Hadronization and Color Propagation in e-A Scattering at Jefferson Lab

Taisiya Mineeva

Experimental Physics Division seminar

Institute for High Energy Physics

Beijing, May 20th 2025

Universidad de La Serena is a public university in Chile with approximately 8,000 enrolled students in 6 campuses

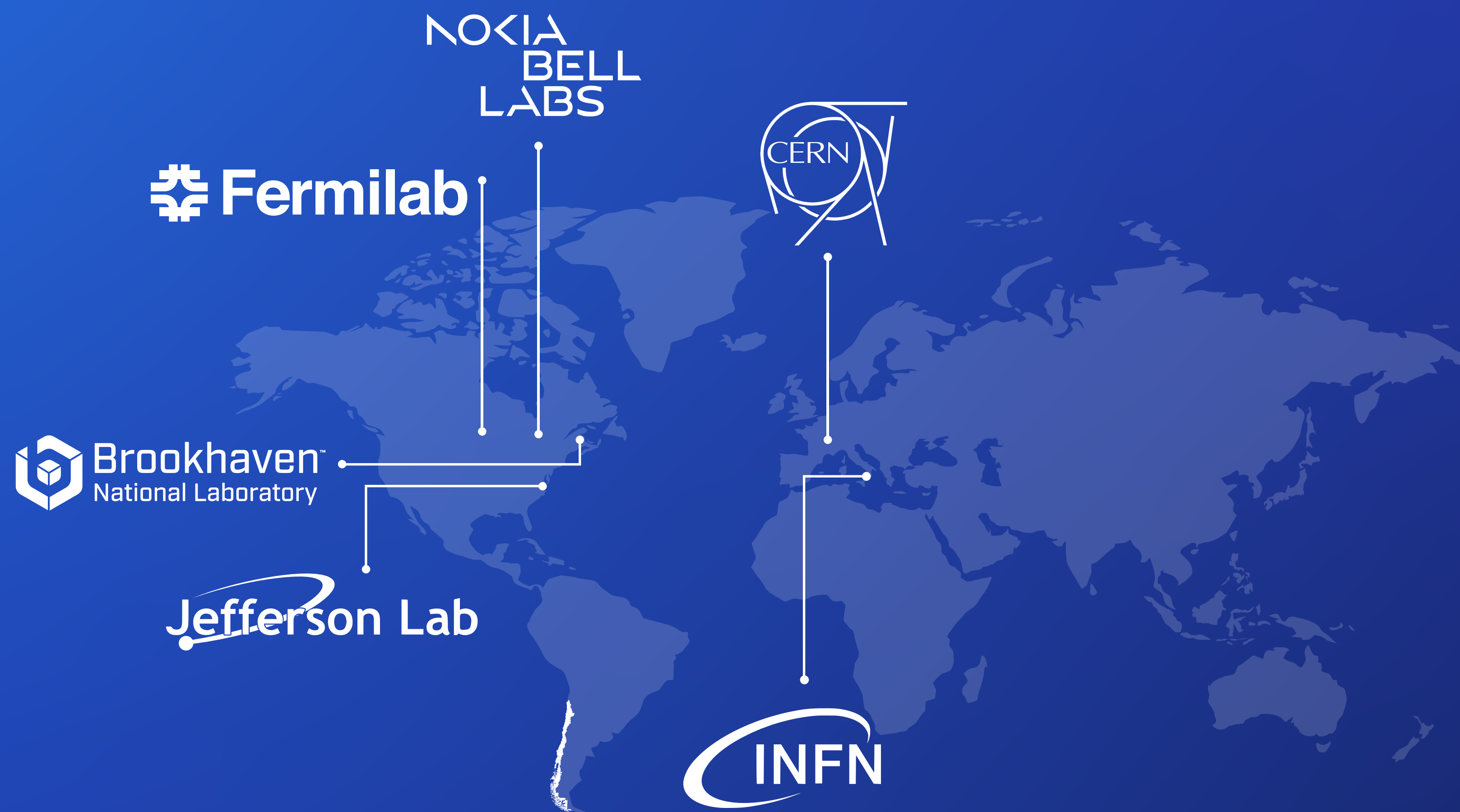
The physics group at ULS is actively engaged in a broad spectrum of research areas:

- experimental particle physics at high and medium energies, with key collaborations at CERN (ATLAS, NA64) and Jefferson Lab (CLAS and CLAS12)
- astroparticle and astrophysics projects (SWGO, AURA), leveraging Chile's unparalleled observational advantages
- theoretical research on BSM physics, with a particular focus on novel physics at colliders, dark matter and neutrino physics

CCTVal

CENTRO CIENTÍFICO TECNOLÓGICO DE VALPARAÍSO

- Particle physics
- Nanotechnology
- Biotechnology
- Electronics
- Telematics
- Industrial design and manufacturing
- Chemistry
- Metallurgy
- Mechanics
- Computing

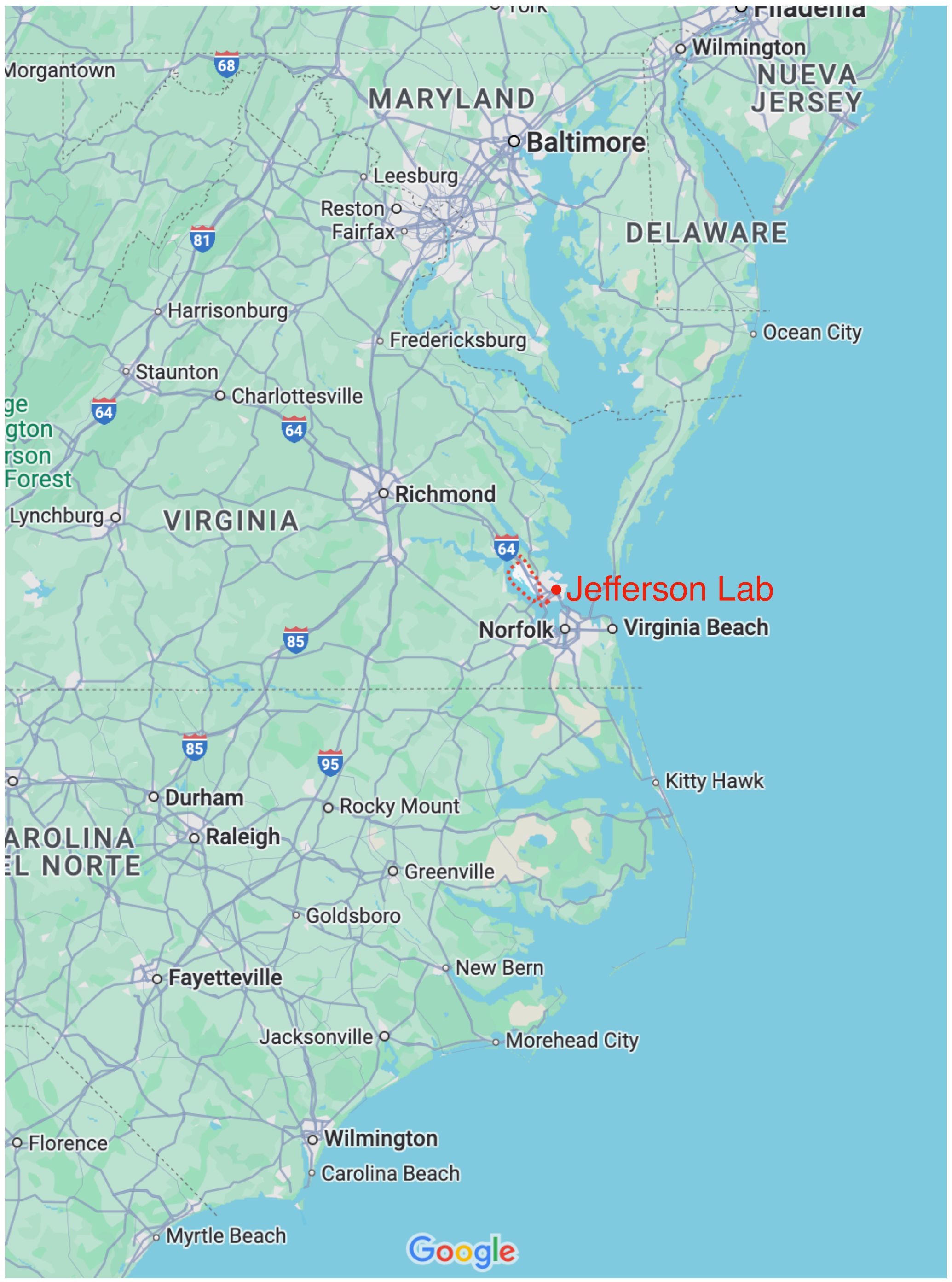


36 researches	**50** technical and administrative staff	**+2.000** publications	**+100.000** quotes	**12** patents	**4** spin-off

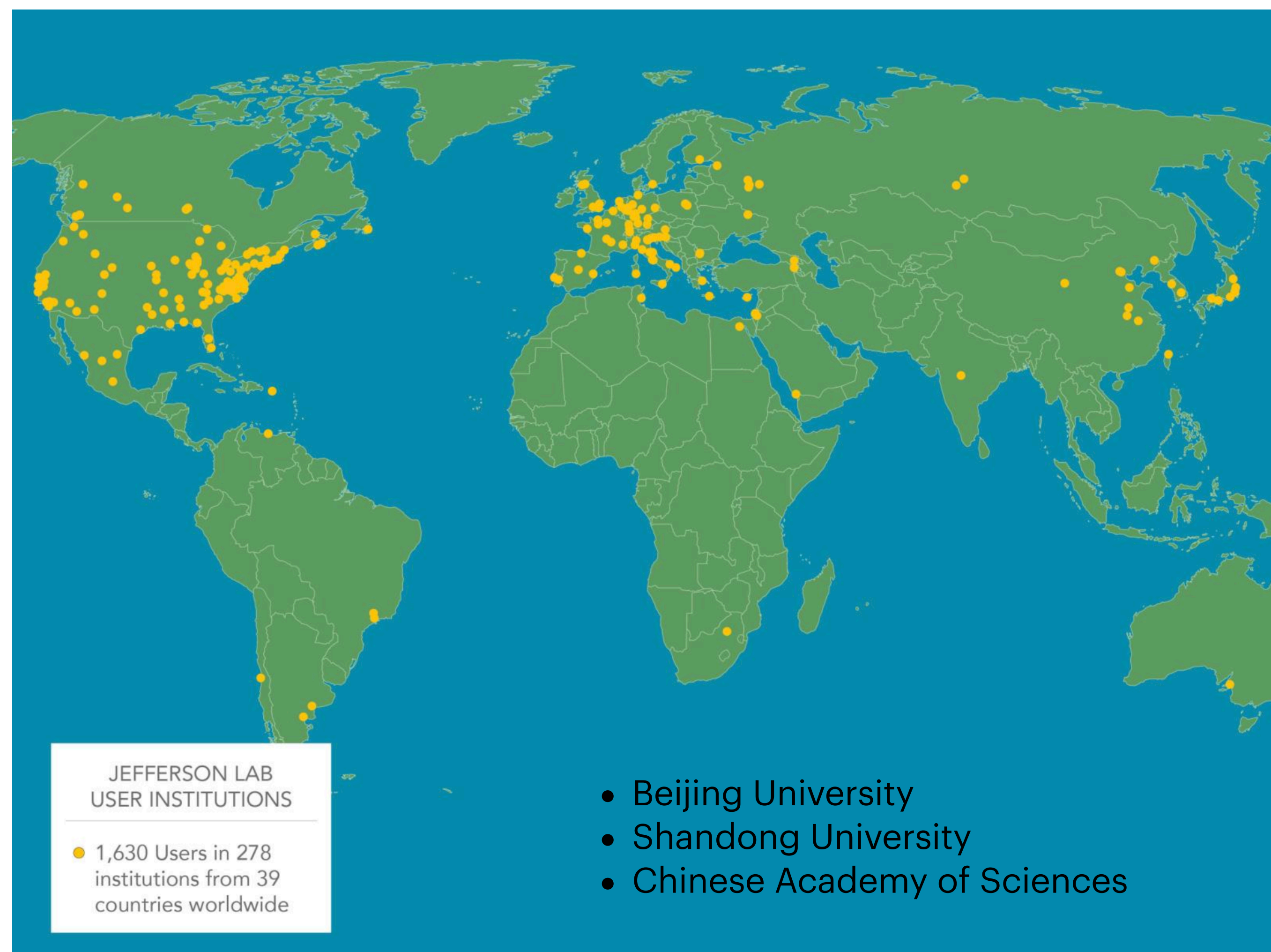
Jefferson Lab

Thomas Jefferson National Accelerator Facility

Newport News, VA



- Continuous Electron Beam Accelerator Facility (CEBAF) housing 1.4 km linear electron accelerator @ 12 GeV (2017)
- Three experimental Halls (A,B,C,D)
- Center for Theoretical and Computational Physics; LQCD
- future High Performance Data Facility (HPDF)

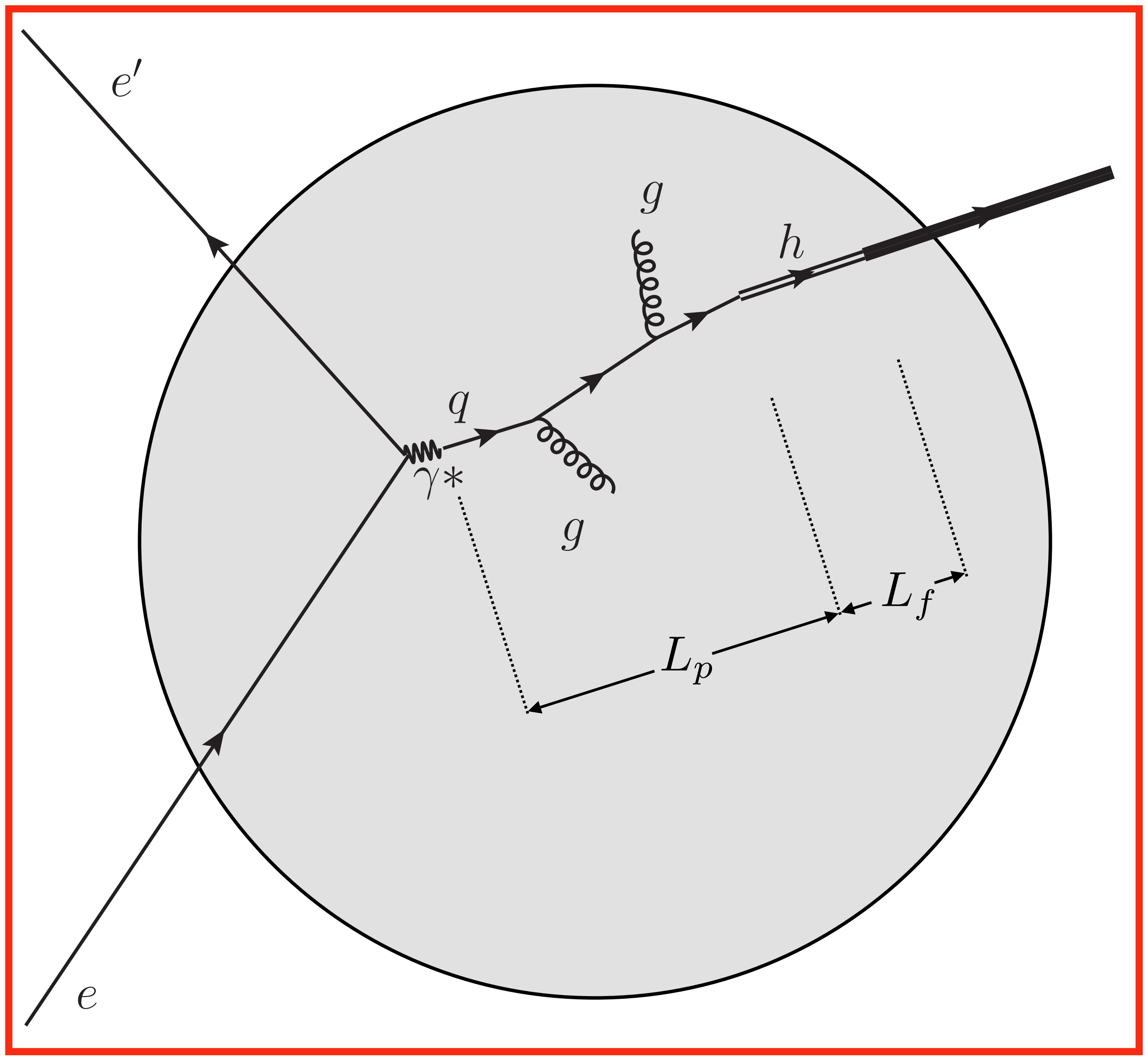


- Beijing University
- Shandong University
- Chinese Academy of Sciences

Hadronization and Color Propagation

Hadronization and Color Propagation

Hadronization is process by which an energetic quark fragments into many further quarks, which then, on later timescales, undergo a transition to hadrons



Hadronization and Color Propagation

Hadronization is the fundamental process representing the transition of a system of quarks and gluons into a state in which the degrees of freedom are color-neutral hadrons

- The fundamental degrees of freedom in QCD, quarks and gluons, form bound states in conditions of temperature and energy density typical of ordinary matter
- Complication: Color *Confinement*. Not understood from the first principles.

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Clay Mathematics Institute

Millenium price of $1 000 000 for proving that $SU_c(3)$ gauge theory is mathematically well-defined which will necessarily prove or disprove confinement conjecture

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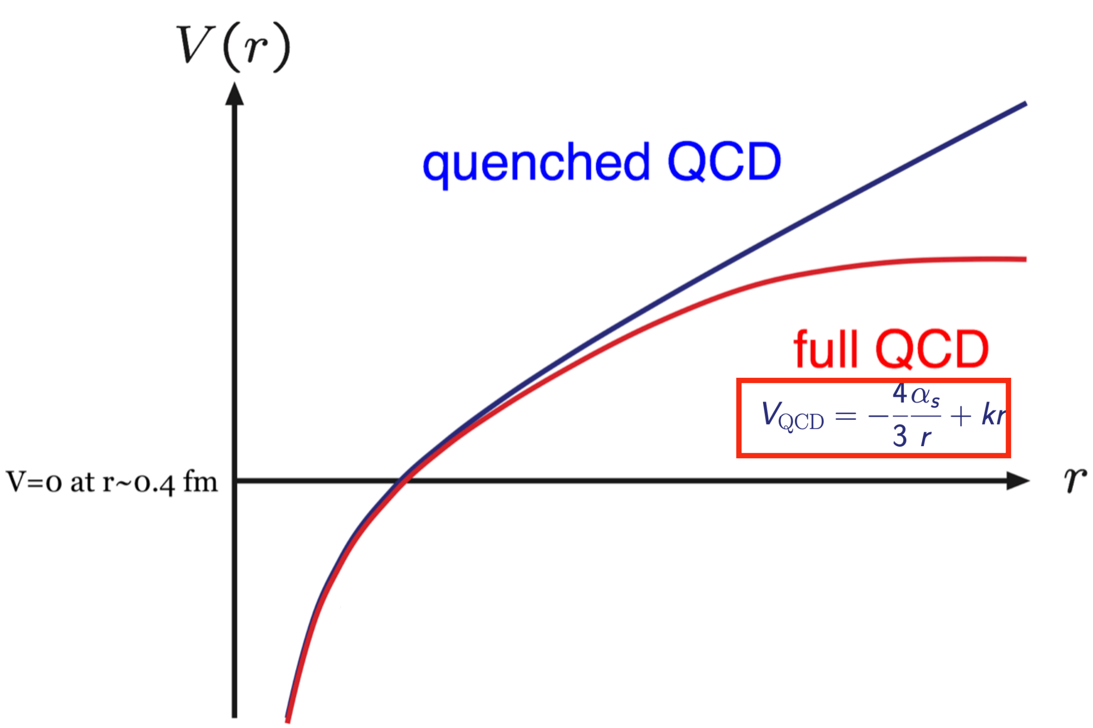
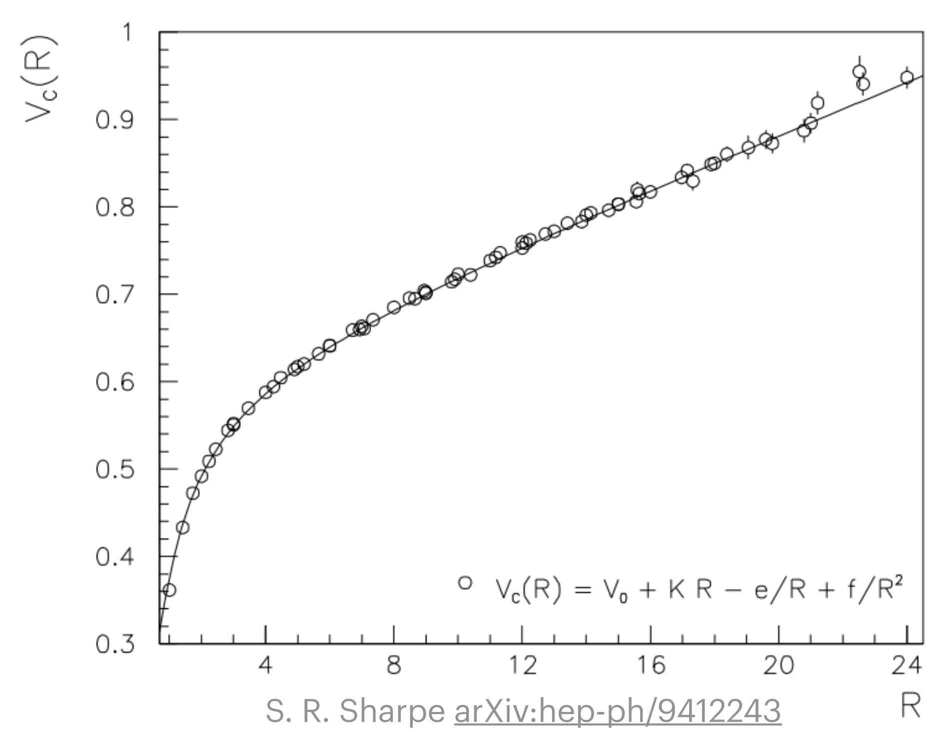


Linear confinement confirmed by the lattice



S. R. Sharpe arXiv:hep-ph/9412243

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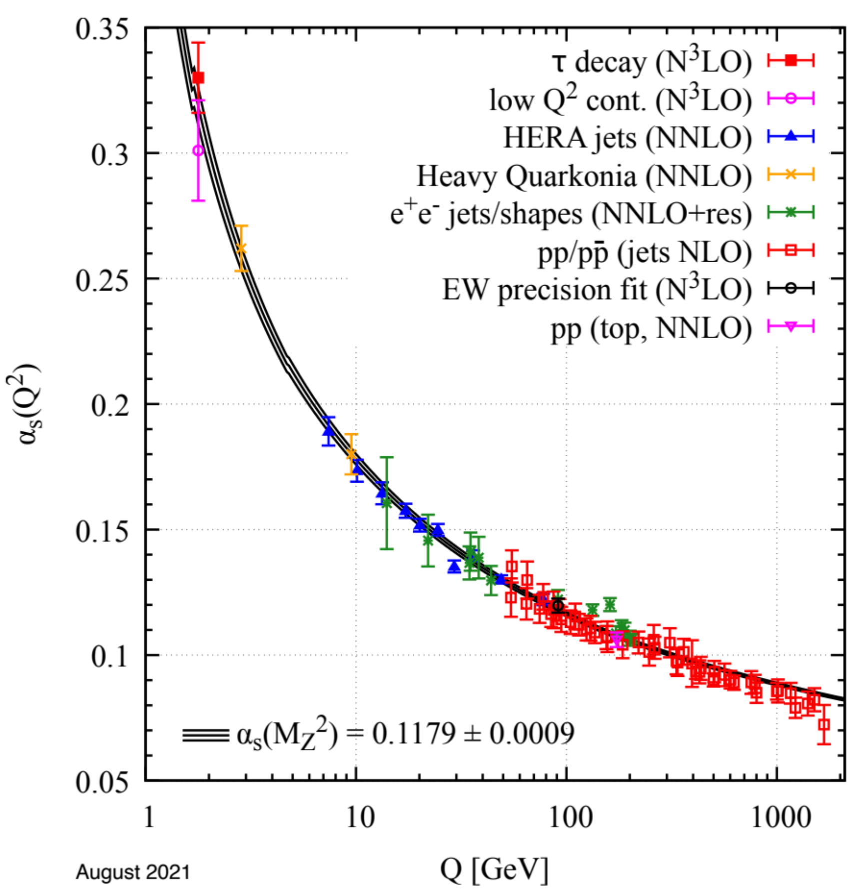
- Coupling constant α_s runs. Hadronization involves partonic processes characterized by small momentum transfers Q^2, hence large values of α_s, perturbative QCD calculations are not conceivable.



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- The MC event generators (Pythia, Jetset, Herwig, Beagle, GiBUU, Genie for ν) 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

How *confinement* is studied experimentally?

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- *Hadron spectroscopy: mass, spin, decay modes of mesons/baryons, exotic states*

  Light meson & baryon resonances. Regge trajectories. *CLAS12, COMPASS, BESIII.*

  Quarkonium states and its suppression in QGP. *BaBar, Belle; Belle II, BESIII; LHCb.*

  Exotic hadrons (tetra- and pentaquarks). Glueballs and hybrid mesons.
  LHCb, BelleII, BESIII. GlueX and BESIII.

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- *Hadronization studies via string-breaking mechanism*

Jet Fragmentation Studies: fragmentation functions, jet quenching, and hadron multiplicities. *LHC (ATLAS, CMS, ALICE, LHCb), RHIC (STAR/PHENIX).*

Semi-Inclusive Deep-Inelastic Scattering: hadron multiplicities, fragmentation functions. *HERMES, CLAS/CLAS12.*

Exclusive process: unpolarized FF. *BESIII.*

How *confinement* is studied experimentally?

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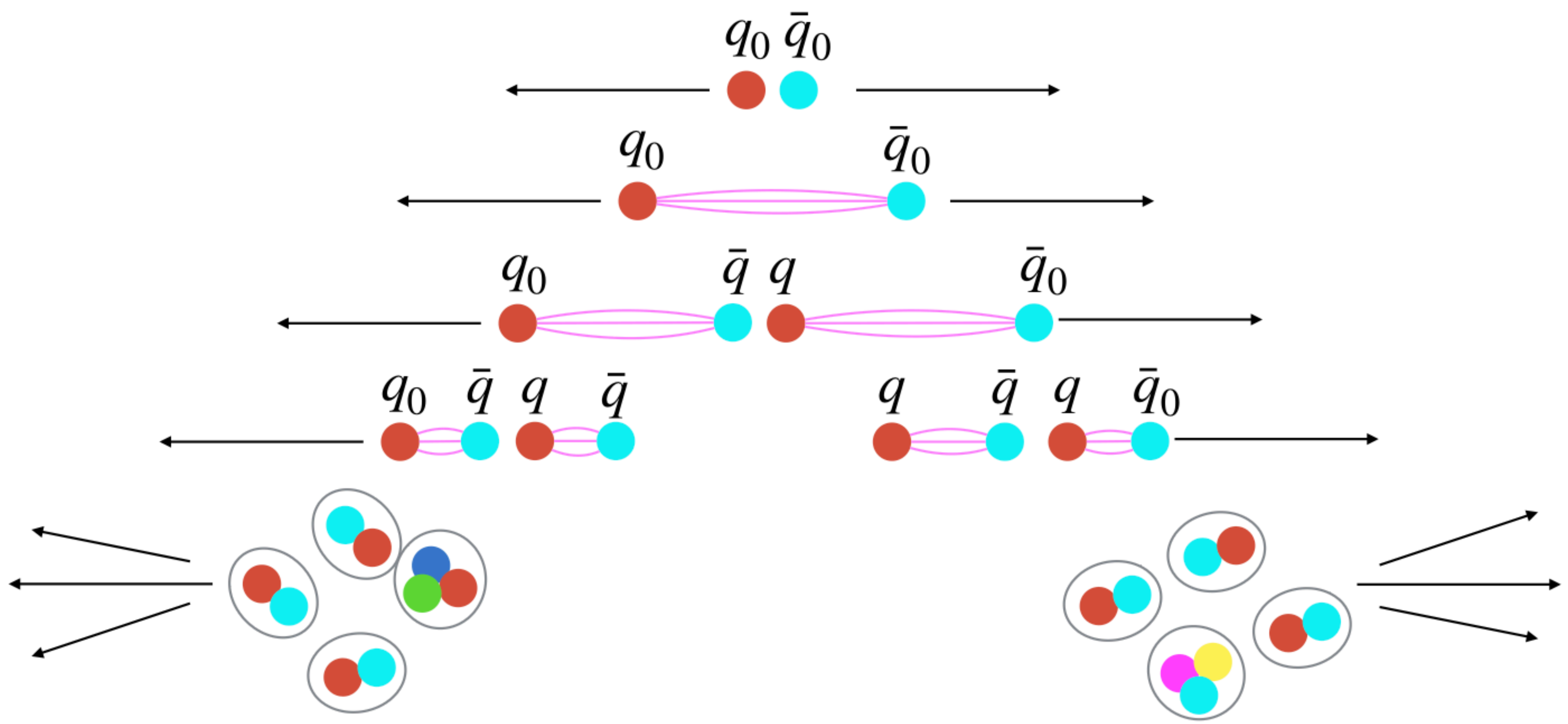
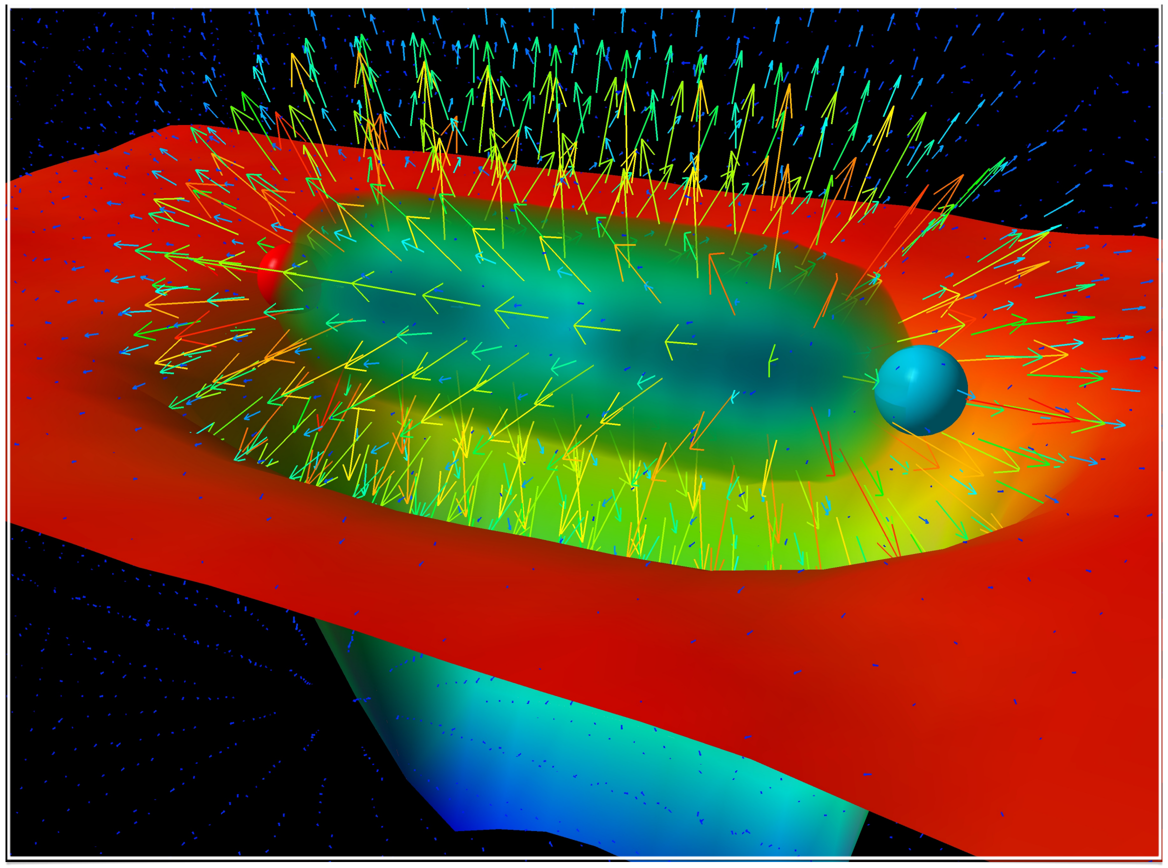
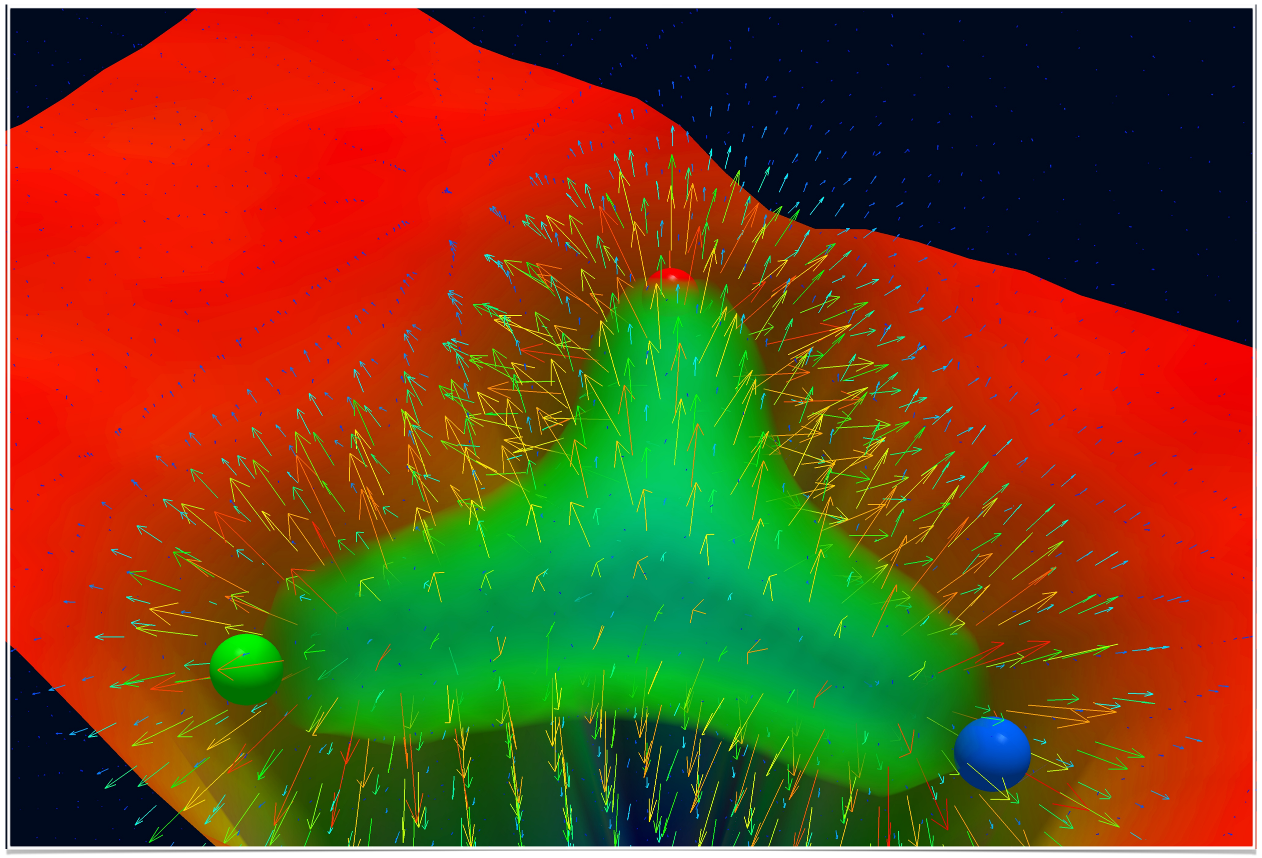


Hadronization in a picture of string fragmentation: a new qqbar pair is created in the field between the original qqbar breaking string into smaller ones ~ hadrons

Flux tube on the Lattice

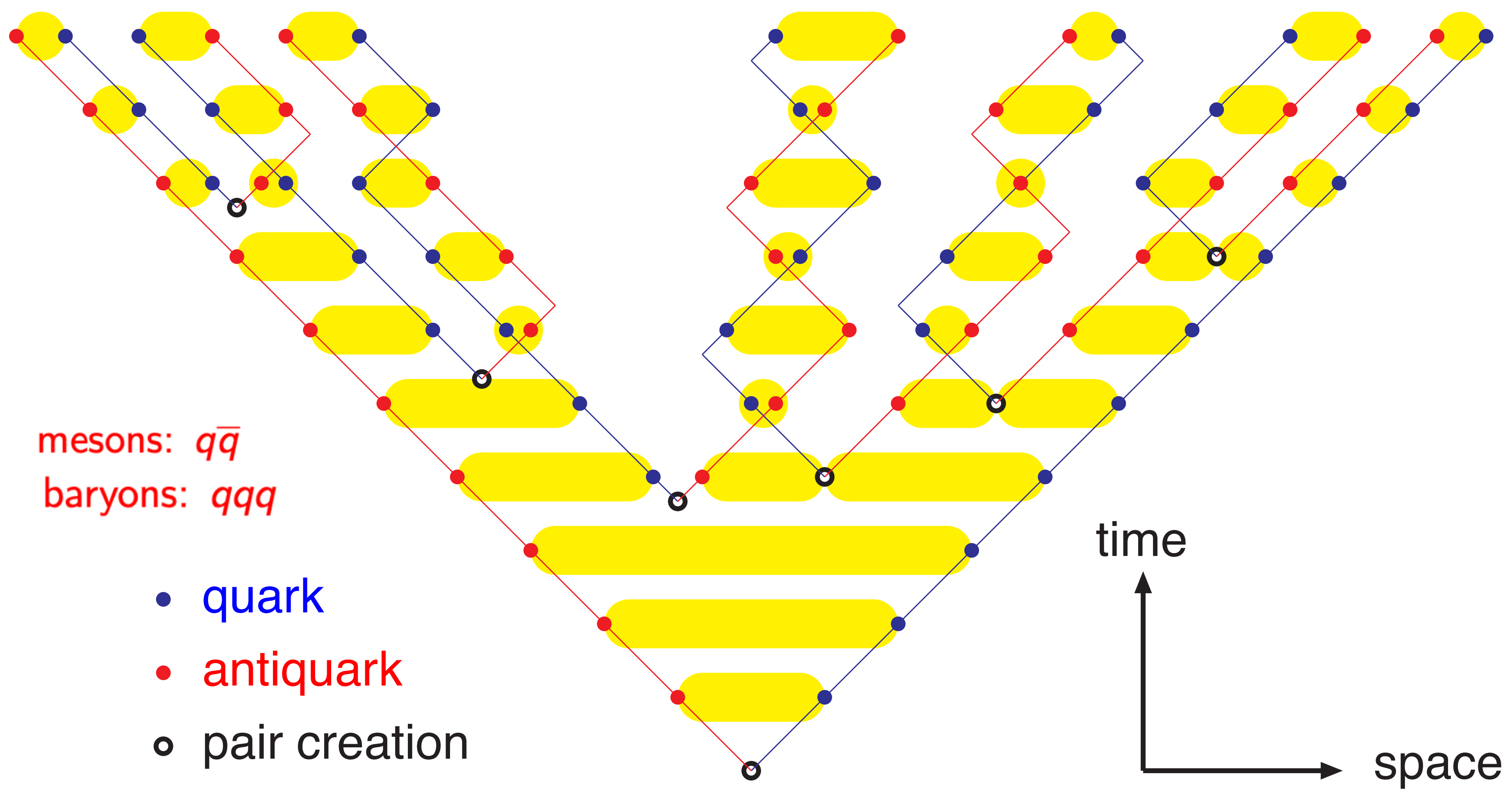
Visualization of color flux tube from Lattice QCD: qqbar and proton





Derek Leinweber: http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/

Lund string model (1980’s)



Uses only linear potential V(r) ≈ κr to trace string motion, where κ is a constant string tension κ ≈ 1 GeV/fm (fixed from Regge slopes)

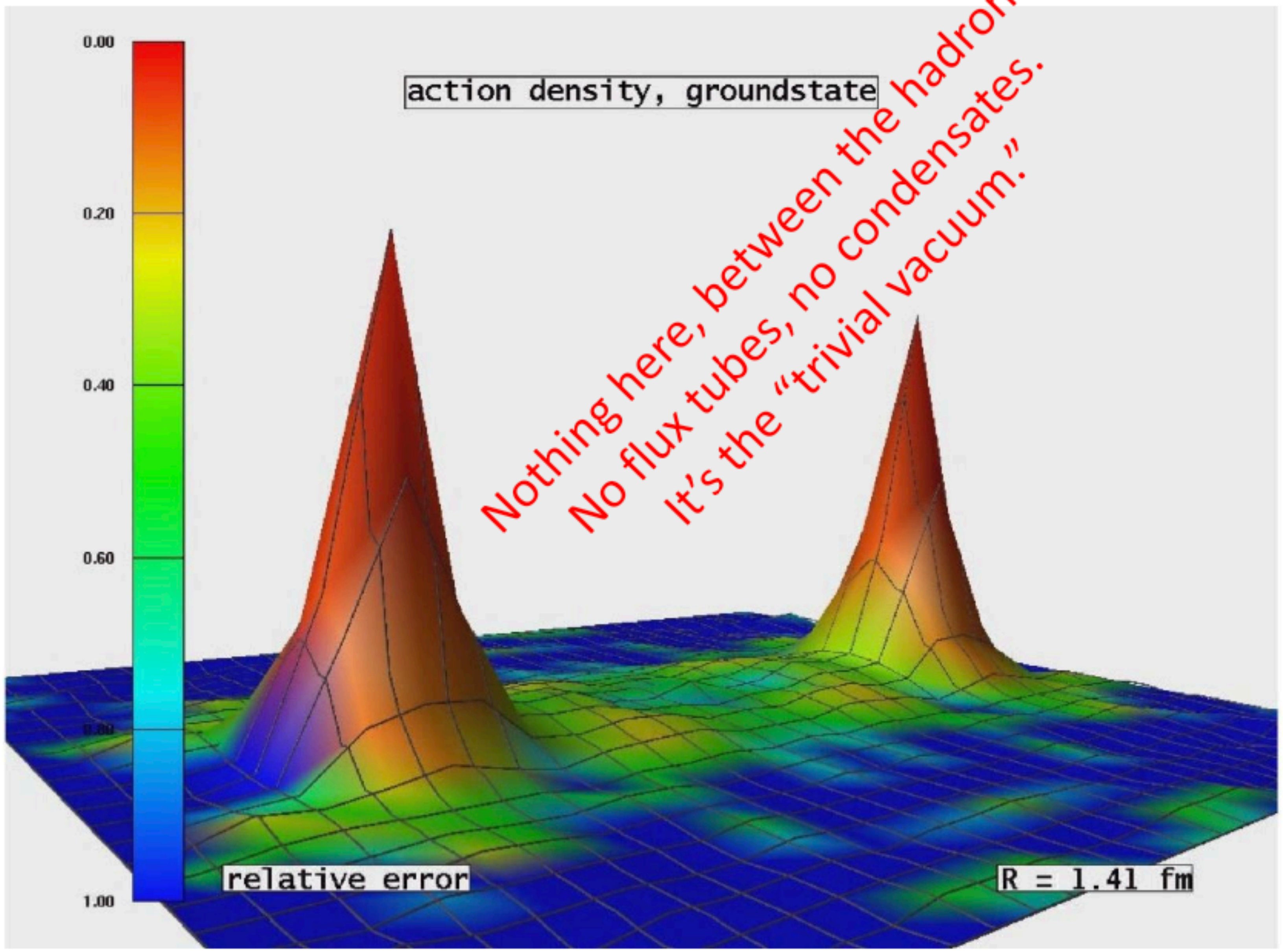
Gives simple but powerful picture of hadron production, strong support in data and lattice QCD, yet, few connections to the fundamental QCD.

PYTHIA is the main and original implementation of the Lund model

Light quarks & Confinement

- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in hadron physics***

Confinement contains condensates
Brodsky, Roberts, Shrock,Tandy
arXiv:1202.2376 [nucl-th], Phys. Rev. C85 (2012) 065202



Connecting the World of QCD to the visible World

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.

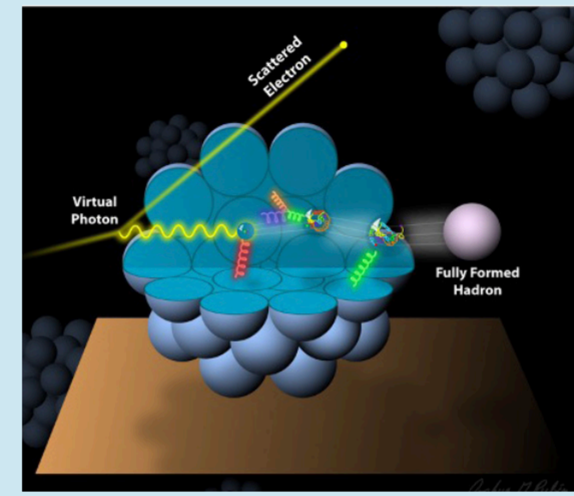


Figure 1. Representation of a high energy collision [S12]

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.

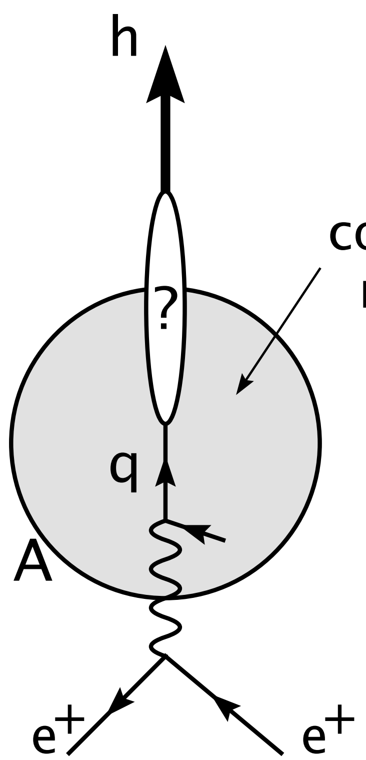
To date, most efforts have focused on studying the production of a single hadron at a time along the same direction as the outgoing parton. However, in recent years, we have started to study hadronization in more sophisticated ways. Highlights since the 2015 Long Range Plan include spin–momentum correlation 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.

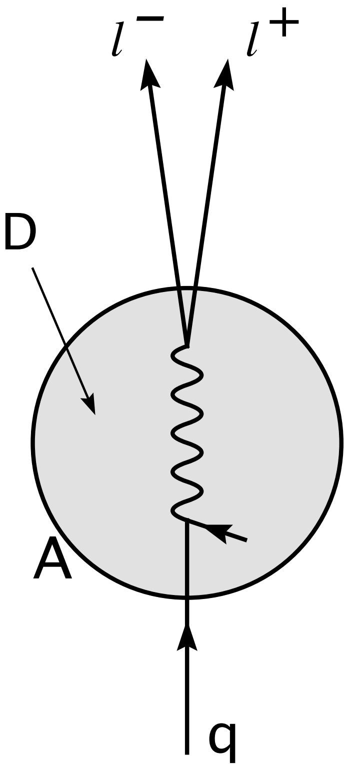
- What are the timescales of color neutralization and hadron formation?
- What are the differences in hadronization of quarks versus gluons and of light quarks versus heavy quarks?
- How are the various hadrons produced in a single scattering process correlated with one another, and how does hadronization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

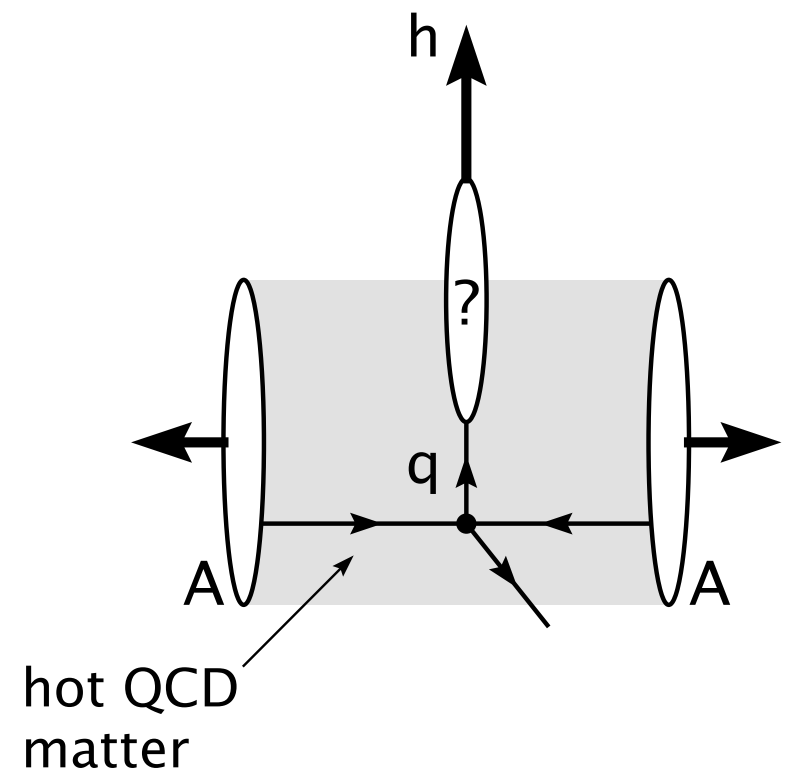
Experimental processes to study hadronization



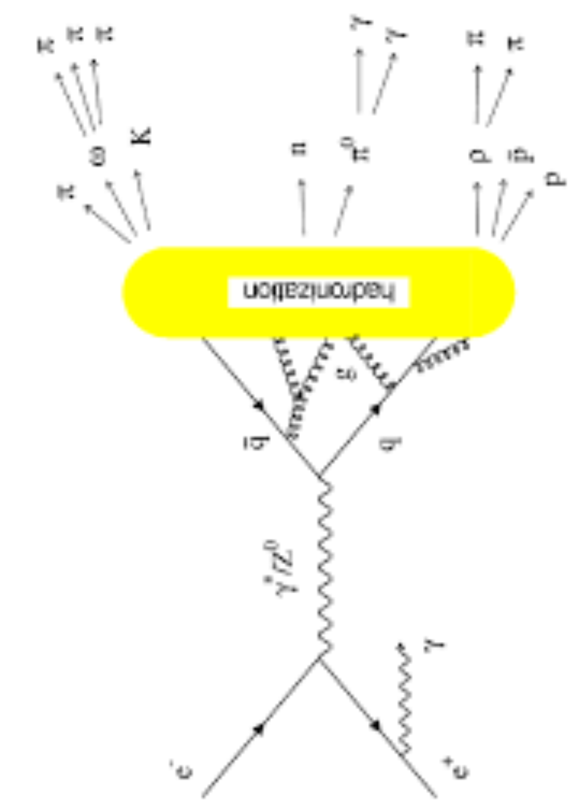
DIS
(DESY, Jefferson Lab)



Drell-Yan
(Fermilab, CERN)



Heavy-Ion
(RHIC, LHC)

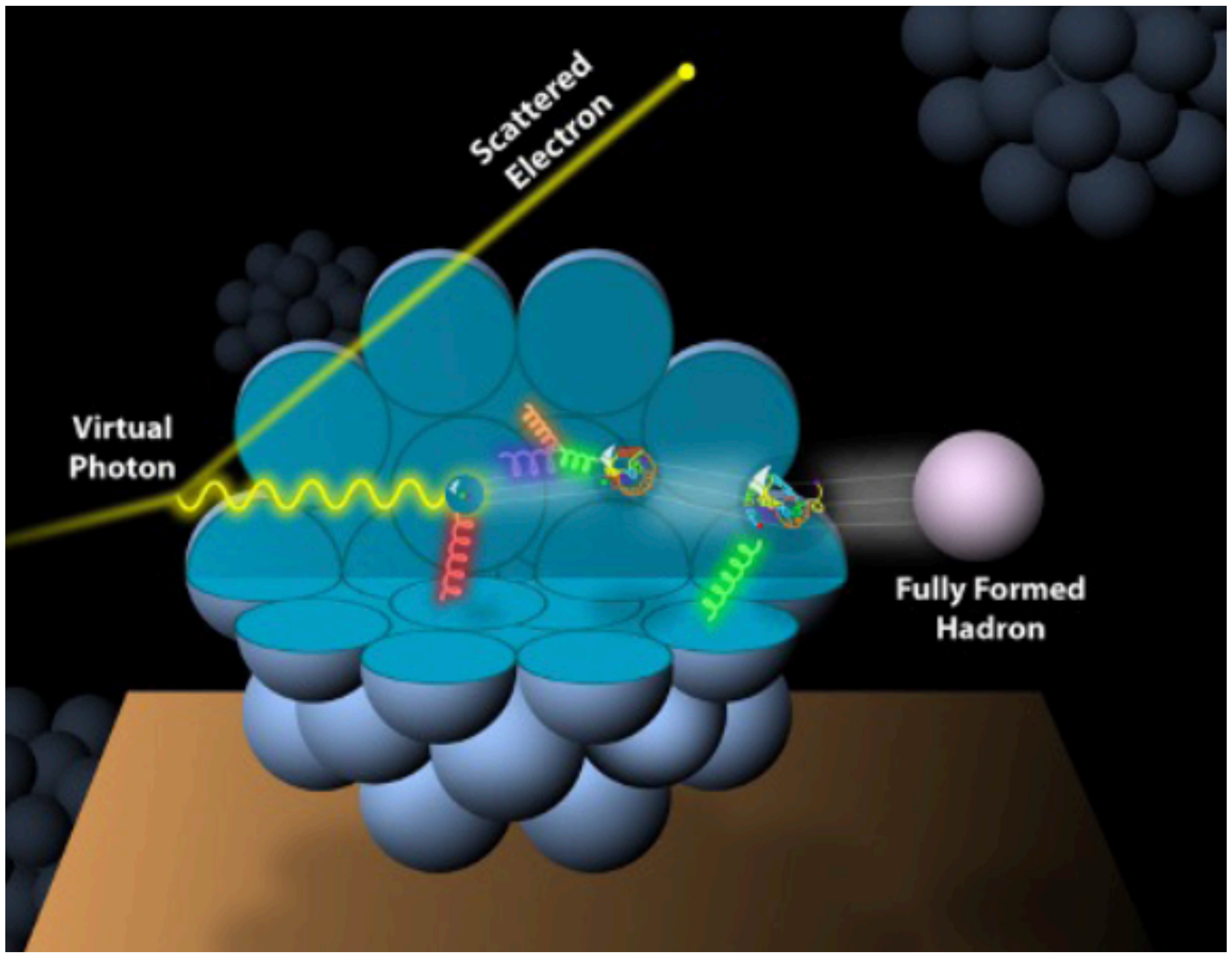


Electron-Positron
(SLAC, BEPC)

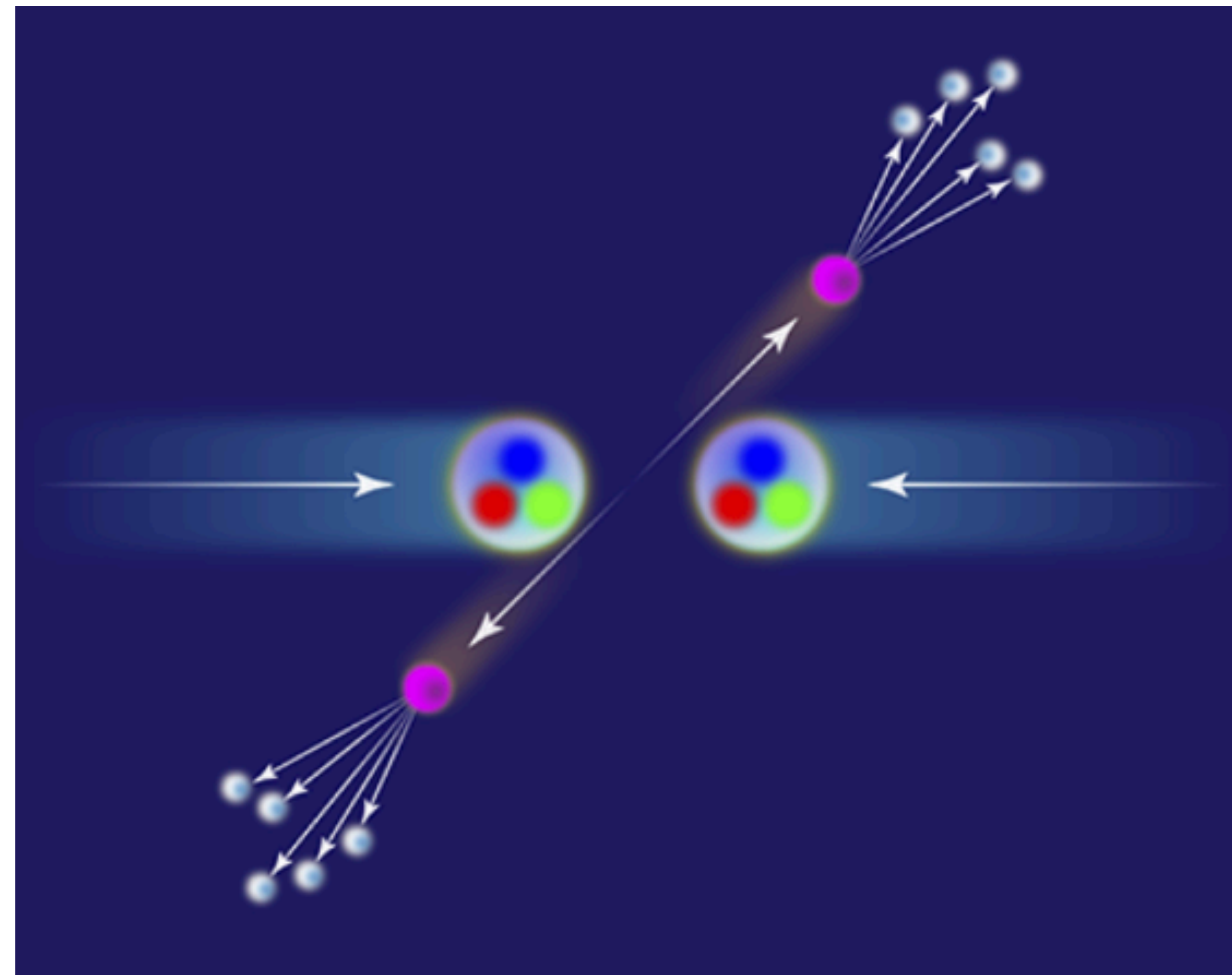
Accardi, Arleo, Brooks, d'Enterria, Muccifora Riv.Nuovo Cim.032:439553,2010 [arXiv:0907.3534]

Experimental processes to study hadronization

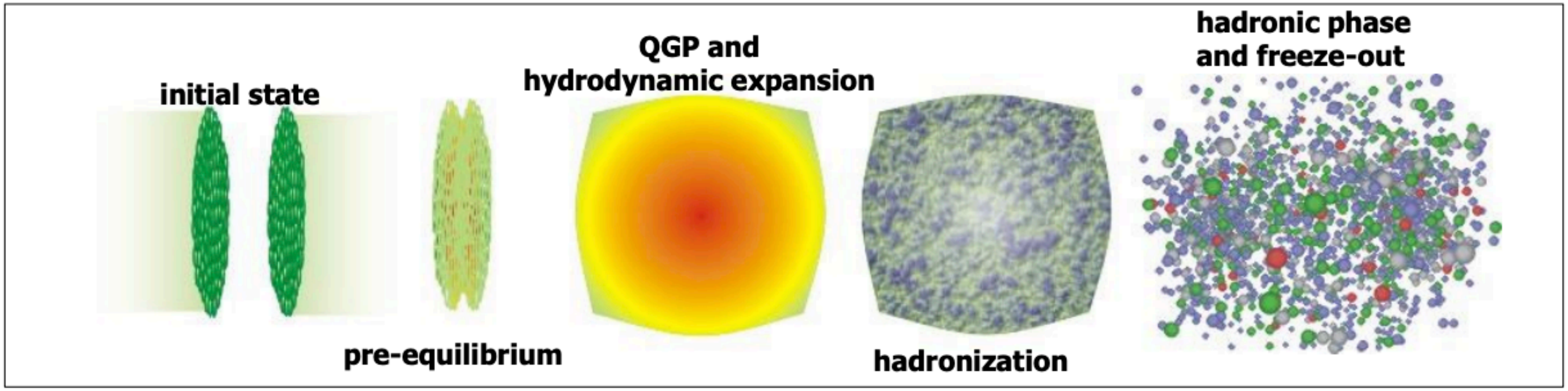
Deep inelastic electron scattering off nuclei



High-energy proton-proton collision



Heavy-Ion collisions



- The only way we can create the QGP in the laboratory!
- By colliding heavy ions it is possible to create a large (»1fm^3) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally mainly the final state particles are observed, so the conclusions have to be inferred via models

Ratio $\mathbf{R_{AA}}$

is the ratio of

the probability of a process in ion-ion collisions (A+A)
to the same probability in proton-proton collisions (pp)

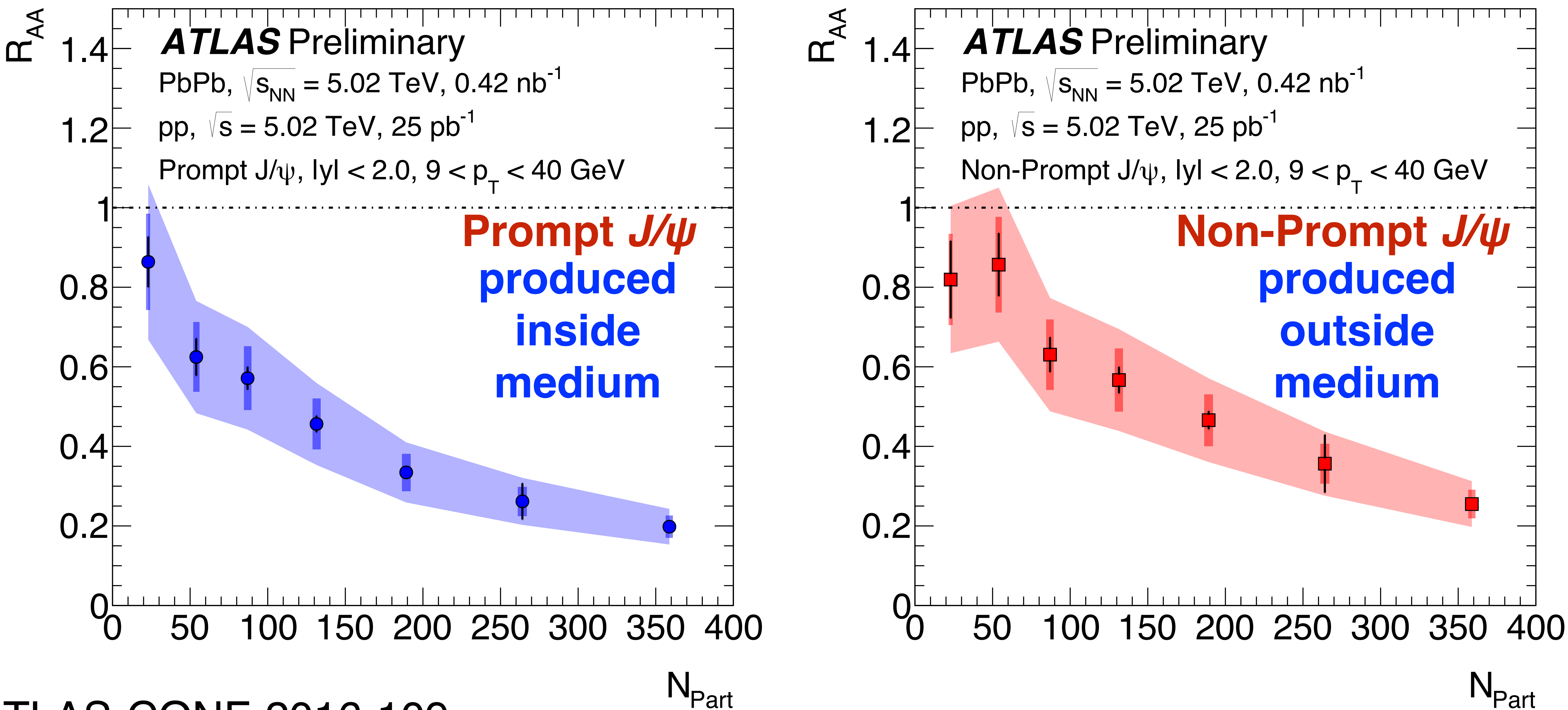
R_{pPb}, R_{PbPb}

if $R_{AA}=1$
then there is no effect due to the nucleus

if $R_{AA}<1$ we call it *suppression*

if $R_{AA}>1$ we call it *enhancement*

J/ψ nuclear modification factor R_{AA}



ATLAS-CONF-2016-109

- **R_{AA} strongly dependent on collision centrality.**
- **Suppression pattern and magnitude are very similar for both production mechanisms.**

eA DIS: past, present, future

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

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

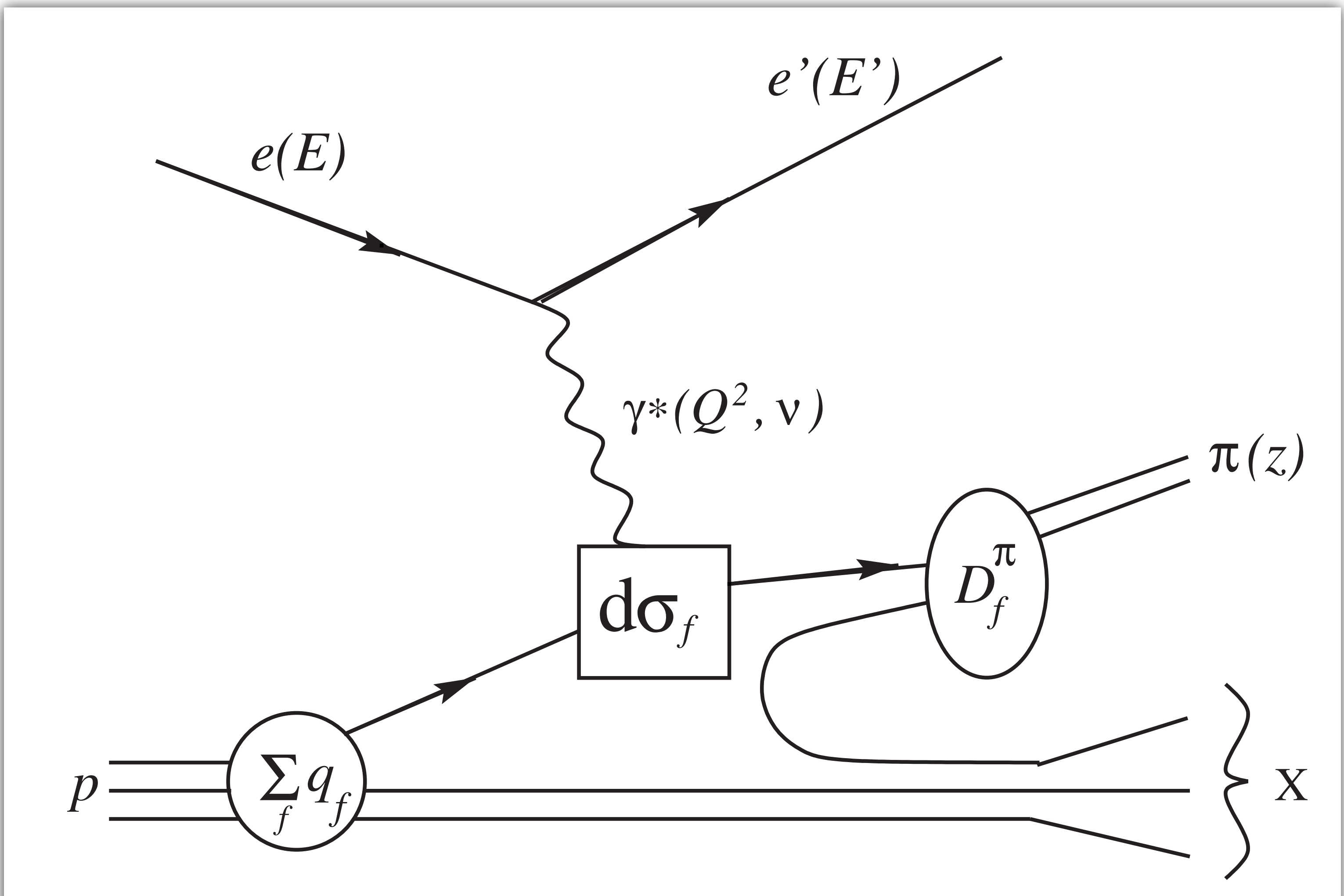
CLAS @11 GeV: $\sqrt{s}$ = 4.6 GeV

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

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

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

SIDIS variables



Q2 = -q2 four-momentum transferred by the electron

ν = E-E′ (lab) energy transferred by the electron;

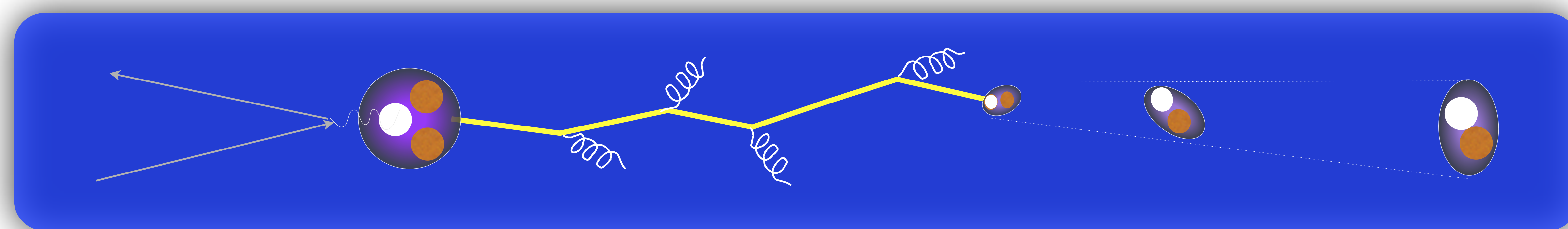
z = Eh/ν fraction of initial quark energy carried by hadron;

pT hadron momentum transverse to the initial γ′ direction

Deep-Inelastic Scattering

Color Propagation and Hadron formation in cold nuclear matter

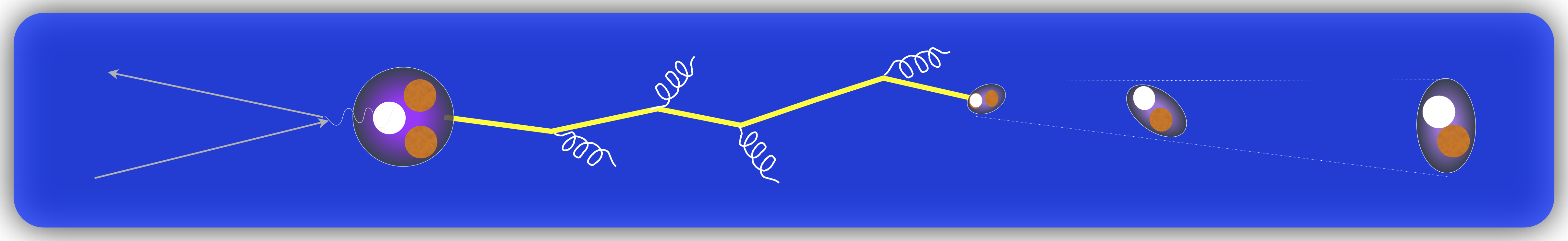
Partonic elastic scattering in medium	Gluon bremsstrahlung Parton rescattering Quark energy loss	Color neutralization Hadron formation Final state interaction

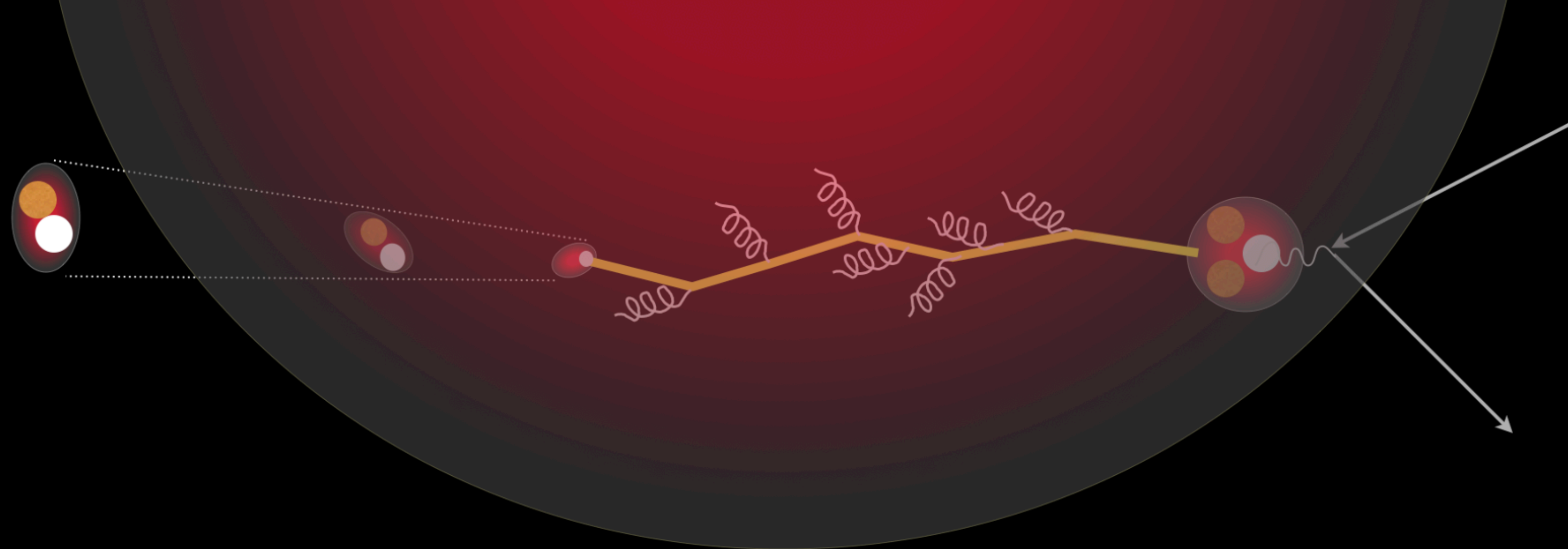


Deep-Inelastic Scattering

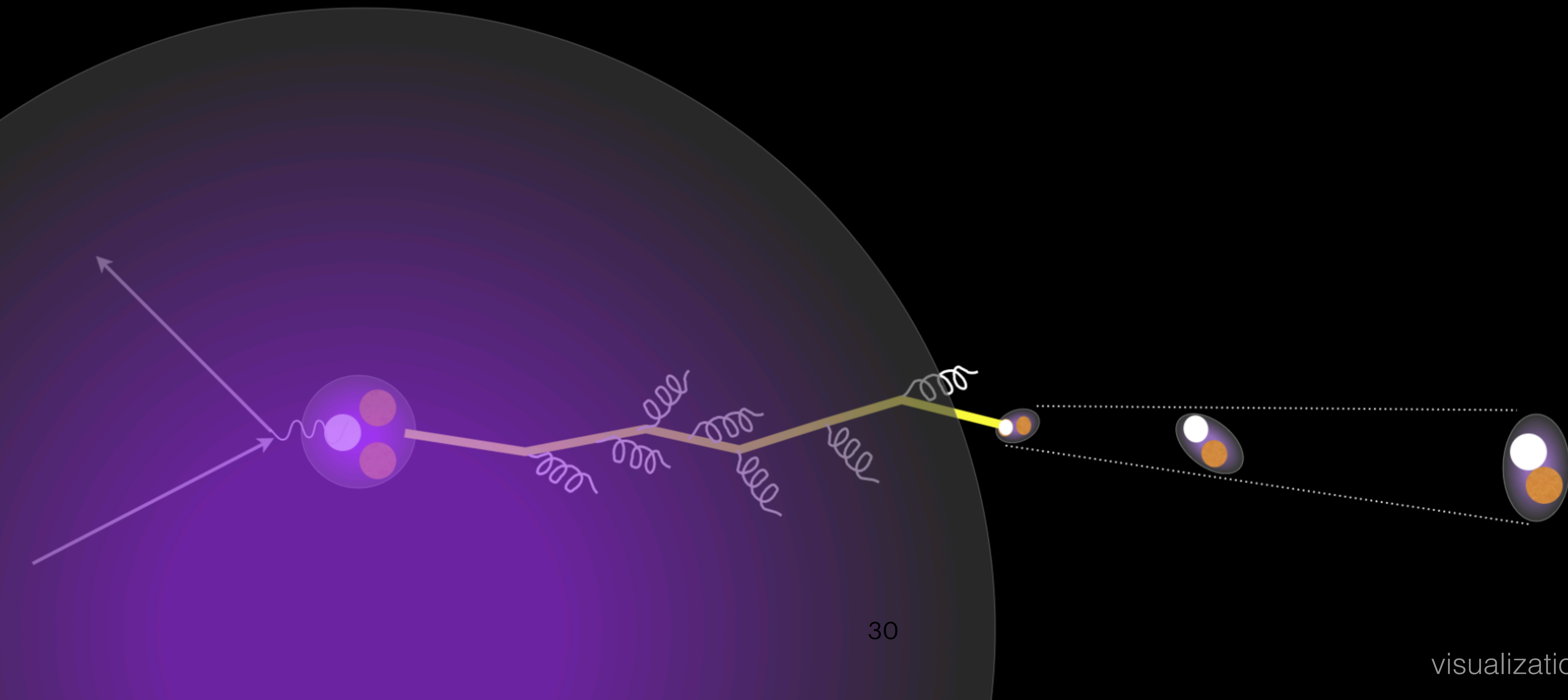
Color Propagation and Hadron formation in cold nuclear matter

What are timescales of color neutralization and hadron formation?

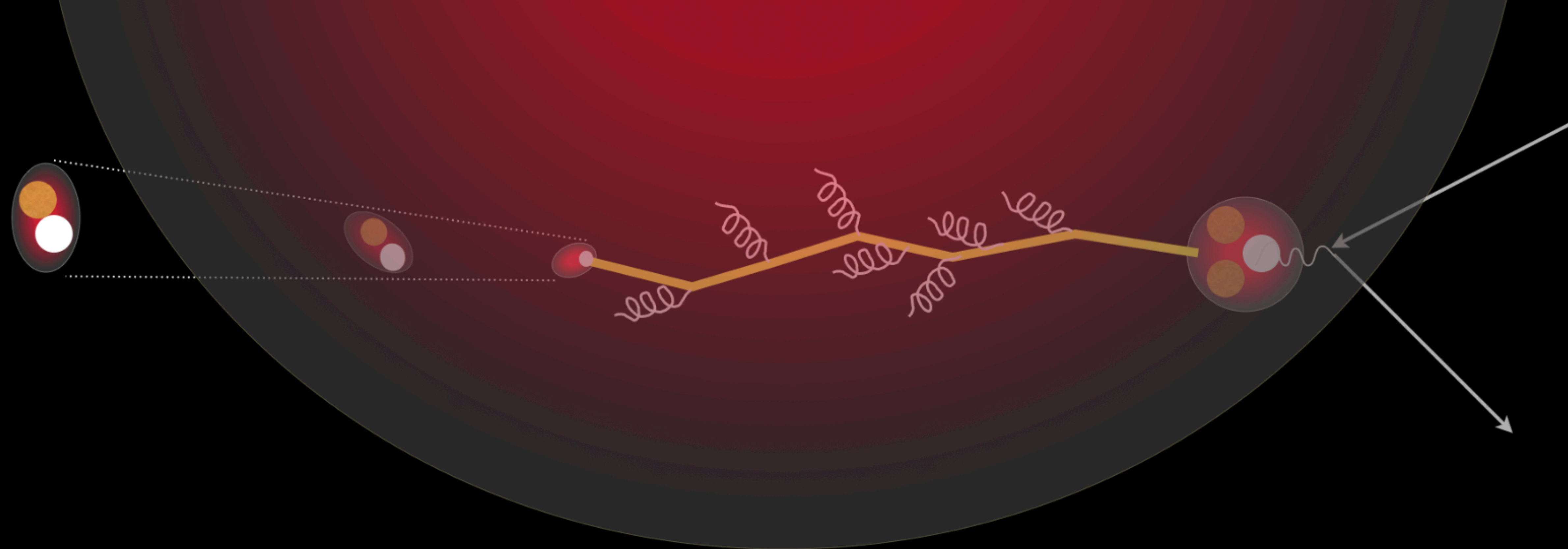




e A : nuclei of increasing size act as space-time analyzer



visualization: W. Brooks



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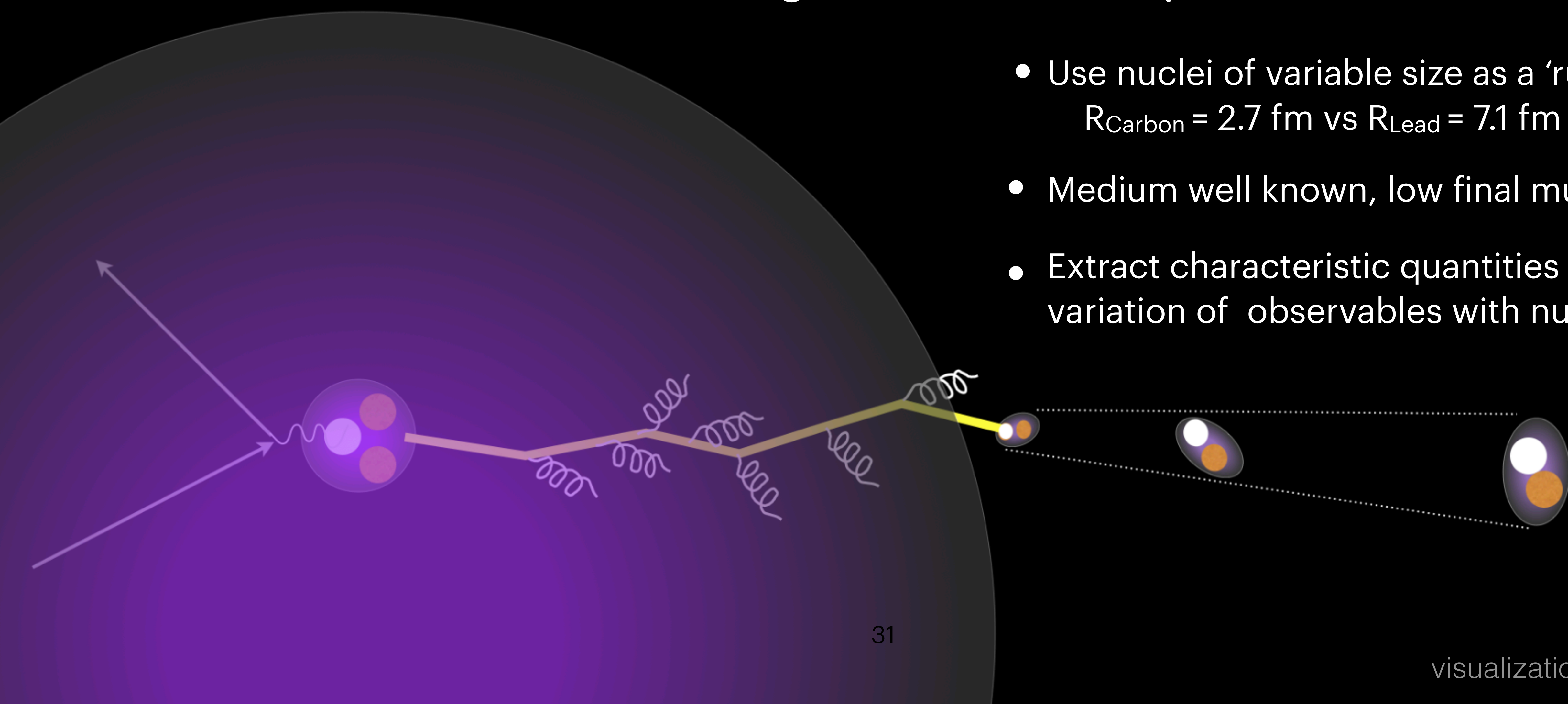


- Use nuclei of variable size as a 'ruler':
  R_{Carbon} = 2.7 fm vs R_{Lead} = 7.1 fm
- Medium well known, low final multiplicities
- Extract characteristic quantities as a variation of observables with nuclear size

visualization: W. Brooks

Back-of-the envelope τ_p

Energy conservation: if hadron carried away energy $E_h = z\nu$, string only has $\nu - E_h$

$$t_p = \frac{\nu}{\left.\frac{dE}{dx}\right|_{vacuum}}(1 - z_h)$$

If take, e.g., $z = E_h/\nu = 0.6$, $\nu = 5$ GeV, then

$\tau_p \sim 2$ fm/c

$$\left.\frac{dE}{dx}\right|_{vacuum} \approx \kappa \approx 1 \quad GeV/fm$$

Back-of-the envelope τ_f

Given hadron of size R_h, can build color field of hadron in its rest frame in time no less than $t_0 \sim R_h/c$. In lab frame this is boosted.

$$t_f \geq \frac{E}{m} R_h$$

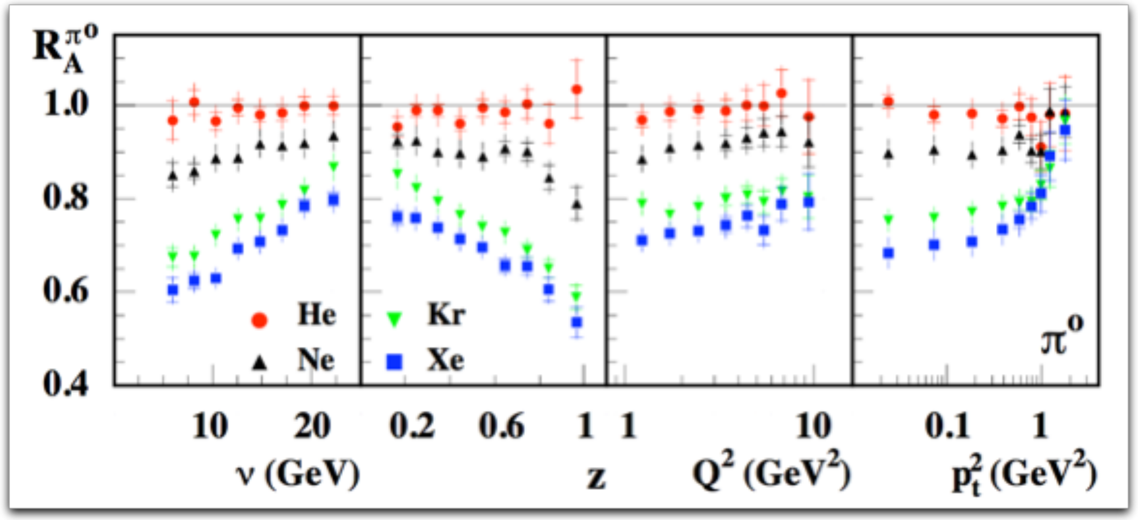
If take, e.g., the pion mass, radius 0.66 fm, $E = 4$ GeV, then ***$\tau_f \sim 20$ fm/c***

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



Multiplicity ratio R_M is just like $\mathbf{R_{AA}}$

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)

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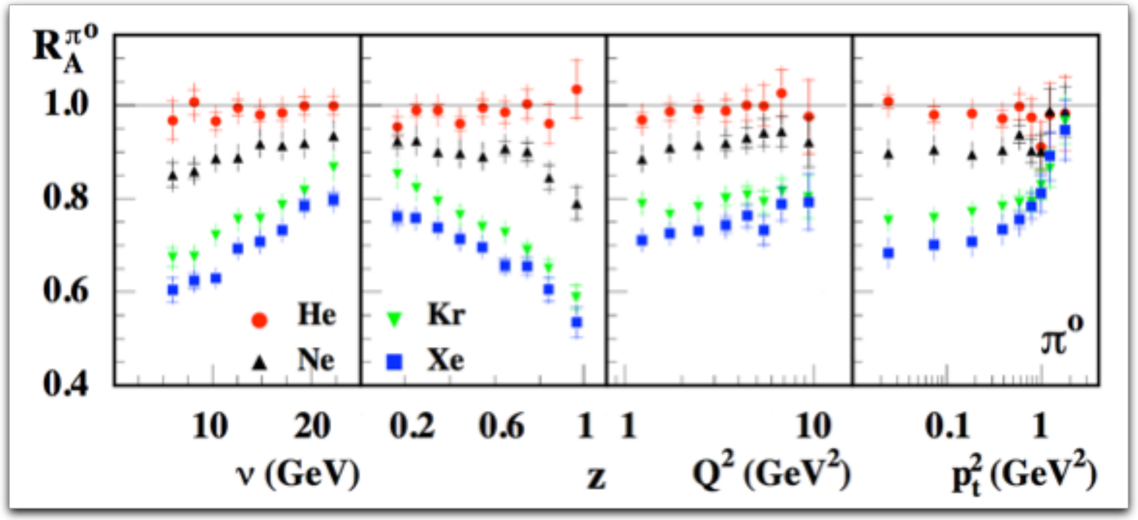

Experimental Observables

Hadronic Multiplicity ratio

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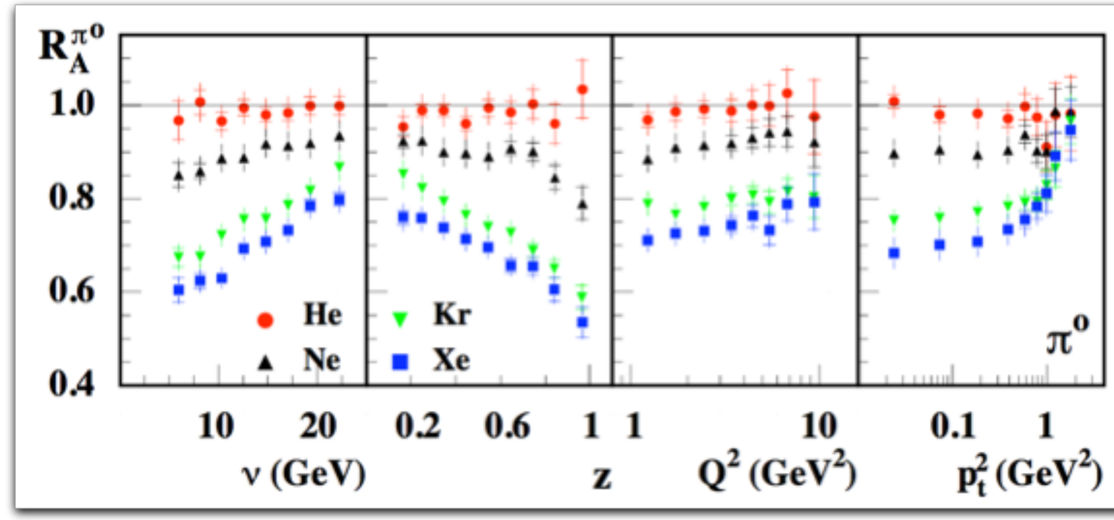
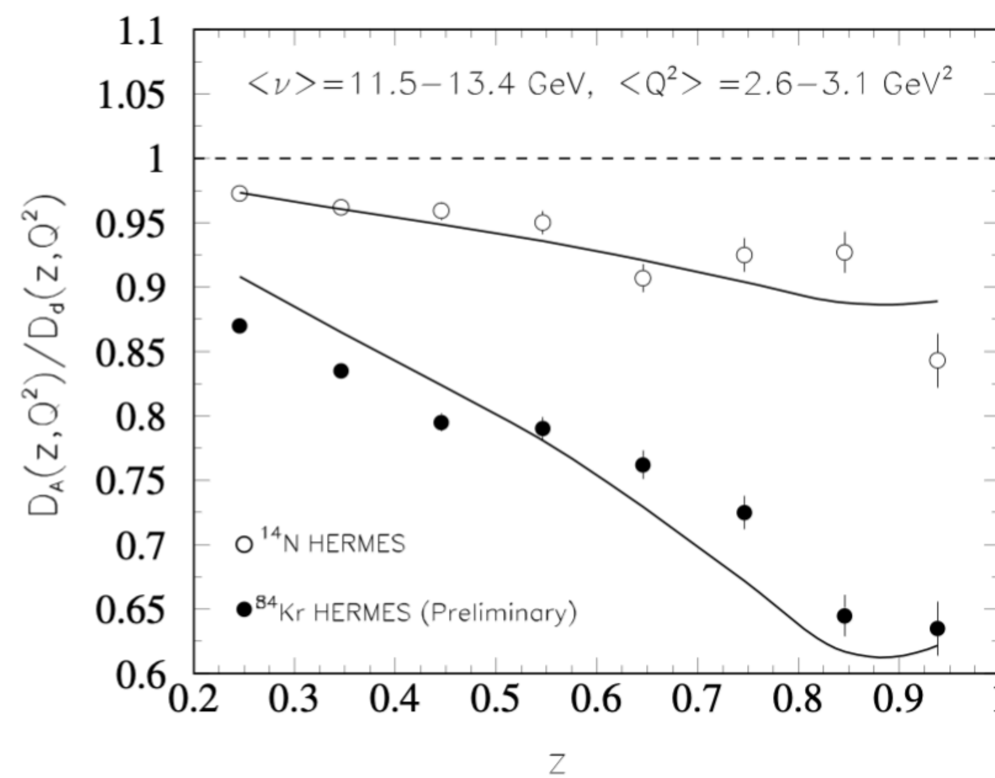


In Quark Parton Model it is the ratio of FF

$$R_M^h(z,\nu) = \frac{\left\{\frac{N_h(z,\nu)}{N_e(\nu)}\right\}_A}{\left\{\frac{N_h(z,\nu)}{N_e(\nu)}\right\}_D} = \frac{\left\{\frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right\}_A}{\left\{\frac{\sum_f e_f^2 q_f(x) D_f^h(z)}{\sum_f e_f^2 q_f(x)}\right\}_D}$$

GuoXandWangXN2000*Phys.Rev.Lett.*853591 Wang E and Wang X N 2002 *Phys. Rev. Lett.* 89 162301-1



Experimental Observables

Hadronic Multiplicity ratio

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

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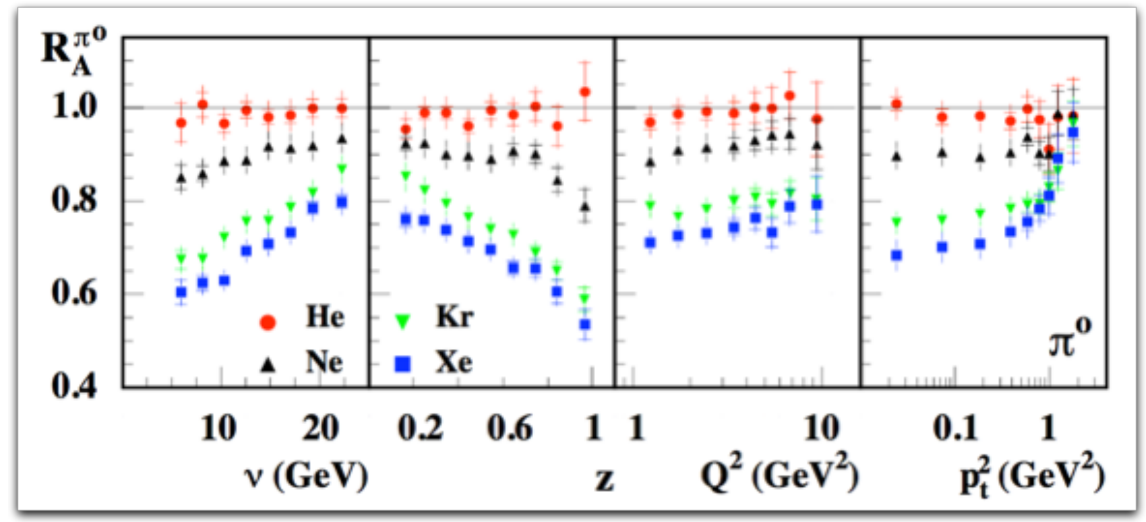
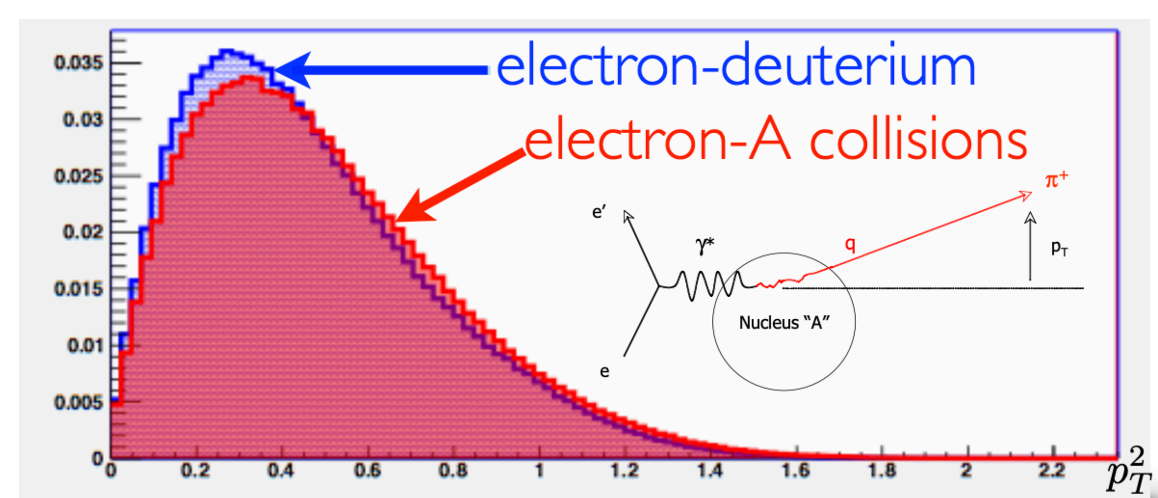


Transverse momentum broadening

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

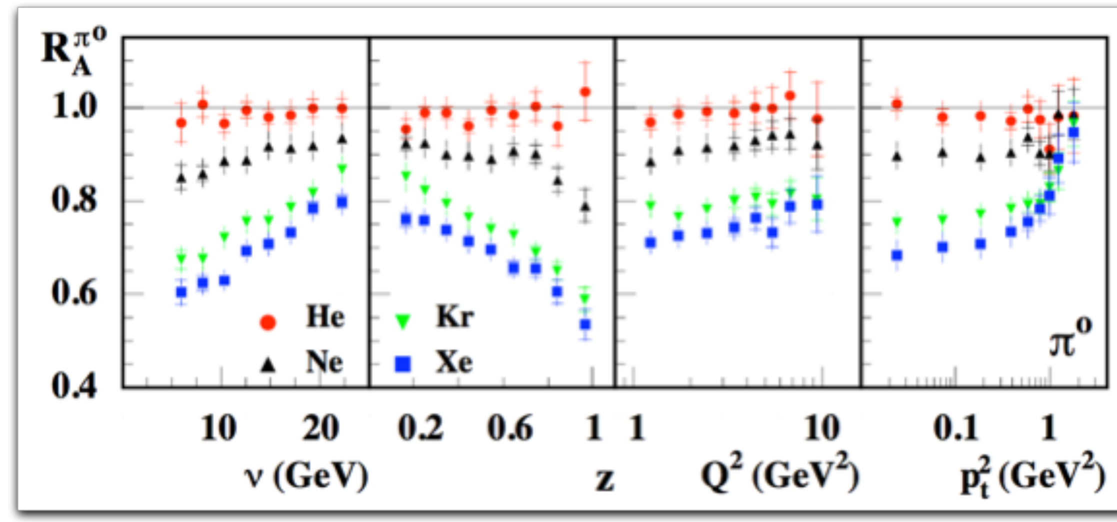


Experimental Observables

Hadronic Multiplicity ratio

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

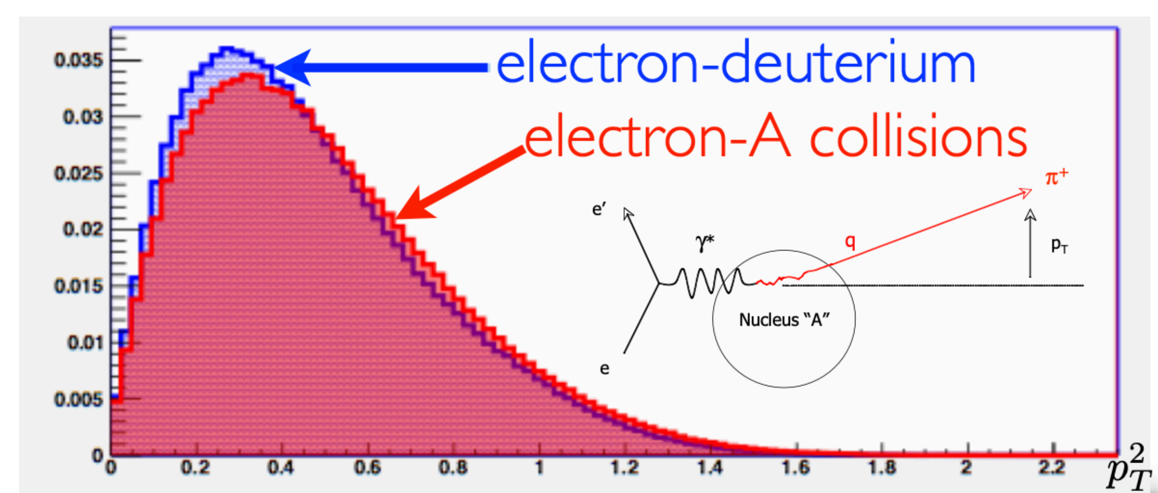
HERMES Collaboration, A.Airapetian et. al., Nucl. Phys. B 780 (2007) 1–27



Formation time τ_f time required for a colored system to evolve into a colorless

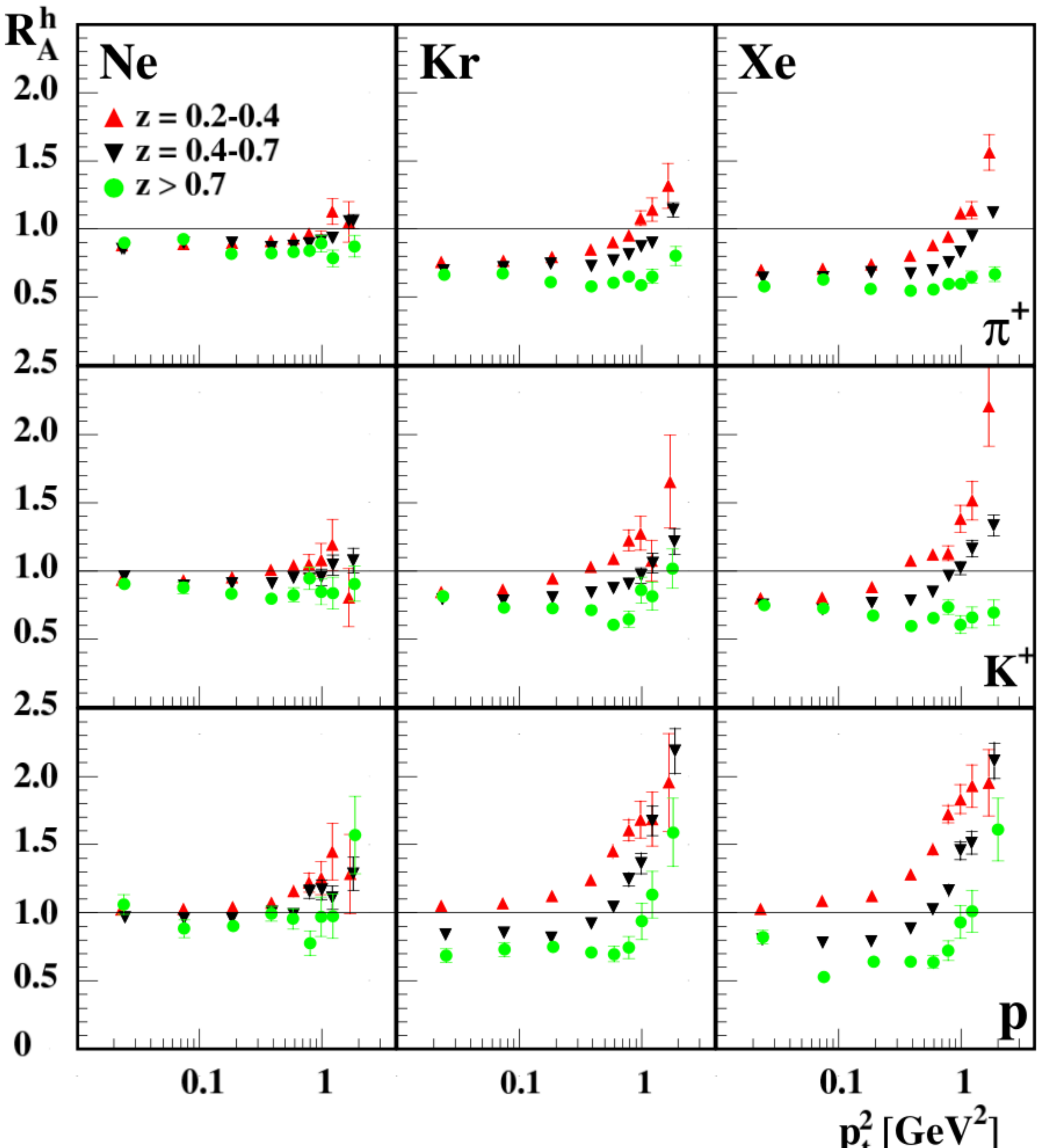
Transverse momentum broadening

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

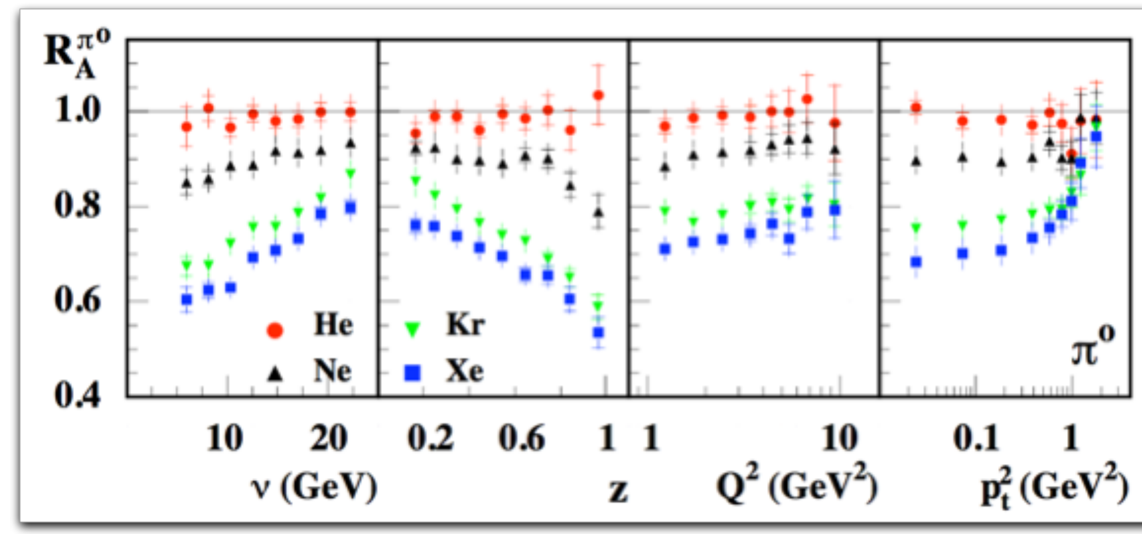


Color lifetime τ_c lifetime of highly virtual 'free' quark

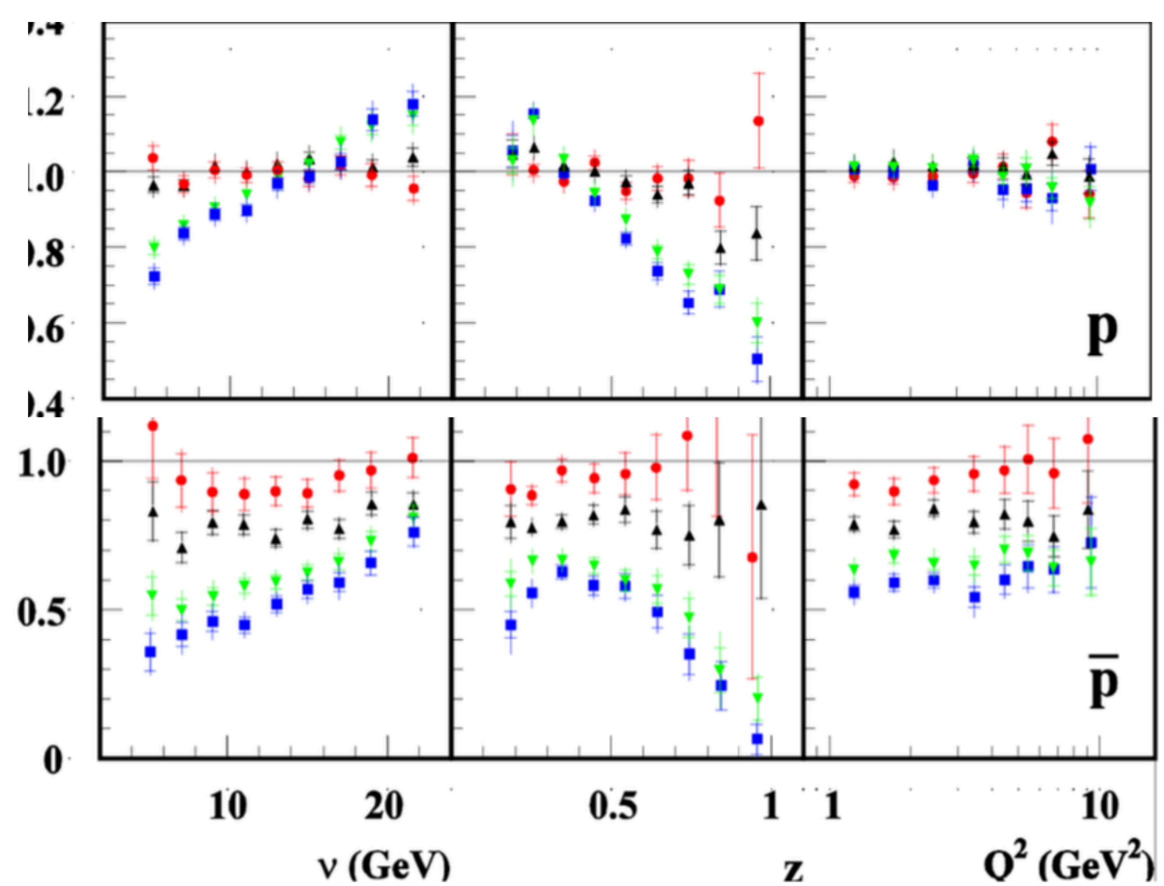
HERMES: 2D and 1D multiplicities



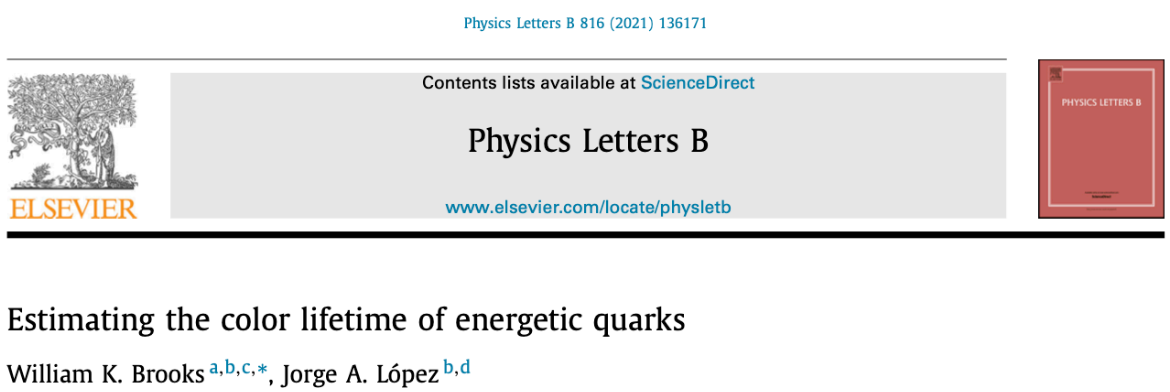
arXiv:1107.3496v3 [hep-ex] 13 Sep 2011
Eur. Phys. J. A47:113, 2011



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



Extraction of color lifetime Brooks-Lopez model


Physics Letters B 816 (2021) 136171

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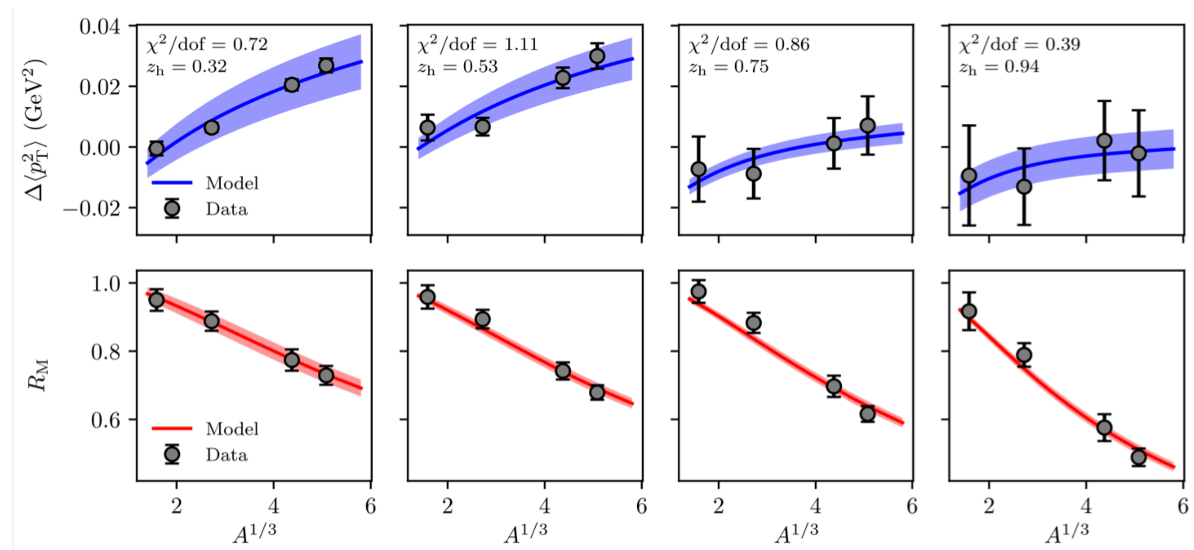
www.elsevier.com/locate/physletb

ELSEVIER

Estimating the color lifetime of energetic quarks

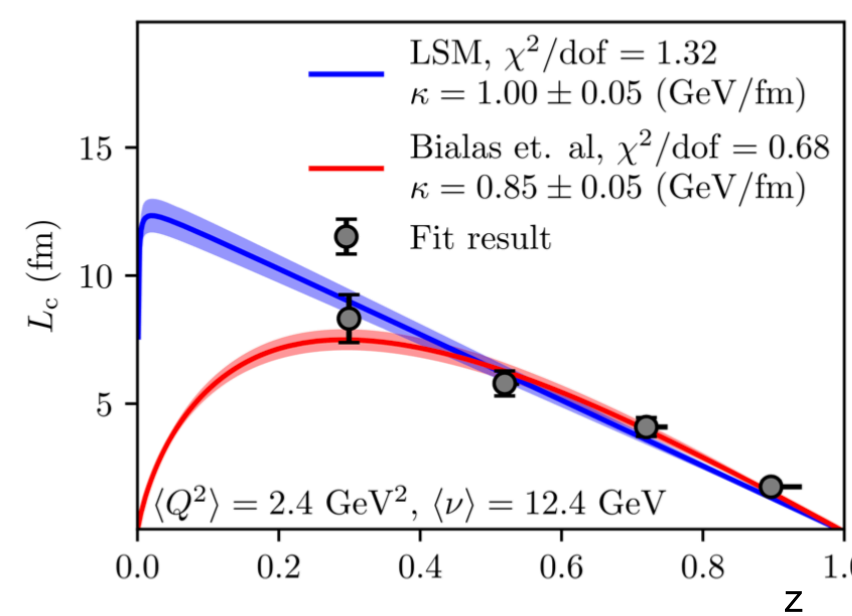
William K. Brooks [a,b,c,*], Jorge A. López [b,d]

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



- 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: *k = 1 GeV/fm*
- Measurement of transport coefficient

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

Experimental realization

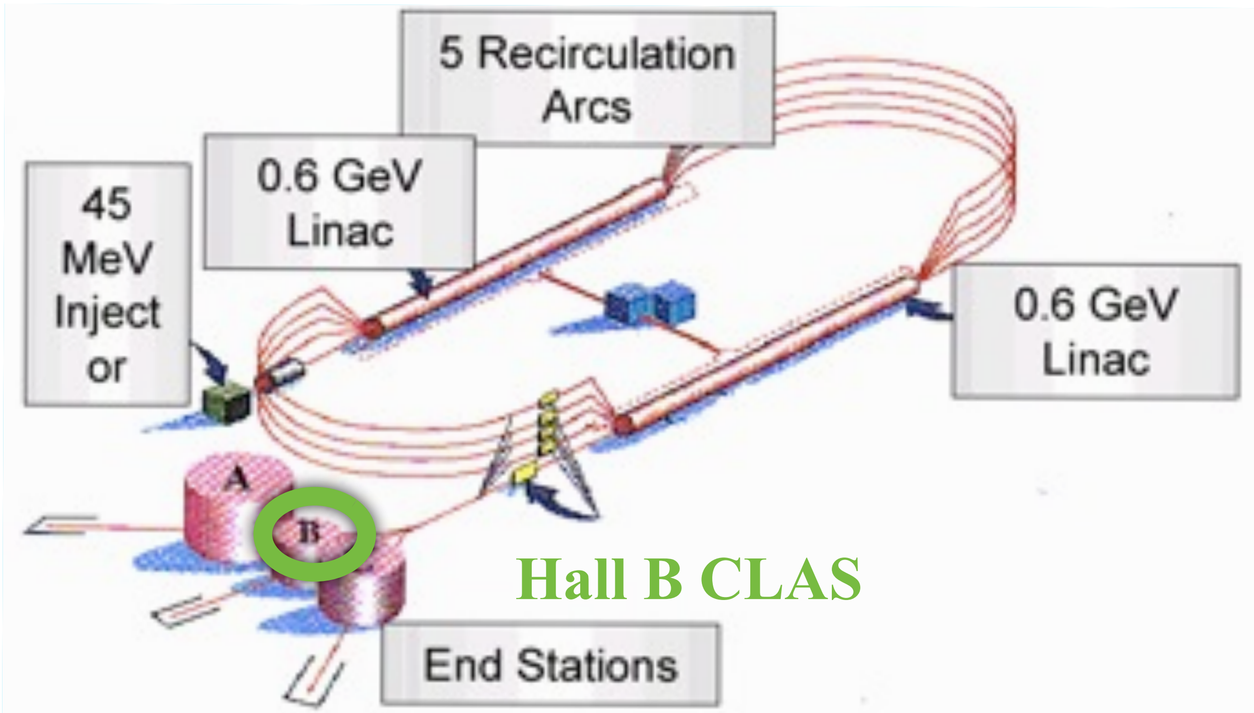
Jefferson Lab

clas

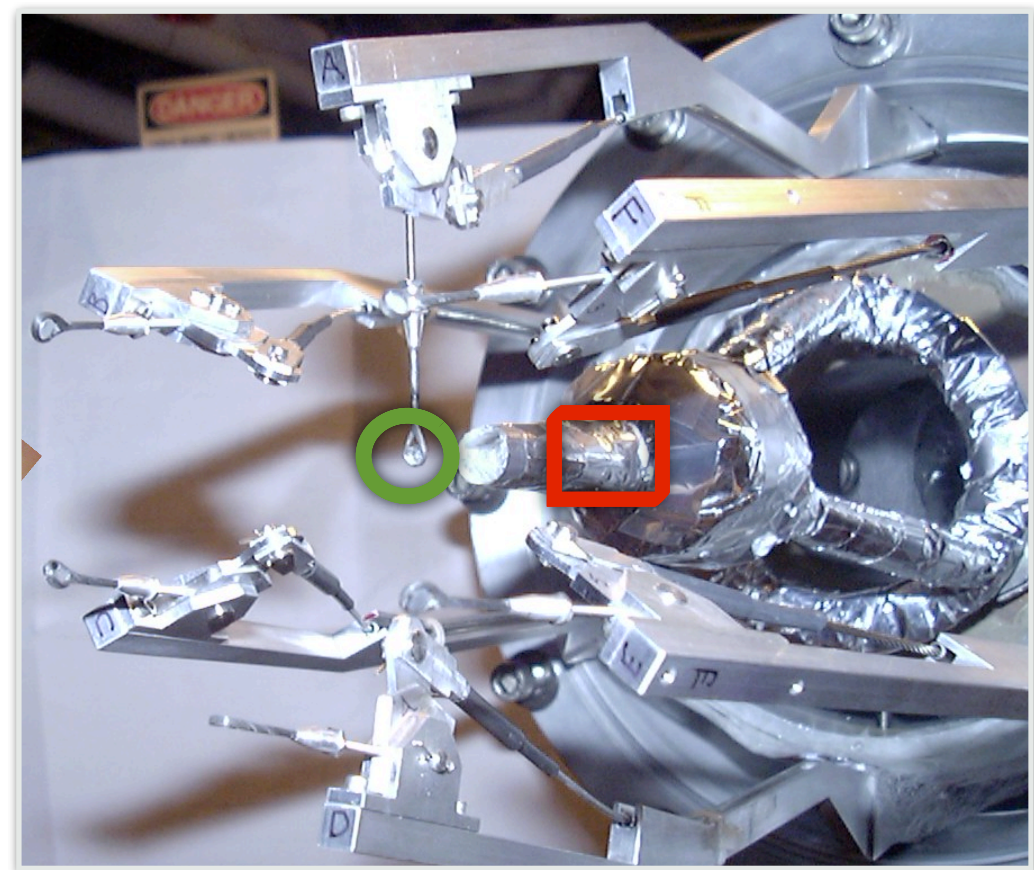
CEBAF Large Acceptance Spectrometer

Jefferson Lab

EG2 experiment @ 5 GEV



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



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

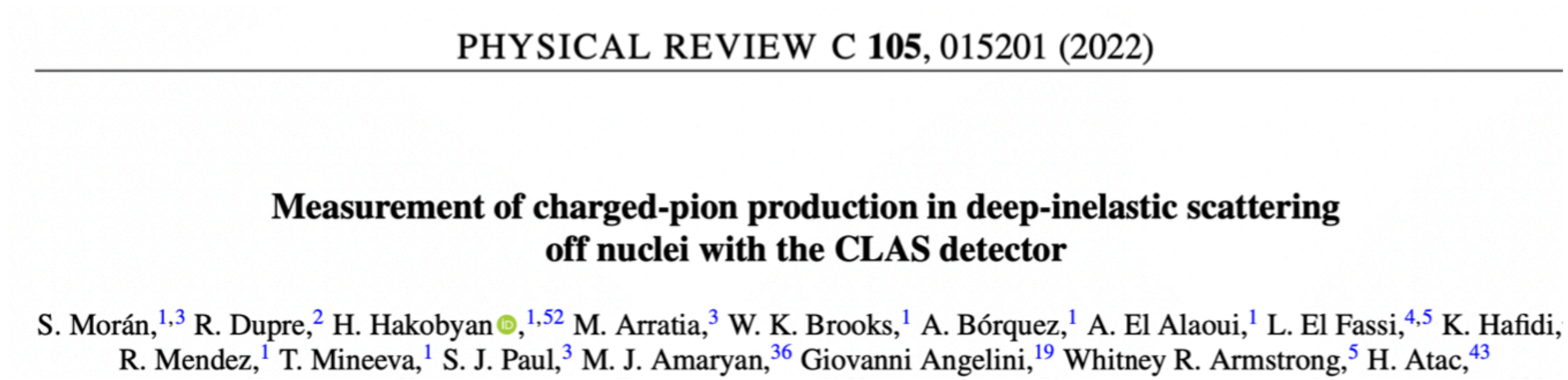
EG2 experiment running conditions

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

CLAS integrated luminosity is 100 times greater than HERMES!!

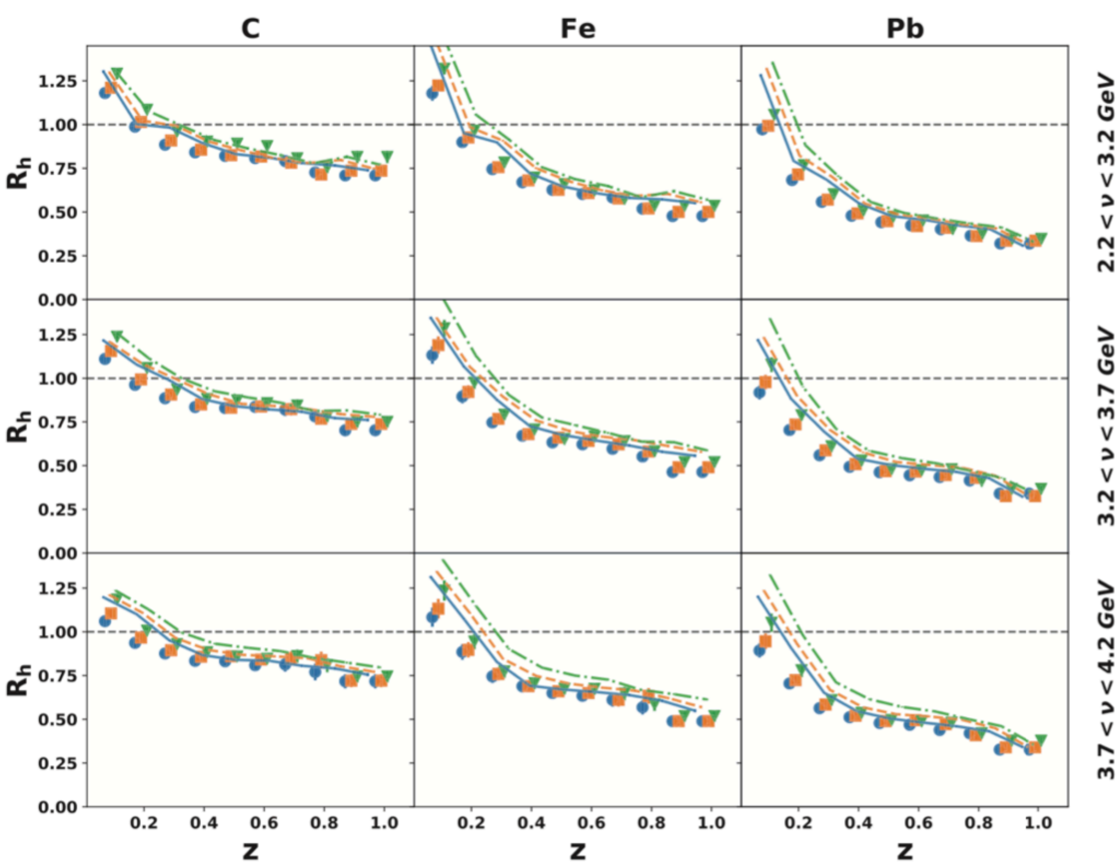
Light hadrons

CLAS: 3D pion multiplicities

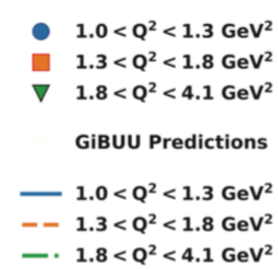

PHYSICAL REVIEW C **105**, 015201 (2022)

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

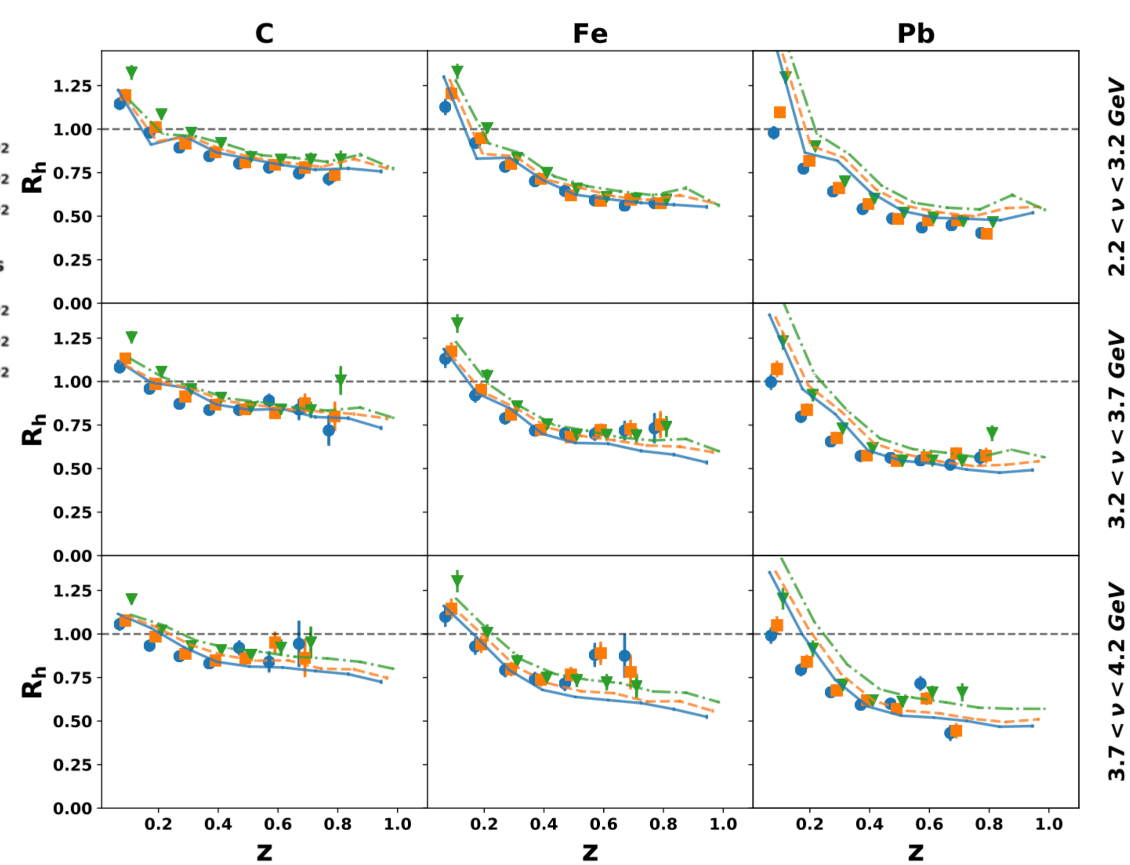
S. Morán,[1,3] R. Dupre,[2] H. Hakobyan,[1,52] M. Arratia,[3] W. K. Brooks,[1] A. Bórquez,[1] A. El Alaoui,[1] L. El Fassi,[4,5] K. Hafidi, R. Mendez,[1] T. Mineeva,[1] S. J. Paul,[3] M. J. Amaryan,[36] Giovanni Angelini,[19] Whitney R. Armstrong,[5] H. Atac,[43]



π^+



3D



π^-

CLAS: 3D pion multiplicities

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

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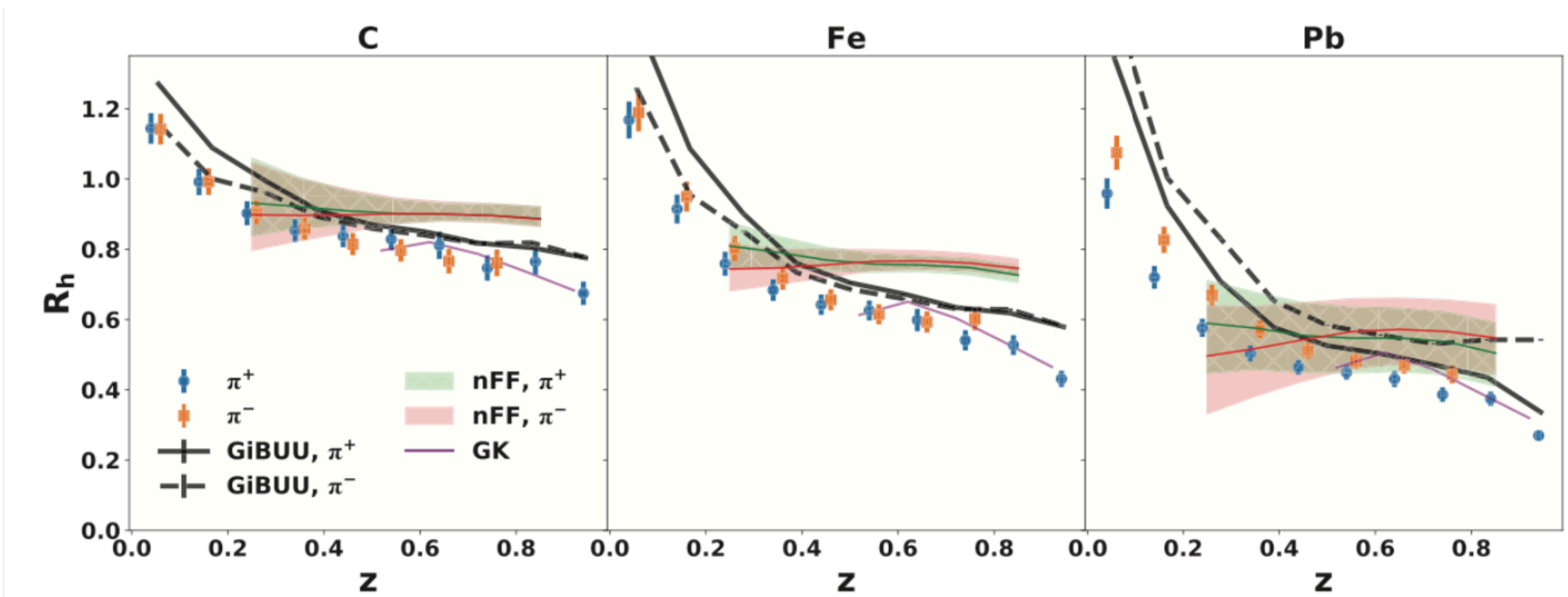
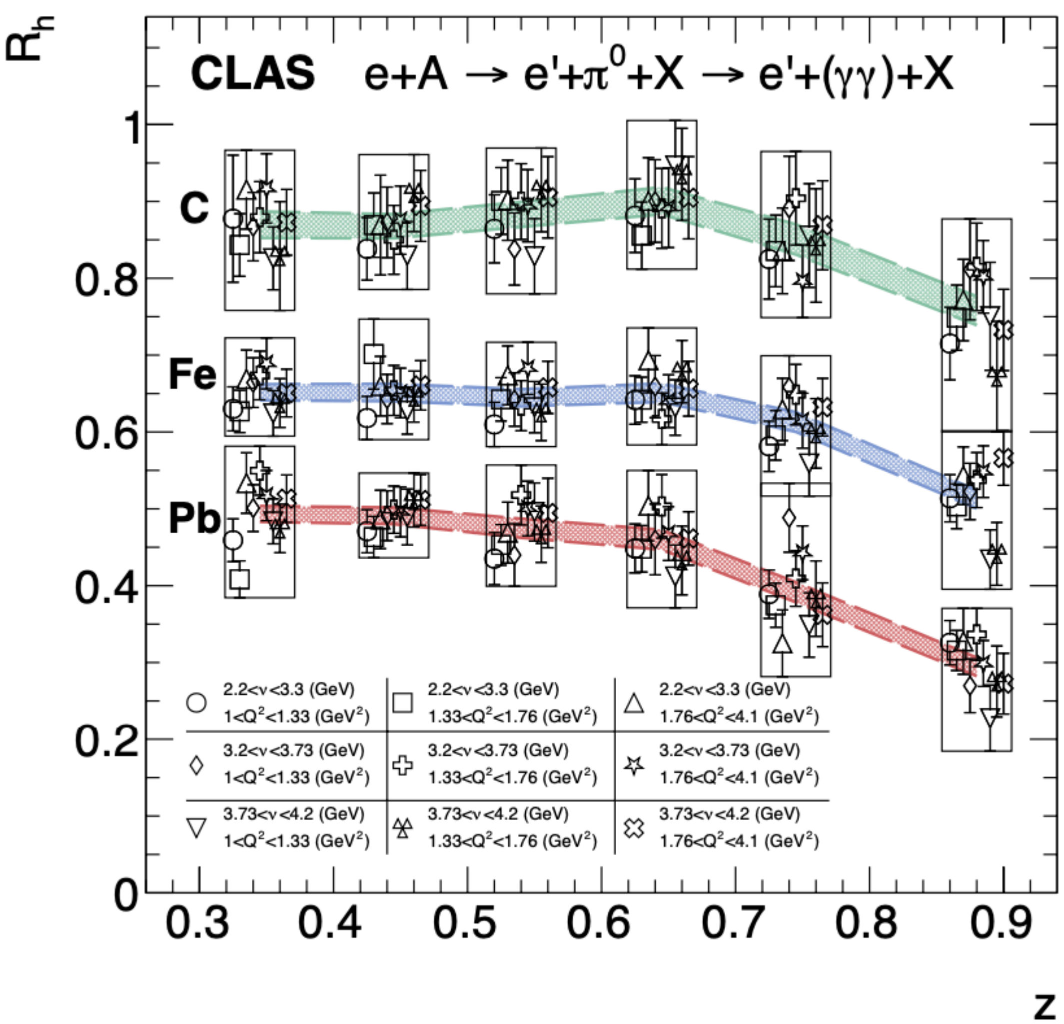


High-precision three-dimensional data is compared to the model predictions; GiBUU and Guiot-Kopeliovich models find semi-qualitative agreement

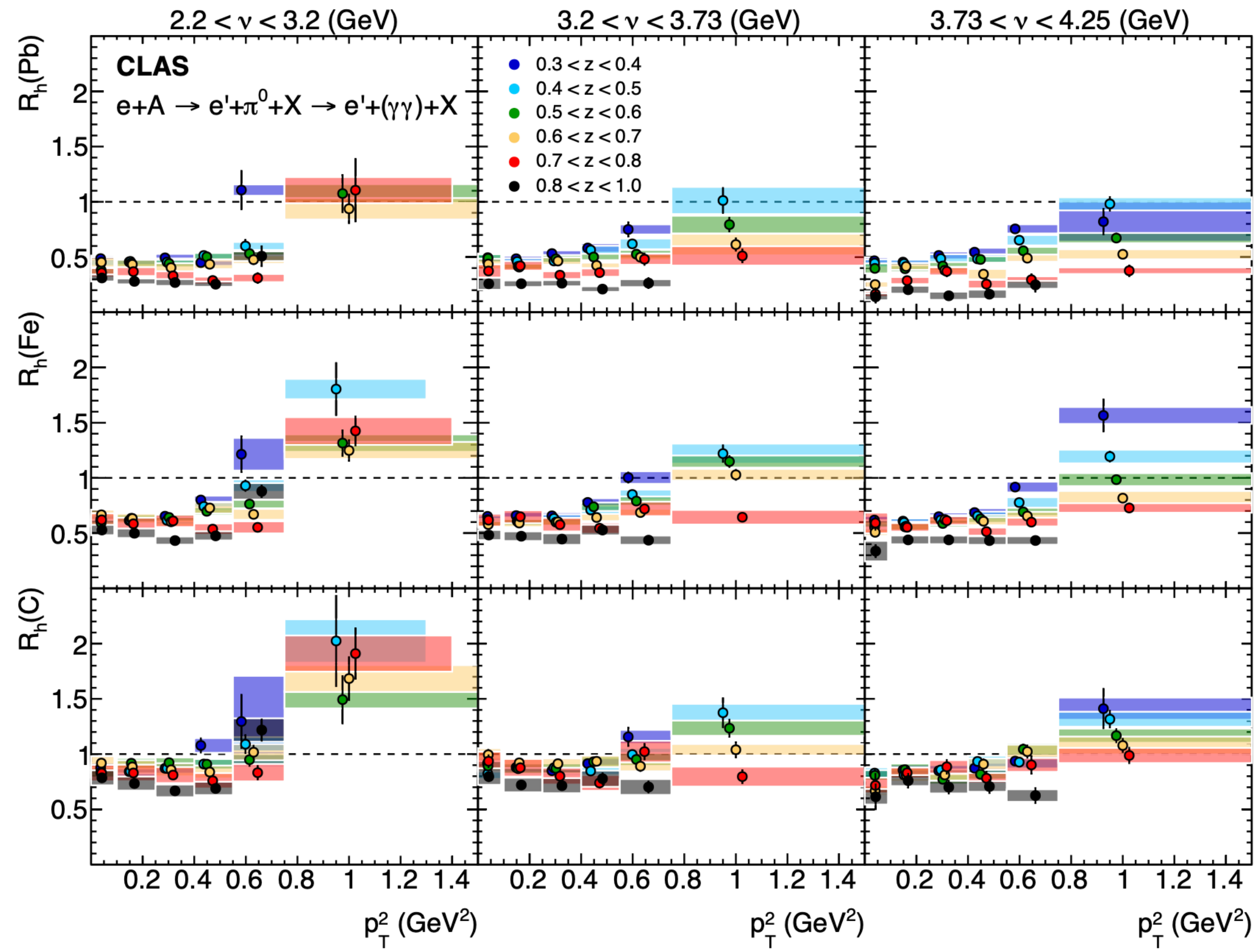
CLAS: 3D pion multiplicities

T.Mineeva et al. arXiv:2406.04513



π^0

3D

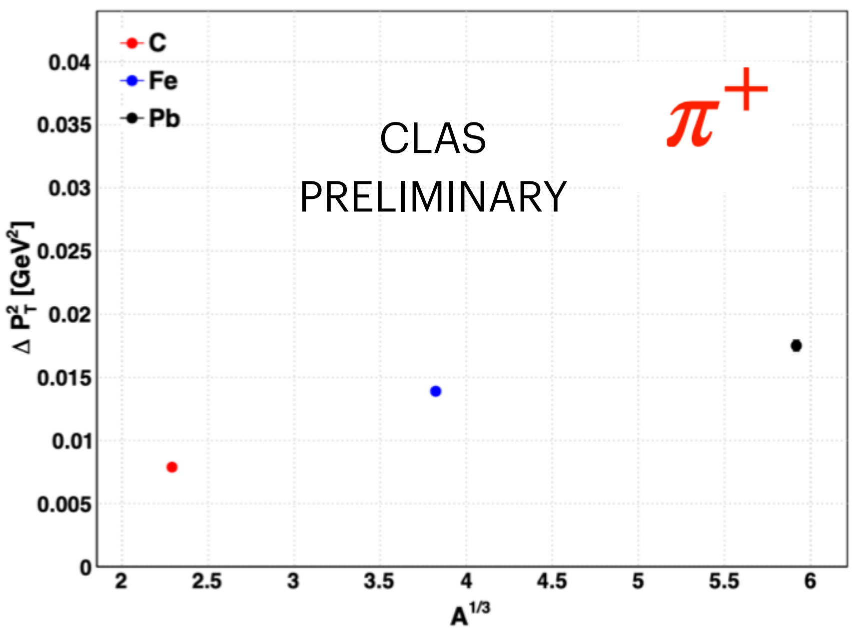


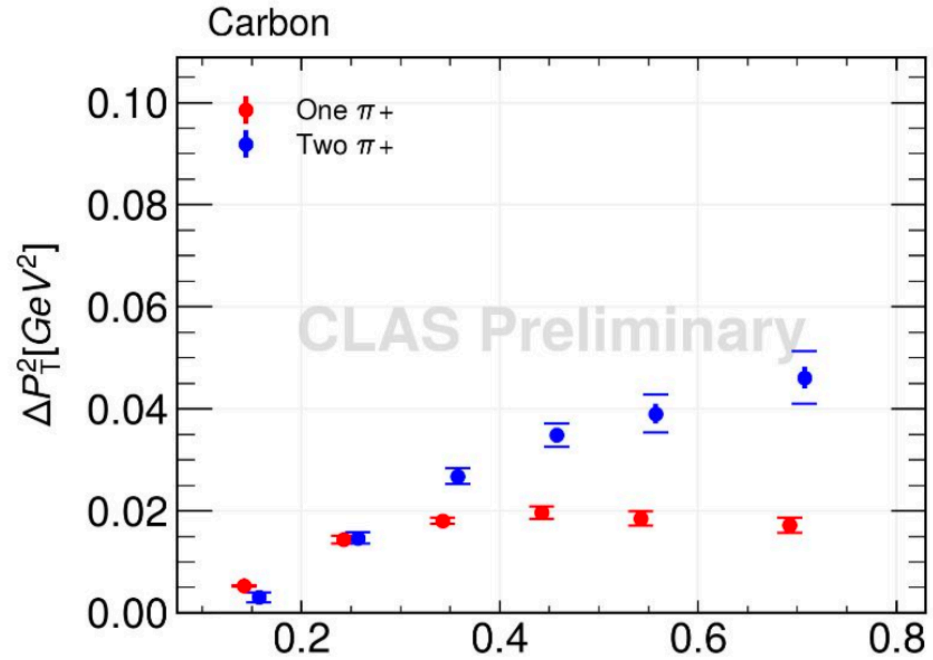
- Attenuation depends on nuclear size *A*
- Suppression for leading hadrons: 25% on C to 75% on Pb
- No dependence on Q^2 and ν observed

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

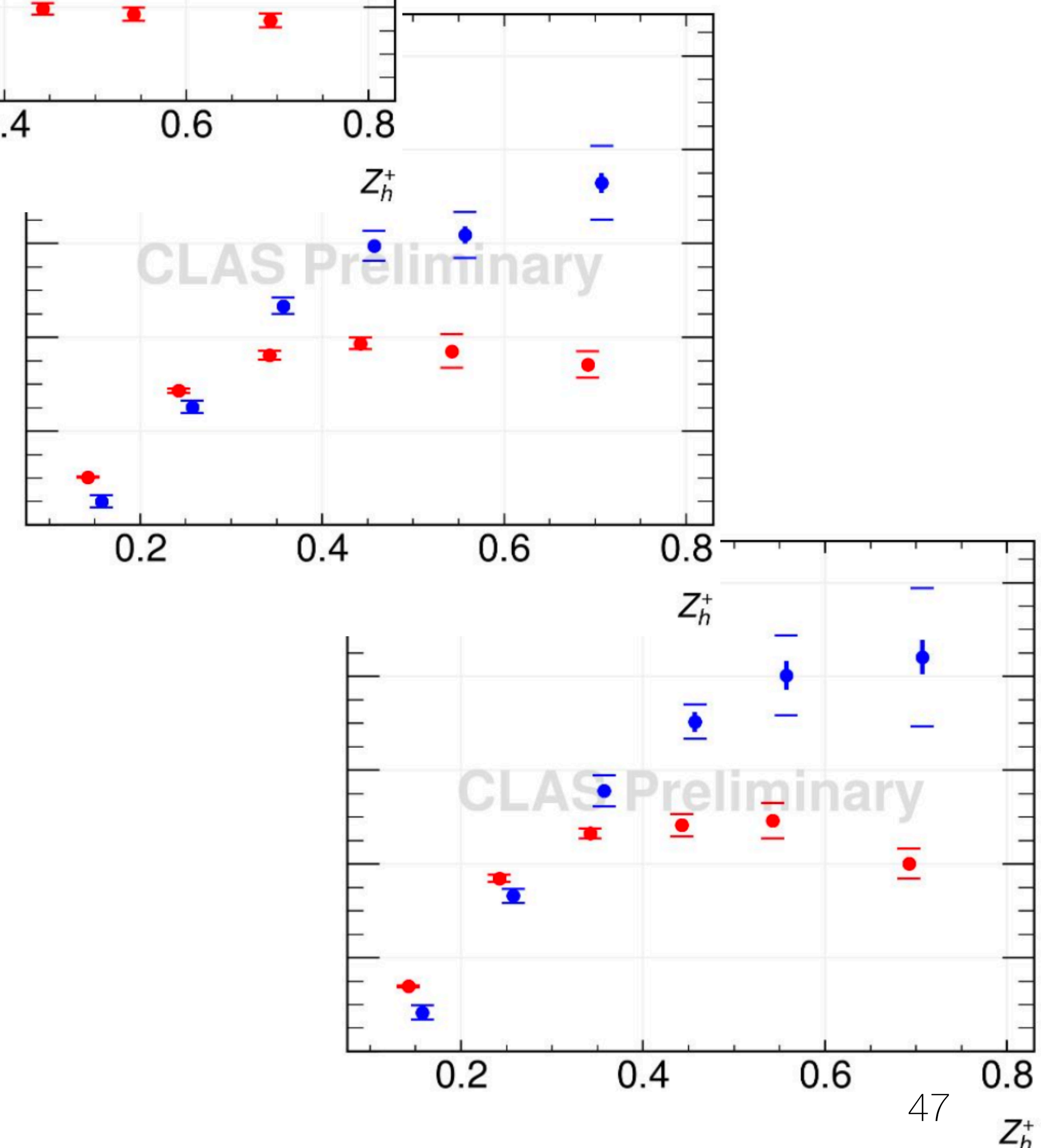
pT² broadening for multiple π⁺ events

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

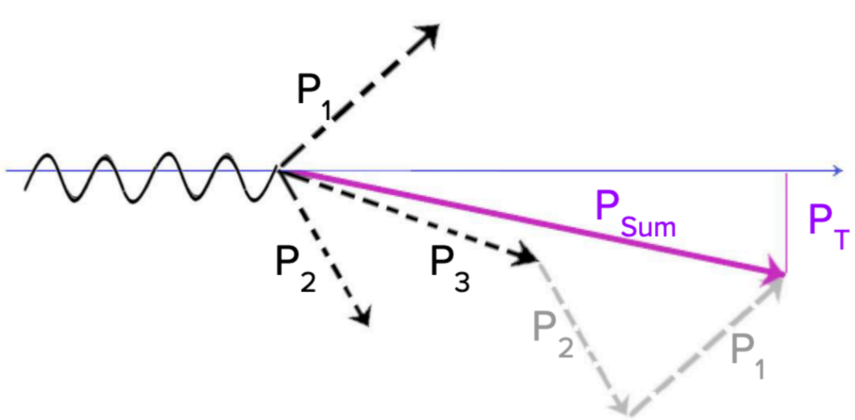




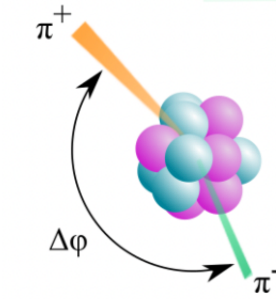
M.Barría Thesis
https://repositorio.usm.cl/handle/11673/56688



- 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?

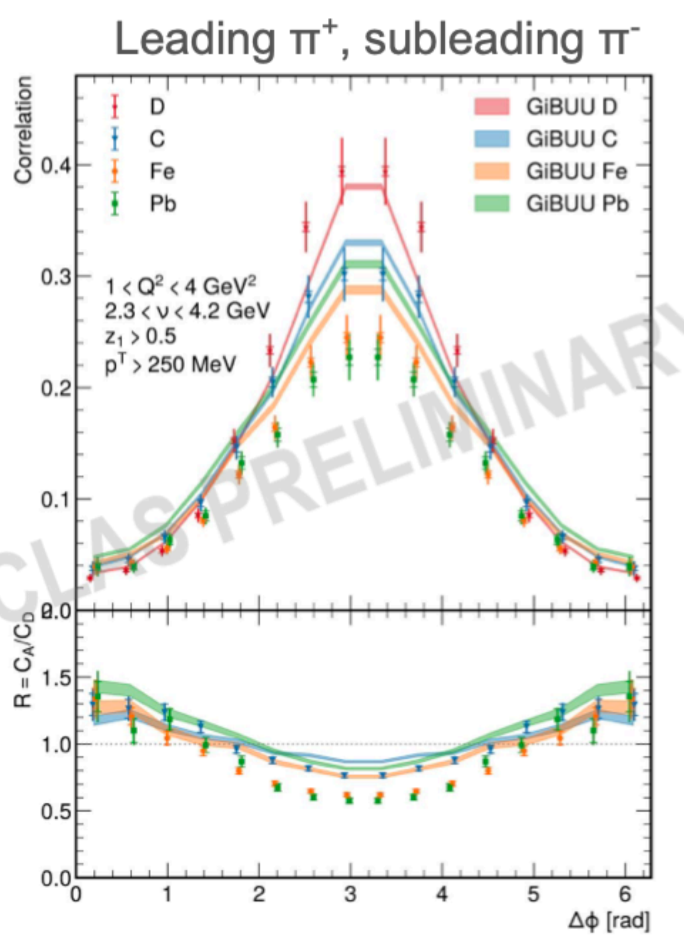
$$C(\Delta\phi) = C_0 \frac{1}{N_{eh}} \frac{dN_{ehh}}{d\Delta\phi}$$

$\Delta\varphi$ 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



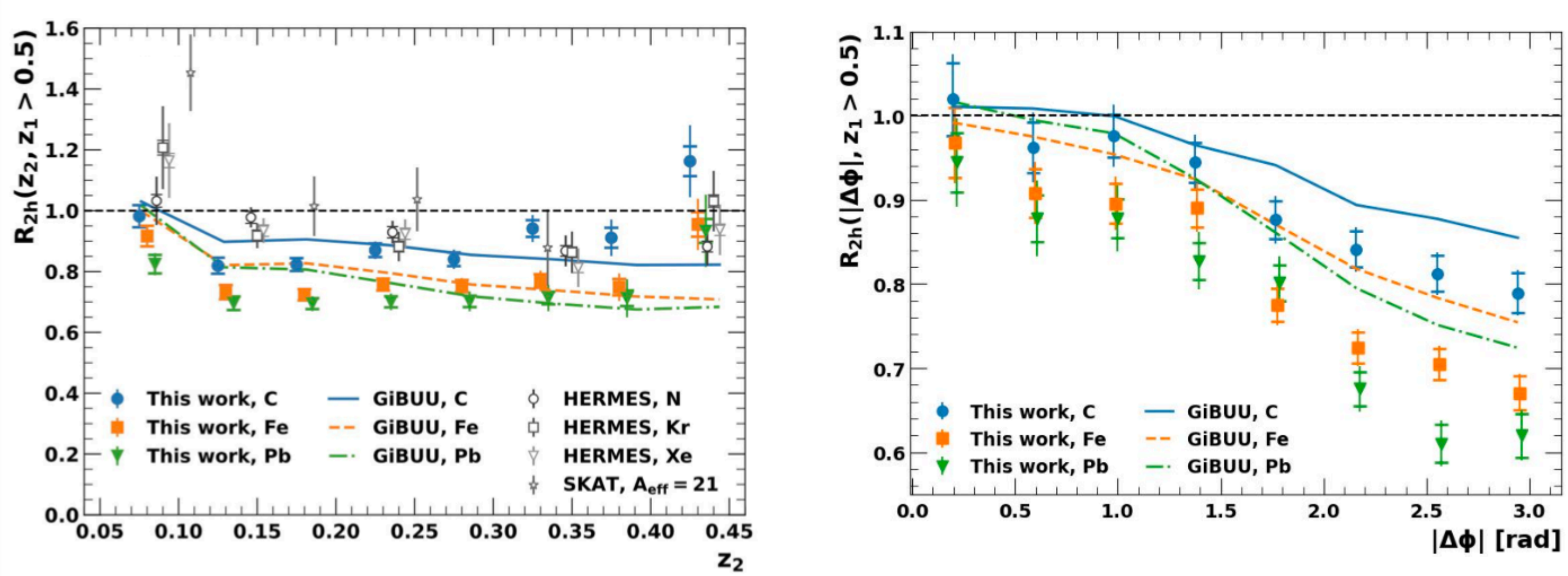
S.J Paul et al, in CLAS ad-hoc review

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



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

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

Theoretically, BEC is the ratio of the two particles' inclusive cross section to the single-particle cross sections

$$R_{(p1,p2)} = \frac{D(p_1,p_2)}{D(p_1)D(p_2)}$$

D(p1, p2) two-particle probability density

D(p1), D(p2) are one-particle probability densities

Experimentally constructed BEC correlation

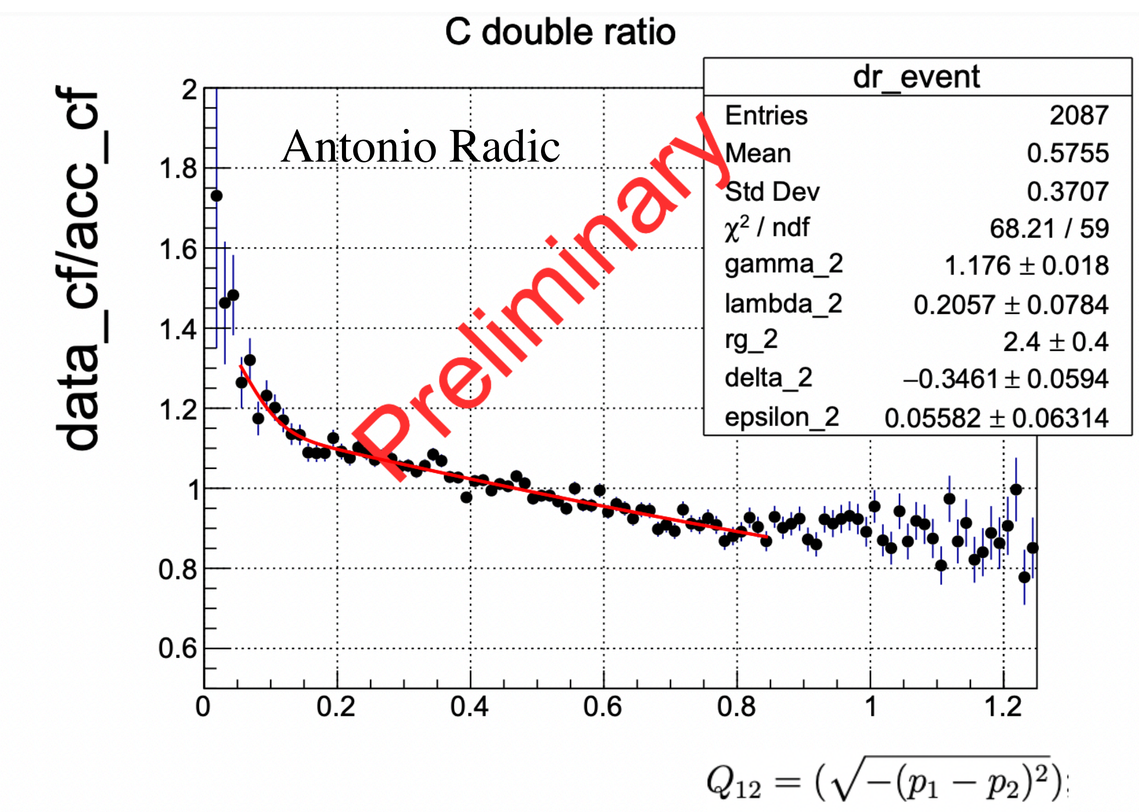
$$\boxed{R_{(p_1,p_2)} = \frac{D(p_1,p_2)}{D_b(p_1,p_2)}}$$

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)

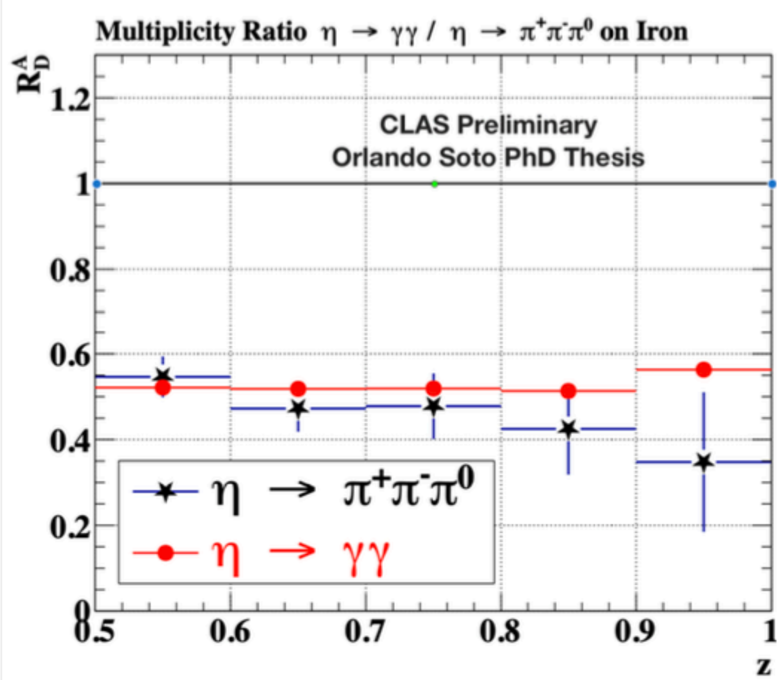
$$\boxed{R(Q_{12}) = \left(\frac{D(Q_{12})}{D(Q_{12})_{mix}}\right)^{data} / \left(\frac{D(Q_{12})}{D(Q_{12})_{mix}}\right)^{simul}}$$

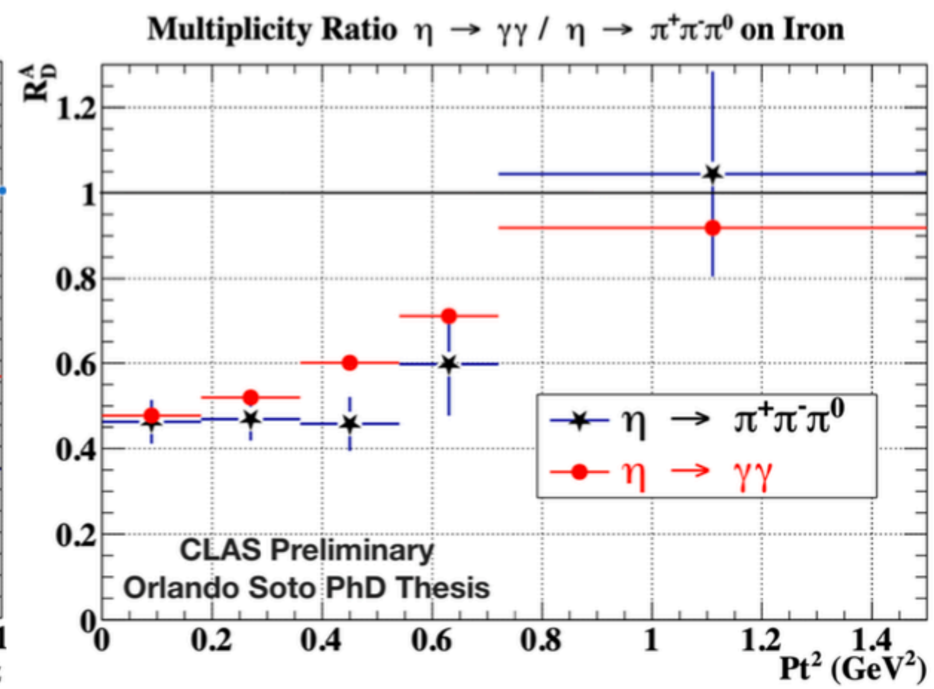
https://www.jlab.org/Hall-B/general/thesis/ARadic_thesis.pdf



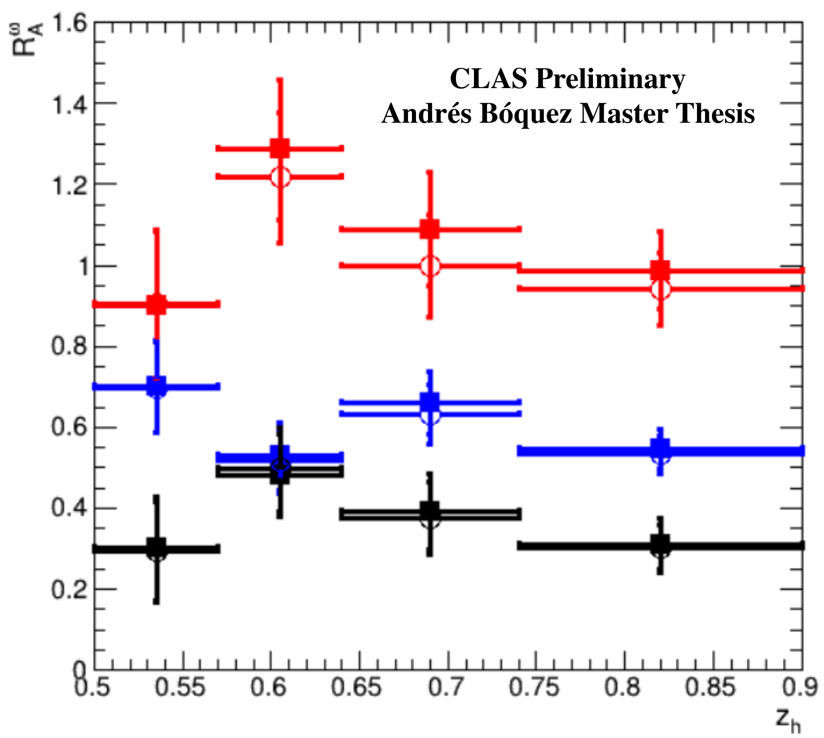
Light hadrons: η and ω preliminary results

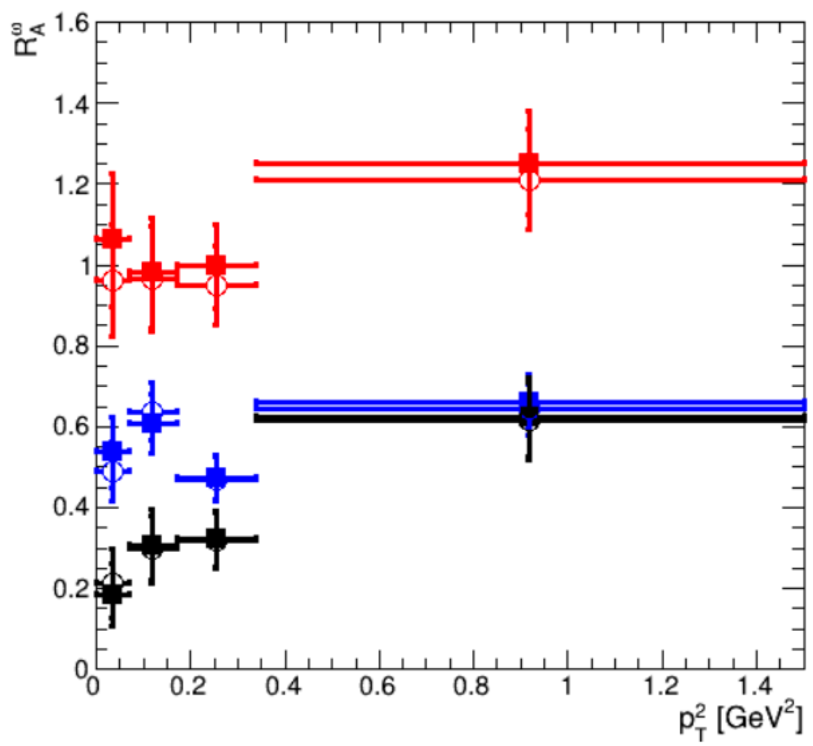
η





ω

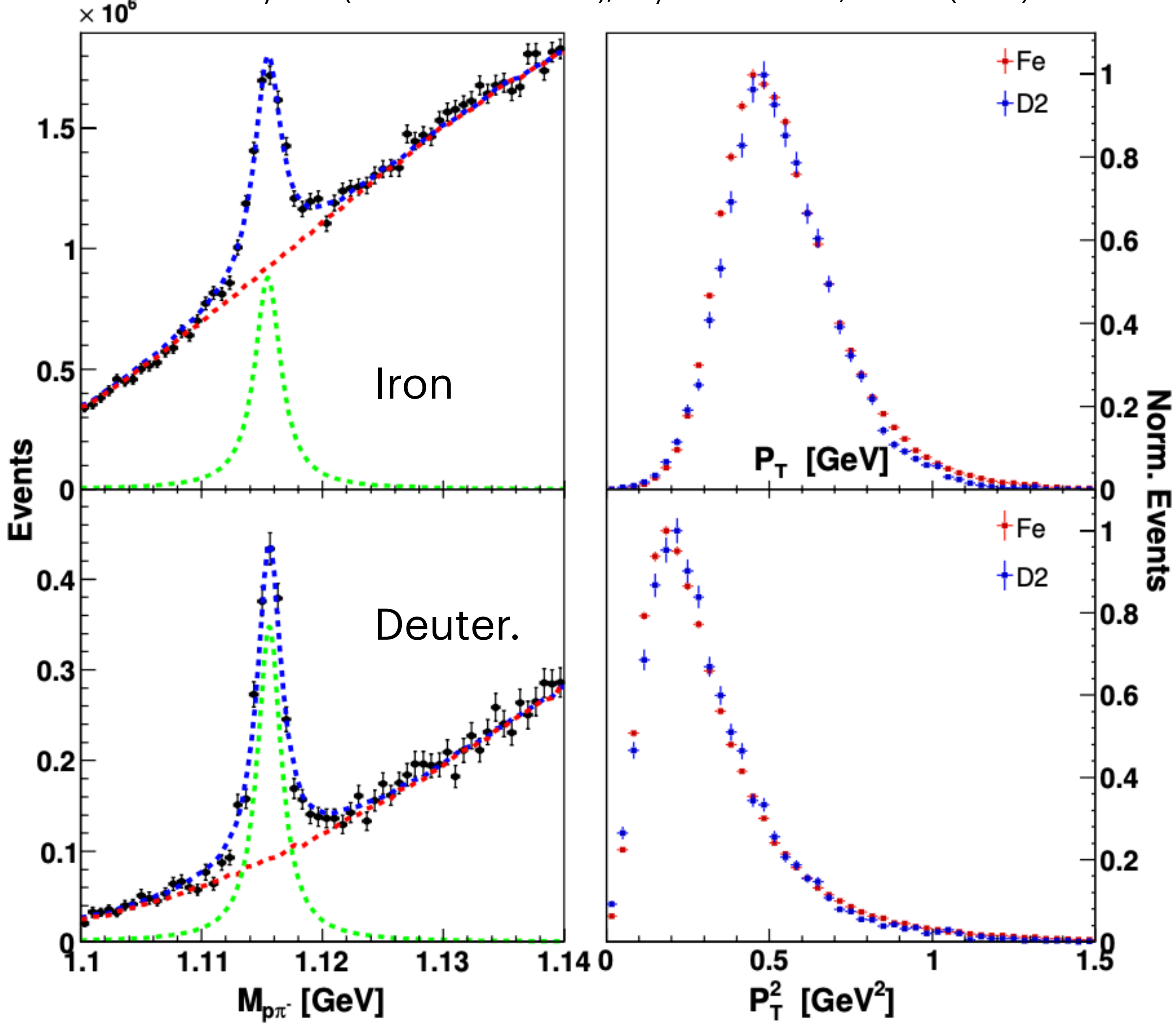




Results on Lambda and Proton

Λ hyperon identification

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



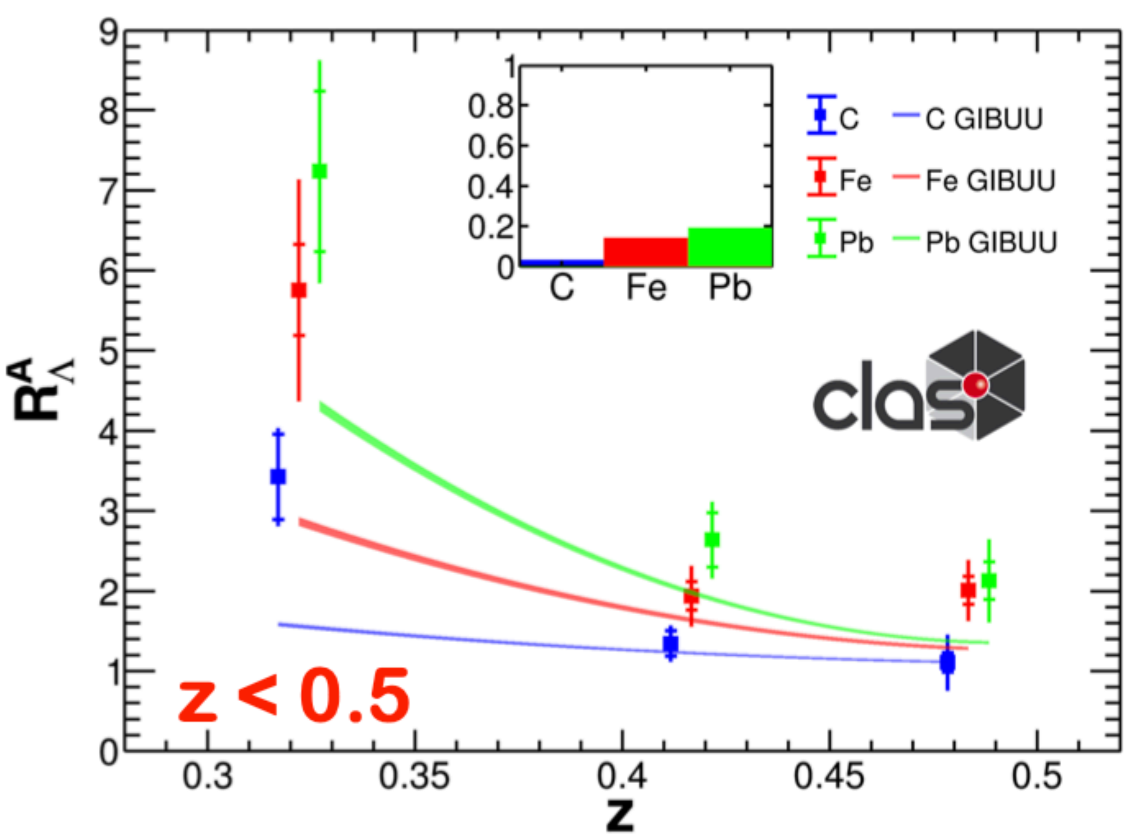
Λ^0 hyperons (1115 GeV/fm) were identified through their invariant mass $M(\pi^- p)$

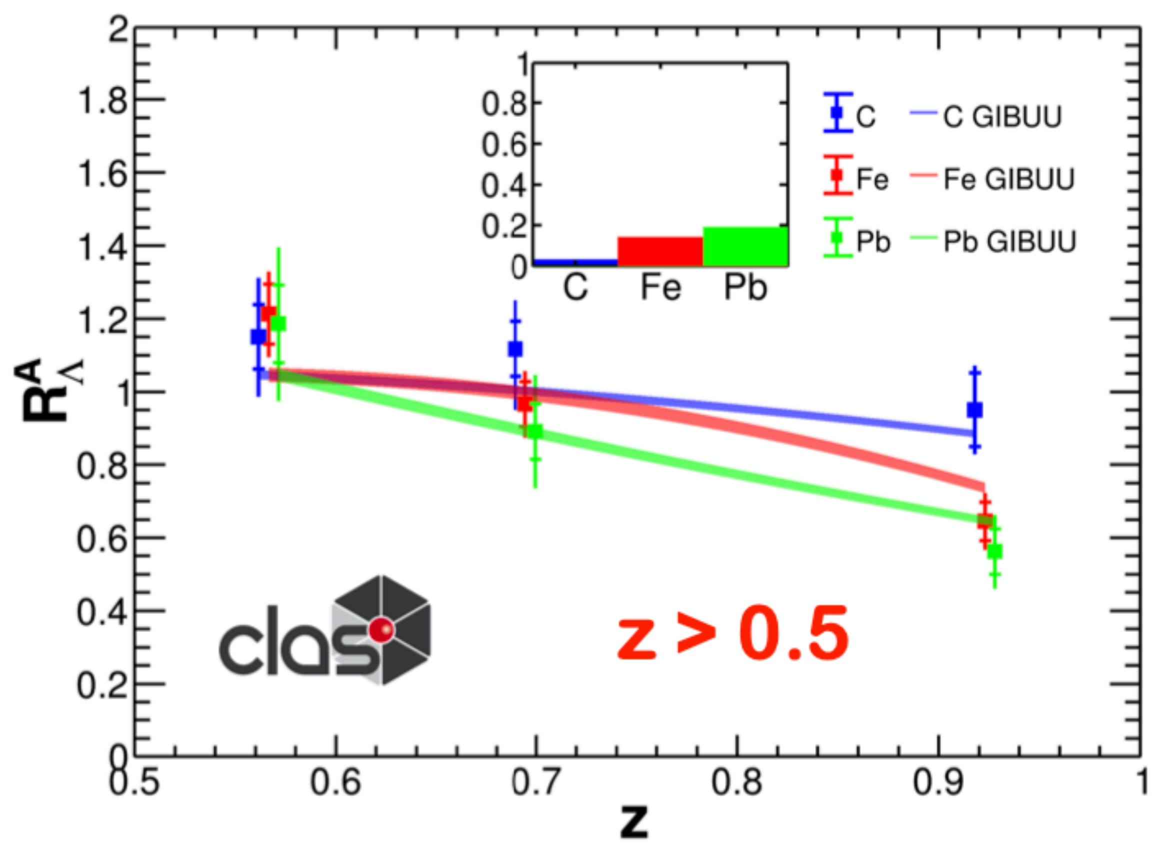
Λ hyperon Multiplicity Ratios

First lambda baryon *multiplicity ratio 1D now 2D in CLAS12*

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

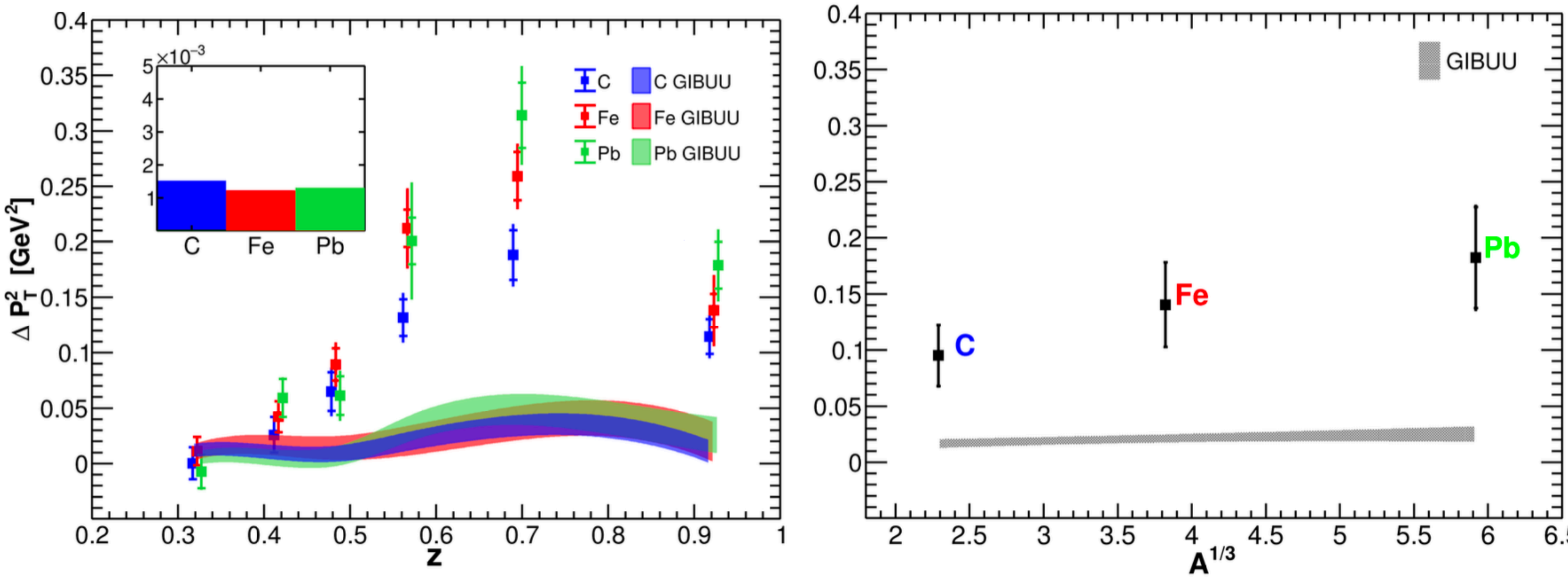


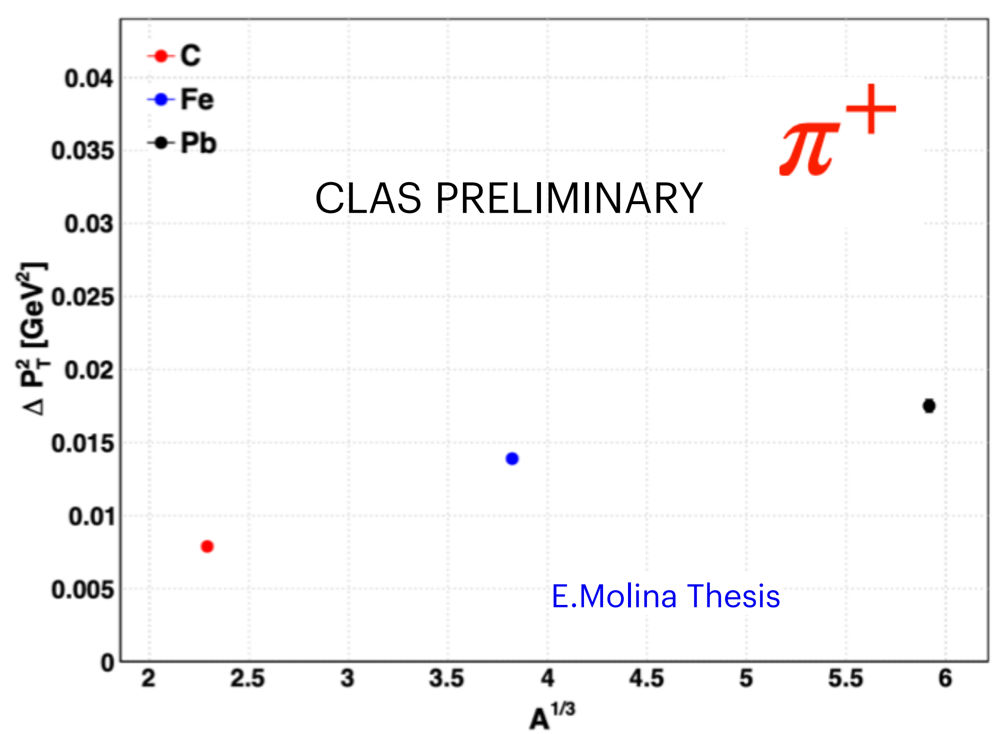


- At low-z there is a “pile up” of events 7 times more than for pion! Underpredicted by GiBUU.
- At high-z there is little attenuation compared to that on the pion. Agrees with GiBUU.

Λ hyperon pT2 Broadening

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

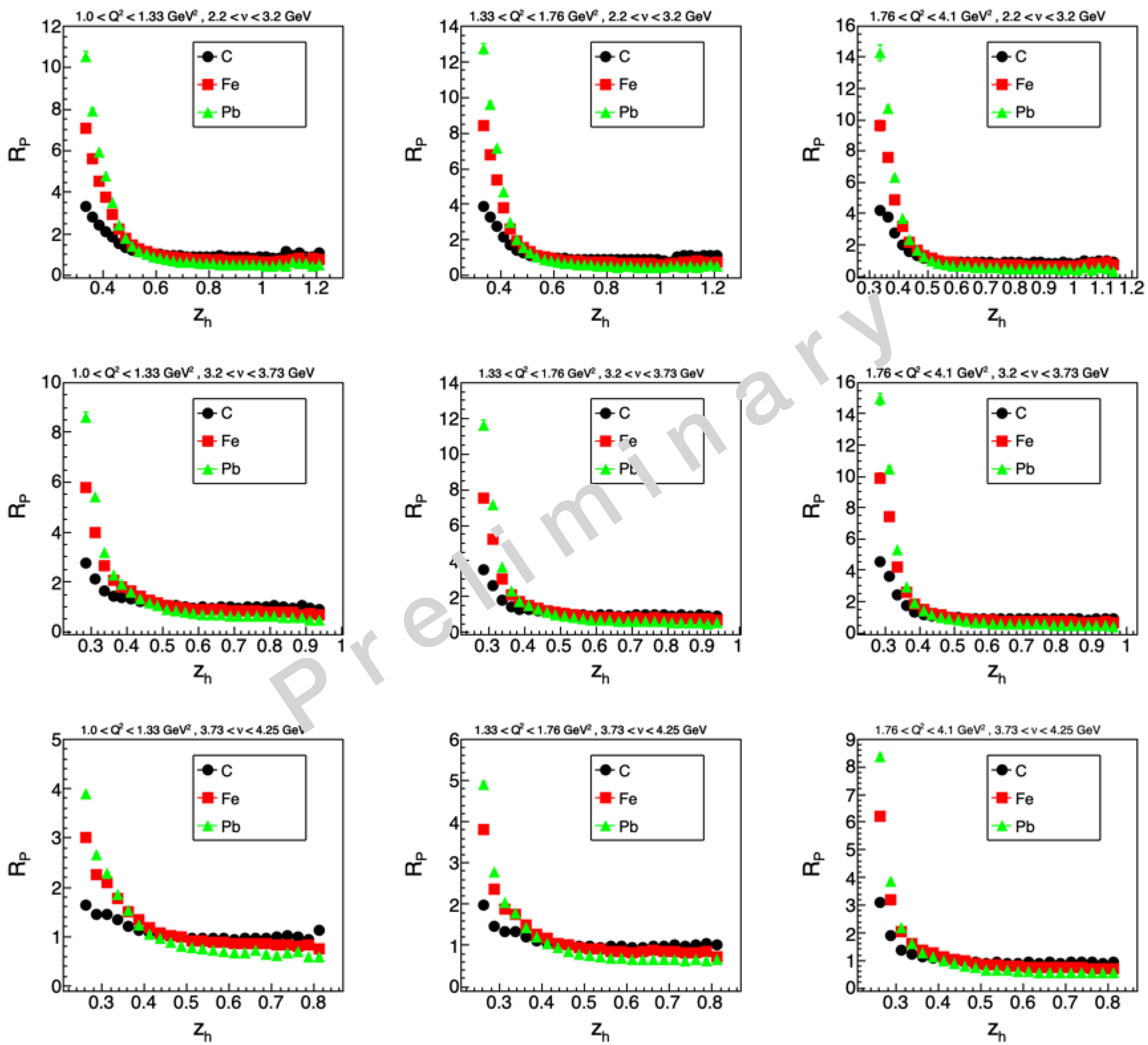




ΔpT2 on Λ is huge compared to pion: 0.15 vs 0.015 GeV² (Fe)

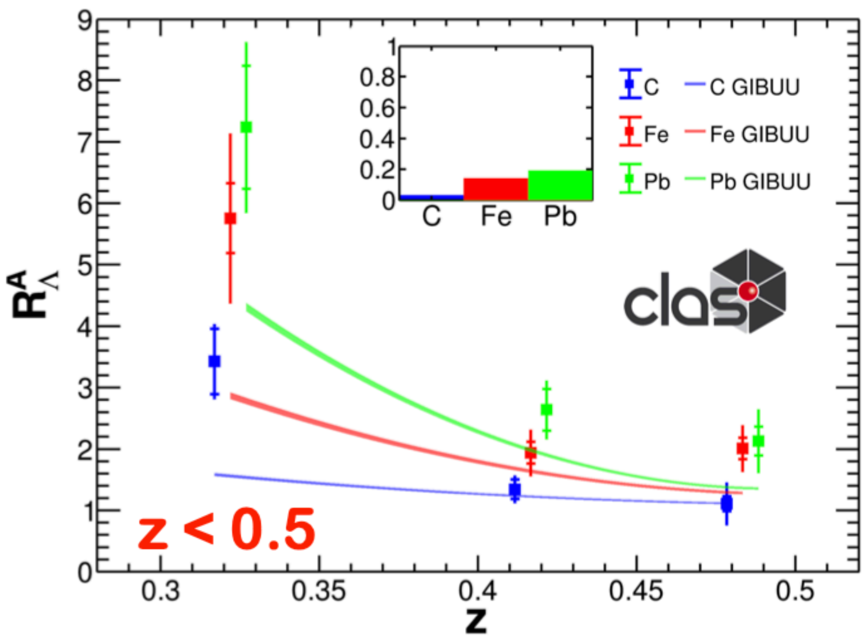
CLAS: 3D proton multiplicities

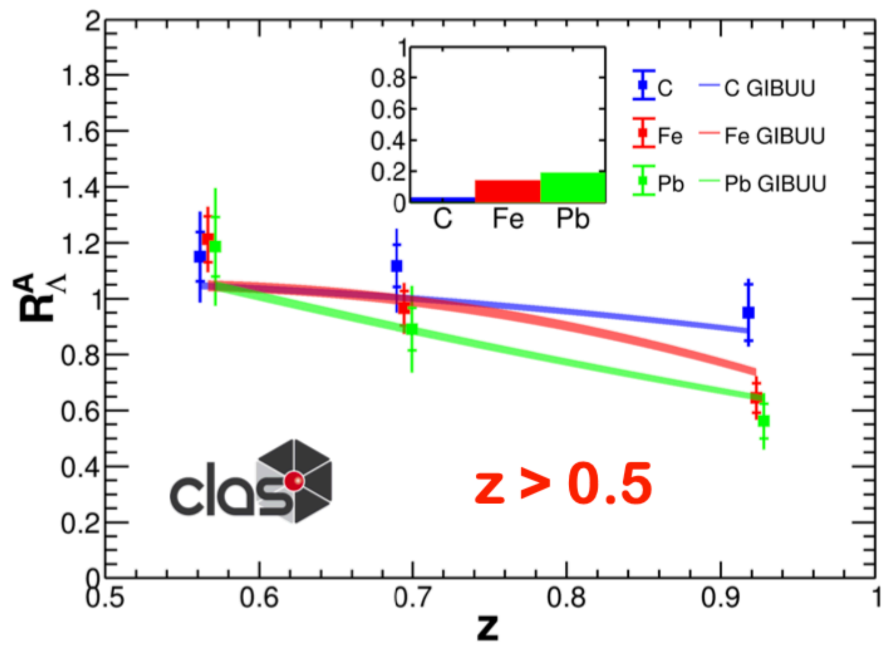
Mike Wood analysis in CLAS review

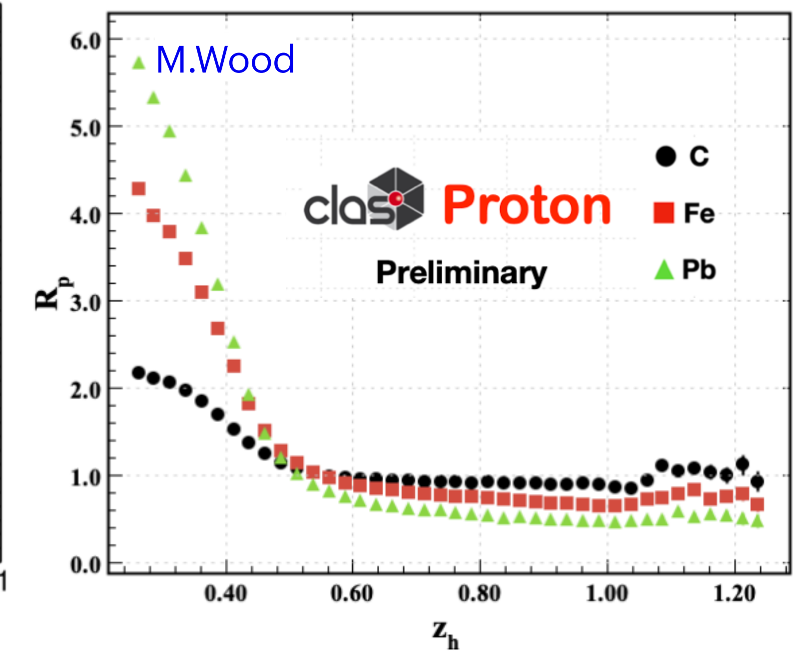


Proton multiplicity ratio:
3D now in Review
4D in CLAS12

Comparing Λ and p multiplicities







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

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?

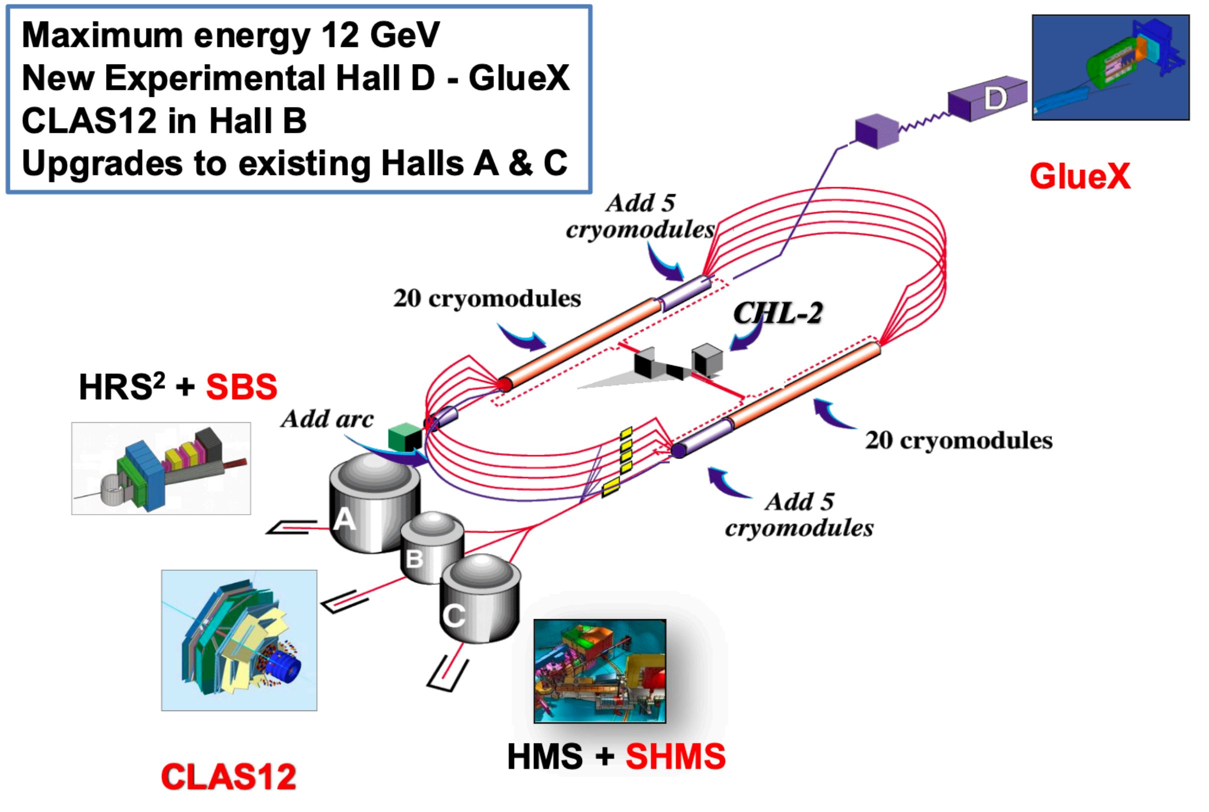
Or is there difference between light vs heavy spectator quark?

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

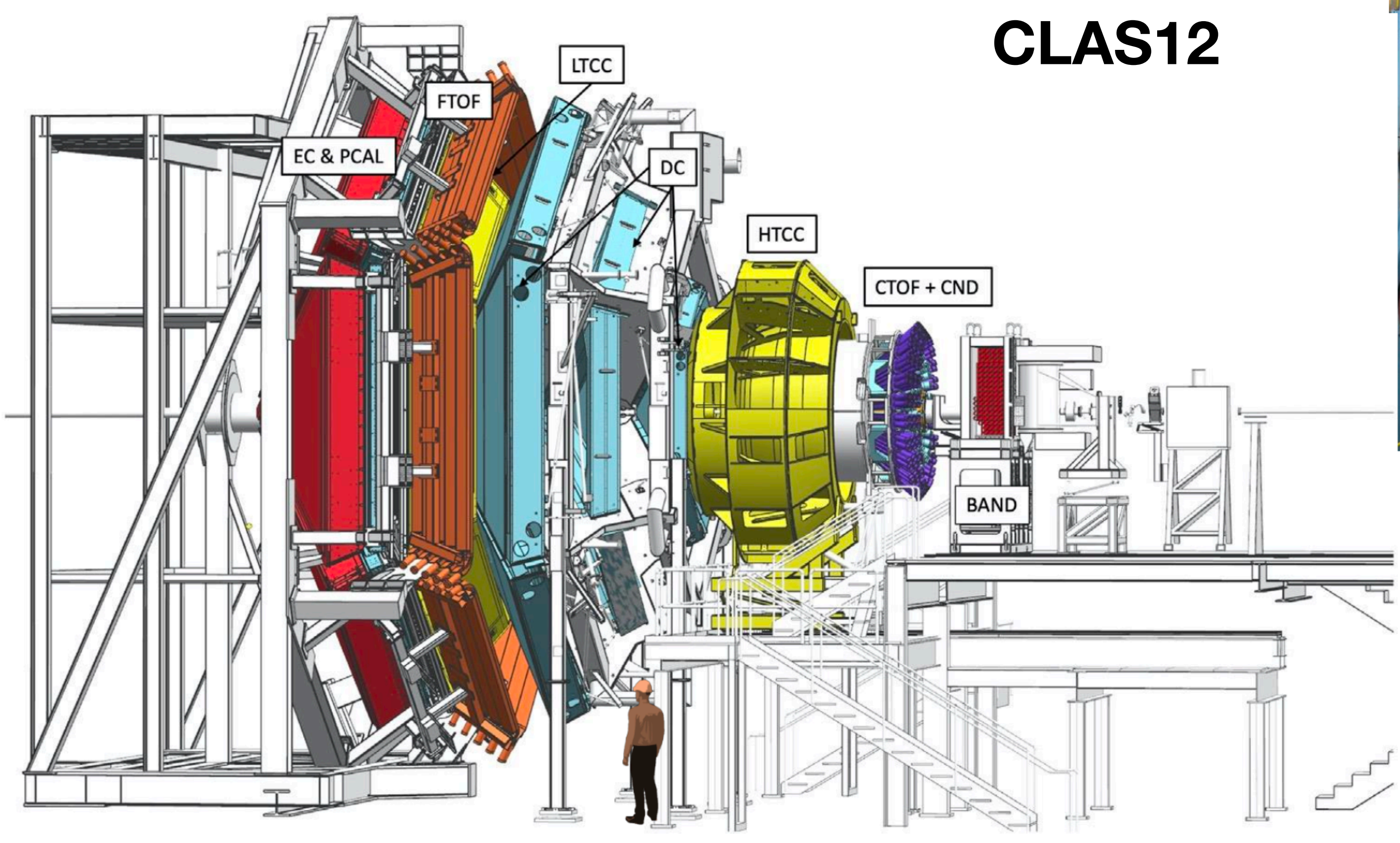
Experimental realization @ 11GeV

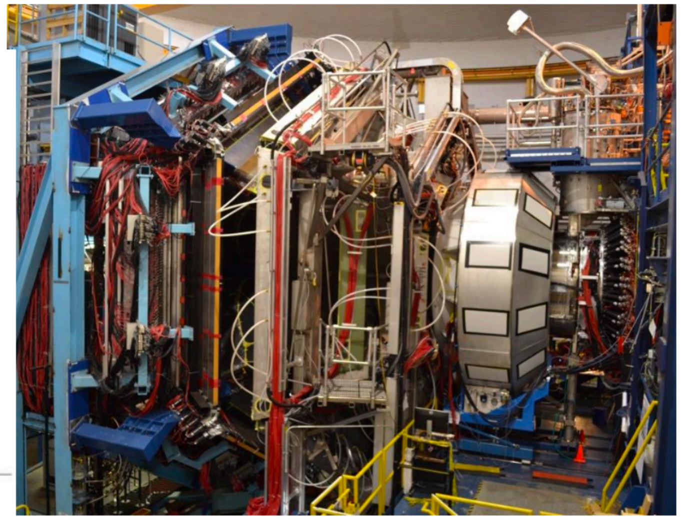
Jefferson Lab CLAS12

The Jefferson Lab Energy Upgrade



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

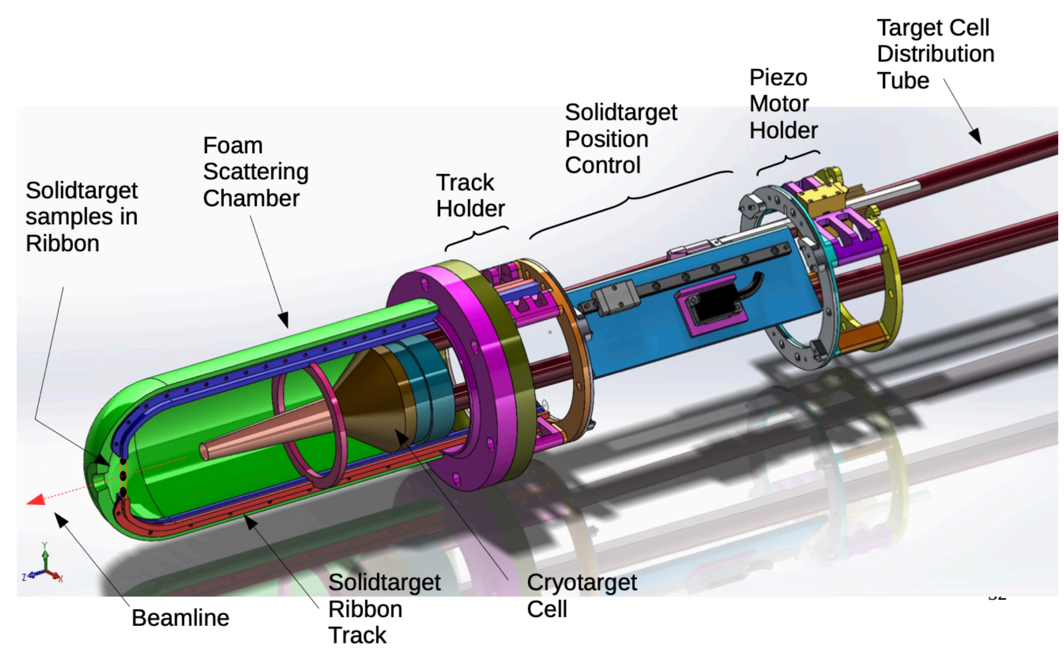
RG-E experiment @ 10.5 GEV

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

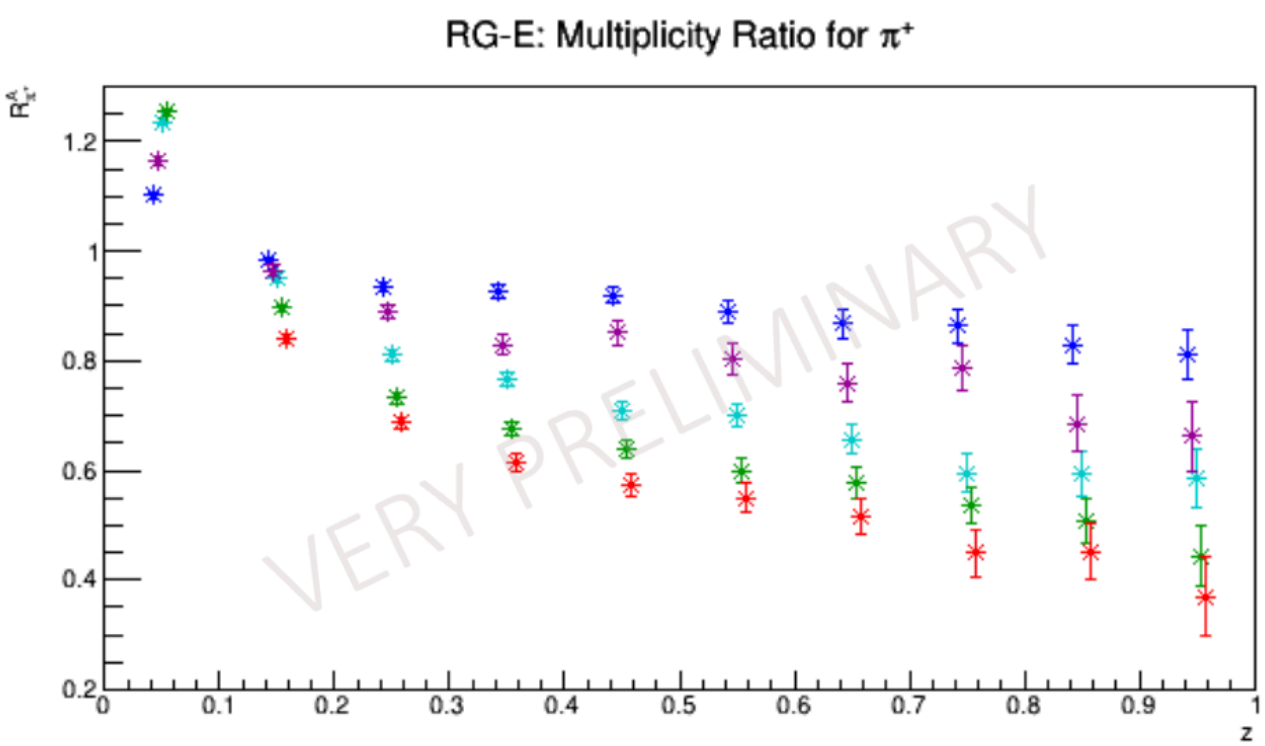
- Electron beam 10.5 GeV
- Targets ^{2}H, ^{12}C, ^{x}Al, ^{x}Cu, ^{x}Sn, ^{207}Pb
- Integrated Luminosity ~ 10^{41} 1/(s · cm^{2})
- Extreme conditions: high vacuum and high magnetic field, low temperatures, radiation hardness, reduced space

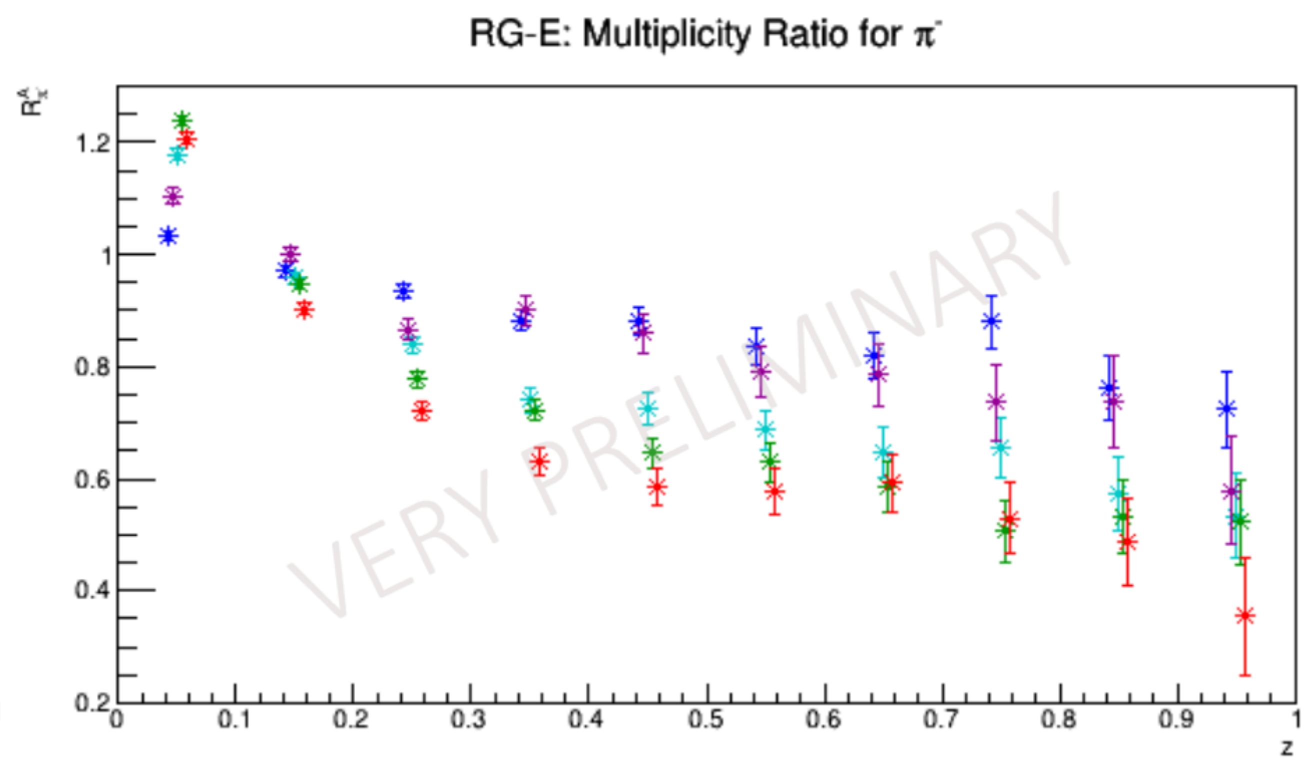


Highlights of double target are in JLUO weekly: https://mailchi.mp/89a150f4d755/jlab-weekly-for-scientific-users-april-3-2024?e=a8d43a7cbe

Plus polarized electron beam - a wealth of data for spin physics

Online RG-E Multiplicity Ratios





- carbon
- aluminum
- copper
- tin
- lead

consistent with previously published CLAS6 charged pion multiplicity ratio results

CLAS6 results

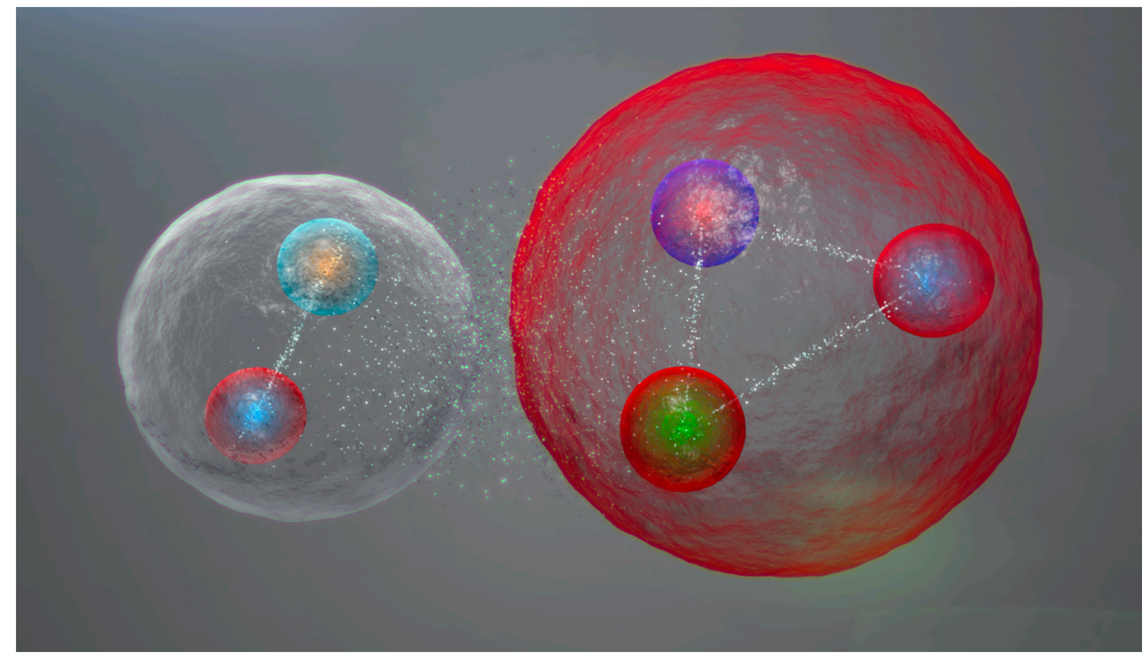
hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	uūdd̄	5.7% (sys)
π^+, π^-	7.8 m	0.14	ud̄, dū	3.2% (sys)
η	170 pm	0.55	uūdd̄ss̄	6.2% (sys)
ω	23 fm	0.78	uūdd̄ss̄	6.7% (sys)
η’	0.98 pm	0.96	uūdd̄ss̄	8.5% (sys)
ϕ	44 fm	1	uūdd̄ss̄	5.0% (stat)*
f1	8 fm	1.3	uūdd̄ss̄	-
K^0	27 mm	0.5	ds̄	4.7% (sys)
K^+, K^-	3.7 m	0.49	us̄, ūs	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
p̄	stable	0.94	ūd̄	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	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

Published or currently under review

CLAS12 results: more!

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	ud	3.2% (sys)
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	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	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

CLAS12 integrated luminosity is ~ 10^7 greater than @CLAS6!!



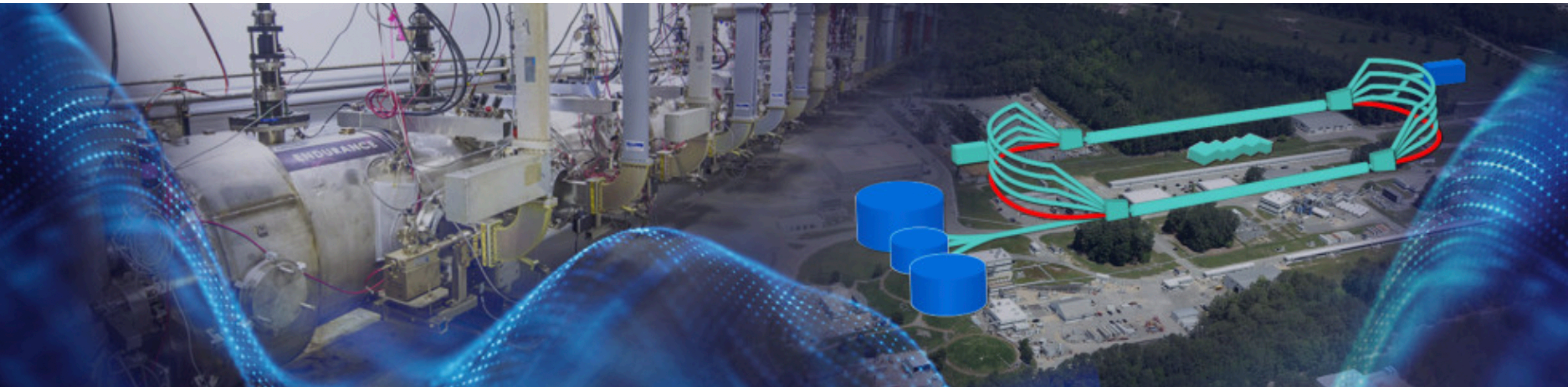
Can study rare and complex cases of hadrons probing mass, strangeness and rank dependence of hadron formation and color propagation

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

Future prospectives

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

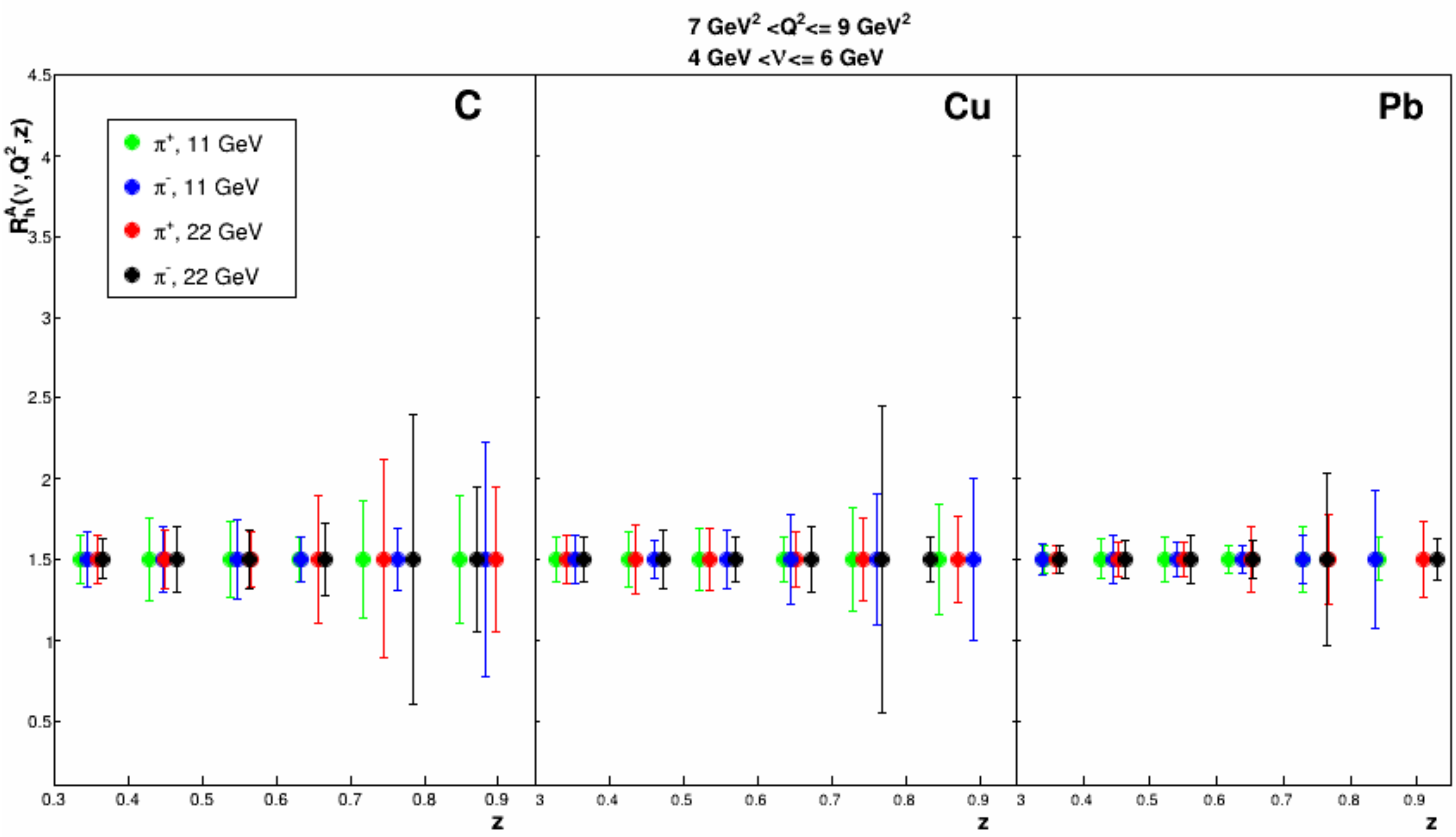
A. Accardi, P. Achenbach, D. Adhikari, A. Afanasev, C.S. Akondi, N. Akopov, M. Albaladejo, H. Albataineh, M. Albrecht, B. Almeida-Zamora, M. Amaryan, D. Androić, W. Armstrong, D.S. Armstrong, M. Arratia, J. Arrington, A. Asaturyan, A. Austregesilo, H. Avagyan, T. Averett, C. Ayerbe Gayoso, A. Bacchetta, 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, [illegible] 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)

Download

- 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

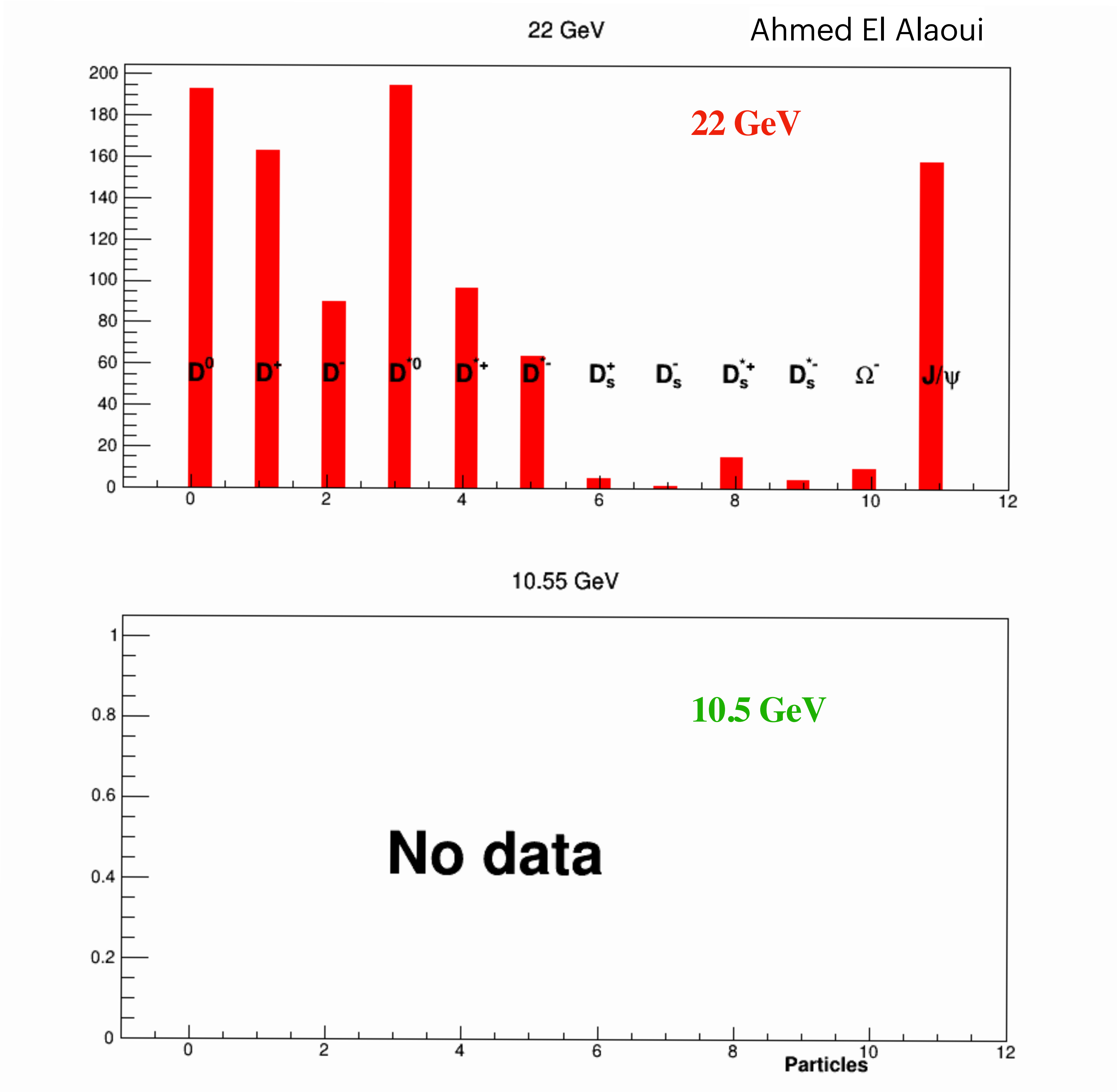
Polarized gluon distribution, longitudinal/transverse separations, hadron formation in nuclei, meson form factors and more!

Projected multiplicity ratios: 10.5 and 22 GeV



Projected multiplicity ratios: 10.5 and 22 GeV

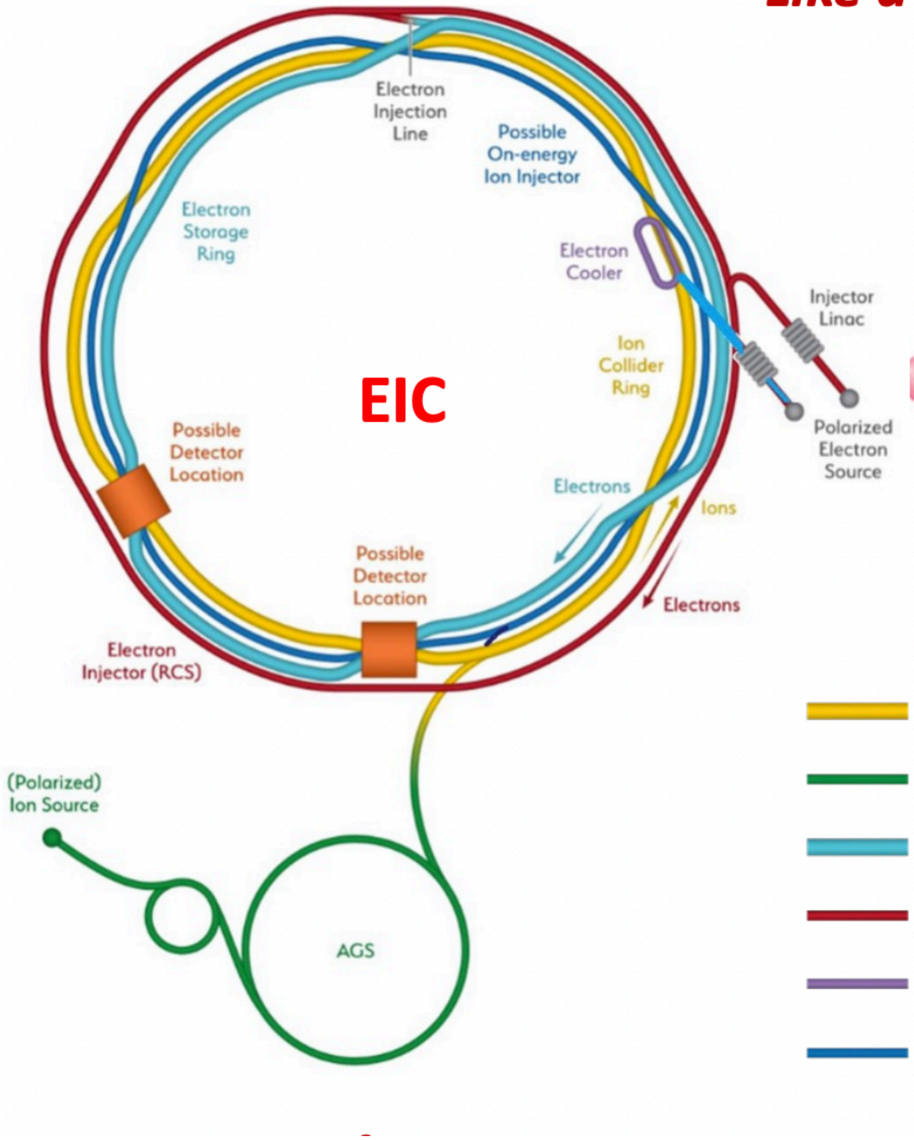
CLAS22: access to charm and strangeness



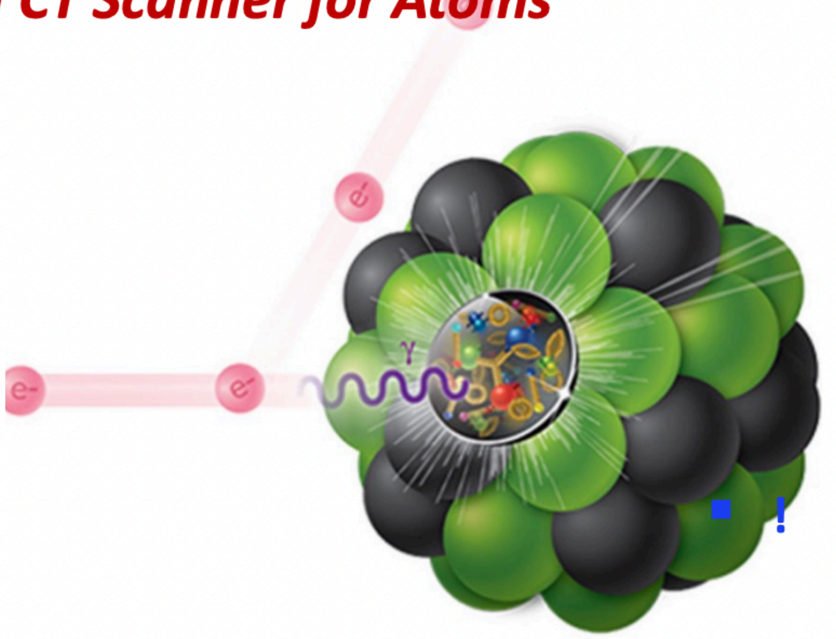
EIC @ Brookhaven

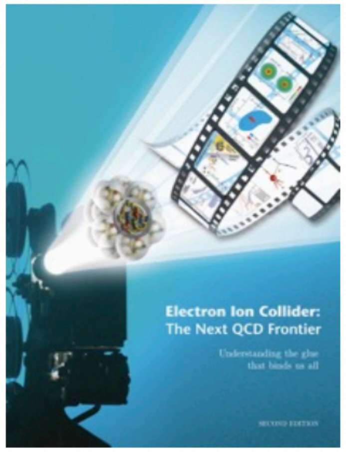
A machine that will unlock the secrets of the strongest force in Nature

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



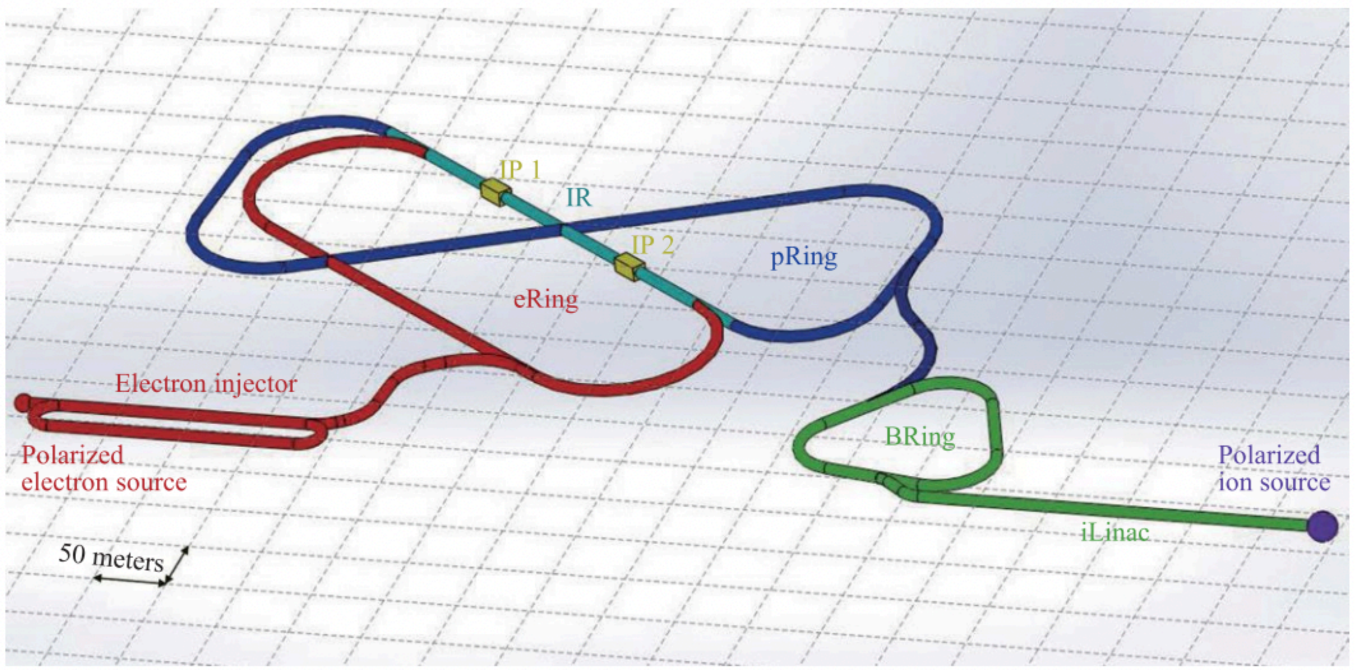


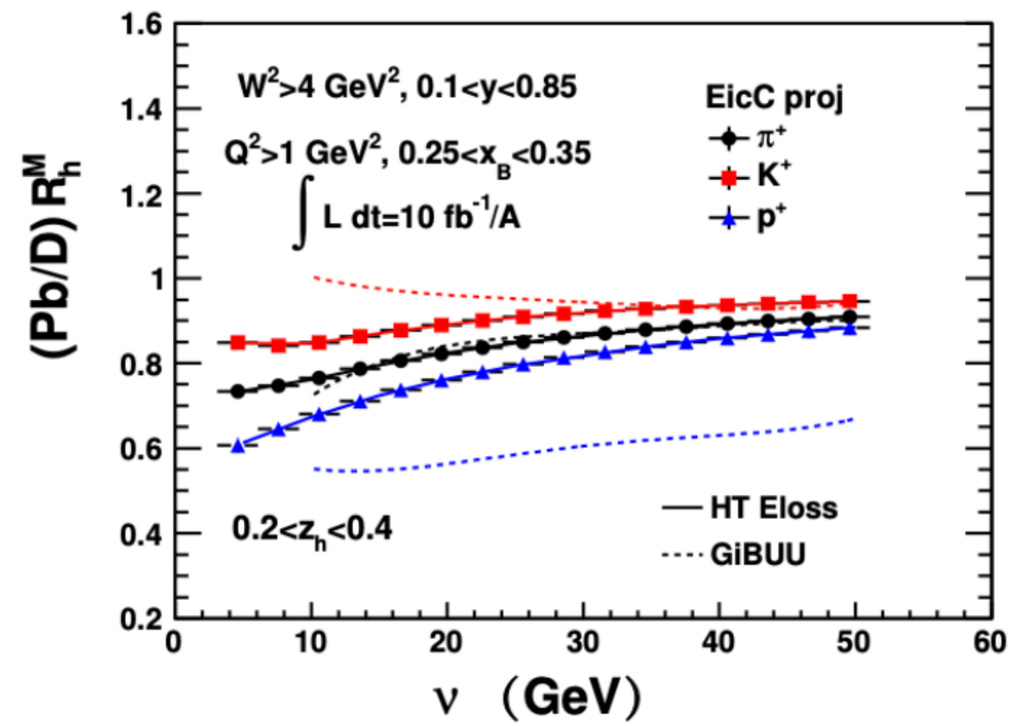
Basic Tech Requirements

- **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

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

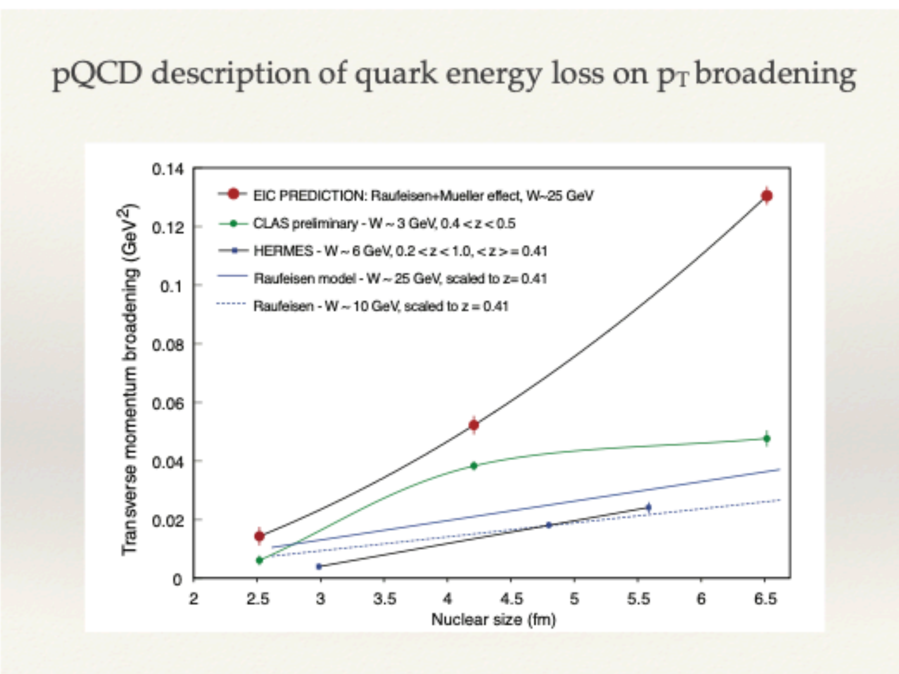
EicC allows to disentangle two mechanisms: parton energy loss (Lp ~> Rpb) vs hadron absorption (GiBUU)

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: $Q_s \sim k_T$

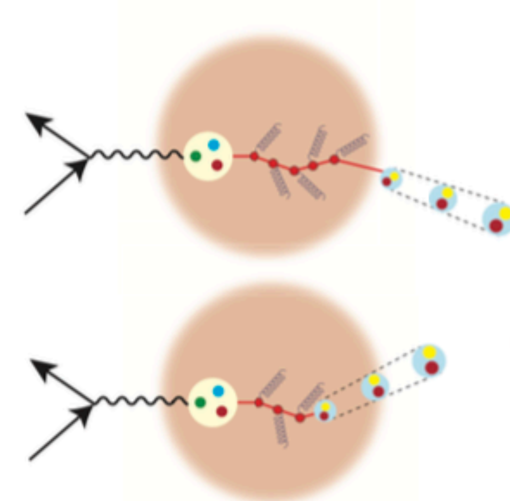
$$Q^2_{sat}(b,E) = \Delta p_T^2(b,E)$$ *

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



- 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)

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, Λ *multiplicity ratios and* $\Delta pT2$; *di-hadron* production. In process: *p* multiplicities, $\Delta pT2$ *for* π^+ and double pion, *Bose-Einstein correlations*

- Successful realization of CLAS12 experiment (E12-06-117) at 10.5 GeV. Access to 4D multiplicities and large spectrum of heavy mesons and baryons.

- Future continuation of *eA* hadronization program with JLab @ 22 GeV, EIC and EicC

Thank you!