# Implications for Diquark Investigations from the Measurement of Proton Multi-dimensional Multiplicity Ratios

Dr. Michael H. Wood, Canisius University
for the CLAS Collaboration

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# Hadronization

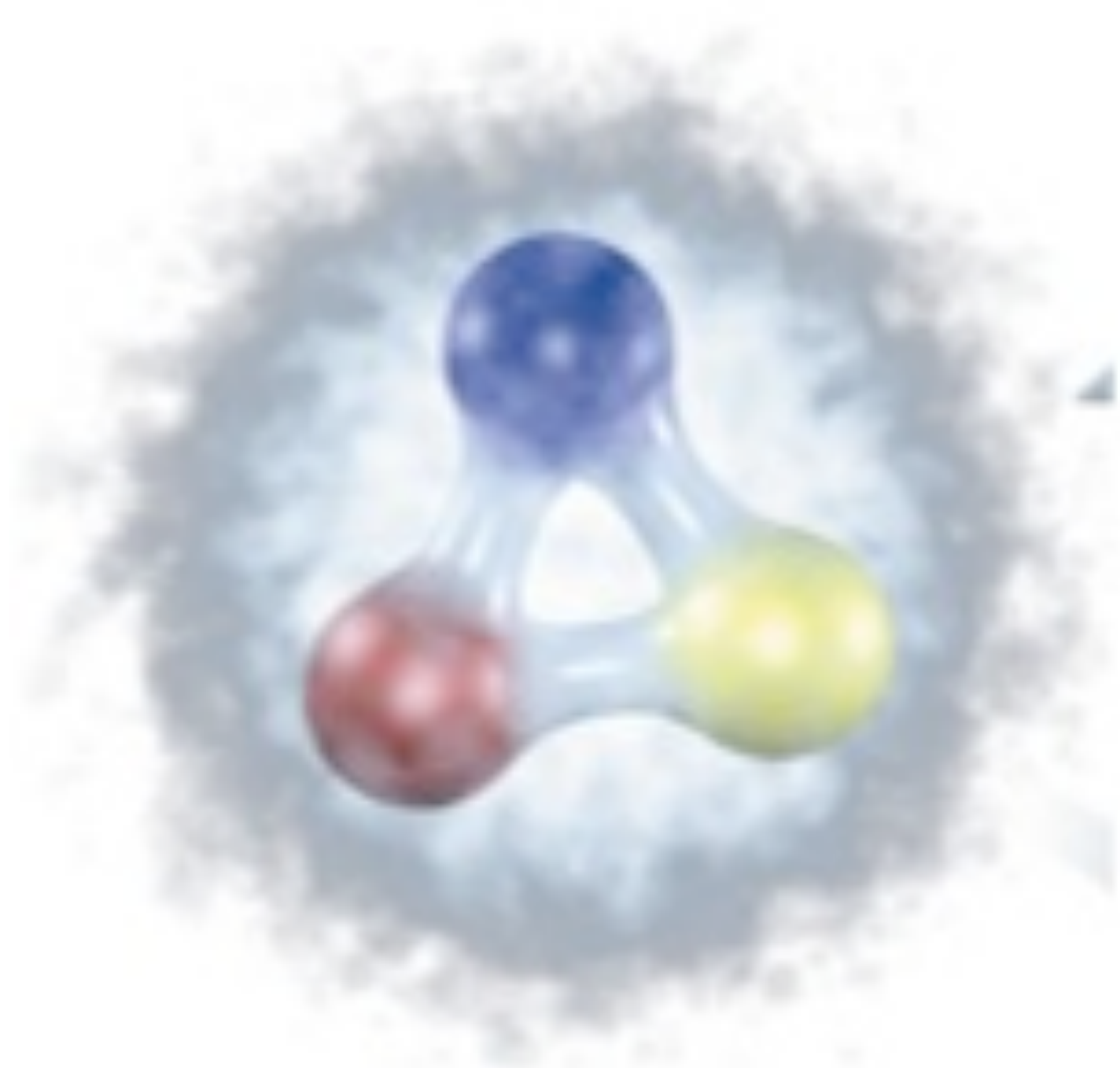
The challenge of calculating the strong interaction is to have a continuous description from high-energy, short range phenomena (perturbative QCD) to the low-energy, low-range phenomena (non-perturbative QCD).

In the perturbative regime, the binding between quarks is weak, so they can move around more freely.

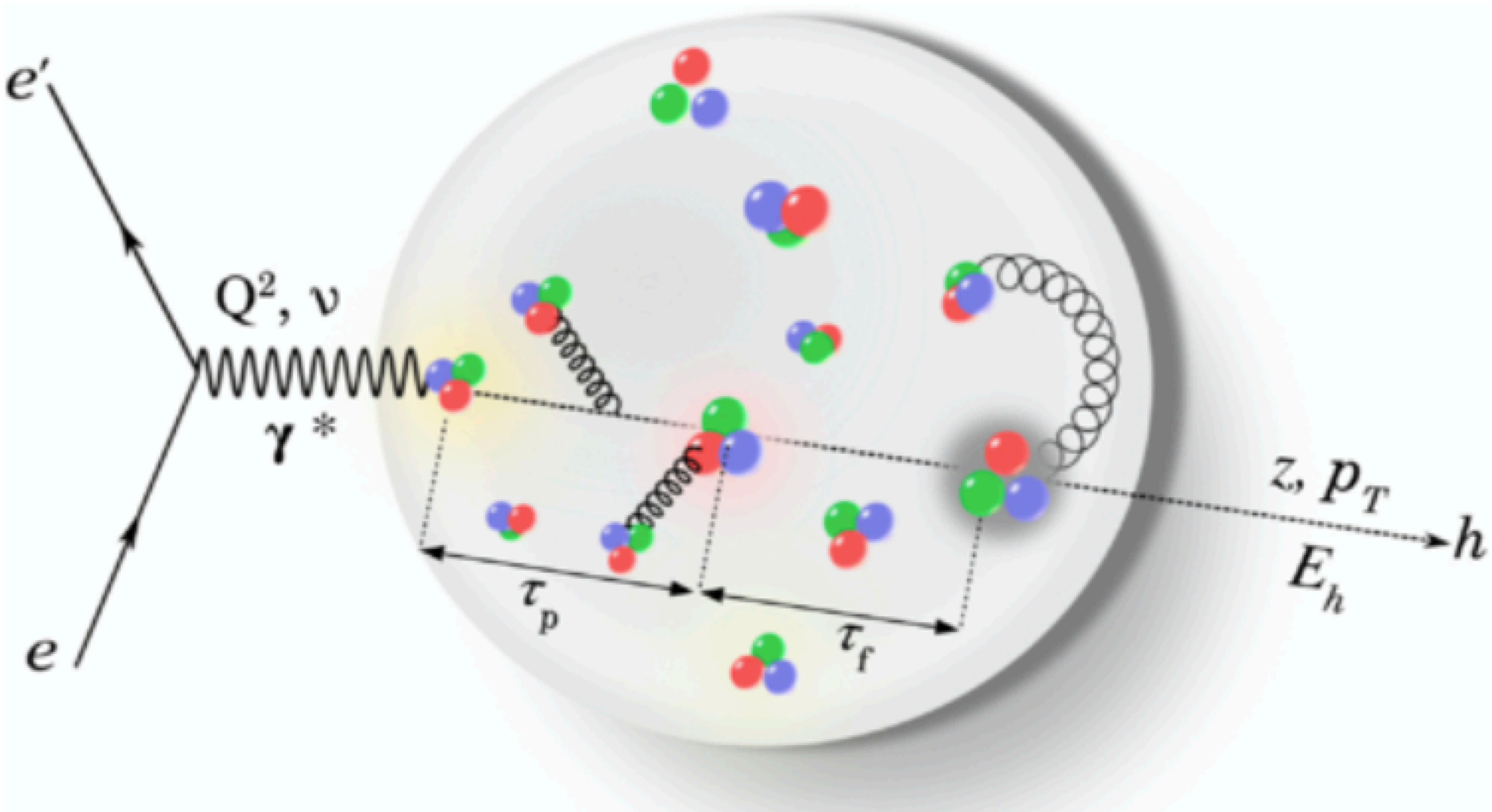
In the non-perturbative regime, quarks are confined to color-neutral hadrons.

Hadronization is the process of a free quarks evaluating into a color-neutral object

This presentation will describe the study of the hadronization of protons from deep-inelastic scattering (DIS) of electrons from cold nuclei.



# Deep Inelastic Scattering




$E$ - incident electron energy

$E'$ - scattered electron energy

$M_N$ - nucleon mass

$\theta_e$ - polar angle of the scattered electron

Energy transfer by virtual photon

$$\nu = E - E'$$

Four-momentum transfer

$$Q^2 = EE' \sin\left(\theta_e/2\right)$$

Mass squared of the final state

$$W^2 = M_N^2 - Q^2 + 2M_N\nu$$

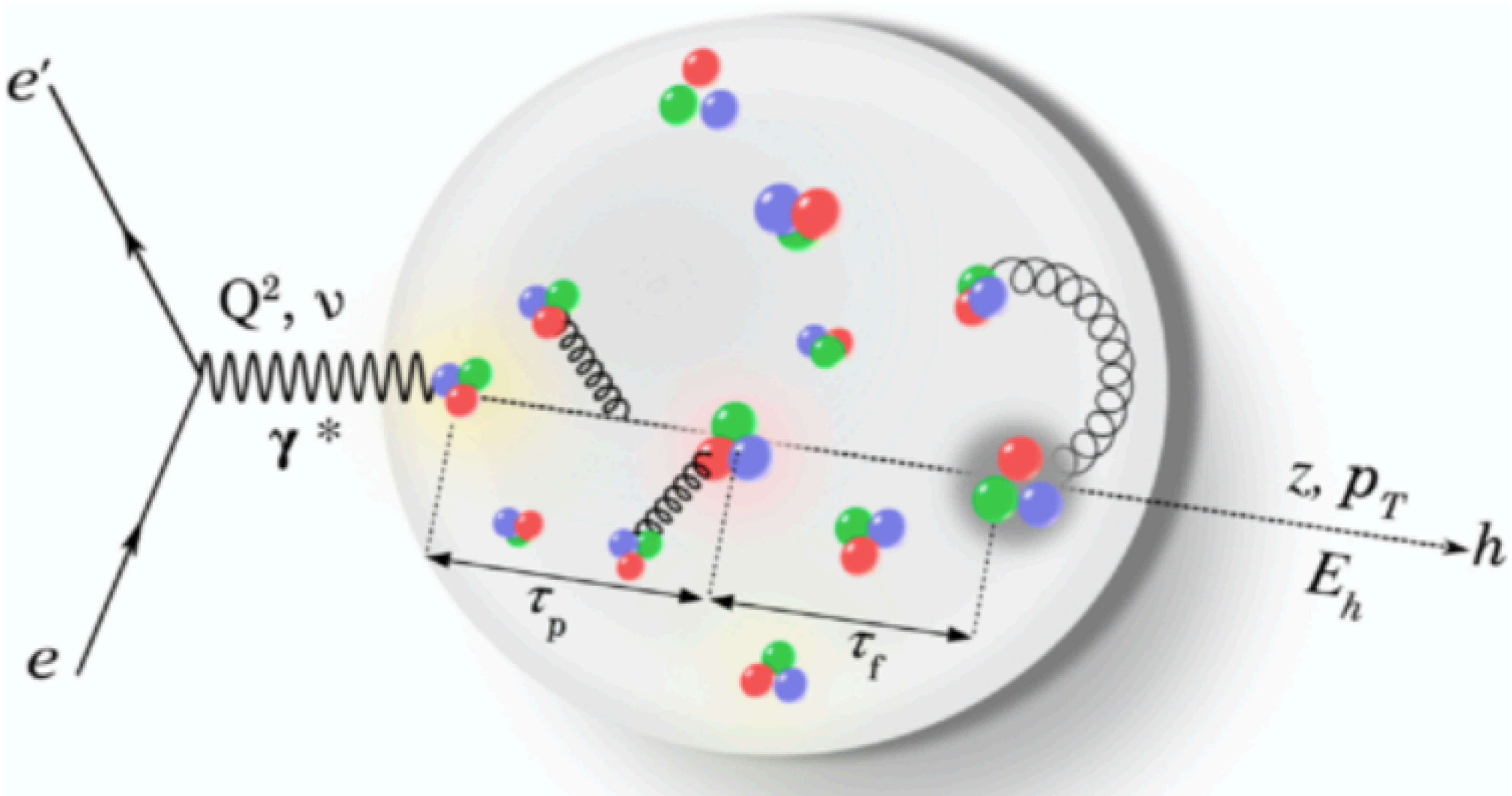
Bjorken $x$

$$x_B = \frac{Q^2}{2M_N\nu}$$

Fraction of energy transferred

$$y = \frac{\nu}{E}$$

# Hadronization - Variables



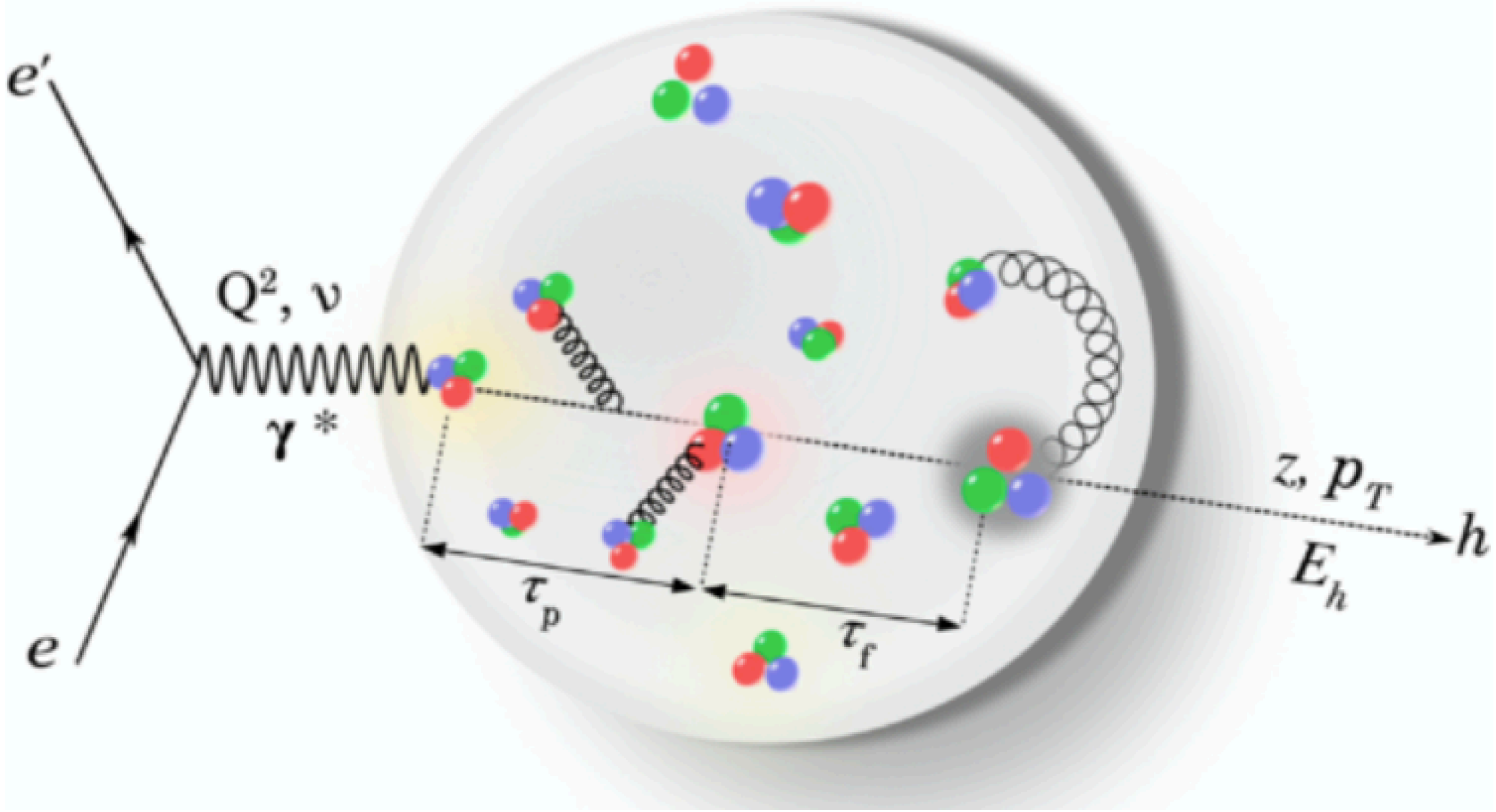

Fractional energy carried by hadron

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

Transverse momentum $p_T^2$

Underlying philosophy: learn about the hadronization process at femtometer distance scales by implanting this process within an atomic nucleus. The modifications of the final produced hadrons can give insight into the intermediate processes producing them.

# Hadronization - Observables




Multiplicity Ratio

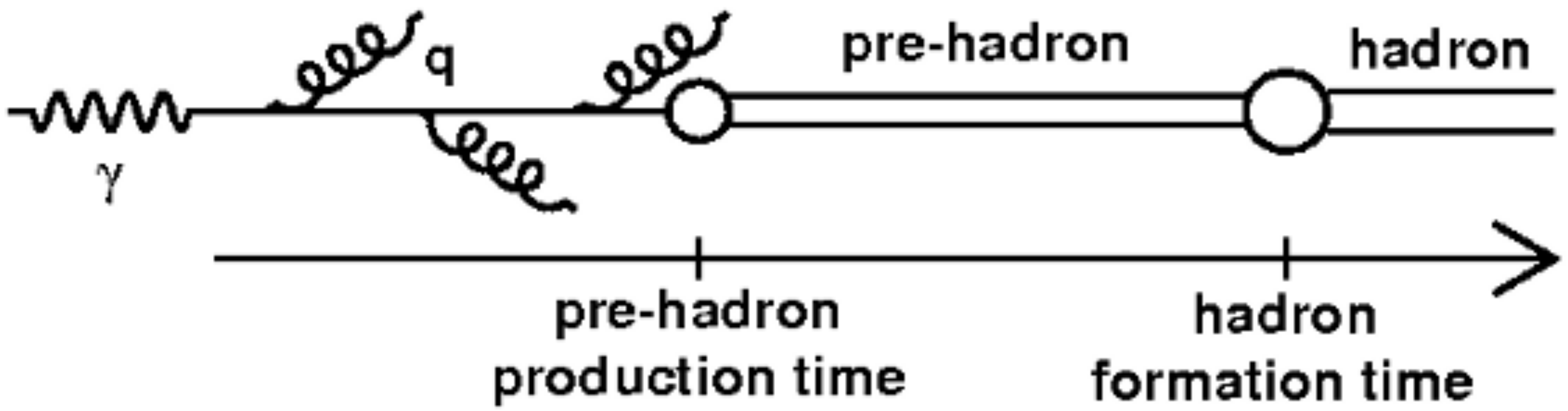
$$R_h(z, p_T^2, \nu, Q^2) = \frac{N_h^A(z, p_T^2, \nu, Q^2)/N_e^A(\nu, Q^2)}{N_h^D(z, p_T^2, \nu, Q^2)/N_e^D(\nu, Q^2)}$$

Transverse Momentum Broadening

$$\Delta p_T^2 = < p_T^2 >_A - < p_T^2 >_D$$

$\tau_p$ - production time or color lifetime

$\tau_f$ - formation time



$$R_h(z, p_T^2, \nu, Q^2) = \frac{N_h^A(z, p_T^2, \nu, Q^2)/N_e^A(\nu, Q^2)}{N_h^D(z, p_T^2, \nu, Q^2)/N_e^D(\nu, Q^2)}$$

$R_h(z, p_T^2, \nu, Q^2)$ measures the effects of the nuclear medium of nucleus A on the final production of hadron *h*.

When $R_h(z, p_T^2, \nu, Q^2) = 1.0$, there are no measureable nuclear effects in a fourfold dimensional bin in $(z,\ p_T^2,\ \nu,\ Q^2)$.

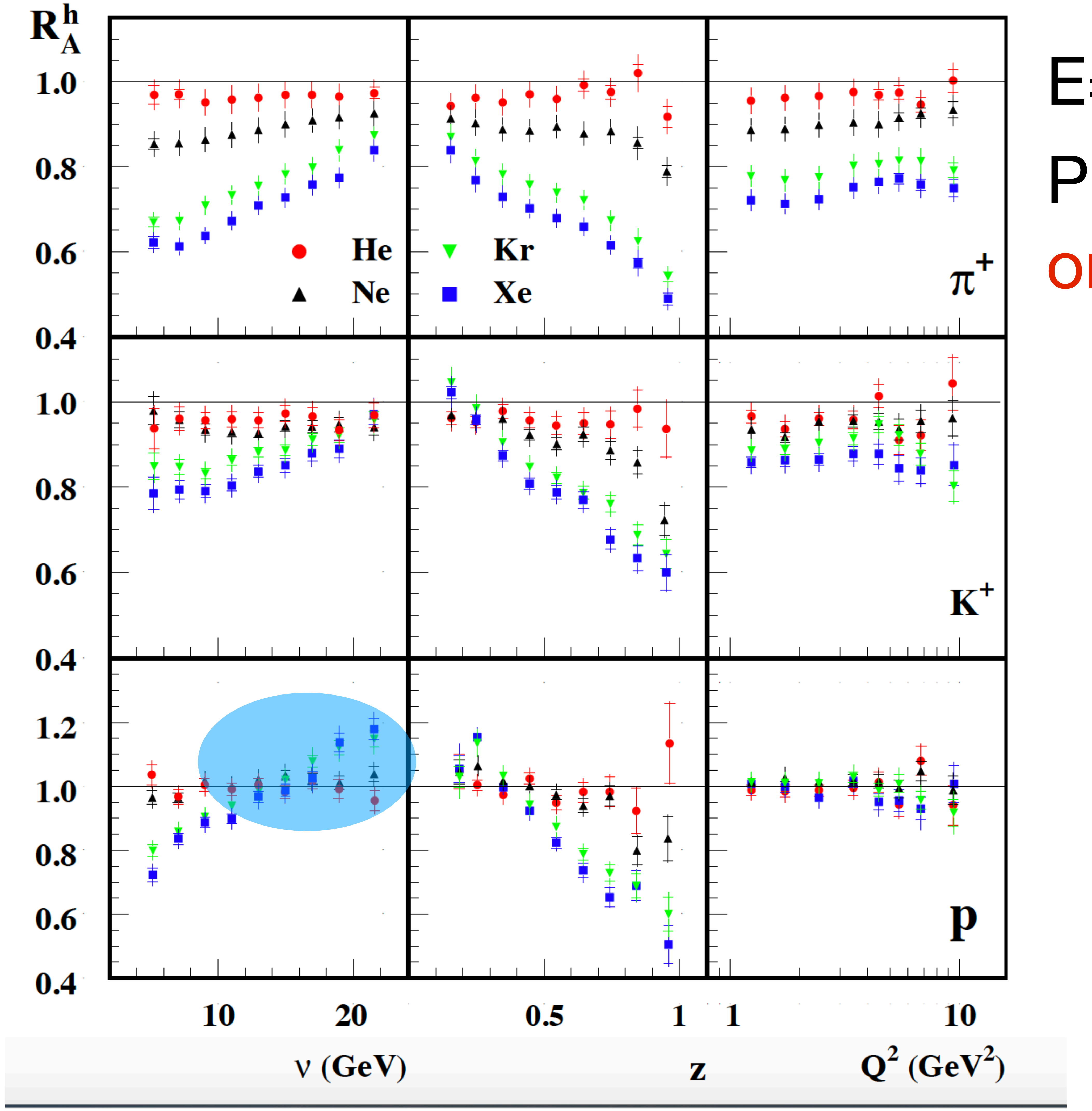
When $R_h(z, p_T^2, \nu, Q^2) < 1.0$, we refer to it as "attenuation" caused by absorption of the hadron, partonic energy loss in the medium, hadronic energy loss, etc.

When $R_h(z, p_T^2, \nu, Q^2) > 1.0$, we refer to it as "enhancement" caused by a **large cross section of the hadronization products** in-medium compared to deuterium, **migration of events** into the $(z,\ p_T^2,\ \nu,\ Q^2)$ bin from other bins (e.g. due to energy loss), etc.

Integrating over some or all of $(z,\ p_T^2,\ \nu,\ Q^2)$ can combine attenuation and enhancement, so a fully multidimensional measurement is preferred when possible.

# One-Dimensional $R_A^h$ - HERMES

## A. Airapetian, *et al.*, Nucl. Phys. B 780 (2007) 1



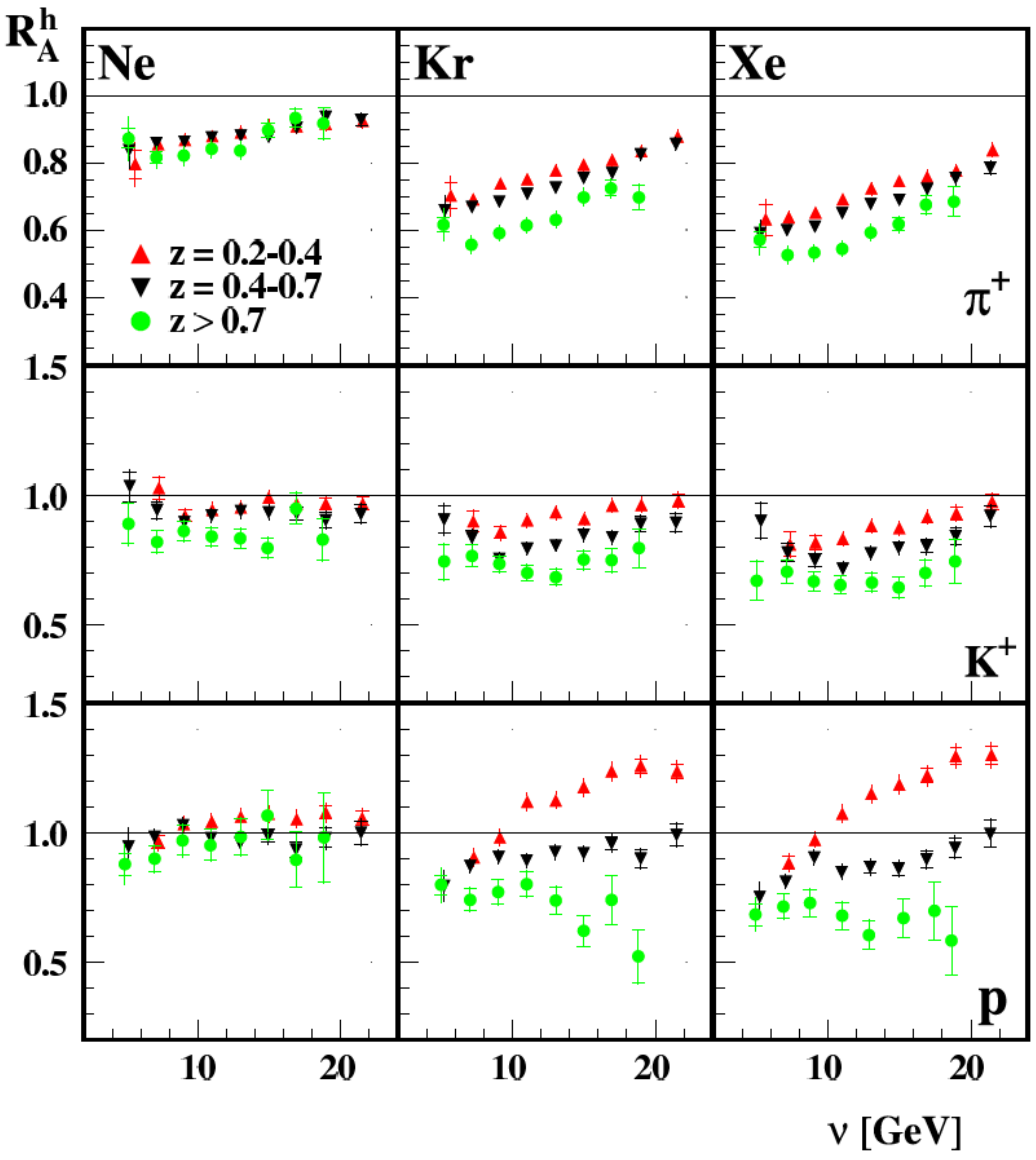

E= 27 GeV; Positron beam

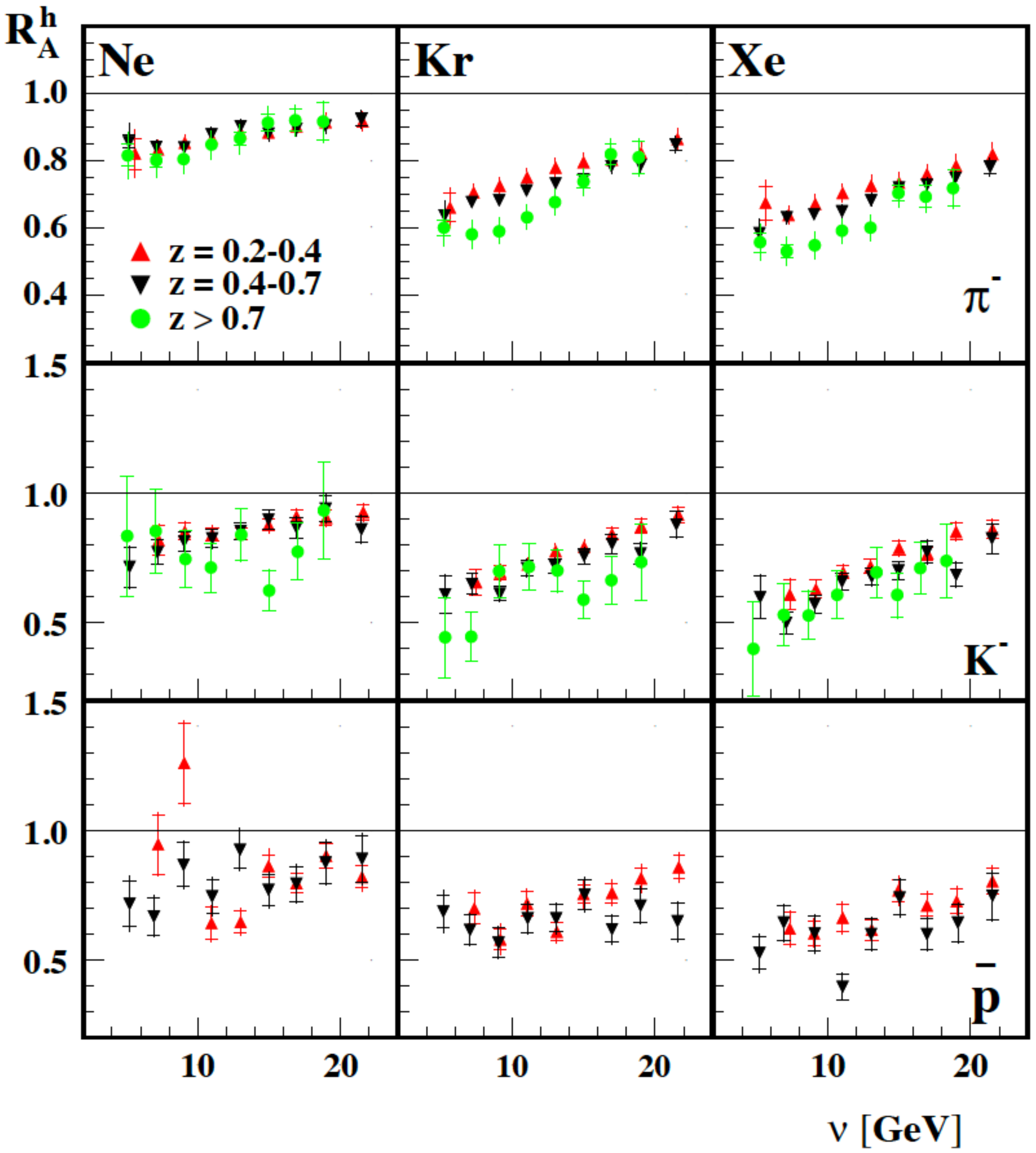
Pions and kaons show similar attenuation; only proton shows enhancement at high $\nu$.

*They suggested that the results for protons cannot be directly compared to those for any of the other hadrons. Because protons are already present in a nucleus, some fraction of them may come from other processes such as proton knockout.*

# Multi-Dimensional $R_A^h$ - HERMES

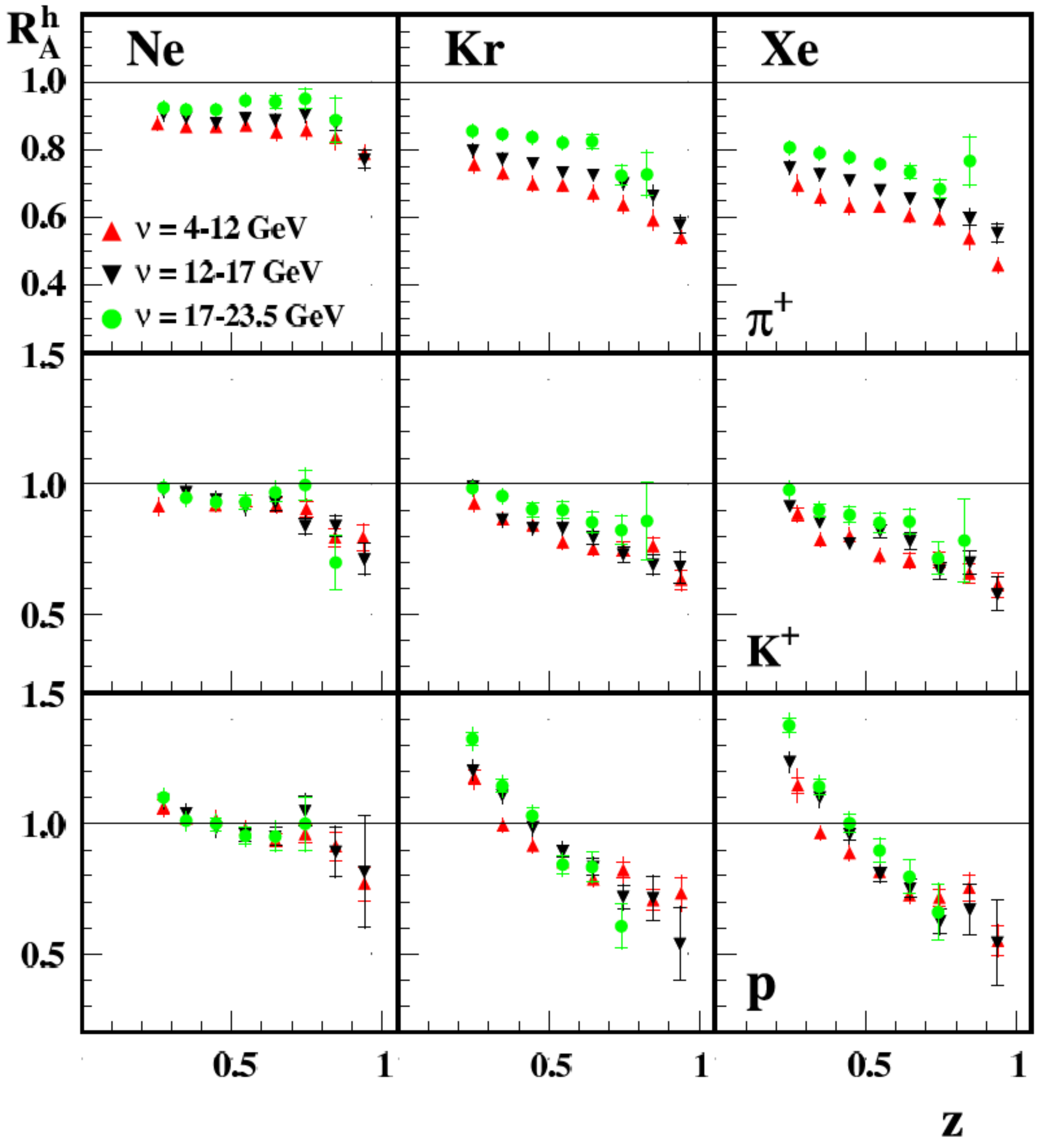
## A. Airapetian, *et al.*, Eur. Phys. J. A (2011) 47: 113

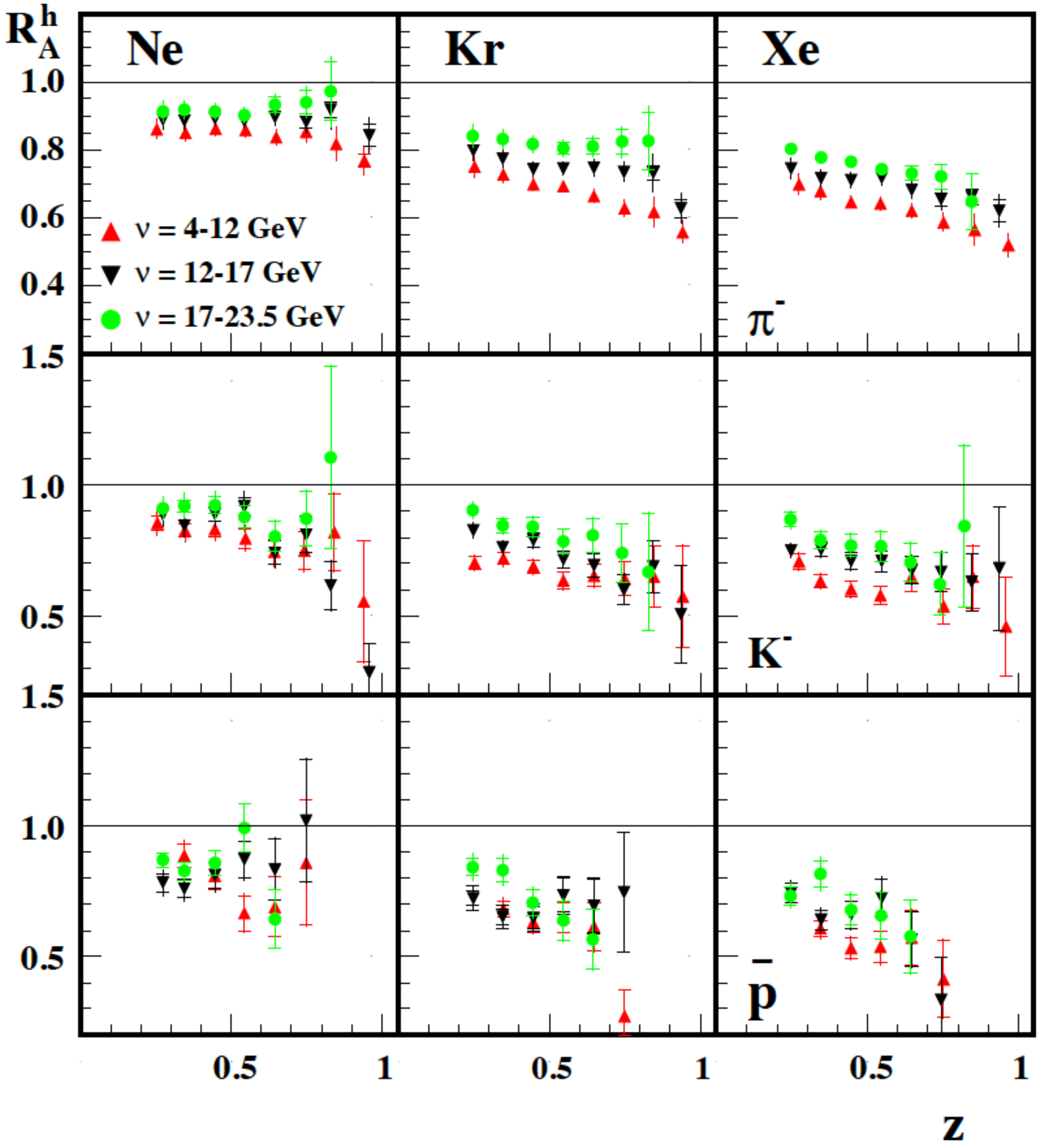


# Multi-Dimensional $R_A^h$ - HERMES

## A. Airapetian, *et al.*, Eur. Phys. J. A (2011) 47: 113



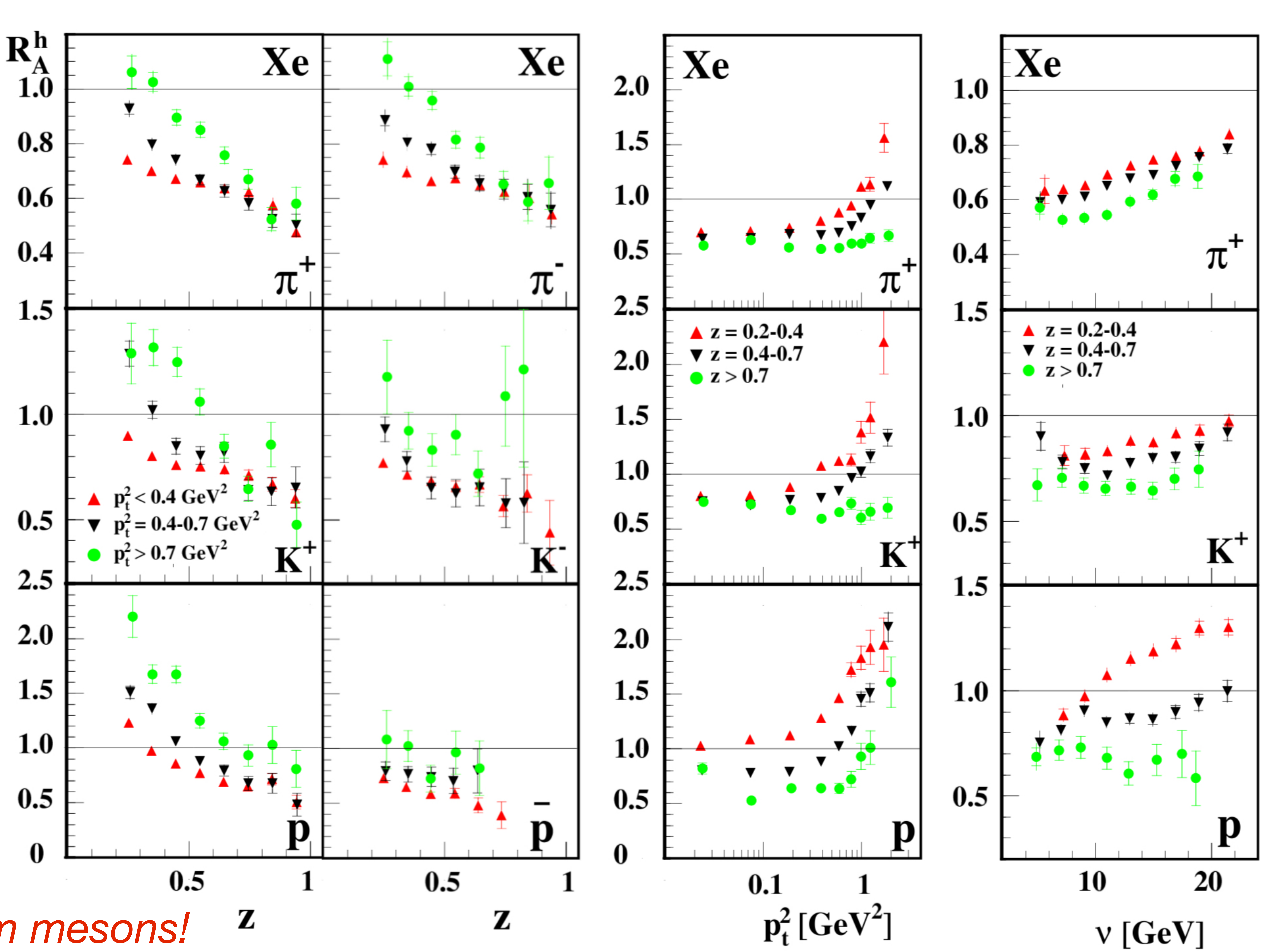



Large $R_A^h$ corresponds to a very disruptive object traveling through the nucleus

Antiproton is very different from proton, so not a hadron mass effect.

Ordering of $R_A^h$ in $z_h$ disappears at high $p_t^2$

$R_A^h$ much greater than 1.0 for low $z_h$ and high $\nu$




*All very different from mesons!*

# Observations from the HERMES 2-D $R_A^h$

- Proton production data are qualitatively different from mesons and anti-proton.

- Proton $R_A^h(p_T^2, z_h)$ shows a *very* large enhancement ($R_A^h(p_T^2, z_h) \approx 2$) for low $z_h$ and high $p_T^2$.

- Proton $R_A^h(\nu, z_h)$ exceeds values of 1.0 while no other hadron exceeds 1.0.

- Ordering of $R_A^h$ in $z_h$ disappears at high $p_t^2$

- For more discussion see M. Yu. Barabanov et al., Progress in Particle and Nuclear Physics, 116 (2021) 103835, https://arxiv.org/abs/2008.07630, Section 4.2

# Jefferson Lab: 6-GeV Era

Superconducting $e^-$ Accelerator

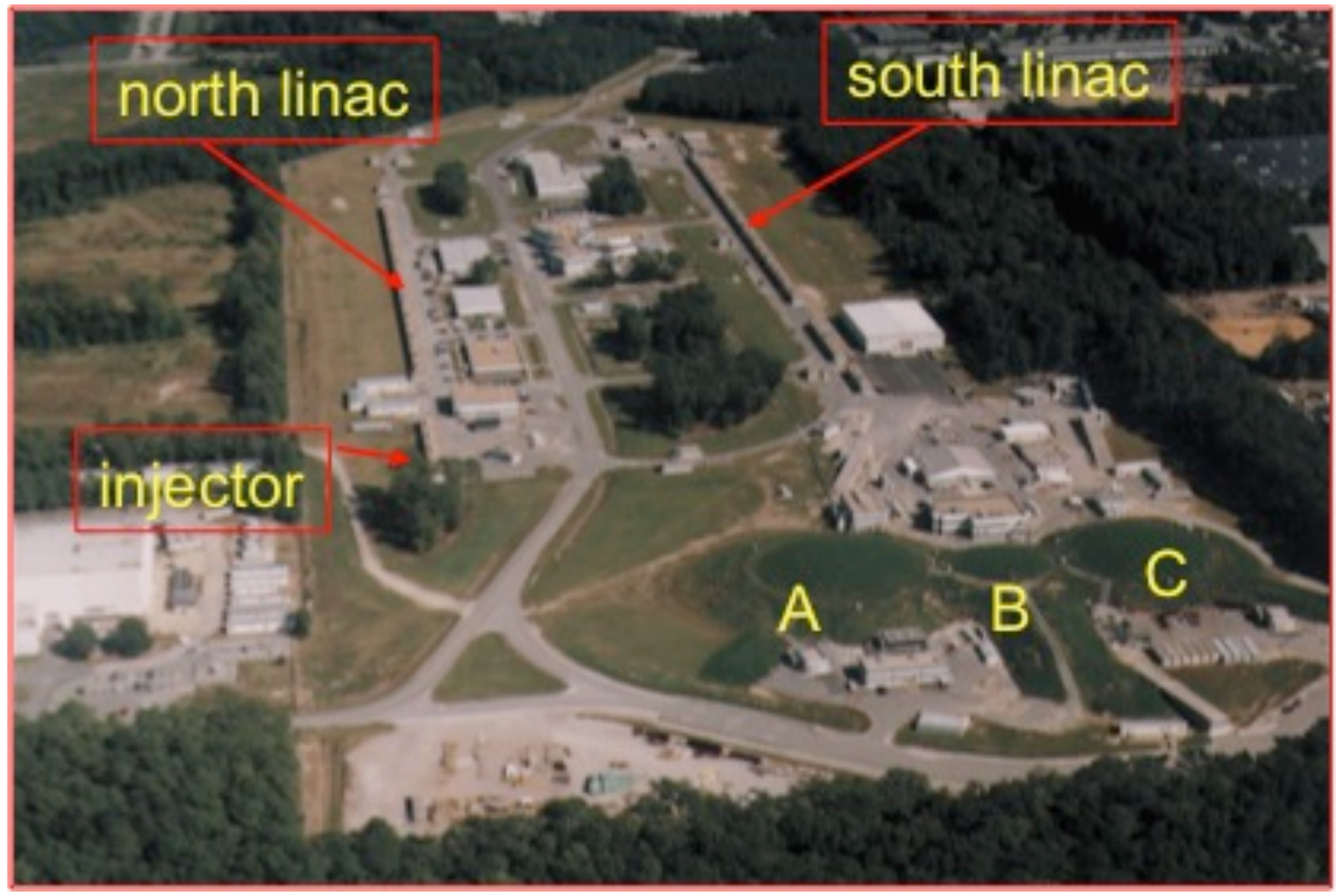
Max I=200μA

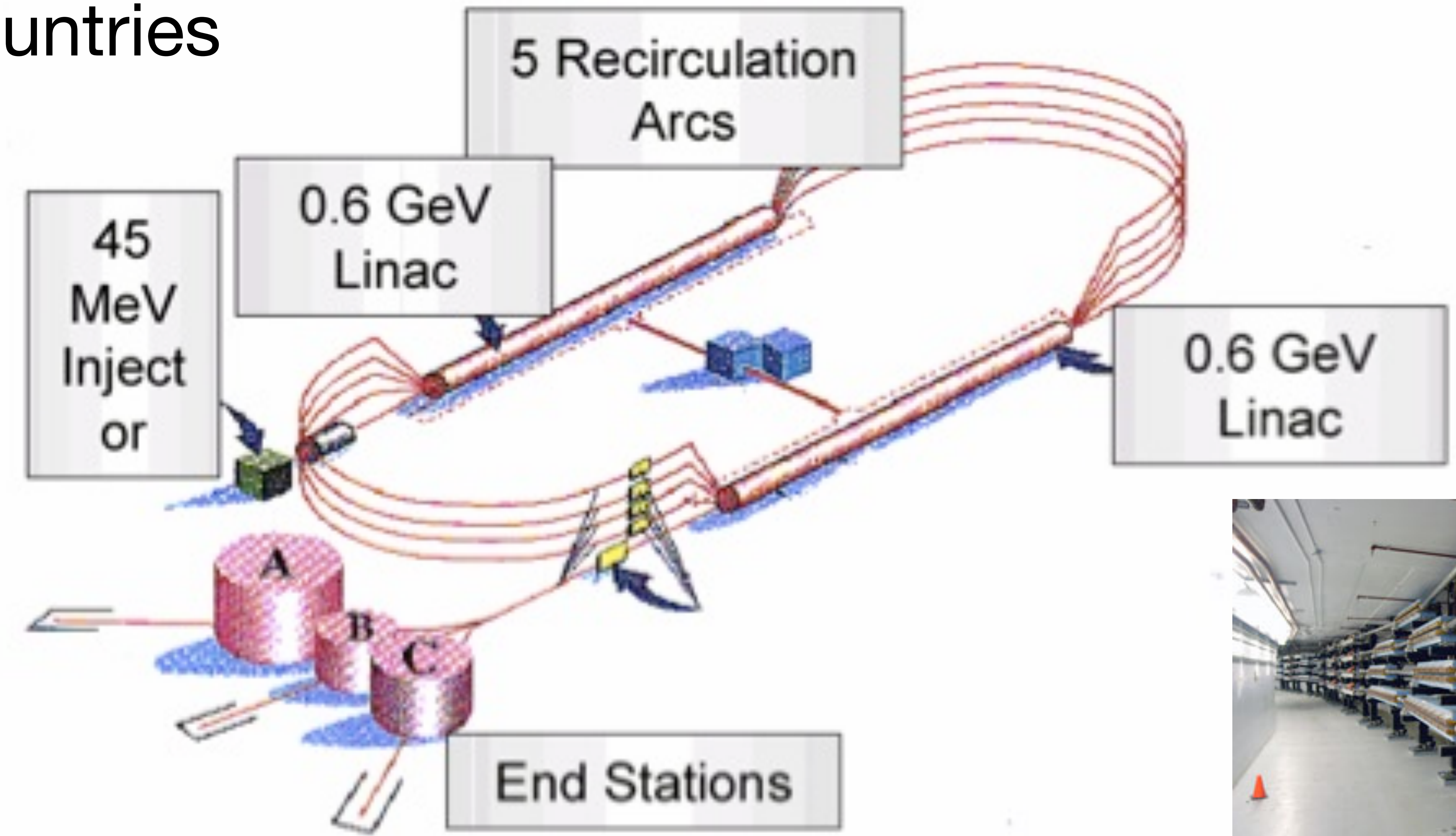
Max E=6 GeV, $dE/E=10^{-5}$

Run 3 experiments simultaneously (Halls A,B,C)

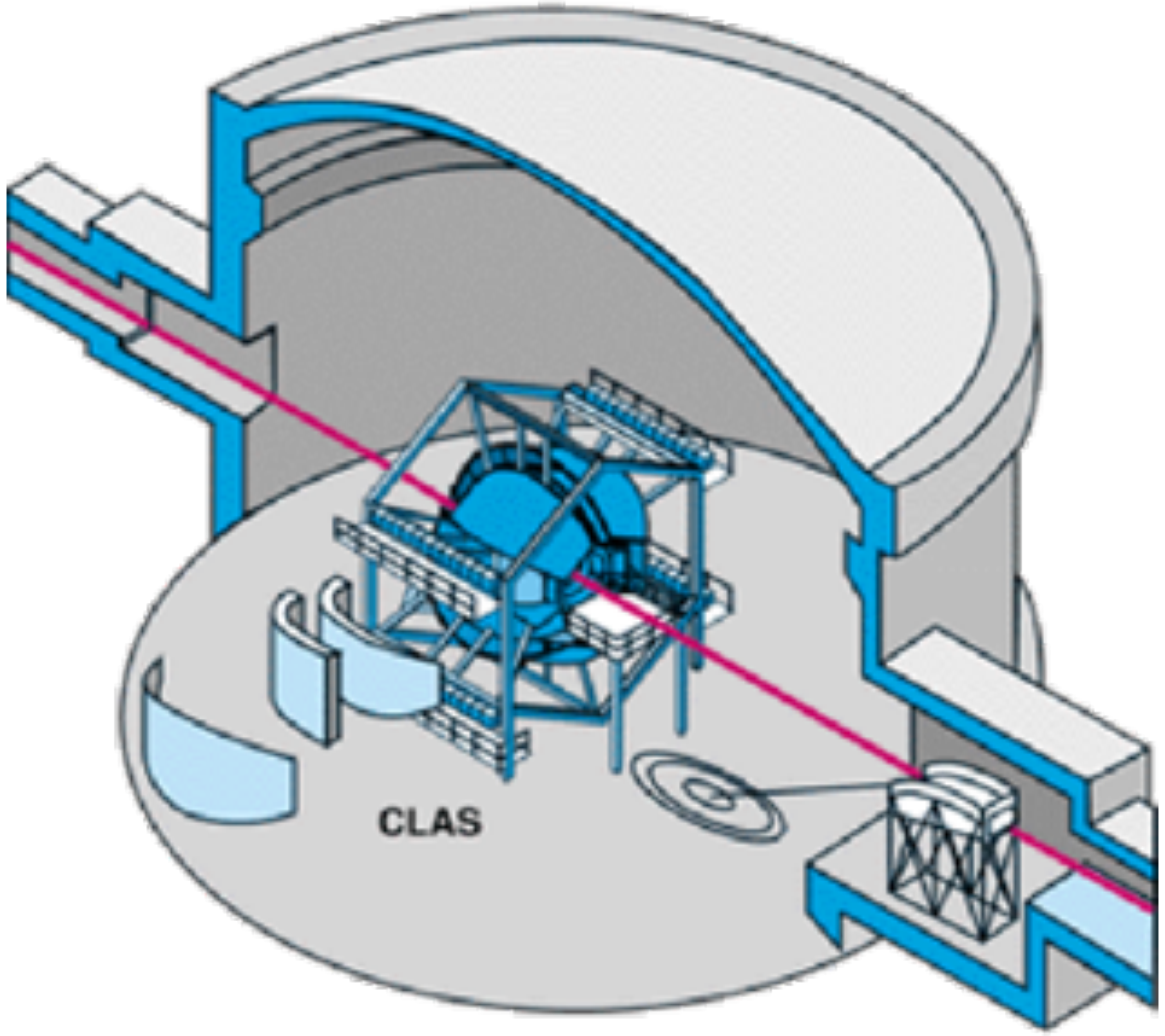
1500 physicists from ~30 countries

Operational since 1997



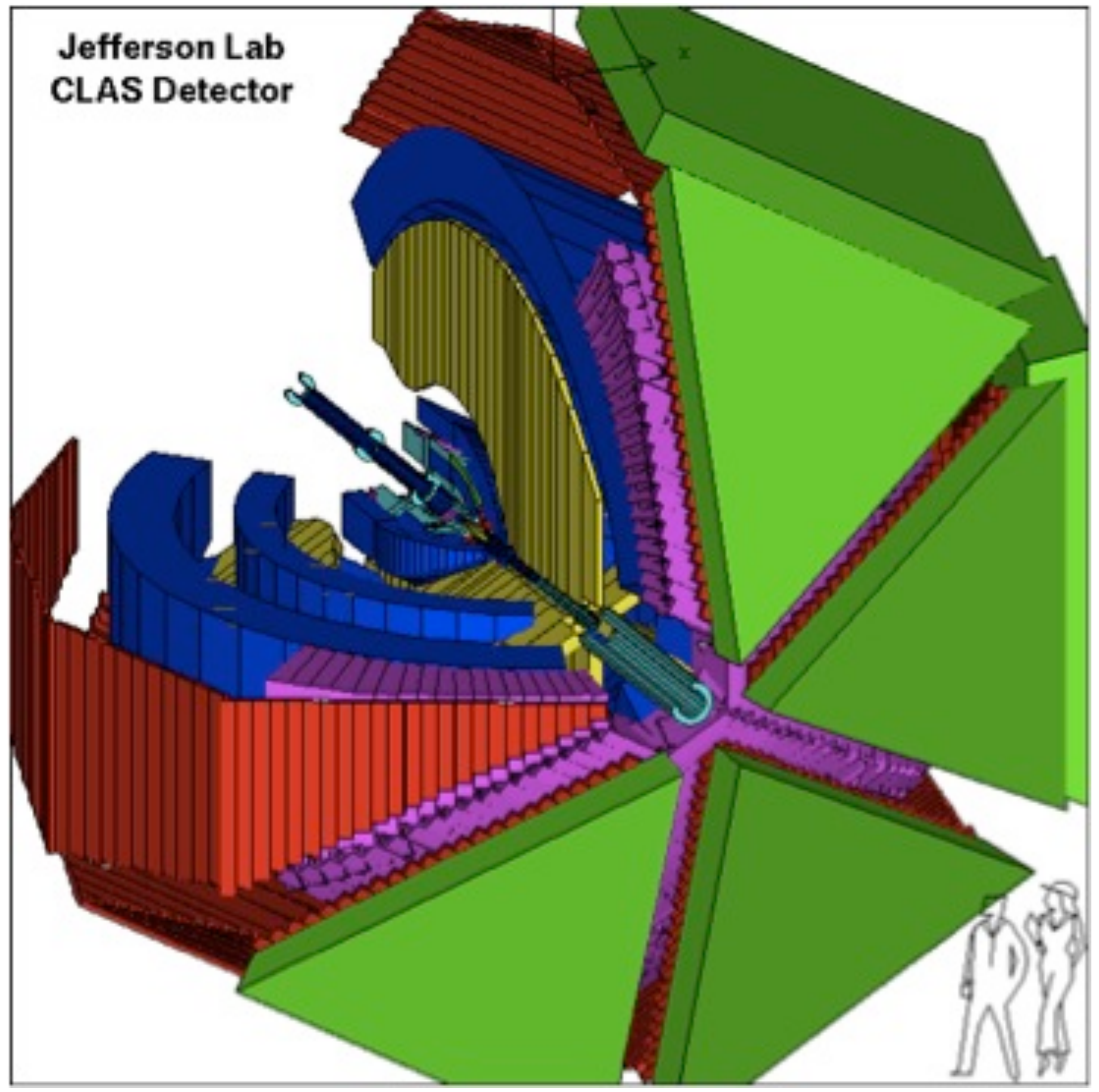




# Hall B and CLAS6 Detector




The 6-GeV Configuration

- Smallest experimental hall in size.
- Most complicated detector system.
- Six separate spectrometers for the most spatial coverage.
- Designed for detecting many particles per event.
- Two beams: electron or photon
- ~200 physicists from about 10 countries




Electromagnetic Calorimeters - $e^-$ ID

Cherenkov Counters - $e^-/\pi^-$ discrimination

Drift Chambers - Particle tracking

Time-Of-Flight Counters - particle velocity

Superconducting Toroidal Magnet

# EG2 Experiment

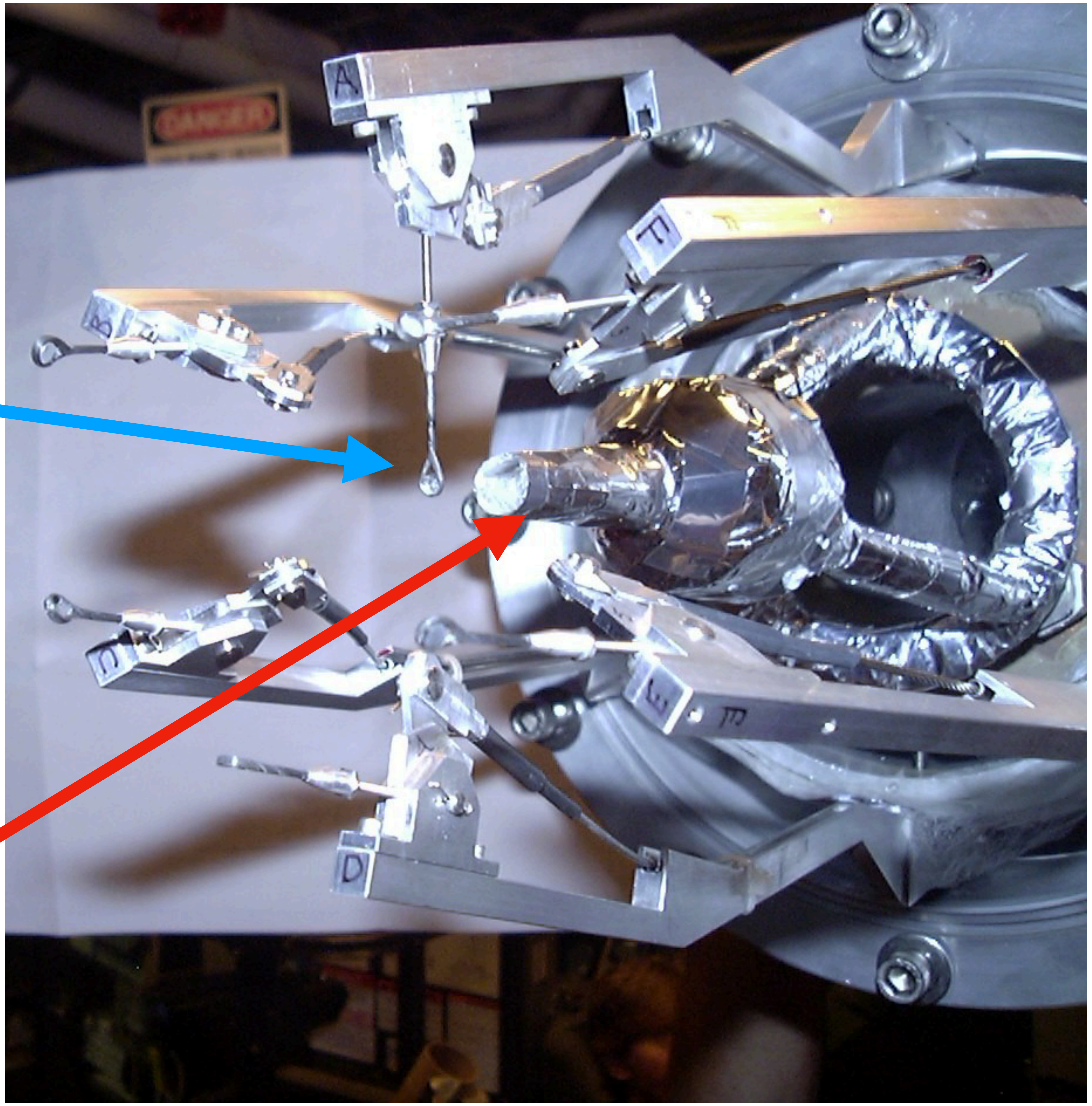
5.1-GeV electron beam

on a variety of targets.

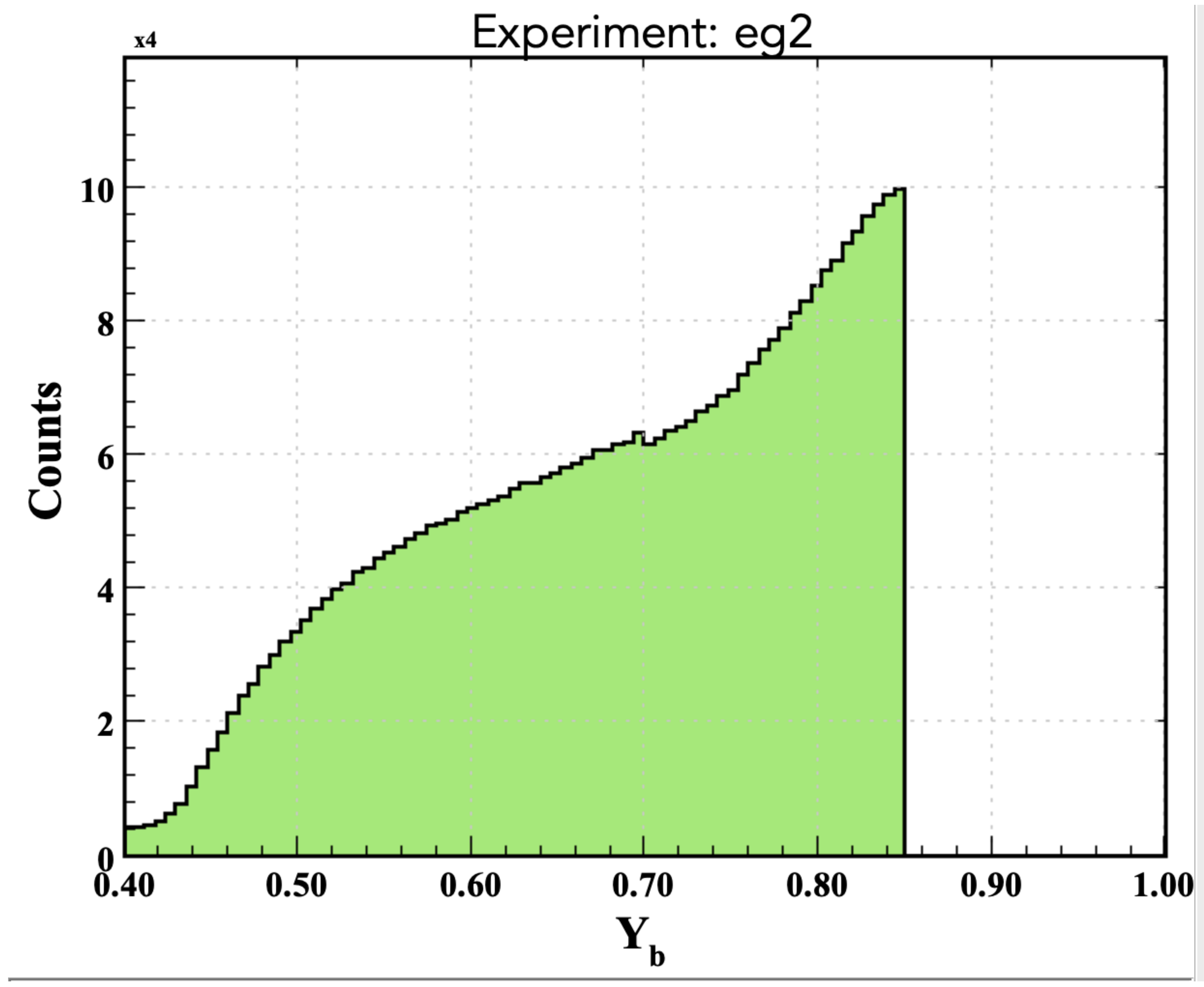
Solid Targets

| Target | Thickness (cm) | Density(A)/ Density(D) |
|---|---|---|
| **C** | 0.17 | 0.894 |
| **Fe** | 0.04 | 0.949 |
| **Pb** | 0.014 | 0.478 |

Liquid Deuterium
2-cm cryogenic target



# DIS Kinematics

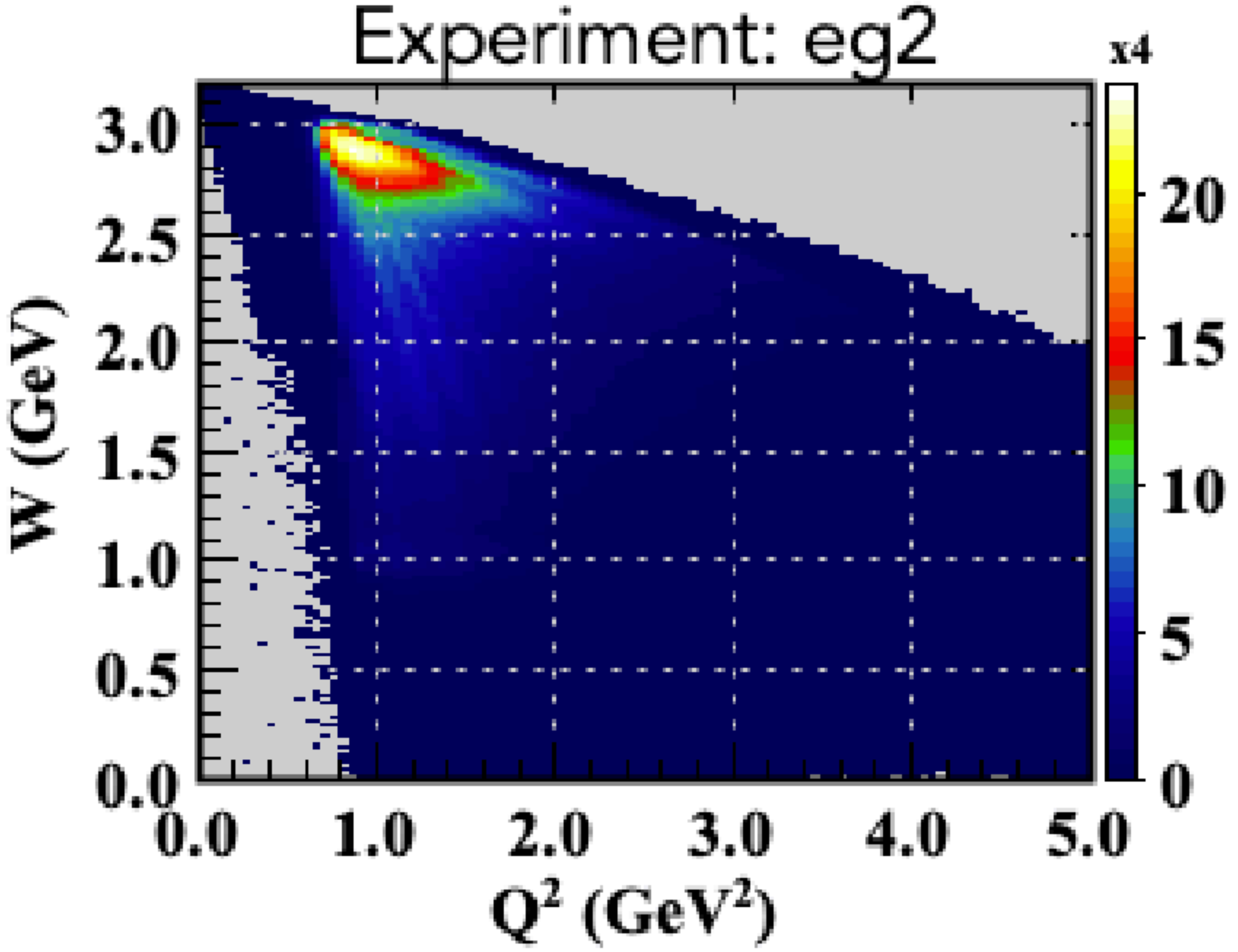


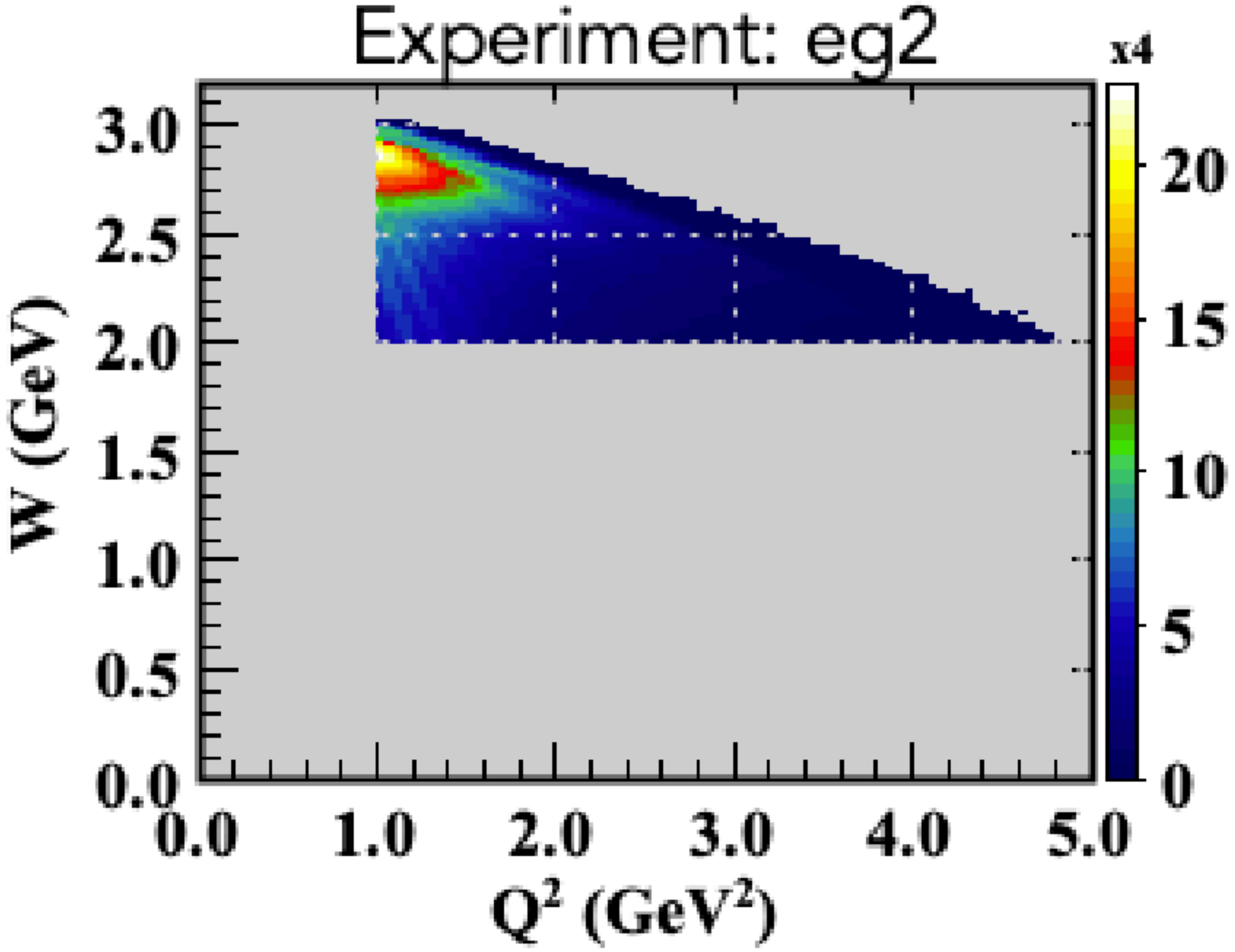

Kinematical cuts

$$Q^2 \geq 1 \text{ GeV}^2$$

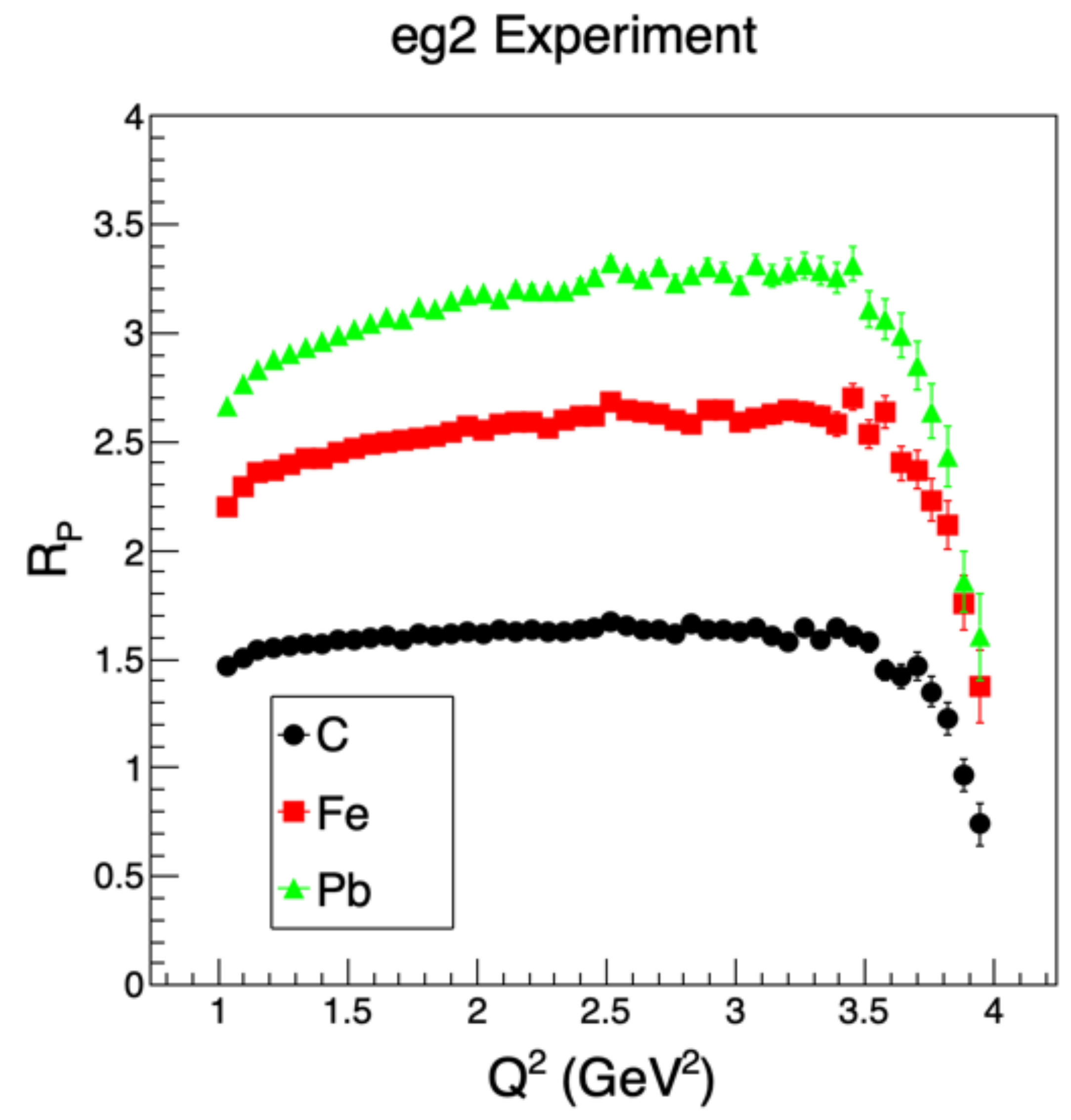
$$W \geq 2GeV$$

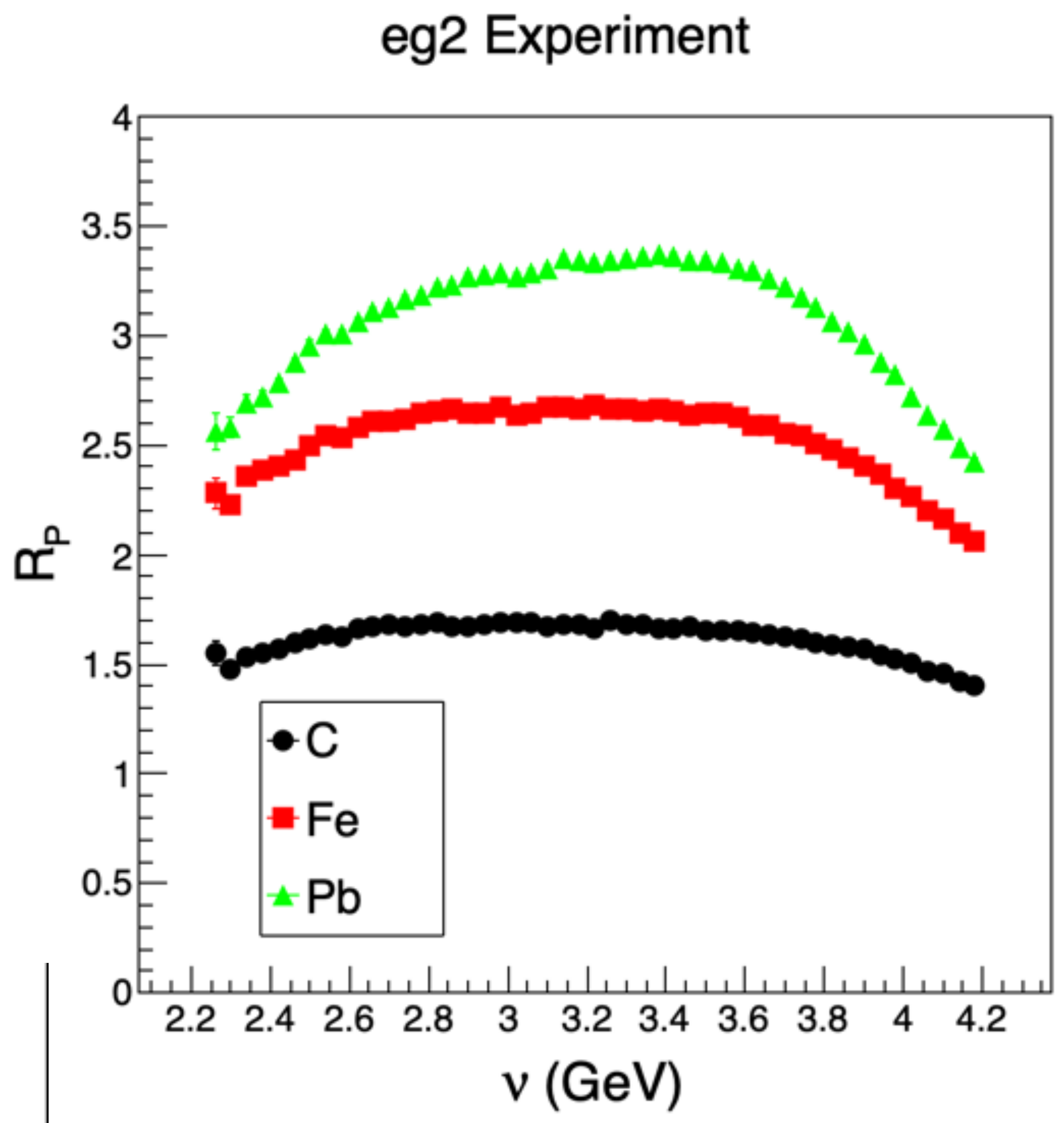
$$y = \frac{\nu}{E} \leq 0.85$$

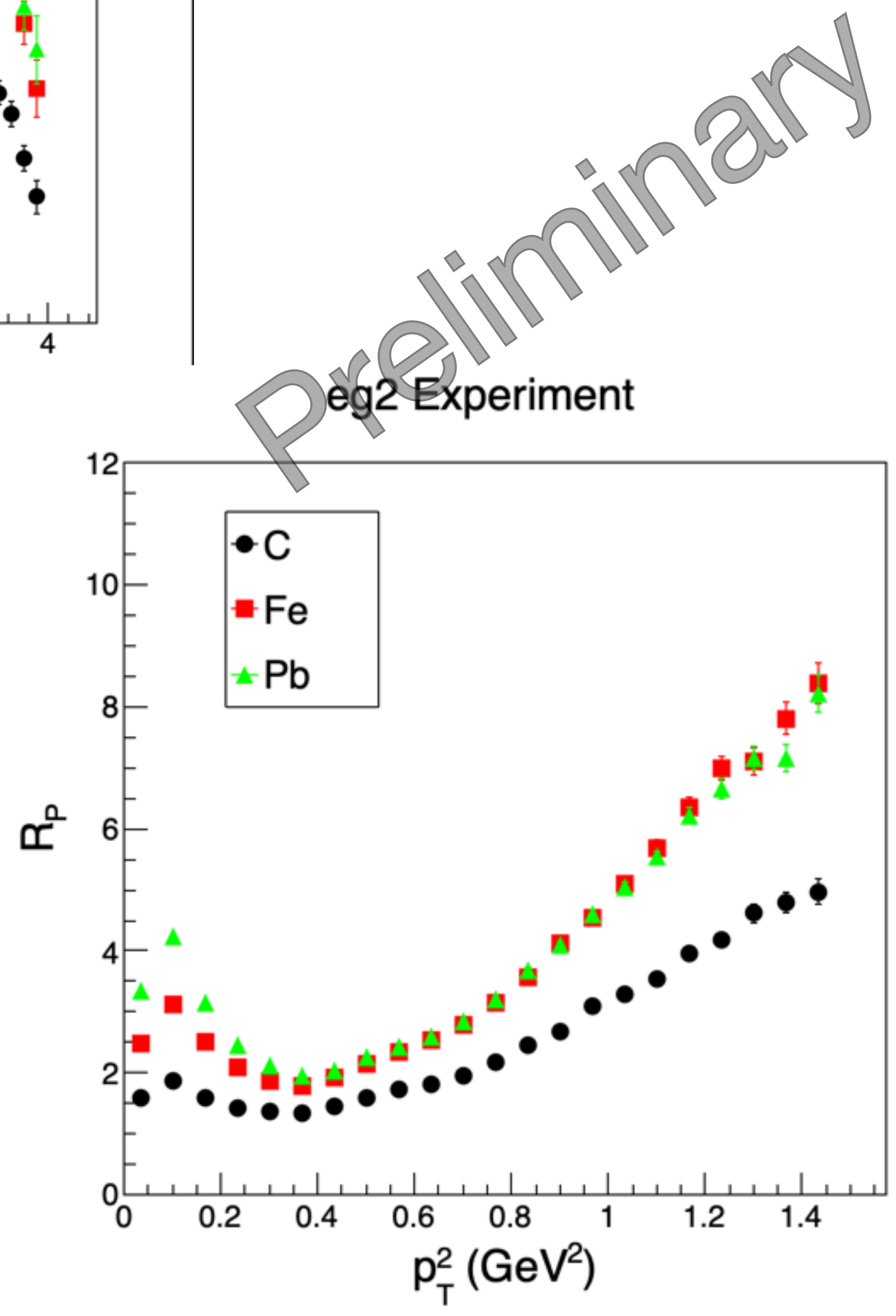


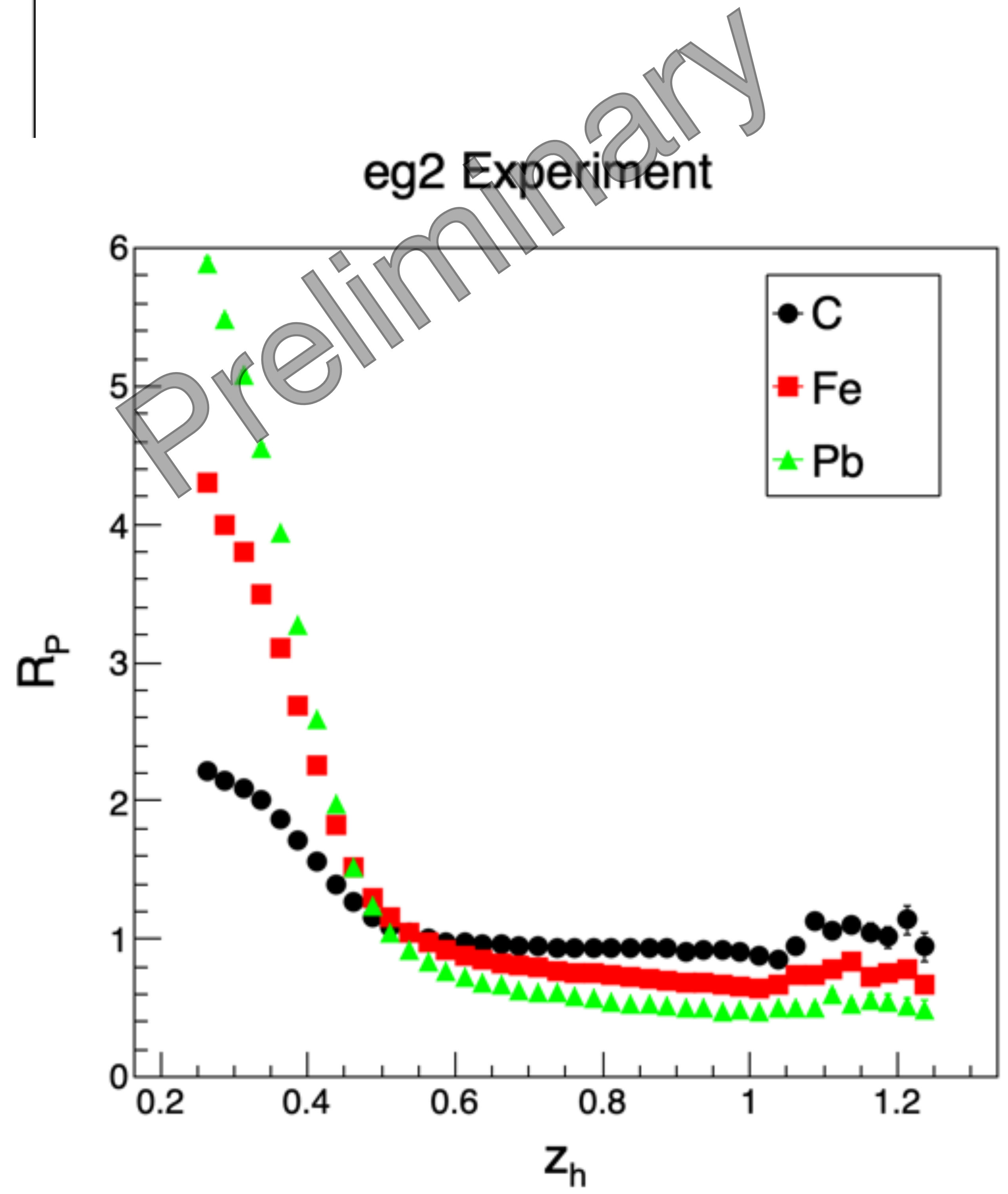



# One-Dimensional Proton Multiplicity Ratios



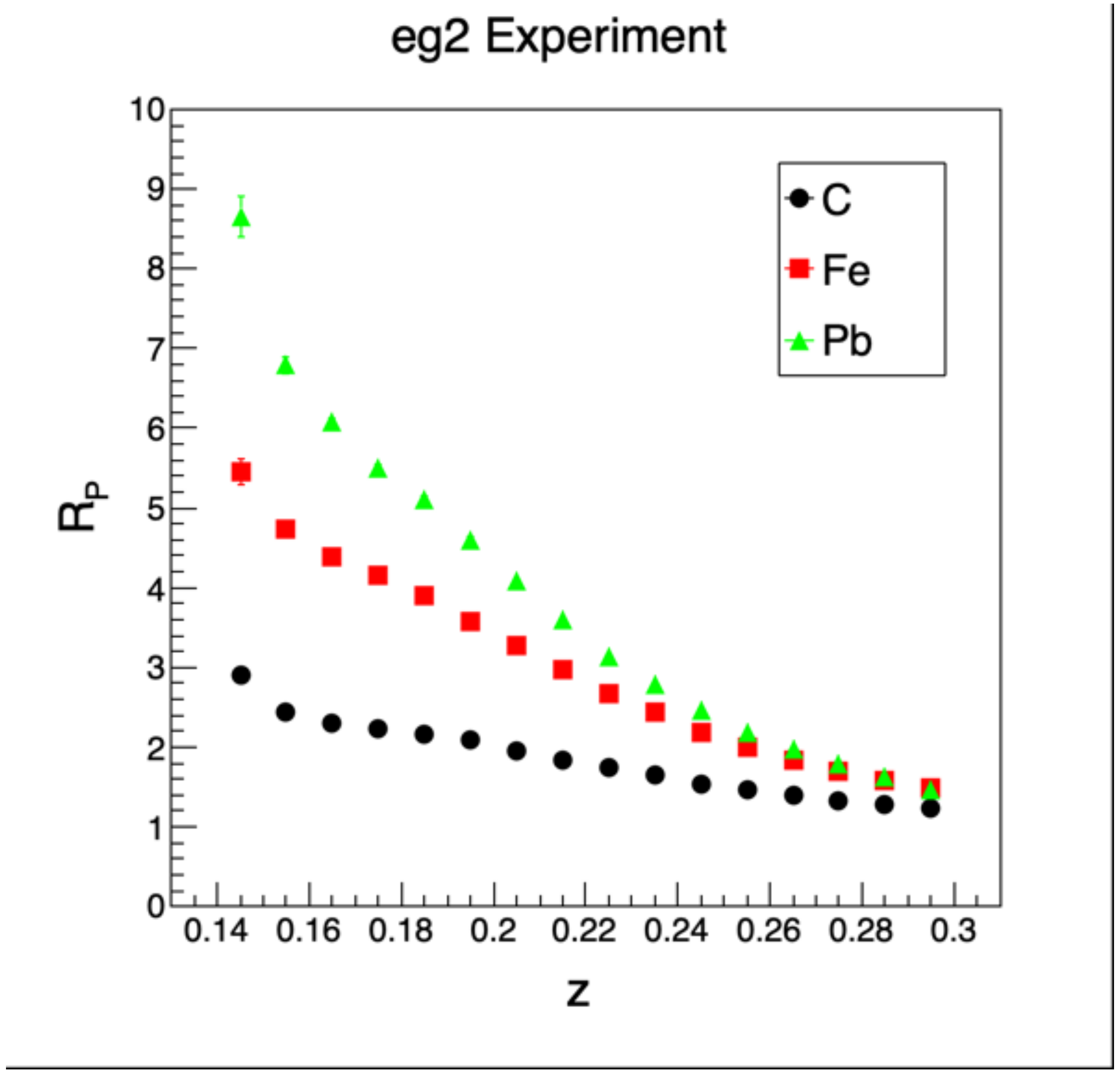



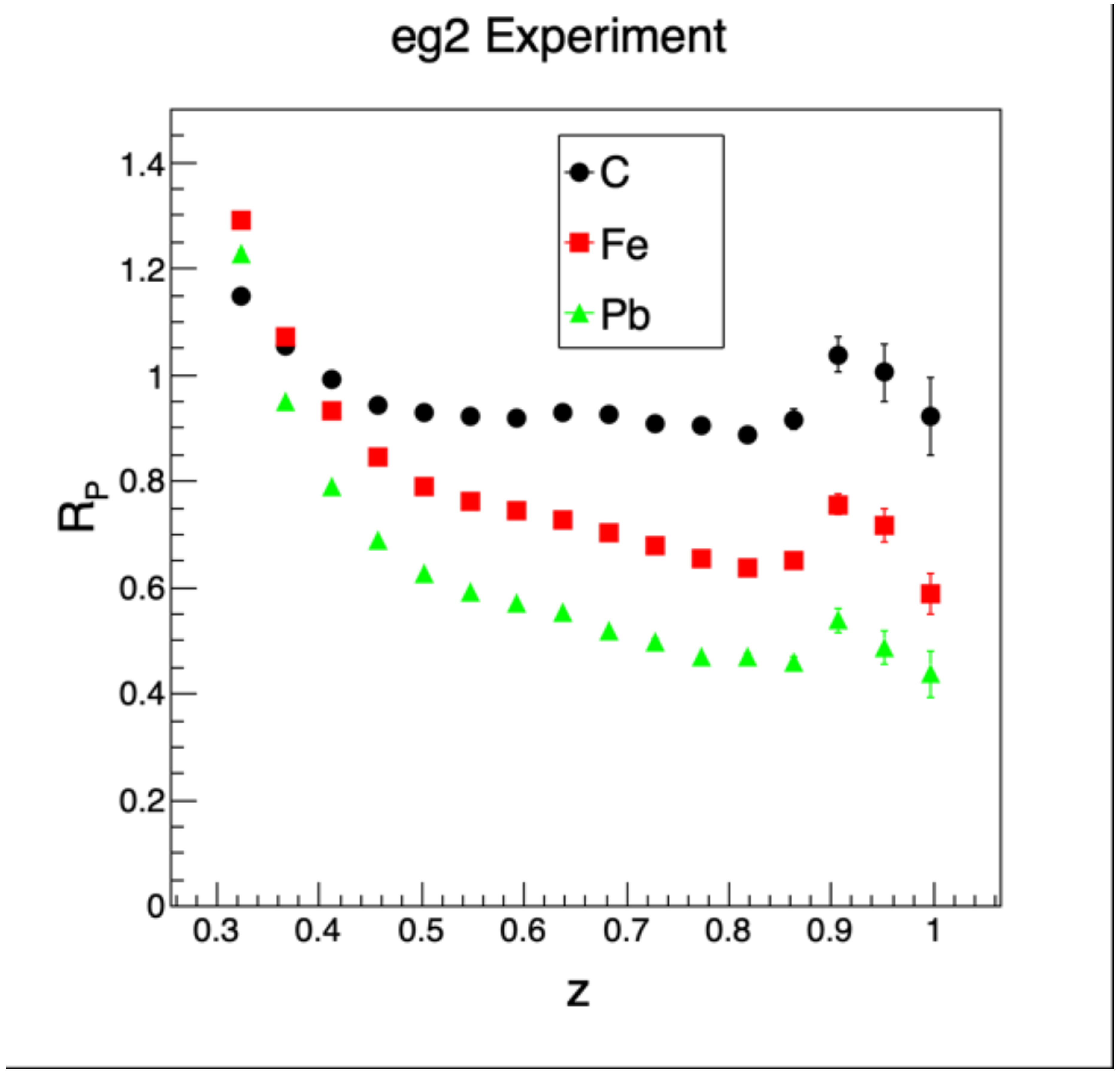

Systematic uncertainties
~3-4% for C
~4-5% for Fe, Pb

# One-Dimensional Proton Multiplicity Ratios

$$z = \frac{p_h^+}{P^+}$$

where light-cone variables of
$p_h^+$ = hadron energy/momentum
$P^+$= total energy/momentum

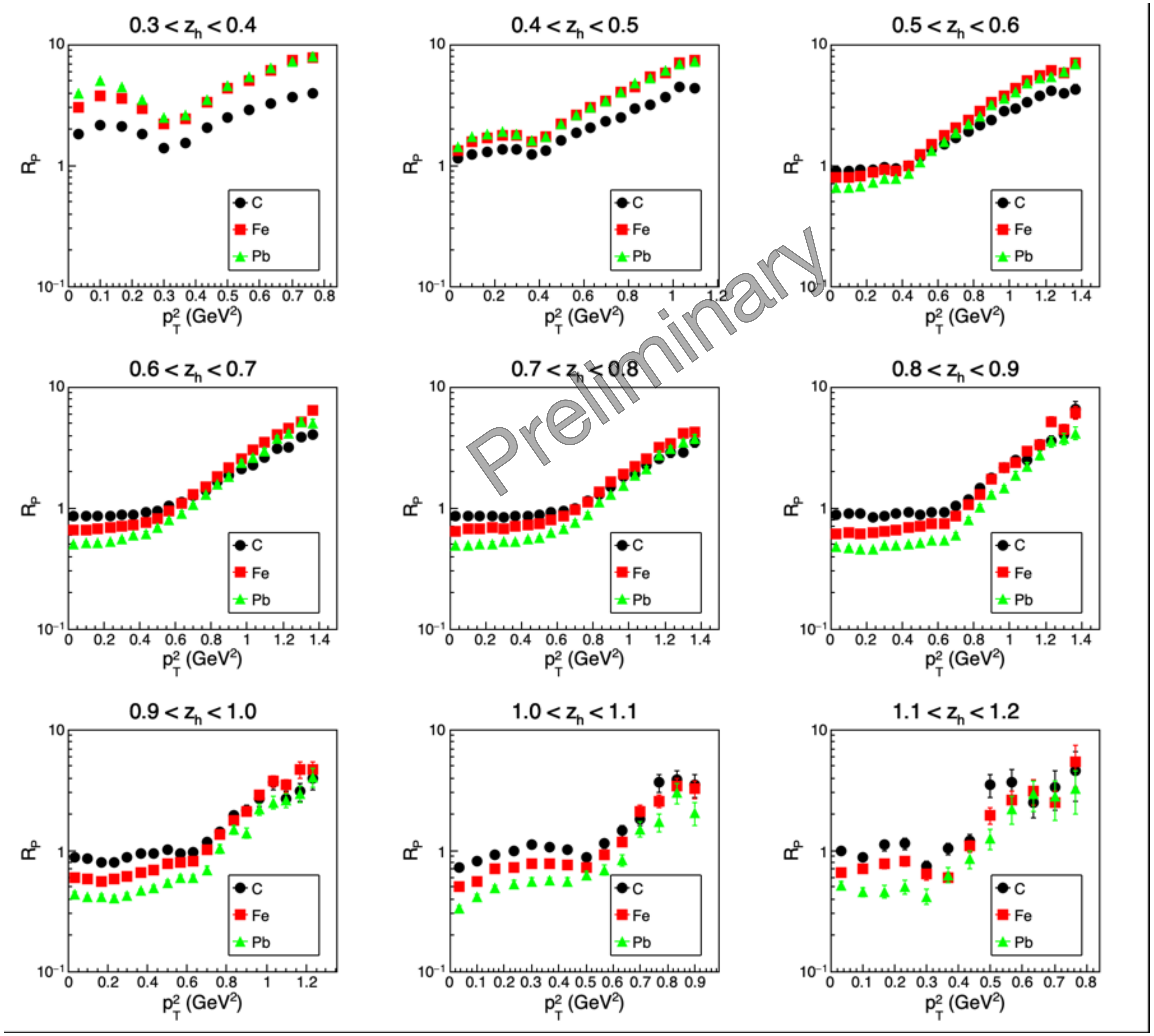



Systematic uncertainties
~3-4% for C
~4-5% for Fe, Pb

# Two-Dimensional Proton Multiplicity Ratios

● C
■ Fe
▲ Pb




Systematic uncertainties ~3-4% for C ~4-5% for Fe, Pb

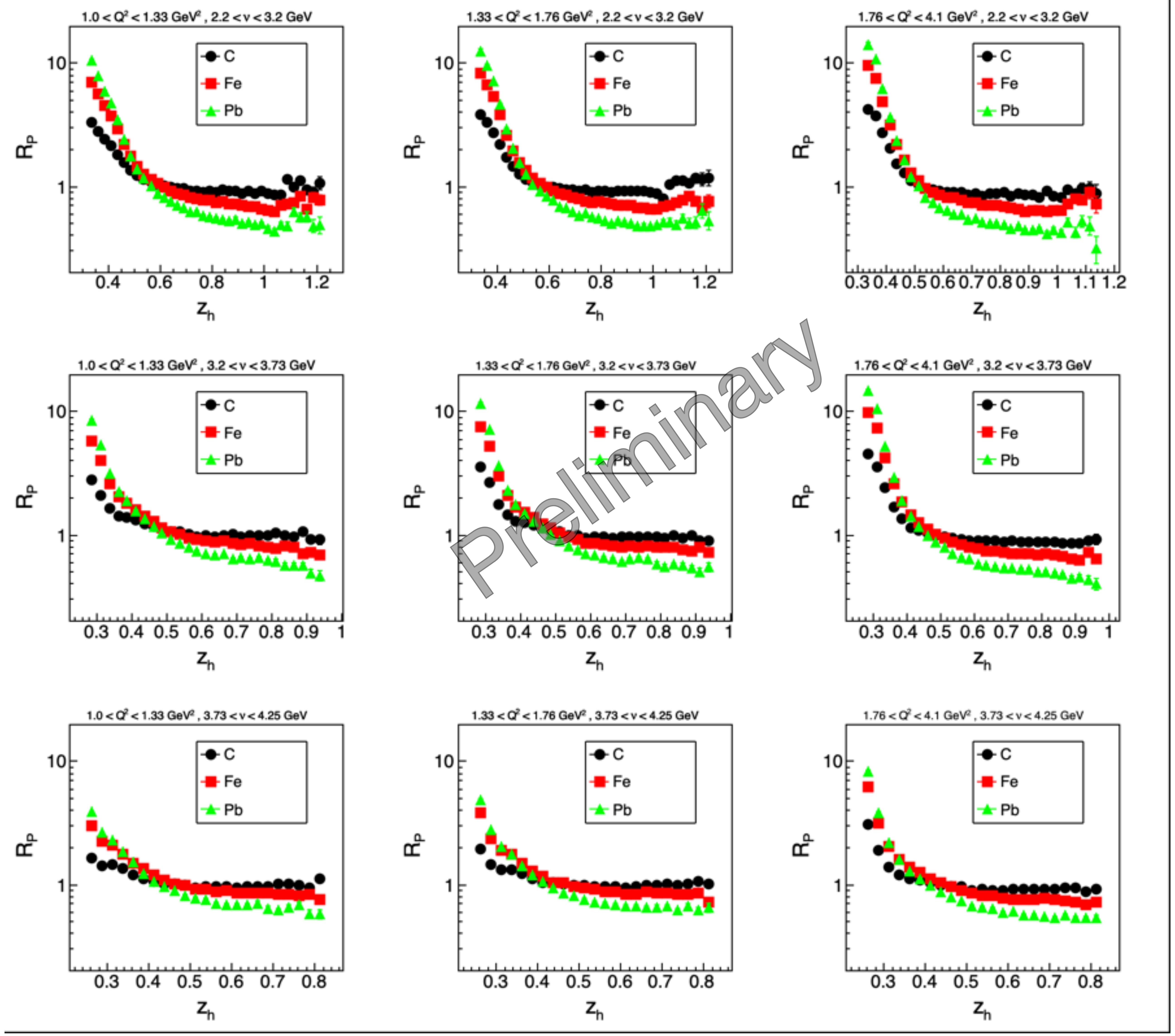
**Maximum values are up to 2 orders of magnitude more than mesons! And up to 10 times larger than HERMES protons!**

# Three-Dimensional Proton Multiplicity Ratios

- ● C
- ■ Fe
- ▲ Pb

**Visible dependence on these variables. Time in medium? Size of struck object?**

Systematic uncertainties
~3-4% for C
~4-5% for Fe, Pb




Low $\nu$

High $\nu$

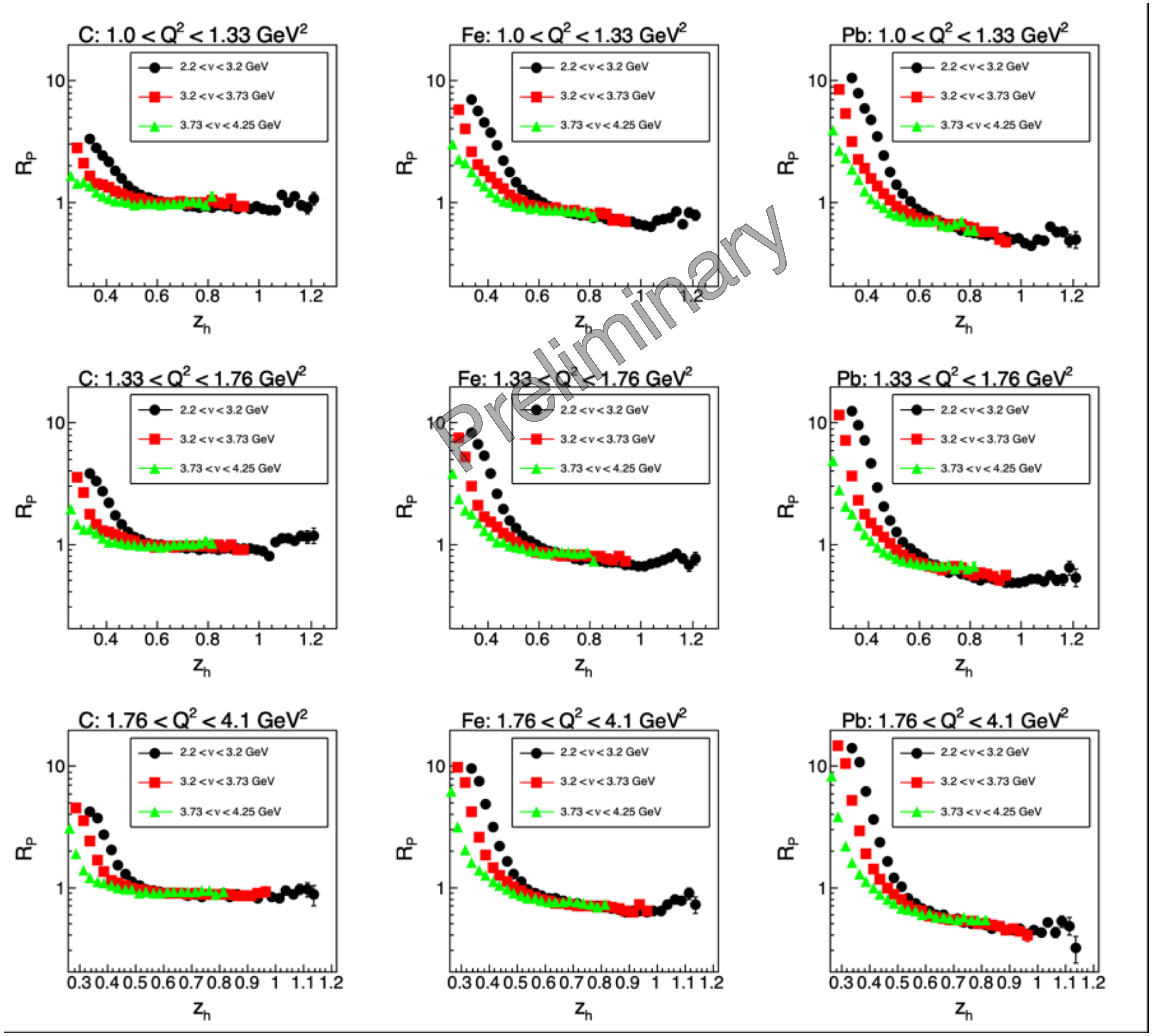
Low $Q^2$

High $Q^2$

# Three-Dimensional Multiplicity Ratios

- ● $2.2 < \nu < 3.2$ GeV
- ■ $3.2 < \nu < 3.73$ GeV
- ▲ $3.73 < \nu < 4.25$ GeV

Systematic uncertainties ~3-4% for C ~4-5% for Fe, Pb



# Diquark Correlations

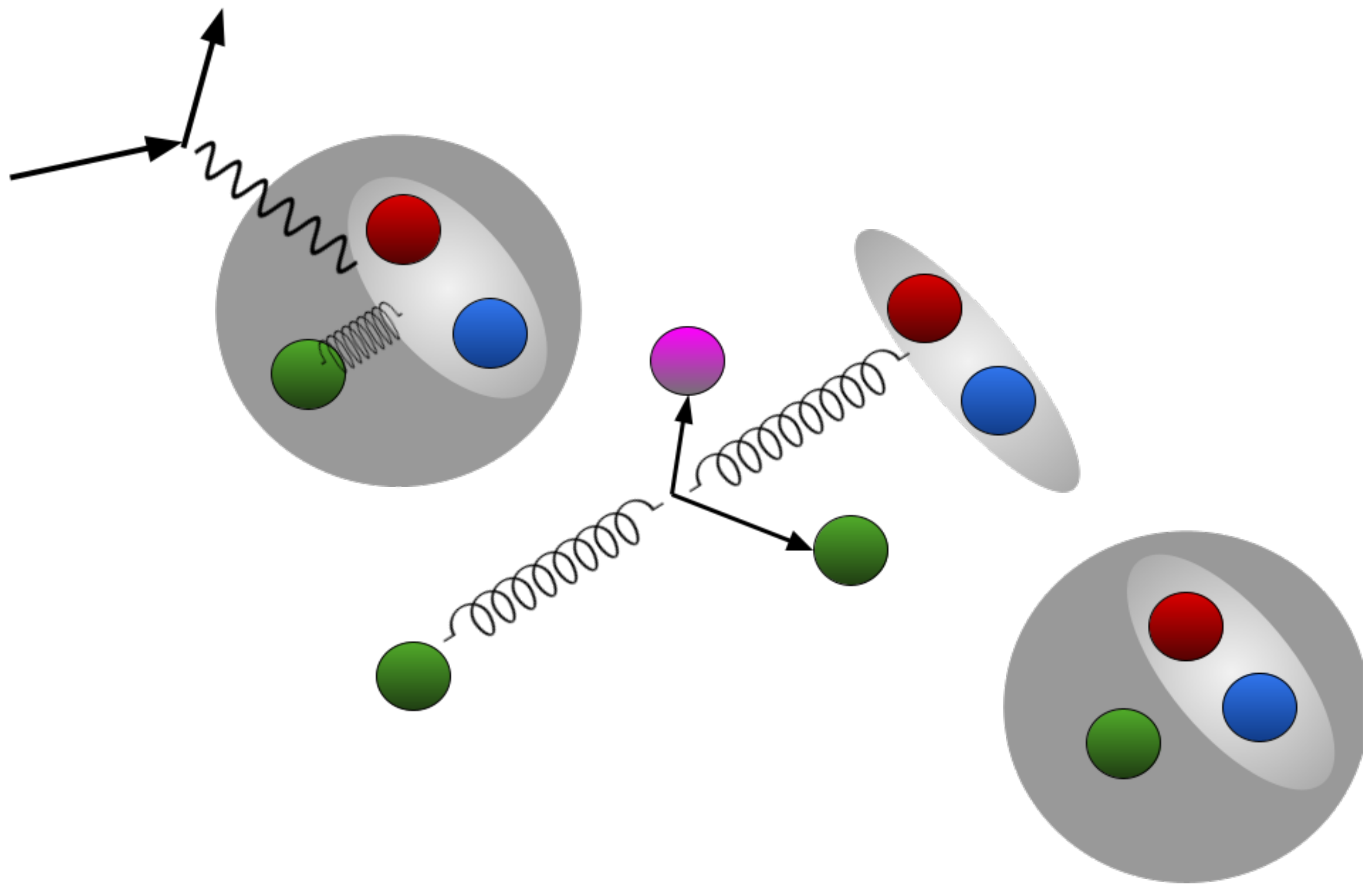
Observations of the HERMES proton data could have an explanation in terms of diquark correlations.

- Direct Diquark Scattering (DDS) - if diquark correlations are a large component of the proton's wavefunction: the diquark can be knocked out and either remain intact, or disintegrate while propagating. As a **large and massive object carrying QCD color**, it should be much more **disruptive** to the nucleus than a single quark.

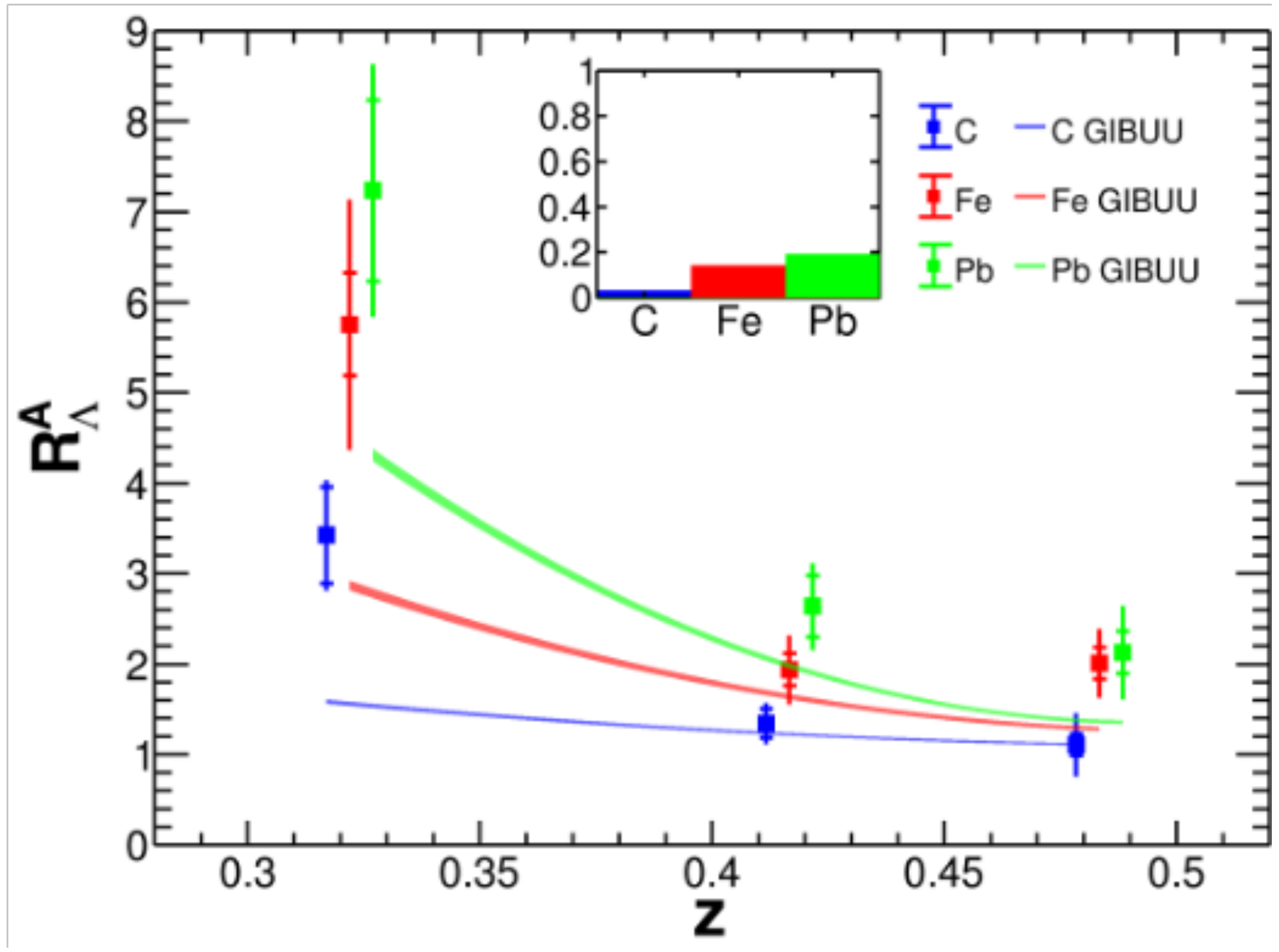
- DDS would also cause an increase in $< p_T^2 >$ because the color field for a diquark is distributed over a larger volume than for a single quark.

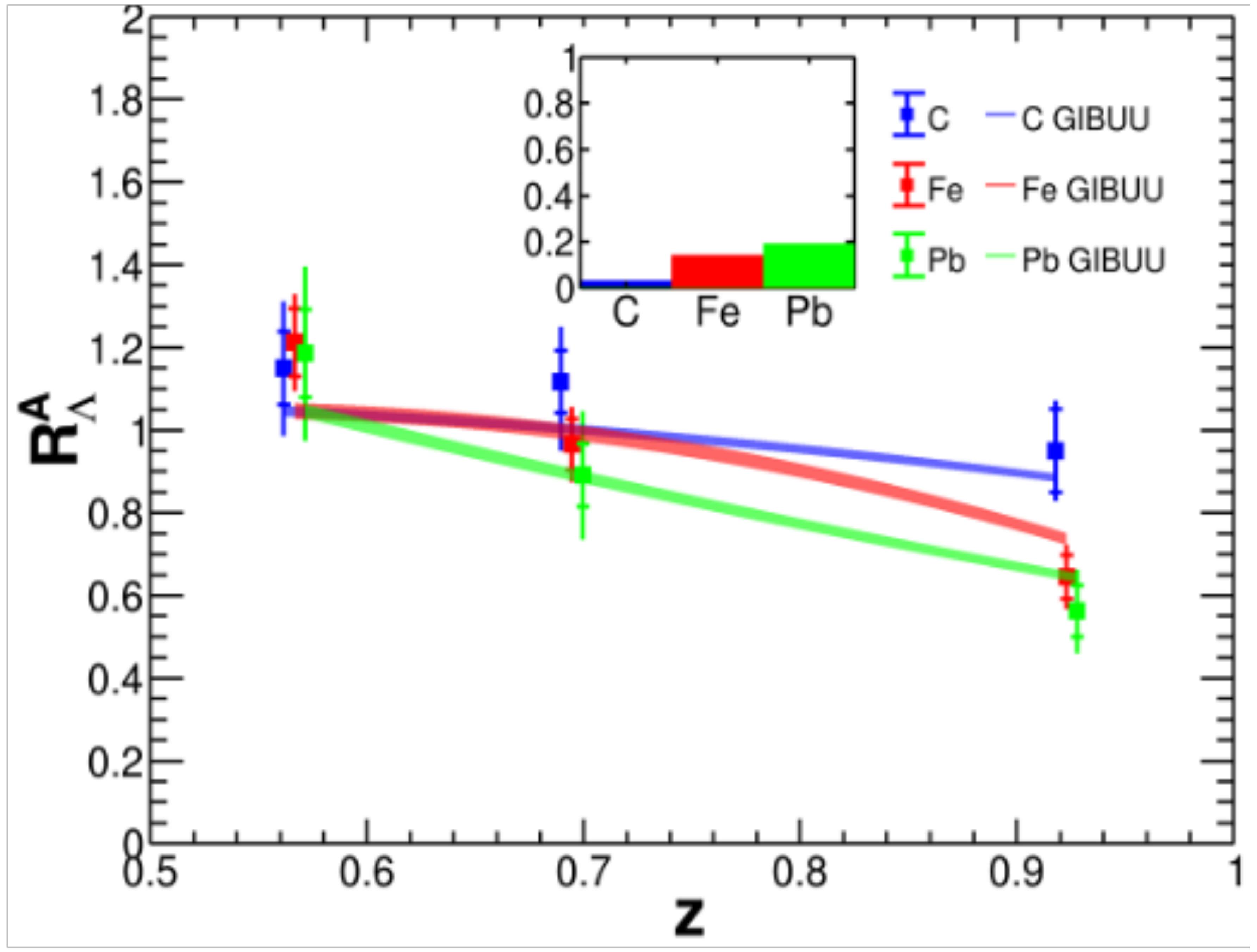
- Proton, neutron, and $\Lambda$ have the same $[ud]$ correlation while $\Sigma$ and $\Xi$ have a $[us]$ correlation. Knocking the $[ud]$ diquark out of a target proton or neutron will easily allow a new neutron, proton, or $\Lambda$ to form, while creating a new $[us]$ diquark will be suppressed. The multiplicity ratios will be similar for particles with the same diquark correlation. (The $\Omega$ can be expected to be quite different from all others.)

# Diquark Correlations



| Baryon | Diquark Correlations |
|---|---|
| p | [ud]u |
| n | [ud]d |
| Λ | [ud]s |
| Σ | [us]u |
| Ξ | [us]s |



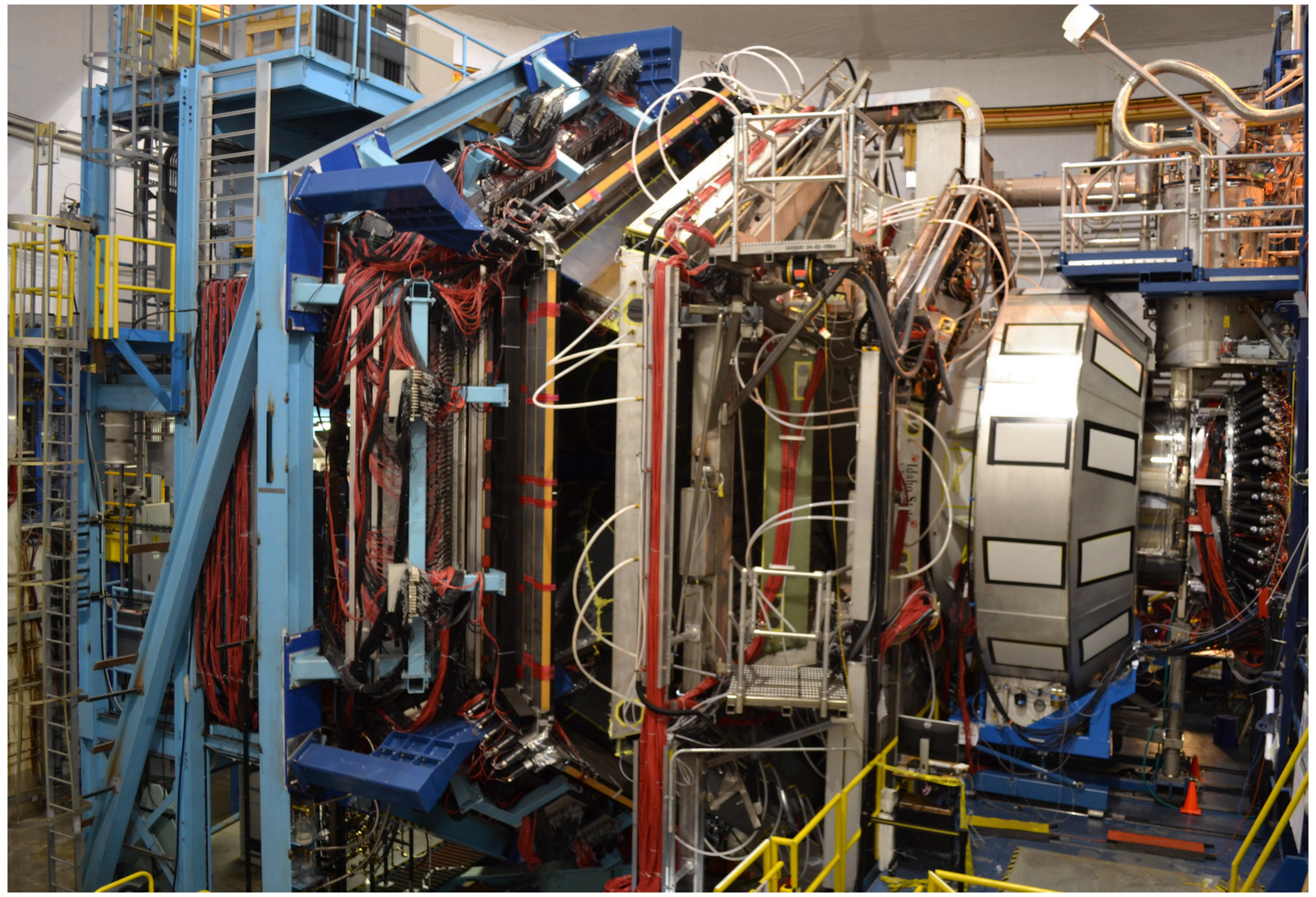




T. Chetry *et al. (CLAS Collaboration)*, Phys. Rev. Lett. 130, 14 (2023)

# The 11-GeV Program

The 11-GeV experiment:
March 15, 2024 - May 15, 2024

Targets: C, Al, Cu, Sn, and Pb



CLAS12

DIS channels: *stable* hadrons, accessible with 11 GeV
JLab experiment PR12-06-117

Actively underway with existing 5 GeV data

| *meson* | cτ | mass | flavor content |
|---|---|---|---|
| $\pi^0$ | 25 nm | 0.13 | $u\bar{u}d\bar{d}$ |
| $\pi^+$, $\pi^-$ | 7.8 m | 0.14 | $u\bar{d}$, $d\bar{u}$ |
| $\eta$ | 170 pm | 0.55 | $u\bar{u}d\bar{d}s\bar{s}$ |
| $\omega$ | 23 fm | 0.78 | $u\bar{u}d\bar{d}s\bar{s}$ |
| $\eta'$ | 0.98 pm | 0.96 | $u\bar{u}d\bar{d}s\bar{s}$ |
| $\phi$ | 44 fm | 1.0 | $u\bar{u}d\bar{d}s\bar{s}$ |
| $f1$ | 8 fm | 1.3 | $u\bar{u}d\bar{d}s\bar{s}$ |
| $K^0$ | 27 mm | 0.50 | $d\bar{s}$ |
| $K^+$, $K^-$ | 3.7 m | 0.49 | $u\bar{s}$, $\bar{u}s$ |

| *baryon* | cτ | mass | flavor content |
|---|---|---|---|
| $p$ | stable | 0.94 | ud |
| $\bar{p}$ | stable | 0.94 | $\overline{ud}$ |
| $\Lambda$ | 79 mm | 1.1 | uds |
| $\Lambda(1520)$ | 13 fm | 1.5 | uds |
| $\Sigma^+$ | 24 mm | 1.2 | us |
| $\Sigma^-$ | 44 mm | 1.2 | ds |
| $\Sigma^0$ | 22 pm | 1.2 | uds |
| $\Xi^0$ | 87 mm | 1.3 | us |
| $\Xi^-$ | 49 mm | 1.3 | ds |

# Summary

- Proton multiplicity ratios for C, Fe, and Pb have been presented for one-, two-, and three-dimensional dependencies with 5.0-GeV electron beam from a DIS reaction.

- These results show much larger $R_p$ than in the HERMES results and in the CLAS6 meson results.

- One-dimensional analysis of $R_p$ vs. $z_h$ shows a behavior similar to the $\Lambda$ baryon.

- Currently collecting data from a new experiment with an 10.5 GeV electron beam at JLab with the CLAS12 detector.

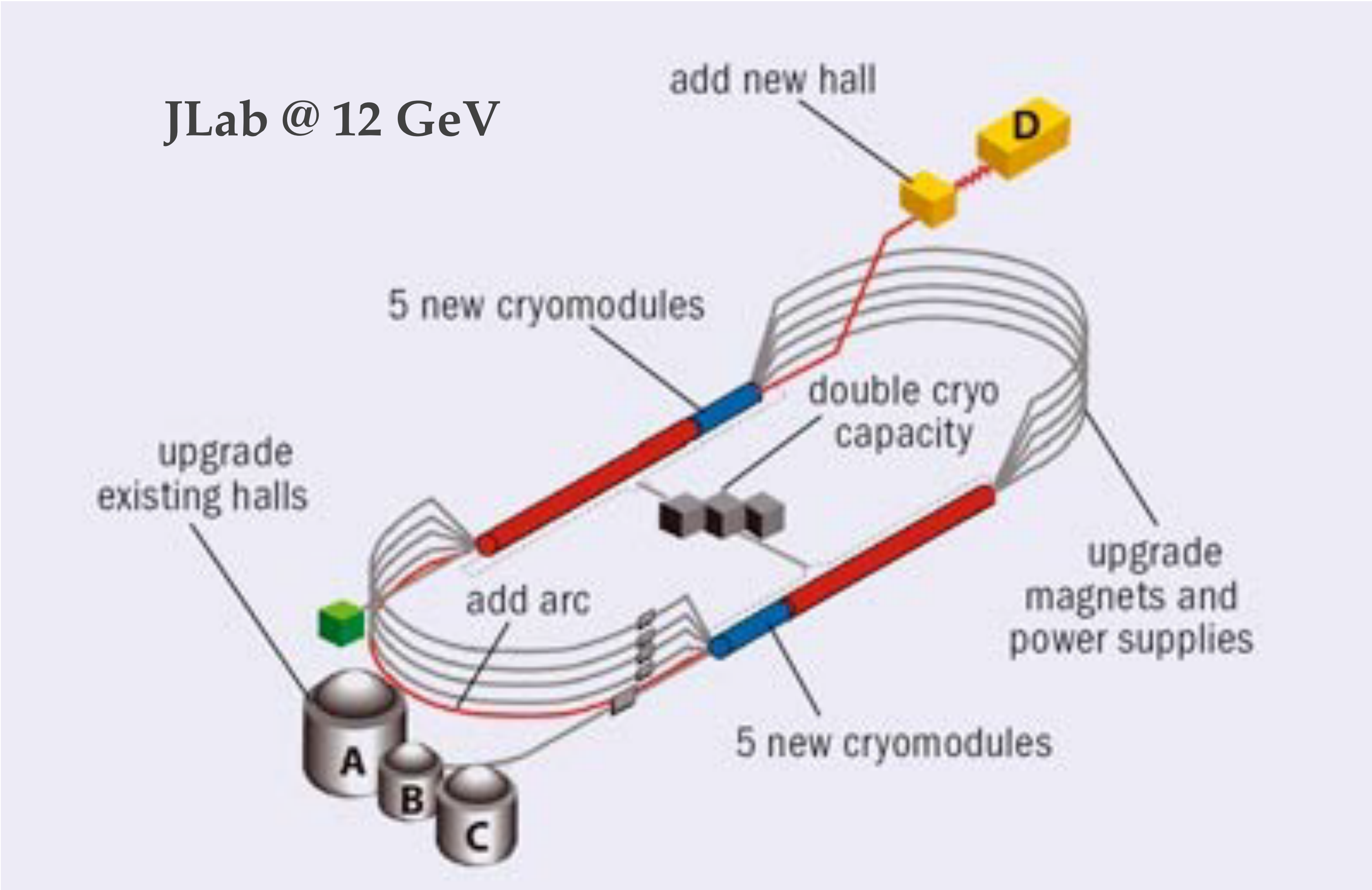
**The full, conclusive program of studies will consist of measuring these observables for proton (neutron), $\Lambda, \Sigma, \Xi, \Omega$ in conjunction with theory modeling to observe the patterns revealing the properties of diquarks!**

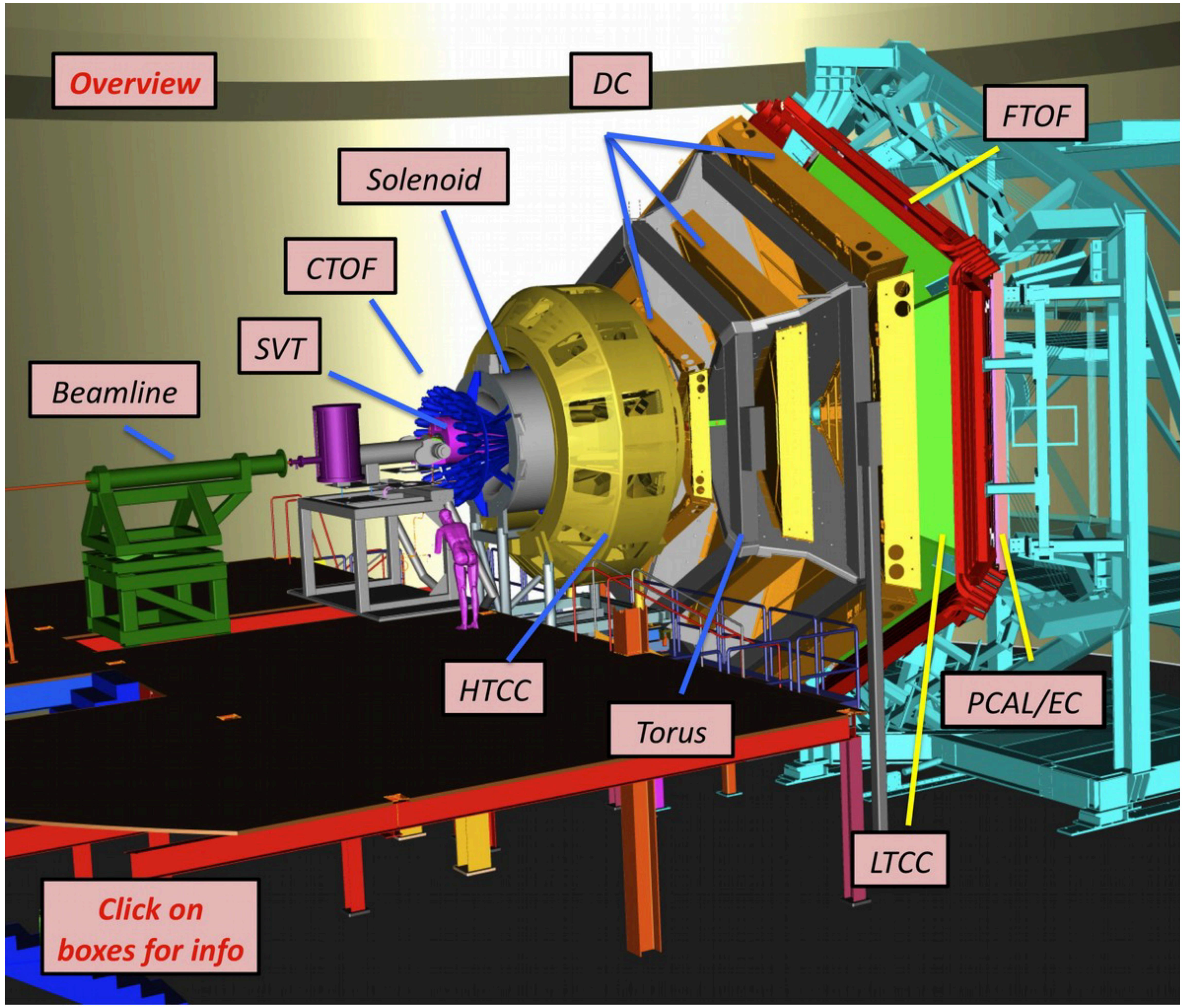
# Acknowledgements

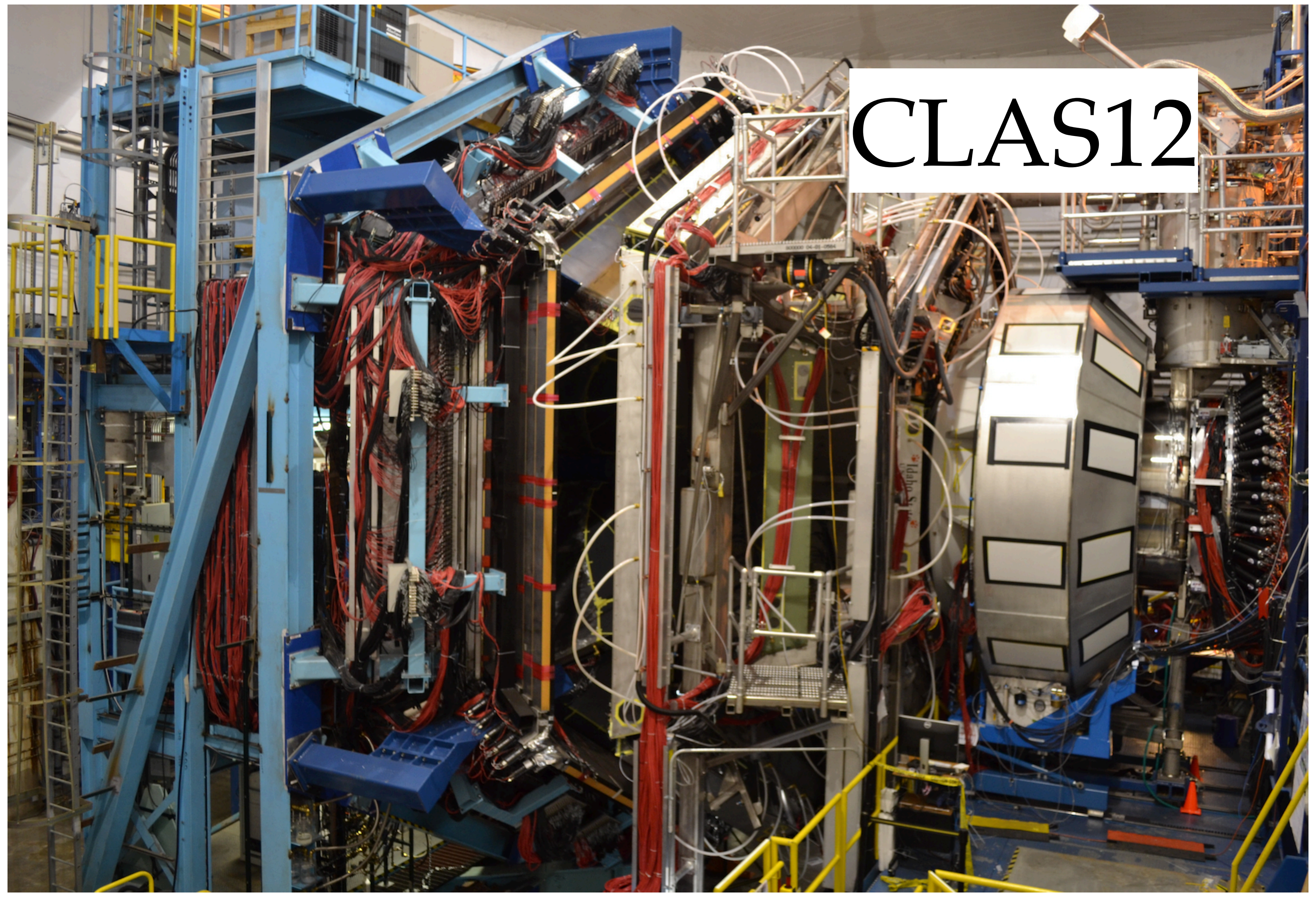

- The work of Prof. Michael Wood is supported by the US Department of Energy
- Many thanks to Canisius students
    - Alexis Grassl
    - Kyle Urban
    - Julie Heard
    - Plu Reh

# Backup slides

# The 12-GeV Program

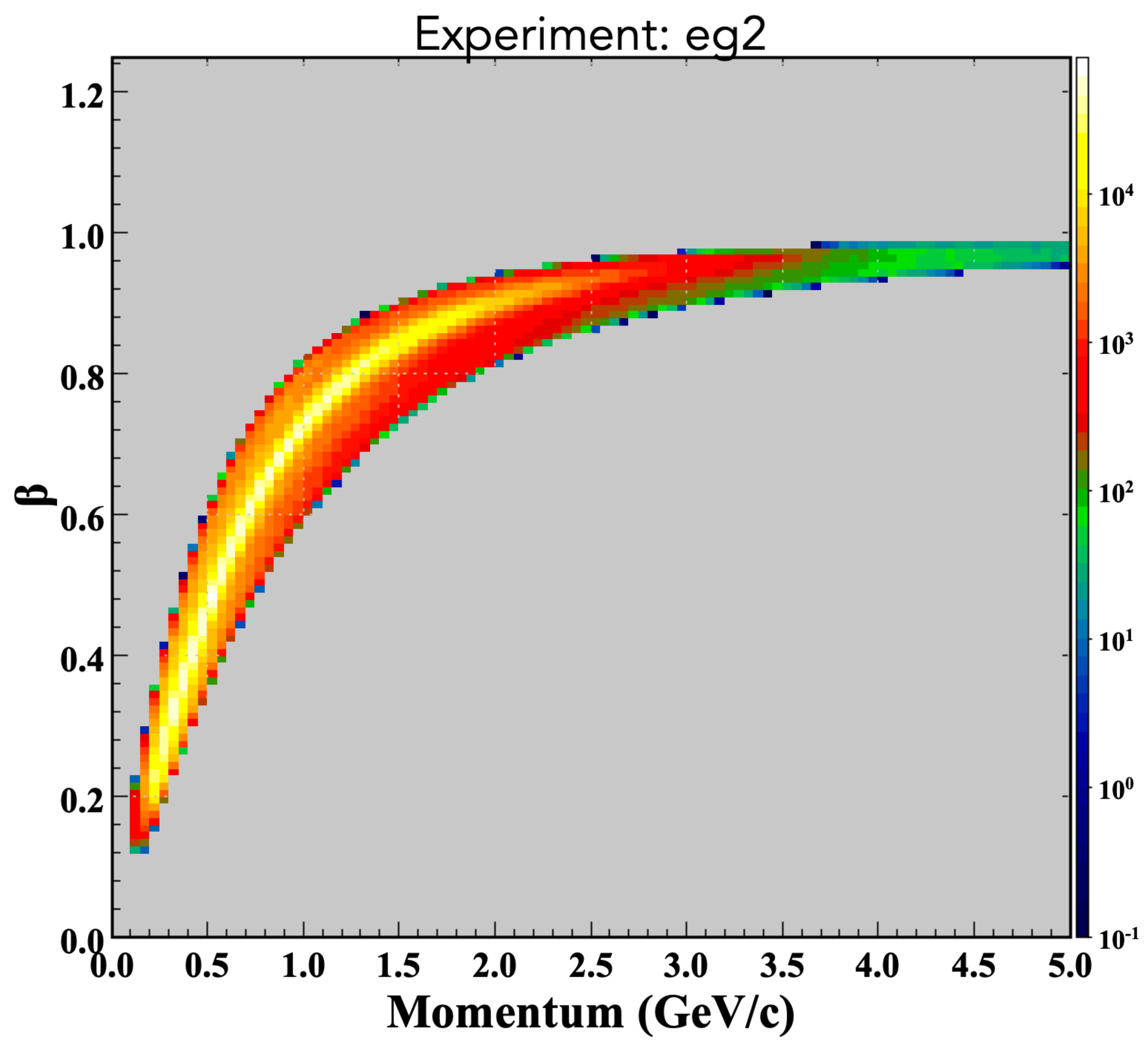



From 2011-2017, the accelerator was upgraded to double the beam energy. Hall B was upgraded with the CLAS12 detector to accept a maximum of an 11-GeV and 10x the luminosity.

# Proton Identification



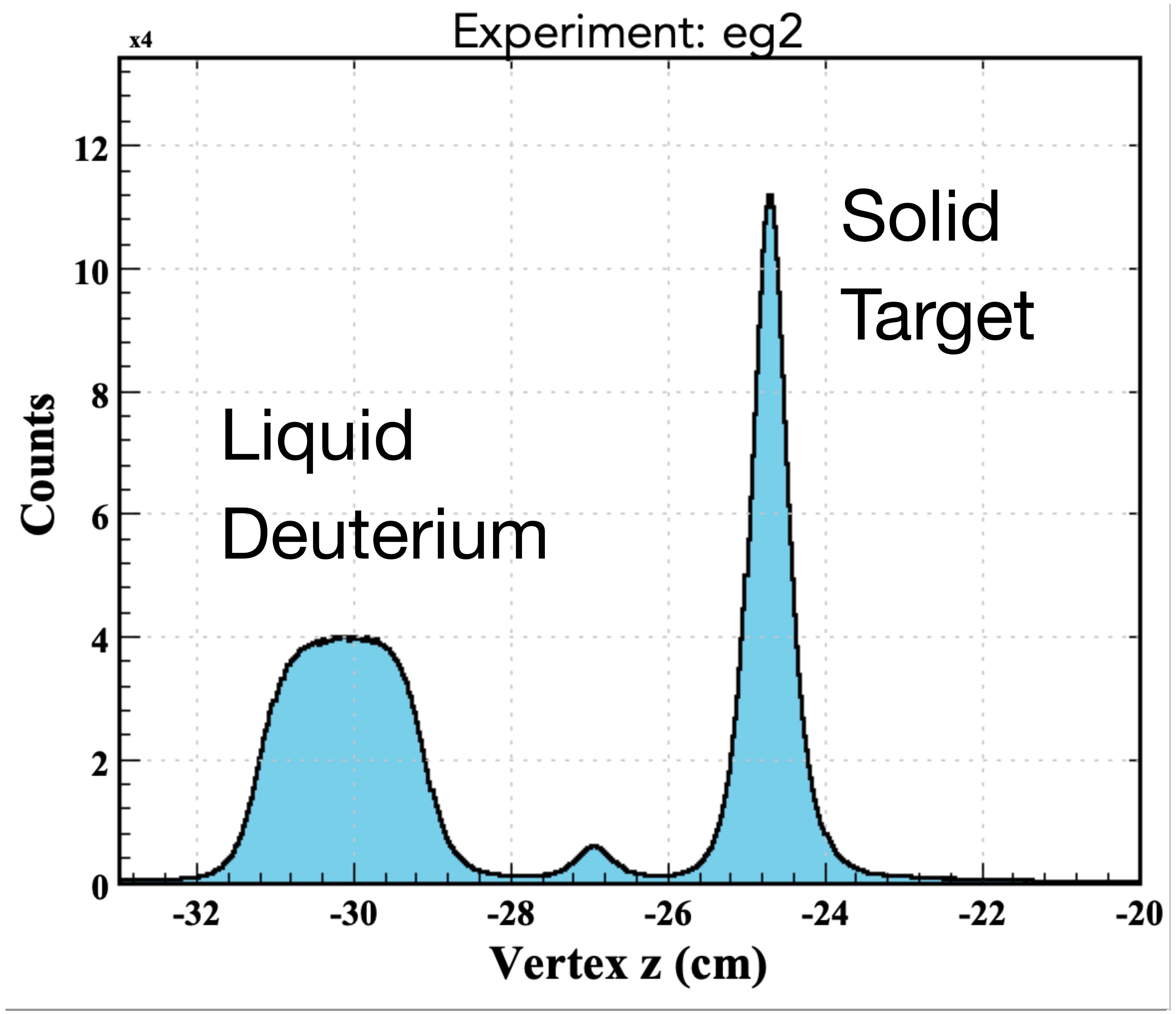



TABLE 2.1.1. Scalar and axial-vector diquark masses, $M^{\rm sc}$ and $M^{\rm av}$, respectively, computed by means of the relativised QM Hamiltonian of Refs. [114, 179]. Notation: $q$ indicates light, $u$ or $d$, quarks. These results were previously reported in Ref. [178, Table 1].

| Flavour content | $M^{\rm sc}$ (MeV) | $M^{\rm av}$ (MeV) |
|---|---|---|
| $qq$ | 691 | 840 |
| $qs$ | 886 | 992 |
| $ss$ | – | 1136 |
| $qc$ | 2099 | 2138 |
| $sc$ | 2229 | 2264 |
| $cc$ | – | 3329 |
| $qb$ | 5451 | 5465 |
| $sb$ | 5572 | 5585 |
| $cb$ | 6599 | 6611 |
| $bb$ | – | 9845 |

Taken from Barabanov et al.

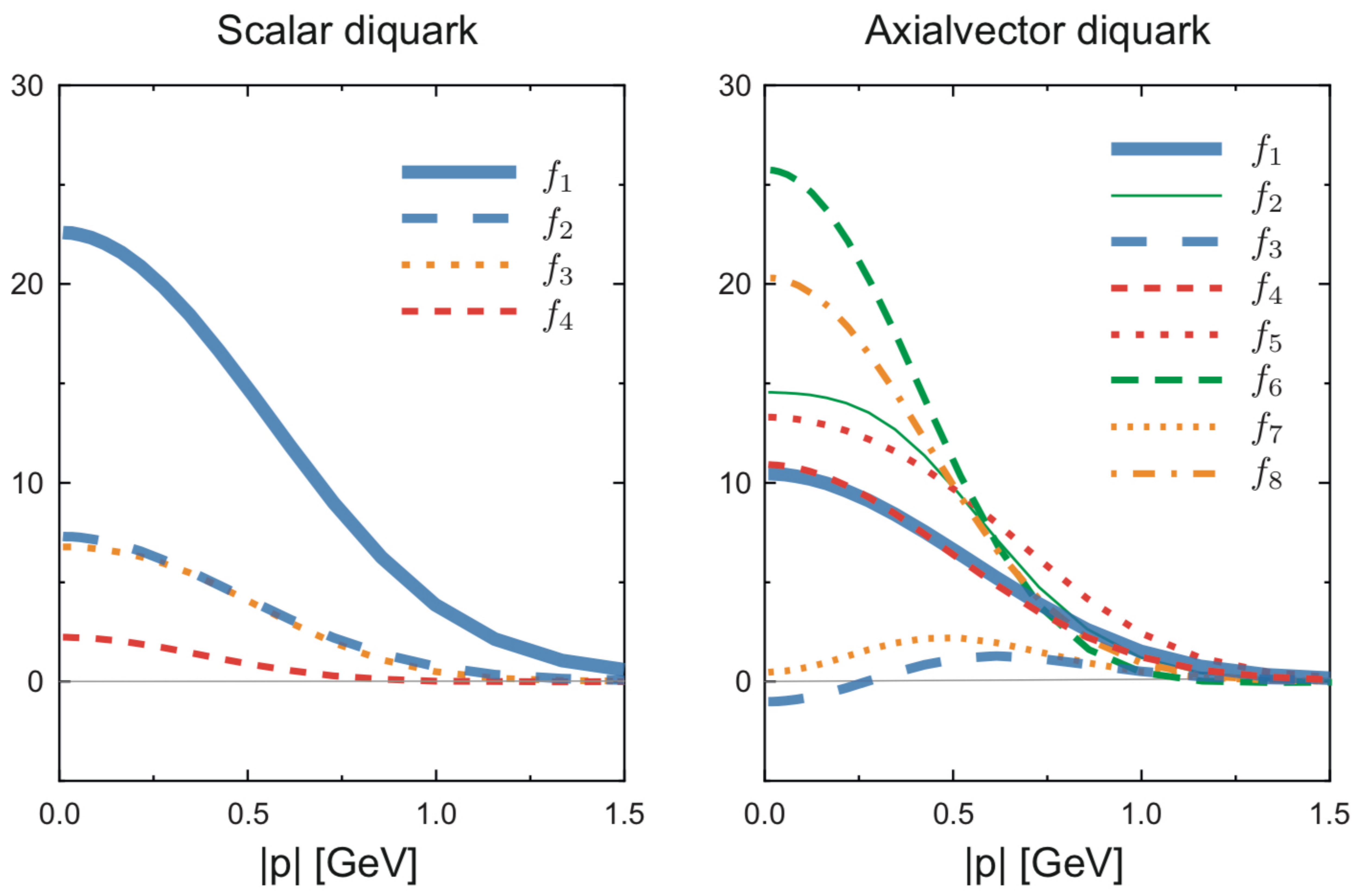



FIG. 2.2.6. Dimensionless dressing functions in the correlation amplitudes of the light-quark scalar- (left) and axial-vector-diquark (right).

"The diquarks calculated… are not pointlike objects. Far from it: their Bethe-Salpeter amplitudes carry a rich tensorial structure that depends on the relative and total momentum, with four tensors for J = 0 and eight for J = 1 diquarks. This structure is illustrated in Fig.2.2.6, which depicts oft used projections of the Poincaré-covariant scalar dressing functions associated with the various tensor structures characterising scalar and pseudovector diquarks."

Taken from Barabanov et al.

TABLE 2.3.3. Effective masses $M_q$ of $u, d$ quarks, $M_s$ of the strange quark, and those of diquarks ($m_{0^+}$ and $m_{1^+}$), computed in Landau gauge and extrapolated to the chiral limit.

| | $M_q$ (MeV) | $M_s$ (MeV) | $m_{0^+}$ (MeV) | $m_{1^+}$ (MeV) | $m_{1^+} - m_{0^+}$ (MeV) |
|---|---|---|---|---|---|
| c02 | 492(19) | 575(23) | 797(24) | 1127(28) | 330(35) |
| c005 | 427(25) | 586(16) | 725(20) | 1022(44) | 297(48) |
| f004 | 413(12) | 603(15) | 690(47) | 990(60) | 300(76) |

Taken from Barabanov et al.

# Masses of ground-state mesons and baryons, including those with heavy quarks

Pei-Lin Yin,[1,*] Chen Chen,[2,†] Gastão Krein,[2] Craig D. Roberts,[3,‡] Jorge Segovia,[4] and Shu-Sheng Xu[1]

arXiv 1903.00160

Phys. Rev. D 100, 034008 (2019)

| Baryon | $M^{e/l}$ | $M^{CI}$ | dom. corr. |
|---|---|---|---|
| $p$ (B.5a) | 0.94 | 0.94 | $[ud]u$ |
| $\Lambda$ (B.5b) | 1.12 | 1.06 | $[ud]s$ |
| $\Sigma$ (B.5c) | 1.19 | 1.20 | $[us]u$ |
| $\Xi$ (B.5d) | 1.32 | 1.24 | $[us]s$ |
| $\Lambda_c$ (B.5e) | 2.29 | 2.50 | $[uc]d - [dc]u$ |
| $\Sigma_c$ (B.5f) | 2.45 | 2.53 | $\{uu\}c$ ? almost |
| $\Xi_c$ (B.5g) | 2.47 | 2.66 | $[uc]s - [sc]u$ |
| $\Xi'_c$ (B.5h) | 2.58 | 2.68 | $\{us\}c$ |
| $\Omega_c$ (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 (neutron) and lambda will behave similarly; the others will be different.**

**We can test this prediction already, with our new preliminary data on the proton!**

https://arxiv.org/abs/2004.07236

Physics Letters B 816 (2021) 136171

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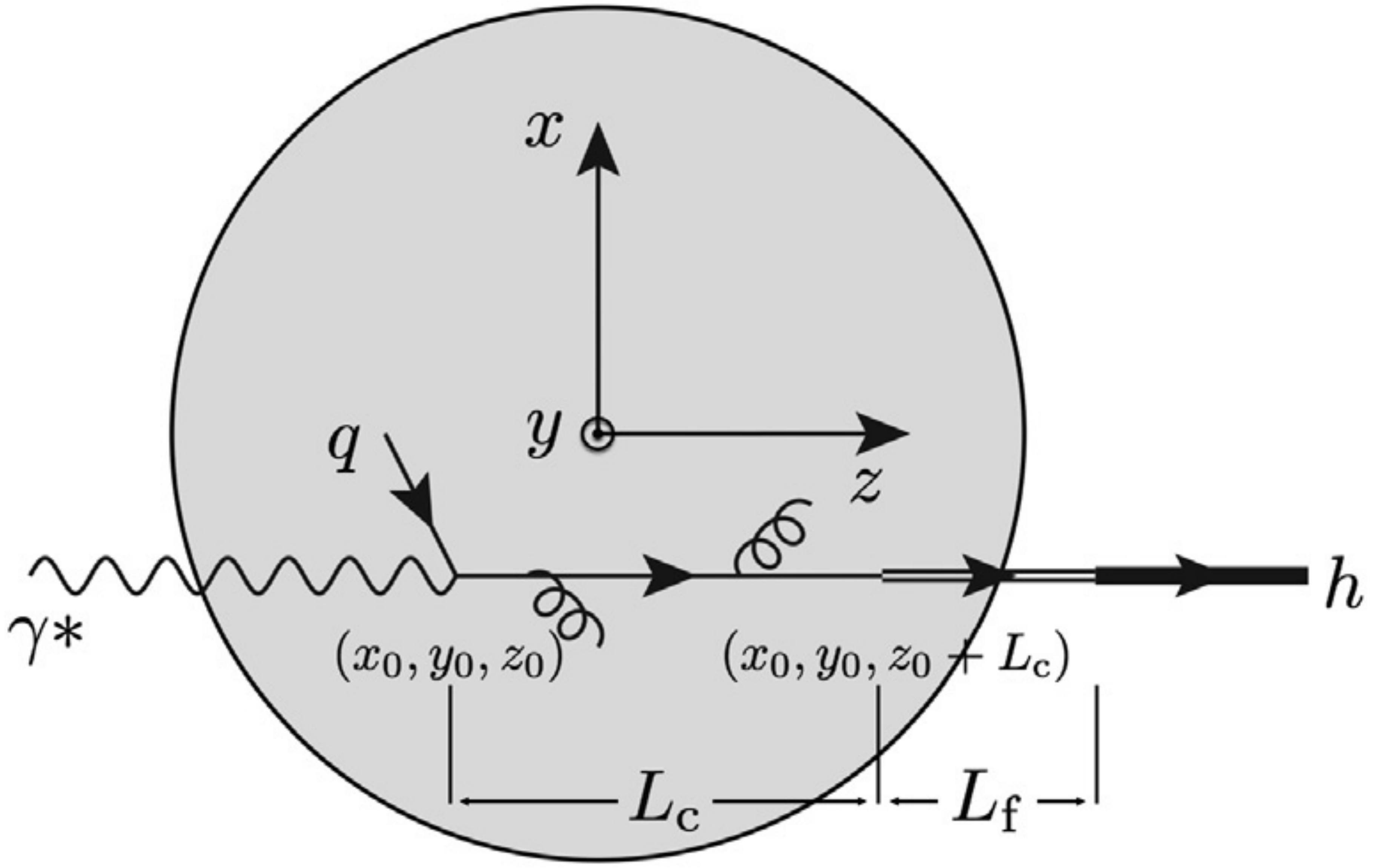
# Estimating the color lifetime of energetic quarks

William K. Brooks[a,b,c,*], Jorge A. López[b,d]

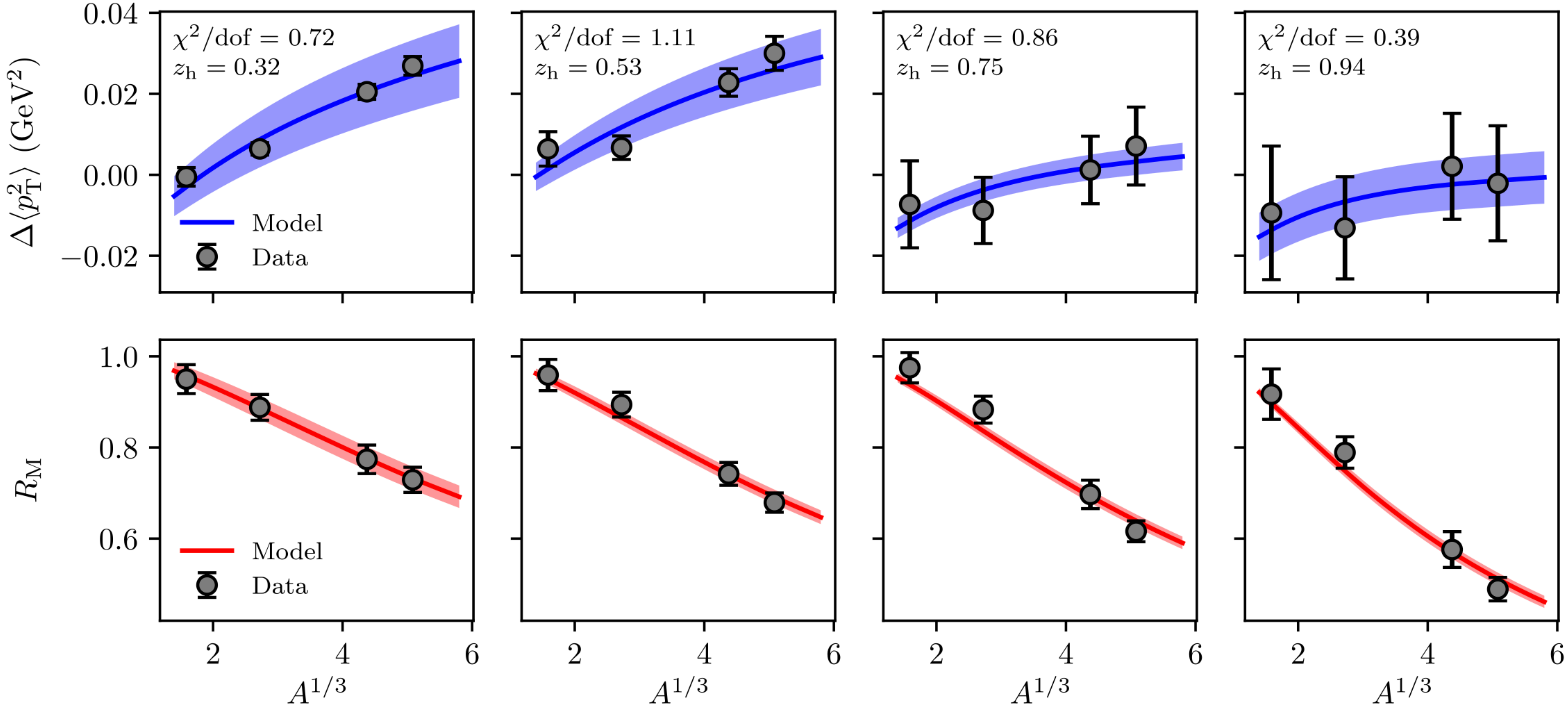
[a] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[b] Centro Científico Tecnológico de Valparaíso, Valparaíso, Chile
[c] Department of Physics and Astronomy, University of New Hampshire, Durham NH, USA
[d] Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany

**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.**



# These are the results of the simultaneous fit to two observables

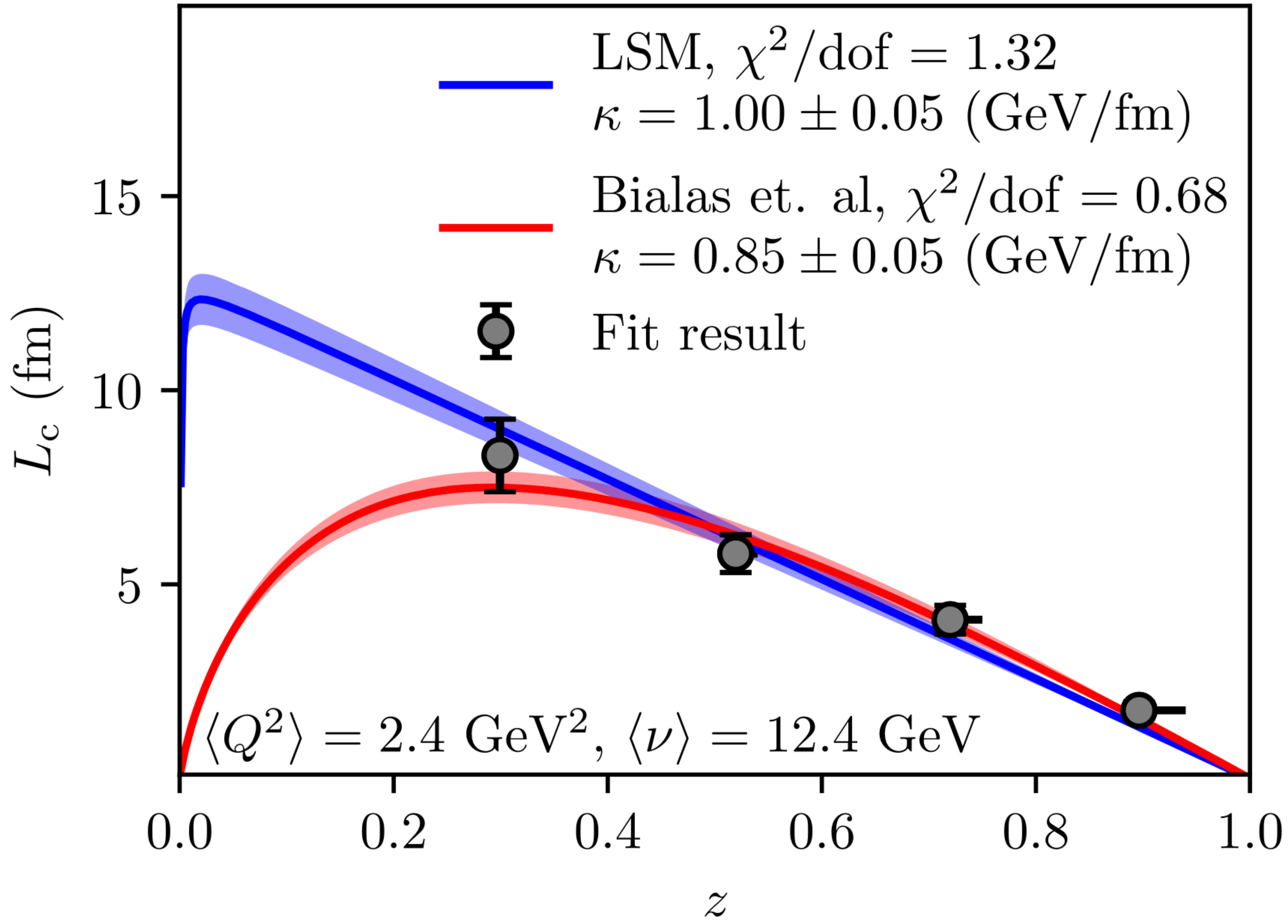



This 3-parameter space-time model that fits two observables simultaneously gives the semi-classical limit of the true quantum-mechanical system

W. K. Brooks, Baryons 2022

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**.

W. K. Brooks, Baryons 2022

https://arxiv.org/abs/2004.07236

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

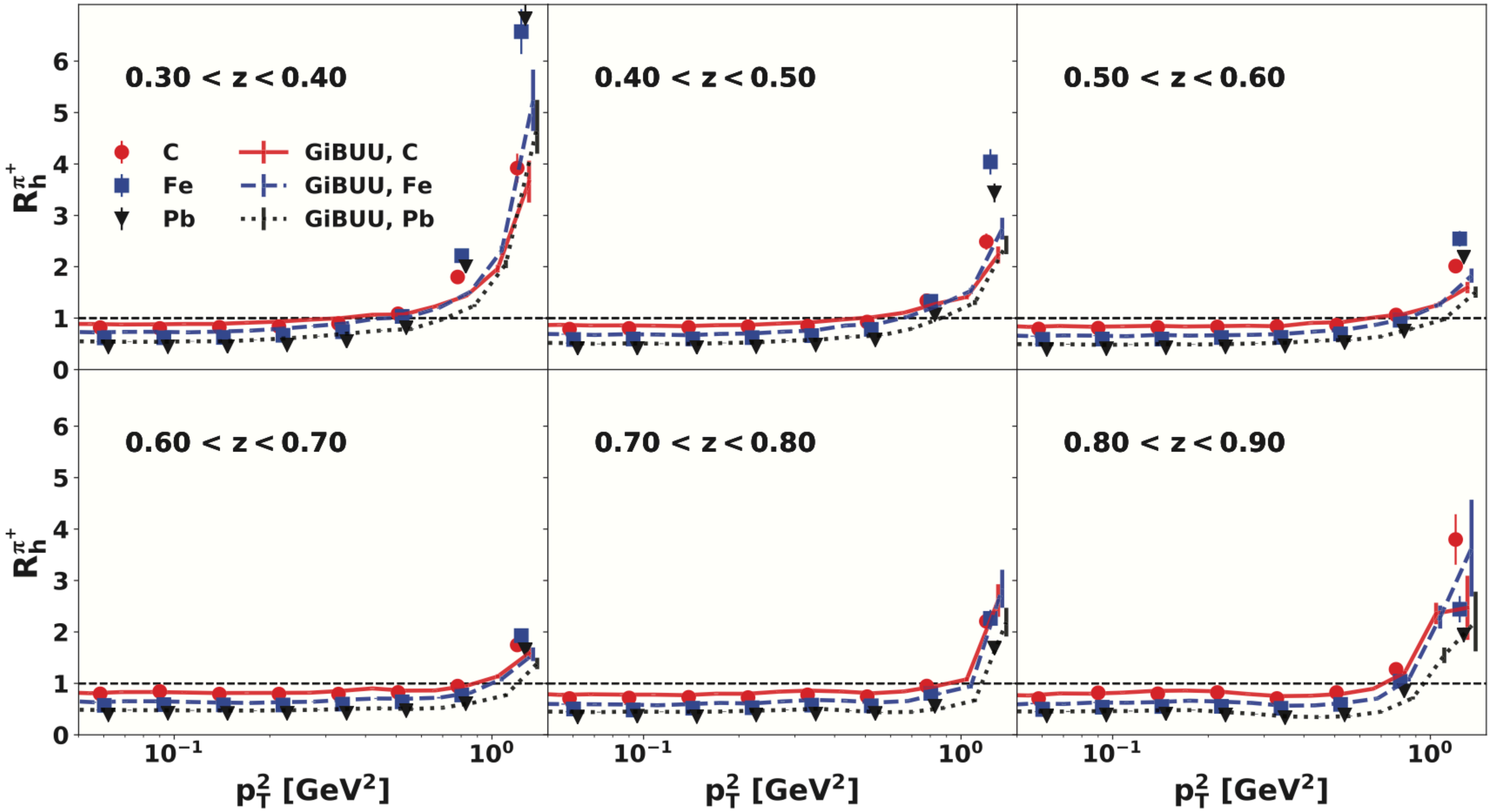
**Measurement of charged-pion production in deep-inelastic scattering off nuclei with the CLAS detector**

S. Morán,[1,3] R. Dupre,[2] H. Hakobyan,[1,52] M. Arratia,[3] W. K. Brooks,[1] A. Bórquez,[1] A. El Alaoui,[1] L. El Fassi,[4,5] K. Hafidi, R. Mendez,[1] T. Mineeva,[1] S. J. Paul,[3] M. J. Amaryan,[36] Giovanni Angelini,[19] Whitney R. Armstrong,[5] H. Atac,[43]

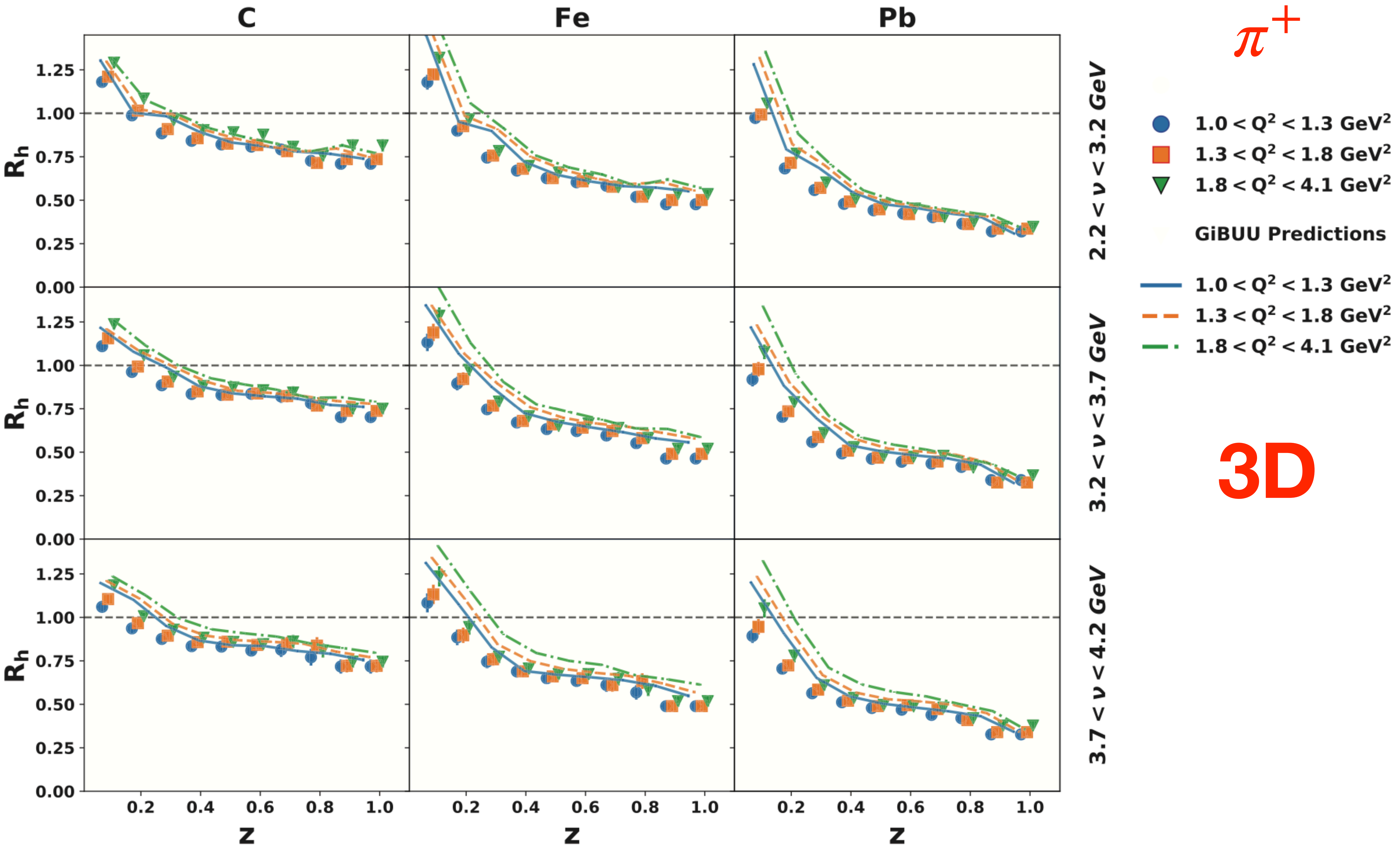
In this paper we compare high-precision CLAS data with the predictions of the **GiBUU** and **GK** models for charged pions in a *three dimensional analysis*, finding semi-quantitative **agreement**.

# 2D

**Lines are *predictions* from the GiBUU event generator with standard parameters**




W. K. Brooks, Baryons 2022




$\pi^+$

**3D**

**Lines are *predictions* from the GiBUU event generator with standard parameters**

*Phys. Rev. C 105, 015201 (2022)*

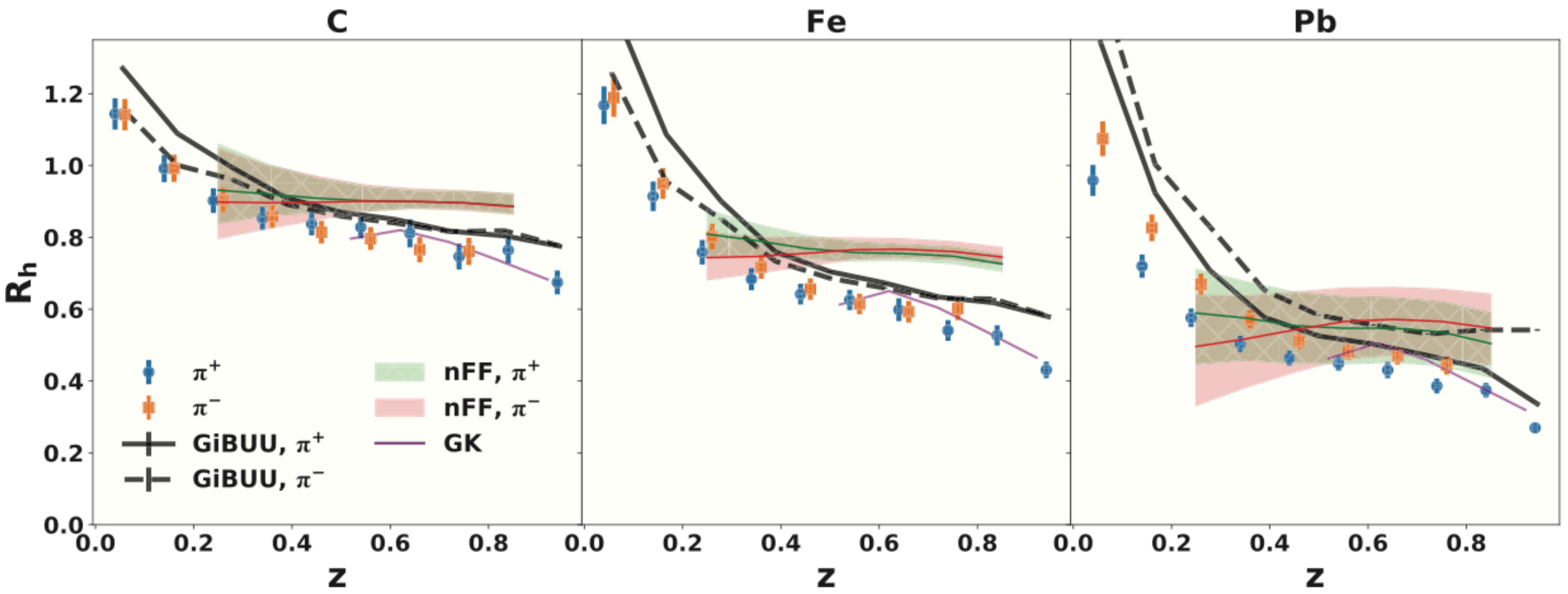
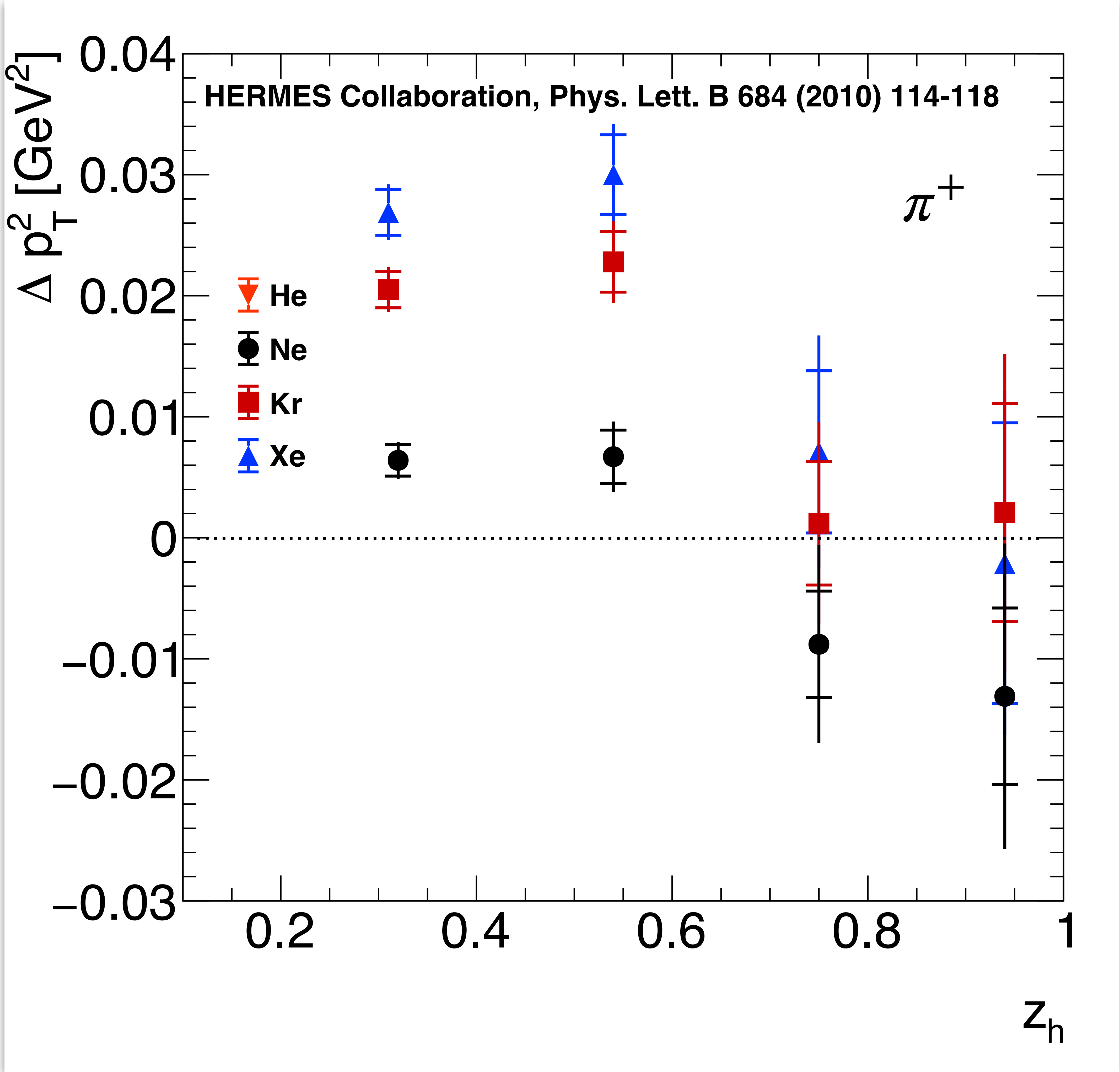



FIG. 1. Multiplicity ratio of $\pi^+$ and $\pi^-$ as a function of $z$; the three different panels show results for C, Fe, and Pb targets, respectively. The error bars represent the quadrature sum of systematic and statistical uncertainties, which is dominated by the systematic uncertainties that are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

Message: GiBUU can describe up to 3D **pion** production
We *believe* we have a correct physical picture.

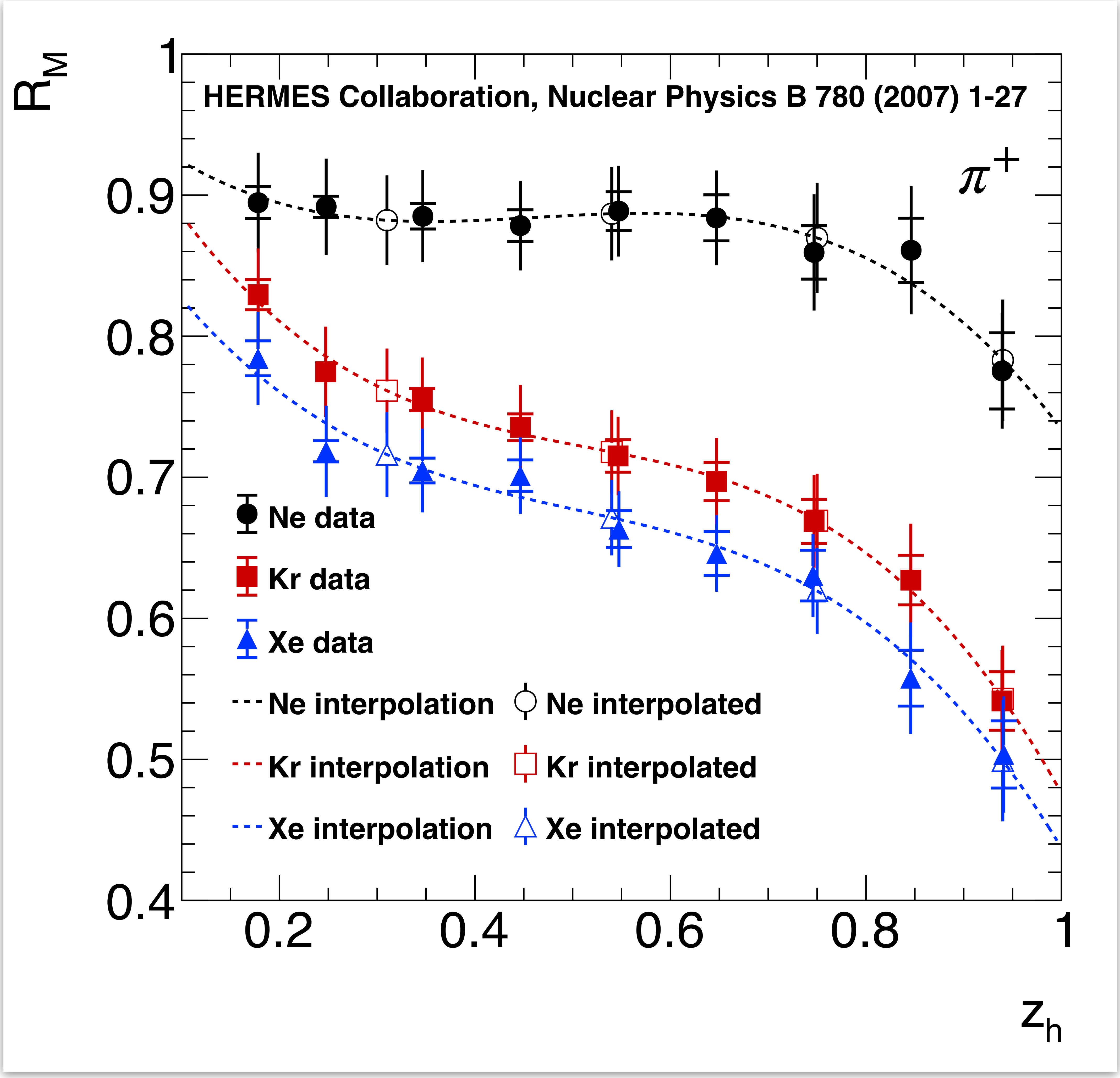
GiBUU uses hadronic degrees of freedom, it incorporates formation times, "prehadron" interactions,[3] color transparency, and nuclear shadowing. These ingredients have been postulated to be necessary to describe nuclear modification of hadrons produced in DIS by the HERMES and EMC experiments. The default parameters of GiBUU 2019 are used.

# Hermes data for $p_T$ broadening vs. $z_h=E/\nu$




**Note for later discussion: maximum is 0.03 GeV²**

# Hermes data, hadronic multiplicity ratio vs. $z_h = E/\nu$




Note for later discussion: for this range in $z_h$,

$$R_M^\pi < 1$$

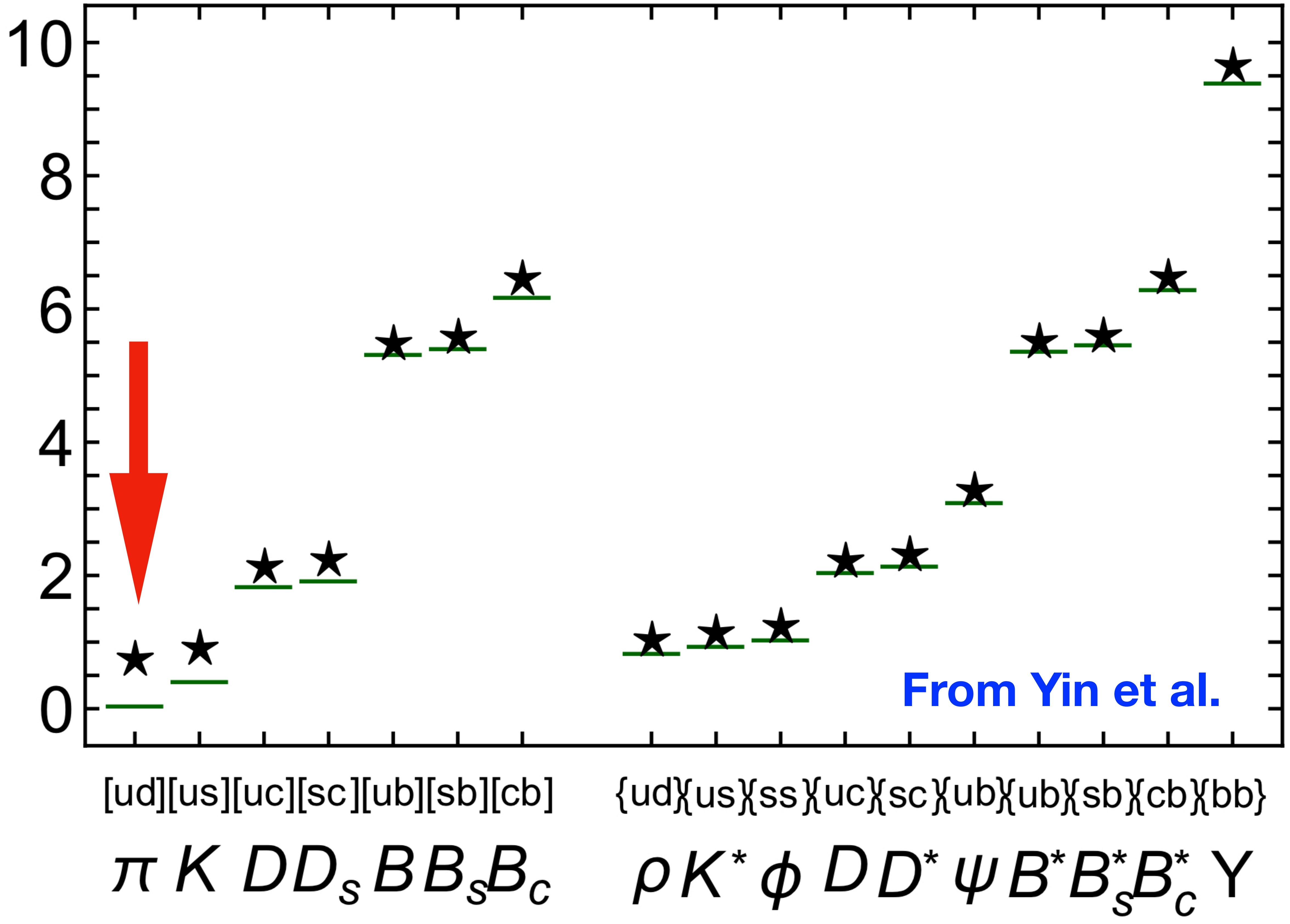
Always attenuation, never enhancement

Masses of ground-state mesons and baryons, including those with heavy quarks

Pei-Lin Yin,[1,*] Chen Chen,[2,†] Gastão Krein,[2] Craig D. Roberts,[3,‡] Jorge Segovia,[4] and Shu-Sheng Xu[1]

**arXiv 1903.00160**

Phys. Rev. D 100, 034008 (2019)




**The ud diquarks are heavy, as seen previously in the lattice calculation.**

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
Eur. Phys. J. A47:113, 2011

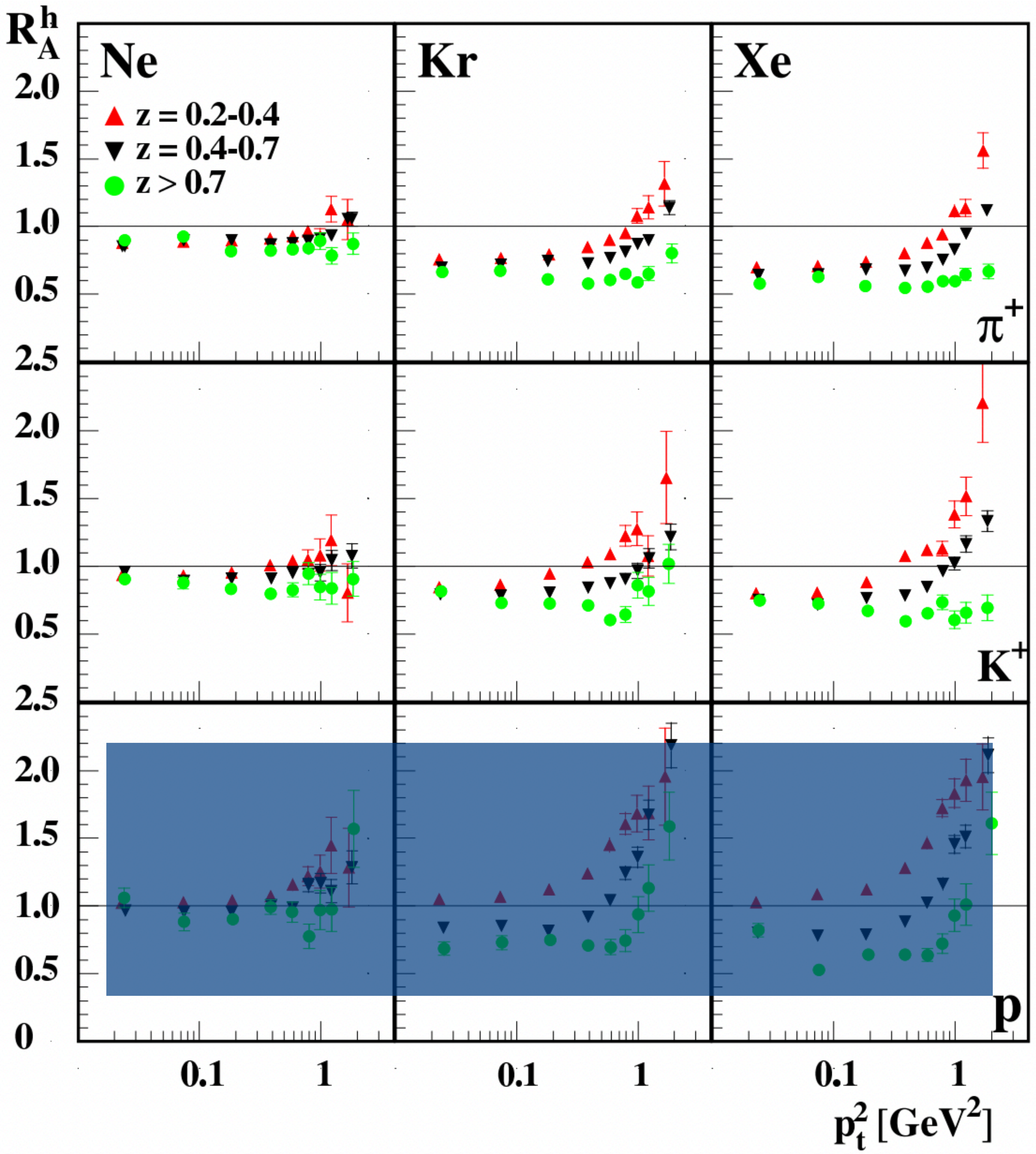
# Interpreting HERMES Nuclear DIS DATA: <u>MESONS</u>

The multiplicity ratio measures effects of the nuclear medium. "No nuclear effects" means R=1.0

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

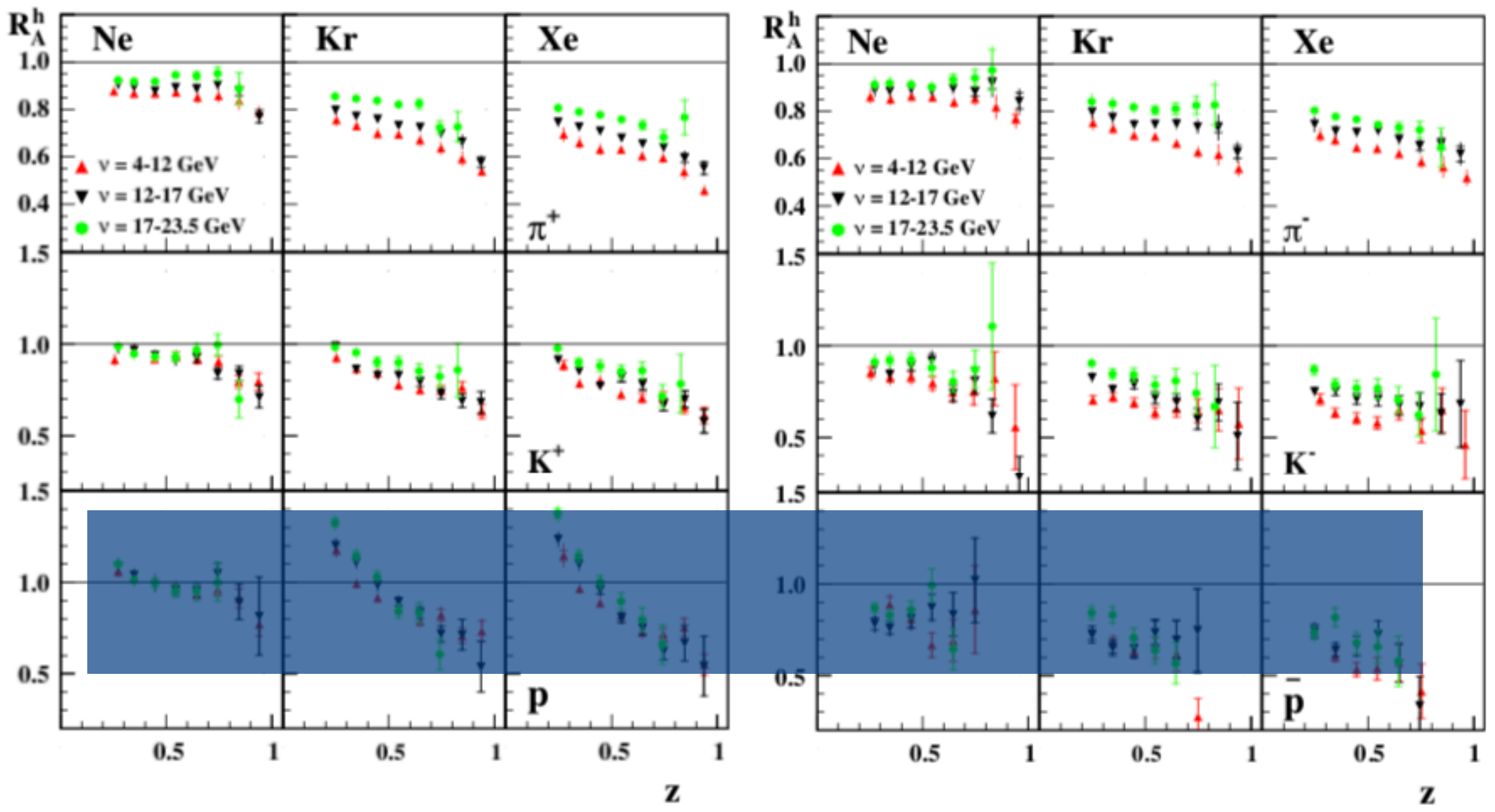
Most basic indicator is $p_T$ dependence of multiplicity ratio.

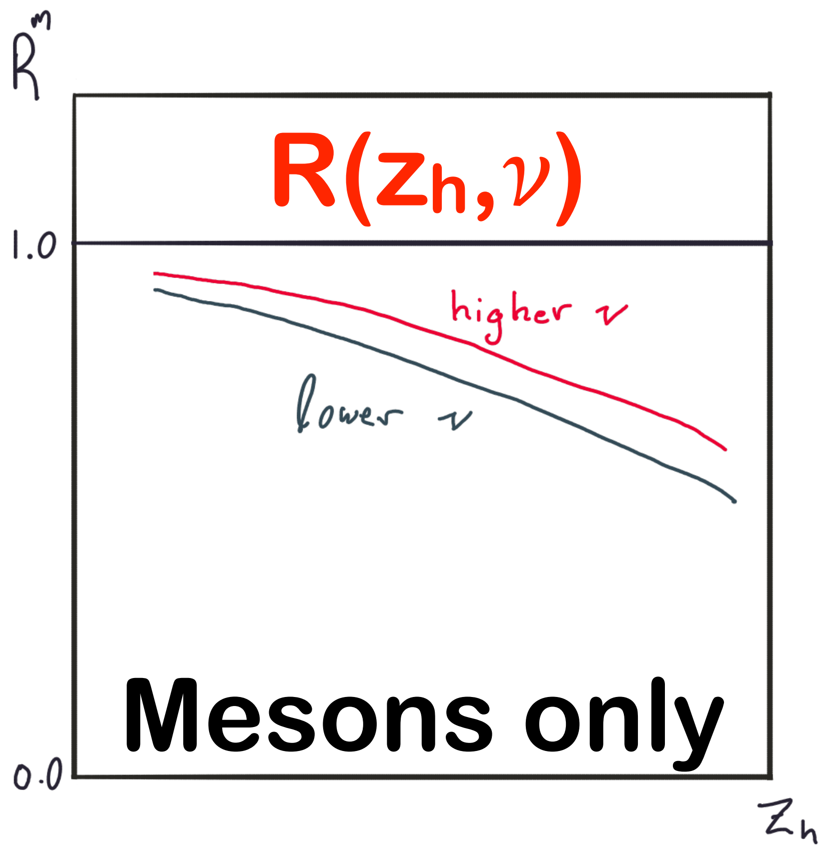
R>1 at high $p_T$ because particles that interact with the medium acquire more $p_T$ than those that don't interact as much.



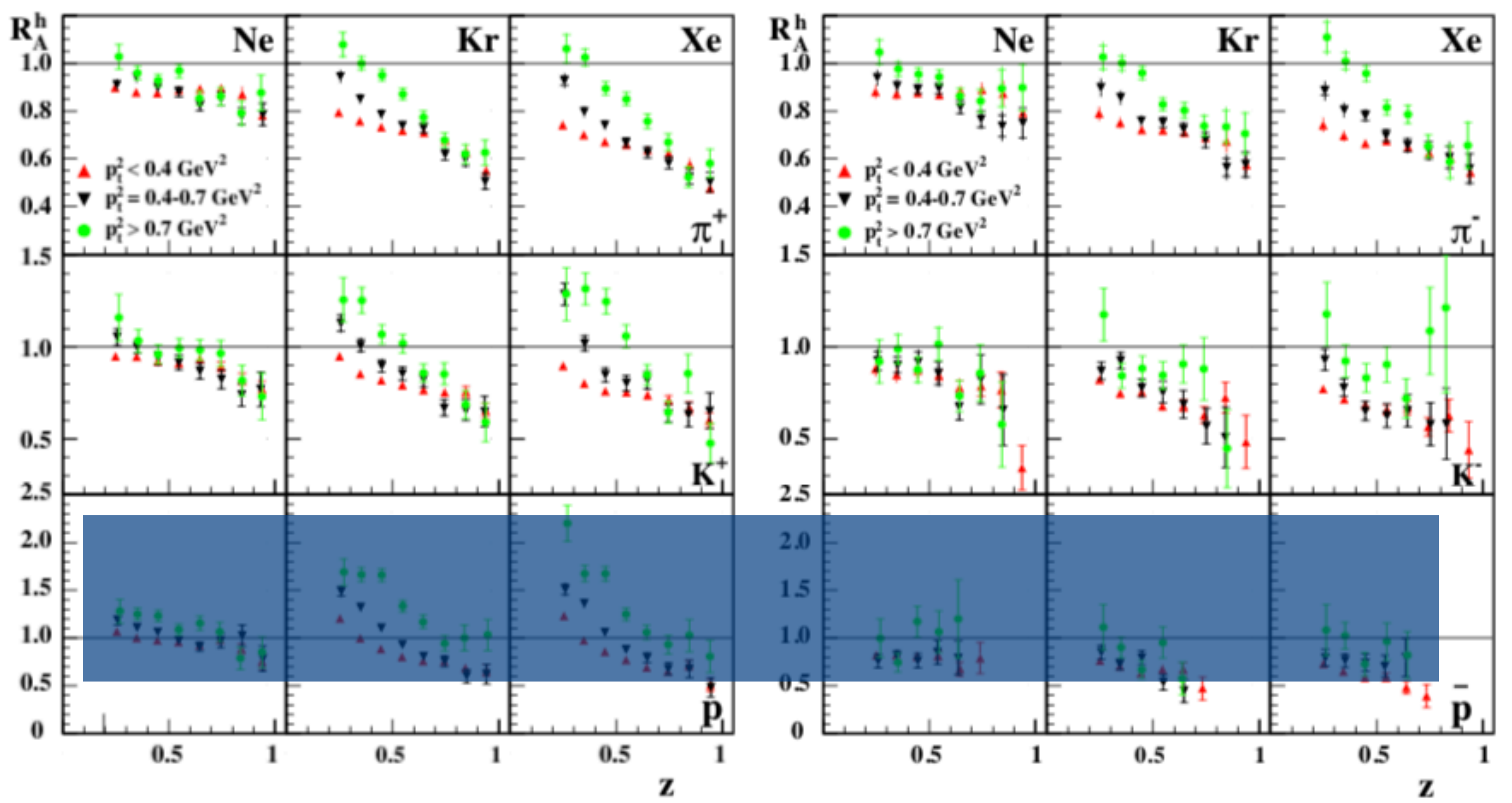

"Interact" = hadronic interaction + partonic multiple scattering

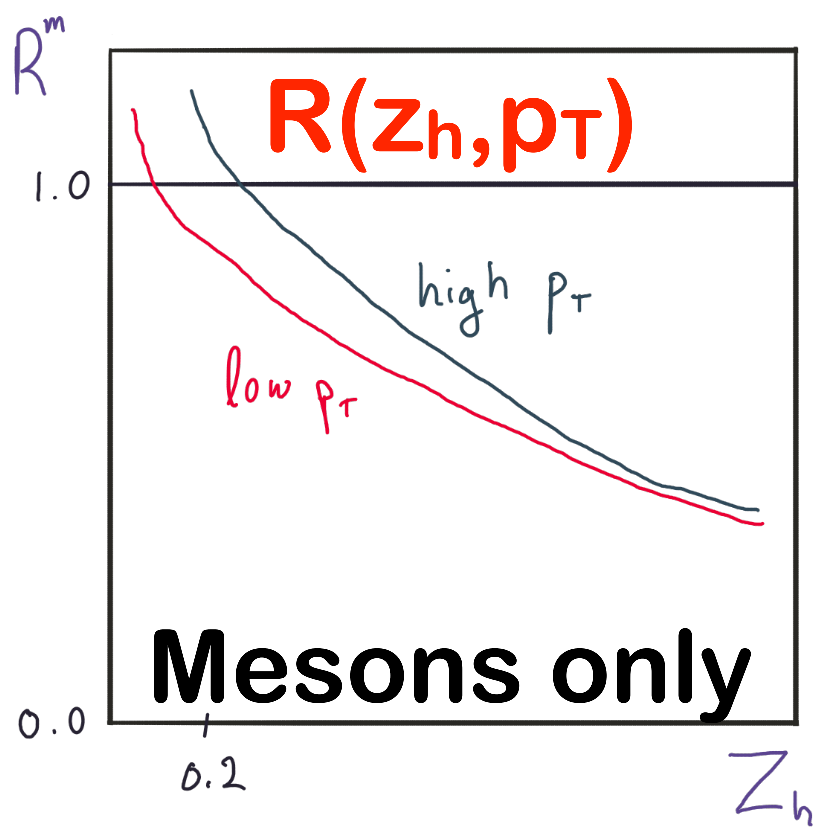
Empirically, from these plots, low-z <u>mesons</u> acquire more $p_T$ than high-z.



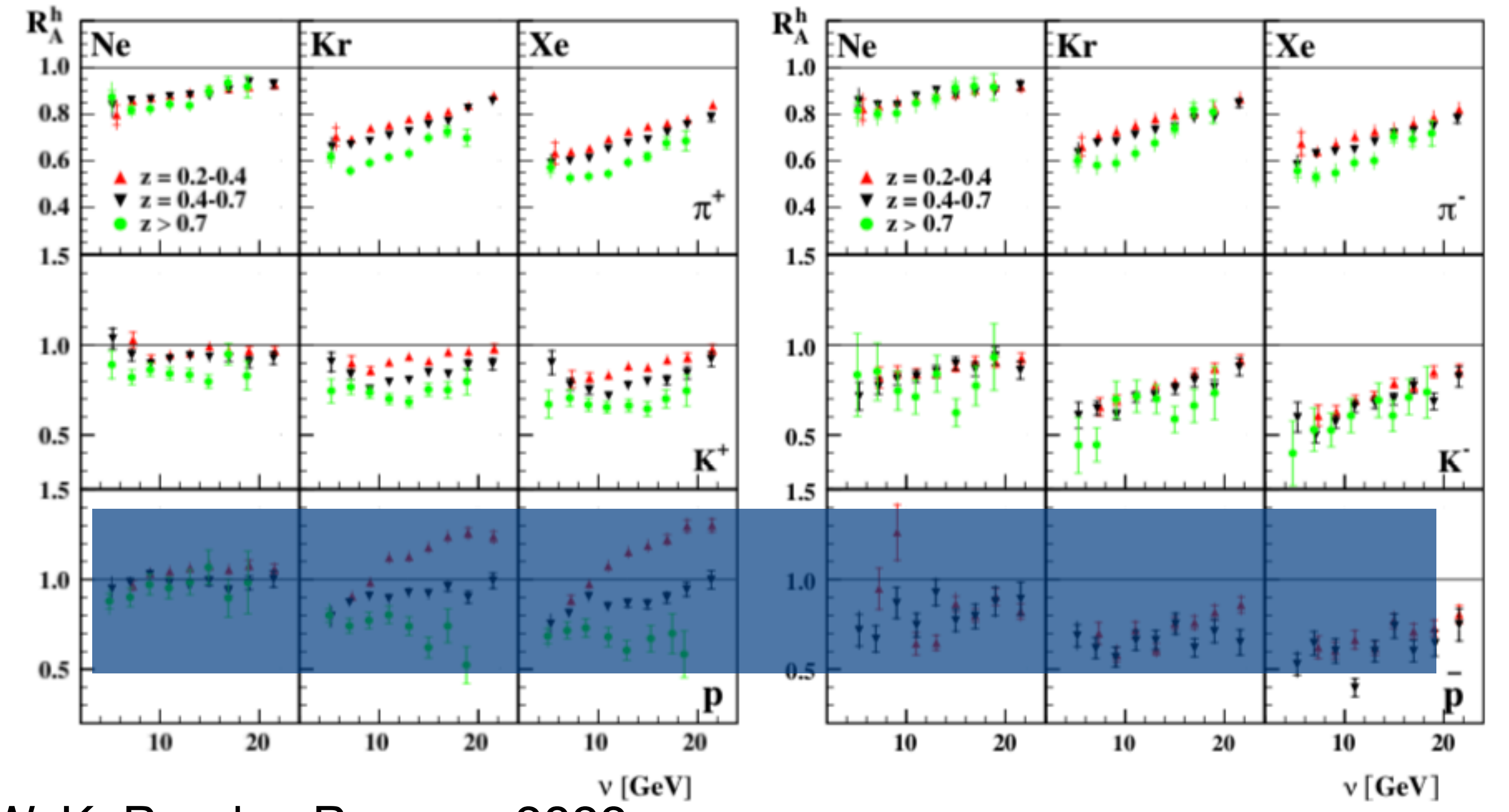



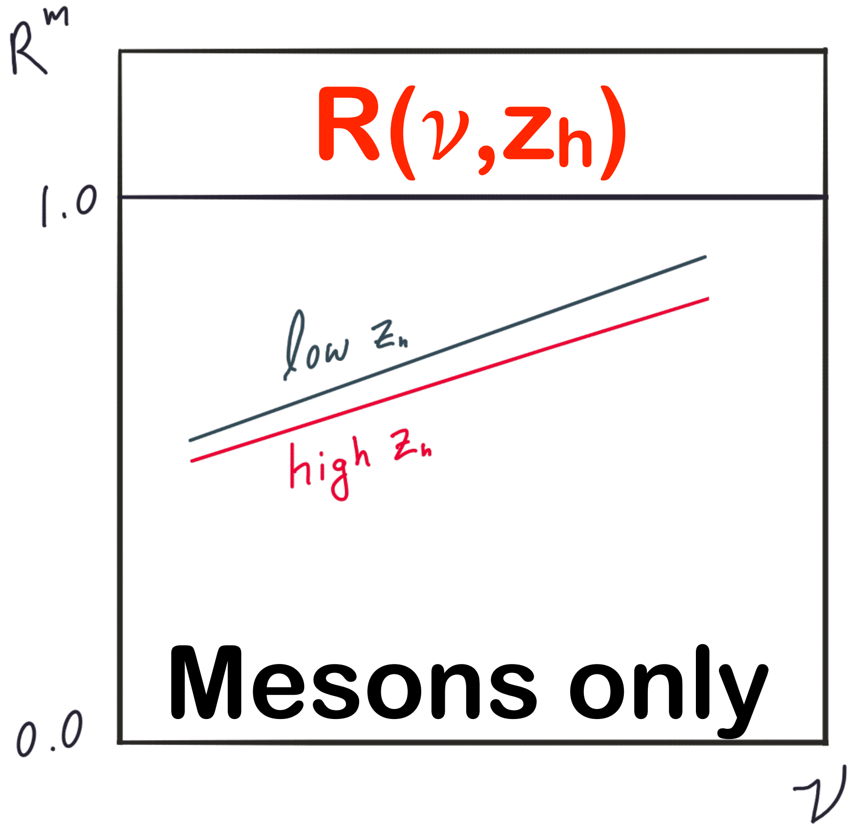

Integrated over $p_T$, so always < 1. At higher $\nu$, less attenuation because of time dilation of color lifetime.




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 $\nu$. Slow approach to 1.0 at infinite $\nu$. Color lifetime goes to zero at high z, so high z is attenuated more.