Overview of *eA* experimental results from Jefferson Lab and future prospectives in *eA*

Strong QCD 2024, Nanjing, China

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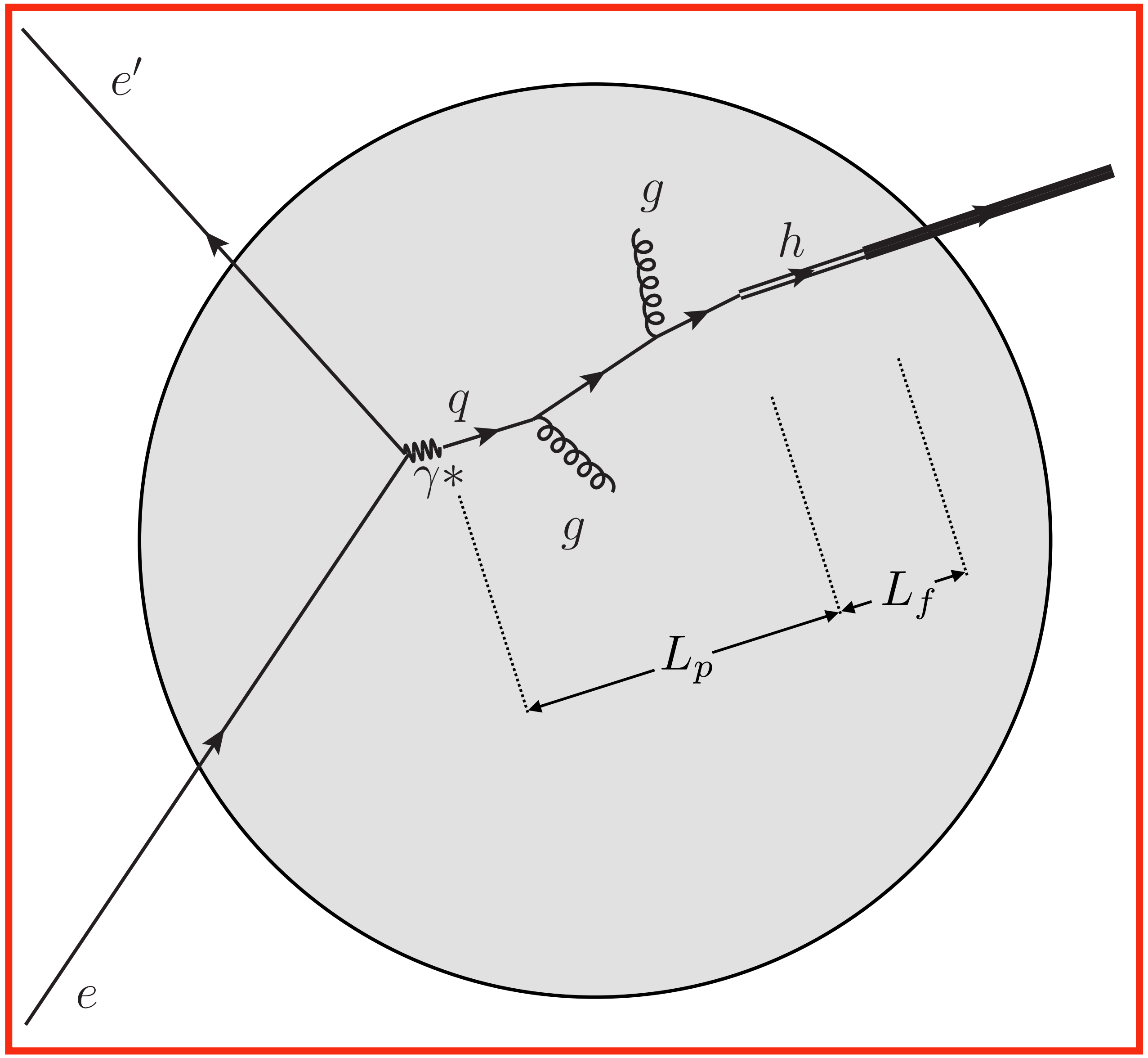
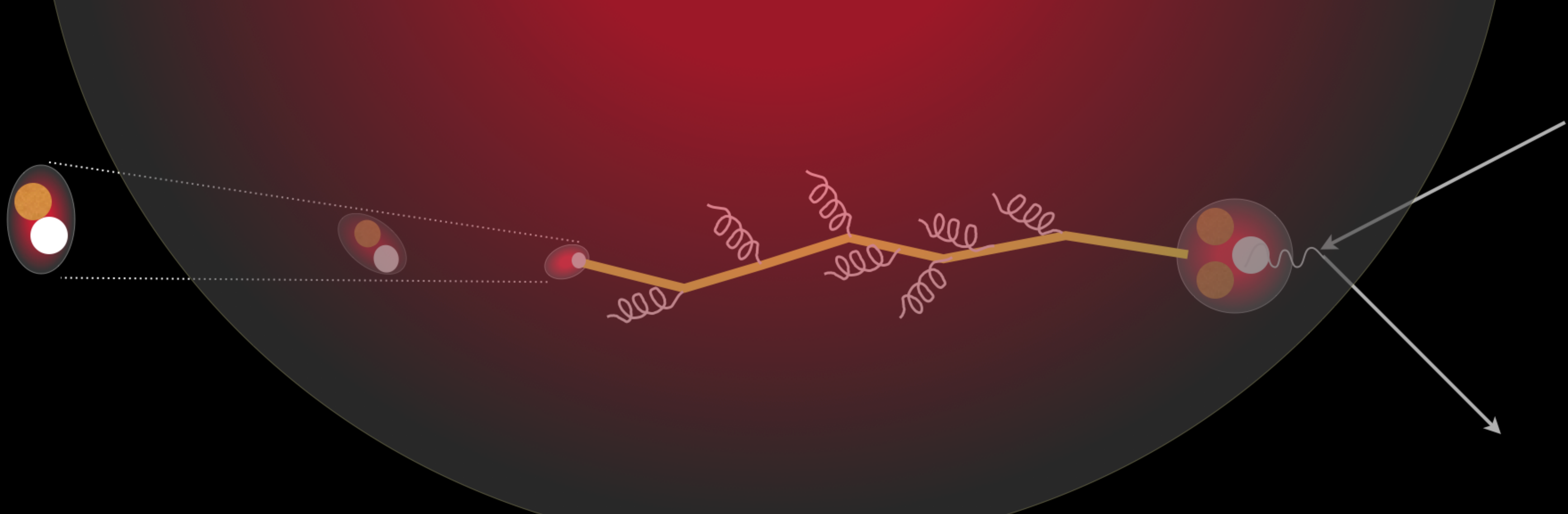
clas CEBAF Large Acceptance Spectrometer
CCTVal Centro Científico Tecnológico de Valparaíso
Universidad Tecnica Federico Santa Maria

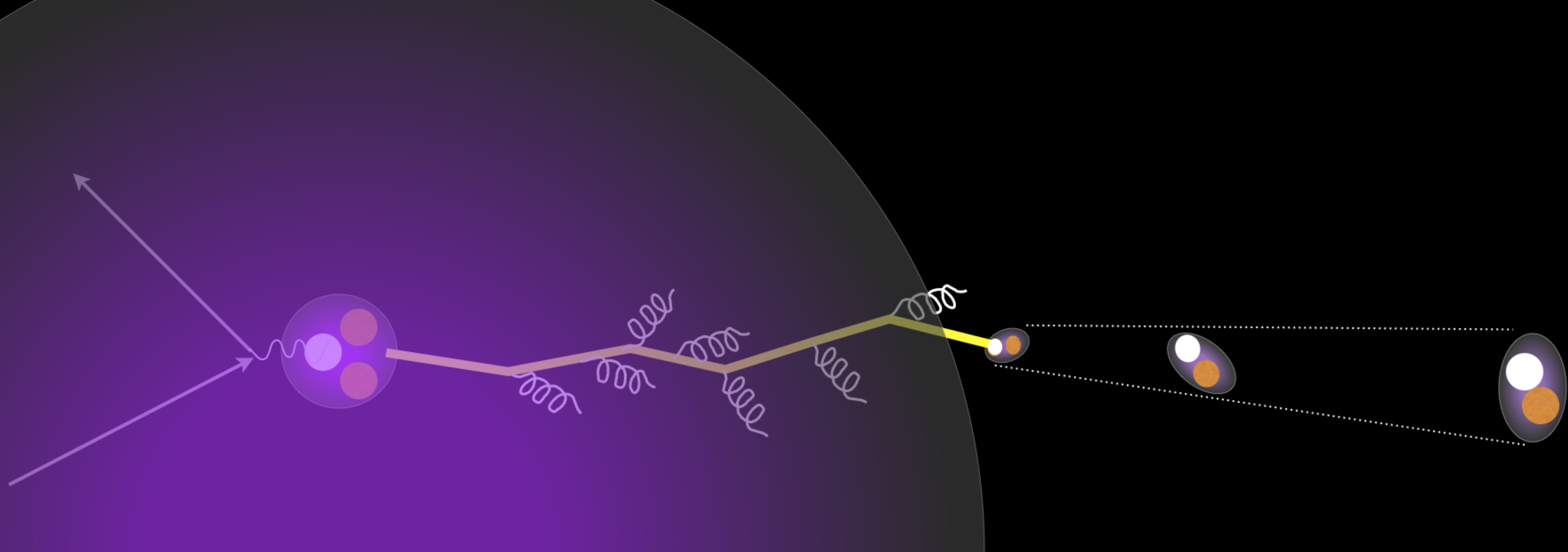
Color Propagation and Hadron formation in Cold Matter



DIS (Desy, Jefferson Lab)



SIDIS on nuclear targets: from the modification of kinematic observables in **A(e, e′*h*)X** scattering, we can infer hadronization mechanisms for *h*



visualization from W. Brooks

Questions highlighted in the 2023 Long Range Plan for Nuclear Science

Sidebar 3.3 Connecting the World of QCD to the Visible World

Because of confinement, we never observe the color-charged particles of QCD—quarks and gluons—in isolation; they are confined to color-neutral hadrons. Thus, every time a high-energy collision breaks up a proton, the energy of the collision allows the creation of more quark–antiquark pairs by converting energy into mass (E = mc2), and the new quarks and antiquarks rapidly bind to the various constituents of the broken-up proton, "snapping" into mesons and baryons, the QCD bound states, which can be detected.

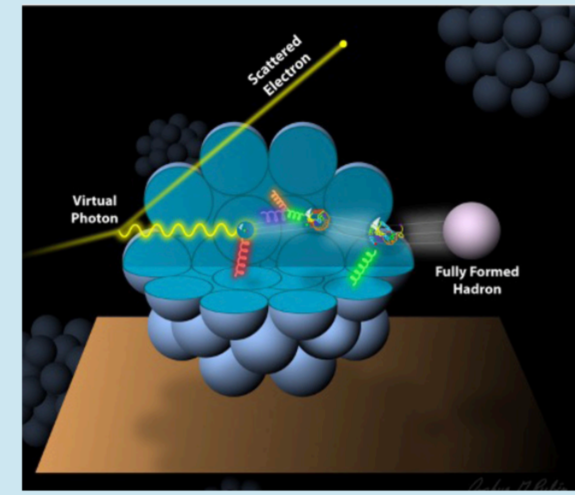


Figure 1. Representation of a high energy collision [S12]

Like blowing soap bubbles from the film with a bubble wand, when every free-streaming bubble must have closed off to become a whole bubble, every free-streaming product of a high-energy collision must have somehow become a "whole" color-neutral particle (Fig 1). Each time you blow on the soap film, a different number of bubbles of varying sizes may be produced. Likewise, each time a high-energy collision involving a proton occurs, a different number of hadrons of varying masses and quantum numbers may be produced.

To date, most efforts have focused on studying the production of a single hadron at a time along the same direction as the outgoing parton. However, in recent years, we have started to study hadronization in more sophisticated ways. Highlights since the 2015 Long Range Plan include spin–momentum correlation measurements in hadronization by the STAR experiment at RHIC, multivariable measurements of identified hadron production in jets by the LHCb experiment at CERN, an investigation by the CLAS experiment at Jefferson Lab of how hadron-pair production is modified in cold nuclear matter, and the modifications to hadrons in jets induced by interactions with the quark–gluon plasma, observed at both RHIC and the LHC.

These exciting results naturally point to more questions.

- What are the timescales of color neutralization and hadron formation?
- What are the differences in hadronization of quarks versus gluons and of light quarks versus heavy quarks?
- How are the various hadrons produced in a single scattering process correlated with one another, and how does hadronization change in a dense partonic environment?

The upcoming decade holds great promise for advancements, both in how we think about hadronization theoretically and in our ability to experimentally untangle the various mechanisms that contribute to this phenomenon. Theoretically, recent developments in quantum computing provide unique opportunities to explore the inherent dynamic nature of hadronization as a process unfolding in time. Experimentally, hadron identification capabilities at the STAR experiment at RHIC, CLAS12 experiment at Jefferson Lab, LHCb and ALICE experiments at CERN, Belle II experiment in Japan, and the ePIC experiment at the future EIC will allow us to measure and compare a wide range of traditional and novel observables related to hadronization.

Color Propagation and Hadron formation

- In-medium color propagation and hadronization
- Light and heavy hadron formation and attenuation
- Bose-Einstein Correlations, di-hadron correlations
- Diquark search
- eA Monte-Carlo generators
- Physics in future facilities

Important kinematic variables

- Four-momentum transfer squared Q^2
- Energy transfer ν (=E-E' in the laboratory frame)
- Energy transferred from the γ^* to the hadron: $z = E_h / \nu$
- Momentum transverse to the γ^* direction: p_T

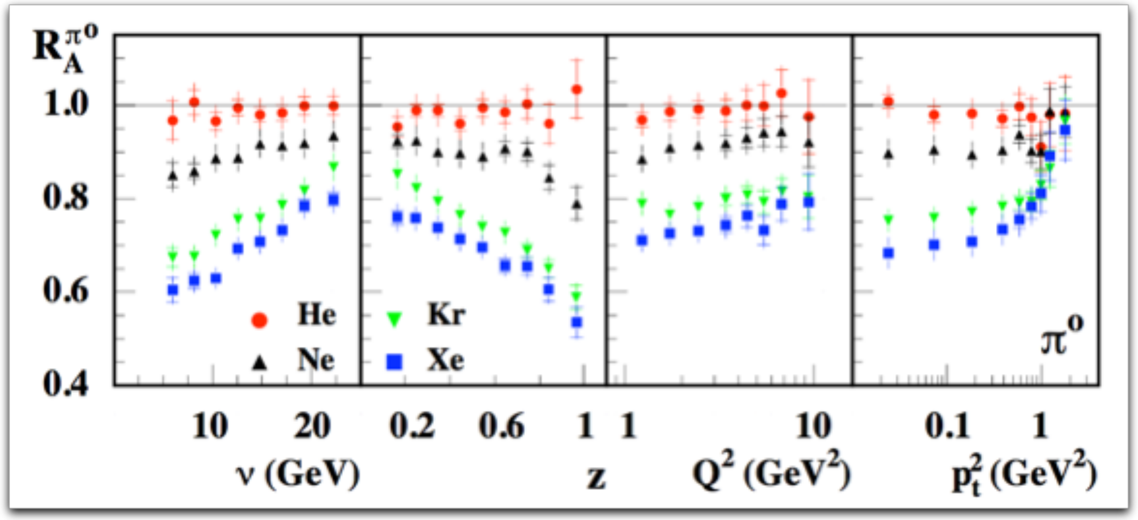
Note: if the virtual photon is absorbed by a light object like a single quark then $z \leq 1$, *but if it is absorbed by a heavy object, it can be greater than 1.0*

Experimental Observables

Hadronic Multiplicity ratio

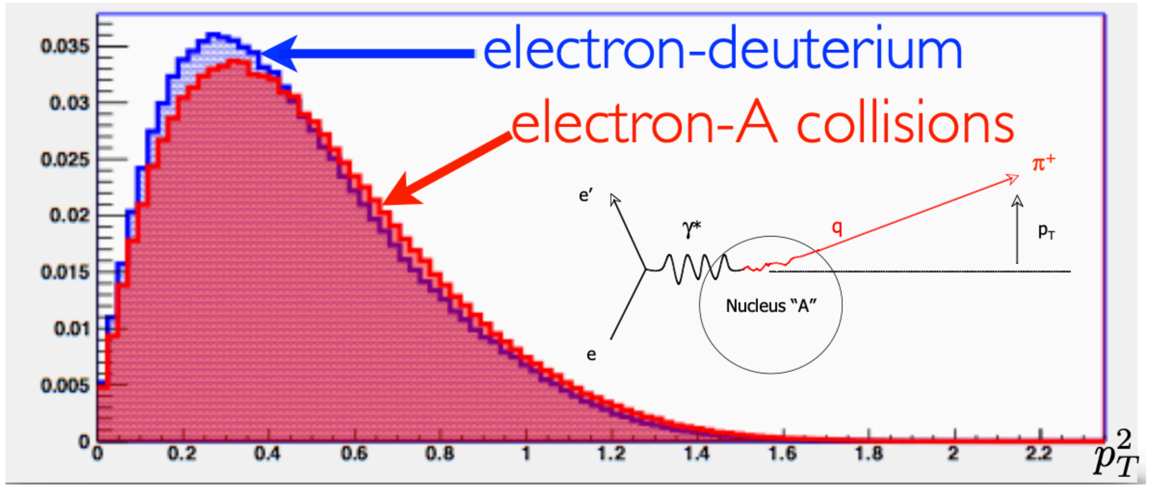
$$R_{\rm A}^{h}\left(\nu, Q^2, z, p_T\right) = \frac{\left.\frac{N_h(\nu,Q^2,z,p_T)}{N_e(\nu,Q^2)|_{\rm DIS}}\right|_{\rm A}}{\left.\frac{N_h(\nu,Q^2,z,p_T)}{N_e(\nu,Q^2)|_{\rm DIS}}\right|_{\rm D}}$$

HERMES Collaboration, A.Airapetian et. al., Nucl. Phys. B 780 (2007) 1–27

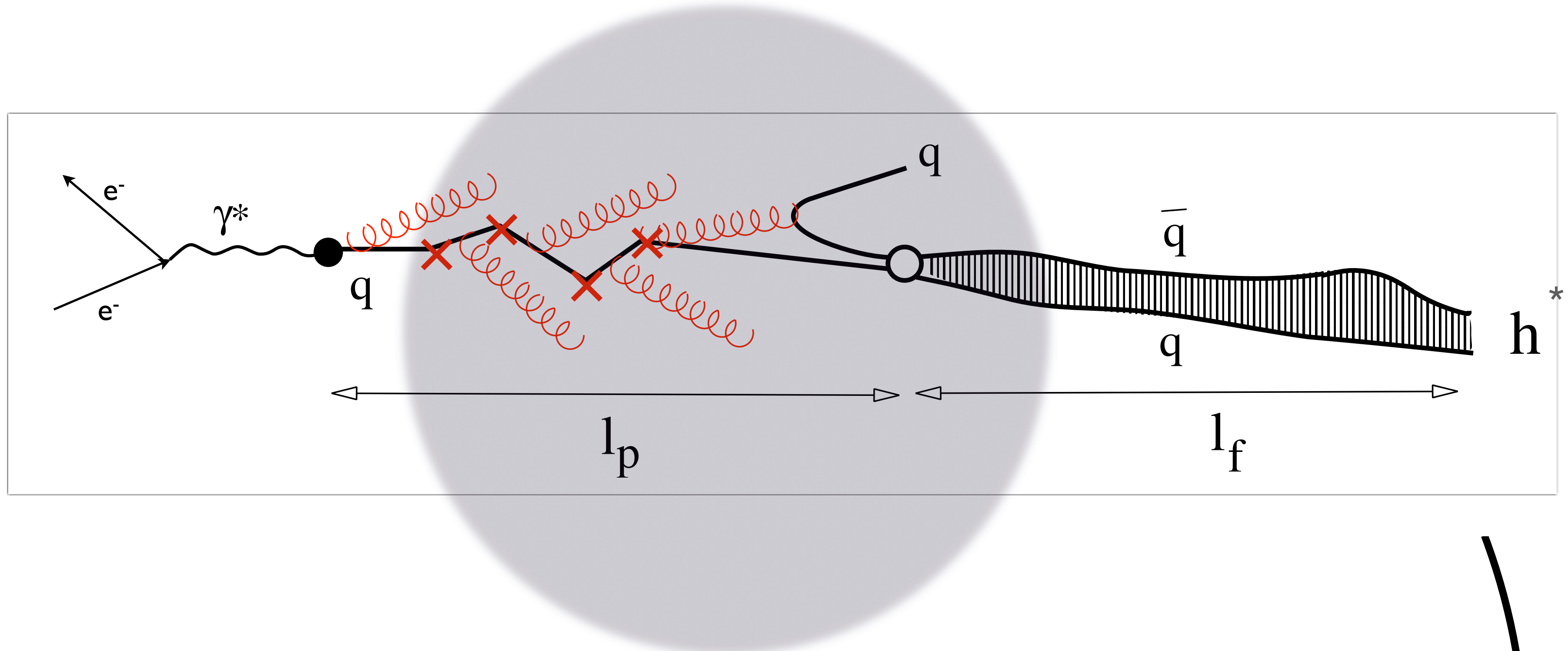


Transverse momentum broadening

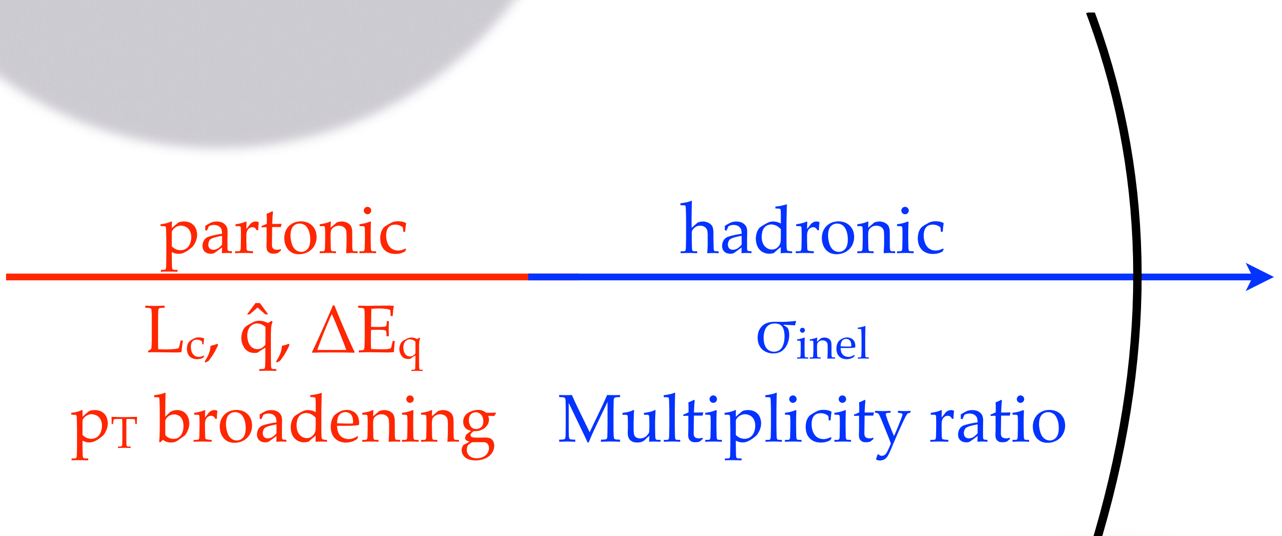
$$\Delta p_T^2(Q^2,\nu,z_h) \equiv \langle p_T^2(Q^2,\nu,z_h)\rangle|_A - \langle p_T^2(Q^2,\nu,z_h)\rangle|_D$$



eA: in medium Color Propagation and Hadron formation



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



Partonic energy losses
Increase of transverse momentum

Hadron inelastic scattering
Decrease number of obs. hadrons

Extraction of color lifetime Brooks-Lopez model

Physics Letters B 816 (2021) 136171

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Estimating the color lifetime of energetic quarks

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

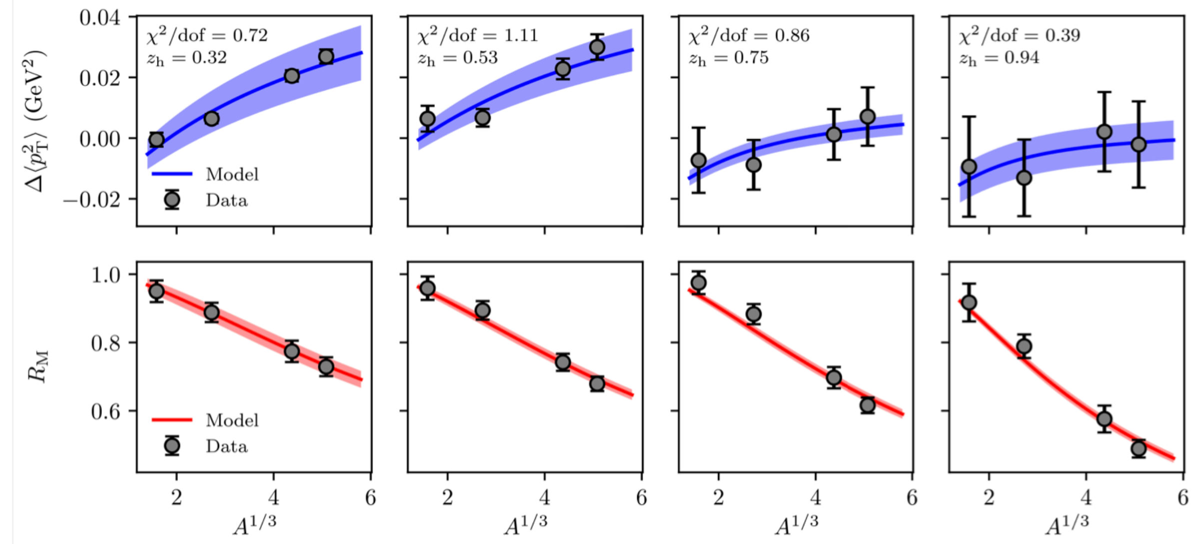
- The **color lifetime** was estimated using simultaneous fit to two observables in the **HERMES** data with 3-parameter space-time model

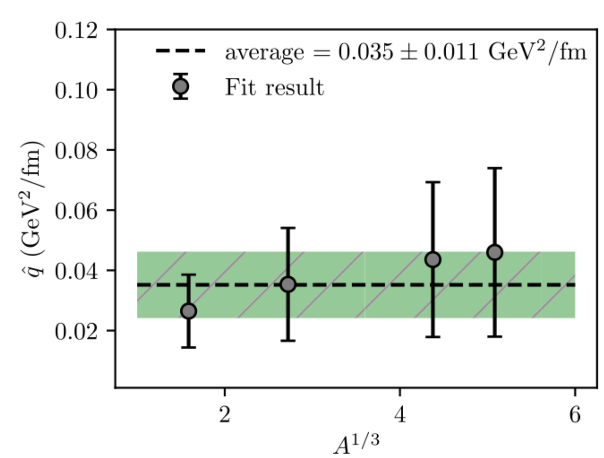
- The answer depends on the kinematics and ranges from **2 to 8 fm/c**

- Independent determination of the string constant of the LSM!

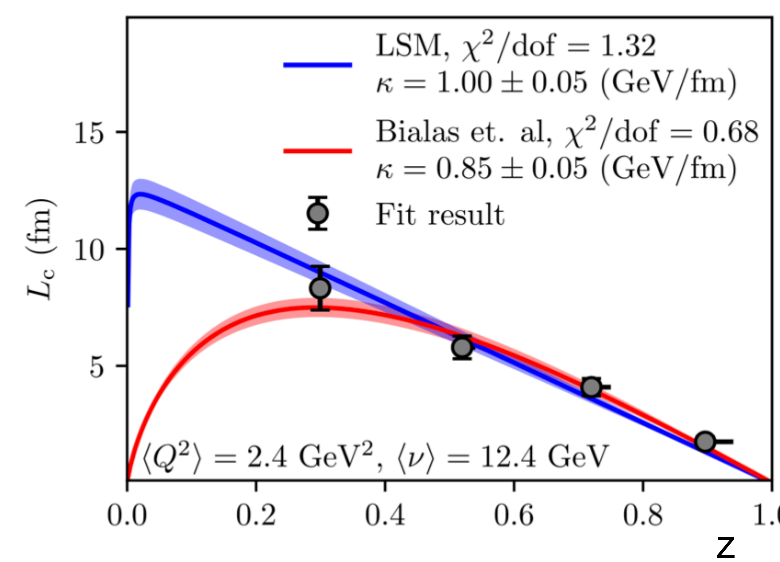
- Measurement of transport coefficient

Simultaneous fit to two observables, *ΔpT2* and *R* for charged pions



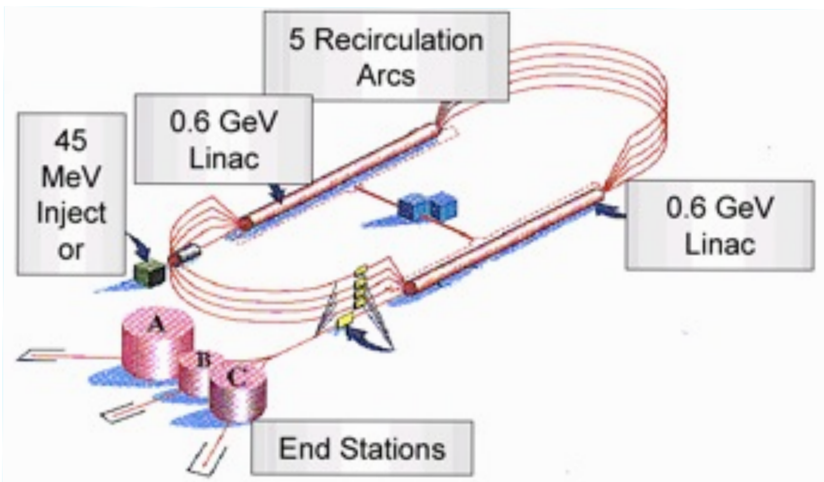


The values of the color length **L_c** resulting from simultaneous fit to *pT2* and *R*



Phys. Let. B 816 (2021) 136171
https://arxiv.org/abs/2004.07236

EG2 experiment @ 5 GEV



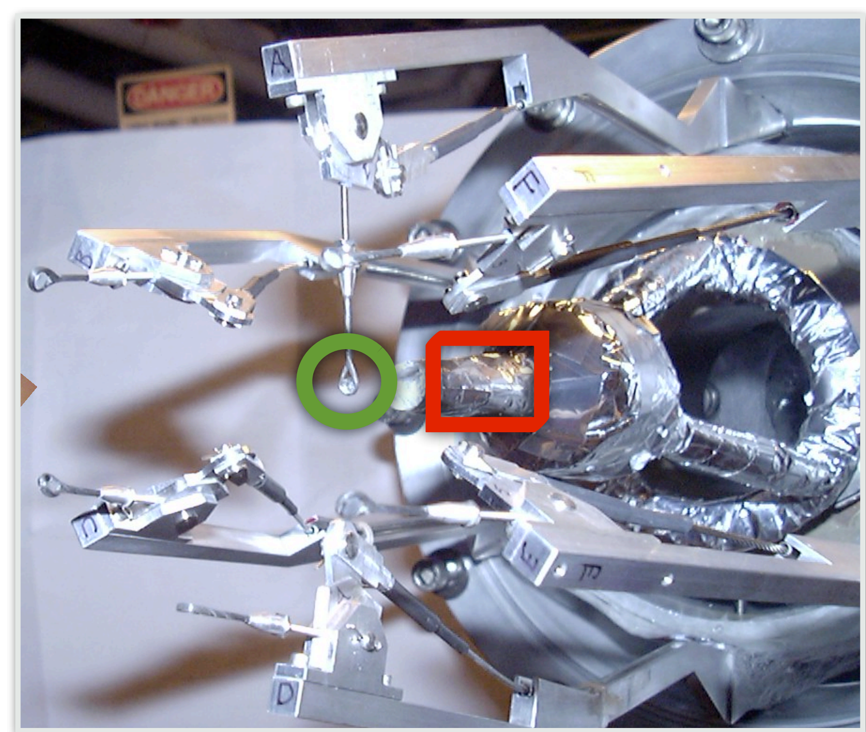
CLAS experiment at Hall B with 5 GeV electron beam

By using dual target approach, EG2 experiment makes a *precise* comparison of observables in a large nucleus ***A*** with respect to ***D***

EG2 experiment running conditions

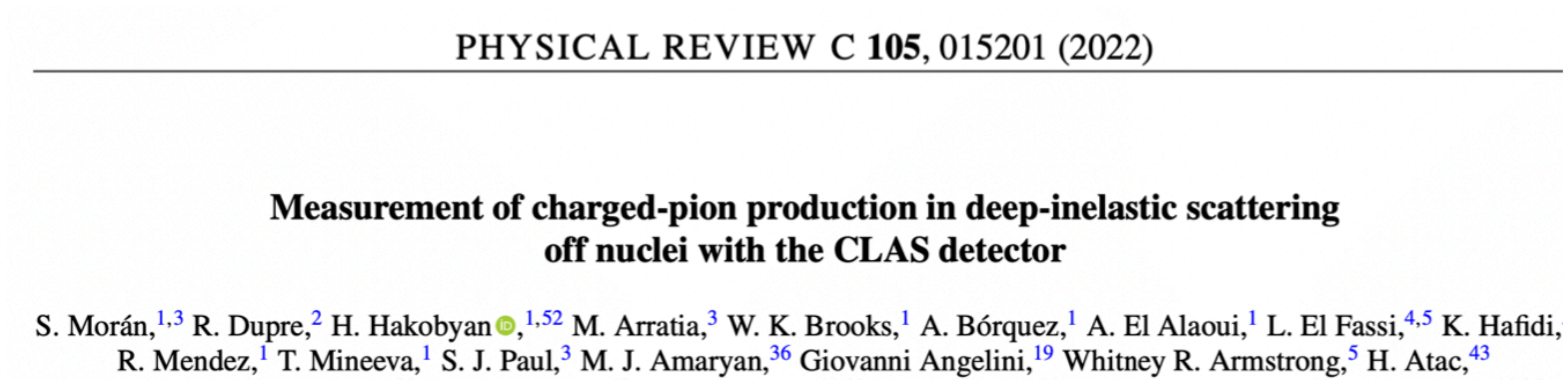
- Electron beam 5.014 GeV
- Targets ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb (Al, Sn)
- Luminosity $2 \cdot 10^{34}$ $1/(s \cdot cm^{2})$

"A double-target system for precision measurements of nuclear medium effects," H. Hakobyan et al. NIM A 592 (2008) 218– 223



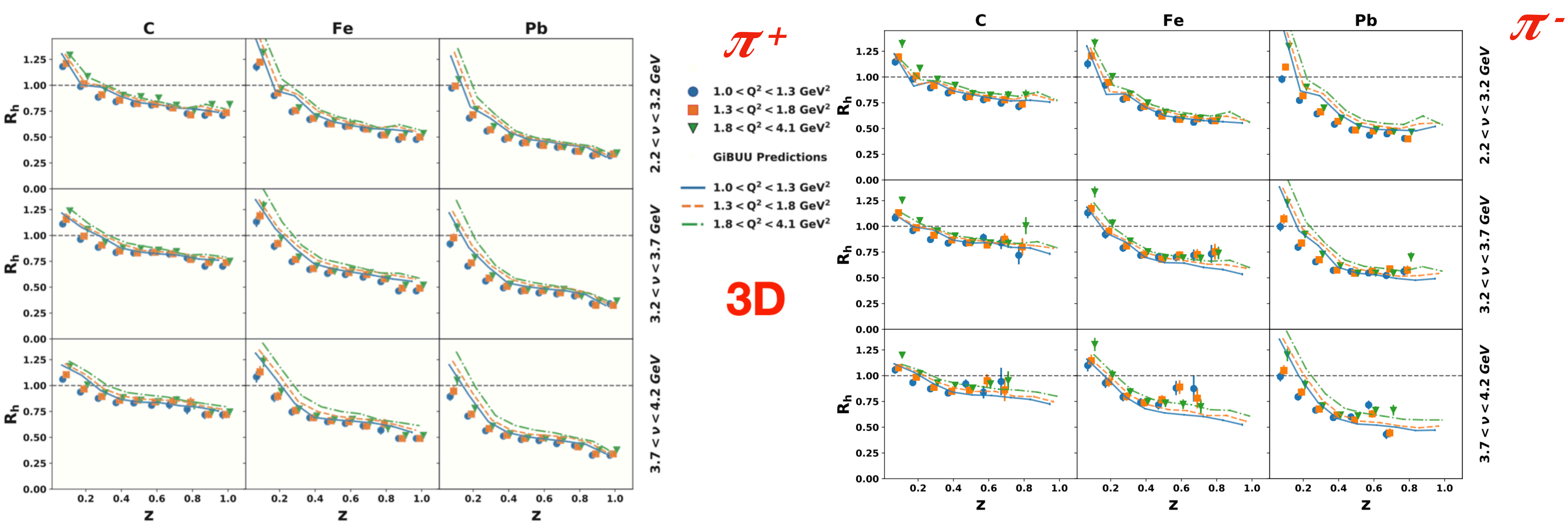
Light and heavy hadrons

Light hadrons: results from EG2


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]



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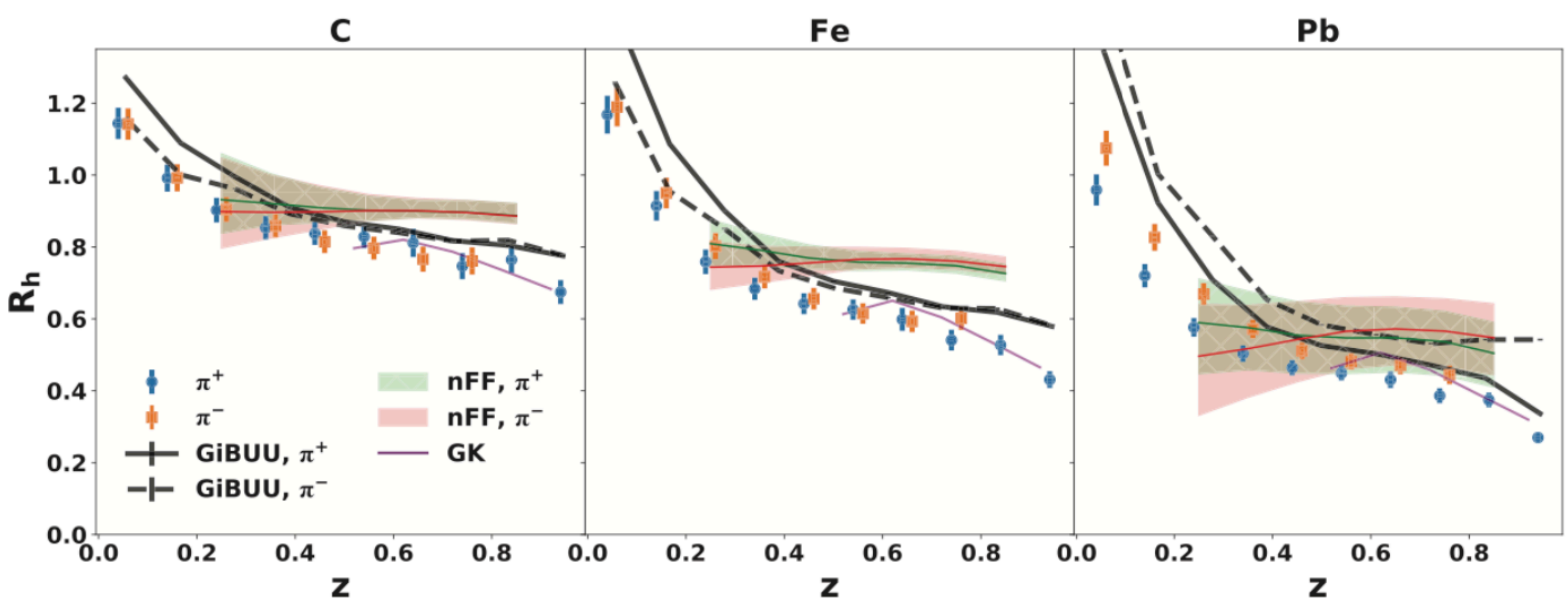
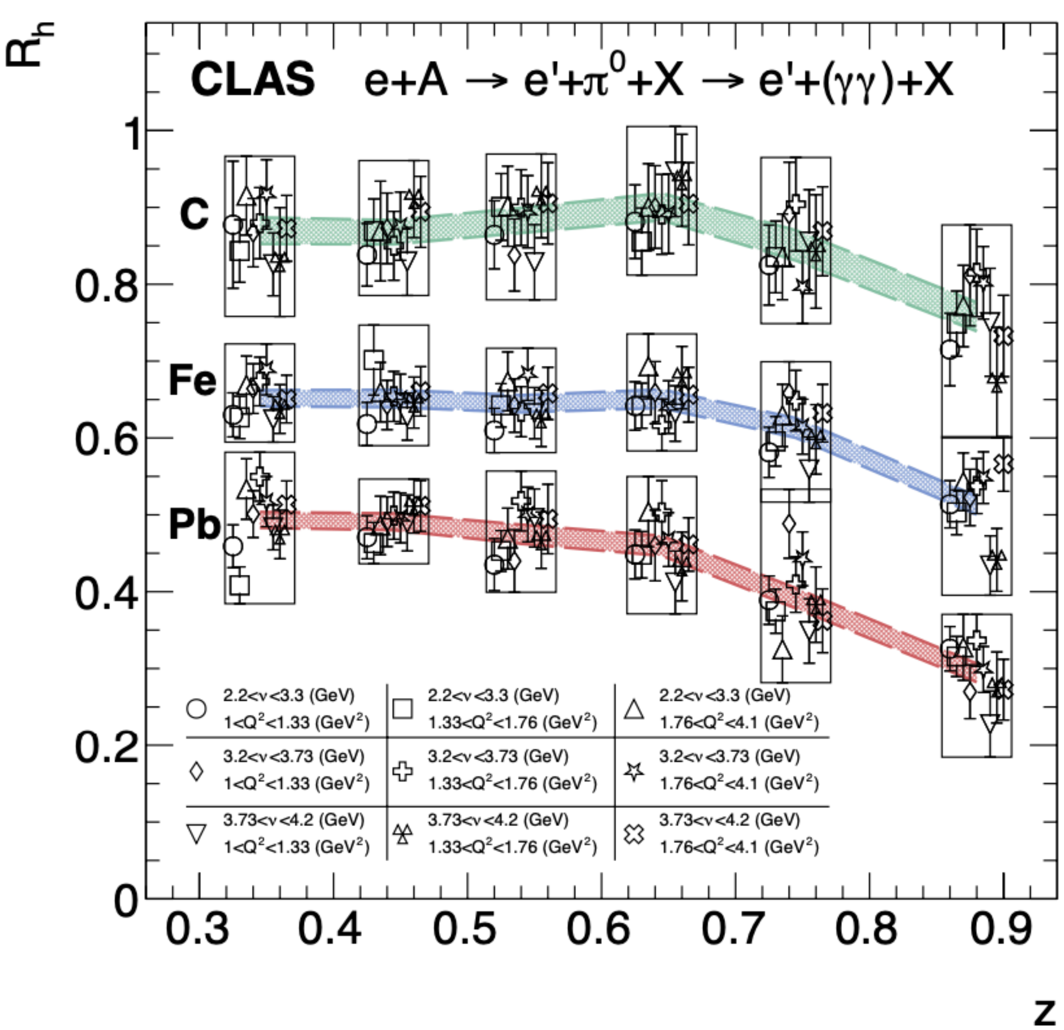


π^+
π^-

High-precision three-dimensional data is compared to the model predictions; GiBUU and Guiot-Kopeliovich models find semi-qualitative agreement

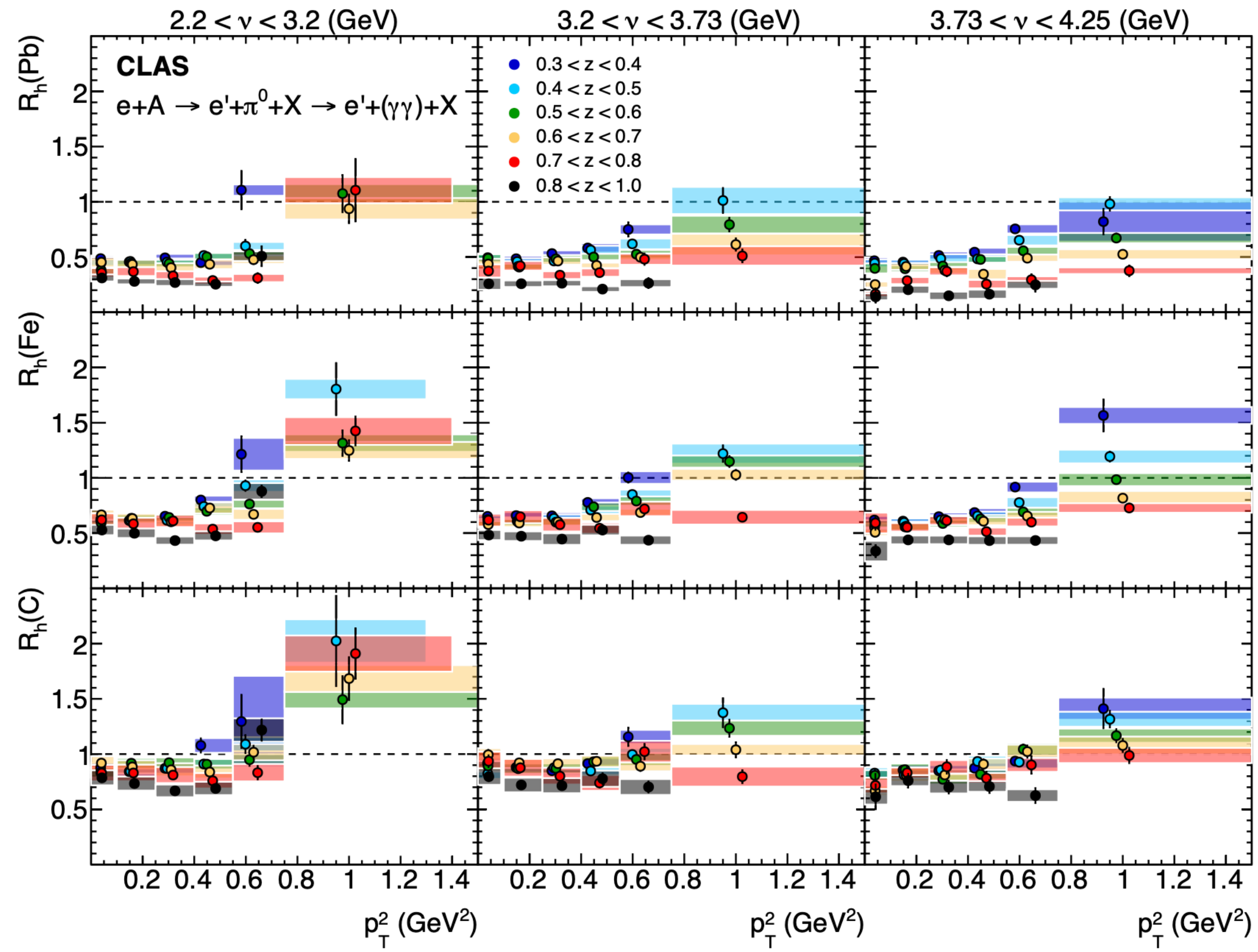
Light hadrons: results from EG2

T.Mineeva et al. CLAS approved paper.



π^0

3D

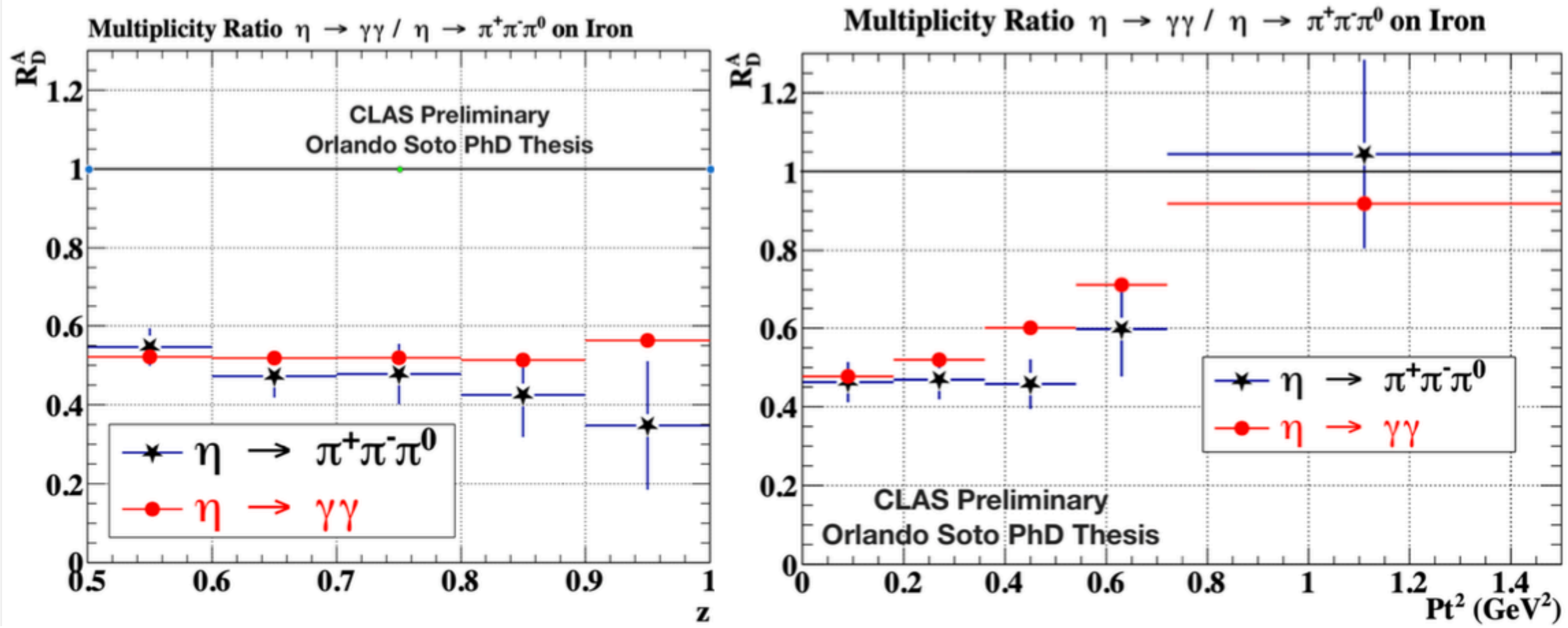


- Attenuation depends on nuclear size *A*
- Suppression for leading hadrons: 25% on C to 75% on Pb
- No dependence on Q^2 and ν observed
- Quantitative behavior compatible with Hermes

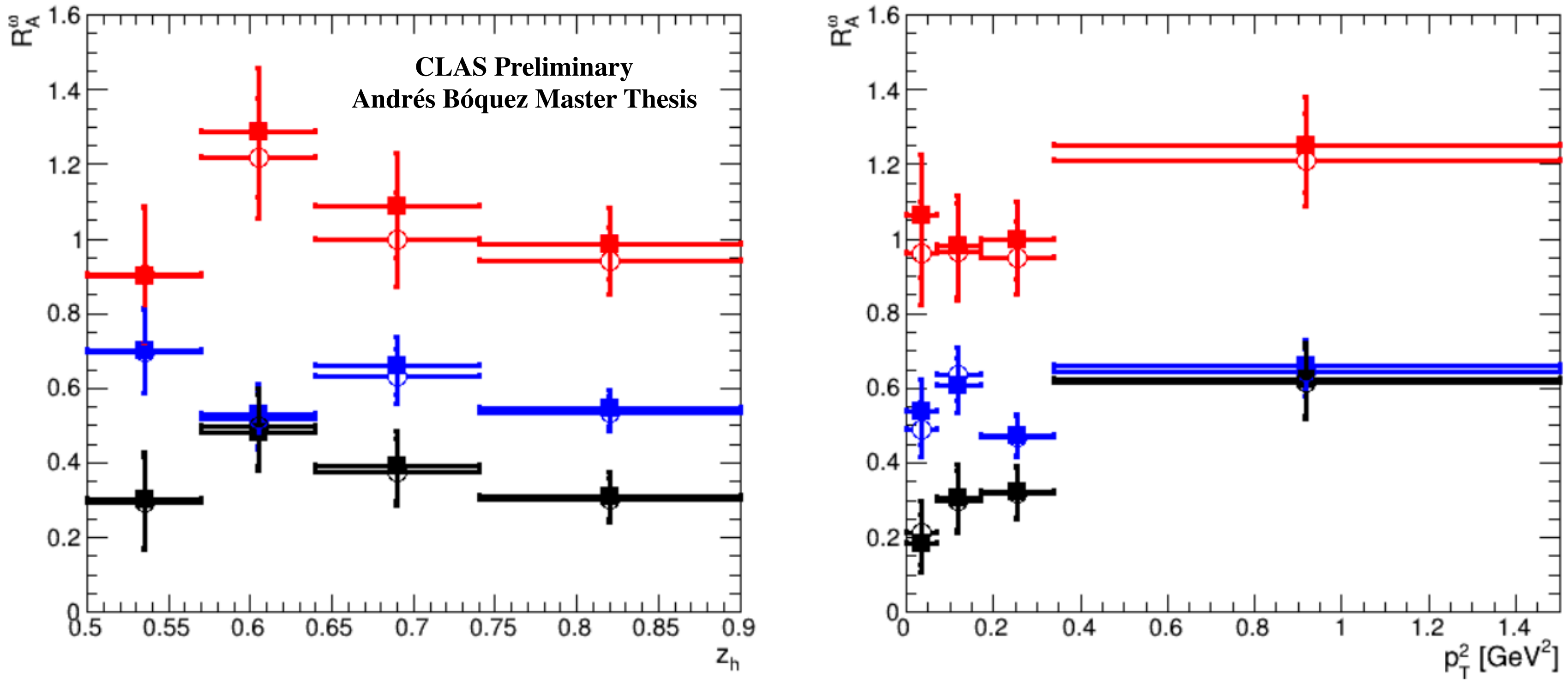
- Enhancement of $R_{\pi 0}$ at low *z* and high on *pT2*
- Largest enhancement at hight pT2 for C, lowest - for Pb
- Opposite to CLAS and HERMES data on charged pions

Light hadrons: η and ω preliminary results

η



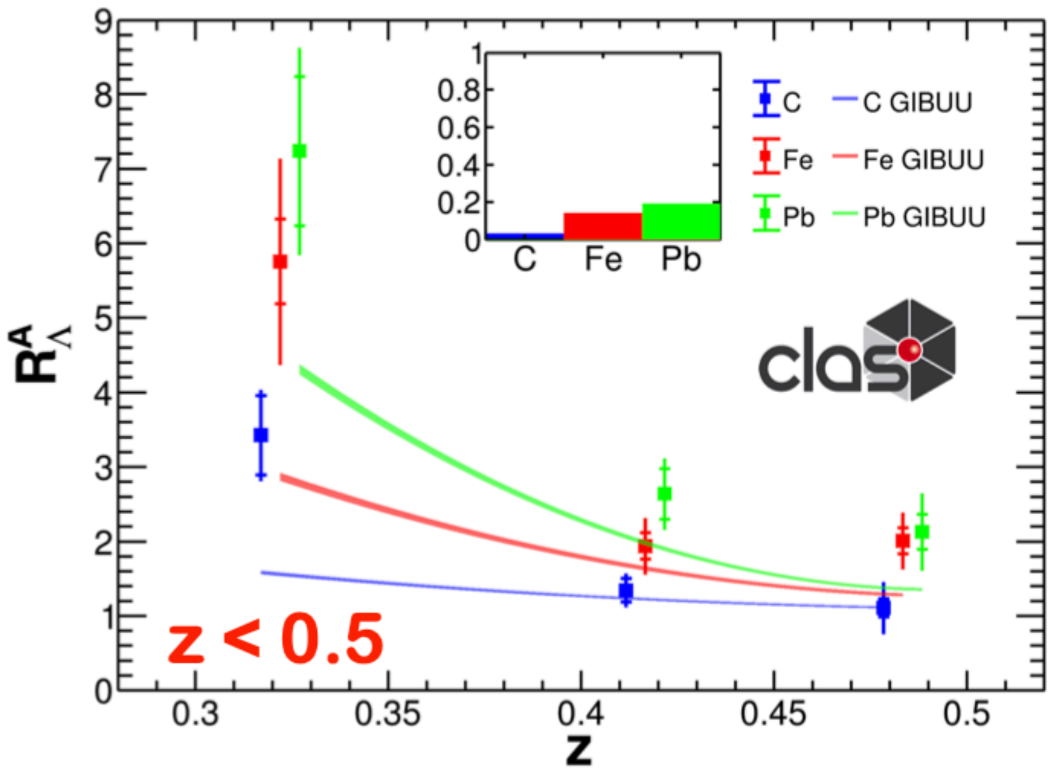
ω

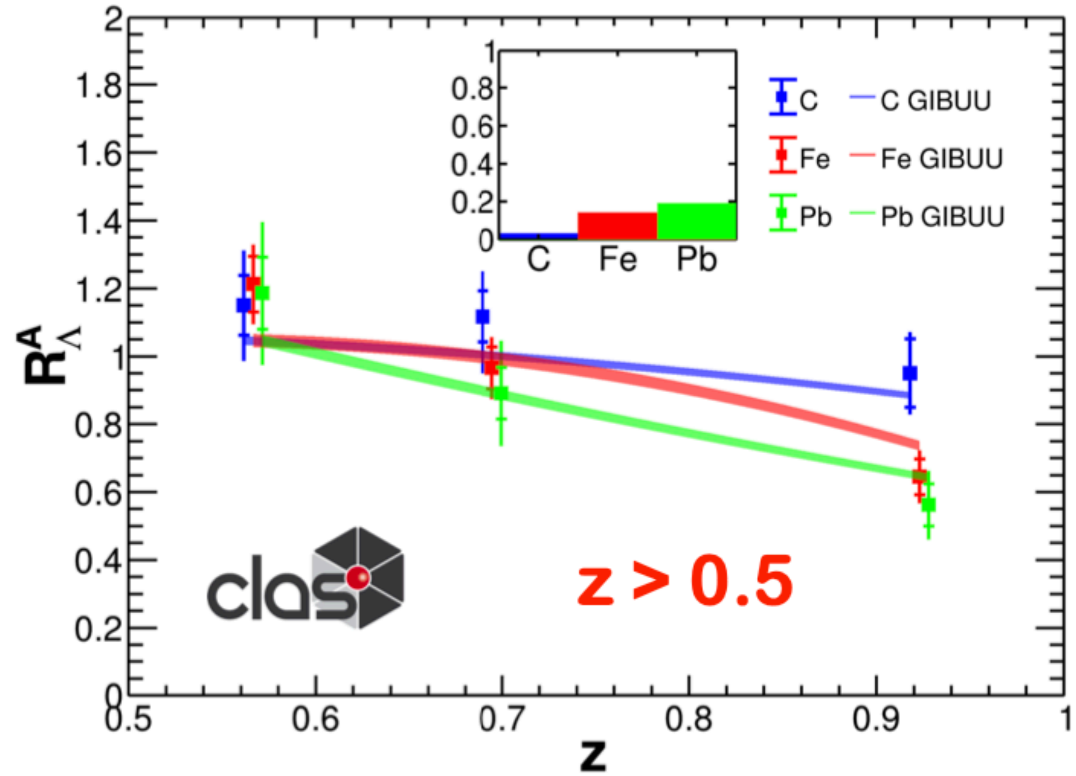


Heavy hadrons: Λ multiplicities

First Measurement of Λ Electroproduction off Nuclei in the Current and Target Fragmentation Regions

T. Chetry *et al.* (CLAS Collaboration)
Phys. Rev. Lett. **130**, 142301 – Published 4 April 2023

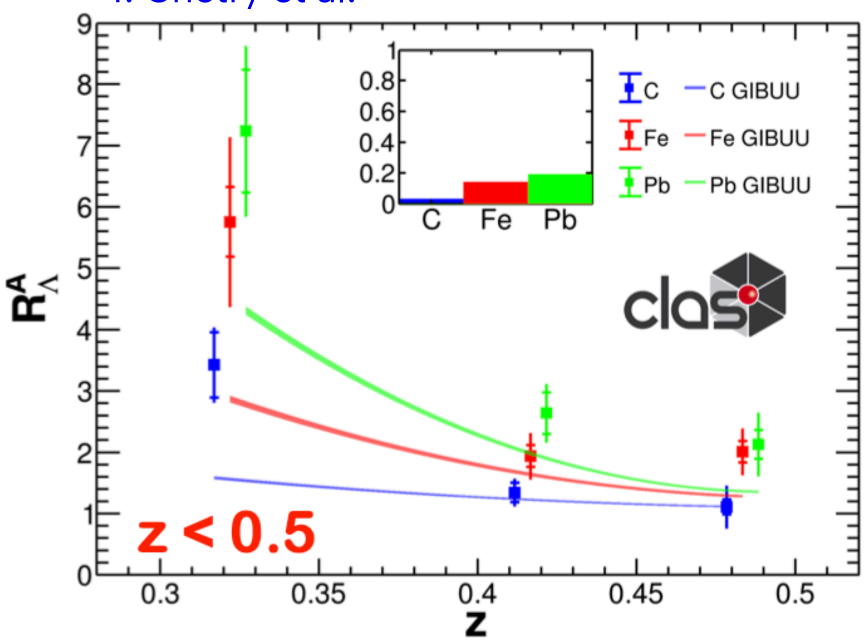


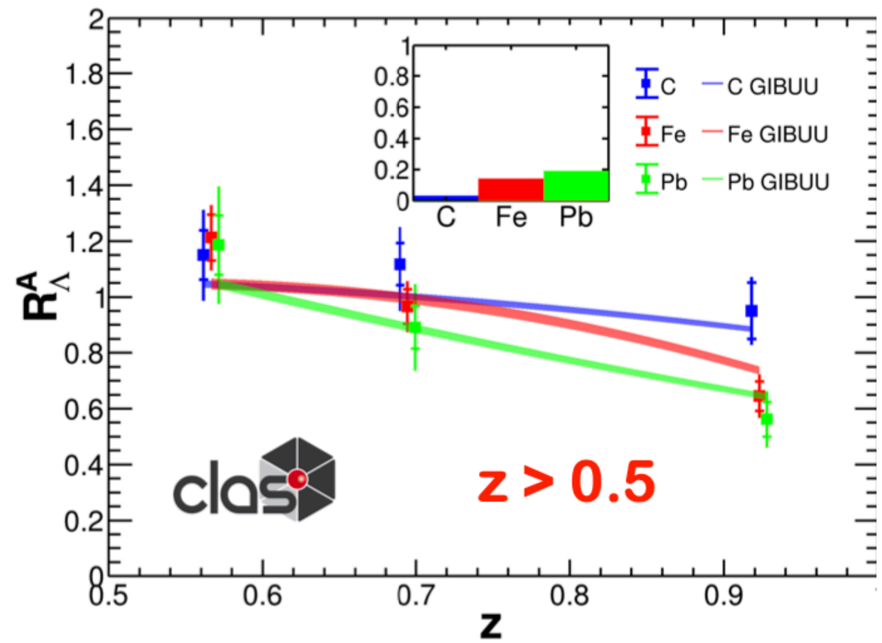


- At low-z there is a “pile up” of events 7 times more than for pion! Underpredicted by GiBUU.
- At high-z there is little attenuation compared to that on the pion. Agrees with GiBUU.

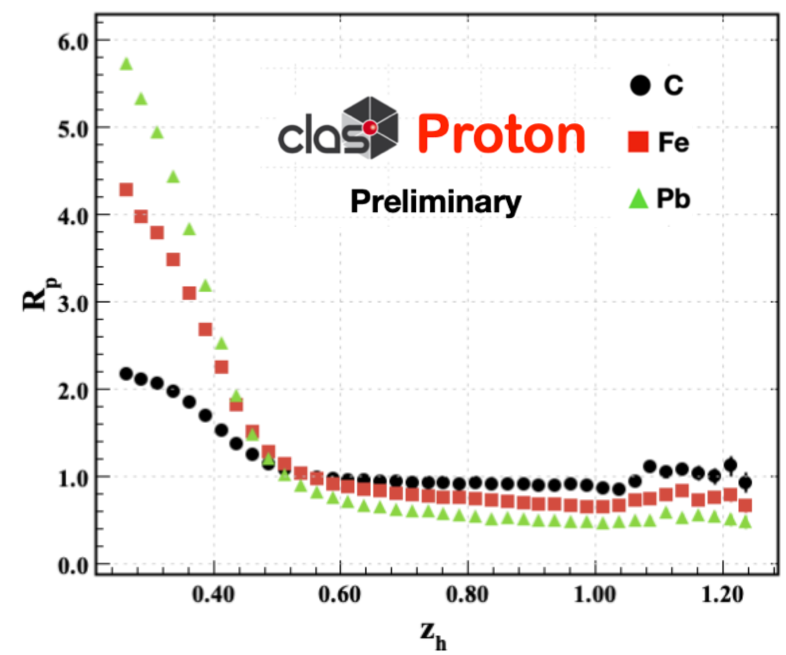
Results from EG2: comparing Λ and p multiplicities

T. Chetry et al.





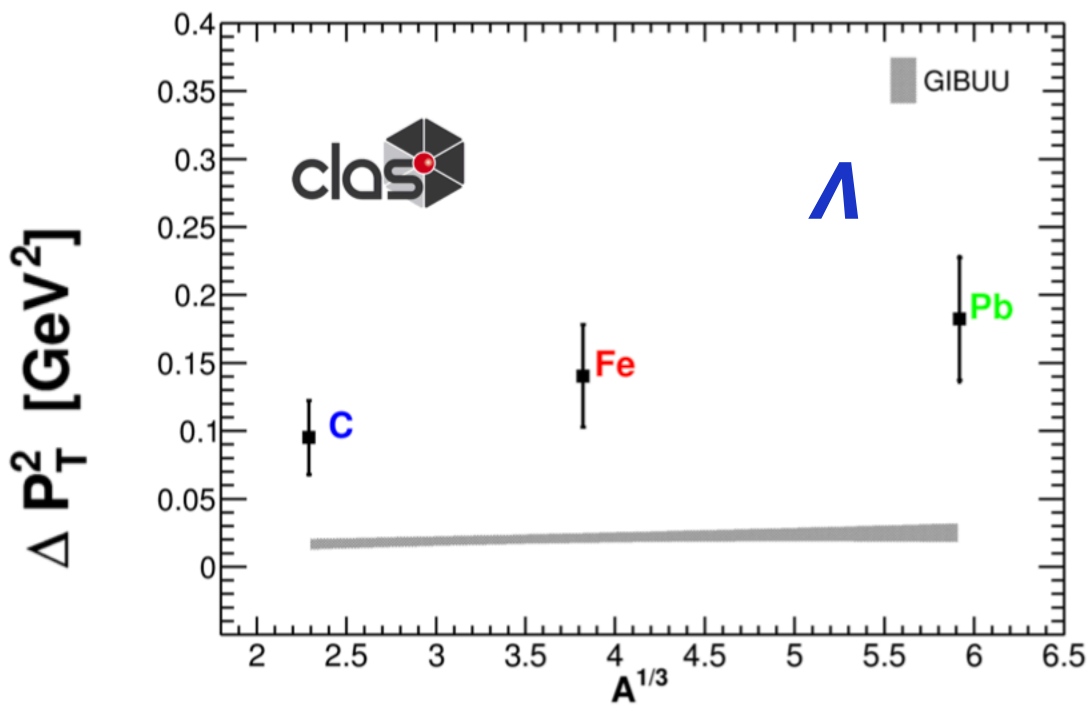
M.Wood



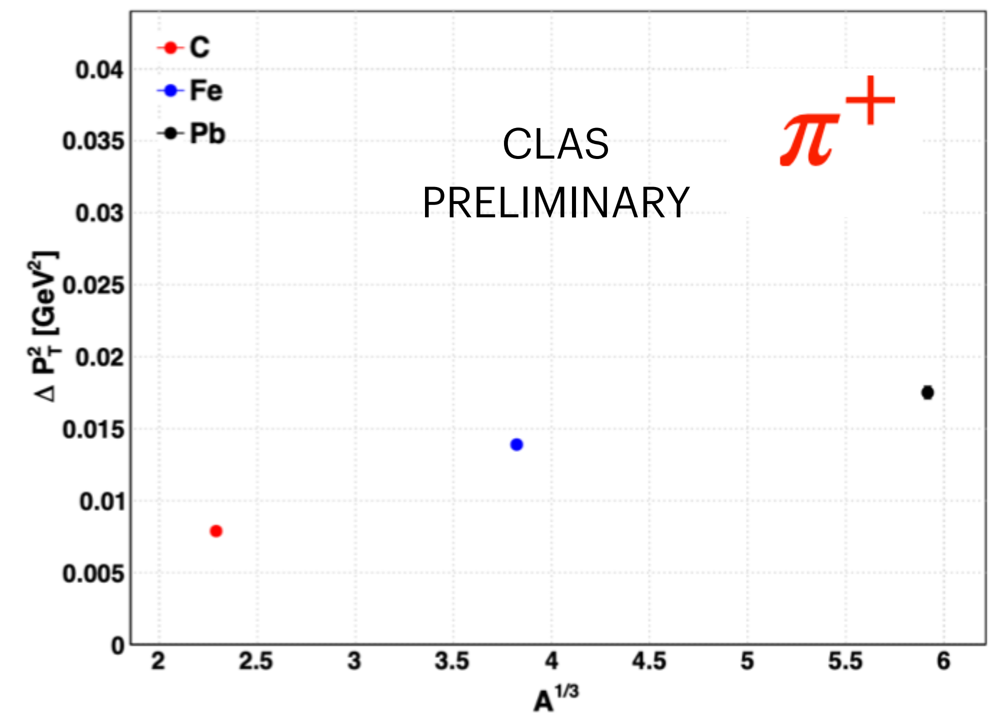
The multiplicity ratio for the lambda and the proton have similar magnitude and the same pattern of ordering at low and high z

Results from EG2: Λ and π⁺ pT broadening

T. Chetry *et al.* (CLAS Collaboration)
Phys. Rev. Lett. **130**, 142301 – Published 4 April 2023



E.Molina Thesis
https://repositorio.usm.cl/handle/11673/53373



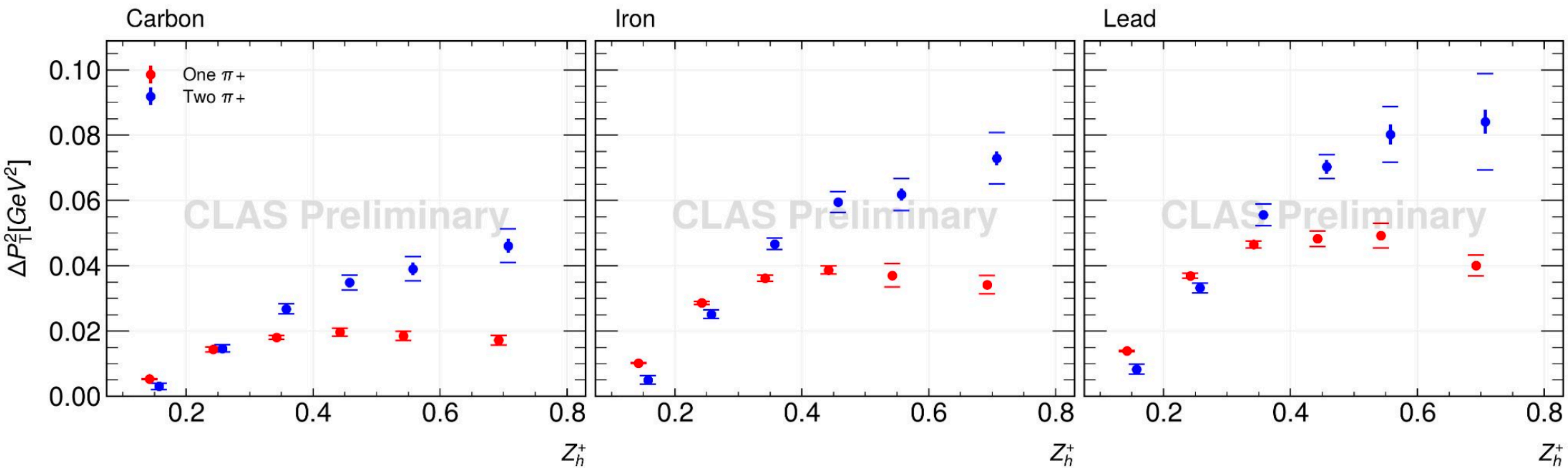
Maximum for **Λ** is 0.3 GeV^2

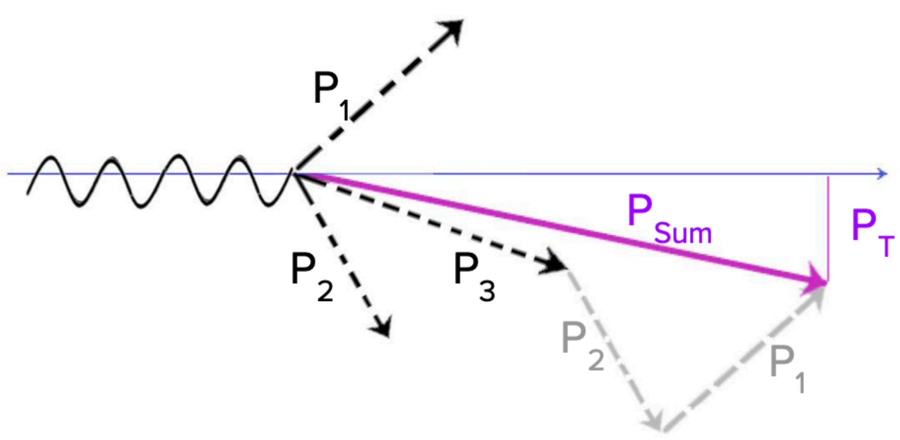
Maximum for π⁺ of 0.03 GeV^2

GiBUU cannot predict pT-broadening observable. We apparently do not have the correct physical picture in the case of baryon hadronization.

pT broadening for multiple π^+ events

M.Barría Thesis
https://repositorio.usm.cl/handle/11673/56688





The pT broadening is larger for two pion events for $Z_h > 0.3$ and this difference increases with Z_h

Bose Einstein correlations ($\pi^+\pi^+$)

What are the properties of produced particles in the collision, such as their source size and lifetime?

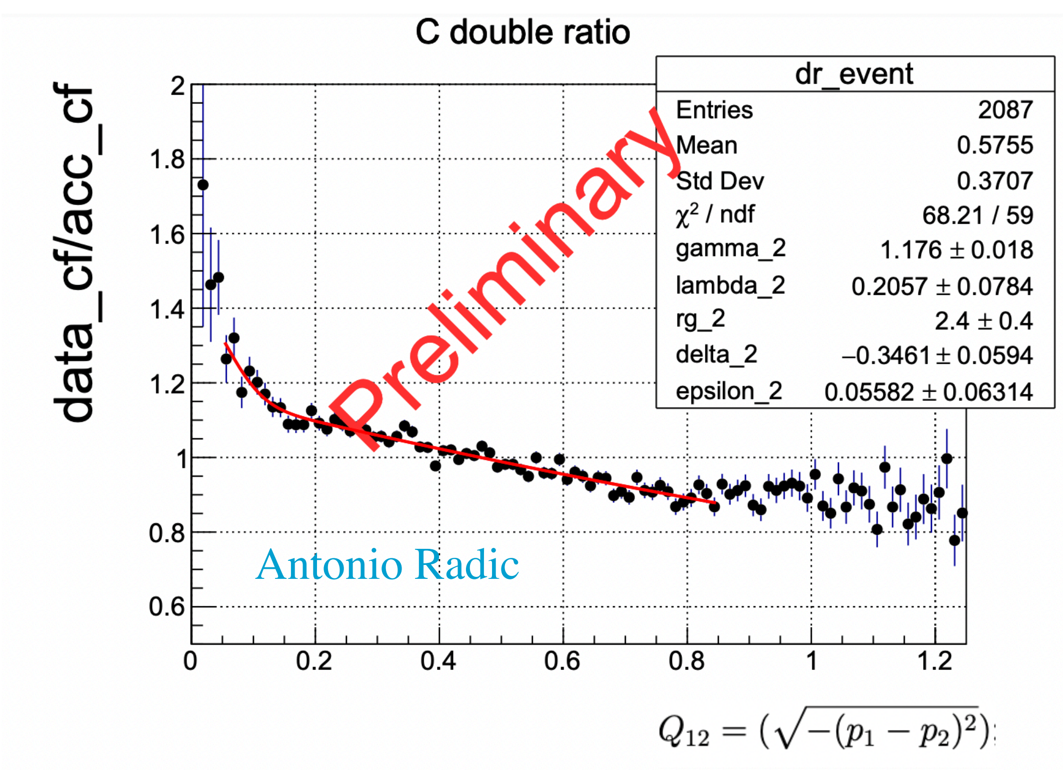
Experimentally constructed BEC correlation

$$R_{(p_1,p_2)} = \frac{D(p_1,p_2)}{D_b(p_1,p_2)}$$

Db(p1, p2) - background distribution from uncorrelated pion pairs that behave as D(p1), D(p2)

Double ratio correction: correct experimental systematic biases found in the correlation function $R(p_1,p_2)$

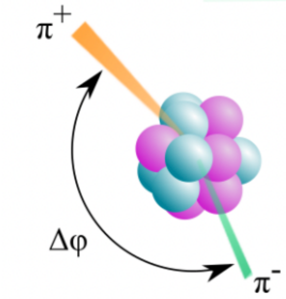
$$R(Q_{12}) = \left(\frac{D(Q_{12})}{D(Q_{12})_{mix}}\right)^{data} / \left(\frac{D(Q_{12})}{D(Q_{12})_{mix}}\right)^{simul}$$



Target	r [fm]	λ
C	2.64 ± 0.51	0.19 ± 0.09
Fe	2.79 ± 0.32	0.40 ± 0.11
Pb	2.43 ± 0.49	0.35 ± 0.14

https://www.jlab.org/Hall-B/general/thesis/ARadic_thesis.pdf

Dihadron correlations



How various hadrons produced in scattering event are correlated with each other?

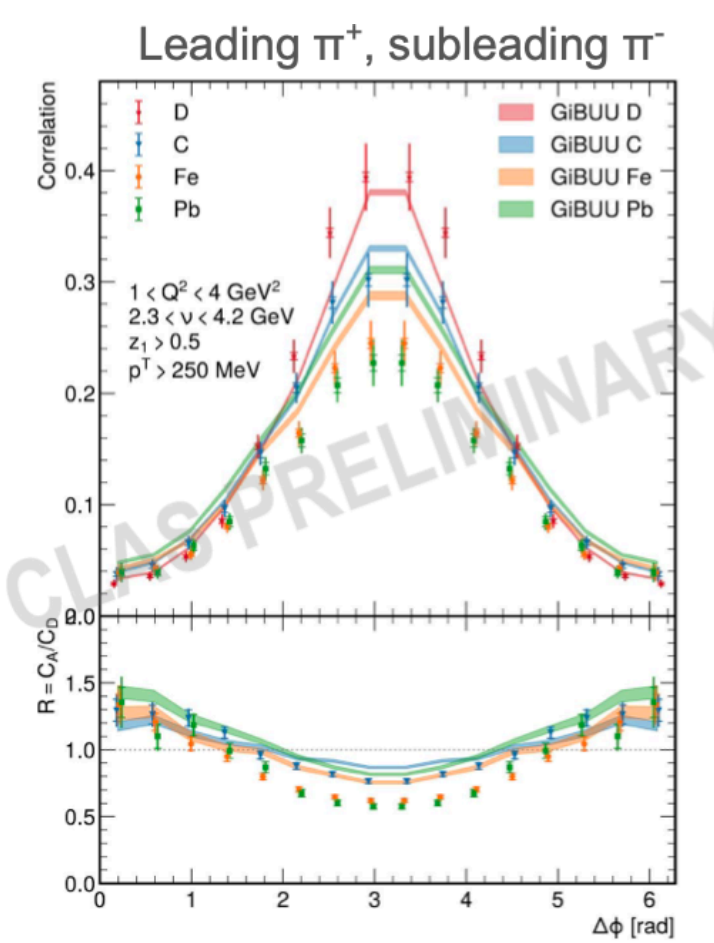
$$C(\Delta\phi) = C_0 \frac{1}{N_{eh}} \frac{dN_{ehh}}{d\Delta\phi}$$

Δφ is the difference in azimuth

N_{eh} is the number of events with scattered *e* and a "leading *h*" (z>0.5)

N_{ehh} is the number of "subleading hadrons" in those events

C_0 is the normalization factor



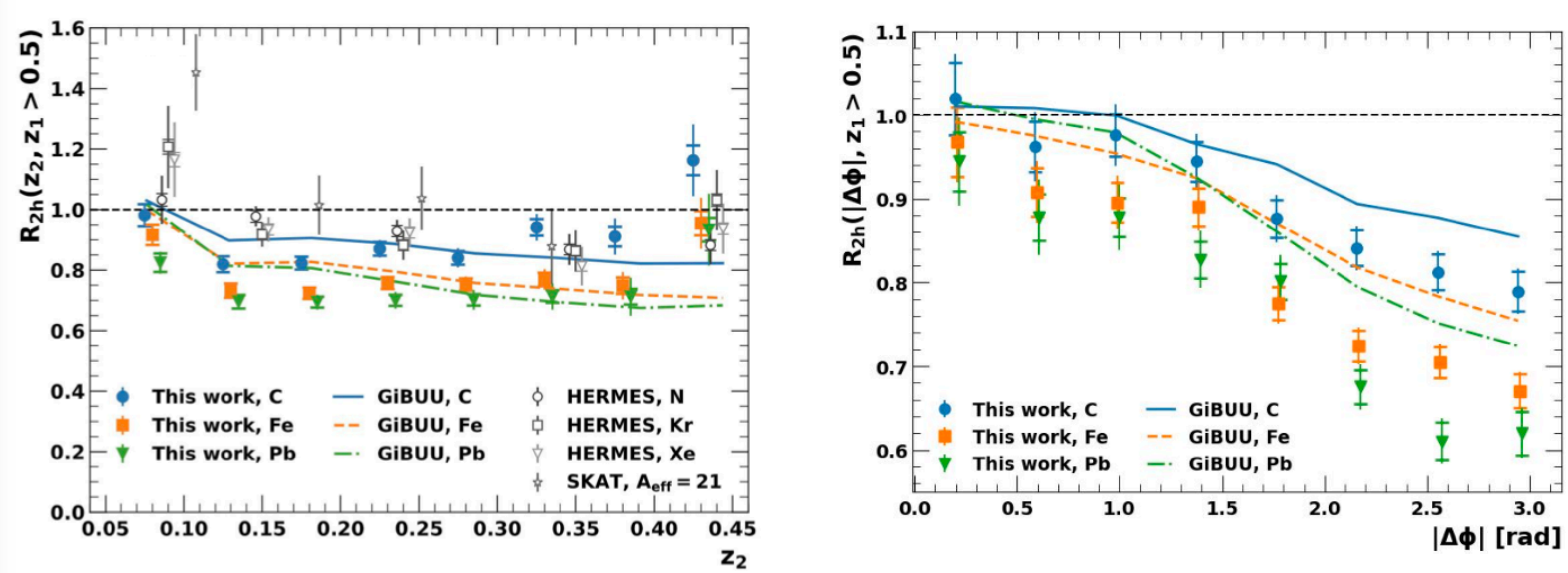
S.J Paul et al, in CLAS ad-hoc review

Observation of Azimuth-Dependent Suppression of Hadron Pairs in Electron Scattering off Nuclei

S. J. Paul *et al.* (CLAS Collaboration)
Phys. Rev. Lett. **129**, 182501 – Published 25 October 2022

Conditional suppression factor, R2h, as a function of sub-leading hadron z:

$$R_{2h}(z_2) = \frac{(dN^A_{2h}(z_2)/dz_2)/N^A_h}{(dN^D_{2h}(z_2)/dz_2)/N^D_h}$$



Diquarks search

Diquarks: recent comprehensive review

ELSEVIER

Progress in Particle and Nuclear Physics
Volume 116, January 2021, 103835

Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6 7], E. Cisbani [8], M. Ding [9], G. Eichmann [10 11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15 12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18 19], P. Rossi [12 20], G. Salmé [21]…
B.B. Wojtsekhowski [12]

https://doi.org/10.1016/j.ppnp.2020.103835
https://arxiv.org/pdf/2008.07630.pdf

Diquark correlations seem to exist in QCD. They date back to the foundations of quark model and are an important ingredient in hadron structure.

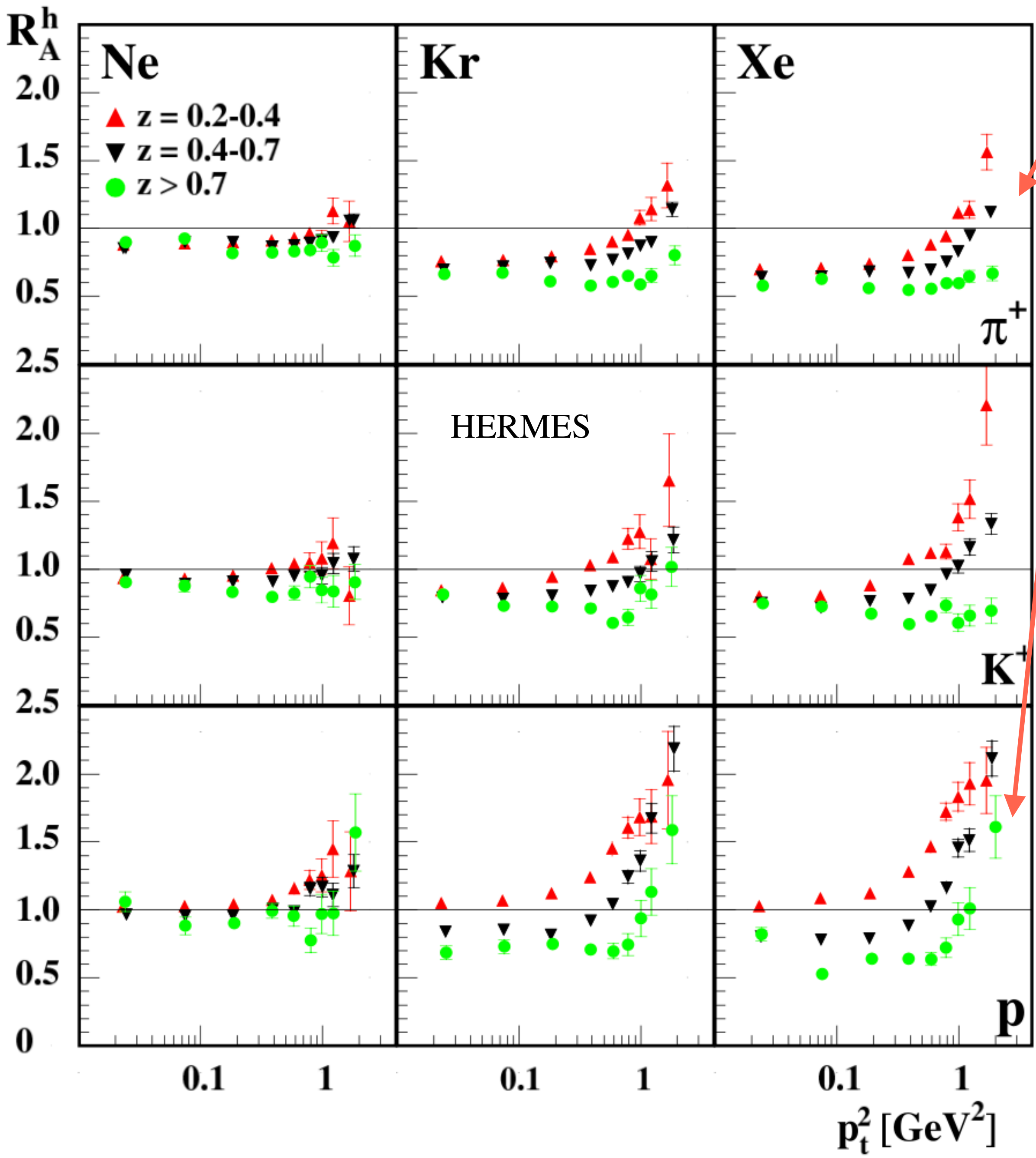
<u>But how to consistently describe it through experiment?</u>

Diquark properties from full QCD lattice simulations: https://link.springer.com/article/10.1007/JHEP05(2022)062

Diquark mass differences from unquenched lattice QCD: https://iopscience.iop.org/article/10.1088/1674-1137/40/7/073106/pdf

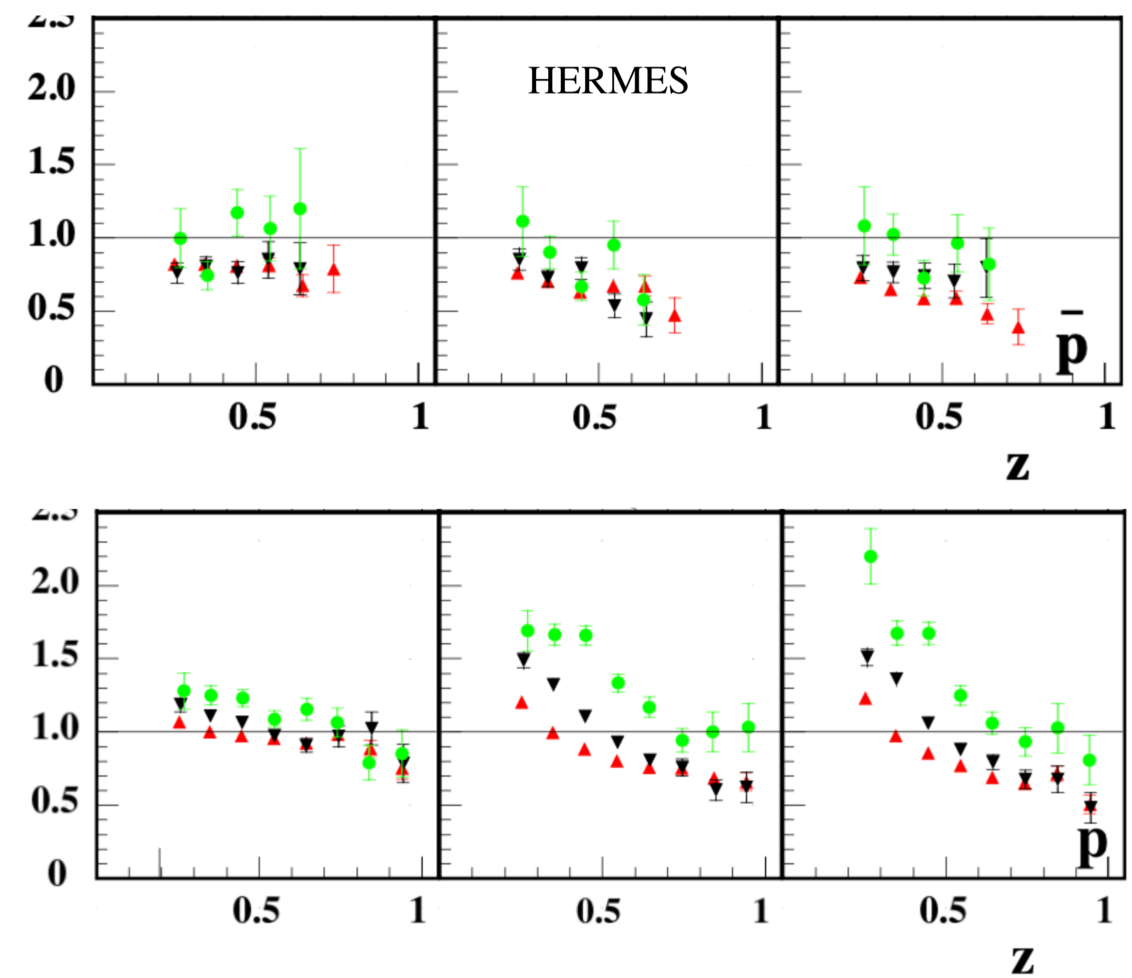
Diquarks: mesons vs baryon behavior

Baryon nDIS data from HERMES and CLAS behave qualitatively differently from mesons, in multiplicity ratios and in transverse momentum broadening



Ordering seen for mesons at high pT disappears for baryons, strong interaction occurs for all values of z

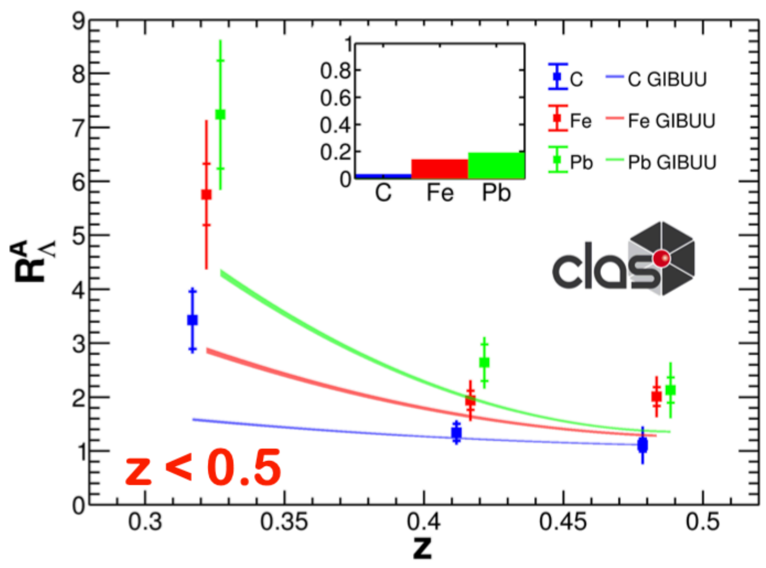
Proton and antiproton are totally different!

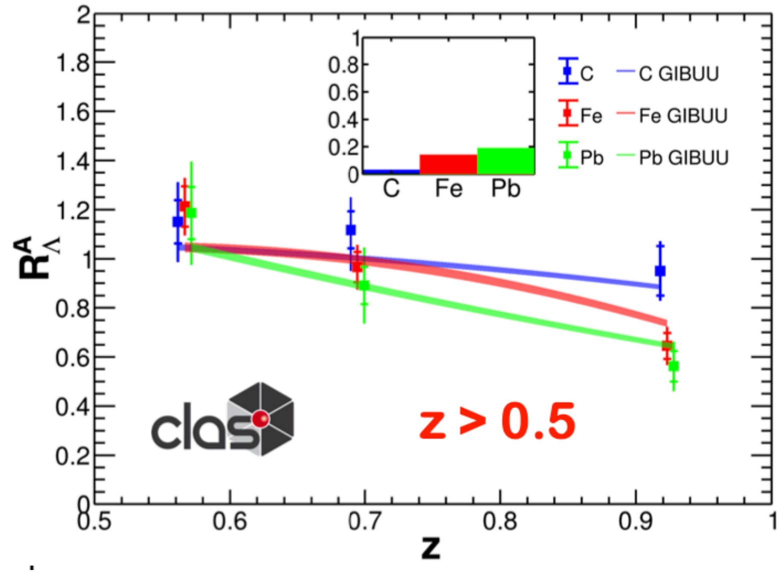


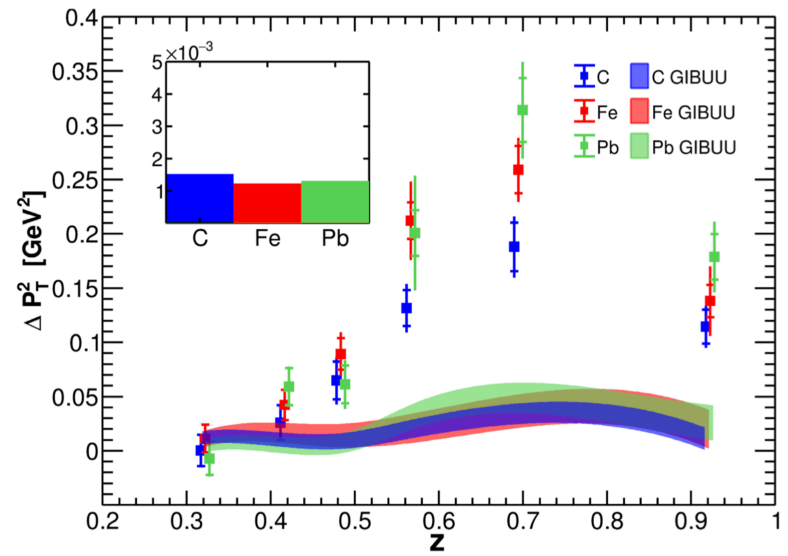
arXiv:1107.3496v3 [hep-ex] 13 Sep 2011
Eur. Phys. J. A47:113, 2011

Diquarks: mesons vs baryon behavior

T. Chetry *et al.* (CLAS Collaboration)
Phys. Rev. Lett. **130**, 142301 – Published 4 April 2023







Enhancement of Λ events at low z is huge compared to pion production: 7 vs. ~1.0

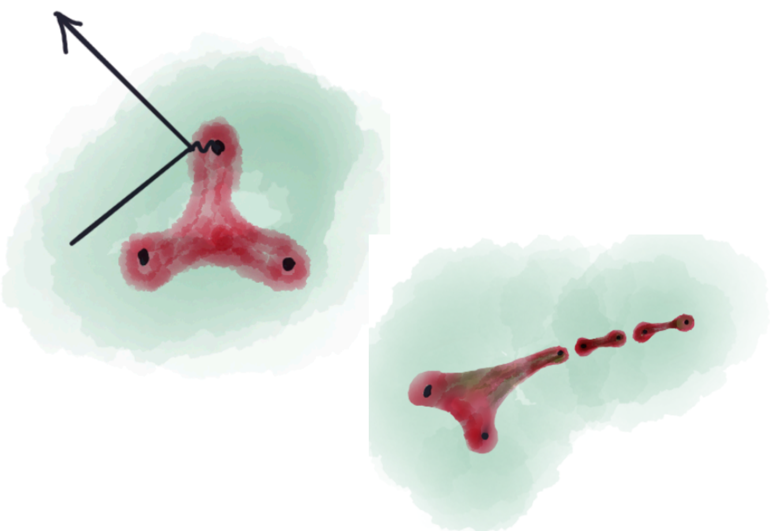
Less attenuation at high z

ΔpT2 on Λ is huge compared to pion: 0.3 vs 0.03 GeV²

The object passing through the medium in case of Λ is 'large' and disruptive!

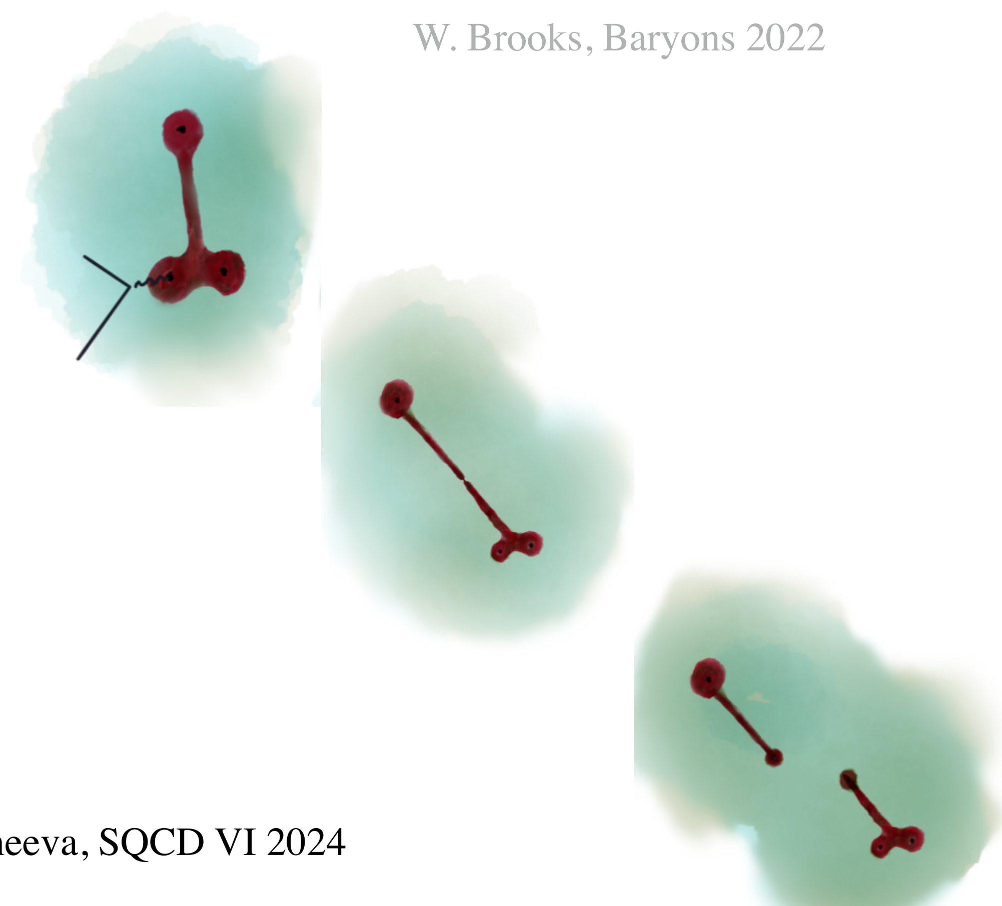
Could it be possible that a virtual photon is absorbed by a diquark?

Traditional picture



Alternative: direct diquark scattering

W. Brooks, Baryons 2022



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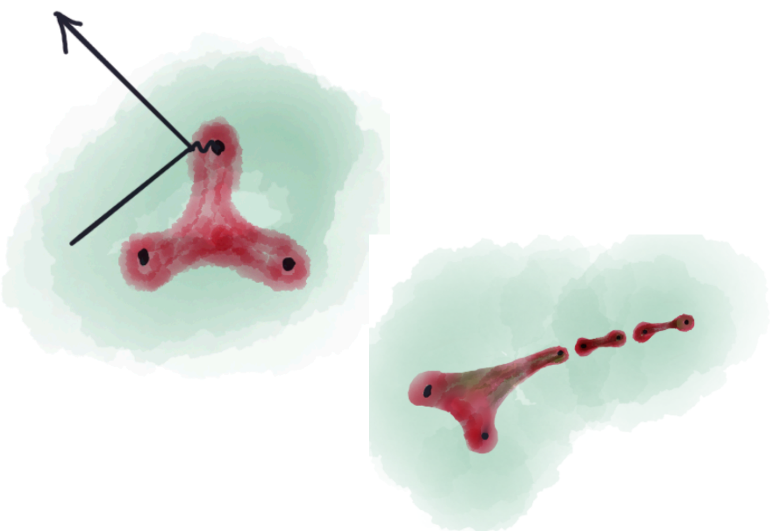
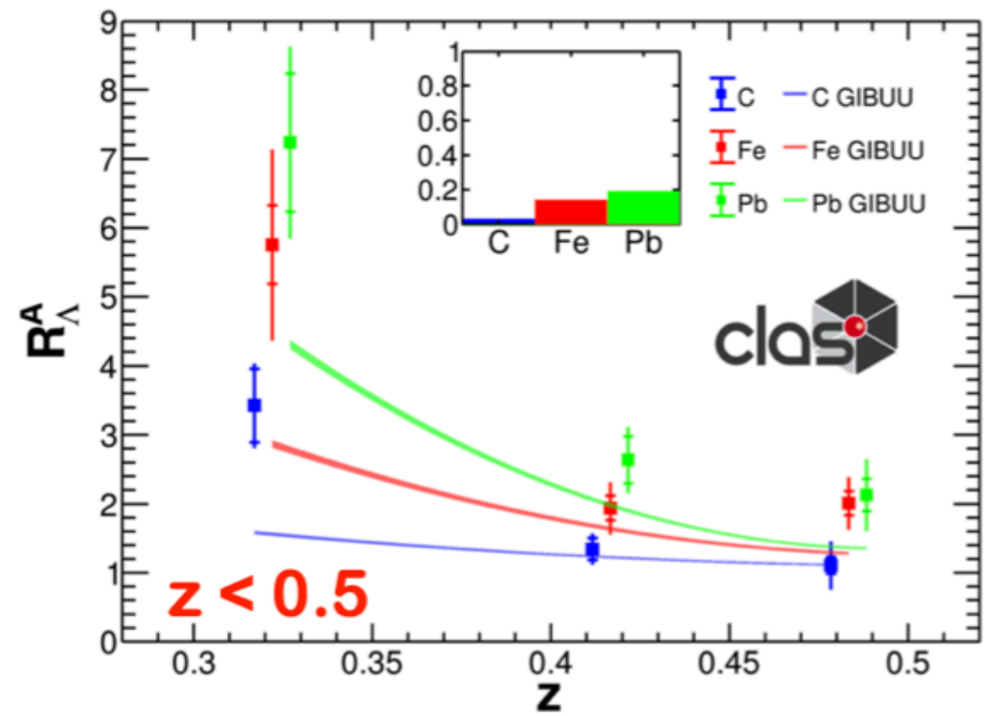
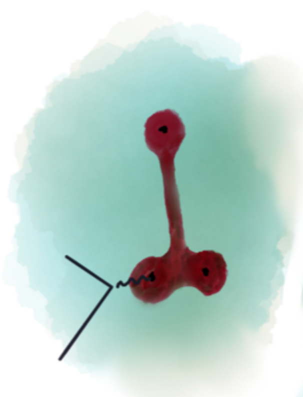
Traditional picture

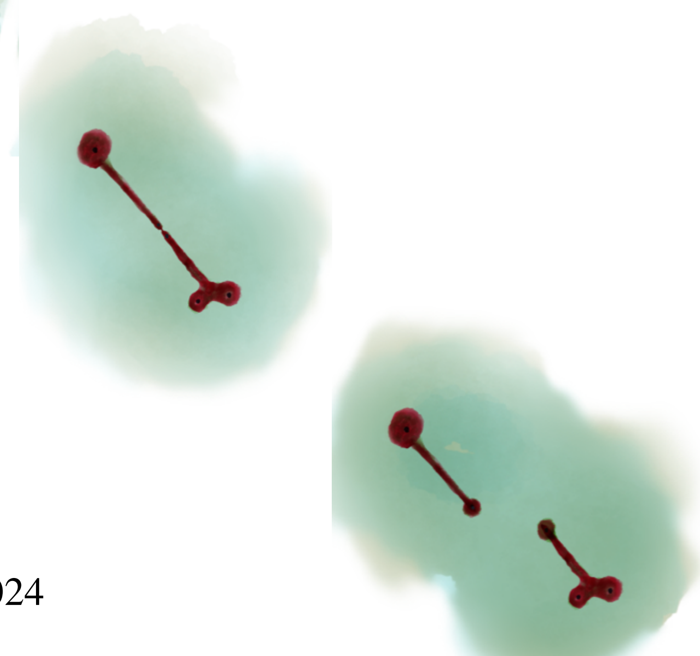


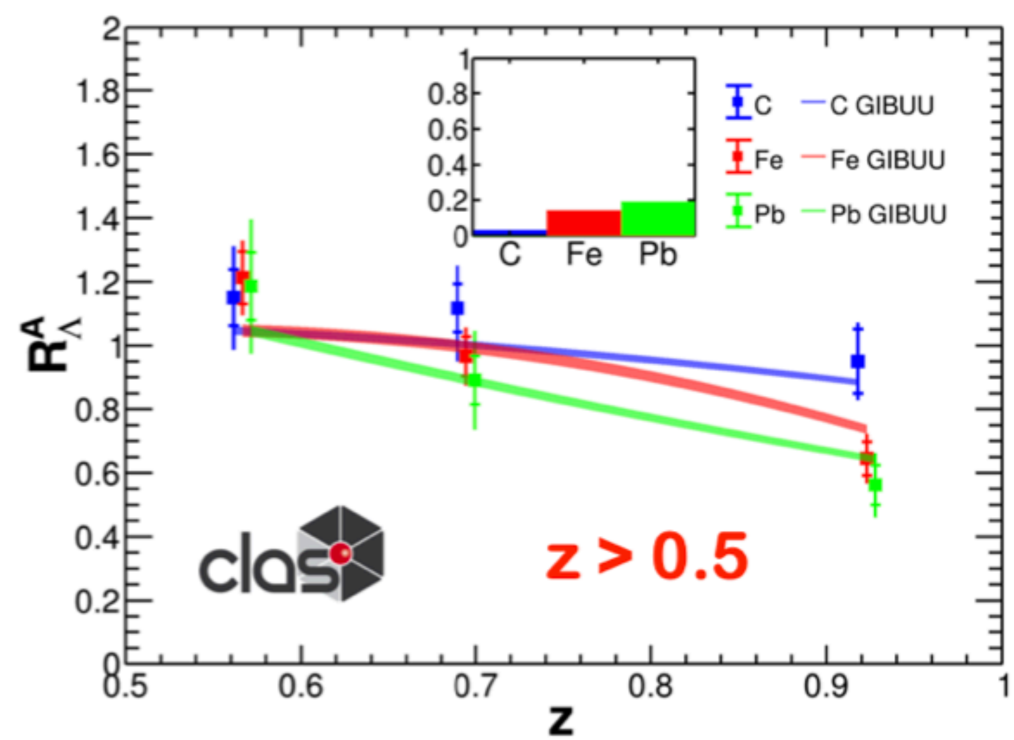


Alternative: direct diquark scattering

W. Brooks, Baryons 2022







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

Baryon	$M^{e/l}$	M^{CI}	dom. corr.
p (B.5a)	0.94	0.94	$[ud]u$
Λ (B.5b)	1.12	1.06	$[ud]s$
Σ (B.5c)	1.19	1.20	$[us]u$
Ξ (B.5d)	1.32	1.24	$[us]s$

Phys. Rev. D 100, 034008 (2019)

Protons, neutrons and Λ can be easily formed by the scattering off diquark; they must then behave similarly
This can be soon testes tested on CLAS and CLAS12 data.

More theoretical work is needed to determine the feasibility of this interpretation and distinguish it from other hadronization mechanisms (e.g, color recombination)

eA Monte Carlo generators

GiBUU

Giessen Boltzmann-Uehling-Uhlenbeck (equation)

- EMC, HERMES, CLAS data
- Describes the time evolution of the reaction based on the transport theory
- LUND string fragmentation (Pythia)
- Hadron absorption cross sections
- Final-state interactions
- Color transparency
- Nuclear shadowing
- Particle tracking

gibuu.hepforge.org
https://arxiv.org/pdf/2202.12804.pdf

BeAGLE

Benchmark eA Generator for LEptoproduction

- CLAS dihadron data, E665, predictions for EIC
- Hybrid, multistep model
- Hard interaction, jet fragmentation (Pythia6)
- Parton energy loss (PyQM)
- Intranuclear cascade, nuclear geometry (DPMJet)
- Nuclear response (DPMJet/FLUKA)
- Nuclear parton distribution functions (LHAPDF5)

https://arxiv.org/abs/2204.11998

eHIJING

Event Heavy-Ion Jet Interaction Generator

- NEW! CLAS, HERMES, EMC, predictions for EIC
- Parton medium interaction ~ gluon TMD
- Lund string fragmentation is applied to the colorless system

https://arxiv.org/abs/2304.10779

Jefferson Lab @ 12 GeV era

RG-E experiment @ 10.5 GEV

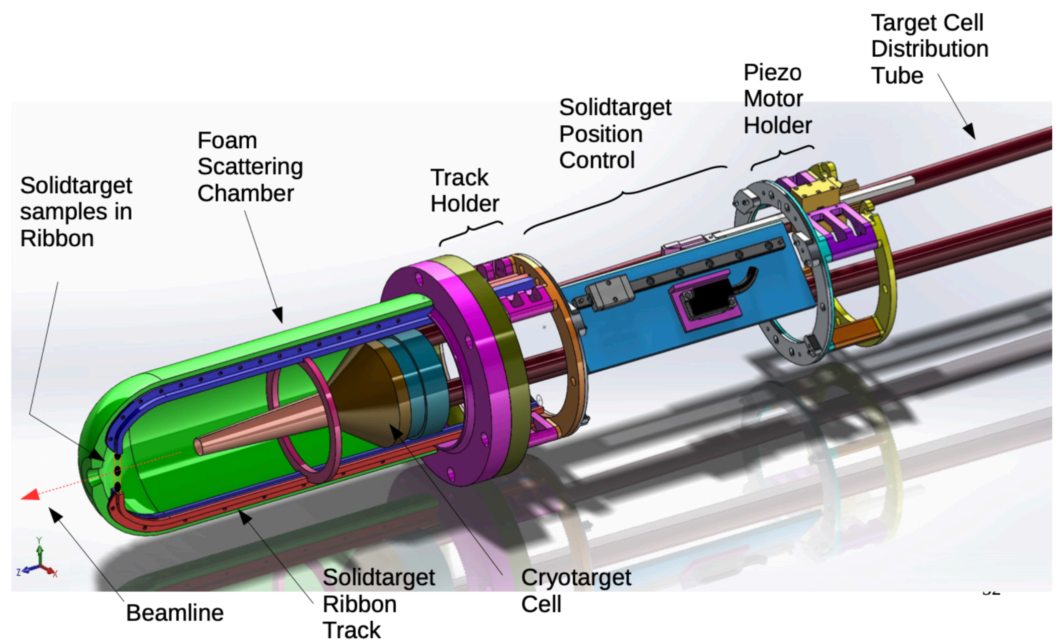
Approved experiment Run Group E (E-12-06-117)
PAC assigned 66 calendar days (33 PAC days)

Taking RG-E data with CLAS12 since March, 2024

RG-E experimental conditions

- Electron beam 10.5 GeV
- Targets ^{2}H, ^{12}C, ^{27}Al, ^{63}Cu, ^{118}Sn, ^{208}Pb
- Integrated Luminosity ~ 10^{41} $1/(s \cdot cm^2)$

- Extreme conditions: high vacuum and high magnetic field, low temperatures, radiation hardness, reduced space

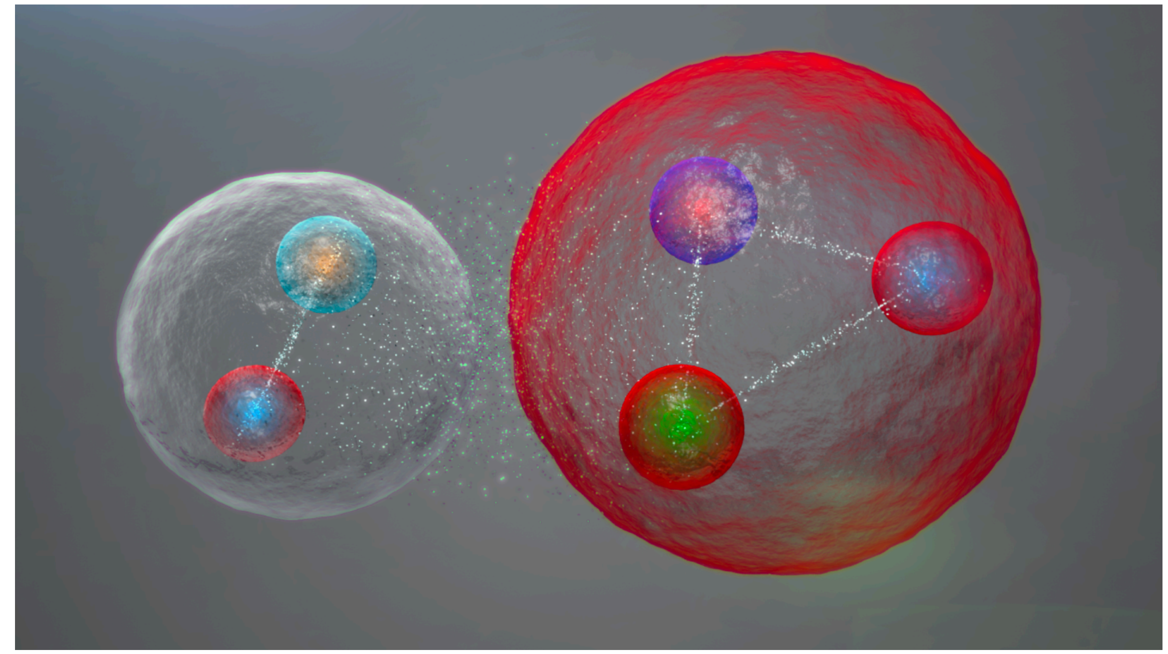


Highlights of double target are in JLUO weekly: https://mailchi.mp/89a150f4d755/jlab-weekly-for-scientific-users-april-3-2024?e=a8d43a7cbe

Quark Propagation and Hadronization at CLAS12

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	uūdd̄	5.7% (sys)
π^+, π^-	7.8 m	0.14	ud̄, dū	3.2% (sys)
η	170 pm	0.55	uūdd̄ss̄	6.2% (sys)
ω	23 fm	0.78	uūdd̄ss̄	6.7% (sys)
η'	0.98 pm	0.96	uūdd̄ss̄	8.5% (sys)
ϕ	44 fm	1	uūdd̄ss̄	5.0% (stat)*
f1	8 fm	1.3	uūdd̄ss̄	-
K^0	27 mm	0.5	ds̄	4.7% (sys)
K^+, K^-	3.7 m	0.49	us̄, ūs	4.4% (sys)
p	stable	0.94	uud	3.2% (sys)
$\bar{p}$	stable	0.94	ūūd̄	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	uus	6.6% (sys)
Σ^-	44 mm	1.2	dds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	uss	16% (stat)*
Ξ^-	49 mm	1.3	dss	7.8% (stat)*

More Luminosity More Acceptance Better Particle ID



Can study rare and complex cases of hadrons probing mass, strangeness and rank dependence of hadron formation and color propagation

New baryon structure information to reveal diquark degrees of freedom for n, p and Λ

eA kinematics past, present & future

HERMES @27 GeV: $\sqrt{s}$ = 7.2 GeV

CLAS @ 5 GeV: $\sqrt{s}$ = 3.2 GeV

CLAS @11 GeV: $\sqrt{s}$ = 4.6 GeV

CLAS @ 22 GeV: $\sqrt{s}$ = 6.4 GeV

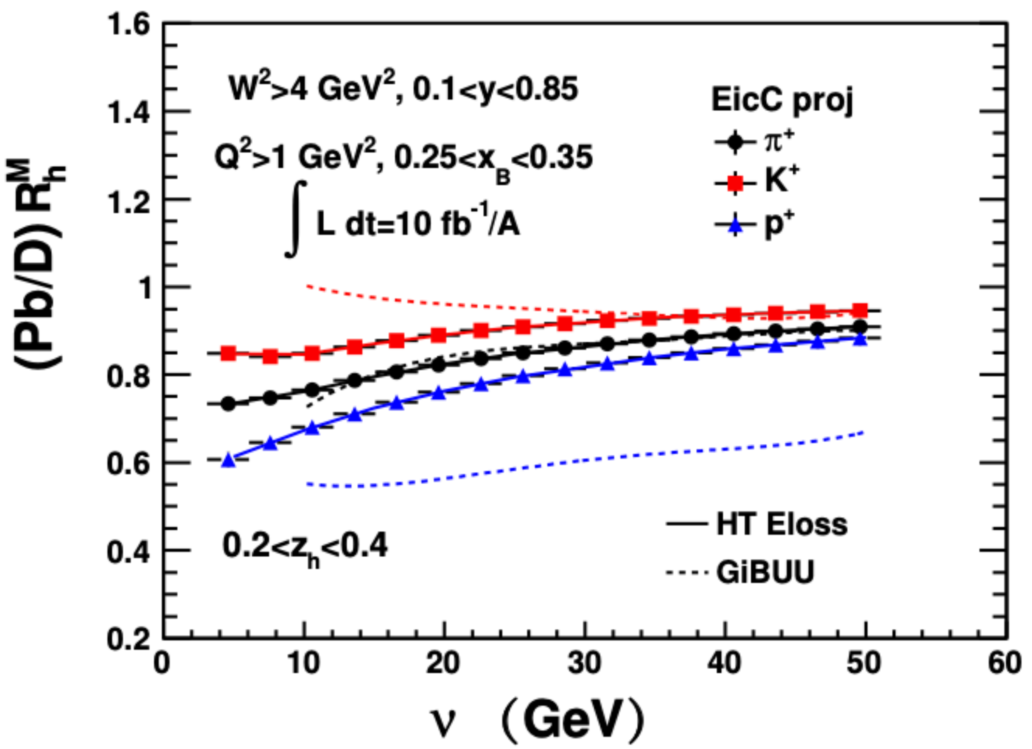
EicC: $\sqrt{s}$ = 11.9 - 16.7 GeV

EIC eRHIC: $\sqrt{s}$ = 20 - 140 GeV

EicC

[EicC white paper: https://doi.org/10.1007/s11467-021-1062-0](https://doi.org/10.1007/s11467-021-1062-0)

Particle	Momentum (GeV/c/u)	CM energy (GeV/u)	Average Polarization	Luminosity at the nucleon level ($cm^{-2}s^{-1}$)	Integrated luminosity (fb^{-1})
e	3.5		80%		
p	20	16.76	70%	2.00×10^{33}	50.5
d	12.90	13.48	Yes	8.48×10^{32}	21.4
$^{3}He^{++}$	17.21	15.55	Yes	6.29×10^{32}	15.9
$^{7}Li^{3+}$	11.05	12.48	No	9.75×10^{32}	24.6
$^{12}C^{6+}$	12.90	13.48	No	8.35×10^{32}	21.1
$^{40}Ca^{20+}$	12.90	13.48	No	8.35×10^{32}	21.1
$^{197}Au^{79+}$	10.35	12.09	No	9.37×10^{32}	23.6
$^{208}Pb^{82+}$	10.17	11.98	No	9.22×10^{32}	23.3
$^{238}U^{92+}$	9.98	11.87	No	8.92×10^{32}	22.5



Ranges of color lifetime l_p in HERMES, CLAS and extrapolation to EIC

Q2	nu	beta*gamma	lp, z=0.32	lp, z=0.53	lp, z=0.75	lp, z=0.94	Experiment
2.40	14.50	9.31	8.57				HERMES
2.40	13.10	8.40		6.39			HERMES
2.40	12.40	7.94			4.63		HERMES
2.30	10.80	7.05				2.40	HERMES
3.00	4.00	2.08	1.92	1.58	1.21	0.71	CLAS
7.00	7.00	2.45	2.26	1.86	1.43	0.83	CLAS12
1.00	4.00	3.87	3.57	2.95	2.26	1.32	CLAS
2.00	9.00	6.28	5.79	4.78	3.66	2.14	CLAS12
12.00	32.50	9.33	8.59	7.10	5.44	3.18	EIC
8.00	37.50	13.22	12.17	10.06	7.71	4.50	EIC
45.00	140.00	20.85	19.20	15.86	12.15	7.10	EIC
27.00	150.00	28.85	26.57	21.96	16.82	9.82	EIC

W. Brooks INT 2017

At EicC we can disentangle two mechanisms: parton energy loss (Lp ~> Rpb) vs hadron absorption (GiBUU)

Which measurements can be accessed at the EIC with hadronization observables?

- **pT broadening observables**

  Saturation scale

Gluon transverse momentum k_T characterizes degree to which saturation is occurring: $Q_s \sim k_T$

p_T broadening is a boost-invariant way of sampling the transverse gluon density distribution; proportional to the gluon density

$$\Delta p_T^2 \propto G(x, Q^2)\rho L$$

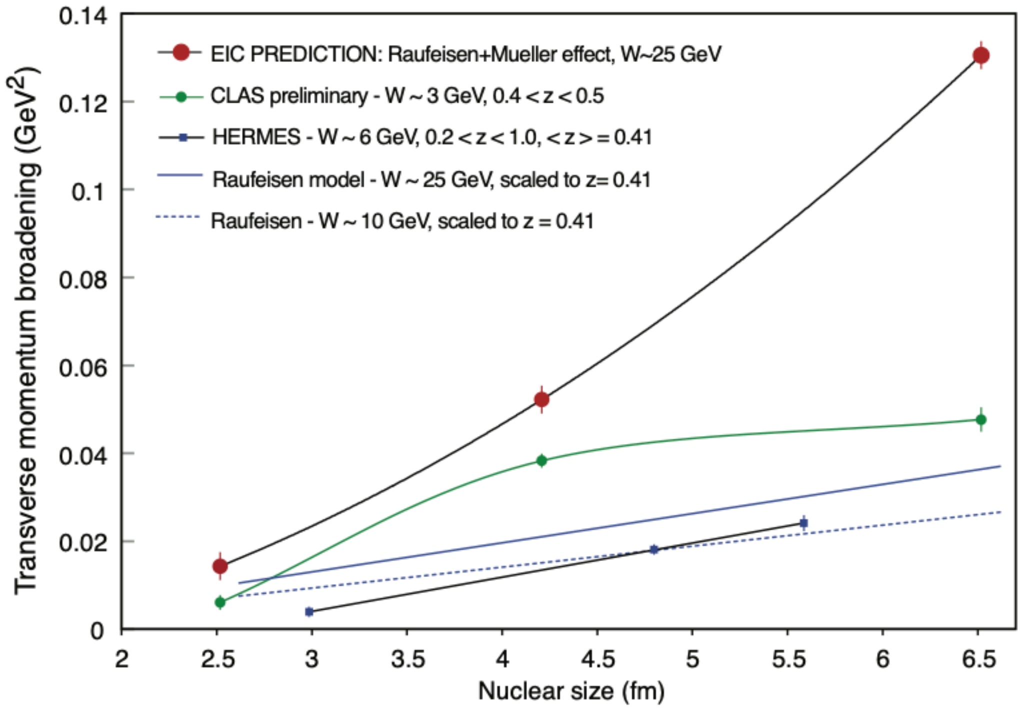
Which measurements can be accessed at the EIC with hadronization observables?

- **pT broadening observables**

  Saturation scale

  pQCD energy loss

pQCD prescription of quark energy loss



Which measurements can be accessed at the EIC with hadronization observables?

- **pT broadening observables**

  Saturation scale

  pQCD energy loss

  Effective quark lifetime

  Transport coefficient

Which measurements can be accessed at the EIC with hadronization observables?

- **pT broadening observables**

  Saturation scale

  pQCD energy loss

  Effective quark lifetime

  Transport coefficient

- **Multiplicity ratio observables**

  Mass dependence of hadronization

  Hadron formation length

Summary

- The microscopic information on space-time dynamics of hadronization can be accessed in DIS using nuclear medium *A* of increasing size

- Transverse momentum broadening and hadronic multiplicity ratio observables provide insights on the lifetime of ‘free’ quark, formation of hadrons and E_{loss}

- Baryon data from HERMES and CLAS behave qualitatively different from meson. Pion data is well described by GiBUU, while baryon data needs more understanding

- The hypothesis of diquarks may be one of the mechanisms in baryon formation

- CLAS at 6 GeV high luminosity data on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb:
  - Published results on multi-dimensional π^+ and π^- multiplicities (S.Morán et al.); CLAS approved paper on the multi-dimensional π^0 multiplicity ratios (T.Mineeva et al.)
  - Published results on Λ multiplicity ratios and ΔpT2 (T.Chetry et al.)
  - Published results on di-hadron production (S.Paul el al.)
  - In process: p multiplicities (M.Wood), ΔpT2 for π^+ (E.Molina), ΔpT2 for double pion production (M.Barria), π^+ azimuthal dependencies (C. San Martin), Bose-Einstein correlations (A.Radic), ω and η multiplicities (A.Borguez, O.Soto)

- Running CLAS12 experiment (E12-06-117) at 11 GeV. 4D multiplicities, large spectrum of hadrons