PDFs and their Nuclear Modifications

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Physics Opportunities at the Electron-Ion Collider 2021 - on-line

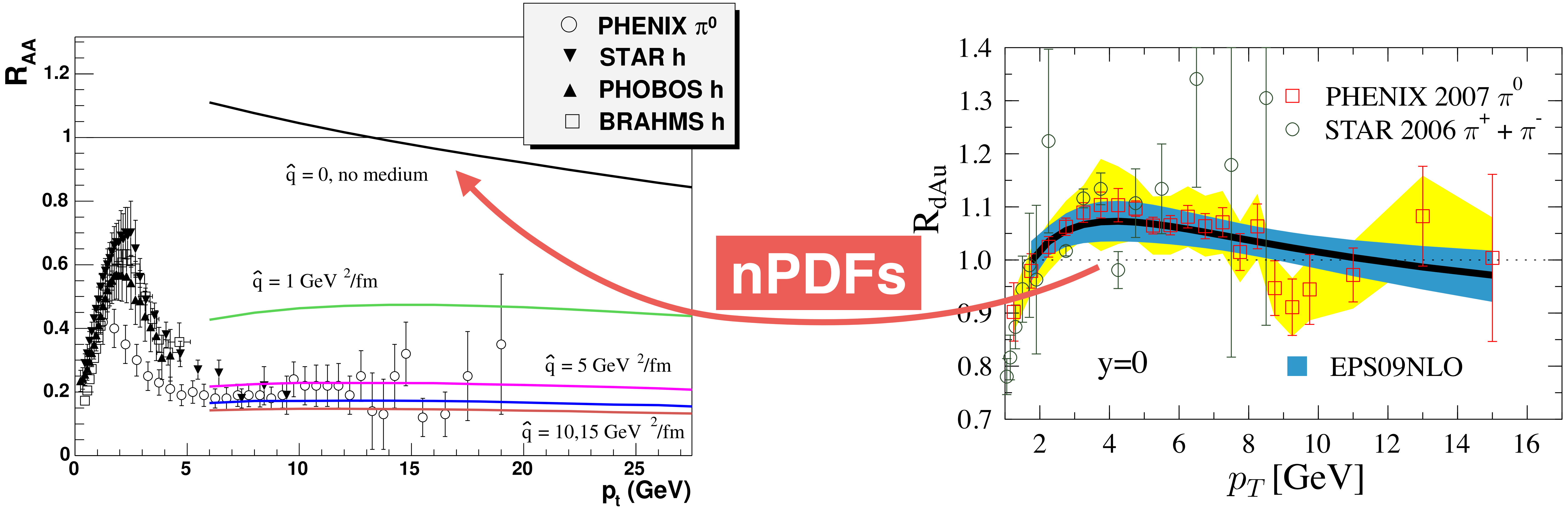
Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
An ERC Advanced Grant 2019 · 2024
erc
European Research Council
Established by the European Commission
IGFAE
Instituto Galego de Física de Altas Enerxías
USC
XUNTA DE GALICIA
EXCELENCIA MARÍA DE MAEZTU

Why nuclear PDFs

Short answer - same reasons as for proton PDFs

- Benchmarking in search for new phenomena (saturation of partonic densities and hot matter effects).
- Partonic structure of the nuclei - universality of nuclear PDFs?

Example



[Eskola, Honkanen, Salgado, Wiedemann 2005]

[Eskola, Paukkunen, Salgado, 2009]

Example

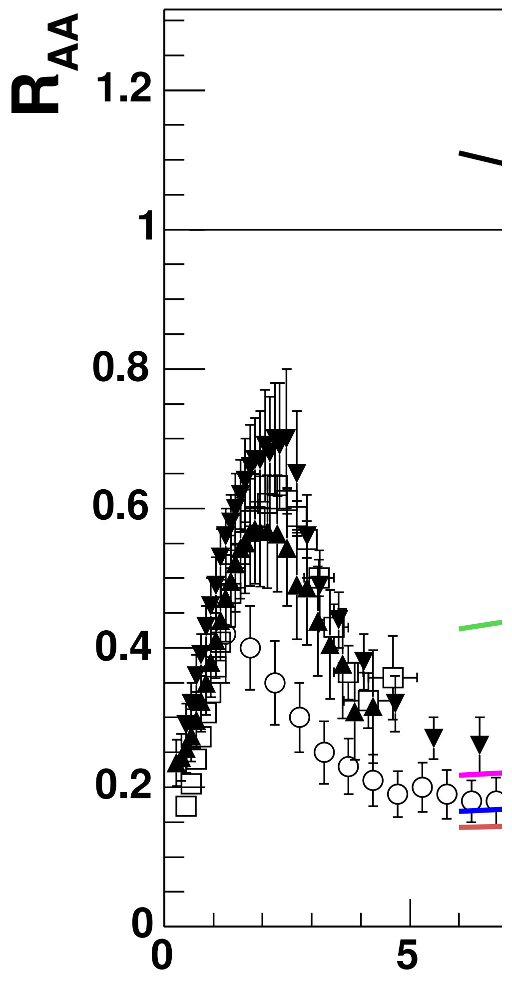
Jet quenching is a final-state effect

Why nuclear PDFs

Short answer - same reasons as for proton PDFs

- Benchmarking in sea … and hot matter effects).
- Partonic structure of

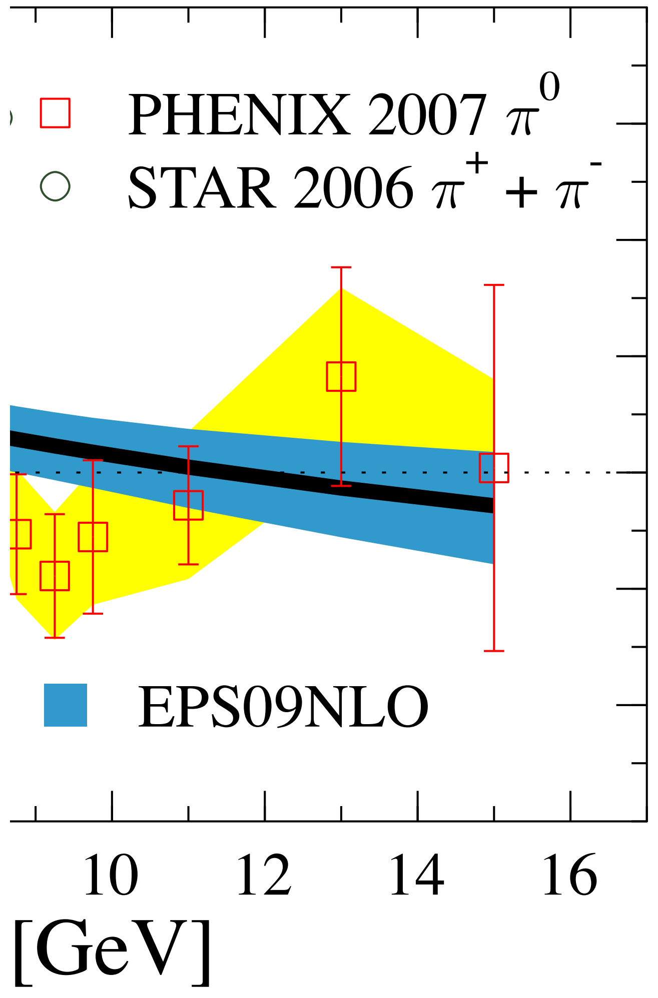
Example



[Eskola, Hon

proton - nucleus
essential
in nPDF analyses

[especially with limited nuclear DIS data]

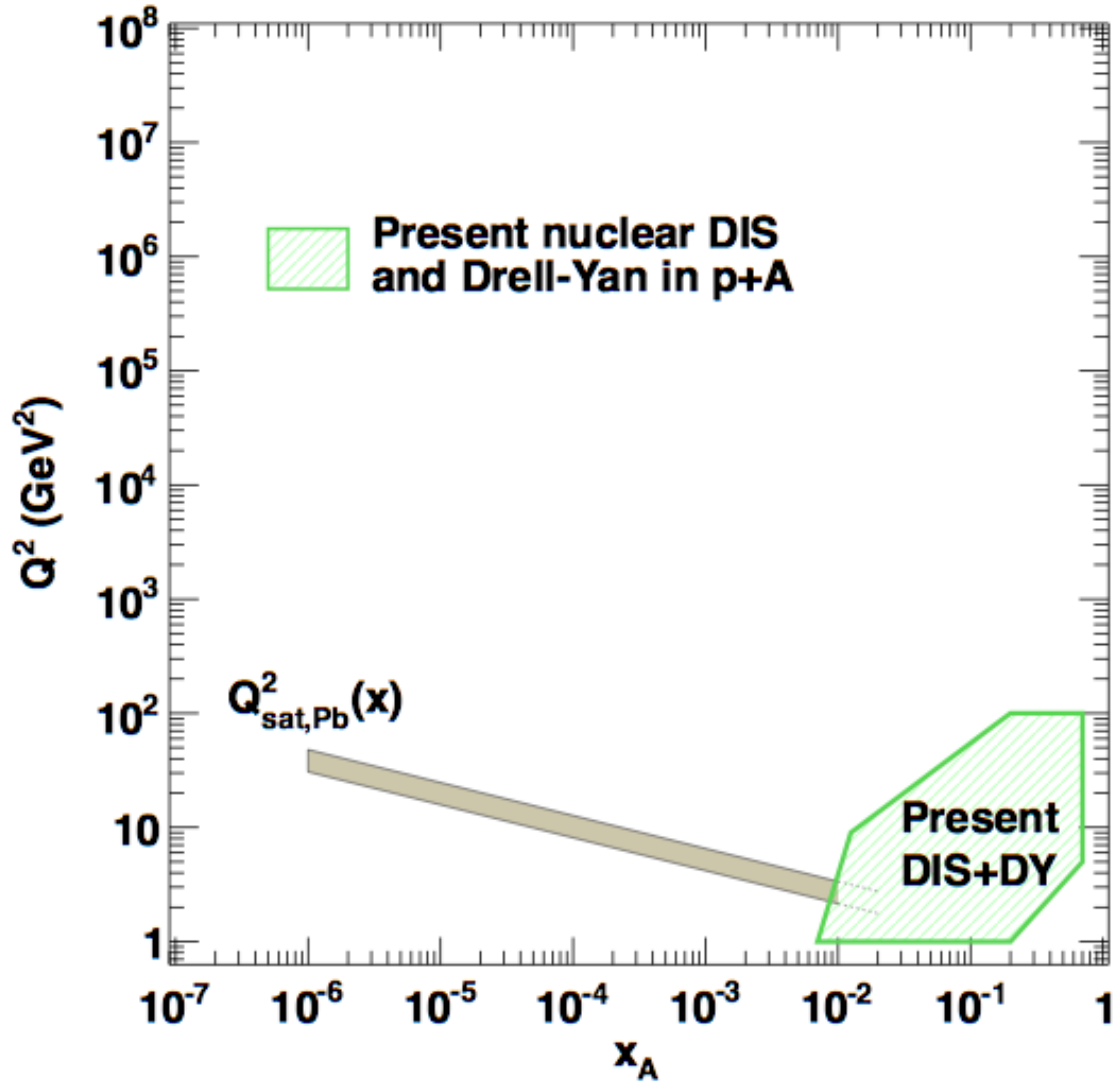


en, Salgado, 2009]

Jet quenching is a final-state effect

Example

nPDFs vs time



EKS98 [Eskola, Kolhinen, Ruuskanen, Salgado]

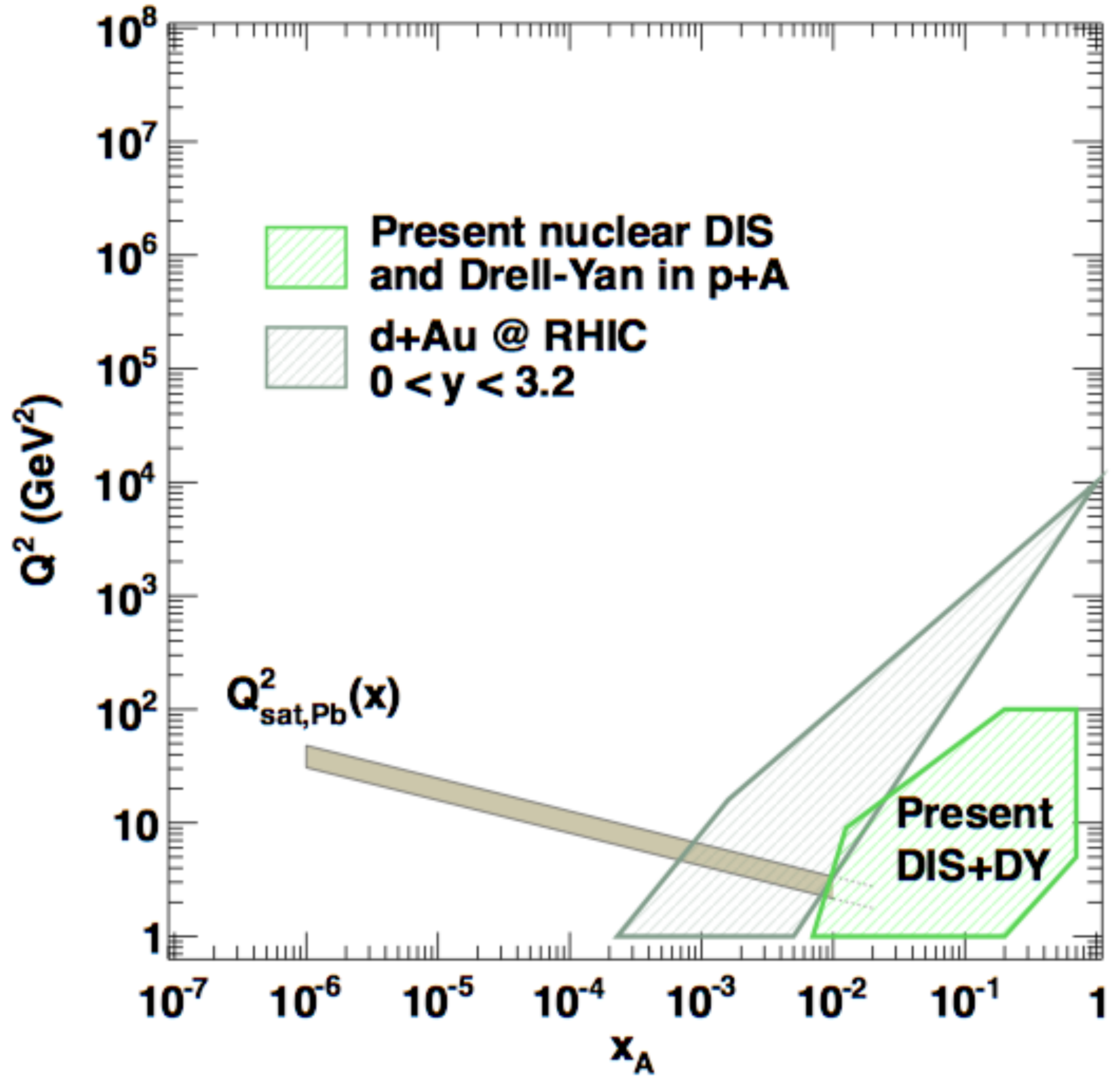
HKM01, HKN04 [Hirai, Kumano, Miyama, Nagai]

HKN04 - **first Hessian error analysis**

de Florian, Sassot 2004

First NLO analysis

nPDFs vs time



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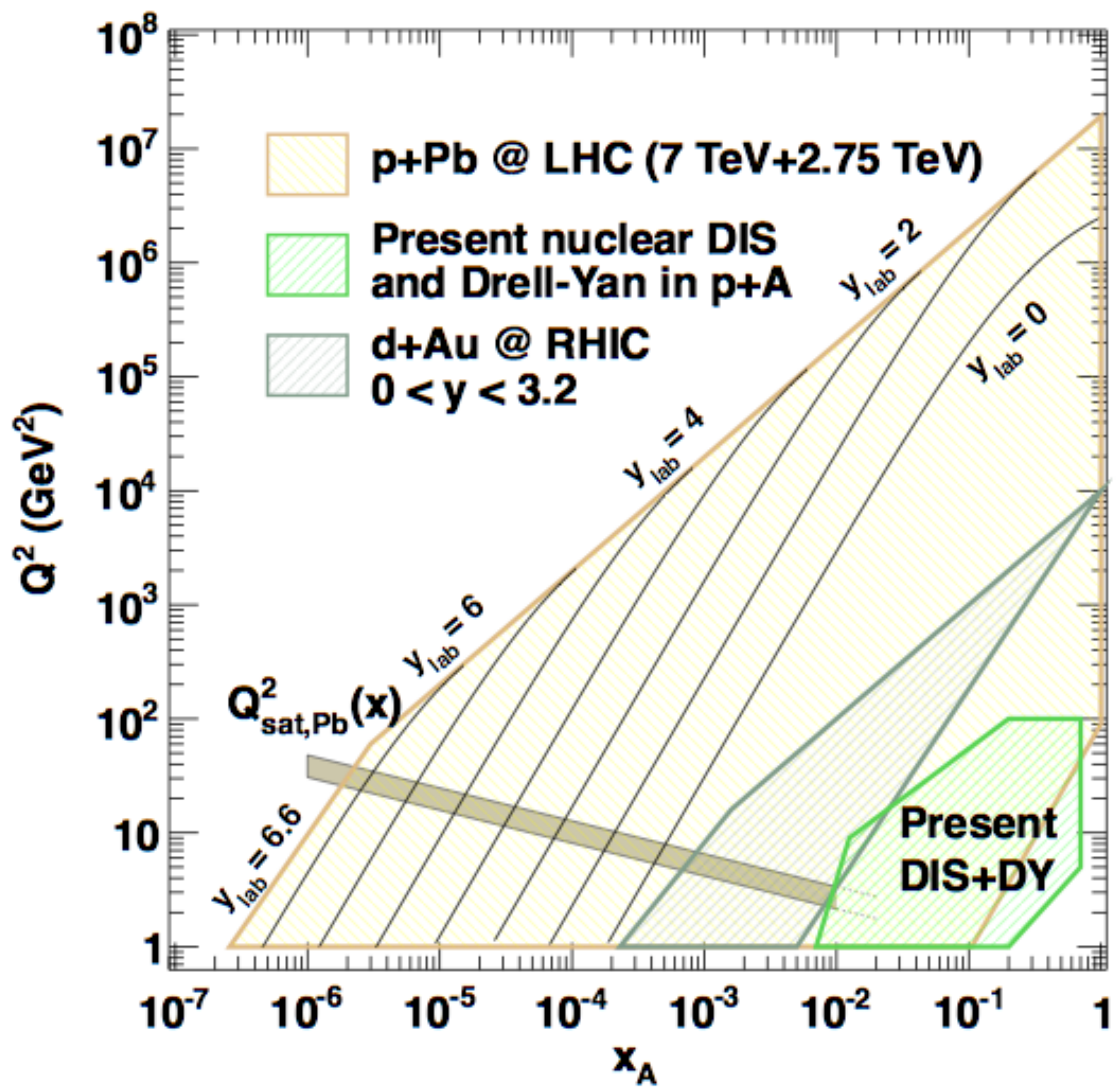
RHIC data included for 1st time

DSSZ-2012 [de Florian, Sassot, Stratmann, Zurita]

Neutrino data included in fit

nCTEQ - 2015 [Kovarik et al.]

nPDFs vs time



LHC: large extension in kinematic reach: **proton-lead**

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EPPS16 [Eskola,Paakkinen,Paukkunen,Salgado]
LHC data included for first time

KA15, KSASG20 [Khanpour, Soleymaninia,Tehrani, Spiesberger, Guzey]
TUJU19 [Walt, Helenius, Vogelsang]
nNNPDF1.0/2.0 [Abdul Khalek, Ethier, Rojo, van Weelden]

nPDFs vs time

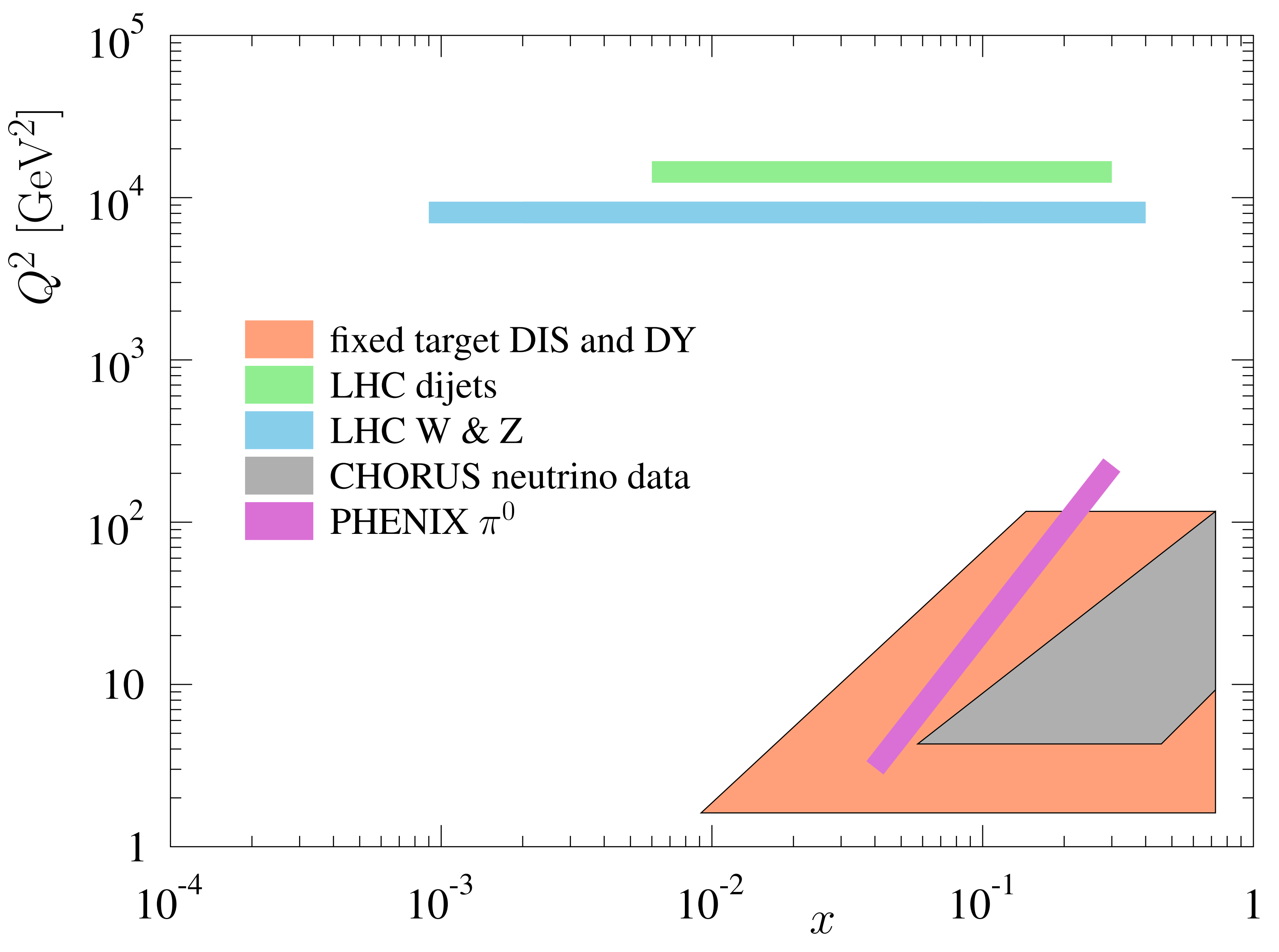

Fig. 2 The approximate regions in the (x, Q^2) plane at which different data in the EPPS16 fit probe the nuclear PDFs.

But still rather limited amount of experimental data

Would be nice to fill the gap at small-x and large Q

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Recall DGLAP

Collinear factorization - perturbative cross sections

$$\frac{d\sigma^{AB\to X}}{dk} = f_i^A(x,\mu^2) \otimes f_j^B(y,\mu^2) \otimes \frac{d\hat{\sigma}^{ij\to X}}{d\hat{k}}$$

Parton distribution functions are **universal** - evolution given by DGLAP

$$\frac{\partial q_i}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\left[P_{qq}\otimes q_i + P_{qg}\otimes g\right]$$

$$\frac{\partial g}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\left[P_{gq}\otimes q + P_{gg}\otimes g\right]$$

- Non-perturbative (long-distance)
- Differential equations **need initial conditions**
- We cannot compute I.C. - **fit from data**
- DGLAP predicts (perturbative) scale evolution

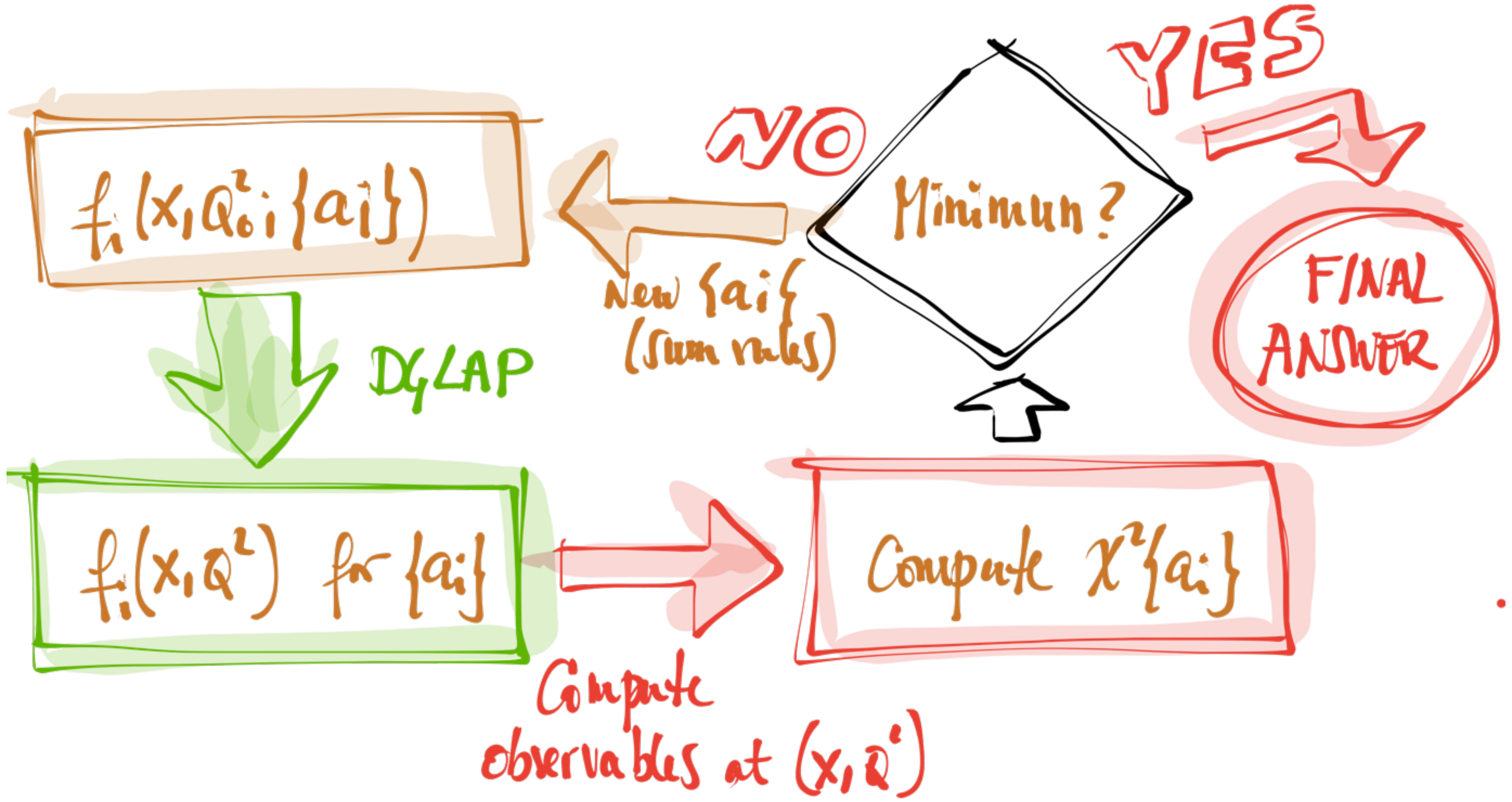
→ Gluons evolve very fast
↳ drive sea quark evolution

→ Valence quarks ≈ evolve by themselves

Knowledge about PDFs **reflects used/available experimental data** in the fit

Global PDF fits

- **One of the most standardized procedures in High-Energy Physics.**
- Main goal: provide a set of Parton Distribution Functions (PDFs)



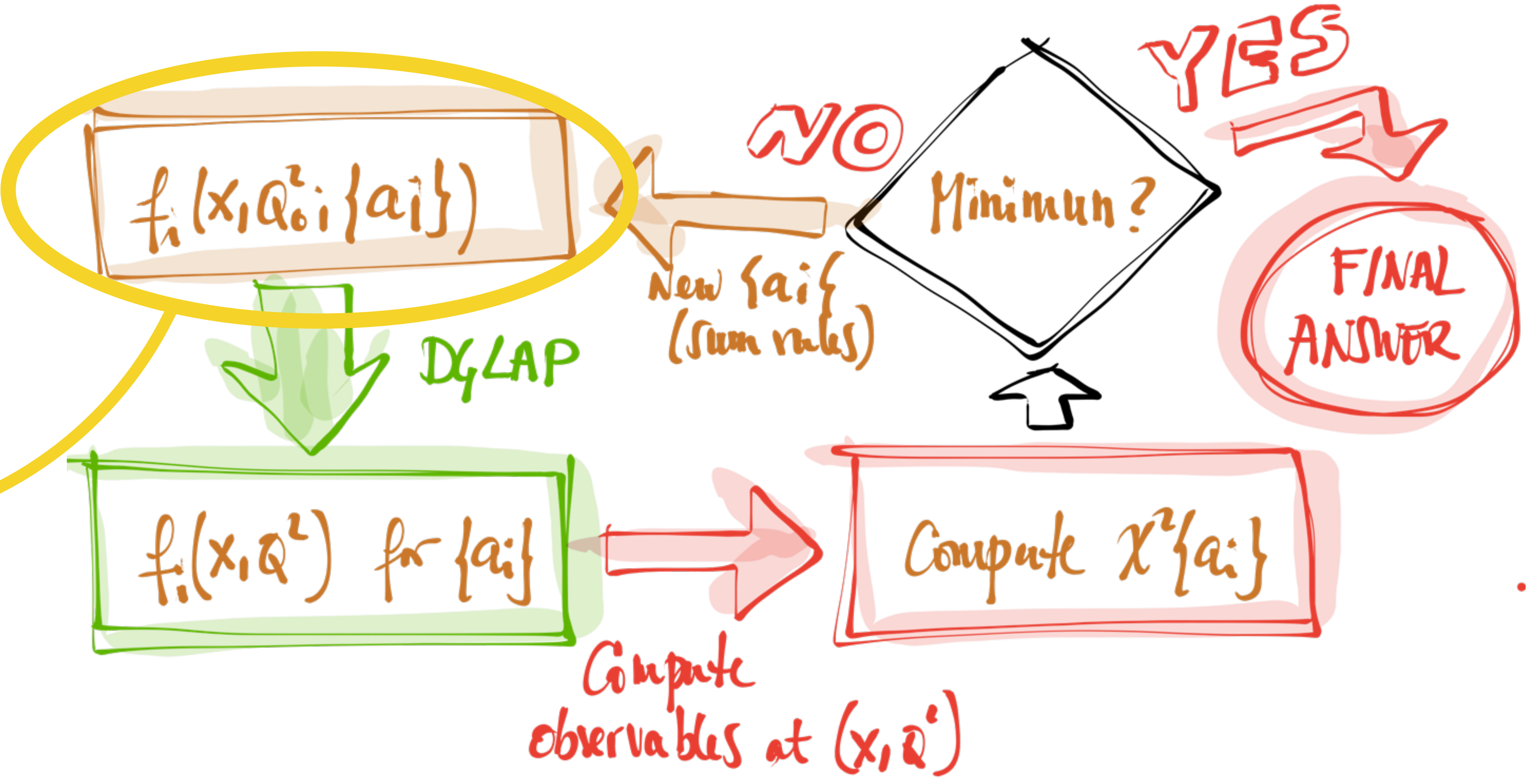
Different sets differ mostly on how I.C. are parametrized and how to treat the error analysis

Global PDF fits

- **One of the most standardized procedures in High-Energy Physics.**
- Main goal: provide a set of Parton Distribution Functions (PDFs)

Input is a set of PDFs at at initial scale Q_0

This is the fitting function



Different sets differ mostly on how I.C. are parametrized and how to treat the error analysis

(Hessian) Error analysis

[Alternative approach: NNPDF]

Define chi2 in terms of the initial parameters **a** (N-dim vector)

$$\chi^2(\mathbf{a}) \equiv \sum_k \chi_k^2(\mathbf{a}) \equiv \sum_{i,j} [T_i(\mathbf{a}) - D_i] \, C_{ij}^{-1} \, [T_j(\mathbf{a}) - D_j] \, .$$

Compute the Hessian matrix and diagonalize

$$\chi^2(\mathbf{a}) \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j , \quad \longrightarrow \quad \chi^2(\mathbf{z}) \approx \chi_0^2 + \sum_i z_i^2 \, .$$

vectors **z** are linear combinations of original **a** now **uncorrelated**

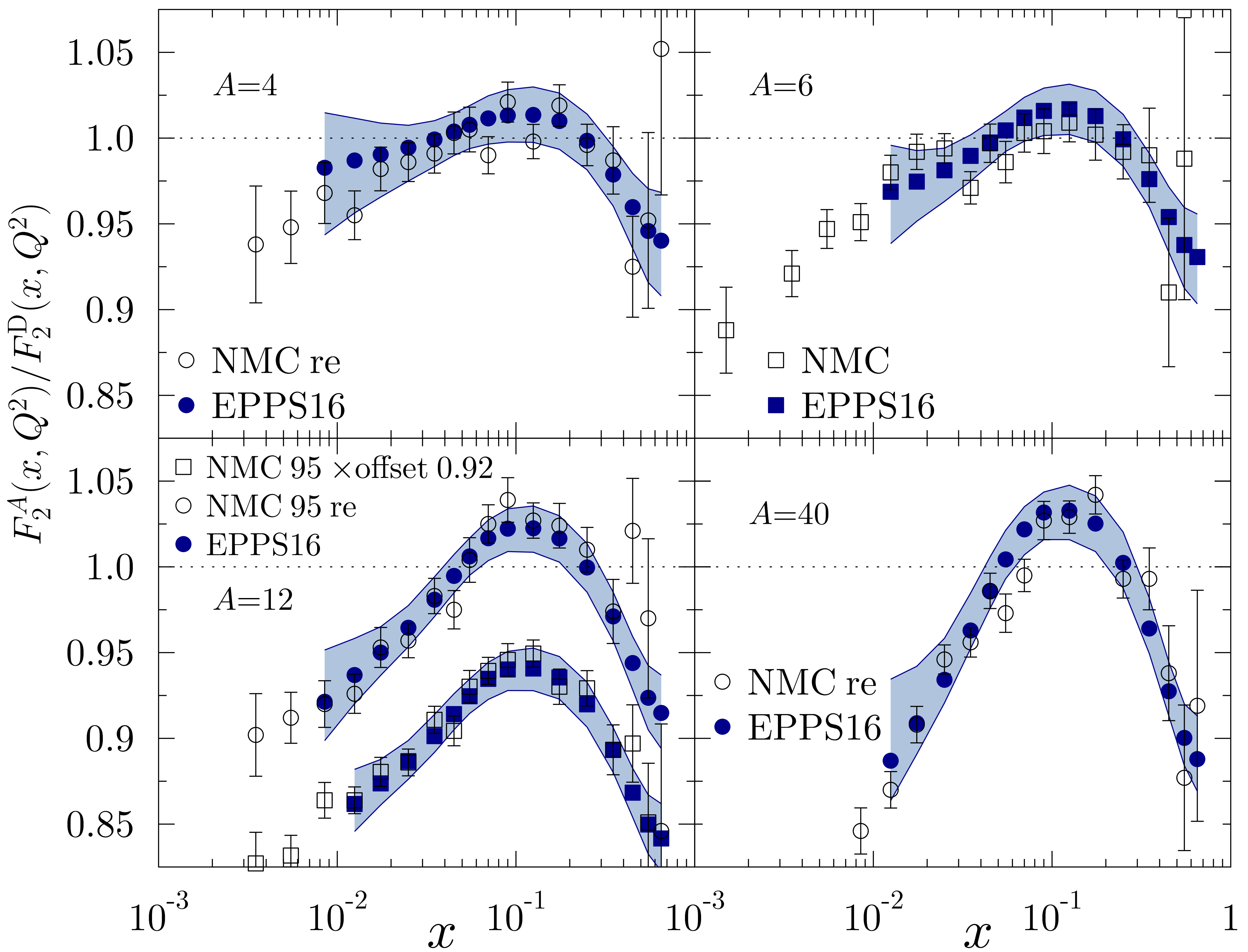
$$\int_0^{M_k} \frac{d\chi^2}{2\Gamma(N_k/2)} \left(\frac{\chi^2}{2}\right)^{N_k/2-1} \exp\left(-\chi^2/2\right) = 0.90, \quad \longrightarrow$$

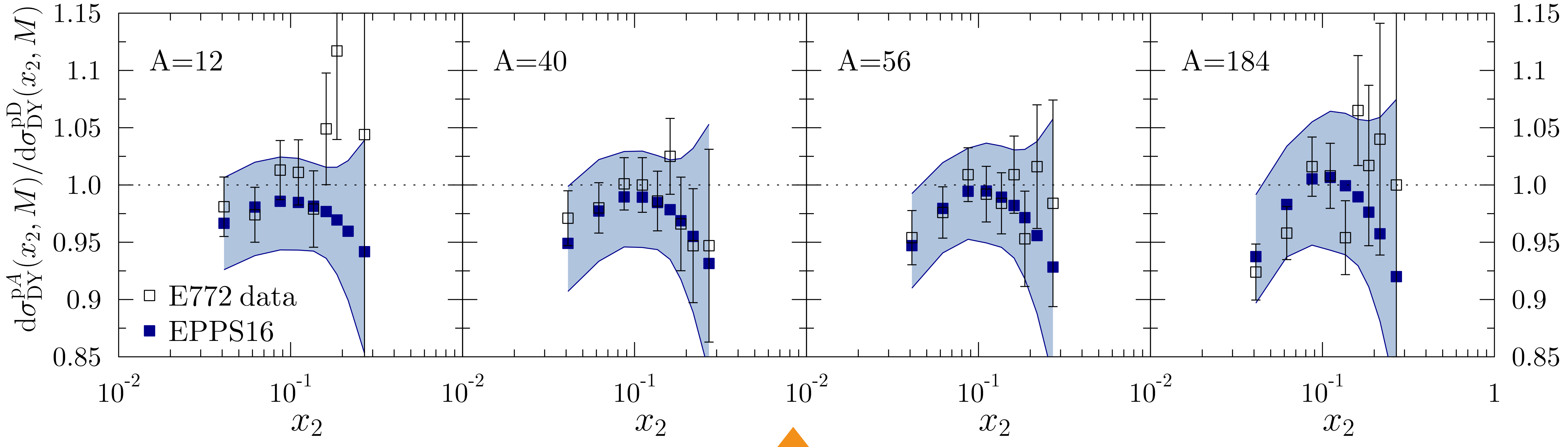
Tolerance factor for EPPS16

$$\Delta\chi^2 = 52$$

Example of nuclear data

Fixed target DIS



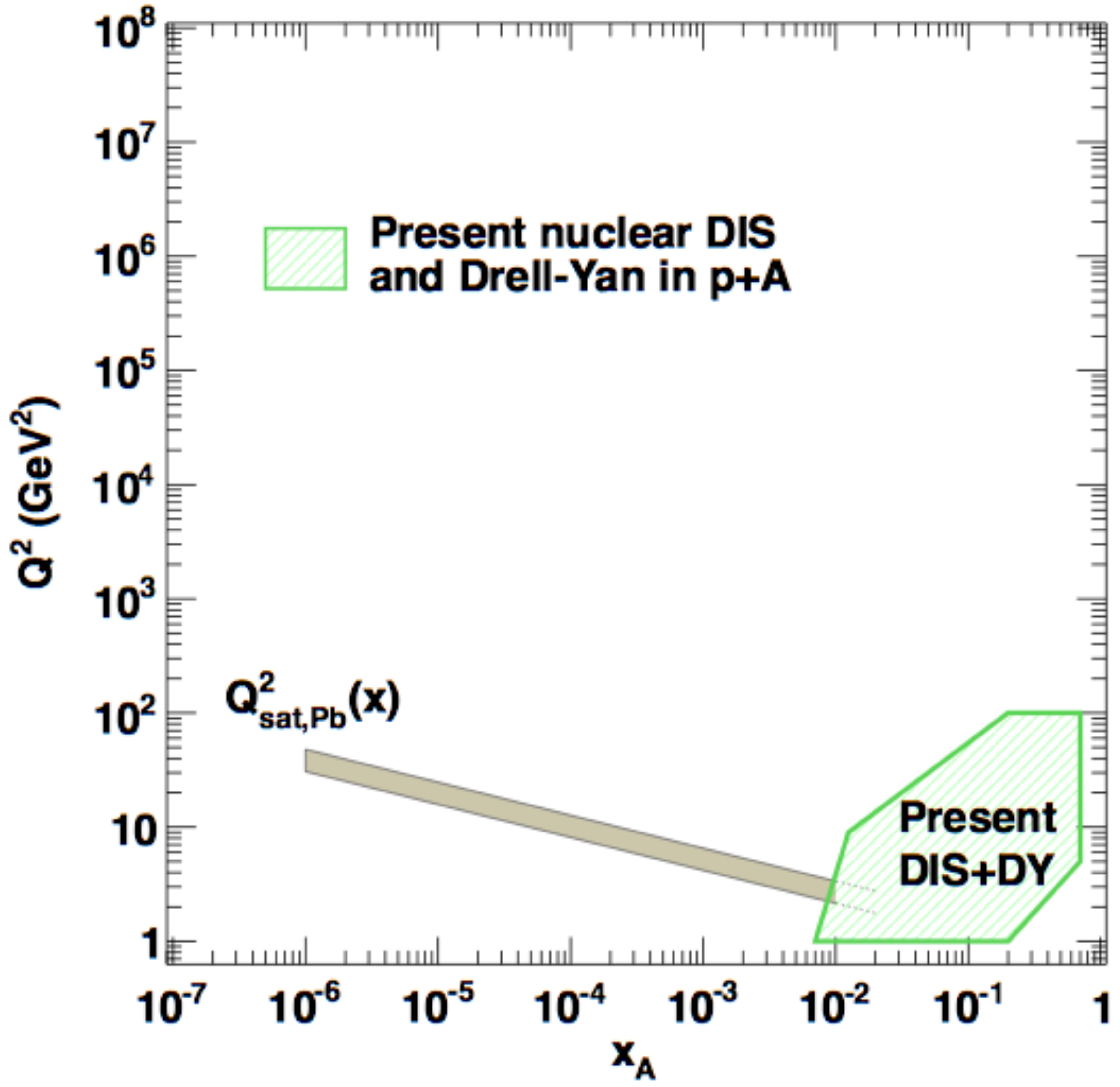


Fixed target DY

Data usually in terms of ratios (with proton, deuteron or other reference nucleus, e.g. C)

Extremely mild constraints for gluon distributions before LHC data

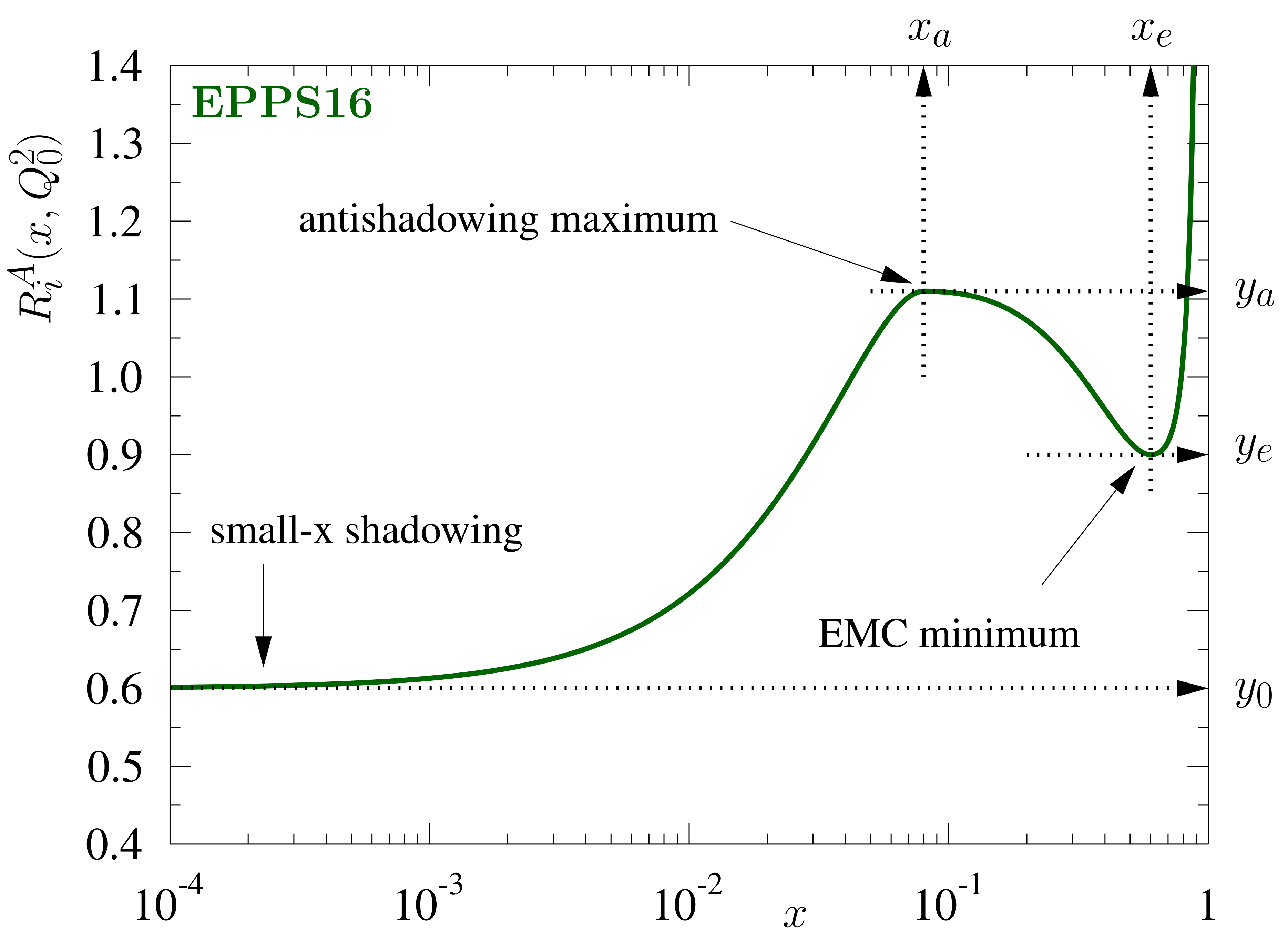
Nuclear PDFs



Main historical disadvantage - **Lack of data**

- No collider DIS data - only fixed target from 90's
- Data taken with different nuclei - nPDFs have an extra variable: A-dependence
- however… nPDFs known to differ from proton PDFs

Nuclear PDFs



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

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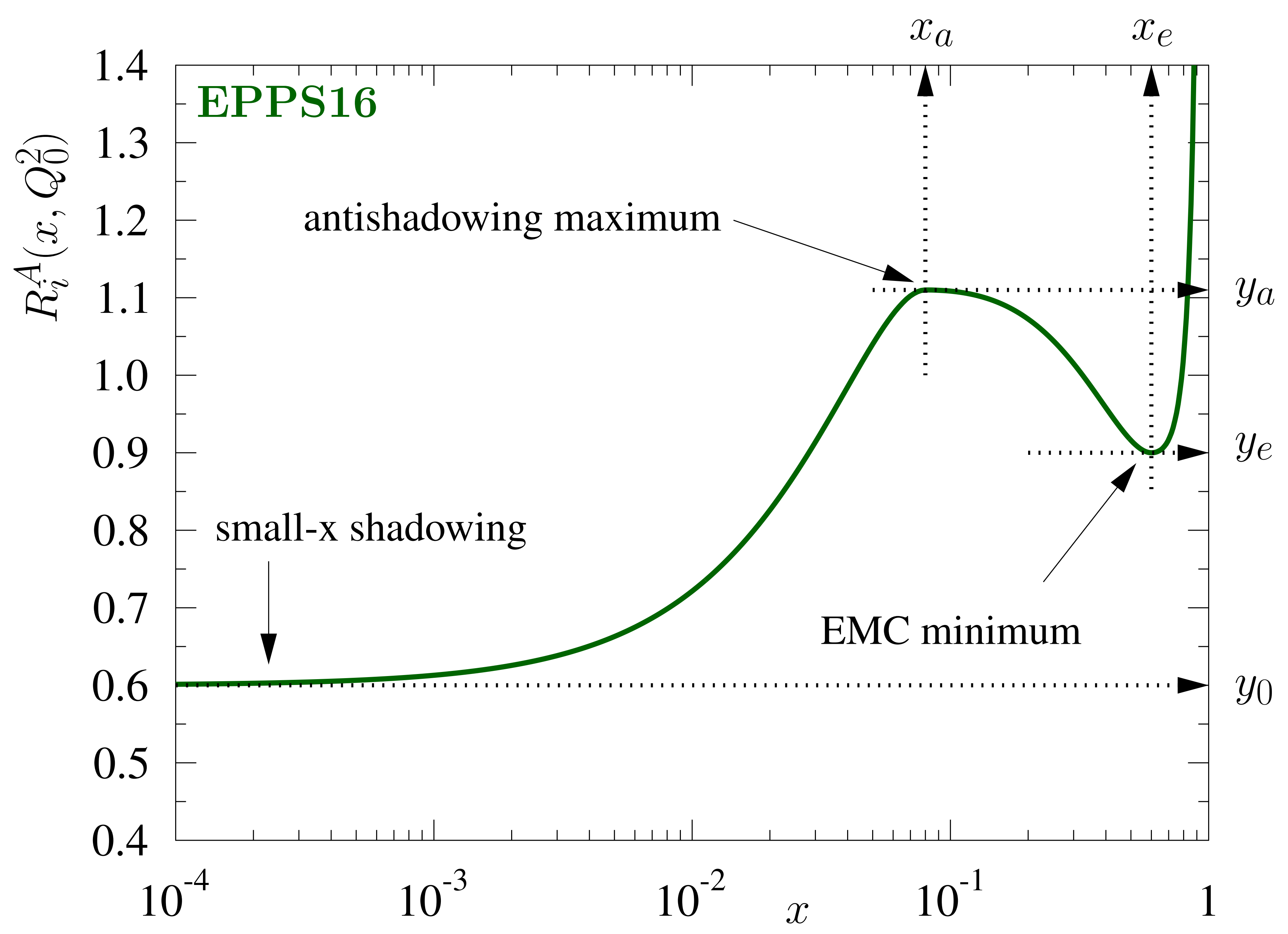
Solution - use **ratios with proton PDFs**

- **Advantage**: huge amount of data included for proton
- **Disadvantage**: inherits problems from proton PDF / lack of freedom / treatment of correlations in error analyses

Nuclear PDFs



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For neutrons - use isospin symmetry

$$f_i^A(x,Q^2) = Z\,\underbrace{f_i^{p/A}}_{\text{bound-proton PDF}}(x,Q^2) + (A-Z)\,\underbrace{f_i^{n/A}}_{\text{bound-neutron PDF}}(x,Q^2),$$

and assume $f_i^{p/A} \overset{\text{isospin}}{\longleftrightarrow} f_j^{n/A}$

A-dependence

All sets of nPDFs have A-dependence, but e.g. LHC have only collided Pb (and some Xe)

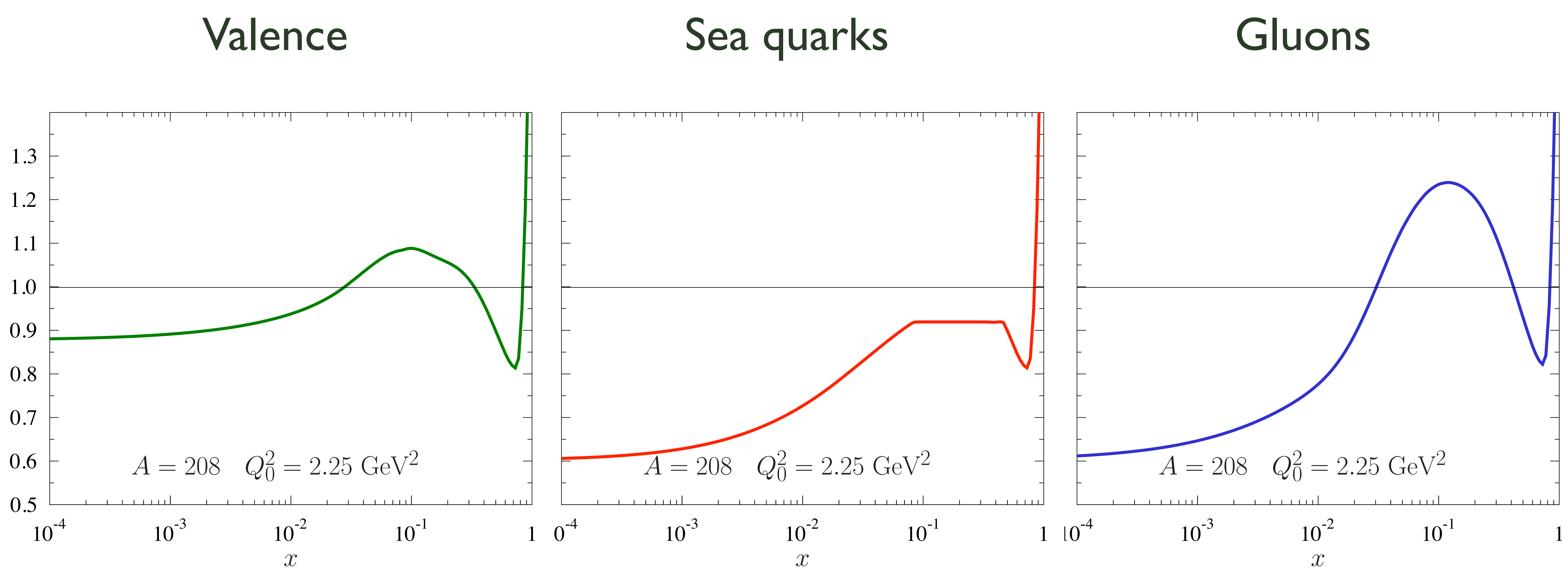
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[72]
CERN CMS★	$W^\pm$	pPb(208)	10	8.8	[43]
CERN CMS★	Z	pPb(208)	6	5.8	[45]
CERN ATLAS★	Z	pPb(208)	7	9.6	[46]
CERN CMS★	dijet	pPb(208)	7	5.5	[34]
CERN CHORUS★	DIS	νPb(208), $\bar{\nu}$Pb(208)	824	998.6	[47]

Before the LHC basically only 15 data points for Pb!

- Other nuclei are interesting for phenomenological reasons (e.g. benchmarking in heavy-ion experiments) but data is still very limited - old data from the 90's in fixed target DIS or Drell-Yan
- A-dependence included in the parameters but some needs to be fixed by hand to ensure convergence.

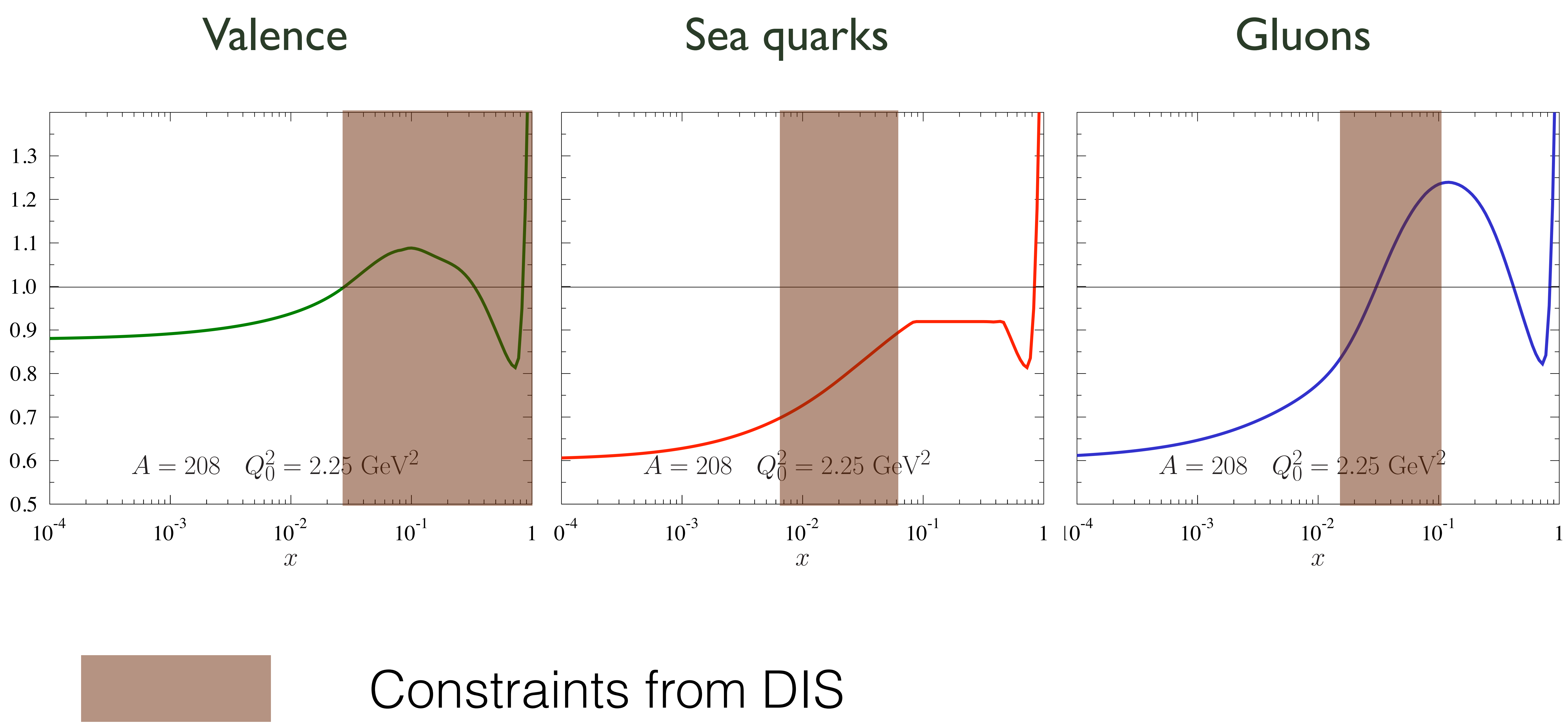
E.g. EPPS16 $$y_i(A) = y_i(A_{\rm ref})\left(\frac{A}{A_{\rm ref}}\right)^{\gamma_i[y_i(A_{\rm ref})-1]}$$

Pre-LHC constraints



Parametrization bias reduced with new data

Pre-LHC constraints



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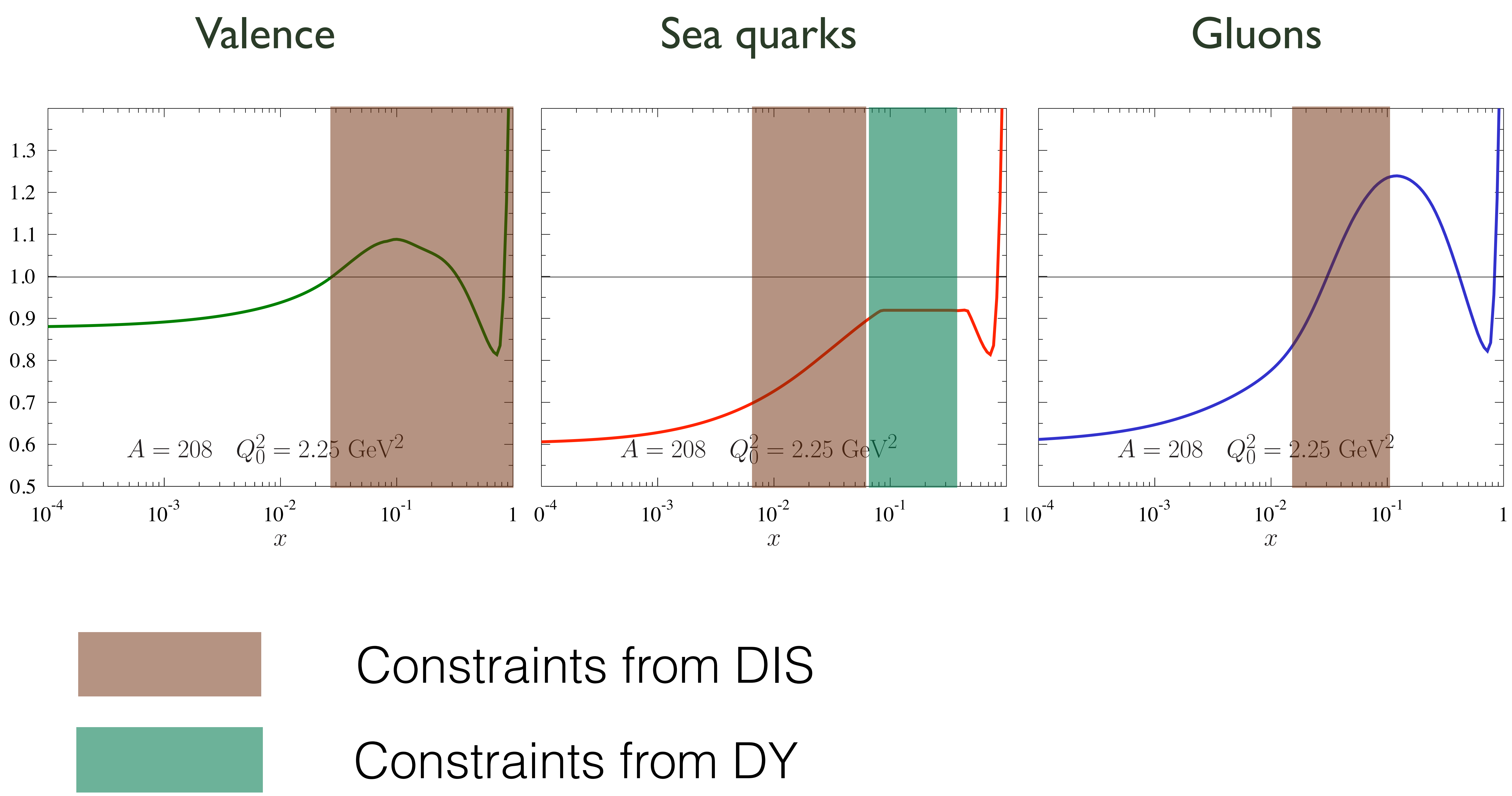

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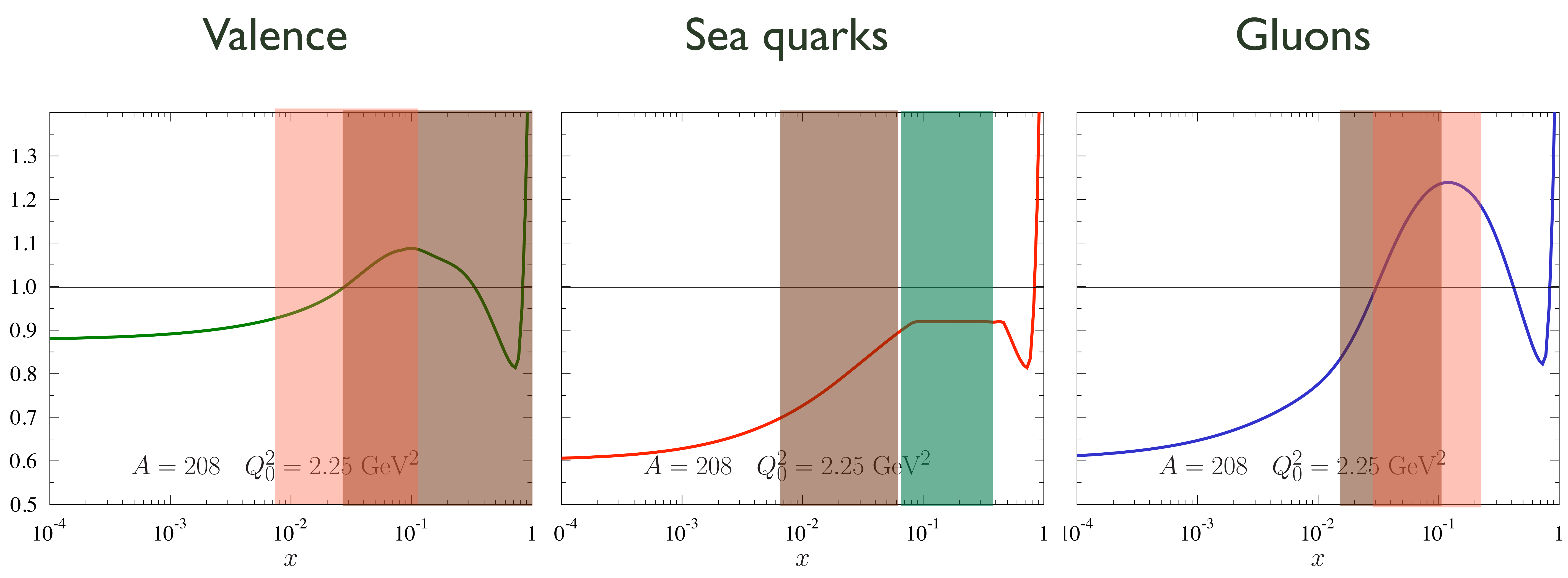


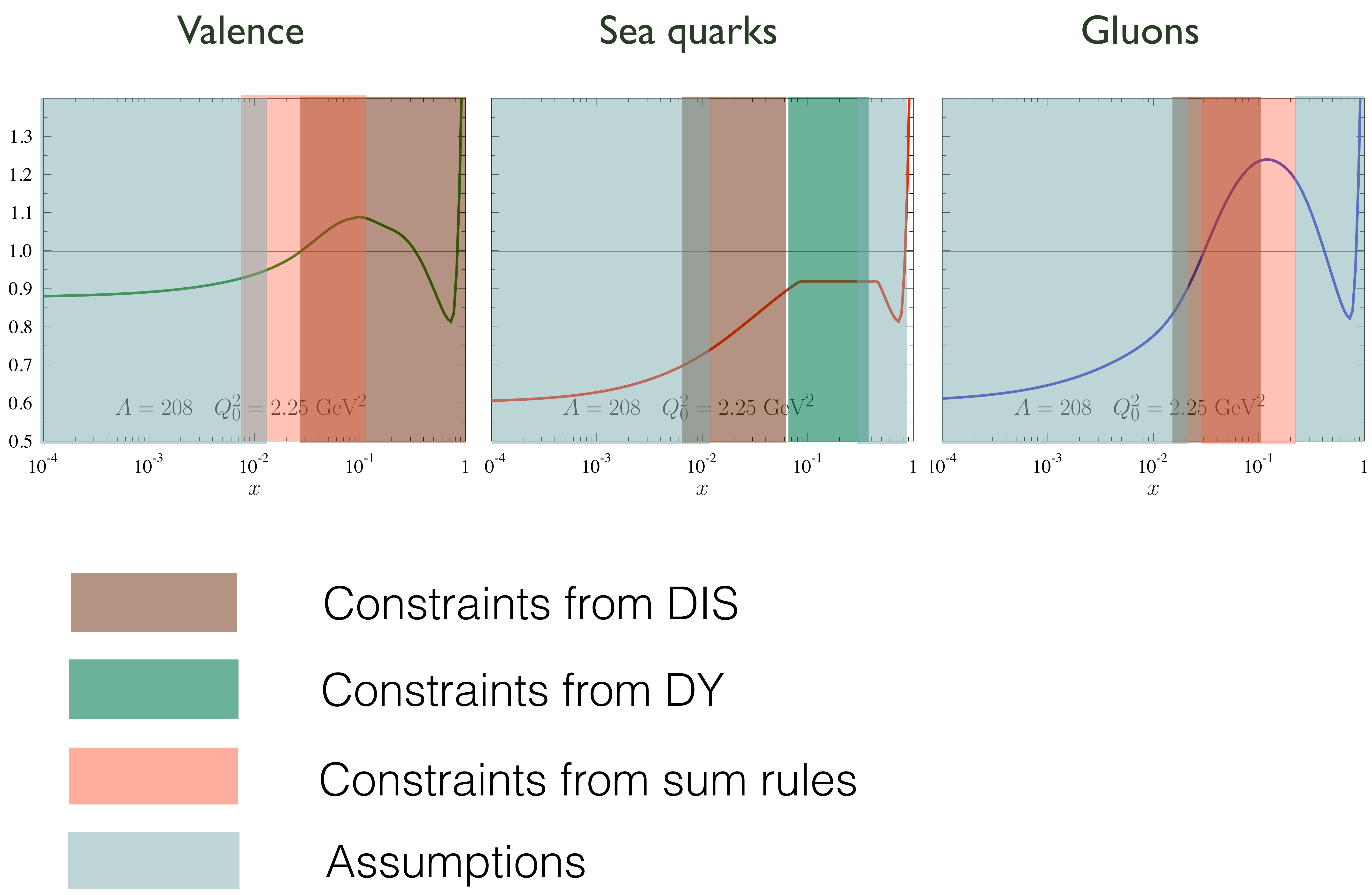
Constraints from DIS

Constraints from DY

Constraints from sum rules

Parametrization bias reduced with new data

Pre-LHC constraints



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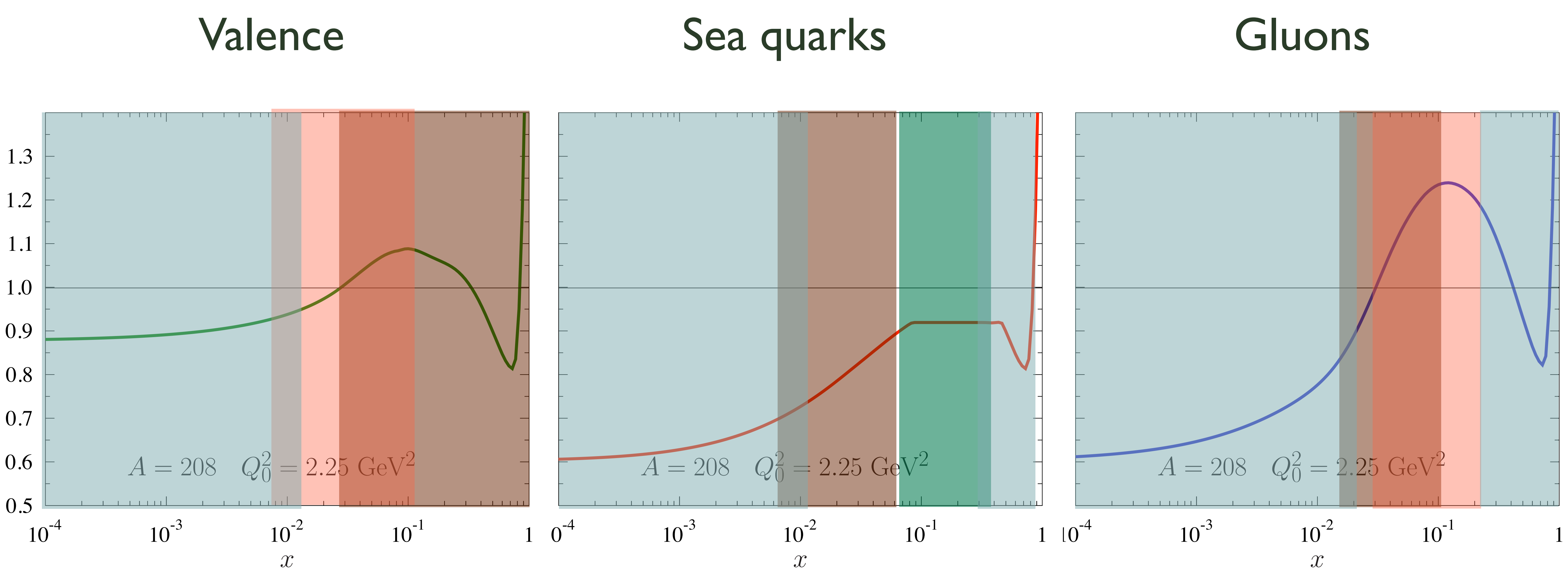


Constraints from DIS

Constraints from DY

Constraints from sum rules

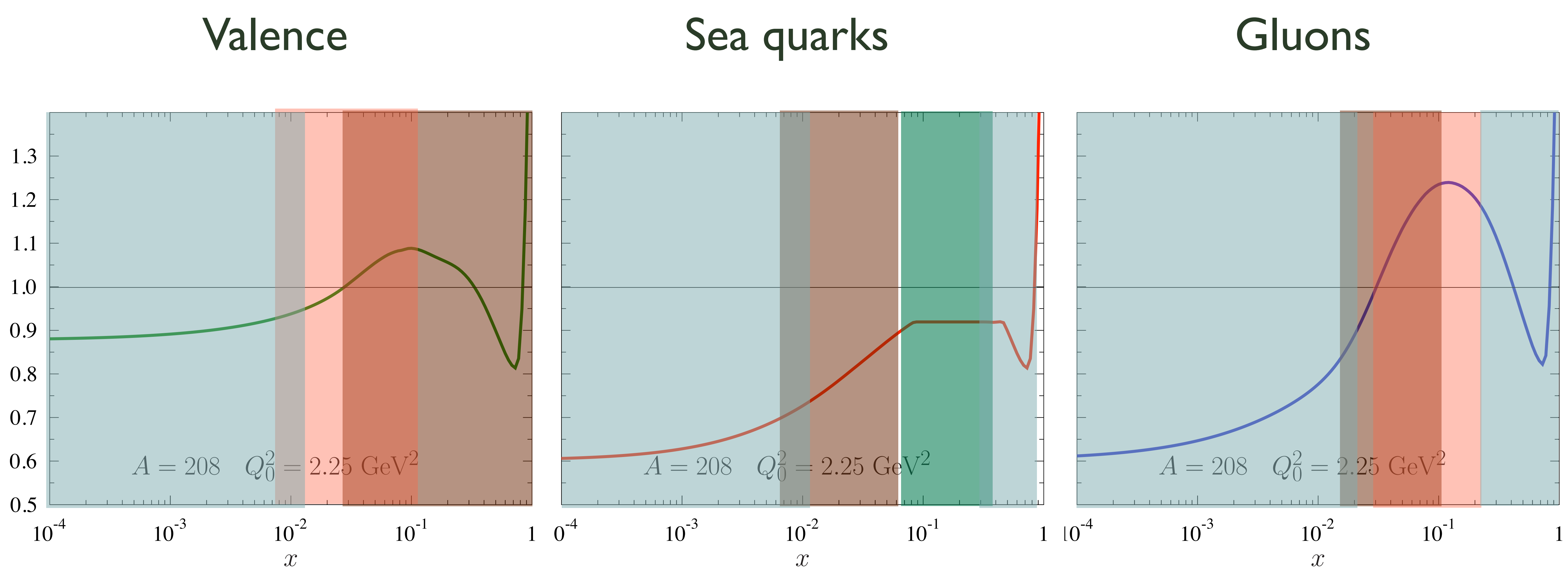
Assumptions

Parametrization bias reduced with new data

RHIC data – "high-pt" π^0 production
↳ gluon antishad.
← hadronization?

LHC data – dijets → gluons ←
W/Z → sea quarks + gluons

Pre-LHC constraints



Everything works!
but
strong checks of nPDF
universality?

Constraints from DIS

Constraints from DY

Constraints from sum rules

Assumptions

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↳ gluon antishad.

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Parametrization bias reduced with new data

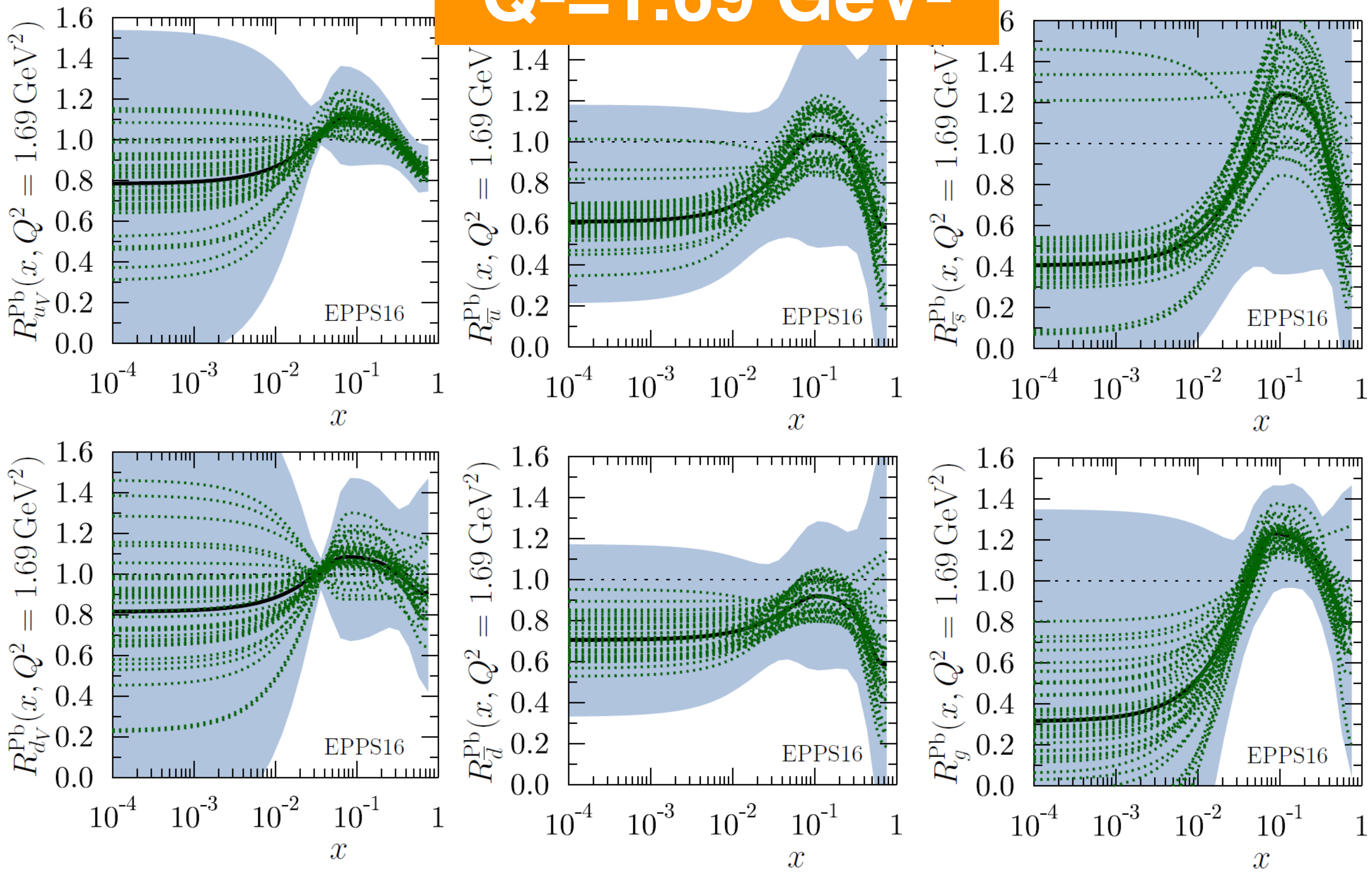
Latest and next generation NLO nPDF global fits

	EPPS16	nNNPDF2.0	nCTEQ15WZ	nCTEQ15HIX	EPPS21 prelim.
lA NC DIS	✓	✓	✓	✓	✓
+ JLab NC DIS				✓	✓ new!
νA CC DIS	✓	✓			✓
pA DY	✓		✓	✓	✓
πA DY	✓				✓
RHIC dAu/pp π^0	✓		✓		✓
LHC pPb dijet R_{FB}	✓				
$\rightarrow$ dijet R_{pPb}					✓ new!
LHC pPb D^0					✓ new!
LHC pPb W,Z Run 1	✓	✓	✓		✓
+ Run 2 pPb W		✓	✓		✓ new!
Q cut in DIS	1.3 GeV	1.87 GeV	2 GeV	1.3 GeV	1.3 GeV
Data points	1811	1467	828	1564	2023 prelim.
Free parameters	20	256	19	19	24 prelim.
Error analysis	Hessian	Monte Carlo	Hessian	Hessian	Hessian
Error tolerance $\Delta\chi^2$	52	N/A	35	35	35 prelim.
Free-proton PDFs	CT14	NNPDF3.1	~CTEQ6M	~CTEQ6M	CT18A prelim.
HQ treatment	S-ACOT	FONLL	S-ACOT	S-ACOT	S-ACOT
Indep. flavours	6	6	5	4	6
Reference	EPJC 77, 163	JHEP 09, 183	EPJC 80, 968	PRD 103, 114015	TBA

[Slide from P. Paakkinen - Hadrons2021]

EPPS16 - results

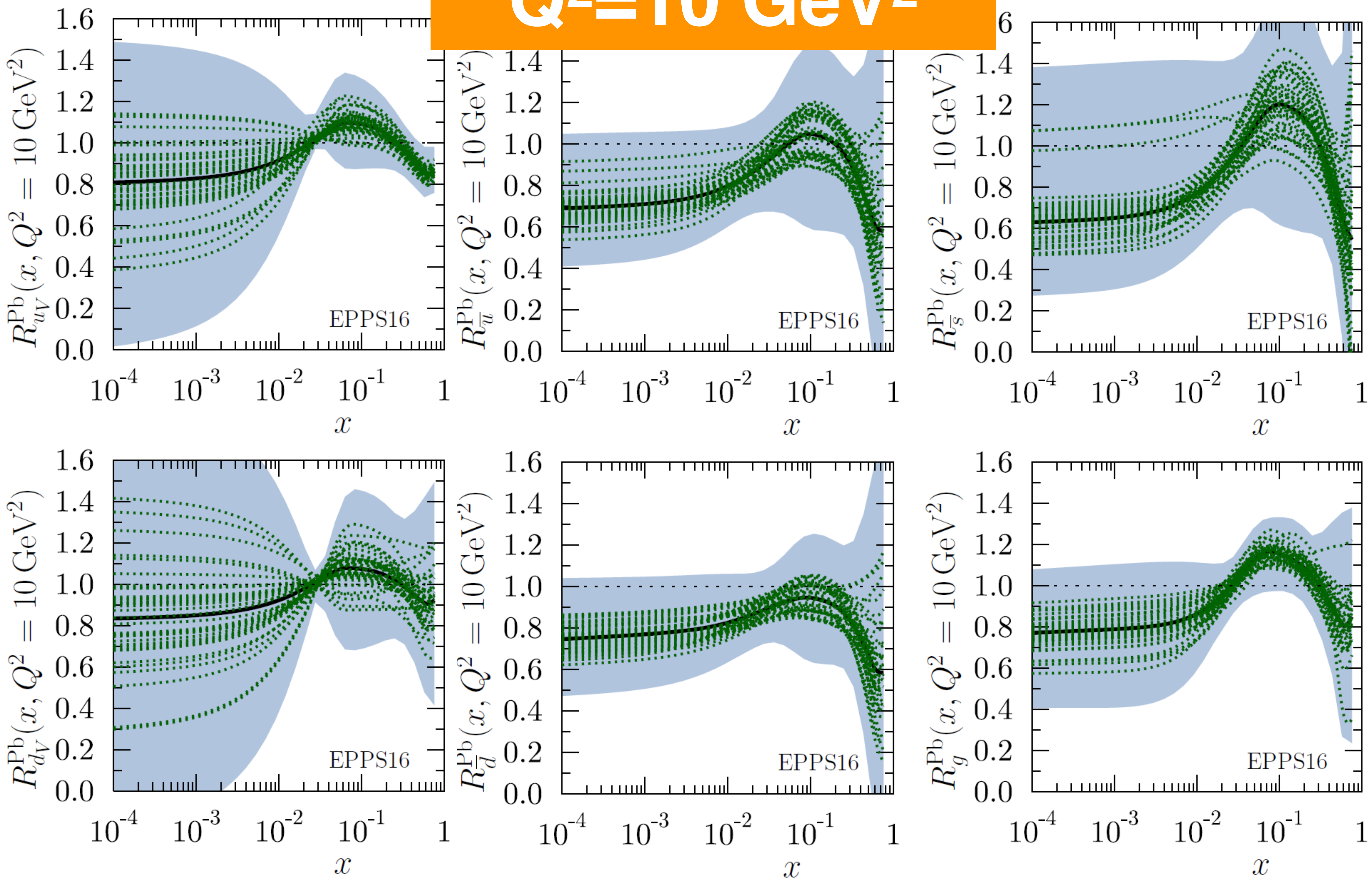
Q²=1.69 GeV²



Best fit + 40 error sets. Large uncertainties, **<u>decrease with evolution</u>**

EPPS16 - results

Q²=10 GeV²



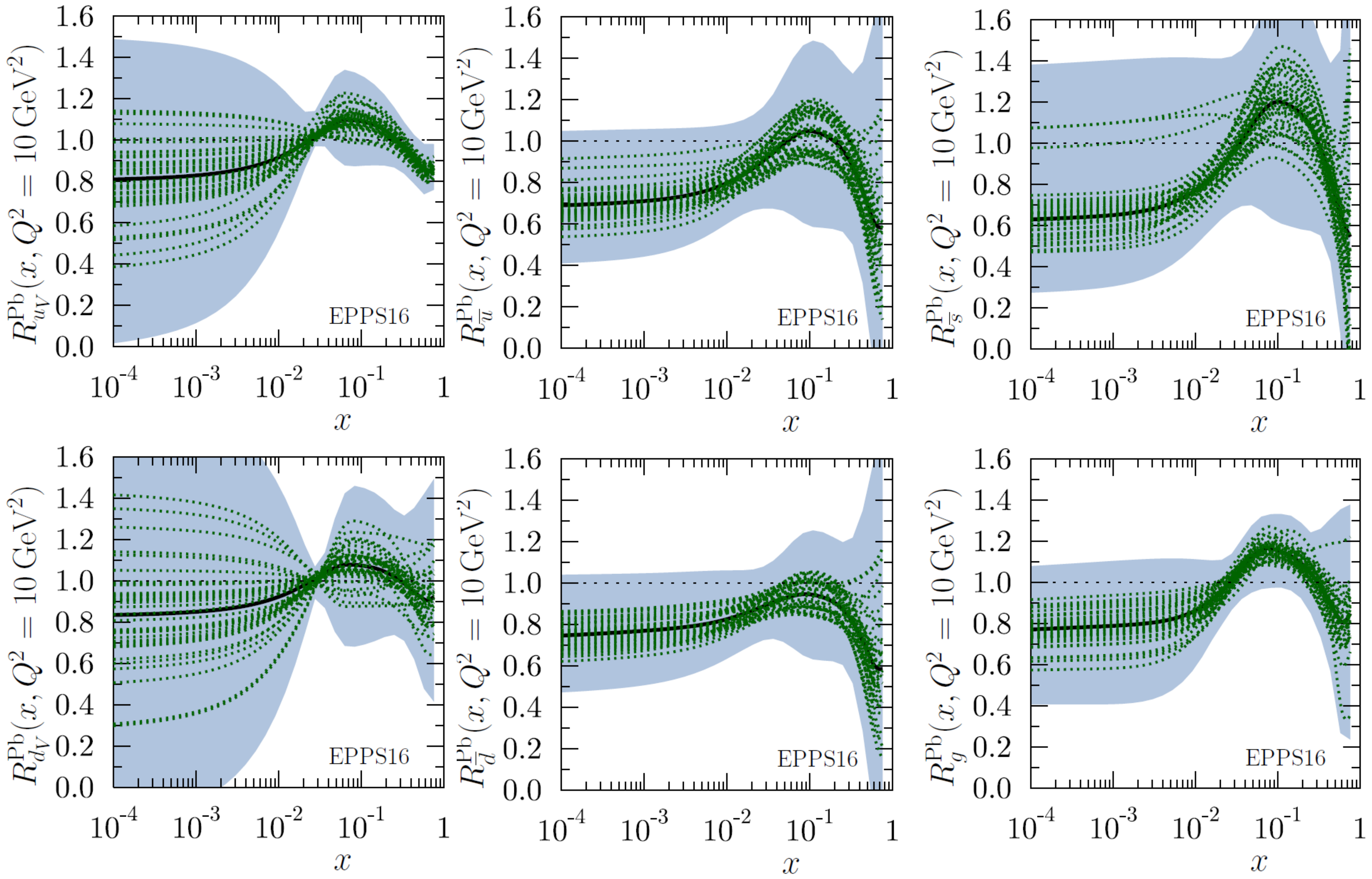
Best fit + 40 error sets. Large uncertainties, **decrease with evolution**

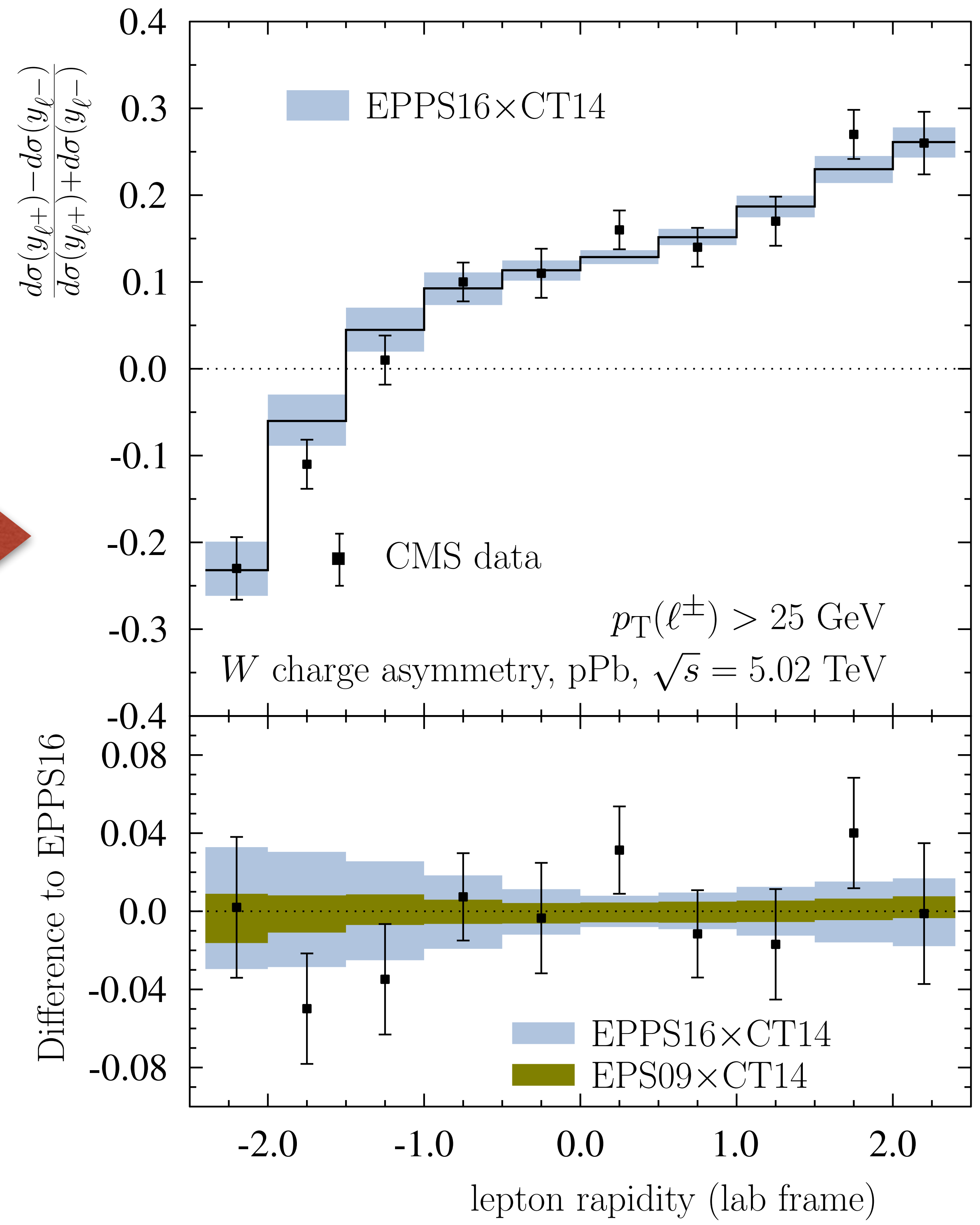
Computing errors

[Standard technology in PDF analyses]

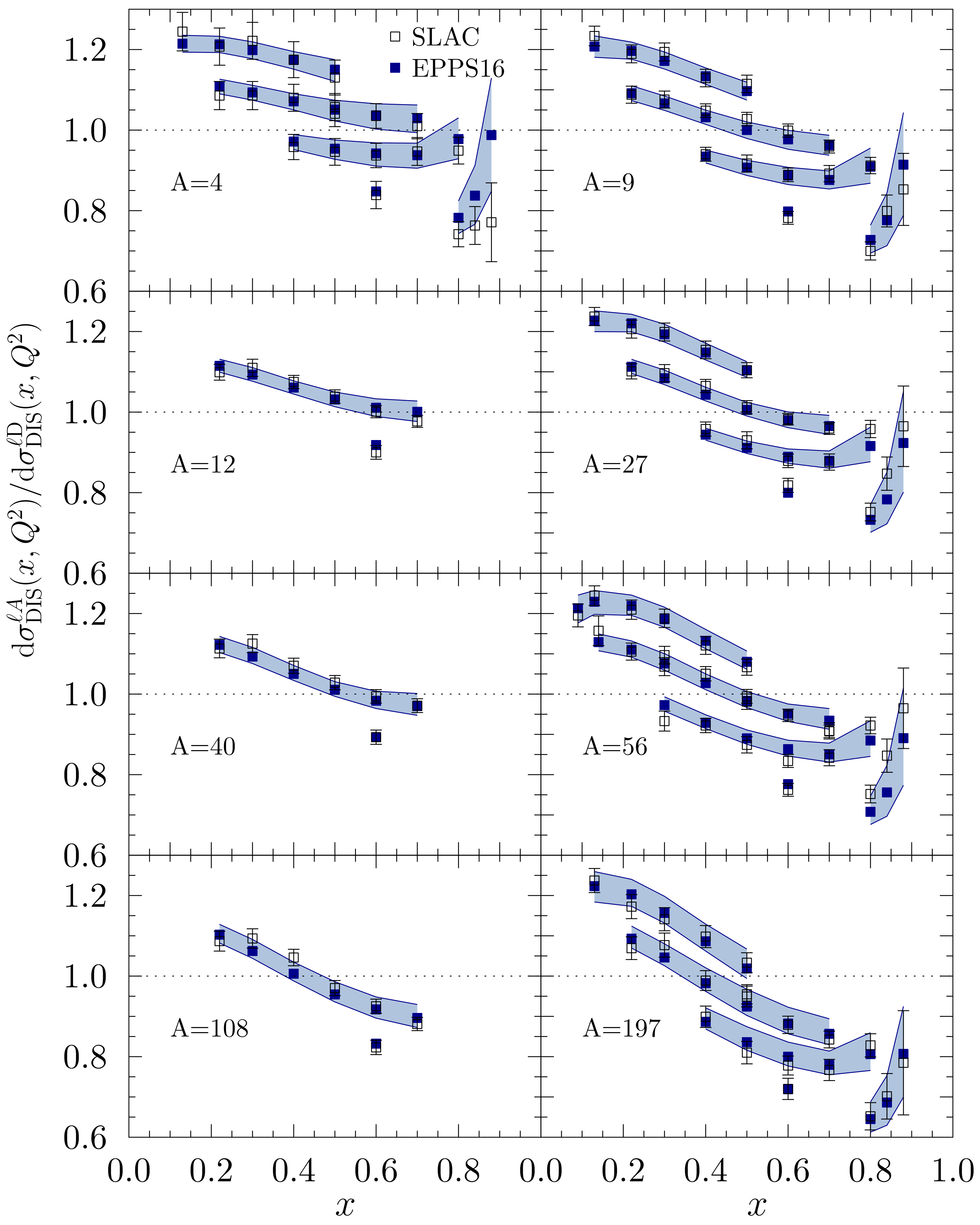
EPPS16 provides nPDF error sets. **You can compute uncertainties**

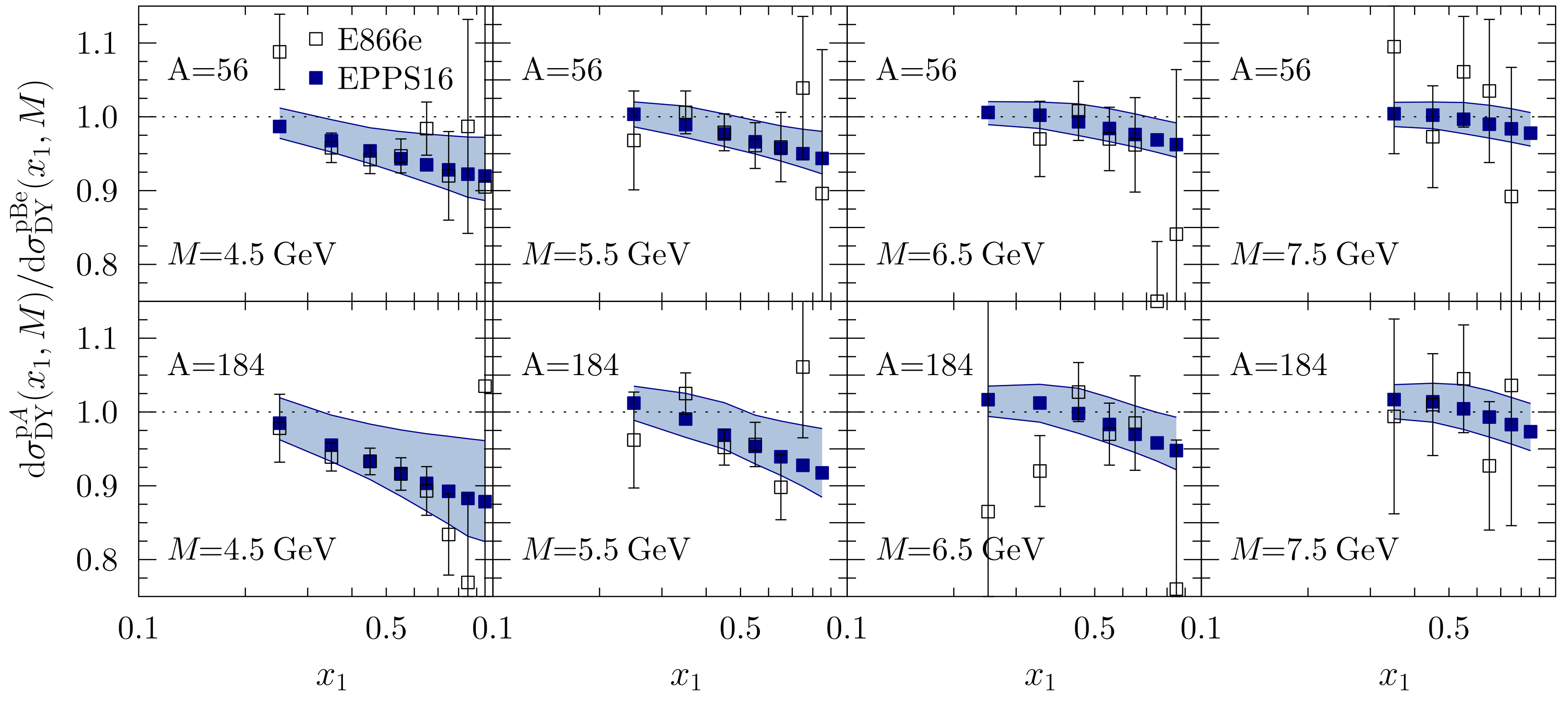
$$\left(\delta\mathcal{O}^{\pm}\right)^2 = \sum_i \left[{}^{\max}_{\min} \left\{ \mathcal{O}\left(S_i^+\right) - \mathcal{O}\left(S_0\right), \mathcal{O}\left(S_i^-\right) - \mathcal{O}\left(S_0\right), 0 \right\} \right]^2,$$





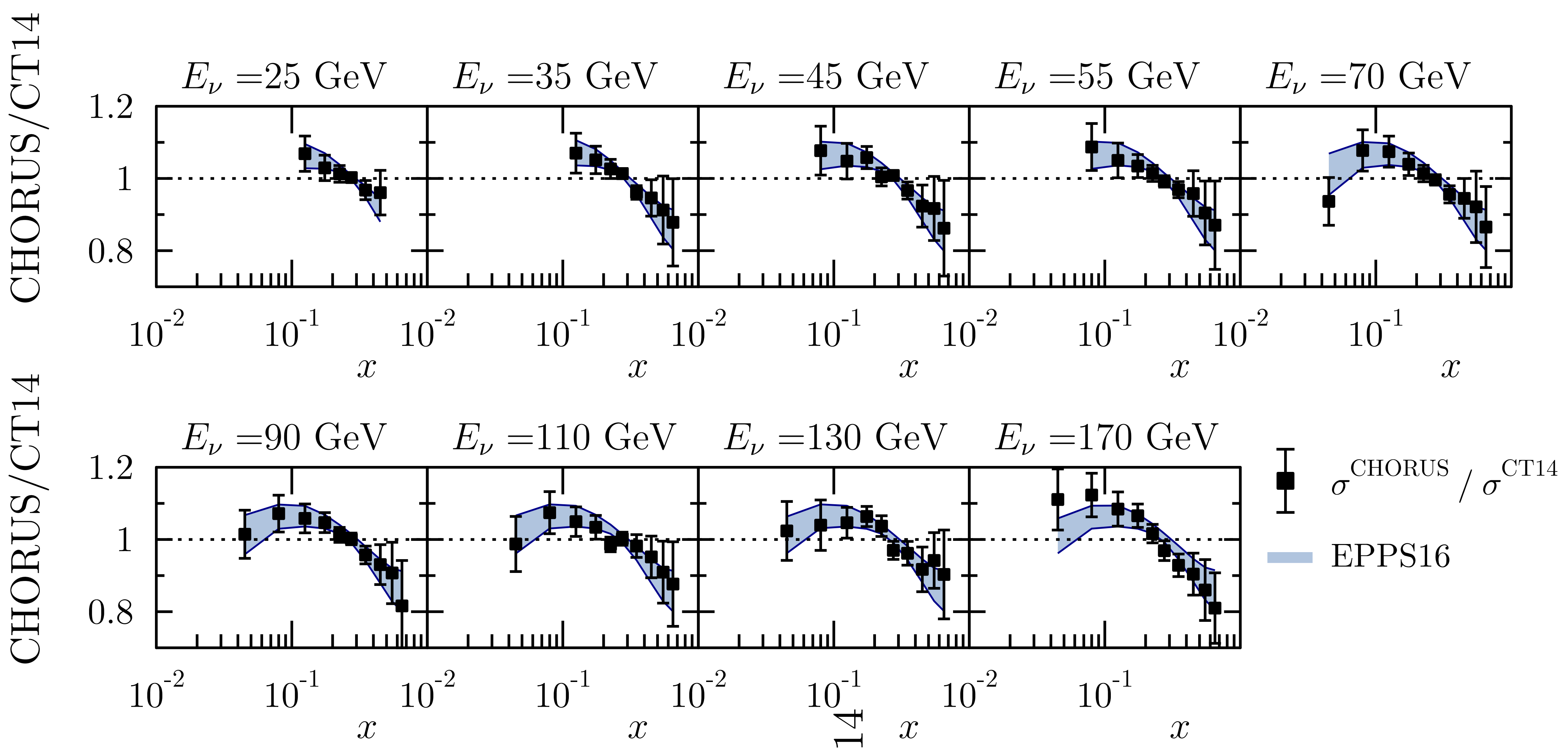
EPPS16 vs DIS/DY

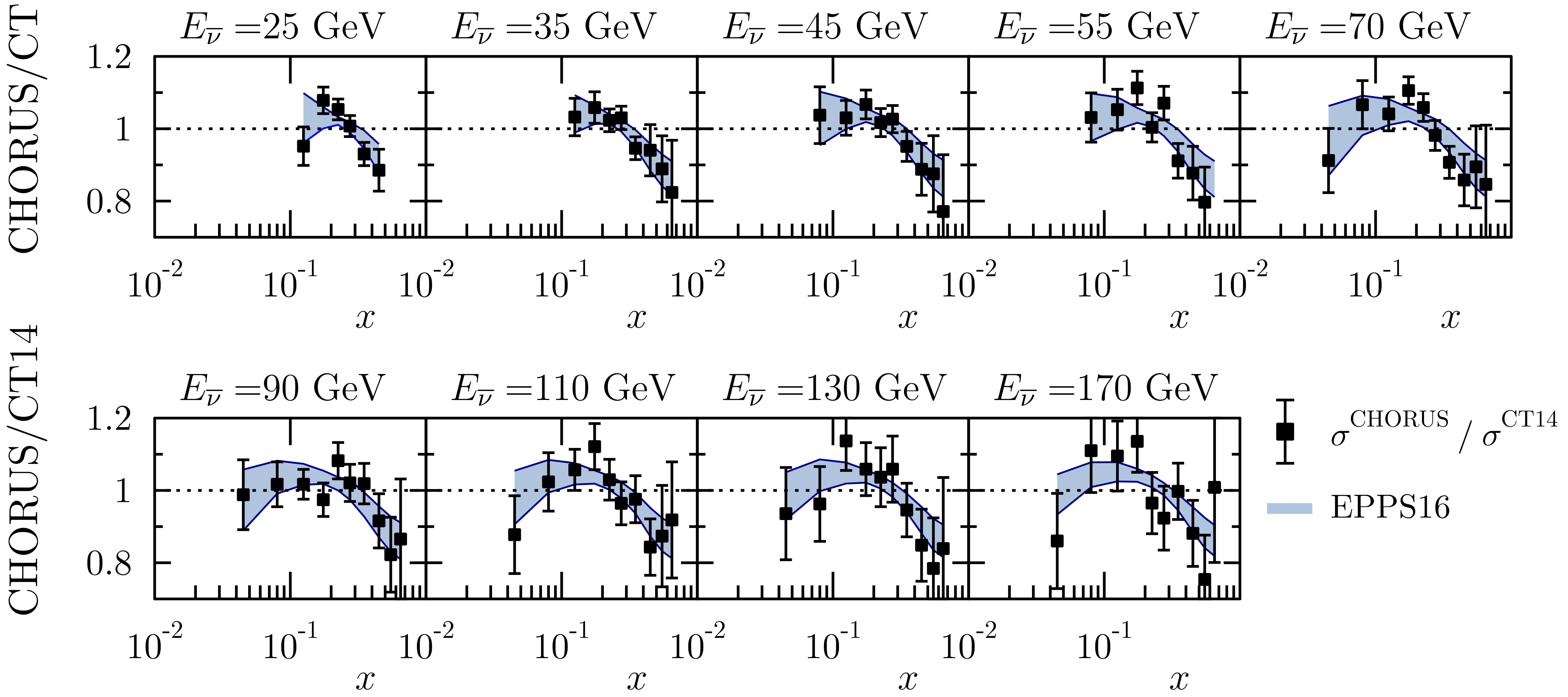




(Just a sample of plots)
Good description, these data were already included in the previous analyses.

EPPS16 vs neutrinos





Neutrino data essential for flavor decomposition in EPPS16

A comment on neutrino DIS

In conclusion, we have demonstrated that disposing the overall normalization by dividing the data by the integrated cross section in each neutrino energy bin separately, all large-Q^2 neutrino data show practically identical nuclear effects, consistent with the present nuclear PDFs. Our numerical consistency test based on the Hessian method of propagating uncertainties confirms that these data could be included in a global fit without causing disagreement with the other data.

[Paukkunen, Salgado arXiv:1302.2001 / PRL110 (2013) 212301]

CONCLUSIONS

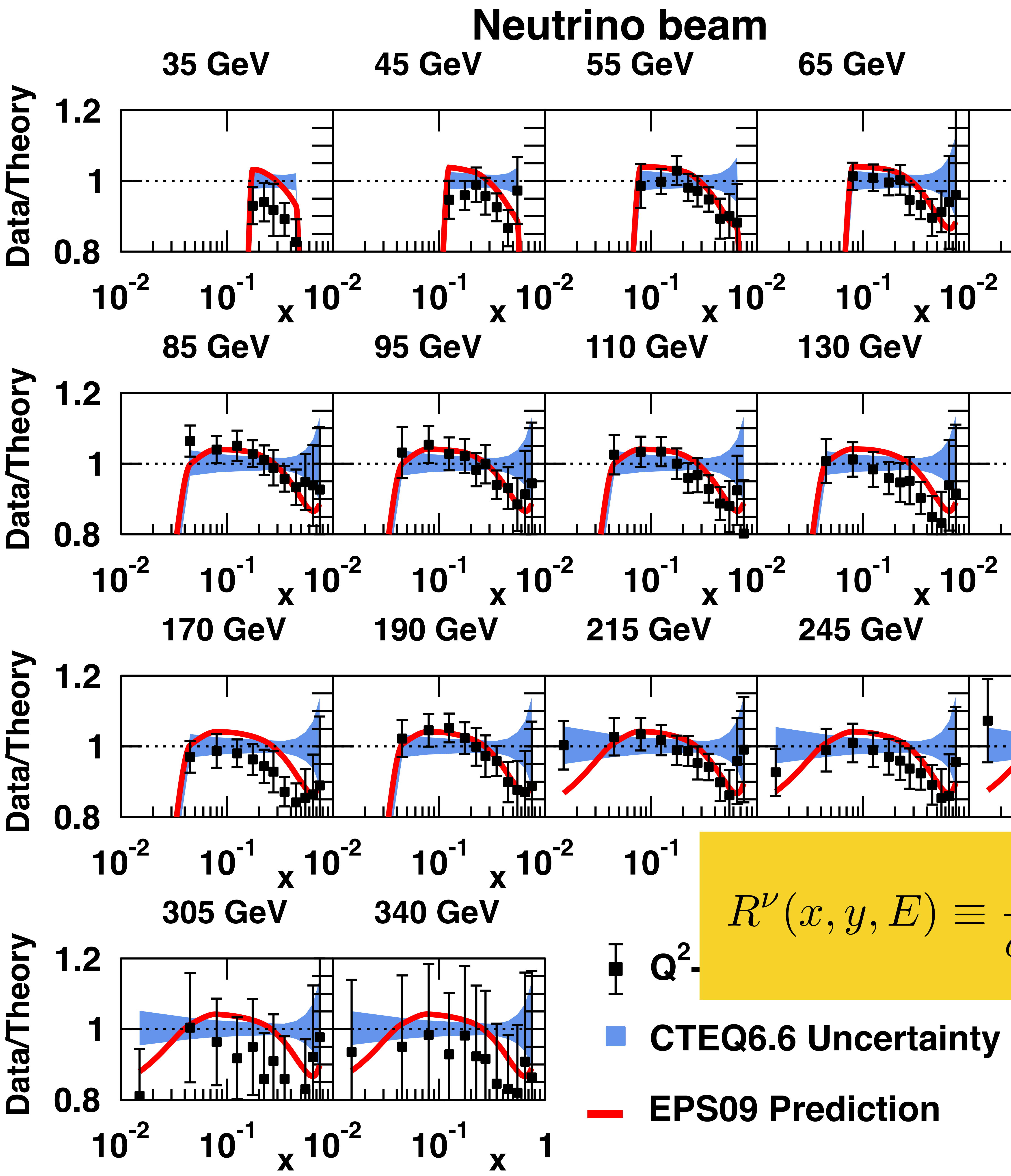
- Incompatibility of neutrino DIS with charged lepton DIS (?)
  - conclusions heavily rely on only NuTeV data - most precise
  - incompatibility a "precision" effect - the result changes e.g. when using uncorrelated errors
  - tension in NuTeV data → high χ^2 of the fit to NuTeV alone → problem of NuTeV data ?
  - NOMAD data can help decide

[Slide from K. Kovari's talk at DIS 2012]

ν-DIS with Pb/Fe included in proton PDF analyses

$\Downarrow$

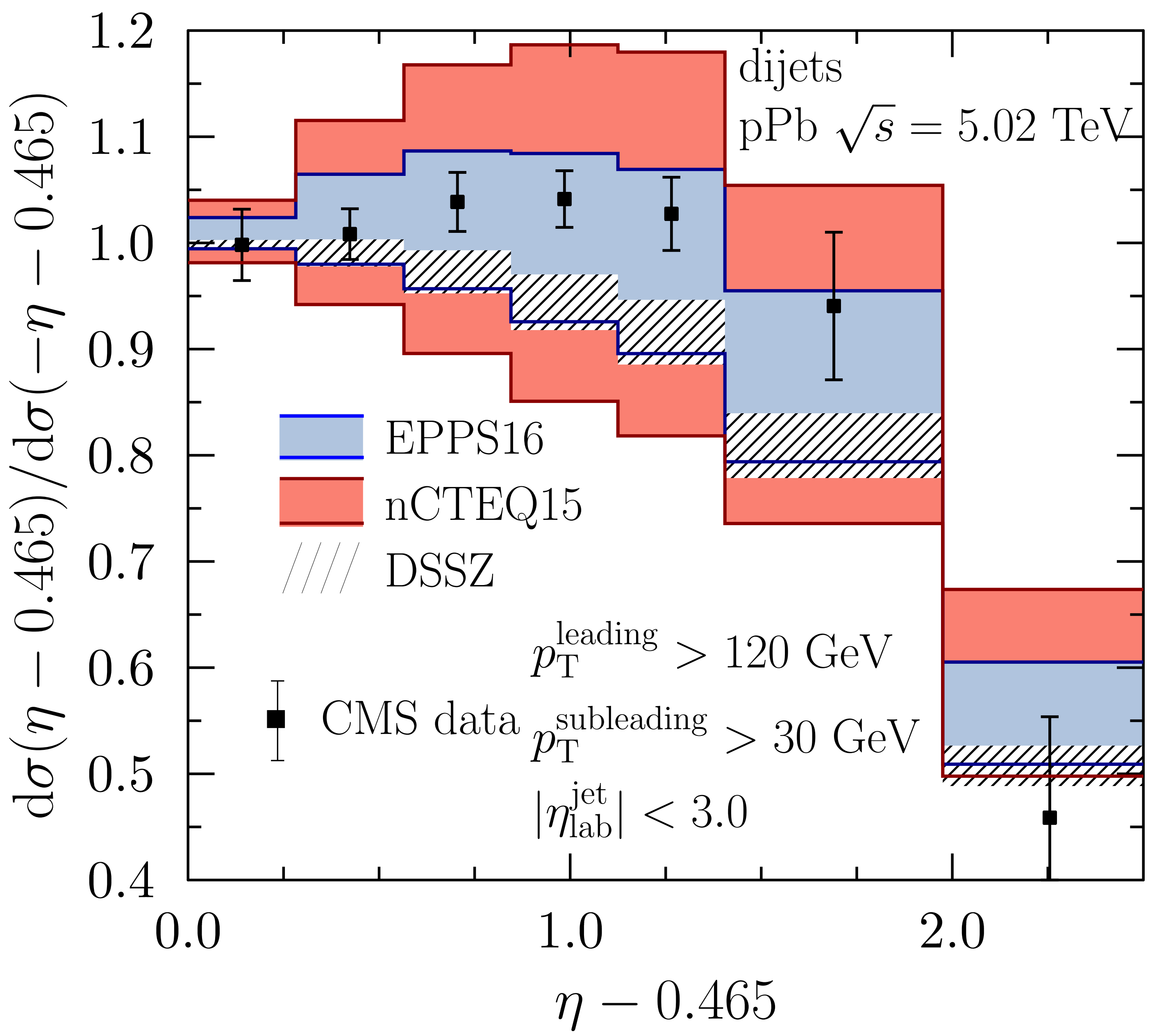
Factorization?

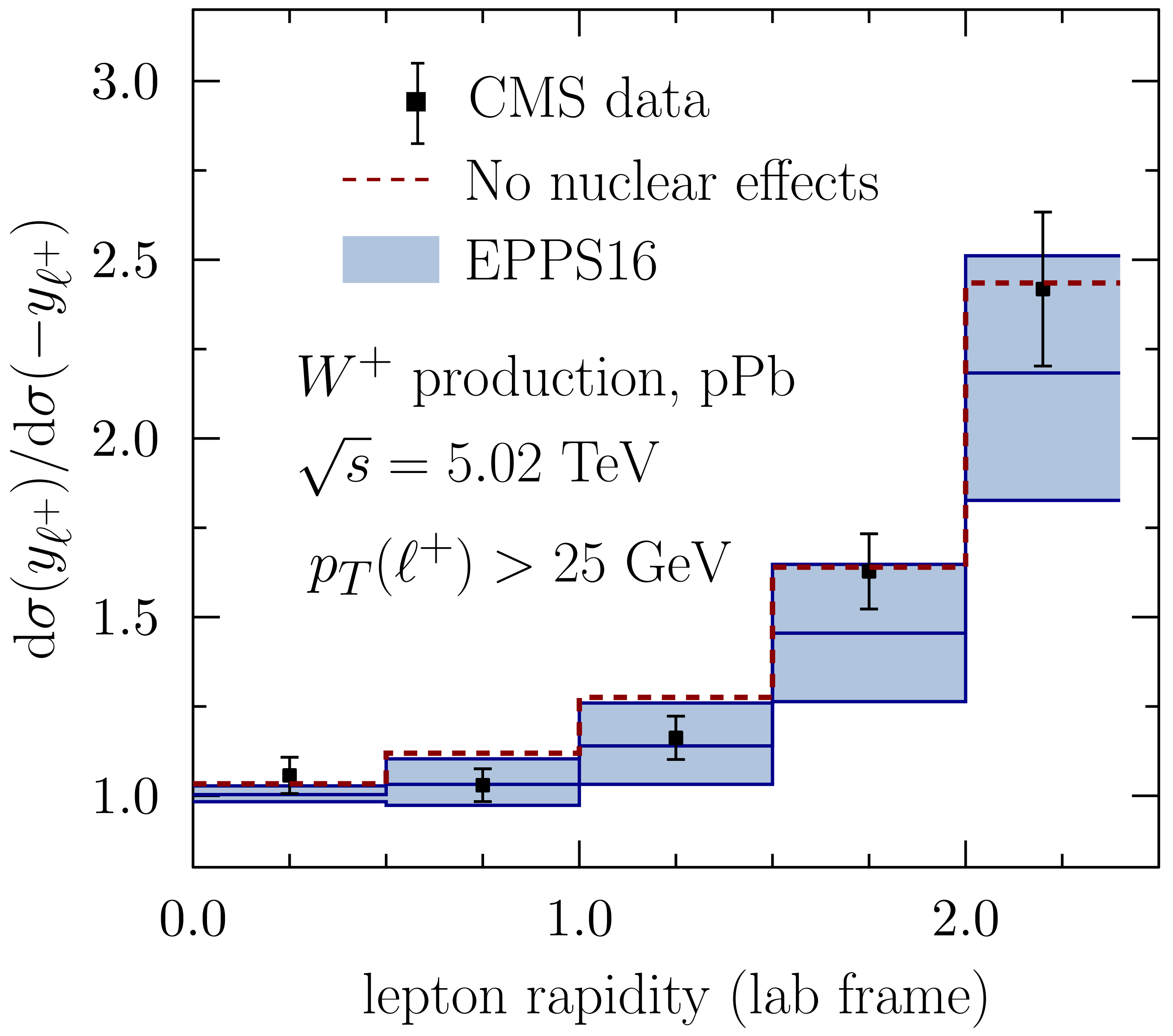


$$R^{\nu}(x,y,E) \equiv \frac{\sigma^{\nu}_{\mathrm{exp}}(x,y,E)}{\sigma^{\nu}_{\mathrm{CTEQ6.6}}(x,y,E)},$$

[Paukkunen, Salgado / arXiv:1004.3140,1302.2001]

EPPS16 vs LHC





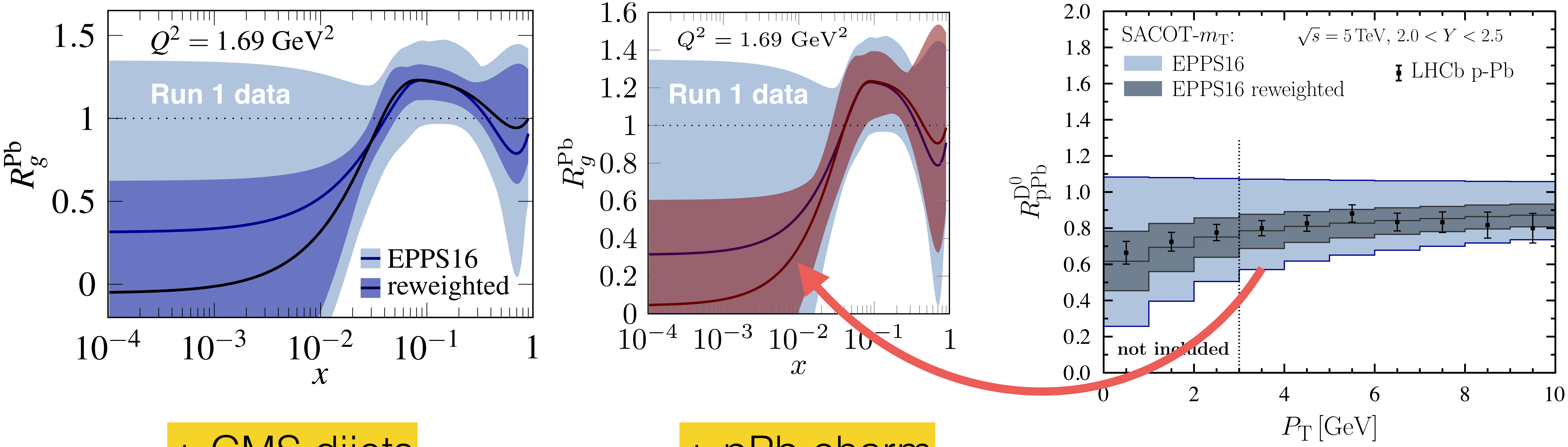
LHC Run 2
More statistics
Better Systematics

Dijet data constrains gluon distributions - only FB ratios used in the analysis.

Good description of heavy boson production but limited constraining power on the fit

nPDFs — reweighting

[Eskola, Paakkinen, Paukkunen 2019]



+ CMS dijets

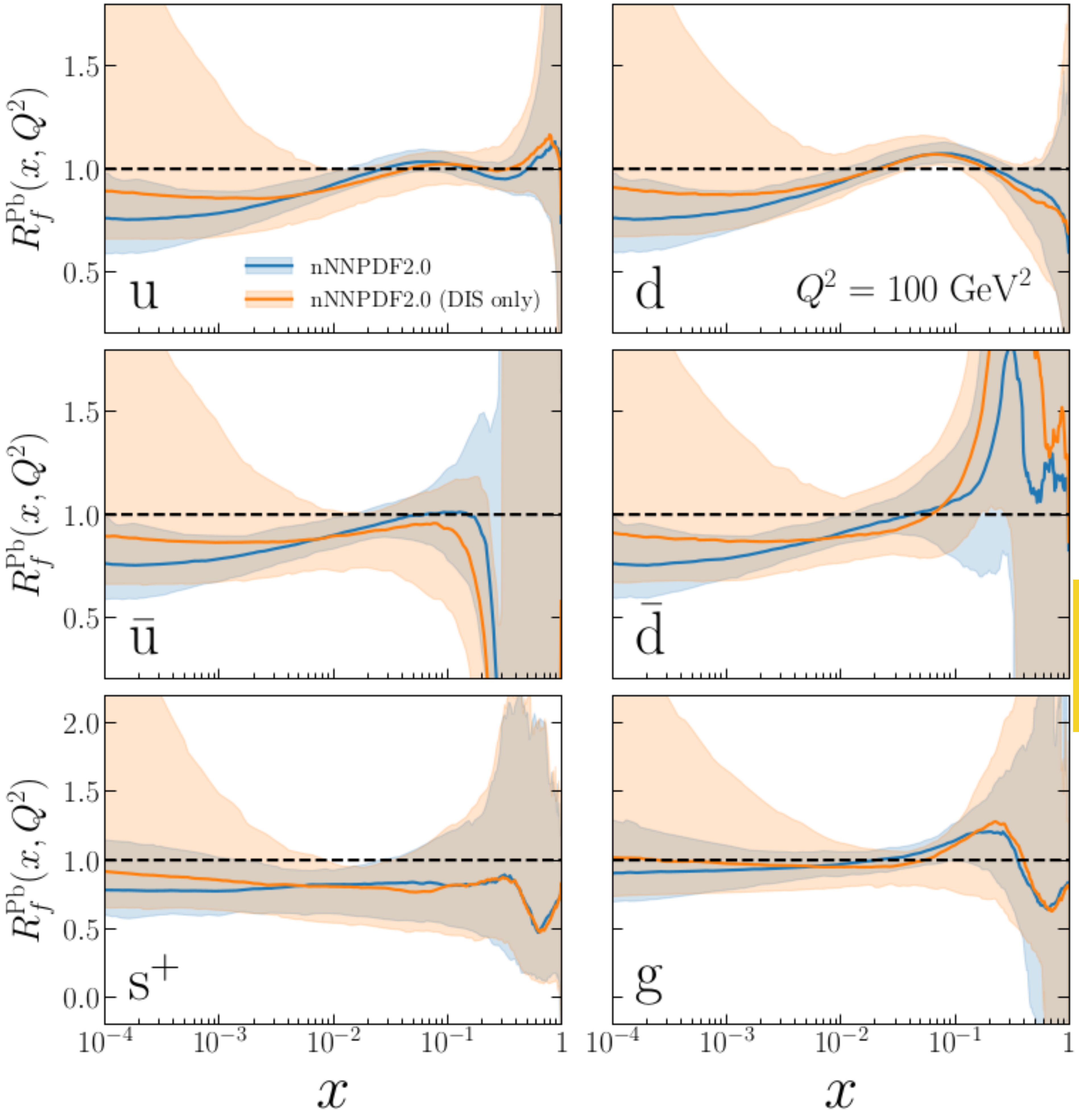
+ pPb charm

Run 2 data provides much stronger constraints in gluons
Both dijets and high-pt D production modify gluons in the same direction

Including LHC Run2 - nNNPDF

[Slide P. Paakkinen IS2021]

[Abdul Khalek, Ethier, Rojo & van Weelden, JHEP 09 (2020) 183]



Flexible neural-network parametrization (256 free parameters)

Includes CMS and ATLAS W/Z data

Compared to DIS-only fit:

- Preference for EMC effect both in u and d
- Enhanced shadowing for all quarks
- Some preference for gluon shadowing & antishadowing

nNNPDF2.0 does not use fixed-target DY data

→ W/Z data have to compensate for this

Here:

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

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High-precision LHC data makes old fixed target less relevant

↓

Tests of universality?

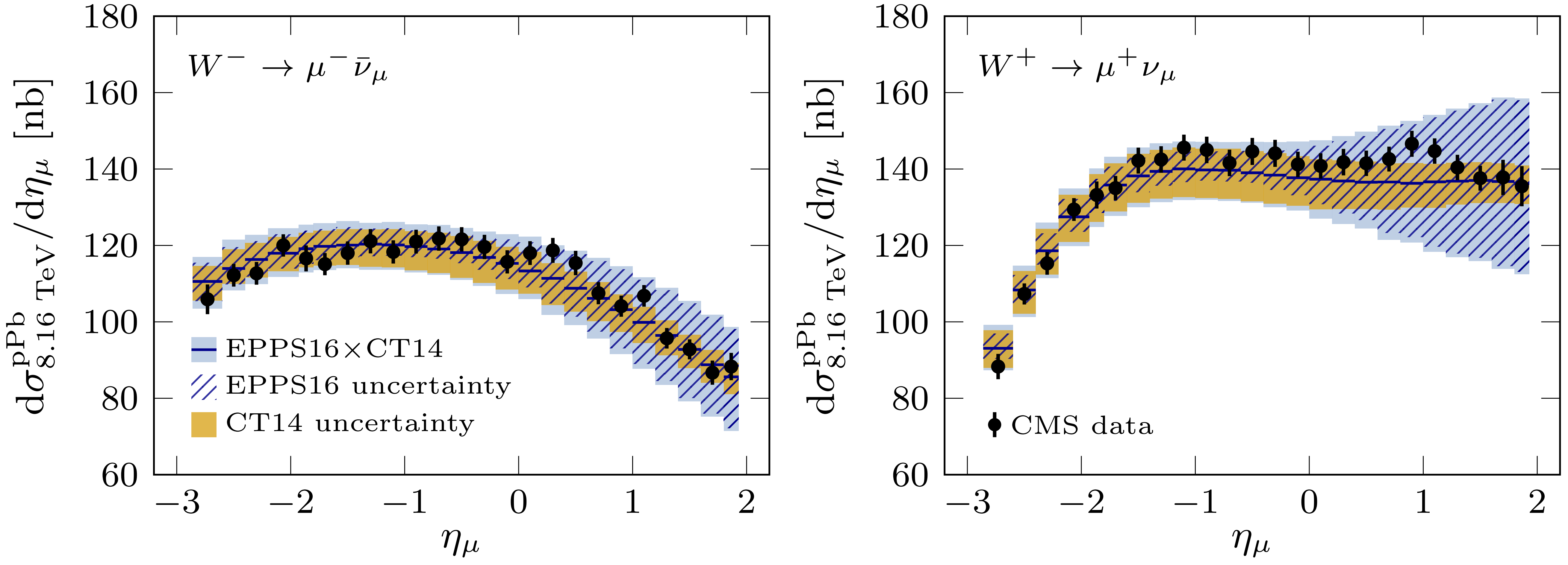
EPPS21 preview

[slides shamelessly stolen from P. Paakkinen talk at DIS21]

Need to mitigate free-proton PDF uncertainty

Absolute cross sections carry large proton-PDF uncertainty!

Should not be neglected when fitting the nPDFs!

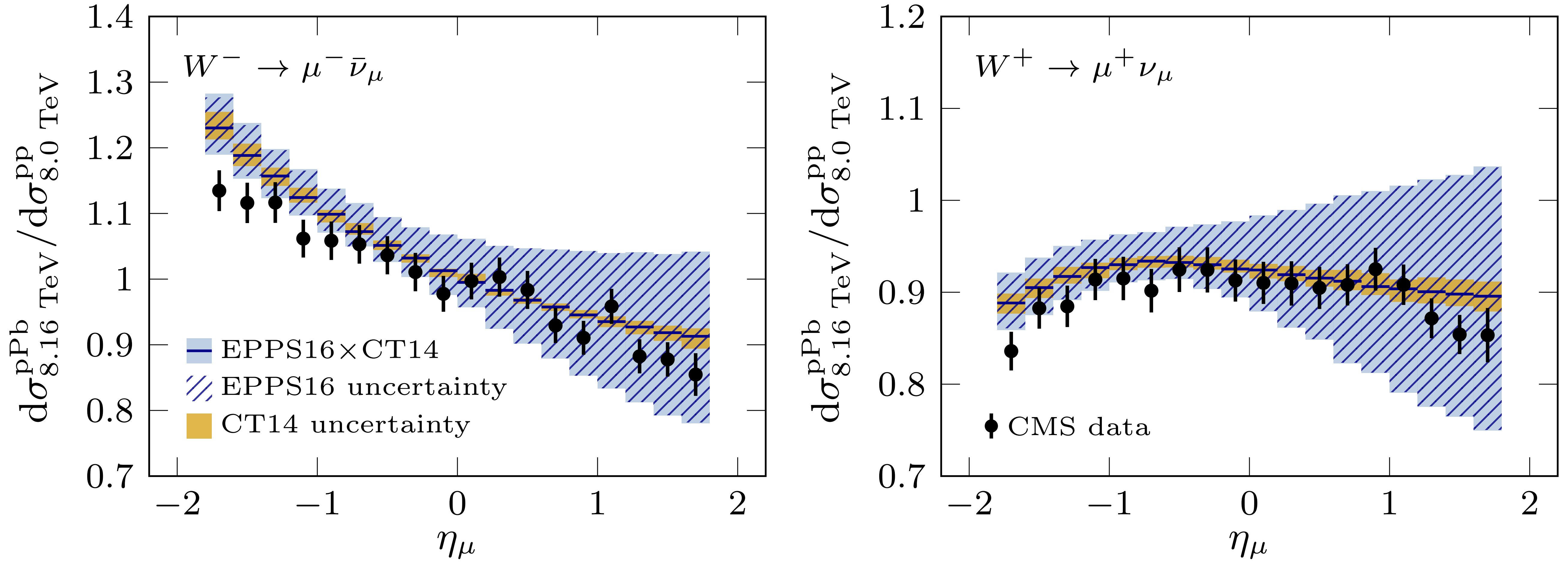


↓ Cancel proton-PDF uncertainty ↓

Wherever possible, we use nuclear modification ratios to cancel the free-proton PDF uncertainty

For Ws at 8.16 TeV, we formulate a mixed-energy nuclear modification ratio

$$R_{\mathrm{pPb}} = \frac{d\sigma^{\mathrm{pPb}}_{8.16\ \mathrm{TeV}}/d\eta_\mu}{d\sigma^{\mathrm{pp}}_{8.0\ \mathrm{TeV}}/d\eta_\mu}$$



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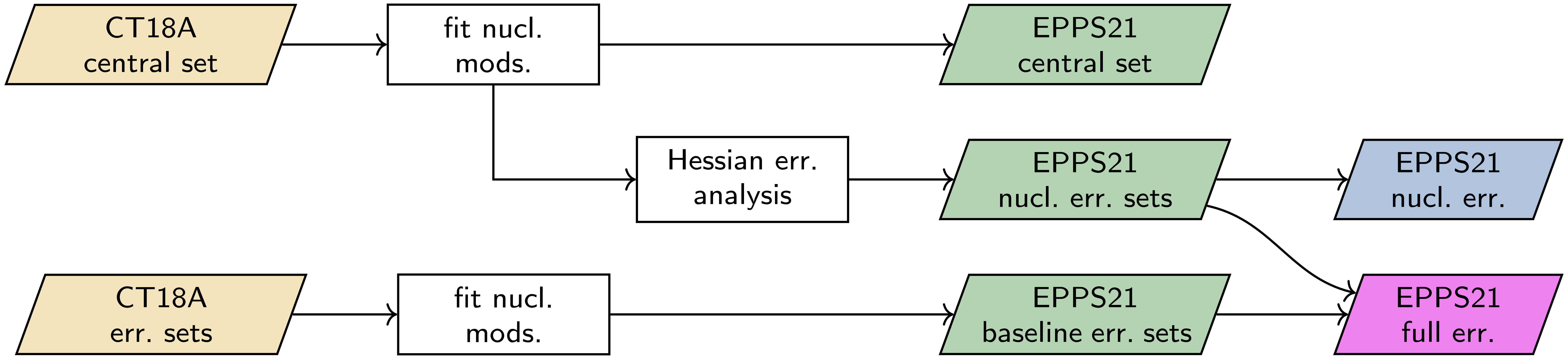
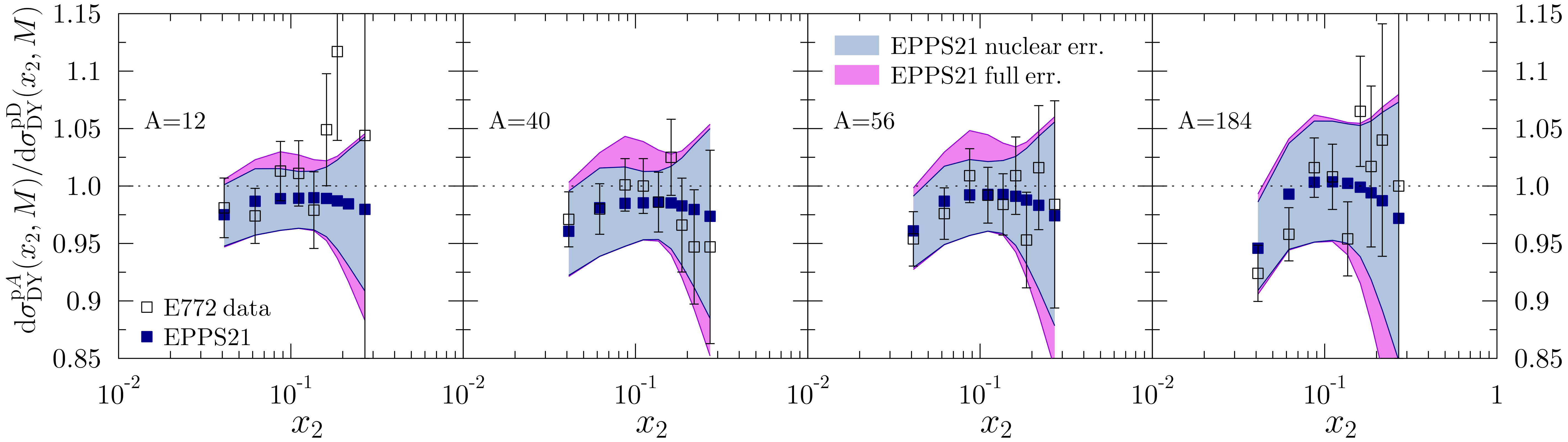
Charting the baseline proton-PDF uncertainty *new!*

We study baseline-PDF sensitivity by fitting nuclear modifications separately for each CT18A error set

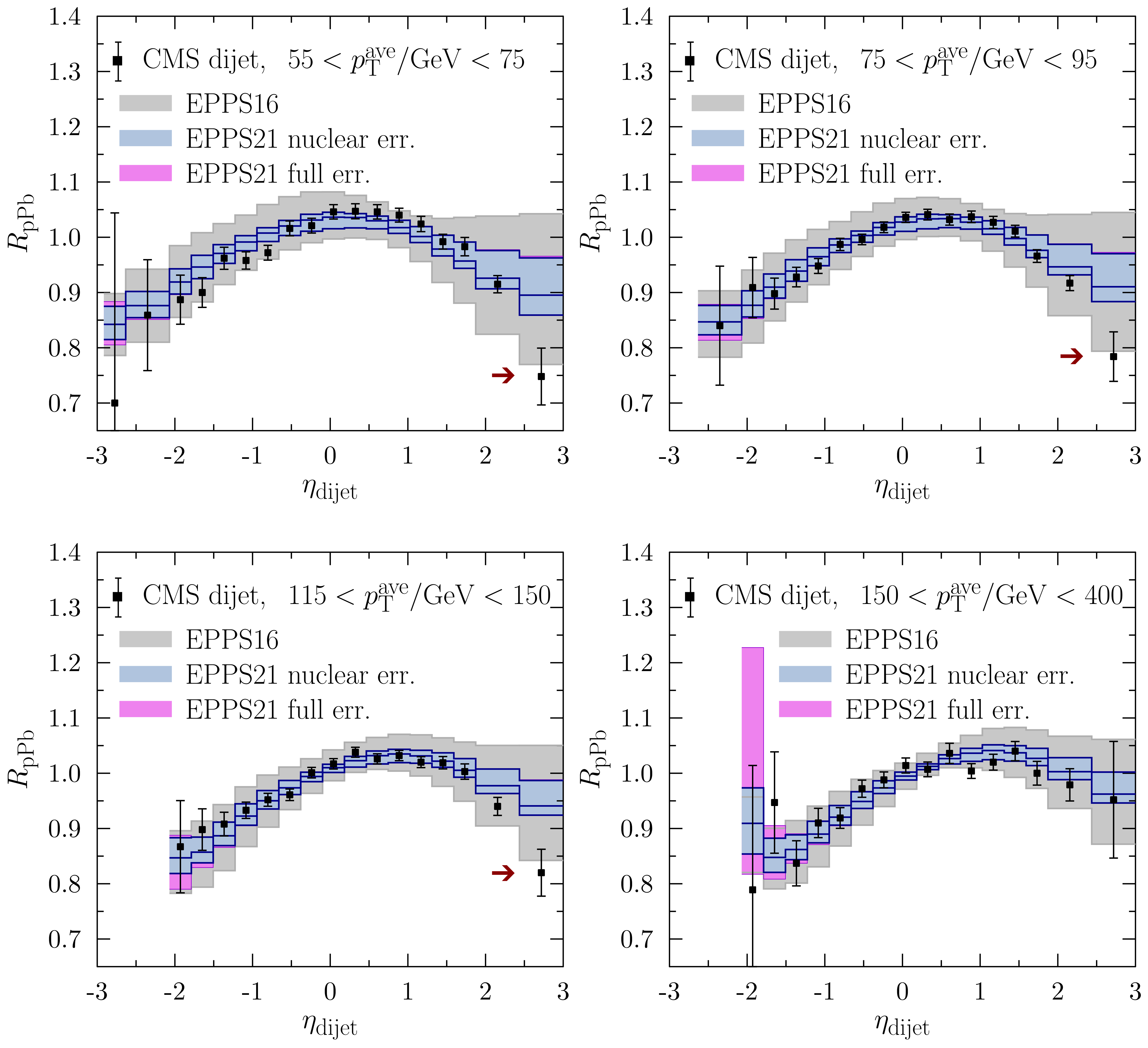


Baseline error mostly subdominant in the observables we fit, but shows up e.g. in the fixed-target DY



Dijets at 5.02 TeV *new!*

data from: [CMS Collaboration, Phys.Rev.Lett. 121 (2018) 062002]



Results in line with the reweighting study

[Eskola, PP & Paukkunen, Eur.Phys.J.C 79 (2019) 511]

Still finding it difficult to fit the forwardmost data points

➔ currently excluded from the fit

D^0s at 5.02 TeV – backward *new!*

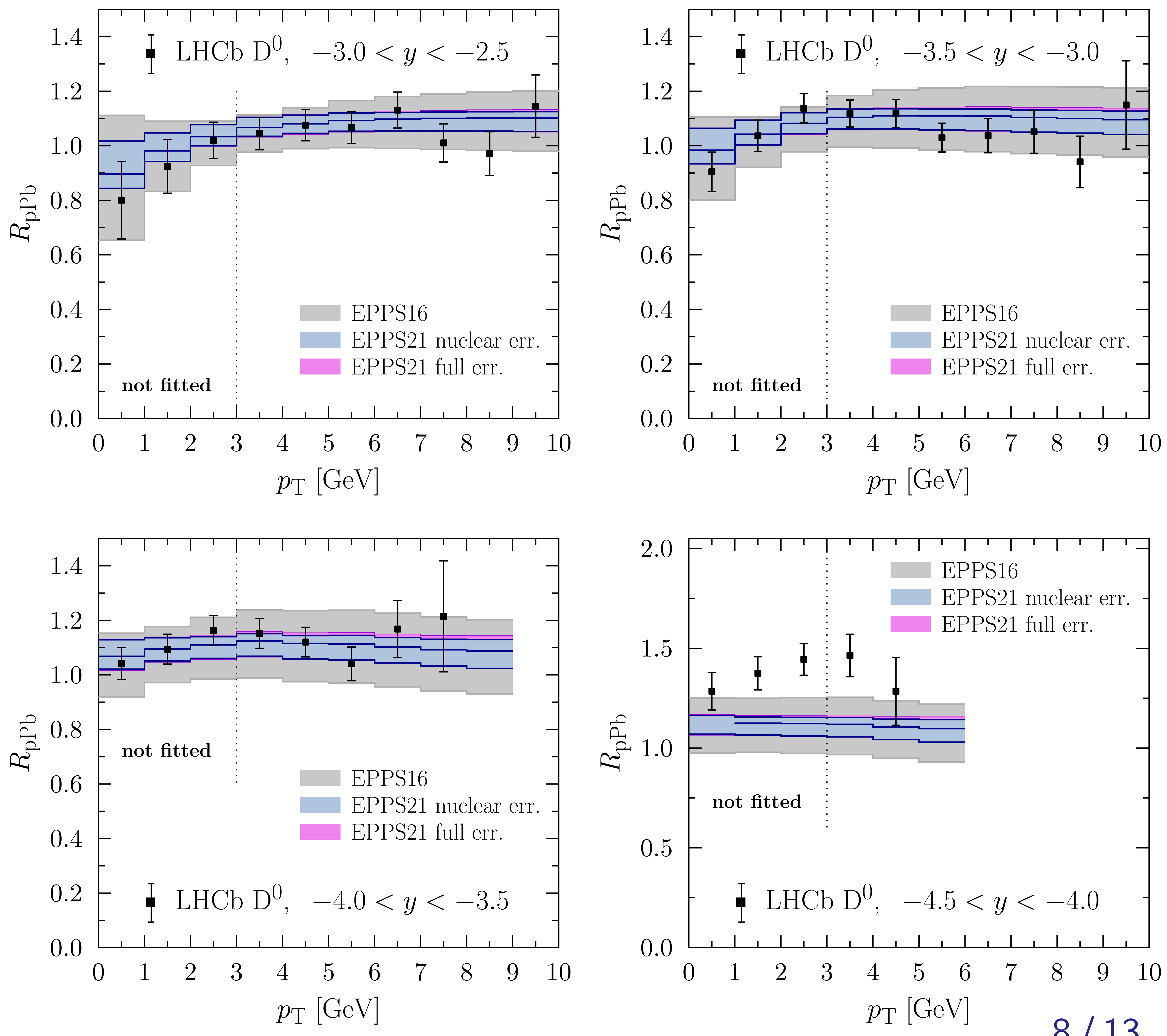
data from: [LHCb Collaboration, JHEP 10 (2017) 090]

Excellent fit!

Results in line with the reweighting study
[Eskola, Helenius, PP & Paukkunen, JHEP 05 (2020) 037]

Using the NLO pQCD S-ACOT-m_T GM-VFNS
[Helenius & Paukkunen, JHEP 05 (2018) 196]

Using a $p_T > 3$ GeV cut to reduce theoretical uncertainties



D^0s at 5.02 TeV – forward *new!*

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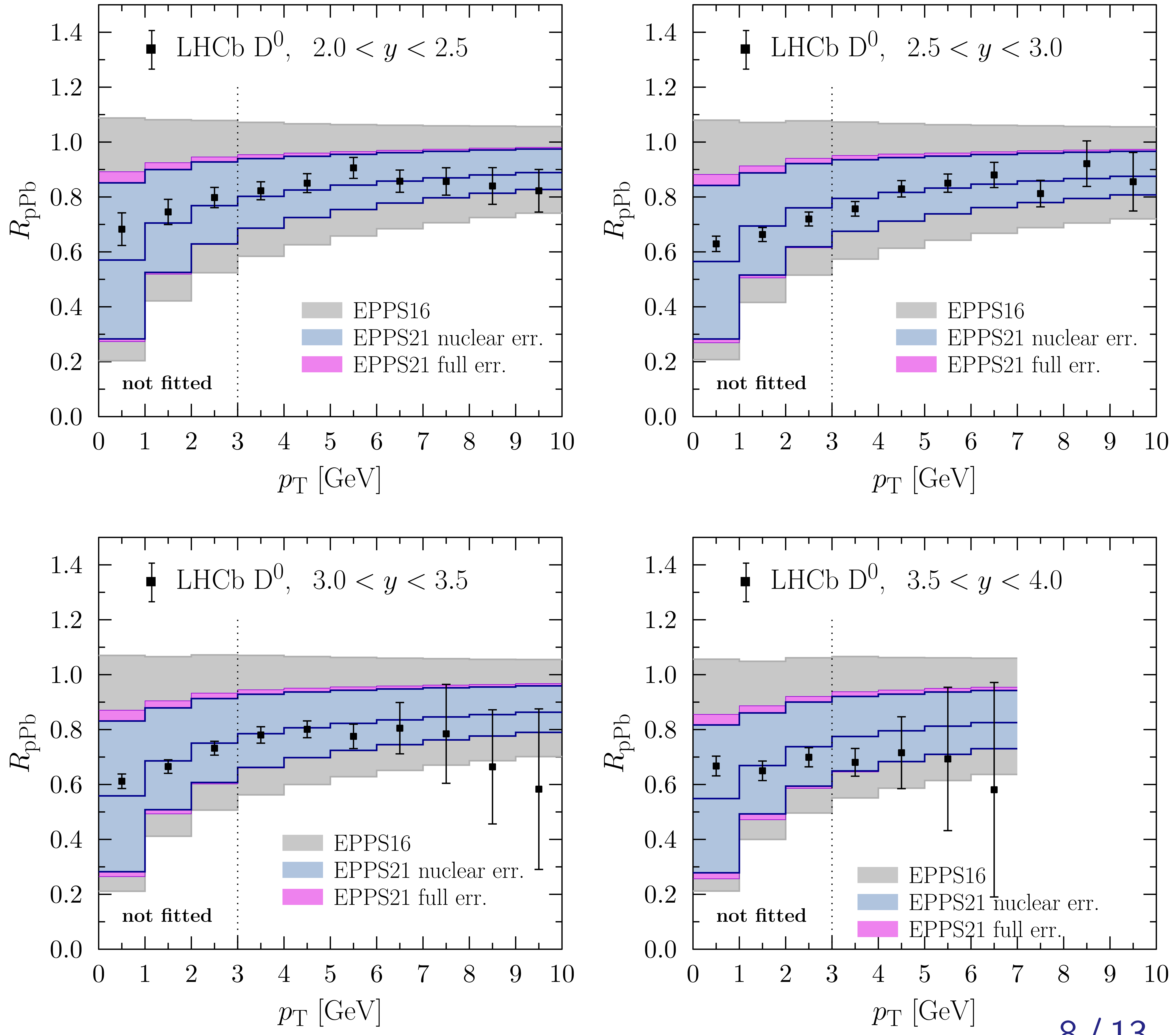


Ws at 8.16 TeV *new!*

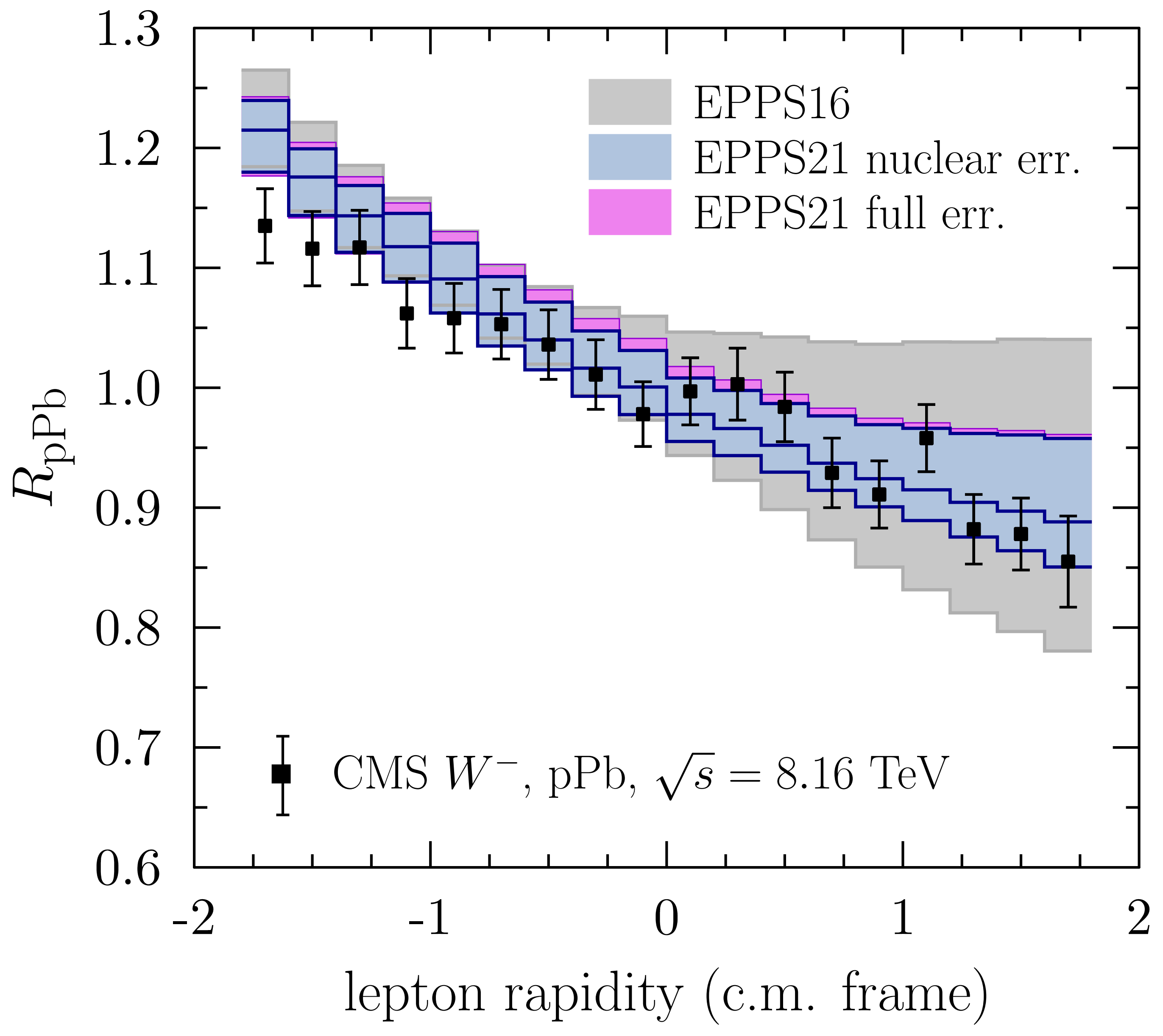
data from: [CMS Collaboration, Phys.Lett.B 800 (2020) 135048, Eur.Phys.J.C 76 (2016) 469]

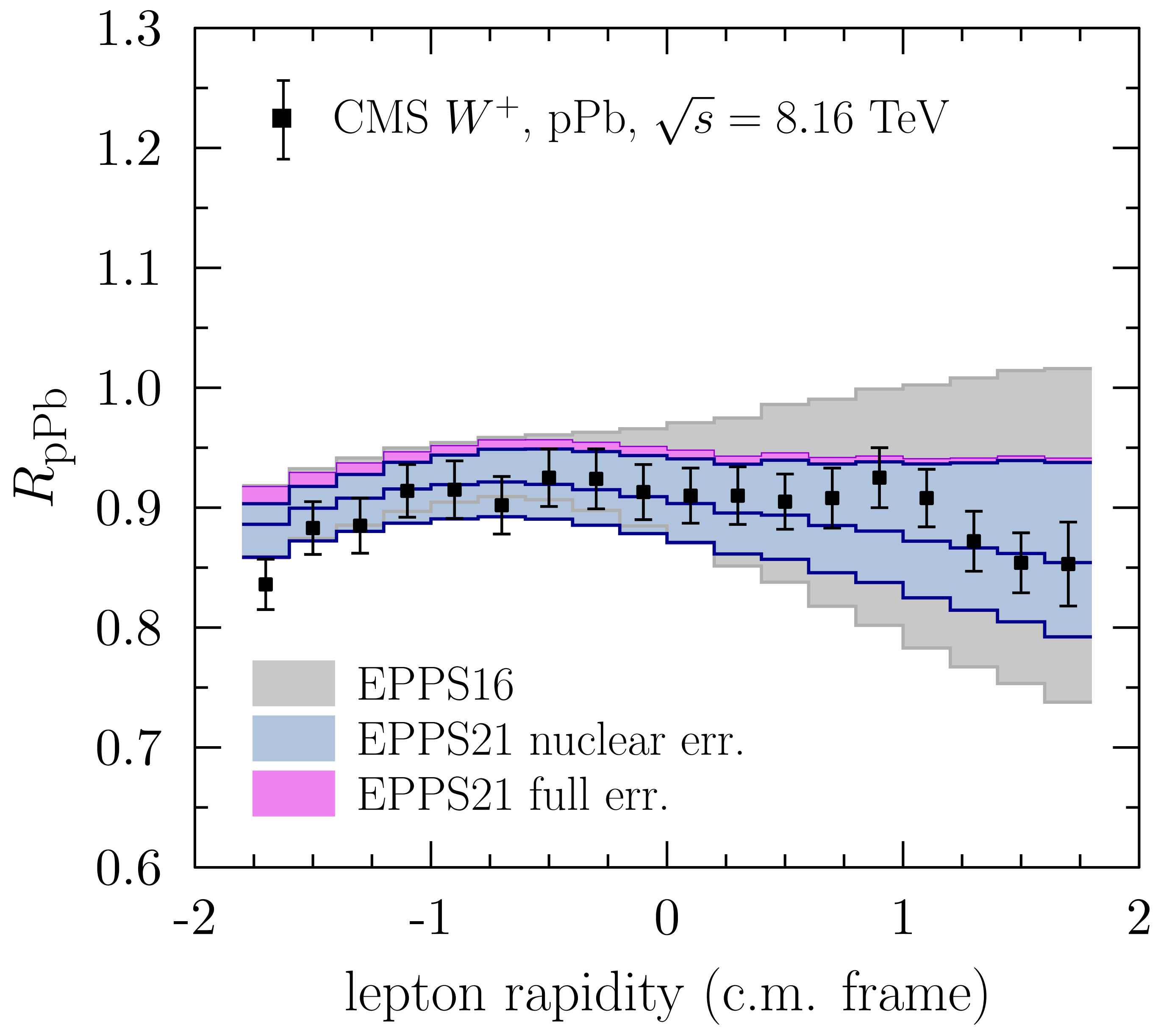
Excellent fit!

Using the mixed-energy nuclear modification ratio

$$R_{\mathrm{pPb}} = \frac{\mathrm{d}\sigma^{\mathrm{pPb}}_{8.16\ \mathrm{TeV}}/\mathrm{d}\eta_\mu}{\mathrm{d}\sigma^{\mathrm{pp}}_{8.0\ \mathrm{TeV}}/\mathrm{d}\eta_\mu}$$

to cancel the free-proton PDF uncertainty





Fully consistent with the dijets and D^0s

- Important check on the nPDF universality & factorization

These data do not appear to give additional flavour-separation constraints on top of those we had already in EPPS16

- Looking forward to increased precision at LHC Run 3

Fit results – valence

Bound-proton modifications *prelim.*

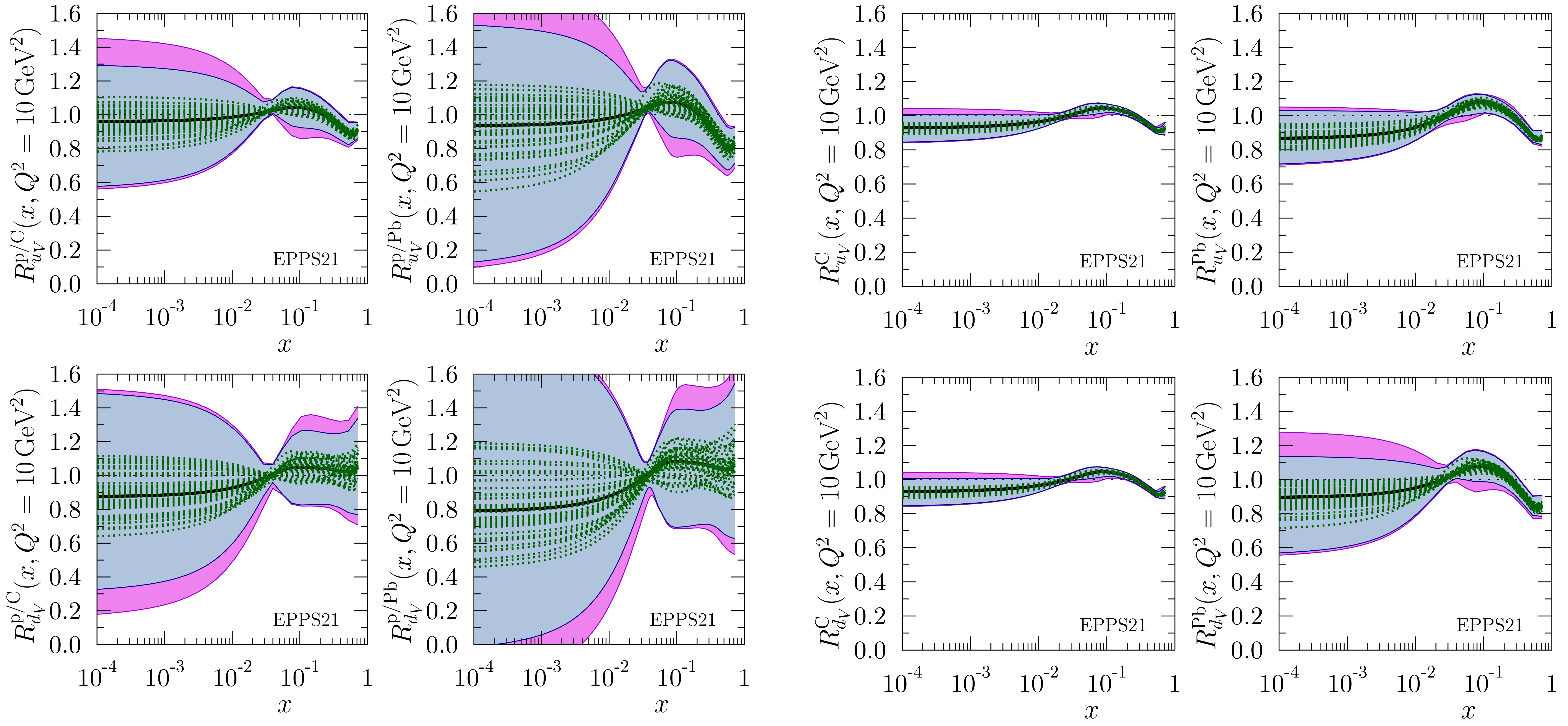
Carbon Lead

Full-nucleus modifications *prelim.*

Carbon Lead

u_V

d_V

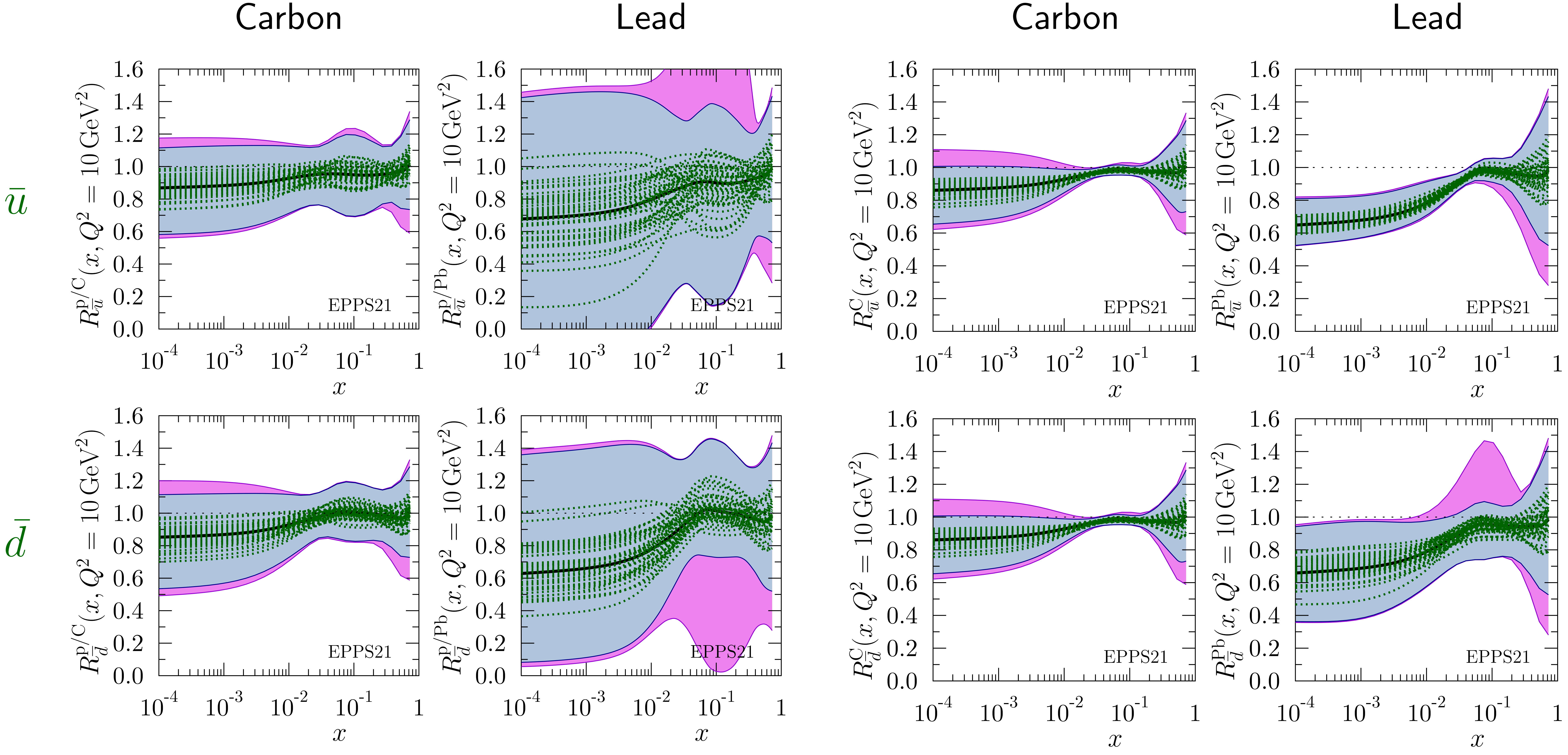


$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

Fit results – sea

Bound-proton modifications *prelim.* **Full-nucleus modifications** *prelim.*



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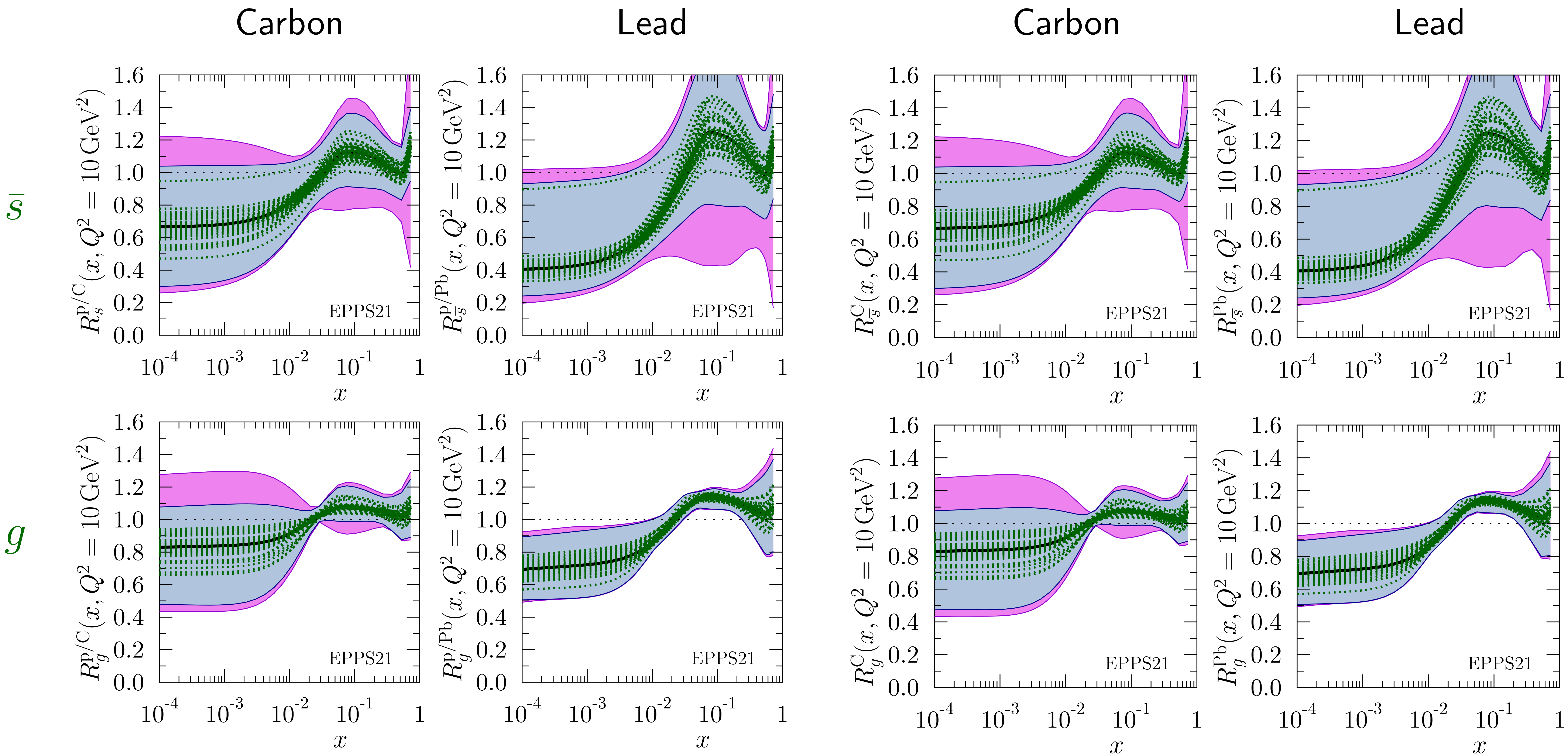
$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

Fit results – strange and glue

Bound-proton modifications *prelim.* **Full-nucleus modifications** *prelim.*



$$R_i^{p/A} = \frac{f_i^{p/A}}{f_i^p}$$

$$R_i^A = \frac{Z f_i^{p/A} + N f_i^{n/A}}{Z f_i^p + N f_i^n}$$

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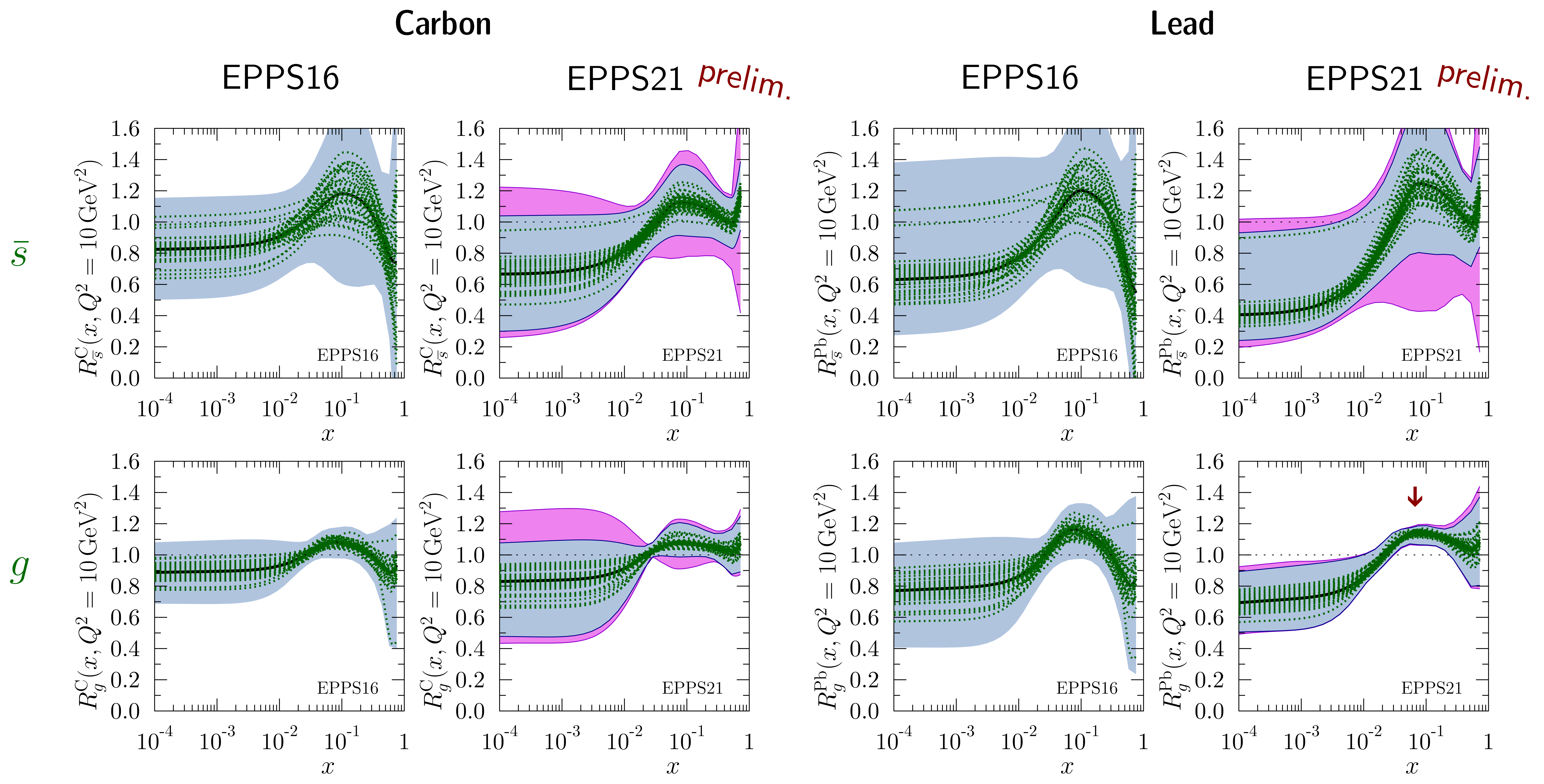
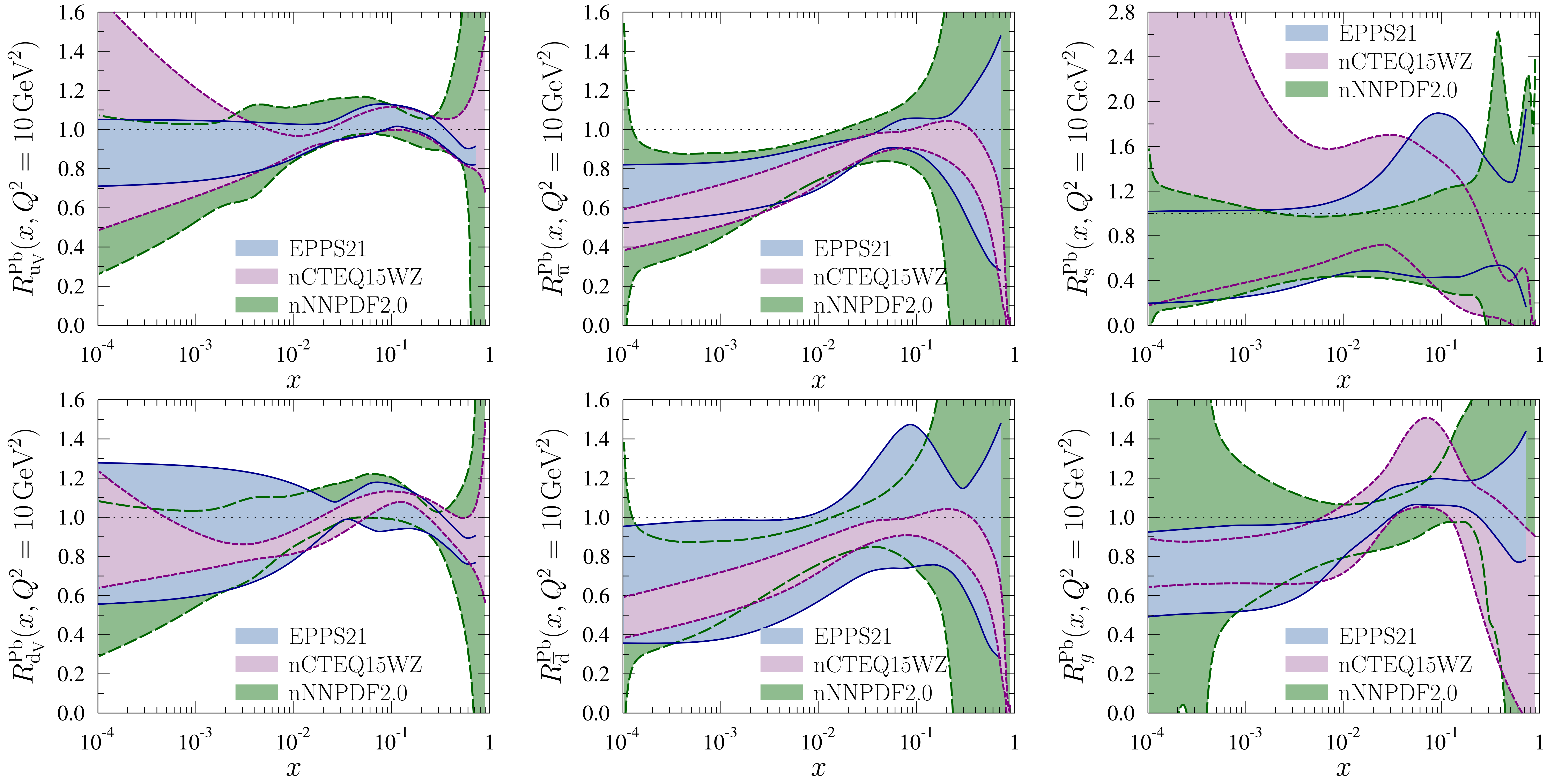
Comparison with EPPS16



- Better control over gluon (anti)shadowing ➔ sub-10% level uncertainties at mid-x!
- Flavour separation (esp. strangeness) remains a difficult beast to tame

Comparison with nNNPDF2.0 and nCTEQ15WZ

prelim.

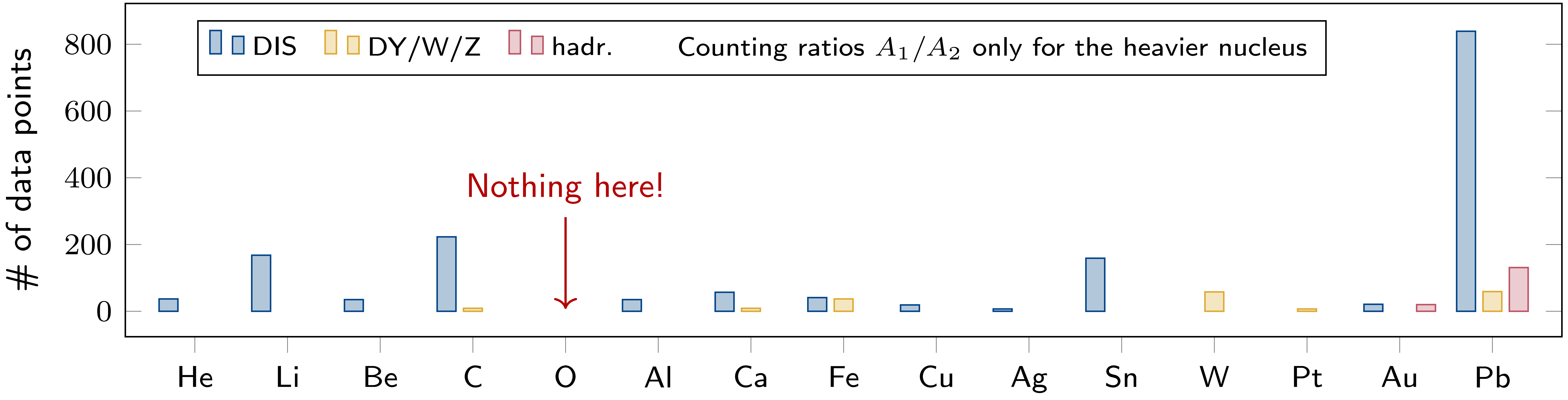


- All three consistent within uncertainties, but significant differences in the uncertainty estimates
- Best constrained gluons in the (prelim.) EPPS21 fit!

Data availability w.r.t. A

[P Paakkinen OO-pO Workshop 2021]

EPPS16 + LHC pPb dijets, D-mesons & 8.16 TeV Ws + JLab CLAS NC DIS



$\sim 50\%$ of the data points are for Pb!

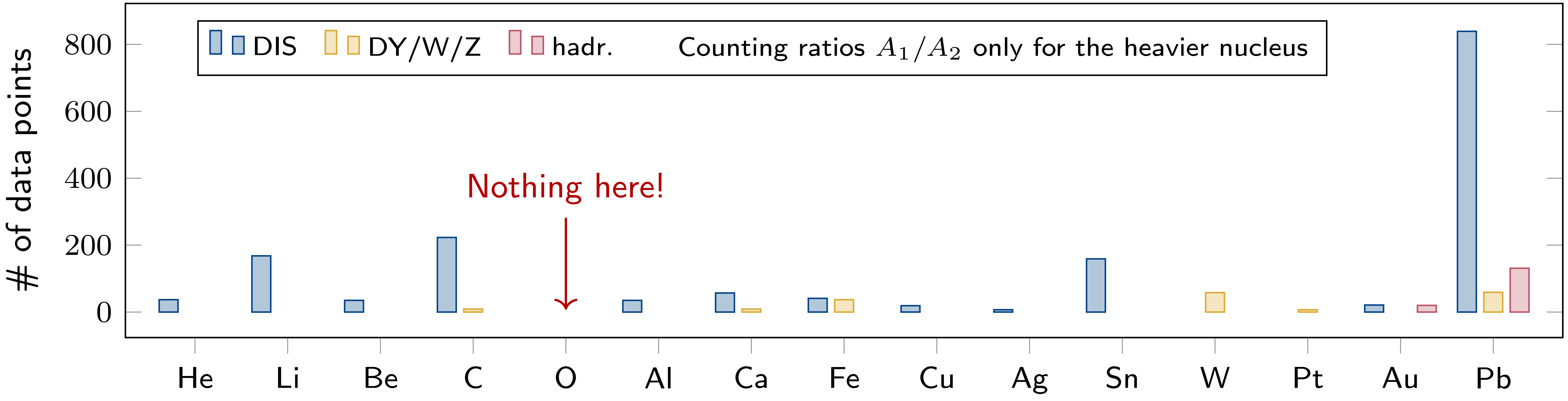
- ☺ Good coverage of DIS measurements for different A
- 😐 DY data more scarce, but OK A coverage
- ☹ Hadronic observables available only for heavy nuclei!

Light-ion runs at LHC could:

- Complement other light-nuclei DY data with W and Z production (strangeness!)
- Give first direct constraints (e.g. dijets, D-mesons) on light-nuclei gluon distributions!

Data availability w.r.t. A

EPPS16 + LHC pPb dijets, D-mesons & 8.16 TeV Ws + JLab CLAS NC DIS



[P Paakkinen OO-pO Workshop 2021]

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Light-ion runs at LHC could:

- Complement other light-nuclei DY data with W and Z production
- Give first direct constraints (e.g. dijets, D-mesons) on light-nuclei g

Increasing interest in small nuclei

$\Downarrow$

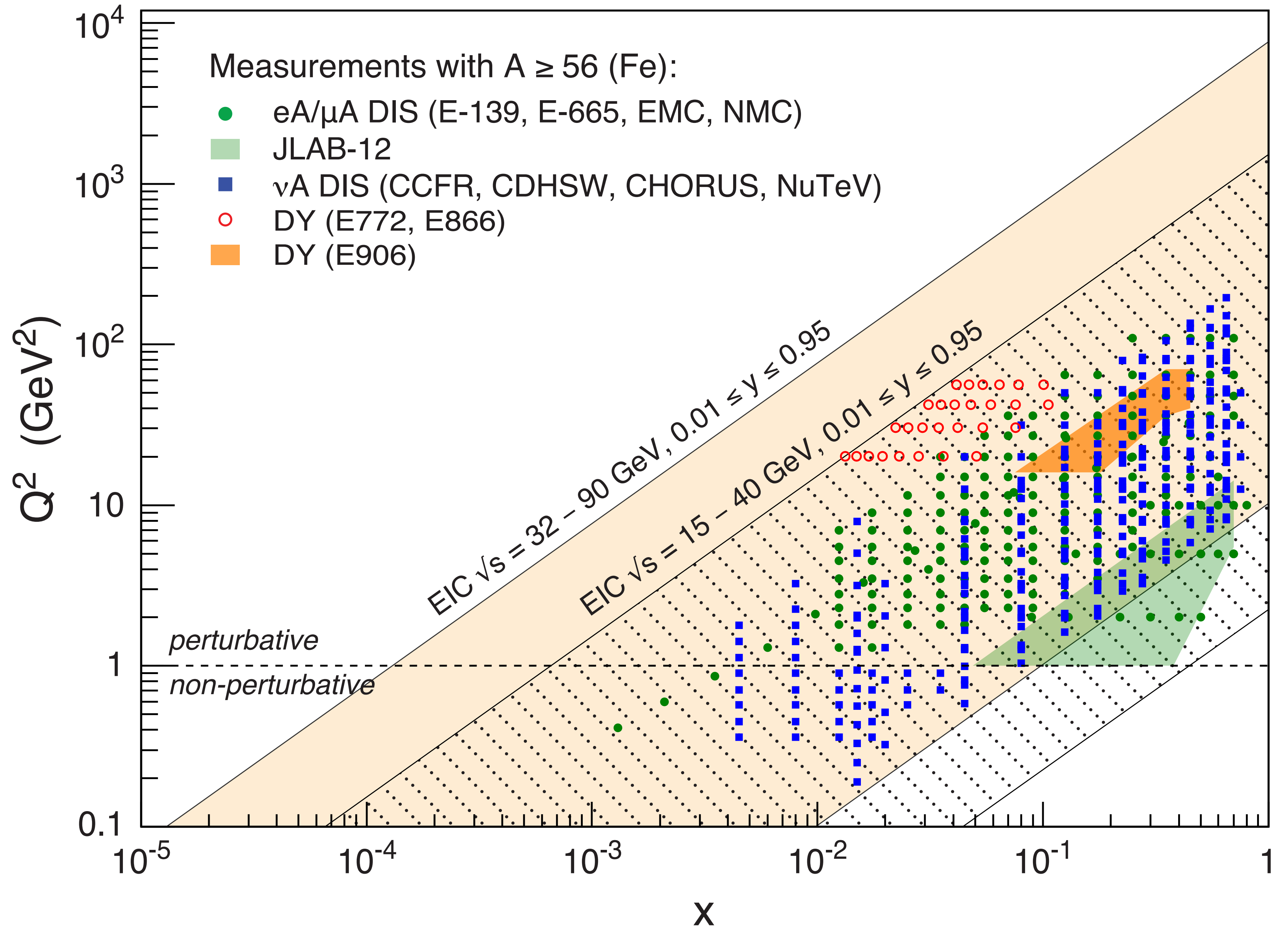
Extremely limited exp. information

EIC

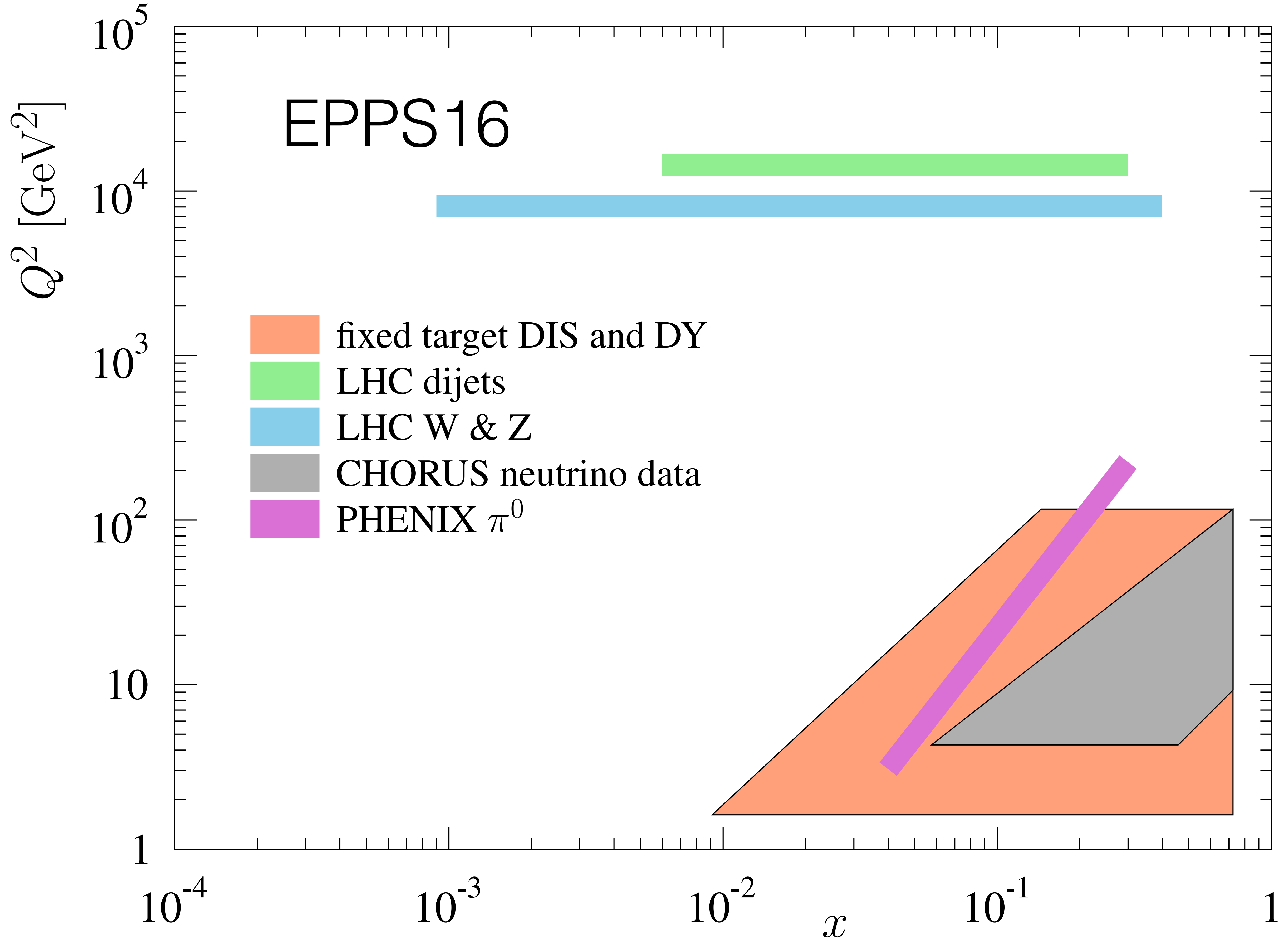
nuclear DIS

40ys later!!

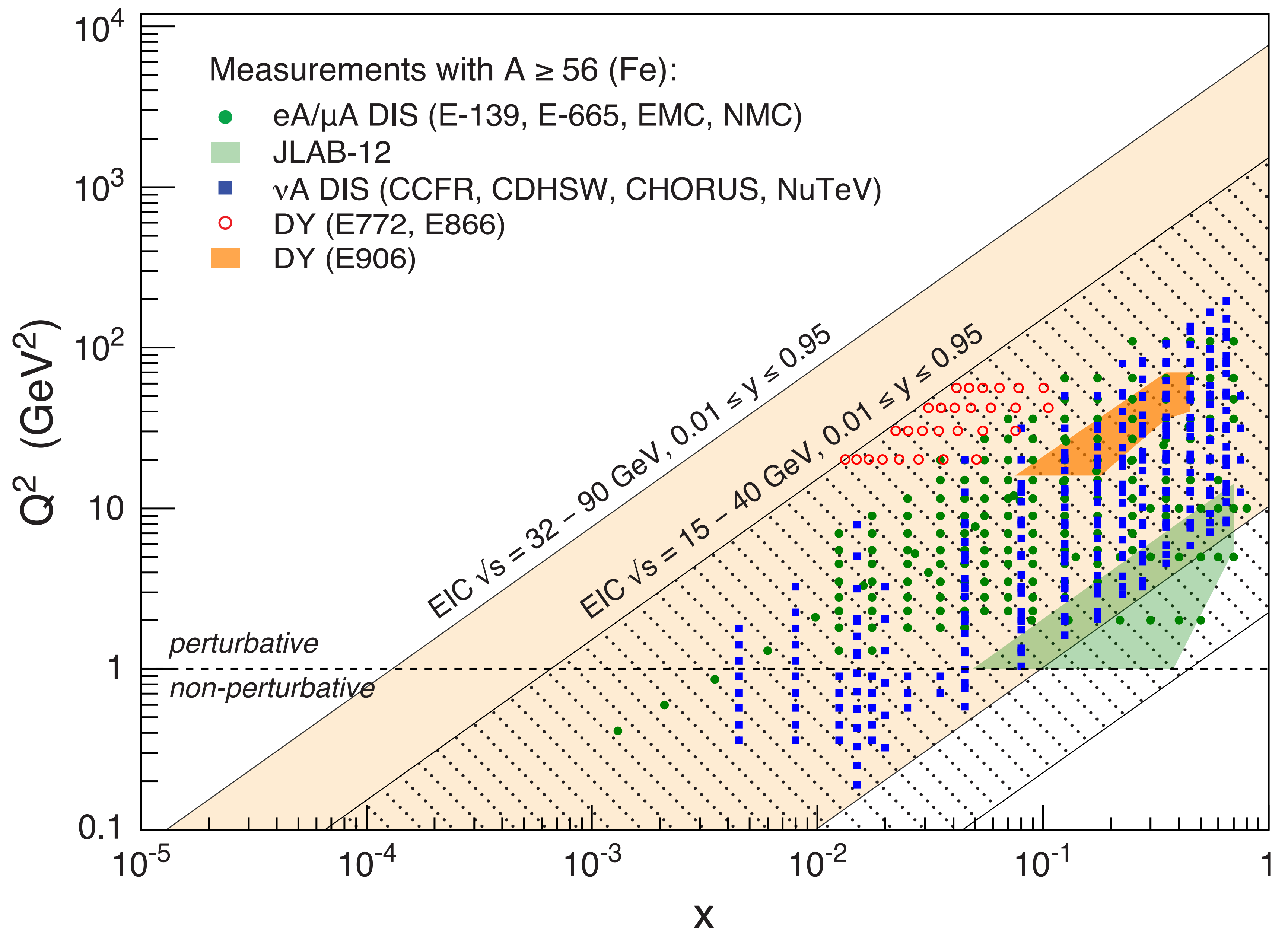
EIC for nPDFs

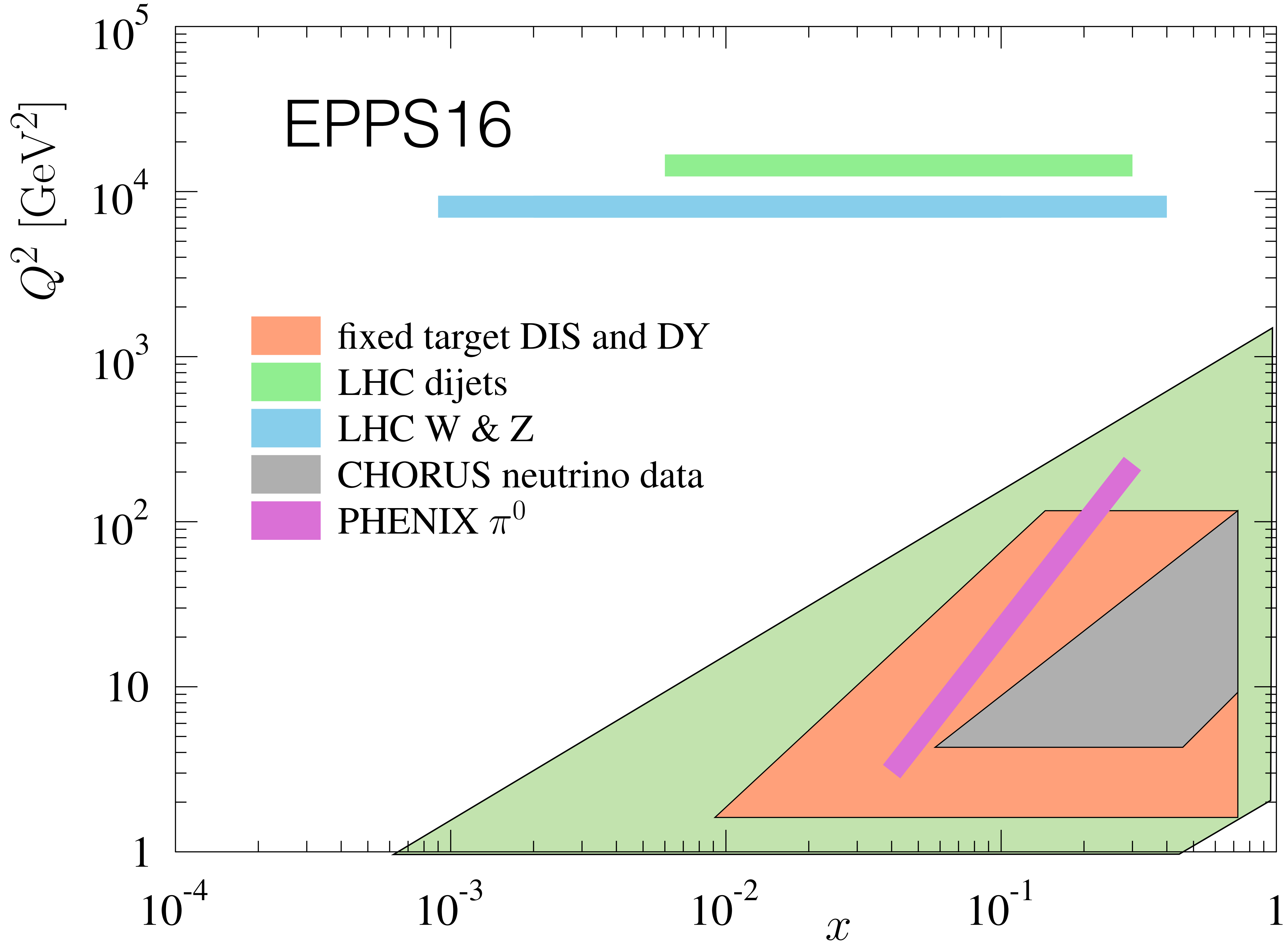


EIC extends the range to lower-x and lower-Q2



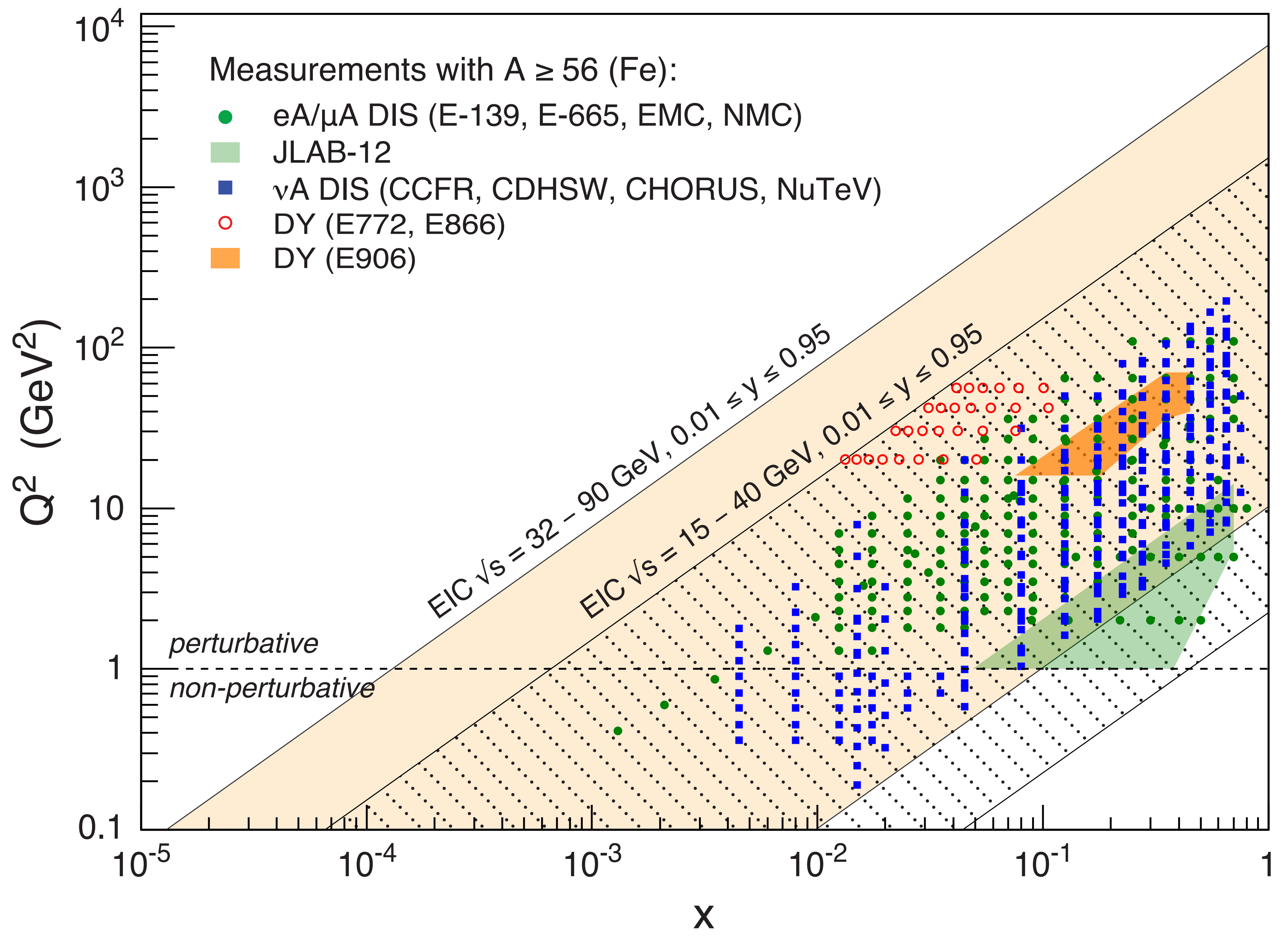
EIC for nPDFs



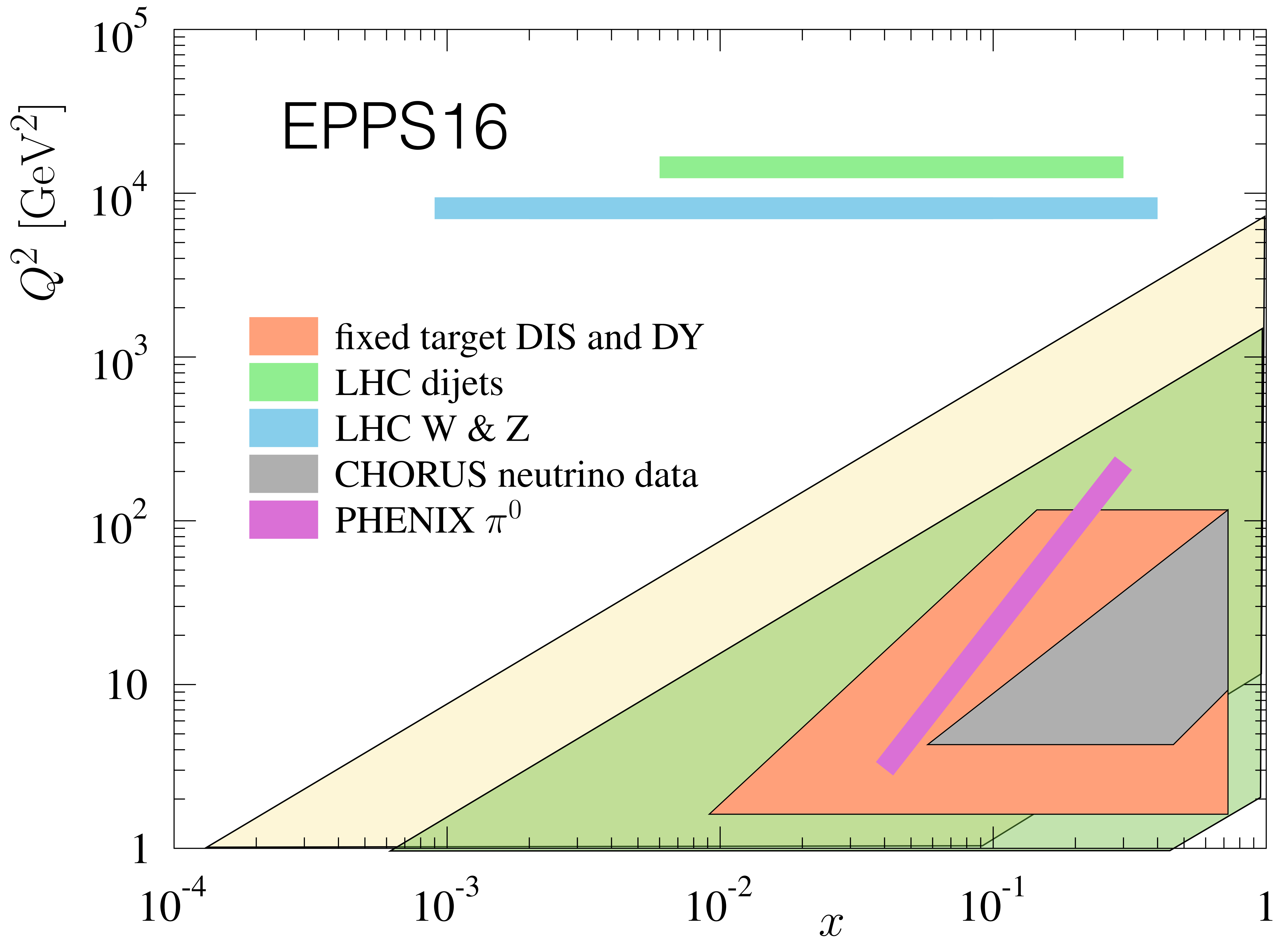


EIC extends the range to lower-x and lower-Q2

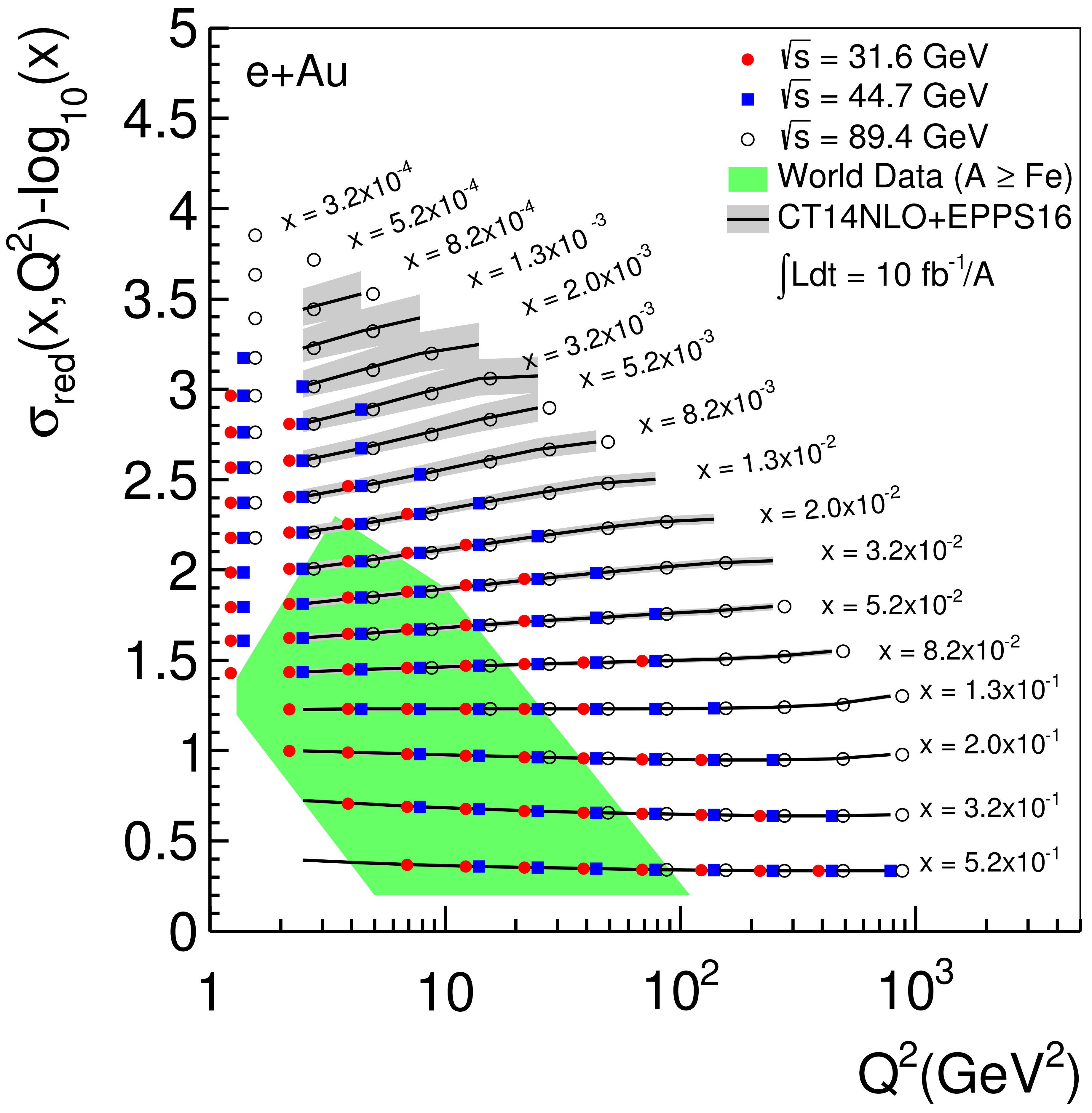
EIC for nPDFs

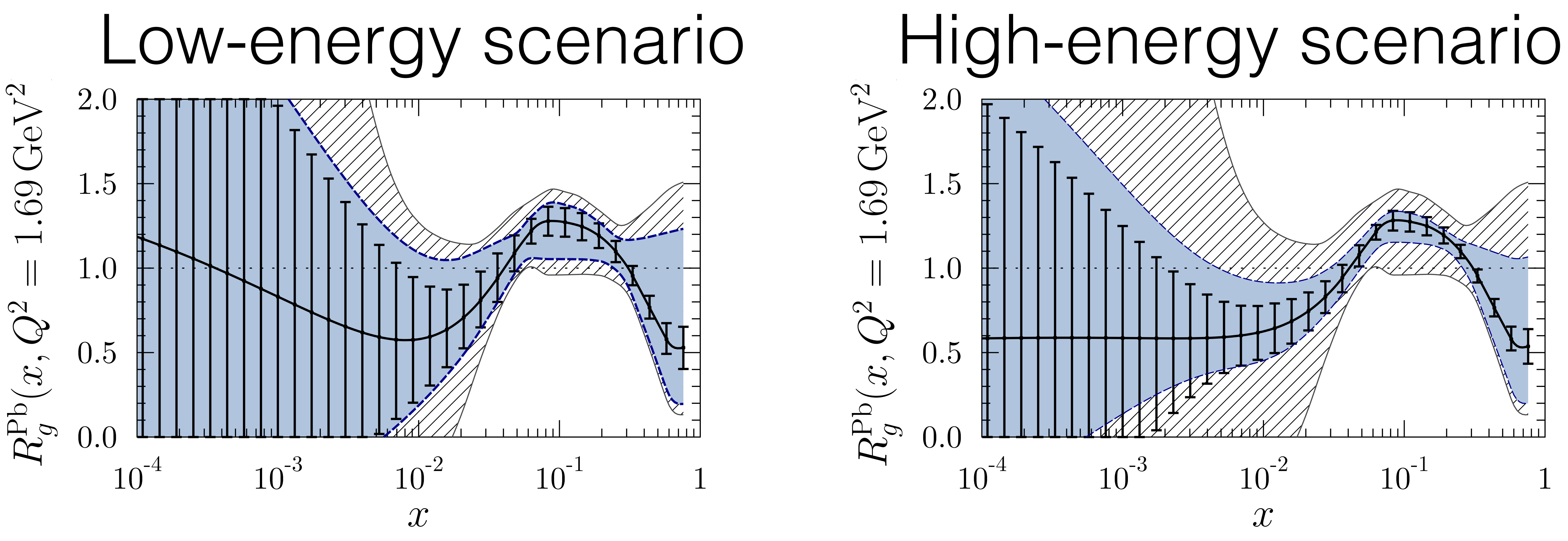


EIC extends the range to lower-x and lower-Q2



EIC - Expected impact





EIC has a clear impact in gluon
[However, no LHC Run2 data included in this analysis]

[Aschenauer, Fazio, Lamont, Paukkunen, Zurita 2017]

EIC - Expected impact

[From the EIC yellow report]

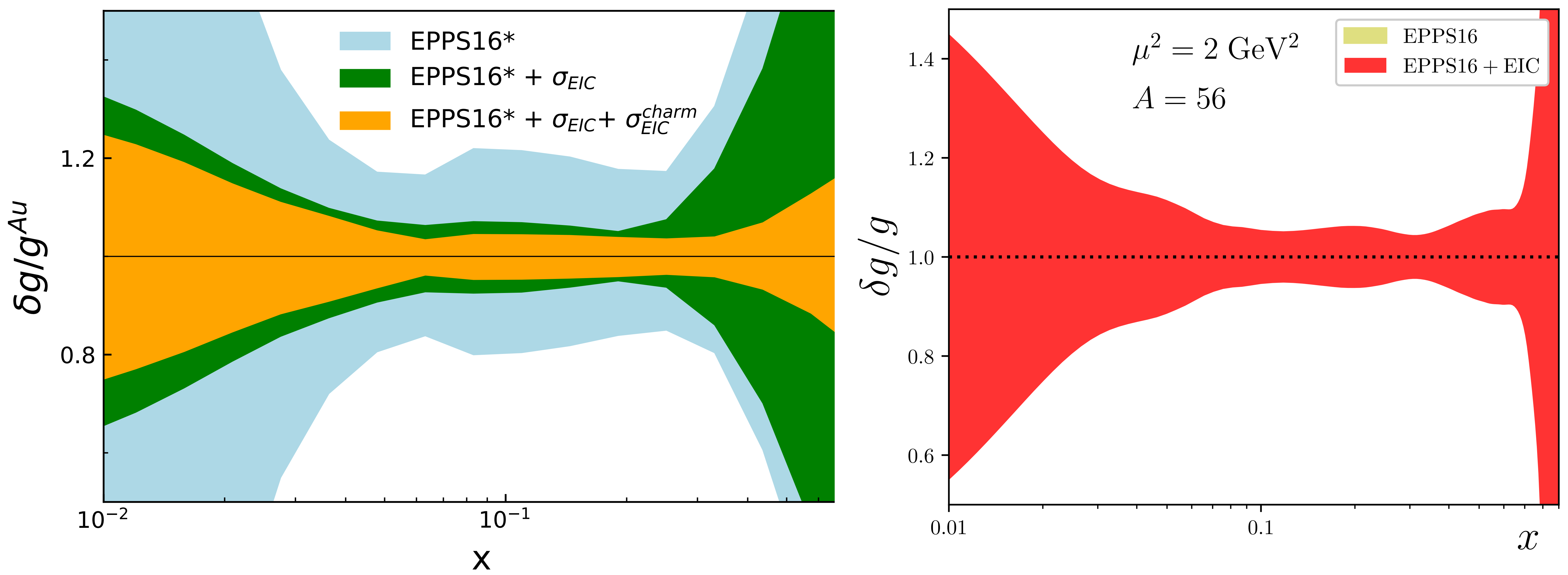


Figure 7.69: Left: Relative uncertainty bands of the gluon for Au at $Q^2 = 1.69$ GeV^2 for EPPS16* (light blue), EPPS16*+EIC σ (green) and EPPS16*+EIC σ^{charm} (orange). Right: same as left panel but for Fe at $Q^2 = 2$ GeV^2 for EPPS16 (yellow) and EPPS16+EIC σ^{charm} (red).

Notice that no LHC Run2 data has been included in EPPS16
(EPPS21 has more constraints for gluons)

Conclusions

Nuclear PDFs had strong progress in the last years after LHC data becomes available

- **Rather good control on gluons with dijet and D meson data**
- Large uncertainties at the IC rapidly get smaller with evolution.

Some problems still persist

- Flavour decomposition
- A-dependence
- Lack of constraints in strange quarks…

EIC should have a big impact

- Not clearly seen in re-weighting studies IMHO
- But… fills the gap from small to large virtualities (LHC kinematics) - **checks of universality**
- Flexibility for A-dependence
- Proton PDF - nucleus PDF joint analyses.
- DIS observables are THE observables for PDF studies - many years with very limited data

List of experimental data in EPPS16

Experiment	Observable	Collisions	Data points	χ^2	Ref.
SLAC E139	DIS	e^-He(4), e^-D	21	12.2	[69]
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0	[70]
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2	[71]
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9	[69]
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4	[72]
SLAC E139	DIS	e^-C(12), e^-D	7	6.4	[69]
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0	[71]
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6	[71]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7	[70]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9	[70]
FNAL E772	DY	pC(12), pD	9	11.3	[73]
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7	[69]
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6	[72]
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8	[69]
FNAL E772	DY	pCa(40), pD	9	3.33	[73]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6	[70]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5	[70]
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4	[72]
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6	[69]
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0	[73]
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8	[72]
FNAL E866	DY	pFe(56), pBe(9)	28	20.1	[74]
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4	[75]
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0	[69]
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5	[72]
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6	[76]
FNAL E772	DY	pW(184), pD	9	7.2	[73]
FNAL E866	DY	pW(184), pBe(9)	28	26.1	[74]
CERN NA10*	DY	π^-W(184), π^-D	10	11.6	[49]
FNAL E615*	DY	π^+W(184), π^-W(184)	11	10.2	[50]
CERN NA3*	DY	π^-Pt(195), π^-H	7	4.6	[48]
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4	[69]
RHIC PHENIX	π^0	dAu(197), pp	20	6.9	[28]
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[72]
CERN CMS*	$W^\pm$	pPb(208)	10	8.8	[43]
CERN CMS*	Z	pPb(208)	6	5.8	[45]
CERN ATLAS*	Z	pPb(208)	7	9.6	[46]
CERN CMS*	dijet	pPb(208)	7	5.5	[34]
CERN CHORUS*	DIS	νPb(208), $\overline{\nu}$Pb(208)	824	998.6	[47]
Total			1811	1789	