Chasing QCD Signatures in Nuclei with Lambda Fragmentation Study

“Exploring QCD with Tagged Processes” Workshop

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clas CEBAF Large Acceptance Spectrometer

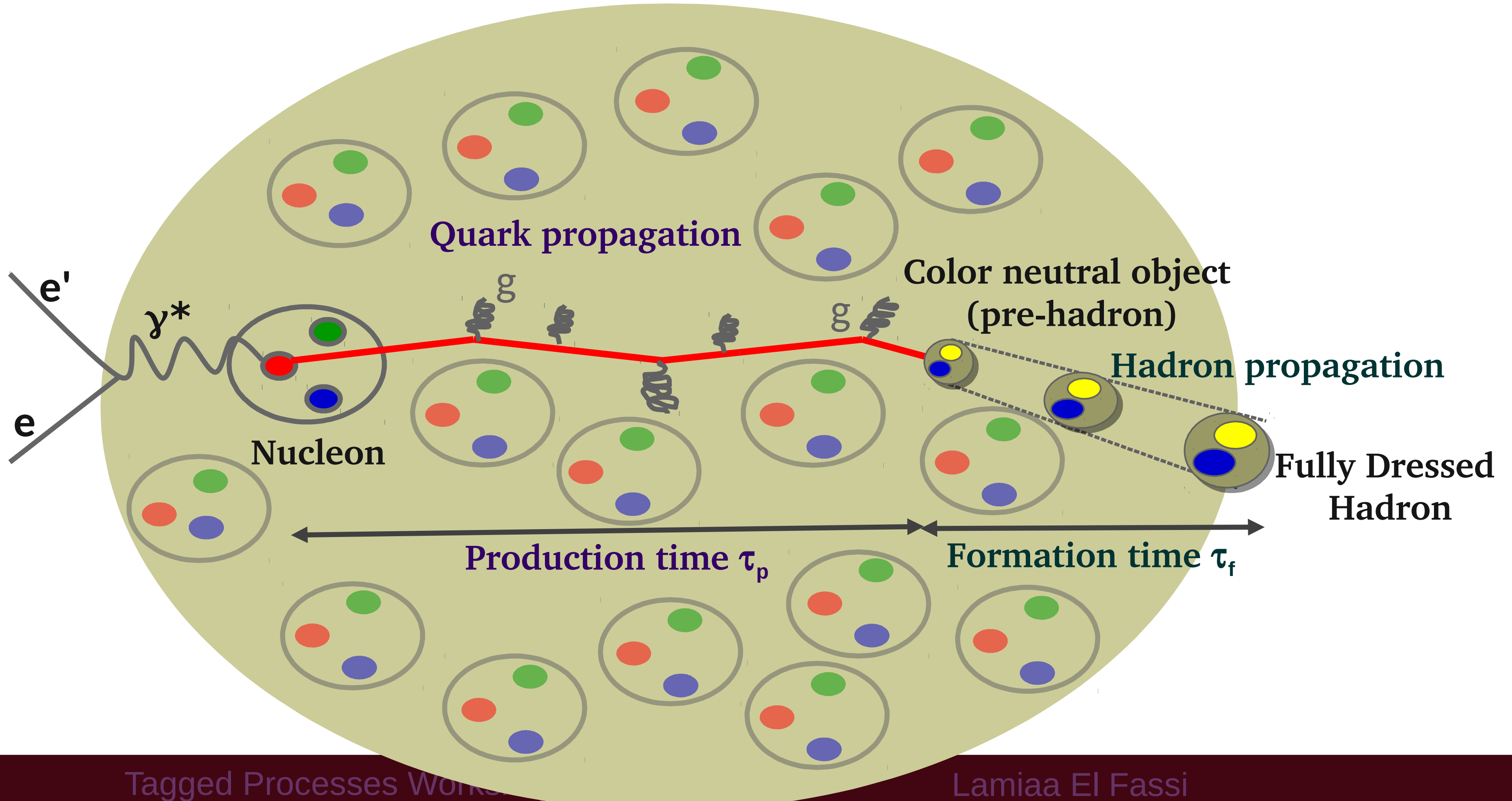
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Physics Motivation
- Highlights of Previous Measurements
  - CLAS6 Lambda Fragmentation Study
- Summary and Outlook

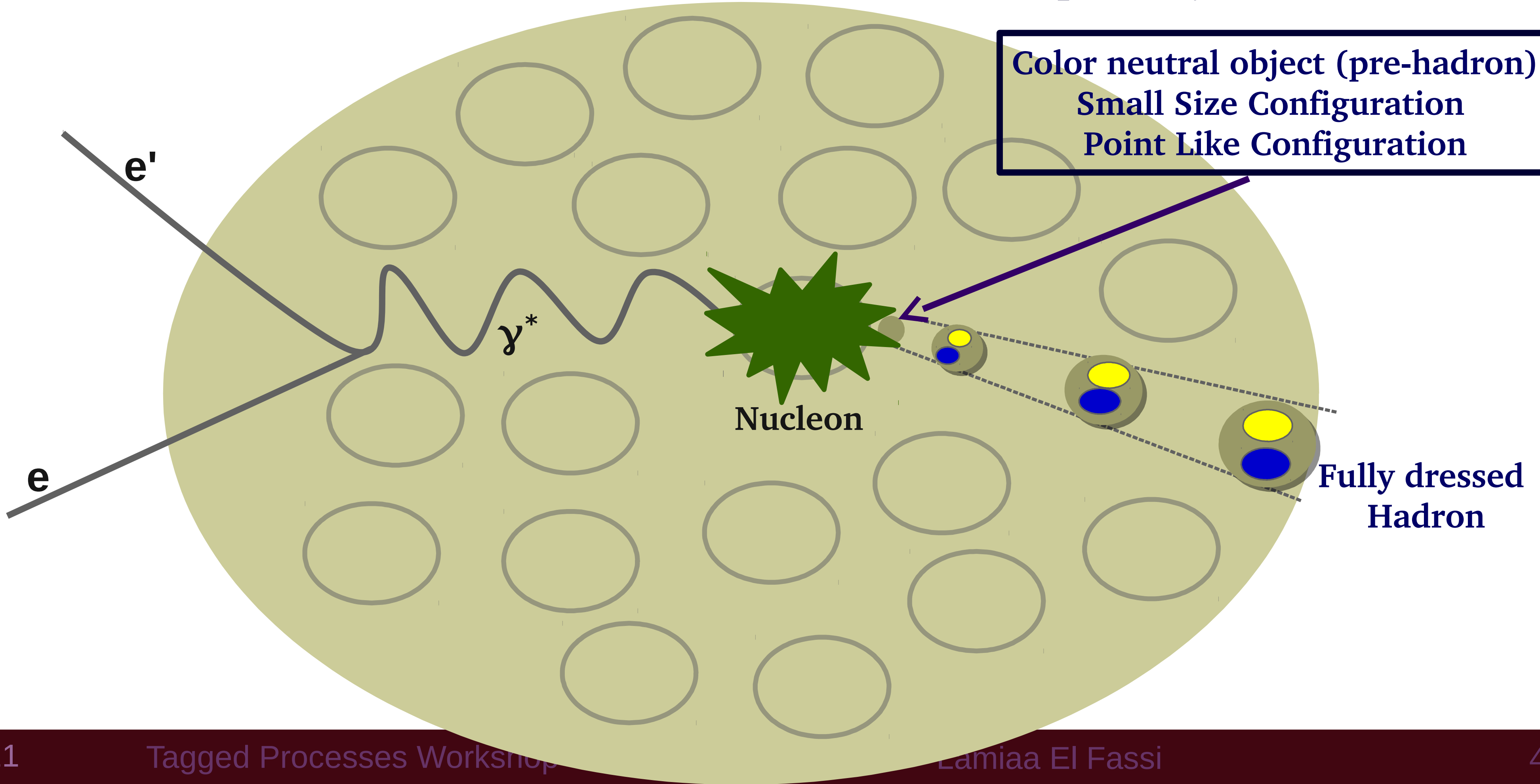
How does the colored bare, quark, evolves to a fully dressed hadron?

- Study hard processes in nuclei to probe the QCD confinement dynamics:
  - Color propagation and fragmentation - **Hadronization process**



How does the colored bare, quark, evolves to a fully dressed hadron?

- Study hard processes in nuclei to probe the QCD confinement dynamics:
  - Color propagation and fragmentation - **Hadronization process**
  - Creation and evolution of small size hadrons - **Color Transparency (CT)**



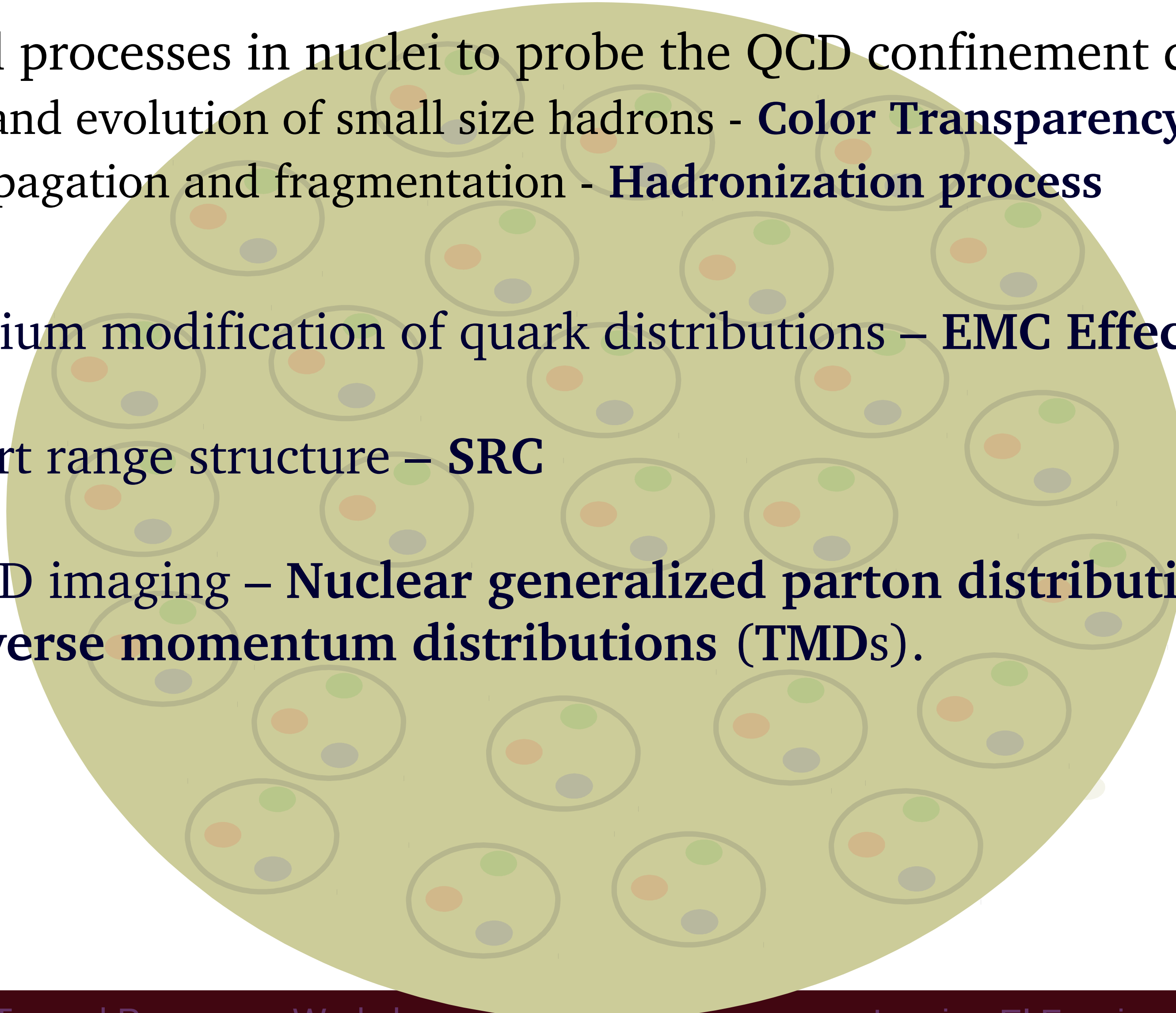
Hard Probe .vs. Medium

- Study hard processes in nuclei to probe the QCD confinement dynamics:
  - Creation and evolution of small size hadrons - **Color Transparency (CT)**
  - Color propagation and fragmentation - **Hadronization process**

- Study medium modification of quark distributions – **EMC Effect**

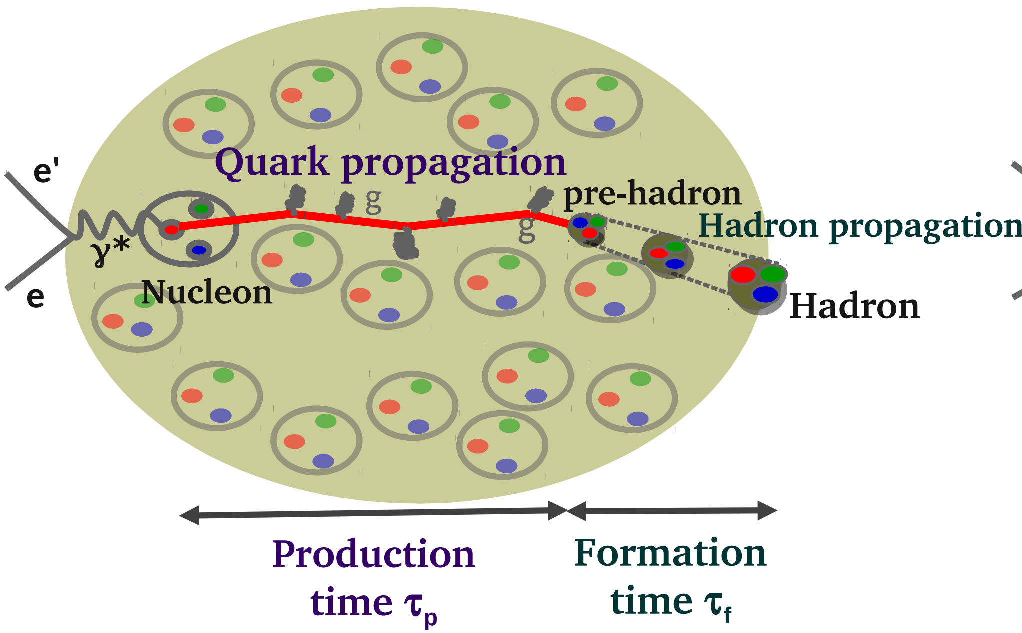
- Access short range structure – **SRC**

- Perform 3-D imaging – **Nuclear generalized parton distributions** (**GPD**s) and **transverse momentum distributions** (**TMD**s).

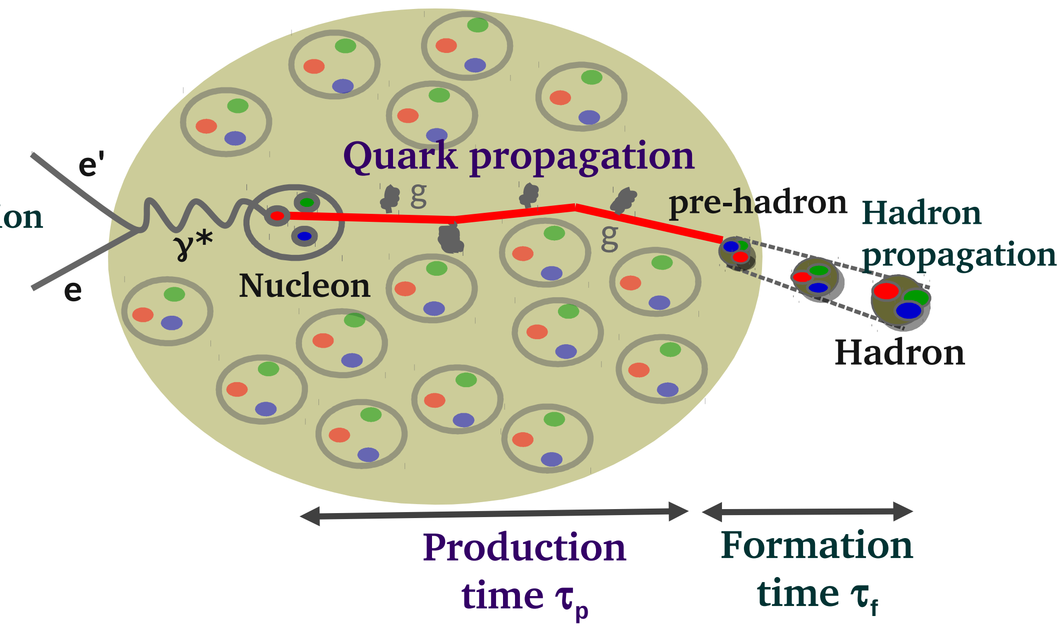


Hadronization Process: Probe of QCD Dynamics

- Explore semi-inclusive deep inelastic scattering (SIDIS) production to access the hadronization time-scales:
  - ✓ **Production time τ_p**: time spent by a deconfined quark to neutralize its color charge.
  - ✓ **Formation time τ_f**: time required to form a regular hadron (h).



Hadron formation inside the medium is manifested at low energies

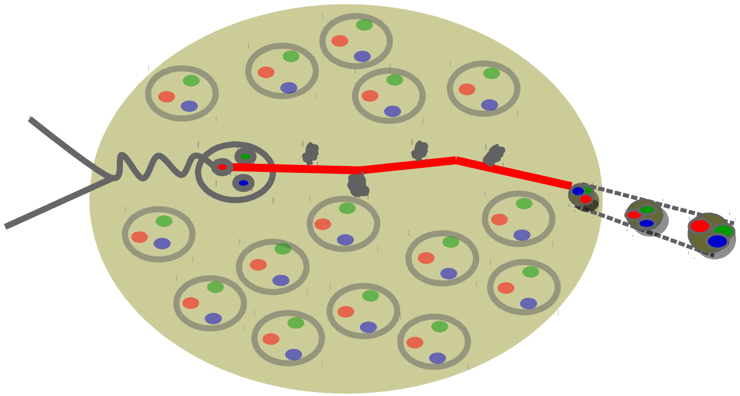


Hadron formation outside the medium dominates at high energies

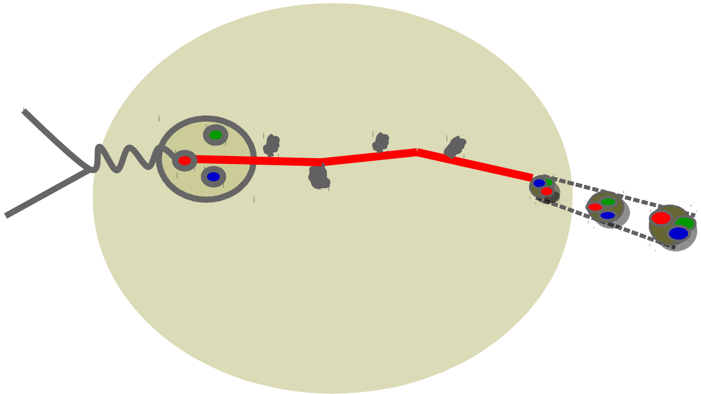
Hadronization Process: Probe of QCD Dynamics

- Explore semi-inclusive deep inelastic scattering (SIDIS) production to access the hadronization time-scales, and extract them via a comparison of QCD dynamics in

Medium



Vacuum



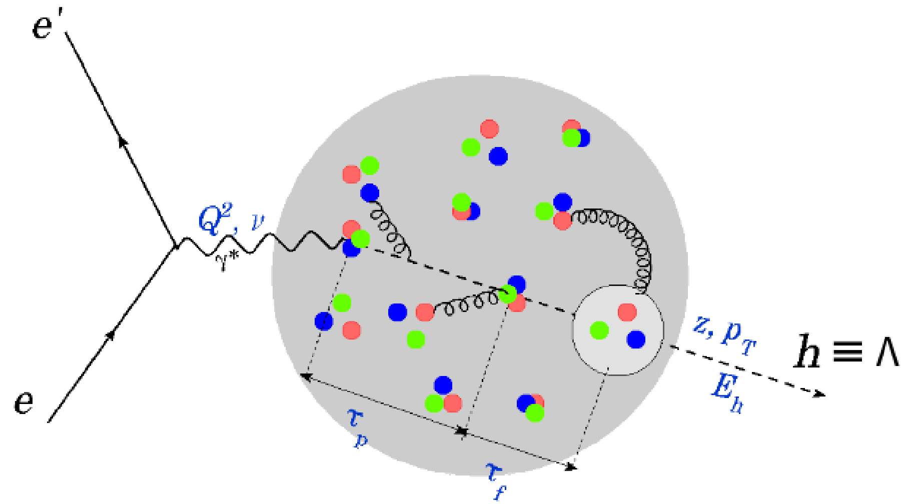
- ✓ **Production time τ_p**: time spent by a deconfined quark to neutralize its color charge.

  ⟹ Stimulated by medium-energy loss via a gluon emission, which lead to transverse momentum (p_T) broadening.

- ✓ **Formation time τ_f**: time required to form a regular hadron (h).

  ⟹ Signaled by interactions with known hadron cross sections responsible of hadron suppression in the measured multiplicity ratios.

SIDIS Kinematics: Lambda Production



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

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

$y = \nu/E_{beam}$: Electron energy fraction transferred to a struck quark,

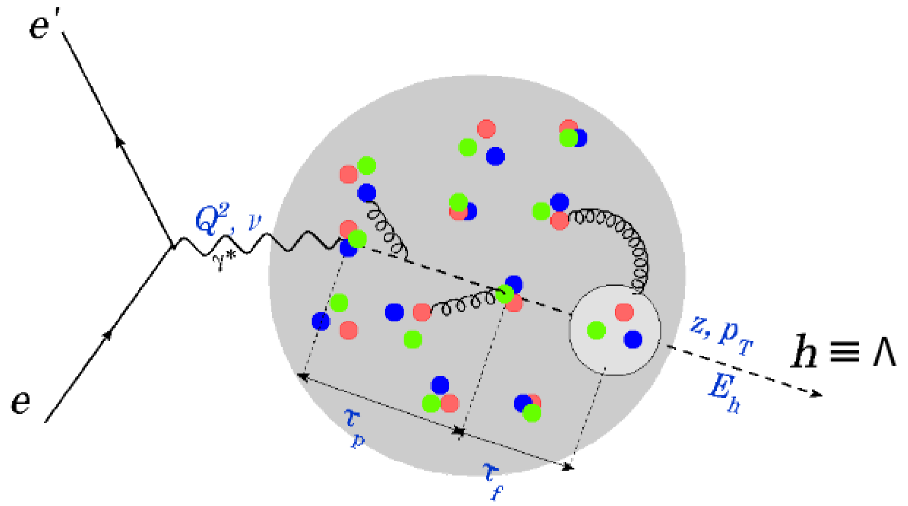
$W = \sqrt{M_n^2 + 2\nu M_n - Q^2}$: Total mass of the hadronic final state, where M_n is the nucleon mass

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

p_T: Hadron transverse momentum with regard to the virtual photon direction.

$x_F = \frac{P_L}{P_L^{max}}$, Feynman variable: Fraction of the center-of-mass (CM) longitudinal momentum carried by the observed hadron

SIDIS Kinematical Cuts: Lambda Production



Q^2: Four-momentum transferred,

> 1 GeV^2, to probe the intrinsic structure of nucleons

$y = \nu/E_{beam}$: Electron energy fraction transferred to a struck quark,

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

$W = \sqrt{M_n^2 + 2\nu M_n - Q^2}$: Total mass of the hadronic final state, where M_n is the nucleon mass

> 2 GeV, to avoid a contamination from the resonance region

x_F: Fraction of the CM longitudinal momentum carried by the observed hadron

> 0, selects the forward (current) fragmentation region

< 0, selects the backward (target-remnant) fragmentation region

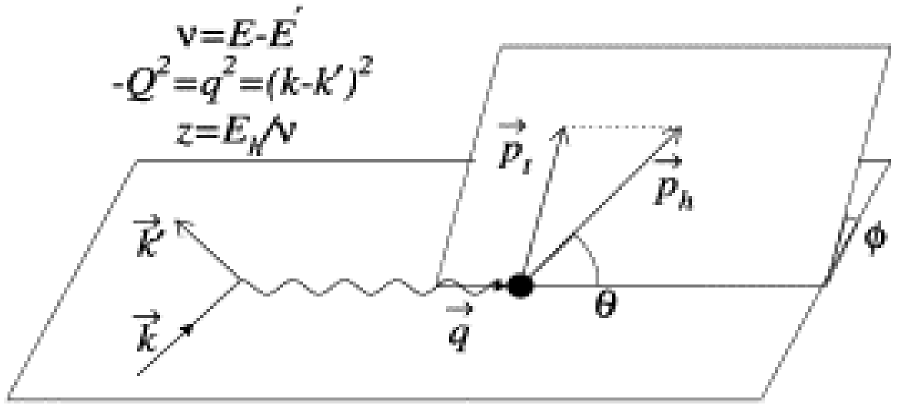
Experimental Observables

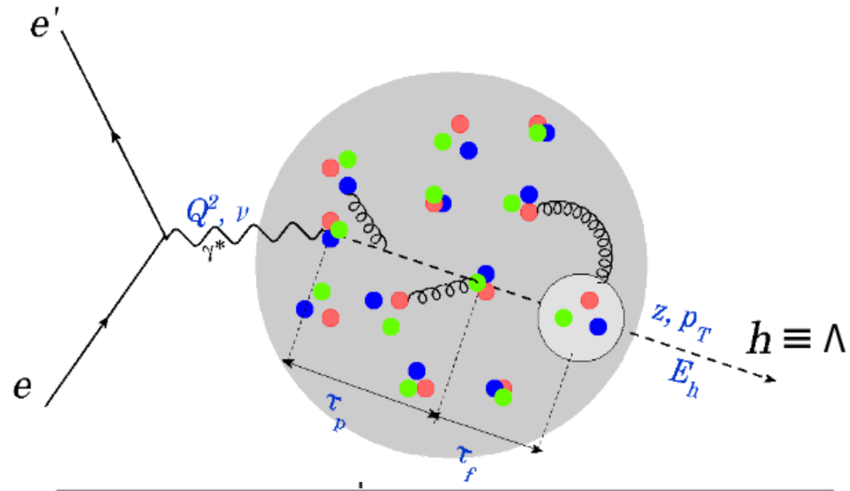
Transverse Momentum Broadening

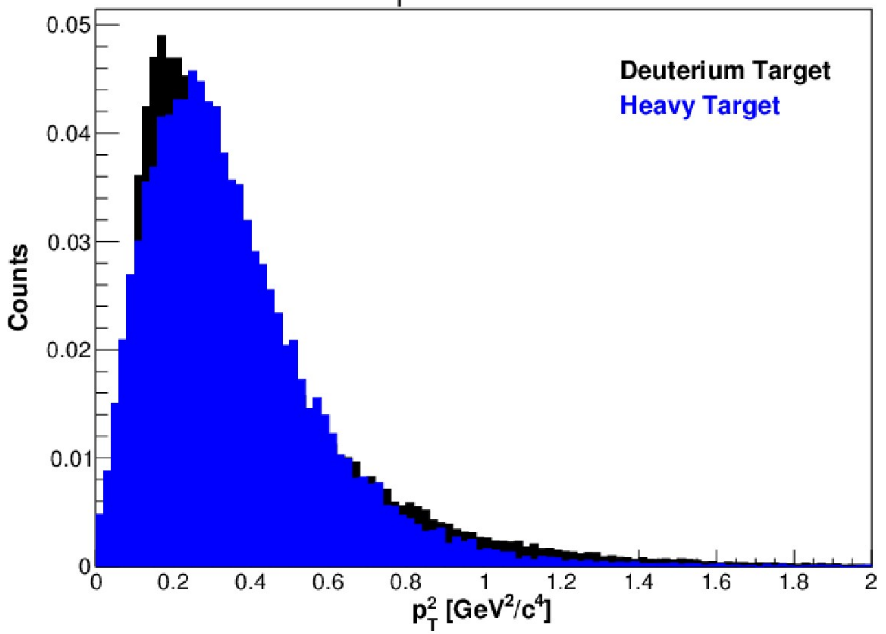
$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

⬍

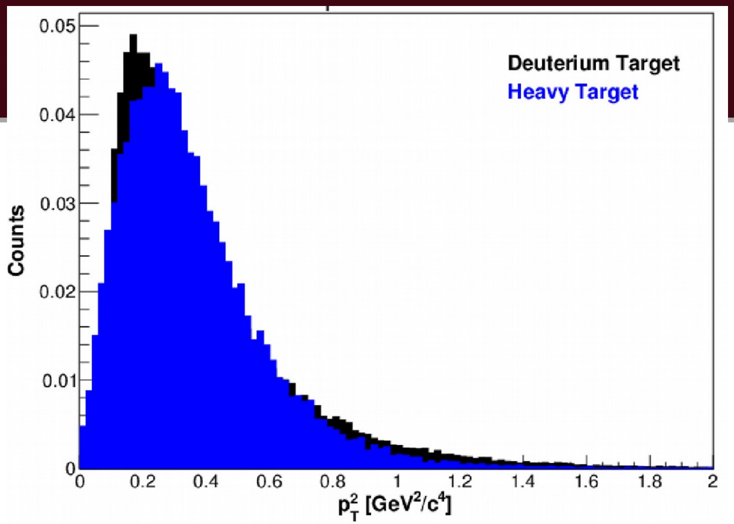
Allow access to τ_p via production of different hadrons and quark flavors







Experimental Observables



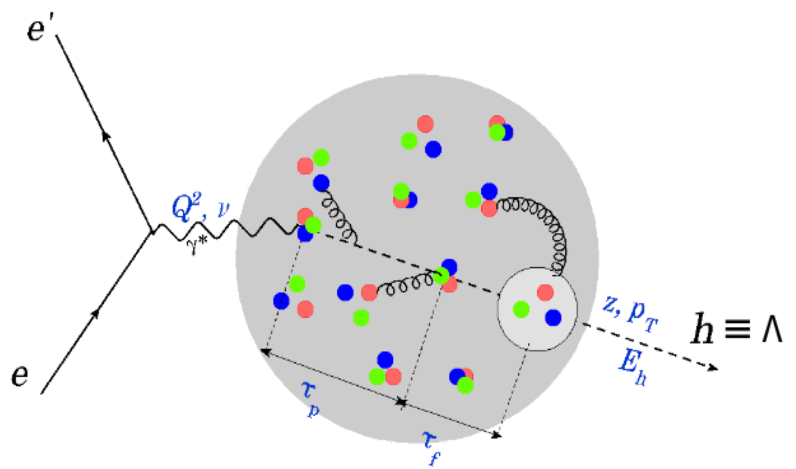
Transverse Momentum Broadening

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

Allow access to τ_p via production of different hadrons and quark flavors

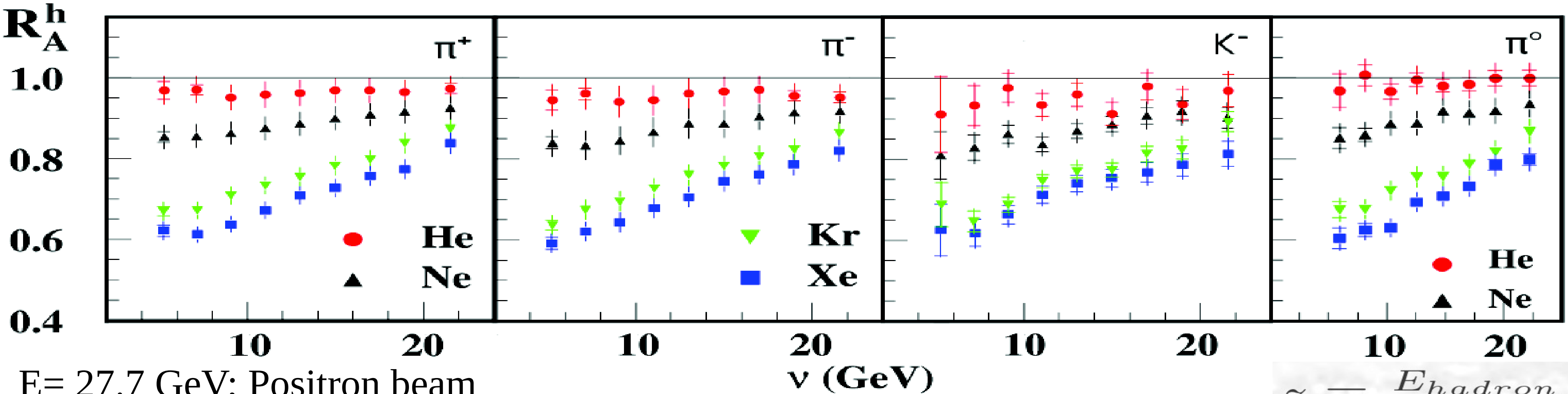
Hadron Multiplicity Ratio

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



Access τ_f after the extraction of τ_p and R^h_M

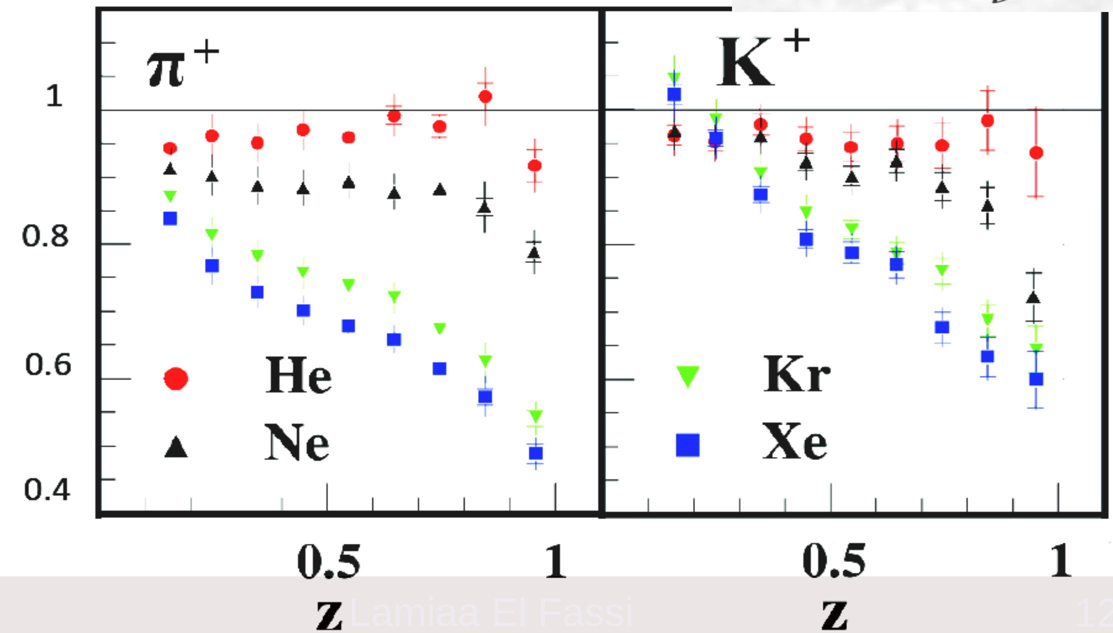
Former Measurement: Hermes Multiplicity Ratios



E= 27.7 GeV; Positron beam

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

- Pions flavors and K⁻ experienced similar attenuation.
- K⁺ is less attenuated compared to π⁺ most likely due to the contamination of $\pi + p \Longrightarrow \Lambda + K$ (B. Kopeliovich *et al.*) from the target fragmentation.



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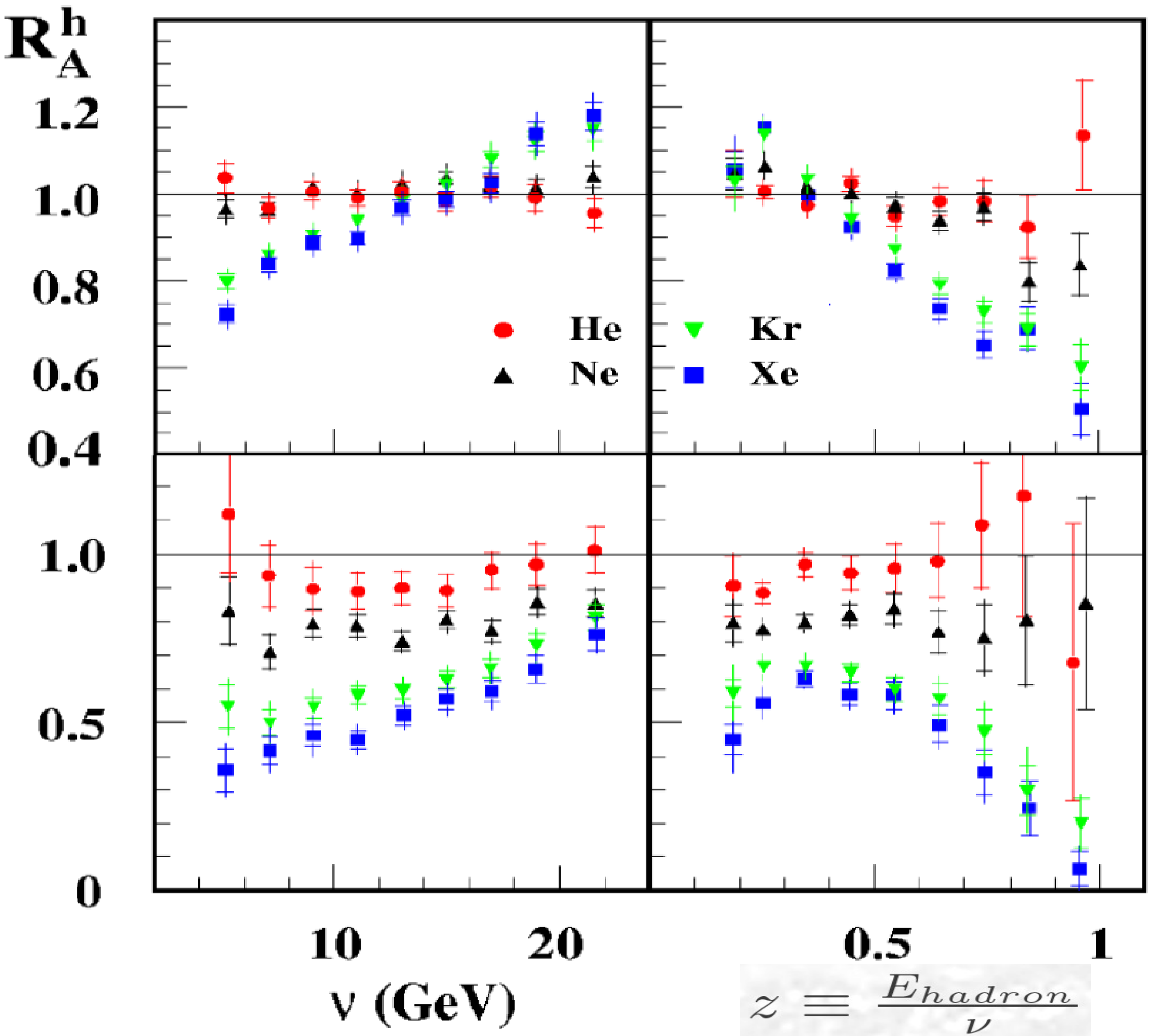

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A. Airapetian et al.
Phys.Lett., vol. B684, pages 114–118, 2010

proton

anti-proton

E= 27.7 GeV; Positron beam

Former Measurement: Hermes p_T Broadening

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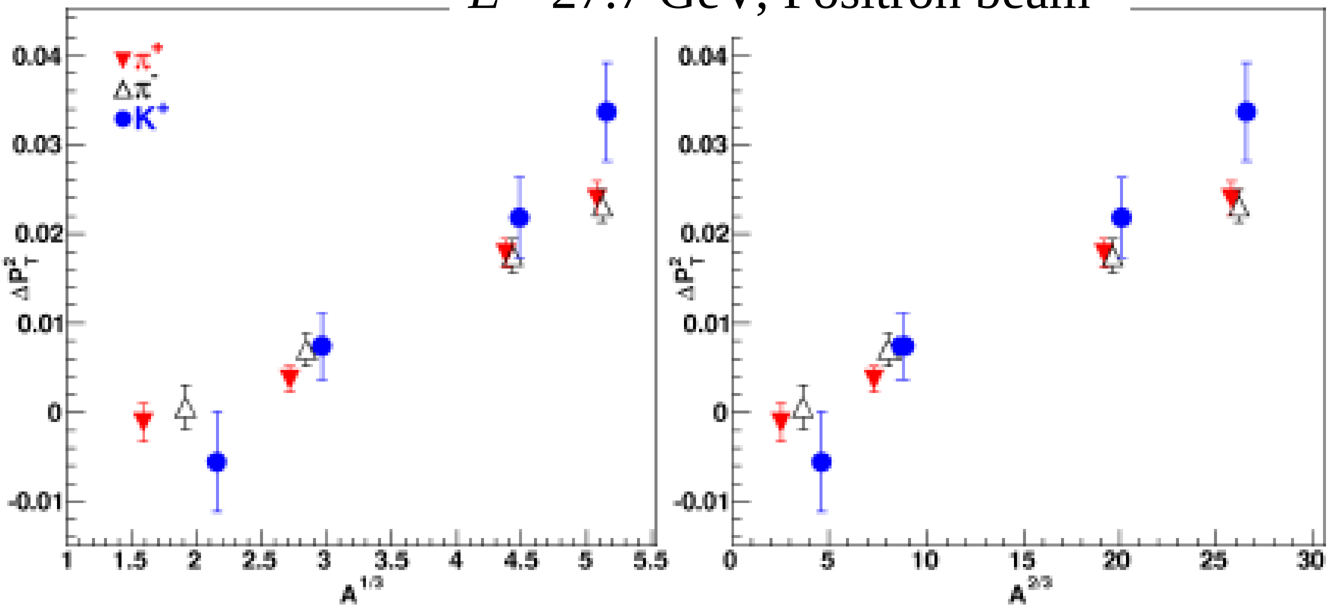
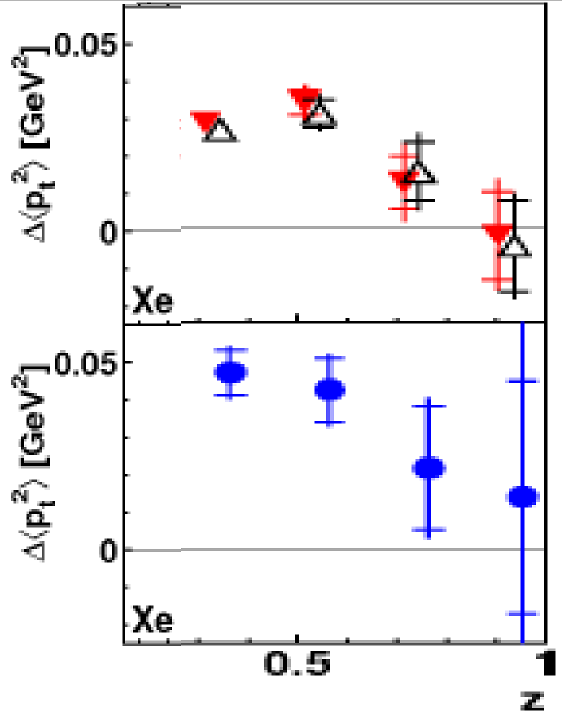




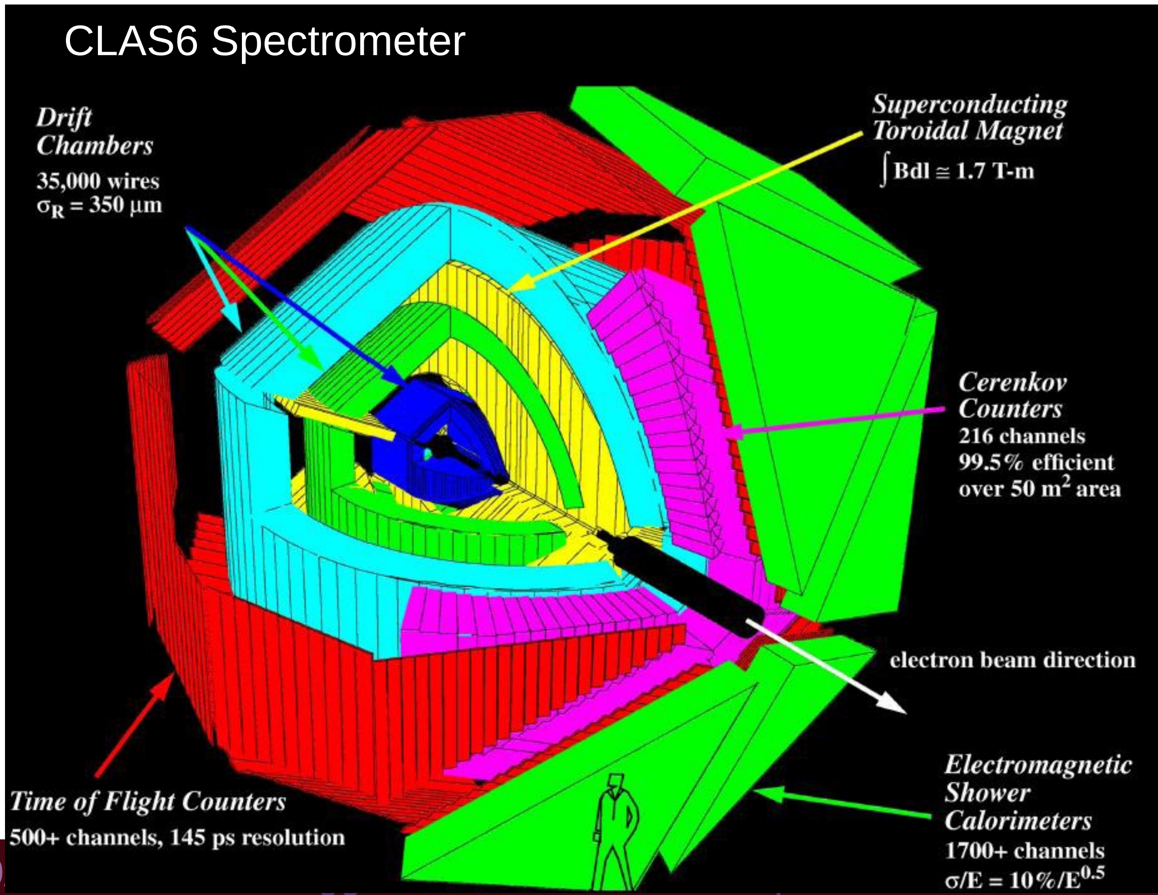
- Reduced broadening at high z favors no prehadron interaction,
- Different K^+ p_T broadening behavior compared to pions ⟹ Flavor dependence?
- Perturbative QCD description of p_T broadening:

$$\Delta p_T^2 \propto \frac{dE}{dx}, \text{ where}$$
$$\Delta p_T^2 \propto L \propto A^{1/3} \;\&\; dE \propto L^2 \propto A^{2/3}$$

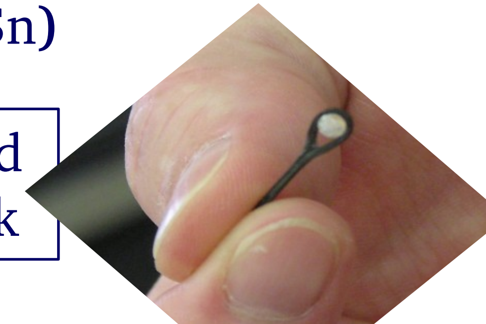
- Similar dependence of Δp_T^2 on $A^{1/3}$ & $A^{2/3}$ ⟹ Motivation for more studies!

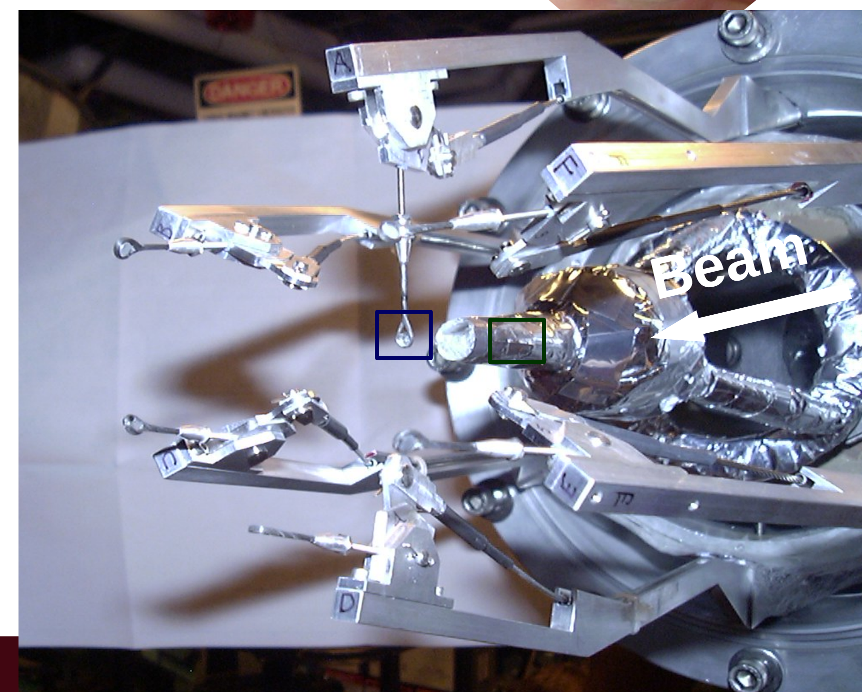
CLAS6 EG2 Run-group Experiments

- Took data with the decommissioned CLAS6 spectrometer in its standard configuration and a dual targets assembly:
  - ➔ **Liquid deuteron (LD2)** + **solid target (C or Fe or Pb** or Al or Sn)



Solid disk

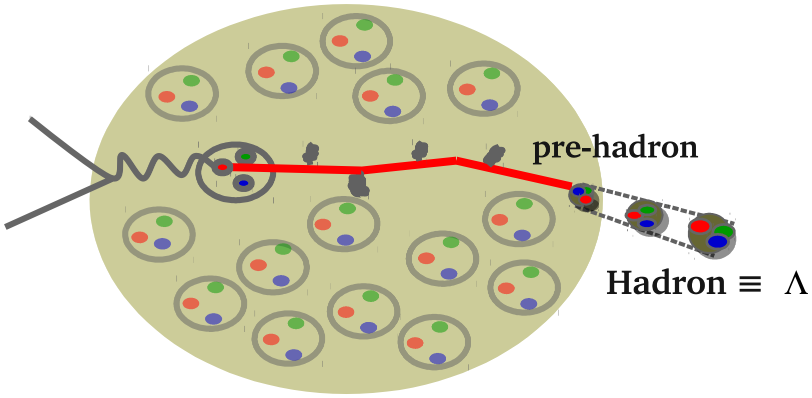


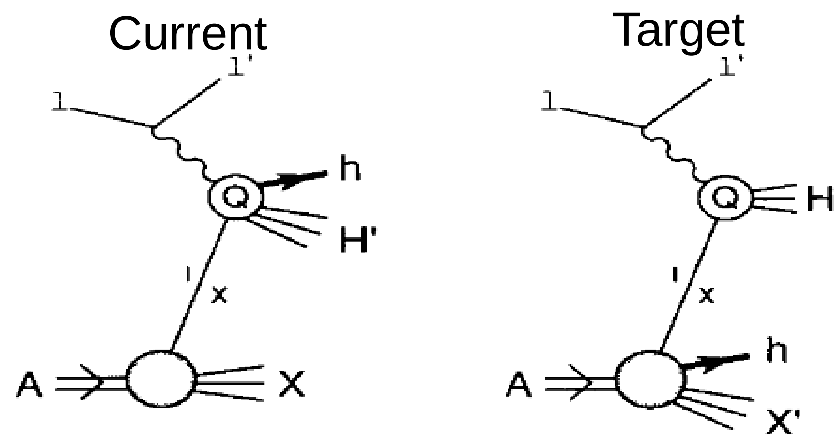


CLAS6 Hadronization Study: Lambda Channel

- First ever study of the hadronization process of Λ hyperon which probes the forward (current*) and backward (target**) fragmentation regions.
  - Separating the two regions is crucial given Λs carry a significant fraction of the incoming proton momentum ($\equiv x_F < 0$) and small transverse momenta.

F. Ceccopieri and D. Mancusi, Eur. Phys. J. C **73**, 2435 (2013)
F. Ceccopieri, Eur. Phys. J. C 76, 69 (2016)





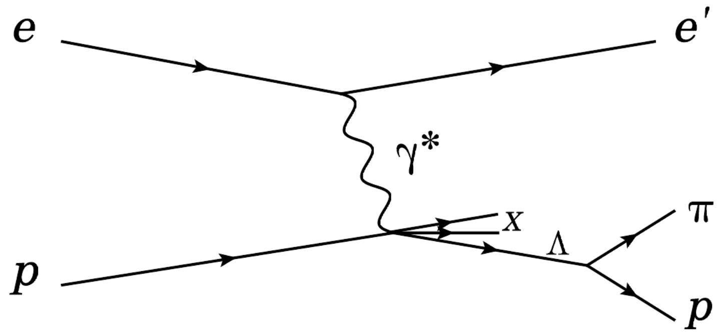
L. Trentadue & G. Veneziano, Phys. Lett. B **323**, 201-211 (1994)

* Current fragmentation: struck quark initiates the hadronization process

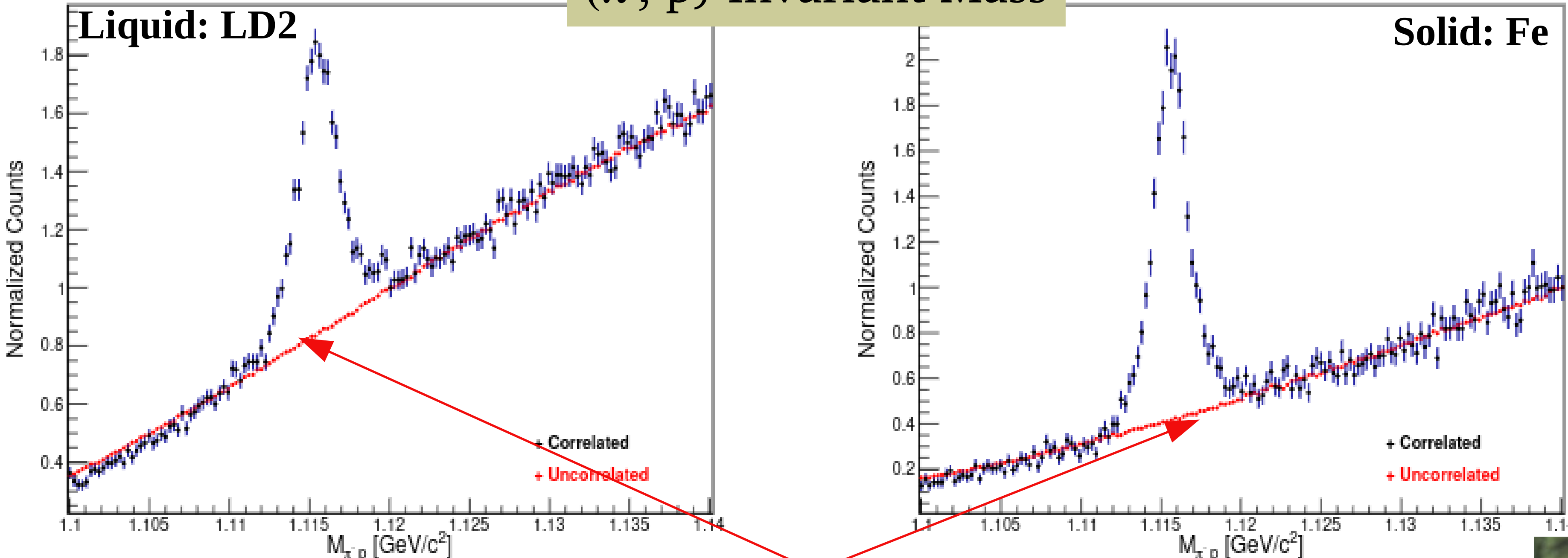
** Target fragmentation: target remnant moves reciprocally with regard to the virtual photon direction undergoing a target fragmentation.

CLAS6 Hadronization Study: Lambda Channel

- Identify Λ via its decay particles, π^- and p.
- Use the event mixing technique to subtract the combinatorial background.



(π-, p) Invariant Mass



Combinatorial Background

Postdoc
Taya Chetry

CLAS6 Hadronization Study: Lambda Channel

- Identify Λ via its decay particles, π^- and p.
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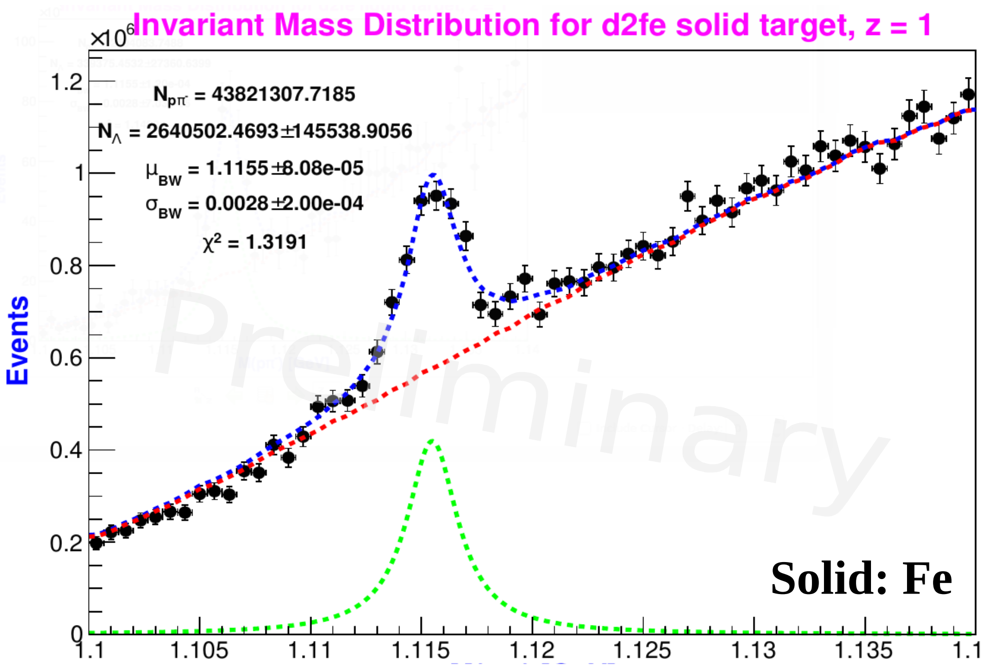
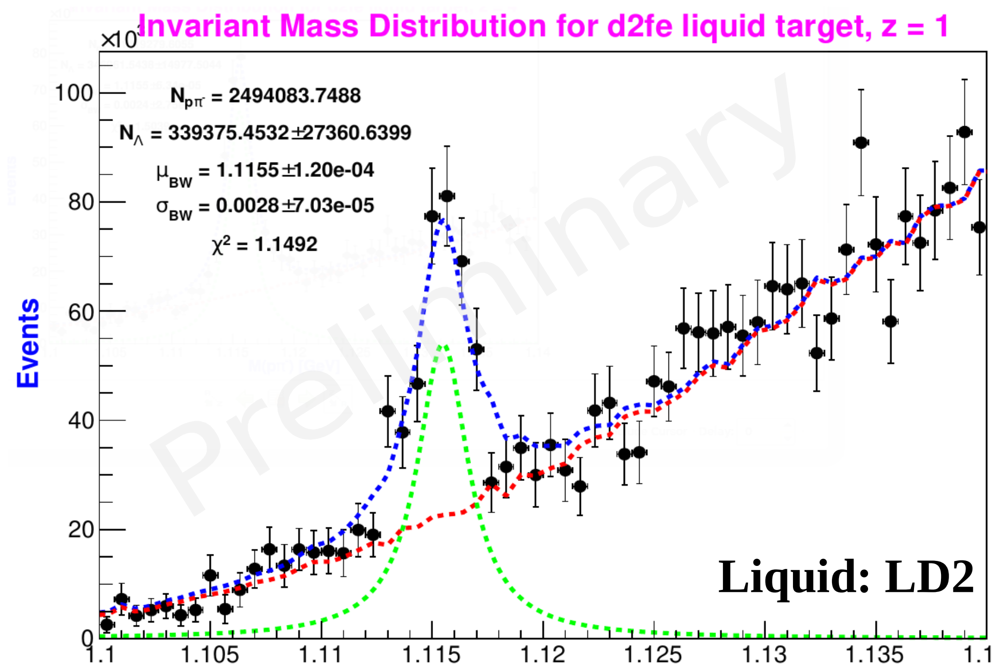
- A sample of (π^-, p) invariant mass for one z (= E_Λ / ν) bin after the combinatorial background subtraction to extract the Λ yield (*dashed distribution*).





Bin #	1	2	3	4	5	6
z_{min}	0.28	0.38	0.44	0.51	0.60	0.75
z_{max}	0.38	0.44	0.51	0.60	0.75	1.00

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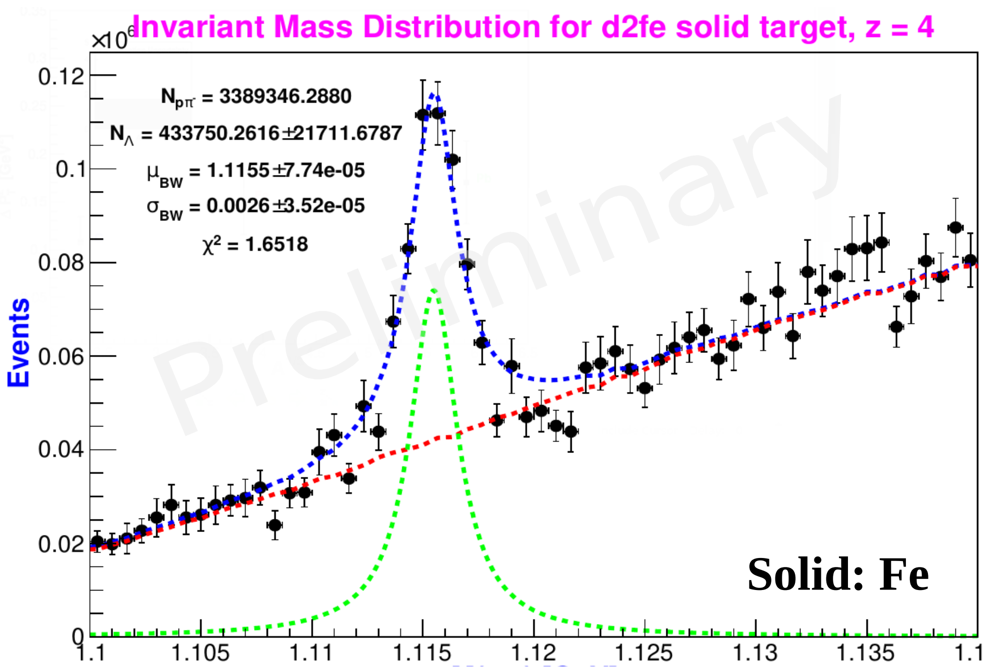

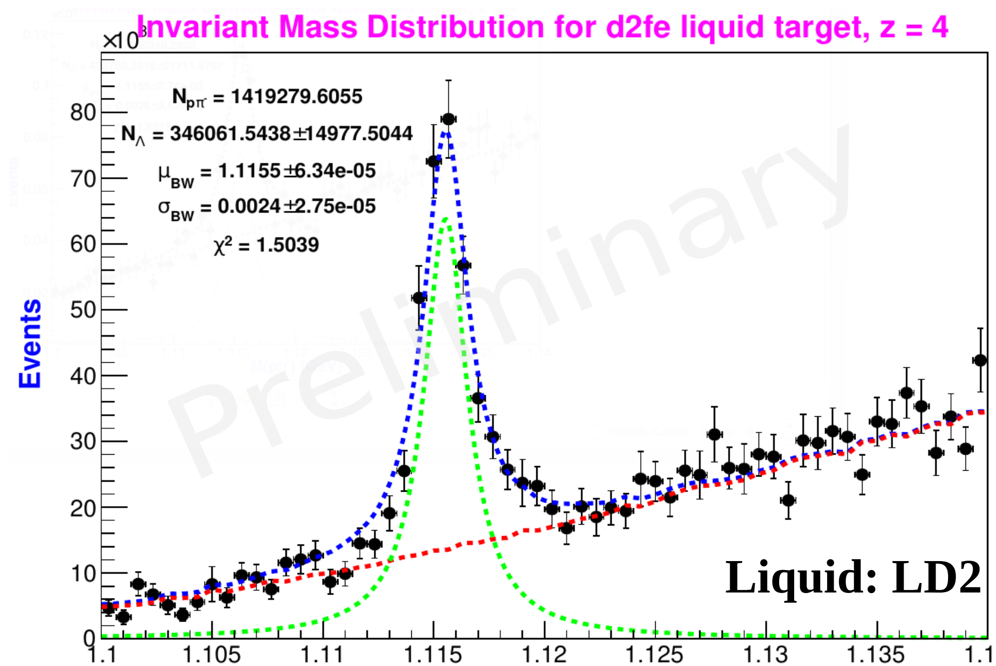

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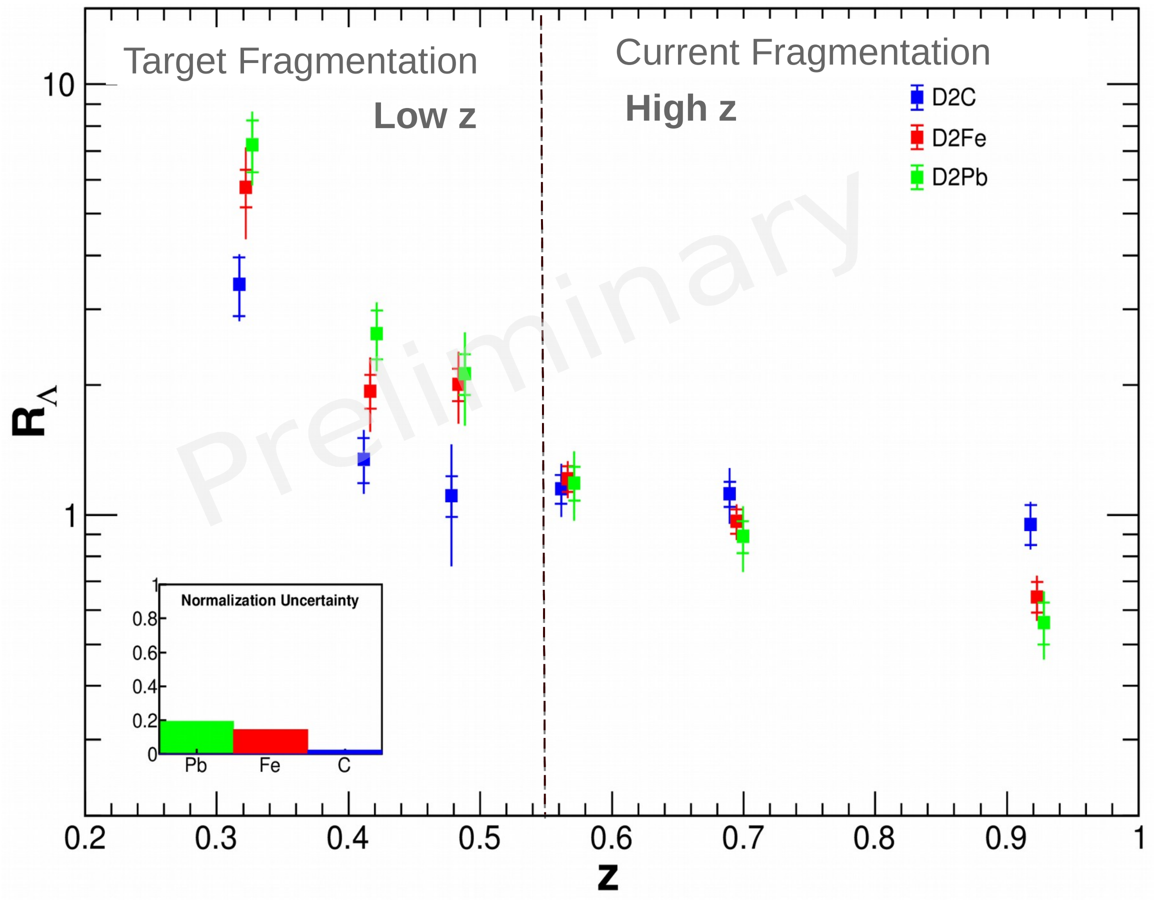
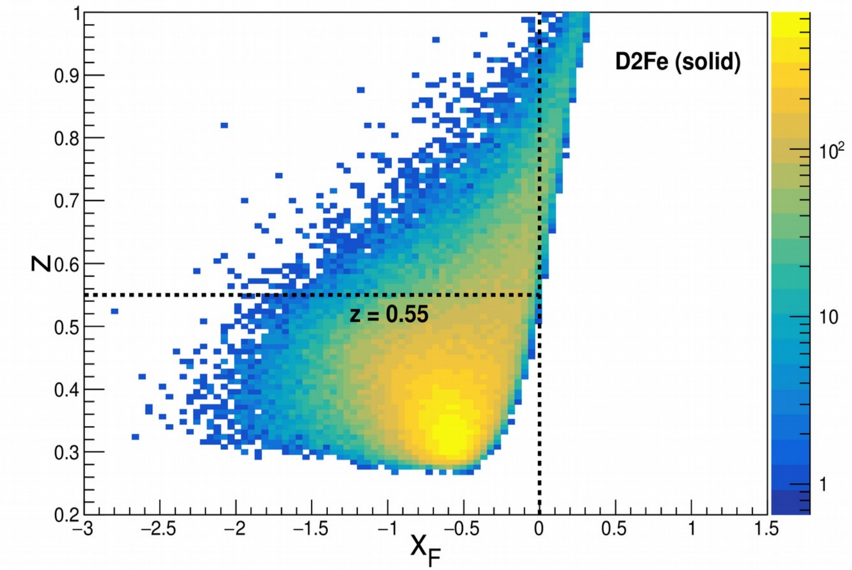
Preliminary CLAS6 Λ Multiplicity Ratio Results



$$R_M^h(z) = \frac{\left\{\frac{N_h^{DIS}(z)}{N_e^{DIS}}\right\}_A}{\left\{\frac{N_h^{DIS}(z)}{N_e^{DIS}}\right\}_D}$$



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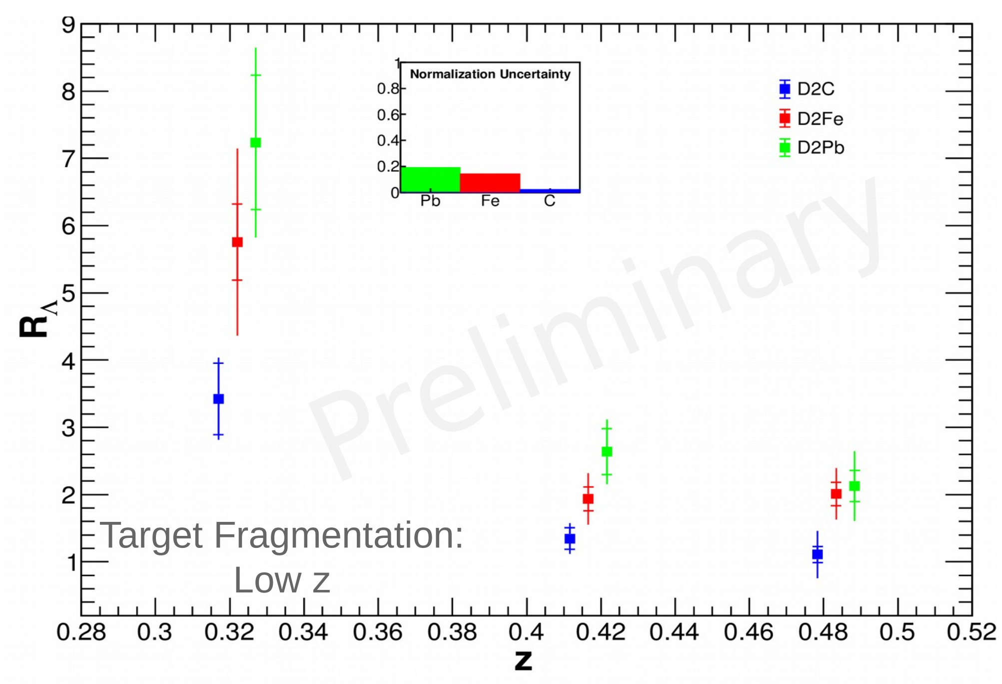
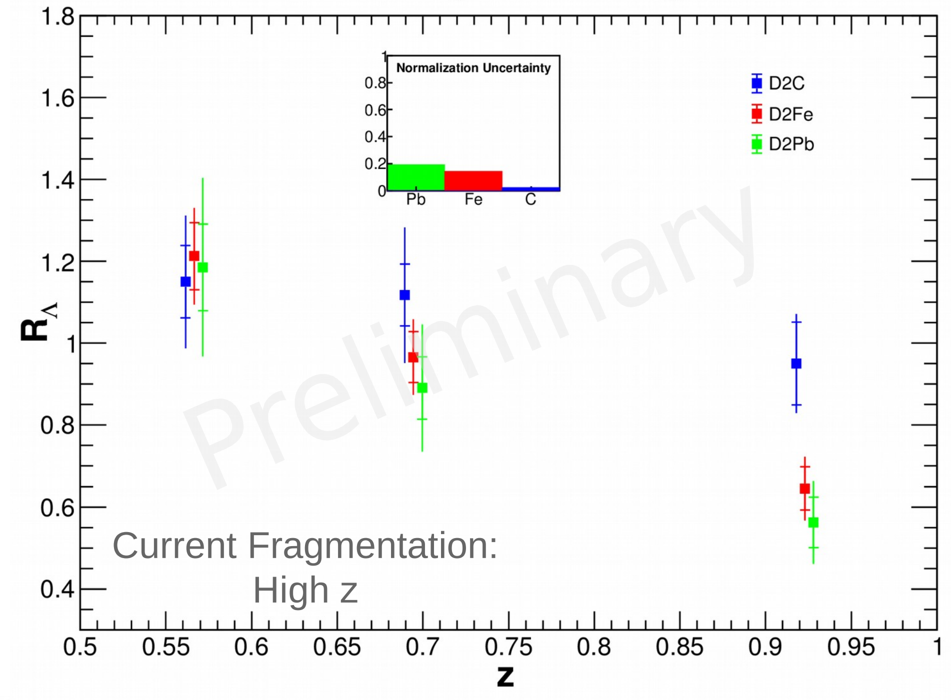
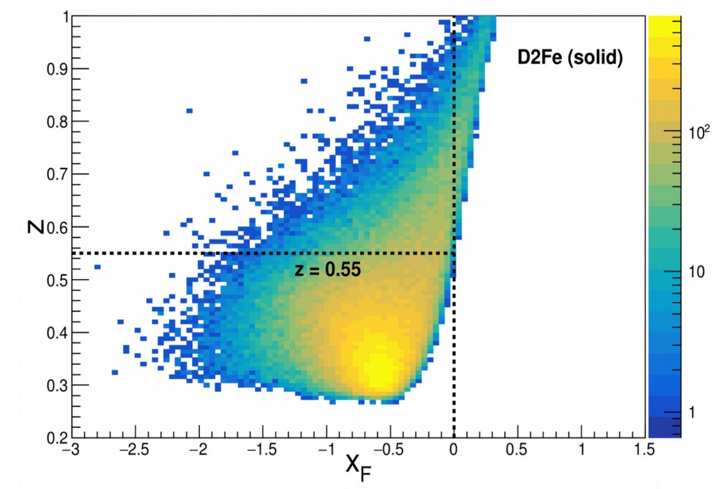


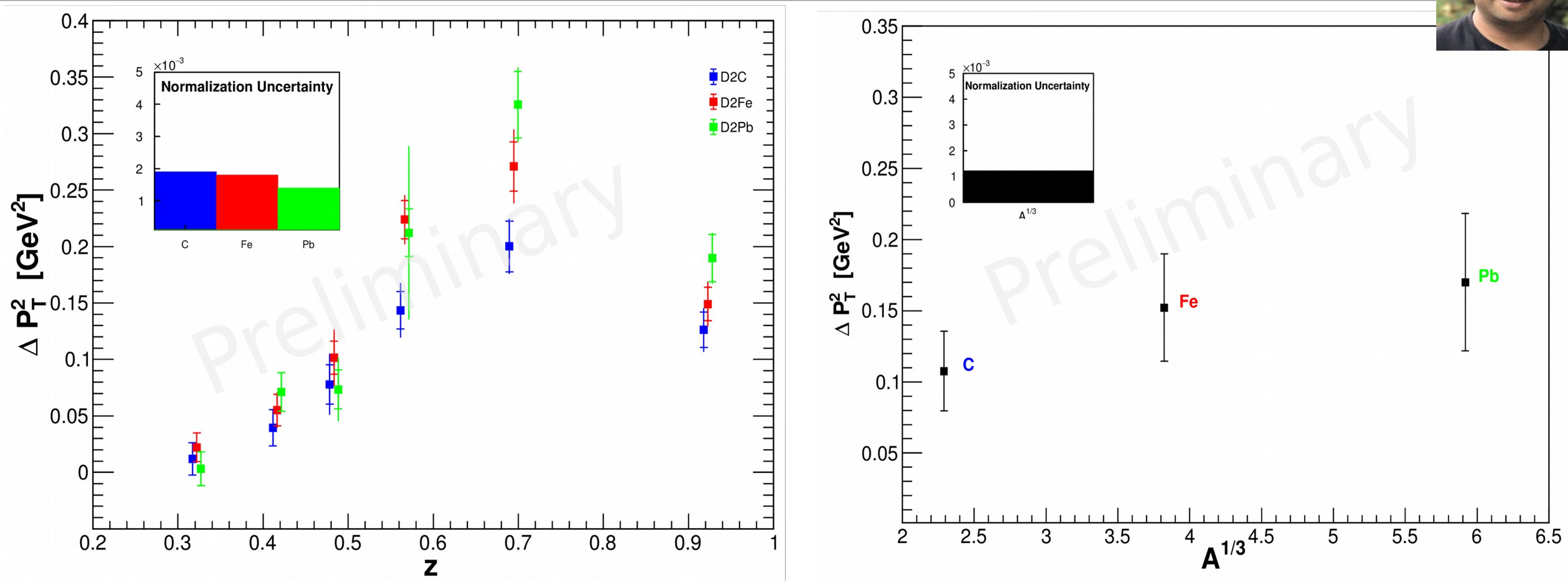


$$R_M^h(z) = \frac{\left\{ \dfrac{N_h^{DIS}(z)}{N_e^{DIS}} \right\}_A}{\left\{ \dfrac{N_h^{DIS}(z)}{N_e^{DIS}} \right\}_D}$$



CEBAF Large Acceptance Spectrometer

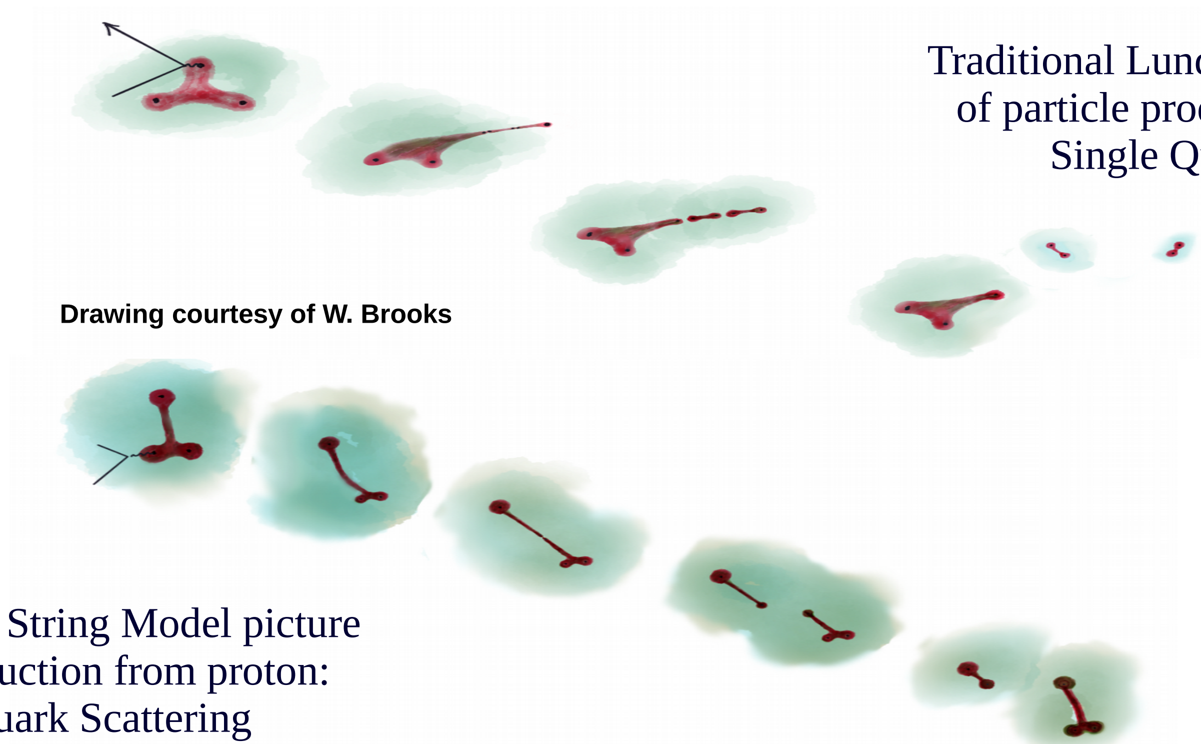
CLAS6 Λ p_T Broadening Results: Preliminary



- Increased broadening with z and A
- Larger p_T broadening compared to HERMES mesons' results
  - ✔ *Could be due to the size and mass of propagating color object?*

Preliminary CLAS6 Λ p_T Broadening Results

- Increased broadening with z and A
- Larger p_T broadening compared to HERMES mesons' results
  - Could be due to the size and mass of propagating color object?
  - Would it possible that the *virtual photon is absorbed by a diquark instead of a single quark*?



Traditional Lund String Model picture of particle production from proton: Single Quark Scattering

Alternative Lund String Model picture of particle production from proton: Direct Diquark Scattering

M. Barabanov *et al.*, Prog. Part. Nucl. Phys. 116 (2021)

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

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Actively underway with existing 5 GeV data

meson	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$

baryon	cτ	mass	flavor content
p	stable	0.94	ud

- Span a wider range of nuclei masses ⟹ Better understanding of the A dependence,
- Study the production of various hadrons ⟹ Improve our understanding of hadrons' formation mechanism,
- Cover much larger kinematical coverage,
- 10 times higher luminosity compared to CLAS6 (1000 higher than Hermes),
  ⟹ Determines the two hadronization time-scales and constrain the competing theoretical models with the correct production picture!

Summary and Outlook

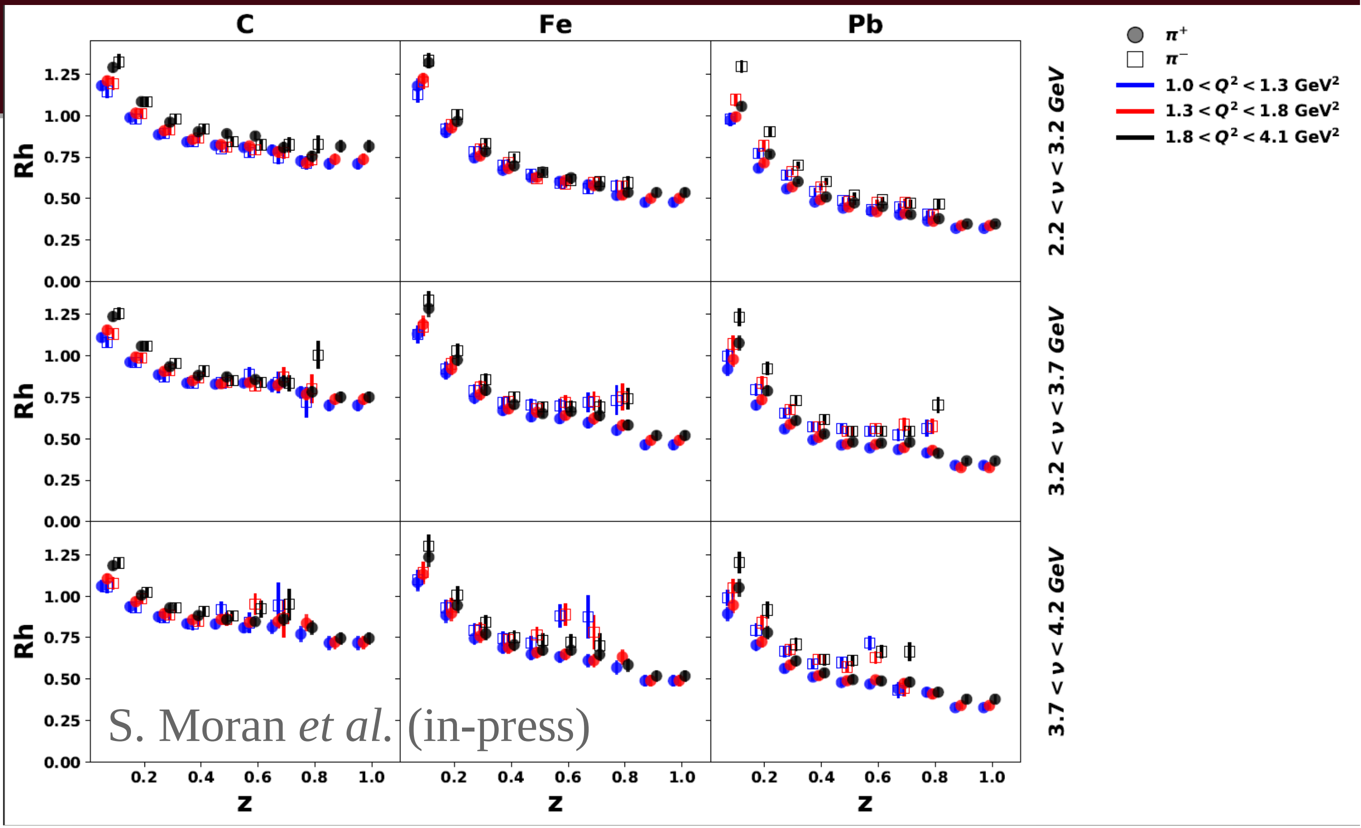
- The hadronization study is a direct probe of the QCD confinement in cold and hot nuclear matter.
- A detailed comprehension of its mechanism helps constraining the existing theoretical models.
- Preliminary Lambda fragmentation results have a similar trend as HERMES proton results while its transverse momentum broadening is larger than those of mesons.
- CLAS12 measurements will provide the multi-dimensional data needed to extract the production and formation time-scales.
- The future EIC will allow the study of hadronization dynamics of heavy quarks in cold nuclear matter and provide a wider kinematics coverage to study the in-medium evolution as well as parton energy loss.

This work is supported in part by the US DOE contract# DE-FG02-07ER41528

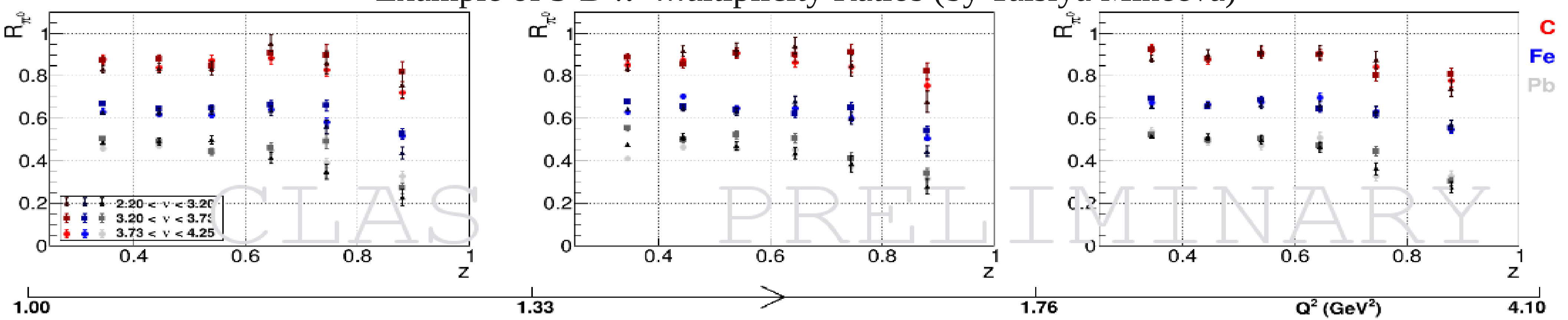
Backup

CLAS6 Hadronization Results: Meson Channels

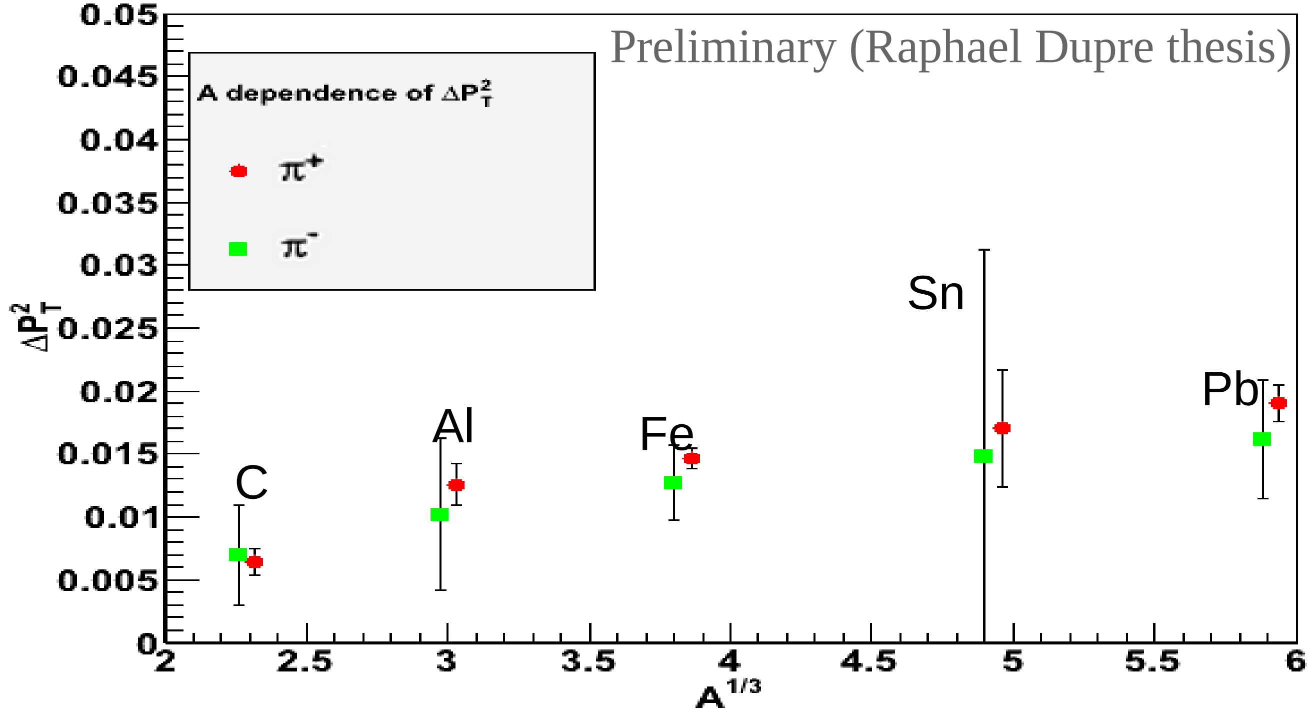
- Similar behavior of 3-fold π^0, $\pi^\pm$ and K^0 (Phys. Lett. B **706**, 26-31 (2011)) multiplicity ratio results.
- Consistent with Hermes results!



Example of 3-D π^0 Multiplicity Ratios (by Taisiya Mineeva)

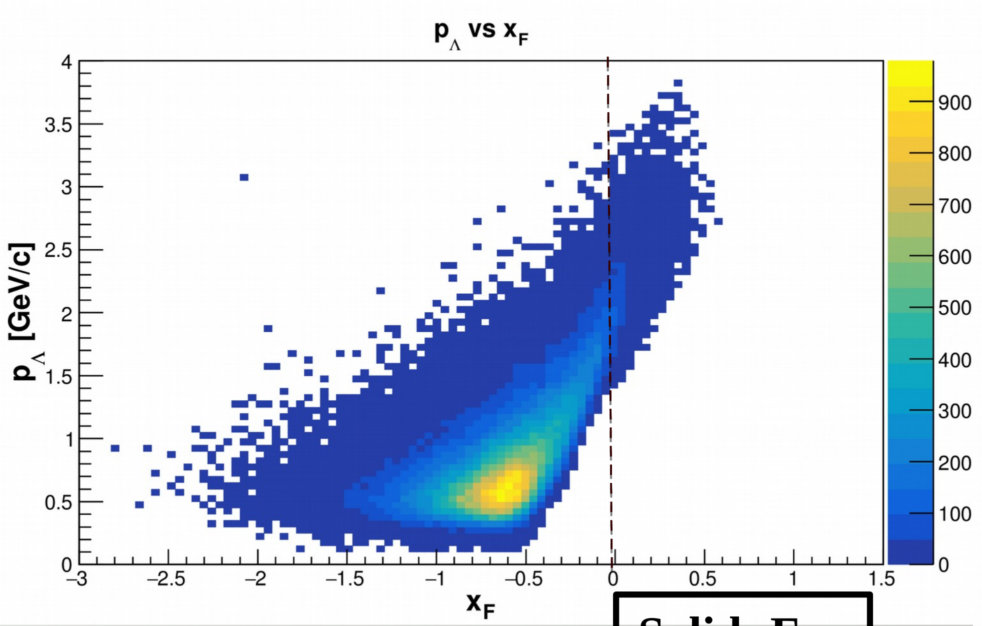


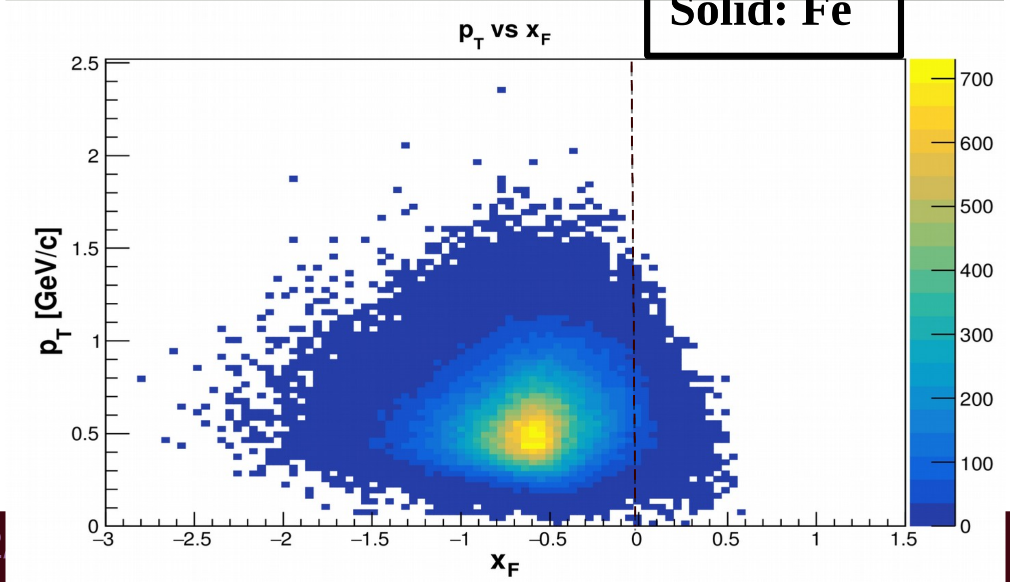
Preliminary CLAS6 Hadronization Results: Pions Channels



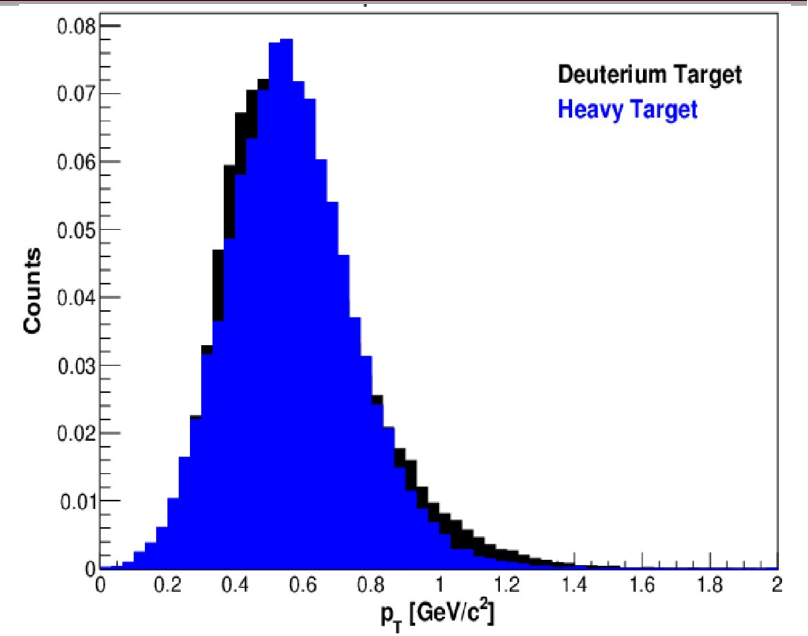
- Preliminary CLAS6 charged pions results exhibit a similar behavior but smaller broadening (*slight shift was added for a clarity*).

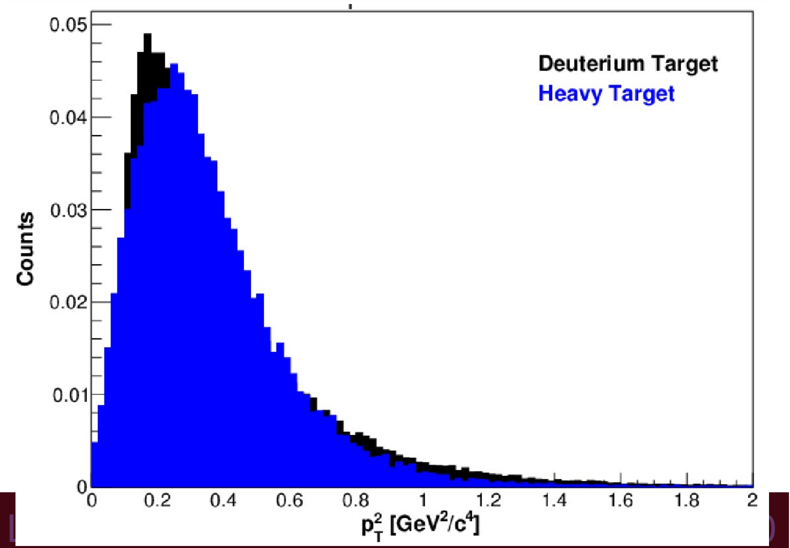
Lambda Channel: Kinematical Distributions



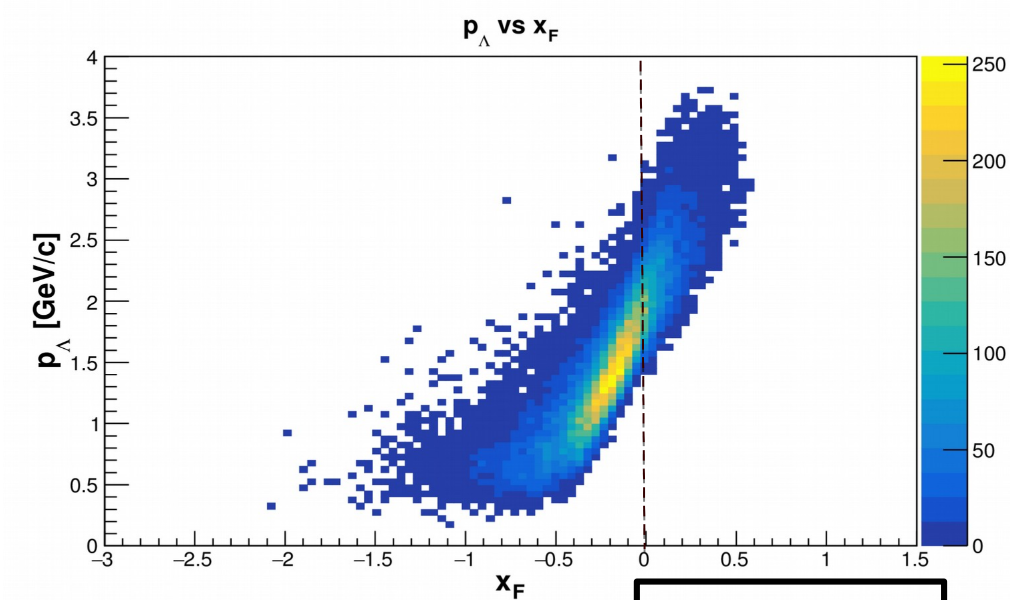


Solid: Fe





Lambda Channel: Kinematical Distributions



Liquid: LD2