

Hadronization in nuclei: what does *baryon production* tell us?

Multiplicity ratios and transverse-momentum broadening of identified hadrons

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SAPHIR

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CCTVal CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO

The nucleus provides a *space-time filter*

Hard interaction → *color* propagation → hadron formation

$$e + A \rightarrow e' + h + X$$

Changing A, *kinematics*, and *hadron species* changes which part of the hadronization process occurs inside the atomic nucleus.

Two complementary nuclear observables

$$R_M^h = \frac{(N_h/N_e)_A}{(N_h/N_e)_D}$$

attenuation / enhancement / redistribution

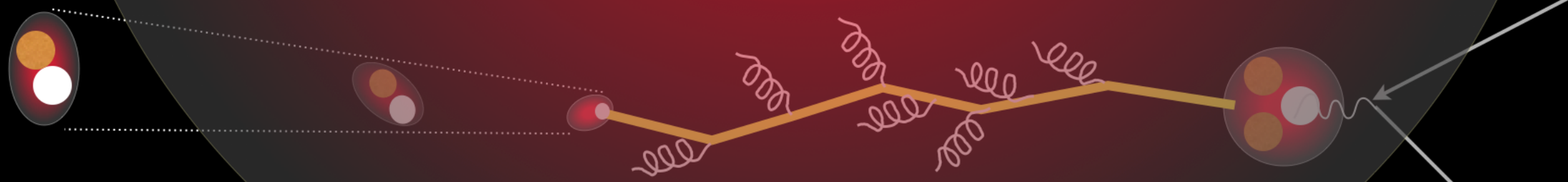
$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

transverse interactions during propagation

$$z_h = \frac{E_h}{\nu}$$

fractional hadron energy relative to the virtual-photon energy

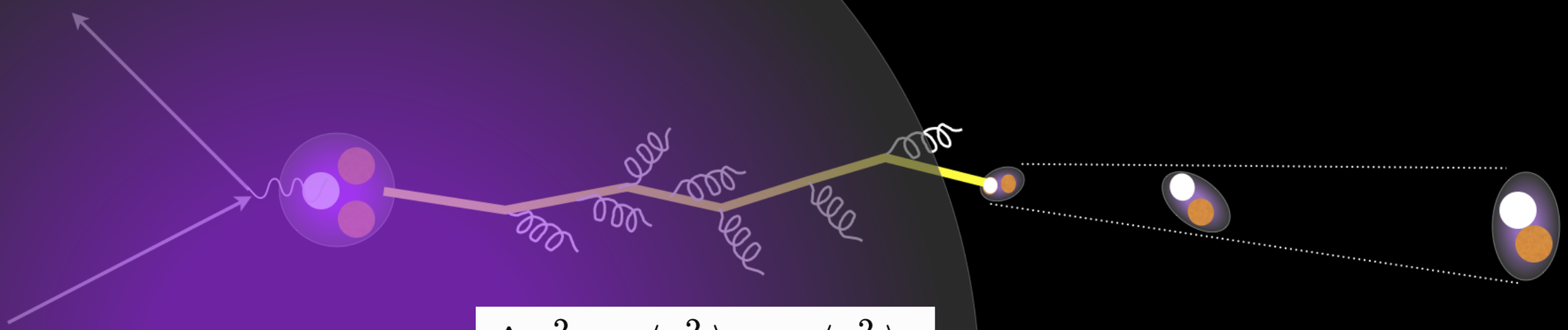
$$\gamma^* + A \rightarrow \textit{colored system} + X$$



$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

What produces transverse-momentum broadening?

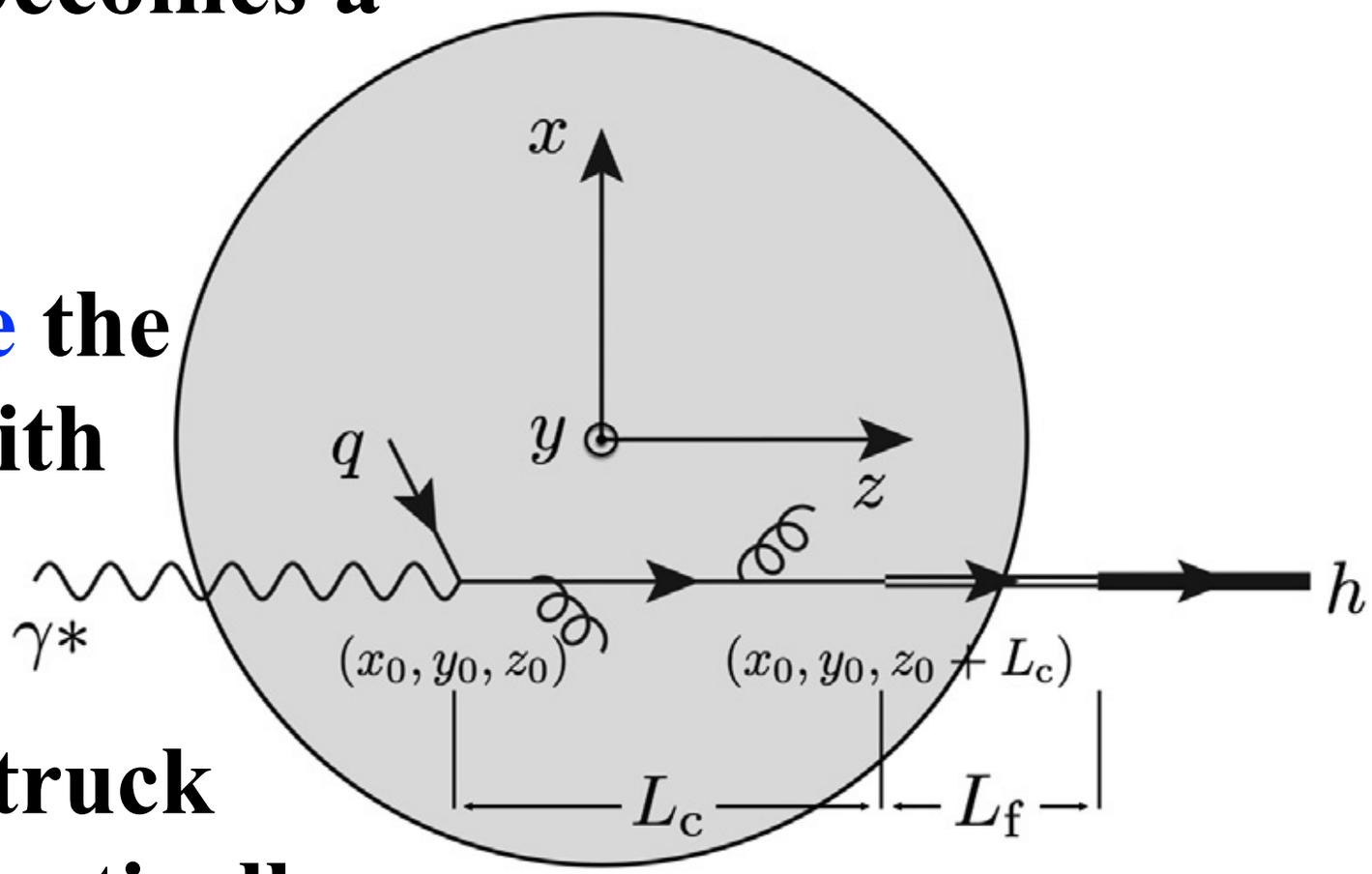
More colored path ⇒ more broadening



$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

How to understand the hadronization observables for pion SIDIS

Struck quark moves a distance L_c as a colored object, then becomes a hadron.

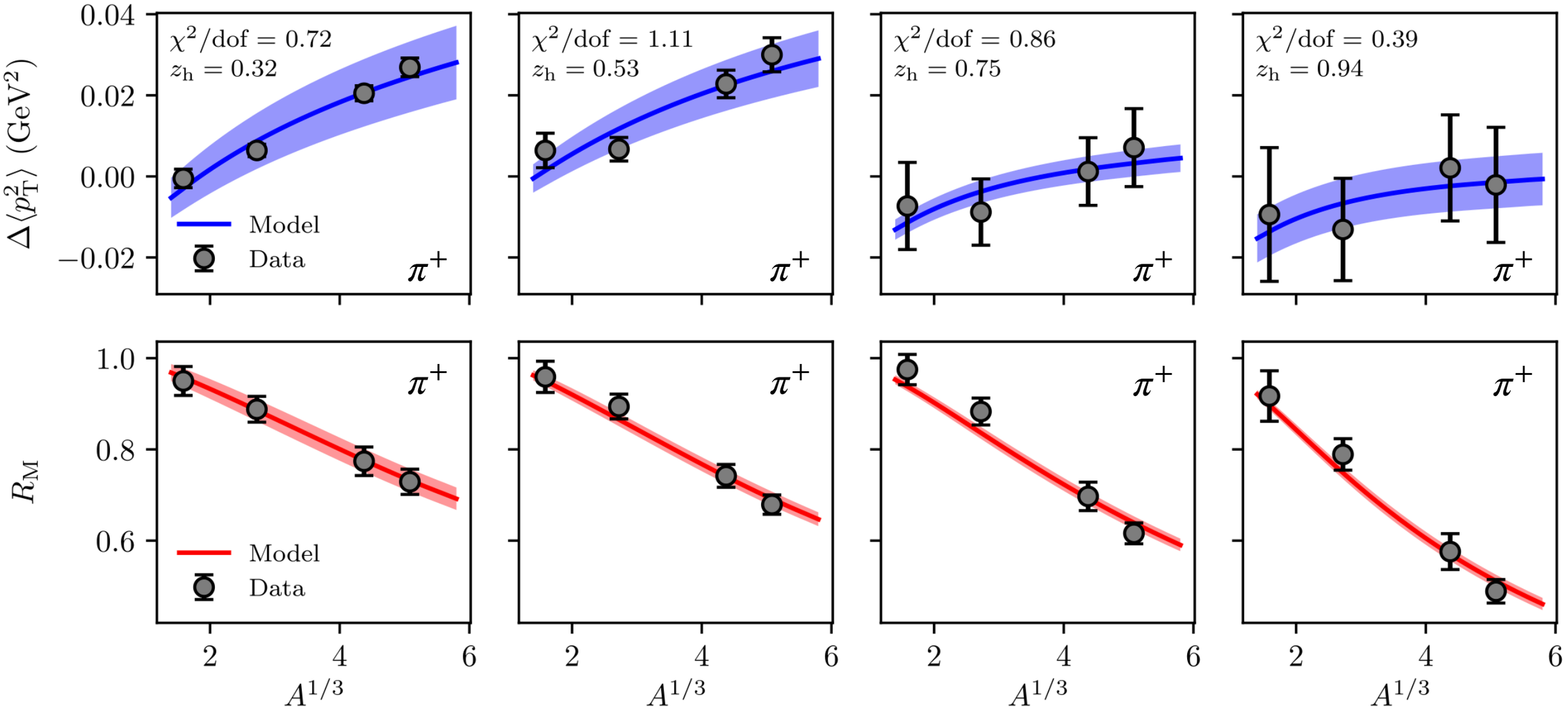


If the hadron forms inside the medium, it can interact with hadronic cross section.

The color lifetime of the struck quark is distributed stochastically as a decaying exponential.

https://arxiv.org/abs/2004.07236

Mesons: the established reference



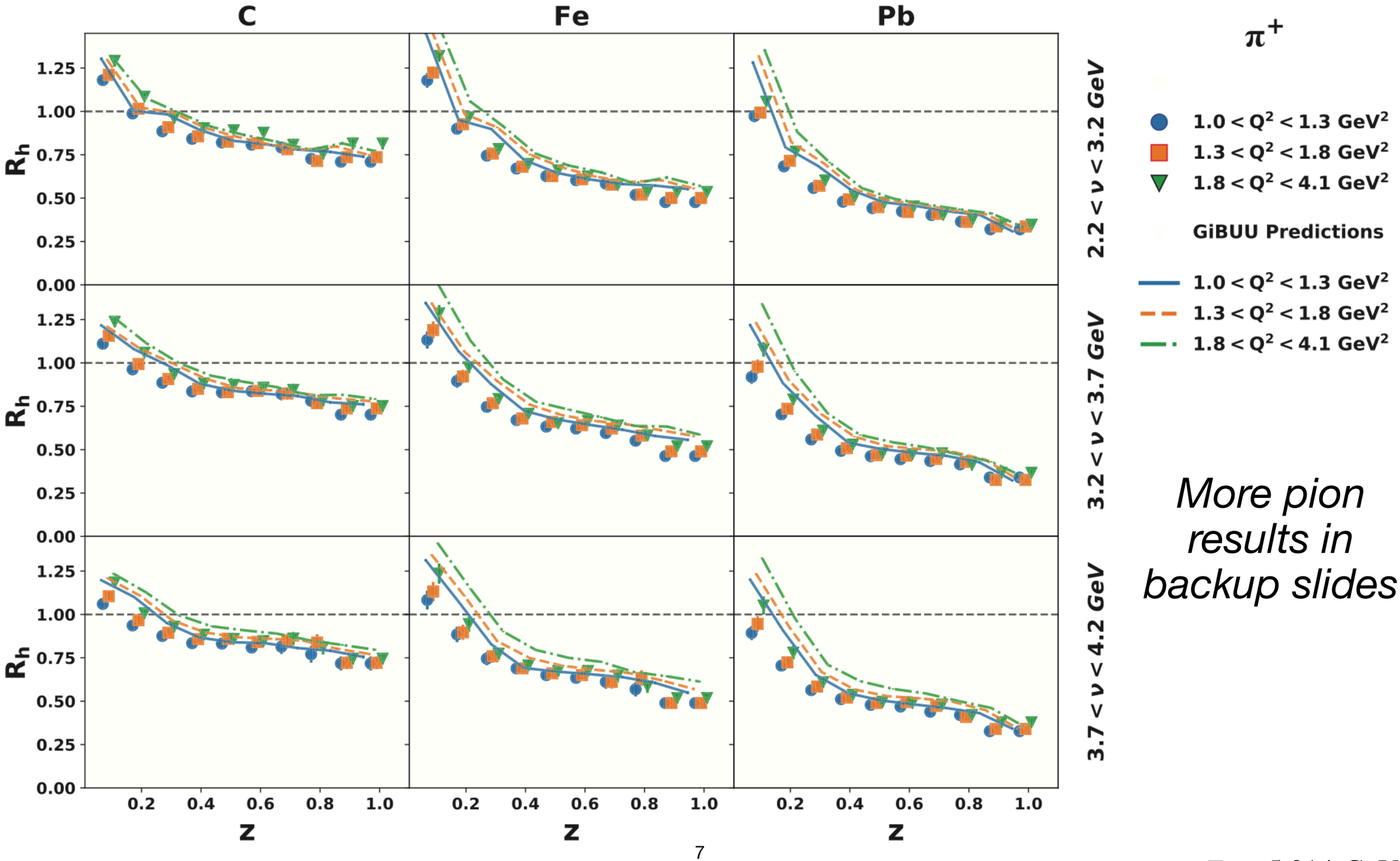
This 3-parameter space-time model fits two HERMES observables simultaneously

Physics Letters B, Volume 816, 2021, 136171, ISSN 0370-2693

https://arxiv.org/abs/2004.07236

HERMES · $E_{e^+} = 27.6$ GeV

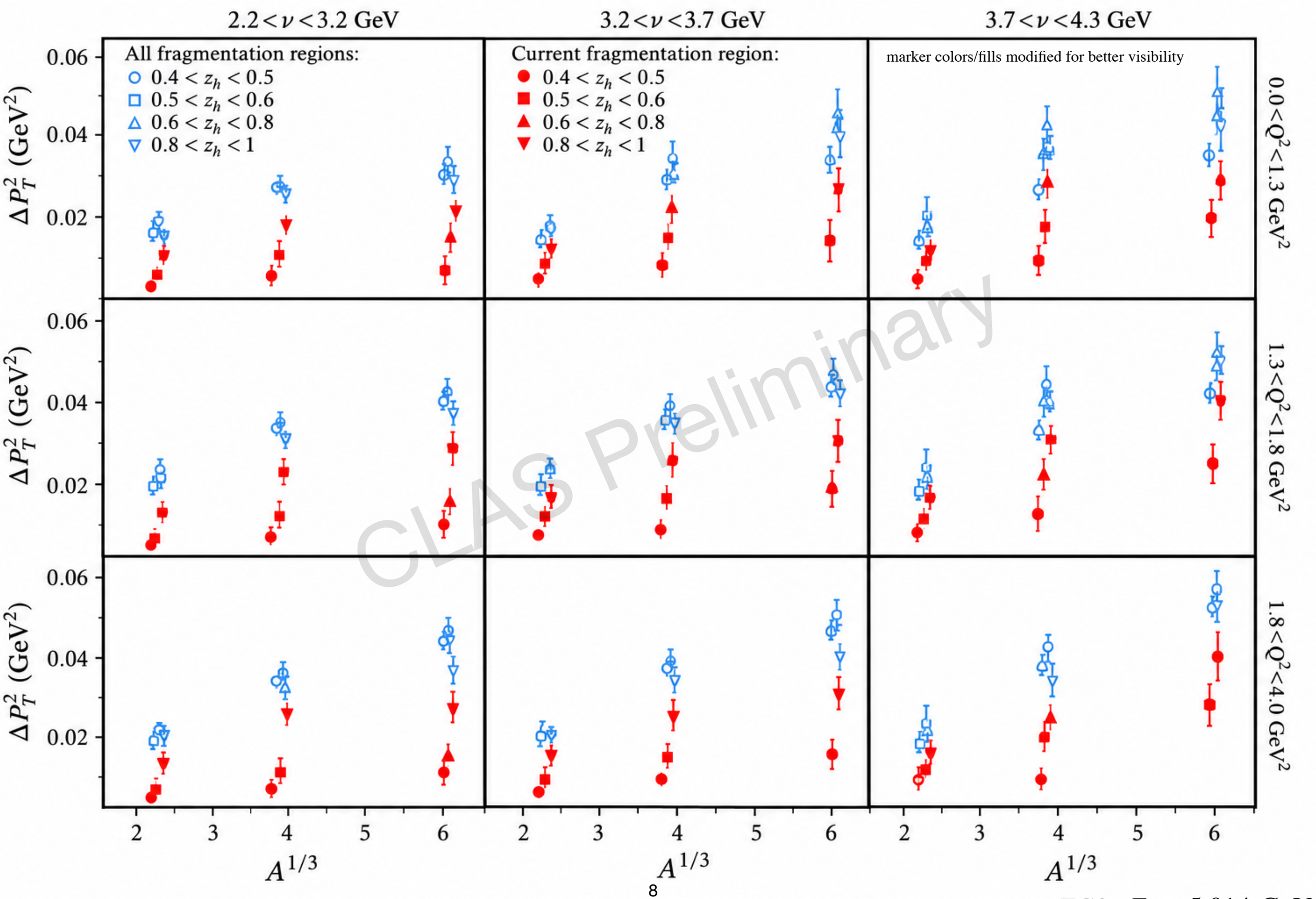
Published results: 5 GeV EG2 charged pion *multiplicity ratios* — $R_M^{\pi^+}$



More pion results in backup slides

EG2 · $E_e = 5.014$ GeV

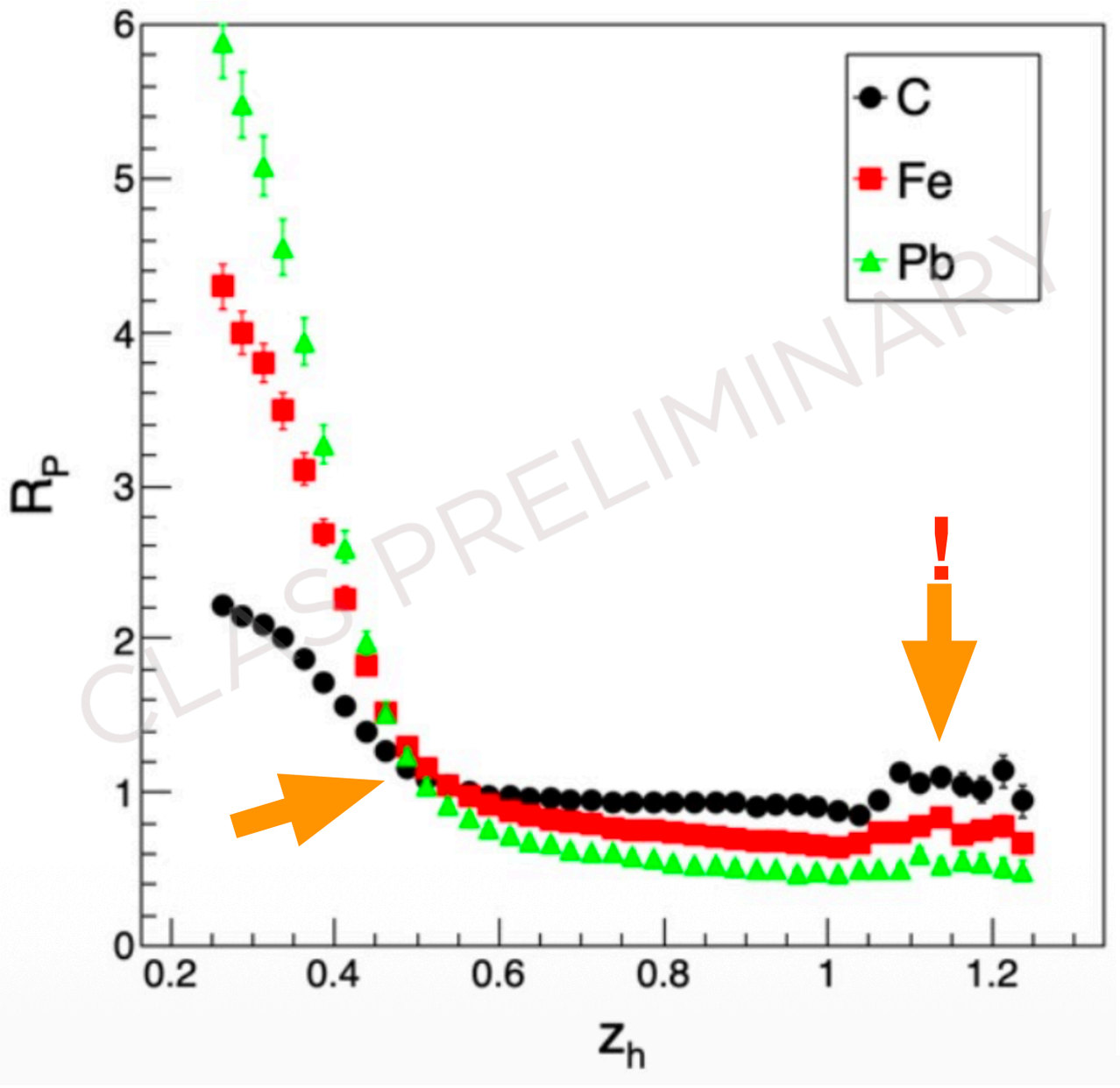
Preliminary results: 5 GeV EG2 π^+ transverse momentum broadening— Δp_T^2

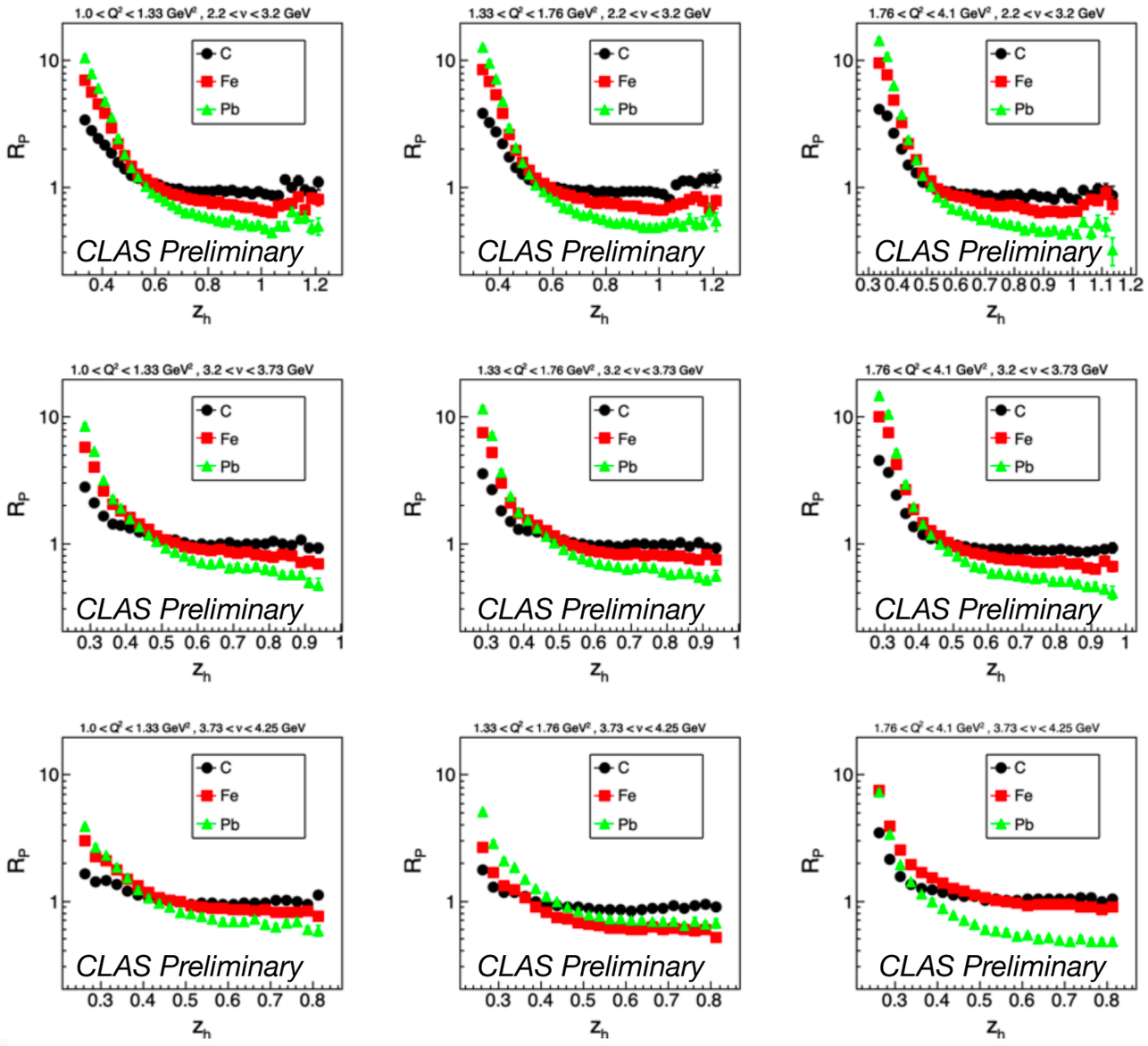


CLAS Preliminary

EG2 · $E_e = 5.014$ GeV

EG2 5 GeV electron beam: *protons* look very different!





Enhancement reaches $\sim 6\times$ at lower z_h. A crossover is evident.

Analysis Leader: Prof. Michael Wood (Canisius University) with students Juan Pablo Garces (UTFSM), Alexis Grasl and Ahmed Almashiakhy (Canisius University).

EG2 · $E_e = 5.014$ GeV

What does $z_h > 1$ mean for a proton?

$$z_h = \frac{E_h}{\nu}$$

z_h=1 is not a fundamental kinematic boundary.

In current fragmentation, the struck light quark receives approximately ν, making $z_h \lesssim 1$ natural.

But $z_h > 1$ is *kinematically allowed*: energy and momentum from the target system can also enter the detected hadron.

The real question is **how much** of the observed high-z_h region is accessible to **ordinary kinematics**?

How far can ordinary proton kinematics go?

Could the high-z_h proton enhancement simply reflect available phase space?

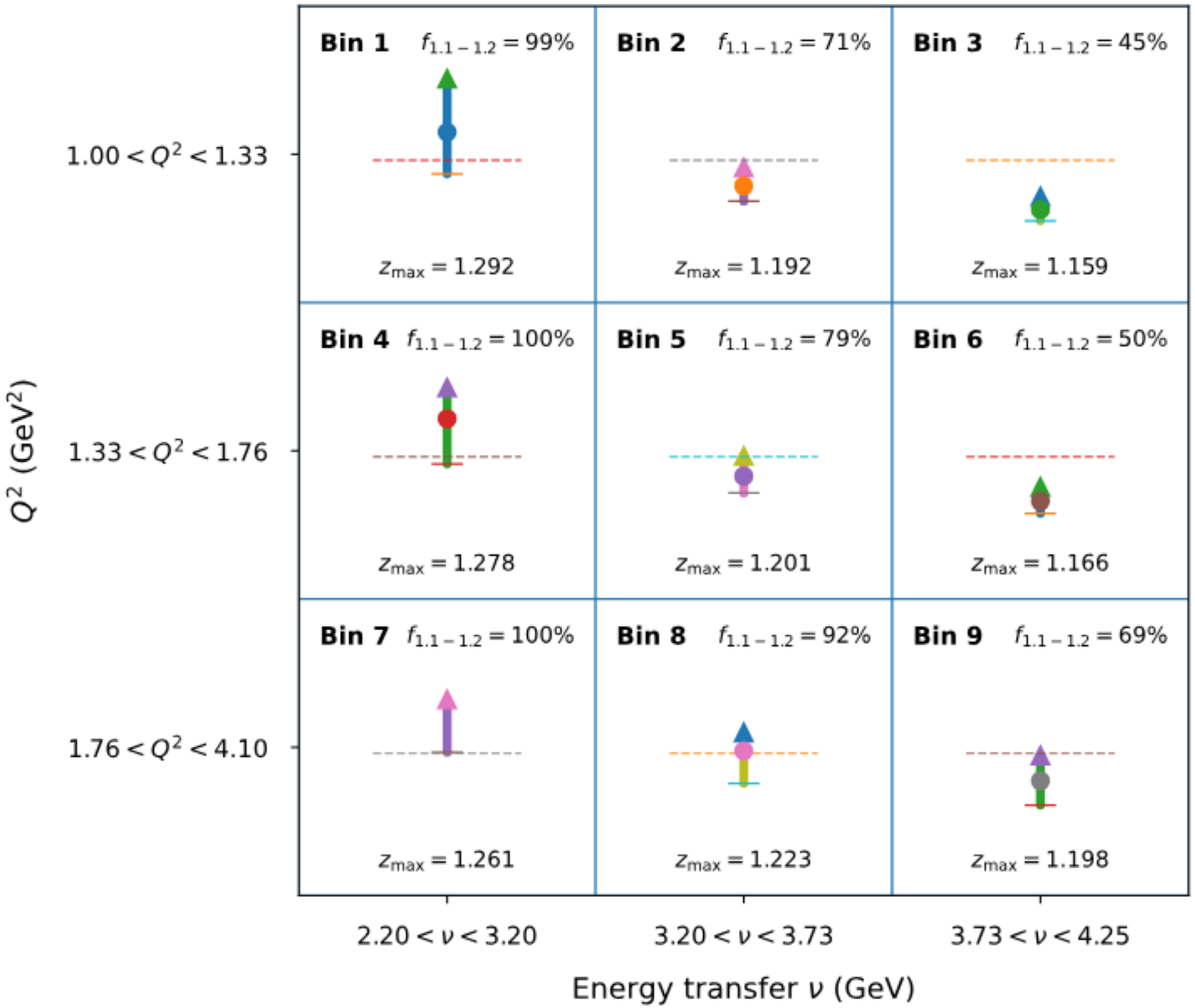
$$\gamma^* + p_{\text{stationary}} \to p + X, \qquad M_X \geq m_{\pi^0}.$$

For each measured (Q^2, ν) bin, we calculate the maximum proton energy allowed by four-momentum conservation, hence

$$z_p^{\max} = \frac{E_p^{\max}}{\nu},$$

while applying the analysis cuts $W > 2\ \text{GeV}$ and $y < 0.85$.

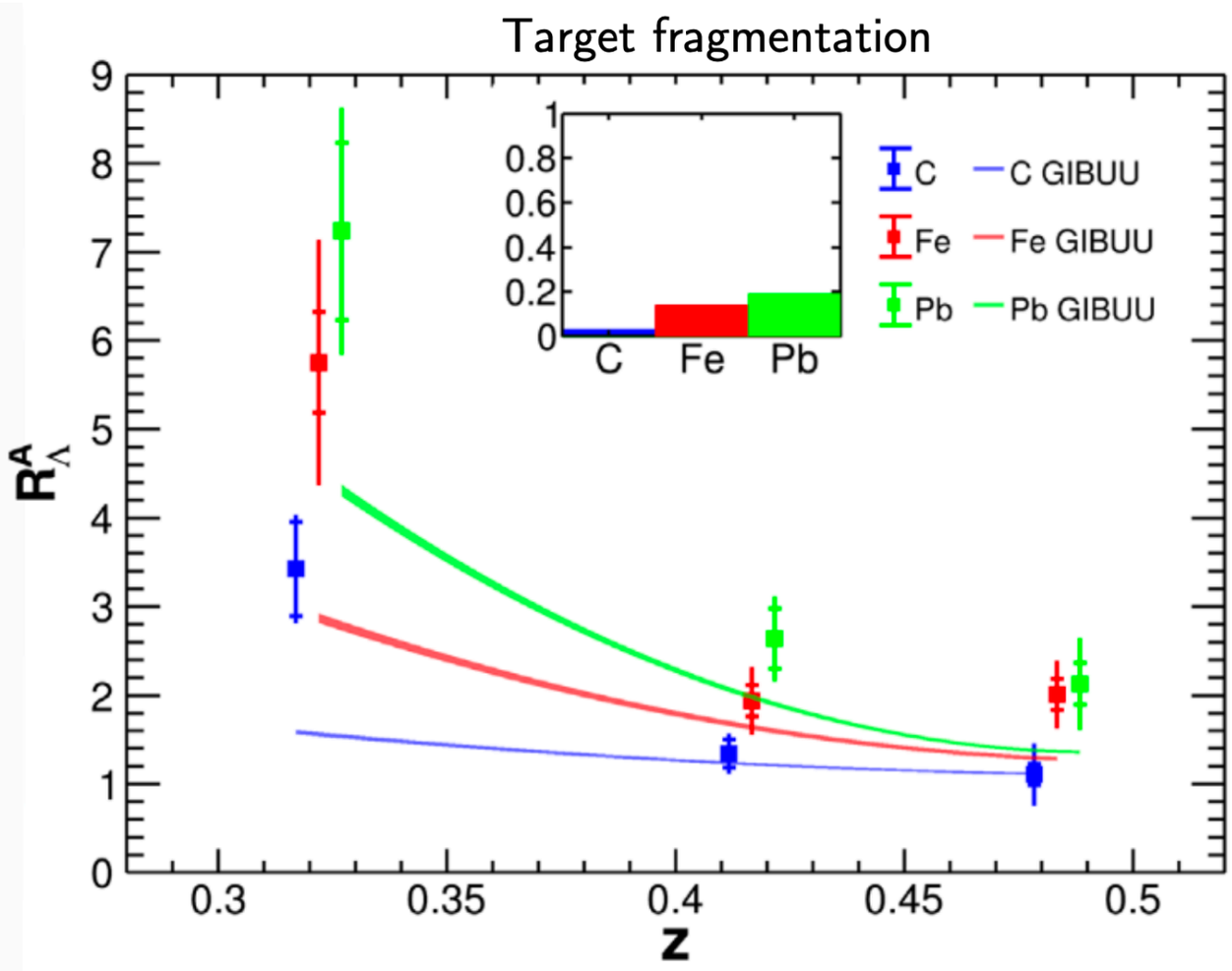
Where can stationary-proton $p + \pi^0$ production reach high z_h?

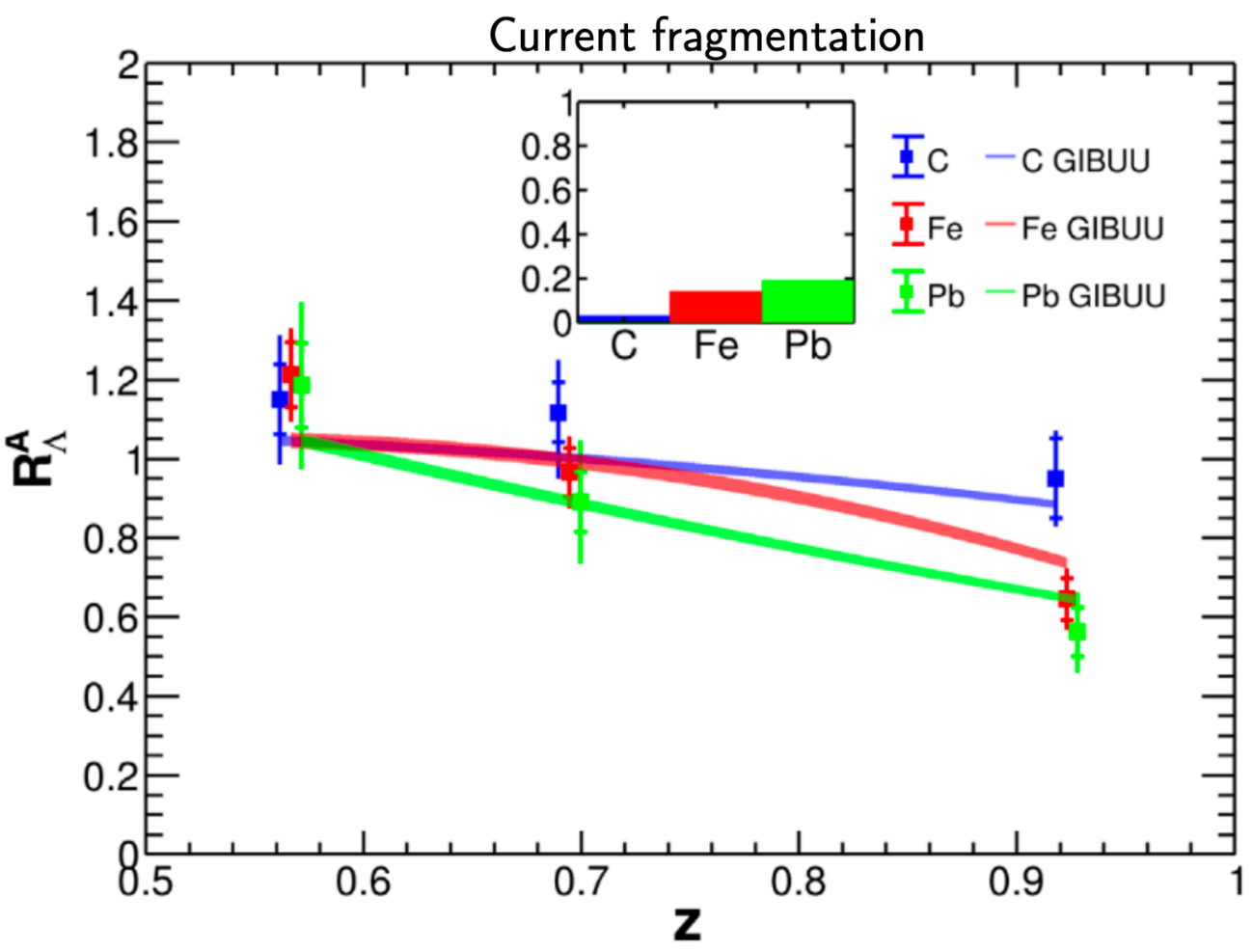


$f_{1.1-1.2}$ = kinematically allowed fraction of the measured $1.1 < z_h < 1.2$ bin. Bars: endpoint min–max; circle: bin center; dashed: $z_h = 1.2$.
$E_e = 5.014$ GeV; $W > 2$ GeV; $y < 0.85$. Bin 7 has no physical bin-center point.

EG2 · $E_e = 5.014$ GeV

The proton is not alone: Λ production in the EG2 dataset





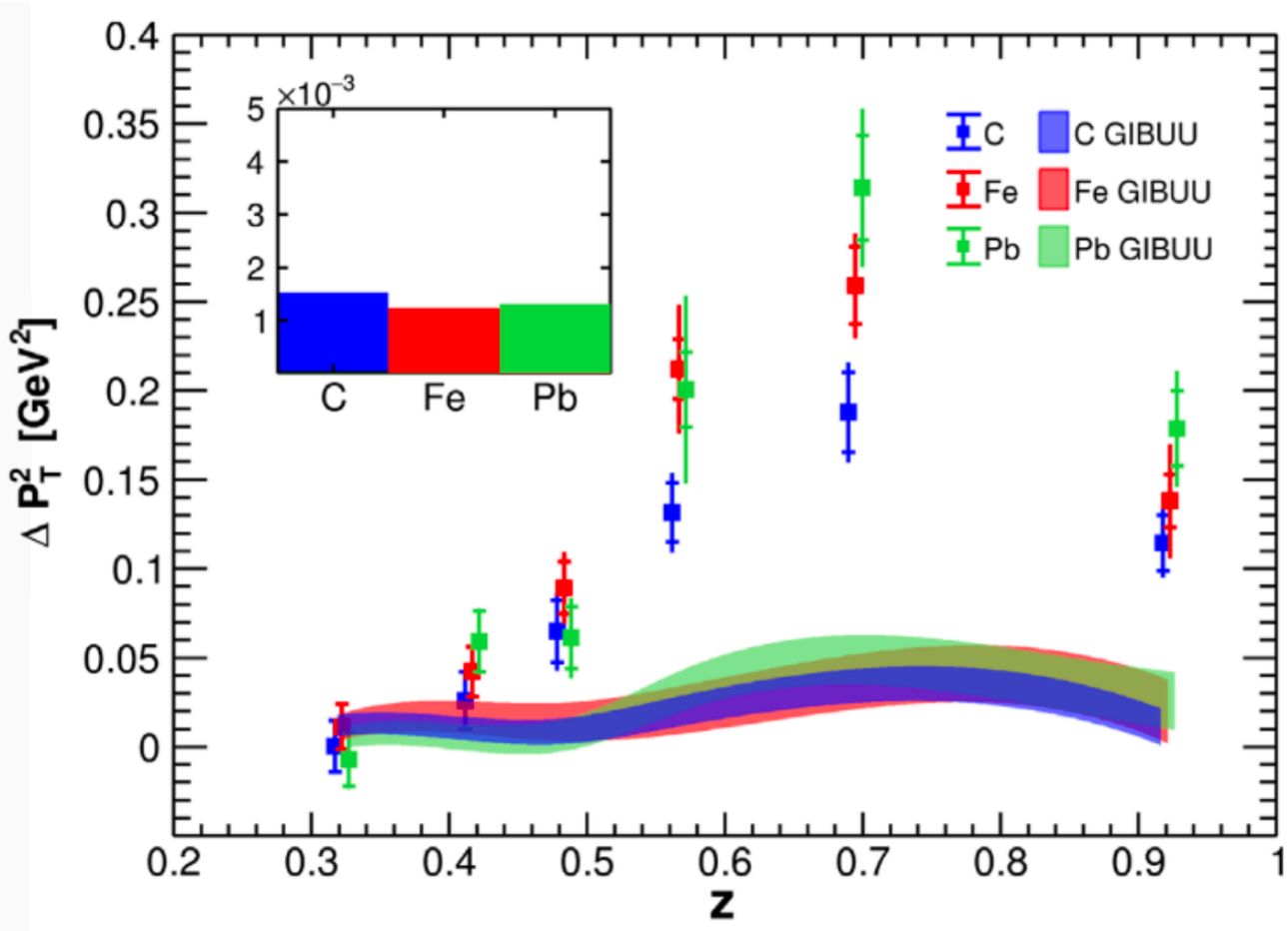
[T. Chetry, L. El Fassi, CLAS Collaboration (2023)]

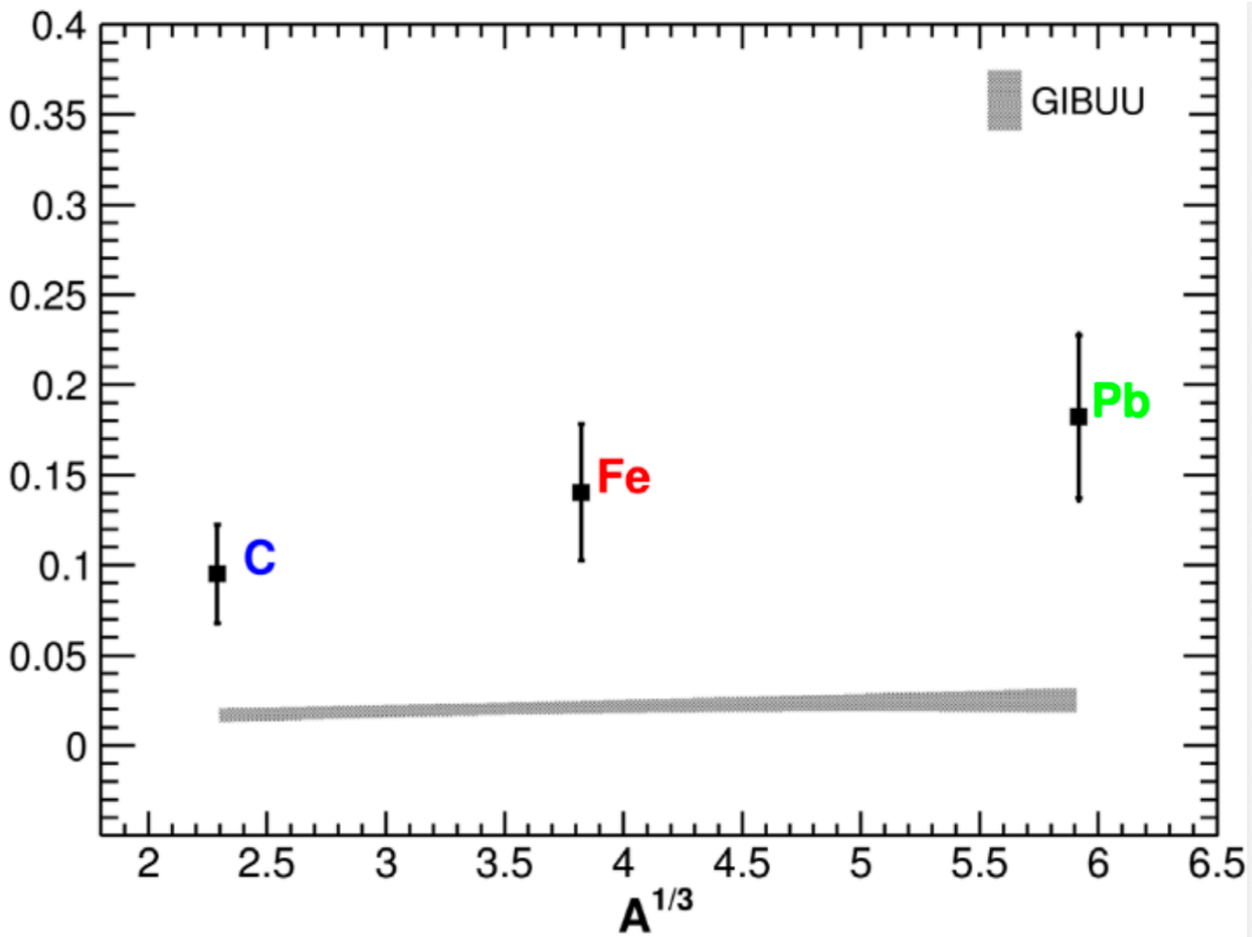
Phys. Rev. Lett. **130**, 142301

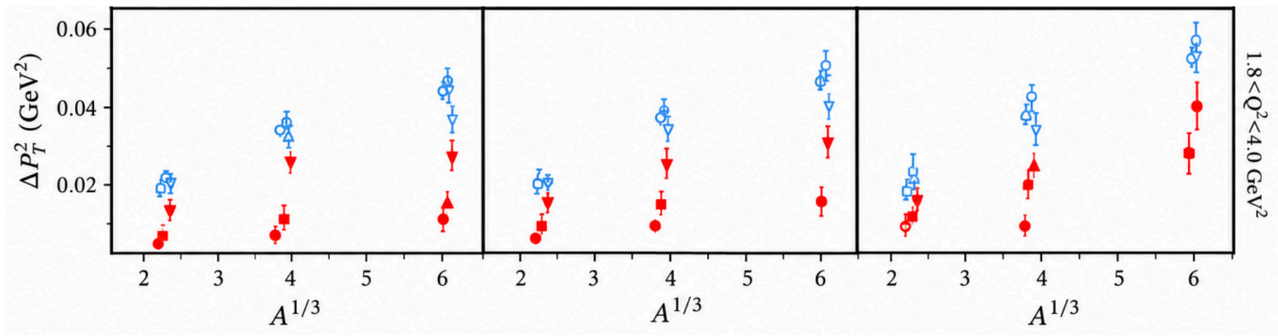
$\mathrm{EG2} \cdot E_e = 5.014$ GeV

The Λ also shows unusually large *p_T broadening*

And GiBUU strongly underpredicts it







(Reminder: π^+ *broadening* ~<0.03)

T. Chetry, L. El Fassi, CLAS Collaboration (2023)

Phys. Rev. Lett. **130**, 142301

EG2 · $E_e = 5.014$ GeV

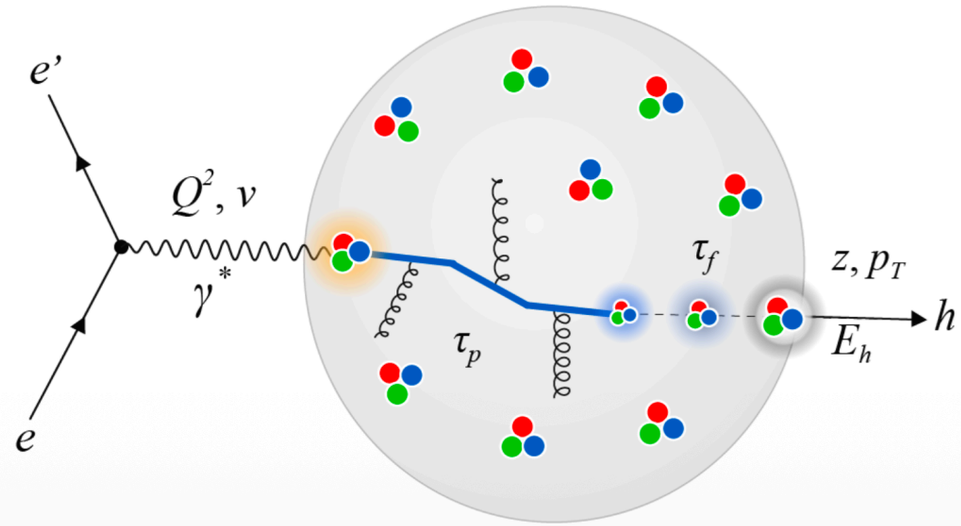
Why is the **Lambda broadening** so *large*?

$$\Lambda(uds) \longrightarrow [ud]_{S=0} + s$$

Recall: Lambda is thought to include a

strong scalar ud correlation

Not a generic baryon effect



Hypothesis: a strong scalar $[ud]_{S=0}$ correlation may change the interaction of the propagating colored system with nuclear matter.

How can we test the scalar-diquark hypothesis?

1. Change ***hadron species***

If the effect is connected with a strong scalar $[ud]_{s=0}$ correlation, it should **not simply follow "baryon vs. meson":**

$$[\text{proton},\ \Lambda]\ \text{vs.}\ [\bar{p},\ \Sigma,\ \Xi]$$

Does the nuclear effect track the $[ud]_{S=0}$ correlation rather than baryon identity?

2. Change the ***resolution***

Use Q^2 as a second handle:

lower Q^2 : $\gamma^* \rightarrow [ud]$

higher Q^2 : $\gamma^* \rightarrow u\ \ d$

Does the effect change as the virtual photon increasingly resolves the correlated pair?

Two *independent* tests: change the hadron structure, or change the probe resolution.

Species dependences:

1) *Target Correlation:* Correlated $[ud]_{S=0}$ pair *already present* in the target nucleon may survive into the produced p, n, or Λ.

2) *Hadron-structure correlations:* Comparing final-state hadrons with similar or different diquark structure tests whether nuclear modification is sensitive to correlated two-quark structure during hadronization.

Semi-stable hadrons CLAS12 can measure

hadron	$c\tau$	mass (GeV)	flavor content	detection channel	Production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	$\pi\pi\pi\pi$	-
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	530
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

Interesting example comparison: Σ^0 and Λ

$$\Lambda(uds) \quad \text{vs.} \quad \Sigma^0(uds)$$

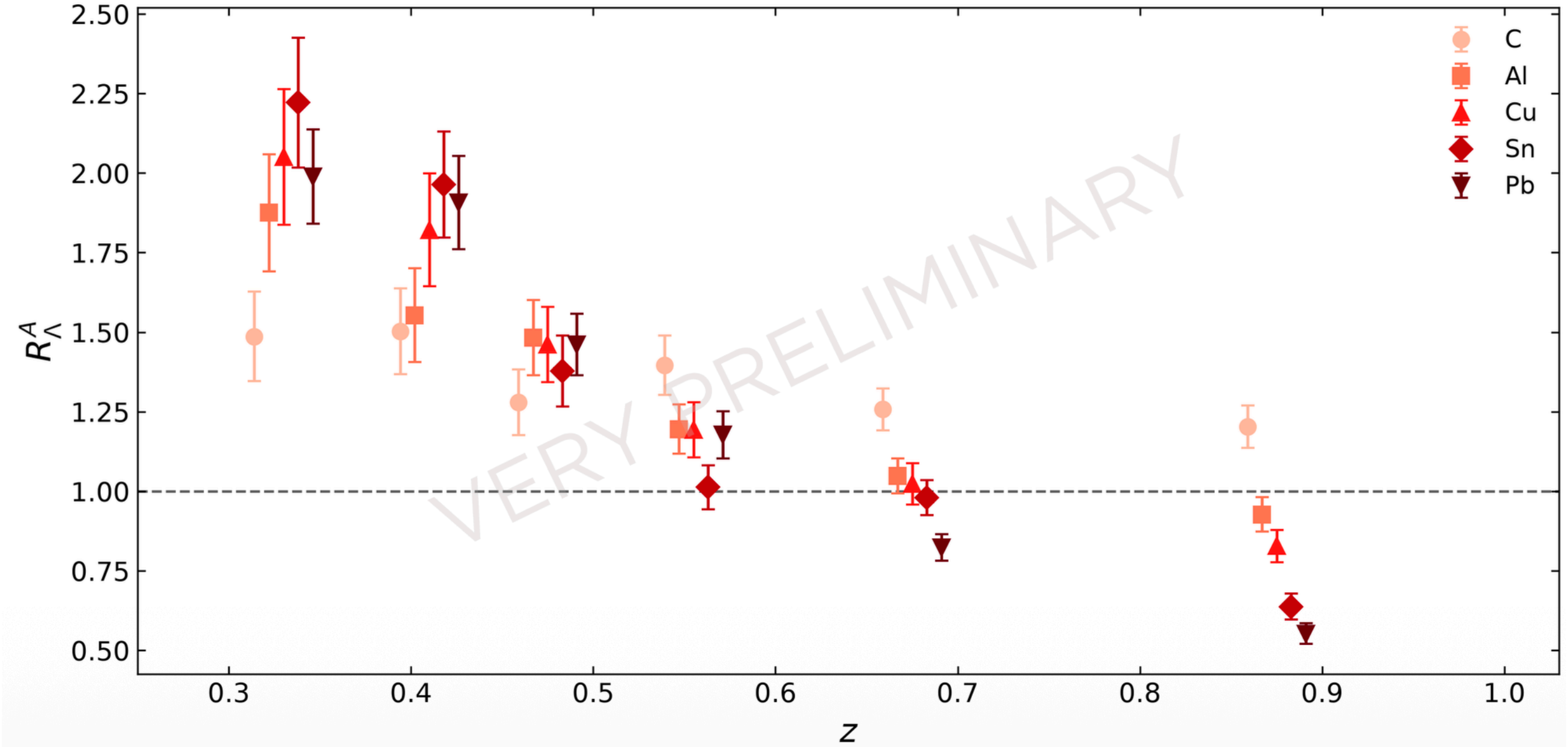
"Same valence-quark content", mass (MeV) 1115 vs. 1192 (7% different)

So the **valence-quark content is identical**, but according to Yin (2019) the favored correlated pair is different:

$$\begin{aligned} \Lambda: &\quad [ud]\, s, \\ \Sigma^0: &\quad [us]\, d / [ds]\, u \end{aligned}$$

Pei-Lin Yin, Chen Chen, Gastão Krein, Craig D. Roberts, Jorge Segovia, Shu-Sheng Xu, PHYSICAL REVIEW D 100, 034008 (2019), https://arxiv.org/pdf/1903.00160.

Higher energy (and Q^2) CLAS data for Λ in Run Group E (1/2)

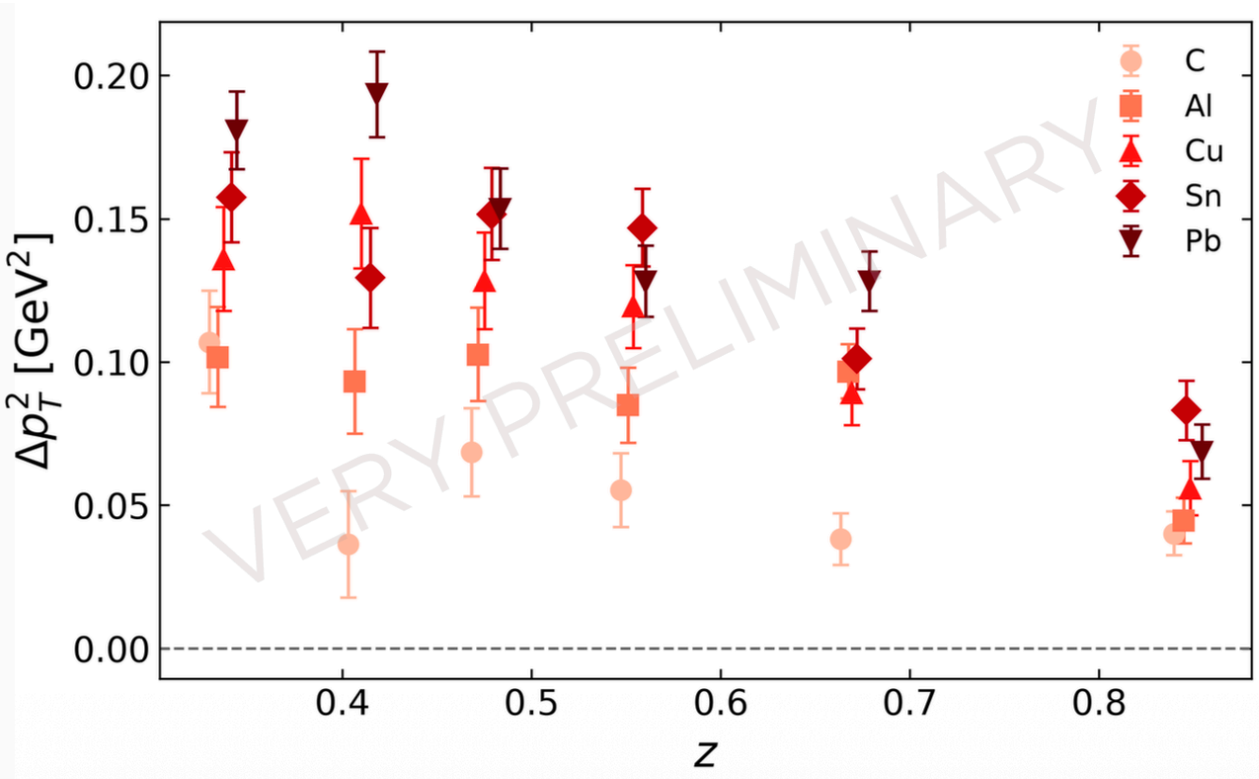


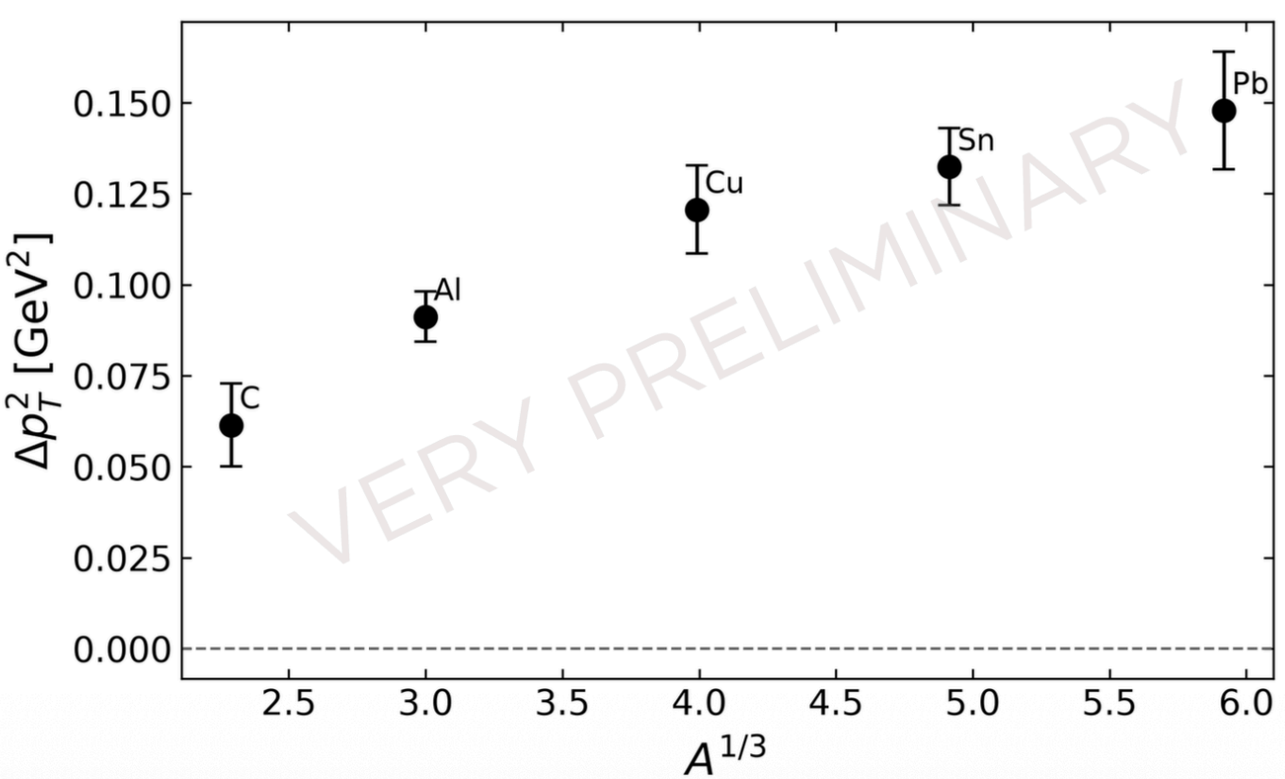
Multiplicity ratio: maximum is ~2.1 for heaviest targets, **much smaller** than for EG2 at R^A_Λ=7.5, still **much bigger** than for π^+ at z_h=0.3 at $R^A_{\pi^+}$<1.0

Prof. Lamiaa El Fassi and Uditha Weerasinghe, MSU, analysis leaders

Run Group E · E_e = 10.5 GeV

Higher energy (and Q^2) CLAS data for Λ in Run Group E (2/2)



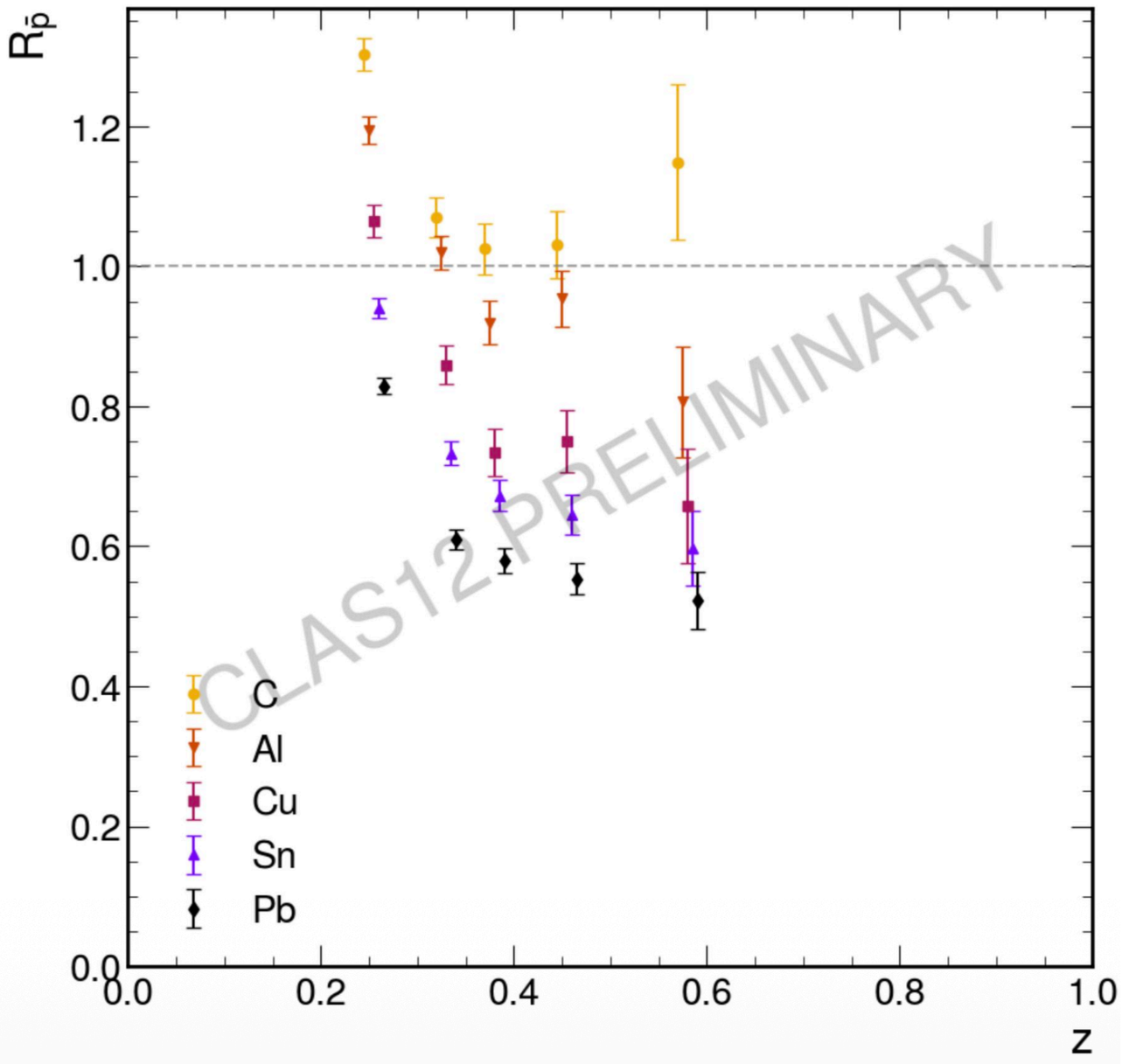


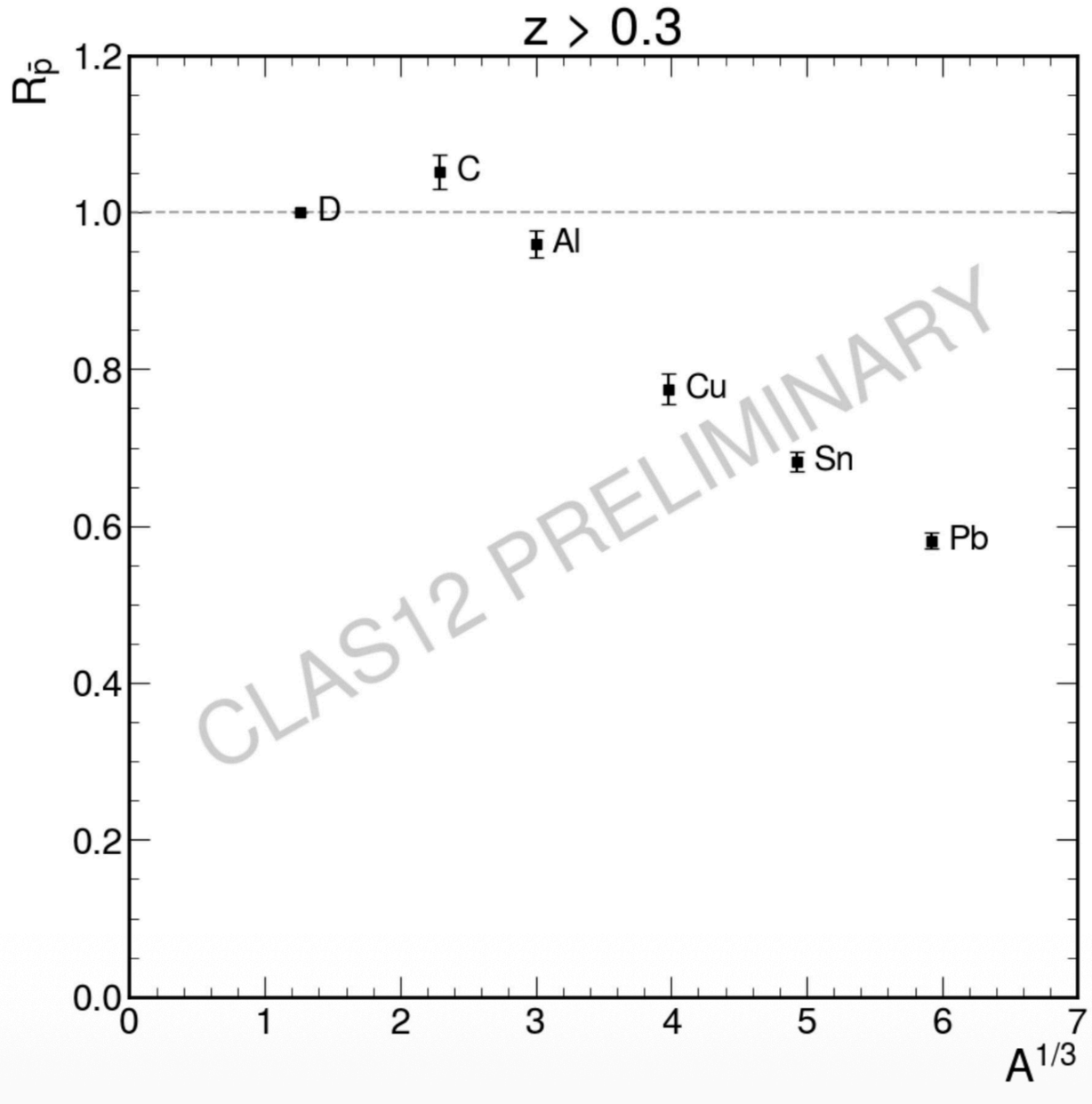
Transverse momentum broadening: maximum is ~0.2 GeV^2 for heaviest targets, **smaller** than for EG2 at Δp_T^2=0.3 GeV^2, still **much bigger** than for π^+ at Δp_T^2<0.05 GeV^2

Prof. Lamiaa El Fassi and Uditha Weerasinghe, MSU, analysis leaders

Run Group E · E_e = 10.5 GeV

Antiprotons!

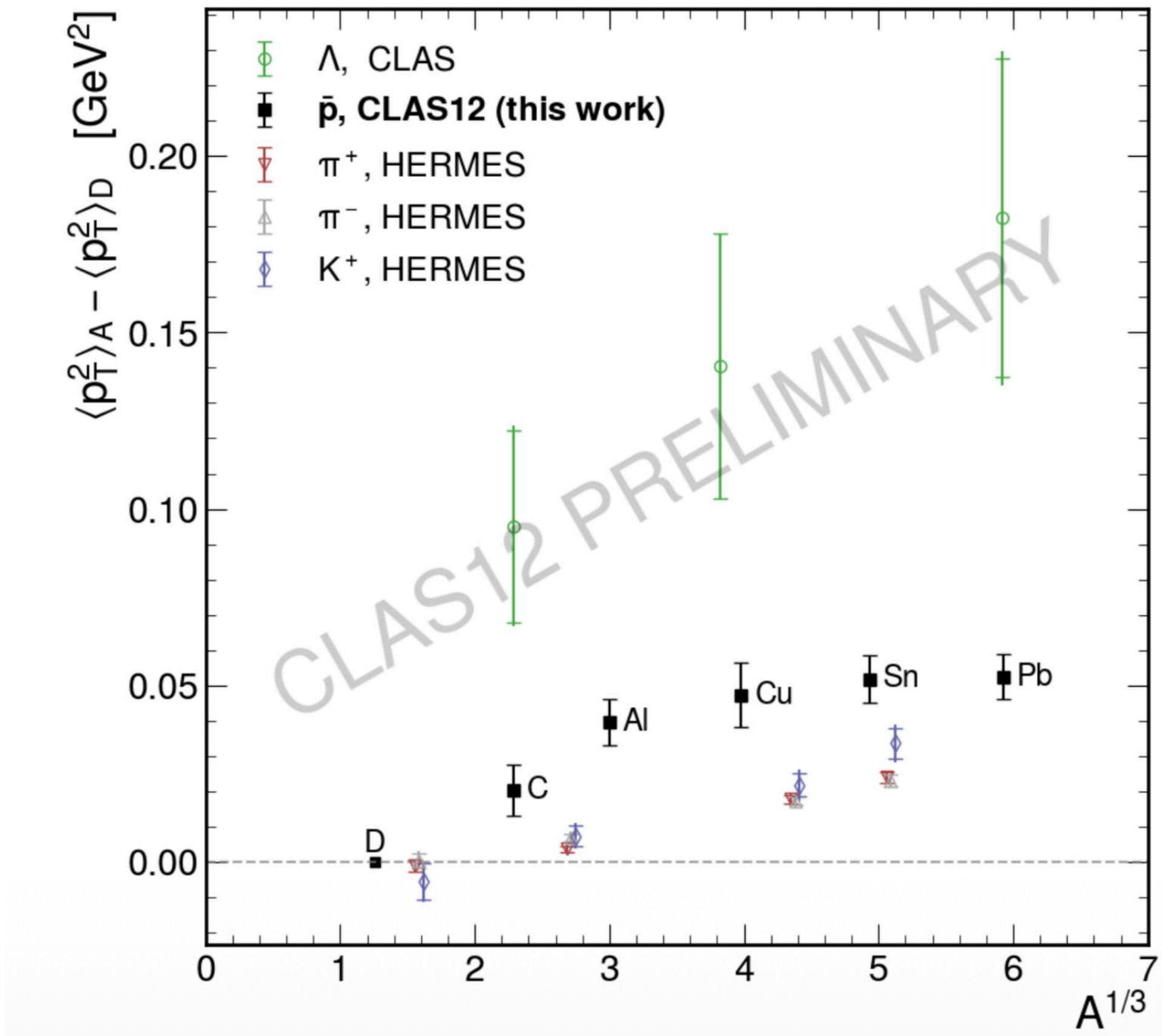




Dr. Sebouh Paul, analysis leader.

Run Group E · $E_e = 10.5$ GeV

Antiprotons!



Dr. Sebouh Paul, analysis leader.

Run Group E · $E_e = 10.5$ GeV

Conclusion: What are baryons telling us?

- p and Λ show nuclear effects qualitatively unlike the familiar pion systematics.
- Λ transverse broadening is particularly large and is strongly underpredicted by GiBUU.
- A strong $[ud]_{S=0}$ correlation is one possible organizing hypothesis - not an established interpretation.
- Test it by changing **hadron structure** $\Lambda/\Sigma^0, \bar{p}/p, \Sigma, \Xi$ and **probe resolution** Q^2.

Does the nucleus interact only with a propagating quark, or sometimes with a correlated colored subsystem?

Backup Slides

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]

Baryon	$M^{e/l}$	M^{CI}	s^{r_1}	s^{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 (B5a)	0.94	0.94	0.89		−0.35	−0.14	0.25	0.098	$[ud]u$
Λ (B5b)	1.12	1.06	0.67	0.59			−0.42	−0.16	$[ud]s$
Σ (B5c)	1.19	1.20	0.87		−0.42	0.004	0.25	0.071	$[us]u$
Ξ (B5d)	1.32	1.24	0.90		−0.29	−0.028	0.31	0.11	$[us]s$
Λ_c (B5e)	2.29	2.50	0.21	0.86			−0.35	−0.32	$[uc]d - [dc]u$
Σ_c (B5f)	2.45	2.53	0.48		−0.21	0.84	0.090	0.064	$\{uu\}c$
Ξ_c (B5g)	2.47	2.66	0.22	0.84			−0.36	−0.34	$[uc]s - [sc]u$
Ξ'_c (B5h)	2.58	2.68	0.50		−0.22	0.83	0.093	0.061	$\{us\}c$
Ω_c (B5i)	2.70	2.83	0.51		−0.22	0.82	0.097	0.058	$\{ss\}c$
Λ_b (B5j)	5.62	5.74	0.13	0.93			−0.31	−0.13	$[ub]d - [db]u$
Σ_b (B5k)	5.81	5.85	0.30		−0.12	0.94	0.041	0.087	$\{uu\}b$
Ξ_b (B5l)	5.79	5.88	0.13	0.93			−0.31	−0.13	$[ub]s - [sb]u$
Ξ'_b (B5m)	5.94	5.99	0.33		−0.12	0.93	0.045	0.099	$\{us\}b$
Ω_b (B5n)	6.05	6.12	0.37		−0.12	0.91	0.049	0.12	$\{ss\}b$
Ξ_{cc} (B5o)	3.62	3.72	0.90		−0.32	0.26	0.097	0.057	$[uc]c$
Ξ_{cb} (B5p)	6.94*	7.10	0.12	−0.73			0.62	−0.27	$[cb]u$
Ξ'_{cb} (B5q)	6.97*	7.03	0.90		0.13	0.24	−0.33	0.012	$[uc]b + [ub]c$
Ξ_{bb} (B5r)	10.14*	10.37	0.87		−0.33	0.35	0.043	0.057	$[ub]b$
Ω_{cc} (B5s)	3.74*	3.90	0.88		−0.33	0.30	0.15	0.074	$[sc]c$
Ω_{cb} (B5t)	7.00*	7.22	0.068	−0.79			0.49	−0.37	$[cb]s$
Ω'_{cb} (B5u)	7.03*	7.15	0.85		−0.32	−0.099	0.18	0.35	$[sc]b + [sb]c$
Ω_{bb} (B5v)	10.27*	10.48	0.85		−0.36	0.37	0.065	0.085	$[sb]b$
Ω_{ccb} (B5w)	8.01*	8.19	0.39		−0.18	0.90	0.070	0.071	$\{cc\}b$
Ω_{cbb} (B5x)	11.20*	11.37	0.81		−0.38	0.39	0.16	0.14	$[cb]b$

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Baryon	$M^{e/l}$	M^{CI}	fff	Other		Dom. corr.
Δ (B7a)	1.23	1.23	1			$\{uu\}u$
Σ^* (B7b)	1.38	1.37		0.60	0.80	$\{us\}u$
Ξ^* (B7c)	1.53	1.49		0.85	0.52	$\{us\}s$
Ω (B7d)	1.67	1.62	1			$\{ss\}s$
Σ_c^* (B7e)	2.52	2.56		0.64	0.77	$\{uc\}u$
Ξ_c^* (B7f)	2.66	2.70		0.63	0.77	$\{uc\}s + \{sc\}u$
Ω_c^* (B7g)	2.77	2.85		0.62	0.79	$\{sc\}s$
Σ_b^* (B7h)	5.83	5.84		0.71	0.71	$\{uu\}b \approx \{ub\}u$
Ξ_b^* (B7i)	5.95	5.98		0.67	0.74	$\{ub\}s + \{sb\}u$
Ω_b^* (B7j)	6.09*	6.11		0.63	0.78	$\{sb\}s$
Ξ_{cc}^* (B7k)	3.69*	3.75		0.98	0.20	$\{uc\}c$
Ξ_{cb}^* (B7l)	6.99*	7.07		0.21	0.98	$\{uc\}b + \{ub\}c$
Ξ_{bb}^* (B7m)	10.18*	10.34		1.00	0.078	$\{ub\}b$
Ω_{cc}^* (B7n)	3.82*	3.94		0.96	0.28	$\{sc\}c$
Ω_{cb}^* (B7o)	7.06*	7.21		0.31	0.95	$\{sc\}b + \{sb\}c$
Ω_{bb}^* (B7p)	10.27*	10.47		0.99	0.12	$\{sb\}b$
Ω_{ccc}^* (B7q)	4.80*	5.00	1			$\{cc\}c$
Ω_{ccb}^* (B7r)	8.04*	8.19		0.65	0.76	$\{cb\}c$
Ω_{cbb}^* (B7s)	11.23*	11.38		0.96	0.28	$\{cb\}b$
Ω_{bbb}^* (B7t)	14.37*	14.57	1			$\{bb\}b$

Published results: 5 GeV charged pion *multiplicity ratios* $R_M^{\pi^+}$ *and* $R_M^{\pi^-}$

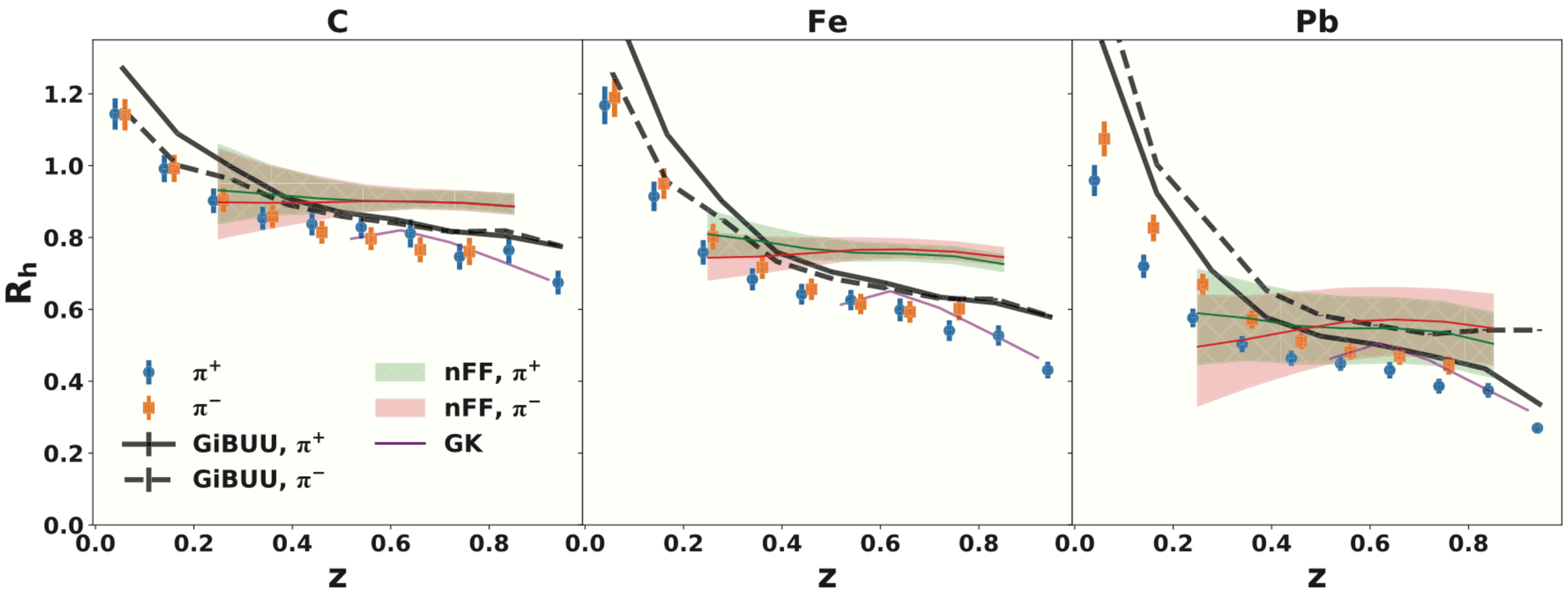


FIG. 1. Multiplicity ratio of π^+ and π^- as a function of z; the three different panels show results for C, Fe, and Pb targets, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties, which is dominated by the systematic uncertainties that are partially correlated point to point. The points have a small horizontal shift for better visualization. The lines correspond to model calculations from GiBUU, GK, and the LIKEn21 nFFs. The bands represent the uncertainty of the LIKEn21 nFF set. The numerical values of the data points and associated errors of this figure are shown in Table II in the Appendix section of the article.

Unprecedentedly small uncertainties due to high statistical precision and excellent control of systematic uncertainties!

Published results: 5 GeV charged pion *multiplicity ratios* — $R_M^{\pi^+}$

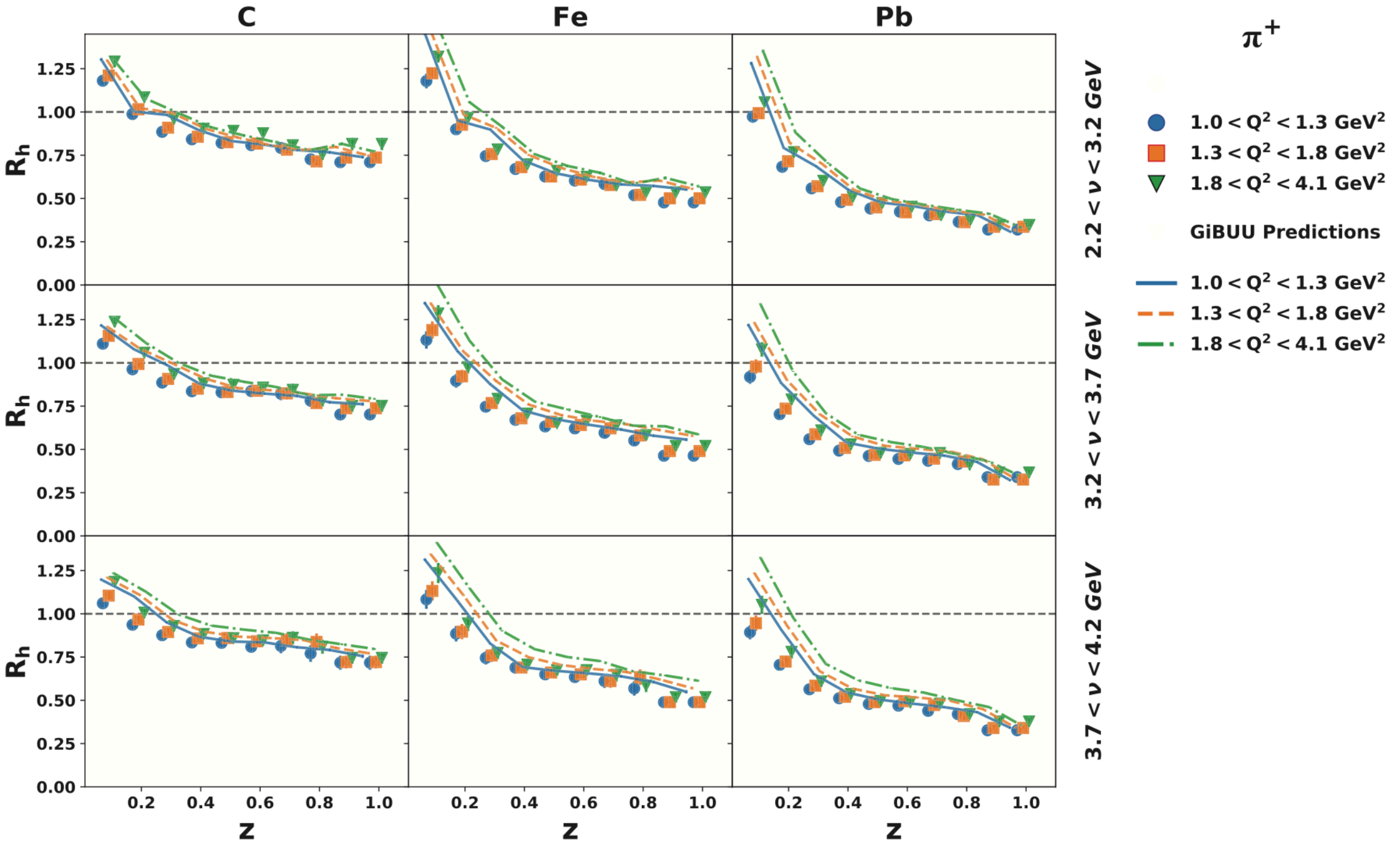


FIG. 2. Multiplicity ratios of π^+ as a function of z for various intervals of ν (in different rows) and Q^2 (different marker colors). The left, middle, and right panels correspond to C, Fe, and Pb, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties. The numerical values of the data points and associated errors of this figure are shown in Tables III–V in the Appendix section of the article.

Published results: 5 GeV charged pion *multiplicity ratios* — $R_M^{\pi^-}$

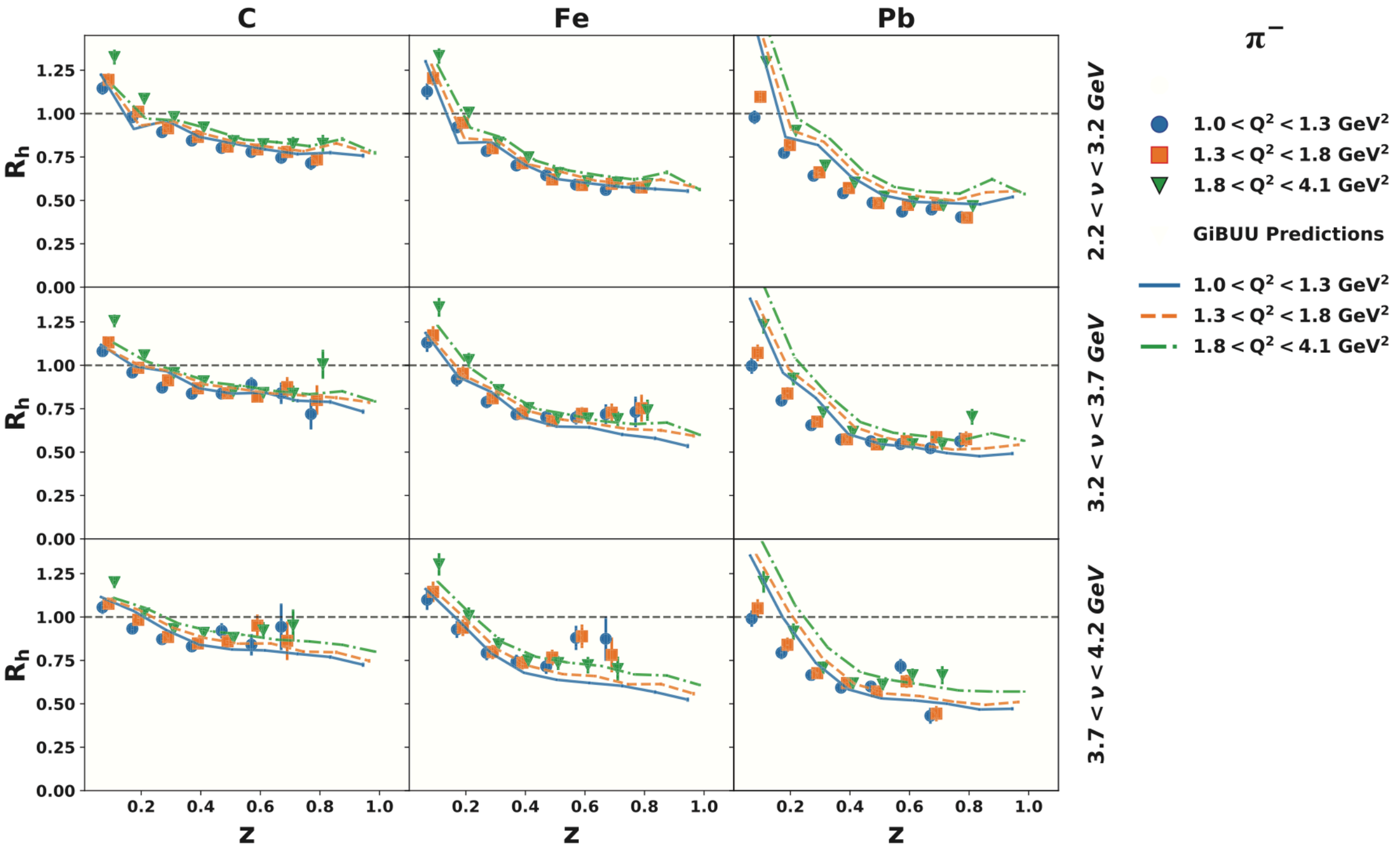


FIG. 3. Multiplicity ratios of π^- as a function of z for various intervals of ν (in different rows) and Q^2 (different marker colors). The left, middle, and right panels correspond to C, Fe, and Pb, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties. The numerical values of the data points and associated errors of this figure are shown in Tables VI–VIII in the Appendix section of the article.

Published results: 5 GeV charged pion *multiplicity ratios* — $R_M^{\pi^+}$

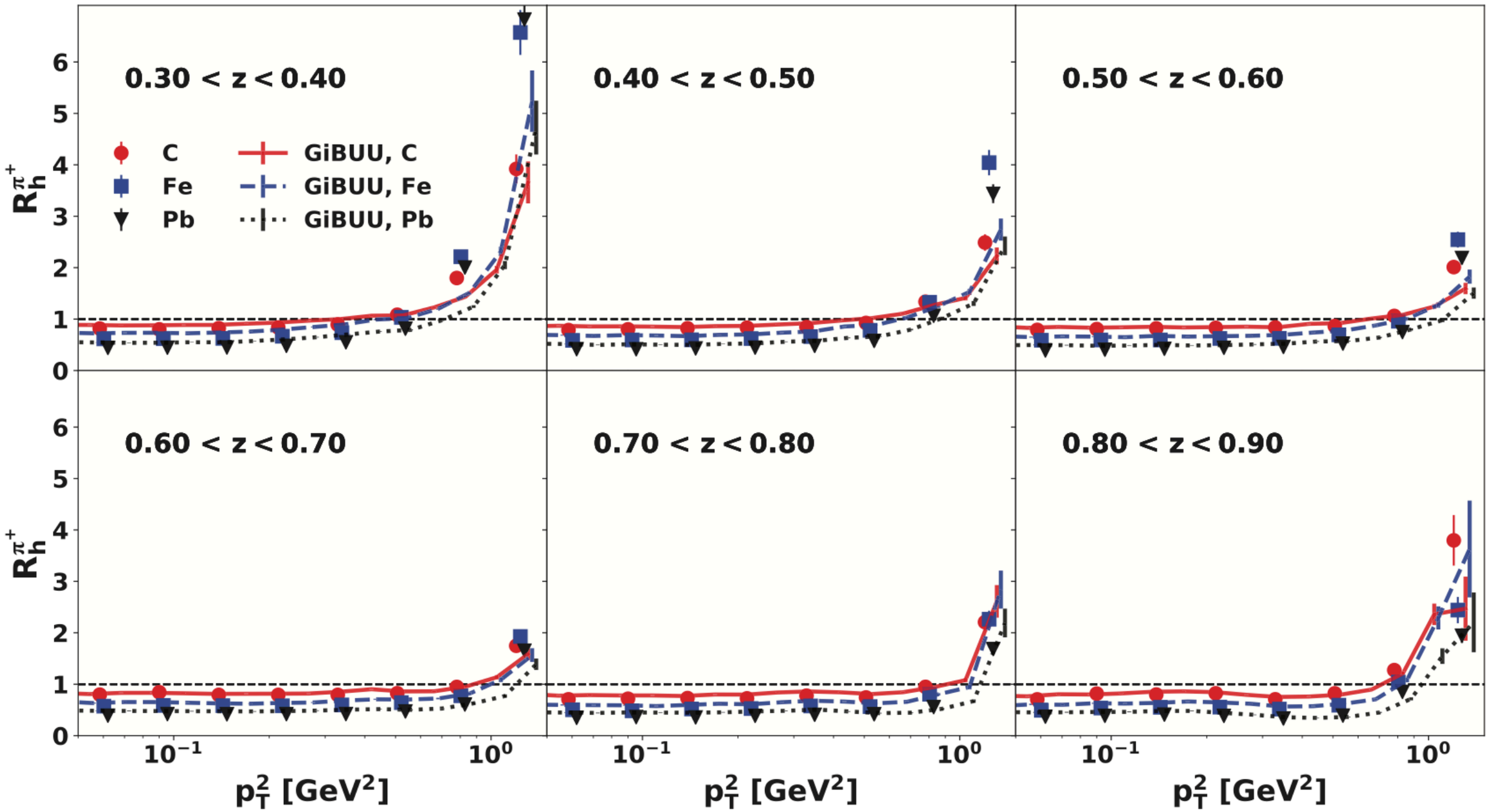


FIG. 4. Multiplicity ratio of π^+ as a function of p_T^2 for various z intervals; the red, blue, and black markers show the measured results for C, Fe, and Pb targets. The error bars represent the quadrature sum of systematic and statistical uncertainties. Lines of the same colors represent the results from the GiBUU model. The numerical values of the data points and associated errors of this figure are shown in Tables IX and X in the Appendix section of the article.

Published results: 5 GeV charged pion *multiplicity ratios* — $R_M^{\pi^-}$

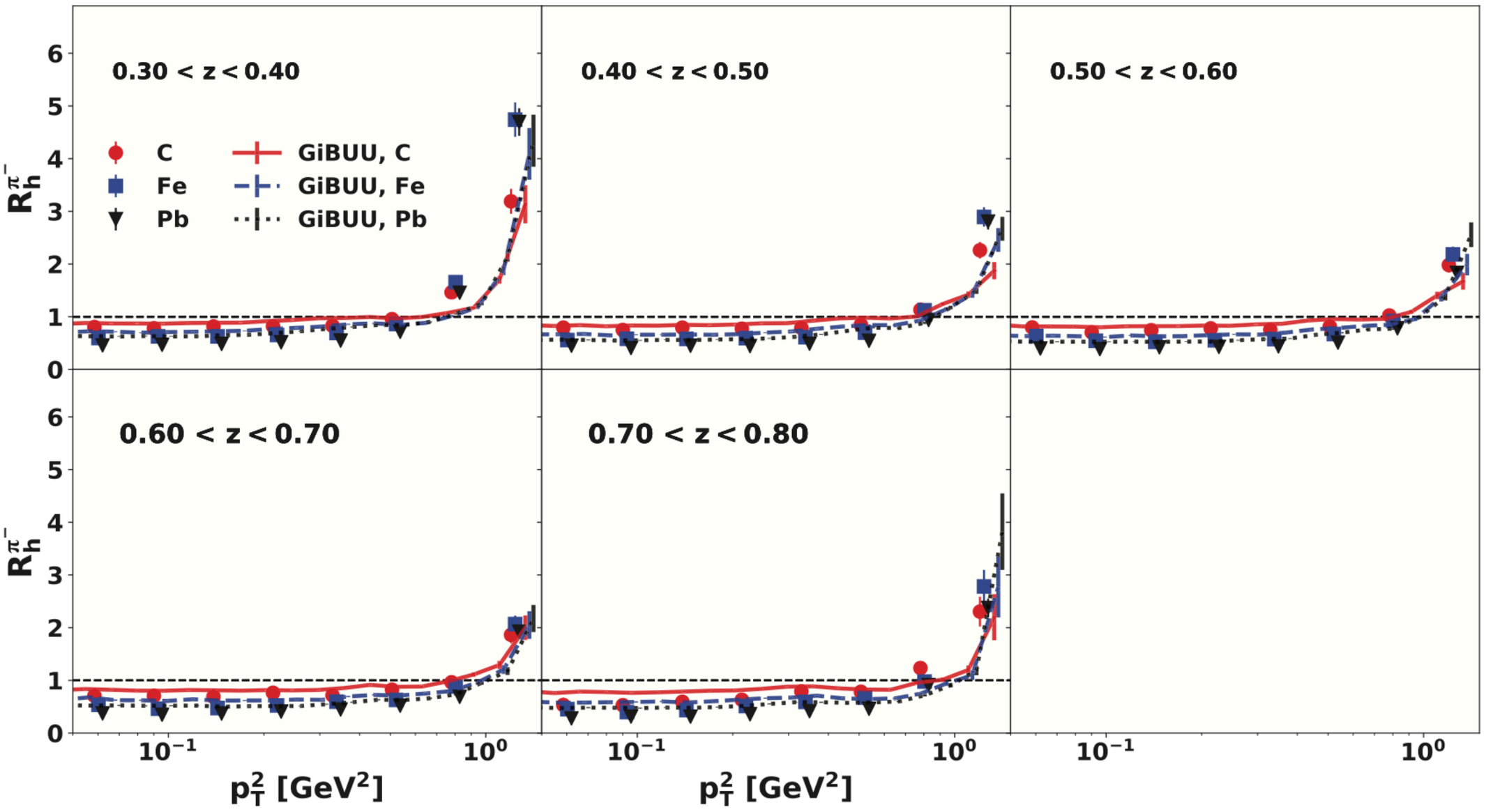


FIG. 5. Multiplicity ratio of π^- as a function of the p_T^2 for various z intervals; the red, blue, and black markers show the measured results for C, Fe, and Pb targets. The error bars represent the quadrature sum of systematic and statistical uncertainties. Lines of the same colors represent the results from the GiBUU model. The last panel is blank, as there is insufficient data for π^- at $z > 0.8$. The numerical values of the data points and associated errors of this figure are shown in Table XI and XII in the Appendix section of the article.

Published results: 5 GeV neutral pion *multiplicity ratios* $R_M^{\pi^o}$

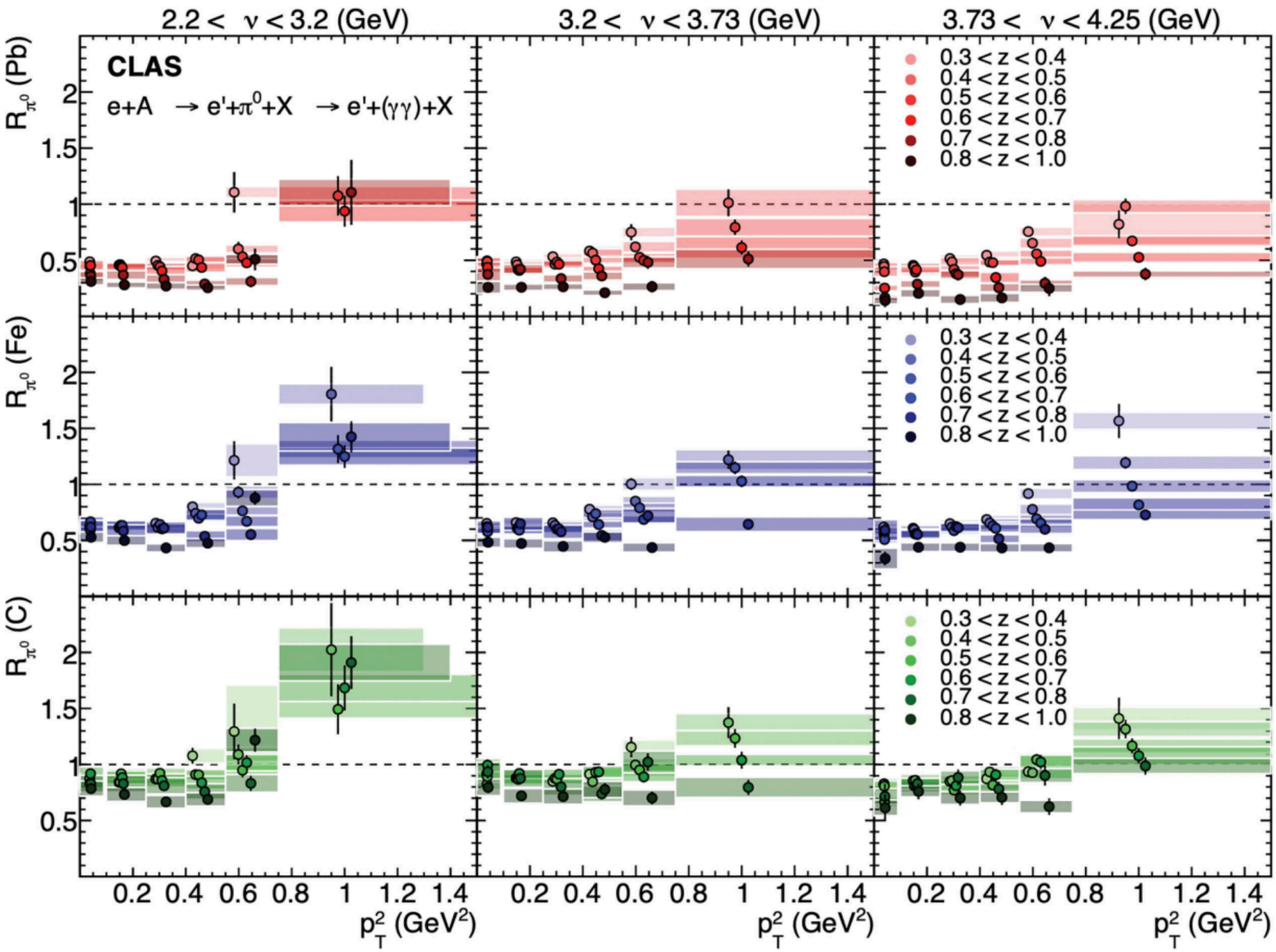


FIG. 3. π^0 multiplicity ratios for C, Fe, and Pb in (ν, z, p_T^2) bins plotted as a function of p_T^2 in bins of ν (top horizontal line) and z (indicated by the color). Points are shifted for ease of visualization around the mean value of p_T^2. Statistical uncertainties are indicated by black vertical lines; systematic uncertainties by the color bars. Horizontal uncertainties are related to the size of the bin: while for most bins in p_T^2 they are the same for each bin in z and the target, a few bins have smaller uncertainty bands related to the interval of data significance in the bin.

Published results: 5 GeV Neutral pion *multiplicity ratios* $R_M^{\pi^o}$

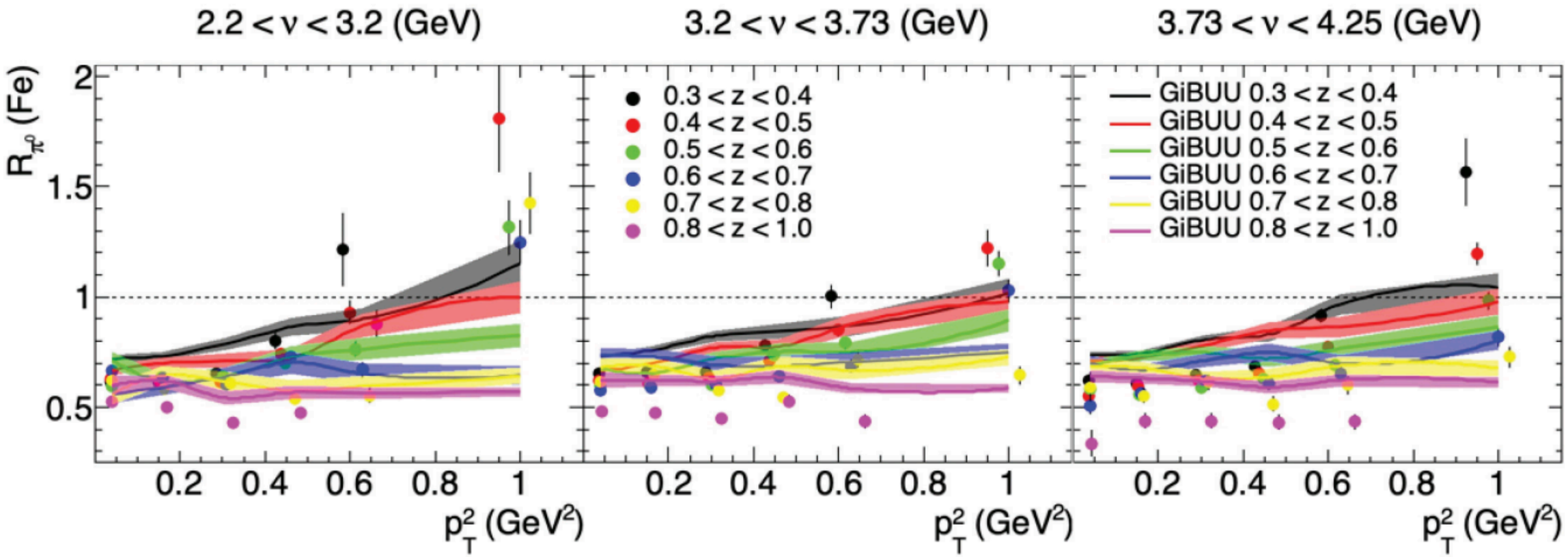


FIG. 4. π^0 multiplicity ratios for Fe in (ν, z, p_T^2) as a function of p_T^2 in bins of ν (each panel) and z (indicated by the color). Markers correspond to data points; the solid lines correspond to GiBUU projections with the width of the band indicating statistical errors of the simulation.

Invariant mass peak and combinatorial background calculation.

Example of **one out of 480** 3-dimensional bins!

