Hadronization with JLab 6/12 GeV

Next generation nuclear physics with JLab12 and EIC

Florida International University
February 10-13th, 2016

Lamiaa El Fassi

(On behalf of EG2 and CLAS Collaborations)

MISSISSIPPI STATE UNIVERSITY

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- Brief introduction
- Highlight of previous measurements
- Past and future JLab (CLAS) experiments
- Summary and Outlook

NUCLEAR HADRONIZATION COLLABORATION

CLAS6 & CLAS12 EXPERIMENTS

W. K. Brooks, H. Hakobyan, A. El Alaoui, R. Mendez,(UTFSM)

R. Dupré (U Paris S.)

L. El Fassi (Mississippi State U)

K. Joo, T. Mineeva (U Connecticut)

K. Hicks (Ohio U)

K. Hafidi (Argonne National Lab)

L. Weinstein (Old Dominion U)

J. Gilfoyle (U. Richmond)

I. Niculescu, G. Niculescu (JMU),

M. Wood (Canesius Coll.)

M. Holtrop (U. New Hampshire)

CLAS6 EG2 group members (initially) active in this analysis.

Former EG2 Graduate students

Brief introduction

- Understand the QCD dynamics in terms of colored objects,

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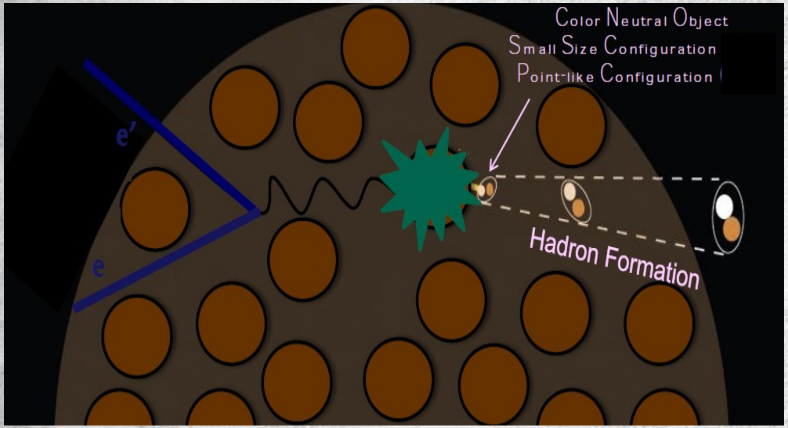

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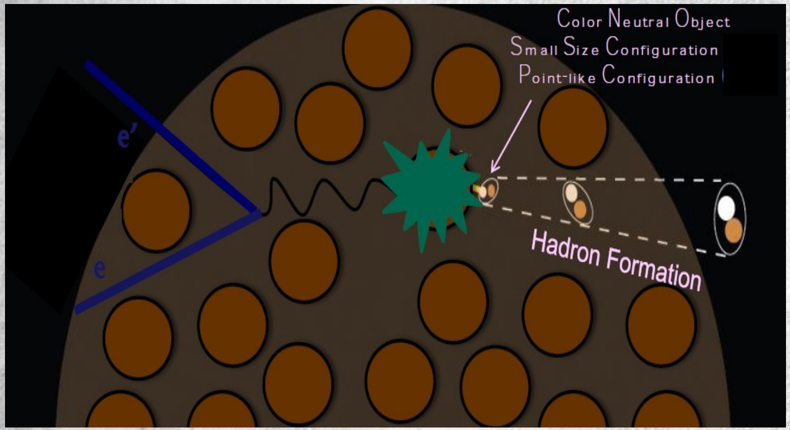
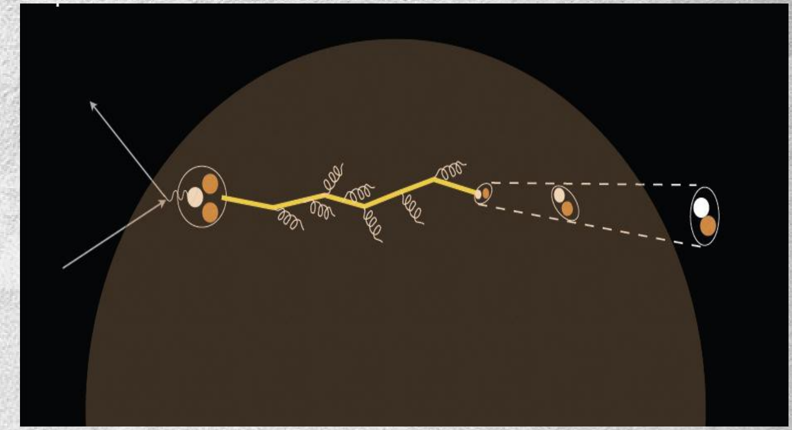
  * Evolution of a colored bare quark into a fully dressed hadrons – Hadronization





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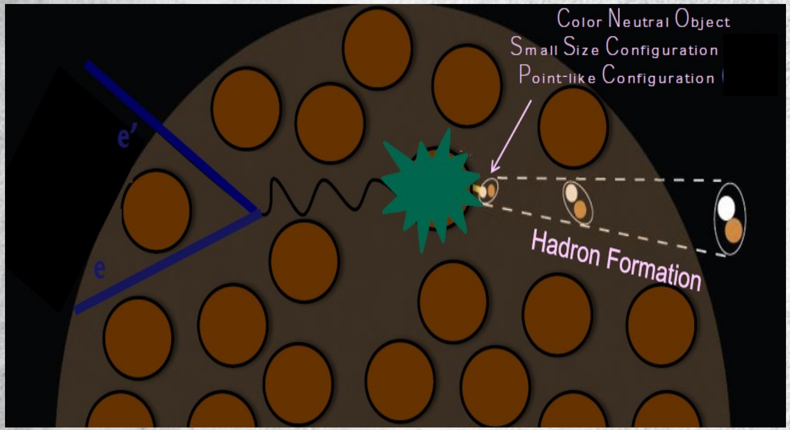

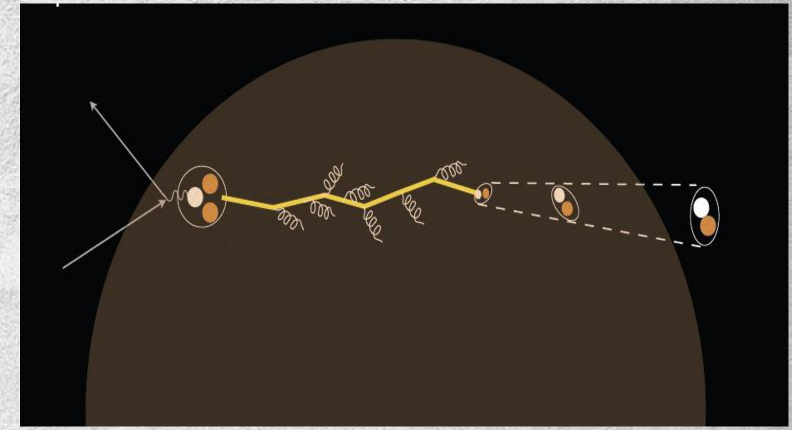

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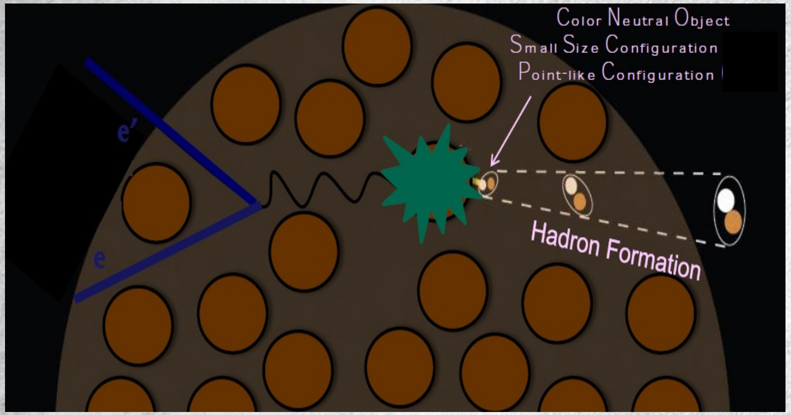
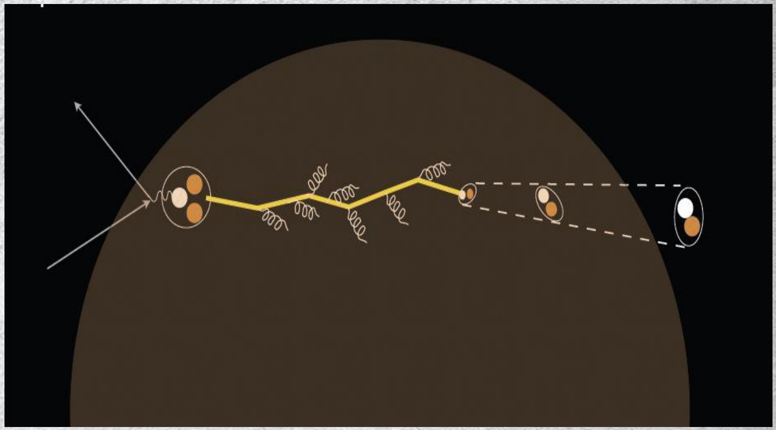
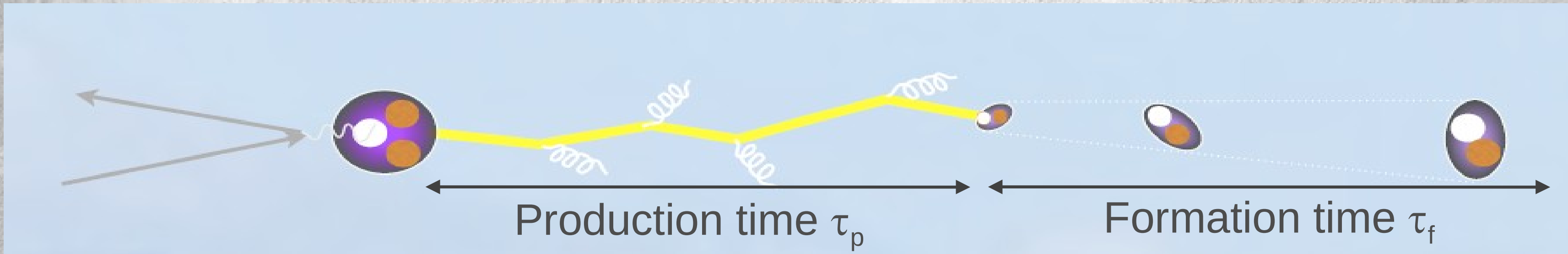




is a direct probe of the QCD confinement,

- A study of hard interactions in nuclei explores also:
  - * Nuclear modification of quark distributions – EMC
  - * Nuclear modification of GPDs and TMDs

Hadronization Timescales



Use semi-inclusive deep inelastic scattering (SIDIS) to access:

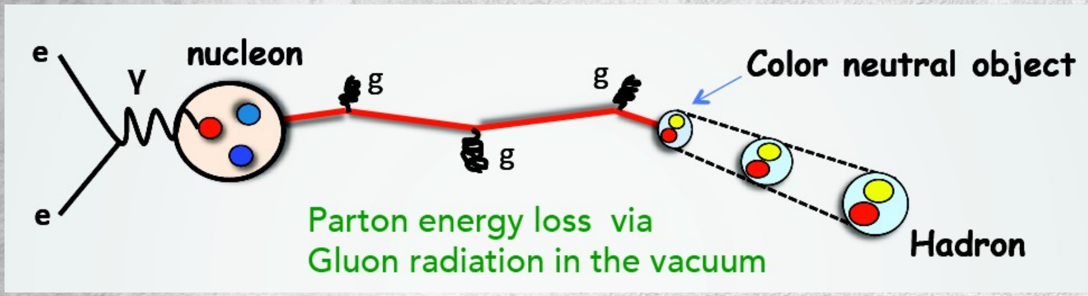
Production time τ_p: Time spent by a de-confined quark to neutralize its color charge.

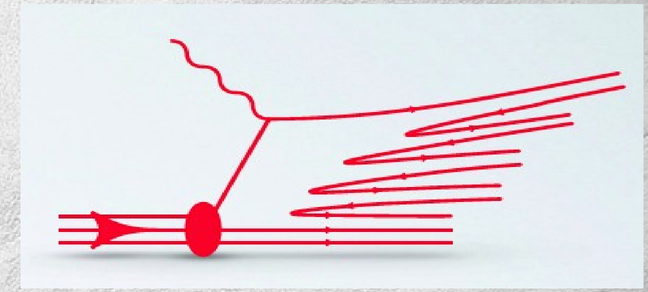
Formation time τ_f: Time required to form a regular hadron (h), like a pion.

How do we experimentally access these characteristic timescales?

SIDIS: In the vacuum (Nucleons) .vs. In the medium

Free Nucleon Scattering:





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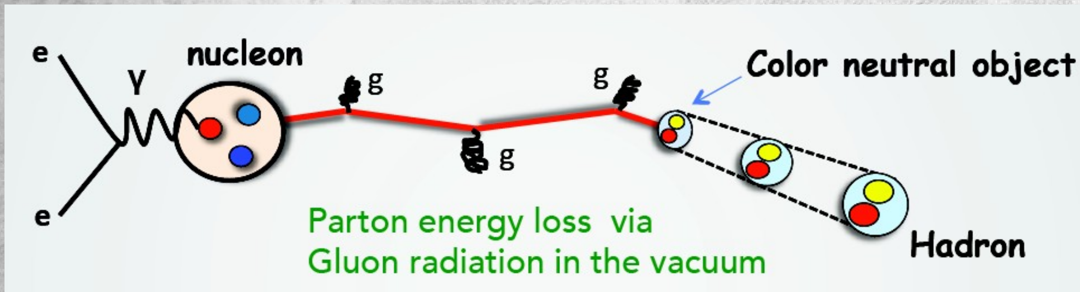
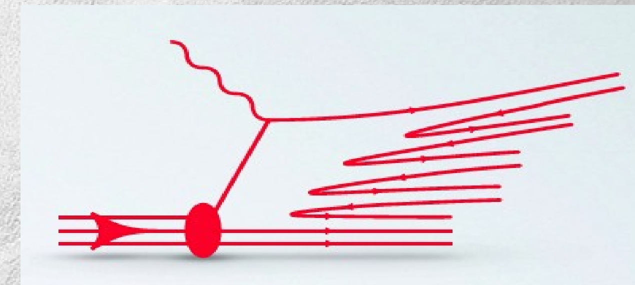
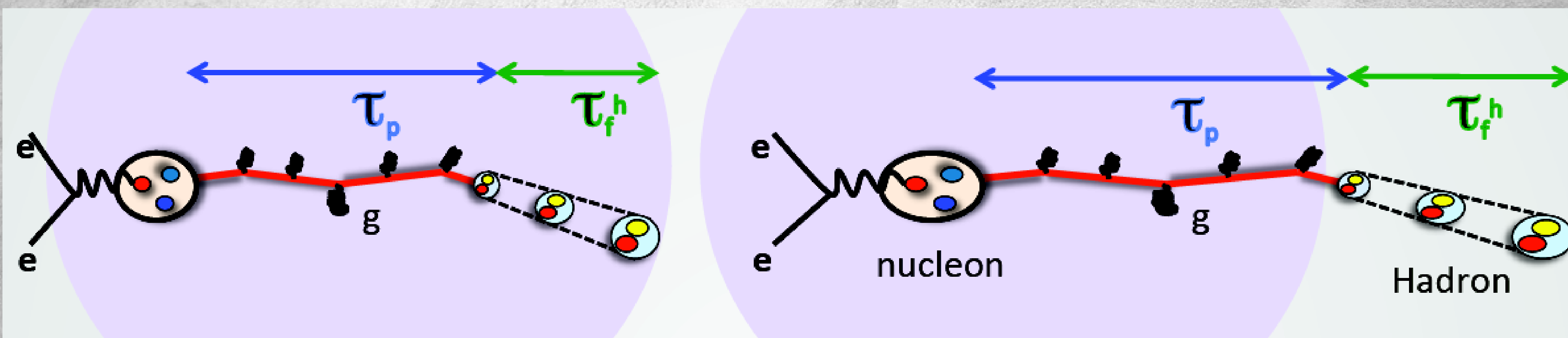




vs

Bound Nucleons Scattering:

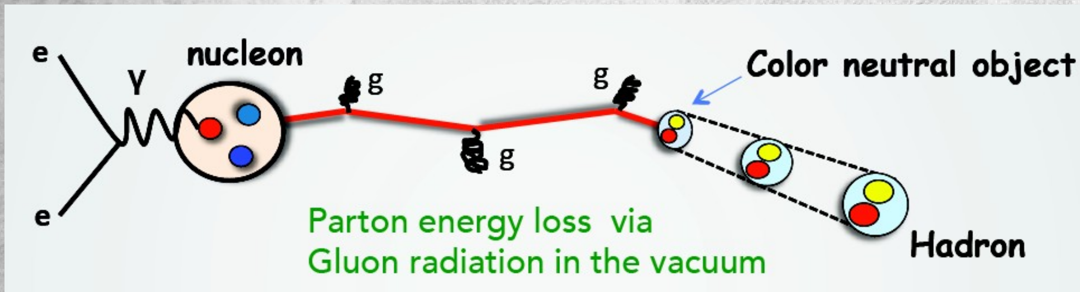


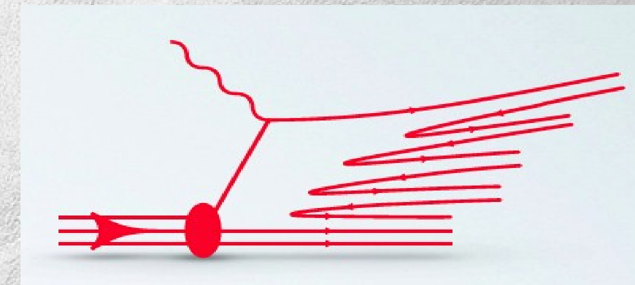
Hadron forms inside the medium
Accessible at low energies

Hadron forms outside the medium
dominant at high energies

SIDIS: In the vacuum (Nucleons) .vs. In the medium

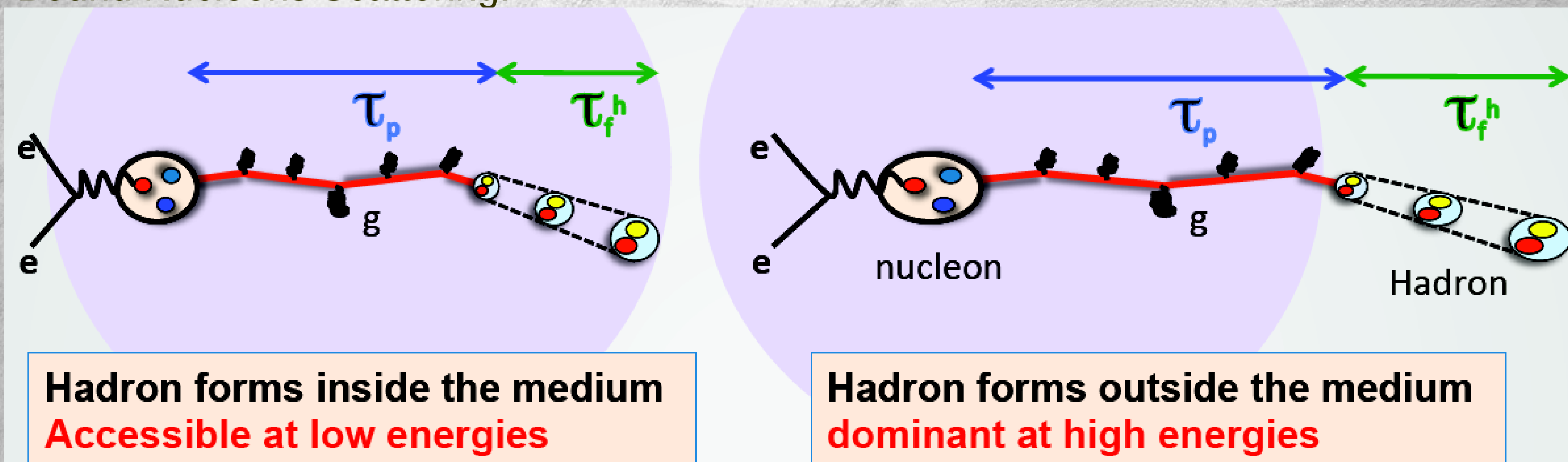
Free Nucleon Scattering:





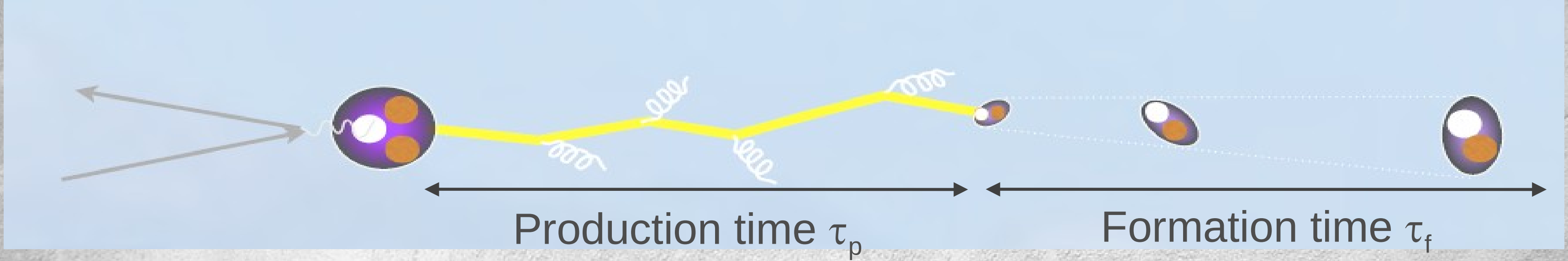
→ Parton fragmentation in the vacuum

Bound Nucleons Scattering:



→ Parton energy loss in the medium: medium induced gluon emission,
Modification of the fragmentation functions in the medium,
Hadron/pre-hadron formation and interaction with the medium.

How do we experimentally access the Hadronization timescales?

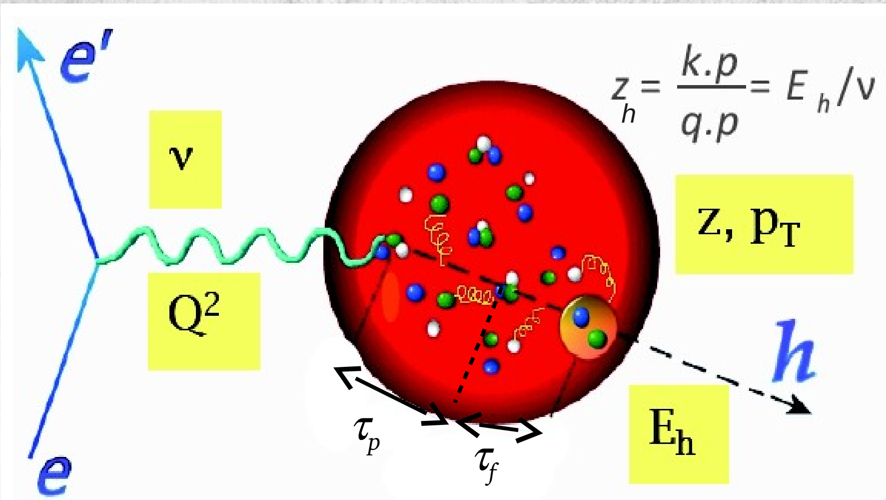


Use semi-inclusive deep inelastic scattering (SIDIS) to access:

Production time τ_p: Time spent by a de-confined quark to neutralize its color charge.
Stimulated by a medium-energy loss via a gluon emission
➡ Transverse momentum (p_T) broadening.

Formation time τ_f: Time required to form a regular hadron (h), like a pion.
Signaled by interactions with known hadron cross sections.
➡ Hadron attenuation by measuring hadron multiplicity ratios.

SIDIS Kinematics



Variables:

ν : Electron energy loss,
≡ Initial energy of a struck quark

Q^2: Four-momentum transferred,
~ 1/(spatial resolution) of the probe

y : ν/E_{beam}, Electron energy fraction transferred to a struck quark,

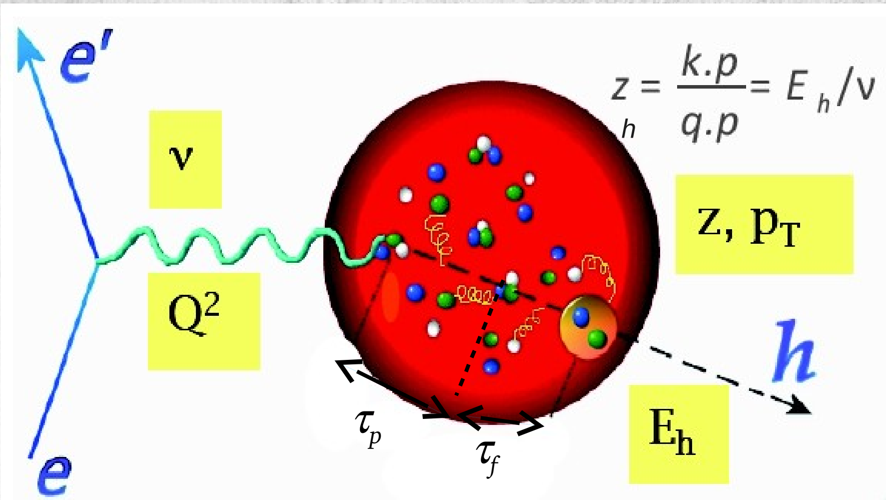
$W : \sqrt{M_n^2 + 2\nu M_n - Q^2}$ *w/. M_n is a nucleon mass*, is the mass of the total hadronic final state,

z_h: Fraction of the struck quark's initial energy carried by the formed hadron ($0 < z_h < 1$)

p_T: Hadron momentum transverse to a virtual photon direction.

x_F: $\frac{P_L}{P_L^{max}}$, *Feynman variable*, a fraction of the maximum longitudinal momentum carried by the observed hadron.

SIDIS Kinematics



Experimental cuts:

Q^2: Four-momentum transfer,

> 1, to probe the intrinsic structure of nucleons,

y : ν/E_h, Electron energy fraction transferred to a struck quark,

< 0.85, to reduce the size of the radiative effects on multiplicity ratios

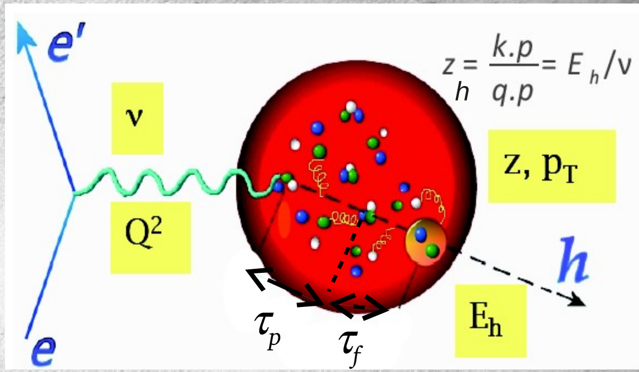
$W : \sqrt{M_n^2 + 2\nu M_n - Q^2}$ *w/. M_n is a nucleon mass*, is the mass of the total hadronic final state,

> 2, to avoid a contamination from the resonance region

x_F: Fraction of the maximum longitudinal momentum carried by the observed hadron.

> 0, to select the current fragmentation region.

Experimental Observables



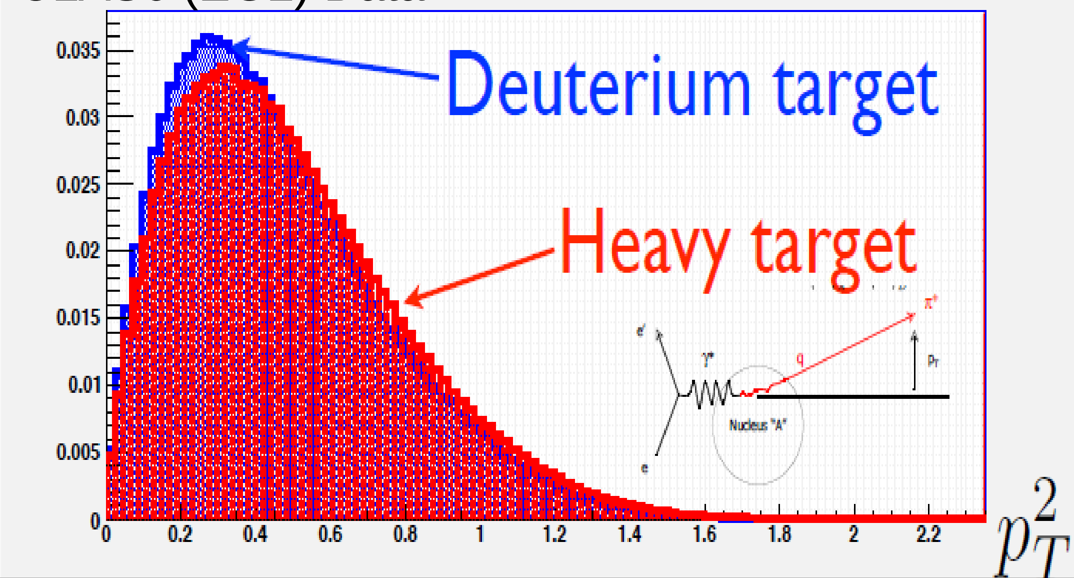
Transverse momentum broadening

$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

↕

Allow access to τ_p via production of different hadrons and quark's flavor.

CLAS6 (EG2) Data



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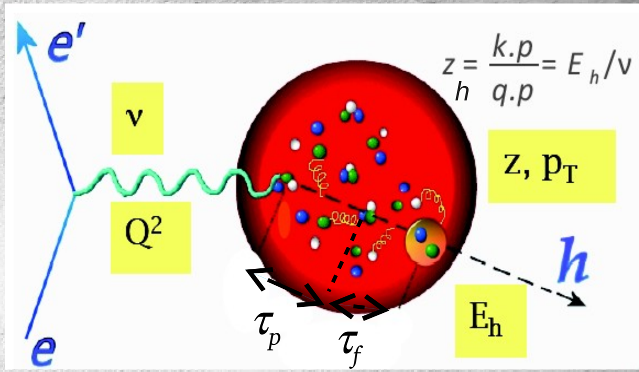


Hadron multiplicity ratio

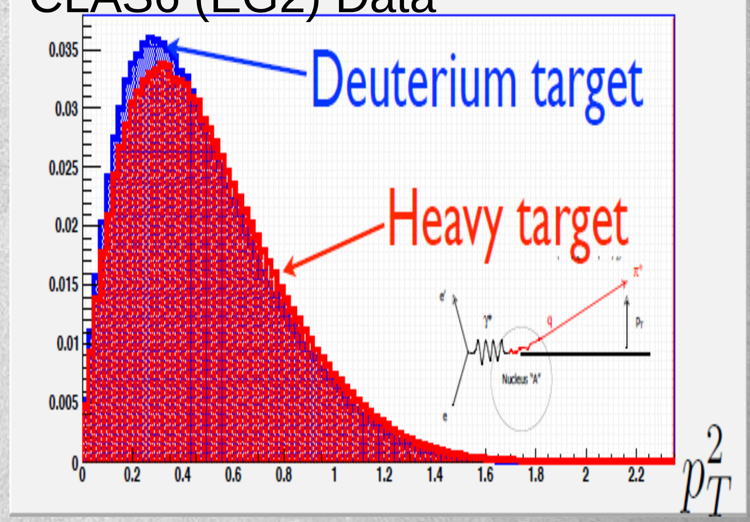
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_A}{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_D}$$

Access τ_f after the extraction of τ_p and R^h_M

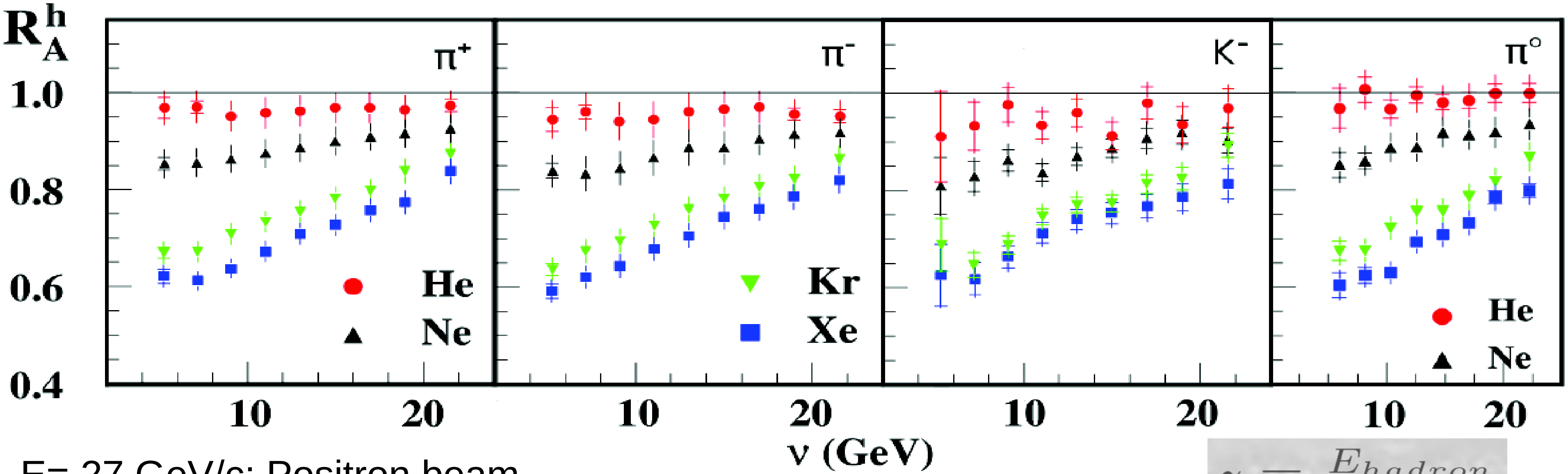
Transverse momentum broadening

$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

CLAS6 (EG2) Data

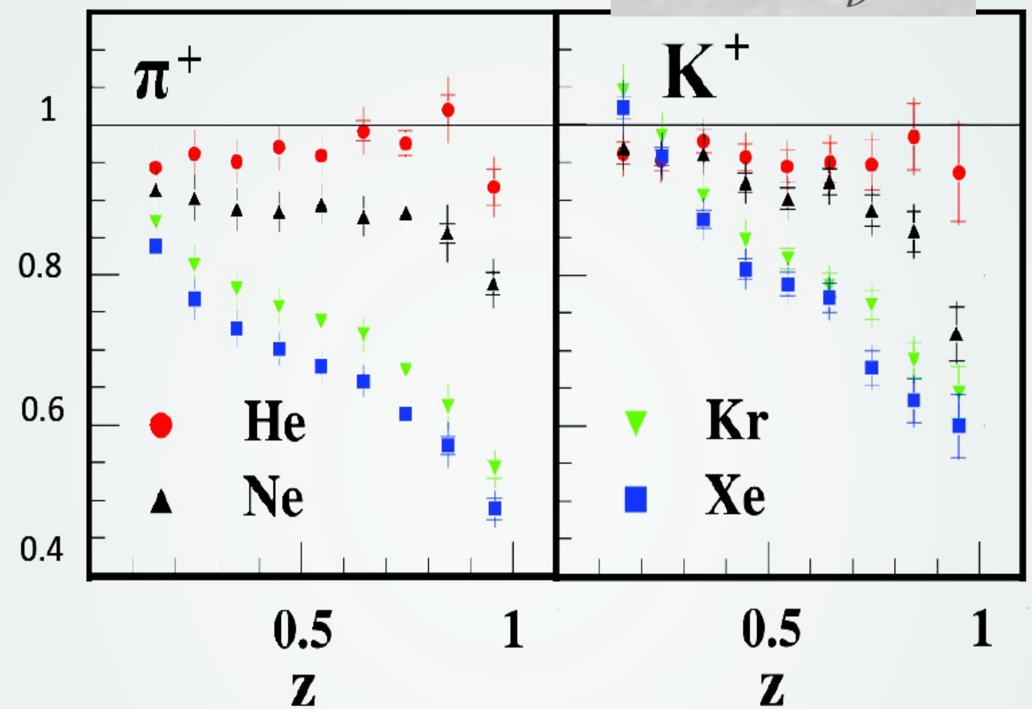


Hermes: Multiplicity Ratios



E= 27 GeV/c; Positron beam

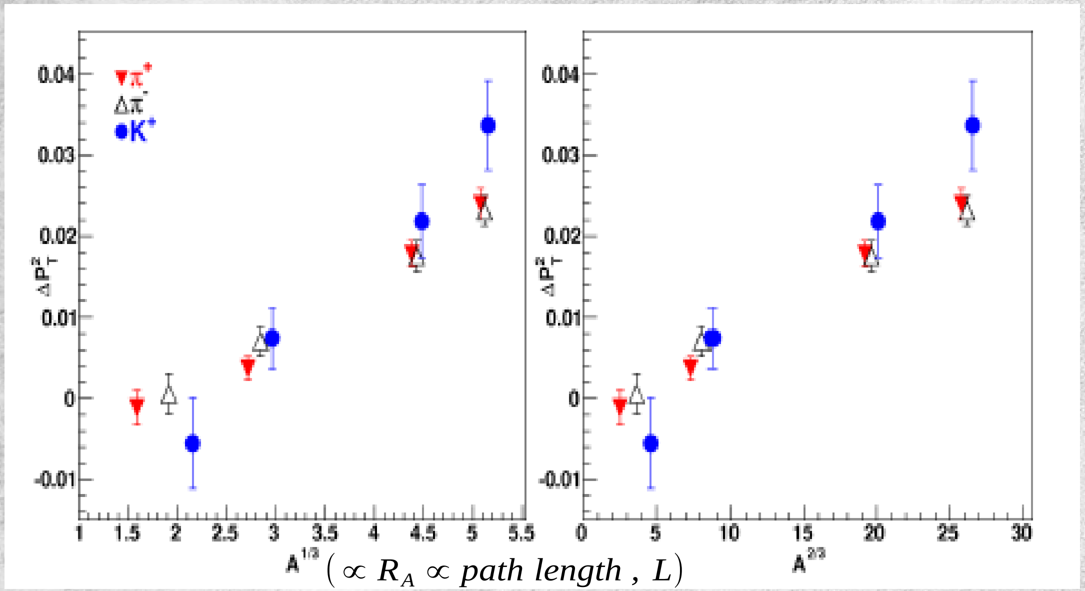
$z \equiv \frac{E_{hadron}}{\nu}$

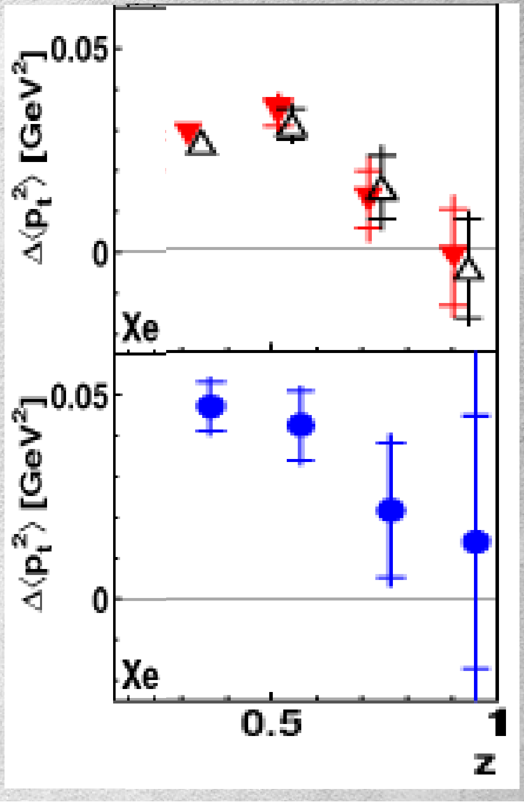


- All pion's flavors and K^- experience similar attenuation.
- K^+ is less attenuated compared to π^+ most likely due to a contamination from $\pi + p \to \Lambda + K$ (B. Kopeliovich et al.)

Hermes: Transverse Momentum Broadening

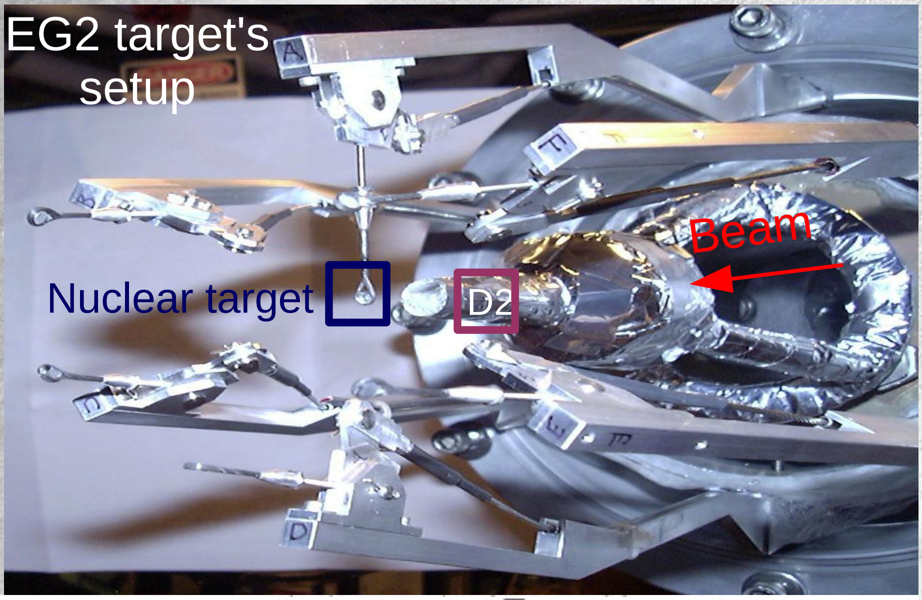
E= 27 GeV/c; Positron beam

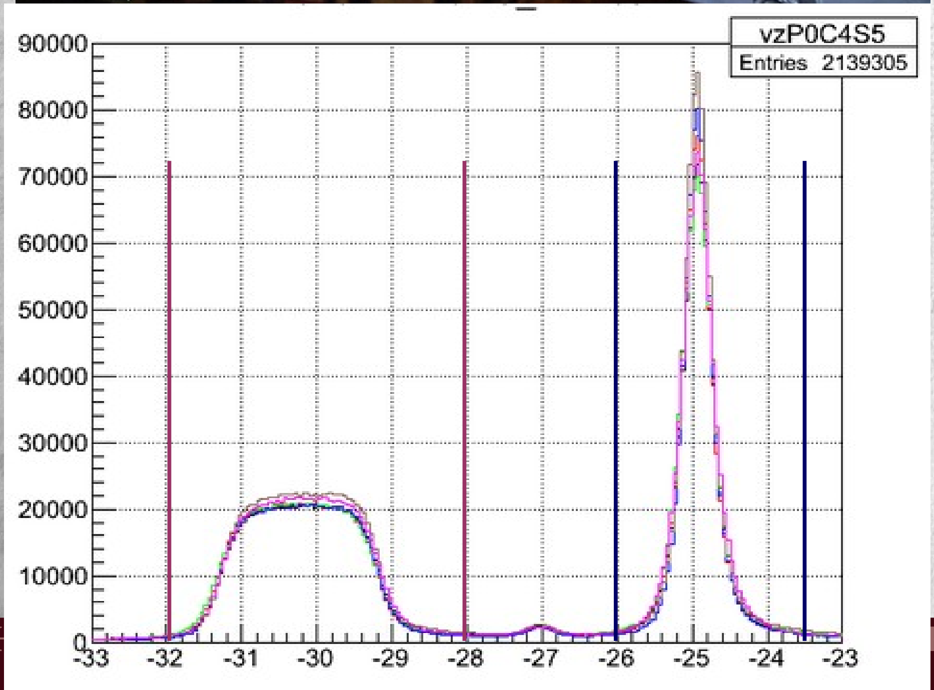


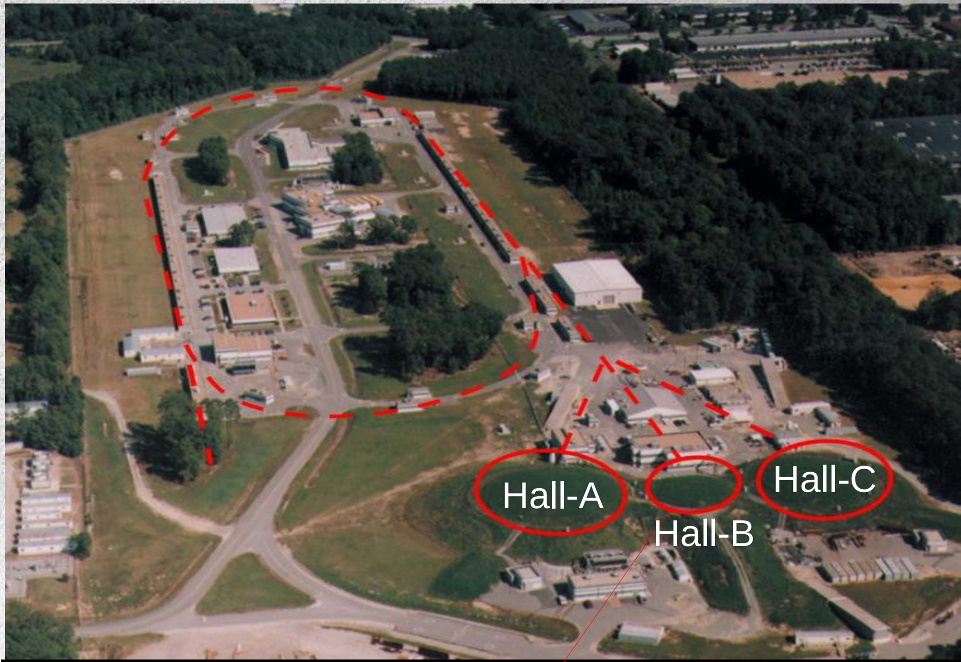


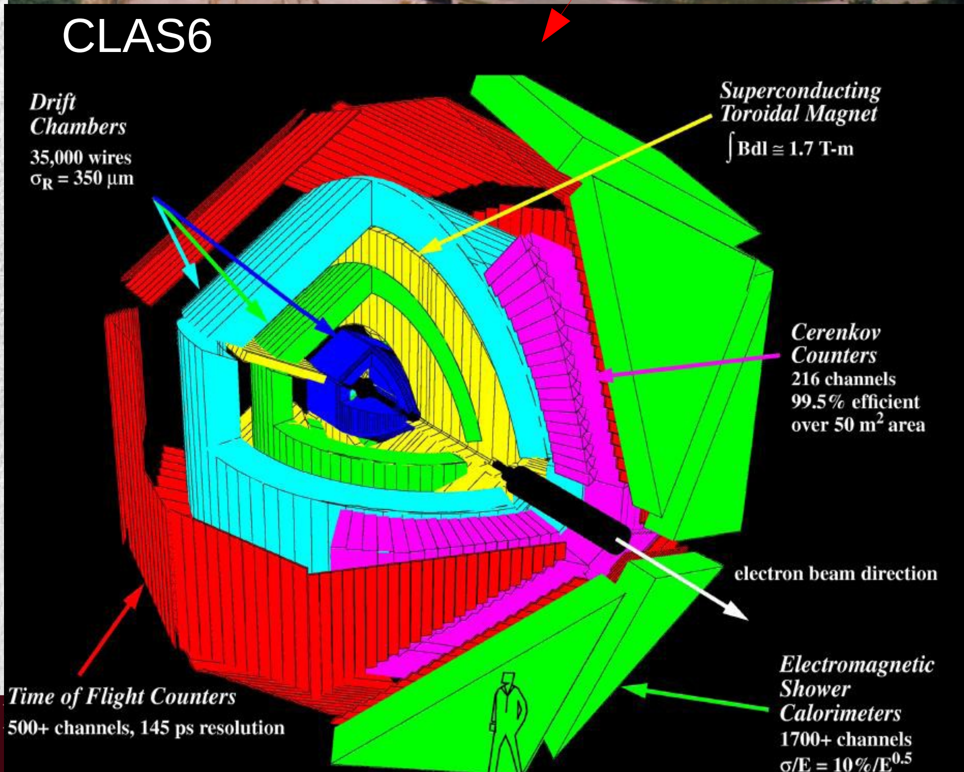
- Reduced broadening at high z favors no prehadron interaction,
- Different K^+ p_T broadening behavior compared to pions → Flavor dependence?
- Perturbative QCD description of p_T broadening: $\Delta\, p_T^2 \propto \frac{dE}{dx}$ *while* $\Delta\, p_T^2 \propto L \;\&\; dE \propto L^2$
- A similar dependence of $\Delta\, p_T^2$ *on* $A^{1/3}$ & $A^{2/3}$? → More data are needed!

JLab/CLAS6 EG2 Experiment: 5 GeV Run

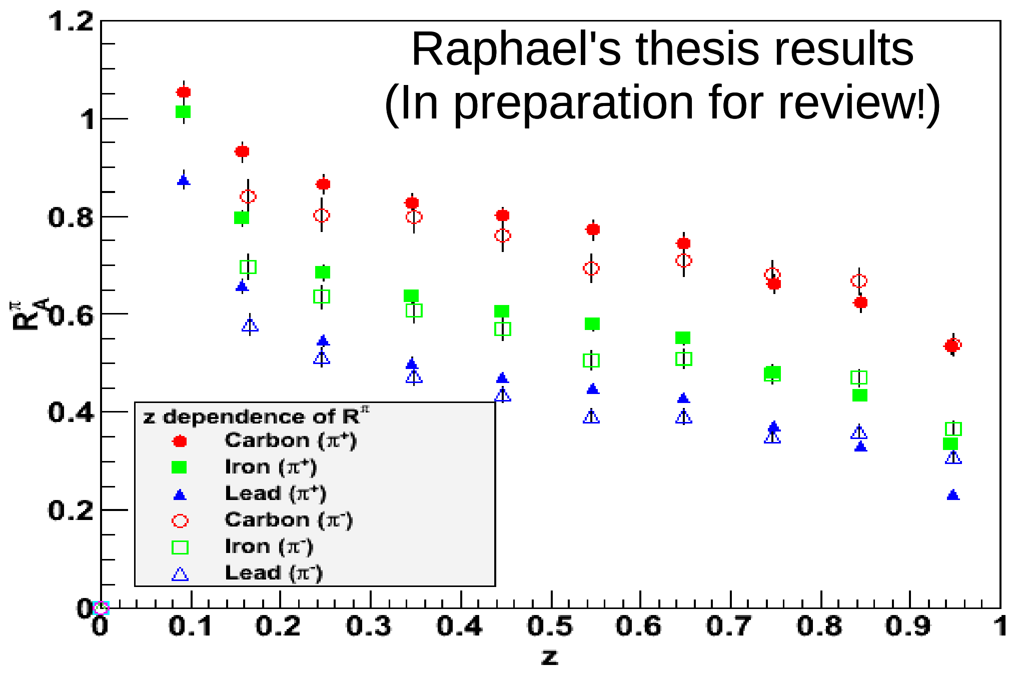








5 GeV CLAS6/EG2 Results



- 3-dimensional CLAS6 multiplicity ratios, fully corrected for radiative processes and acceptance, normalized to target thicknesses; C, Fe, Pb.
- Similar behavior for π^0 (Taya's thesis results; under review), π^+ (Hayk's thesis) and K^0 (A. Daniel, Ken Hicks et al.; published!)
- Consistent with Hermes results!

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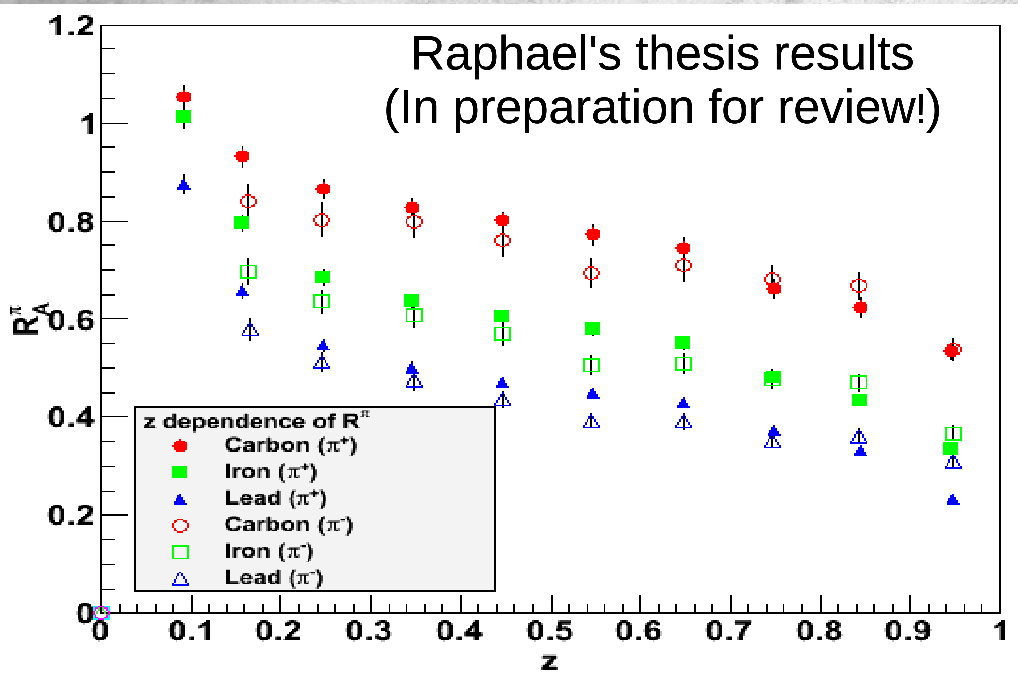

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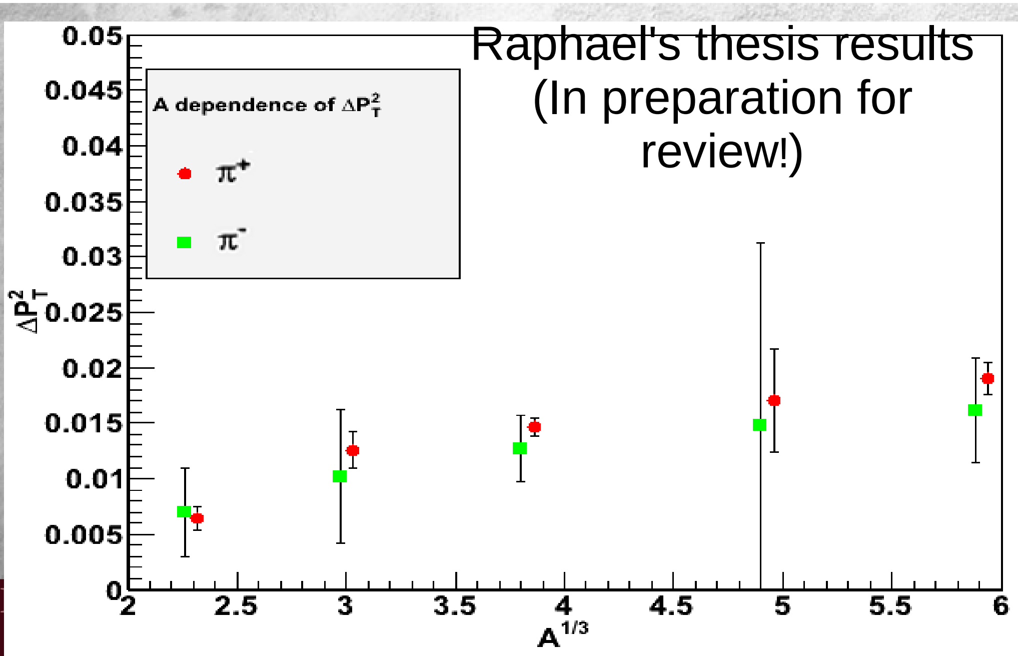


- CLAS6 transverse momentum broadening results for charged pions shows a similar behavior (a slight shift was added for a clarity!).
- Saturation behavior for large nuclei.

CLAS12 Hadronization Mesurements: PR12-06-117

- Span a wider range of nuclei masses → Better understanding of the A dependence,
- Study the production of a variety of hadrons → Improve our understanding of hadron's formation mechanism,
- Cover much larger kinematical coverage,
- 10 times higher luminosity compared to CLAS6 (1000 higher than Hermes),

→ Determines the two hadronization timescales and validate the existing theoretical models with the correct production picture!

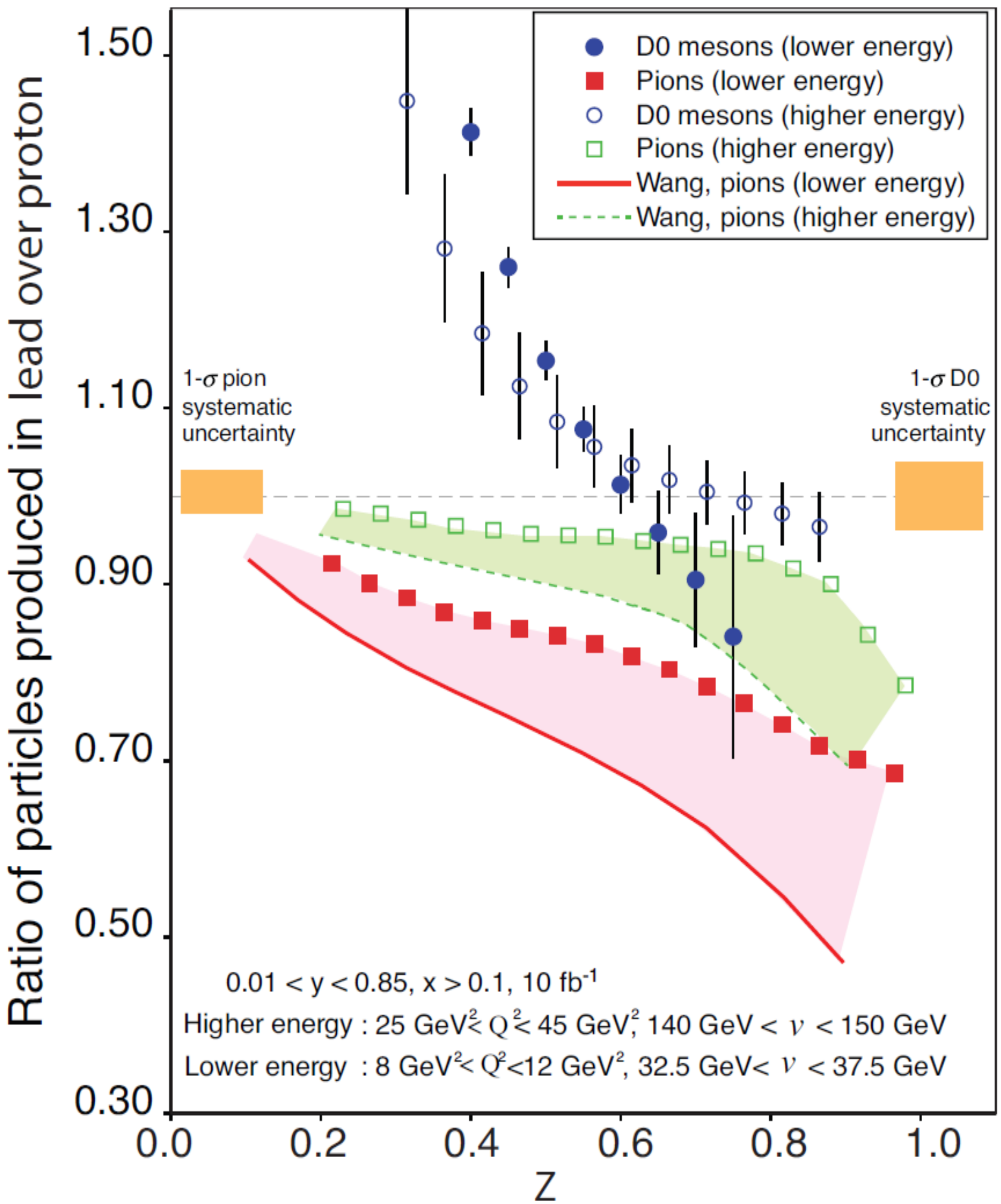
DIS channels: *stable* hadrons, accessible with 11 GeV JLab experiment PR12-06-117

Actively underway with existing 5 GeV data

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$
π^+, π^-	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$
K^0	27 mm	0.50	$d\bar{s}$
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$

baryon	cτ	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	$\overline{ud}$
Λ	79 mm	1.1	uds
$\Lambda(1520)$	13 fm	1.5	uds
Σ^+	24 mm	1.2	us
Σ^-	44 mm	1.2	ds
Σ^0	22 pm	1.2	uds
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

Expected Hadronization Measurements at the EIC



- EIC will extend the hadronization measurement to a wider kinematics range

  ➡ Improve our understanding of the hadronization mechanisms and a parton energy loss.

- Access to heavy flavors for a comparison with heavy ion collisions.

Summary & Outlook

- The hadronization study is a complementary probe of the QCD confinement in cold and hot nuclear matter.
- A detailed comprehension of its mechanism helps constraining the existing theoretical models.
- Consistent results were extracted by HERMES and CLAS6/EG2 collaborations in the last decades.
- The future CLAS12 will provide the multi-dimensional data needed to extract the production and formation timescales.
- EIC will allow the study of hadronization dynamics of heavy quarks in cold nuclear matter for a comparison with heavy ions collisions' data of RHIC and LHC, and provide a large Q^2 coverage to study the in-medium evolution.

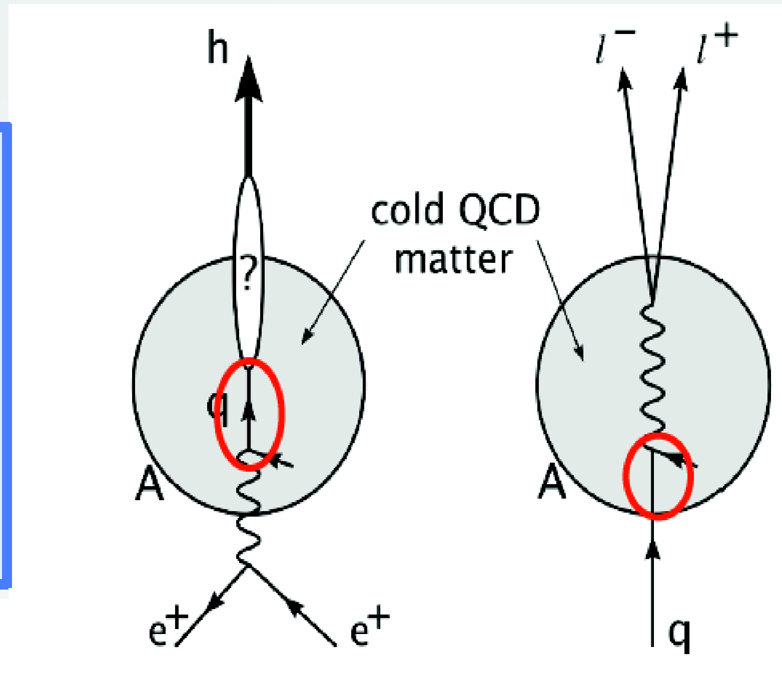
Backup Slides

COMPLEMENTARY PROCESSES TO STUDY HADRONIZATION

Kawtar's POETIC VI slide

Deep Inelastic scattering

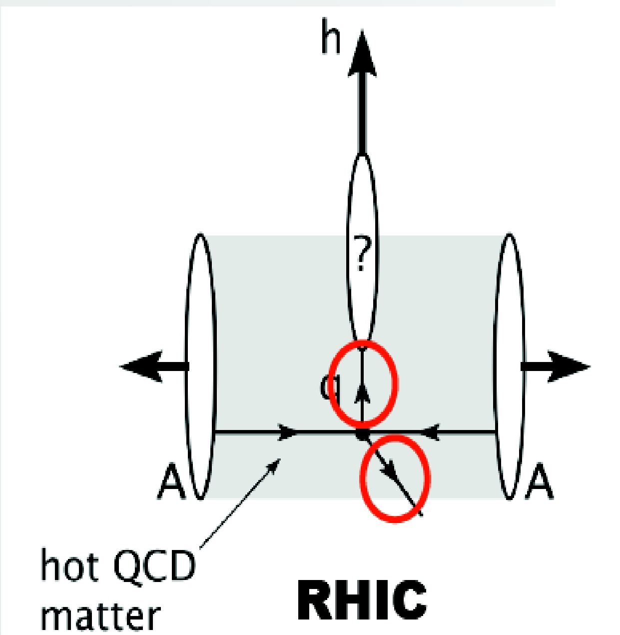
- ✧ Quark propagation
- ✧ Hadron formation
- ✧ Final state effects



DIS **DY**

Drell-Yan

- ✧ Quark propagation
- ✧ Initial state effects



RHIC

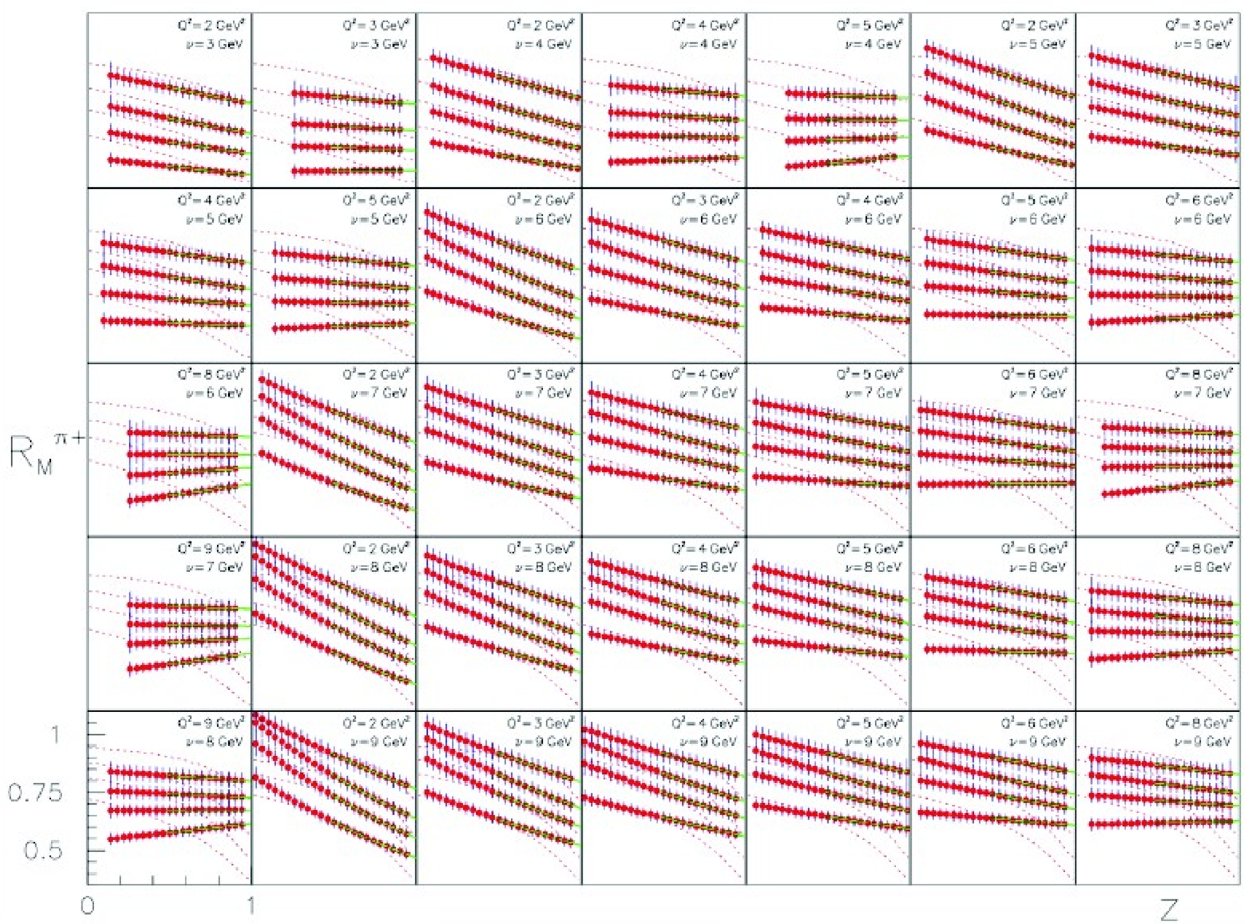
Relativistic Heavy ion collisions

- ✧ Quark propagation in strongly interacting matter
- ✧ Hadron formation
- ✧ Initial and final state effects

http://arxiv.org/pdf/0907.3534.pdf, A. Accardi, W. Brooks et al.

FUTURE SIDIS HADRONIZATION MEASUREMENTS @ JLAB

Examples of Experimental Data and Theoretical Predictions



CLAS12 experiment
E12-06-117

- ✓ Improved particle identification
- ✓ Access to higher masses
- ✓ Much larger kinematical range

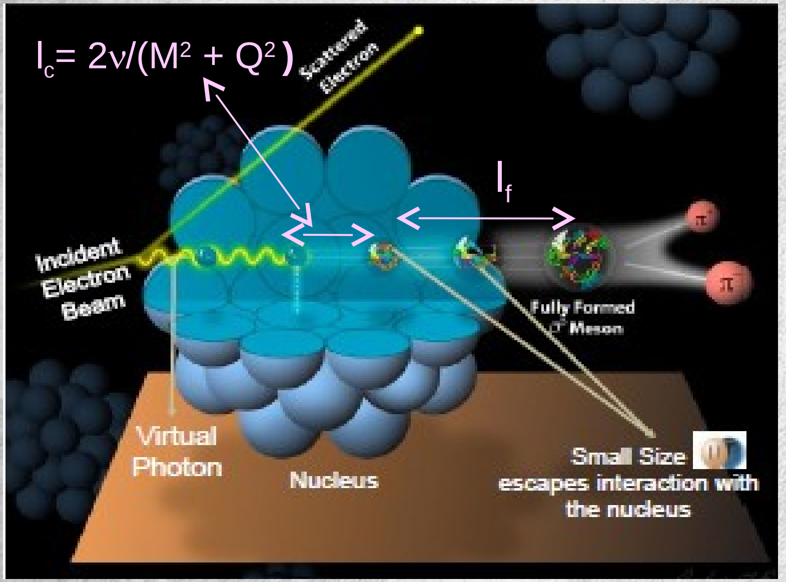
✓ CLAS12 has 10 times more luminosity than CLAS and 1000 times more than HERMES

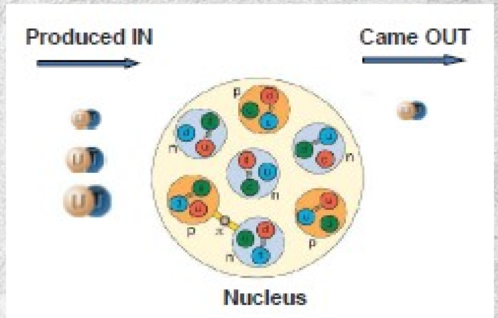
Kawtar's POETIC VI slide!

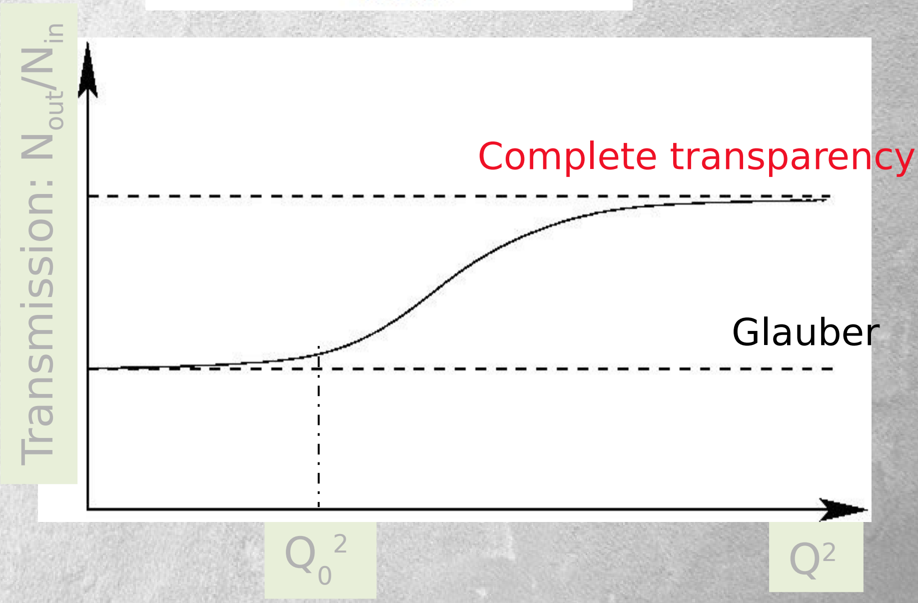
Other experiment (Not DIS) providing information about a hadron information is: Color Transparency

Color Transparency is the proposal that under certain circumstances the strong interactions can be controlled and in some cases reduced in magnitude.

P. Jain et al. Phys. Reports 271 (1996)







- Coherence length, l_c, is the lifetime of the qq-bar pair.
- l_f, is the lifetime of the small size configuration before evolving to a full ρ^0 meson.

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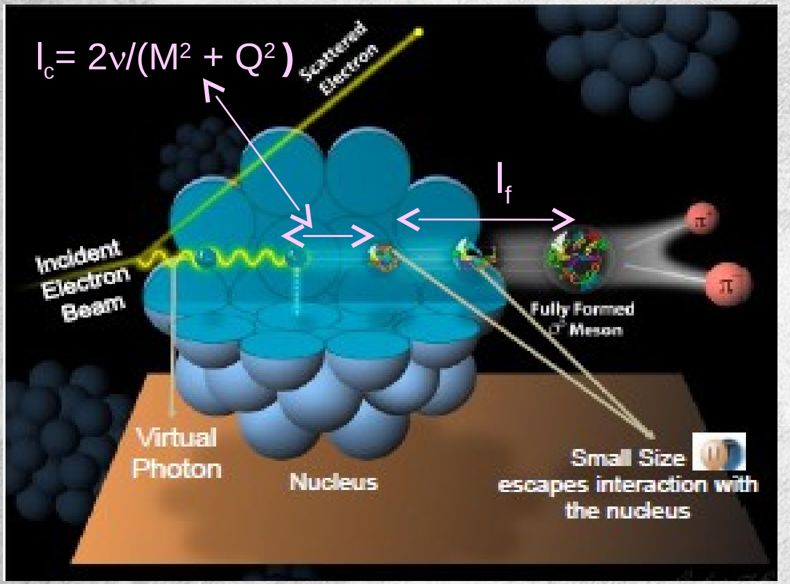

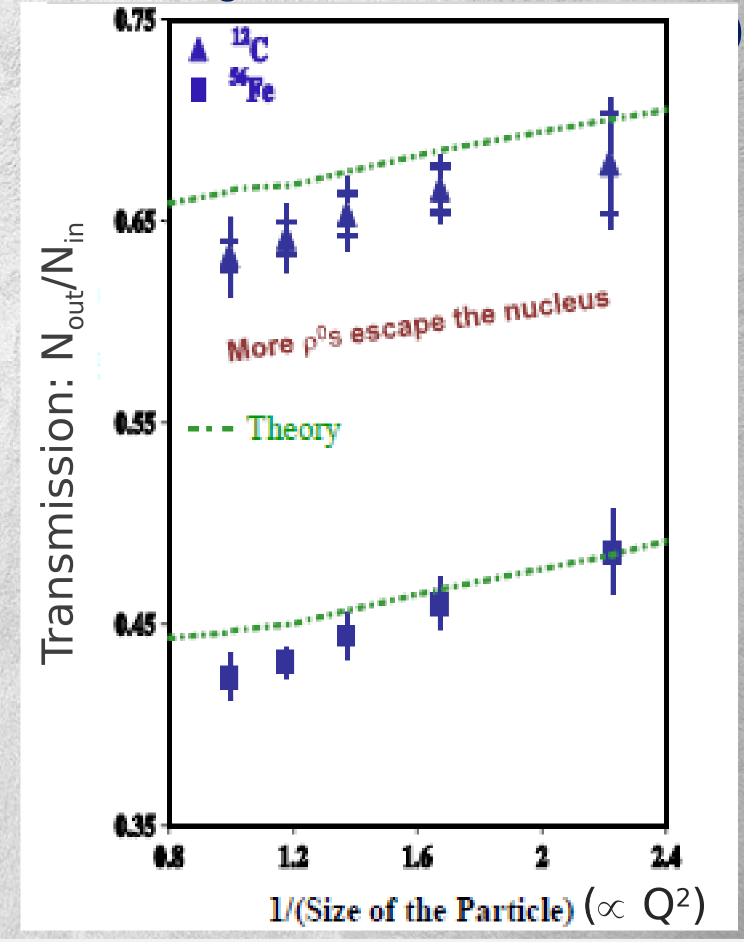

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L. El Fassi et al., Phys. Lett. B712 (2012) 326-330

L. Frankfurt, G. A. Miller and M. Strikman, Private Communication based on Phys. Rev. C 78, 015208 (08)

K. Hafidi, L. El Fassi et al., http://www.jlab.org/exp_prog/proposals/06/PR12-06-106.pdf