Hadronization data in cold nuclear medium: past, present and future (Jefferson Lab and EIC)

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Jefferson Lab
clas CEBAF Large Acceptance Spectrometer
CCTVal CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO
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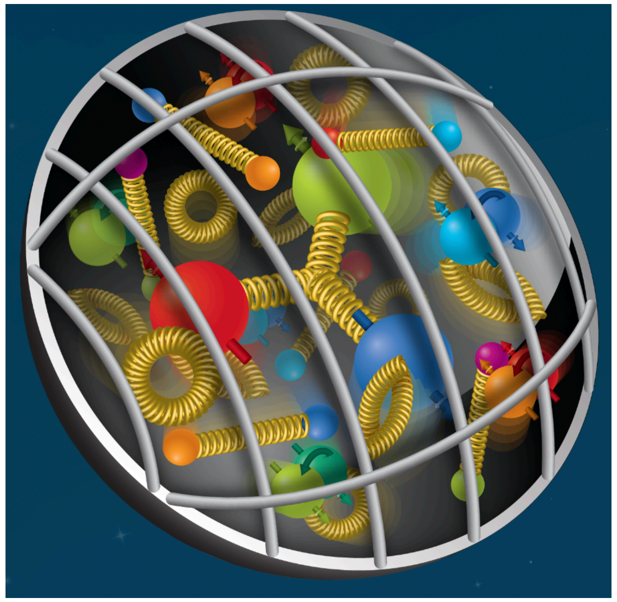
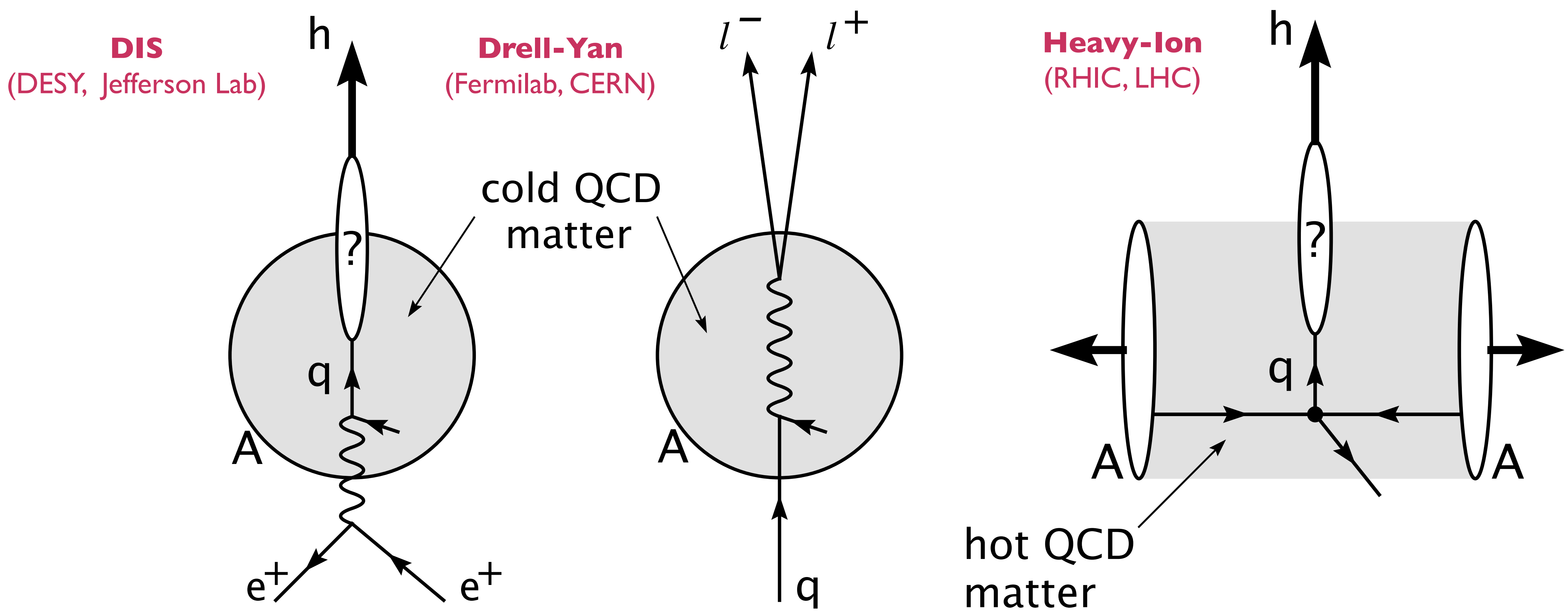
Hadronization: what's the deal?

Process by which an energetic parton fragments into many further partons, which then, on later timescales, undergo a transition to hadrons

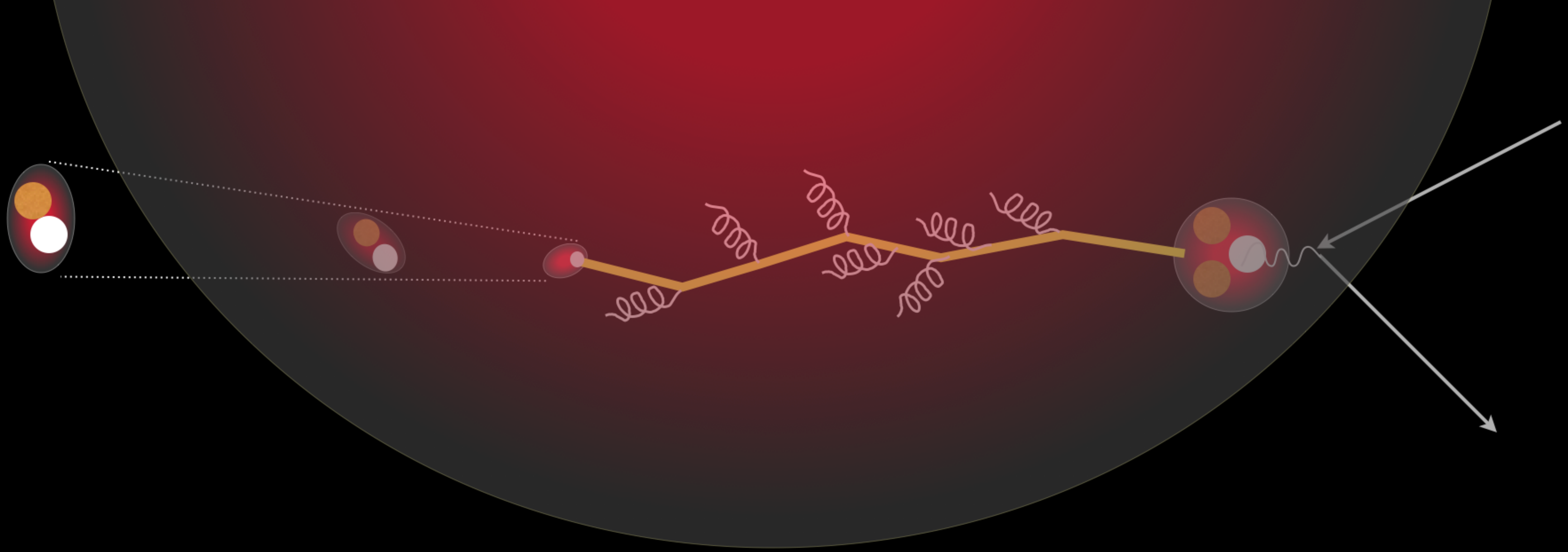


- The fundamental degrees of freedom in QCD, quarks and gluons, form bound states at low energies. Complication: Confinement.
- Quarks and gluons must be in color singlet bound states, i.e. mesons or baryons.
- Confinement is not understood from first principles. Challenge is to model it.
- The MC event generators (Pythia, Jetset, Herwig, Beagle, GiBUU) are the products of a physics development program in close touch with experimental reality.
- There are variety of phenomenological models (Rescaling model, Quark energy loss model, Color Dipole model, Higher-twist pQCD model, etc.) that need input from experimental data

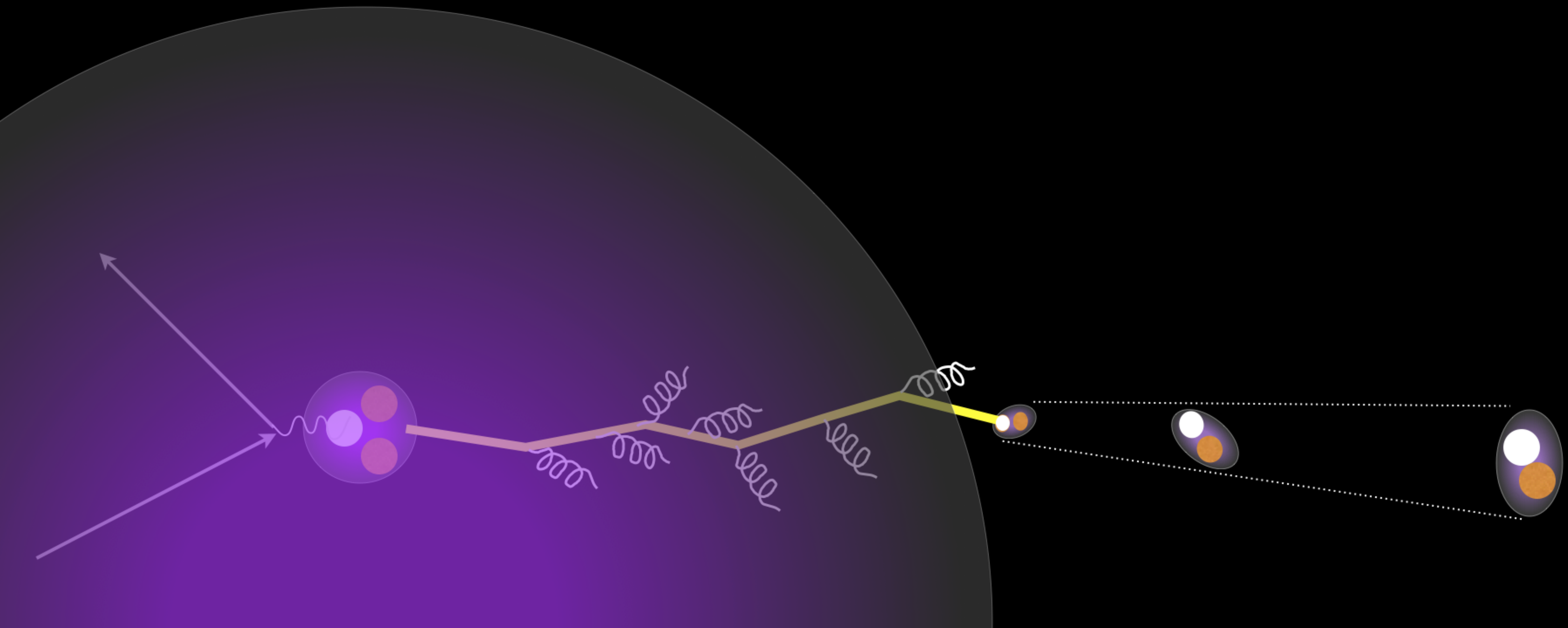
Quark Propagation & Hadronization



Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]



e A : nuclei of increasing size act as space-time analyzer



eA DIS: 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

- *What are timescales of color neutralization and hadron formation?*
- *What are the differences in hadronization of light quarks vs heavy quarks*

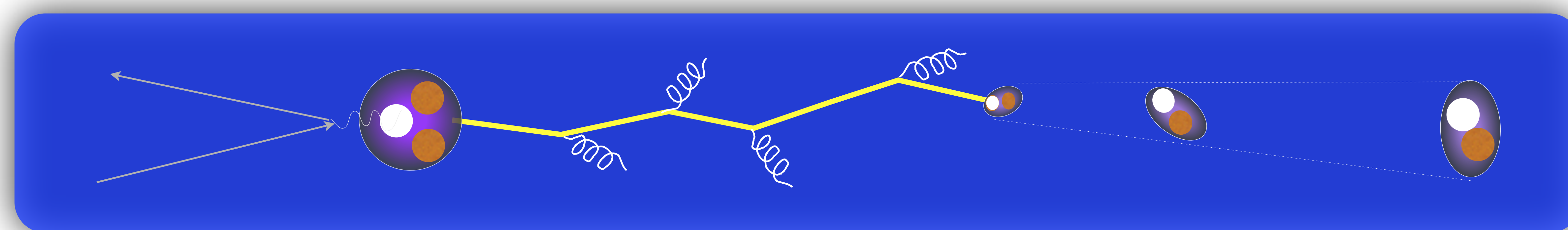
In-medium hadron formation in DIS

How long can an energetic quark remain ‘free’?
How do hadrons form from quarks?

Partonic elastic scattering in medium

Gluon bremsstrahlung
Parton rescattering
Quark energy loss

Color neutralization
Hadron formation
Final state interaction



τ_C

Color lifetime τ_C

lifetime of highly virtual ‘free’ quark

τ_f

Formation time τ_f

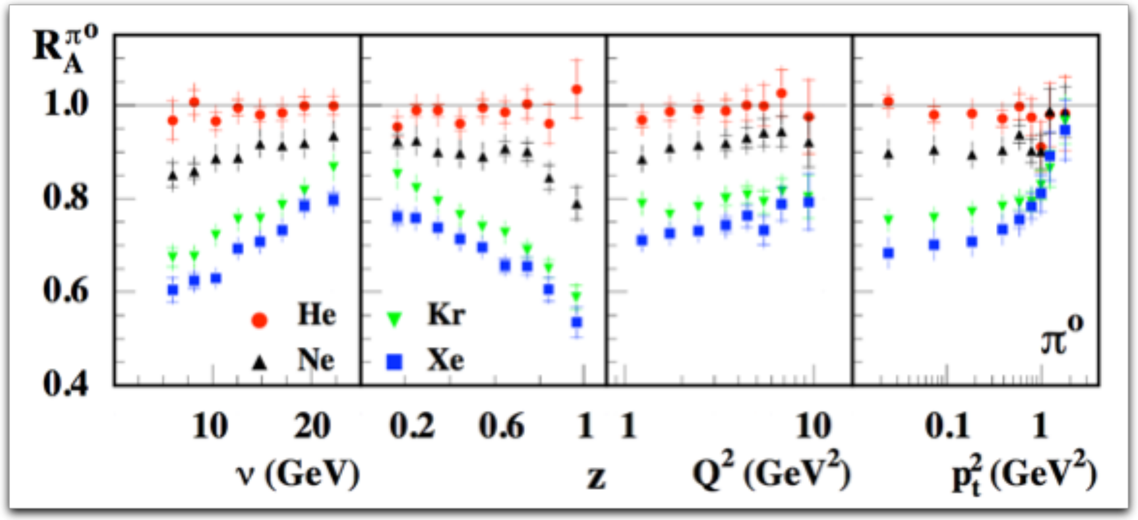
time required for a colored system to evolve into a colorless

Experimental Observables

Hadronic Multiplicity ratio

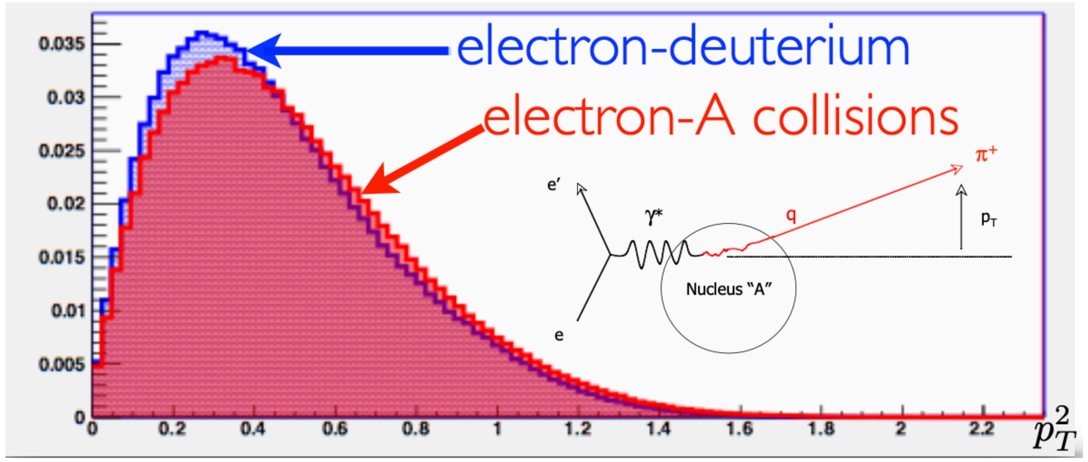
$$R_{\mathrm{A}}^{h}\left(\nu, Q^{2}, z, p_{T}\right) = \frac{\left.\frac{N_h(\nu,Q^2,z,p_T)}{N_e(\nu,Q^2)|_{\mathrm{DIS}}}\right|_{\mathrm{A}}}{\left.\frac{N_h(\nu,Q^2,z,p_T)}{N_e(\nu,Q^2)|_{\mathrm{DIS}}}\right|_{\mathrm{D}}}$$

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



Transverse momentum broadening

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



Extraction of color lifetime Brooks-Lopez model

Physics Letters B 816 (2021) 136171

Contents lists available at ScienceDirect

Physics Letters B

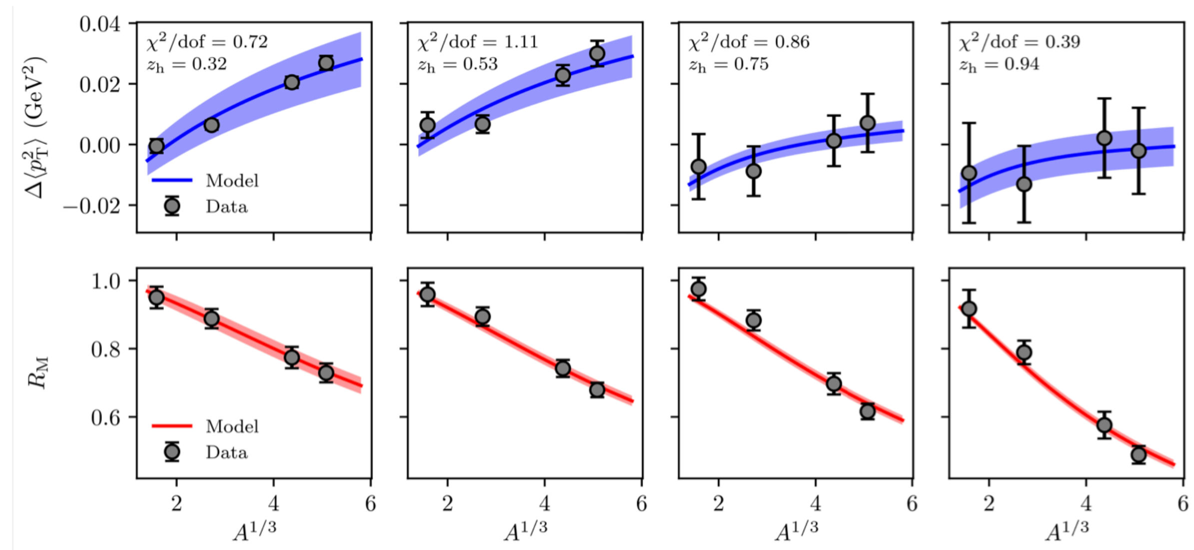
www.elsevier.com/locate/physletb

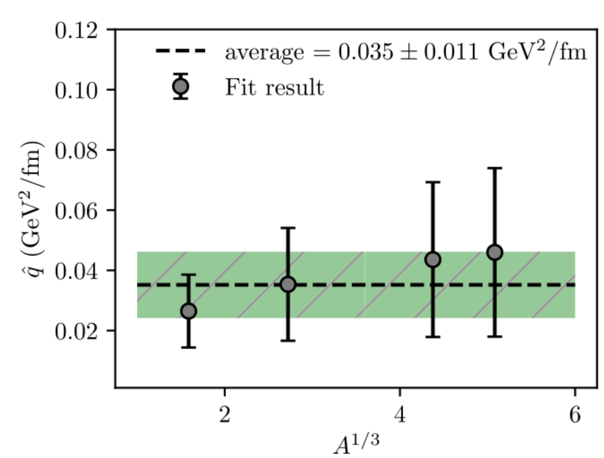
Estimating the color lifetime of energetic quarks

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

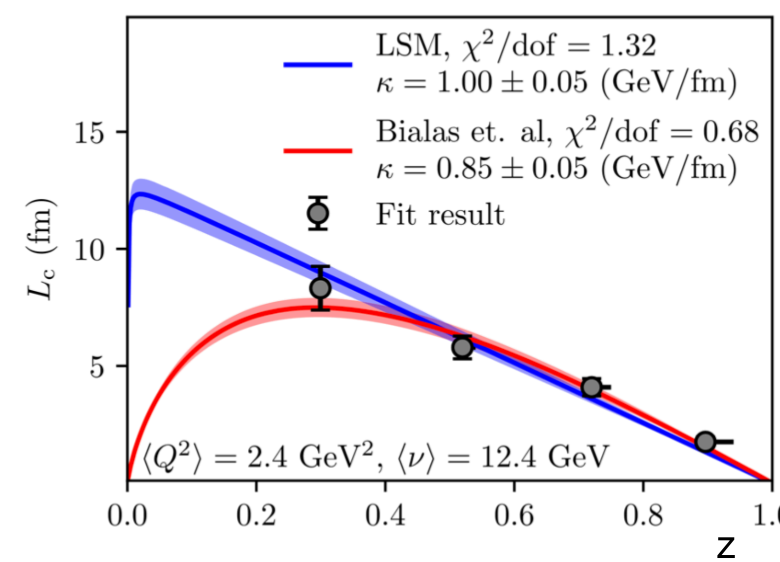
- The **color lifetime** was estimated using simultaneous fit to two observables in the **HERMES** data with 3-parameter space-time model
- The answer depends on the kinematics and ranges from **2 to 8 fm/c**
- Independent determination of the string constant of the LSM!
- Measurement of transport coefficient

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

Experimental realization

Jefferson Lab

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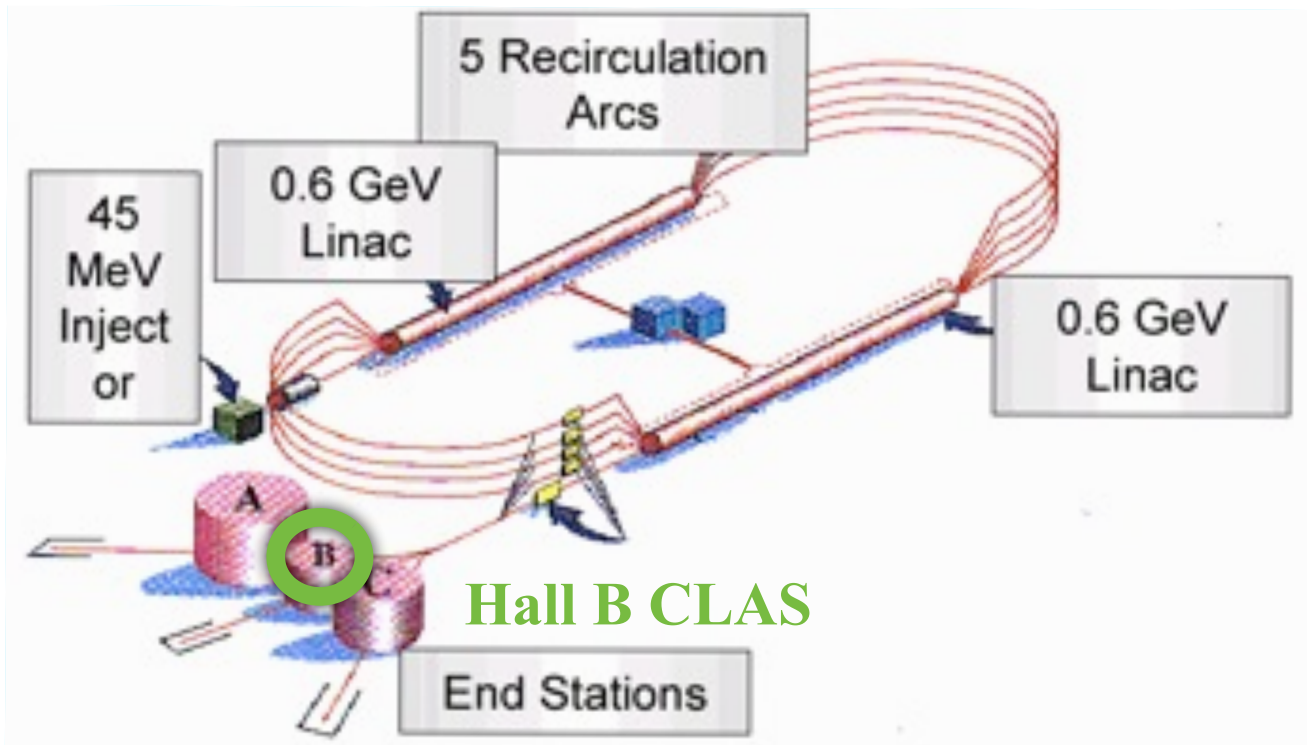
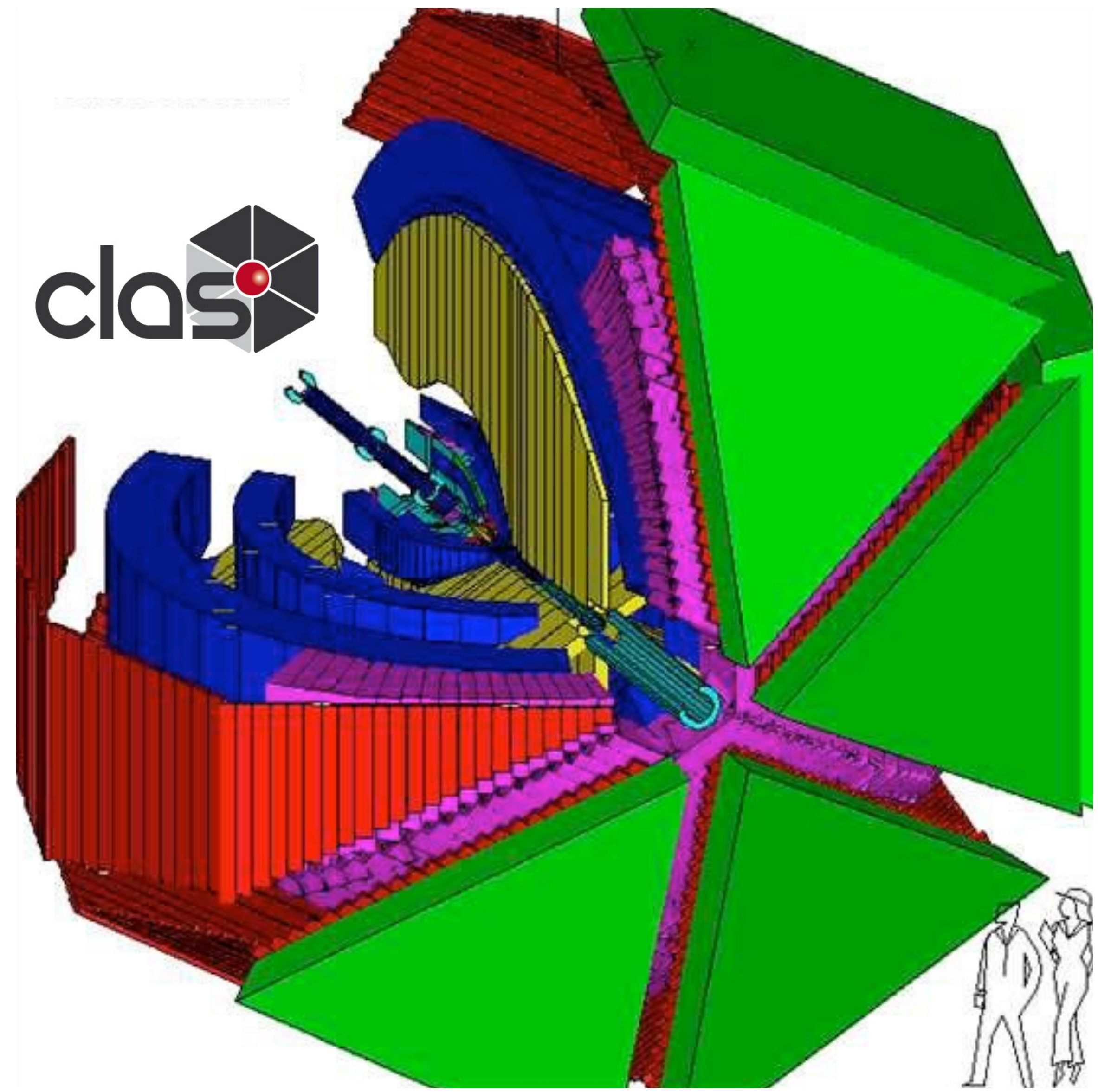
CEBAF Large Acceptance Spectrometer

CEBAF and CLAS @ 6 GEV





CEBAF Large Acceptance Spectrometer

- Charged particle angles 8° - 144°
- Neutral particle angles 8° - 70°
- Momentum resolution ~0.5% (charged)
- Angular resolution ~0.5 mr (charged)
- Identification of p, π^+/π^-, K^+/K^-, e^-/e^+

N. A. Mecking *et al.*, *The CEBAF large acceptance spectrometer (CLAS)*, Nucl. Inst. and Meth. A 503, 513 (2003).

EG2 experiment @ 5 GEV

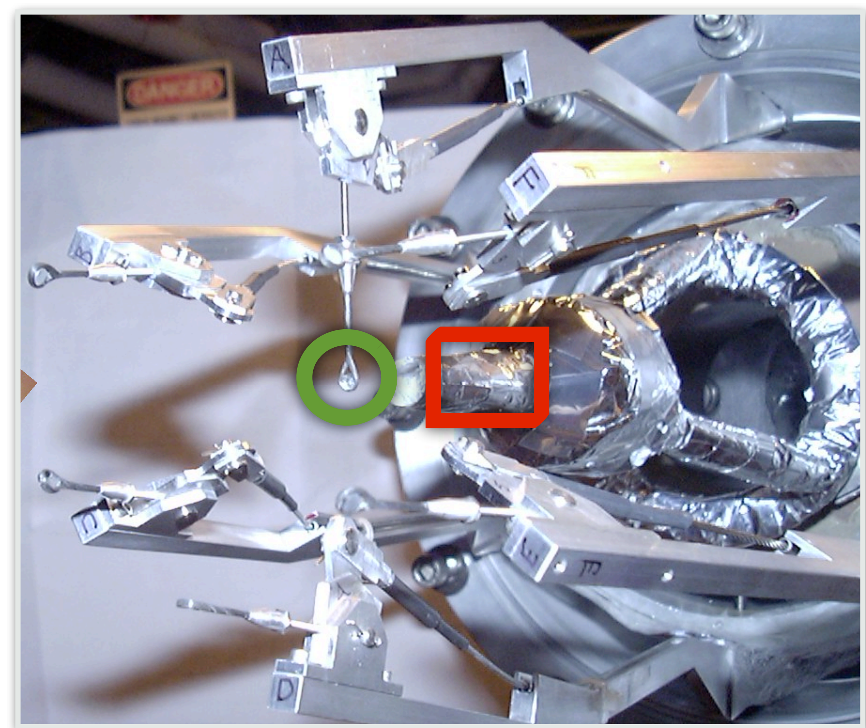
Jefferson Lab

clas

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

Results on light and heavy hadrons

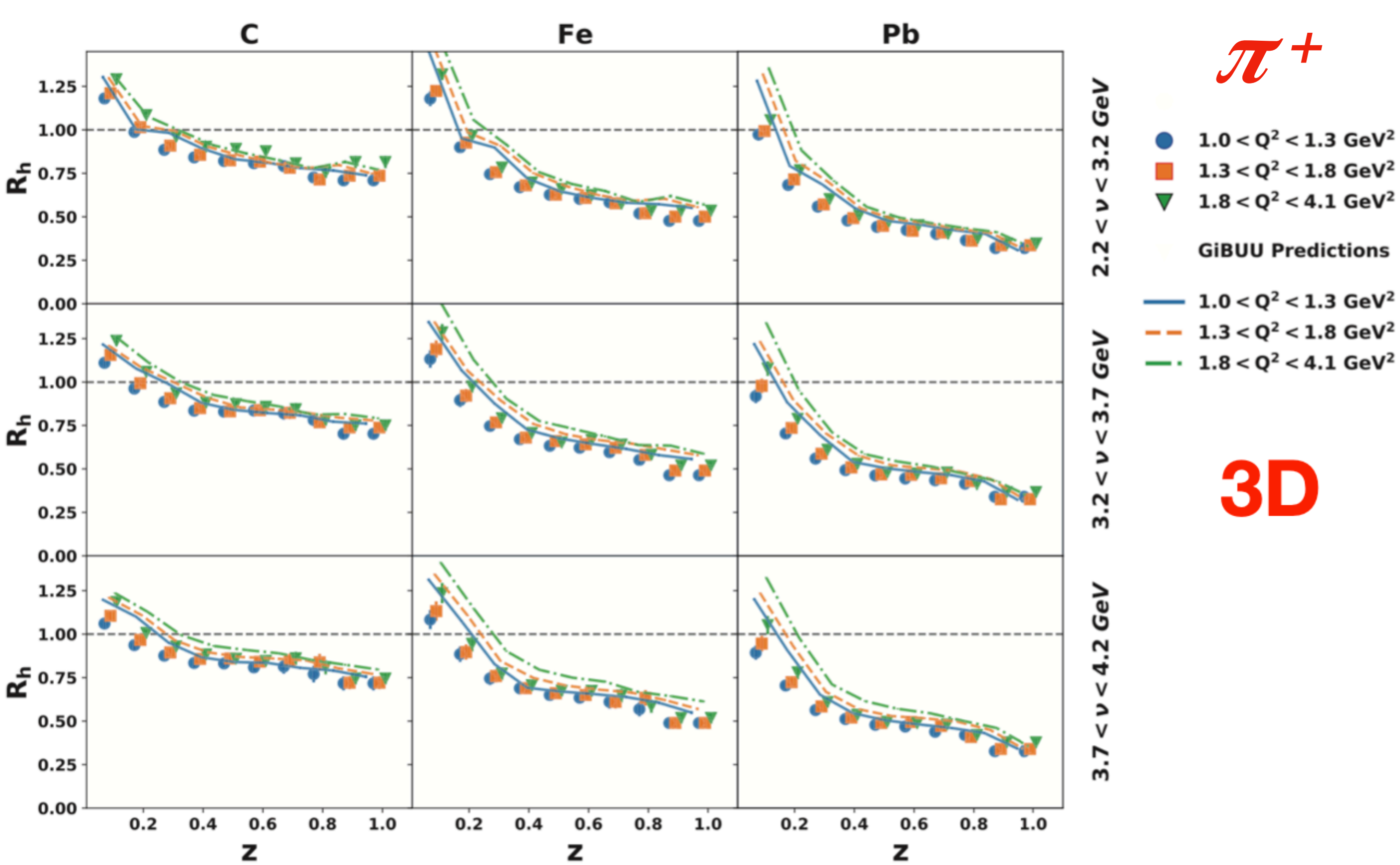
Light hadrons: multiplicity ratios from EG2

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

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

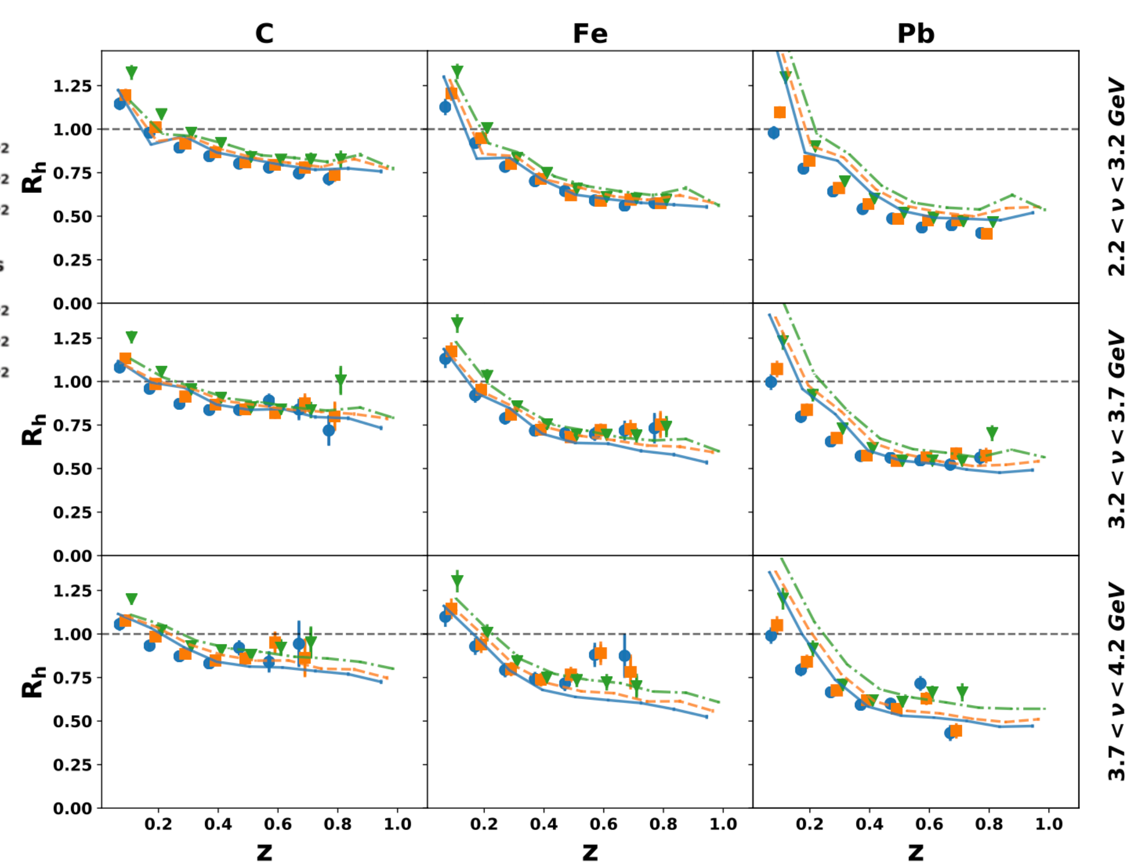
S. Morán,[1,3] R. Dupre,[2] H. Hakobyan,[1,52] M. Arratia,[3] W. K. Brooks,[1] A. Bórquez,[1] A. El Alaoui,[1] L. El Fassi,[4,5] K. Hafidi, R. Mendez,[1] T. Mineeva,[1] S. J. Paul,[3] M. J. Amaryan,[36] Giovanni Angelini,[19] Whitney R. Armstrong,[5] H. Atac,[43]

π^+



3D

π^-



Light hadrons: multiplicity ratios from EG2

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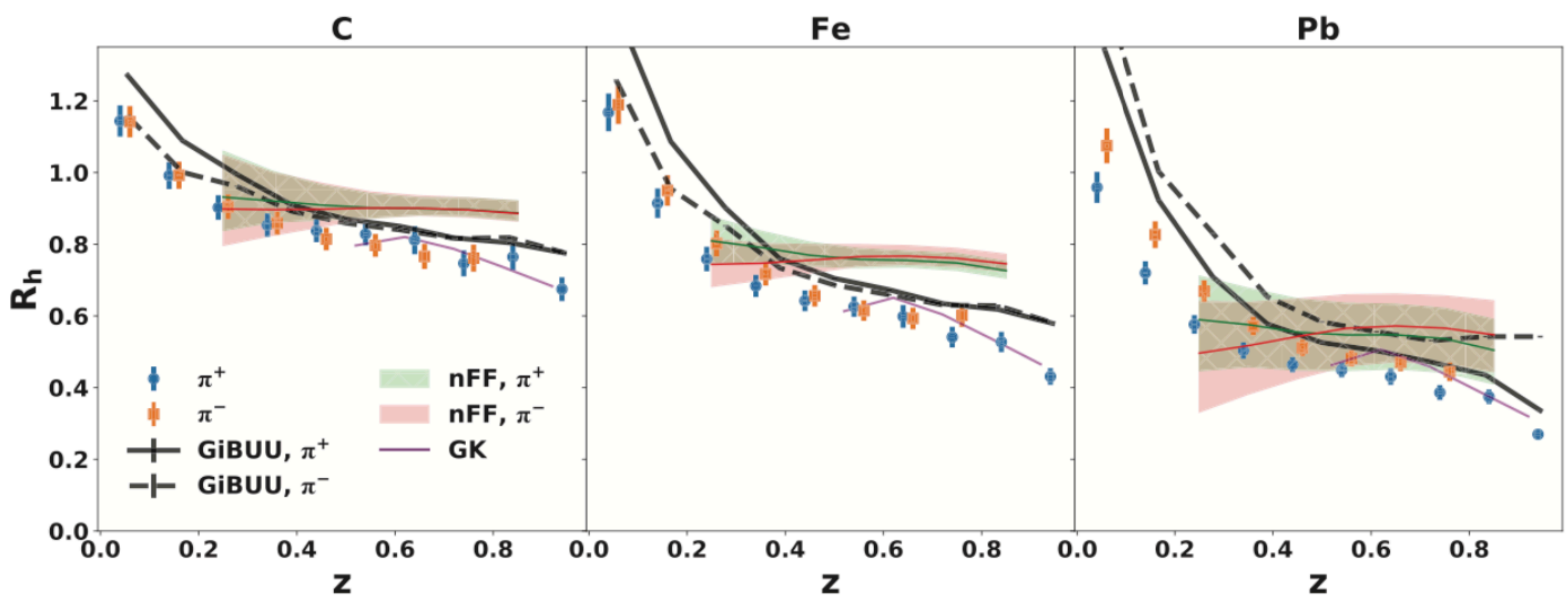
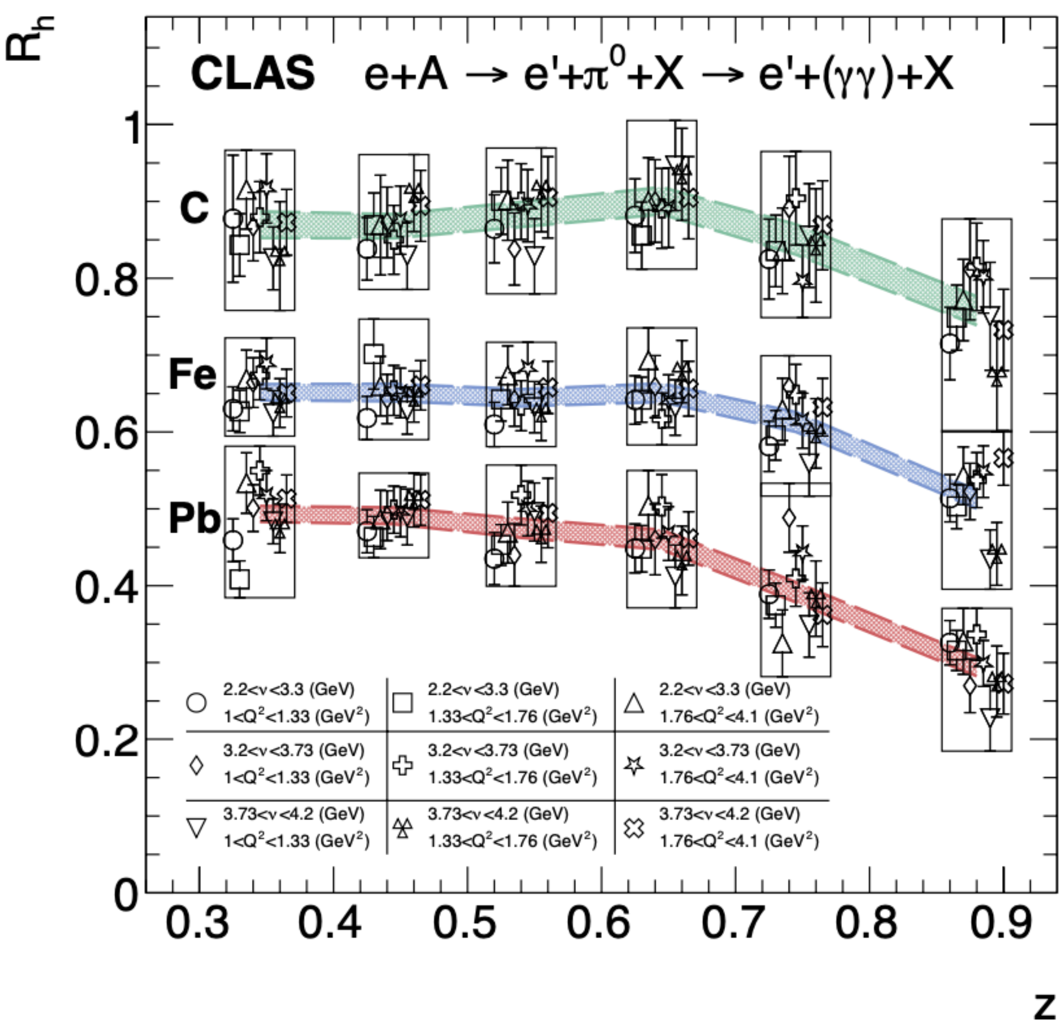


High-precision three-dimensional data is compared to the model predictions; GiBUU and Guiot-Kopeliovich models find semi-qualitative agreement

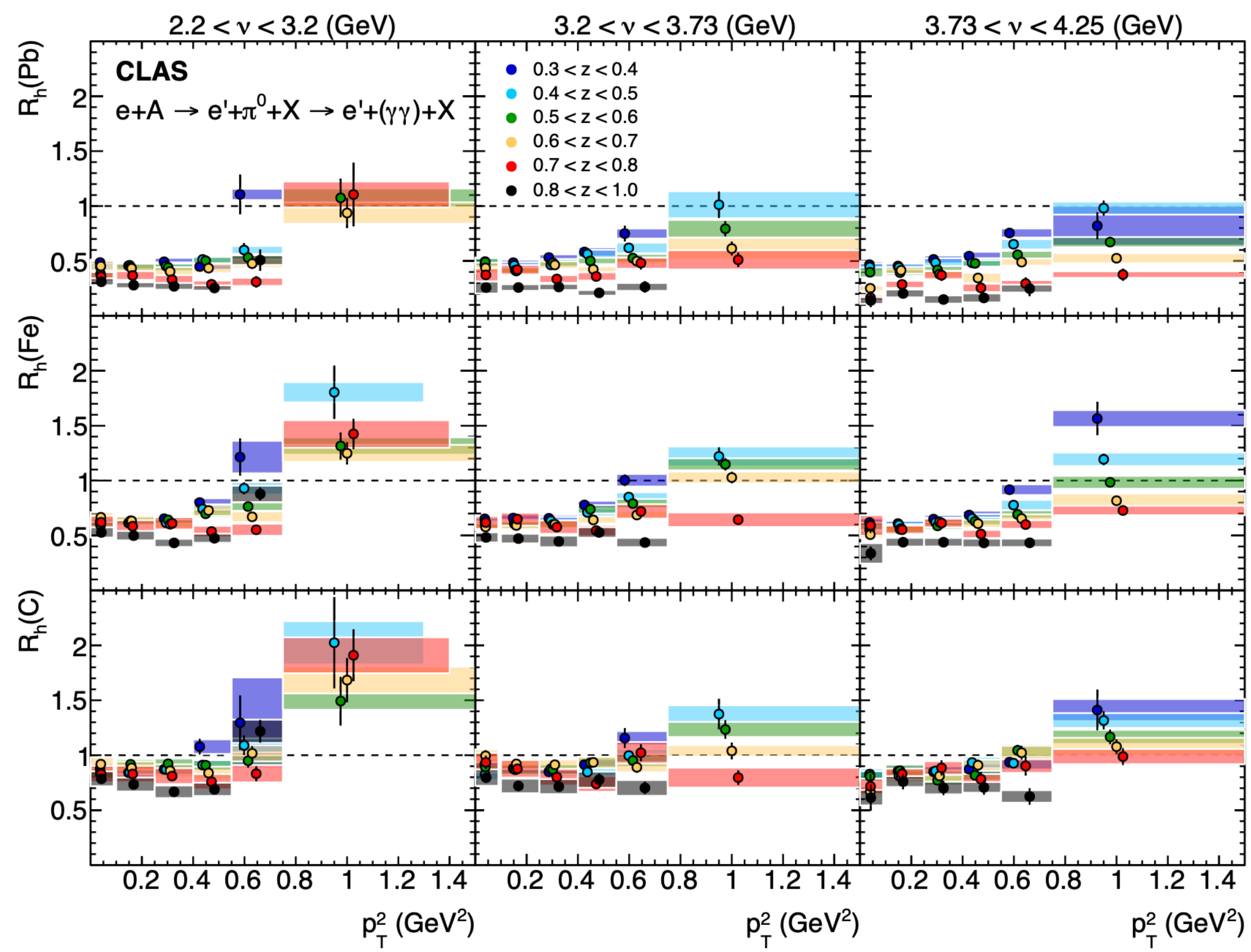
Light hadrons: multiplicity ratios from EG2

T.Mineeva et al. arXiv:2406.04513



π^0

3D

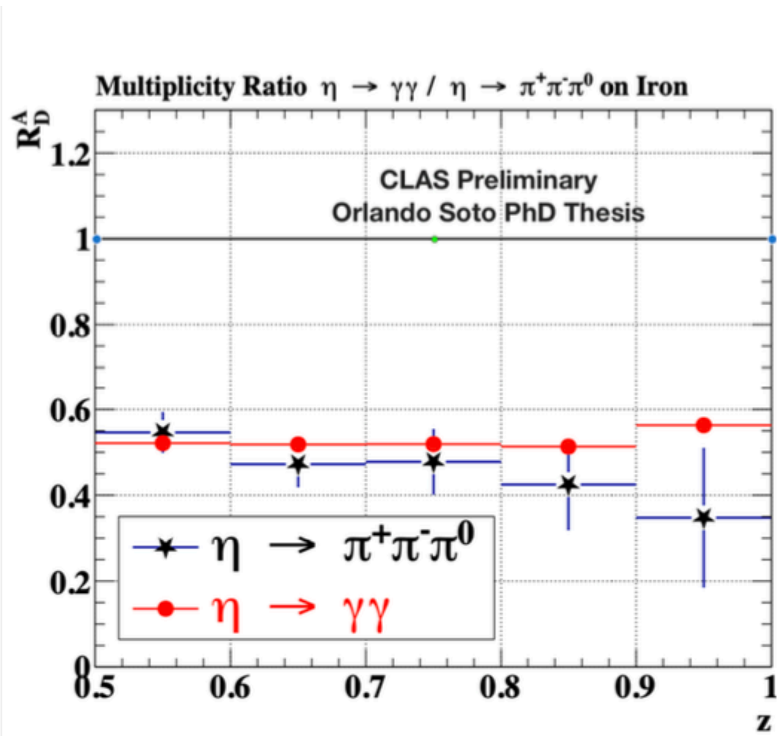


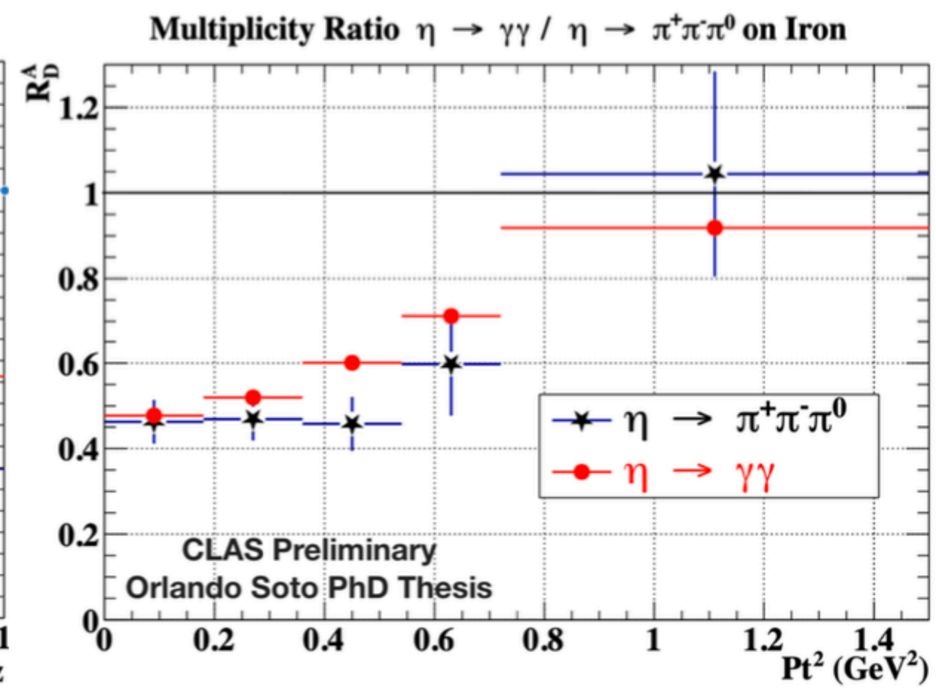
- Attenuation depends on nuclear size *A*
- Suppression for leading hadrons: 25% on C to 75% on Pb
- No dependence on Q^2 and ν observed

- Enhancement of $R_{\pi 0}$ at low *z* and high on *pT2*
- Largest enhancement at hight pT2 for Fe and Pb
- Quantitative behavior compatible with CLAS & Hermes

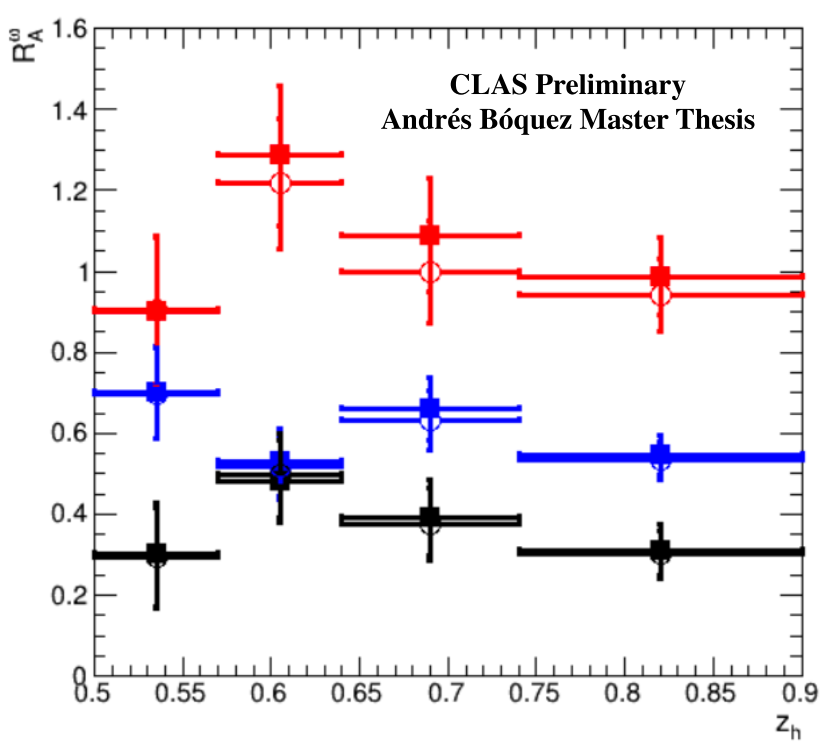
Light hadrons: η and ω preliminary results

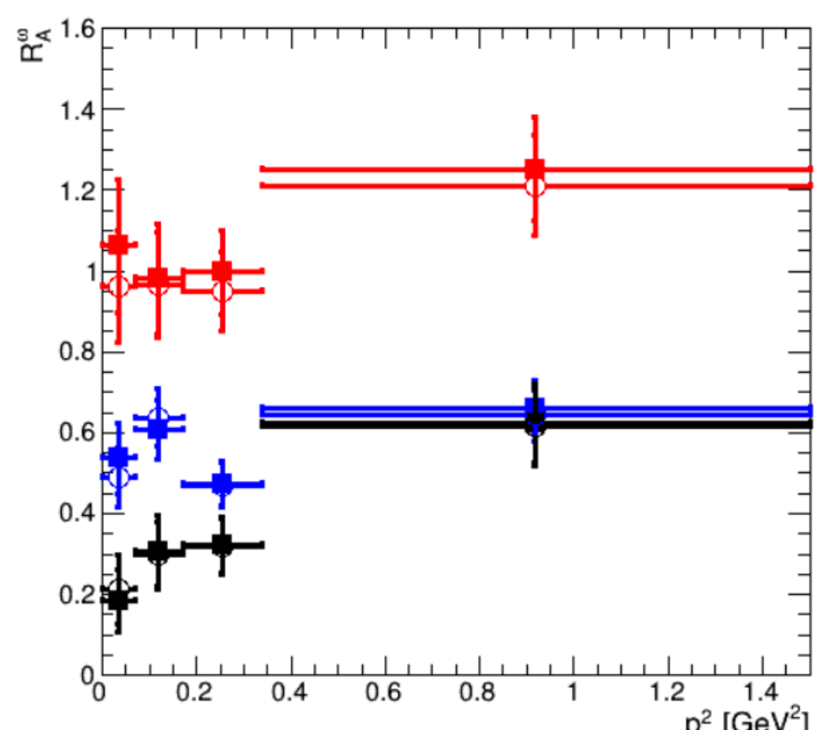
η





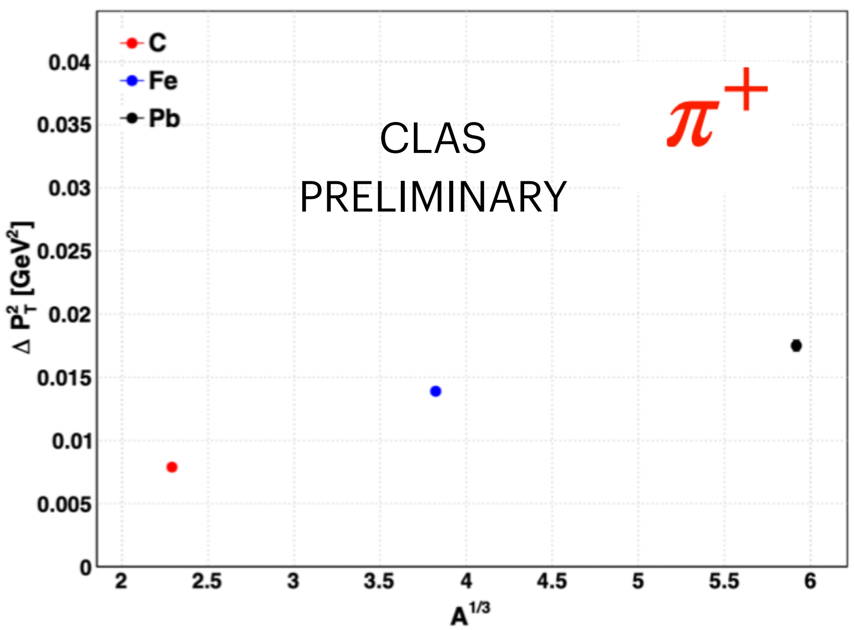
ω



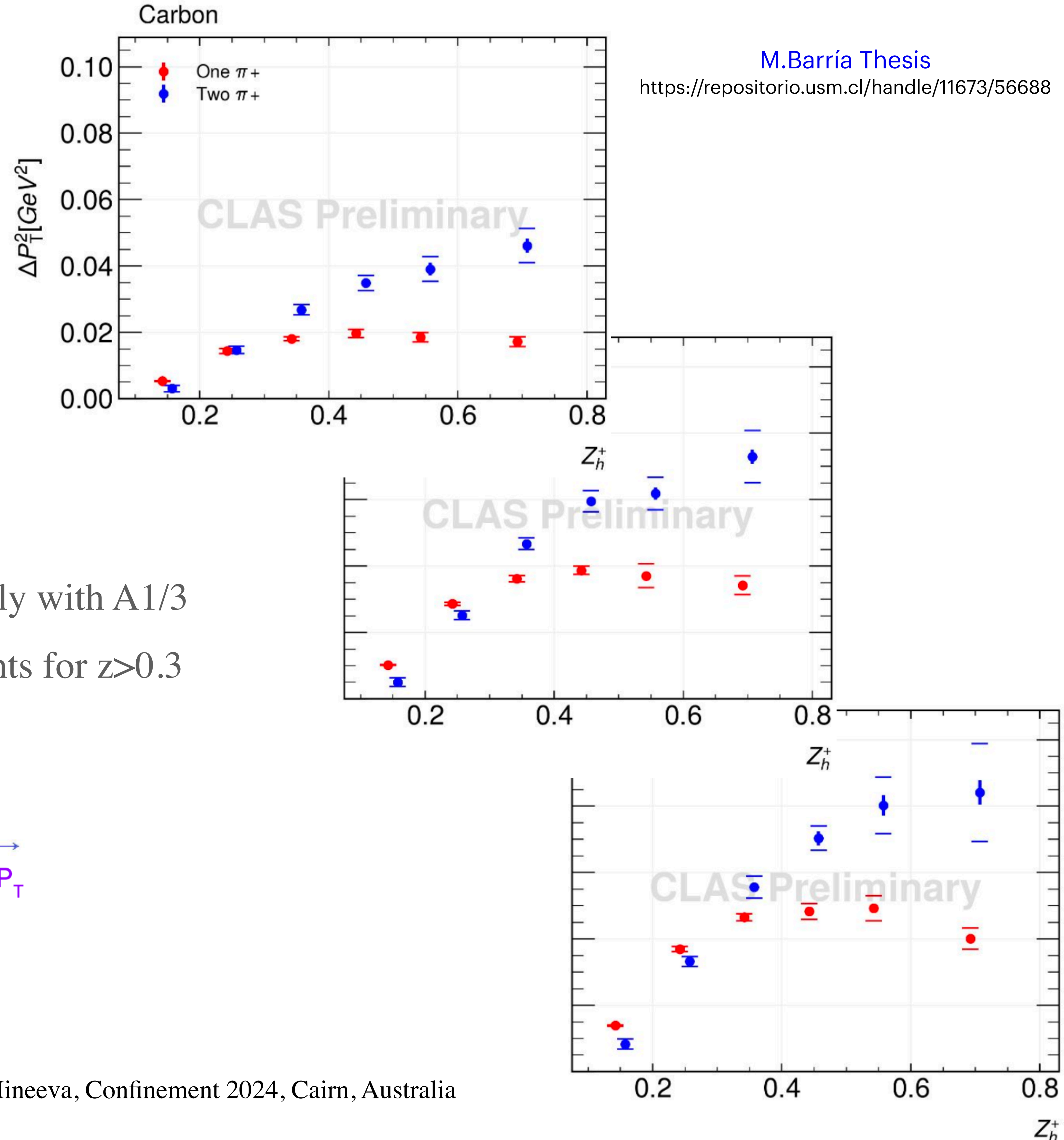


pT² broadening for multiple π⁺ events

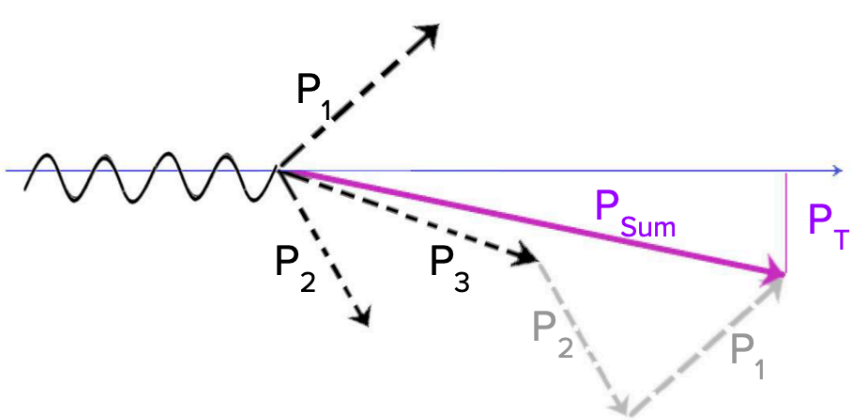
E.Molina Thesis
https://repositorio.usm.cl/handle/11673/53373



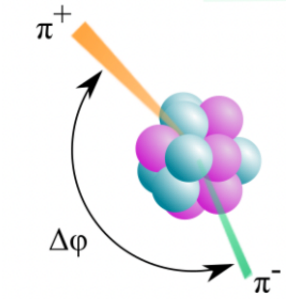
M.Barría Thesis
https://repositorio.usm.cl/handle/11673/56688



- pT² broadening for π⁺ grows linearly with A1/3
- pT² broadening is larger for 2π events for z>0.3



Dihadron correlations



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

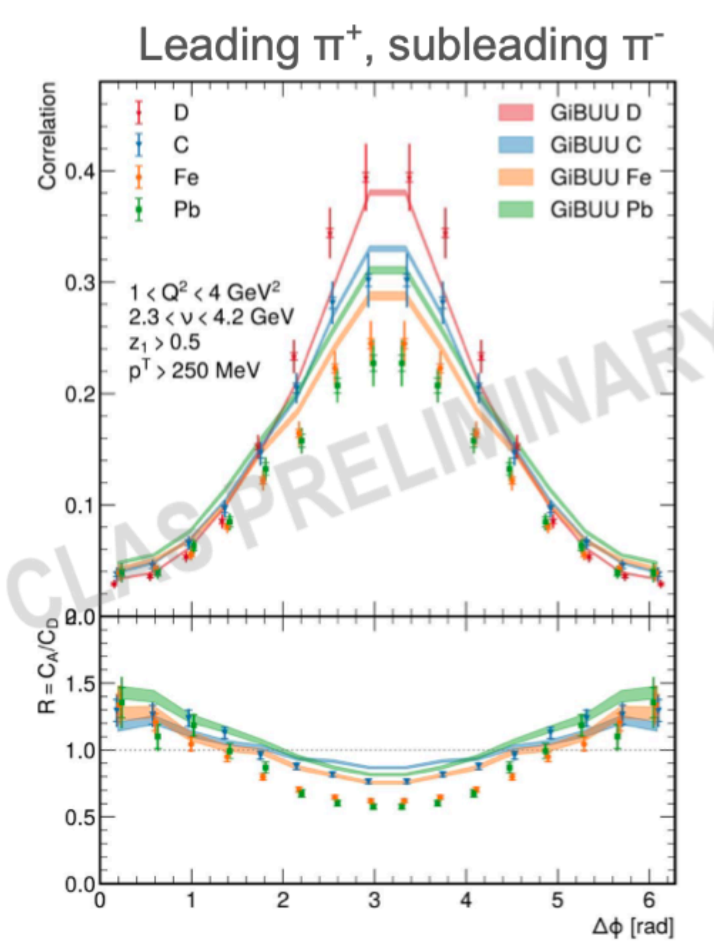
$$C(\Delta\phi) = C_0 \frac{1}{N_{eh}} \frac{dN_{ehh}}{d\Delta\phi}$$

$\Delta\varphi$ 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

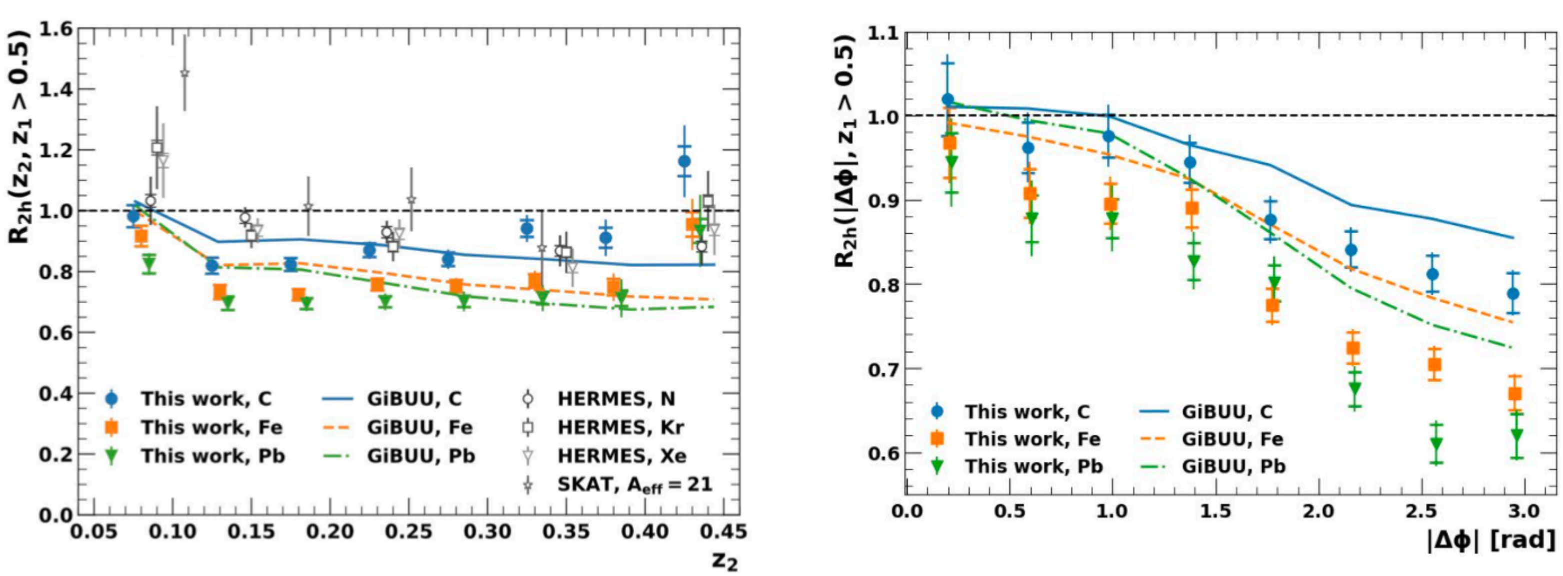


S.J Paul et al, in CLAS ad-hoc review

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

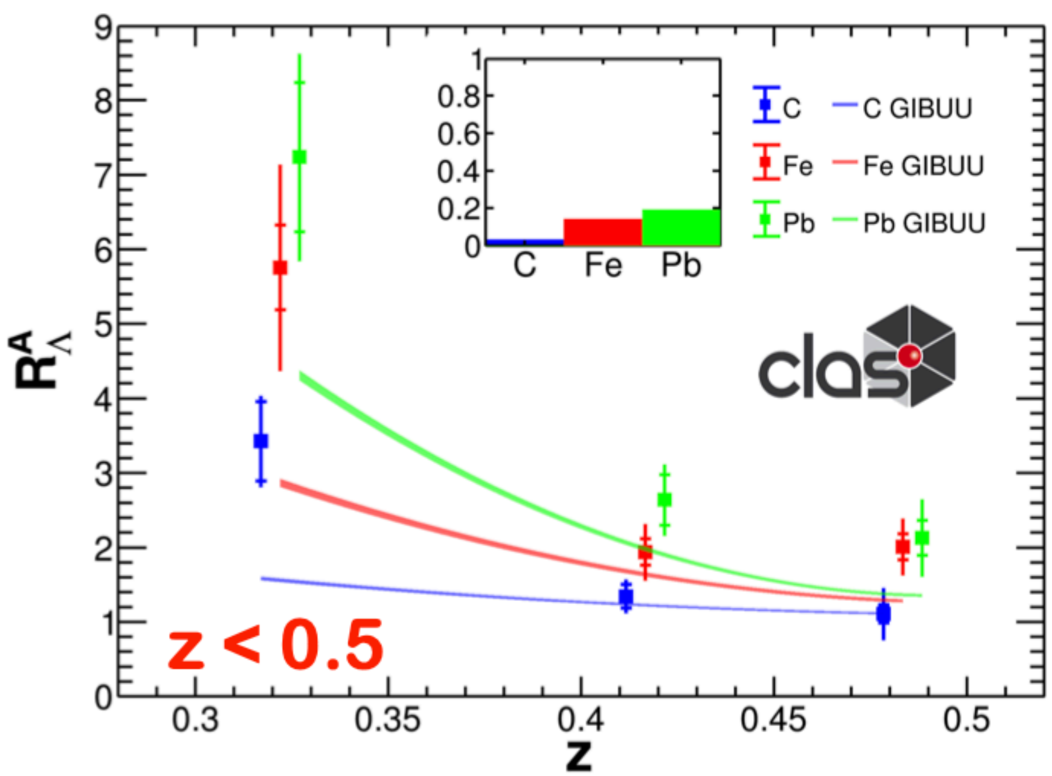
Conditional suppression factor, R2h, as a function of sub-leading hadron z: $R_{2h}(z_2) = \frac{(dN^A_{2h}(z_2)/dz_2)/N^A_h}{(dN^D_{2h}(z_2)/dz_2)/N^D_h}$

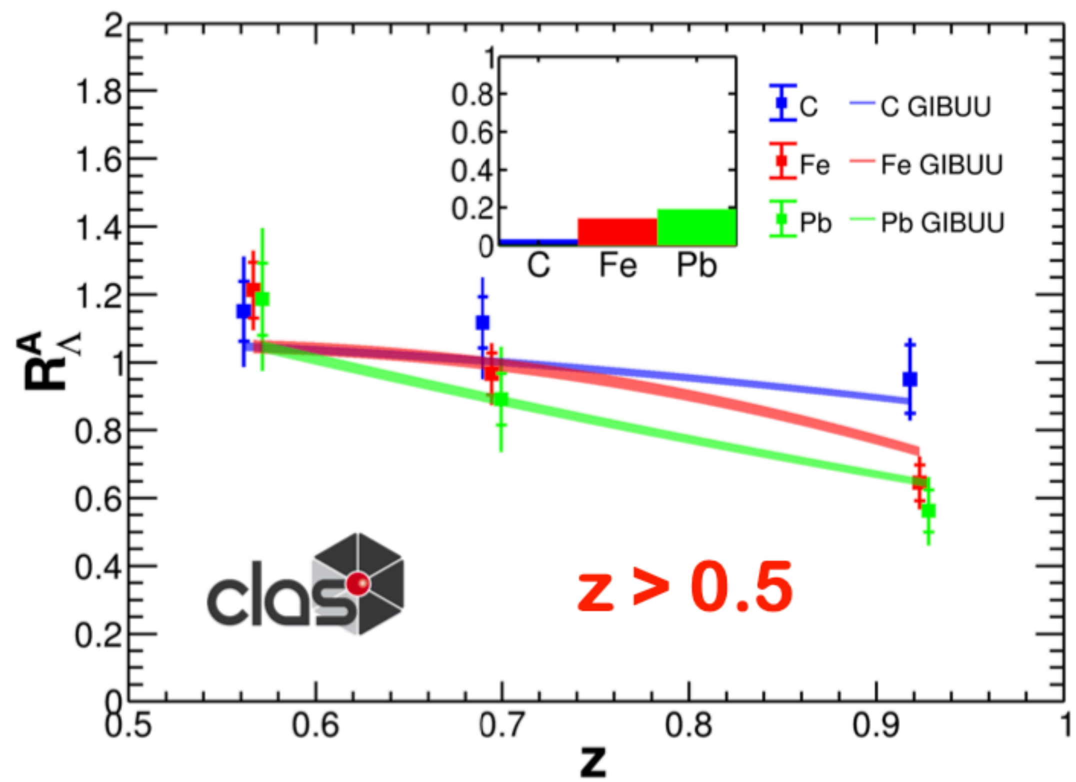


Heavy hadrons: Λ multiplicities and pT broadening

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

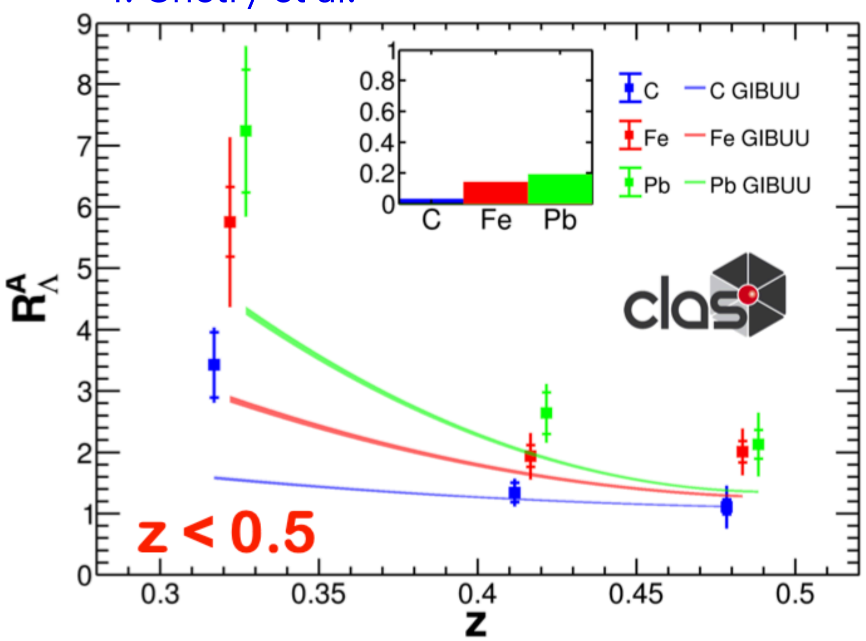


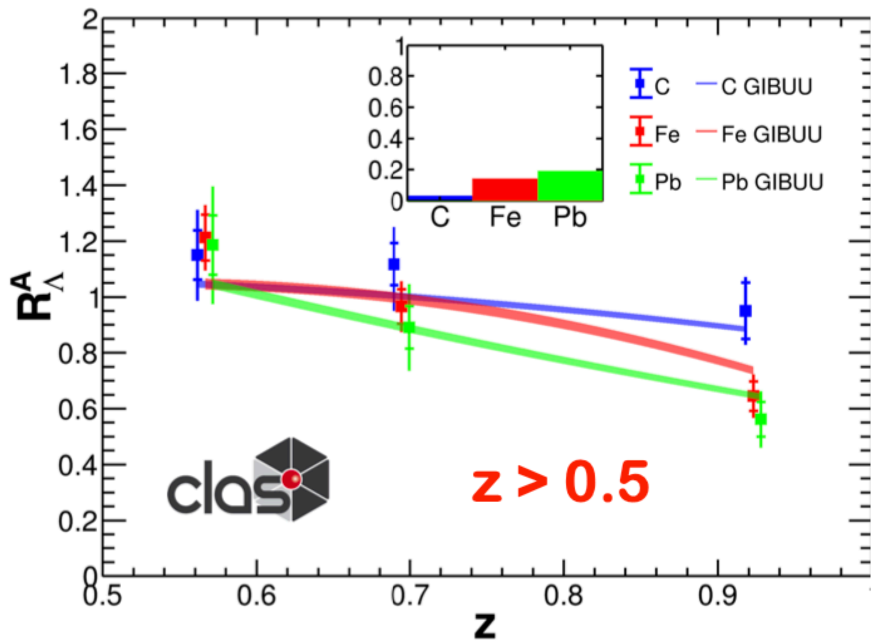


- At low-z there is a "pile up" of events 7 times more than for pion! Underpredicted by GiBUU.
- At high-z there is little attenuation compared to that on the pion. Agrees with GiBUU.

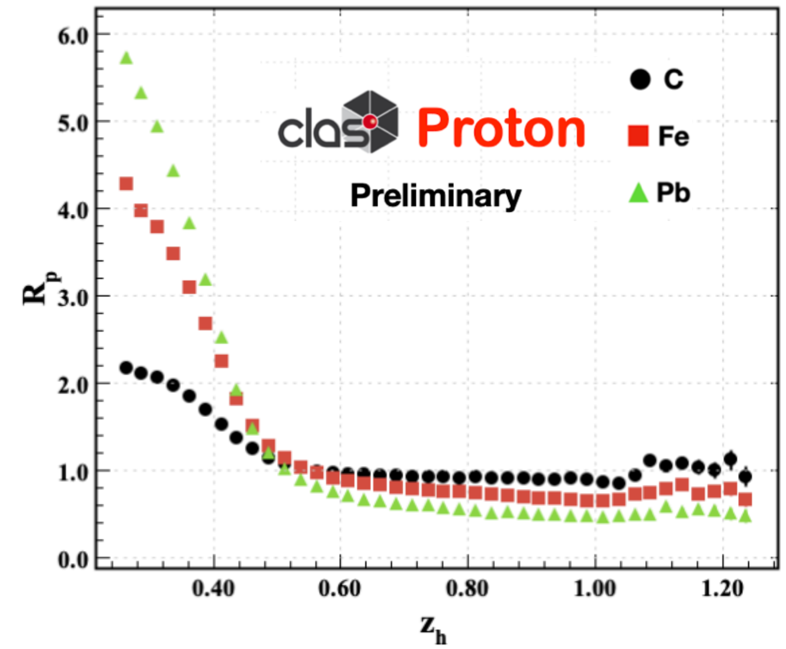
Results from EG2: comparing Λ and p multiplicities

T. Chetry et al.





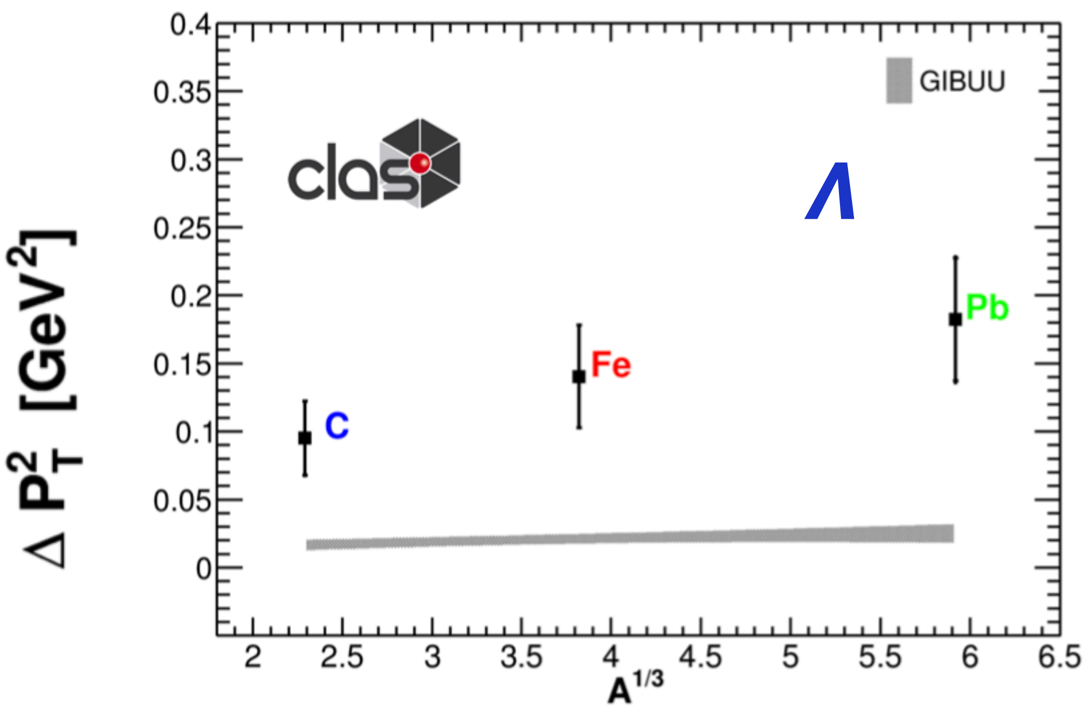
M.Wood



The multiplicity ratio for the lambda and the proton have the same 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



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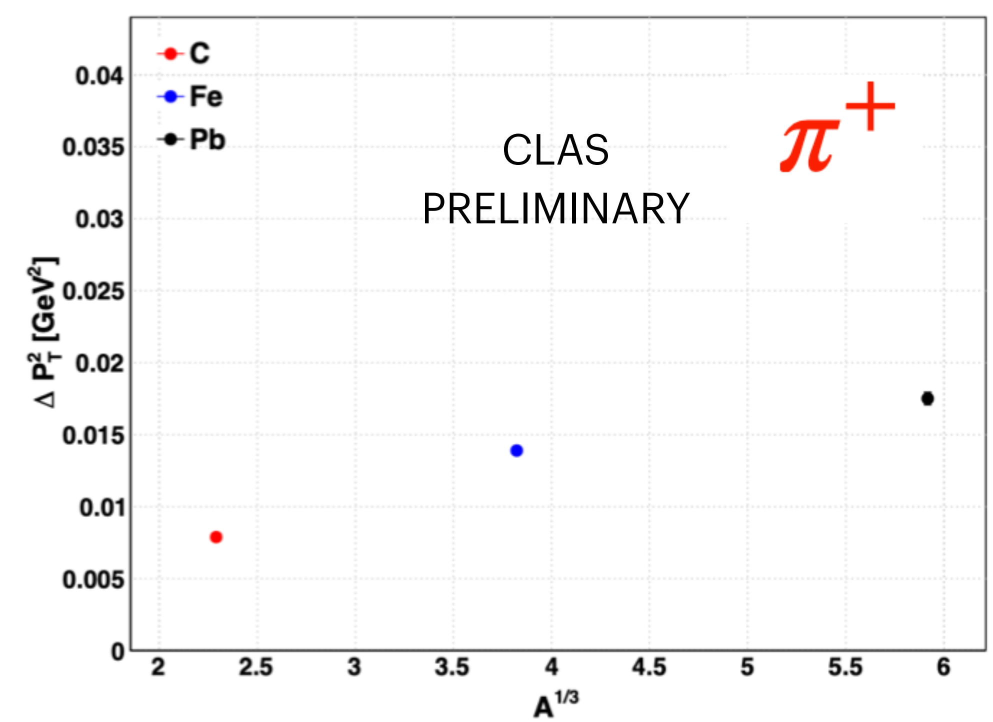


Maximum for **Λ** is 0.3 GeV^2

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.

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.

But how to consistently describe it through experiment?

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

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 85-30
5 March 1985

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

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

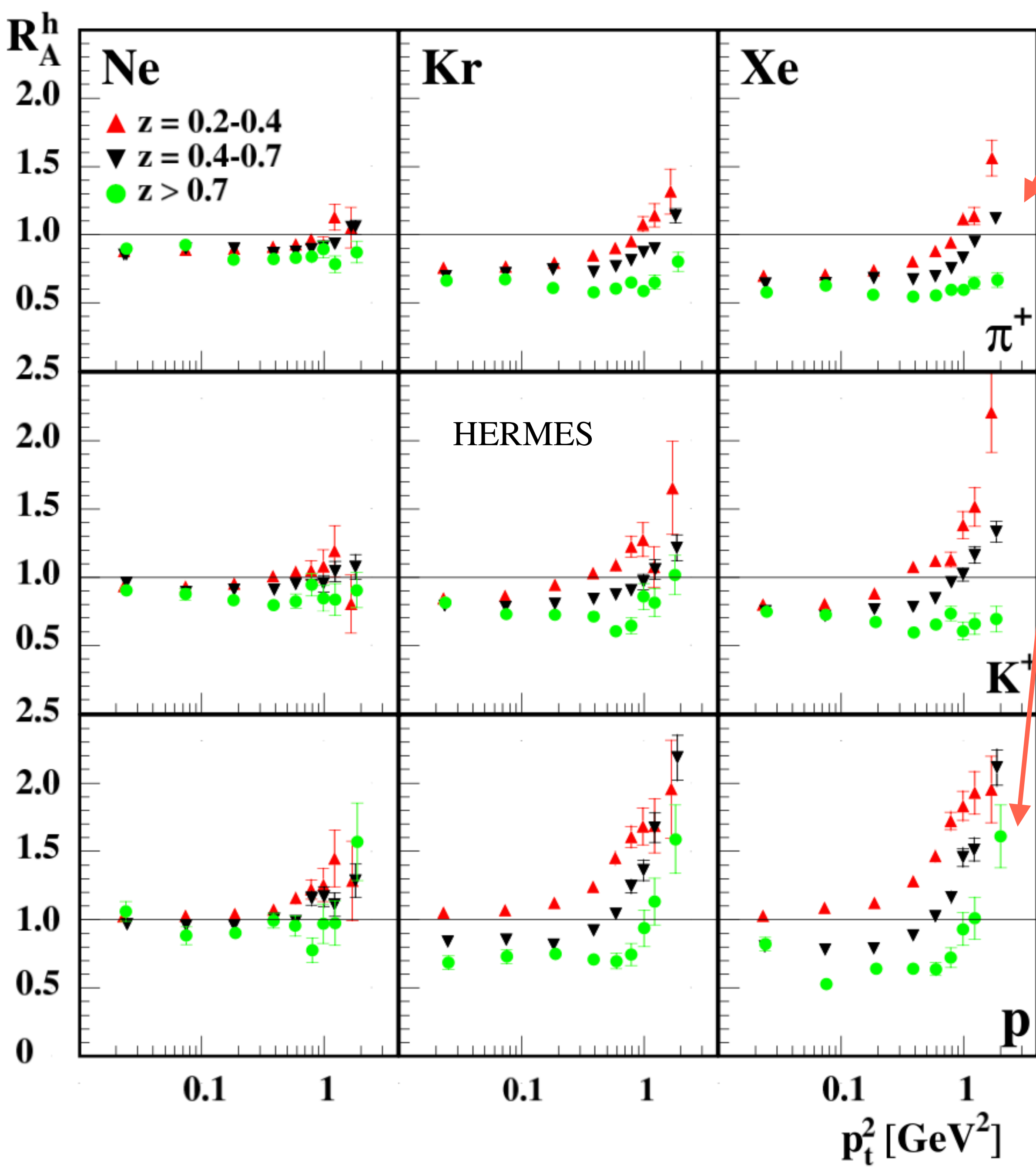
A. Breakstone[1(+)], H.B. Crawley[1], G.M. Dallavalle[5], K. Doroba[6], D. Drijard[3],

Diquarks have been invoked for hadron beam scattering to explain anomalies in proton production!

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

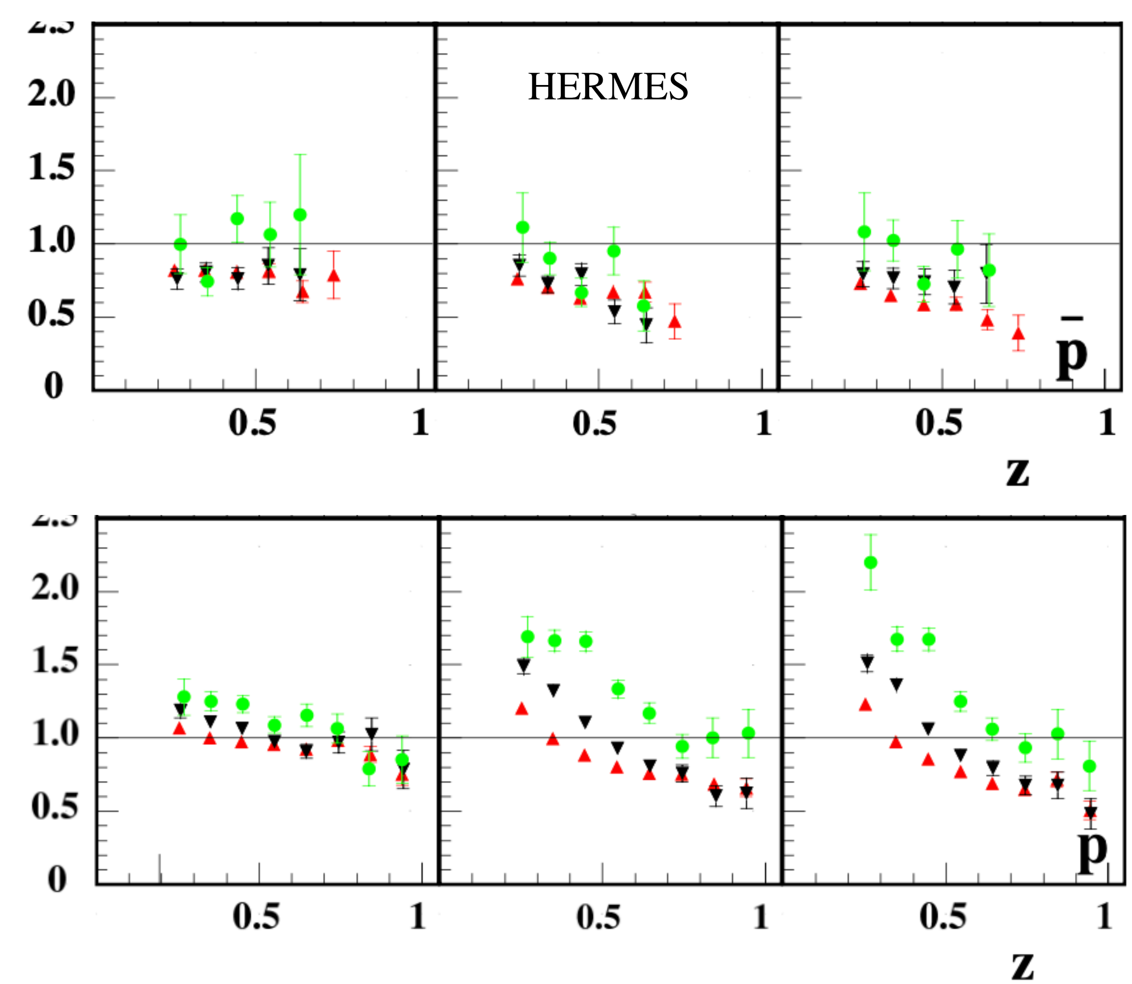
Diquarks: mesons vs baryon behavior

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

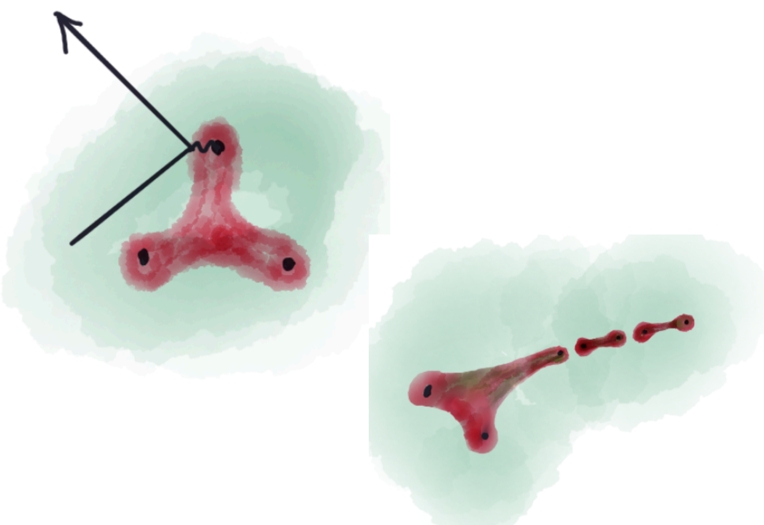
Proton and antiproton are totally different!

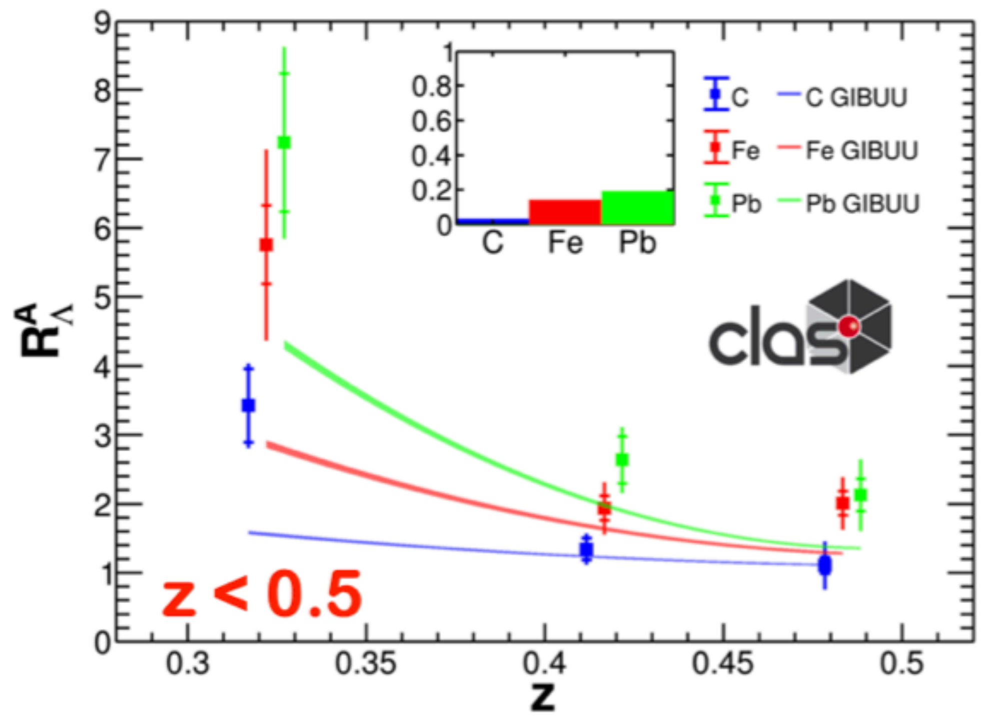


arXiv:1107.3496v3 [hep-ex] 13 Sep 2011
Eur. Phys. J. A47:113, 2011

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

Traditional picture

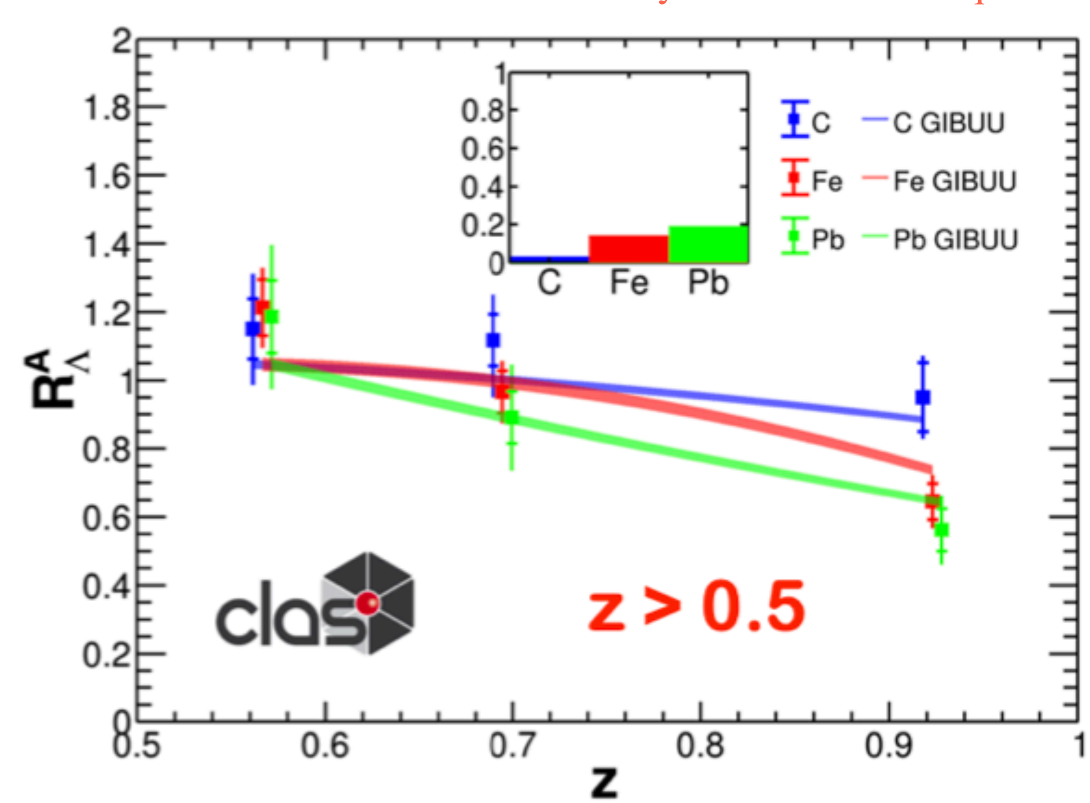




Alternative: direct diquark scattering

W. Brooks, Baryons 2022

For z>0.5 observed hadron is likely to contain struck quark



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)

P, n and Λ could be formed by the scattering off diquark

Will they behave similarly as to containing (ud) diquark?

Or is there difference between light vs heavy spectator quark?

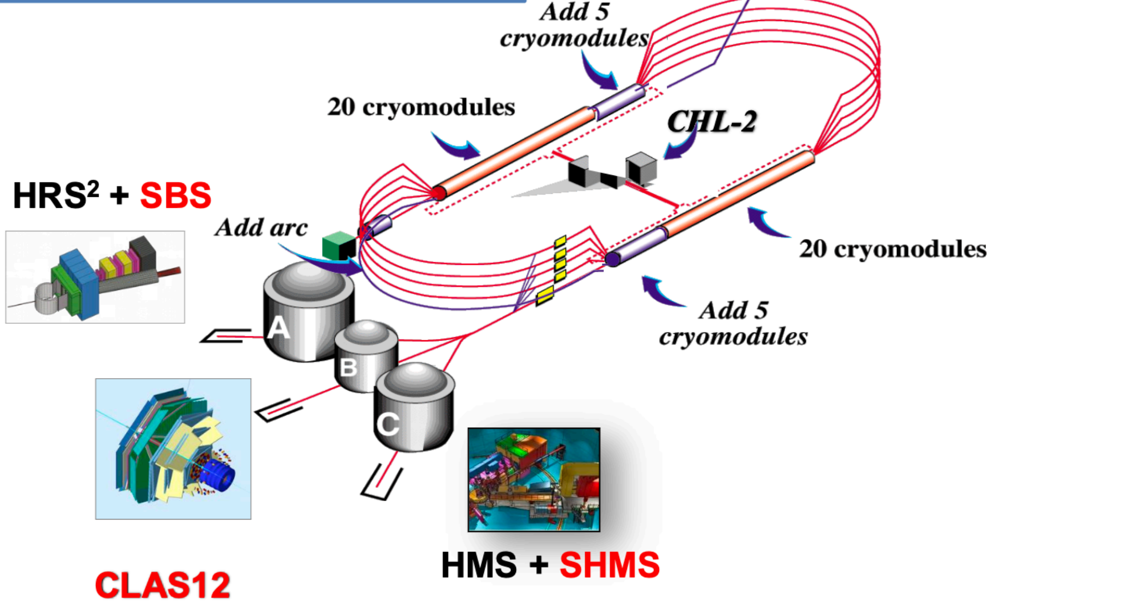
See Anthony Francis talk

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

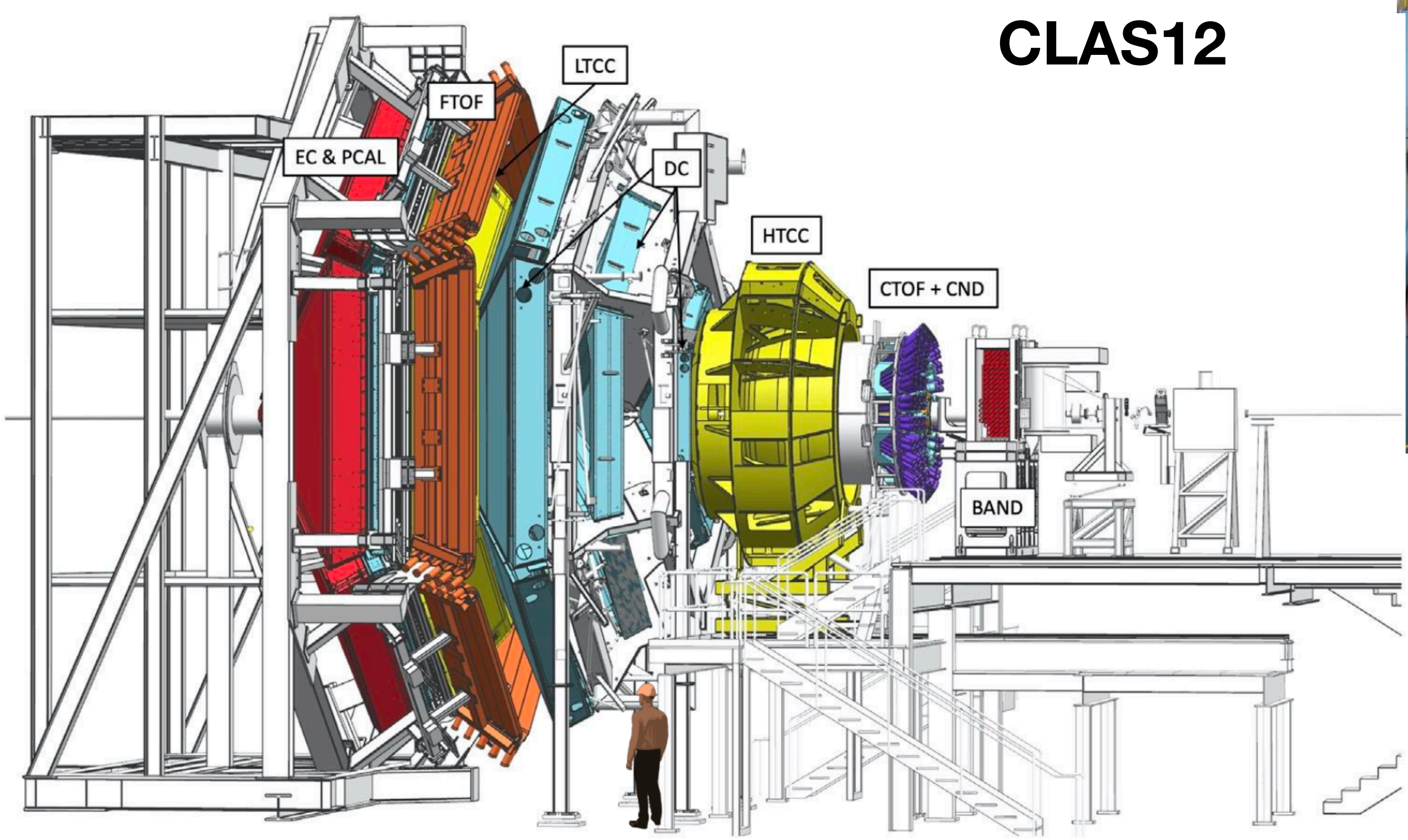
Experimental realization @ CLAS12

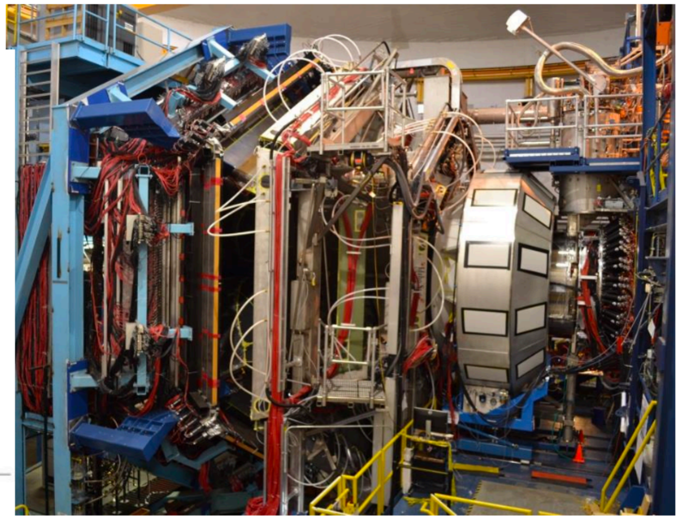
The Jefferson Lab Energy Upgrade

- Maximum energy 12 GeV
- New Experimental Hall D - GlueX
- CLAS12 in Hall B
- Upgrades to existing Halls A & C



CLAS12





- Luminosity - 10^{35}cm^{-2}s^{-1}
- Polarized target operation at 5T
- Charged particle tracking and ID
- Neutron and photon detection
- Data rate 1 Gigabyte/sec
- Charged Particle ID to 8 GeV/c

Latifa Elouadrhiri

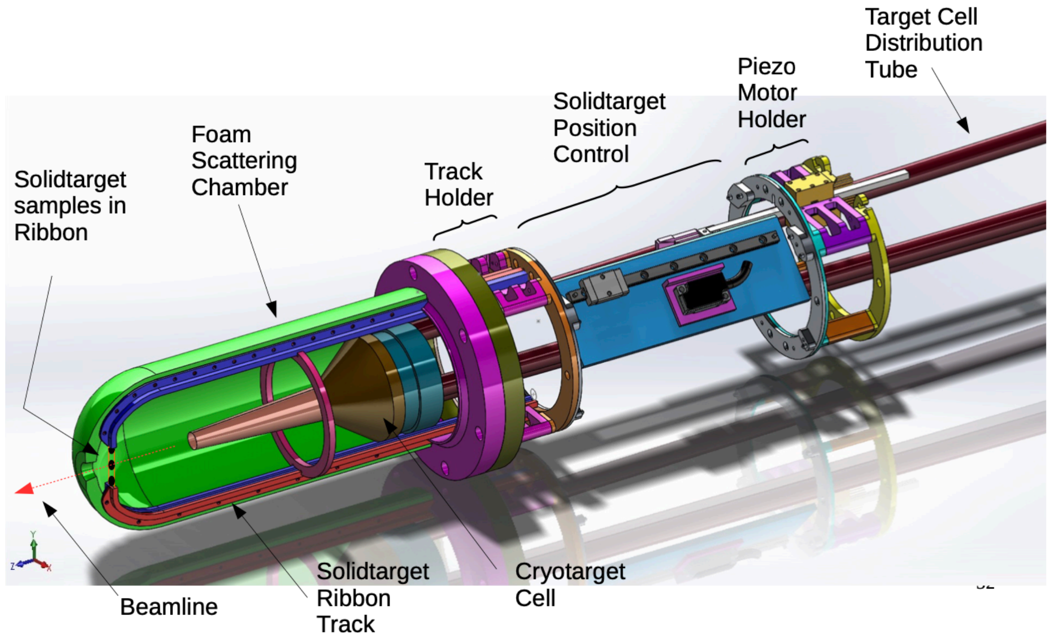
RG-E experiment @ 10.5 GEV

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

Data successfully taken with CLAS12 in Spring, 2024!

RG-E experimental conditions

- Electron beam 10.5 GeV
- Targets ^{2}H, ^{12}C, ^{x}Al, ^{x}Cu, ^{x}Sn, ^{207}Pb
- Integrated Luminosity ~ 10^{41} 1/(s · cm^2)
- Extreme conditions: high vacuum and high magnetic field, low temperatures, radiation hardness, reduced space

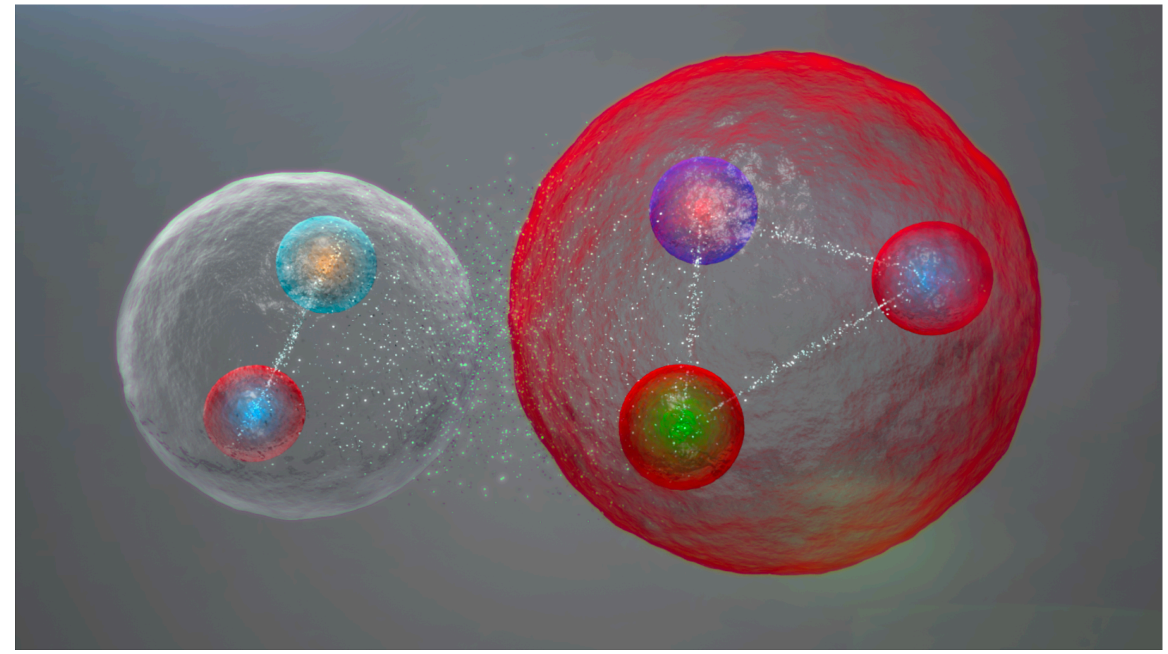


Highlights of double target are in JLUO weekly: https://mailchi.mp/89a150f4d755/jlab-weekly-for-scientific-users-april-3-2024?e=a8d43a7cbe

Quark Propagation and Hadronization at CLAS12

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	5.7% (sys)
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$	3.2% (sys)
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	6.2% (sys)
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	6.7% (sys)
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	8.5% (sys)
ϕ	44 fm	1	$u\bar{u}d\bar{d}s\bar{s}$	5.0% (stat)*
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	-
K^0	27 mm	0.5	$d\bar{s}$	4.7% (sys)
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$	4.4% (sys)
p	stable	0.94	uud	3.2% (sys)
$\bar{p}$	stable	0.94	$\bar{u}\bar{u}\bar{d}$	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



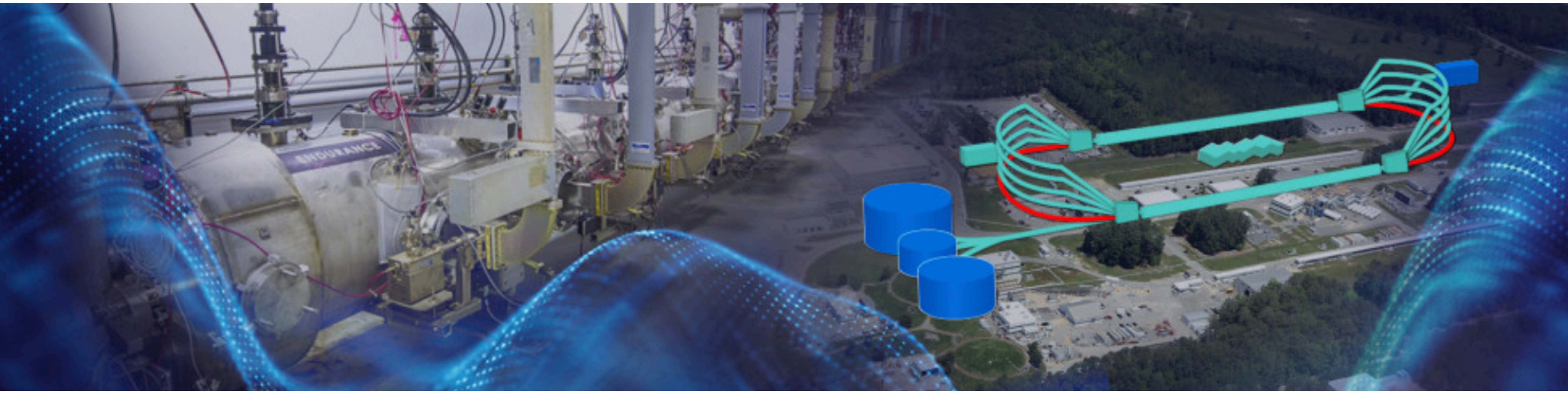
Can study rare and complex cases of hadrons probing mass, strangeness and rank dependence of hadron formation and color propagation

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

eA physics in future facilities

Jefferson Lab at 22 GeV

Replacing the highest-energy arcs with Fixed Field Alternating Gradient arcs to achieve 22 GeV e beam energy

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Nuclear Experiment

[Submitted on 13 Jun 2023]

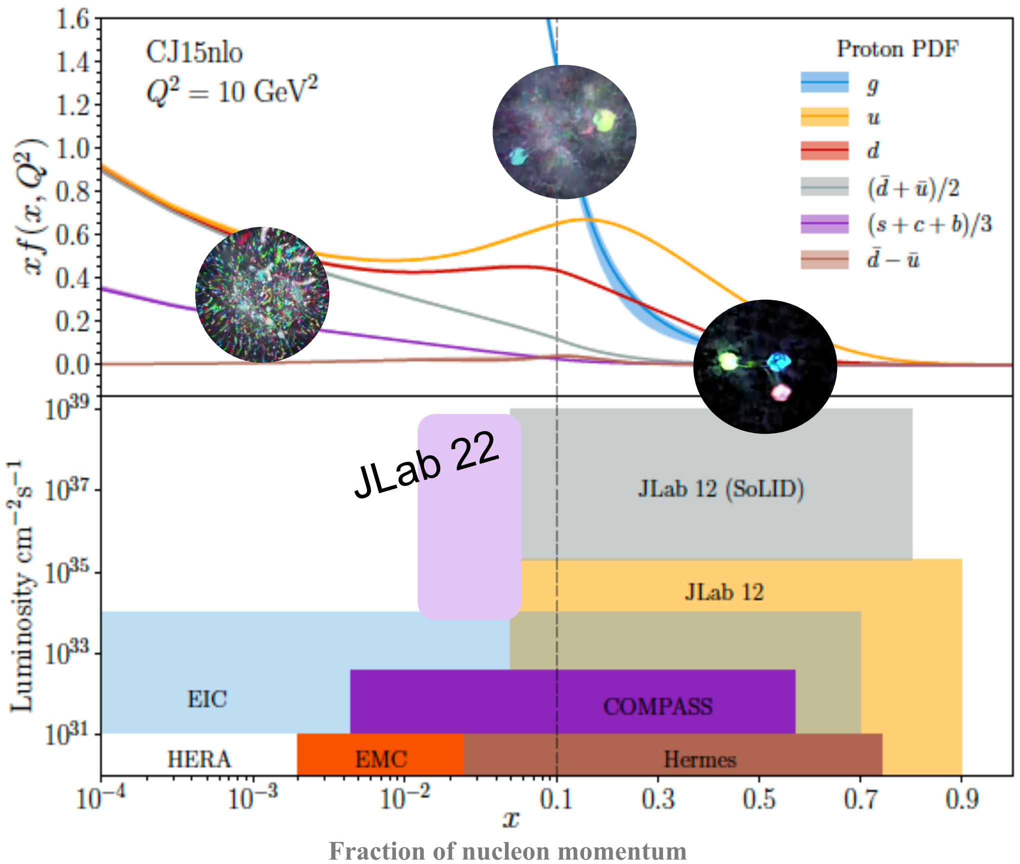
Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

A. Accardi, P. Achenbach, D. Adhikari, A. Afanasev, C.S. Akondi, N. Akopov, M. Albaladejo, H. Albataineh, M. Albrecht, B. Almeida-Zamora, M. Amaryan, D. Androić, W. Armstrong, D.S. Armstrong, M. Arratia, J. Arrington, A. Asaturyan, A. Austregesilo, H. Avagyan, T. Averett, C. Ayerbe Gayoso, A. Bacchetta, A.B. Balantekin, N. Baltzell, L. Barion, P. C. Barry, A. Bashir, M. Battaglieri, V. Bellini, I. Belov, O. Benhar, B. Benkel, F Benmokhtar, W. Bentz, V. Bertone, H. Bhatt, A. Bianconi, L. Bibrzycki, R. Bijker, D. Binosi, D. Biswas, M. Boër, W. Boeglin, S.A. Bogacz, M. Boglione, M. Bondí, Download P. Bosted, G. Bozzi, E.J. Brash, R. A. Briceño, P.D. Brindza, W.J. Briscoe, S.J Brodsky, W.K. Brooks, V.D. Burkert, A. Camsonne, T. Cao, L.S. D.S. Carman, M Carpinelli, G.D. Cates, J. Caylor, A. Celentano, F.G. Celiberto, M. Cerutti, Lei Chang, P. Chatagnon, C. Chen, J-P Chen, T. Chetry, A. Christopher, E. Chudakov, E. Cisbani, I. C. Cloët, J.J. Cobos-Martinez, E. O. Cohen, P. Colangelo, P.L. Cole, M. Constantinou, M. Contalbrigo, G. Costantini, W. Cosyn, C. Cotton, S. Covrig Dusa, Z.-F. Cui, A. D'Angelo, M. Döring, M. M. Dalton, I. Danilkin, M. Davydov, D. Day, F. De Fazio, M. De Napoli, R. De Vita, D.J. Dean, M. Defurne, M. Deur, B. Devkota, S. Dhital et al. (335 additional authors not shown)

- CEBAF will remain prime facility for fixed target e scattering with programs stretching well into 2030s
- A new round of upgrades to CEBAF are presently under technical development: an energy upgrade to 22 GeV and an intense polarized positron beams
- 22 GeV program is a bring between JLab@ 12 GeV and EIC to test theory from lower to higher energies with high precision

Polarized gluon distribution, longitudinal/transverse separations, hadron formation in nuclei, meson form factors and more!

Jefferson Lab at 22 GeV

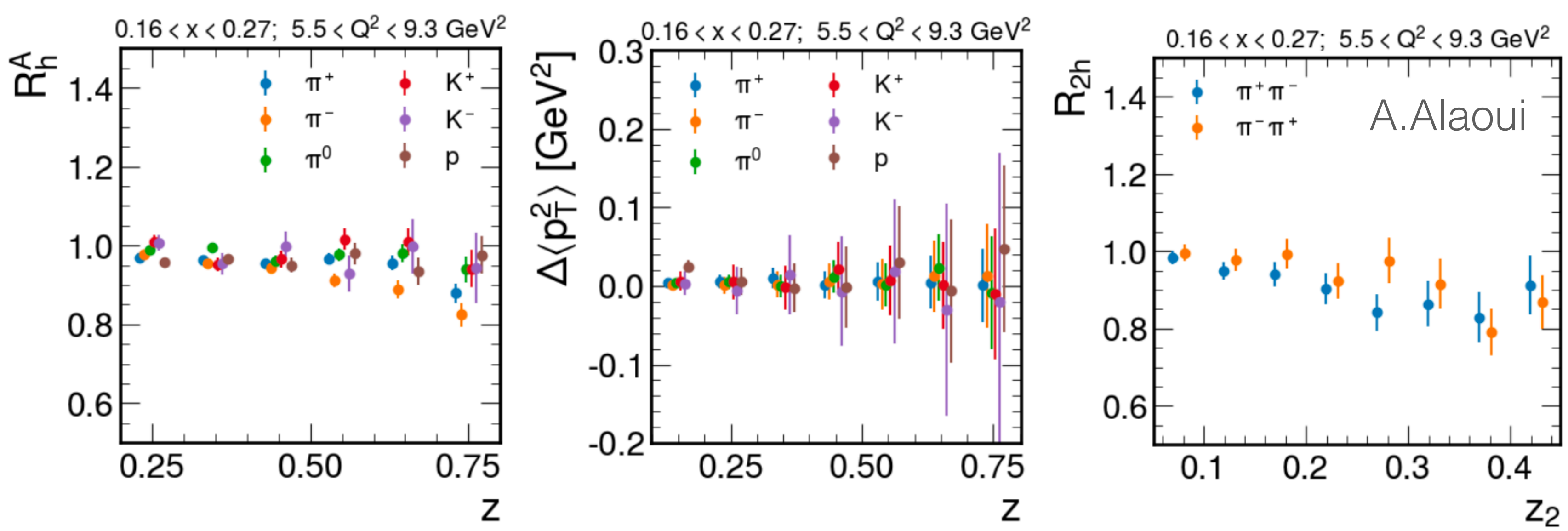


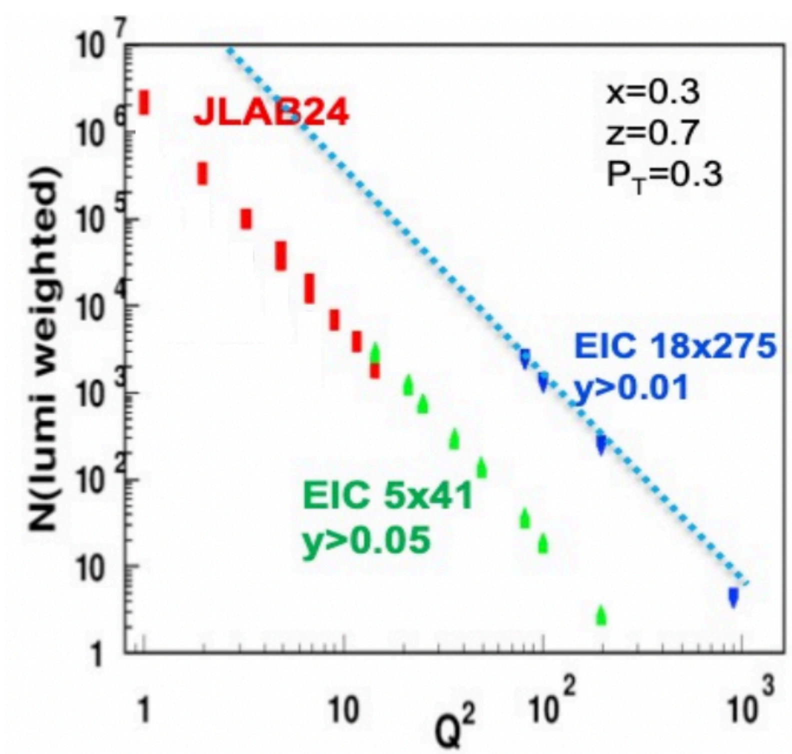
-Large x, low Q^2 evolves to low x, high Q^2 via pQCD, extract parton distribution shape and strength ***from data***

Precision measurements (2D,3D) in the valence regime requiring high luminosity are the purview of JLab, providing overlap with EIC into the low x region

see Thia Keppel's talk

https://arxiv.org/abs/2306.09360



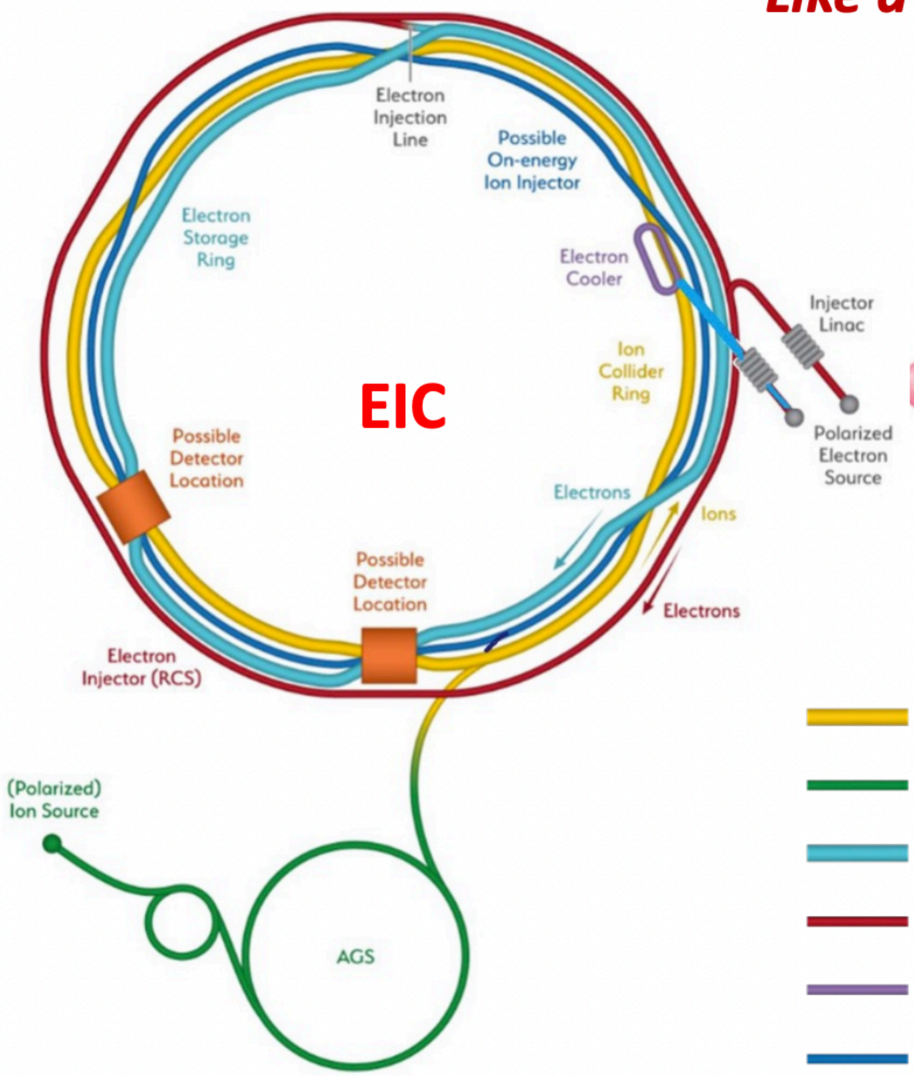


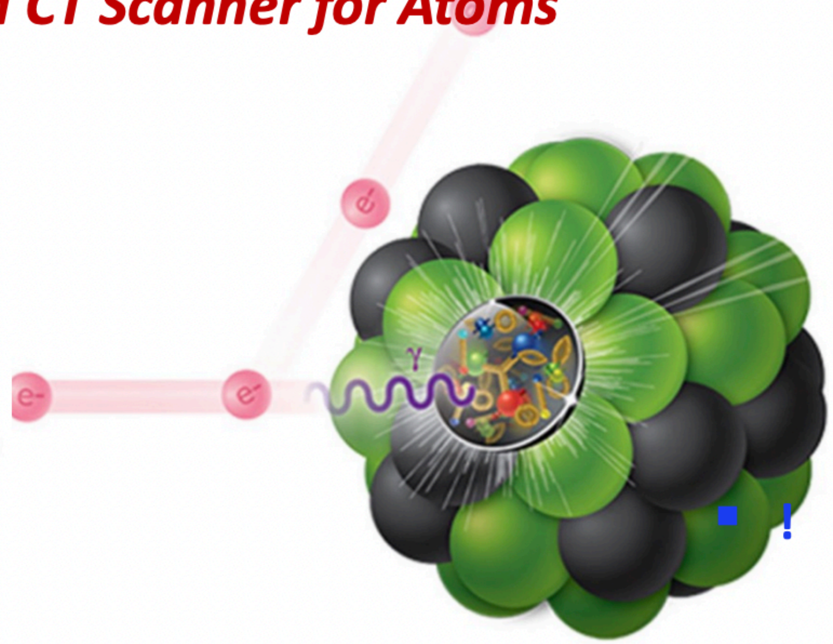
P.Rossi IWHHS-2023

EIC @ Brookhaven

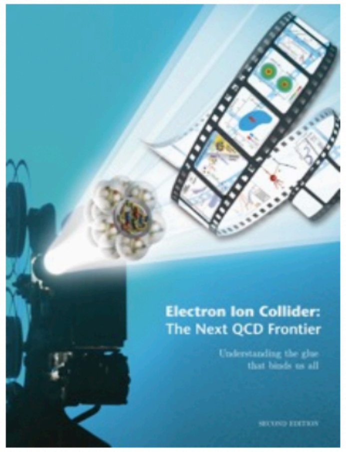
A machine that will unlock the secrets of the strongest force in Nature

Like a CT Scanner for Atoms





- Hadron Storage Ring
- Hadron Injector Complex
- Electron Storage Ring
- Electron Injector Synchrotron
- Electron Cooler
- Possible On-energy Hadron Injector Ring



Basic Tech Requirements

- **Center of Mass Energies:**
  20 GeV – 141 GeV
- **Required Luminosity:**
  10^{33} - 10^{34} $cm^{-2}s^{-1}$
- **Hadron Beam Polarization:**
  80%
- **Electron Beam Polarization:**
  80%
- **Ion Species Range:**
  p to Uranium
- **Number of interaction regions:**
  up to two

from Jianwei Qiu

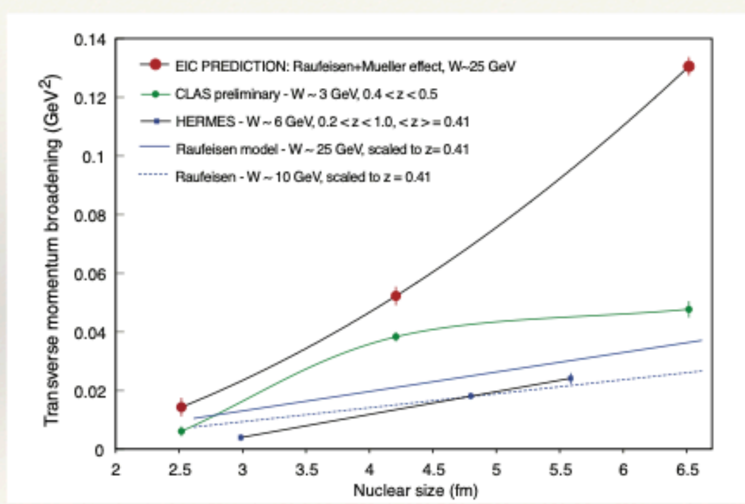
Emergence of hadrons @ EIC

- Saturation for parton densities, particularly for gluons. Enhanced in lower energy in eA then in ep
  Gluon transverse momentum k_T characterizes degree to which saturation is occurring: $Q_s \sim k_T$

$$Q^2_{sat}(b, E) = \Delta p^2_T(b, E)$$ *

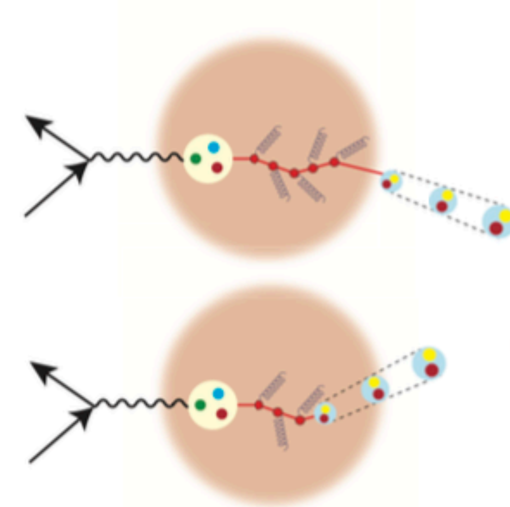
- Access to purely partonic energy losses
  Proportional to the gluon and parton density of the medium **

pQCD description of quark energy loss on p_T broadening



- Understanding *energy loss of light vs heavy quarks* transversing the cold nuclear matter. Connection to energy loss in hot QCD.

❑ Femtometer sized detector:



$$\nu = \frac{Q^2}{2mx}$$

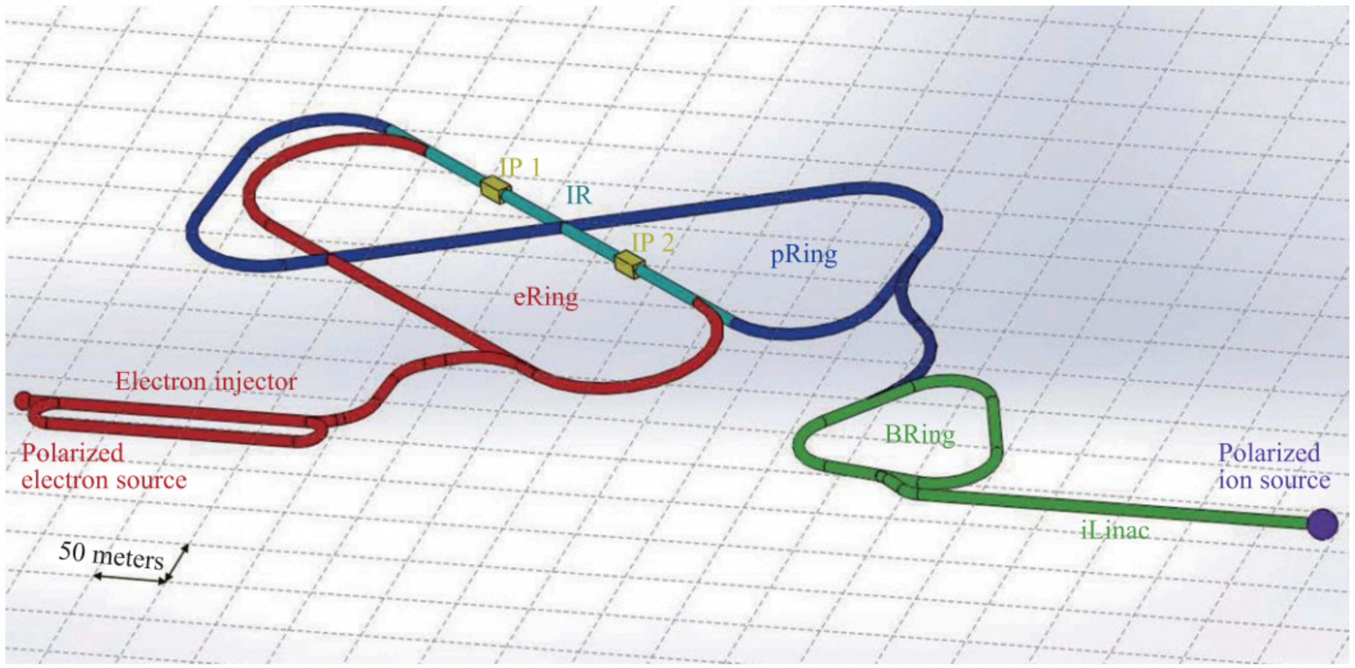
Control of ν and medium length!

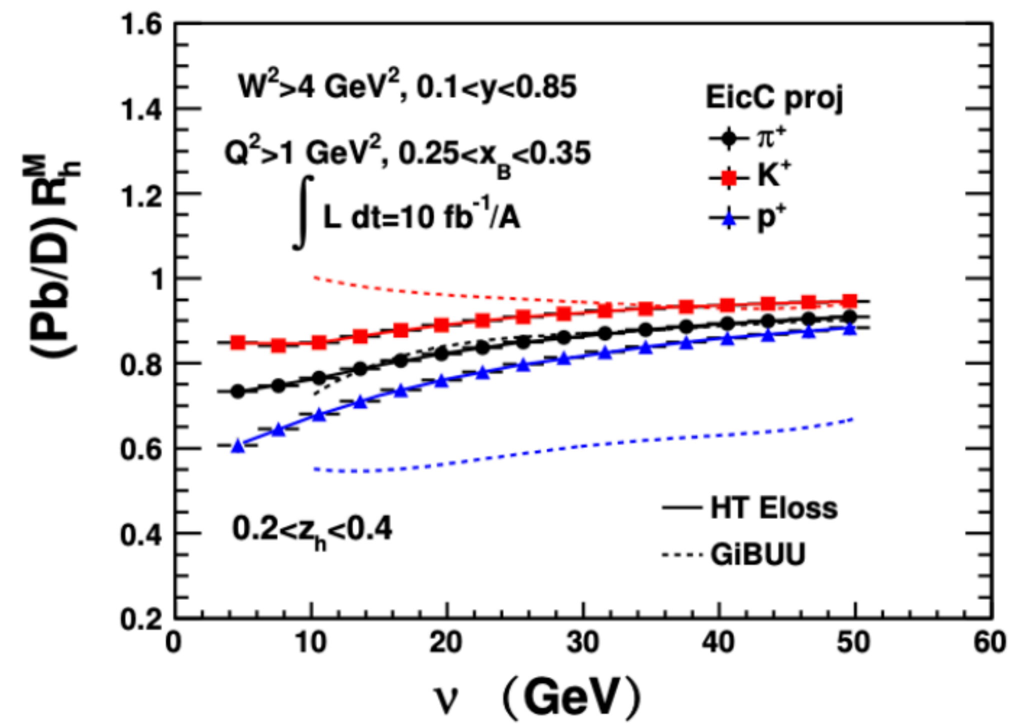
Mass dependence of hadronization

* B. Z. Kopeliovich, I. K. Potashnikova, and Iván Schmidt, Phys. Rev. C 81 (2010)

** R. Baier, Y.L. Dokshitzer, A.H. Muller, D. Schiff, Nucl. Phys.B531 (1998)

EicC (China)





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

EicC allows to disentangle two mechanisms: parton energy loss (Lp ~> Rpb) vs hadron absorption (GiBUU)

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 and time scale for the formation of hadrons
- Pion data is well described by GiBUU, 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^+ / π^- and π^0 multiplicities; Λ multiplicity ratios and $\Delta pT2$; di-hadron production
  - In process: p multiplicities, $\Delta pT2$ for π^+ (E.Molina), $\Delta pT2$ for double pion production, π^+ azimuthal dependencies, Bose-Einstein correlations, ω and η multiplicities

- Successful realization of CLAS12 experiment (E12-06-117) at 11 GeV. Access to 4D multiplicities and large spectrum of hadrons
- Future continuation of *eA* hadronization program with JLab @ 22 GeV, EIC and EicC

HEP NP 2025

9TH International Conference on High Energy Particle and Nuclear Physics in the LHC Era

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- NEUTRINO PHYSICS
- PARTICLE DETECTORS AND INSTRUMENTATIONS
- FUTURE EXPERIMENTAL FACILITIES
- BEYOND THE STANDARD MODEL PHYSICS
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