Color transparency and hadronization at CLAS

Taisiya Mineeva

Universidad Técnica Federico Santa María,
Valparaiso, Chile
For the CLAS collaboration

Outline of talk

- Color Transparency
  ρ^0 electroproduction at CLAS *

- Hadronization
  Pion multiplicity ratios at CLAS **

- Conclusion

CLAS experiments at 6 GeV era:

* Jefferson Lab Experiment E-02-110
K. Hafidi, M. Holtrop, B. Mustapha, spokespersons

** Jefferson Lab Experiment E-02-104
W.Brooks, K.Joo, et al. spokespersons

Measured effects from nuclear medium

- ✔ **EMC effect:** modification of quark distributions functions in nuclei
  → N.Fomin talk "EMC: past, present, future"
- ✔ **Short-range correlations:** short distance structure, correlated nucleons
  → A.Schmidt talk on Short-Range Correlations
- ✔ **Nuclear DVCS:** 3D tomography of partonic structure of nuclei

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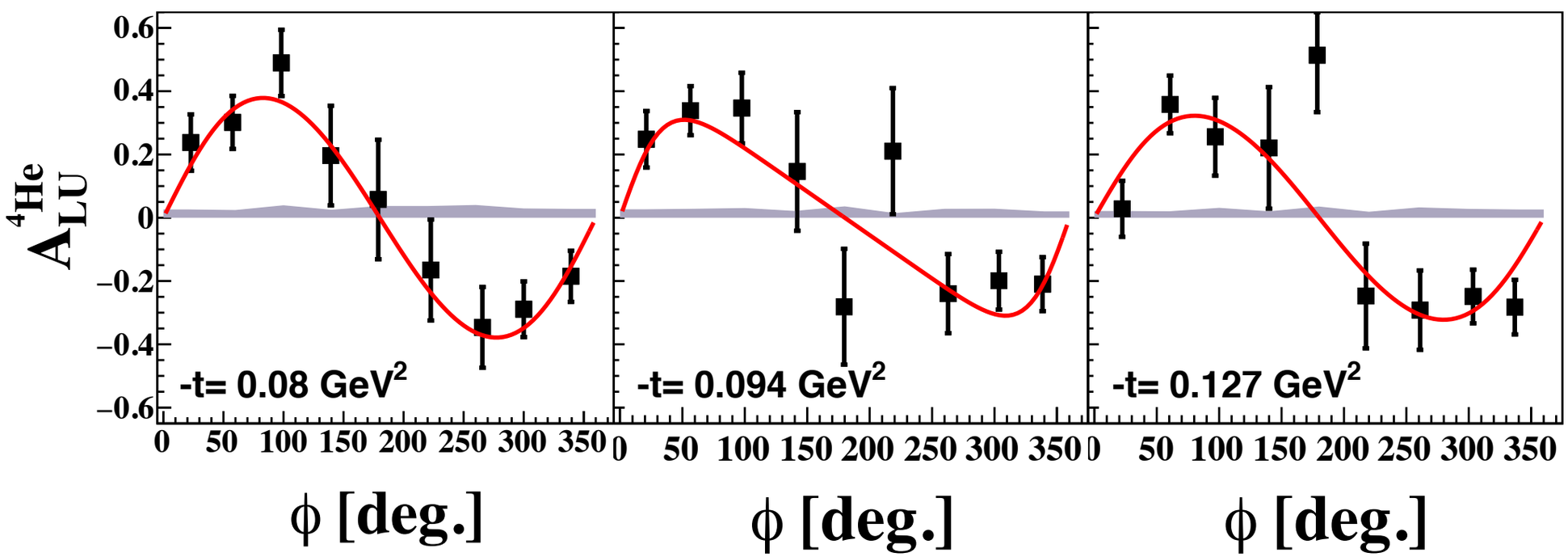

M.Hattaway *et al.*, "First exclusive measurement of DVCS off 4He" Phys. Rev. Lett. 2017

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- ✔ **Short-range correlations:** short distance structure, correlated nucleons
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- ✔ **Nuclear DVCS:** 3D tomography of partonic structure of nuclei
- ✔ **Color transparency:** decreased interaction of small size configuration
- ✔ **Hadronization:** color propagation and hadron formation in medium

Color Transparency and hadronization

Why is it interesting?

Relies on key properties of QCD as a color gauge theory

Neutralization of color charge in hard processes is dynamical enforcement of confinement

Factorization separates long and short distance behavior relies on *asymptotic freedom*

Color propagation and creation of color neutral object - *Hadronization*

Evolution of small size color field configuration - *Color Transparency (CT)*

Color Transparency

Color Transparency (CT)

- Creation of small size object. Its interaction cross section is smaller than that of hadron: $\sigma_{SSC} \sim \sigma_h \bullet (r_\perp / R_h)^2$
- Transverse size of produced system in electroproduction: $r_\perp \sim 1 / Q$
- If small size object is created, it can experience reduced interaction with nuclear medium (in exclusive processes at high momentum transfer)
- Color field of the color neutral object vanishes with decreasing size of the object (similar to the charge screening of small dipole in QED)
- Onset of CT is related to onset of factorization required for access to GPDs in deep exclusive (q,q-bar) production

D.Dutta *et al.* "Color transparency: past, present and future" Progress in Particle and Nucl.Phys. 69 (2013)

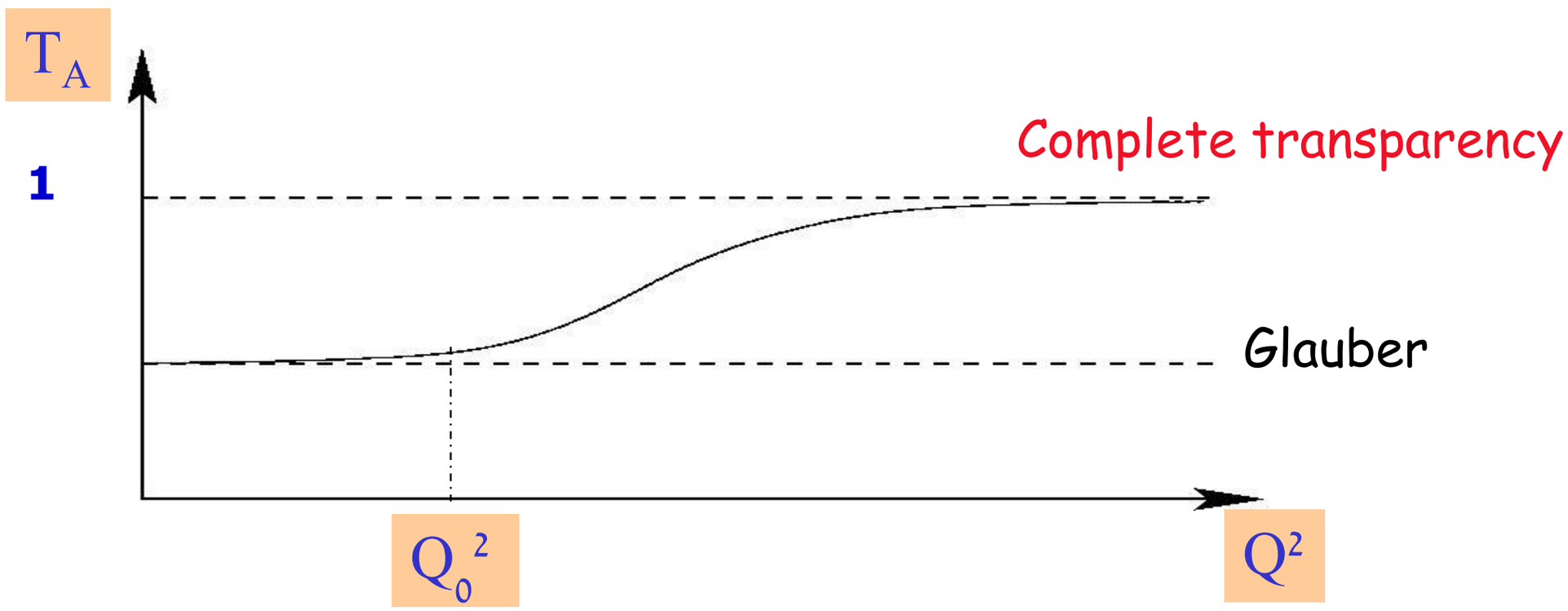
Observable: Nuclear Transparency

Signature of CT: increase of medium 'nuclear' transparency as a function of momentum transfer Q^2

$$T_A = \frac{\sigma_A}{A\sigma_N}$$

σ_A is the nuclear cross section

σ_N is the free (nucleon) cross section

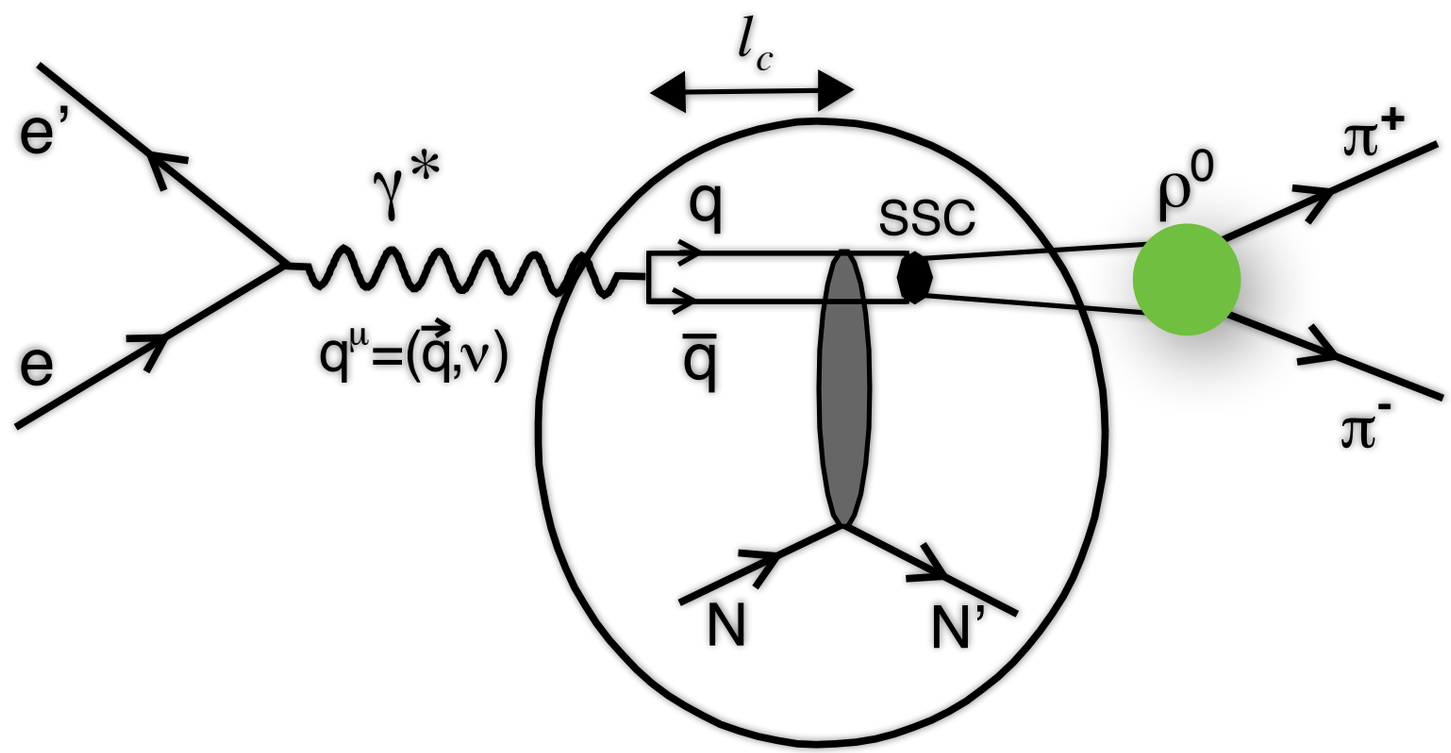


DIS ρ^0 production on nuclei

Small size ρ^0 pre-hadron is directly produced from the virtual photon

coherence length for q-qbar propagation:

$l_c = 2\nu/(M_\rho^2 + Q^2)$



Focus on ρ^0 production:

- Exclusive (z>0.9)
- Incoherent diffractive (-0.4<t<-0.1 GeV^2)
- Non-resonant (W>2GeV)

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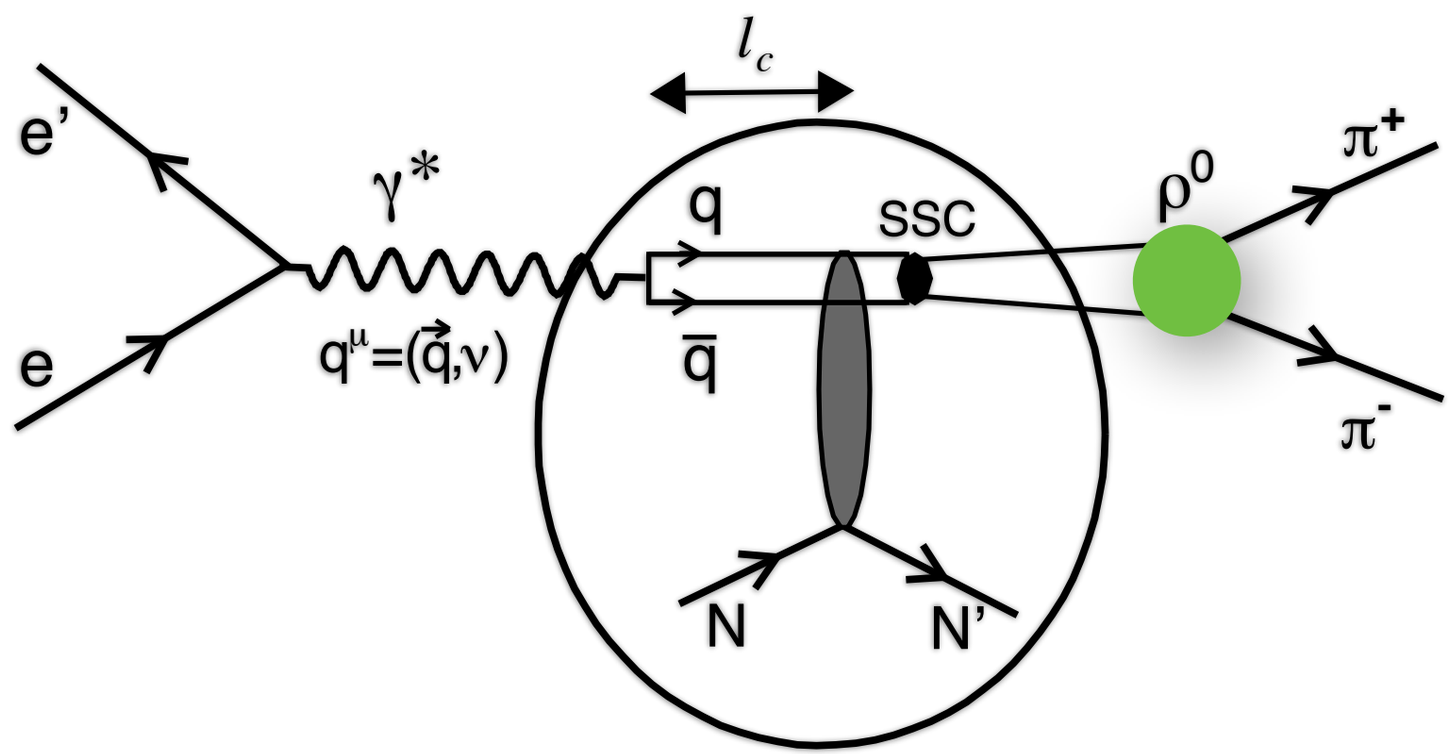


To exclude effects of coherence length that can mimic CT, the Q^2 dependence of T_A must be measured at small or fixed l_c.

Color Transparency Experiments

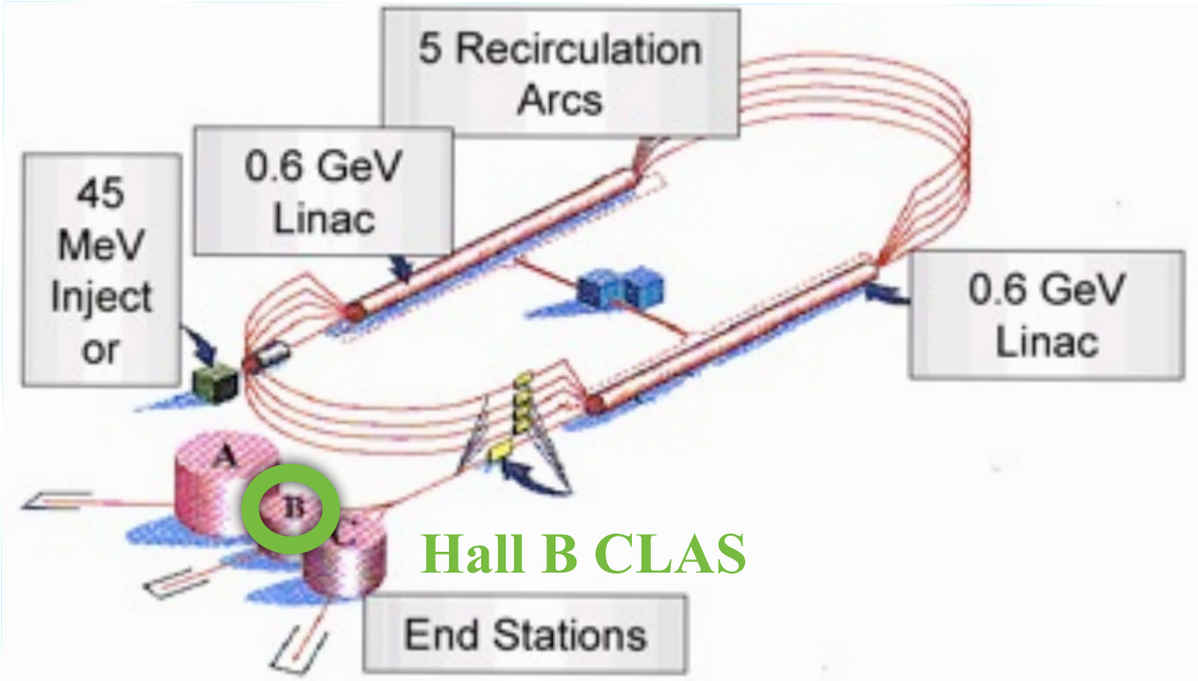
Baryon

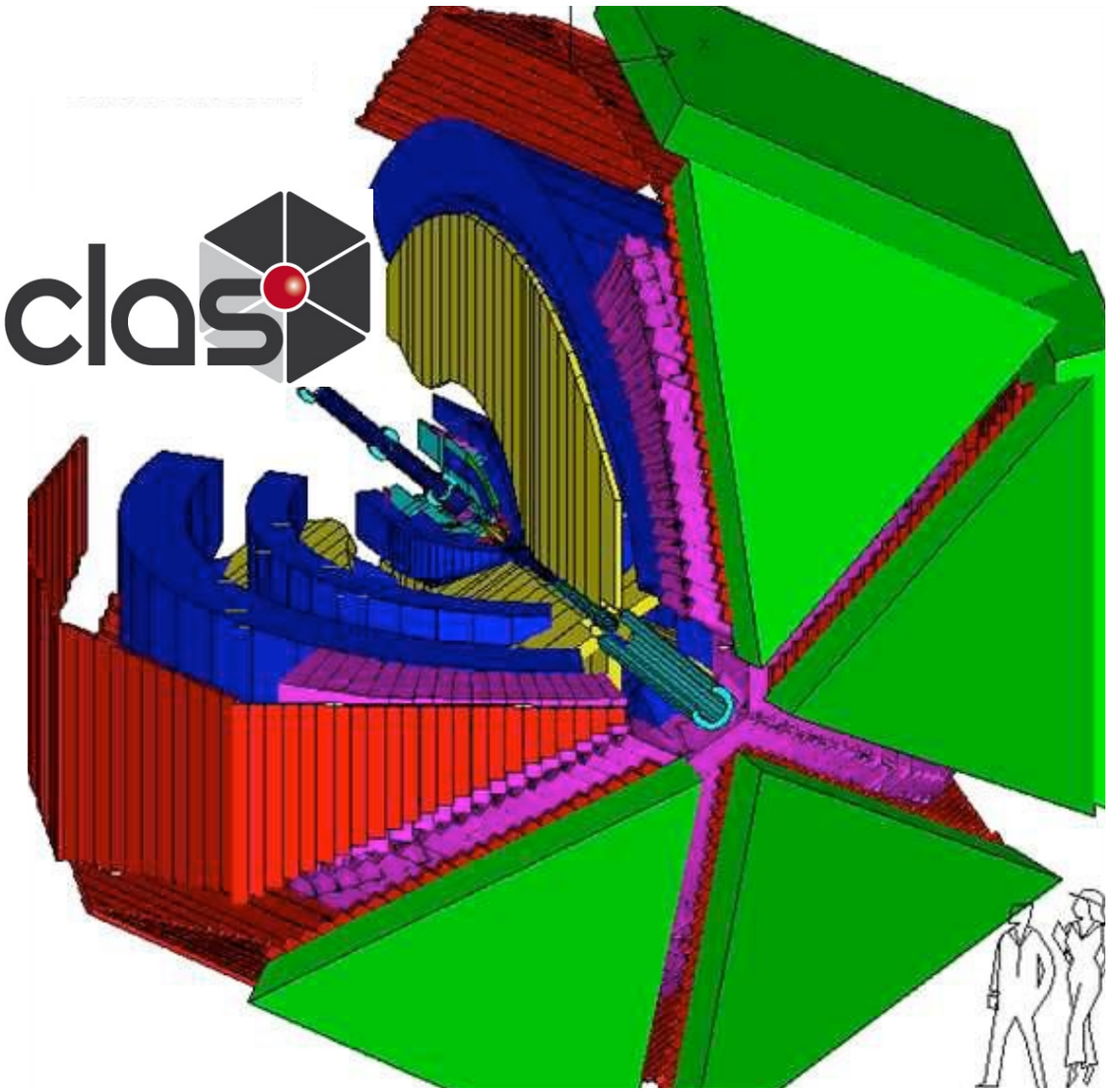
- A(p, 2p) BNL
- A(e, e'p) SLAC & JLab

Meson

- A(π,di-jet) FNAL
- A(γ, πp) JLab
- A(e, e'π) Jlab
- A(μ, μ'ρ) FNAL
- A(e, e'ρ) DESY & JLab

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 @ CLAS

Two targets in the beam simultaneously!

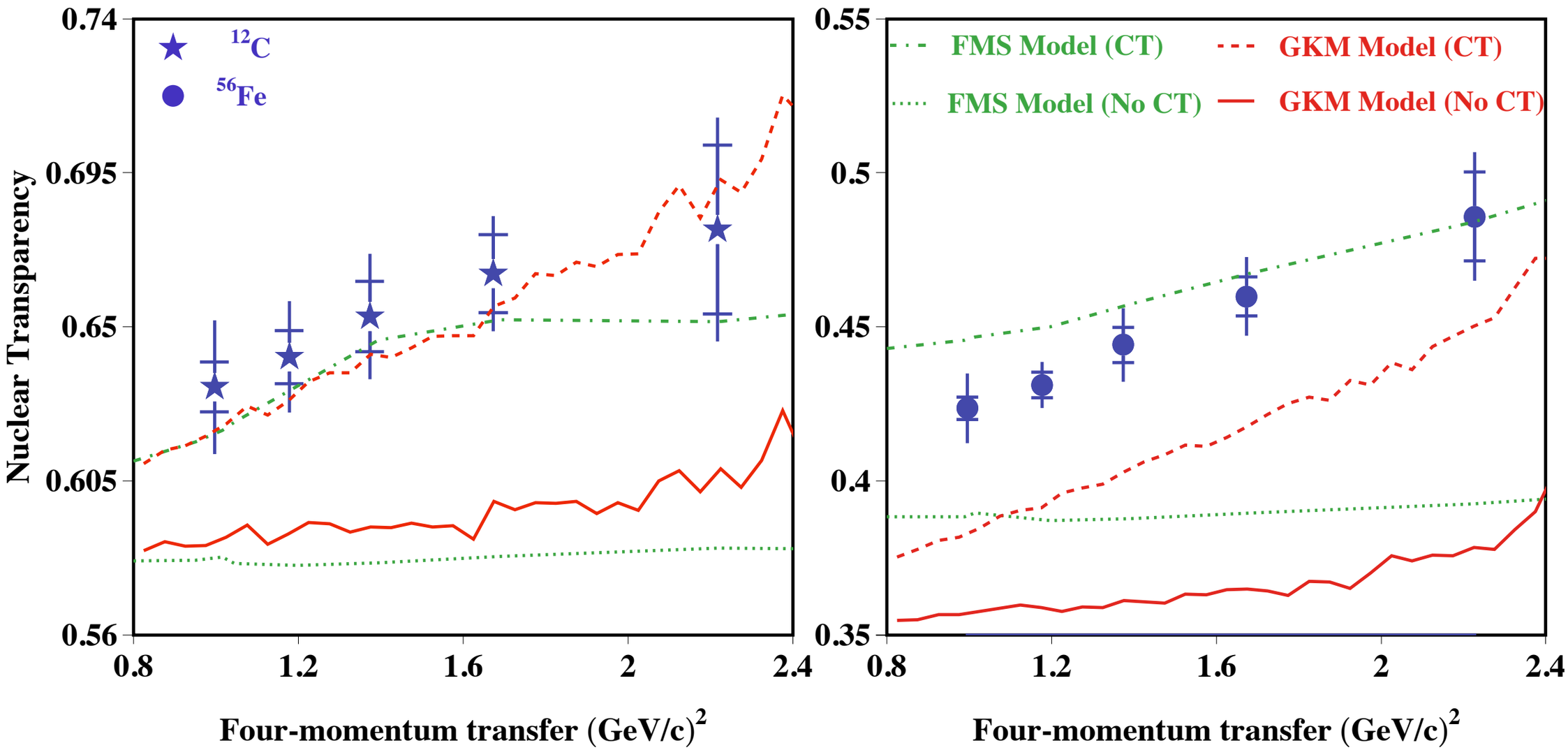
CLAS **EG2** experimental conditions:

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

- ^{2}H is liquid target 2 cm long
- ^{12}C, ^{56}Fe, ^{207}Pb are 0.014, 0.04, 0.17 cm thick
- Separation is 4 cm

Color Transparency Result from CLAS

L. El Fassi et al. PLB 2012



FMS (Glauber Model): Frankfurt, Miller & Strikman, PRC 78, 015208 (2008)

GKM (Transport Model): Gallmeister, Kaskulov & Mosel, PRC 83, 015201 (2011)

KNS (LC QCD Model): Kopeliovich, Nemchik & Schmidt, PRC 76, 015205 (2007)

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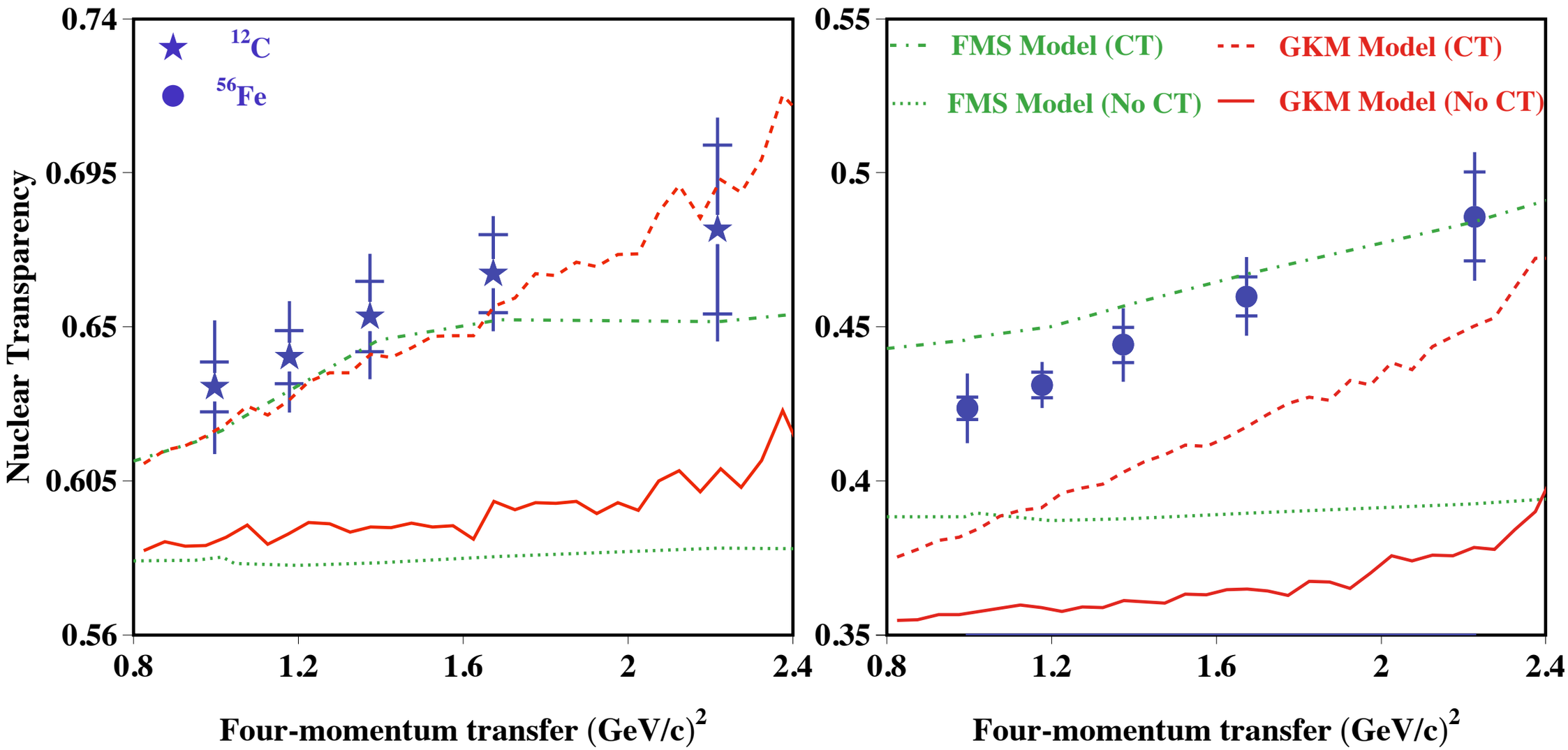


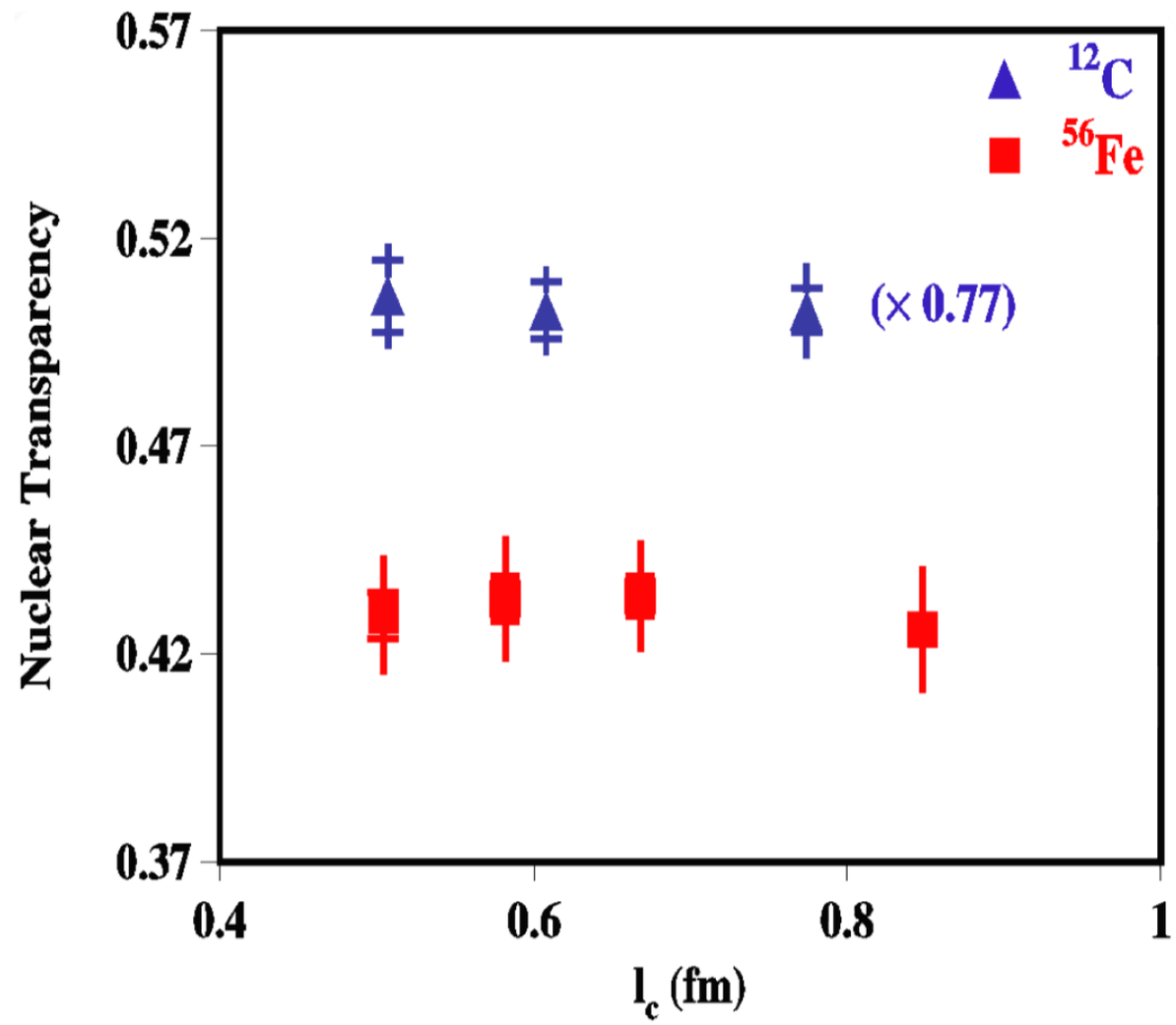
11 ± 2.3% (12.5 ± 4.1%) decrease in the absorption of ρ in iron (carbon)

Color Transparency Result from CLAS

The transparency does not depend on coherence length in the region $l_C < 0.9$ fm

Nuclear size: $R_C = 2.7$ fm $R_{Fe} = 4.6$ fm

L. El Fassi et al. PLB 2012



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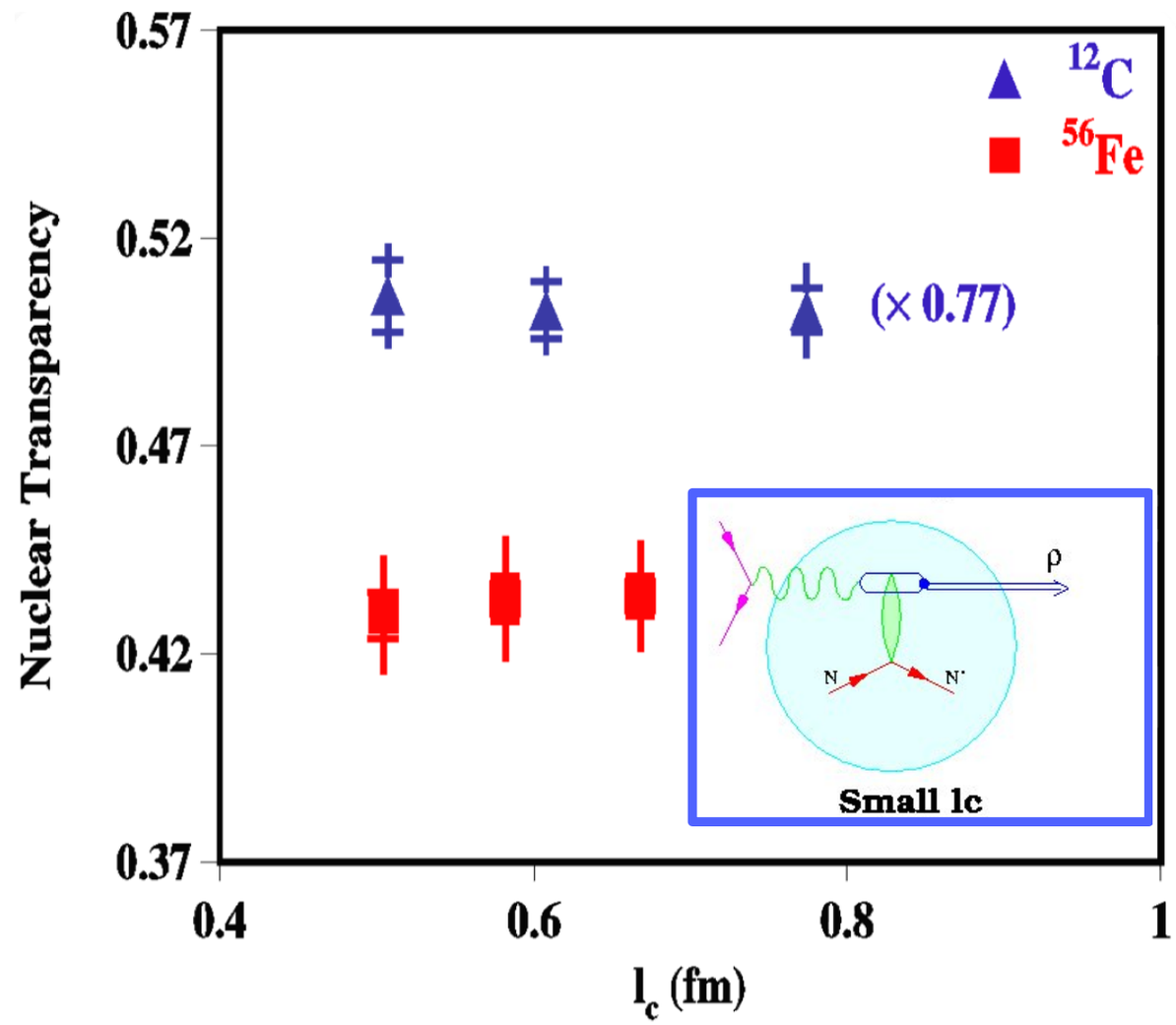

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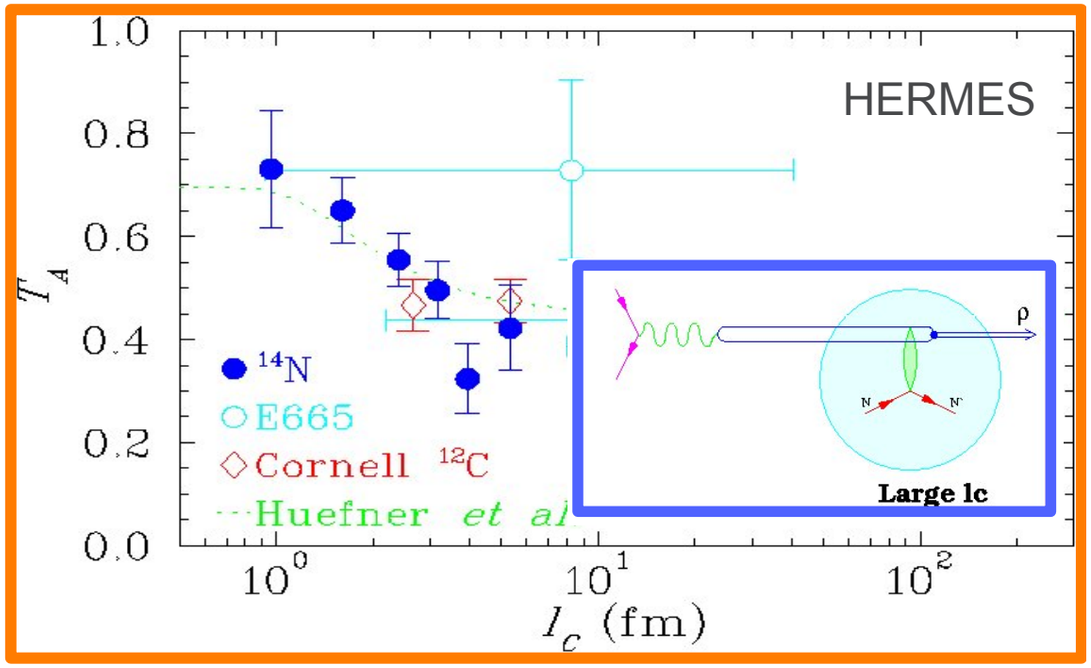
Airapetian et al. PRL 90 (2003)



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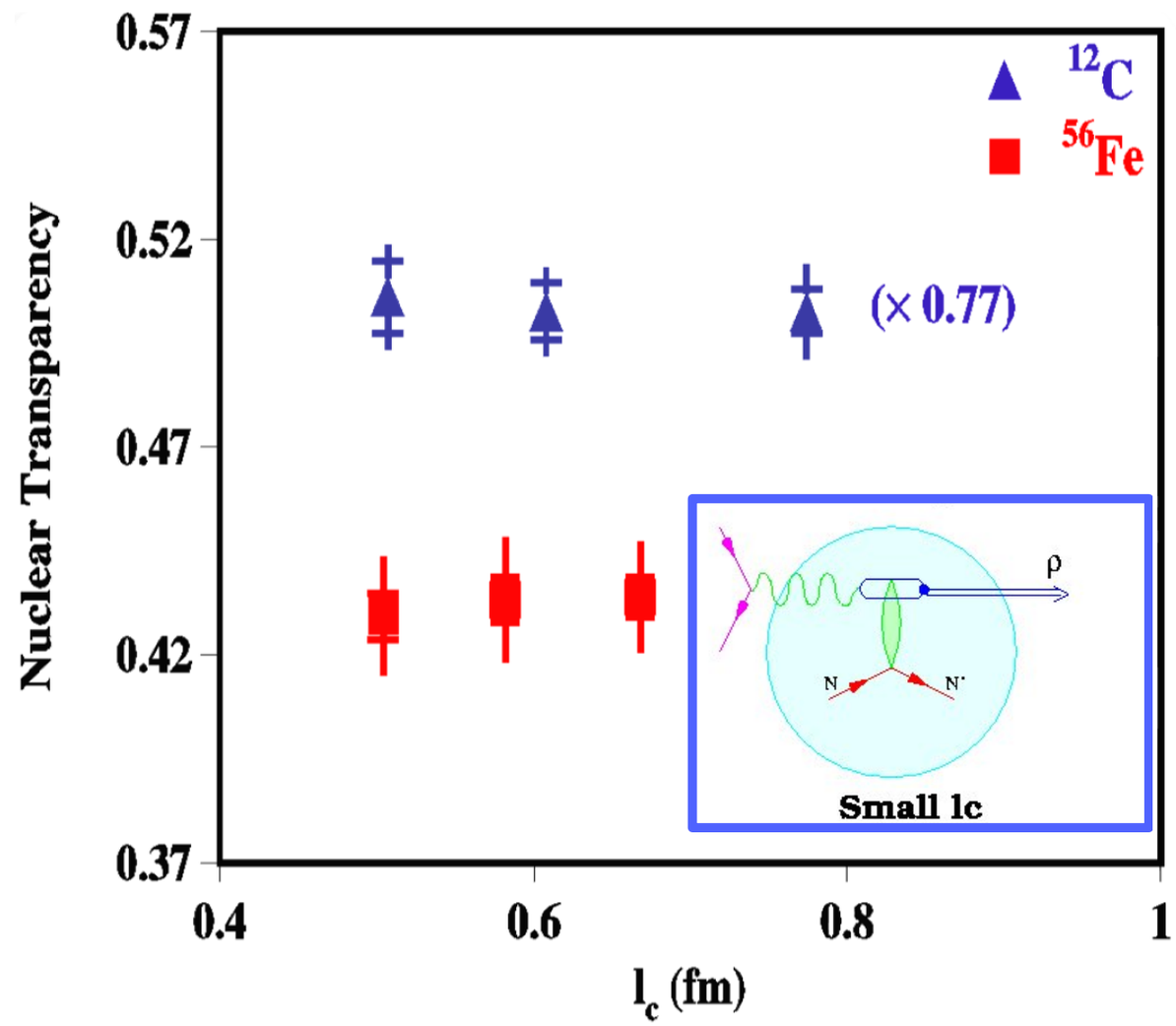


Hadronization

Hadronization

How all the color of parton is neutralized into colorless hadrons?
>> Dynamical enforcement of confinement <<

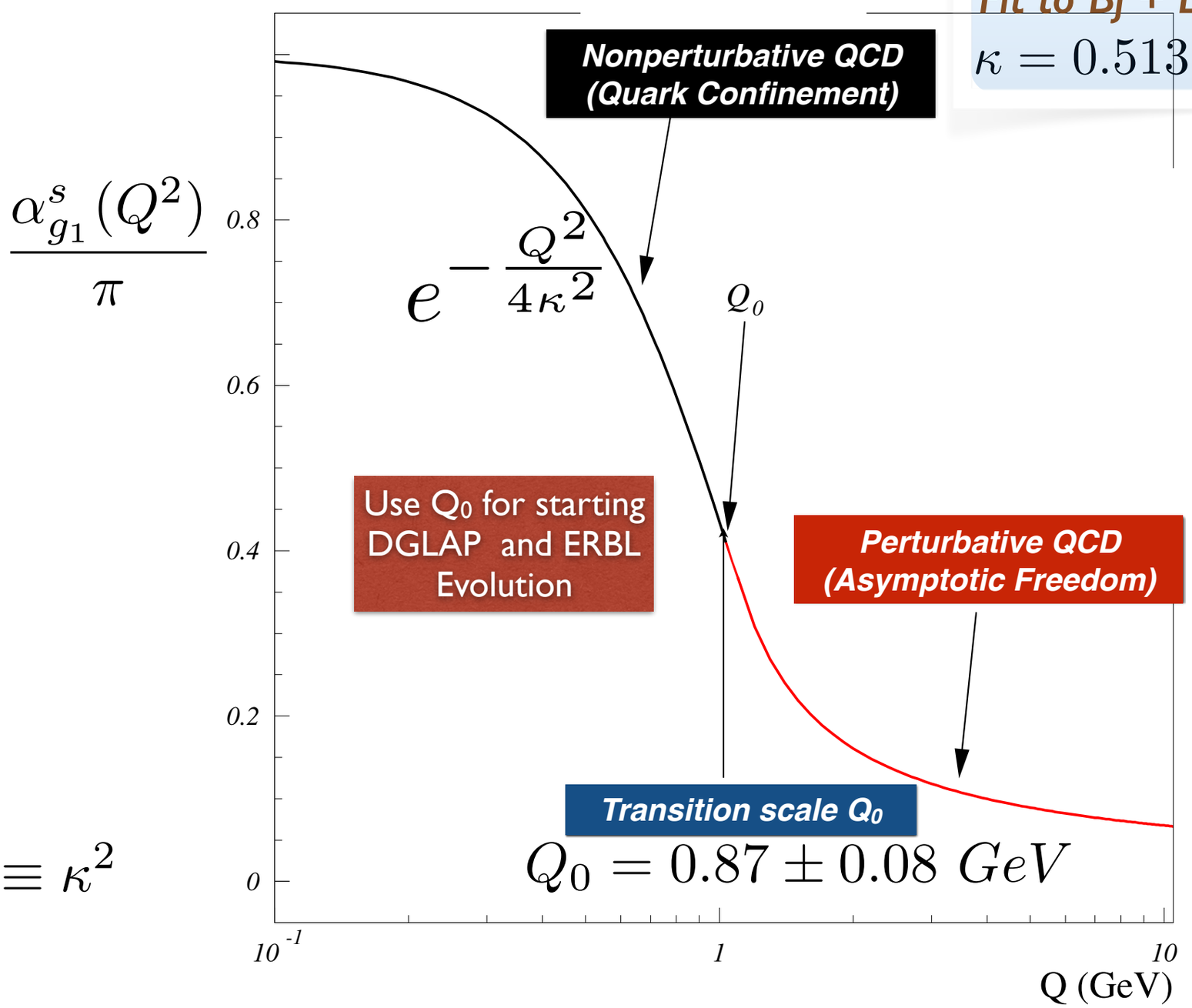
- ✔ Study dynamics of parton propagation in QCD
- ✔ Explore hadron formation mechanisms
- ✔ Characteristic timescales of these processes
- ✔ Testing calibrating theoretical tools used to determine the properties of Quark Gluon Plasma
- ✔ Reduction of systematic uncertainties in ν experiments

Deur, de Tèramond, sjb

All-Scale QCD Coupling

Fit to Bj + DHG Sum Rules:

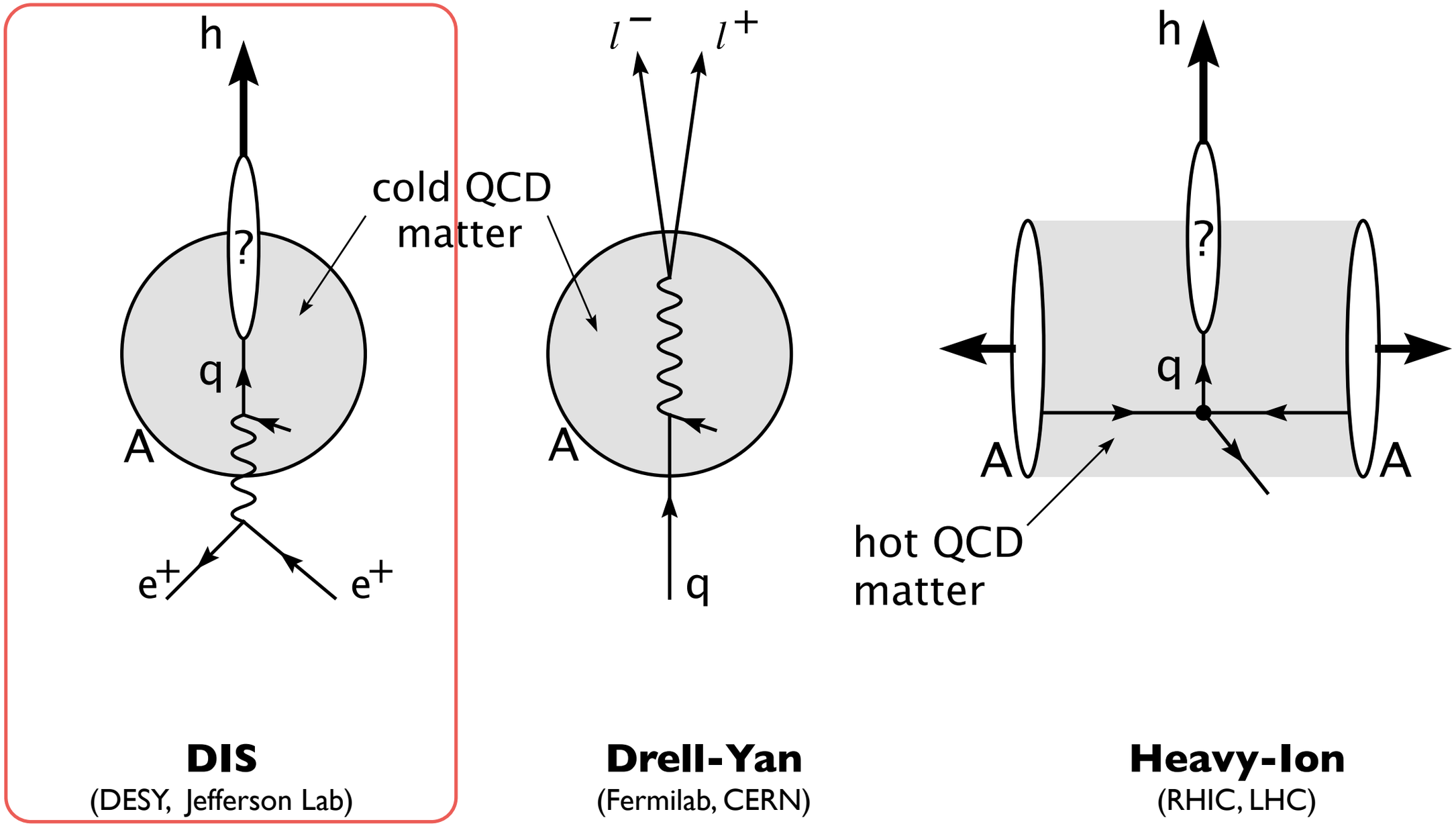
$$\kappa = 0.513 \pm 0.007\ GeV$$



$$\lambda \equiv \kappa^2$$

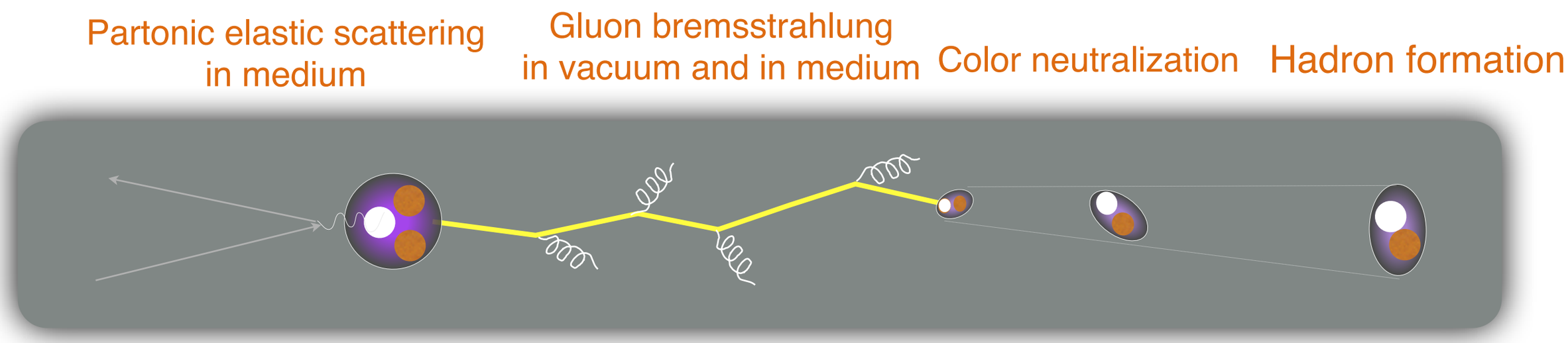
from Stan Brodsky

Hadronization



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

Fundamental QCD proceses in DIS



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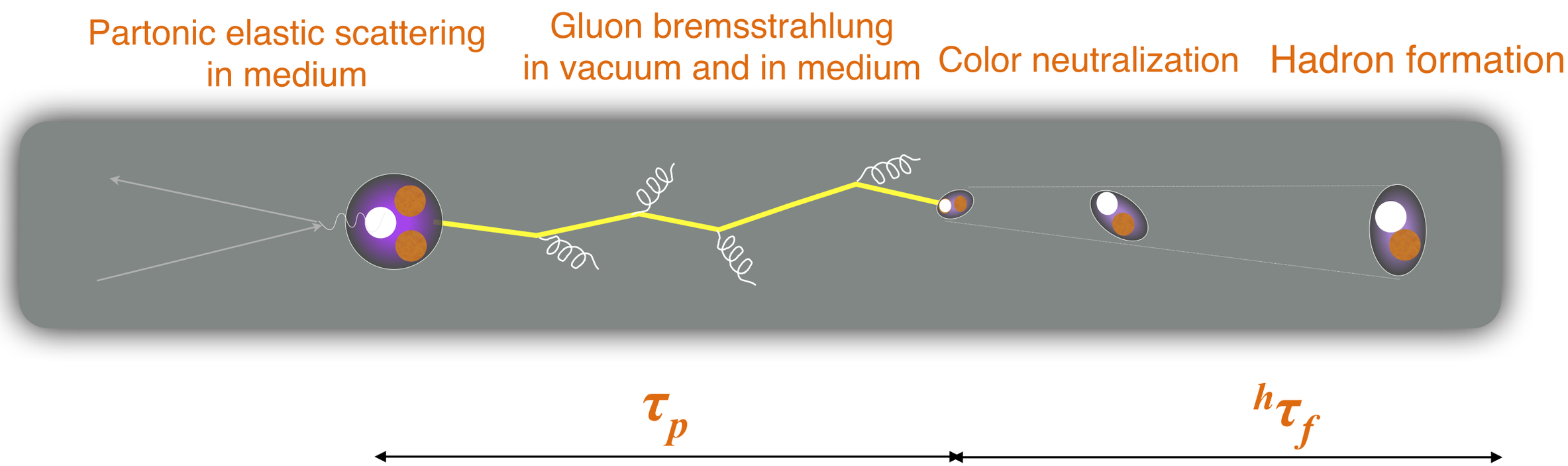
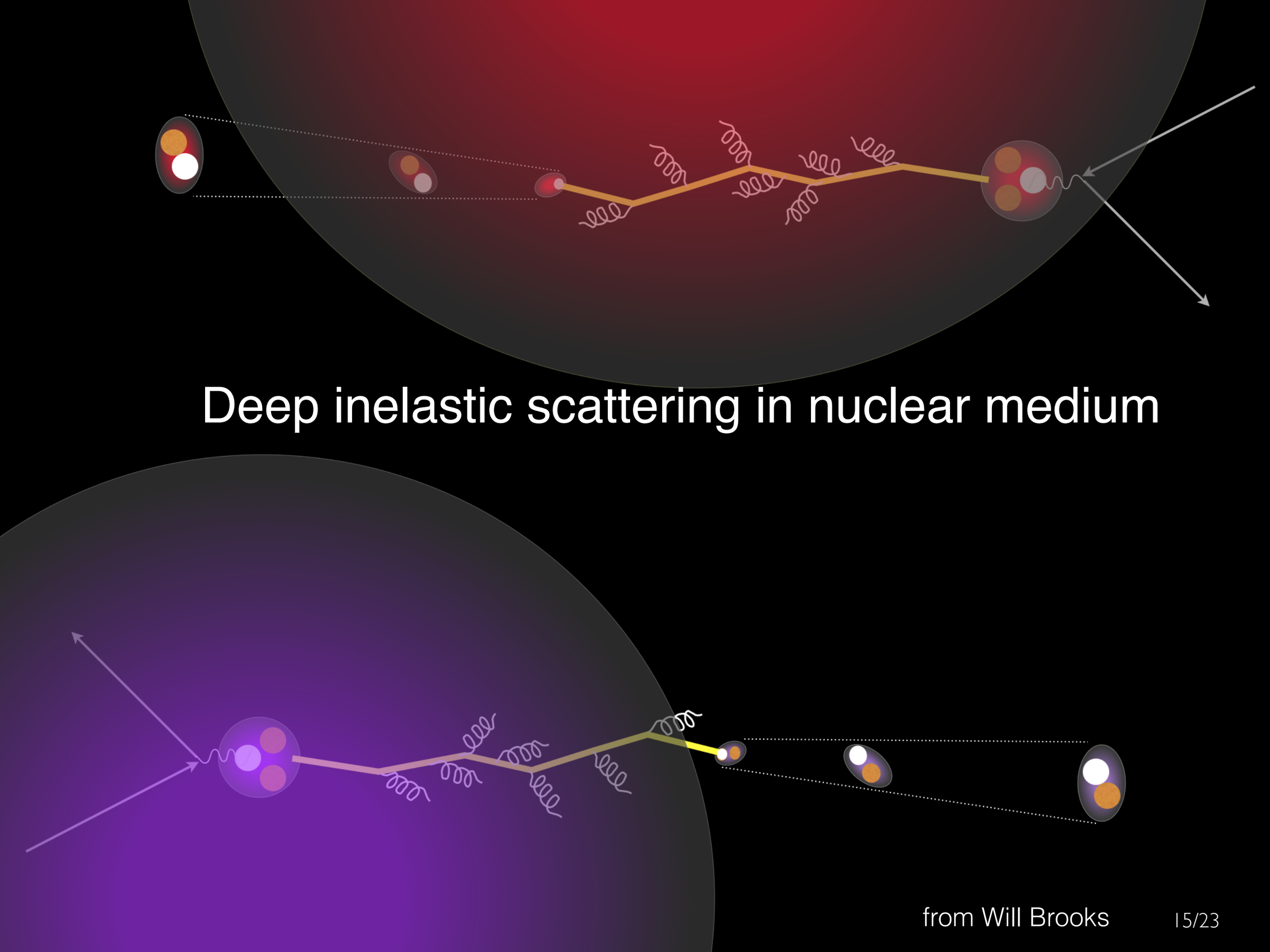


Production time τ_p is the color lifetime or lifetime of highly virtual quark following hard processes

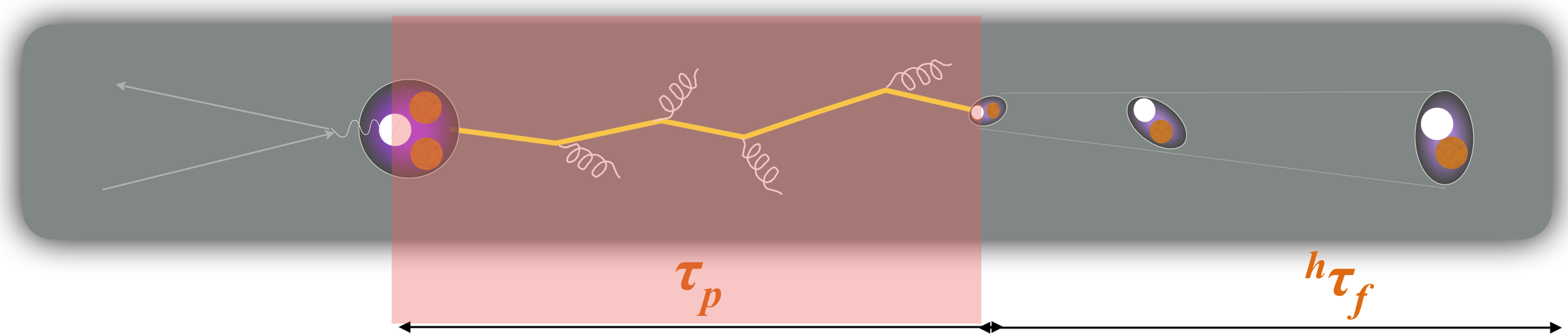
Formation time ${}^h\tau_f$ is the time or distance required for a colored system to evolve into a color singlet system



Deep inelastic scattering in nuclear medium

from Will Brooks

Observables: p_T broadening



Connects to color propagation phase:

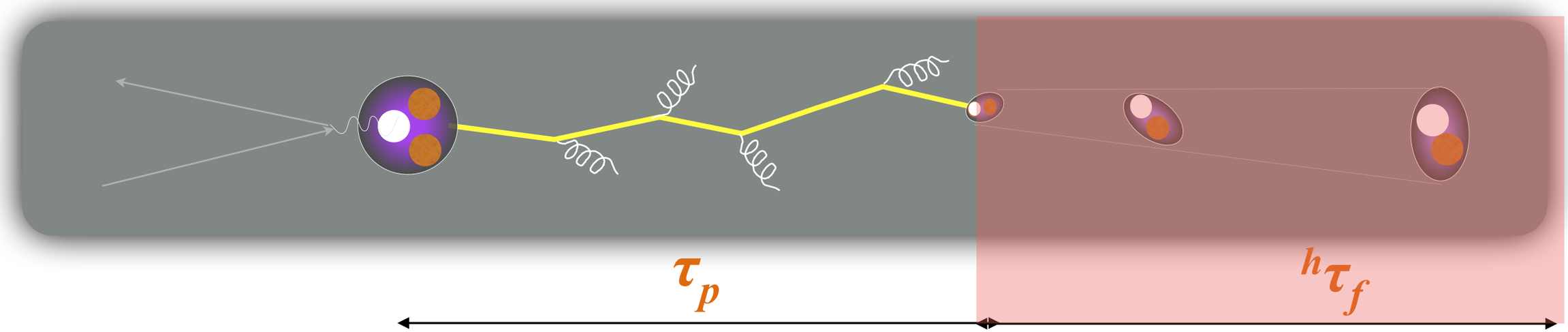
- how long color object propagates?
- **quark energy loss**

➤ see talk of J.Lopez

Transverse momentum broadening

$$\Delta p_T^2 = < p_T^2 >_{\mathrm{A}} - < p_T^2 >_{\mathrm{D}}$$

Observables: multiplicity ratio



Connects to hadronic phase:

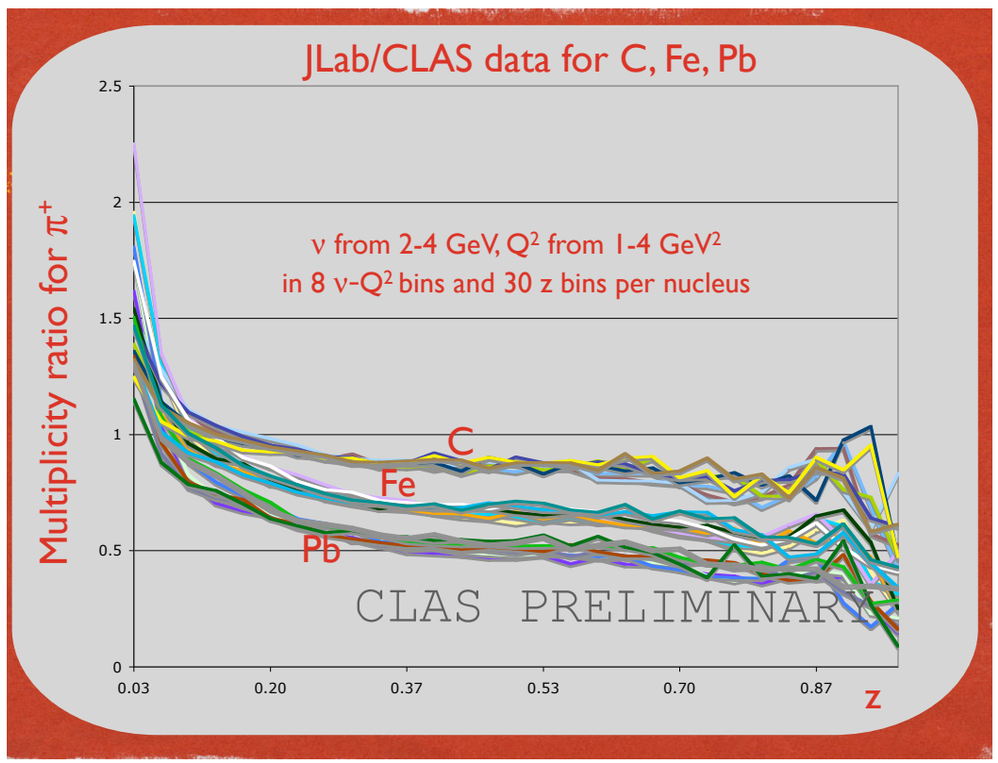
- how long it takes to form full hadron?
- space-time description of hadronization

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

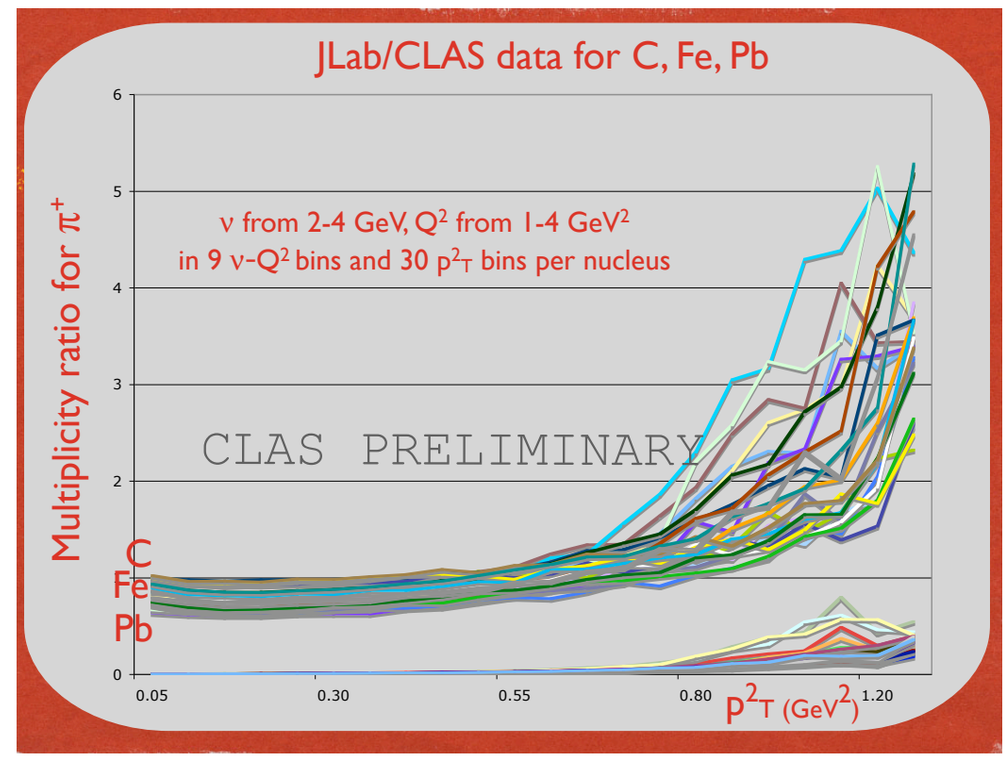
Multiplicity ratios: data from EG2

3D π^+ Multiplicities on ^{12}C,^{56}Fe,^{207}Pb to D

$R_{\pi+}$ in (Q^2, ν, z) integrated over p_T^2



$R_{\pi+}$ in (Q^2, ν, p_T^2) integrated over z



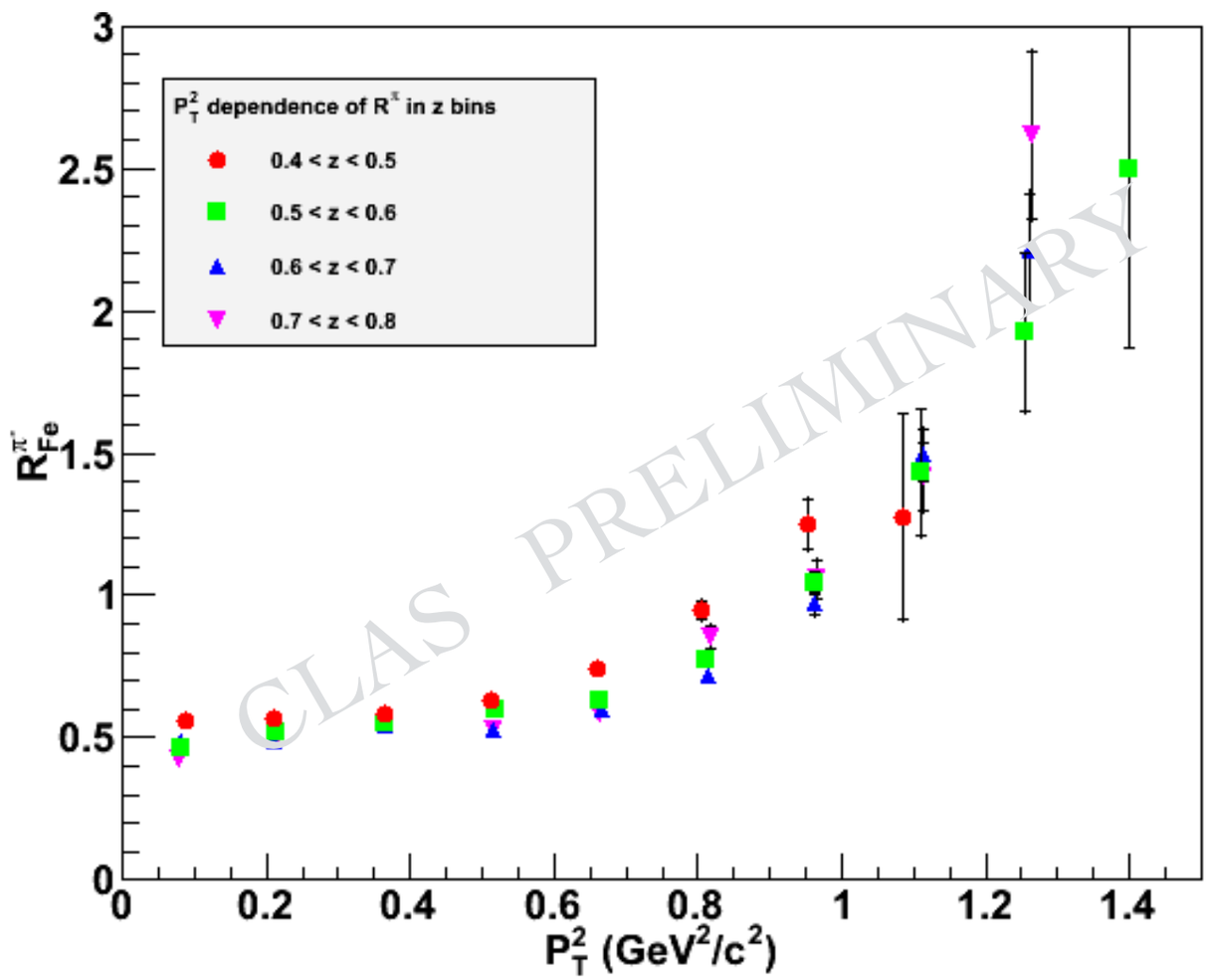
Hayk Hakobyan

- Attenuation depends on nuclear size
- Increase of hadrons at low z, attenuation at high z
- Bears resemblance to Cronin effect at high pT2
- Quantitative behavior compatible with Hermes

Multiplicity ratios: data from EG2

2D π^- Multiplicities on ^{12}C,^{56}Fe,^{207}Pb to D

R_{π^-} in (z, p_T^2) integrated over ν, Q^2



Raphael Dupré

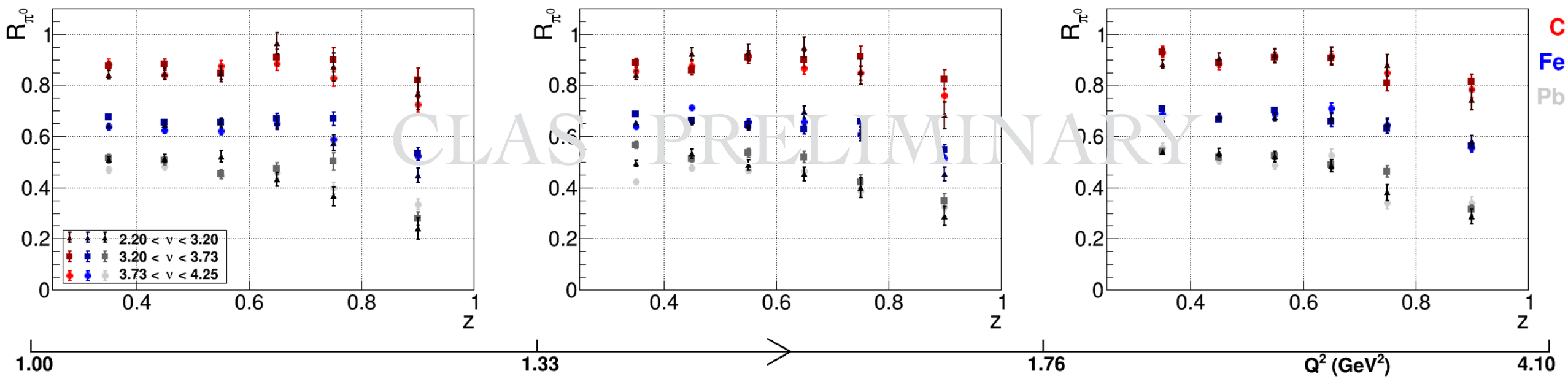
Analysis under review

Multiplicity ratios: data from EG2

3D π^0 Multiplicities on ^{12}C,^{56}Fe,^{207}Pb to D

$R_{\pi 0}$ in (Q^2, ν, z) integrated over p_T^2

Results are acceptance corrected only. Statistical uncertainties included. Systematics: 3-6%.



Taisiya Mineeva

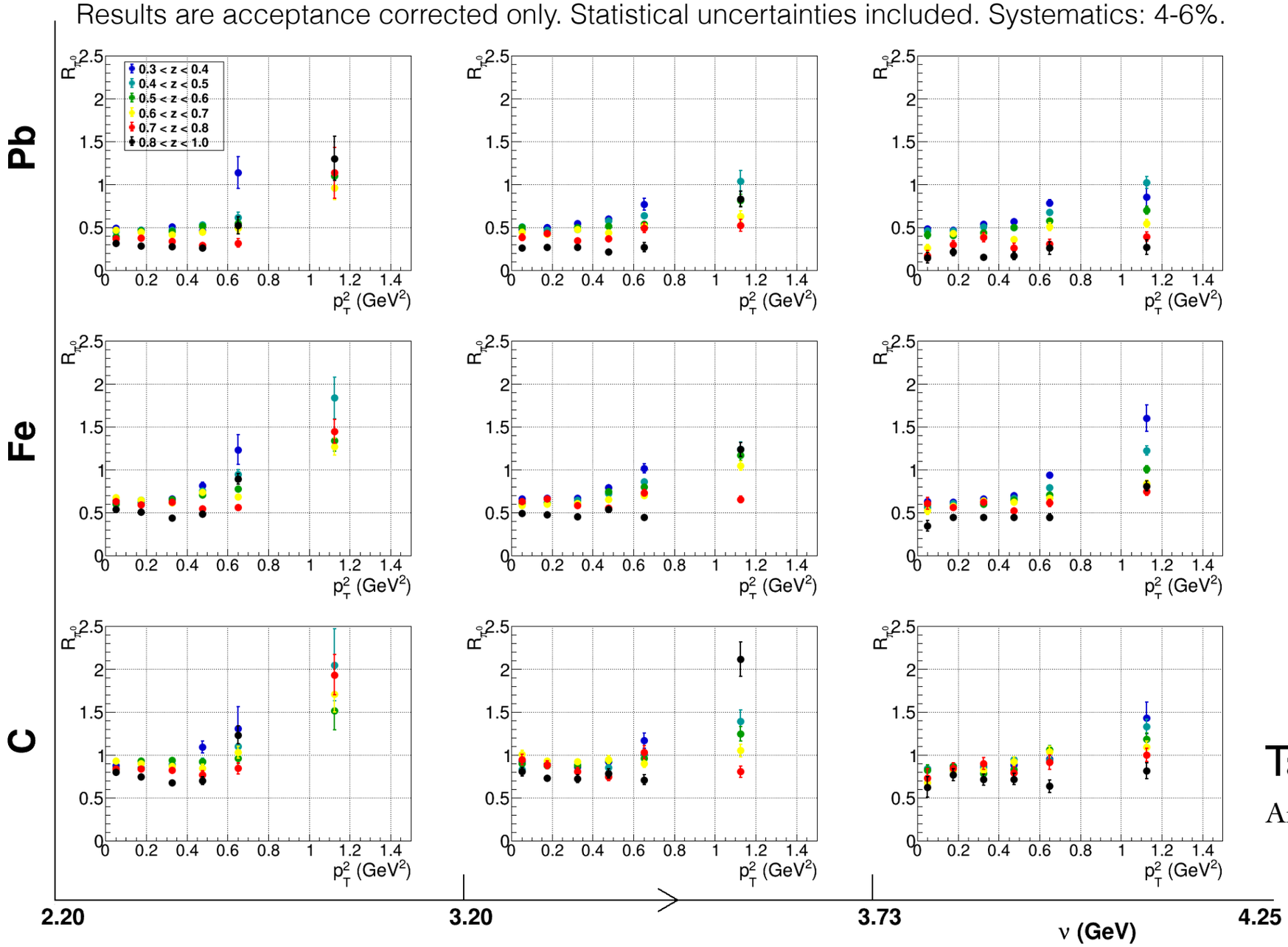
Analysis under review

Multiplicity ratios: data from EG2

3D π^0 Multiplicities on ^{12}C,^{56}Fe,^{207}Pb to D

$R_{\pi 0}$ in (ν, z, p_T^2) integrated over Q^2

Results are acceptance corrected only. Statistical uncertainties included. Systematics: 4-6%.

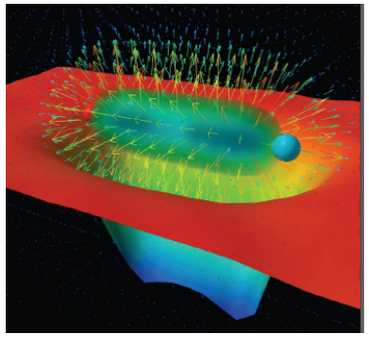


Taisiya Mineeva

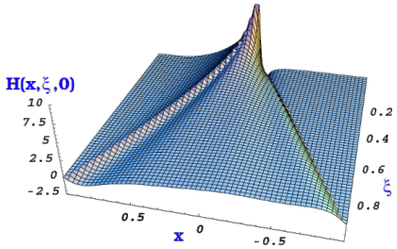
Analysis under review

CLAS12 Science Program

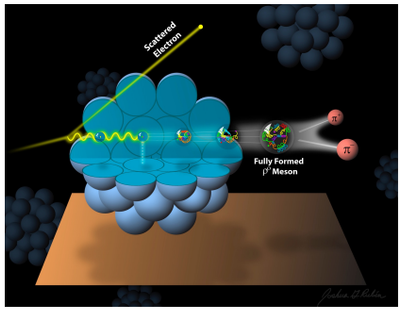
- Quark confinement and the role of the glue in hadron spectroscopy



- Unraveling confinement forces in the proton. Studying the multi-dimensional structure of the nucleon – from form factors and PDFs to GPDs and TMDs



- **The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons**



- Search for science beyond the Standard Model – precision and intensity frontiers

from L.Elouadrhiri

Conclusion: Color Transparency

- ✔ At intermediate energies, CT provides unique probe of the space-time evolution of special configurations of the hadron wave function
- ✔ Strong evidence for the onset of Color Transparency using ρ^0 electroproduction off C and Fe at JLab (11 ± 2.3% (12.5 ± 4.1%) decrease in the absorption of ρ)
- ✔ The transparency does not depend on coherence length in region l_c<0.9
- ✔ Future experiment at CLAS 12 will help to disentangle different CT effects (SSC creation, its formation and interaction with the nuclear medium)
- ✔ Future Electron Ion Collider (EIC)

Conclusion: Hadronization

- ✔ Hadronization is a fundamental process of QCD
  - Link between perturbative and non-perturbative domains
  - A way to probe nuclear media, either cold or hot
- ✔ Past results gave the global picture of hadronization in medium
  - CLAS high luminosity data on ^{2}H, ^{12}C, ^{56}Fe, ^{207}Pb
  - Extraction of multidimensional multiplicities and momentum broadening
  - Analysis under review
- ✔ Multi-dimensional analysis is crucial to constrain existing models
  - CLAS12 experiment (E-12-06-117) will provide high statistics data and access to 4D multiplicities in meson and baryon channels
- ✔ Future Electron Ion Collider (EIC)