Probing diquark degrees of freedom using hadron formation dynamics

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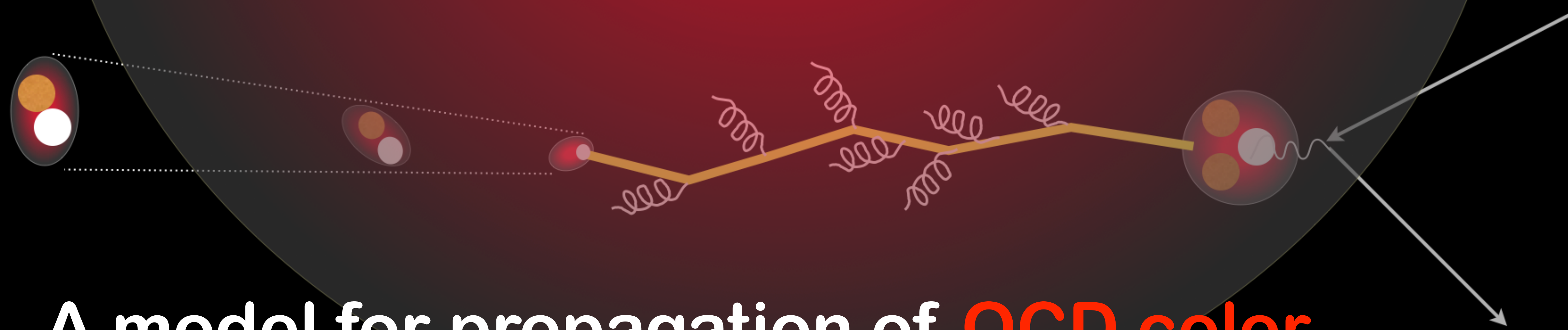
Outline

A model that describes meson production in nDIS

The puzzle of nDIS baryon production: the link to diquarks

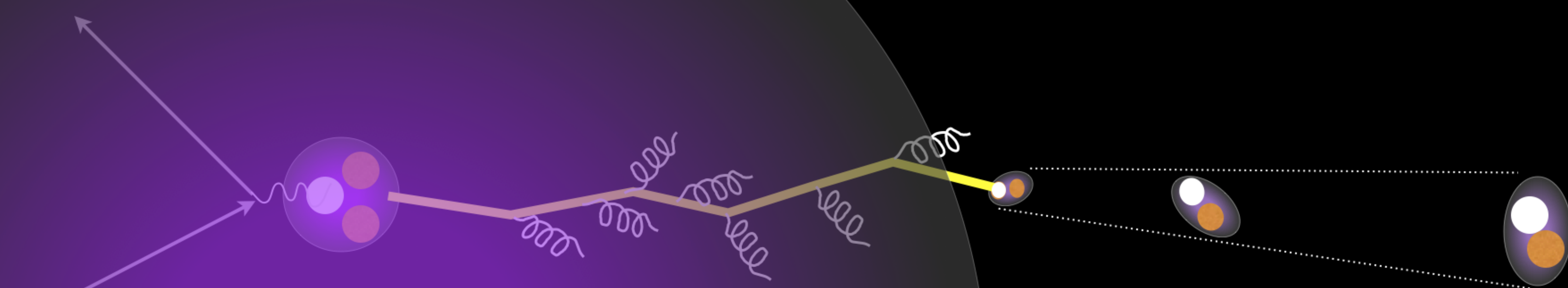
Near-future prospects for new baryon-diquark studies

Predictions for future measurements



A model for propagation of QCD color through strongly interacting systems

Will Brooks and Jorge López
(UTFSM) (Heidelberg)



About this model

- A new analysis of two published HERMES measurements. We isolate the roles of quark energy loss and pre-hadron formation in describing the data.
- Two observables are analyzed simultaneously.
- The primary ingredient is the well-known density distribution in nuclei.
- BDMPS-Z description needs to be validated by experiment. Important assertions recently challenged: (Zakharov, https://arxiv.org/abs/1807.09742).
- These kinds of studies will be important in the future at the Electron Ion Collider.

Motivations

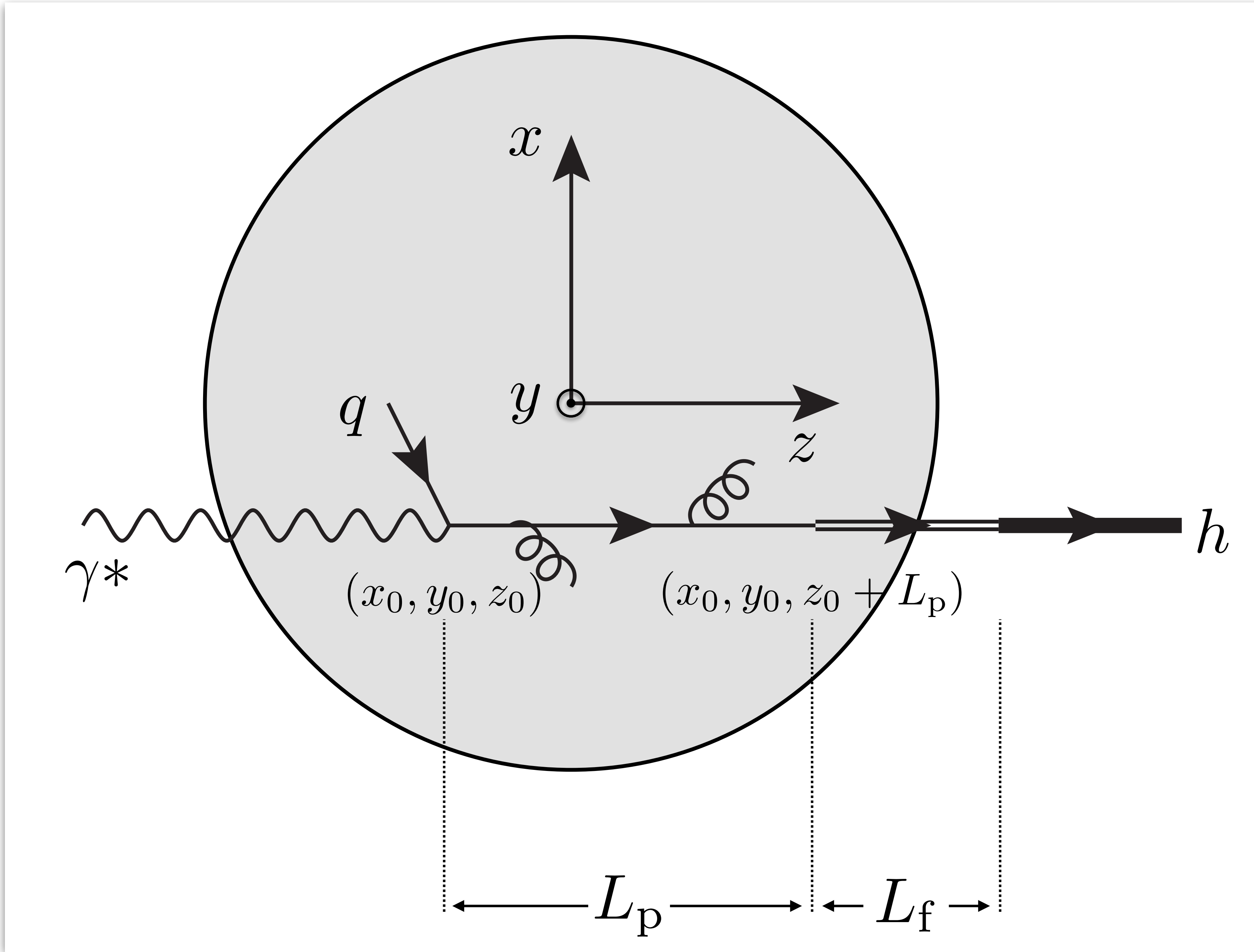
Measure characteristic lifetimes for color propagation in QCD

Constrain the functional form of the color lifetime using nuclear medium

Develop space-time concepts for QCD factorization in ep and eA, possibly pp

Develop consistent picture of quark interactions in nuclei

Semi-inclusive DIS has unique features for these studies

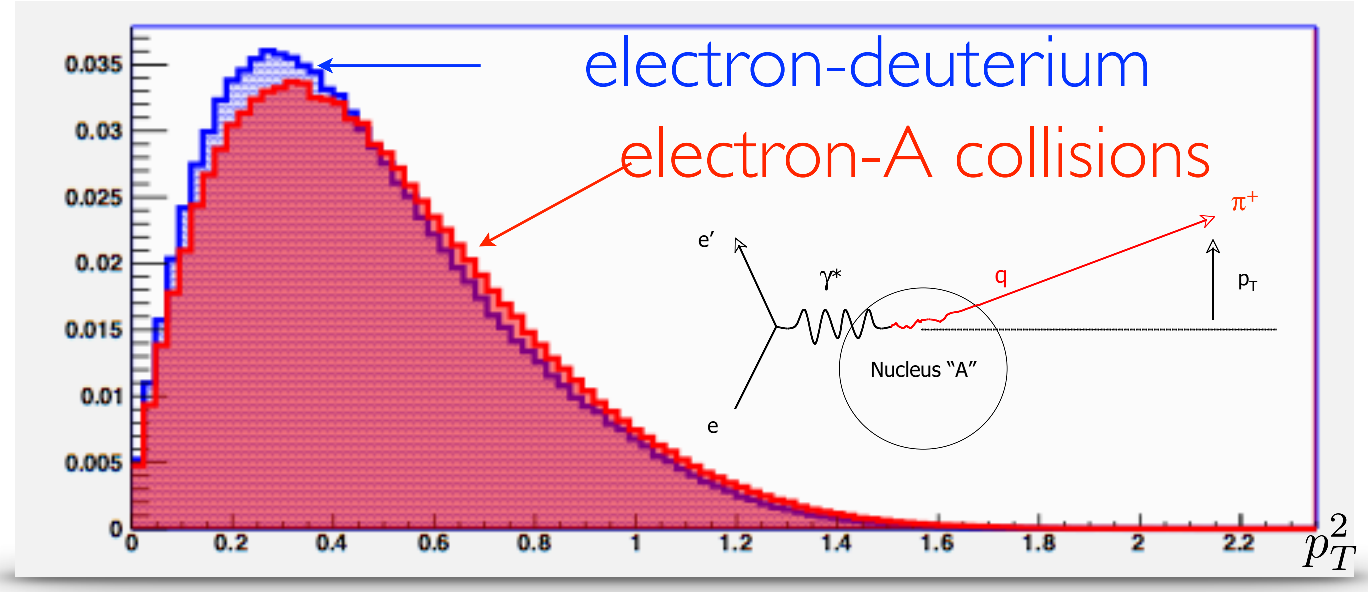


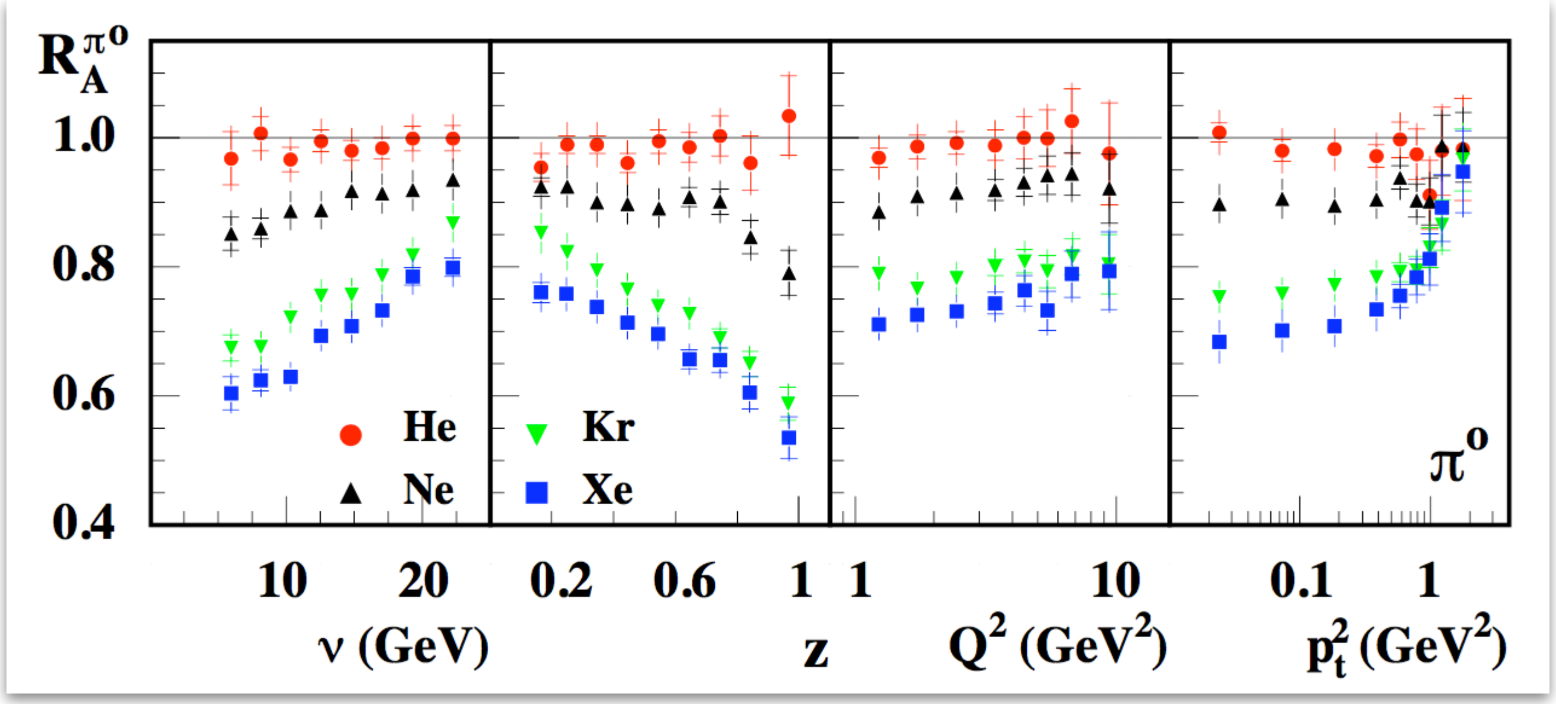
In DIS for x>0.1, we know the **quark initial energy and momentum very precisely**.
There are ~no initial state interactions, only final state interactions.

$$\Delta p_T^2(Q^2,\nu,z_h) \equiv \langle p_T^2(Q^2,\nu,z_h)\rangle|_A - \langle p_T^2(Q^2,\nu,z_h)\rangle|_D$$

Experimental observables

Transverse momentum broadening

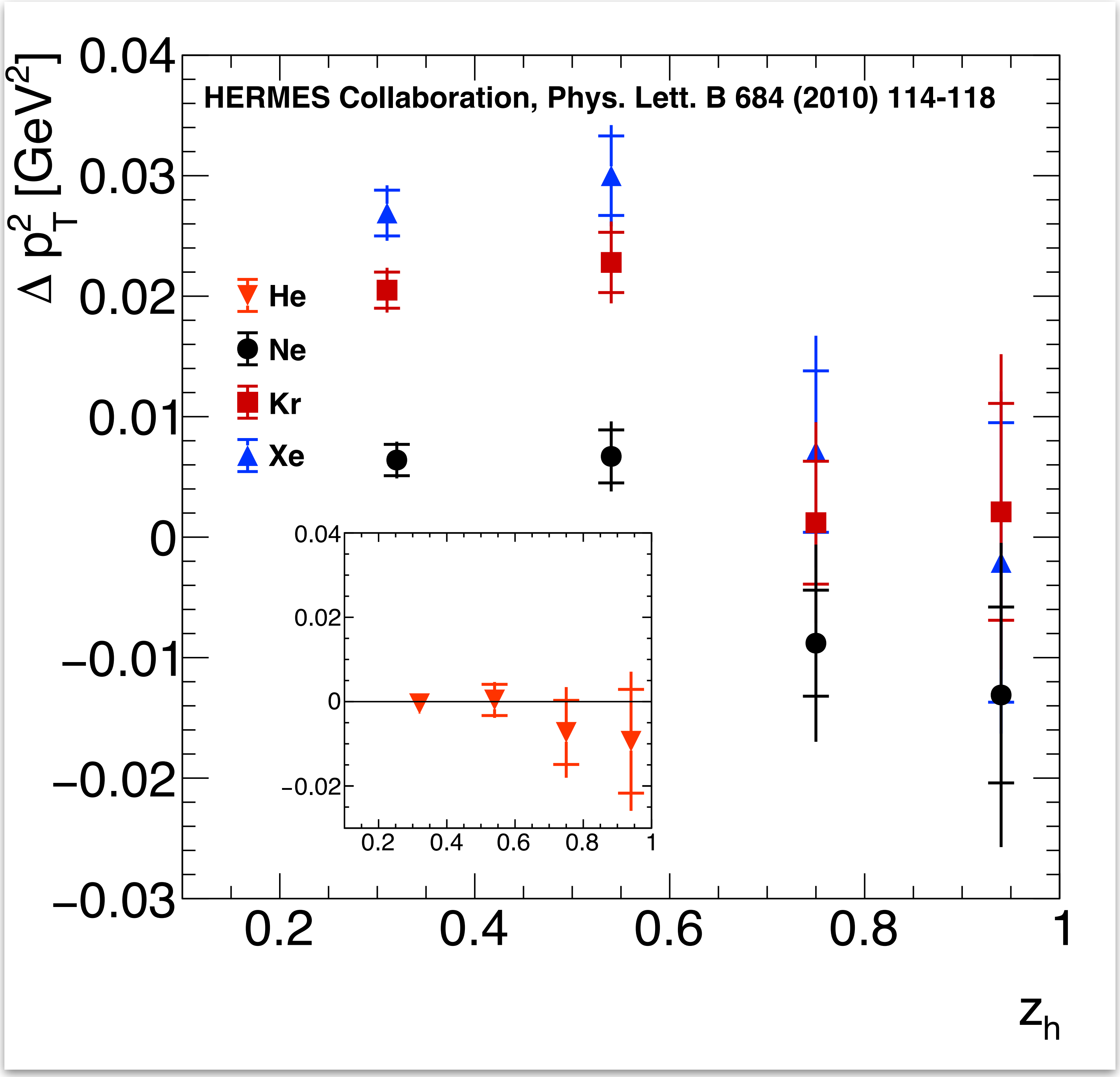




Hadronic multiplicity ratio

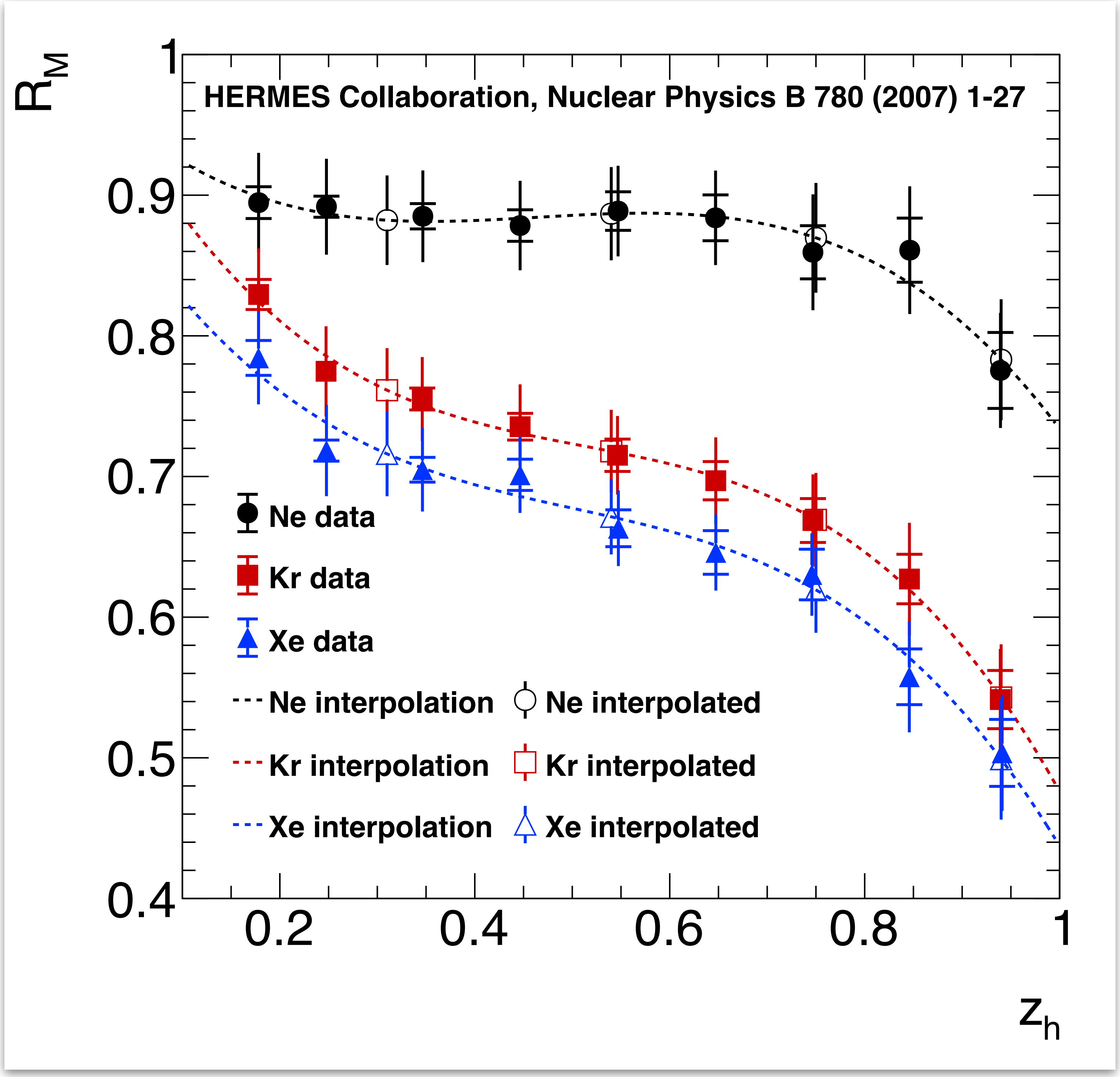
$$R_M^h(Q^2,\nu,z_h,p_T) \equiv \frac{\frac{1}{N_e(Q^2,\nu)} \cdot N_h(Q^2,\nu,z_h,p_T)|_A}{\frac{1}{N_e(Q^2,\nu)} \cdot N_h(Q^2,\nu,z_h,p_T)|_D}$$

Hermes data for p_T broadening vs. z_h=E/ν



Note for later discussion: maximum is 0.03 GeV²

Hermes data, hadronic multiplicity ratio vs. $z_h=E/\nu$

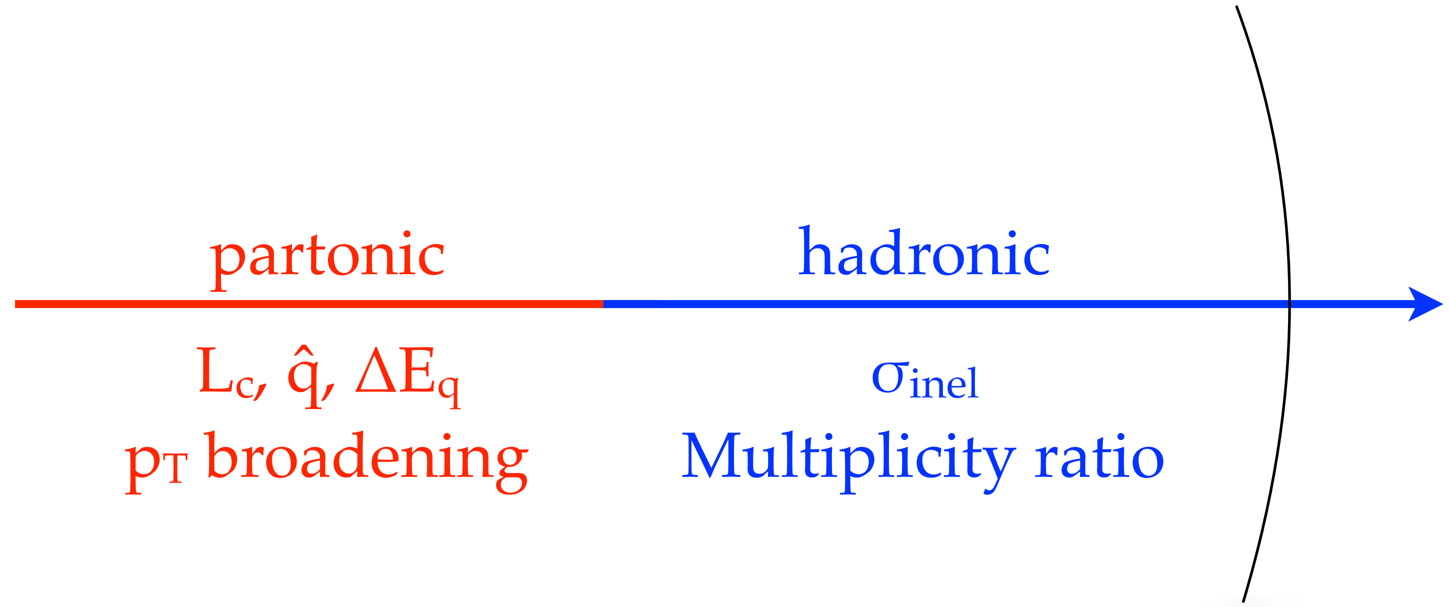


The interpolation is used to match the bins in p_T broadening (in previous slide)

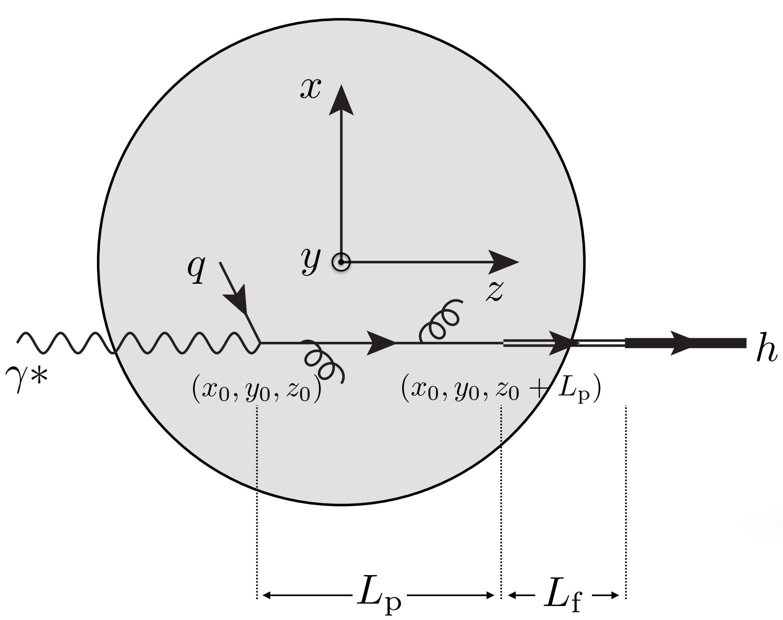
Definition of the model

Division into *partonic* and *hadronic* phases

Path of quark is divided into "partonic phase" and "hadronic phase"

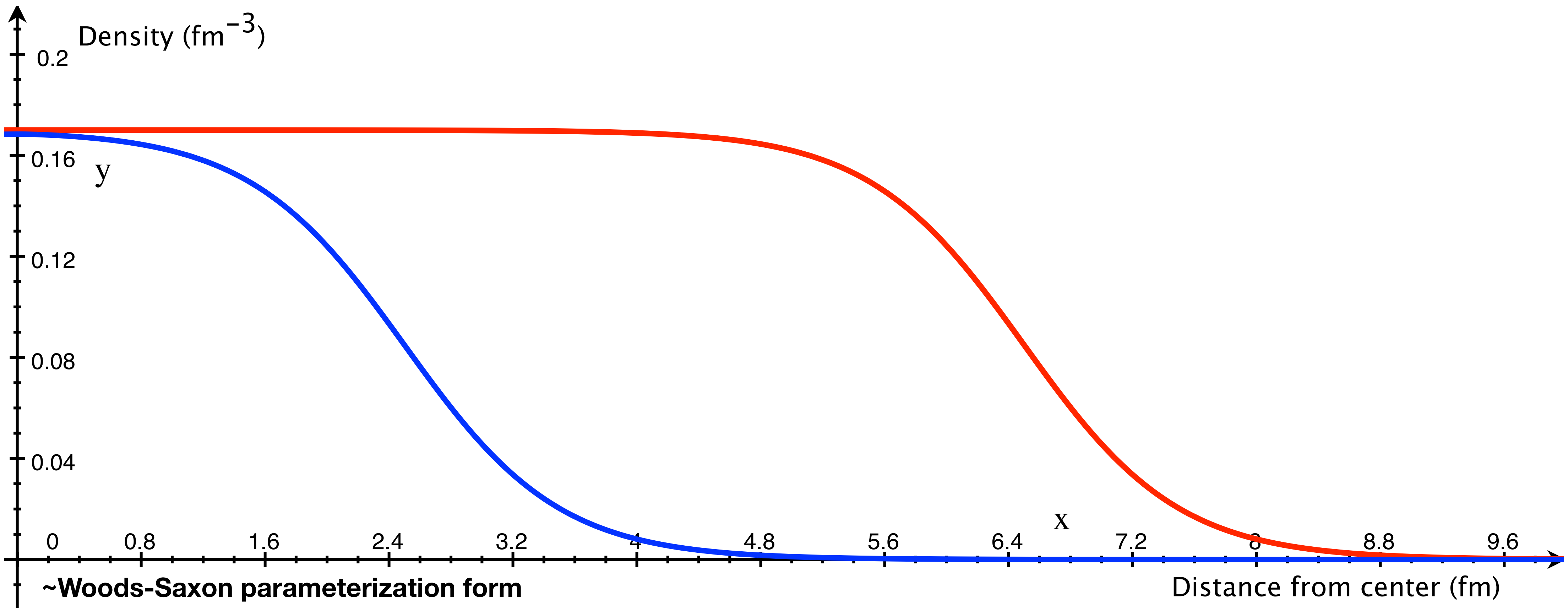


The partonic phase persists for a distance L_c, over which p_T broadening via $\hat{q}$, and partonic energy loss ΔE_q, occur



The hadronic phase follows the partonic phase, passing through the remainder of the medium, and causing attenuation of hadrons by an inelastic interaction cross section σ_{inel}

Density distribution according to H. P. Blok and L. Lapikás, PHYSICAL REVIEW C 73, 038201 (2006)



~Woods-Saxon parameterization form

Baseline Model Ingredients

p_T broadening is modeled as a line integral over a realistic density in the partonic phase, with 1 unique parameter, averaged over volume and color length L_c

$$\langle \Delta p_T^2 \rangle = \langle \; q_0 \int_{z=z_0}^{z=z_0+L_c^*} \rho(x_0, y_0, z) \; dz \; \rangle_{x_0, y_0, z_0, L_c}$$

unique parameter

common parameter

Multiplicity ratio is modeled as a line integral over a realistic density in the hadronic phase, with 1 unique parameter, averaged over volume and color length L_c.

unique parameter

common parameter

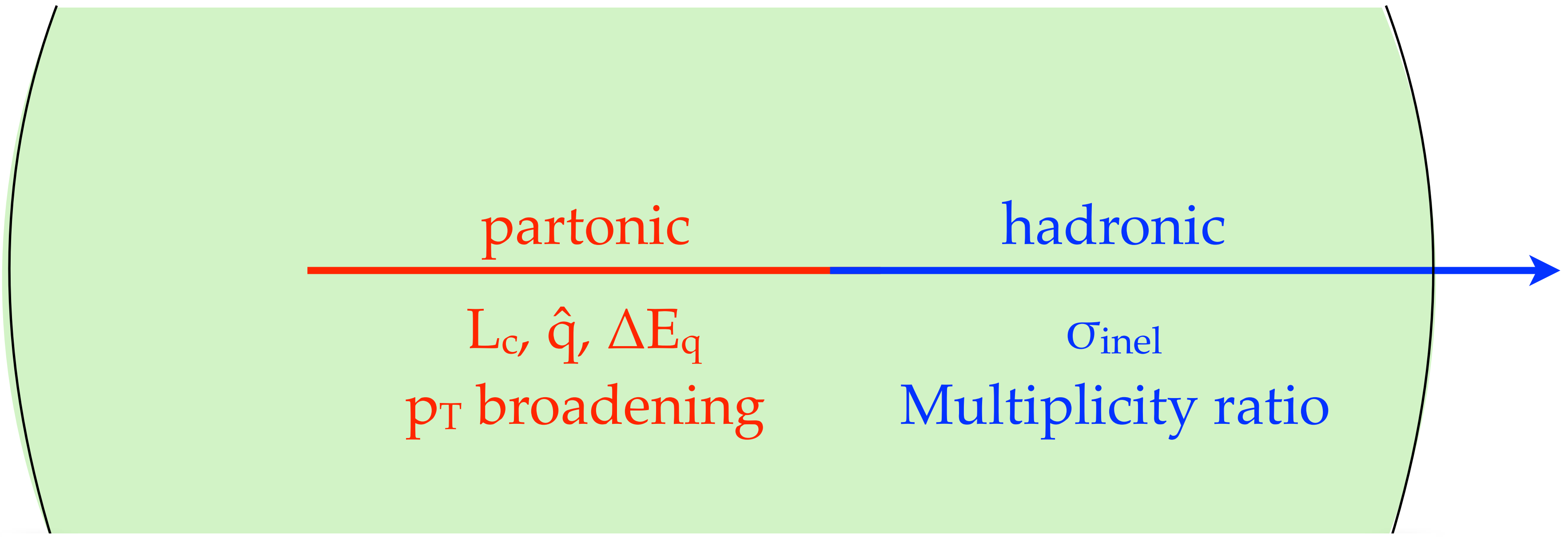
$$\langle R_M \rangle = \langle \; \exp(-\sigma \int_{z=z_0+L_c}^{z=z_{max}} \rho(x_0, y_0, z) \; dz \;) \; \rangle_{x_0, y_0, z_0, L_c}$$

Total of 3 parameters in the baseline model. We often fix sigma at 30 or 40 mbarn.

The "common" parameter L_c *couples* the two observables together.

The coupling of the observables through L_c is the feature of this model that gives it much more discriminating power than the single-observable models used previously.

For example, for fixed q_0 and fixed σ, if L_c is *longer* (longer partonic phase) it simultaneously *increases* p_T broadening and *decreases* the multiplicity ratio. The amount of increase and decrease depends on the size of the nucleus and on the size of L_c. Thus the description is highly constrained.

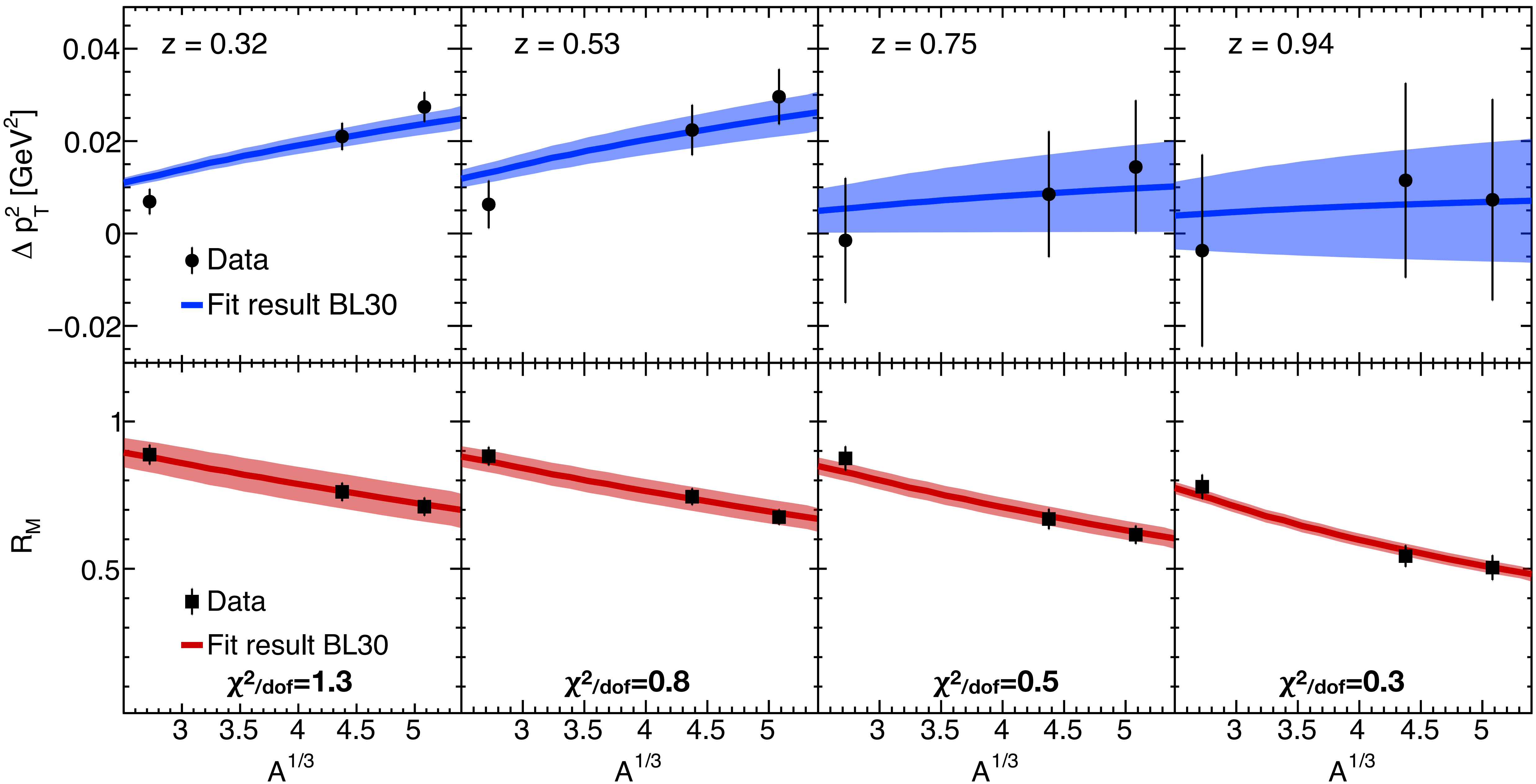


Model Assumptions

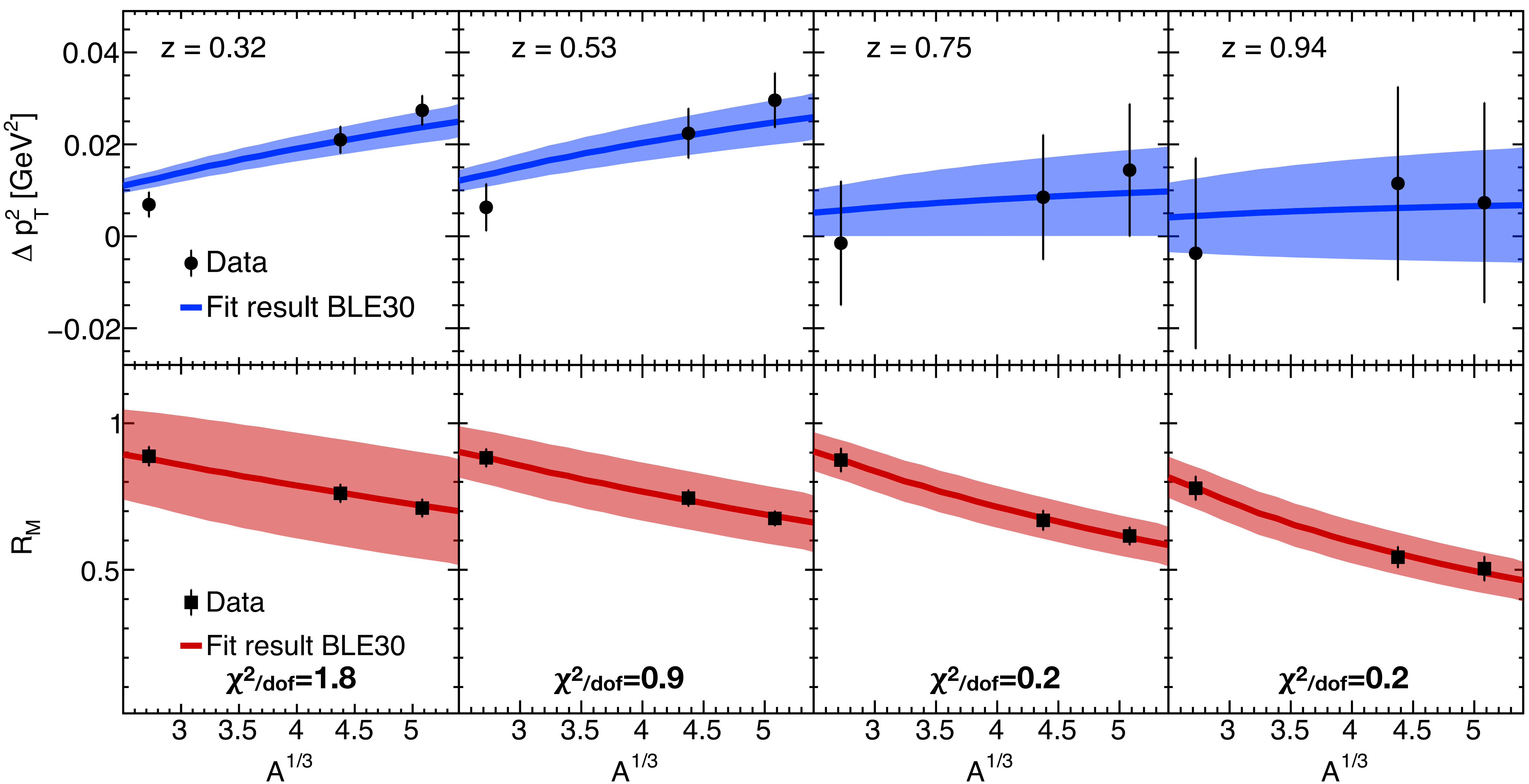
- Only two dynamical processes are involved - quark energy loss and (pre-)hadron inelastic interactions
- Straight-line propagation of the struck quark (soft-gluon assumption)
- Two stages of propagation: first, as a color octet system, and second as a color singlet system.
- Non-zero hadron formation time (reduced inelastic cross section).
- Fluctuations affecting the yield are neglected (only average values). Decreasing exponential form for pre-hadron cross section.
- Functional form of the color lifetime: either exponential or constant.

Results of the model fit to two observables from HERMES data

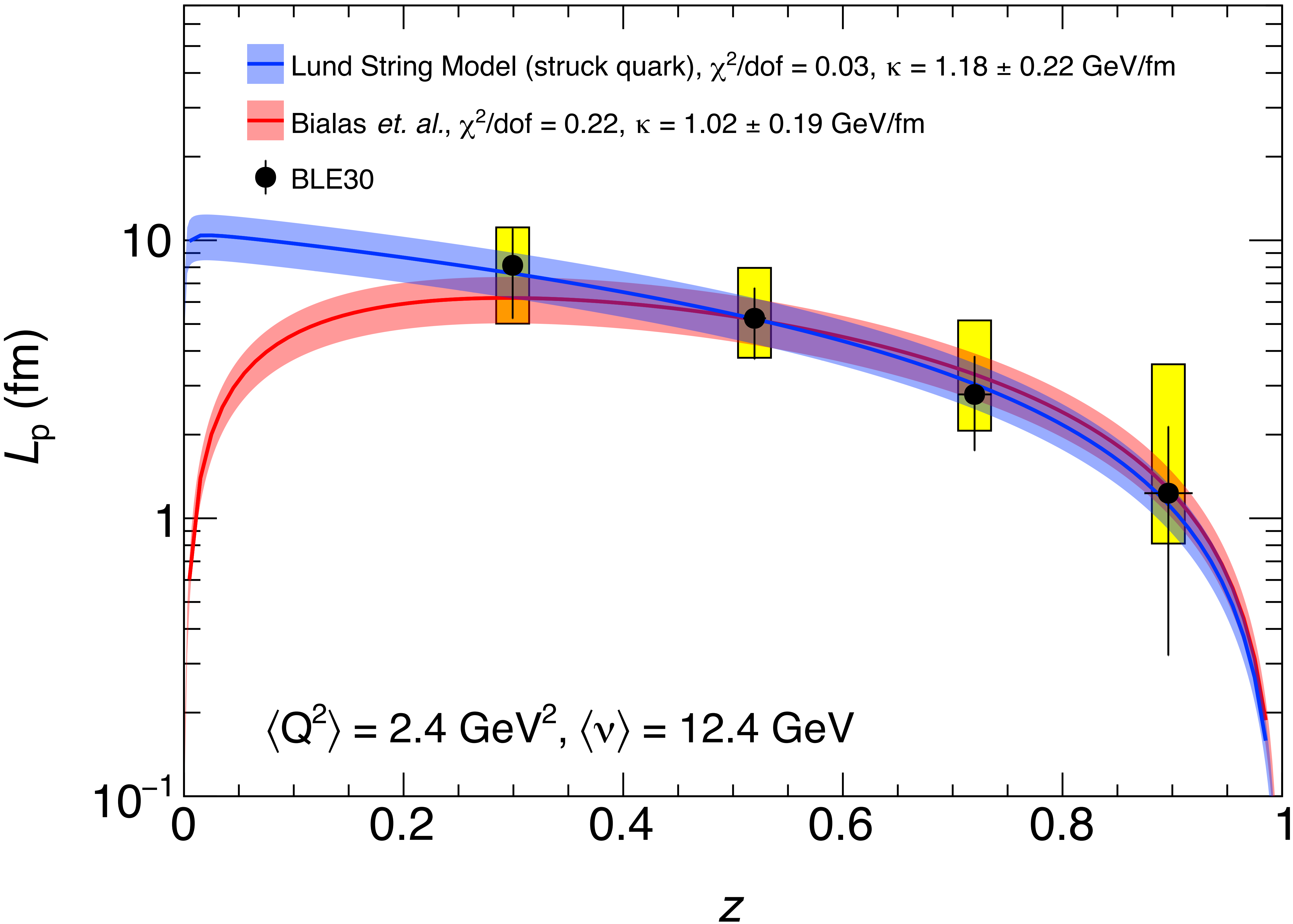
Model fit to HERMES data
Simultaneous fit to 2 observables
3 parameter variant (q_0, L_c, σ_h=30 mb)
(Baseline model, BL30)



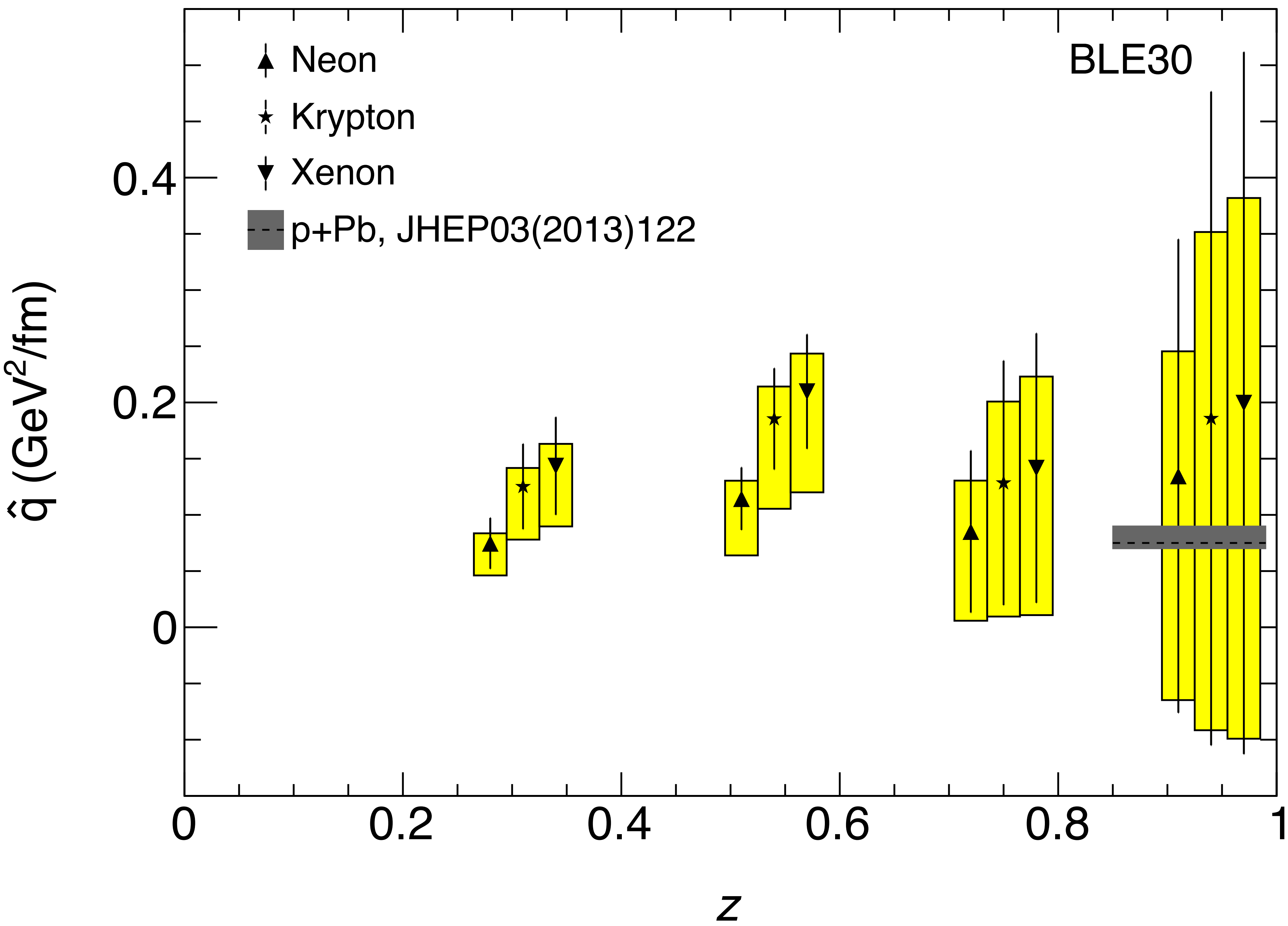
Model fit to HERMES data
Simultaneous fit to 2 observables
4 parameter variant (q_0, L_c, ΔE, σ_h=30 mb)
(Baseline model plus quark energy loss, BLE30)



Color lifetime - the main result of the model

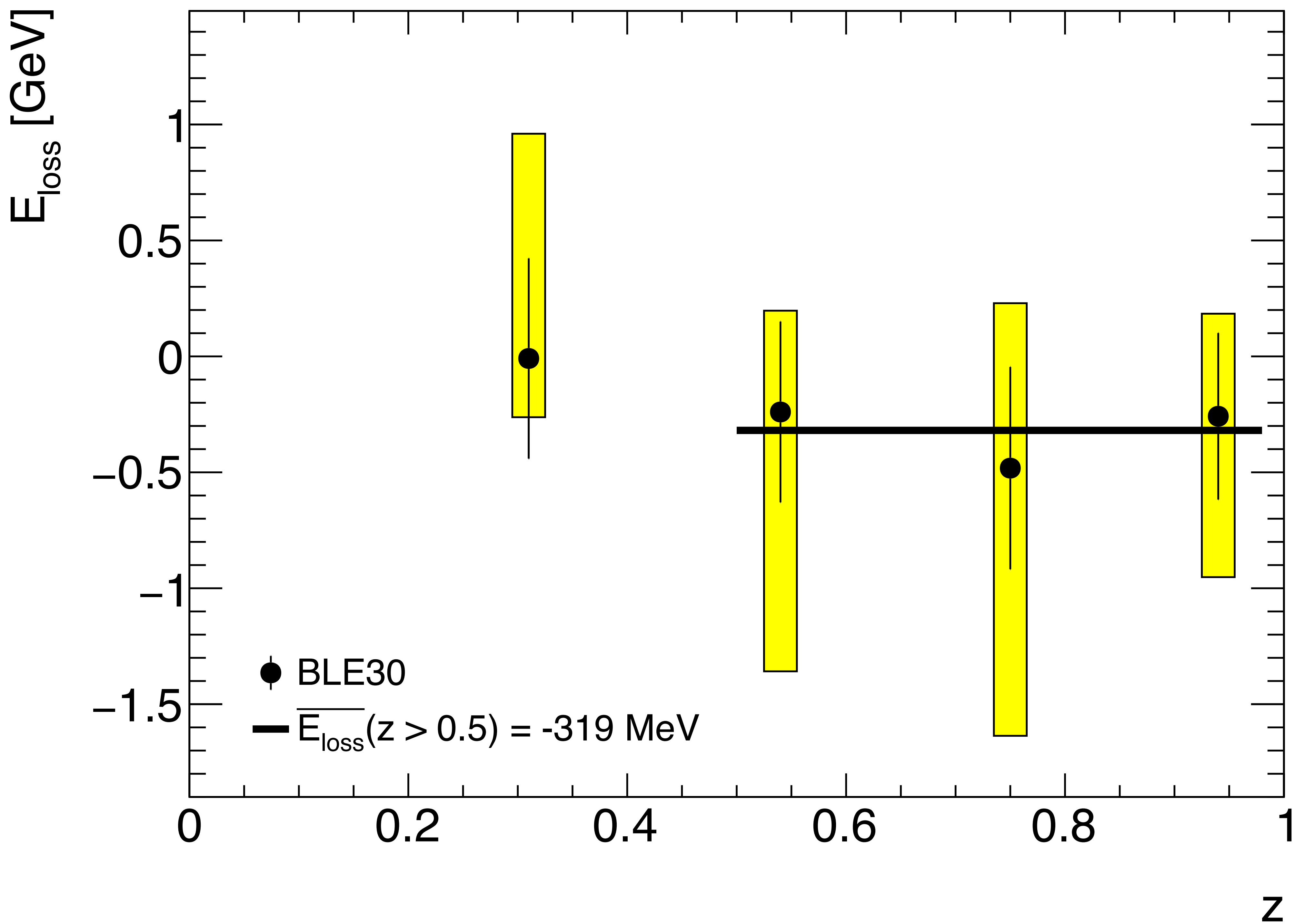


Transport Coefficient $\hat{q}$



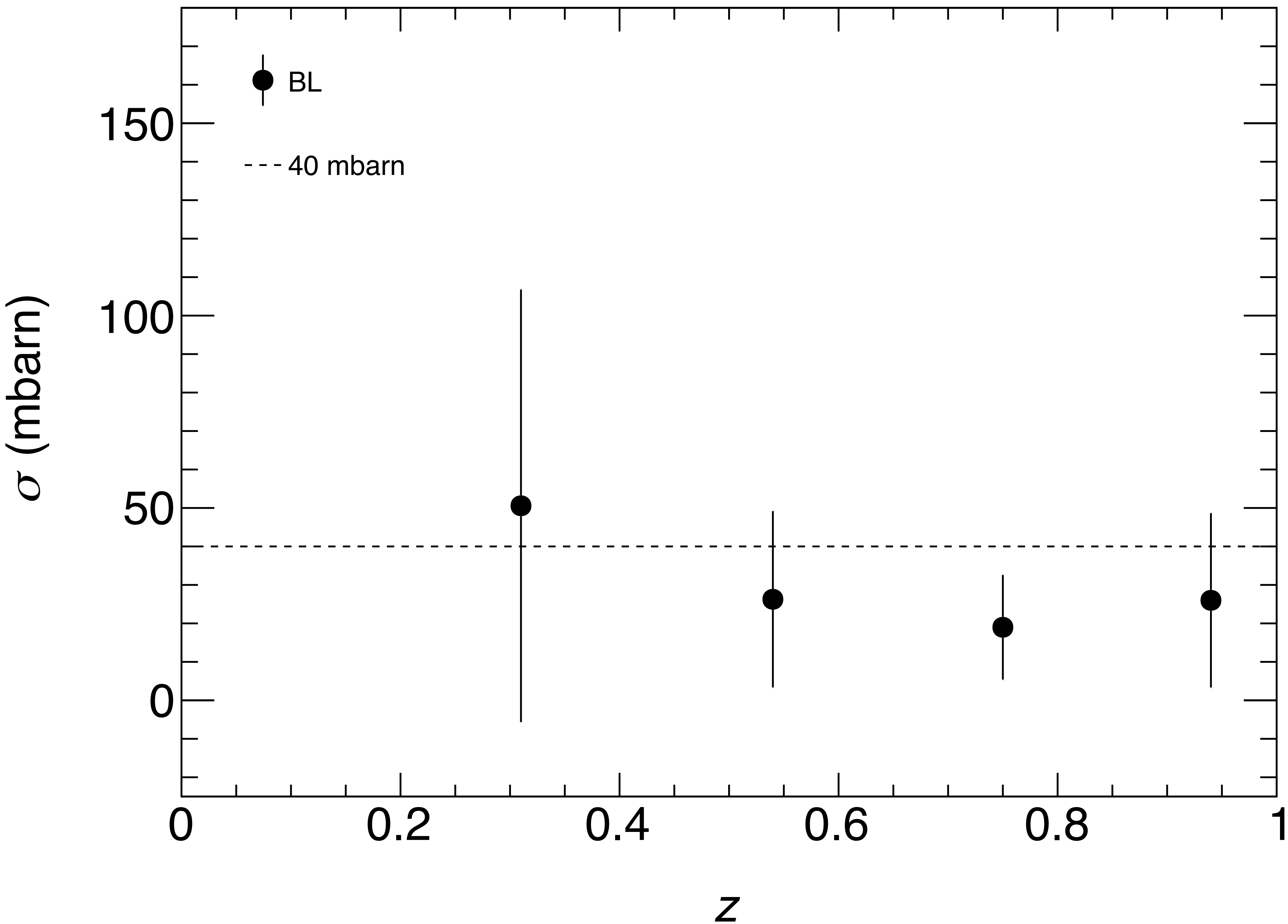
We find a value consistent with other published estimates, ~0.075 GeV^2/fm.
We find an A-dependence, but with large uncertainties.
We do not see a significant z_h dependence.

Quark energy loss



We get plausible values for the quark energy loss, but with large uncertainties. Values are consistent with other analyses for cold matter. The model fit to the data is essentially of equal quality with and without quark energy loss.

Inelastic pion-nucleon cross section

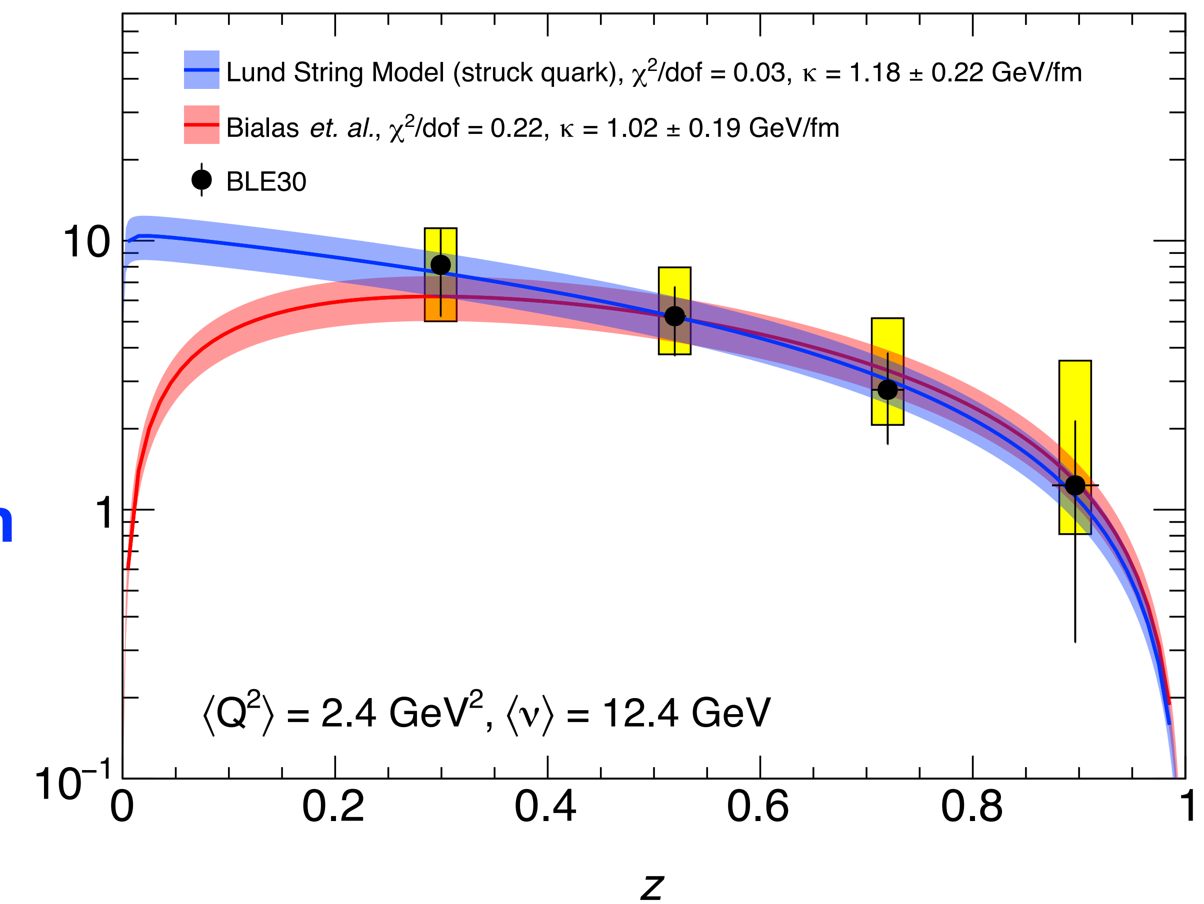


Extracted value consistent with ~25-30 mbarns for $z_h > 0.5$

Color lifetime - the main result of the model

Comments:

- **This parameter, Lc, is perfectly stable in all model variants**
- **A fit of our results to the Lund String Model form gives the well-known string constant of 1 GeV per fm to 20% accuracy**
  - **We consider this independent result to be a strong validation of our model**
- **We find a z-dependent color lifetime for HERMES kinematics ranging from 1 to 10 fm**
- **As this is a *time interval*, we can boost to different reference frames to obtain the time-dilated color lifetime for other experiments, such as EIC and JLab.**
- **Future experiments can test to see if time dilation can be observed, which would further validate our approach.**



About this model

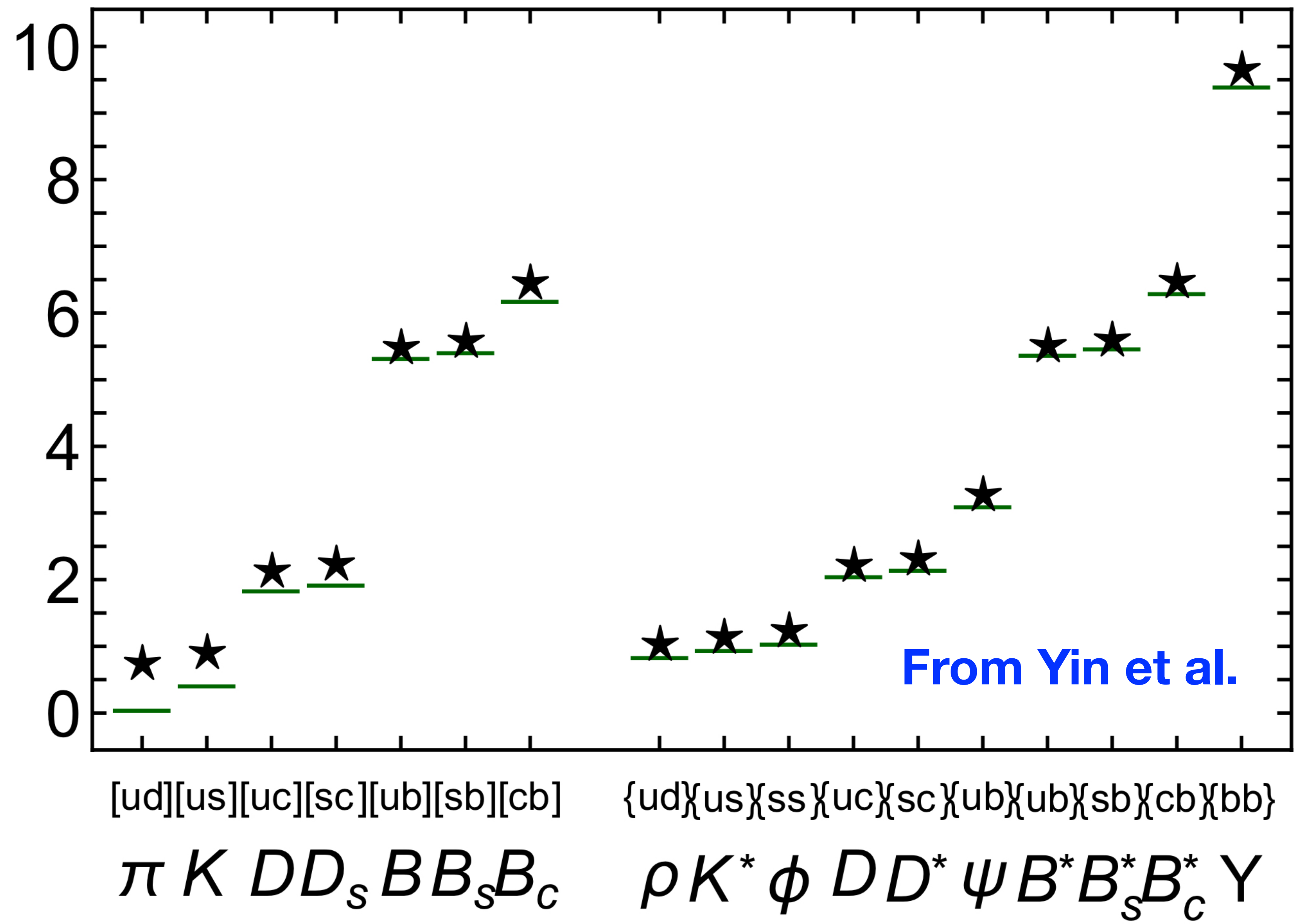
- We have extracted the color lifetime from published HERMES data using a simultaneous fit of two observables, finding z-dependent values from 1-10 fm/c.
- The results are perfectly consistent with Lund String Model forms for this observable, and independently yield a value of the string constant κ = 1 GeV/fm, strongly validating our approach.
- We also extracted the $\hat{q}$ transport coefficient, the quark energy loss, and the reduced inelastic pion-nucleon cross section, finding values consistent with expectations and other analyses, but with large uncertainties.
- We consider that we “understand” nDIS meson production based on these results. New data are needed to prove otherwise.

On to diquarks!

Masses of ground-state mesons and baryons, including those with heavy quarks

Pei-Lin Yin,[1,*] Chen Chen,[2,†] Gastão Krein,[2] Craig D. Roberts,[3,‡] Jorge Segovia,[4] and Shu-Sheng Xu[1]

arXiv 1903.00160

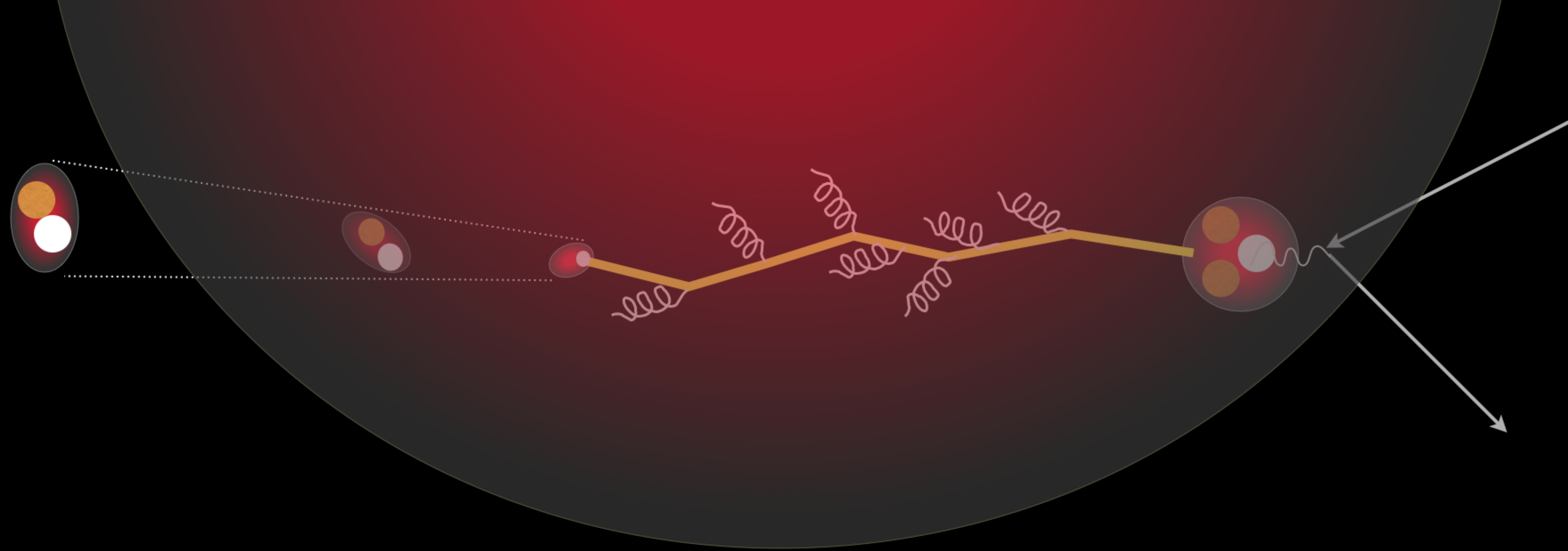


The ud diquarks are heavy. This is very relevant to what follows in this talk.

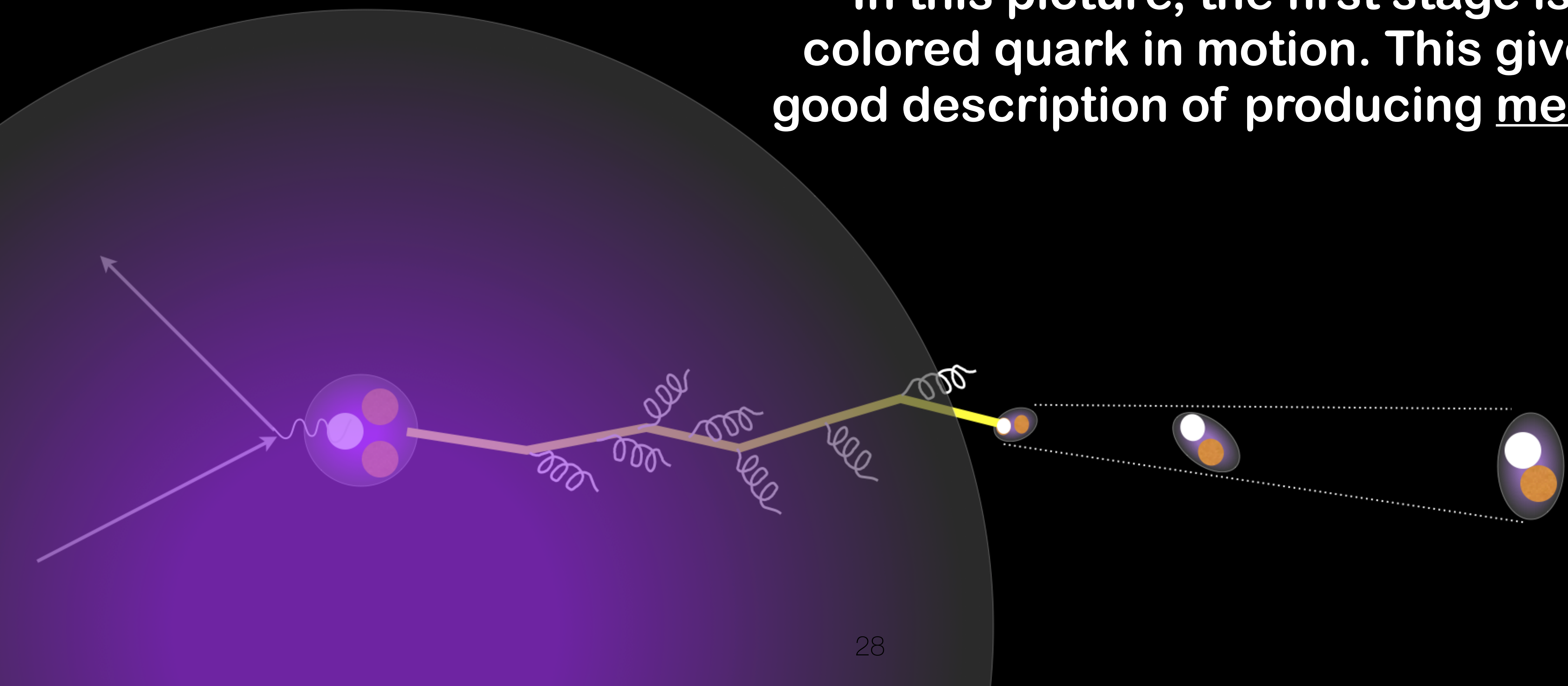
FIG. 2. Comparison between computed masses of diquark correlations and their symmetry-related meson counterparts: diquarks – (black) stars and mesons – (green) bars.

Experimental evidence of diquark scattering from the HERMES data for SIDIS on nuclear targets

"***Multidimensional*** study of hadronization in nuclei"
arXiv:1107.3496v3 [hep-ex] 13 Sep 2011



In this picture, the first stage is a colored quark in motion. This gives a good description of producing <u>mesons</u>.



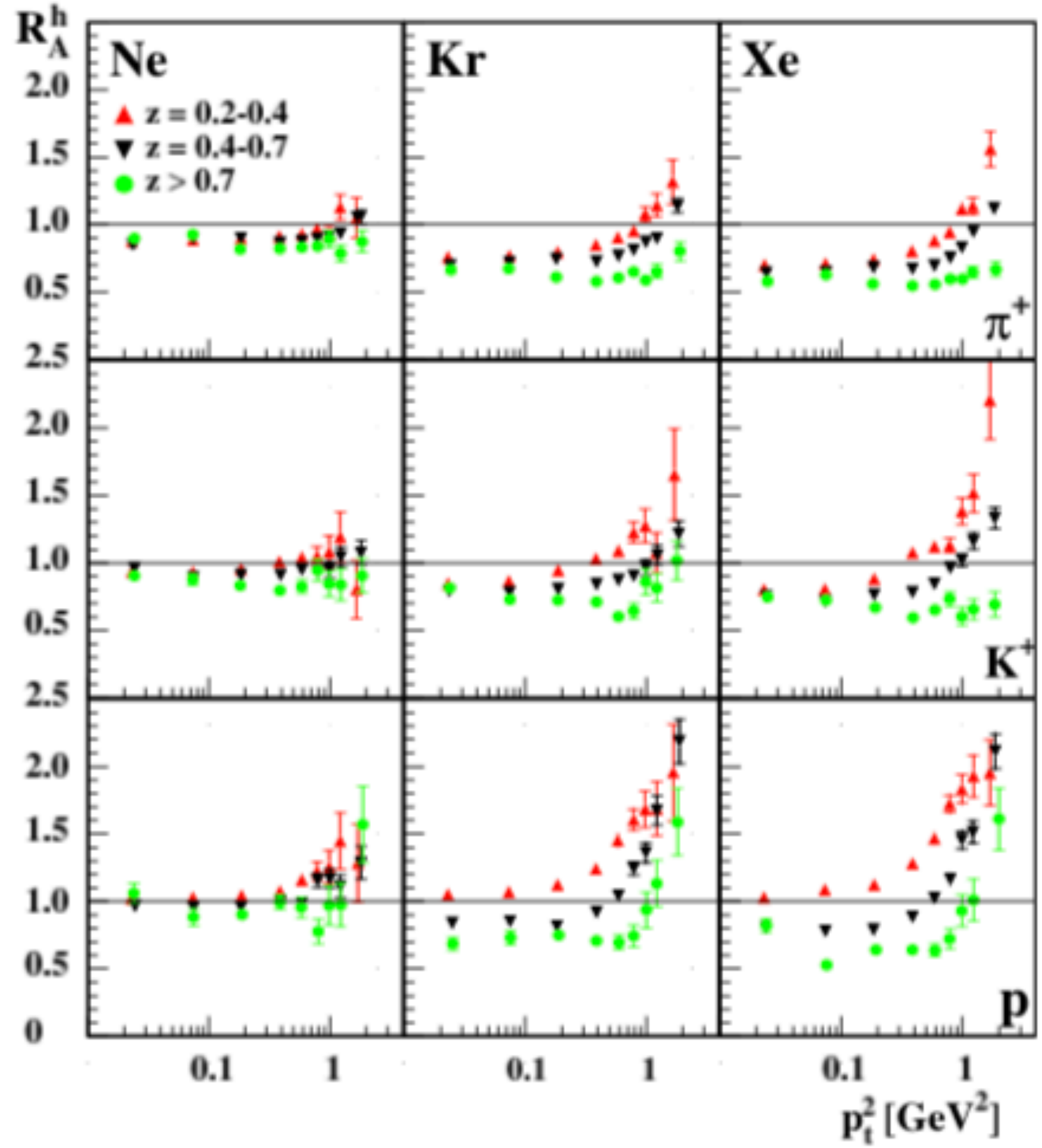
Interpreting HERMES Nuclear DIS DATA: MESONS

The multiplicity ratio measures effects of the nuclear medium.
"No effects" means R=1.0

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

Most basic indicator is pT dependence of multiplicity ratio.

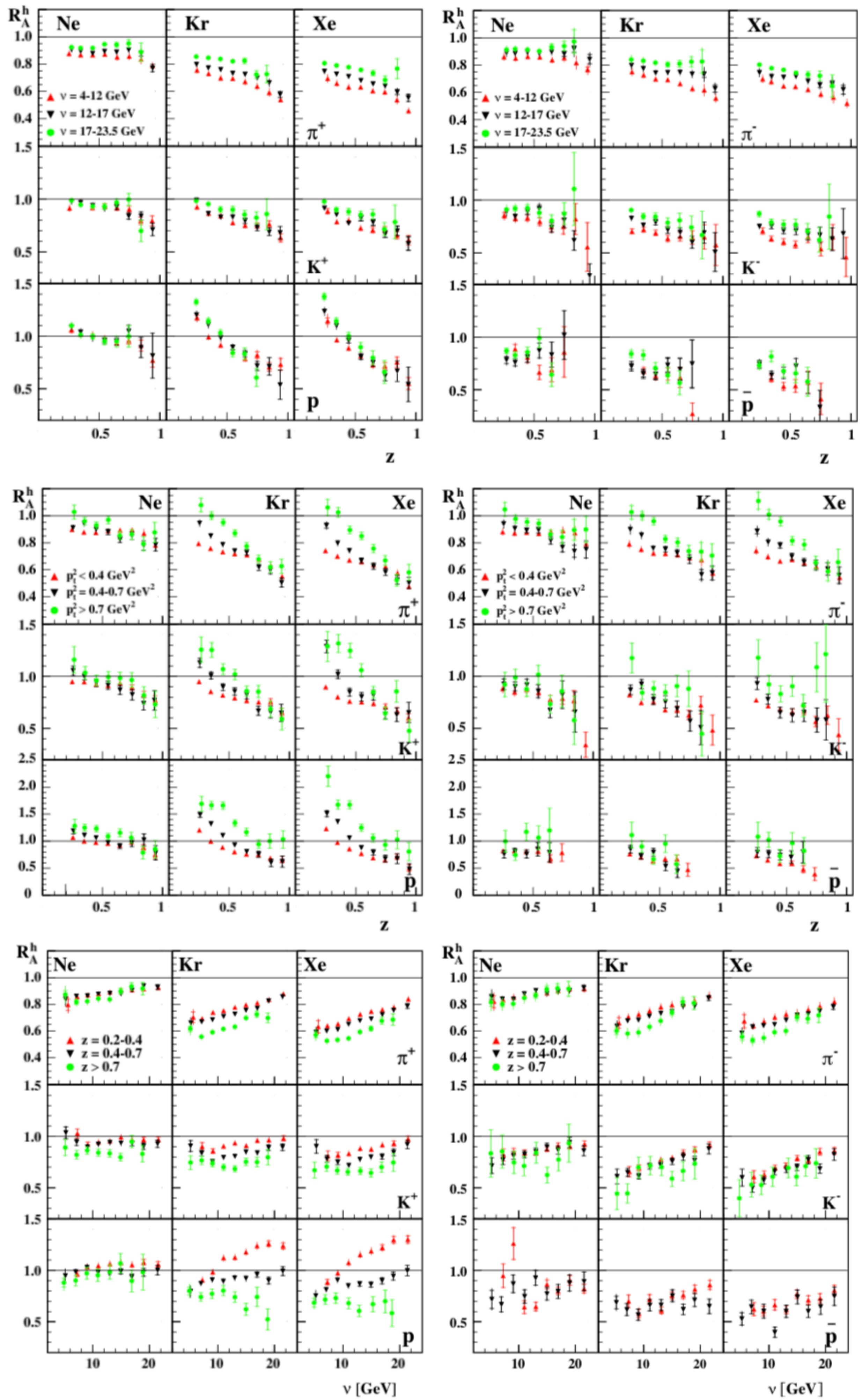
R>1 at high pT because particles that strongly interact with the medium acquire more pT than those that don't interact as much.

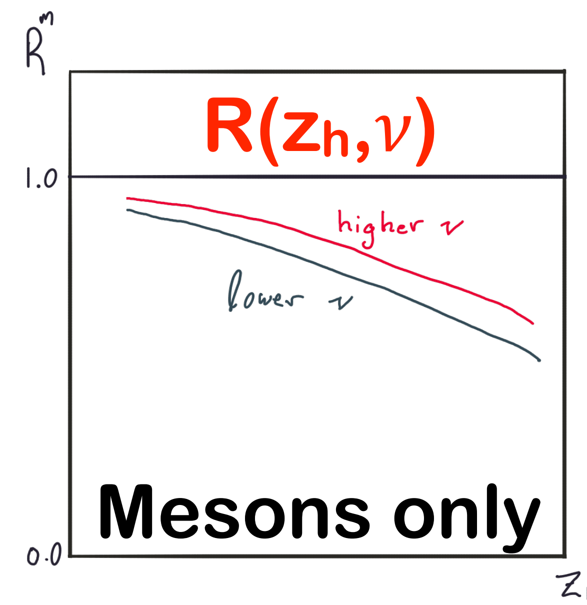


"Interact" = hadronic interaction of forming hadrons, + quark energy loss.

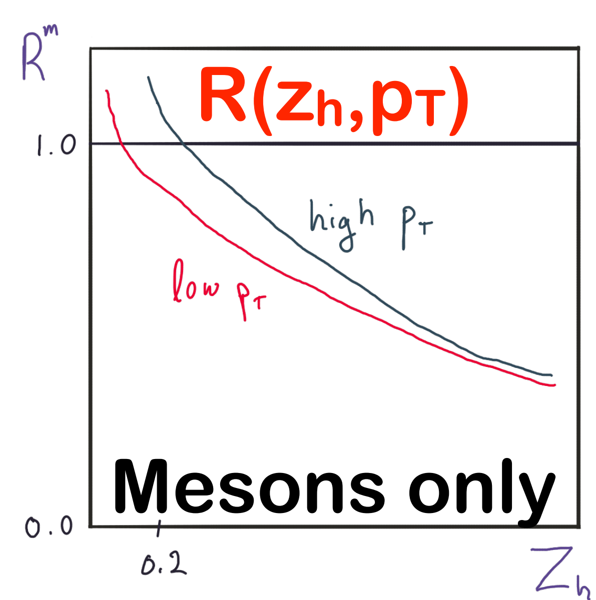
Empirically, from these plots, low-z mesons acquire more pT than high-z.

Enhancement at high pT mostly caused by hadronic interactions at low z.

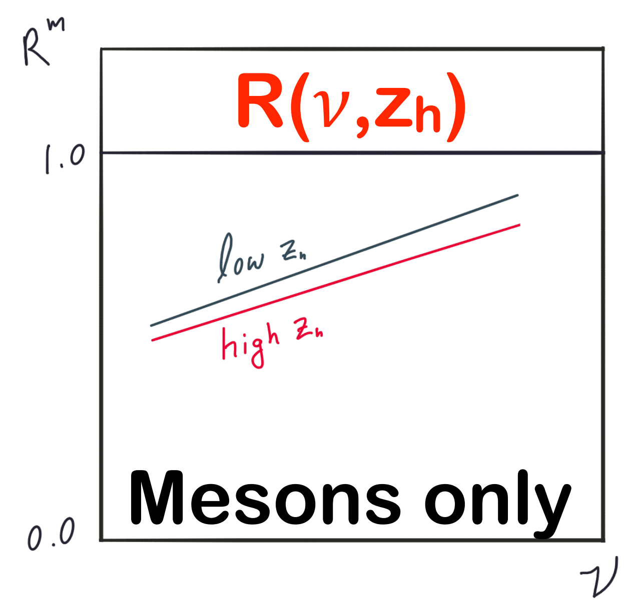




Integrated over pT, so always < 1. At higher nu, less attenuation because of time dilation of quark lifetime



Not integrated over pT, so can exceed 1. Exceeds 1 faster for higher pT, so crossing point is pT dependent.



Time dilation is proportional to nu. Slow approach to 1.0 at infinite nu. Quark lifetime goes to zero at high z, so high z is attenuated more.

So far, we have a reasonable qualitative interpretation for mesons that explains multi-dimensional behavior completely.

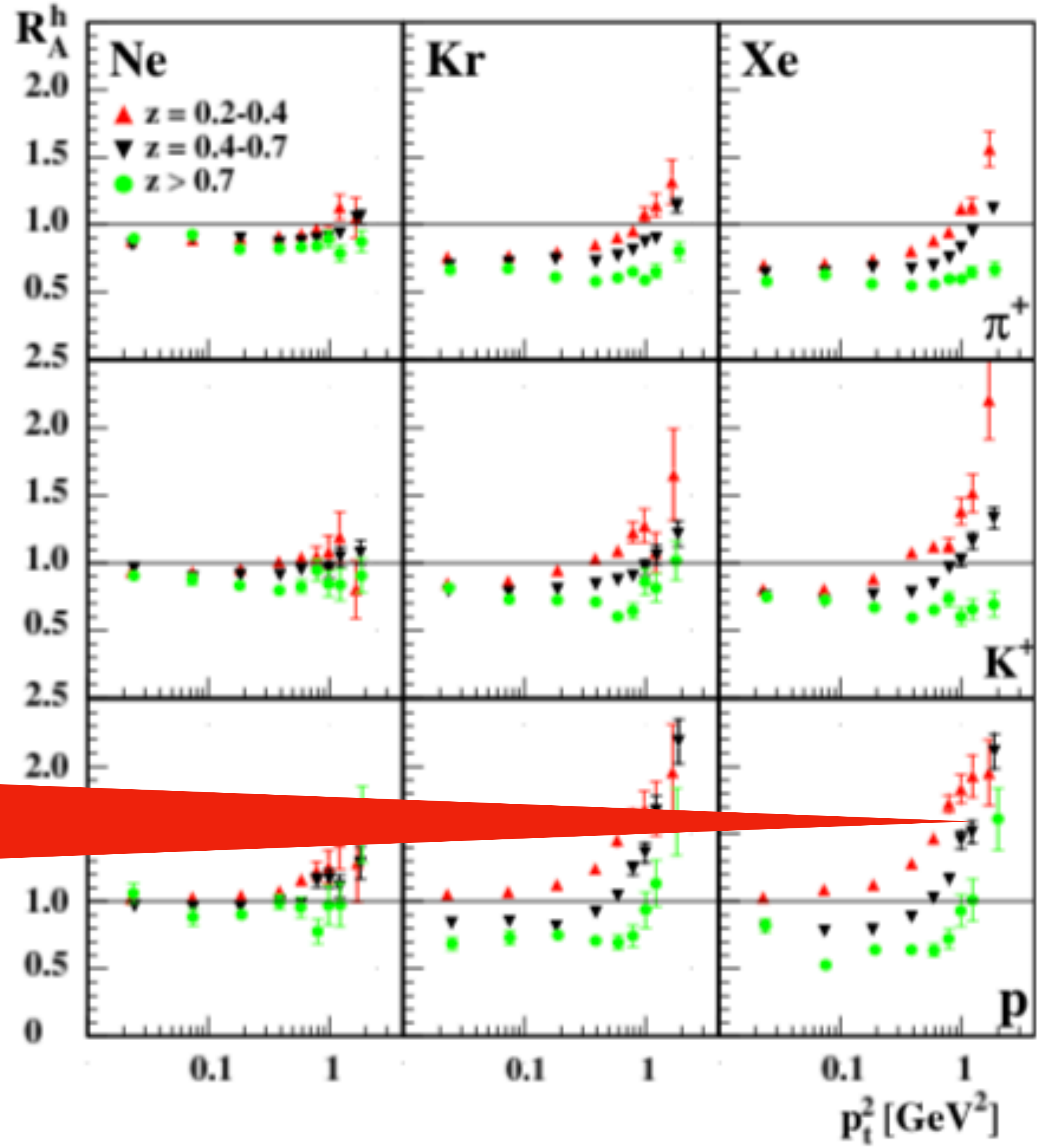
BUT: mesons don't have diquarks

Let's see if we can understand HERMES baryon data

Interpreting HERMES Nuclear DIS DATA: MESONS

The multiplicity ratio measures effects of the nuclear medium. "No effects" means R=1.0

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



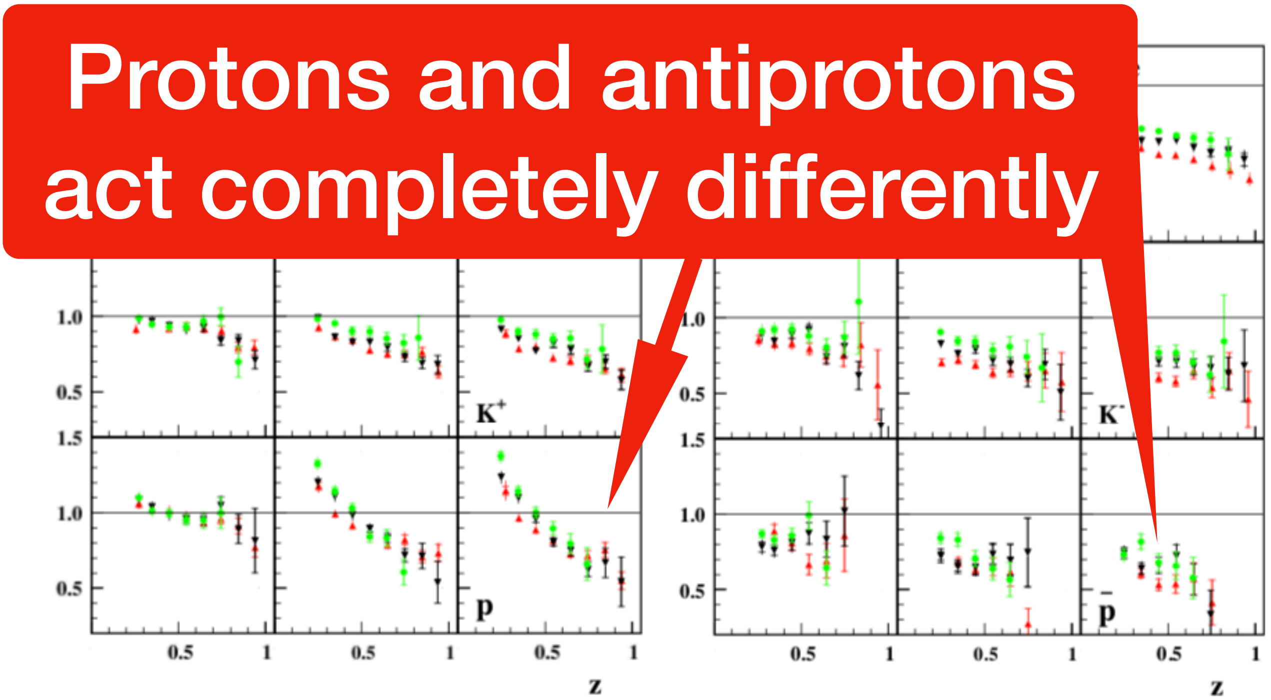
The ordering in z seen for mesons disappears at high pT for protons.

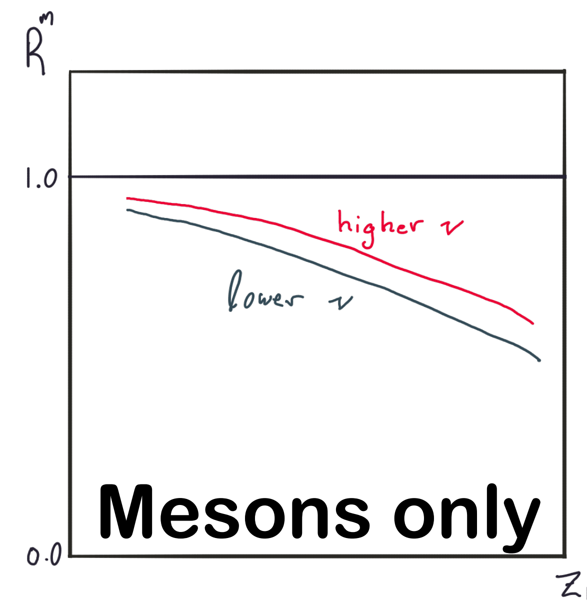
<u>Strong interaction</u> occurs at all values of z.

of forming hadrons, + quark energy loss.

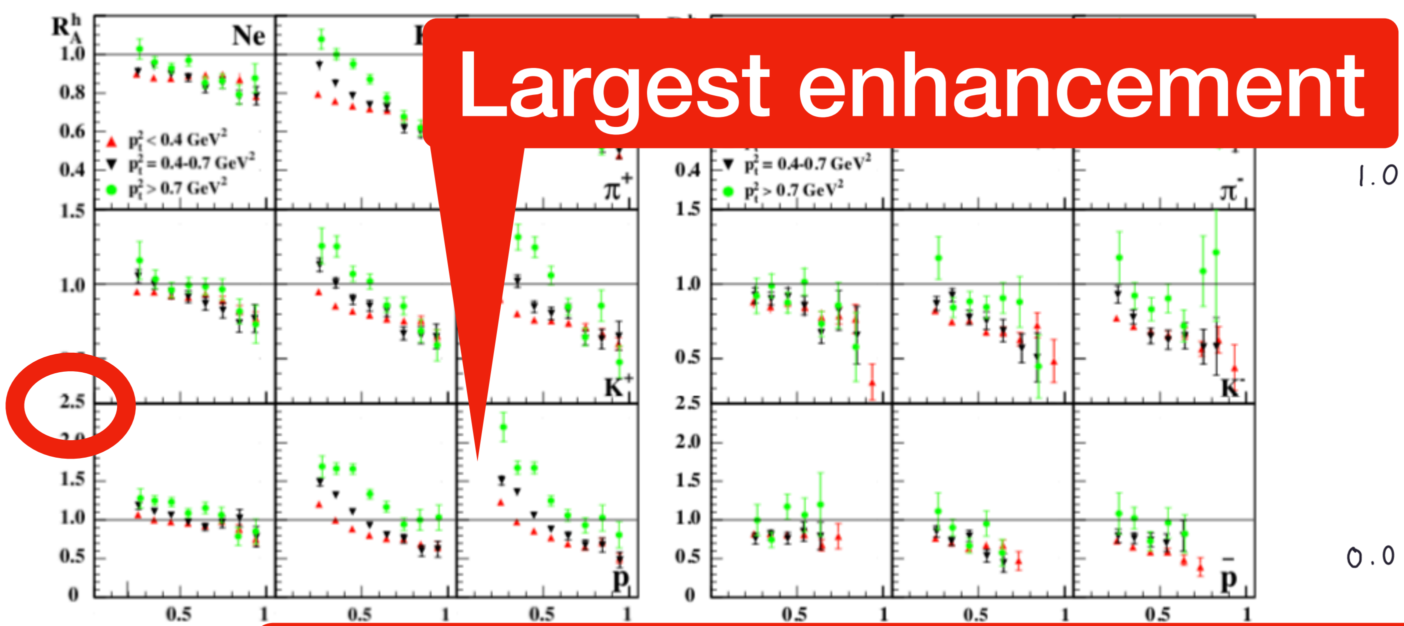
Empirically, from these plots, low-z mesons acquire more pT than high-z.

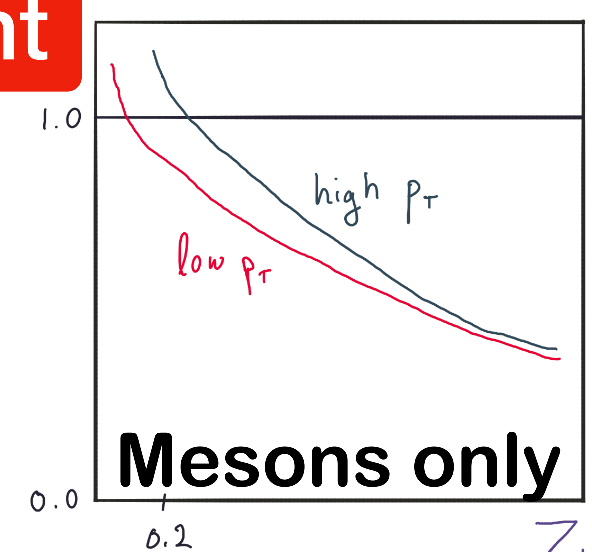
Enhancement at high pT mostly caused by hadronic interactions at low z.



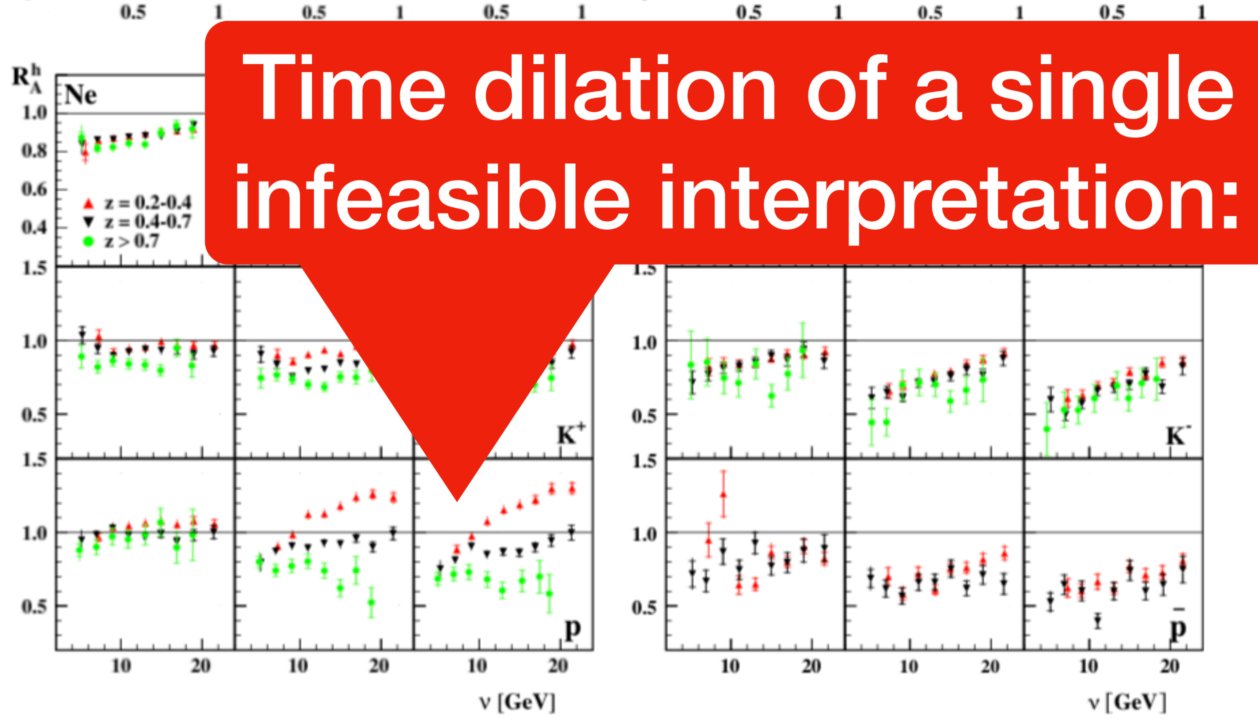


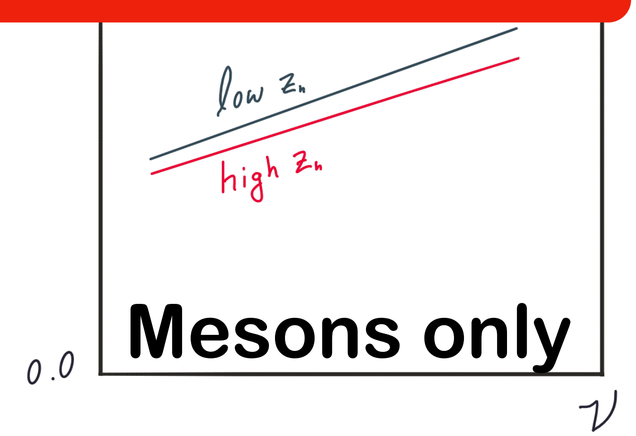
Integrated over pT, so always < 1. At higher nu, less attenuation because of time dilation of quark lifetime





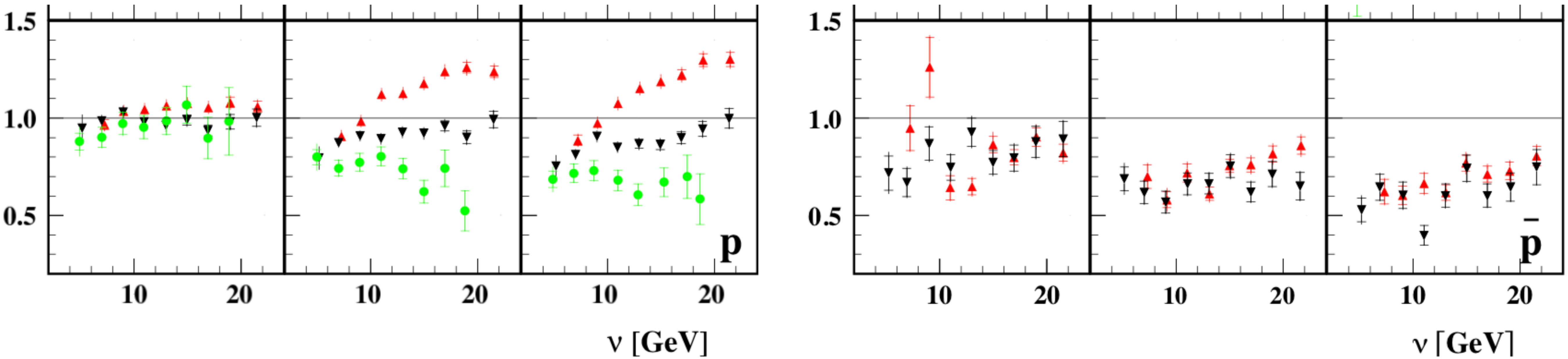
Not integrated over pT, so can exceed 1. Exceeds 1 faster for higher pT, so crossing point is pT dependent.





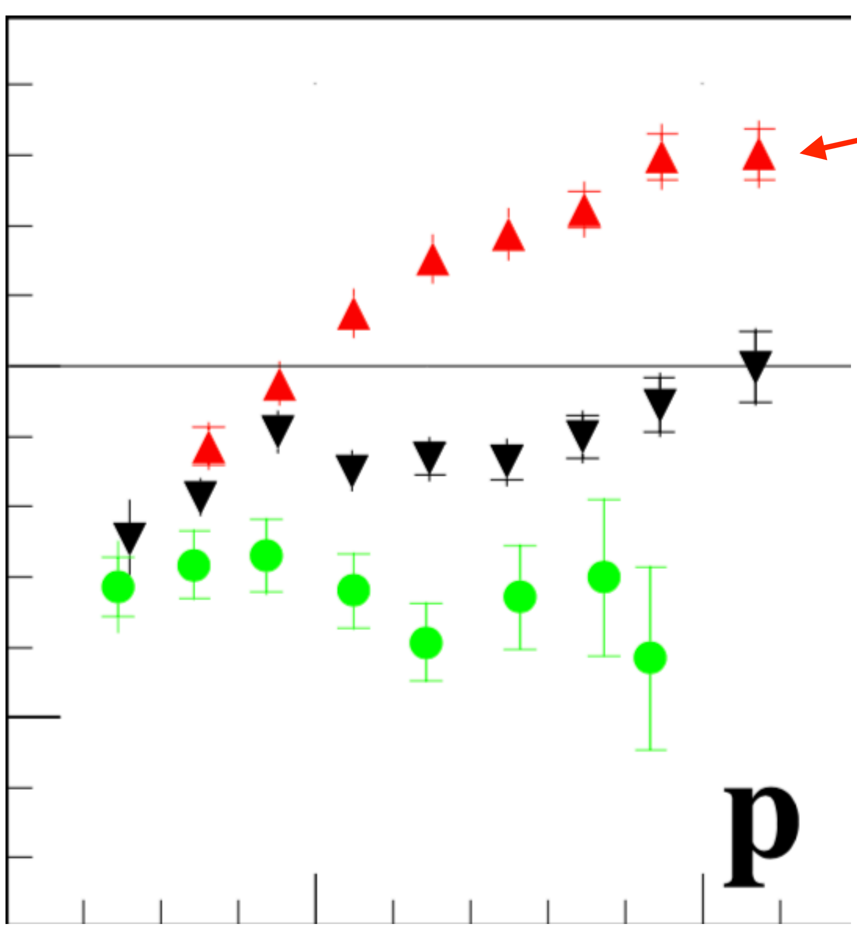
Time dilation is proportional to nu. Slow approach to 1.0 at infinite nu. Quark lifetime goes to zero at high z, so high z is attenuated more.

HERMES Proton Multiplicity Ratios

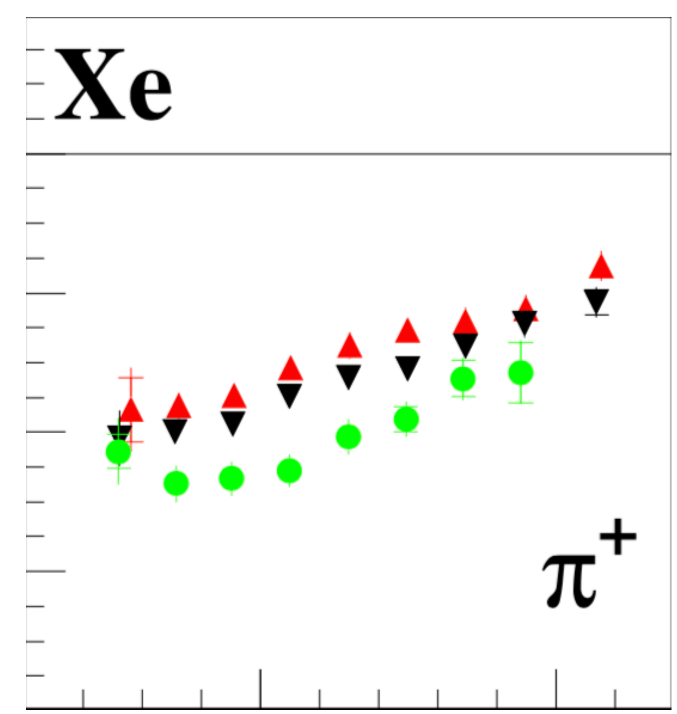


proton (left) and antiproton (right) are totally different

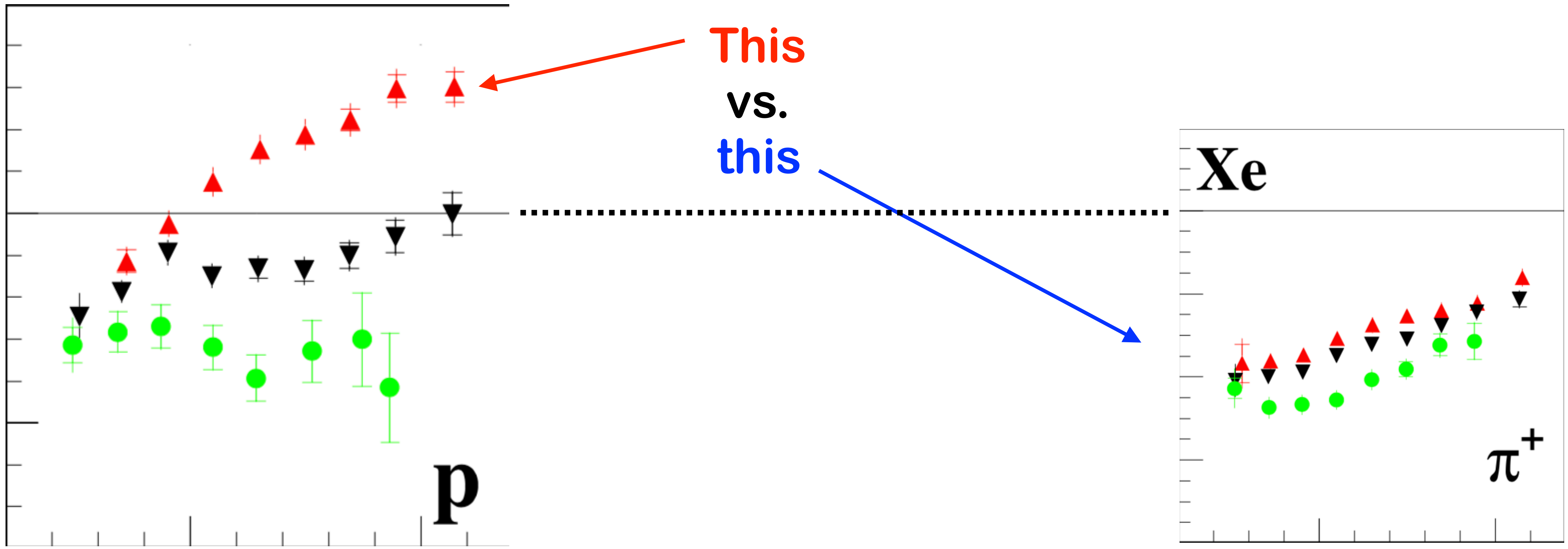
Proton multiplicity ratios qualitatively different from mesons.



This
vs.
this



I will argue that this behavior is due to diquarks



HERMES paper explanation: FSI are "knocking out protons."
Maybe. But, @ high W and Q^2, = virtual photon strikes one quark: need to make a pion in-medium to knock out a proton

But maybe it could be diquarks knocking them out. Diquark "size" must be similar to that of a proton (mass is similar to and larger than that of a proton).

= diquark color field much more extended in space

Test this hypothesis: CLAS preliminary nDIS data for Lambda Baryons

CLAS6 preliminary nDIS data for Lambda Baryons

Analysis Team from Mississippi State University:

Prof. Lamiaa El Fassi (Group Leader)

Dr. Latif-ul Kabir

Dr. Taya Chetry

Analysis Contributions from U. Técnica Fed. Santa María:

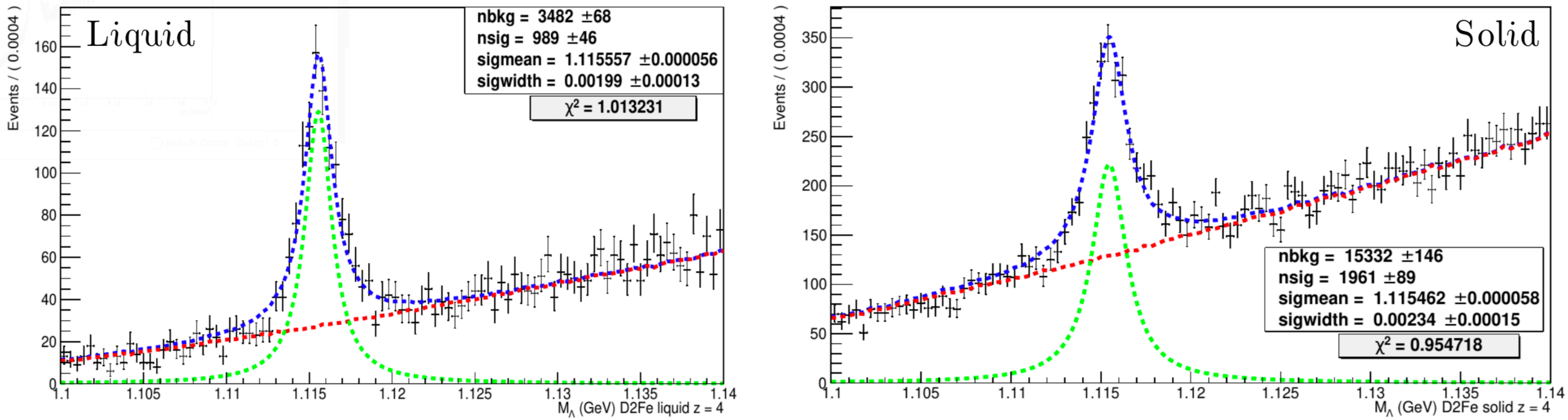
Dr. Ahmed El Alaoui

Some early work performed at ANL.

Uncorrected preliminary results released March 2019 by Nuclear Physics Working Group of CLAS Collaboration.

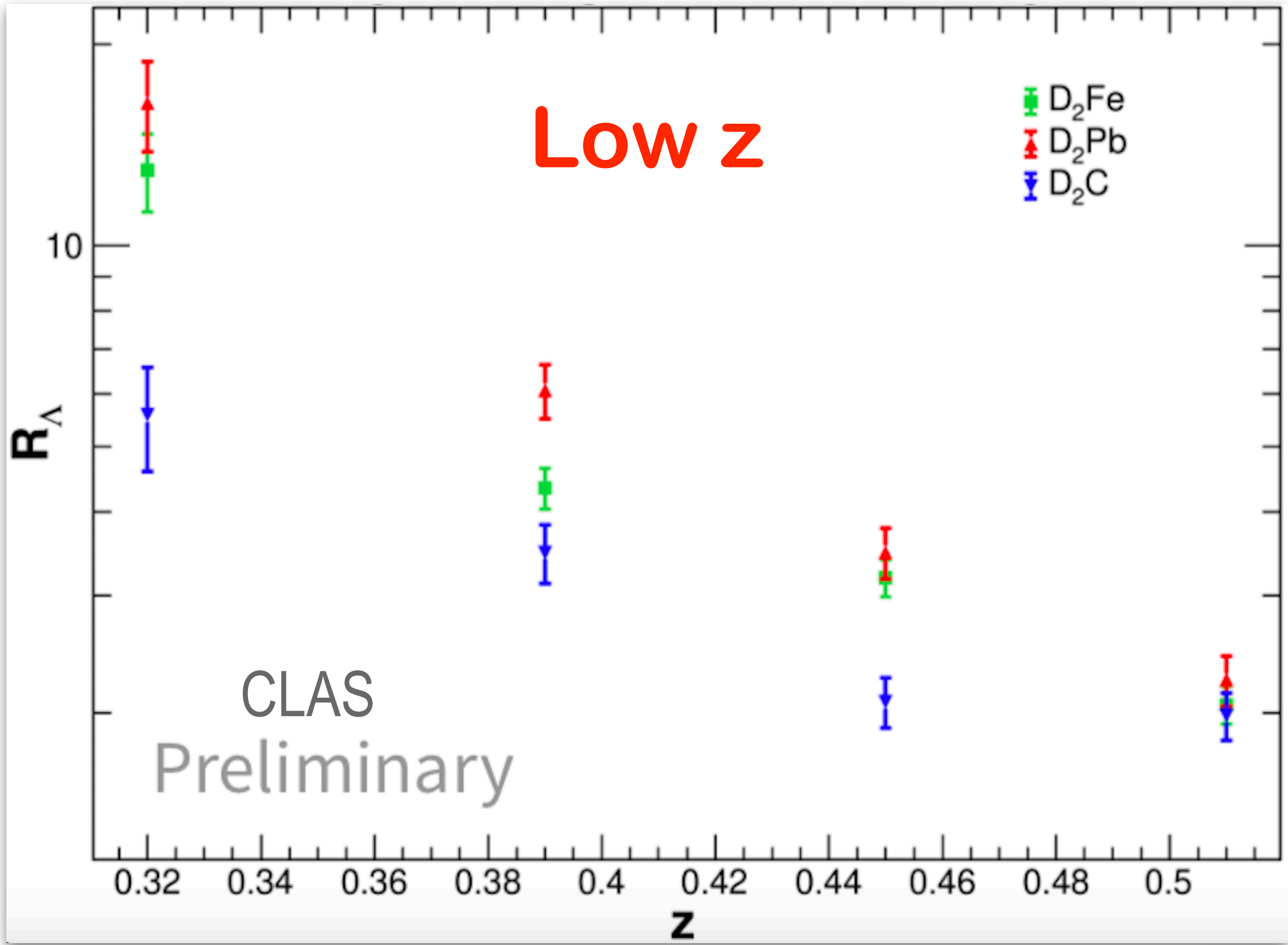
Lambda Baryons are well-identified in π^-p channel

$z = [0.48,\ 0.54)$



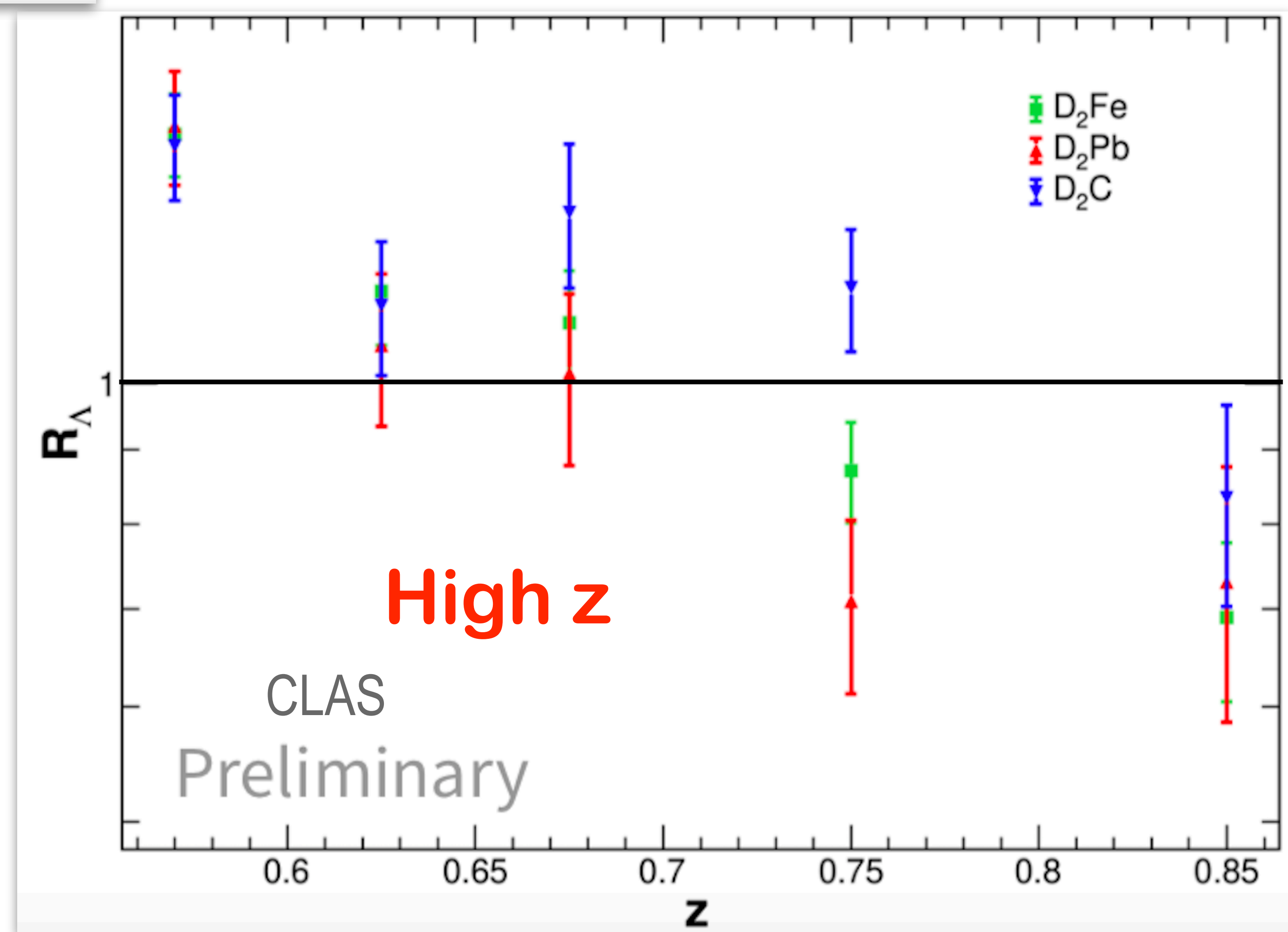
M_Λ M_Λ

Backgrounds are under control - three different extraction methods agree



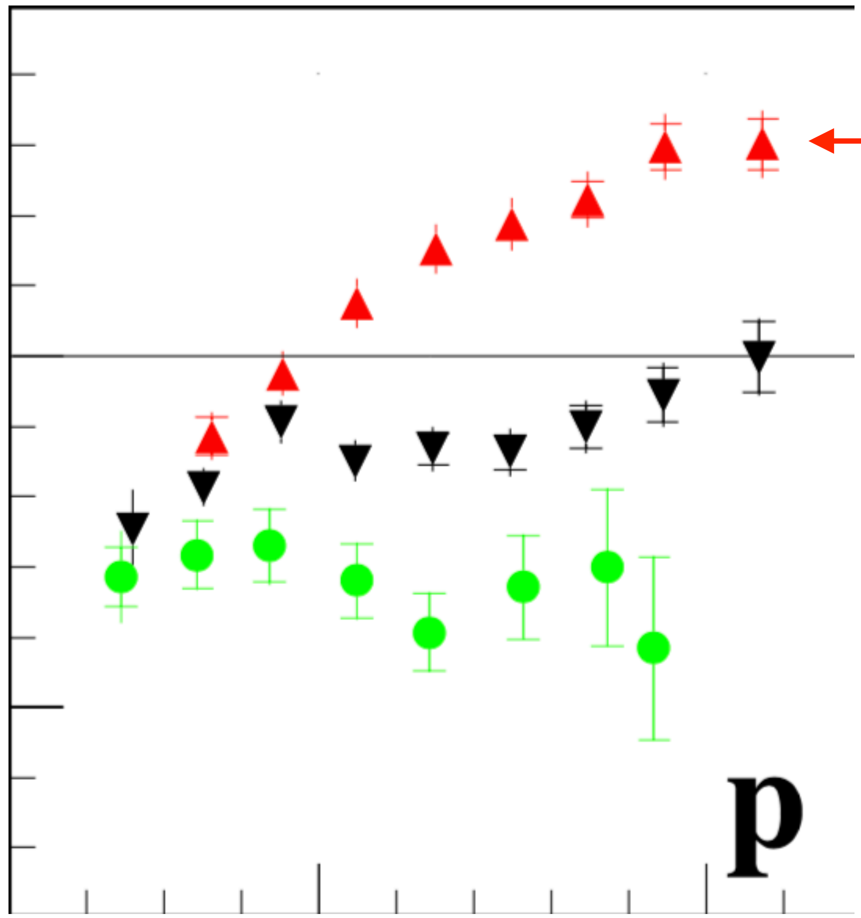
"Pile-up" of events at low z - <u>huge</u> effect compared to pion production

Order inverted as expected: heavy-to-light



At higher z, there is relatively little attenuation.

Order as expected: light-to-heavy



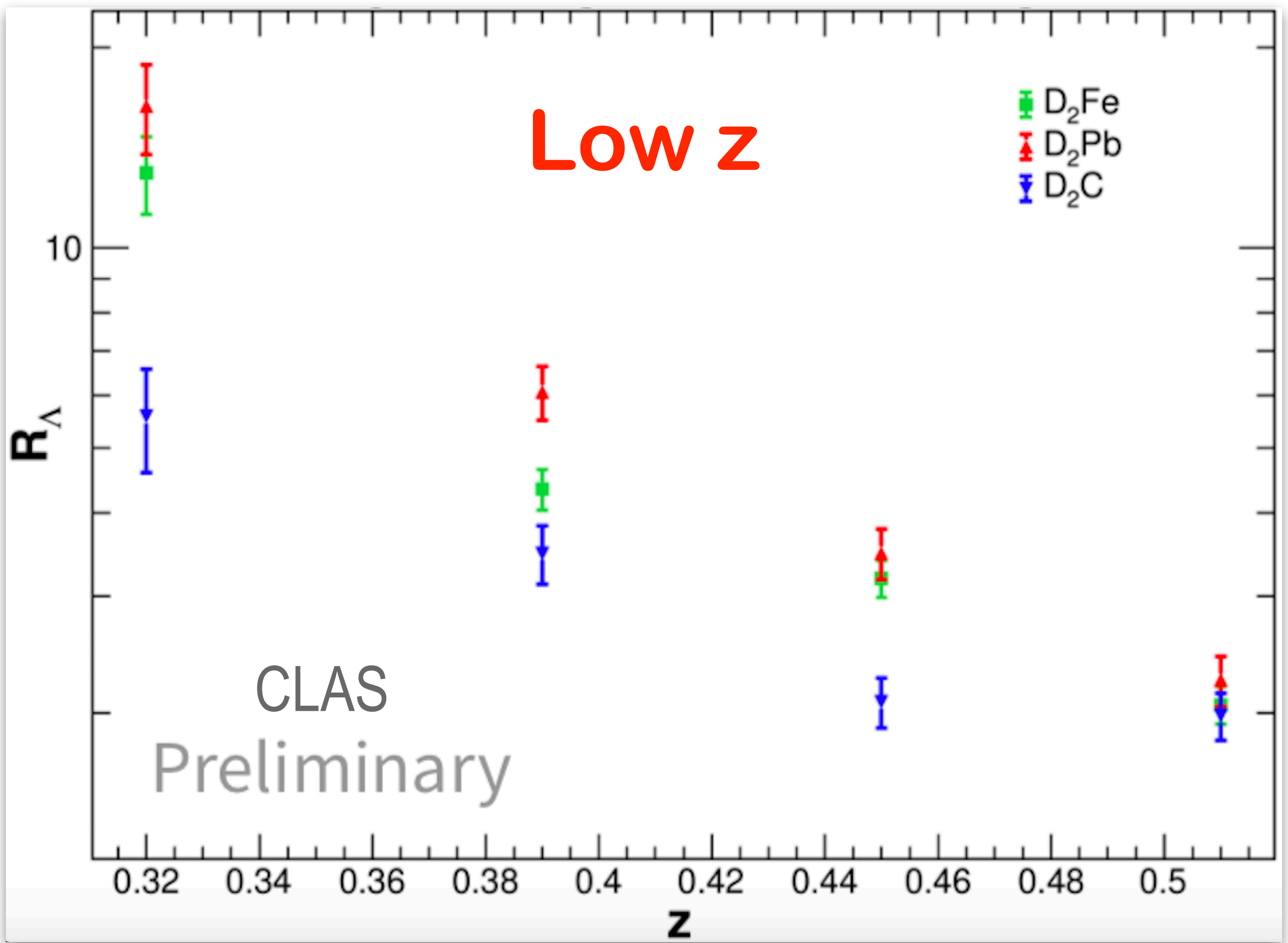
Excess of low-z protons in HERMES data

Explanation: FSI are "knocking out protons"??

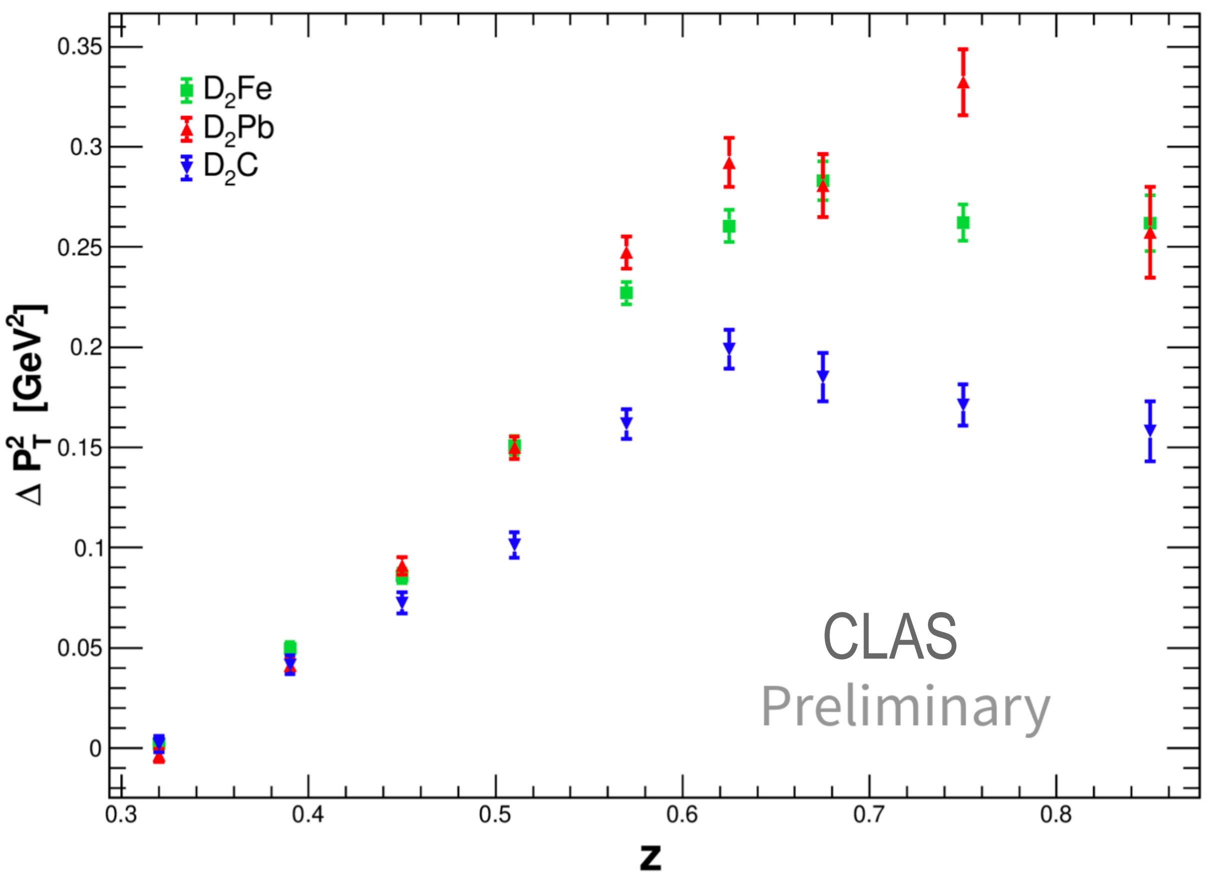
Excess of low-z Lambdas in CLAS data

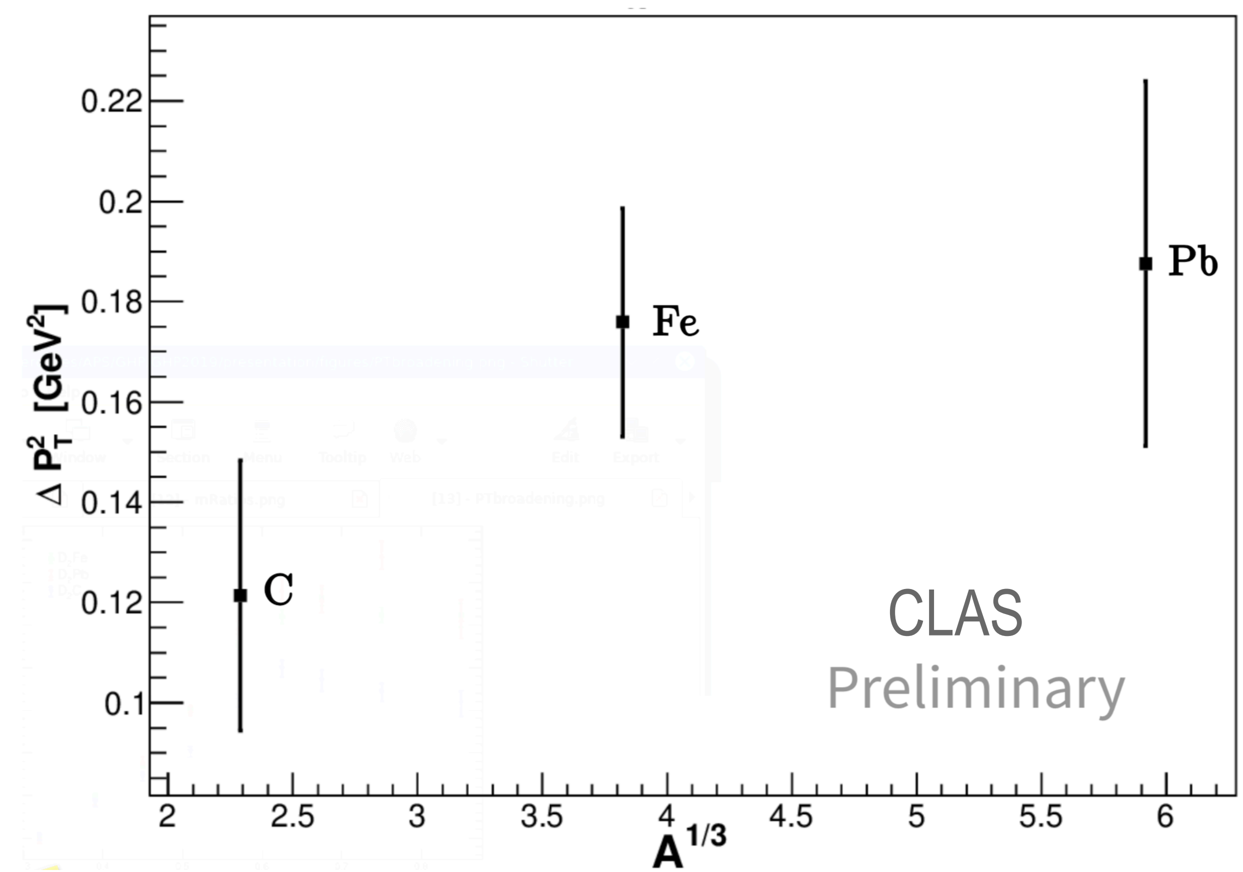
Not explained by FSI "knocking out Lambdas"!!

I have a better explanation



Transverse Momentum Broadening is Large





Maximum is 0.3 GeV²

Compare to maximum for pions of 0.03 GeV²!

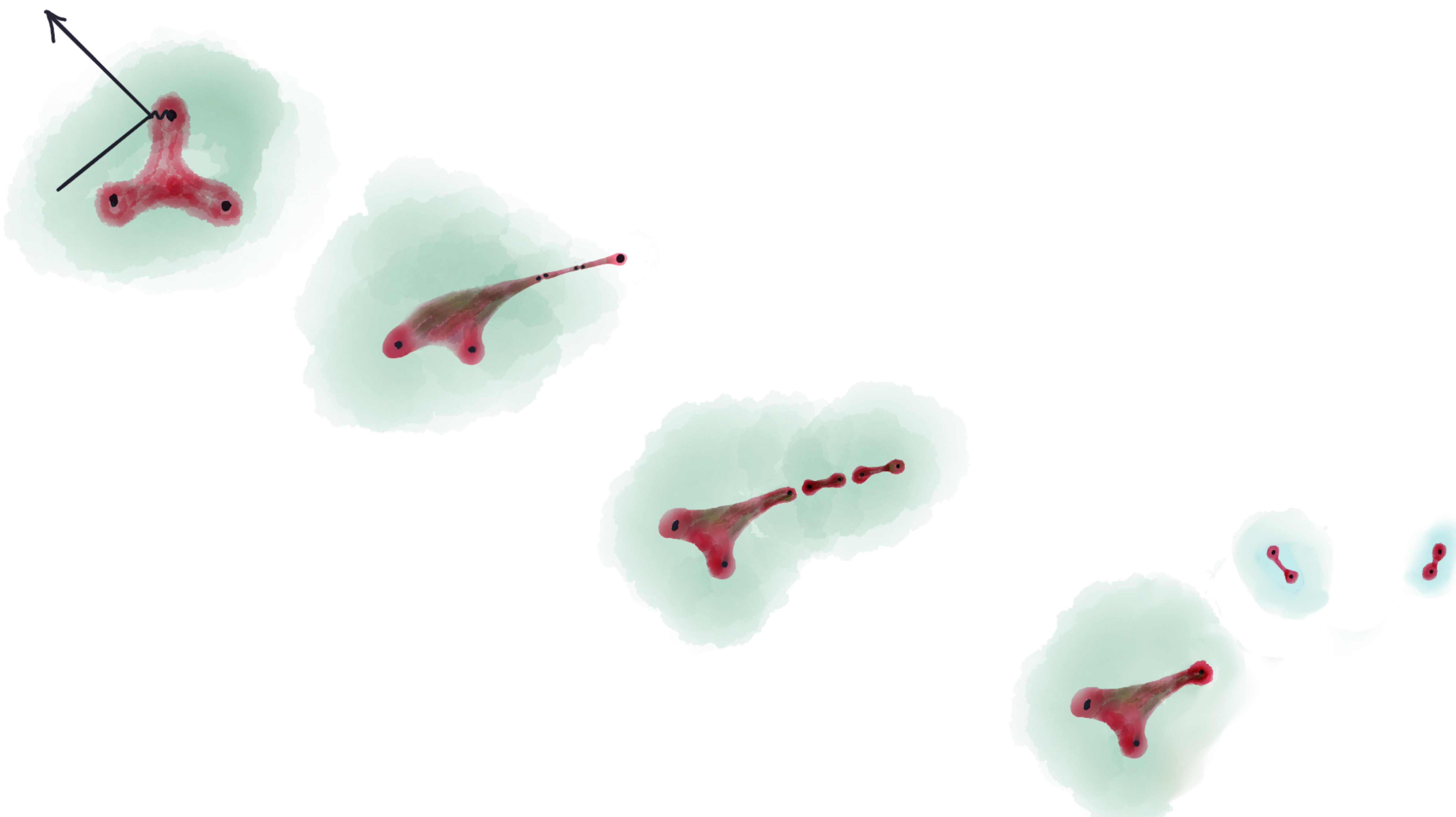
The object passing through the medium is disruptive!

E.g., it is "large" (has an extended color field).

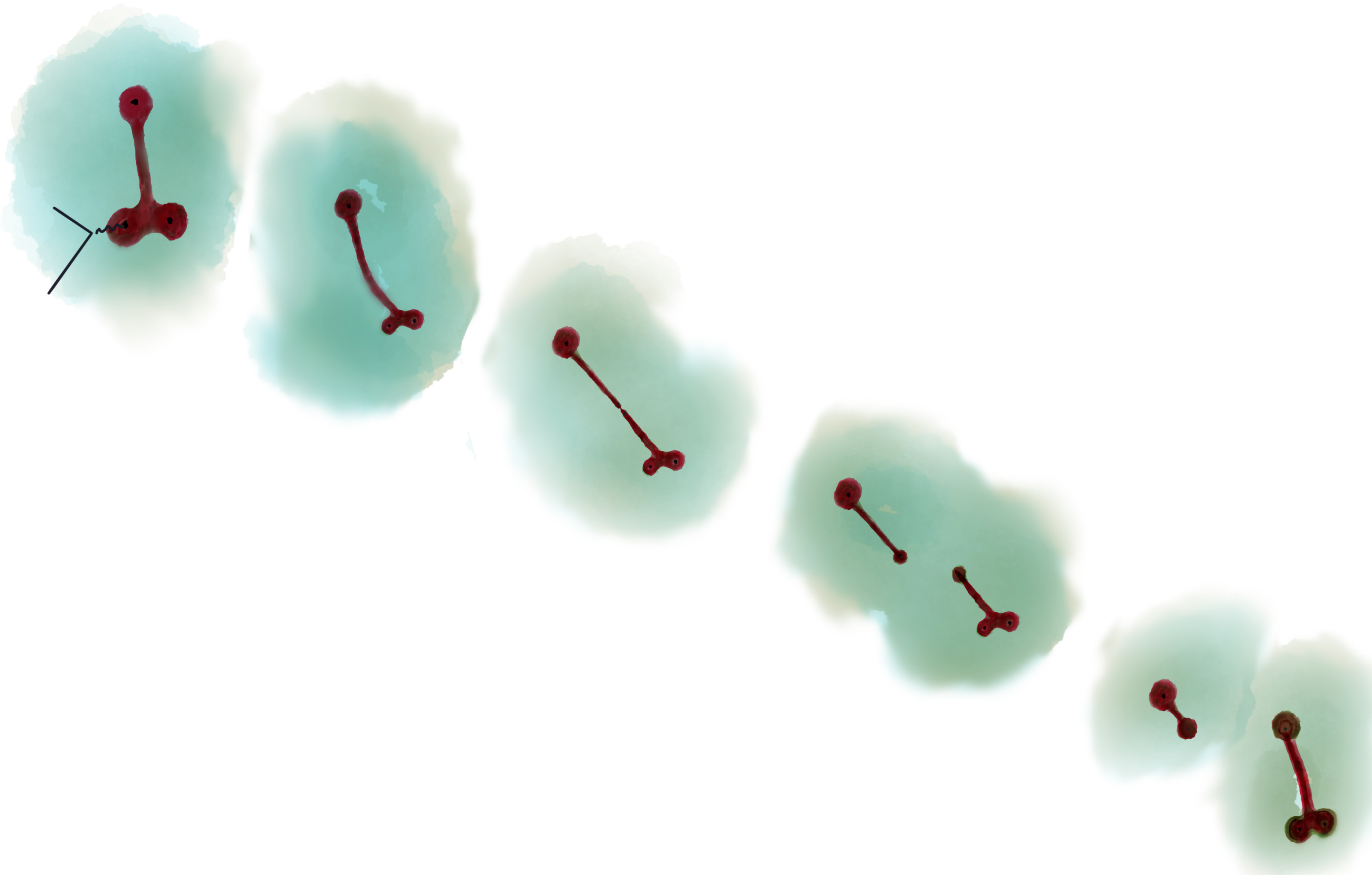
Could it be possible that the virtual photon is absorbed by a diquark?

Let's call this Direct Diquark Scattering (DDS)

Traditional Lund String Model picture of particle production from proton: Single Quark Scattering



Alternative Lund String Model picture of particle production from proton: Direct Diquark Scattering

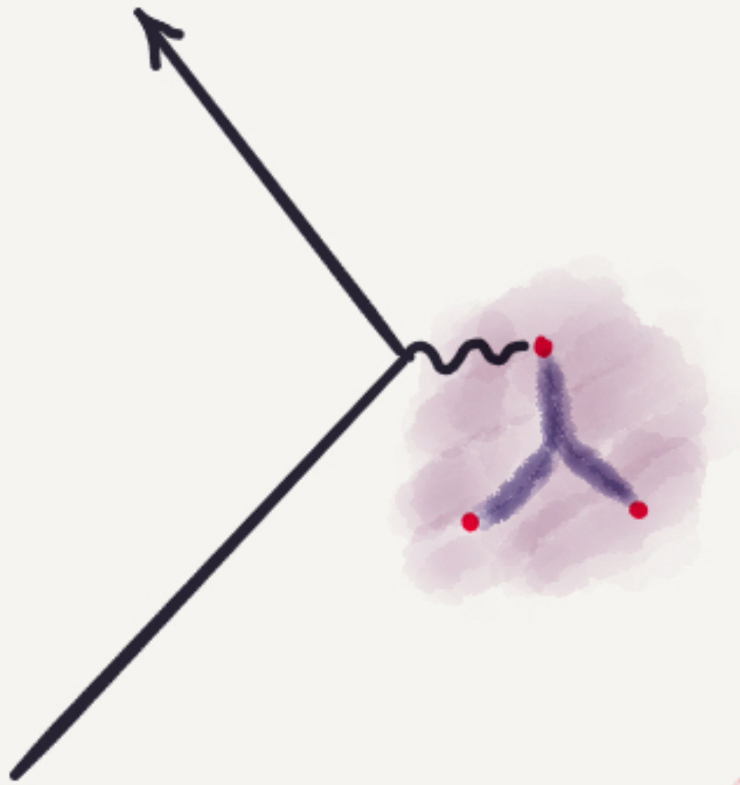


This DDS mechanism makes it a lot easier to form a proton. Making a proton in the Lund String Model is famously problematic.

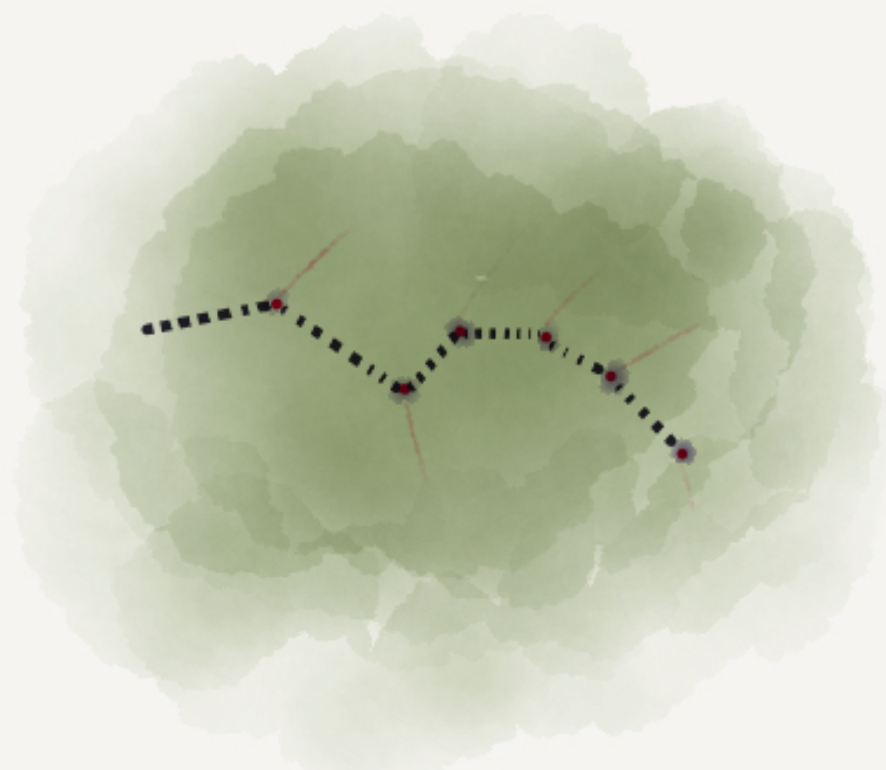
With nDIS baryon production, we will be able to gather a lot of evidence to test this idea.

Multiplicity ratio, pT broadening, and correlations between hadrons will provide the evidence.

The pT broadening by a single quark was seen to be at the level of 0.03 GeV^2 by HERMES: not much interaction with the nuclear medium.

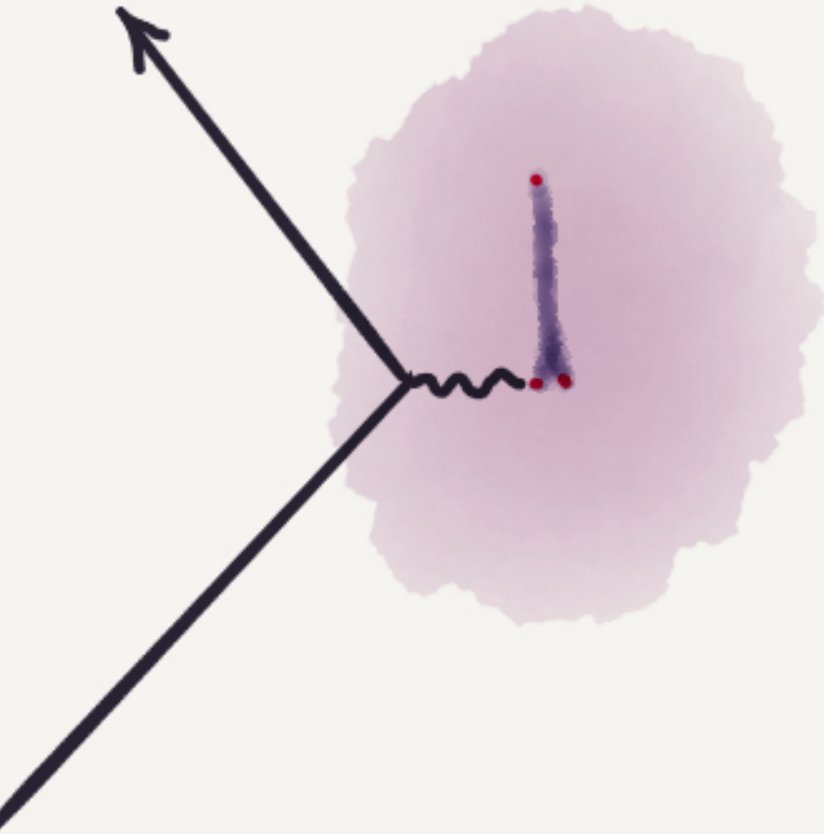


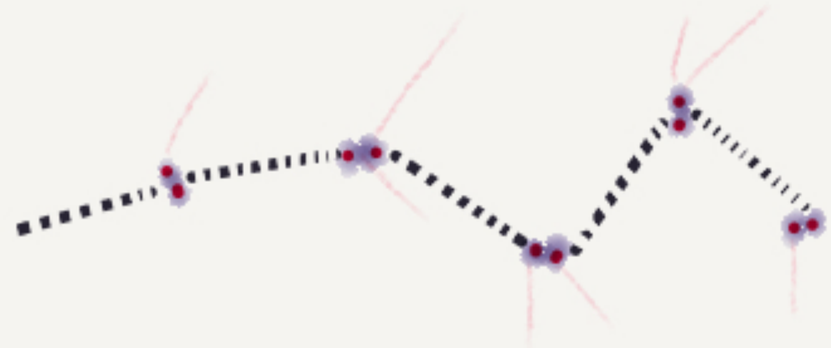
in vacuum



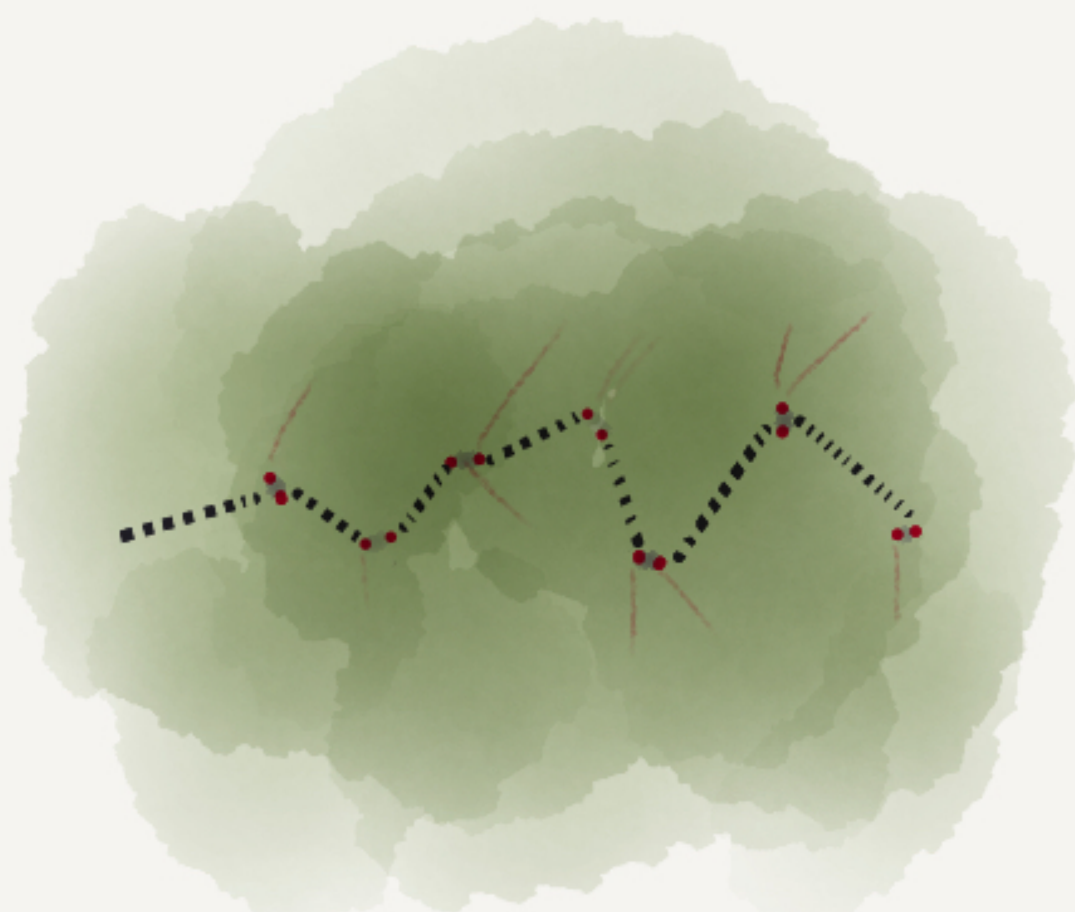
in medium

The pT broadening by a diquark might be much larger: CLAS lambdas showed up to 0.3 GeV².





in vacuum



in medium

Further tests of the Direct Diquark Scattering hypothesis with CLAS12 nDIS on baryons

Actively underway with existing 5 GeV data

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	$\overline{ud}$
Λ	79 mm	1.1	uds
$\Lambda(1520)$	13 fm	1.5	uds
Σ^+	24 mm	1.2	us
Σ^-	44 mm	1.2	ds
Σ^0	22 pm	1.2	uds
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

Baryon	$M^{e/l}$	M^{CI}	s^{r_1}	s^{r_2}	$a_1^{r_2}$	$a_2^{r_2}$	$a_1^{r_3}$	$a_2^{r_3}$	dom. corr.
p (B.5a)	0.94	0.94	0.89		−0.35	−0.14	0.25	0.098	$[ud]u$
Λ (B.5b)	1.12	1.06	0.67	0.59			−0.42	−0.16	$[ud]s$
Σ (B.5c)	1.19	1.20	0.87		−0.42	0.004	0.25	0.071	$[us]u$
Ξ (B.5d)	1.32	1.24	0.90		−0.29	−0.028	0.31	0.11	$[us]s$
Λ_c (B.5e)	2.29	2.50	0.21	0.86			−0.35	−0.32	$[uc]d - [dc]u$
Σ_c (B.5f)	2.45	2.53	0.48		−0.21	0.84	0.090	0.064	$\{uu\}c$
Ξ_c (B.5g)	2.47	2.66	0.22	0.84			−0.36	−0.34	$[uc]s - [sc]u$
Ξ_c' (B.5h)	2.58	2.68	0.50		−0.22	0.83	0.093	0.061	$\{us\}c$
Ω_c (B.5i)	2.70	2.83	0.51		−0.22	0.82	0.097	0.058	$\{ss\}c$

From Yin et al.

Baryon	$M^{e/l}$	M^{CI}	dom. corr.
p (B.5a)	0.94	0.94	$[ud]u$
Λ (B.5b)	1.12	1.06	$[ud]s$
Σ (B.5c)	1.19	1.20	$[us]u$
Ξ (B.5d)	1.32	1.24	$[us]s$
Λ_c (B.5e)	2.29	2.50	$[uc]d - [dc]u$
Σ_c (B.5f)	2.45	2.53	$\{uu\}c$? almost
Ξ_c (B.5g)	2.47	2.66	$[uc]s - [sc]u$
Ξ_c' (B.5h)	2.58	2.68	$\{us\}c$
Ω_c (B.5i)	2.70	2.83	$\{ss\}c$

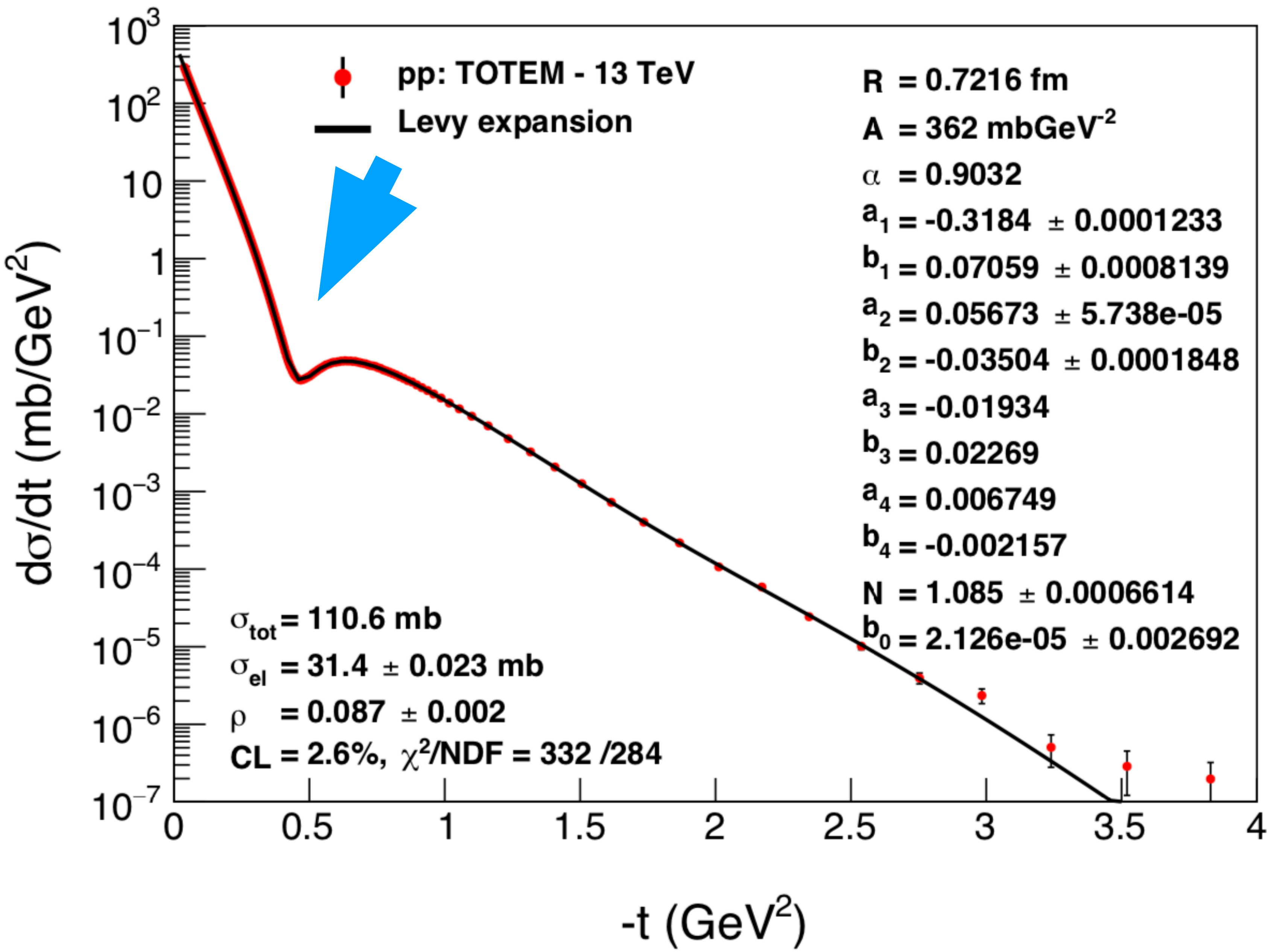
This suggests a specific behavior for DDS.

Only p, n, lambda can easily be formed by DDS.

Prediction: proton and lambda will behave similarly; the others will be different.

Diquarks have been invoked for hadron beam scattering

"Convergence properties of Lévy expansions: implications for Odderon and proton structure,"
T. Csörgő, R. Pasechnik, A. Ster,
https://arxiv.org/pdf/1903.08235



Having only one minimum implies there are only two internal substructures, such as quark-diquark.

https://arxiv.org/abs/1903.08235
https://arxiv.org/abs/1902.00109
https://arxiv.org/abs/1811.08913
https://arxiv.org/abs/1807.02897

Diquarks have been invoked for hadron beam scattering

To explain anomalies in proton production!

Breakstone et al. (following 2 slides) 1985 ISR data

http://cds.cern.ch/record/158001/files/198503162.pdf

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 85-30
5 March 1985

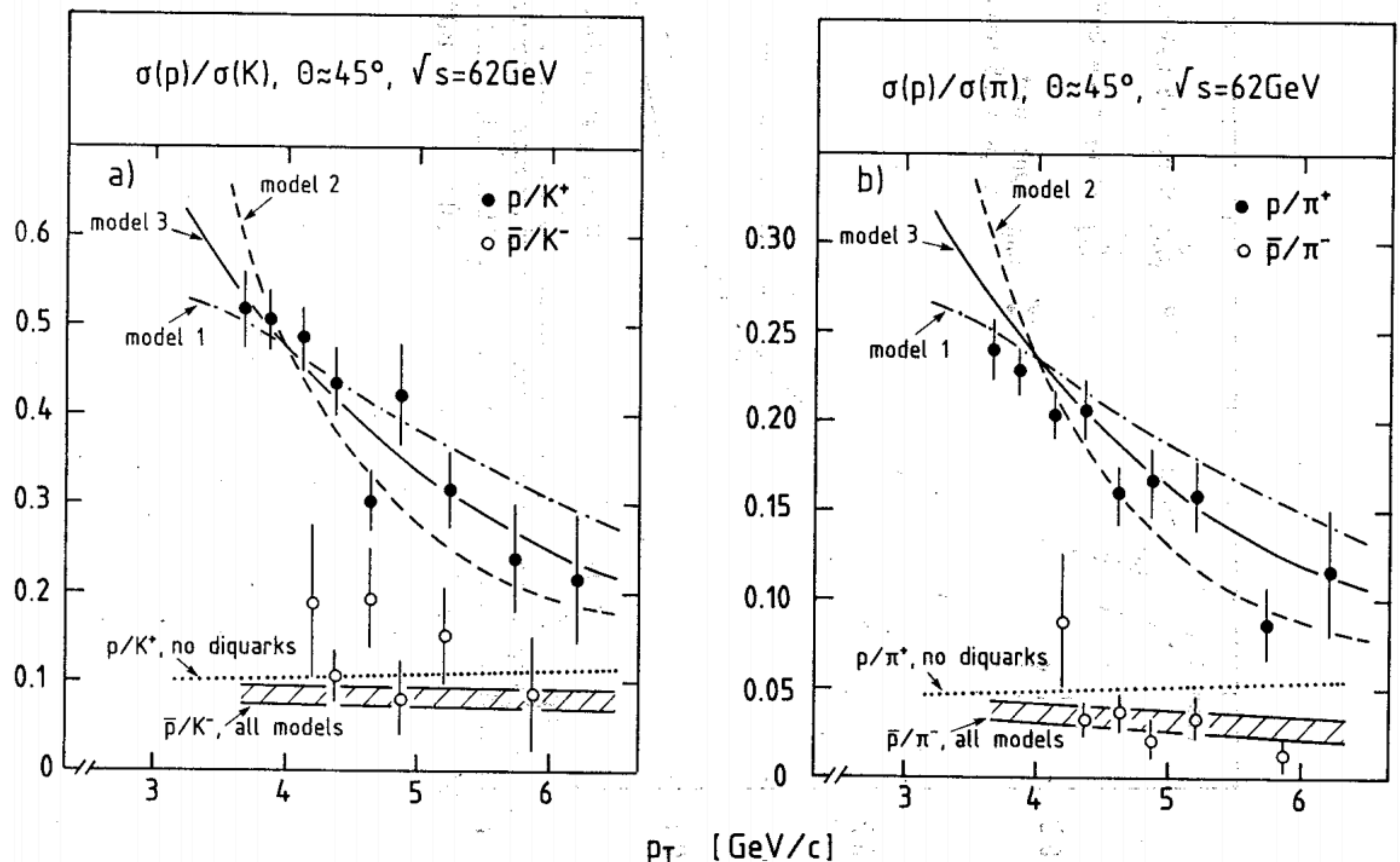
A DIQUARK SCATTERING MODEL FOR HIGH p_T PROTON PRODUCTION IN pp COLLISIONS AT THE ISR

Ames-Bologna-CERN-Dortmund-Heidelberg-Warsaw Collaboration

A. Breakstone[1(+)], H.B. Crawley[1], G.M. Dallavalle[5], K. Doroba[6], D. Drijard[3], F. Fabbri[3], A. Firestone[1], H.G. Fischer[3], H. Frehse[3(*)], W. Geist[3(**)], G. Giacomelli[2], R. Gokieli[6], M. Gorbics[1], P. Hanke[5], M. Heiden[3(**)], W. Herr[5], E.E. Kluge[5], J.W. Lamsa[1], T. Lohse[4], R. Mankel[4], W.T. Meyer[1], T. Nakada[5(***)], M. Panter[3], A. Putzer[5], K. Rauschnabel[4], B. Rensch[5], F. Rimondi[2], M. Schmelling[4], G. Siroli[2], R. Sosnowski[6], M. Szczekowski[3], O. Ullaland[3] and D. Wegener[4]

Breakstone et al.

http://cds.cern.ch/record/158001/files/198503162.pdf



Breakstone et al.

http://cds.cern.ch/record/158001/files/198503162.pdf

Fig. 1

Conclusions

- A very simple model is able to successfully describe meson production in nDIS. In contrast, baryon data from HERMES and CLAS behave qualitatively differently from mesons.
- The hypothesis is that Direct Diquark Scattering may be the main mechanism for formation of protons and lambdas. Scattering on nuclei yields new insights.
- More theoretical work is needed to determine the feasibility and plausibility of this interpretation.
- The planned and approved CLAS12 Color Propagation program is ideal for testing these ideas: access to production of nine long-lived baryons.

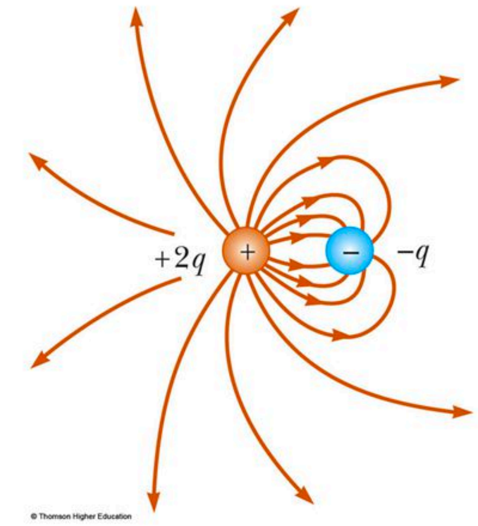
Possible objections to the Direct Diquark Scattering hypothesis

- What about "slingshot" mechanism?
    - Hard to reach high z with that. We clearly see large pT broadening up to high z.

Evidence supporting the Direct Diquark Scattering hypothesis

- **pT broadening of the Lambda is huge compared to that of any meson.**

Problem: how to hit a diquark?



- Scattering off an electric dipole field?
  - The ud system in close proximity presents an asymmetric electric dipole
  - This would leave the u and d without a large momentum imbalance
  - Clearly possible in classical picture; not sure how it translates to quantum picture
- Scattering off one quark in close proximity to another quark
  - Followed by gluon exchanges to keep momentum balance from getting too large
  - Smaller phase space, like LHC MPI's.

Alternative hypotheses

- Quark recombination
  - Accepted as a mechanism needed to explain aspects of heavy ion collisions, such as J/psi production at low pT.
  - Can explain excess hadron production, in principle.
  - Detailed calculations are needed to see if it can work for lambda, proton, etc.
  - A key feature of producing recombination is elevated temperatures + deconfined system. Unlikely for nDIS.
- Instant proton/lambda formation
  - Might help to explain proton results, but not excess of Λ.