Initial and final state effects in the collinear approach

(nPDFs and nFFs)

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Correlations in Partonic and Hadronic Interactions (CPHI-2022)

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Universität Regensburg

HRT

Outline

- Why study nuclear effects?
- The initial state: nPDFs.
- Perspectives of improvement.
- The final state: nFFs.
- Summary.

Why exactly put effort into it?

- We do a lot of experiments with nuclei:

ACE
AMANDA
ANTARES
ArgoNeuT
ATLAS
Bevatron
Borexino
Bubble Chamber
CDHS
CLAS detector
CMS
COMPASS (NA58)
Cowan–Reines experiment
CUORE
DAPHNE
DONUT
Enriched Xenon Observatory
EMC
FASER
Fermilab E-906/SeaQuest
Gargamelle
Germanium Detector Array
HARP
HERA-B
HERMES
IceCube
Irvine–Michigan–Brookhaven
Kamioka Liquid Scintillator
Antineutrino Detector
Kamioka Observatory
KM3NeT
Large Volume Detector
LAND
LHCb
MINOS
Modular Neutron Array
Monopole, Astrophysics and Cosmic
Ray Observatory
Mu to E Gamma
Mu2e
Mu3e
NA32
NA35
NA49
NA60
NA61
NA63
NESTOR Project
NEVOD
Kolar Gold Fields
PHENIX
PUMA
Rutherford gold foil experiment
SAGE
SciBooNE
SNO+
Soudan 1
Soudan 2
STAR
Sudbury Neutrino Observatory
Super-Kamiokande
...

- At the end of the day most matter we see is made out of nuclei. Even ourselves.

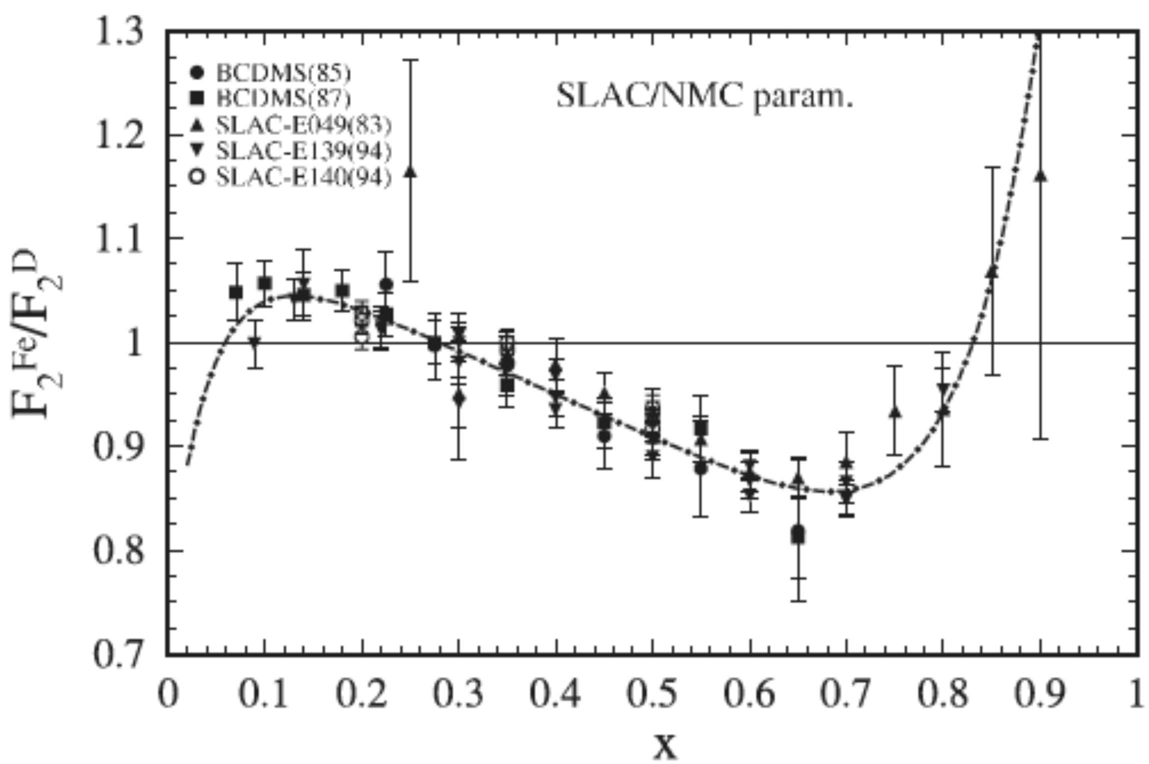
What are PDFs?

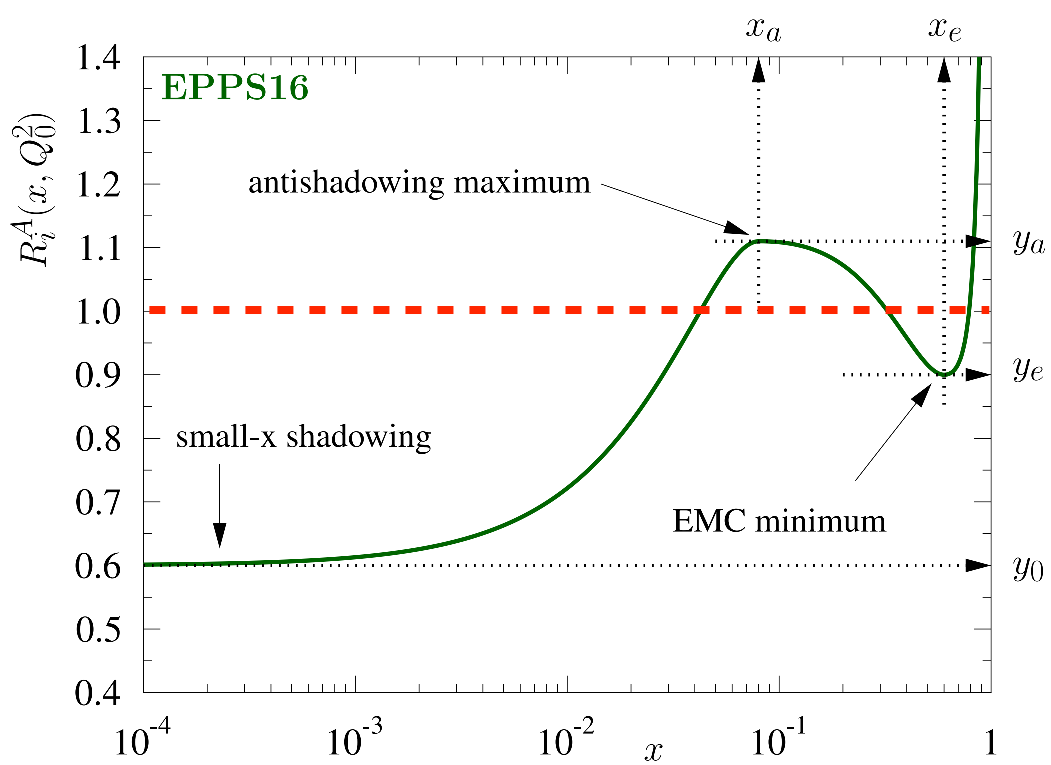
We have factorisation theorems that allow us to write

$$\frac{d\sigma^{p+p'\to some.}}{d\mathbf{p}} = \sum_{a,b,c,\dots} \frac{d\hat{\sigma}_{a+b\to c+\dots}}{d\mathbf{p}} \otimes f_{a/p} \otimes f_{b/p'} \otimes D_{c\to some.}$$

- In the collinear approximation. Collinear PDFs, a.k.a. "PDFs".
- We can't compute them, so we use data:
    - Propose a functional form depending on several parameters.
    - Use as much data from as many experiments and observables as possible ("global").
    - Fit the parameters.

And now let's add one nucleus (or more):





$$\frac{d\sigma^{A+p'\to some.}}{d\mathbf{p}} = \sum_{a,b,c,\dots} \frac{d\hat{\sigma}_{a+b\to c+\dots}}{d\mathbf{p}} \otimes f_{a/A} \otimes f_{b/p'} \otimes D_{c\to some.}$$

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

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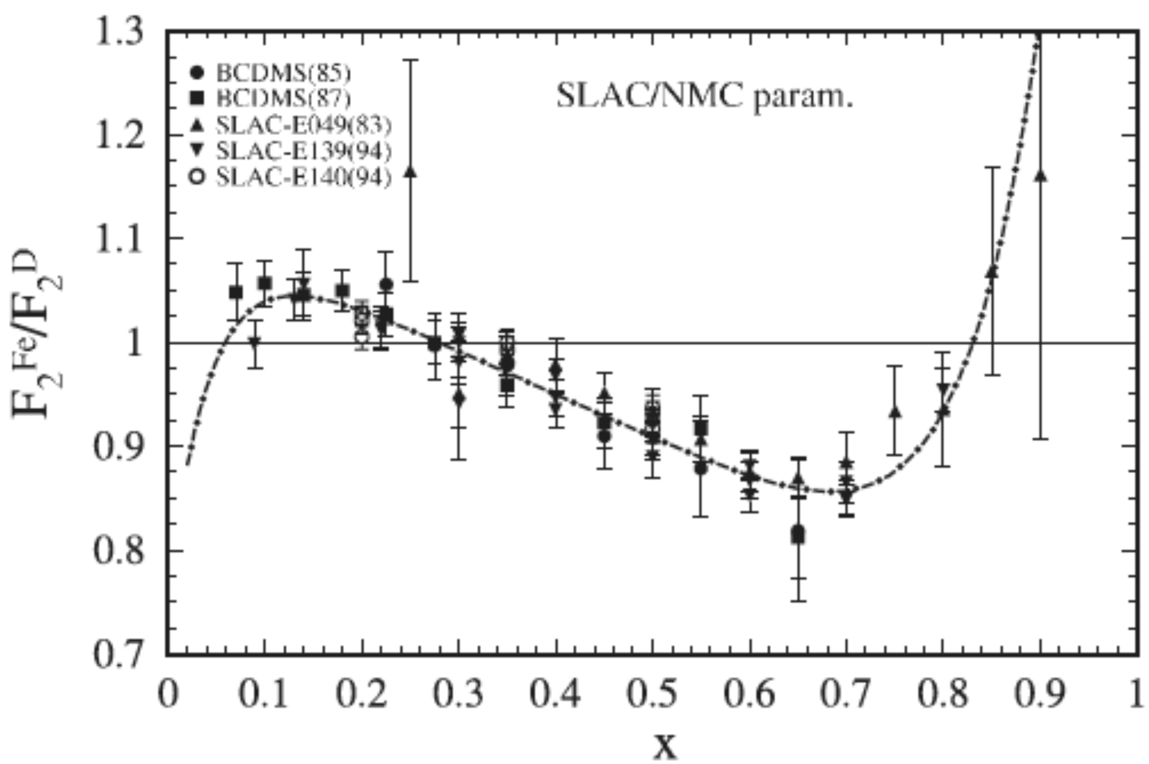

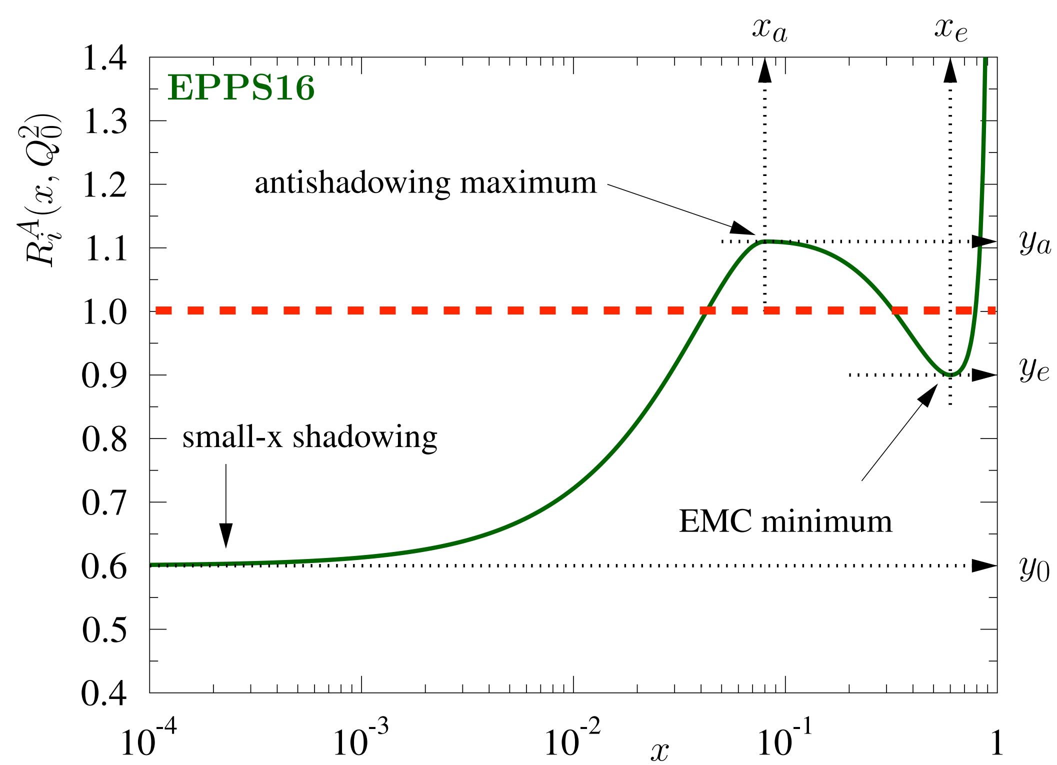

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The naive interpretation

fails. **Miserably**. 😓

What to do then?

- What happens in Vegas stays in Vegas.

- Construct theoretical models:

shadowing: **441** (1973-2022)

anti-shadowing: 38 (1978-2020)

EMC effect: **369** (1983-2021)

Fermi motion: 93 (1968-2021)

- Phenomenological approach: nuclear PDFs

$$\frac{d\sigma^{A+p'\to some.}}{d\mathbf{p}} = \sum_{a,b,c,\ldots} \frac{d\hat{\sigma}_{a+b\to c+\ldots}}{d\mathbf{p}} \otimes f_{a/A} \otimes f_{b/p'} \otimes D_{c\to some.}$$

- We **assume** that the factorisation theorem is valid in the nuclear environment. For now, it seems to hold.

- Usually we connect the nPDF with some baseline PDF.

$$f_{a/p/A}(x, Q_0^2, A) = F(x, Q_0^2, A)$$

$$\rightarrow f_{a/p}(x, Q_0^2) R_a(x, A)$$

$$\rightarrow f_{a/p}(x, Q_0^2) \otimes R_a(x, A)$$

$$\rightarrow f_{a/p/A}(x, Q_0^2, A)$$

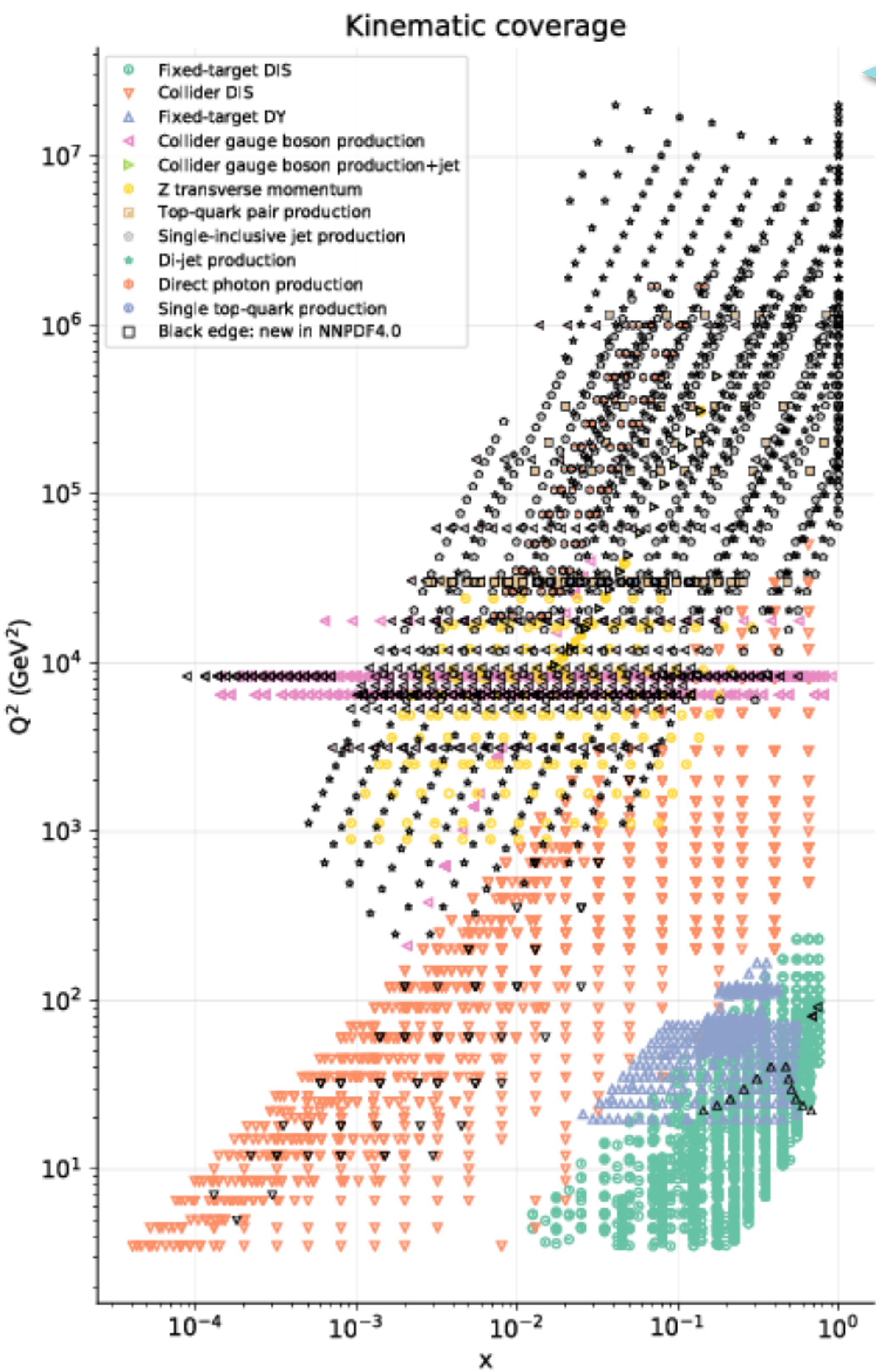
$\rightarrow$ NN

- Use isospin symmetry to construct the full nPDF (yes, we do know that it is not a prefect symmetry).

- We proceed as for proton PDFs: do a global fit.

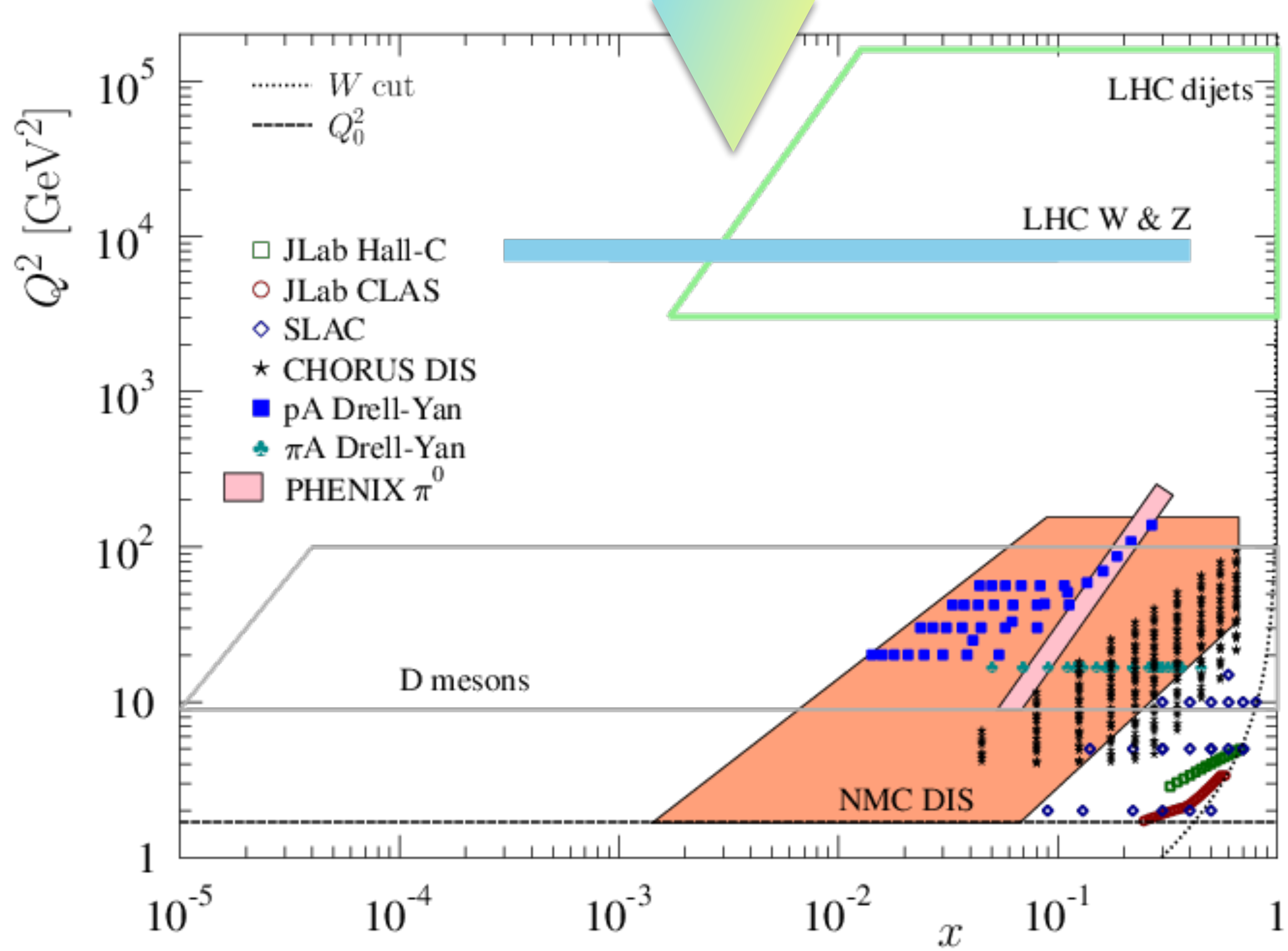
Issues we have to deal with

- The kinematic coverage:



PDFs, arXiv:2109.02653

nPDFs, arXiv:2109.02653



- The proton baseline contains some nuclear effects:

  - The “cleanest” data to extract PDFs is DIS 🥰
  - We need a different combination of PDFs to do *flavour separation*.

    - **CC** DIS. But most experiments are done with neutrino beams on **nuclear** targets.
    - **Neutron** target. Use of neutron star not possible. Next best option: deuterium. But it is a nucleus.

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- The amount of data:

NC DIS data	FT, proton/nucleus (16)	FT deuterium	Collider
proton PDF fit e.g. EPJC 81 (2021) 4, 341	433	513	1264
nuclear case	1314	615	**0**

- The type of data:

  - Most data from FT DIS: ~ 60% given as ratios, the rest as F_2; *information on F_L is lost forever*.
  - Drell-Yan data are scarce and have large uncertainties.
  - Doble counting effects with CC DIS.
  - Jets/di-jets, hadron production: any final state effect?

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  - choice of parametrisation.
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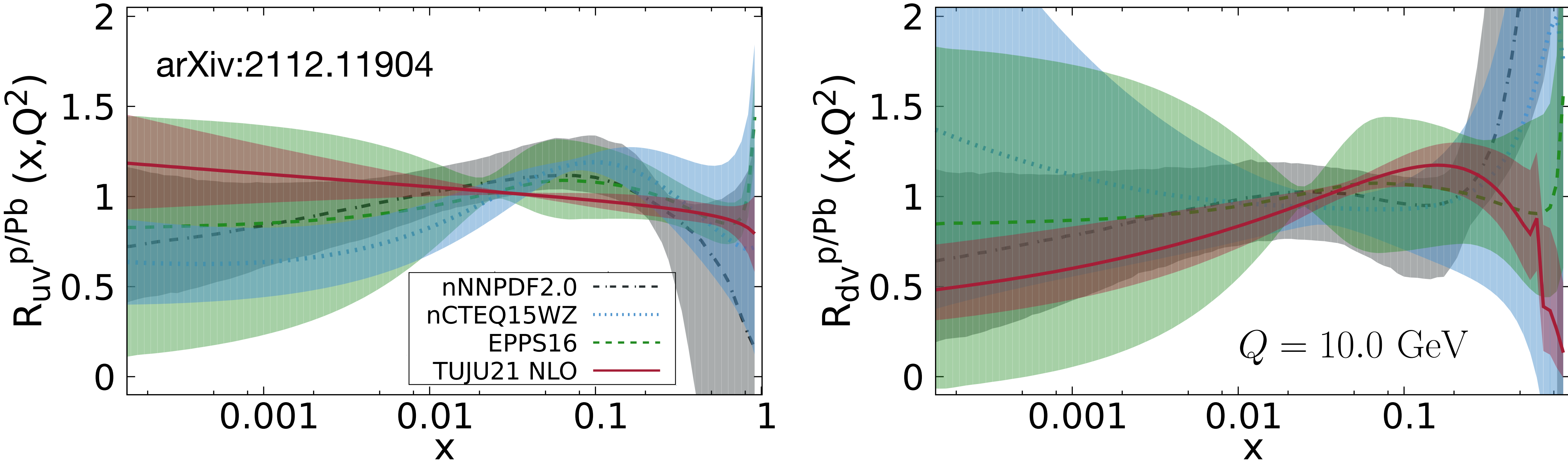
- And every single issue that appears in proton PDF fits.

Available sets

- 🇺🇸 and 🇺🇸-🇩🇪: **nCTEQ15**: PRD 93, 085037. **nCTEQ15WZ**: EPJC 80, 968. **nCTEQ15HiX**: PRD 103, 114015.
- 🇦🇷 and 🇦🇷-🇩🇪: **nDS**: PRD 69, 074028. **DSSZ**: PRD 85, 074028.
- 🇫🇮-🇩🇪: **nTuJu19**: PRD 100, 096015. **nTuJu21**: arXiv:2112.11904.
- 🇫🇮-🇪🇸: **EKS**: EPJC 9, 61. **EPS09**: JHEP 0904, 065. **EPPS16**: EPJC 77, 163. **EPPS21**: arXiv:2112.12462.
- 🇯🇵 family: **HKM**: PRD 64, 034003. **HKN07**: PRC 76, 065207.
- 🇮🇷 and 🇮🇷-🇩🇪: **KA15**: PRD 93, 014026. **KSASG20**: Phys.Rev.D 104, 034010.
- **NN**: **nNNPDF1.0**: EPJC 79, 471. **nNNPDF2.0**: JHEP 09, 183. **nNNPDF3.0**: arXiv:2201.12363.

Comparing the latest sets: the valence quarks



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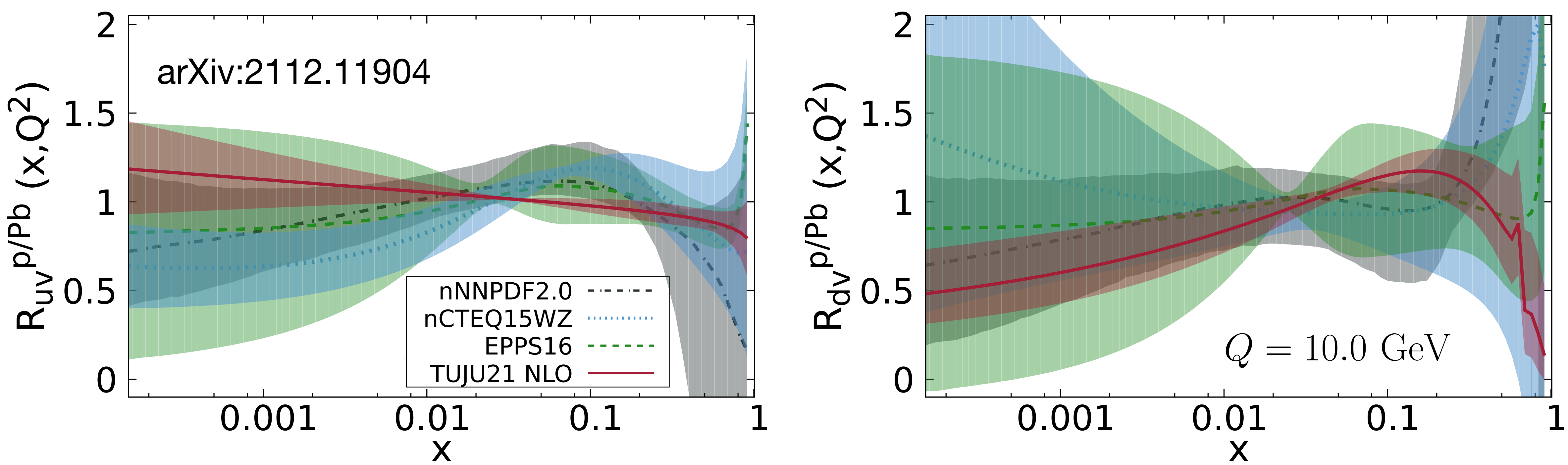

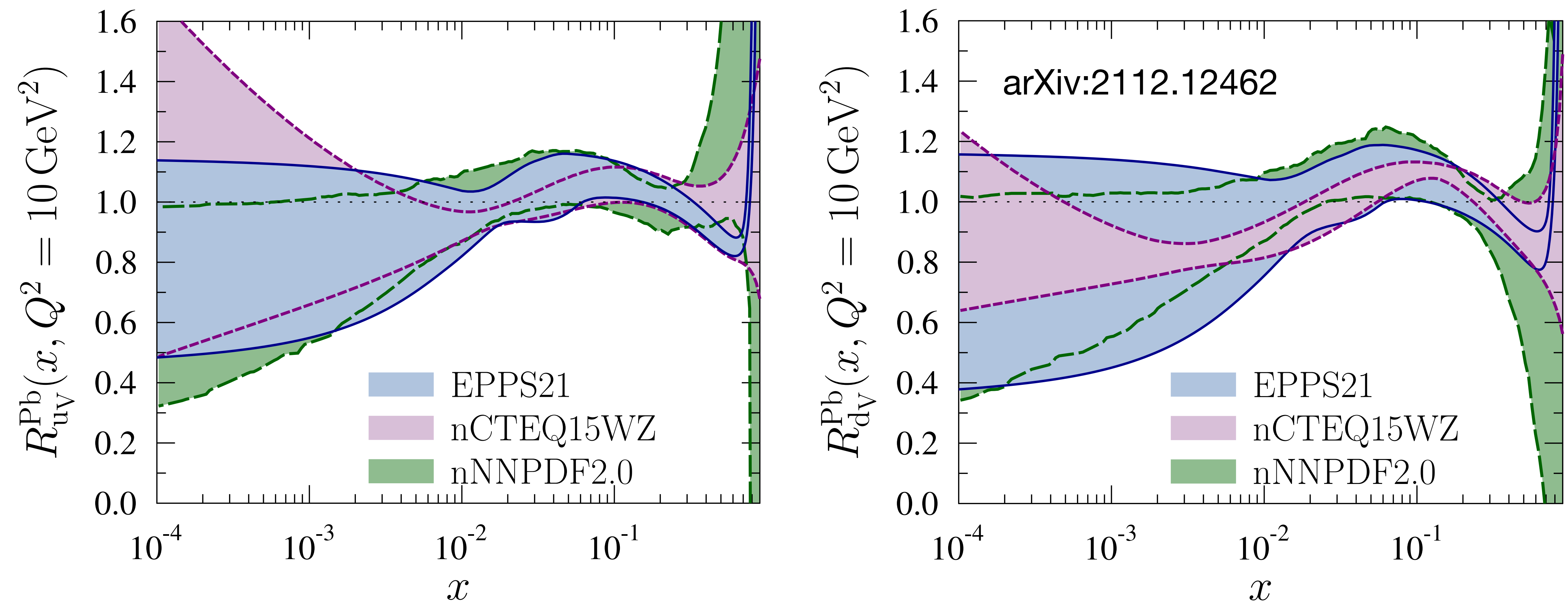

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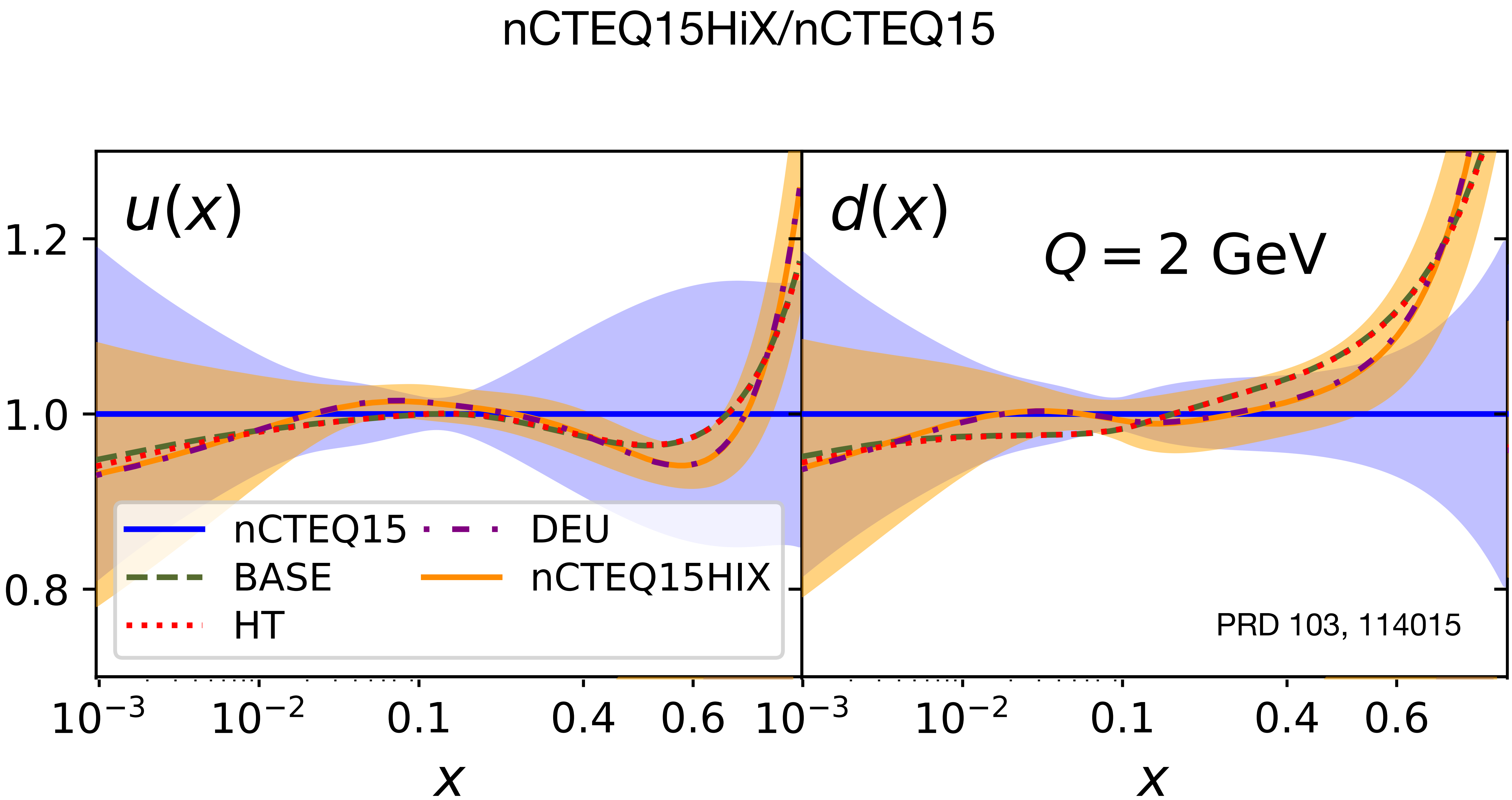
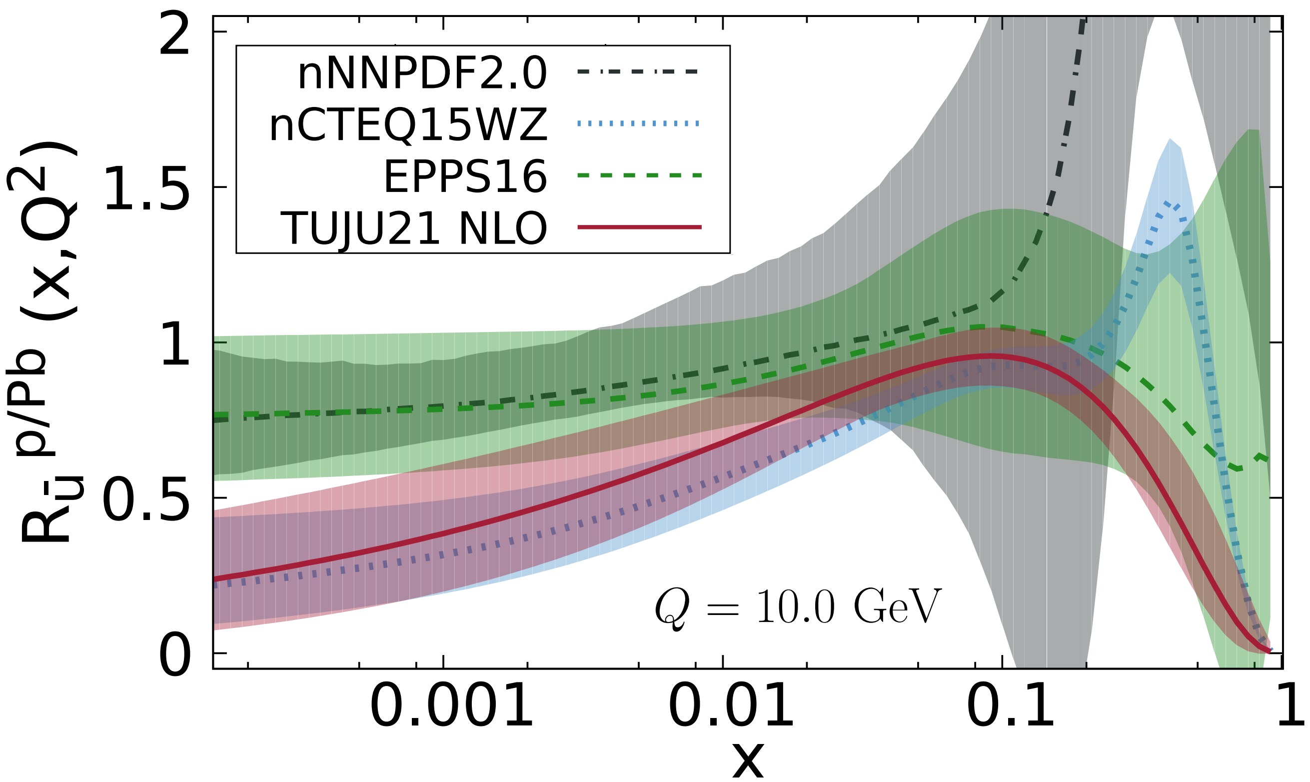


Comparing the latest sets: the sea quarks



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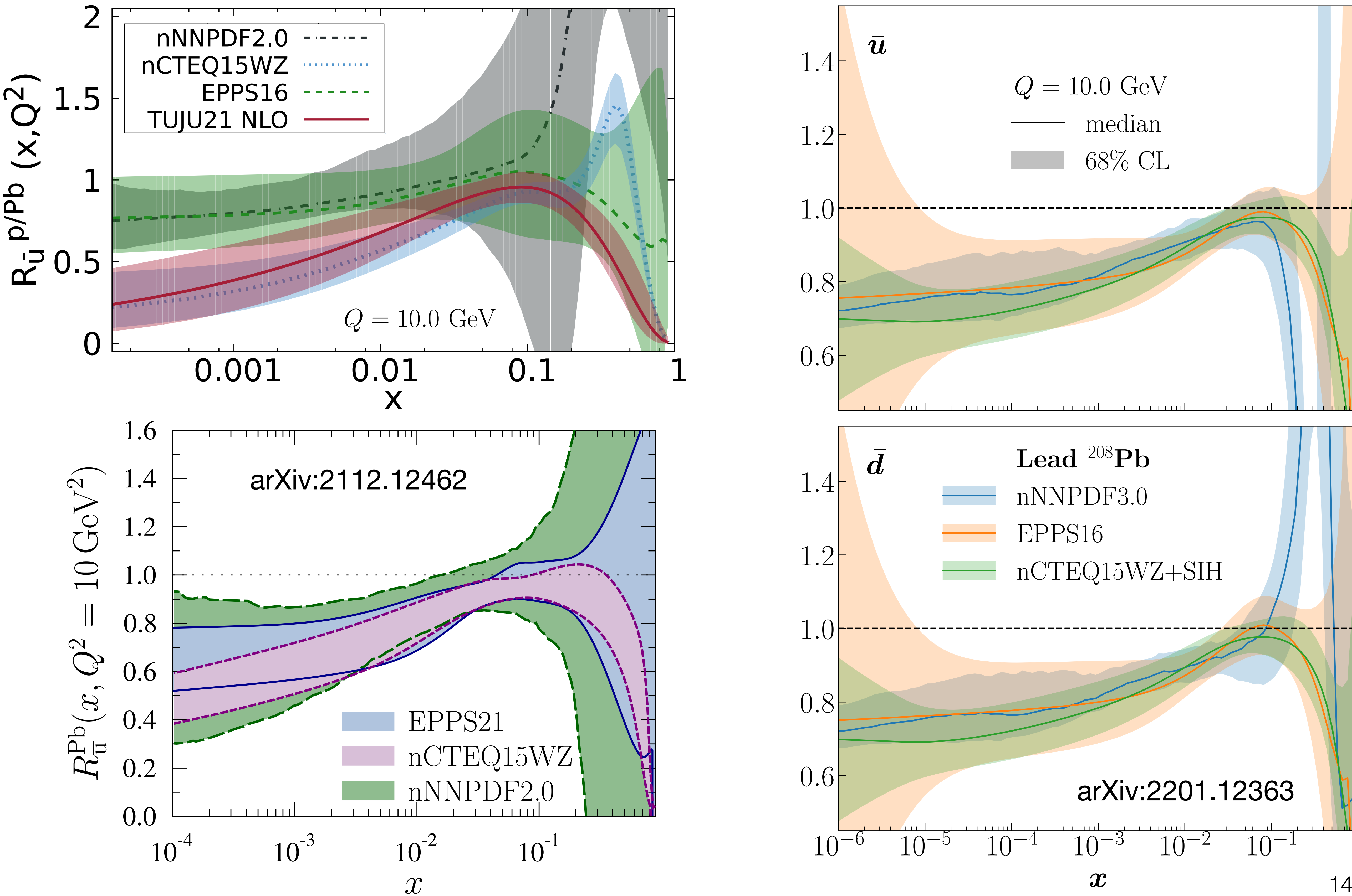
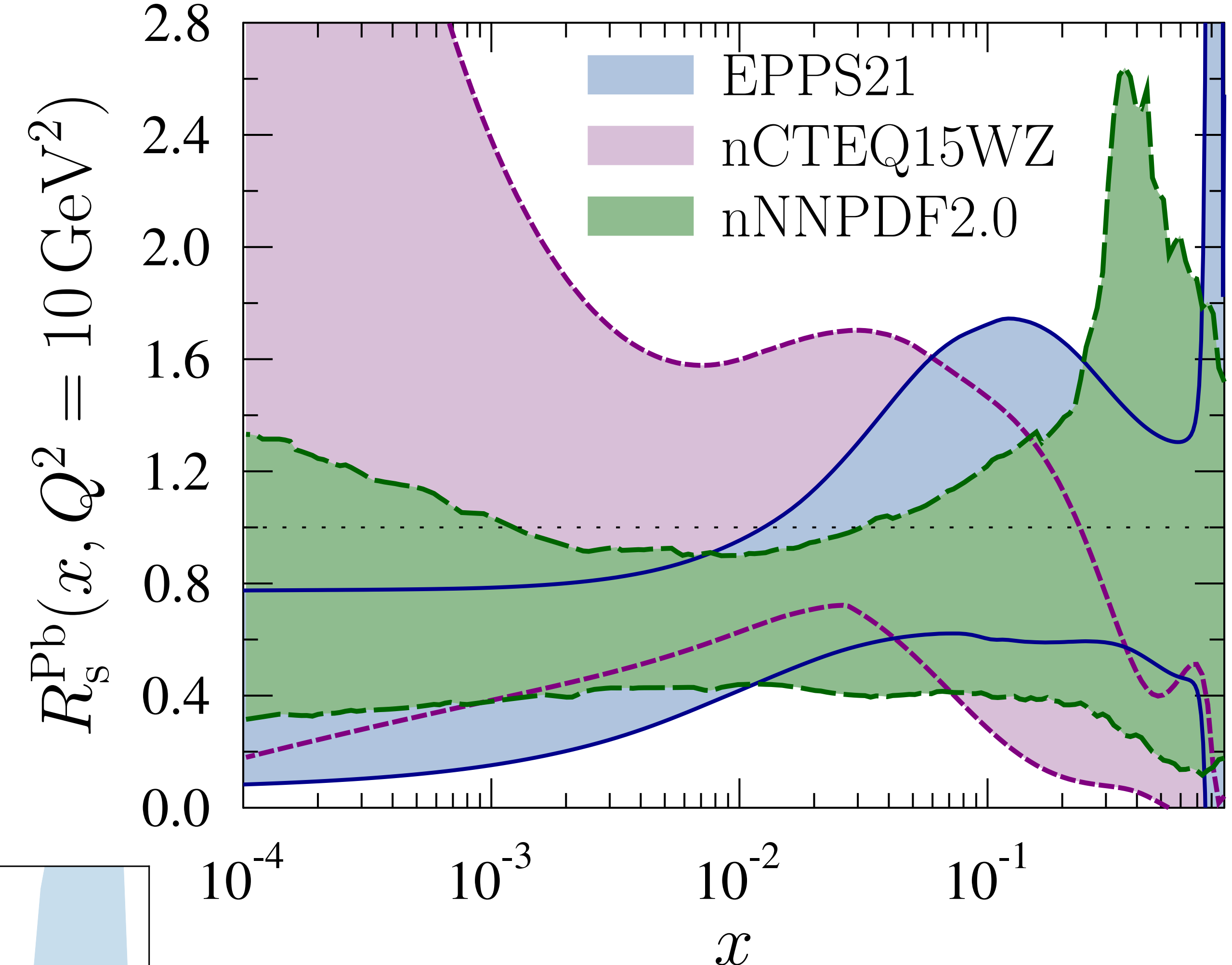
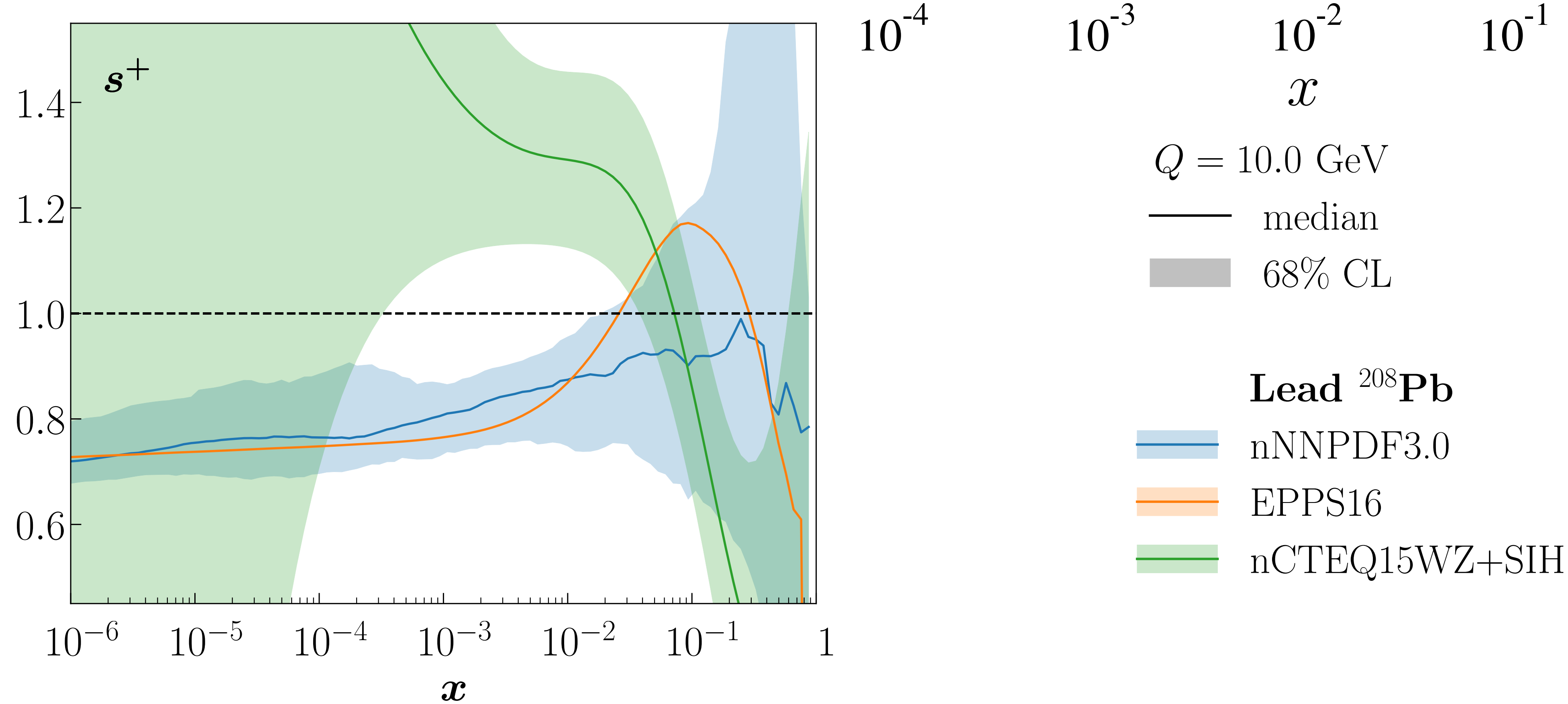
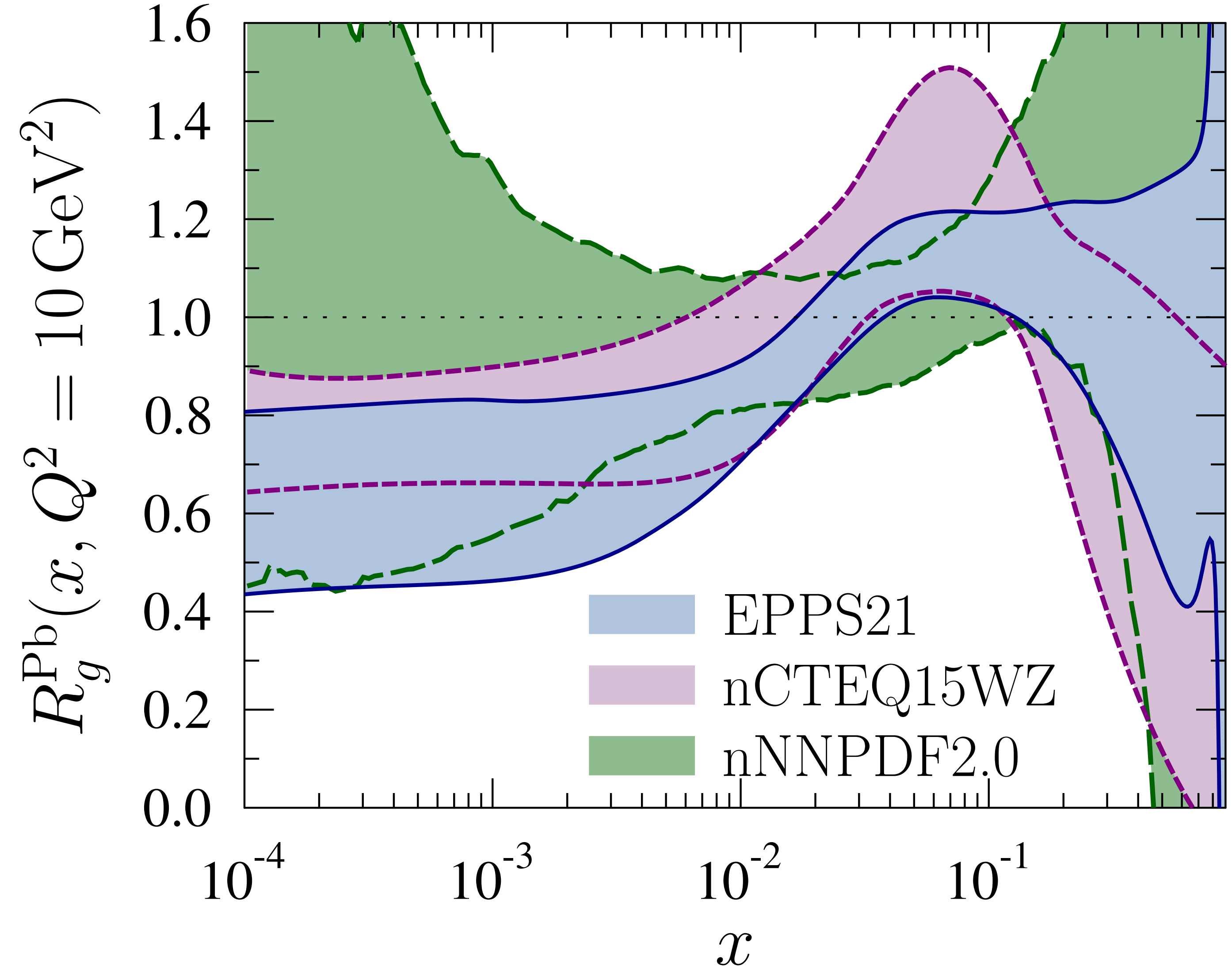


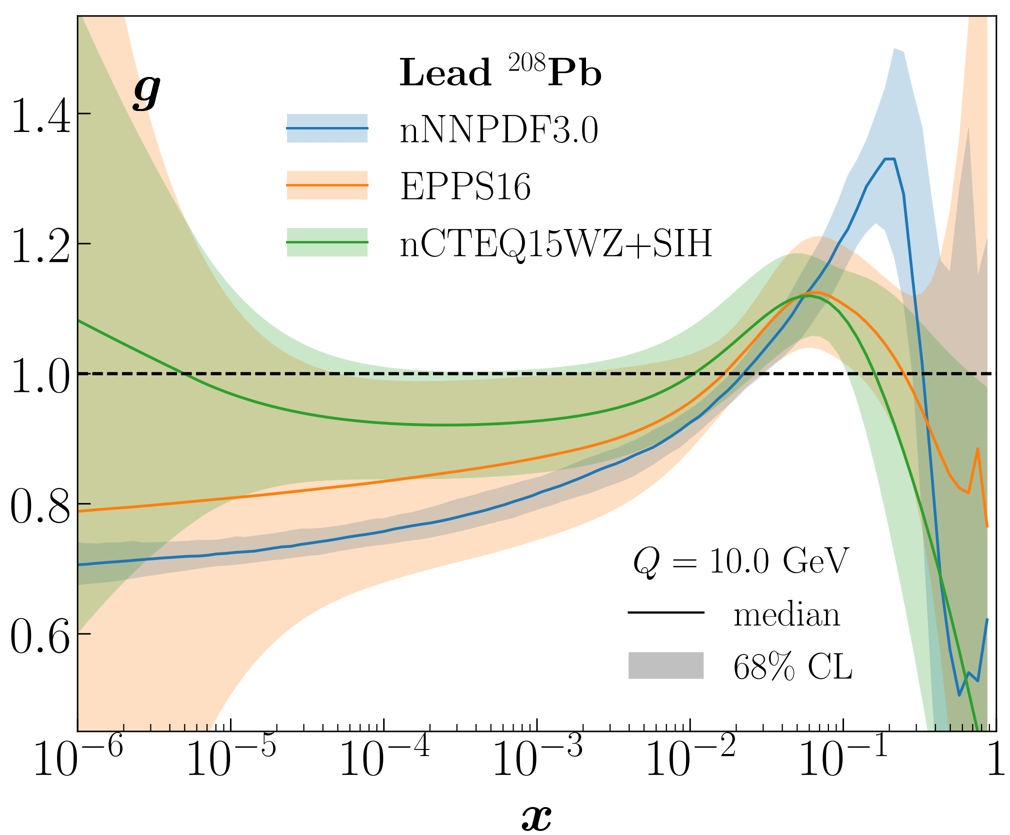
Comparing the latest sets: the strange quark

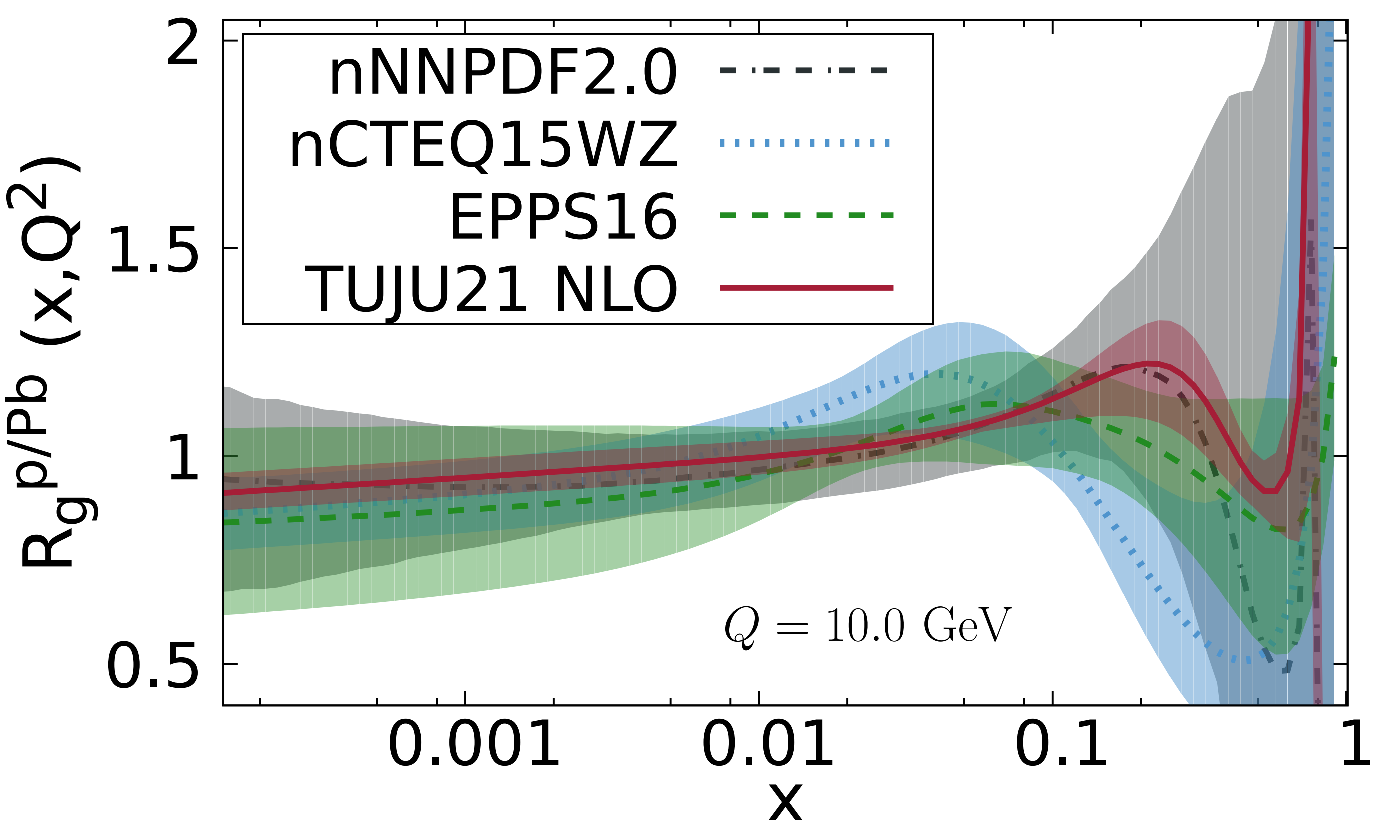




Comparing the latest sets: the gluon 😈







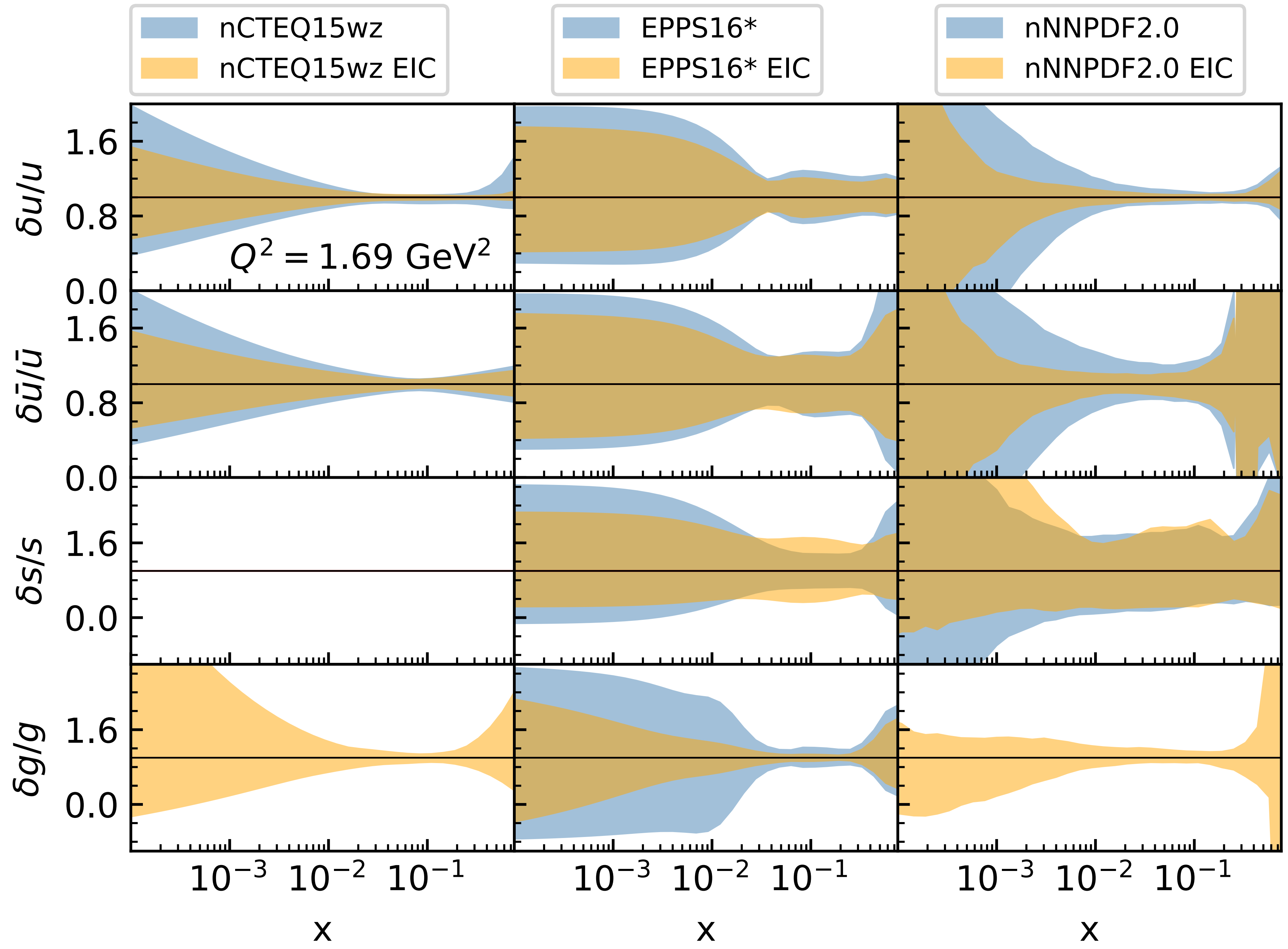
Improvements on nPDFs

- Add more data: LHC, JLAB, “new” data (e.g. DY in $\pi + A$).
- Add more observables: e.g. D meson production.
- Relax kinematic cuts.
- Seriously explore the issues in CC DIS.
- Carefully study the proton baseline.

Improvements on nPDFs

- Future experiments: EIC, LHeC, FCC-eh, AFTER?

EIC Yellow Report: arXiv:2103.05419



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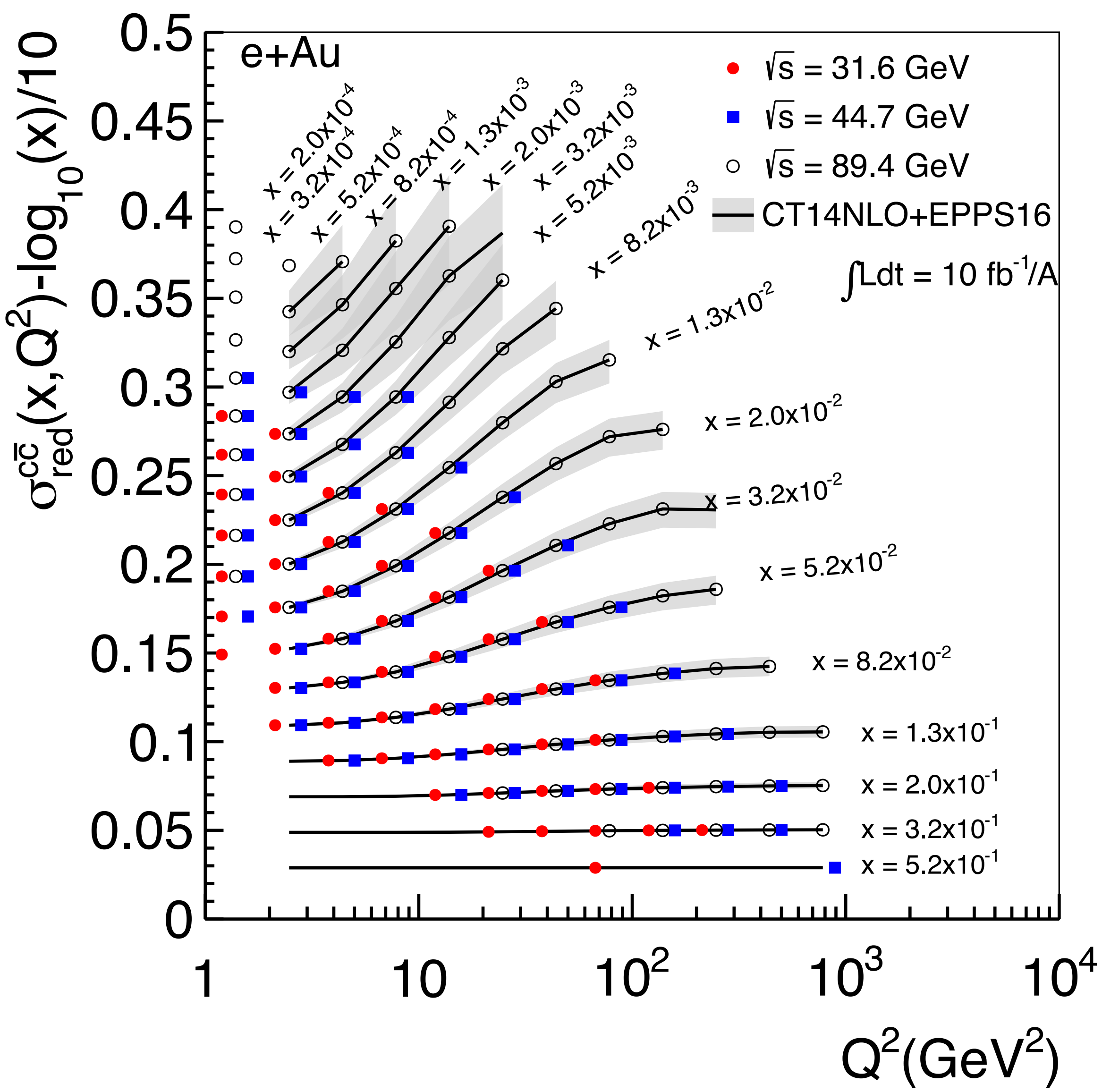

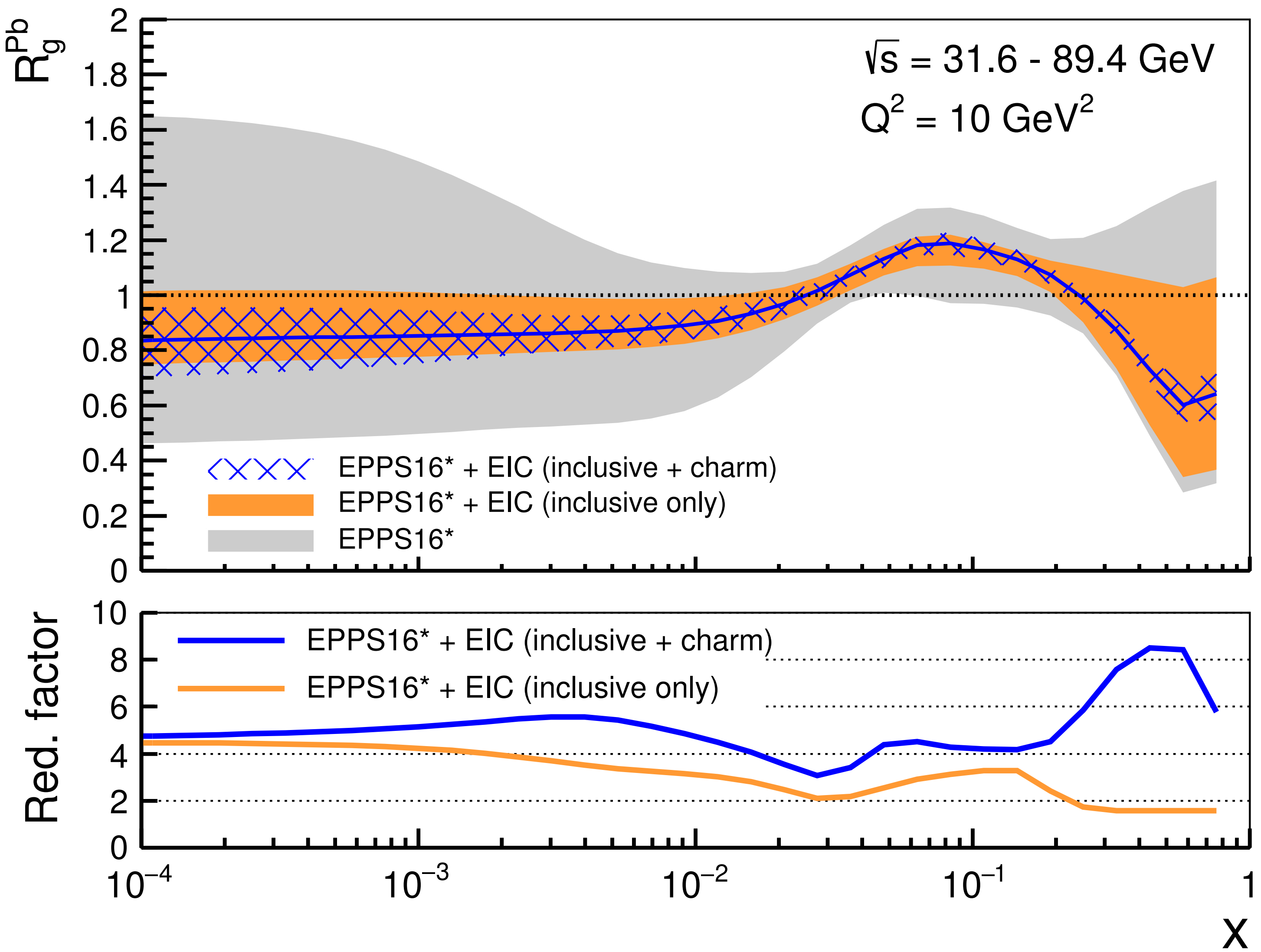

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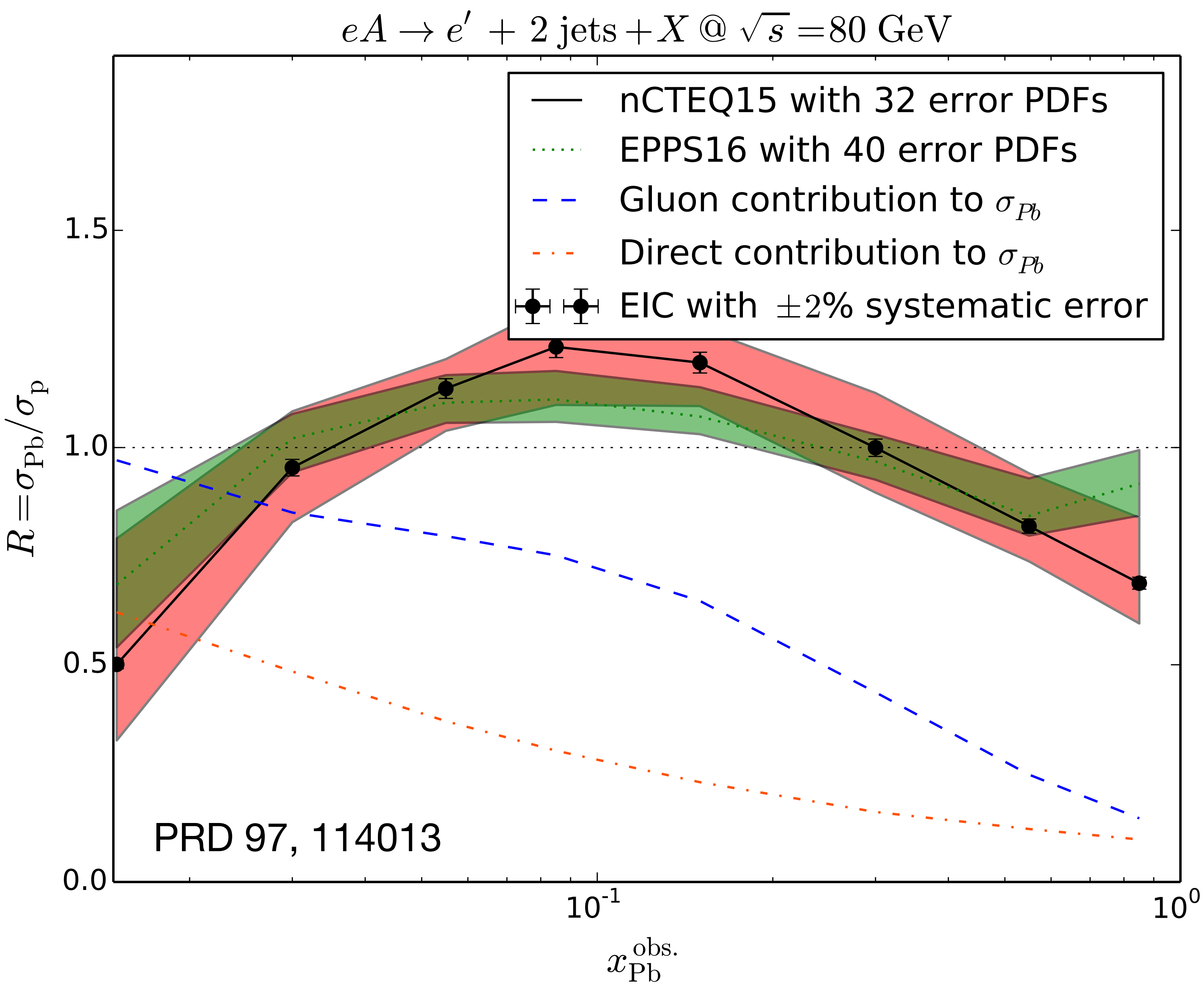

sensitivity to the gluon PDF at low and high x

Improvements on nPDFs

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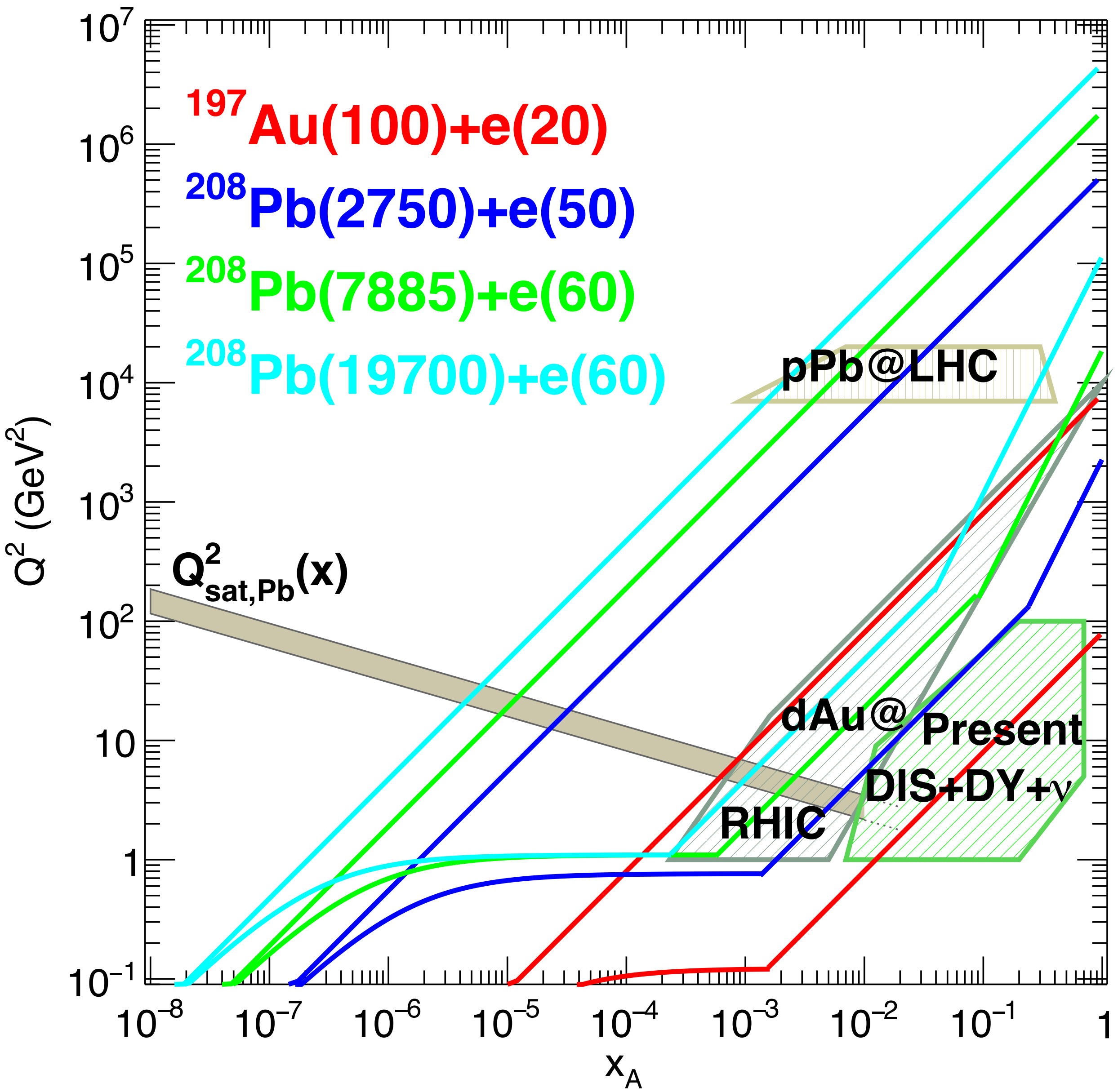
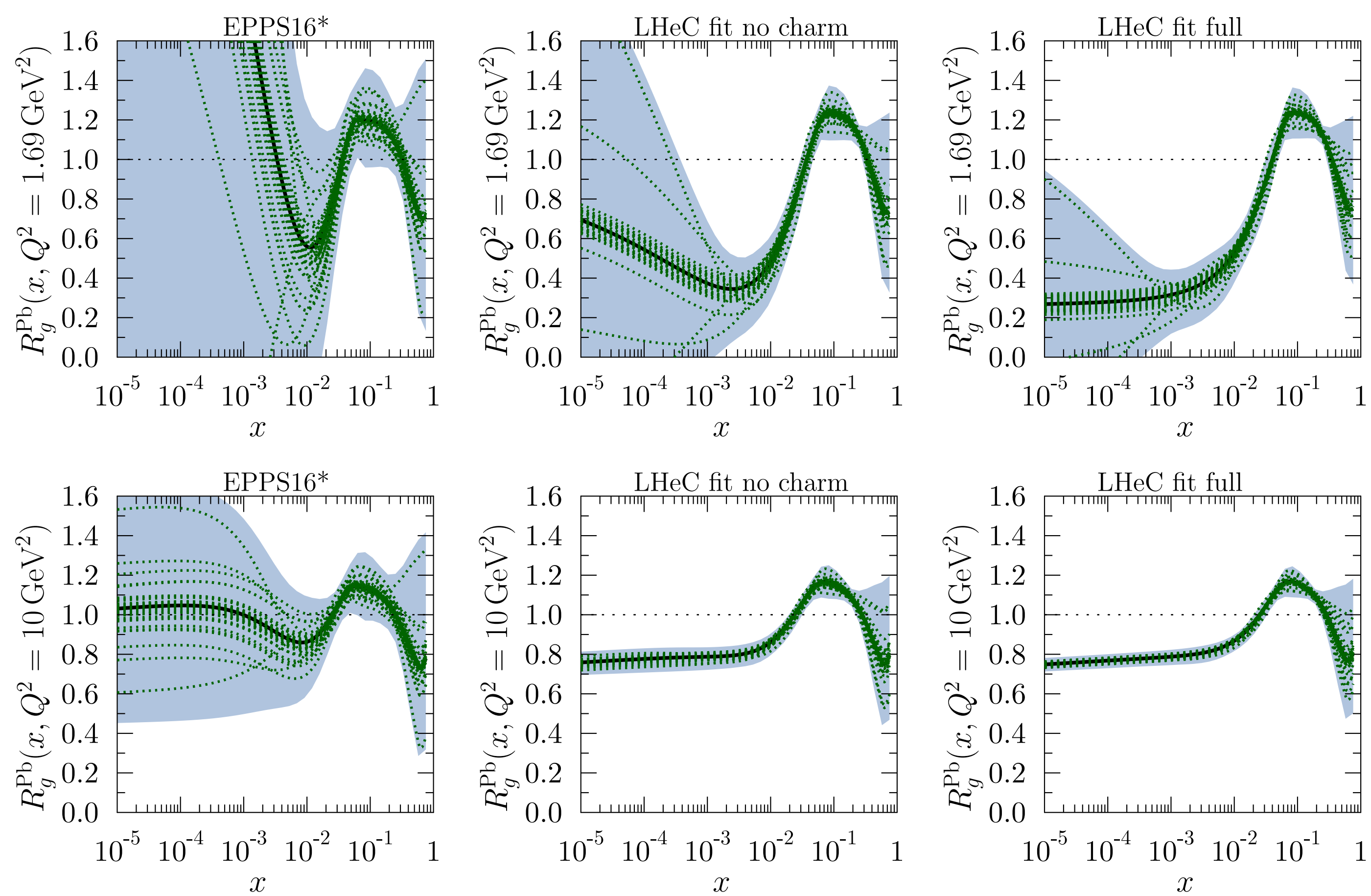
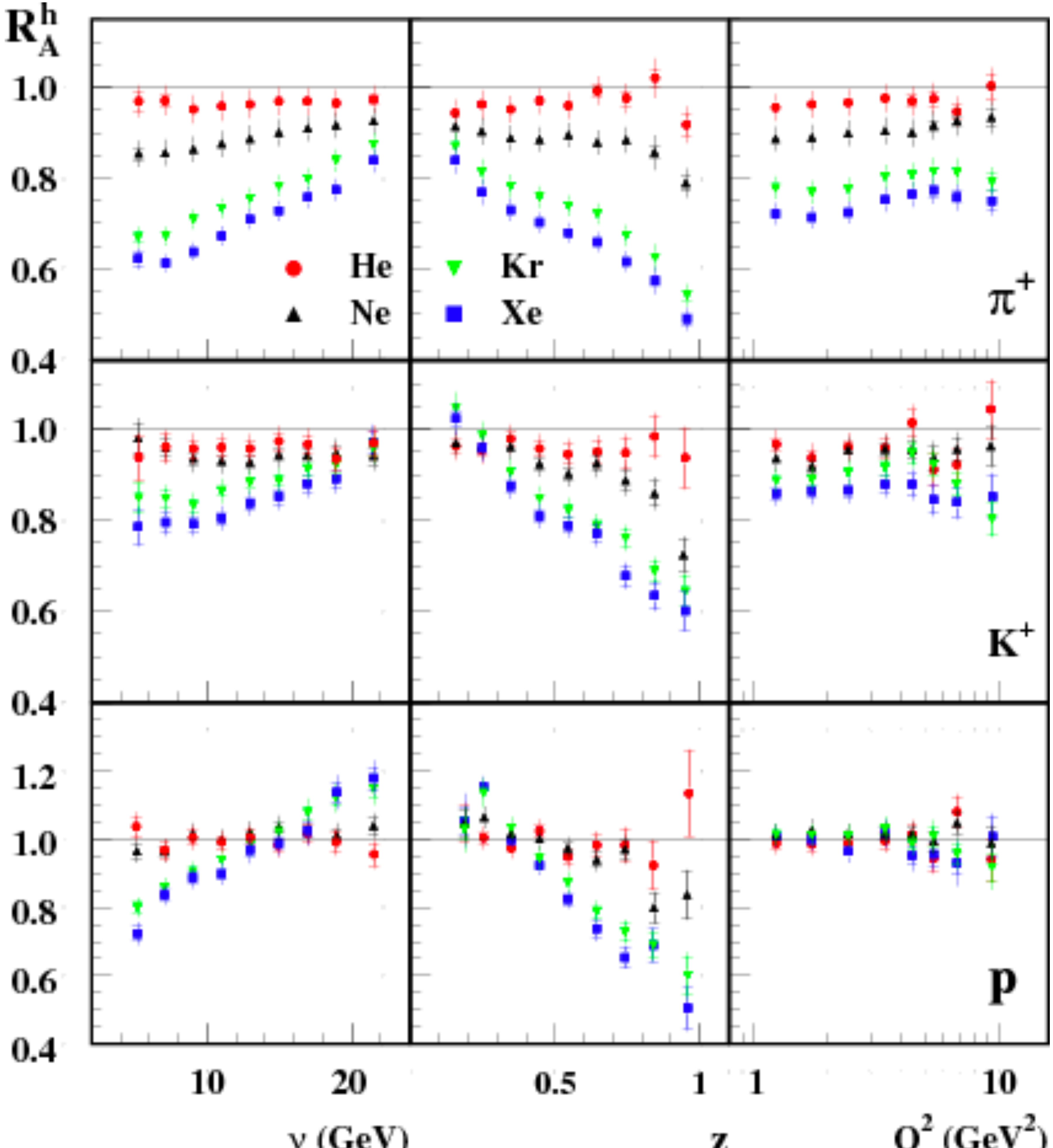




J.Phys.G 48, 110501

A possible issue with some observables

- What can be affected by final state effects?
    - SIH production.
    - D meson production.
    - Jets and di-jets.
- We know that in HI collisions there is jet-quenching, what about in p+A? e+A?
- SIH and D meson production depend on the FFs.
- FFs are extracted from SIA and SIDIS.
- We have seen medium modifications in SIDIS at low $\sqrt{s}$ but also at $\sqrt{s} \approx 30$ GeV.



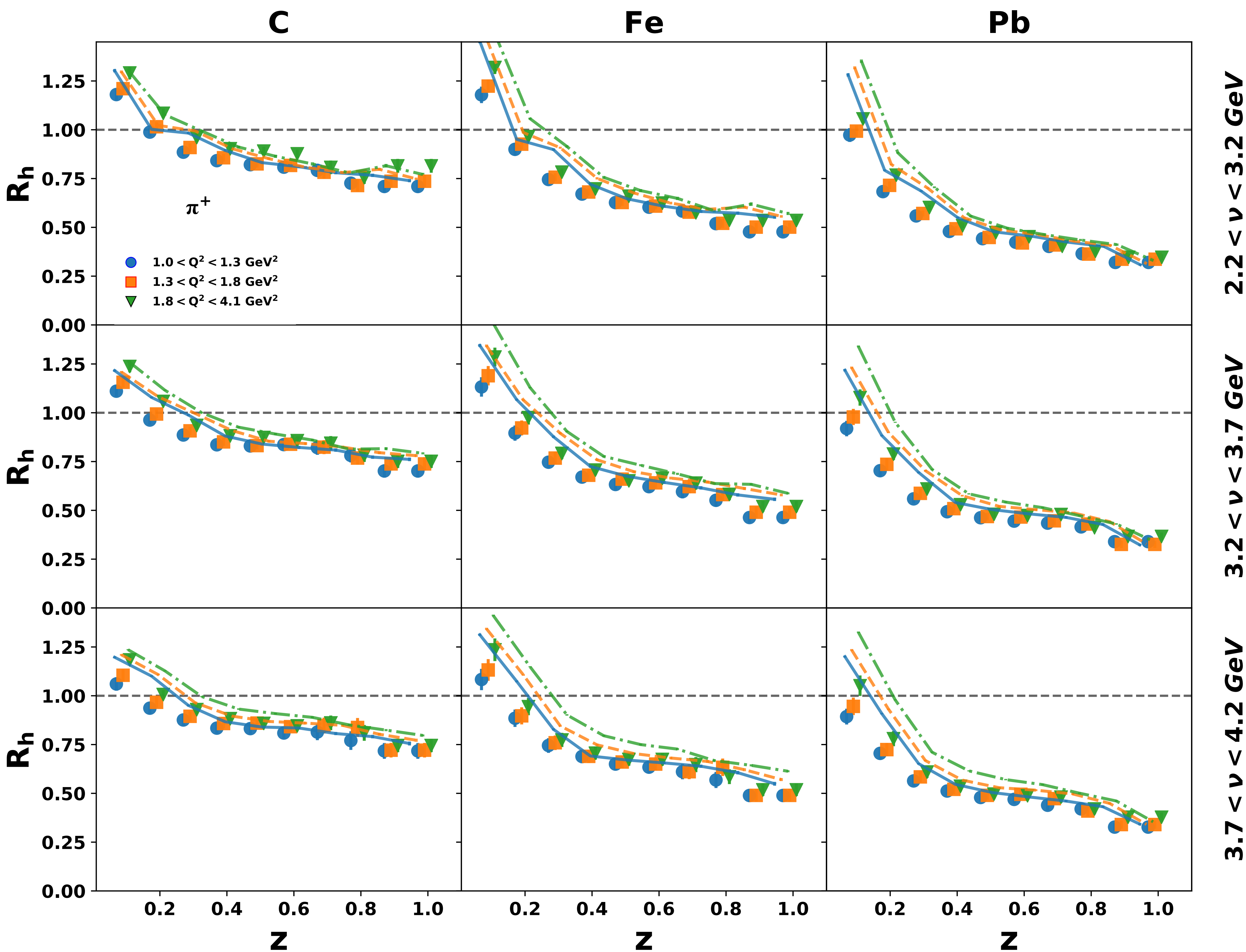
Nucl. Phys. B 780, 1.

E_{beam} = 27.6 GeV

A= D, He, N, Ne, Kr, Xe

PRC 105, 015201

E_{beam} = 5.014 GeV

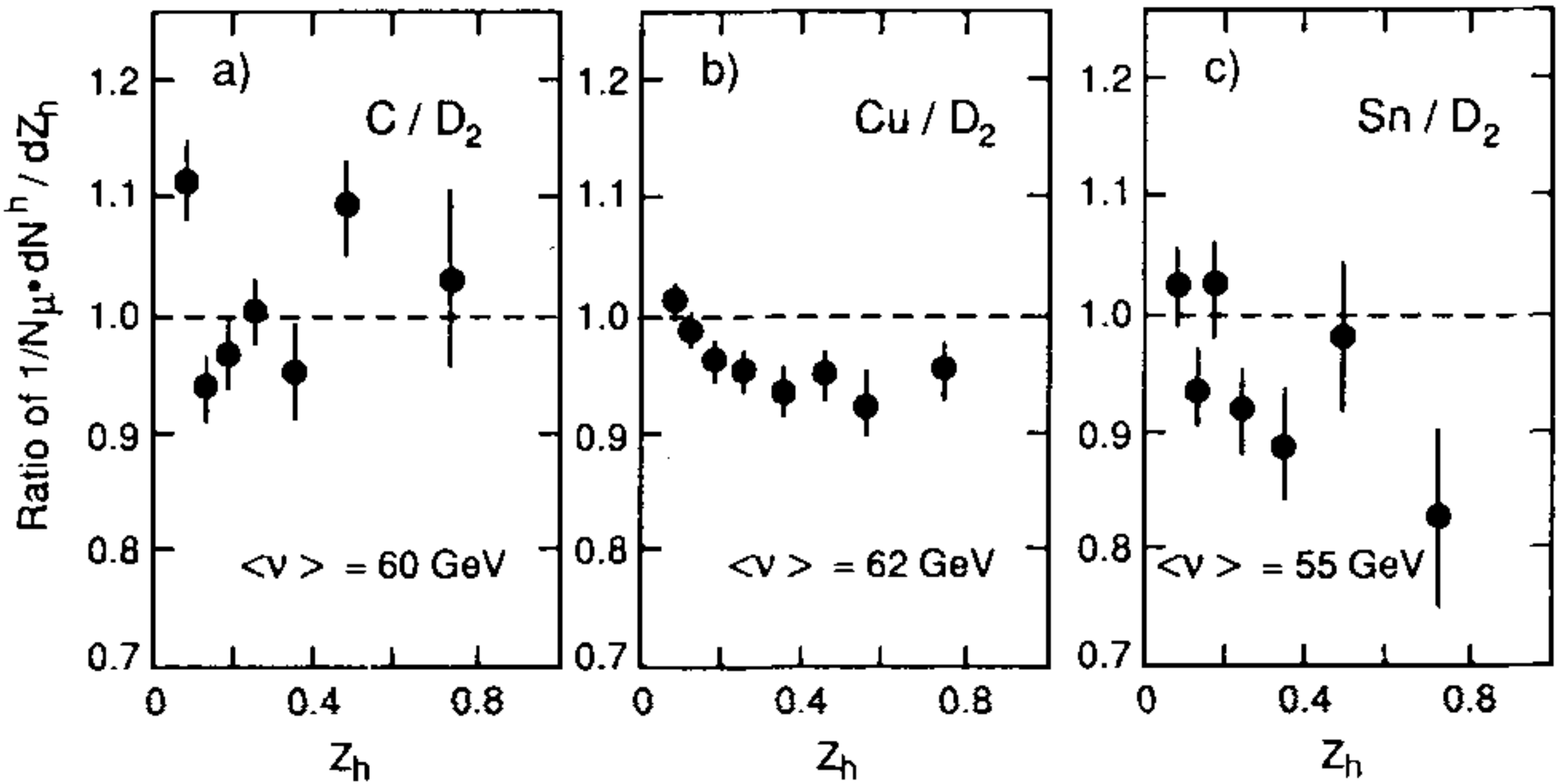


$\mu + A \to \mu + h^{\pm} + X$

A= D, C, Cu, Sn

E_{beam} = 100, 120, 200, 280 GeV

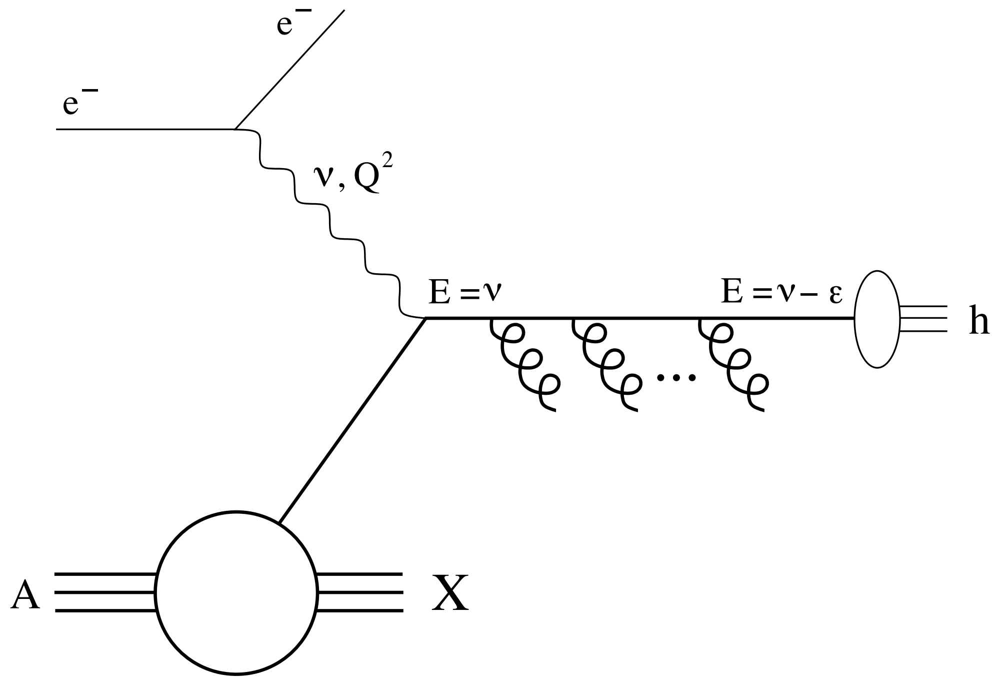
$$R_A^h(\nu, z, Q^2, p_t^2) = \frac{\left(\frac{N^h(\nu, z, Q^2, p_t^2)}{N^e(\nu, Q^2)}\right)_A}{\left(\frac{N^h(\nu, z, Q^2, p_t^2)}{N^e(\nu, Q^2)}\right)_D}$$



Z. Phys.C 52, 1.

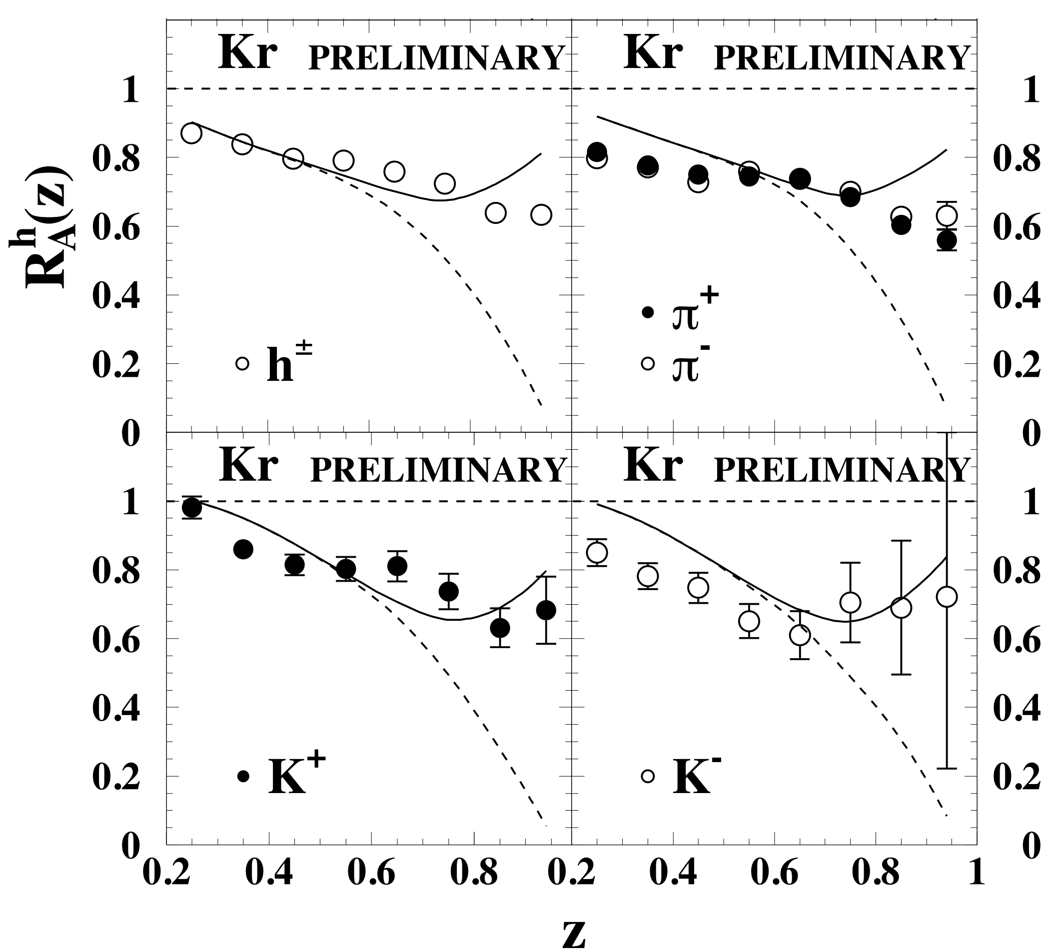
Some ideas in the market (not up-to-date)

- Energy loss



$$z = \frac{E_h}{\nu} \rightarrow z^* = \frac{E_h}{\nu - \epsilon} = \frac{z}{1 - \epsilon/\nu}$$

$$zD_q^h(z, Q^2, A) = \int_0^{\nu - E_h} d\epsilon \; D(\epsilon, \nu) \; z^* \, D_q^h(z^*, Q^2)$$



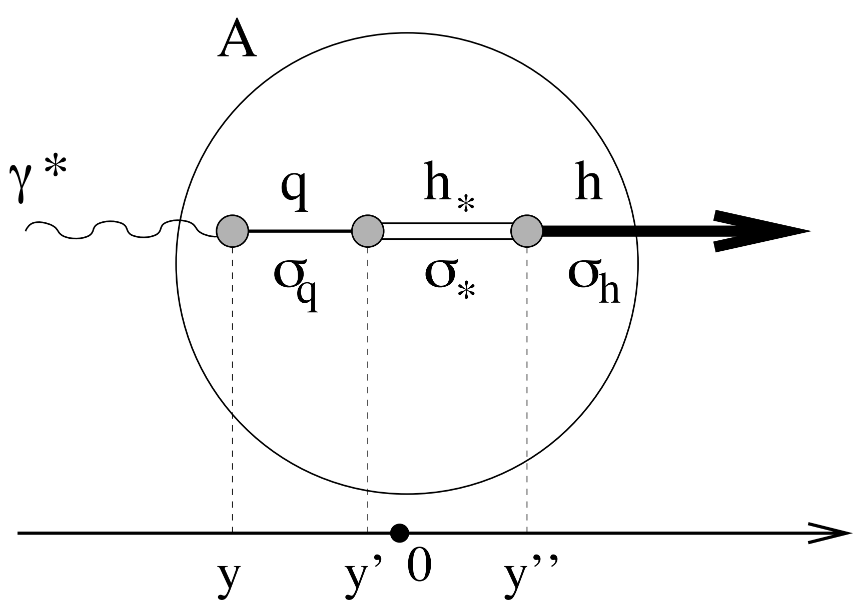
$D(\epsilon, \nu)$ depends on the length crossed by the parton and a coefficient that characterises the medium.

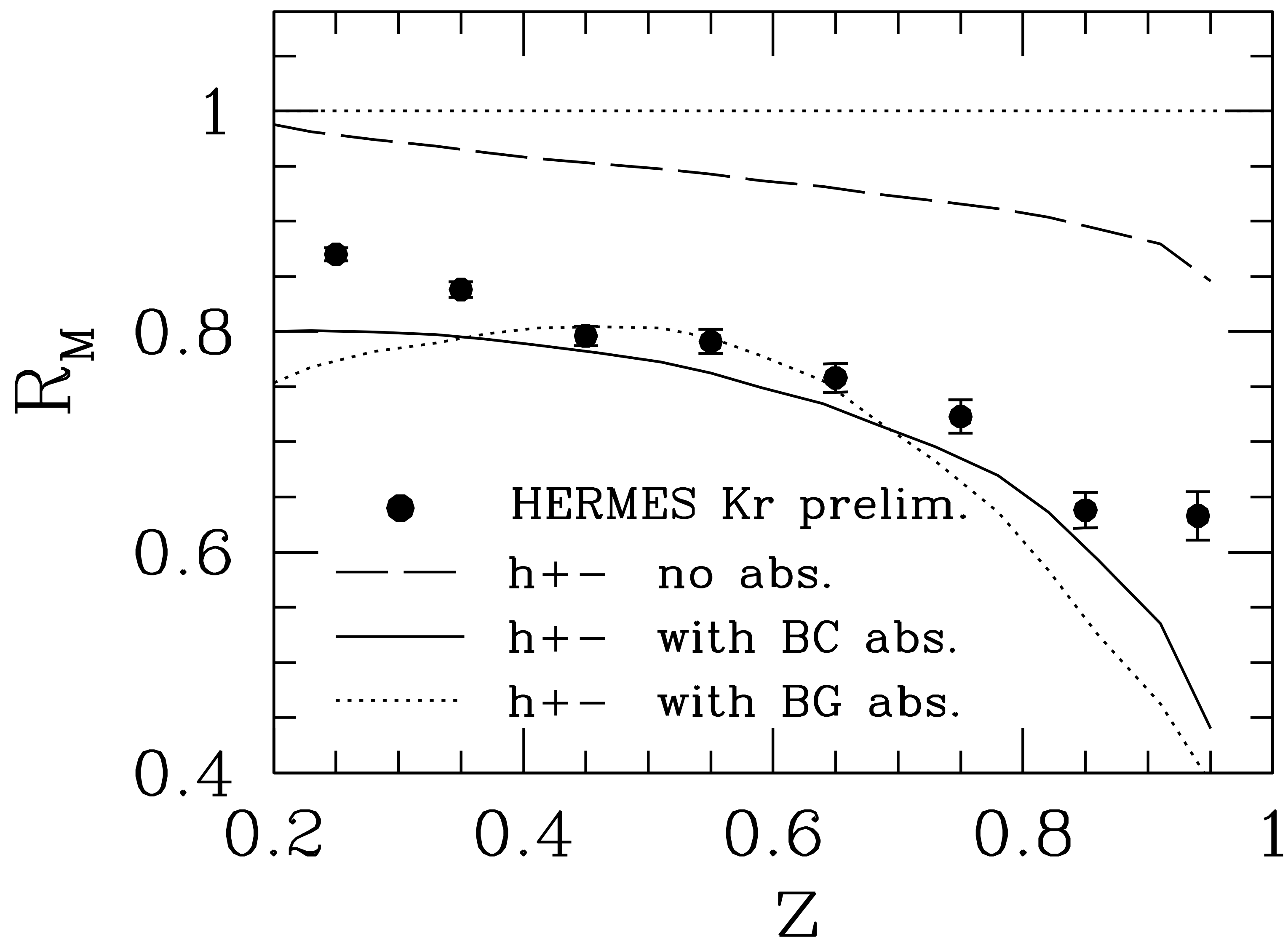
EPJC 30, 213. EPJC 76, 475.

Some ideas in the market (not up-to-date)

- Nuclear absorption

NPA 720, 131.





quark
pre-hadron
hadron

$$\frac{1}{N_A^{DIS}}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\ell A}}\int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x, \xi_A\, Q^2)\, \frac{d\sigma^{\ell q}}{dx\, d\nu}\, D_f^h(z, \xi_A\, Q^2)\, \mathcal{N}_A(z,\nu)$$

Let's go phenomenological

- If FFs are "similar" to PDFs… why not have something akin to nPDFs for the final state?

- Introduce the idea of a purely phenomenological nFF.

    - If we can't fit the data, then we might be wrong.
    - If we can fit the data, then we might not be right.

- Just go back to my initial slides and change "(n)PDF" by "(n)FF".

- Extra issues:

    - Less data.
    - Higher complexity of the observable than FFs (e.g. need PDFs and nPDFs).

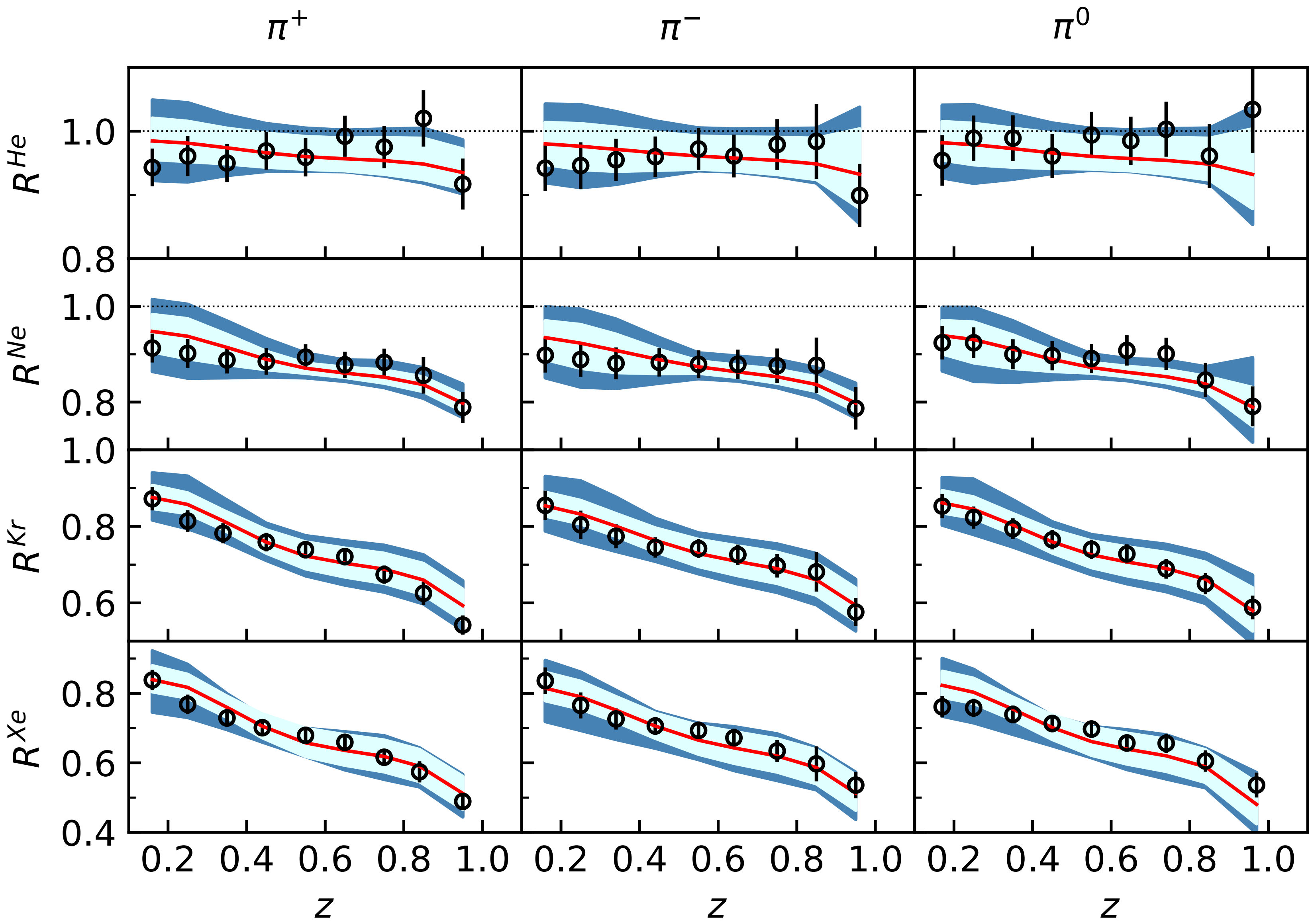
Fitting

- Baseline FFs: DEHSS (PRD 91, 014035).

$$D_i^h(z,Q_0) = N_i x^{\alpha_i}(1-x)^{\beta_i}\Big[1+\gamma_i(1-x)^{\delta_i}\Big]$$

$$N_i \to N_i\Big[1+\mathbf{N_{1,i}}(1-A^{\mathbf{N_{2,i}}})\Big]$$

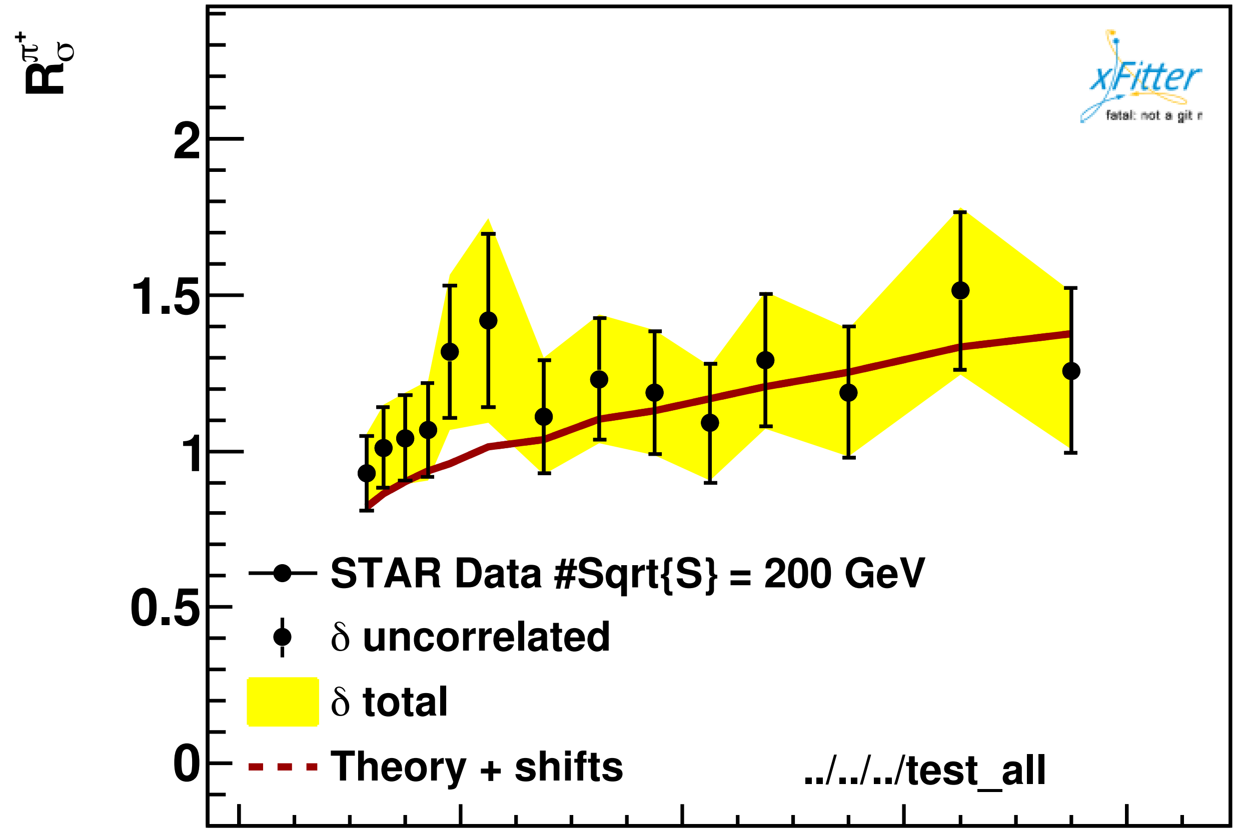
$$p_i \to p_i+\mathbf{p_{1,i}}(1-A^{\mathbf{p_{2,i}}})$$

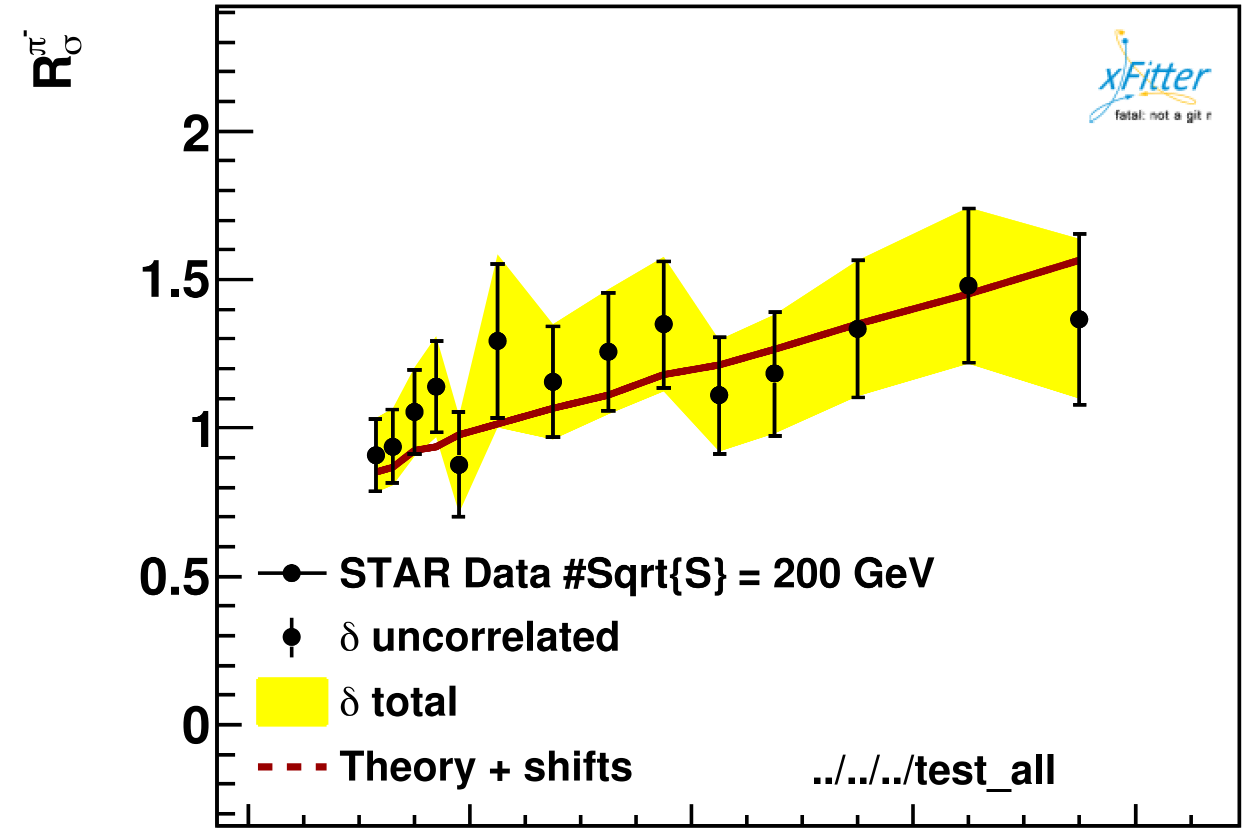


- Proton PDFs only (initial effect cancels in the ratio).
- 7 parameters
- $\chi^2/d.o.f. = 0.776.$
- No control over the gluon.

arXiv:2101.01088

Constraining the gluon: add RHIC data.





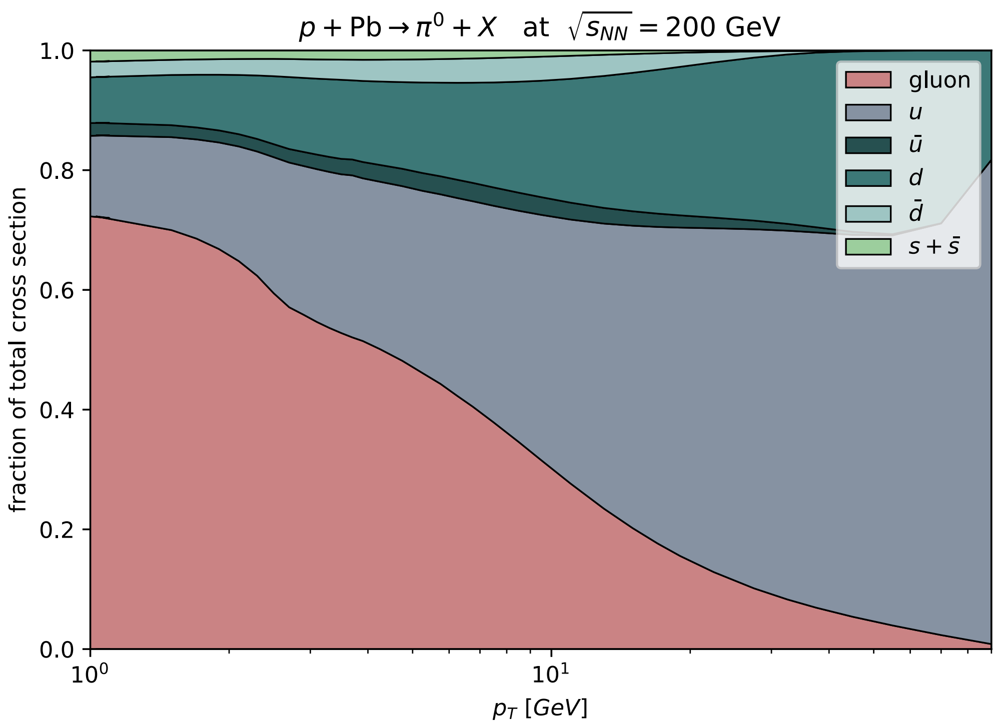
- χ^2 similar to those obtained in nPDFs fits.
- Is it a pure initial/final (or both) state effect?

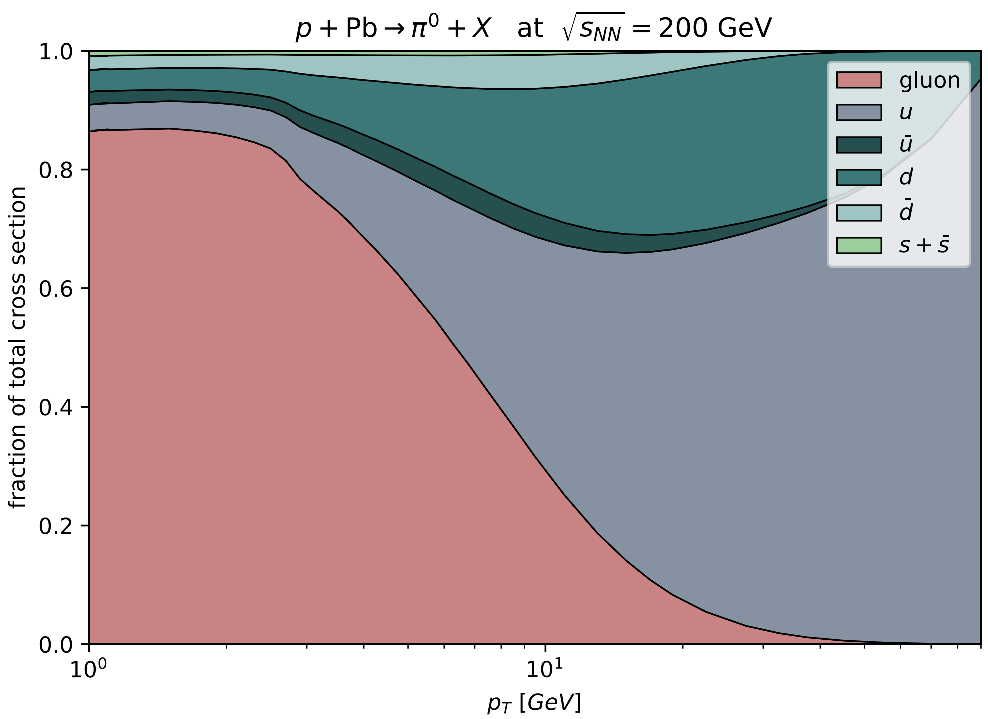
Experiment	Nº points	χ^2
STAR π^0	13	4.65
STAR π^-	15	7.51
STAR π^+	15	11.29

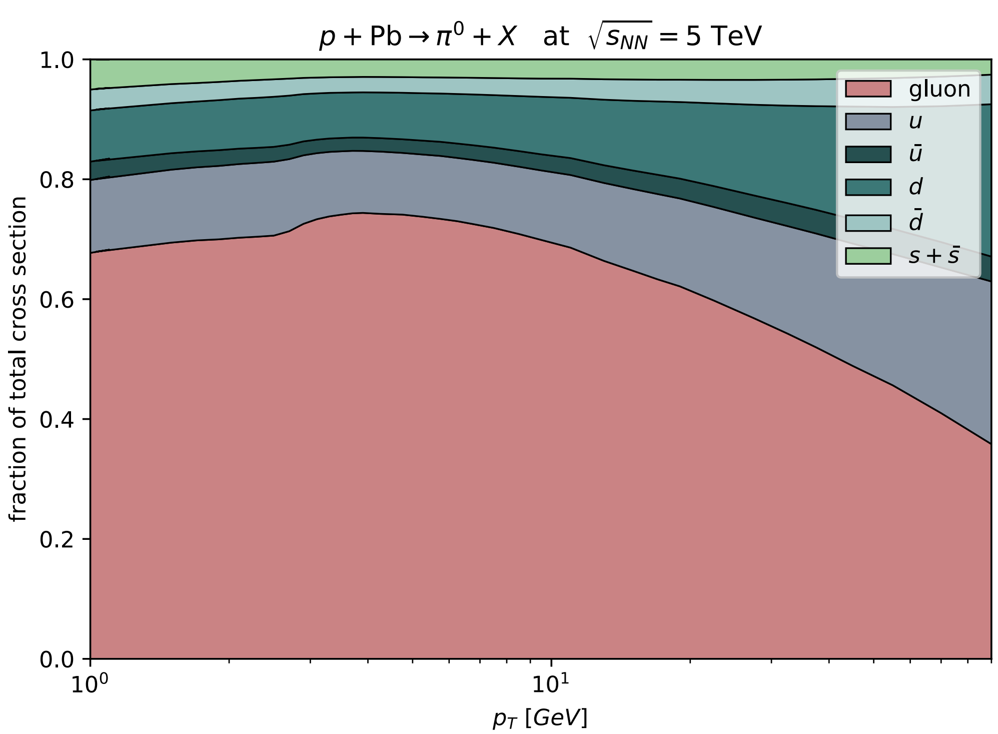
contribution of each PDF

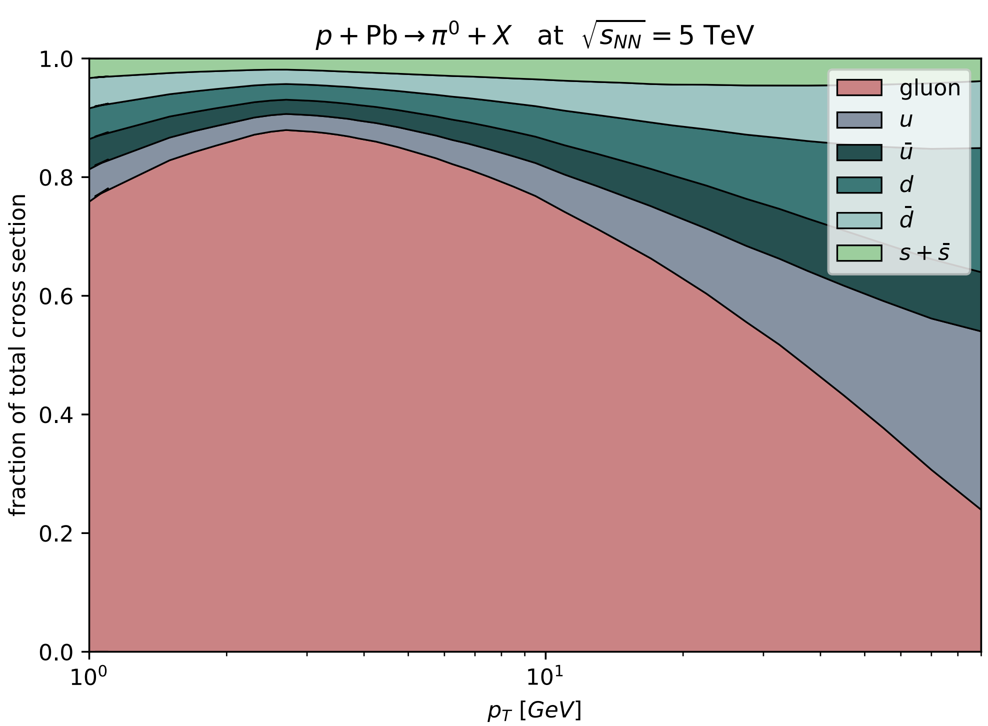
contribution of each FF

PRD 104, 094005.









Summary

- Initial state effects:

    - are a **must** for proton and nuclear observables.
    - there are great researchers working on them 😉, new ideas and new/“new” data coming into the game.
    - can be described by nPDFs (not the only way!).
    - nPDFs use the same framework as proton PDFs.
    - nPDFs are much behind proton PDFs, but **soon*** the EIC (and hopefully other facilities) will help us catch up.
    - many different sets of nPDFs available for use. All “good” and in constant improvement.

* Time is relative.

Summary

- Final state nuclear effects:
  - they exist, but most of the data comes from HI collisions (QGP+CNM).
  - SIDIS data are scarcer, and nuclear effects in SIDIS are under-explored.
  - there are many different approaches, and they all give reasonable descriptions of the data.
  - one possibility is to use nFFs, equivalent to nPDFs.
  - **But be careful**! We can fit data $\neq$ correct physics.

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  - one possibility is to use nFFs, equivalent to nPDFs.
  - **But be careful**! We can fit data $\neq$ correct physics.

Beware! To properly interpret calculations done with any set of parton distributions, you must know the details!