Light flavor suppression in DIS and recent CLAS results

From HERMES to CLAS to the EIC

Will Brooks and collaborators, 5 November 2020

Outline

- Introductory comments
- The HERMES data for hadronization in nuclei
- The controversy over interpretation of HERMES data
- Model ingredients: nuclear geometry, and deterministic vs. stochastic color length
- The Brooks-López model applied to HERMES data
- Recent CLAS results on light-quark hadron production in nuclei, and future plans
- Conclusions

QCD and Hadronization

Hadronization is the process that generates new gravitational mass from energetic quarks and gluons.

It is a fundamental process contained in the QCD Lagrangian that enforces color confinement in dynamical interactions.

In the past:

Theory - too difficult to pose, let alone solve → Effective models.

Experiment - multiplicities, hadron ratios (K/π). No microscopic information available. No significant advances for decades in cold matter studies.

Now:

Experiment - Microscopic interactions inside nuclear medium provide access to mechanisms and timescales of the fundamental processes involved.

Theory - the recent data are stimulating new phenomenology efforts. New ideas are emerging and being tested and refined.

HERMES data for nuclear hadronization

The first data for nuclear hadronization *with identified hadrons* came from the HERMES experiment.

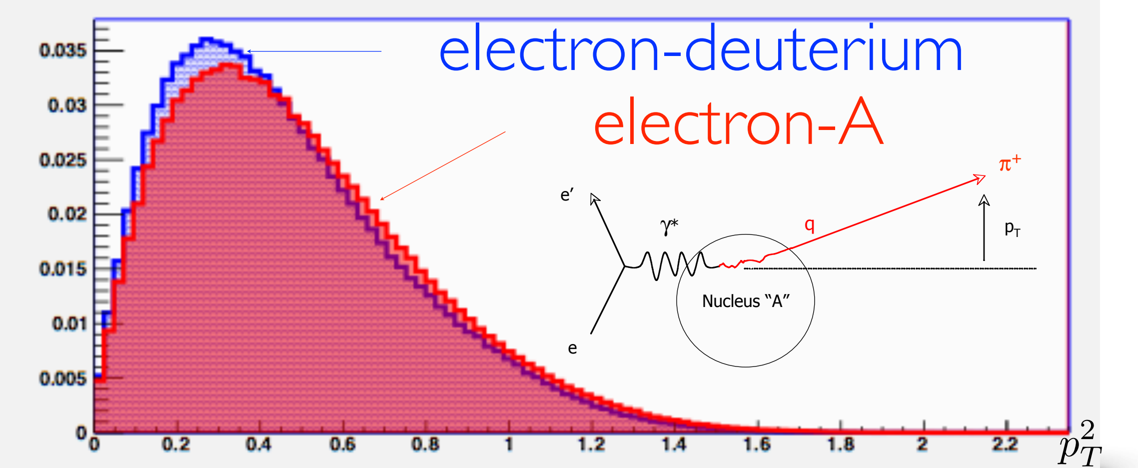
- Multidimensional Study of Hadronization in Nuclei, A. Airapetian et al., Eur. Phys. J. A 47 (**2011**) 113 https://arxiv.org/abs/1107.3496
- Transverse momentum broadening of hadrons produced in semi-inclusive deep-inelastic scattering on nuclei, A. Airapetian et al., Phys. Lett. B 684 (**2010**) 114-118 https://arxiv.org/abs/0906.2478
- Hadronization in semi-inclusive deep inelastic scattering on nuclei, A. Airapetian et al., Nucl. Phys. B 780 (**2007**) 1-27 https://arxiv.org/abs/0704.3270
- Double-hadron Leptoproduction in the Nuclear Medium, Airapetian et al., Phys. Rev. Lett. 96 (**2006**) 162301, 5pp. https://arxiv.org/abs/hep-ex/0510030
- Quark Fragmentation to $\pi^{+/-}$, π^0, $K^{+/-}$, p and $\bar{p}$ in the Nuclear Environment, A. Airapetian et al., Phys. Lett. B 577 (**2003**) 37-46, https://arxiv.org/abs/hep-ex/0307023
- Hadron Formation in Deep-Inelastic Positron Scattering in a Nuclear Environment, A. Airapetian et al, Eur. Phys. J. C 20 (**2001**) 479-486, https://arxiv.org/abs/hep-ex/0012049

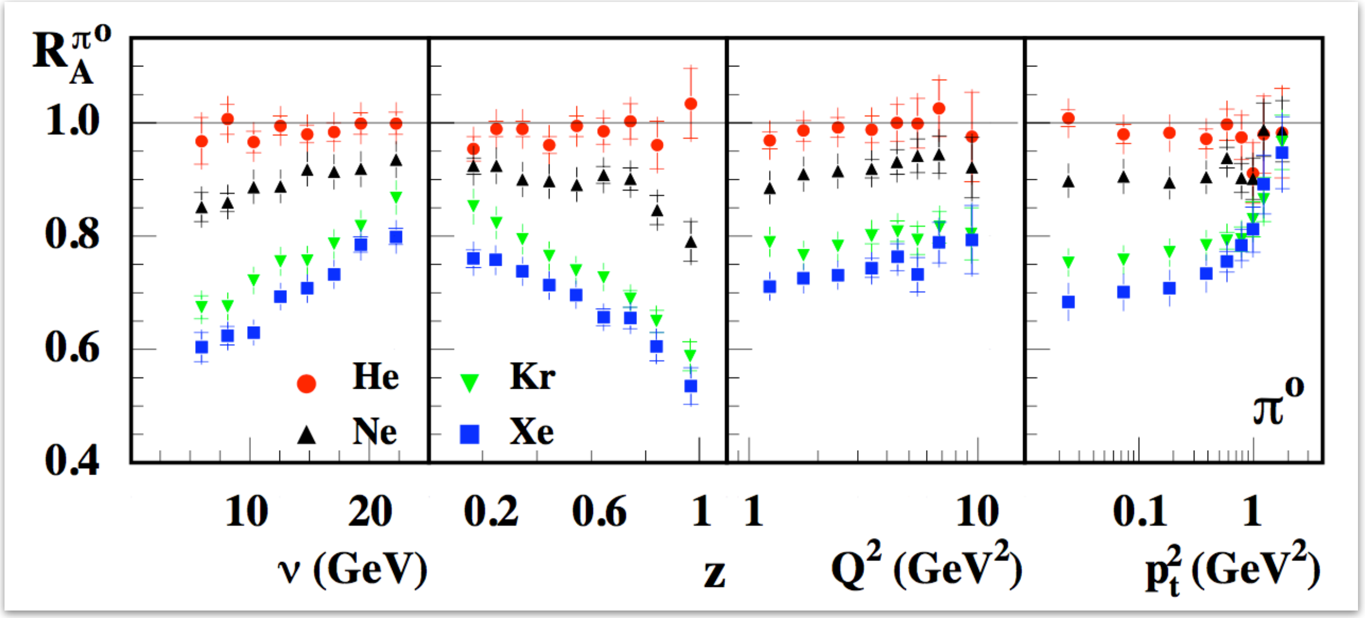
$$\Delta p_T^2(Q^2,\nu,z_h) \equiv \langle p_T^2(Q^2,\nu,z_h)\rangle|_A - \langle p_T^2(Q^2,\nu,z_h)\rangle|_D$$

Experimental Observables

Transverse momentum broadening

typical value <0.05 GeV^2





Hadronic multiplicity ratio (MR)

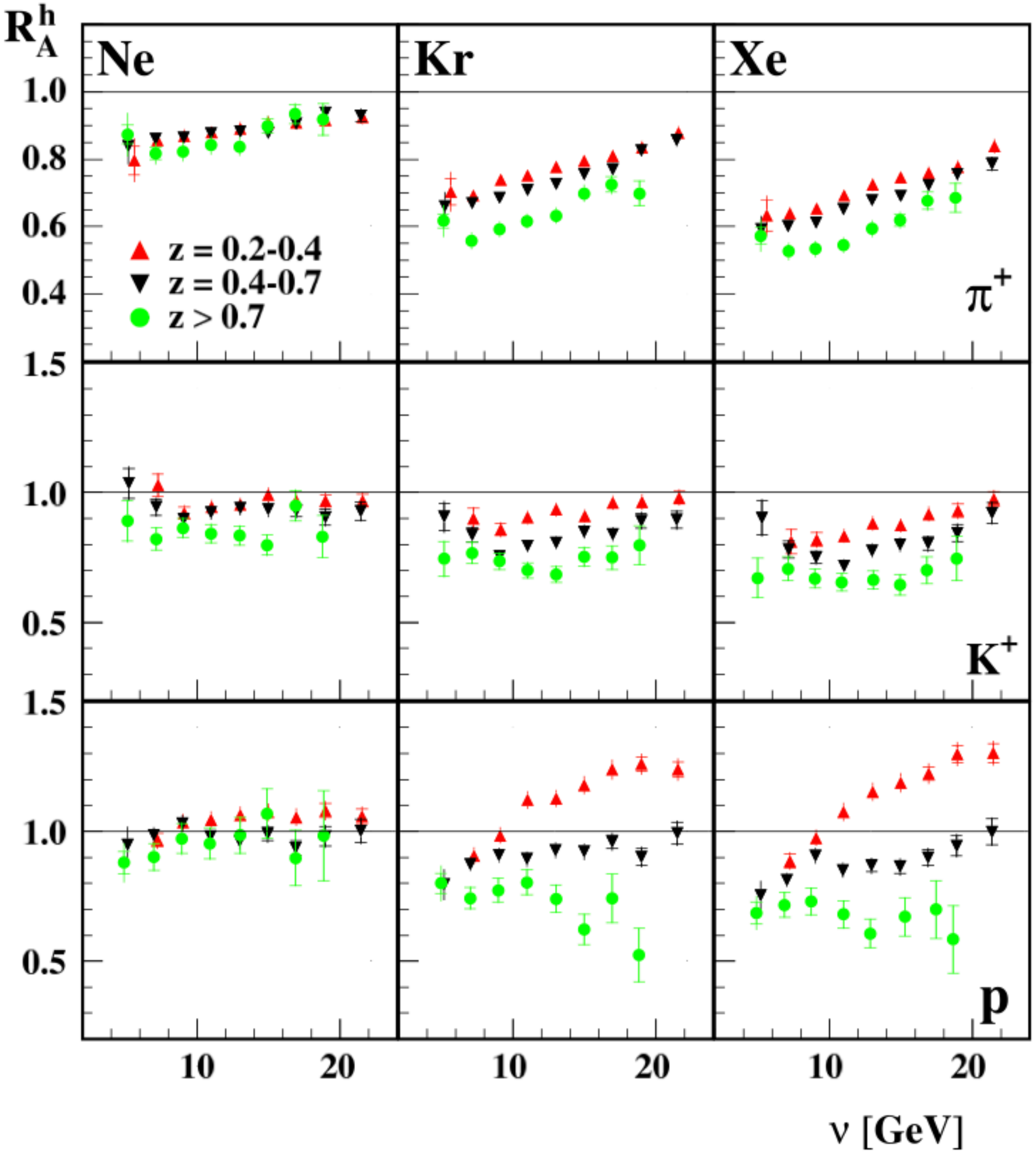
= 1 if no nuclear effects

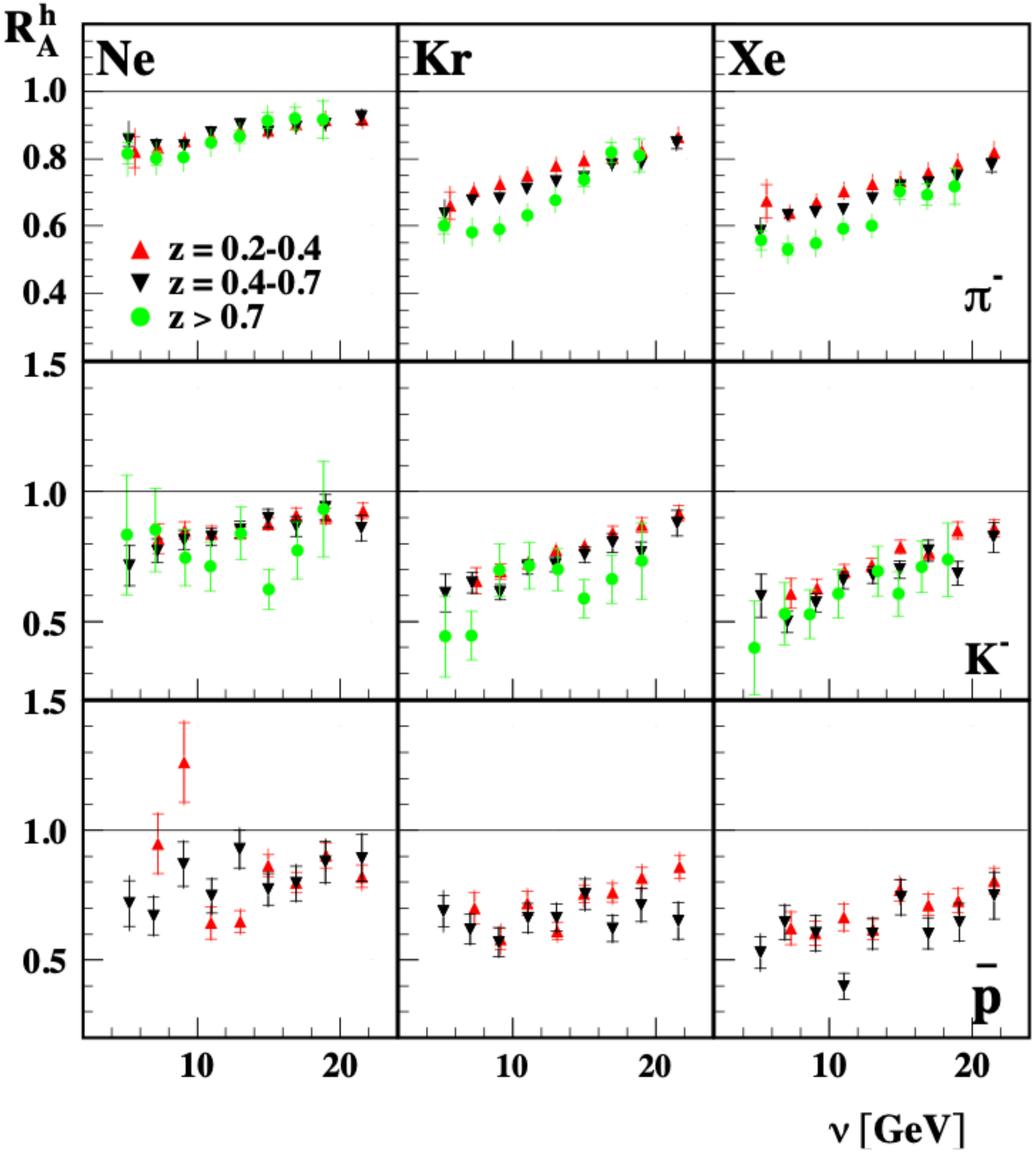
← **Neutral pion MR from HERMES**

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

Hermes 2-D multiplicity ratios, 6 hadrons

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





Hermes 2-D multiplicity ratios, 6 hadrons

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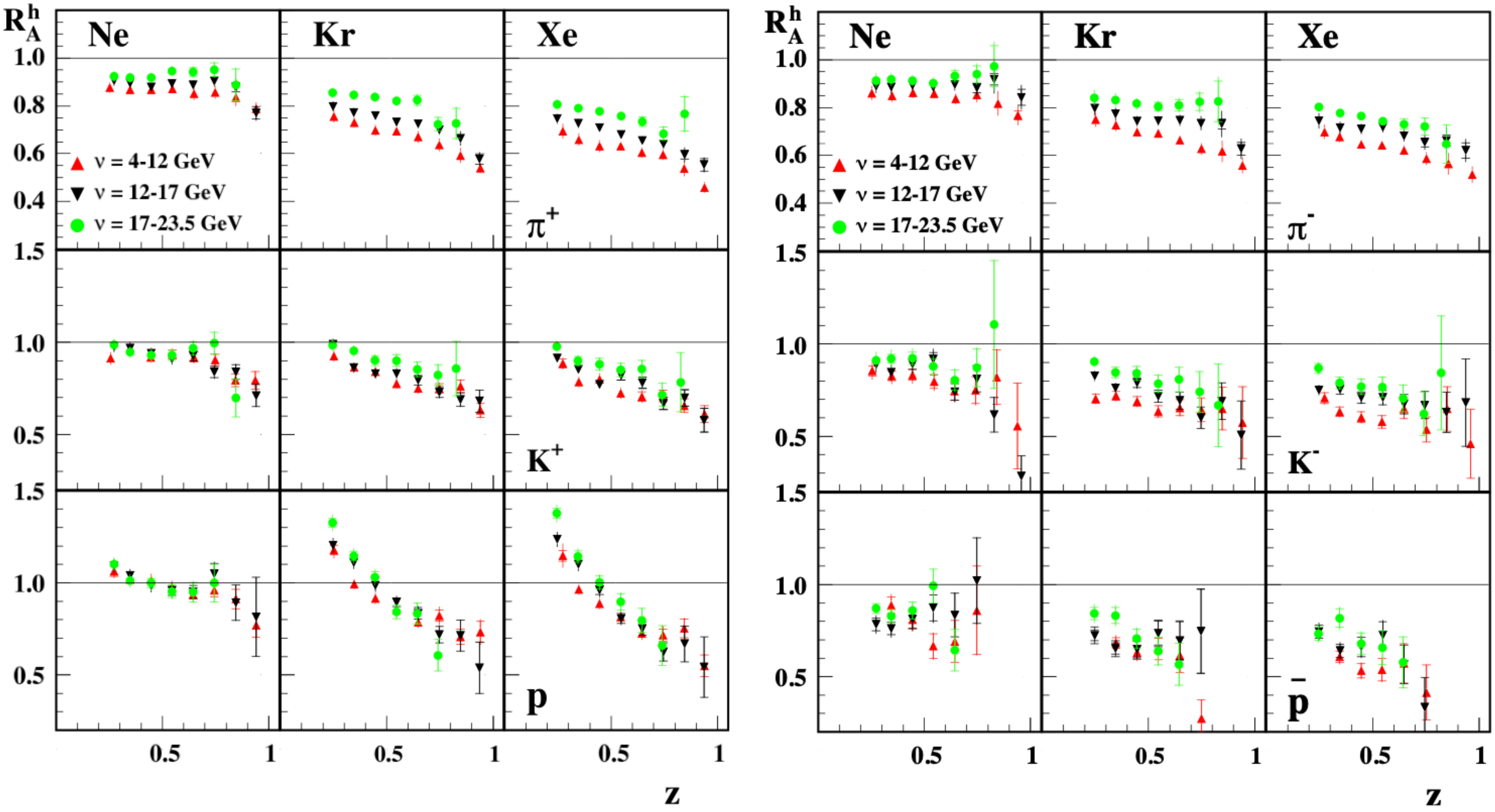
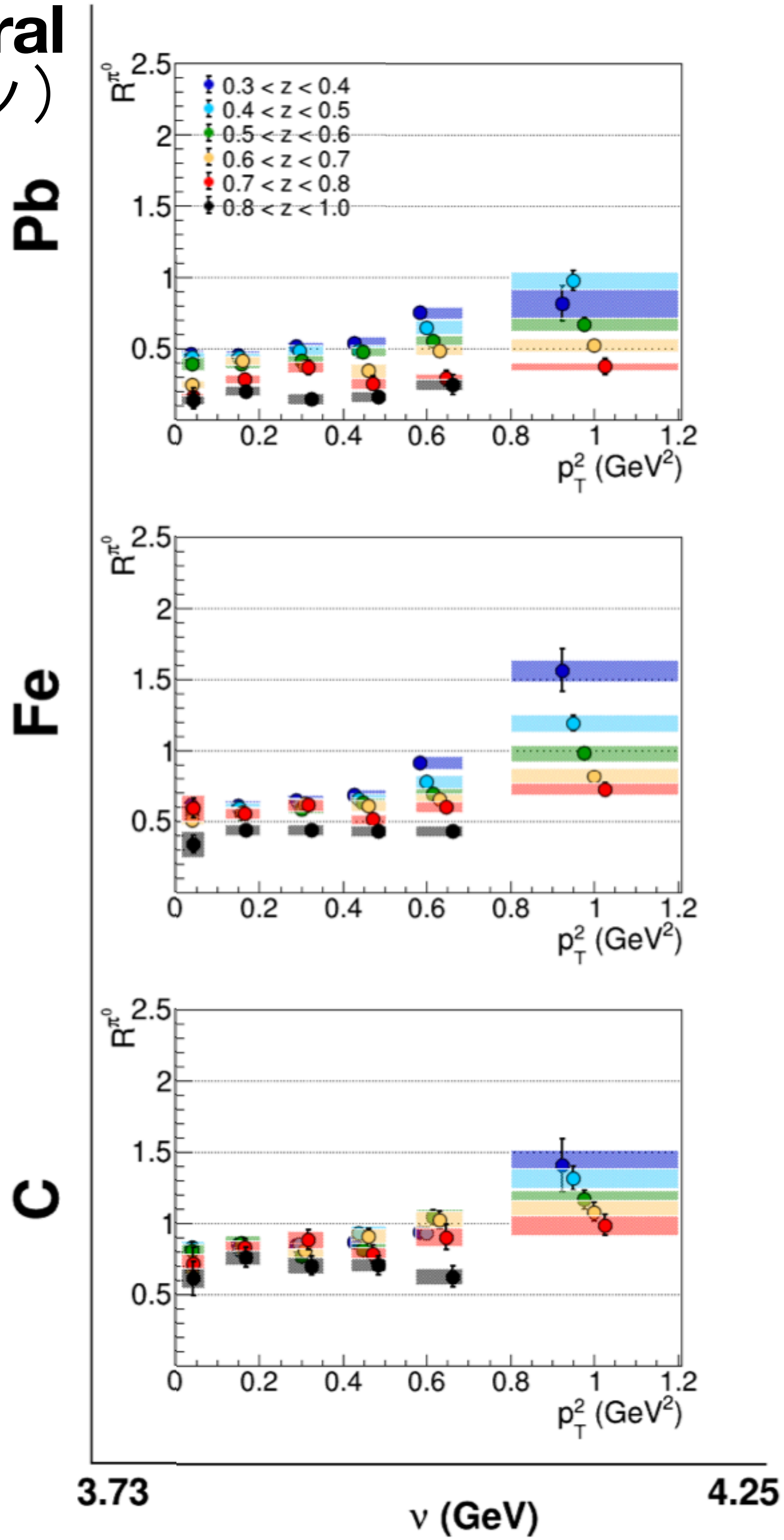
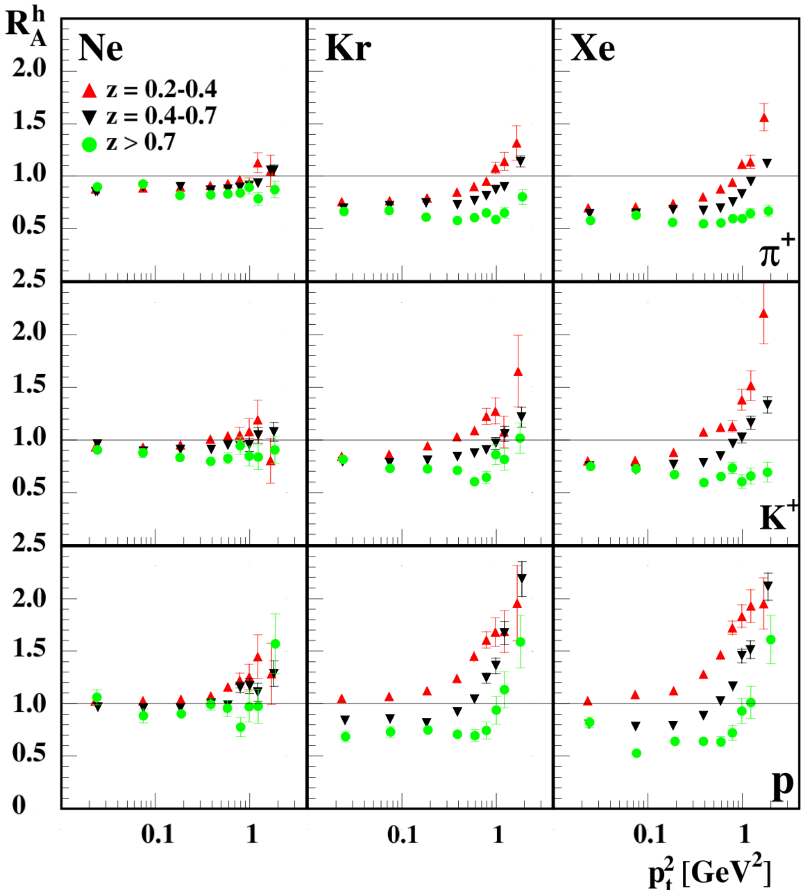


CLAS 3-D multiplicity ratios, neutral pions (one of three bins in ν)



We call it **hadron attenuation** but sometimes it's **hadron enhancement** such as the Cronin-type enhancement in p_T^2 and the behavior of the proton multiplicity ratio vs. z_h seen on previous page.

Hermes 2-D multiplicity ratios, 3 hadrons



The controversy over HERMES nuclear DIS data

What are the **primary causes** of hadron attenuation? Hadronic (inelastic hadron scattering) or partonic (partonic energy loss)?

Partonic-only: Accardi; Arleo & Peigne; Majumder; Wang + many different collaborators; Song & Liu et al.

Partonic+Hadronic: Kopeliovich and Guiot, Brooks and López

Hadronic-only: Mosel & Gallmeister

The controversy over HERMES nuclear DIS data

Origins: selected examples of key work influencing development of this topic.

Basics of pQCD (Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller, S. I. Troyan): Pocket formulas for **light-quark** and **heavy-quark total hadron formation times:**

$$t_q^{hadr} \approx E^2 R \qquad t_Q^{hadr} \approx \frac{E}{m_Q} R;$$

Jet Tomography of Hot and Cold Nuclear Matter

E. Wang, X-N Wang, https://arxiv.org/abs/hep-ph/02021050202105, Phys. Rev. Lett. **89**, 162301(2002). **330 citations**

“t_f^h is > 40 fm for HERMES pions”

WKB: this uses a r**ough order-of-magnitude** estimate to **answer the wrong question**. The question is not: how long does it take to form a pion in its entirety? The question should be: how long does it take a forming pion to develop an appreciable hadronic interaction cross section? I will show later that the answer in our model, and independently in the Lund String Model, is **2 fm-8 fm,** which is **inside the nucleus.**

Nuclear Hadronization: Within or Without?

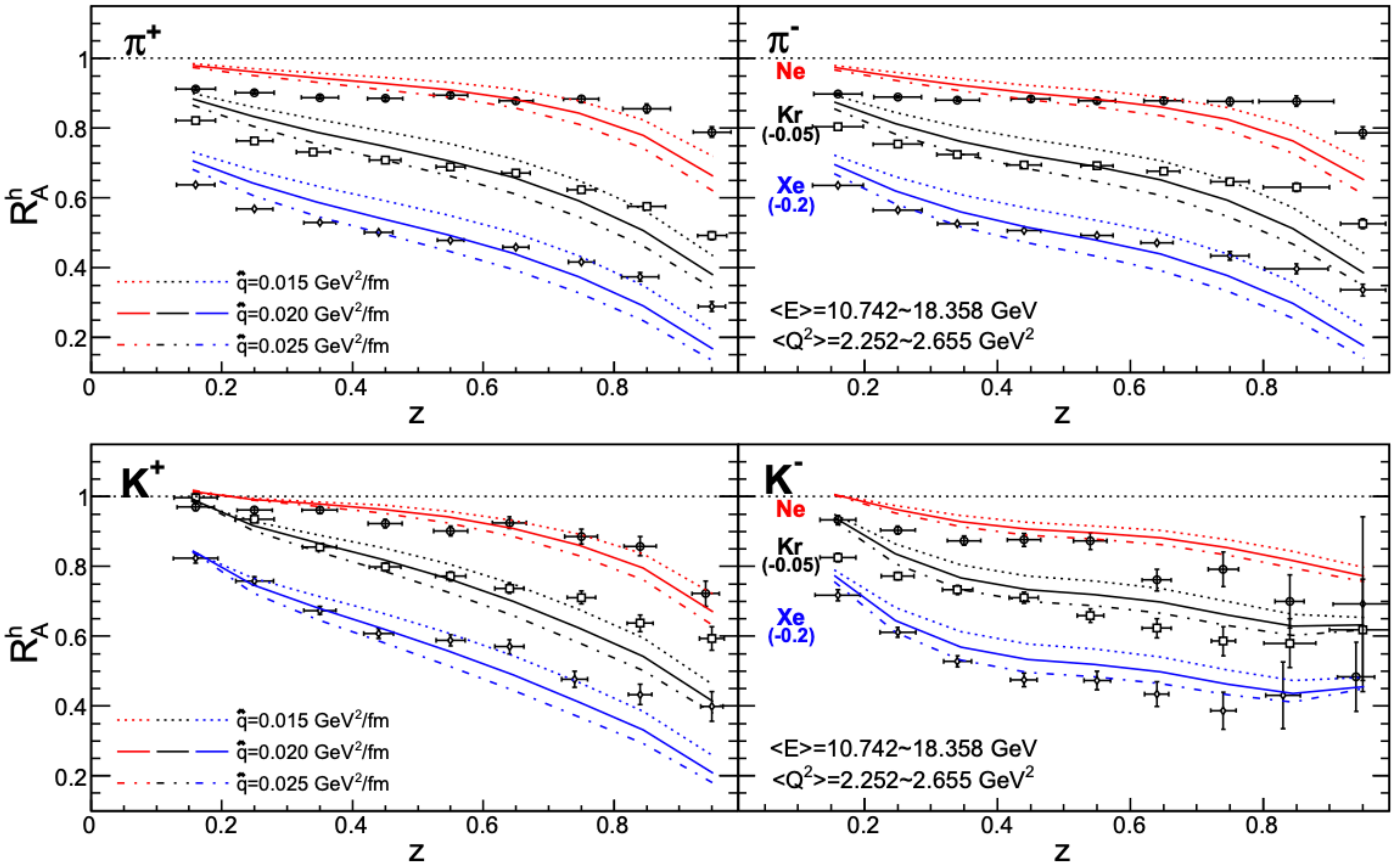
B.Z. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki, https://arxiv.org/abs/hep-ph/0311220, Nucl.Phys. A740 (2004) 211-245, **125 citations**

“main source of nuclear suppression of the hadron production rate is attenuation of colorless pre-hadrons in the medium”

WKB: this work found **10%** of HERMES hadron suppression due to quark energy loss, **90% due to prehadron attenuation.**

Takeaway: the HERMES nuclear DIS data cannot be described solely using partonic energy loss.

In fact, it can be described very well with no reference to partonic energy loss at all.

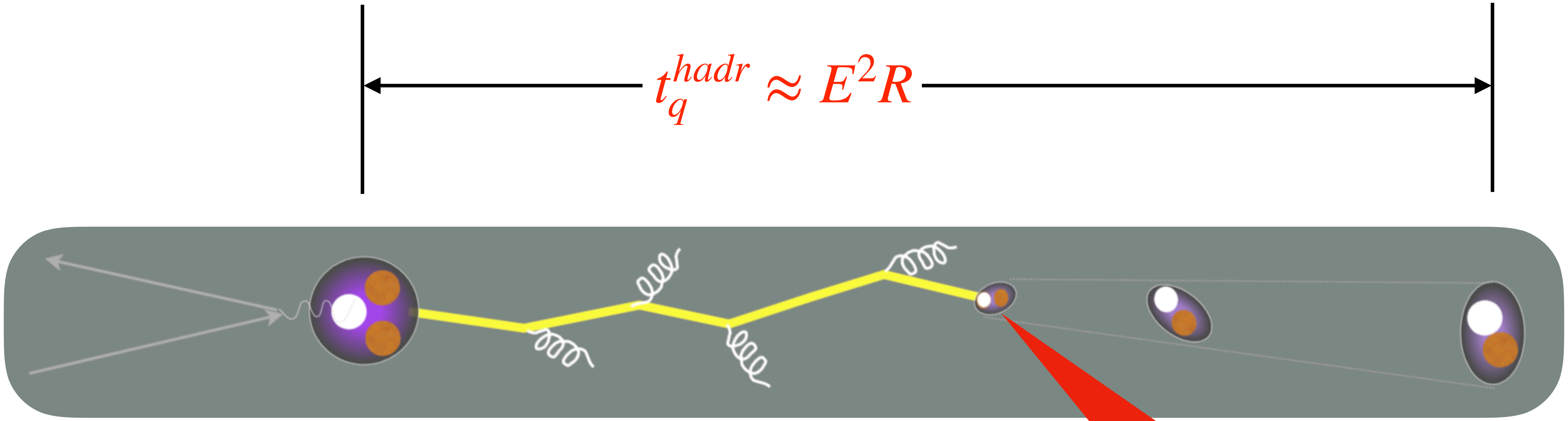


WKB: It is possible to reach the right order of magnitude with only parton energy loss, but not the correct functional form. A chi-squared/dof calculation illustrates this most clearly. This plot clearly demonstrates that something important is missing from the description. (cf. Bevington)

Ning-Bo Chang, Wei-Tian Deng, and Xin-Nian Wang Phys. Rev. C **89**, 034911, https://arxiv.org/pdf/1401.5109.pdf

You may say, “what about the pocket formulas? are you saying they’re wrong?”

WKB: We are not saying they’re wrong. They apply to the overall process *by construction*, not to the part of the process that matters. At high z_h the struck quark becomes a new hadron immediately, including inside the nucleus, and so it automatically interacts hadronically inside the nucleus.



$t_q^{hadr} \approx E^2 R$

This length **shrinks to zero** at high z_h *by energy conservation*

Hadronic interactions within the nucleus begin at this point

Nuclear Geometry

Nuclear geometry effect and transport coefficient in semi-inclusive lepton-production of hadrons off nuclei

Na Liu, Wen-Dan Miao, Li-Hua Song, Chun-Gui Duan, https://arxiv.org/abs/1511.00767v1, Phys.Lett. B749 (2015) 88-93.

“It is necessary to consider the detailed nuclear geometry in studying the semi-inclusive hadron production in deep inelastic scattering on nuclear targets.”

WKB: We completely agree with this point. A detailed, realistic description of the nuclear density density distribution is mandatory for any quantitative description. We use the Blok and Lapikás density distribution in our calculations (A-dependence of hadronization in nuclei, Phys. Rev. C 73, 038201).

Deterministic or Stochastic Color Lifetime distribution?

Nuclear geometry effect and transport coefficient in semi-inclusive lepton-production of hadrons off nuclei

Na Liu, Wen-Dan Miao, Li-Hua Song, Chun-Gui Duan, https://arxiv.org/abs/1511.00767v1, Phys.Lett. B749 (2015) 88-93.

"…we set $t > 2R_A$ with the hadron formation time $t = z^{0.35}(1-z)\nu/\kappa$, which is defined as the time between the moment that the quark is struck by the virtual photon and the moment that the prehadron is formed. This assumption can make sure that the hadron is produced outside target nucleus rather than inside the nucleus. "

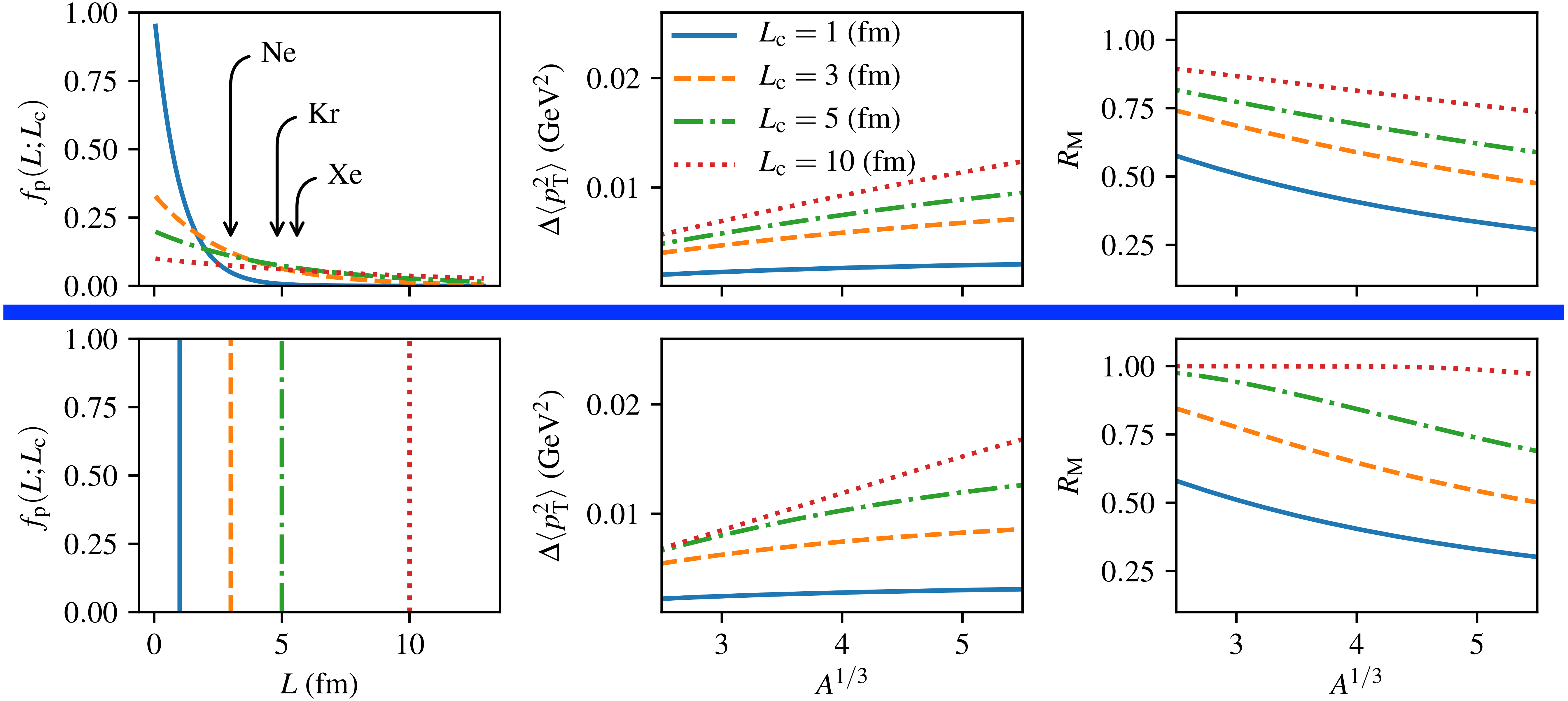
WKB: We call this a 'deterministic' or 'fixed' color lifetime, where t can be calculated for each and every event from ν and z_h. We feel that a stochastic color lifetime distribution is more physically realistic (see following slides). This choice has a measurable impact on the observables, and we argue it could be studied in future data.

“how does this confinement occur in the fast non-adiabatic process?”

Basics of pQCD (Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller, S. I. Troyan**)**

WKB: The stochastic emission of gluons in the gluon emission process means the color lifetime is a stochastically varying quantity. We explored the consequences of choosing a deterministic vs. stochastic distribution.

Stochastic form (exponential distribution)



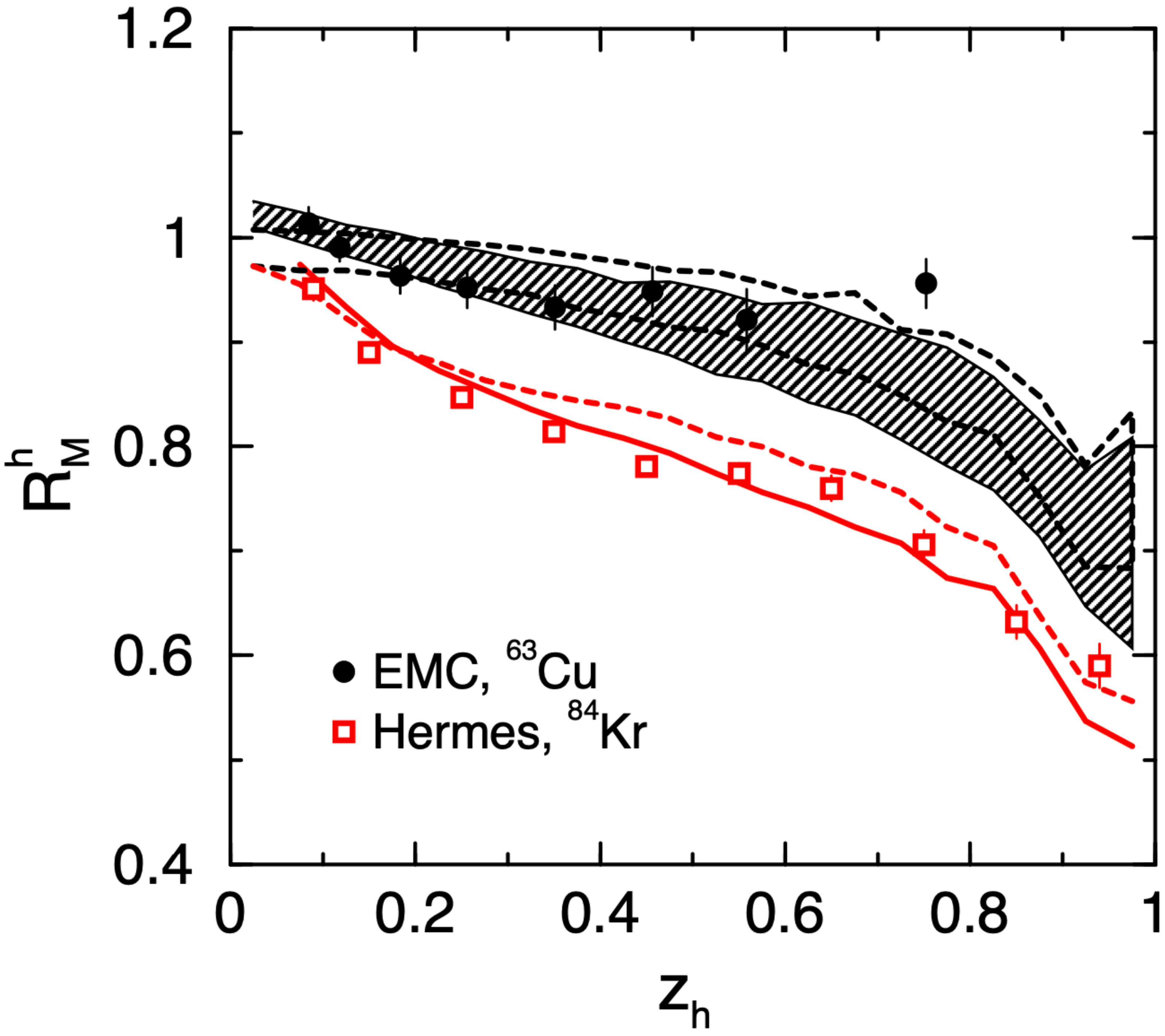
Deterministic/fixed form

The shape of the multiplicity ratio depends on this choice.
There may be experimental sensitivity to the distribution.

Gallmeister and Mosel

https://arxiv.org/pdf/nucl-th/0701064.pdf

DIS off nuclei as measured by HERMES with 12 and 27 GeV and by EMC with **100** and **280 GeV** lepton beam energies.

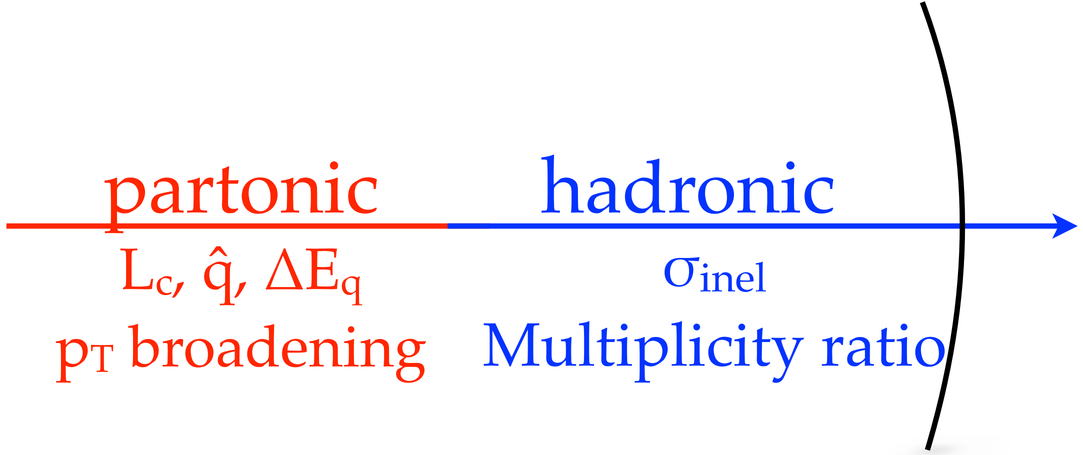


The ultimate test of whether the color lifetime is deterministic/fixed or not. This calculation has NO parton energy loss.

The Brooks-López model of Color Propagation in Cold Matter
WKB and Jorge López (UTFSM)

Division of the process into *partonic* and *hadronic* stages

Path of (struck) quark is divided into "partonic phase" and "hadronic phase"


partonic

L_c, $\hat{q}$, ΔE_q

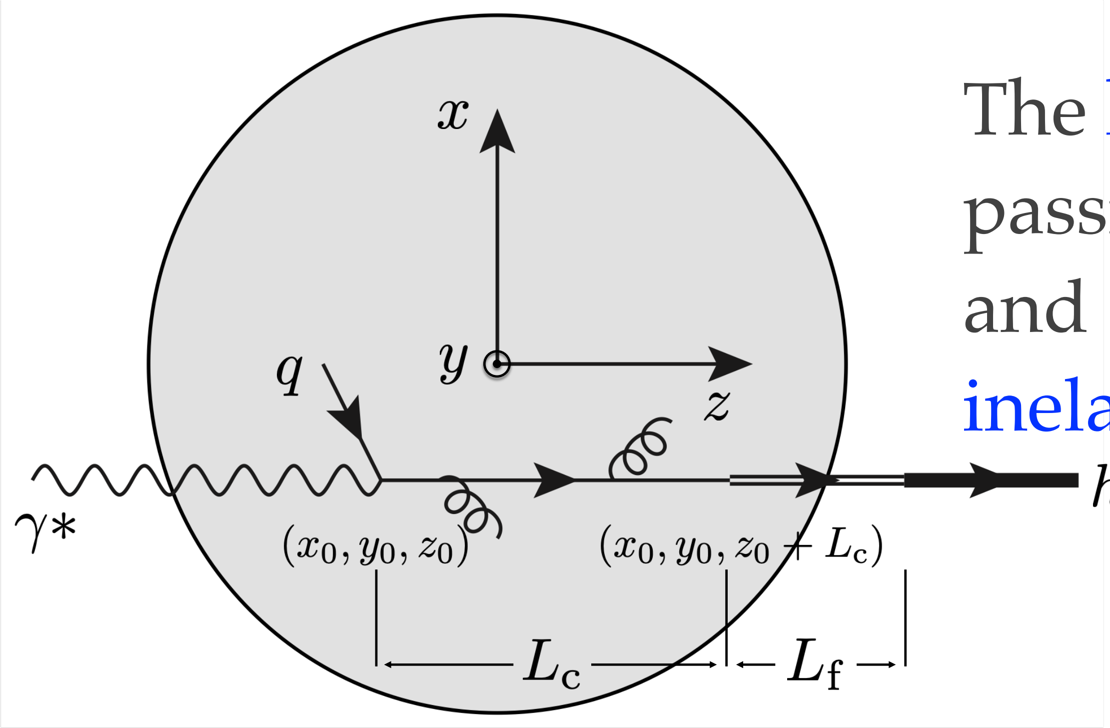
p_T broadening

hadronic

σ_{inel}

Multiplicity ratio

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

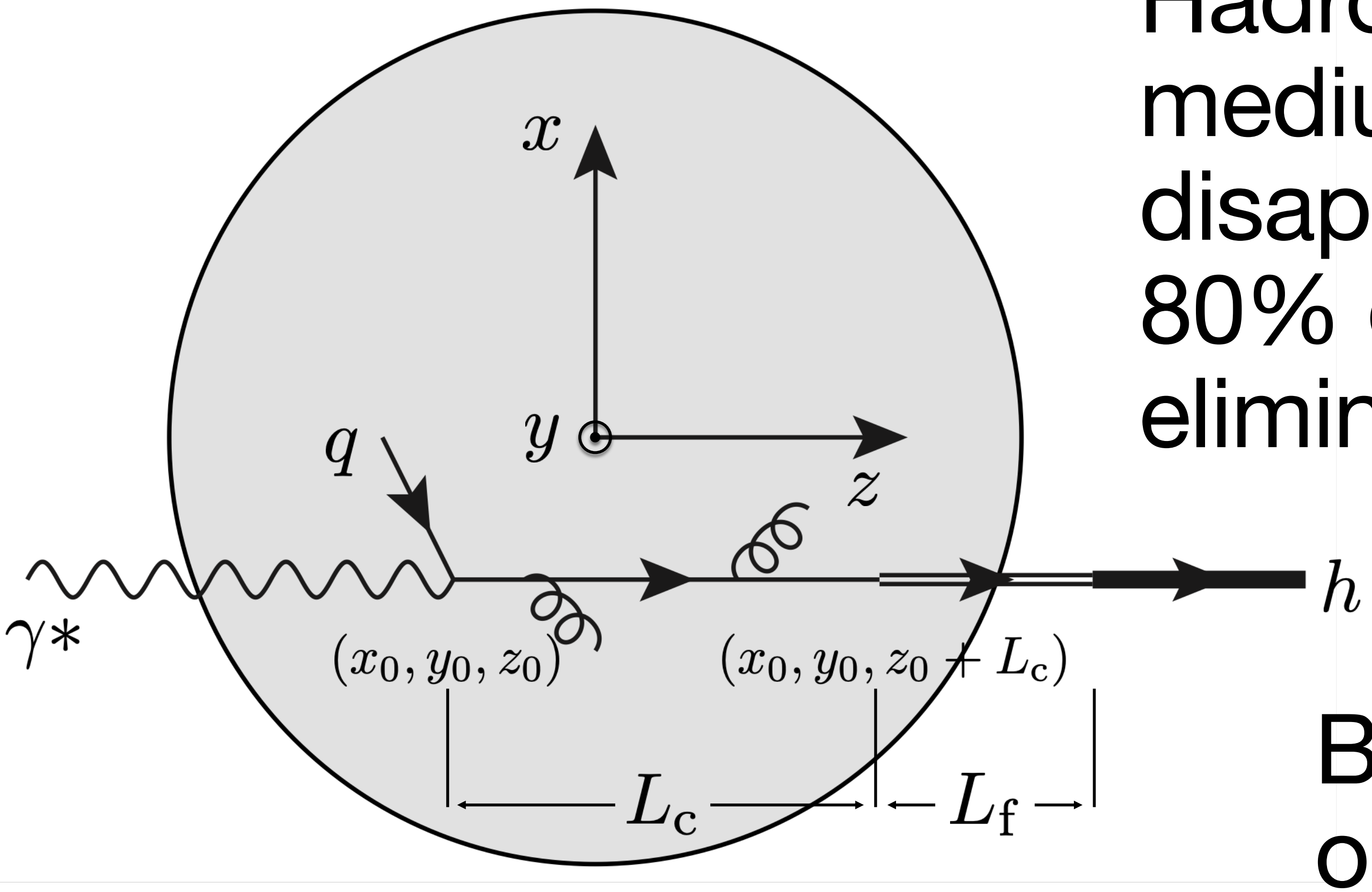


The hadronic phase follows the partonic phase, passing through the remainder of the medium, and causing attenuation of hadrons by an inelastic interaction cross section σ_{inel}

QCD and Hadronization

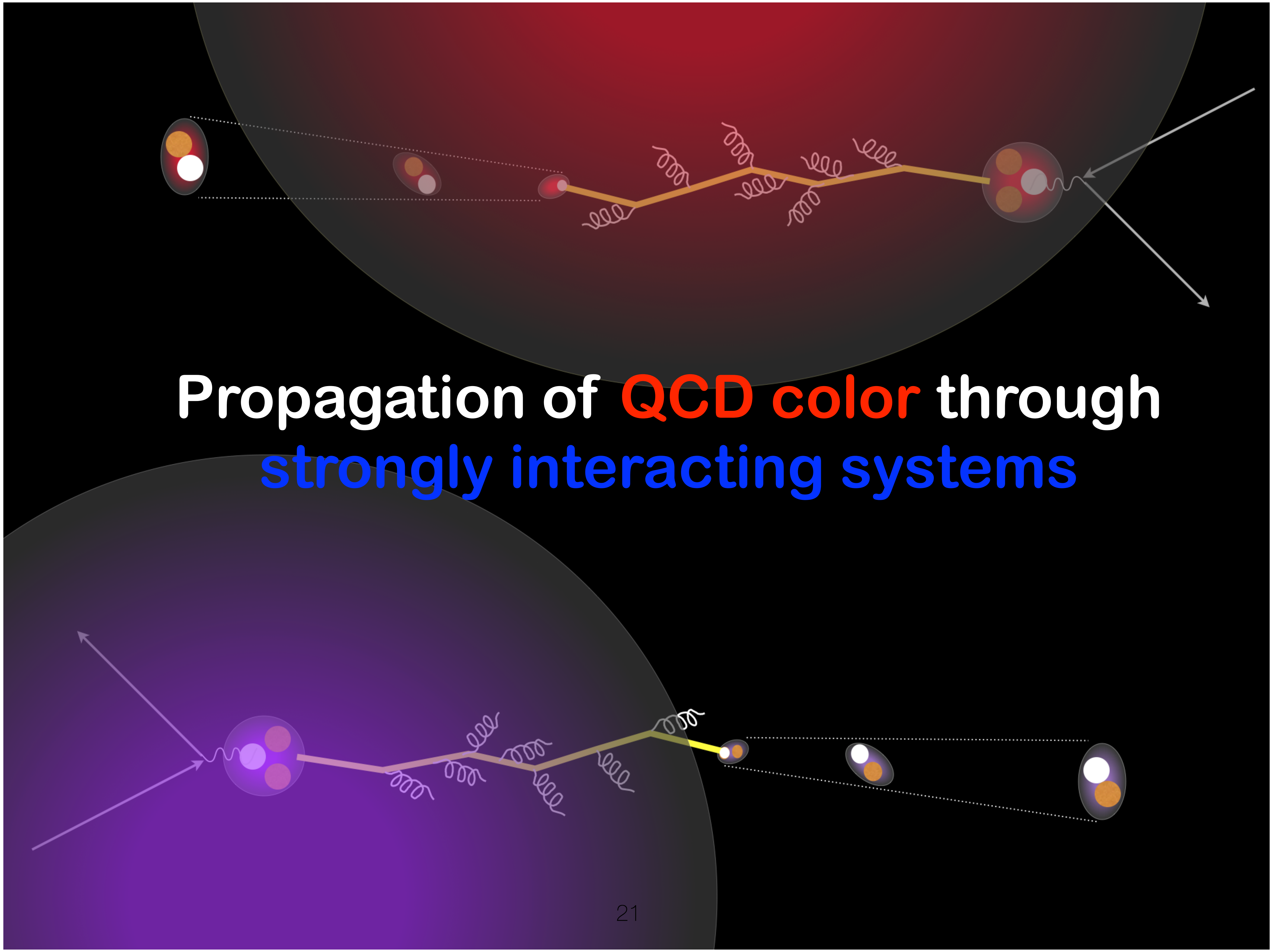
Hadronization inside of nuclei:

Energetic quarks interact gently with the medium, producing an increase in the average transverse momentum of ~0.03 GeV^2.

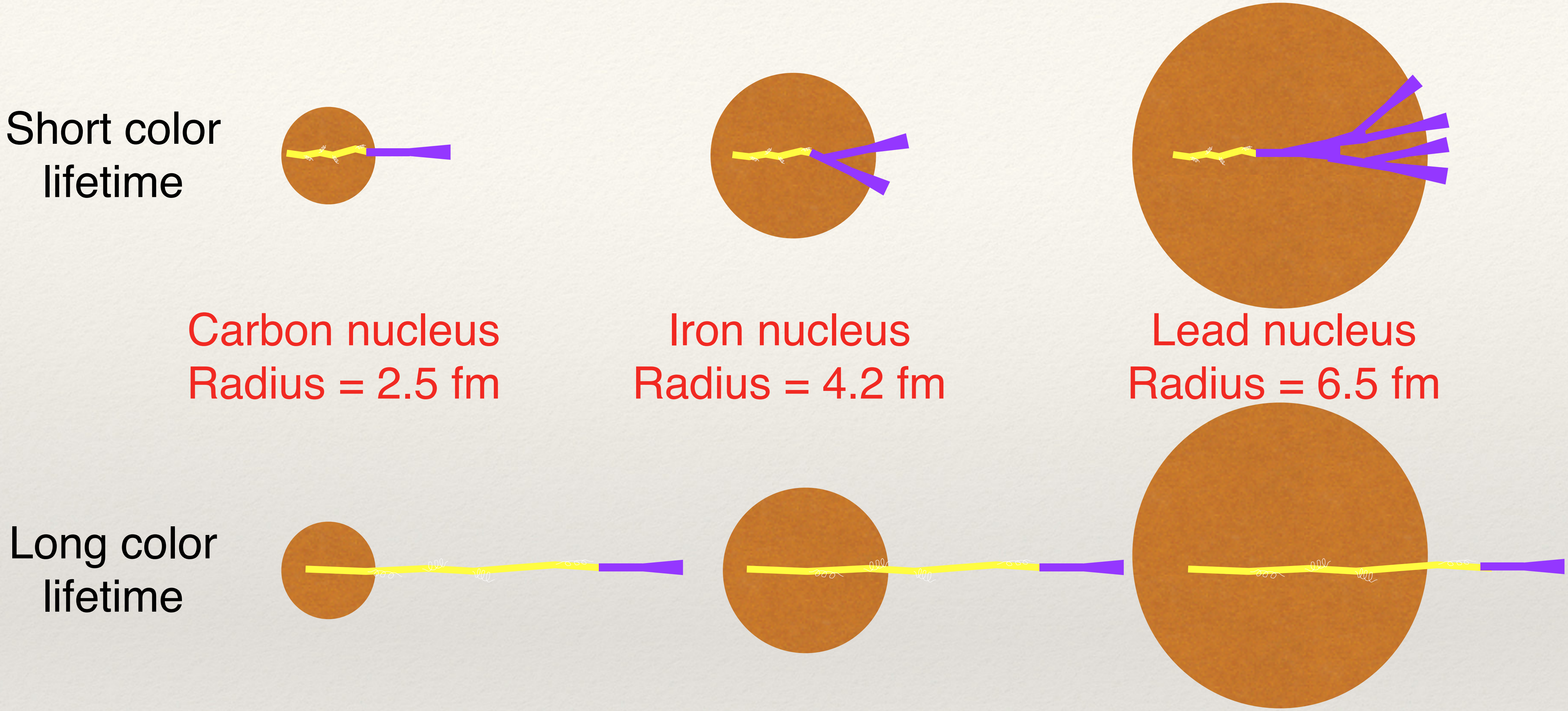


Hadrons that form inside the medium interact very violently, disappearing from the flux. Up to 80% of high-z pions are eliminated in the Pb nucleus.

By contrasting these two observables, we probe the process ***microscopically***.



Propagation of QCD color through strongly interacting systems



Short color lifetime

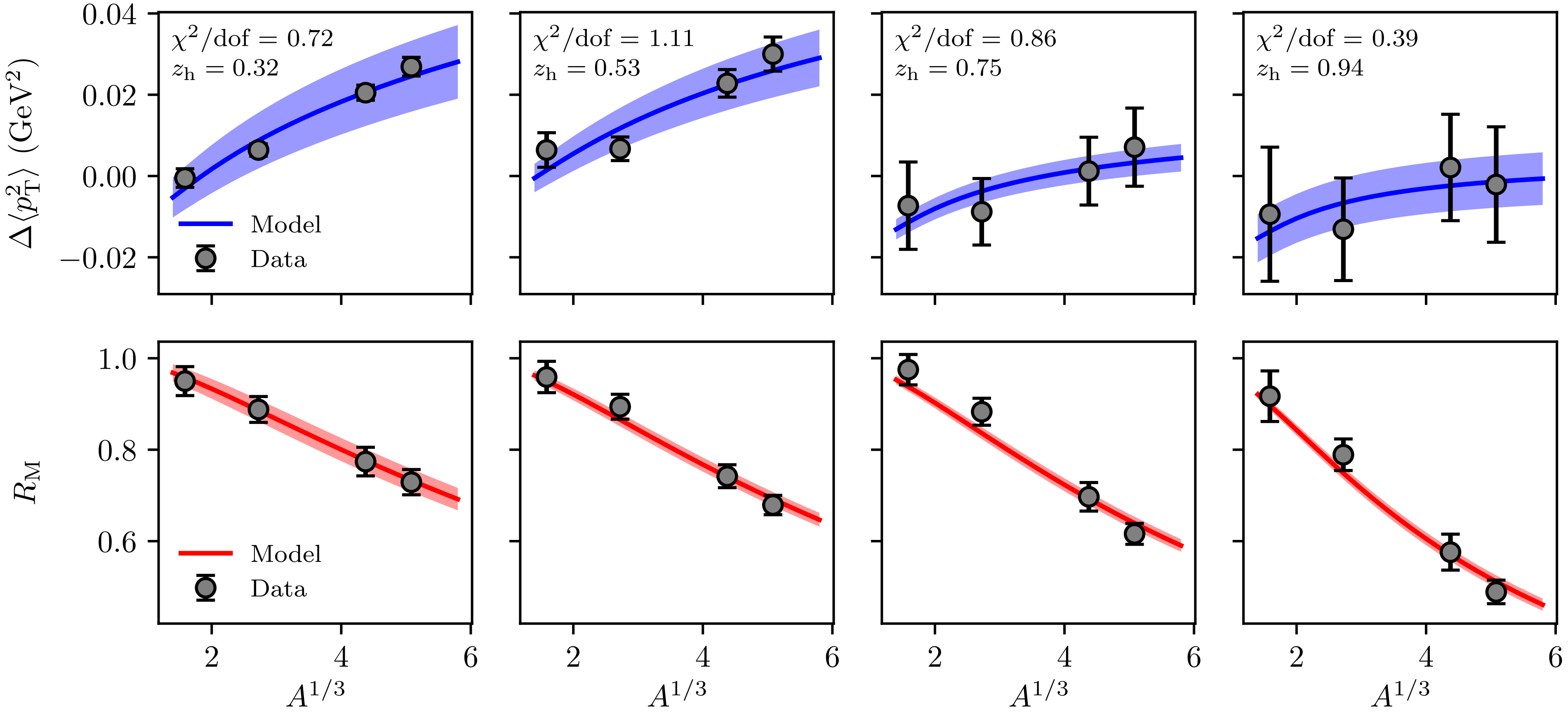
Long color lifetime

Carbon nucleus
Radius = 2.5 fm

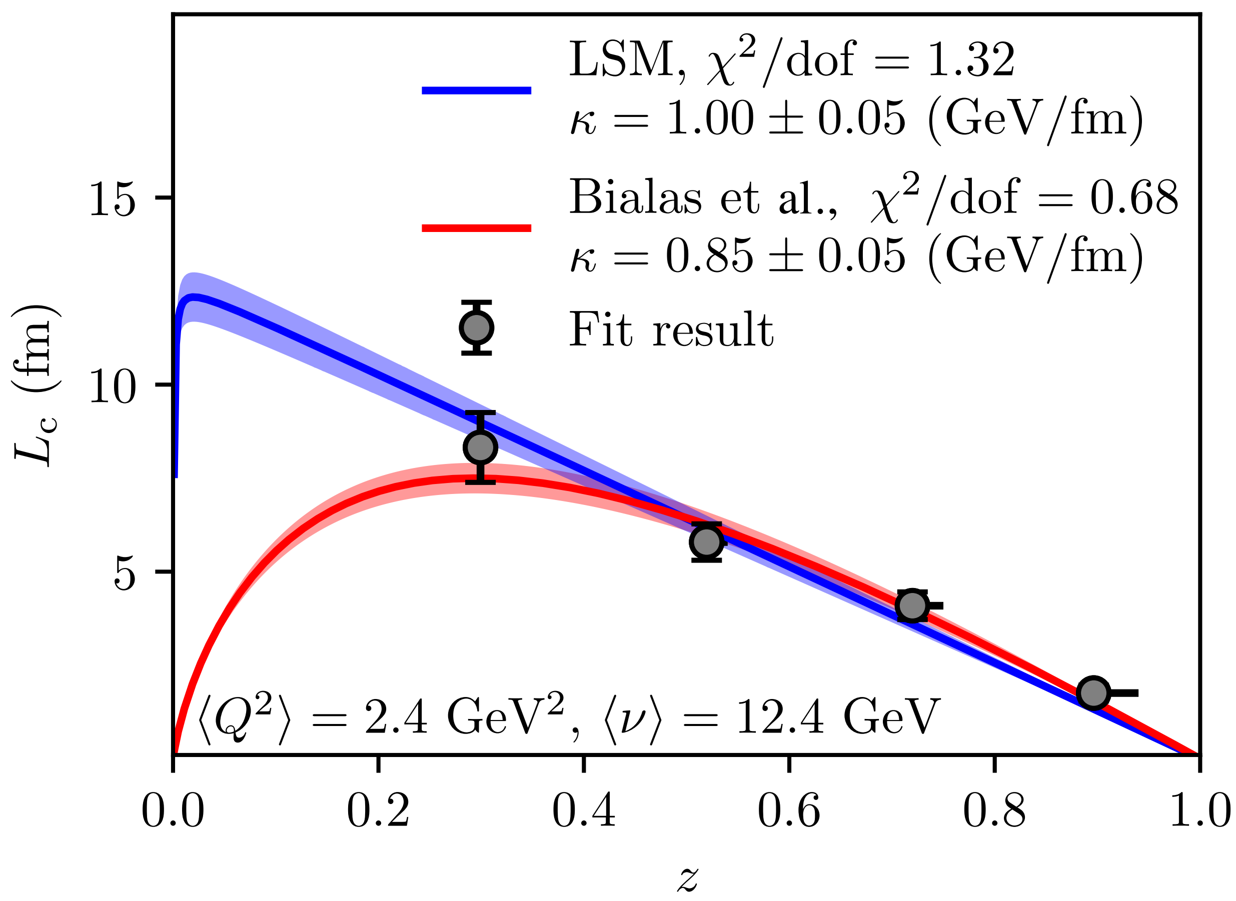
Iron nucleus
Radius = 4.2 fm

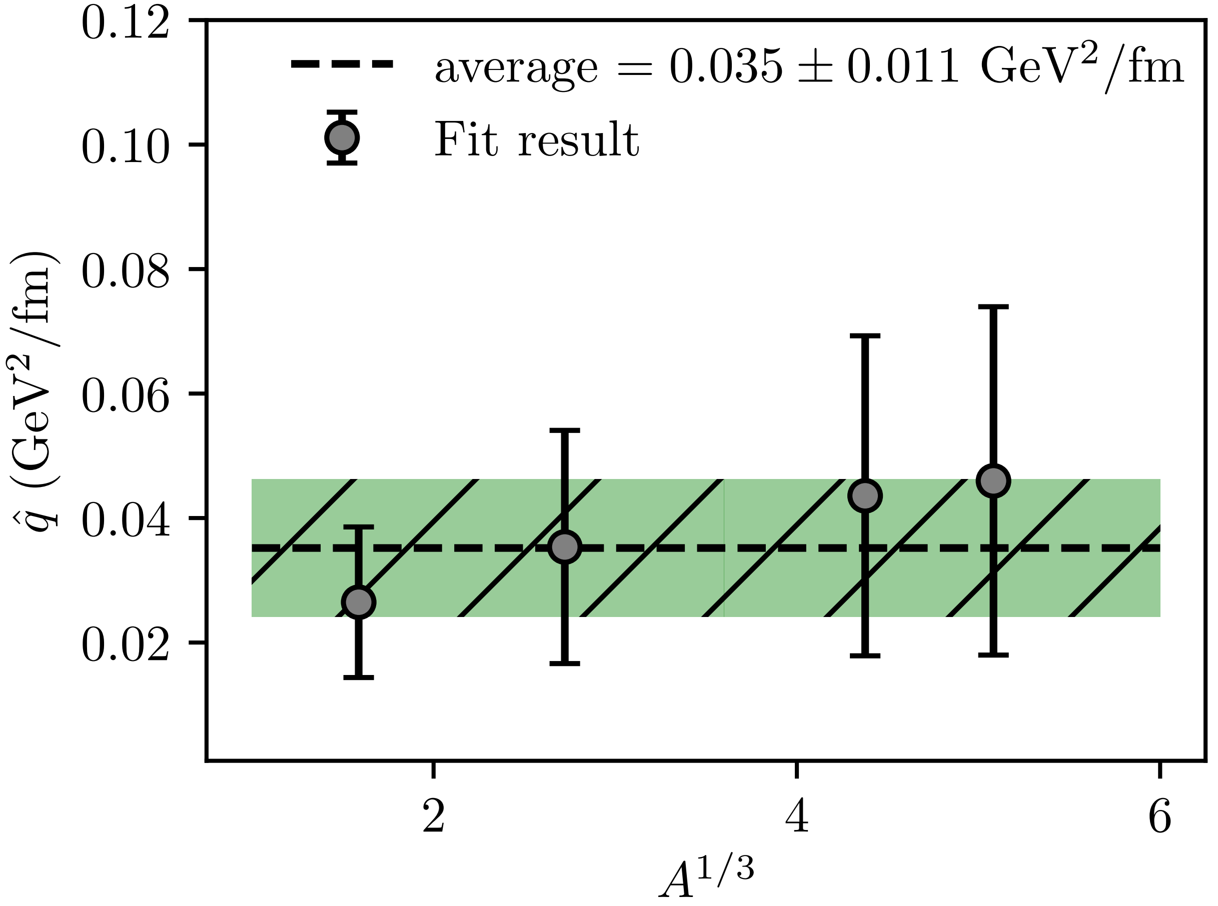
Lead nucleus
Radius = 6.5 fm

By comparing p_T broadening and hadron attenuation in nuclei of different sizes, one can measure the *length* of the color propagation process (femtometer scale)



Recent fit to HERMES data validates this physical picture for π^+





Simultaneous 3-parameter fit to multiplicity ratio and p_T broadening

https://arxiv.org/abs/2004.07236

The 12 GeV Experiment

First-ever measurement, rare heavy *meson* hadronization:

ϕ(1019), $c\tau$ ~44 fm, $J^P=1^-$, $s\bar{s}$

f1(1285), $c\tau$ ~8 fm, $J^P=1^+$

η'(958), $c\tau$ ~1 pm, $J^P=0^-$

First look at GeV-scale meson formation!

First-ever measurement of *baryon* hadronization of:

Λ(1519), *uds*, $c\tau$ ~ 13 fm

Σ^+(1189), uus, Σ^-(1197), dds, S=-1

Σ^0(1193) S=-1, *uds*

Ξ^0(1315), uss, Ξ^-(1322), dss, S=-2

Systematic search for direct scattering of *ud* diquark!

Theory interest since 2010

Extracting many-body color charge correlators in the proton from exclusive DIS at large Bjorken x.
Adrian Dumitru, Gerald A. Miller, Raju Venugopalan
Phys. Rev. D 98, 094004 (2018)

Transverse momentum broadening in semi-inclusive deep inelastic scattering at next-to-leading order.
Zhong-Bo Kang, Enke Wang, Xin-Nian Wang, and Hongxi Xing
Phys. Rev. D 94, 114024 (2016)

A global extraction of the jet transport coefficient in cold nuclear matter.
Peng Ru, Zhong-Bo Kang, Enke Wang, Hongxi Xing, Ben-Wei Zhang
arXiv:1907.11808 [hep-ph] (2019)

Initial conditions for the modified evolution of fragmentation functions in the nuclear medium
Ning-Bo Chang, Wei-Tian Deng, and Xin-Nian Wang
Phys. Rev. C 89, 034911 (2014)

Spacetime development of in-medium hadronization: Scenario for leading hadrons. Benjamin Guiot and Boris Z. Kopeliovich
arXiv:2001.00974 [hep-ph] (2020)

Quenching of high-pT hadrons: a non-energy-loss scenario.
B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, and I. Schmidt.
EPJ Web Conf., 71:00070 (2014).

Parton transport via transverse and longitudinal scattering in dense media.
Guang-You Qin and Abhijit Majumder
Phys. Rev. C 87, 024909 (2013)

Diquark Correlations in Hadron Physics: Origin, Impact and Evidence
M. Yu. Barabanov, M. A. Bedolla, W. K. Brooks, G. D. Cates, C. Chen, Y. Chen, E. Cisbani, M. Ding, G. Eichmann, R. Ent, J. Ferretti, R. W. Gothe, T. Horn, S. Liuti, C. Mezrag, A. Pilloni, A. J. R. Puckett, C. D. Roberts, P. Rossi, G. Salme, E. Santopinto, J. Segovia, S. N. Syritsyn, M. Takizawa, E. Tomasi-Gustafsson, P. Wein, B. B. Wojtsekhowski
arXiv:2008.07630 [hep-ph] (2020)

The theory and phenomenology of perturbative QCD based jet quenching. A. Majumder and M. van Leeuwen.
Progress in Particle and Nuclear Physics, 66(1):41 – 92 (2011).

Quark energy loss in semi-inclusive deep inelastic scattering of leptons on nuclei. Li-Hua Song and Chun-Gui Duan.
Phys. Rev. C, 81:035207 (2010).

Systematic analysis of the incoming quark energy loss in cold nuclear matter. Li-Hua Song, Chun-Gui Duan, and Na Liu.
Physics Letters B, 708(1-2):68–74 (2012).

Atomic mass dependence of hadron production in semi-inclusive deep inelastic lepton-nucleus scattering. Li-Hua Song, Na Liu, and Chun-Gui Duan.
Chinese Physics C, 37(8):084102 (2013).

Hadron formation in semi-inclusive deep inelastic lepton-nucleus scattering. Li-Hua Song, Na Liu, and Chun-Gui Duan.
Chinese Physics C, 37(10):104102, (2013)

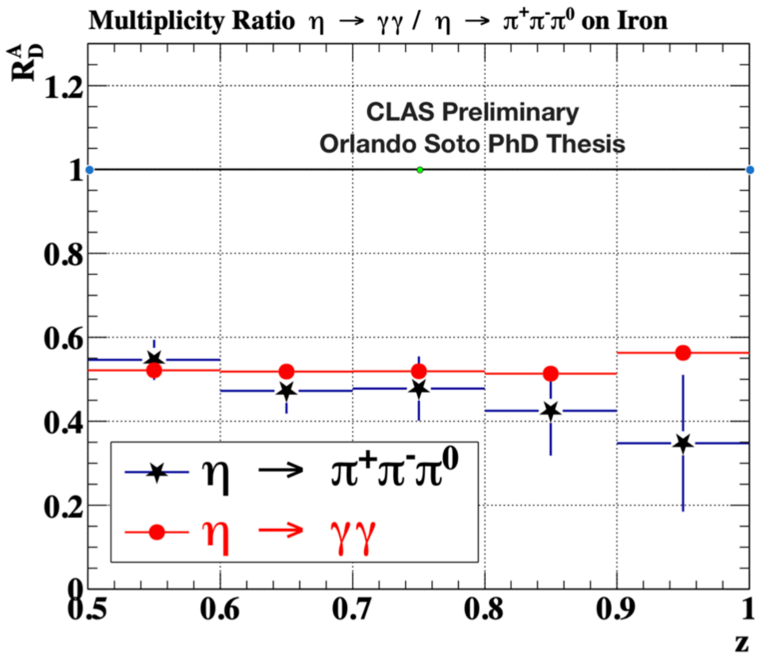
The energy loss and nuclear absorption effects in semi-inclusive deep inelastic scattering on nucleus. Li-Hua Song, Shang-Fei Xin, and Na Liu.
J. Phys., G45(2):025005 (2018).

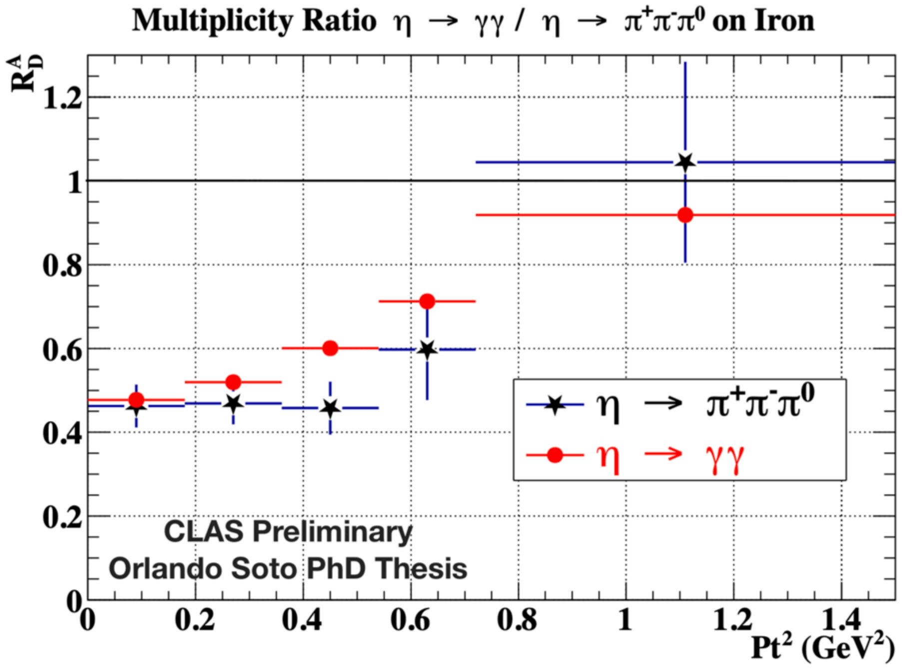
The study of the incoming parton energy loss effect on the NLO nuclear Drell–Yan ratios.
Li-Hua Song, Shang-Fei Xin, and Yin-Jie Zhang.
J. Phys. G: Nuclear and Particle Physics, 47(5):055002, (2020)

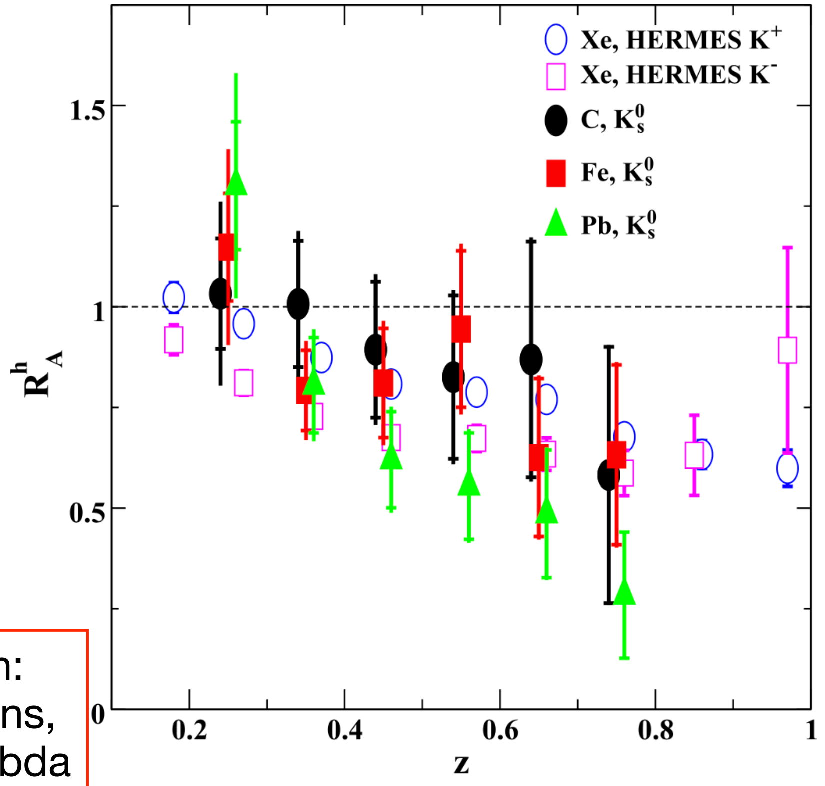
Nuclear geometry effect and transport coefficient in semi-inclusive lepton-production of hadrons off nuclei.
Na Liu, Wen-Dan Miao, Li-Hua Song, and Chun-Gui Duan.
Physics Letters B, 749:88–93 (2015).

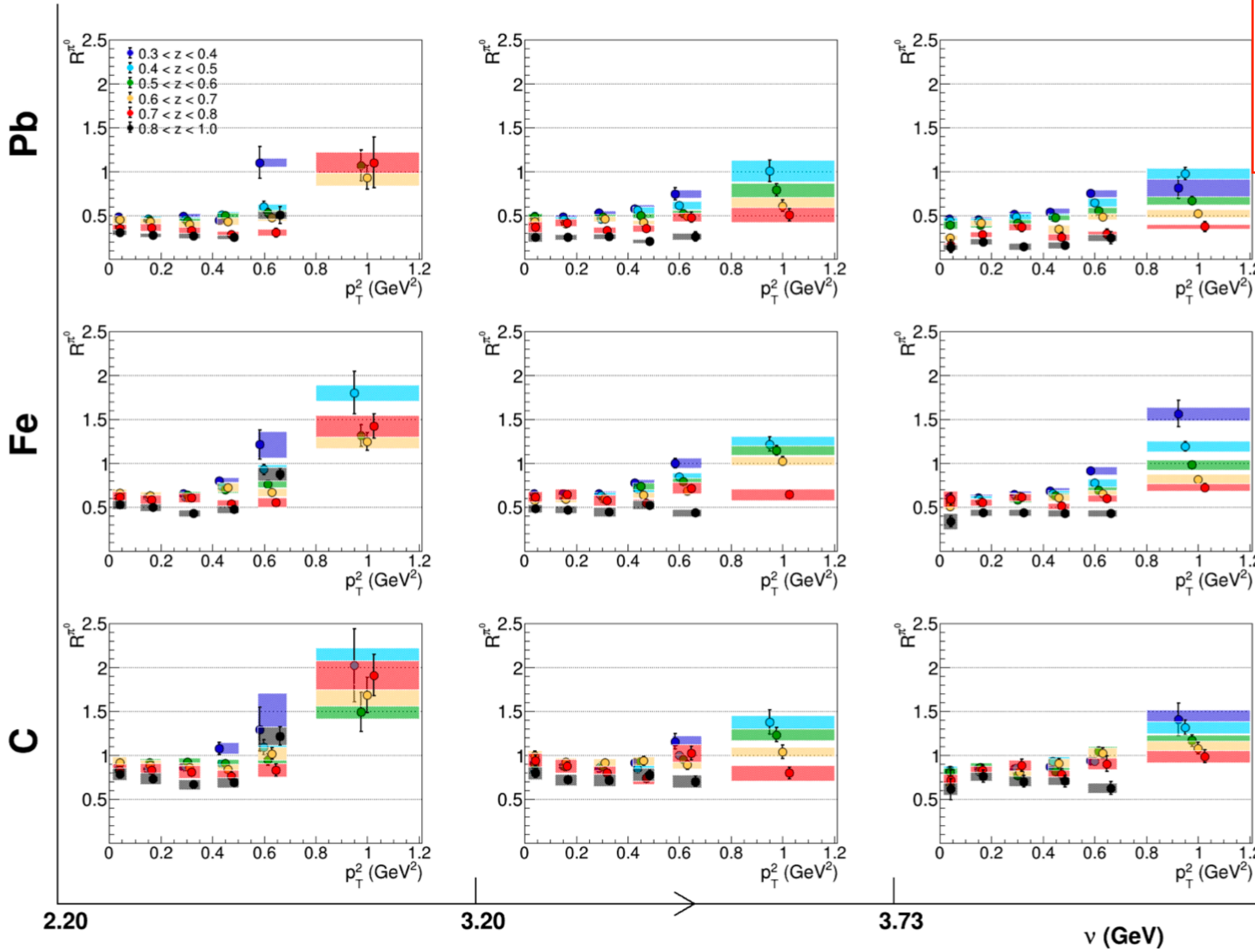
Additional relevant data/theory: pA@LHC, dAu@RHIC, DY@FNAL

Selected results from 5 GeV CLAS since 2010



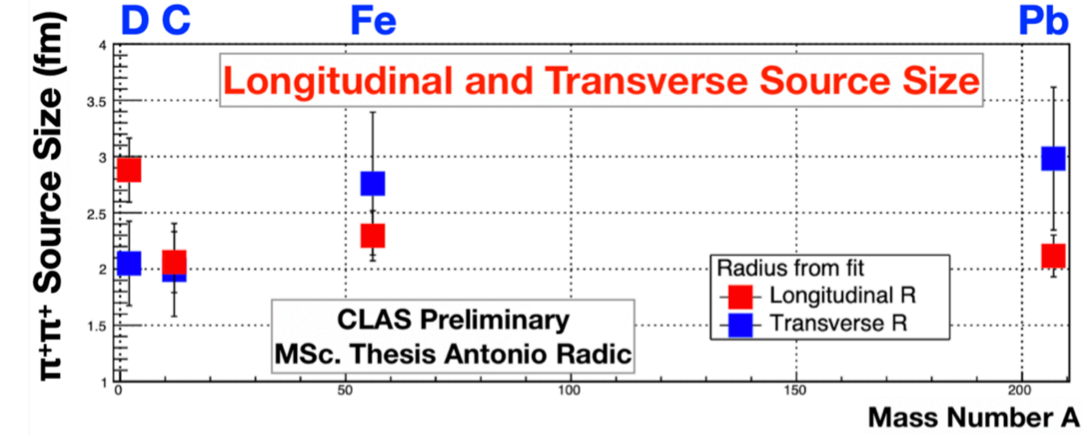


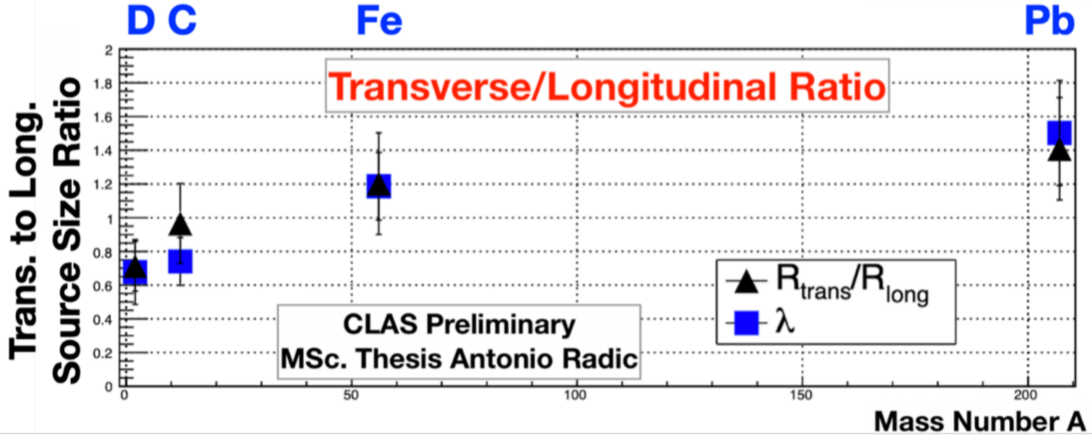


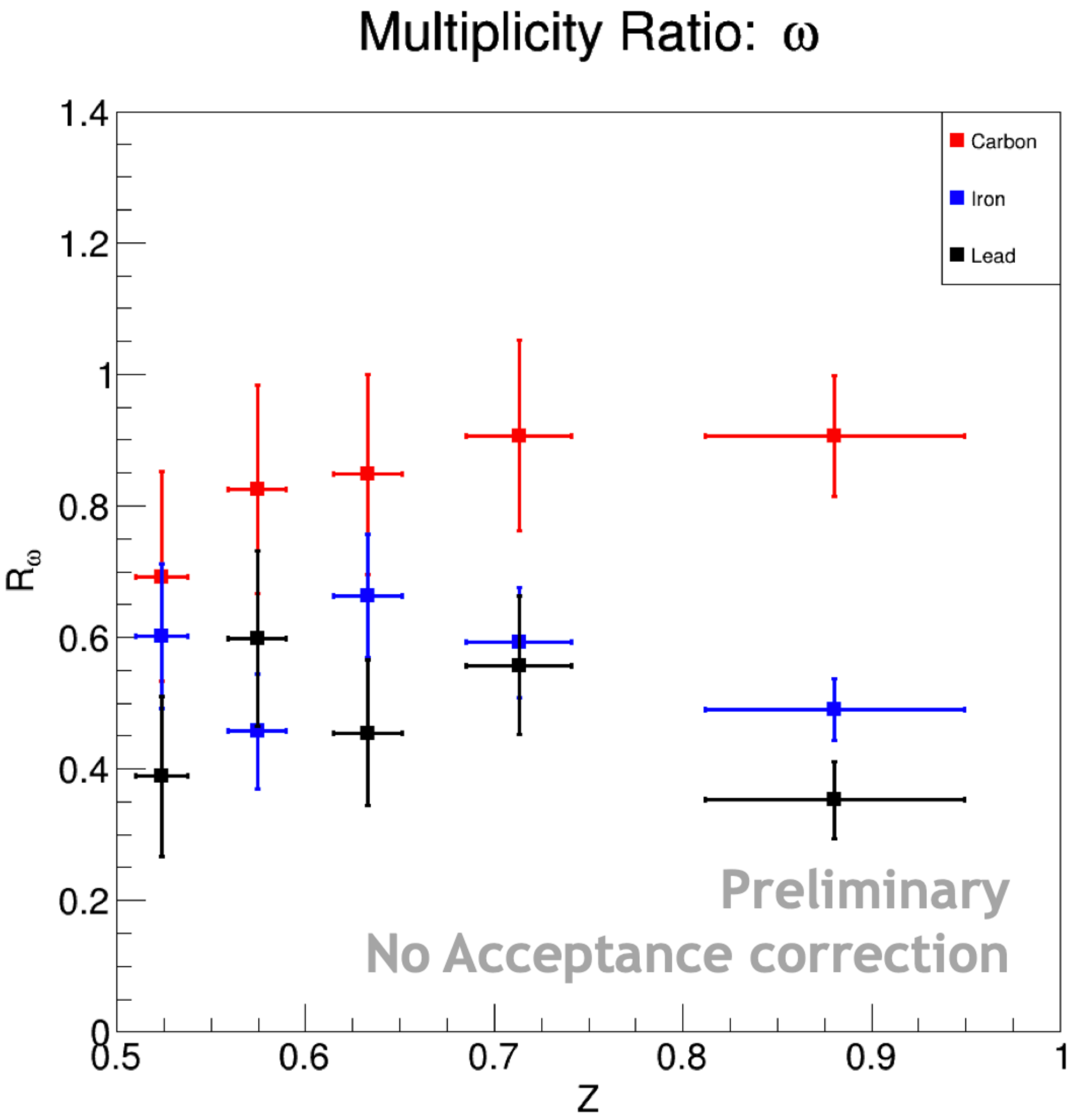


Not shown:
charged pions,
protons, lambda
pT broadening

BOSE-EINSTEIN Correlations for $\pi^+\pi^+$







World's first omega meson multiplicity ratio
Andres Bórquez MSc student thesis topic
Prof. Michael Wood, Canisius College
Prof. Hayk Hakobyan, UTFSM

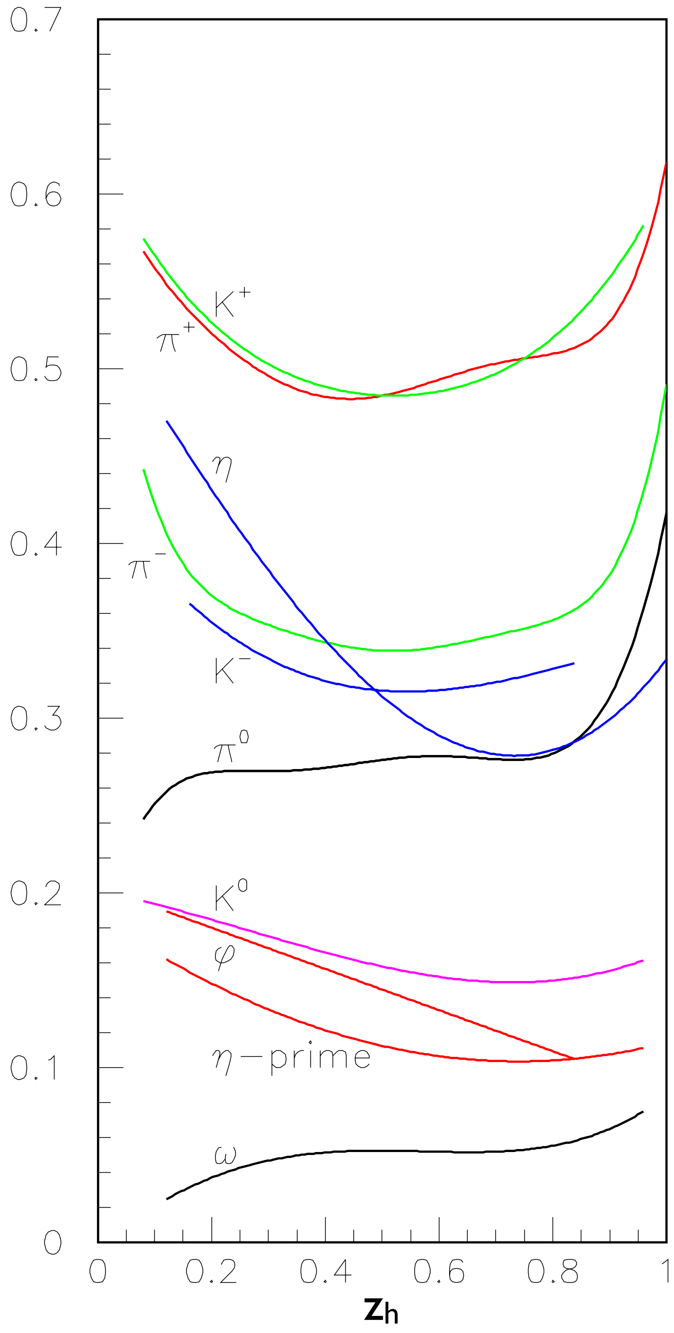
Quark Propagation and Hadron Formation with 11 GeV Beam

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	uūdd̄	5.7% (sys)
π^+, π^-	7.8 m	0.14	ud̄, dū	3.2% (sys)
η	170 pm	0.55	uūdd̄ss̄	6.2% (sys)
ω	23 fm	0.78	uūdd̄ss̄	6.7% (sys)
η'	0.98 pm	0.96	uūdd̄ss̄	8.5% (sys)
ϕ	44 fm	1	uūdd̄ss̄	5.0% (stat)*
$f1$	8 fm	1.3	uūdd̄ss̄	-
K^0	27 mm	0.5	ds̄	4.7% (sys)
K^+, K^-	3.7 m	0.49	us̄, ūs	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	ūd̄	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

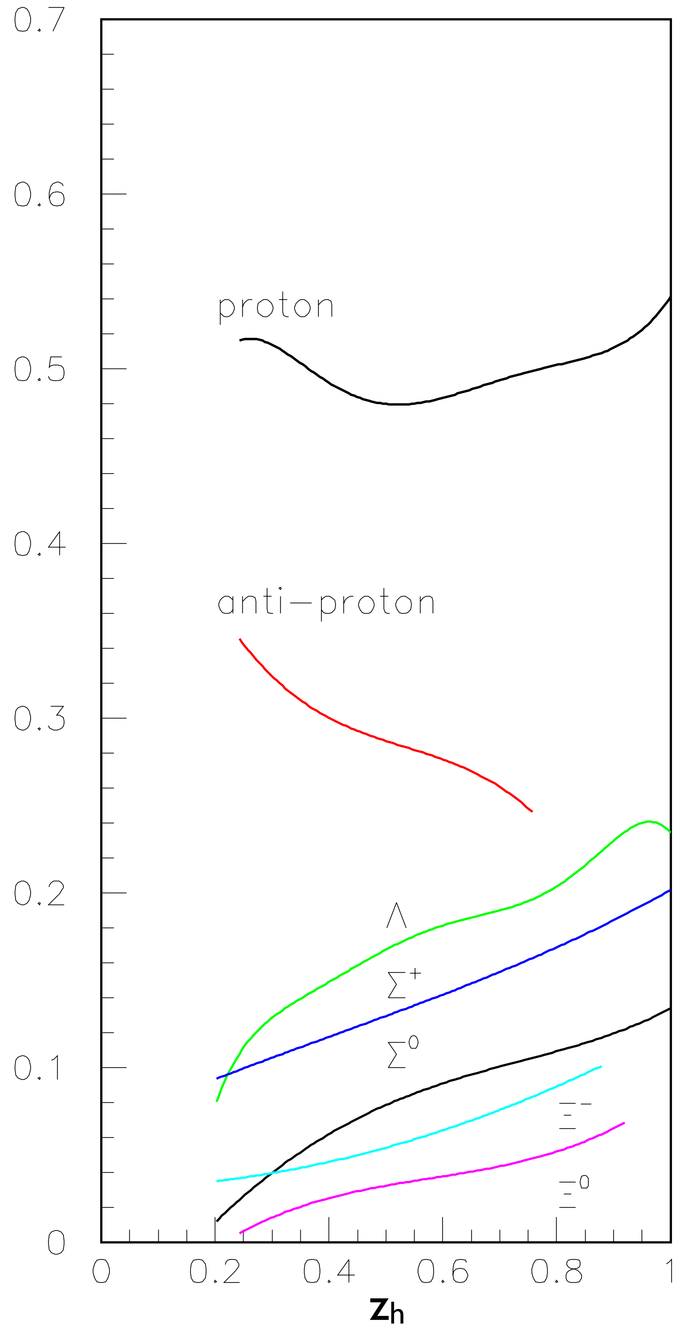
*in a bin in z from 0.7-0.8, integrated over all ν, p_T, ϕ_{pq}, and $Q^2>5$ GeV^2

**in a bin in z from 0.6-0.7, integrated over all ν, p_T, ϕ_{pq}, and $Q^2>5$ GeV^2

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks

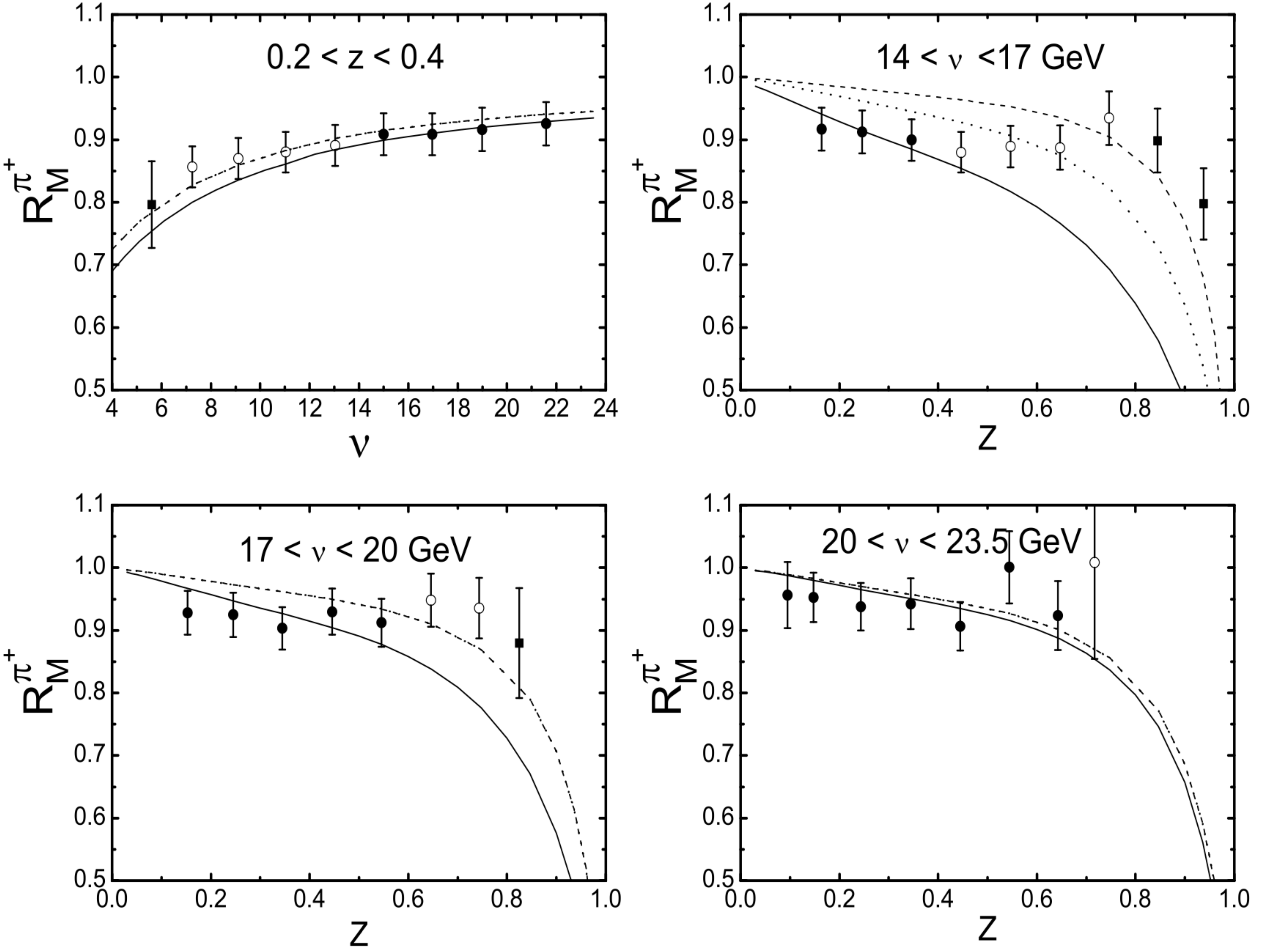


CLAS12 Acceptance for Mesons



CLAS12 Acceptance for Baryons

Selected theory examples



https://arxiv.org/abs/1511.00767v1

Na Liu,[1,2,*] Wen-Dan Miao,[1,†] Li-Hua Song,[1,3,‡] and Chun-Gui Duan[1,§]

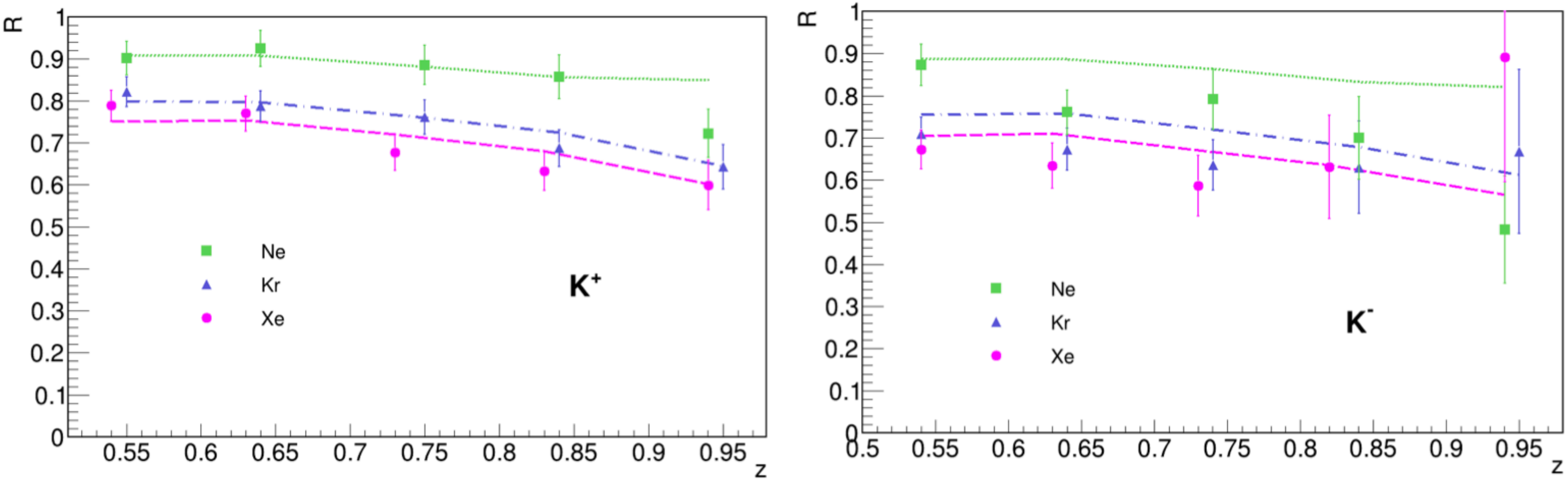


Figure 11: HERMES multiplicity ratio for kaons.

Benjamin Guiot and Boris Z. Kopeliovich, https://arxiv.org/pdf/2001.00974.pdf

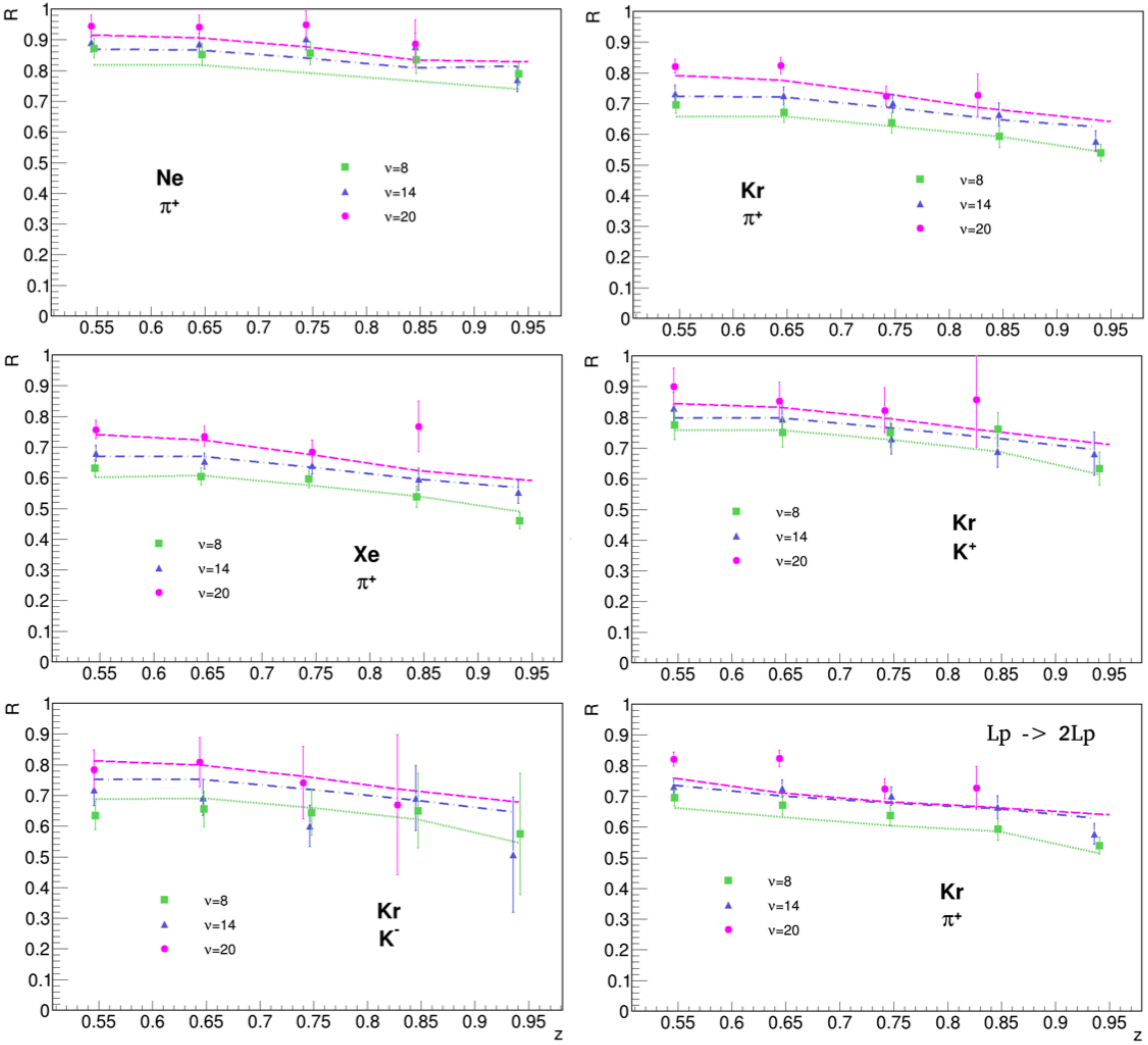


Figure 12: z-dependence of the multiplicity ratio for different energy slices. The bottom right panel shows the same data as the top right panel, but with our calculations based on a larger Lp.

Benjamin Guiot and Boris Z. Kopeliovich, https://arxiv.org/pdf/2001.00974.pdf

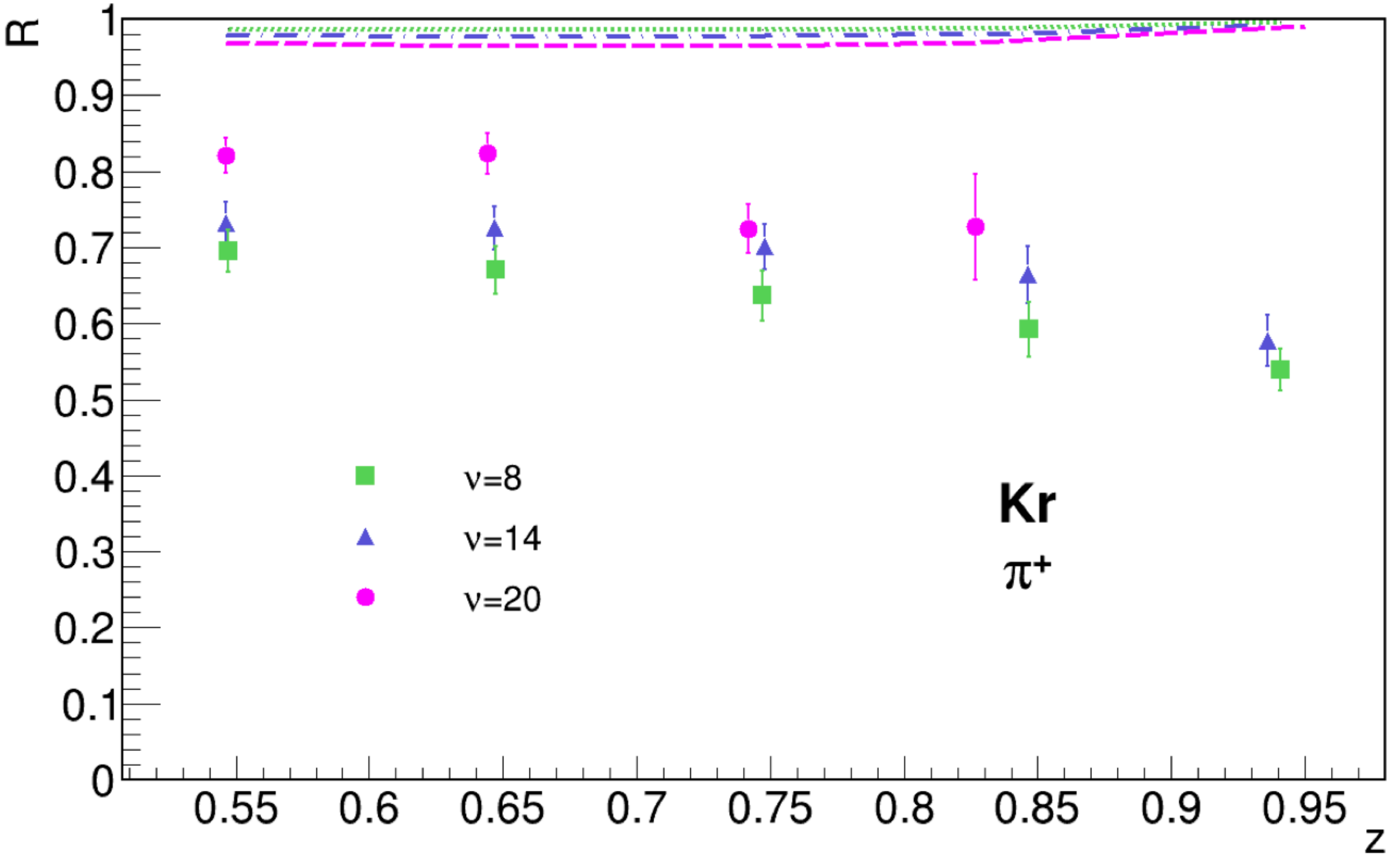


Figure 13: Induced energy loss contribution to the HERMES 2-dimensional multiplicity ratio.

Benjamin Guiot and Boris Z. Kopeliovich, https://arxiv.org/pdf/2001.00974.pdf

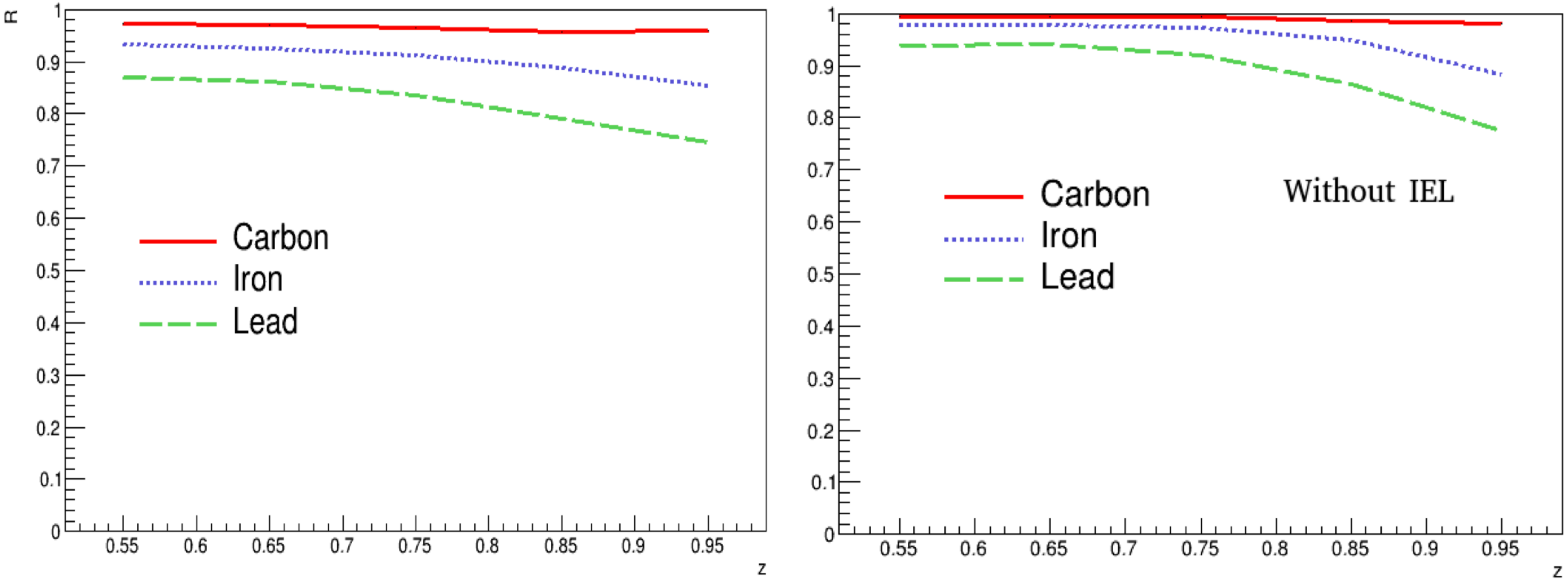


Figure 15: Results for the multiplicity ratio for $Q^2 = 40$ GeV^2 and $\nu = 100$ GeV. The right plot has been computed without IEL.

Benjamin Guiot and Boris Z. Kopeliovich, https://arxiv.org/pdf/2001.00974.pdf

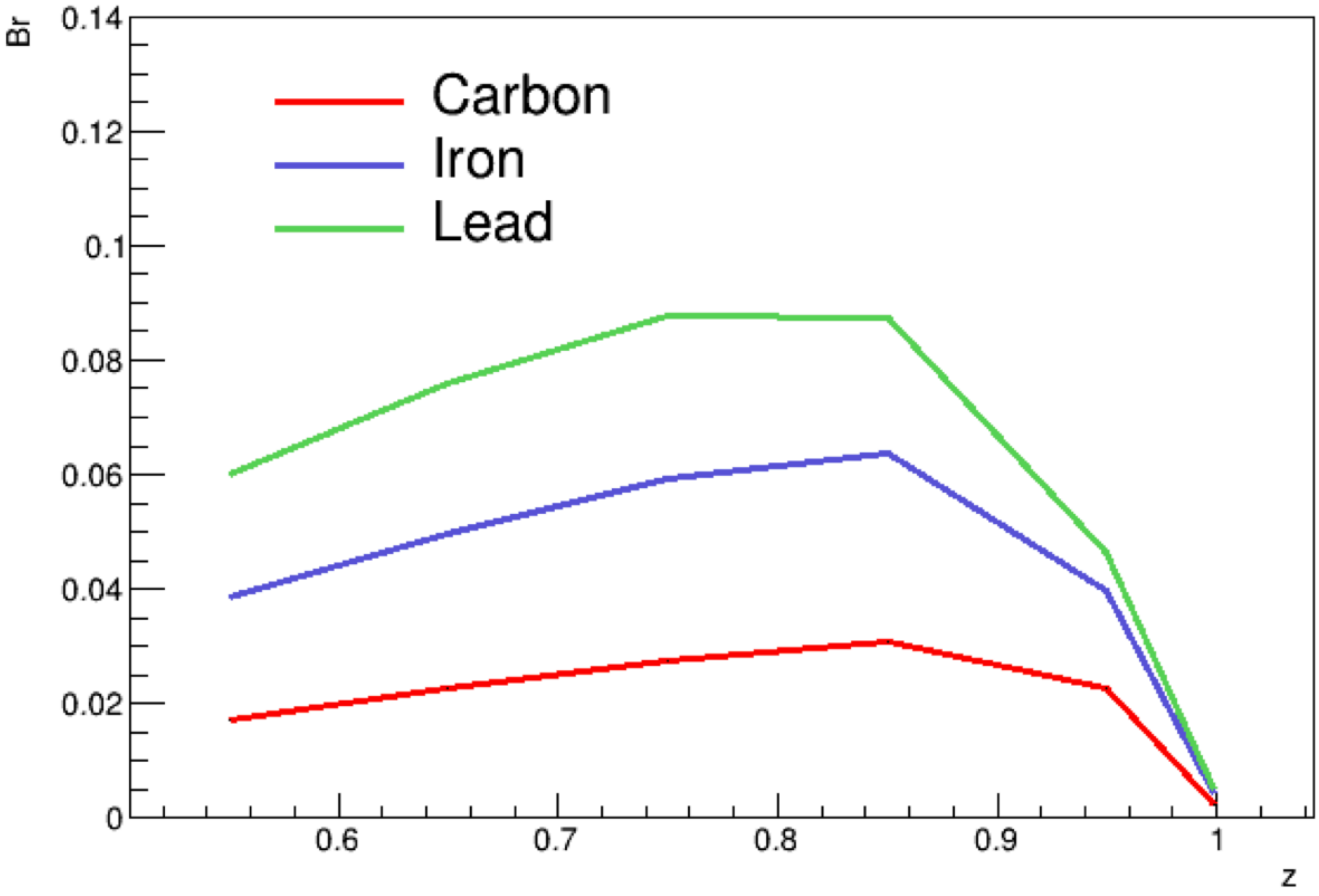


Figure 16: Quark p_t-broadening at $Q^2 = 40$ GeV^2 and $\nu = 100$ GeV.

Benjamin Guiot and Boris Z. Kopeliovich, https://arxiv.org/pdf/2001.00974.pdf

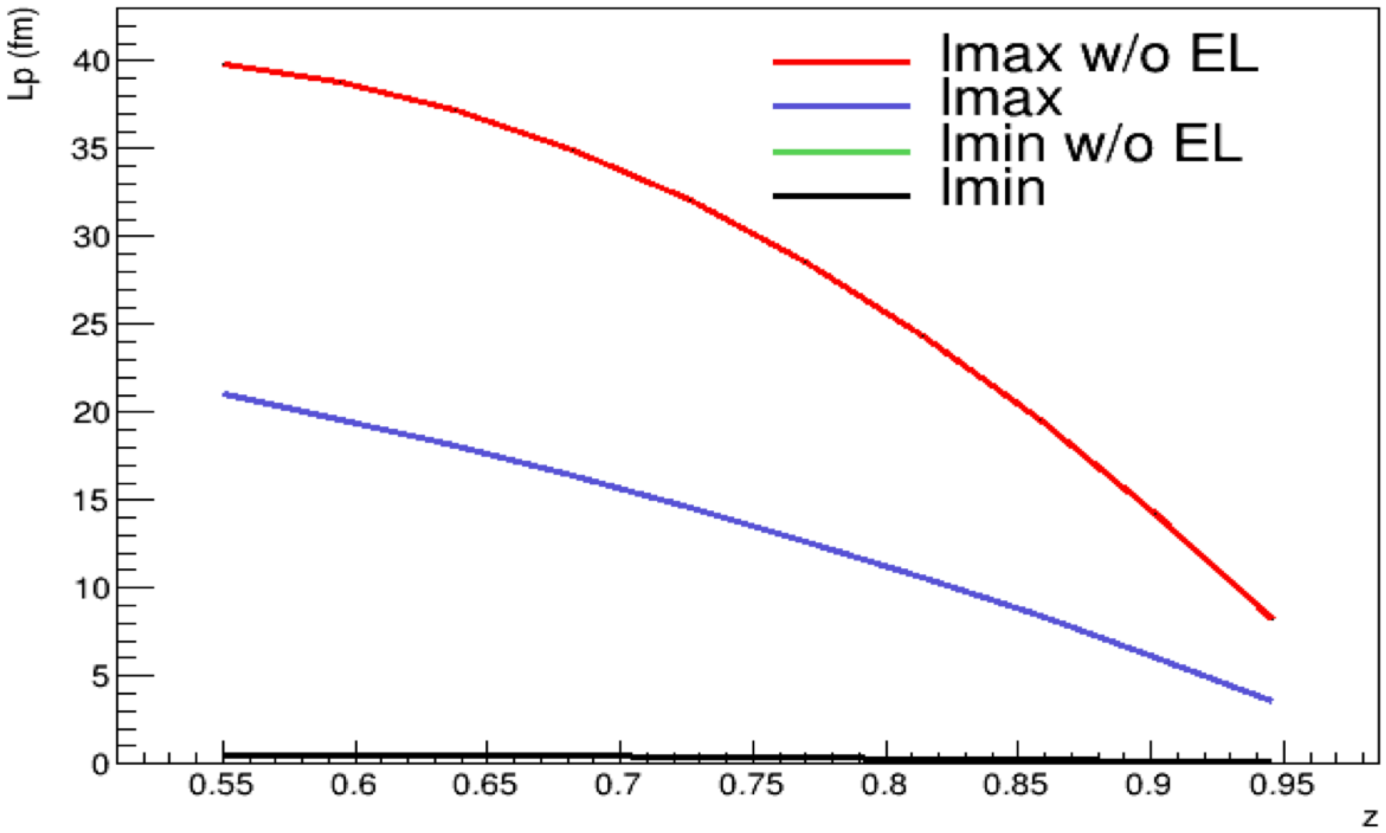


Figure 14: Results for minimum and maximum values of production length, in fm, as a function of z. The green line is hidden by the black line. The kinematic is $Q^2 = 40$ GeV^2 and $\nu = 100$ GeV, and the calculations are for lead. The red line has been obtained in the Born approximation (no energy loss).

Benjamin Guiot and Boris Z. Kopeliovich, https://arxiv.org/pdf/2001.00974.pdf

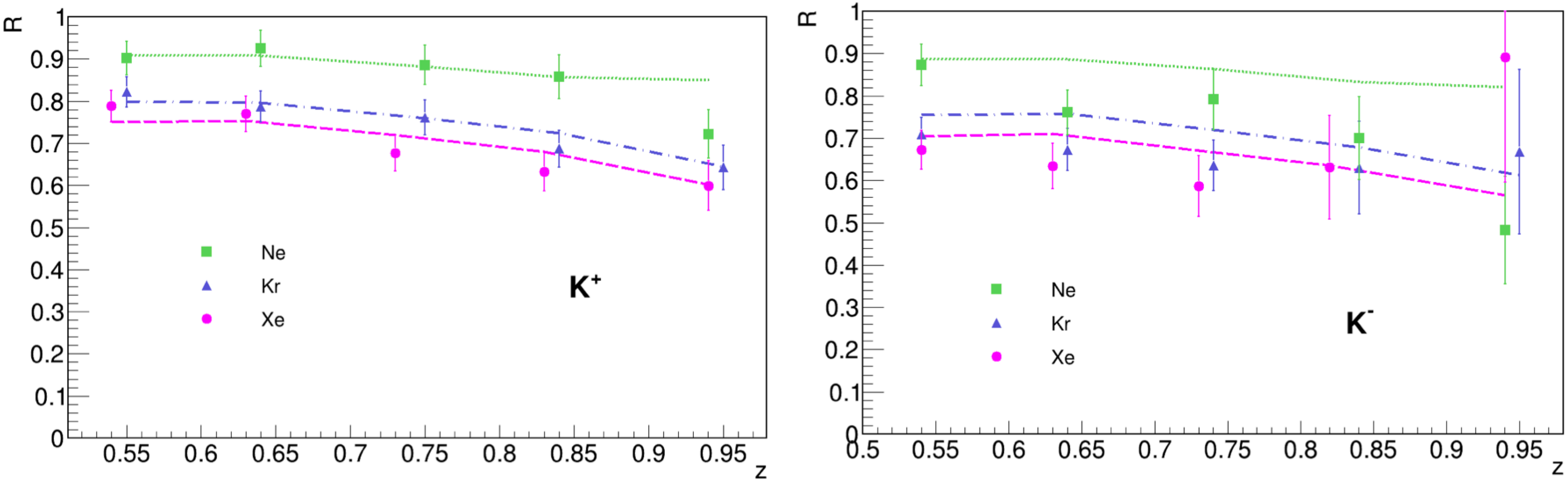


Figure 11: HERMES multiplicity ratio for kaons.

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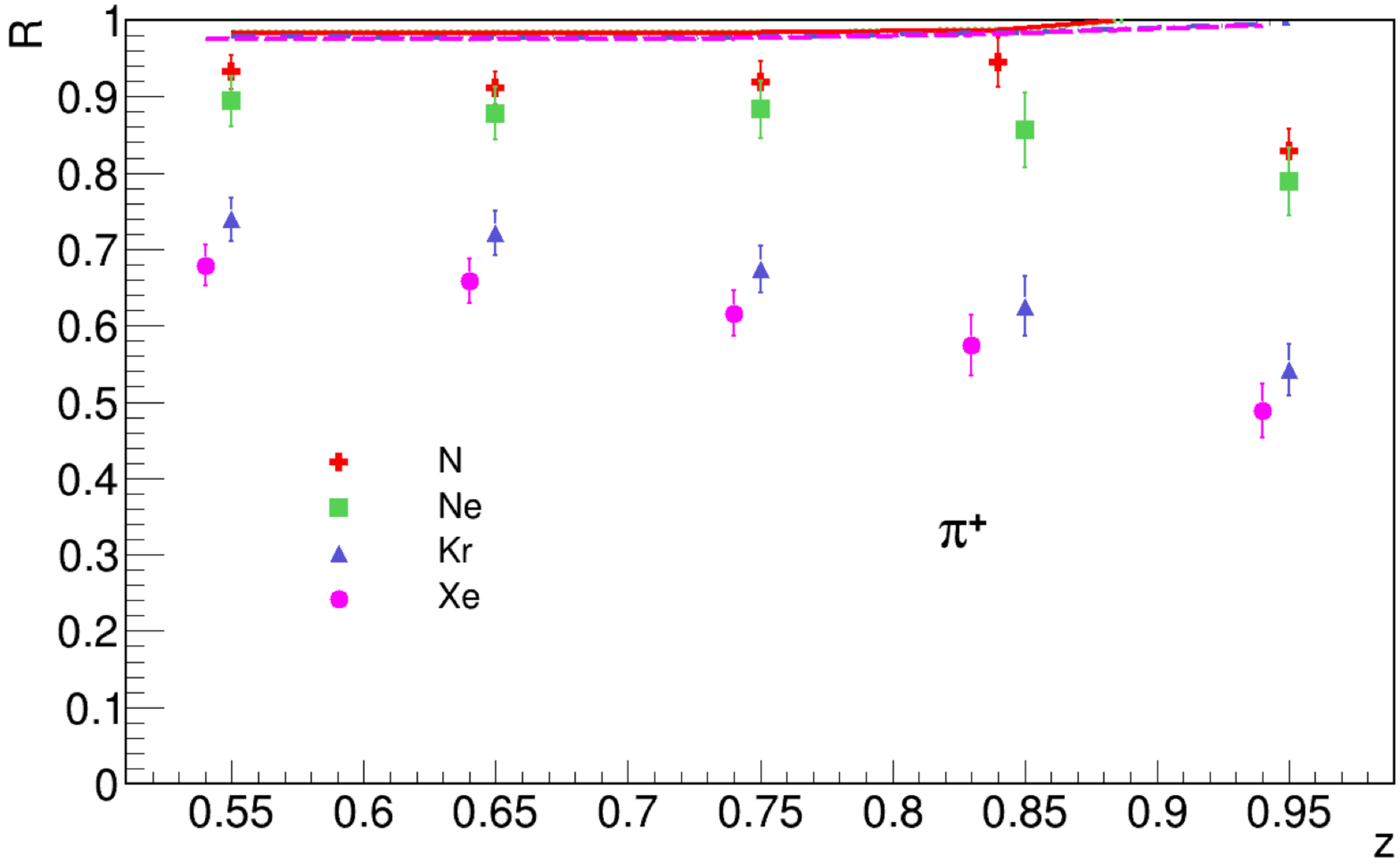

Figure 9: Same as Fig. 7, taking into account only the effect of induced energy loss (nuclear absorption turned off).

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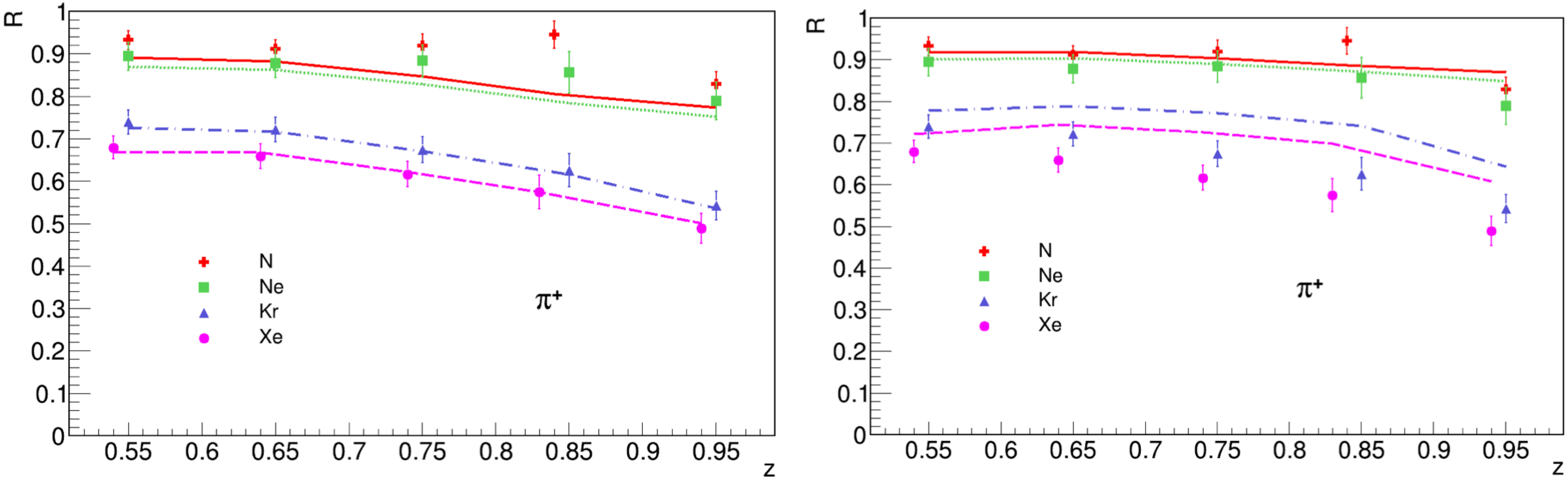

Figure 8: Left: same as Fig. 7 with x_0 [see Eq. (57)] multiplied by 5. Right: same as Fig. 7 with a_f changed from 0.9 to 2.5.

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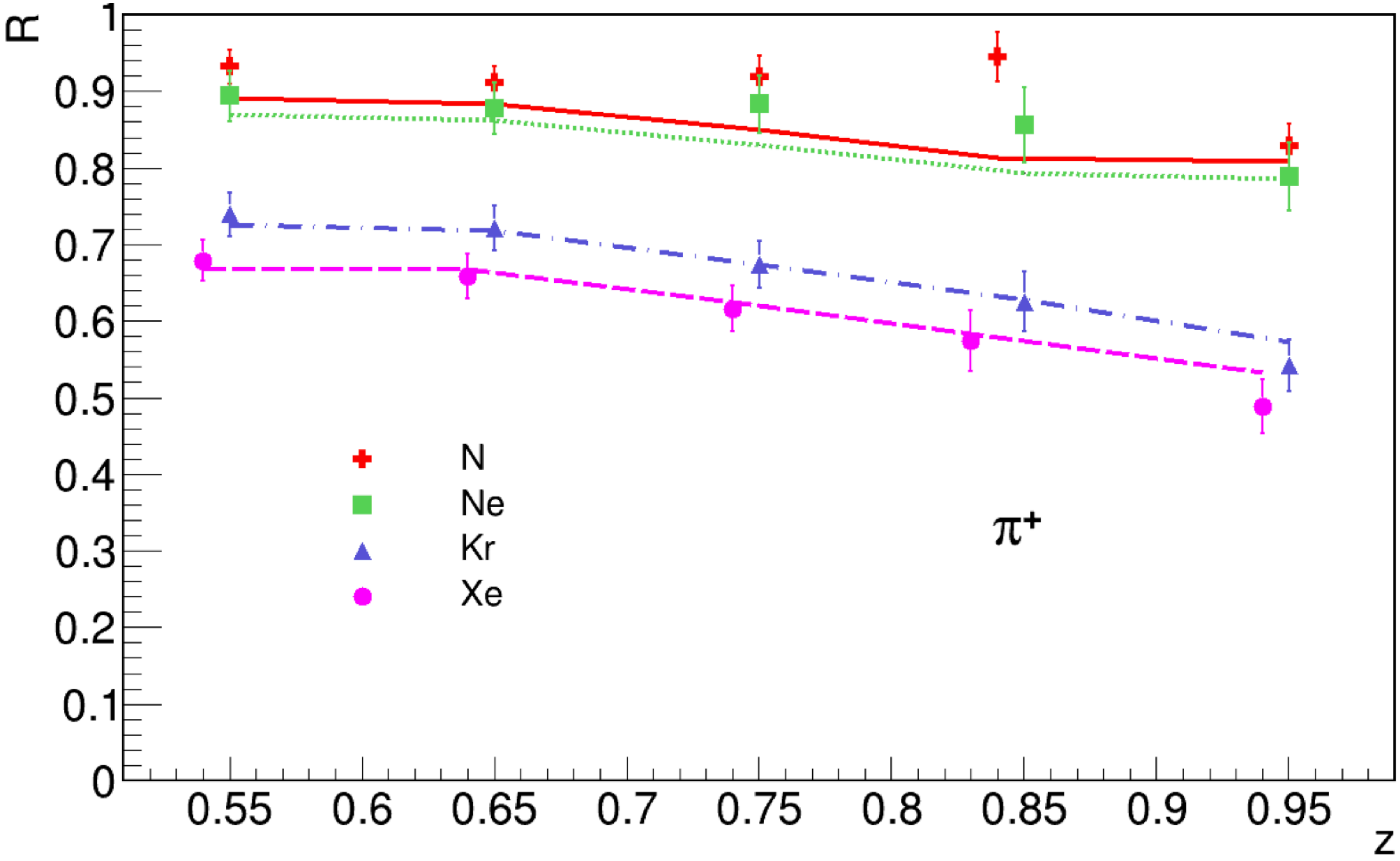

Figure 7: Multiplicity ratio for π^+, compared to HERMES data [10, 11]. The solid line is for nitrogen, the dotted line for neon, the dashed-dotted line for krypton and the dashed line for xeon.

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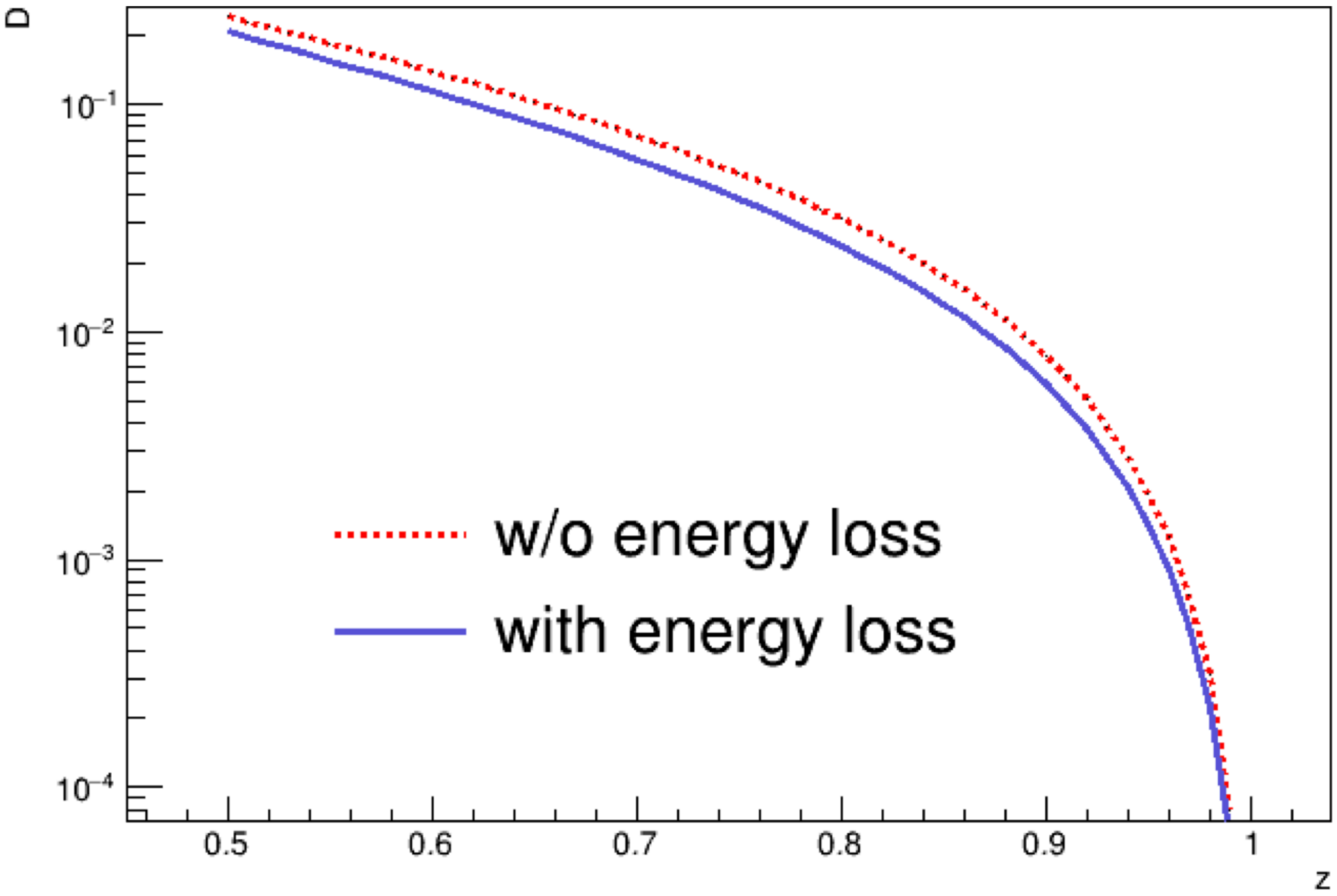

Figure 5: Fragmentation function with and without energy loss. We used $E = 13$ GeV and $Q^2 = 2.5$ GeV^2. The absolute normalization is not computed, this factor will cancel in the ratio.

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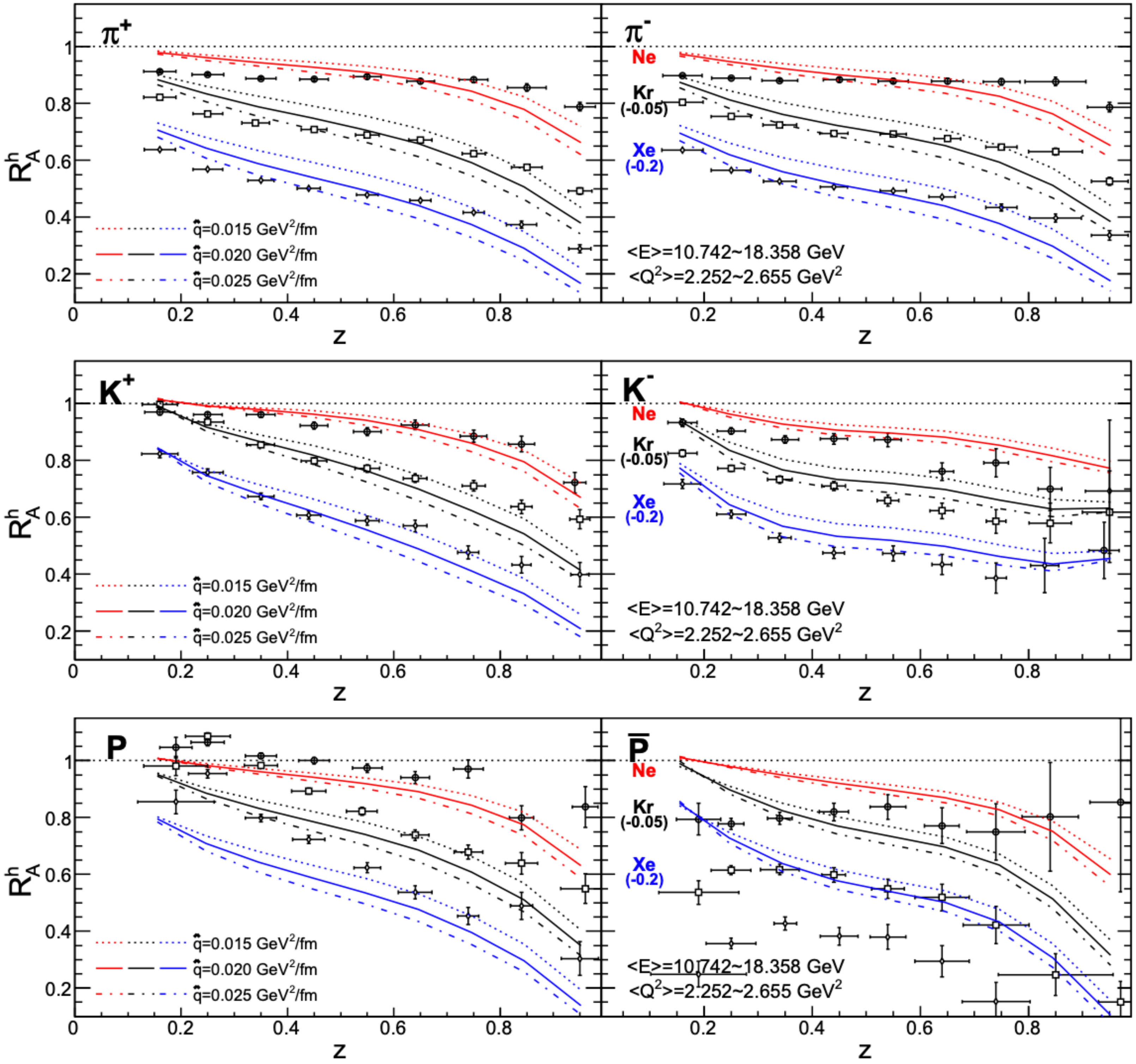

FIG. 2: (color online) The z dependence of calculated R_A^h for pions (top), kaons (middle), protons and anti-protons (bottom panel) with the convoluted initial condition for different values of $\hat{q}_0$ compared with HERMES data[42] for Ne, Kr and Xe targets. For clarity, values of R_A^h for Kr and Xe targets are displaced by -0.05 and -0.2, respectively.

Ning-Bo Chang, Wei-Tian Deng, and Xin-Nian Wang Phys. Rev. C **89**, 034911, https://arxiv.org/pdf/1401.5109.pdf

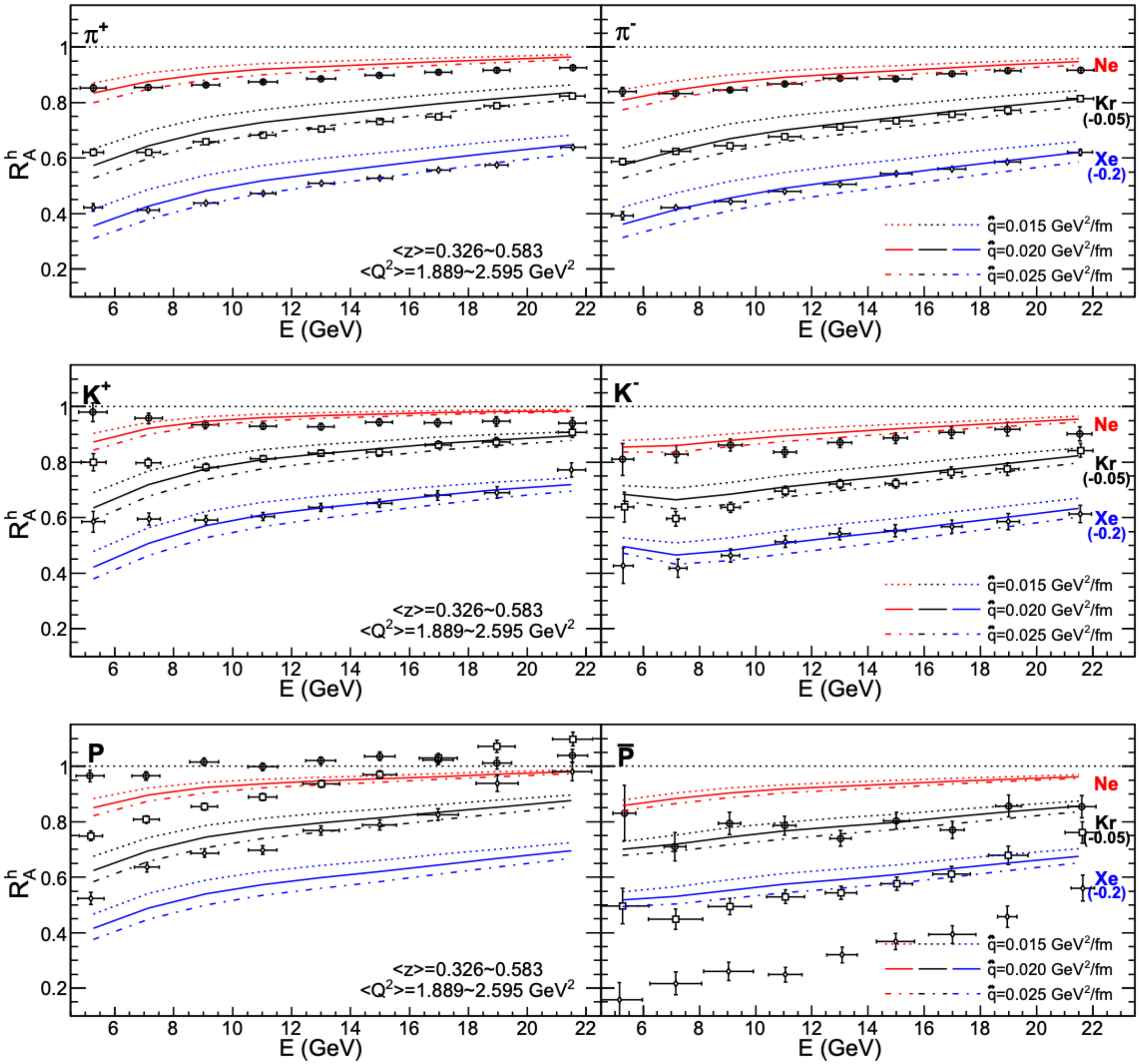

FIG. 3: (color online) The same as Fig. 2 except for the suppression factor as a function of initial quark energy E.

Ning-Bo Chang, Wei-Tian Deng, and Xin-Nian Wang Phys. Rev. C **89**, 034911, https://arxiv.org/pdf/1401.5109.pdf

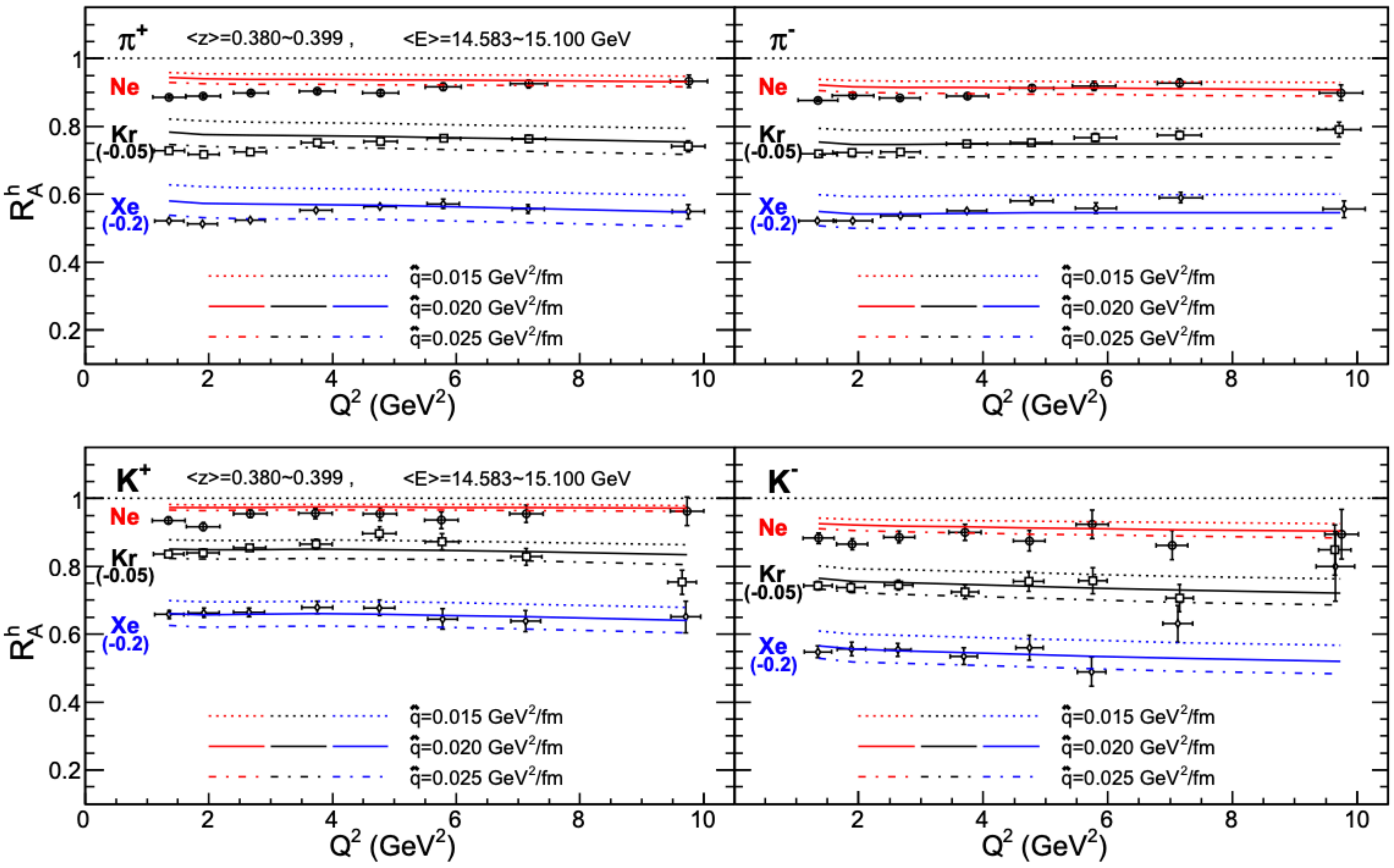

FIG. 4: (color online) The same as Fig. 2 except for the suppression factor as a function of initial quark virtuality Q^2.

Ning-Bo Chang, Wei-Tian Deng, and Xin-Nian Wang Phys. Rev. C **89**, 034911, https://arxiv.org/pdf/1401.5109.pdf

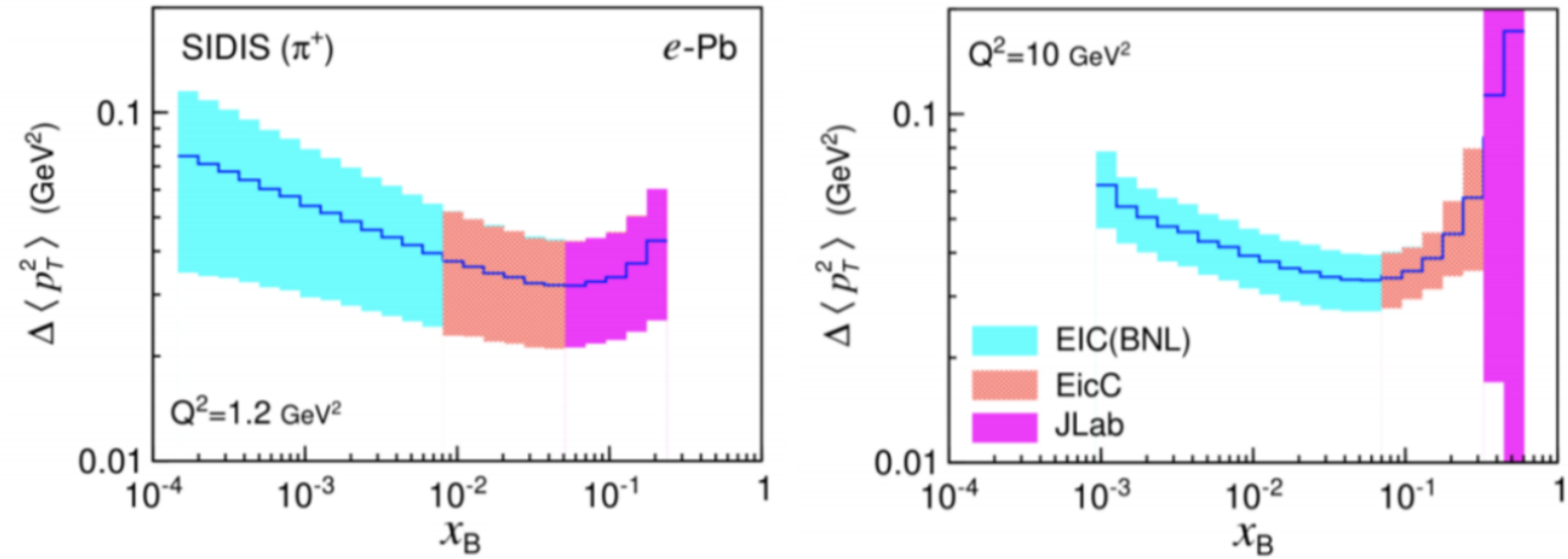

Figure 2: Transverse momentum broadening predicted as a function of Bjorken x and momentum squared transfer Q^2 The light blue, brown, and purple color show kinematics that can be accessed at JLab, and future Electron-Ion Colliders.

Ru presentation, Hard Probes 2020

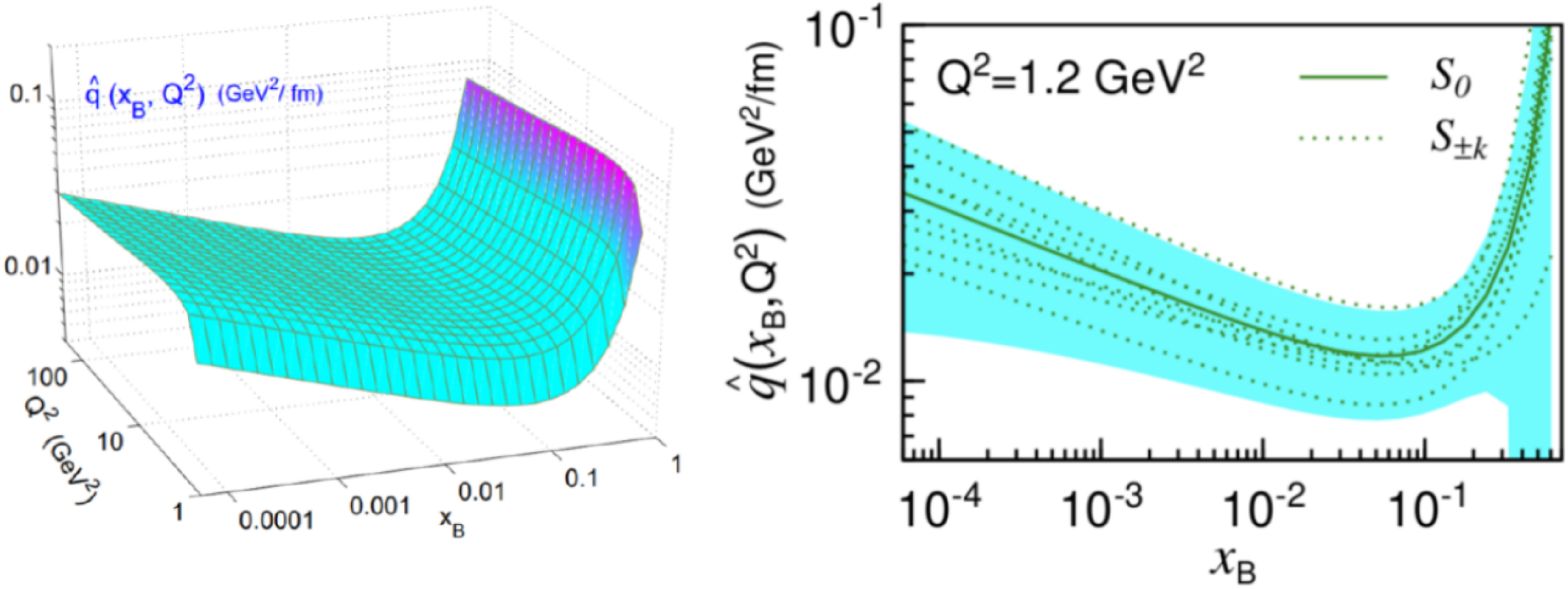

Figure 1: Kinematic dependence of the transport parameter coefficient $\hat{q}$ which was obtained by Ru et al. [8] with a global analysis to SIDIS, Drell-Yan, and quarkonia in proton-nucleus collisions.

Zhongbo Kang et al.