



Recent Results on Hadronization Studies

And Related Topics in Leptonuclear Scattering

Will Brooks on behalf of the CLAS Collaboration, 11 September 2026



CENTRO CIENTÍFICO
TECNOLÓGICO
DE VALPARAÍSO



Outline of main topics:

Hadronization:

- *Mechanisms* for formation of meson and baryon final states up to strange and charmed hadronic systems.
- Prospects and expected impact of large statistical samples on *higher-mass hadrons* such as $K, \eta, \phi, \omega, J/\psi$ mesons and $p, \bar{p}, \Lambda, \Sigma, \Xi$ baryons.

Connections of these studies to *diquark correlations*:

- Production of hadrons with *[ud] spin-zero diquarks* that are part of protons and neutrons.
- Exploration of production of hadrons with *same [n,m] diquarks*.

Hadronization in QCD

- Nonperturbative process in QCD, yet present in essentially all high-energy interactions that produce hadrons.
- Modeled by several leading event generators: Pythia, Herwig, Sherpa.
- Hadronization was historically constrained by data from ep and pp interactions, but now pA and eA data are available with identified hadrons in the final state, which bring new constraints.
- Final states with atomic nuclei add significant information about processes that occur at the ≤ 1 fm distance scale, inferred indirectly by observing the dependence of observables on the in-medium path length (nuclear radii of a variety of nuclei).

Leptonuclear hadronization studies with hadron PID

- Recent history starts with hadron PID in *HERMES* (DESY) with nuclear targets.
 - Need to know hadron species to make any detailed model.
 - Need to have larger nuclei to use as a spatial analyzer.
- <https://inspirehep.net/experiments/1108781> “the HERMES era” (1995-2007).
- “The HERMES dual-radiator ring imaging Cherenkov detector” [https://doi.org/10.1016/S0168-9002\(01\)00932-9](https://doi.org/10.1016/S0168-9002(01)00932-9) (e , π , K , p) published 2002.
- Ultimately the published nuclear targets ranged from deuterium to xenon (avg mass 131.3 u, approx radius 5.6 fm)

Datasets for $eA \rightarrow e'hX$ and $eA \rightarrow e'h_1h_2X$

- Hermes at the DESY laboratory (data taking 1995 - 2007).
Pioneers of eA on nuclear targets, established baseline at higher energies and momentum transfer.
- CLAS at Jefferson Lab:
 - The EG2 run period of the “6 GeV era” (1998 - 2012). $\sim 60\times$ HERMES integrated luminosity - JLab experiment [E02-104](#)
 - The Run Group E (RGE) of the “12 GeV era” (2017 to present) $\sim 4\times$ EG2 integrated luminosity. JLab [E12-06-117](#)

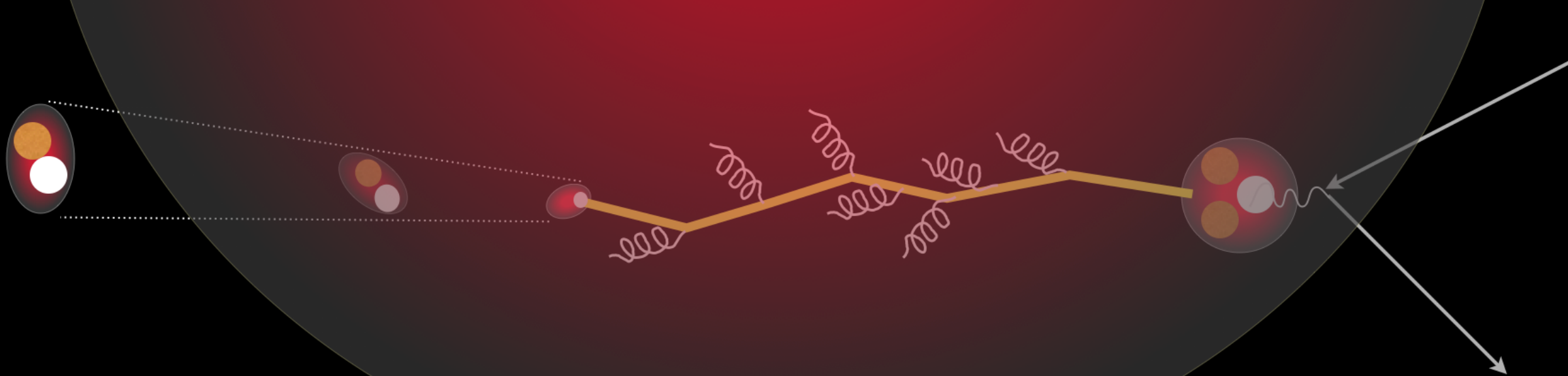
RGE: another **factor of two in luminosity** in next experimental run.

These are hadrons that are measurable in CLAS and which have a $c\tau$ (lifetime) larger than nuclear dimensions (fm)

They can therefore be employed to probe the **partonic stage** preceding hadron formation

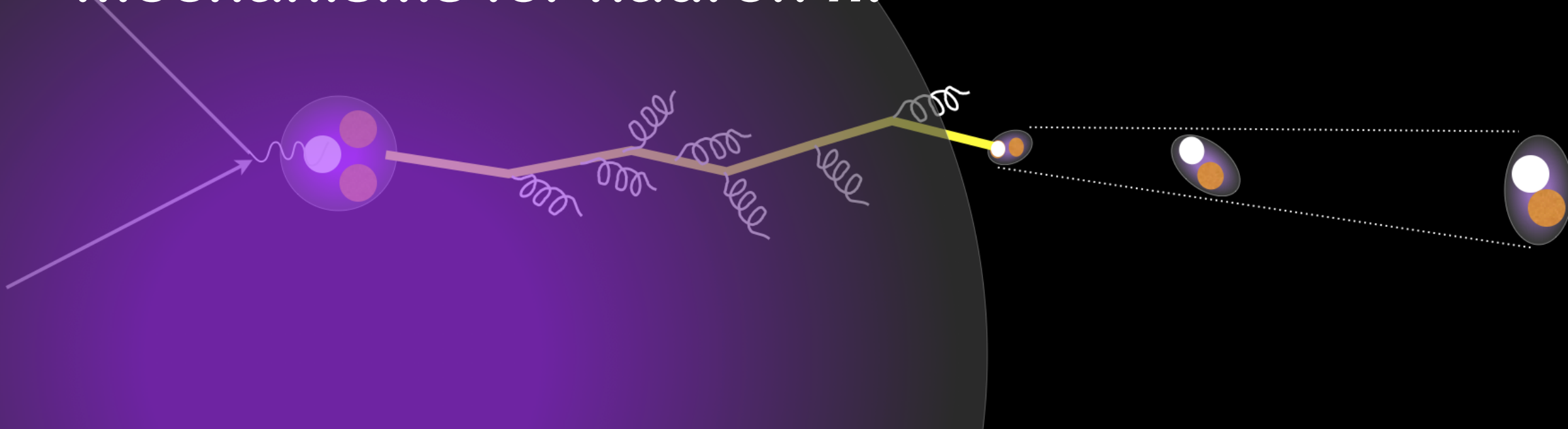
Table 1 from the original **12 GeV** proposal to PAC 30 in 2006 (two decades ago!)

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
f_1	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



By implanting the hadronization process within a nucleus, we gain new dynamical information at *femtometer distance scales*.

From the modifications of kinematic distributions for $A(e,e'h)X$ scattering, we can infer hadronization mechanisms for hadron h .



Important kinematic variables used here

Four-momentum transfer squared Q^2

Energy transfer ν ($=E-E'$ in the laboratory frame)

“Relative energy” $z_h = \frac{E_{hadron}}{\nu}$

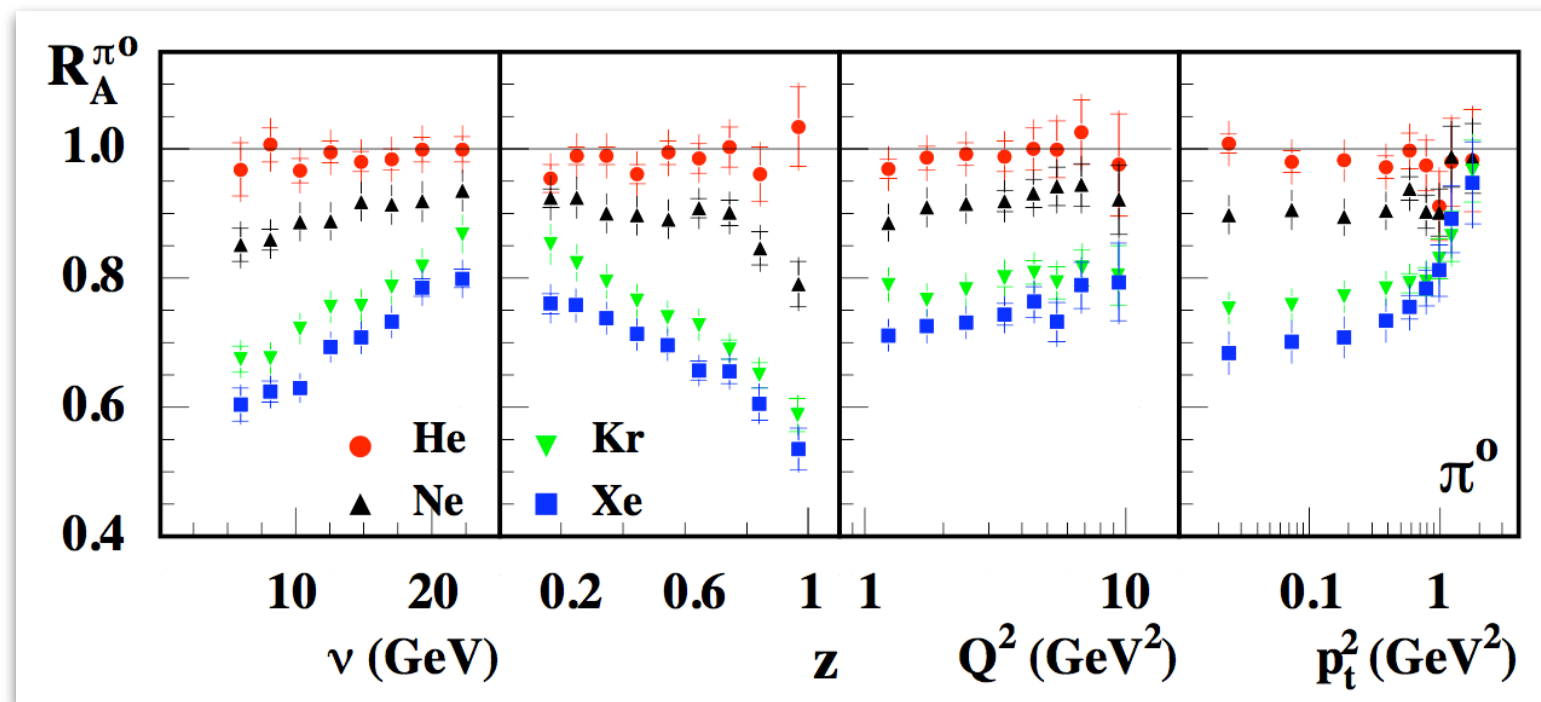
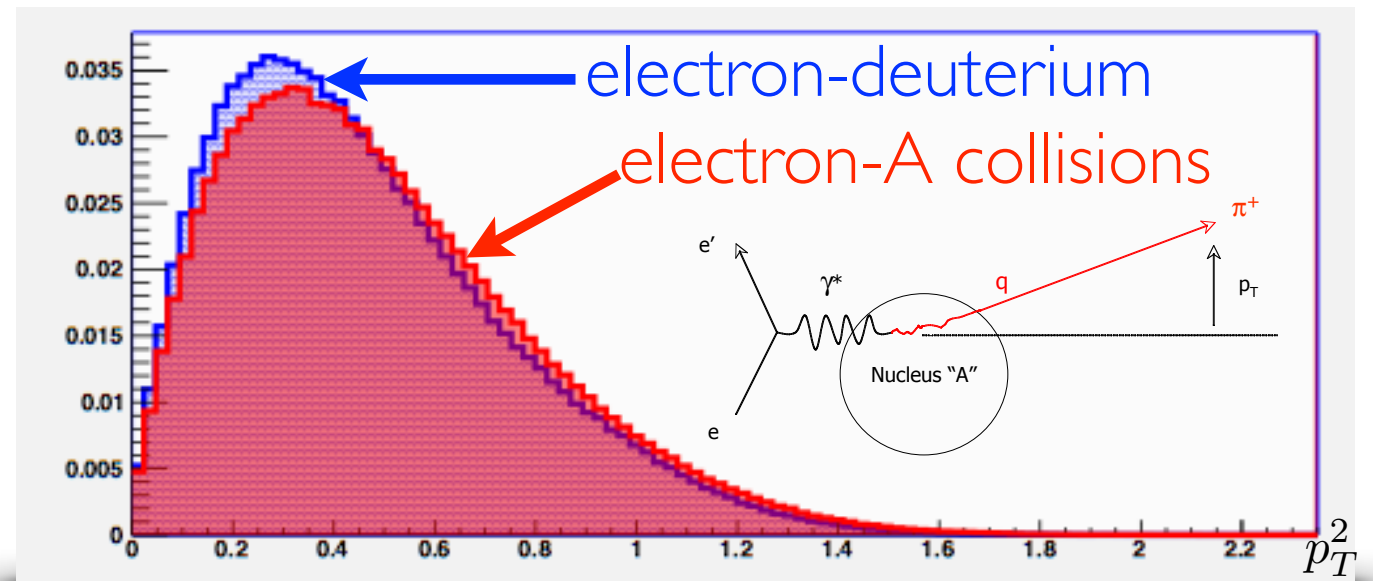
Note: if the virtual photon is absorbed by a light object like a single quark, $z_h \leq 1.0$, but if it is absorbed by a heavy object, it can be **greater than 1.0** (*foreshadowing of diquark discussion later.*)

Momentum transverse to the virtual photon direction p_T

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

Experimental
observables

Transverse momentum broadening



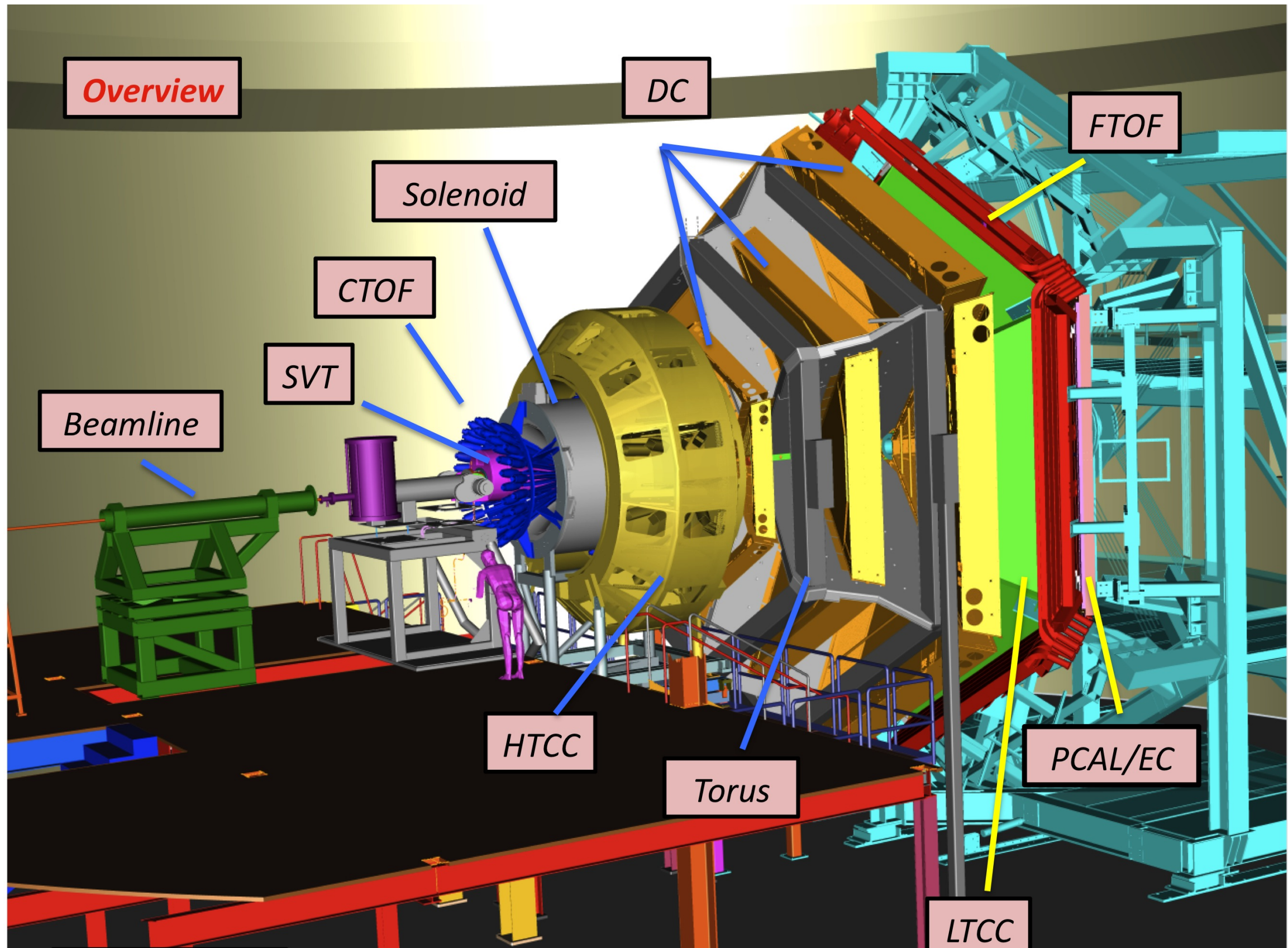
**Hadronic
multiplicity ratio**

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

The Continuous Electron Beam Accelerator at Jefferson Lab



The CEBAF Large Acceptance Spectrometer in Hall B



<https://www.jlab.org/physics/hall-b/clas12>

Leptonuclear hadronization studies with hadron PID

- The **CLAS detector** in **Hall B** of **Jefferson Lab** has a large amount of data for **5 GeV e⁻ beam** (D, C, [Al], Fe, [Sn], Pb) 1998-May 2012 and for **10.5 GeV e⁻ beam** (D, C, Al, Cu, Sn, Pb) 2012-present.
- The 5 GeV beam: unpolarized, 10.5 GeV beam: highly polarized.
- Electrons/positrons, charged and neutral pions, protons and antiprotons are identified for a wide range of momentum. Other particles, such as lambda baryons, are also identified through their decay products. With the 10.5 GeV data, kaons with momentum up to 3 GeV can be separated from pions.

How to understand the hadronization observables

<https://arxiv.org/abs/2004.07236>

Physics Letters B 816 (2021) 136171



Estimating the color lifetime of energetic quarks

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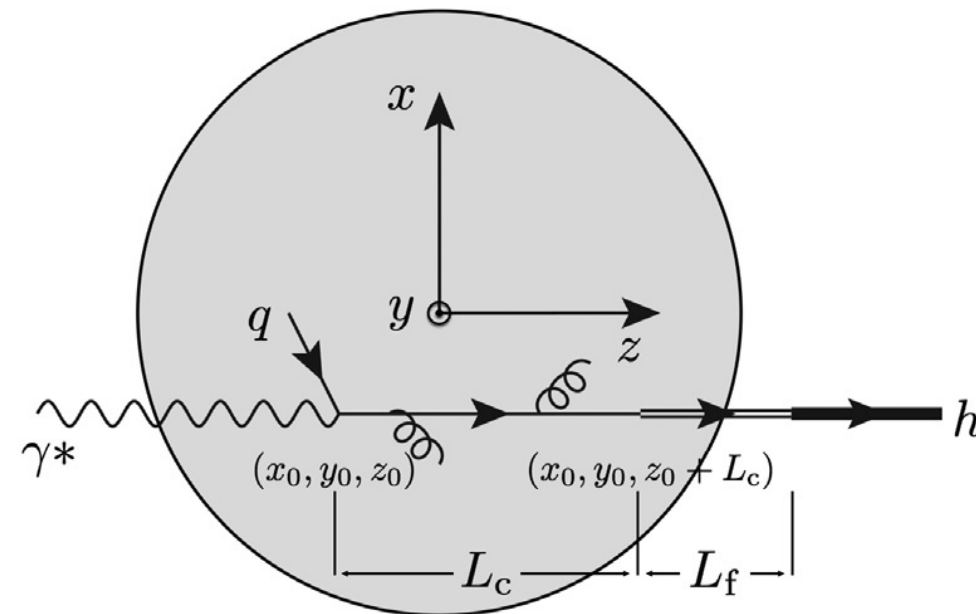


Struck quark moves a distance

L_c as a **colored** object, then becomes a **hadron**.

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

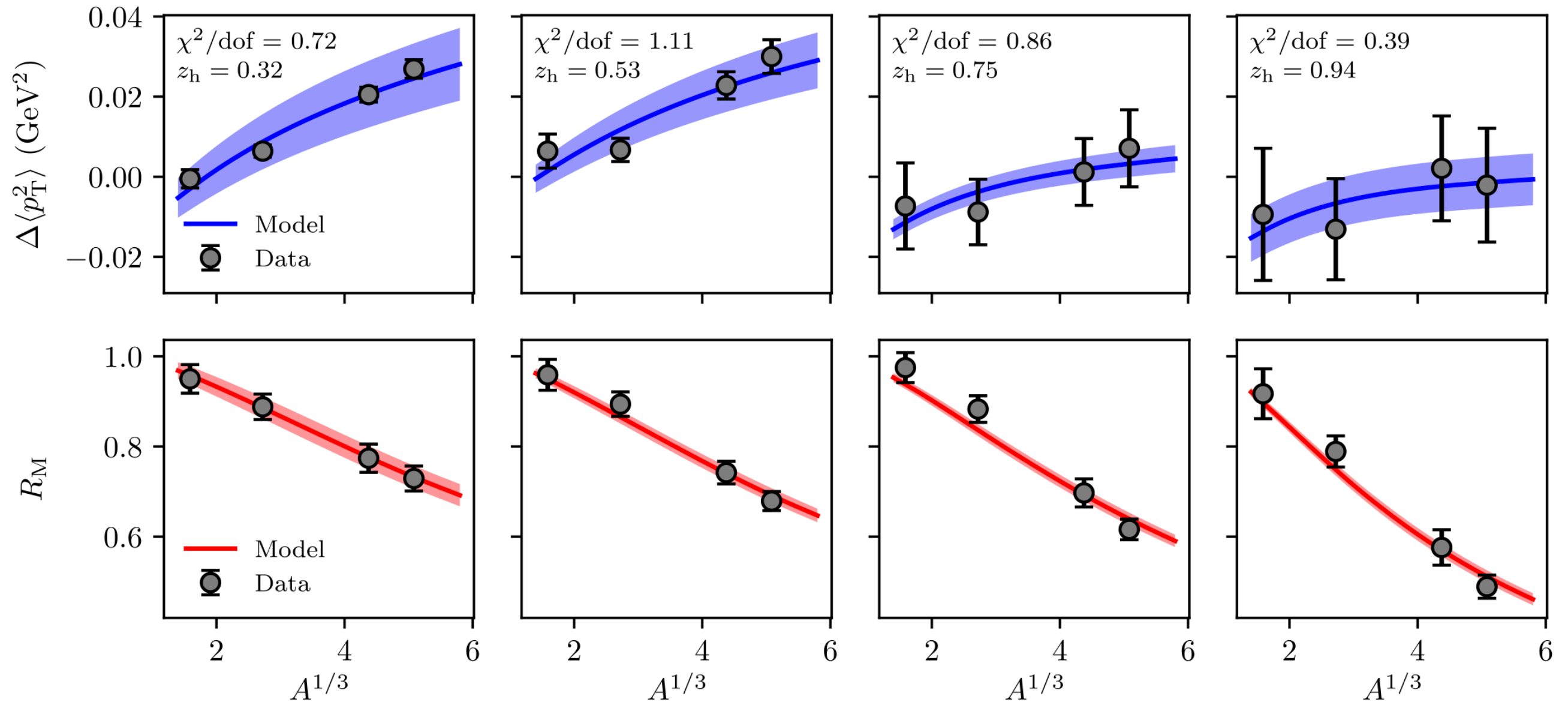
The color lifetime of the struck quark is distributed stochastically as a decaying exponential.



About this model

- A **unique analysis** of two published HERMES measurements. We isolate the roles of **quark energy loss and pre-hadron formation** in describing the data.
- **Two observables** are fitted **simultaneously**.
- The primary ingredient is the **well-known density distribution** in nuclei.
- A second ingredient is the measured π -N cross section
- Only **3** parameters

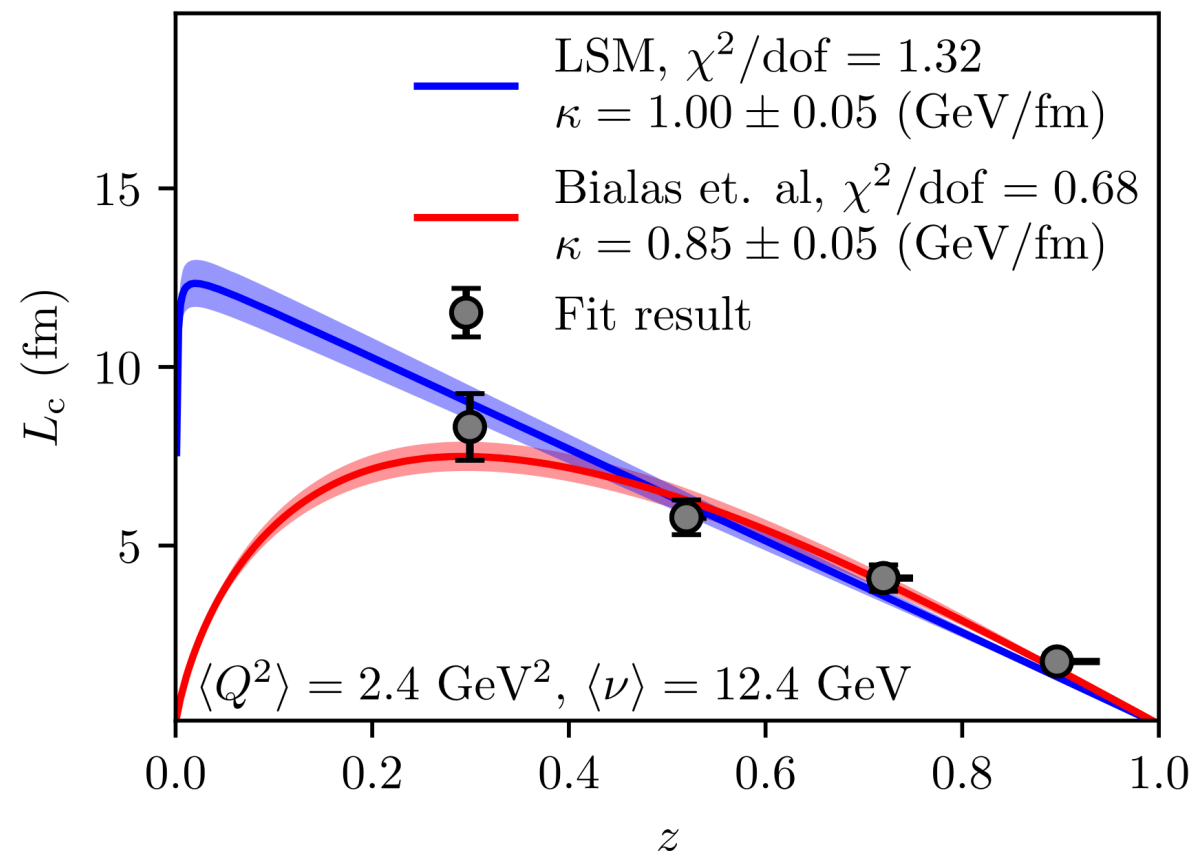
These are the results of the simultaneous fit to two observables



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

<https://arxiv.org/abs/2004.07236>

This is a fit of the color lifetime parameter L_c we find to the color lifetime calculated in the Lund String Model



The blue line
only describes
the **struck
quark**

The red line
describes the
**struck quark and
the residual
quarks**

Independent determination of the string constant of the LSM!

Message: our space-time model is **consistent** with known **string fragmentation**, and for HERMES the **time range is 2-8 fm/c**.

We believe we have a correct physical picture for **pion formation**.

<https://arxiv.org/abs/2004.07236>

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

S. MORÁN *et al.*

PHYSICAL REVIEW C **105**, 015201 (2022)

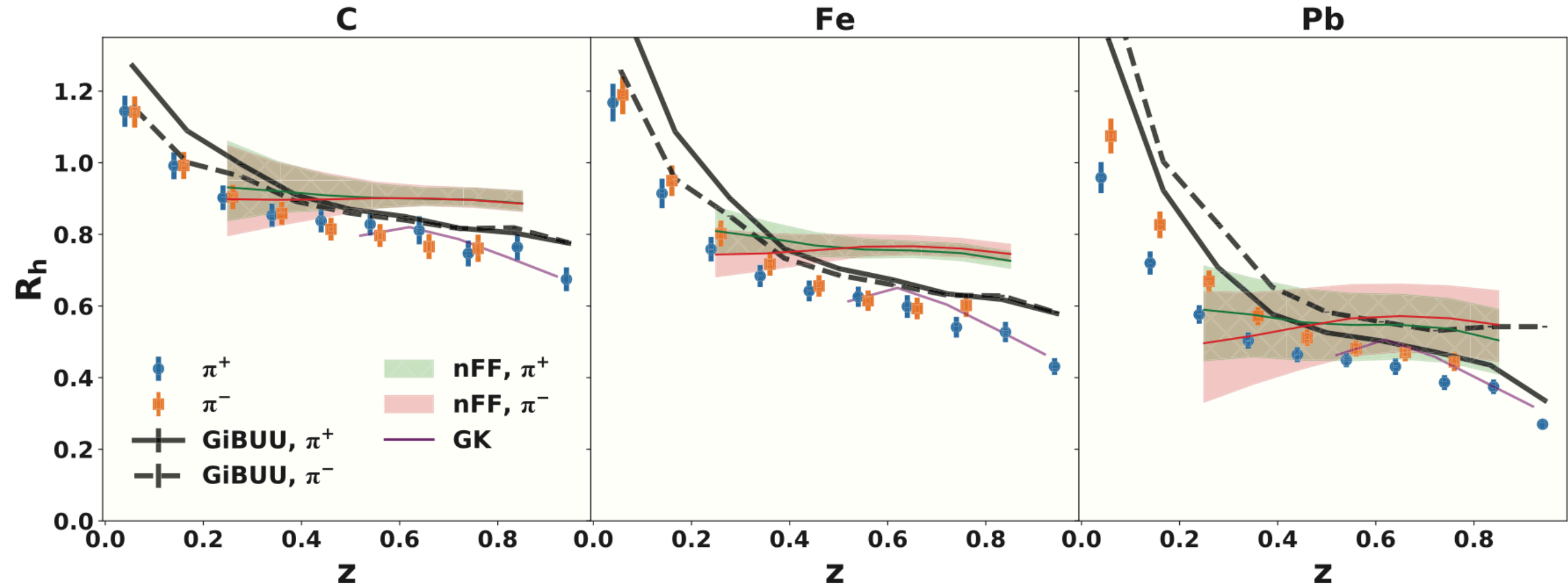


FIG. 1. Multiplicity ratio of π^+ and π^- as a function of z ; the three different panels show results for C, Fe, and Pb targets, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties, which is dominated by the systematic uncertainties that are partially 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 — $R_M^{\pi^+}$

MEASUREMENT OF CHARGED-PION PRODUCTION ...

PHYSICAL REVIEW C **105**, 015201 (2022)

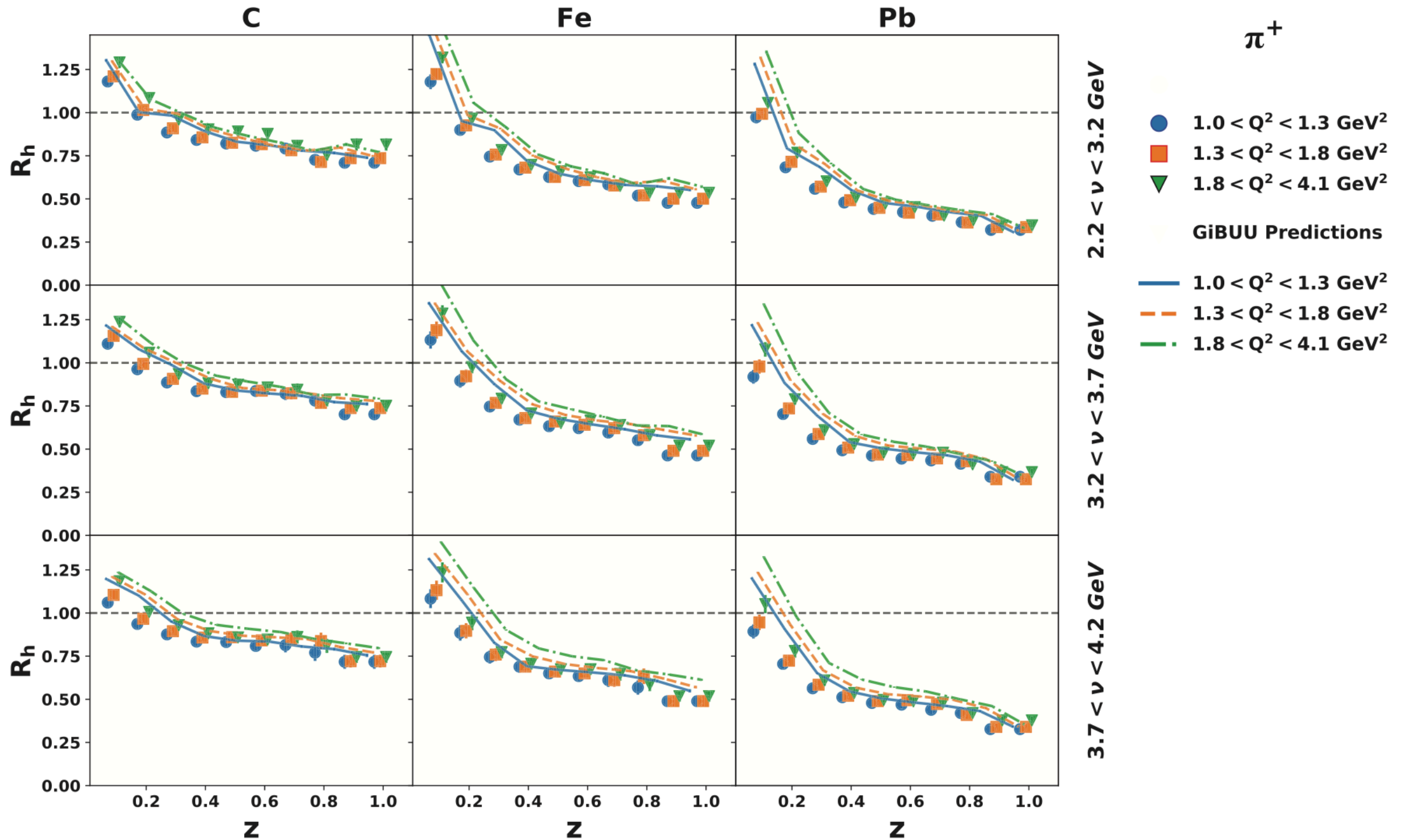


FIG. 2. Multiplicity ratios of π^+ as a function of z for various intervals of ν (in different rows) and Q^2 (different marker colors). The left, middle, and right panels correspond to C, Fe, and Pb, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties. 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 — $R_M^{\pi^-}$

S. MORÁN *et al.*

PHYSICAL REVIEW C **105**, 015201 (2022)

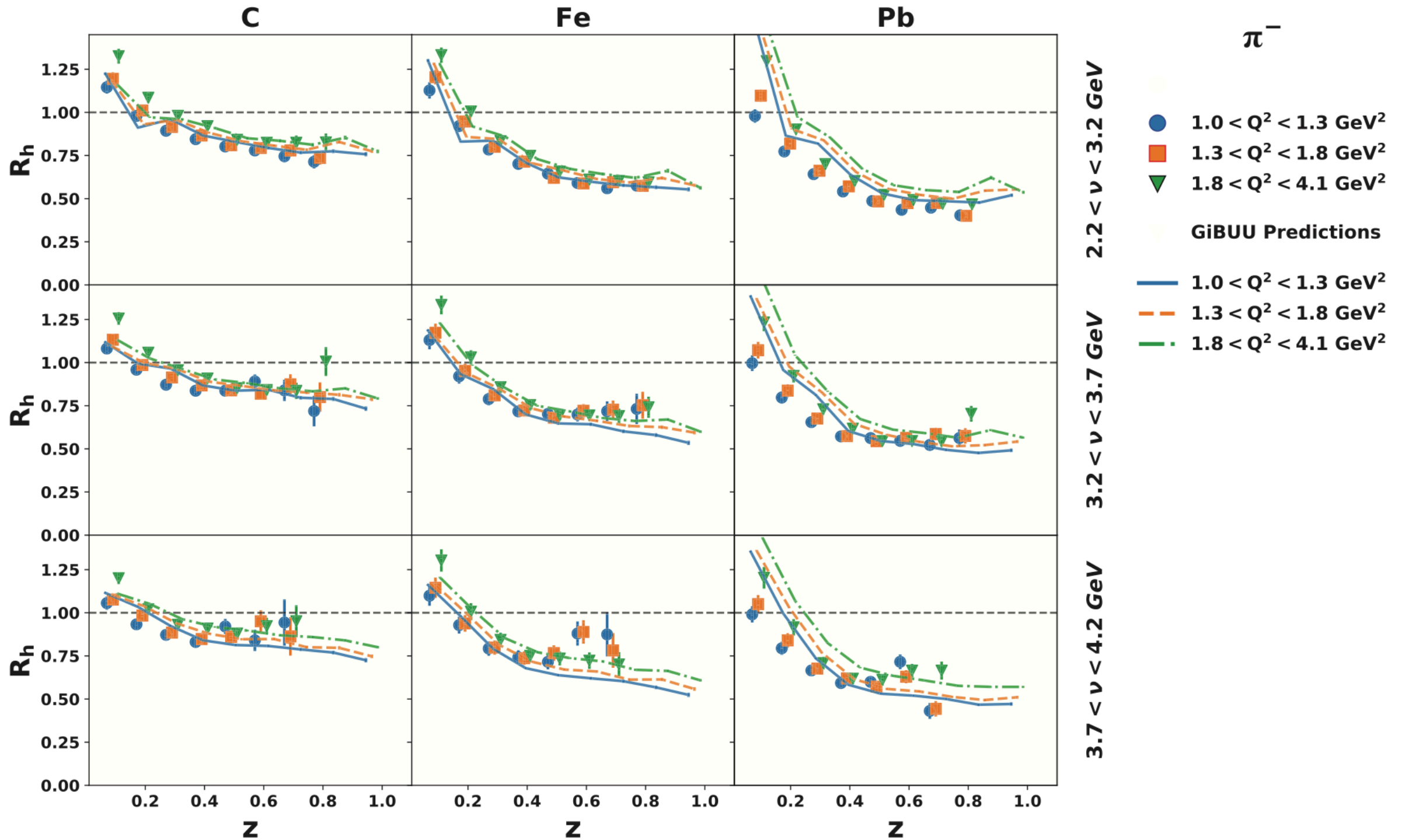


FIG. 3. Multiplicity ratios of π^- as a function of z for various intervals of ν (in different rows) and Q^2 (different marker colors). The left, middle, and right panels correspond to C, Fe, and Pb, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties. 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 – $R_M^{\pi^+}$

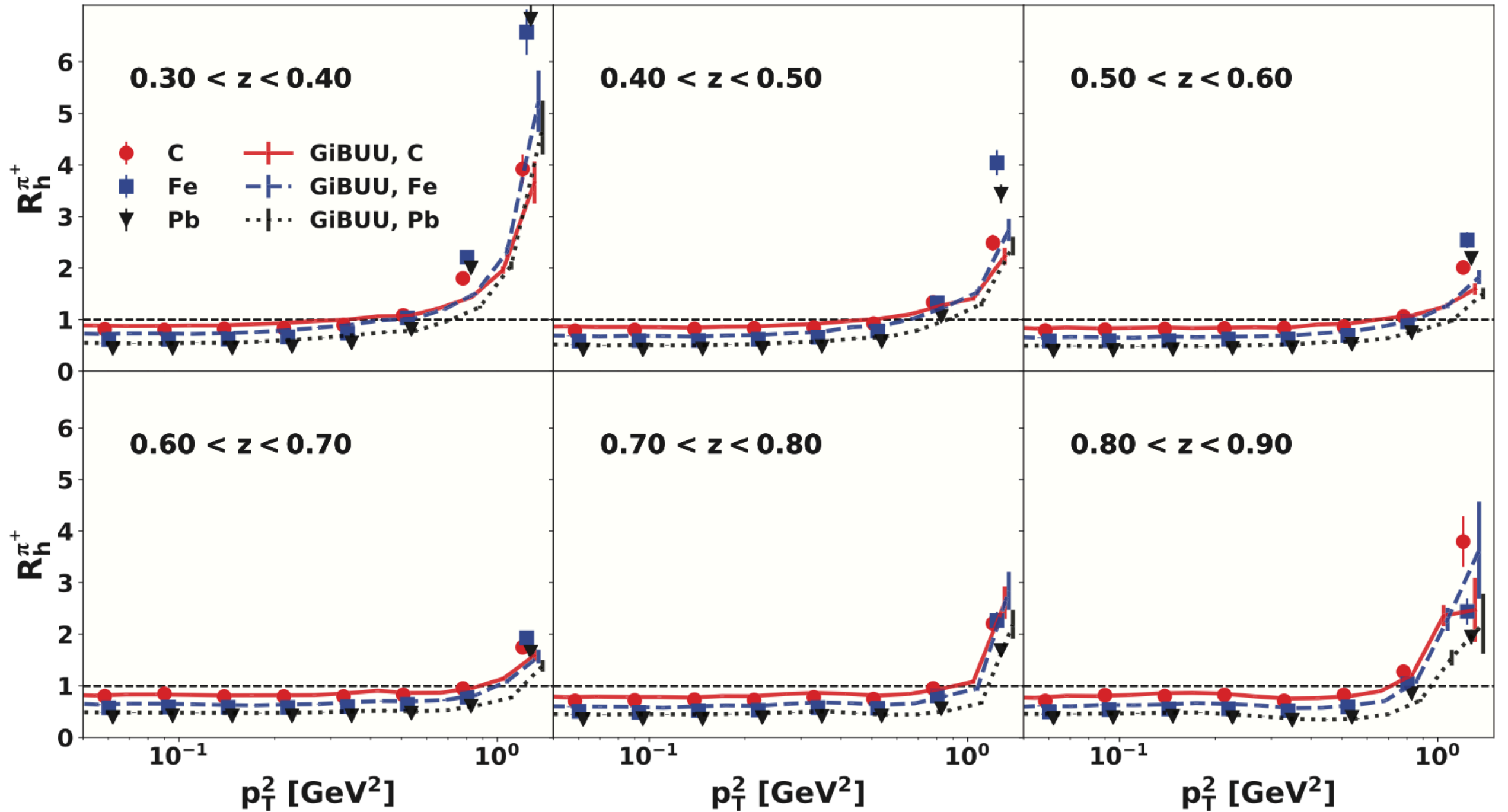


FIG. 4. Multiplicity ratio of π^+ as a function of p_T^2 for various z intervals; the red, blue, and black markers show the measured results for C, Fe, and Pb targets. The error bars represent the quadrature sum of systematic and statistical uncertainties. Lines of the same colors represent the results 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 – $R_M^{\pi^-}$

MEASUREMENT OF CHARGED-PION PRODUCTION ...

PHYSICAL REVIEW C **105**, 015201 (2022)

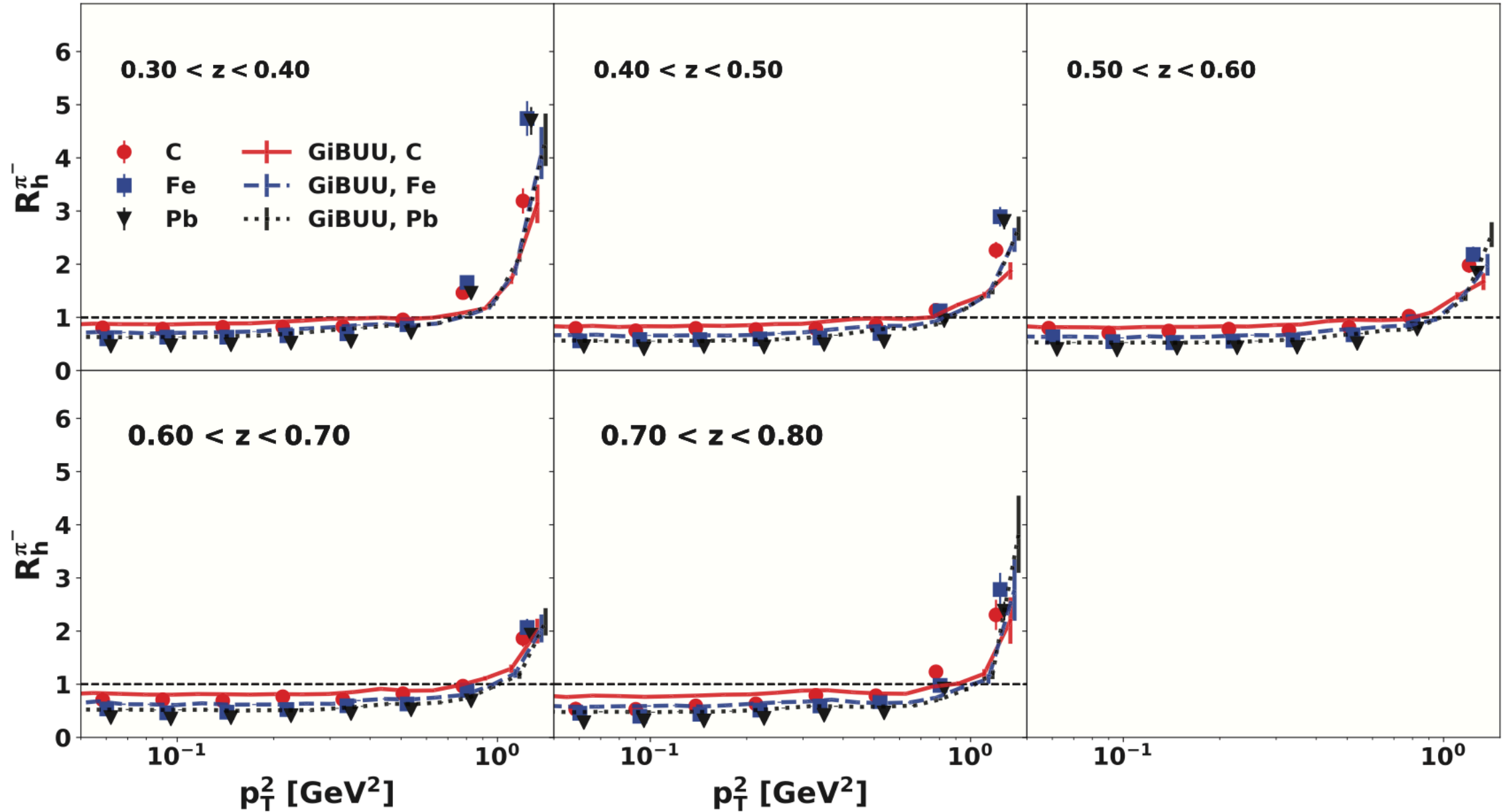


FIG. 5. Multiplicity ratio of π^- as a function of the p_T^2 for various z intervals; the red, blue, and black markers show the measured results for C, Fe, and Pb targets. The error bars represent the quadrature sum of systematic and statistical uncertainties. Lines of the same colors represent the results 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* $R_M^{\pi^0}$

T. MINEEVA *et al.*

PHYSICAL REVIEW C **112**, 035203 (2025)

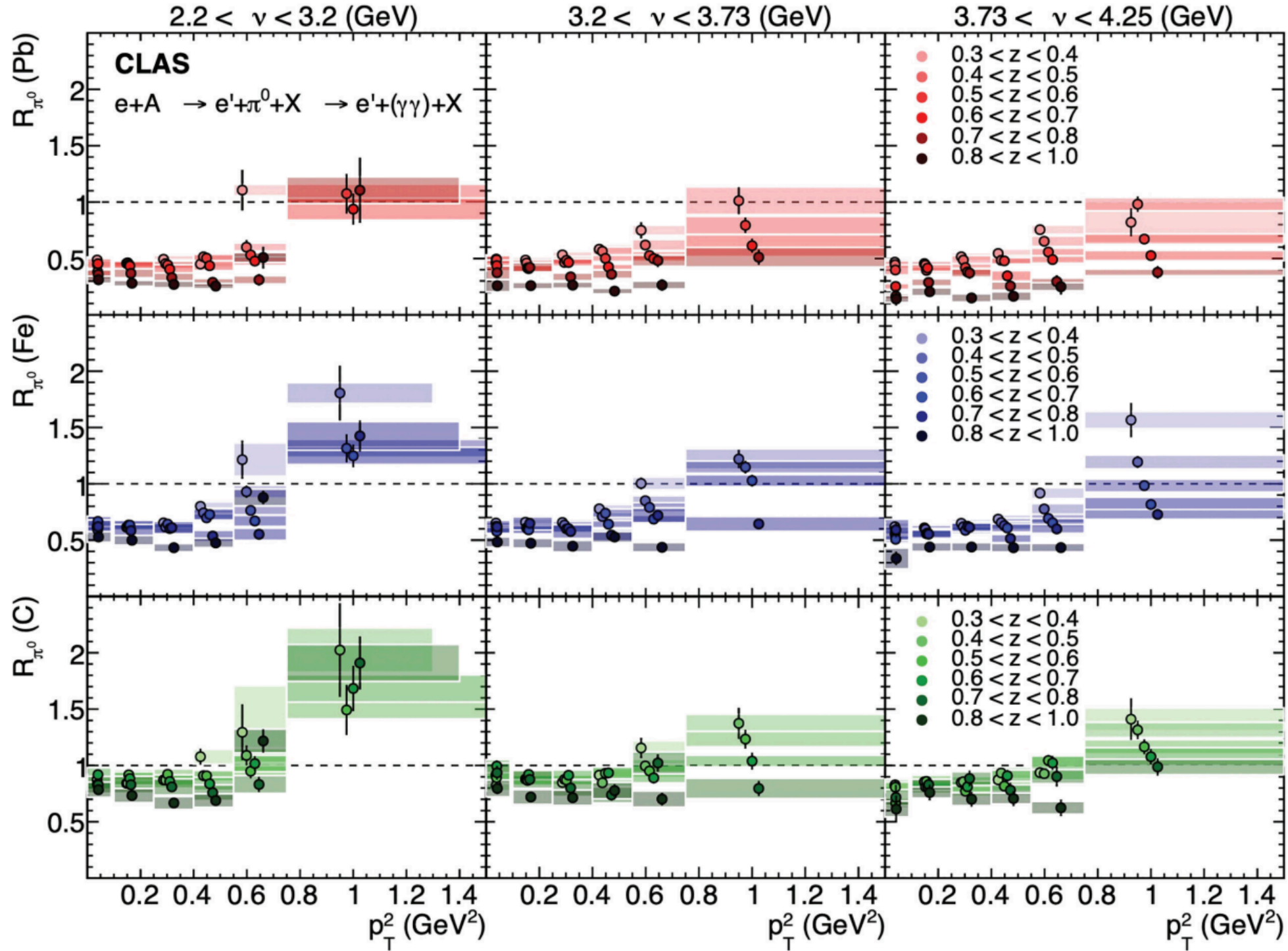


FIG. 3. π^0 multiplicity ratios for C, Fe, and Pb in (ν, z, p_T^2) bins plotted as a function of p_T^2 in bins of ν (top horizontal line) and z (indicated by the color). Points are shifted for ease of visualization around the mean value of p_T^2 . Statistical uncertainties are indicated by black vertical 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 $R_M^{\pi^0}$

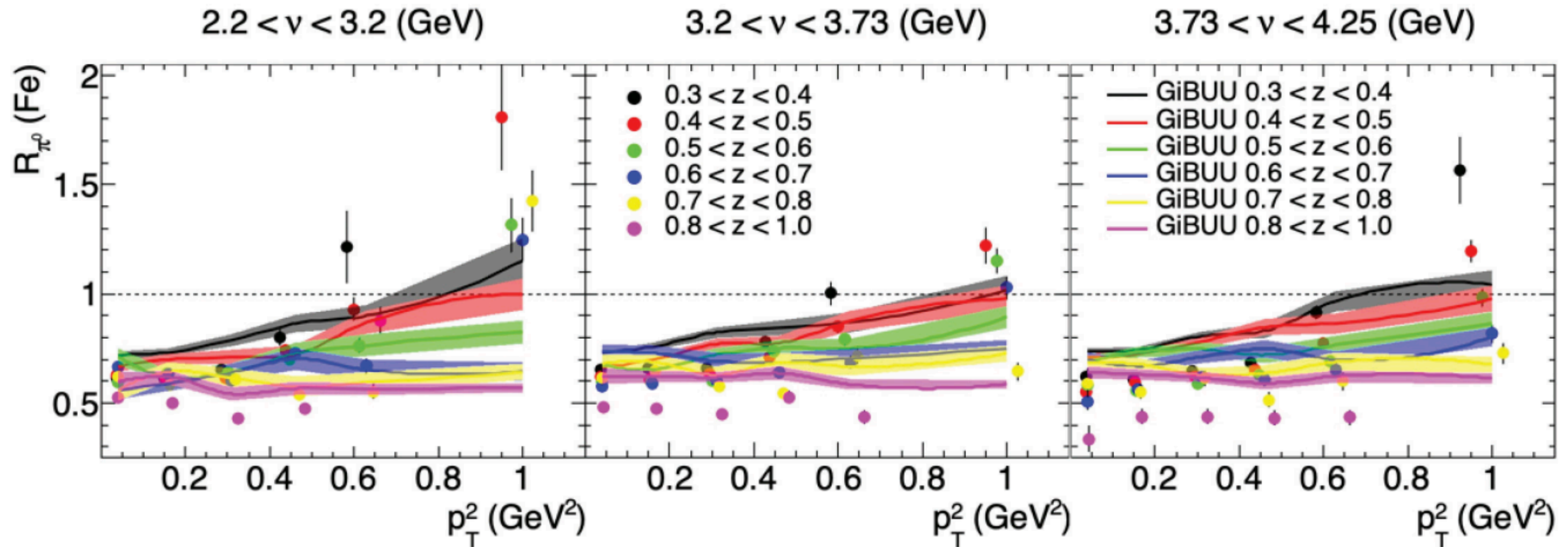
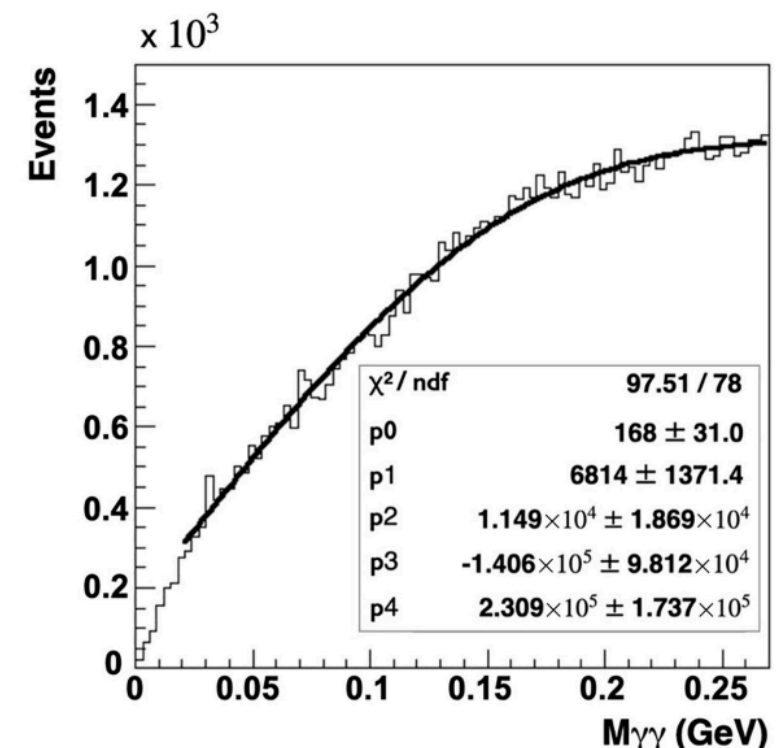
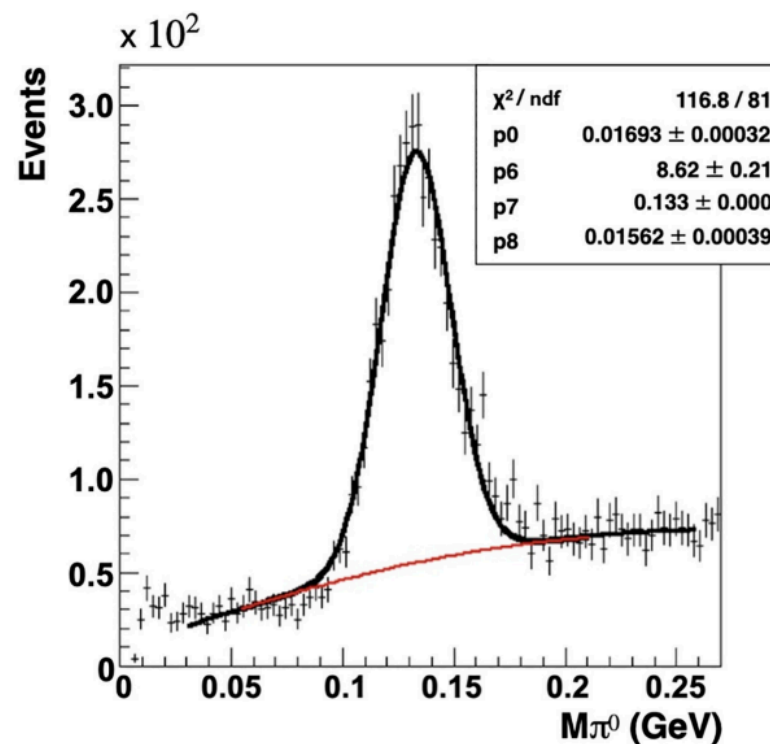


FIG. 4. π^0 multiplicity ratios for Fe in (v, z, p_T^2) as a function of p_T^2 in bins of v (each panel) and z (indicated by the color). Markers correspond to data points; the solid lines correspond to GiBUU projections with the width of the band indicating statistical errors of the simulation.

Invariant mass peak and combinatorial background calculation.

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



Published results: 5 GeV *lambda baryon multiplicity ratio* $R_M^{\Lambda^0}$

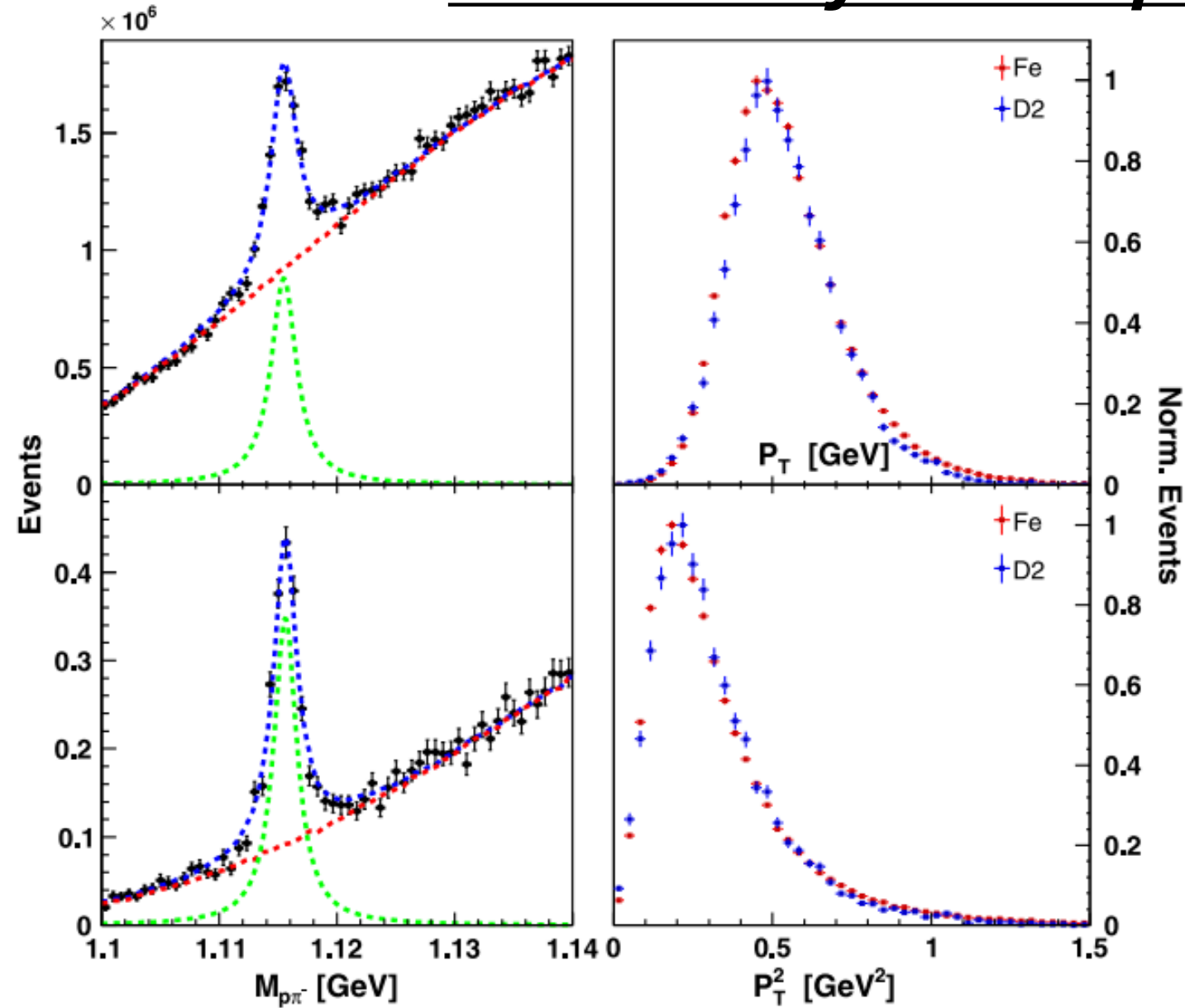


FIG. 2. Left: acceptance-weighted (p, π^-) invariant mass distributions for the Fe/LD2 (top/bottom) targets. Blue curves represent the RooFit χ^2 minimization using a simple Breit-Wigner (BW) function for the Λ signal and event mixing for the combinatorial background (red dotted curves). The green distributions are the fit results that are integrated to obtain the Λ yields. Right: comparison of Fe (red) and LD2 (blue) acceptance-weighted p_T/p_T^2 (top/bottom) normalized distributions to their peak height.

Published results: 5 GeV lambda baryon multiplicity ratio $R_M^{\Lambda^0}$

PHYSICAL REVIEW LETTERS **130**, 142301 (2023)

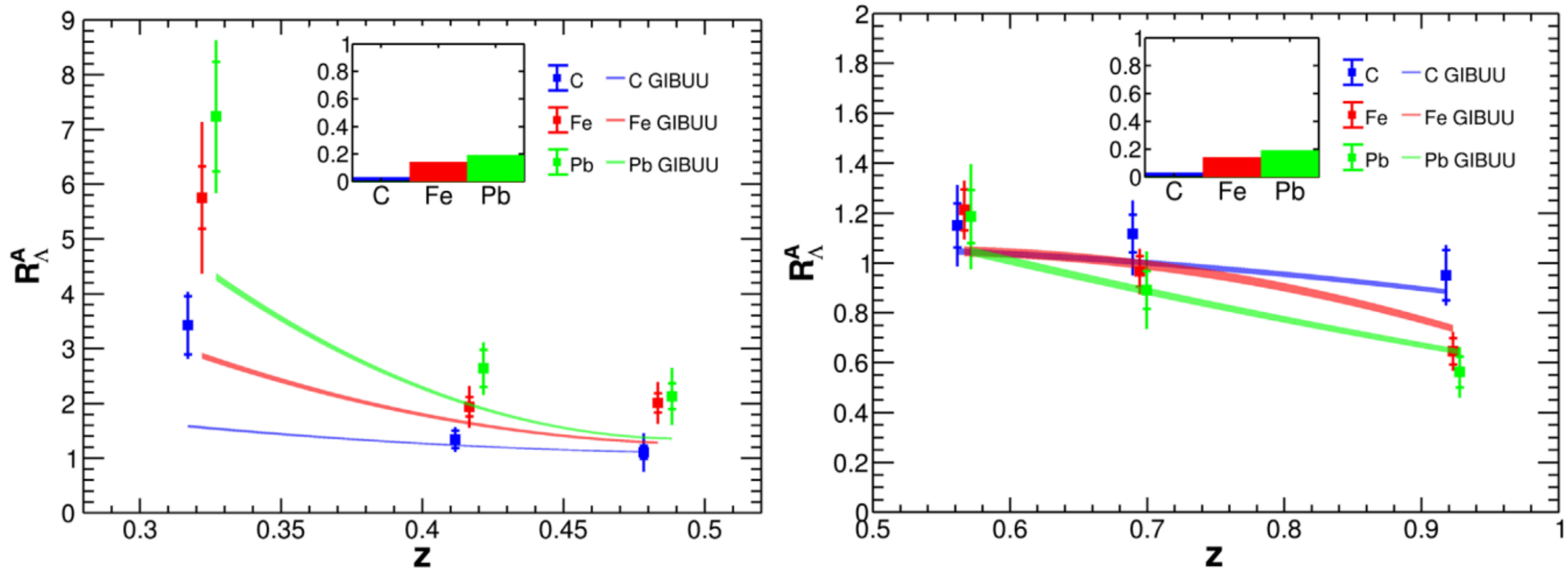


FIG. 3. Λ z -binned multiplicity ratios for carbon, iron, and lead (the results are horizontally shifted for clarity). The outer error bars are the $p2p$ systematic uncertainties added in quadrature with the statistical uncertainties. The inset contains the total normalization uncertainties for each nucleus. The plots illustrate the results of the low (left) and high (right) z ranges corresponding, respectively, to the target and current fragmentation regions. The curves correspond to GiBUU model calculations [43].

Extremely large values: $>700\%$ for Pb at low z !

Published results: 5 GeV *lambda baryon* p_T broadening $\Delta p_T^2(\Lambda^o)$

PHYSICAL REVIEW LETTERS **130**, 142301 (2023)

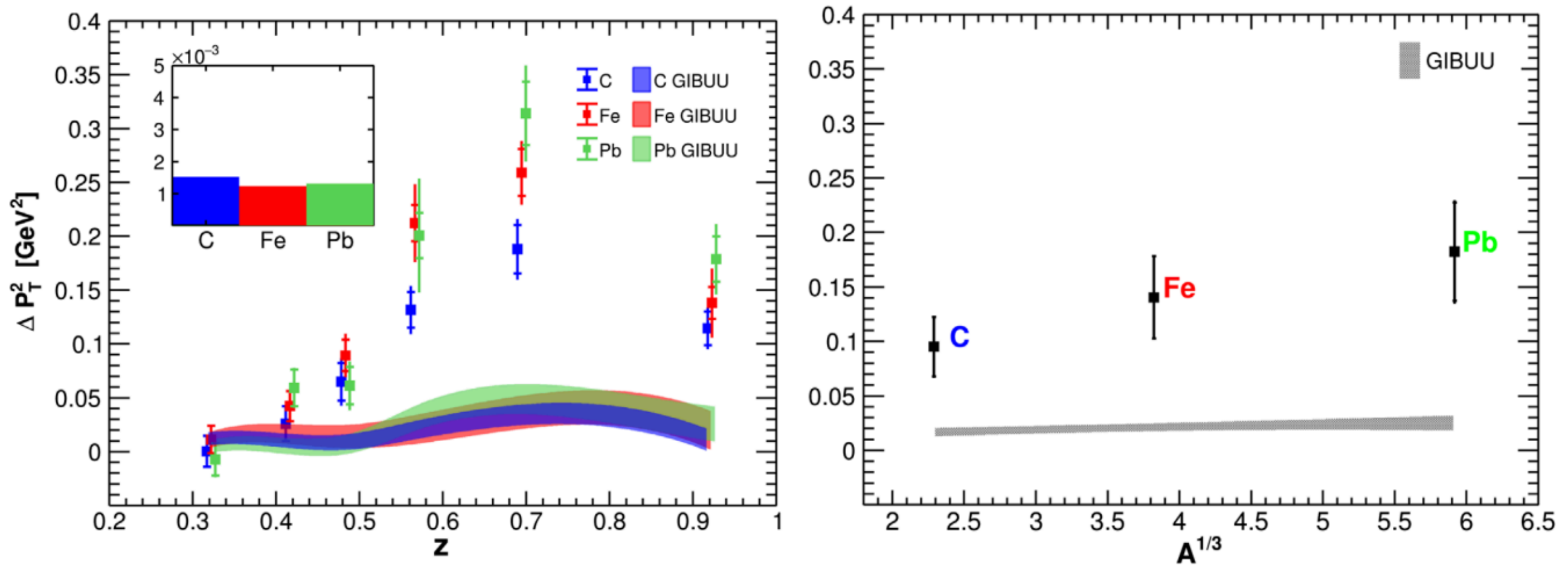
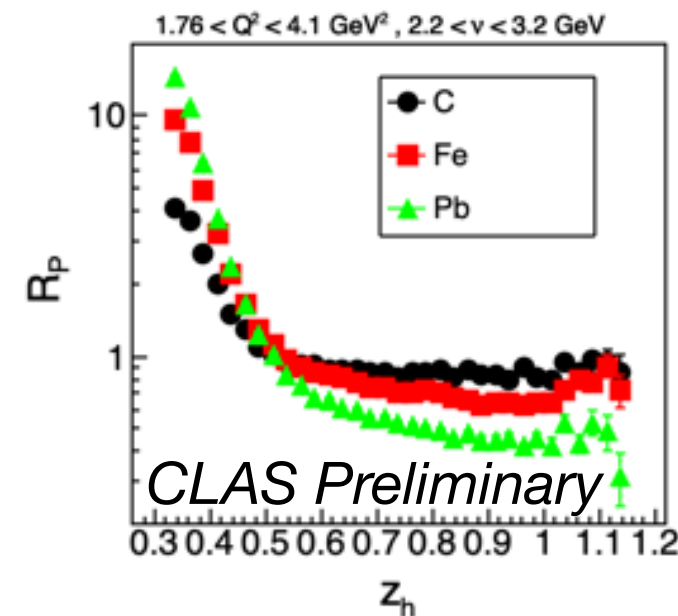
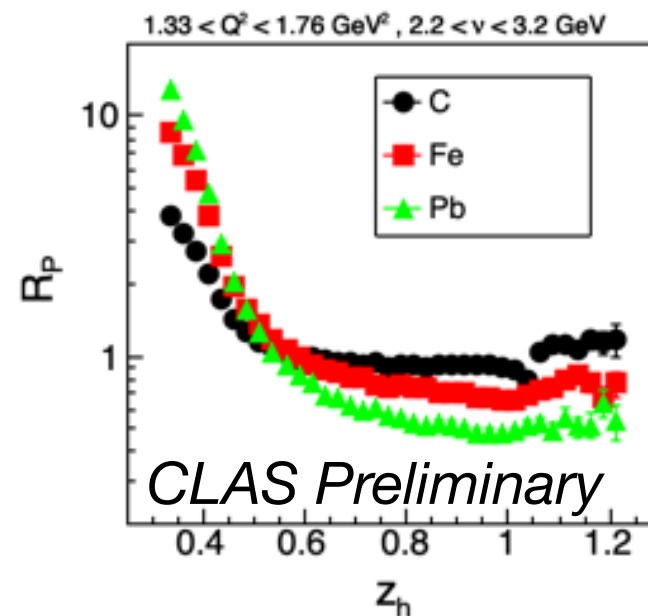
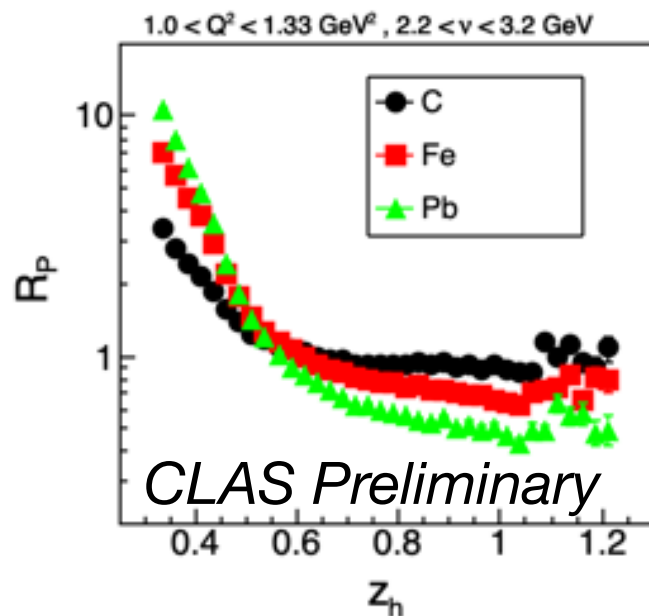


FIG. 4. Left (right): the z (nuclear radius)-dependent Δp_T^2 results for the three nuclei (results are horizontally shifted for clarity). The outer error bars are the $p2p$ systematic uncertainties added in quadrature with the statistical uncertainties, while the normalization uncertainties are presented in the inset for the z dependence and found to be less than 1% for the A dependence. The GiBUU model calculations are represented by the colored (left) and shaded (right) bands obtained by interpolating the model points and their statistical uncertainties.

Extremely large values: >0.3 GeV² for Pb at $z=0.7$!
All results greatly exceed GiBUU predictions!

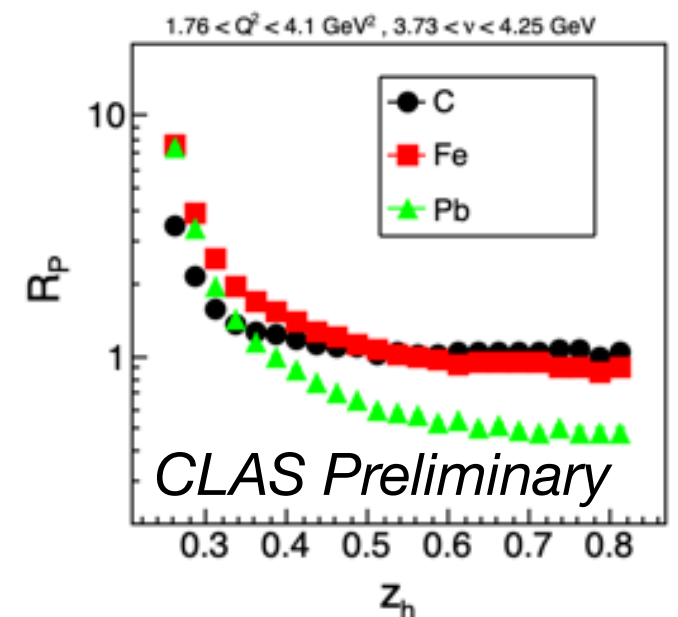
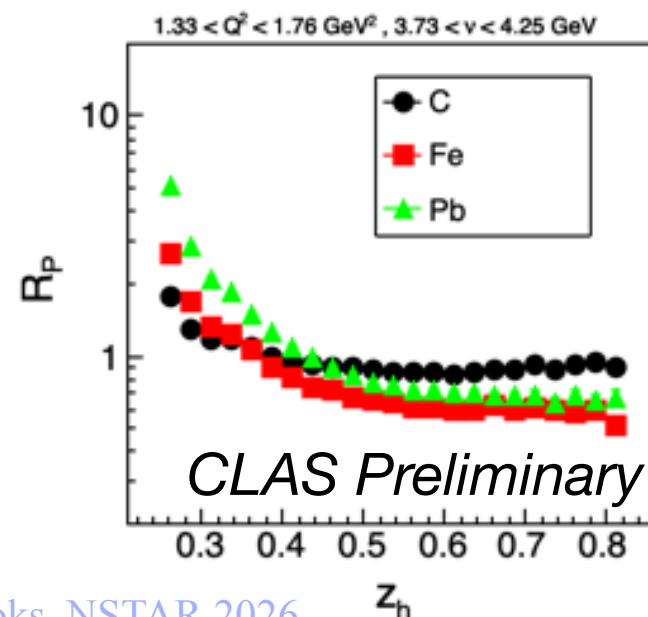
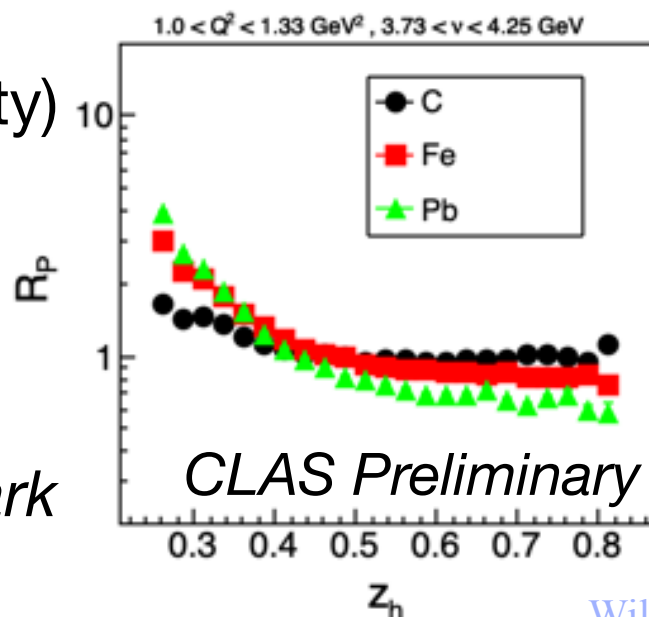
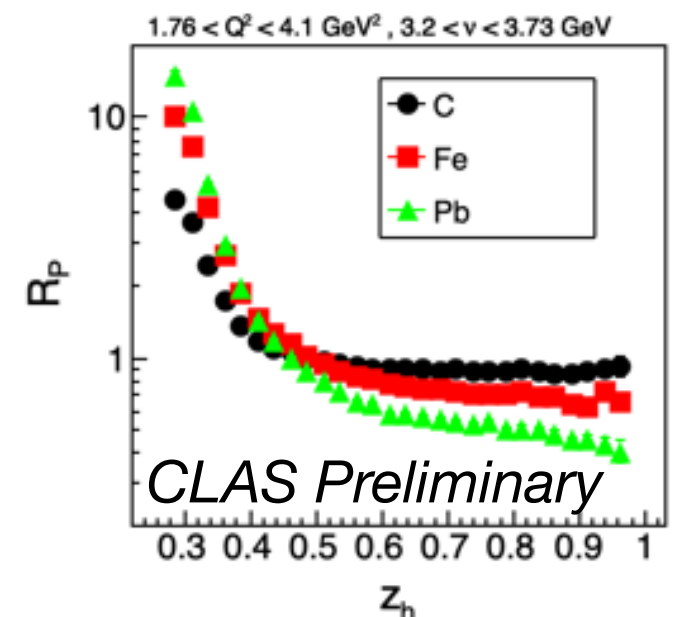
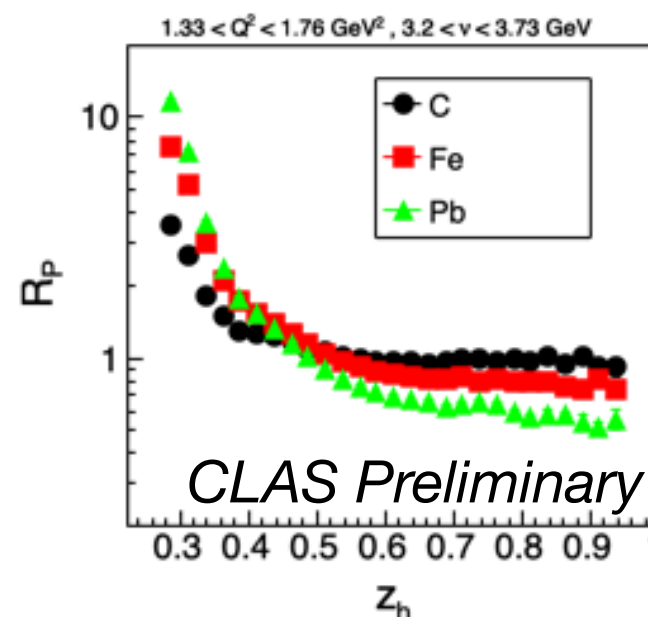
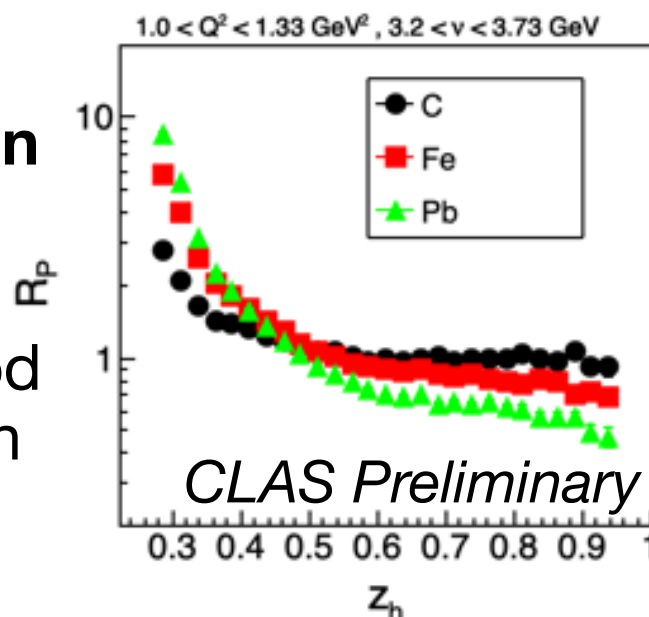
PROTON

Enhancement is a factor of 10 at lower z_h . A crossover is evident.



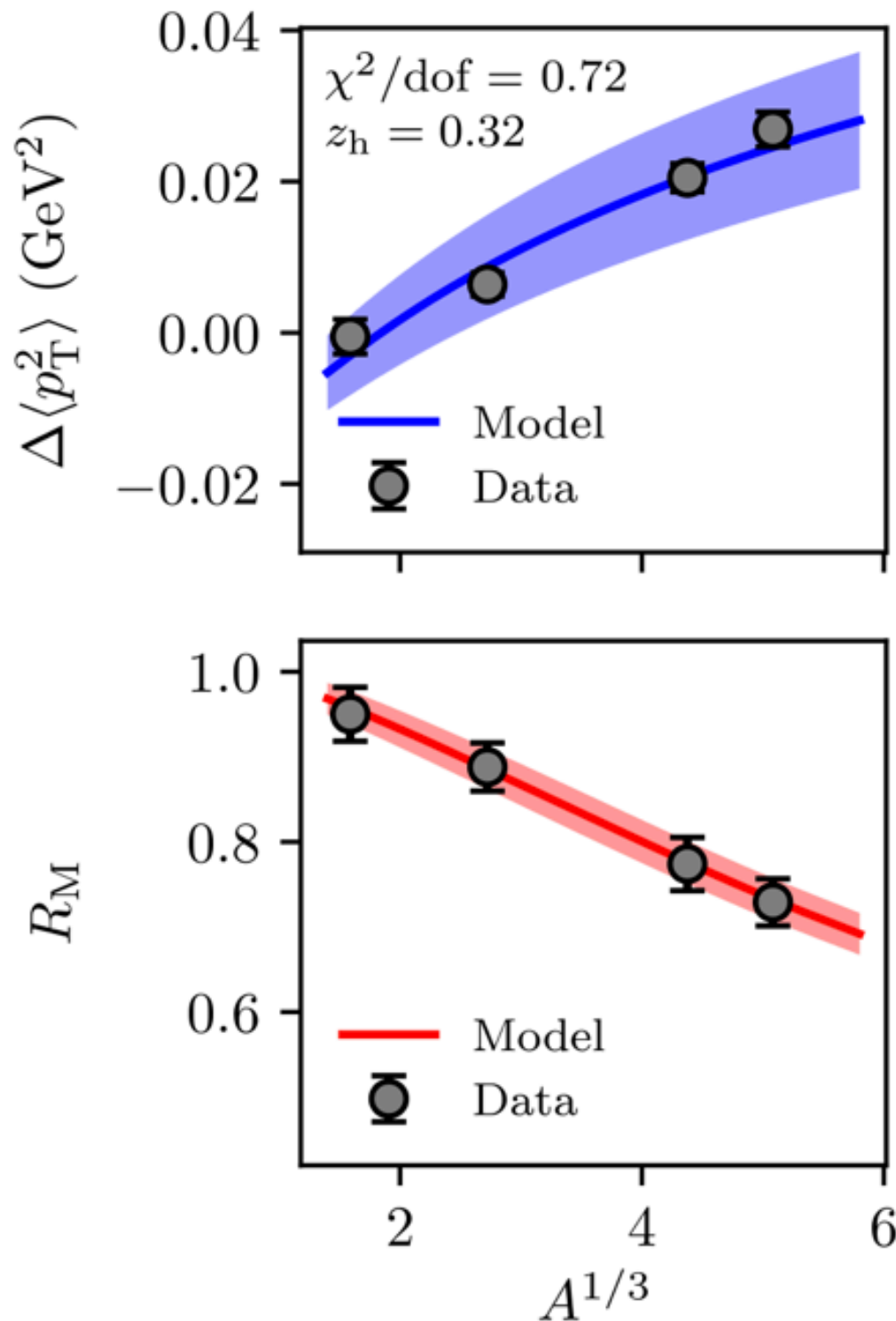
CLAS EG2 SIDIS Proton Production Analysis

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



Note behavior at high $z_h \sim 1.2$; *Diquark correlations?!*

Diquark degrees of freedom?



Compare *pion* broadening of **0.02 GeV²** to **0.2 GeV²** (lambda baryon) and multiplicity ratio of ~ 0.8 to a **factor of 7** (lambda baryon) and a **factor of 10** (proton)!

The struck object traveling through the nucleus is an **order of magnitude** more **disruptive** for **proton** and **lambda** than for pion production!

Diquark evidence
in at least two kinds
of places:

(1) Production of
hadrons
containing the
[ud] spin 0
diquark,
because target
nucleons (p, n)
contain it.

(2) Final state
hadrons that
contain the
same diquark
(e.g., Λ and Σ^0 ,
or Σ^+ and Ξ^0)

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
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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
f_1	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
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CLAS Preliminary

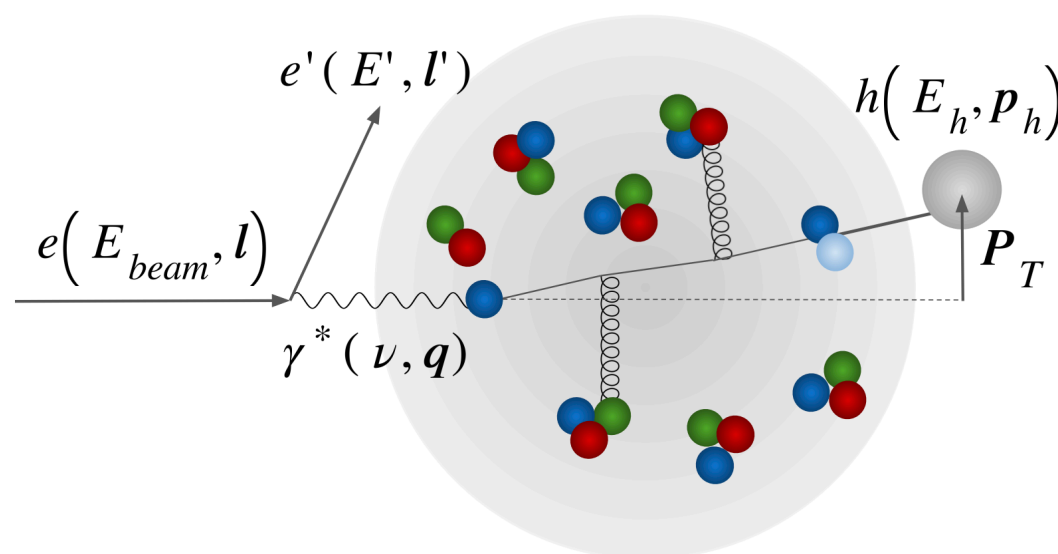
First multidimensional measurement of transverse momentum broadening of positive pions in nuclei at CLAS

Esteban F. Molina Cardenas^a, Hayk Hakobyan^{a,b}, Taisiya Mineeva^{a,b}, William Brooks^{a,b}, Raphaël Dupré^c, Jorge Lopez^a, Sebastian Moran^a and the CLAS Collaboration!

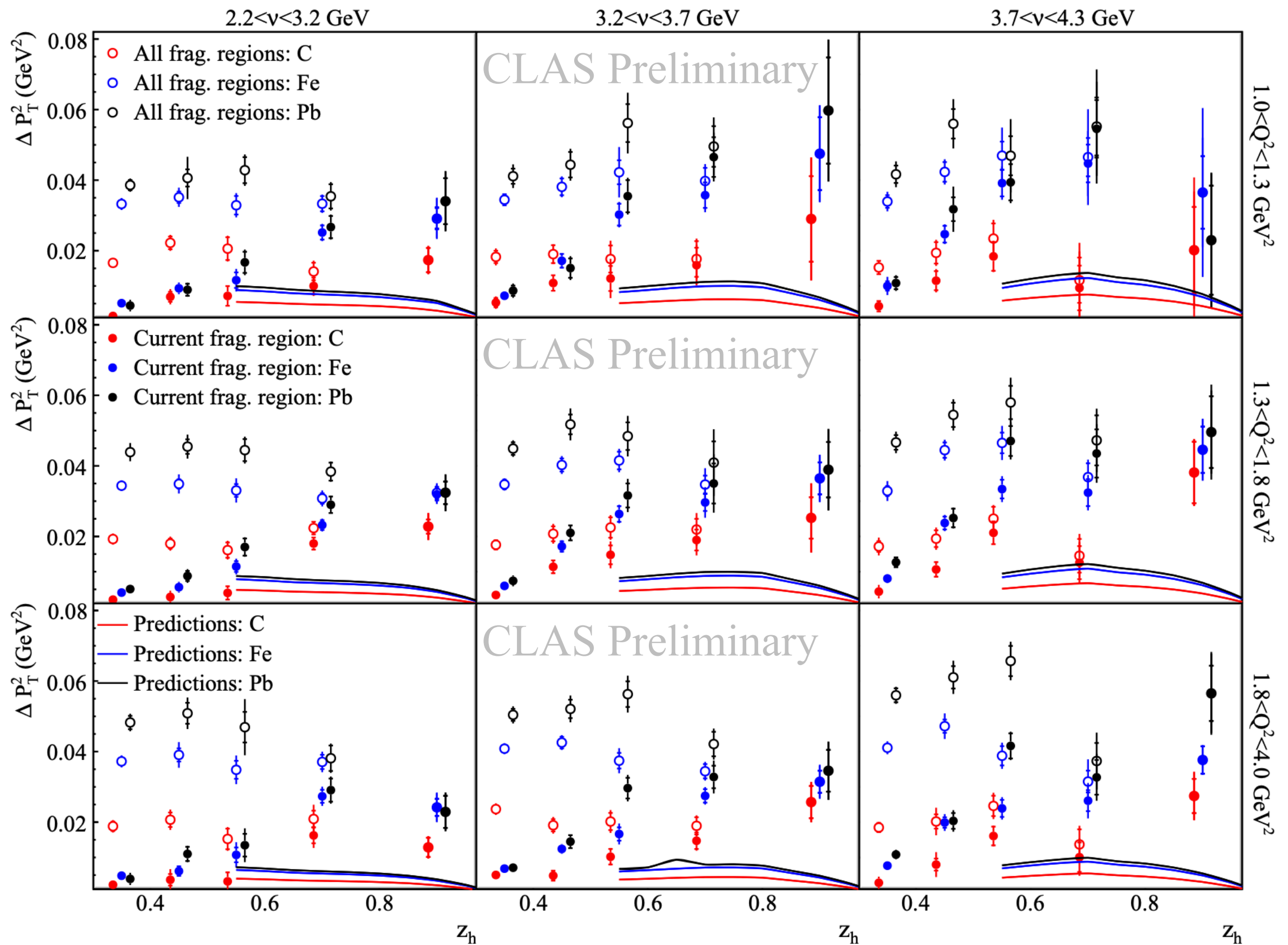
^a*Centro Científico Tecnológico de Valparaíso-CCTVal, Universidad Técnica Federico Santa María, General Bari 699, Valparaíso, Chile*

^b*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Casilla 110-V, Chile*

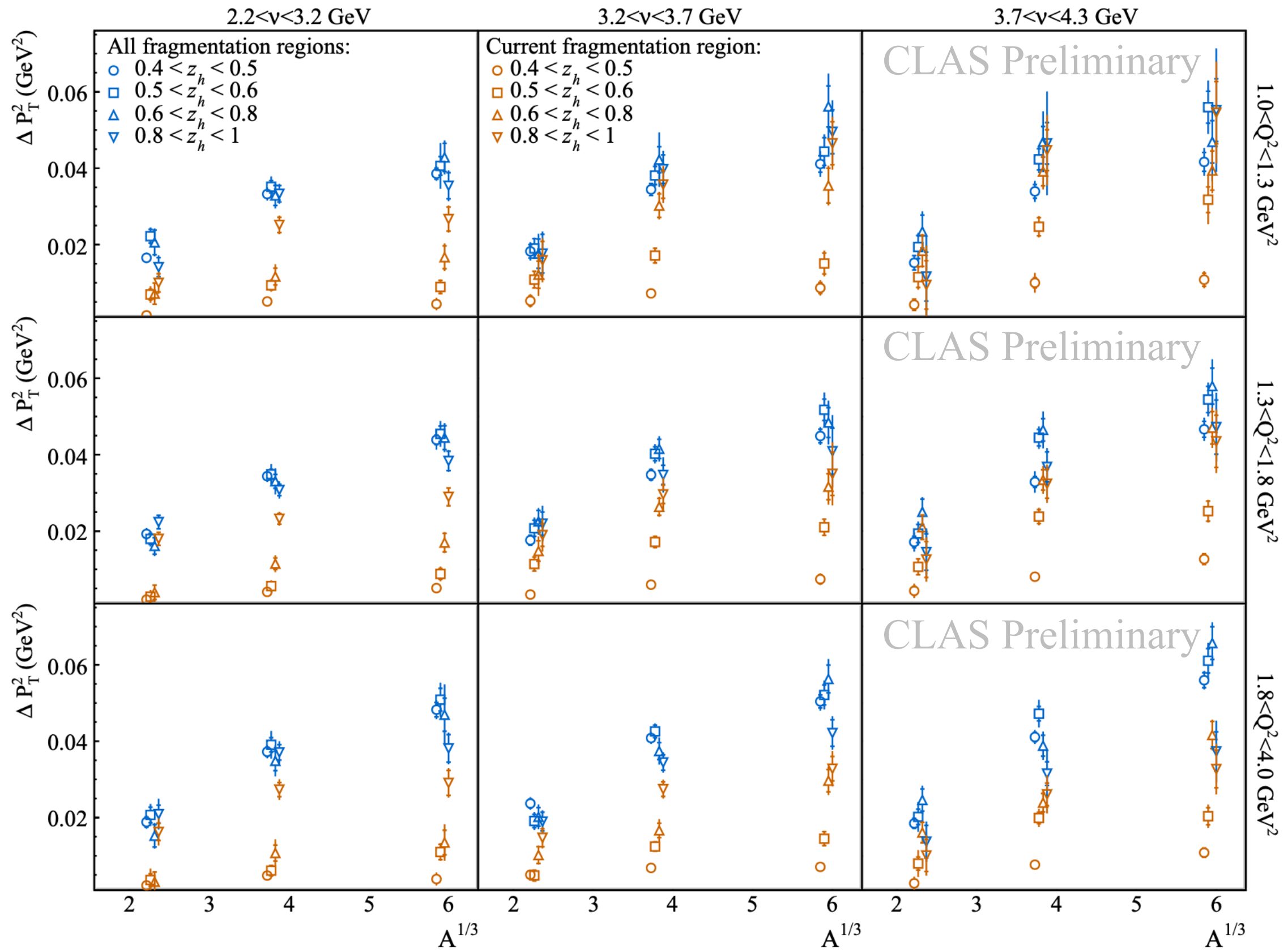
^c*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, 91405, France*



Preliminary results: Multi-dimensional π^+ p_T broadening $\Delta p_T^2(\pi^+)$



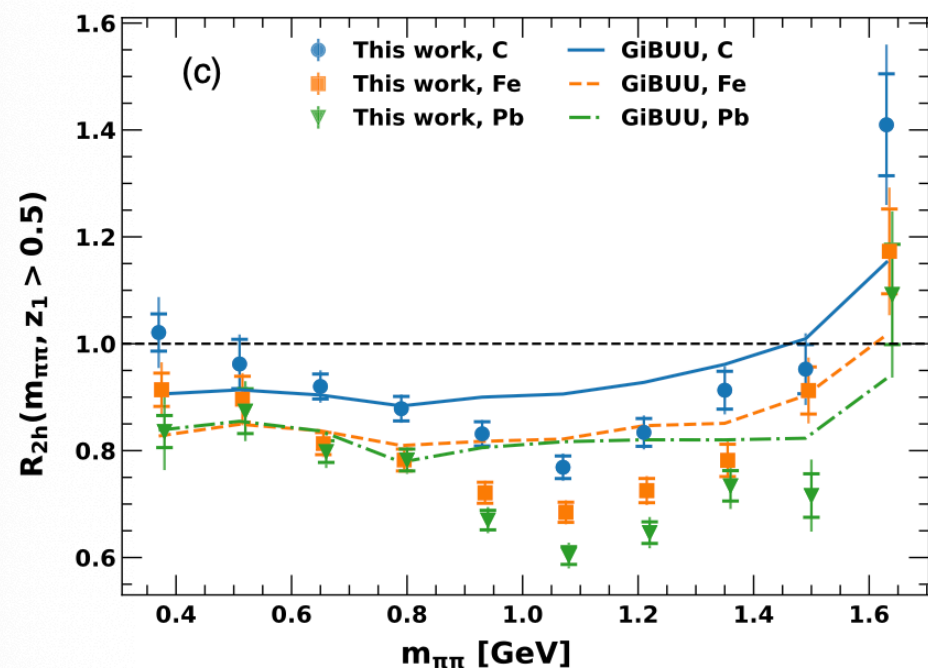
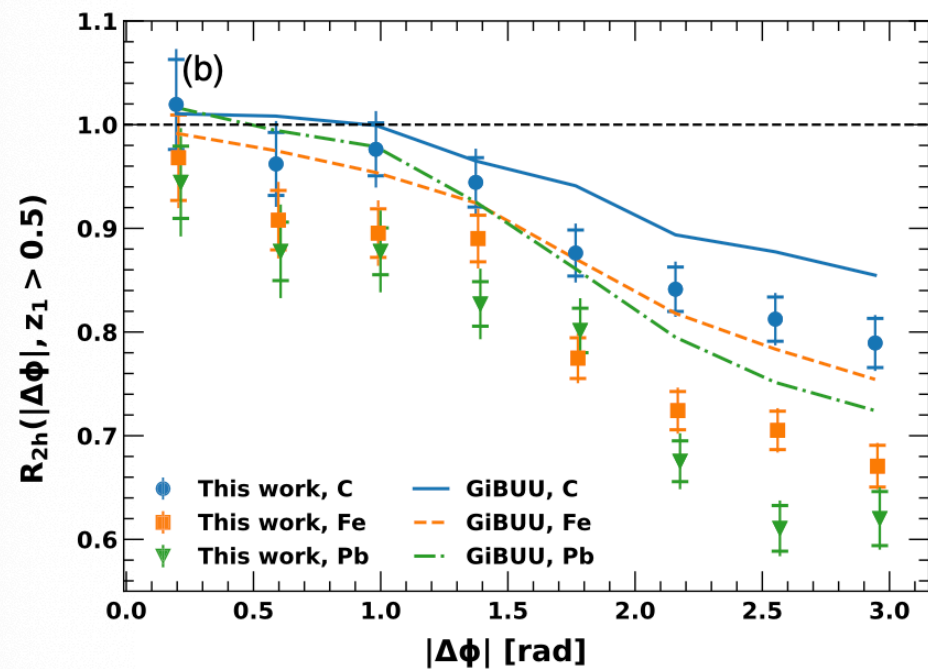
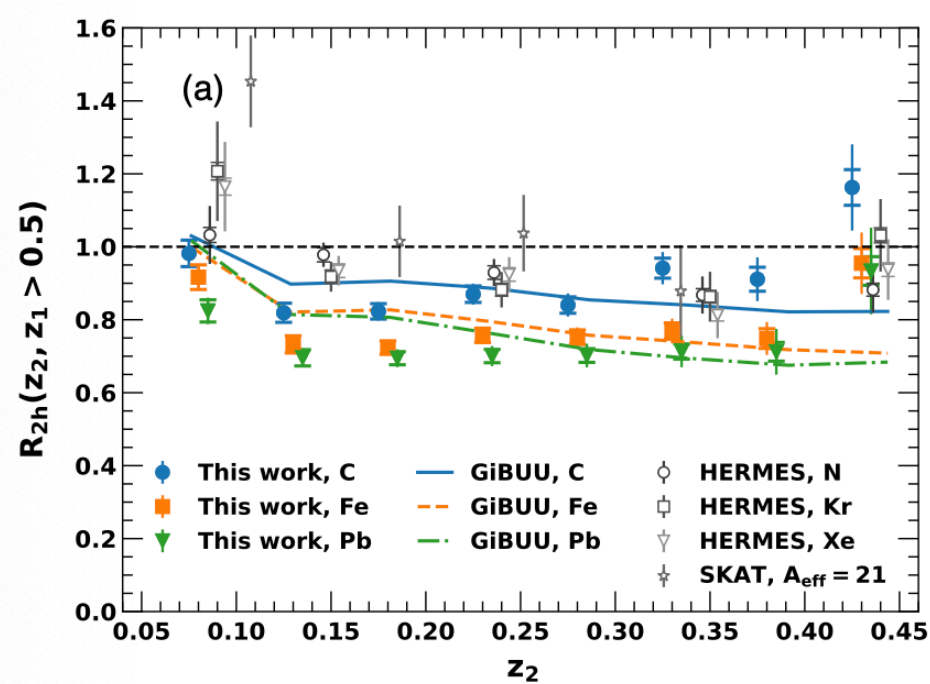
Preliminary results: Multi-dimensional π^+ p_T broadening $\Delta p_T^2(\pi^+)$



Next, *three published papers* that measure several different **two-particle correlation functions**. These test the *details* of the hadronization mechanisms in physics models.

PHYSICAL REVIEW LETTERS **129**, 182501 (2022)

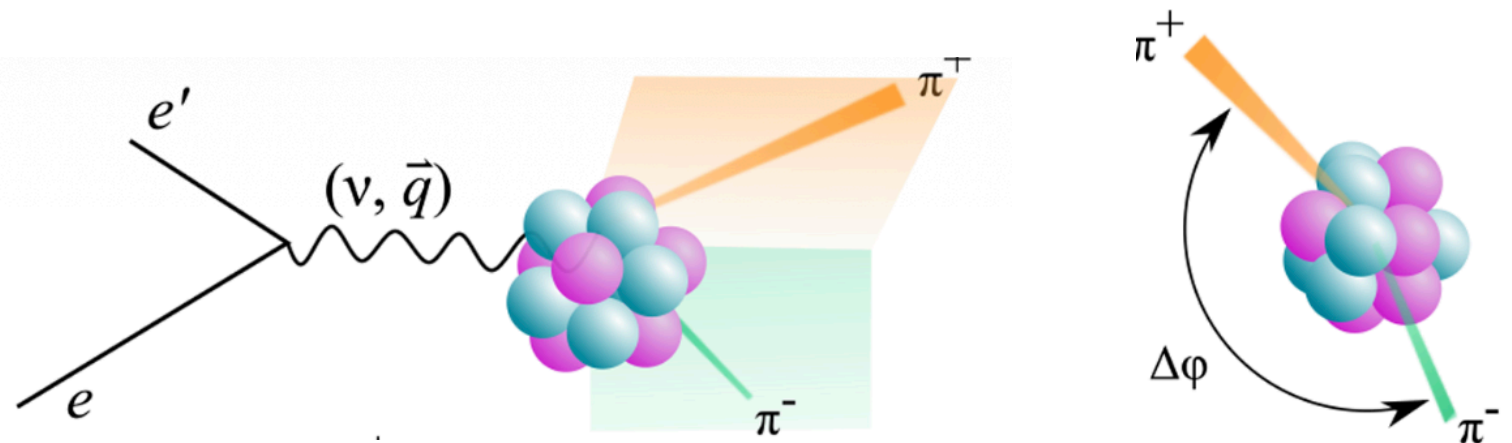
“Observation of Azimuth-Dependent Suppression of Hadron Pairs in Electron Scattering off Nuclei,”
Sebouh J. Paul, Sebastian Morán, Miguel Arratia,
Ahmed El Alaoui, Hayk Hakobyan, WKB et al.
(CLAS Collaboration).



GiBUU 2019 default parameters

$$eA \rightarrow e'\pi^+\pi^-X$$

$$0.05 < z_2 < 0.45 \quad z_1 = E_h/\nu > 0.5$$



Conditional modification factor R_{2h} :

$$R_{2h}(z_2) = \frac{[dN_{2h}^A(z_2)/dz_2]/N_h^A}{[dN_{2h}^D(z_2)/dz_2]/N_h^D}$$

“Dihadron azimuthal correlations in deep-inelastic scattering off nuclear targets”

Sebouh Paul, Sebastián Morán, Miguel Arratia, WKB, Hayk Hakobyan, Ahmed El Alaoui, et al. (CLAS Collaboration)

Di-pion correlation function:

$$C(\Delta\phi) = C_0 \times \frac{1}{N_{e'\pi^+}} \frac{dN_{e'\pi^+\pi^-}(\Delta\phi)}{d\Delta\phi}$$

$$\text{with } C_0 = \frac{N_{e'\pi^+}^D}{N_{e'\pi^+\pi^-}^{D,\text{tot}}}$$

$$\text{The rapidity is: } Y_h = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$

The broadening of the correlation function vs. nucleus is b : $b = \sqrt{\sigma_A^2 - \sigma_D^2}$ where σ_A and σ_D represent the RMS widths of the correlation functions.

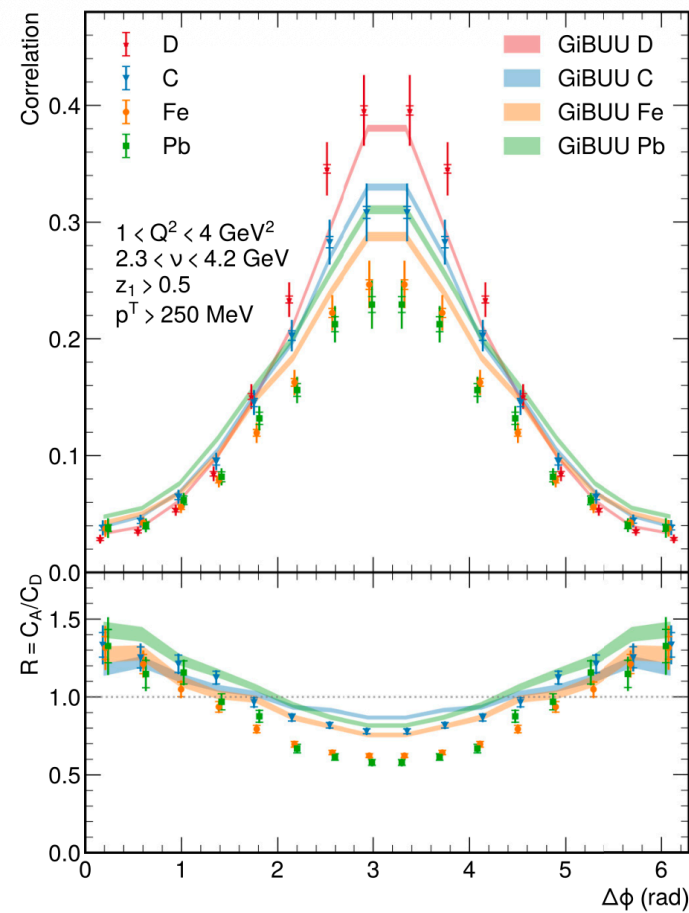


FIG. 2. Top: Correlation functions for all four targets. Bottom: Ratio of nuclear target correlations to deuterium. Data points are

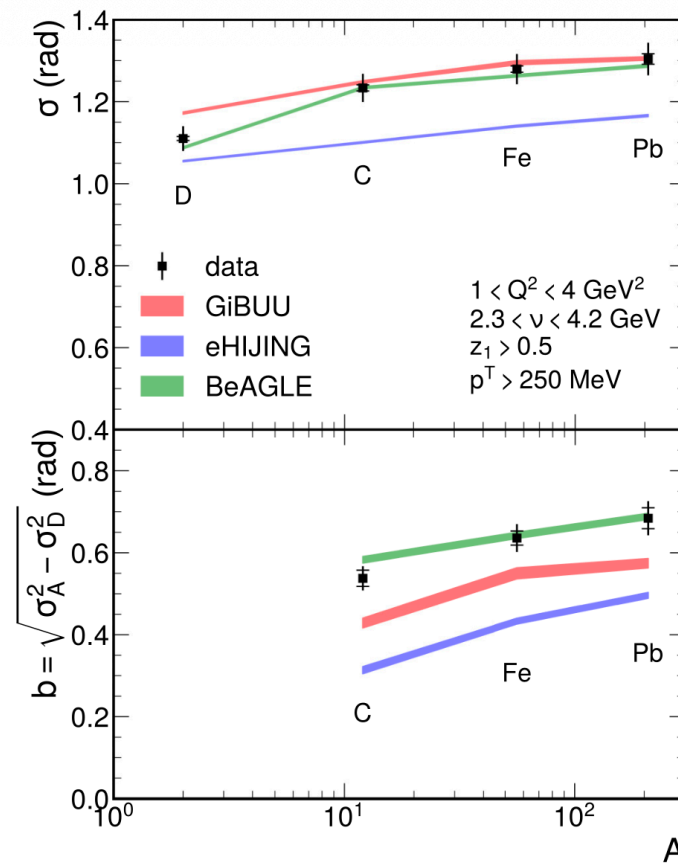
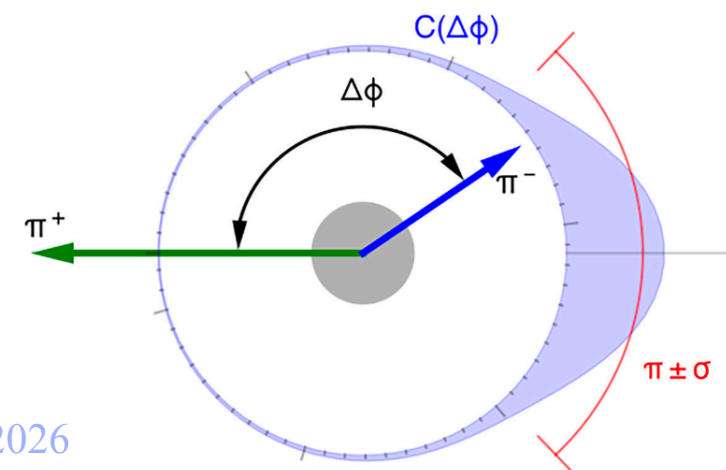
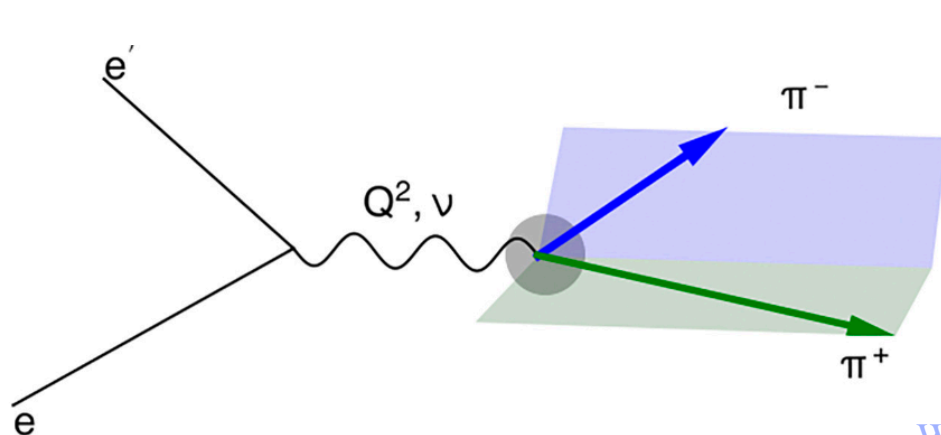


FIG. 3. Top: Correlation function widths for all four targets. Bottom: Relative broadenings of nuclear targets compared to deuterium. The inner error bars represent statistical uncertainties, while the vertical extent of the error bars shows the combined systematic and



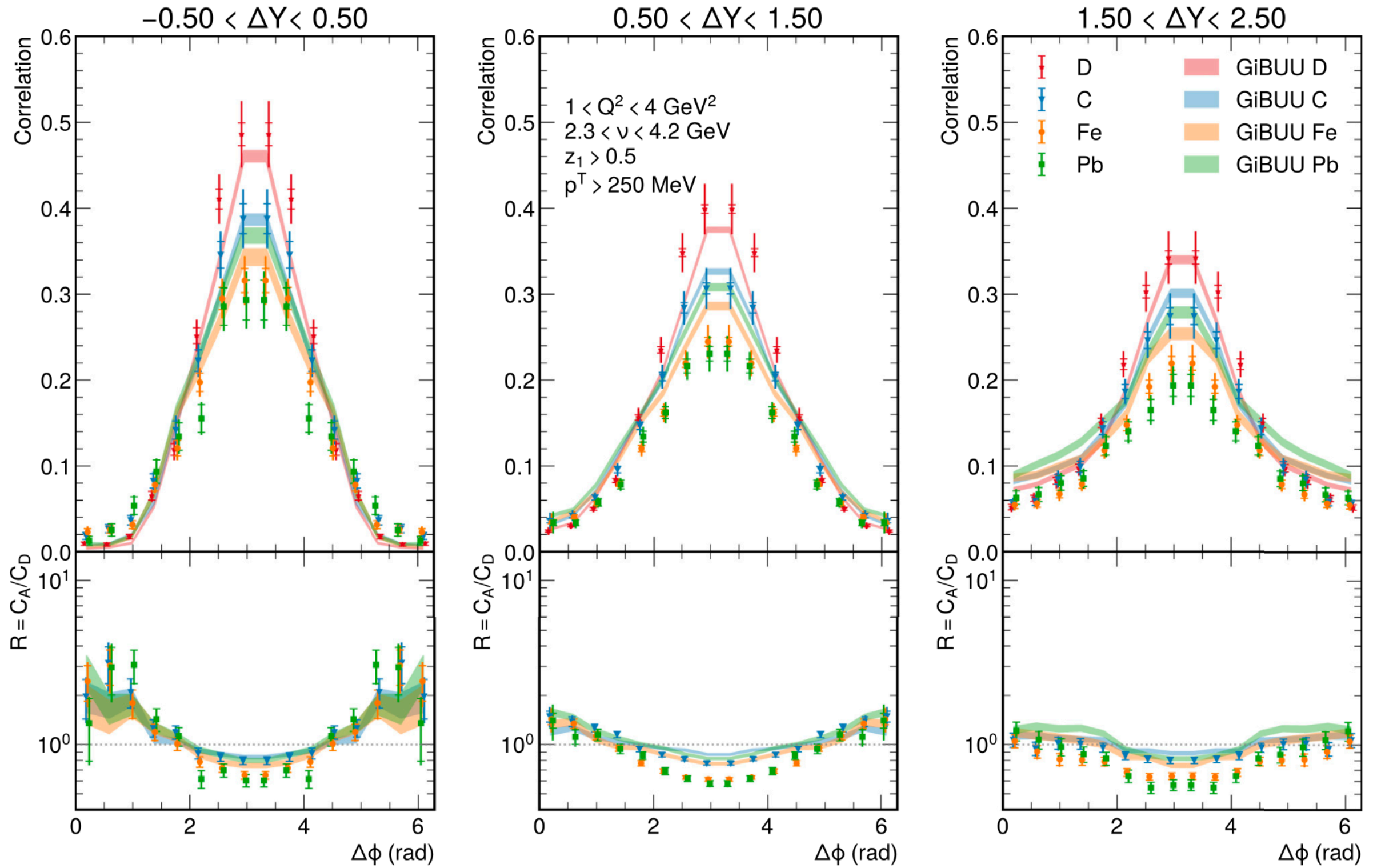


FIG. 4. Top row: Correlation functions in bins of rapidity difference, ΔY . These are compared to the GIBUU calculations (curves). The inner error bars represent the statistical uncertainties, while the vertical extent of the error bars represents the total uncertainty (the systematic and statistical uncertainties added in quadrature). The width of the curves represents the statistical precision of the simulated sample. Bottom: Ratios of the correlation functions for the nuclear targets to that of deuterium.

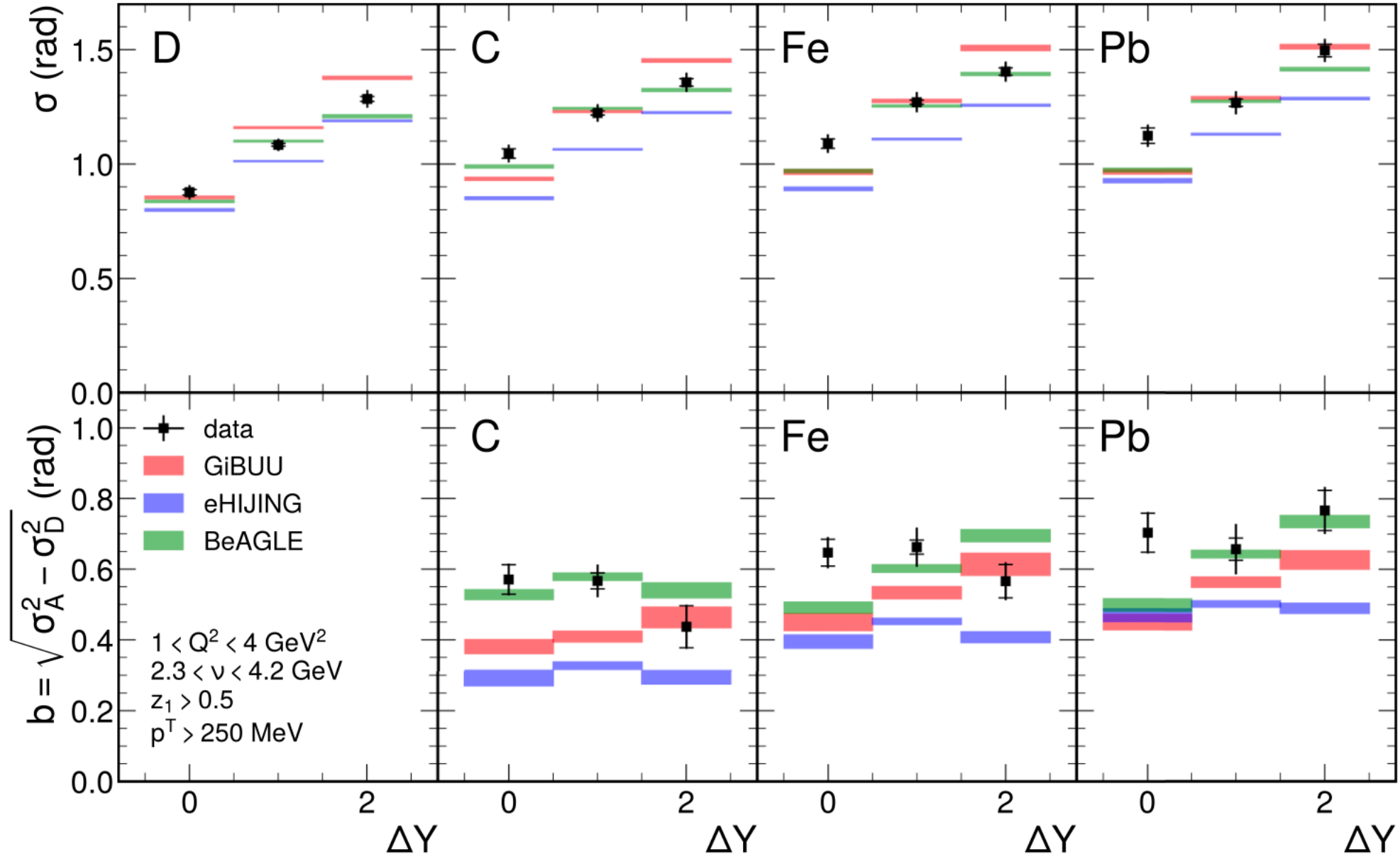


FIG. 5. Top row: RMS widths of the correlation functions in slices of ΔY for each target. Bottom row: Same for the broadening. These are compared to the GiBUU (red), eHIJING (blue), and BeAGLE (green) models, where the widths of the curves indicate the statistical precision of each model's simulation. The inner error bars represent statistical uncertainties, while the vertical extent of the error bars shows the combined systematic and statistical uncertainties (quadrature addition).

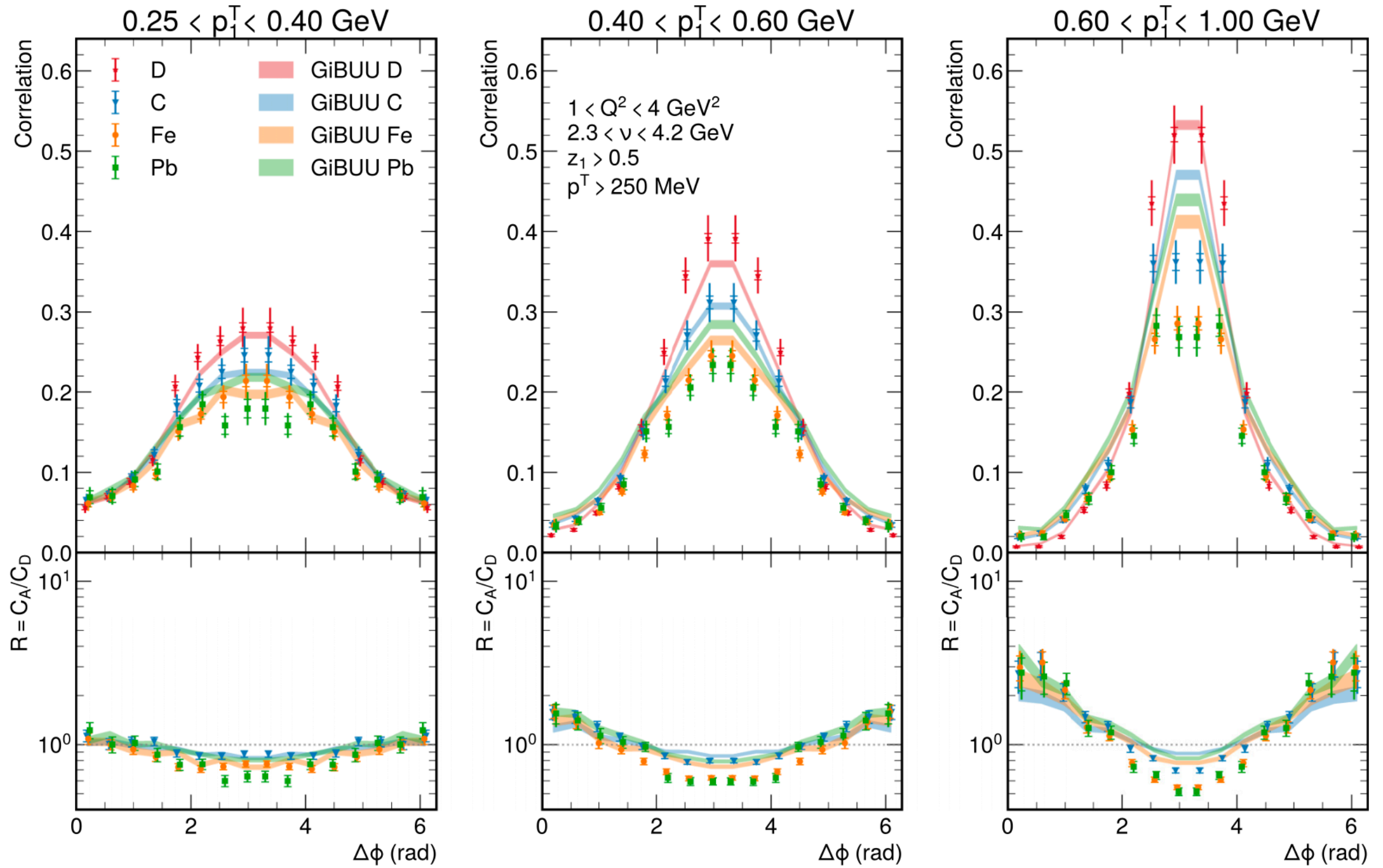


FIG. 6. Top row: Correlation functions in bins of the leading pion's transverse momentum, p_1^T . These are compared to the GIBUU calculations (curves). The inner error bars represent the statistical uncertainties, while the vertical extent of the error bars represents the total uncertainty (the systematic and statistical uncertainties added in quadrature). The width of the curves represents the statistical precision of the simulated sample. Bottom: Ratios of the correlation functions for the nuclear targets to that of deuterium.

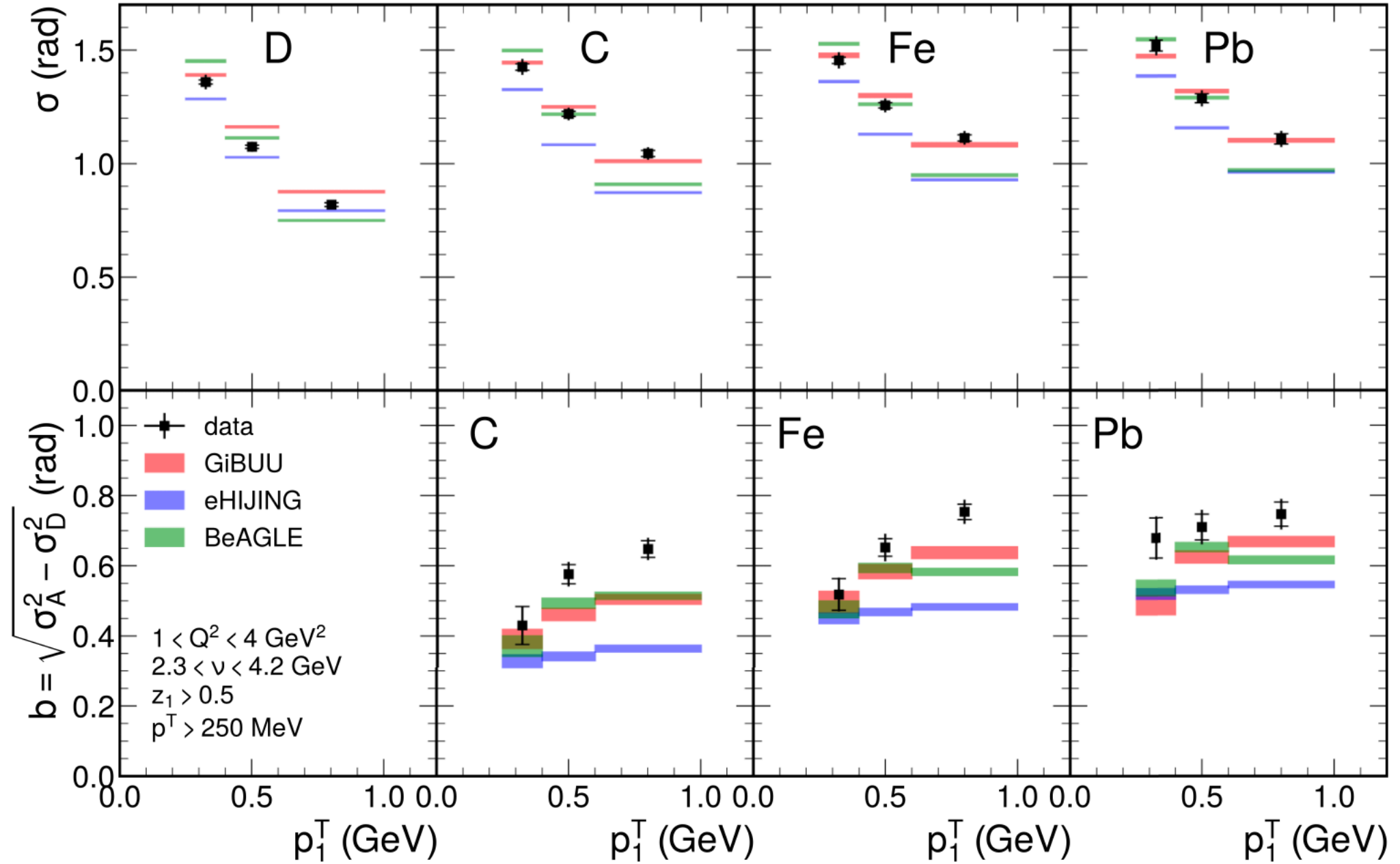


FIG. 7. Top row: RMS widths of the correlation functions in slices of p_1^T for each target. Bottom row: same for the broadening. These are compared to the GiBUU (red), eHIJING (blue), and BeAGLE (green) models, where the widths of the curves indicate the statistical precision of each model's simulation. The inner error bars represent statistical uncertainties, while the vertical extent of the error bars shows the combined systematic and statistical uncertainties (quadrature addition).

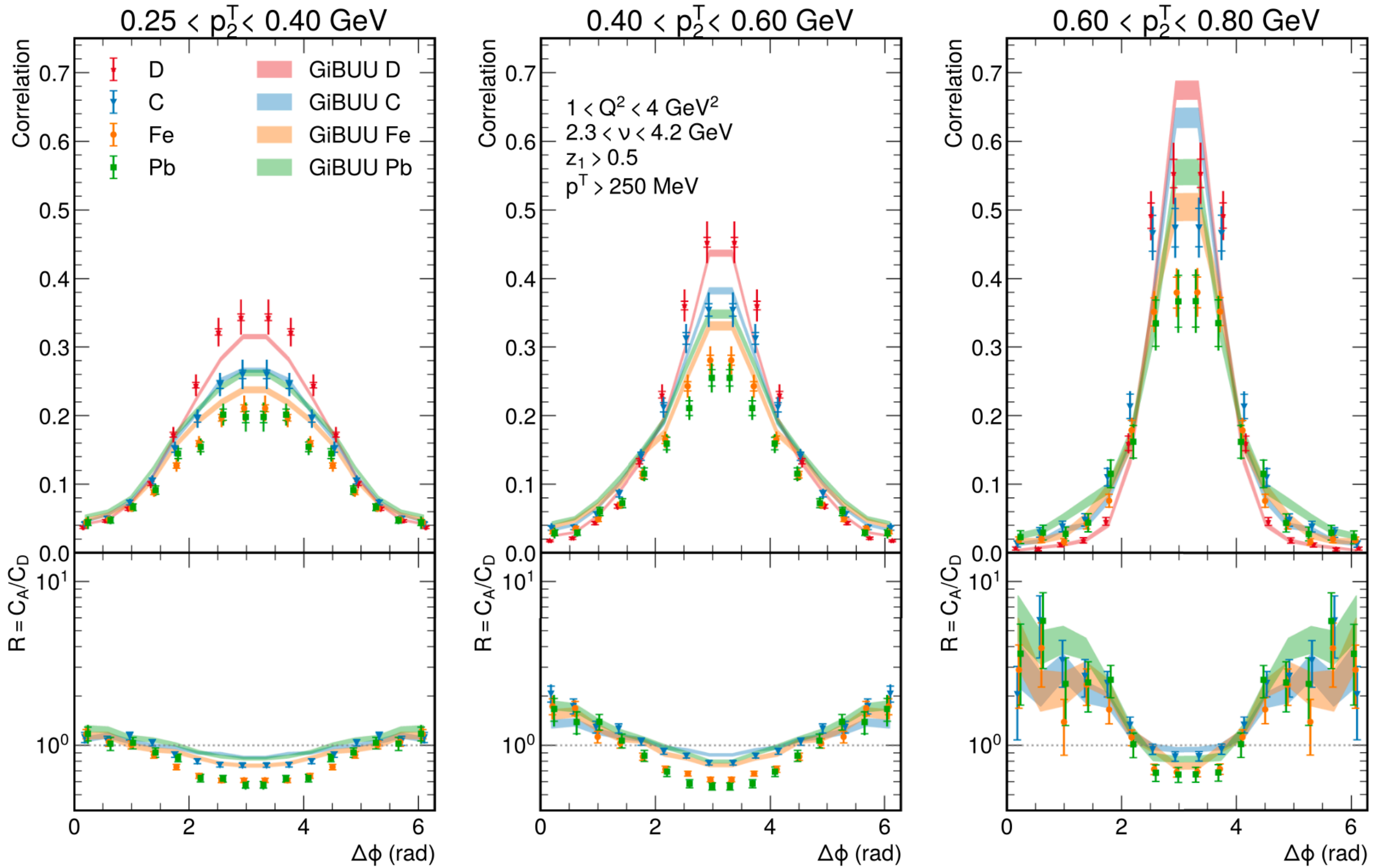


FIG. 8. Top row: Correlation functions in bins of the subleading pion's transverse momentum, p_2^T . These are compared to the GIBUU calculations (curves). The inner error bars represent the statistical uncertainties, while the vertical extent of the error bars represents the total uncertainty (the systematic and statistical uncertainties added in quadrature). The width of the curves represents the statistical precision of the simulated sample. Bottom: Ratios of the correlation functions for the nuclear targets to that of deuterium.

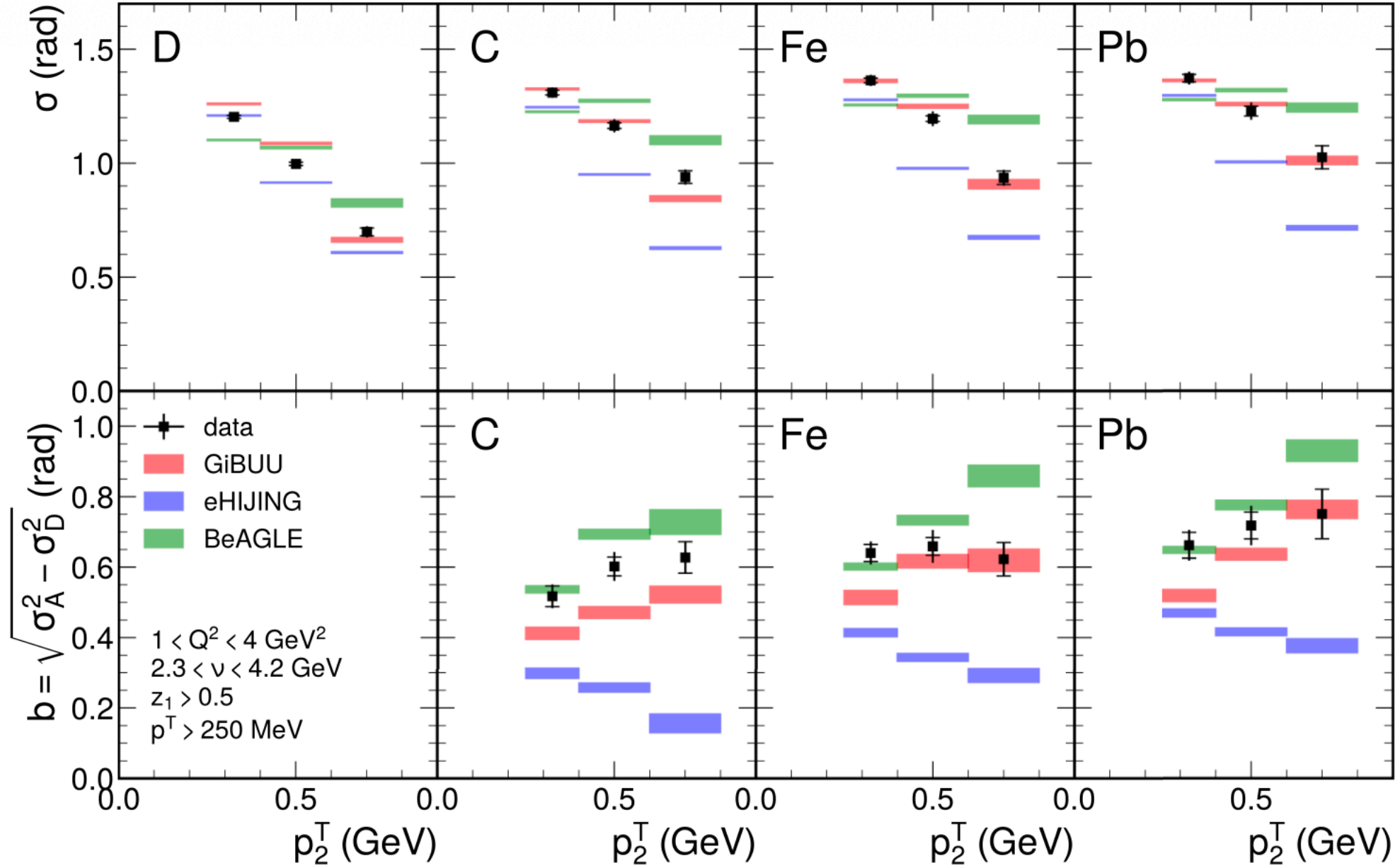


FIG. 9. Top row: RMS widths of the correlation functions in slices of p_2^T for each target. Bottom row: Same for the broadening. These are compared to the GiBUU (red), eHIJING (blue), and BeAGLE (green) models, where the widths of the curves indicate the statistical precision of each model's simulation. The inner error bars represent statistical uncertainties, while the vertical extent of the error bars shows the combined systematic and statistical uncertainties (quadrature addition).



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Letter

First study of the nuclear response to fast hadrons via angular correlations between pions and slow protons in electron-nucleus scattering

Sebouh Paul, Miguel Arratia, Hayk Hakobyan, WKB, and the CLAS Collaboration

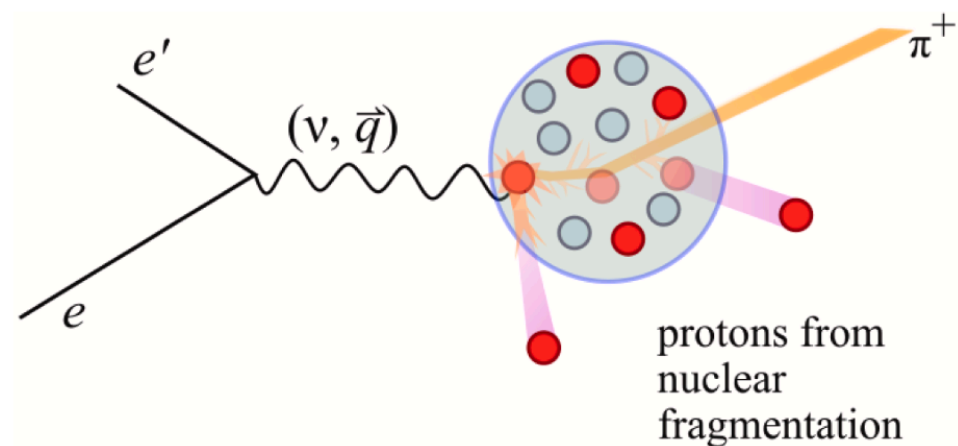


Fig. 1. Illustration of nuclear deep-inelastic scattering featuring a leading charged pion and secondary protons in the final state.

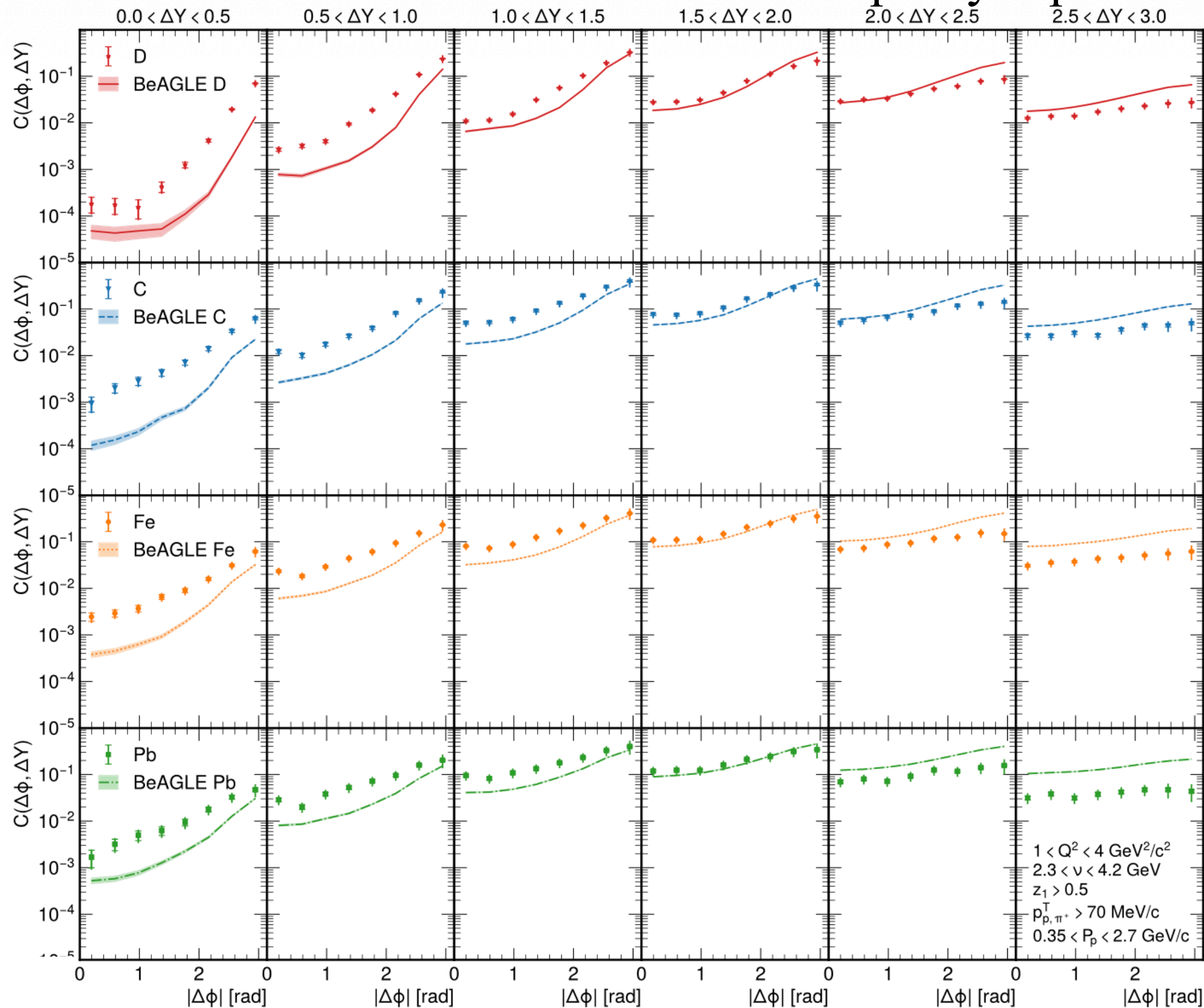
$$C(\Delta\phi, \Delta Y) = C_0 \times \frac{1}{N_{e'\pi}} \left(\frac{d^2 N_{e'\pi p}}{d\Delta\phi d\Delta Y} \right) \quad (\text{leading } \pi^+)$$

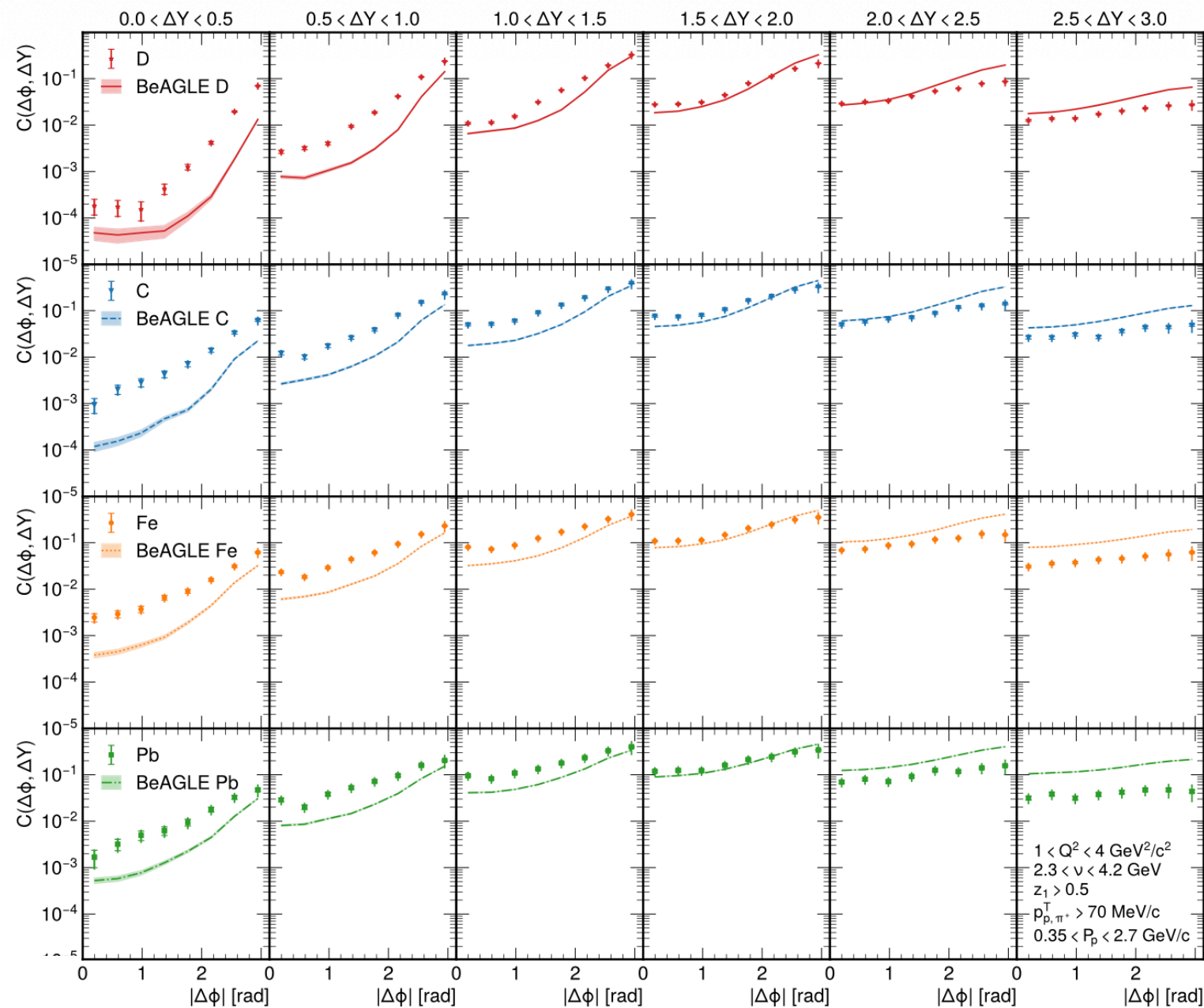
$$\text{with } C_0 = \frac{N_{e'\pi}^D}{N_{e'\pi p}^{D,\text{tot}}} \quad \text{such that } \iint C(\Delta\phi, \Delta Y) = 1$$

Also define $R = \frac{C_A}{C_D}$ nuclear-to-deuterium ratios,

$$R \equiv \frac{N_{e'\pi^+p}^A / N_{e'\pi^+}^A}{N_{e'\pi^+p}^D / N_{e'\pi^+}^D} \quad \sigma = \sqrt{\frac{\sum_{i \in \text{bins}} C_i (\Delta\phi_i - \pi)^2}{\sum_{i \in \text{bins}} C_i}} \quad \text{Azimuthal RMS width of corr. functions } \sigma$$

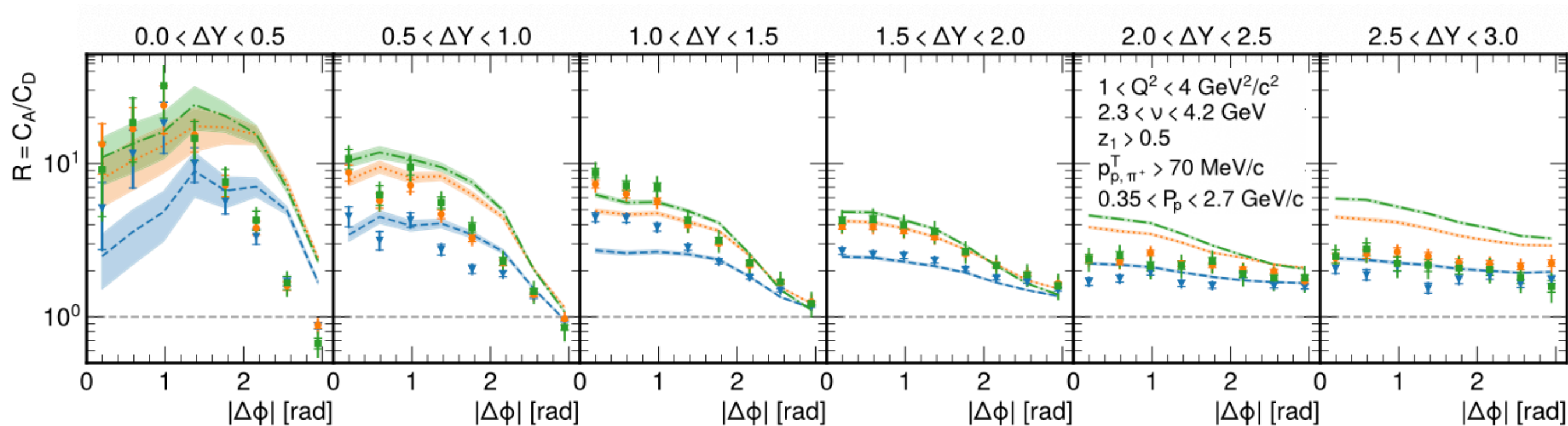
Correlation functions vs. azimuthal and rapidity separations





- Correlation function has a maximum at $|\Delta\phi| = \pi$ (that is, where the two hadrons are azimuthally opposite each other).
- Peak is tallest within the $1.0 < \Delta Y < 1.5$ bin (third column). Average rapidity separation between the γ^*N system and the lab frame is ~ 1.2
- Expected if proton rapidity distribution is peaked at that of the lab frame, initially isotropic

Ratio of correlation functions for nucleus A to Deuterium



These plots are referenced to the carbon nucleus.

(Results for the nuclear targets are more similar to one another than they are to deuterium)

Widths of Correlation Functions vs. Nucleus and Rapidity Difference

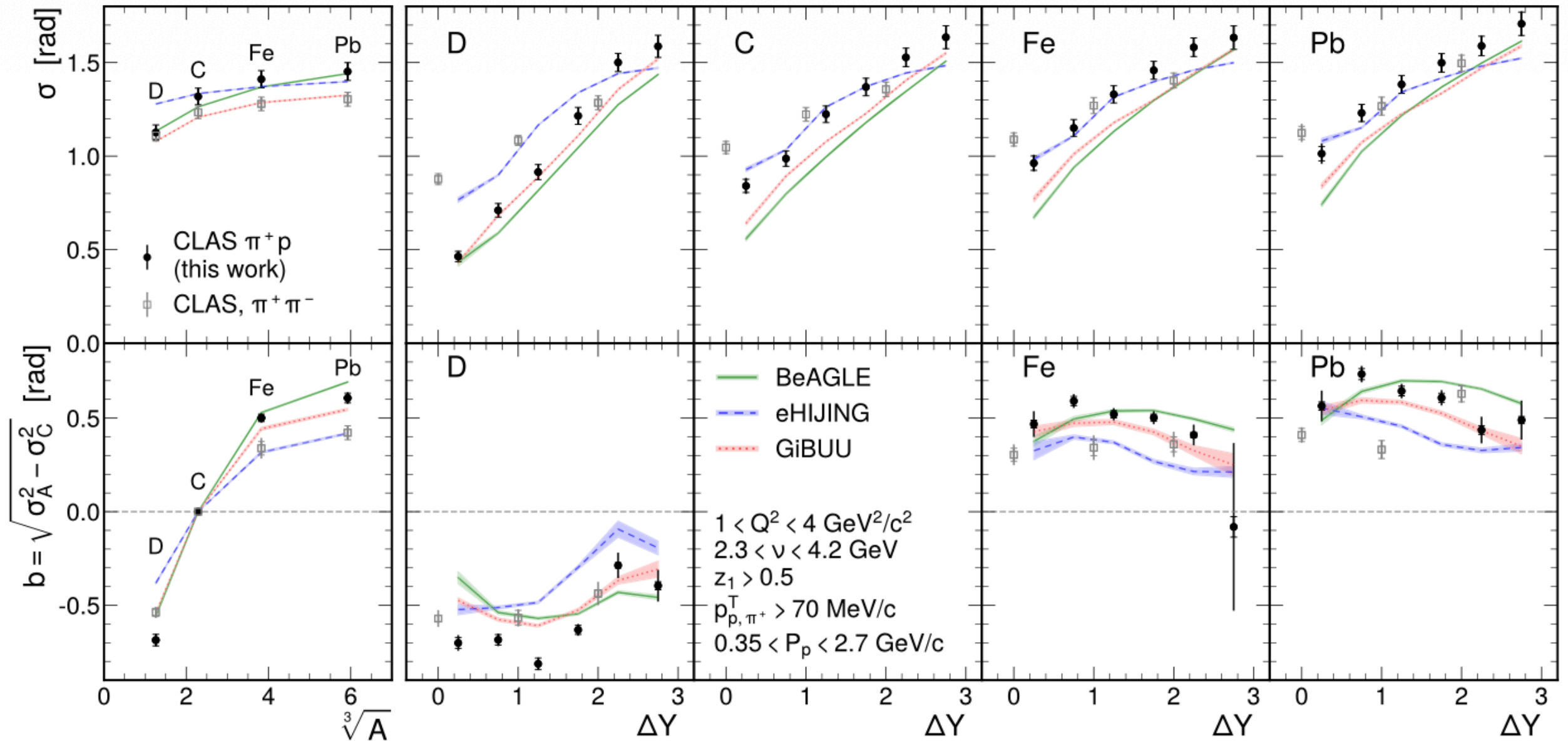


Fig. 3. Top row: RMS width σ as a function of $\sqrt[3]{A}$ (left-most panel), and as a function of ΔY for each target (other panels). Bottom row: same for the azimuthal broadening, b . The horizontal caps in the error bars represent the systematic uncertainties, while the outer bars represent the total systematic and statistical uncertainty (added in quadrature). The results are compared to the predictions from the BeAGLE [9], eHIJING [41], and GiBUU [42] models, as well as analogous measurements of the dipion channel from Ref. [20] (gray, open squares). The broadenings for the dipion channel were reported in Ref. [20] with respect to deuterium, and have been re-calculated with respect to carbon in order to compare them to the results of this work.

$$b = \pm \sqrt{|\sigma_A^2 - \sigma_C^2|}$$

Azimuthal broadening
due to nuclear medium

Conclusions

- A tremendous volume of CLAS results since the year 2000!
- Data precision now exceeds theory precision, due to next generation experimental measurements, particularly with correlation measurements.
- Baryon sector of these data greatly strengthen diquark arguments: proton and lambda baryon production now, others soon.
- First-look 10.5 GeV measurements from RGE in 2024 look extremely promising and will provide first measurements of heavy hadrons: K , η , ϕ , ω , J/ψ mesons and p , $\bar{p}$, Λ , Σ , Ξ baryons

Backup slides

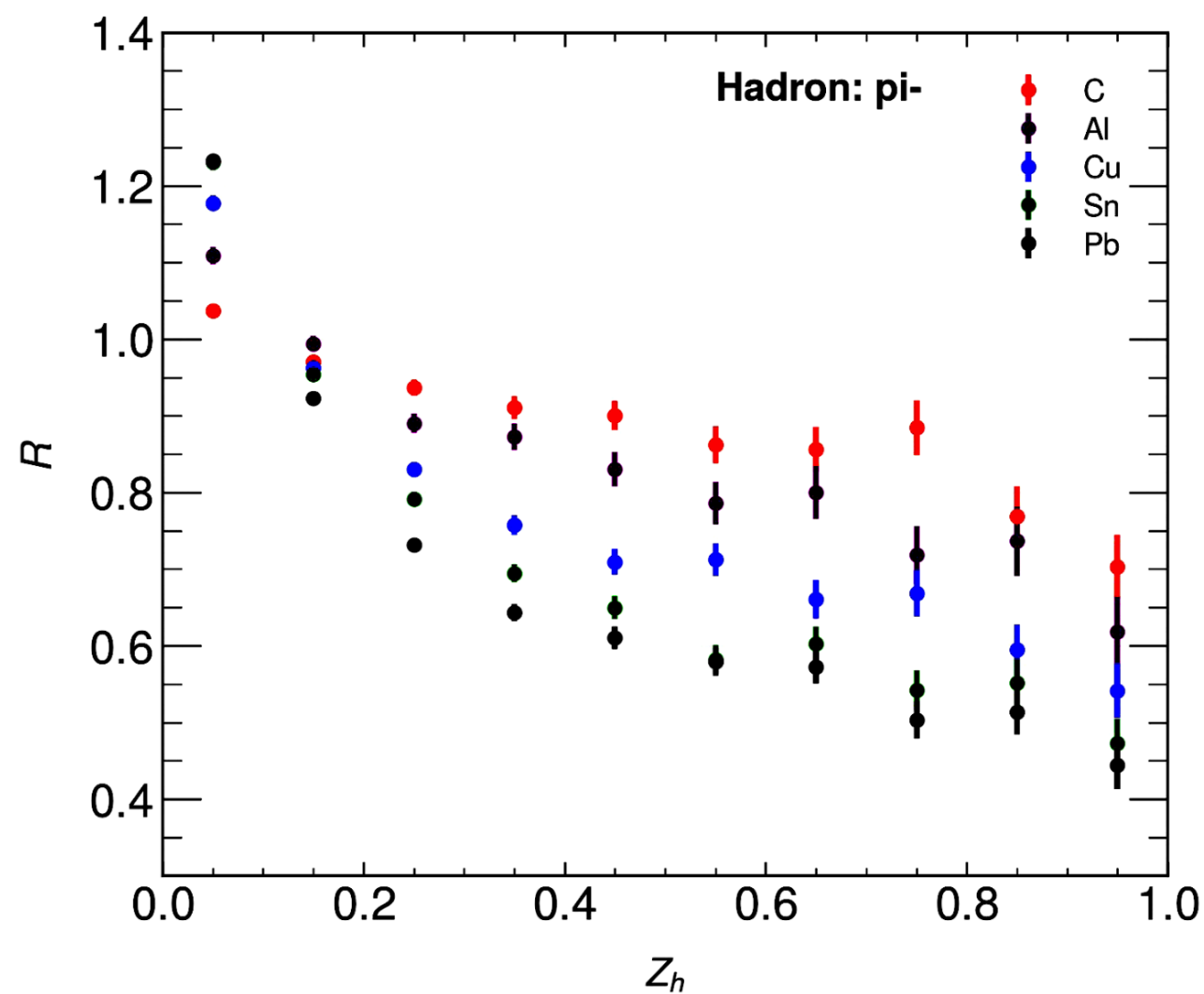
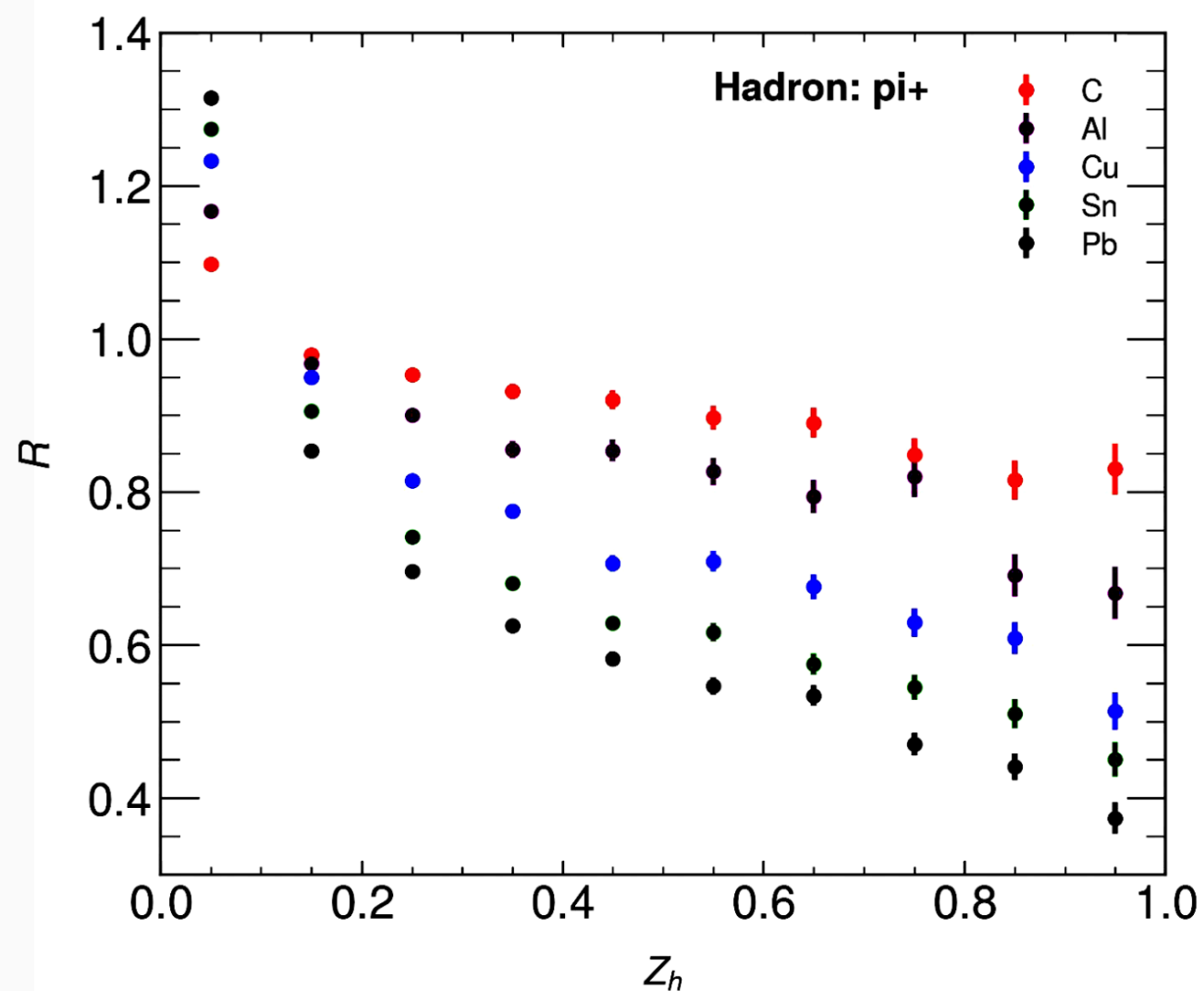
The target configuration during the run (27 PAC days)

	Solid target thickness in mm	Solid target density in g/cm ³	Total Luminosity Achieved
2cm LD2 + C	1.51	1.7	23 1/fb
2cm LD2 + Al	1.21	2.6	24 1/fb
2cm LD2 + Cu	0.34	8.3	22 1/fb
2cm LD2 + Sn	0.29	7.1	22 1/fb
2cm LD2 + Pb	0.14	10.6	26 1/fb

Total so far is 117 1/fb

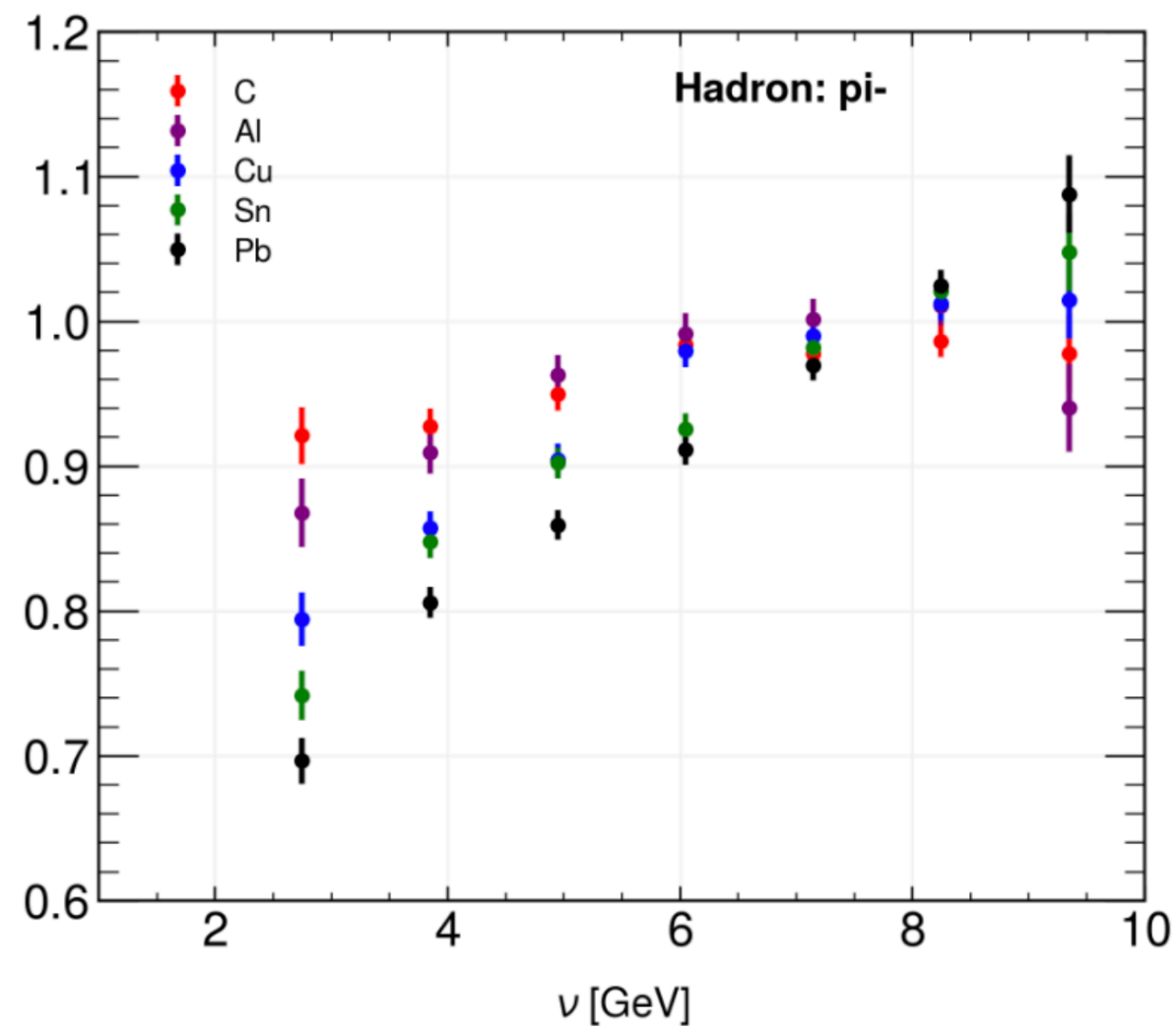
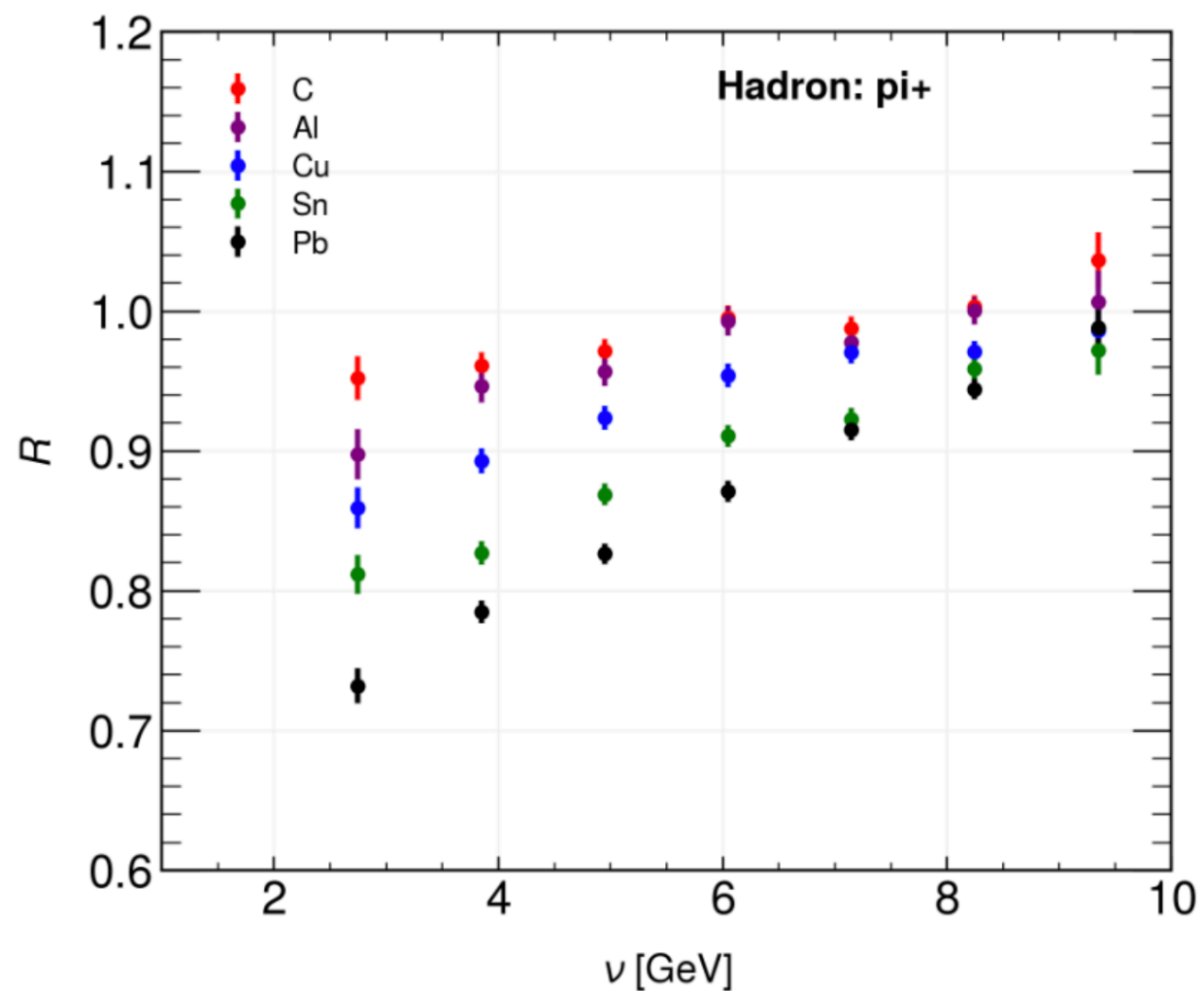
First Preliminary RG-E measurements

Multiplicity Ratio vs Z with DIS cuts (less than 1% of the available data)

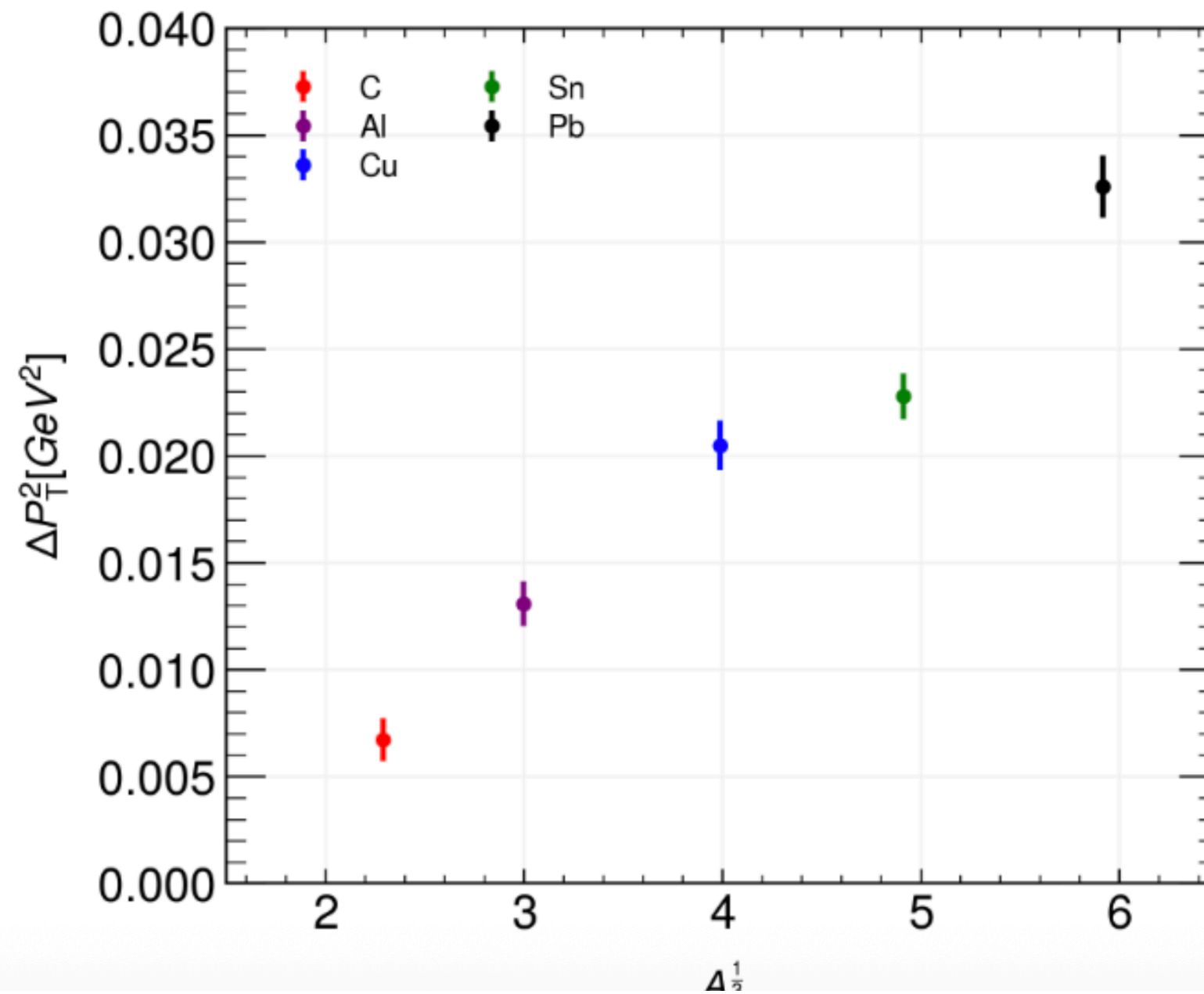


First Preliminary RG-E measurements

Multiplicity Ratio vs Nu with DIS cuts

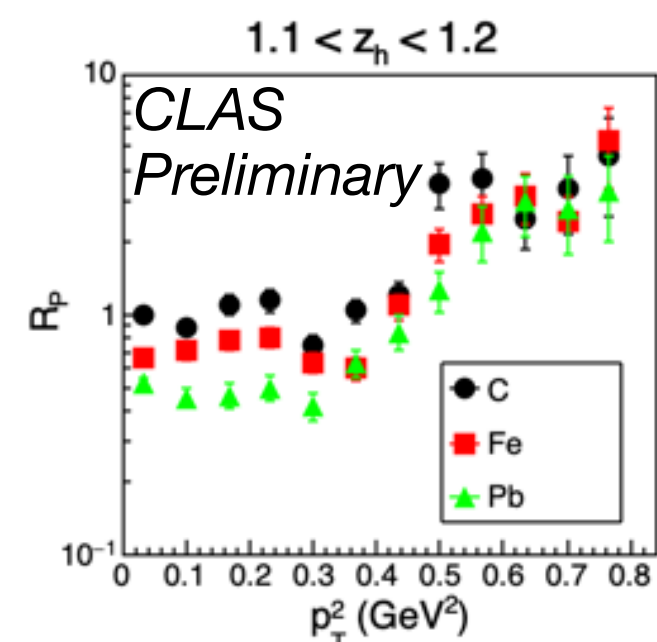
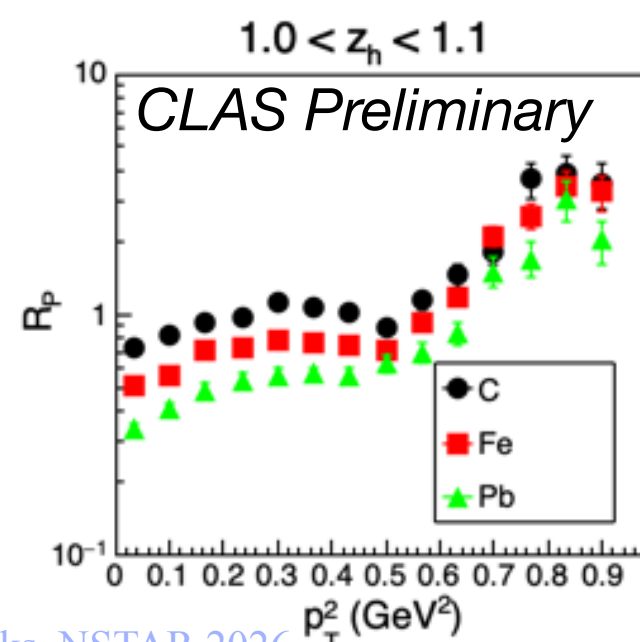
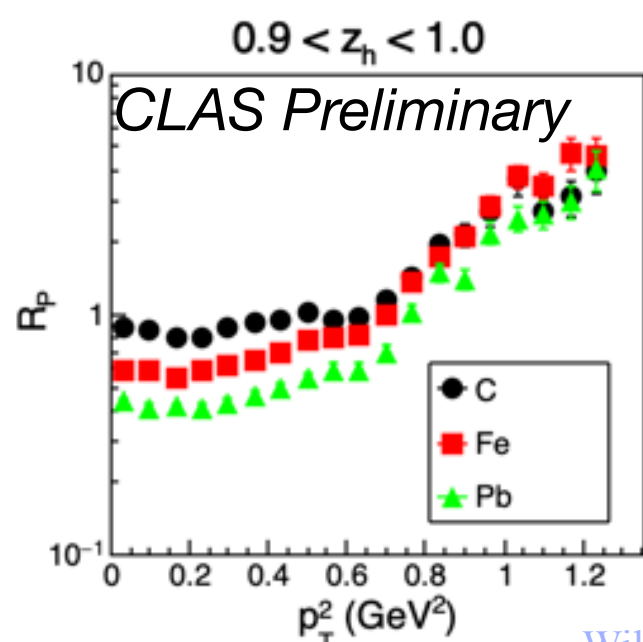
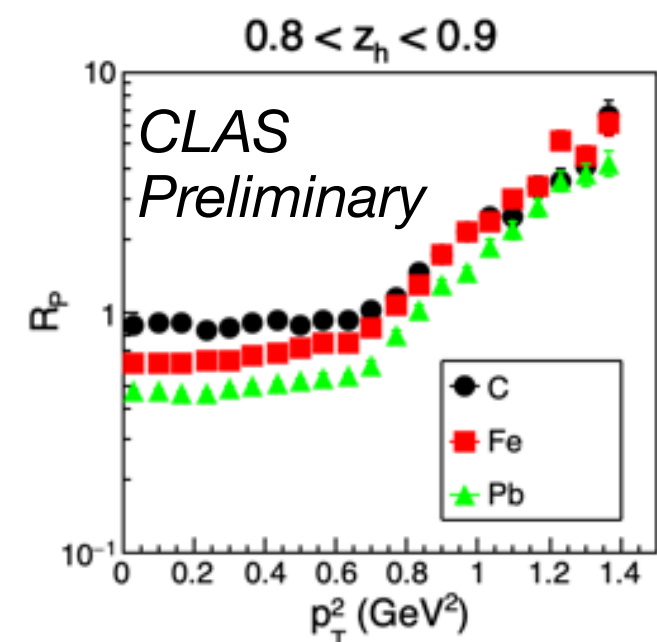
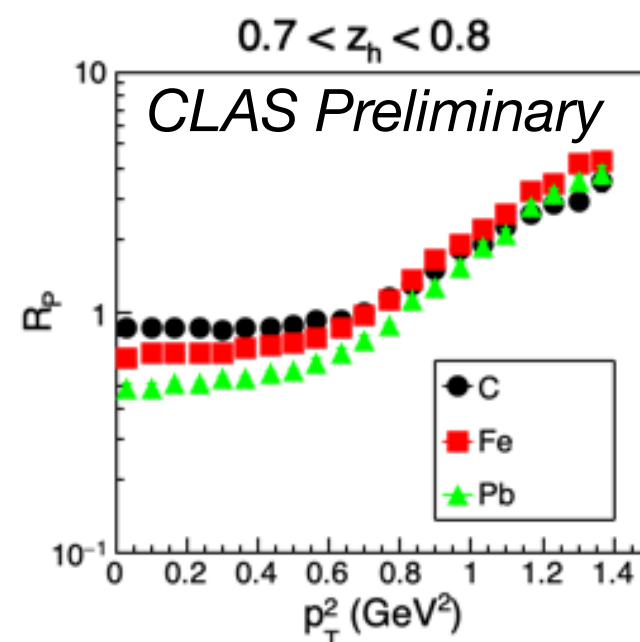
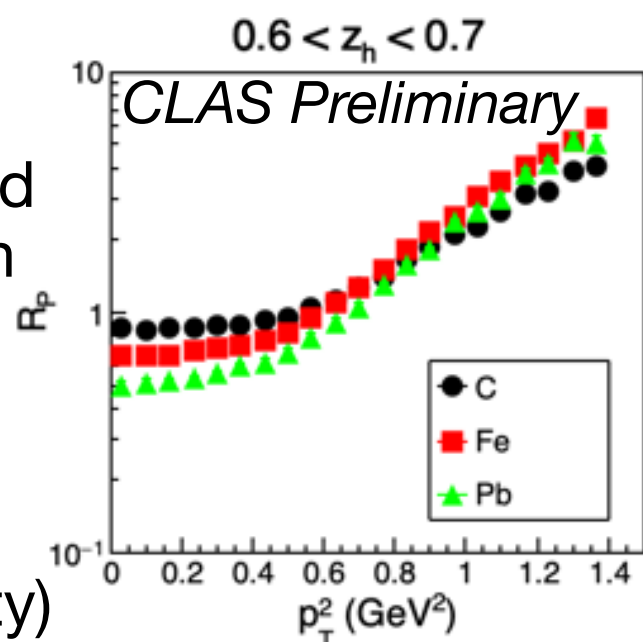
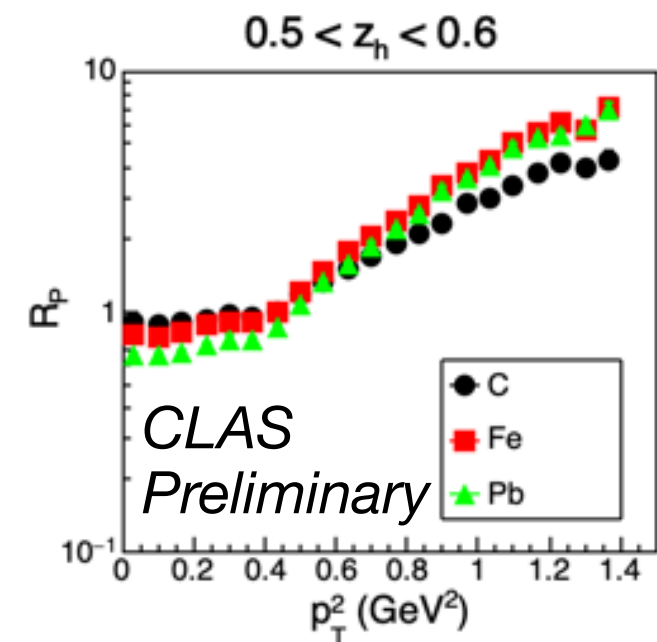
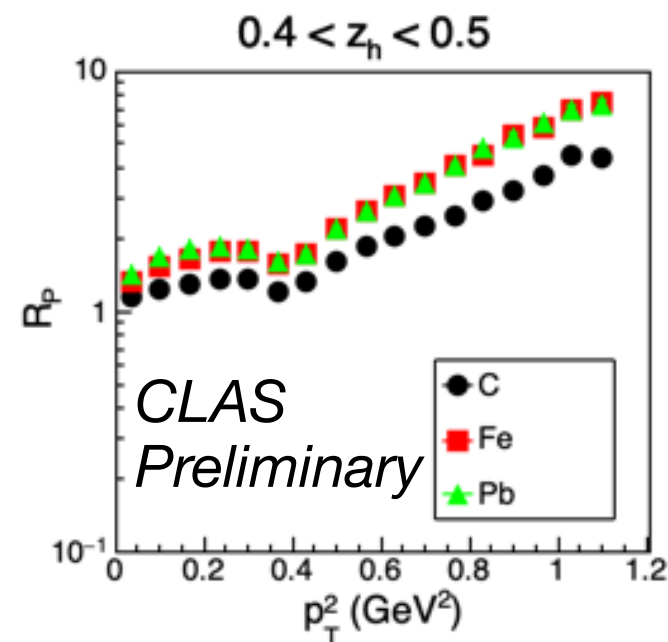
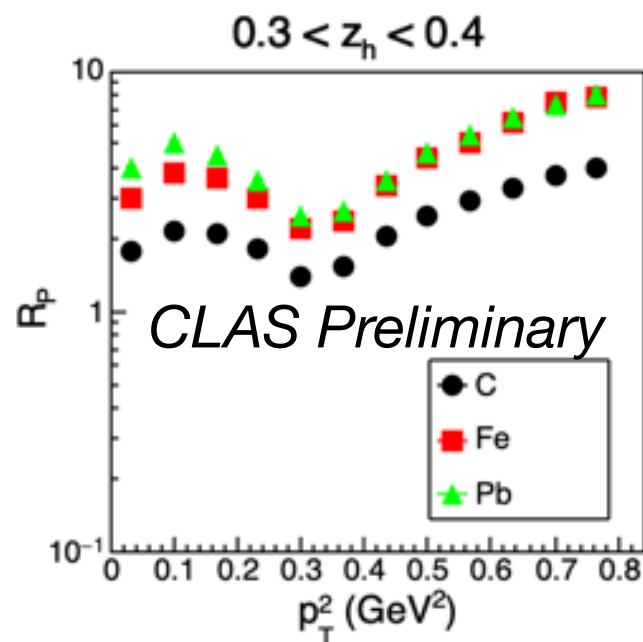


First Preliminary RG-E measurements
Transverse momentum broadening vs $A^{1/3}$ with DIS cuts
(less than 1% of the available data)



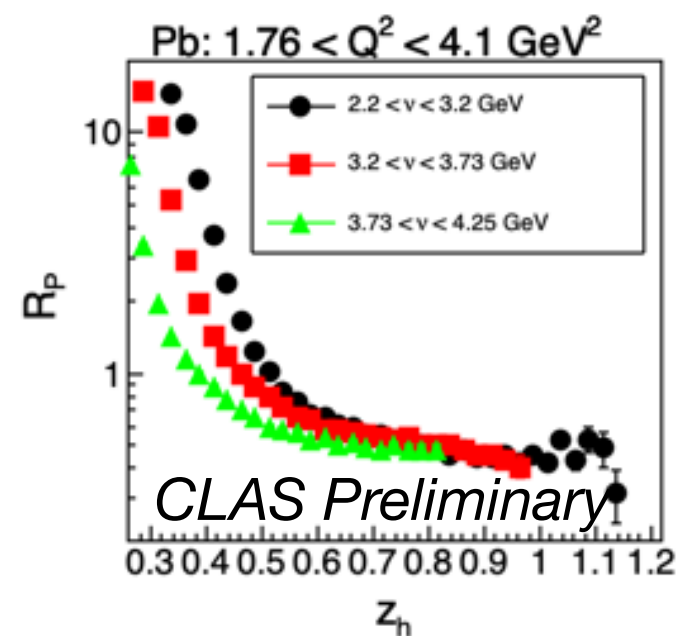
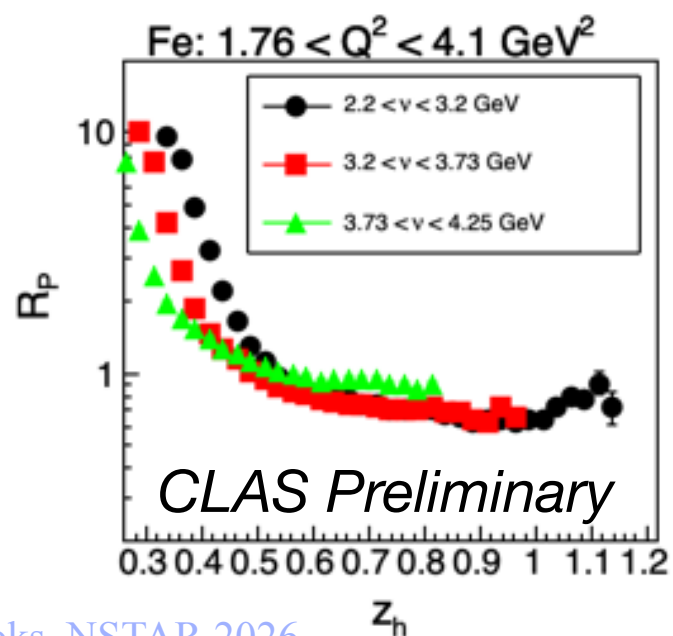
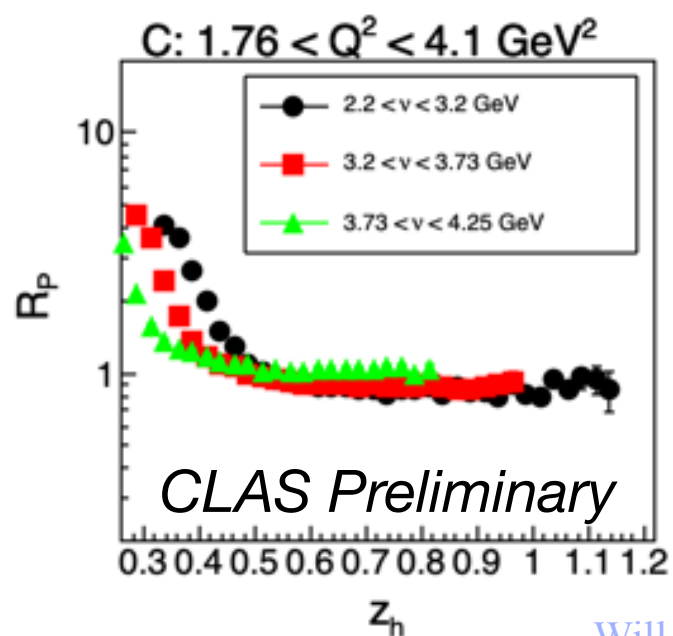
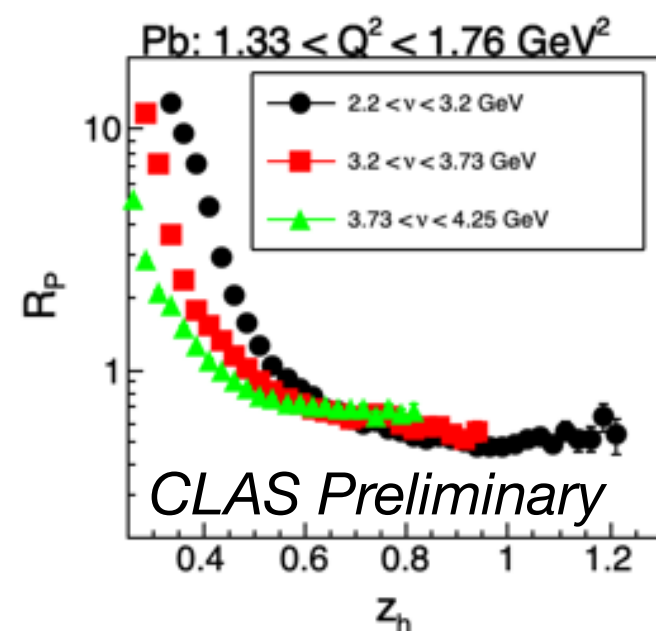
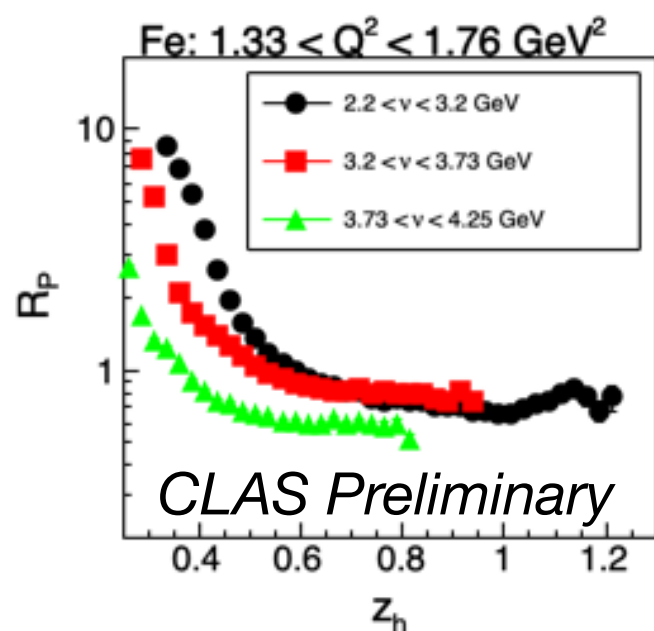
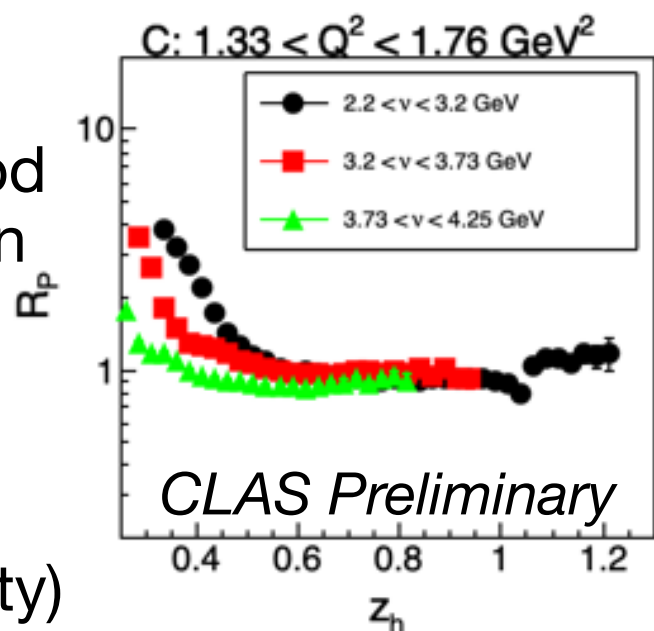
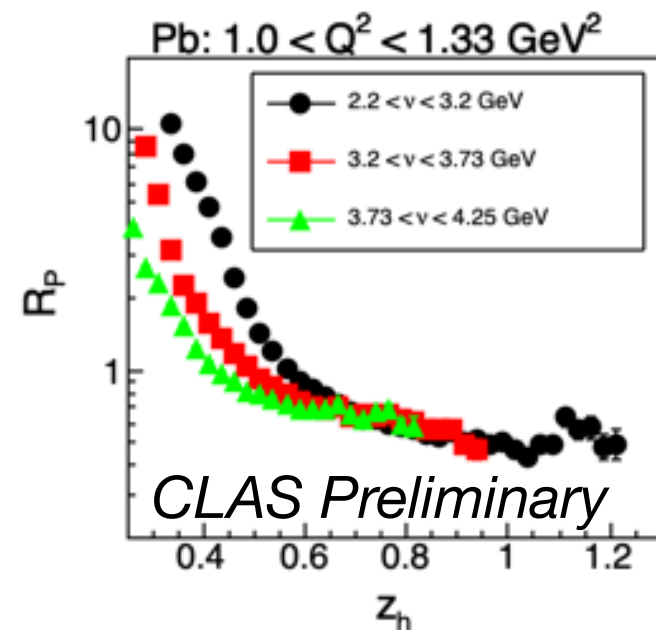
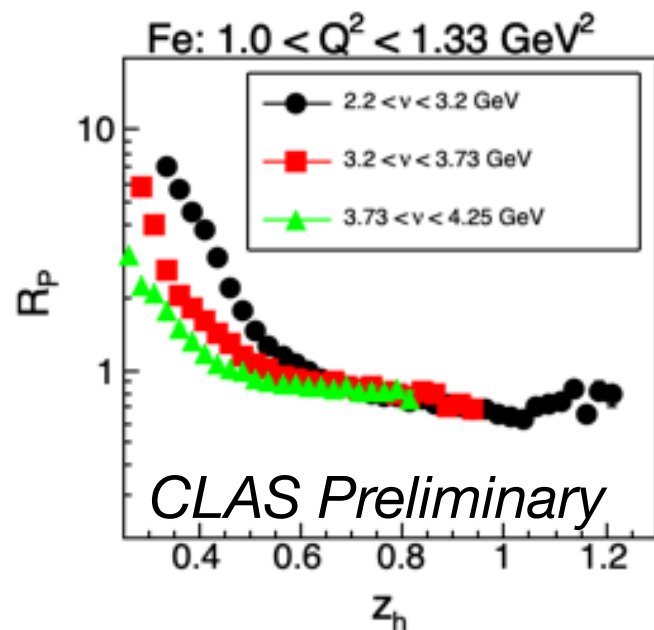
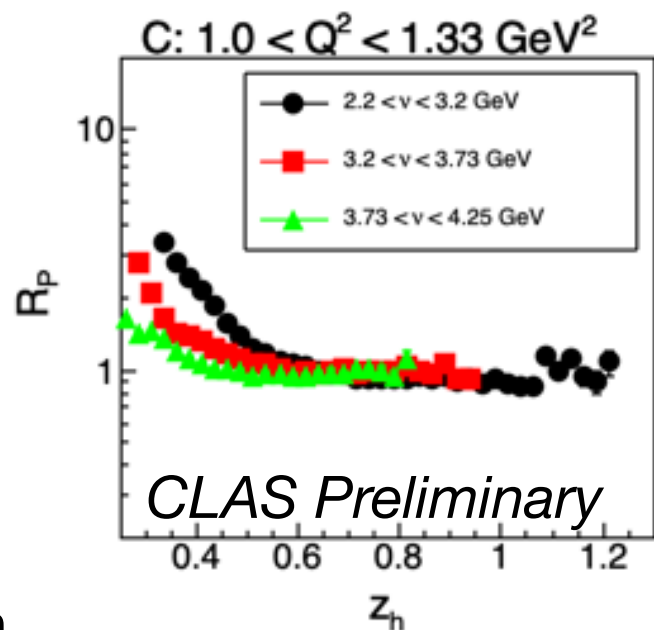
CLAS EG2 SIDIS Proton Production Analysis

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with students Juan
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(UTFSM), Alexis
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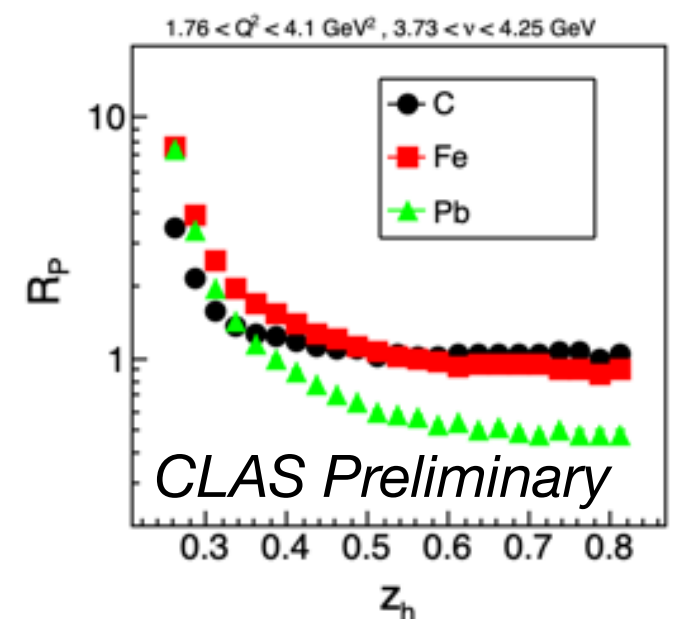
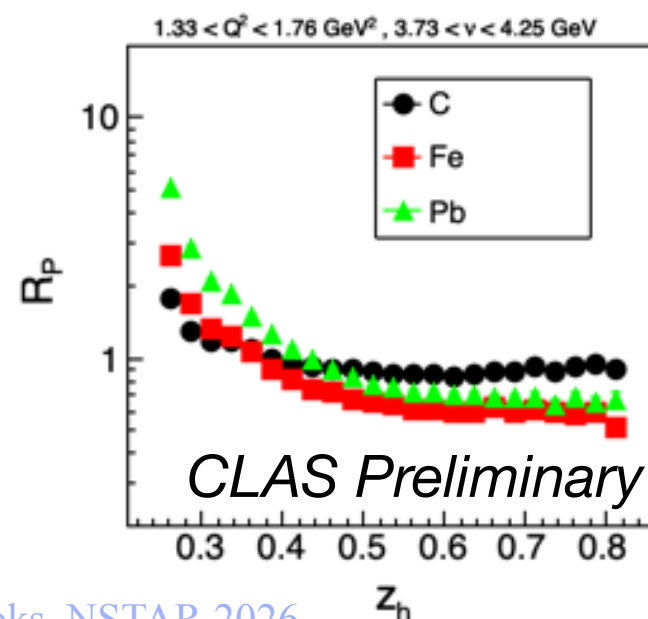
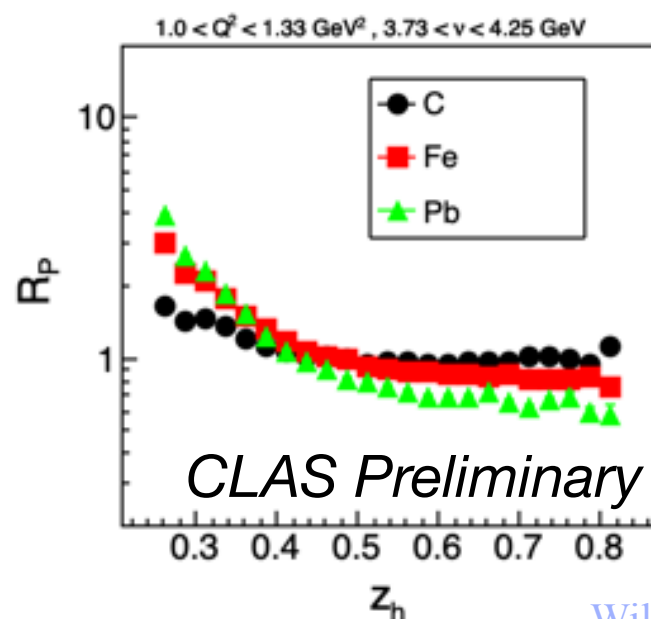
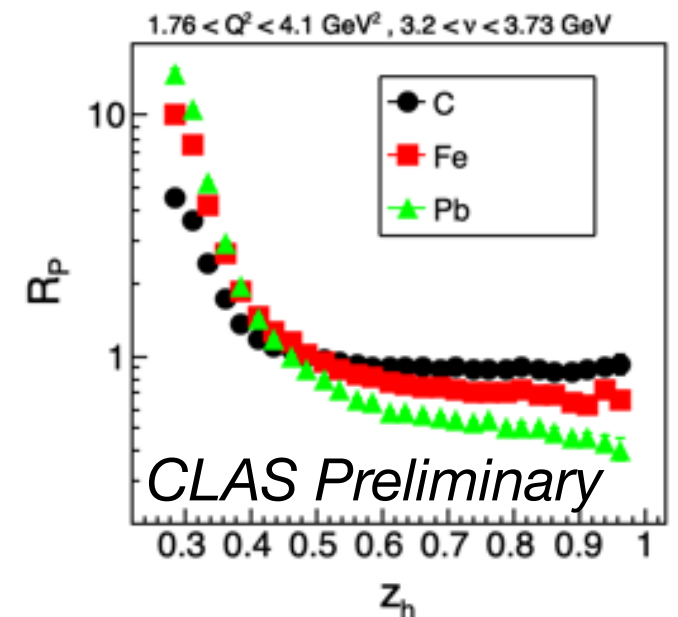
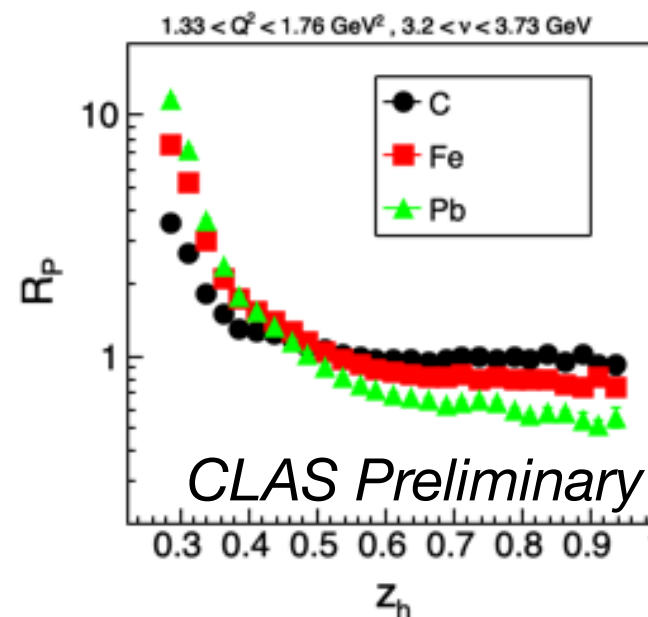
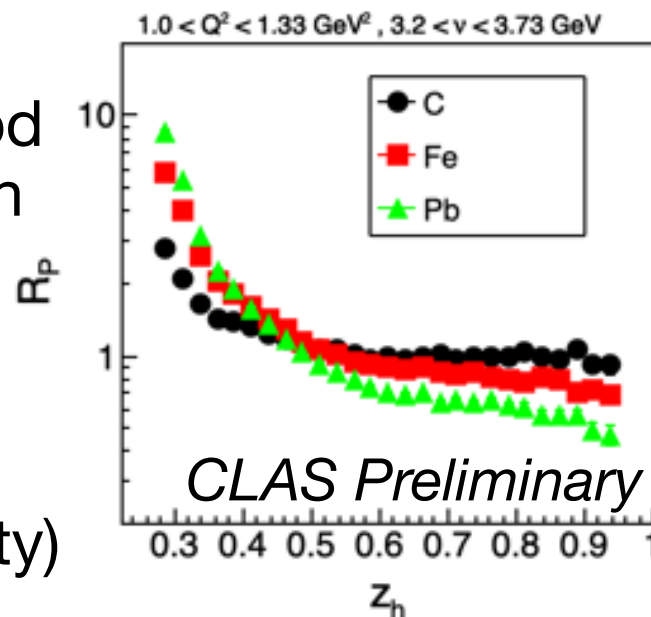
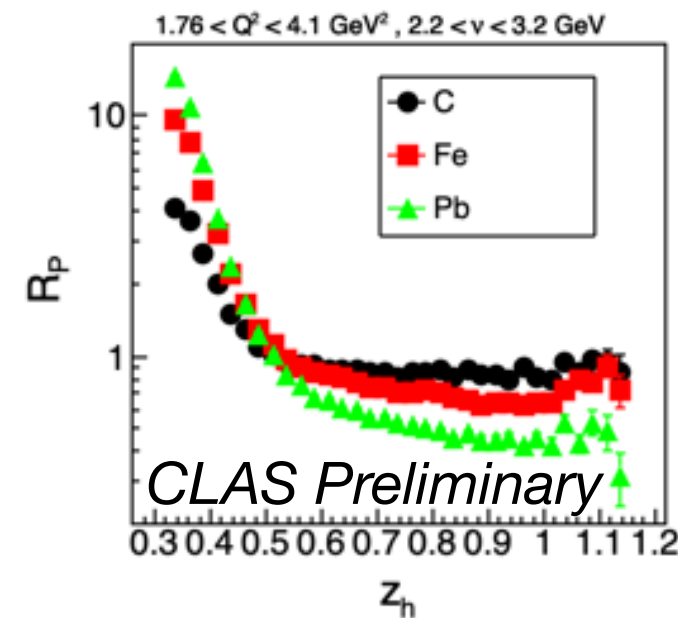
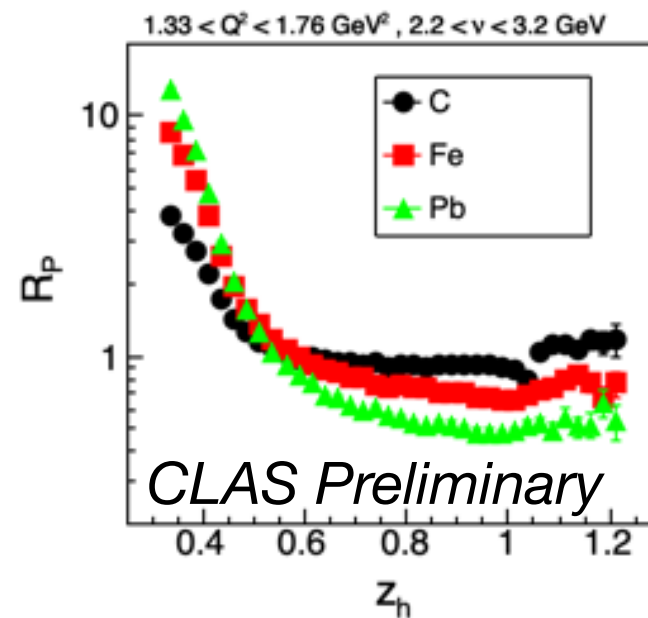
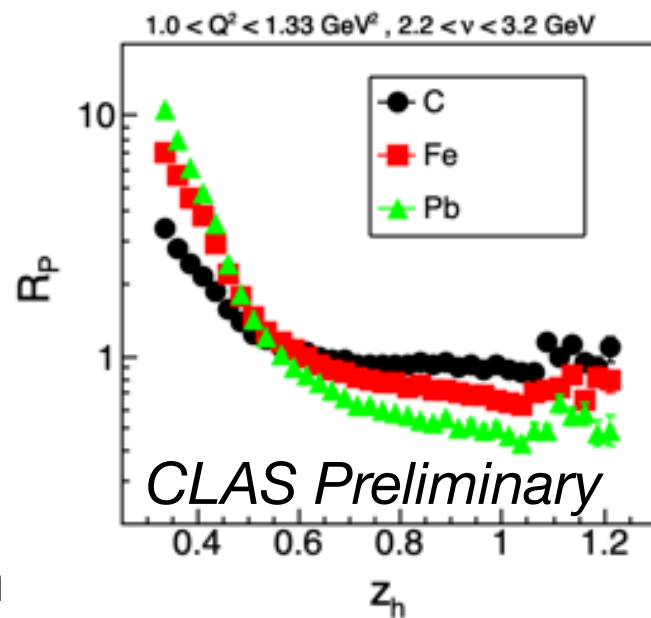
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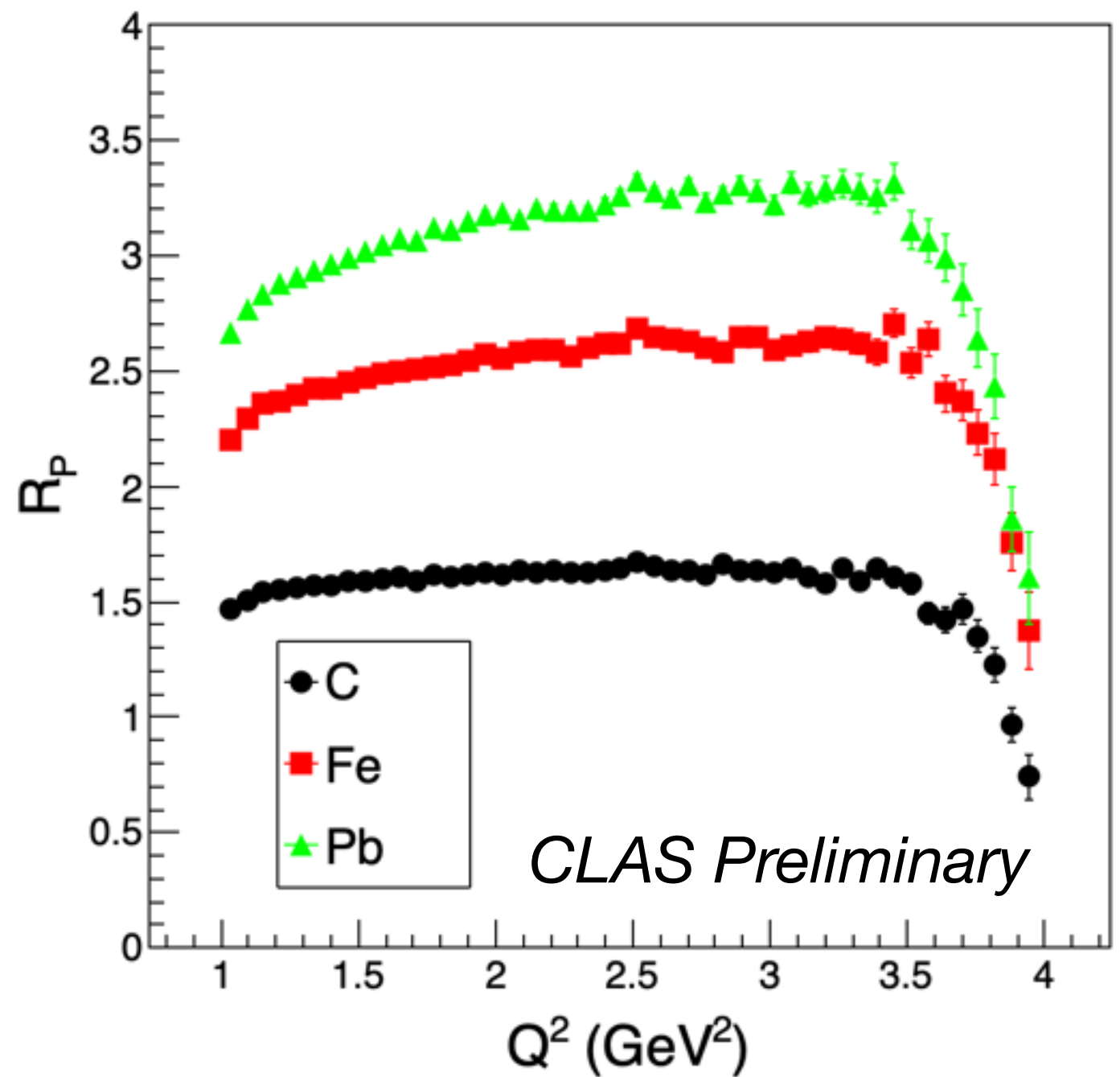


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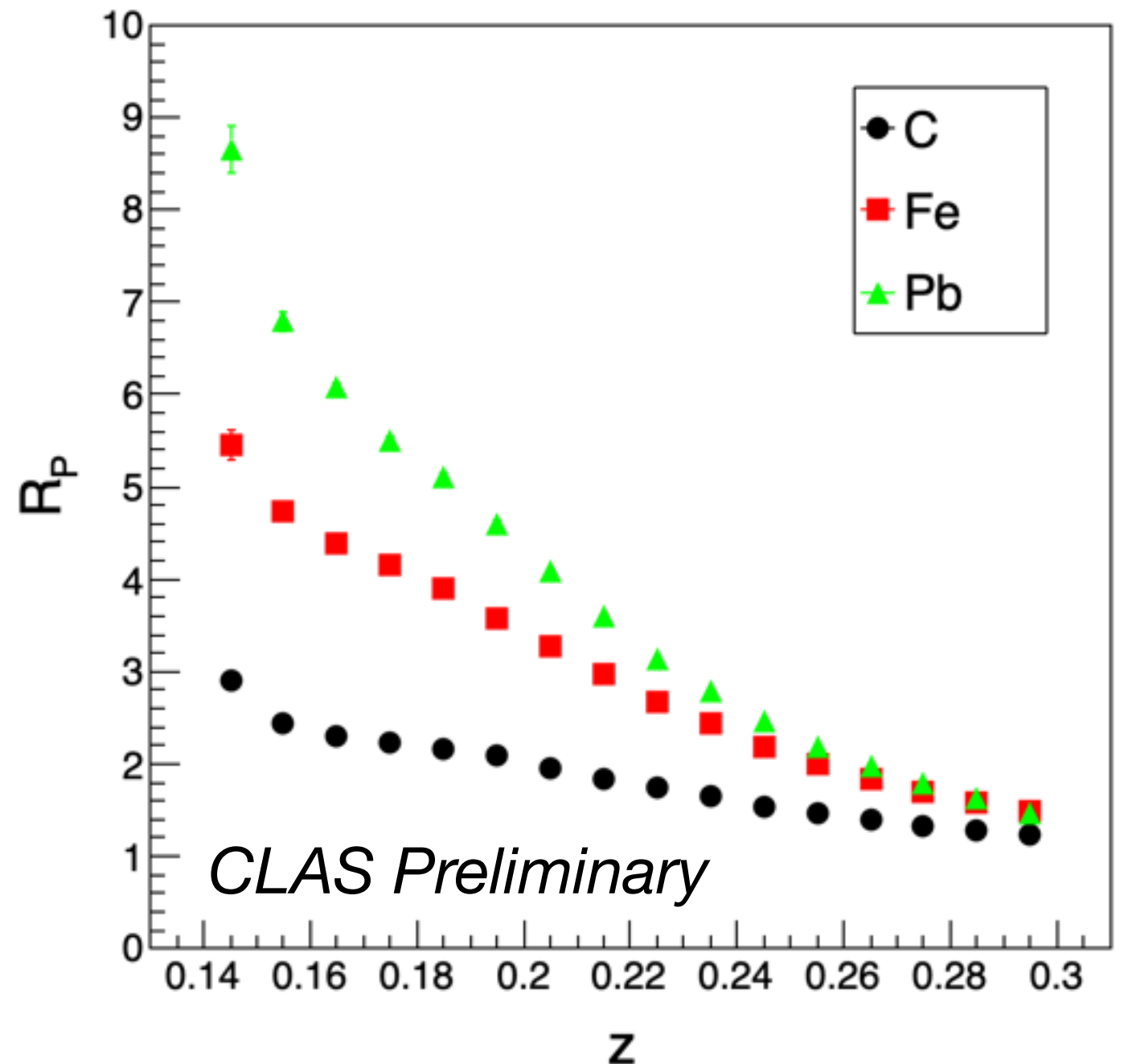
eg2 Experiment



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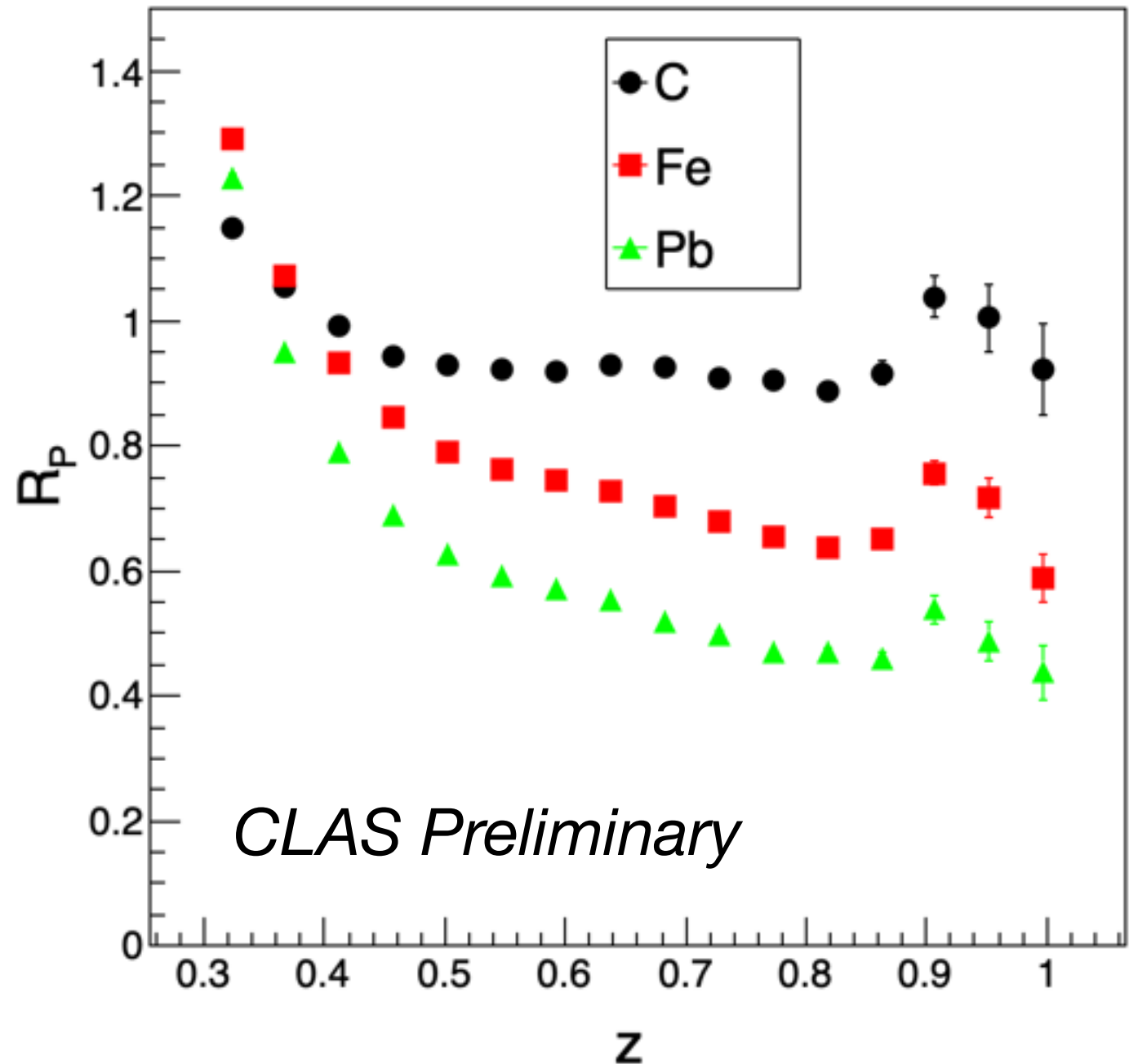
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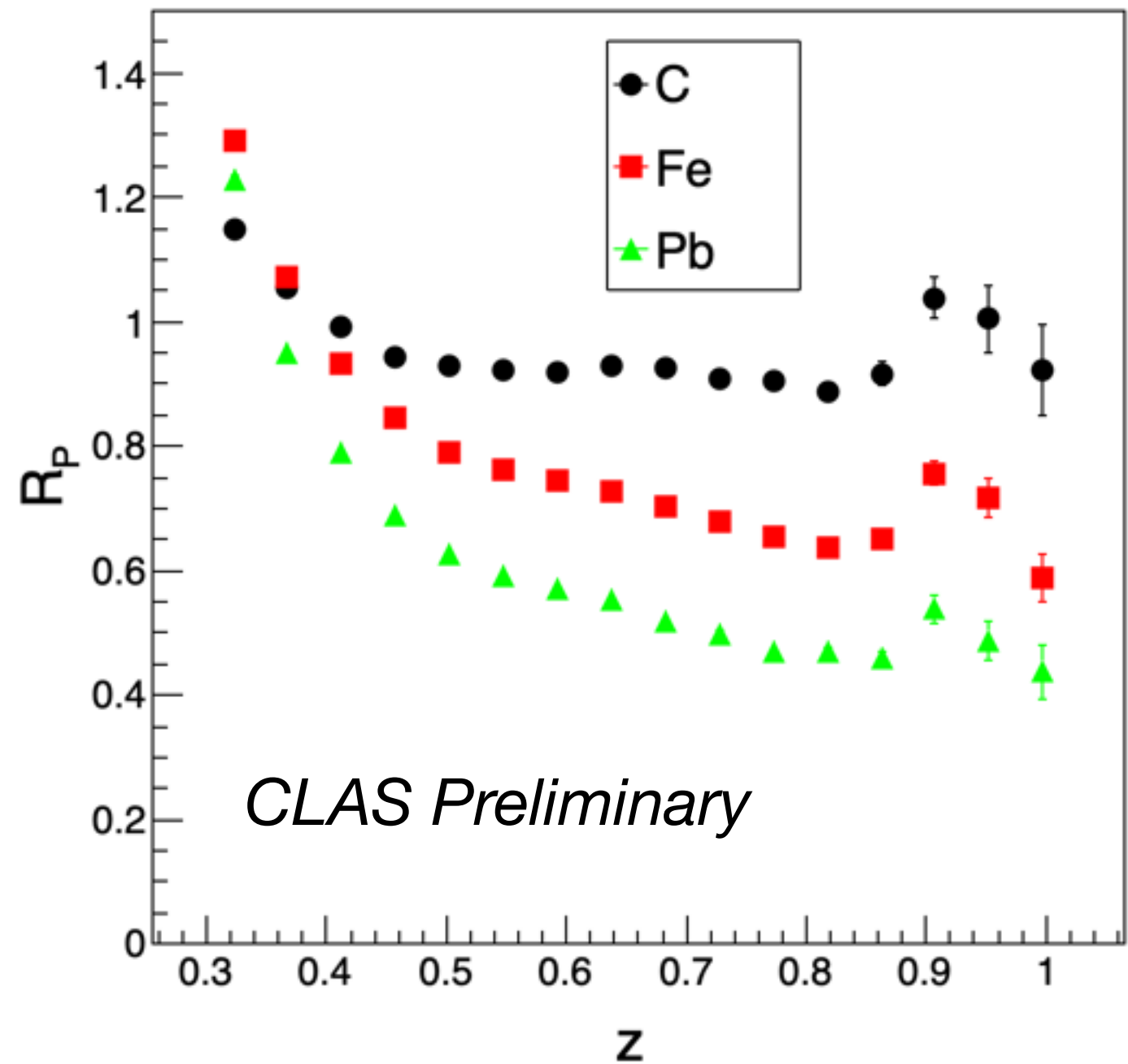
eg2 Experiment



CLAS EG2 SIDIS Proton Production Analysis

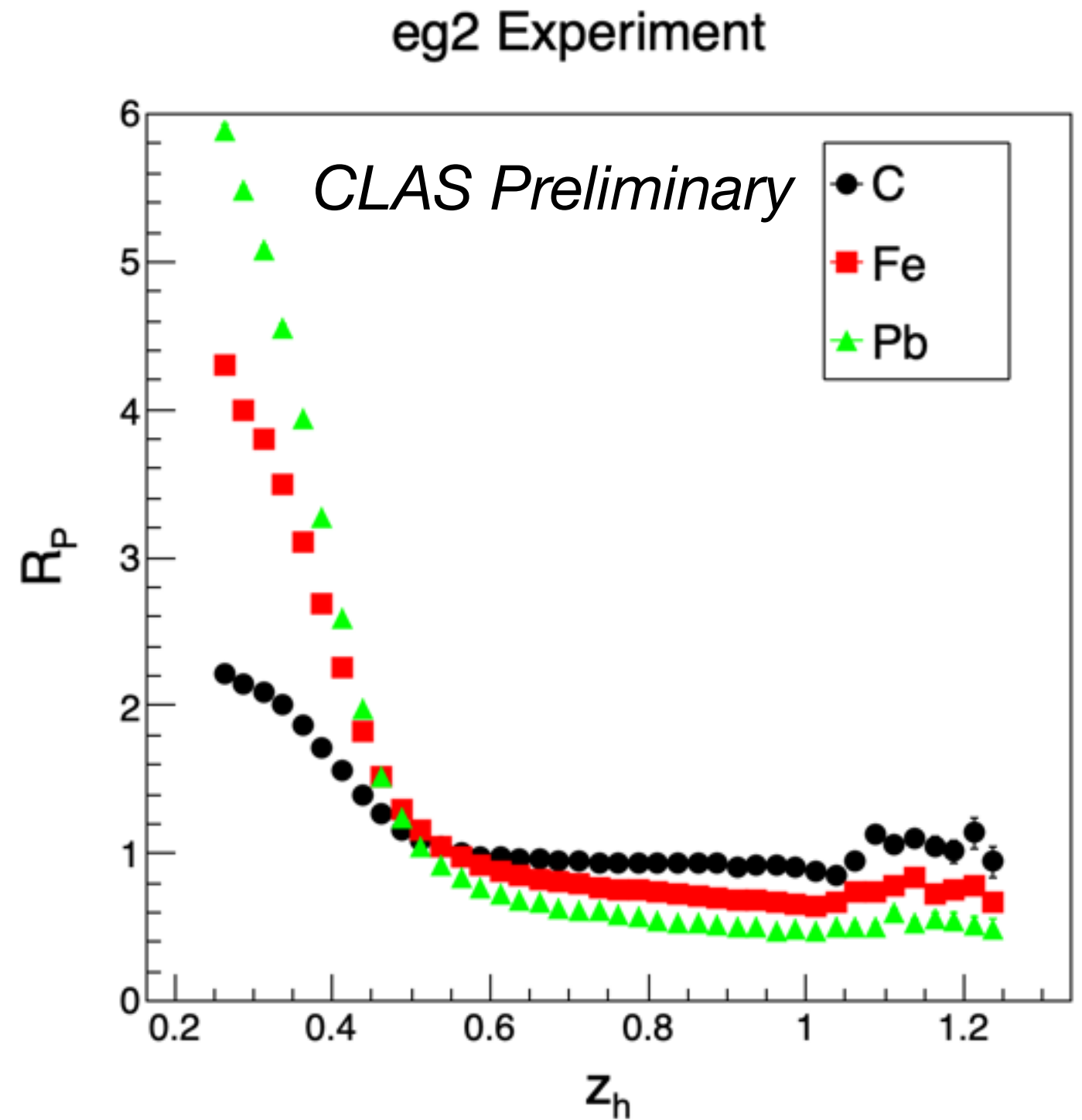
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eg2 Experiment



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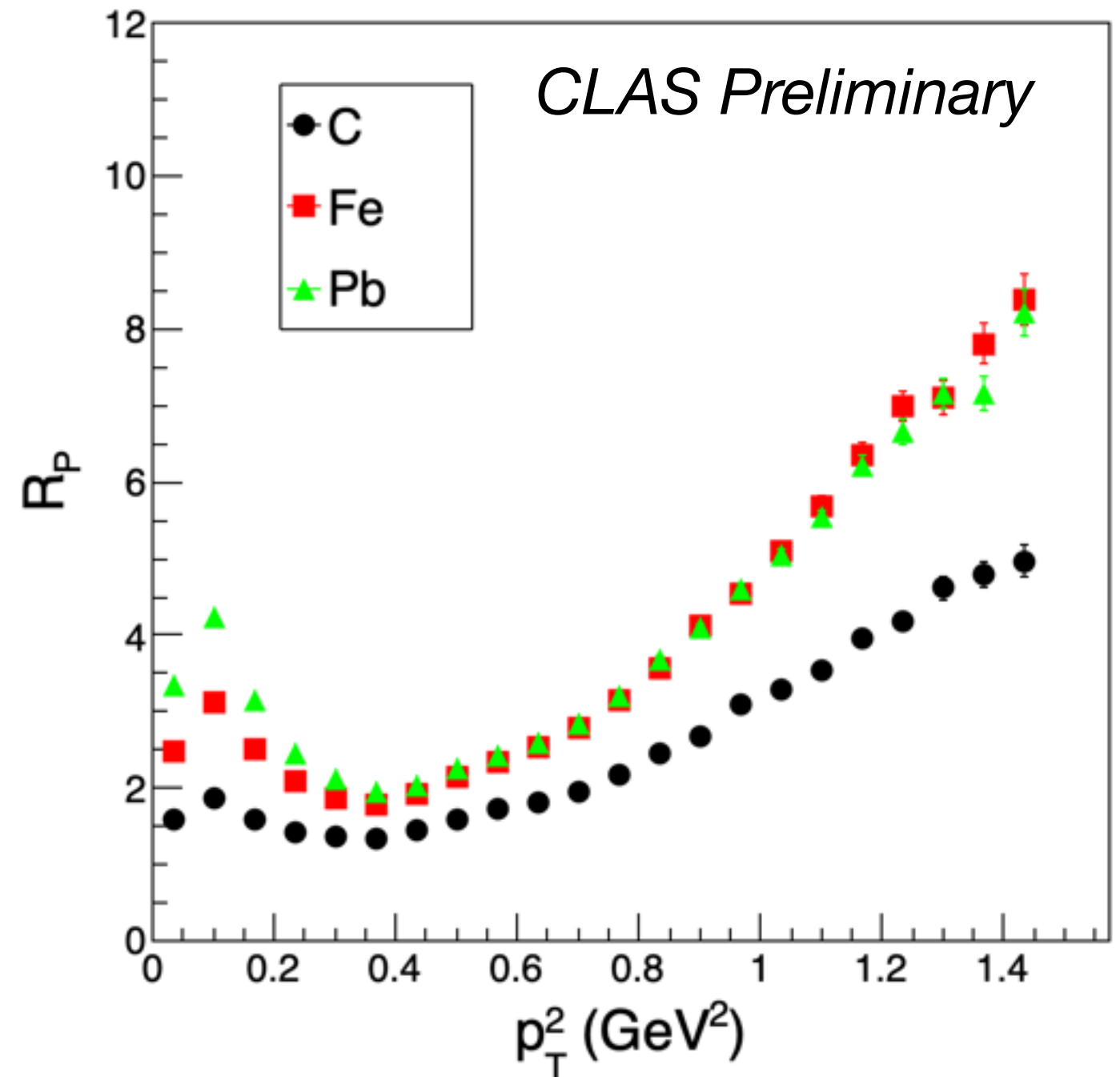
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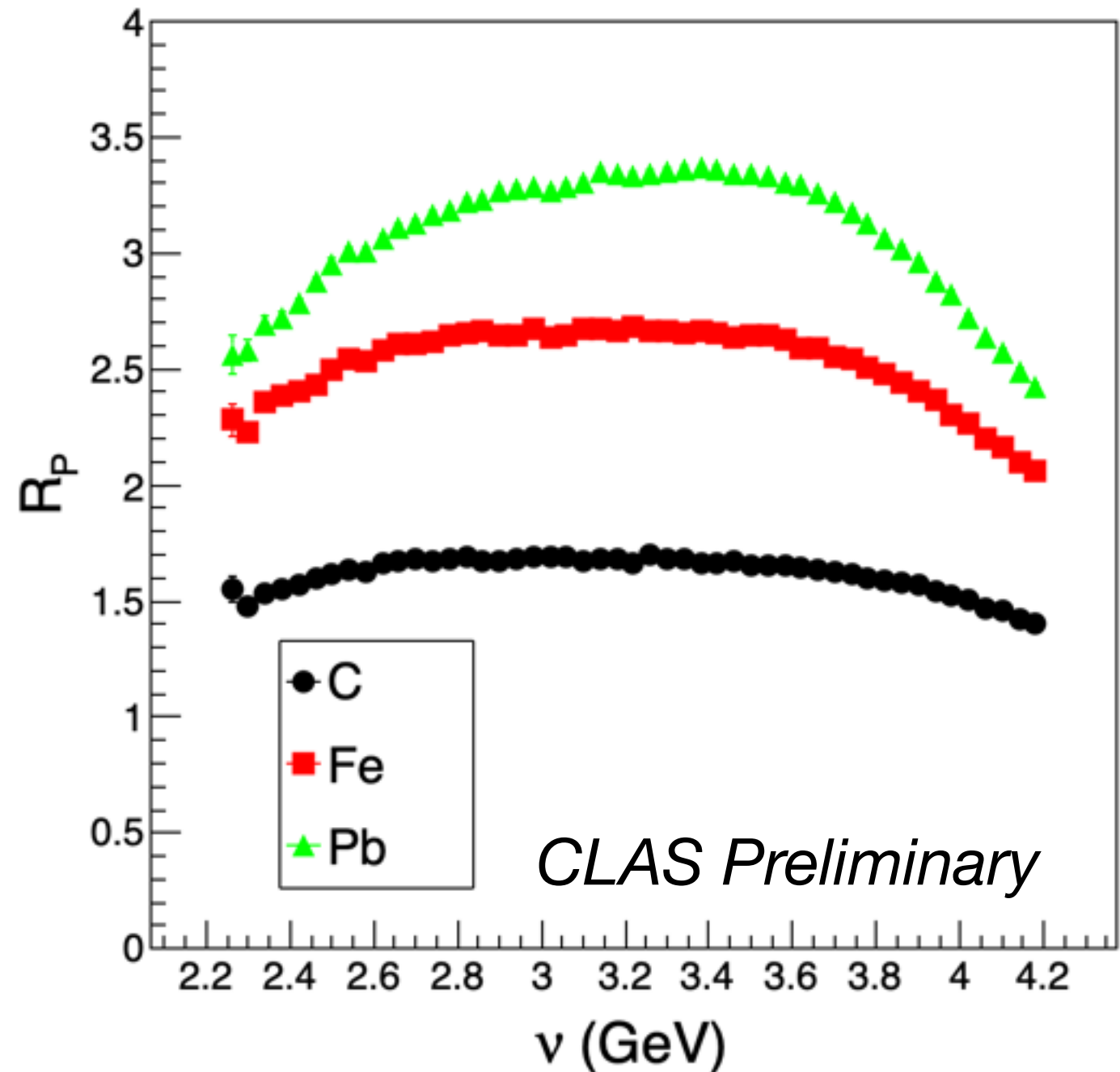
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eg2 Experiment



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YIN, CHEN, KREIN,
ROBERTS, SEGOVIA,
and XU, PHYS. REV.
D 100, 034008 (2019)

TABLE III. Computed masses and amplitudes for the diquark correlations: $[fg]$ indicates a $J^P = 0^+$ diquark, antisymmetric under $f \leftrightarrow g$, and $\{fg\}$ indicates a $J^P = 1^+$ diquark, symmetric under $f \leftrightarrow g$. (Masses listed in GeV.)

Diquark	Mass	E	F
$[ud]$	0.77	2.74	0.31
$[us]$	0.93	2.88	0.39
$[uc]$	2.15	1.97	0.22
$[sc]$	2.26	1.99	0.29
$[ub]$	5.51	1.05	0.059
$[sb]$	5.60	1.05	0.083
$[cb]$	6.48	1.42	0.25
$\{uu\}$	1.06	1.31	
$\{us\}$	1.16	1.36	
$\{ss\}$	1.26	1.43	
$\{uc\}$	2.24	0.89	
$\{sc\}$	2.34	0.87	
$\{cc\}$	3.30	0.69	
$\{ub\}$	5.53	0.51	
$\{sb\}$	5.62	0.50	
$\{cb\}$	6.50	0.62	
$\{bb\}$	9.68	0.48	

YIN, CHEN, KREIN,
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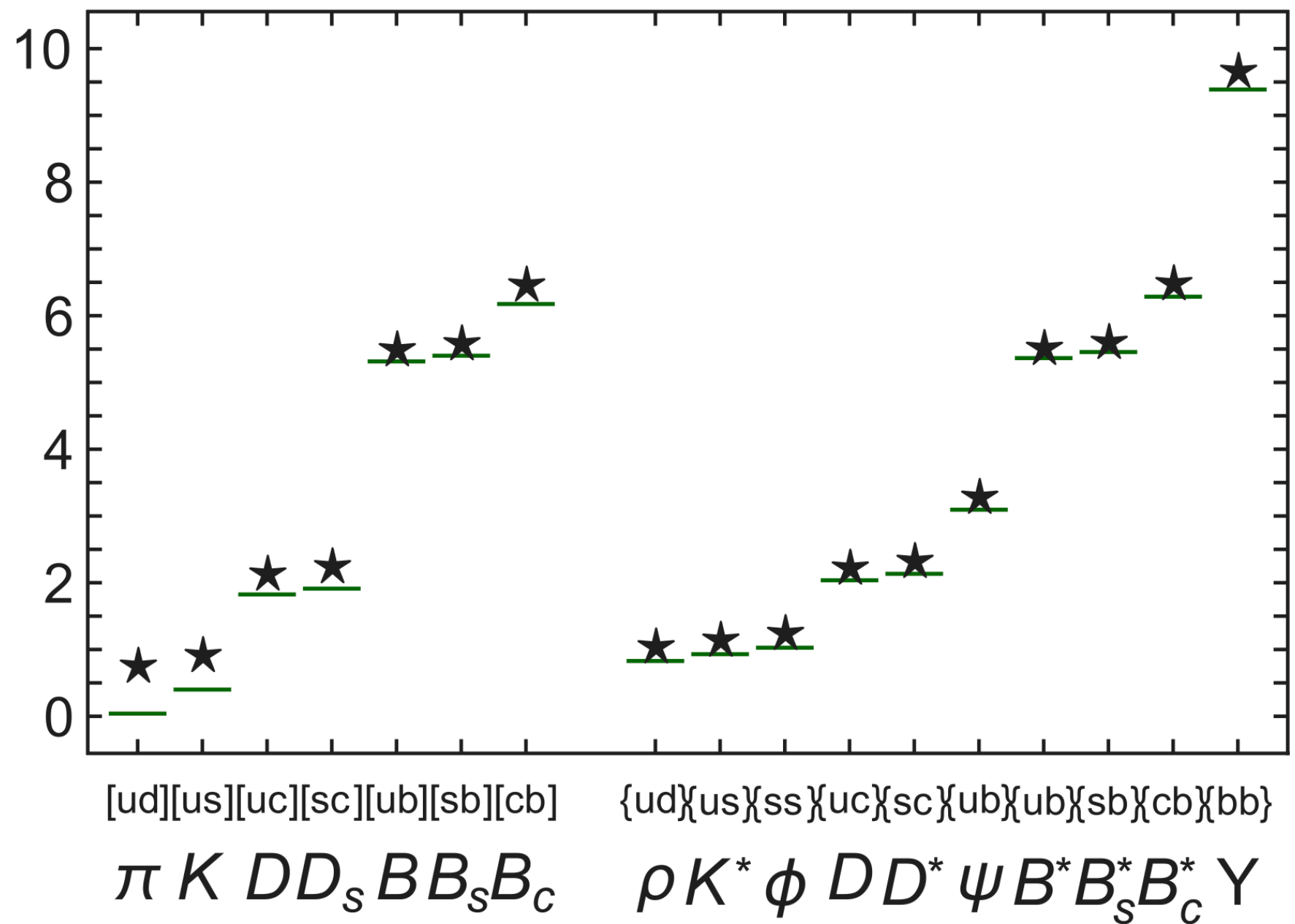


FIG. 2. Comparison between computed masses of diquark correlations and their symmetry-related meson counterparts: diquarks are (black) stars and mesons are (green) bars.

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TABLE III. Computed masses and amplitudes for the diquark correlations: $[fg]$ indicates a $J^P = 0^+$ diquark, antisymmetric under $f \leftrightarrow g$, and $\{fg\}$ indicates a $J^P = 1^+$ diquark, symmetric under $f \leftrightarrow g$. (Masses listed in GeV.)

Diquark	Mass	E	F
$[ud]$	0.77	2.74	0.31
$[us]$	0.93	2.88	0.39
$[uc]$	2.15	1.97	0.22
$[sc]$	2.26	1.99	0.29
$[ub]$	5.51	1.05	0.059
$[sb]$	5.60	1.05	0.083
$[cb]$	6.48	1.42	0.25
$\{uu\}$	1.06	1.31	
$\{us\}$	1.16	1.36	
$\{ss\}$	1.26	1.43	
$\{uc\}$	2.24	0.89	
$\{sc\}$	2.34	0.87	
$\{cc\}$	3.30	0.69	
$\{ub\}$	5.53	0.51	
$\{sb\}$	5.62	0.50	
$\{cb\}$	6.50	0.62	
$\{bb\}$	9.68	0.48	

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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			$\{bb\}b$

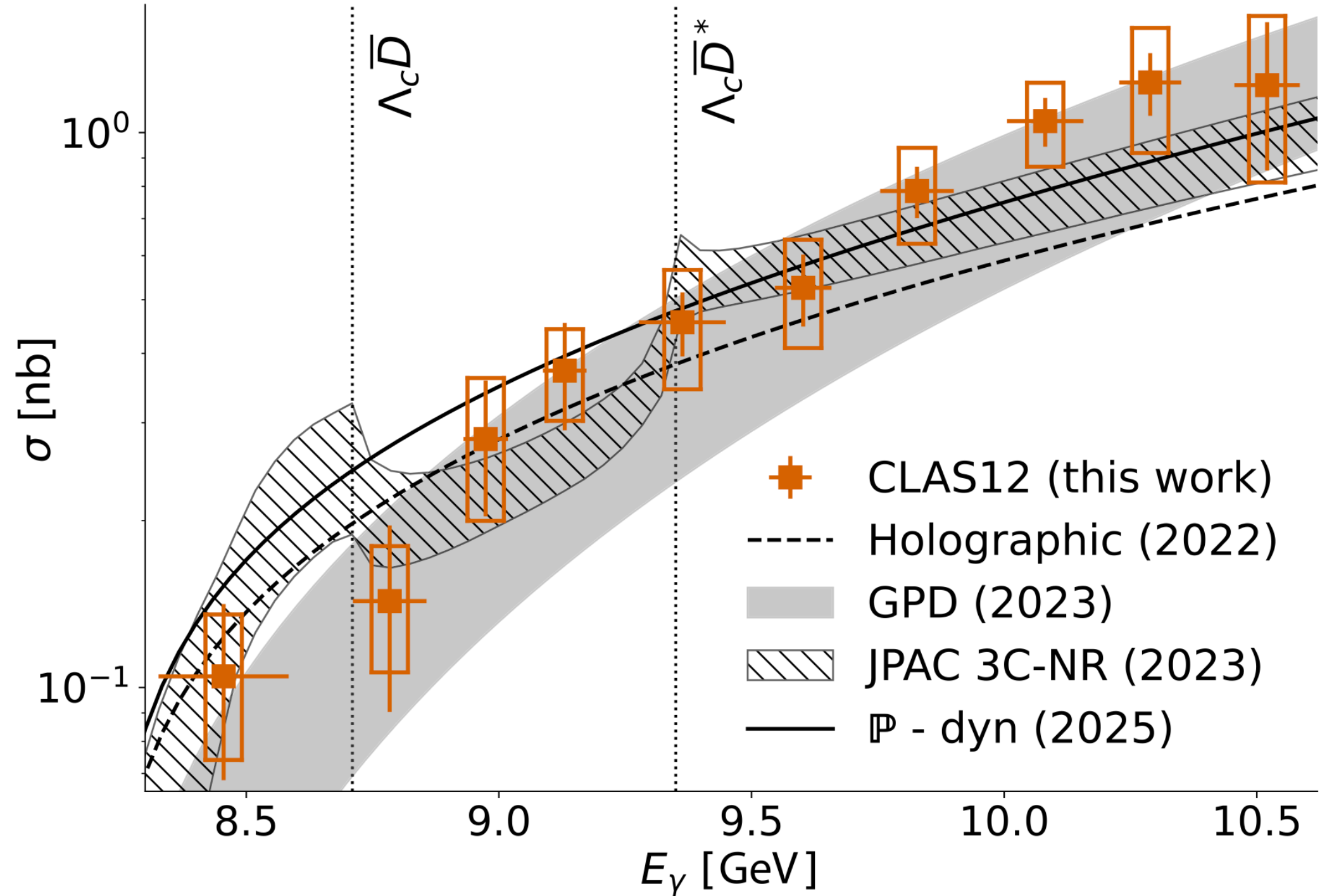
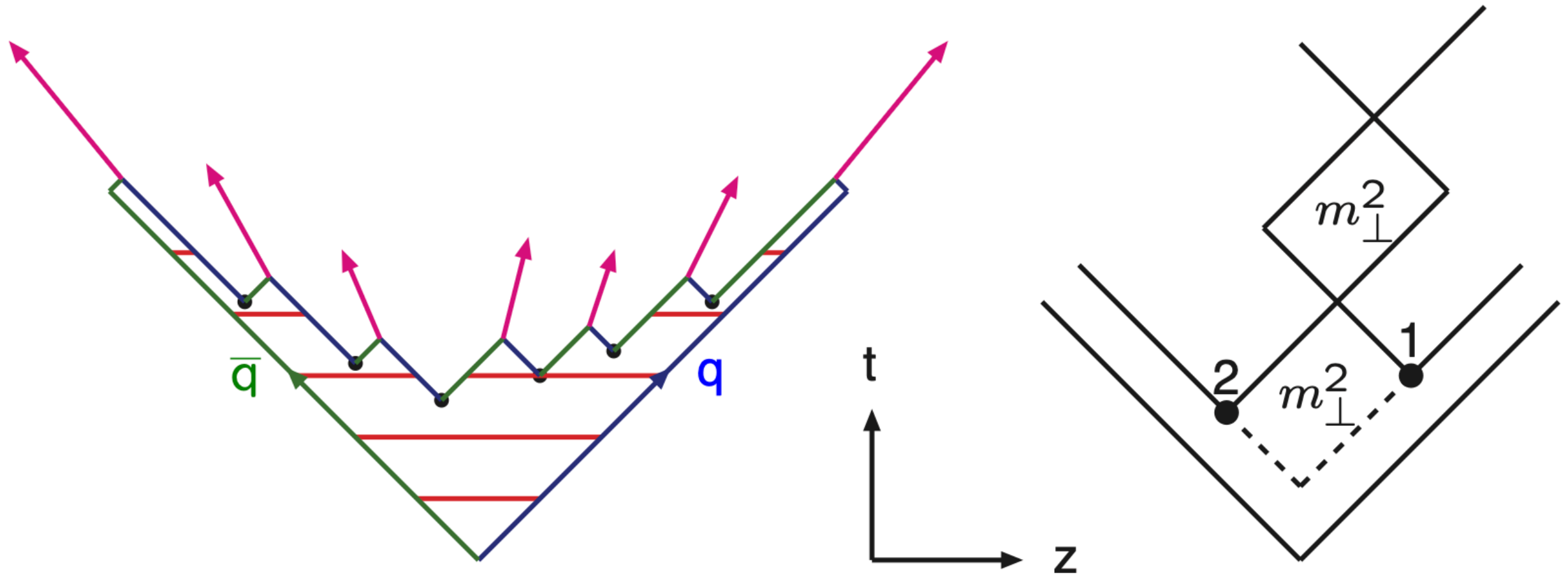


FIG. 7. Total cross sections for J/ψ photoproduction measured with the CLAS12 experiment (orange squares). Vertical error bars represent statistical uncertainties, while the boxes indicate systematic uncertainties. The GPD model prediction [25] is shown as a gray band. The holographic-OCD model prediction [24] is displayed by

Fragmentation starts in the middle and spreads outwards:



$f(z)$, $a = 0.5$, $b = 0.7$

but breakup vertices causally disconnected

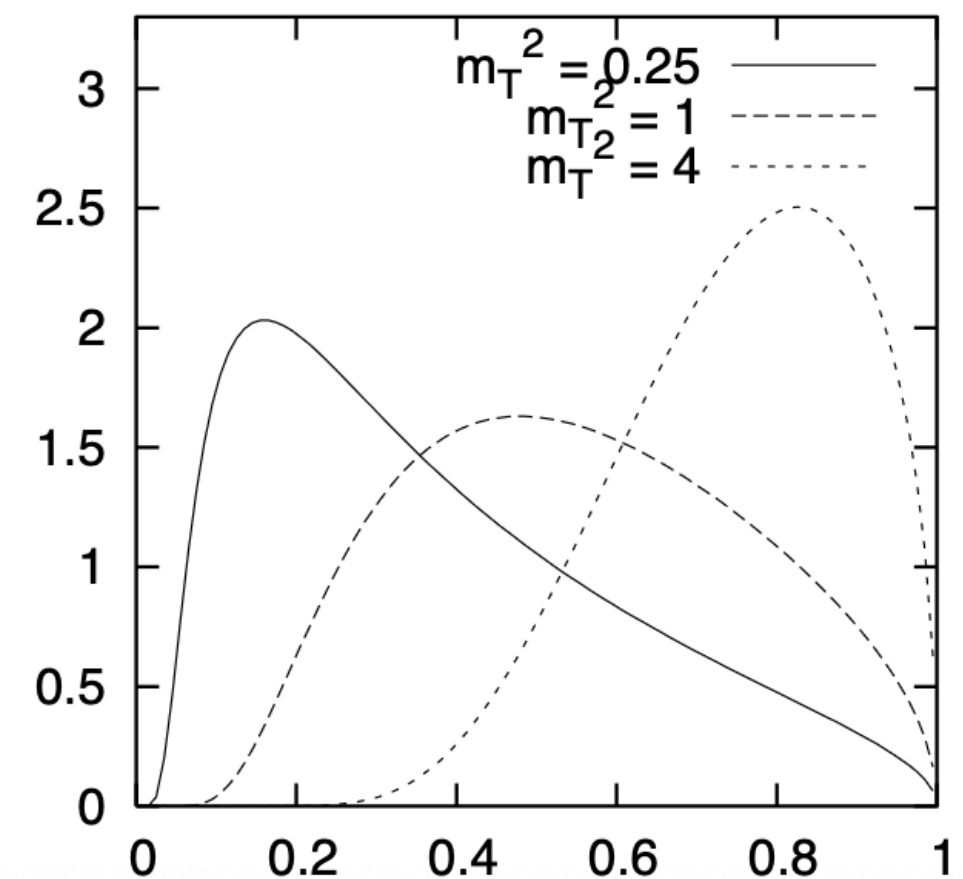
$\Rightarrow$ can proceed in arbitrary order

$\Rightarrow$ *left-right symmetry*

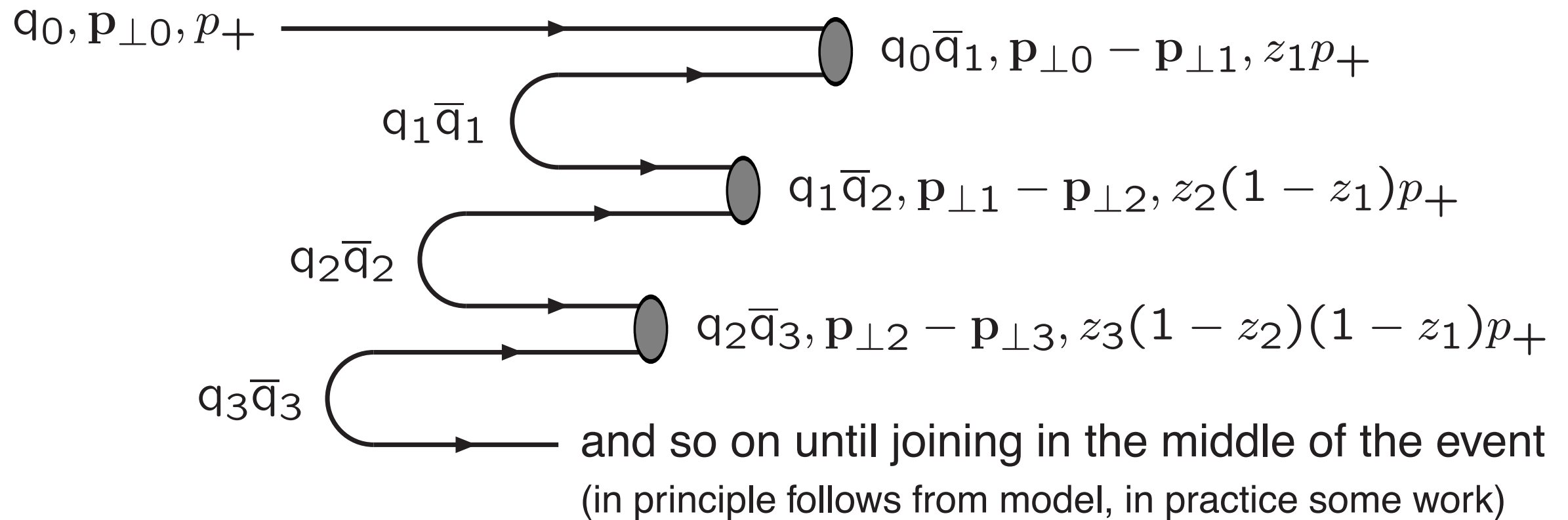
$$\begin{aligned}\mathcal{P}(1, 2) &= \mathcal{P}(1) \times \mathcal{P}(1 \rightarrow 2) \\ &= \mathcal{P}(2) \times \mathcal{P}(2 \rightarrow 1)\end{aligned}$$

$\Rightarrow$ Lund symmetric fragmentation function

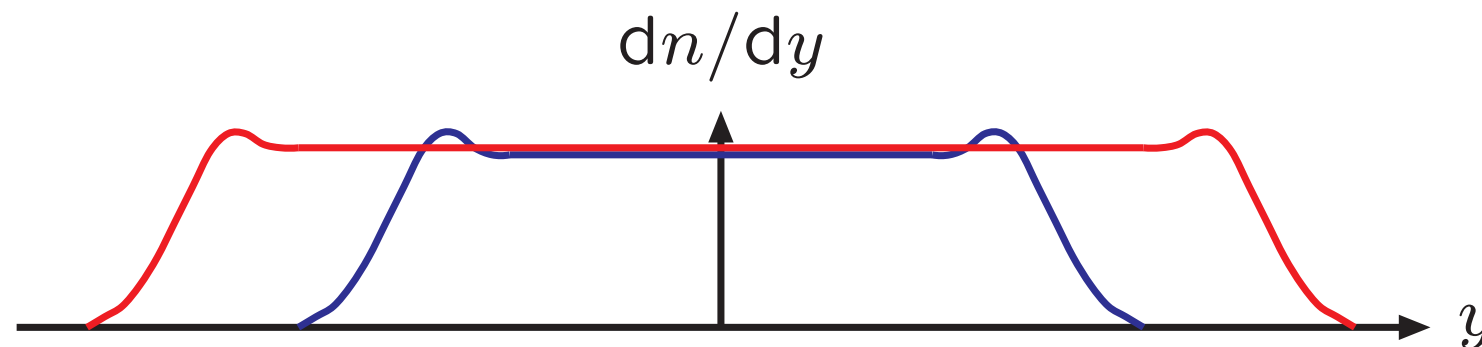
$$f(z) \propto (1/z) (1 - z)^a \exp(-bm_{\perp}^2/z)$$



The iterative ansatz



Scaling in lightcone $p_{\pm} = E \pm p_z$ (for $q\bar{q}$ system along z axis)
 implies flat central rapidity plateau + some endpoint effects:



$$\langle n_{\text{ch}} \rangle \approx c_0 + c_1 \ln E_{\text{cm}}, \sim \text{Poissonian multiplicity distribution}$$