The case for ions: the physics of nuclear PDFs and hadronization studies

Lecture 2

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Comunidad de Madrid

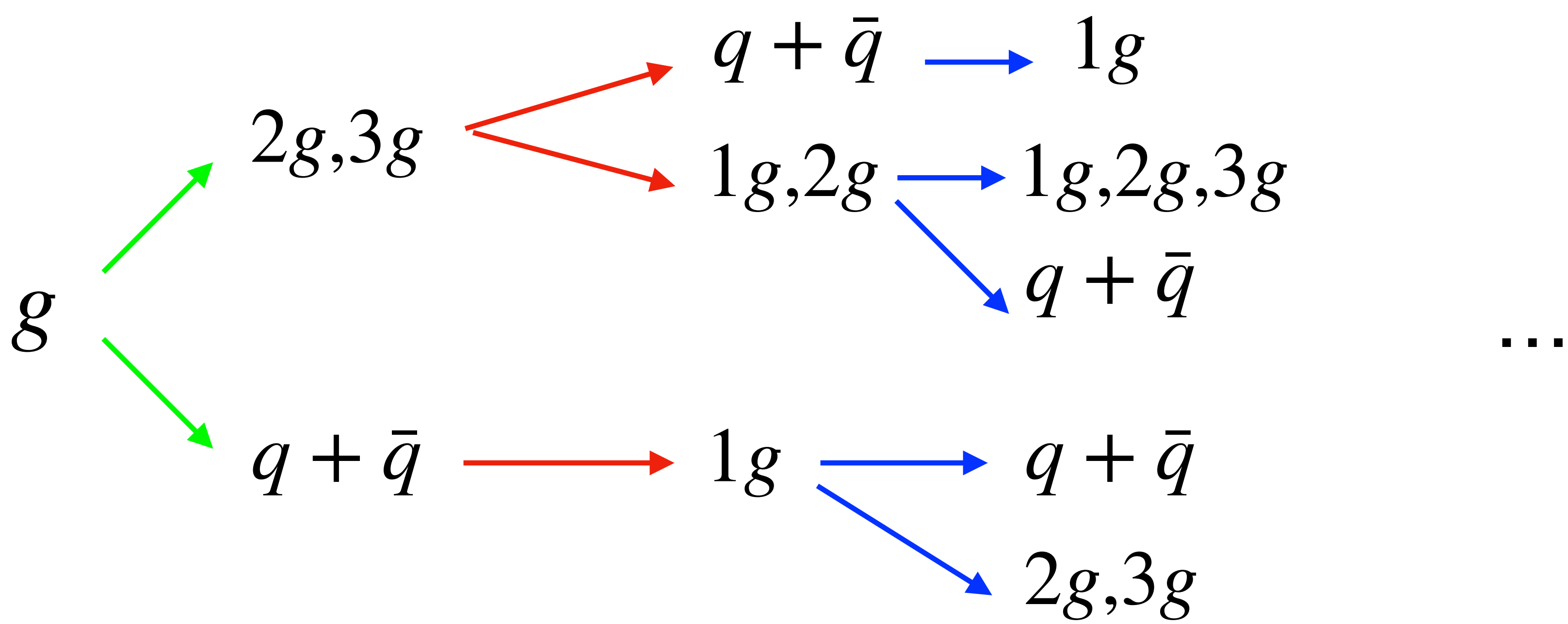
IPARCOS

Outline

- Briefly: what happens in the final state?
- FFs: relevant observables and some results.
- Nuclear data.
- Describing the nuclear data.
- Unresolved issues.
- What can the EIC do for the FFs?
- Summary.

What happens in the final state?

Let us consider a parton coming out of a hard interaction.



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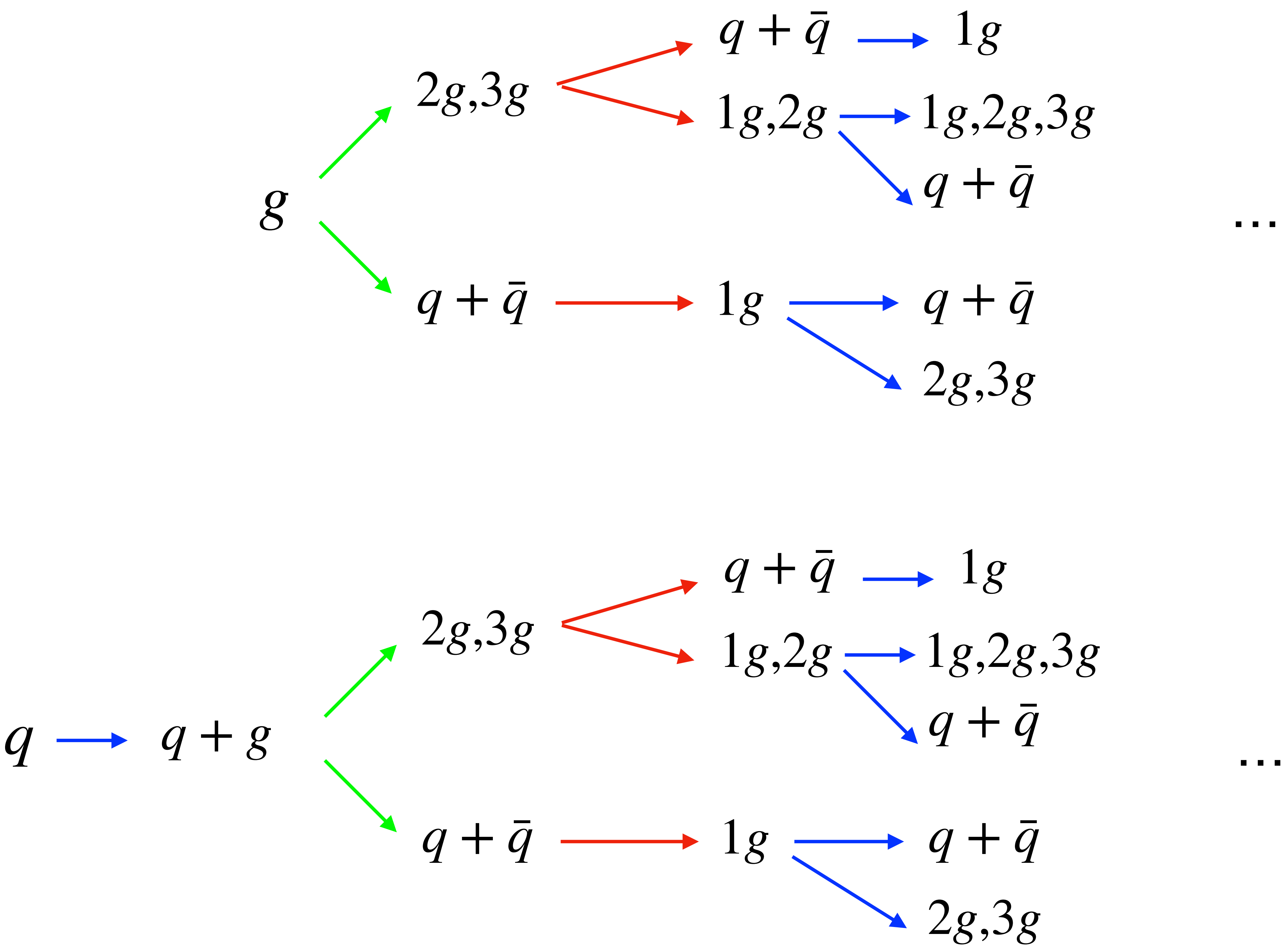
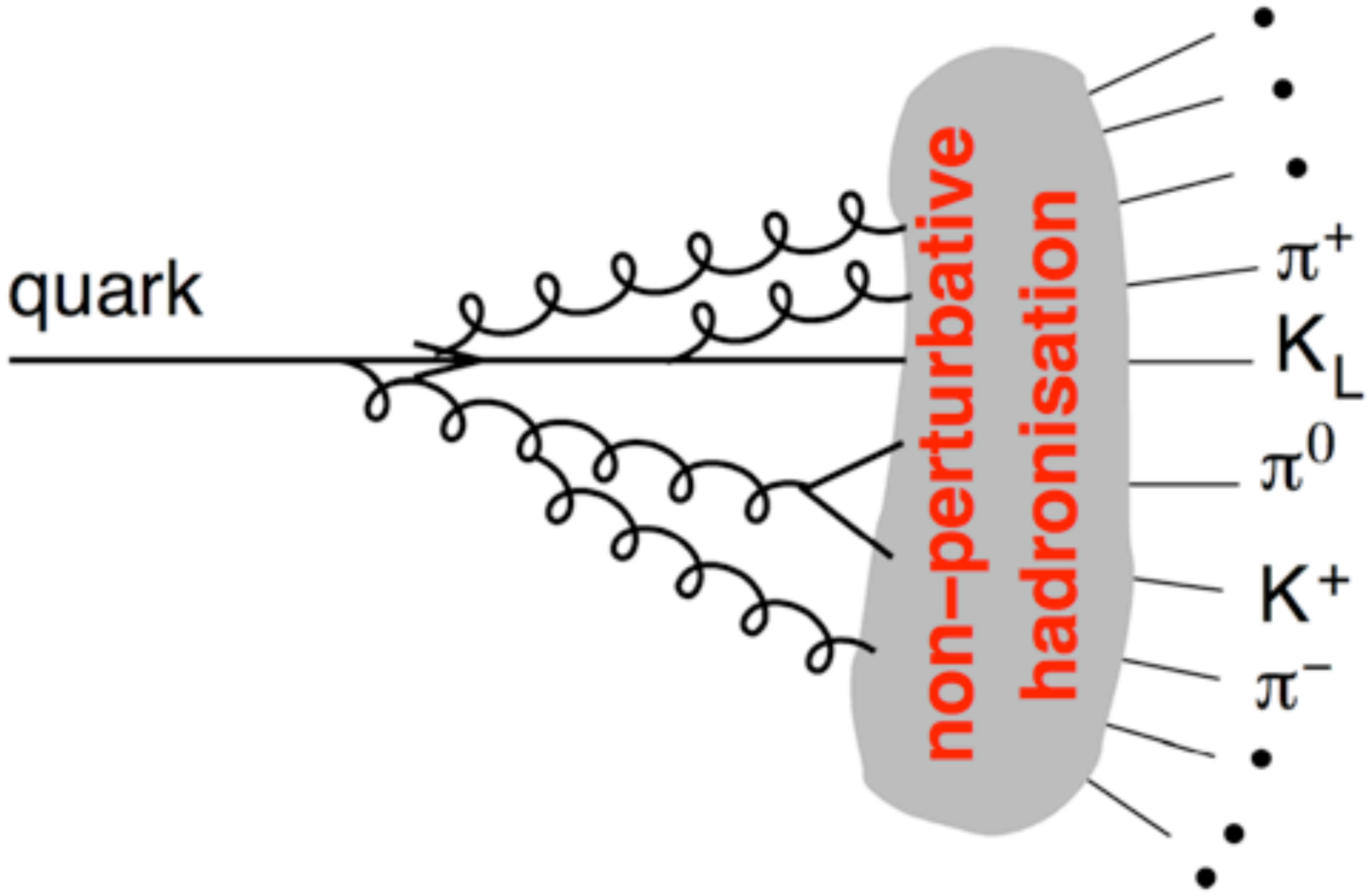
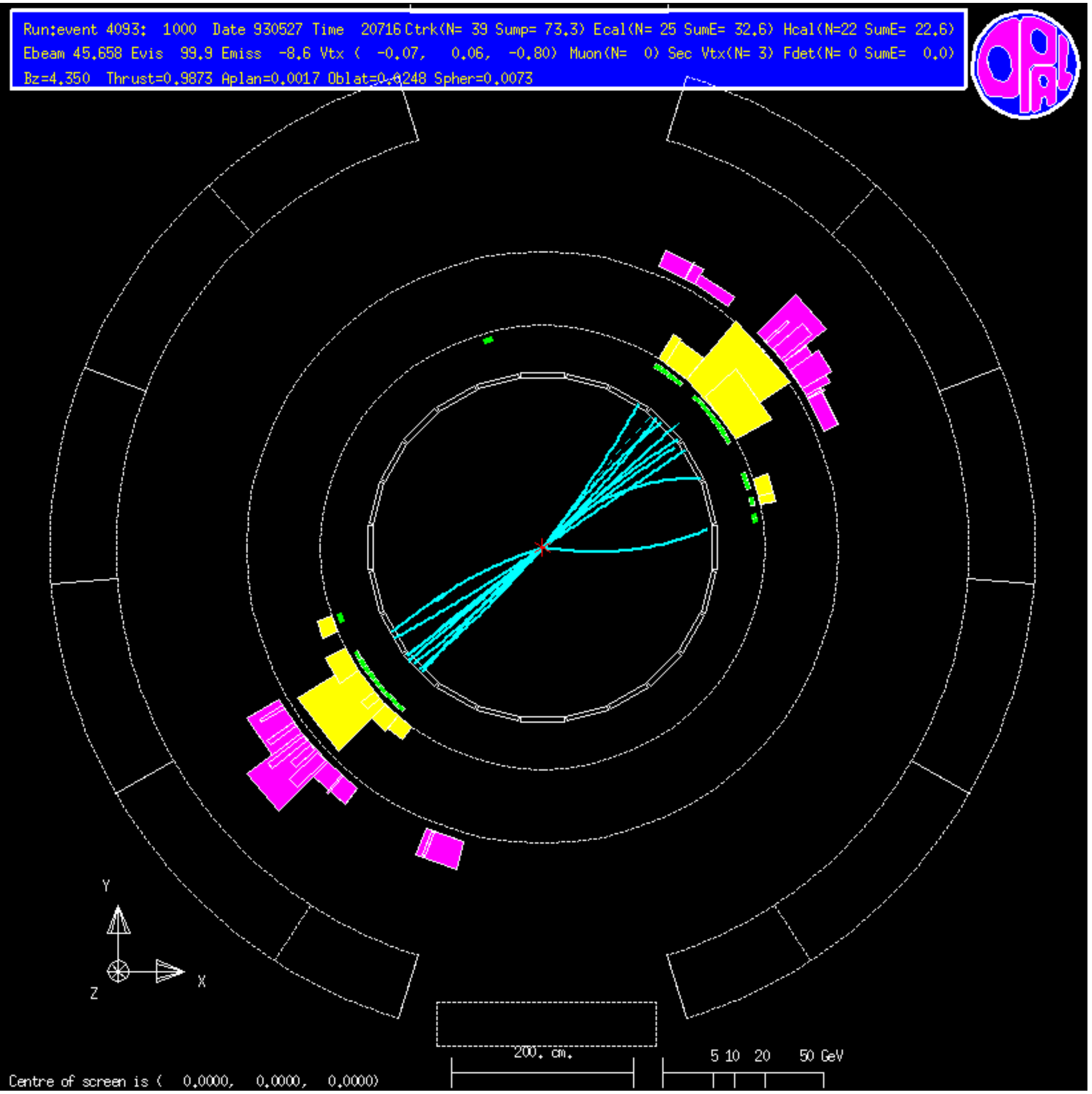
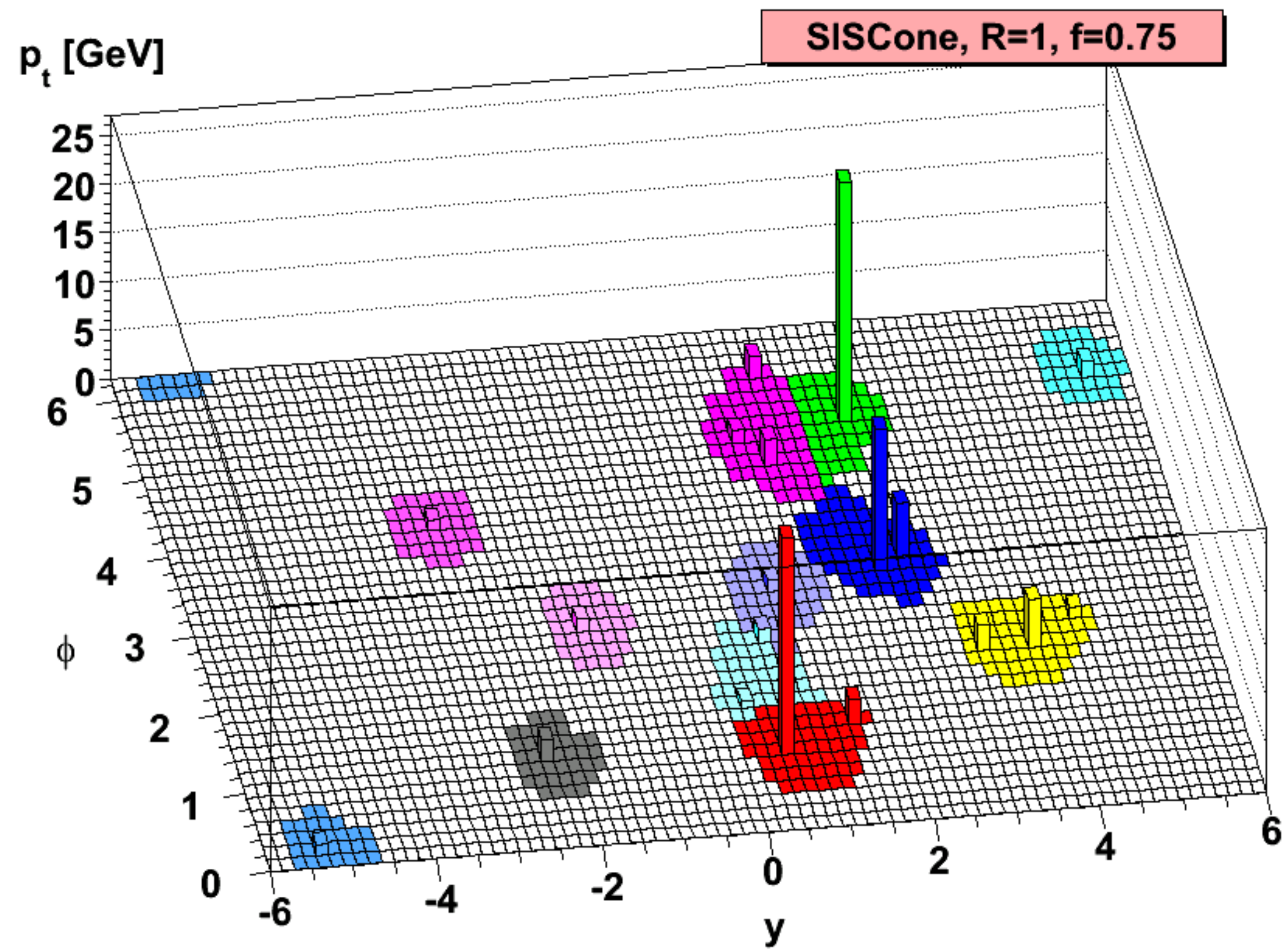




At some point of this chain we have **hadronisation**.



If we're not too picky about which hadron was produced, we can just *add* particles that are *close* and call that a jet.



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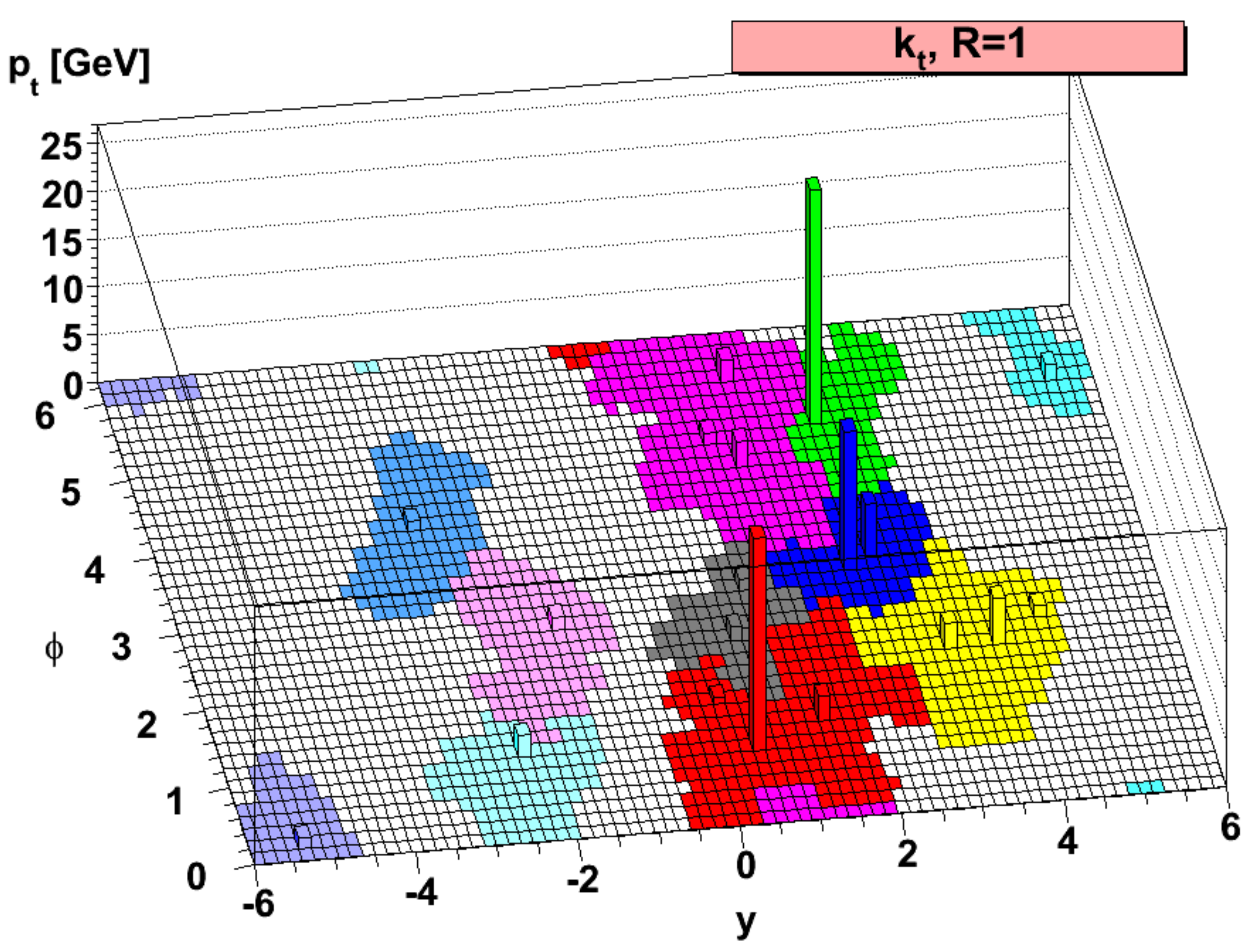

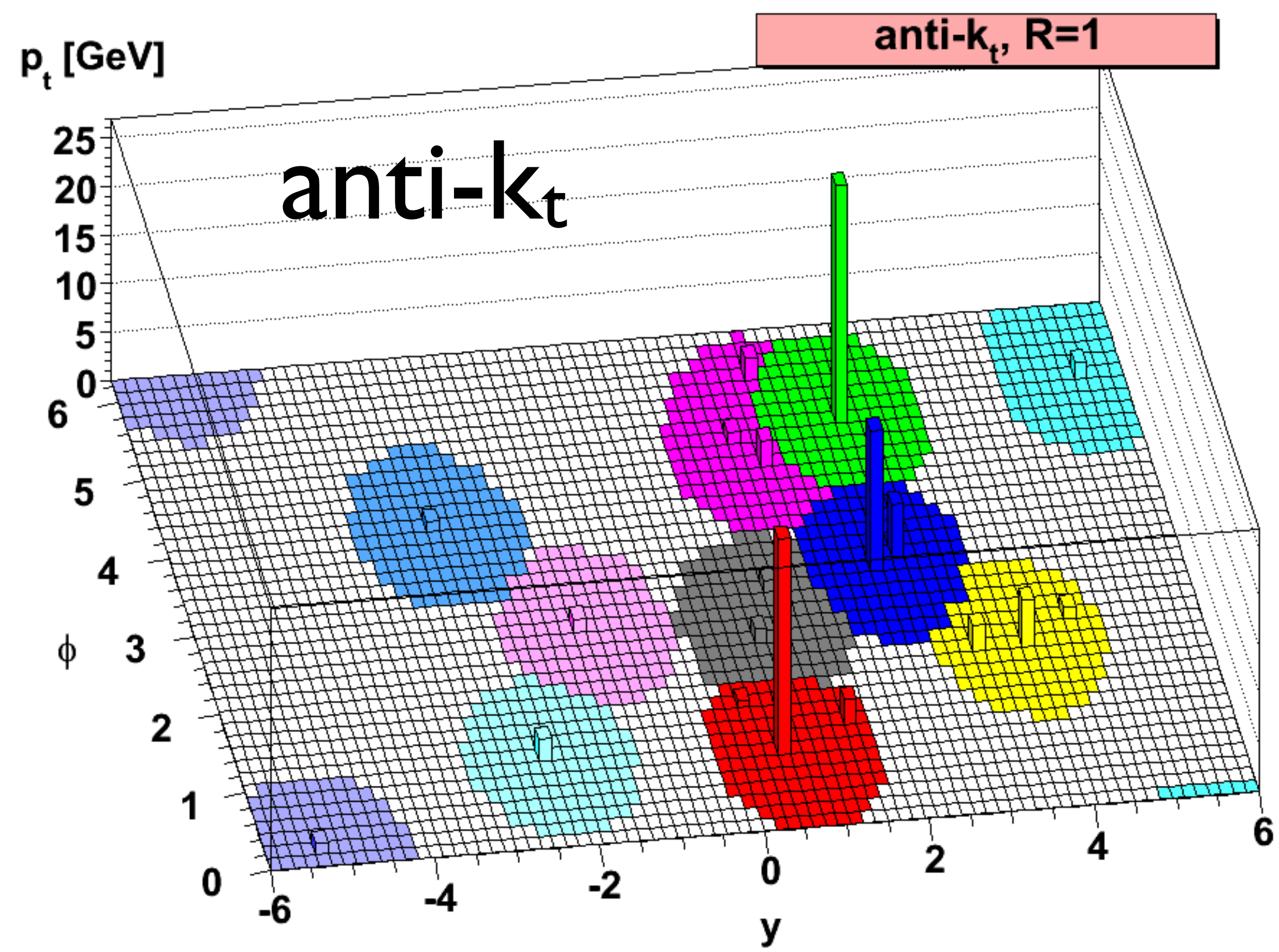

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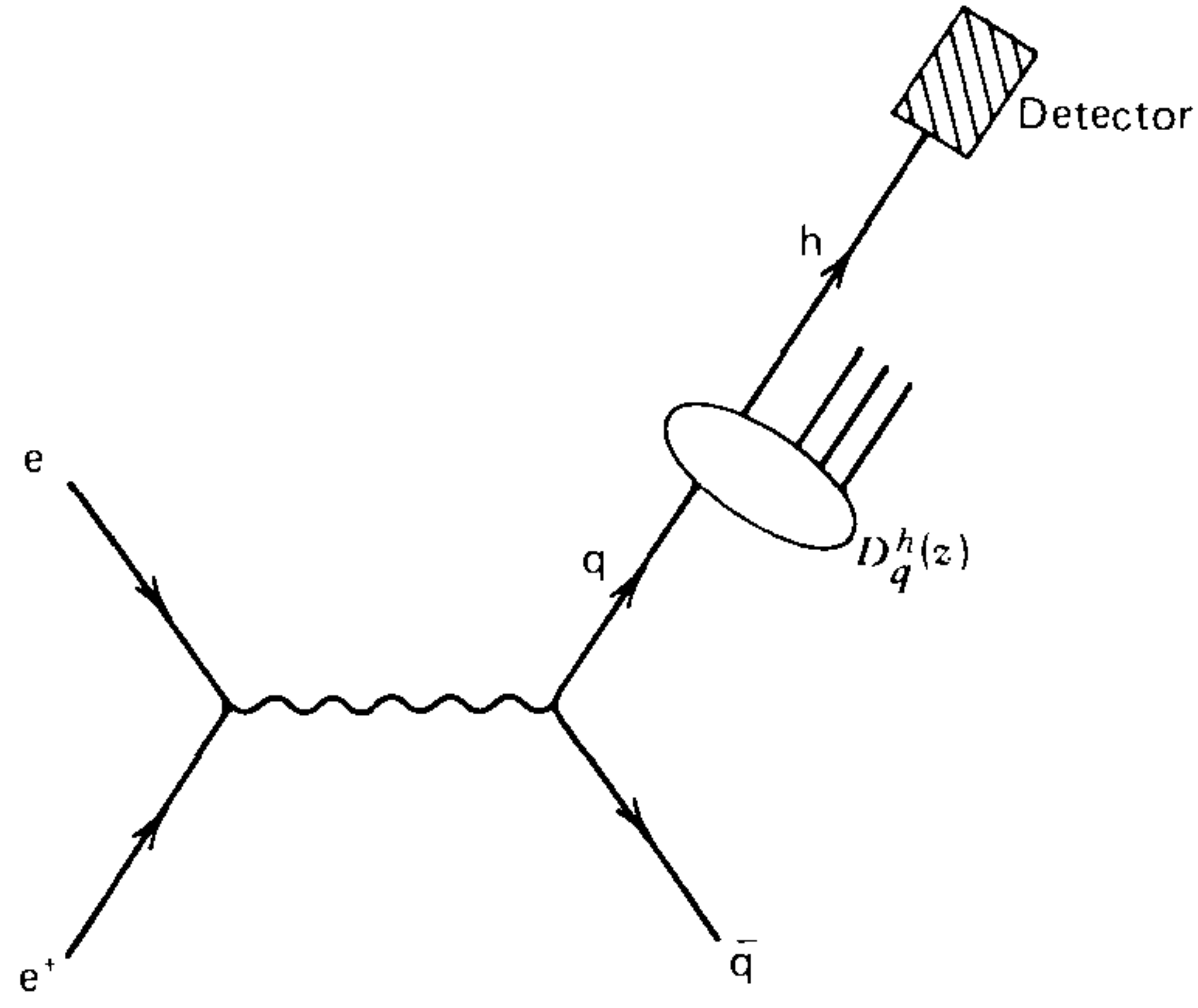

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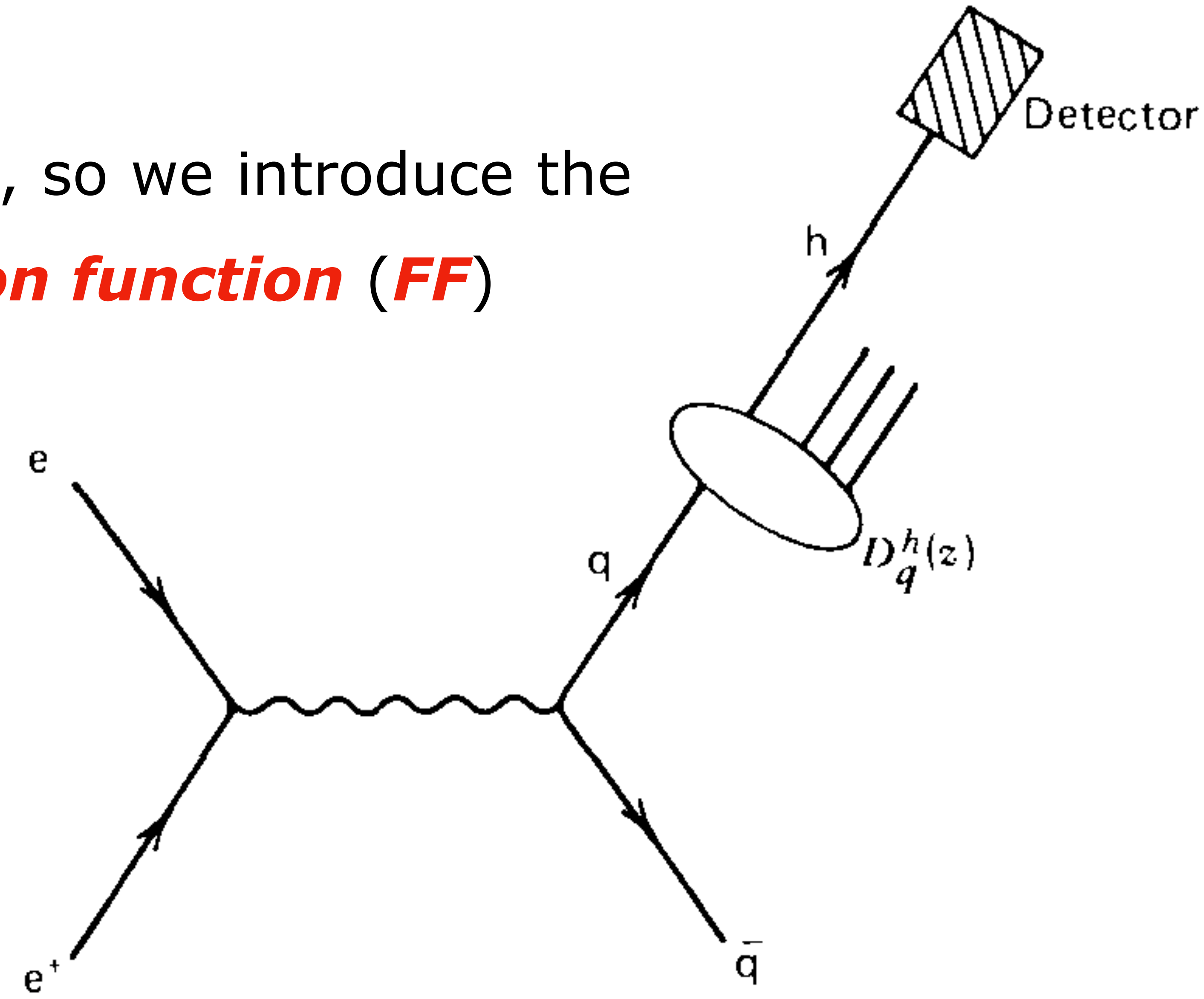

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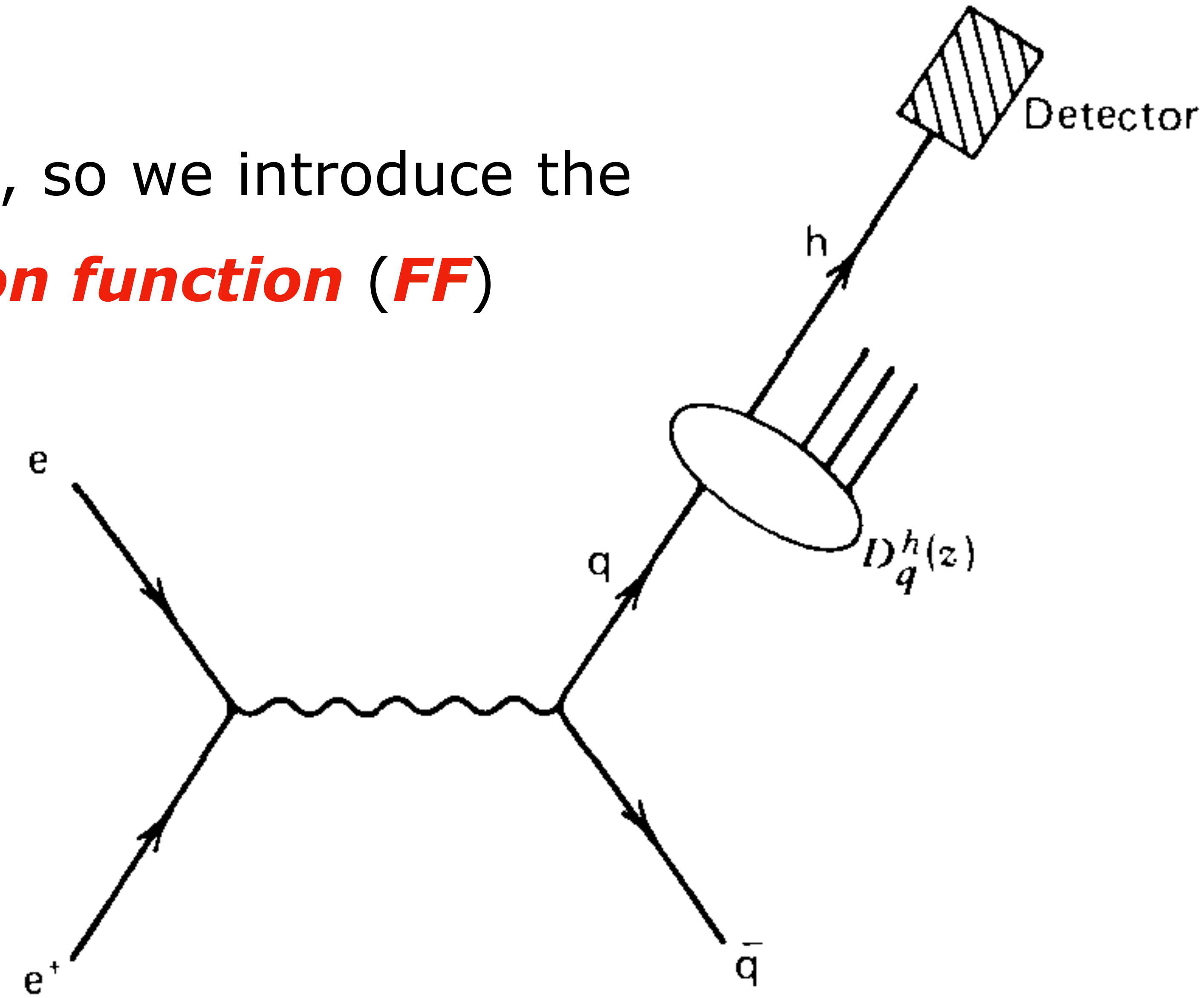

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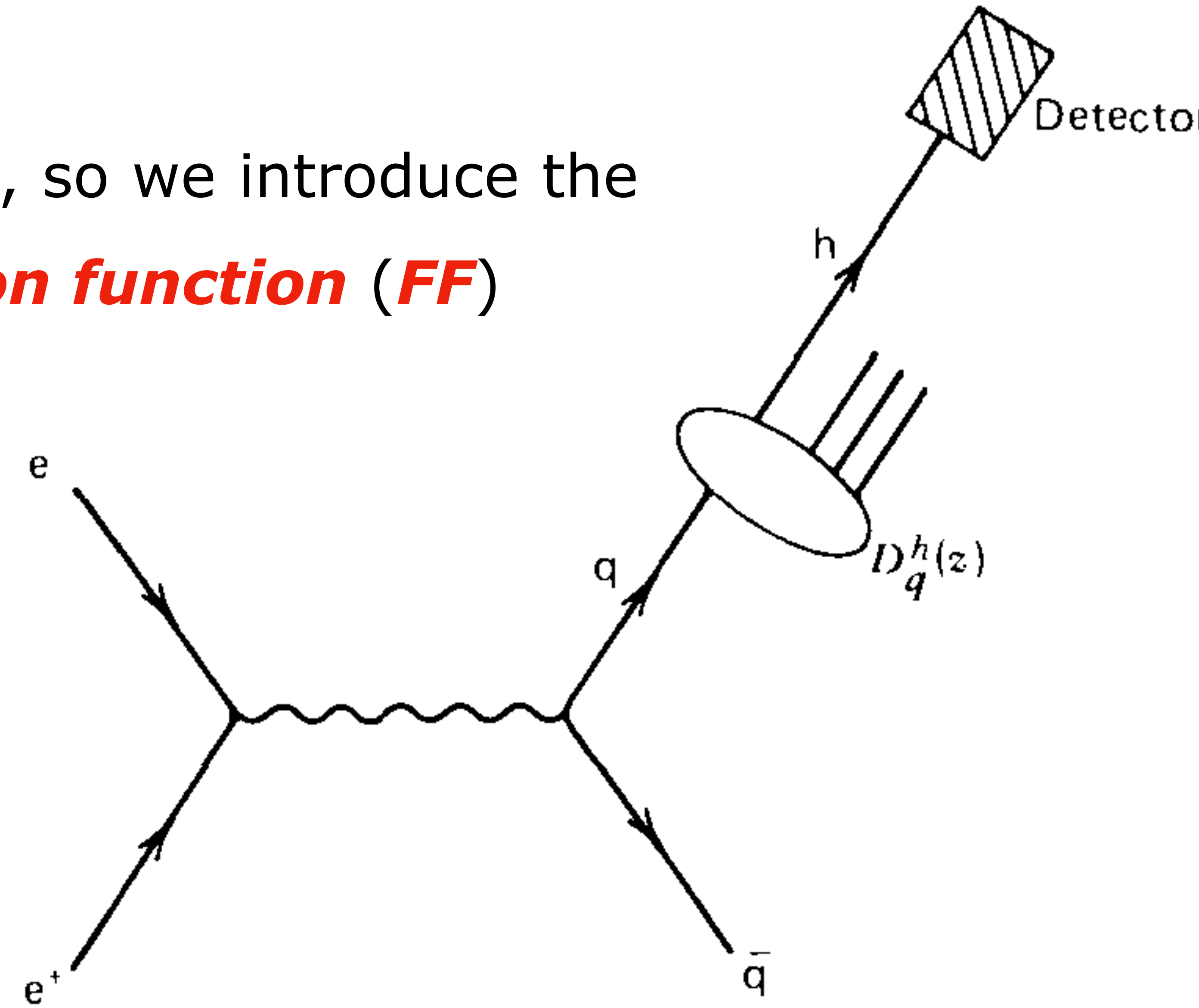

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$$z \equiv \frac{E_h}{E_q}$$

$$\frac{d\sigma}{dz}(e^+e^- \to hX) = \sum_q \sigma(e^+e^- \to q\bar{q})\left[D_q^h(z) + D_{\bar{q}}^h(z)\right]$$

FFs are similar to PDFs. They:

- are **universal** and **non-perturbative** (we can't compute them in pQCD).

- obey evolution equations (time-like DGLAP).

$$\frac{\partial}{\partial \ln(Q^2)} \begin{pmatrix} D_q^h \\ D_g^h \end{pmatrix} = \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} D_q^h \\ D_g^h \end{pmatrix}$$

- obey sum rules

$$\sum_h \int_0^1 z\, D_q^h(z)\, dz = 1$$

conservation of momentum

$$\sum_q \int_{z_{min}}^1 \left[D_q^h(z) + D_{\bar{q}}^h(z) \right] dz = n_h$$

average multiplicity of hadron *h*

But there is a key difference. While normally we work with proton PDFs, **we regularly need many more FFs**:

$$D_i^h \qquad h = \pi^{\pm,0},\ K^{\pm},\ p(\bar{p}),\ n(\bar{n})\ ,\eta\ \ldots$$

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

- 18 lq baryons
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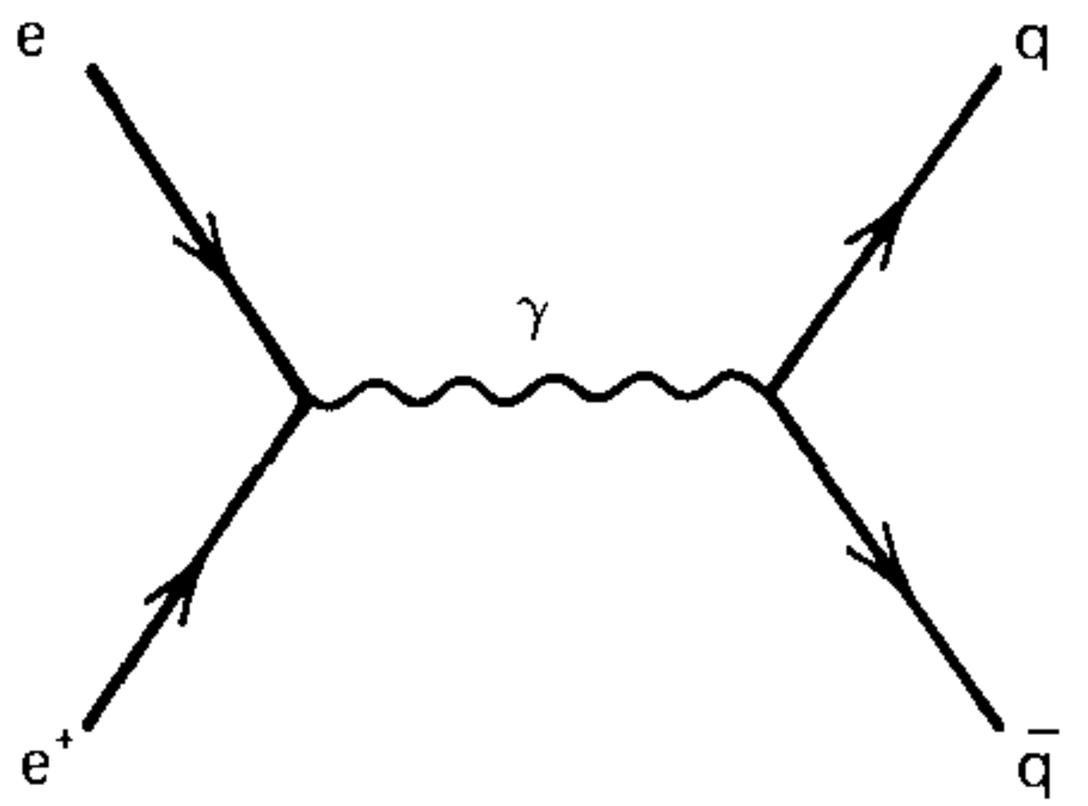
- To get the FFs, all we have to do is *simply make a global fit*.

Relevant observables

The basic process: single inclusive annihilation (**SIA**):

$l^+ + l^- \rightarrow h + \bar{h}$



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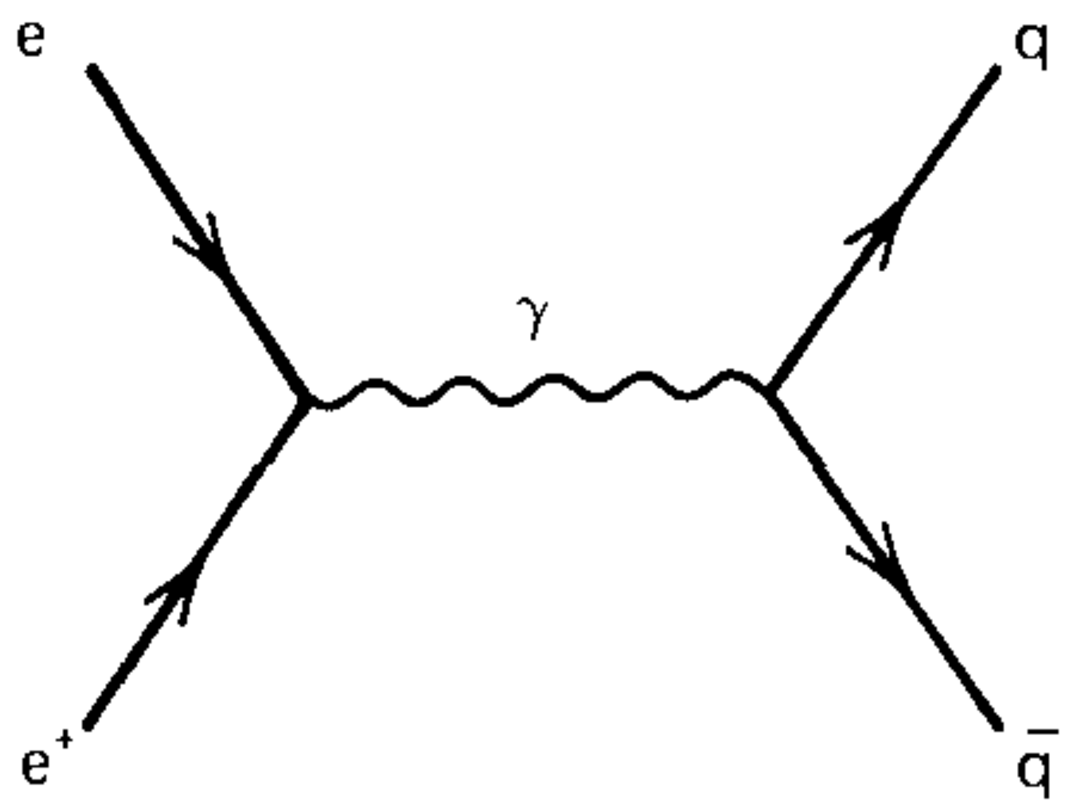

- Very ***clean***, no PDFs needed.
- Many experiments at both high and low c.m. energies (e.g. ALEPH, DELPHI, OPAL and L3 @LEP, Belle@KEKB).
- Symmetric: we obtain $D_i^h + D_{\bar{i}}^h$.

Functional form proposed: $D_i^h(z, Q_0) = N_i \; z^{\alpha} \; (1-z)^{\beta} \; P(z)$

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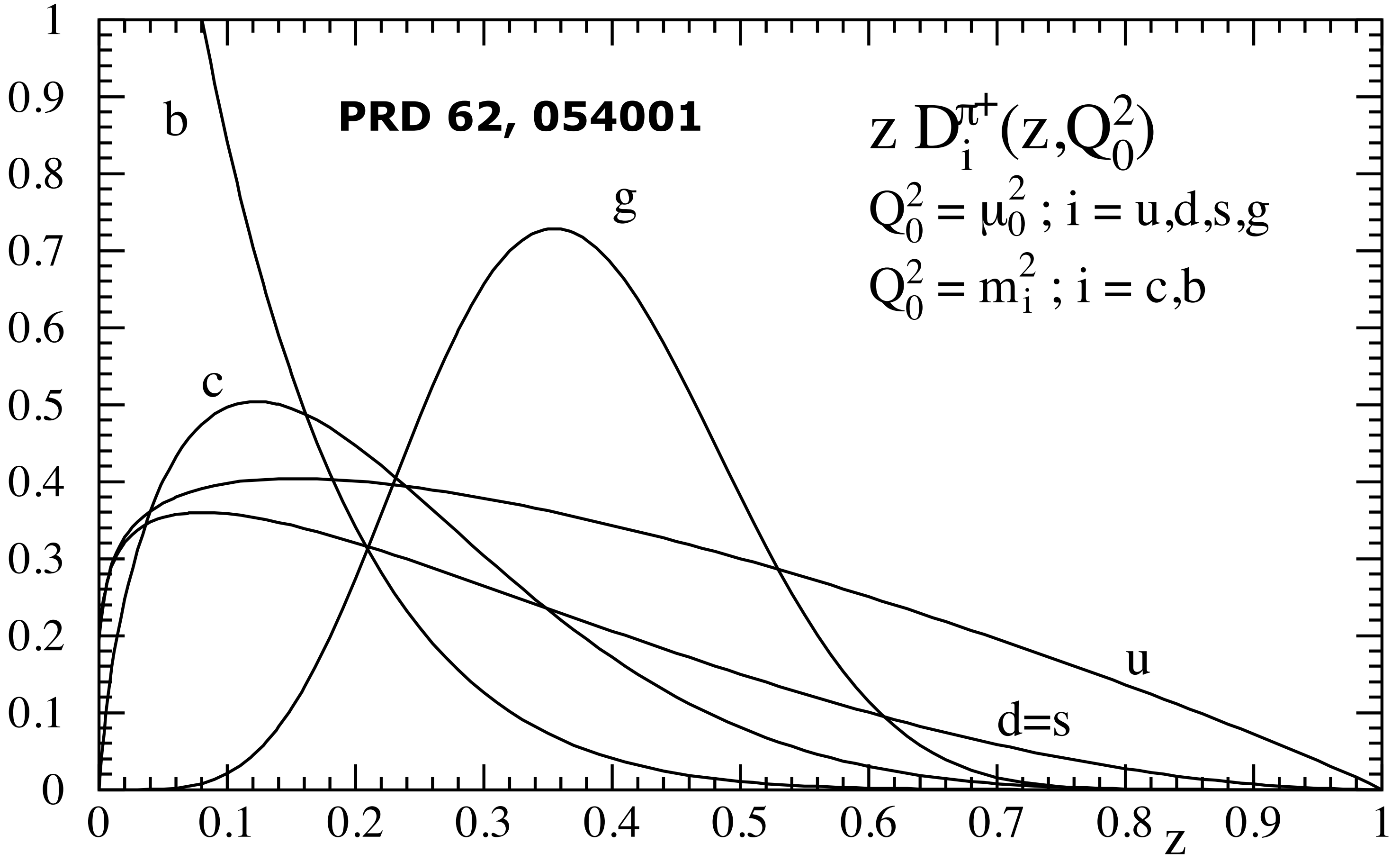
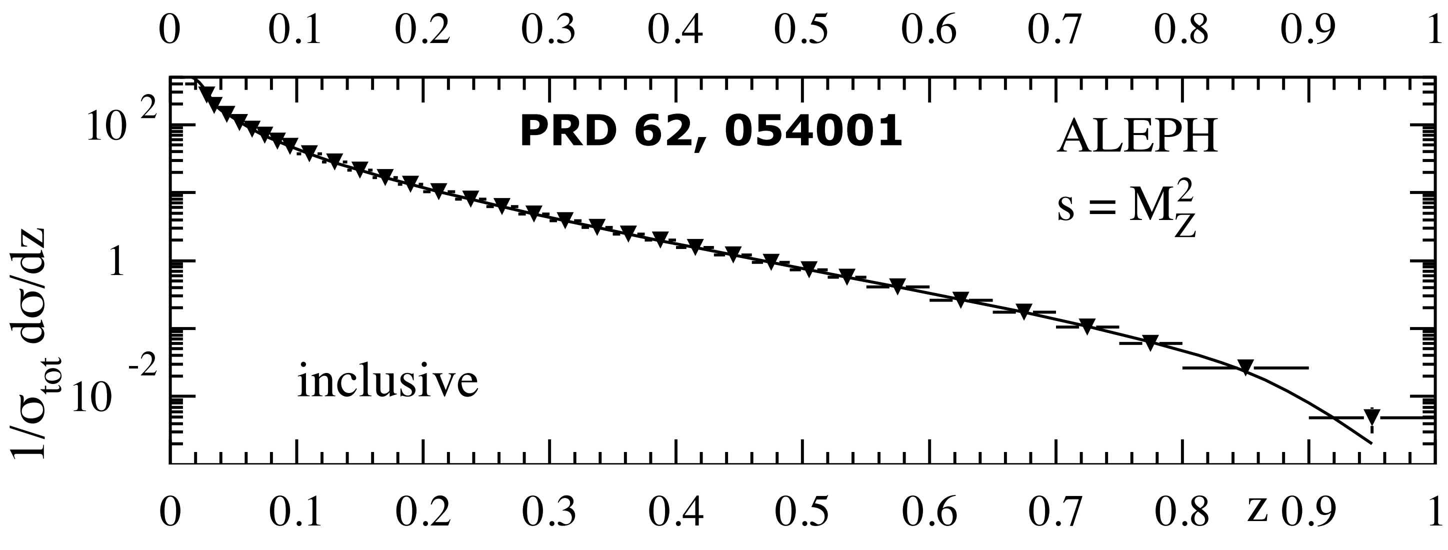


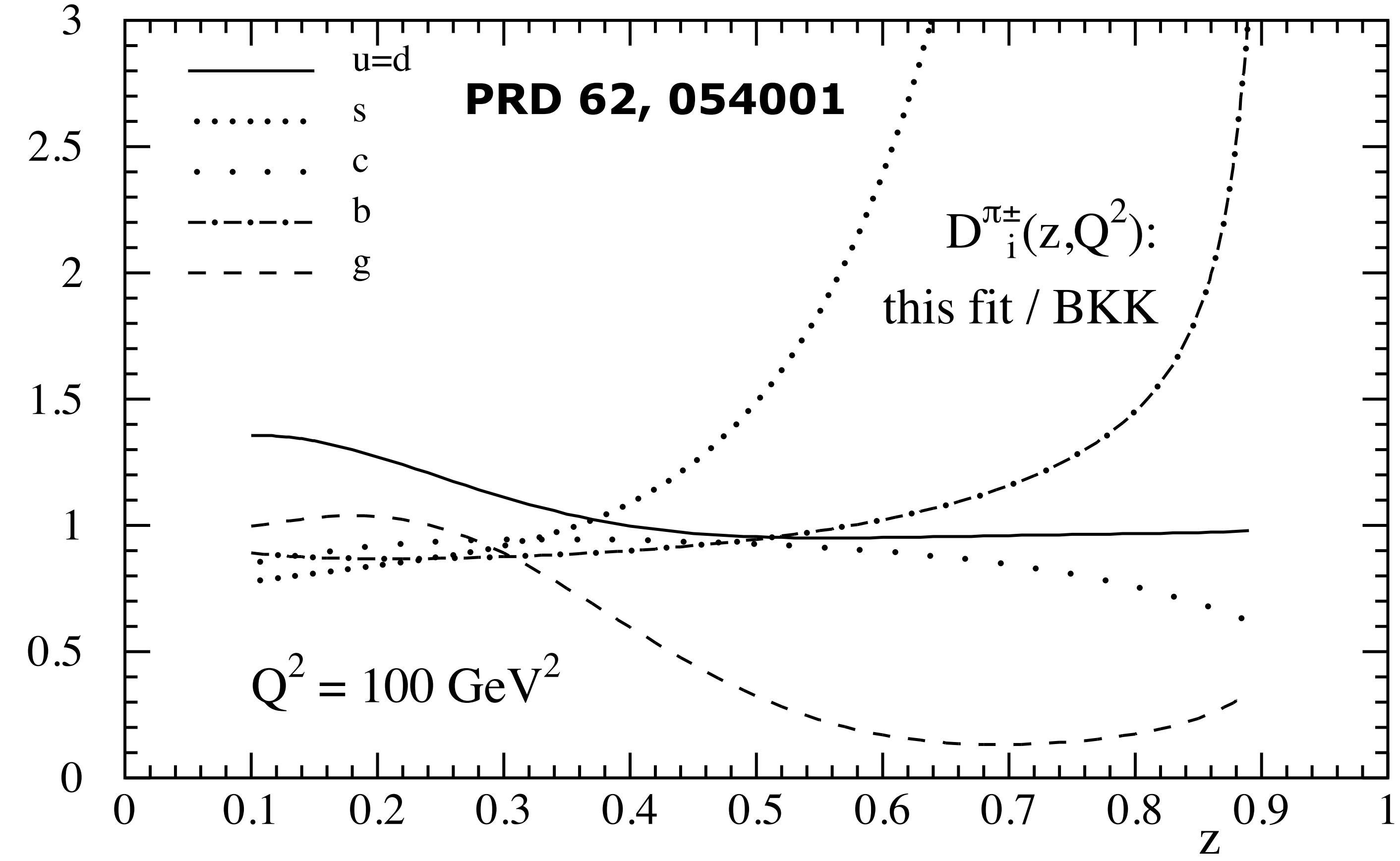
For π^+ it is enough to fix:

$$D_u^{\pi^+} = D_{\bar{d}}^{\pi^+}$$
$$D_{\bar{u}}^{\pi^+} = D_d^{\pi^+}$$
$$D_{\bar{s}}^{\pi^+} = D_s^{\pi^+}$$
$$D_{\bar{c},\bar{b}}^{\pi^+} = D_{c,b}^{\pi^+}$$



Large c.m. energy, annihilation to *Z* boson included in the calculation

Differences between FF extractions tend to be quite large for all the *z* range.



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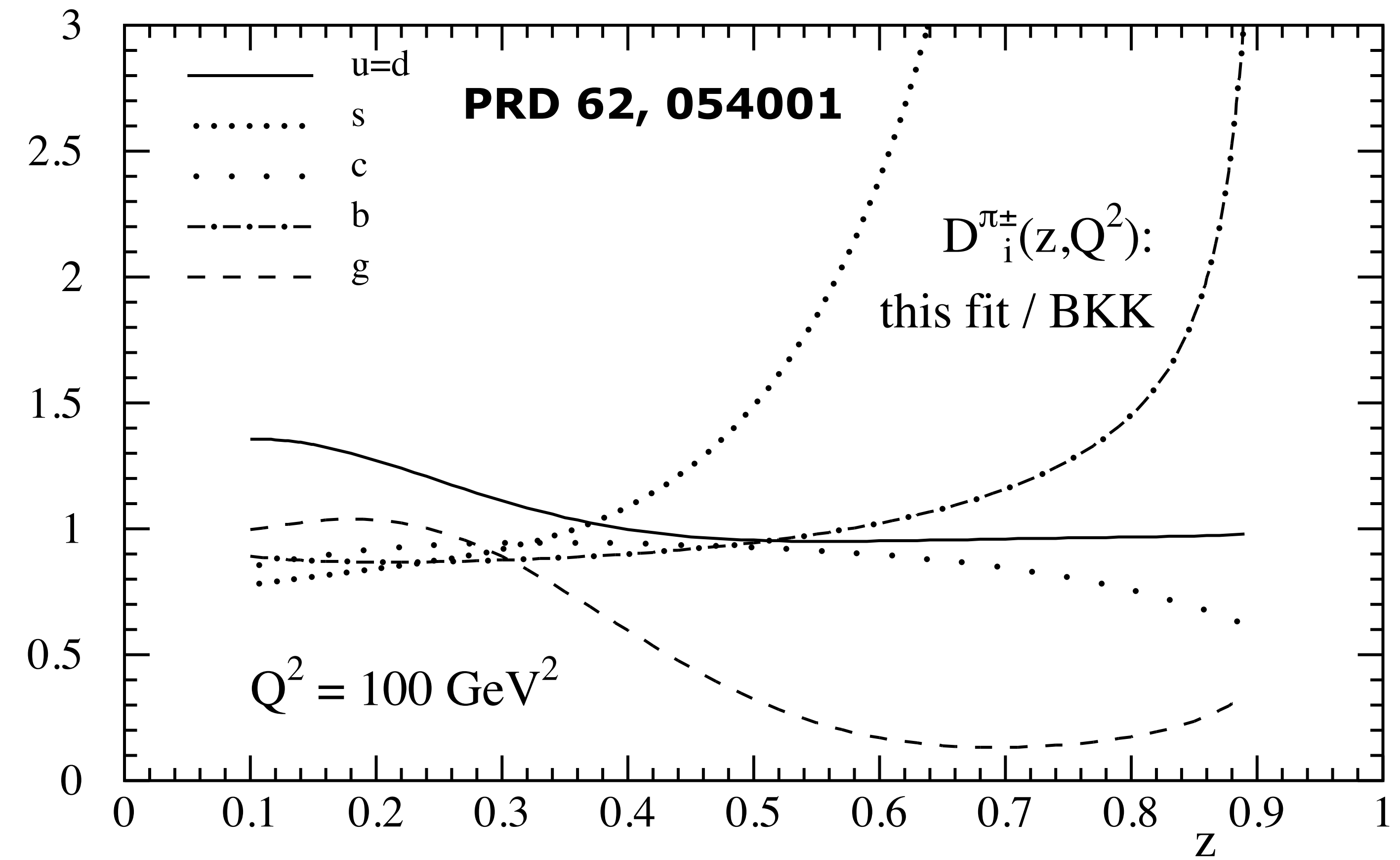

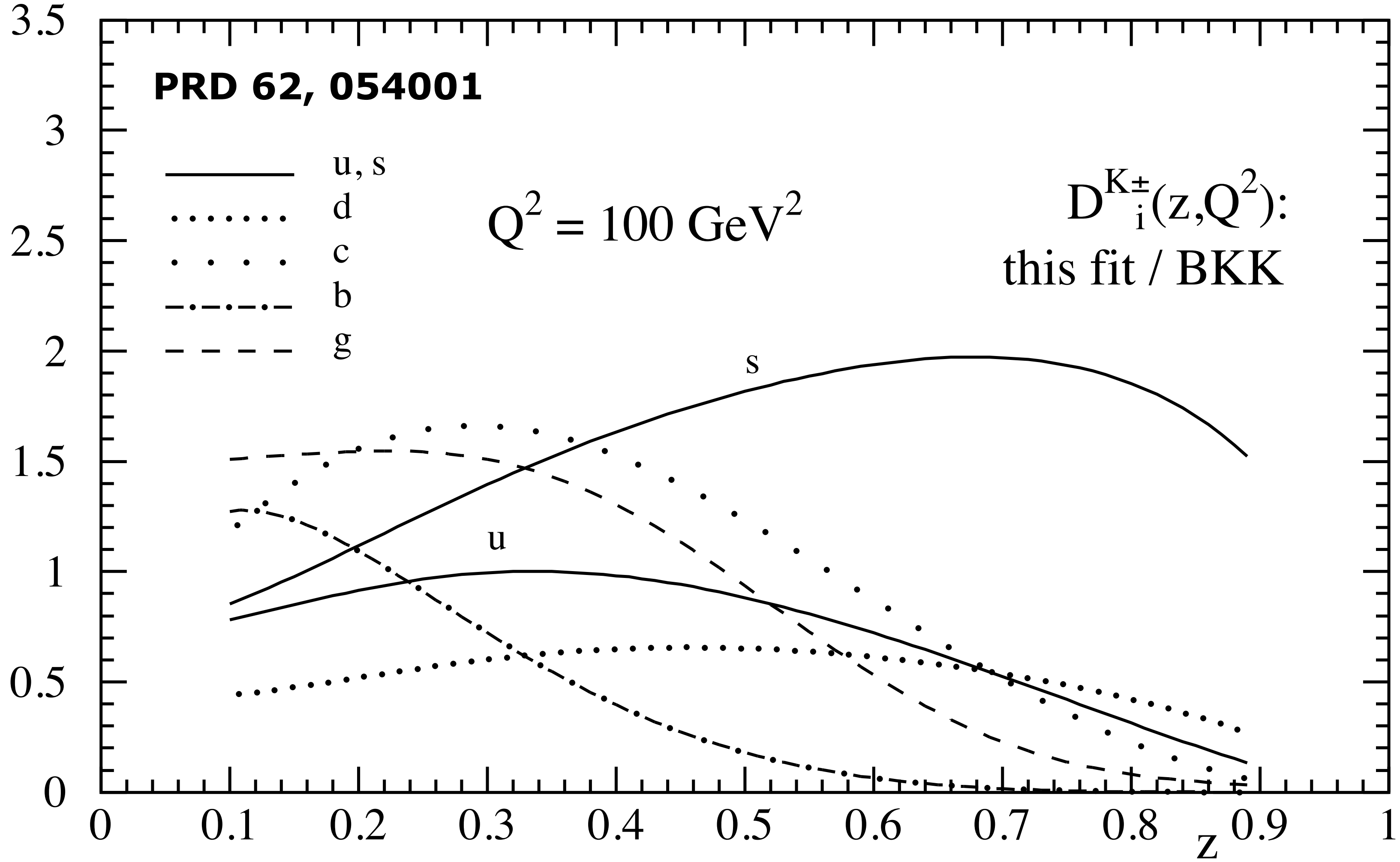

And it keeps getting worse with rarer hadrons.

To further complicate our lives we can do Semi-Inclusive DIS (**SIDIS**):

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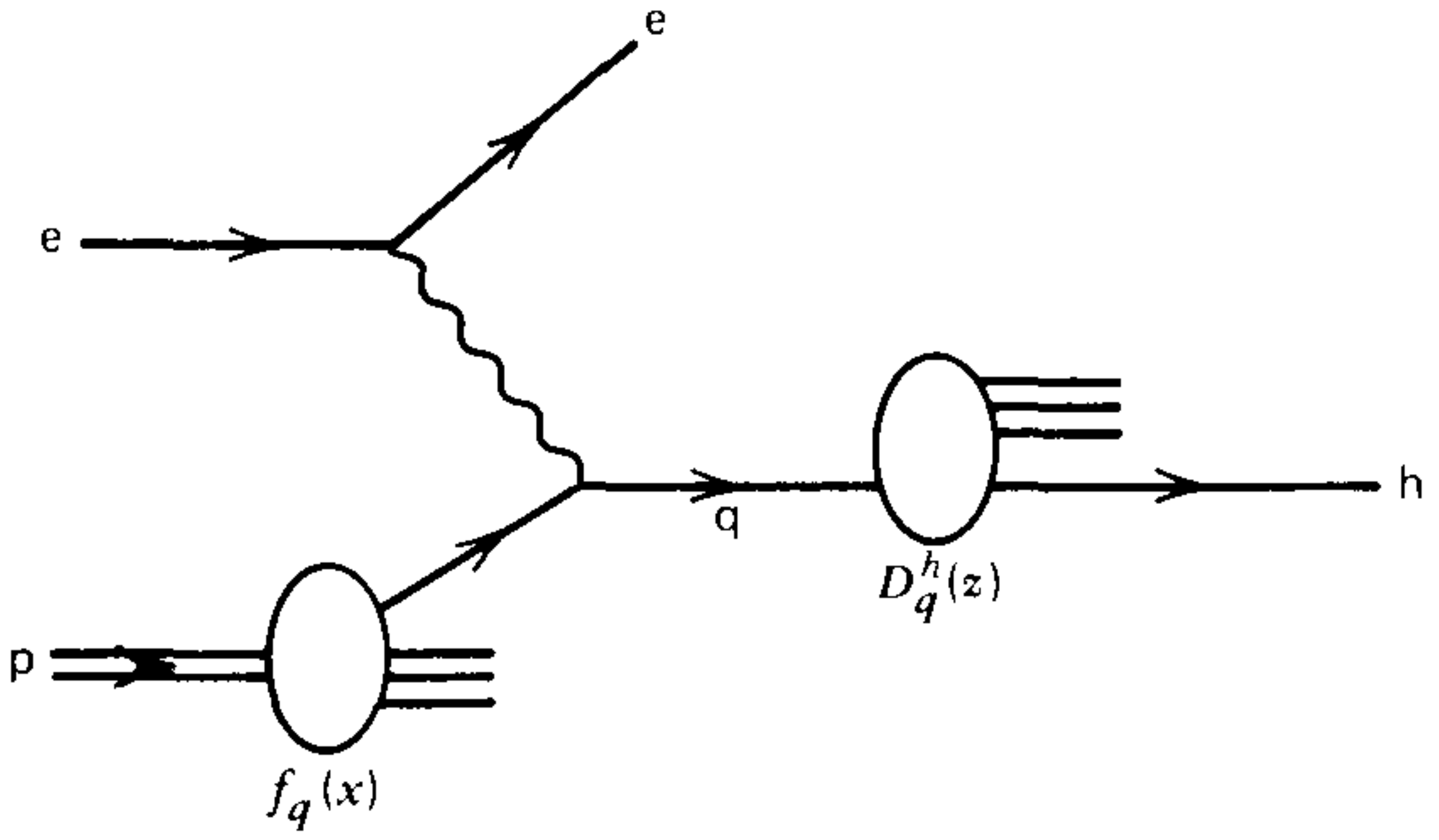

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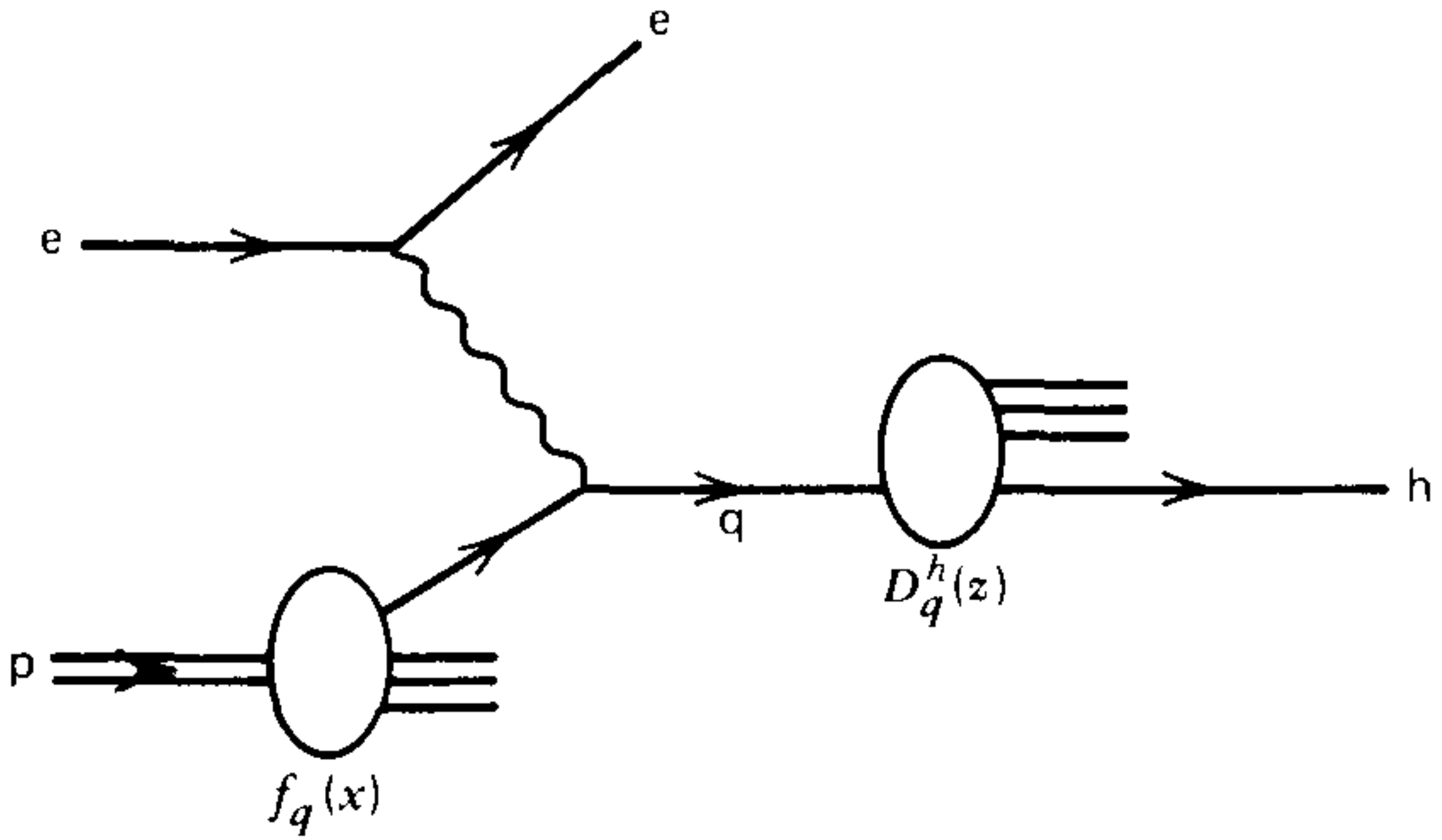

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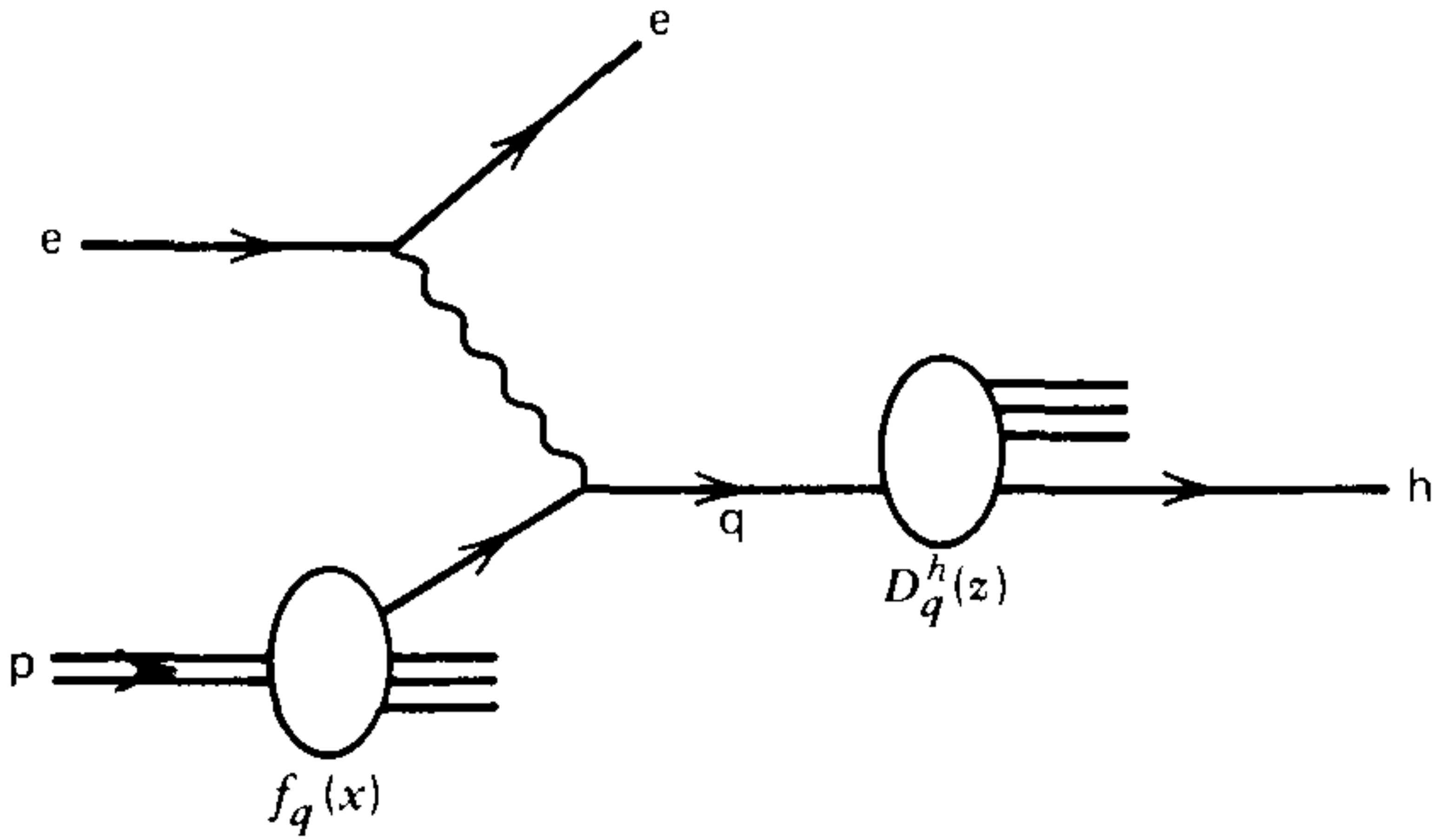

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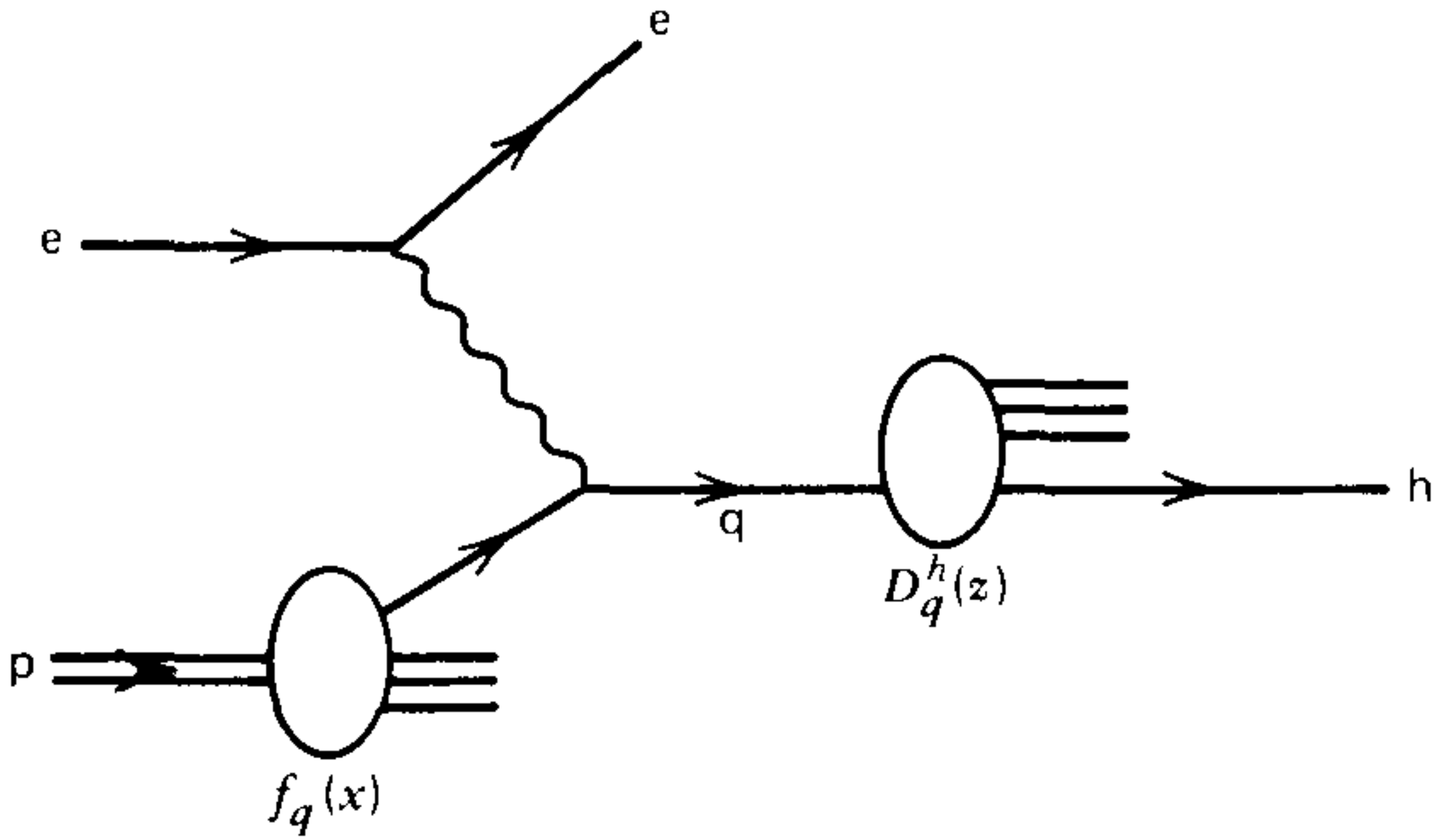

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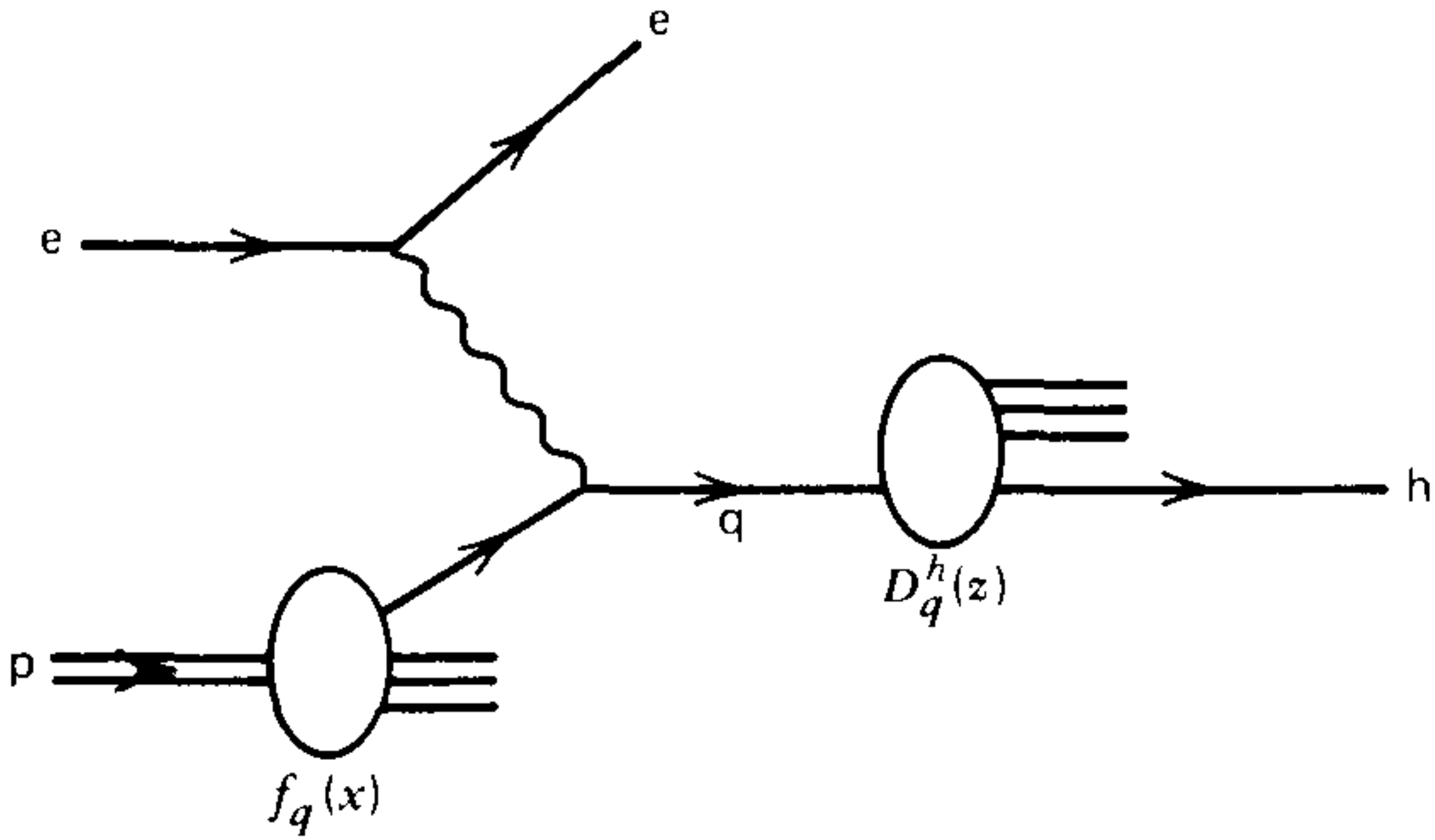

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SIDIS with π^+ gives $D_u^{\pi^+}$

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SIDIS with π^+ gives $D_u^{\pi^+}$

SIDIS with π^- gives $D_{\bar{u}}^{\pi^+}$

Modern SIDIS measured by HERMES and COMPASS.

Data usually given as ratios to DIS (***multiplicities*** *or* M^h)

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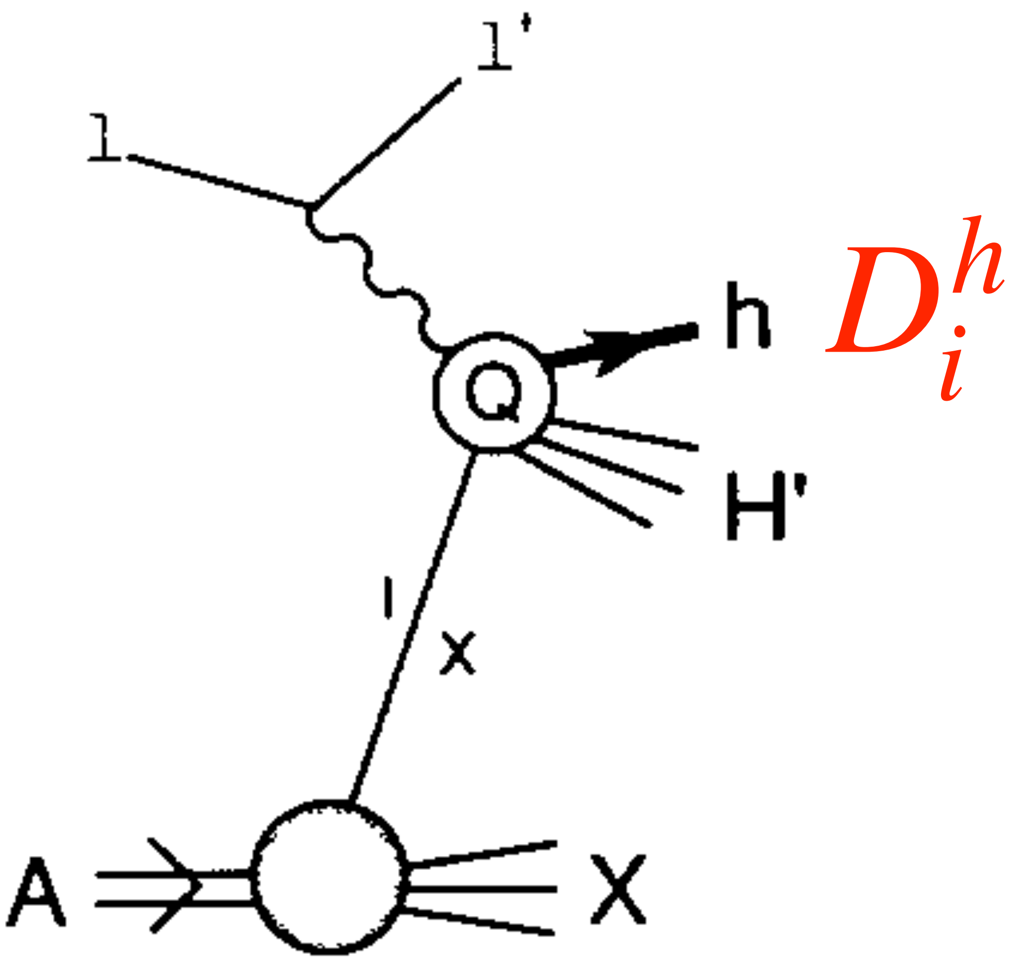

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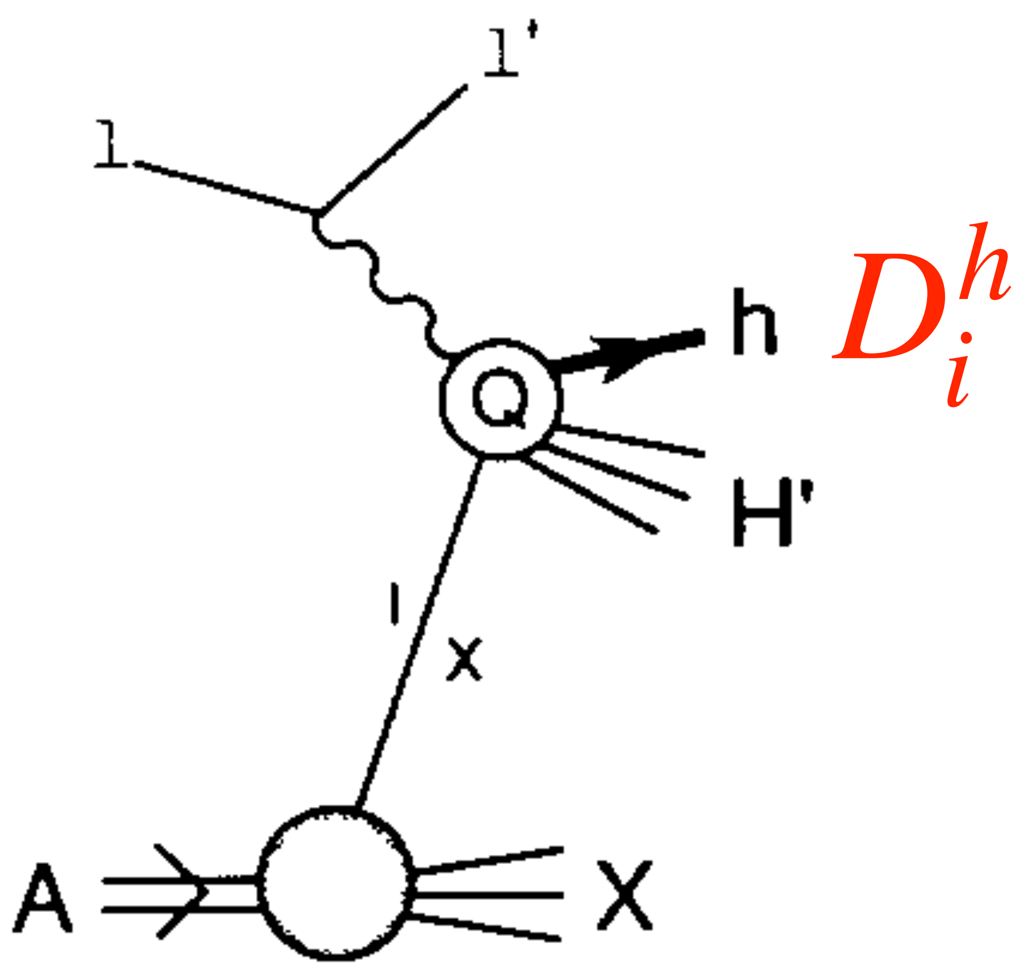

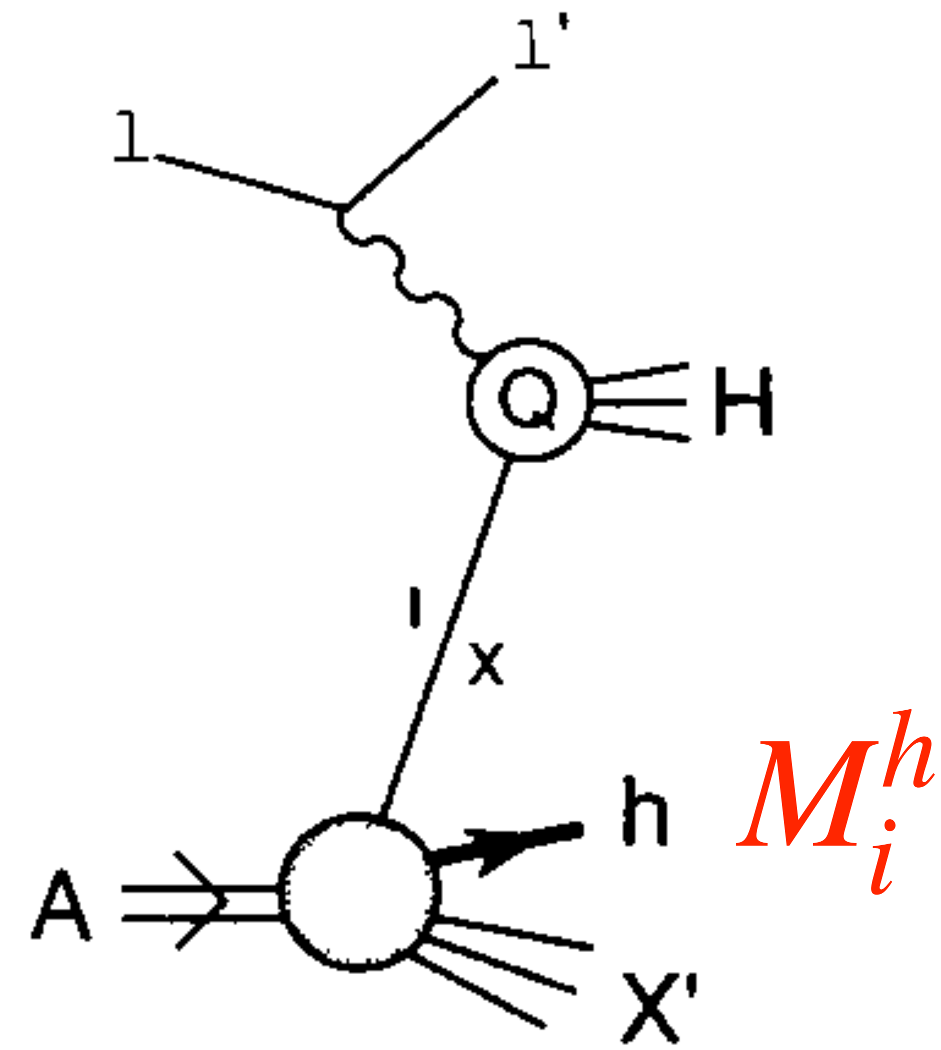

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2. Like SIA, SIDIS gives direct access to the gluon FF at NLO (and higher) making it harder to extract from data.

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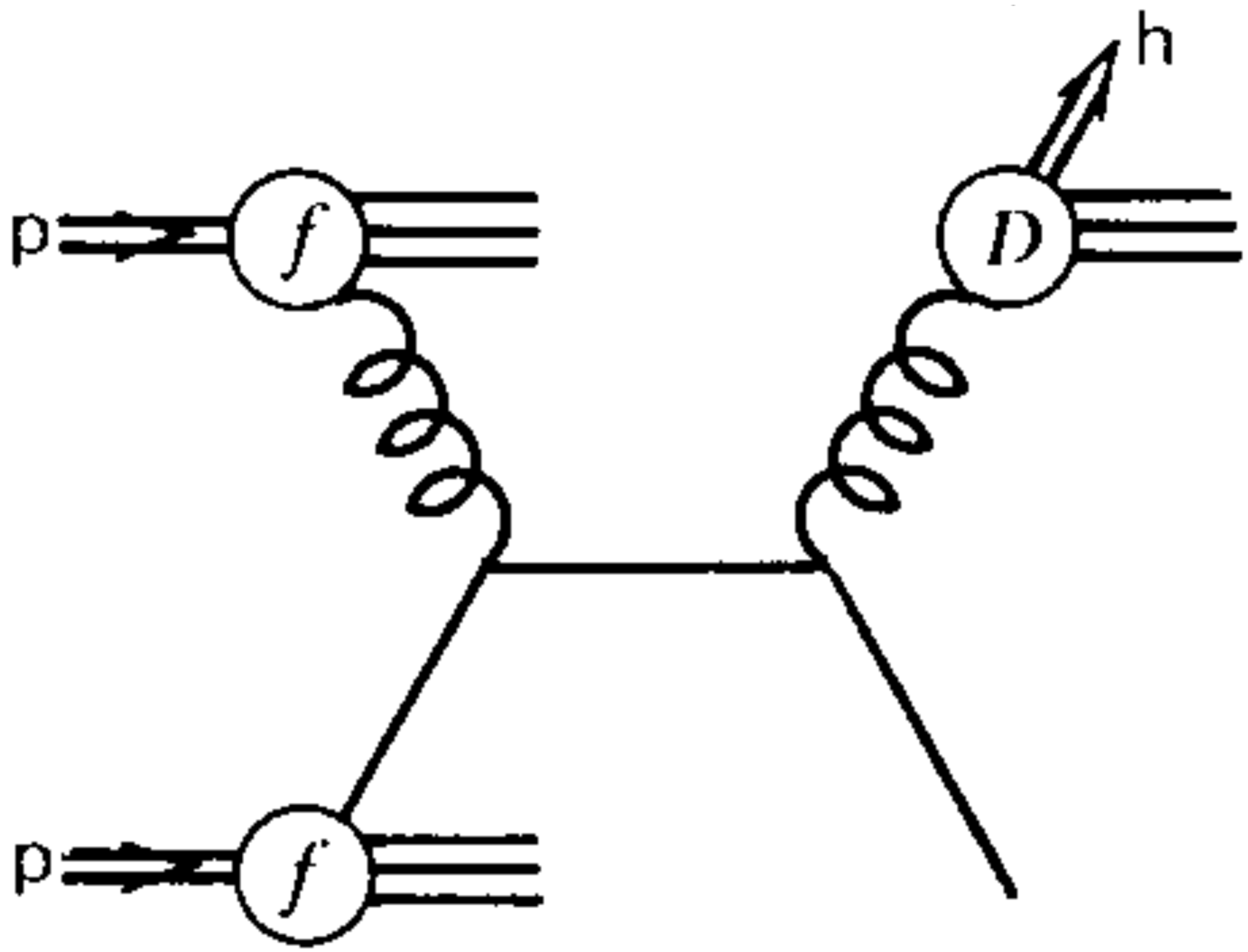
To better extract the gluon, we use *Single Inclusive Hadron* (**SIH**) production in p+p collisions.



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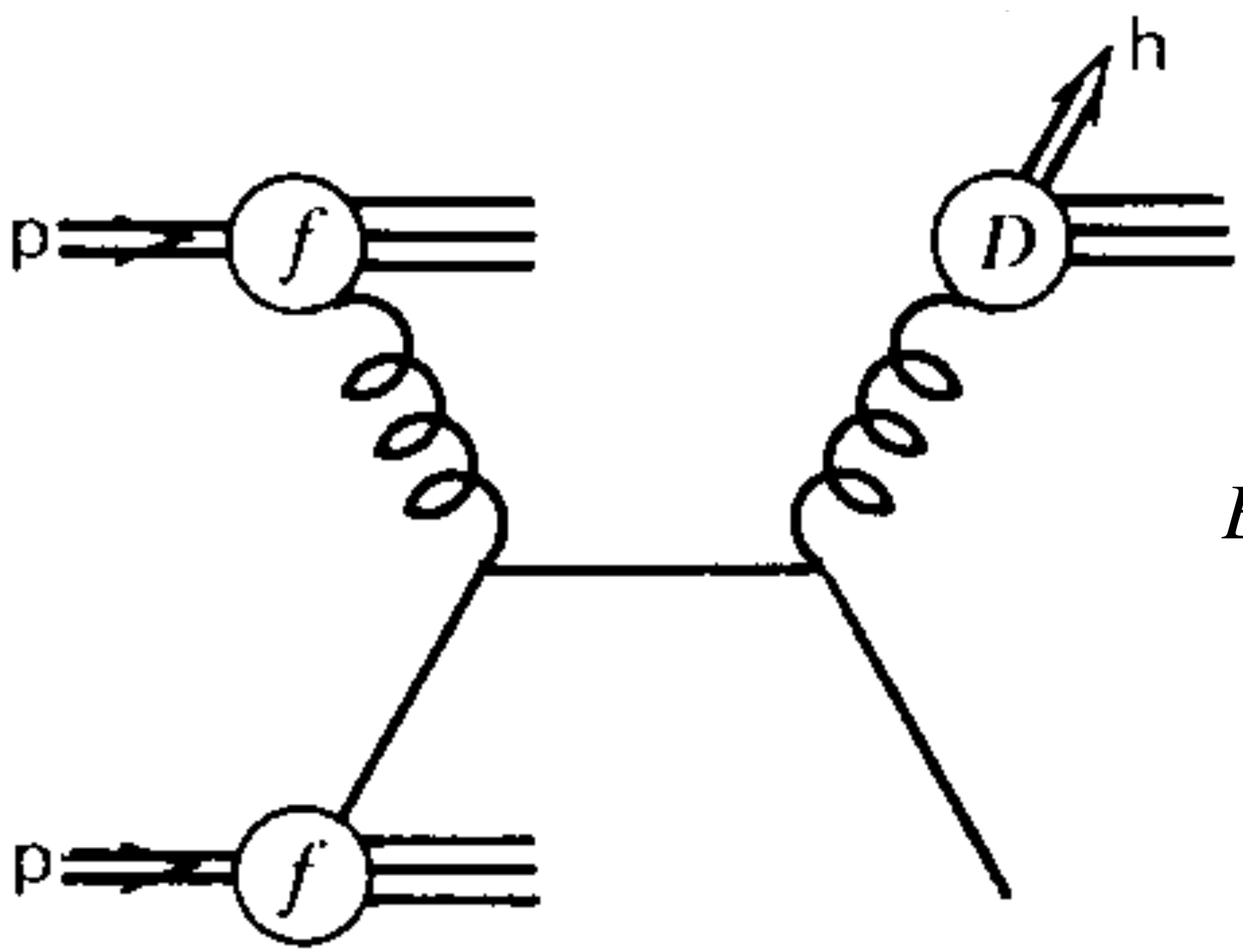
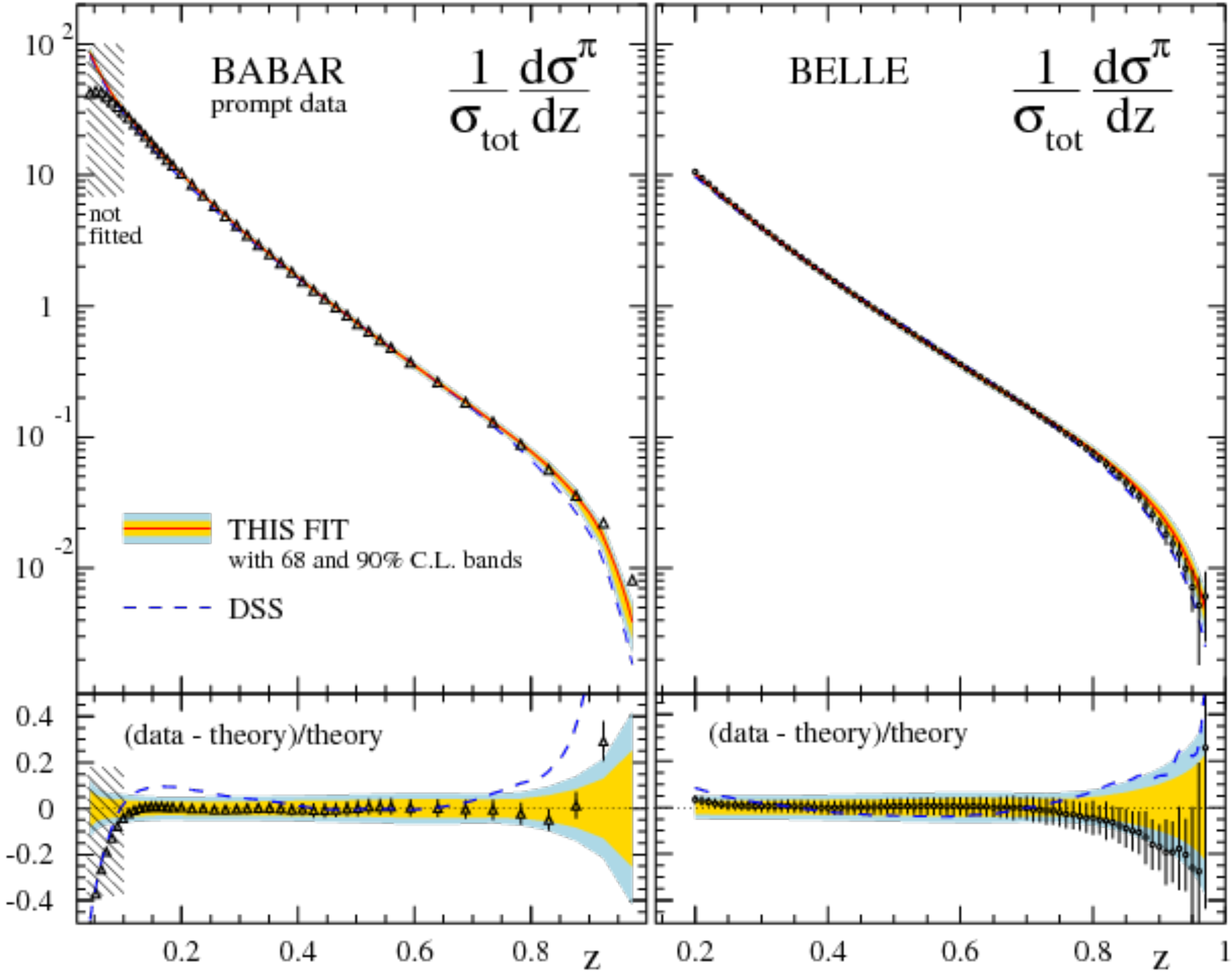


$$E\frac{d^3\sigma^h}{dp^3} = \sum_{i,j,k} \frac{d^3\hat{\sigma}_{ij\to k}}{dp^3} \otimes f_i \otimes f_j \otimes D_k^h$$

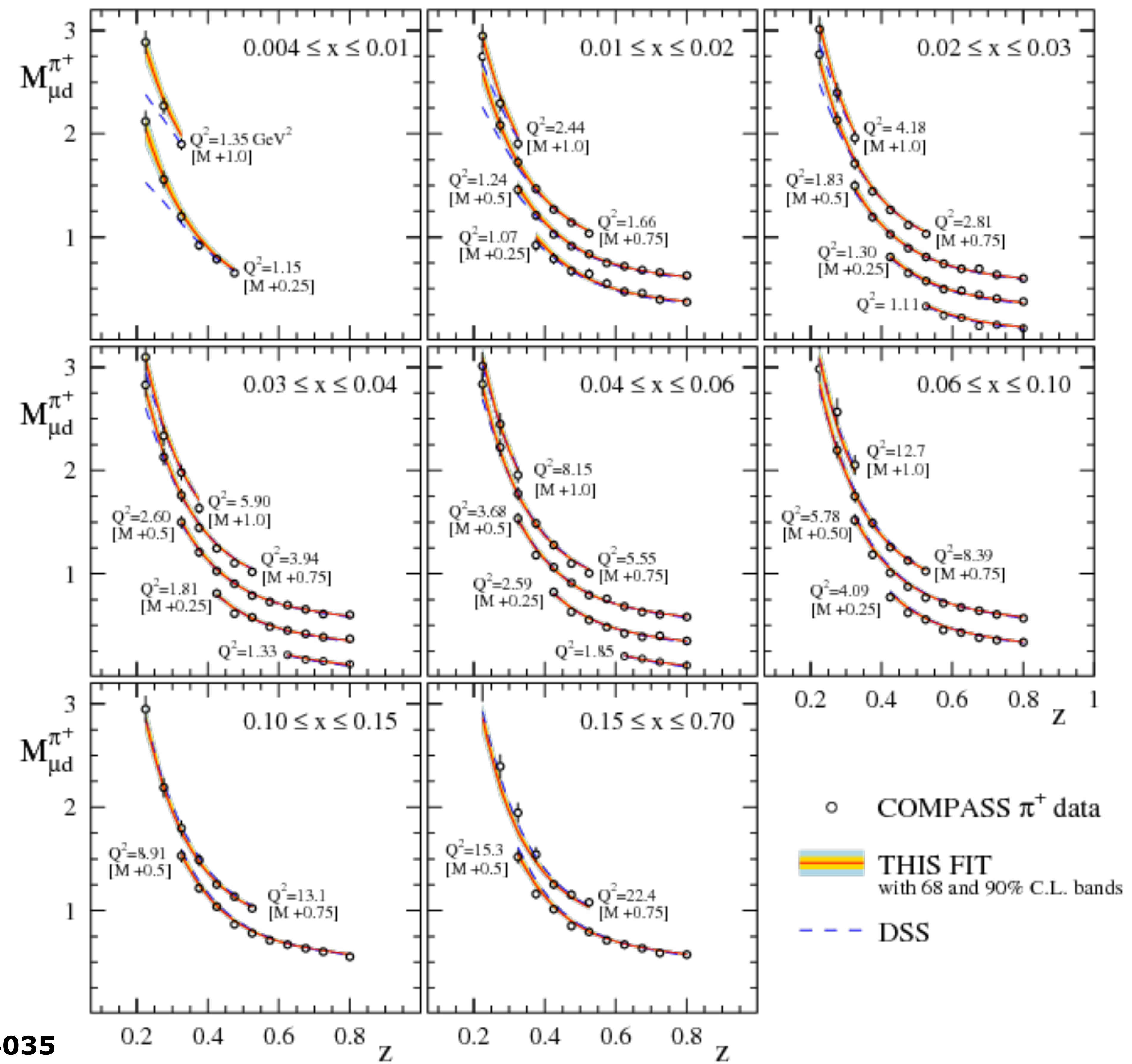
The cross-sections falls quickly several orders of magnitude, so the normalisation is quite a problem. **NPB 883, 615**

NLO FFs from **SIA**, SIDIS and SIH



PRD 91, 014035

NLO FFs from SIA, **SIDIS** and SIH



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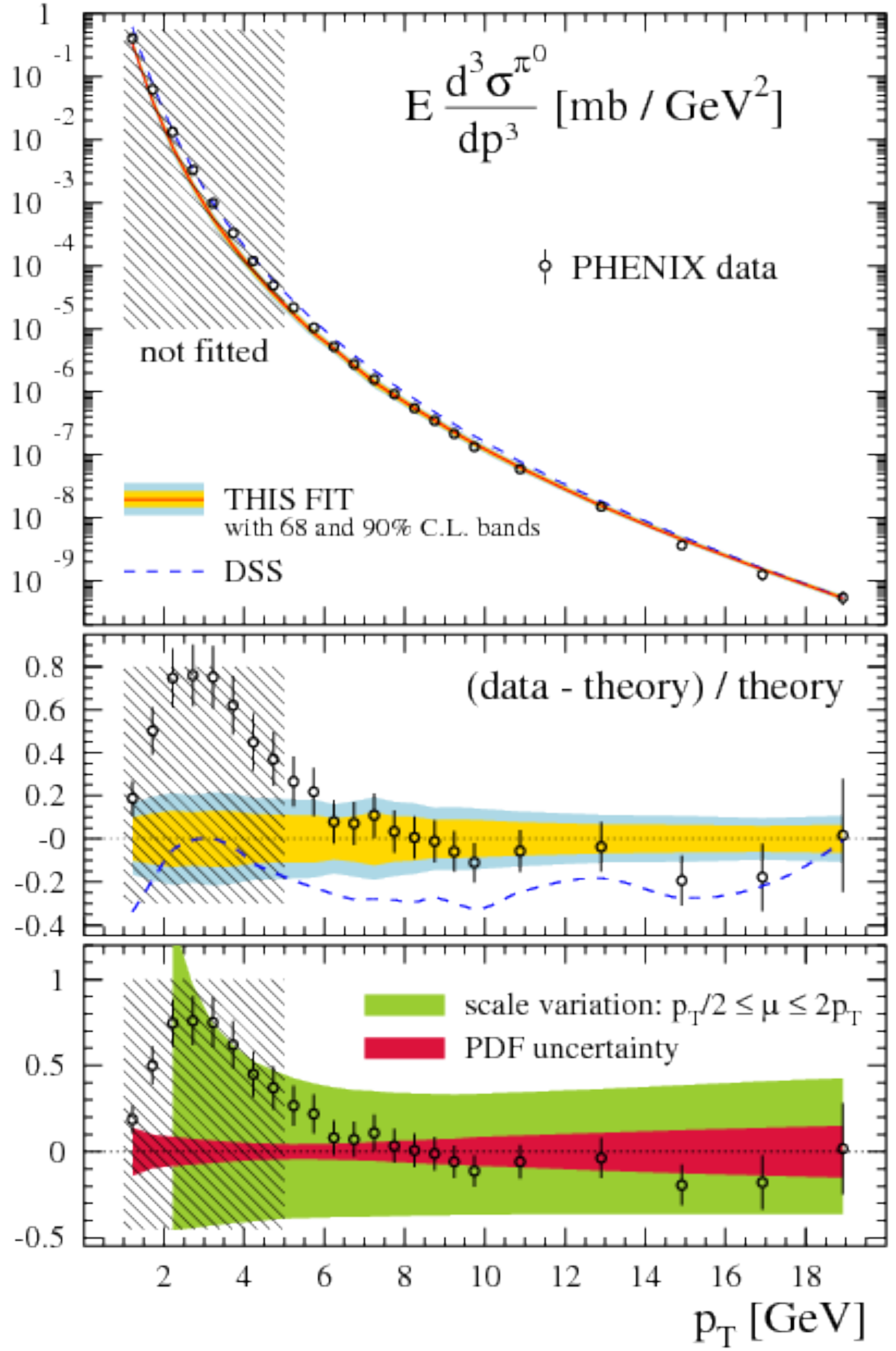

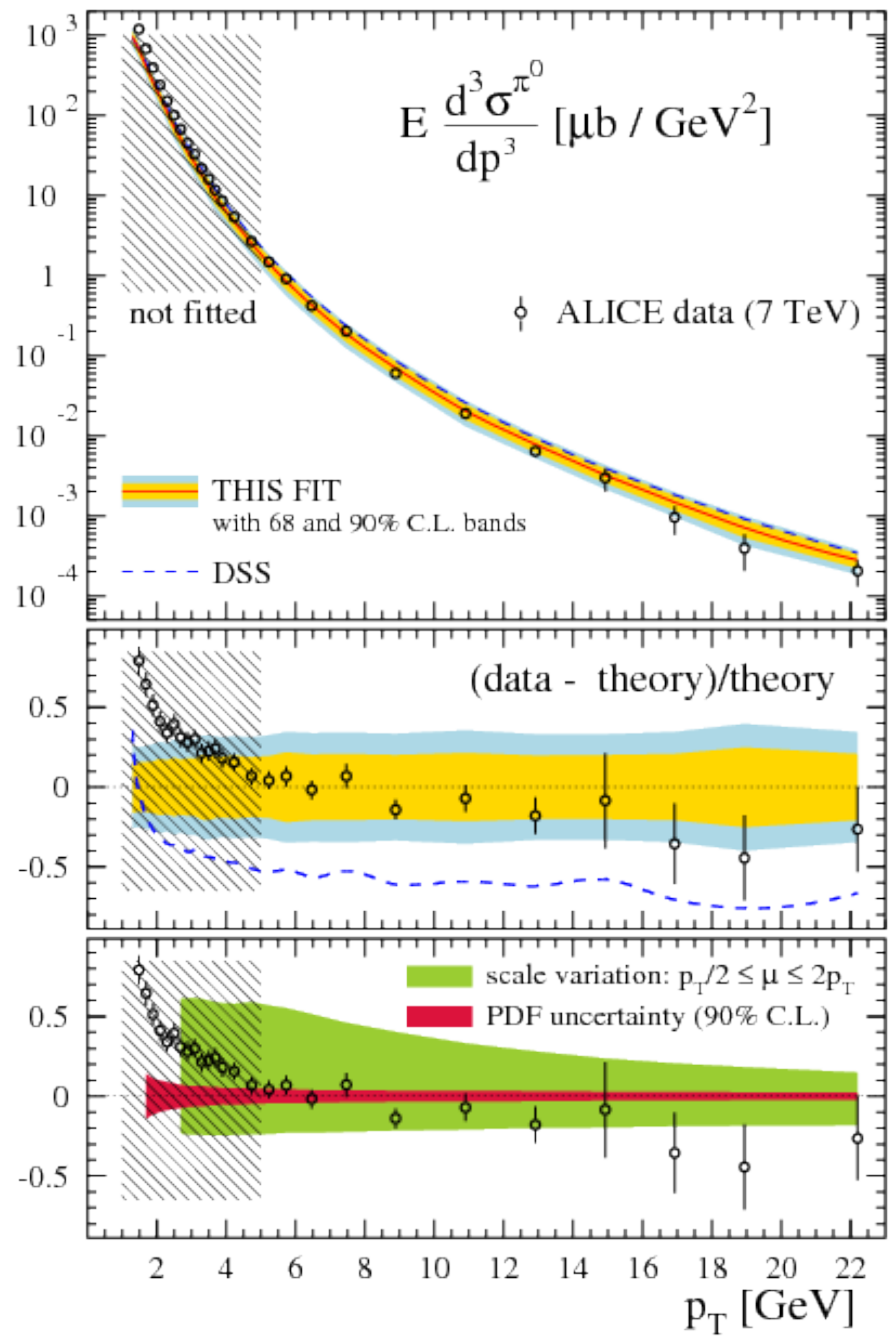

PRD 91, 014035

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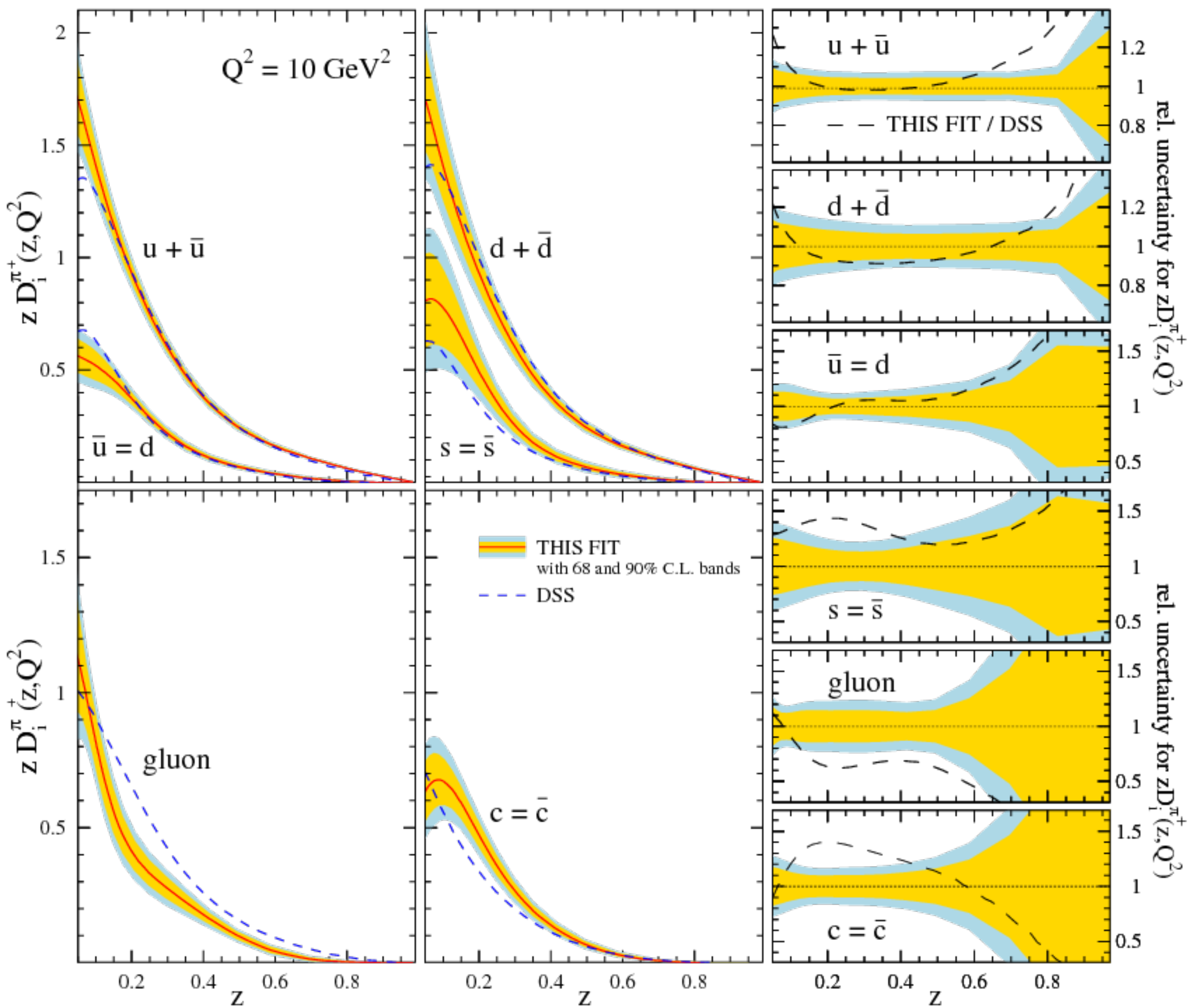
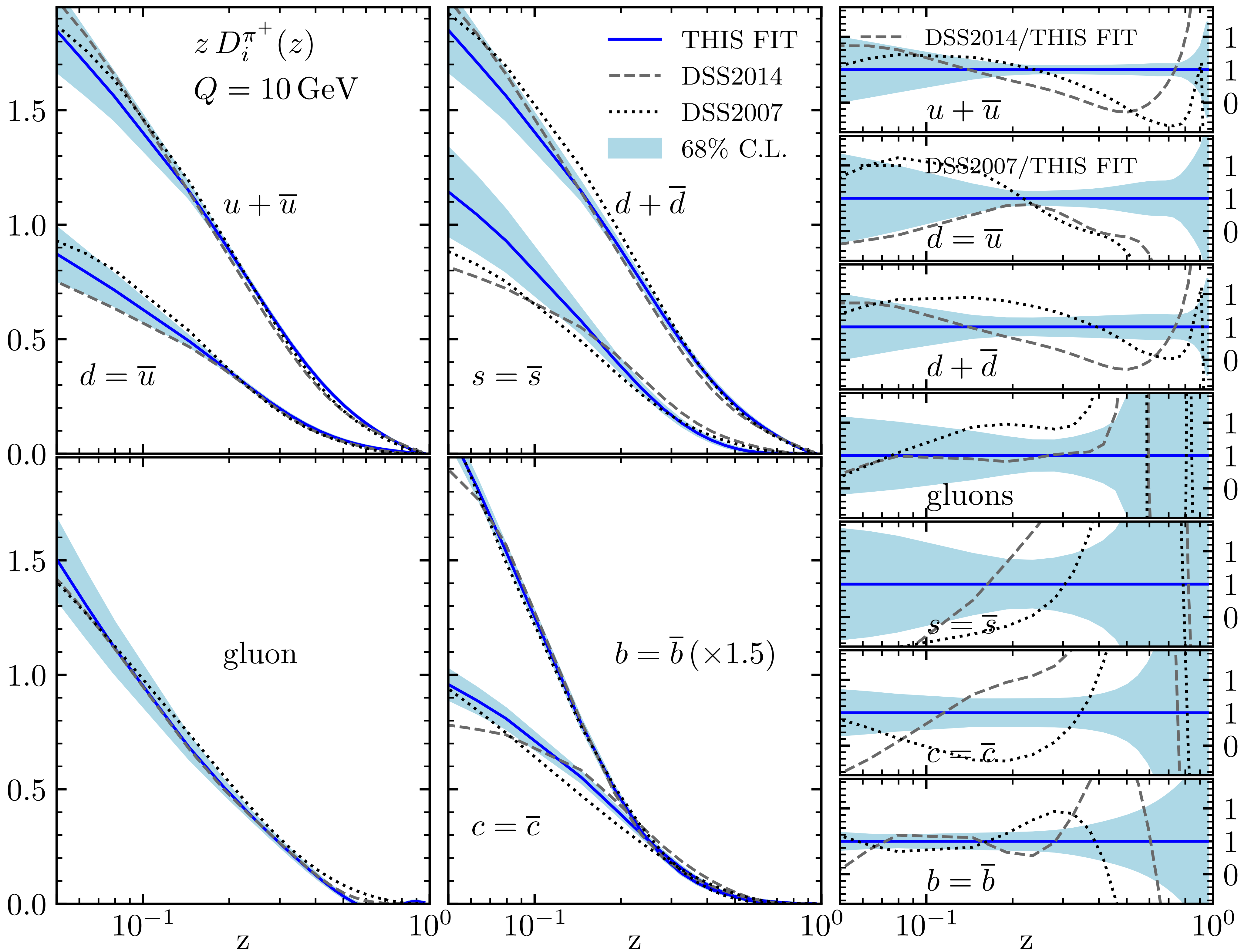


PRD 91, 014035

NNLO FFs from SIA and (approximate) SIDIS



PRD 105, L031502

An incomplete list of vacuum FFs

BKK — Z.Phys.C 65, 471: $\pi^{0,\pm}, K^{\pm}$

KKP — NPB 582, 514: $\pi^{0,\pm}, K^{\pm}$

Kretzer — PRD 62, 054001: $\pi^{0,\pm}, K^{\pm}$

HKNS07 — PRD 75, 094009: $\pi^{0,\pm}, K^{\pm}$

DSS — PRD 75, 114010: $\pi^{0,\pm}, K^{\pm}$

DSS — PRD 76, 074033: $p, \bar{p}, h^{\pm}$

AKK08 — NPB 803, 42: $\pi^{0,\pm}, K^{\pm}$

NNFF — EPJC 77, 516: $\pi^{0,\pm}, K^{\pm}$

JAM20 — PRD 104, 016015, $\pi^{0,\pm}, K^{\pm}$

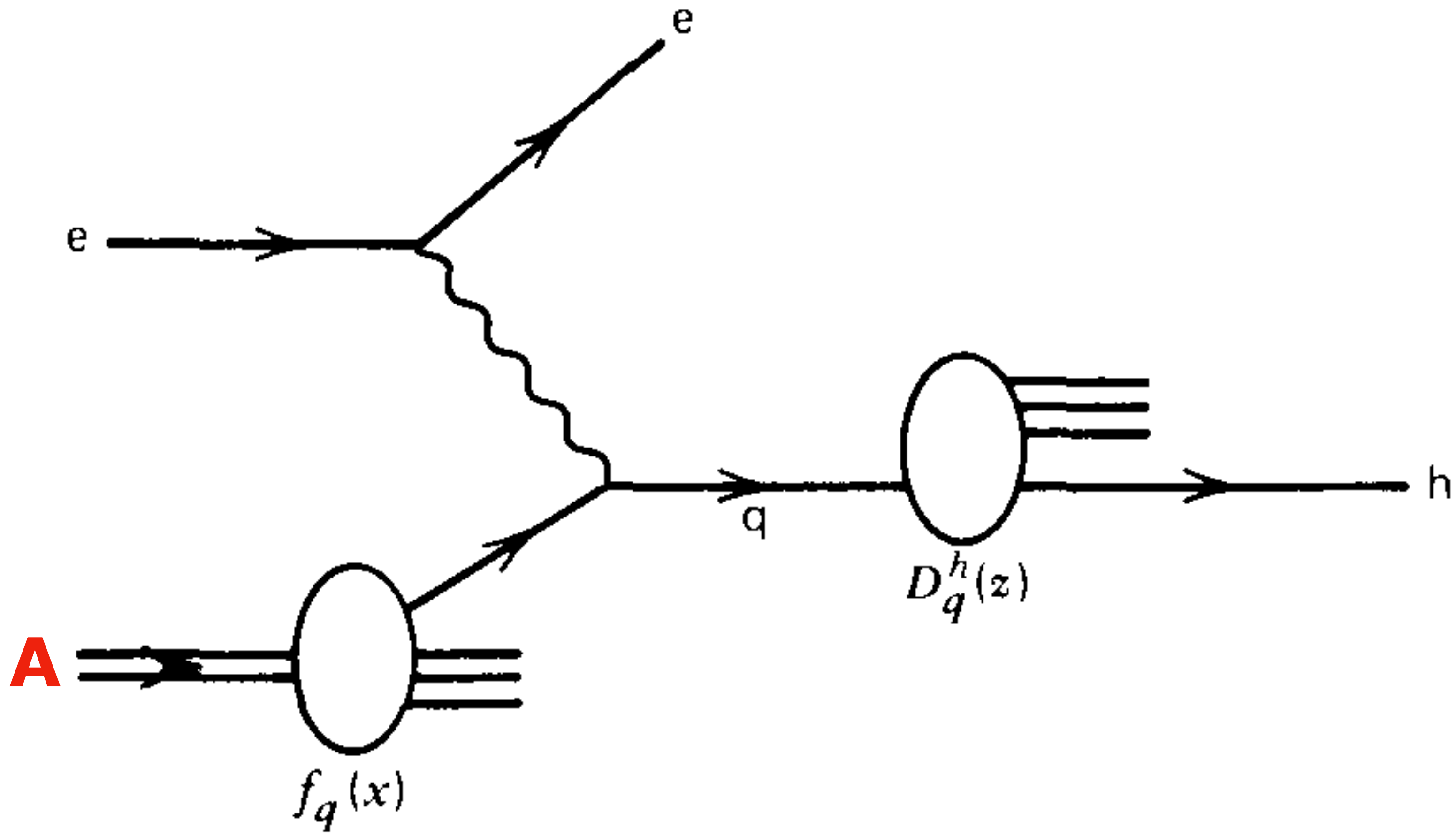
DSS14 — PRD 91, 014035: $\pi^{0,\pm}$

DSS17 — PRD 95, 094019: $K^{\pm}$

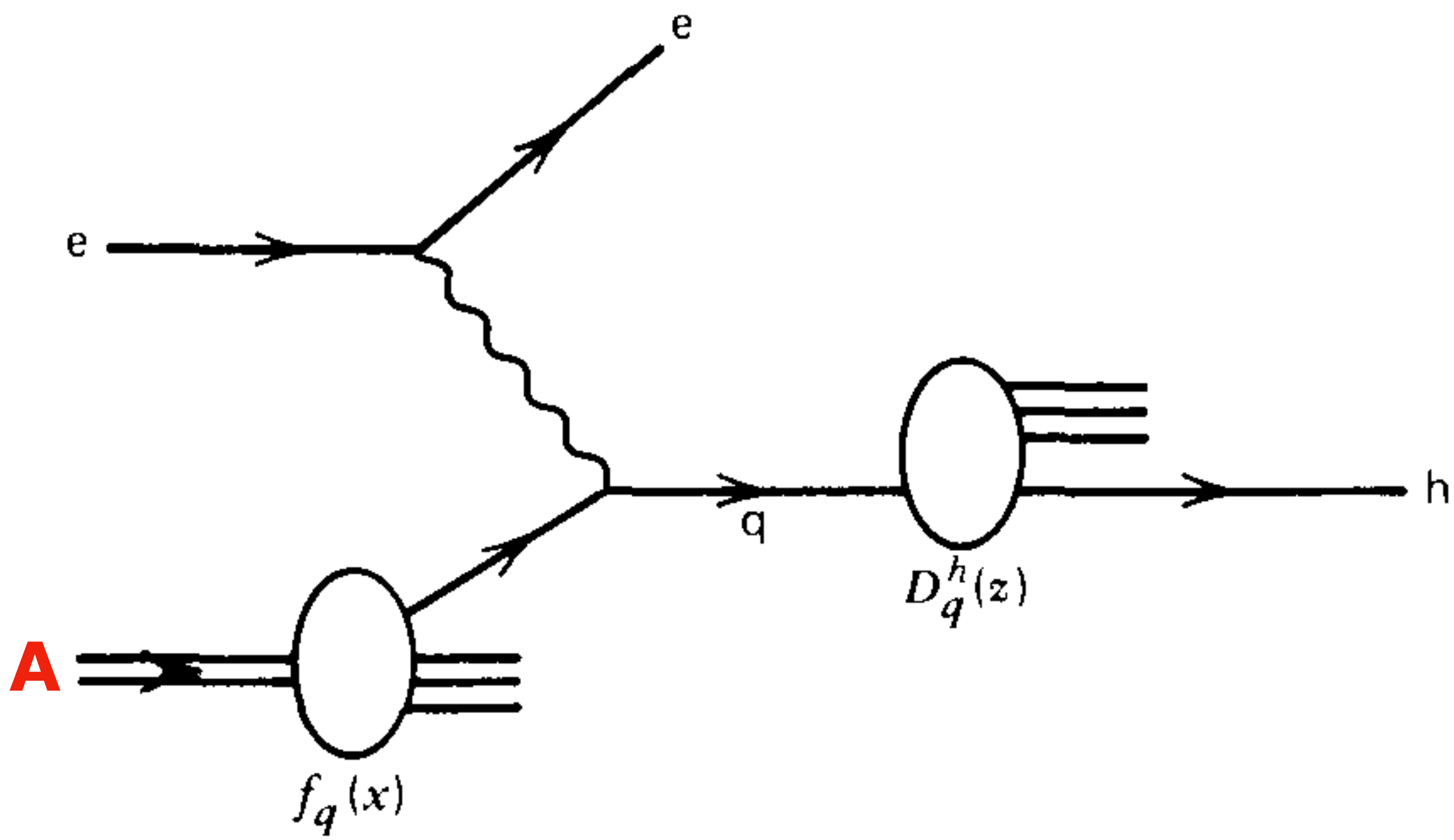
AESSS — PRD 83, 034002: η

Nuclear data

With nuclei there is no such a thing as a *clean* process. The simplest thing we can do is SIDIS off nuclei: $l^{\pm}+A \rightarrow h+X$.



With nuclei there is no such a thing as a *clean* process. The simplest thing we can do is SIDIS off nuclei: $l^{\pm} + A \to h + X$.



$$N = \sigma\, L$$

Number of events.

Luminosity

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

Lab./Exp.	Ref.	Year	Nuclei	Beam	E_{beam} (GeV)
SLAC	PRL 40, 1624	1978	D, Be, C, Cu, Sn	e	20.5
BEBC	NPB 198, 365	1982	D, Ne	(anti-)ν	200
EMC	Z.Phys.C 52, 1	1991	D, C, Cu, Sn	μ	100, 120, 200, 280
E665	PRD 50, 1836	1994	D, Xe	μ	490
HERMES	NPB 780, 1	2007	D, He, N, Ne, Kr, Xe	e	27.6
CLAS	PRC 105, 015201	2022	C, Fe, Pb	e	5.014
Minerva	2209.07852 [hep-ex]	2022	CH, C, H_2O, Fe, Pb	ν	6

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Also pions from BEBC and Minerva

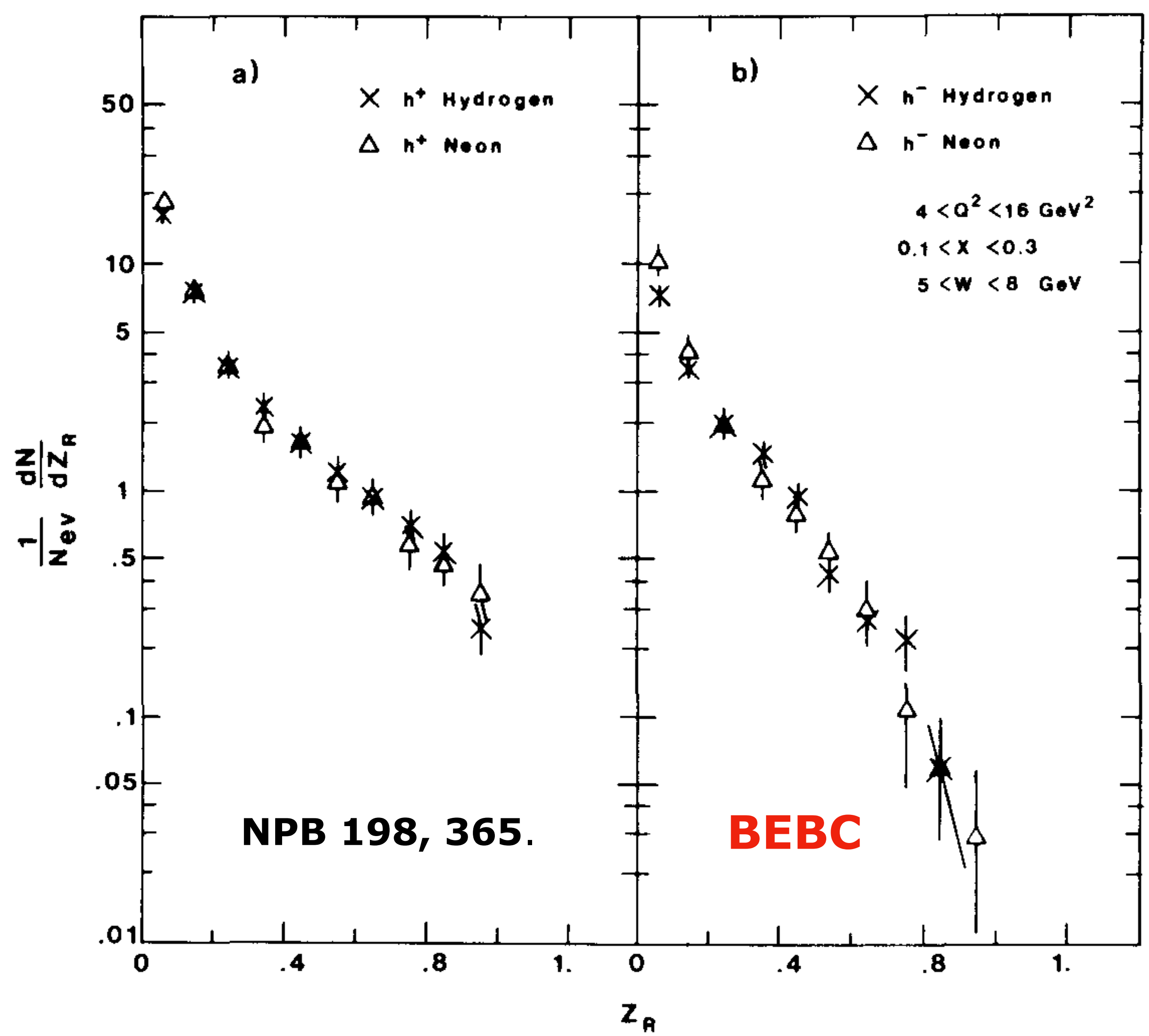
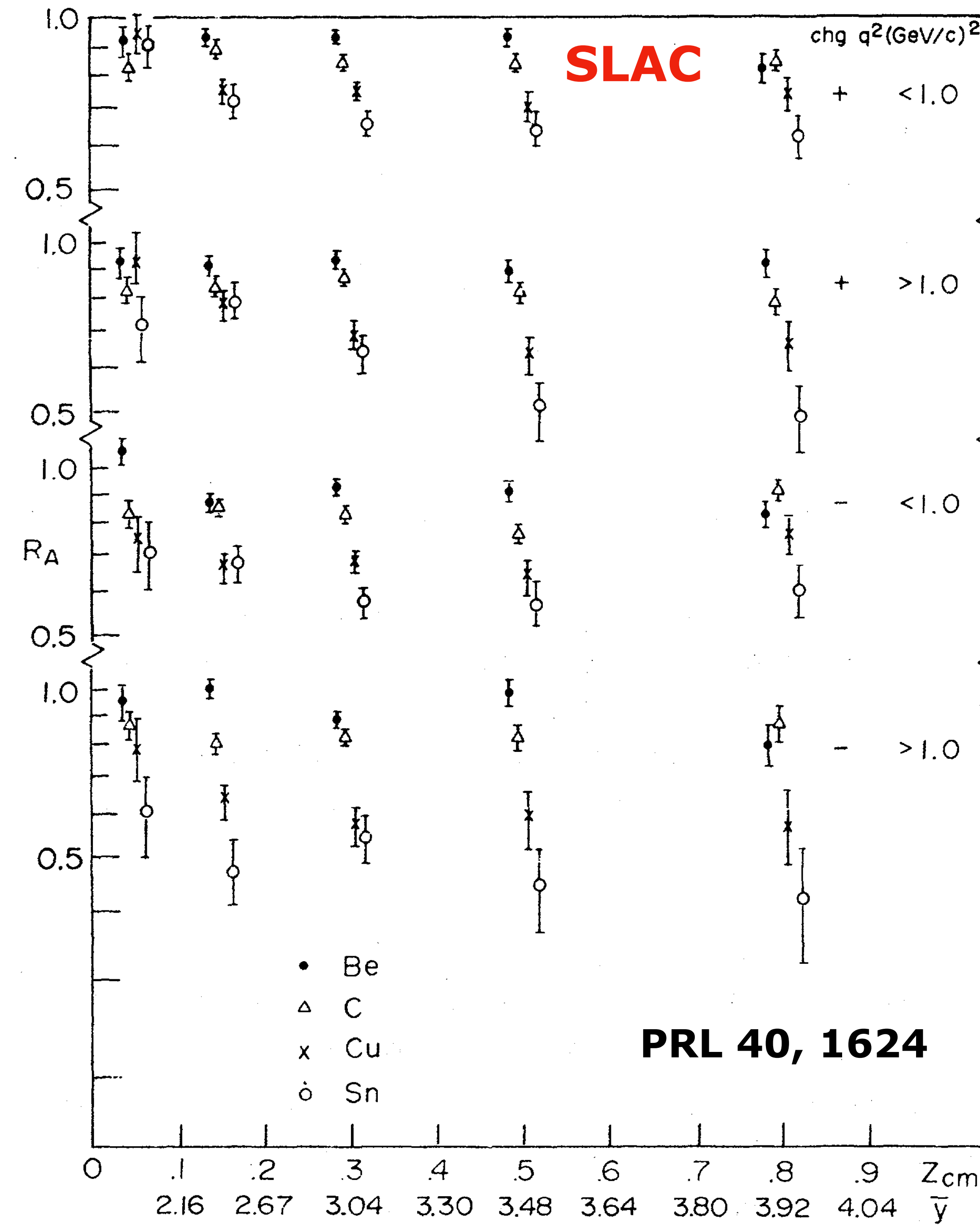
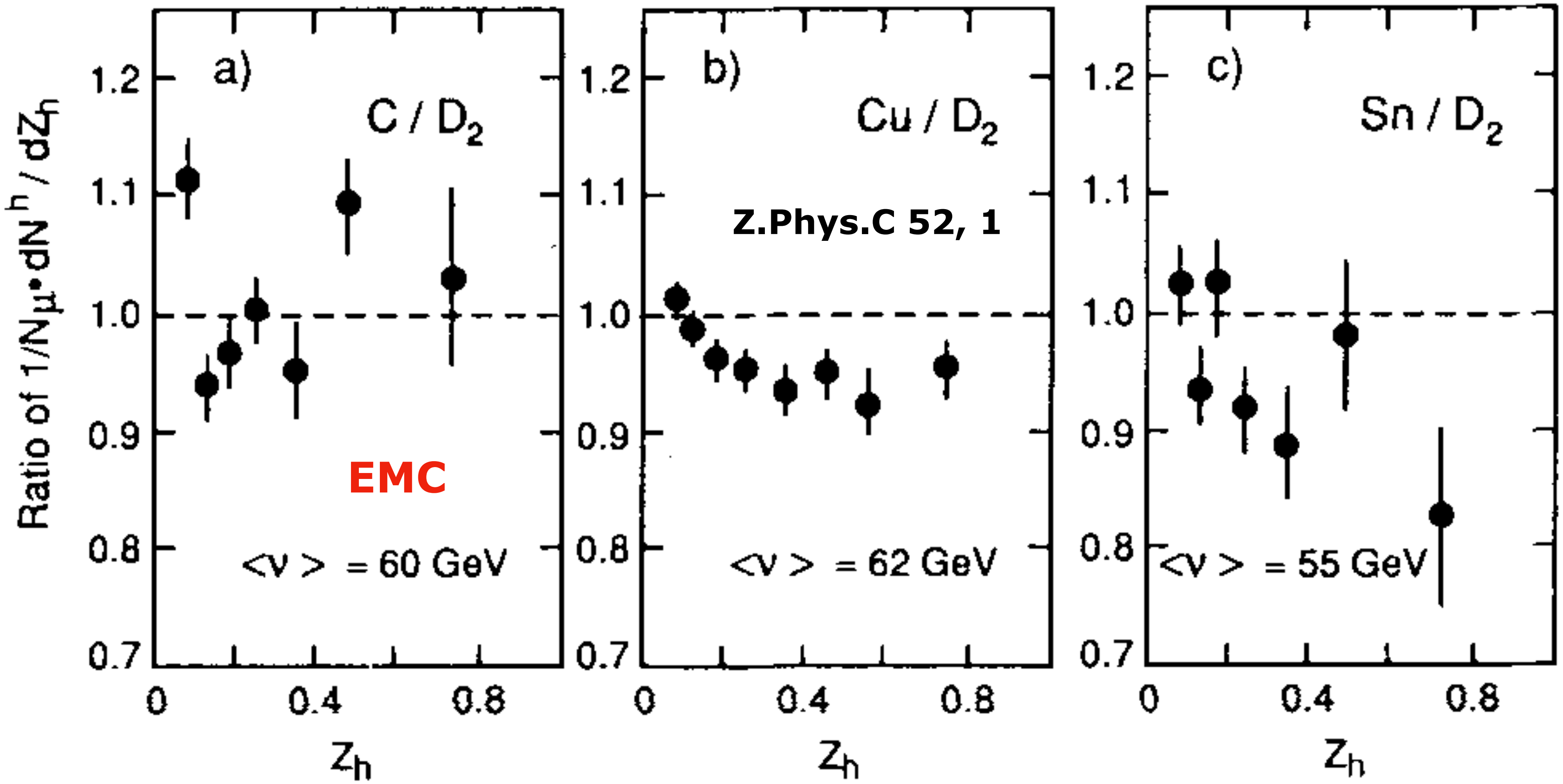


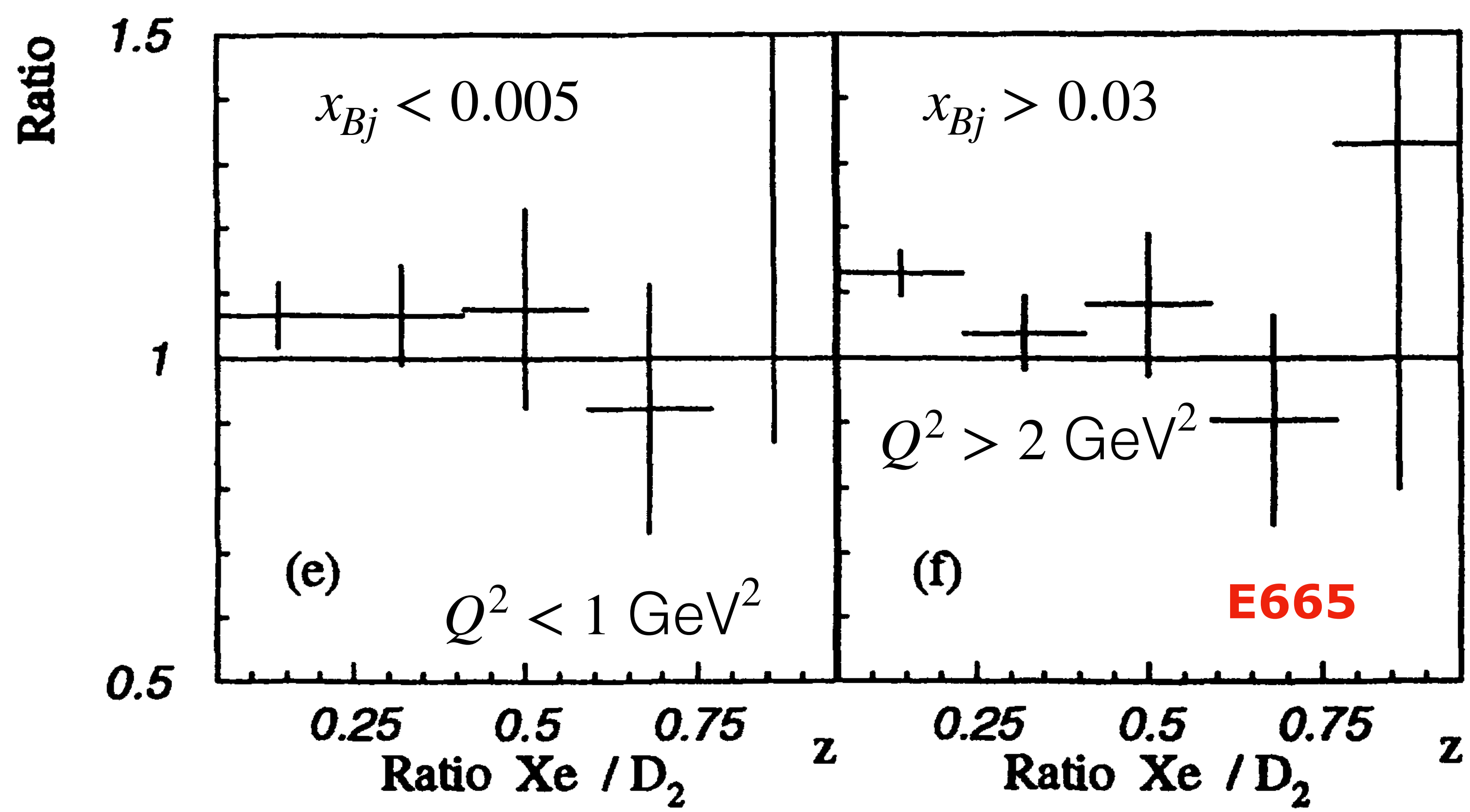
Fig. 2. Comparison of z_R distributions for ν events in the present Ne/H_2 experiment and a H_2 experiment [1], for events in the common kinematic region: $4 < Q^2 < 16$ GeV^2; $5 < W < 8$ GeV and $0.1 < x < 0.3$: (a) for all positive hadrons; (b) for all negative hadrons.





Ratio of 1/Nμ•dN^h / dZh
a)
C / D2
EMC
<ν > = 60 GeV
b)
Cu / D2
Z.Phys.C 52, 1
<ν > = 62 GeV
c)
Sn / D2
<ν > = 55 GeV
Zh

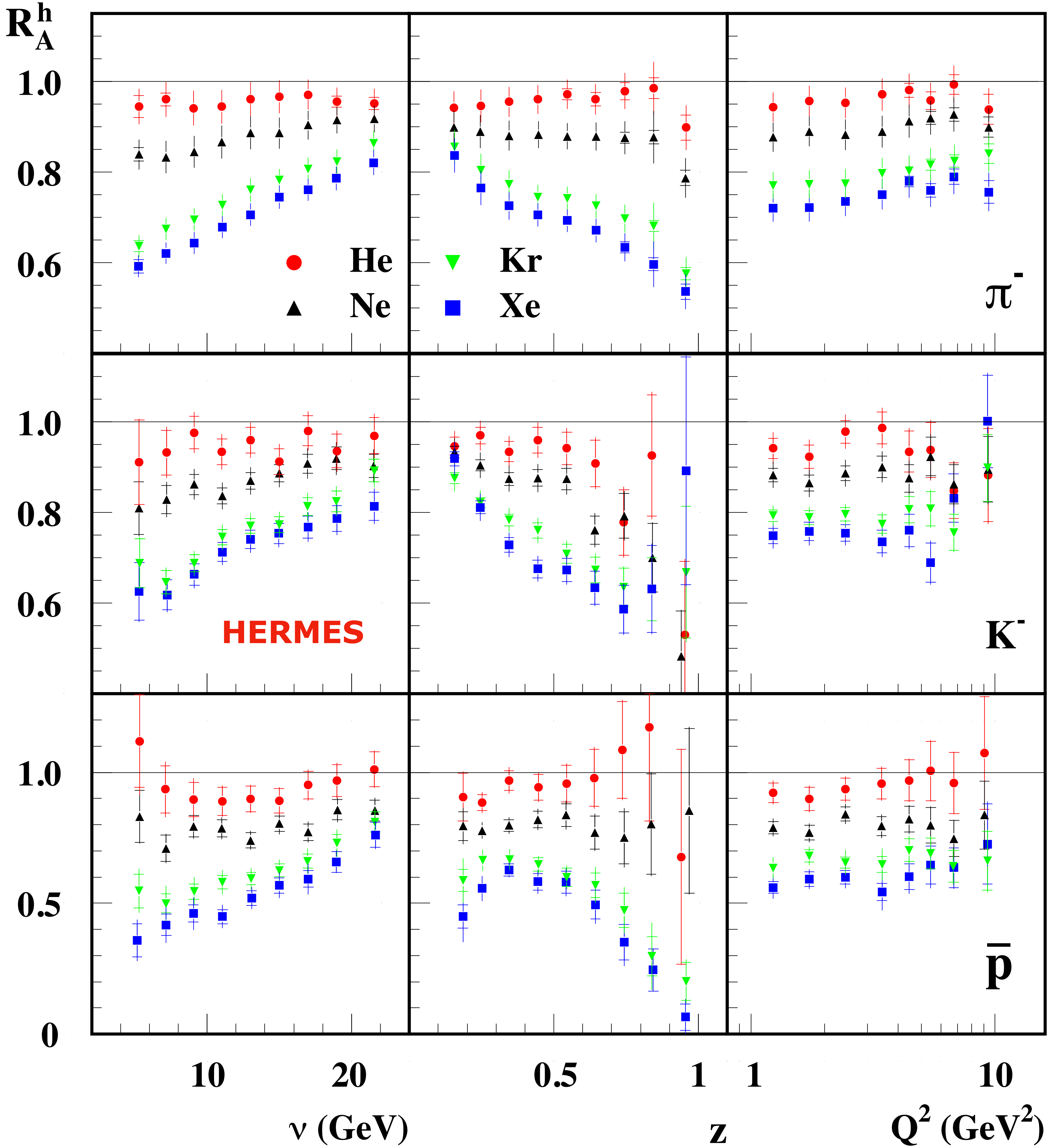
PRD 50, 1836

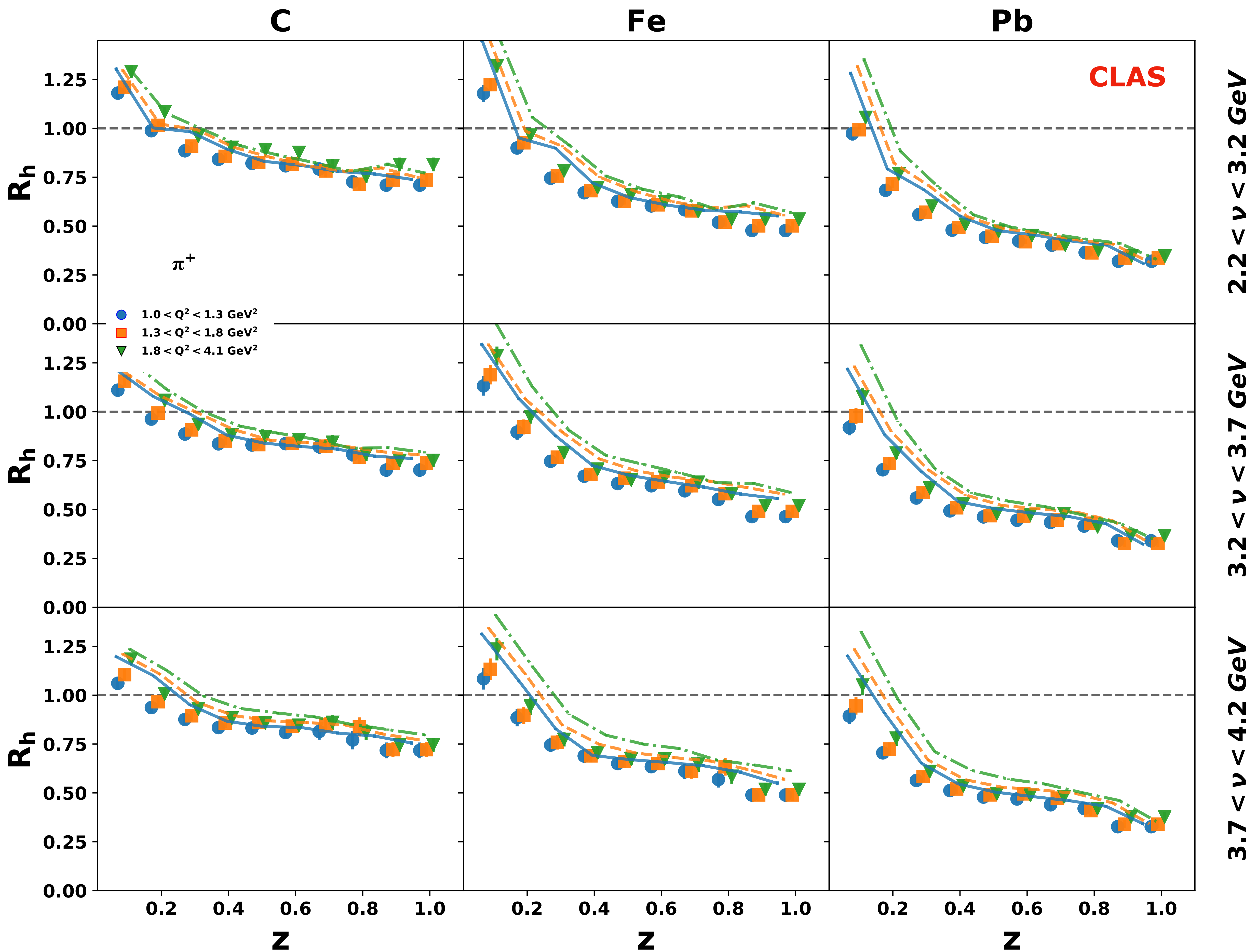


Ratio
x_Bj < 0.005
x_Bj > 0.03
Q^2 > 2 GeV^2
(e)
Q^2 < 1 GeV^2
(f)
E665
z
Ratio Xe / D2
Ratio Xe / D2
z

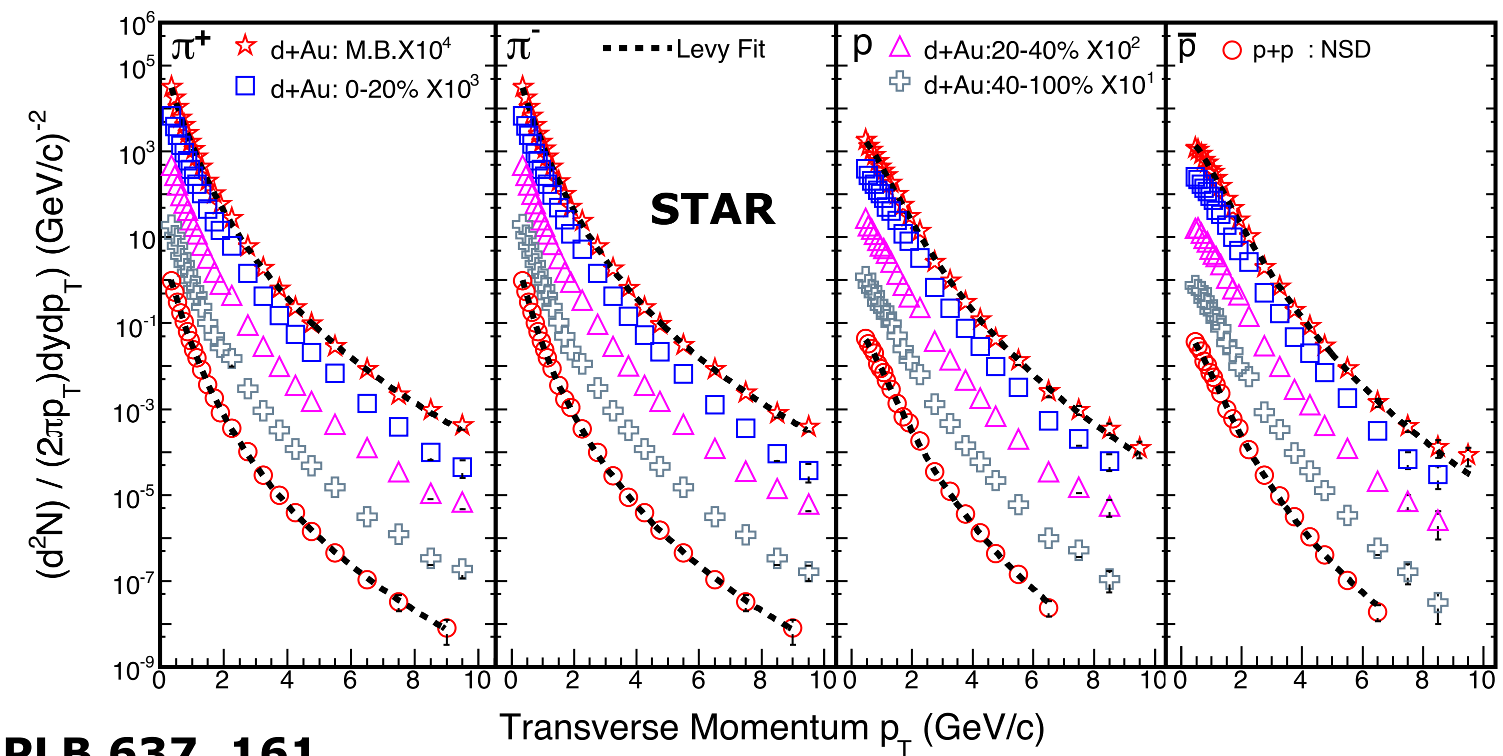
NPB 780, 1

Also h+

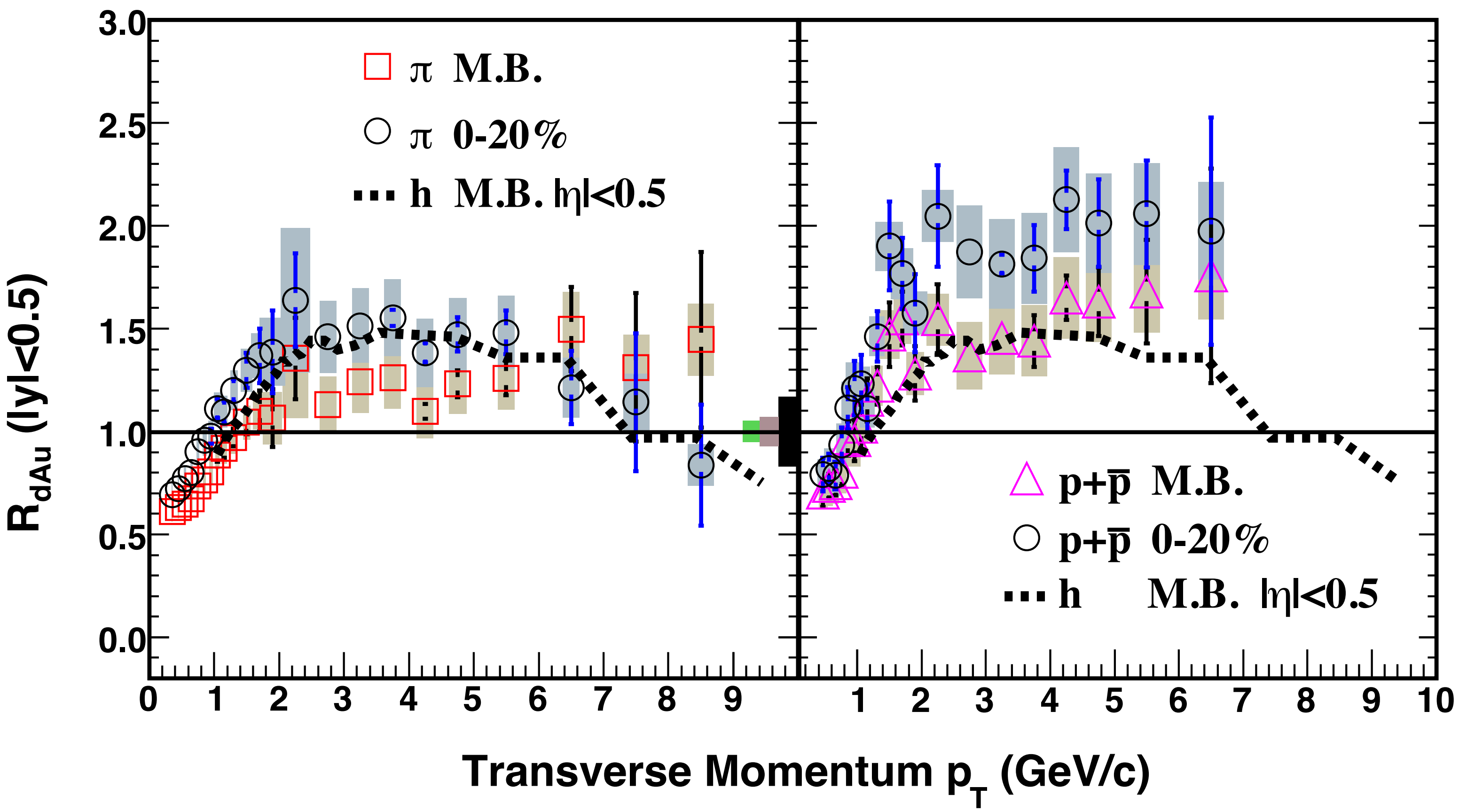


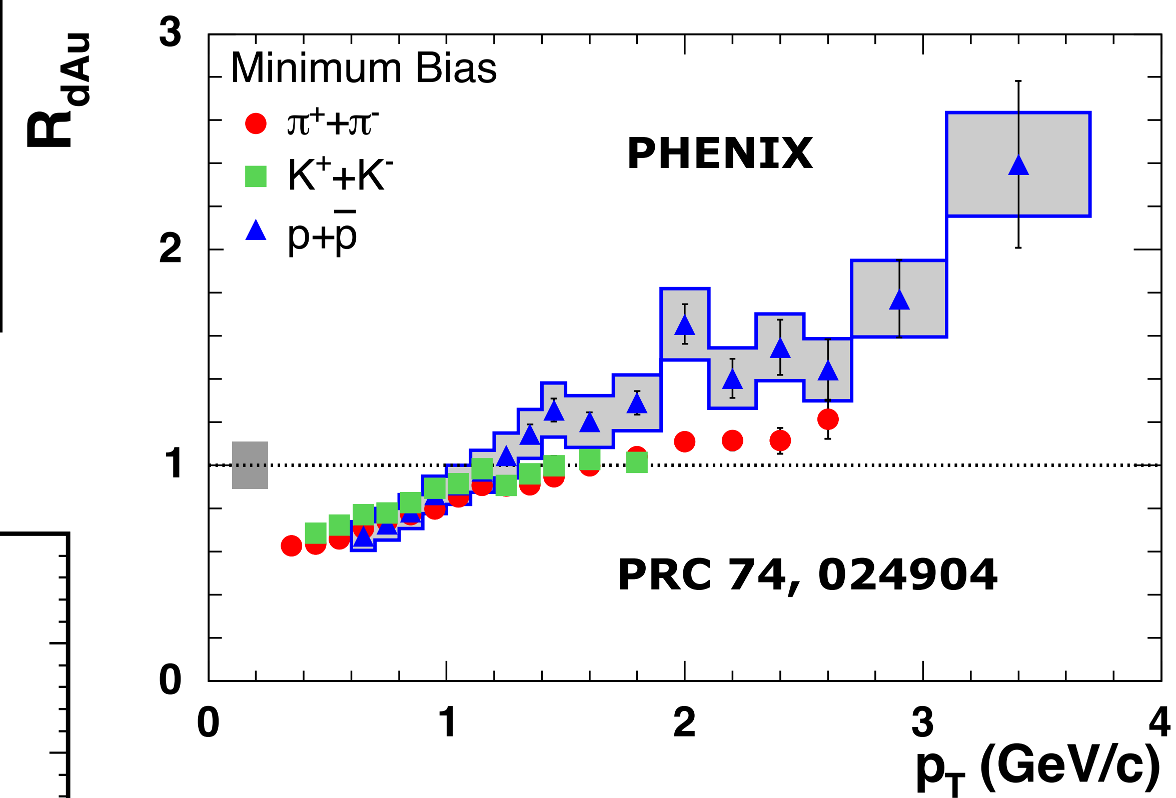

C
Fe
Pb
CLAS
π^+
$1.0 < Q^2 < 1.3$ GeV^2
$1.3 < Q^2 < 1.8$ GeV^2
$1.8 < Q^2 < 4.1$ GeV^2
R_h
z
$2.2 < \nu < 3.2$ GeV
$3.2 < \nu < 3.7$ GeV
$3.7 < \nu < 4.2$ GeV
0.00
0.25
0.50
0.75
1.00
1.25
0.2
0.4
0.6
0.8
1.0

We can up our game with observables in $d + Au$:

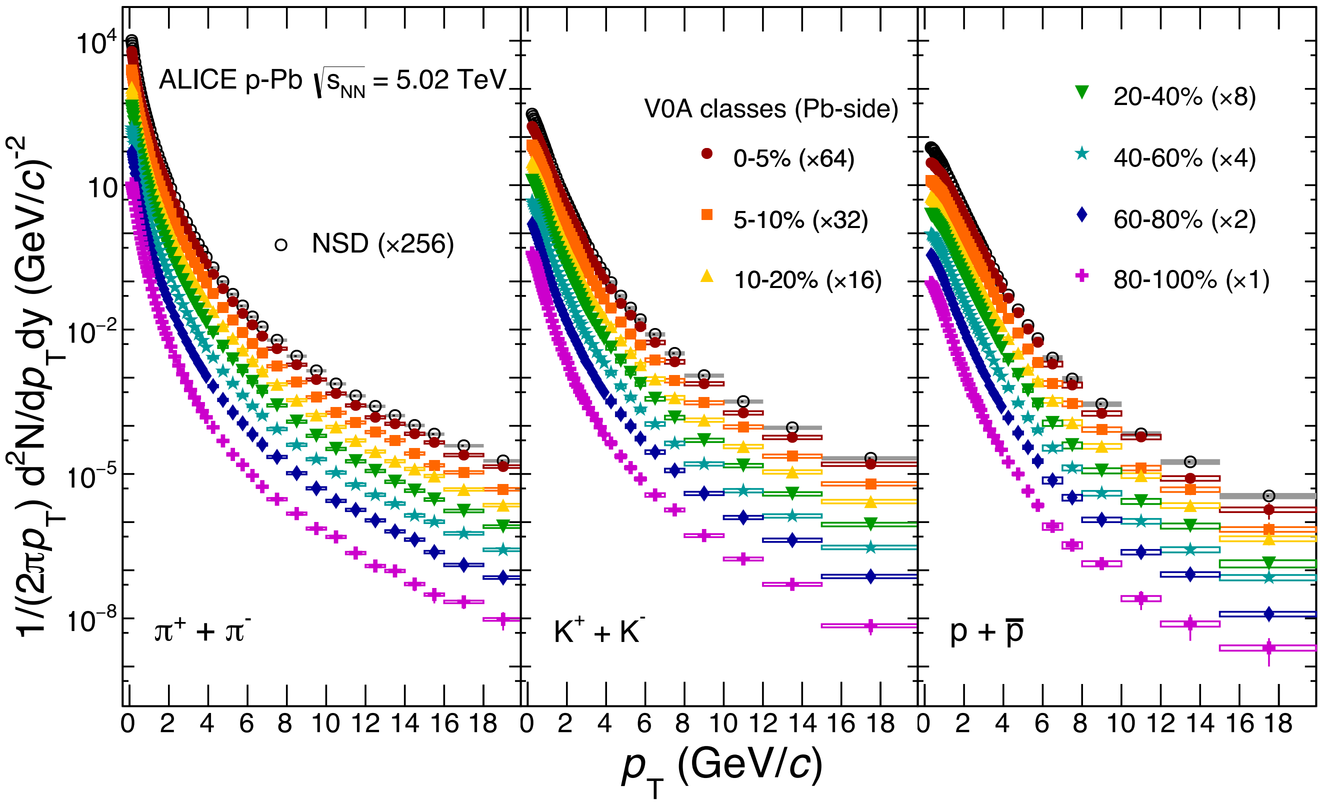


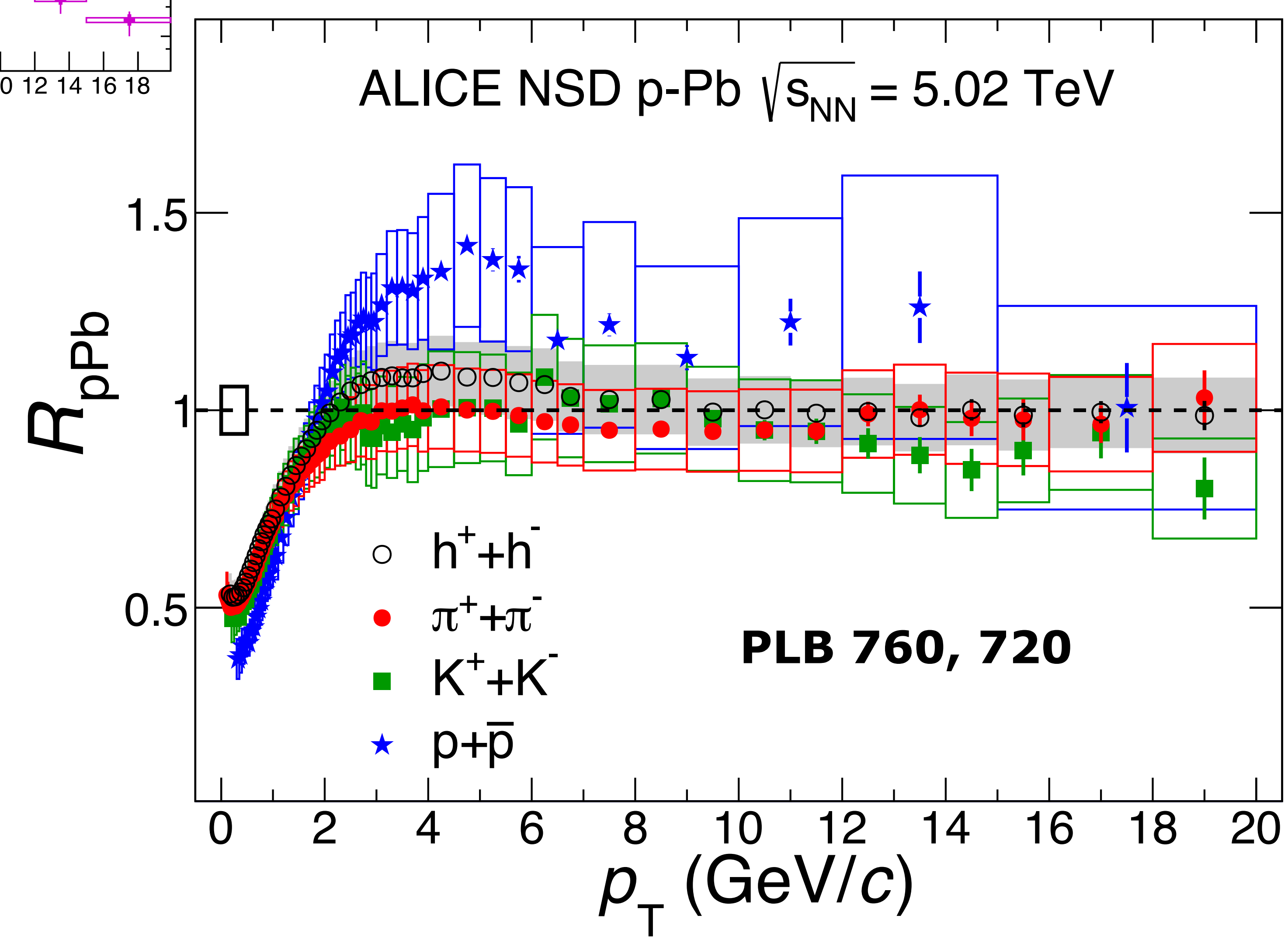
PLB 637, 161





We can up our game with observables in $p + Pb$:

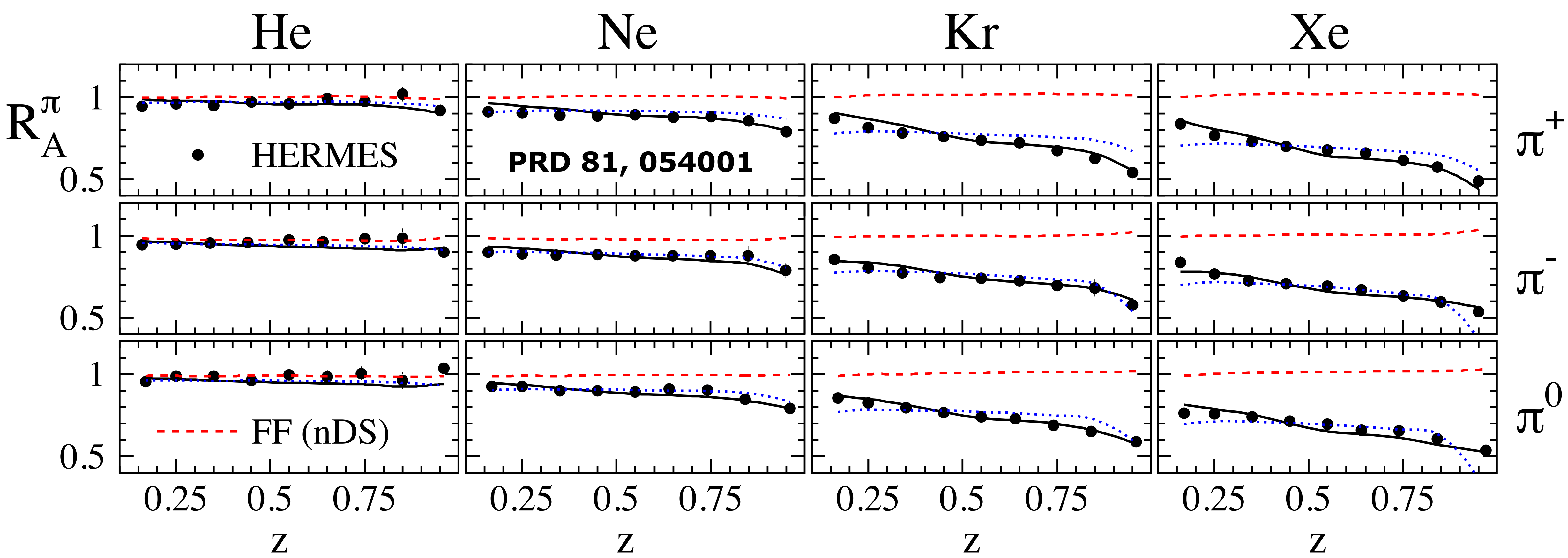




And many more data not shown here!

Describing the nuclear data

Let's start with SIDIS. Clearly there is ***something*** and it increases with the size of the nucleus.



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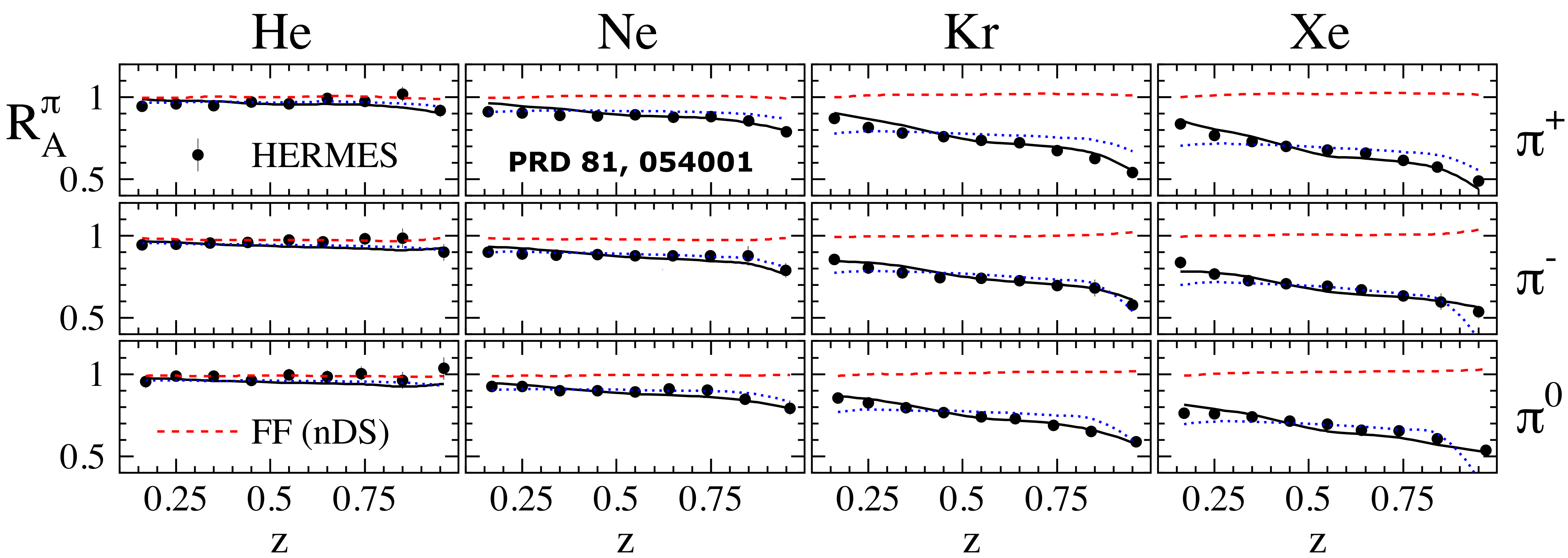

The red lines are predictions using nPDFs (same result with different sets).

Could ***it*** be it an ***initial state effect*** (i.e. due to nPDFs)?

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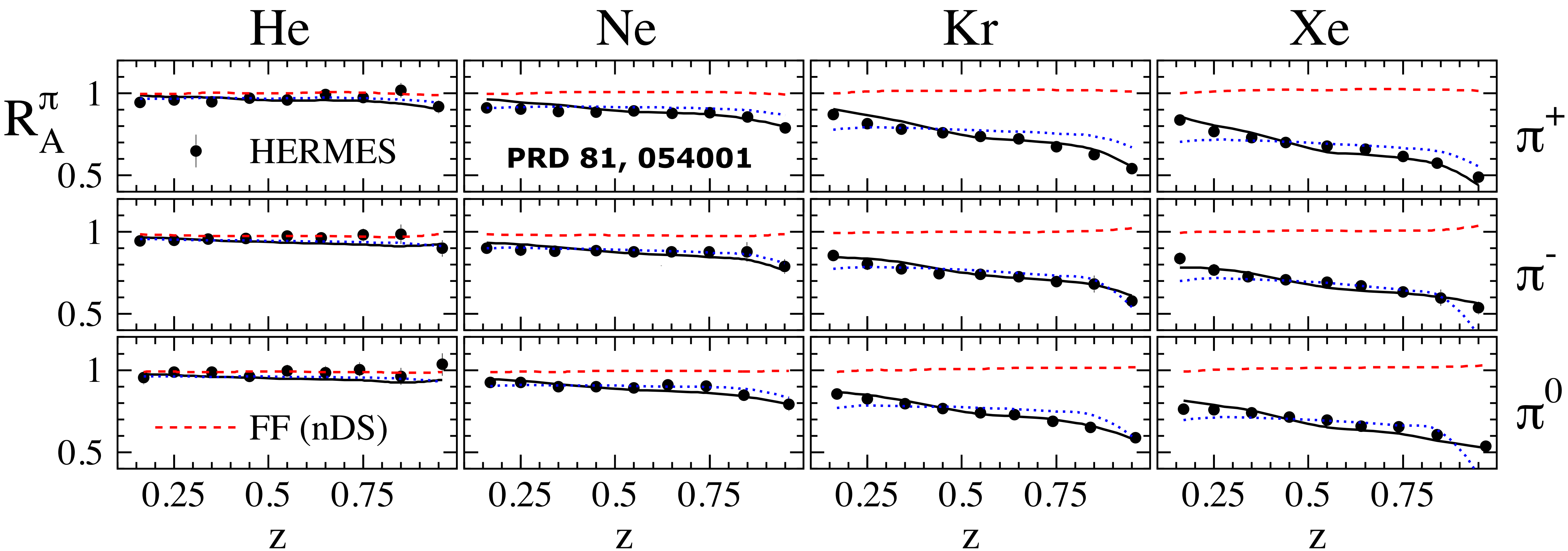


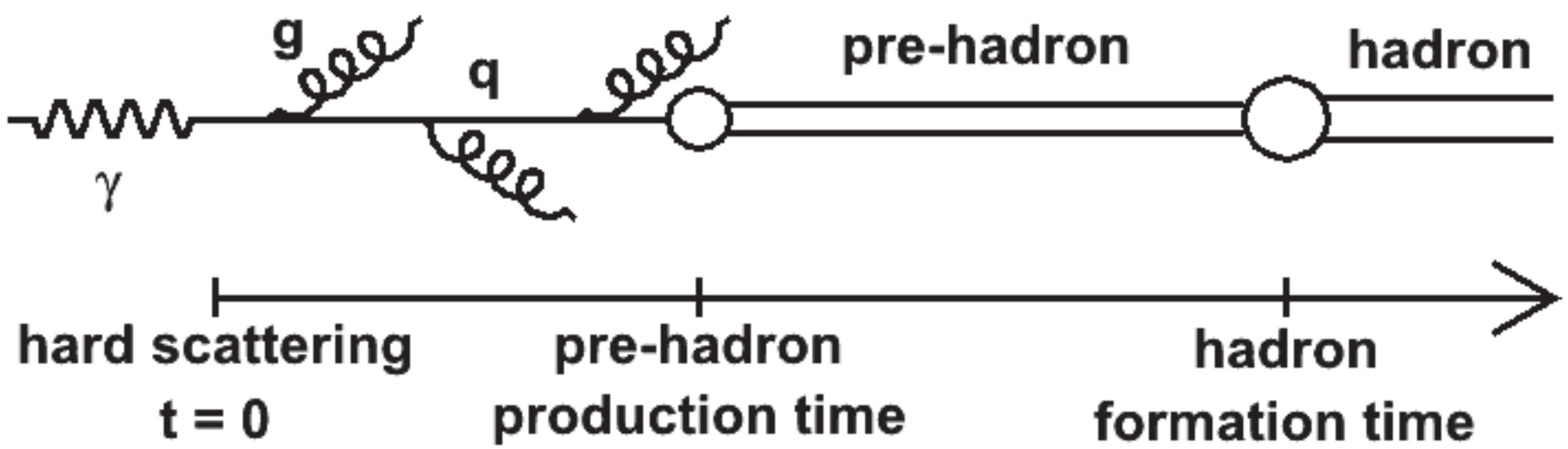
The red lines are predictions using nPDFs (same result with different sets).

Could ***it*** be it an ***initial state effect*** (i.e. due to nPDFs)?

NO. How do we interpret/explain the data?

We can develop *theoretical models* for the hadronization. A popular one is to describe hadronization as having different stages/time scales:

- the quark propagates and emits gluons
- the quark transforms into a color-less pre-hadron
- the pre-hadron becomes the hadronic state



R. Dupré’s thesis

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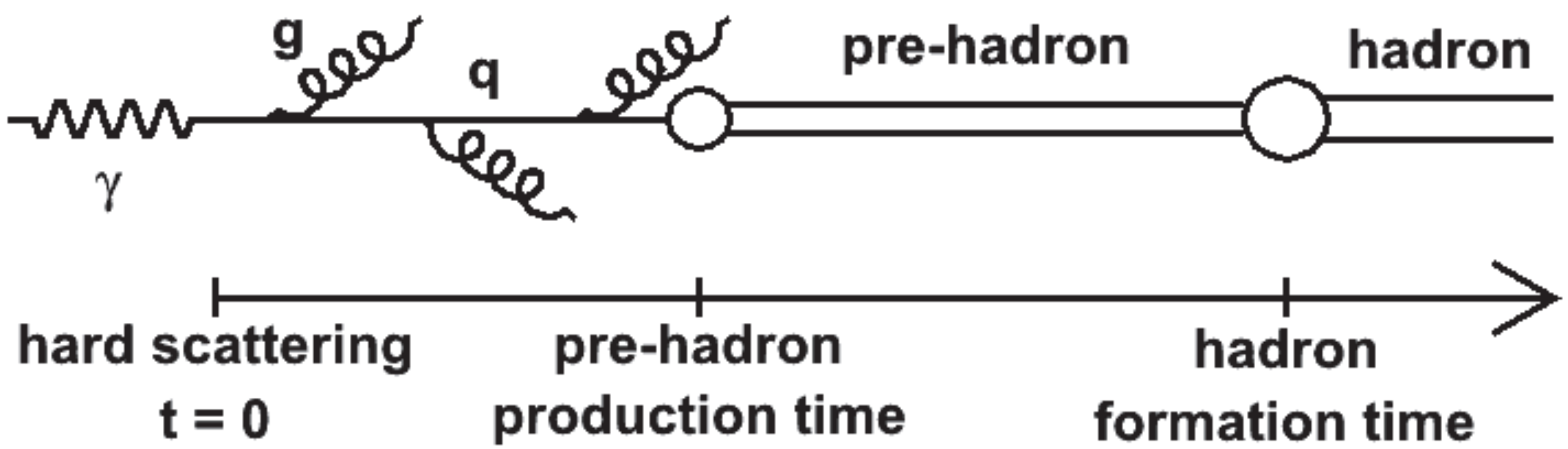
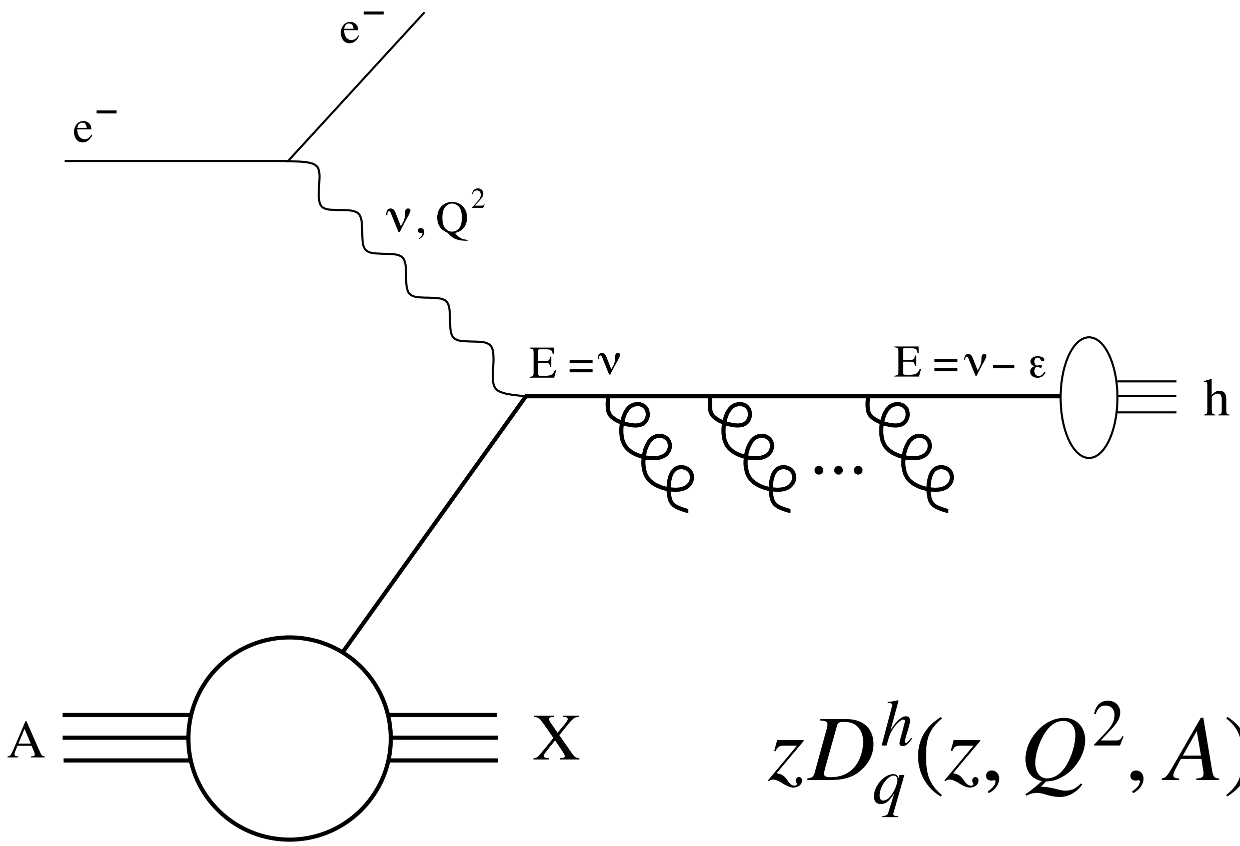


R. Dupré's thesis

Depending *what* happens *where*, we have different interpretations.

1. Energy-loss:

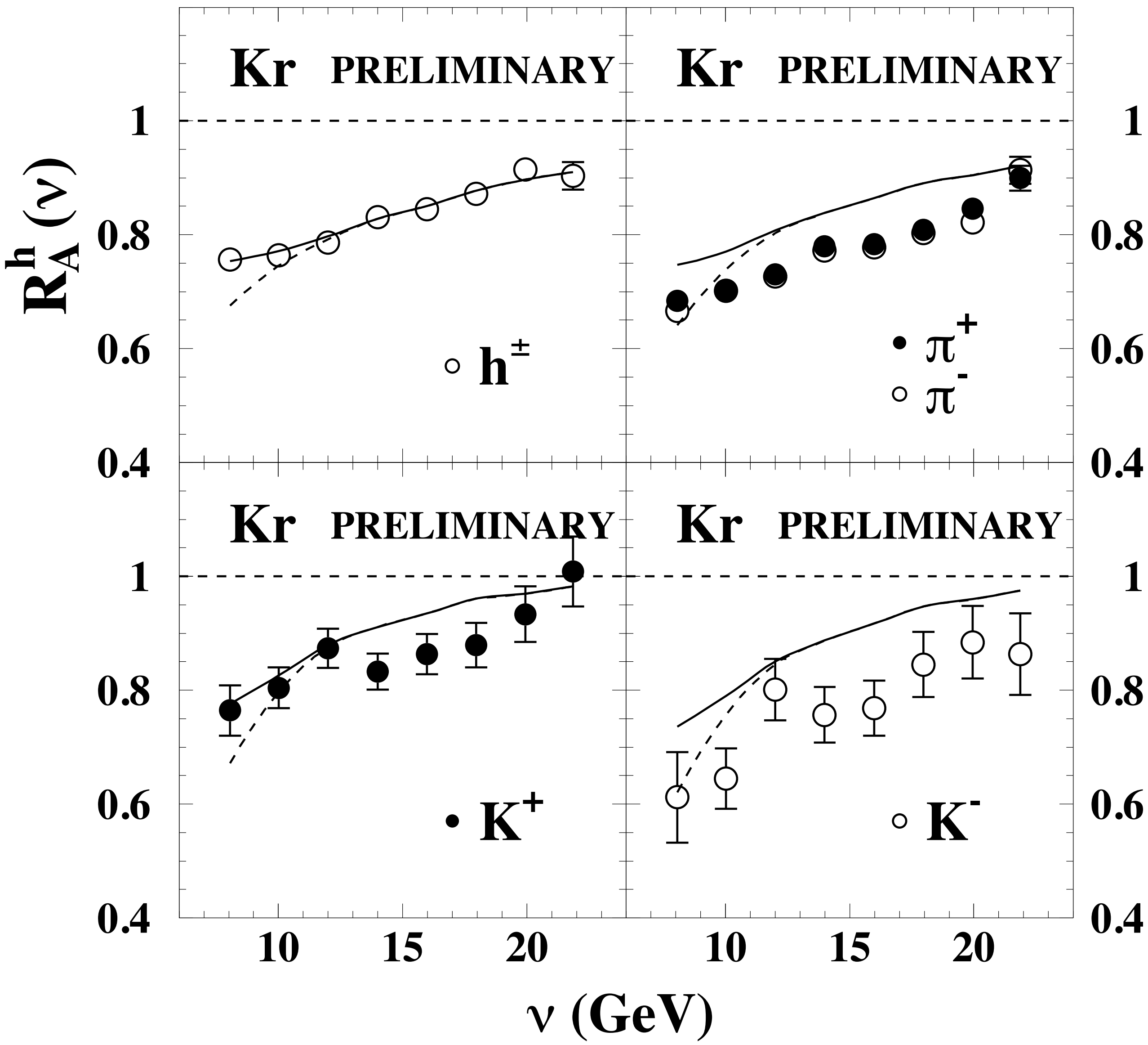


$$z = \frac{E_h}{\nu} \rightarrow z^* = \frac{E_h}{\nu - \epsilon} = \frac{z}{1 - \epsilon/\nu}$$

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

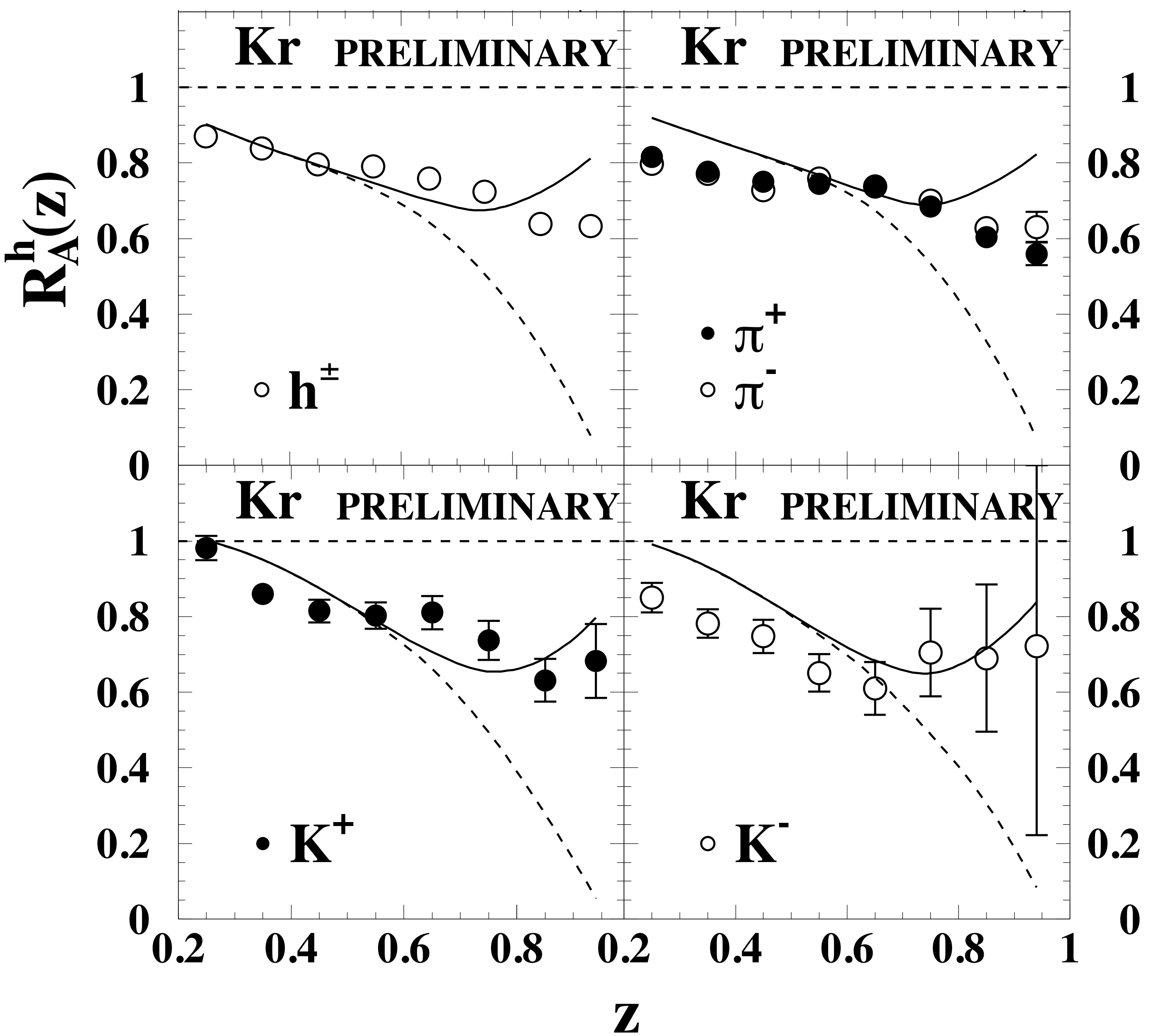
EPJC 30, 213
EPJC 76, 475

- The parton interacts with the medium, losing energy ϵ.
- ϵ depends on the length crossed and a coefficient characterising the medium.
- The hadronization happens completely ***outside*** the nucleus.



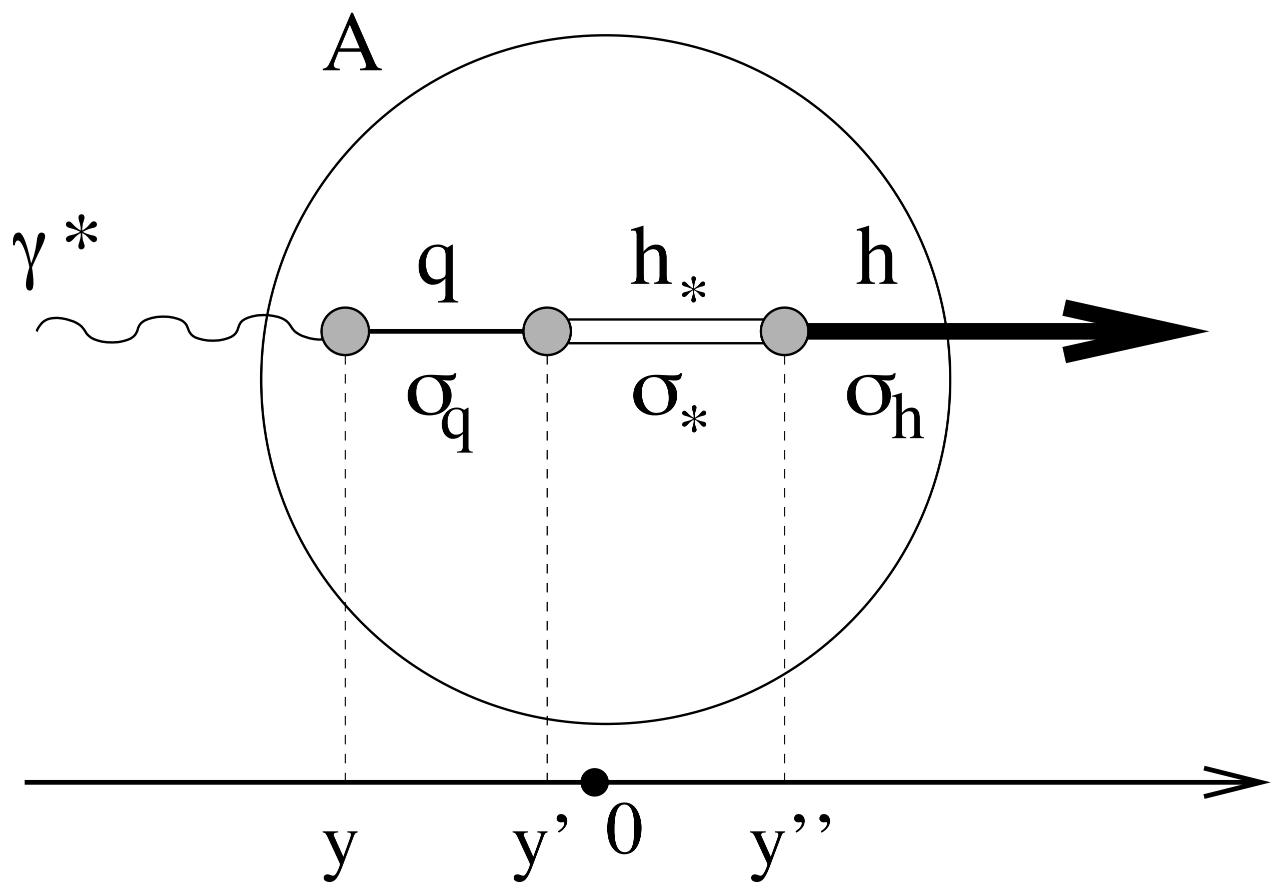
EPJC 30, 213

EPJC 76, 475



- LO calculation.
- FF used from SIA fit.
- Not too bad of a model.

2. Nuclear absorption



NPA 720, 131

q: quark

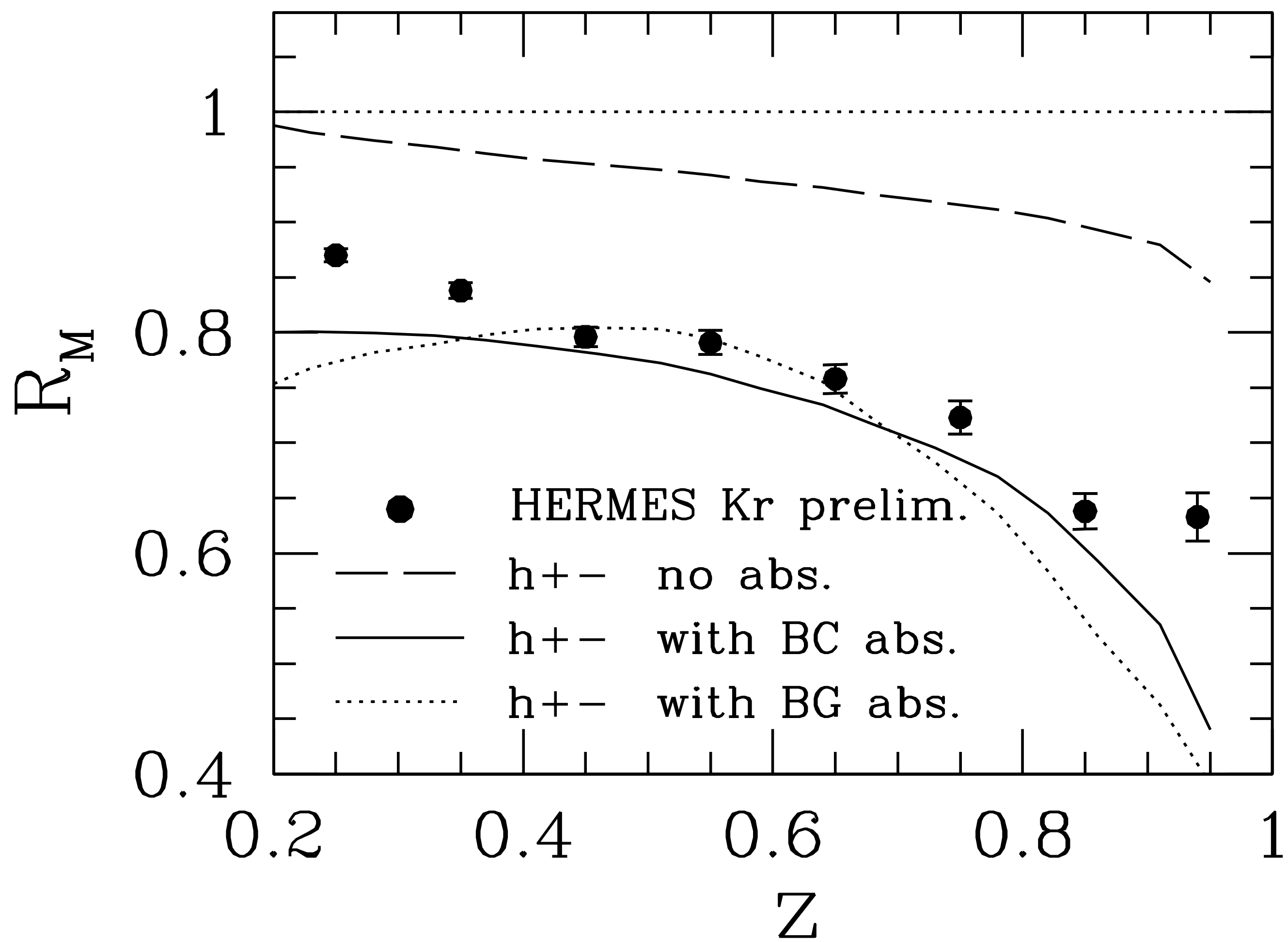
*h**: pre-hadron

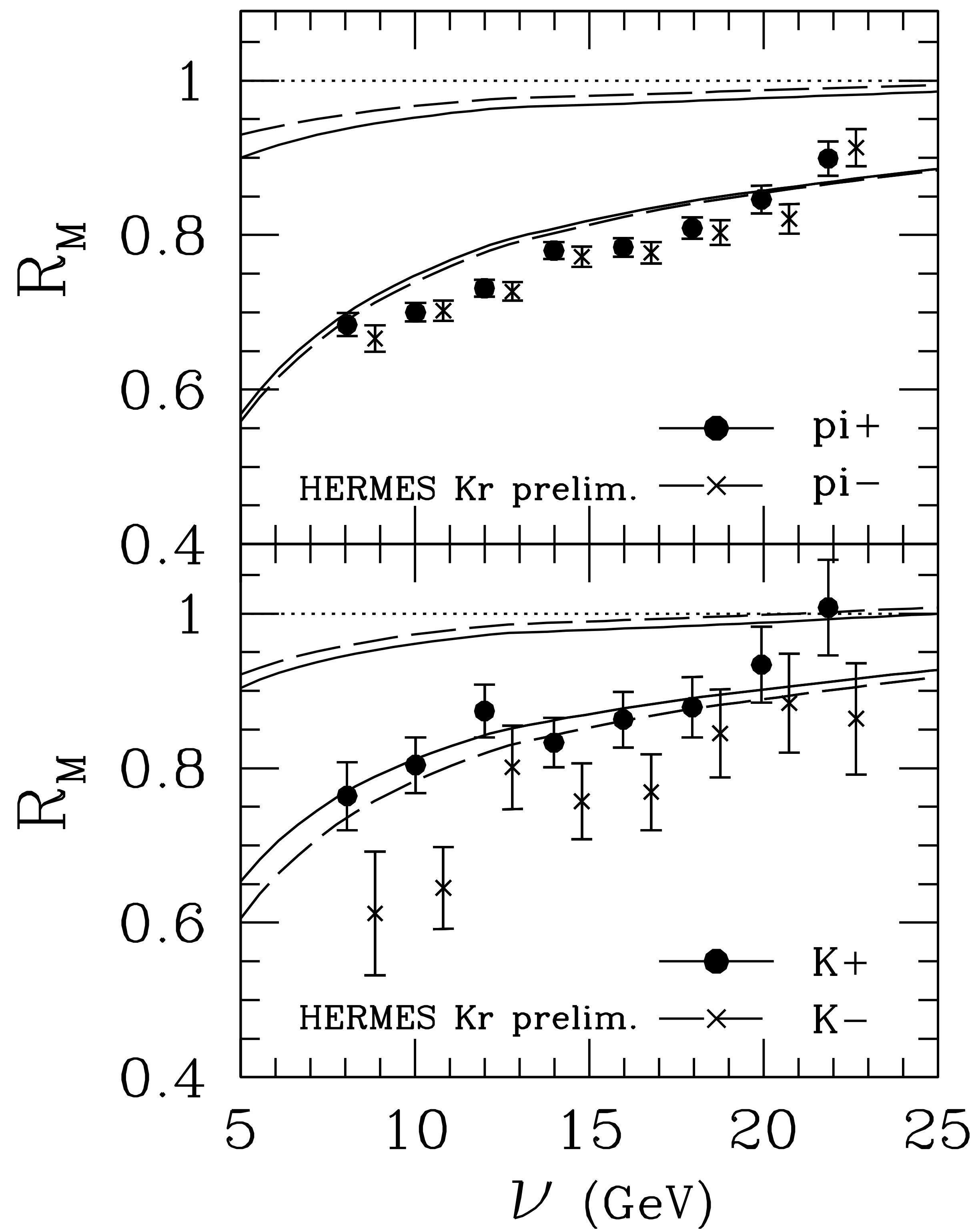
h: hadron

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

$\mathcal{N}_A(z,\nu)$: **nuclear absorption factor** or probability that neither *q*, *h** nor *h* interact with the medium.

NPA 720, 131





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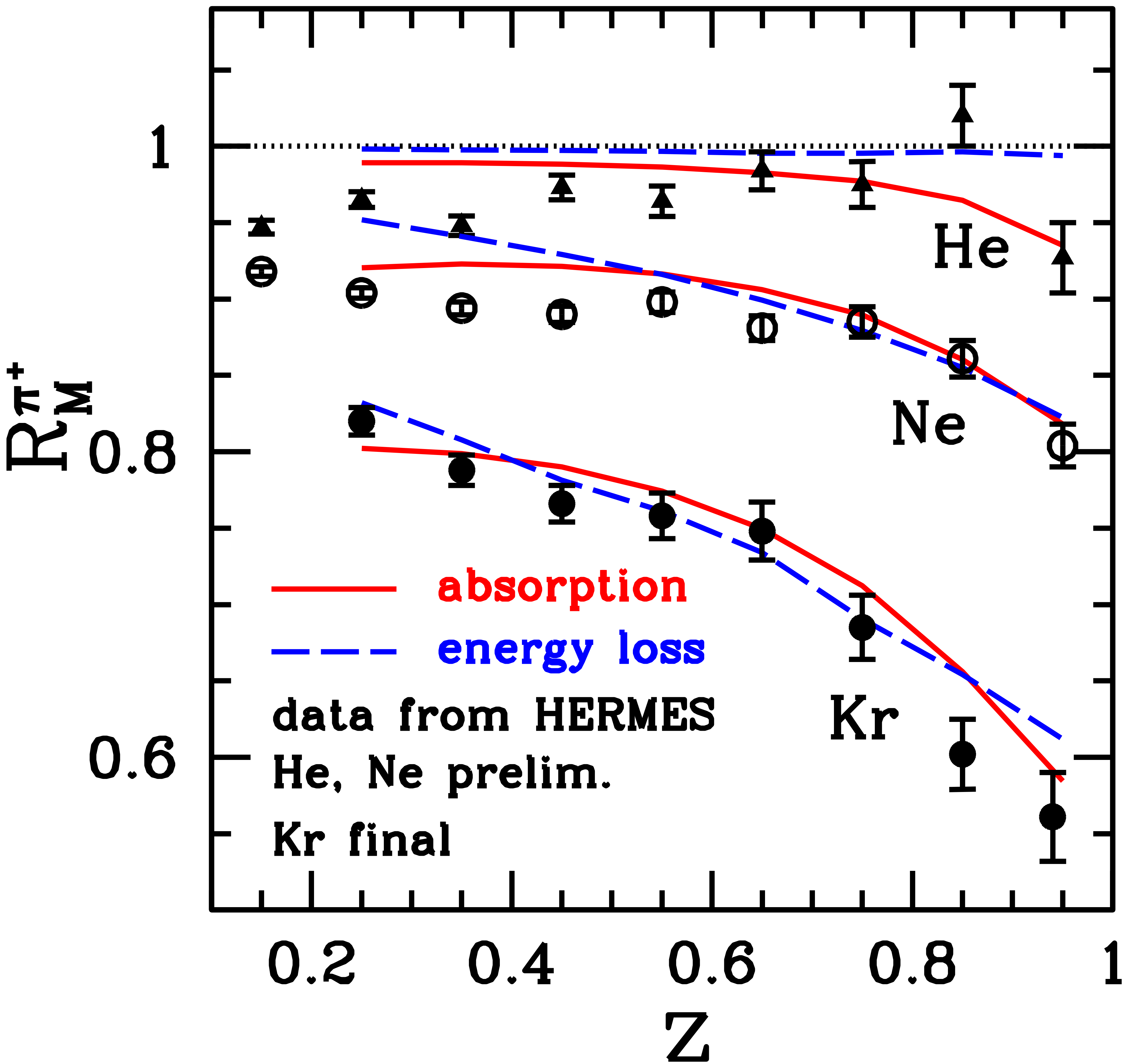
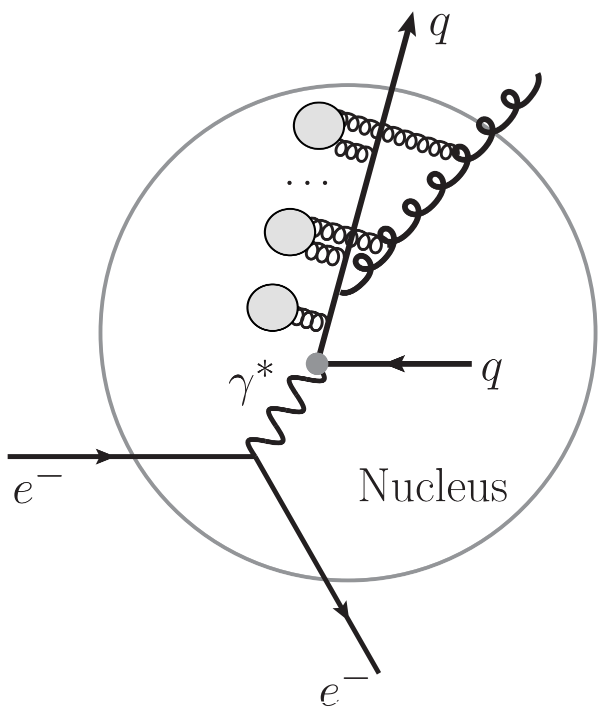
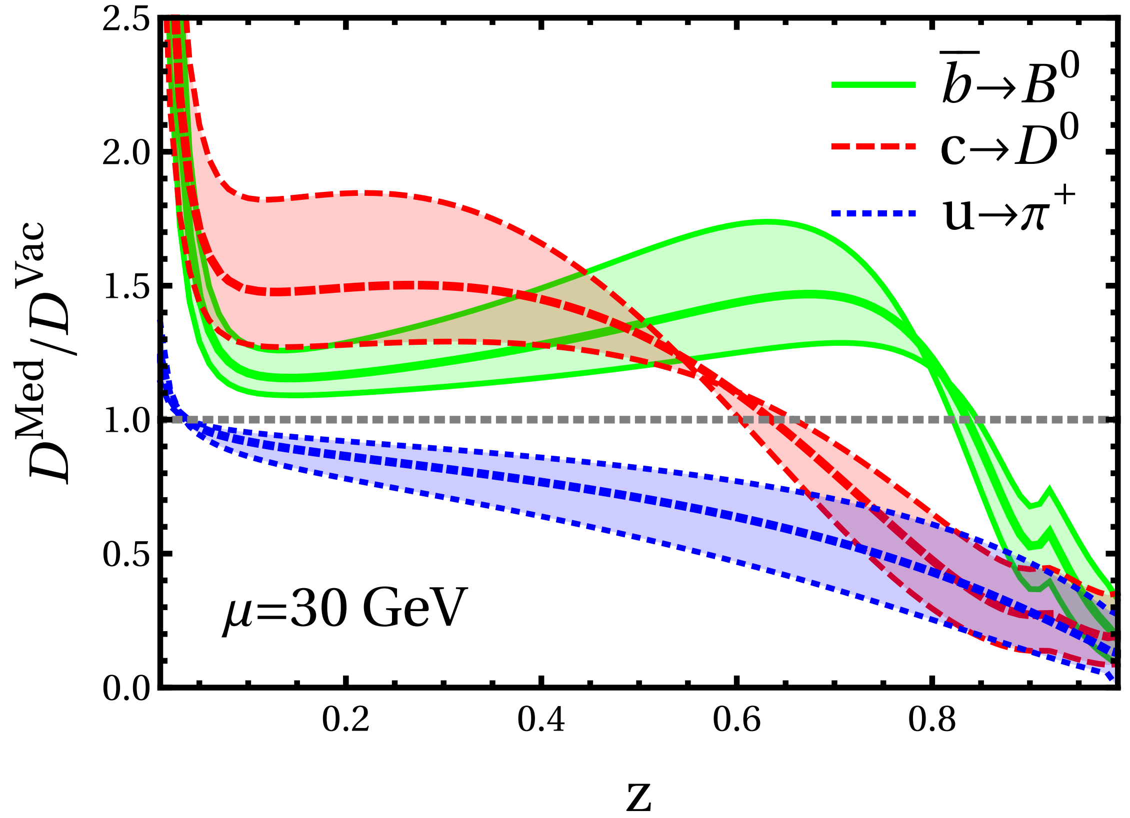
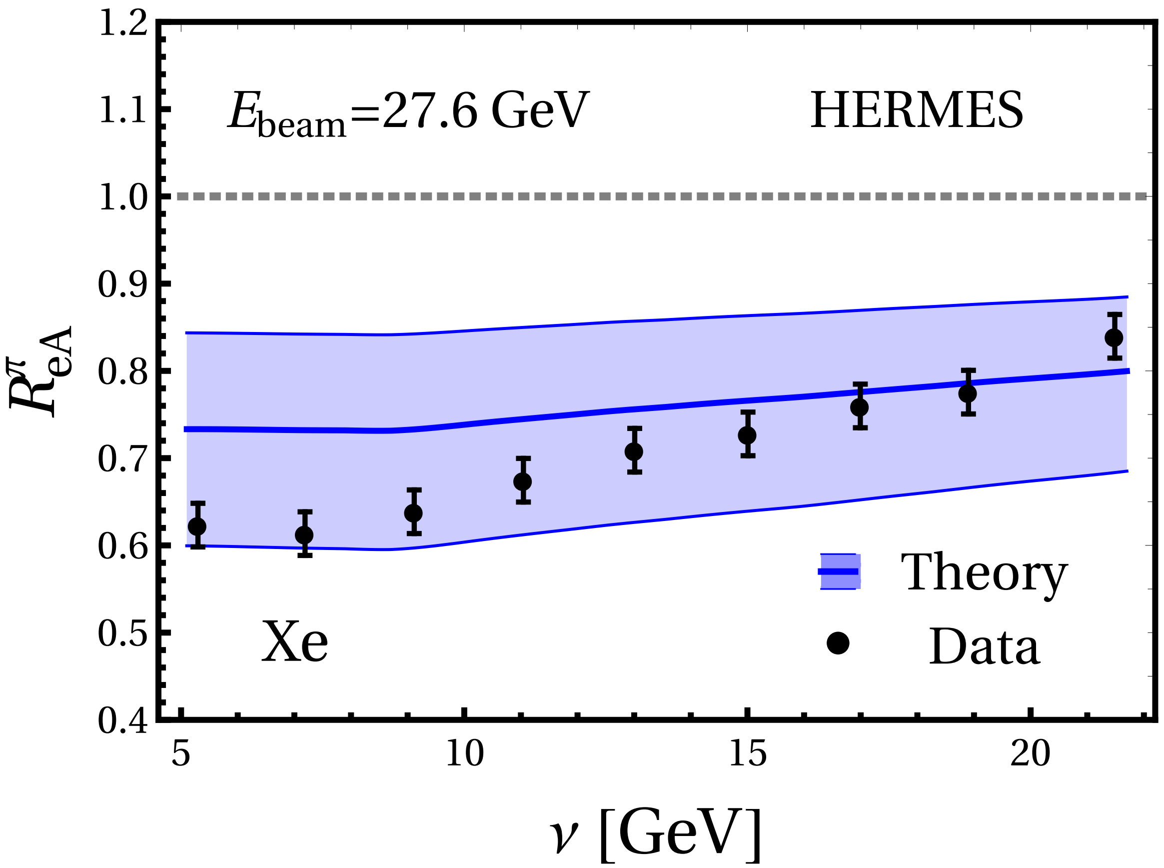

$R_M^{\pi^+}$
1
0.8
0.6
0.2
0.4
0.6
0.8
1
z
He
Ne
Kr
absorption
energy loss
data from HERMES
He, Ne prelim.
Kr final

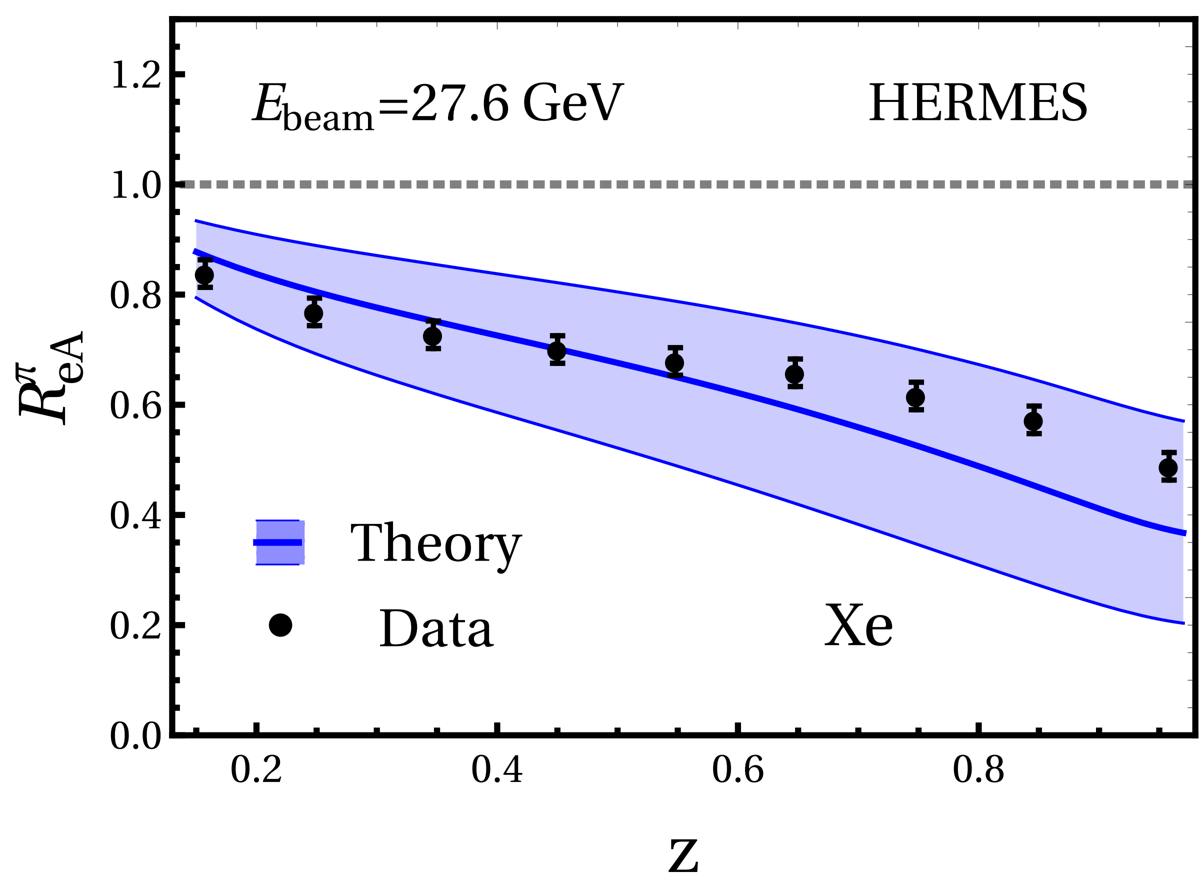
3. Modified evolution



PRC 81, 024902
PLB 816, 136261







4. Phenomenological approach

If FFs are *similar* to PDFs... why not something like *nFFs*?

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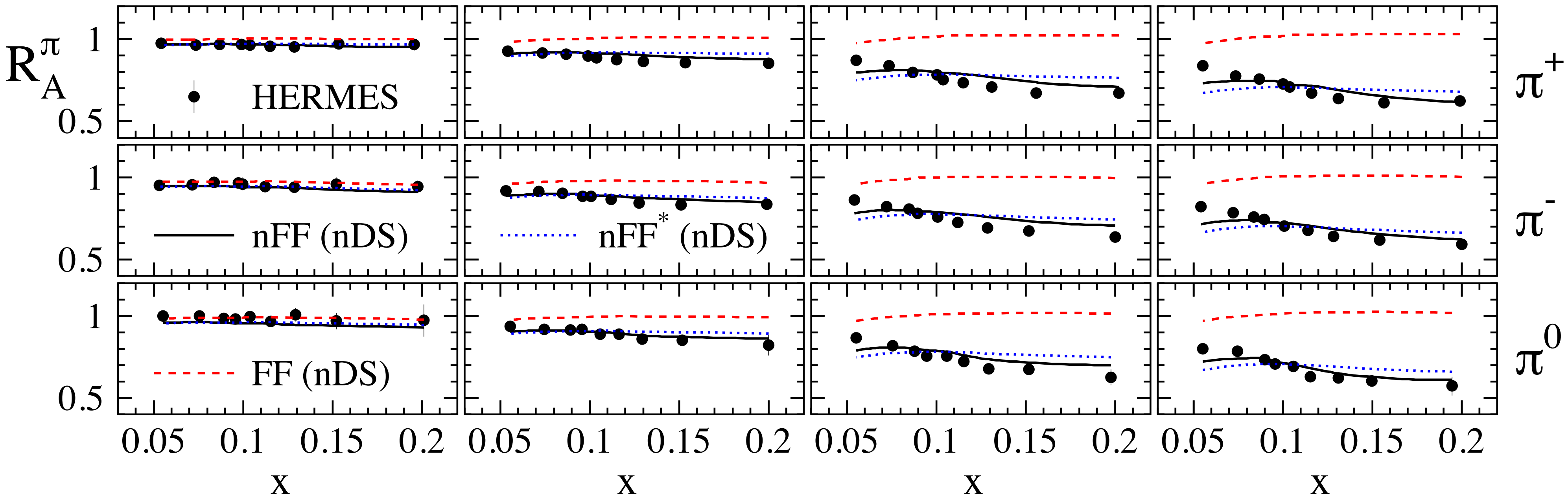
Two NLO studies so far, with different data sets, strategies, parametrizations, baselines, etc.

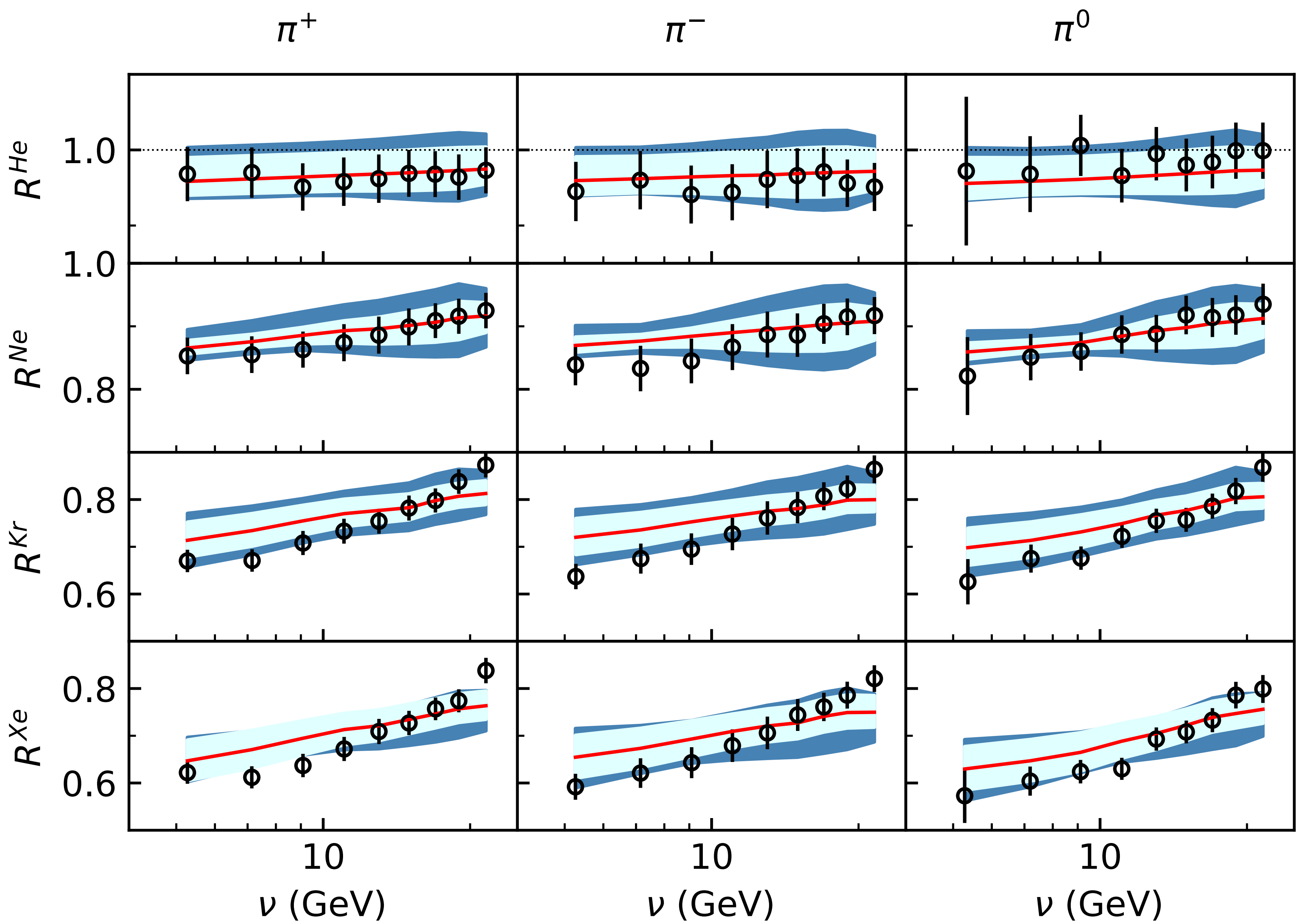
1. SIDIS@HERMES and SIH@RHIC. 14 parameters, $\chi^2/dof = 1.08$. **PRD 81, 054001.**

2. SIDIS@HERMES. 7 parameters, $\chi^2/dof = 0.78$. **arXiv:2101.01088.**

PRD 81, 054001



- 🙂 *z* dependence
- 🙂 Q^2 dependence
- 🙂 *x* dependence except too high/ low *x*



arXiv:2101.01088

Unresolved issues

How about the most recent SIDIS data from JLAB?

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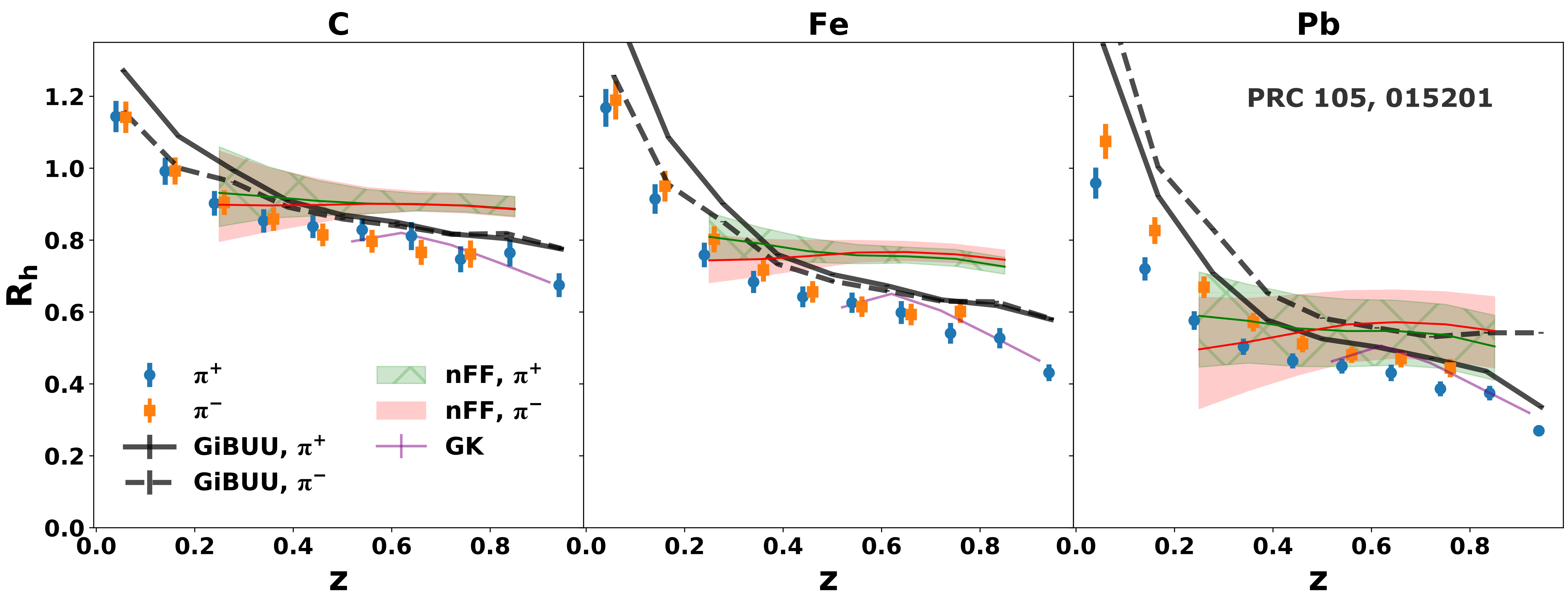


- Fits don't extrapolate well to low z.
- Funny: $He < C < Ne < Fe < Kr < Xe < Pb$ but the best described JLAB data are Pb.
- Can we truly use pQCD at $\sqrt{s} \approx 3.2$ GeV? at $\sqrt{s} \approx 7.3$ GeV?

Why not use the older SIDIS data?

- $\sqrt{s}$ up to 30 GeV and 4 more nuclei. 🙂

Why not use the older SIDIS data?

- $\sqrt{s}$ up to 30 GeV and 4 more nuclei. 

- Not fully differential: time consuming to be included in a fit. 

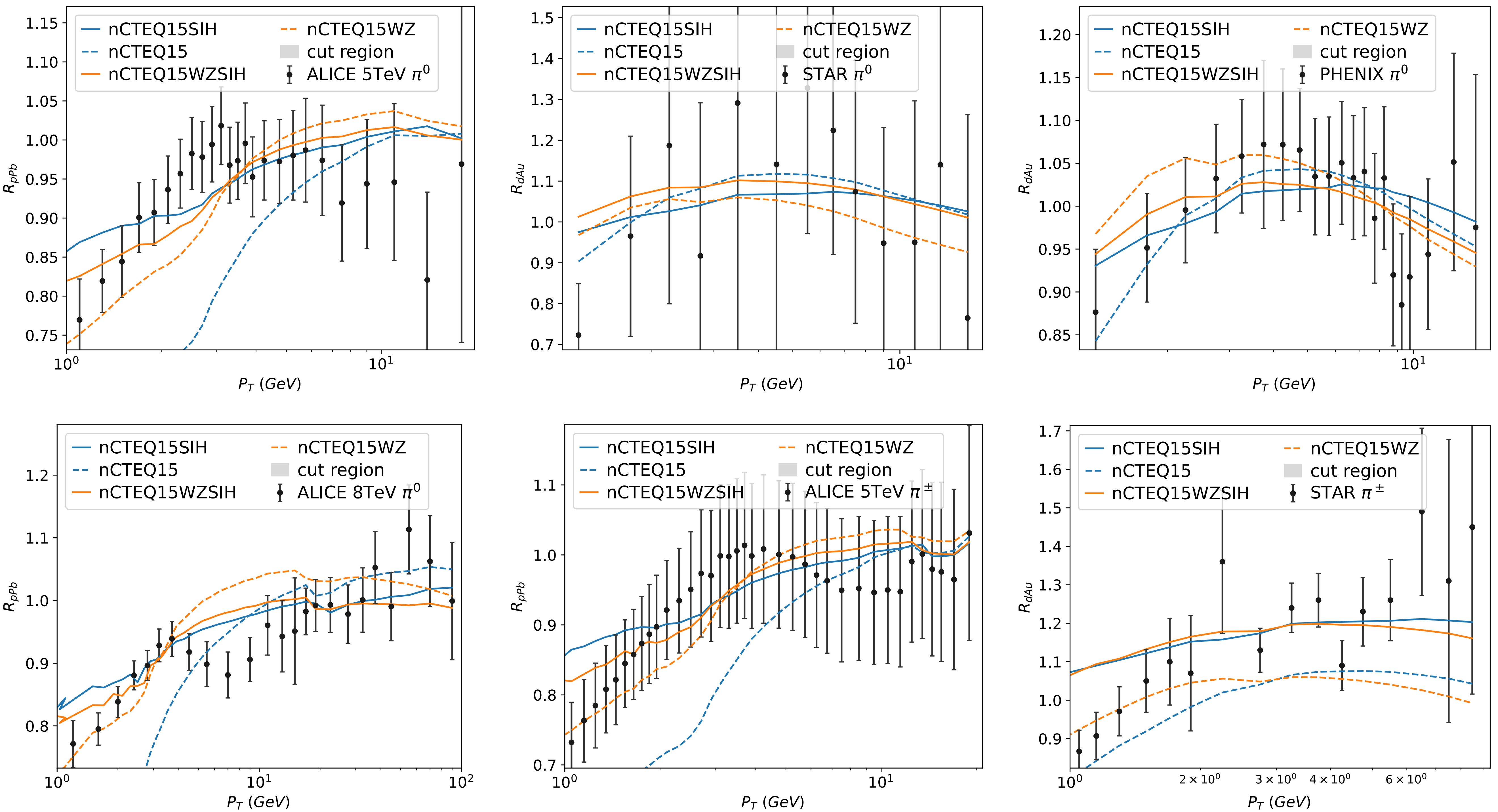
- Quite large uncertainties: little constraining power. 

- Assumptions were made in the analysis that contaminate the data: $h^{\pm}$ is always a $\pi^{\pm}$. 

What about SIH in p+A or d+A data?

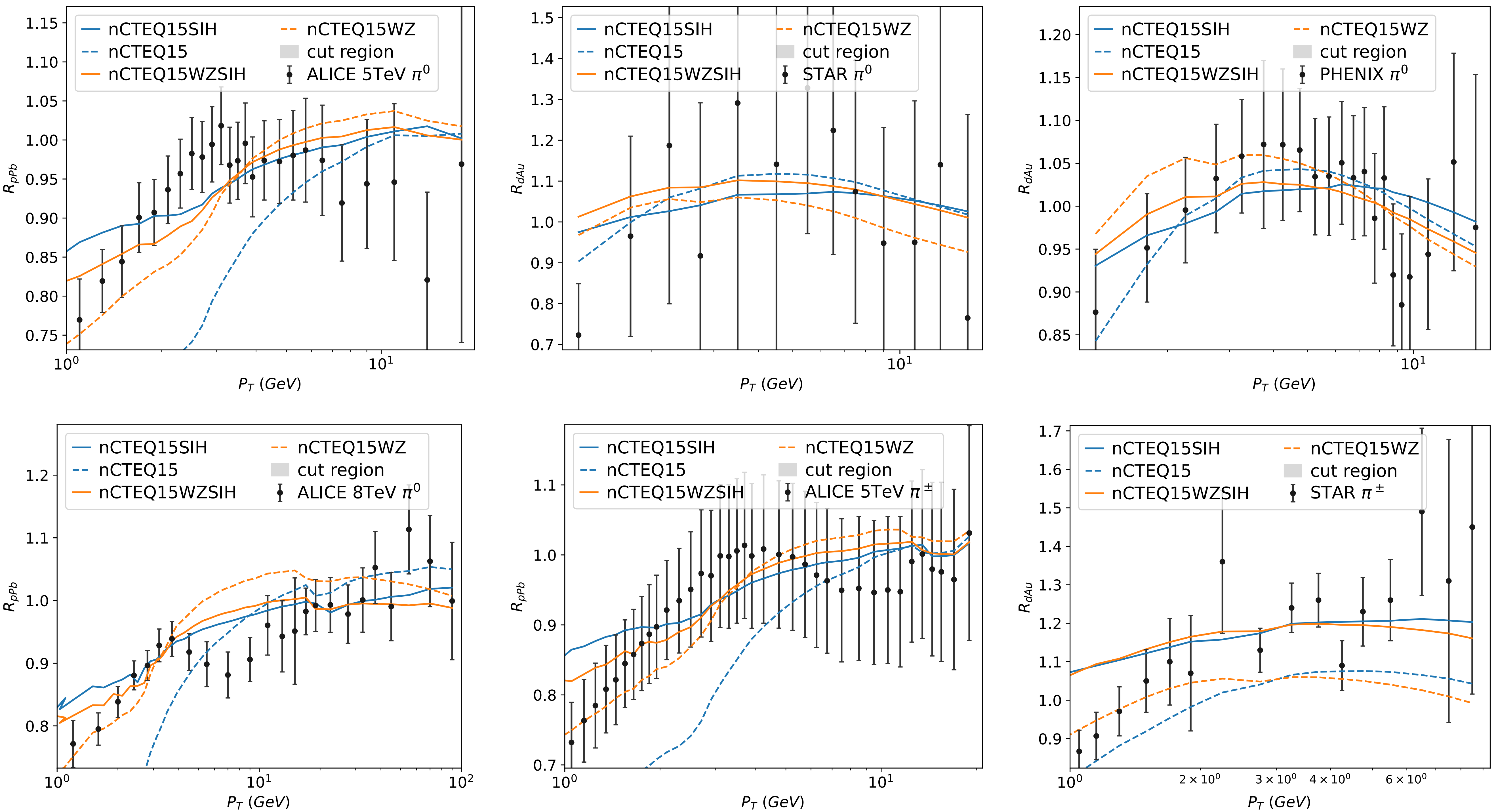
What about SIH in p+A or d+A data?

PRD 104, 094005



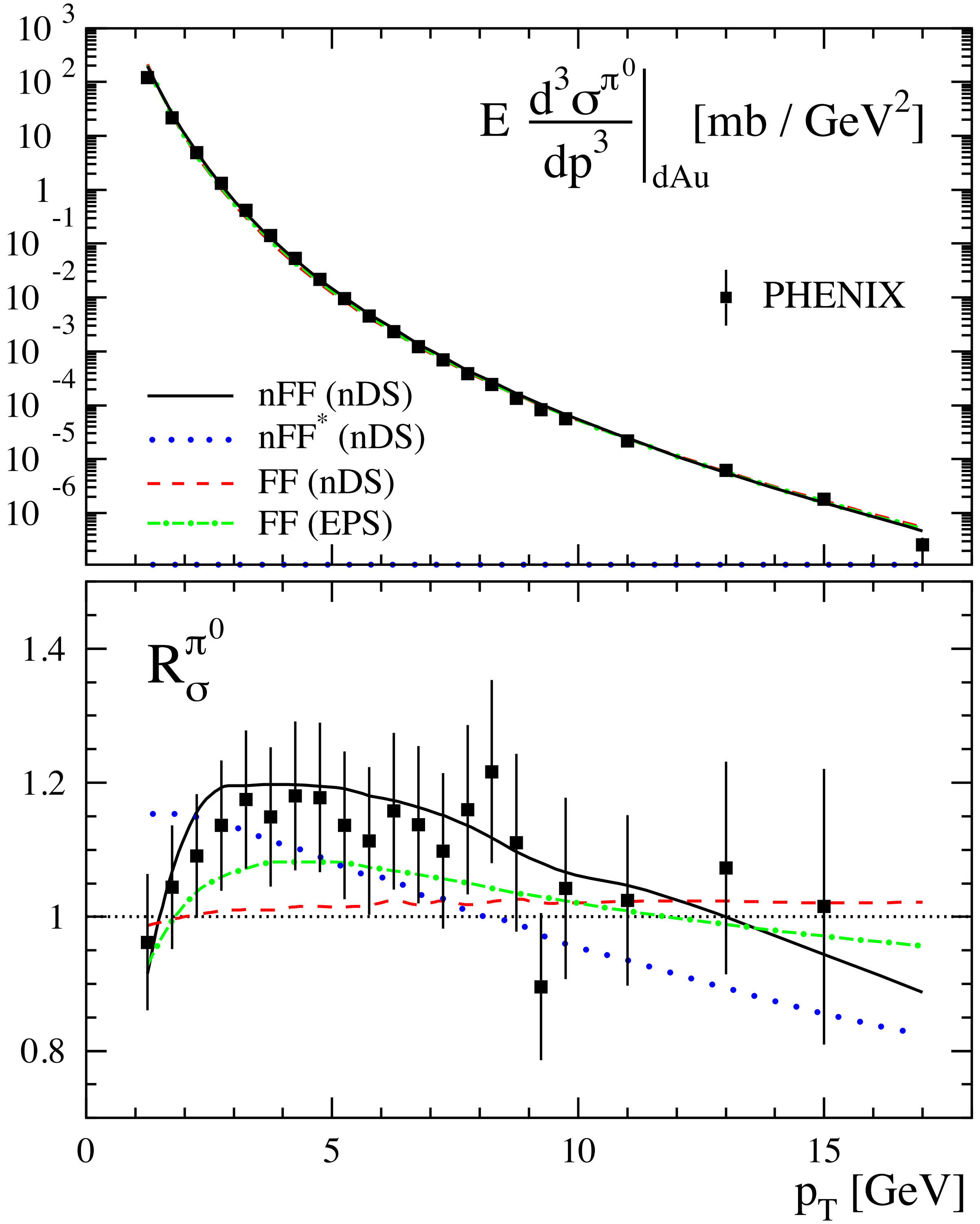
What about SIH in p+A or d+A data?

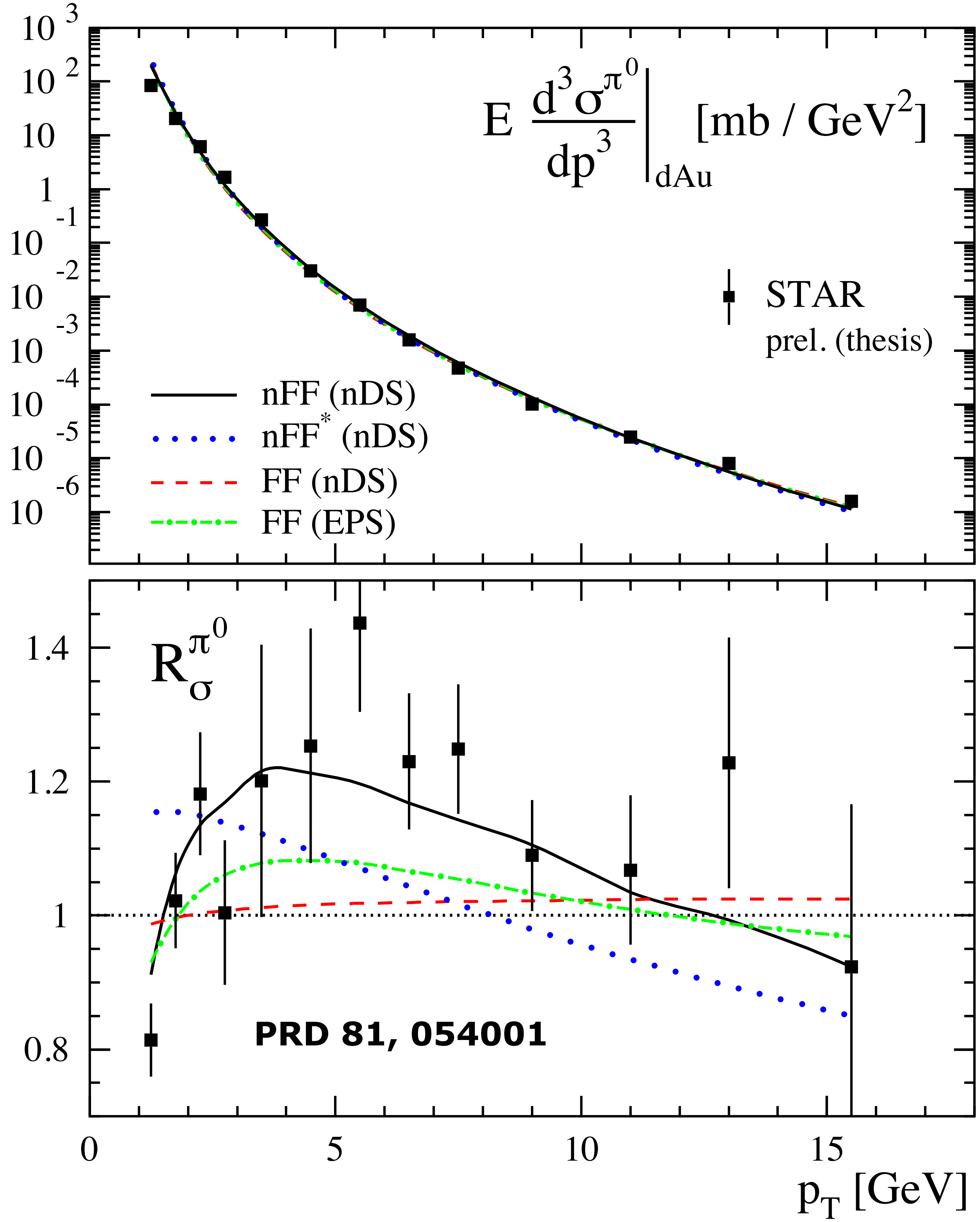
PRD 104, 094005



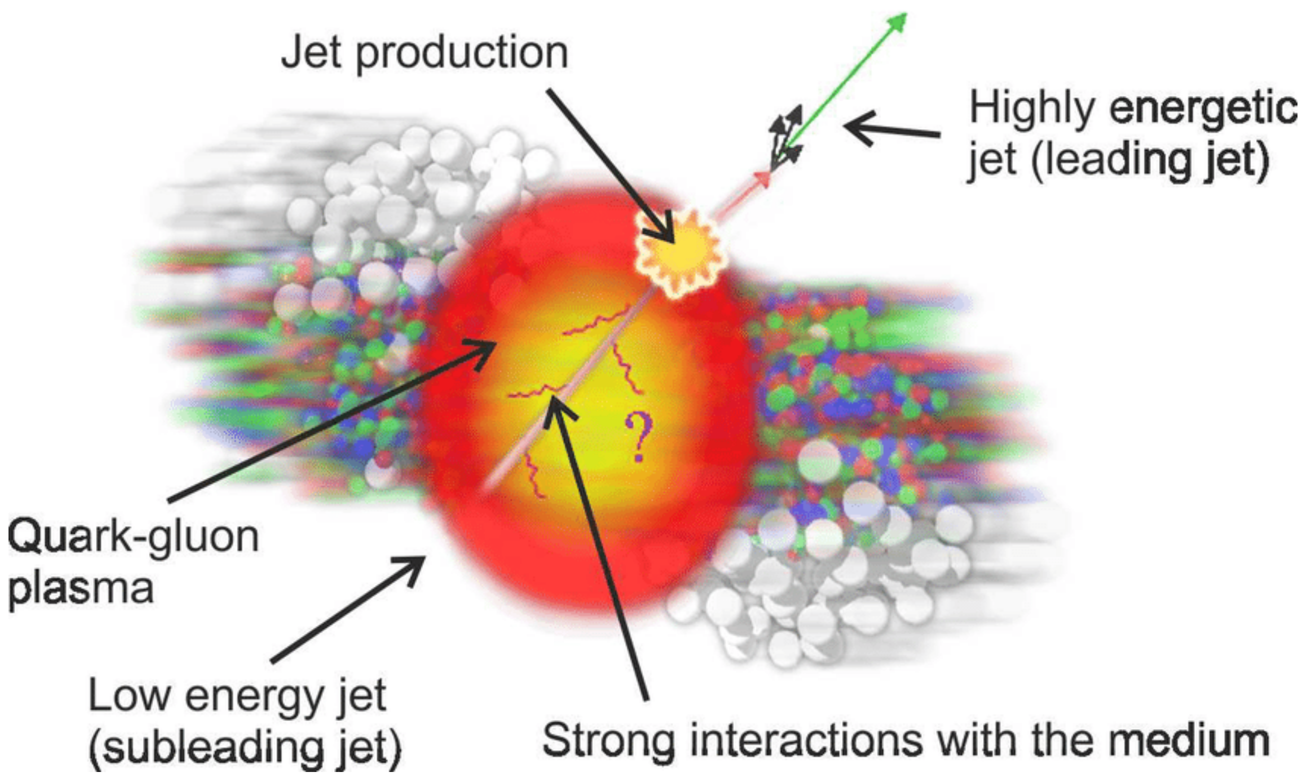
Even the best known particle ($\pi^{\pm,0}$) has large uncertainties.

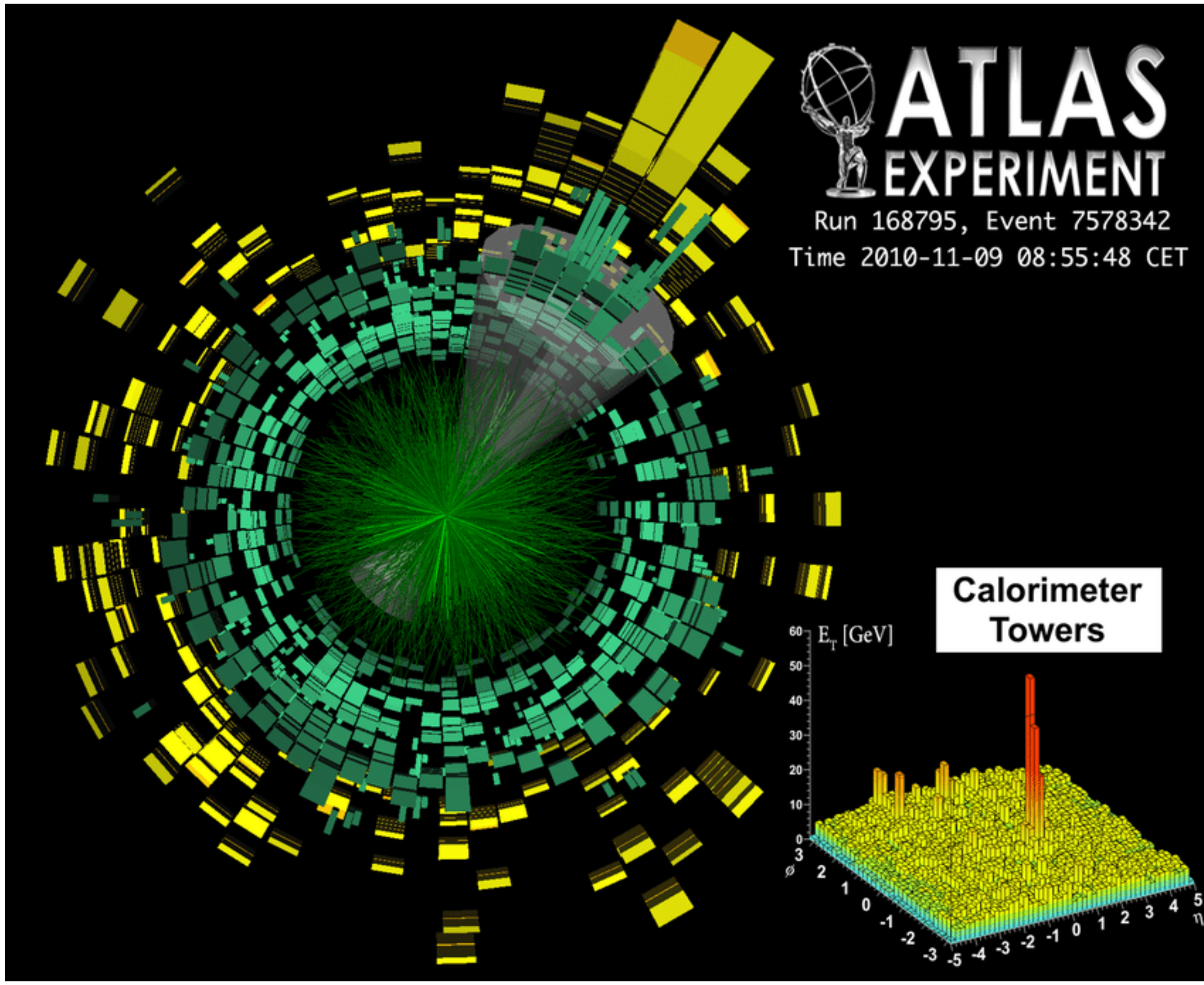
We can also describe these data using nFFs!





For the jet data in $p + Pb$... well, we have *jet-quenching* in $Pb + Pb$.





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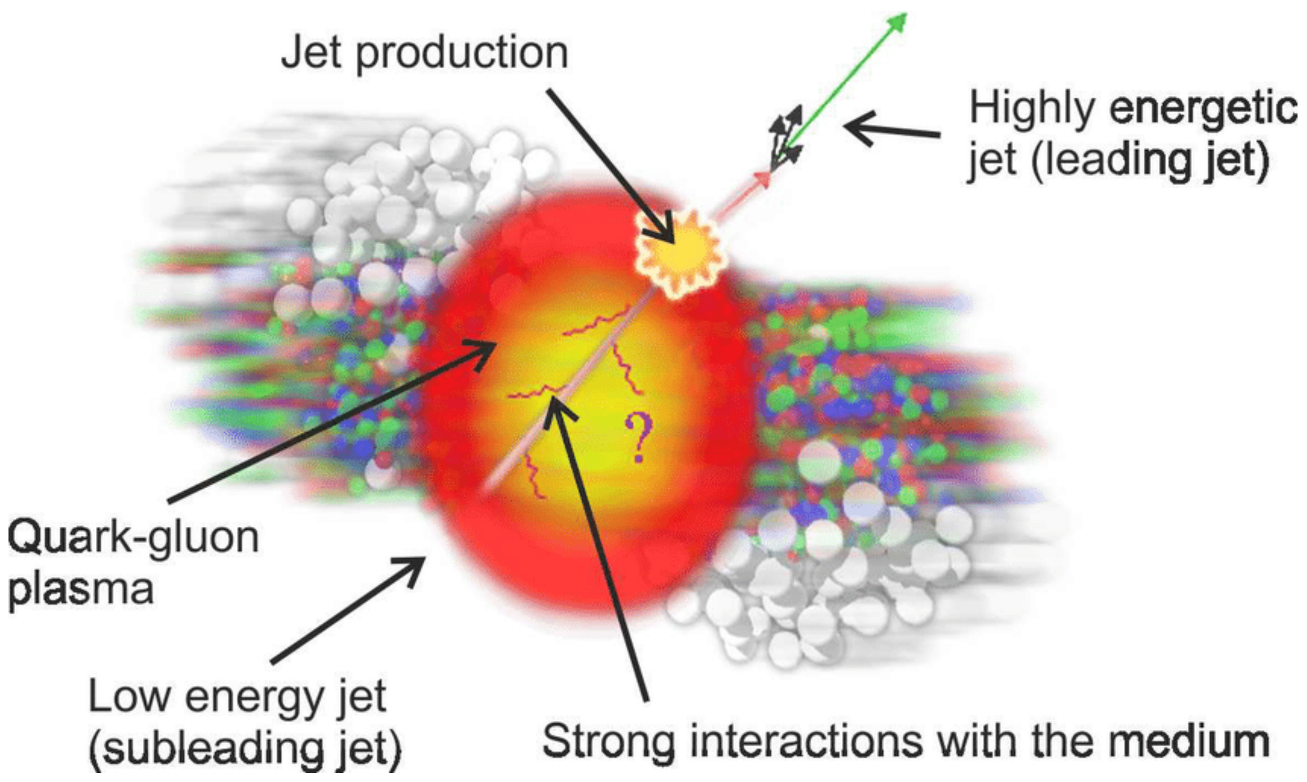

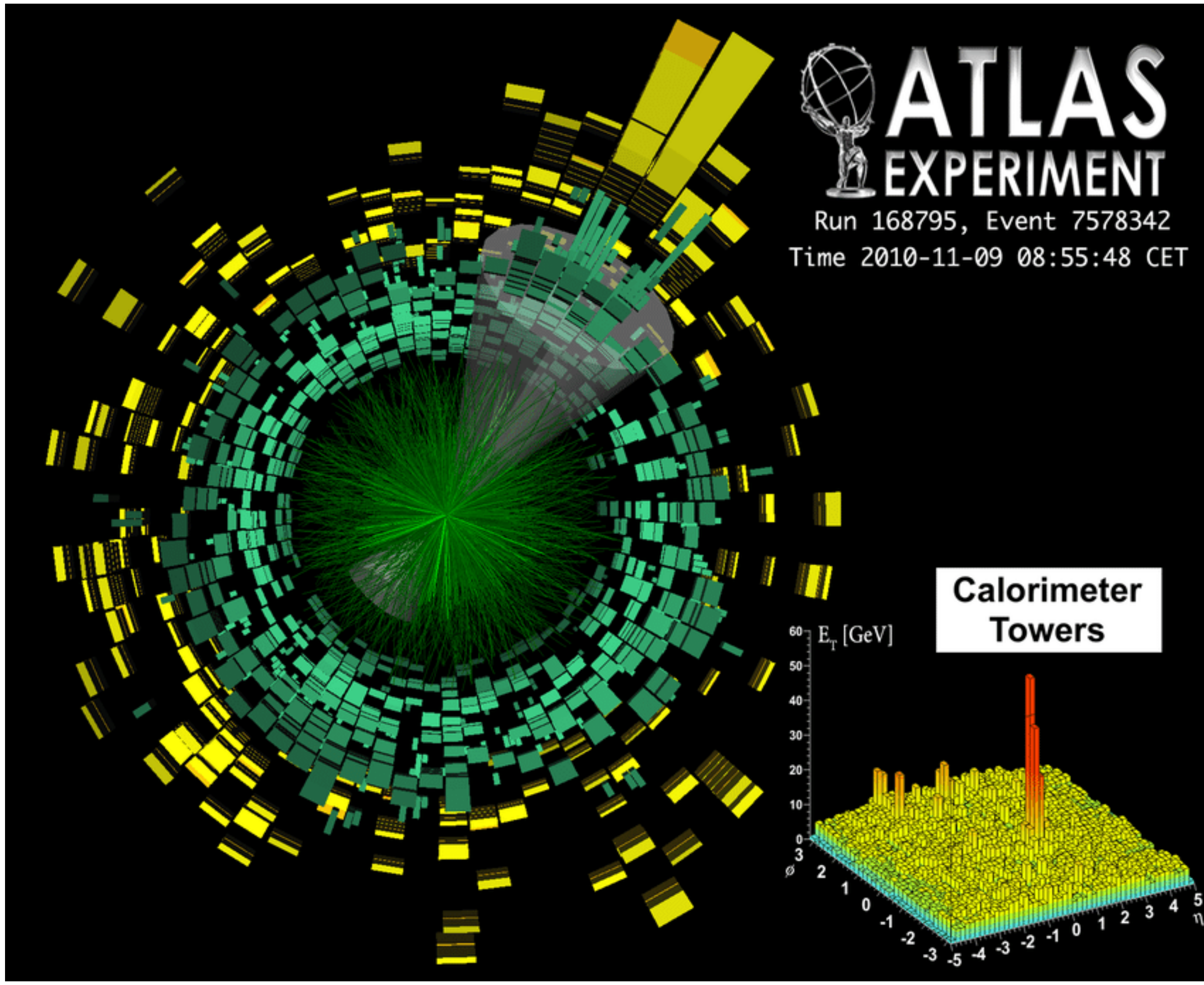

All hadronic data used in nPDF studies are susceptible of final state effects.

So? Which one is it? We don’t know.

So? Which one is it? We don’t know.

Without more detailed data, it is open to interpretation.

A non-terrifying hat.

My drawing didn’t represent a hat. It represented a boa digesting an elephant.

Not a hat.

Thus I draw the interior of the boa, so that grown-ups could understand. They always need explanations.

***Le petit prince*, A. de Saint-Exupéry**

What can the EIC do for the FFs?

Quite a lot.

We have *older* SIDIS experiments with very *low precision* and only charged hadrons.

We have *newer* SIDIS experiments for different hadrons with higher precision but *very low* $\sqrt{s}$.

Quite a lot.

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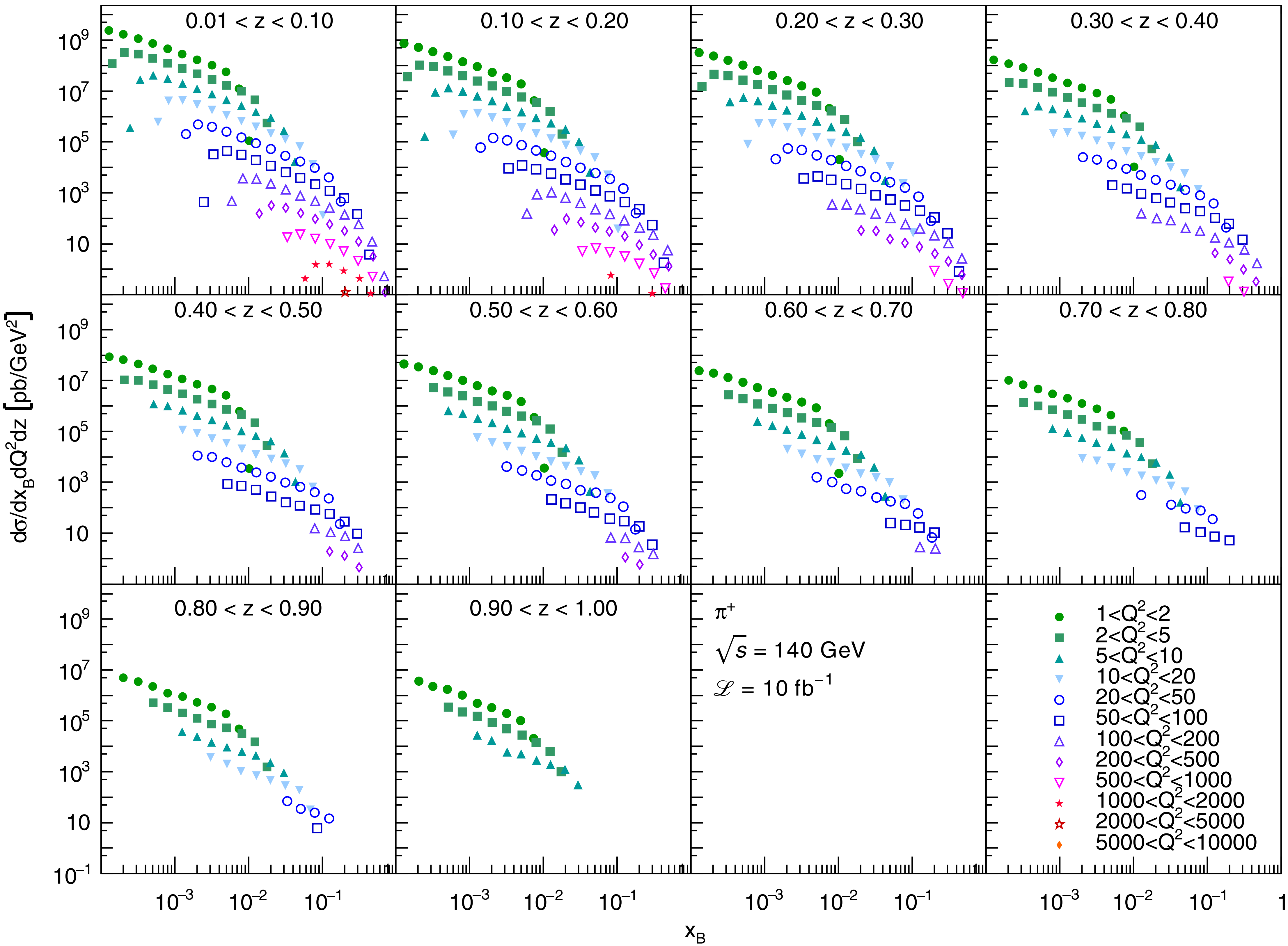
We have *newer* SIDIS experiments for different hadrons with higher precision but *very low* $\sqrt{s}$.

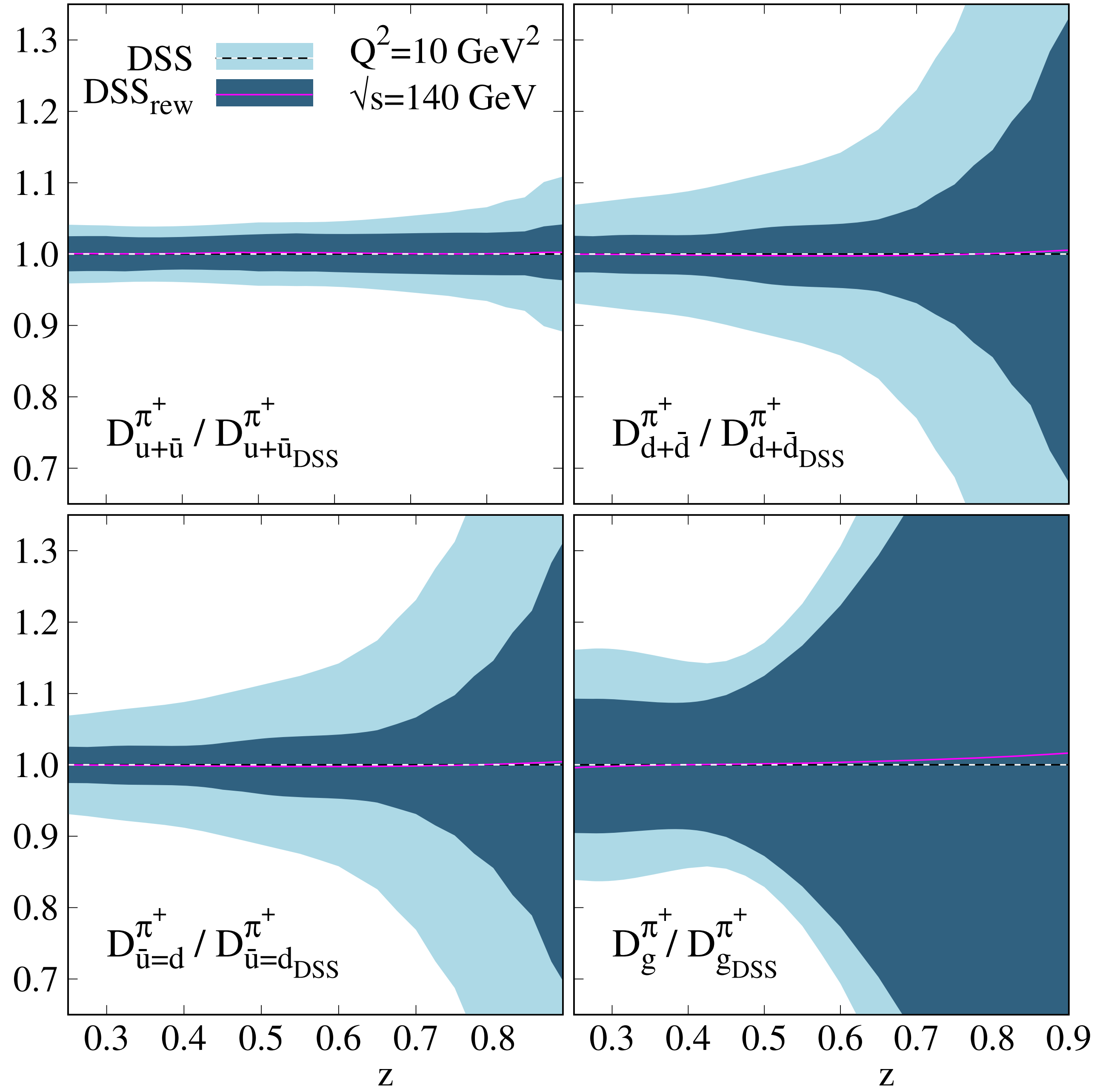
At the EIC we will have ***both***: **high precision and larger** $\sqrt{s_{max}}$.



PRD 99, 094004

pseudo data for EIC

With these we can see how the FFs would change:



PRD 99, 094004

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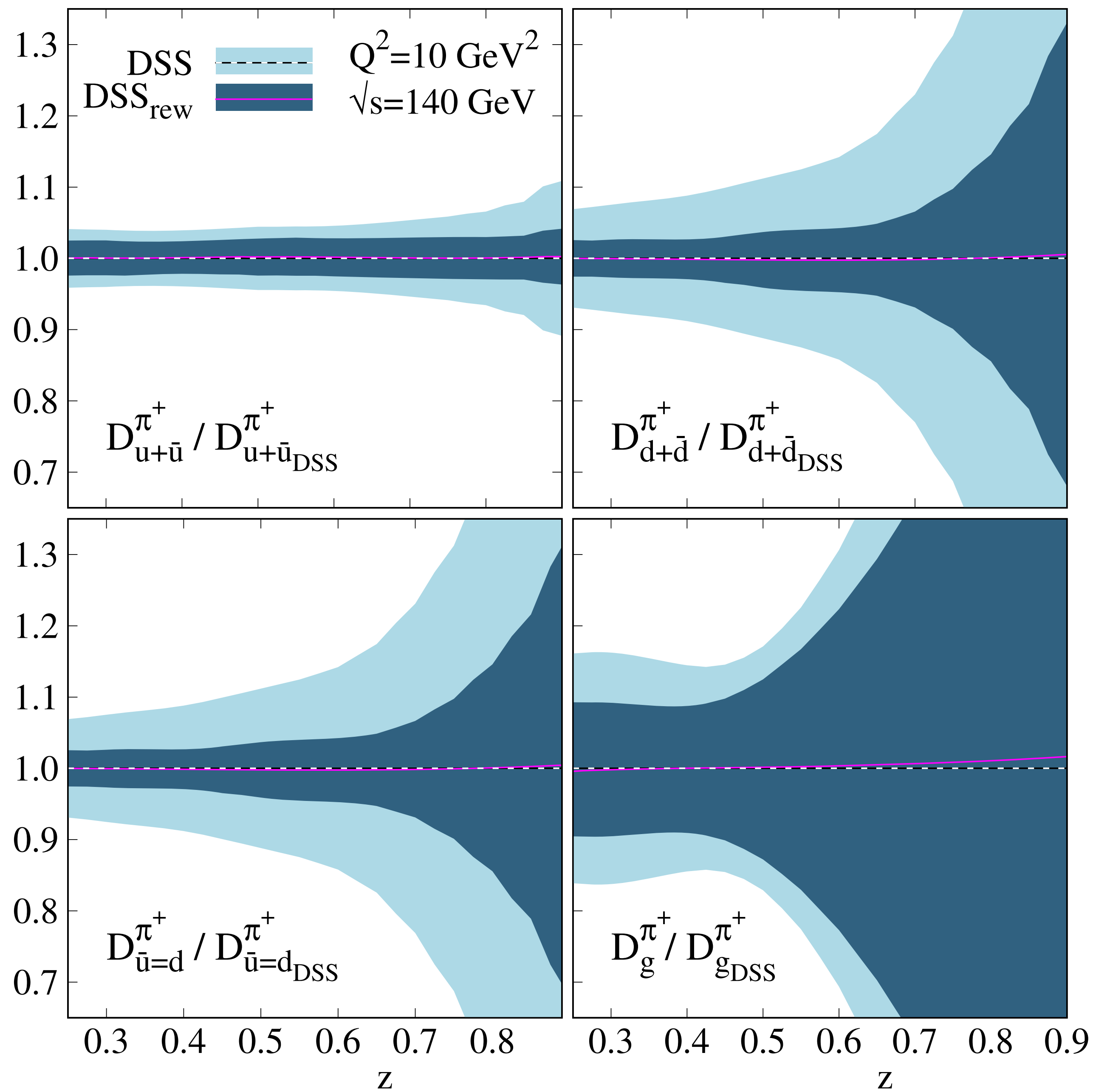
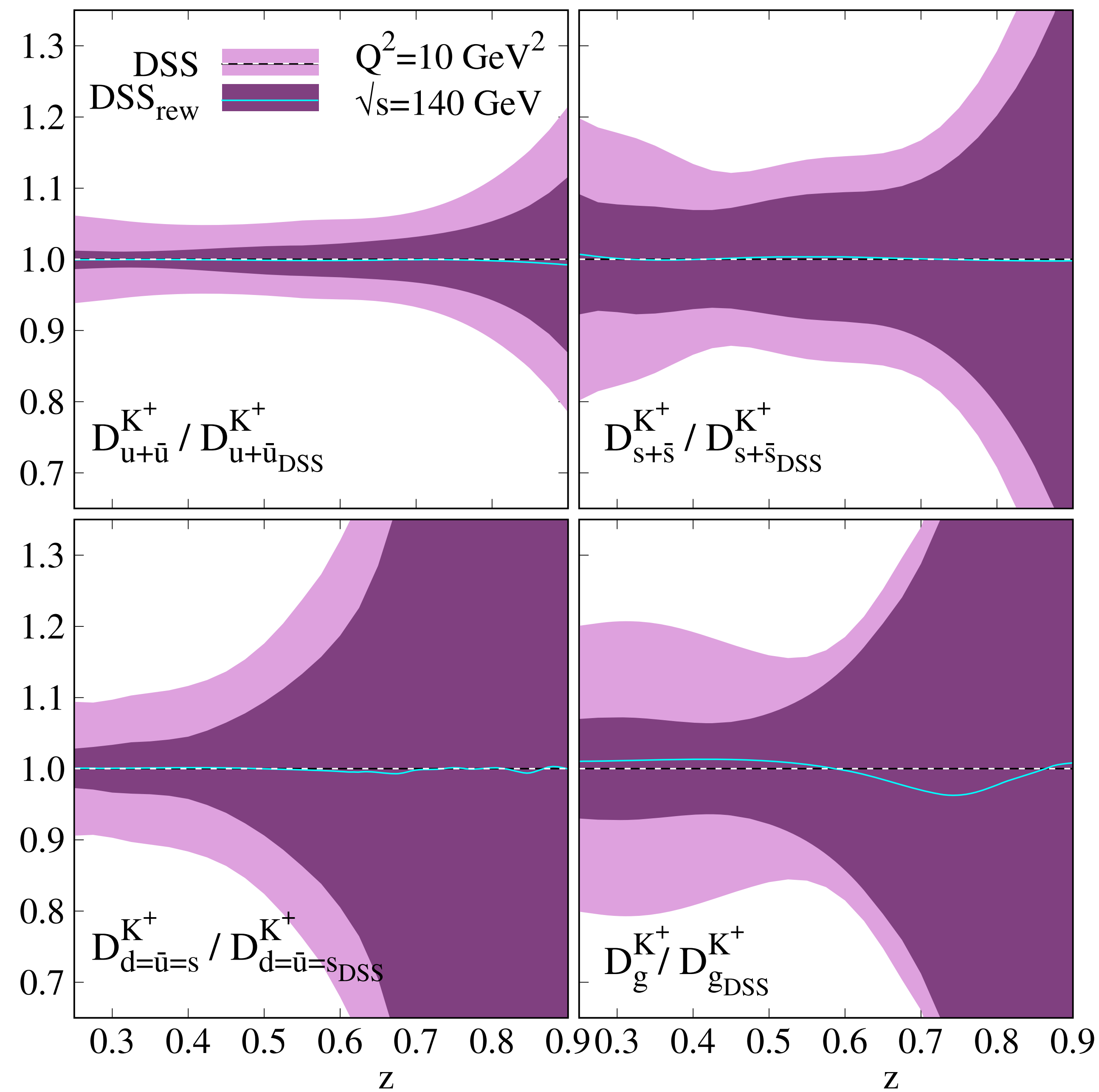
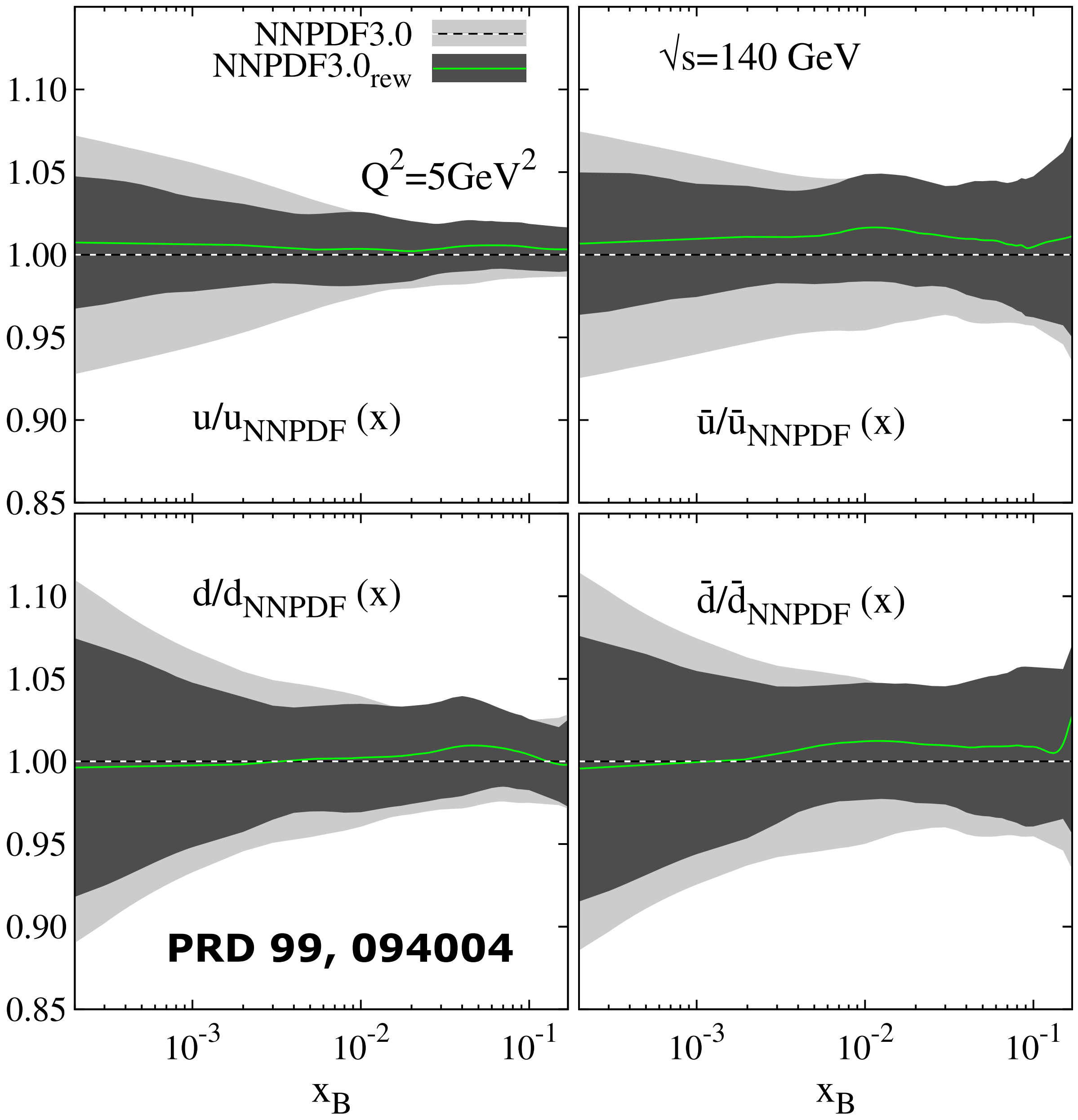
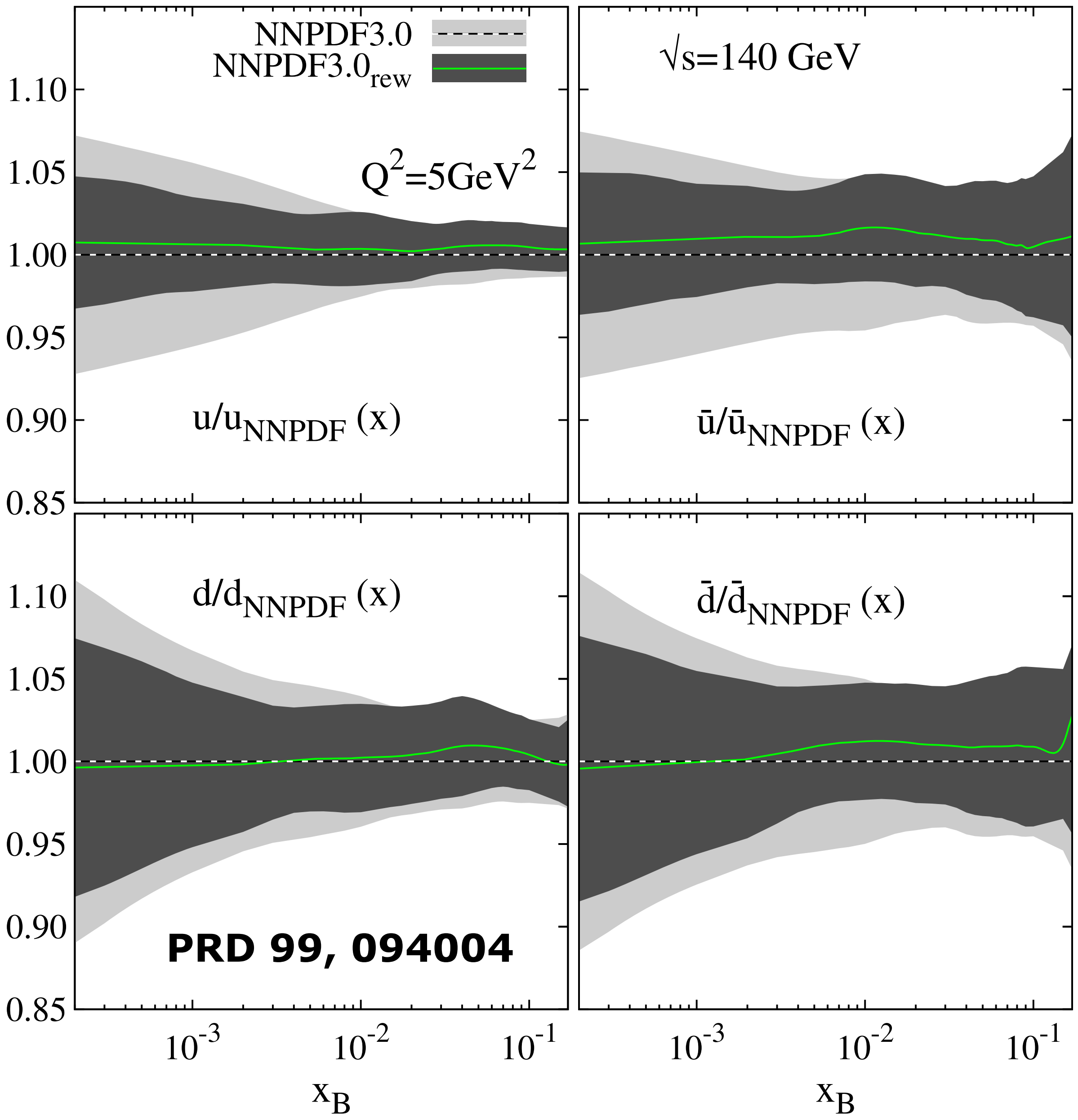


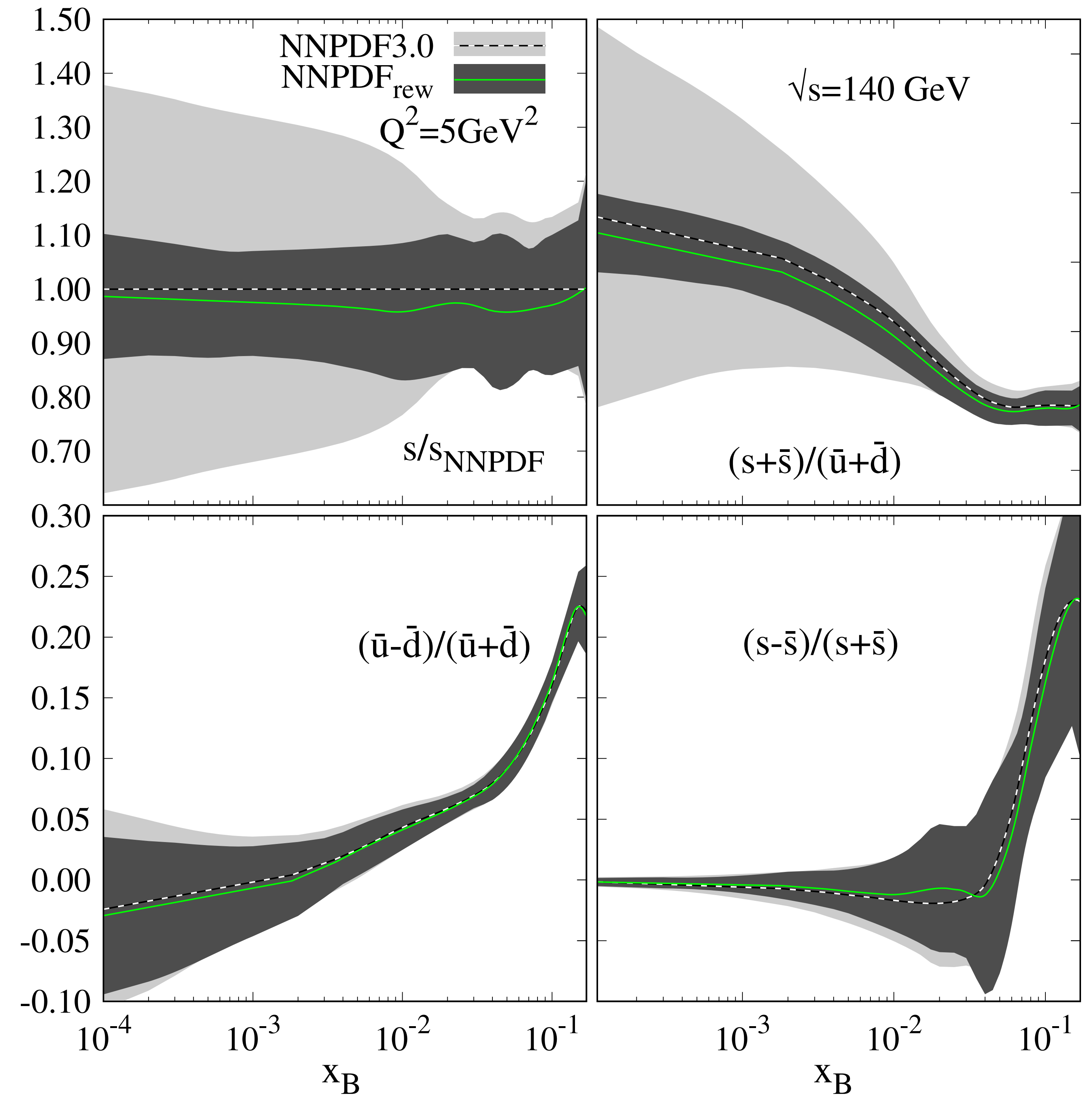


PRD 99, 094004



We can also explore how SIDIS can be used to improve proton PDFs!

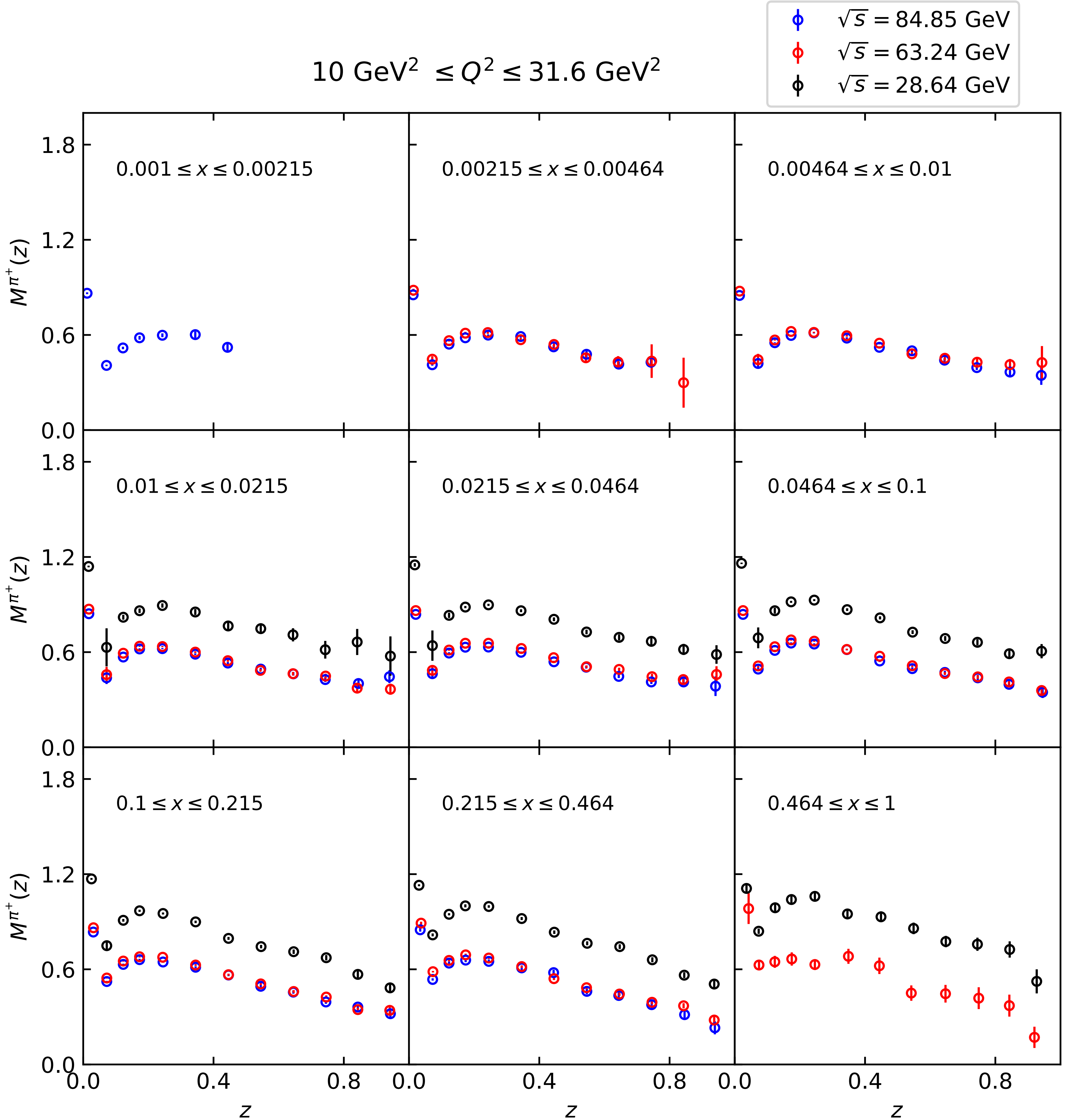




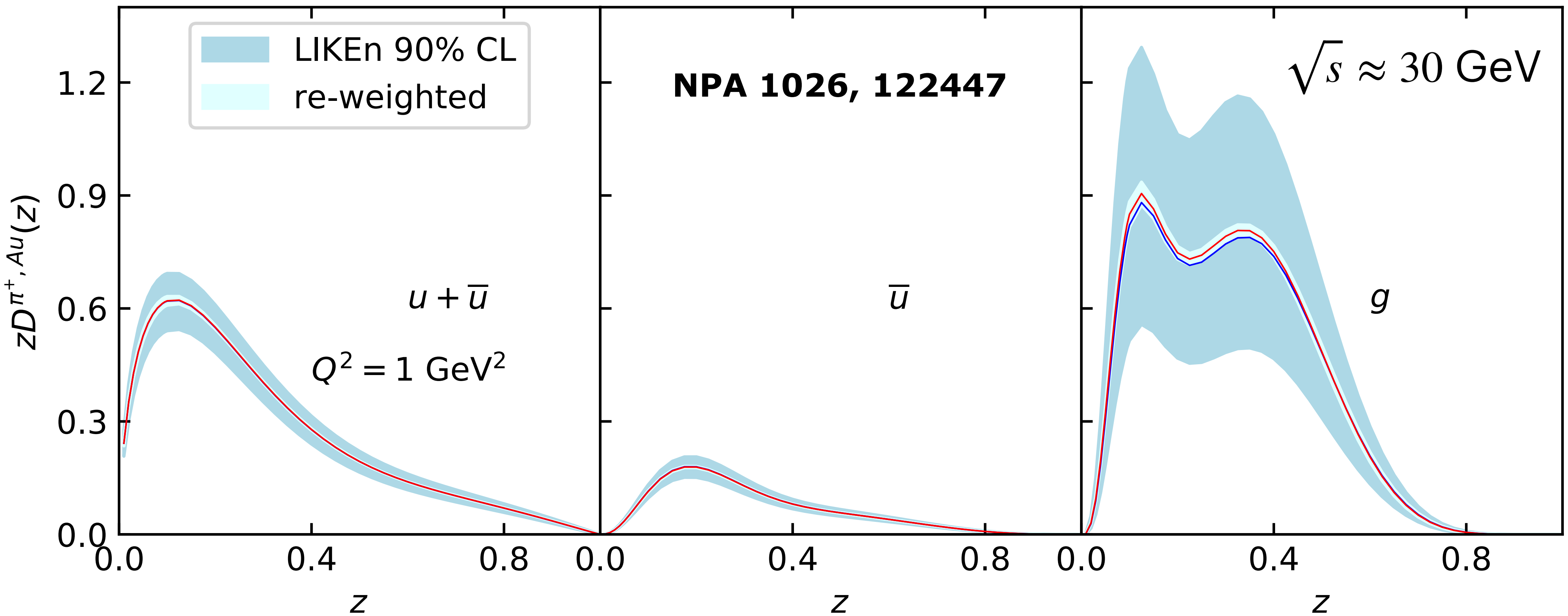
We can also explore how SIDIS can be used to improve proton PDFs!

For the nuclear case we can (try) do the same:

- EIC pseudo-data in e+Au, prepared for the EIC YR.
- These are too different from the low energy data used in nFF fits.
- But we can use the estimated uncertainties.

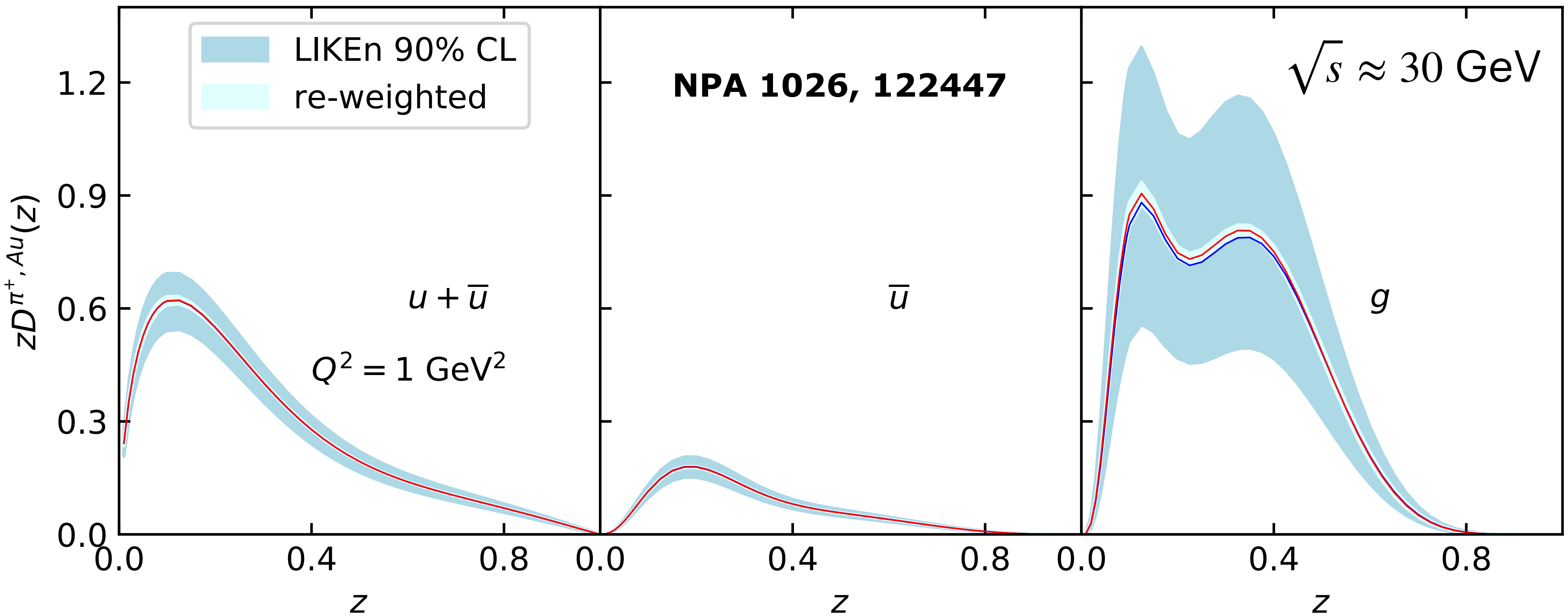


With pseudo-data generated with nFFs and the estimated uncertainties we quantified the reduction of the uncertainty band.



Even the lowest energy is expected to be quite constraining.

With pseudo-data generated with nFFs and the estimated uncertainties we quantified the reduction of the uncertainty band.



Even the lowest energy is expected to be quite constraining.

For the first time ever we will be able to study jets in e+A!

Summary

- The *hadronization* of partons into hadrons is a complex, non-perturbative phenomenon of *great relevance*. One can *encode* the information in *universal* ***FFs***.

- They can undergo *final state effects* in the presence of a nuclear medium, which might affect the extraction of other in-medium partonic densities.

- The main effort for their understanding comes from the ***HI*** community (QGP+CNM); in SIDIS they are under-explored.

- There are *many different approaches* and *models* to describe them; all give reasonably *good* descriptions within limitations.

- ***There is a lot yet to be explored***.