FRAGMENTATION FUNCTIONS IN NUCLEAR MEDIA

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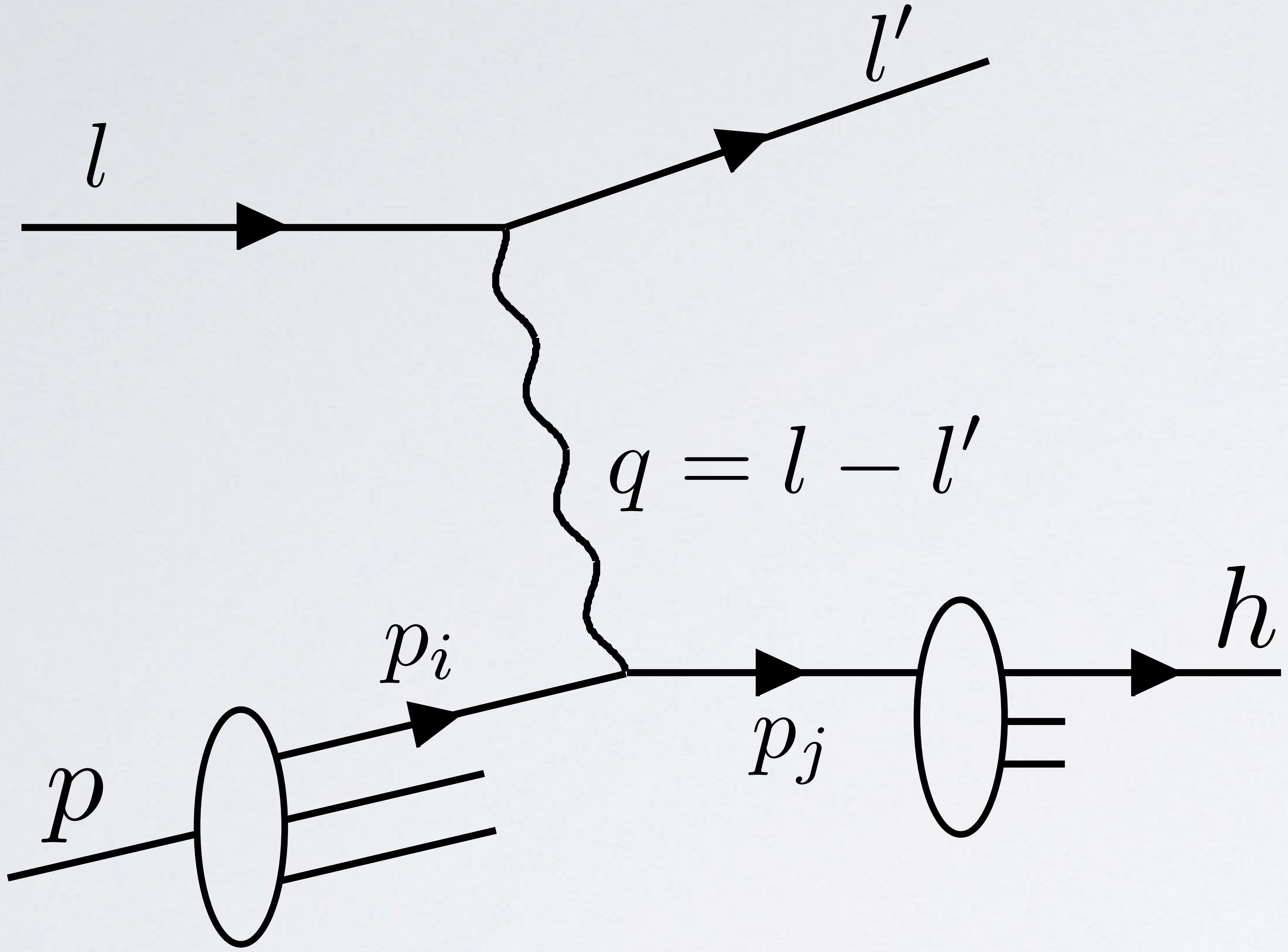
HUGS, June 2024

Semi Inclusive Deep Inelastic Scattering (SIDIS)



$$e^- + p \rightarrow e^- + h + X$$

Factorization Theorem

$$\sigma_{ep\rightarrow e'hX} = \sum_{i,j} f_i(x, \mu_{f'}) \otimes \hat{\sigma}_{ep_i\rightarrow e'p_j} \otimes D_j^h(z, \mu_{f'})$$

PDF — *Parton Distribution Function*

FF — *Fragmentation Function*

What happens in nuclear media?

For example: **Nuclear DIS** $e^- + A \to e^- + X$

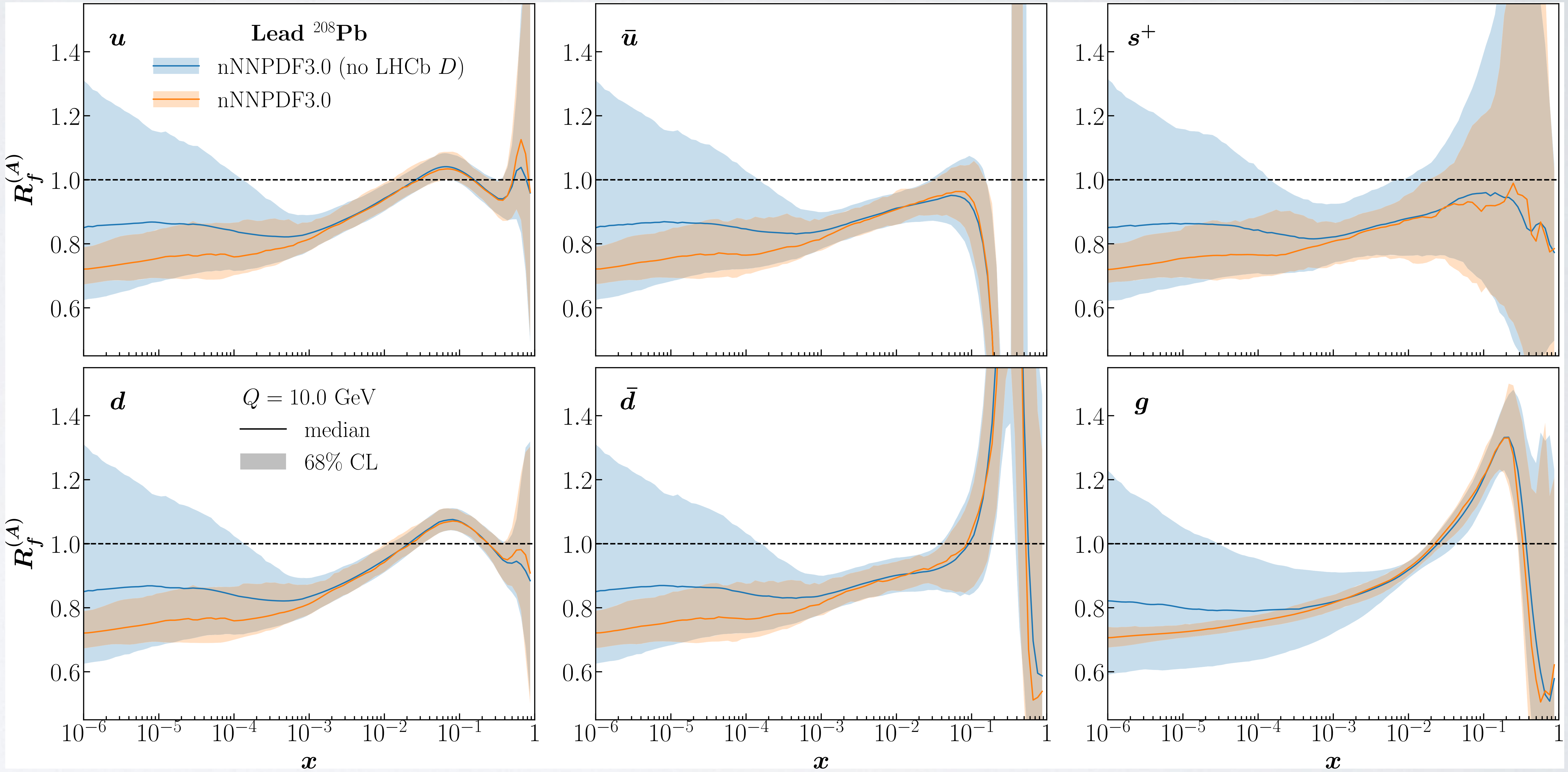
Nuclear PDF

$$R_f^{(A)}(x, Q) \equiv \frac{f^{(p/A)}(x, Q)}{f^{(p)}(x, Q)}$$

Vacuum PDF

Initial-state nuclear effects can be effectively factorized into **nuclear PDFs (nPDFs)**

nNNPDF3.0



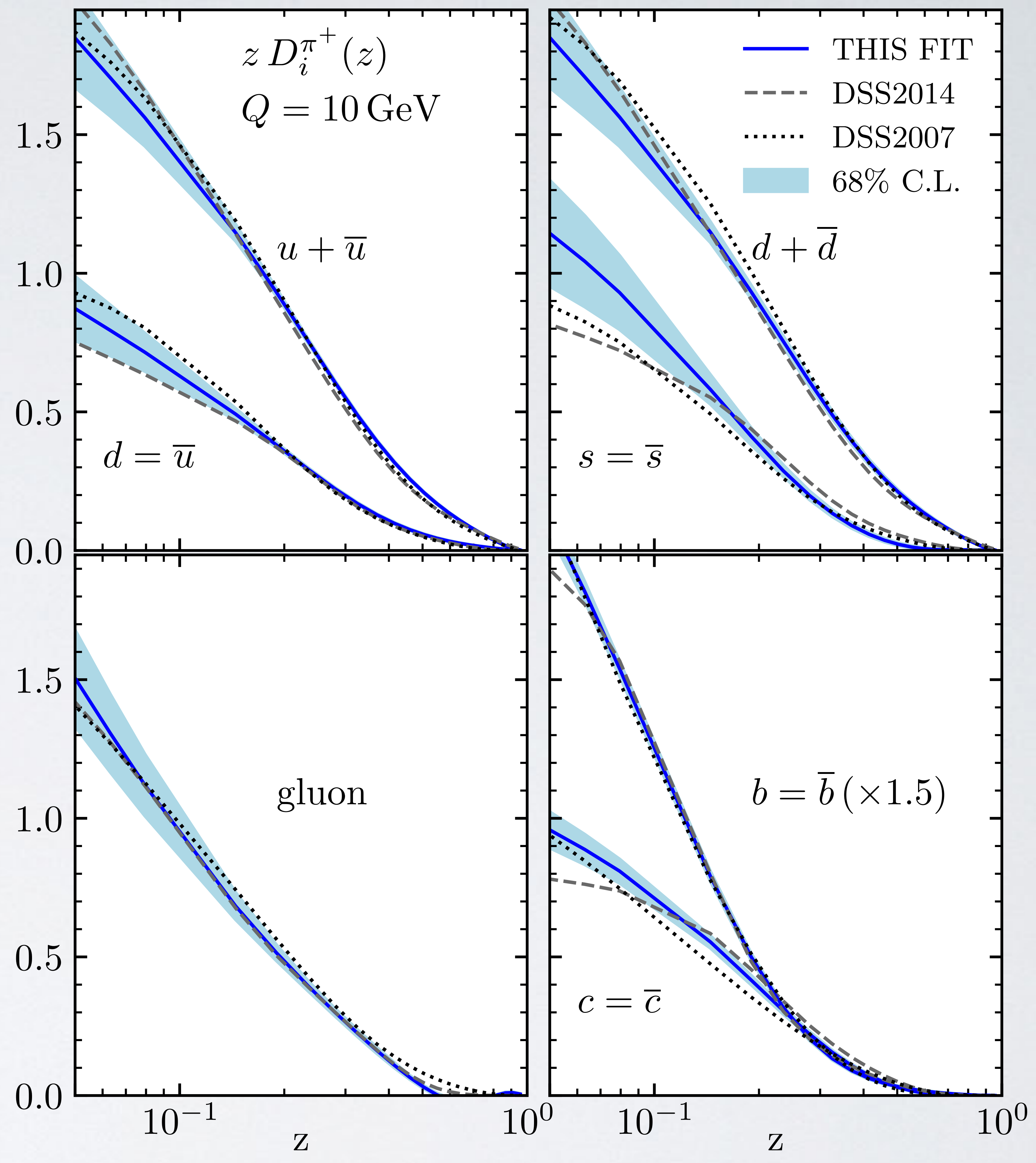
arxiv.org/pdf/2201.12363

What about Fragmentation Functions FF?

$$P_{\text{hadron}} = z\,P_{\text{parton}}$$

$z =$ momentum fraction

Vacuum Fragmentation Functions



I. Borsa, R. Sassot, D. de Florian, M. Stratmann
arXiv: 2110.14015

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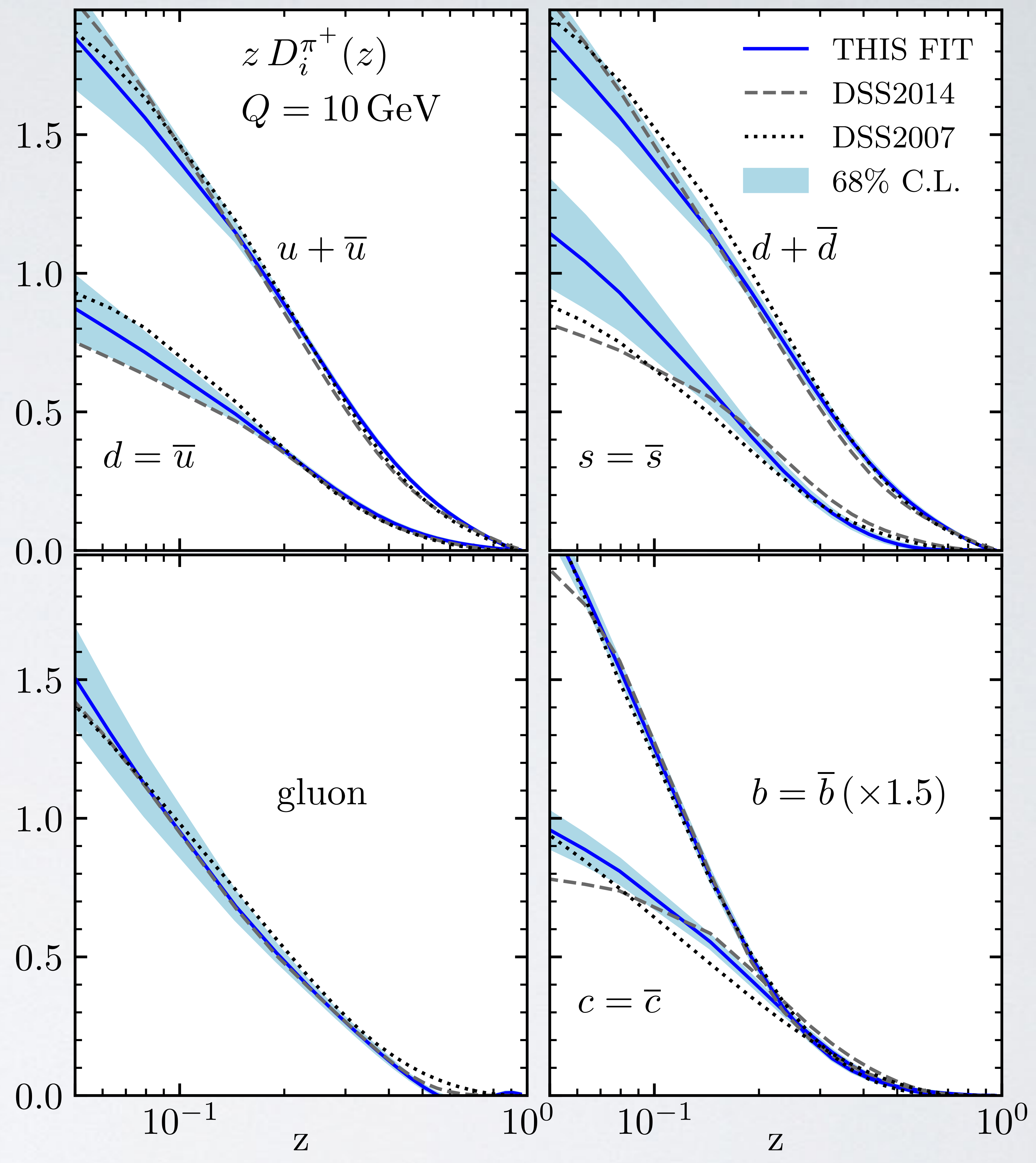
Vacuum Fragmentation Functions



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What about Fragmentation Functions FF?

$$P_{\text{hadron}} = z\, P_{\text{parton}}$$

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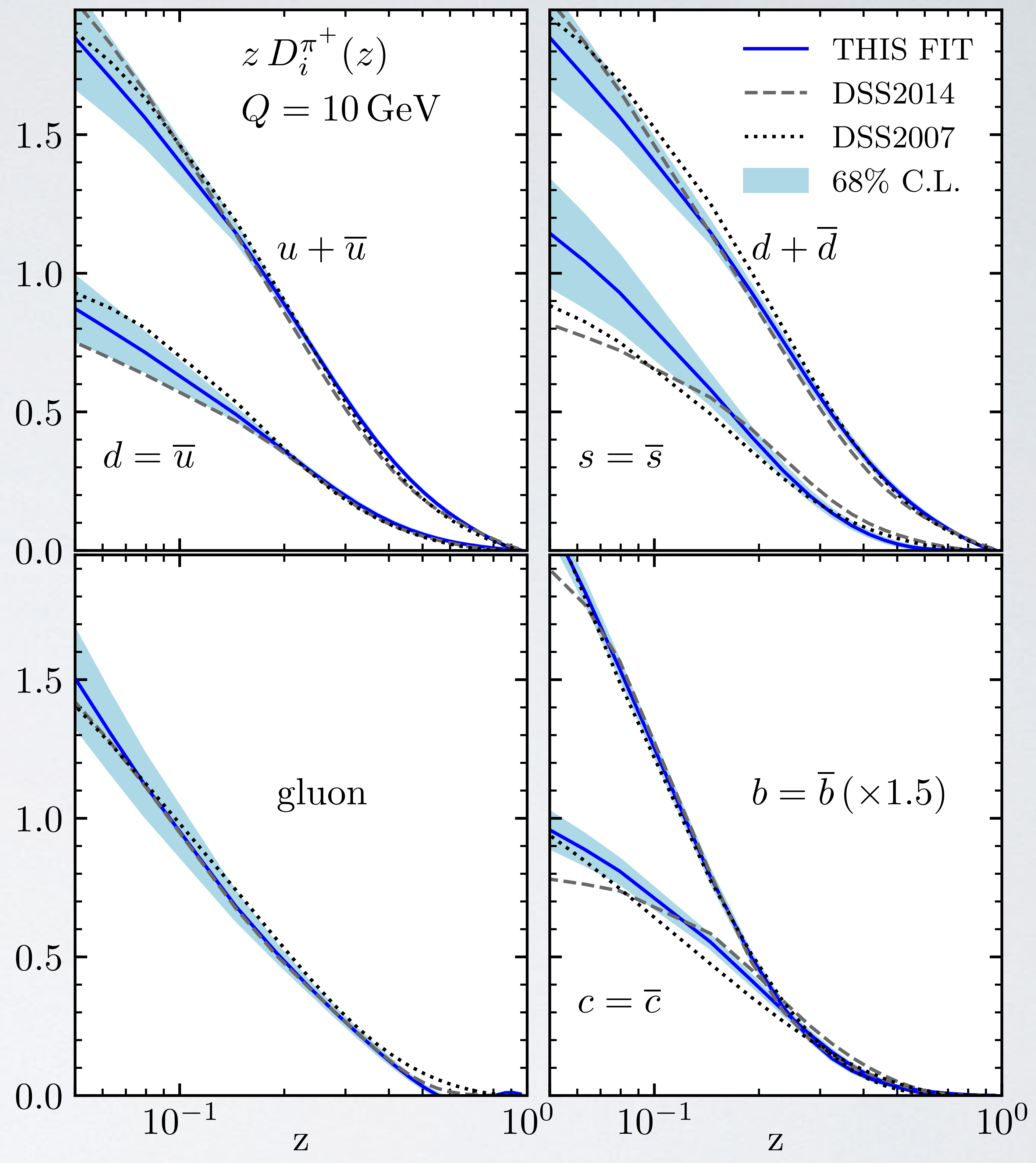
- What happened with the hadronization when it takes place in a nuclear media?
- Is it necessary to take into account **final-state** nuclear effects?

Vacuum Fragmentation Functions



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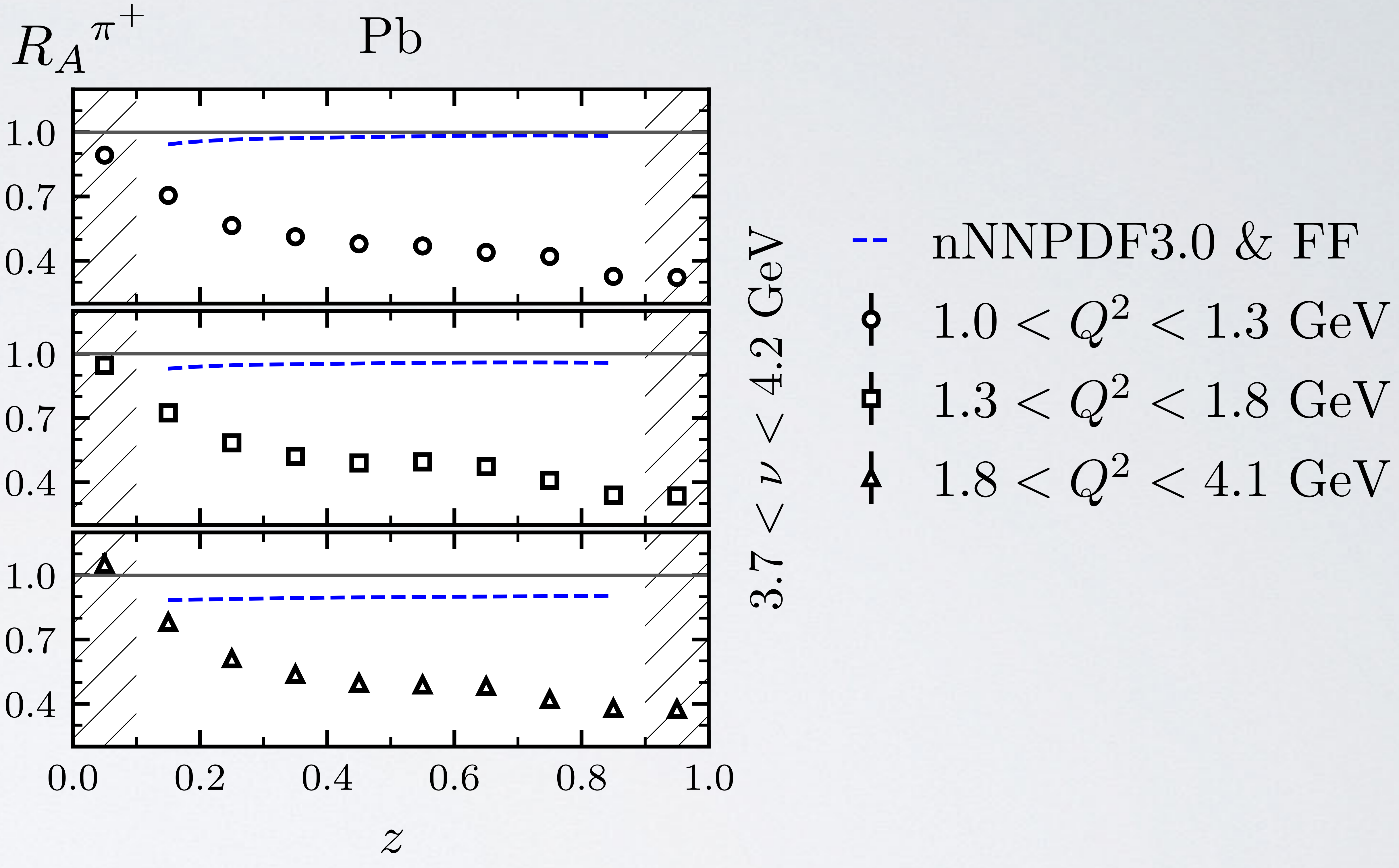
Final-state nuclear effects?

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

$\nu = E_e - E_{e'}$ (Proton rest frame)

A : Mass number



CLAS collaboration at JLab

5.014 GeV electron beam

data from arXiv: 2109.09951

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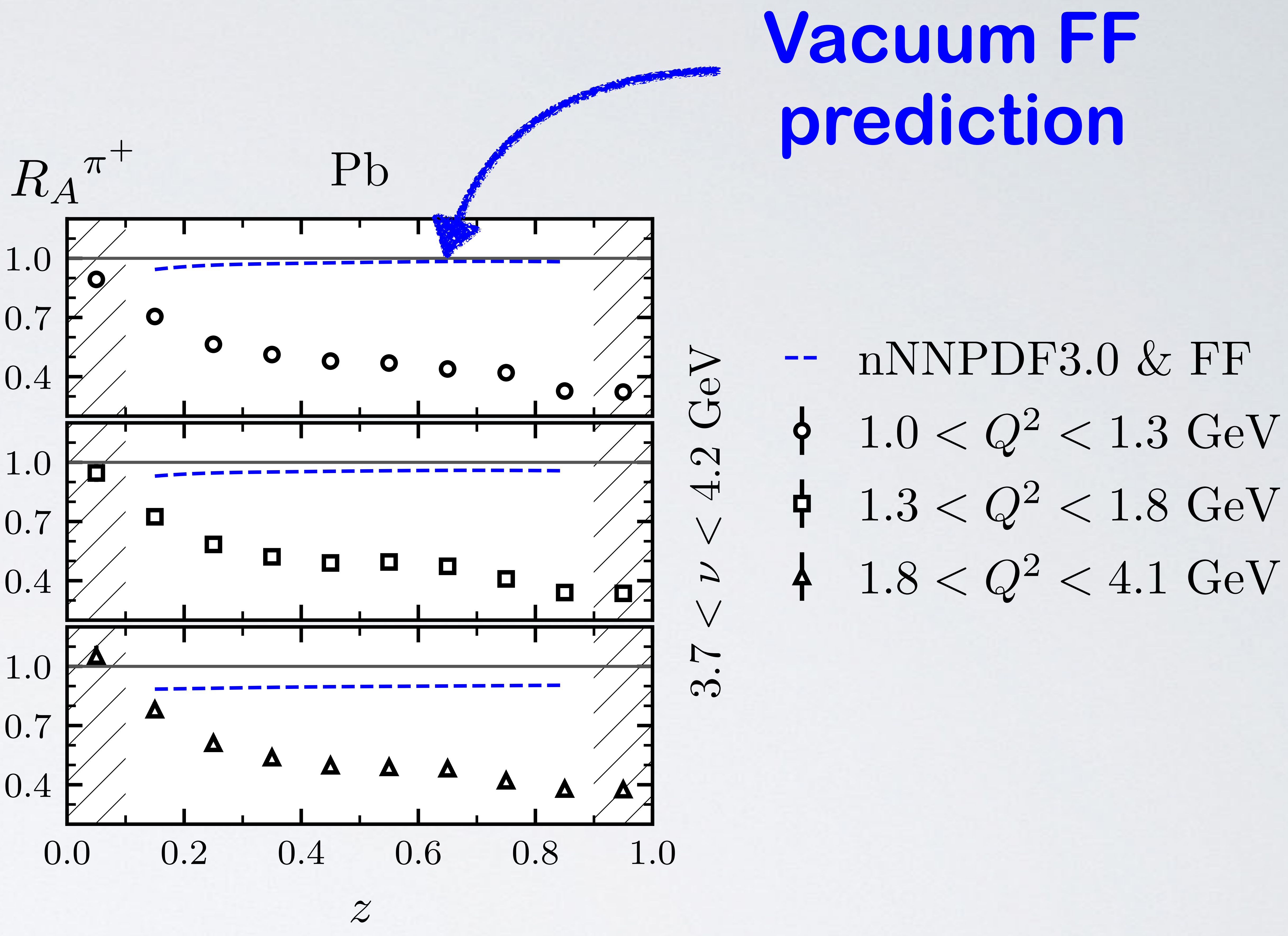

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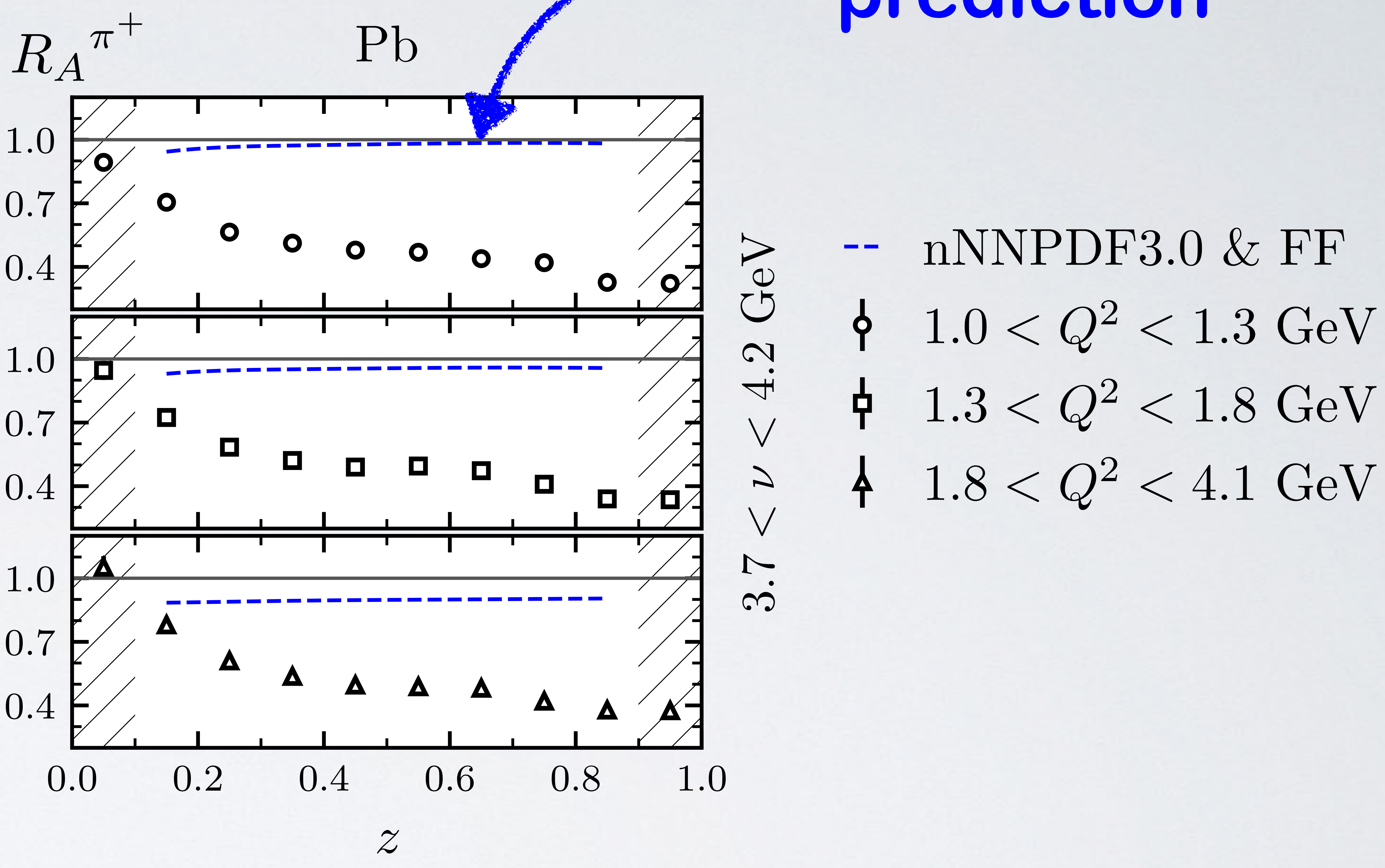
Can the factorization theorem be extended to nuclear FF?

Vacuum FF prediction



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Convolution Approach

$$D^h_{i/A}(z,\mu_0) = \int_z^1 \frac{dy}{y}\, W^h_i(y,A,\mu_0)\; D^h_i\left(\frac{z}{y},\mu_0\right)$$

Nuclear Fragmentation Functions **nFFs**

Weight Function

Vacuum Fragmentation Functions **FFs**

Convolution Approach

$$D^h_{i/A}(z,\mu_0) = \int_z^1 \frac{dy}{y}\, W_i^h(y, A, \mu_0)\; D_i^h\left(\frac{z}{y}, \mu_0\right)$$

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FIT

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Nuclear Fragmentation Functions **nFFs**

Weight Function

Vacuum Fragmentation Functions **FFs**

FIT

Parametrization

Valence quarks $$W_q(z) = n'_q\,\delta(z-(1-\epsilon_q)) + \frac{n_q}{N_q}\, z^{\alpha_q}(1-z^{\beta_q})$$

Gluons $$W_g(z) = n'_g\,\delta(z-1) + \frac{n_g}{N_g}\, z^{\alpha_g}(1-z^{\beta_g})$$

Sea quarks $$W_s(z) = n'_s\,\delta(z-(1-\epsilon_s)) + \frac{n_s}{N_s}\, z^{\alpha_s}(1-z^{\beta_s})$$

Convolution Approach

$$D_{i/A}^{h}(z,\mu_0) = \int_z^1 \frac{dy}{y} W_i^h(y, A, \mu_0)\, D_i^h\left(\frac{z}{y}, \mu_0\right)$$

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mass number

Parameters A dependence:

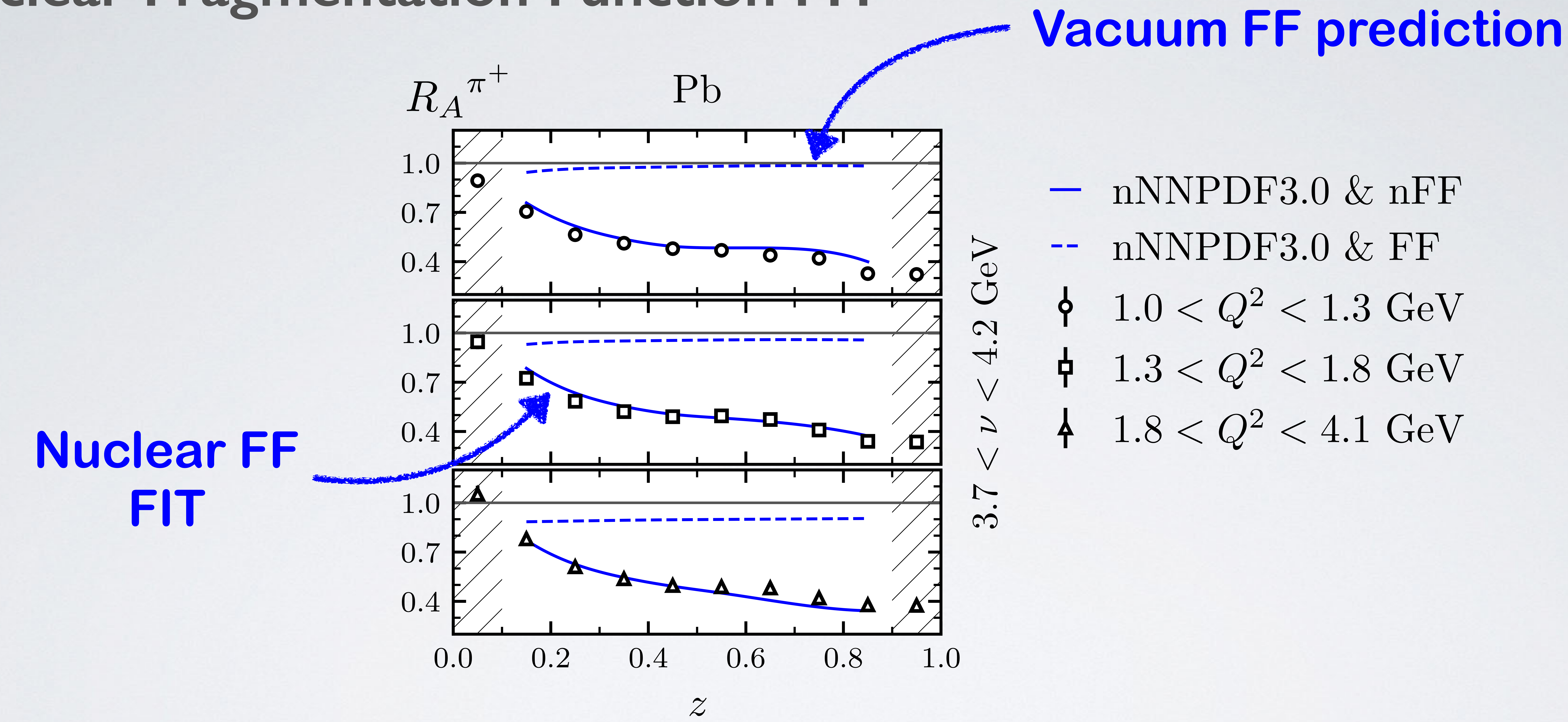
$$\xi = \lambda_\xi + \gamma_\xi A^{\delta_\xi}$$

$\{n_i, n_i', \alpha_i, \beta_i, \epsilon_i\}$

some constrains

24 free parameters

Nuclear Fragmentation Function FIT

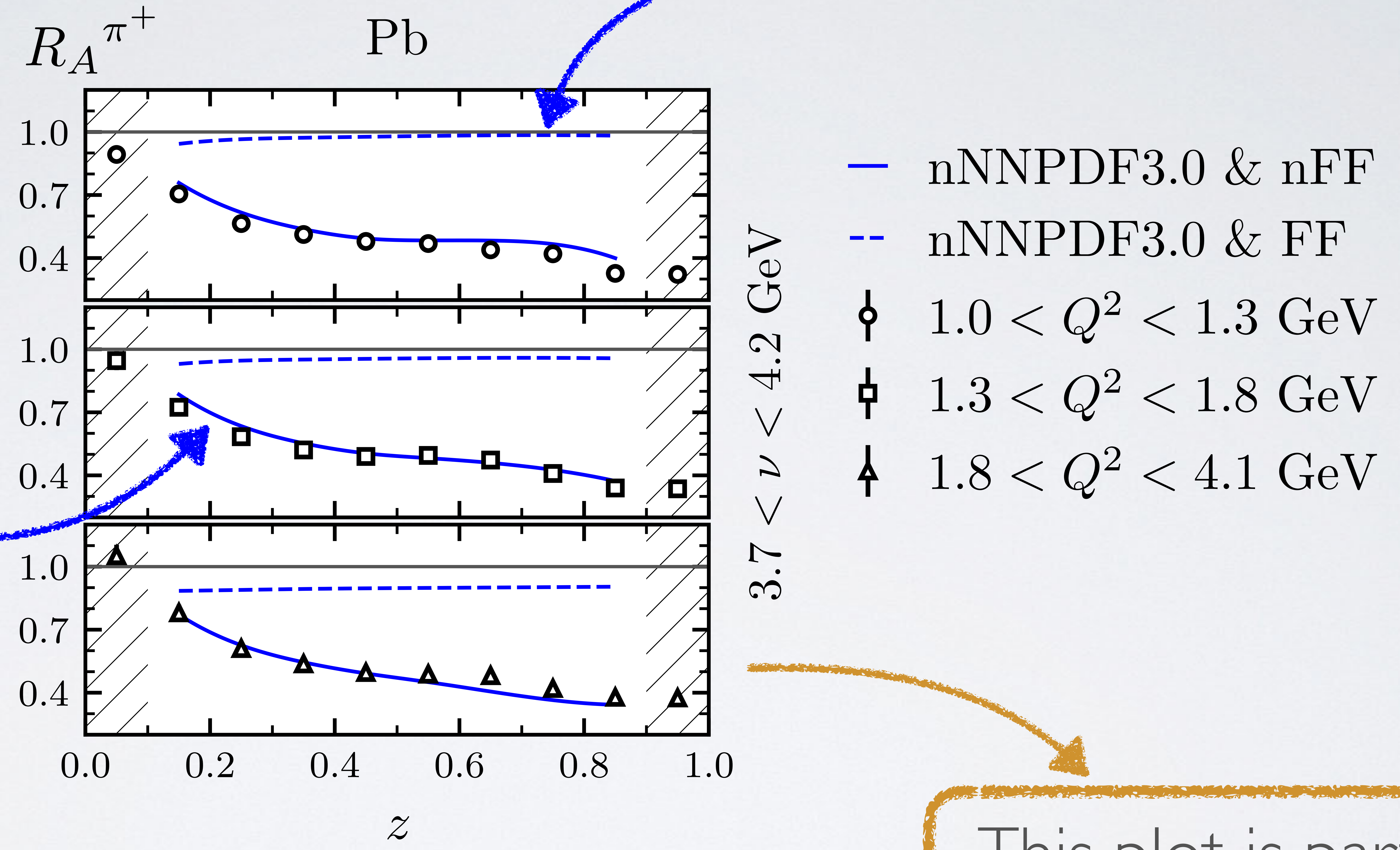


CLAS detector JLab

arXiv: 2109.09951

Nuclear Fragmentation Function FIT

Vacuum FF prediction



Nuclear FF FIT

CLAS detector JLab

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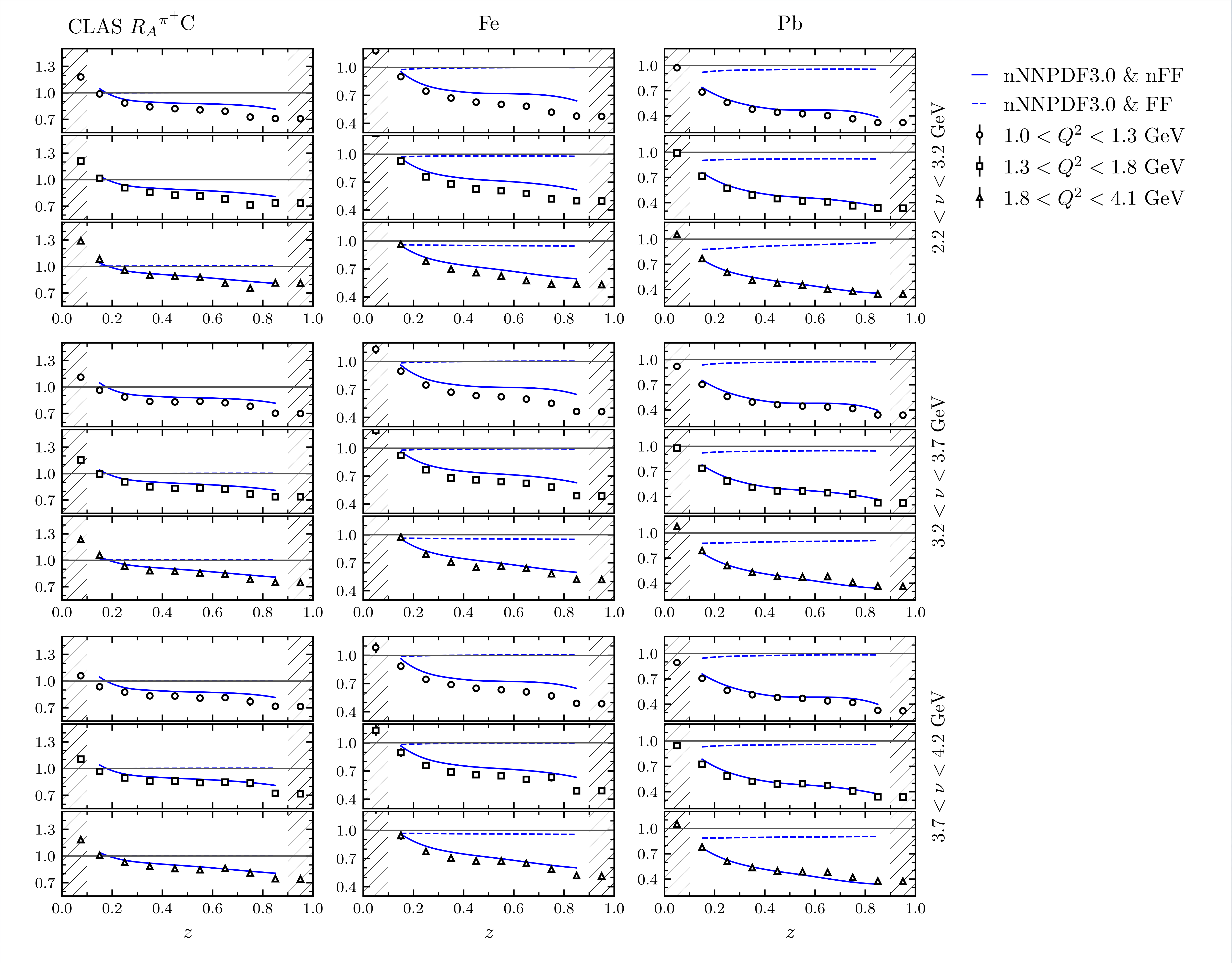
This plot is part of a **Global Analysis**

CLAS π^+data

- Global Analysis



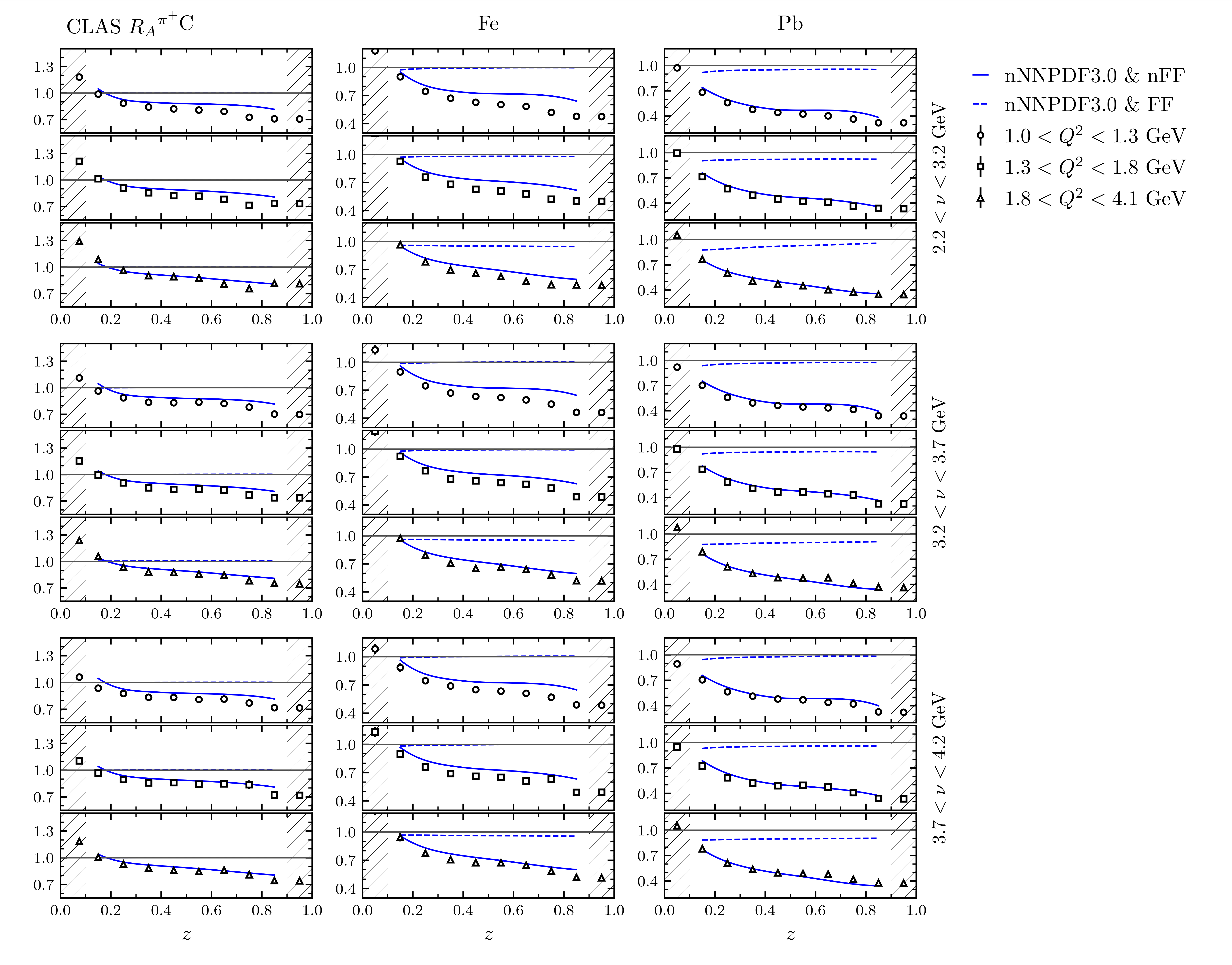
$\nu = E_e - E_{e'}$ (Proton rest frame)

arXiv: 2109.09951

CLAS π^+data

- Global Analysis

- Next to Leading Order (NLO)
  Cross sections up to $\mathcal{O}(\alpha_s)$



$\nu = E_e - E_{e'}$ (Proton rest frame)

arXiv: 2109.09951

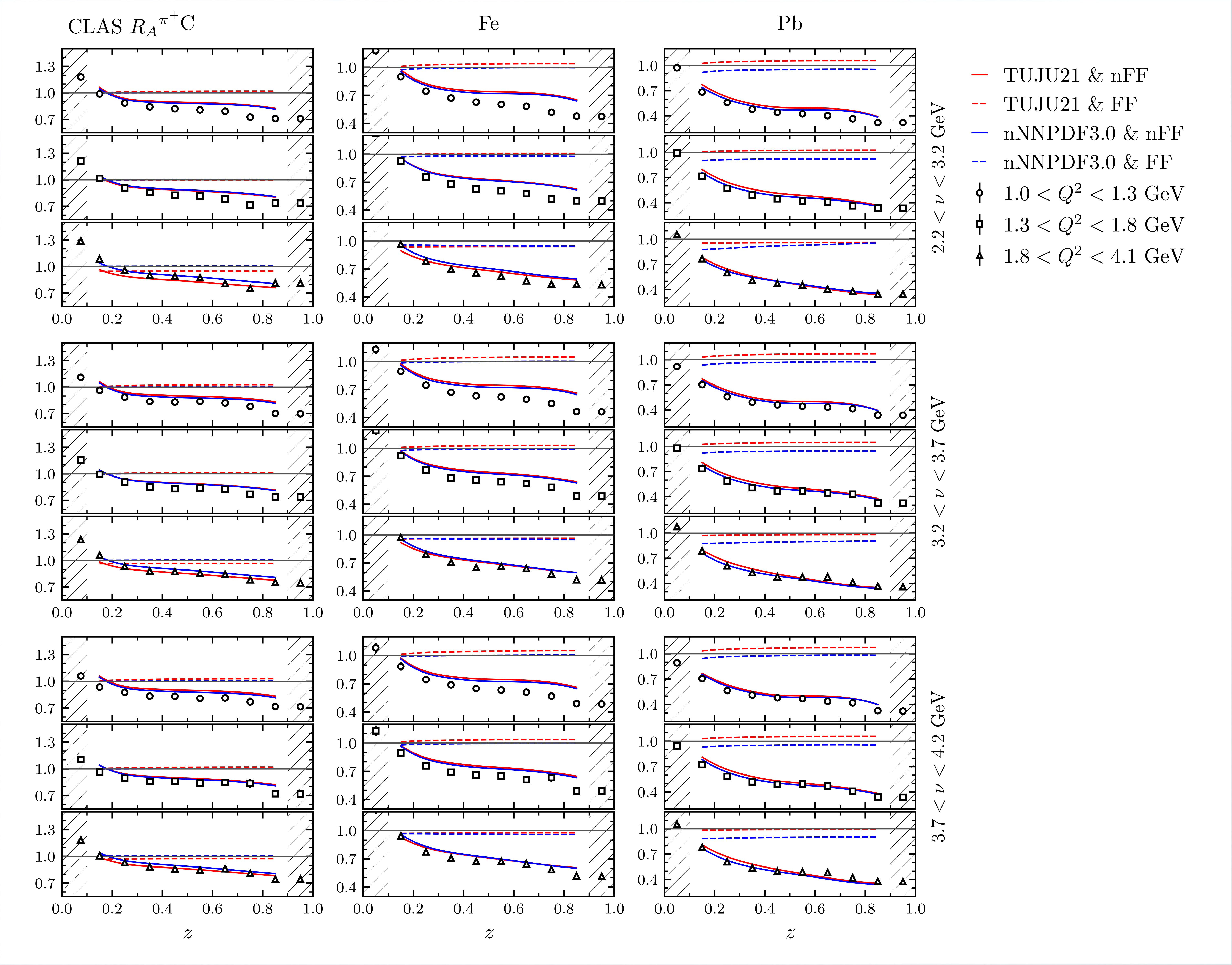
CLAS π^+data

- Global Analysis

- Next to Leading Order (NLO)
  Cross sections up to $\mathcal{O}(\alpha_s)$

- The global analysis was also done with **TUJU21** nPDF set

$\nu = E_e - E_{e'}$ (Proton rest frame)



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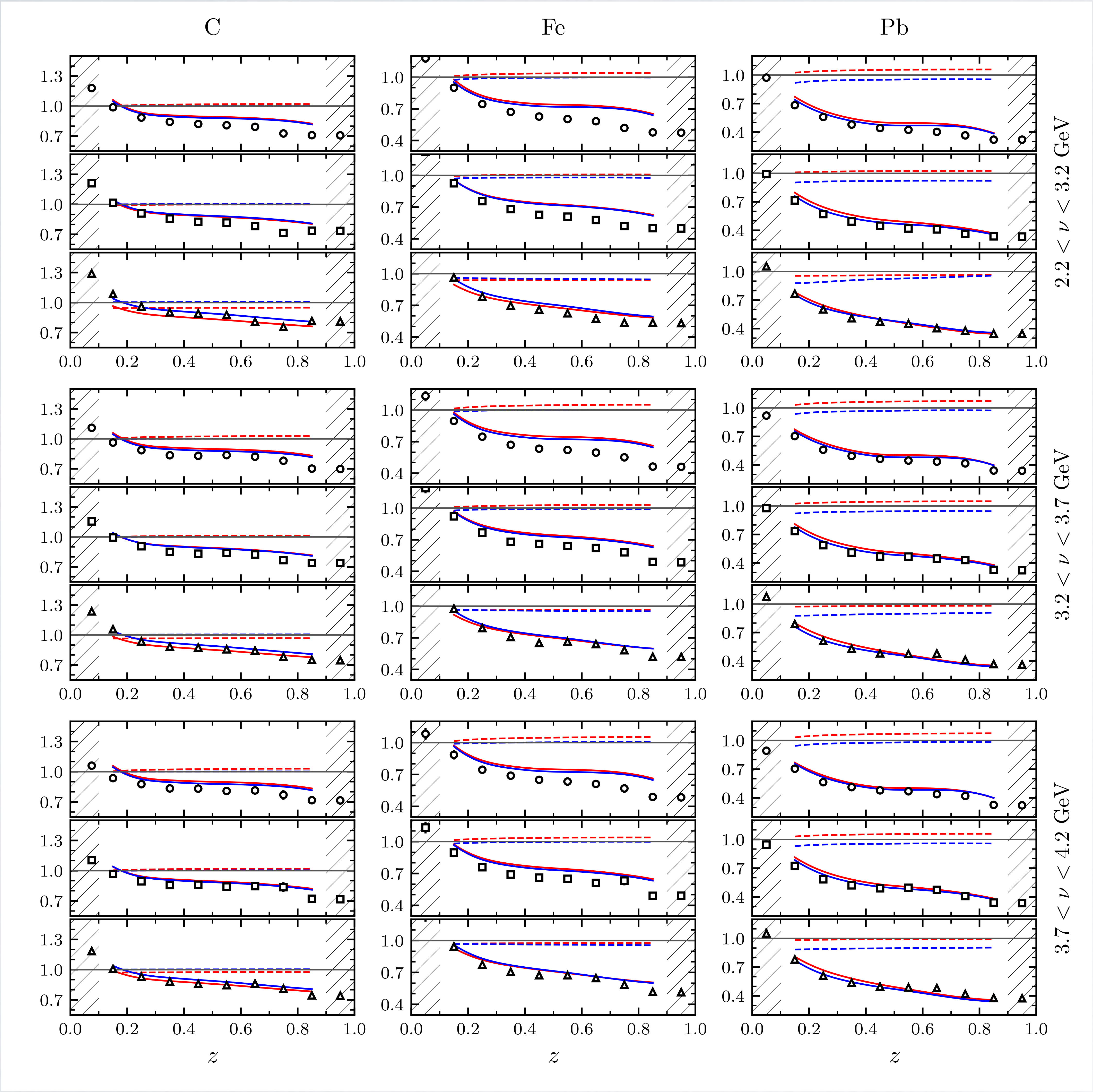
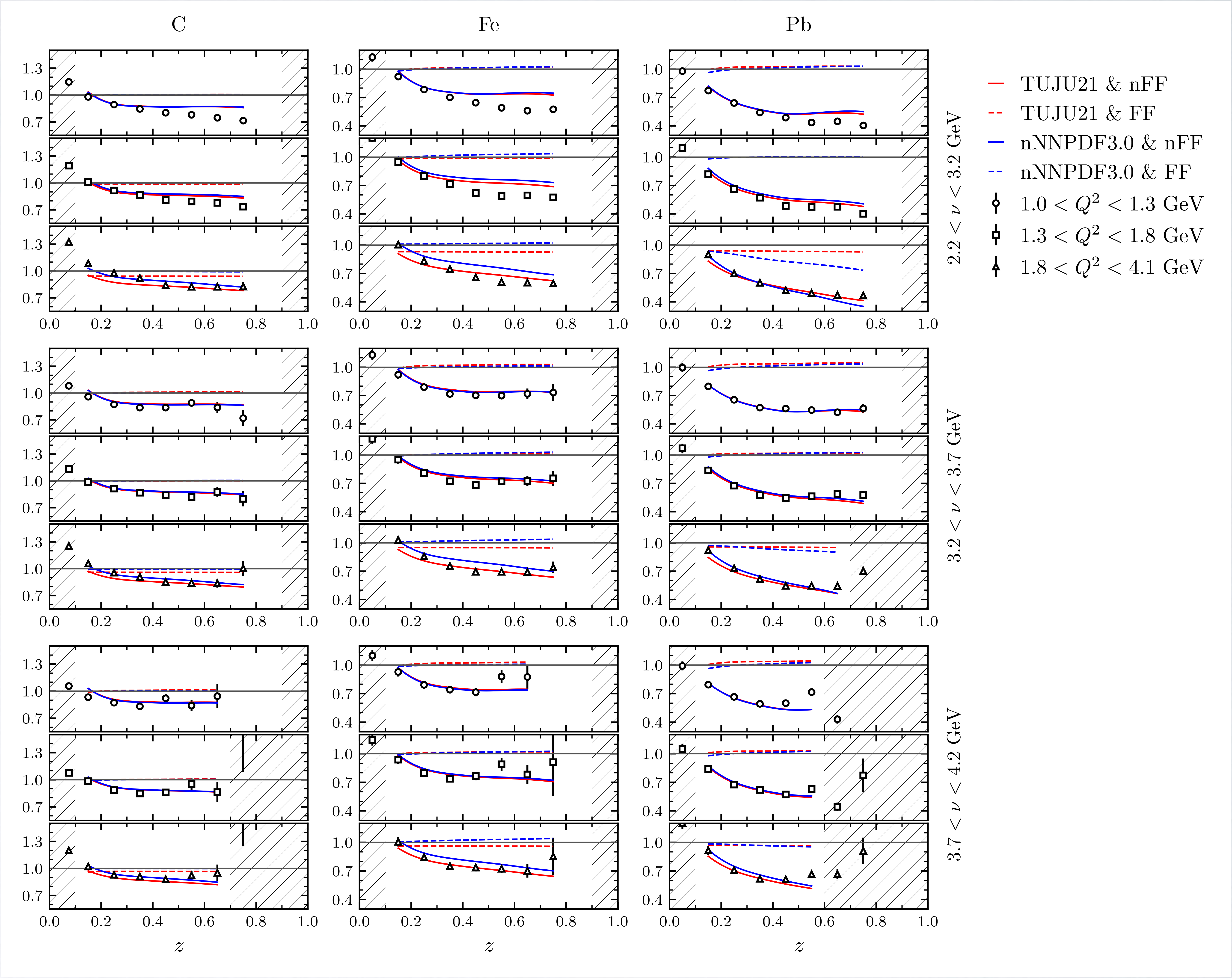
CLAS π^+data



CLAS π^-data



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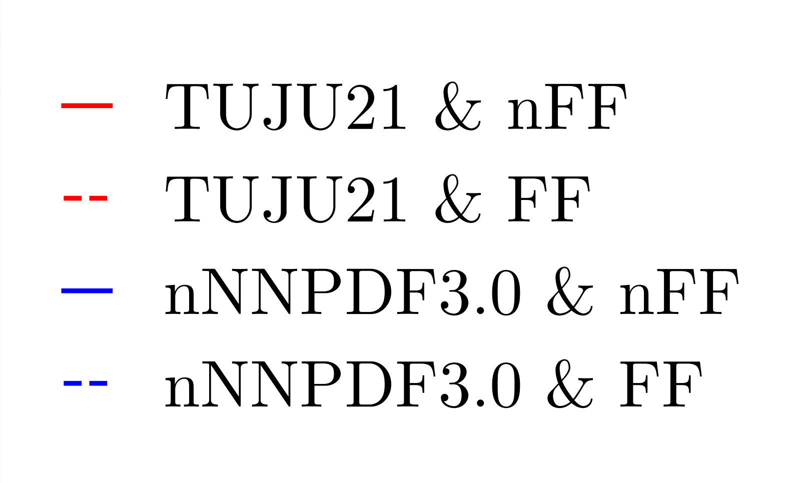
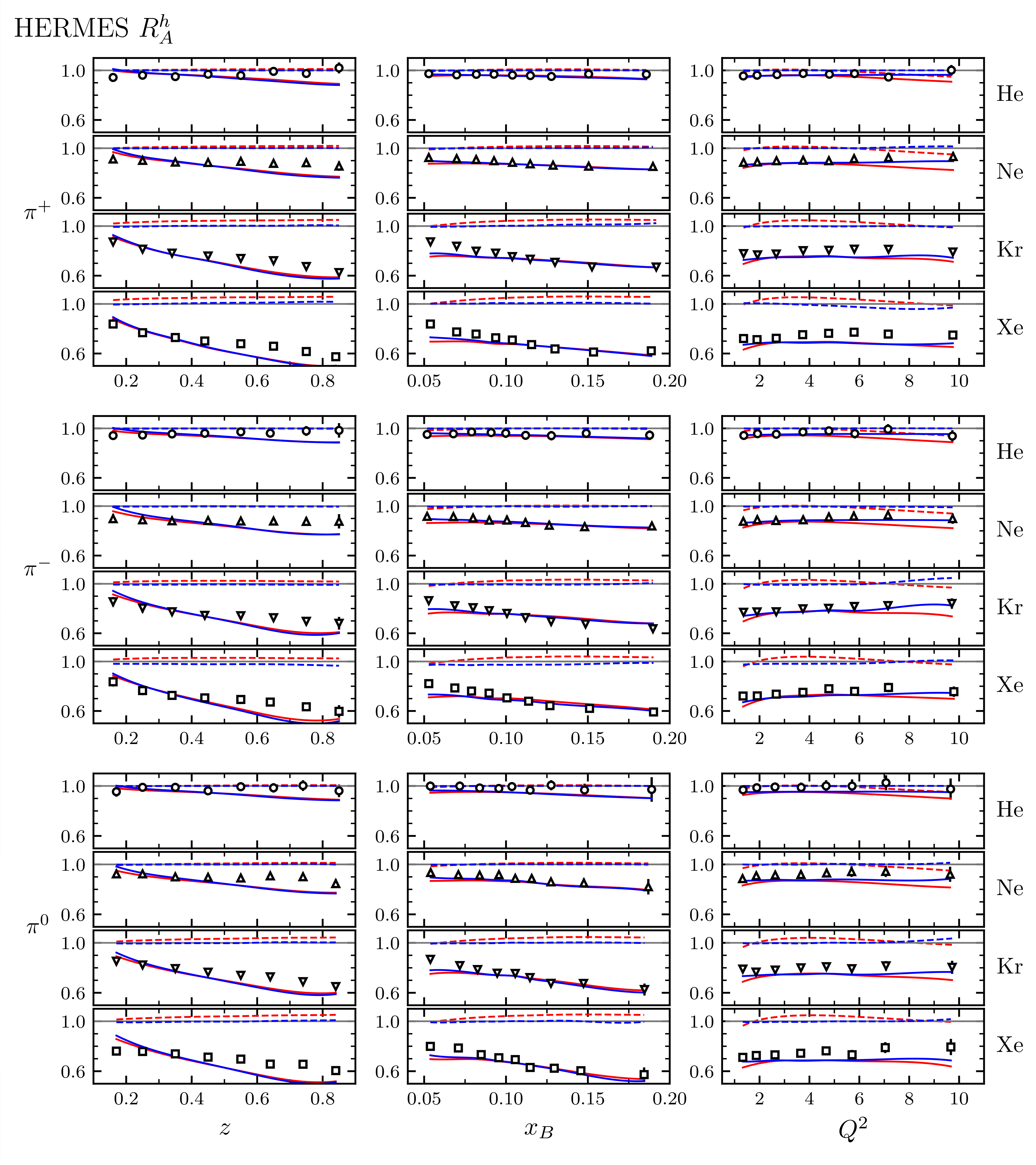
HERMES Collaboration

- 27.6 GeV electron beam store stored in the HERA ring at DESY

- Same observable R_A^h



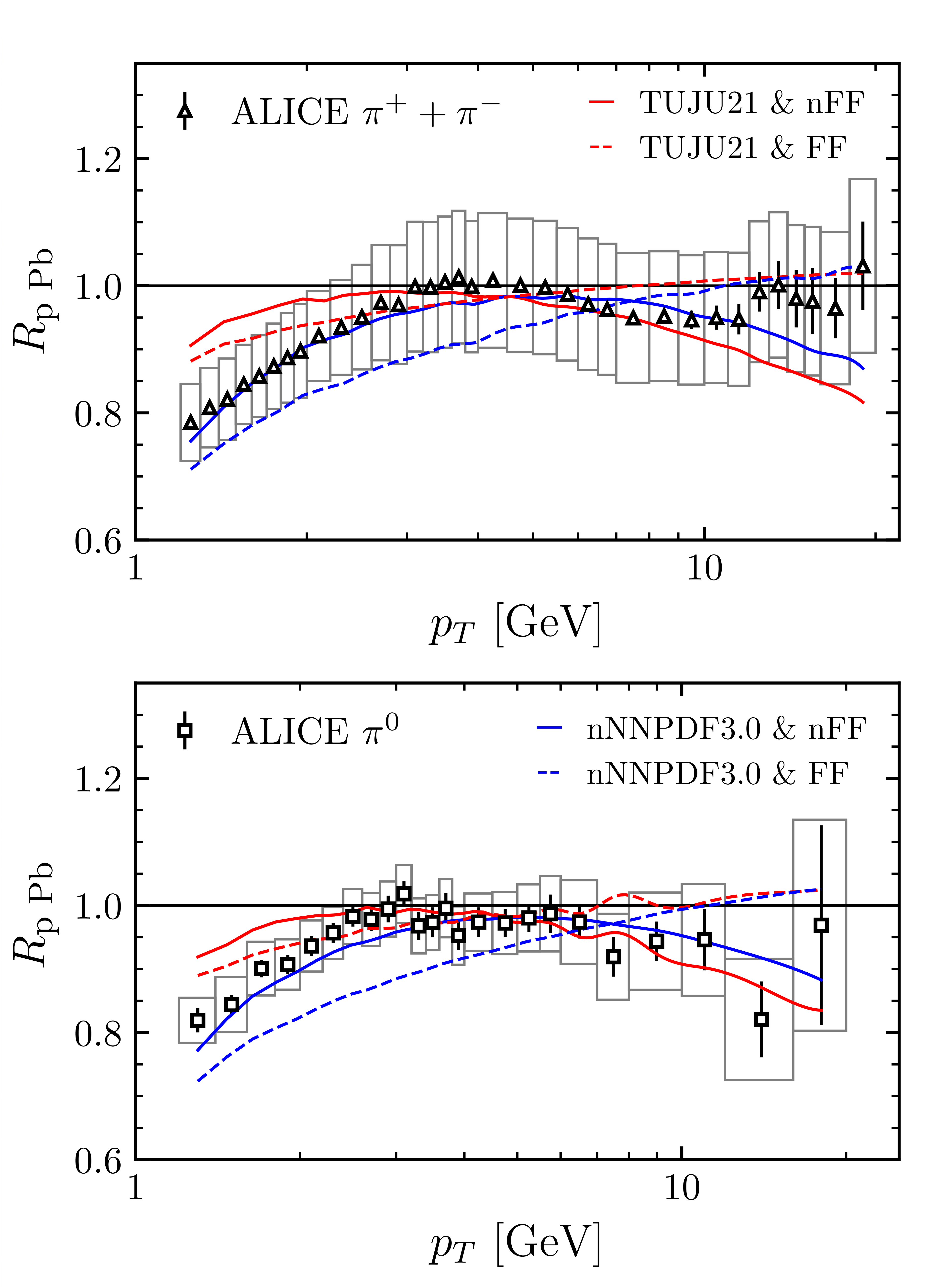


data from arXiv: 0704.3270

p-Pb collisions

ALICE, LHC $\sqrt{s} = 5.02$ TeV

$$R_{pPb} = \frac{\frac{1}{\langle T_{pPb}\rangle}\frac{d^2N^{pPb}}{dy\,dp_T}}{\frac{d^2\sigma^{pp}}{dy\,dp_T}} \sim \frac{\sigma^{pPb}}{\sigma^{pp}}$$



data from arXiv:1801.07051
arXiv: 1601.03658

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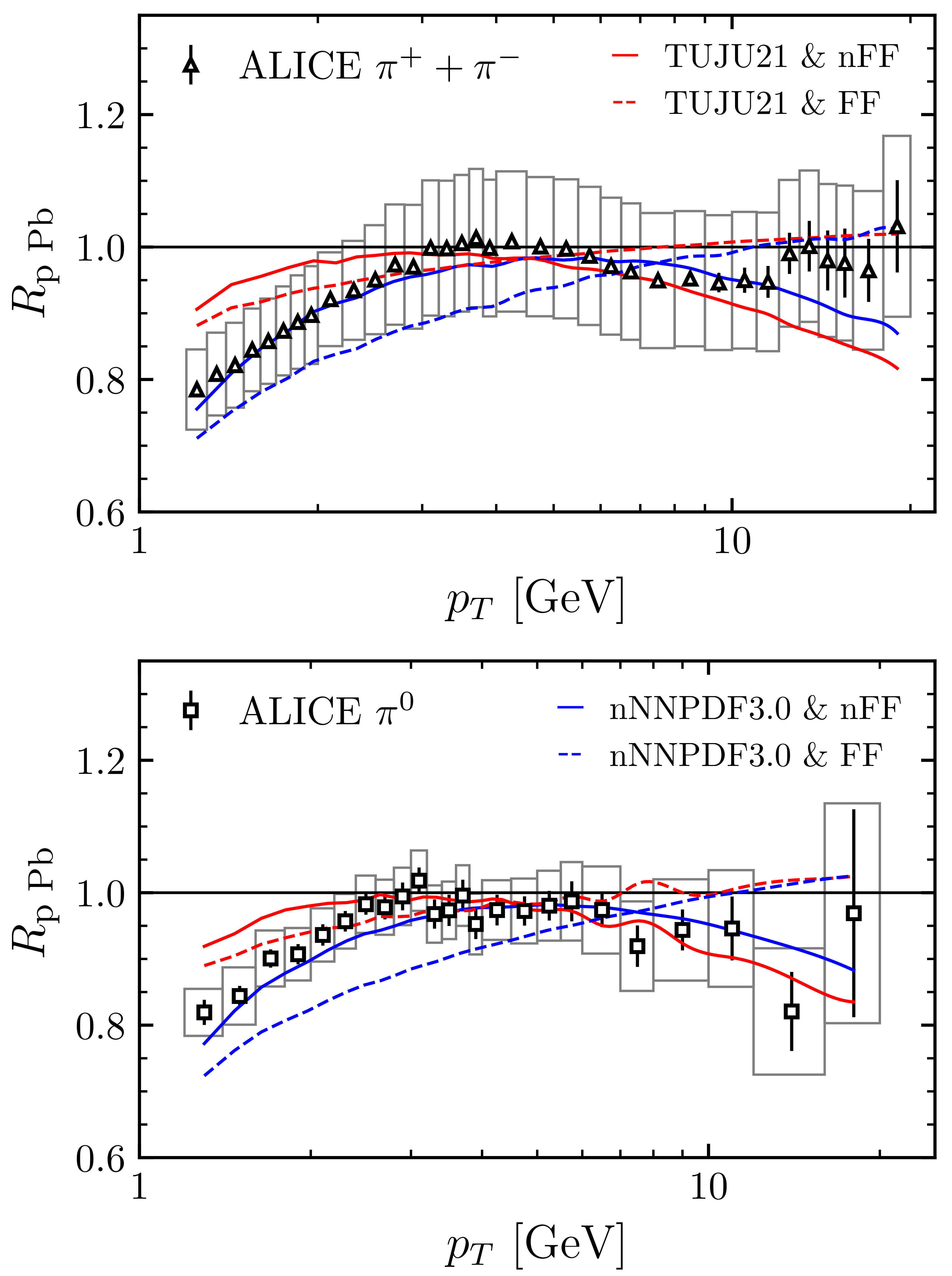
- Big difference between two PDFs set



data from arXiv:1801.07051
arXiv: 1601.03658

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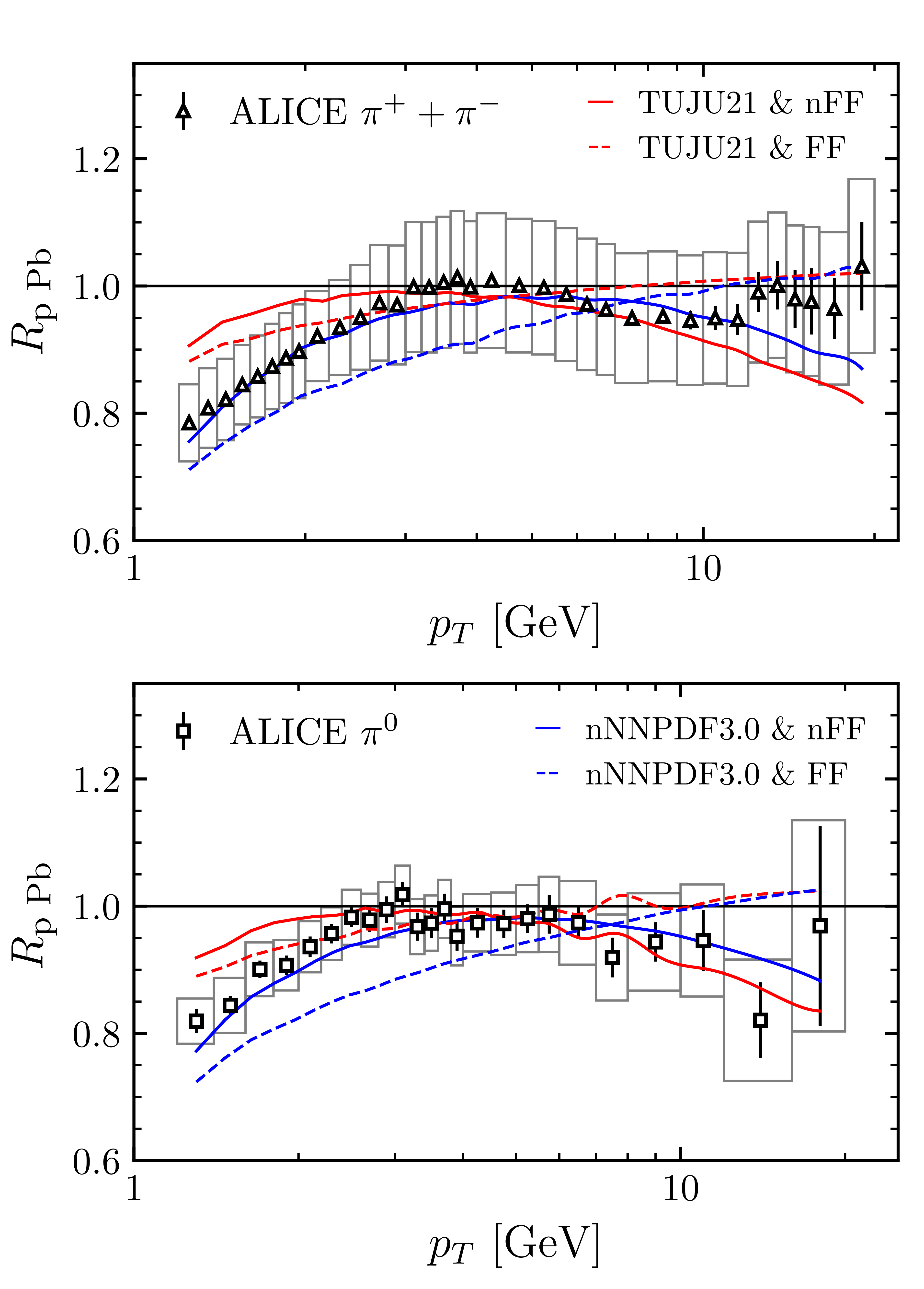
$$R_{pPb} = \frac{\frac{1}{\langle T_{pPb} \rangle} \frac{d^2 N^{pPb}}{dy\, dp_T}}{\frac{d^2 \sigma^{pp}}{dy\, dp_T}} \sim \frac{\sigma^{pPb}}{\sigma^{pp}}$$

- Big difference between two PDFs set
- Dependence on R_{pPb} of the initial-state nuclear effect

data from arXiv:1801.07051
arXiv: 1601.03658



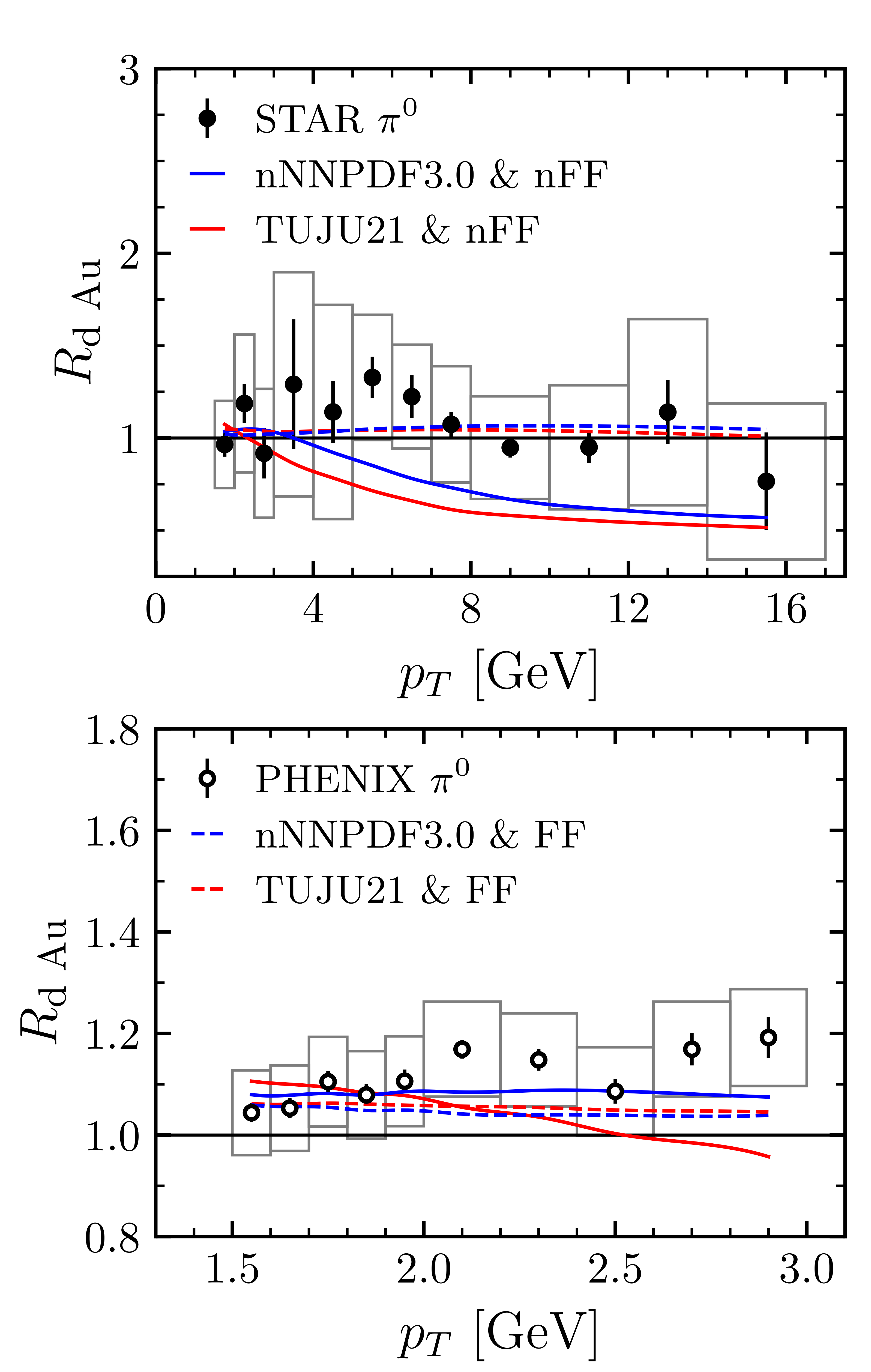
d-Au collisions

STAR, PHENIX Collaborations at
Relativistic Heavy Ion Collider RHIC $\sqrt{s} = 200$ GeV

$$R_{pPb} = \frac{\frac{1}{\langle N_{coll} \rangle} \frac{d^2 N^{d\,Au}}{dy\, dp_T}}{\frac{1}{\langle \sigma_{NN} \rangle} \frac{d^2 \sigma^{pp}}{dy\, dp_T}} \sim \frac{\sigma^{d\,Au}}{\sigma^{pp}}$$

- nNNPDF3.0 appears to fit the data better

data from arXiv: 0912.3838
arXiv: 1304.3410

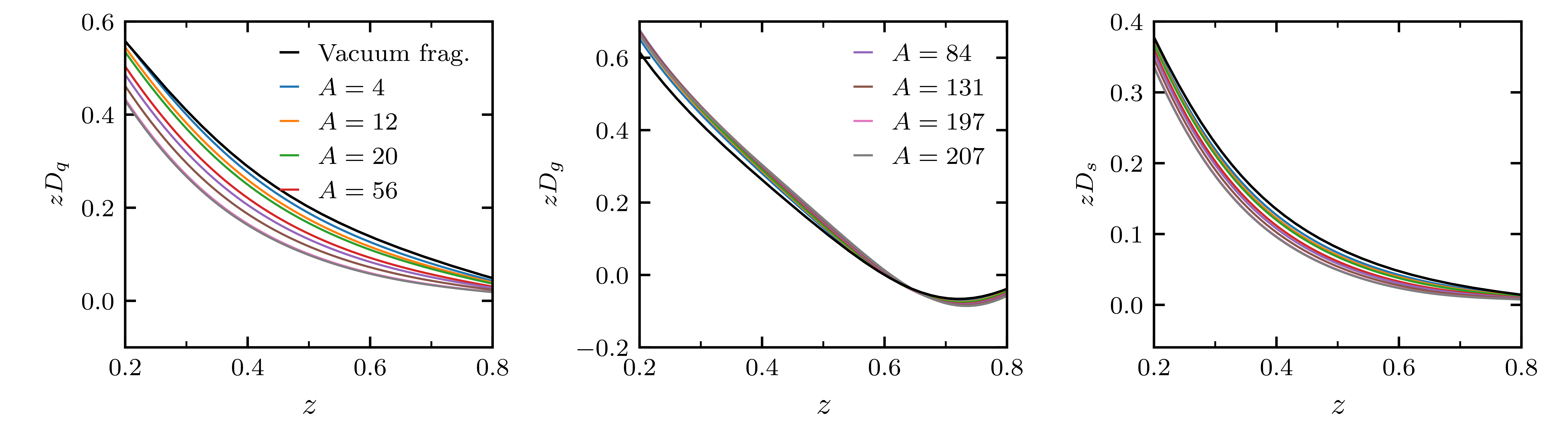


Nuclear Fragmentation Functions

Valence quark nFF

Gluon nFF

Sea quark nFF

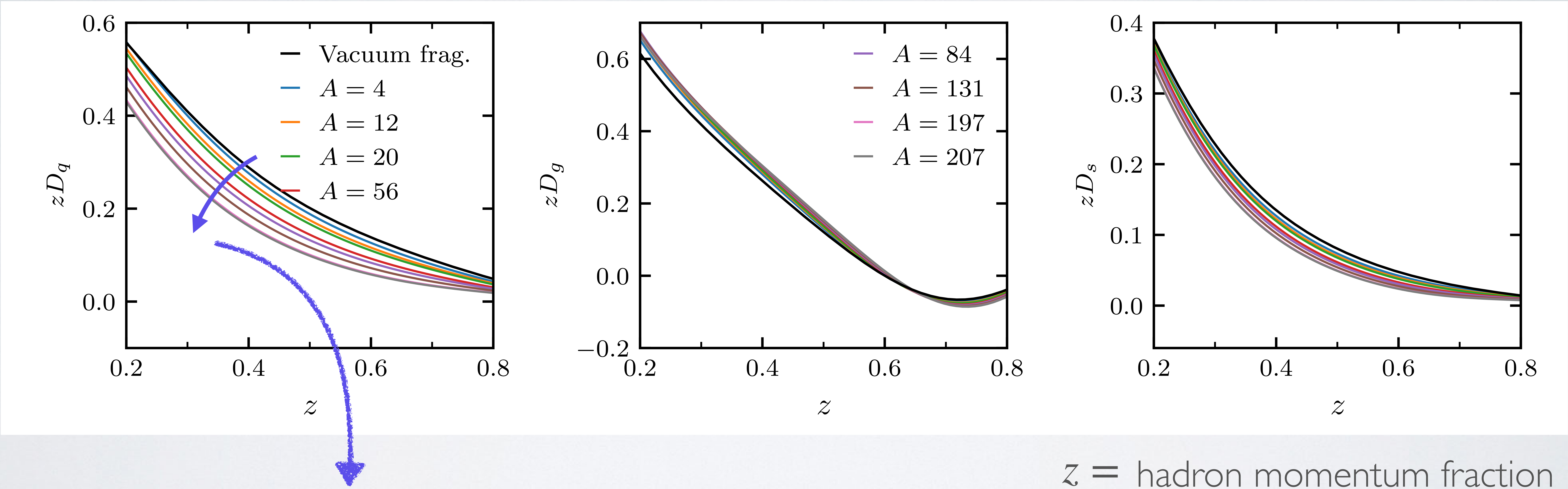


$z =$ hadron momentum fraction

$A =$ Mass number

Nuclear Fragmentation Functions

Valence quark nFF   Gluon nFF   Sea quark nFF



Nuclear effects increase with mass number ***A***

z = hadron momentum fraction

A = Mass number

CONCLUSIONS

- Final-state nuclear effects can be effectively described with **nFFs**

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- The observable R_A^{π} in nuclear SIDIS, measured by CLAS, has proven to be an excellent tool for studying final-state nuclear effects.

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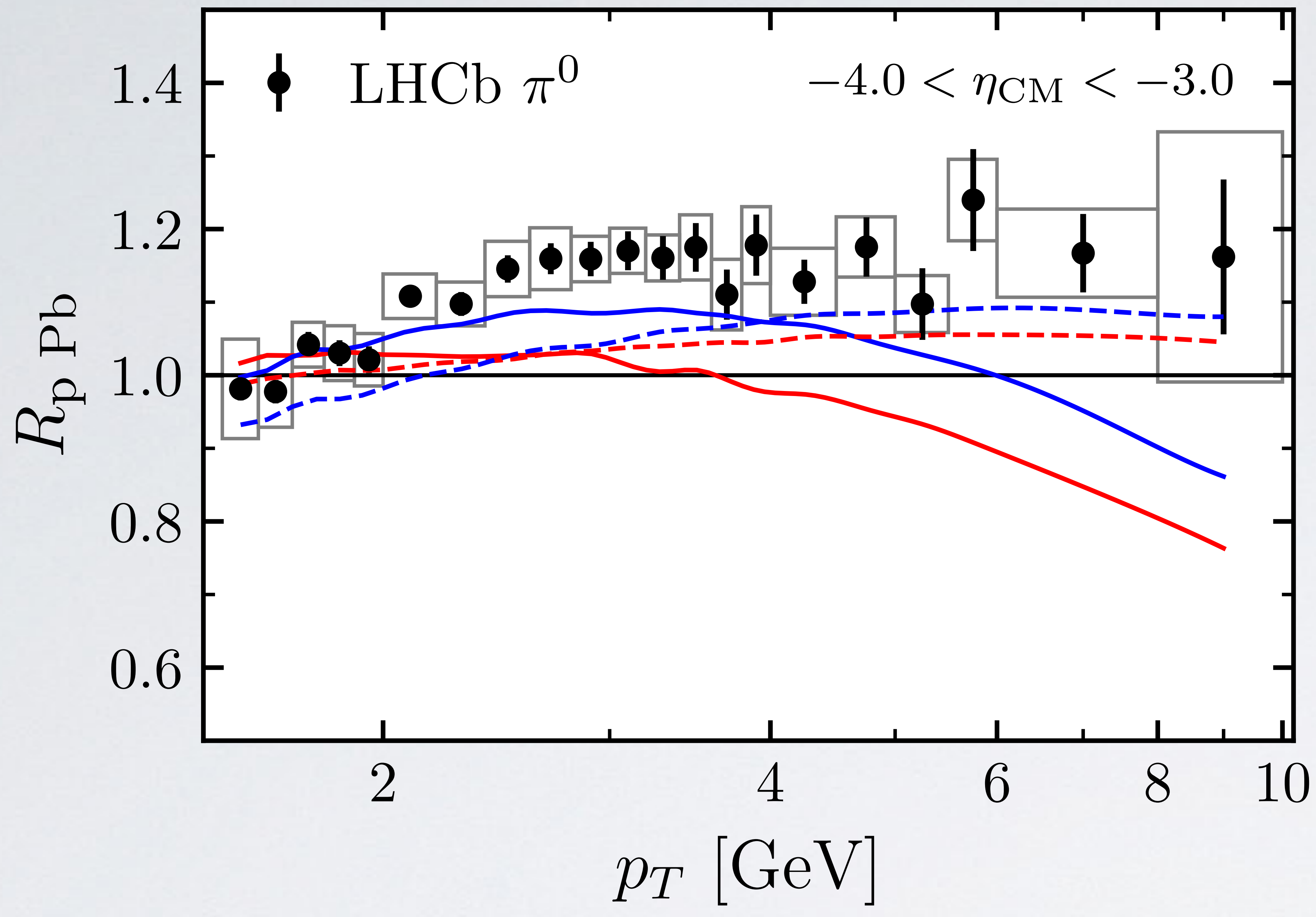
- Final-state nuclear effects can be effectively described with **nFFs**
- The observable R_A^{π} in nuclear SIDIS, measured by CLAS, has proven to be an excellent tool for studying final-state nuclear effects.
- Proton-Nucleus collision observables have a strong dependence on the initial-state nuclear effects **nPDFs**.

BACKUP

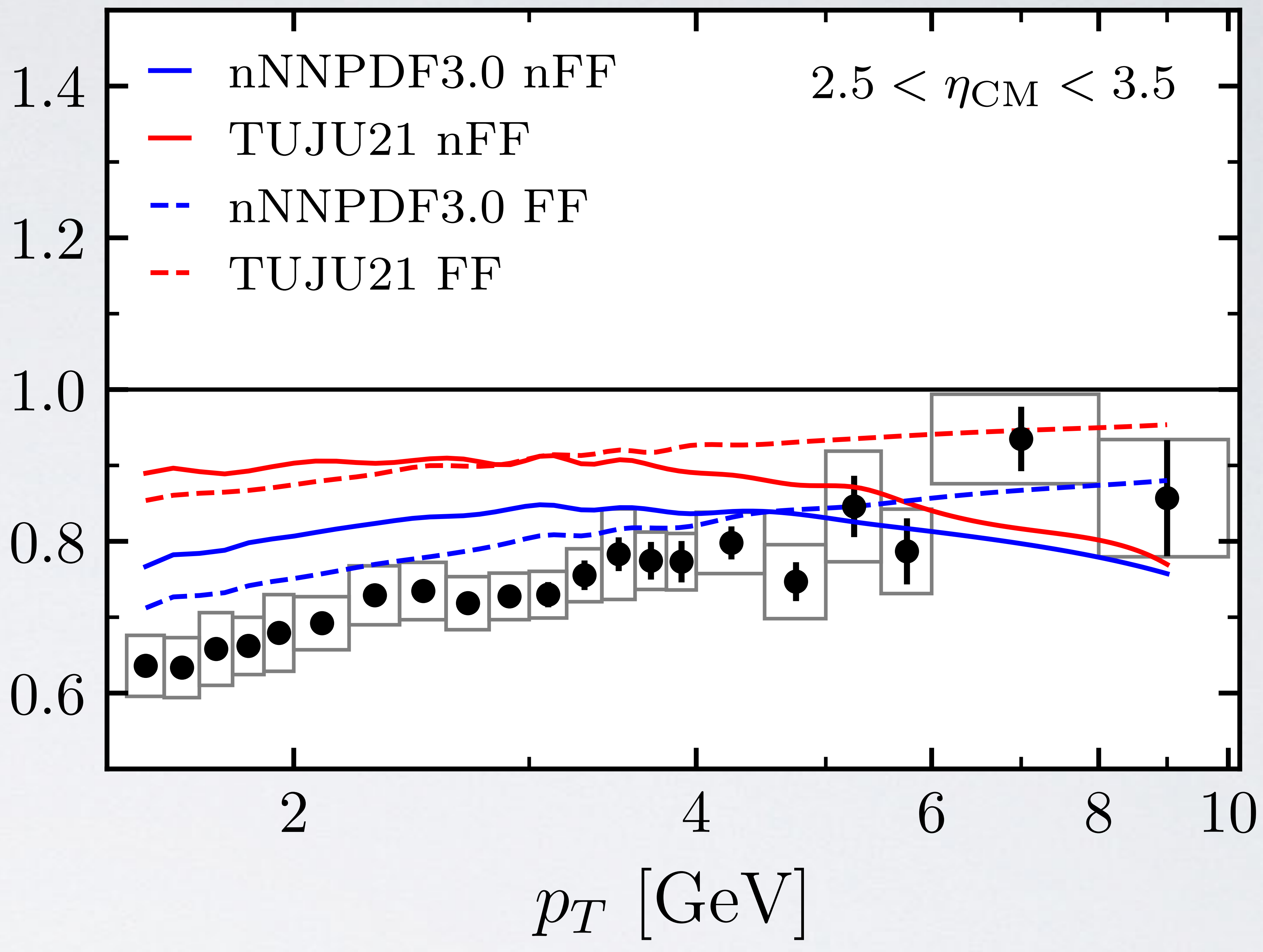
Experiment	Data Type	#Data in Fit	χ^2
HERMES	π^+ (He, Ne, Kr, Xe)	100	259.76
	π^- (He, Ne, Kr, Xe)	100	184.87
	π^0 (He, Ne, Kr, Xe)	100	244.84
CLAS	π^+ (C, Fe, Pb)	216	578.49
	π^- (C, Fe, Pb)	178	661.32
ALICE	$\pi^+\pi^-$ (Pb)	35	9.35
	π^0 (Pb)	24	7.36
STAR	π^0 (Au)	12	8.76
PHENIX	π^0 (Au)	10	3.53
LHCb	π^0 Bwd (Pb)	21	35.66
	π^0 Fwd (Pb)	21	81.72
TOTAL		**817**	**2075.66**

Table 1: Experimental data summary

Backward

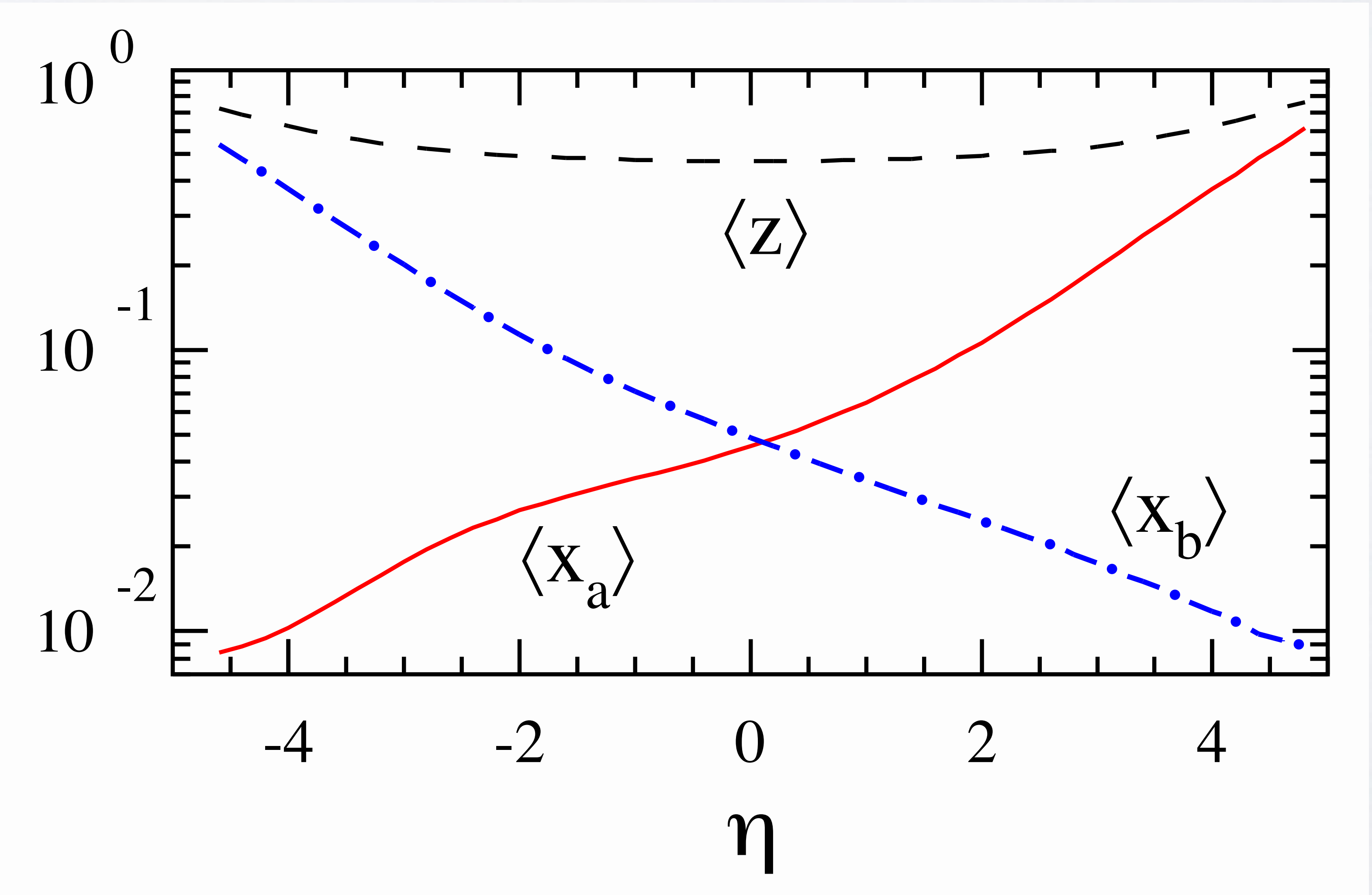


Forward



Mean values of the momentum fractions

$$\langle x_i \rangle \equiv \frac{\int dx_i\, x_i \frac{d\sigma}{dx_i dp_T}}{\int dx_i \frac{d\sigma}{dx_i dp_T}} \quad , \quad \langle z \rangle \equiv \frac{\int dz\, z \frac{d\sigma}{dz dp_T}}{\int dz \frac{d\sigma}{dz dp_T}}$$



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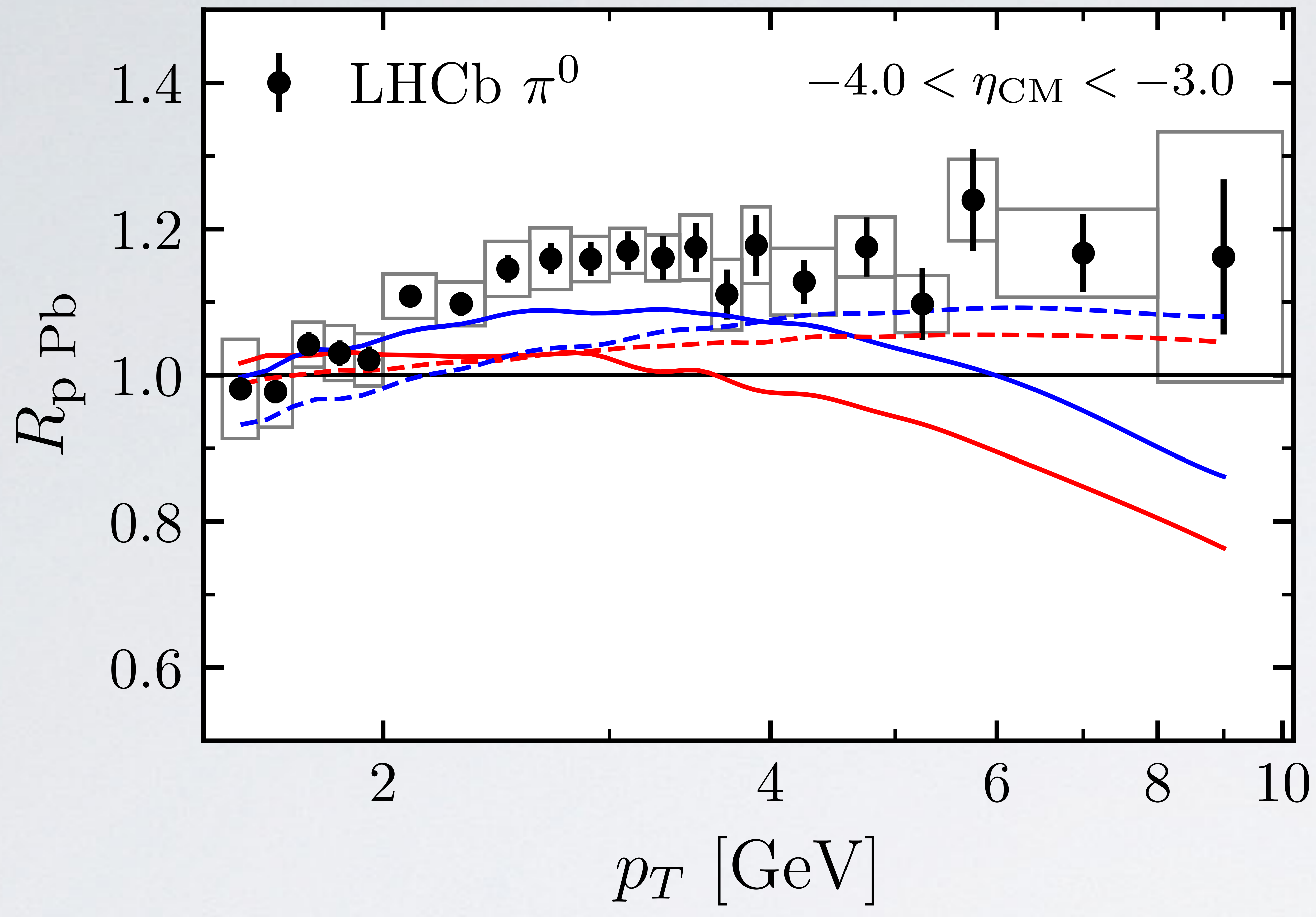
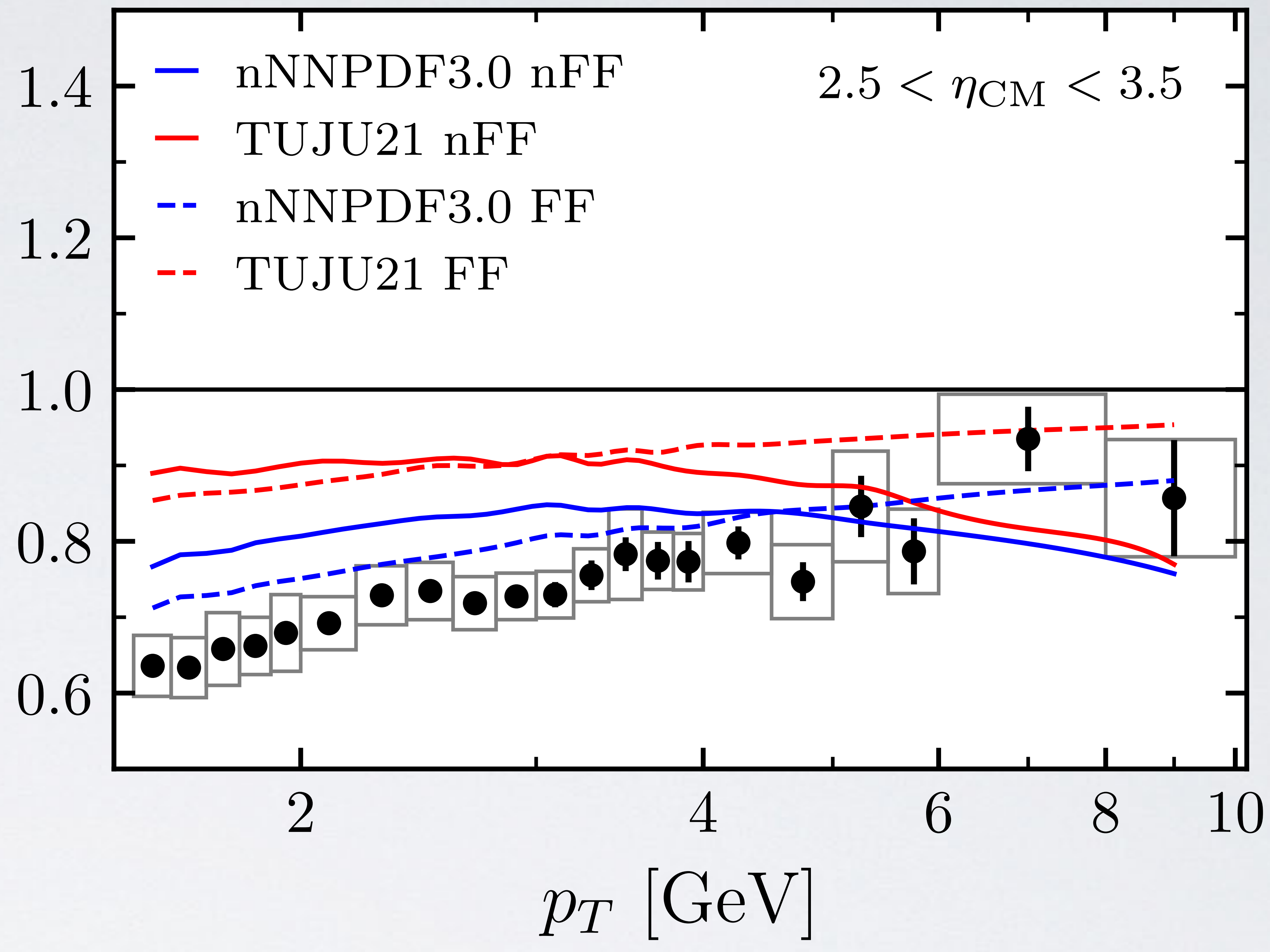
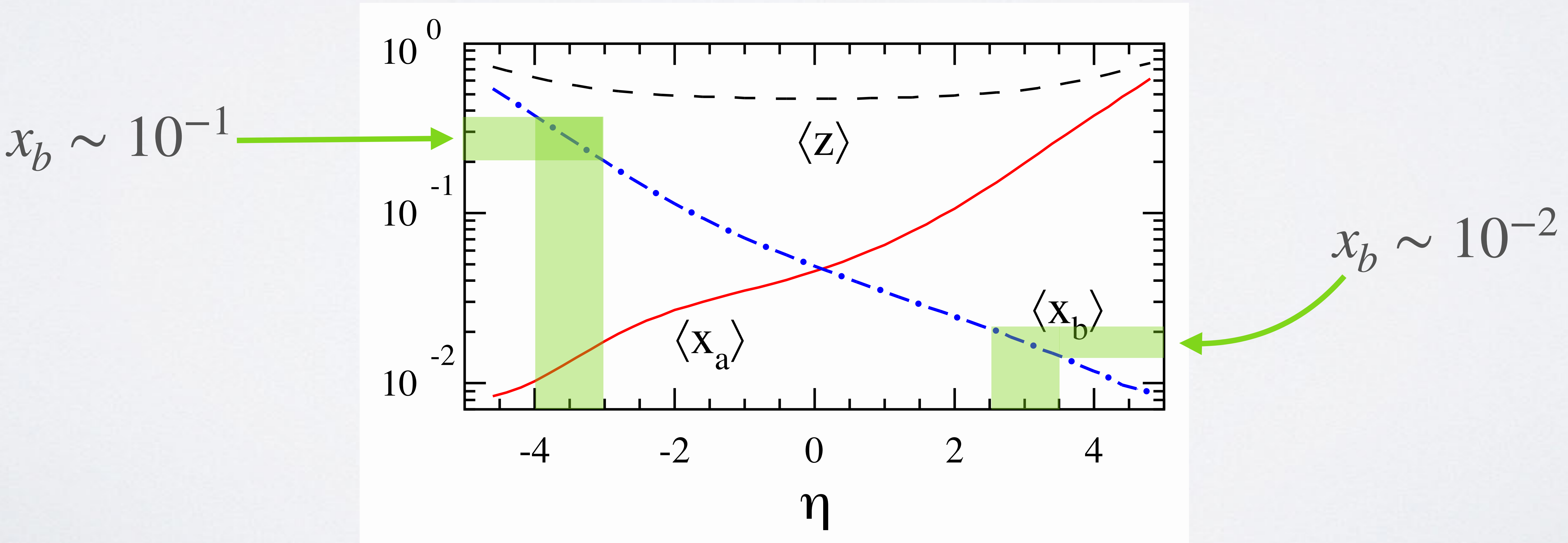
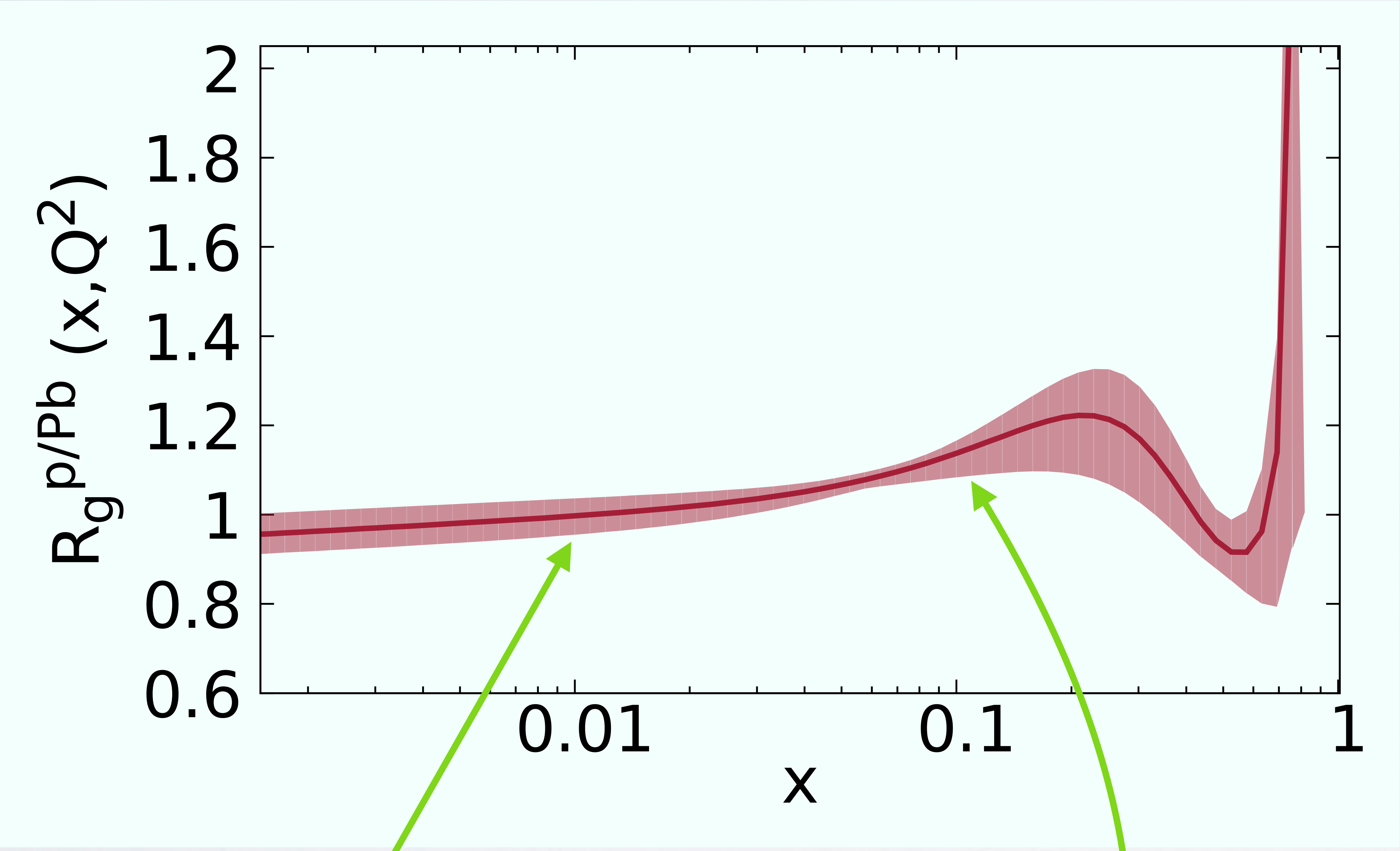


Forward

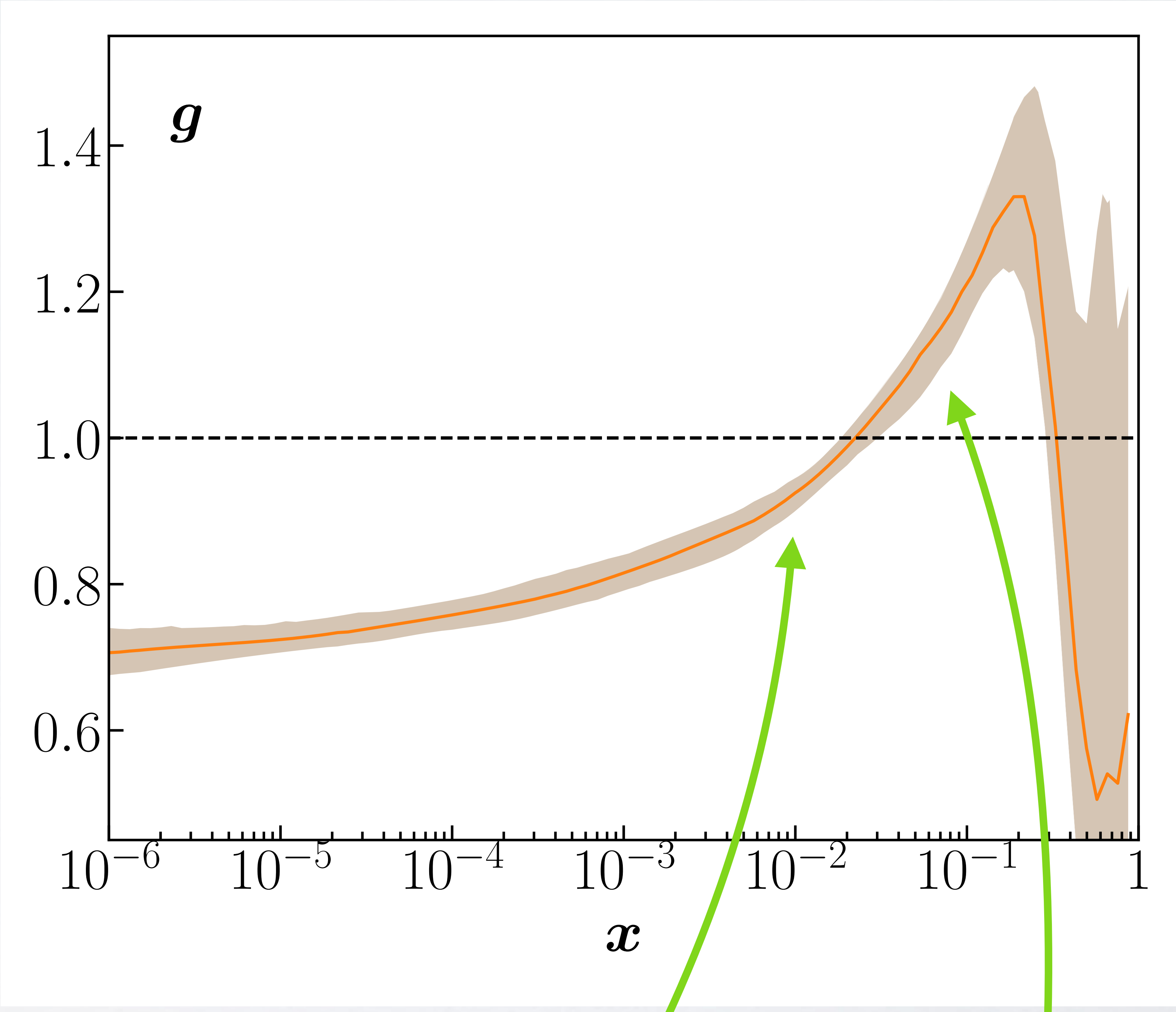




TUJU21



nNNPDF3.0



$x_b \sim 10^{-2}$ $x_b \sim 10^{-1}$

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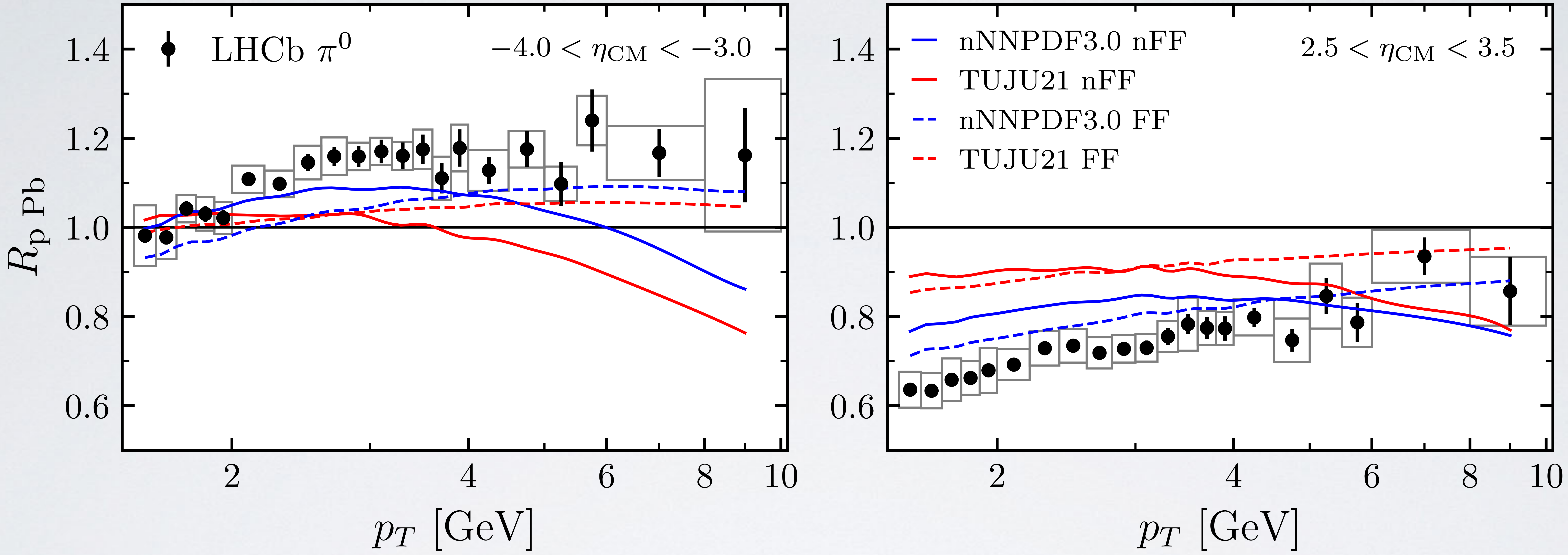
Backward ⟷ Antishadowing

Forward ⟷ Shadowing

Backward ~ Antishadowing Forward ~ Shadowing



In order to fit this data set

- nPDF with more **shadowing** than nNNPDF3.0
- nPDF with **antishadowing** similar to nNNPDF3.0