Incorporating Fragmentation Functions in xFitter

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Outlook

- Fragmentation functions: a quick reminder.
- A bit about xFitter.
- Motivation.
- Incorporating FFs in xFitter.
- Application to in-medium fragmentation.
- Summary.
- Future work.

FFs:

- (collinear) PDFs describe the state of a parton inside a hadron **before** the interaction.

$f_i^{p,n,A,\pi,\dots}(x, Q^2)$

- FFs encode the information on the probability that a certain parton ends up **afterwards** in a certain hadron measured by the detector.

$D_i^{h=\pi^{\pm,0},K^{\pm},p,\bar{p},\dots}(z, Q^2)$

- Just like PDFs, FFs are determined through global fits. In this case to SIA (e.g.: $e^+ + e^- \to K^+ + K^- + X$), SIDIS (e.g.: $l + p \to \pi^+ + X$) and single-inclusive hadroproduction (e.g.: $p + p \to \eta + X$)

- Except for SIA, the extraction of FFs requires a set of PDFs to describe the initial state.

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Eur.Phys.J.C 75 (2015) 12, 580 https://lhapdf.hepforge.org

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- Choice of QCD evolution package, heavy flavour scheme, error estimation, DIS electroweak corrections, re-weighting tool, dipole models, TDM (uPDFs), diffractive PDFs, total and differential $t\bar{t}$ production cross sections, heavy quark production.

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- In May the collaboration presented their FFs analysis (only SIA). Phys. Rev. D 104, 056019

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- Slowly moving fully to C++.
- For now, it is a bit like this →

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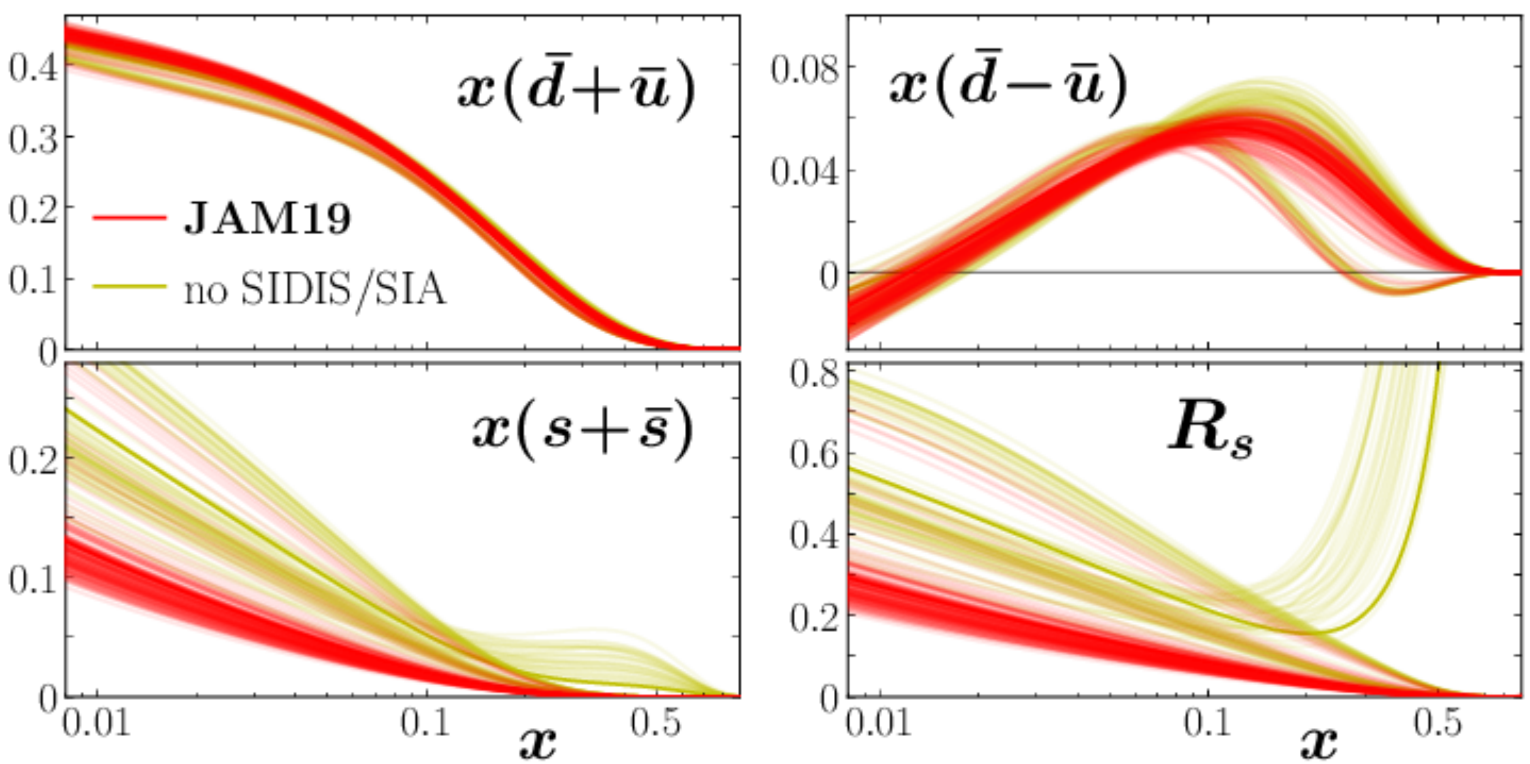
JAM Collaboration, PRD 101 (2020) 7, 074020.



- Not a novel idea. We already do this to constrain the gluon nPDF (with single inclusive hadron production).

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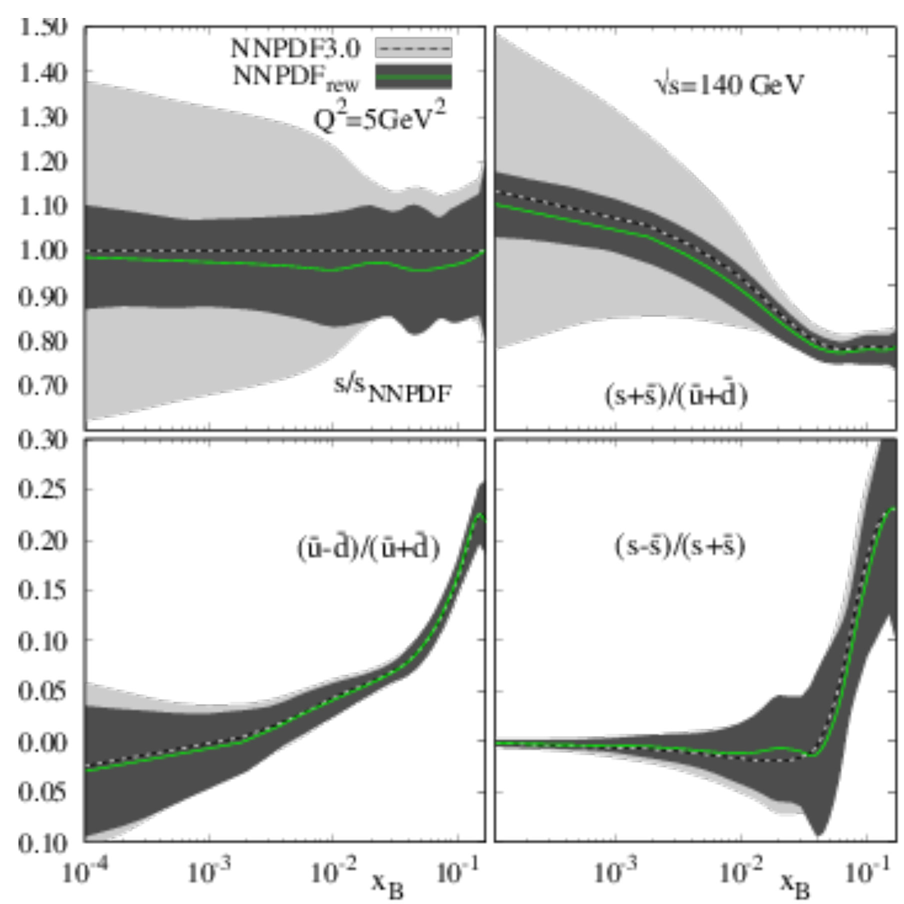
Aschenauer et *al.*, PRD99 (2019) no.9, 094004



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- Also, I was requested to do a phenomenological study of final-state effects in e+A SIDIS for the EIC Yellow Report. arXiv:2103.05419

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- I promised DFG.

Incorporating FFs in xFitter

Read input

Initialisation of theory modules

Initial PDF parametrisation

Evolution

Minimisation routine

Store output

Incorporating FFs in xFitter

Most of the changes made are based on the structure incorporated by Helenius et *al*. for nuclear PDFs.

PRD100 (2019) no.9, 096015

Read input

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Store output

Read input

- **Steering file** → The only thing that the user has to modify. Pick running mode, perturbative order, heavy flavour scheme, data to fit, etc.
- **Experimental data files**
- **Initial parameters**

Running modes: ‘Fit’, ‘LHAPDF Analysis’.

Read input

- **Steering file**
- **Experimental data files**
- **Initial parameters**

- 2 new flags: ***fragfunc*** and ***joint***.
- 4 running modes for 'Fit':

fragfunc	joint	fits	tested?
F	F	PDFs (standard)	yes
T	F	FFs (PDFs fixed)	yes
F	T	PDFs including SIDIS data (FFs fixed)	no
T	T	PDFs and FFs	no

- flag to (de)activate nuclear effects in deuterium.
- choice of nuclear/vacuum FFs.
- *pion* (kaon, proton, hadrons planned).
- style of parametrization: AKK, *DSS*.
- values of A to run PDFs/FFs grids.
- grid for output.
- kinematic cuts for SIA and SIDIS.

Read input

Steering file

Experimental data files → add files for SIA and SIDIS, with all their particularities (at least 8 different normalisations for SIA).

Initial parameters

Read input

Steering file

Experimental data files

Initial parameters

- extend internal number of parameters in MINUIT to accommodate for different species and vacuum/nuclear cases.

- parameters for FFs as in DSS (tested) and other sets (tested).

Initial PDF parametrisation →

+ FF

- Create parametrisation for fragmentation functions with A dependence.
- The parametrisation depends on the FF style selected.

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Evolution

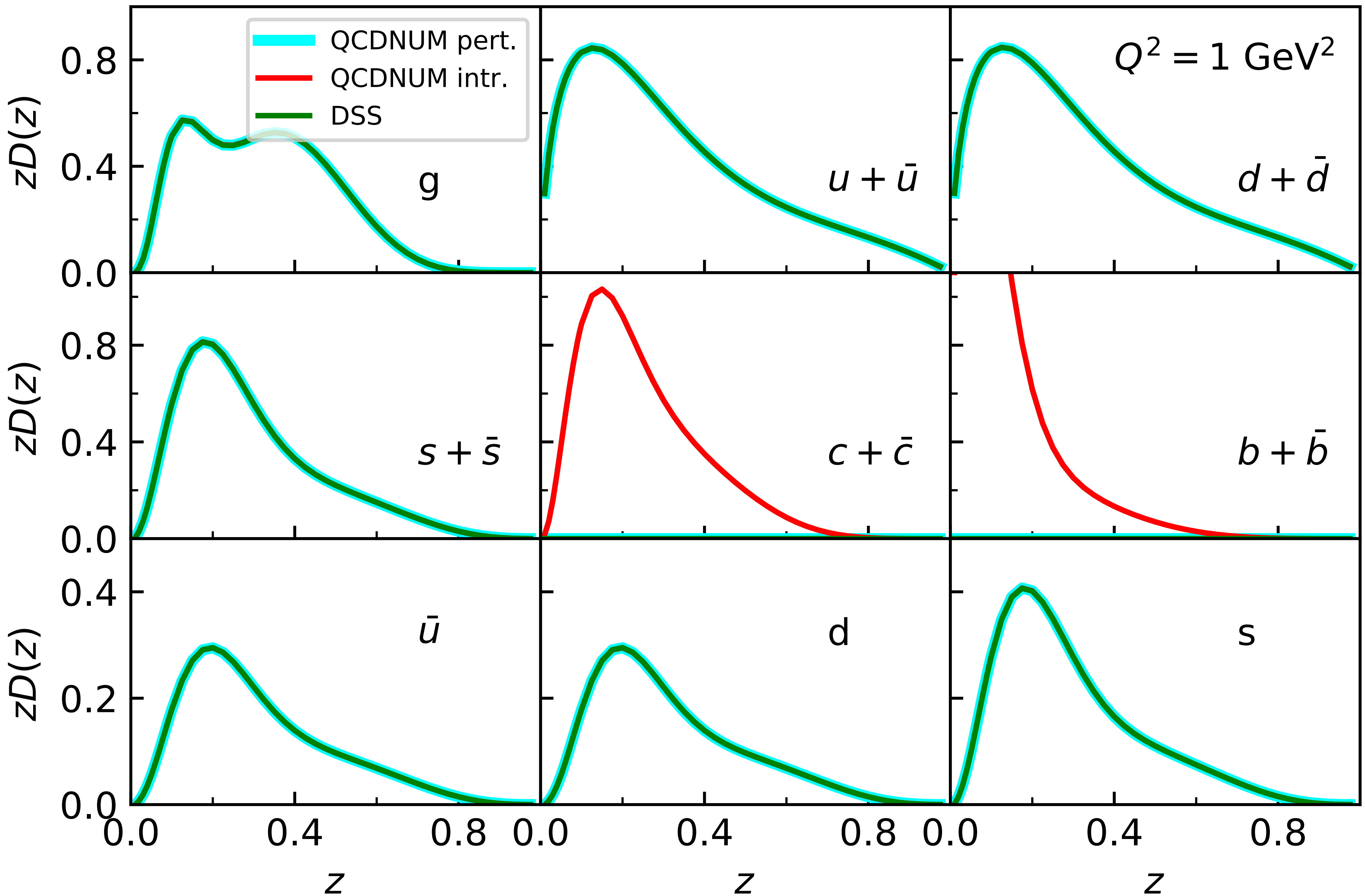
- QCDNUM with intrinsic heavy flavour to replicate baseline FFs.
- APFEL (to be tested) for AKK-style FFs.

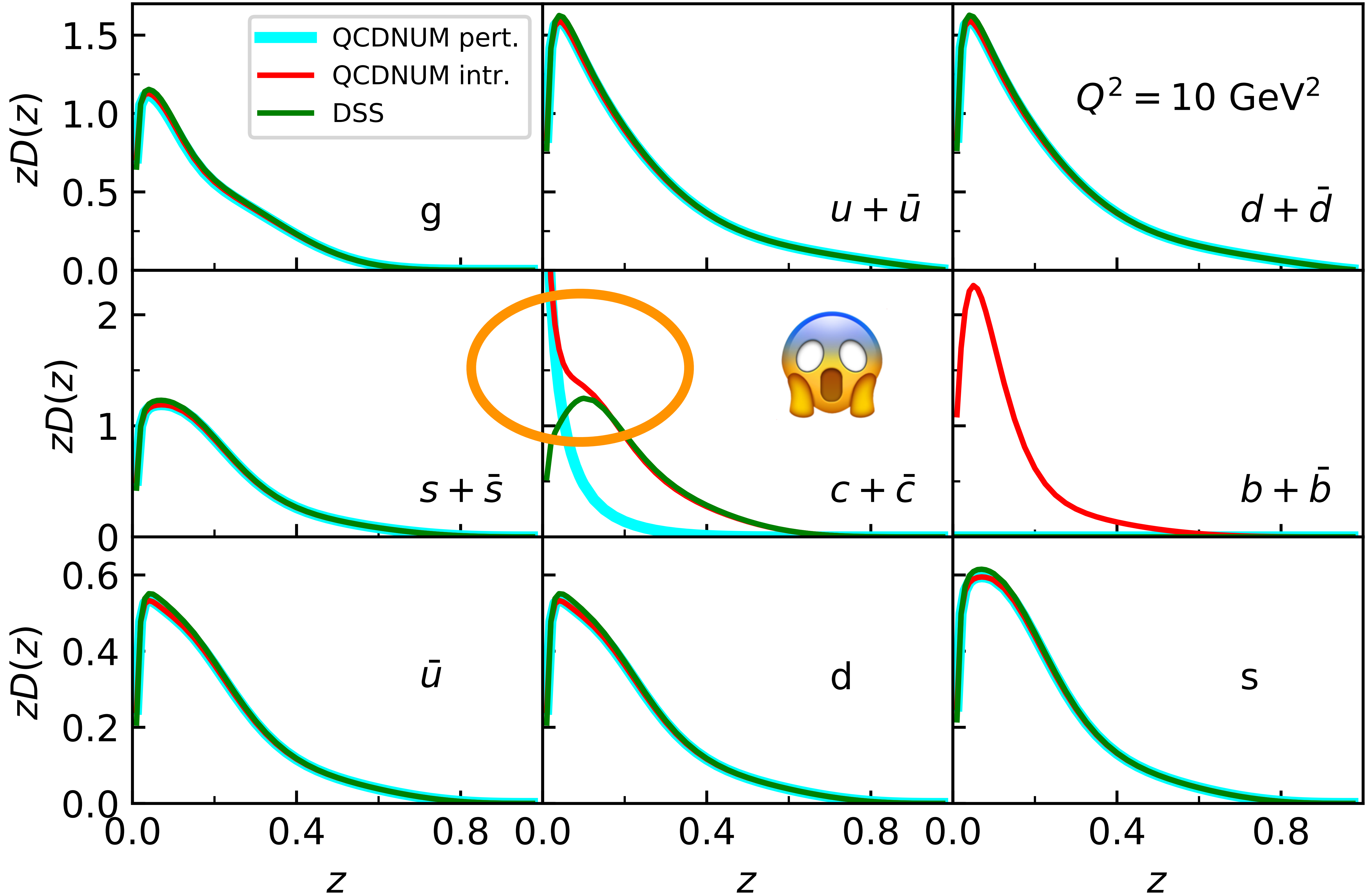
The difference is on the treatment of heavy flavour distributions, particularly the thresholds considered.

vacuum FFs for pions : QCDNUM+DEHSS2014 parametrisation

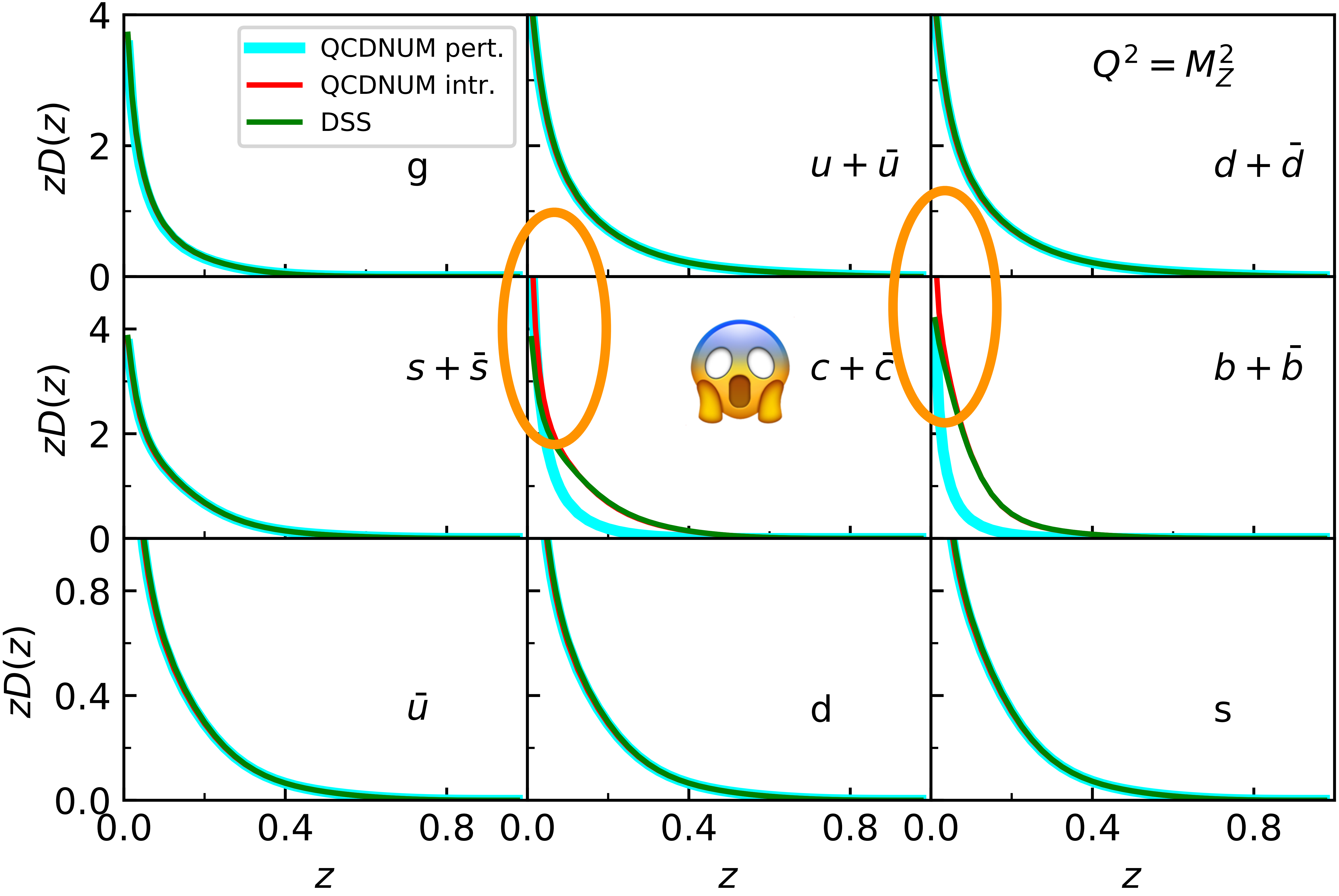
Phys.Rev.D 91 (2015) 1, 014035

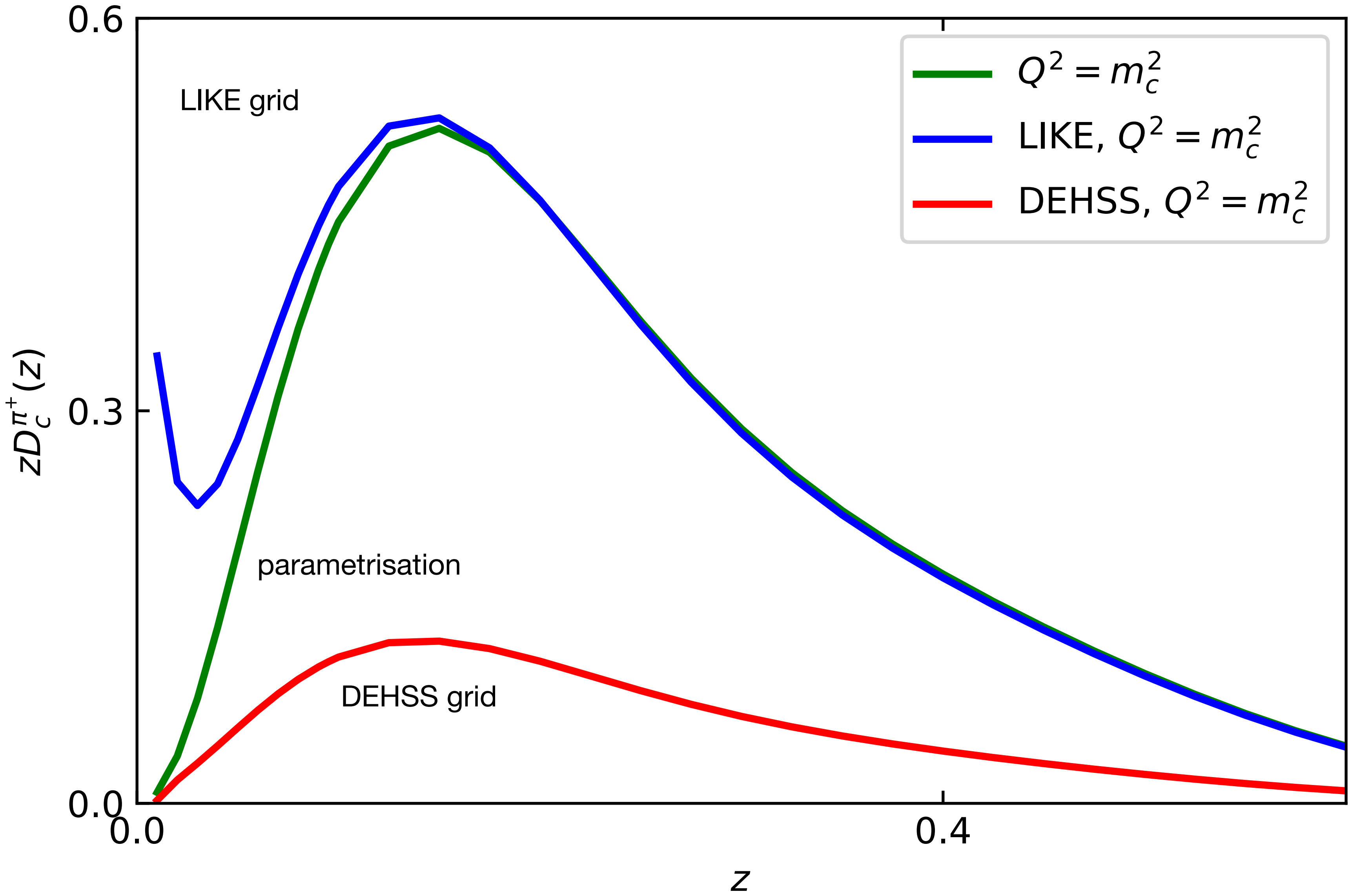
DEHSS2014: charm and bottom fixed to zero for $Q^2 < m_{c,b}^2$





QCDNUM pert.
QCDNUM intr.
DSS
$Q^2 = 10$ GeV^2
g
$u + \bar{u}$
$d + \bar{d}$
$s + \bar{s}$
$c + \bar{c}$
$b + \bar{b}$
$\bar{u}$
d
s
$zD(z)$
z


QCDNUM pert.
QCDNUM intr.
DSS
$Q^2 = M_Z^2$
g
$u + \bar{u}$
$d + \bar{d}$
$s + \bar{s}$
$c + \bar{c}$
$b + \bar{b}$
$\bar{u}$
d
s
$zD(z)$
z
0
2
4
0.0
0.4
0.8



LIKE = DEHSS implementation in xFitter

- Charm and bottom at respective thresholds (from grid) are not as in the DEHSS paper.
- This effect comes from the interpolation over a grid where m_c and m_b are not support points.
- Even when using m_c and m_b as support points the interpolator makes funny things close to the thresholds.
- Possibly solvable modifying the interpolation routine to use three grids.

Minimisation routine

Cross-section

- (massless) SIA and SIDIS routines written from scratch up to NLO accuracy in z-space.
- For SIDIS the output is the ratio of SIDIS/ DIS as required for comparison with data.
- Heavy flavour FFs set to zero below mass thresholds to match DSS style.
- When fitting only one type of parton distribution, a grid containing the convolution of all other quantities is created in the first call (x20 gain in speed for FF fitting).

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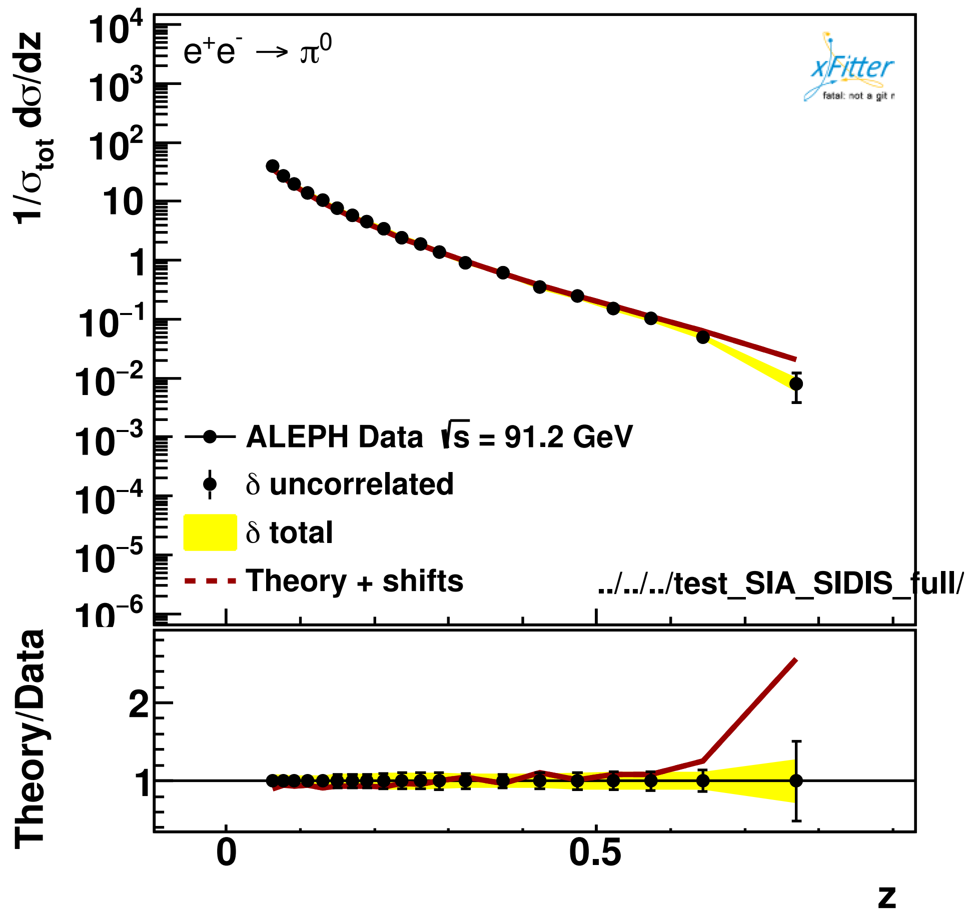

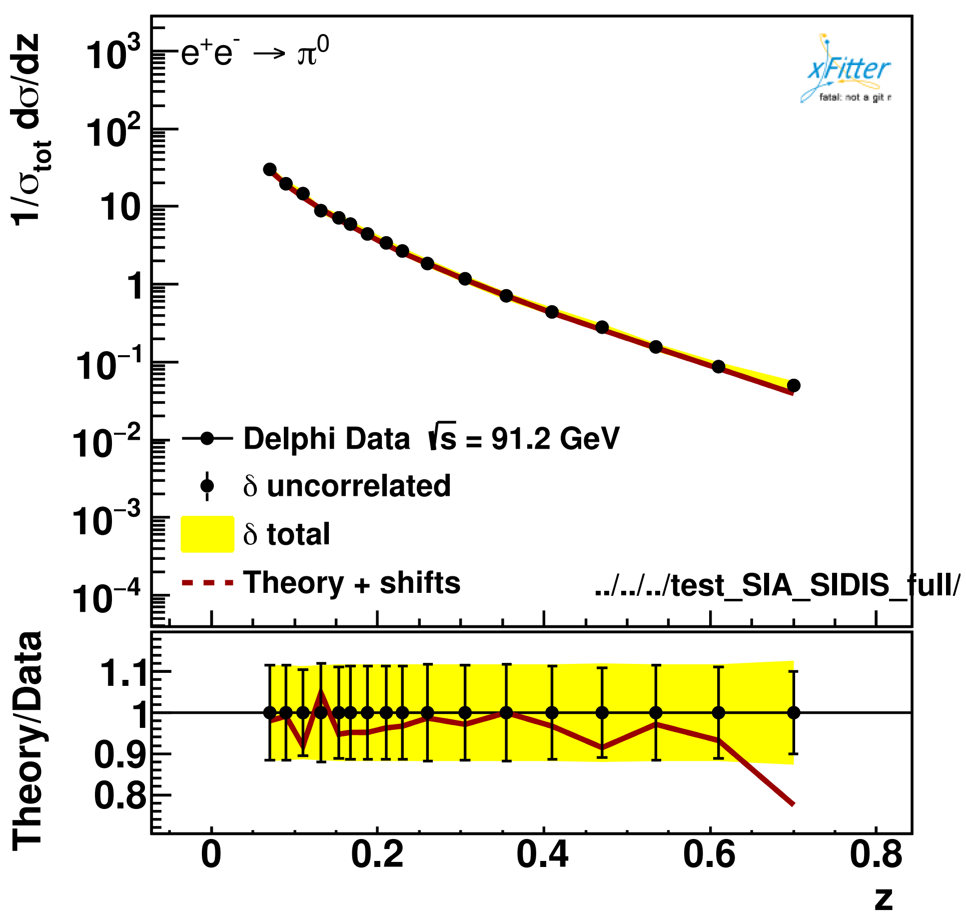

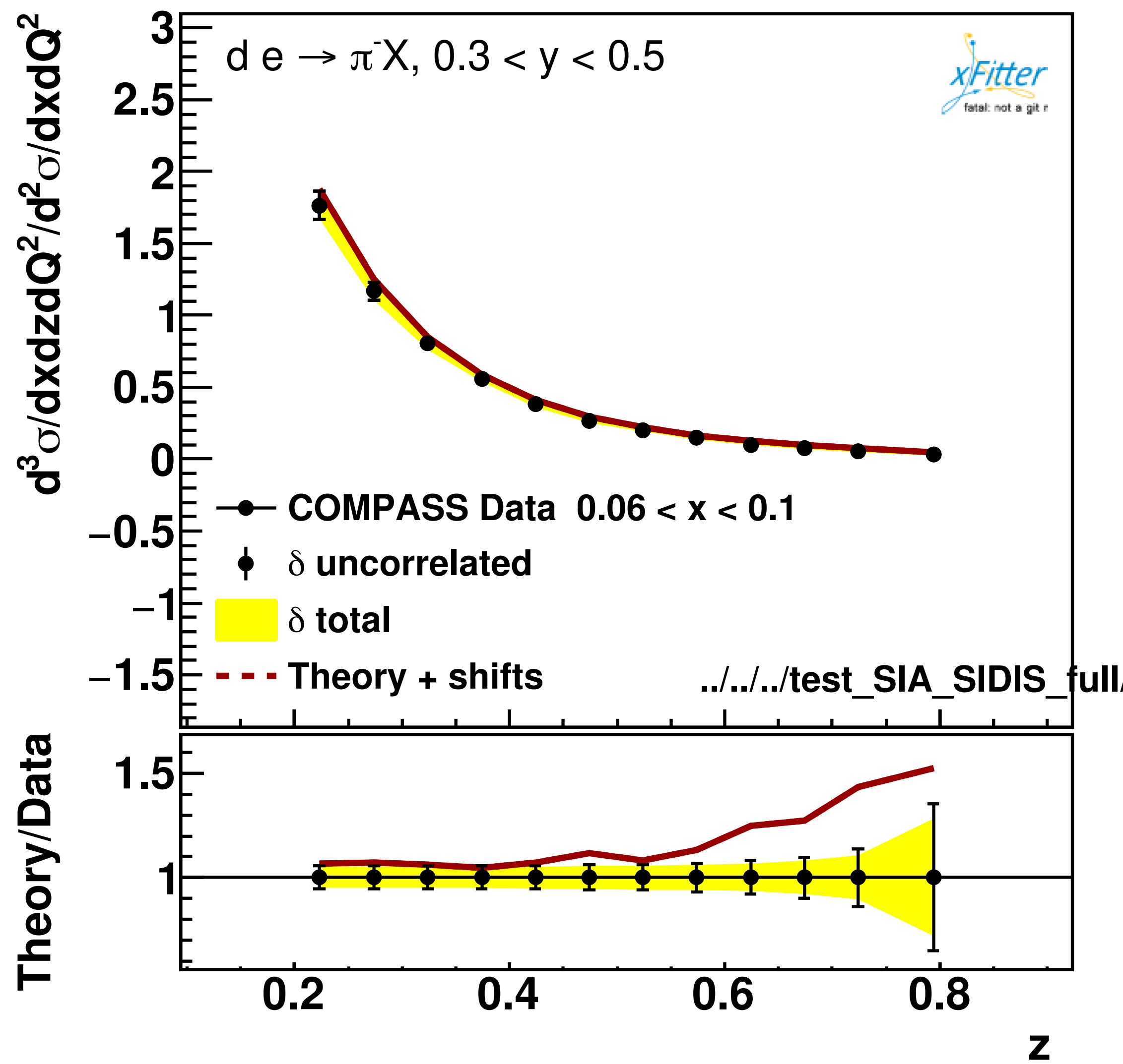

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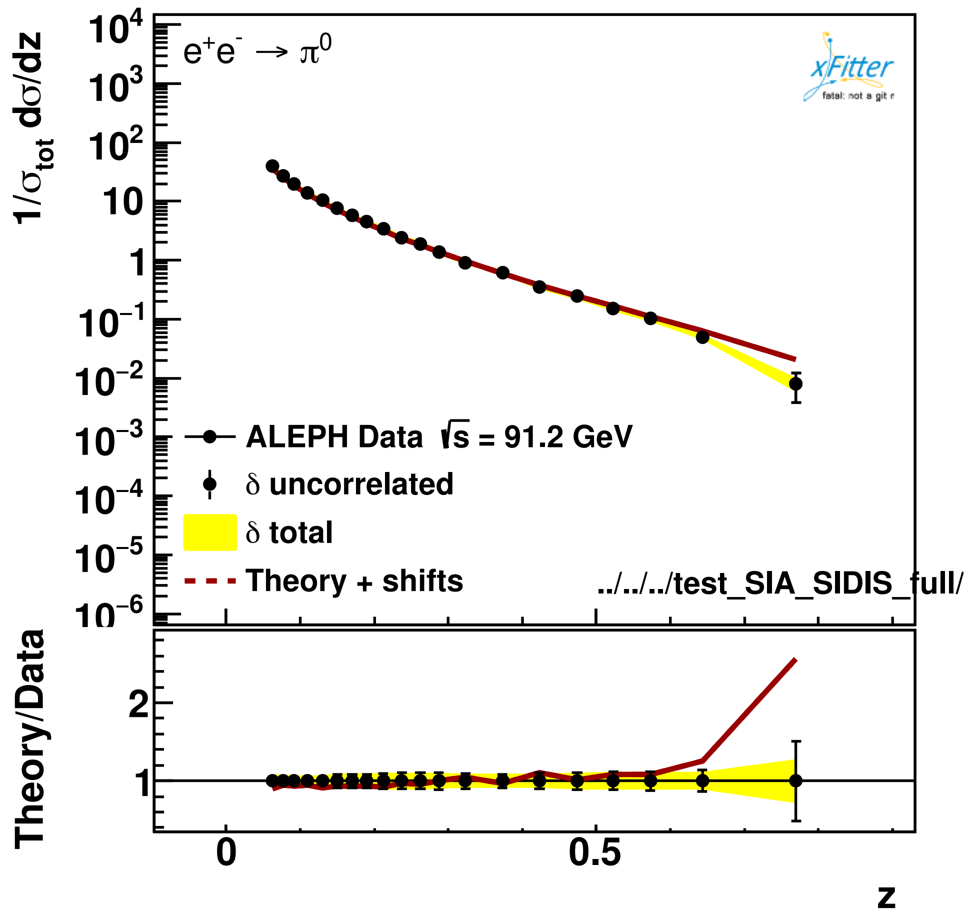

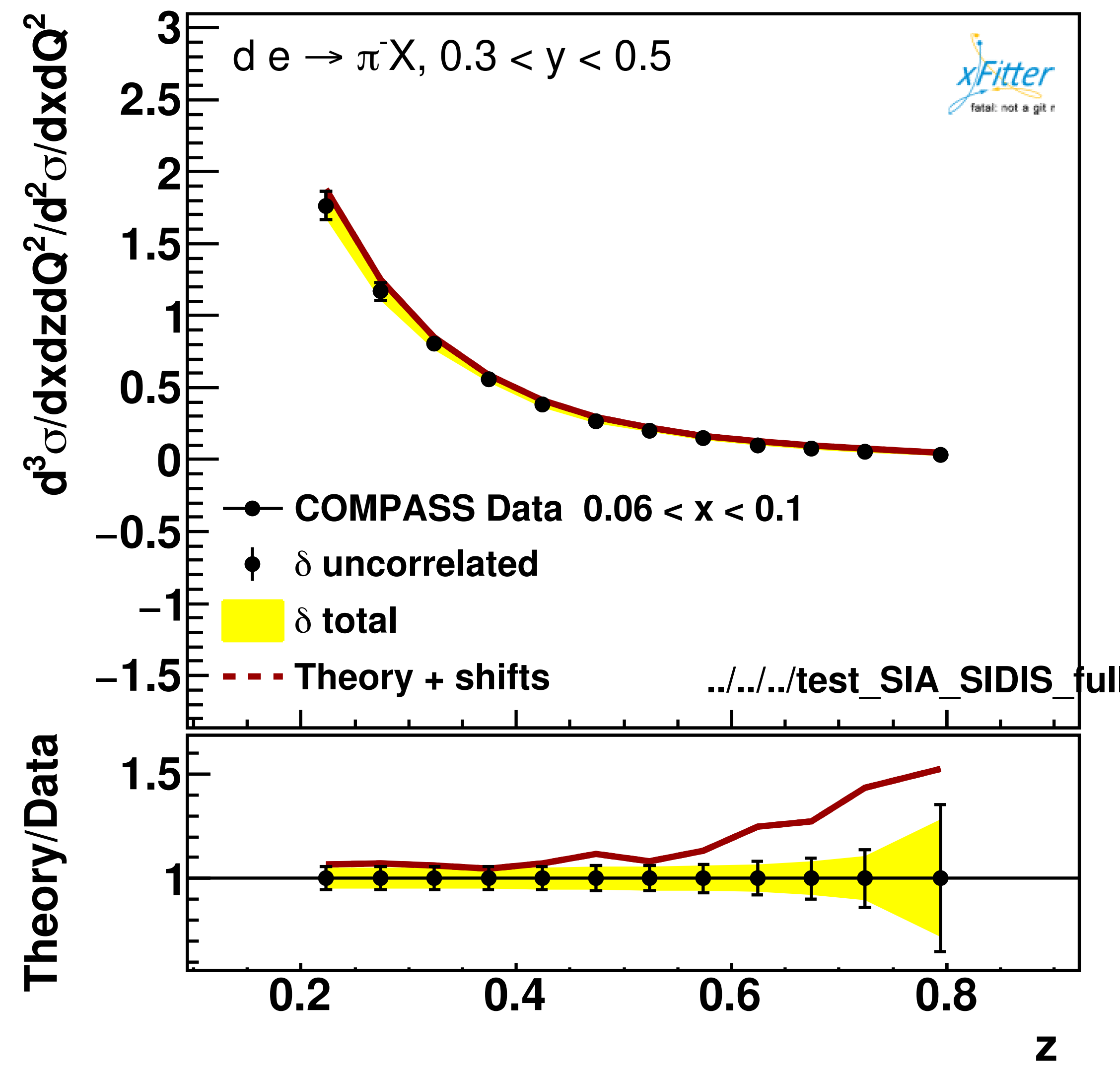

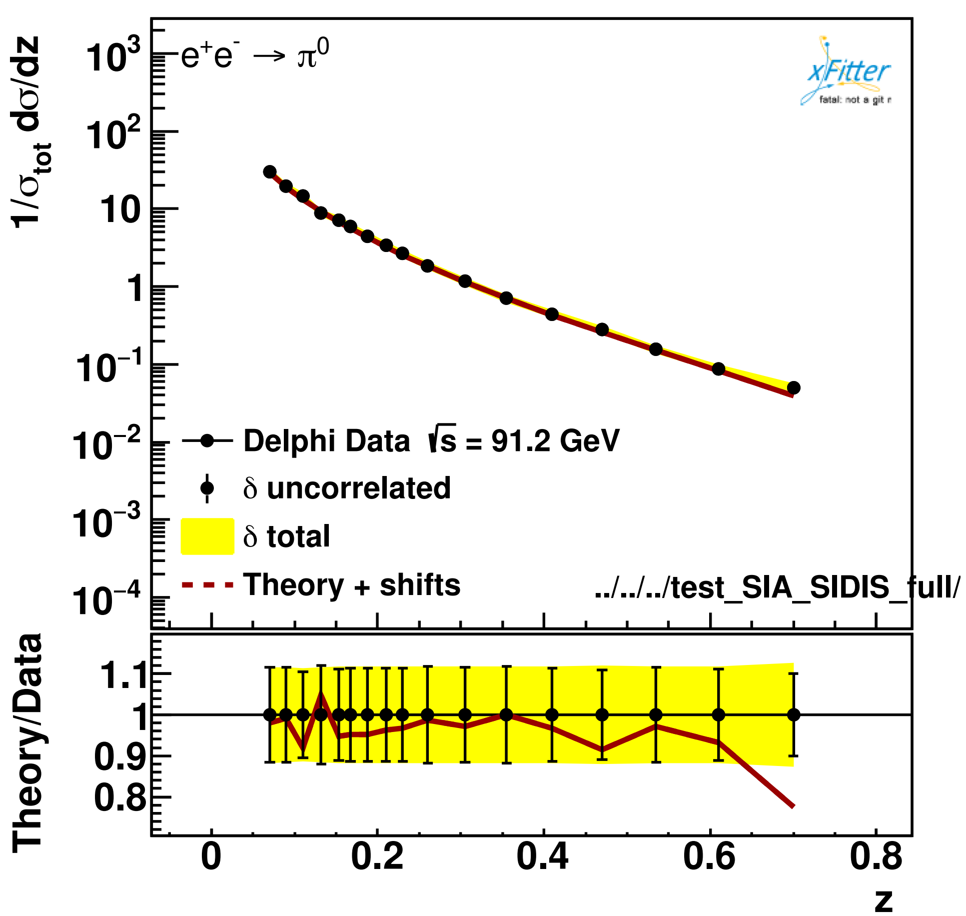

Some tension with:

- HERMES data as this is not integrated over bins.
- the final COMPASS data (not in the original fit).
- one SIA data set (and I would love to know where people got the data from).

Application to in-medium fragmentation

Some old stuff

nuclear effects observed in e+A SIDIS

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

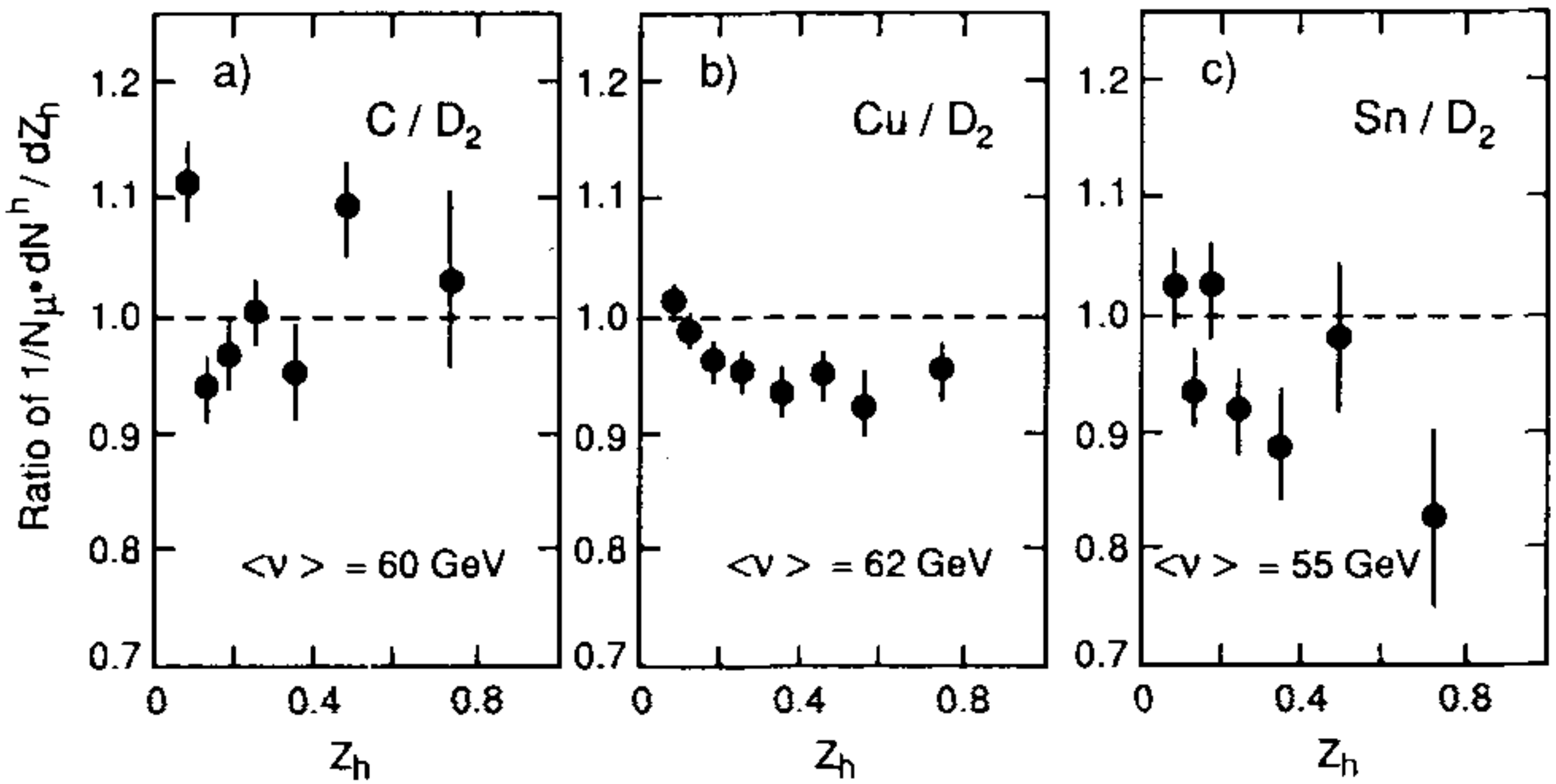

Fig. 4a, b. Ratio of z distributions of nuclear targets relative to D_2. The results on Cu/D_2 shown in **b** are obtained from the high statistics run with the extended target. The errors for multiplicity ratios shown in the following figures always include the error due to the uncertainty in the correction for electron contamination (see text)

EMC Collaboration, Z. Phys. C 52 (1991), 1

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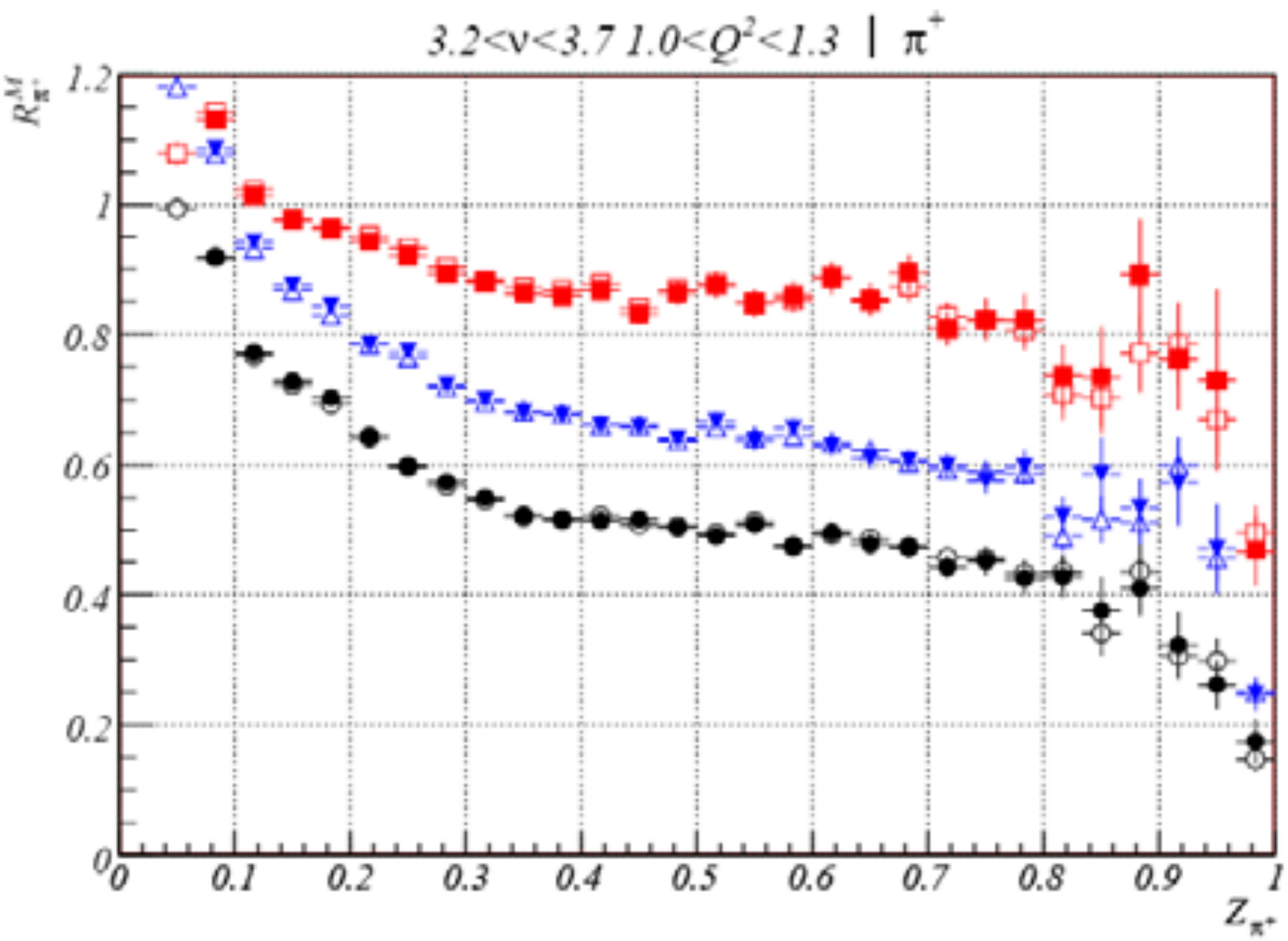
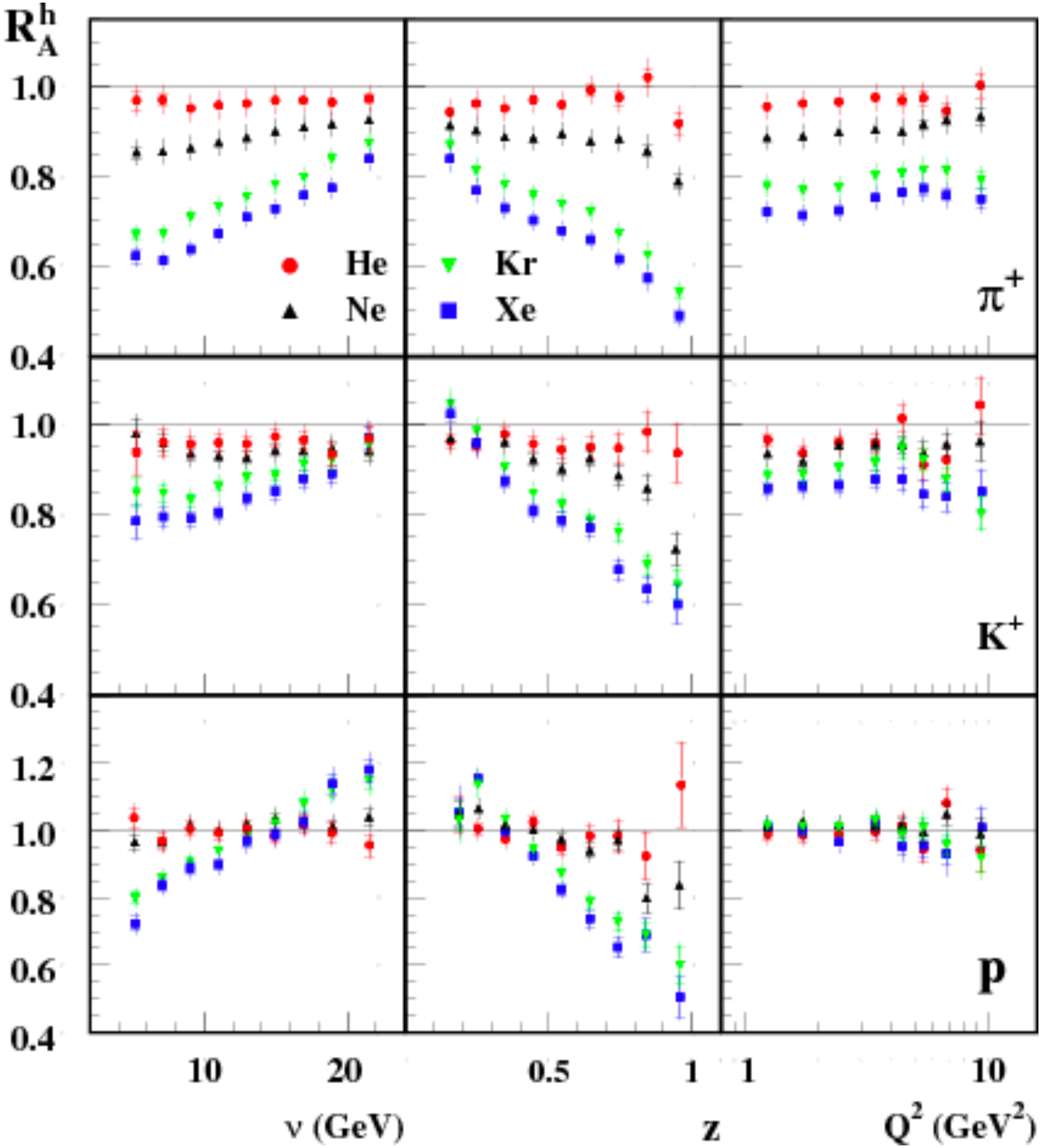


CLAS preliminary data. $E_{beam} \approx 5$ GeV

Preliminary, only statistical uncertainties provided.

HERMES Collaboration, Nucl. Phys. B 780 (2007), 1



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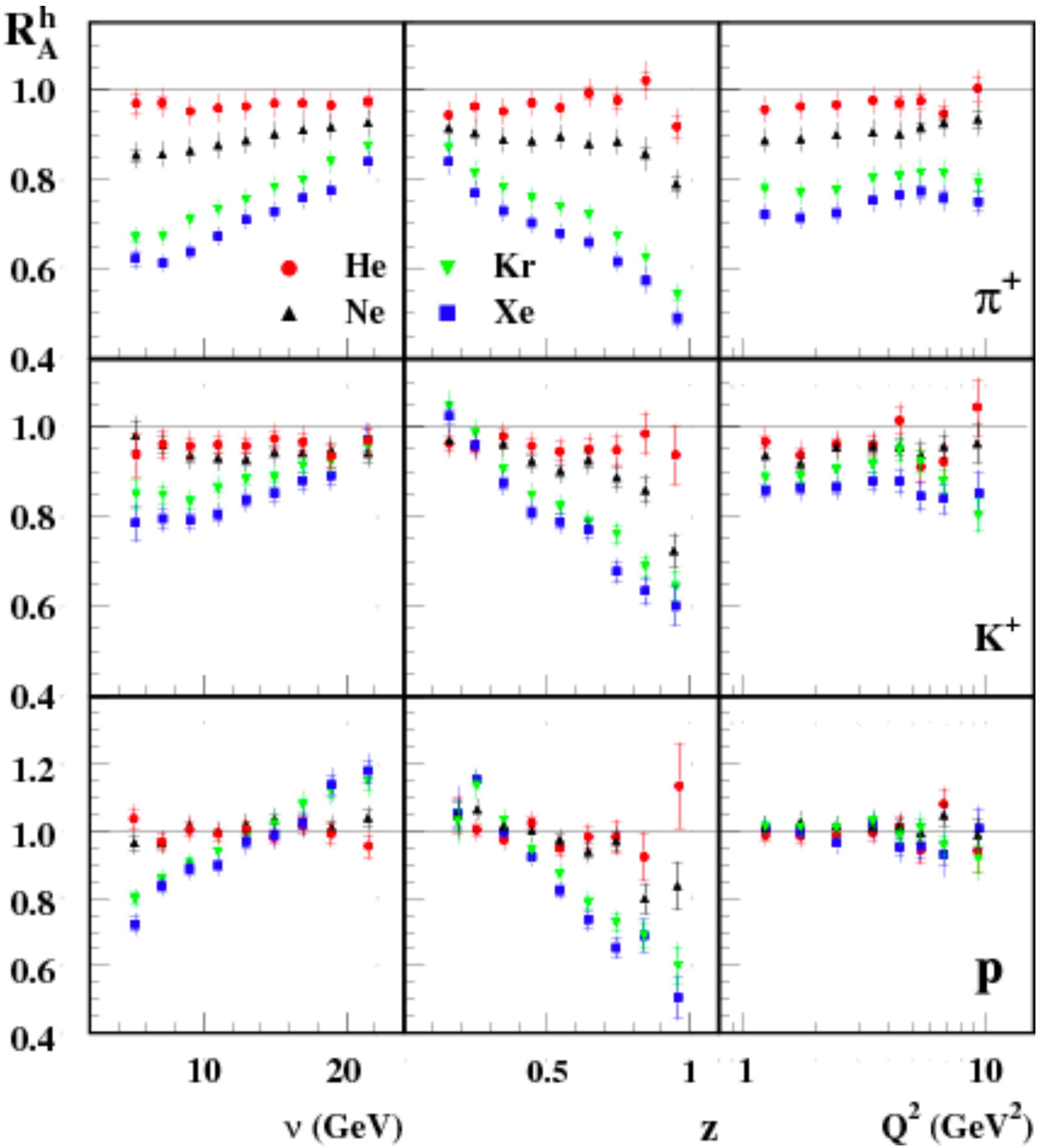
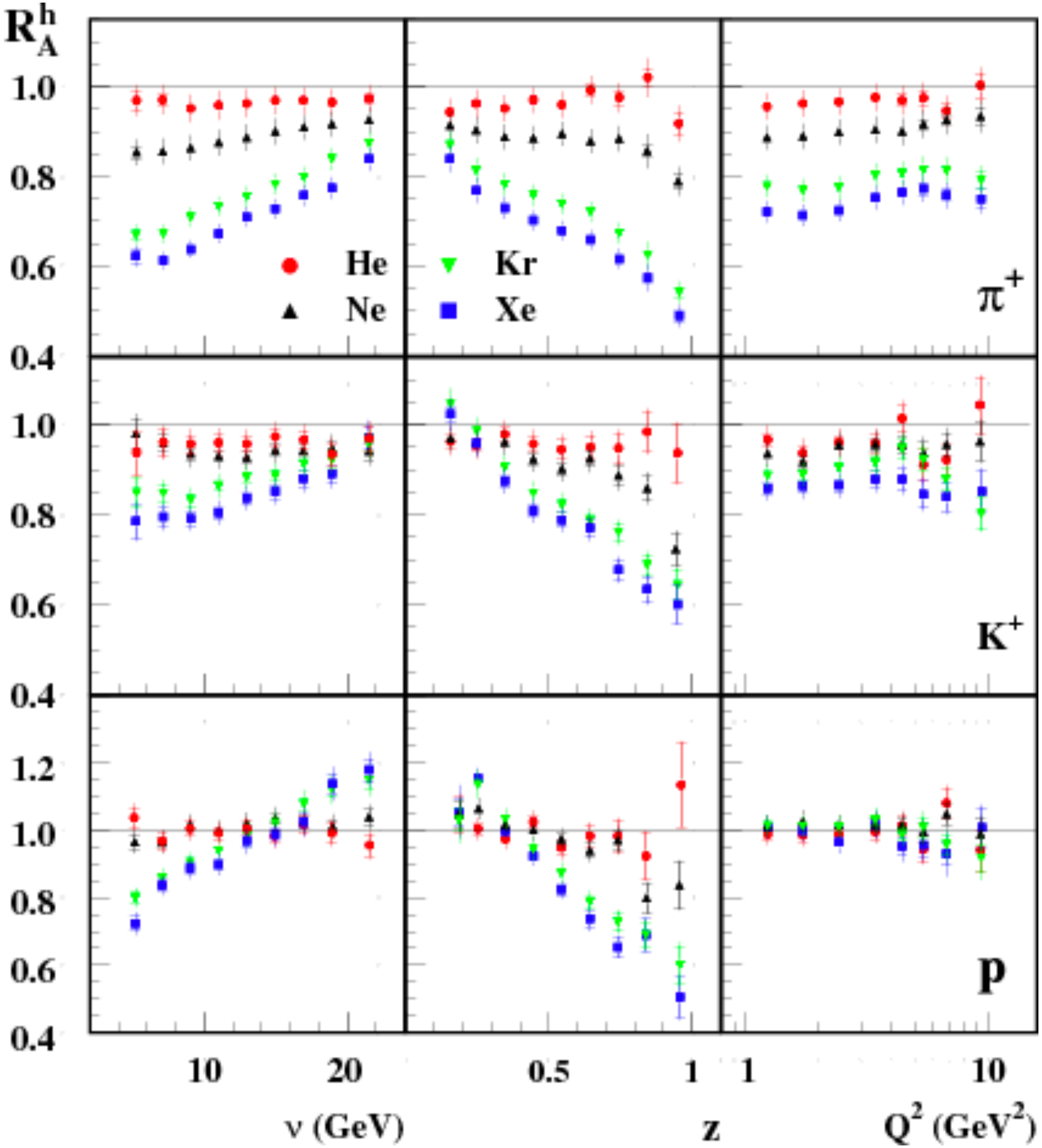


- The effect can't be described with nPDFs.
- Several models in terms of multiple particle interaction, energy loss, etc.

Riv.Nuovo Cim. 32 (2010) 439

HERMES Collaboration, Nucl. Phys. B 780 (2007), 1



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Riv.Nuovo Cim. 32 (2010) 439

- We wanted a phenomenological way of describing the observable.
- *Introduced medium modified FFs (nFFs).*

$$D^h_{i/A}(z, Q_0^2) = \int_z^1 \frac{dy}{y} W_i^h(y, A, Q_0^2)\, D_i^h\left(\frac{z}{y}, Q_0^2\right)$$

vacuum baseline from DSS07: Phys.Rev.D 75 (2007) 114010

$$W_i^h(y, A, Q_0^2) = n_i y^{\alpha_i}(1-y)^{\beta_i}$$

$$c_i = c_1 + c_2 A^{c_3}$$

Phys.Rev.D 81 (2010) 054001.

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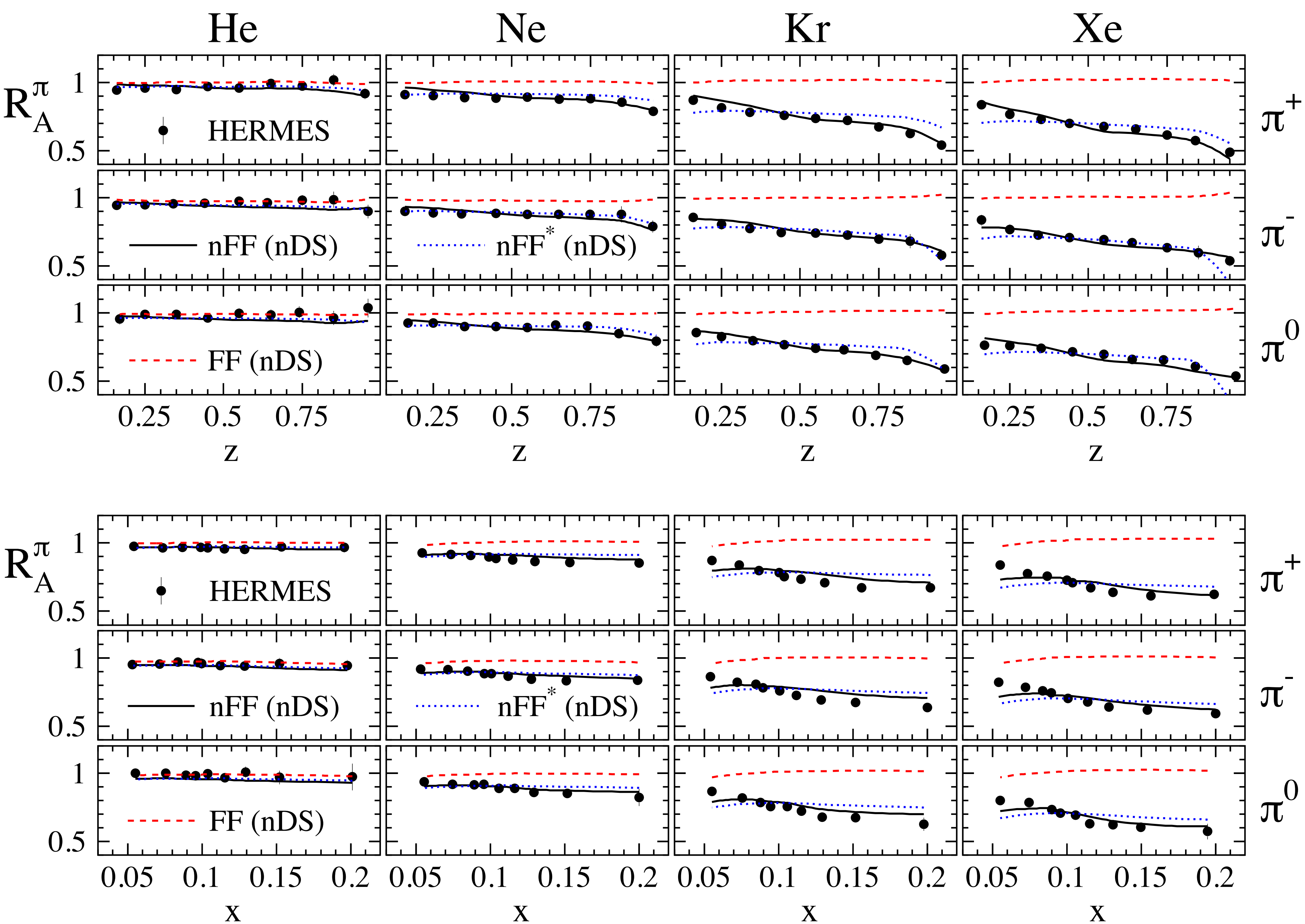
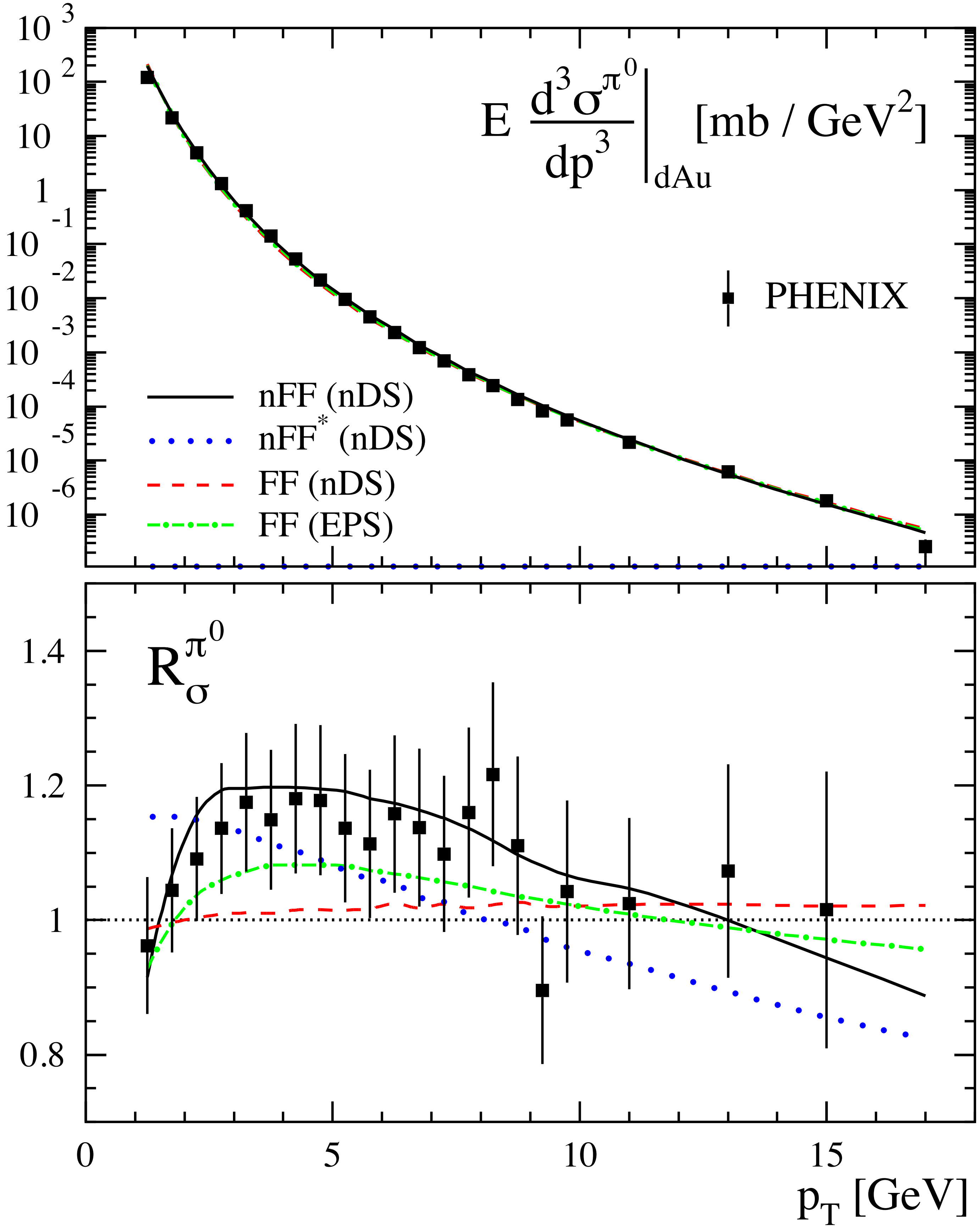


- There is no need for flavour separation for quarks.
- Many parameters are tied together.
- The largest tension comes from the high-x bins of HERMES data.

SIDIS can't constrain the gluon. We used single hadroproduction from RHIC in d+Au collisions:



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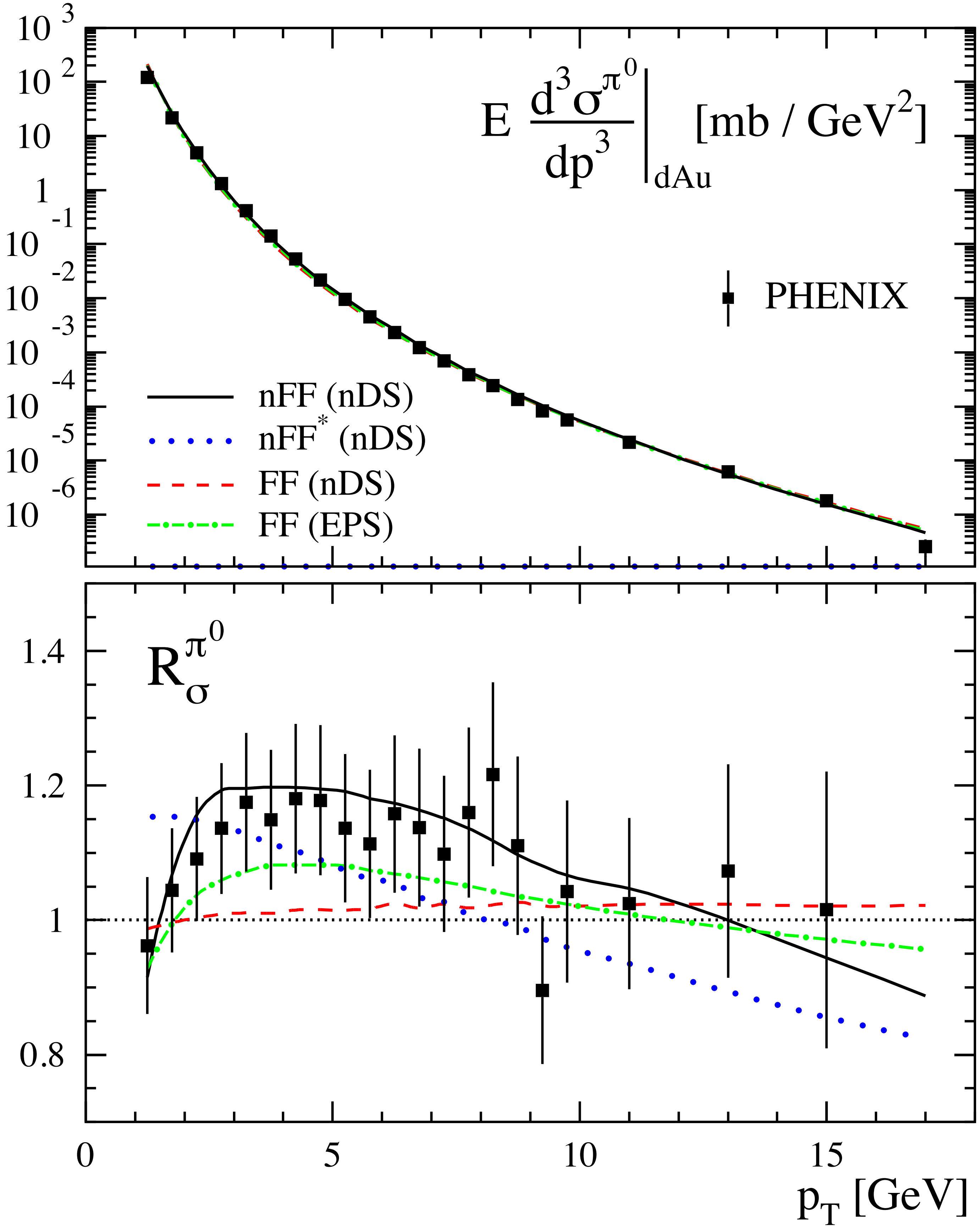
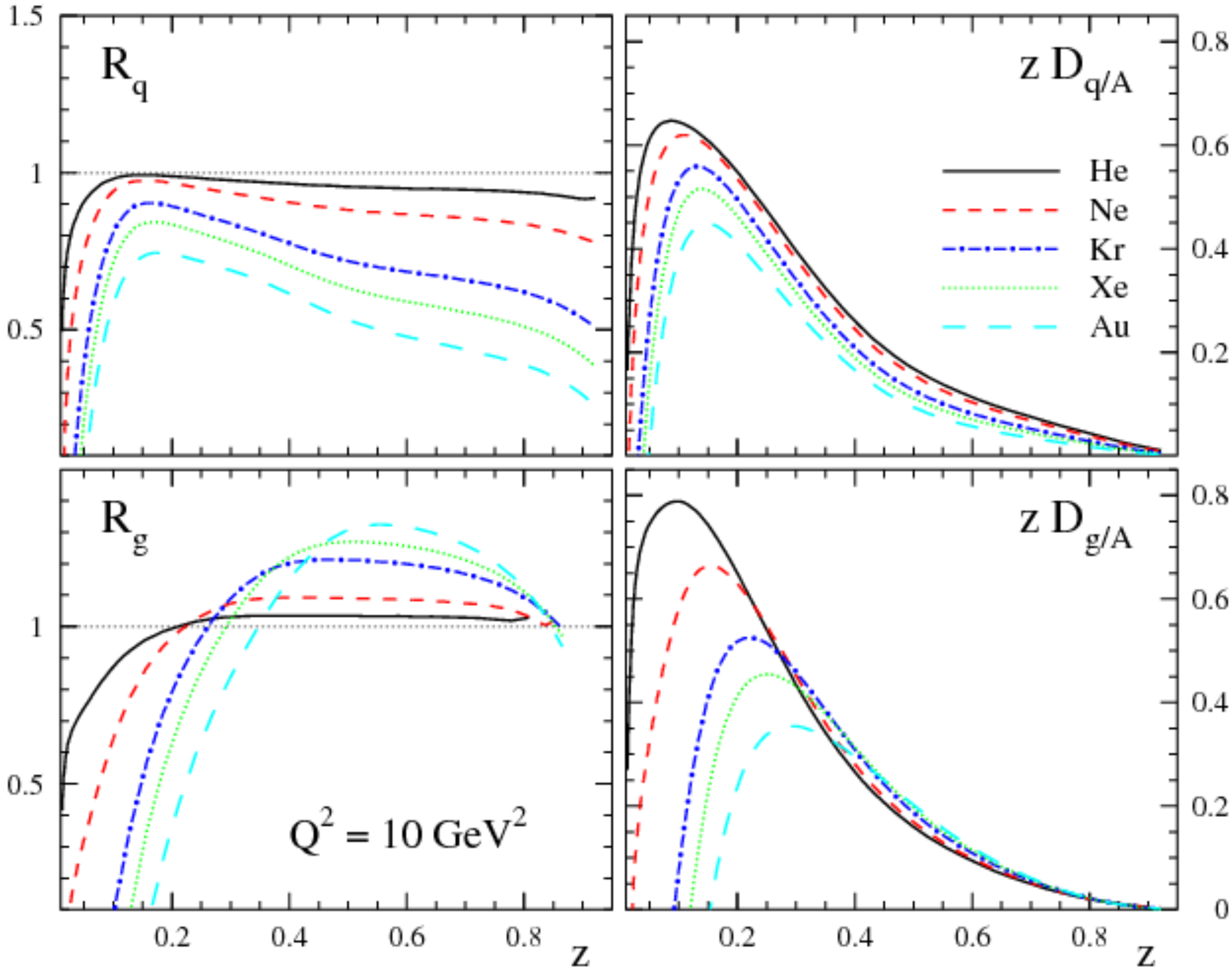
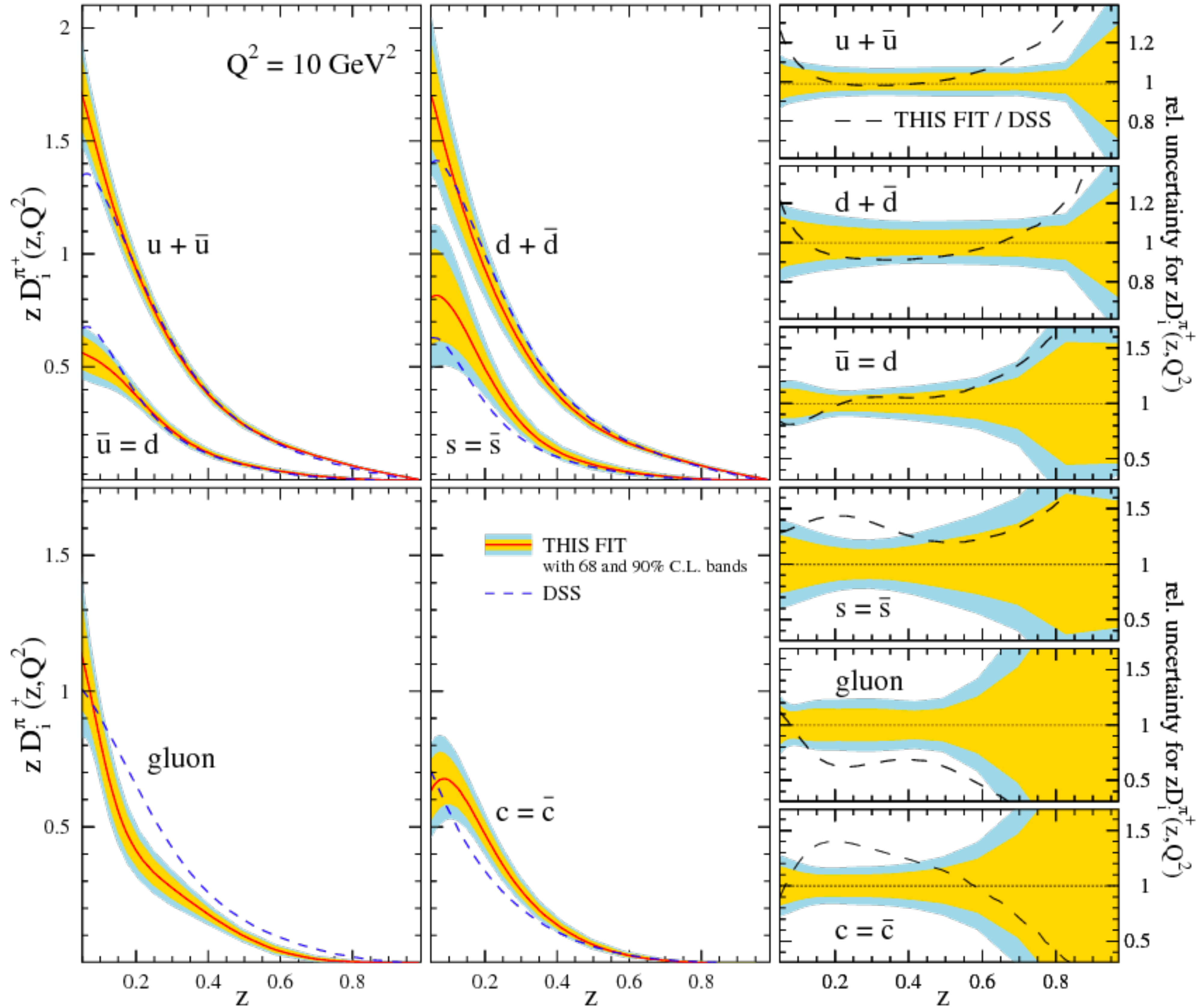


- These data are also used to constrain the gluon nPDF, so we are probably double/triple counting effects.
- But it is true that we found a ~20% decrease of χ^2 for RHIC data in the DSSZ nPDF fit.
- For pions we found a reasonable $\chi^2/d.o.f. = 1.079$ with 14 parameters.
- For kaons the situation was much much worse.

Phys.Rev.D 81 (2010) 054001.



But that was over a decade ago, things have changed significantly with COMPASS.



DEHSS2014, Phys.Rev.D 91 (2015) 1, 014035

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LIKEn21 was determined using xFitter

Take the parametrisation of baseline FFs

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

$i = u+\bar{u}, d+\bar{d}, s+\bar{s}, c+\bar{c}, b+\bar{b}, \bar{u}, g$

$Q_0 = 1\ \textbf{GeV}, m_c, m_b$

and extend it: $D_i^h(z, Q_0) \to D_i^h(z, Q_0, A)$

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

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

$i = q, g$

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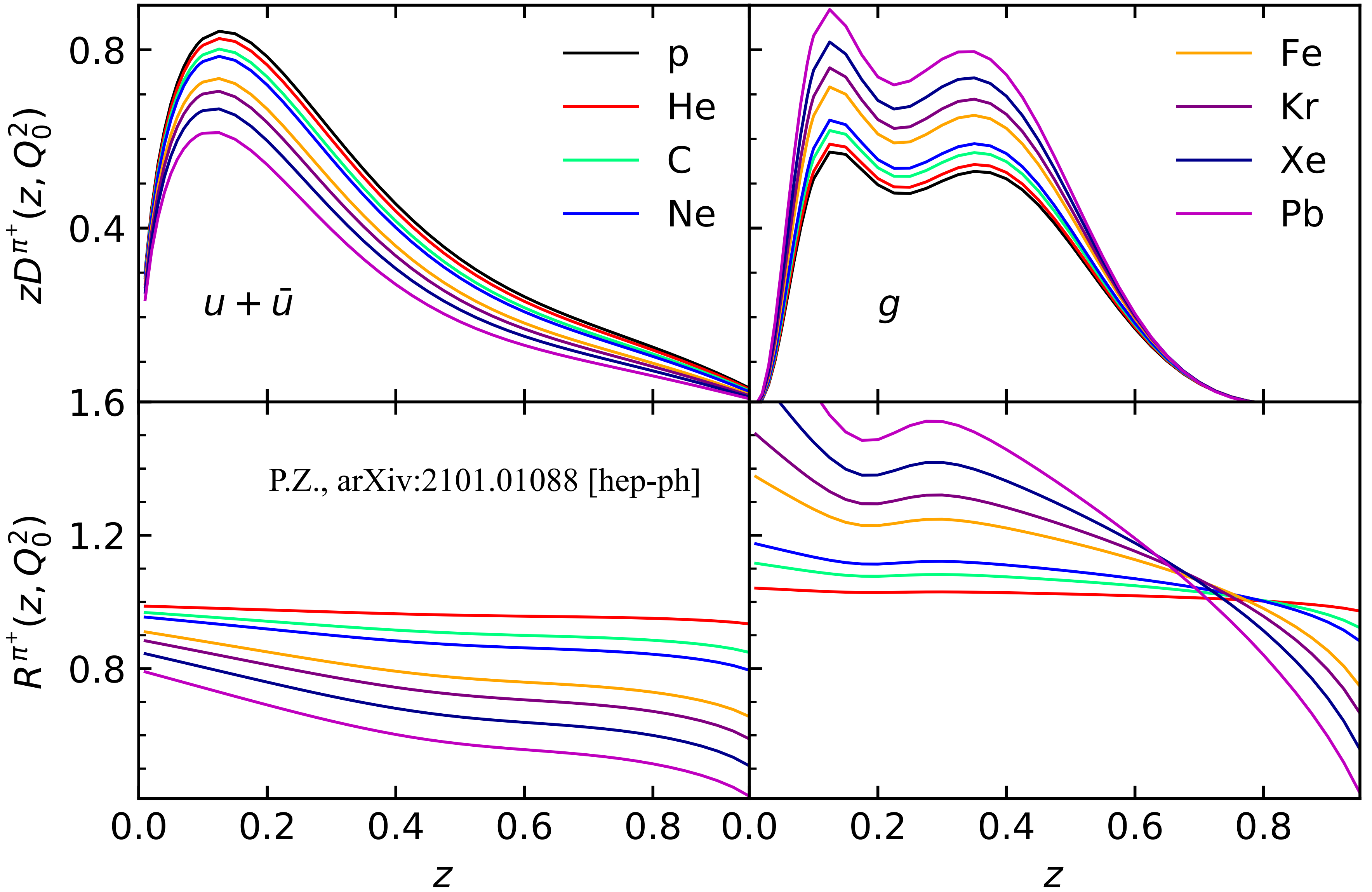
$$i = q, g$$
$$p = \alpha, \beta, \gamma, \delta$$

no flavour sensitivity found

data has no sensitivity at low z $\alpha_{1,i} = \alpha_{2,i} = 0$

- Proton PDFs from MMHT2014 NLO (using LHAPDF).
- No nPDFs (effect cancels in the double ratio).
- We obtain a similar high-z behaviour.



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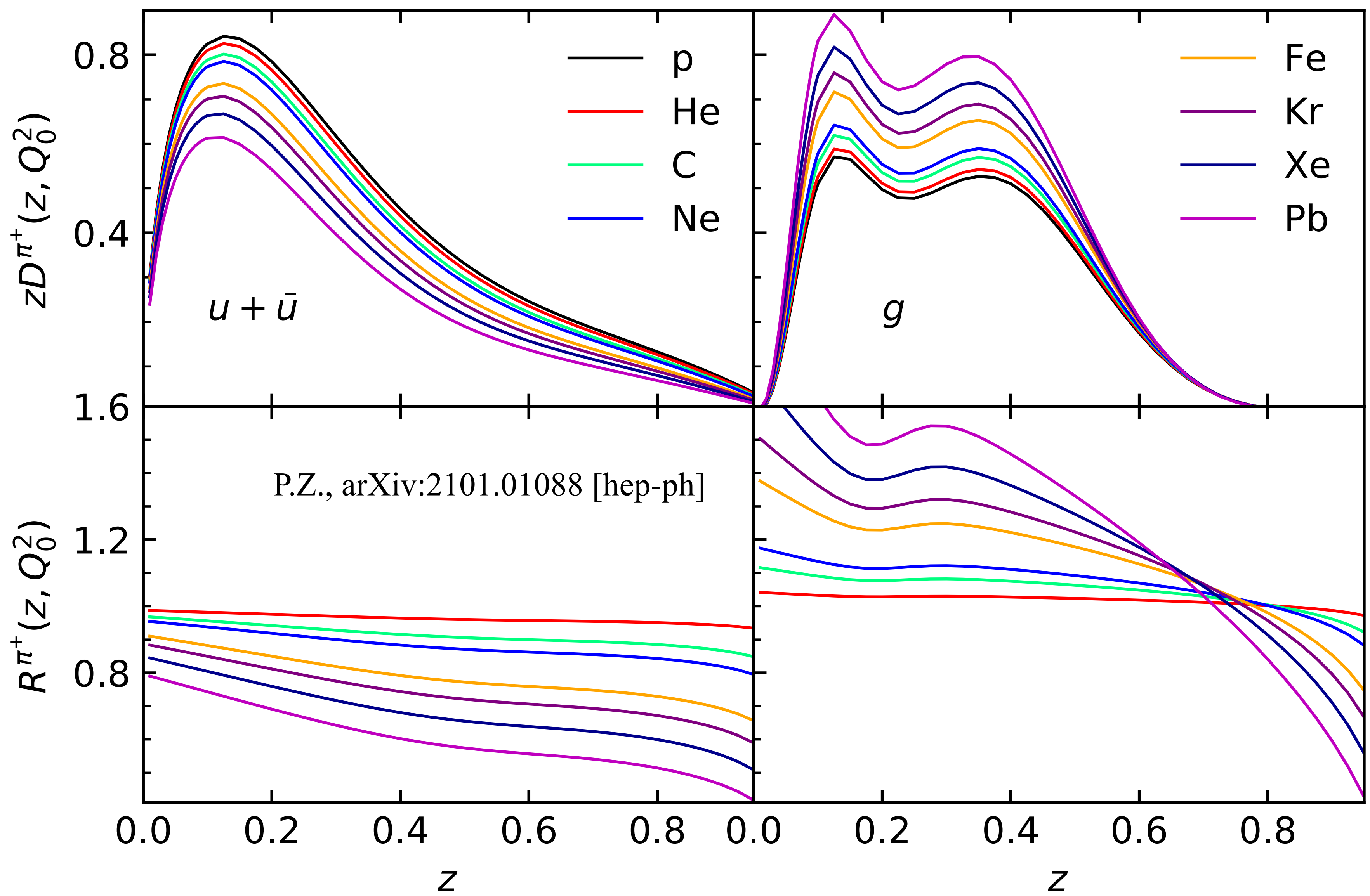

- Without RHIC data the gluon does crazy things at low z if not forced to “behave”.
- Very different low-z behaviour due to artificial constraint on the parameters.
- With the new baseline and different parametrisation, for 7 parameters $\chi^2/d.o.f. = 0.776$
- **-110** units of χ^2 for the HERMES data compared with the 2010 result.

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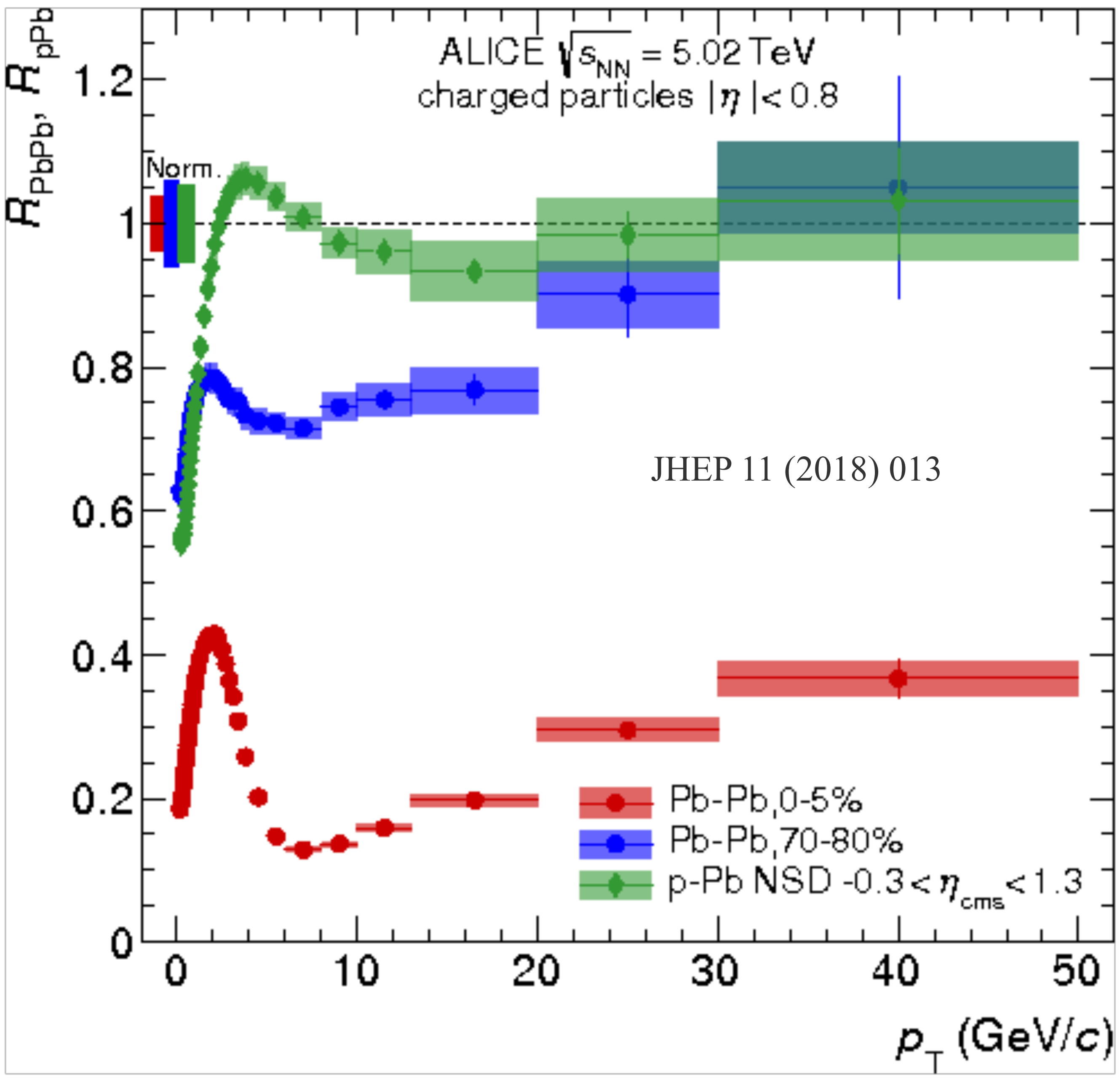

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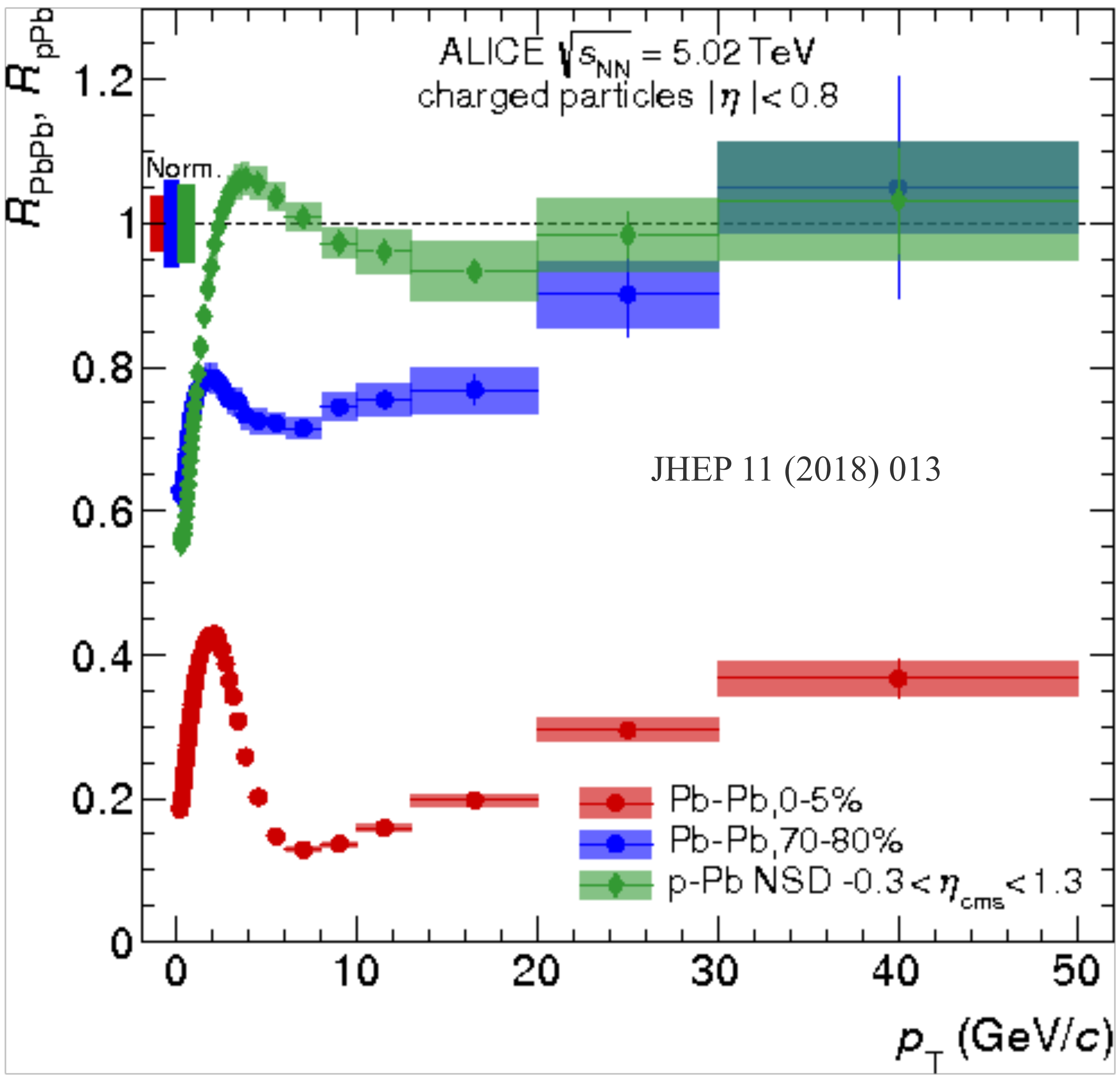

Of course.

But using them requires paying a bias-including price that I am reluctant to pay.

$$\frac{1}{\sigma_{inel}} E \frac{d^3\sigma}{dp^3} = \frac{1}{N_{ev} 2\pi p_T} \frac{d^2N}{dy dp_T}$$

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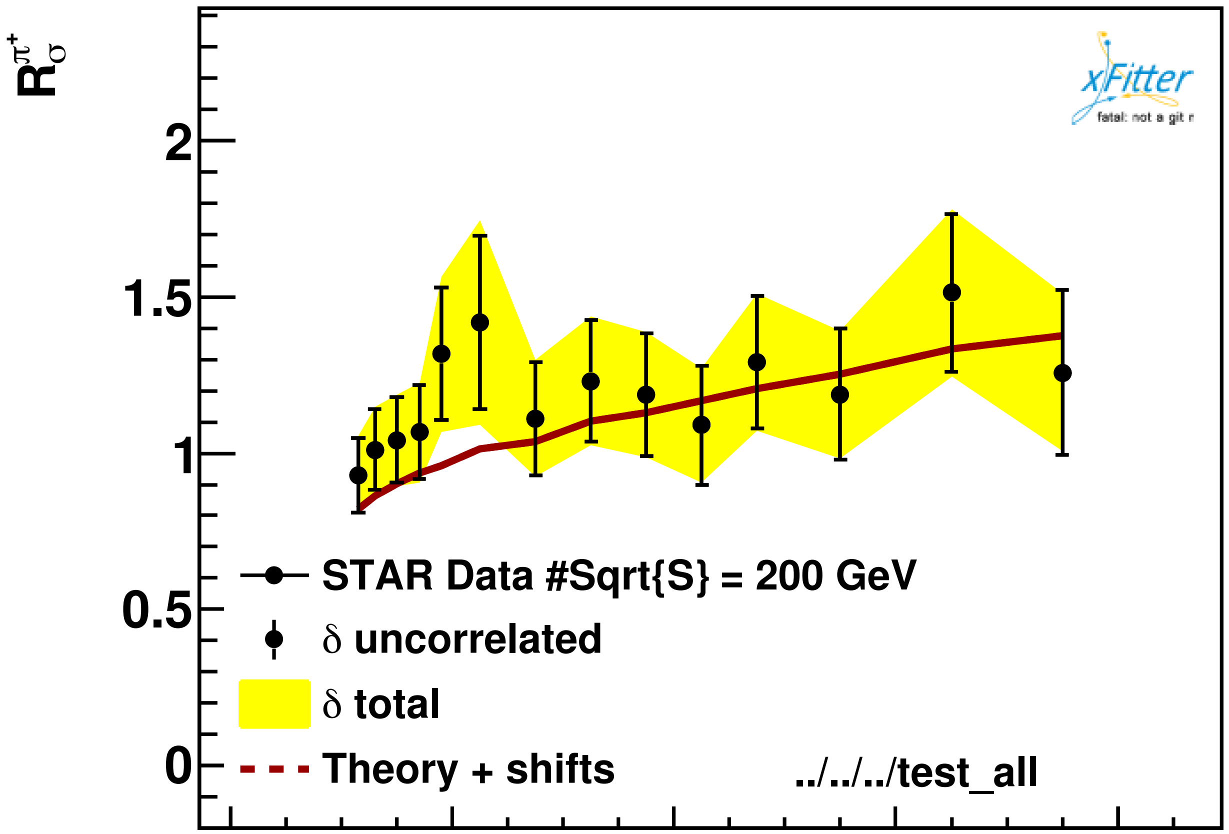
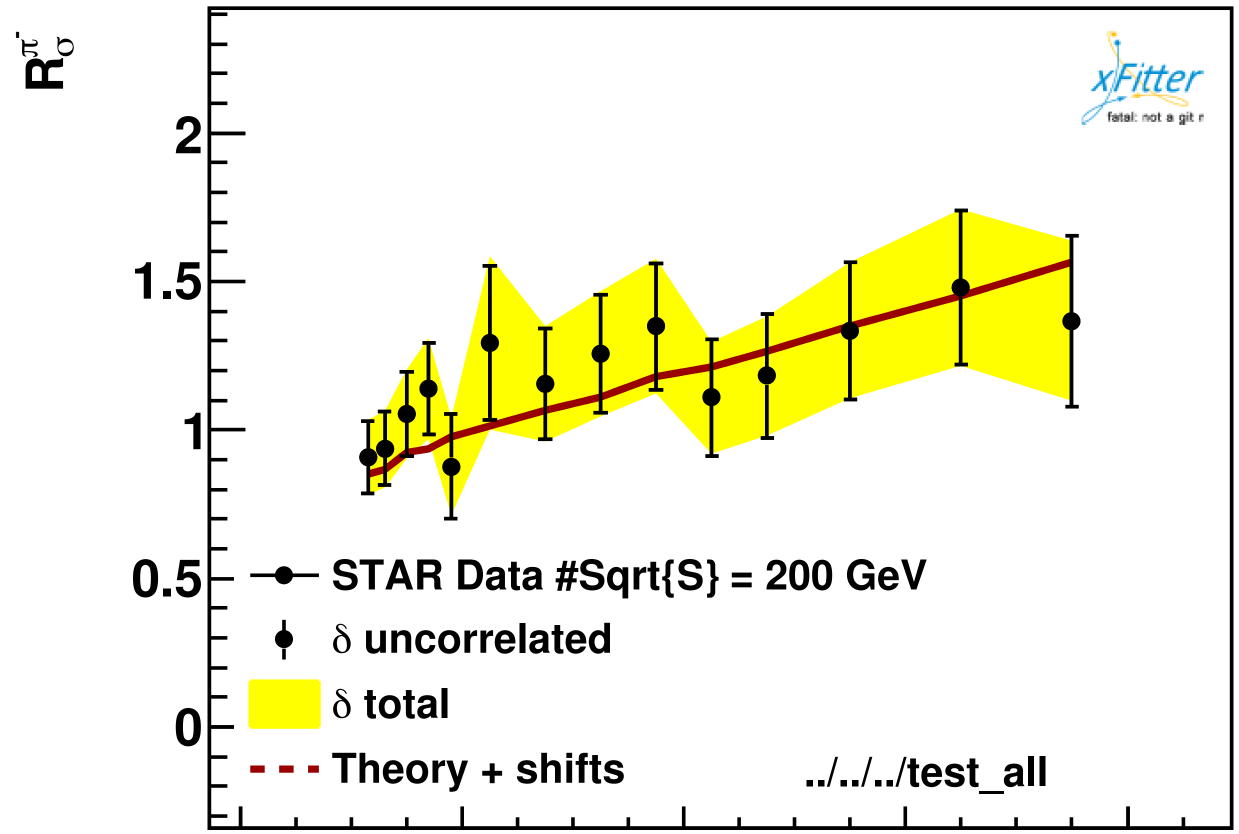
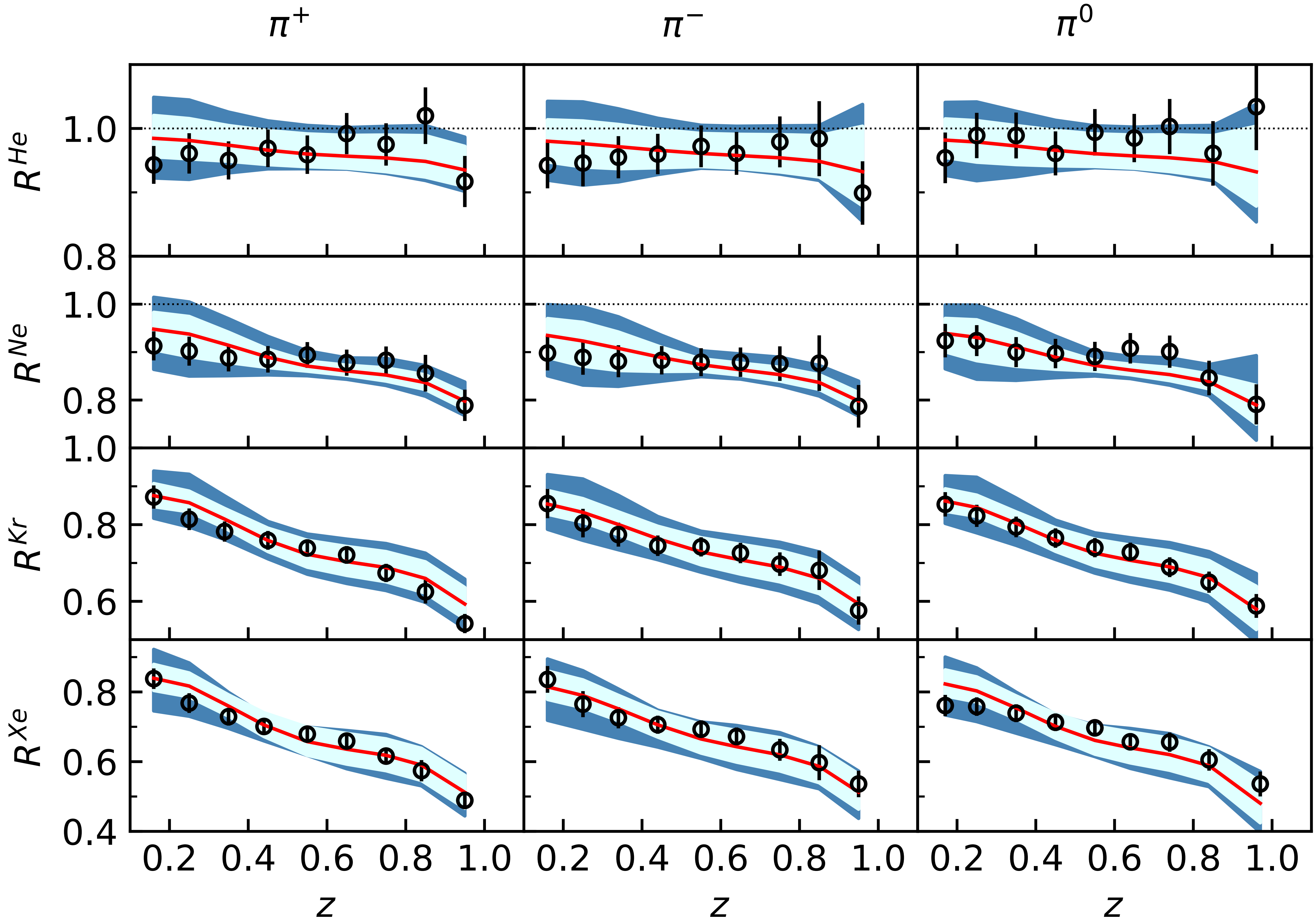
Of course :)

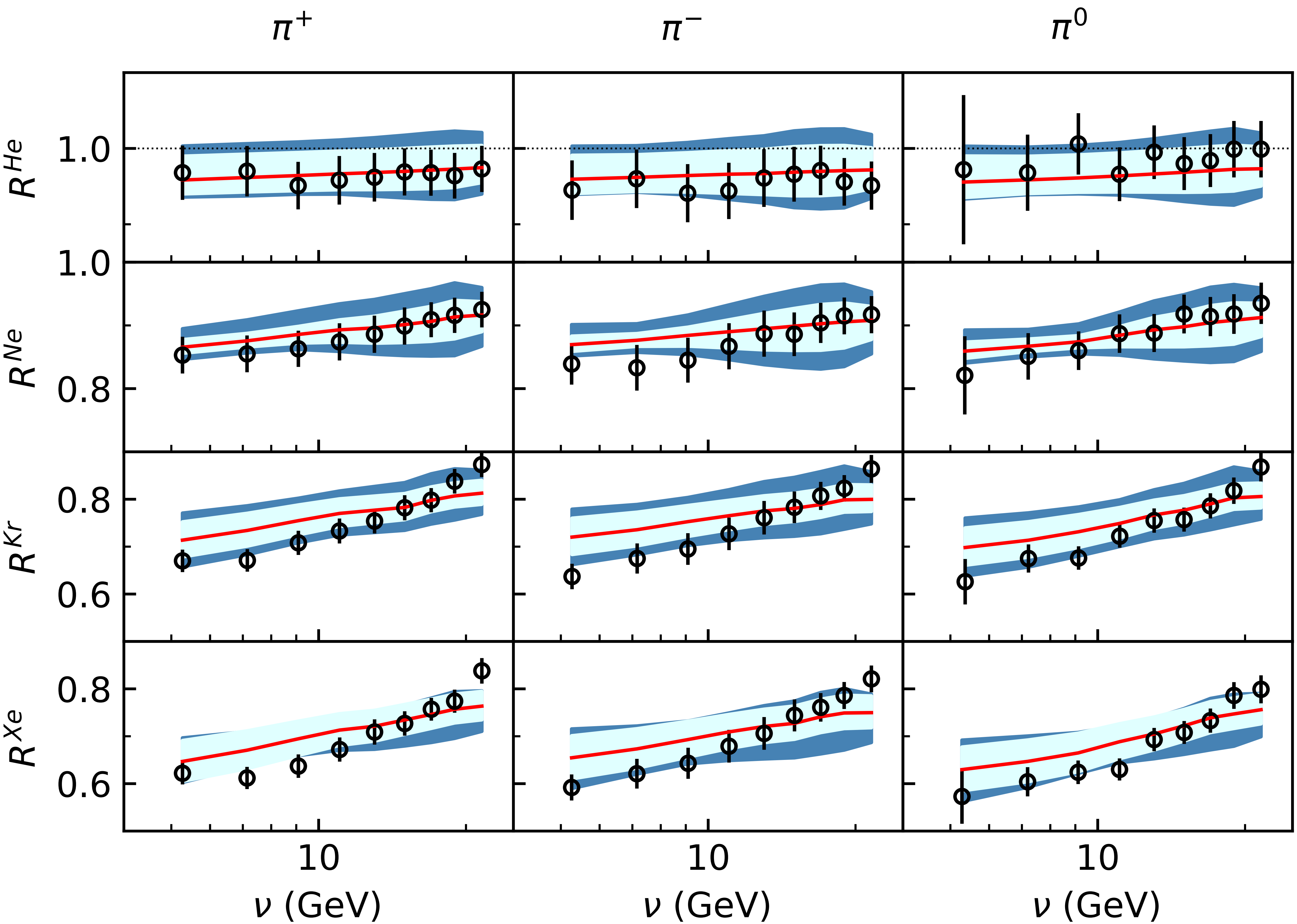




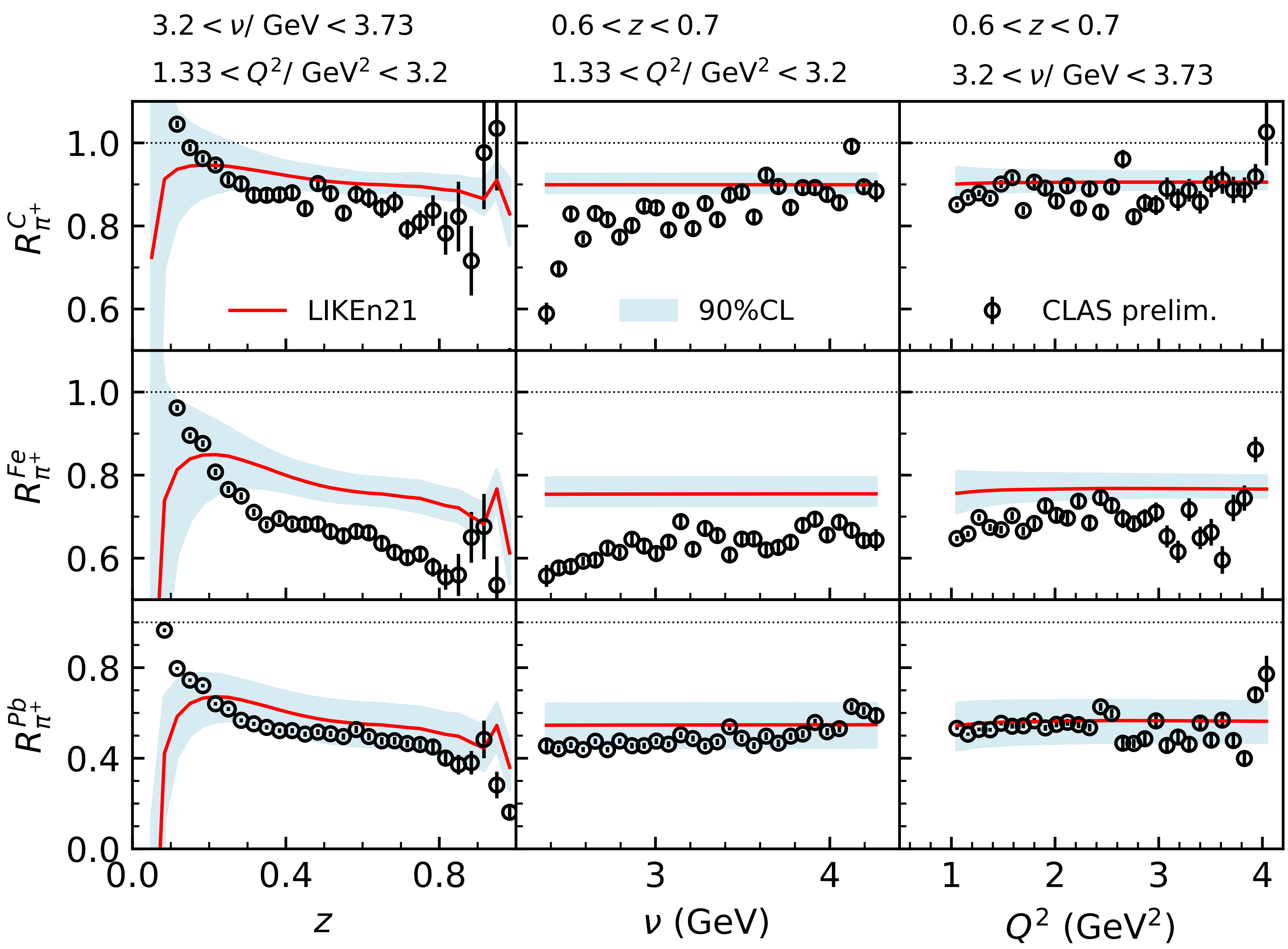
χ^2	Nº points	Experiment
4.65	13	STAR d+Au π^0
7.51	15	STAR d+Au π^-
11.29	15	STAR d+Au π^+

- Fitted the data using proton PDFs and releasing some nFF parameters.
- The fit is quite adequate, but χ^2 similar to those obtained for the same/similar data in nPDFs fits.
- We can’t conclude at this point that this is a purely initial or purely final state effect.
- It is not convenient to fit with the code I have.

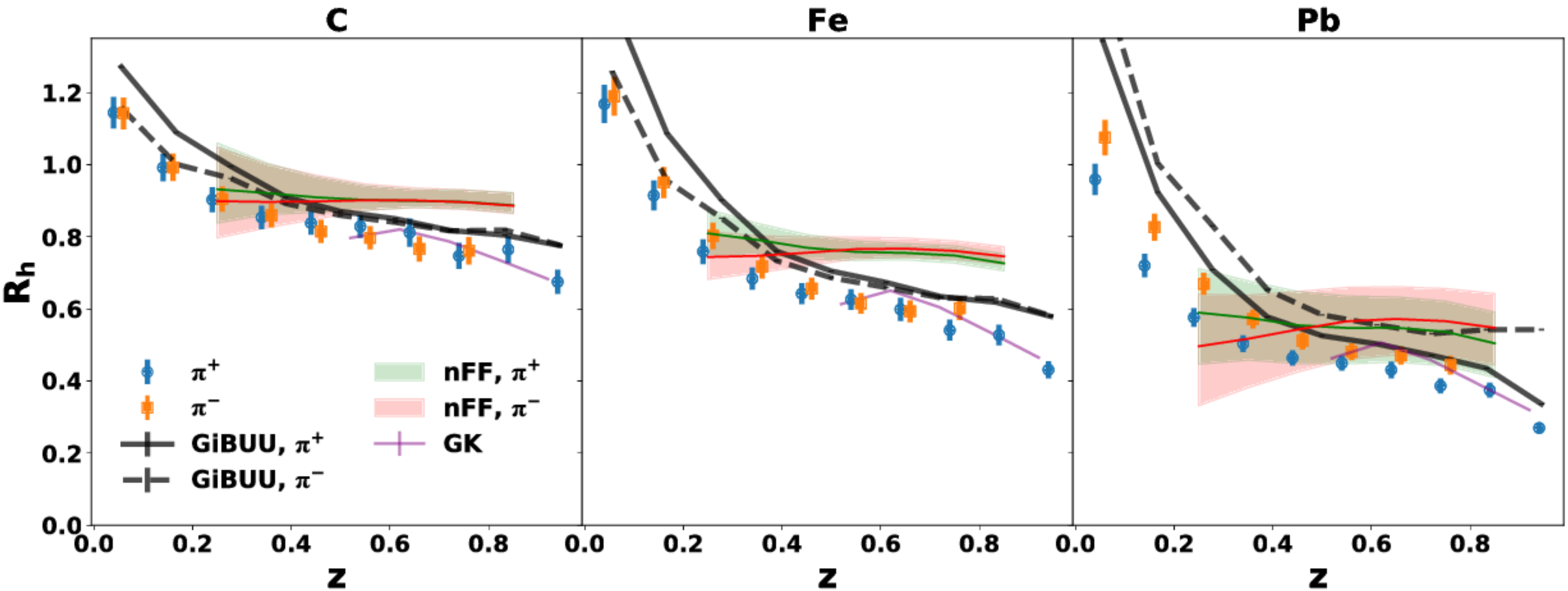

π^+
π^-
π^0
R^{He}
R^{Ne}
R^{Kr}
R^{Xe}
1.0
0.8
1.0
0.8
1.0
0.8
0.6
0.8
0.6
0.4
0.2
0.4
0.6
0.8
1.0
z



π^+
π^-
π^0
R^{He}
R^{Ne}
R^{Kr}
R^{Xe}
1.0
1.0
0.8
0.8
0.6
0.8
0.6
10
10
10
ν (GeV)
ν (GeV)
ν (GeV)



- Preliminary CLAS data roughly described (not in the fit!).
- Prediction for Fe data always too high, but the extrapolation to Pb seems to do fine.



- The final CLAS data came out this week. arXiv:2109.09951
- There is a stronger difference with the C than I would have expected.
- But the comparison with Pb is still reasonable.
- Their plan is to measure this with $E_{beam} = 11$ GeV.

Summary

- xFitter has been extended to fit fragmentation functions using SIA and SIDIS.
- The vacuum FFs are parametrised in the standard form, the nFFs are just an extension.
- The evolution and computation of cross-sections was set to match the style of the DEHSS vacuum FFs, but can be extended to any other form.
- Comparison with data shows reasonable results within the limitation of this implementation.
- The extension was tested by successfully determining a set of nFFs: LIKEn21.

Ongoing work / future work

- Implement the *x/z* bin integration needed by SIDIS data (vacuum).
- Include other hadronic species.
- Modify plotting to add FFs.
- Include NLO CC SIDIS and NNLO SIA.

- Simultaneous run of many FFs.
- Compare MC errors with Hessian.
- Add OPAL tagged data
- Separate SIDIS routine to use different mass-schemes for DIS.
- Test the DIS fit with SIDIS data and the joint fit run modes.
- Test fit in parallel.
- Figure out smart way to include single hadron production.
- Extend nPDFs for other parametrisations.