Exploring the Potential Role of Diquarks in Hadronization: Insights from SIDIS off Nuclear Targets

XV Latin American Symposium on High Energy Physics

4 November, 2024

Taisiya Mineeva

Jefferson Lab

clas
CEBAF Large Acceptance Spectrometer

CCTVal
CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

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.

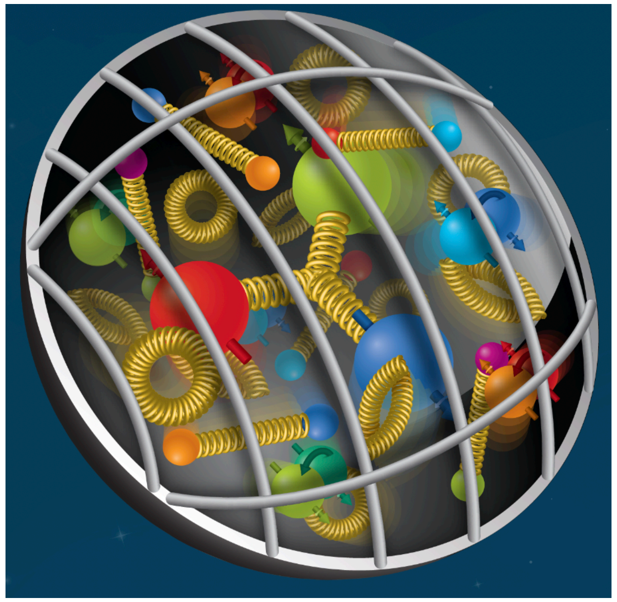
<u>But how to consistently describe it through experiment?</u>

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

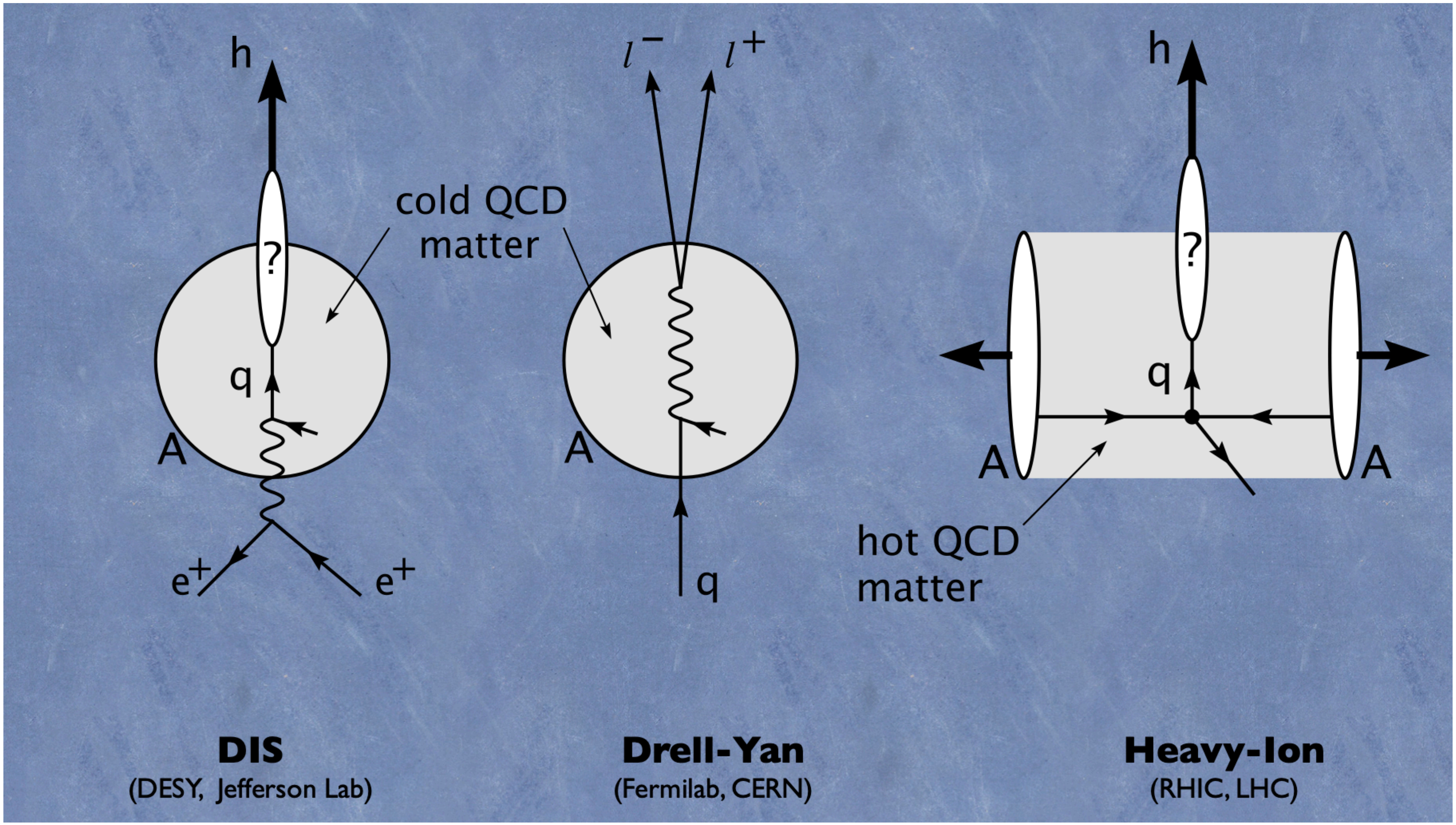
Hadronization: what's the deal?

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]

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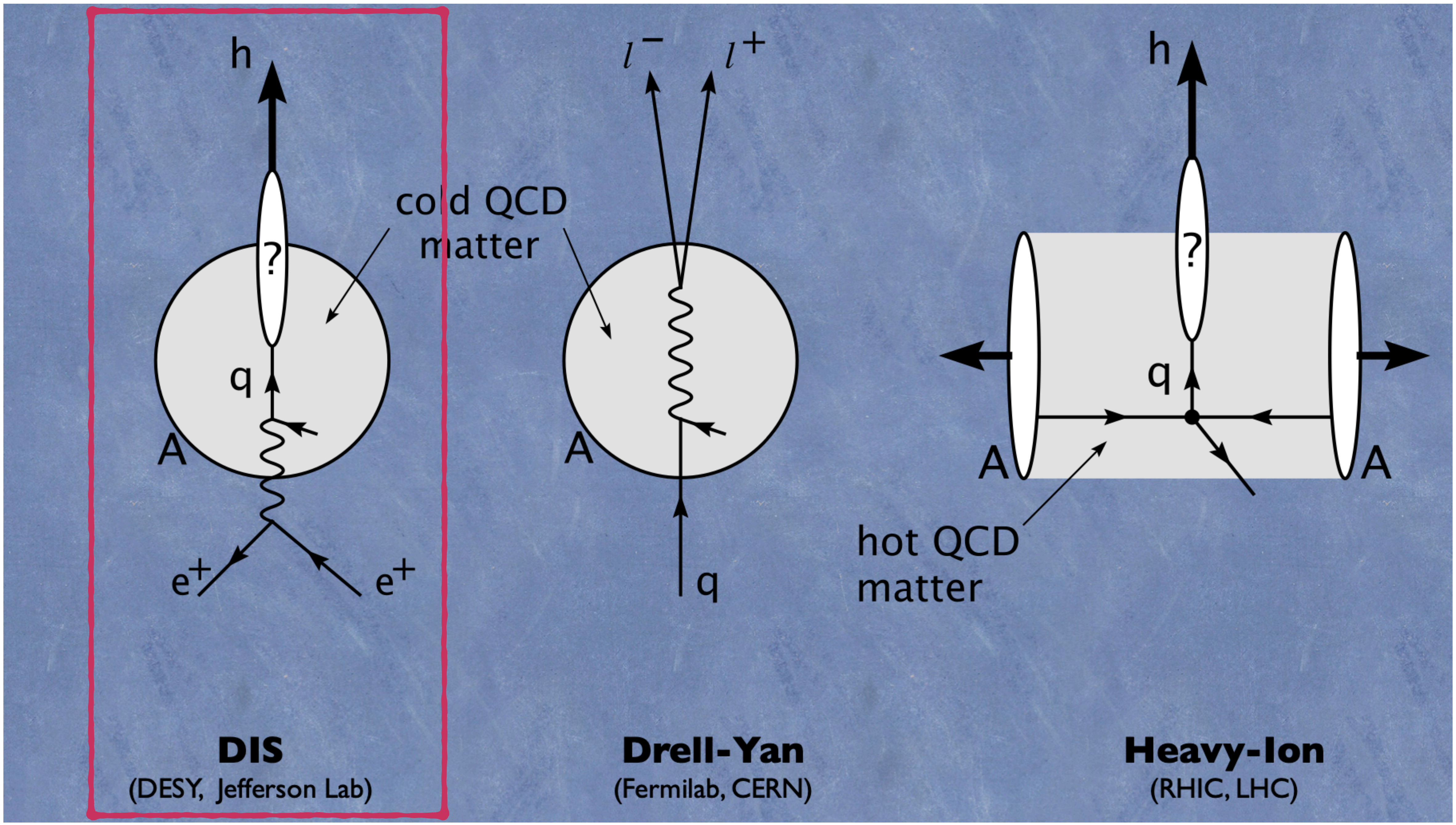
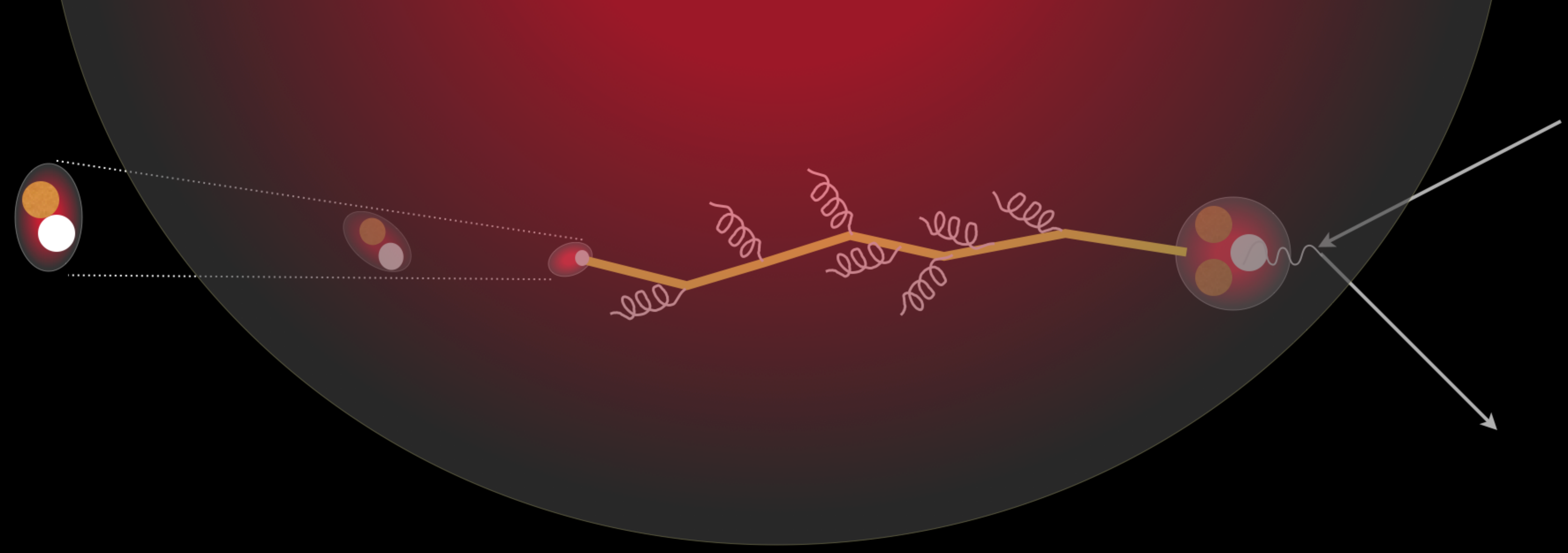
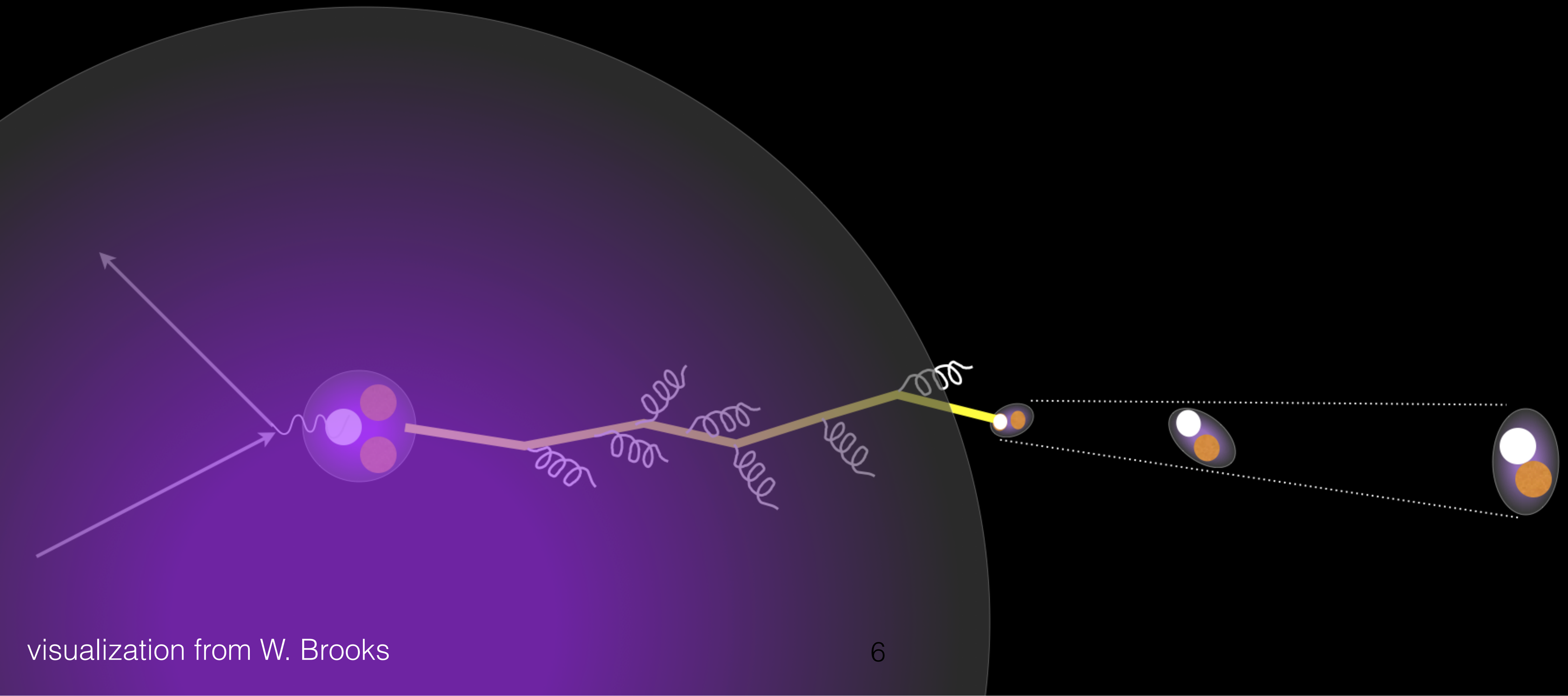


Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]



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



visualization from W. Brooks

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*

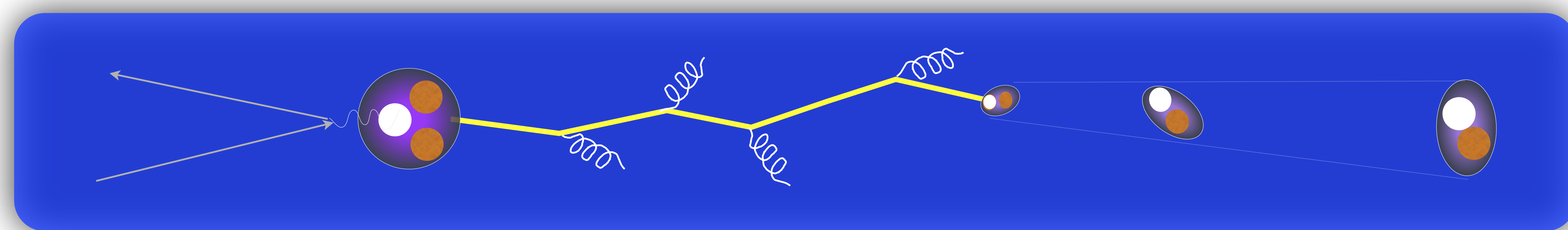
In-medium hadron formation in DIS

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

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

Transverse Momentum Broadening

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

Experimental Observables

Hadronic Multiplicity Ratio

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

Connects to hadron formation phase τ_f

Transverse Momentum Broadening

Connects to color lifetime τ_p and quark energy losses

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

Multiplicity ratio **R_A** is just like **R_{AA}**

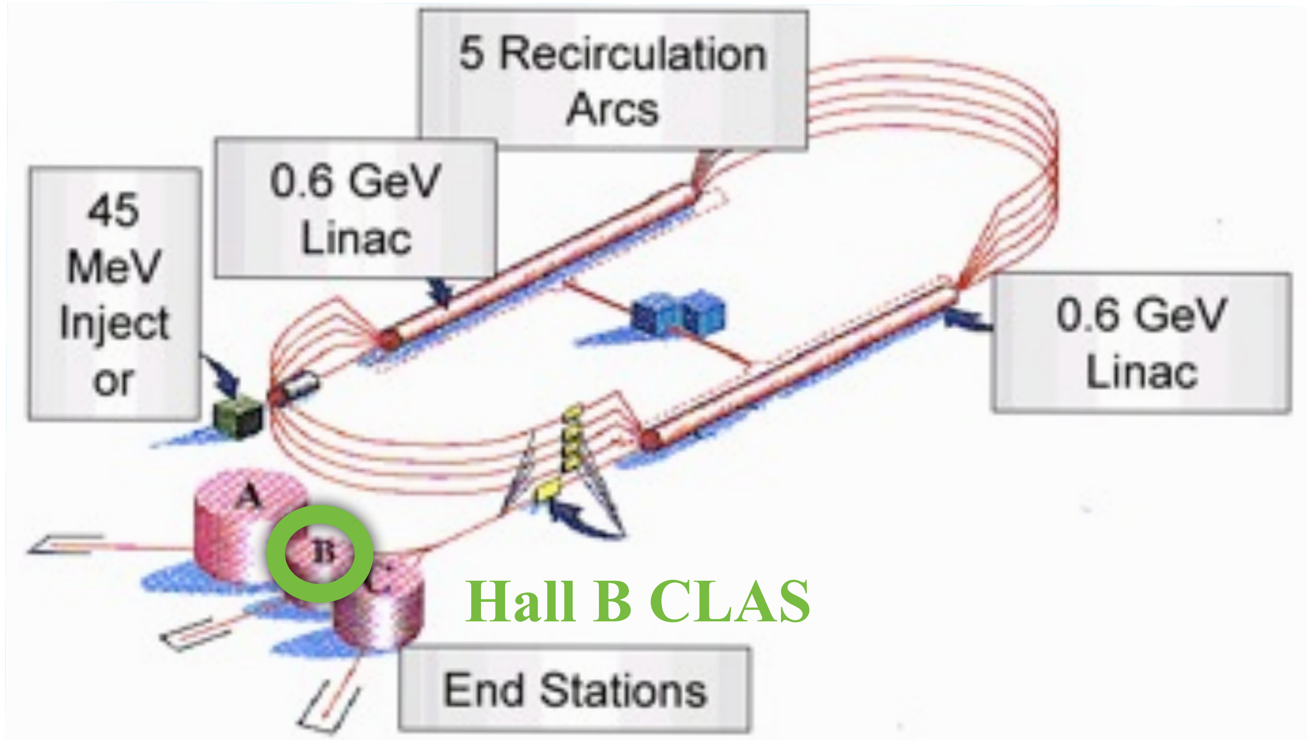
it is the ratio of

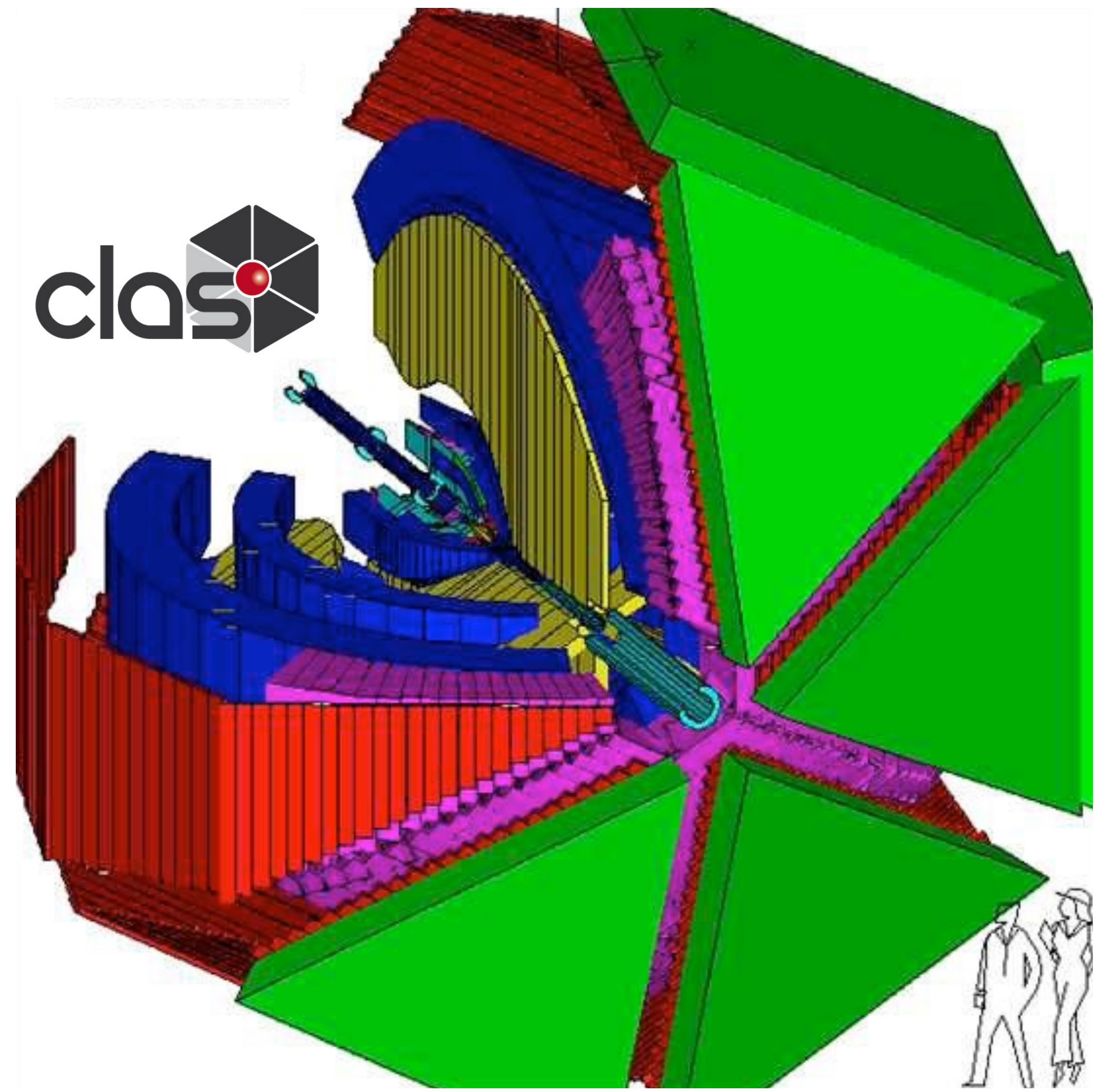
the probability of a process in electron-ion collisions (e+A) to the same probability in electron-deuteron collisions (eD)

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

if R_M =1 no effect due to the nucleus
if R_M <1 we call it suppression
if R_M >1 we call it enhancement

CEBAF and CLAS @ 6 GEV





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

CEBAF **L**arge **A**cceptance **S**pectrometer

- 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^+

EG2 experiment @ 5 GEV

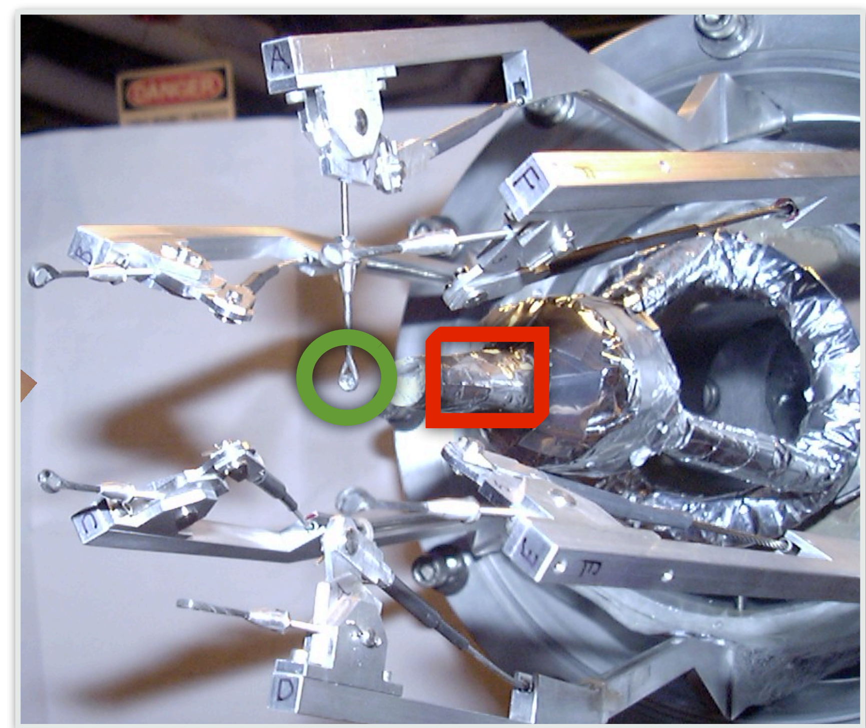
Jefferson Lab

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

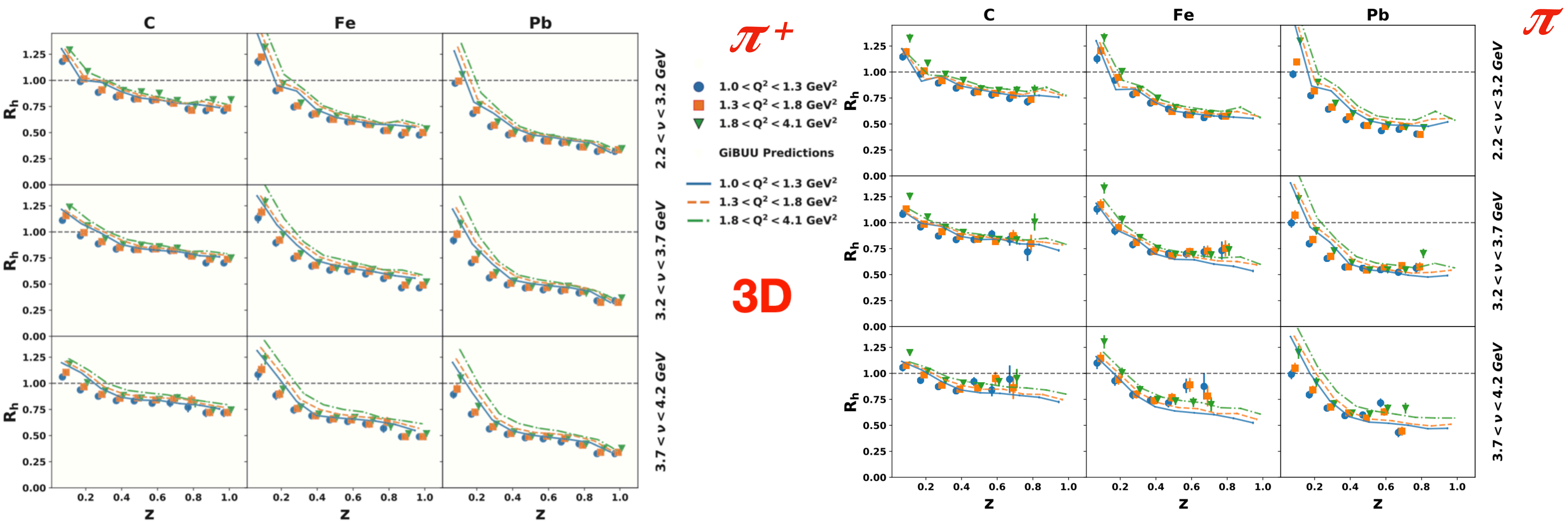


Light hadrons: multiplicity ratios from EG2

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

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

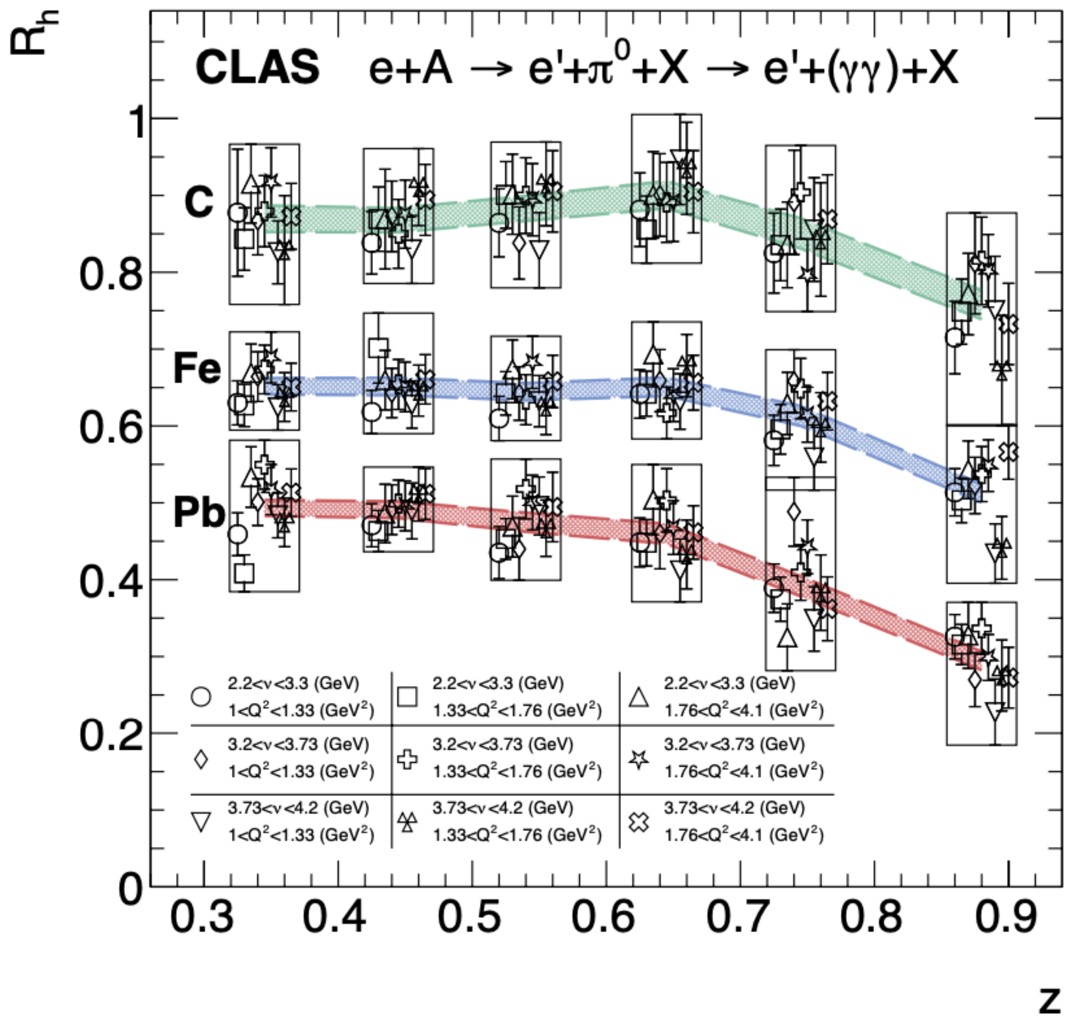
S. Morán,[1,3] R. Dupre,[2] H. Hakobyan,[1,52] M. Arratia,[3] W. K. Brooks,[1] A. Bórquez,[1] A. El Alaoui,[1] L. El Fassi,[4,5] K. Hafidi, R. Mendez,[1] T. Mineeva,[1] S. J. Paul,[3] M. J. Amaryan,[36] Giovanni Angelini,[19] Whitney R. Armstrong,[5] H. Atac,[43]



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

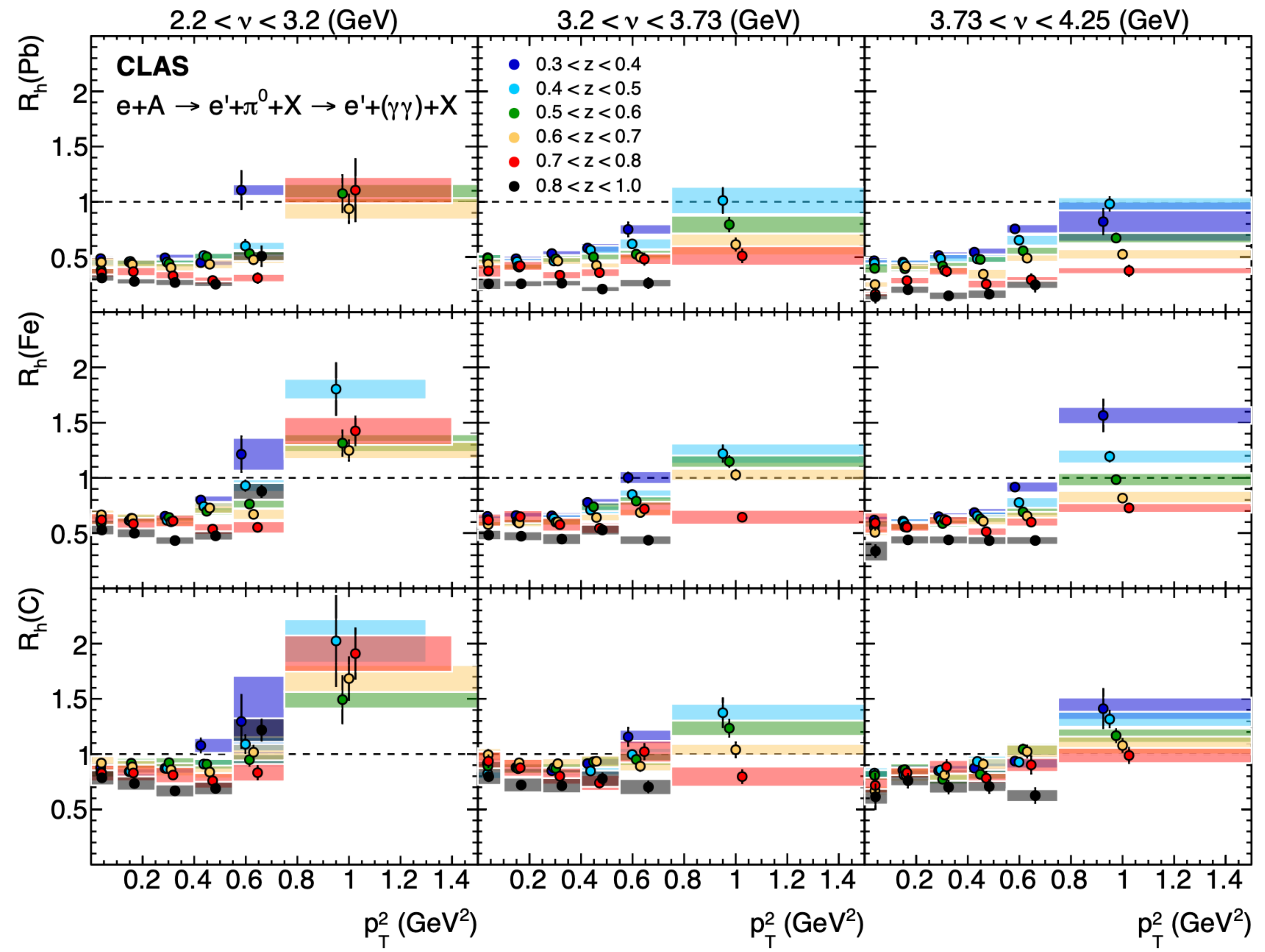
Light hadrons: multiplicity ratios from EG2

T.Mineeva et al. arXiv:2406.04513



π^0

3D



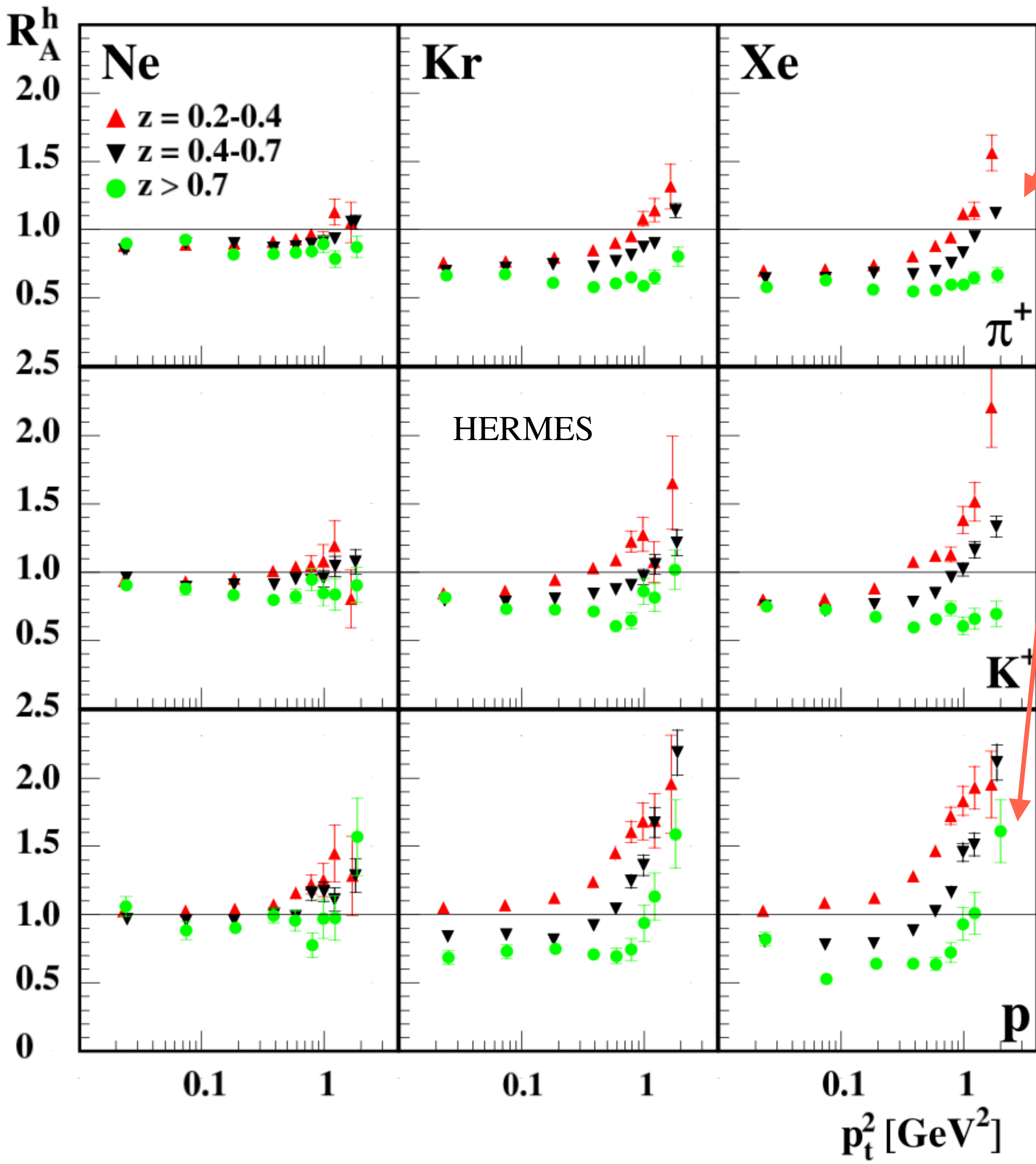
- Attenuation depends on nuclear size *A*
- Suppression for leading hadrons: 25% on C to 75% on Pb
- No dependence on Q^2 and ν observed

- 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

Diquarks search

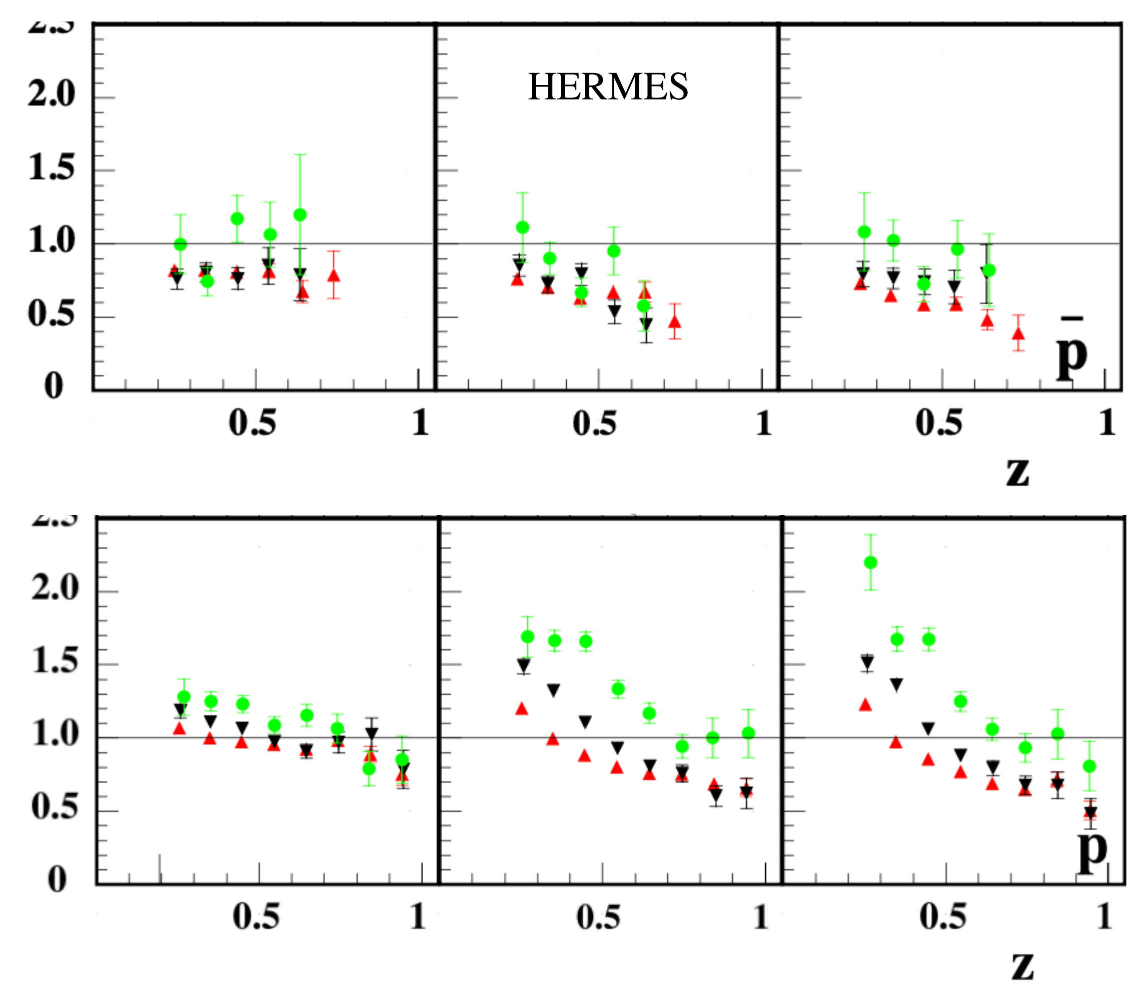
Diquarks: mesons vs baryon behavior

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!

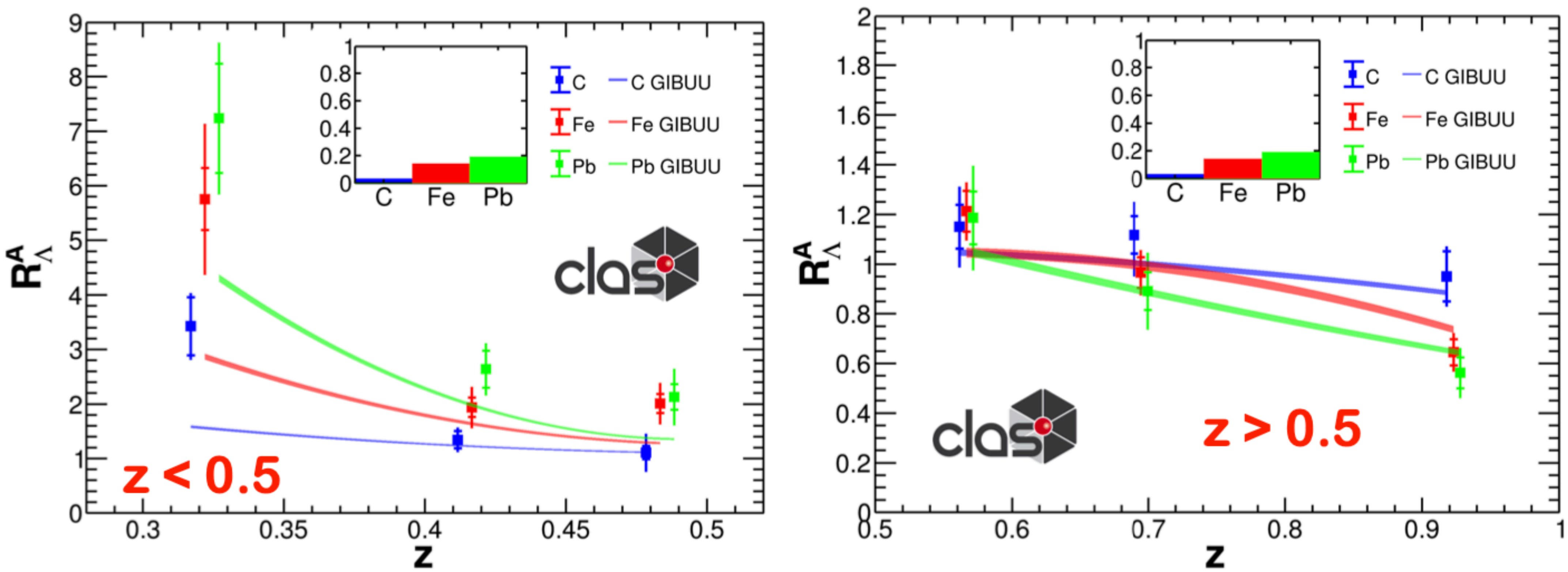


arXiv:1107.3496v3 [hep-ex] 13 Sep 2011
Eur. Phys. J. A47:113, 2011

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



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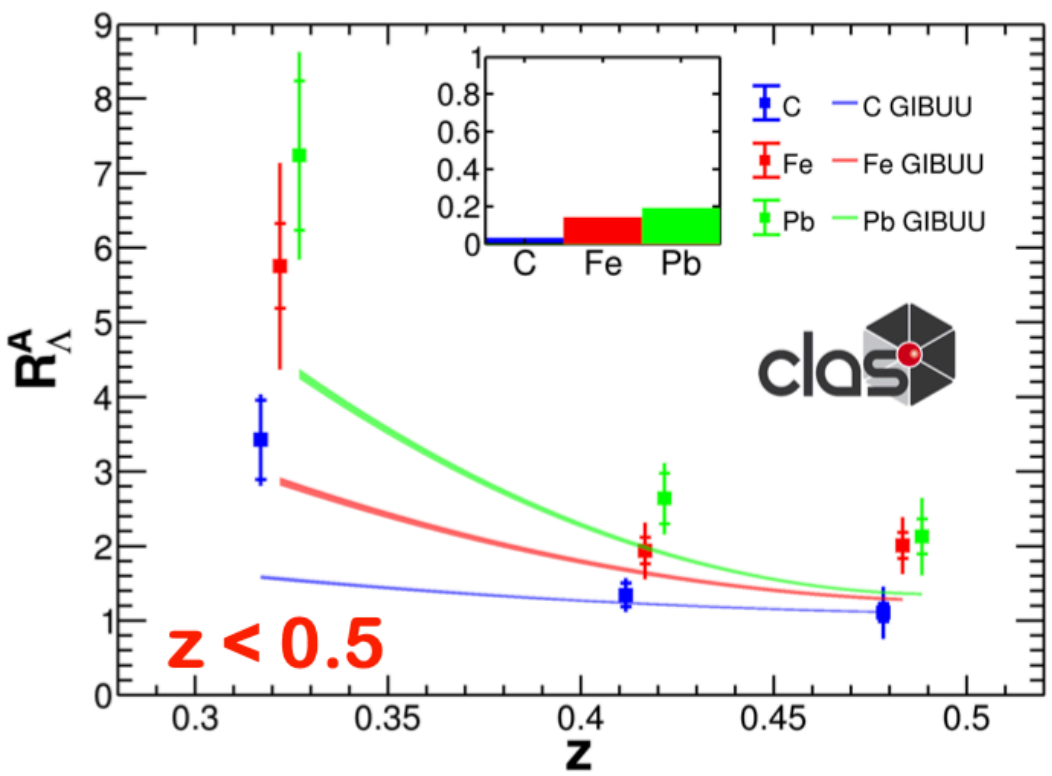
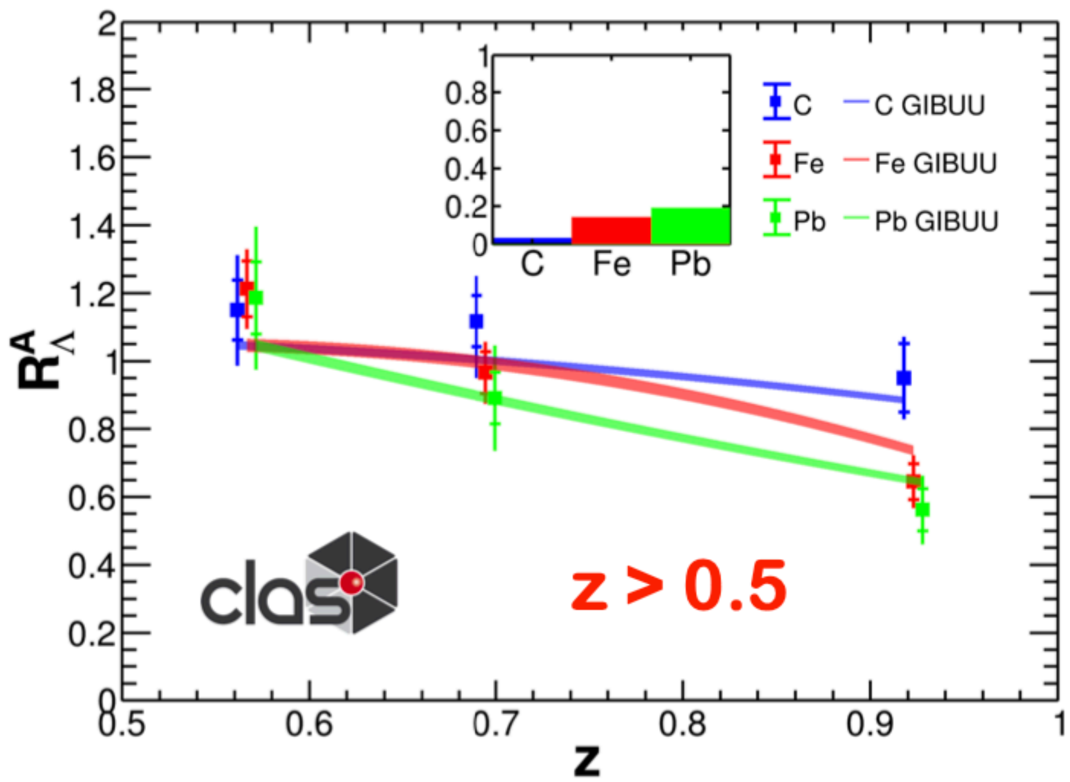
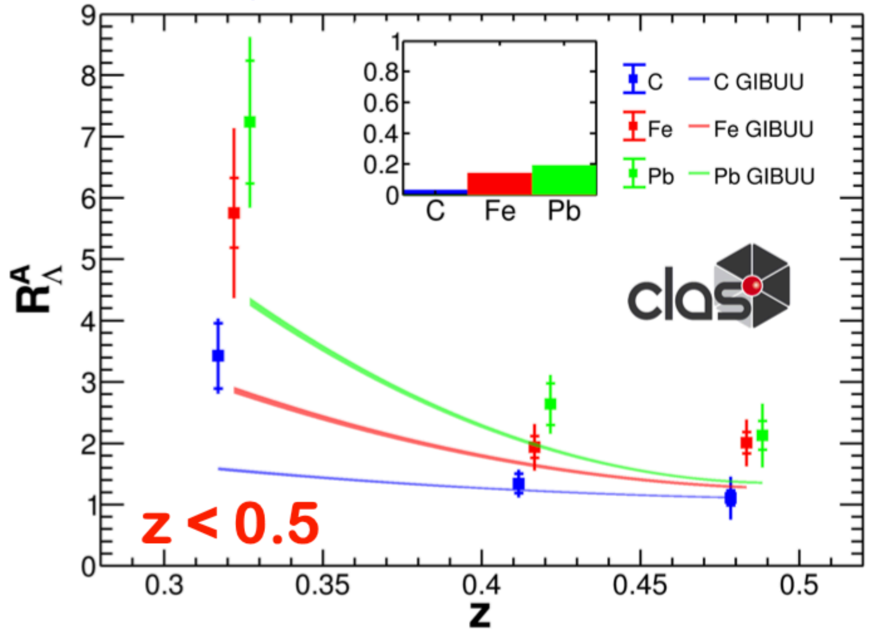


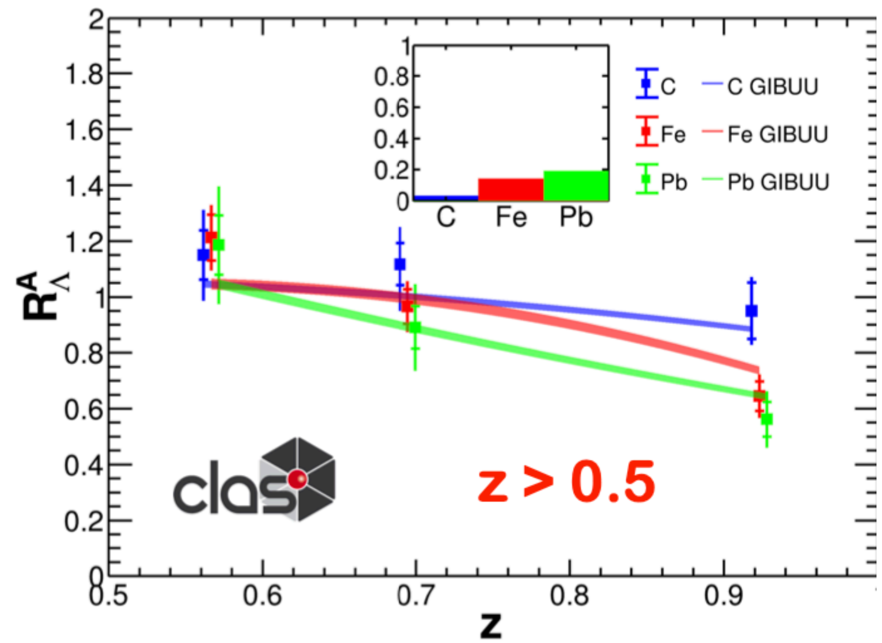


- At low-z there is a “pile up” of events 7 times more than for pion! Underpredicted by GiBUU.
- At high-z there is little attenuation compared to that on the pion. Agrees with GiBUU.

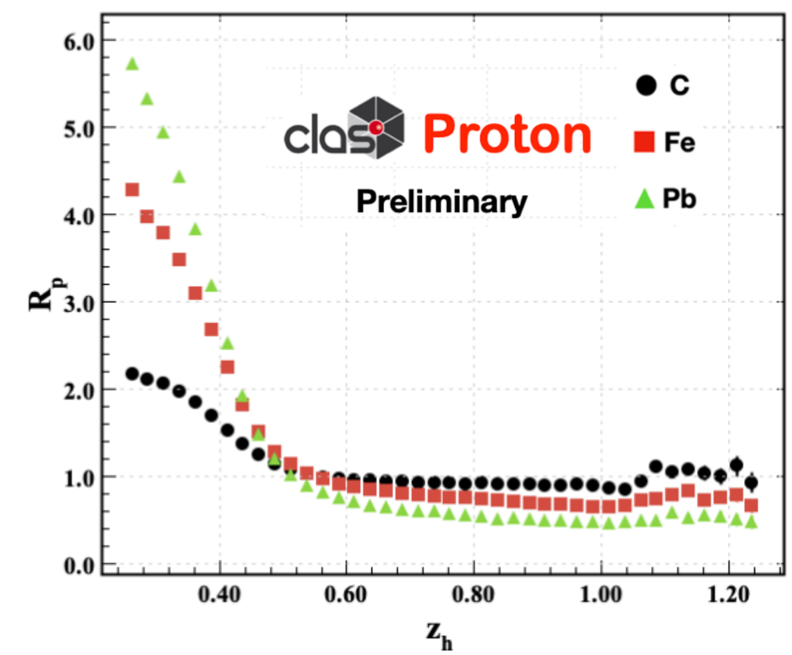
Results from EG2: comparing Λ and p multiplicities

T. Chetry et al.





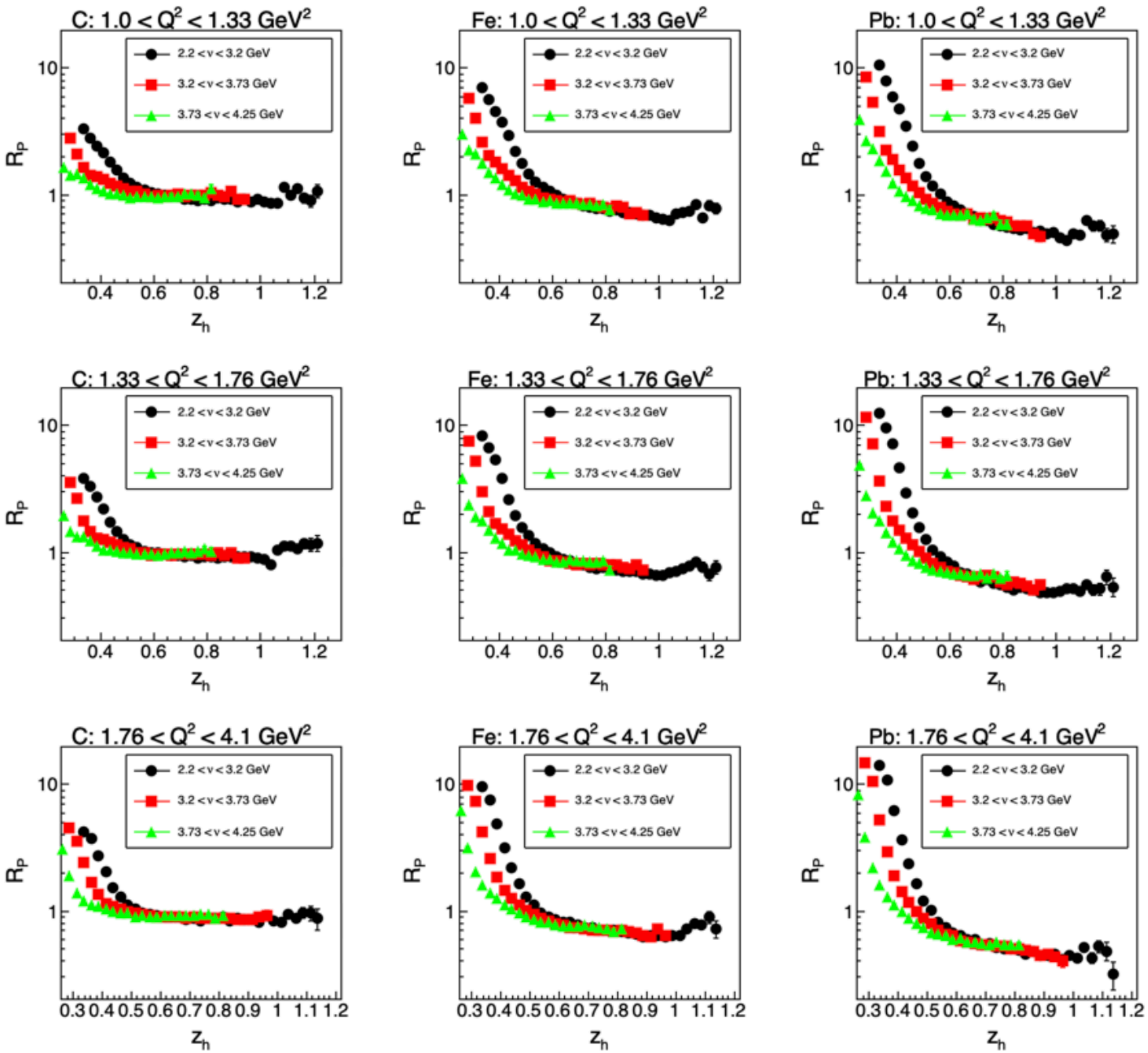
M.Wood



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

3D Multiplicities on proton

Michael Wood



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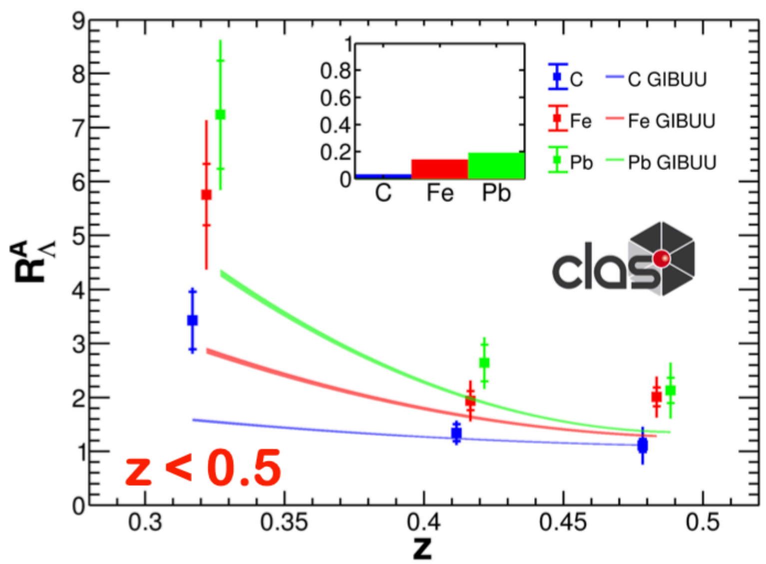
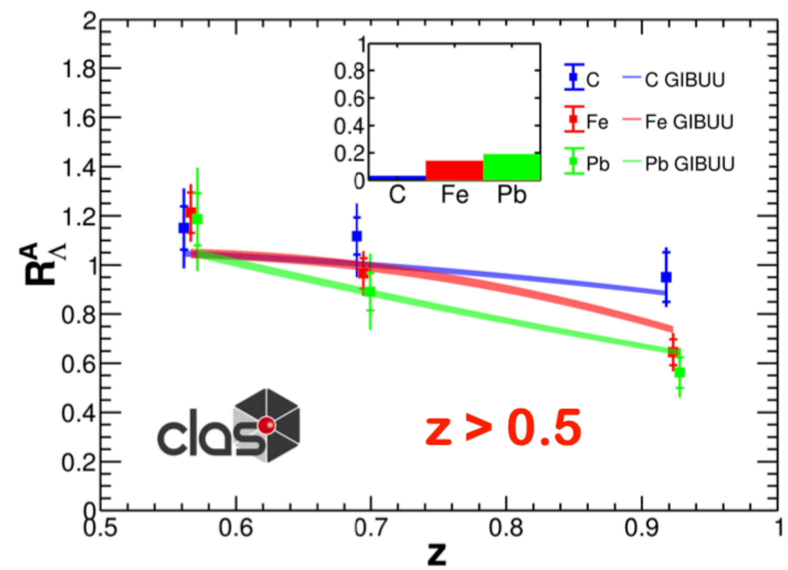
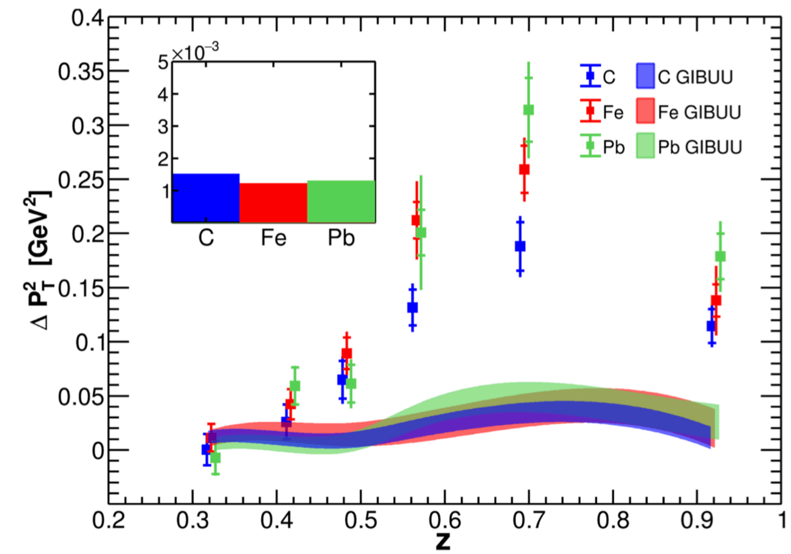


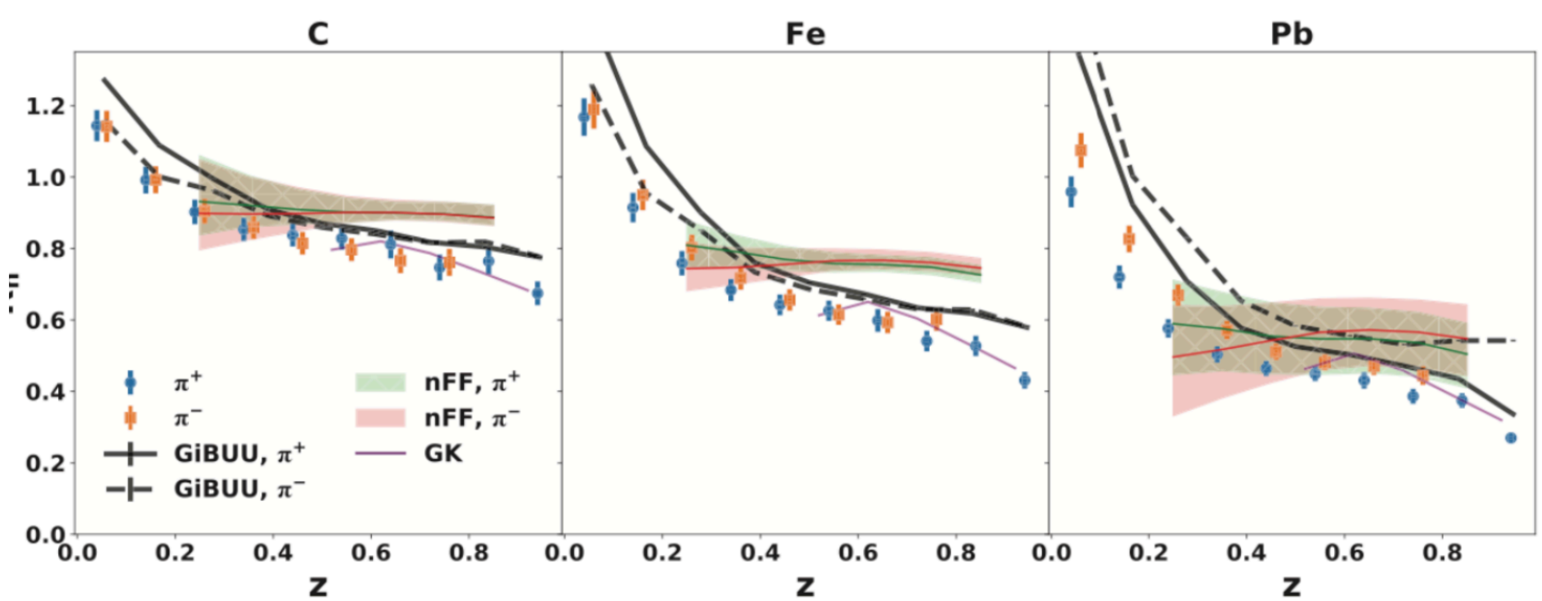




Enhancement of Λ events at low z is huge compared to pion production: 7 vs. ~1.0

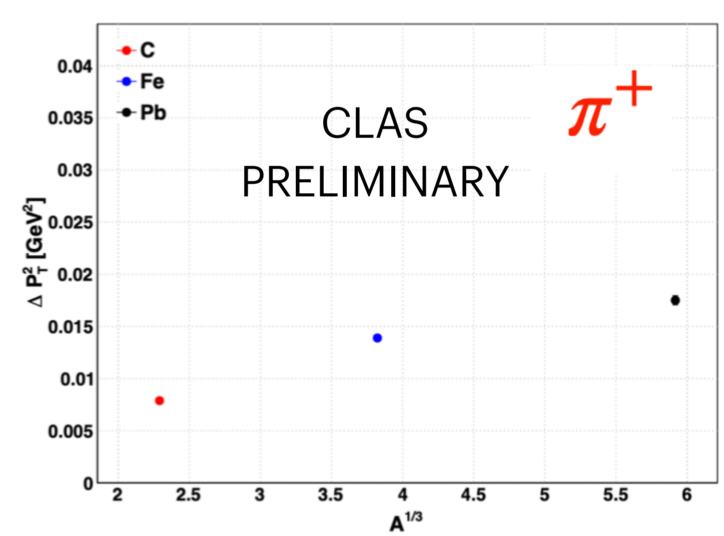
Less attenuation at high z

ΔpT2 on Λ is huge compared to pion: 0.3 vs 0.03 GeV^2



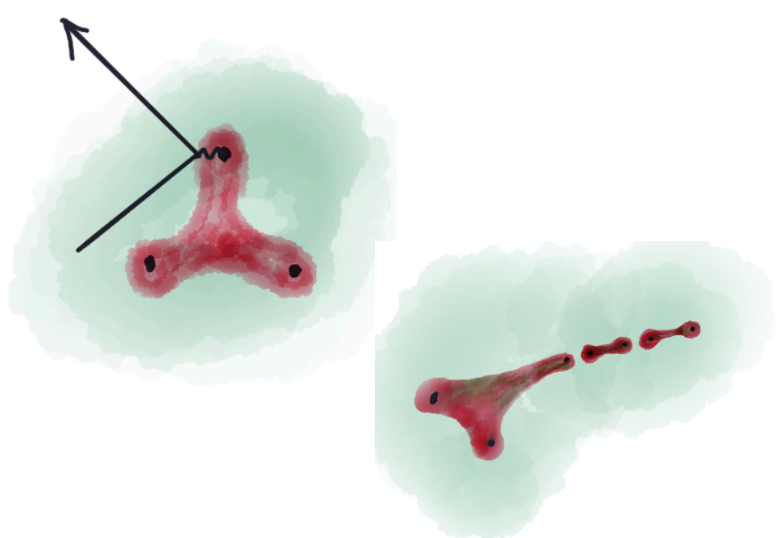
π^+
π^-

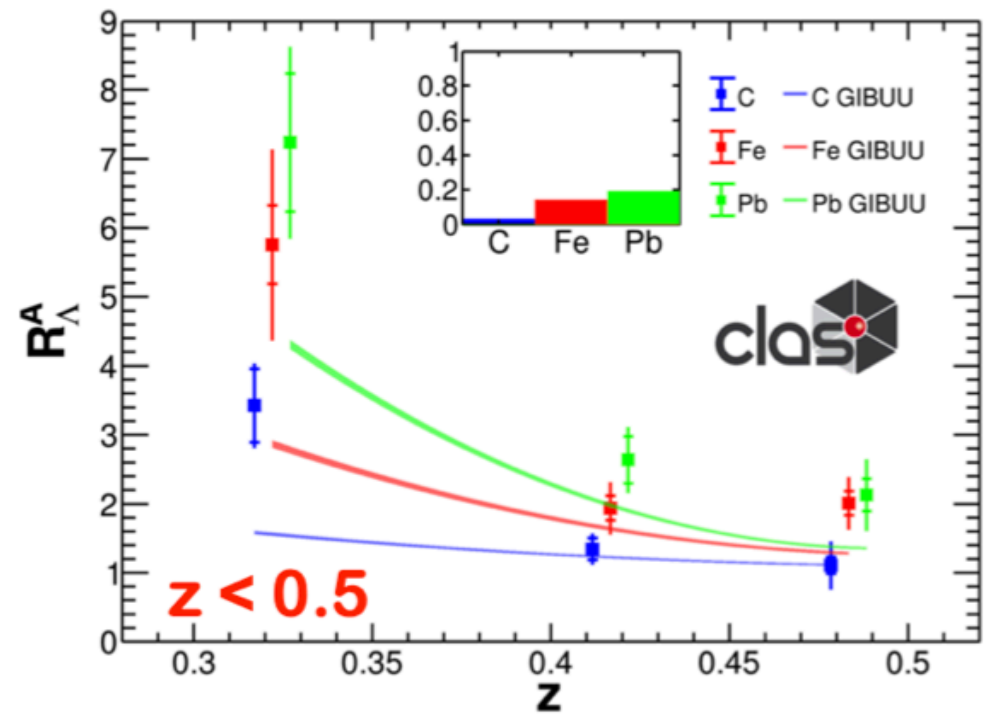
E.Molina Thesis



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

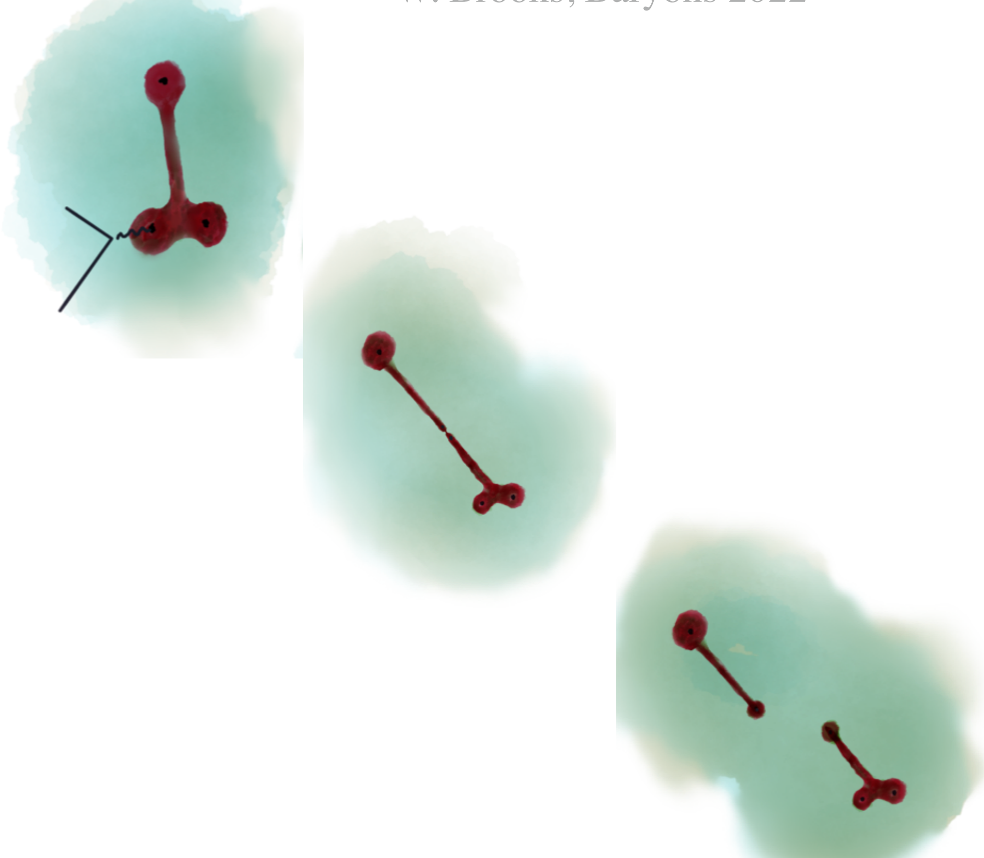
Traditional picture



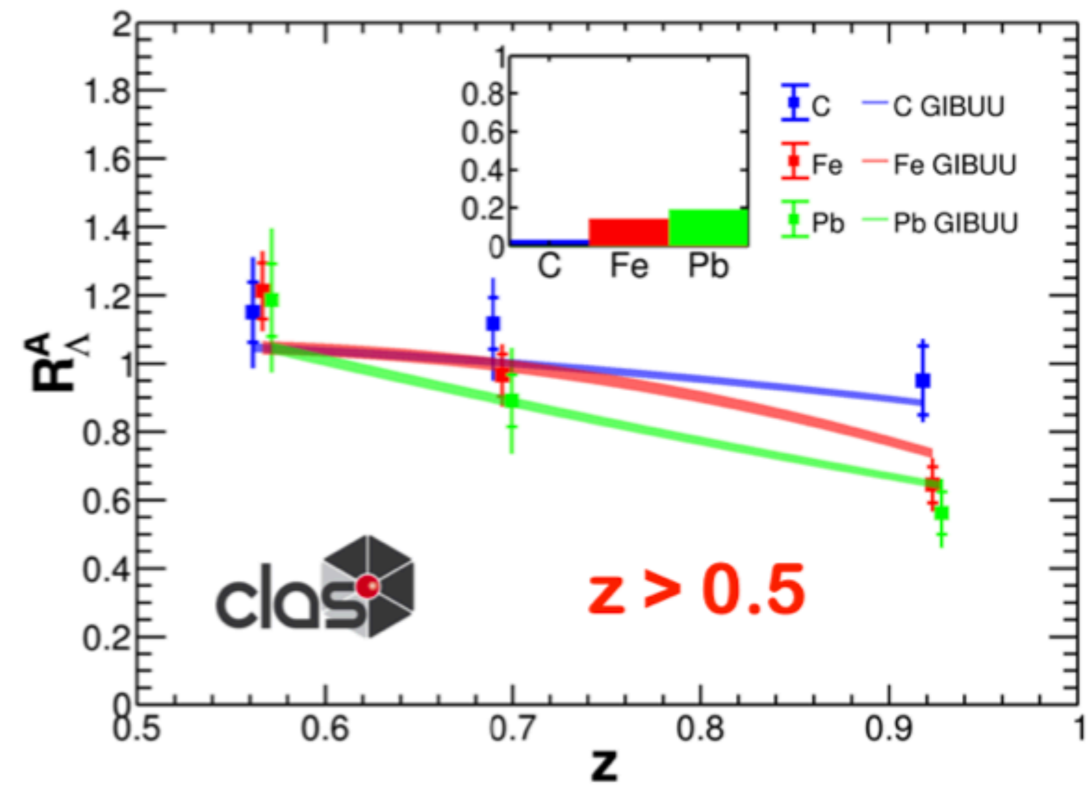


Alternative: direct diquark scattering

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?

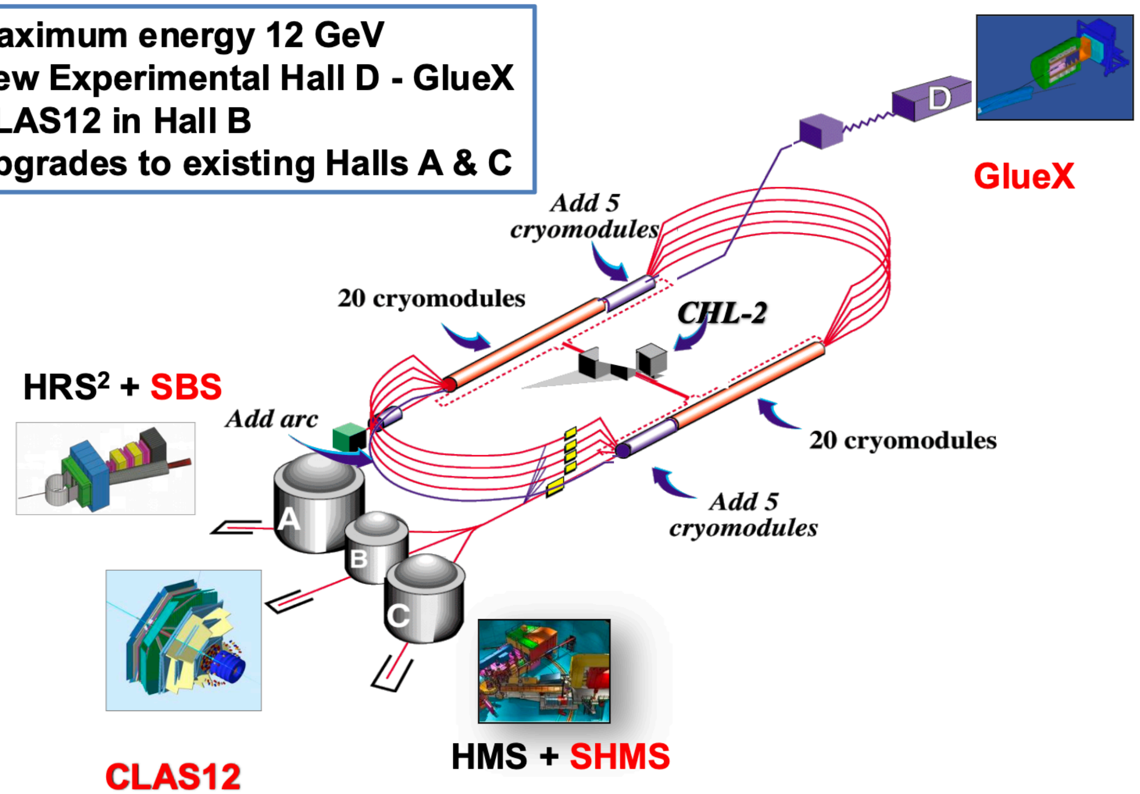
See Anthony Francis talk

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

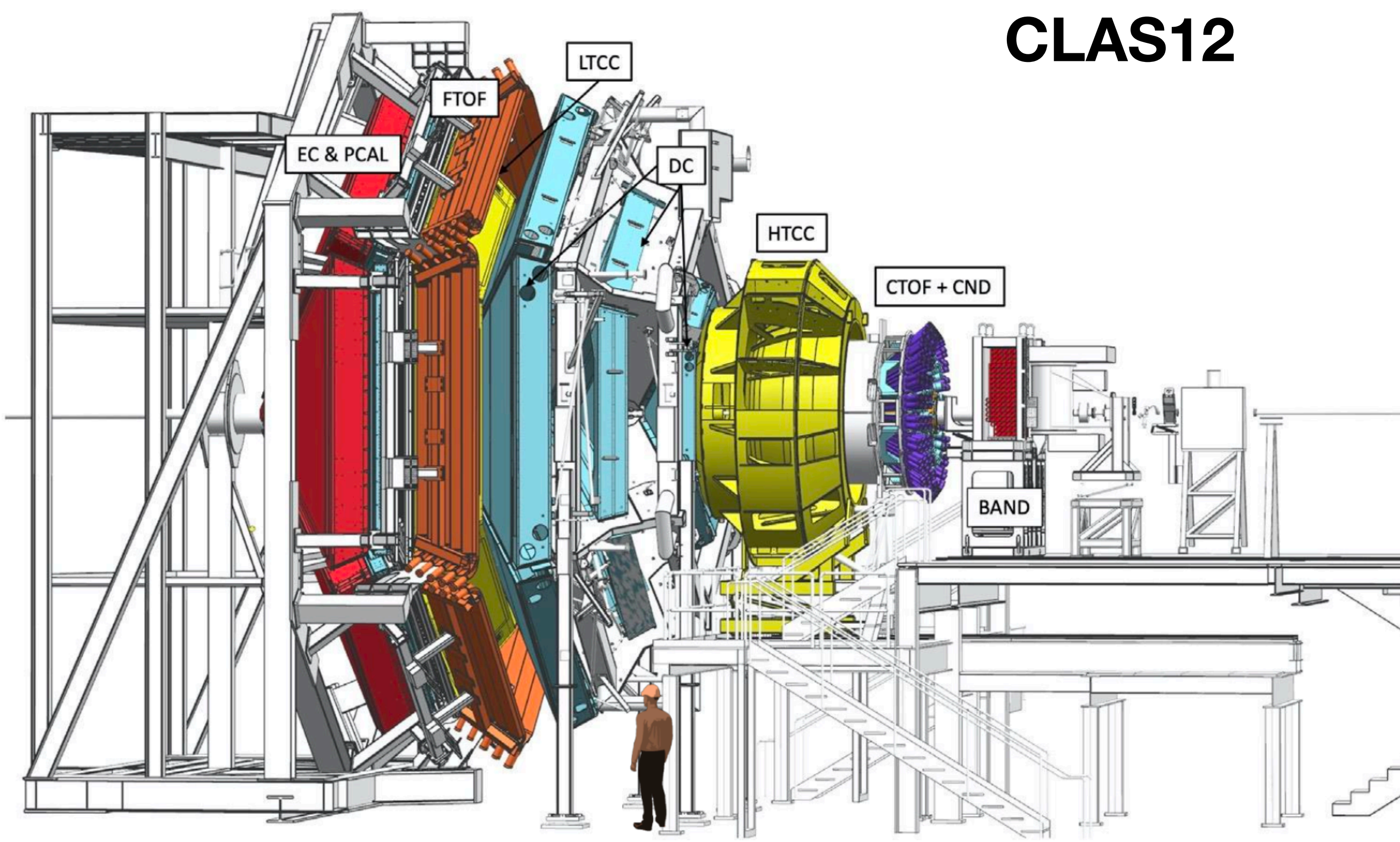
Coming up data

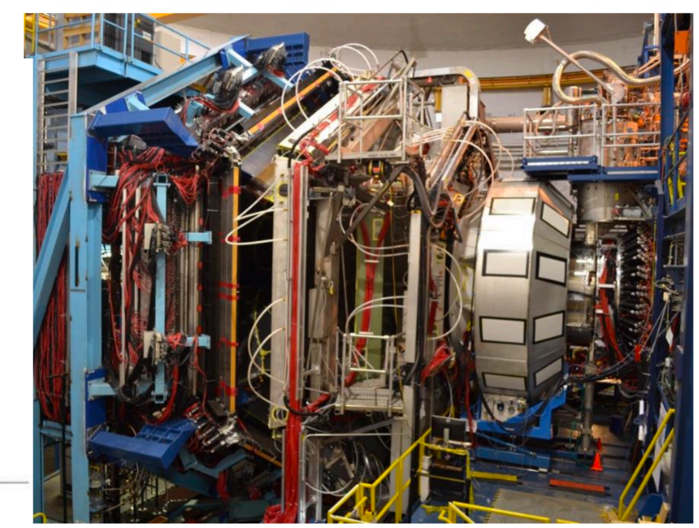
The Jefferson Lab Energy Upgrade

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

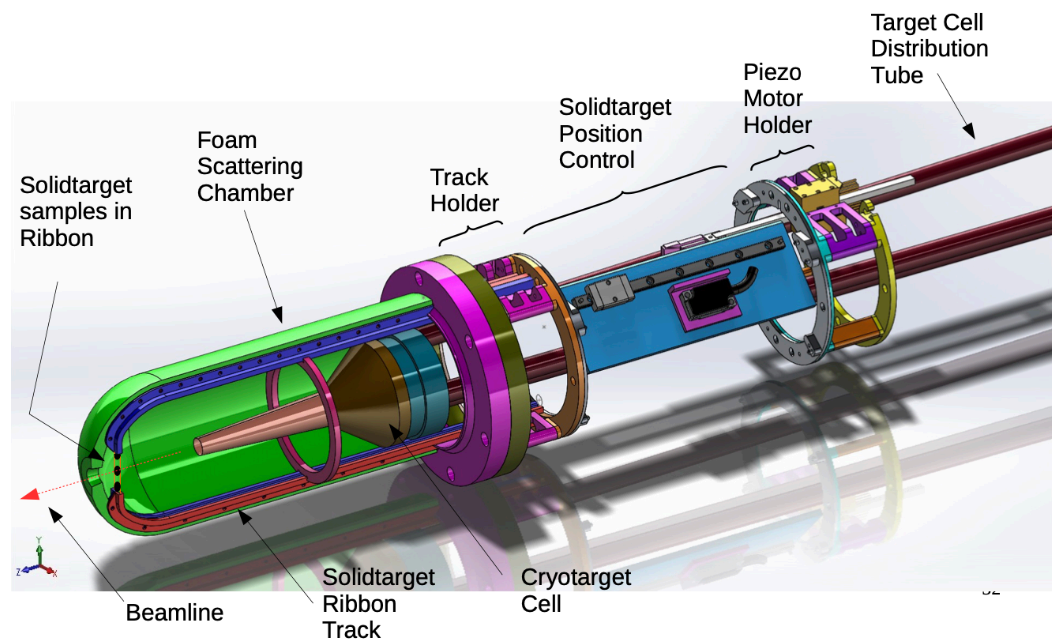
RG-E experiment @ 10.5 GEV

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

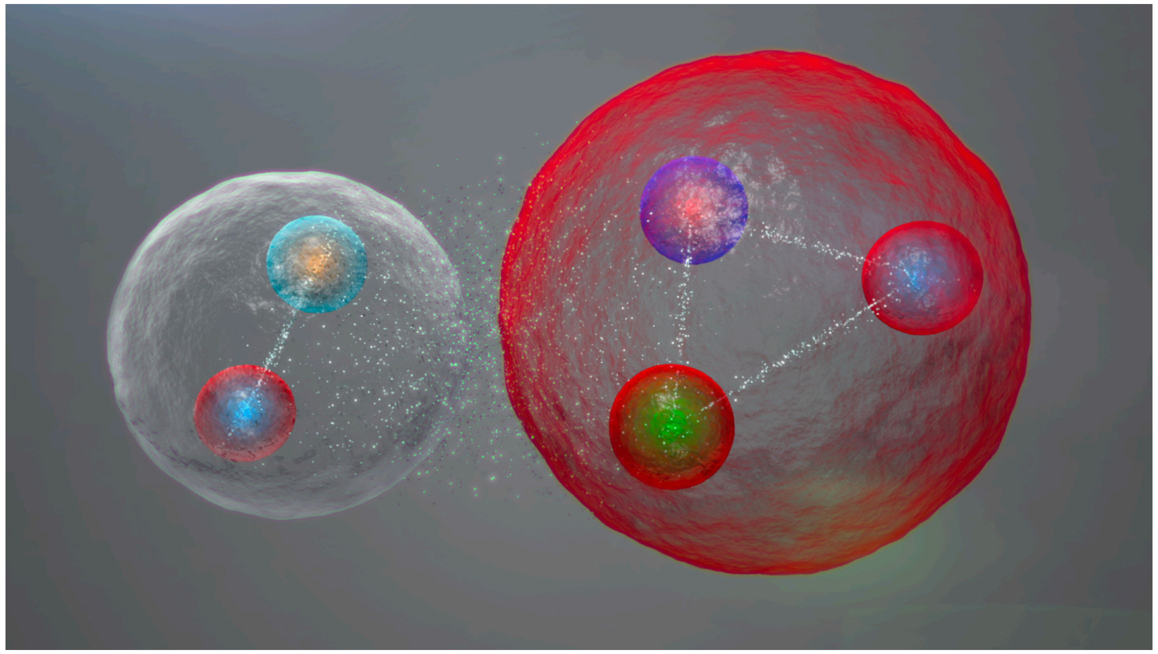


Highlights of double target are in JLUO weekly: https://mailchi.mp/89a150f4d755/jlab-weekly-for-scientific-users-april-3-2024?e=a8d43a7cbe

Quark Propagation and Hadronization at CLAS12

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	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

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 from CLAS is well described by GiBUU, baryon data needs more understanding
- The hypothesis of diquarks may be one of the mechanisms in baryon formation
- Successful realization of CLAS12 experiment (E12-06-117) at 10.5 GeV. Access to 4D multiplicities and large spectrum of hadrons, including baryons and rare mesons
- Future continuation of *eA* hadronization program with JLab @ 22 GeV and EIC

HEP NP 2025

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

6-10 JANUARY

VALPARAÍSO - CHILE

TOPICS

HIGGS AND EW PHYSICS | HEAVY ION COLLISIONS | NUCLEAR PHYSICS

QCD | ASTROPARTICLES | DARK MATTER PARTICLE SEARCHES | NEUTRINO PHYSICS

PARTICLE DETECTORS AND INSTRUMENTATIONS | FUTURE EXPERIMENTAL FACILITIES

BEYOND THE STANDARD MODEL PHYSICS | GRAVITATIONAL WAVES MEASUREMENTS

ORGANIZING COMMITTEE

- Carolina Arbeláez
- William Brooks
- Antonio Cárcamo
- Edson Carquín
- Oscar Castillo Felisola
- Carlos Contreras
- Gorazd Cvetic
- Claudio Dib
- Ahmed El Alaoui
- Benjamin Guiot
- Hayk Hakobyan
- Sonia Kabana
- Boris Kopeliovich
- Taisiya Mineeva
- Sebastián Tapia
- Marat Siddikov
- Alfonso Zerwekh

https://indico.cern.ch/event/1394087/overview

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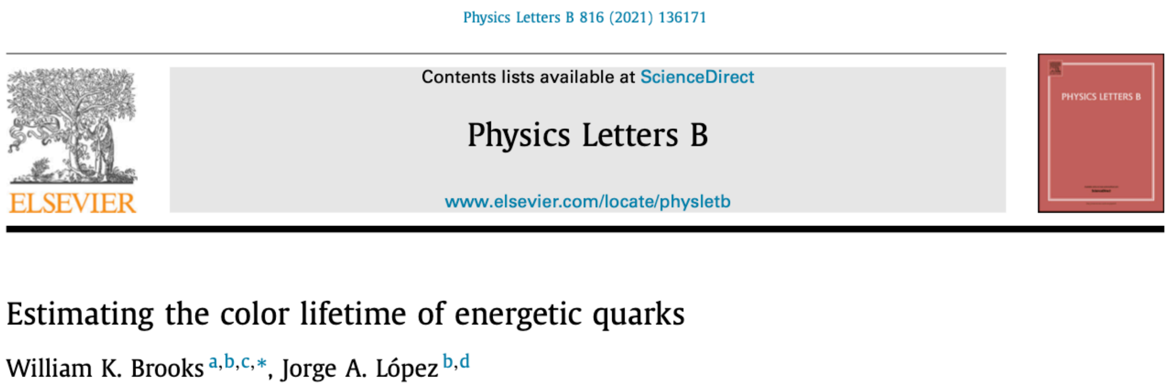
CCTVal CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO

Additional slides

Extraction of color lifetime Brooks-Lopez model


Physics Letters B 816 (2021) 136171

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ELSEVIER

Estimating the color lifetime of energetic quarks

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

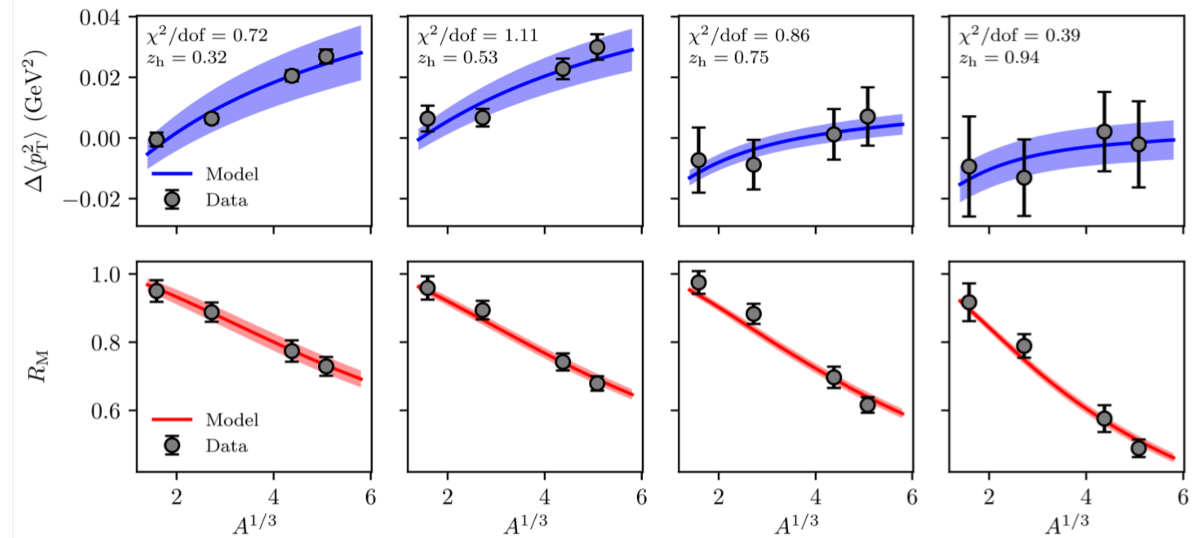
- The **color lifetime** was estimated using simultaneous fit to two observables in the **HERMES** data with 3-parameter space-time model

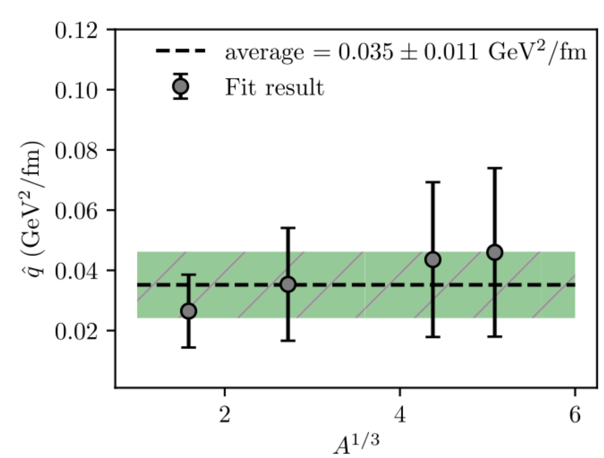
- The answer depends on the kinematics and ranges from **2 to 8 fm/c**

- Independent determination of the string constant of the LSM!

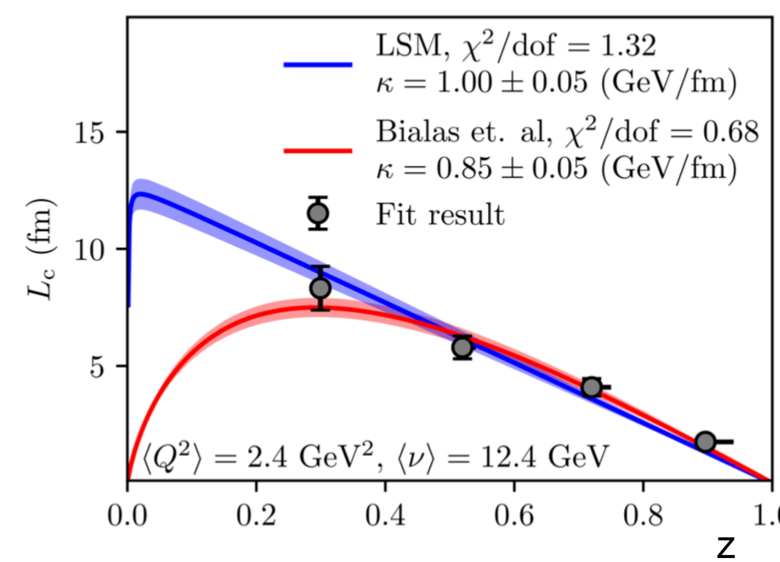
- Measurement of transport coefficient

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





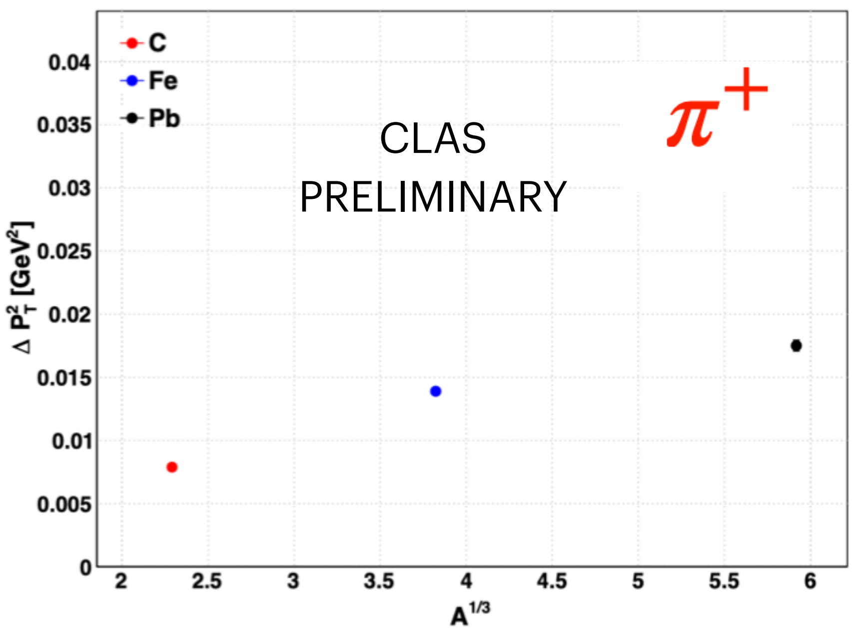
The values of the color length **Lc** resulting from simultaneous fit to *pT2* and *R*



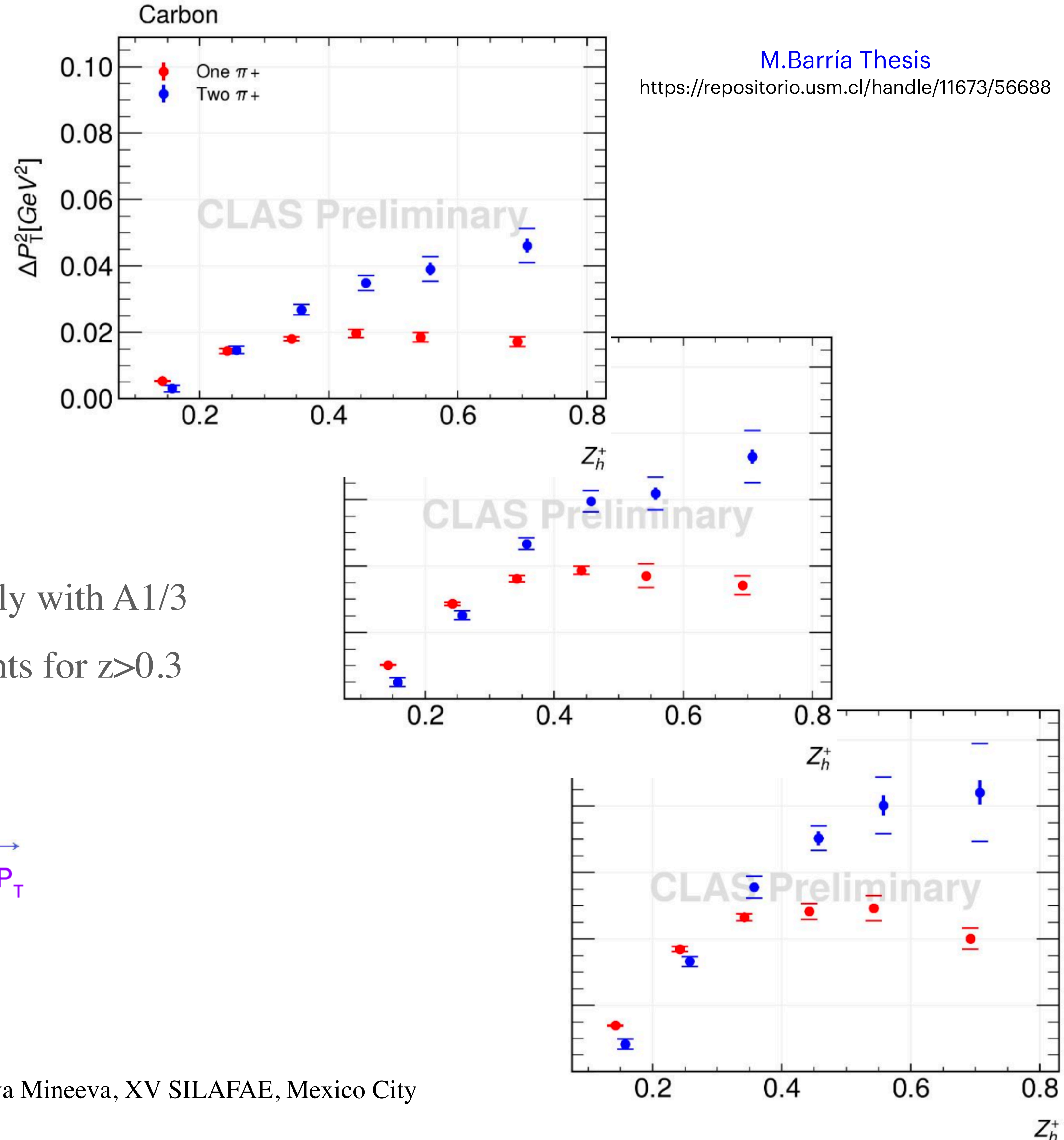
Phys. Let. B 816 (2021) 136171
https://arxiv.org/abs/2004.07236

pT² broadening for multiple π⁺ events

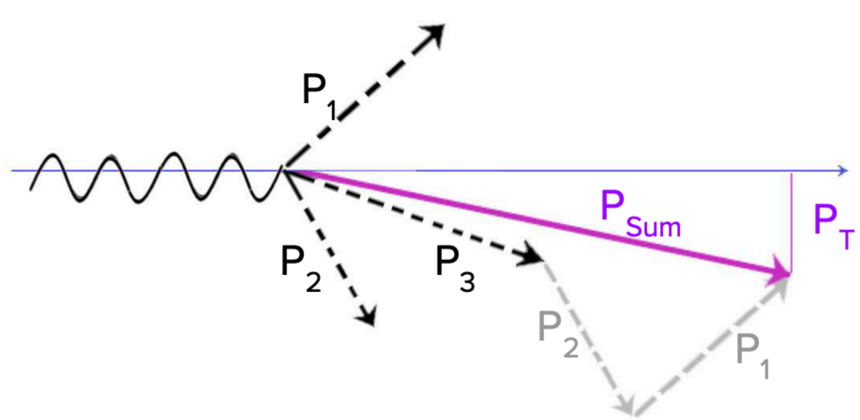
E.Molina Thesis
https://repositorio.usm.cl/handle/11673/53373



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

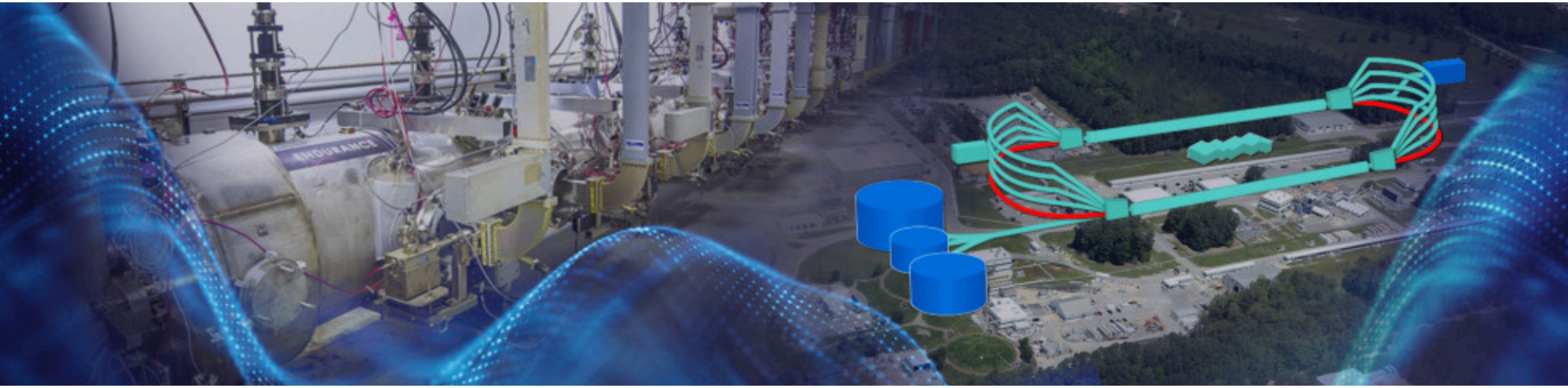


- pT² broadening for π⁺ grows linearly with A1/3
- pT² broadening is larger for 2π events for z>0.3



Jefferson Lab at 22 GeV

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



Cornell University

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arXiv > nucl-ex > arXiv:2306.09360

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Nuclear Experiment

[Submitted on 13 Jun 2023]

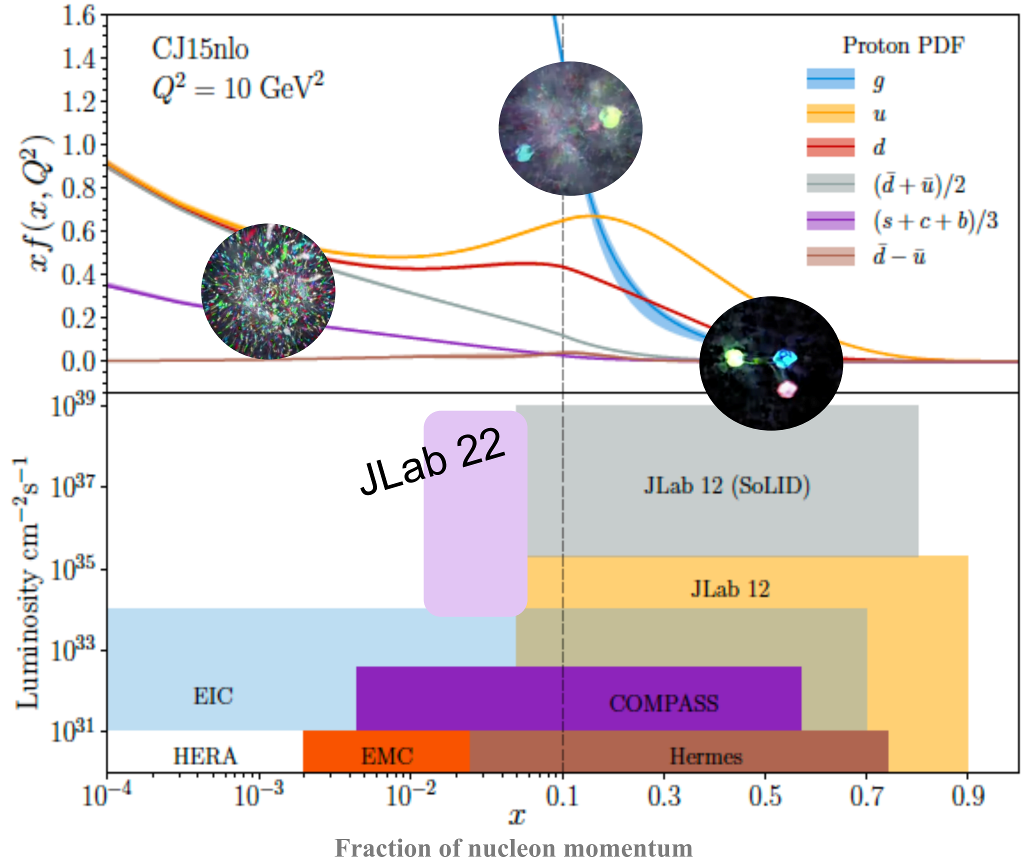
Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

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. [illegible] 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

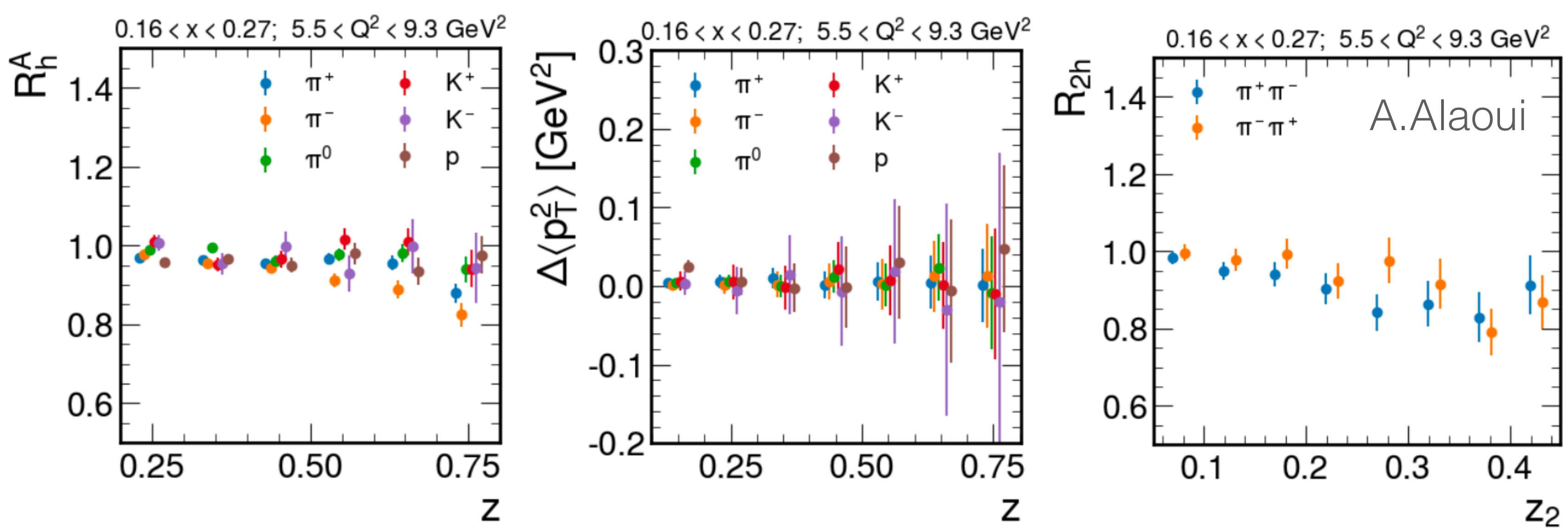


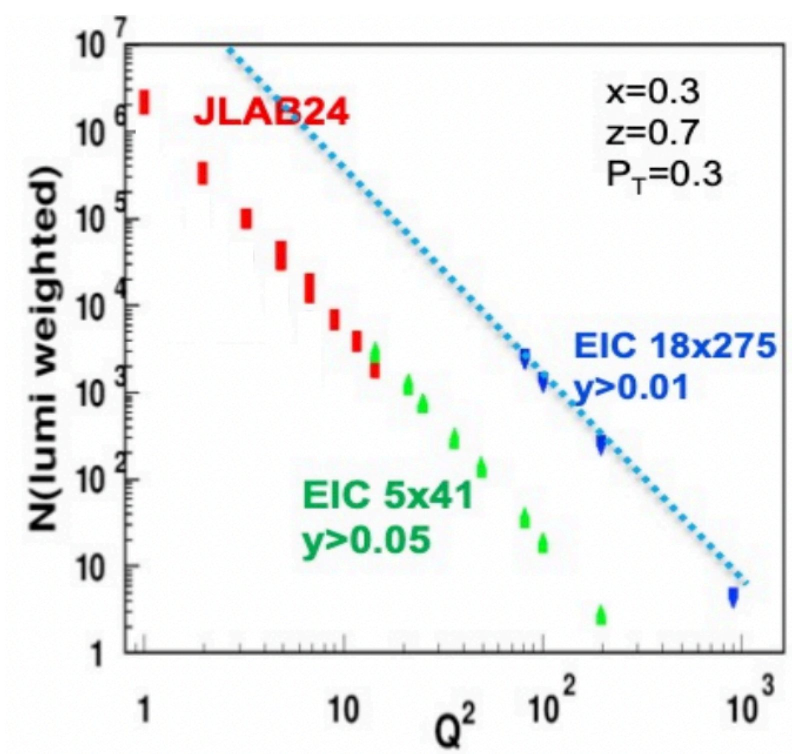
-Large x, low Q² evolves to low x, high Q² via pQCD, extract parton distribution shape and strength ***from data***

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

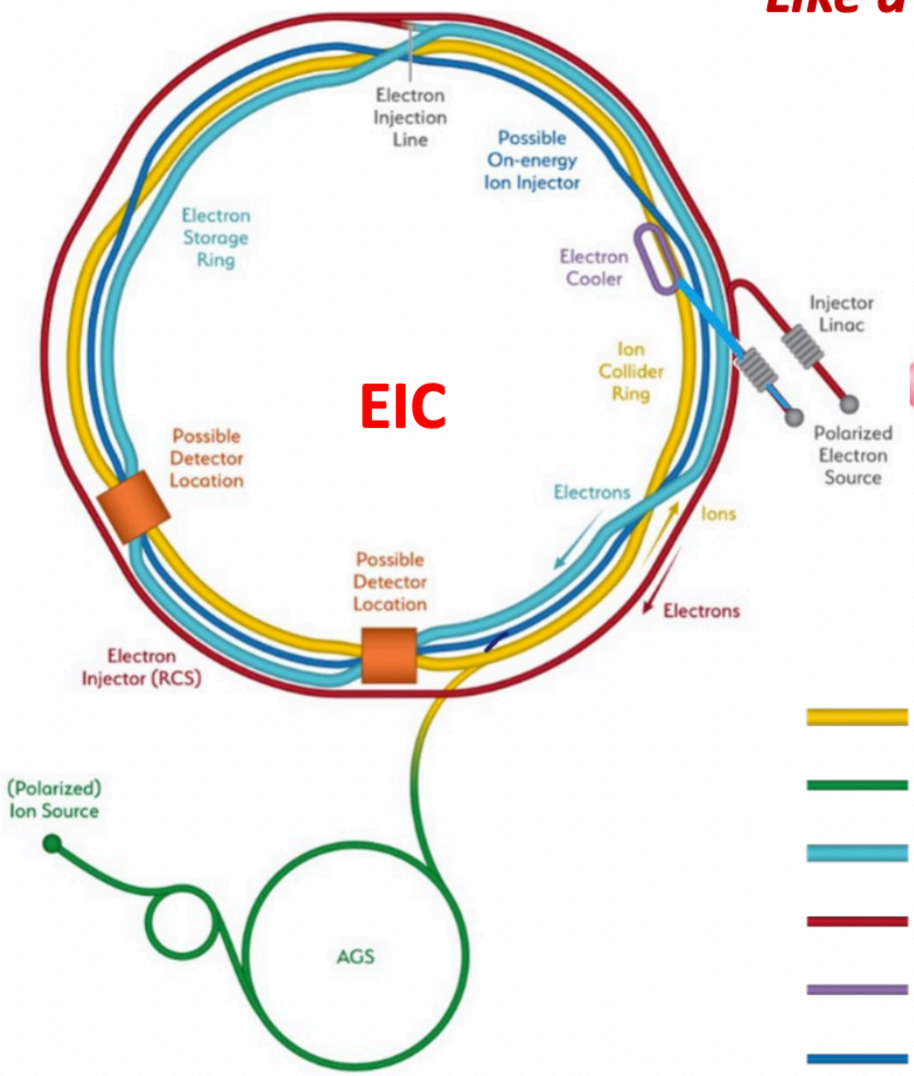


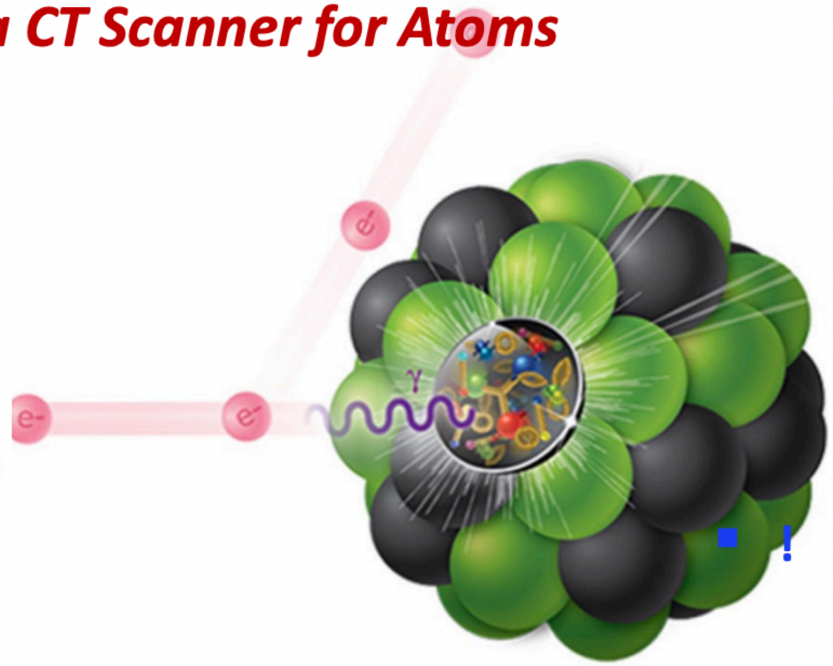


EIC @ Brookhaven

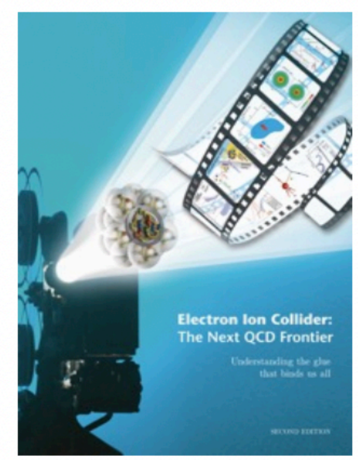
A machine that will unlock the secrets of the strongest force in Nature

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