Color Propagation Studies in CLAS: Present and Future

Will Brooks, for the EG2^{++} CP Group

EG2^{++} Physics

- Color Propagation (today’s topic)
- Color Transparency
- Short-range Nucleon-Nucleon Correlations
- Di-hadron Correlations (some on this today too)
- Much more!

Physics Thrusts of Color Propagation Studies

- Fundamental properties of QCD Color Propagation in hadronization
  - *Characterize* the two stages of color propagation: quasi-free quark and forming hadron (asymptotic freedom ⟶ confinement)
  - Use nuclei as spatial filters to determine time scales via distances
- Quark structure of nuclei
  - the $\hat{q}$ transport coefficient is the primary measure of parton interaction with medium
  - Δp_T^2 observable ($\propto \hat{q}$) measures quark-gluon correlation function $T^A_{qF}(x_{Bj},Q^2)$:

Guo and Qiu, PRD 61 (9) (2000) http://dx.doi.org/10.1103/PhysRevD.61.096003

Luo, Qiu, Sterman, Phys. Rev. D 50 (1994) 1951– 1971. https://link.aps.org/doi/10.1103/PhysRevD.50.1951

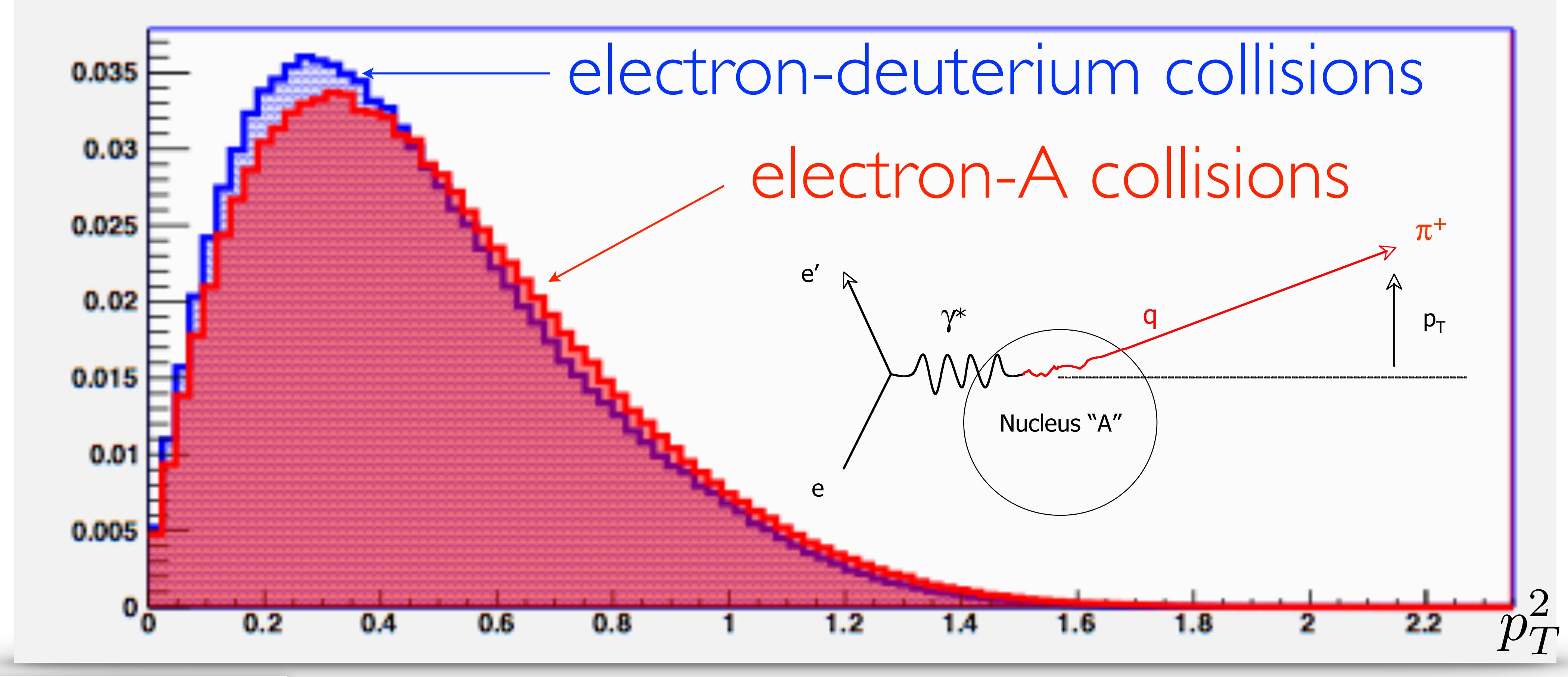
XF Guo, Phys. Rev. D 58, 114033 (1998), https://link.aps.org/doi/10.1103/PhysRevD.58.114033

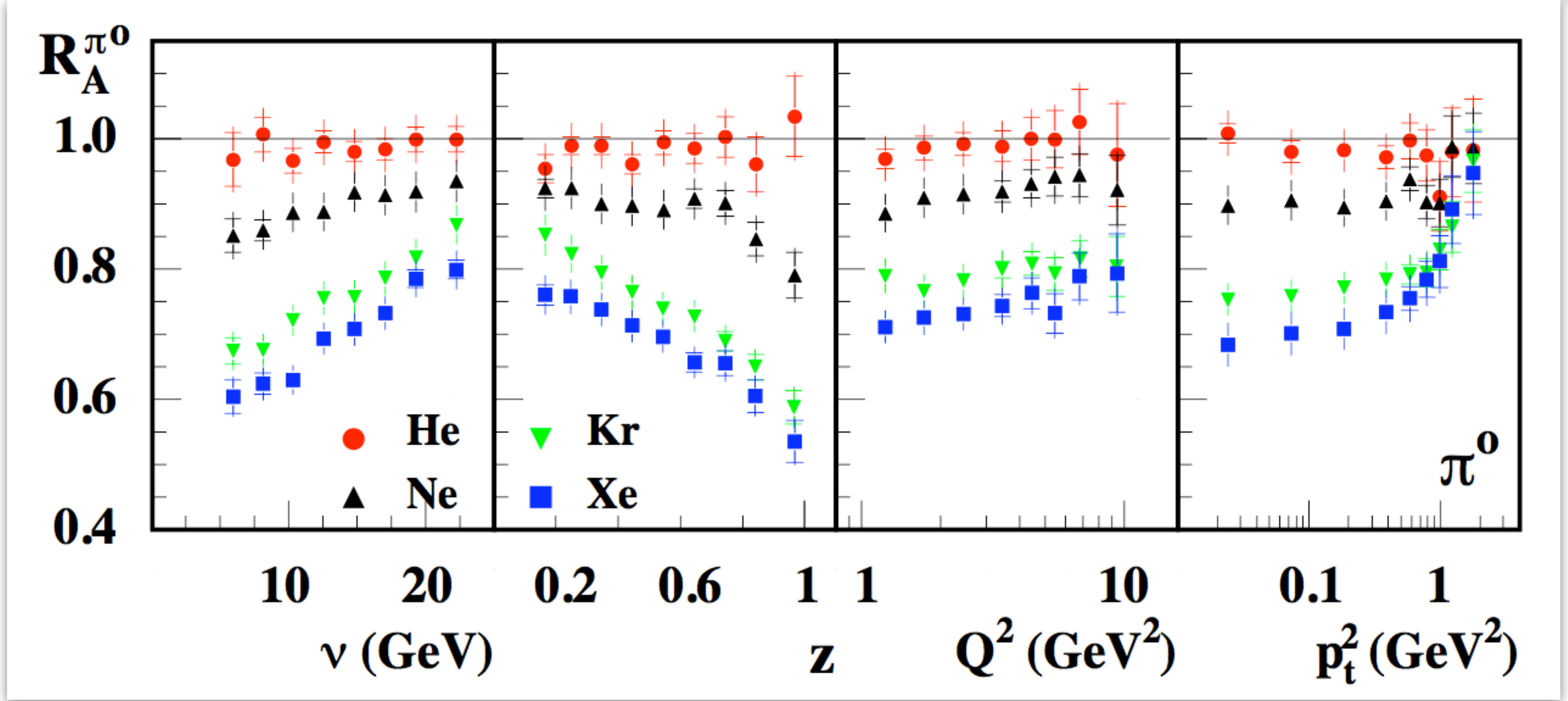
$$\Delta p_T^2(Q^2,\nu,z_h) \equiv \langle p_T^2(Q^2,\nu,z_h)\rangle|_A - \langle p_T^2(Q^2,\nu,z_h)\rangle|_D$$

Experimental Observables

Transverse momentum broadening

typical value <0.05 GeV²



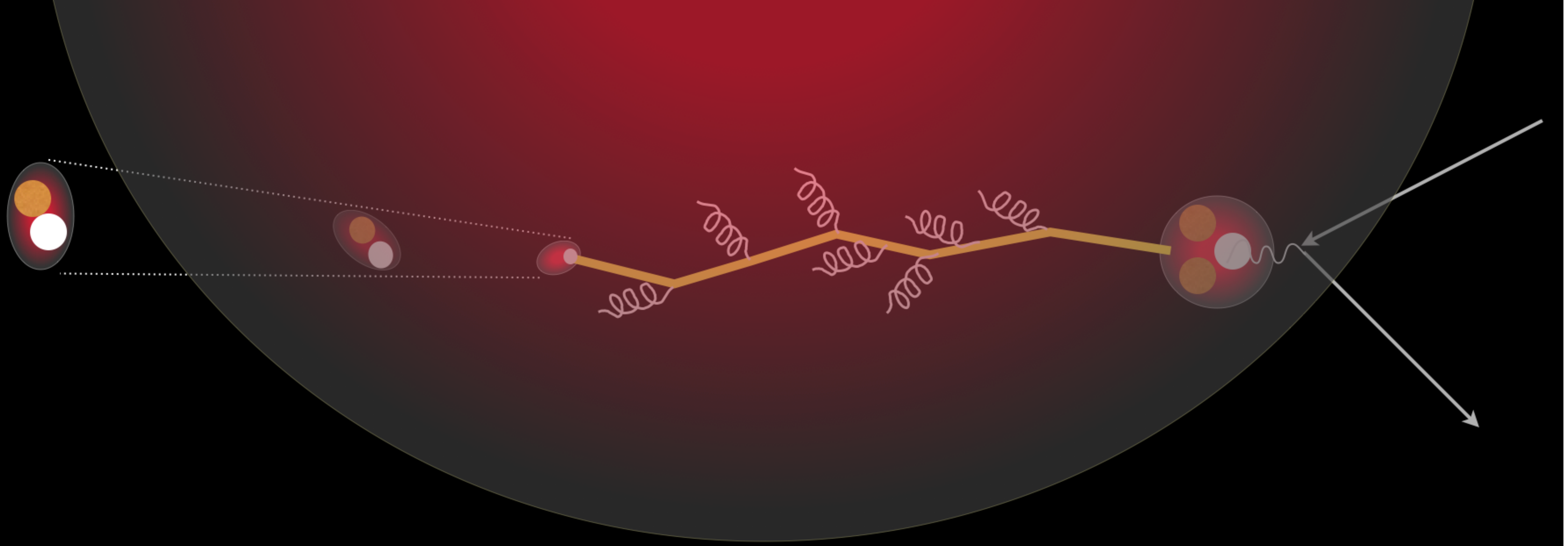


Hadronic multiplicity ratio (MR)

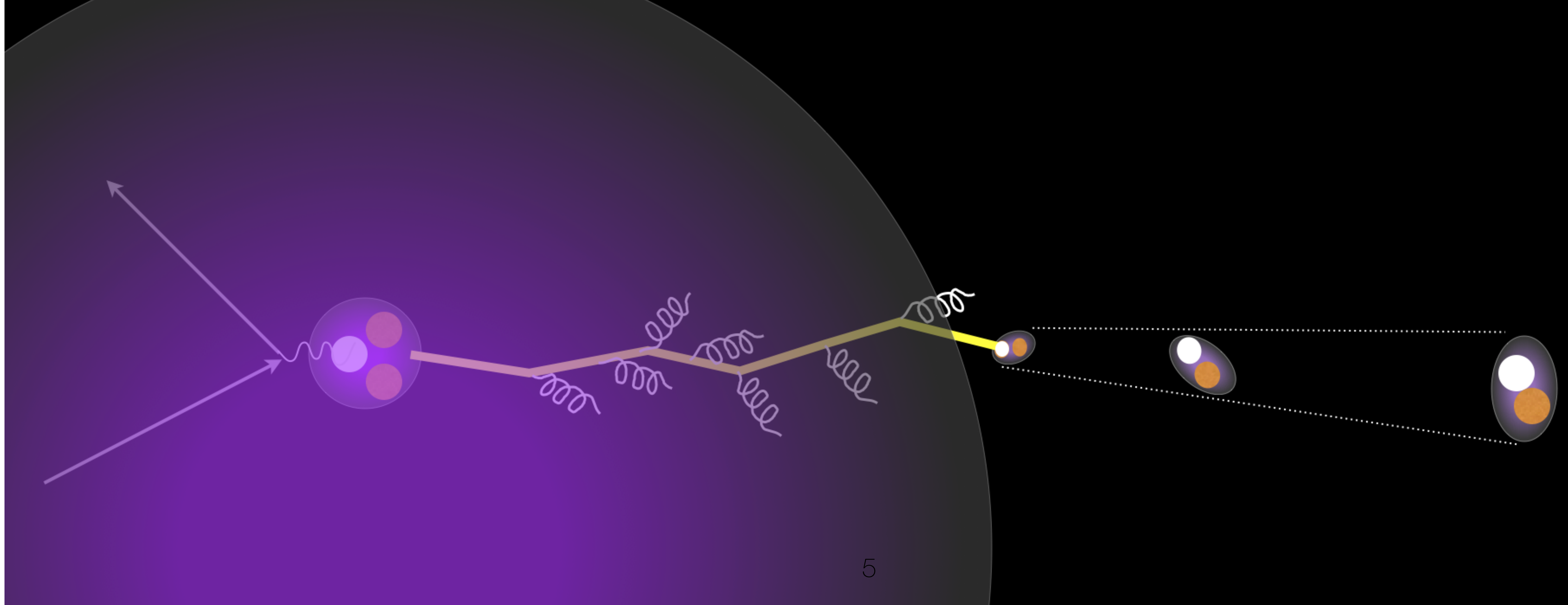
= 1 if no nuclear effects

Neutral pion MR from HERMES. CLAS results will be shown in slides 14-15!

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



Propagation of QCD color through strongly interacting systems

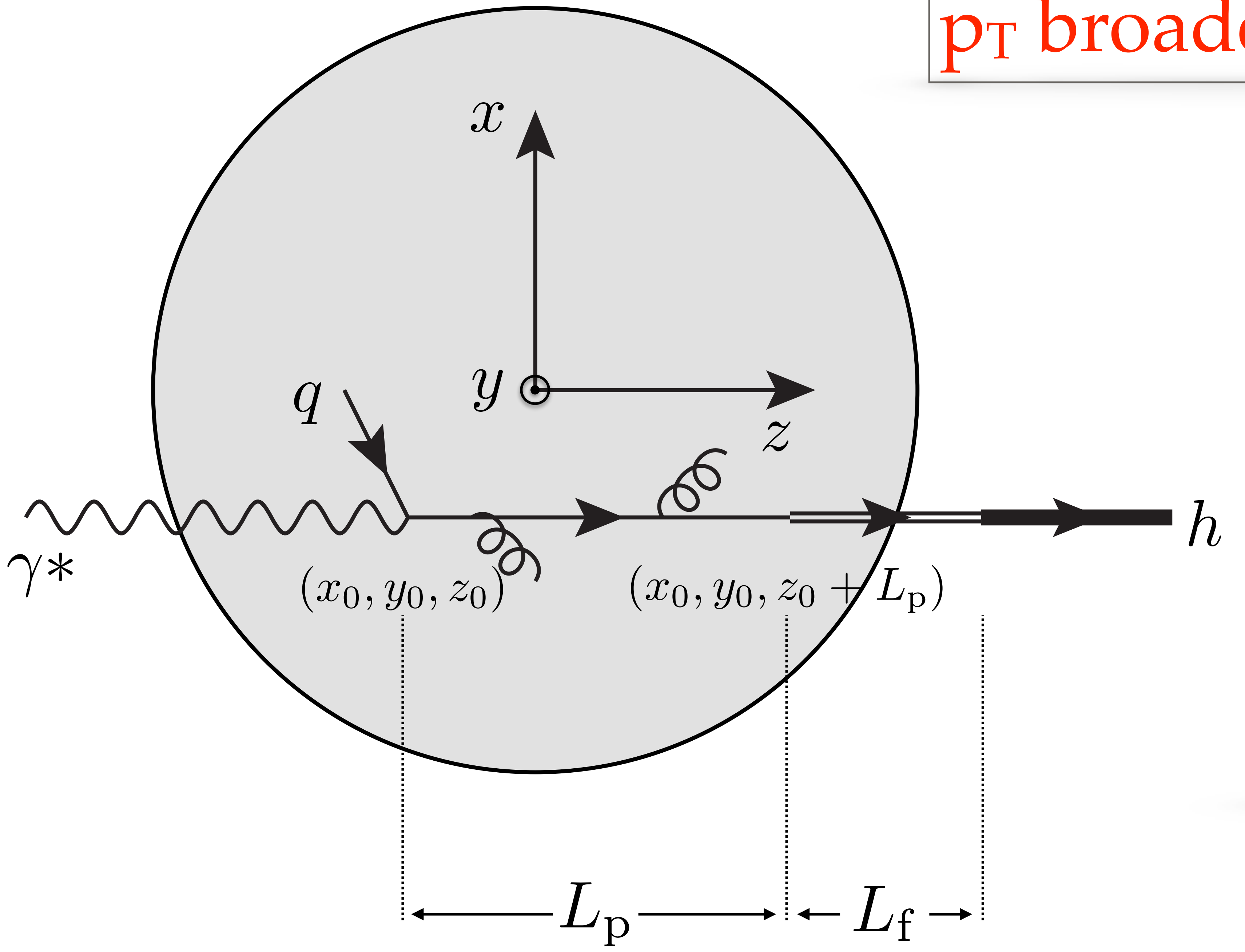


Division of the process into *partonic* and *hadronic* stages

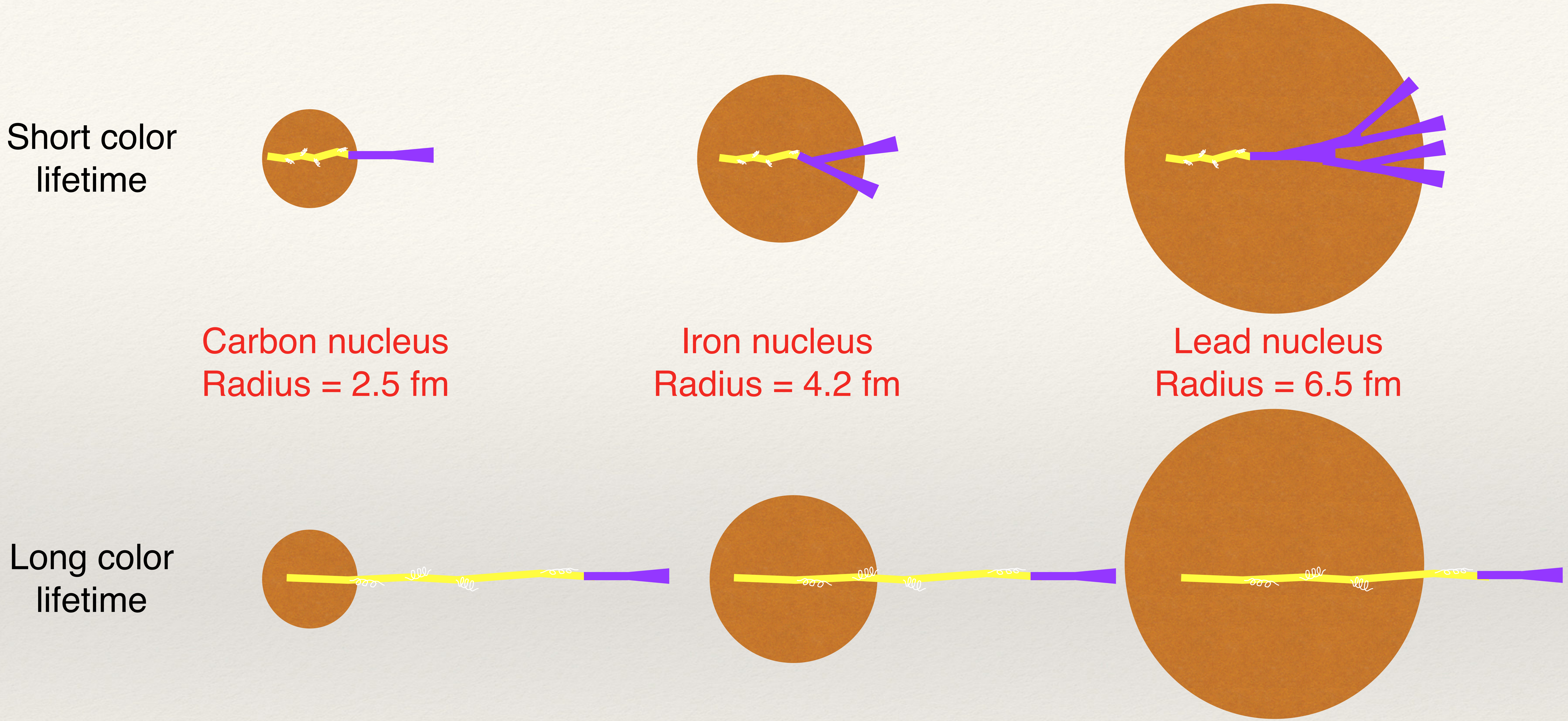
Path of (struck) quark is divided into "partonic phase" and "hadronic phase"

partonic	hadronic
L_c, $\hat{q}$, ΔE_q	σ_{inel}
p_T broadening	Multiplicity ratio

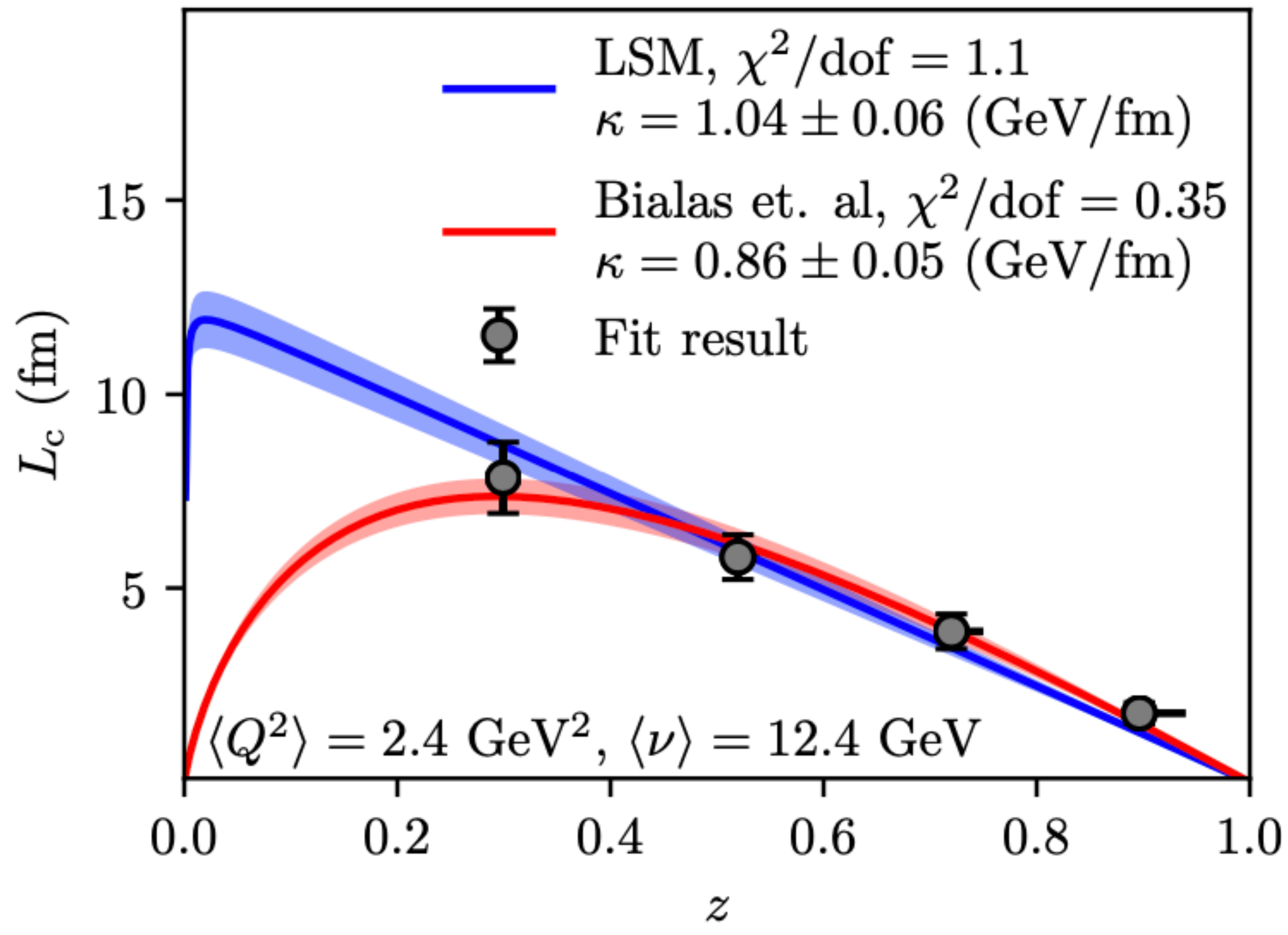
The partonic phase persists for a distance L_c, over which p_T broadening via $\hat{q}$, and partonic energy loss ΔE_q, occur

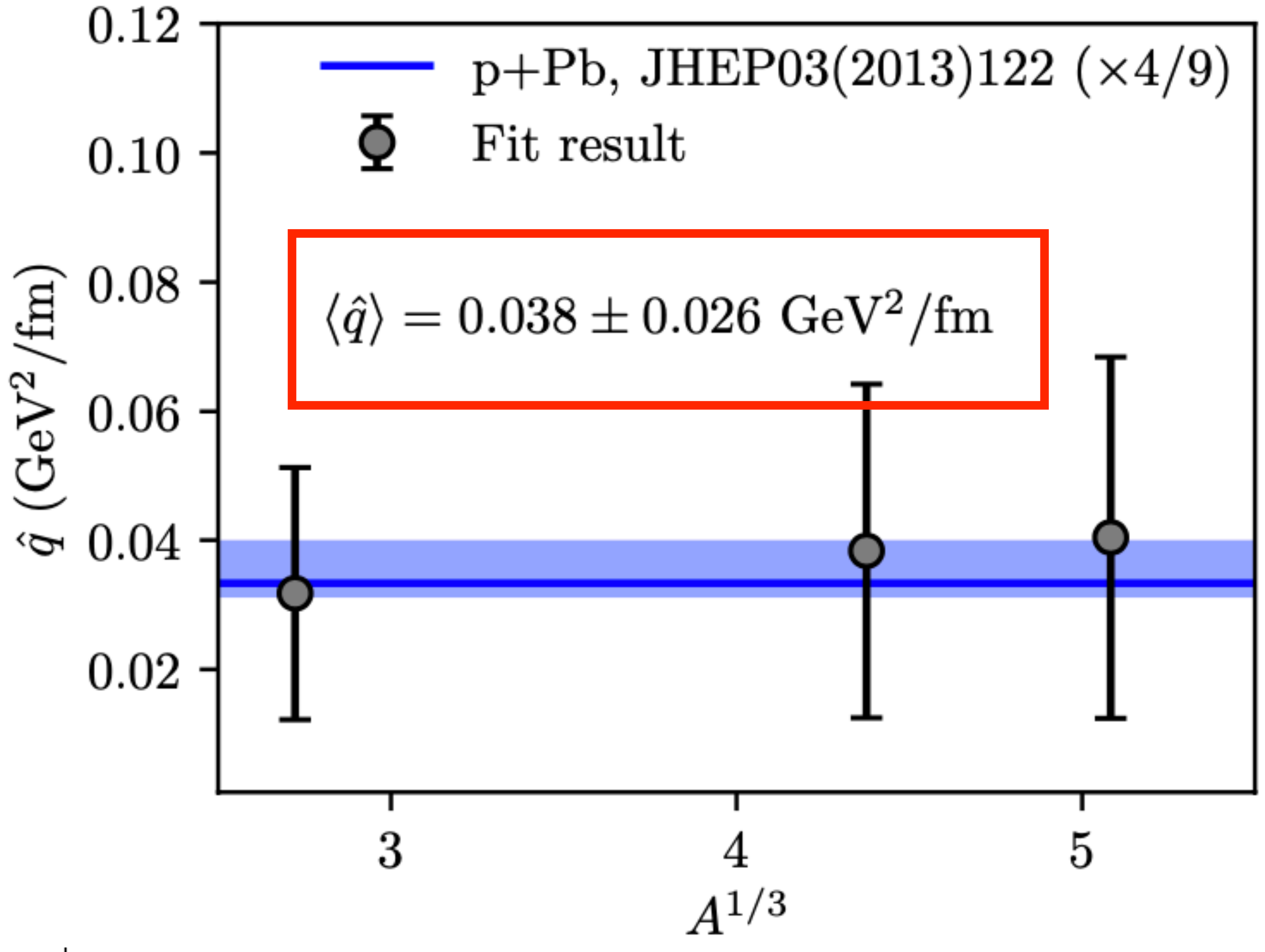


The hadronic phase follows the partonic phase, passing through the remainder of the medium, and causing attenuation of hadrons by an inelastic interaction cross section σ_{inel}



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

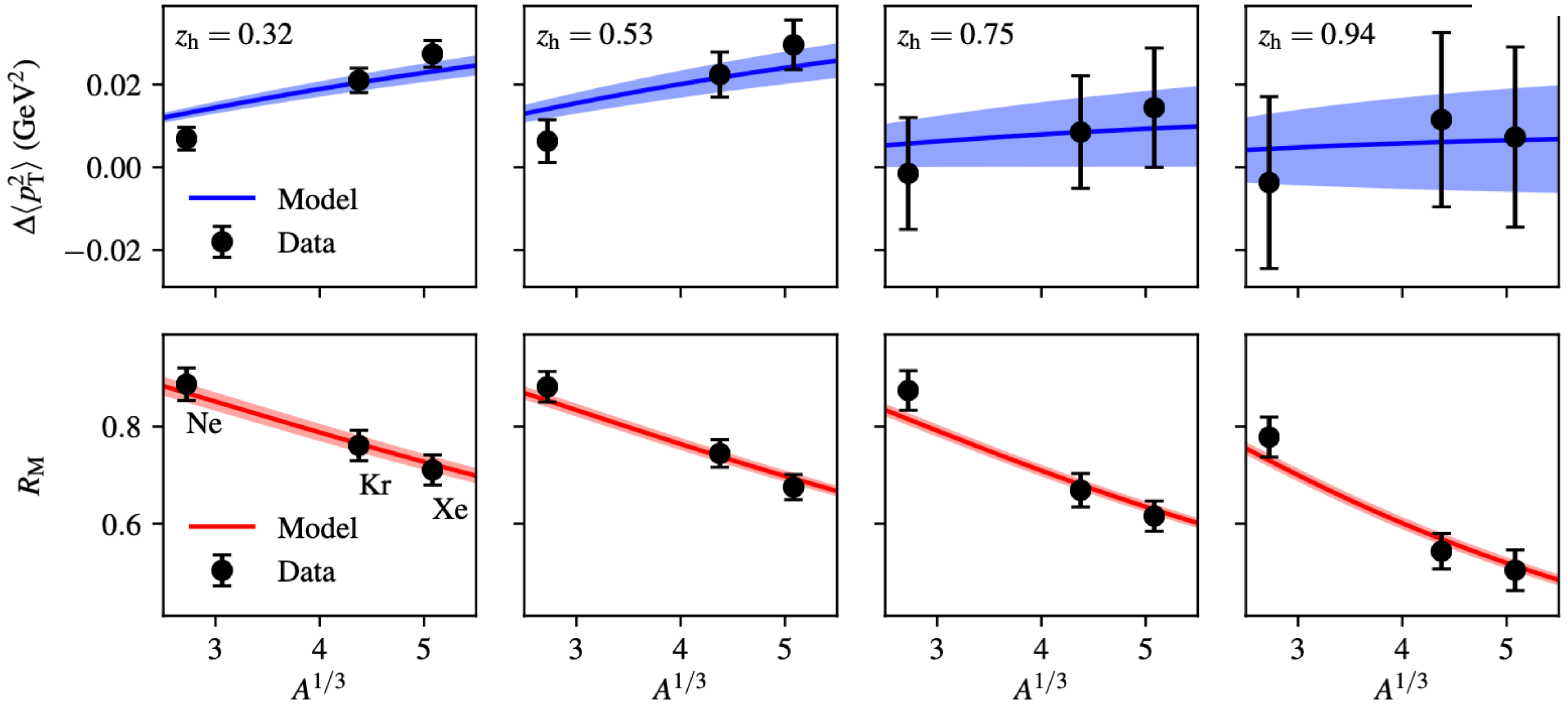


Table 1: Results from fits to the data and to analytical expressions for the color length that are connected to the Lund String Model. The label "struck quark" refers to Equation 3 (see supplementary materials). The label "B&G" refers to a 1987 paper by Bialas and Gyulassy [51].

		χ^2/dof of fit to data vs. z_h				Fit of results to LSM analytical forms		
Model Variant	Free parameters	0.32	0.53	0.75	0.94	Analytical form	κ (GeV/fm)	χ^2/dof
Baseline Model with fixed hadronic cross-section	2	1.8	1.1	0.7	0.5	struck quark	1.04 ± 0.06	1.10
						B&G	0.86 ± 0.05	0.35
Baseline Model with free hadronic cross-section	3	2.3	1.5	0.9	0.7	struck quark	1.02 ± 0.36	0.08
						B&G	0.88 ± 0.31	0.15
Baseline Model with quark energy loss	3	2.4	1.3	0.5	0.3	struck quark	1.23 ± 0.09	0.16
						B&G	1.09 ± 0.08	1.09

Simultaneous fit to multiplicity ratio and p_T broadening

Brooks and López, https://arxiv.org/abs/2004.07236

Independently reproduces the Lund String Model string constant!

What can CLAS+CLAS12 add to these studies?

Much more luminosity than HERMES

- As a result, can study rare and/or complex states: $\boldsymbol{\omega}$ meson, η meson, Λ baryon (now) and ϕ meson, η' meson, Σ and Ξ baryons, and more at 12 GeV!
- This will allow to probe mass, strangeness, and rank dependence of hadron formation and color propagation. This is ***terra incognita!***
- New motivation for studying baryons with these observables: new ideas that may reveal model-independent view of diquark degrees of freedom for neutrons, protons and lambdas. New baryon structure information from nuclear target experiments!

CLAS and CLAS12 Color Propagation Hadrons

Actively underway with existing 5 GeV data

meson	cτ	mass	flavor content	*baryon*	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	p	stable	0.94	ud
π^+, π^-	7.8 m	0.14	$u\bar{d}, d\bar{u}$	$\bar{p}$	stable	0.94	$\overline{ud}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	Λ	79 mm	1.1	uds
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\Lambda(1520)$	13 fm	1.5	uds
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	Σ^+	24 mm	1.2	us
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	Σ^-	44 mm	1.2	ds
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	Σ^0	22 pm	1.2	uds
K^0	27 mm	0.50	$d\bar{s}$	Ξ^0	87 mm	1.3	us
K^+, K^-	3.7 m	0.49	$u\bar{s}, \bar{u}s$	Ξ^-	49 mm	1.3	ds

Advances Beyond HERMES from CLAS6, CLAS12, EIC with Multiplicity Ratio (MR) and p_T broadening

	HERMES	CLAS6	CLAS12	EIC
Neutral pion	1D MR	3D MR	4D MR	
Charged pions	2D MR, 1D p_T broadening 1D two-hadron MR 1D BE correlations	4D MR, 3D p_T broadening Dihadron correlations 2D BE correlations	Precise 4D MR, 3D p_T broadening Dihadron correlations 3D BE correlations	as CLAS6 but high ν, Q^2
Protons	2D MR	4D MR, 3D p_T broadening	Precise 4D MR, 3D p_T broadening	as CLAS6 but high ν, Q^2
Lambda baryons	-	1D MR, 1D p_T broadening	2D MR, 2D p_T broadening	as CLAS6 but high ν, Q^2
Heavy mesons	2D MR ($K^{\pm}$), 1D p_T broadening (K^+)	1D MR for ω and η	2D MR for ω and η (pT broadening?), 1D MR for ϕ, η', K	as CLAS6 but high ν, Q^2
Other heavy baryons	-	-	1D-2D MR for Λ(1520), Σ, Ξ, p-bar	TBD

Plus new observables such as multi-hadron correlations, polarization information, grey tracks, etc.

Spokespersons and Institutions for the CLAS12 Experiment

E12-06-117	Quark Propagation and Hadron Formation	W. Brooks*	Fed. St. Maria
		W. Armstrong	ANL
		M. Arratia	U. California Riverside
		R. Dupre	IPN ORSAY
		A. El Alaoui	Fed. St. Maria
		L. El Fassi	Mississippi State
		G. Gilfoyle	U of Richmond
		H. Hakobyan	Fed. St. Maria
		K. Hicks	Ohio U
		M. Holtrop	U of NH
		K. Joo	U of Conn
		T. Mineeva	Fed. St. Maria
		G. Niculescu	JMU
		M. Niculescu	JMU
		O. Soto Sandoval	INFN
		M. Wood	USCA

Selected results from CLAS6

π^0 3D Multiplicity Ratios

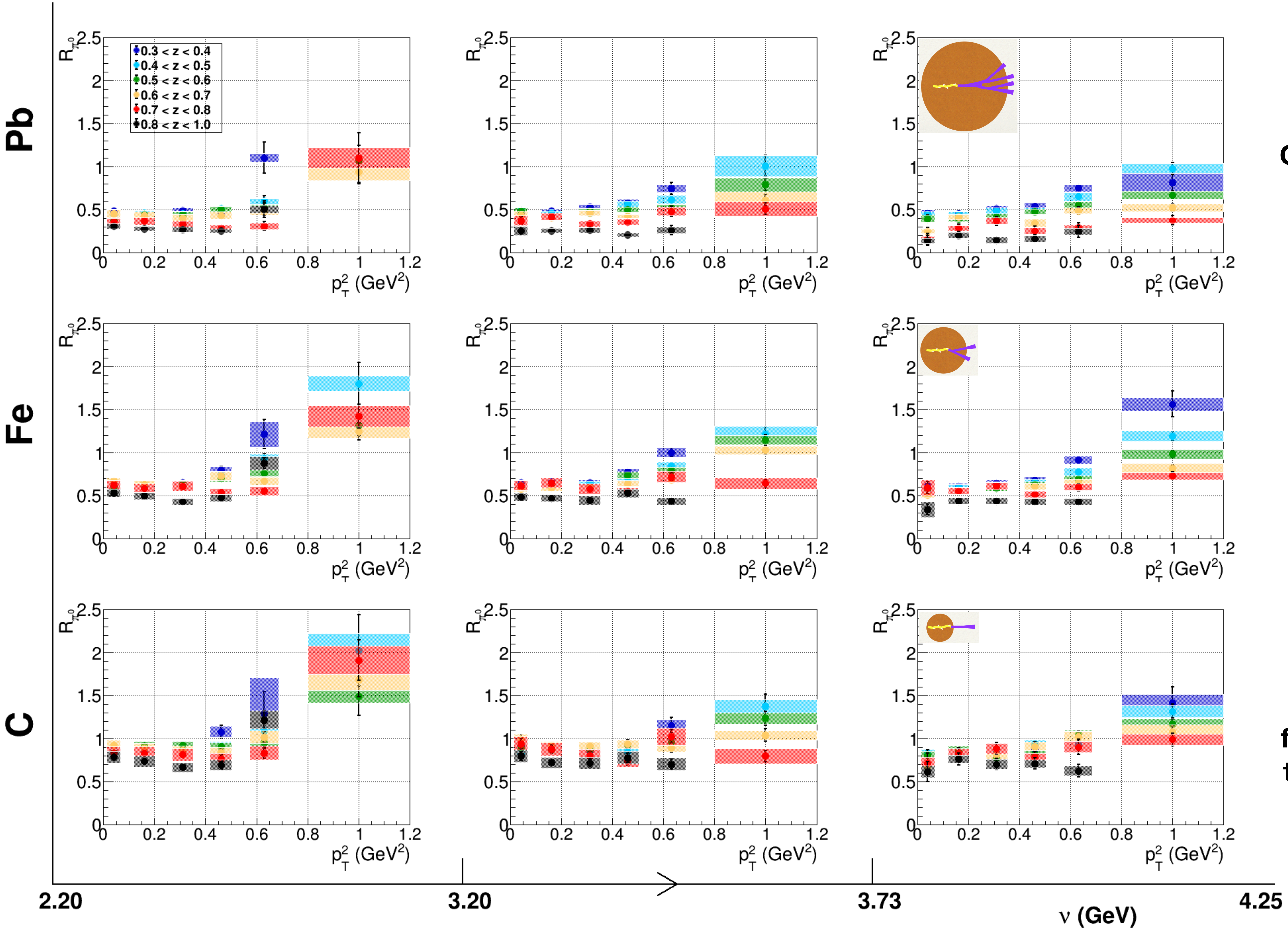
Dr. Taisiya Mineeva, UTFSM

(UConn PhD 2013, K. Joo Thesis Advisor)

(3rd round of analysis review completed)

Note: almost 80% of the neutral pions “disappear” from the high z bin in Pb!
This is a dramatically strong interaction.
Even at low z, half of them are still “missing.”

π⁰ 3D MR (continued), Dr. Taisiya Mineeva, UTFSM



Neutral pion 3D MR

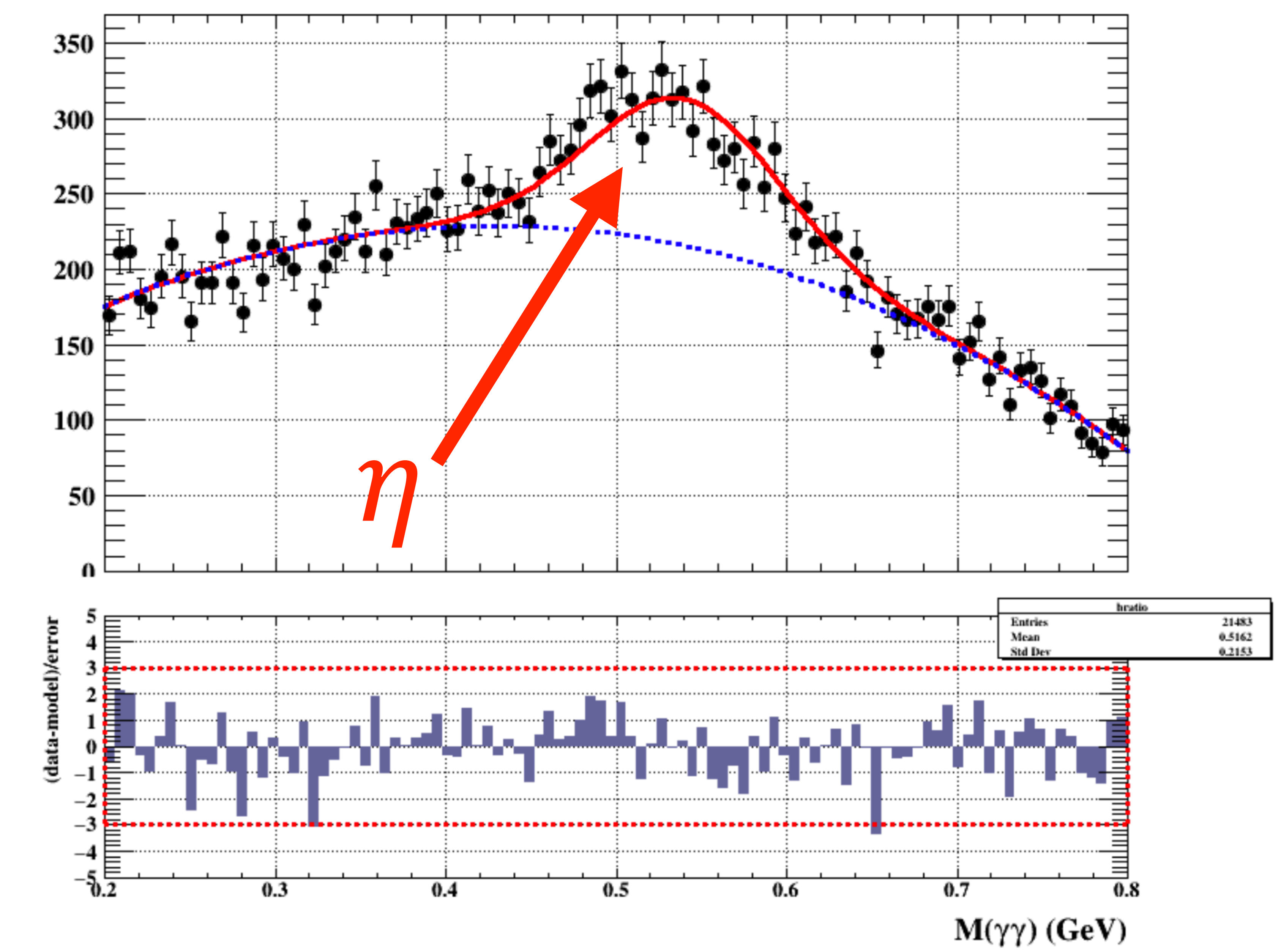
Cronin-like enhancement at high p_T as expected, NOT SEEN by HERMES due to insufficient statistics.

Regular z-ordering at high ν and high p_T, especially for lower-A, consistent with a few-fm average color lifetime that goes to zero at high z as expected.

Eta Meson Multiplicity Ratios

Dr. Orlando Soto, INFN Frascati

- PhD thesis topic from UTFSM, 2018 (Prof. Hayk Hakobyan, thesis advisor)
- A world's first measurement of nuclear DIS production of eta mesons
  - Limited statistics in this pioneering work; will be much better in CLAS12
- Performed in 2 decay channels
  - Cross-check for consistency; decay channel dependence not anticipated due to $c\tau \approx 170$ pm lifetime of eta meson



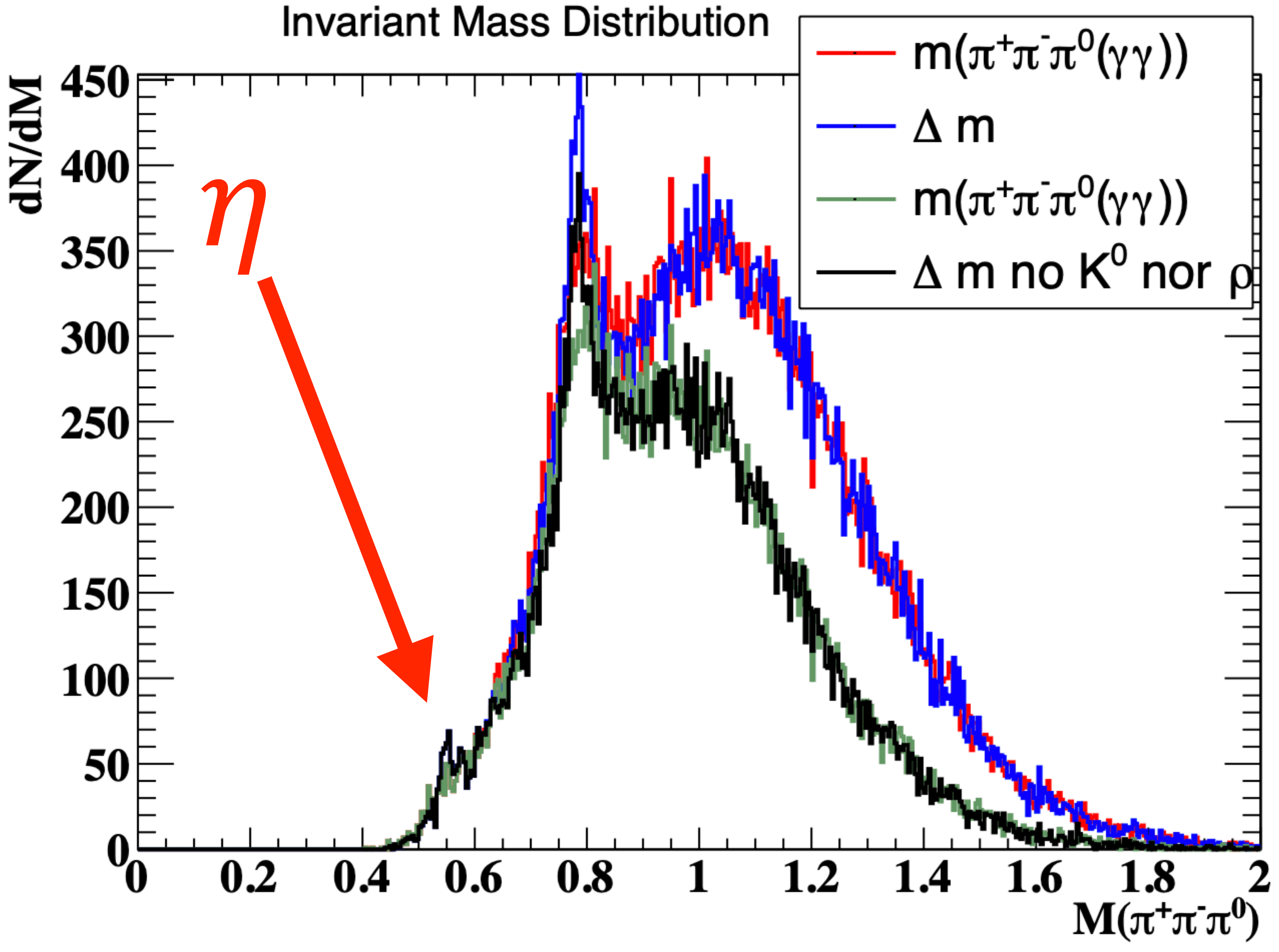
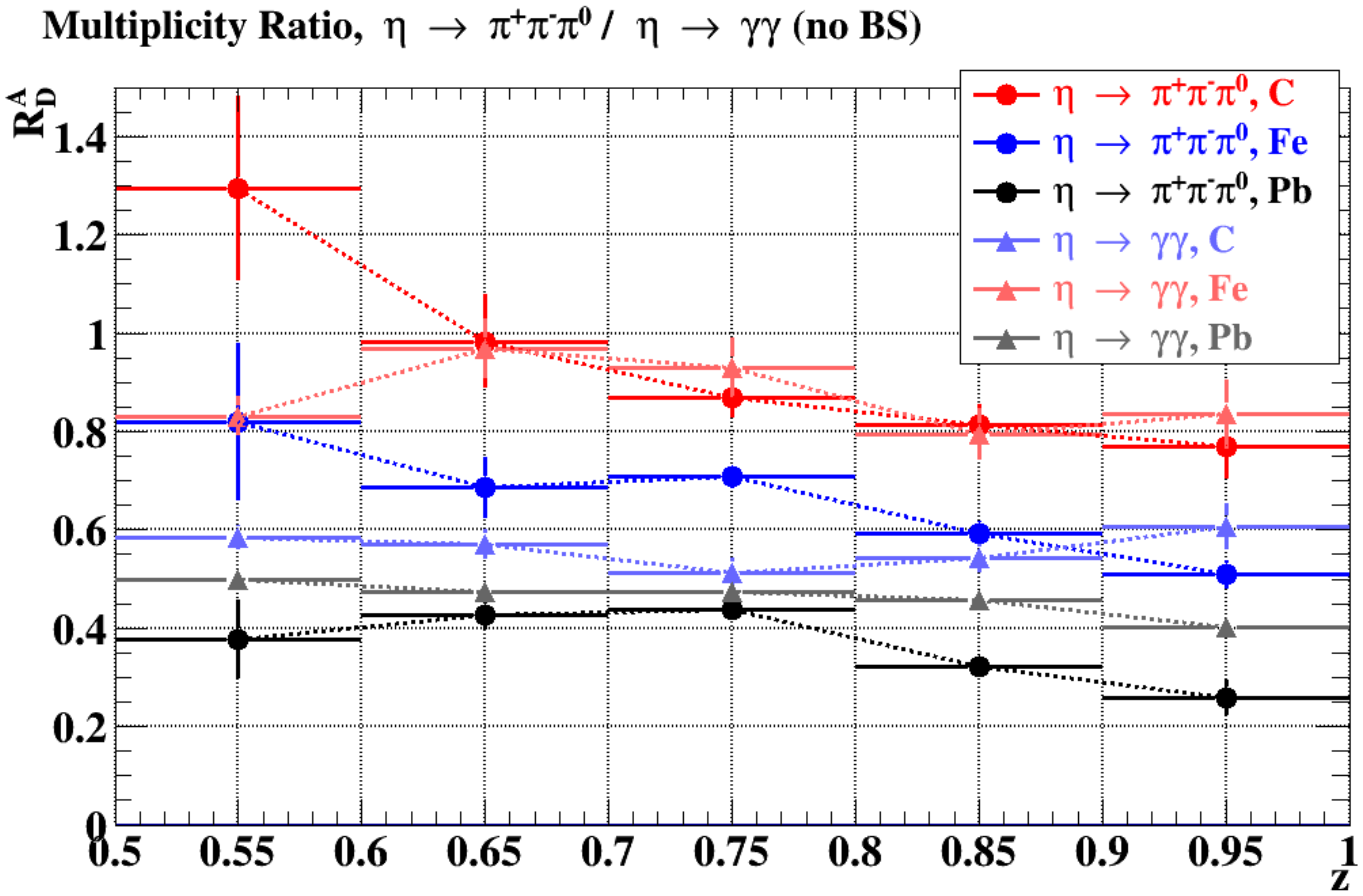


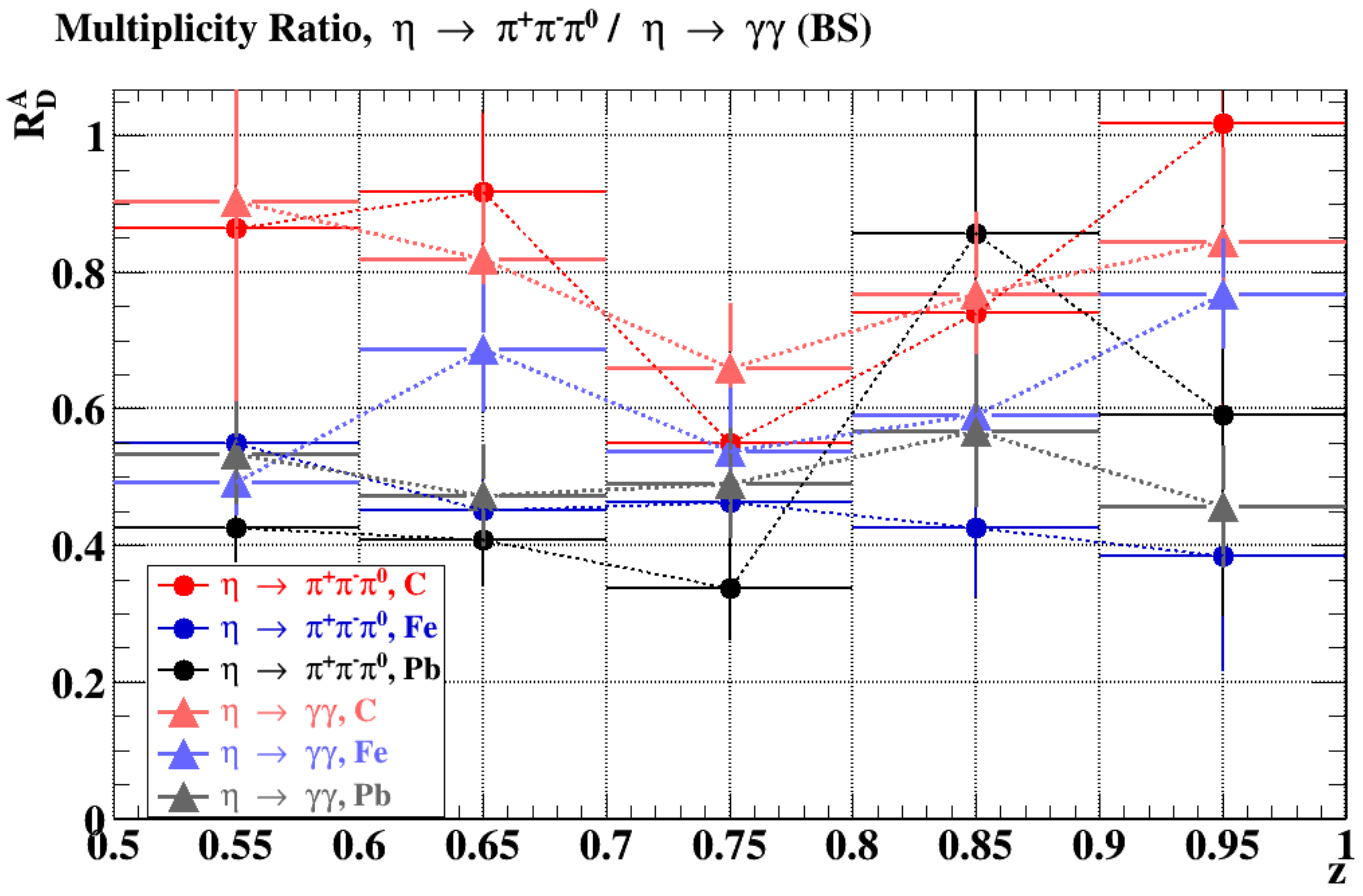
Figure 3.23: Invariant mass $m(\pi^+, \pi^-, \gamma, \gamma)$ with a cut $0.1 < m(\gamma, \gamma) < 0.2$.

Multiplicity Ratio without background subtraction.

(Shows statistical information quality)

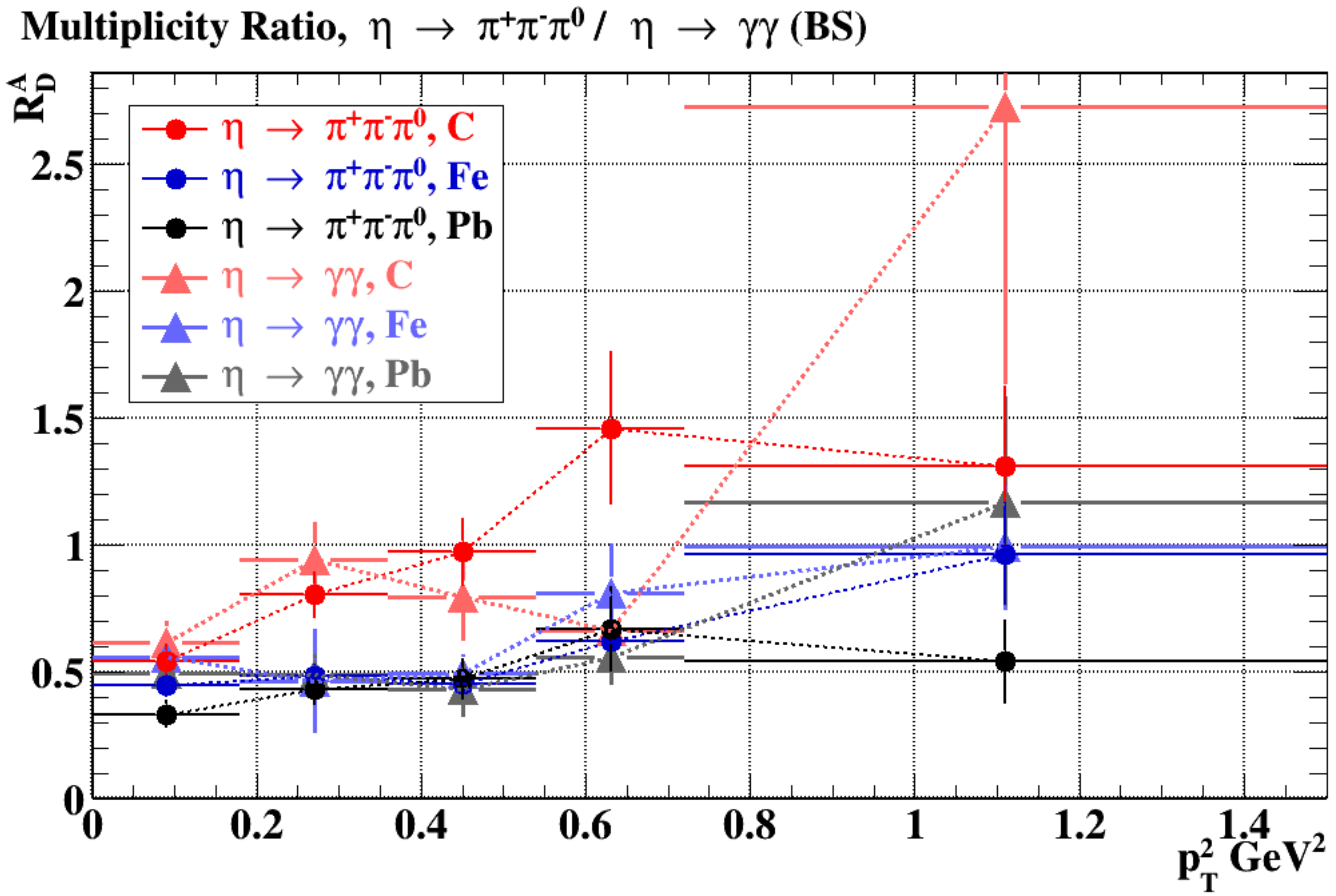
The two decay channels are not consistent without background subtraction.

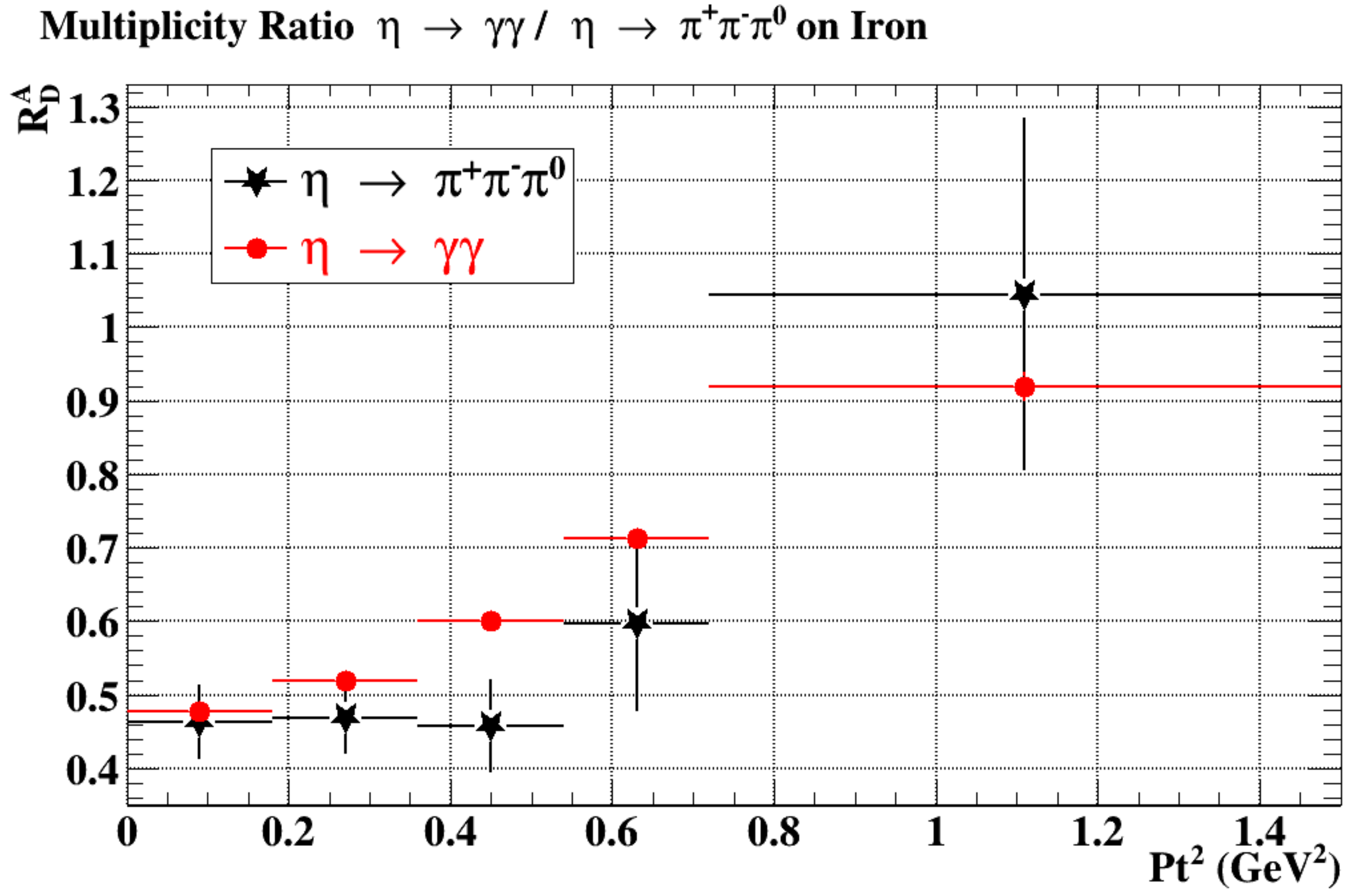




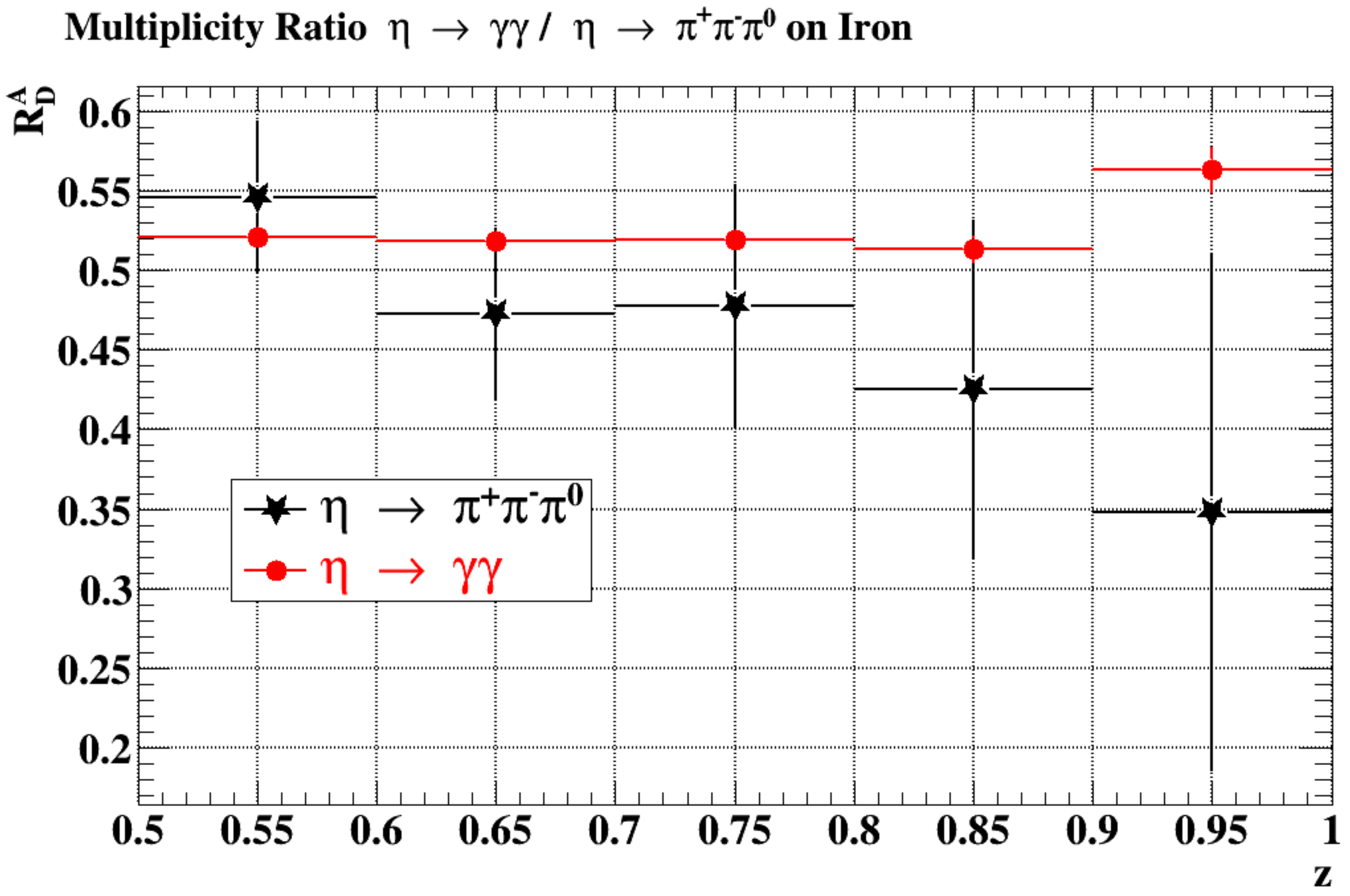
With **background subtraction, there is a hint that the two channels give the same MR for three nuclei, within large statistical uncertainties.**

With **background subtraction, there is a hint that the Cronin-like effect is seen for all three nuclei and both decay channels, with very large statistical uncertainties.**





The expected Cronin-type enhancement is clearly seen in both channels for the iron nucleus where the statistical information is best



The expected attenuation at high z is not yet clearly seen on the iron nucleus

Charged Pion Multiplicity Ratios

Prof. Hayk Hakobyan (PhD 2008) UTFSM, Dr. Raphaël Dupré (PhD 2011) IPN Orsay
Sebastián Morán (MSc student UTFSM, Thesis advisor Prof. Hayk Hakobyan)

- Highest-statistics information for the positive pion - multidimensional studies possible up to 4-fold differential. Negative pion has more complicated acceptance, but multidimensional studies still possible.

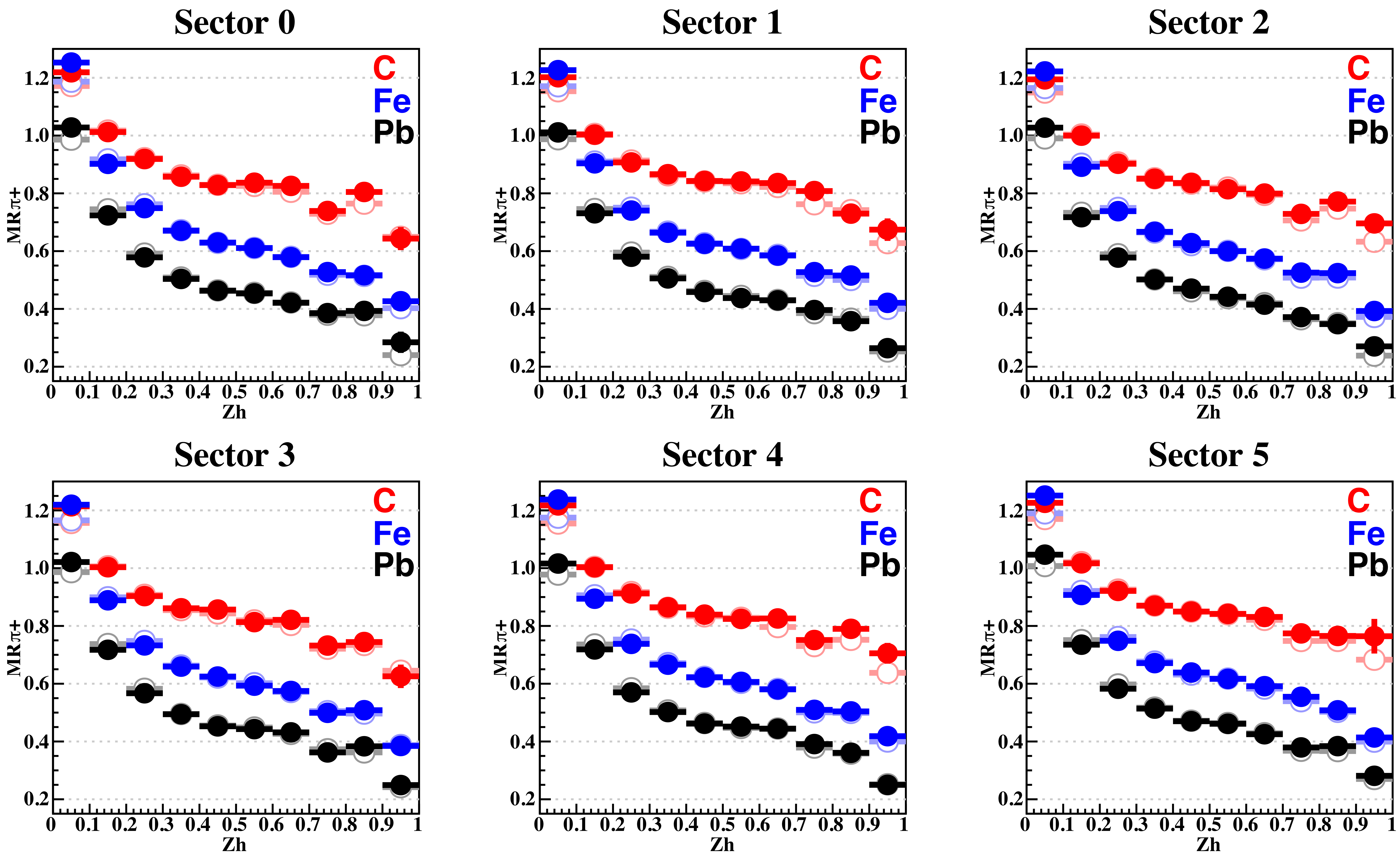
- Detailed comparison recently completed of two different analyses. All discrepancies are now resolved and the analyses agree at the 1% level.

- Analysis note written by Raphaël Dupré in 2016 (42 pages) may need to be slightly updated to reflect the new hybrid analysis; TBD. Previous plan was for a 3-pion 1D/2D paper to compare to HERMES.

https://www.jlab.org/Hall-B/shifts/admin/paper_reviews/2016/AnalysisNote_Dupre-5648485-2016-10-20-v1.pdf

π⁺ 1D MR (can be up to 4D)

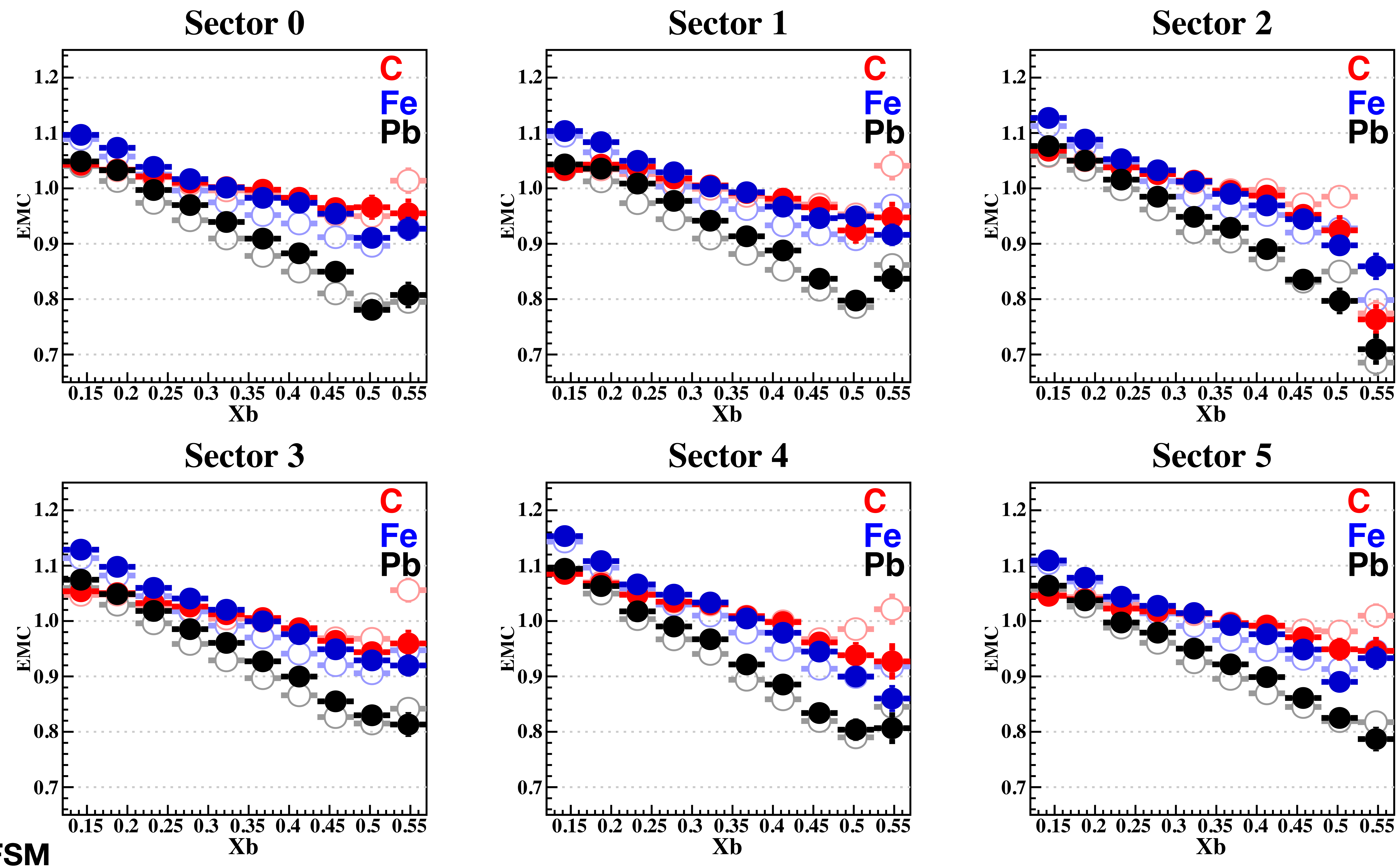
- MR with 5-fold differential acceptance correction, vs sector, SM analysis.
- Hollow symbols: no acceptance corrections



Plot from Sebastián Moran, UTFSM

EMC Effect Plots (normalization for π^+ 1D MR)

- Hollow symbols: no acceptance corrections



Plot from Sebastián Moran, UTFSM

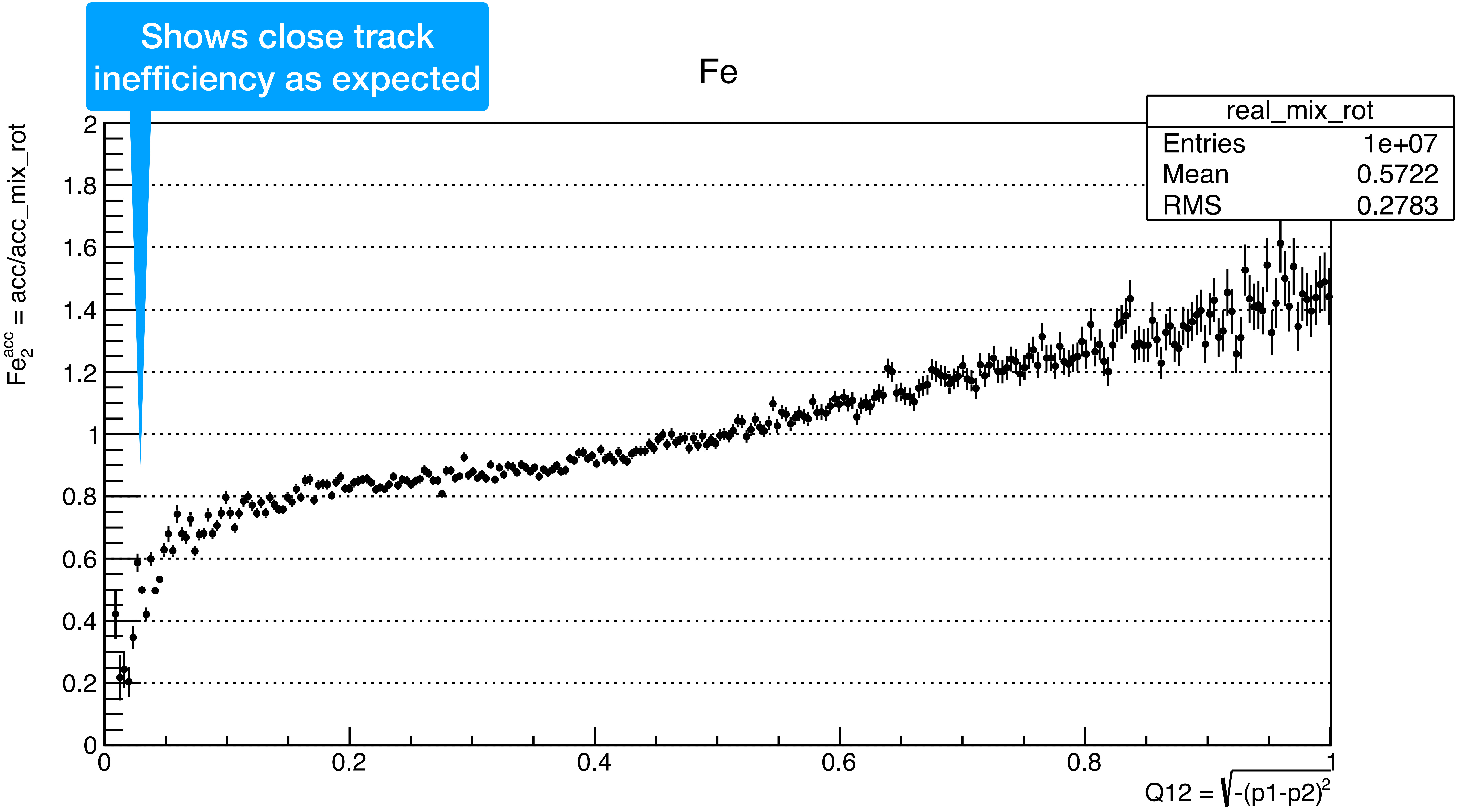
Di-hadron Studies with Nuclear Targets

- **Bose-Einstein Correlations** with DIS pions
    - Antonio Radici (MS student of Prof. Hayk Hakobyan, UTFSM)
- Di-pion **multiplicity ratio**
    - Dr. Ahmed El Alaoui, UTFSM
- Di-pion **azimuthal angular correlations**
    - Prof. Miguel Arratia, Postdoc Sebouh Paul, Sean Preins (PhD student) U. California Riverside; Luciano Arellano (MS student of WB, UTFSM)
- Di-pion **p_T/q_T broadening**
    - Carolina Robles (PhD student of WB, UTFSM)

$\pi^+\pi^+$ Bose-Einstein Correlation Studies on Nuclei

Antonio Radic (MSc student UTFSM, Thesis Advisor Prof. Hayk Hakobyan

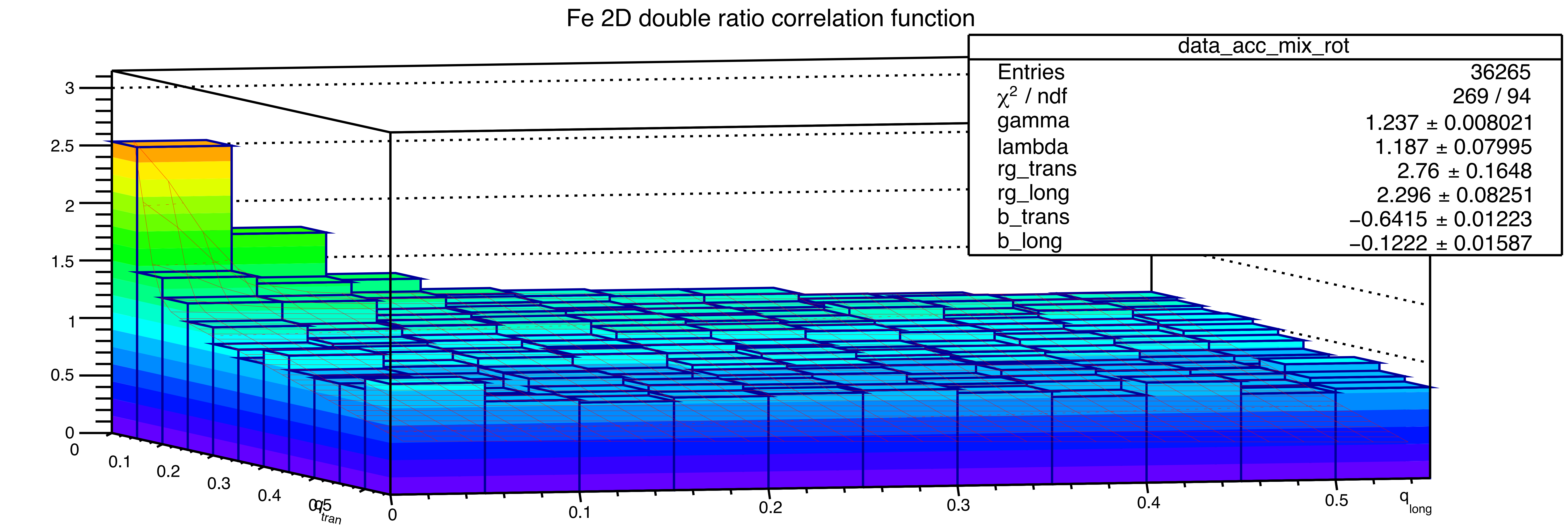
Correlation function calculated only from simulation

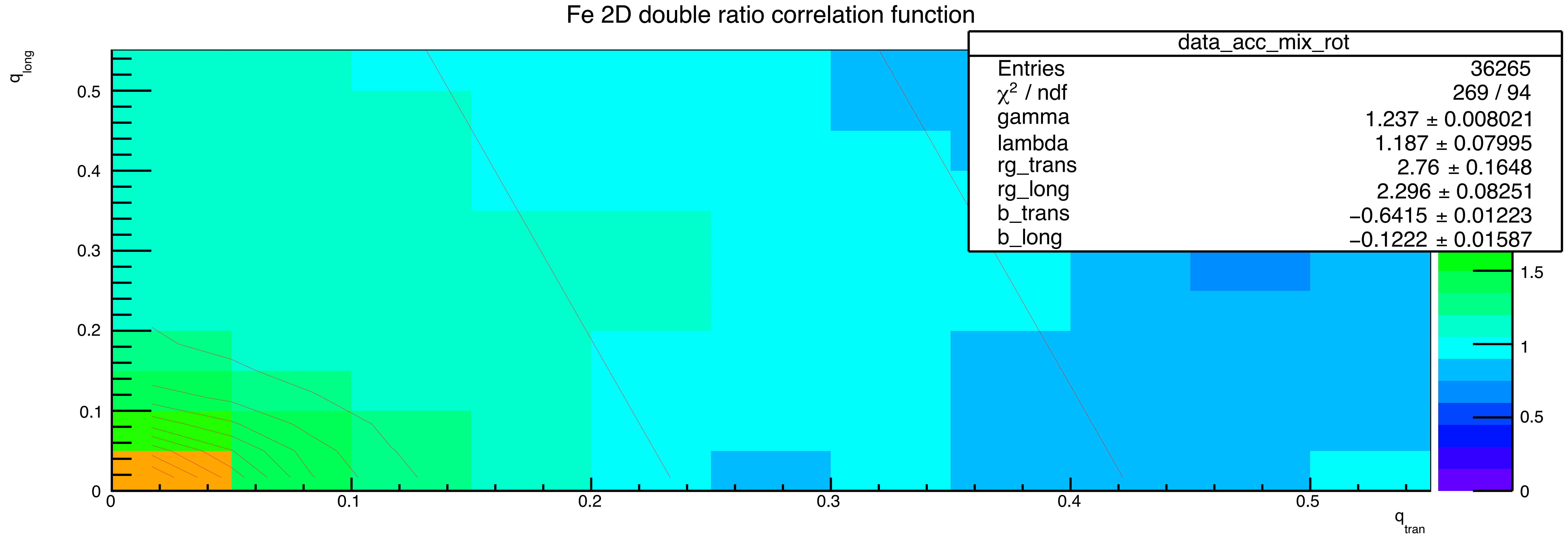


$\pi^+\pi^+$ Bose-Einstein Correlation Studies on Nuclei

Antonio Radic

2D Correlation function (longitudinal and transverse)

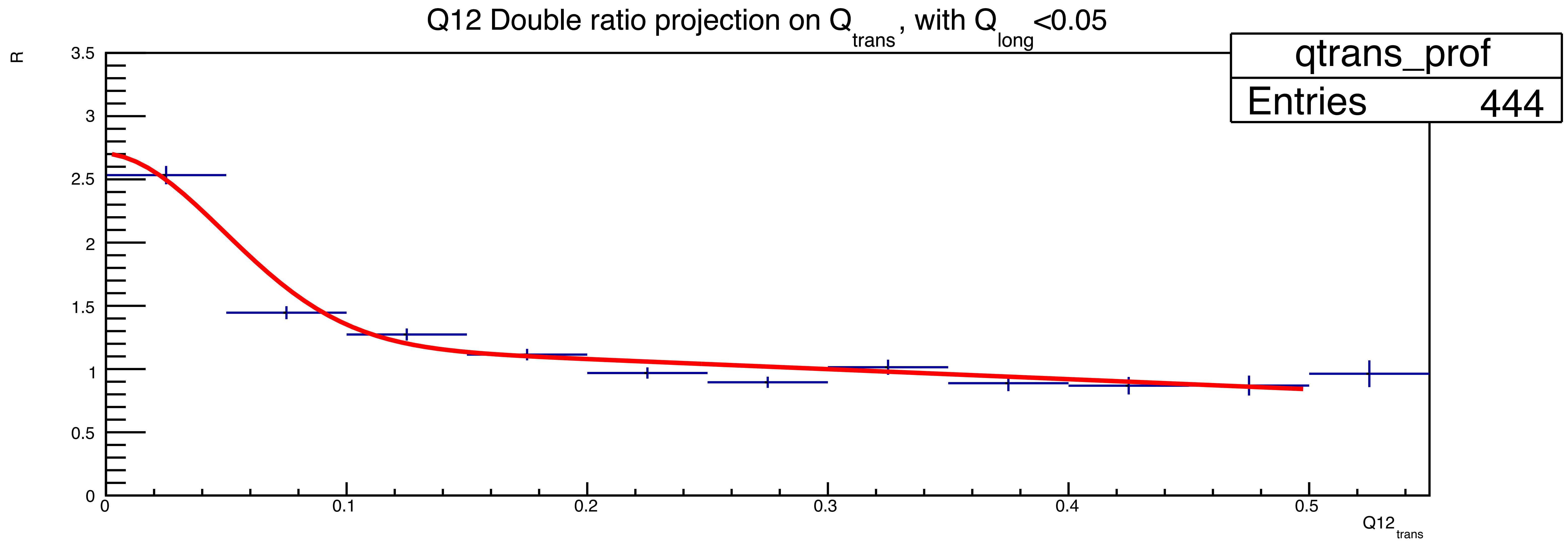


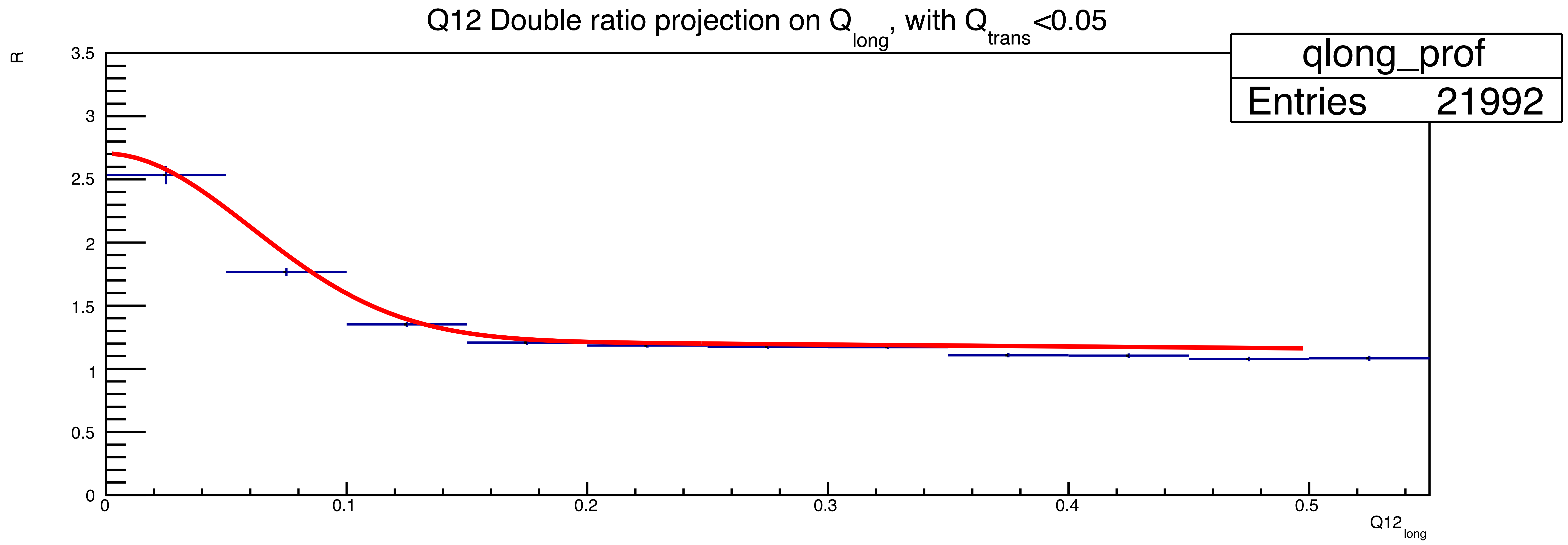


$\pi^+\pi^+$ Bose-Einstein Correlation Studies on Nuclei

Antonio Radic

Projections of 2D Correlation function (longitudinal and transverse)

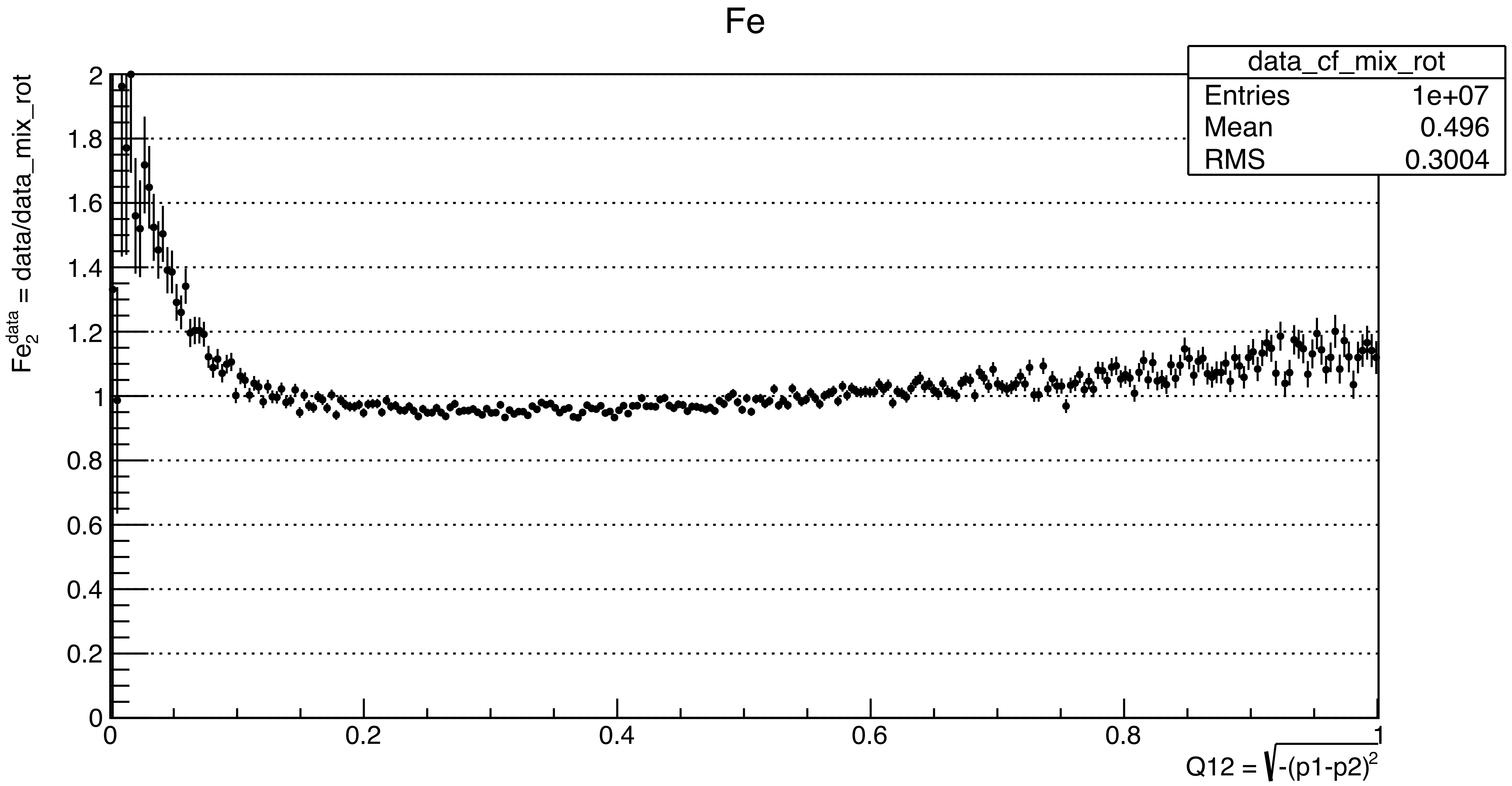




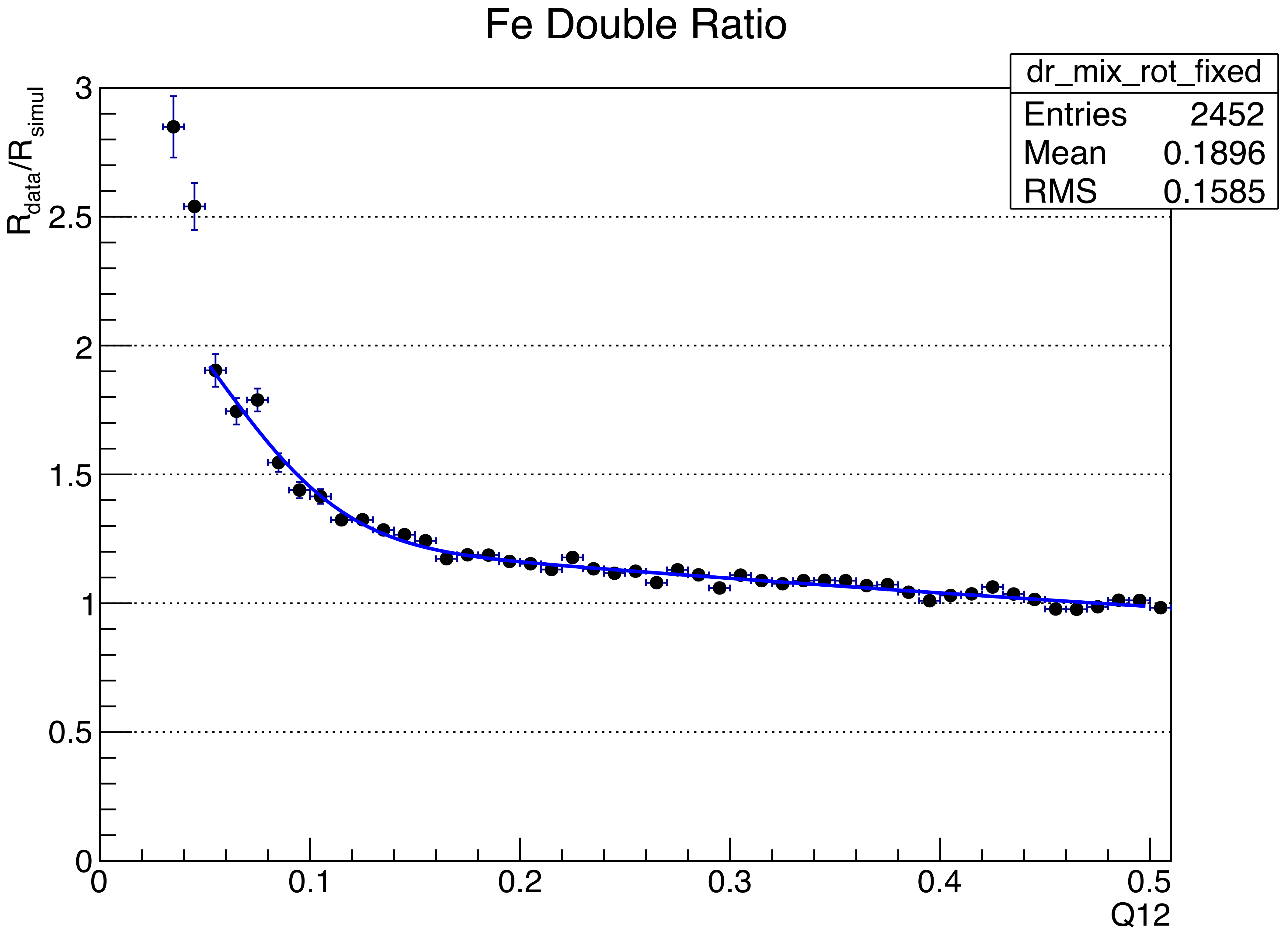
$\pi^+\pi^+$ Bose-Einstein Correlation Studies on Nuclei

Antonio Radic

Data-only 1D Correlation function

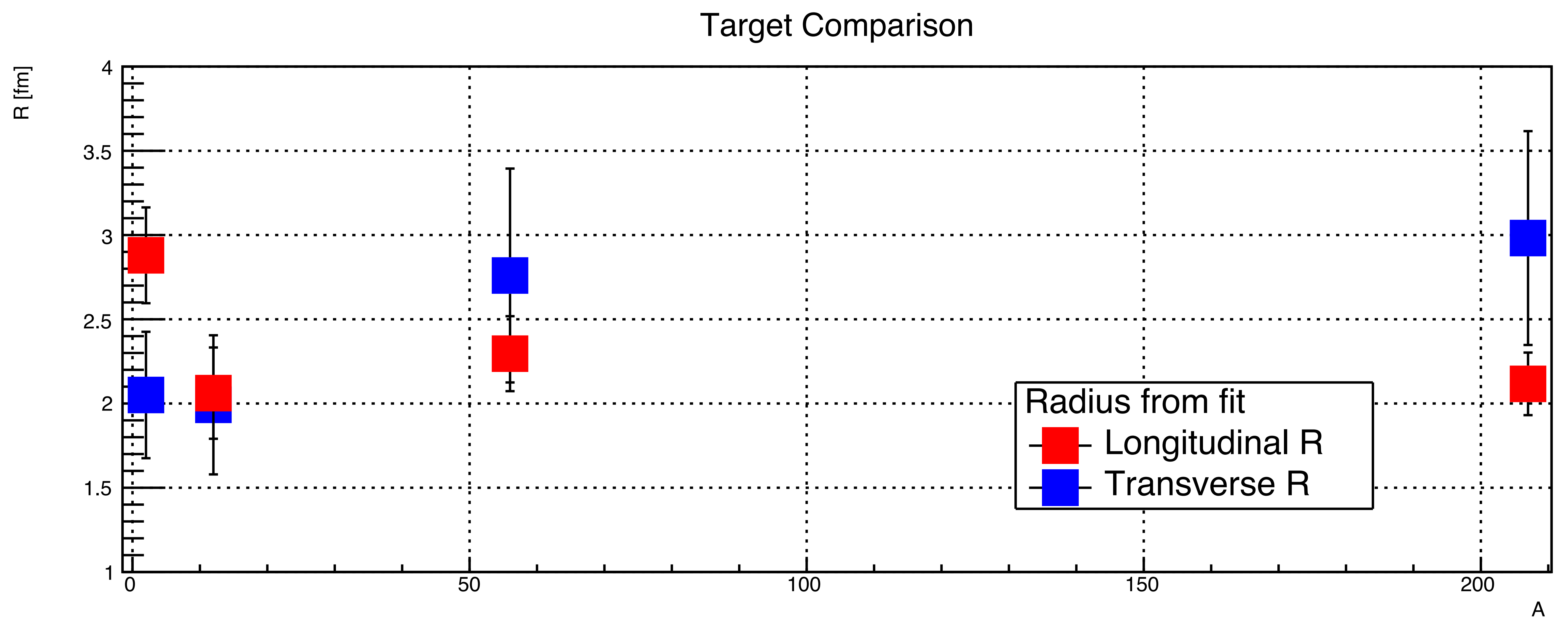


Double ratio 1D Correlation function (normalized to simulation)

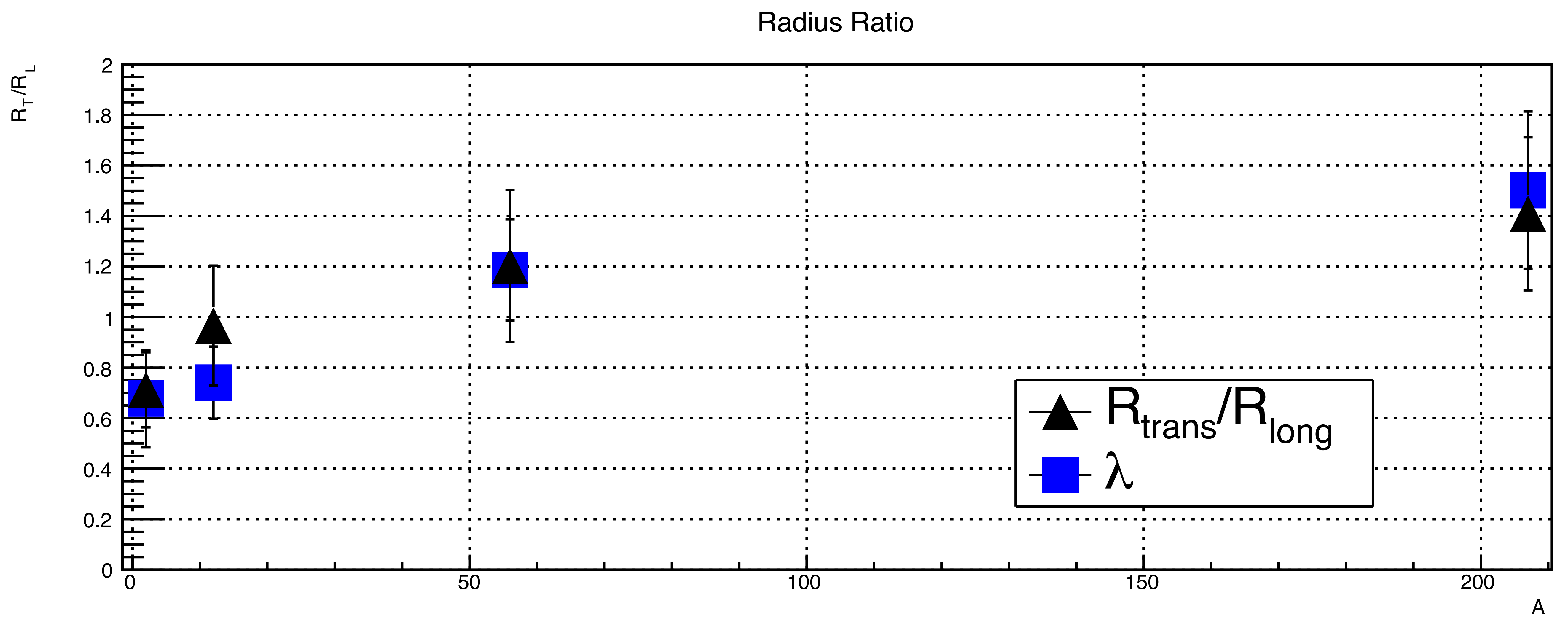


$\pi^+\pi^+$ Bose-Einstein Correlation Studies on Nuclei

Antonio Radic



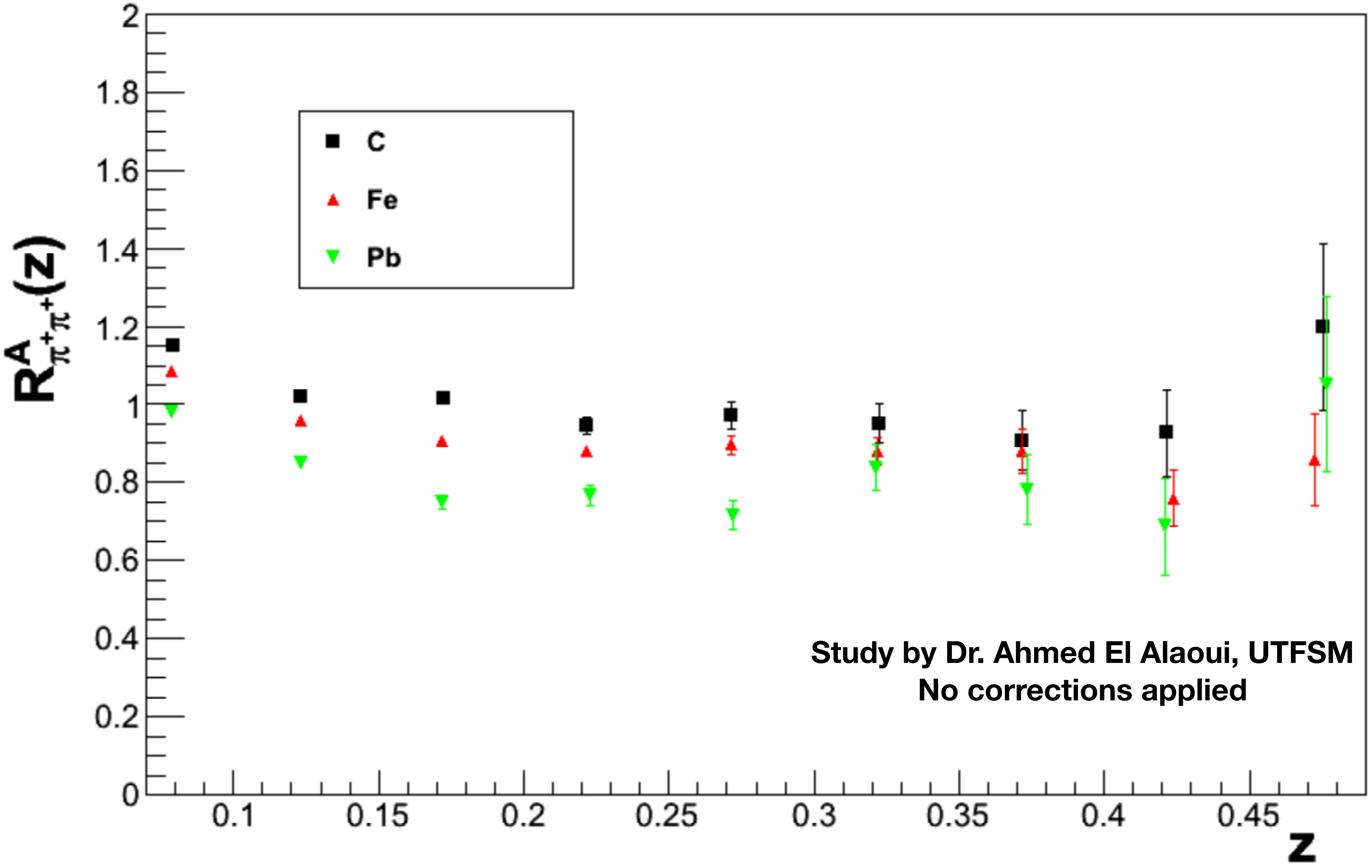
Source size 2-3 fm



Transverse/Longitudinal source size **doubles** with nuclear size!

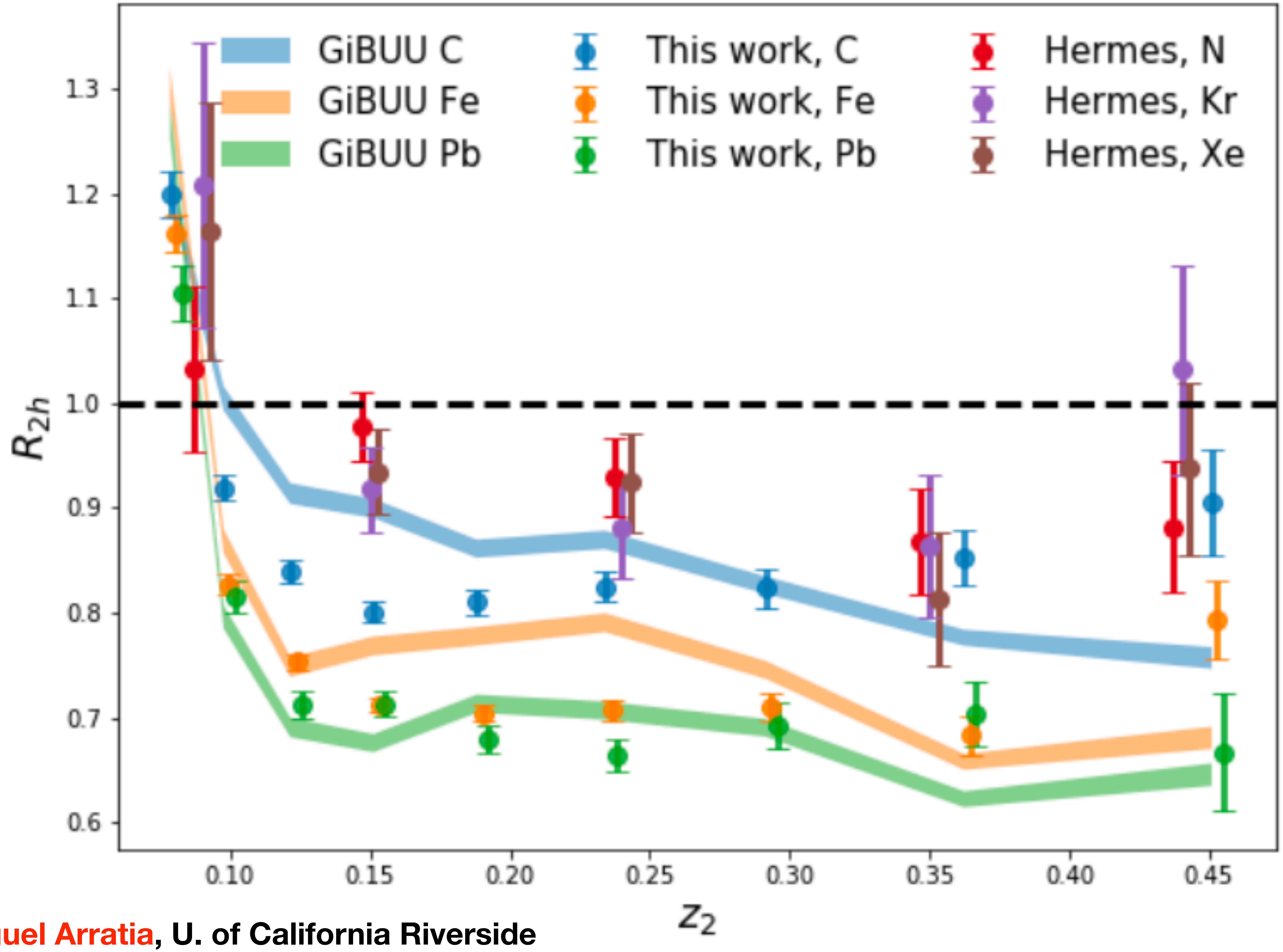
Hadronic cascade?

Two-hadron (conditional, z_1>0.5) multiplicity ratio
Dr. Ahmed El Alaoui, UTFSM



Result is qualitatively consistent with HERMES, with much better statistical precision.

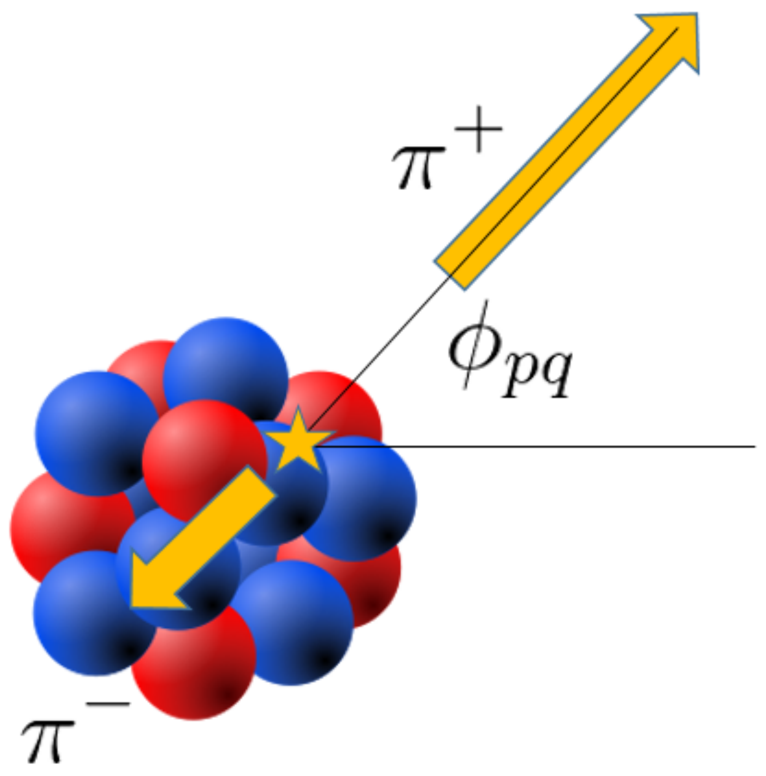
Comparison with HERMES and GiBUU



Study by Prof. Miguel Arratia, U. of California Riverside

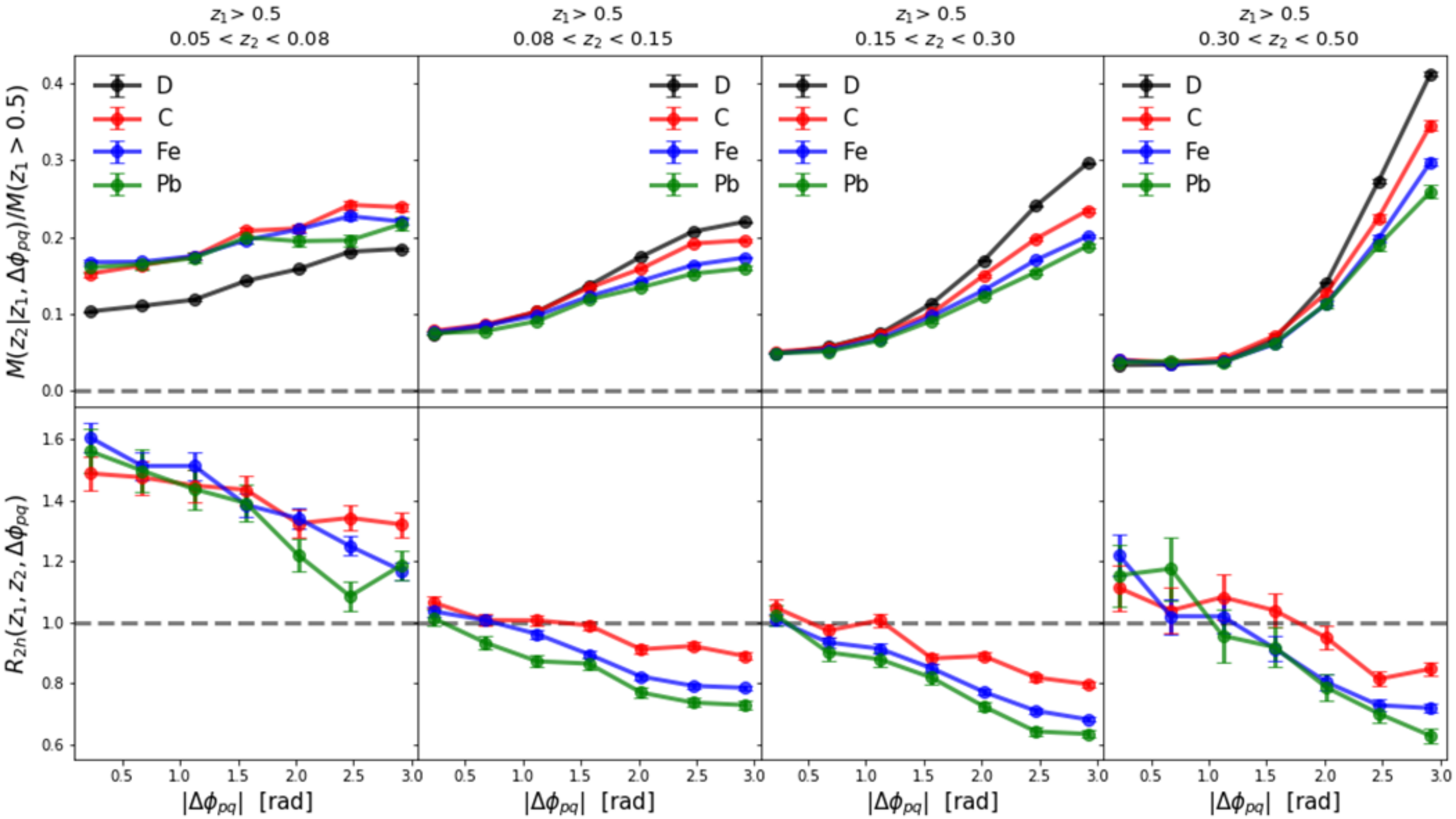
Dihadron azimuthal angle correlations

Study by Prof. Miguel Arratia, U. of California Riverside



Two-pion correlation function

Ratios for Carbon, Iron, and Lead to Deuterium



Spectacular new results on azimuthal angle correlations.
Clear suggestion of surface bias effect.

https://link.aps.org/doi/10.1103/PhysRevC.97.044909, https://arxiv.org/abs/1102.2669, etc.

Direct measurement of quark energy loss, and its connection to p_T broadening

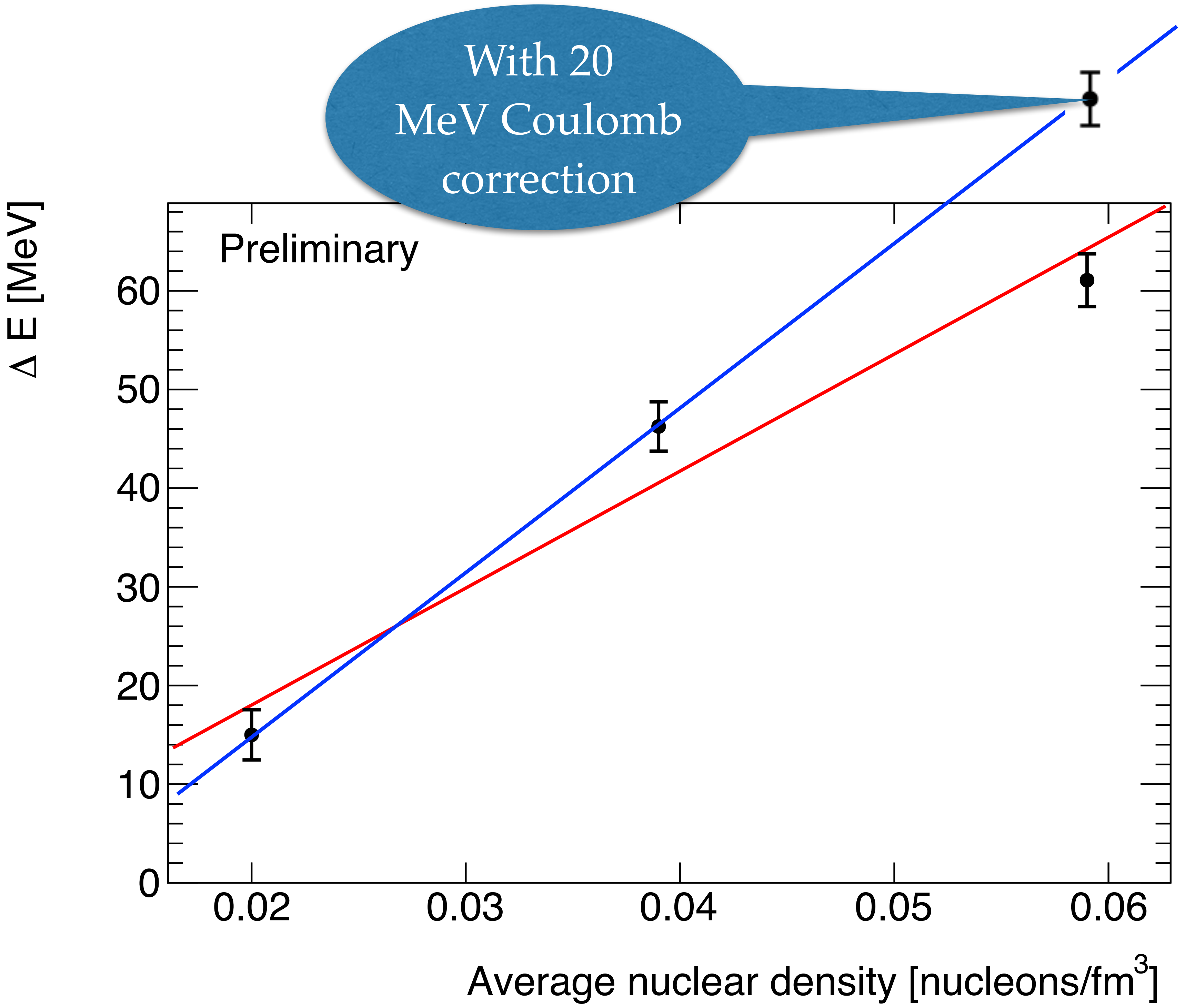
Gabriela Hamilton and René Rios, UTFSM MSc students (thesis advisor WB)

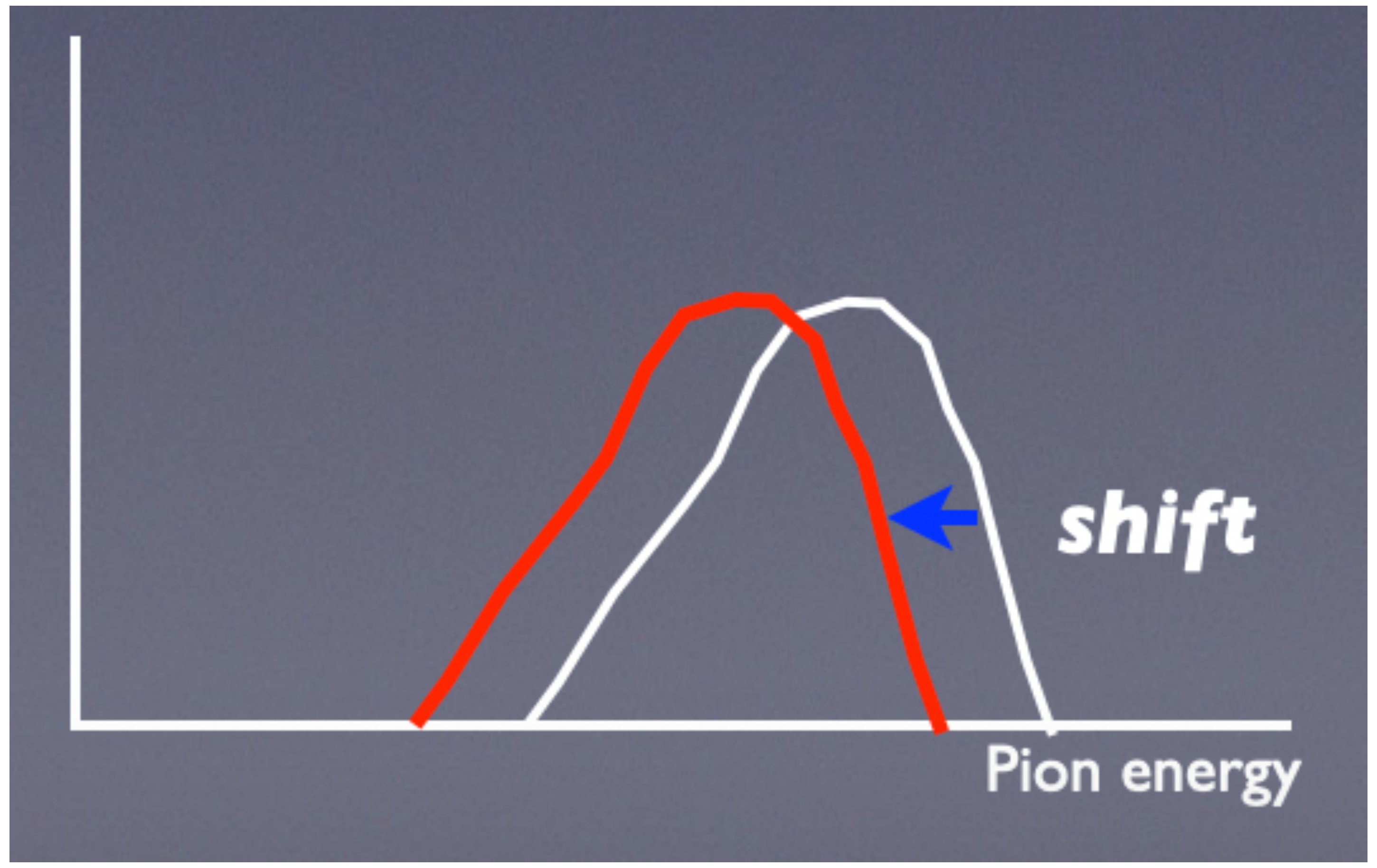
$$-\Delta E_q = \frac{\alpha_s}{4} \Delta k_T^2 \cdot L$$

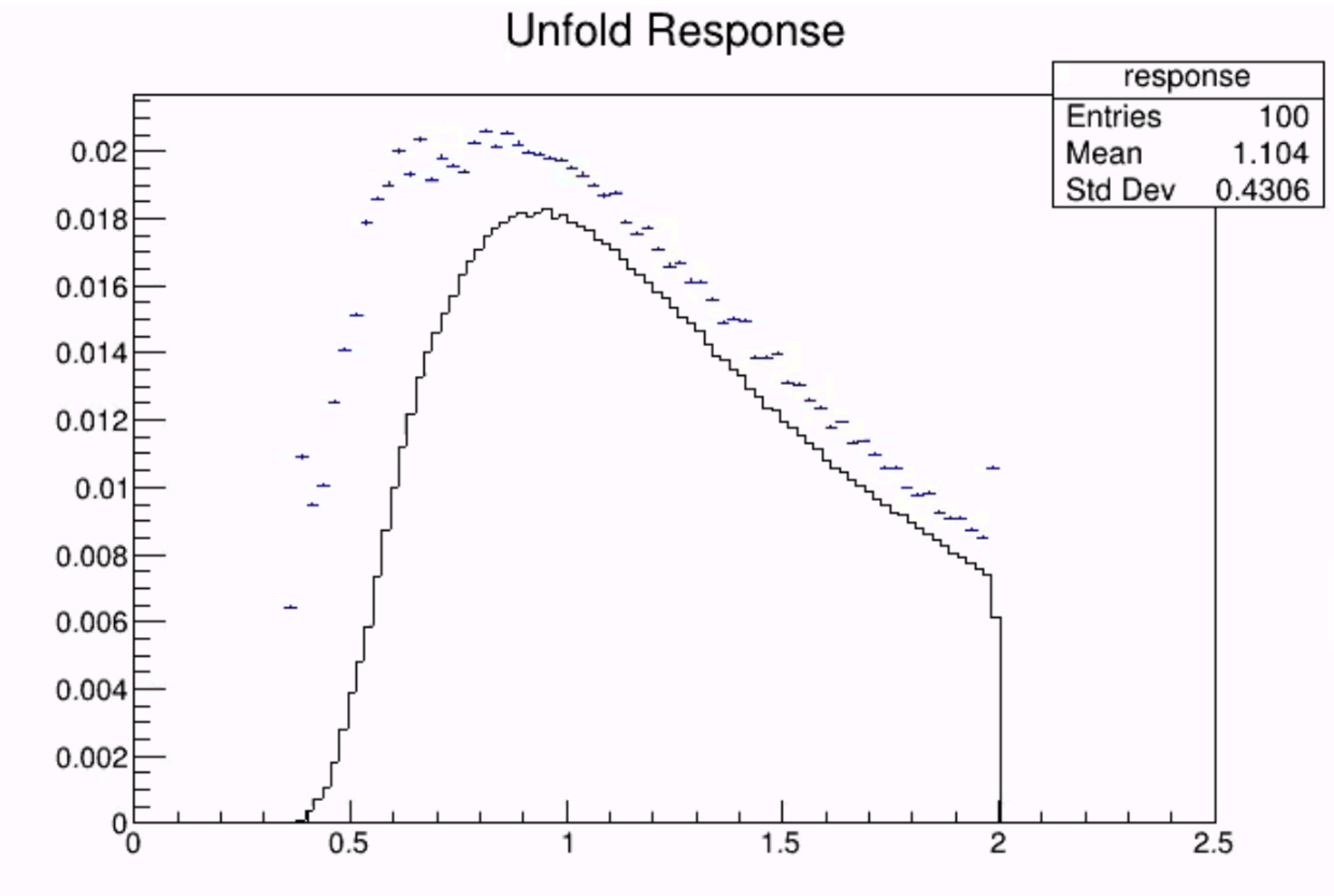
This is the classic equation relating quark energy loss and p_T broadening

We are trying to directly measure quark energy loss and then test this equation

It requires significant unfolding studies because the energy loss is quite small.







Roofit Bayesian unfolding

Conclusions

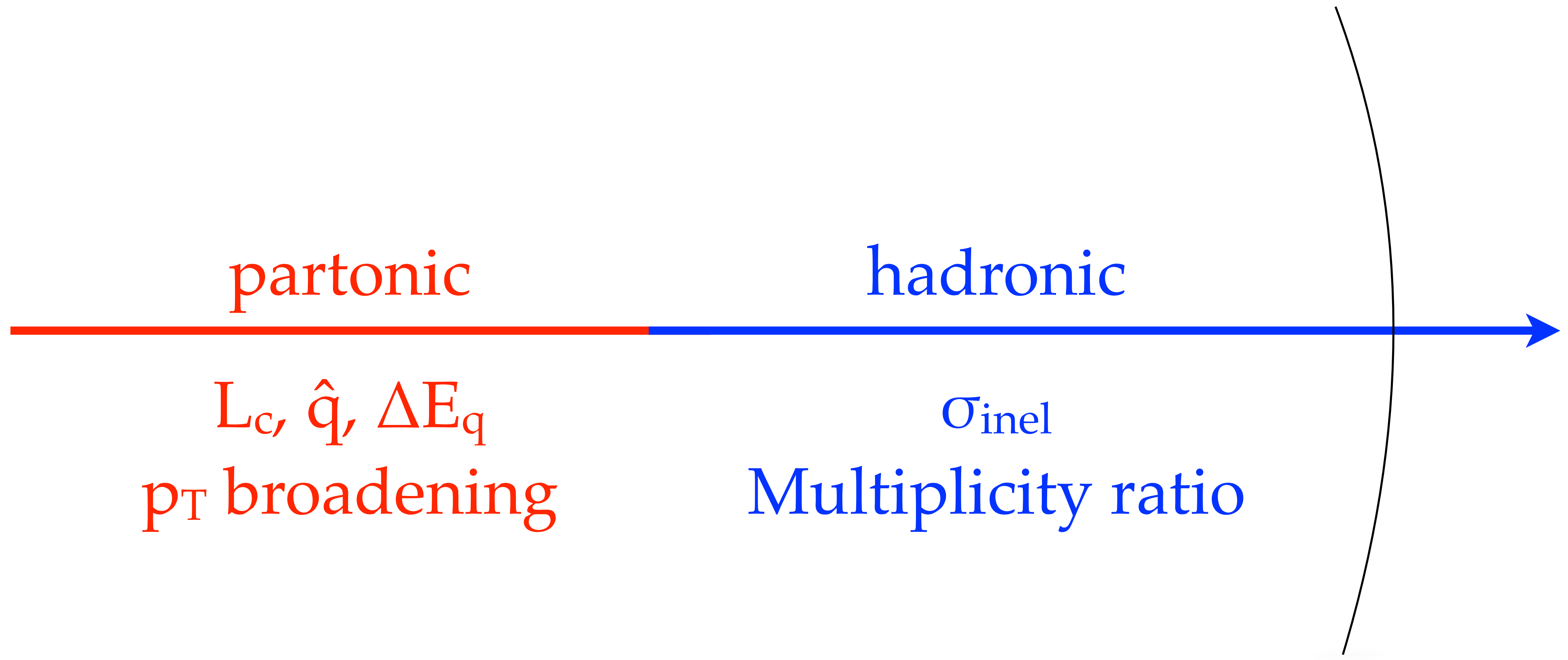
- Many interesting current results from EG2/CLAS6!
- Many more expected from CLAS12. A large and experienced team is waiting to get on the schedule.
- Clear extensions to EIC!

Backup Slides

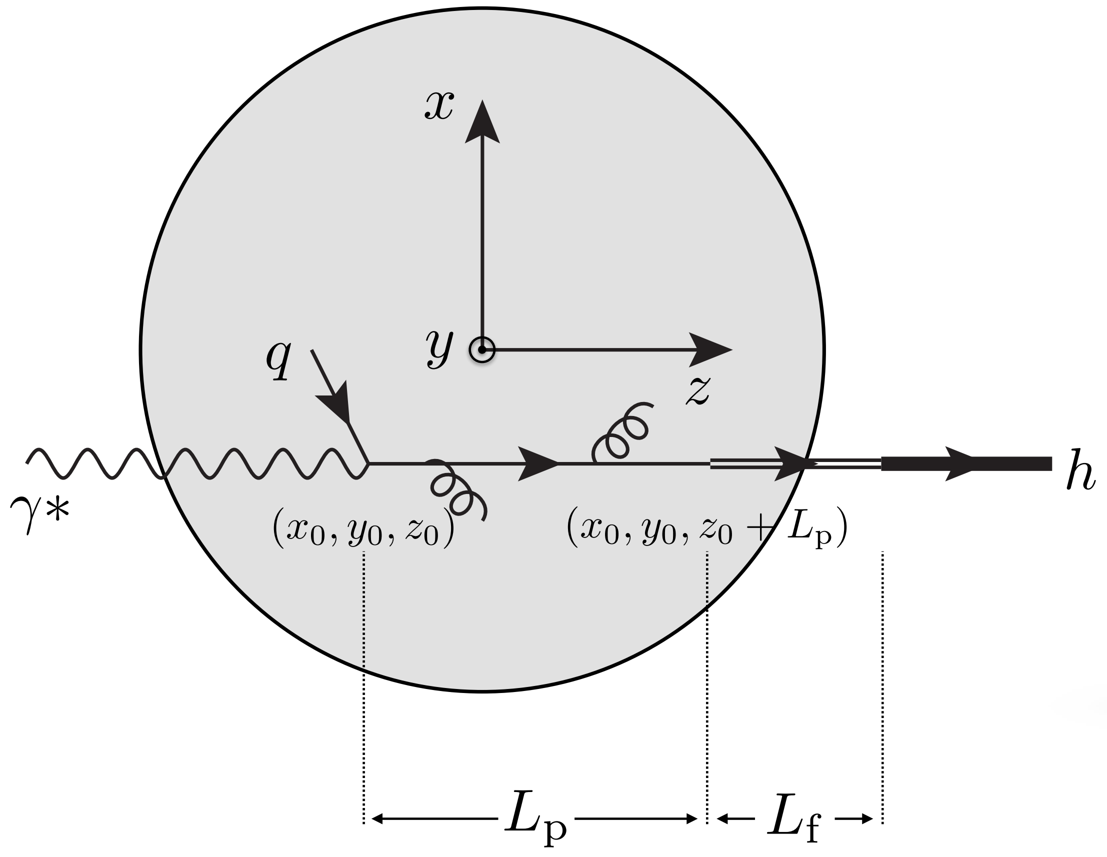
Definition of the BL model

Division into *partonic* and *hadronic* phases

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

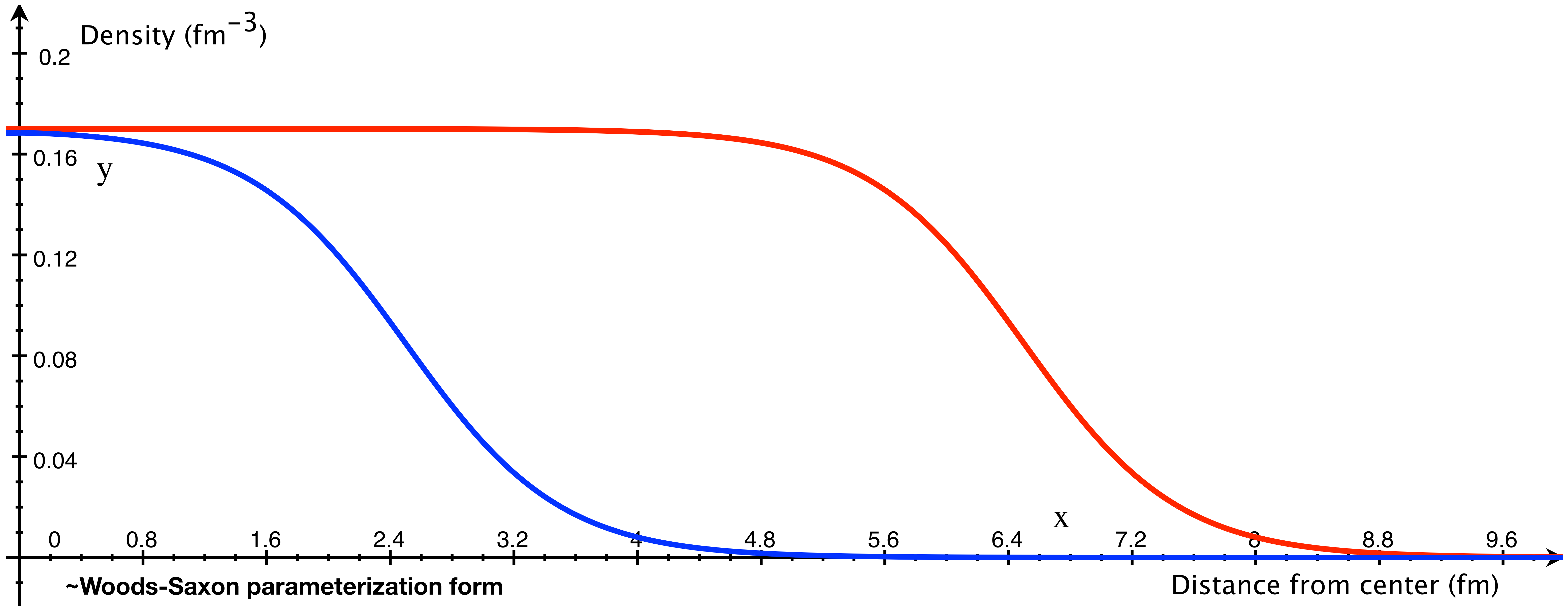


The partonic phase persists for a distance L_c, over which p_T broadening via $\hat{q}$, and partonic energy loss ΔE_q, occur



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)



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

$$\langle \Delta p_T^2 \rangle = \langle \underbrace{q_0}_{\text{unique parameter}} \int_{z=z_0}^{z=z_0+L_c^*} \rho(x_0, y_0, z)\ dz \ \rangle_{x_0, y_0, z_0, \underbrace{L_c}_{\text{common parameter}}}$$

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.

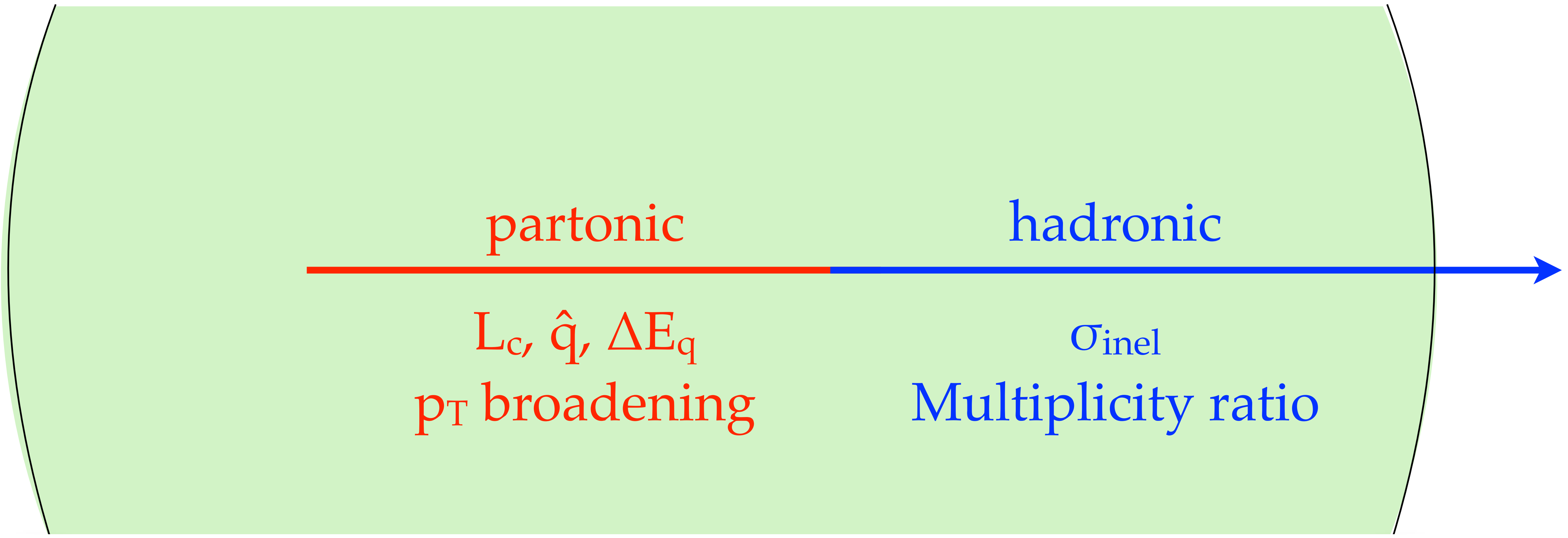
$$\langle R_M \rangle = \langle \exp(-\overbrace{\sigma}^{\text{unique parameter}} \int_{z=z_0+L_c}^{z=z_{max}} \rho(x_0, y_0, z)\ dz\ ) \ \rangle_{x_0, y_0, z_0, \overbrace{L_c}^{\text{common parameter}}}$$

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

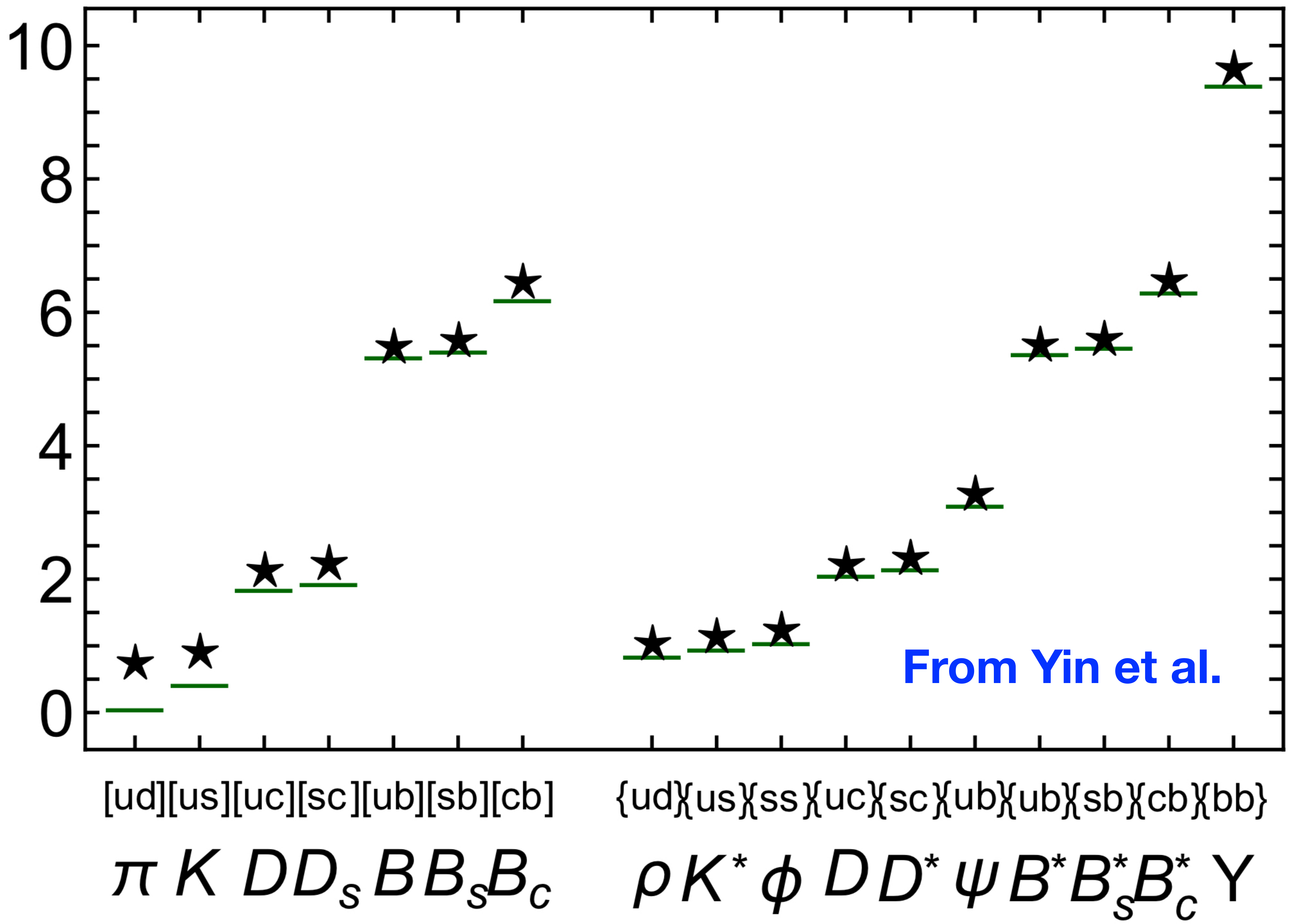
- Only two dynamical processes are involved - quark energy loss and (pre-)hadron inelastic interactions
- Straight-line propagation of the struck quark (soft-gluon assumption)
- Two stages of propagation: first, as a color octet system, and second as a color singlet system.
- Non-zero hadron formation 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.

The Diquark Argument

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

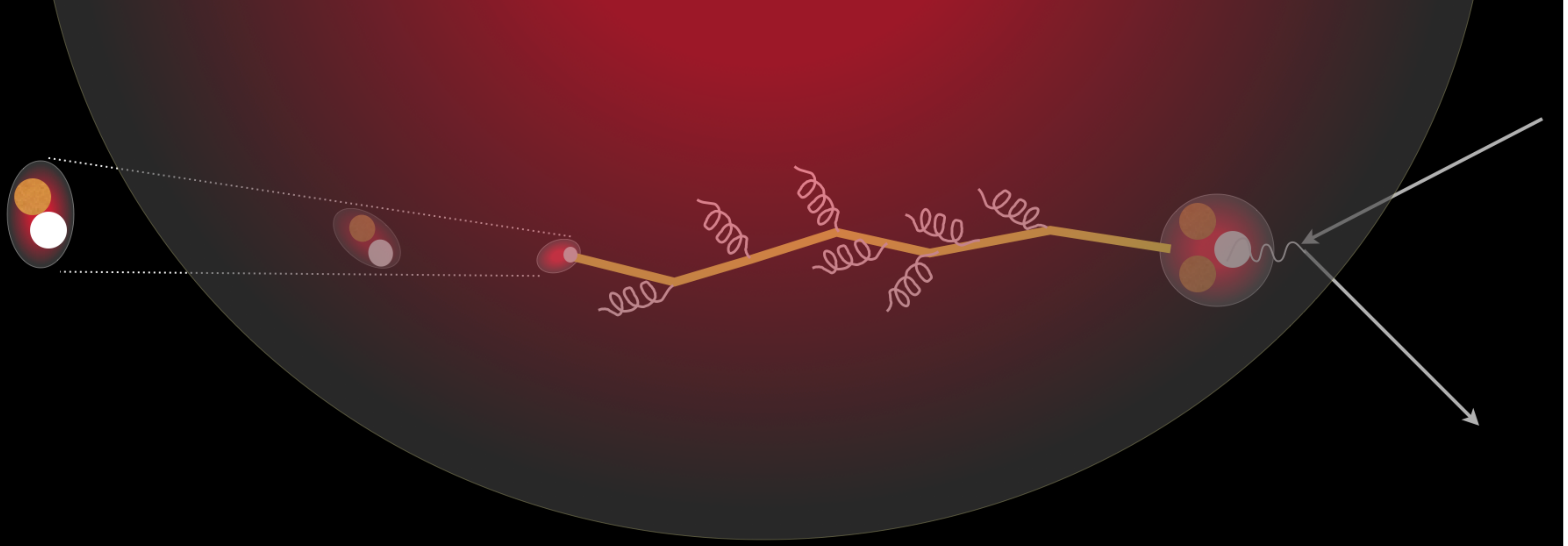


The ud diquarks are heavy. This is very relevant to what follows in this talk.

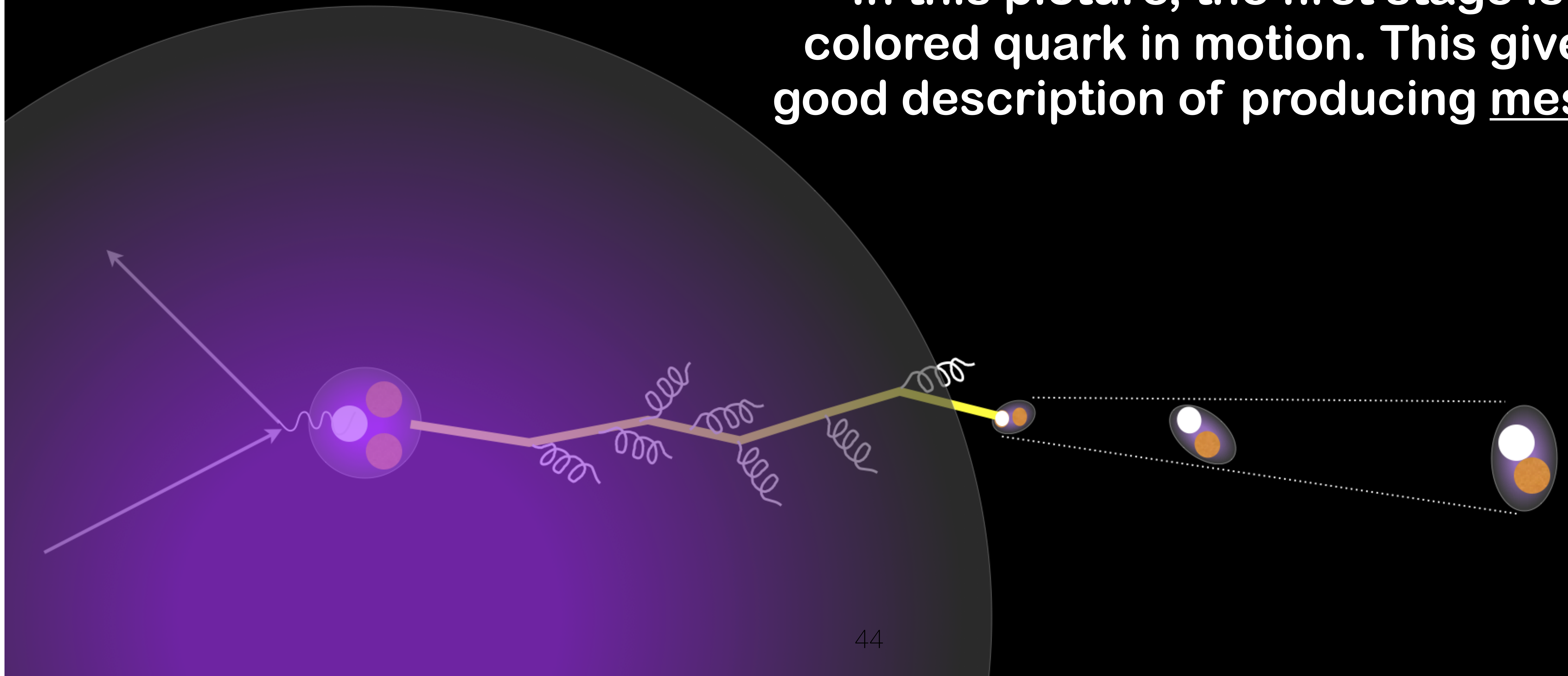
FIG. 2. Comparison between computed masses of diquark correlations and their symmetry-related meson counterparts: diquarks – (black) stars and mesons – (green) bars.

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 mesons.



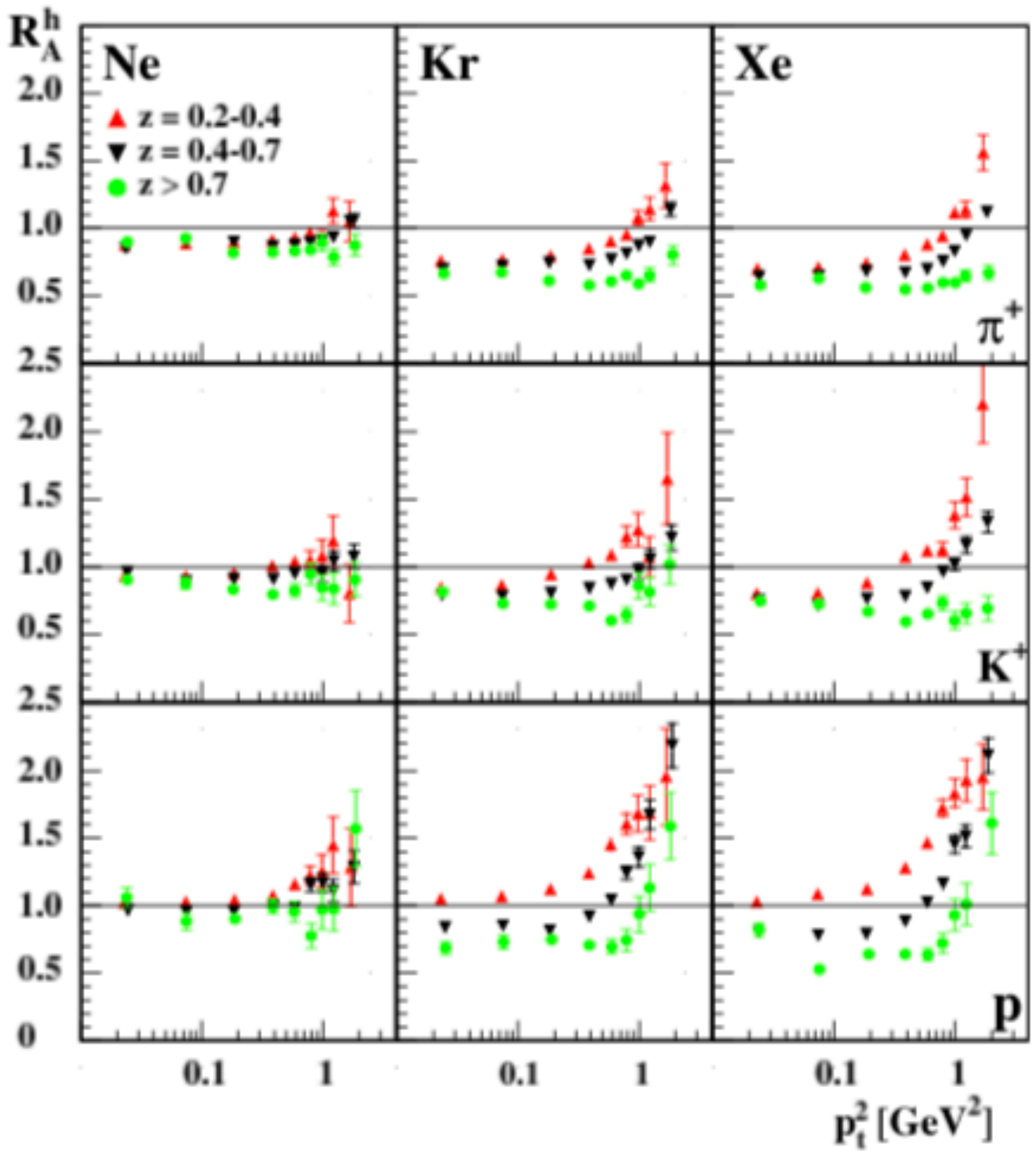
Interpreting HERMES Nuclear DIS DATA: MESONS

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.

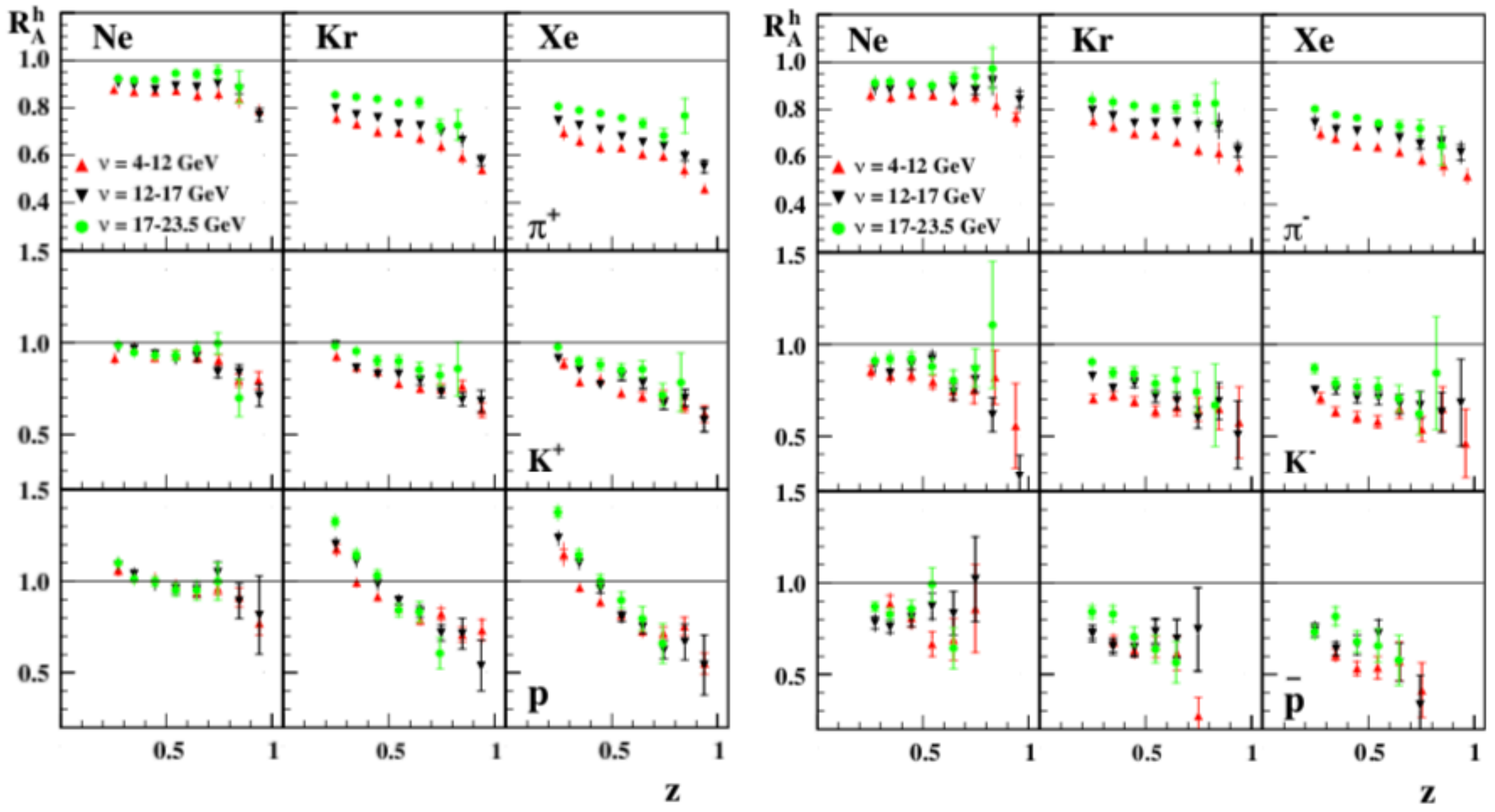
R>1 at high pT because particles that strongly interact with the medium acquire more pT than those that don't interact as much.

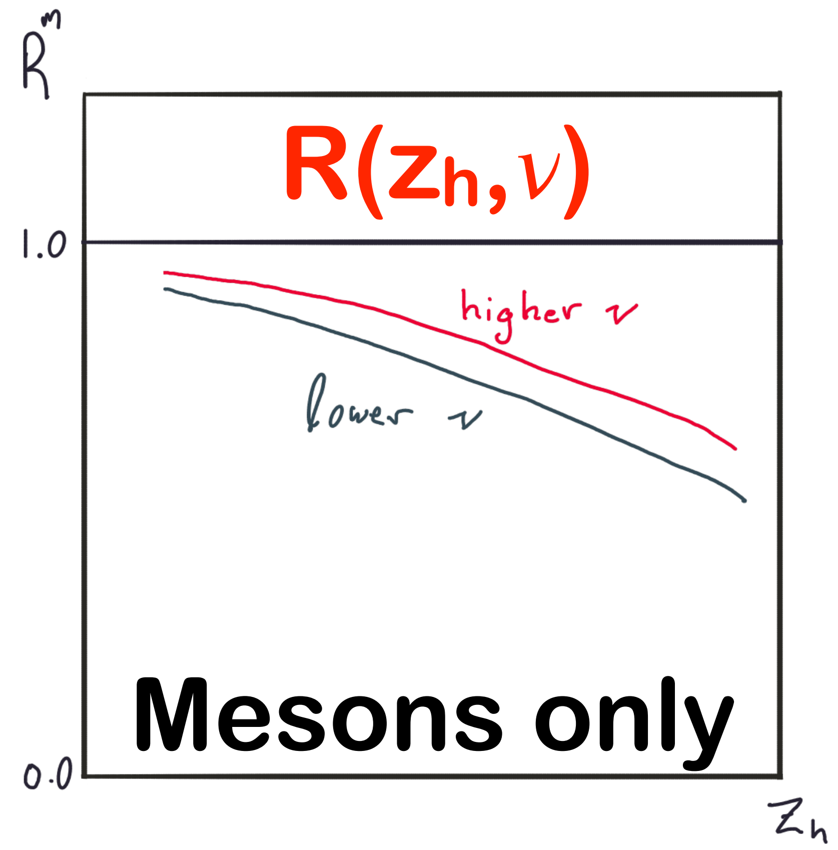


"Interact" = hadronic interaction of forming hadrons, + quark energy loss.

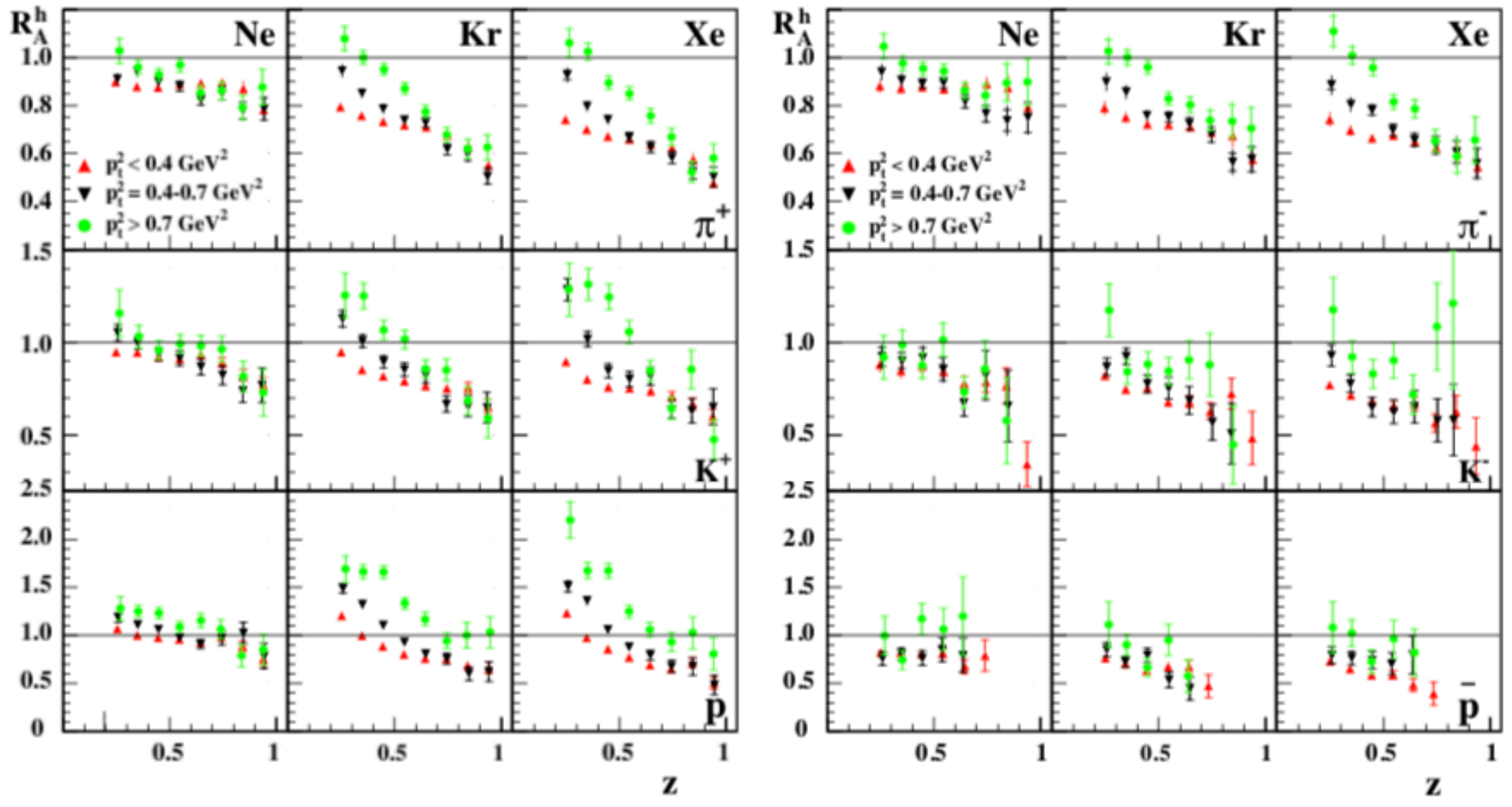
Empirically, from these plots, low-z mesons acquire more pT than high-z.

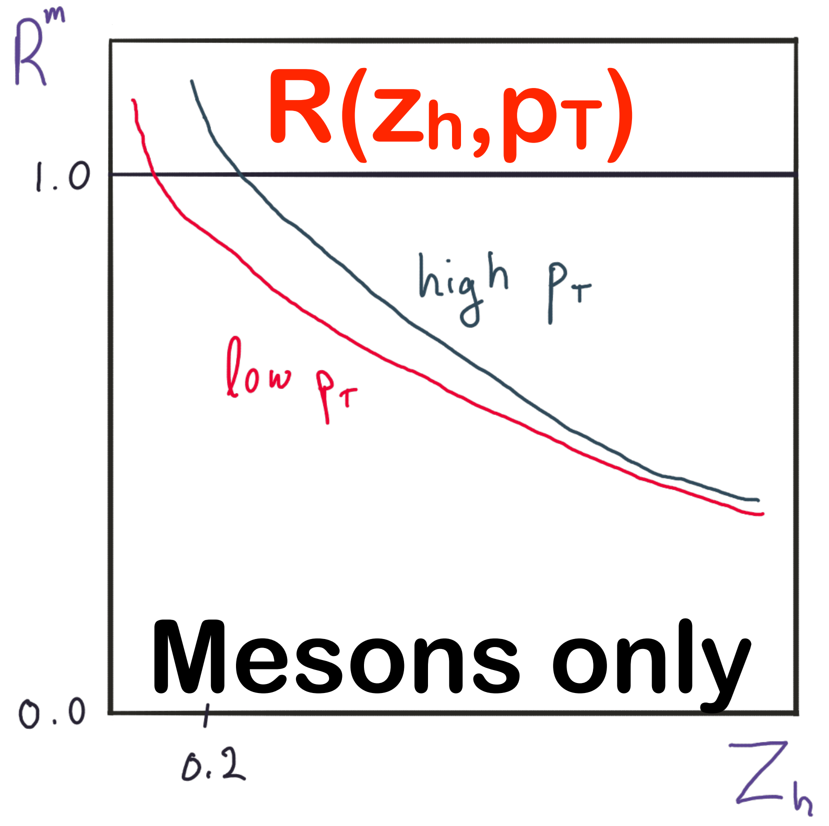
Enhancement at high pT mostly caused by hadronic interactions at low z.



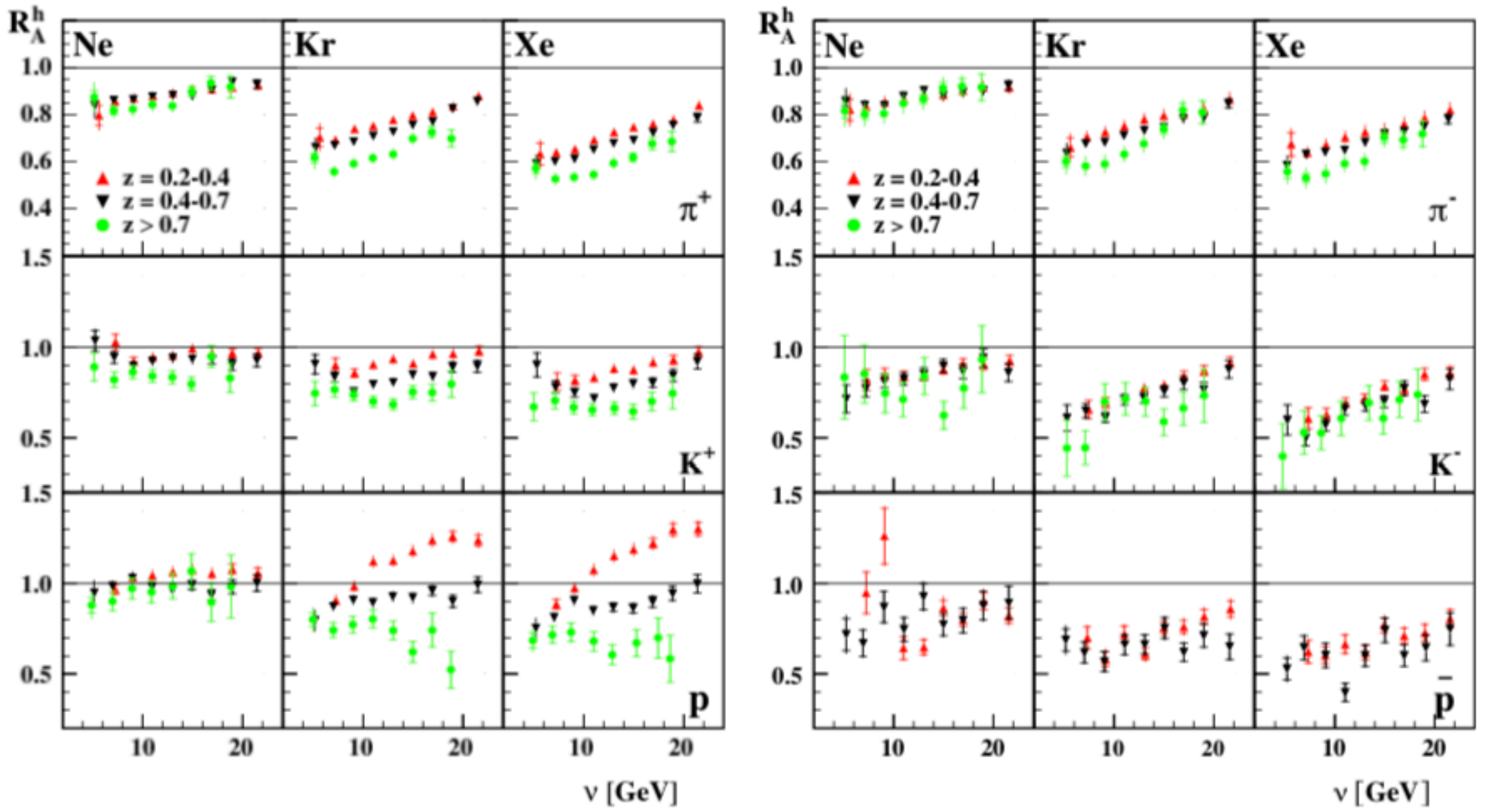


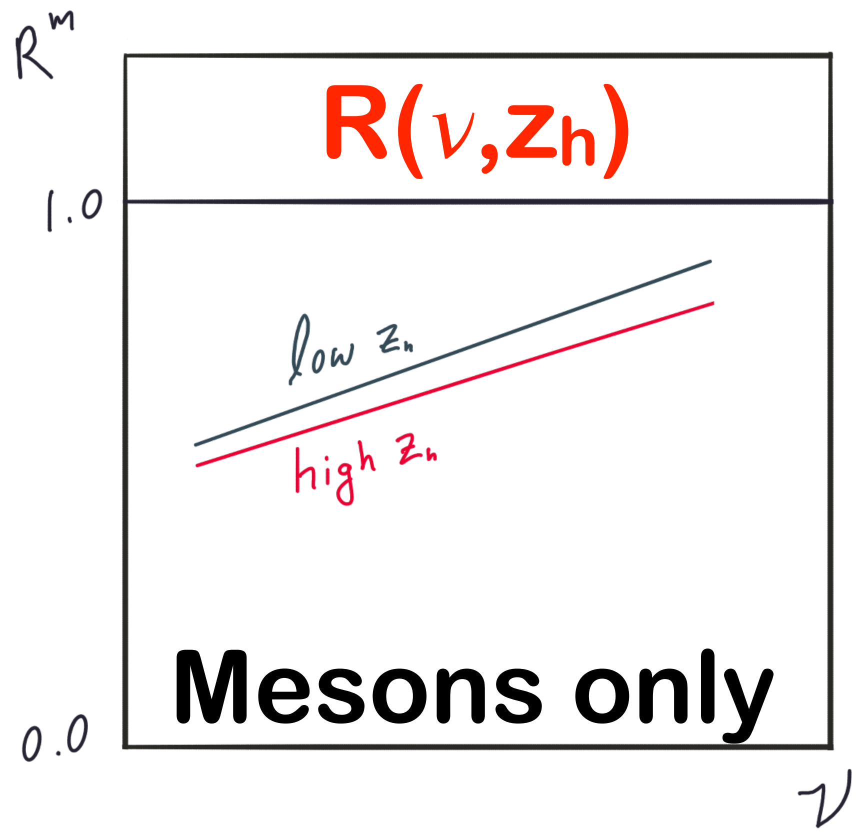
Integrated over pT, so always < 1. At higher nu, less attenuation because of time dilation of quark lifetime





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.

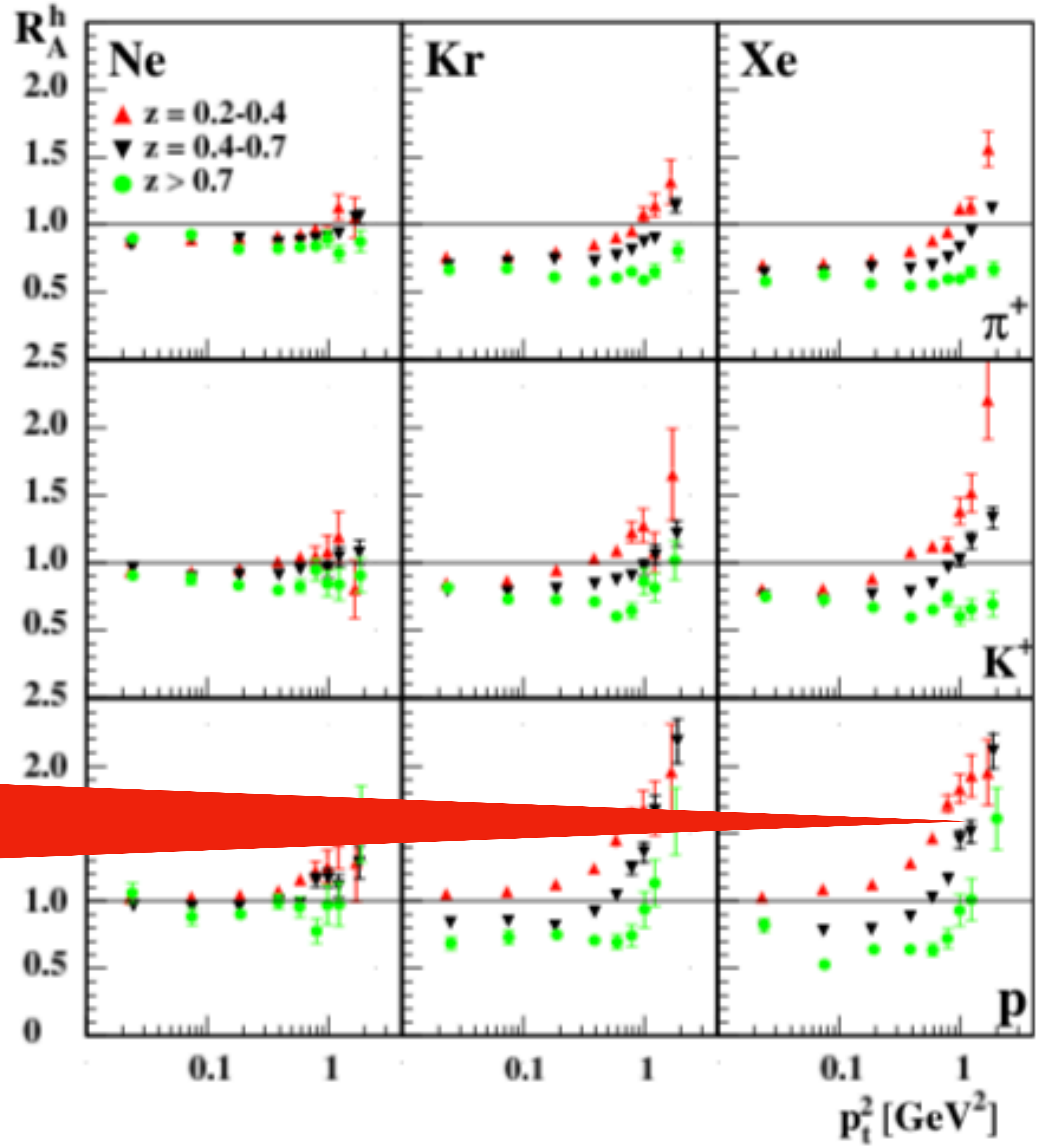
BUT: mesons don’t have diquarks

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

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



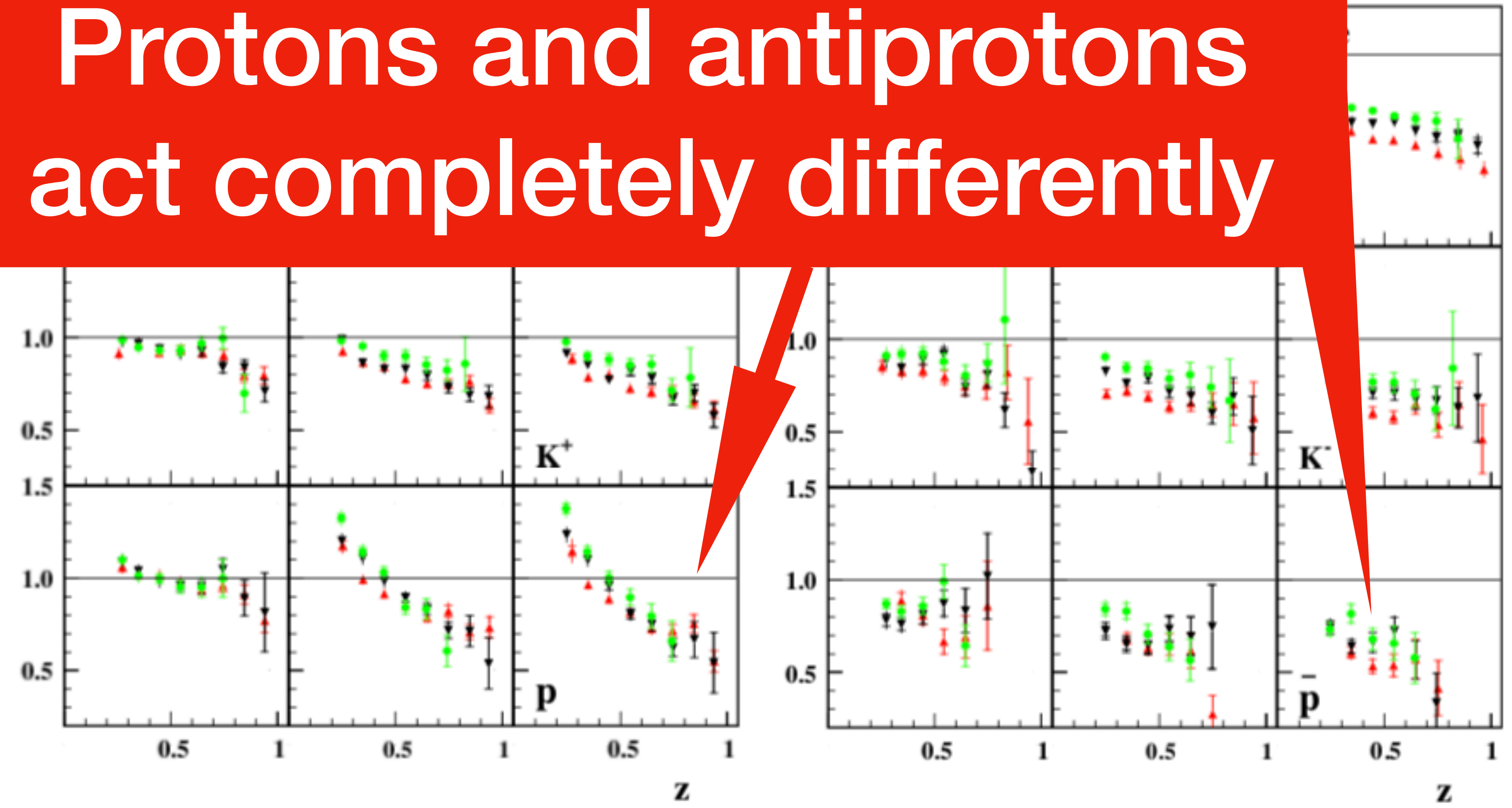
The ordering in z seen for mesons disappears at high pT for protons.

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

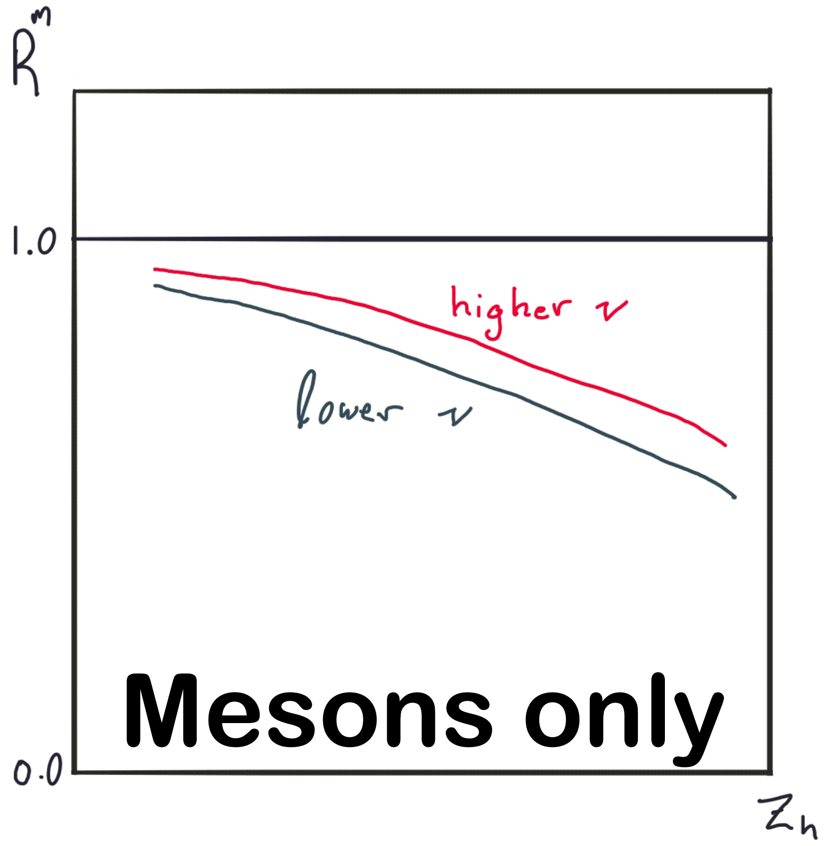
of forming hadrons, + quark energy loss.

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

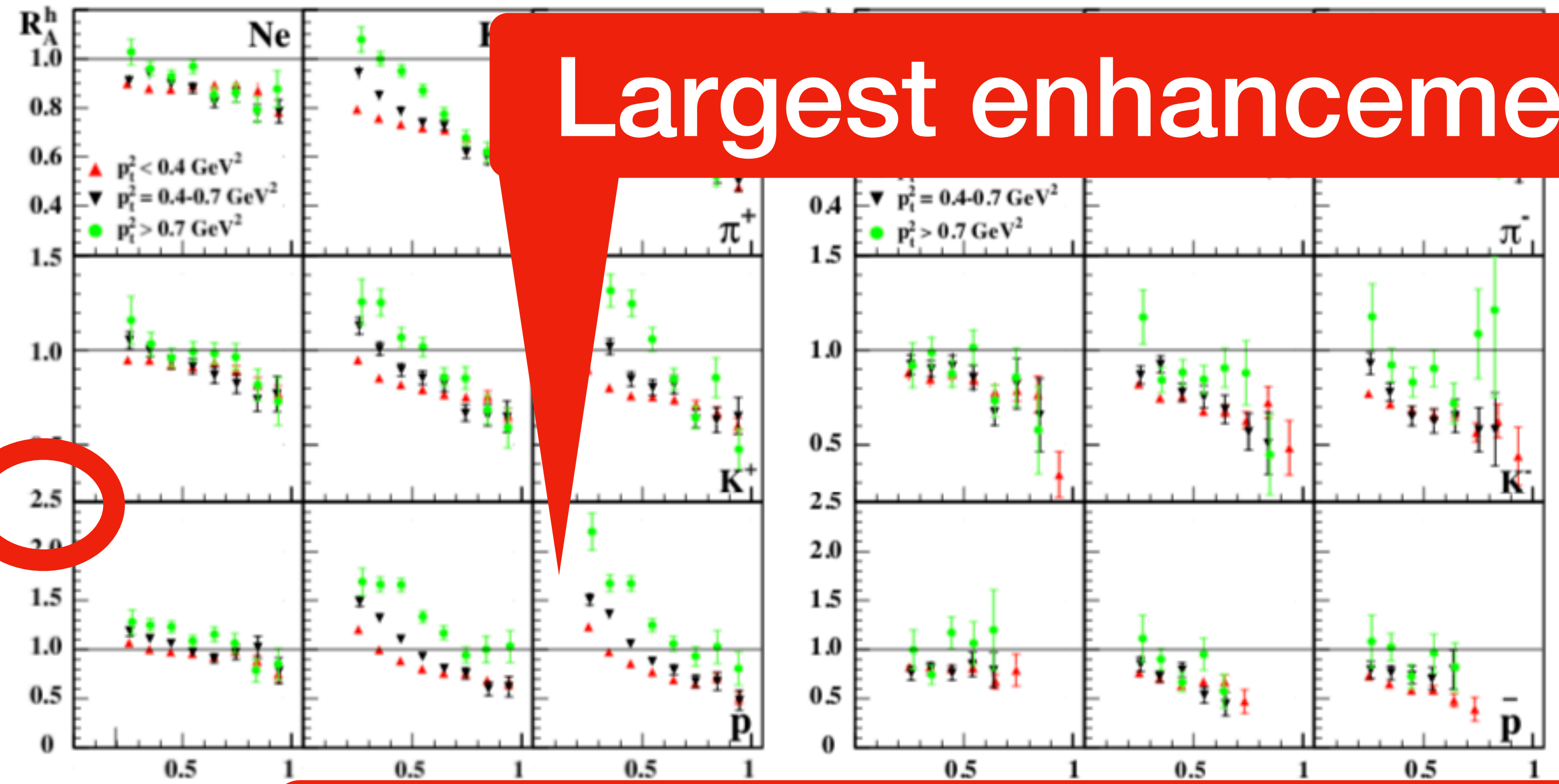
Enhancement at high pT mostly caused by hadronic interactions at low z.



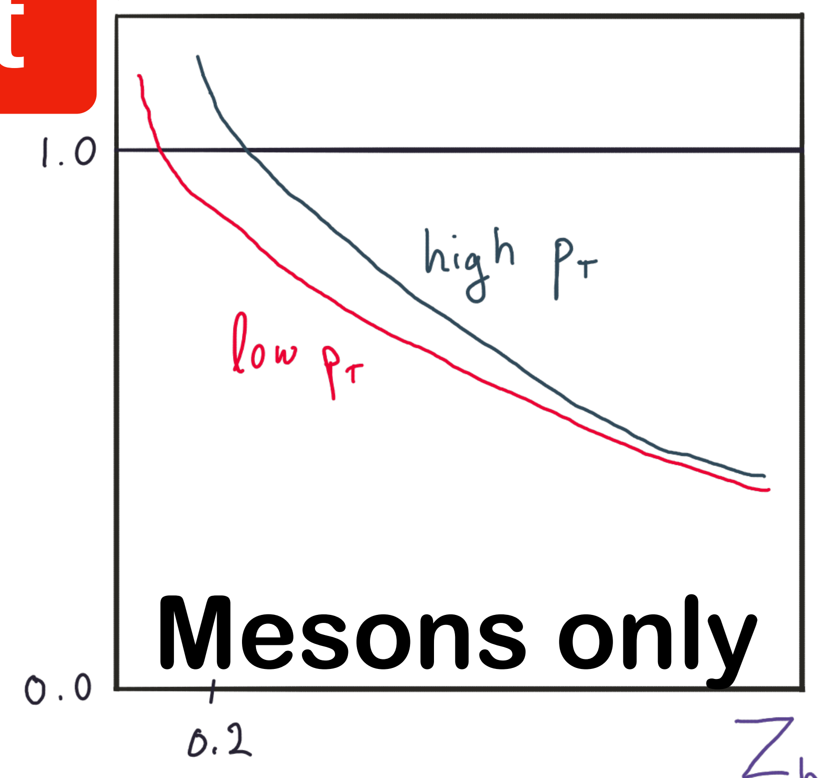
Protons and antiprotons act completely differently



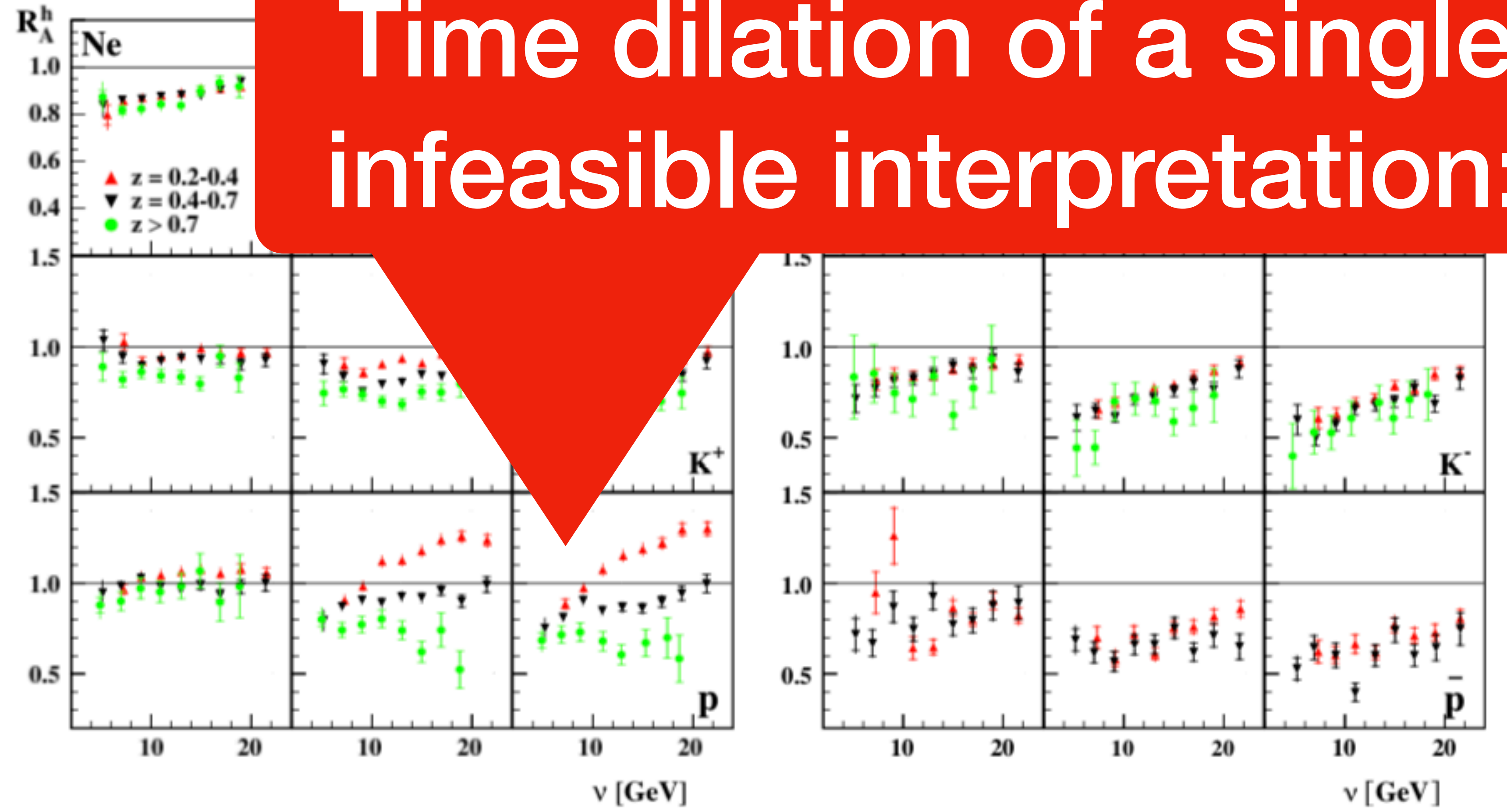
Integrated over pT, so always < 1.
At higher nu, less attenuation because of time dilation of quark lifetime



Largest enhancement



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

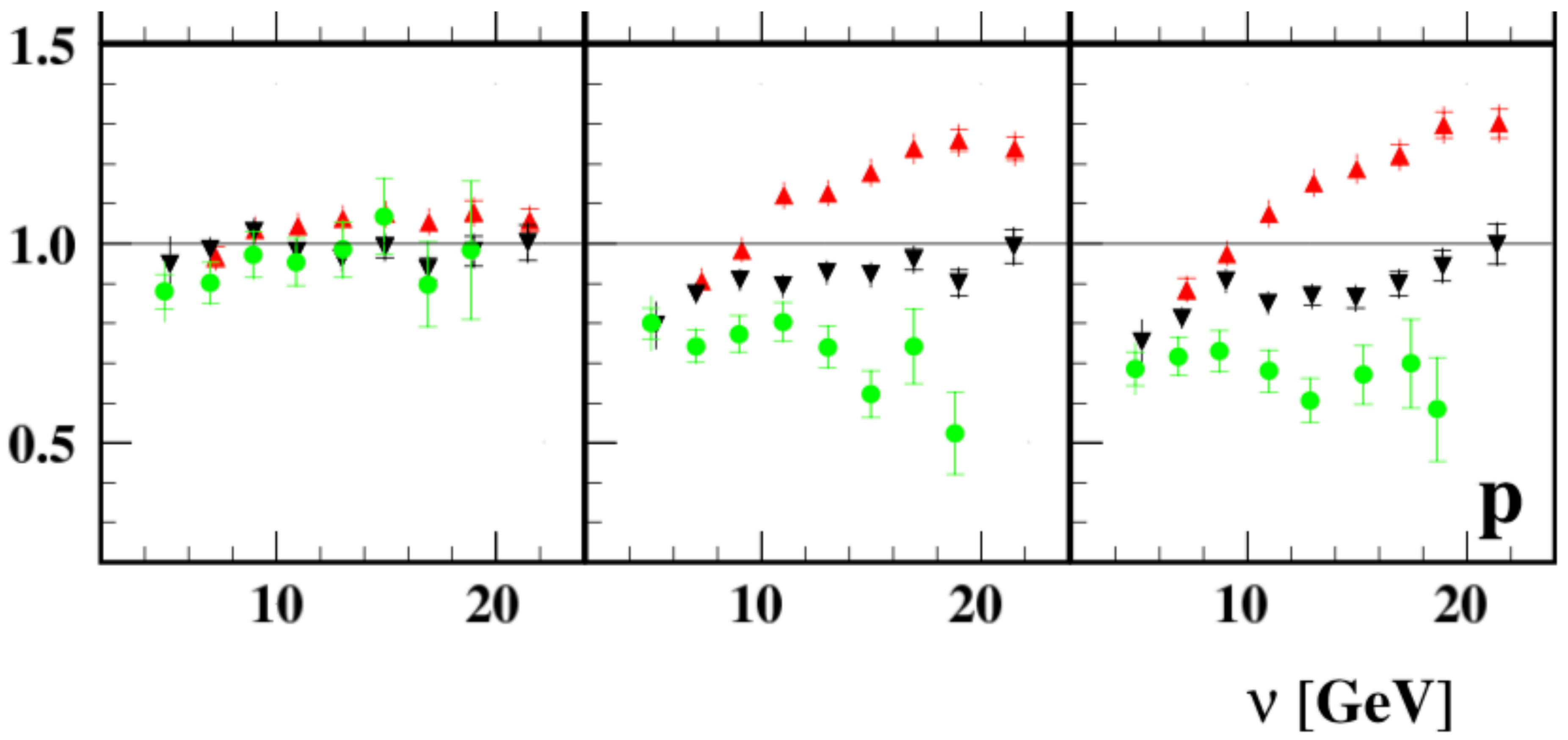


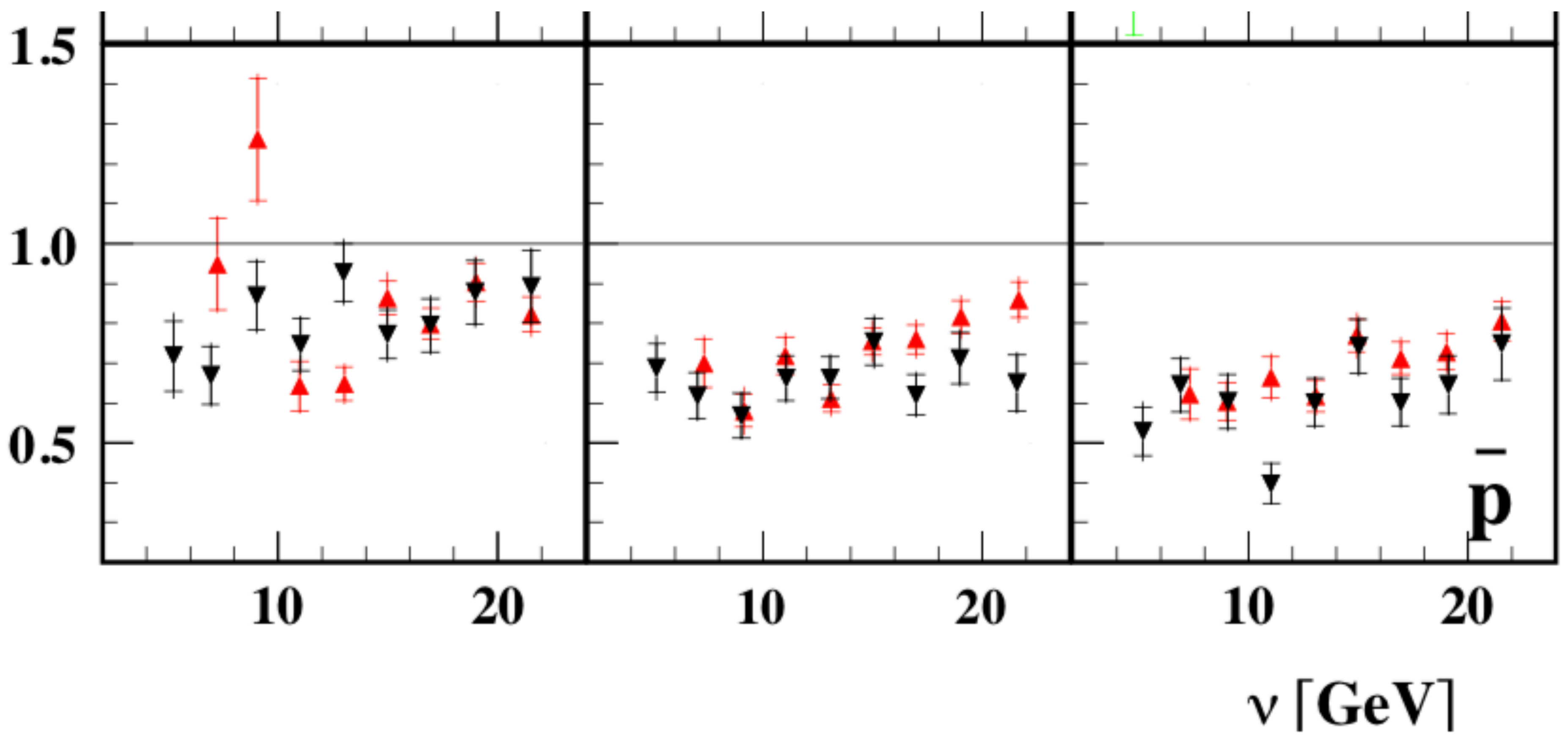
Time dilation of a single quark now an infeasible interpretation: R>>1 at low z.

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

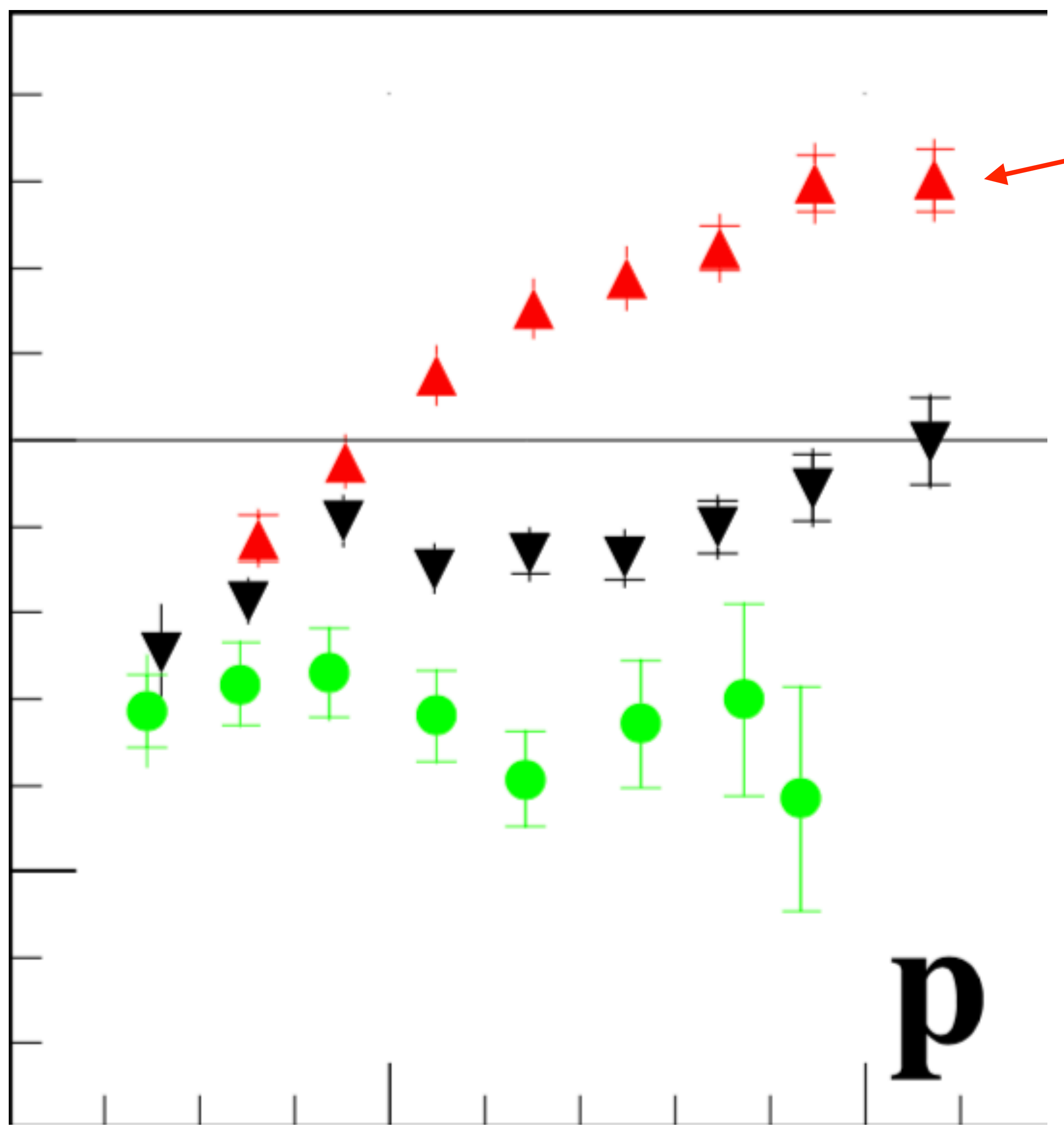
▲ z = 0.2-0.4
▼ z = 0.4-0.7
● z > 0.7





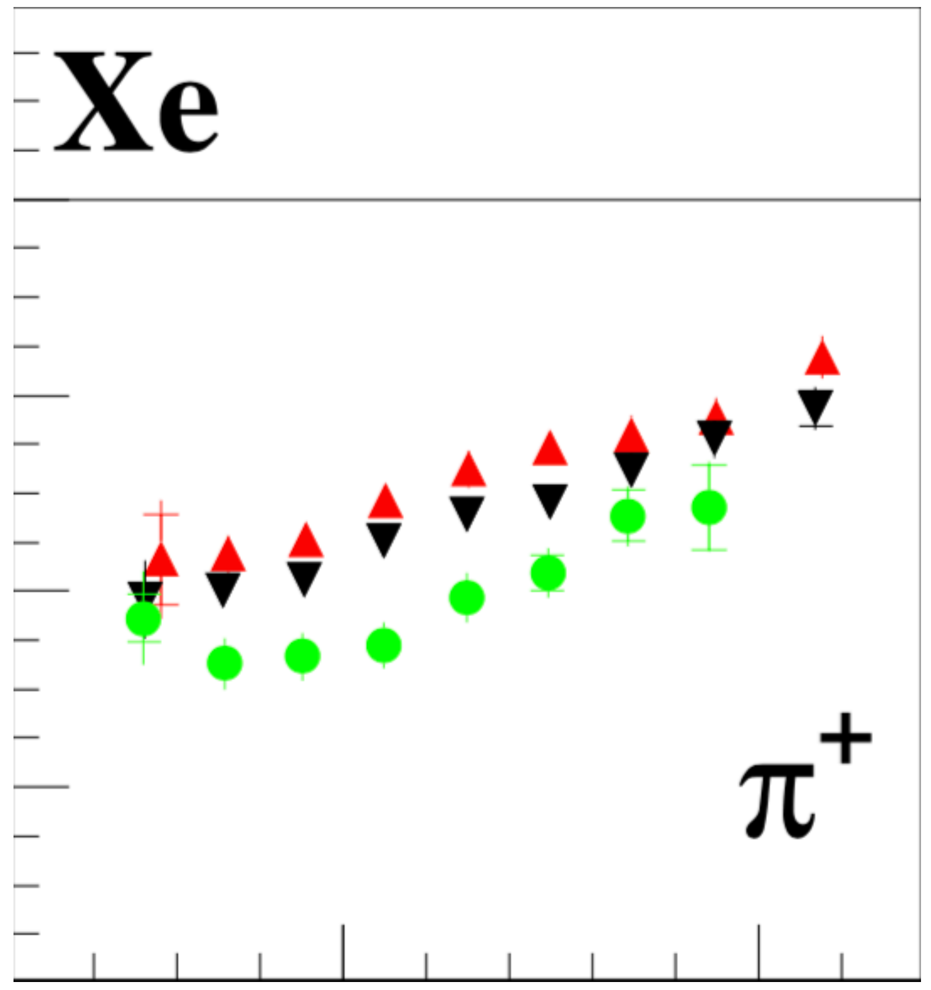
proton (left) and antiproton (right) are totally different

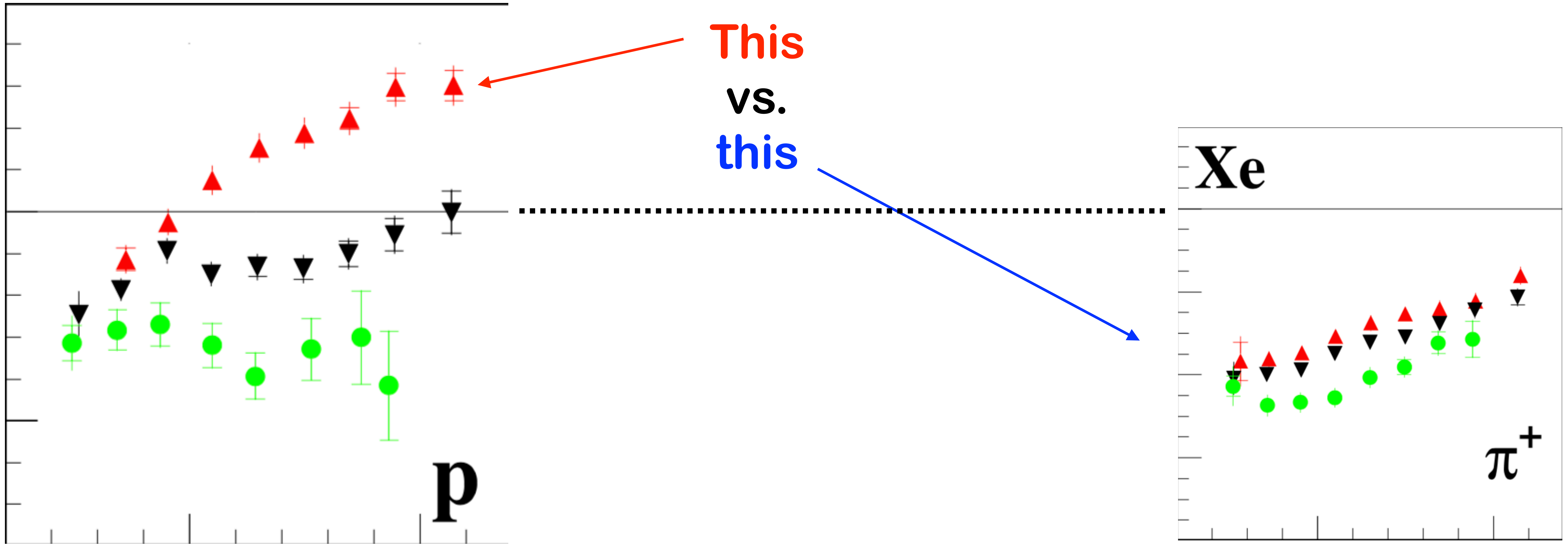
Proton multiplicity ratios qualitatively different from mesons.



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 <u>diquarks</u> 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 <u>Lambda Baryons</u>

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:

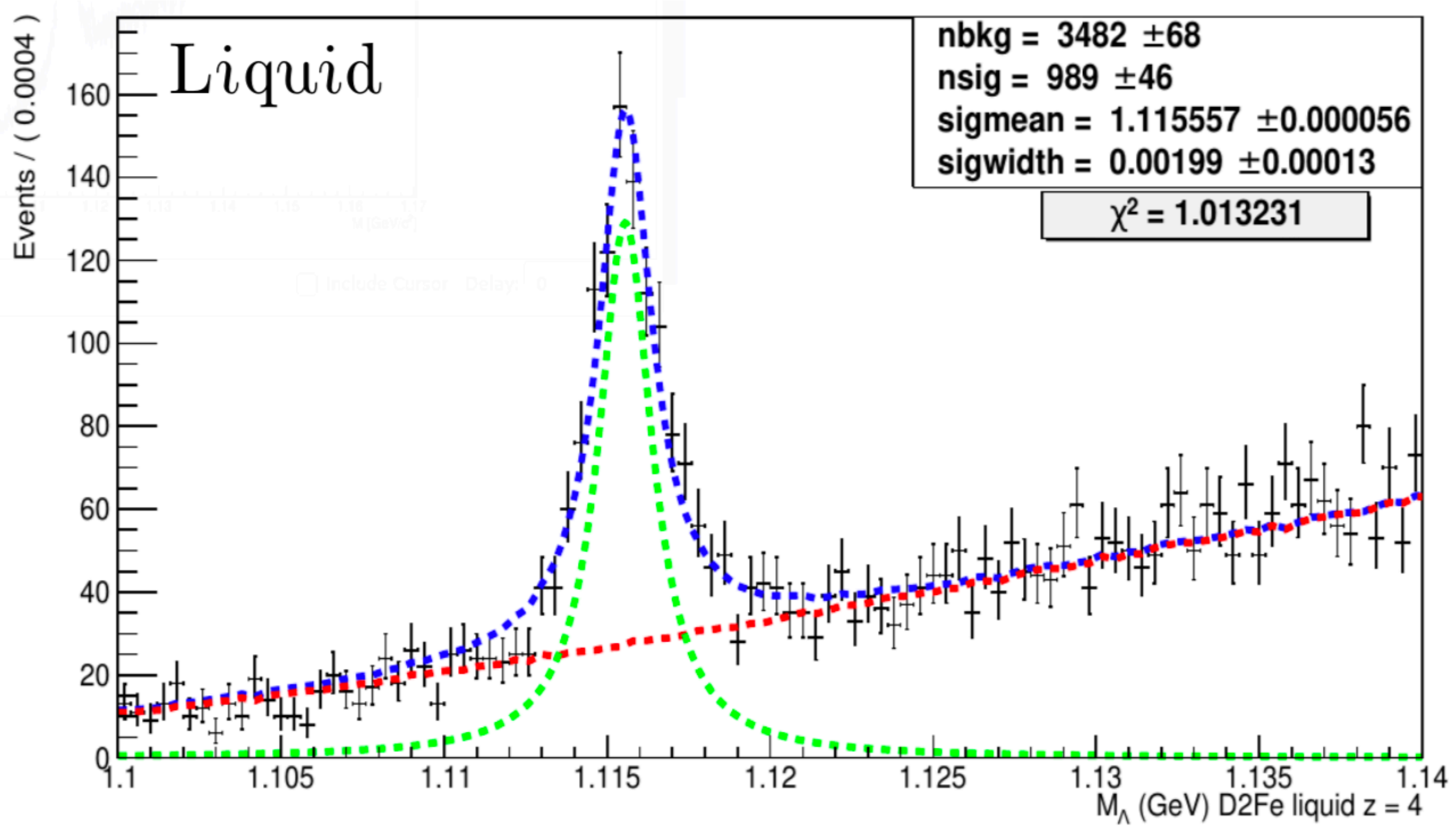
Dr. Ahmed El Alaoui

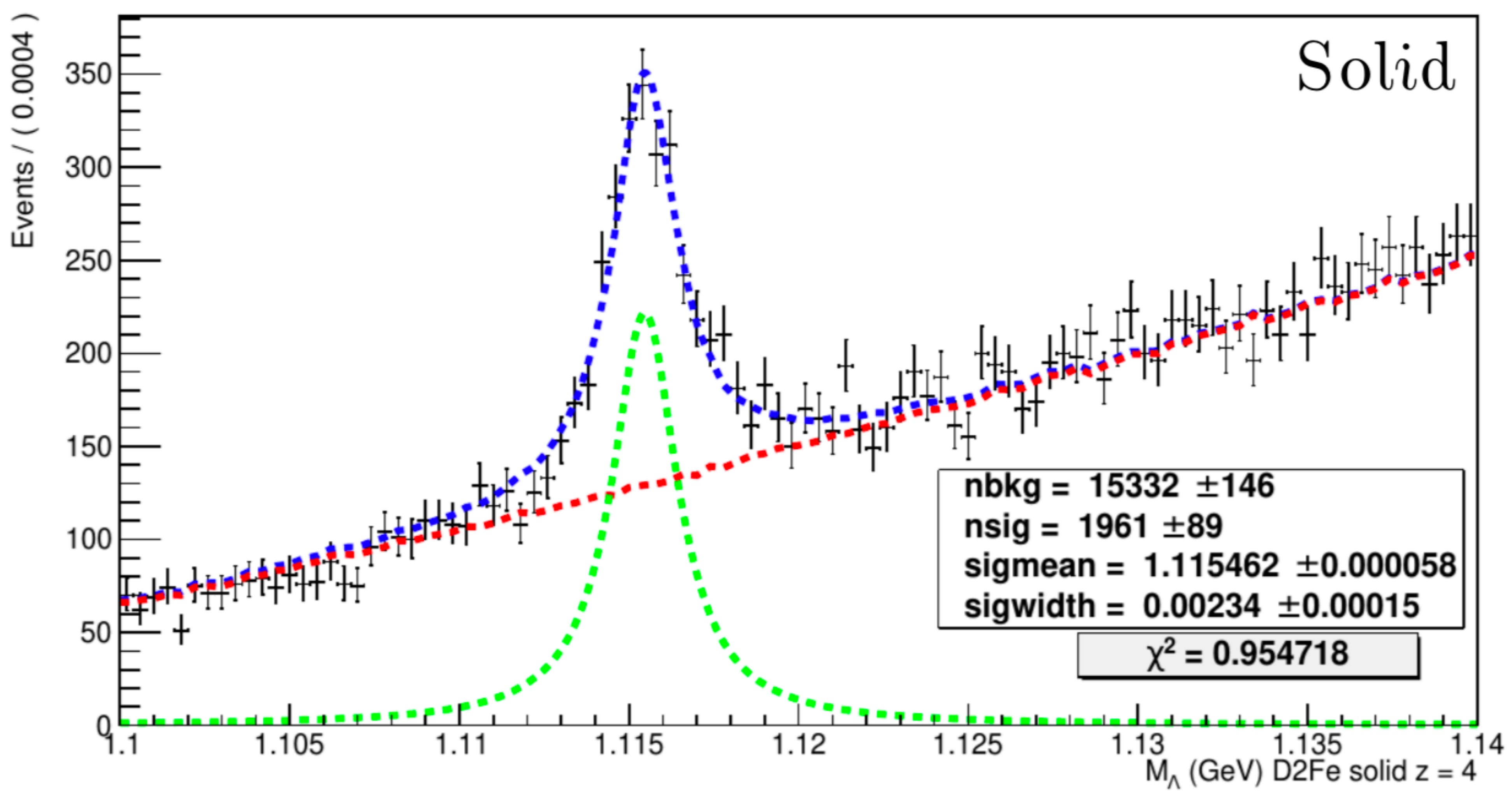
Some early work performed at ANL.

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

Lambda Baryons are well-identified in $\pi^{-}p$ channel

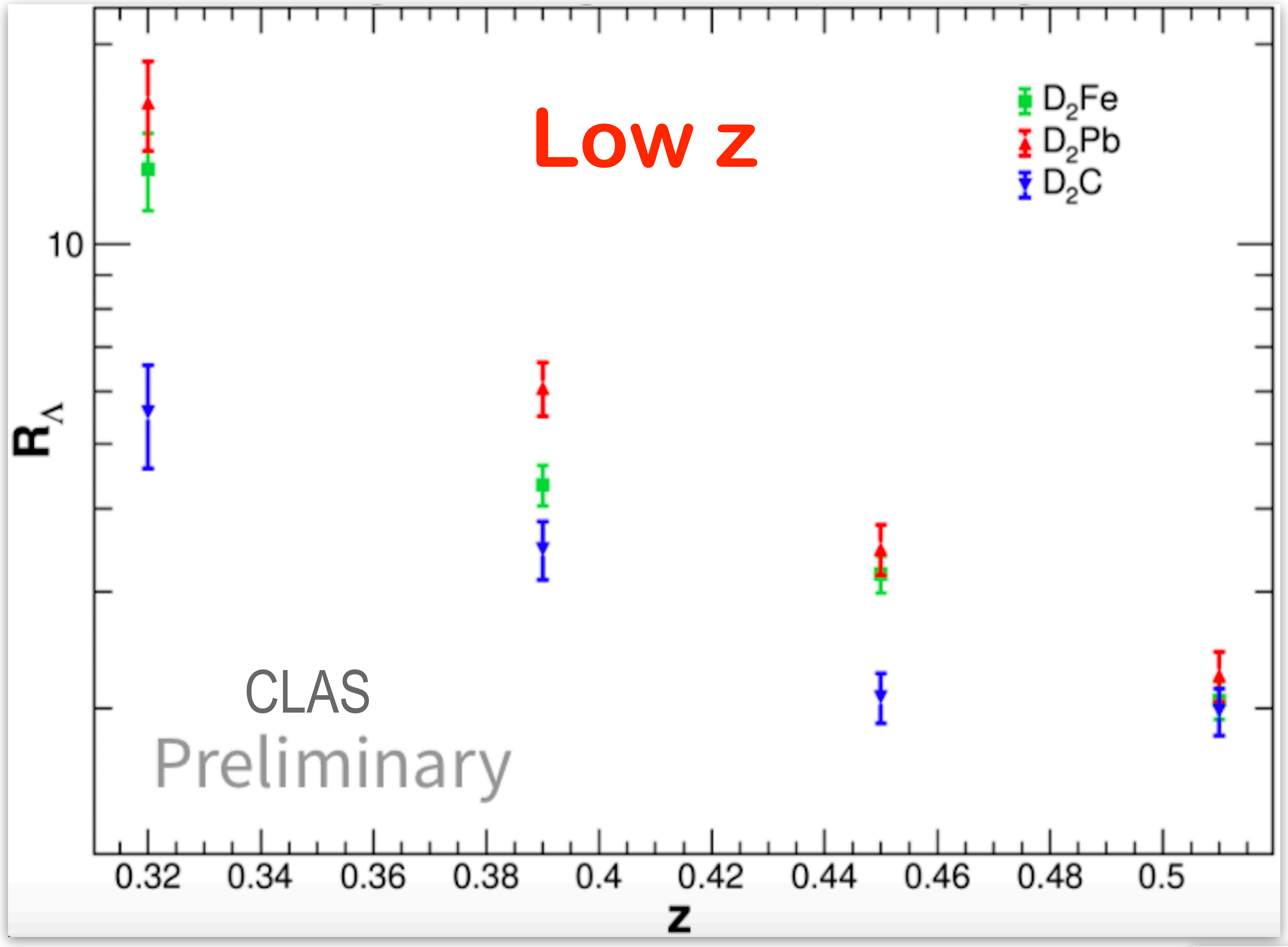
$z = [0.48,\ 0.54)$





M_{Λ} M_{Λ}

Backgrounds are under control - three different extraction methods agree

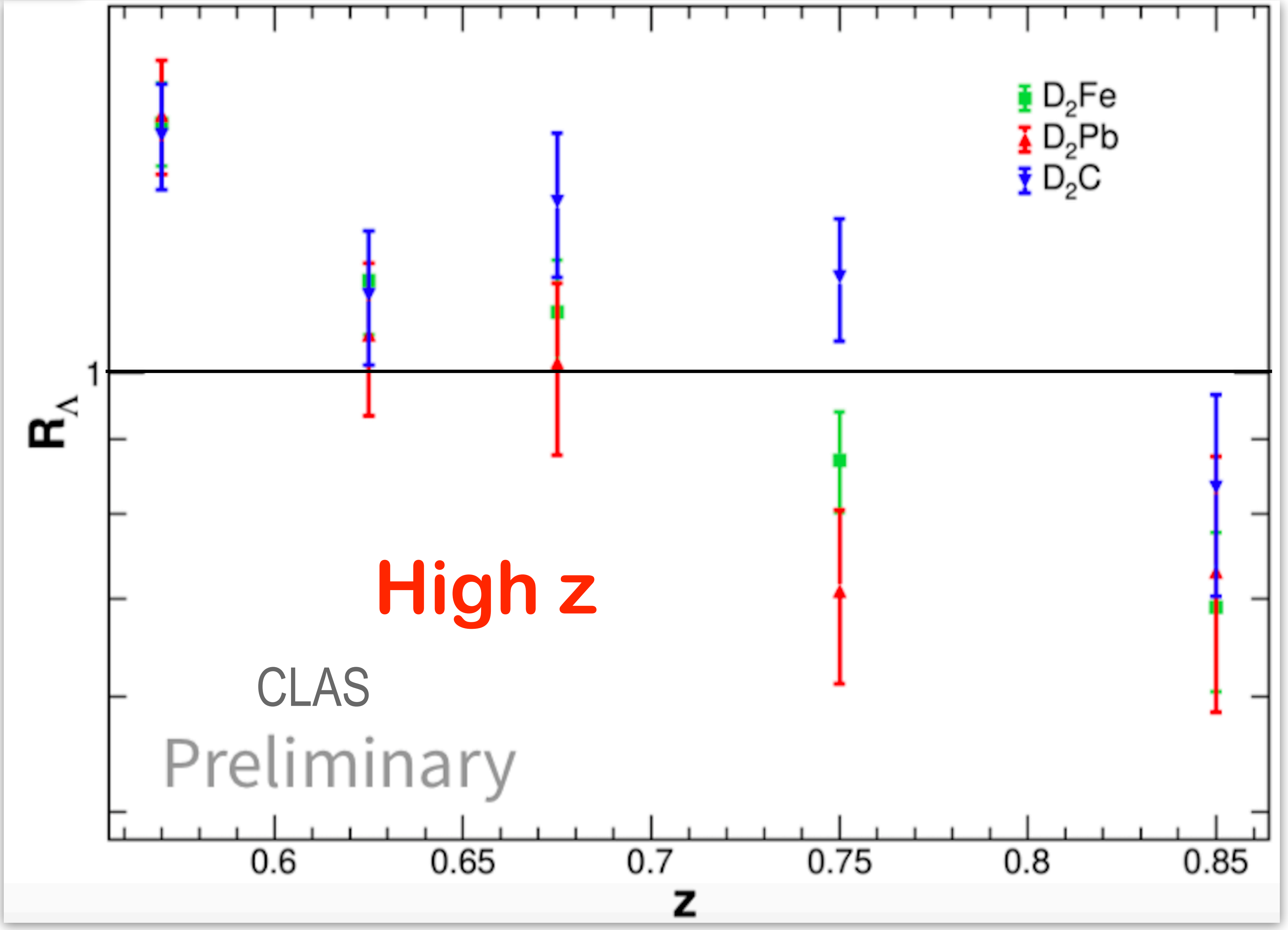


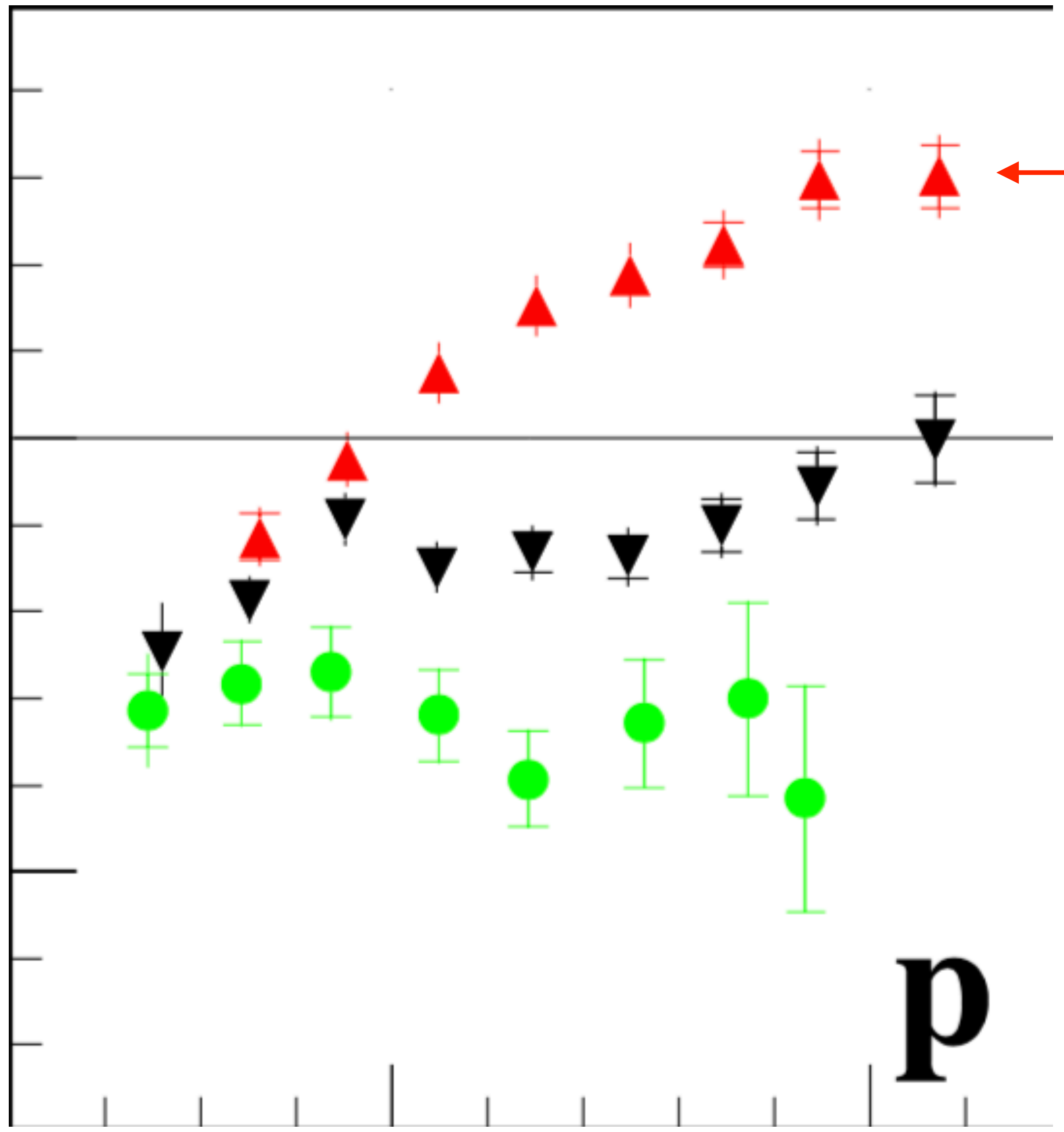
"Pile-up" of events at low z - <u>huge</u> effect compared to pion production

Order inverted as expected: heavy-to-light

At higher z, there is relatively little attenuation.

Order as expected: light-to-heavy





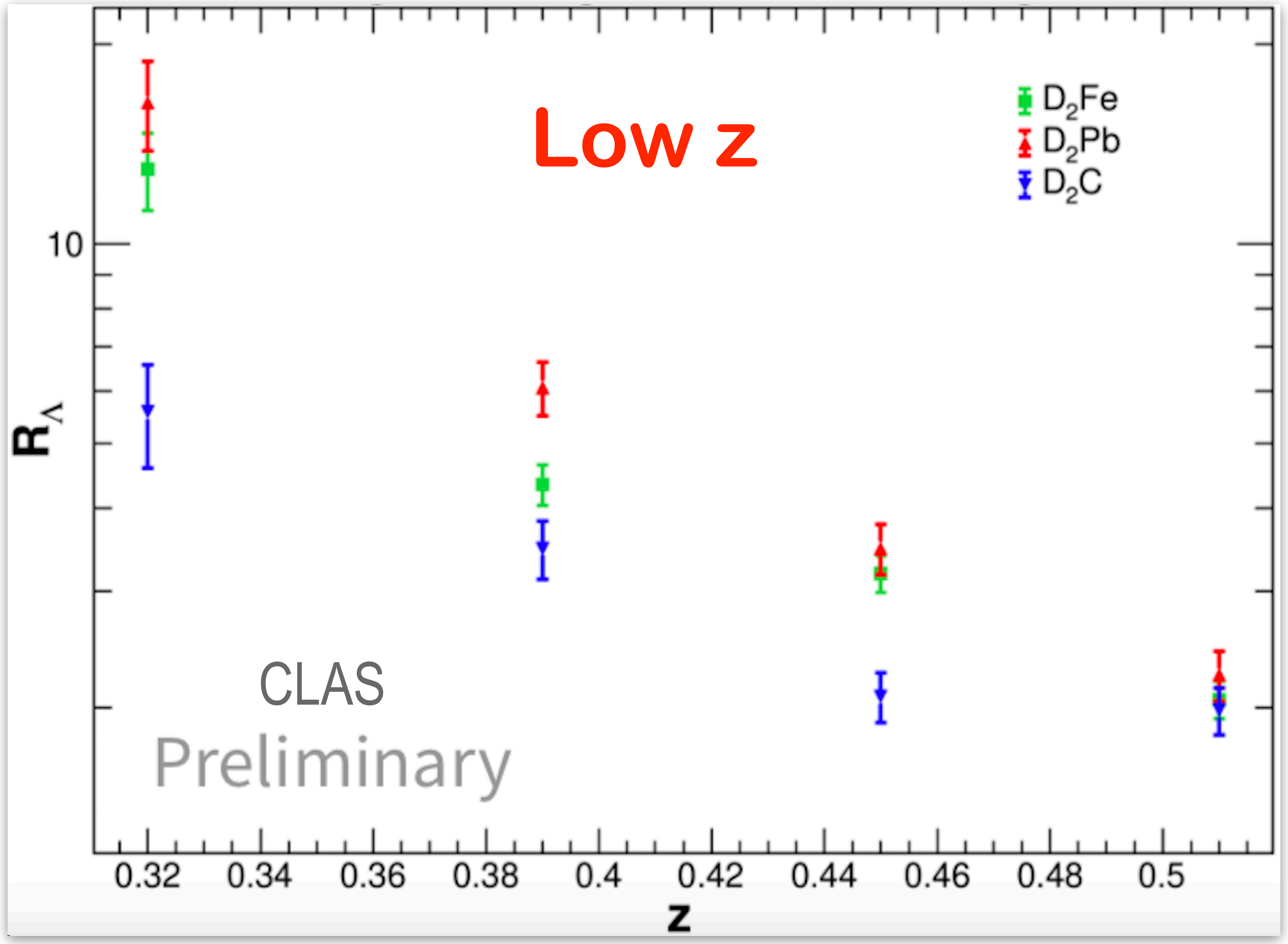
Excess of low-z protons in HERMES data

Explanation: FSI are "knocking out protons"??

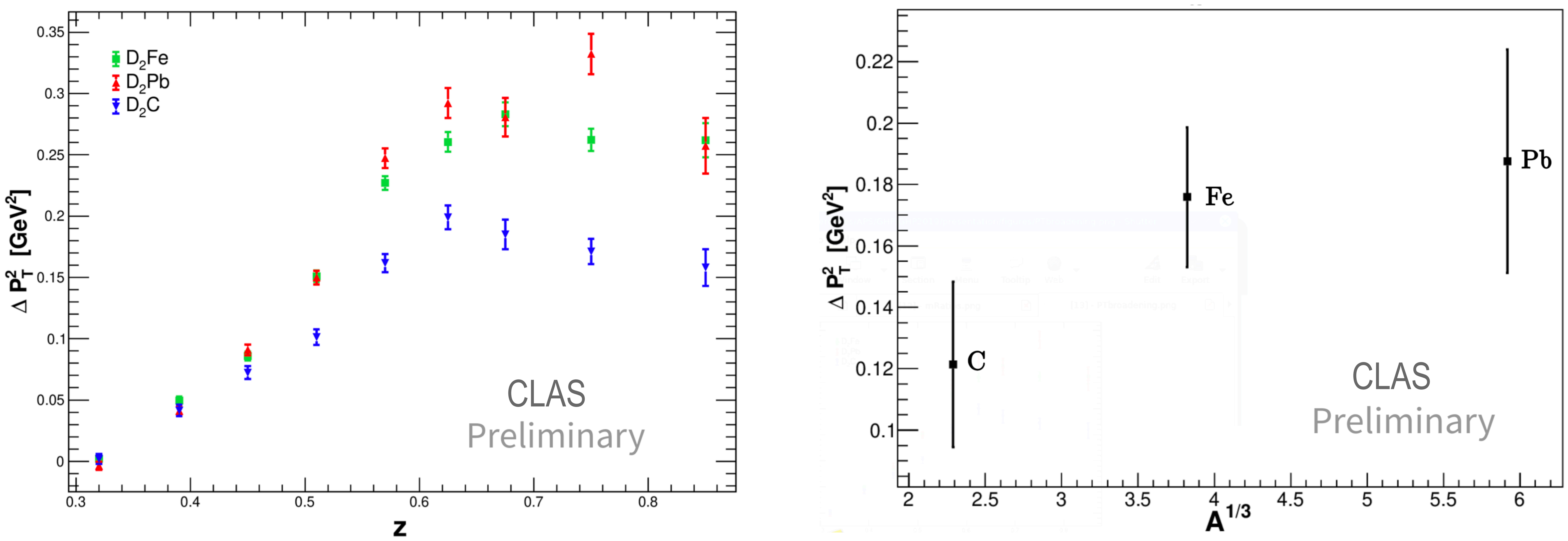
Excess of low-z Lambdas in CLAS data

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!

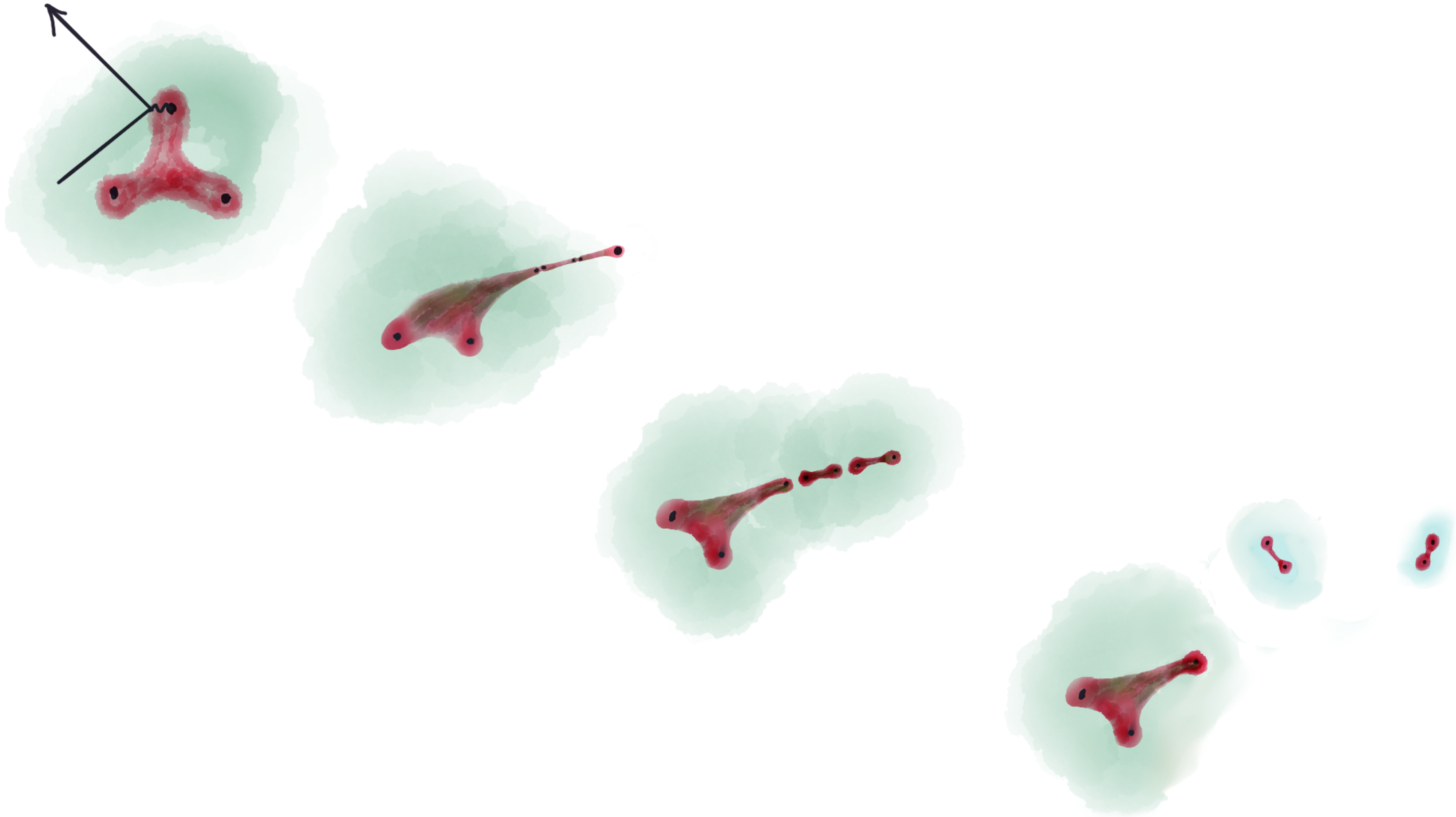
The object passing through the medium is disruptive!

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

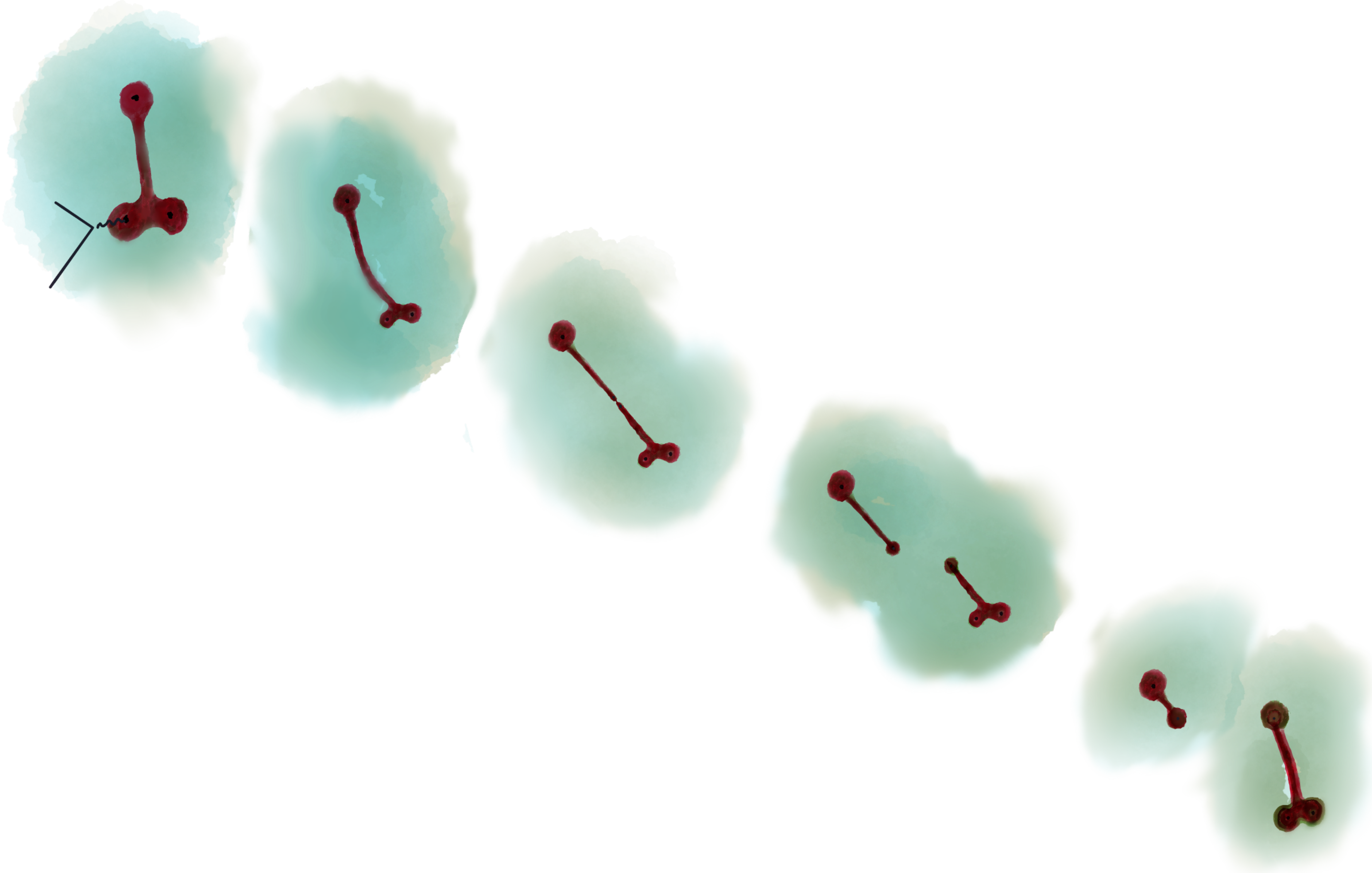
Could it be possible that the virtual photon is absorbed by a diquark?

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

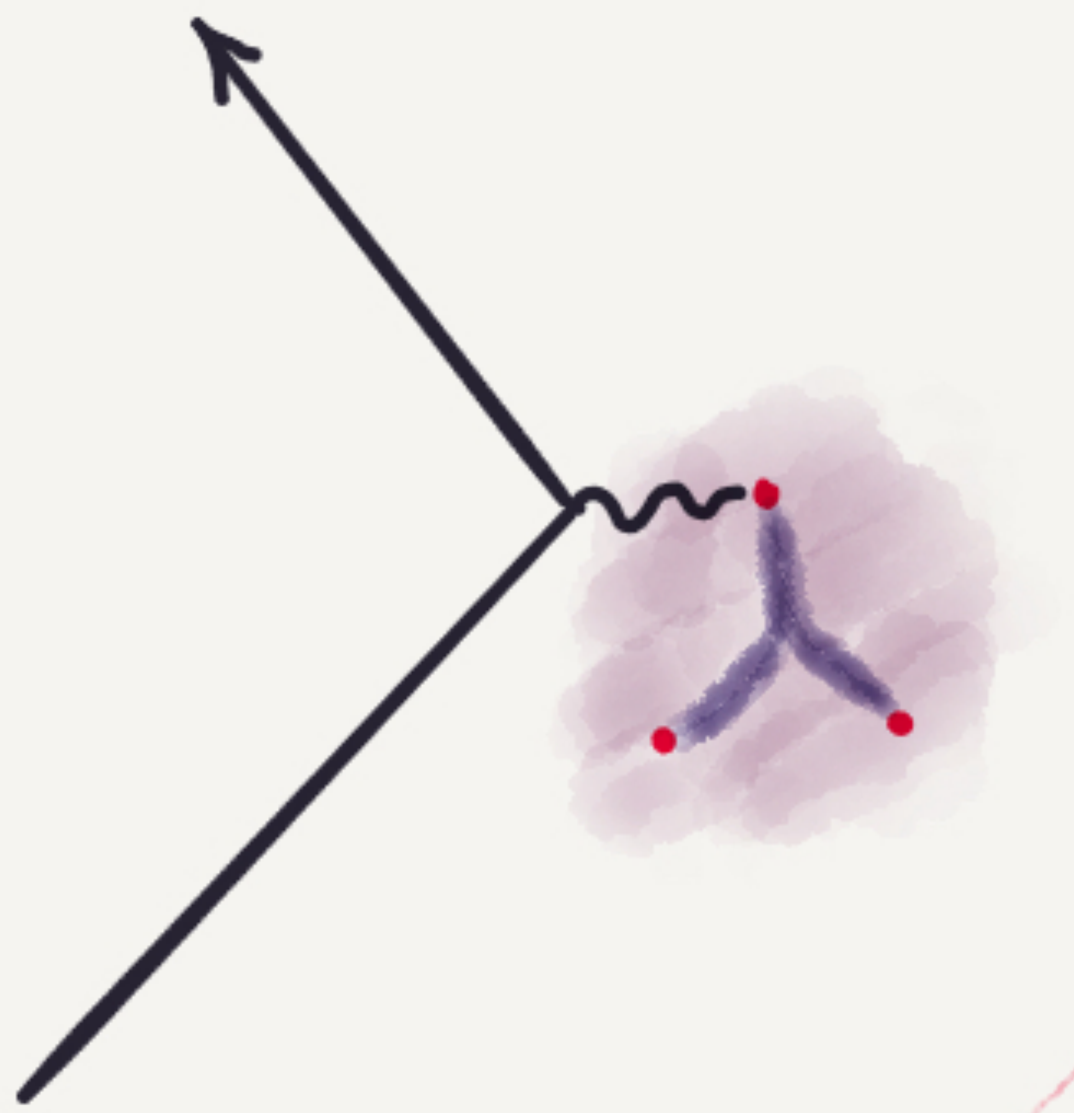


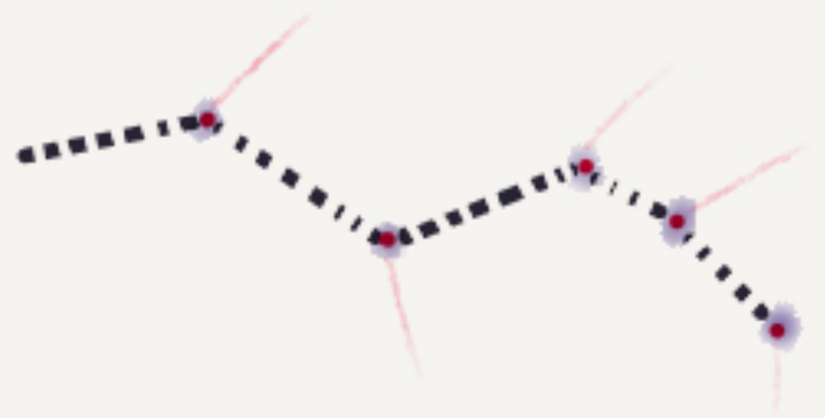
This DDS mechanism makes it a lot easier to form a proton. Making a proton in the Lund String Model is famously problematic.

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

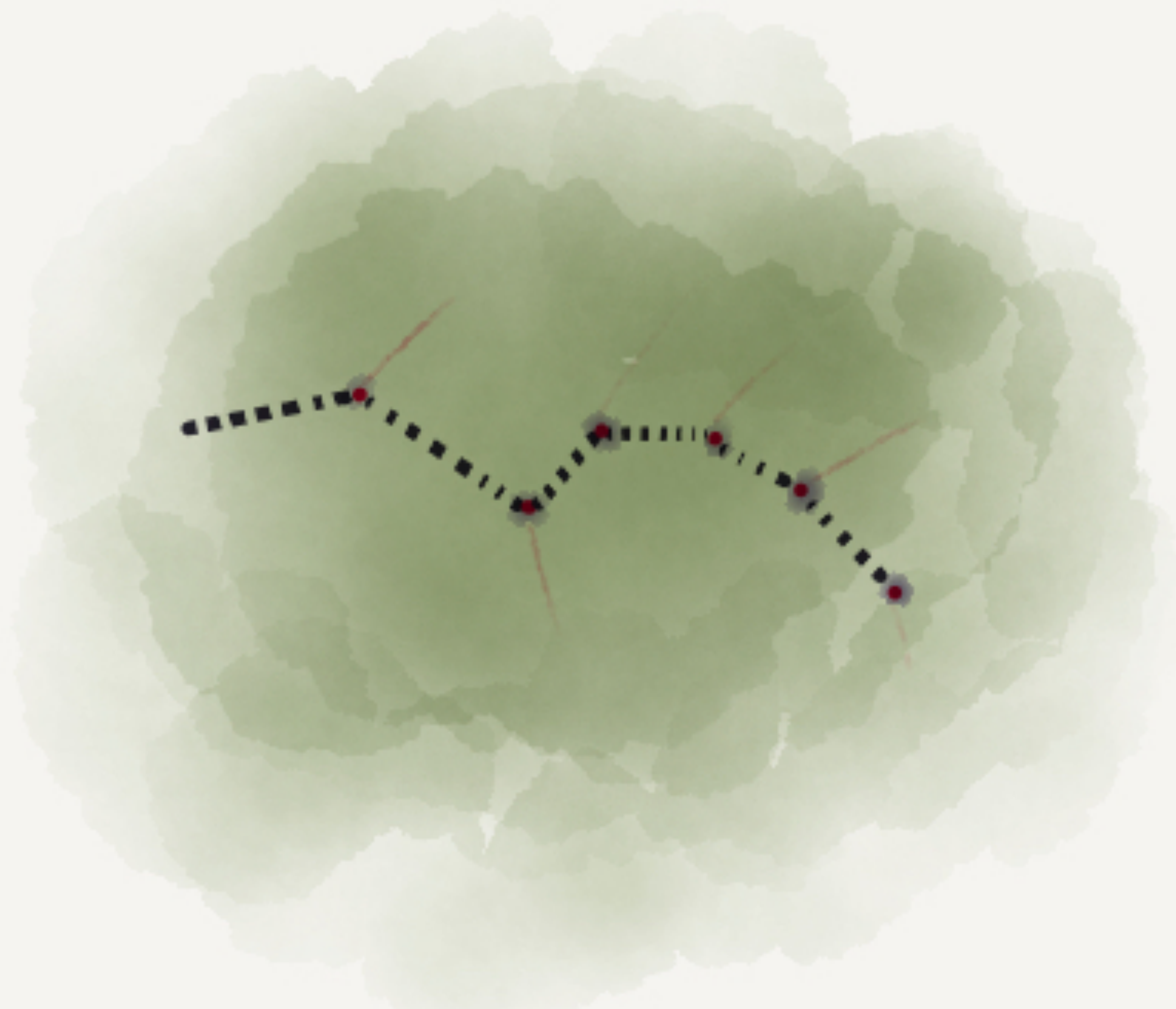
Multiplicity ratio, pT broadening, and correlations between hadrons will provide the evidence.

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



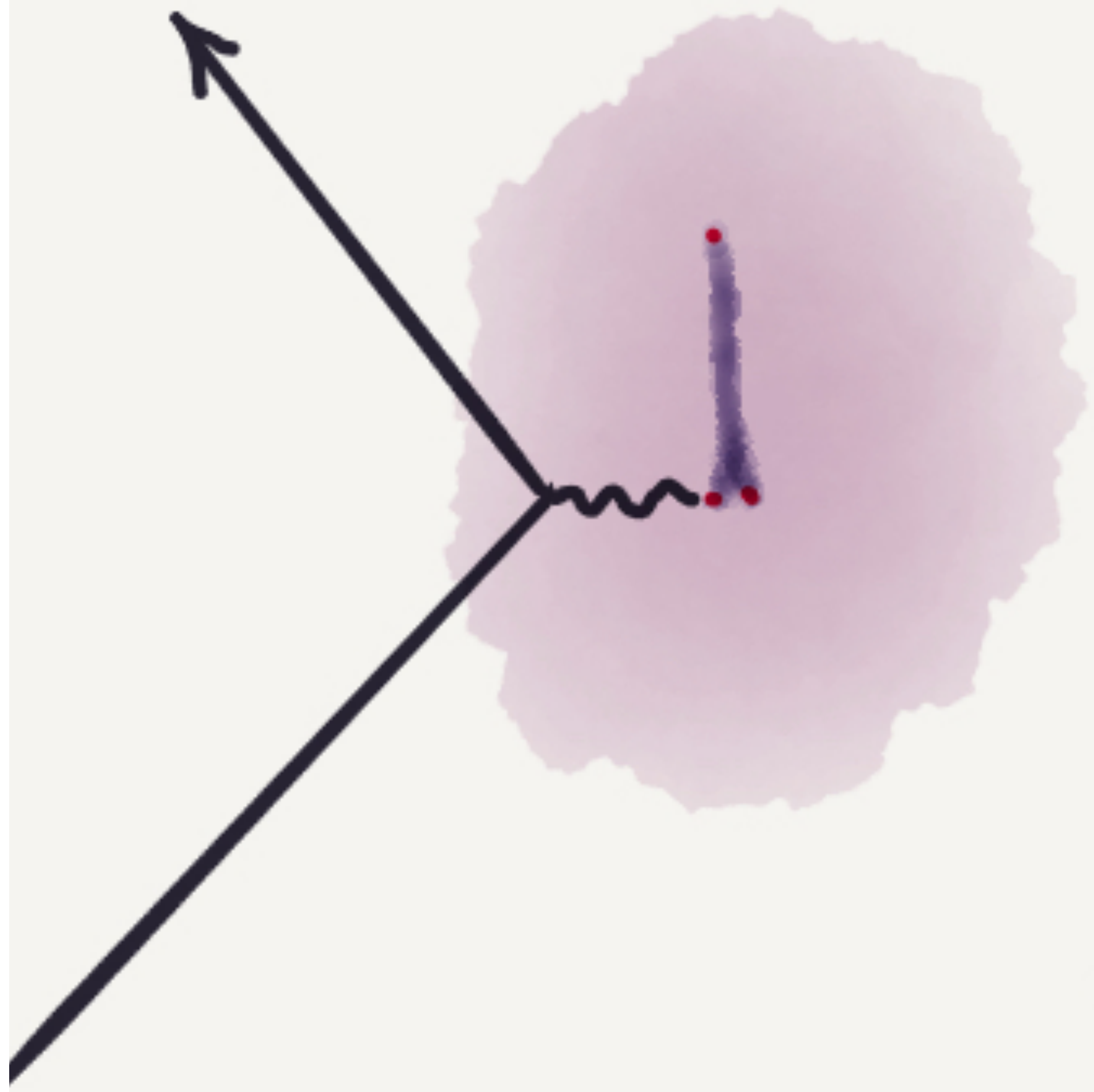


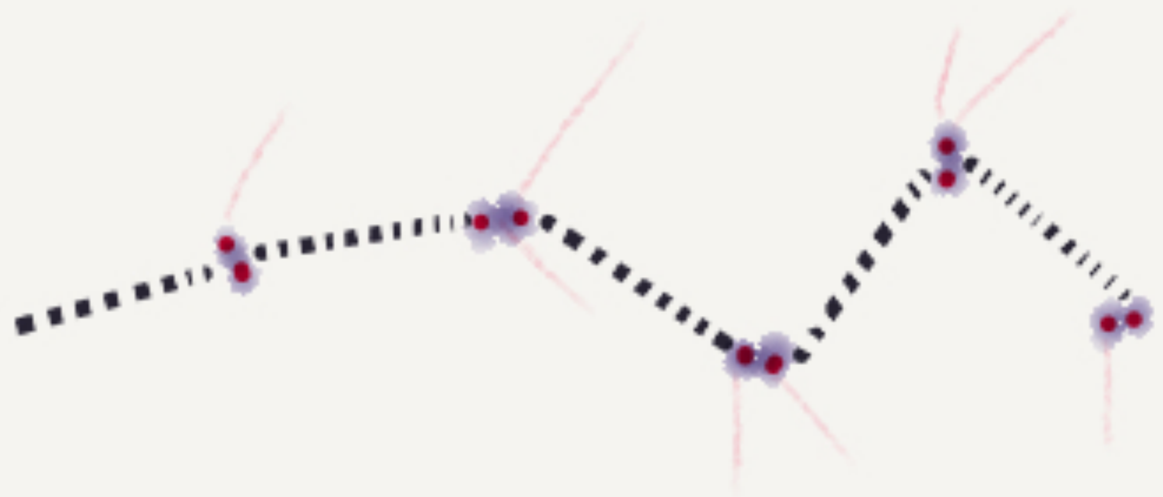
in vacuum



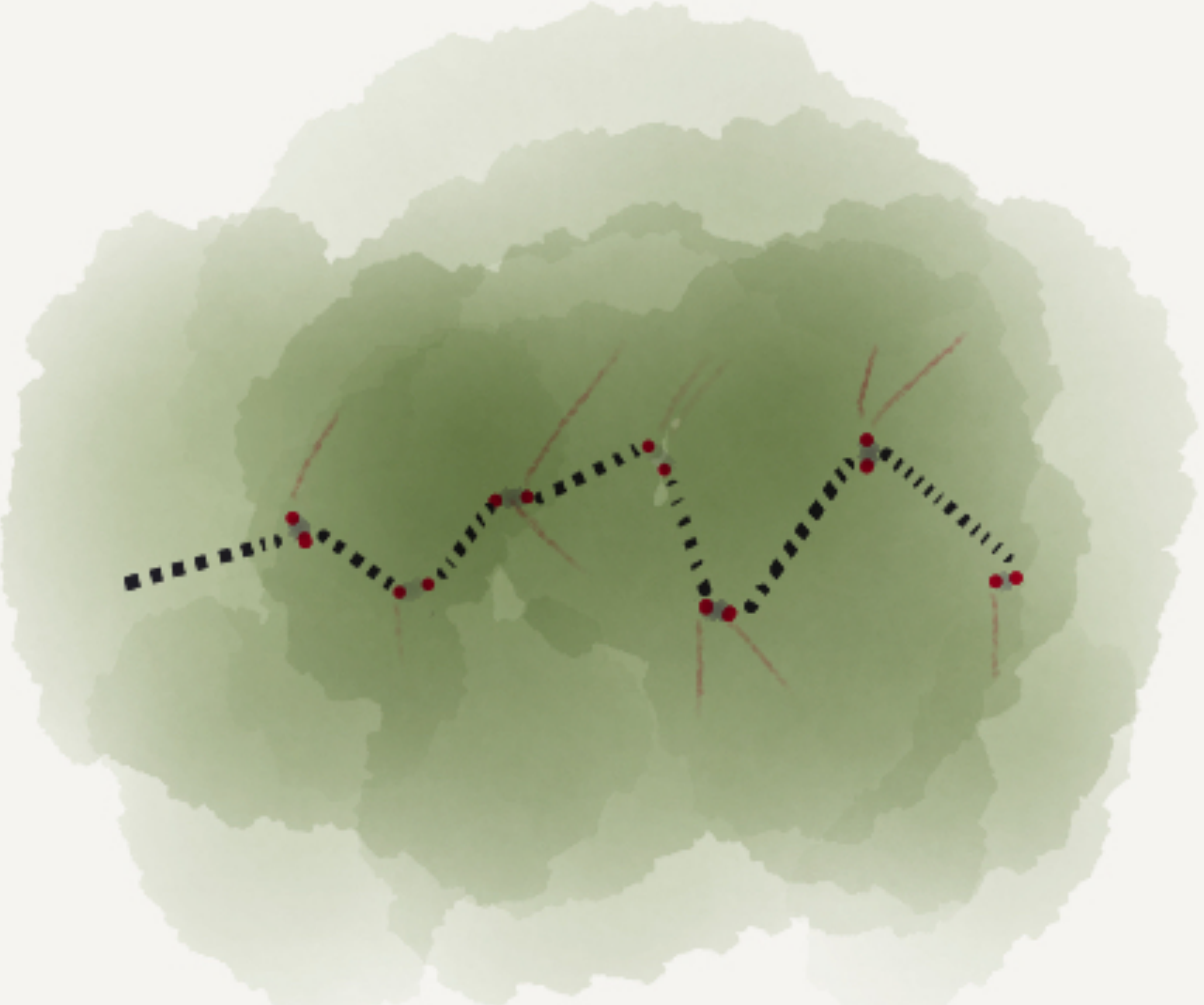
in medium

The pT broadening by a diquark might be much larger: CLAS lambdas showed up to 0.3 GeV^2.





in vacuum



in medium

Further tests of the Direct Diquark Scattering hypothesis with CLAS12 nDIS on <u>baryons</u>

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}	$s^{\mathrm{r}1}$	$s^{\mathrm{r}2}$	$a_1^{\mathrm{r}2}$	$a_2^{\mathrm{r}2}$	$a_1^{\mathrm{r}3}$	$a_2^{\mathrm{r}3}$	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	$\{ss\}c$

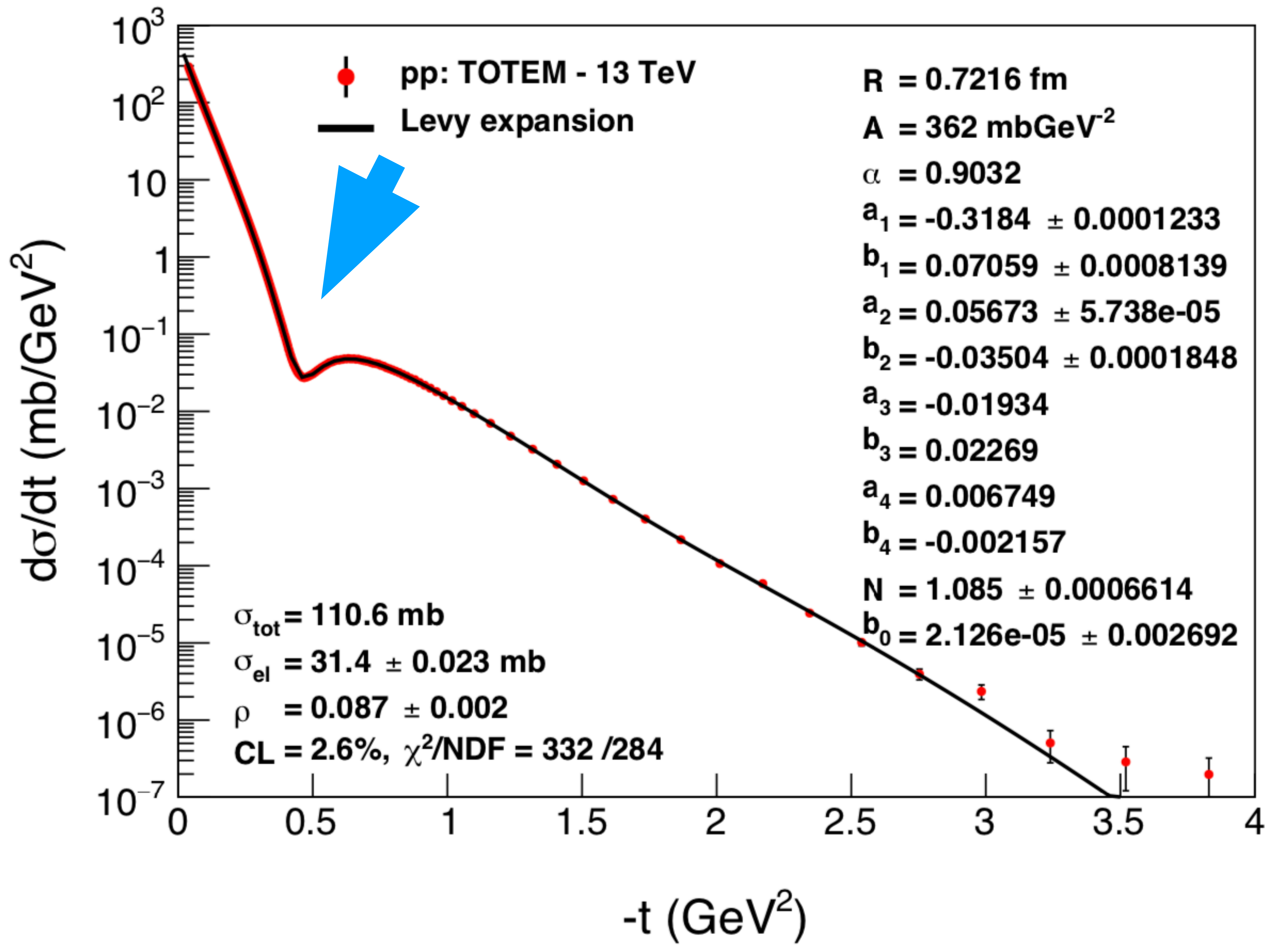
This suggests a specific behavior for DDS.

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

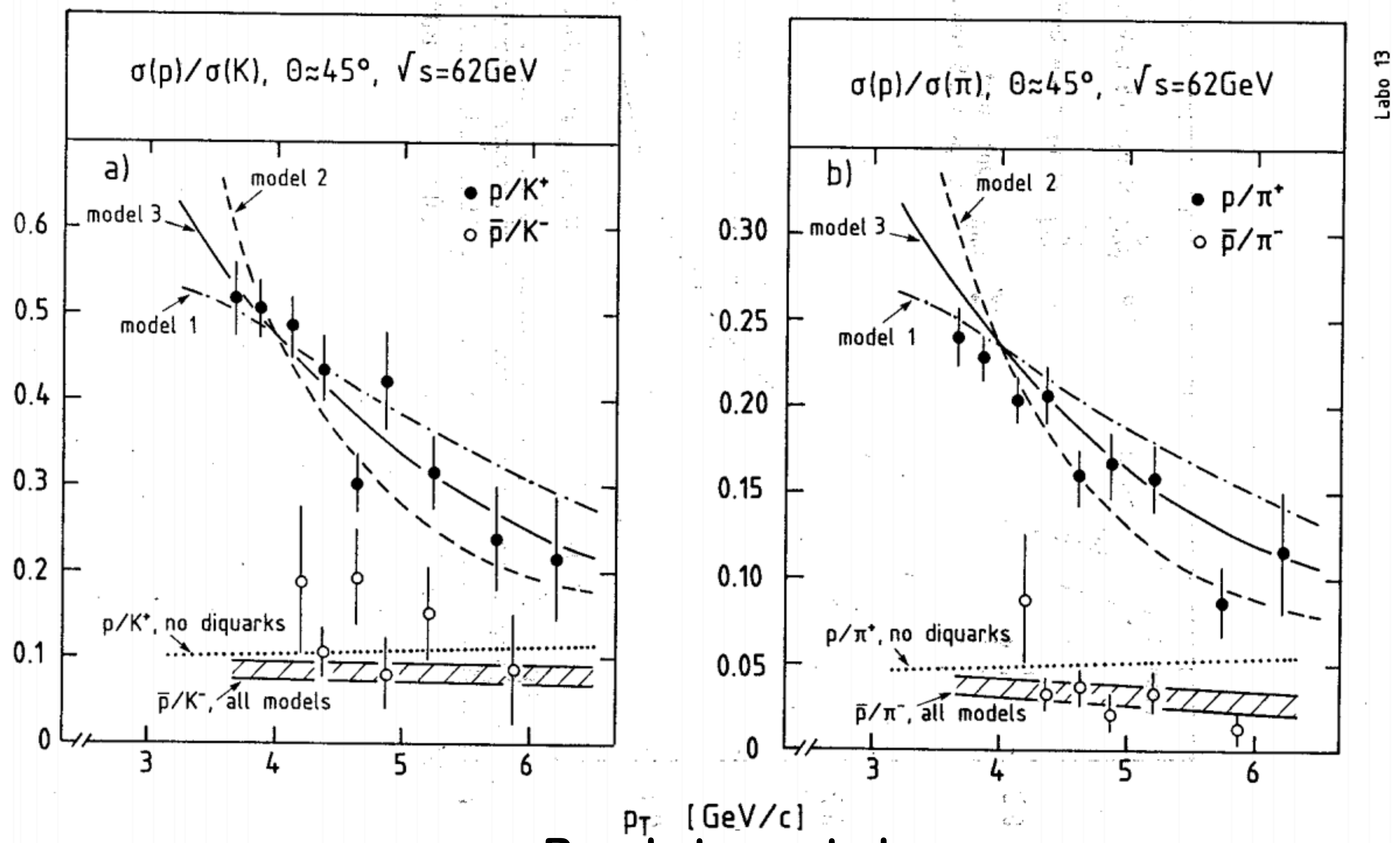
A DIQUARK SCATTERING MODEL FOR HIGH p_T PROTON PRODUCTION IN pp COLLISIONS AT THE ISR

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



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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.

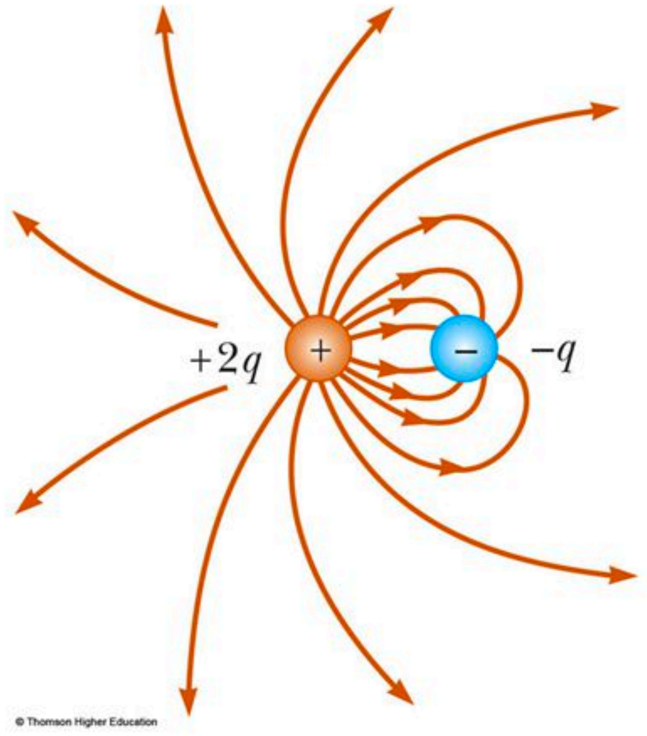
Possible objections to the Direct Diquark Scattering hypothesis

- 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 as
    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.