) 014011.
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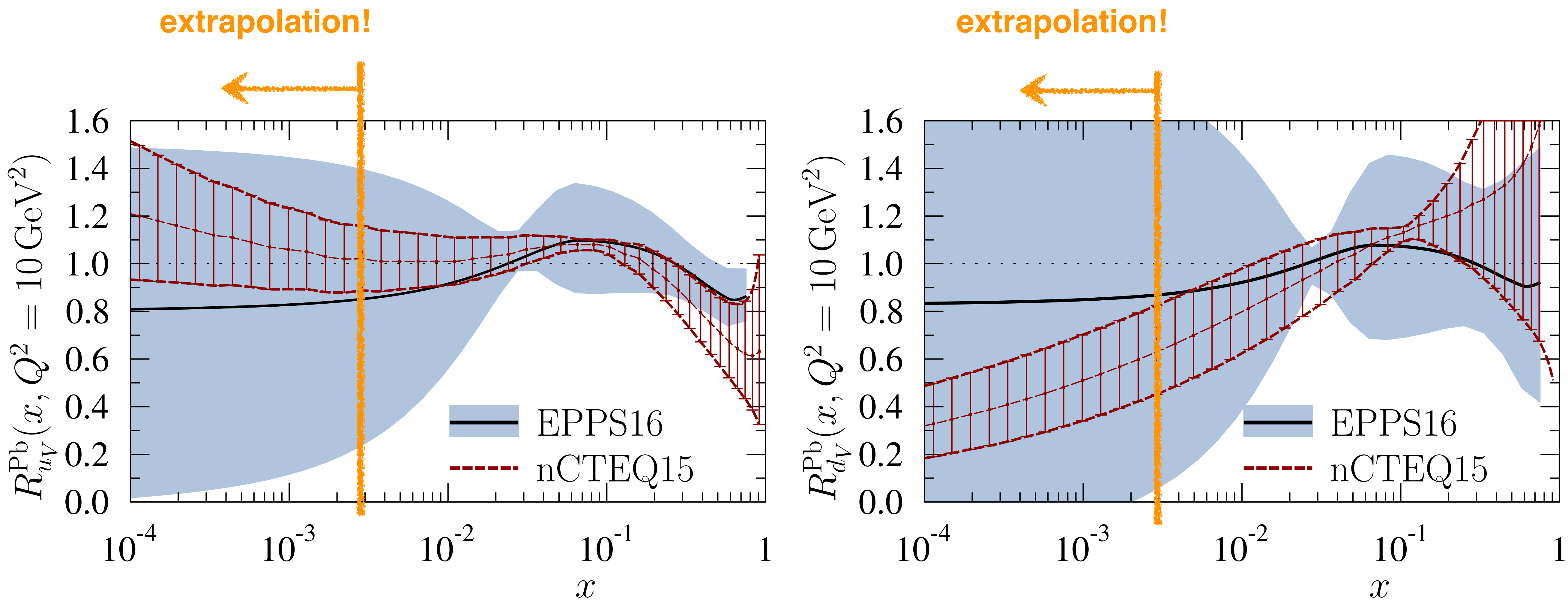
Comparing nPDFs

Comparing nPDFs: the valence



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for NC DIS

proton

$$\frac{4}{9}u + \frac{1}{9}d$$

$\longrightarrow$

nucleus

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

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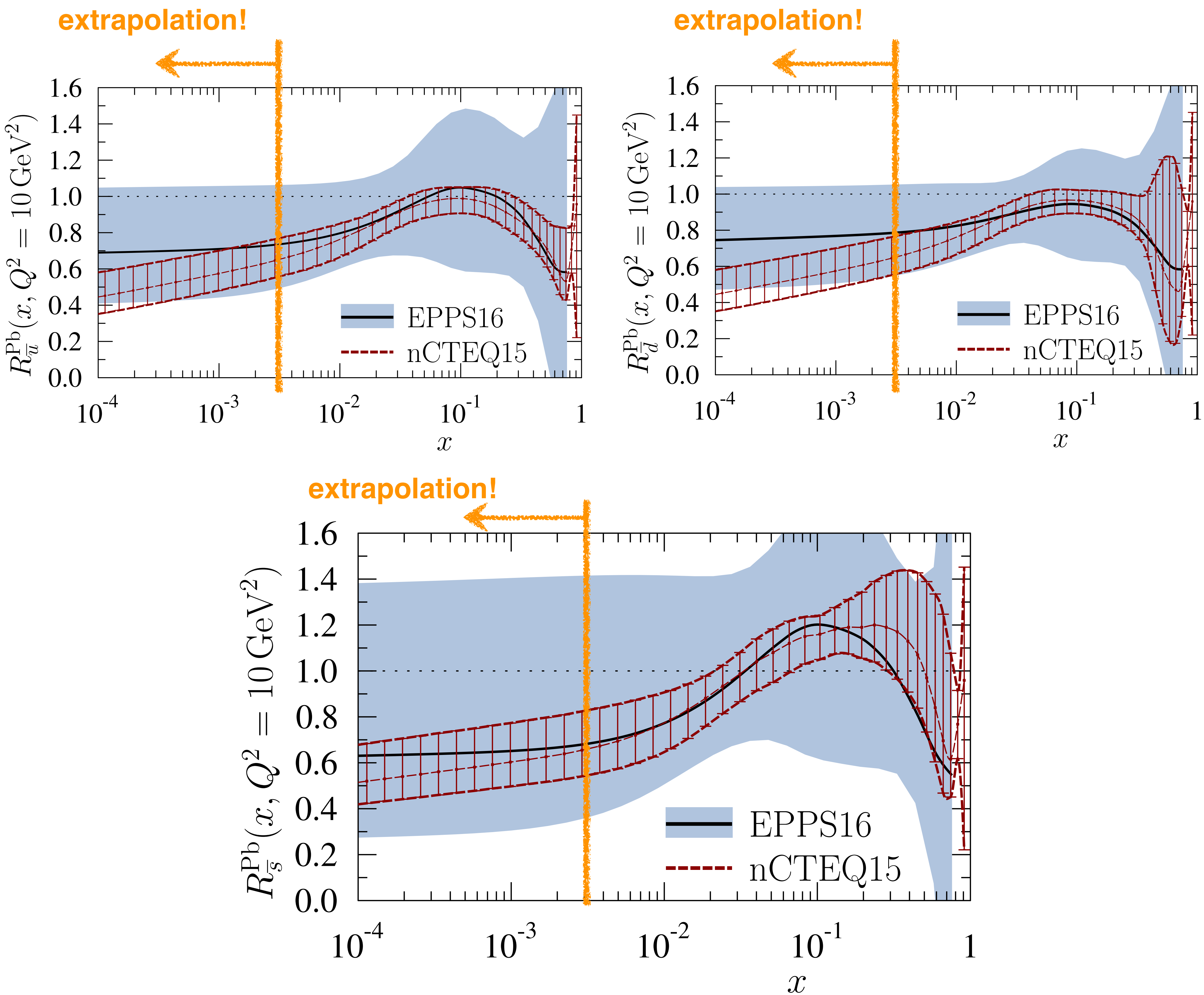
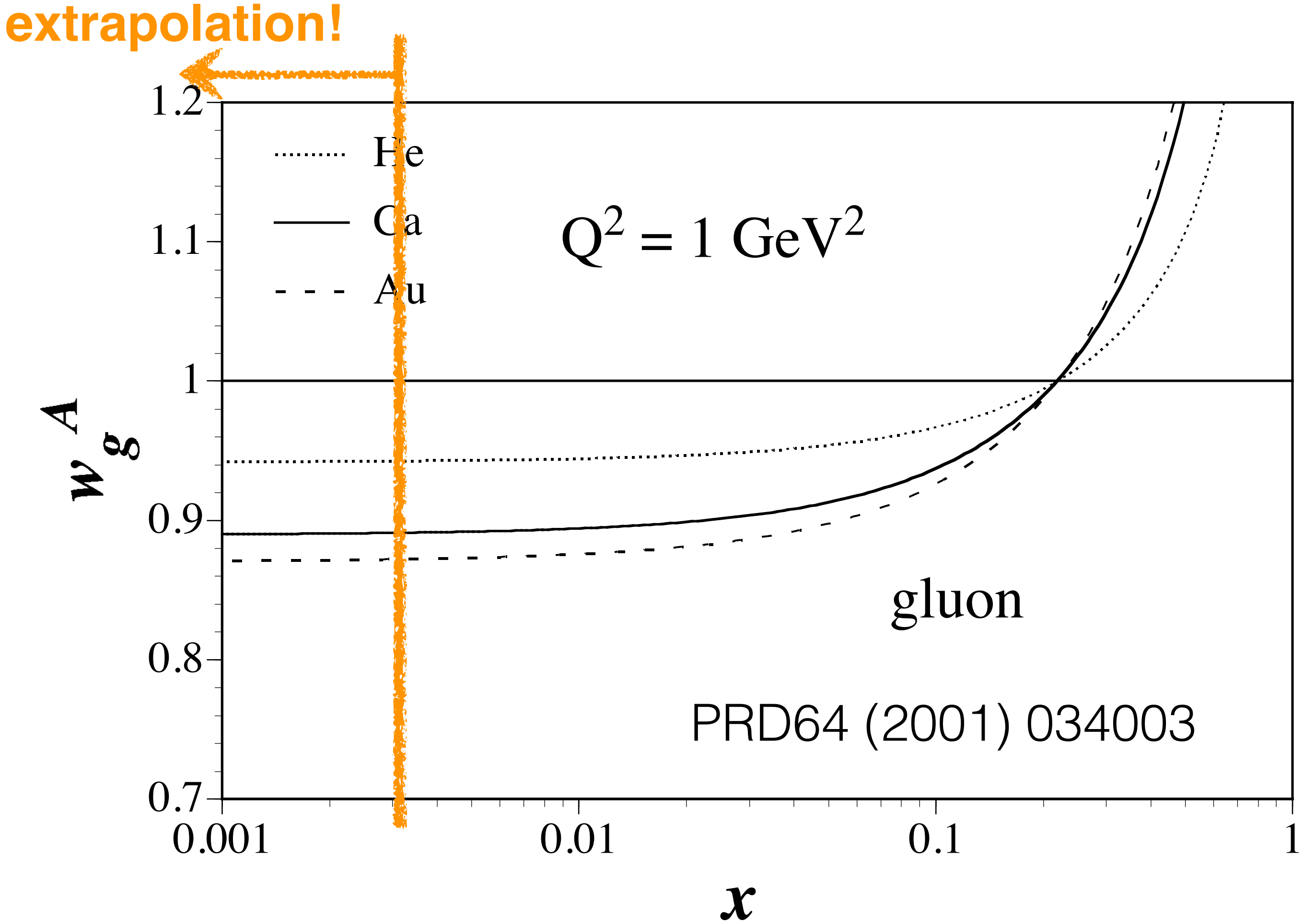
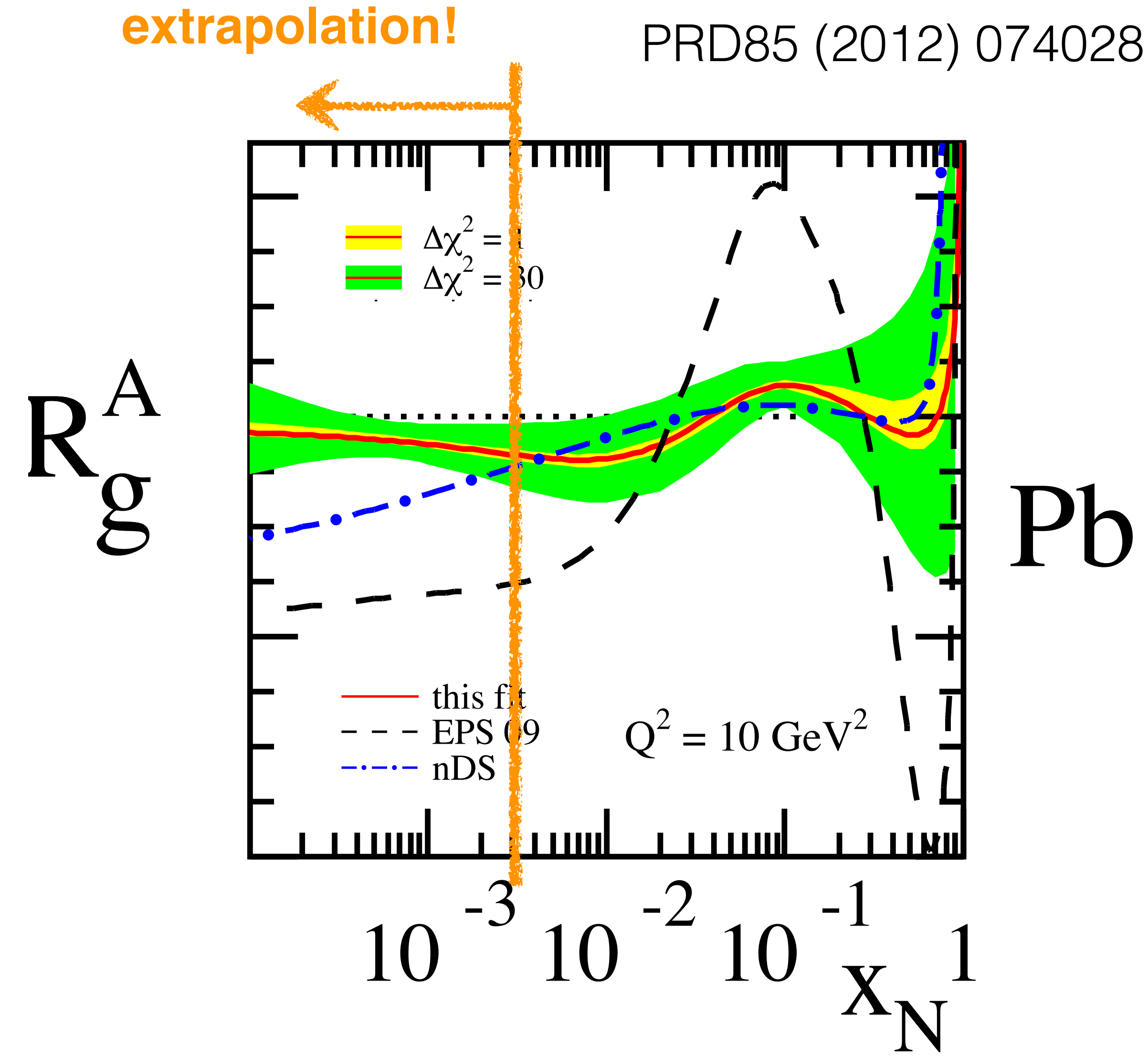
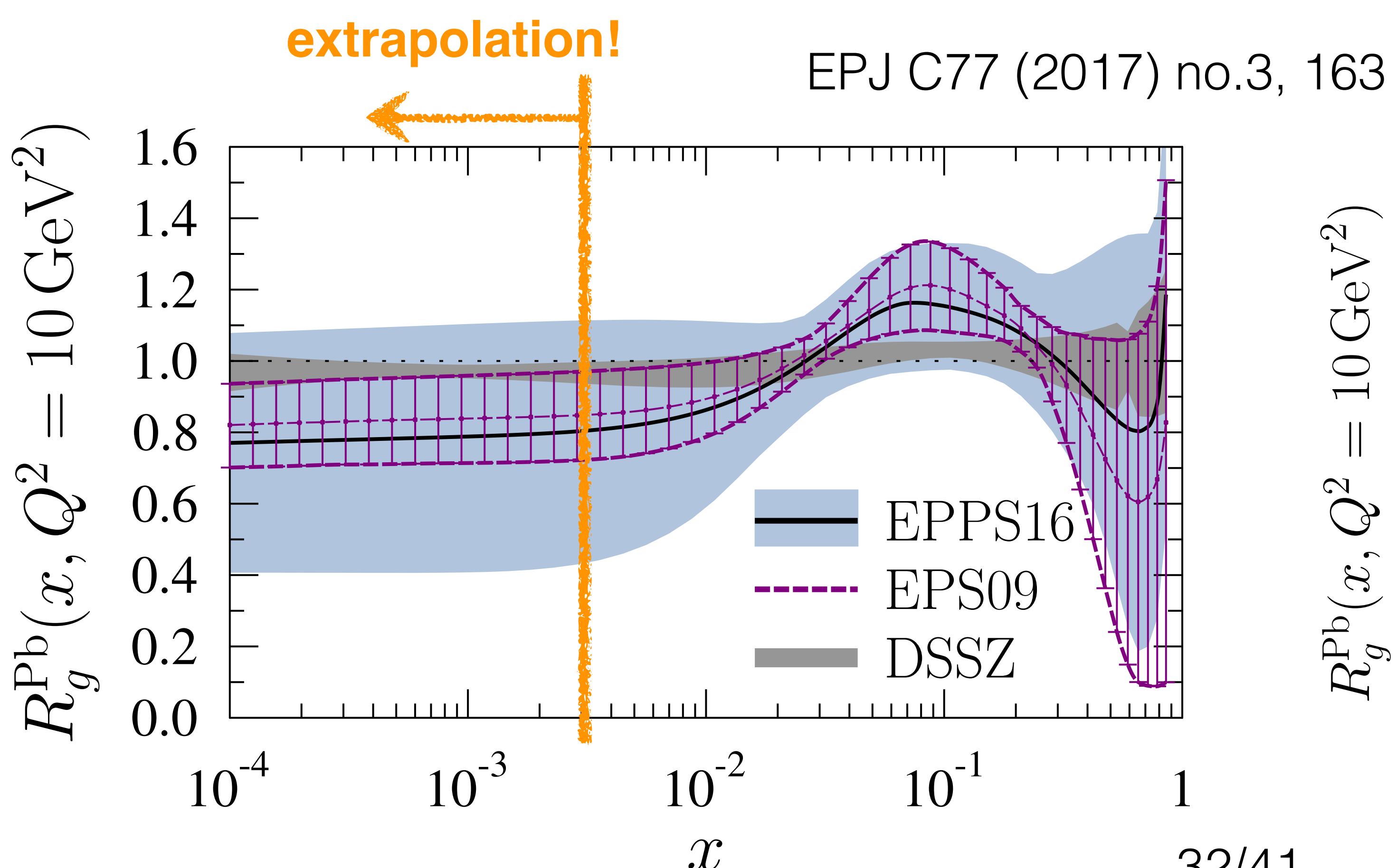
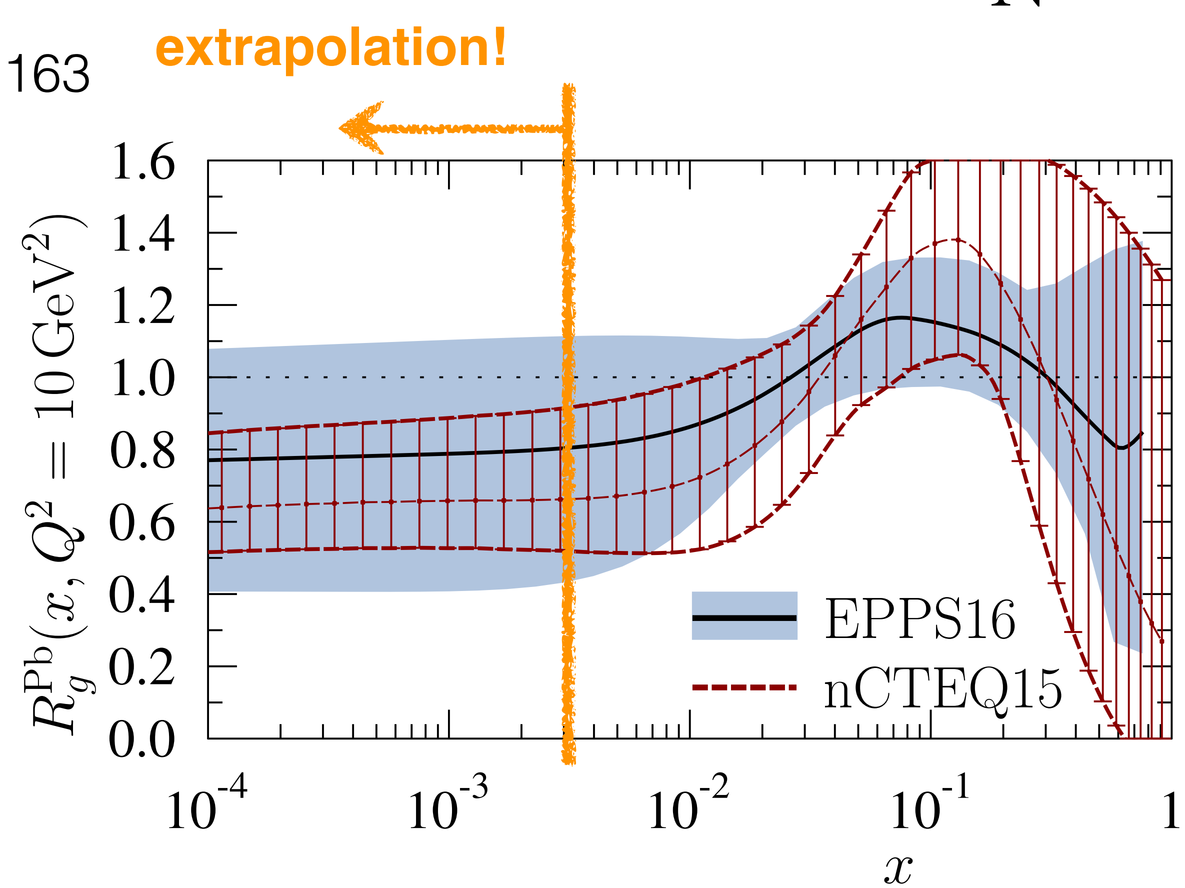


Comparing nPDFs: the gluon



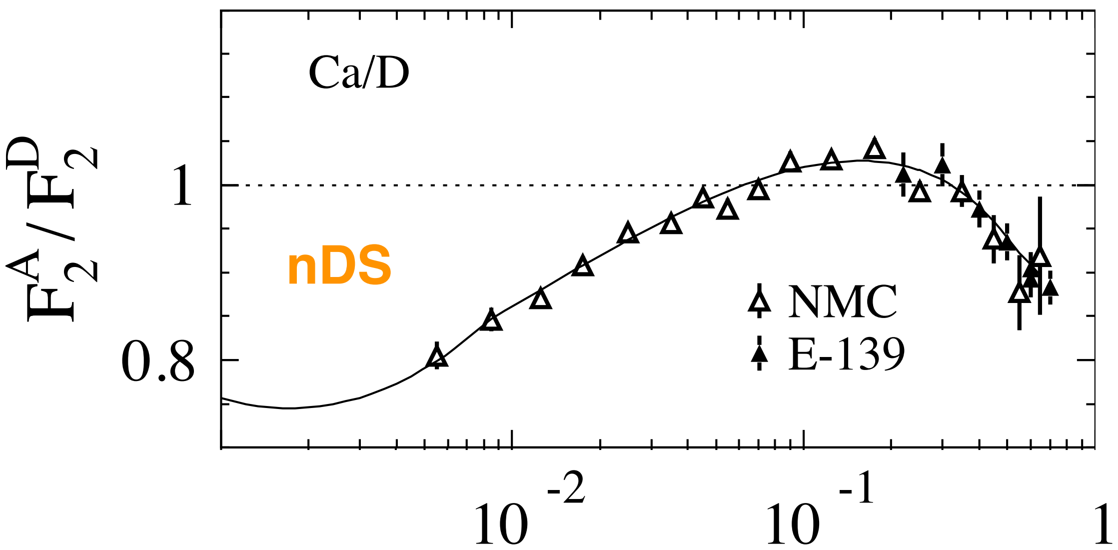


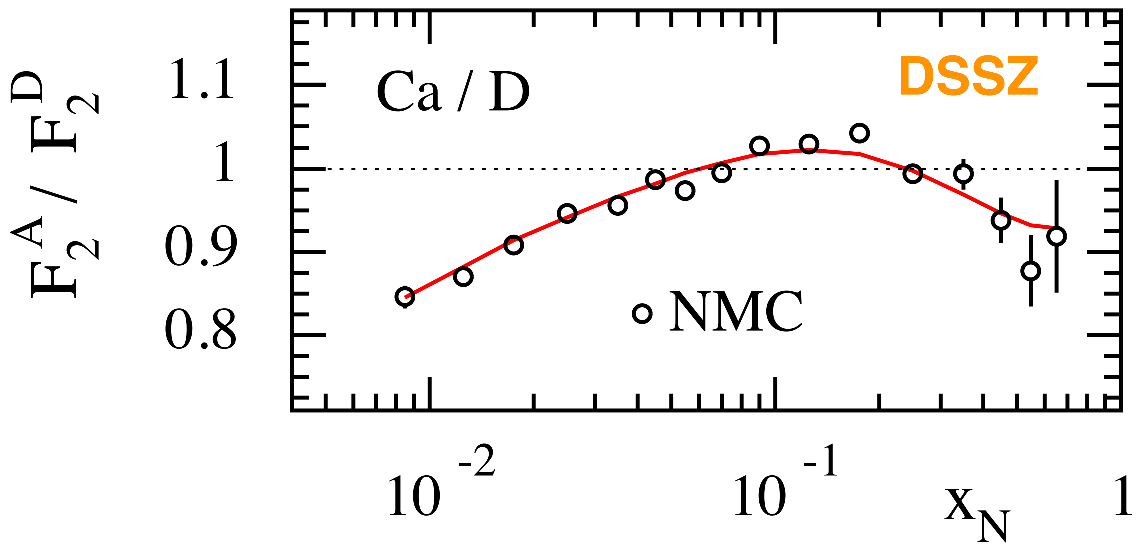


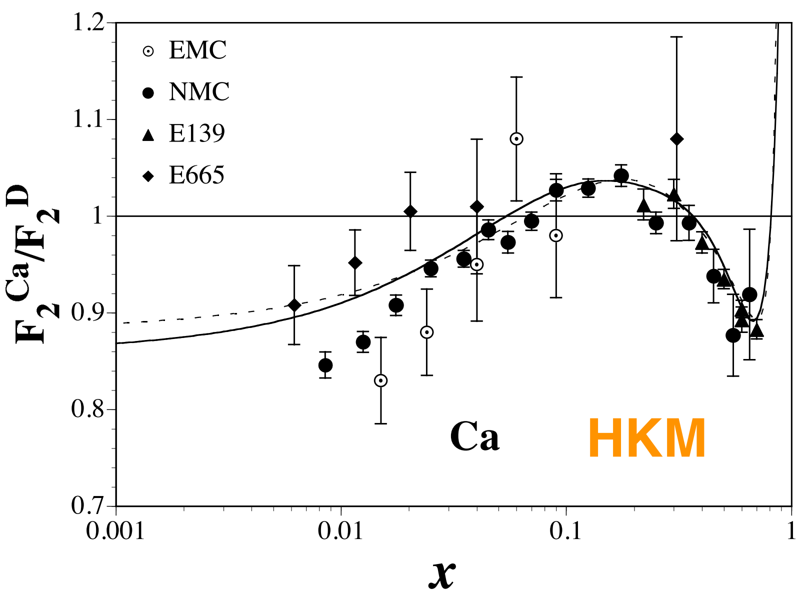


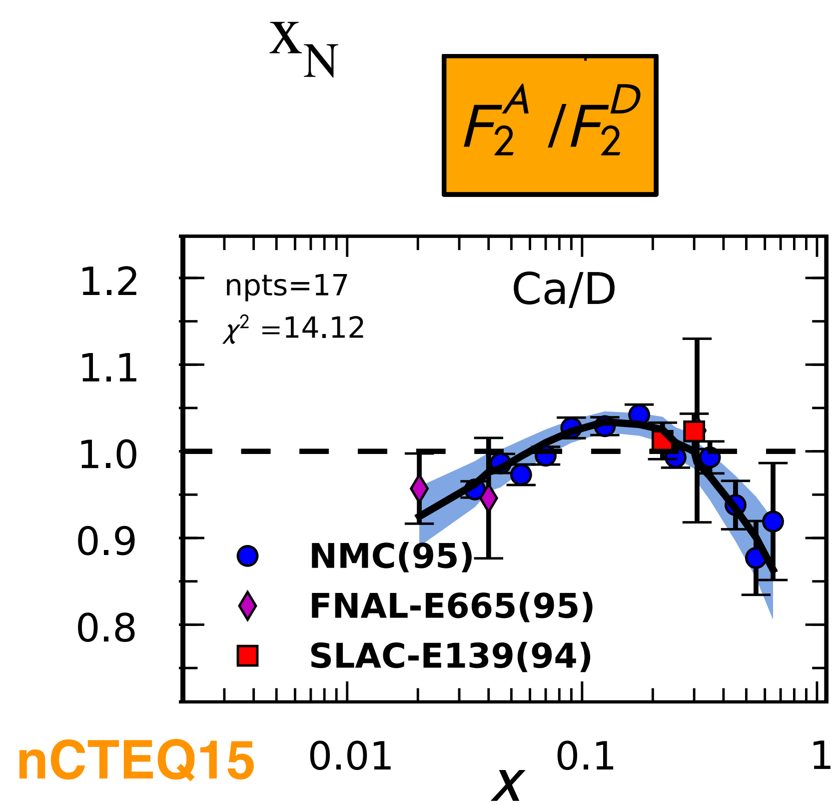
Comparing nPDFs: magic!

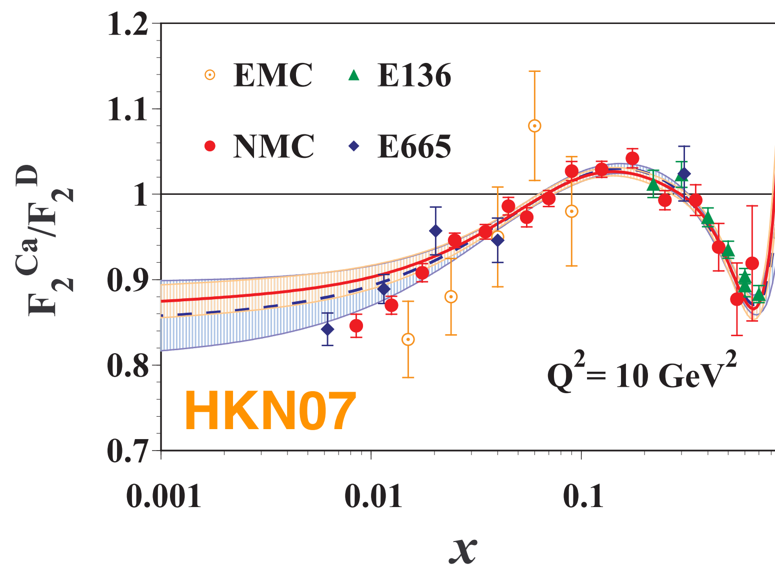
all give nice descriptions of the data

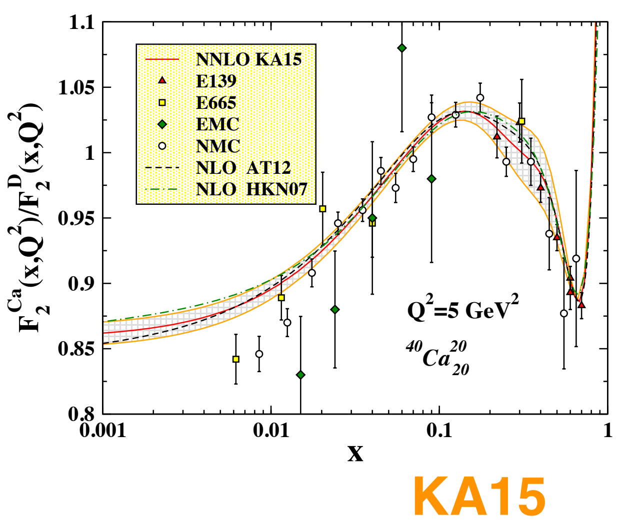


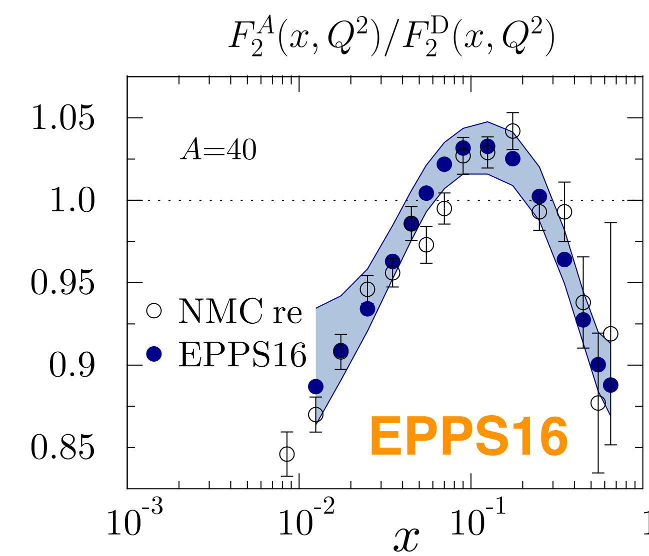










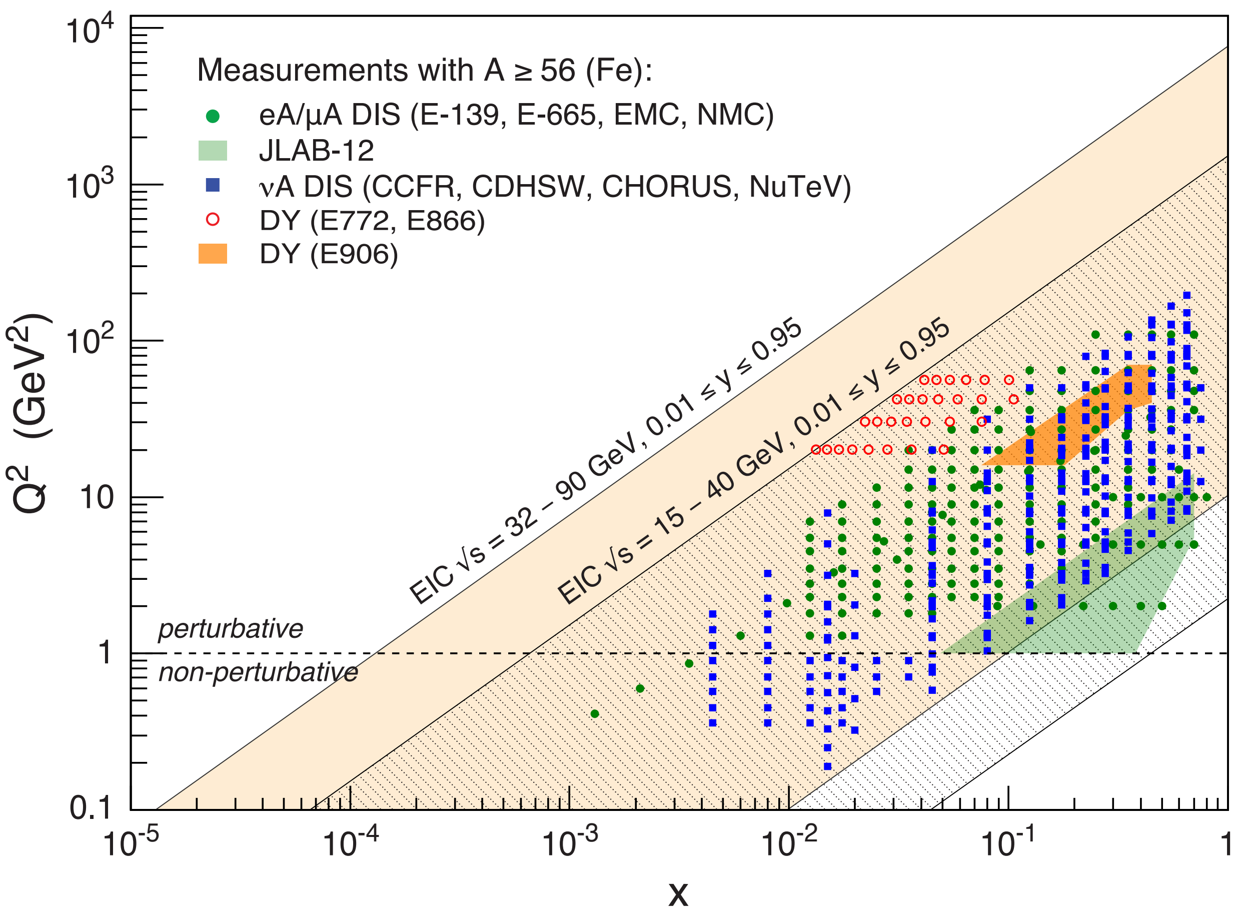


What can we do with an EIC?

Generalities

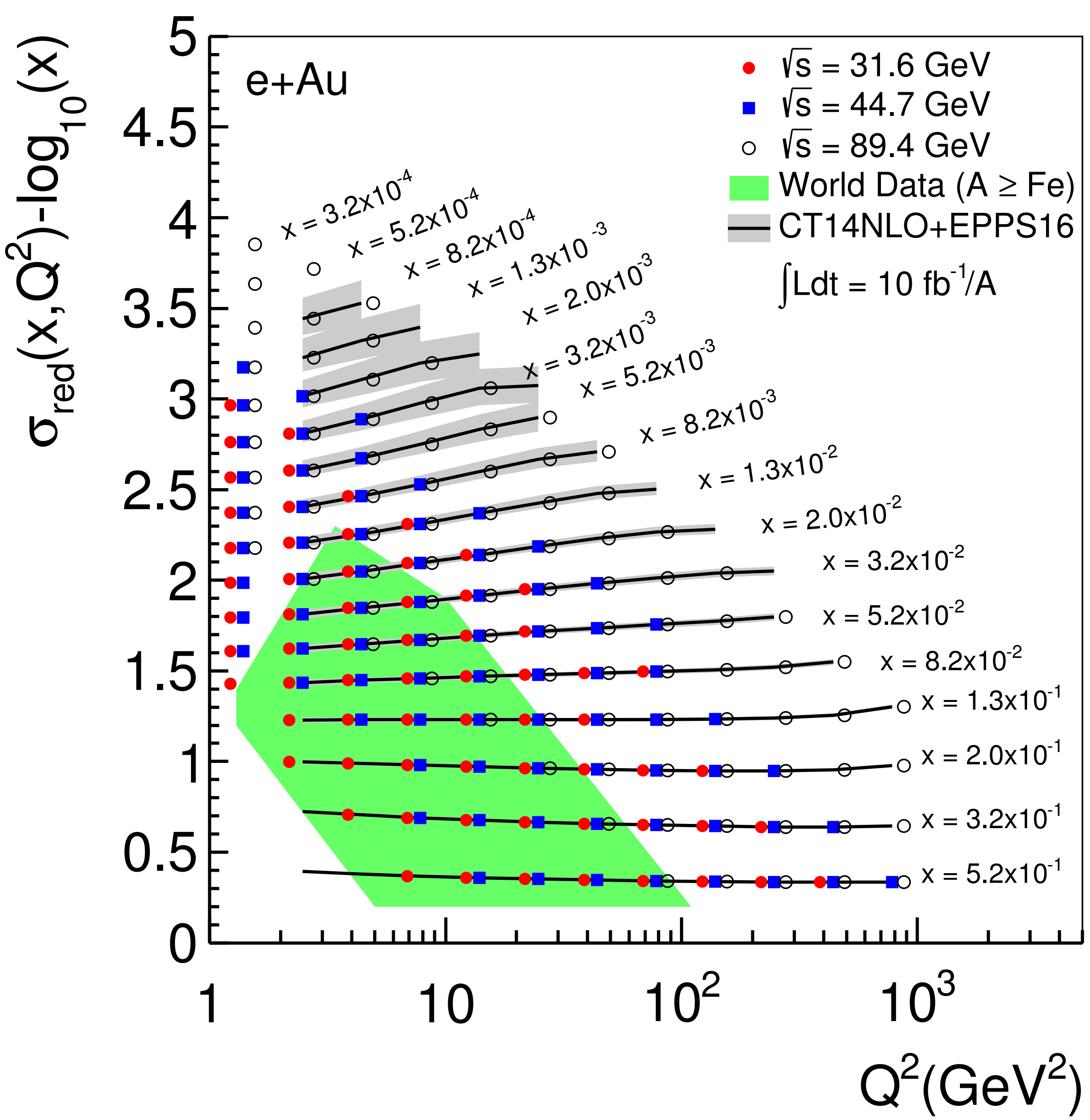
- extend the kinematic coverage!
- more, high precision, “non-modified” data
- get all data (not only structure functions!)
- lever arm in A (doable at the LHeC?)
- publish covariance matrices

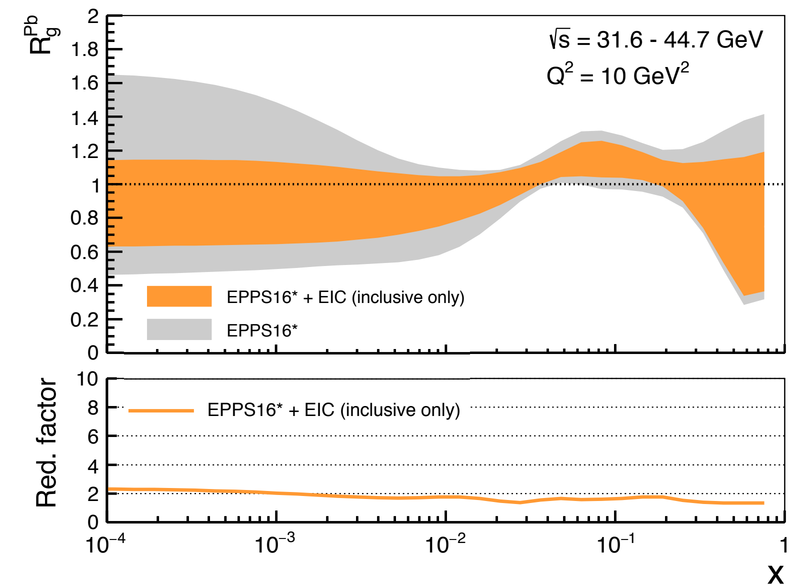
arXiv:1708.01527

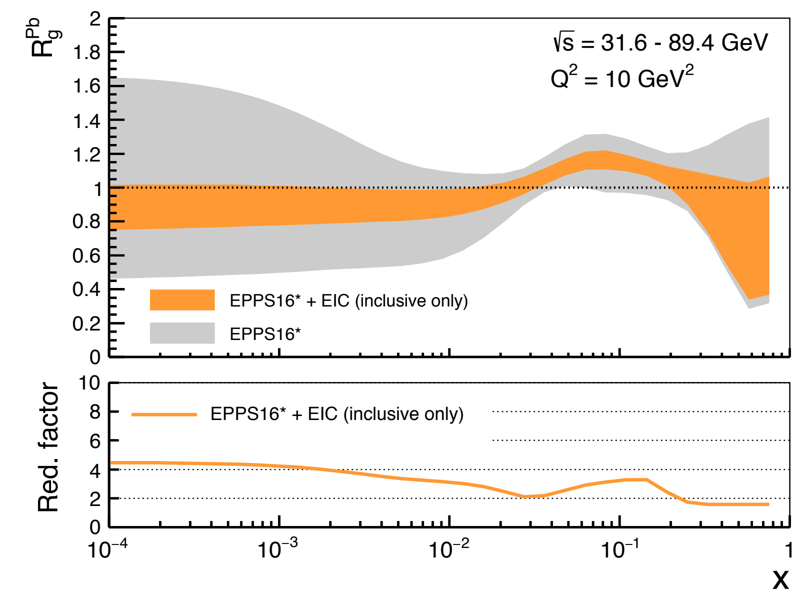


The things we know and have been doing

- study the neutron
- study inclusive cross-sections







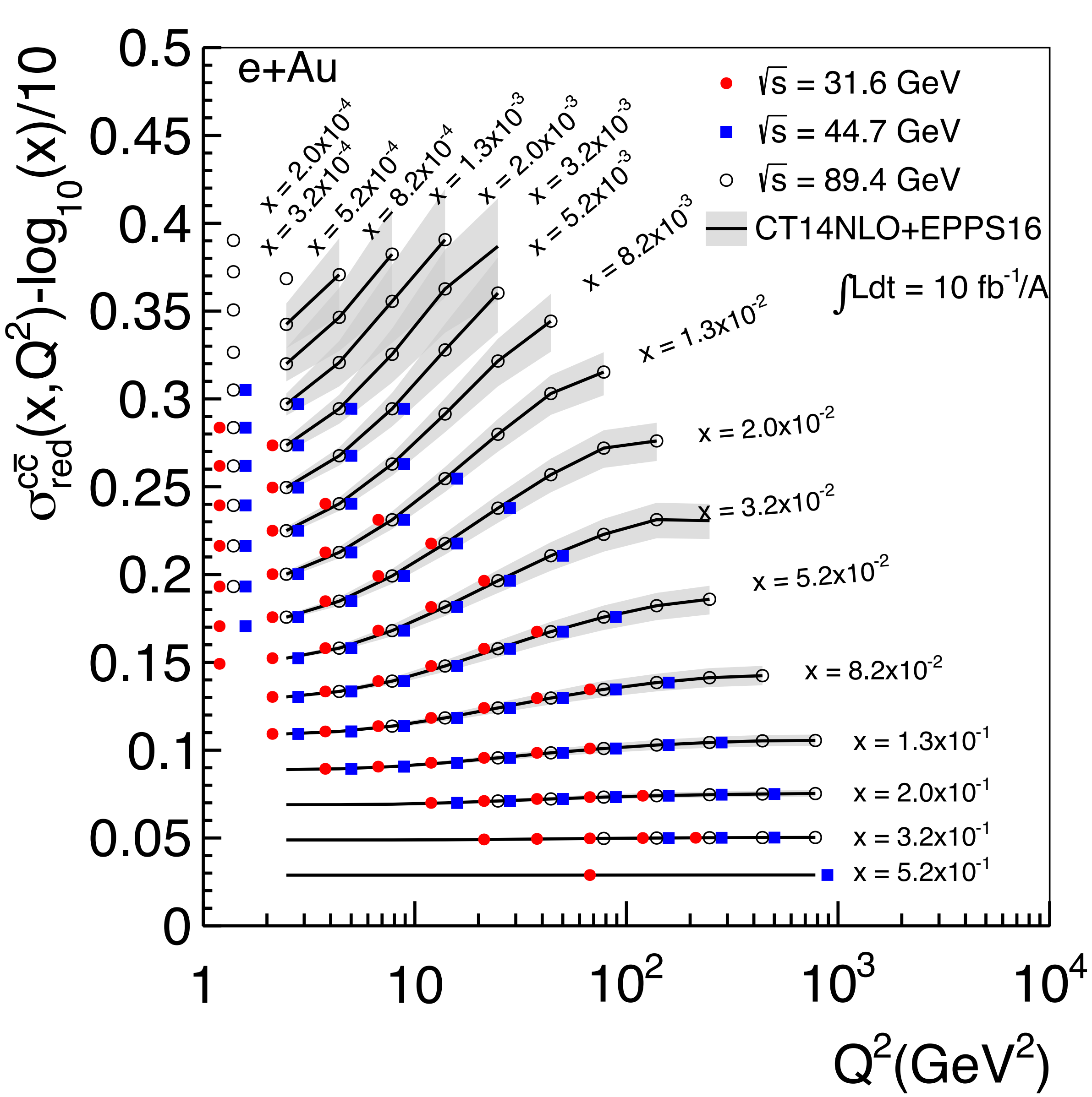
Aschenauer, Fazio, Lamont, Paukkunen,
PZ, PRD96 (2017) no.11, 114005

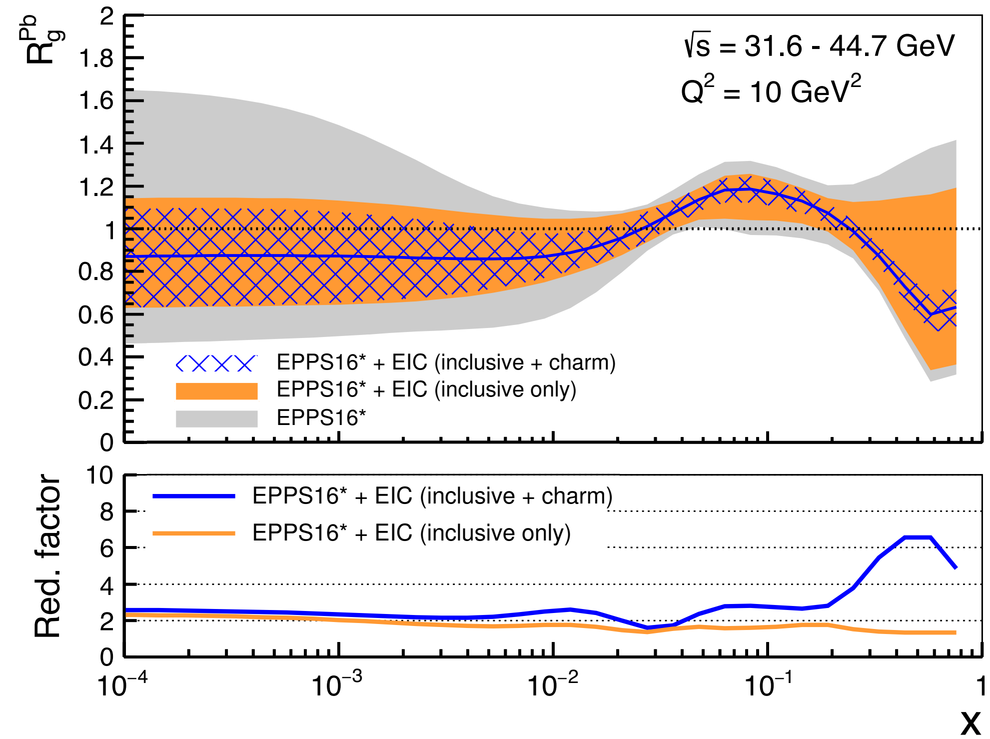
The things we know and have not done

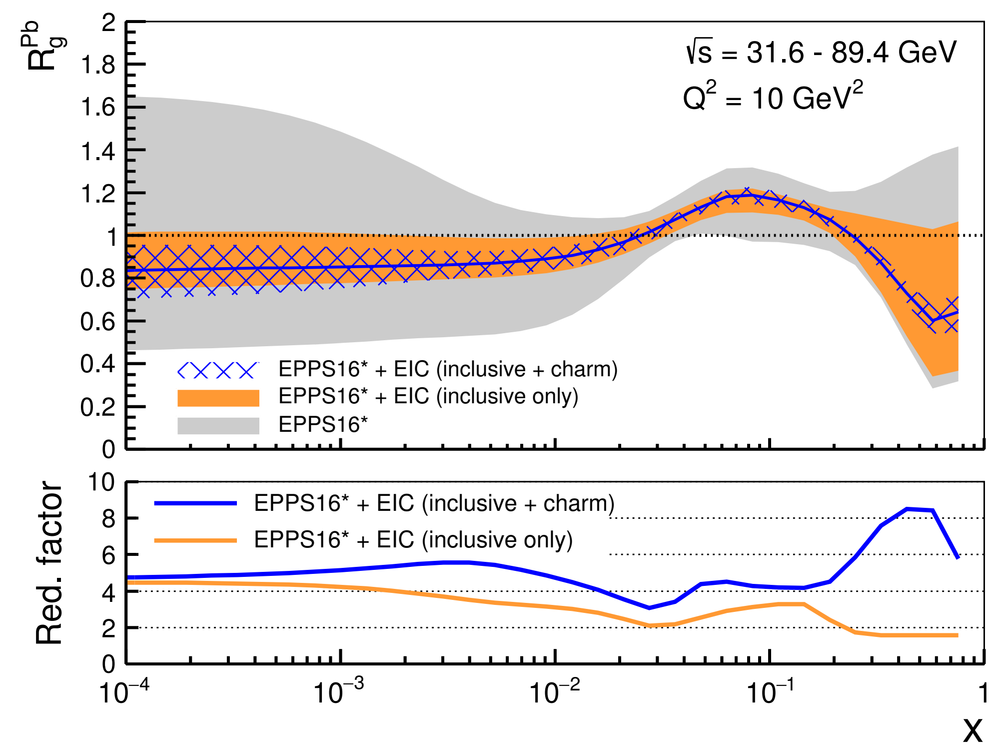
- determine F_L
- (try to) achieve full flavour decomposition using CC
- explore heavy flavour schemes and intrinsic charm
- check for final state nuclear effects in SIDIS, determine them if existing
- study the link between centrality and collision geometry, reach high density effective nuclei?

Zheng, Aschenauer, Lee, Eur.Phys.J. A50 (2014) no.12, 189

study heavy-quark cross-sections







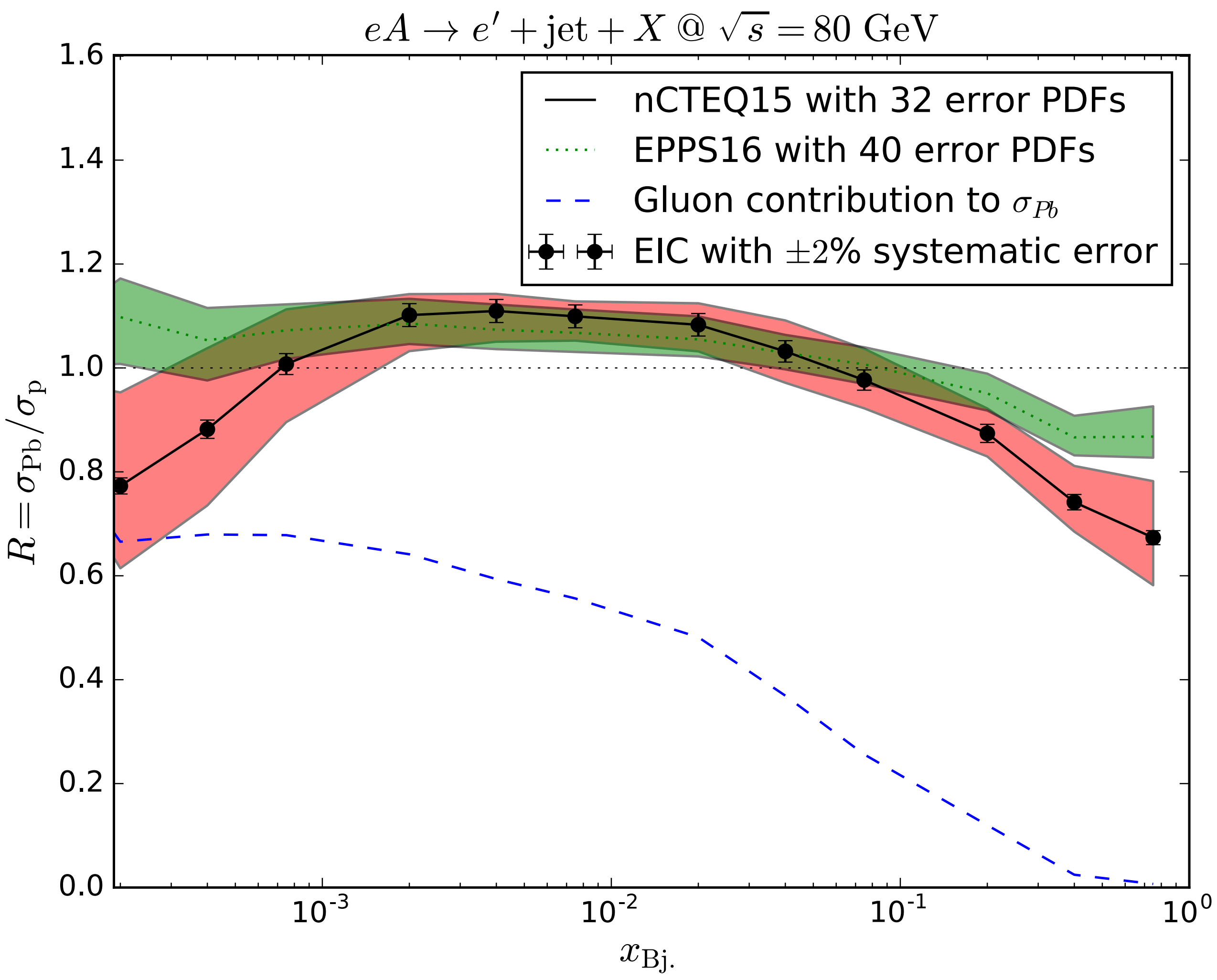
Aschenauer, Fazio, Lamont, Paukkunen, PZ, PRD96 (2017) no.11, 114005

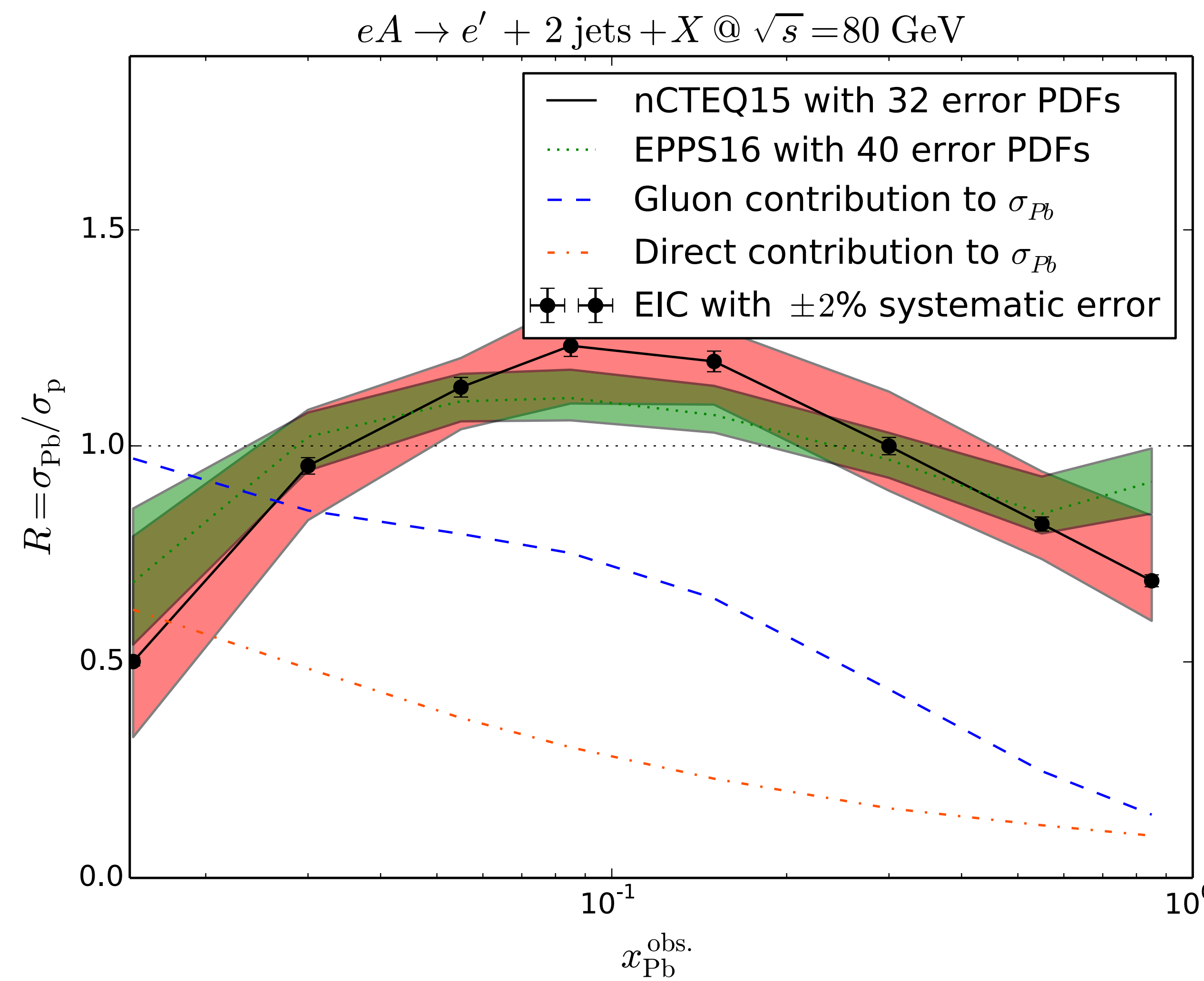
See also C. Weiss talk at “Santa Fe Jets and Heavy Flavor Workshop, 30-Jan-18”

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

include jet data

Klasen and Kovarik, PRD97 (2018) no.11, 114013



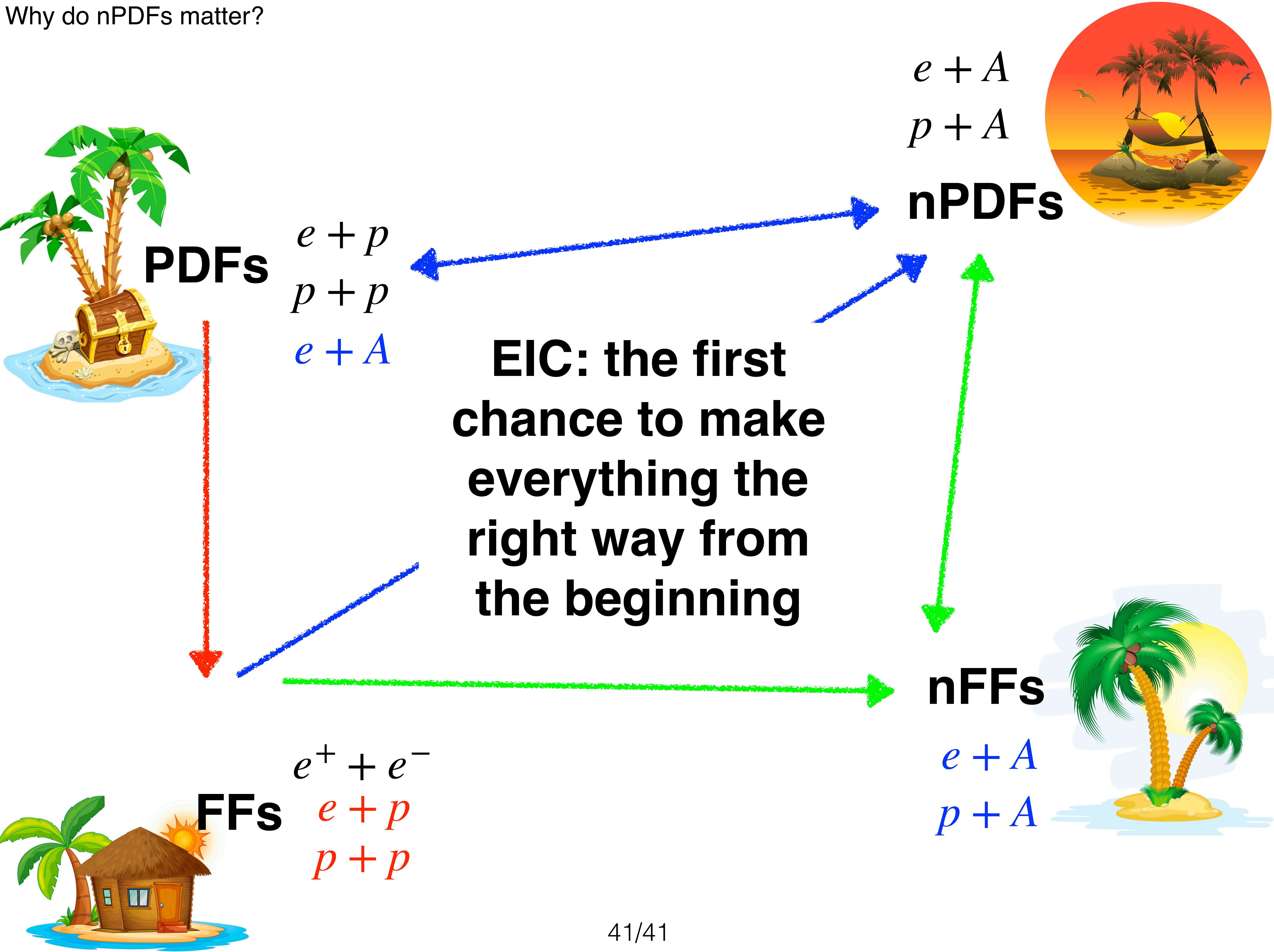


Klasen, Kovarik, Potthoff, PRD95 (2017) no.9, 094013

The things we do not know

- 🕷 validity of the factorisation?
- 🕷 validity of isospin symmetry?
- 🕷 new phenomena (saturation?)
- 🕷 nuclear GPDs and TMDs

🤔 ???


$e + A$
$p + A$
nPDFs
PDFs
$e + p$
$p + p$
$e + A$
EIC: the first chance to make everything the right way from the beginning
nFFs
$e + A$
$p + A$
FFs
$e^+ + e^-$
$e + p$
$p + p$