Nuclear Parton Distributions

Hannu Paukkunen

University of Jyväskylä & Helsinki Institute of Physics, Finland

Outline

I A quick overview of the existing nuclear PDFs

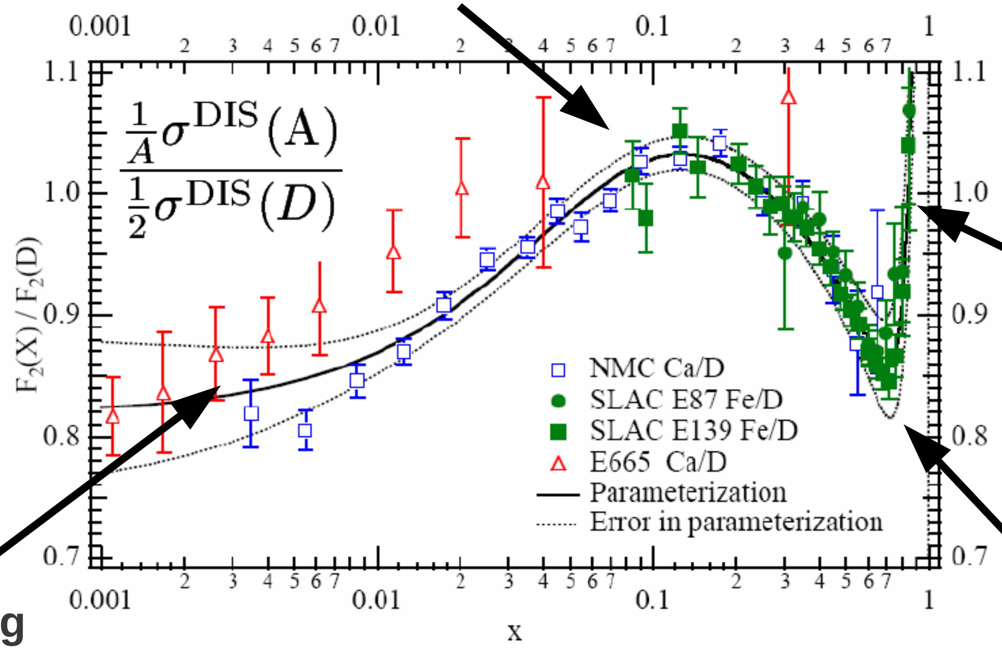
II Evidence for nuclear PDFs in p+Pb dijets?

III Prospects for the LHeC/EIC to measure nPDFs

IV Summary

I A quick overview of the exisiting nuclear PDFs

Global fit of nPDFs – test of factorization



- **General observation:** $\sigma^{\text{bound nucleon}} \neq \sigma^{\text{free nucleon}}$

- **Search for <u>process independent</u> nPDFs to realize such differences**

$$\sigma_{\mathrm{DIS}}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} \underbrace{f_i^A(\mu^2)}_{} \otimes \underbrace{\hat{\sigma}_{\mathrm{DIS}}^{\ell+i\to\ell+X}(\mu^2)}_{}$$

Nuclear PDFs, obeying the standard DGLAP

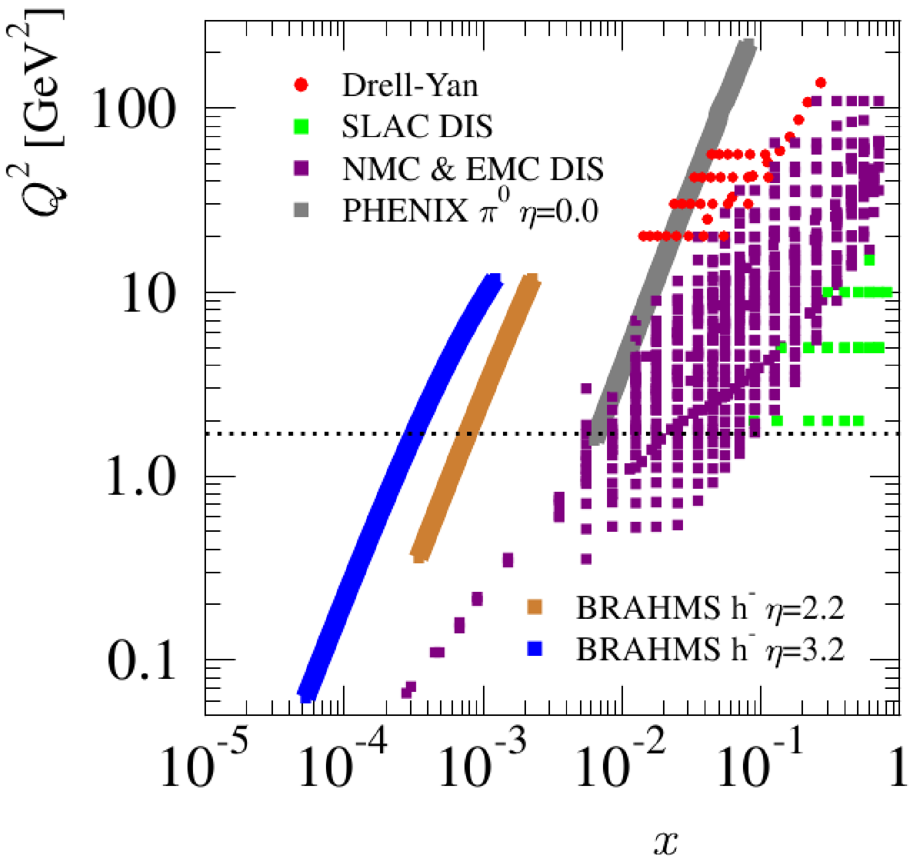
Usual perturbative coefficient functions

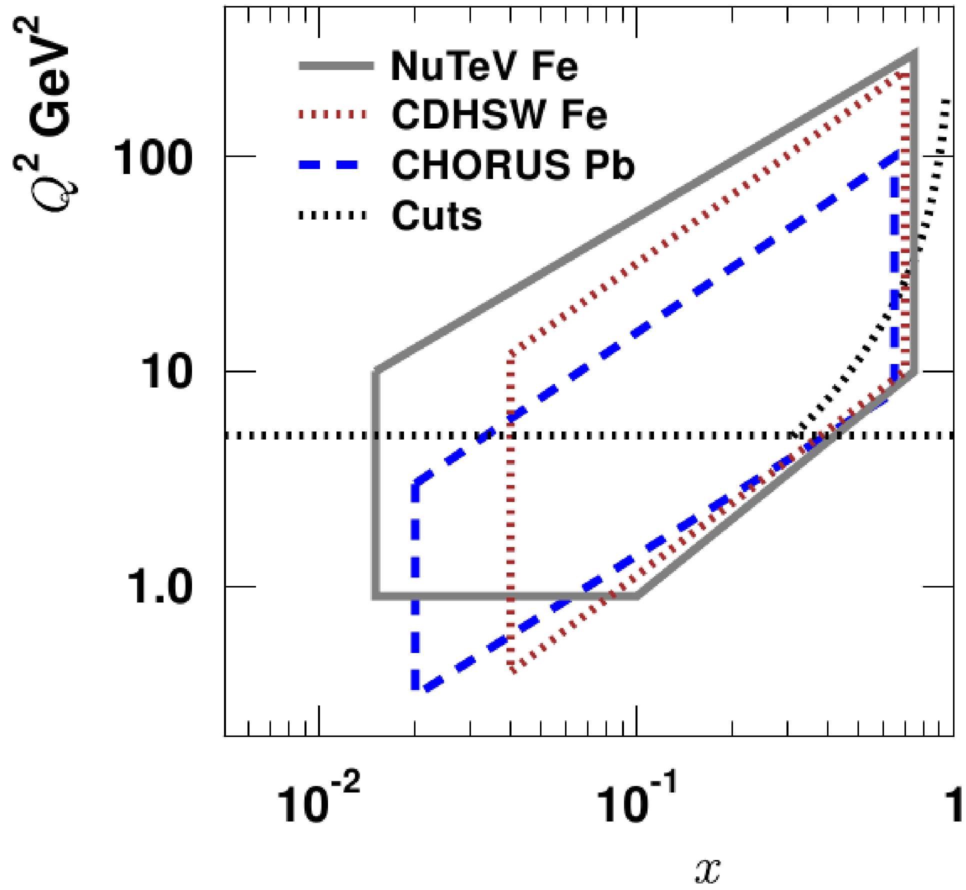
The contemporary NLO nPDF fits

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

	HKN07	EPS09	DSSZ	nCTEQ prelim.
Ref.	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv:1307.3454
Order	LO & NLO	LO & NLO	NLO	NLO
Neutral current e+A / e+d DIS	√	√	√	√
Drell-Yan dileptons in p+A / p+d	√	√	√	√
RHIC pions in d+Au / p+p		√	√	
Neutrino-nucleus DIS			√	
Q^2 cut in DIS	1GeV	1.3GeV	1GeV	2GeV
# of data points	1241	929	1579	708
Free parameters	12	15	25	17
Error sets available		√	√	√
Error tolerance $\Delta\chi^2$	13.7	50	30	35
Baseline	MRST98	CTEQ6.1	MSTW2008	CTEQ6M
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS

Kinematic coverage of the nuclear data



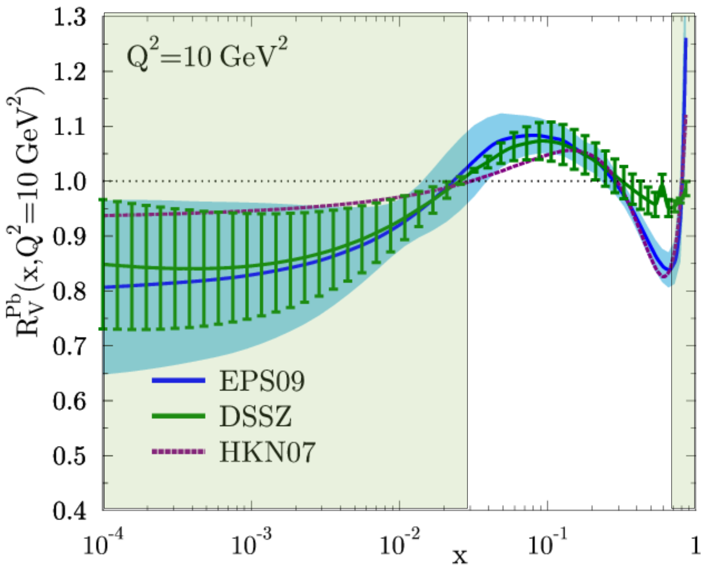


- The kinematic coverage of the data rather restricted (in comparison to the free proton fits)
- The LHC p+Pb runs should enlarge this plane to some degree

Comparison: Valence quarks

- Some differences between EPS09, HKN07 & DSSZ.... (data constraints for x=0.1...1)

No data constraints

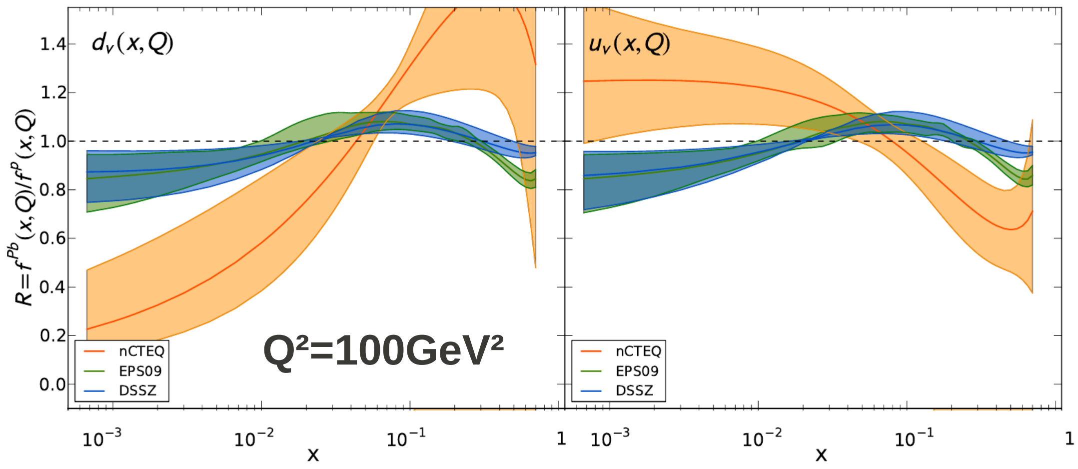


(R_{uV} & R_{dV} almost the same for EPS09, DSSZ, HKN07)

Clear diasgreement at large x. Probably a misinterpretation of the “isospin” corrections.

- …but the preliminary nCTEQ curves show a really drastic difference

$$d\sigma^{\rm DIS} \sim \left(\frac{4}{9}\right) u_v^A + \left(\frac{1}{9}\right) d_v^A$$
$$\sim u_v^A \left[R_{u_v} + R_{d_v}\frac{d_v^p}{u_v^p}\frac{Z+4N}{N+4Z}\right]$$
$$\approx u_v^A \left[R_{u_v} + \frac{1}{2}R_{d_v}\right]$$

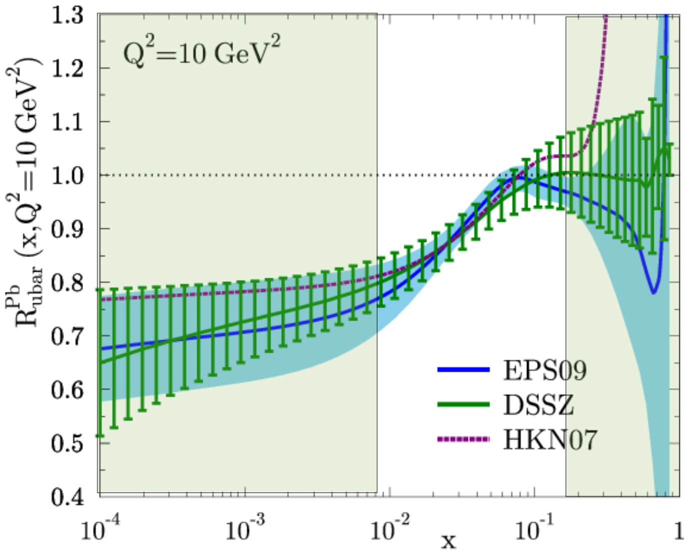


- Other type of data needed to have constraints for R_{uV} and R_{dV} separately!

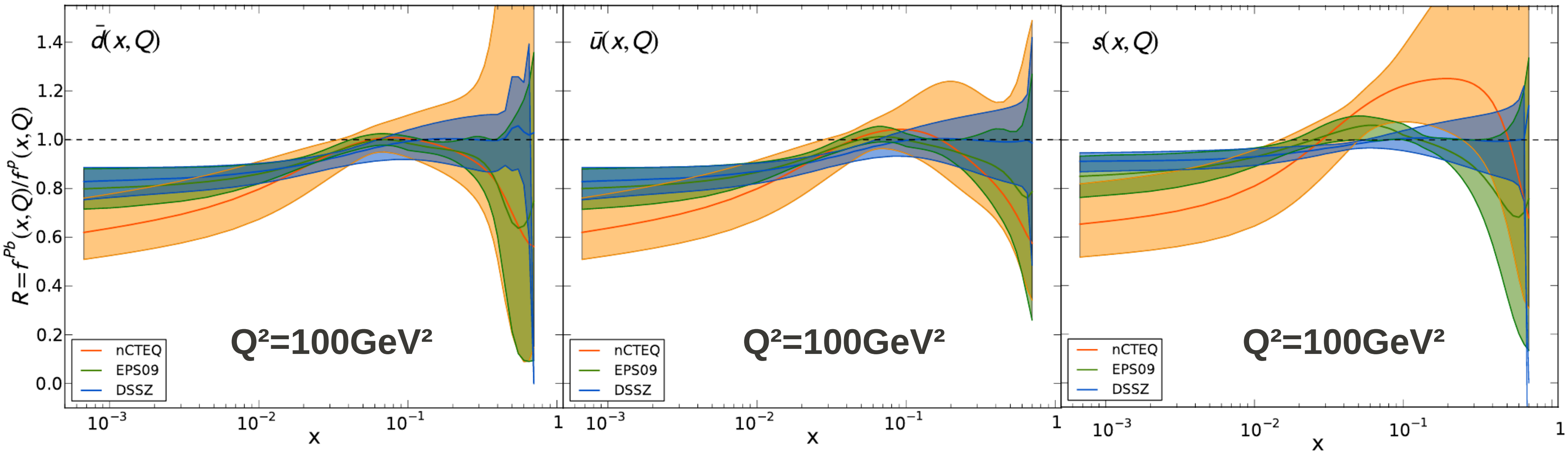
Comparison: Sea Quarks

- No qualitative disagreements in the data constrained region (x=0.01...0.1)

No data constraints



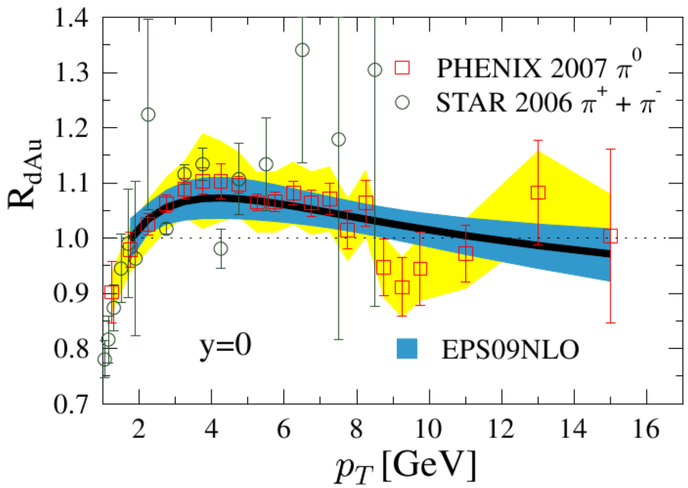
- No qualitative disagreements to preliminary nCTEQ results either

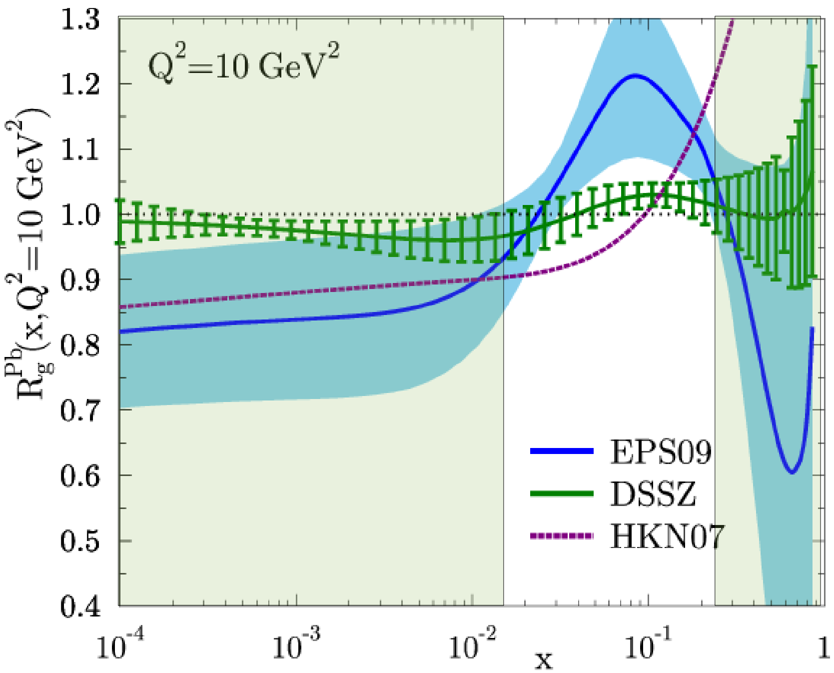


Comparison: Gluons

- **Difference between EPS09 & DSSZ:**

  *The antishadowing and EMC effect in **EPS09** comes from the RHIC pion data*

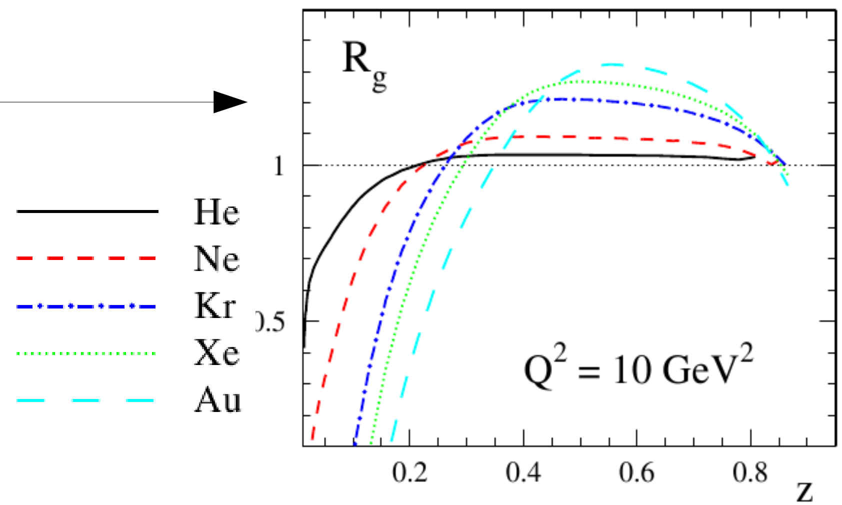




DSSZ advocated nuclear modifications in the fragmentation functions. No antishadowing nor EMC effect.

$$d\sigma^{\mathrm{d+Au}\to\pi+X} = \sum_{i,j,k} f_i^{\mathrm{d}} \otimes d\hat{\sigma}^{ij\to k} \otimes f_j^{\mathrm{Au}} \otimes D^{k\to\pi+X}$$

D(g→pion,A) / D(g→pion,p)

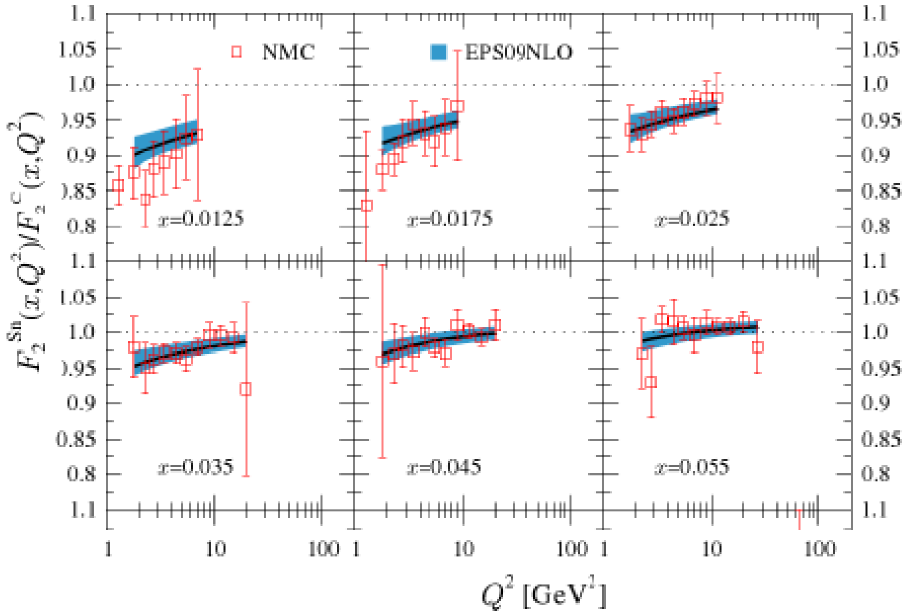


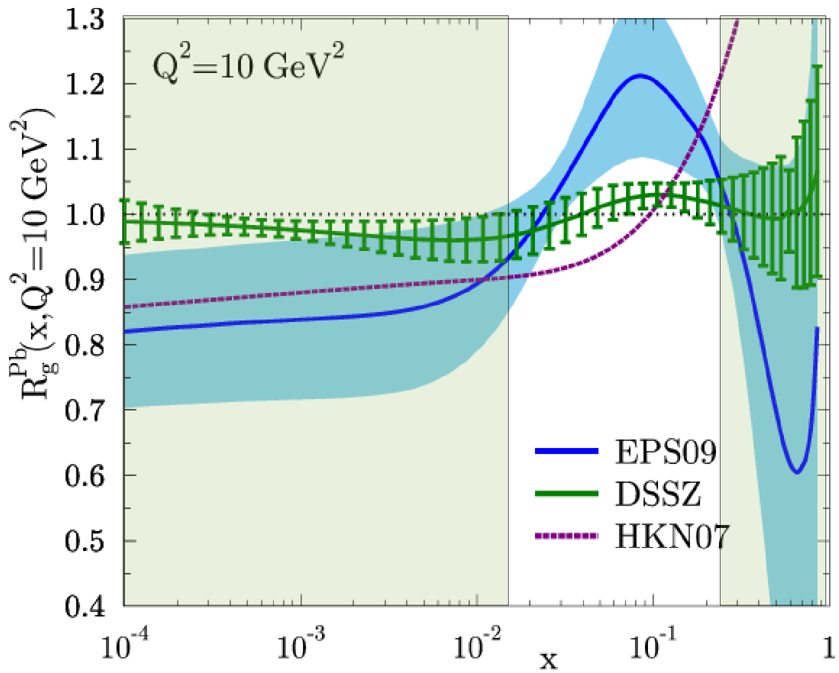
Both can fit the pion data, but the origin of the effect is different physics.

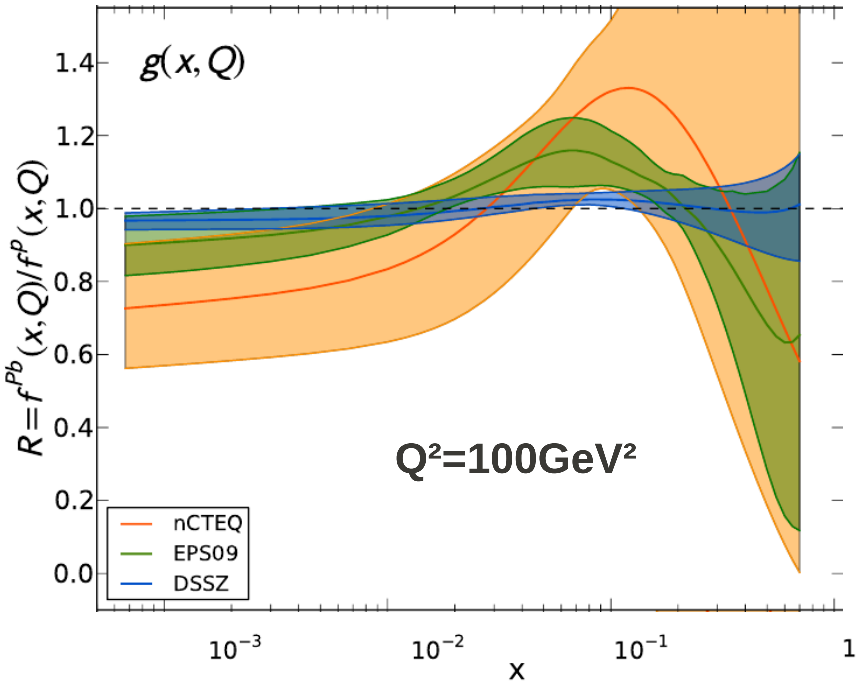
Comparison: Gluons

- ***Strongest shadowing and largest error band in nCTEQ***

Higher Q² cut has removed part of the small-Q² DIS data (largest DGLAP effects).







II Evidence for nuclear PDFs in p+Pb dijets?

The CMS dijets in Pb+p

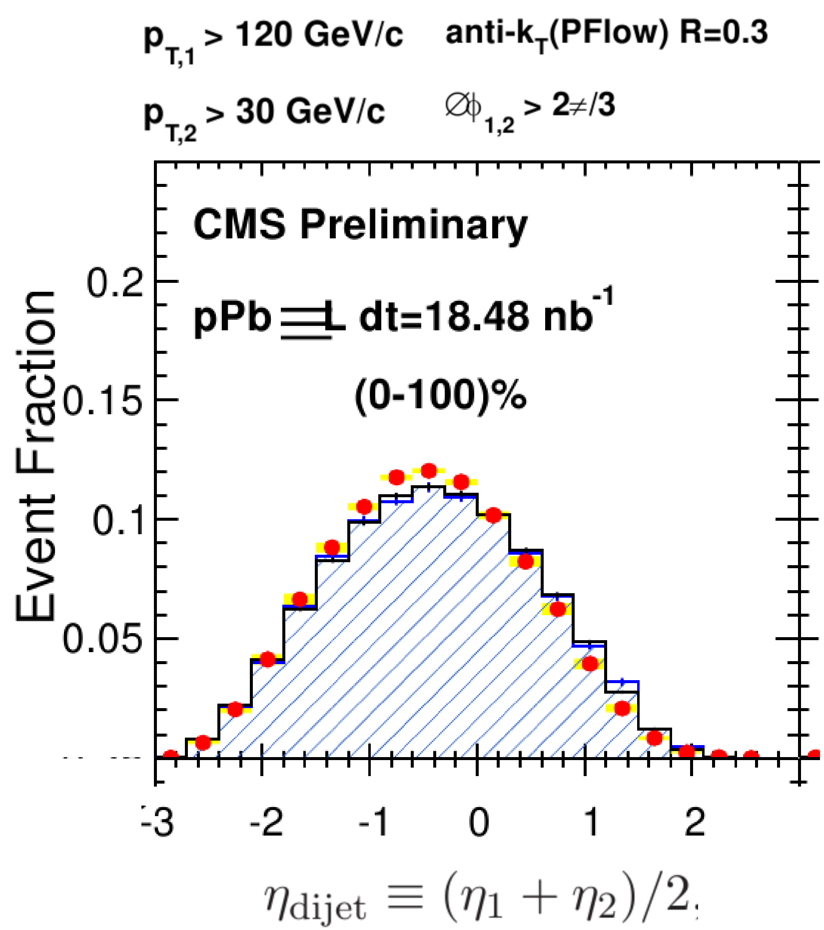
- CMS dijets using the 2013 p+Pb data

CMS PAS HIN-13-001

- Data binned in dijet “pseudorapidity”

$$\eta_{\rm dijet} \equiv (\eta_1 + \eta_2)/2,$$

pseudorapidities of
the individual jets



- Rapidity shift

$$\eta_{\rm shift} \equiv 0.5 \log \left(E_{\rm Pb}/E_{\rm p}\right) \approx -0.465$$

Pb → ← p

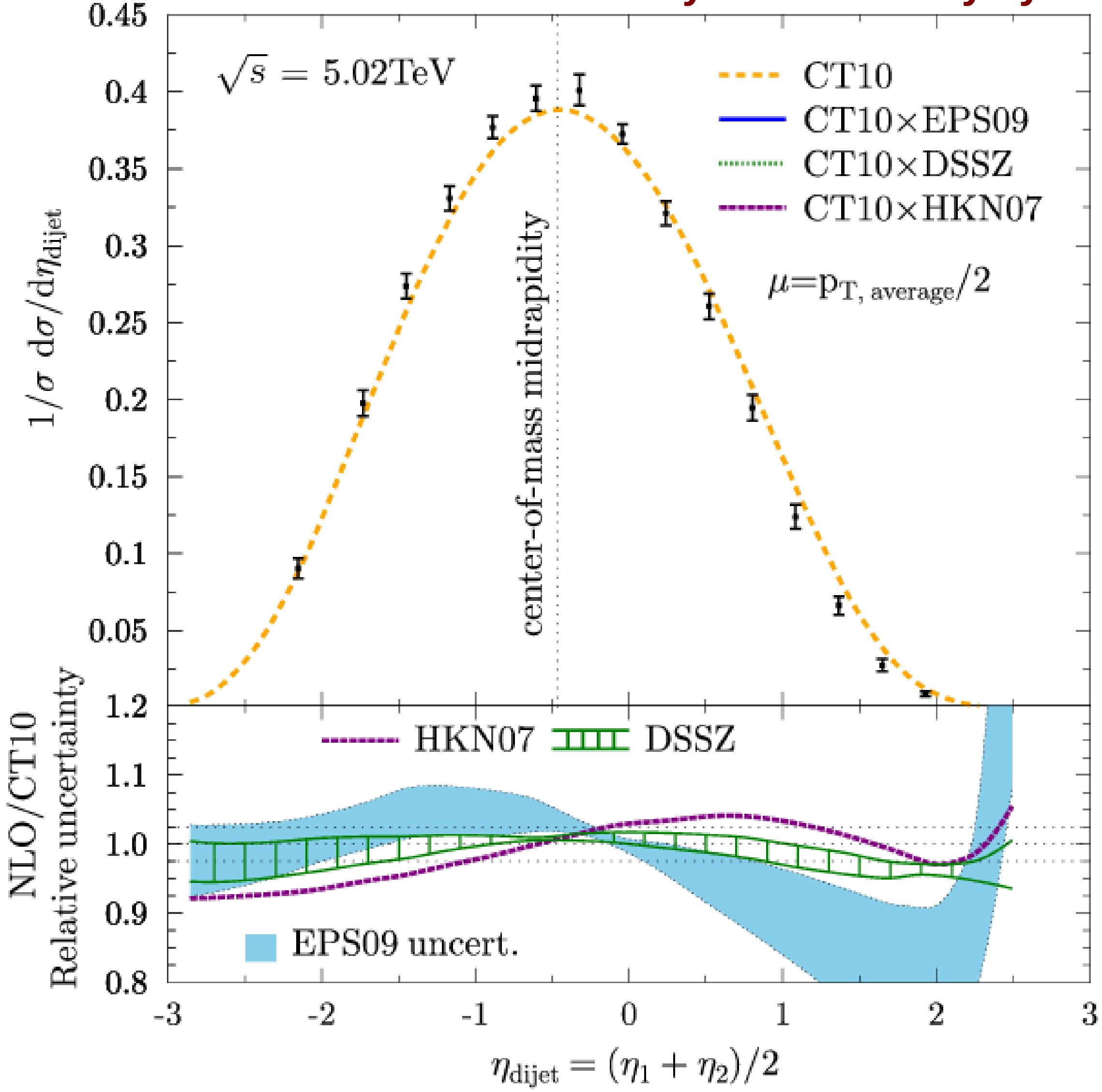
(results presented in the collider frame)

- How sensitive is this to the nuclear (gluon) PDF modifications?

The CMS dijets in p+Pb

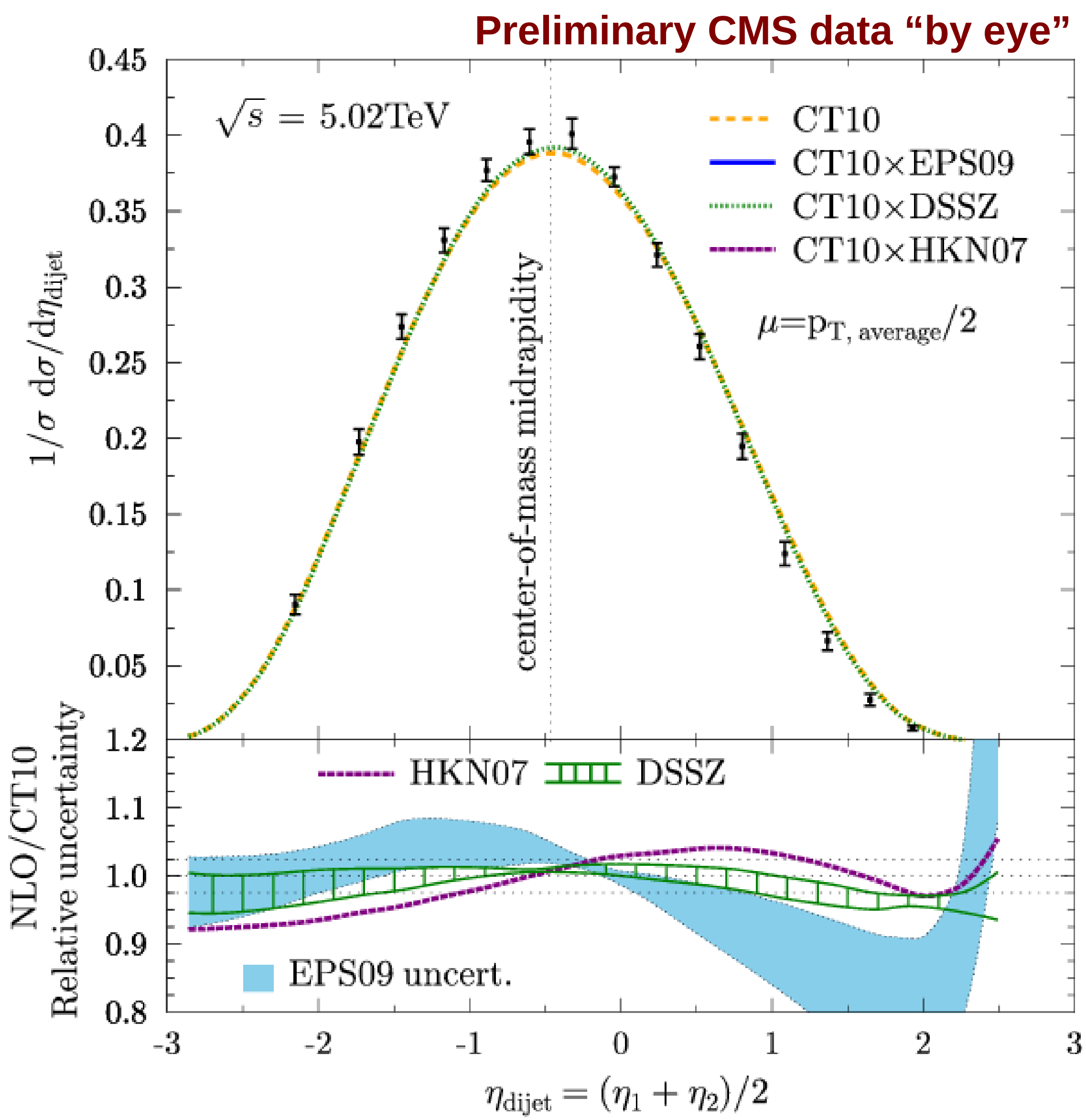
Eskola, Paukkunen, Salgado, arXiv:1308.6733

Preliminary CMS data "by eye"



The CMS dijets in p+Pb

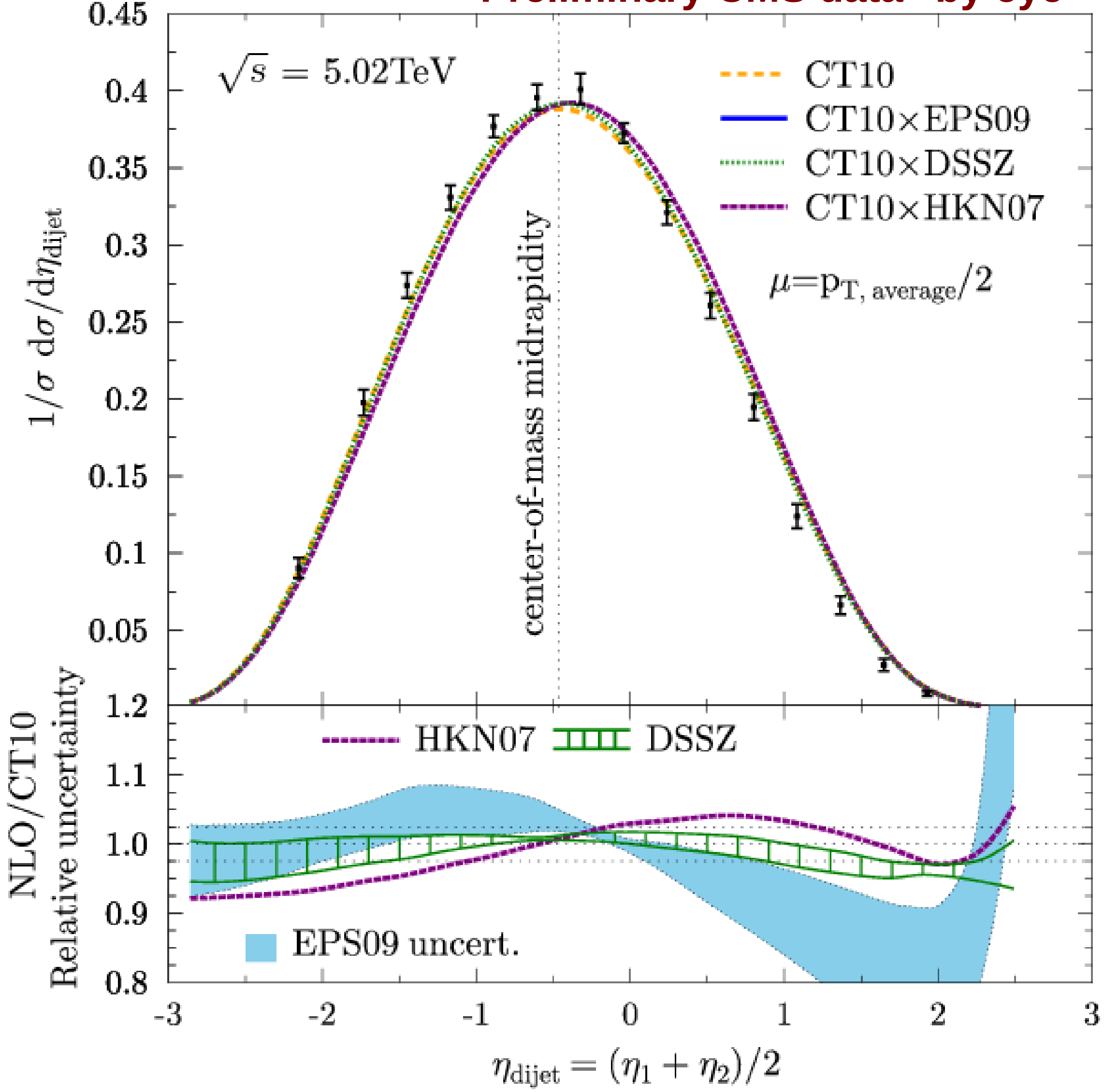
Eskola, Paukkunen, Salgado, arXiv:1308.6733



The CMS dijets in p+Pb

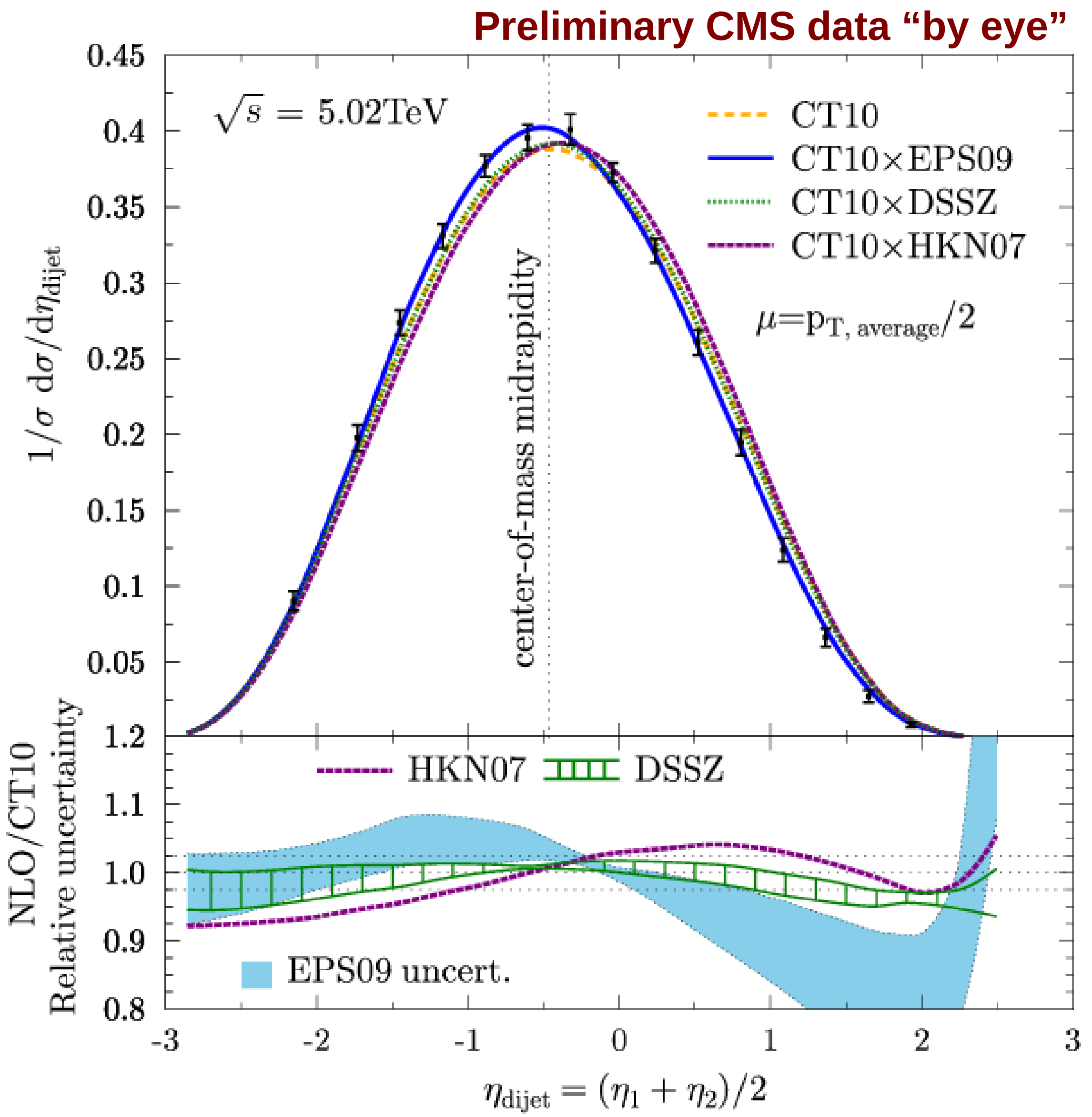
Eskola, Paukkunen, Salgado, arXiv:1308.6733

Preliminary CMS data "by eye"



The CMS dijets in p+Pb

Eskola, Paukkunen, Salgado, arXiv:1308.6733

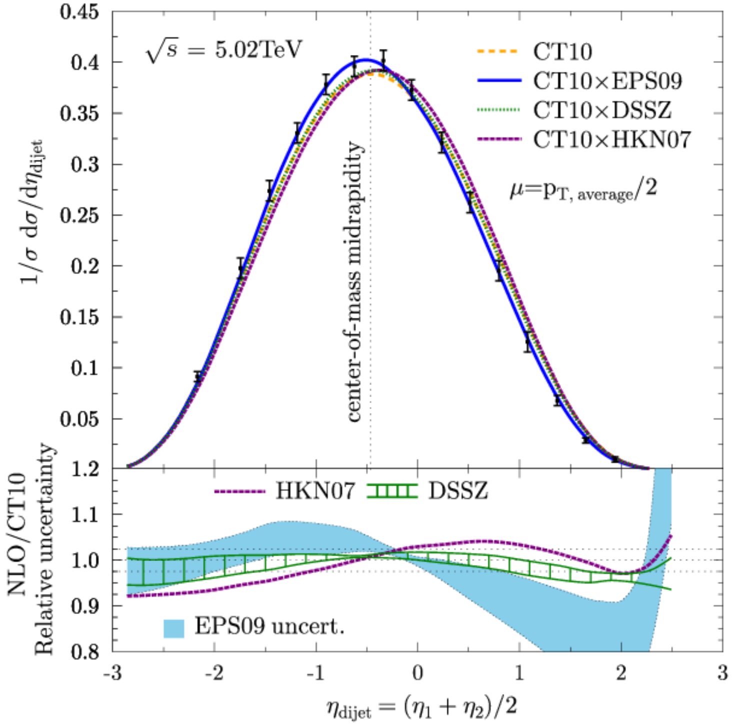


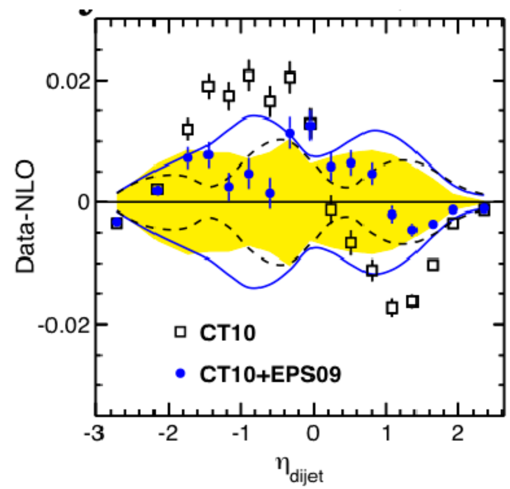
The CMS dijets in p+Pb

Eskola, Paukkunen, Salgado, arXiv:1308.6733

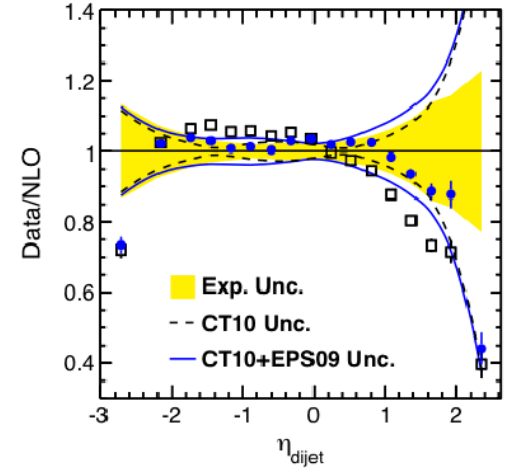
- **Comparison to the NLO calculations – the gluon nuclear mods make a difference!**

Preliminary CMS data "by eye"





Doga Gulhan, IS2013, Spain



- **Should constrain gluons at large x (small x only indirectly)**
- **Much more LHC p+Pb data are expected soon, but for the moment it's still difficult to say how they will affect the global fits of nPDFs.**

III LHeC / EIC prospects for nPDFs

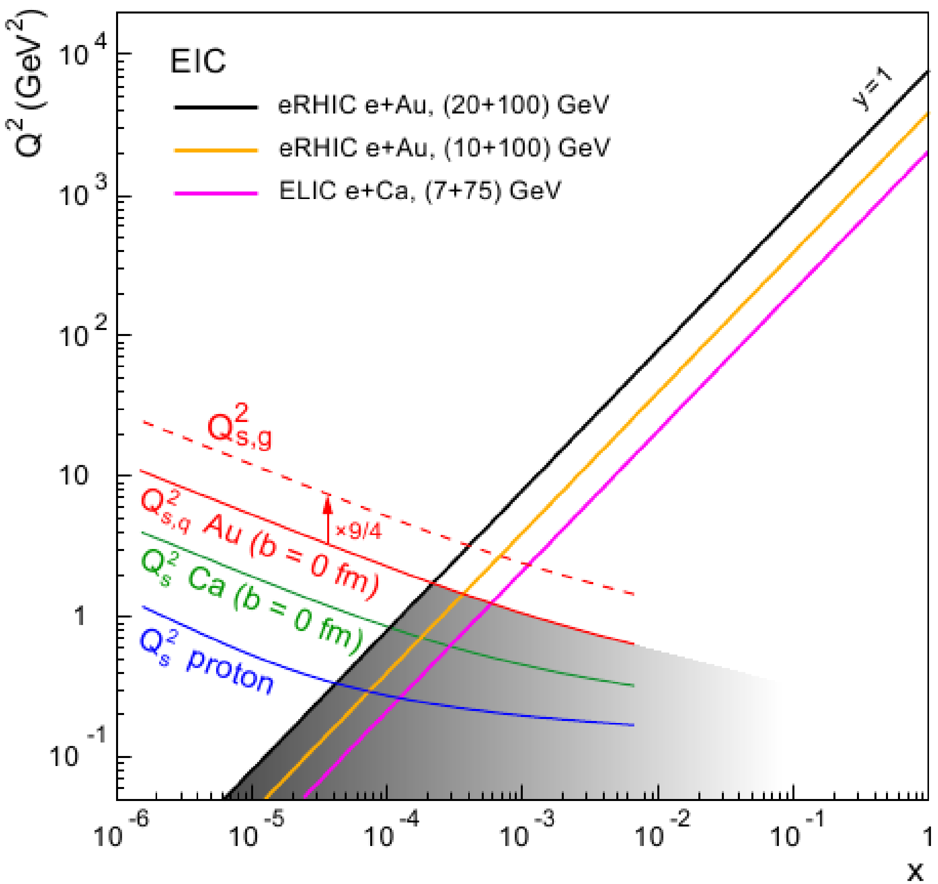
Based on ongoing work:

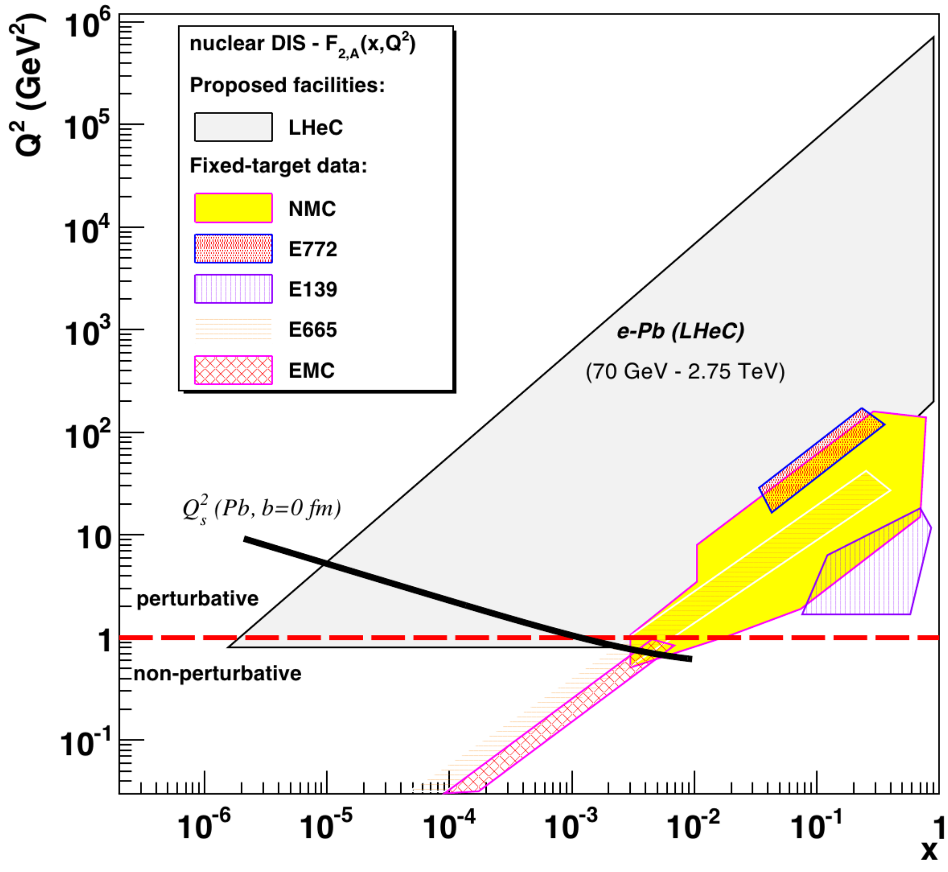
LHeC: H.P, N. Armesto, M. Klein

EIC: H.P, M. Lamont E.C. Aschenauer, T. Ullrich, M. Stratmann, ...

Kinematics: EIC vs. LHeC

- Both colliders would enlarge the kinematic coverage of the present nuclear DIS data - LHeC hugely, EIC a bit less





- Here, we estimate the impact of the LHeC and EIC data on the nPDFs by directly fitting samples of pseudodata

The LHeC & EIC pseudodata

- **Samples of neutral-current DIS pseudodata for reduced cross-sections**

$$\sigma_r = \frac{xQ^4}{2\pi\alpha_{\rm em}^2 Y_+}\frac{d^2\sigma}{dxdQ^2} \qquad Y_+ = 1 + (1-y)^2$$

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha_{\rm em}^2}{Q^4}\frac{1}{x}\left[xy^2F_1 + (1-y)F_2 \pm xy(1-\frac{y}{2})F_3\right]$$

was generated from using assuming:

E_{lepton} = 60 GeV, E_{proton} = 7000 GeV, E_{Pb} = 2750 GeV
E_{lepton} = 20 GeV, E_{proton} = 7000 GeV, E_{Pb} = 2750 GeV
E_{lepton} = 26.9 GeV, E_{proton} = 7000 GeV, E_{Pb} = 2750 GeV

in the kinematical window: $10^{-5} < x < 1$ & $2 < Q^2 < 10^5$ GeV^2

- **For comparison, the foreseen EIC capabilities**

E_{lepton} = 5 GeV, $E_{p,Au,Cu}$ = 50, 75, 100 GeV (Phase 1)
E_{lepton} = 20 GeV, $E_{p,Au,Cu}$ = 50, 75, 100 GeV (Phase 2)

in the kinematical window: $10^{-3} < x < 1$ & $Q^2 < 500$ GeV^2

- **Nuclear effects in cross sections "EPS09 based"**

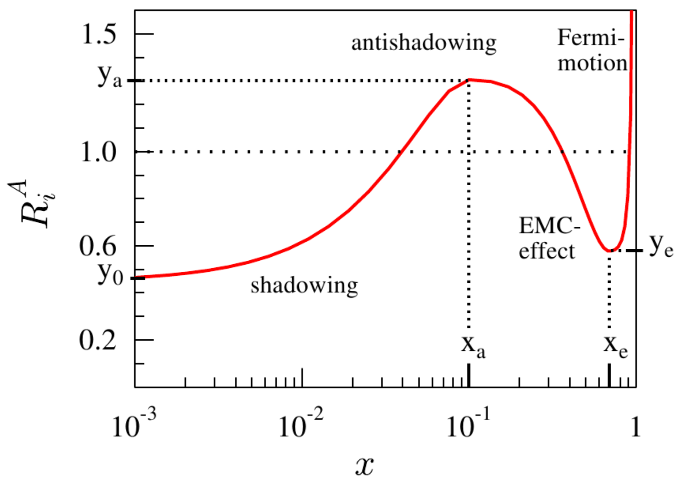
Framework of the pQCD analysis

- The cross-sections are computed at NLO with the SACOT prescription for the heavy quark treatment

- Parametrize the nuclear modifications at Q=1.3 GeV, CTEQ6.6 as the baseline

$$f_k^{\mathrm{proton},A}(x,Q^2) = R_k^A(x,Q^2)\, f_k^{\mathrm{proton}}(x,Q^2)$$

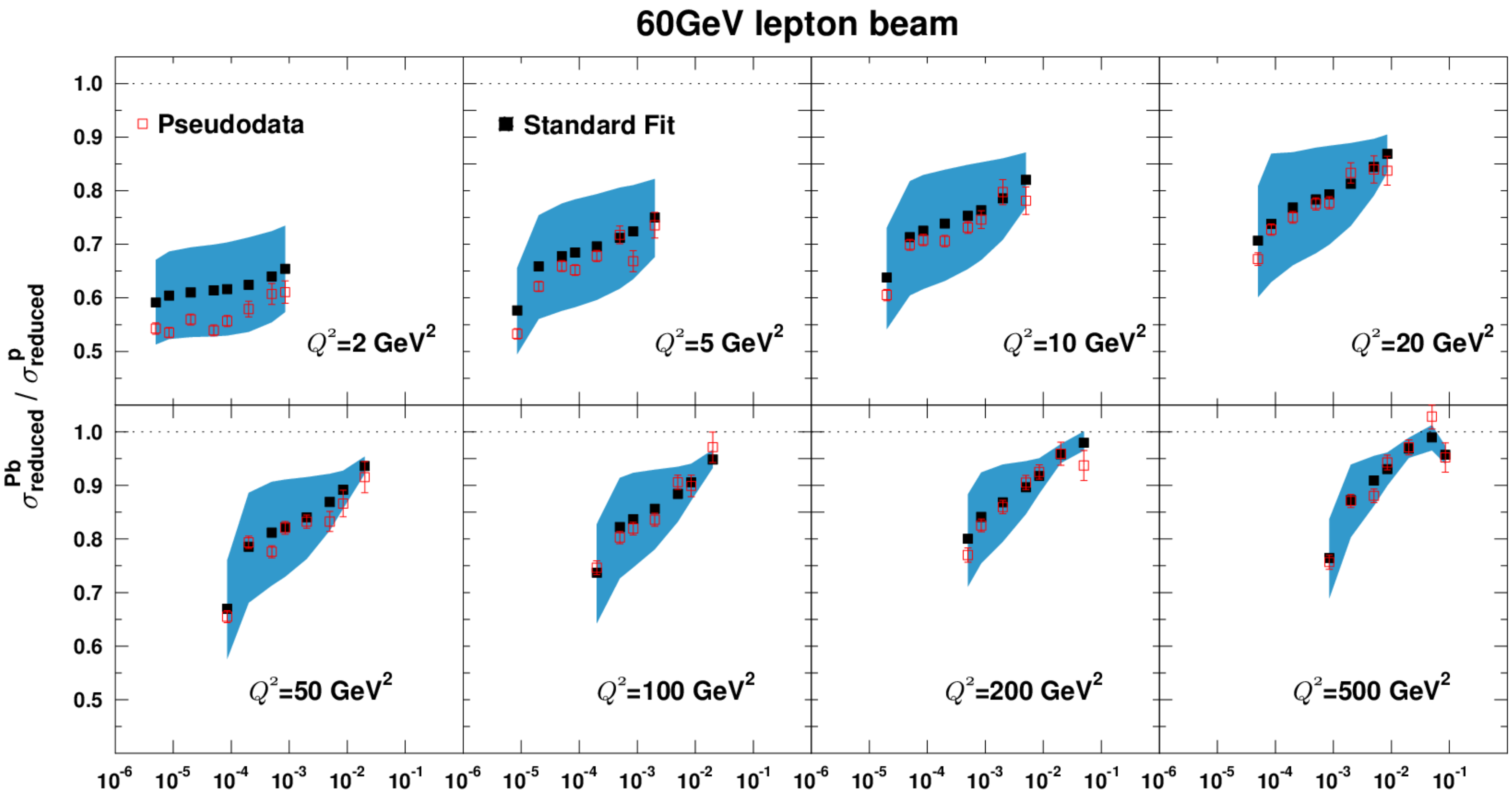
$R_V^A(x,Q_0^2)$	for all valence quarks
$R_S^A(x,Q_0^2)$	for all sea quarks
$R_G^A(x,Q_0^2)$	for gluons



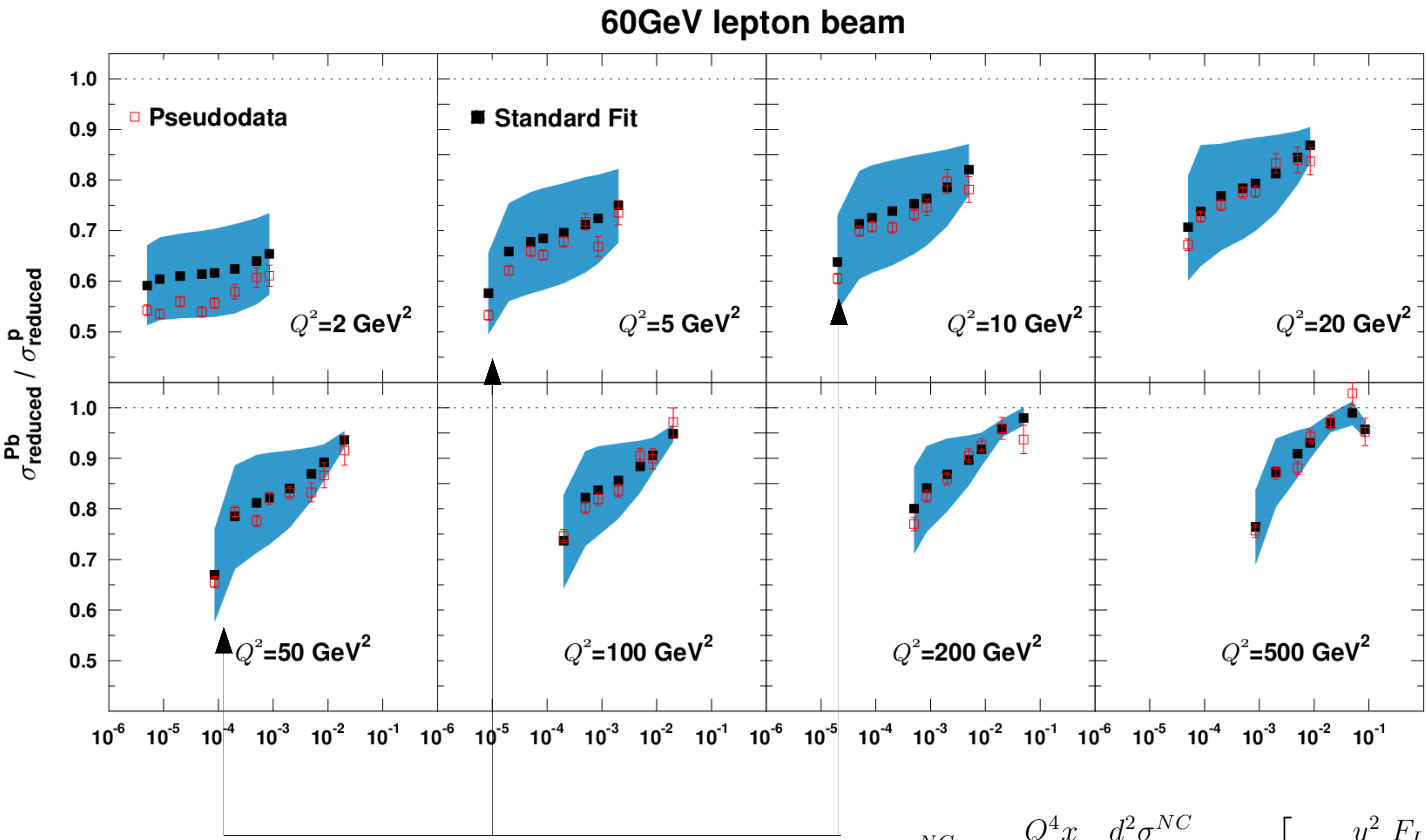
- The LHeC/EIC pseudodata are added on top of all other DIS, Drell-Yan, and inclusive pion data, that were included in EPS09.

- Standard χ^2-fit with Hessian error analysis with $\Delta\chi^2 = 25$

Before the fit: LHeC vs. baseline fit



Before the fit: LHeC vs. baseline fit

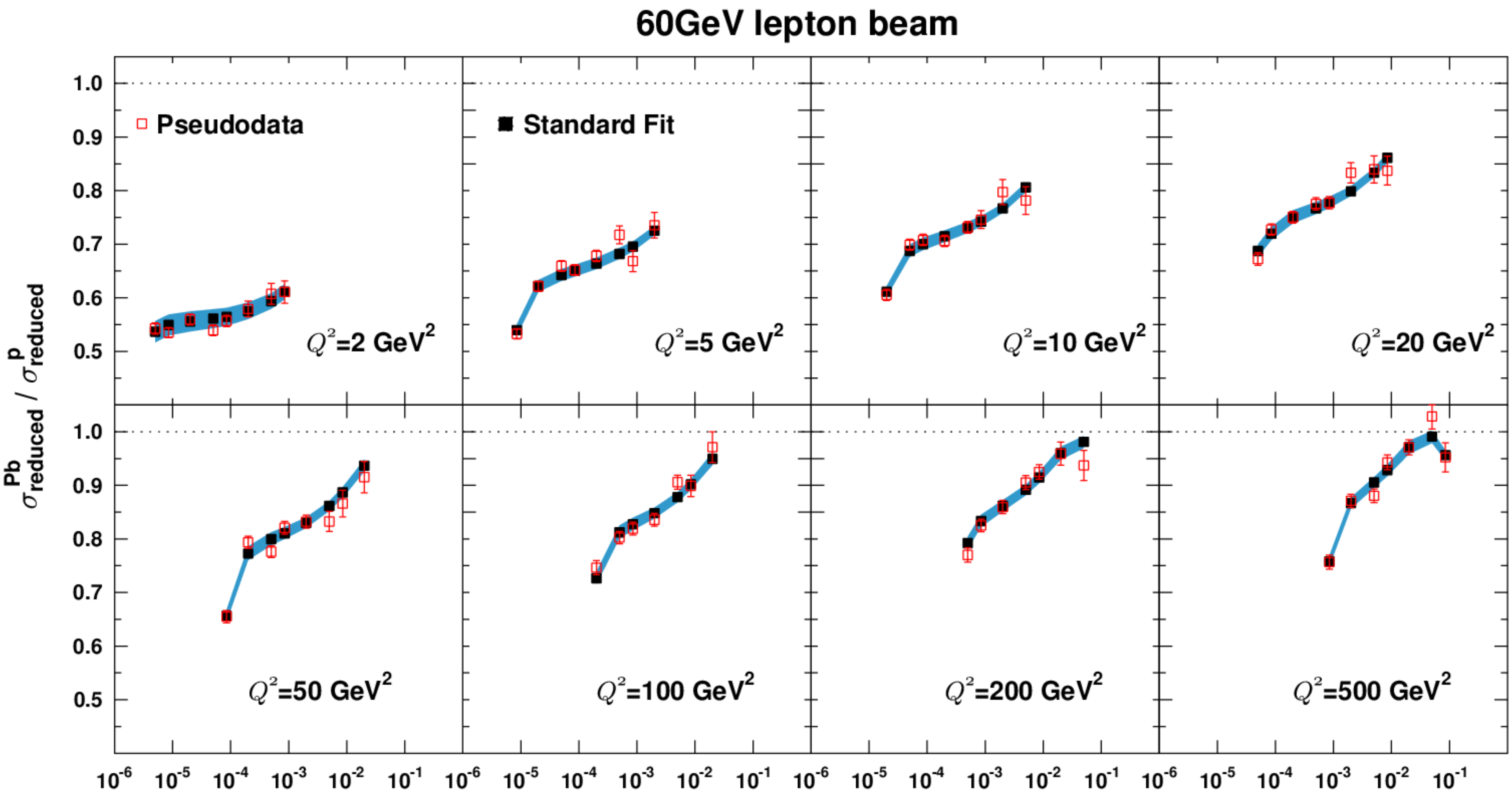


Note the sudden drop here – it's F_L!

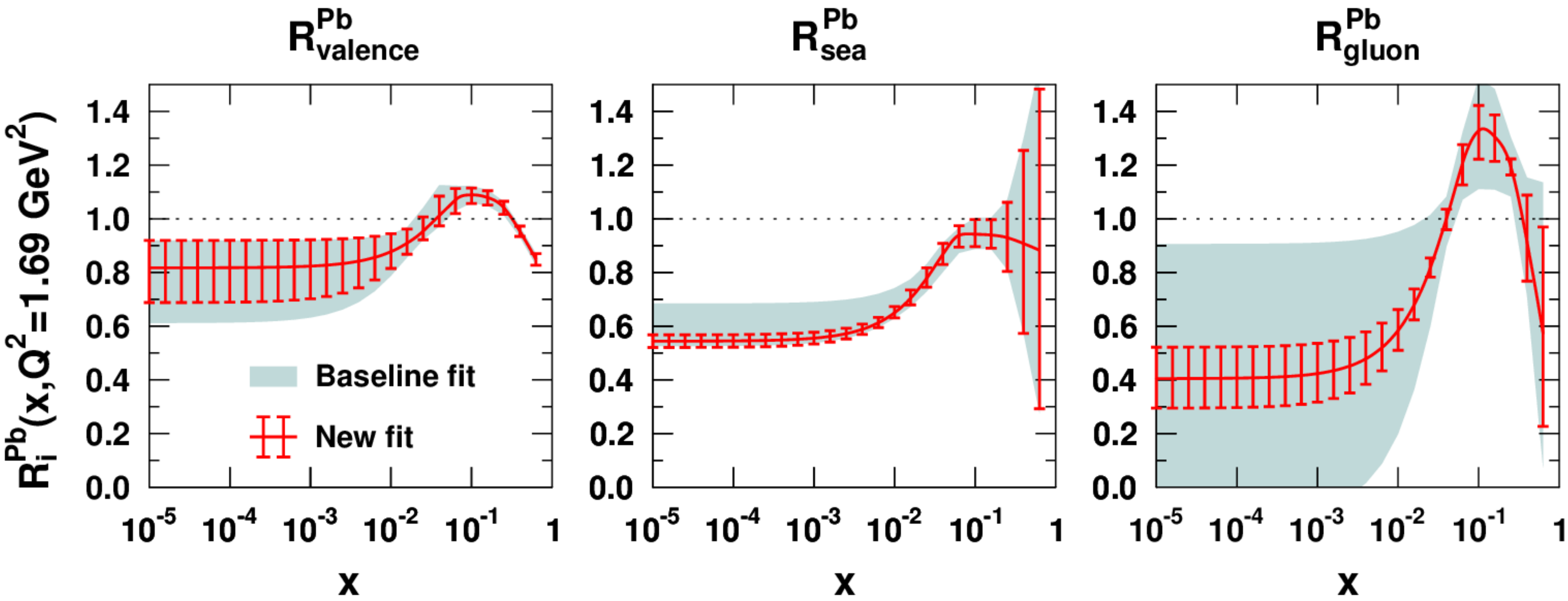
$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+} \frac{F_L}{F_2}\right]$$

small x

After the fit: LHeC vs. new fit



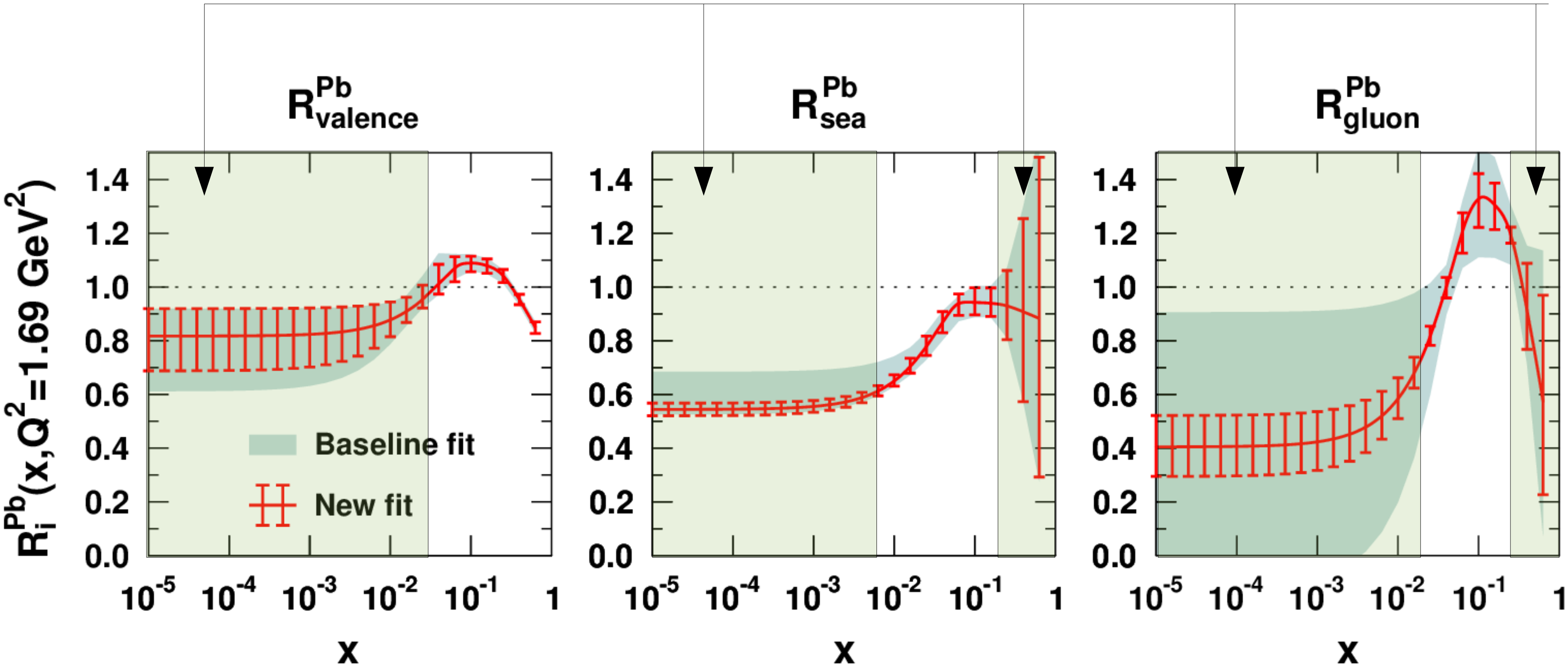
Effects in nPDFs, LHeC



- A drastic reduction in the small-x gluon and sea quark uncertainties

Effects in nPDFs, LHeC

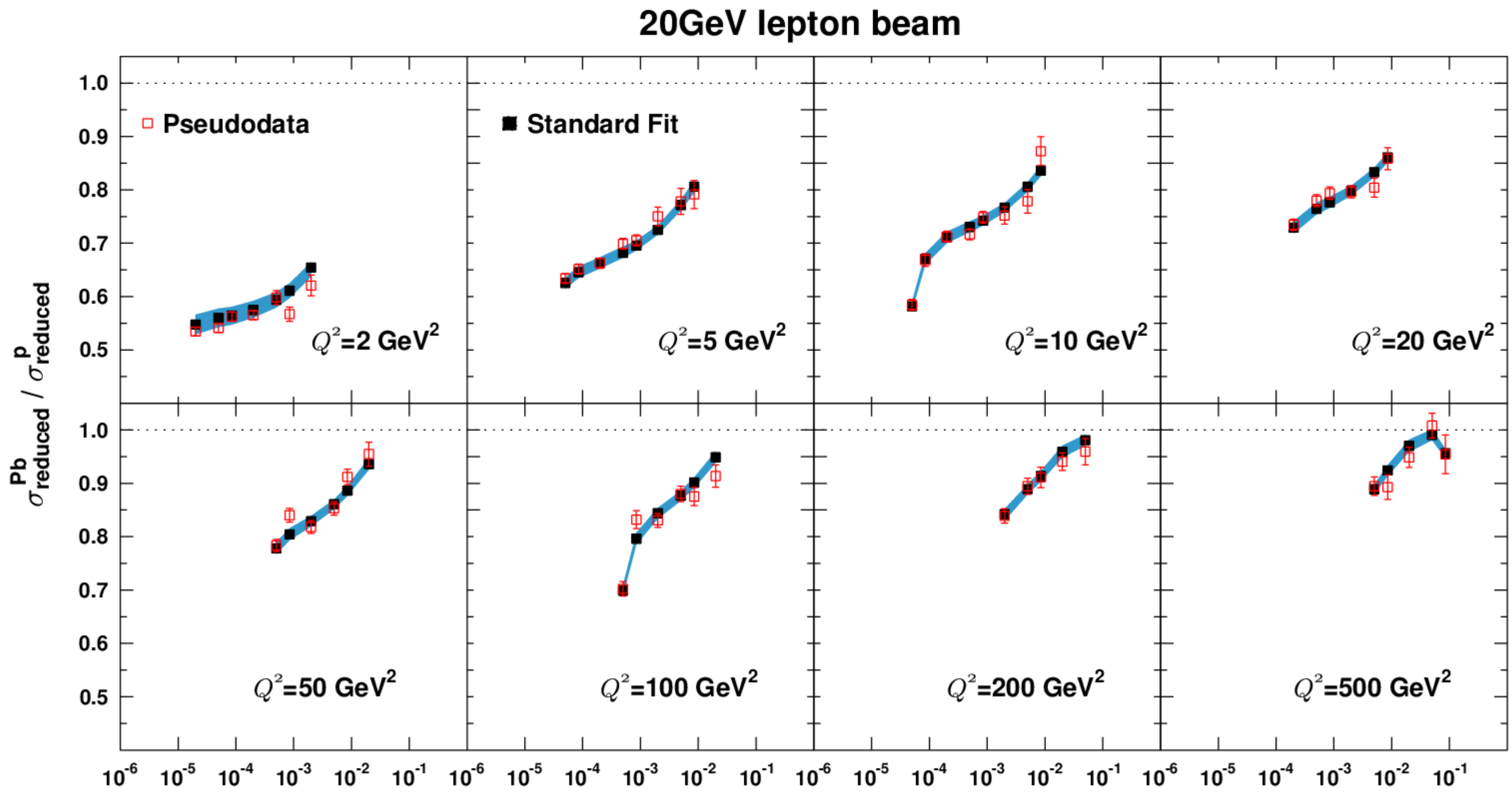
Currently no real data constraints!



- A drastic reduction in the small-x gluon and sea quark uncertainties
- More freedom in the fit function should be allowed – the baseline uncertainty probably underestimated
- Addition of charged-current data should give a handle on the flavor dependence, which is currently (practically) unconstrained

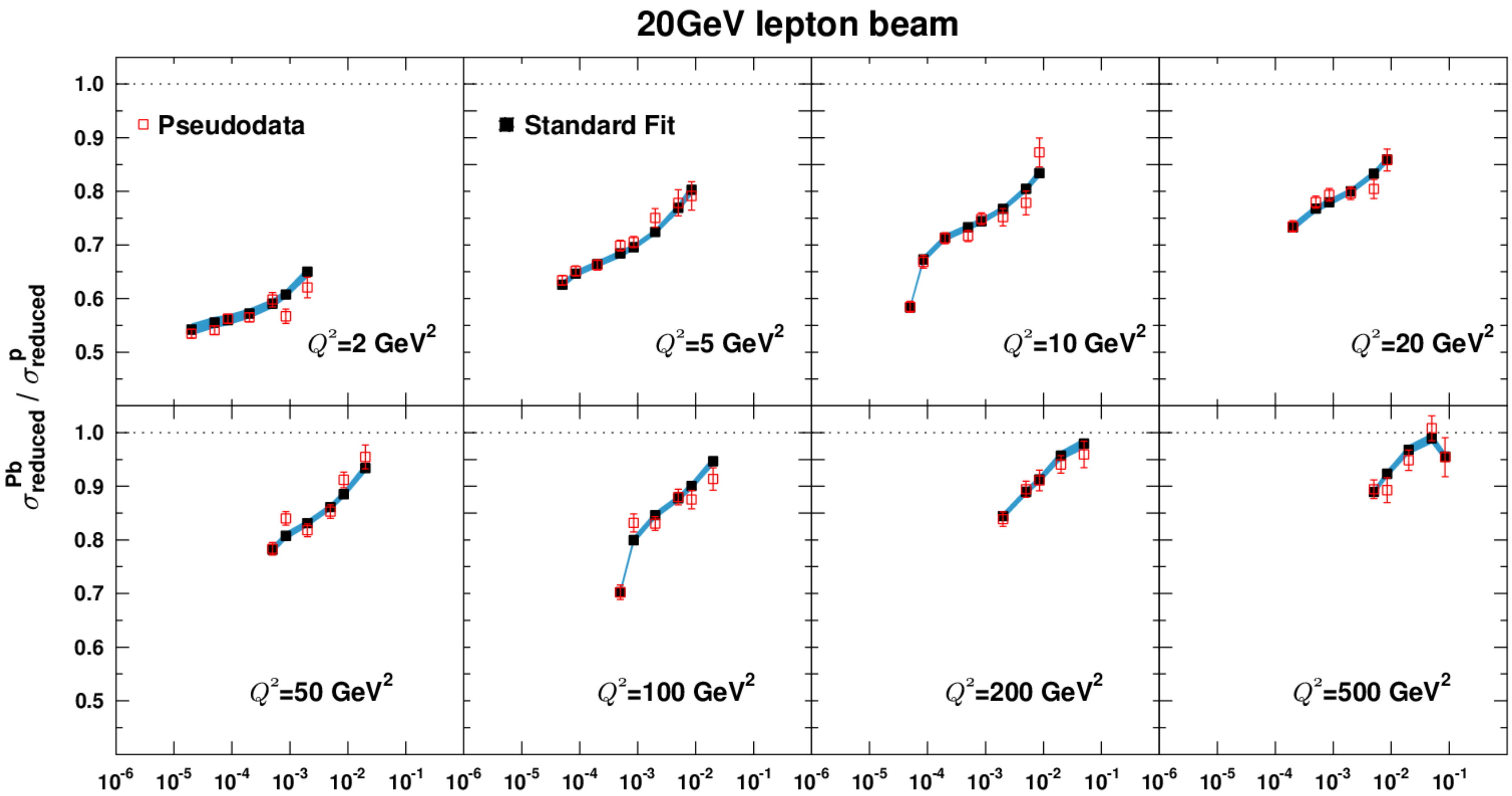
The low-energy data, before inclusion

- Include also the data from the E_{lepton} = 20GeV and E_{lepton} = 26.9GeV runs



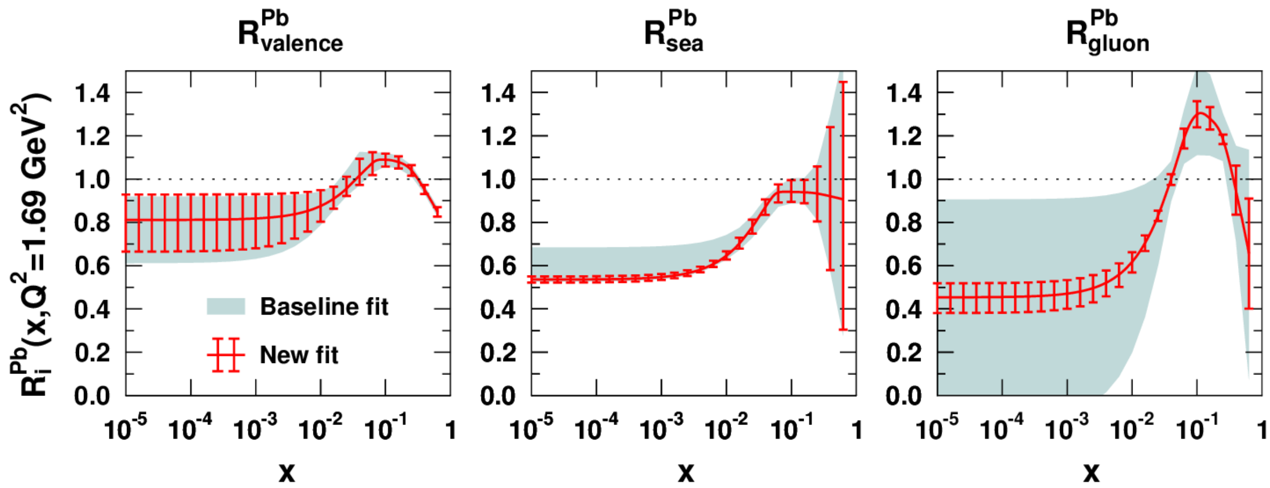
The low-energy data, after inclusion

- Include also the data from the E_{lepton} = 20GeV and E_{lepton} = 26.9GeV runs

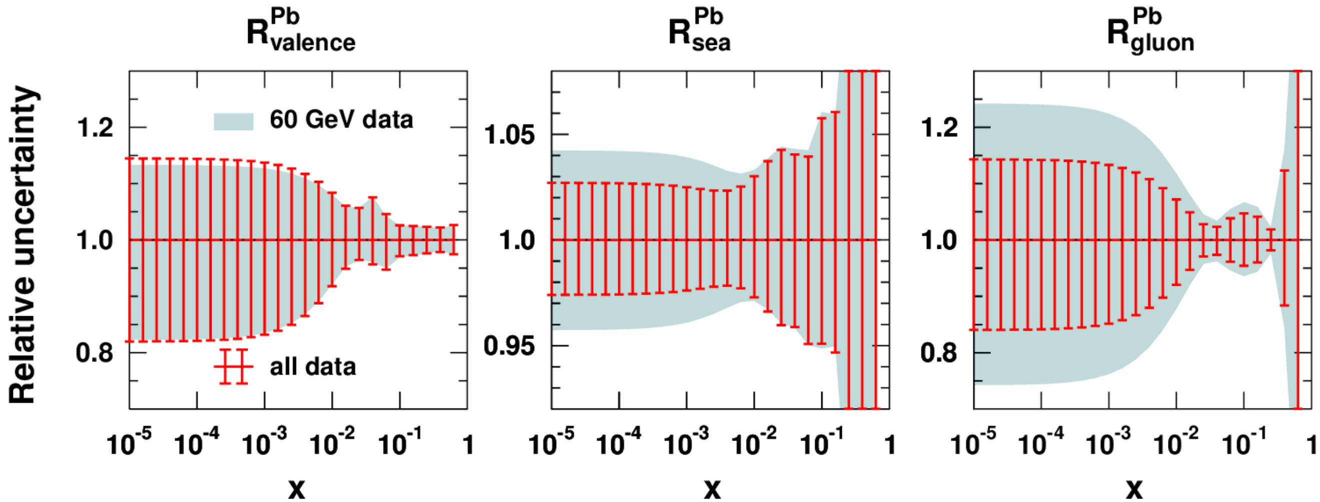


Inclusion of the low-energy data

- Include also the data from the E_{lepton} = 20GeV and E_{lepton} = 26.9GeV runs

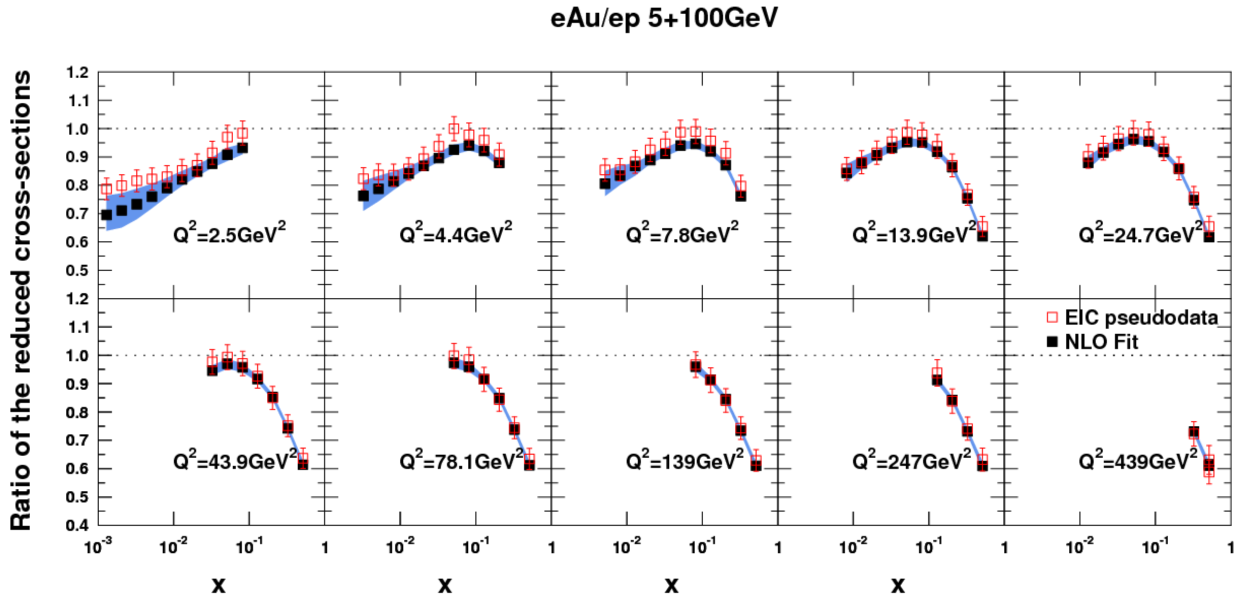


- Relative uncertainties compared to the case with E_{lepton} = 60GeV data only

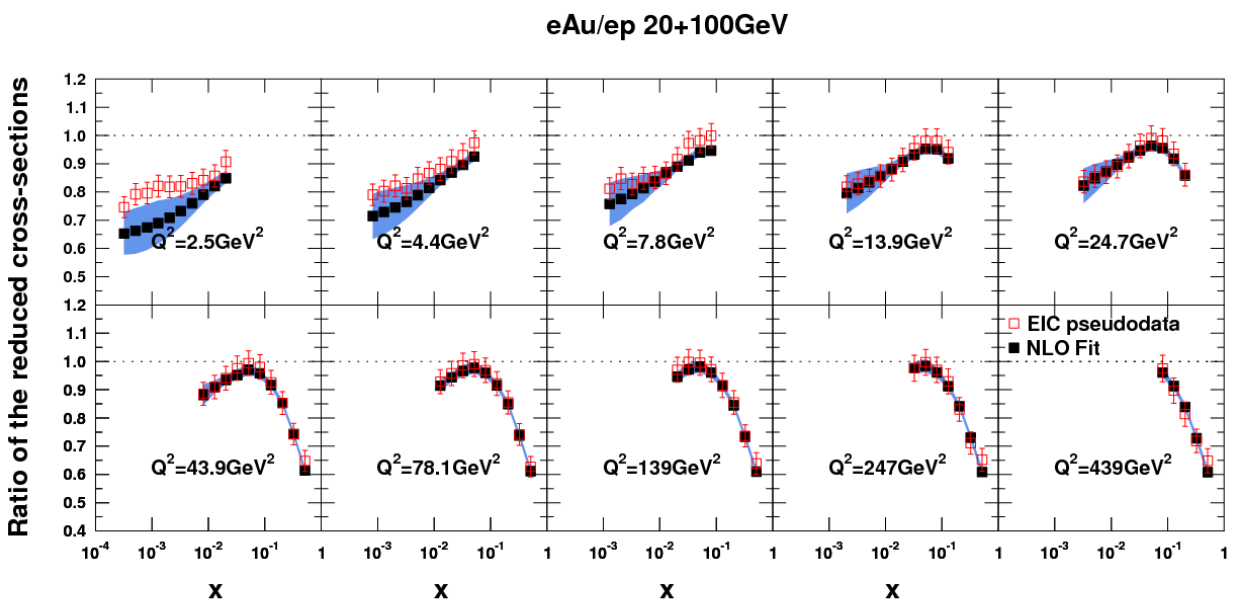


- Even larger reduction in the small-x uncertainties – though not dramatic

Before the fit: some EIC pseudodata vs. baseline fit

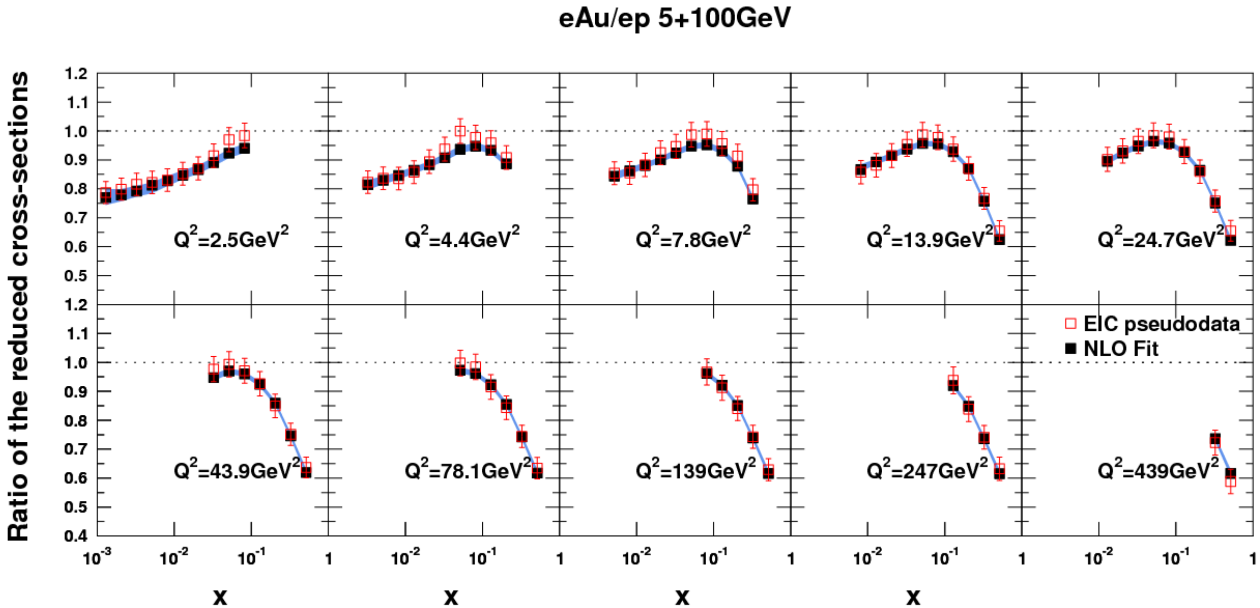


"Phase 1"

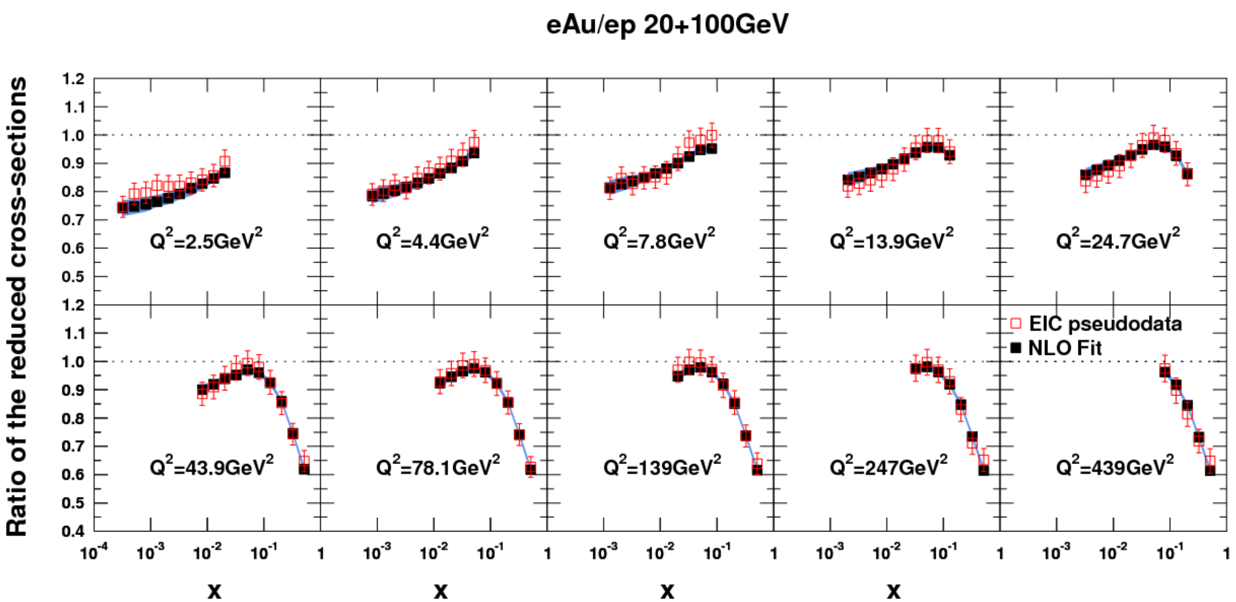


"Phase 2"

After the fit: some EIC pseudodata vs. new fit



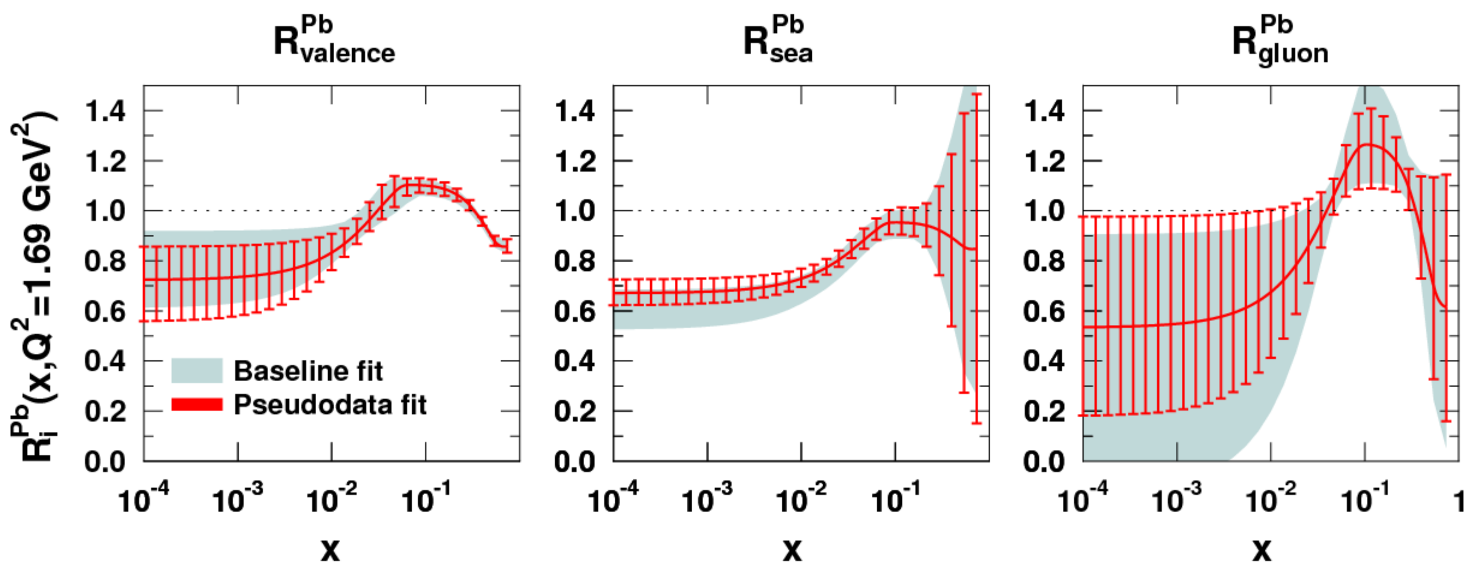
"Phase 1"



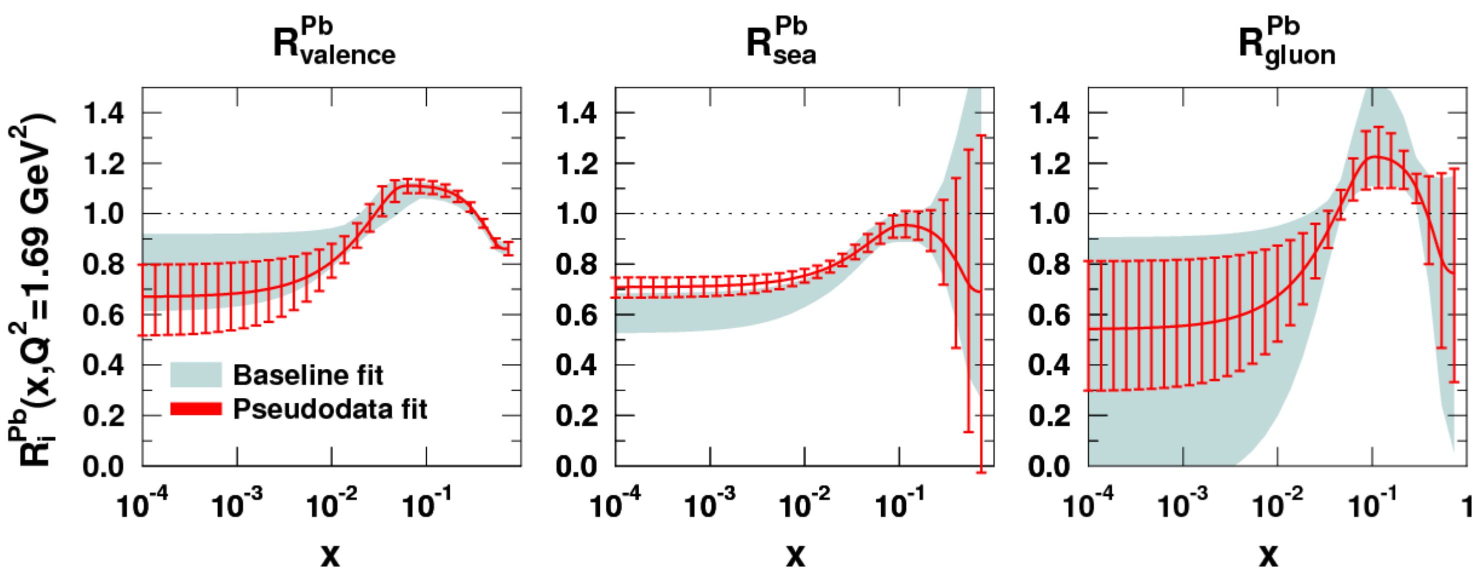
"Phase 2"

Effects in the nuclear modificaton factors: EIC

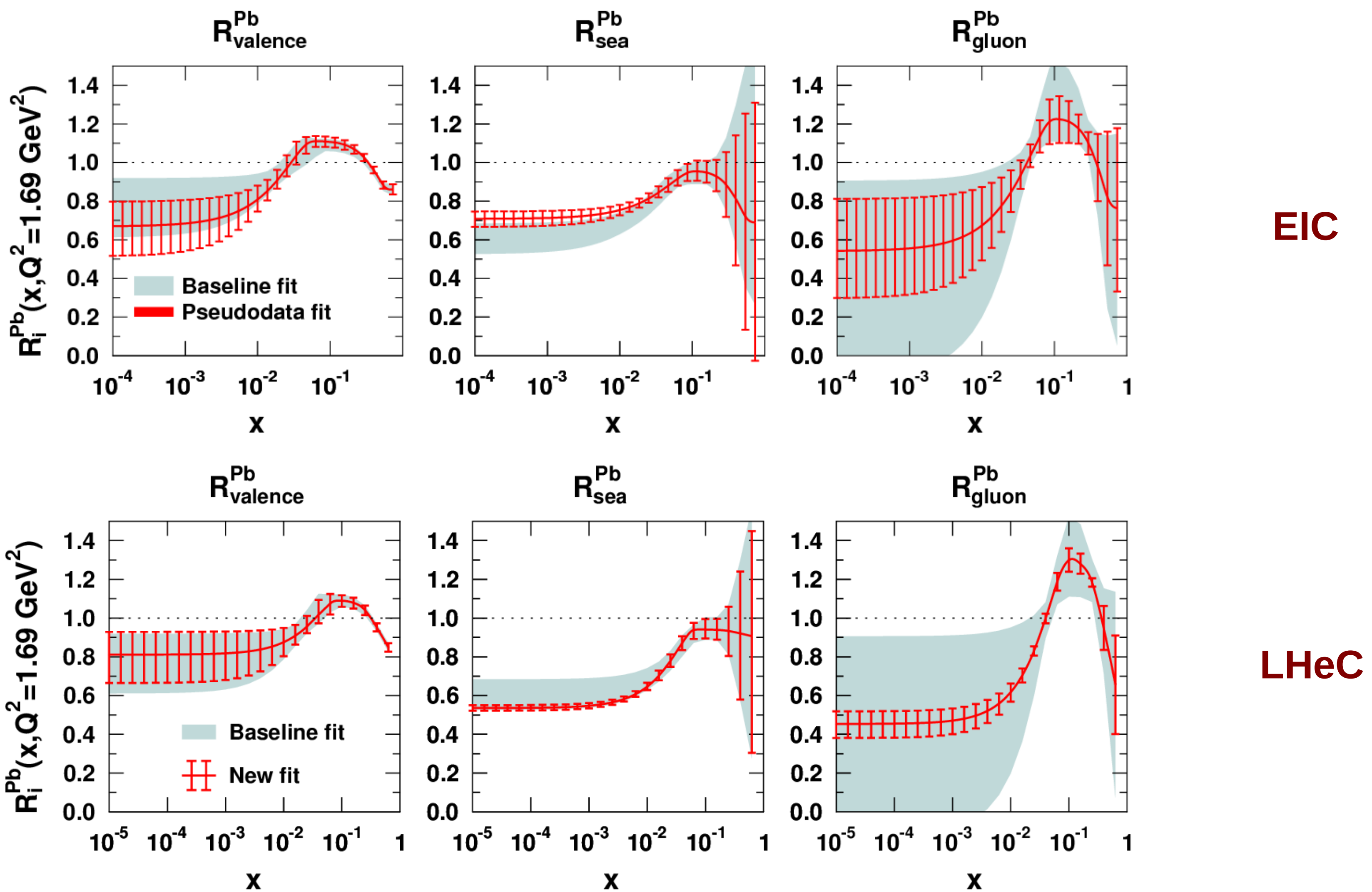
“Phase 1“



“Phase 2“



Constraints for nPDFs: LHeC vs. EIC



- Both fits use only neutral-current DIS pseudodata, $\Delta\chi^2 = 25$
- The advantage of LHeC reaching smaller x is obvious

Summary

- **Quickly reviewed the current status of the global nPDF fits**

  Large differences among independent fits. The LHC p+Pb data are expected to have an impact

- **Flashed first dijet measurements from the LHC p+Pb runs**

  Already this first data could discriminate between different sets of nPDFs. Much more to come (W, Z, direct photon, ...)

- **Discussed LHeC & EIC prospects**

  Would allow to study the nPDFs to a similar precision as done in HERA for the free proton

  The potential constraints for nPDFs huge in LHeC, bit less so for the EIC. Work still in progress...