Probing Hadronization Dynamics with SIDIS Production off Nuclei

10th biennial Workshop of the APS Topical Group on Hadronic Physics

April 13th, 2023

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Mississippi State University

MISSISSIPPI STATE UNIVERSITY™

clas CEBAF Large Acceptance Spectrometer

U.S. DEPARTMENT OF ENERGY | Office of Science

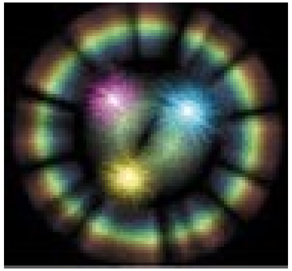
Outline

- Physics Motivation
- Highlights of Previous Measurement
- Recent CLAS Results
    - Mesons Channel: Pions
    - Baryon Channel: Lambda
- Forthcoming CLAS12 Hadronization Studies
- Summary and Outlook

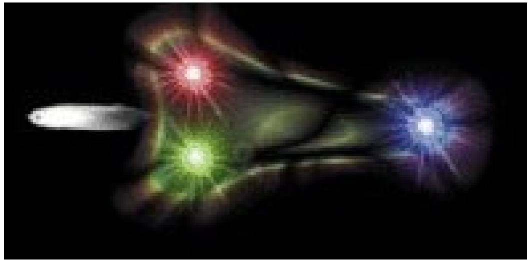
How does the colored bare, quark, evolves to a fully dressed hadron?

- Probe QCD confinement dynamics via hard scattering:

Nucleon



Hard Probe
+
Nucleon



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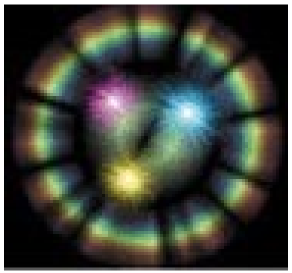

Hard Probe
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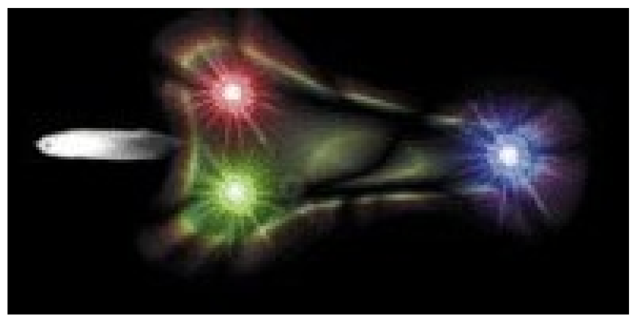
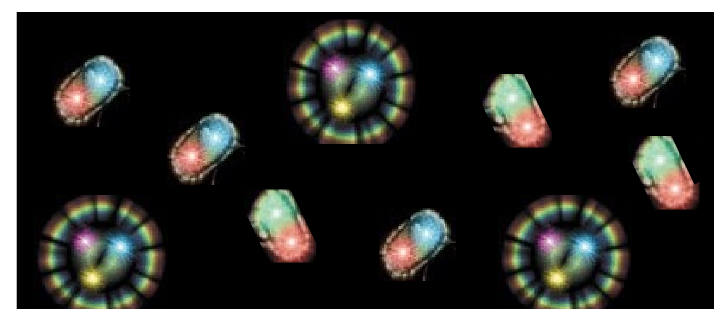


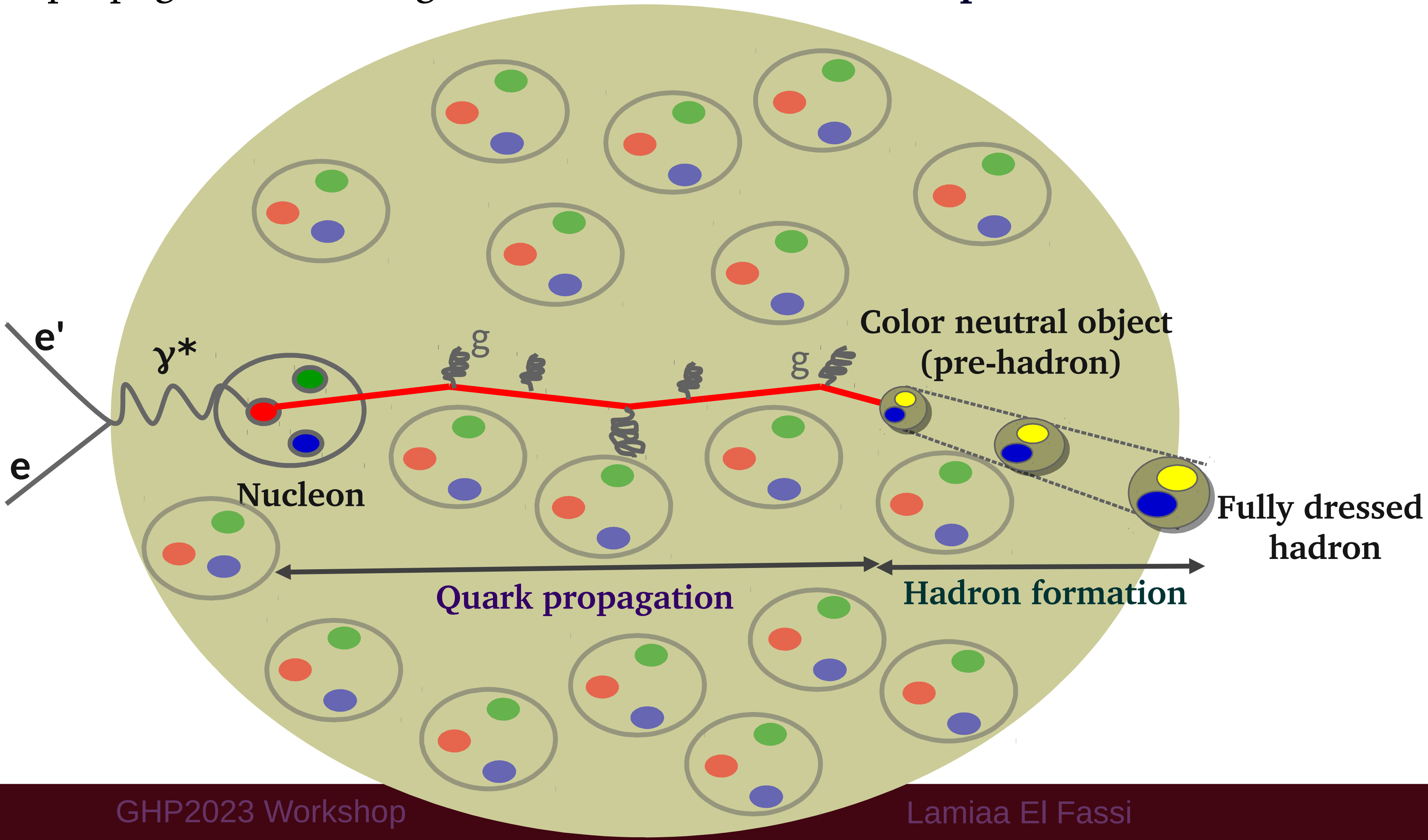
Hadron fragmentation from struck color objects



Images from CERN Courier Strong Interactions Feature (2004)

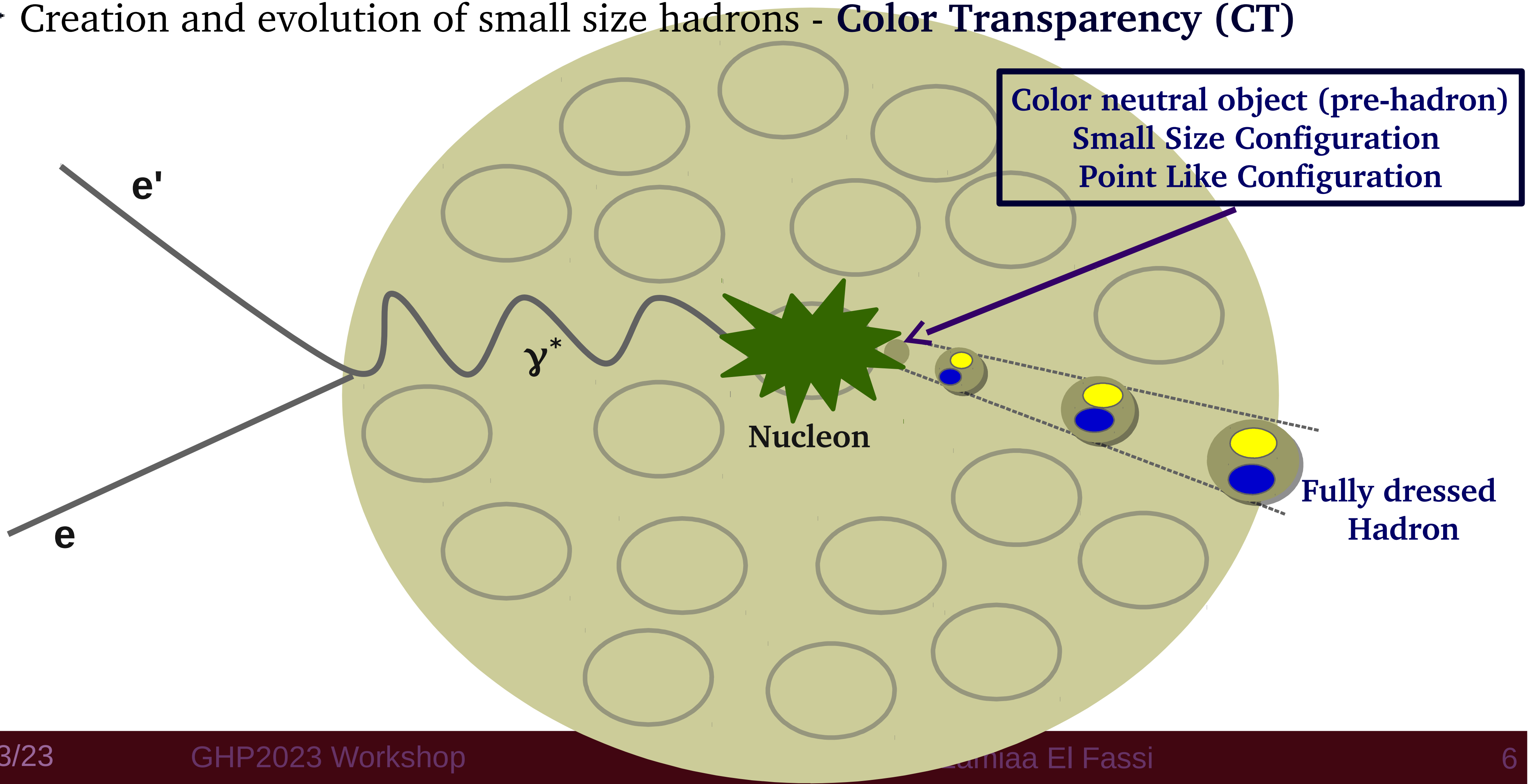
How does the colored bare, quark, evolves to a fully dressed hadron?

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



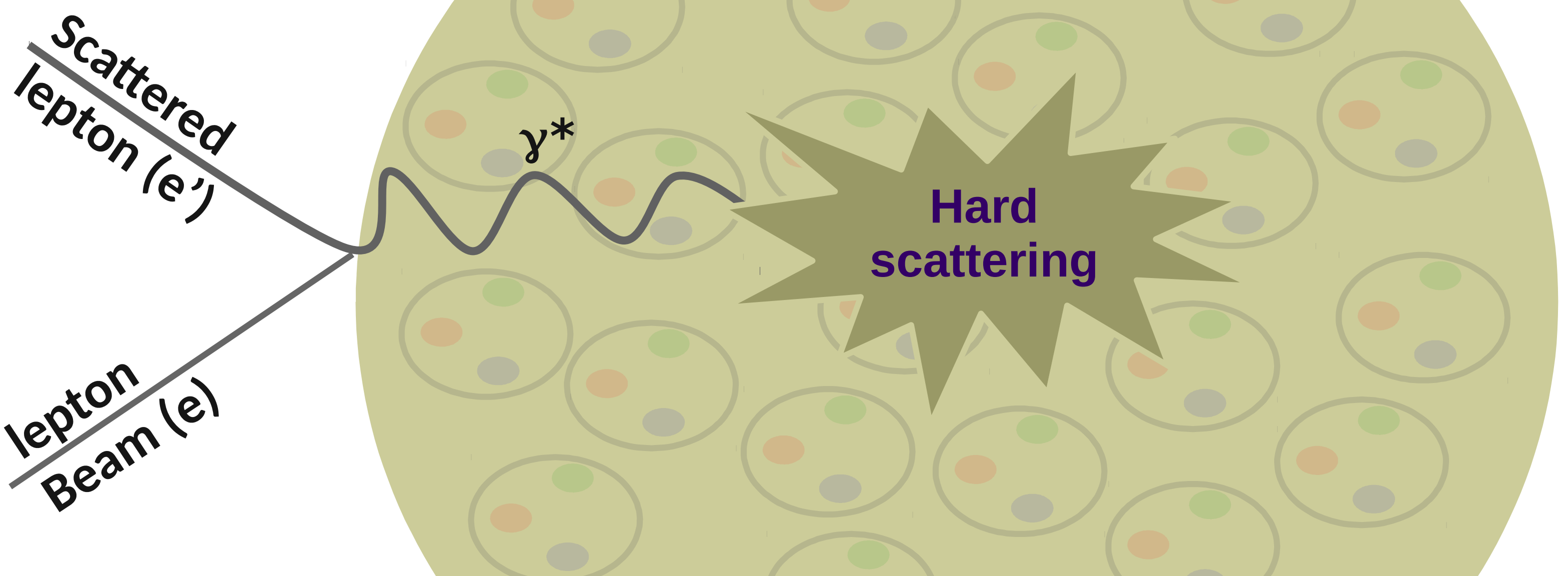
How does the colored bare, quark, evolves to a fully dressed hadron?

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

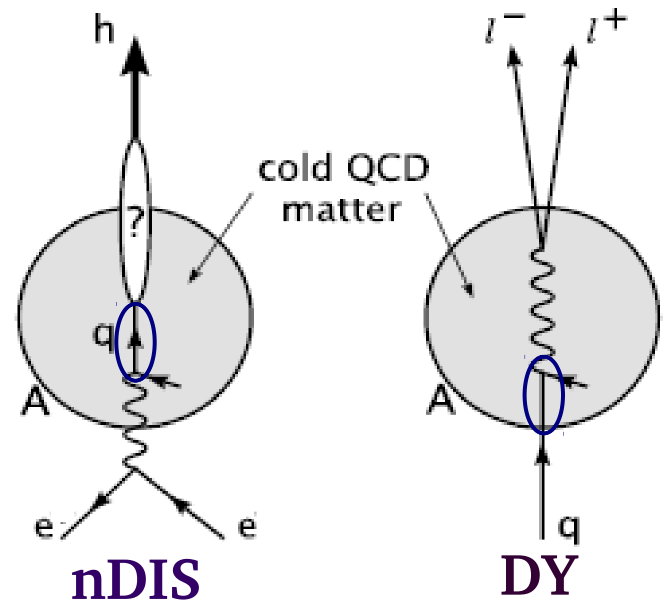


- Study medium modification of parton distributions – **EMC Effect**
- Access short-range structure – **SRC**
- 3-D imaging – **Nuclear generalized parton distributions** (**GPD**s) and **transverse momentum distributions** (**TMD**s)

Complementarity for Studying Hadronization Stages

Nuclear Deep Inelastic Scattering (DESY, JLab):

- Quark propagation
- Hadron Formation
- Final state interactions (FSIs) effects



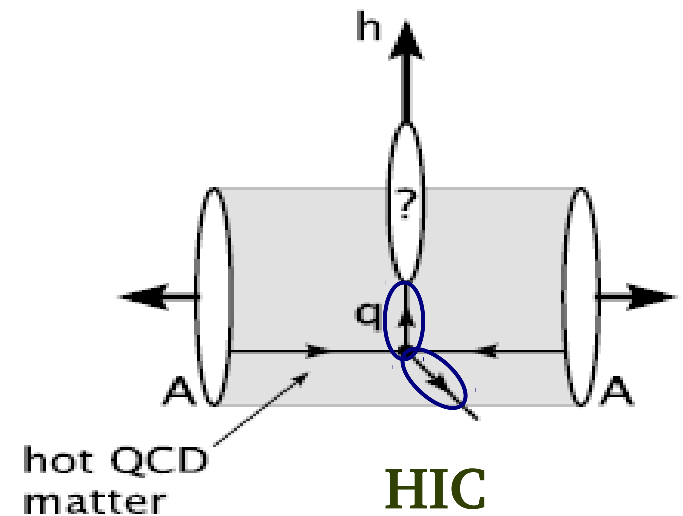
Drell-Yan process (Fermilab, CERN):

- Quark propagation
- Initial state interactions (ISIs) effects

A. Accardi *et al.*, Riv. Nuovo Cim. **32**, 439 (2009)

Heavy Ion Collisions (RHIC, CERN):

- Quark propagation
- Hadron Formation
- ISIs and FSIs effects



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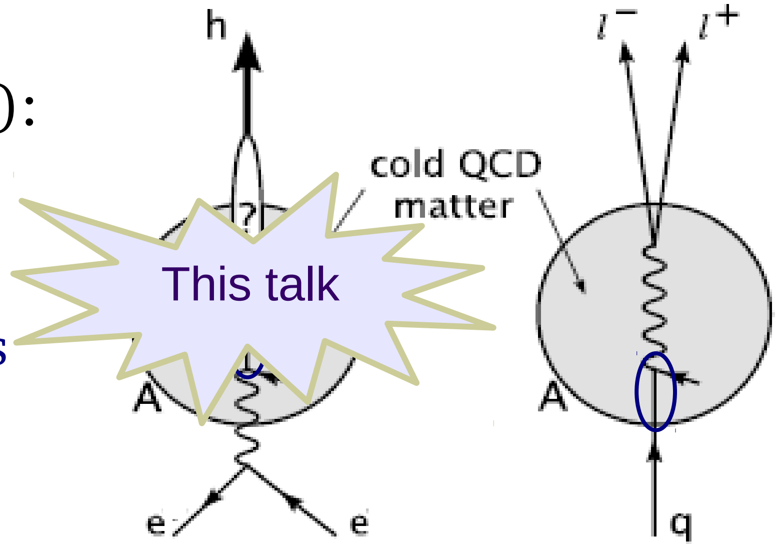

nDIS **DY**

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A. Accardi *et al.*, Riv. Nuovo Cim. **32**, 439 (2009)

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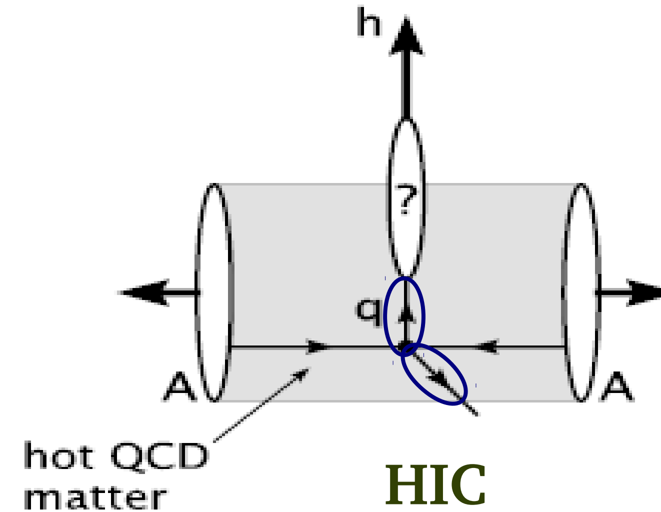
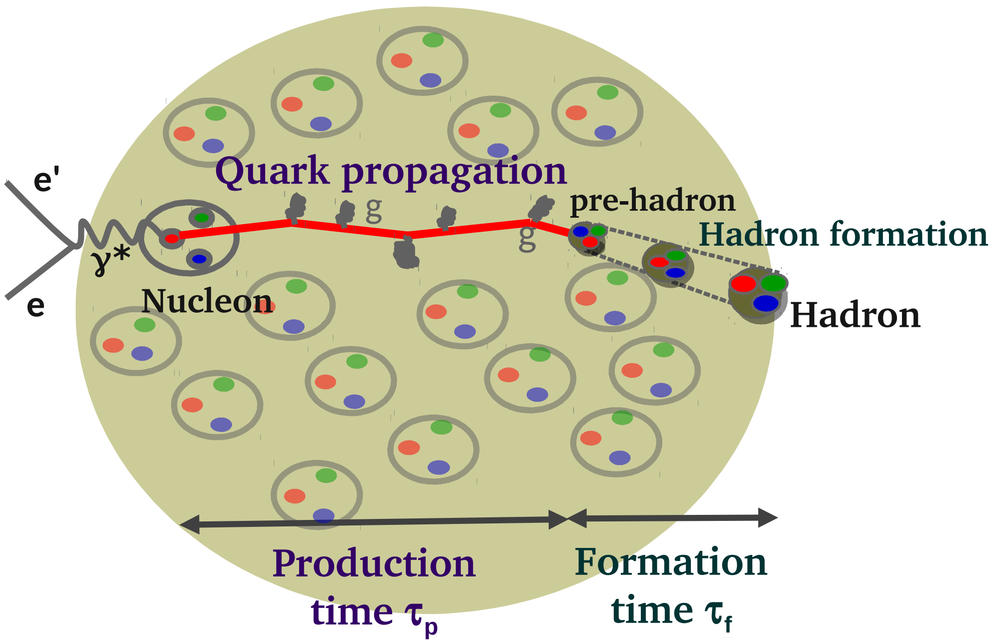
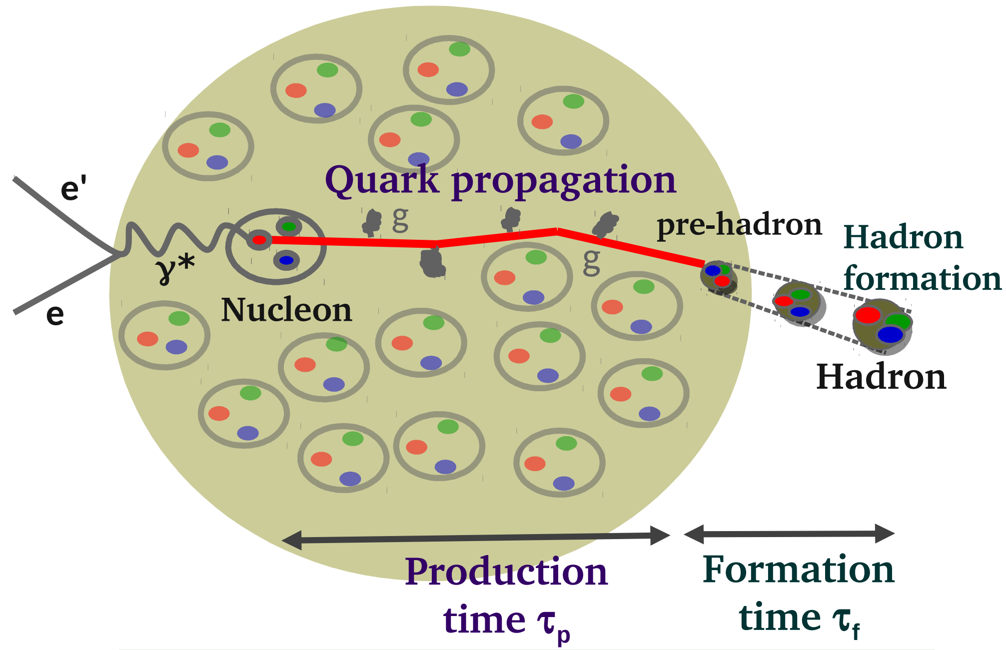


Probe Hadronization Time-distance Scales

- Explore semi-inclusive deep inelastic scattering (SIDIS) production to access the hadronization time-distance 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 nuclear medium is manifested at low energies

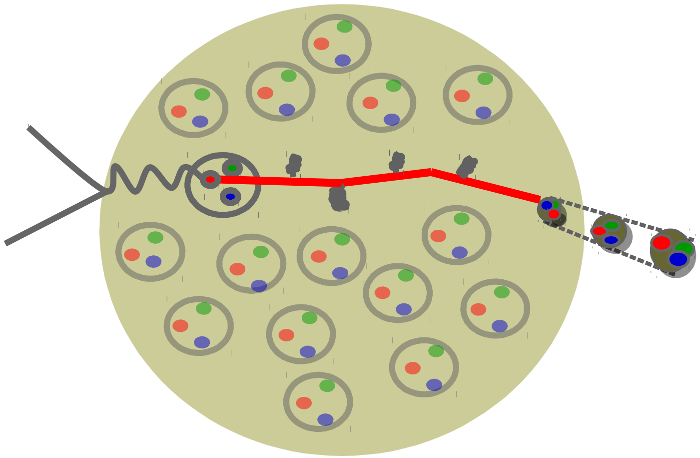


Hadron formation outside the nuclear medium dominates at high energies

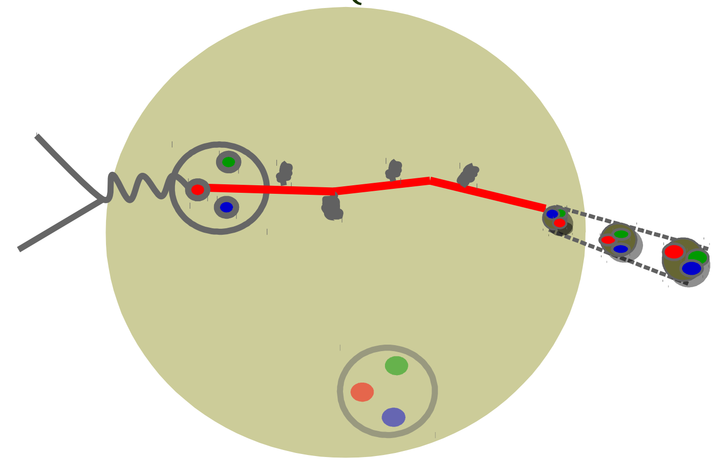
Probe Hadronization Time-distance Scales

- Explore SIDIS production to access the hadronization time-distance scales
  ⟹ their extraction via a comparison of QCD dynamics in

Medium

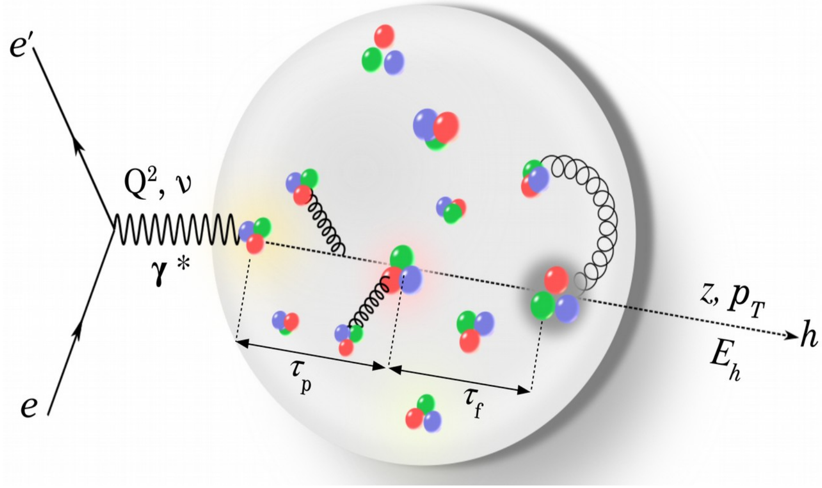


Vacuum *(nucleons or deuteron)*



- ✓ **Production time τ_p**: time spent by a deconfined quark to neutralize its color charge
  ⟹ Medium-stimulated energy loss via gluon bremsstrahlung leads 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 for hadron suppression in measured multiplicity ratios.

SIDIS Kinematics



Drawing courtesy of
T. Chetry
(former postdoc)

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;

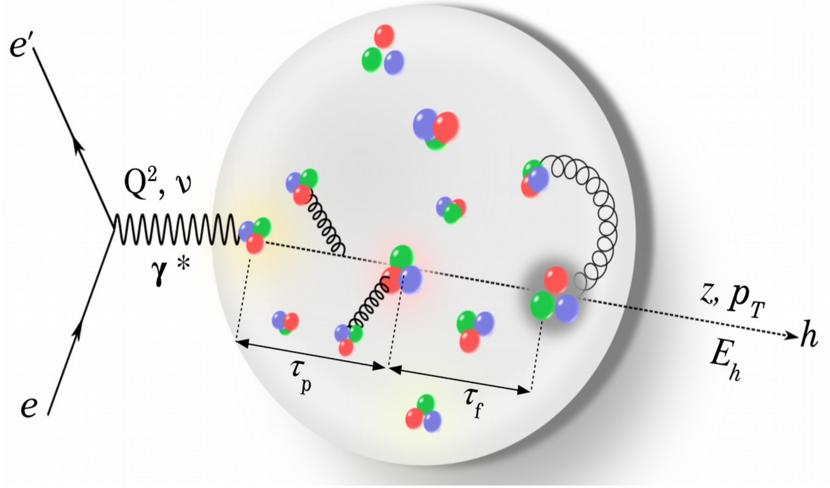
$W = \sqrt{M_n^2 + 2\nu M_n - Q^2}$: Total mass of the hadronic final state, where M_n is the nucleon mass

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 Kinematics and Cuts



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 radiative effects (*based on former HERMES studies*)

$W = \sqrt{M_n^2 + 2\nu M_n - Q^2}$: 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) fragmentation region

Later discussion

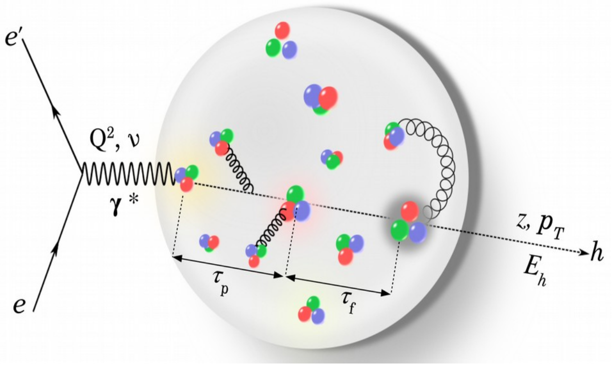
Experimental Observables

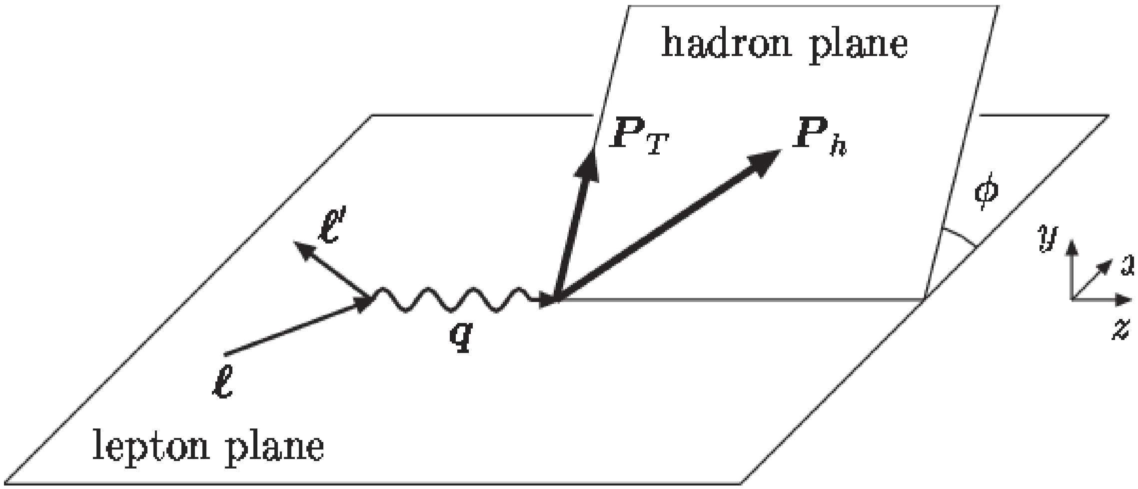
Transverse Momentum Broadening

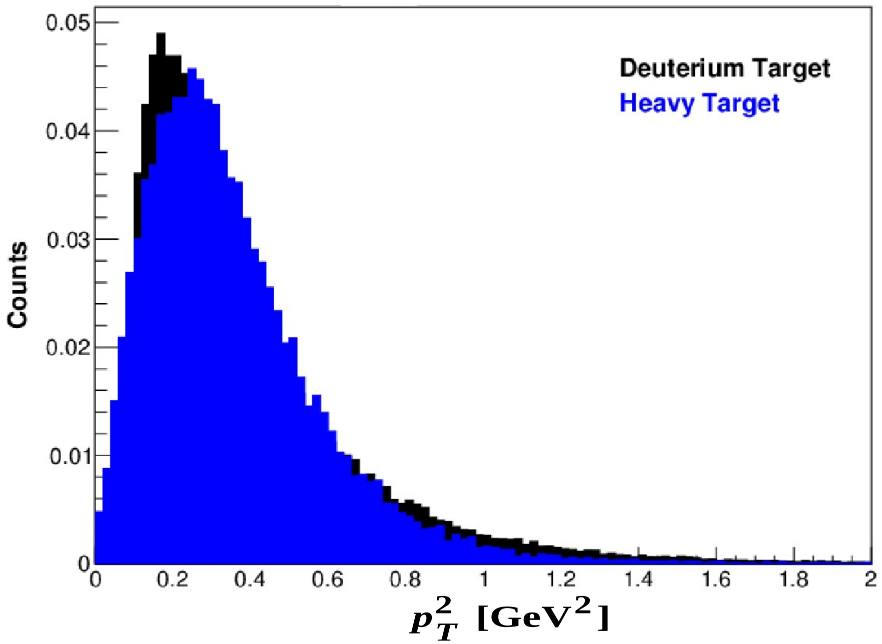
$$\Delta\, p_T^2 = < p_T^2 >_A - < p_T^2 >_D$$

↕

Grant access to τ_p via production of different hadrons and quark's flavor off various nuclei







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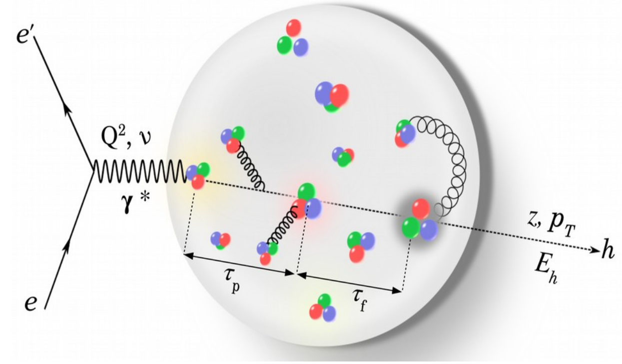
$$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

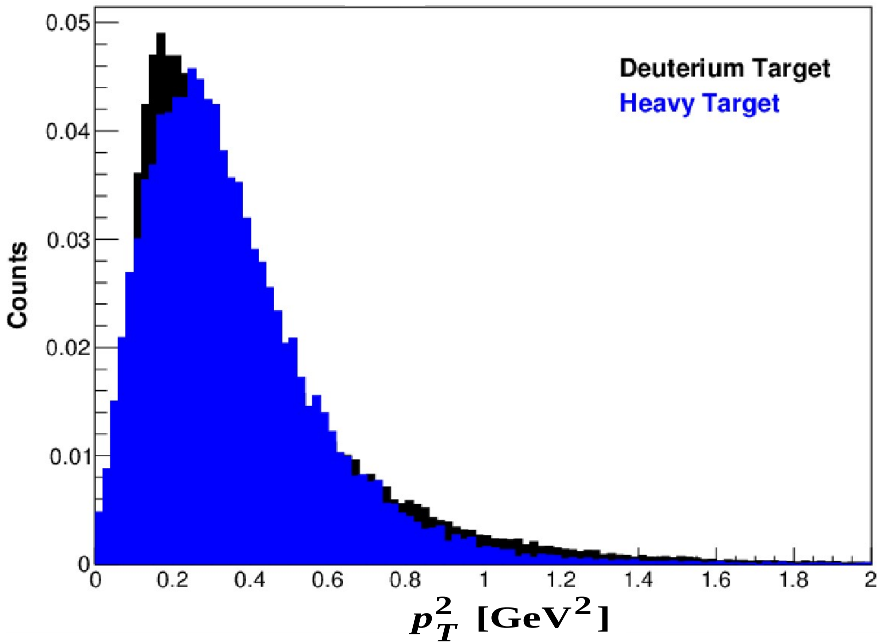


Grant access to τ_p via production of different hadrons and quark's flavor off various nuclei

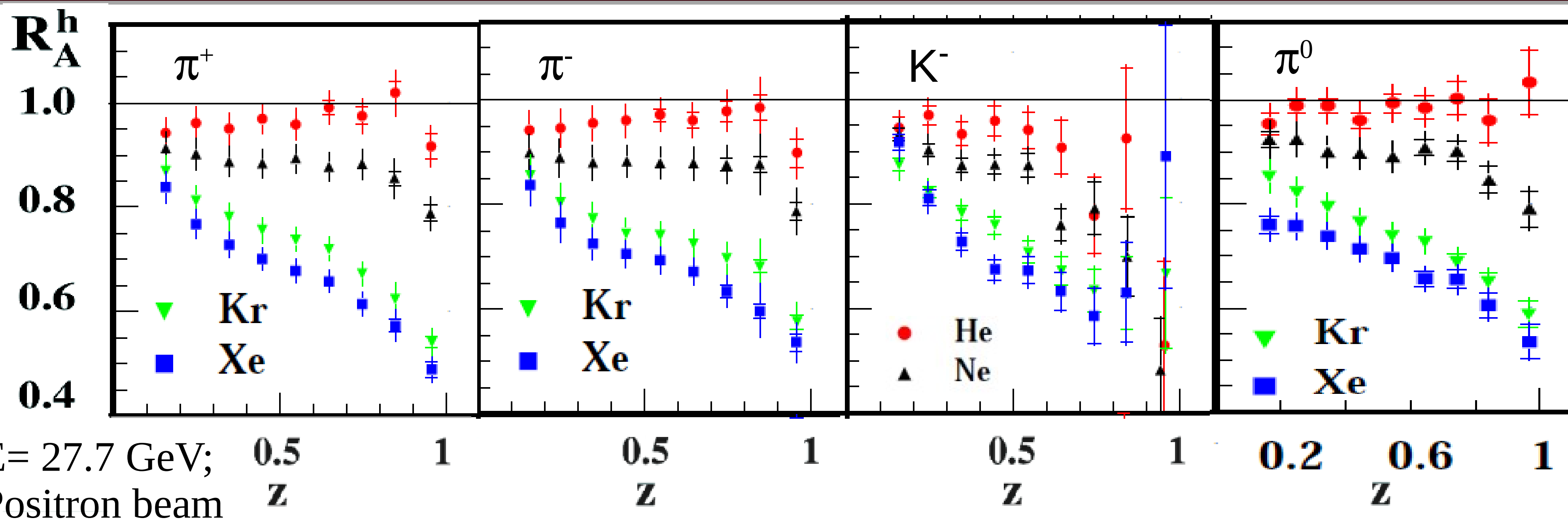
Hadron Multiplicity Ratio

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

Access τ_f after the extraction of τ_p and $R^A{}_h$



Previous Study: HERMES Multiplicity Ratios



E= 27.7 GeV;
Positron beam

Nucl. Phys. B **780**, 1 - 27 (2007)

- Pions flavors and K^- experienced similar attenuation.

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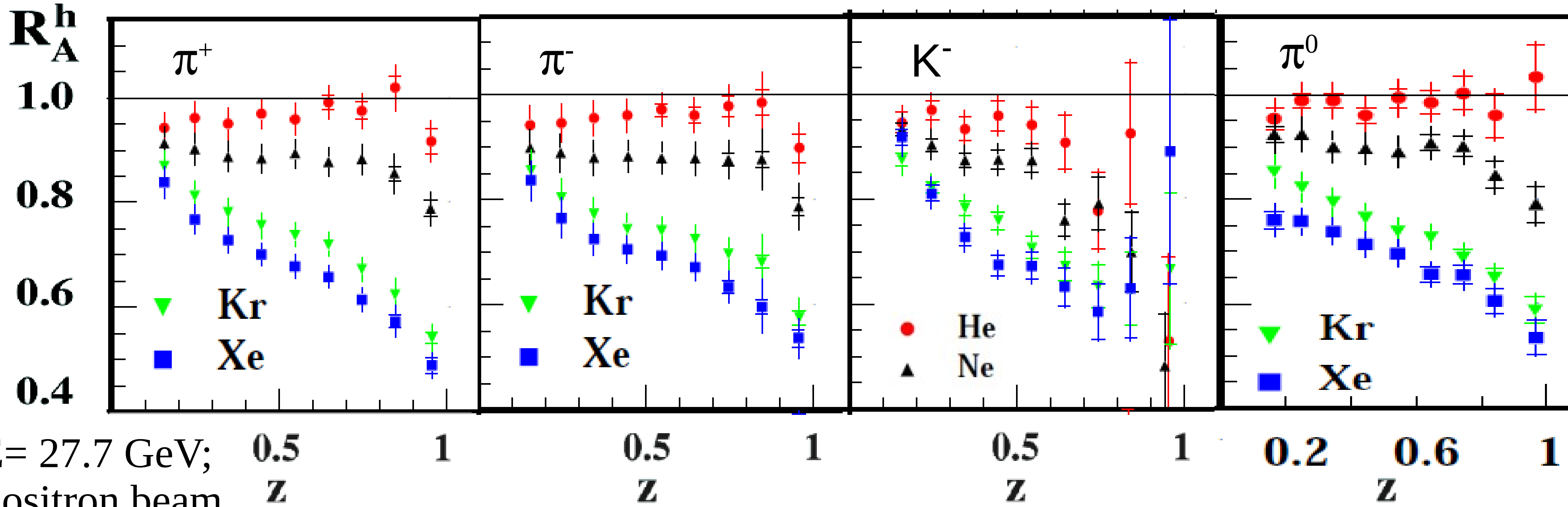

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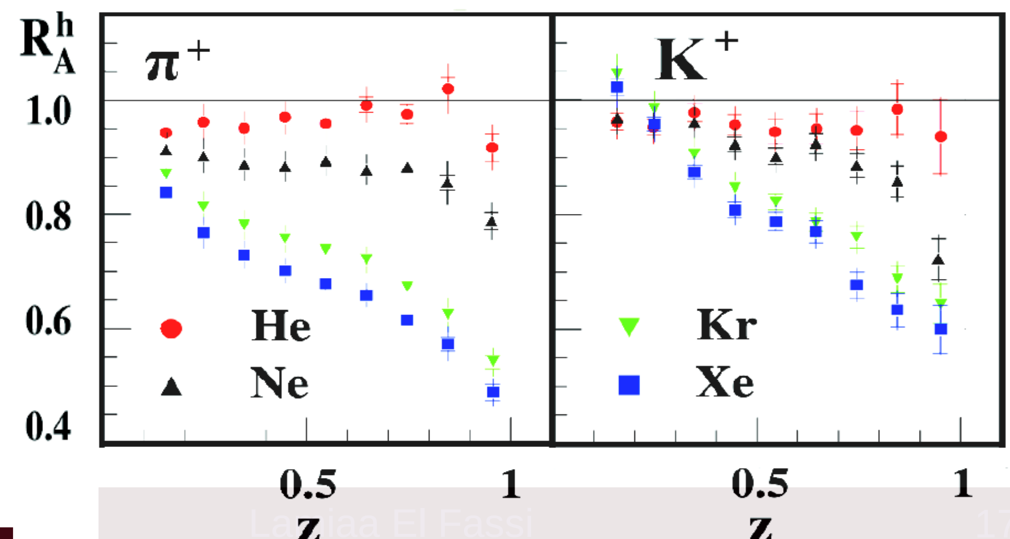
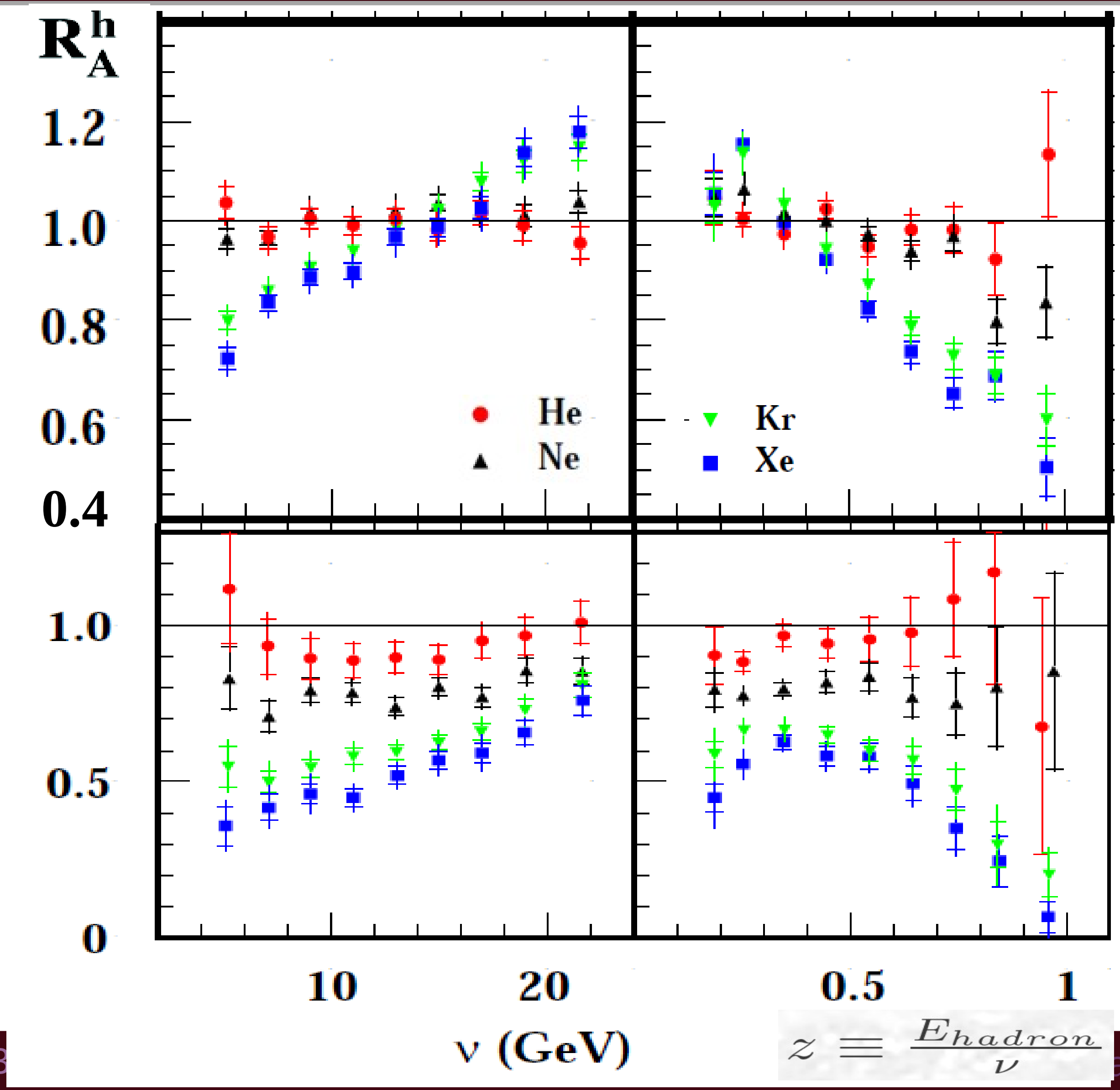


- Pions flavors and K^- experienced similar attenuation.
- K^+ is less attenuated compared to π^+; most likely due to the contamination of $\pi + p \Longrightarrow \Lambda + K$ (Kopeliovich *et al.*) from the target fragmentation.

Previous Study: HERMES Multiplicity Ratios



E= 27.7 GeV; Positron beam

Protons

Antiprotons

Nucl. Phys. B **780**, 1 - 27 (2007)

Previous Study: HERMES p_T Broadening

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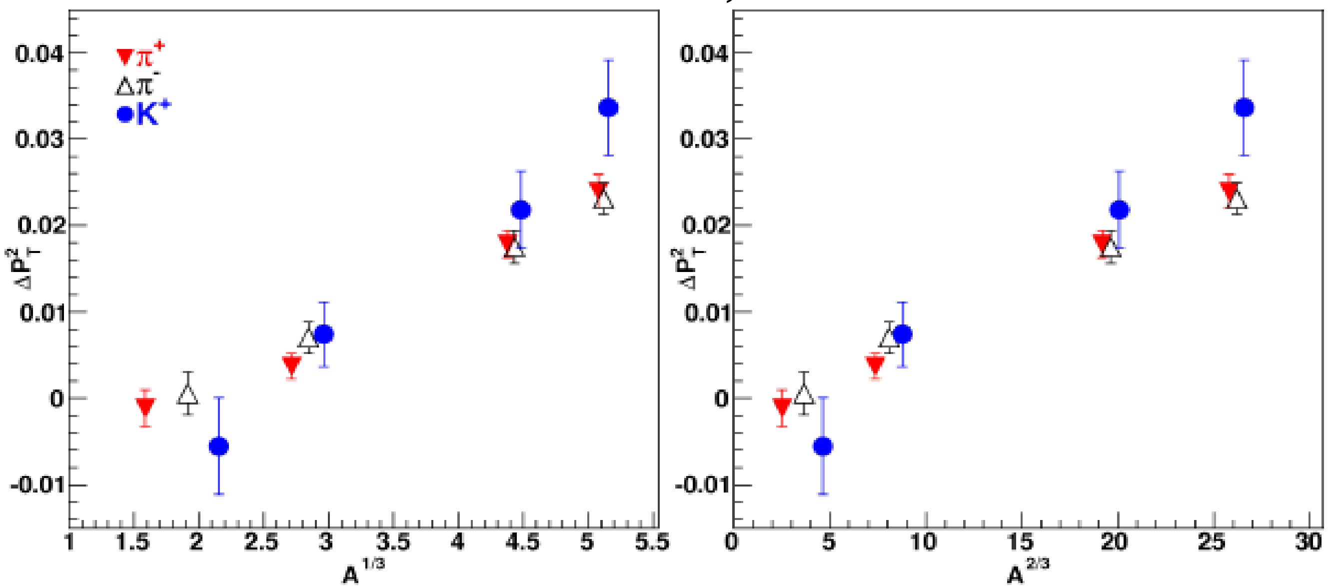
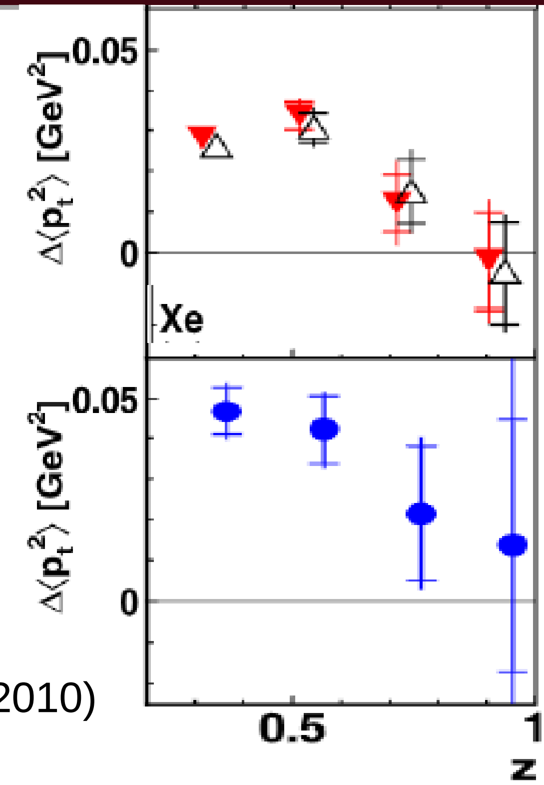


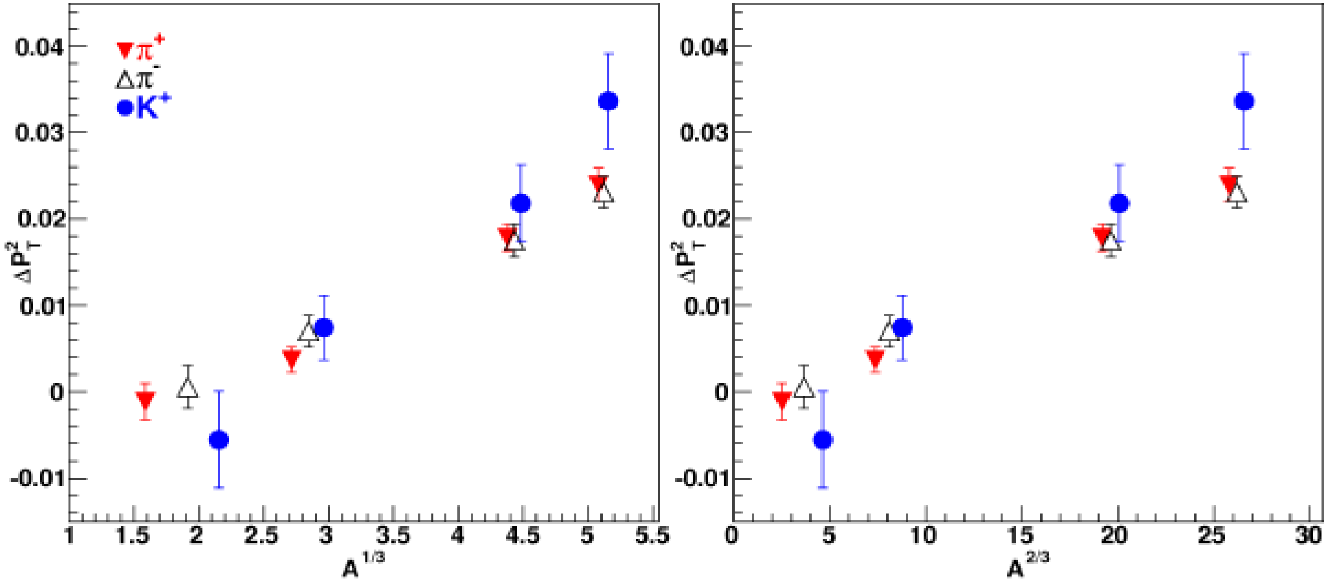


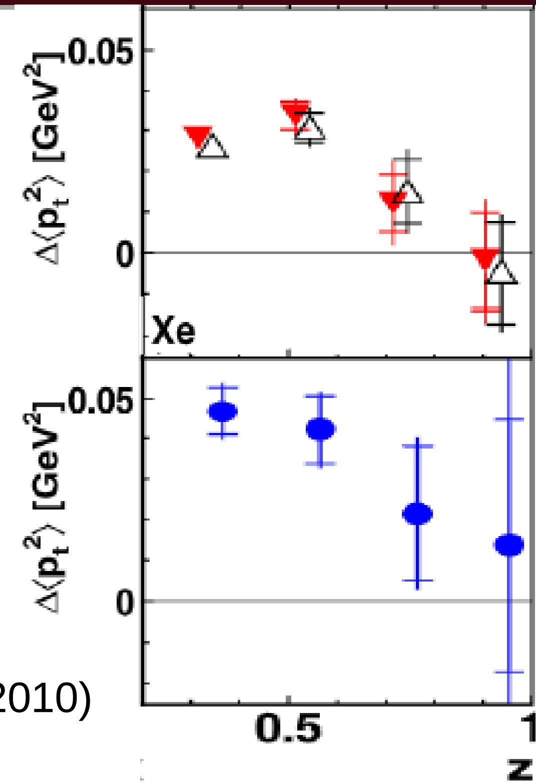
Phys. Lett. B **684**, 114 - 118 (2010)

- Possible flavor dependence due to different behavior of K^+ and pions p_T broadening!
- Reduced broadening at high z indicates no (pre)hadron elastic scattering;

Previous Study: HERMES p_T Broadening

E= 27.7 GeV; Positron beam





Phys. Lett. B **684**, 114 - 118 (2010)

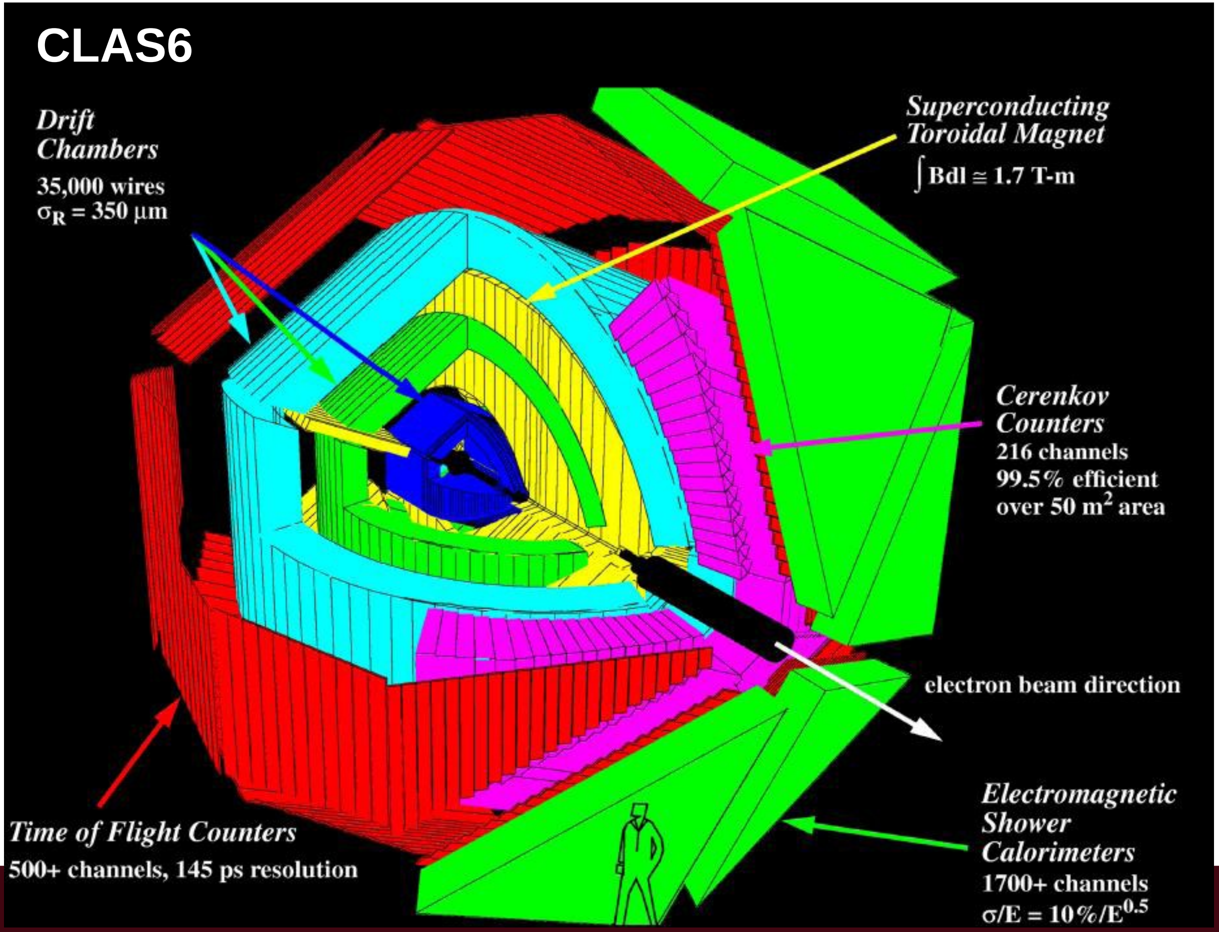
- Possible flavor dependence due to different behavior of K^+ and pions p_T broadening!
- Reduced broadening at high z indicates no (pre)hadron elastic scattering;
- Perturbative QCD description of p_T broadening:

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

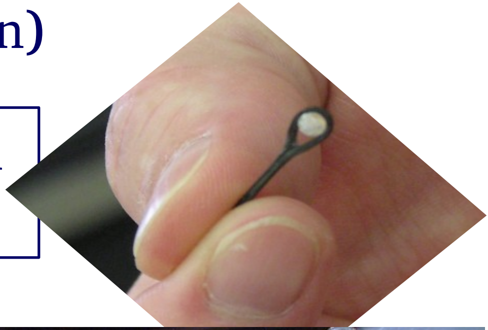
- Similar Δp_T^2 dependence on $A^{1/3}$ & $A^{2/3}$ $\Longrightarrow$ Motivation for JLab/CLAS studies!

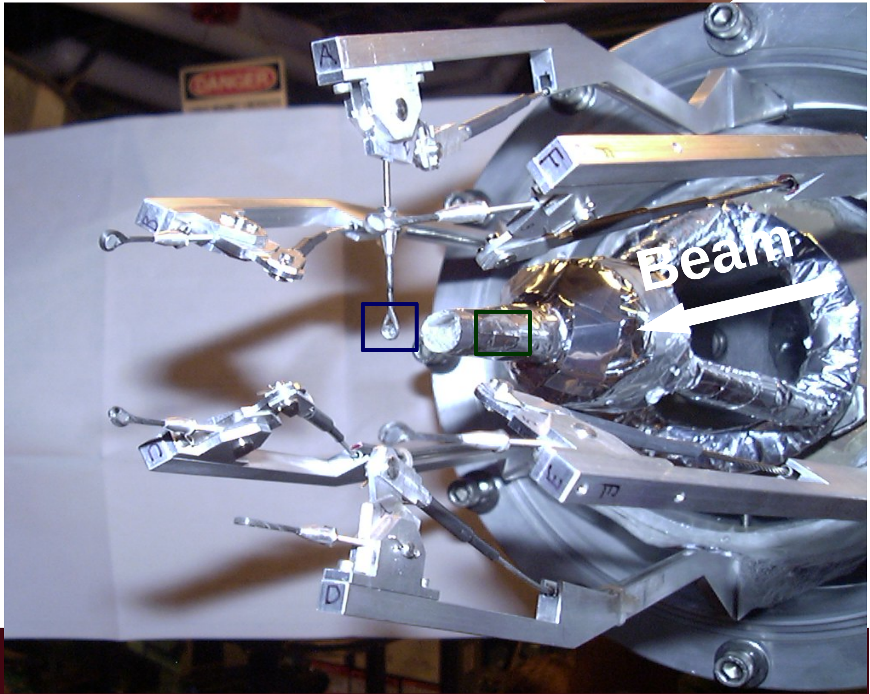
JLab 6 GeV CLAS (CLAS6) Experiment

- Fixed-target experiment performed early 2004 (EG2 run-group) with the now-decommissioned CLAS6 spectrometer and dual targets assembly:
  - → **Liquid deuteron (LD2)** + **solid target (C or Fe or Pb** or Al or Sn**)**

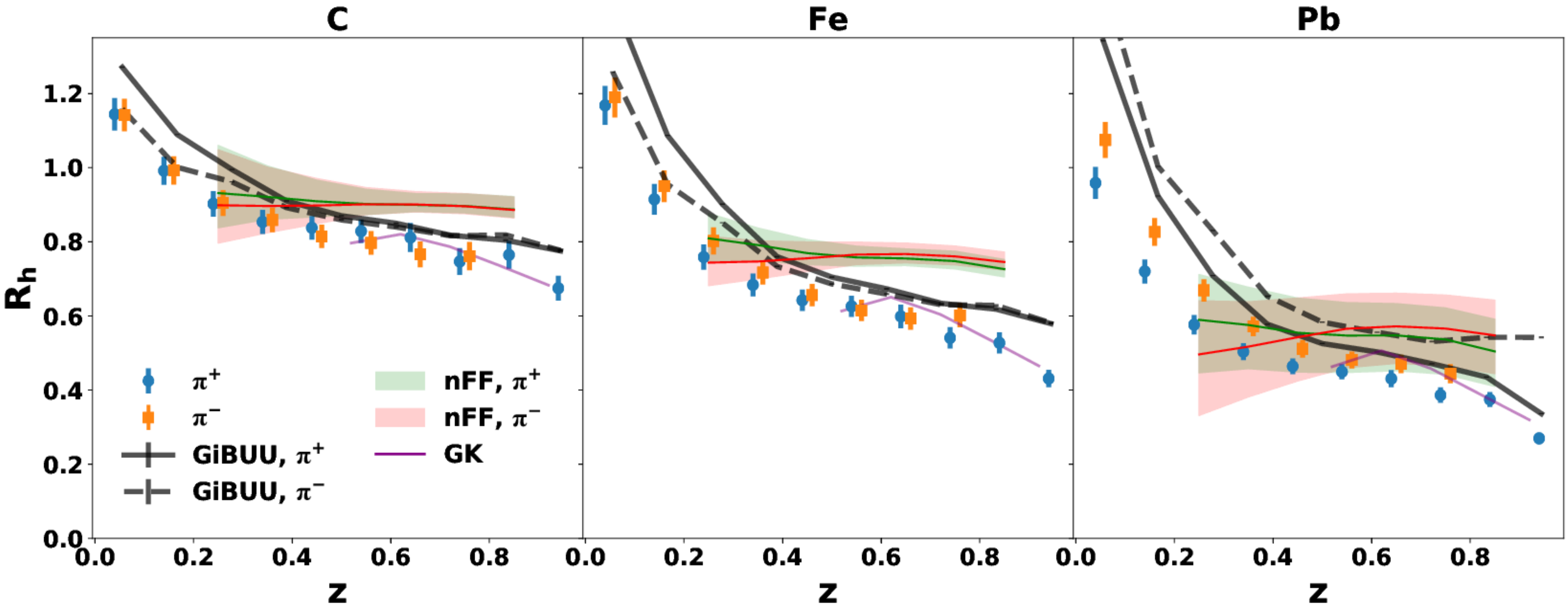


Solid disk





CLAS6 Hadronization Studies: Charged Pions



Phys. Rev. C **105**, 015201 (2022)

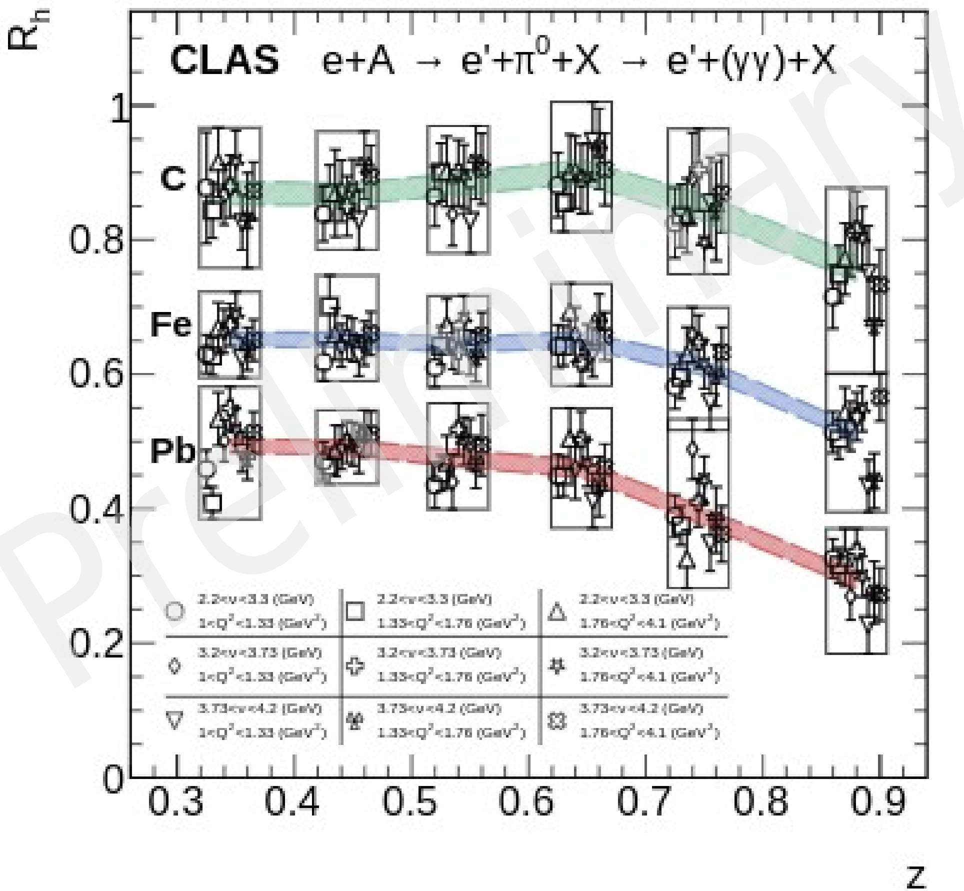
GiBUU (Giessen Boltzmann-Uehling-Uhlenbeck) uses hadronic degrees of freedom, it incorporates formation times, prehadron interactions, CT, and nuclear shadowing. Ingredients successfully used to describe nuclear modifications of DIS hadrons production in the HERMES and EMC experiments.

nFF (nuclear fragmentation functions by P. Zurita) is based on a comparison of the LIKEn21 set of nFFs extracted from a fit to HERMES data and the De Florian / Sassot/Stratmann (DSS) FFs as a baseline. The nFF Q^2 dependence is dictated by the same evolution equations as FFs.

GK (Guiot and Kopeliovich) is based on a combination of quark-energy loss and prehadron absorption. The latter is the most relevant mechanism to describe HERMES data. The model attempts to describe the modification of the leading hadrons only; i.e., z > 0.5.

CLAS6 Hadronization Studies: Neutral Pion

T. Mineeva *et al*. (2023)



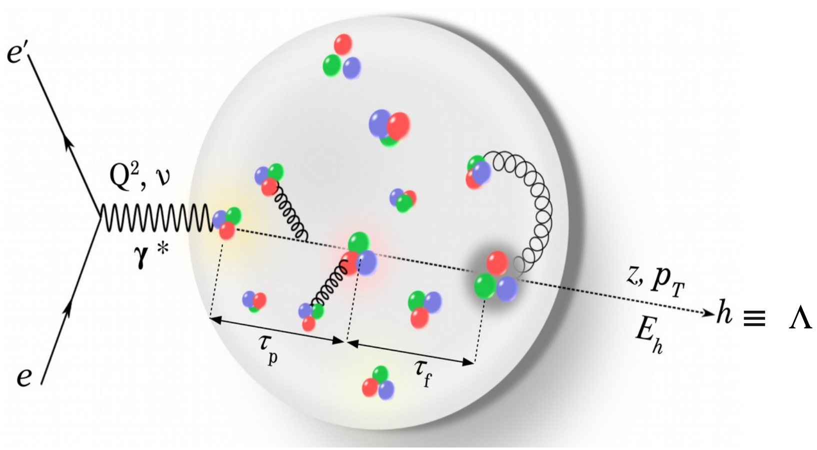
PRL-targeted paper under CLAS Collaboraion review

- Measured attenuation varies from a maximum of 25% on C to 75% on Pb
- No dependence on Q^2 and ν observed
- Results are quantitatively compatible with HERMES data

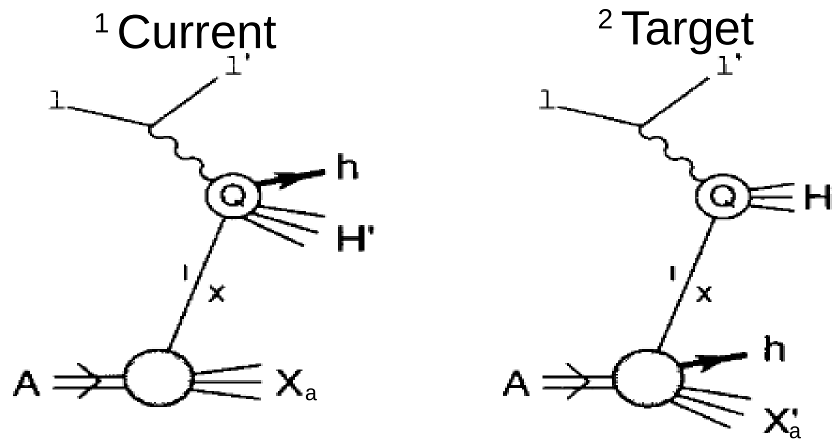
- First-ever study of Λ SIDIS production off C, Fe, and Pb nuclei in the forward[1] and backward[2] fragmentation regions

SIDIS Λ production:

$$e + A \longrightarrow e' + \Lambda + X$$



Phys. Rev. Lett. **130**, 142301 (2023)

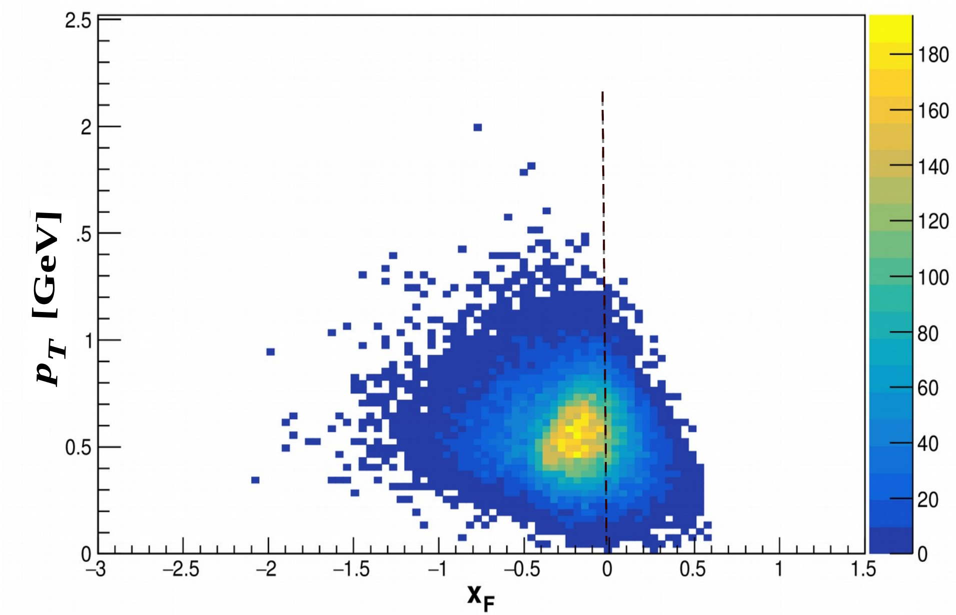


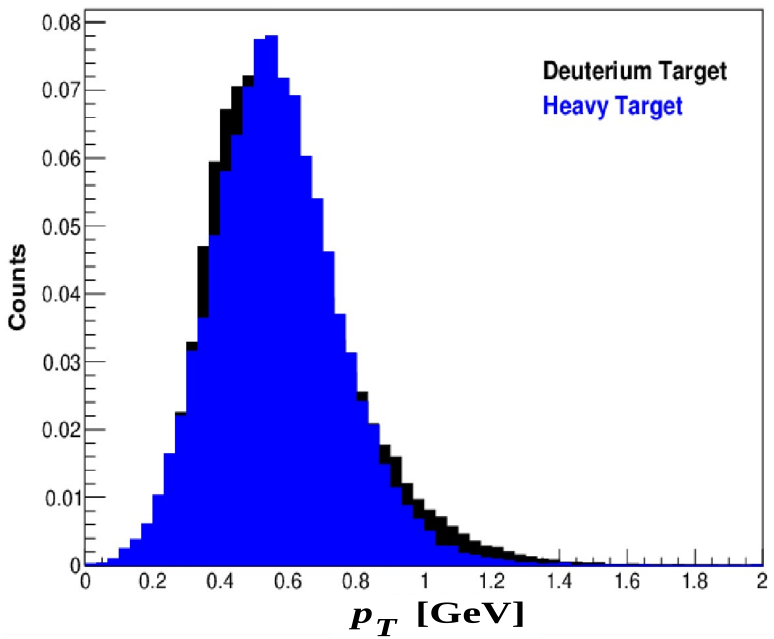
L. Trentadue & G. Veneziano, Phys. Lett. B **323**, 201-211 (1994)

CLAS6 Hadronization Study: Λ Baryon

- First-ever study of Λ SIDIS production off C, Fe, and Pb nuclei in the current and target fragmentation regions;
  - Two-region separation is crucial given Λs play a leading particle role by carrying a substantial fraction of incoming proton momenta ($\equiv x_F < 0$) and thus small p_T

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





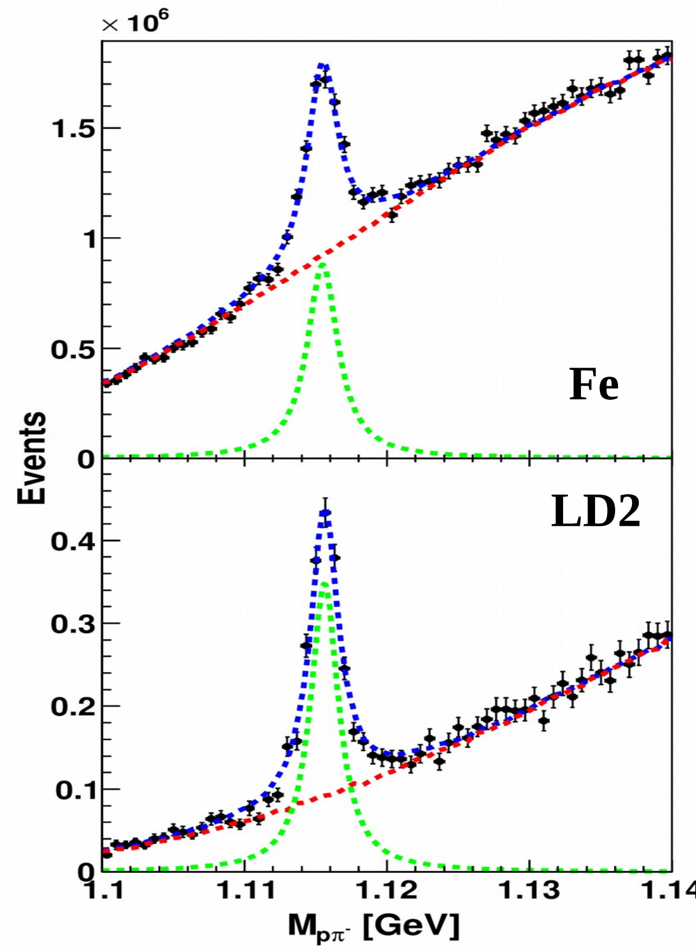
Phys. Rev. Lett. **130**, 142301 (2023)

Lambda Identification and Yield Extraction

- Λ is identified via its decay particles, π^- and proton.
- Combinatorial background is subtracted using the event mixing technique and RooFit modeling and fitting toolkit.

--------- Combinatorial background

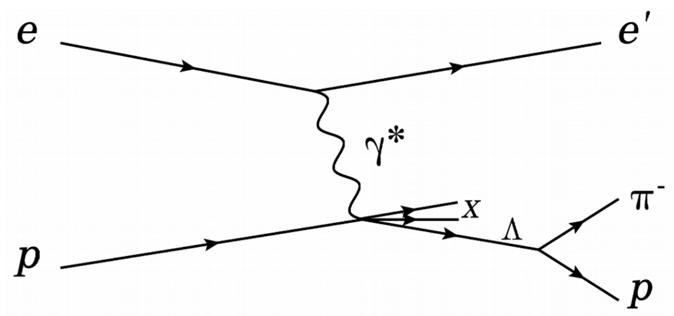
.... Pure Λ signal



Phys. Rev. Lett. **130**, 142301 (2023)

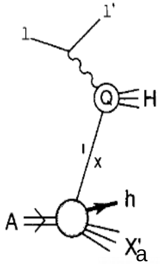
SIDIS Λ production:

e + p ⟶ e' + Λ + X

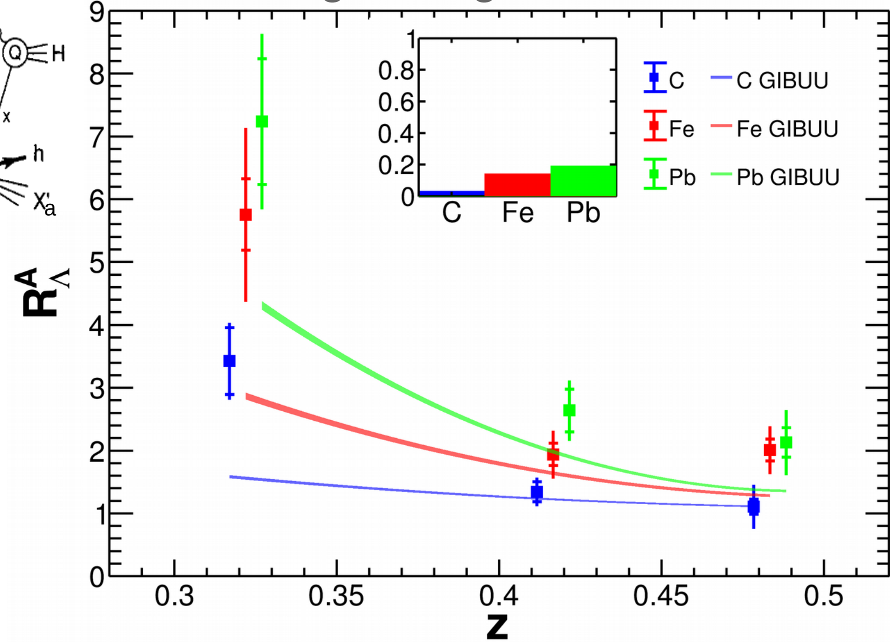


Former Postdoc Taya Chetry

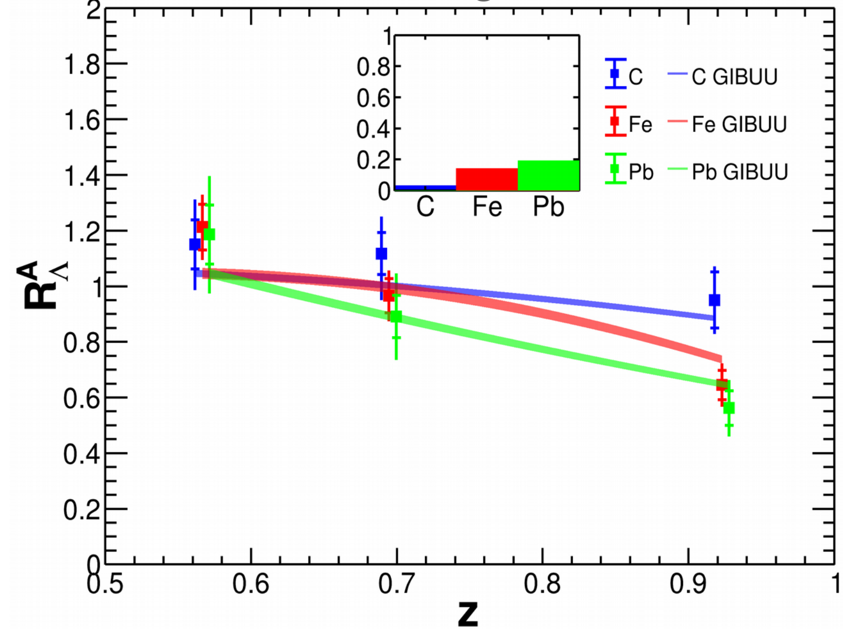
CLAS6 Λ Multiplicity Ratios

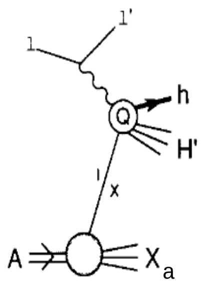


Target Fragmentation



Current Fragmentation

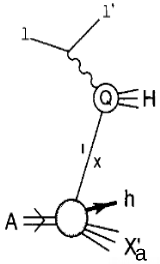




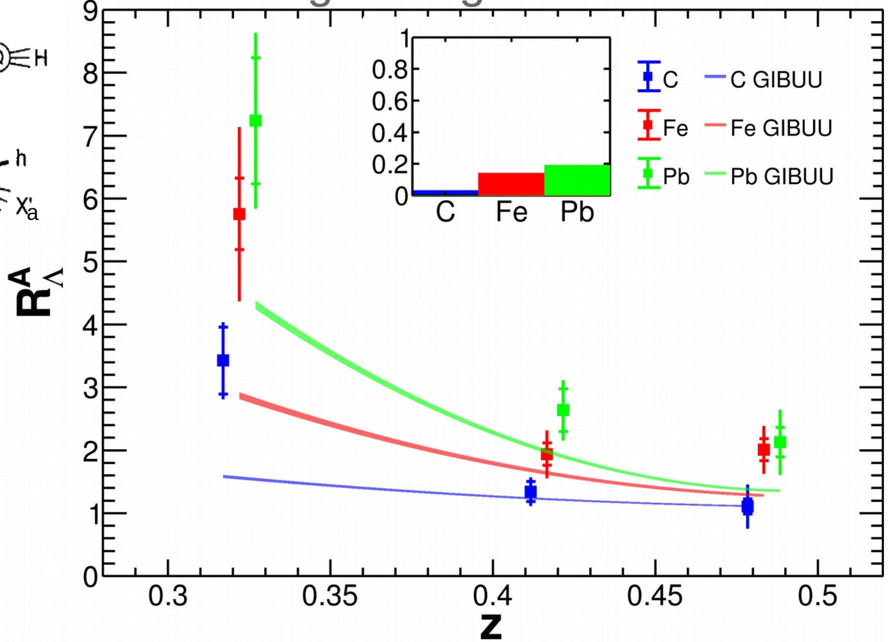
Phys. Rev. Lett. **130**, 142301 (2023)

$$R_{\Lambda}^{A}(z)=\frac{\left\{\frac{N_{\Lambda}^{SIDIS}(z)}{N_{e}^{DIS}}\right\}_{A}}{\left\{\frac{N_{\Lambda}^{SIDIS}(z)}{N_{e}^{DIS}}\right\}_{D}}$$

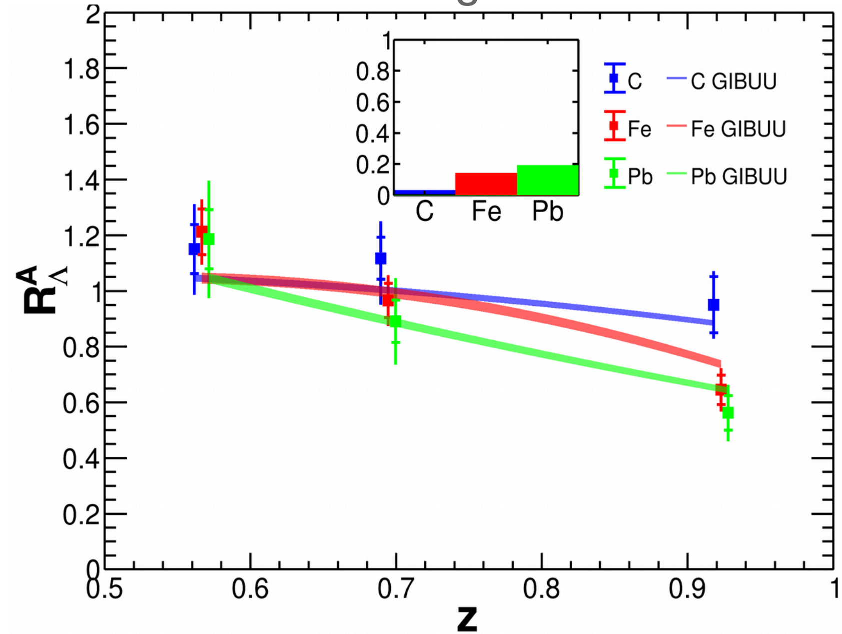
CLAS6 Λ Multiplicity Ratios

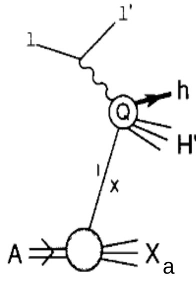


Target Fragmentation

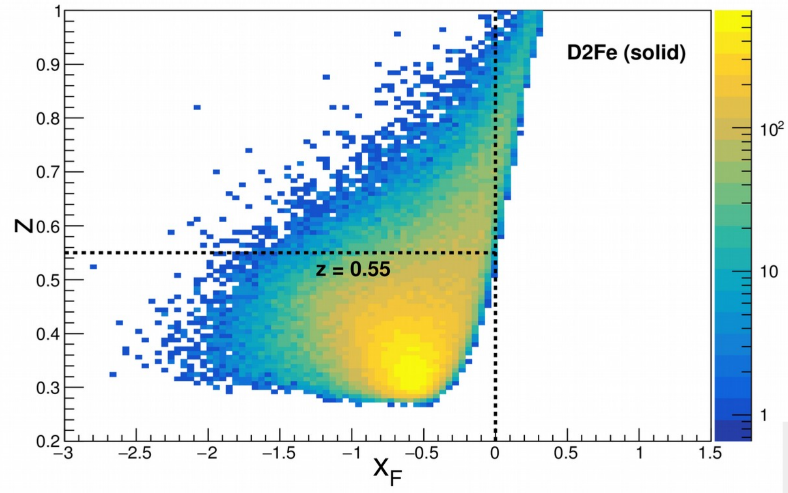


Current Fragmentation





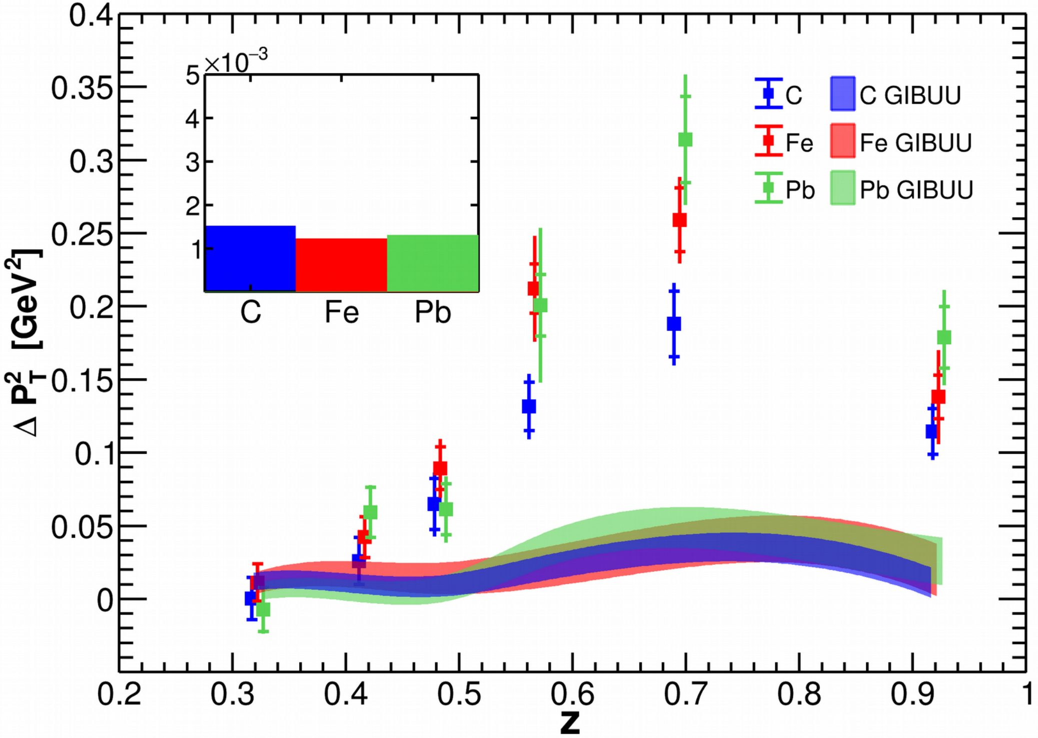
Phys. Rev. Lett. **130**, 142301 (2023)

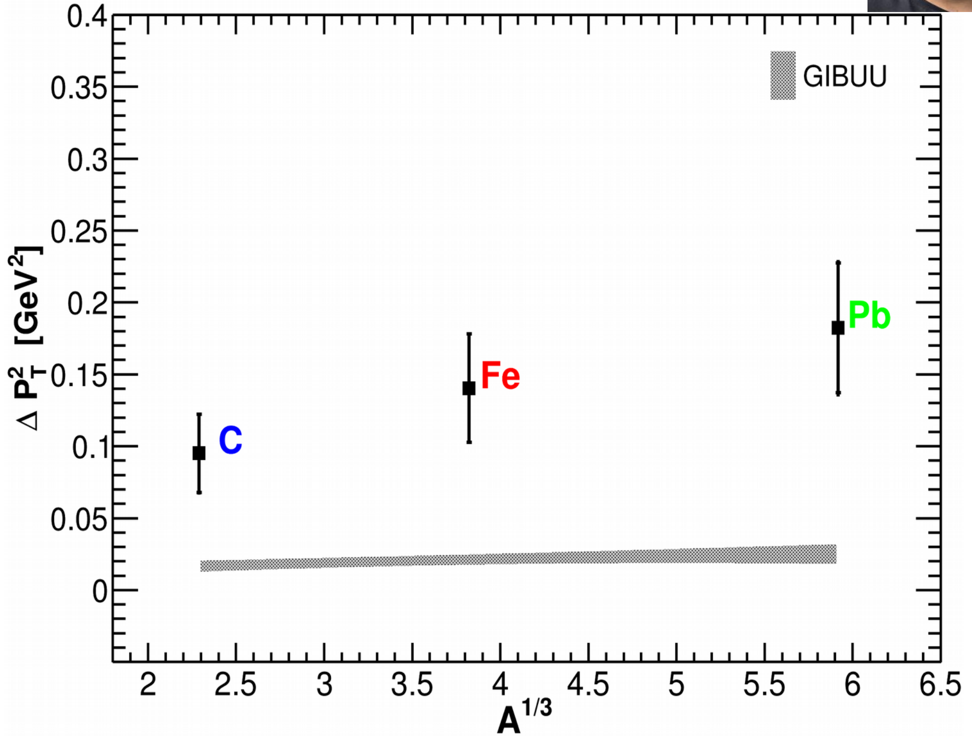


$$R^A_\Lambda(z)=\frac{\left\{\dfrac{N^{SIDIS}_\Lambda(z)}{N^{DIS}_e}\right\}_A}{\left\{\dfrac{N^{SIDIS}_\Lambda(z)}{N^{DIS}_e}\right\}_D}$$

See Supplemental Material

CLAS6 Λ p_T Broadening Results

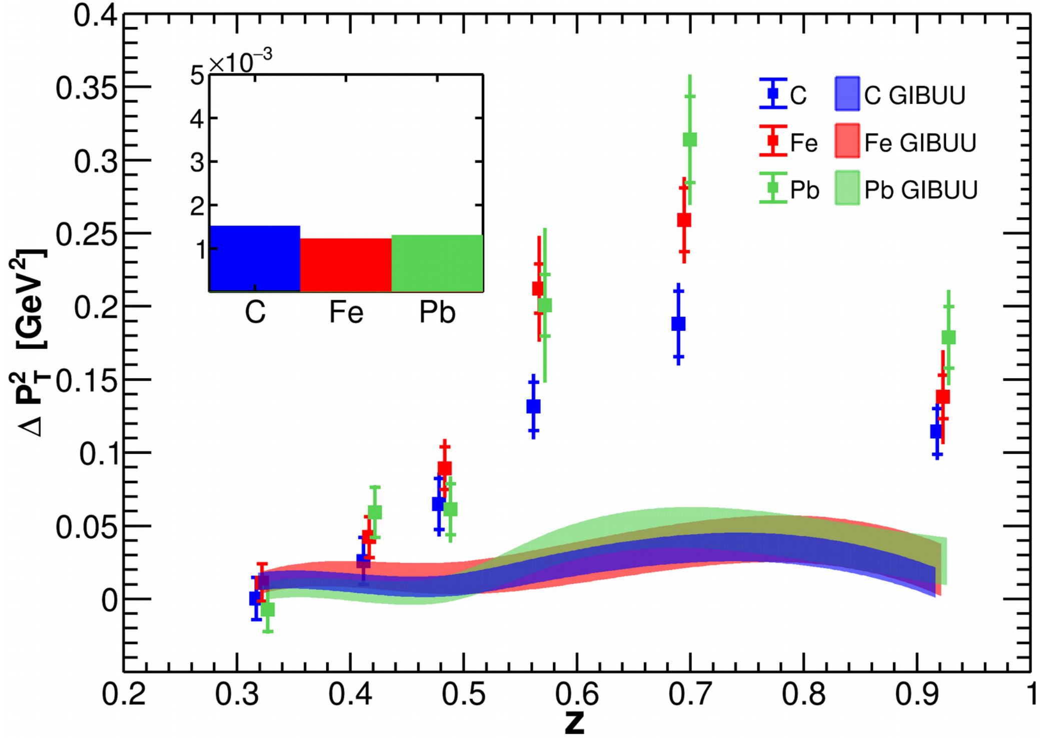




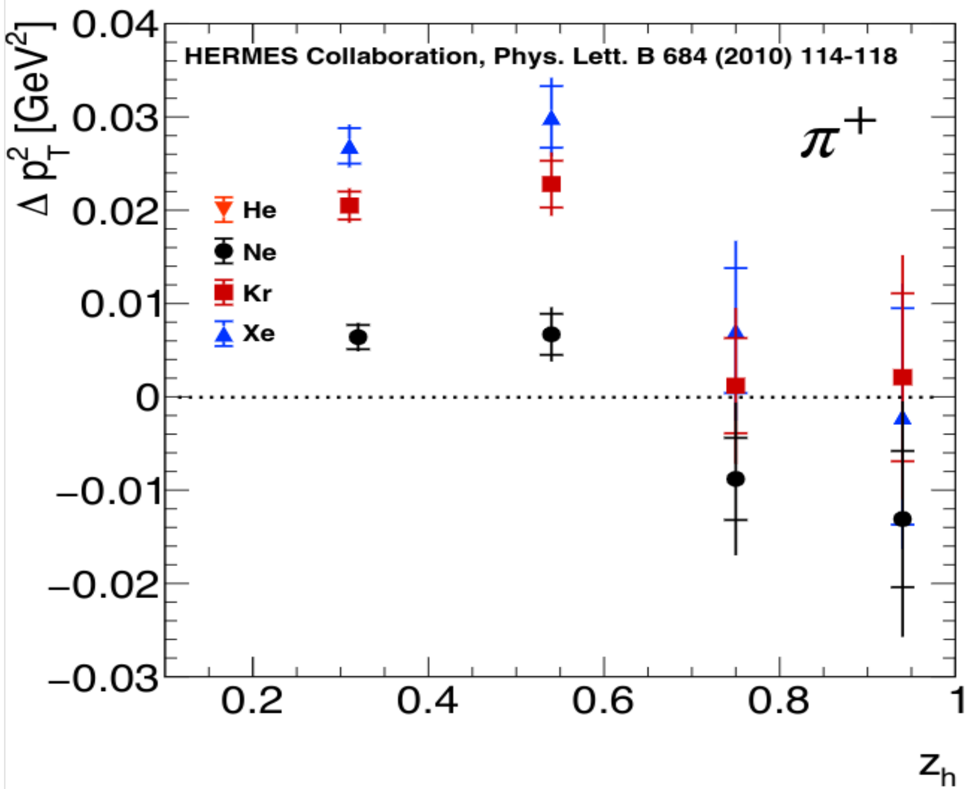
Phys. Rev. Lett. **130**, 142301 (2023)

- Measured p_T broadening increases with z and A;
- Trend favors $A^{1/3}$ dependence ⟹ Dominance of partonic stage within nuclei;

CLAS6 Λ p_T Broadening Results



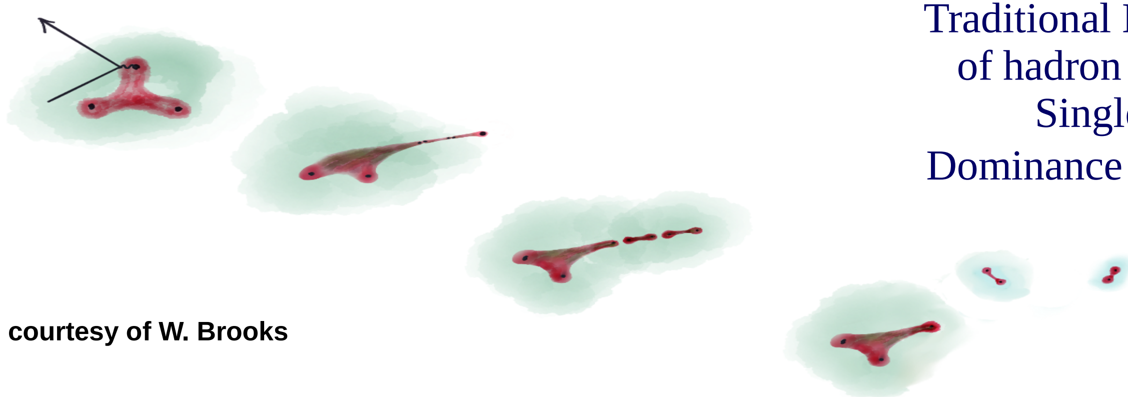
Phys. Rev. Lett. **130**, 142301 (2023)



- Measured p_T broadening increases with z and A;
- Trend favors $A^{1/3}$ dependence ⟹ Dominance of partonic stage within nuclei;
- Larger p_T broadening compared to HERMES meson results;

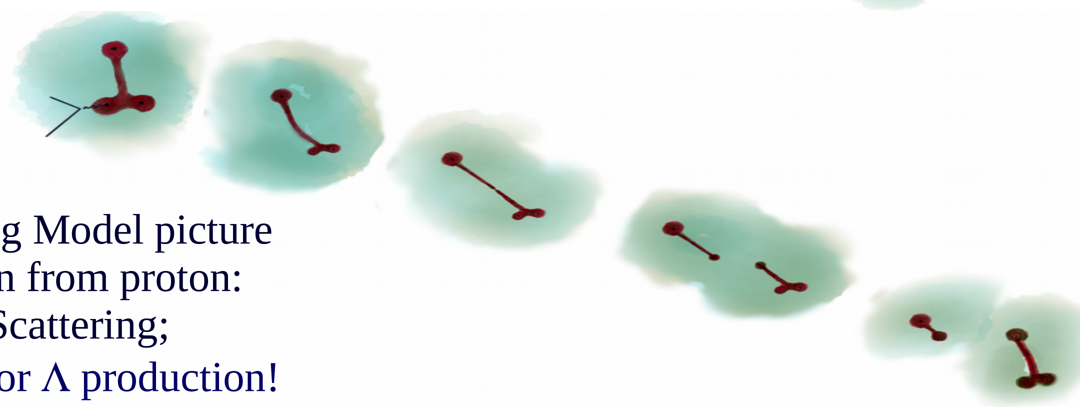
CLAS6 Λ p_T Broadening Results

- Larger p_T broadening compared to HERMES meson results:
  - *Could it be due to the size and mass of the propagating color object?*
  - Could it be that the *virtual photon is absorbed by a diquark instead of a single quark*?



Traditional Lund String Model picture of hadron production from proton: Single Quark Scattering; Dominance at low z for Λ production!

Sketch courtesy of W. Brooks



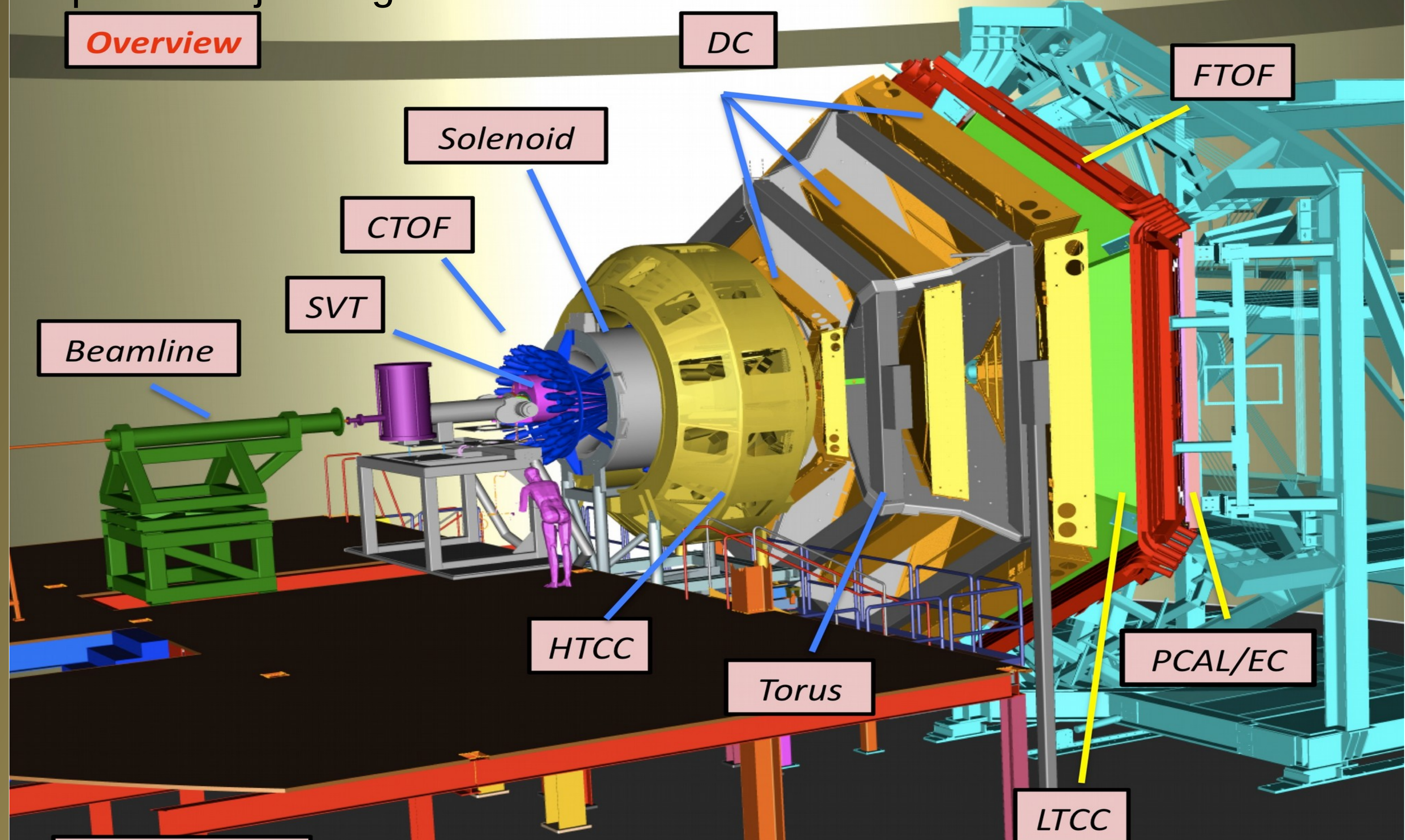
Alternative Lund String Model picture of hadron production from proton: Direct Diquark Scattering; Dominance at high z for Λ production!

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

Forthcoming nDIS Studies with CLAS12 @ JLab

- Design luminosity
  L ~ 10^{35} cm^{-2} s^{-1}
- High luminosity & large acceptance: concurrent measurement of exclusive, semi-inclusive, and inclusive processes
- Acceptance for photons and e⁻s:
  2.5° < θ < 125°
- Acceptance for all charged particles:
  5° < θ < 125°
- Acceptance for neutrons:
  5° < θ < 120°

https://www.jlab.org/Hall-B/clas12-web/



~ 111832 readout channels

Central Detector

Forward Detector

Forthcoming nDIS Studies with CLAS12: E12-06-117 Experiment

HERMES

CLAS6 *(done or ongoing)*

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

Forthcoming nDIS Studies with CLAS12: E12-06-117 Experiment

- Production of various hadrons off a wider range of nuclei

  ⟹ better understanding of hadron formation mechanism and A dependence;

- Cover much broader phase space with 10 times higher luminosity compared to CLAS6 (1E3 higher than Hermes)

  ⟹ Determines the two hadronization time-scales and constrain the competing theoretical models to describe them!

- Investigate the quark-diquark nucleon structure with more baryon channels.

meson	cτ	mass	flavor content	*baryon*	cτ	mass	flavor content
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	p	stable	0.94	ud
π^+, π^-	7.8 m	0.14	$u\bar{d}, d\bar{u}$	$\bar{p}$	stable	0.94	$\overline{ud}$
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	Λ	79 mm	1.1	uds
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K^0	27 mm	0.50	$d\bar{s}$	Ξ^0	87 mm	1.3	us
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HERMES

CLAS6 *(done or ongoing)*

Summary and Outlook

- The hadronization study is a direct probe of QCD confinement dynamics in cold and hot nuclear matter;
  - A detailed understanding of its mechanisms helps constrain the existing theoretical models.
- CLAS6 SIDIS production of lambda in the current and target fragmentation regions show
  - Similar trend as HERMES proton results but with more enhancement at low z;
  - Larger p_T broadening than those of mesons as an indication of diquark scattering!
  - Further calibration of theoretical models is needed to describe these results.
- CLAS12 measurements will provide the multi-dimensional data needed to extract the hadronization production and formation time-scales.
- The future EIC will extend ongoing hadronization studies to heavy quarks and provide a wider kinematics coverage to study the in-medium evolution, parton energy loss, and diquark correlations in nucleon structure.

Thank you !

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

Backup Slides

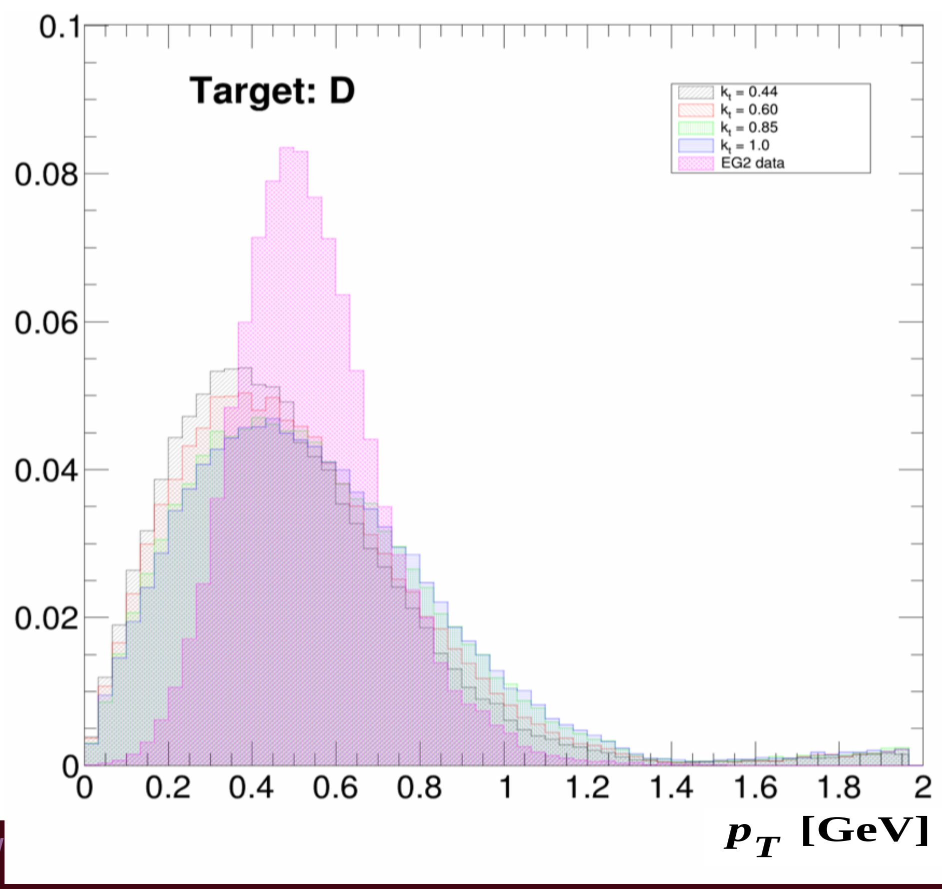
GIBUU Predictions for Lambda nDIS Production

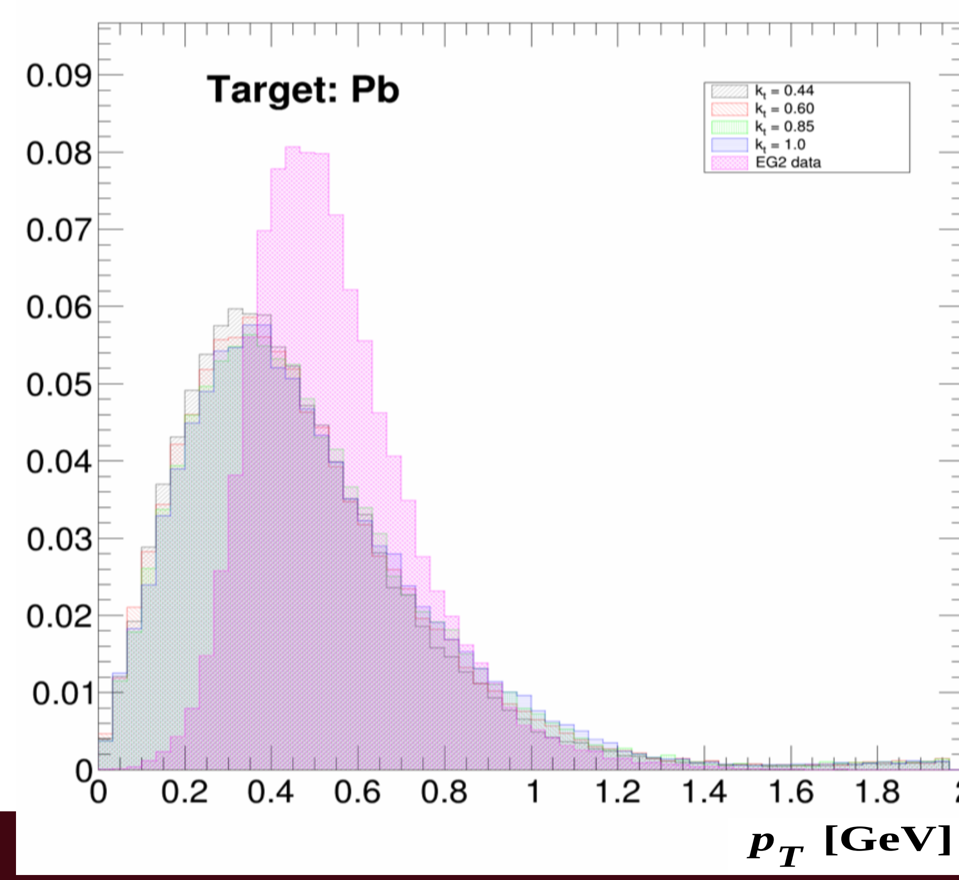
- GIBUU underestimates Λ p_T broadening due to

i. Inaccurate angular distribution in the initial elementary production process of Λ, or

ii. Final state interactions in the current model's string fragmentation functions are not realistic.

K. Gallmeister and U. Mosel, private communication (2022)





Systematic Uncertainties for Λ nDIS Analysis

- Multiplicity Ratios budget:
  - Particle identification cuts
  - Symmetric mass range (9σ)
  - Dual-target vertex corrections
  - Number of combinations of uncorrelated protons and pions pairs.
  - Different AC 6D map variables and bins
  - Variation of AC weight cuts
  - Different shapes of Breit Wigner functions: Relative BW, Ross-Stodolosky, and Soding
  - Variation of LD2 end caps correction
  - Radiative effects corrections
  - **Total point-to-point systematic uncertainties ≈ 6 to 30%**
  - **Total normalization uncertainties ≈ 1 to 3%**

- Transverse Momentum Broadening budget:
  - Particle identification cuts
  - Dual-target vertex corrections
  - Different AC 6D map variables and bins
  - Variation of AC weight cuts
  - Sideband background subtraction
  - Radiative effects corrections
  - **Total point-to-point systematic uncertainties ≈ 10% (1.4%) and 81% (8.5%) for *z (A)* dependence.**
  - **Total normalization uncertainties ≈ 1%**

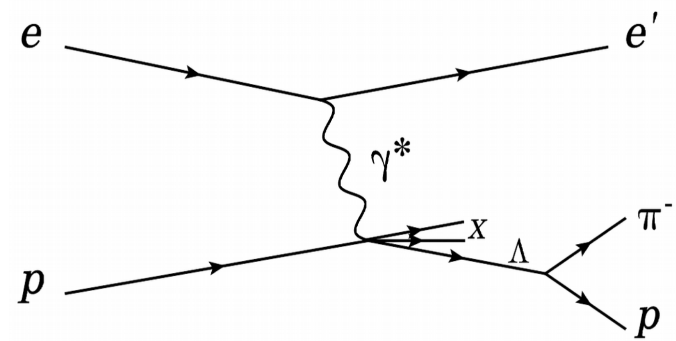
See Phys. Rev. Lett. **130**, 142301 (2023) and its Supplemental Material

Λ-analysis Cuts and Corrections

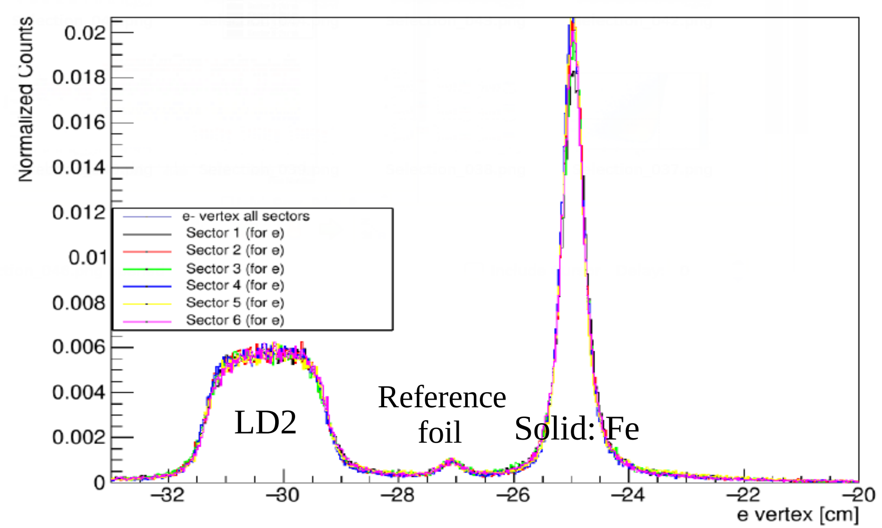
- Final-state lambda events: one e^- and at least one π^- and proton to identify lambdas.

SIDIS Λ production:

$e + p \longrightarrow e' + \Lambda + X$



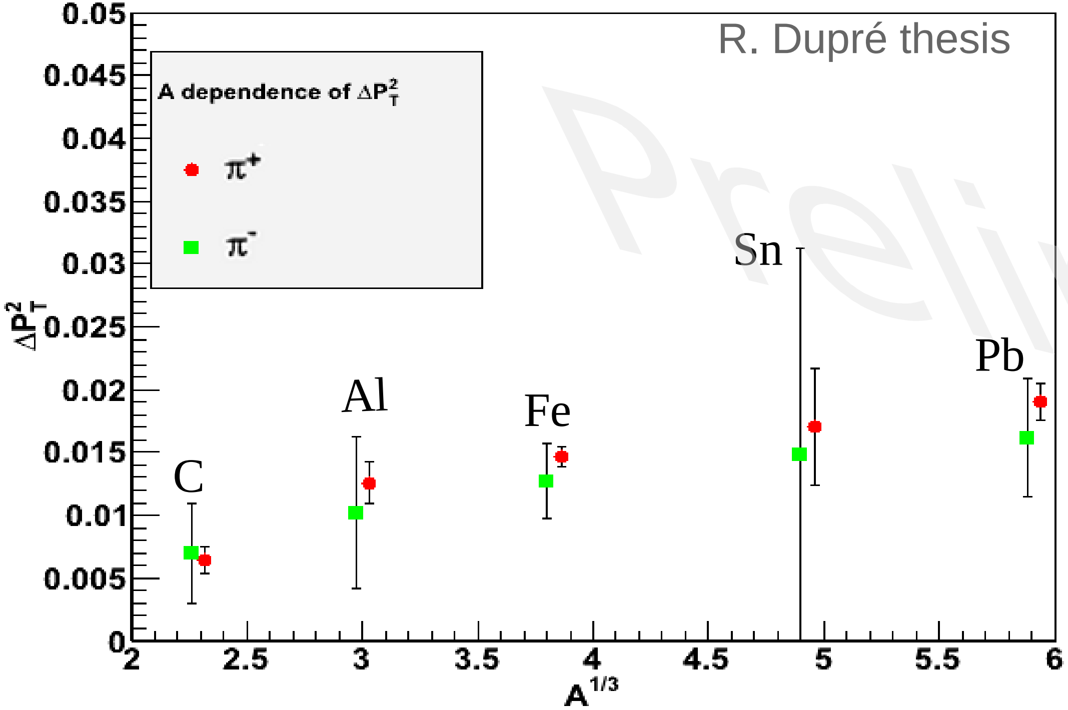
- Electron ID: Positive response in DC, CC, SC, and EC;
- Pion ID: Matching signal in DC and SC;
- Proton ID: Momentum dependent time analysis using ROOT's TSpline method;
- SIDIS cuts: $W > 2$ GeV, $Q^2 > 1$ GeV^2, and $y < 0.85$;
- Corrections:
  - Vertex corrections;
  - Proton energy loss and electron momentum corrections;
  - CLAS6 acceptance corrections (AC);
  - Radiative corrections based on Pythia and RadGen event generators;
  - LD2 end caps corrections.



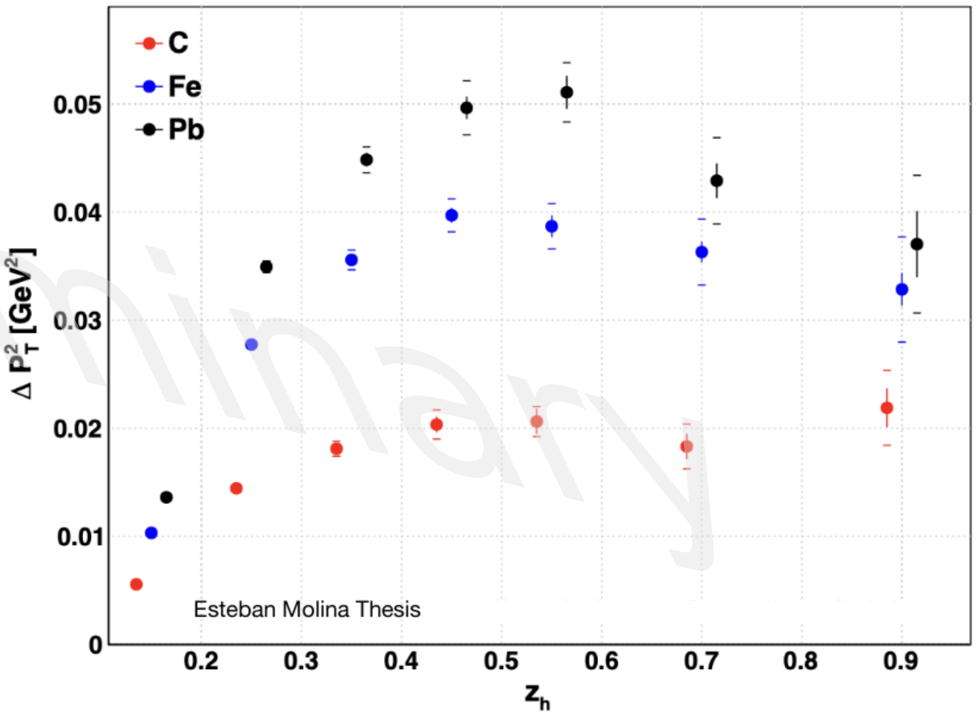
Corrected e^- vertex distributions for CLAS6 six sectors

See Phys. Rev. Lett. **130**, 142301 (2023) and its Supplemental Material

Preliminary CLAS6 p_T Broadening: Charged Pions

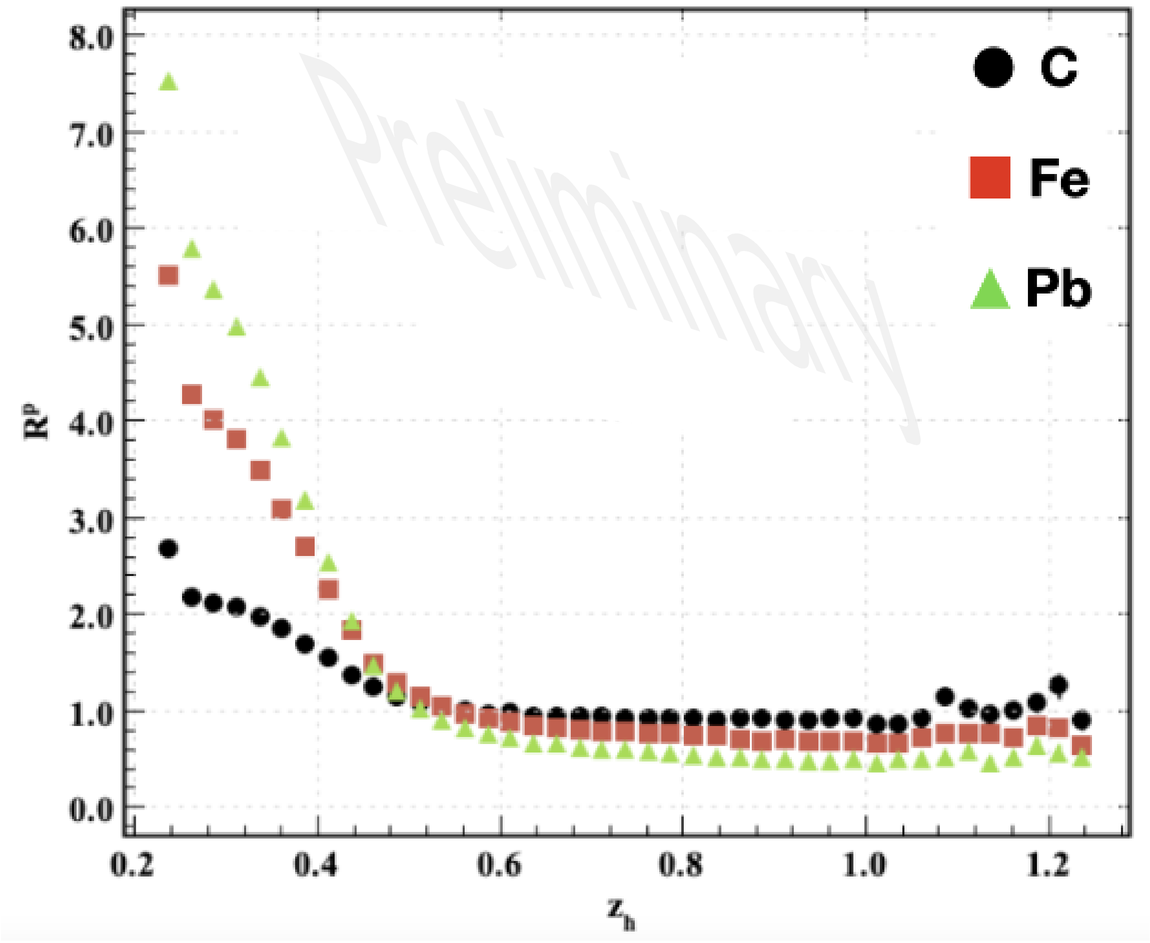


(Slight shift was added for clarity)



- Preliminary charged pions results show similar behavior, but smaller broadening!

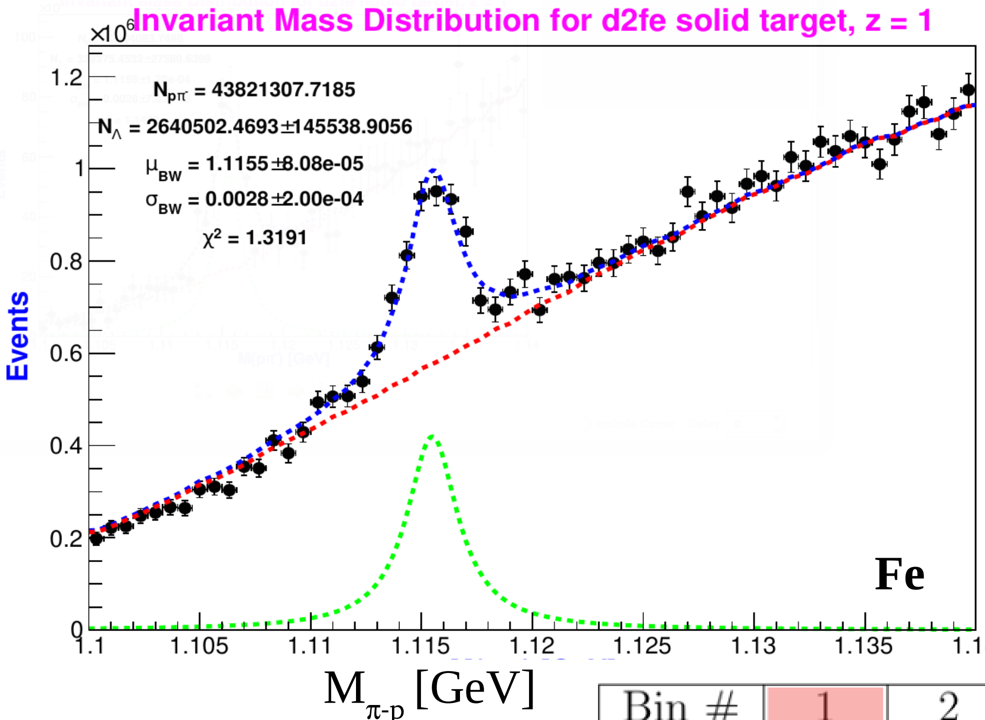
Preliminary CLAS6 Proton Multiplicity Ratios

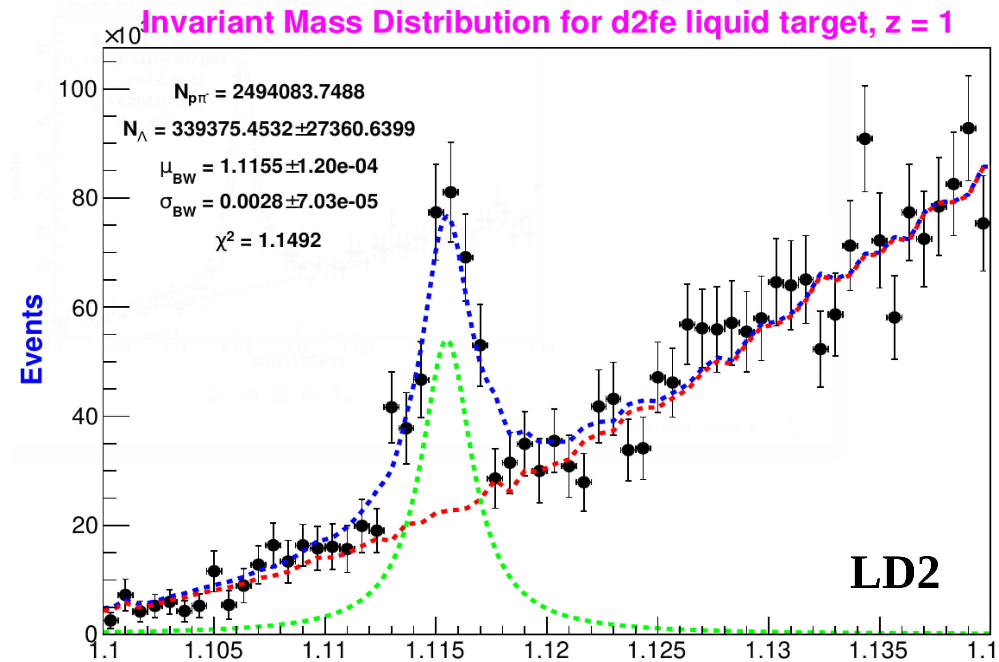


M. Wood, J.P. Garces *et al.* (2023)

Lambda Yield Extraction

- Identify Λ via its decay particles, π^- and p;
- Use event mixing technique and RooFit modeling and fitting toolkit for CB subtraction;
- (π^-, p) invariant mass after CB subtraction to extract Λ yield (*dashed distribution*).





$z\ (= E_\Lambda / \nu)$

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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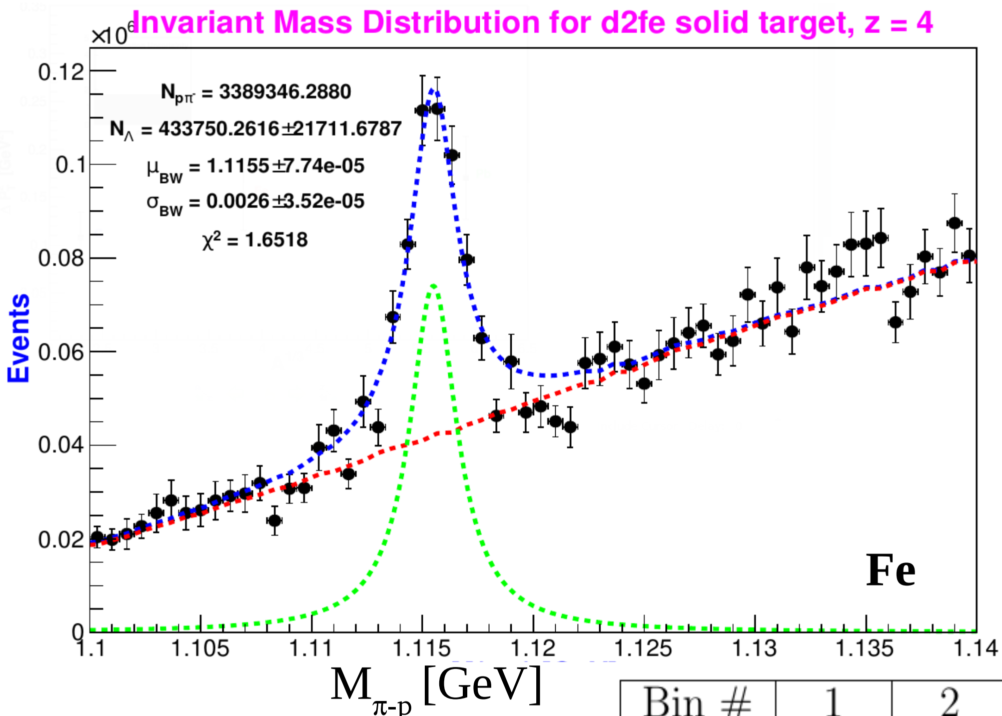

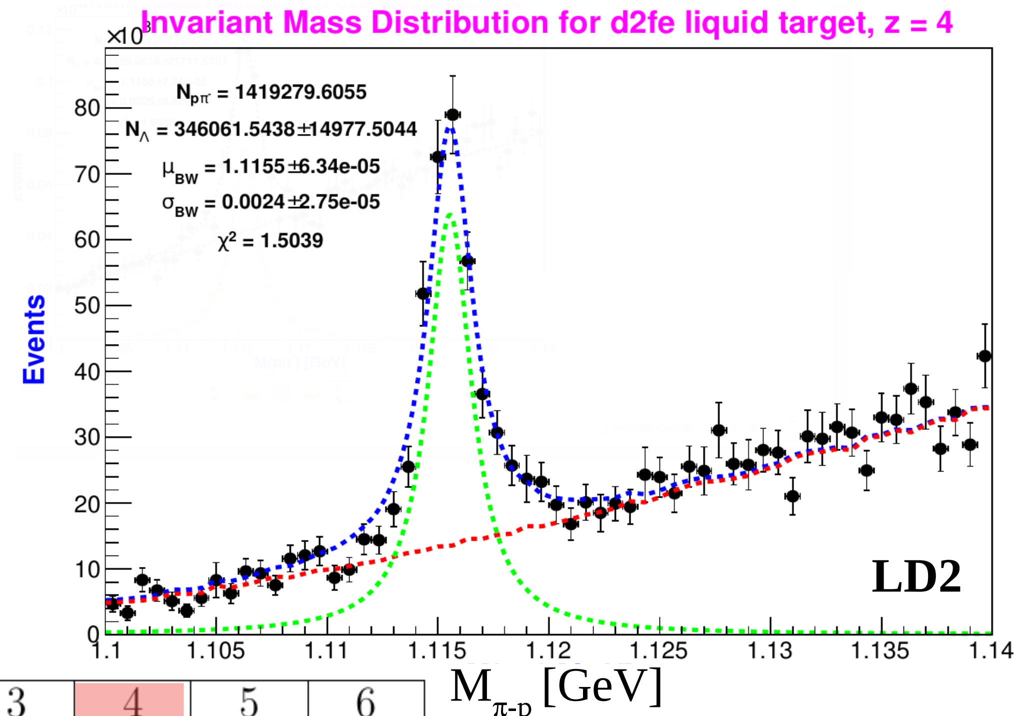

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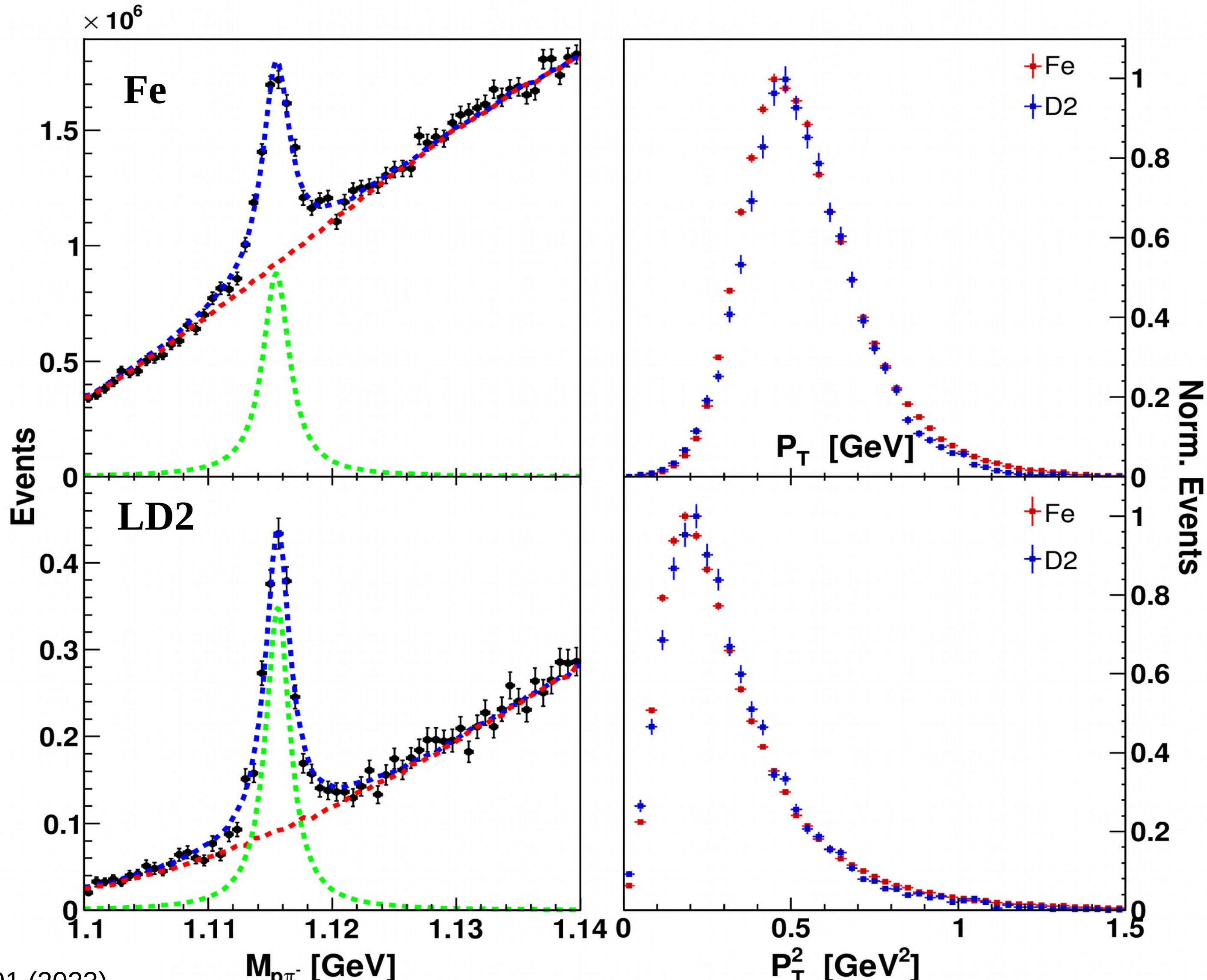
Lambda Kinematics and Mass Distributions



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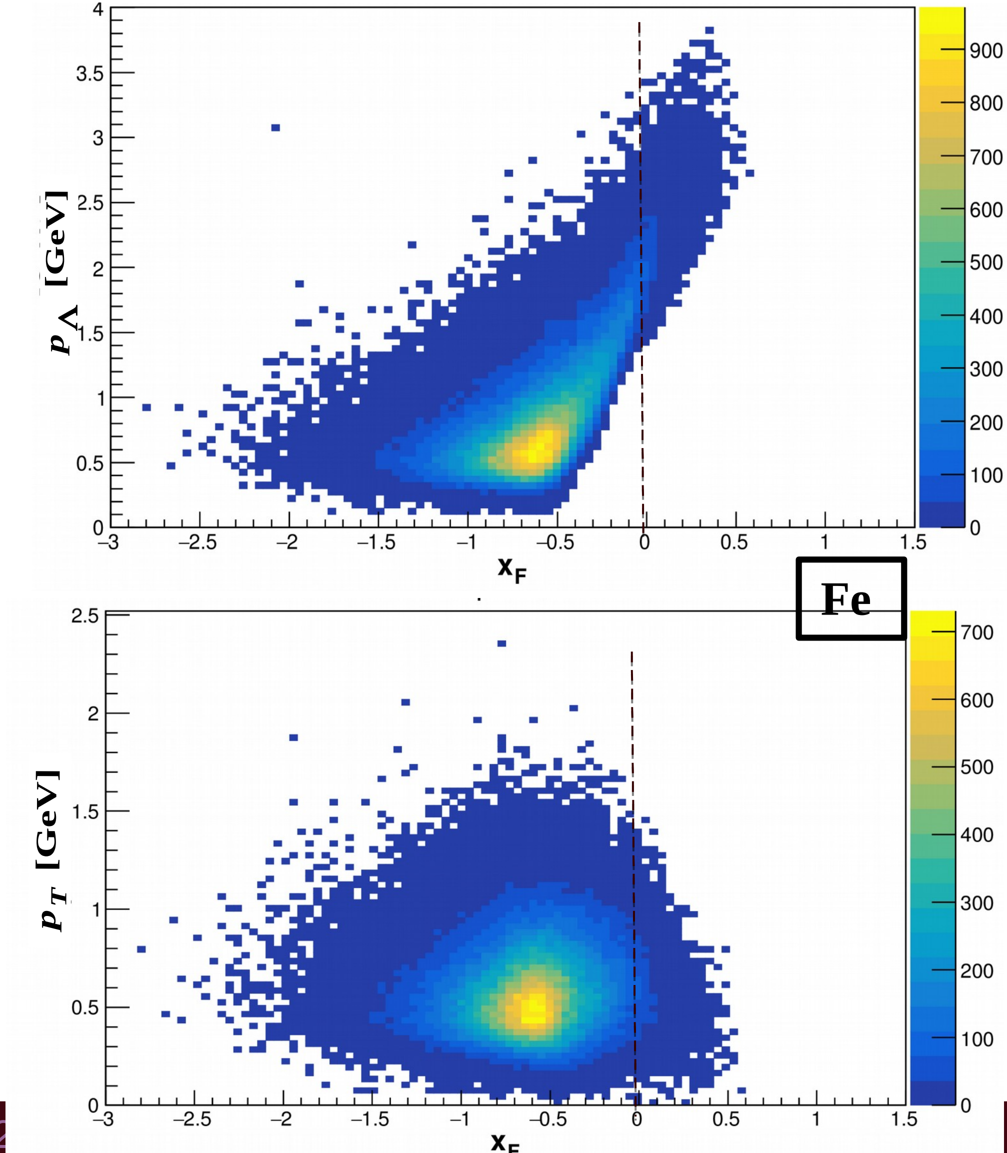
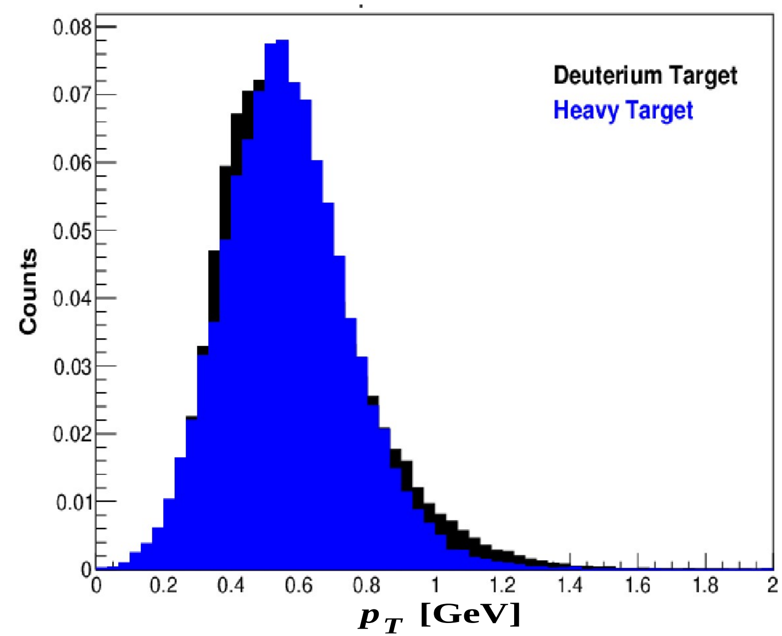
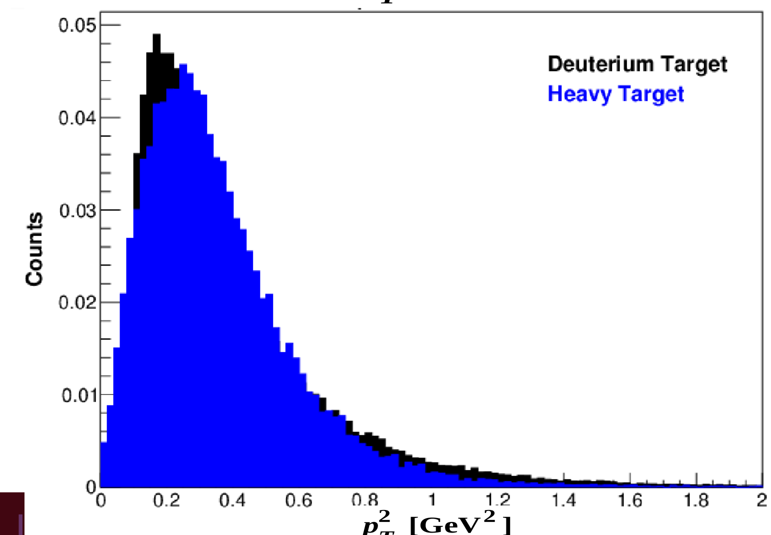
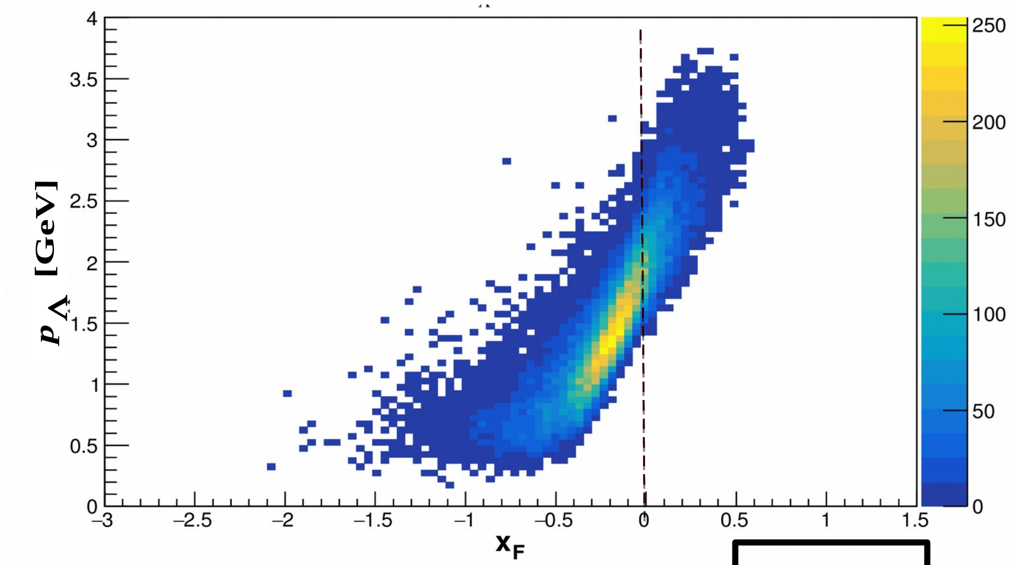
Lambda Kinematics

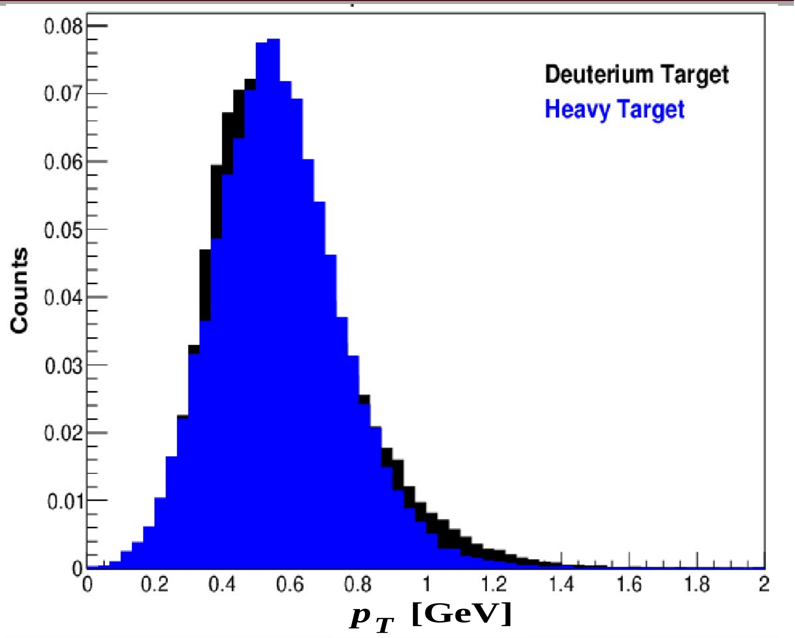




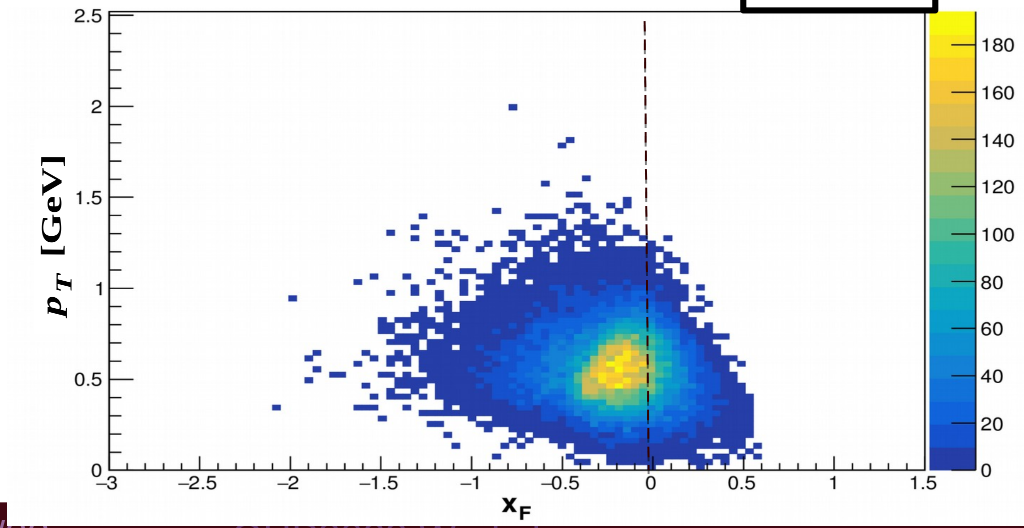


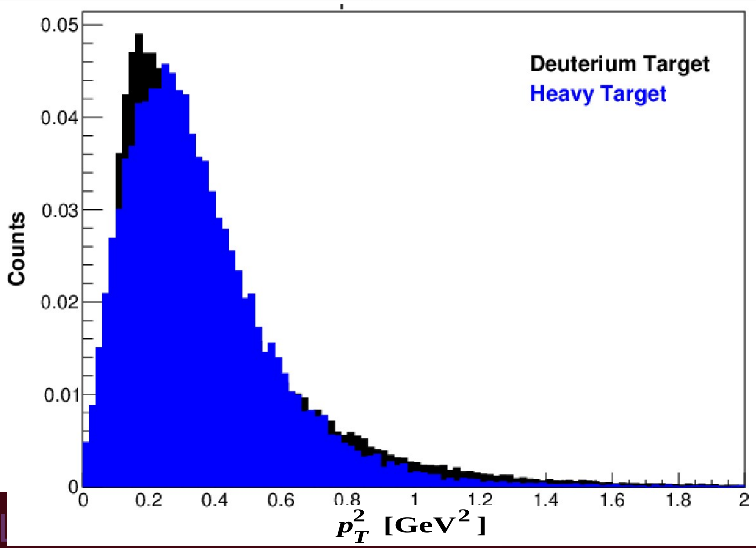
Lambda Kinematics





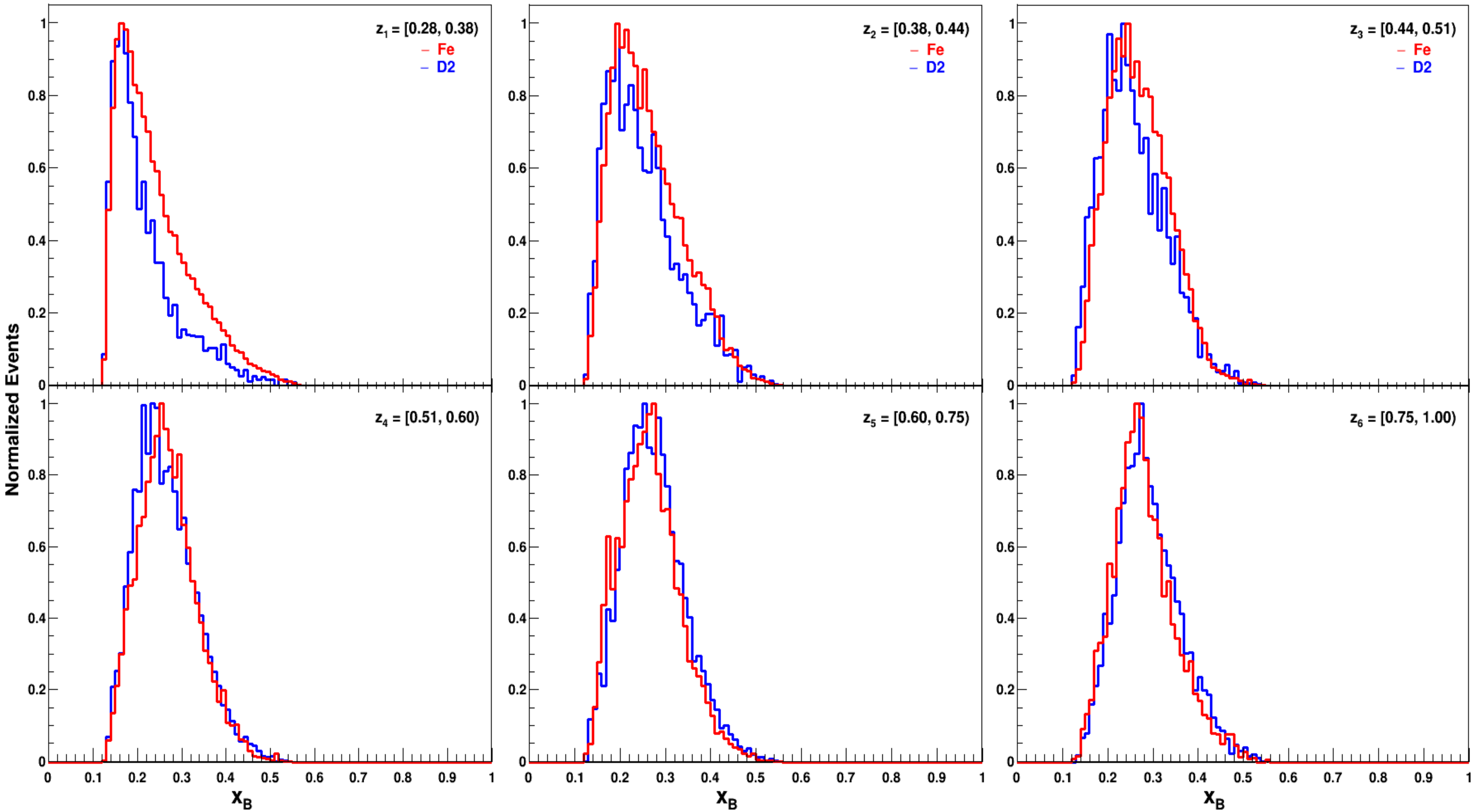
LD2





Lambda Kinematics

See Phys. Rev. Lett. **130**, 142301 (2023) and its Supplemental Material



CLAS6 Acceptance Correction for Λ nDIS Analysis

Total Bins = 648

Variable	Range	# of Bins	Bin width
W [GeV]	2.0 – 2.8	2	0.4
ν	2.25 – 4.25	3	$0.\overline{6}$
$\phi_{\pi-}$ [deg]	0.0 – 360.0	2	180.0
$\Phi_{e'\Lambda}$ [deg]	0.0 – 360.0	3	120.0
p_Λ [GeV/c]	0.1 – 4.25	3	$1.3\overline{83}$
z	0.28 – 1.0	6	vary♦

W: Total CM energy
ν: Electron energy loss
$\phi_{\pi-}$: Decay angle of π^- in Λ rest frame
$\Phi_{e\Lambda}$: Angle between leptonic and hadronic planes
p_Λ: Λ momentum
z: Fraction of the struck quark's initial energy carried by the formed hadron

- Generated 1B Λ events using PYTHIA event generator for each target (Fe, C, Pb, and LD2)
- Six dimensional (6D) binning
- z-bins♦ :

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

$$Bin, \quad k = (W, \nu, \phi^*_{\pi^-}, p_\Lambda, \Phi_{e'\Lambda}, z)$$

$$eff_k = \frac{N_{acc}(W, \nu, \phi^*_{\pi^-}, p_\Lambda, \Phi_{e'\Lambda}, z)}{N_{gen}(W, \nu, \phi^*_{\pi^-}, p_\Lambda, \Phi_{e'\Lambda}, z)}$$

$$\text{Weight}, \quad w_k = \frac{1}{eff_k}$$

See Phys. Rev. Lett. **130**, 142301 (2023) and its Supplemental Material