

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 $\longrightarrow$ 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>

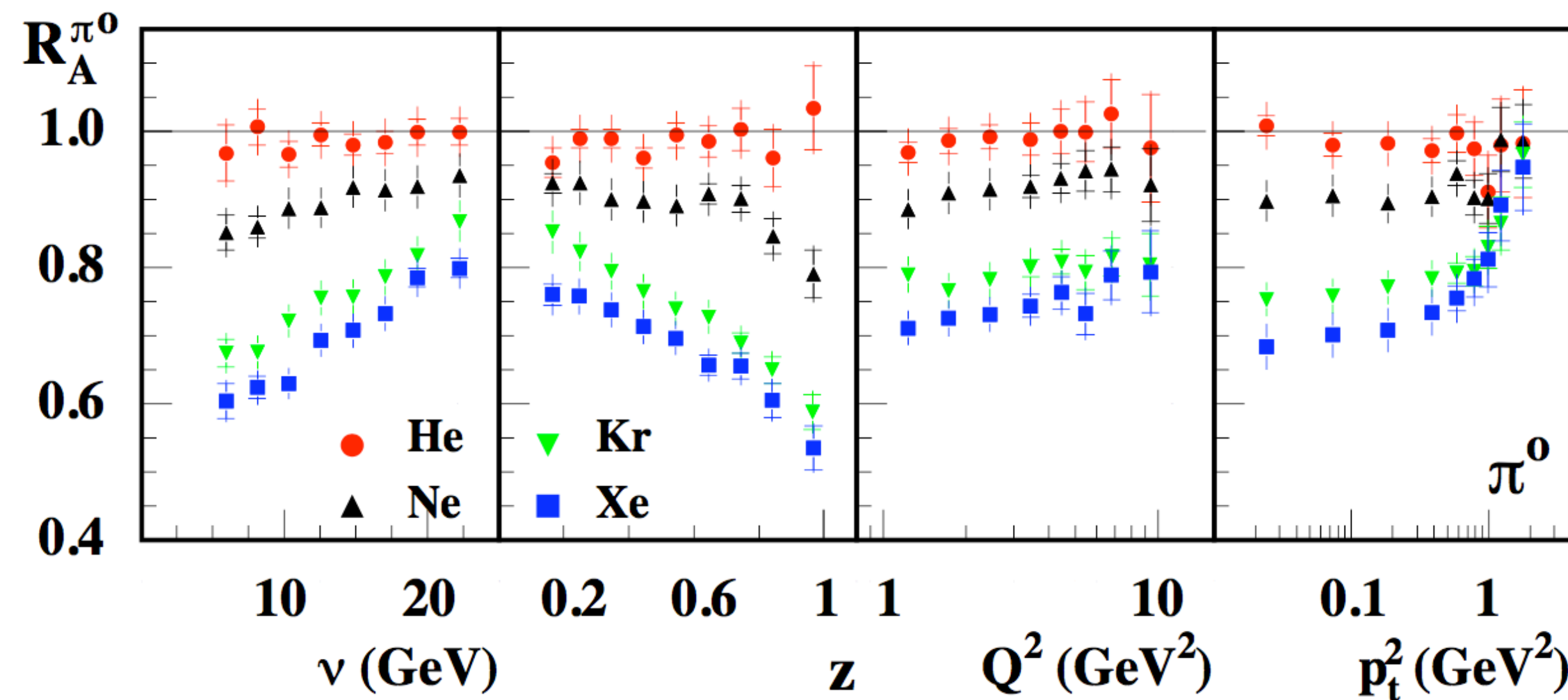
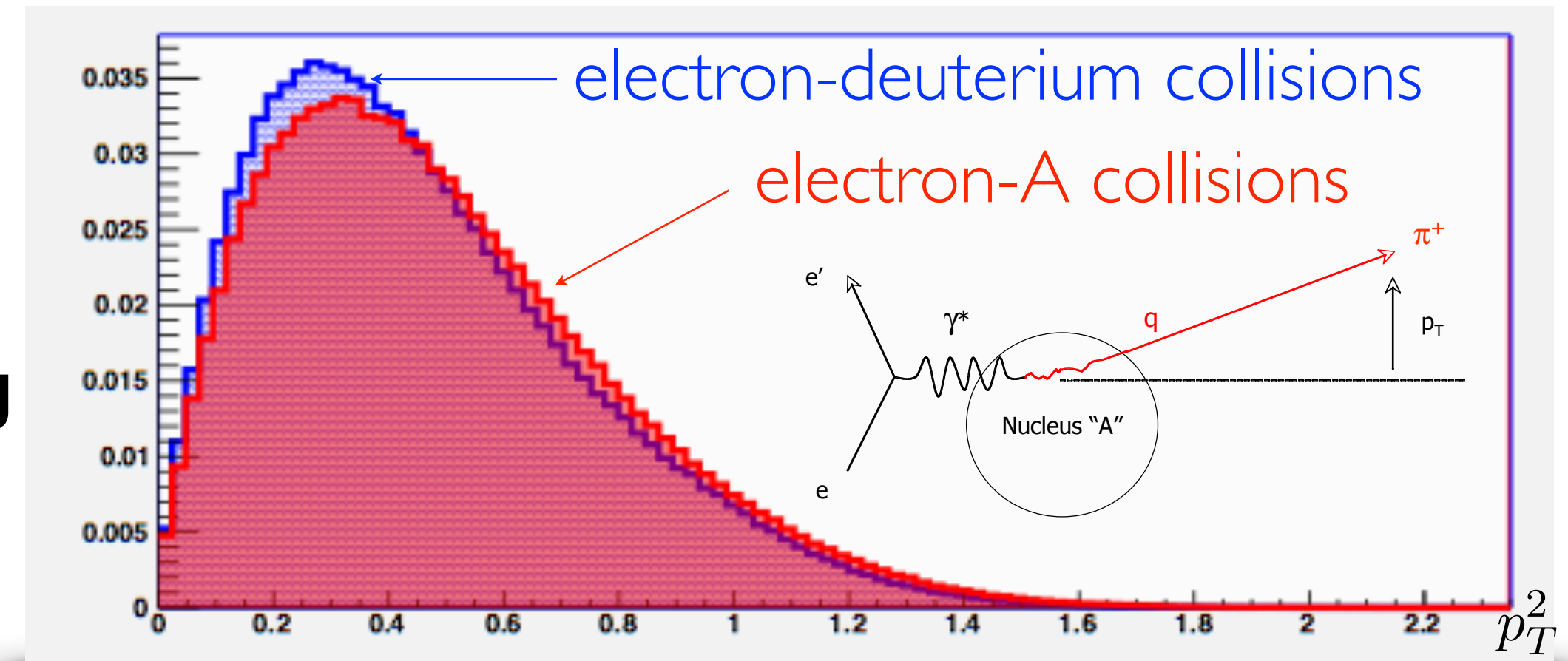
Luo, Qiu, Sterman, Phys. Rev. D 50 (1994) 1951– 1971. <https://link.aps.org/doi/10.1103/PhysRevD.50.1951>

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

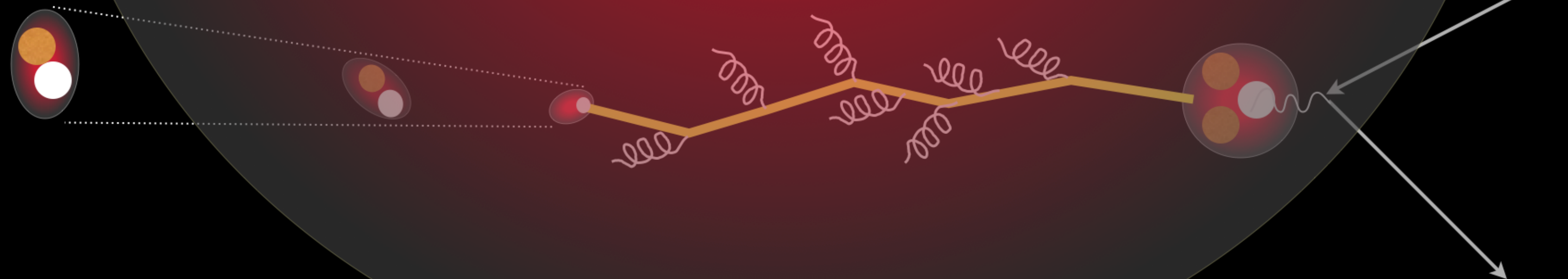
Transverse momentum broadening
typical value $< 0.05 \text{ GeV}^2$



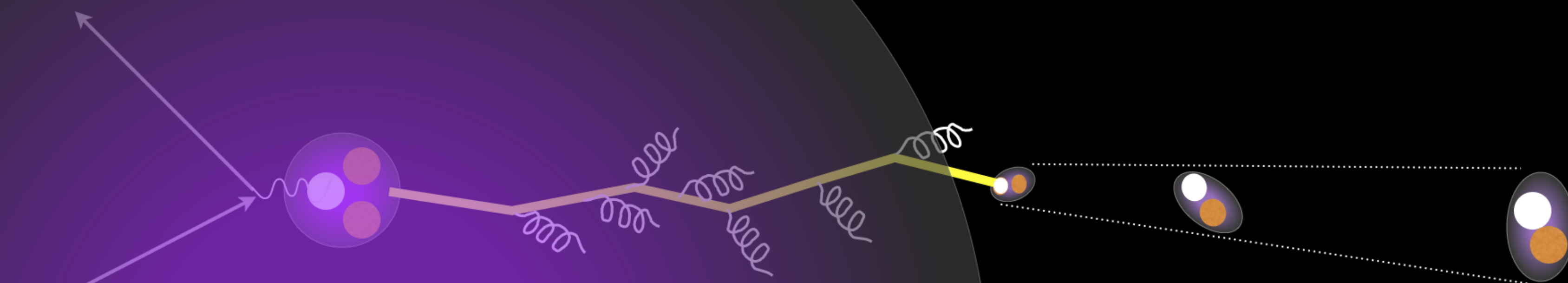
Hadronic multiplicity ratio (MR)
= 1 if no nuclear effects

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

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

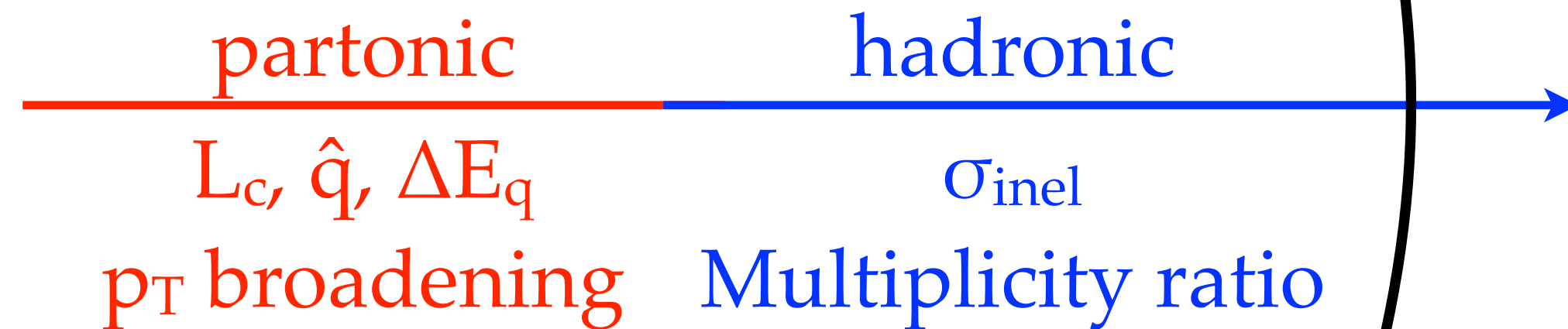


Propagation of **QCD color** through strongly interacting systems

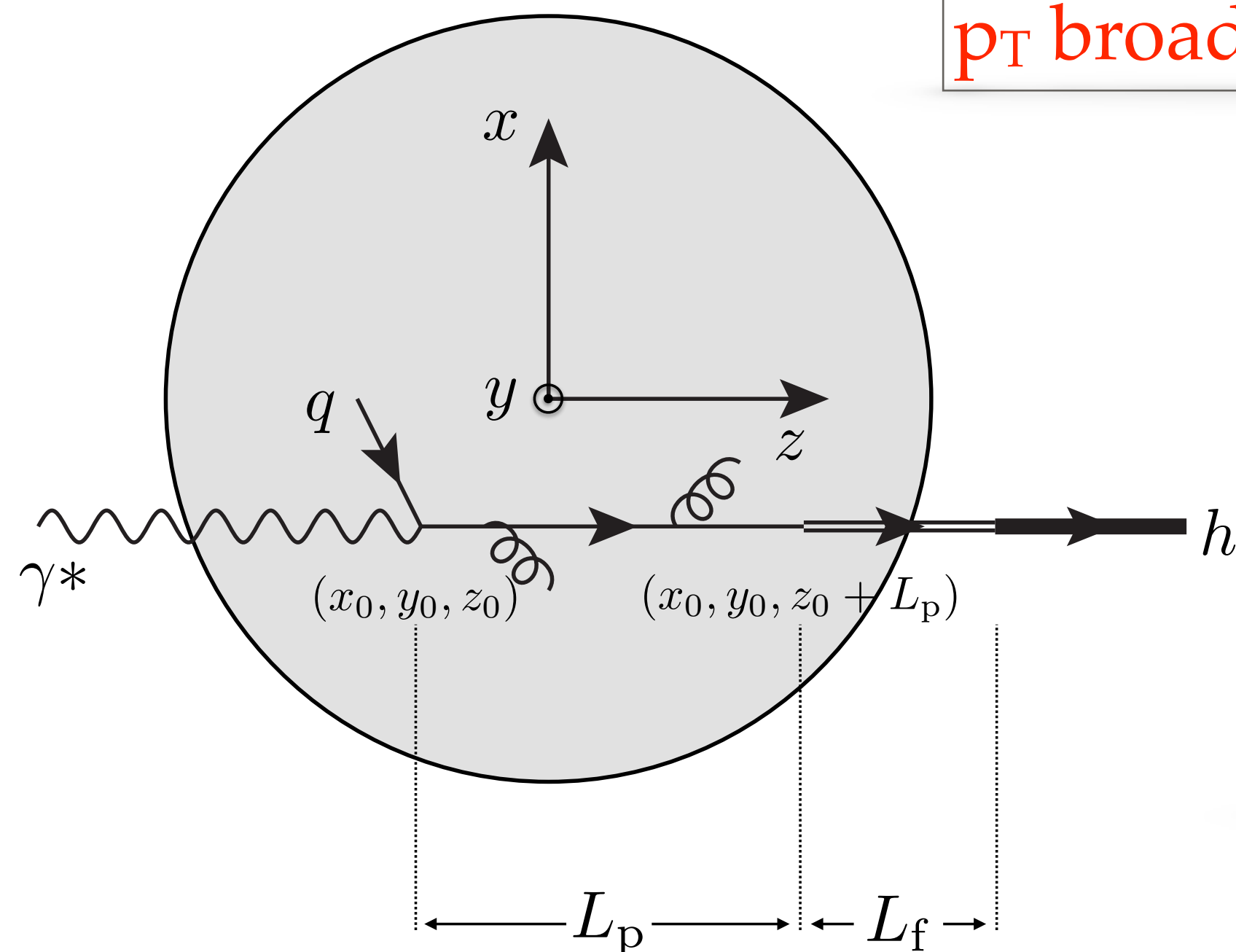


Division of the process into *partonic* and *hadronic* stages

Path of (struck) quark is divided into “*partonic phase*” and “*hadronic phase*”

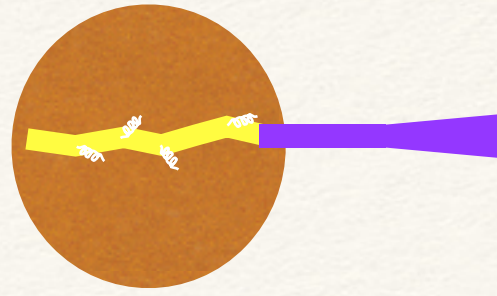


The *partonic phase* persists for a distance L_c , over which p_T broadening via $\hat{q}$, and *partonic energy loss* ΔE_q , occur

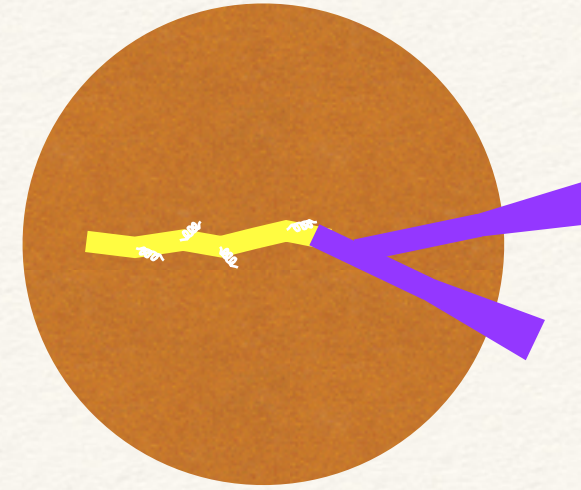


The *hadronic phase* follows the *partonic phase*, passing through the remainder of the medium, and causing attenuation of hadrons by an *inelastic interaction cross section* σ_{inel}

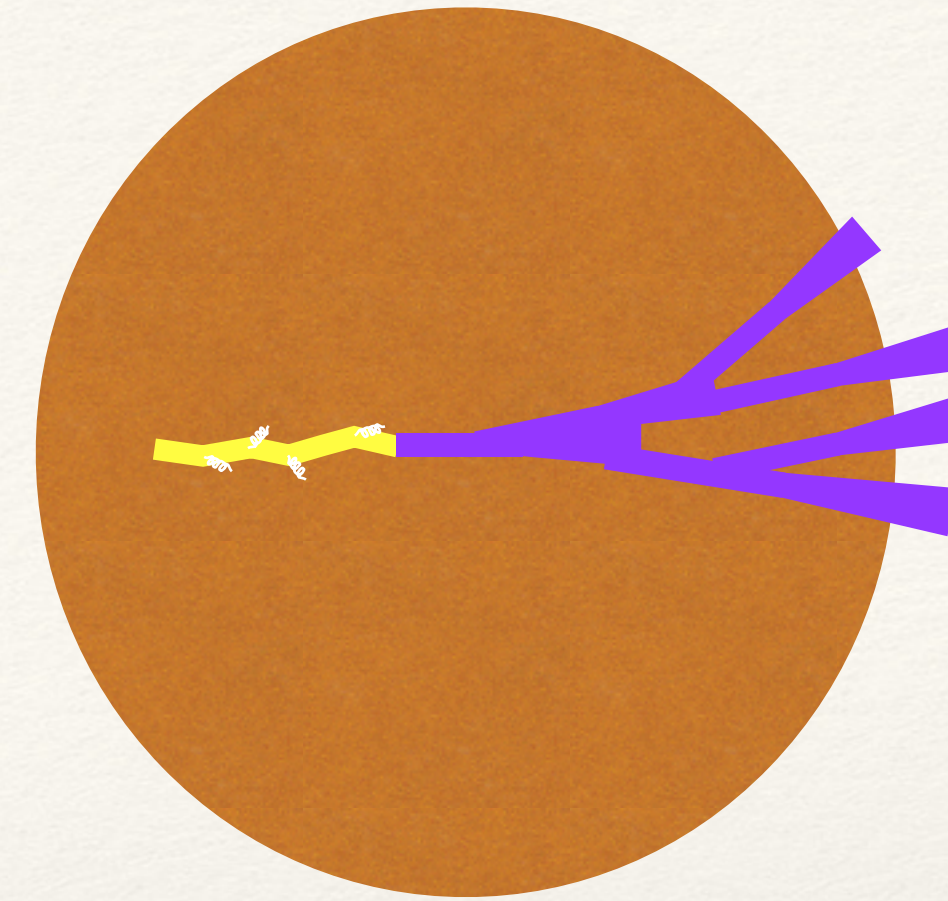
Short color
lifetime



Carbon nucleus
Radius = 2.5 fm

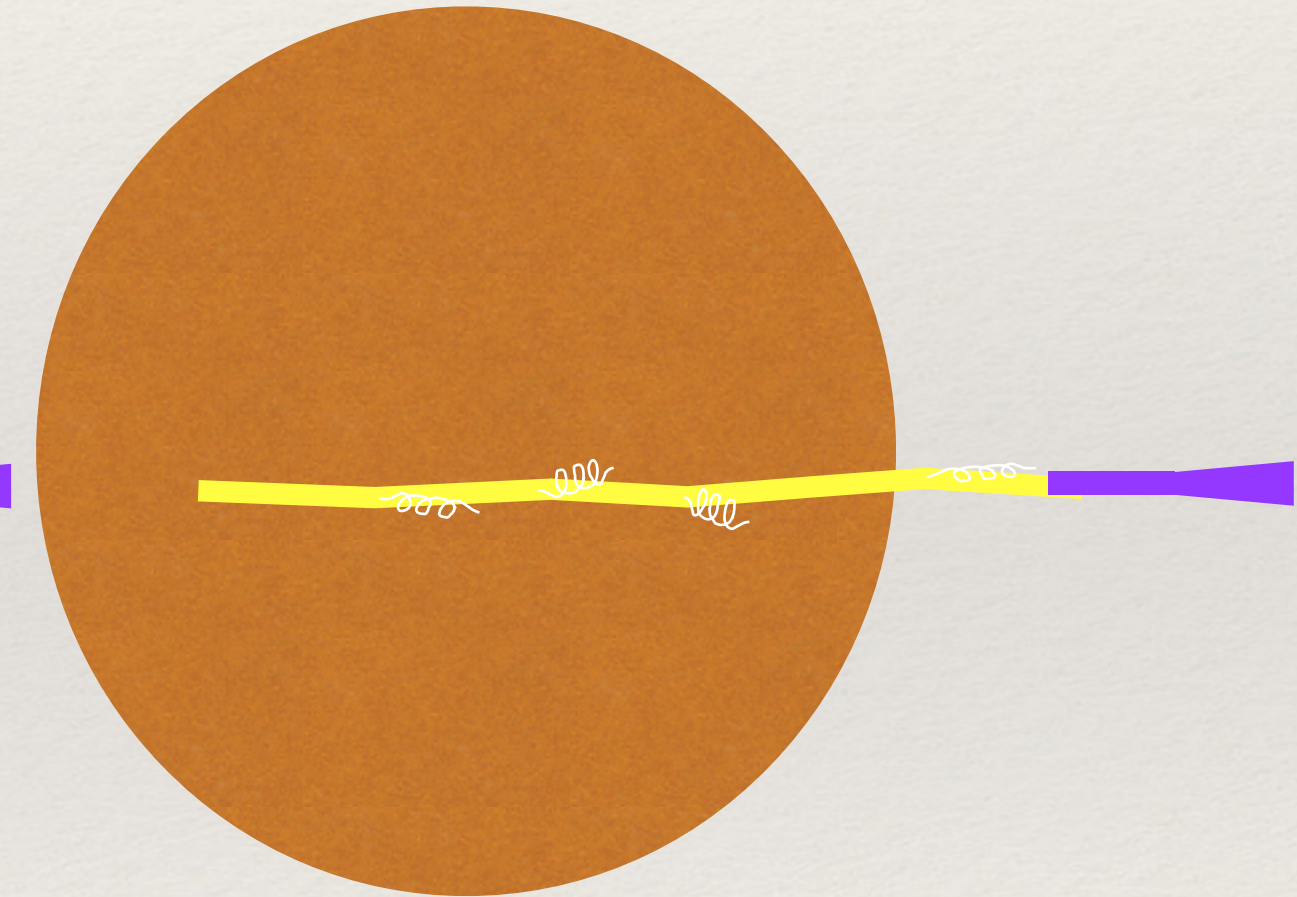
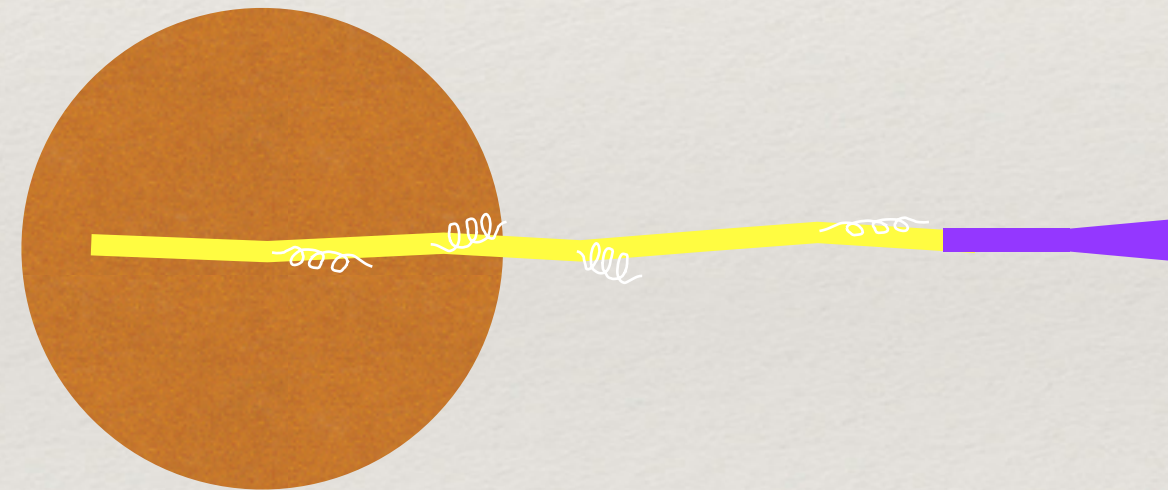


Iron nucleus
Radius = 4.2 fm

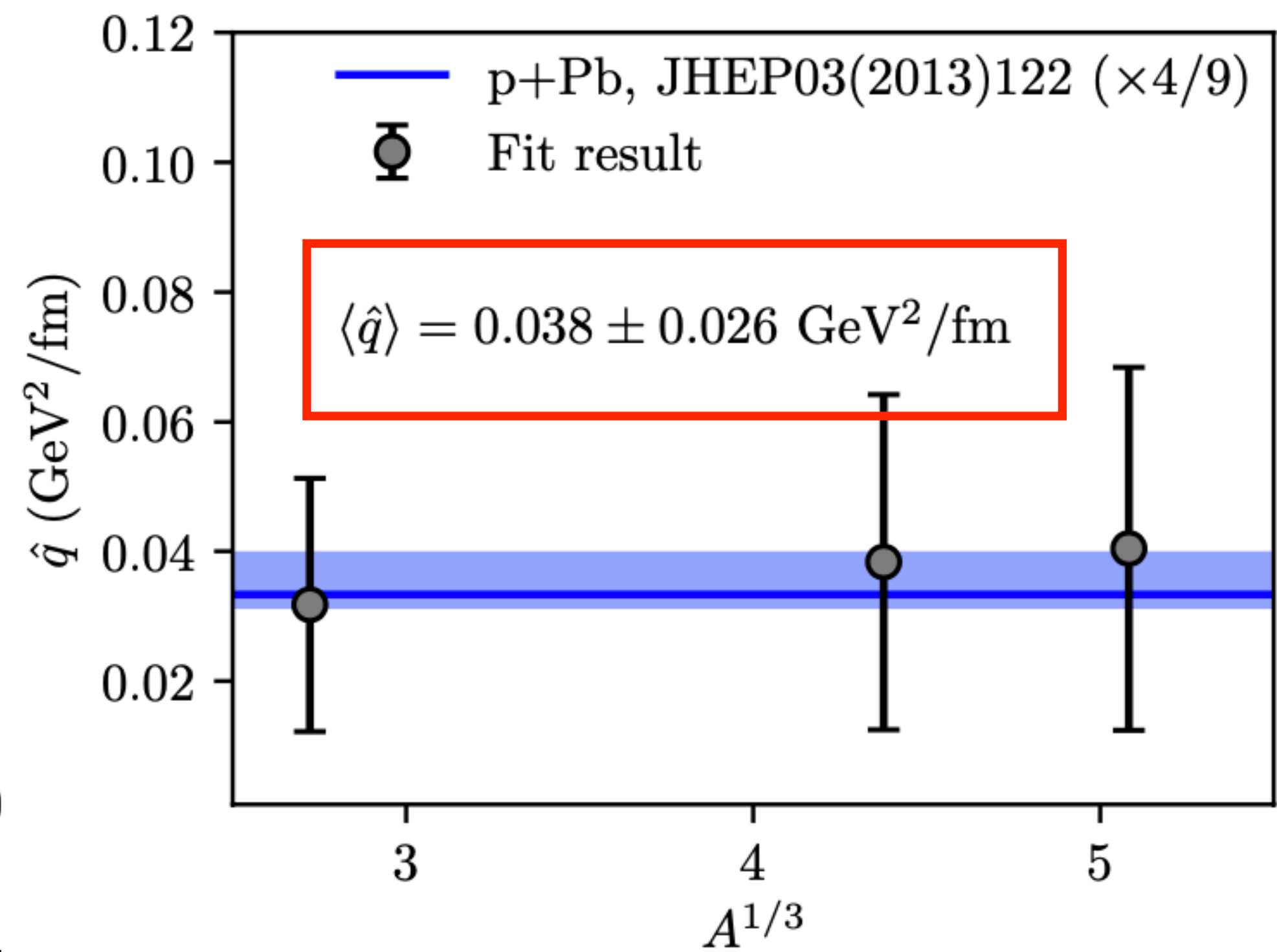
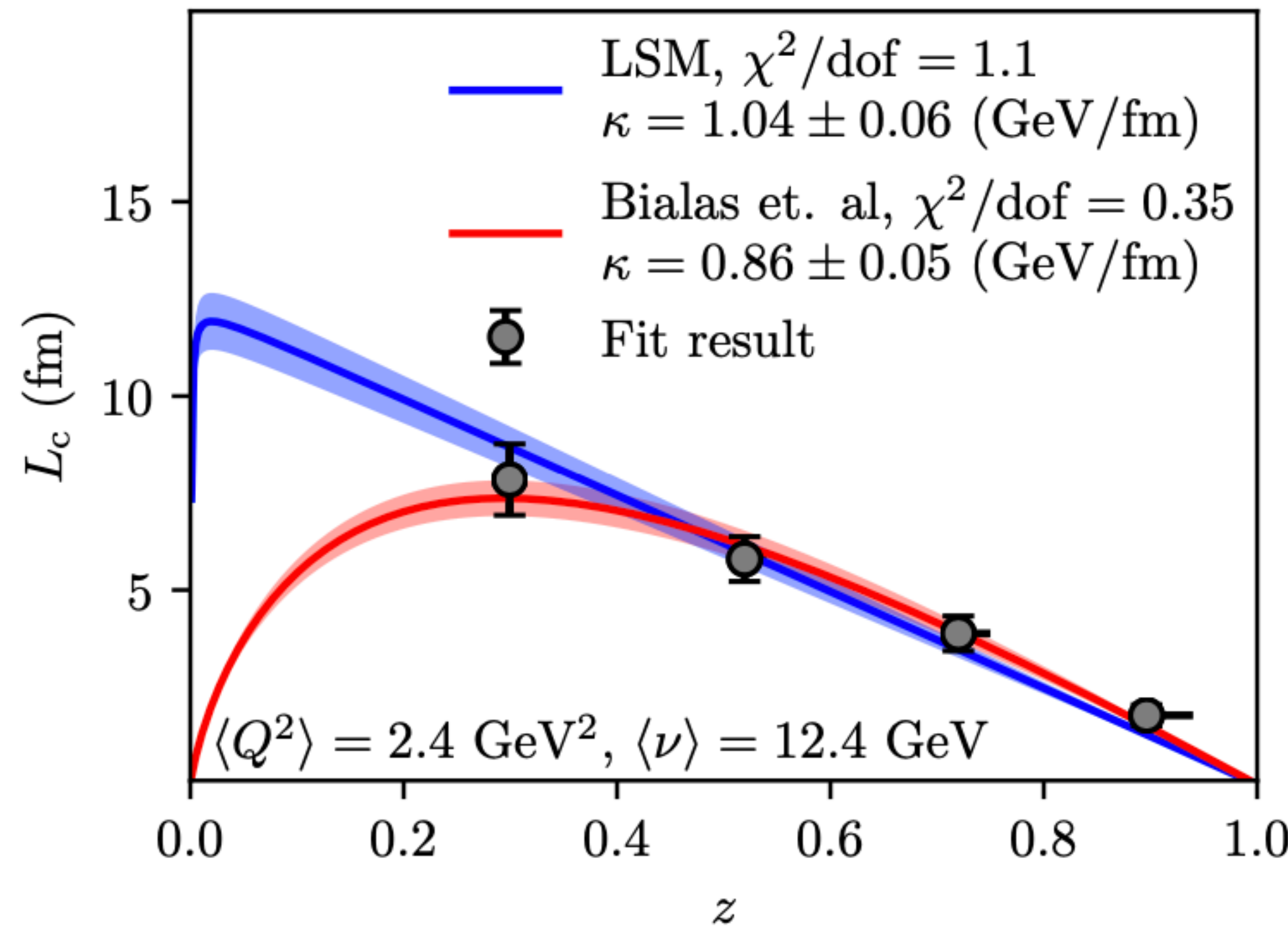


Lead nucleus
Radius = 6.5 fm

Long color
lifetime



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**

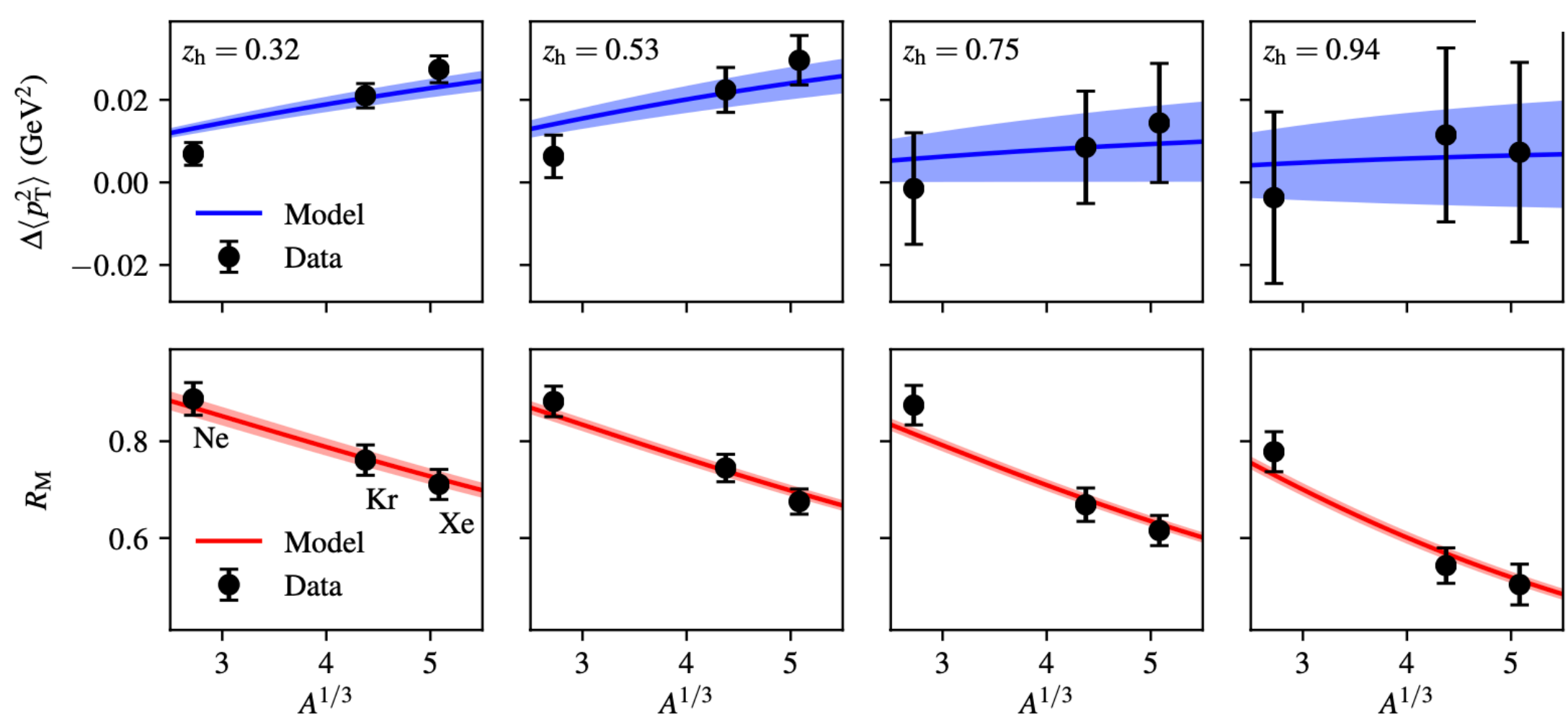


Table 1: Results from fits to the data and to analytical expressions for the color length that are connected to the Lund String Model. The label “struck quark” refers to Equation 3 (see supplementary materials). The label “B&G” refers to a 1987 paper by Bialas and Gyulassy [51].

Model Variant	Free parameters	χ^2/dof of fit to data vs. z_h				Fit of results to LSM analytical forms		
		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

**Independently reproduces
the Lund String Model
string constant!**

Simultaneous fit to multiplicity ratio and p_T broadening
Brooks and López, <https://arxiv.org/abs/2004.07236>

What can CLAS+CLAS12 add to these studies?

Much more luminosity than HERMES

- As a result, can study **rare and/or complex** states: ω 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							
<i>meson</i>	$c\tau$	mass	flavor content	<i>baryon</i>	$c\tau$	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	$\bar{u}\bar{d}$
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
f_1	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	$\bar{u}s, \bar{d}s$	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 (p_T broadening?), 1D MR for ϕ , η' , K	as CLAS6 but high ν , Q^2
Other heavy baryons	-	-	1D-2D MR for $\Lambda(1520)$, 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

<u>E12-06-117</u>	Quark Propagation and Hadron Formation	W. Brooks* W. Armstrong M. Arratia R. Dupre A. El Alaoui L. El Fassi G. Gilfoyle H. Hakobyan K. Hicks M. Holtrop K. Joo T. Mineeva G. Niculescu M. Niculescu O. Soto Sandoval M. Wood	Fed. St. Maria ANL U. California Riverside IPN ORSAY Fed. St. Maria Mississippi State U of Richmond Fed. St. Maria Ohio U U of NH U of Conn Fed. St. Maria JMU JMU INFN USCA
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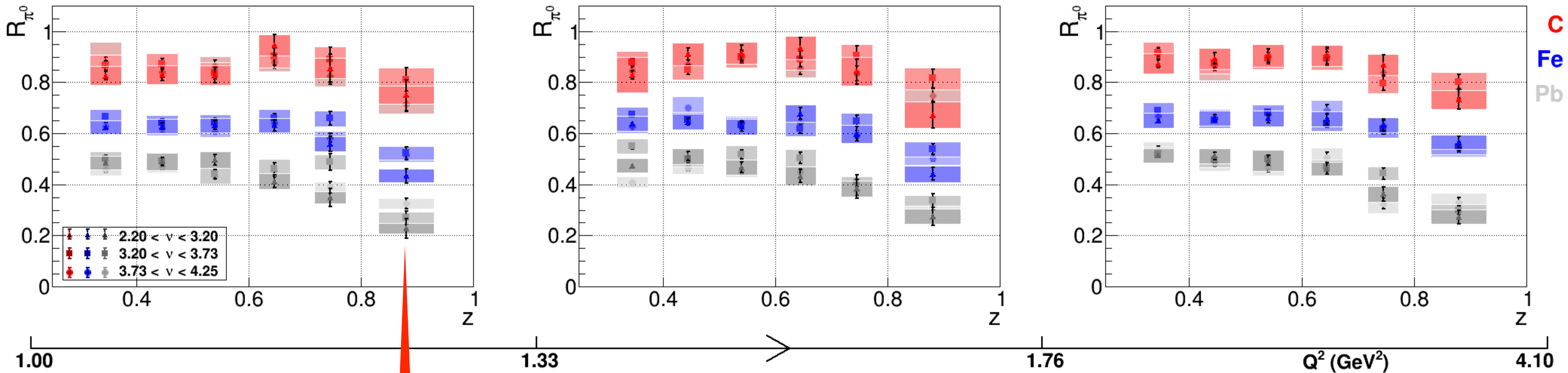
Selected results from CLAS6

π^0 3D Multiplicity Ratios

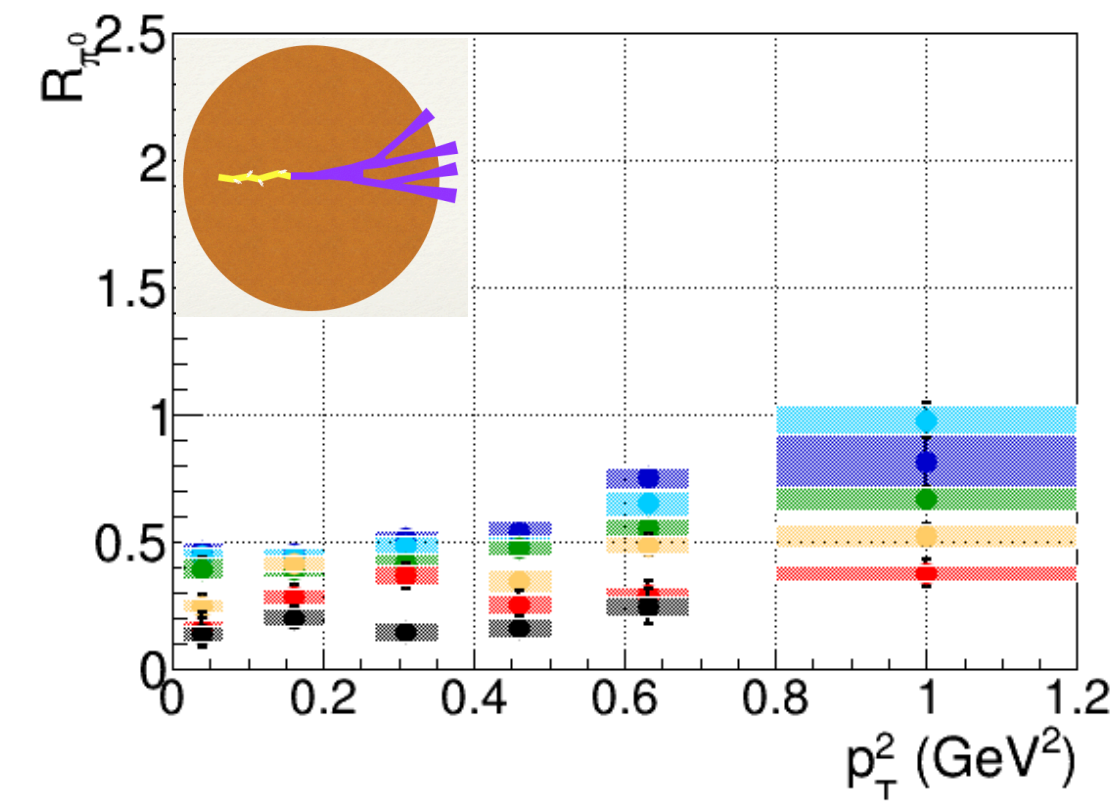
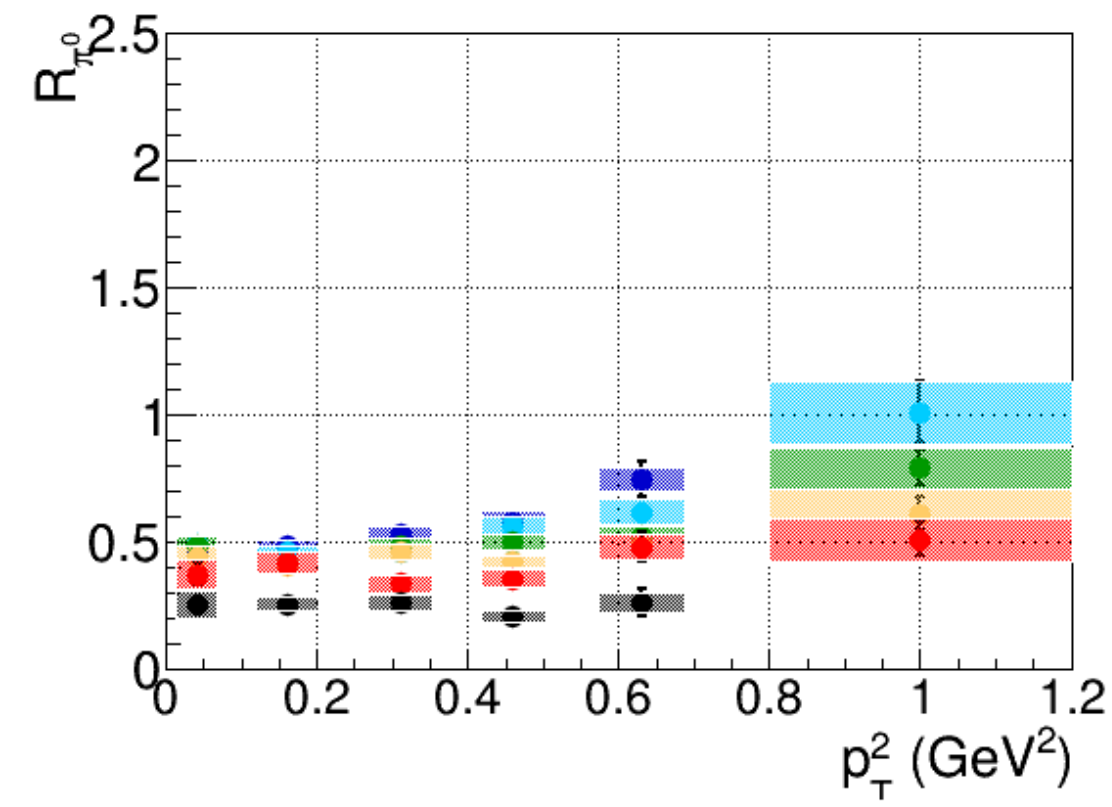
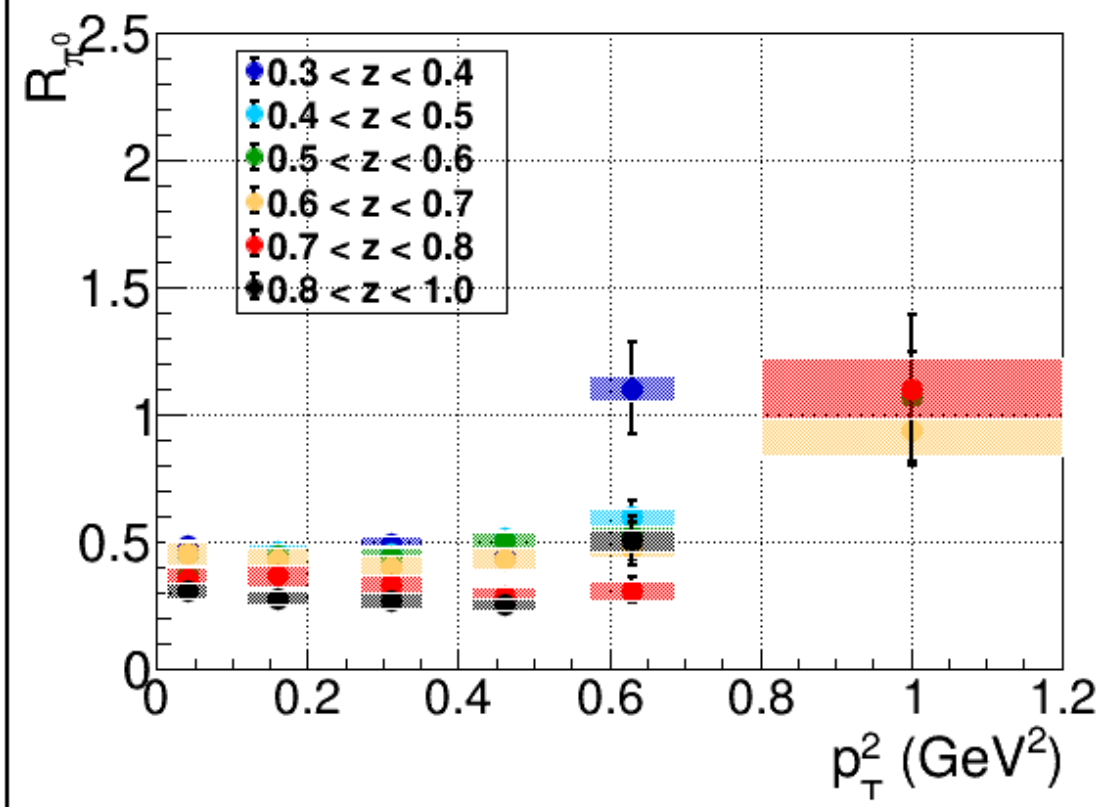
Dr. Taisiya Mineeva, UTFSM

(UConn PhD 2013, K. Joo Thesis Advisor)

(3rd round of analysis review completed)



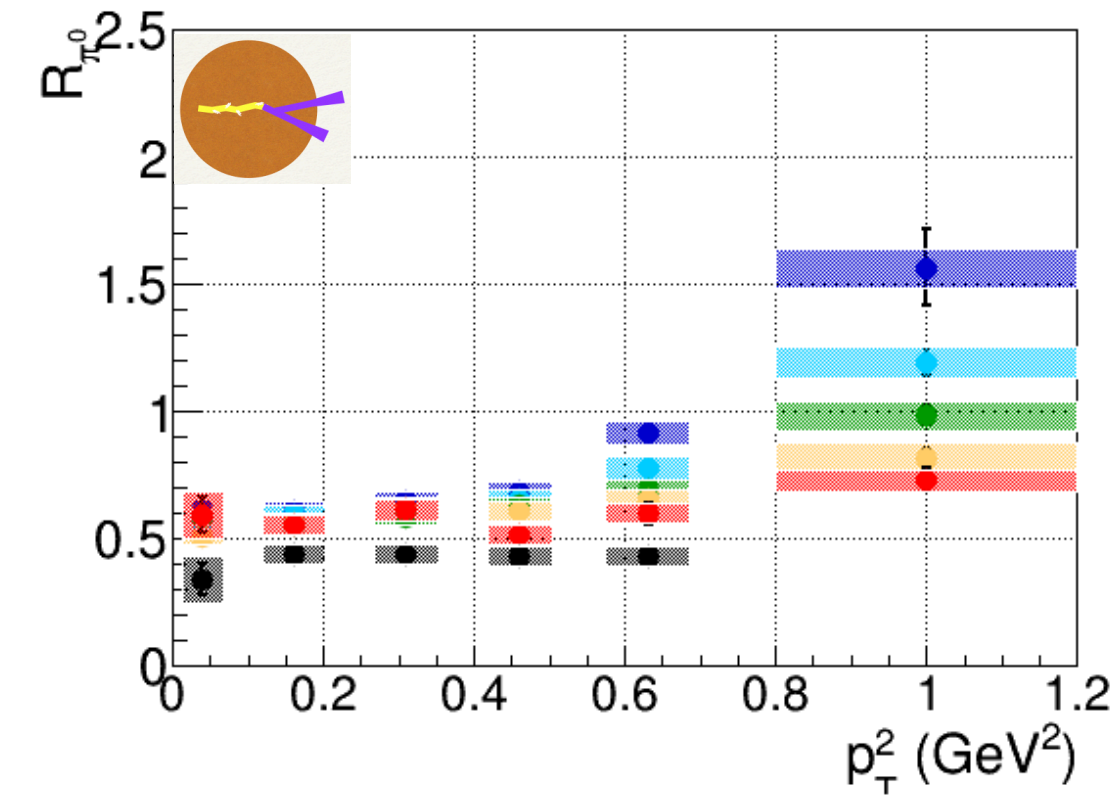
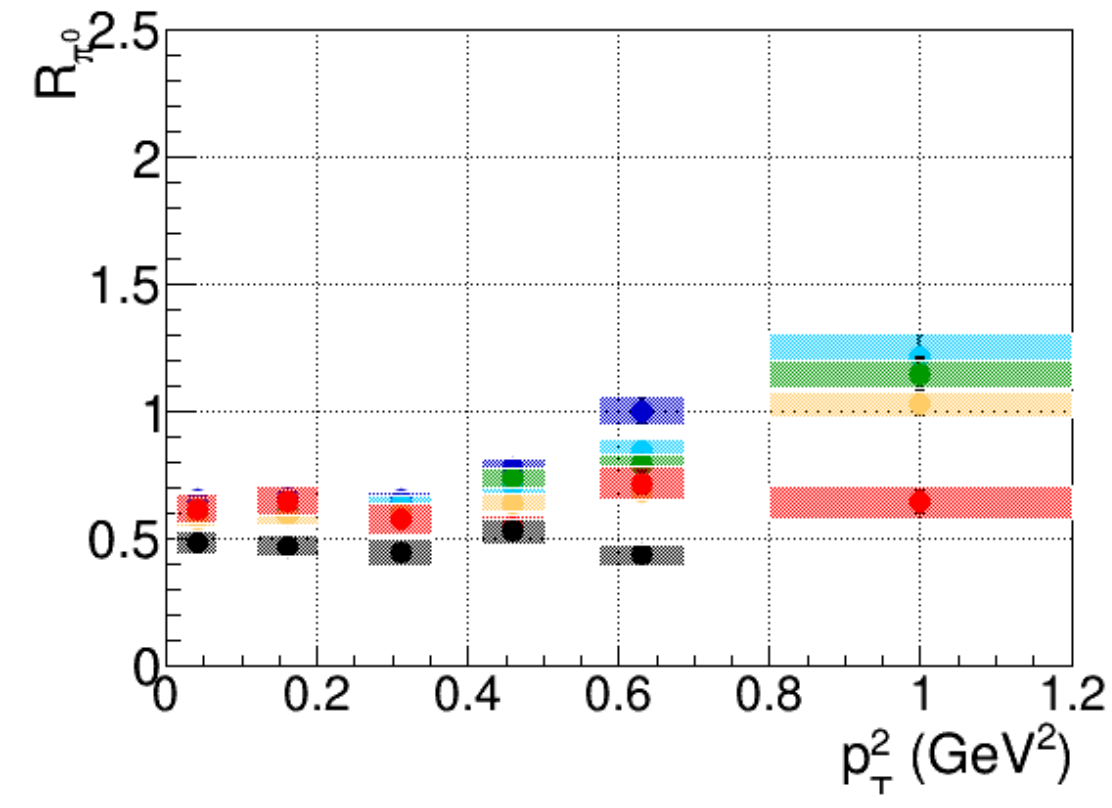
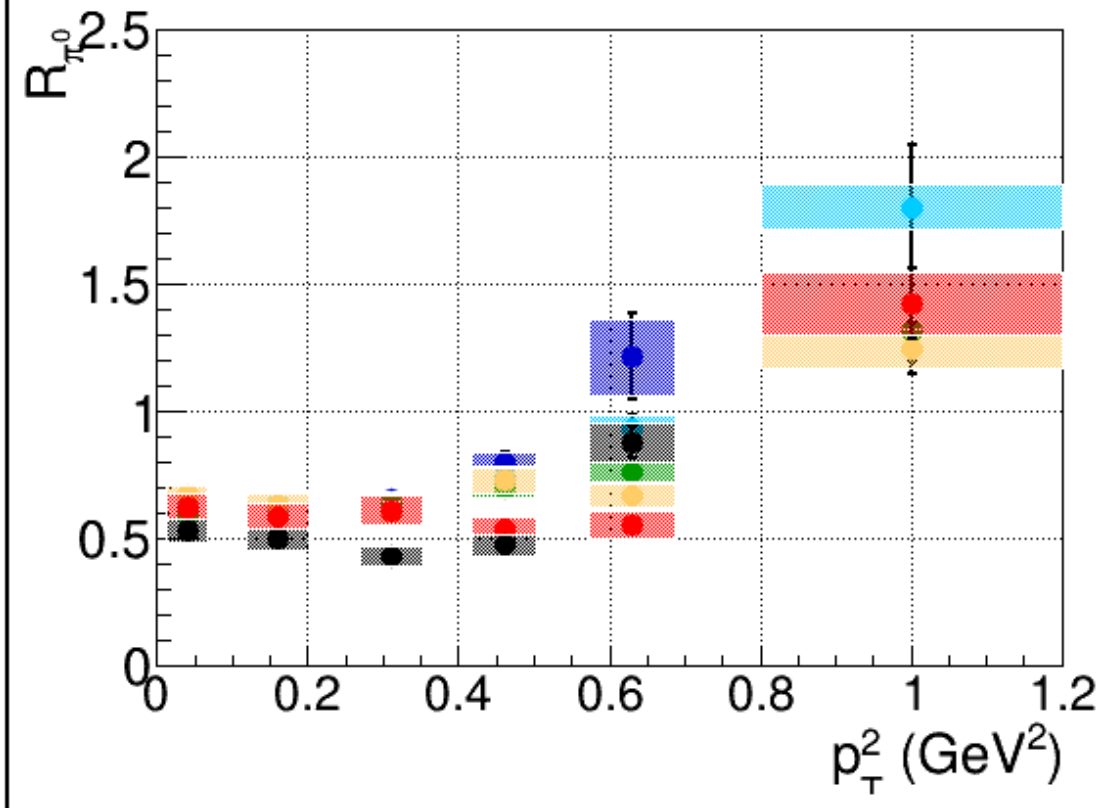
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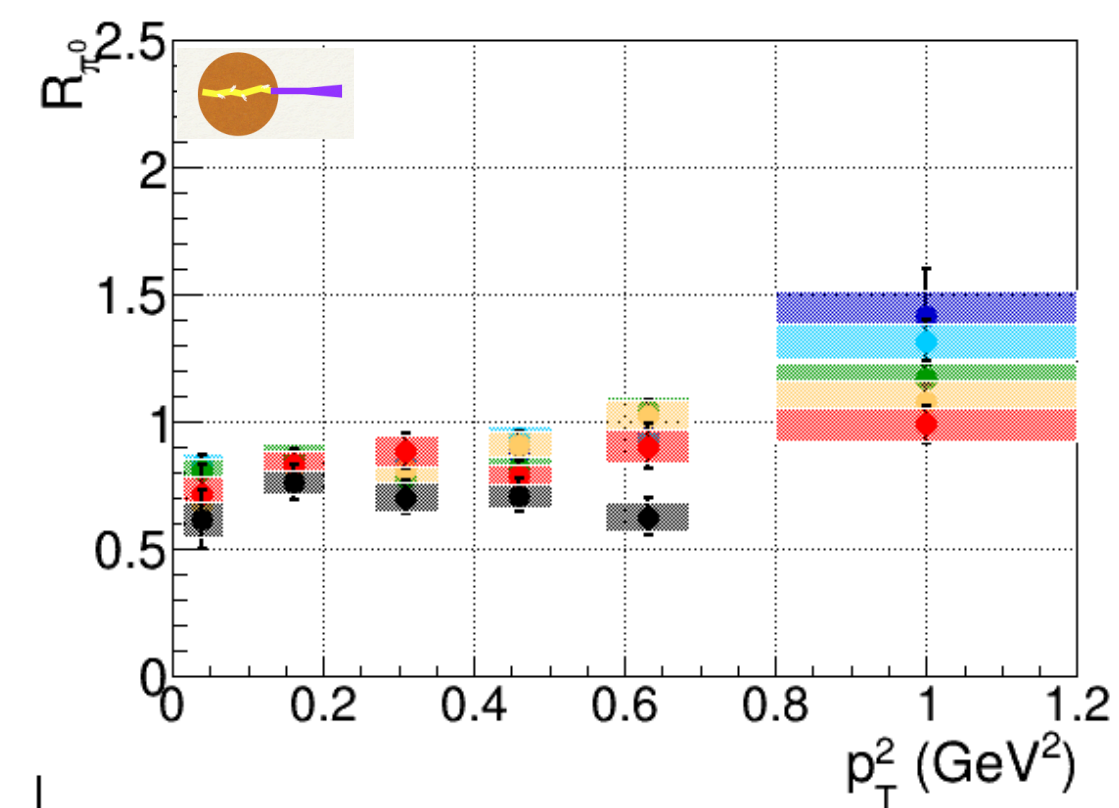
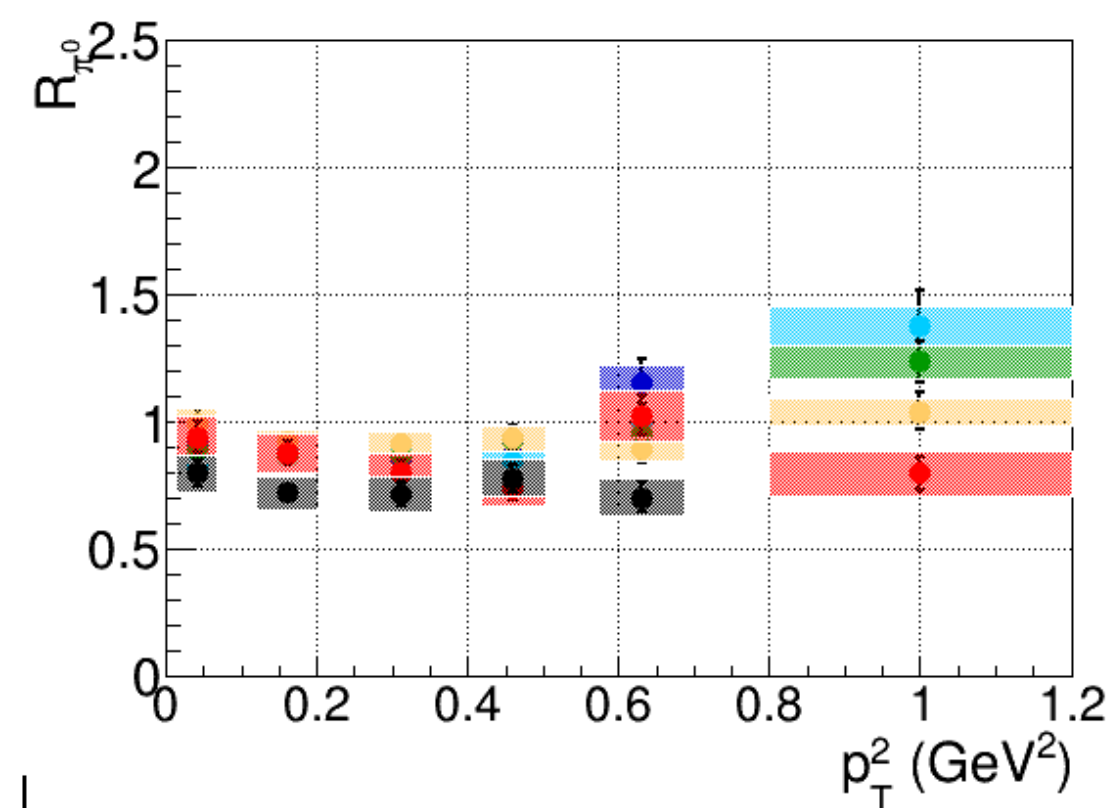
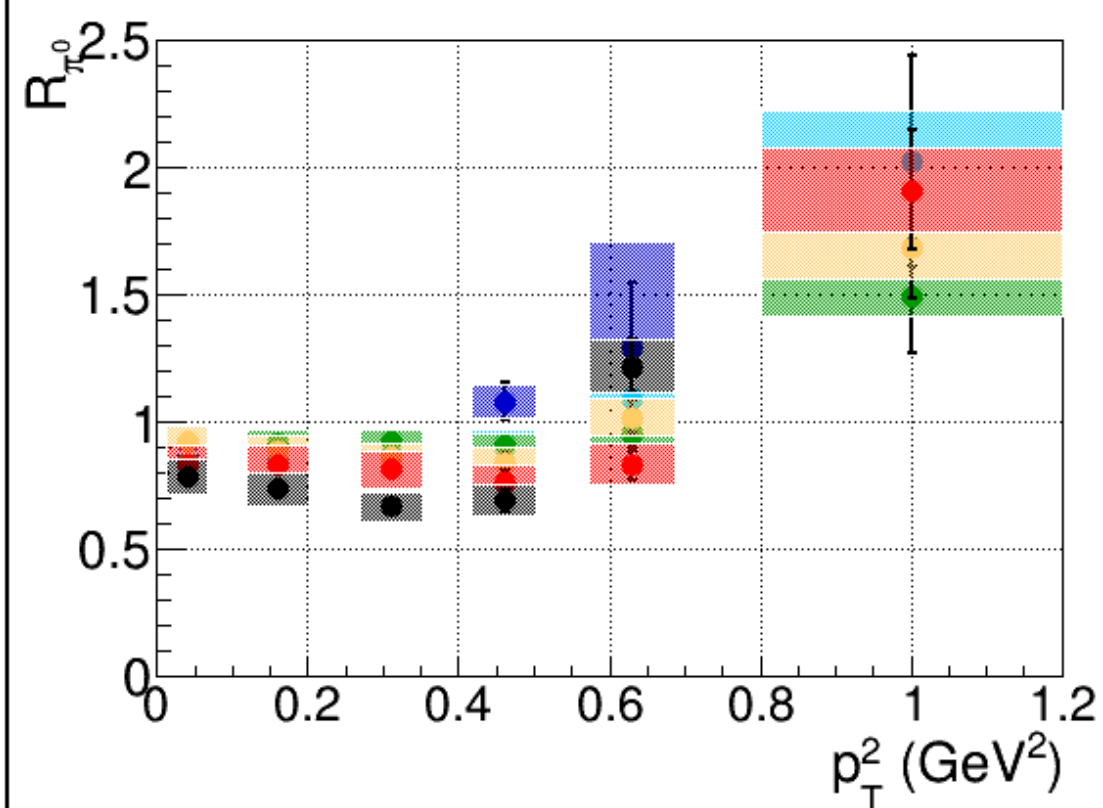
Neutral pion 3D MR

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

Fe



C



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

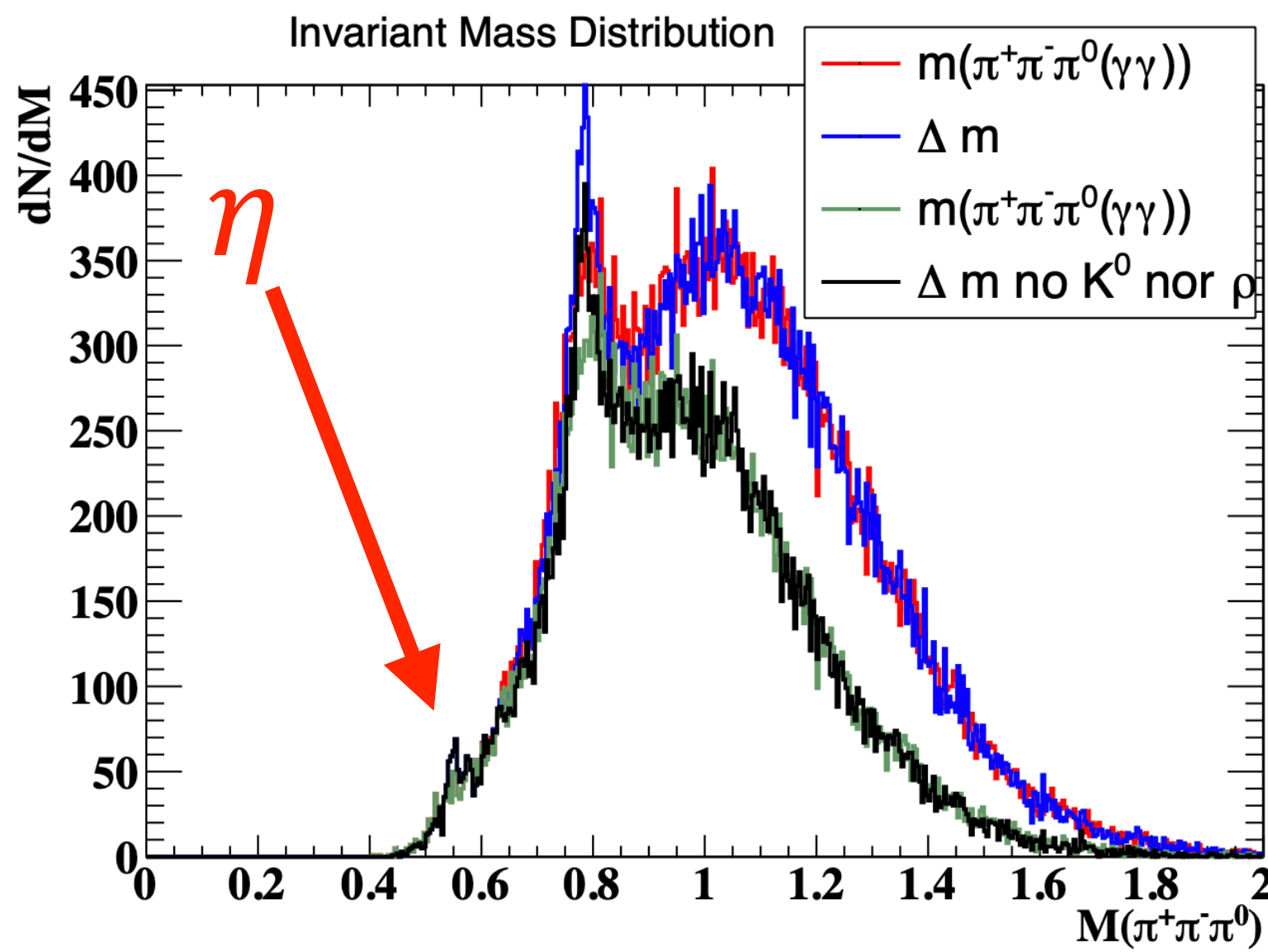
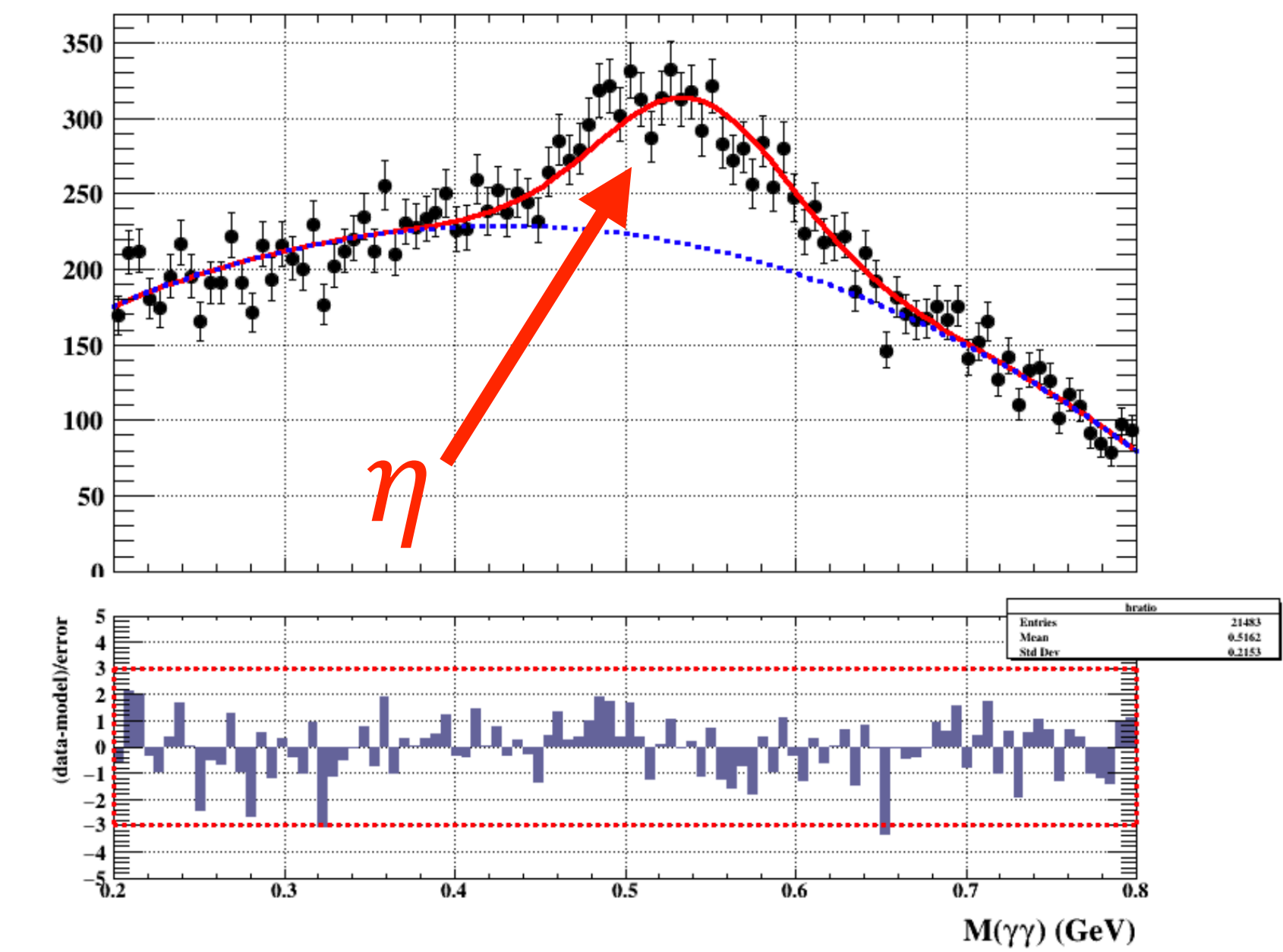
Dr. Orlando Soto, INFN Frascati

- 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

Multiplicity Ratio without background subtraction.

(Shows statistical information quality)

The two decay channels are not consistent without background subtraction.



Multiplicity Ratio, $\eta \rightarrow \pi^+\pi^-\pi^0 / \eta \rightarrow \gamma\gamma$ (no BS)

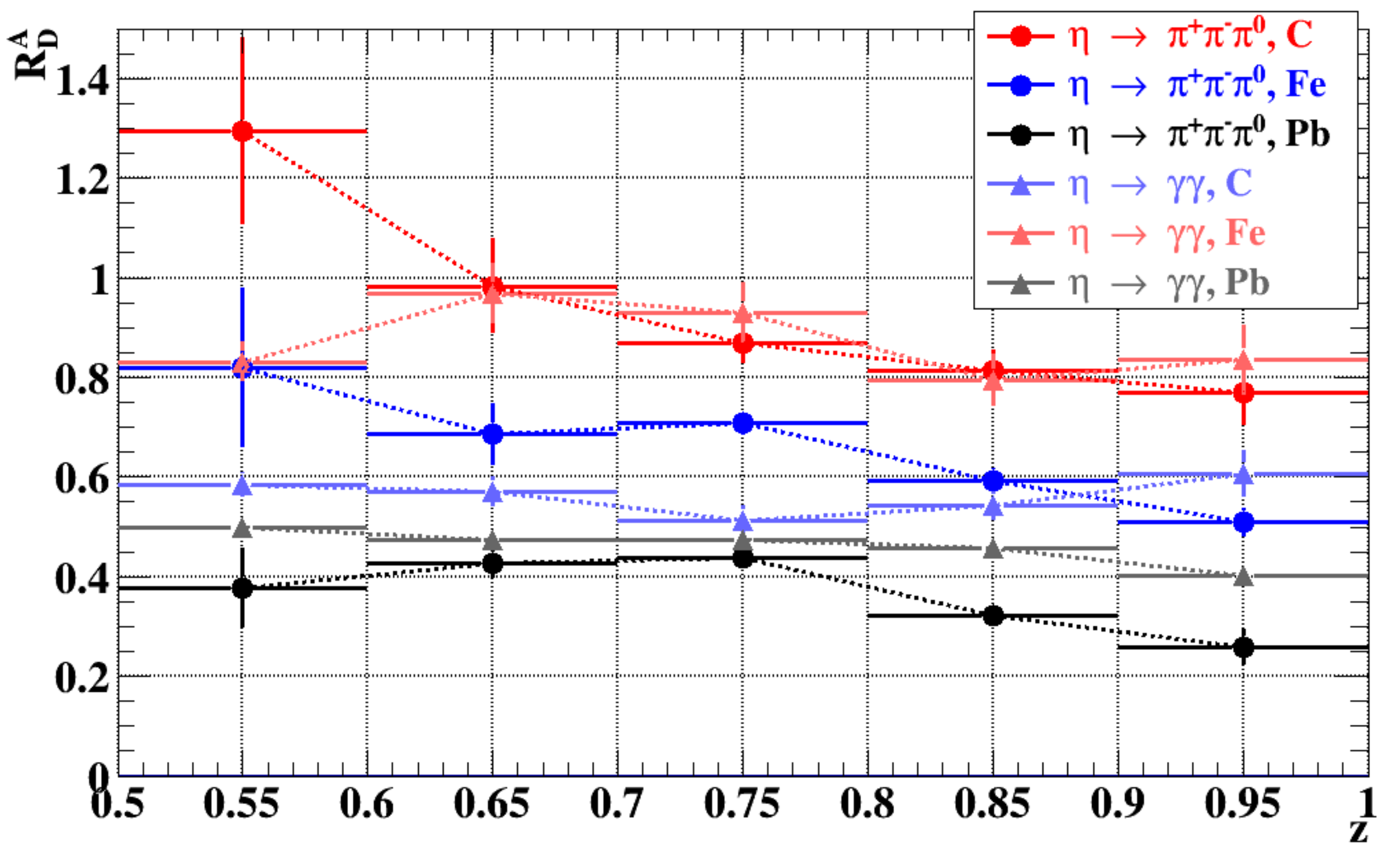
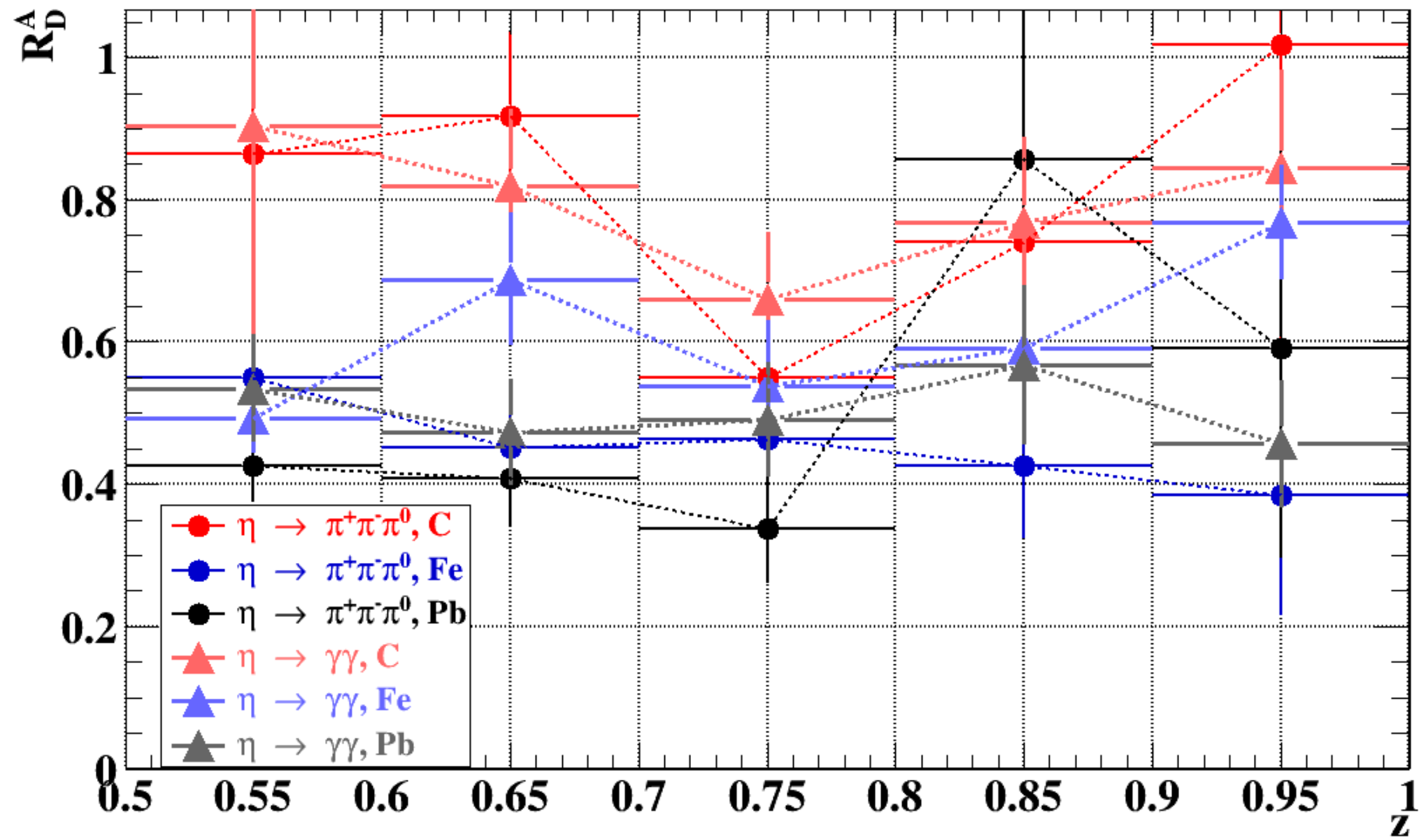


Figure 3.23: Invariant mass $m(\pi^+, \pi^-, \gamma, \gamma)$ with a cut $0.1 < m(\gamma, \gamma) < 0.2$.

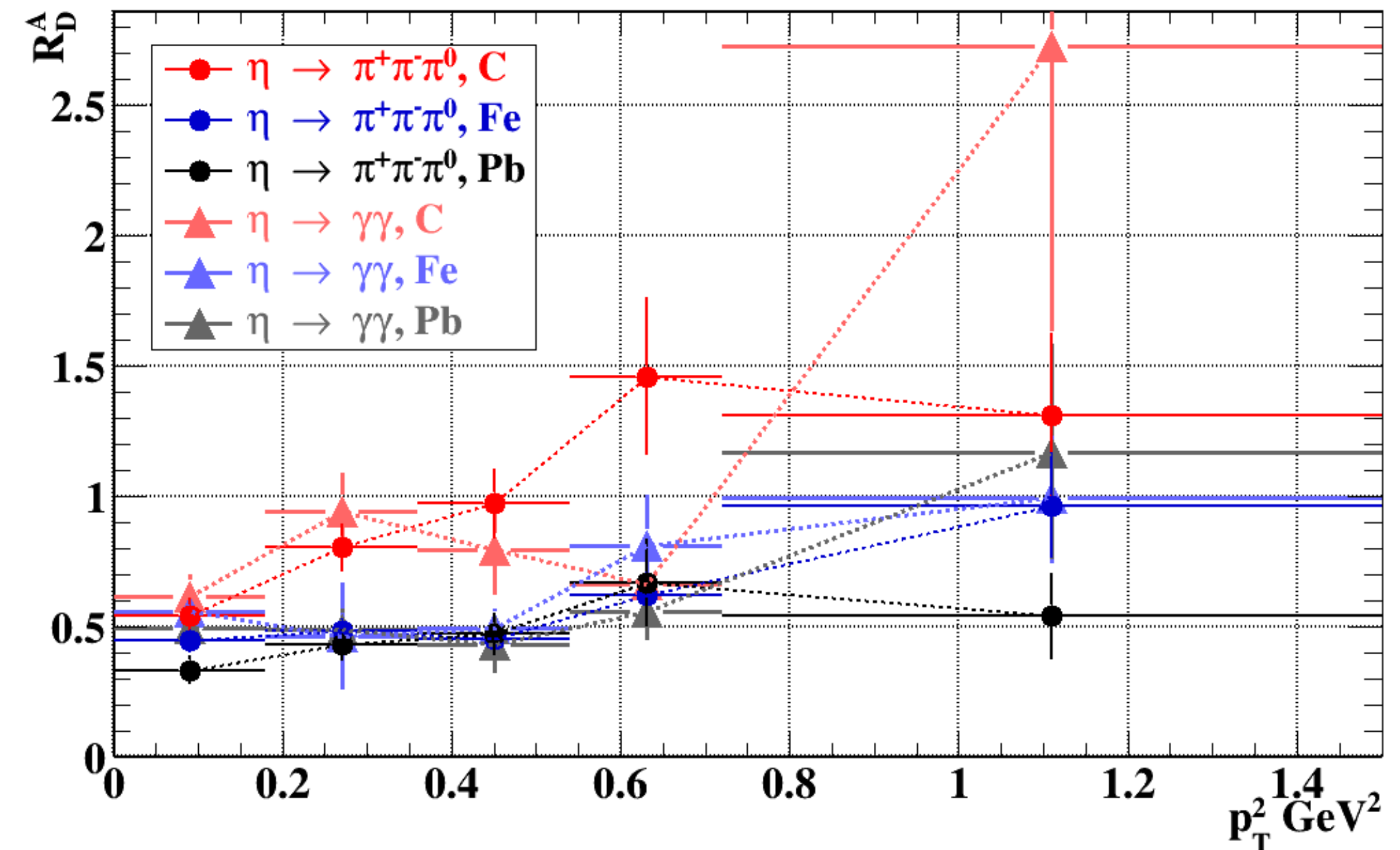
Multiplicity Ratio, $\eta \rightarrow \pi^+\pi^-\pi^0 / \eta \rightarrow \gamma\gamma$ (BS)



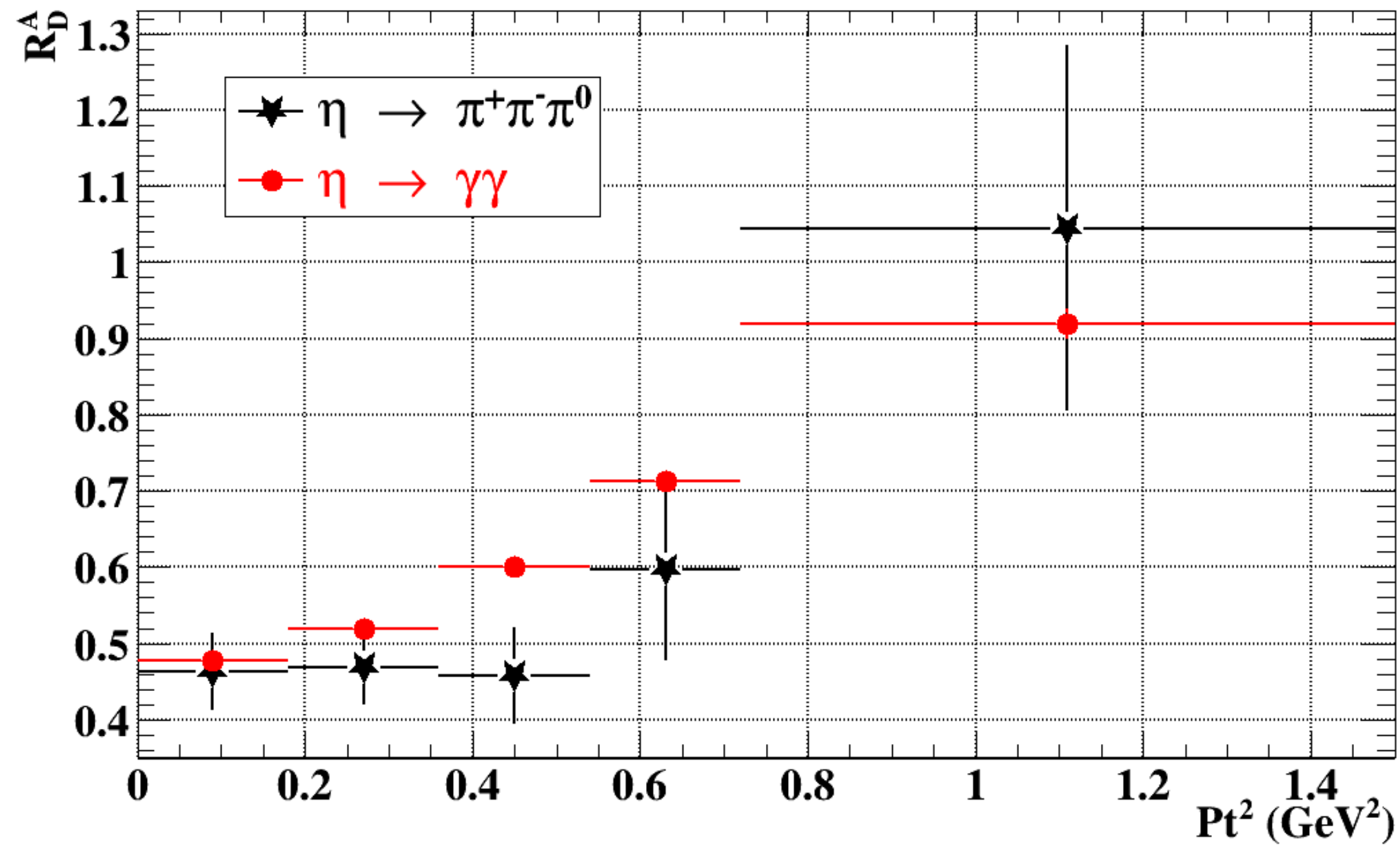
With background subtraction, there is a **hint** that the Cronin-like effect is seen for all three nuclei and both decay channels, with very large statistical uncertainties.

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

Multiplicity Ratio, $\eta \rightarrow \pi^+\pi^-\pi^0 / \eta \rightarrow \gamma\gamma$ (BS)



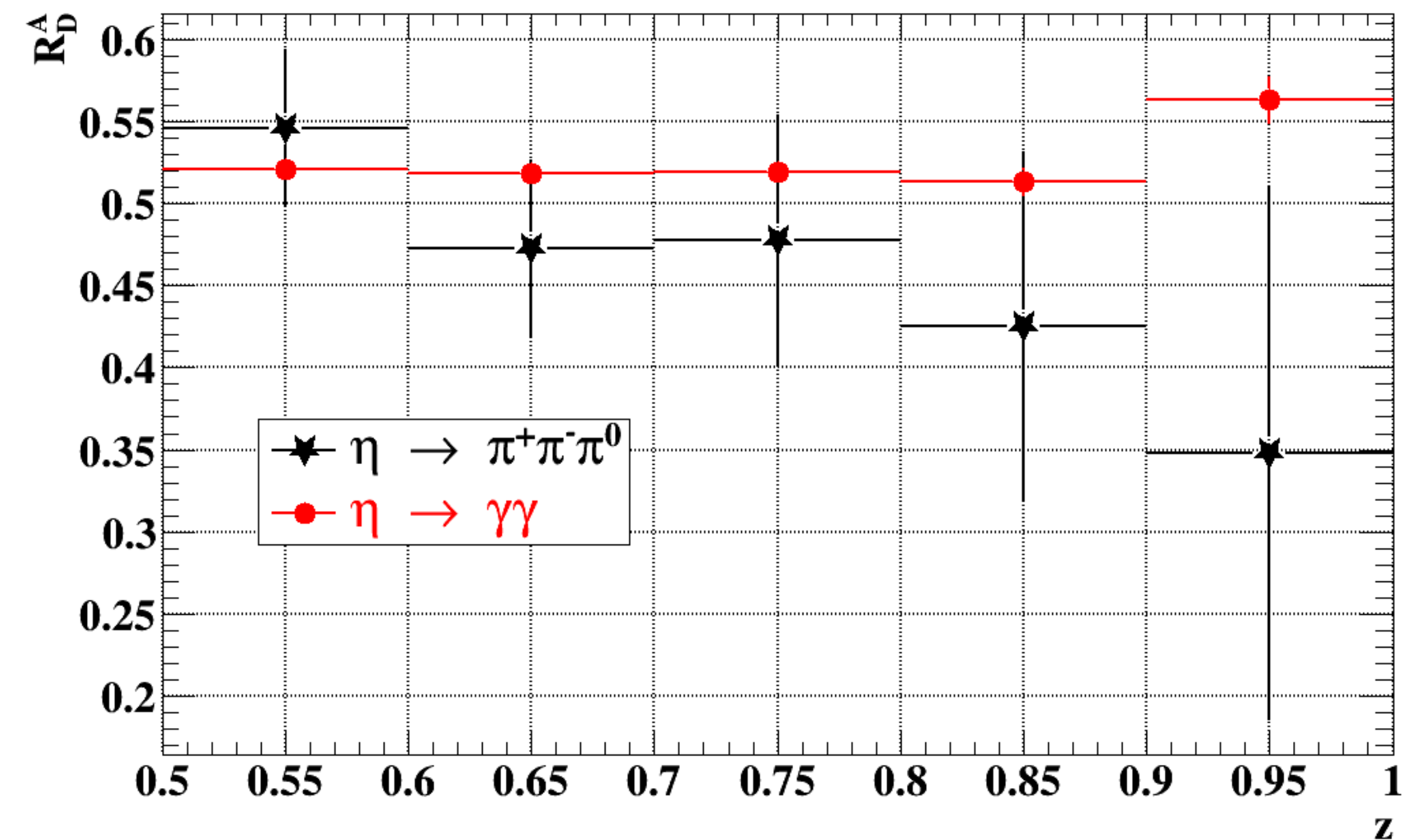
Multiplicity Ratio $\eta \rightarrow \gamma\gamma / \eta \rightarrow \pi^+\pi^-\pi^0$ on Iron



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

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

Multiplicity Ratio $\eta \rightarrow \gamma\gamma / \eta \rightarrow \pi^+\pi^-\pi^0$ on Iron



Charged Pion Multiplicity Ratios

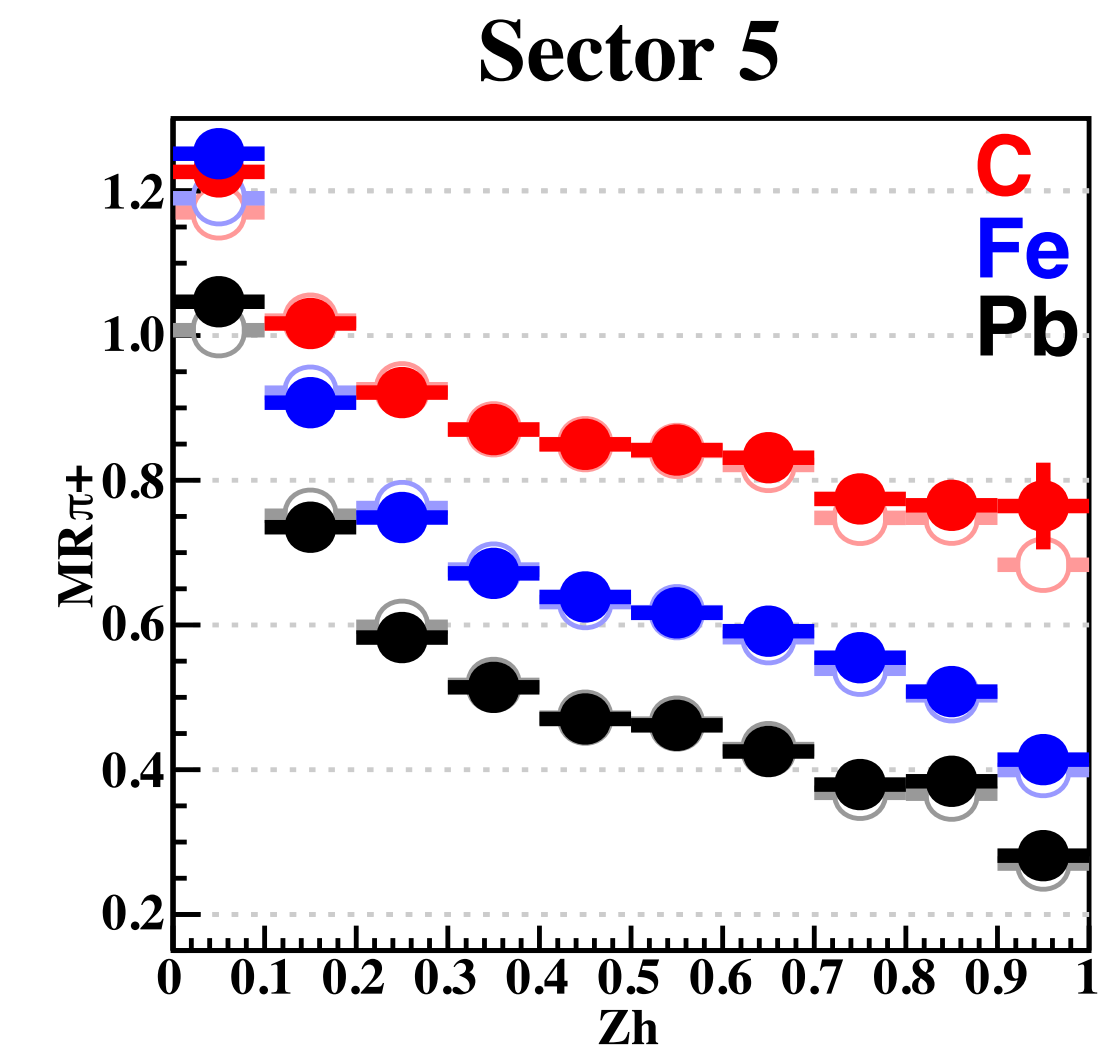
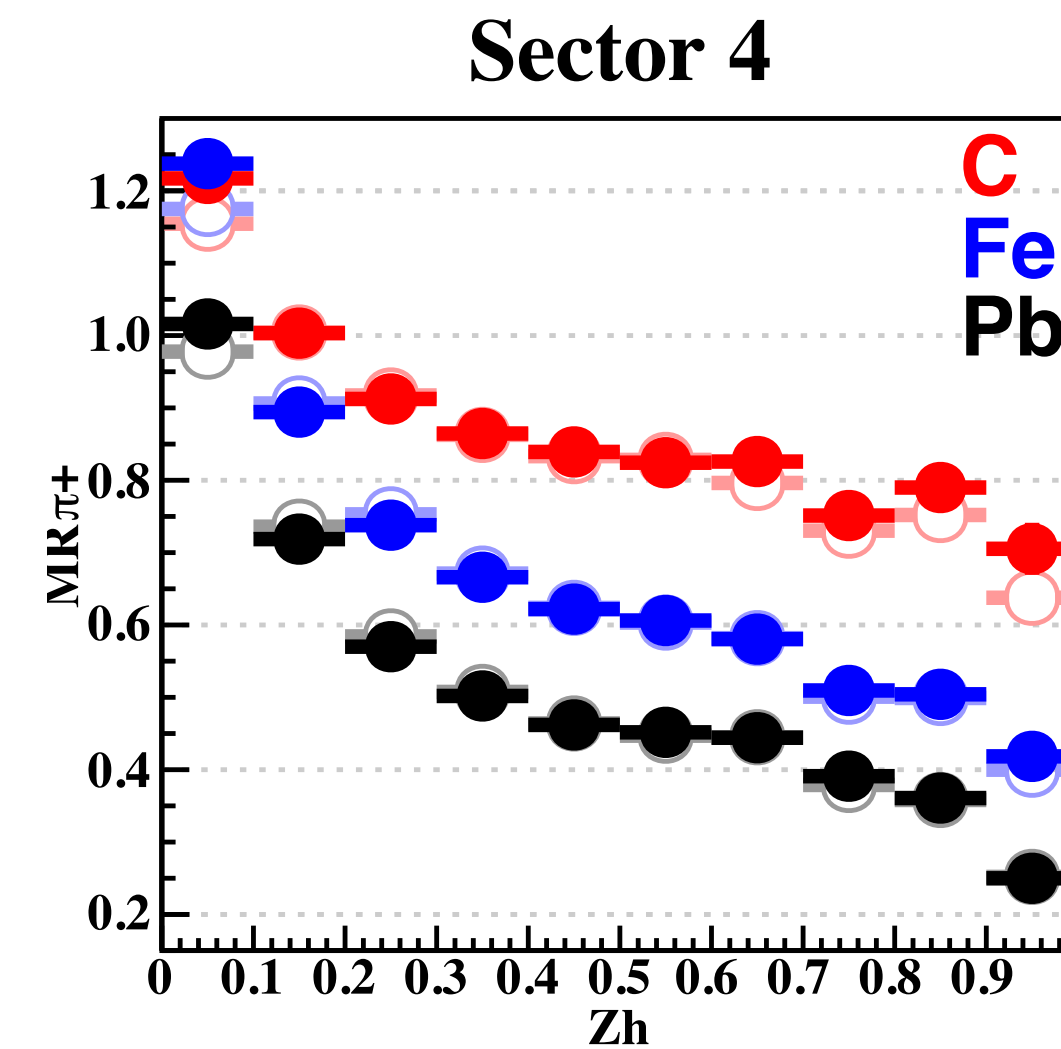
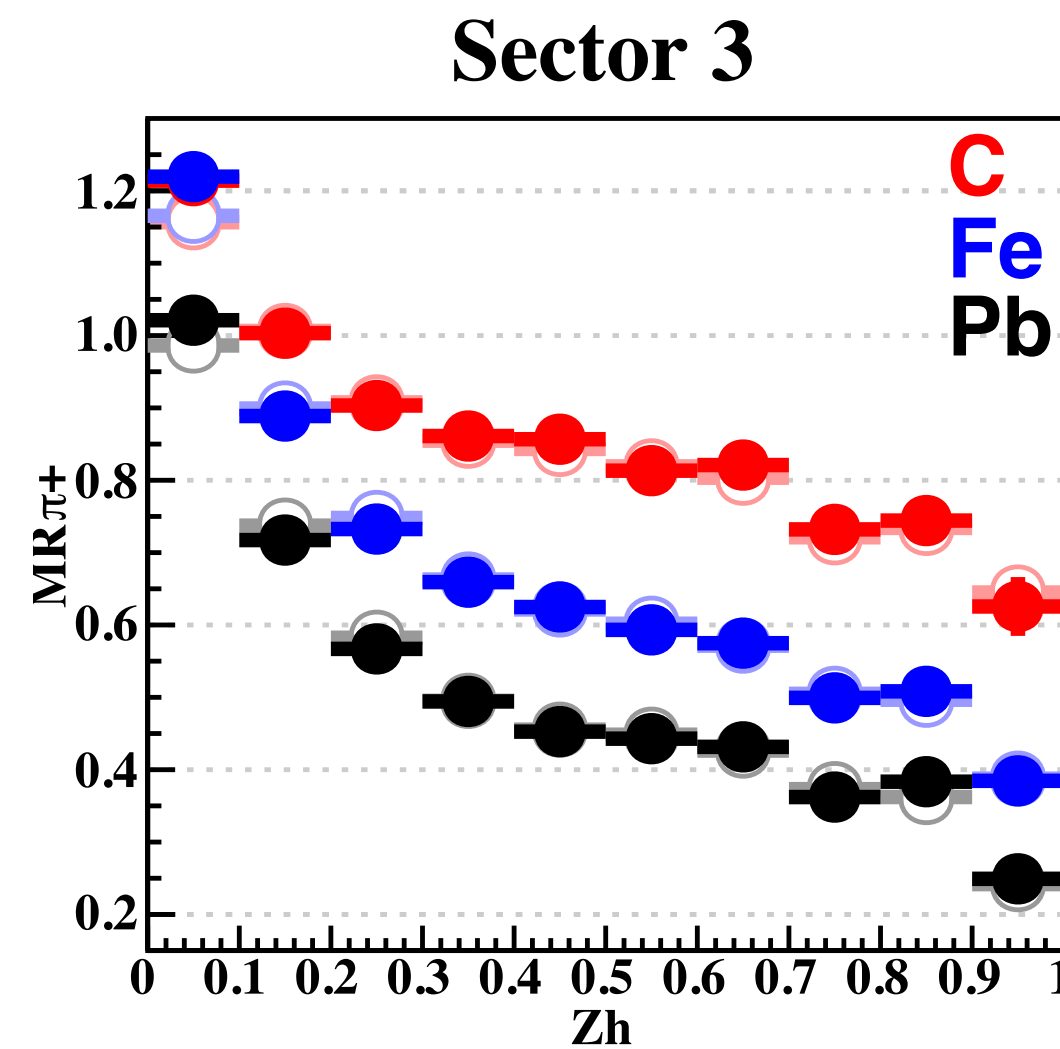
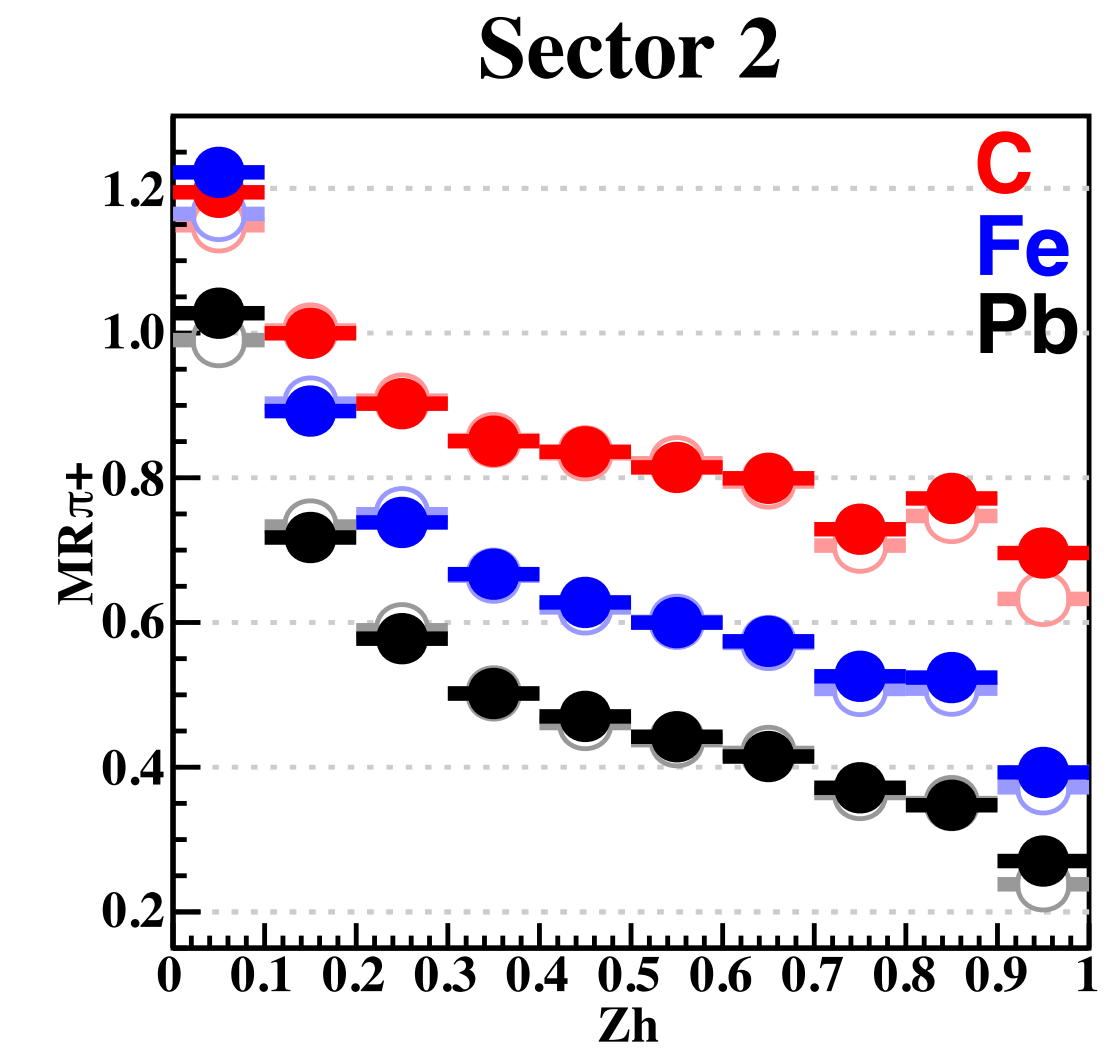
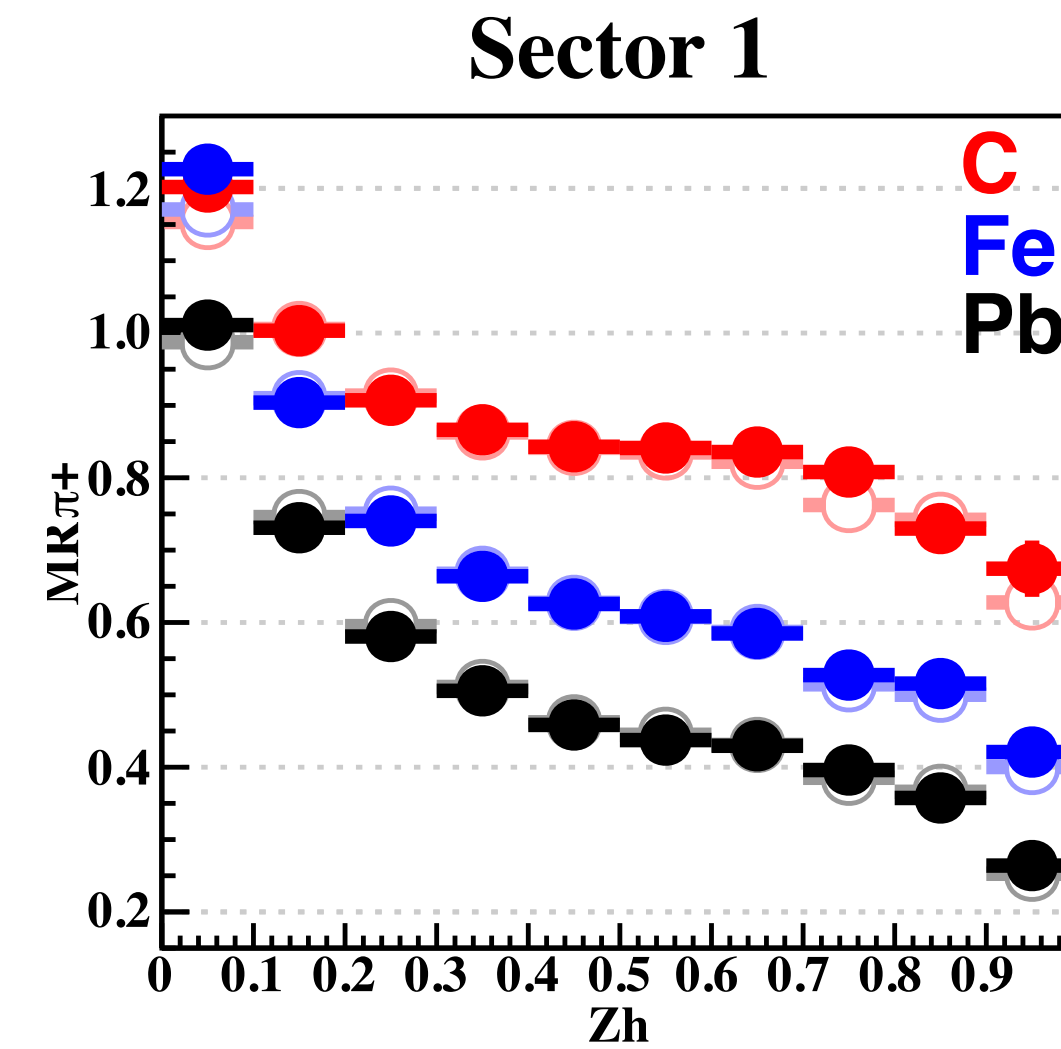
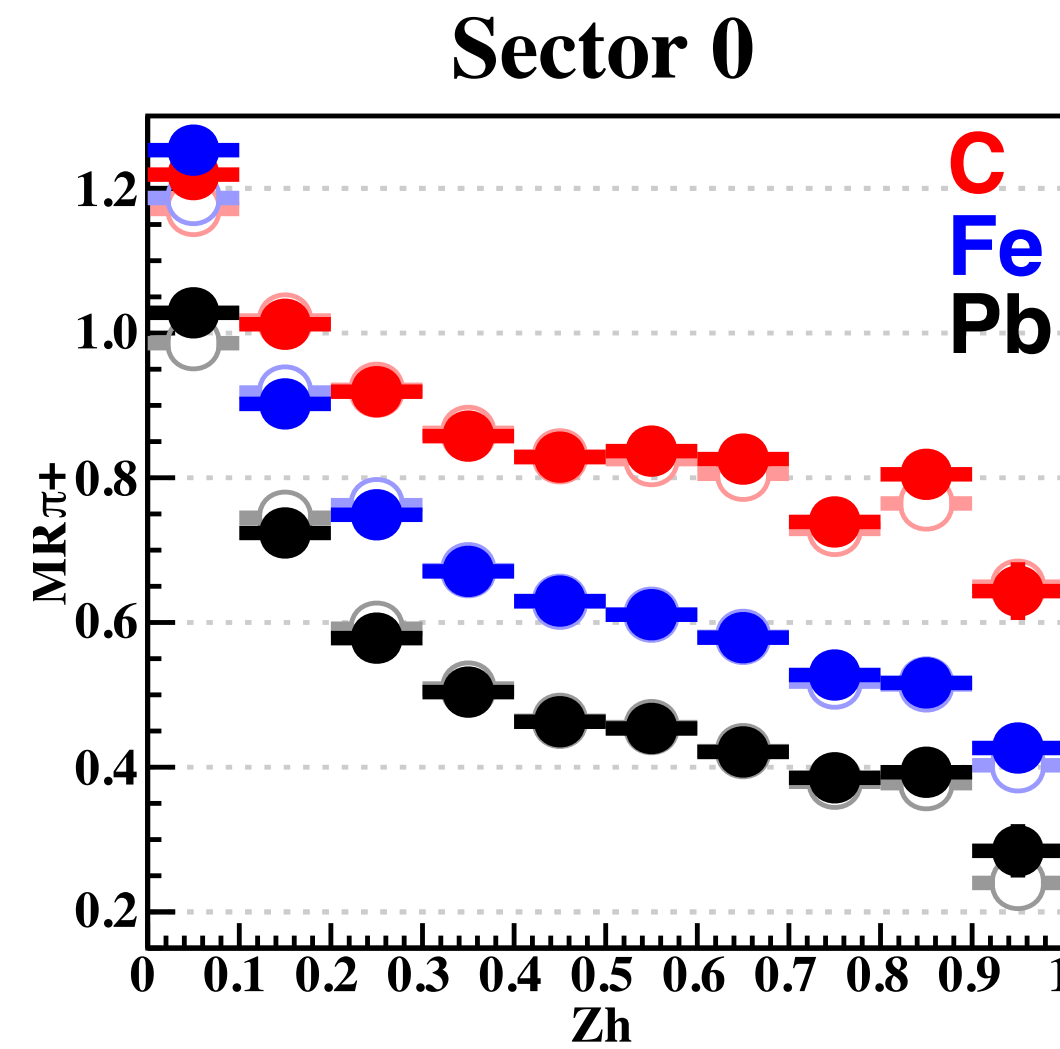
Prof. Hayk Hakobyan (PhD 2008) UTFSM, Dr. Raphaël Dupré (PhD 2011) IPN Orsay
Sebastián Morán (MSc student UTFSM, Thesis advisor Prof. Hayk Hakobyan)

- 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

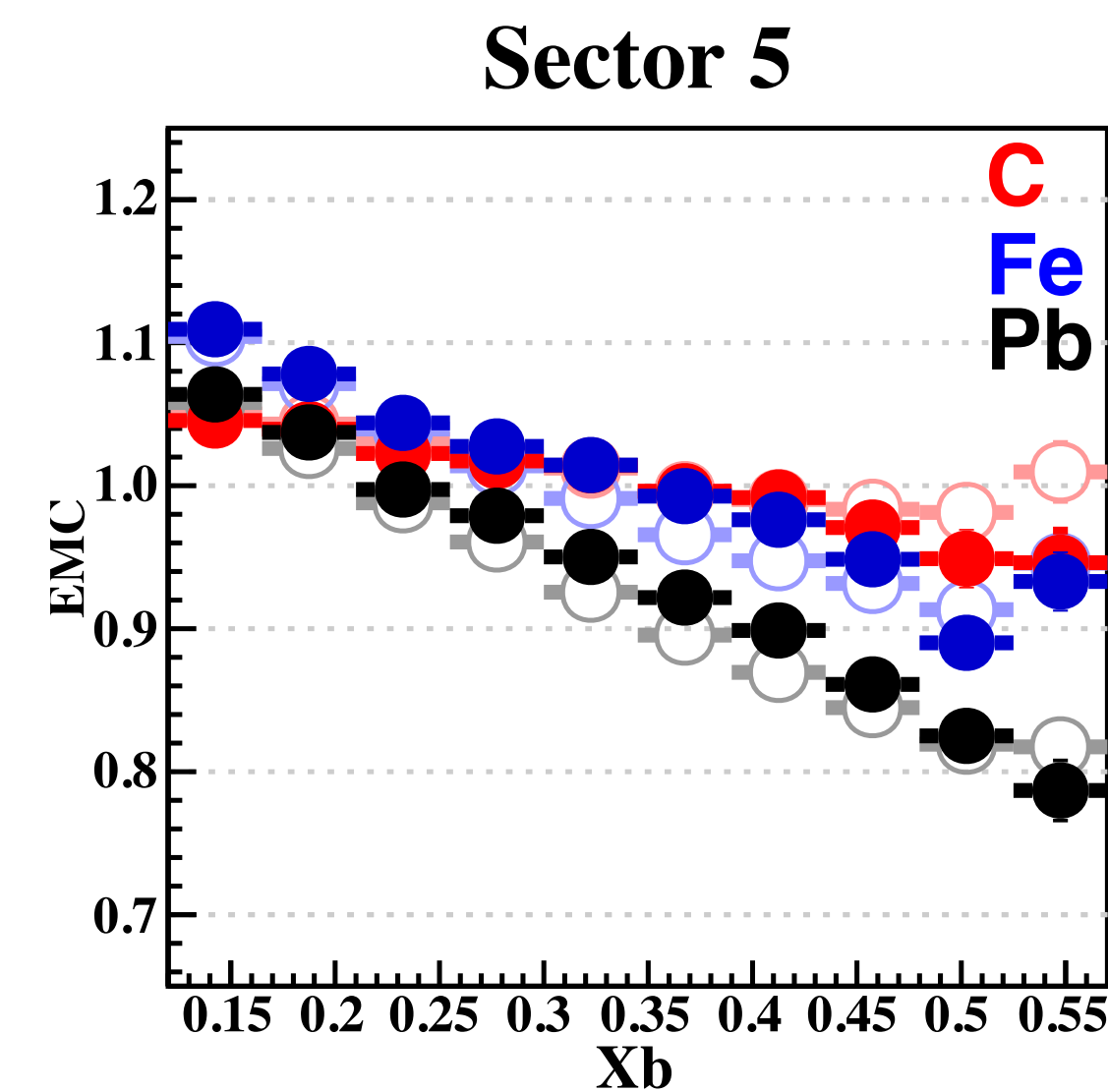
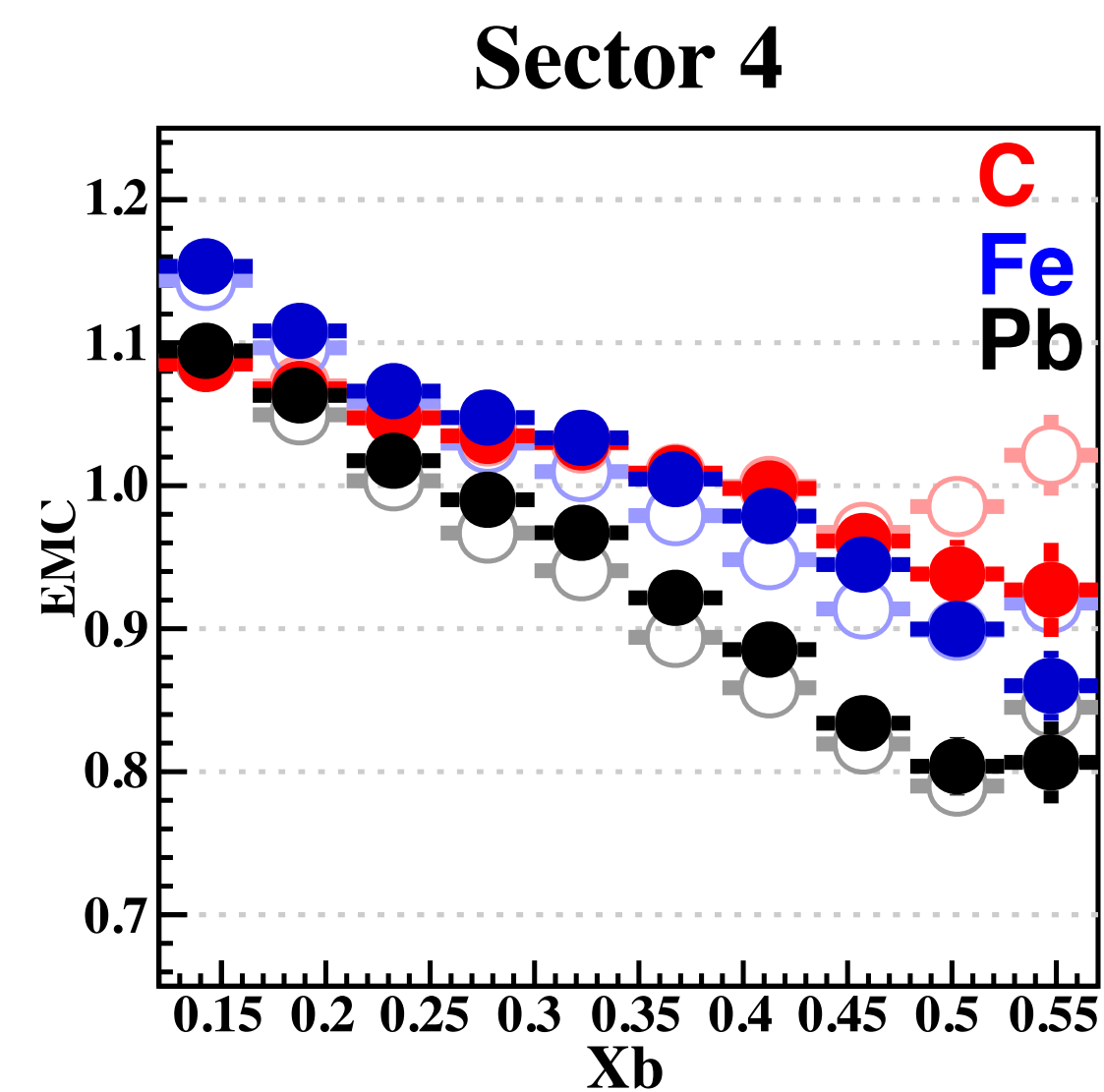
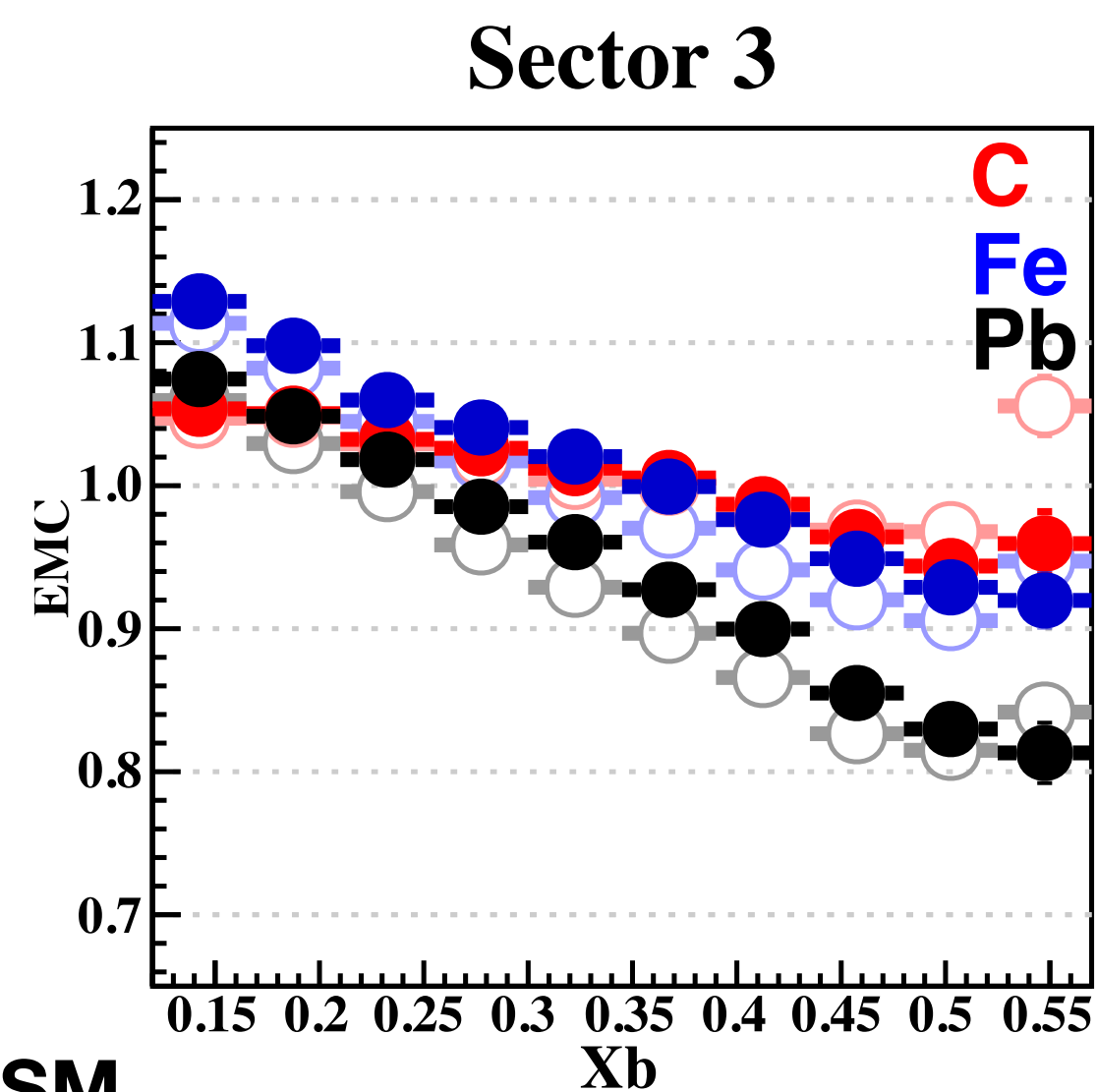
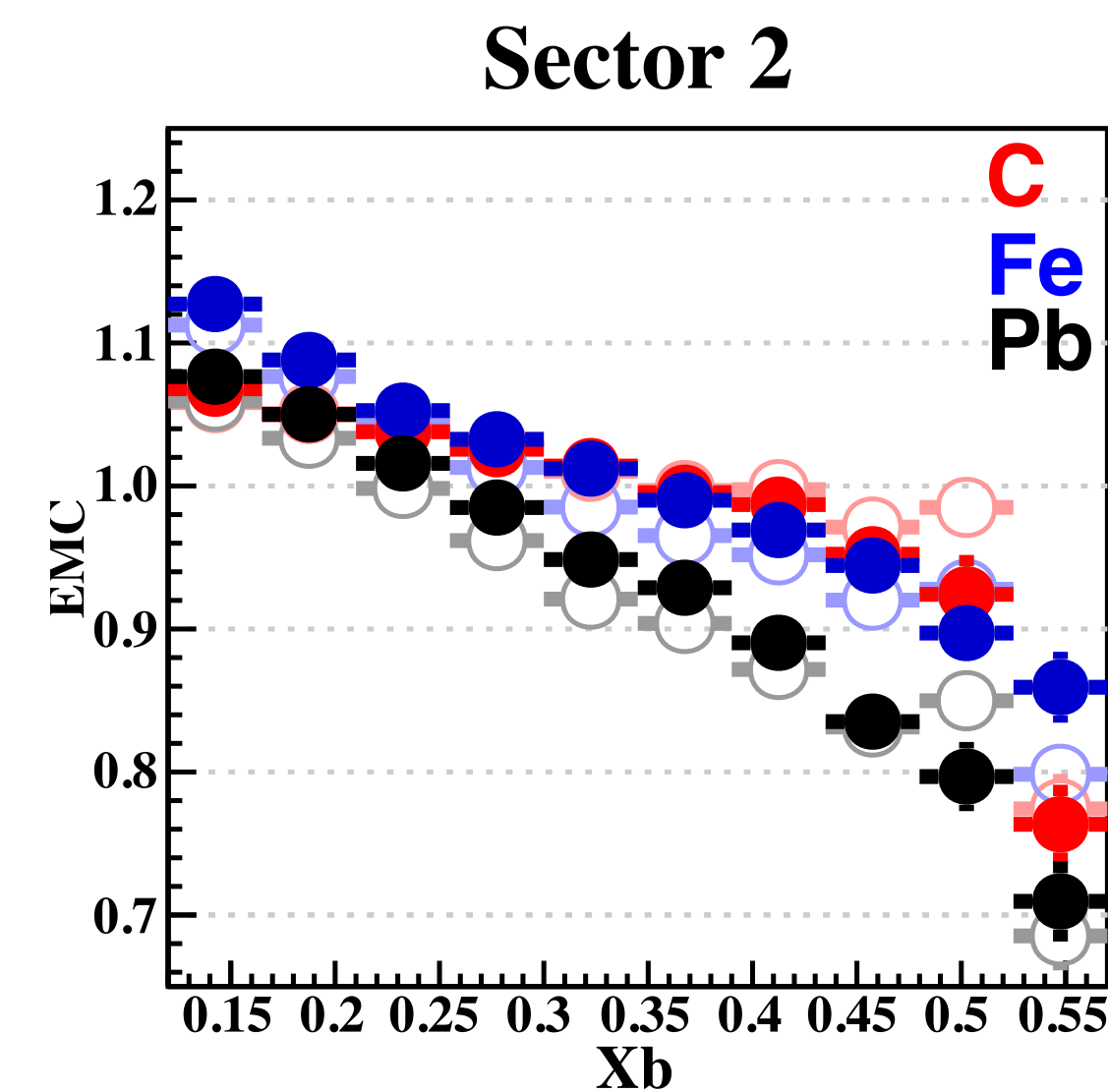
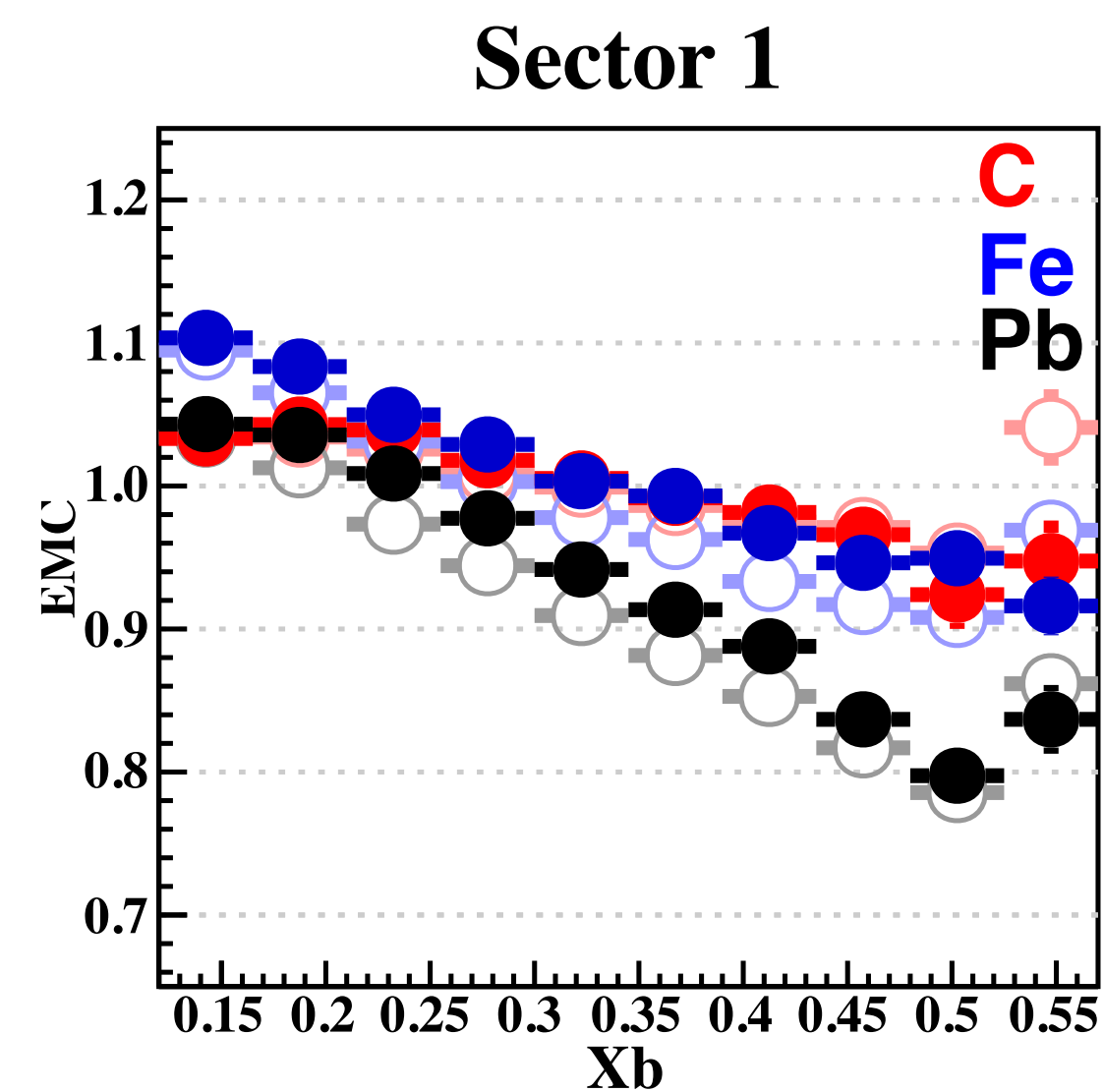
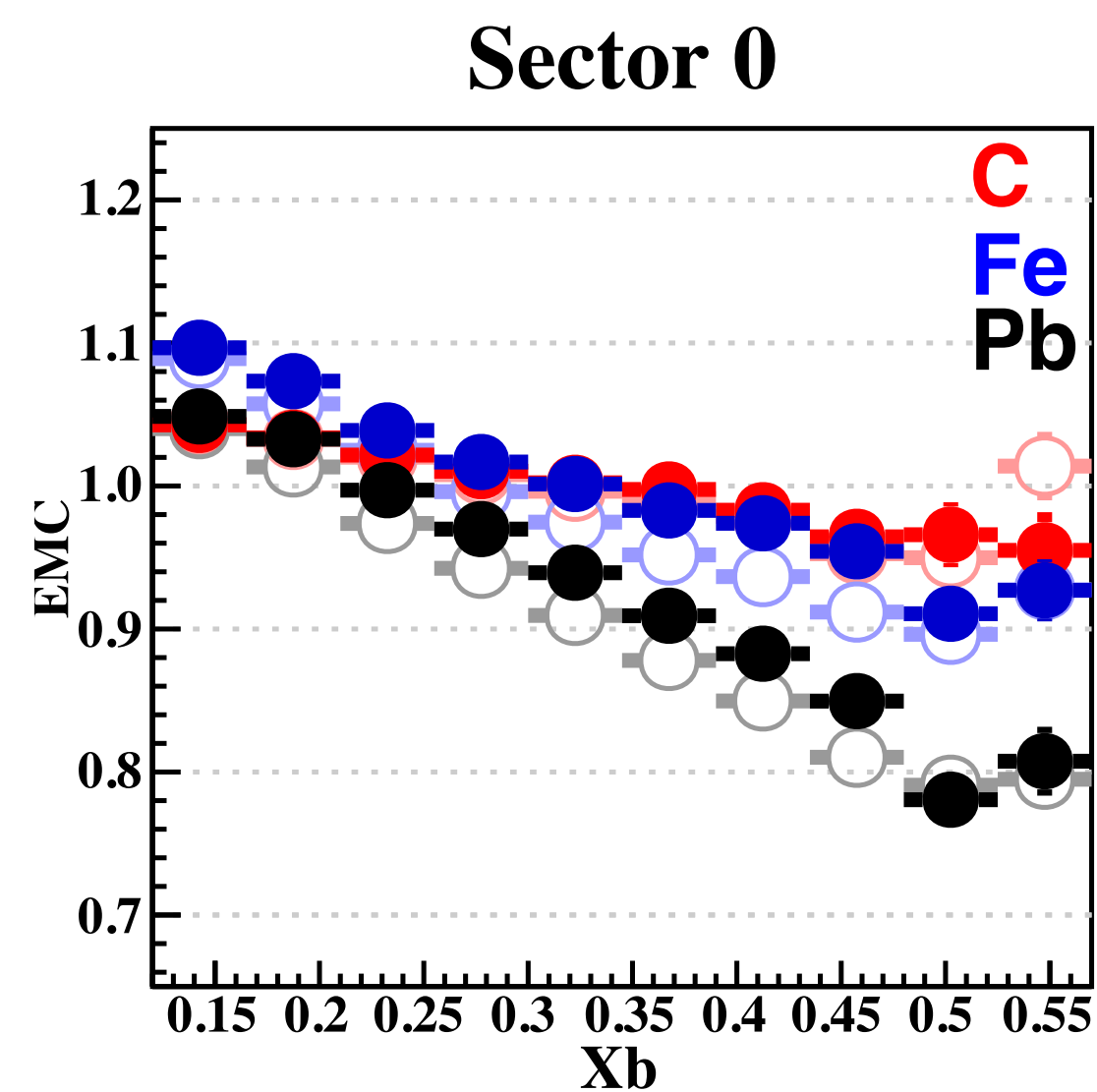
π^+ 1D MR (can be up to 4D)

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



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

- Hollow symbols: no acceptance corrections



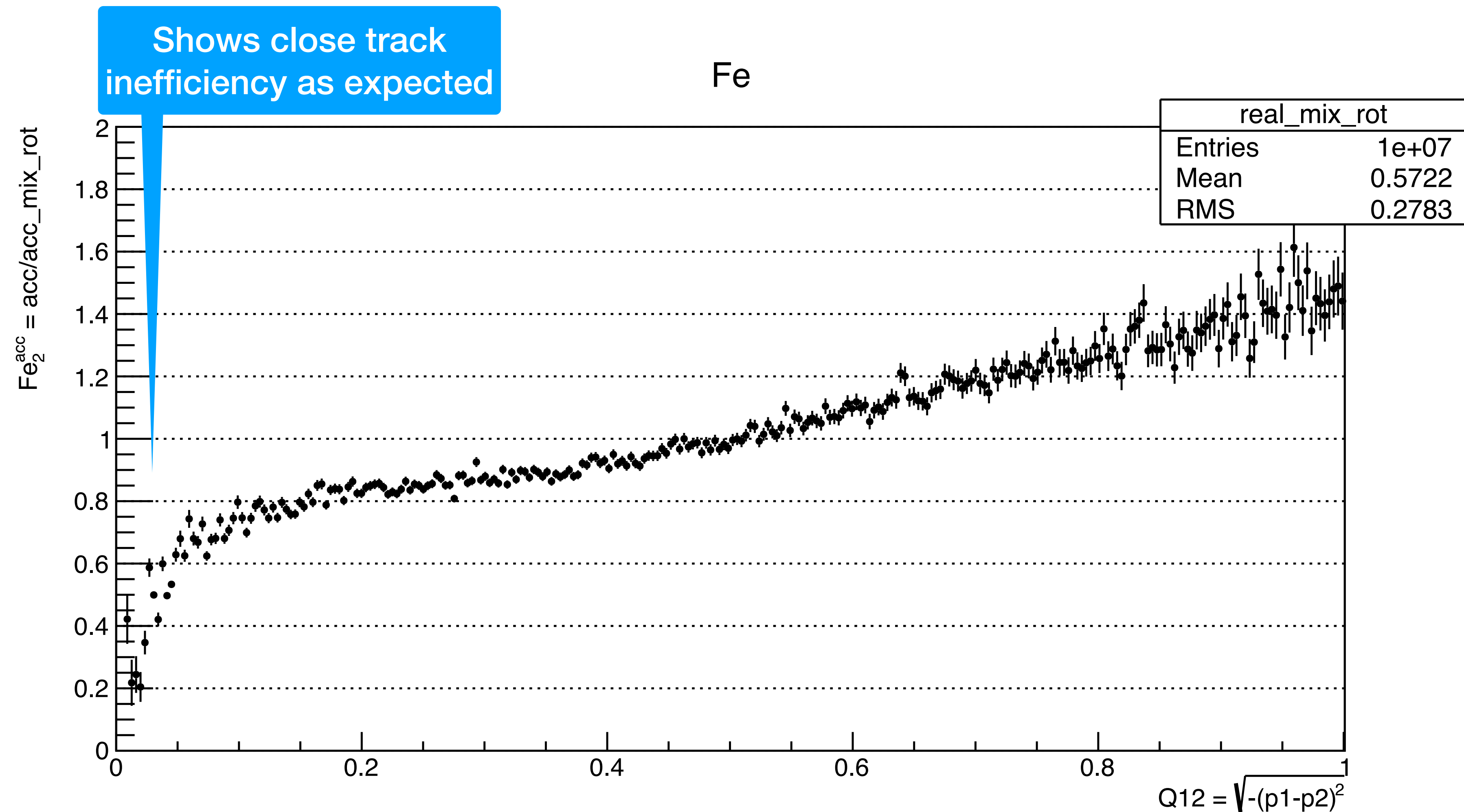
Di-hadron Studies with Nuclear Targets

- **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, 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

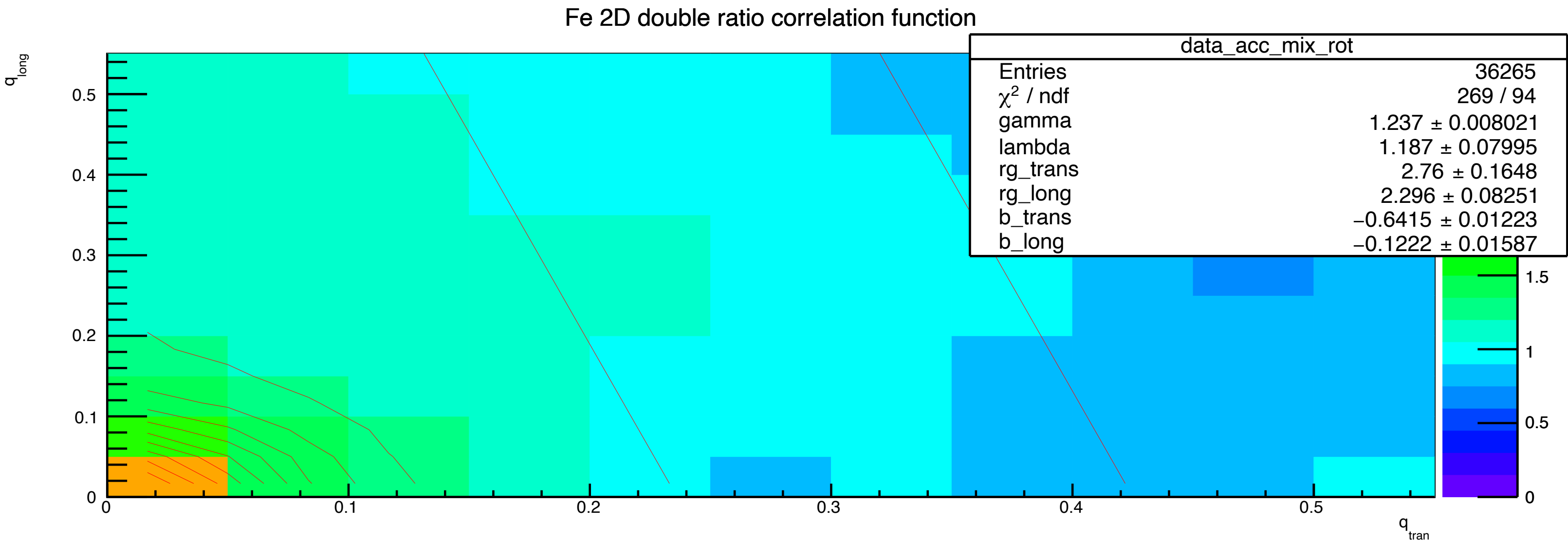
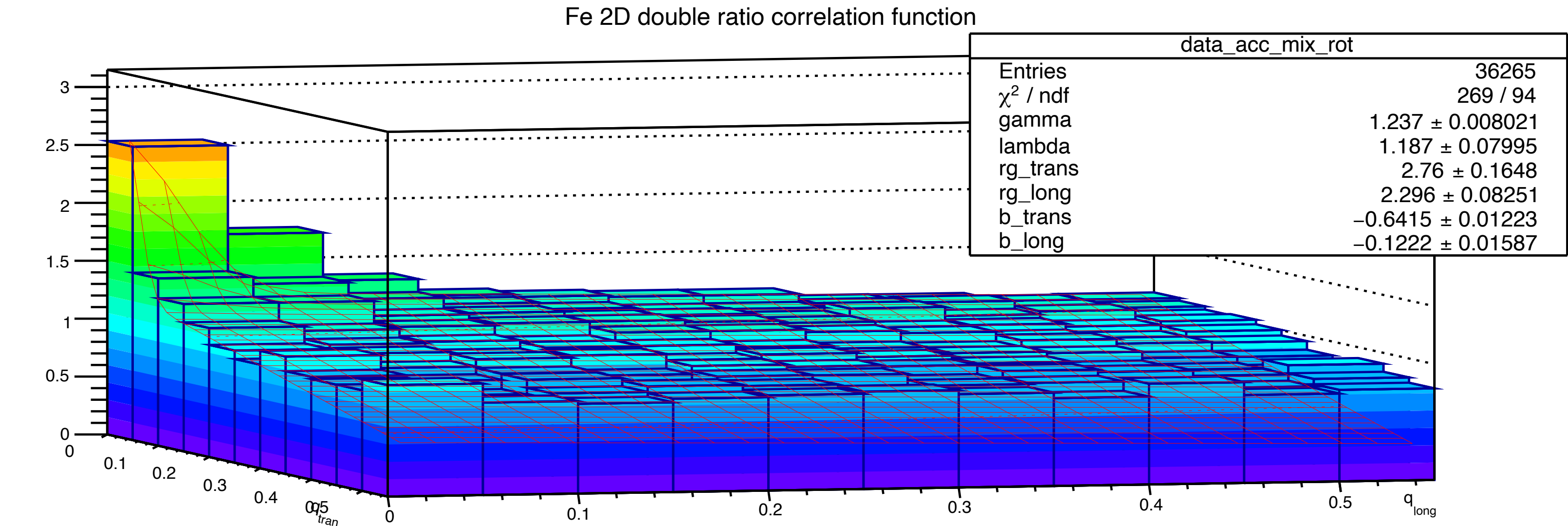
Correlation function calculated only from simulation



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

Antonio Radic

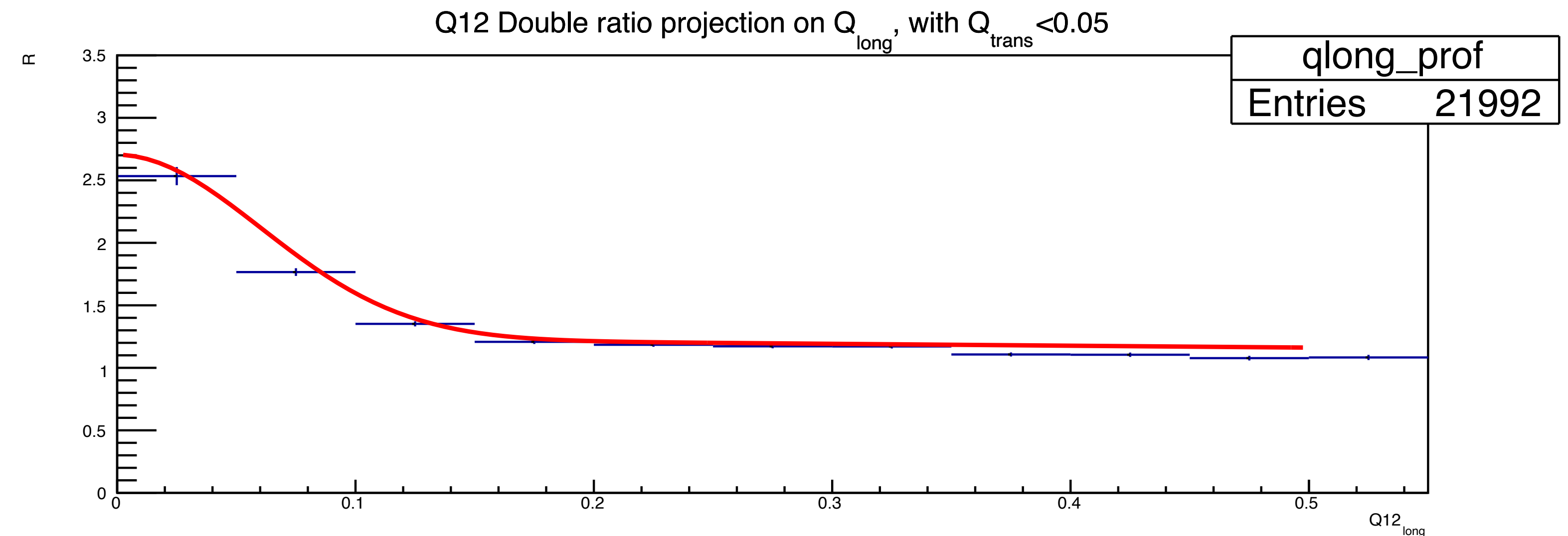
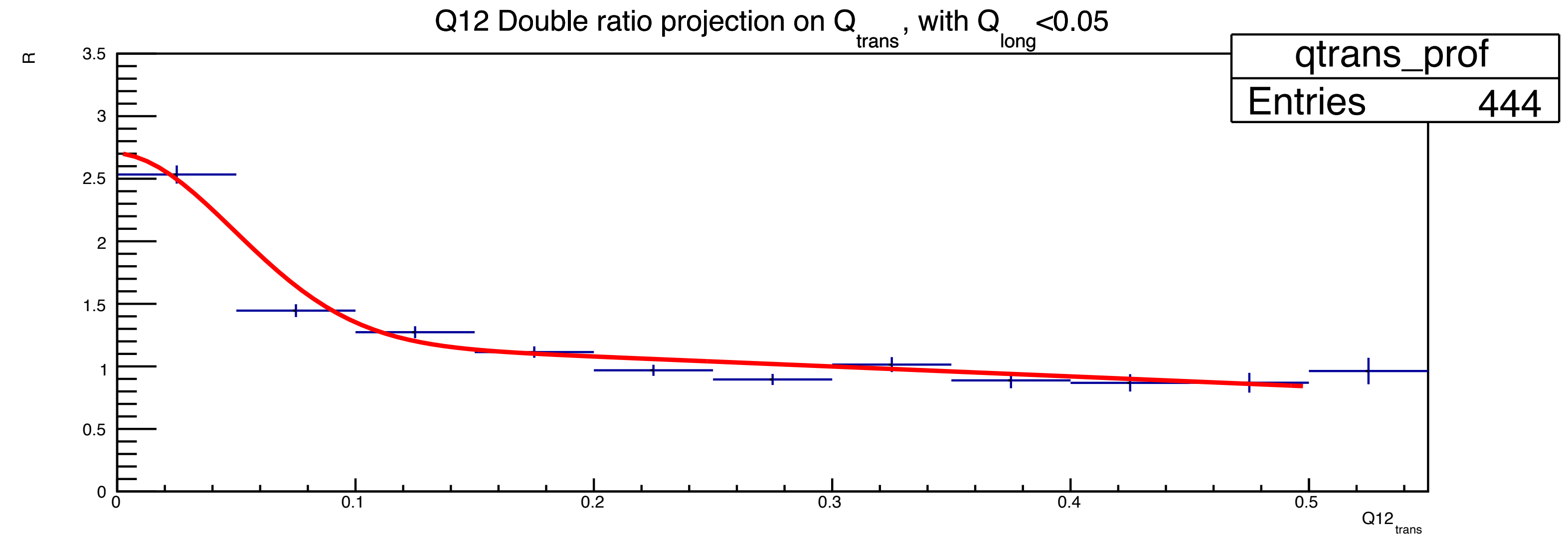
2D Correlation function
(longitudinal and transverse)



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

Antonio Radic

**Projections of
2D Correlation
function
(longitudinal
and transverse)**

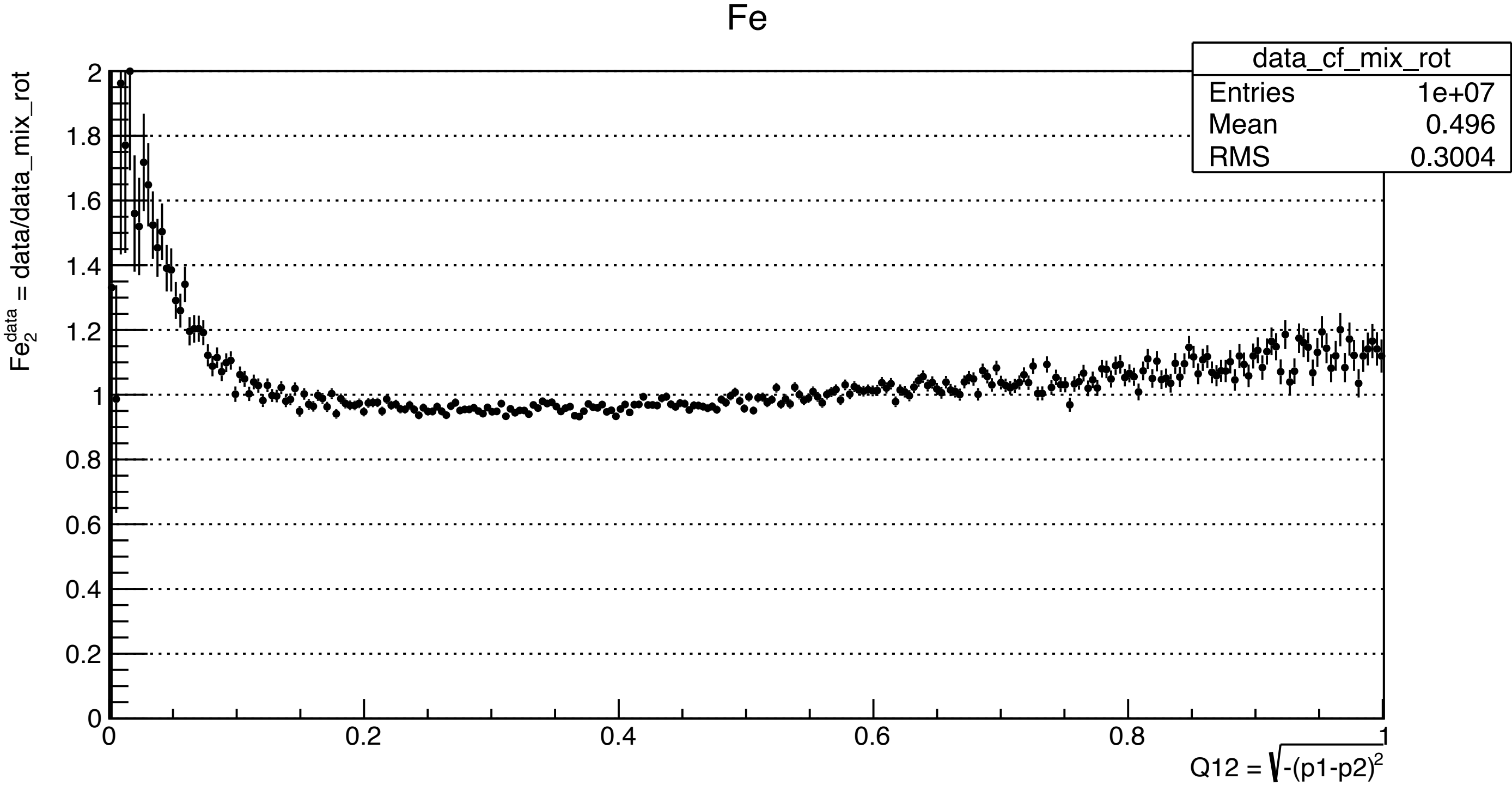


$\pi^+\pi^+$

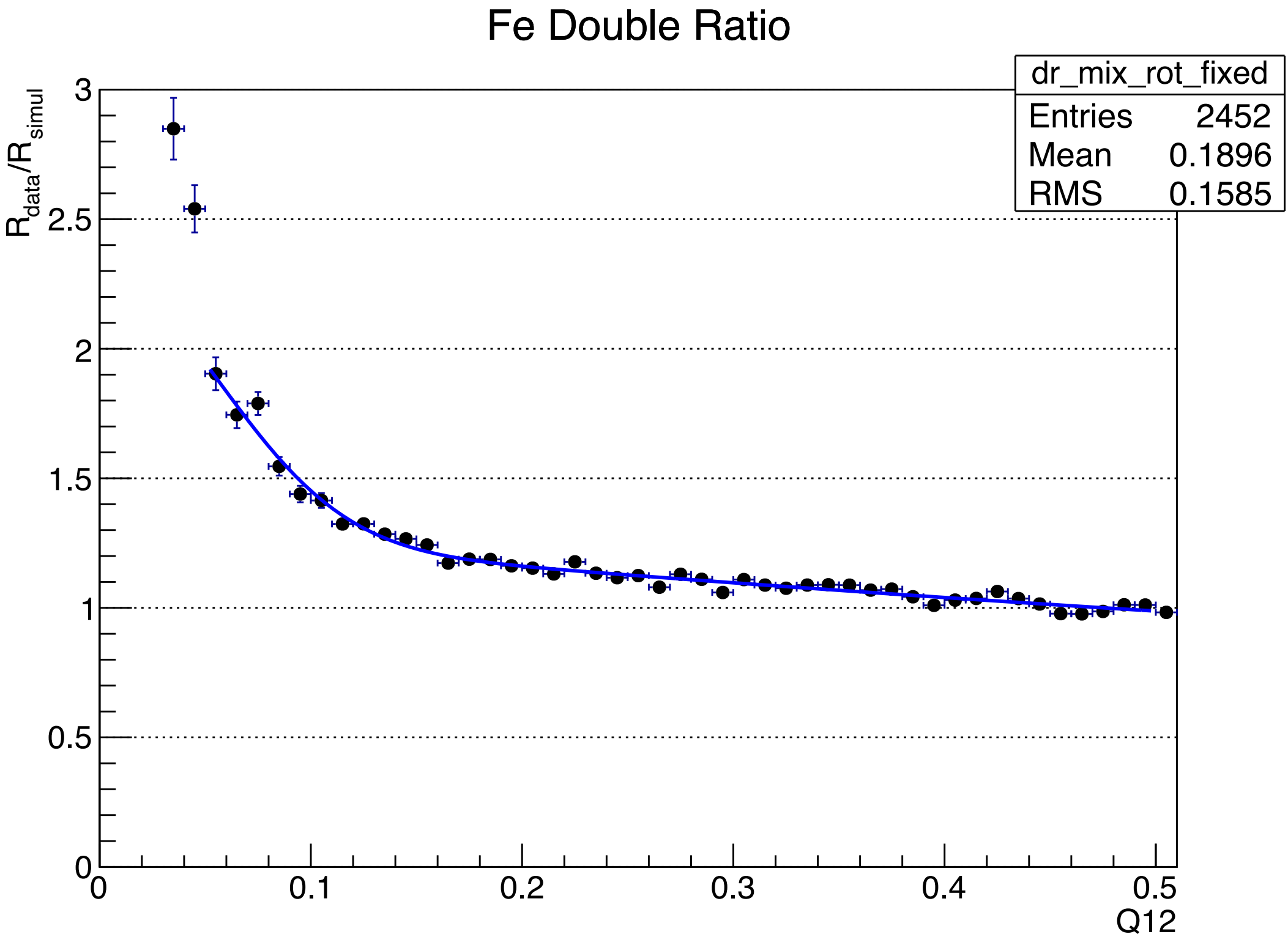
Bose-Einstein Correlation Studies on Nuclei

Antonio Radic

Data-only 1D Correlation function

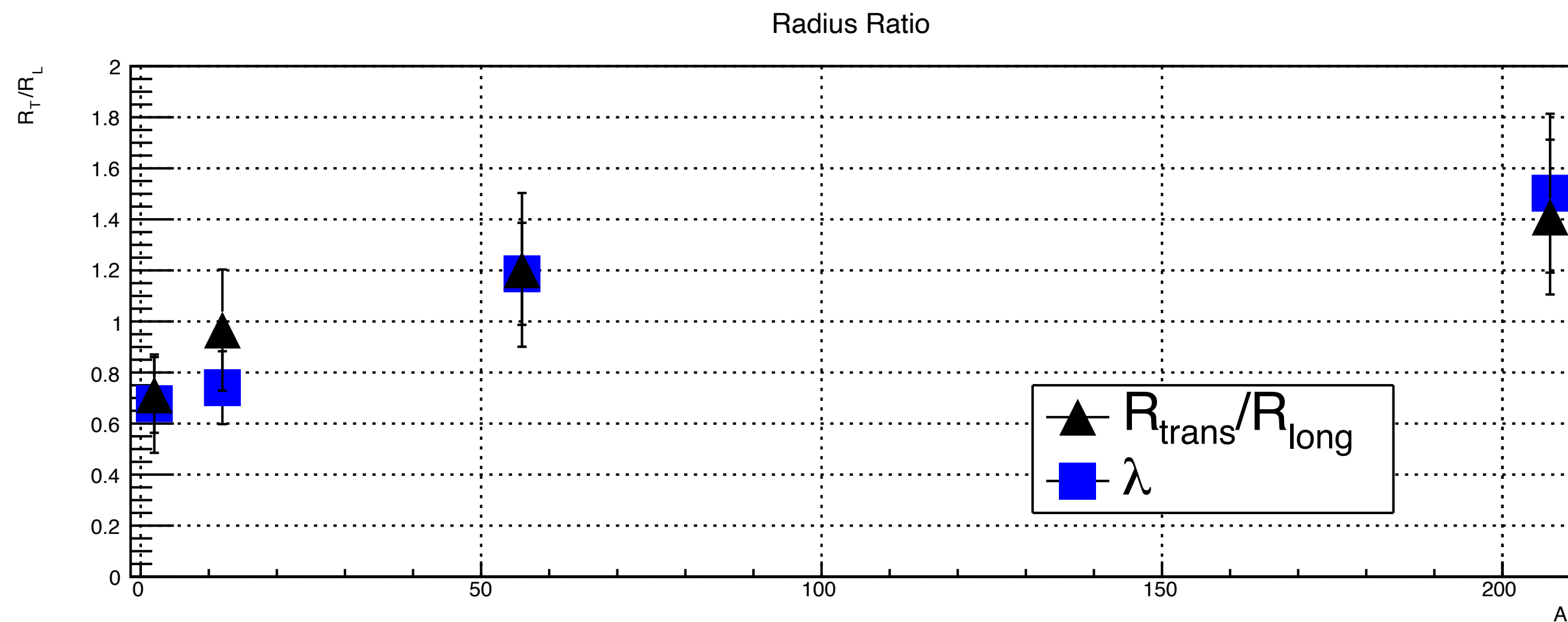
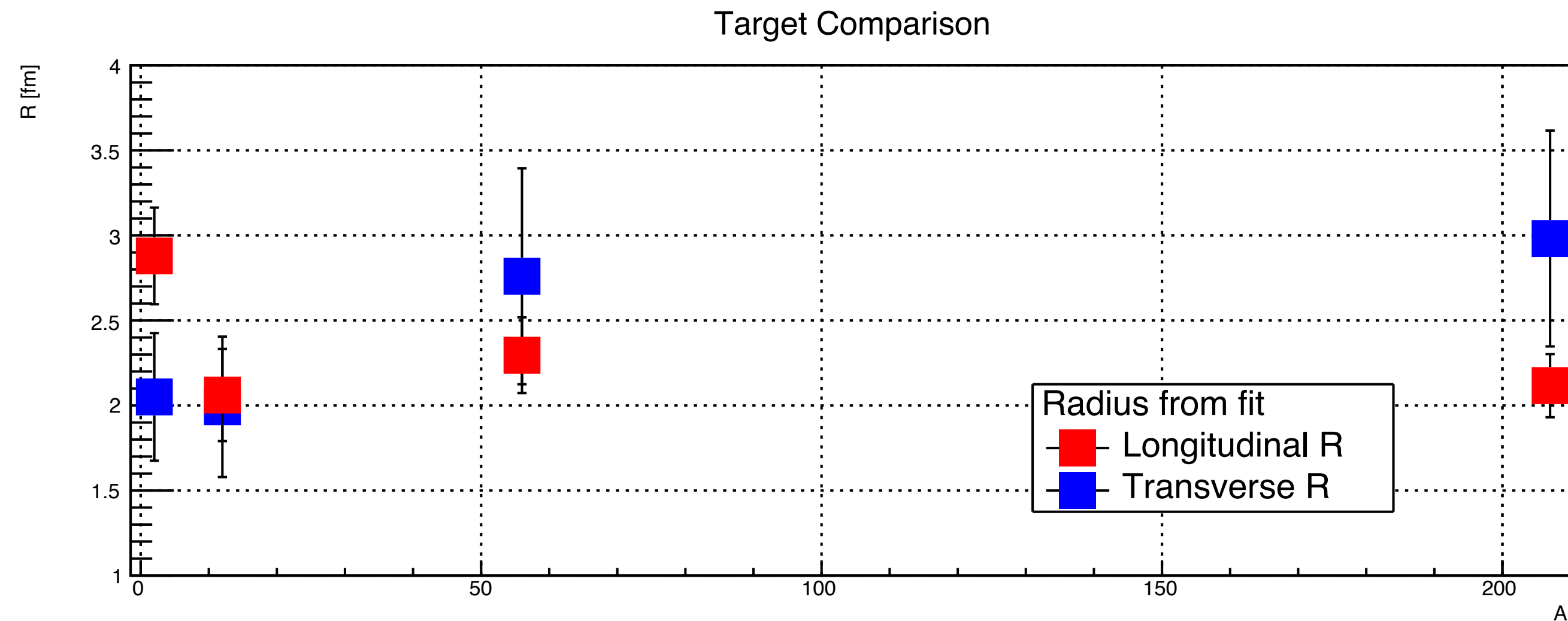


Double ratio 1D Correlation function (normalized to simulation)



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

Antonio Radic

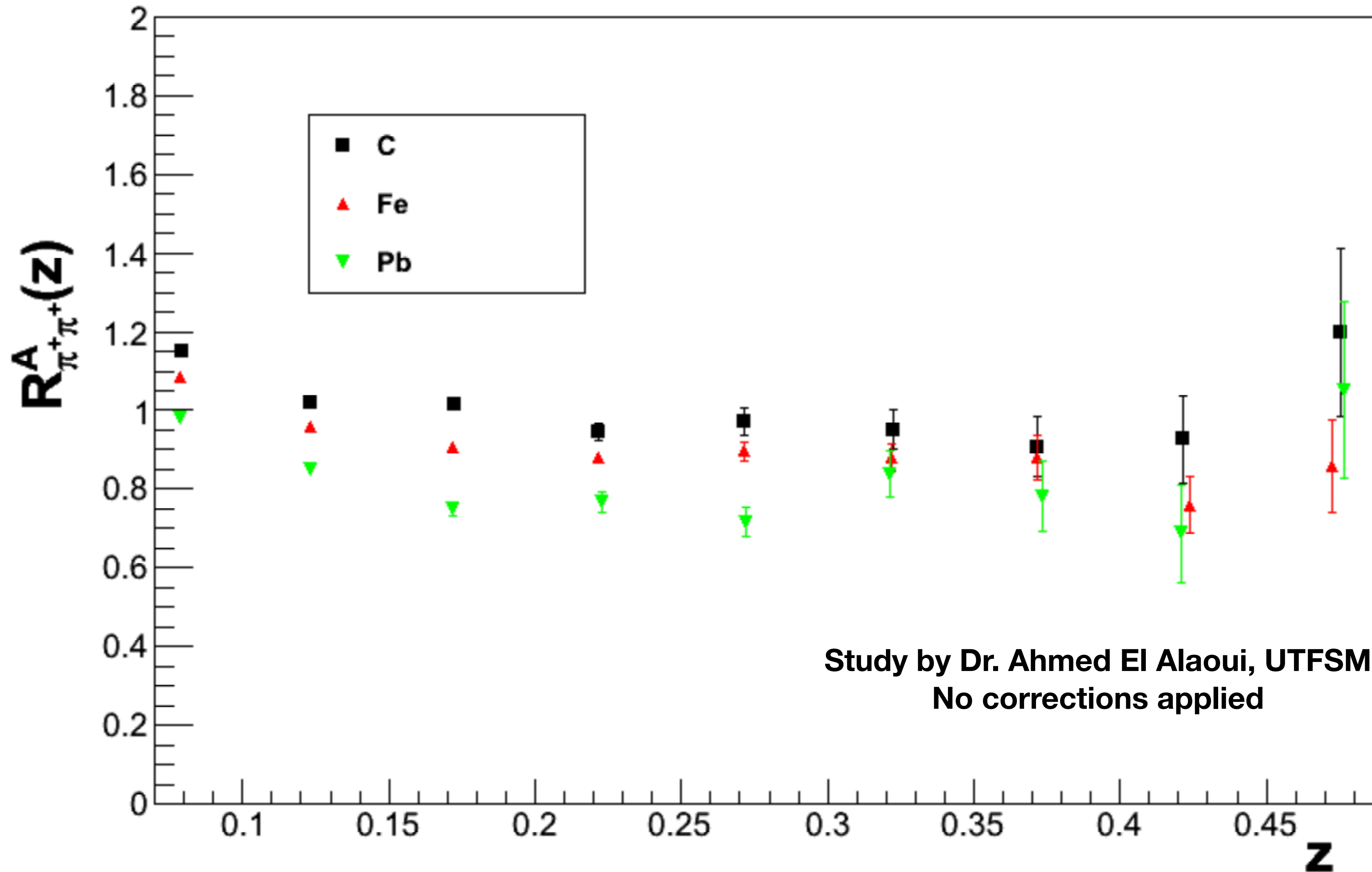


Source size 2-3 fm

Transverse/Longitudinal
source size **doubles** with
nuclear size!
Hadronic cascade?

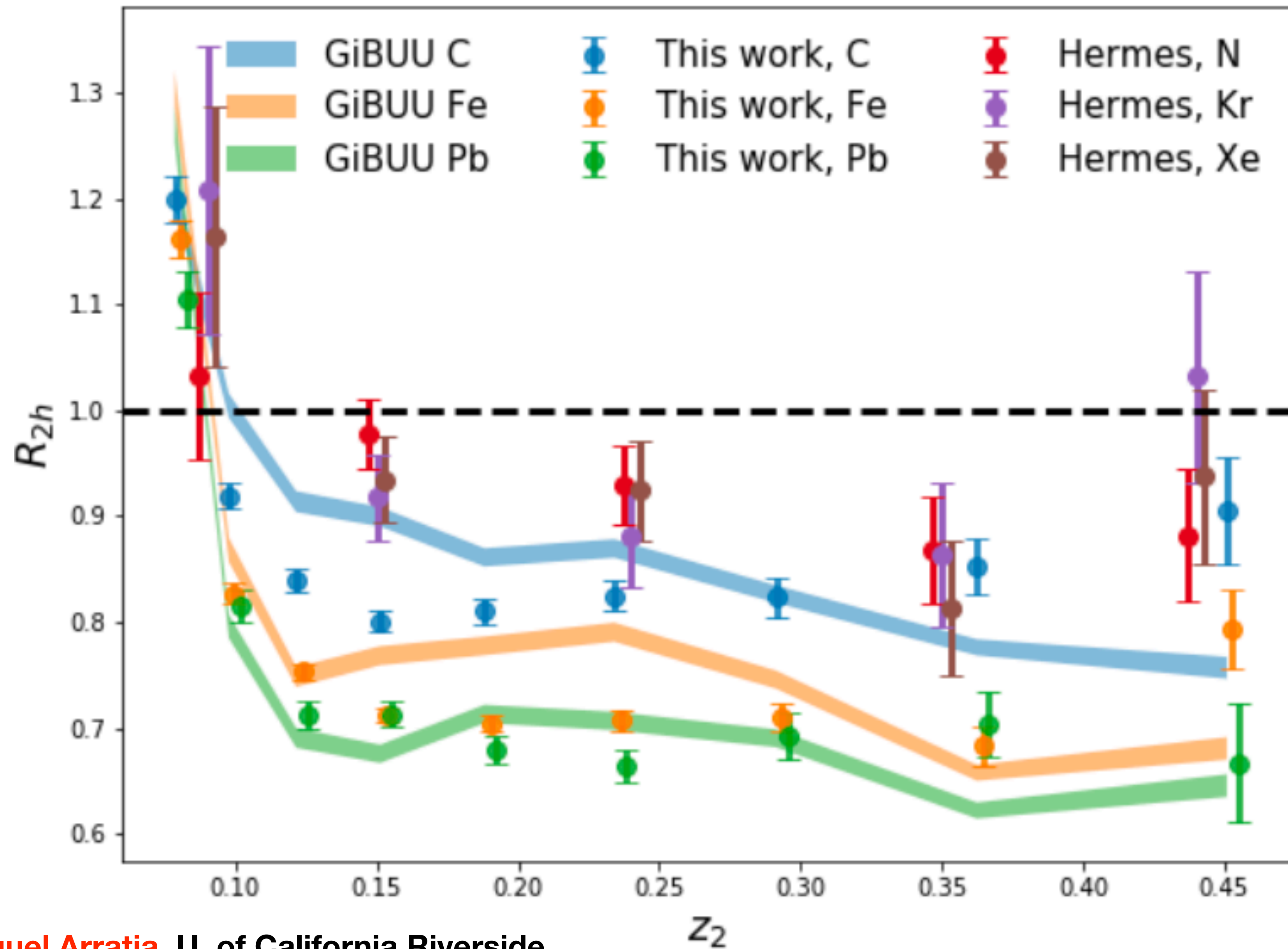
Two-hadron (conditional, $z_1 > 0.5$) multiplicity ratio

Dr. Ahmed El Alaoui, UTFSM



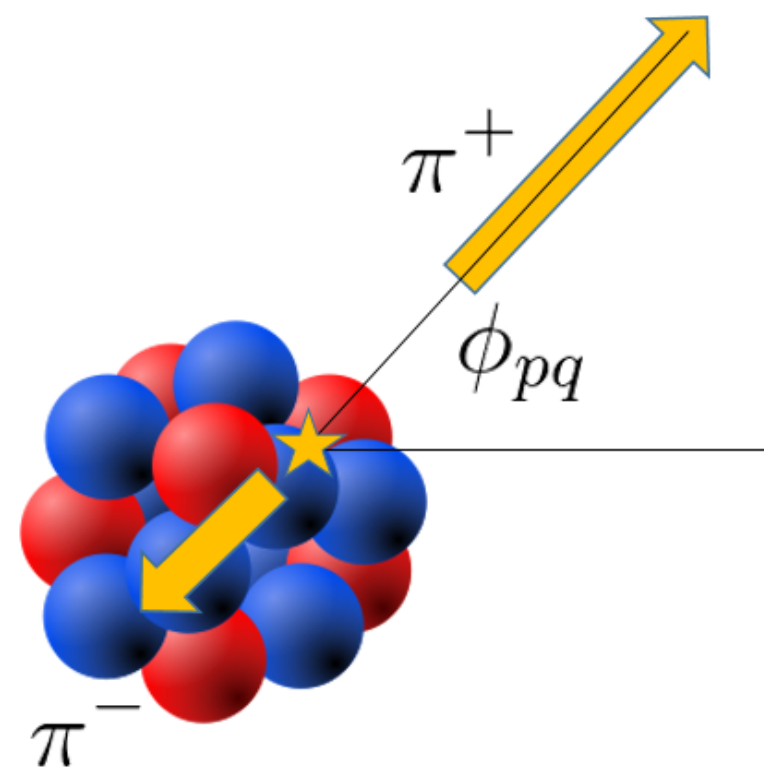
Result is
qualitatively
consistent with
HERMES, with
much better
statistical
precision.

Comparison with HERMES and GiBUU



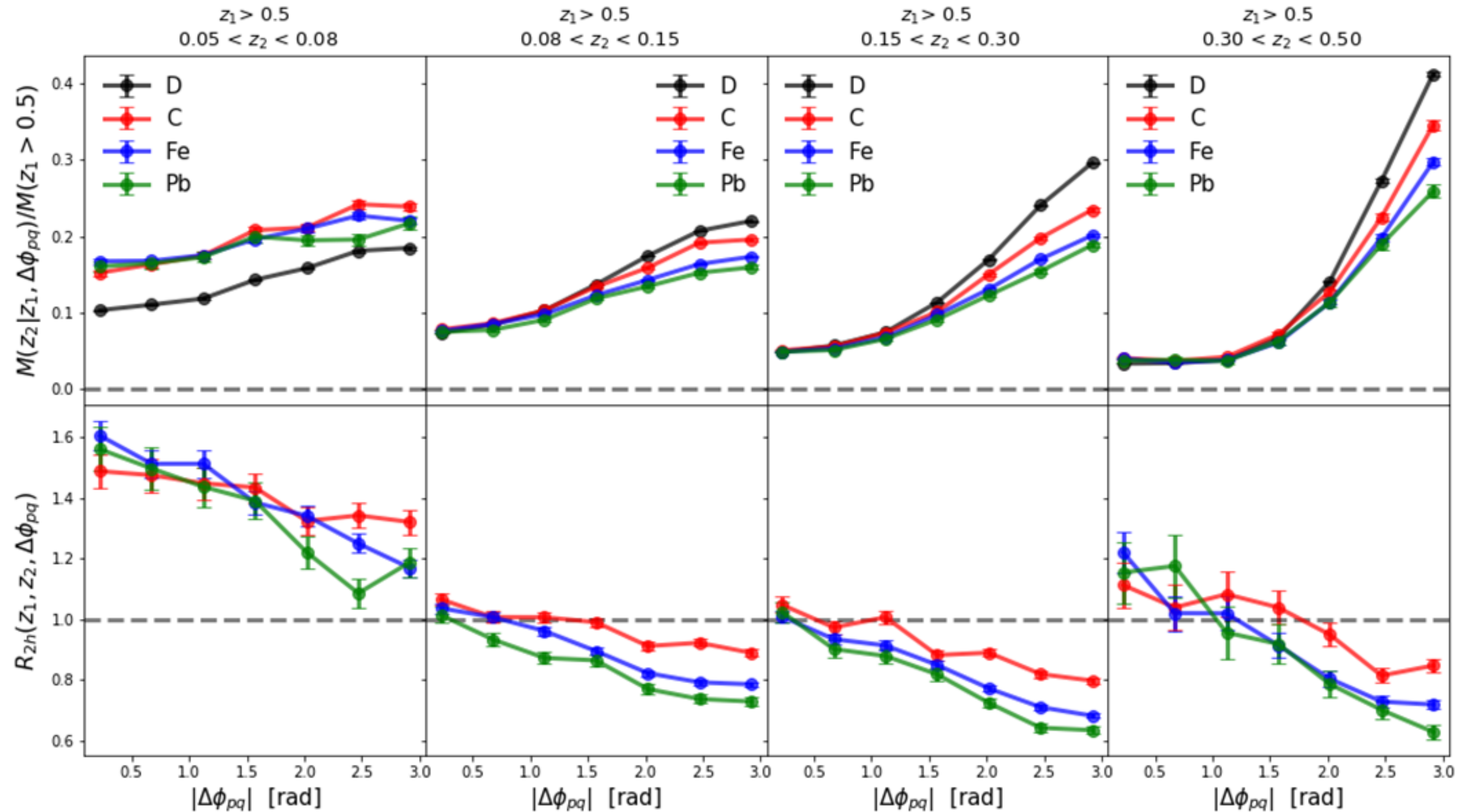
Dihadron azimuthal angle correlations

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.

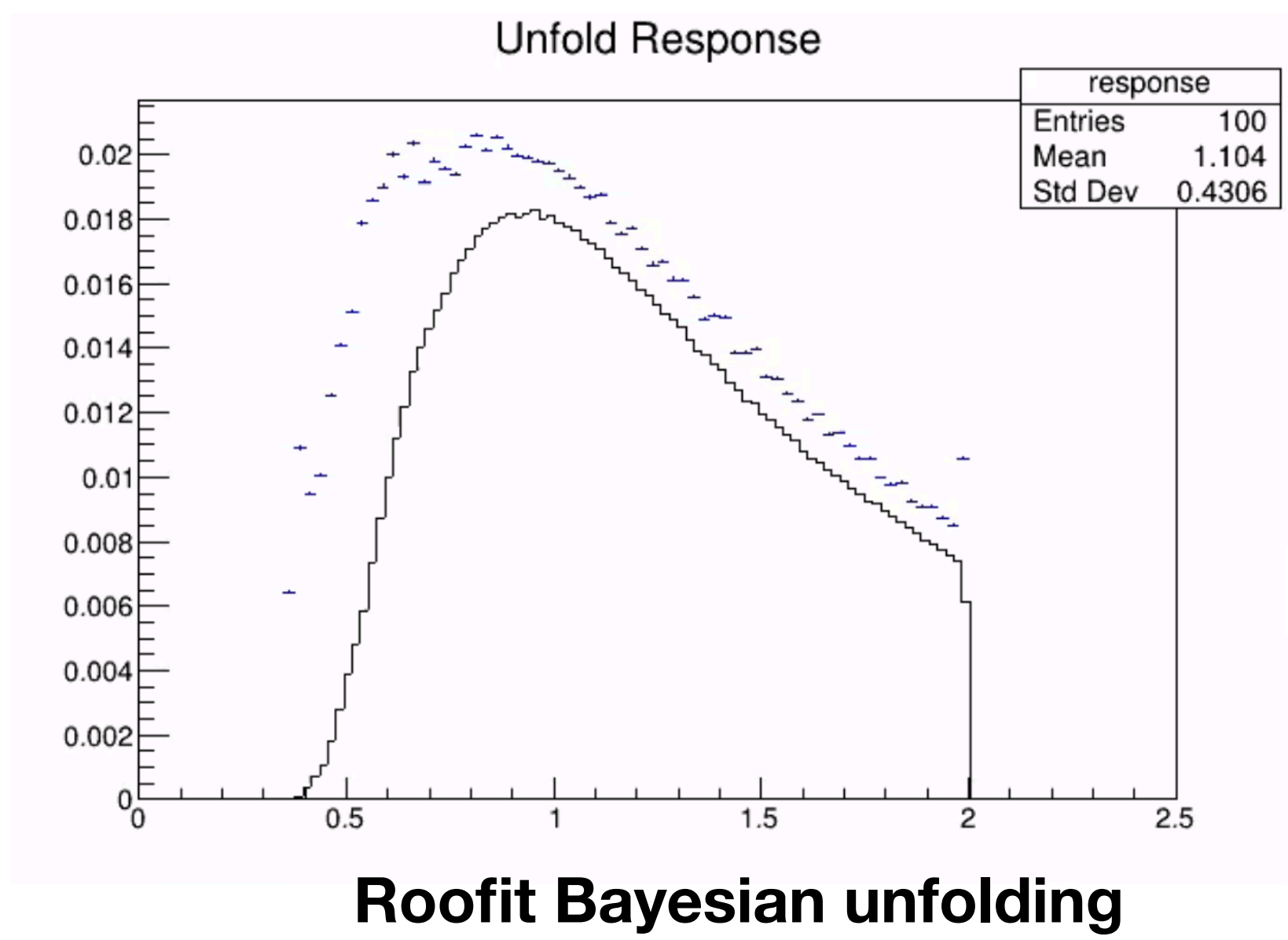
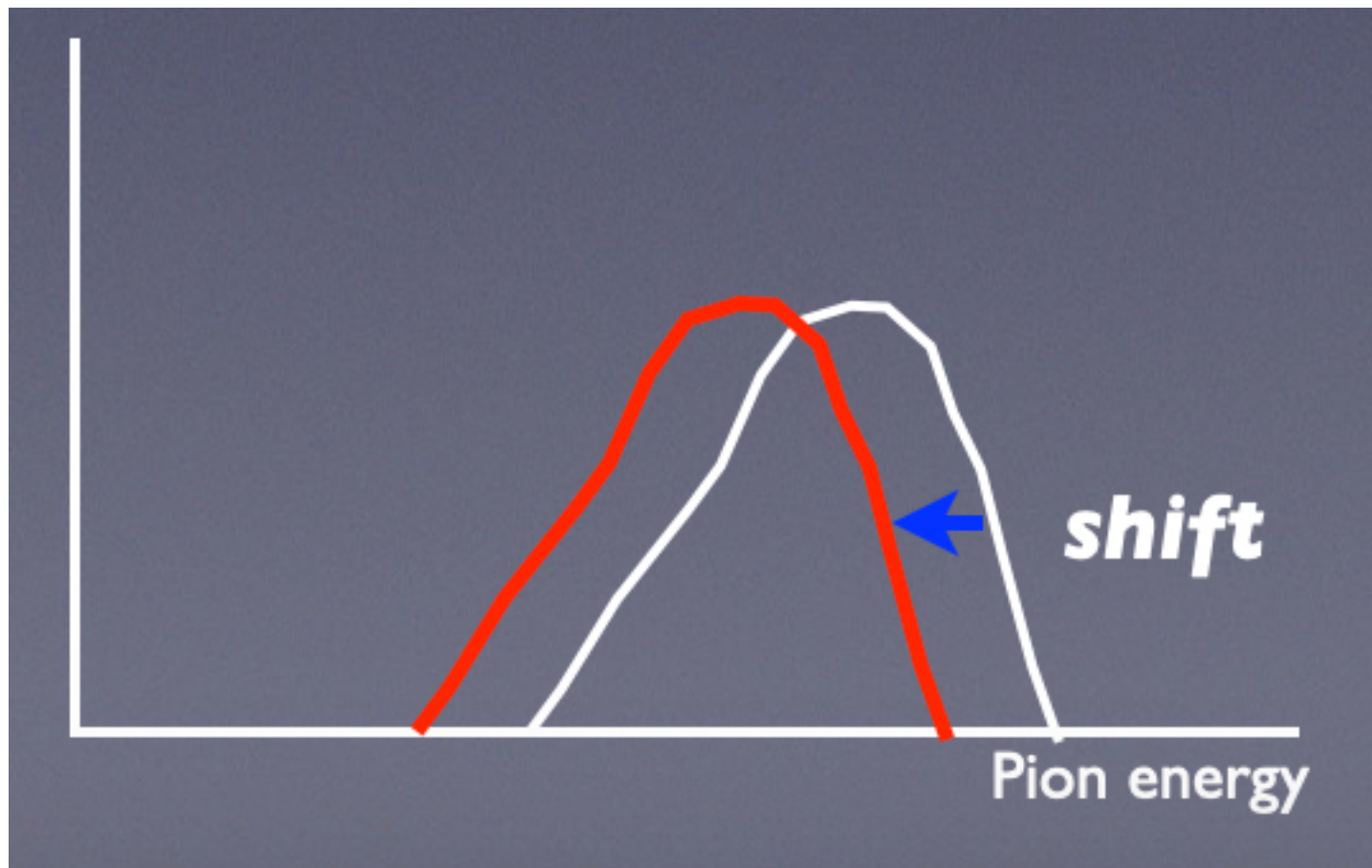
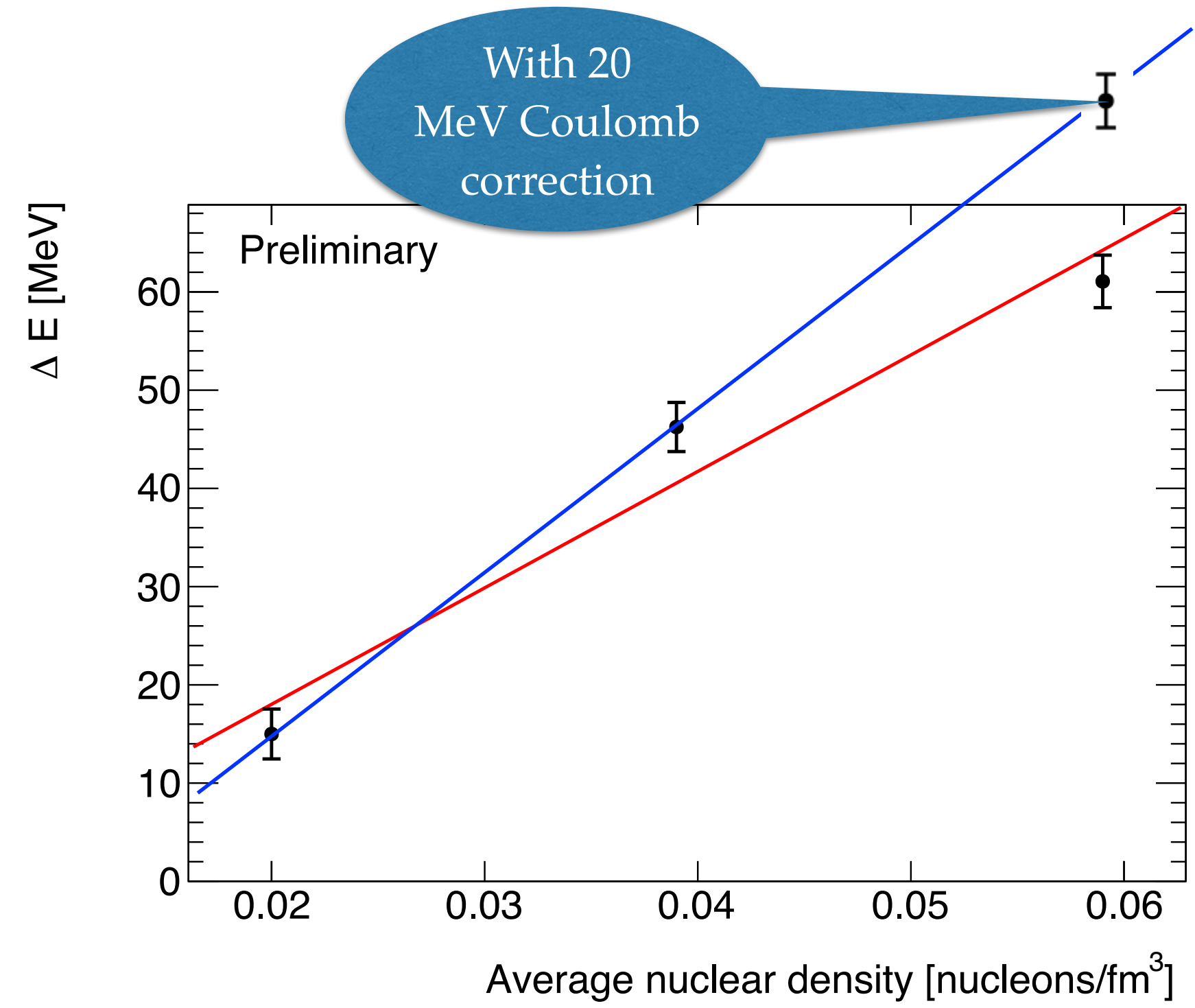
Direct measurement of quark energy loss, and its connection to p_T broadening

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.



Conclusions

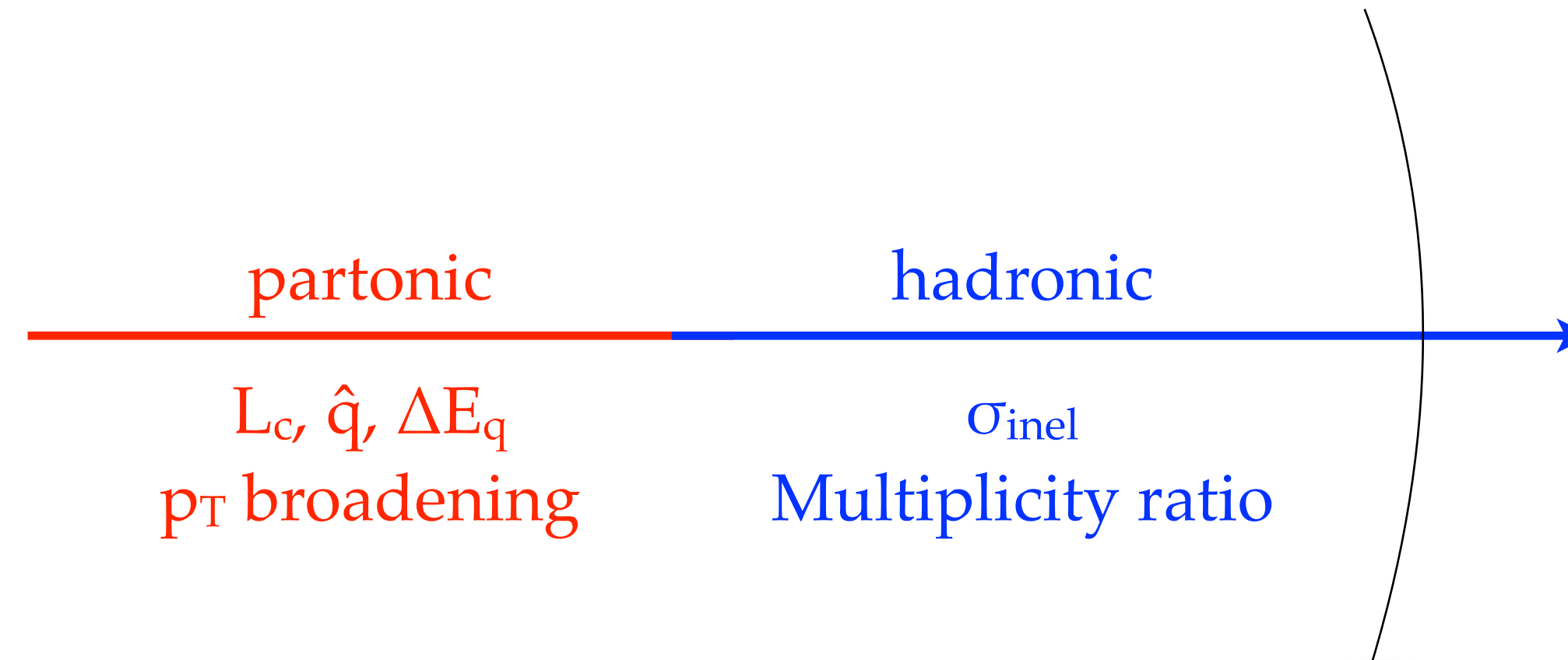
- Many interesting current results from EG2/CLAS6!
- Many more expected from CLAS12. A large and experienced team is waiting to get on the schedule.
- Clear extensions to EIC!

Backup Slides

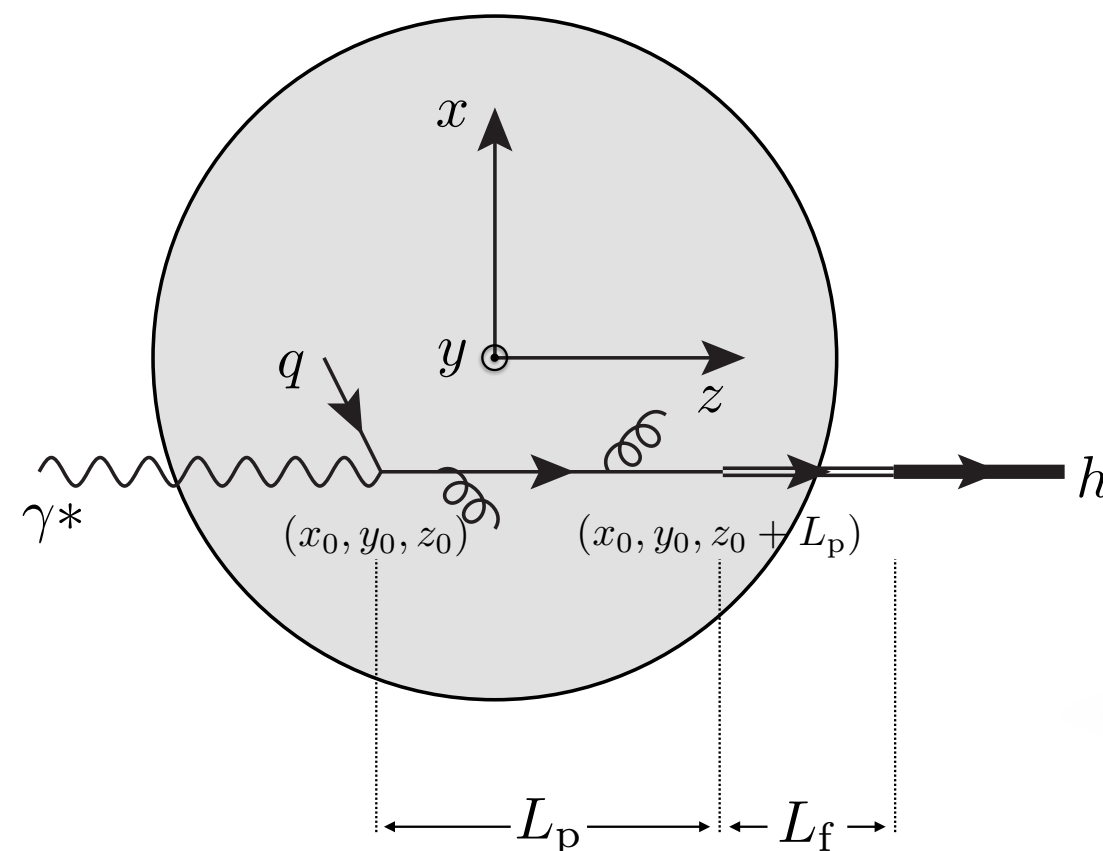
Definition of the BL model

Division into *partonic* and *hadronic* phases

Path of quark is divided into “*partonic phase*” and “*hadronic phase*”

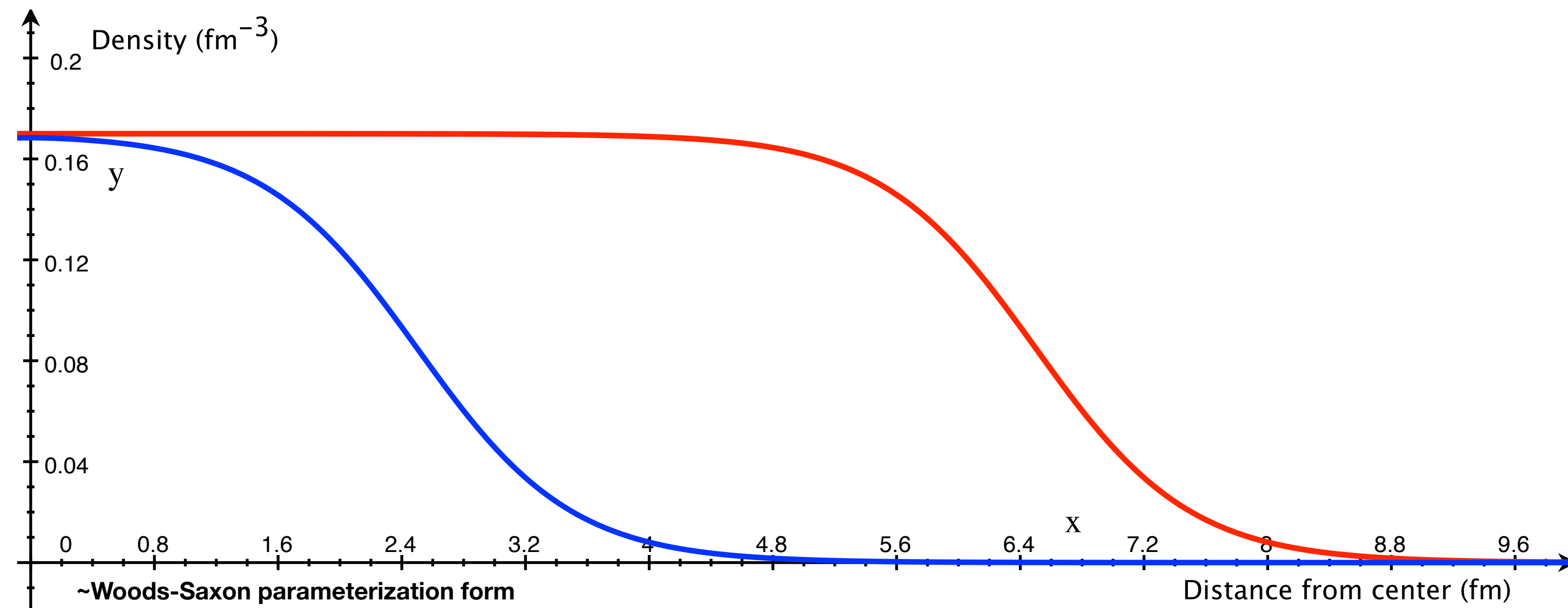


The *partonic phase* persists for a distance L_c , over which p_T broadening via $\hat{q}$, and partonic energy loss ΔE_q , occur



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

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

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 .

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

unique parameter

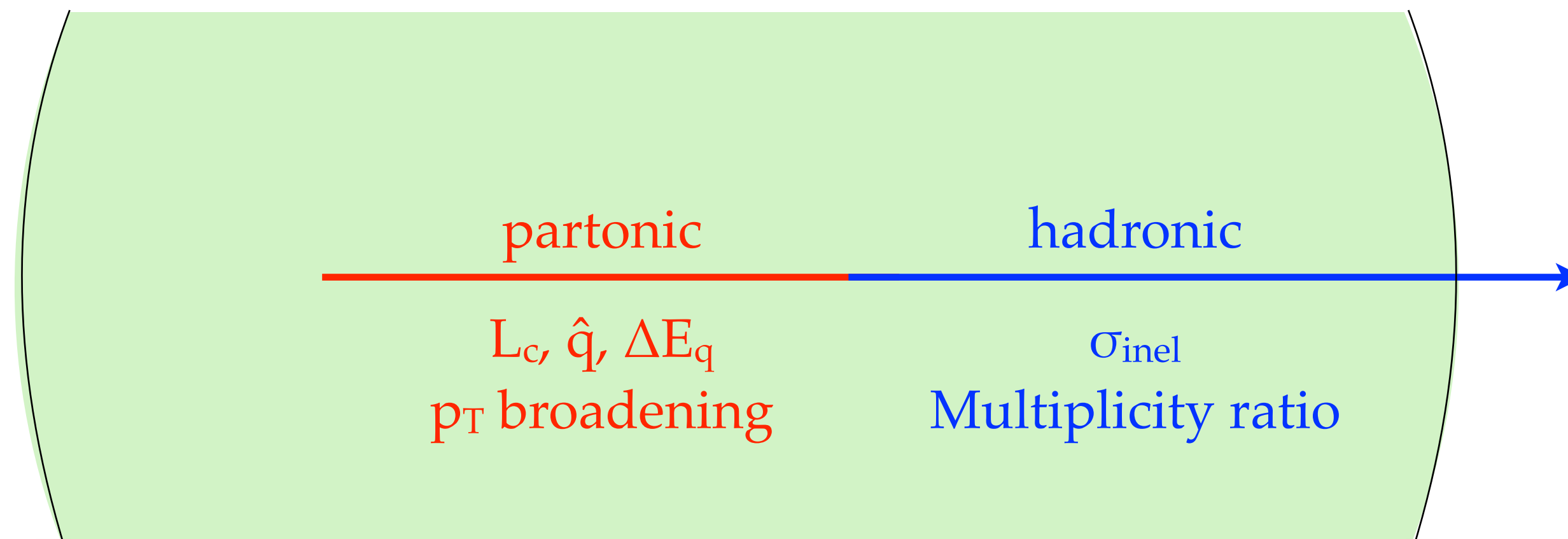
common parameter

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.



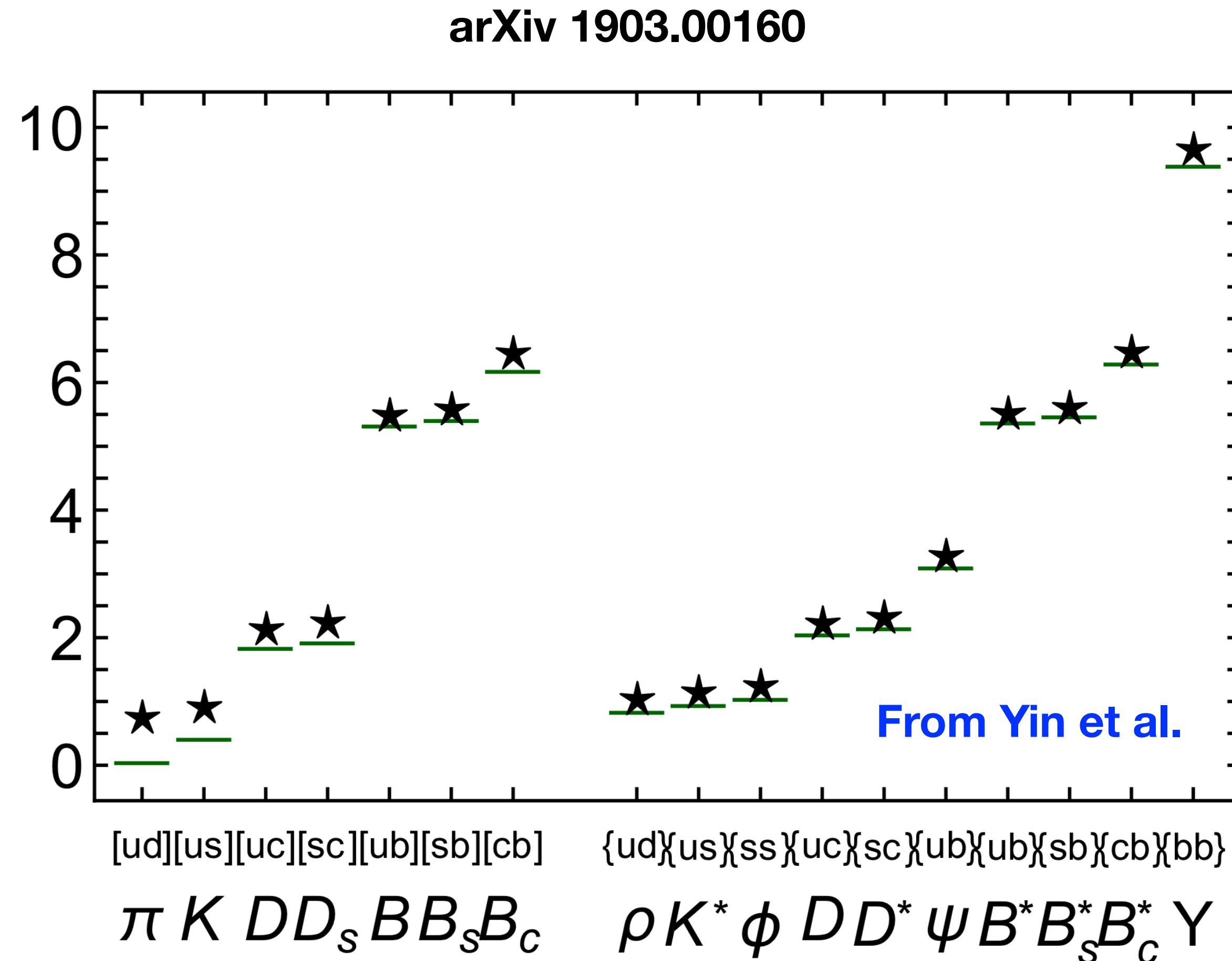
Model Assumptions

- 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 Xu¹

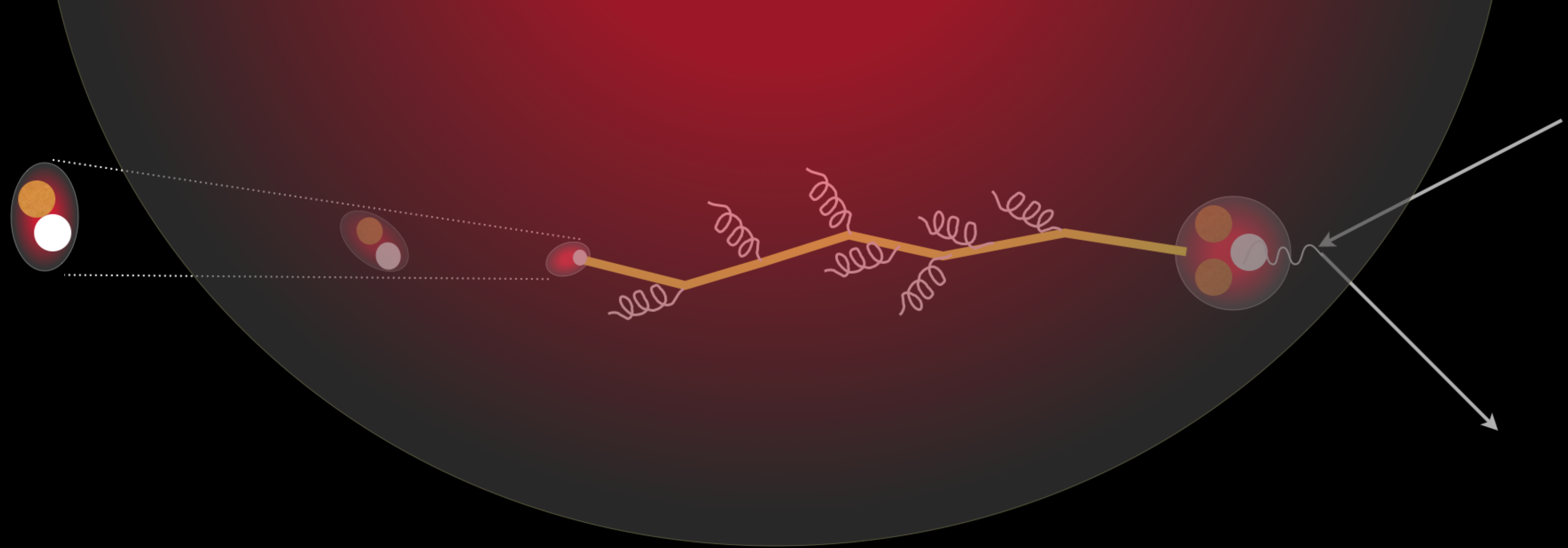


The ud diquarks are heavy. This is very relevant to what follows in this talk.

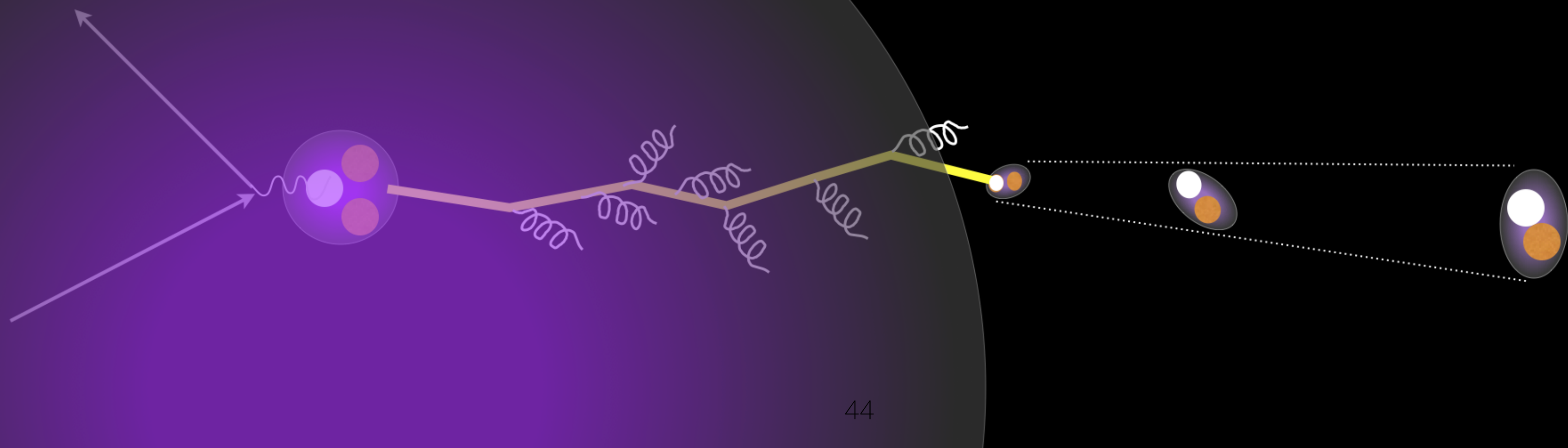
FIG. 2. Comparison between computed masses of diquark correlations and their symmetry-related meson counterparts: diquarks – (black) stars and mesons – (green) bars.

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

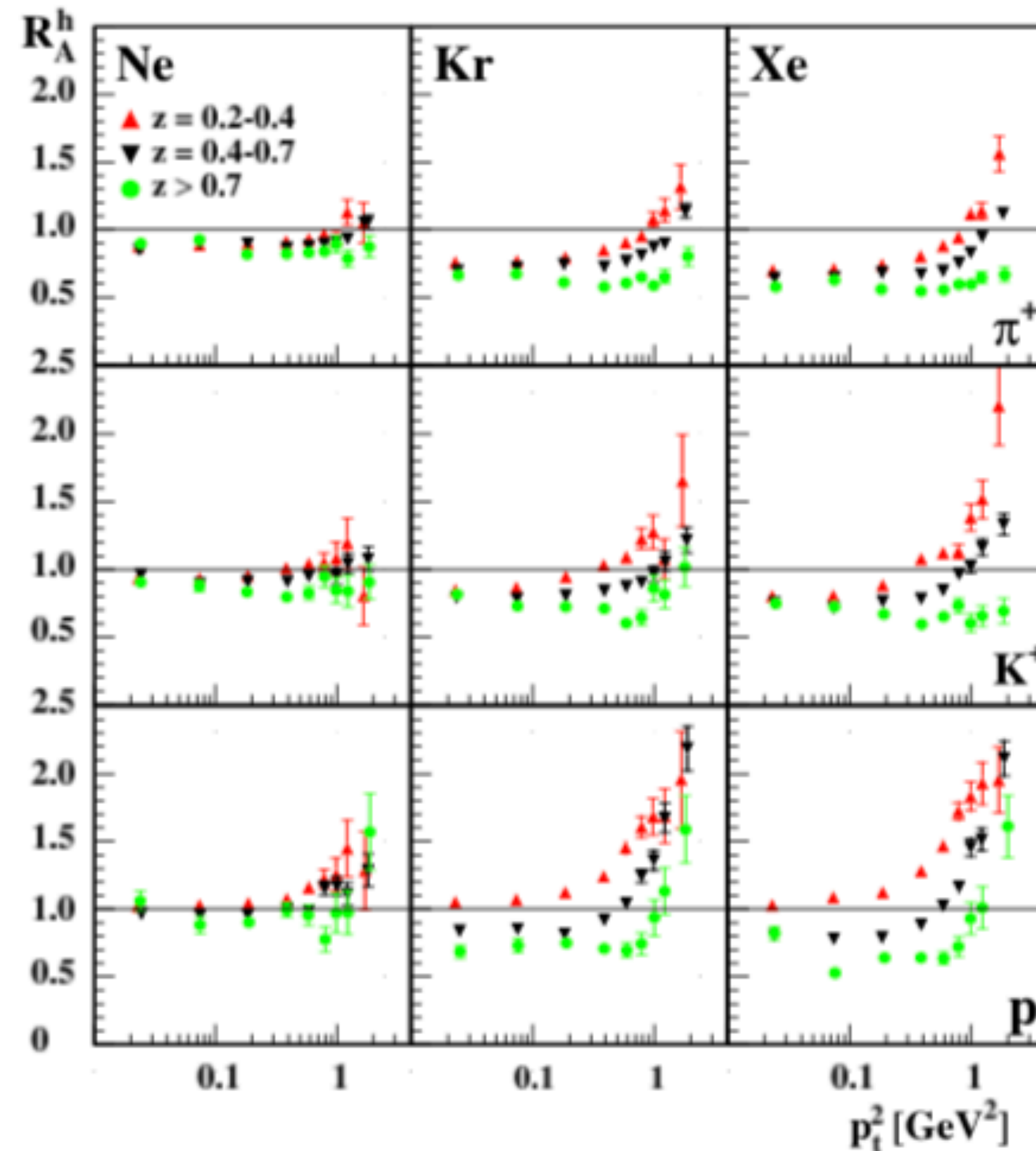
The multiplicity ratio measures effects of the nuclear medium.

“No effects” means $R=1.0$

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

Most basic indicator is p_T dependence of multiplicity ratio.

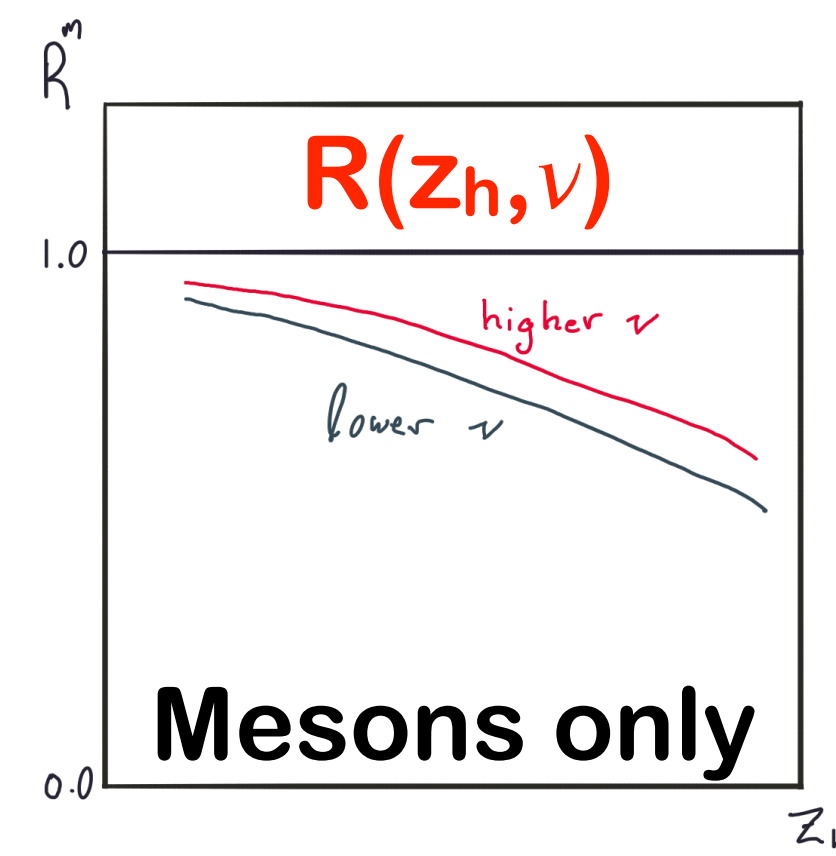
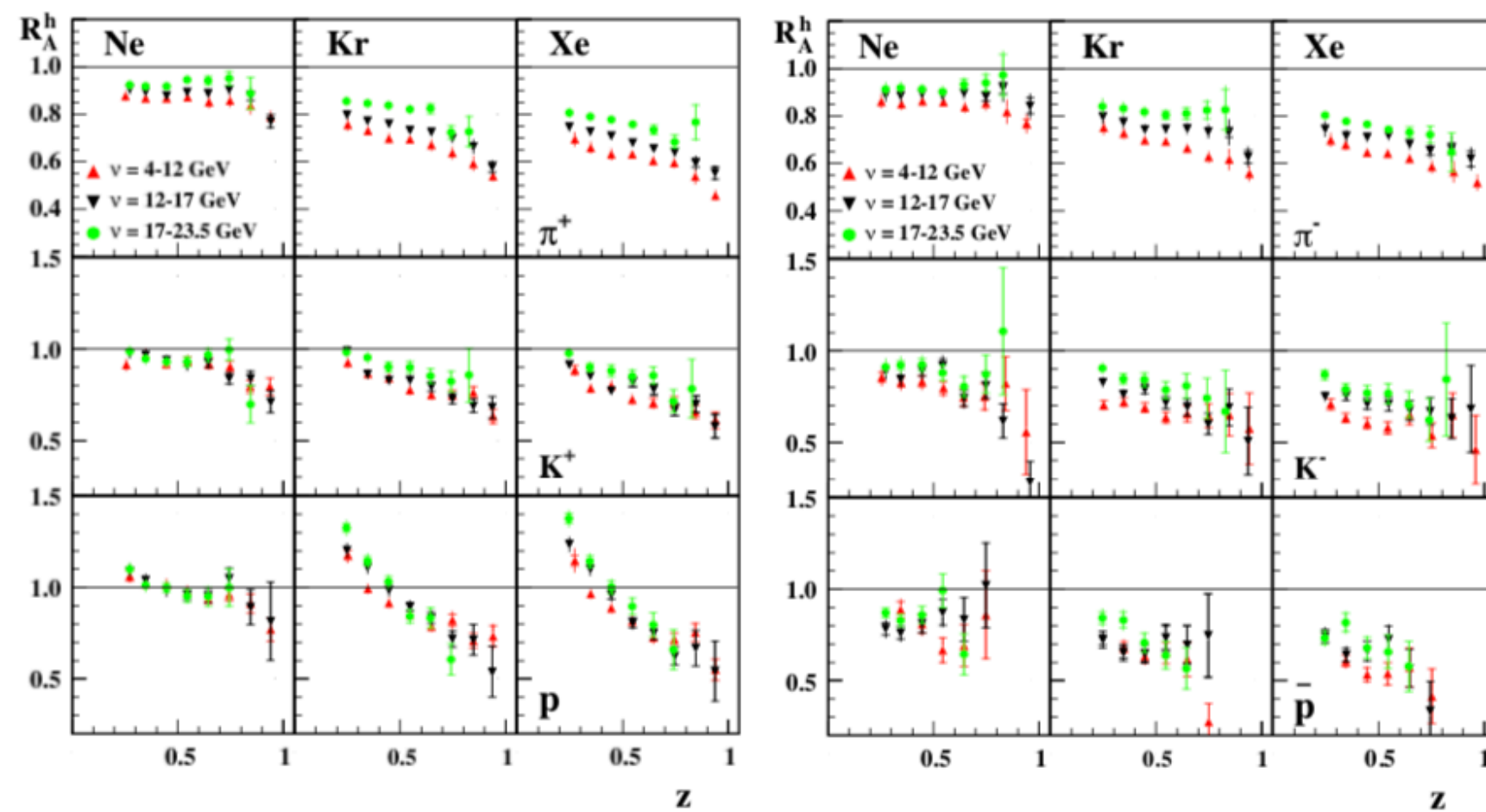
$R > 1$ at high p_T because particles that strongly interact with the medium acquire more p_T than those that don't interact as much.



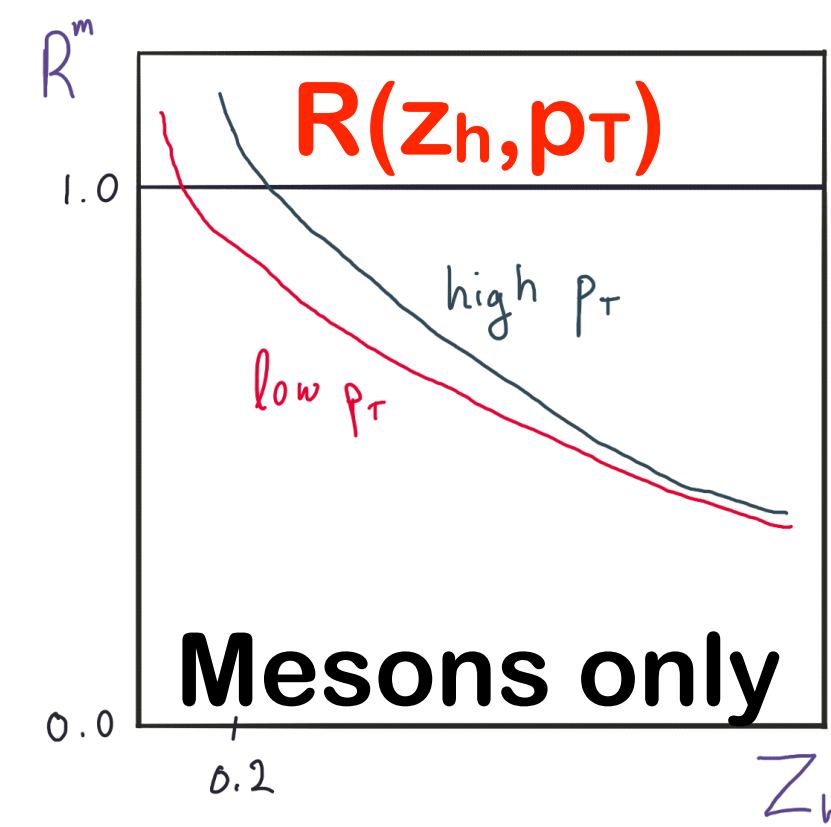
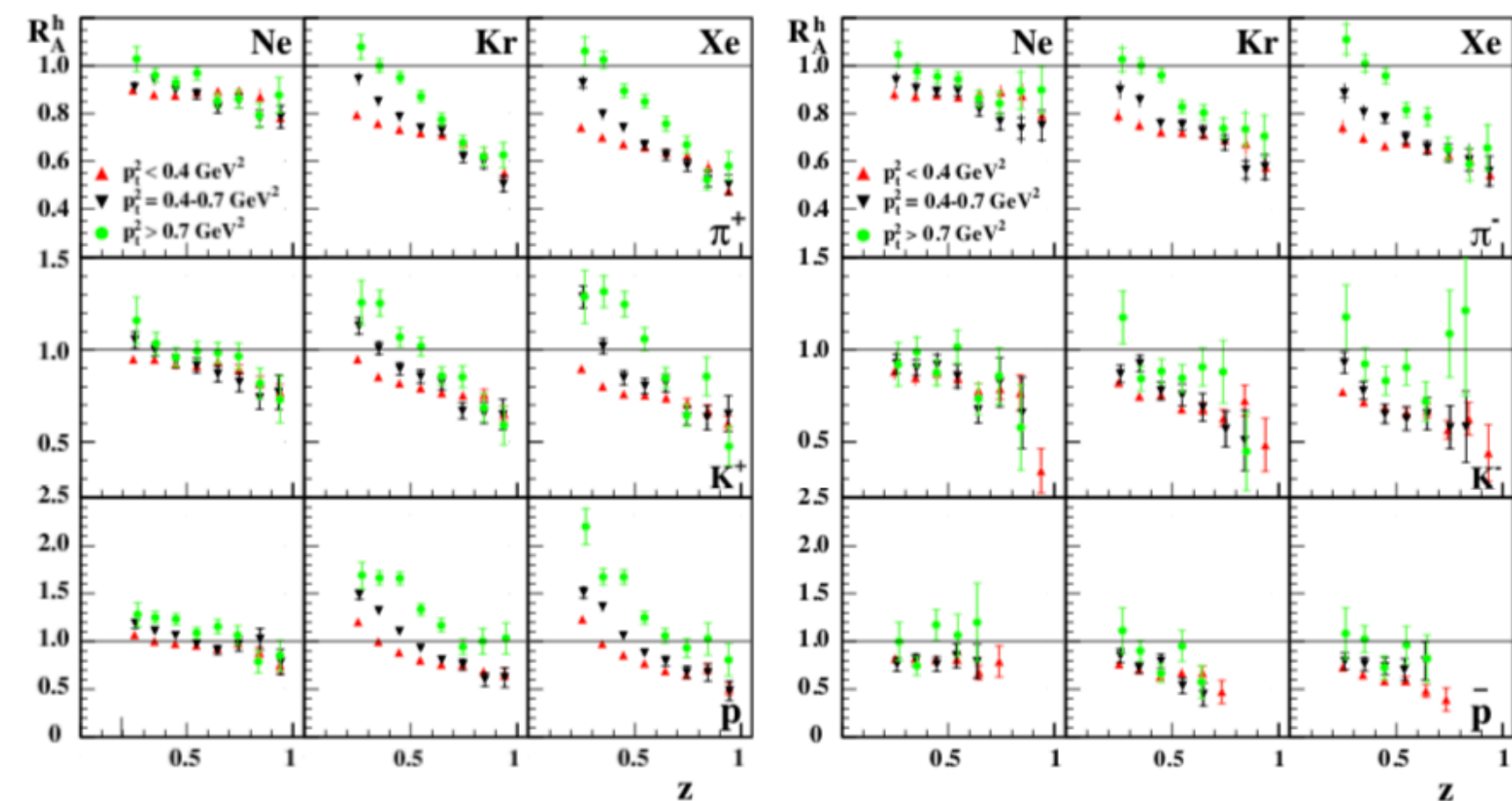
“Interact” = hadronic interaction of forming hadrons, + quark energy loss.

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

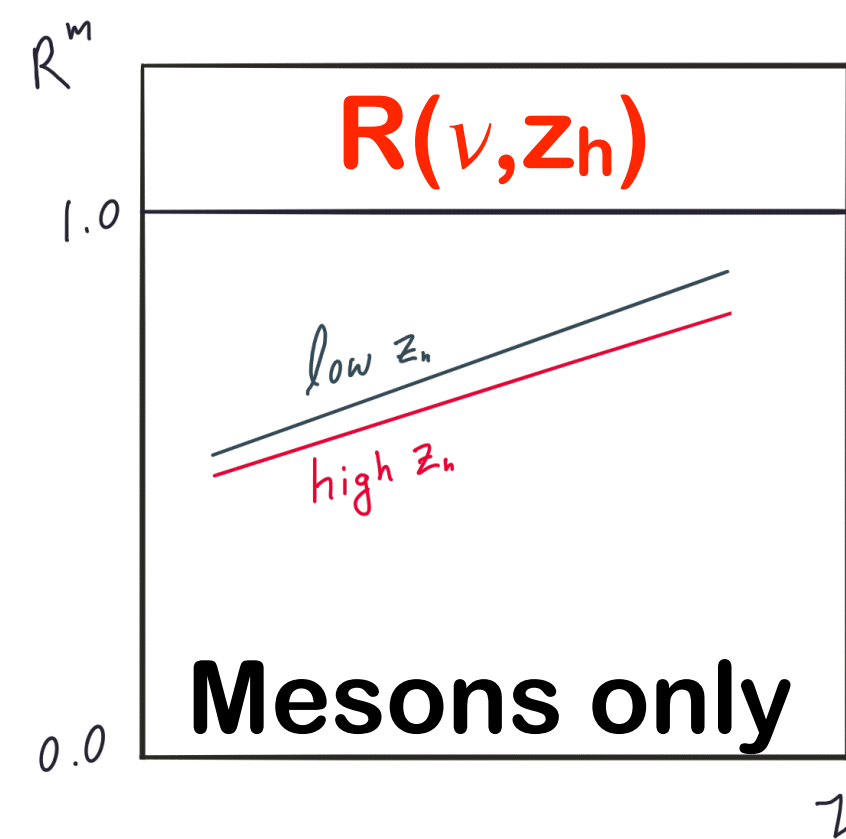
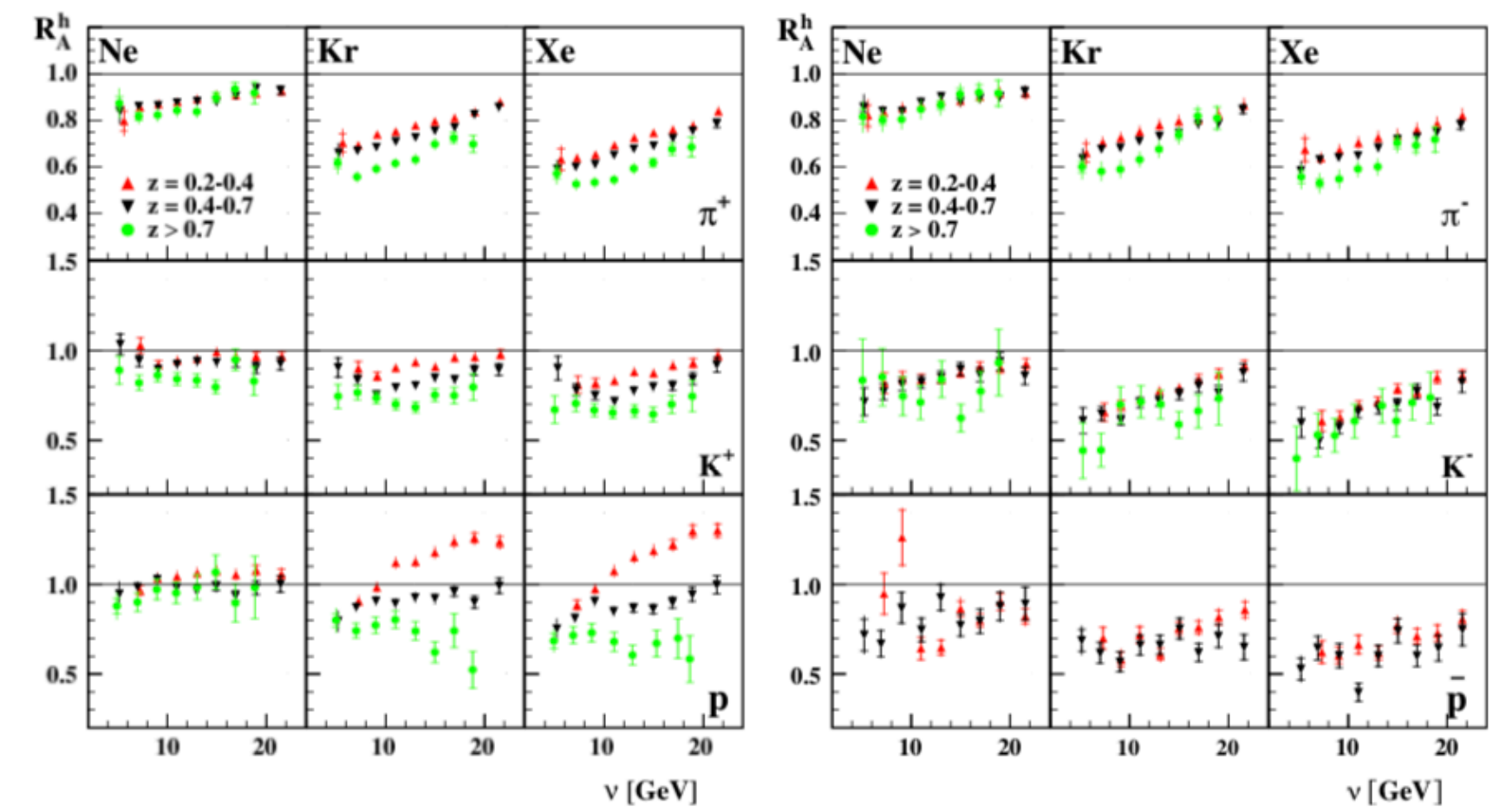
Enhancement at high p_T mostly caused by hadronic interactions at low z .



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



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



Time dilation is
proportional to ν .
Slow approach to 1.0
at infinite ν . 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

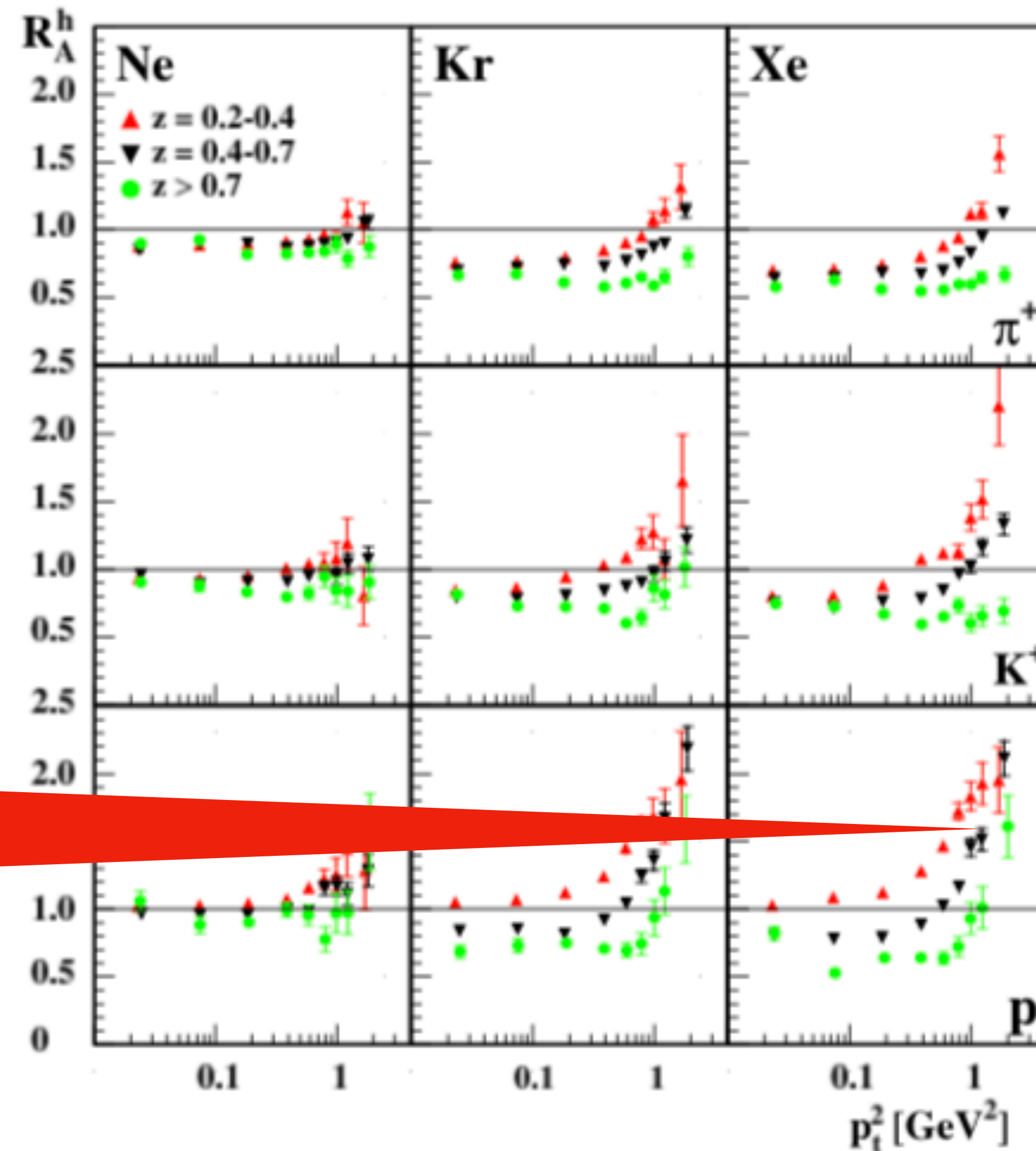
Interpreting HERMES Nuclear DIS DATA: MESONS

The multiplicity ratio measures effects of the nuclear medium.
 “No effects” means $R=1.0$

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

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

Strong interaction occurs at all values of z .

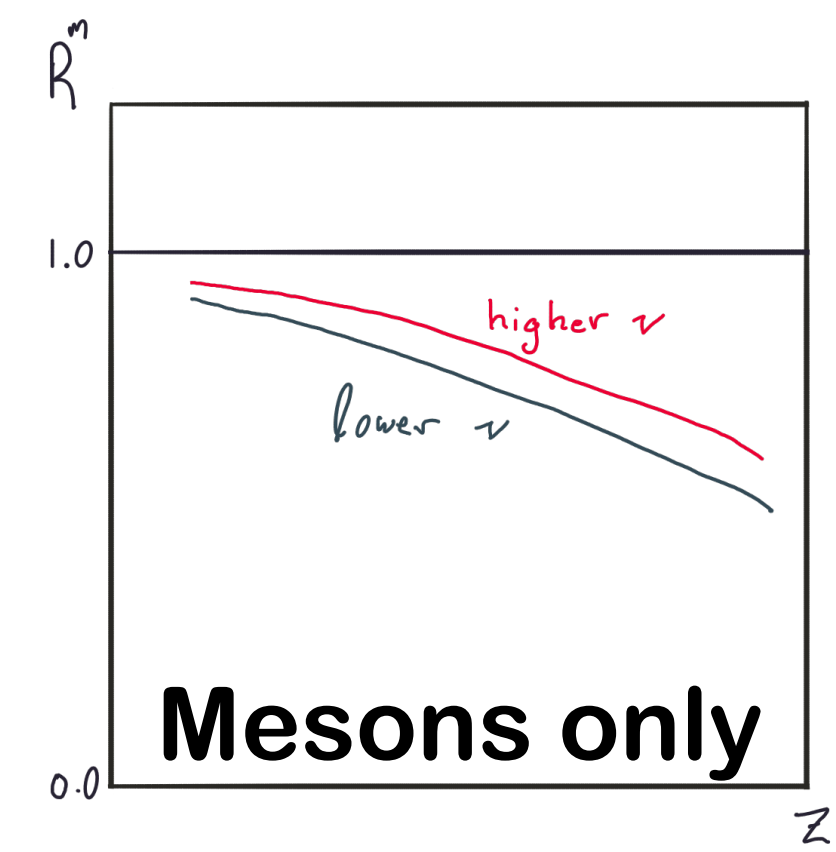
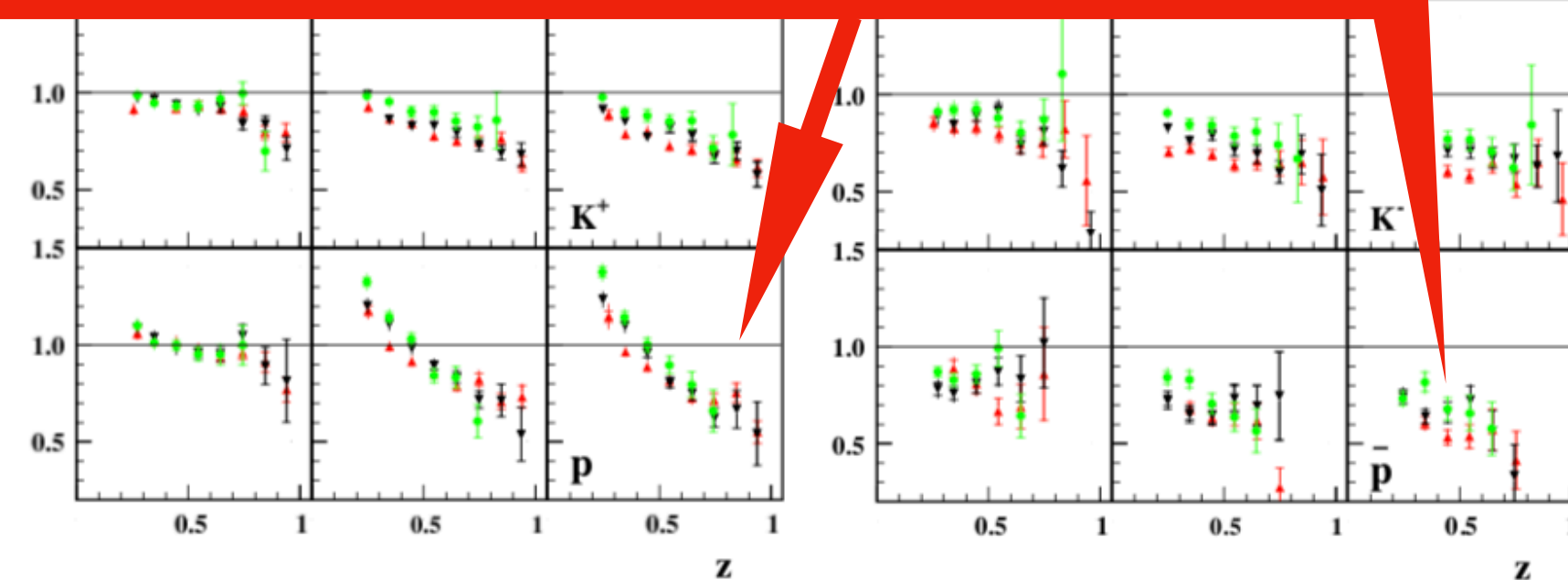


Interact hadronic interaction of forming hadrons, + quark energy loss.

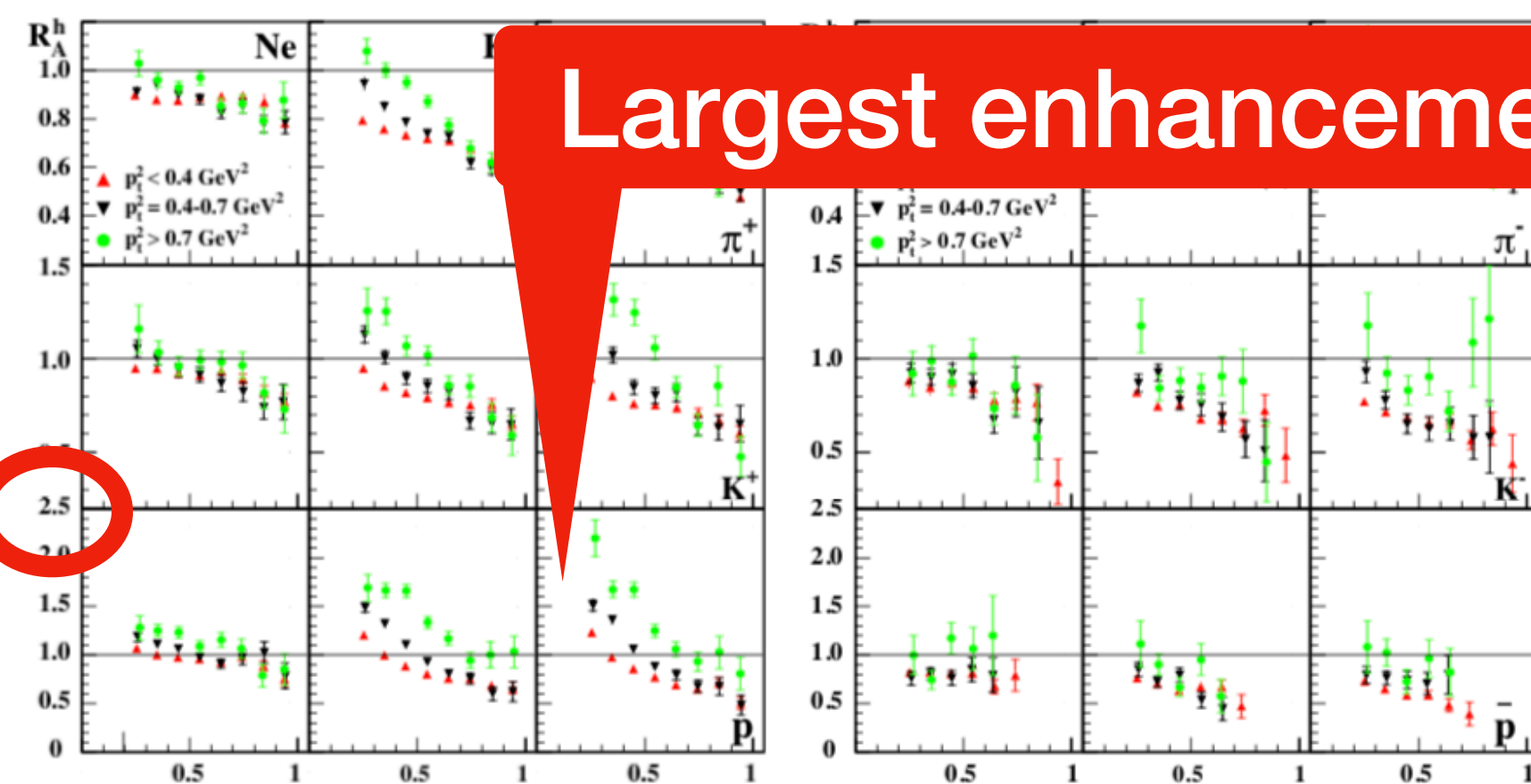
Empirically, from these plots, low- z mesons acquire more p_T than high- z .

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

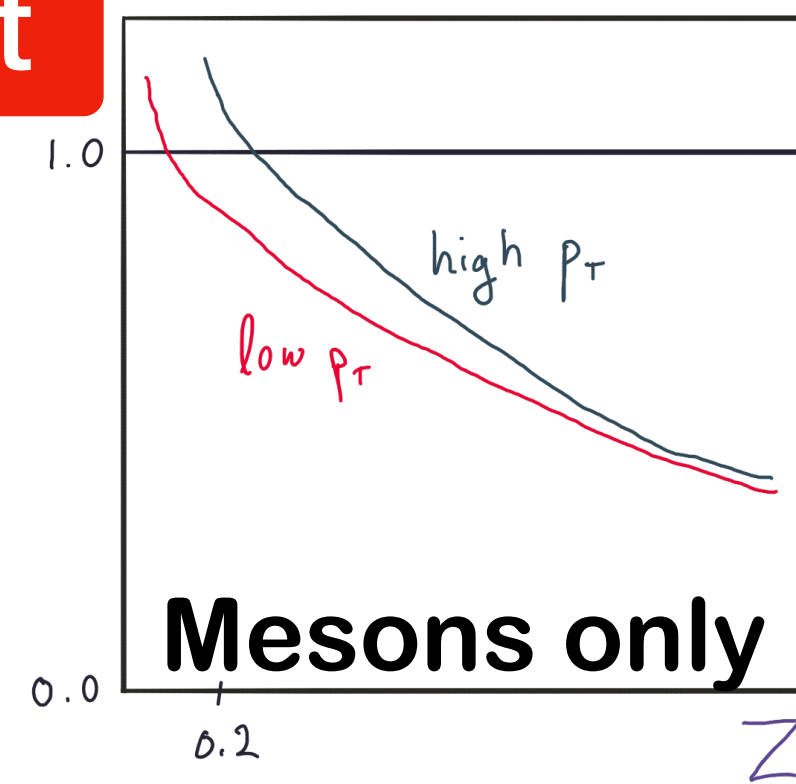
Protons and antiprotons
act completely differently



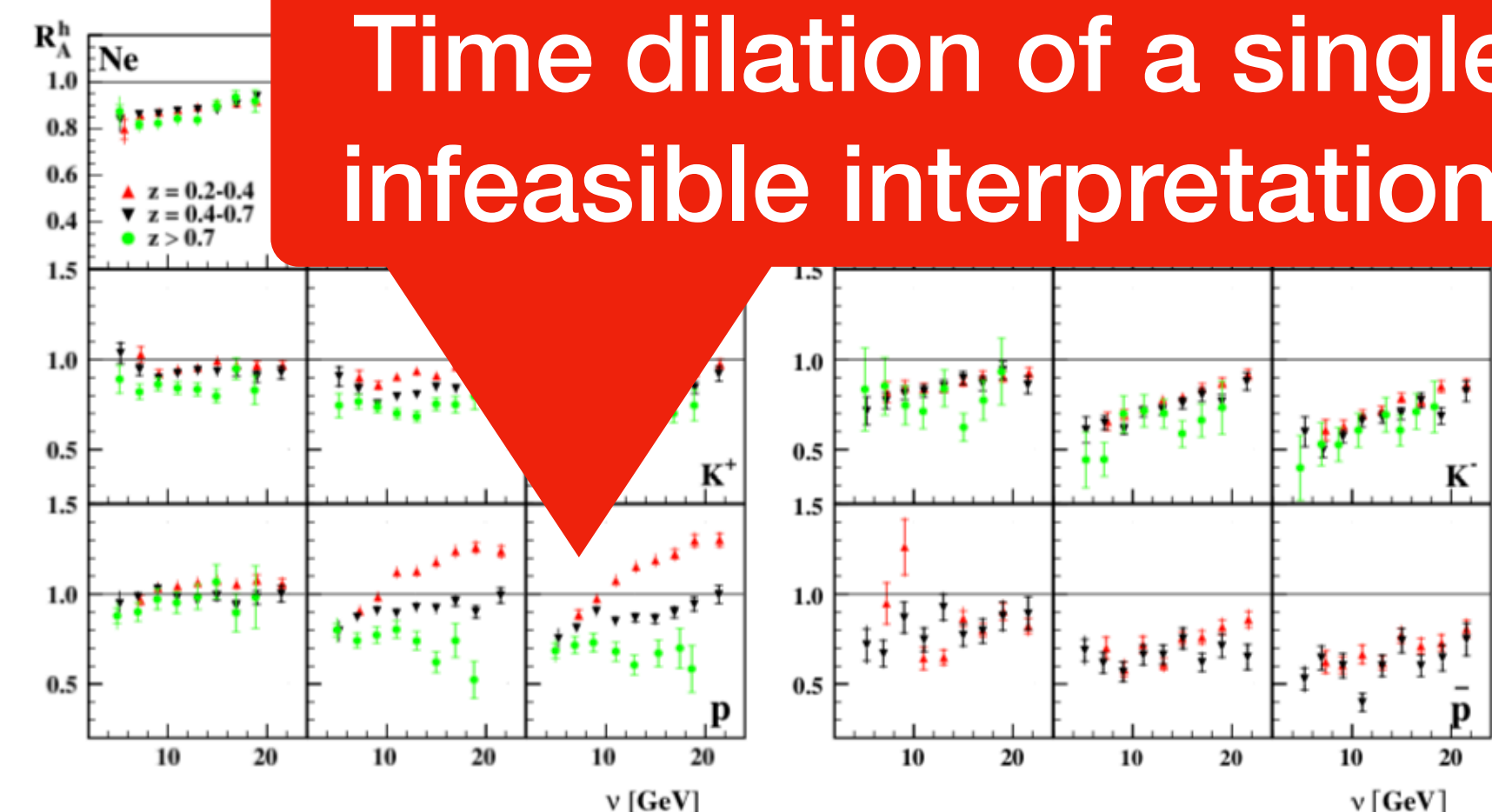
Integrated over p_T ,
so always < 1 .
At higher ν , less
attenuation because
of time dilation of
quark lifetime



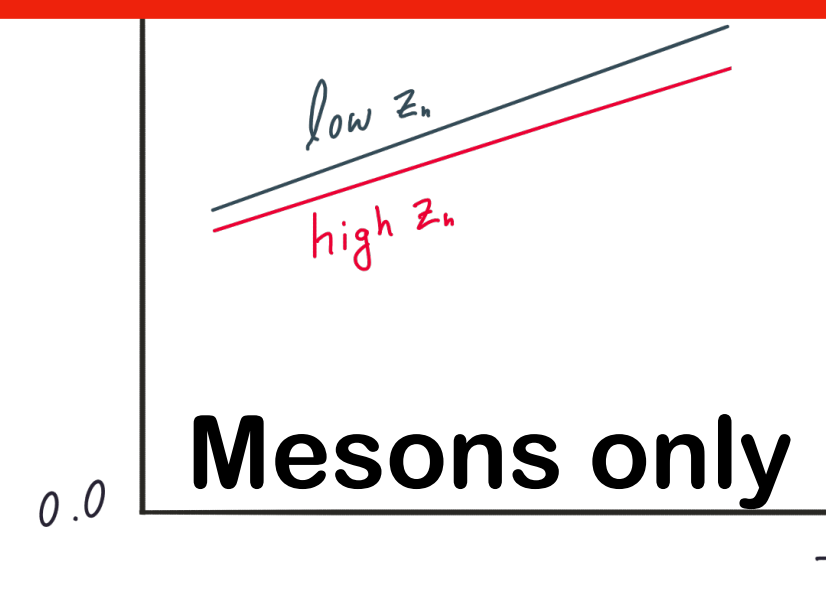
Largest enhancement



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



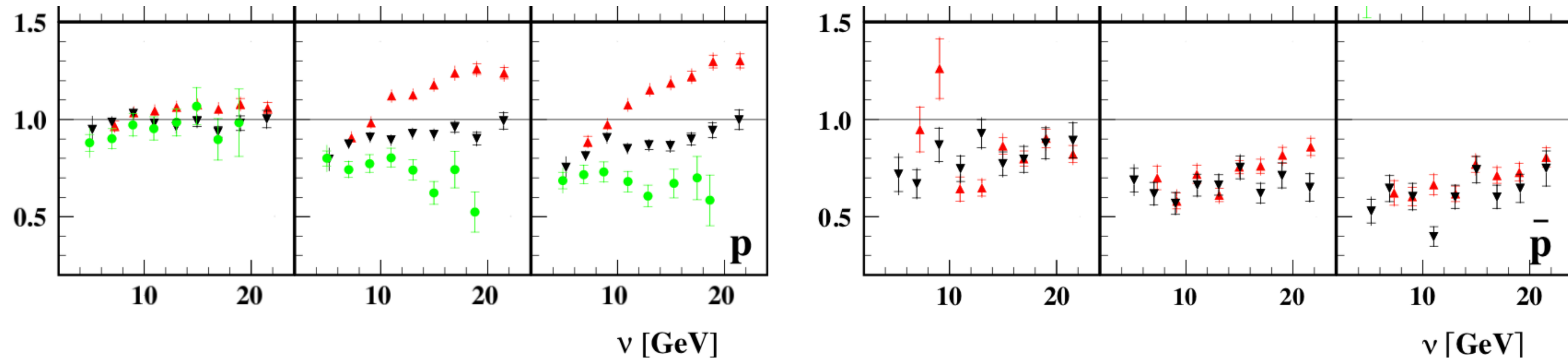
Time dilation of a single quark now an
infeasible interpretation: $R \gg 1$ at low z .



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

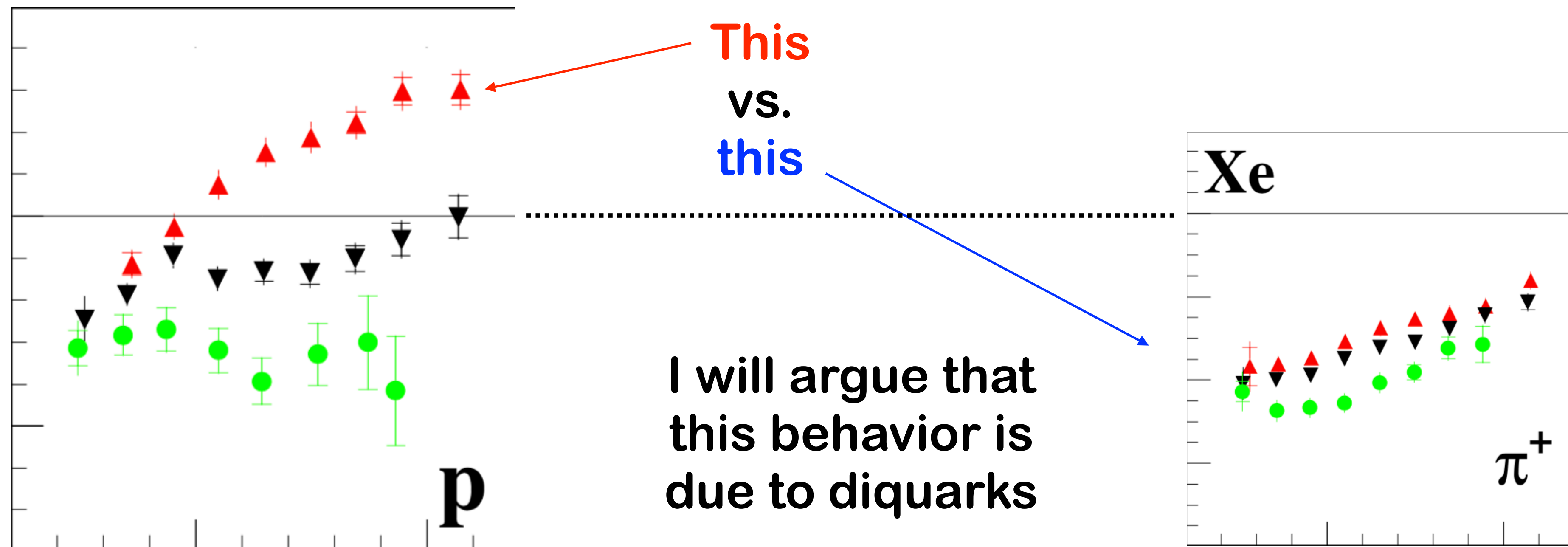
HERMES Proton Multiplicity Ratios

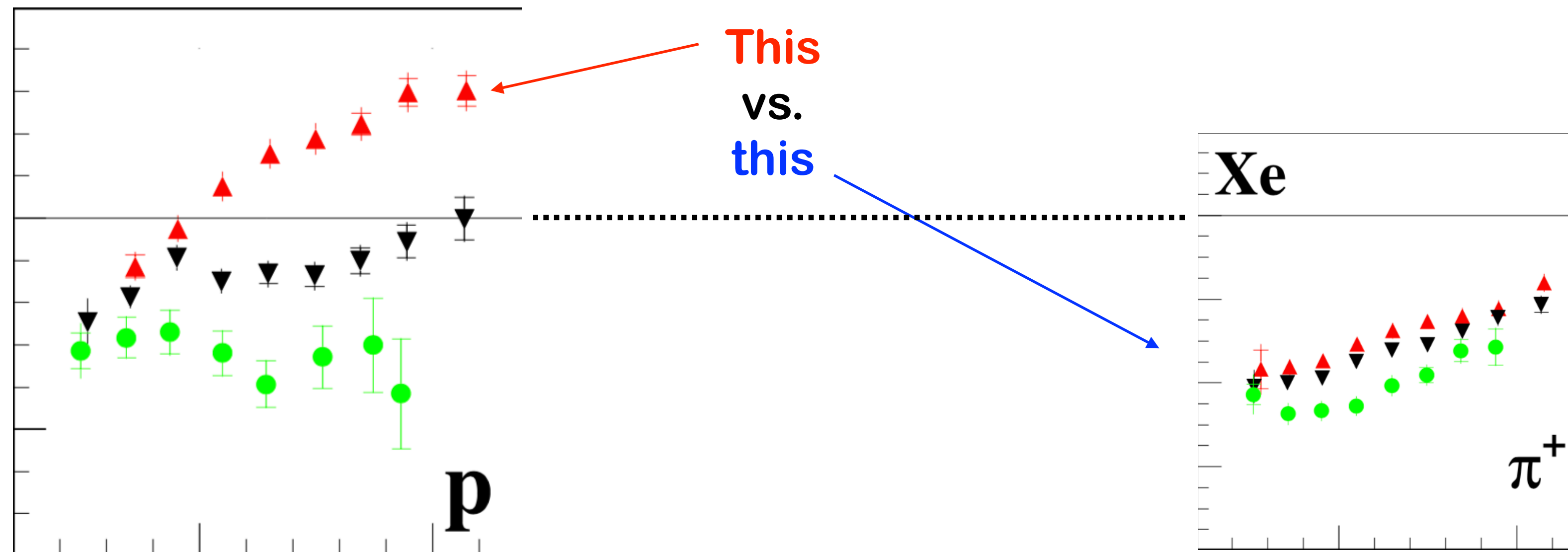
▲ $z = 0.2-0.4$
 ▼ $z = 0.4-0.7$
 ● $z > 0.7$



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

Proton multiplicity ratios qualitatively different from mesons.





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:

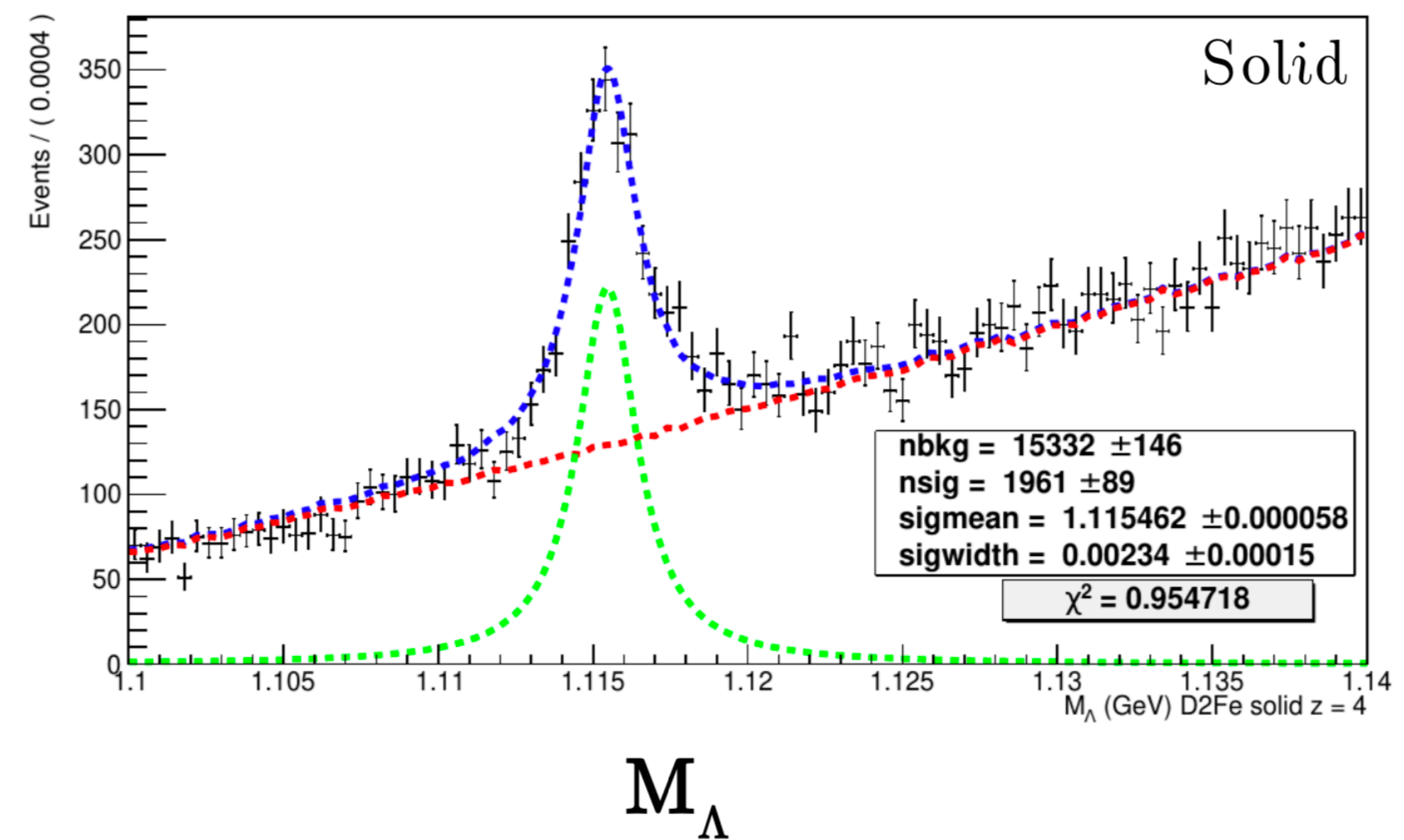
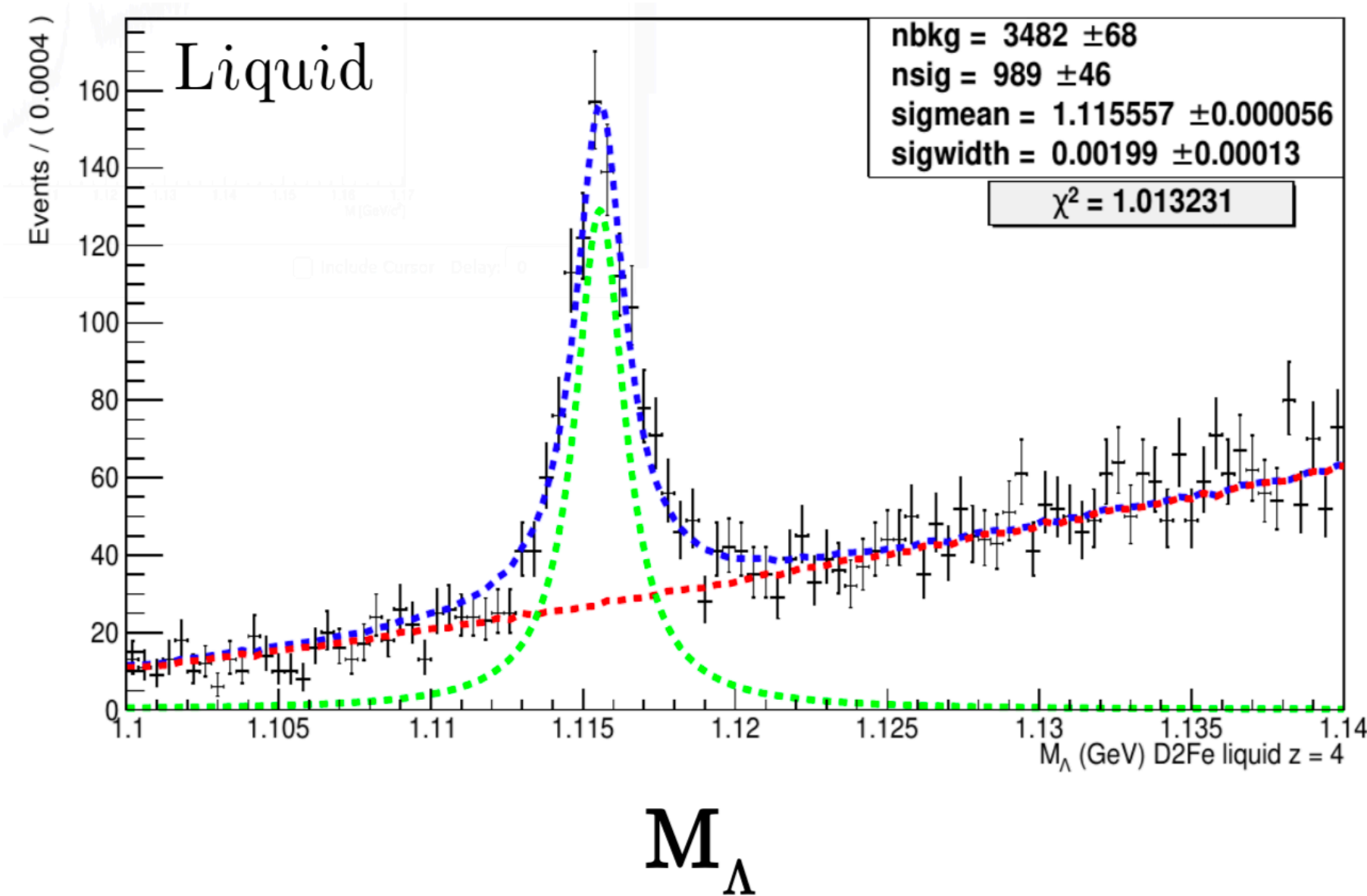
Dr. Ahmed El Alaoui

Some early work performed at ANL.

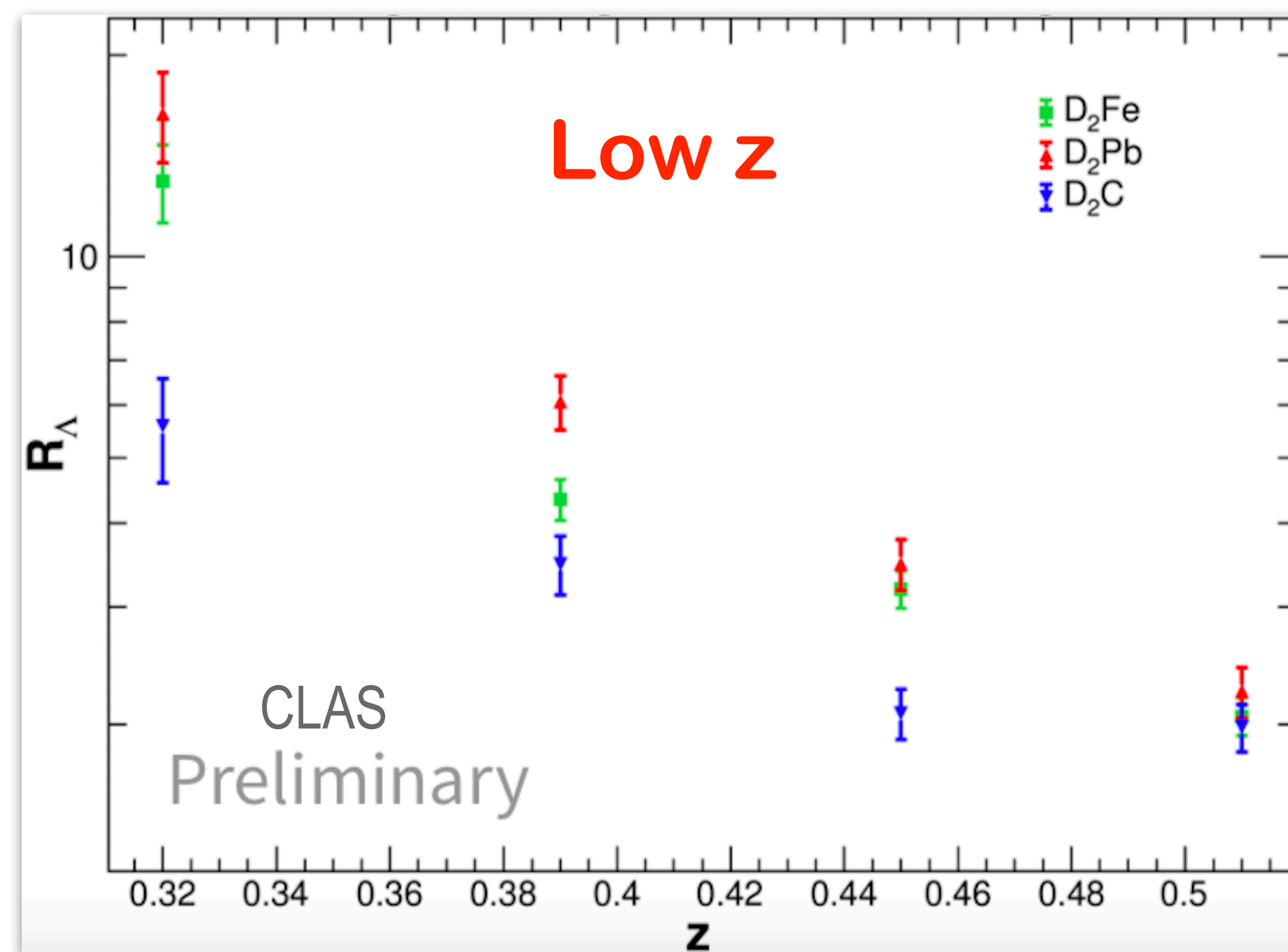
**Uncorrected preliminary results released March 2019 by Nuclear Physics
Working Group of CLAS Collaboration.**

Lambda Baryons are well-identified in π -p channel

$$z = [0.48, 0.54)$$



Backgrounds are under control - three different extraction methods agree

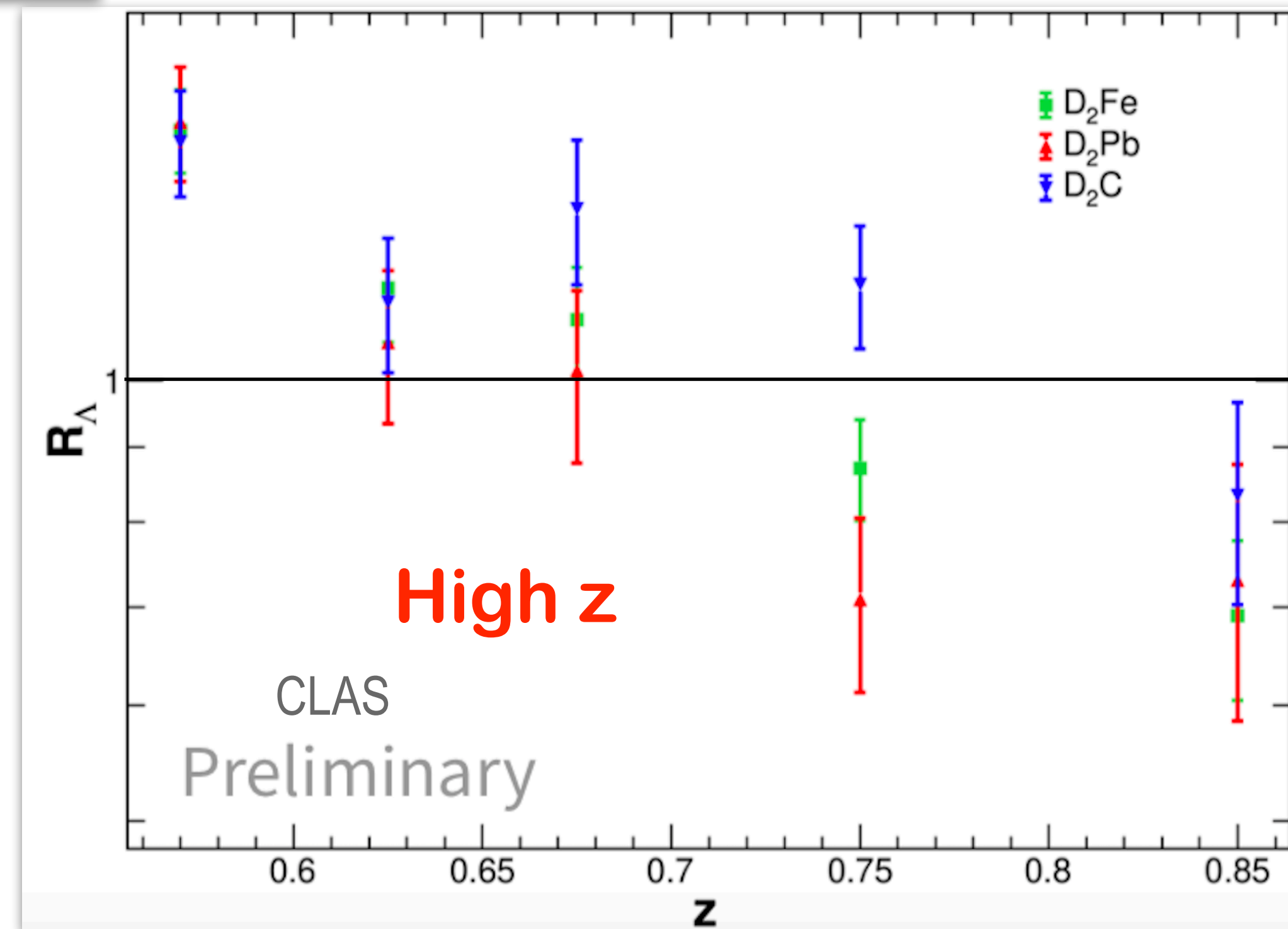


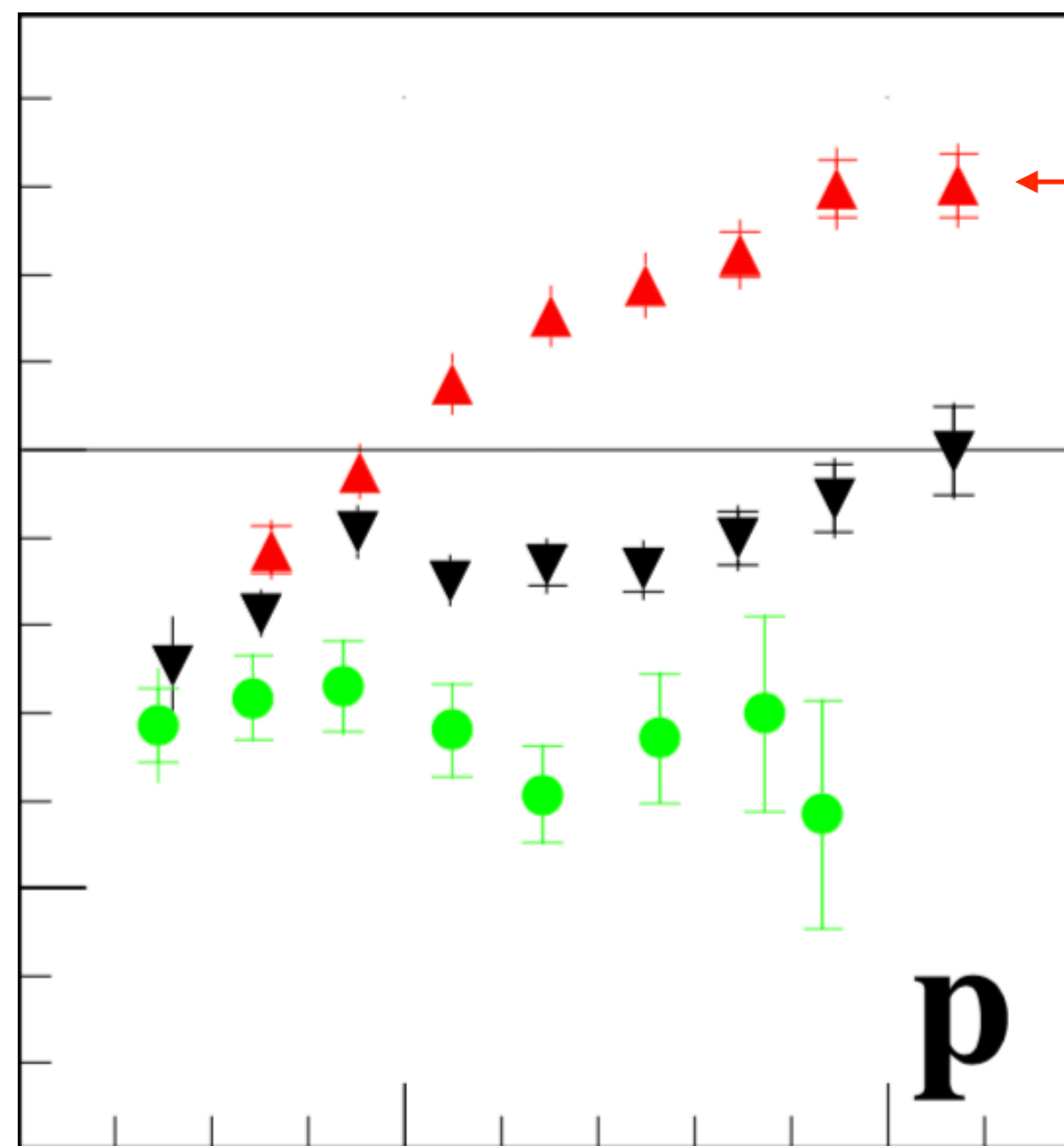
“Pile-up” of events at low z -
huge effect compared to pion
production

Order inverted as expected:
heavy-to-light

At higher z , there is
relatively little
attenuation.

Order as expected:
light-to-heavy





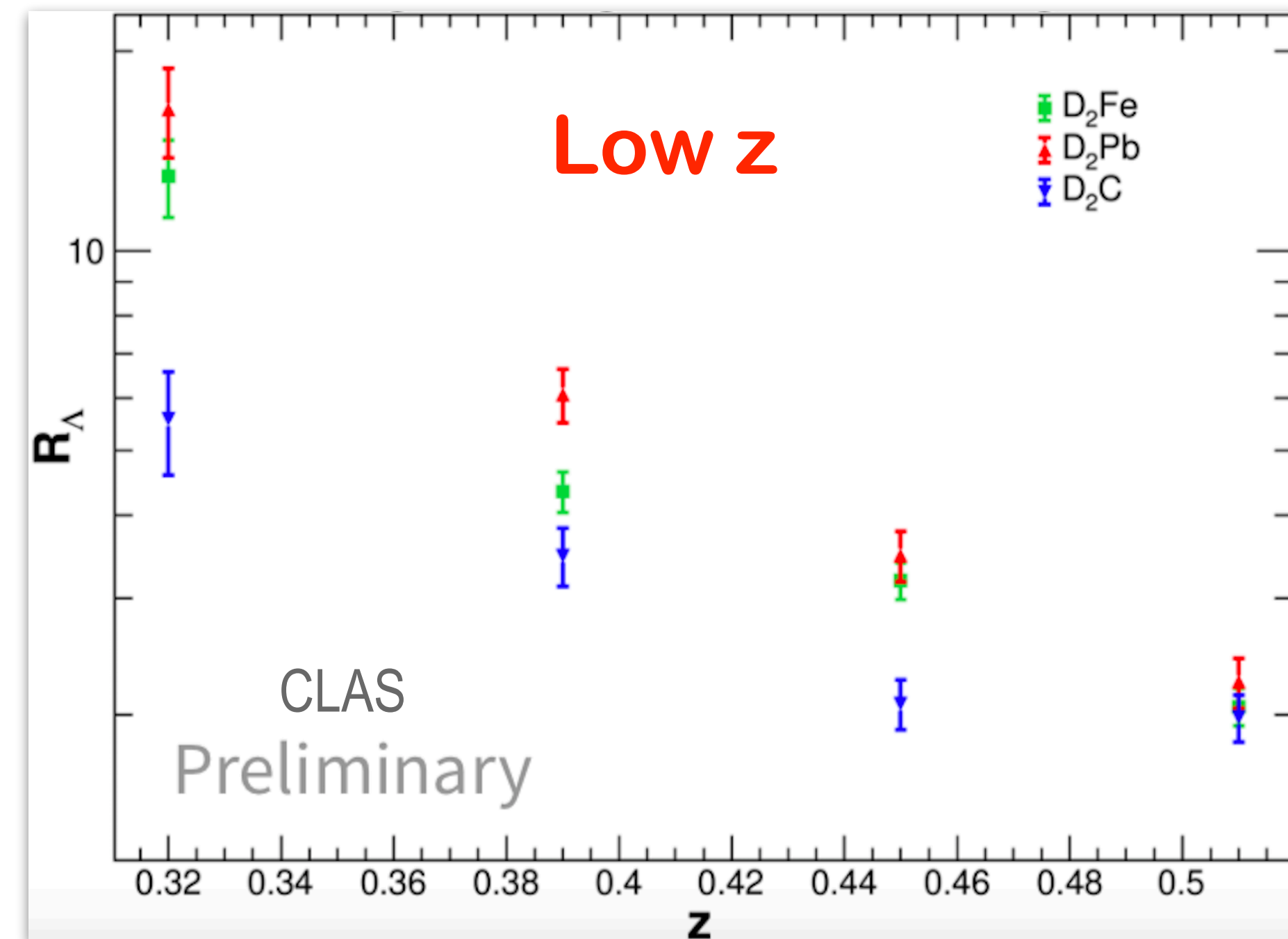
Excess of low- z protons in
HERMES data

Explanation: FSI are
“knocking out protons”??

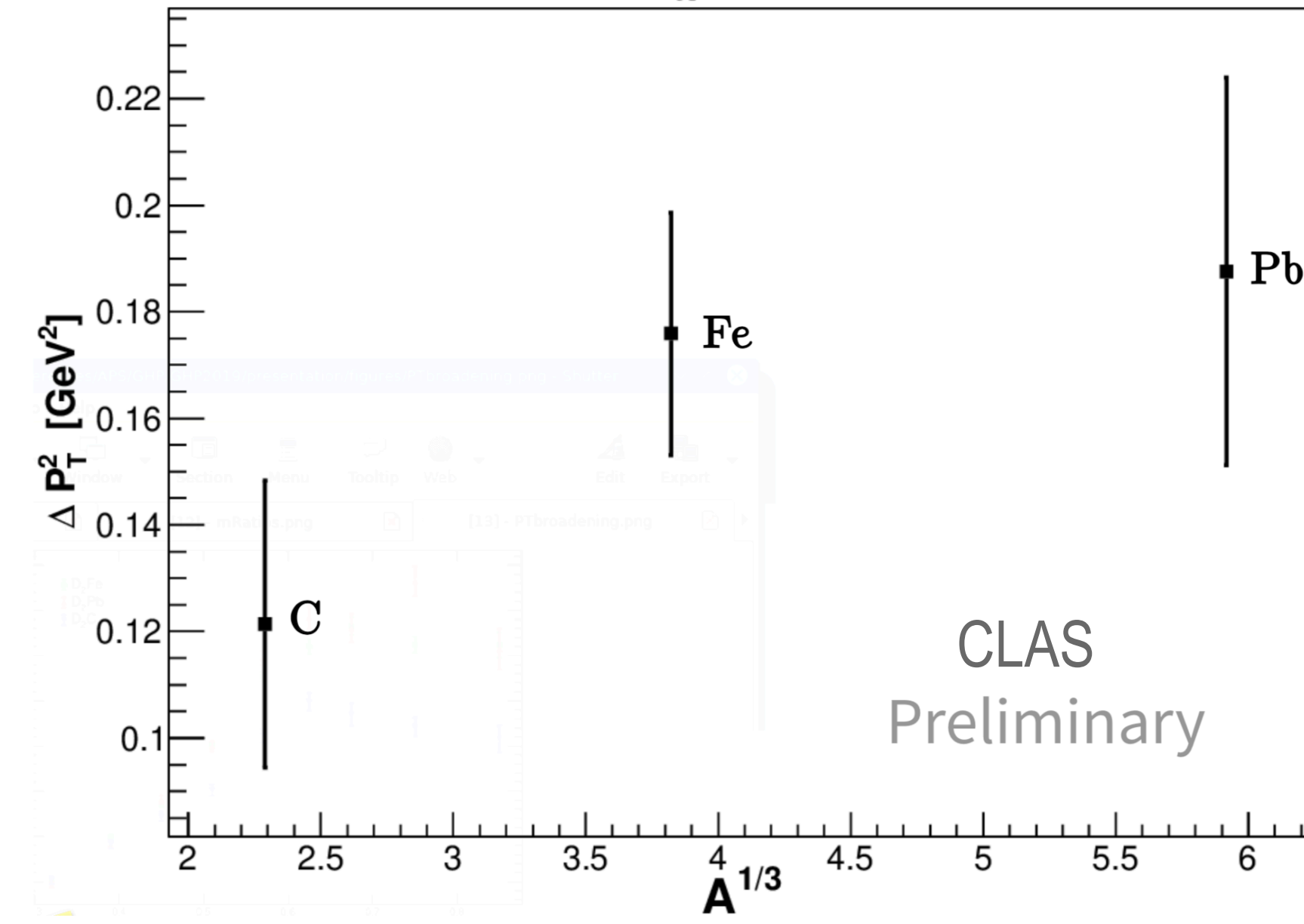
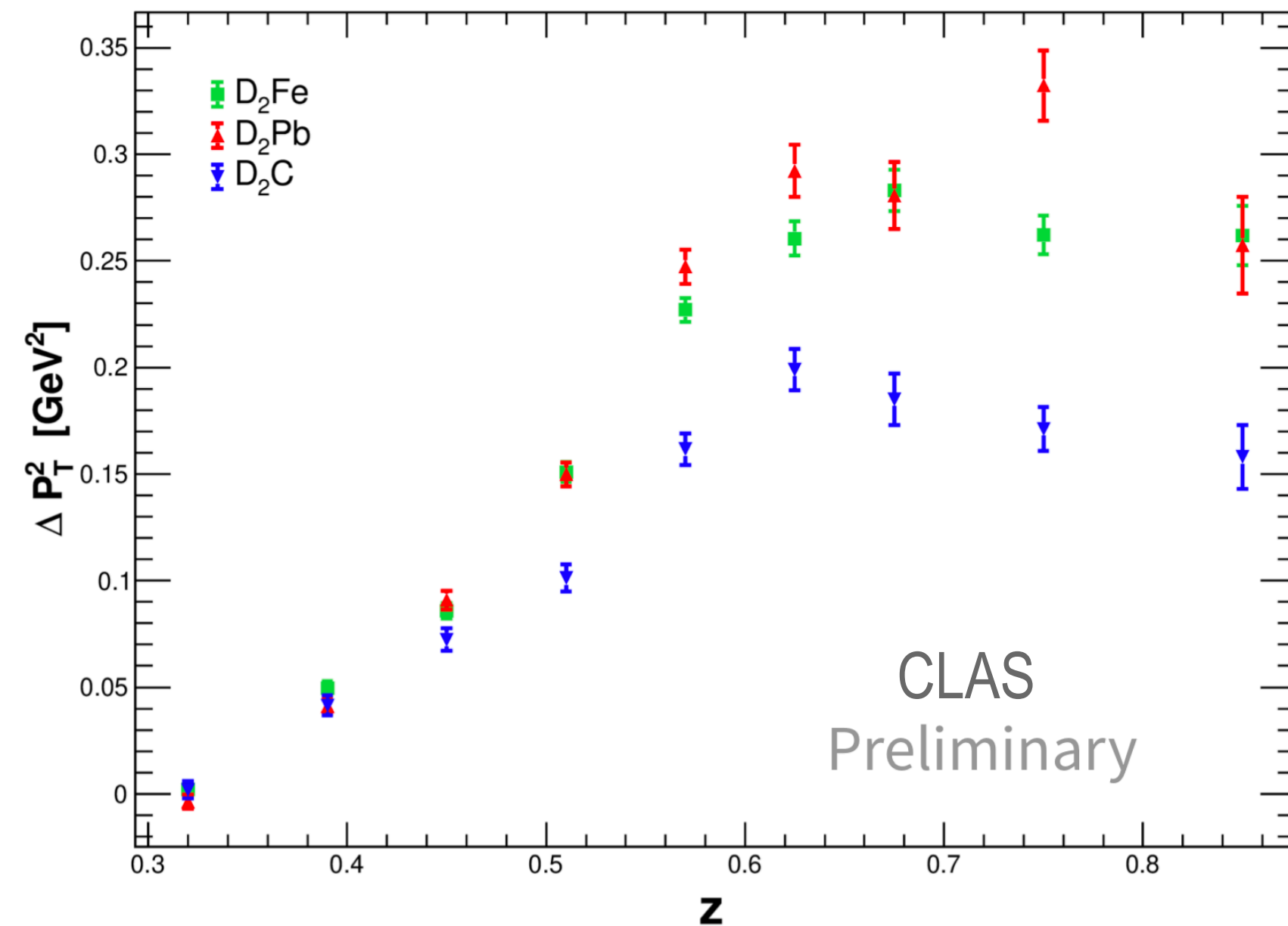
Excess of low- z Lambdas in
CLAS data

Not explained by FSI
“knocking out Lambdas”!!

I have a better explanation



Transverse Momentum Broadening is **Large**



Maximum is 0.3 GeV²

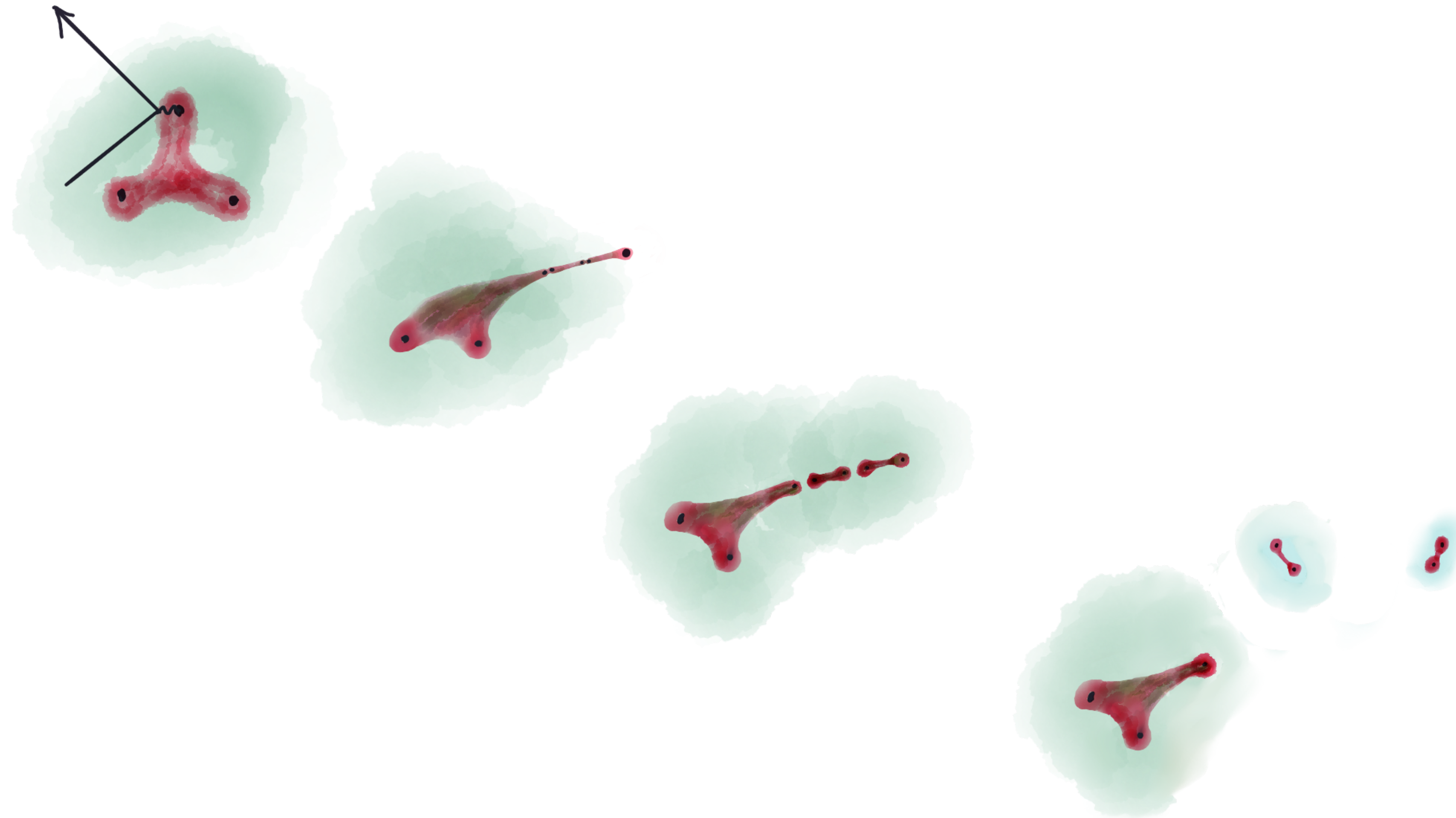
Compare to maximum for pions of 0.03 GeV²!

The **object** passing through the medium is disruptive!
E.g., it is “large” (has an extended color field).

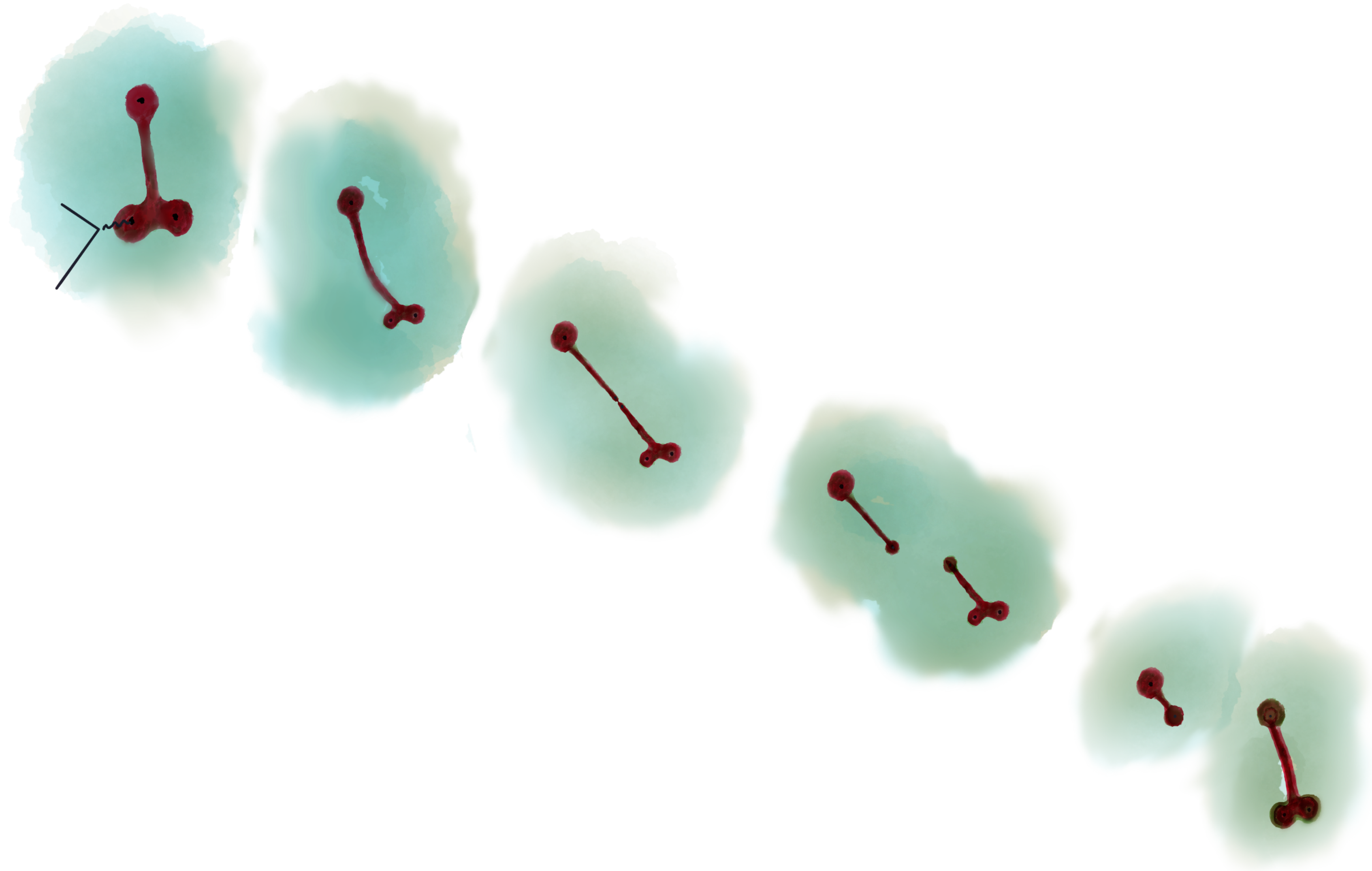
Could it be possible that the **virtual photon is absorbed by a diquark?**

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

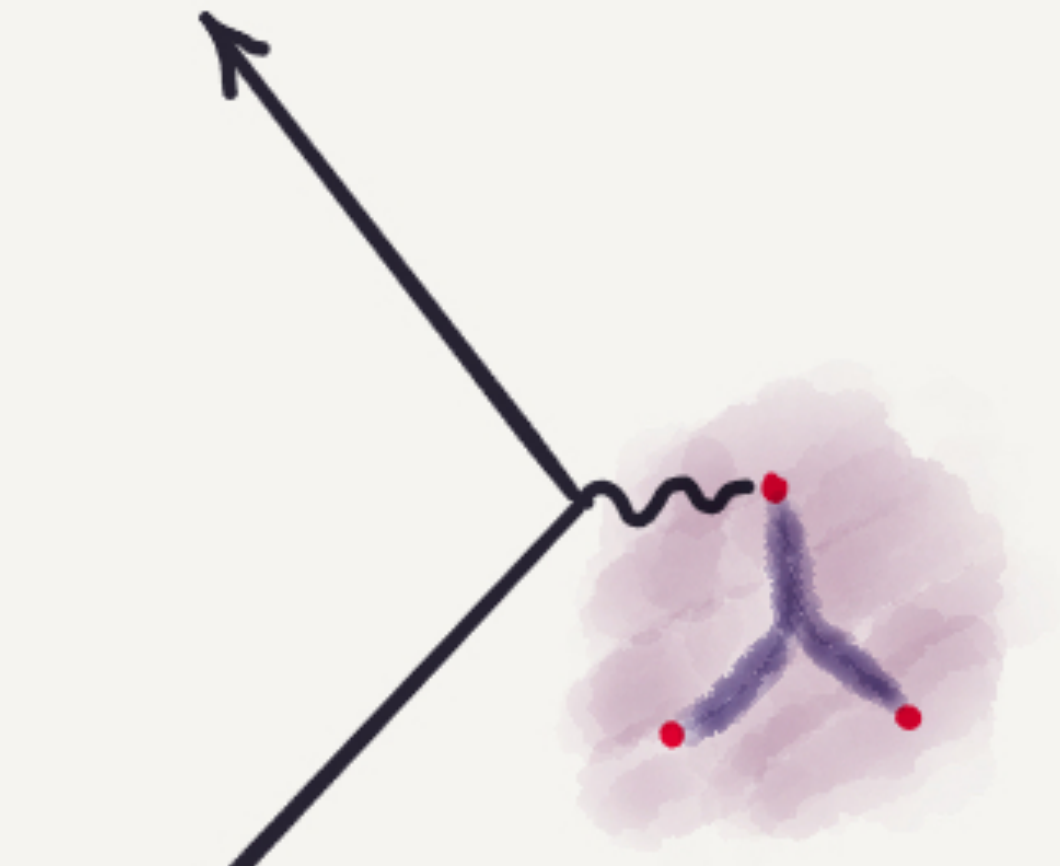


This DDS mechanism makes it a lot easier to form a proton. Making a proton in the Lund String Model is famously problematic.

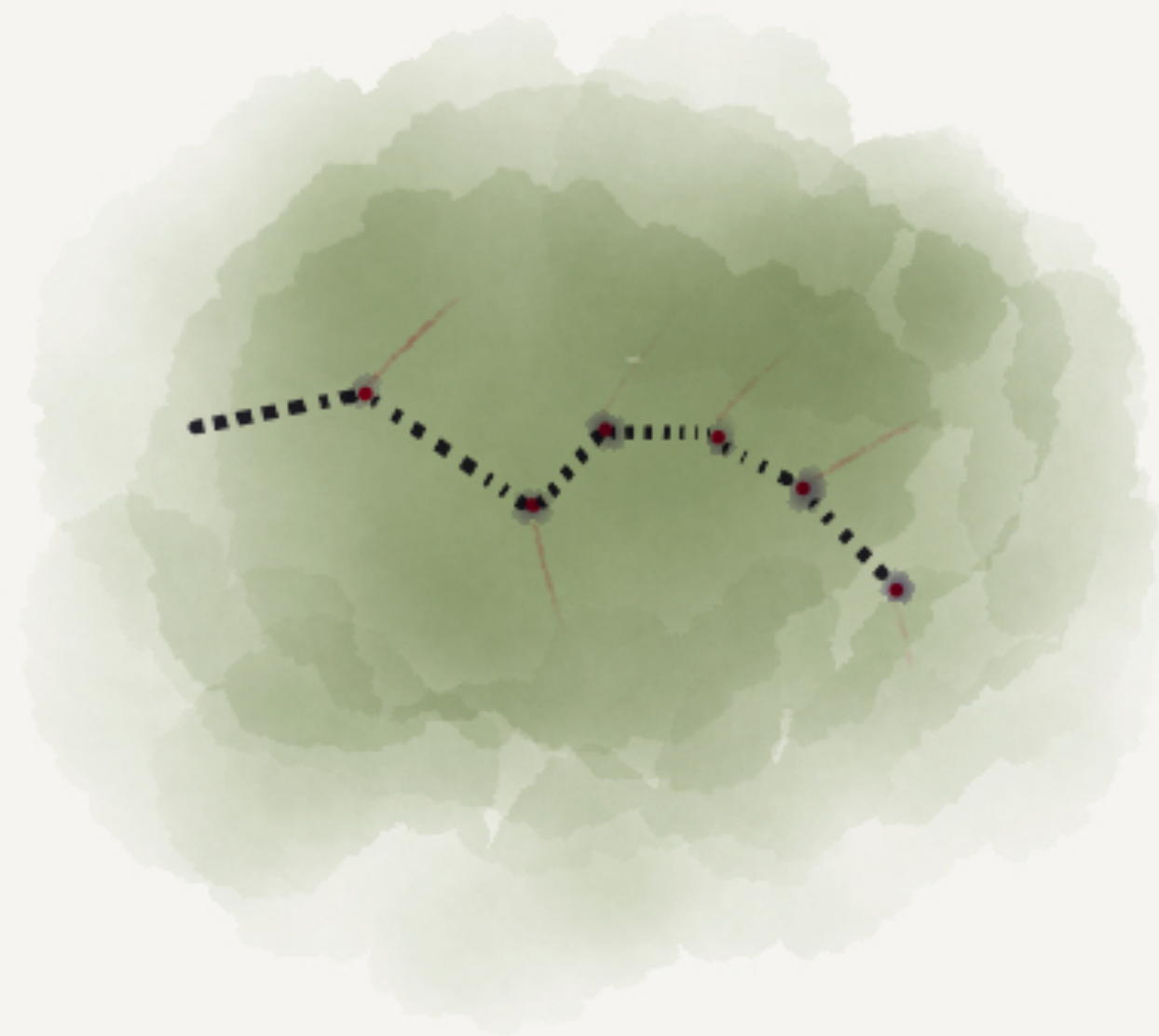
With nDIS baryon production, we will be able to gather a lot of evidence to test this idea.

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

The p_T 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.

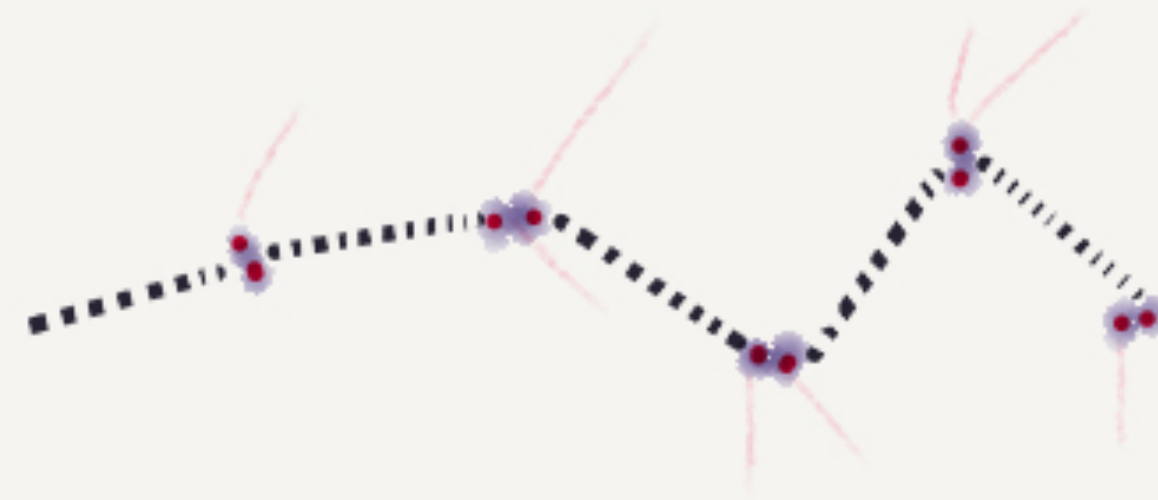
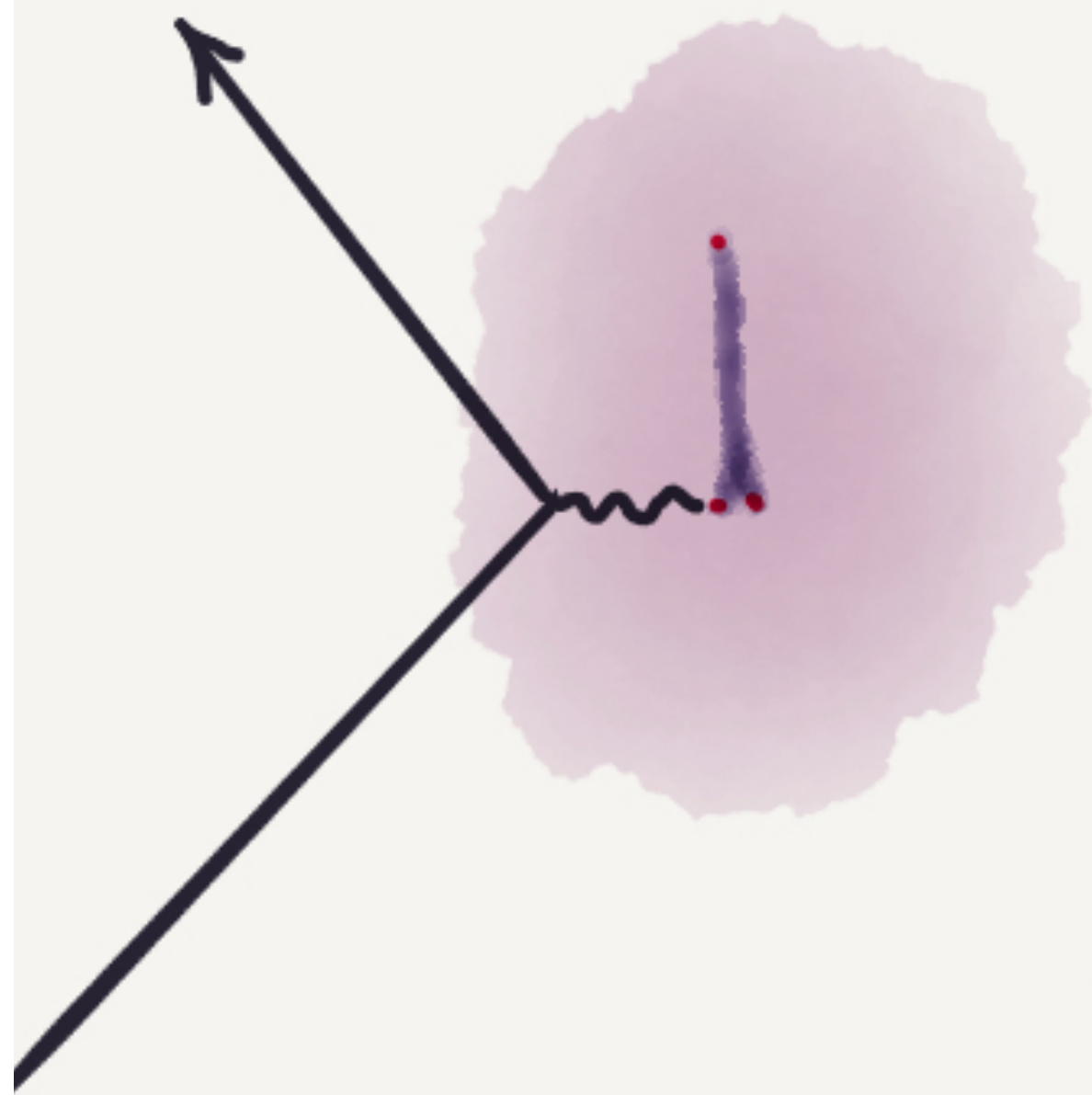


in vacuum

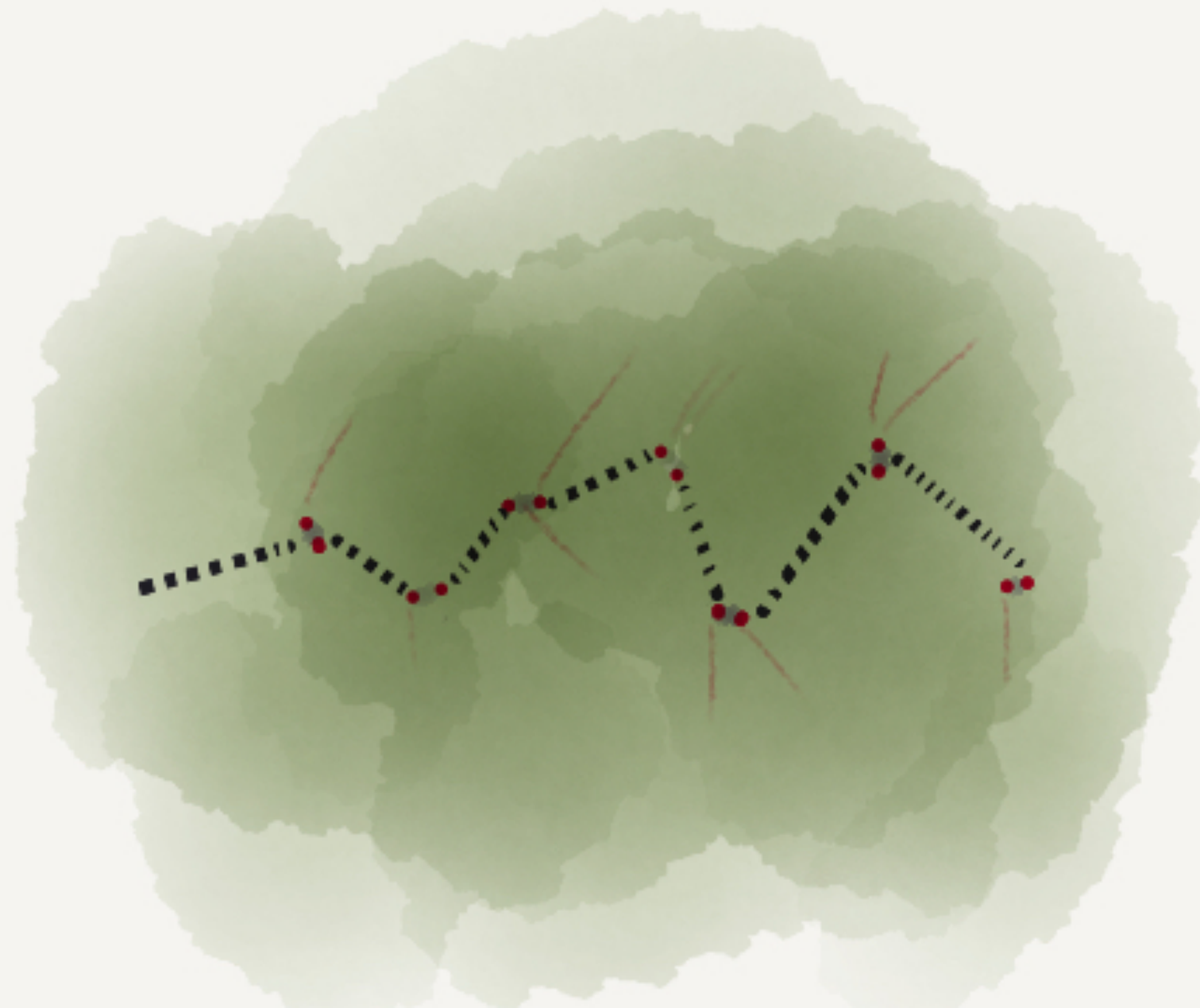


in medium

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



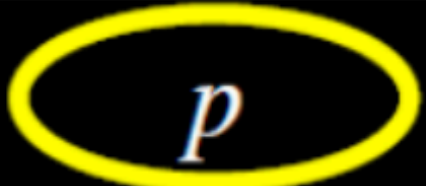
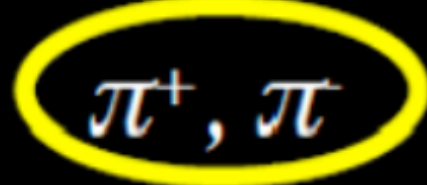
in vacuum



in medium

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

 **Actively underway with existing 5 GeV data**

<i>meson</i>	$c\tau$	mass	flavor content	<i>baryon</i>	$c\tau$	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	$\bar{u}\bar{d}$
 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
f_1	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	$\bar{u}s, \bar{u}\bar{s}$	Ξ^-	49 mm	1.3	ds

Baryon	$M^{e/l}$	M^{CI}	s^{r1}	s^{r2}	a_1^{r2}	a_2^{r2}	a_1^{r3}	a_2^{r3}	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.**

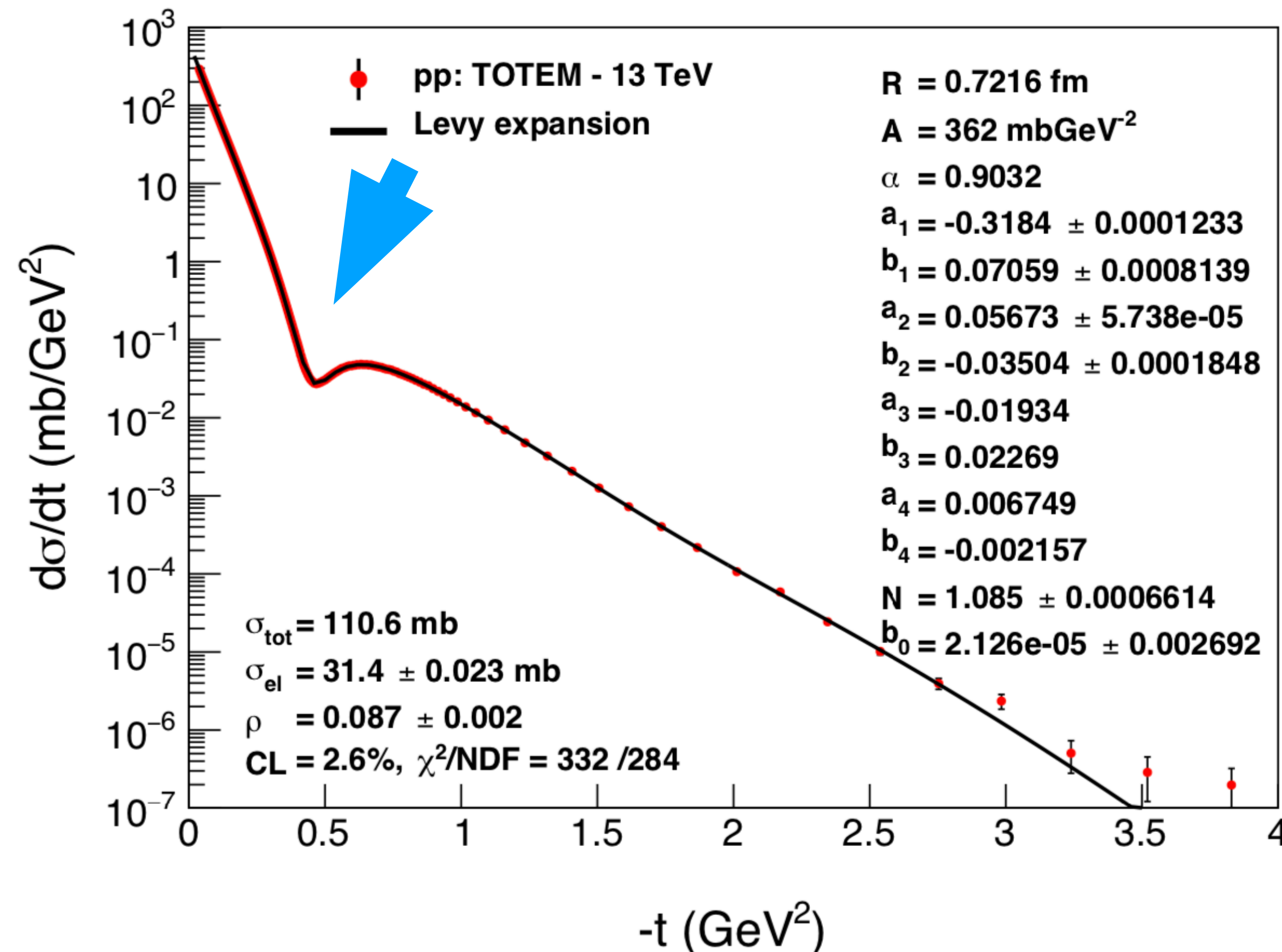
**Only p, n, lambda can
easily be formed
by DDS.**

**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

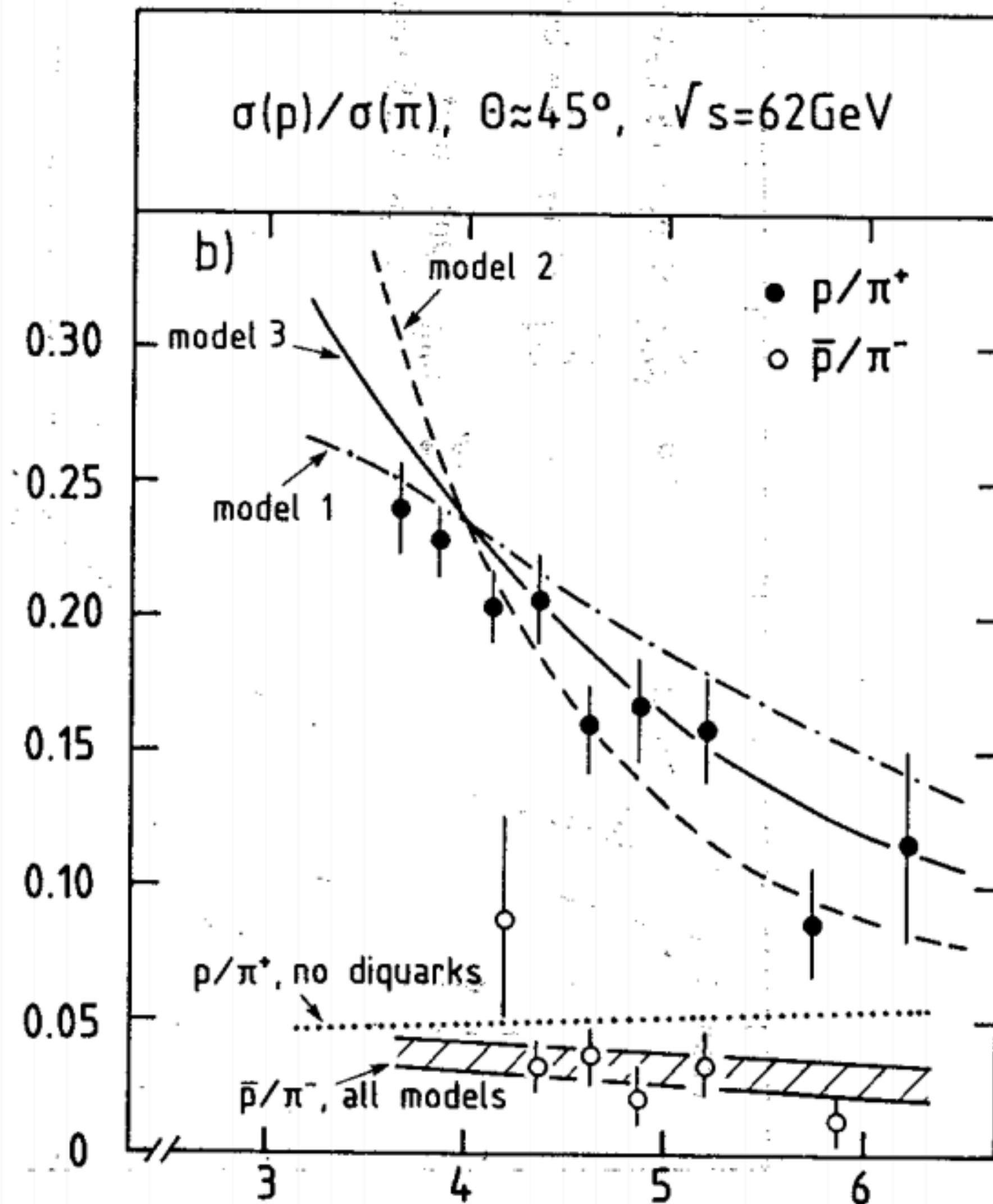
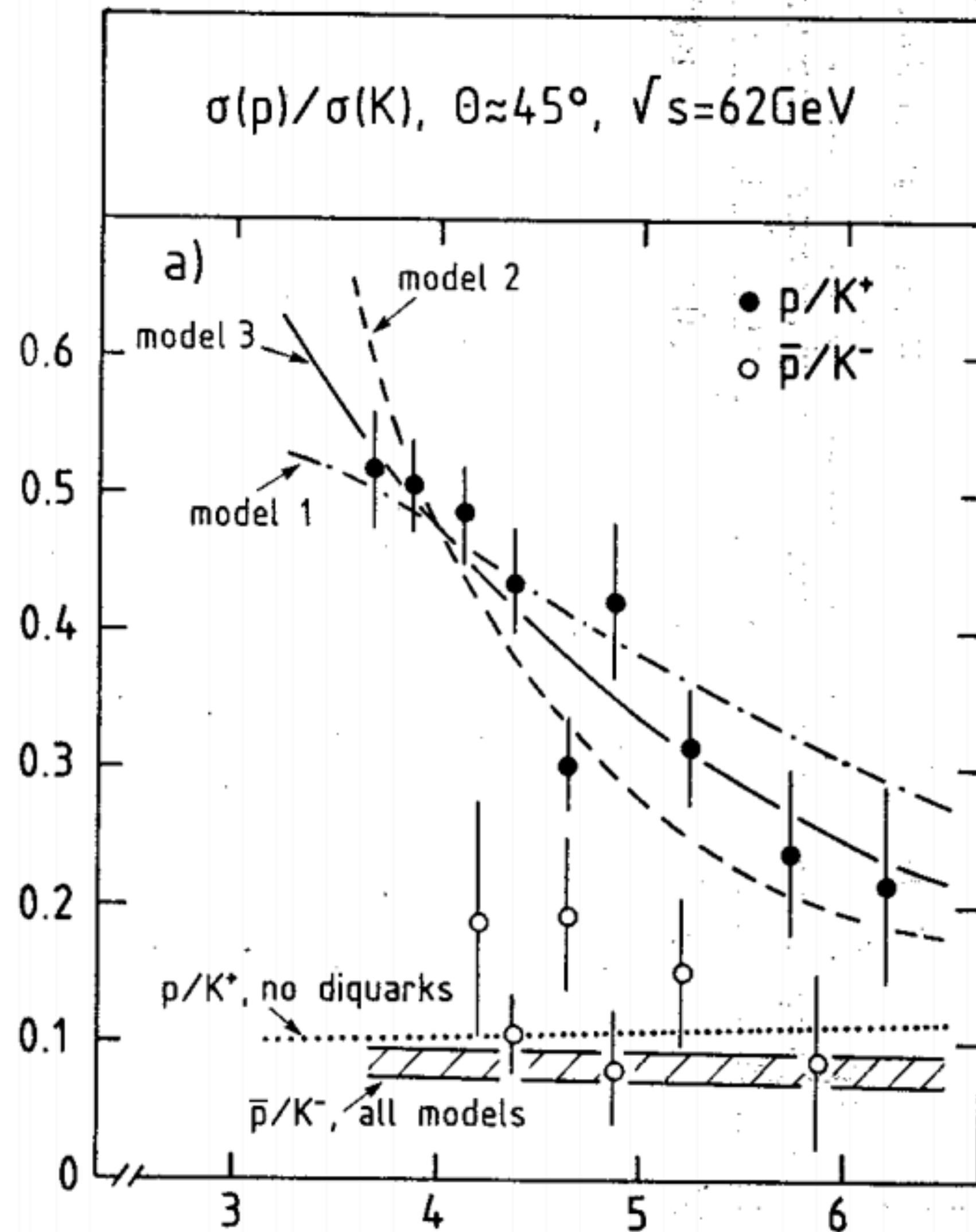
A DIQUARK SCATTERING MODEL FOR HIGH p_T PROTON PRODUCTION IN pp
COLLISIONS AT THE ISR

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

A. Breakstone¹⁽⁺⁾, H.B. Crawley¹, G.M. Dallavalle⁵, K. Doroba⁶, D. Drijard³,
F. Fabbri³, A. Firestone¹, H.G. Fischer³, H. Frehse^{3(*)}, W. Geist^{3(**)},
G. Giacomelli², R. Gokieli⁶, M. Gorbics¹, P. Hanke⁵, M. Heiden^{3(**)},
W. Herr⁵, E.E. Kluge⁵, J.W. Lamsa¹, T. Lohse⁴, R. Mankel⁴, W.T. Meyer¹,
T. Nakada^{3(***)}, M. Panter³, A. Putzer⁵, K. Rauschnabel⁴, B. Rensch⁵,
F. Rimondi², M. Schmelling⁴, G. Siroli², R. Sosnowski⁶, M. Szczekowski³,
O. Ullaland³ and D. Wegener⁴

Breakstone et al.

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



p_T [GeV/c]

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

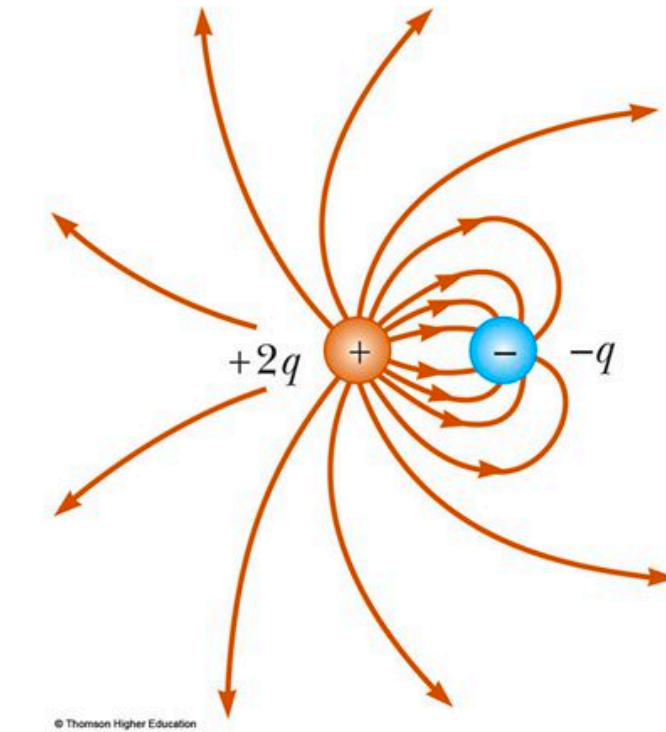
- What about “slingshot” mechanism?
- Hard to reach high z with that. We clearly see large p_T broadening up to high z .

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 .