Study of Hadronization Dynamics via Electroproduction off Nuclei at Jefferson Lab

2024 CP
IWHS COMPASS
Yerevan Armenia

September 30th, 2024

Lamiaa El Fassi
Mississippi State University

MISSISSIPPI STATE UNIVERSITY

clas
CEBAF Large Acceptance Spectrometer

U.S. DEPARTMENT OF ENERGY
Office of Science

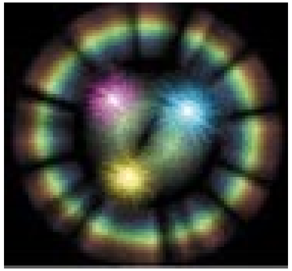
Outline

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

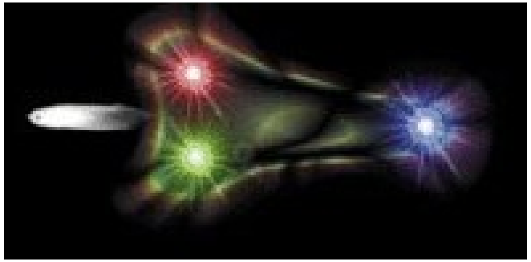
How does the colored bare, quark, evolves to a fully dressed hadron?

- Probe QCD confinement dynamics via hard scattering:

Nucleon



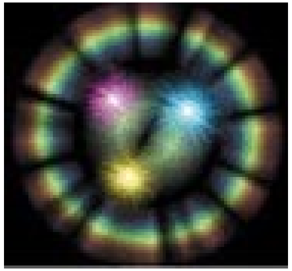
Hard Probe
+
Nucleon



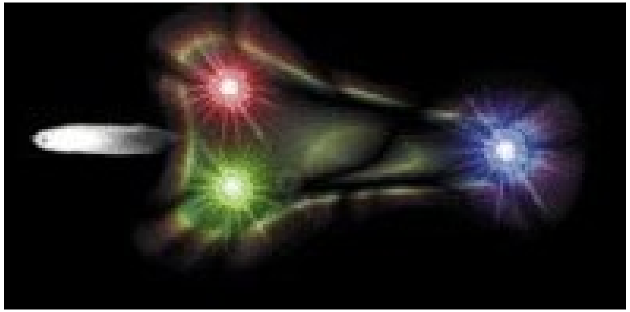
How does the colored bare, quark, evolves to a fully dressed hadron?

- Probe QCD confinement dynamics via hard scattering:

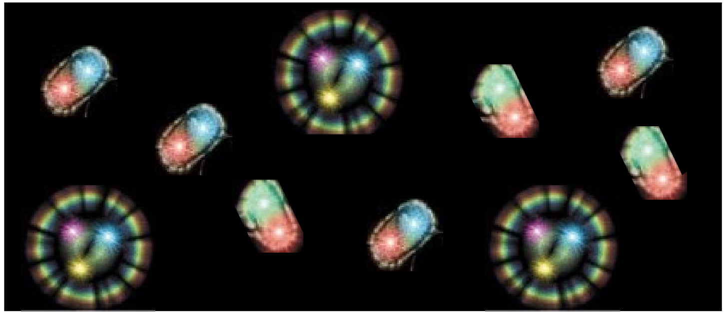
Nucleon



Hard Probe
+
Nucleon



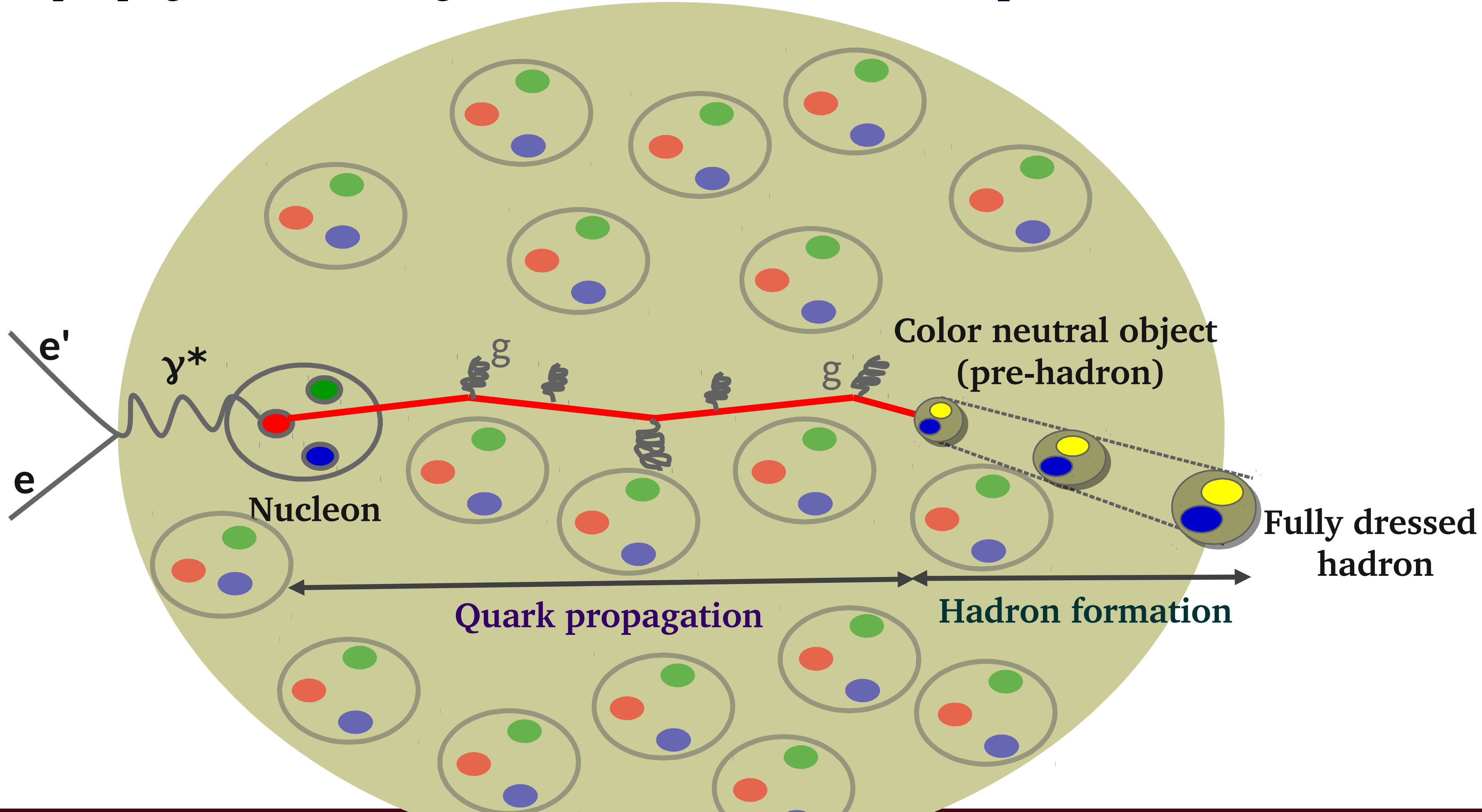
Hadron fragmentation from struck color objects



Images from CERN Courier Strong Interactions Feature (2004)

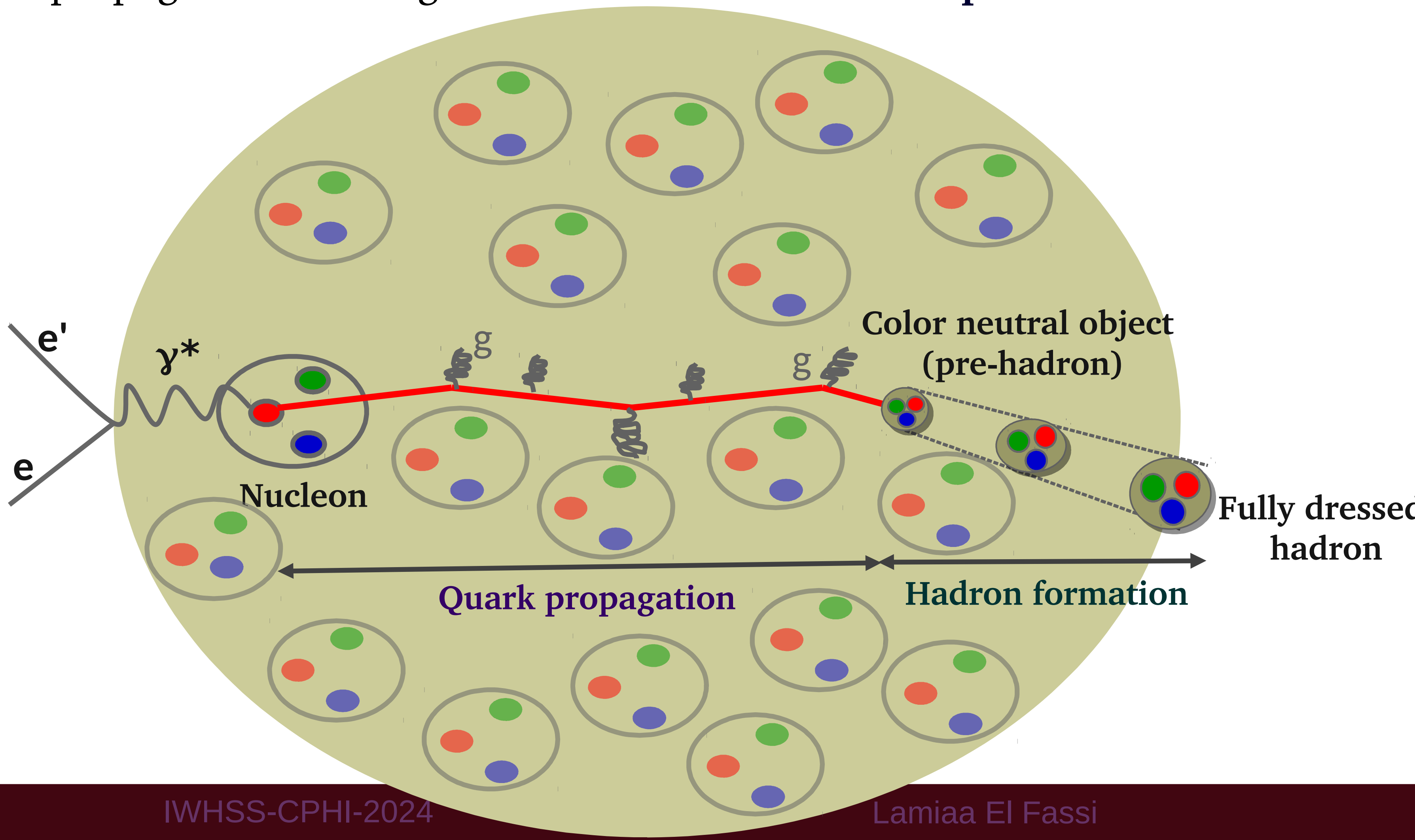
How does the colored bare, quark, evolves to a fully dressed hadron?

- 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?

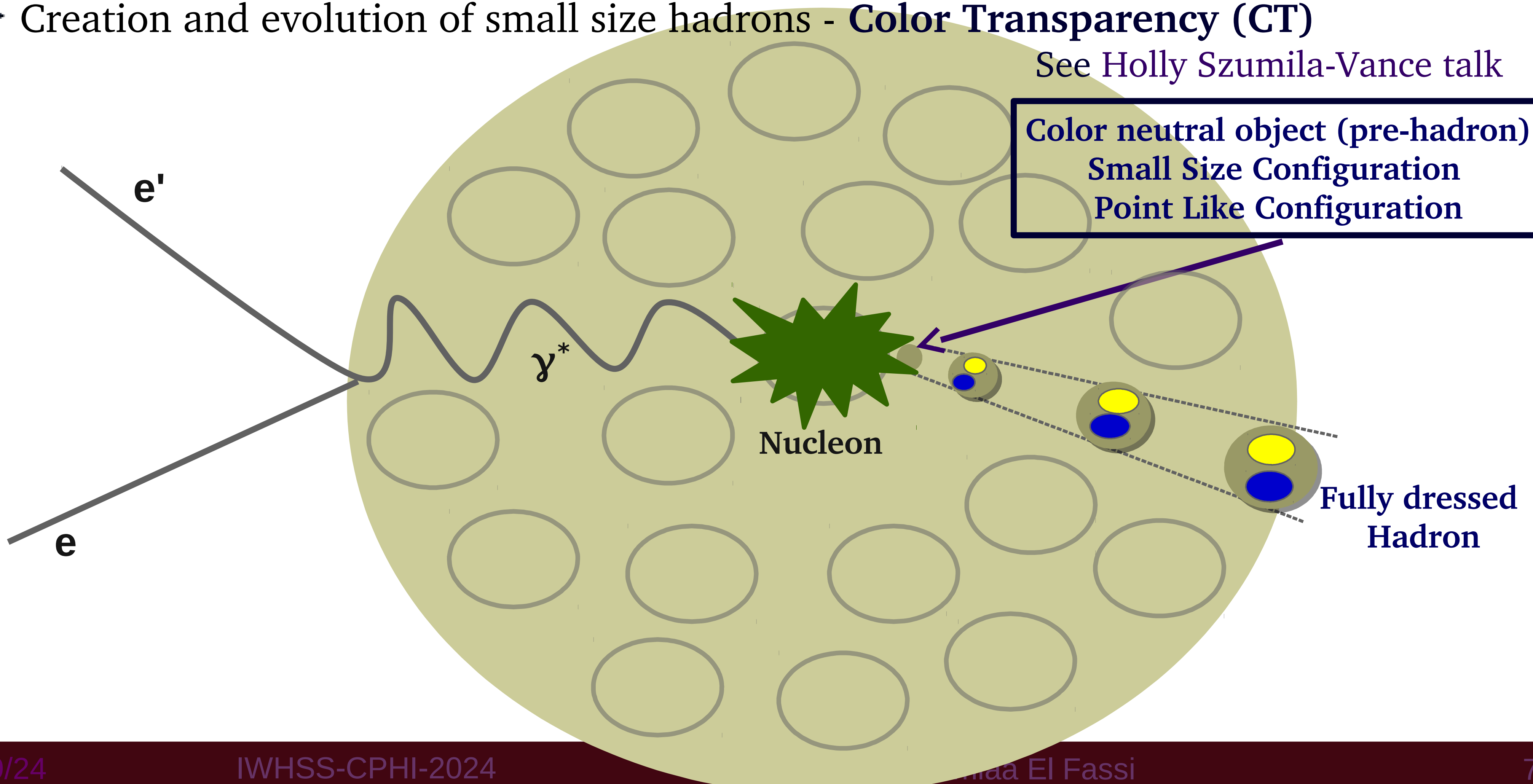
- Study hard processes in nuclei to probe QCD confinement dynamics:
  - Color propagation and fragmentation - **Hadronization process**



Hadron Formation Complementarity

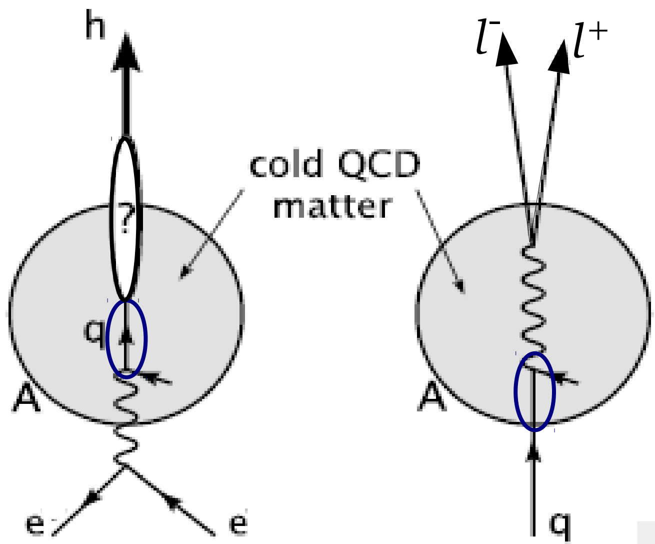
- Study hard processes in nuclei to probe QCD confinement dynamics:
  - Color propagation and fragmentation - **Hadronization process**
  - Creation and evolution of small size hadrons - **Color Transparency (CT)**

See Holly Szumila-Vance talk



Nuclear Deep Inelastic Scattering (DESY, JLab):

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



nDIS DY

Drell-Yan process (Fermilab, CERN):

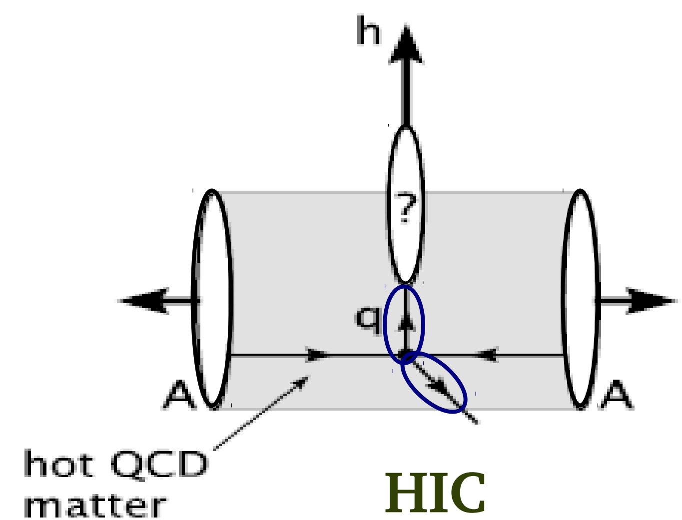
- Quark propagation
- Initial state interactions (ISIs) effects

See Liliet Calero Diaz talk

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

Heavy Ion Collisions (RHIC, CERN):

- Quark propagation
- Hadron Formation
- ISIs and FSIs effects

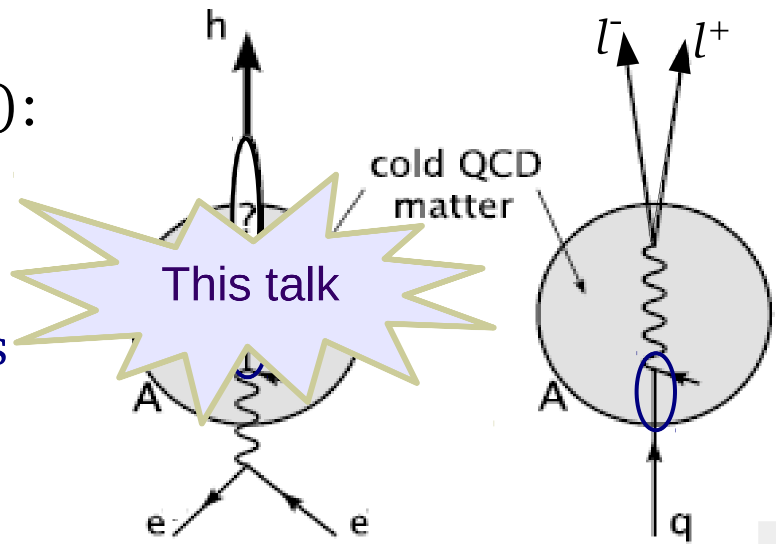


HIC

Complementarity in Studying Hadronization Stages

Nuclear Deep Inelastic Scattering (DESY, JLab):

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



nDIS

DY

Drell-Yan process (Fermilab, CERN):

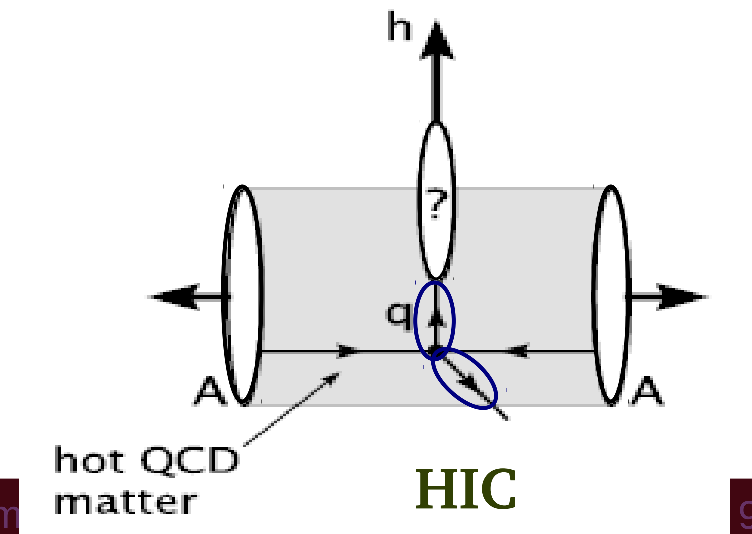
- Quark propagation
- Initial state interactions (ISIs) effects

  See Liliet Calero Diaz talk

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

Heavy Ion Collisions (RHIC, CERN):

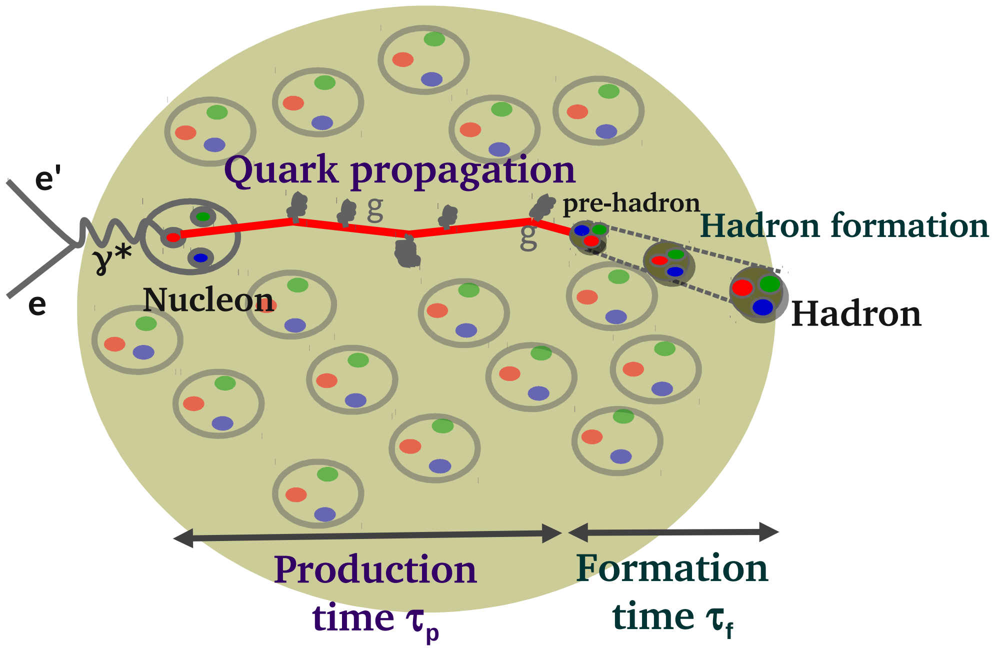
- Quark propagation
- Hadron Formation
- ISIs and FSIs effects



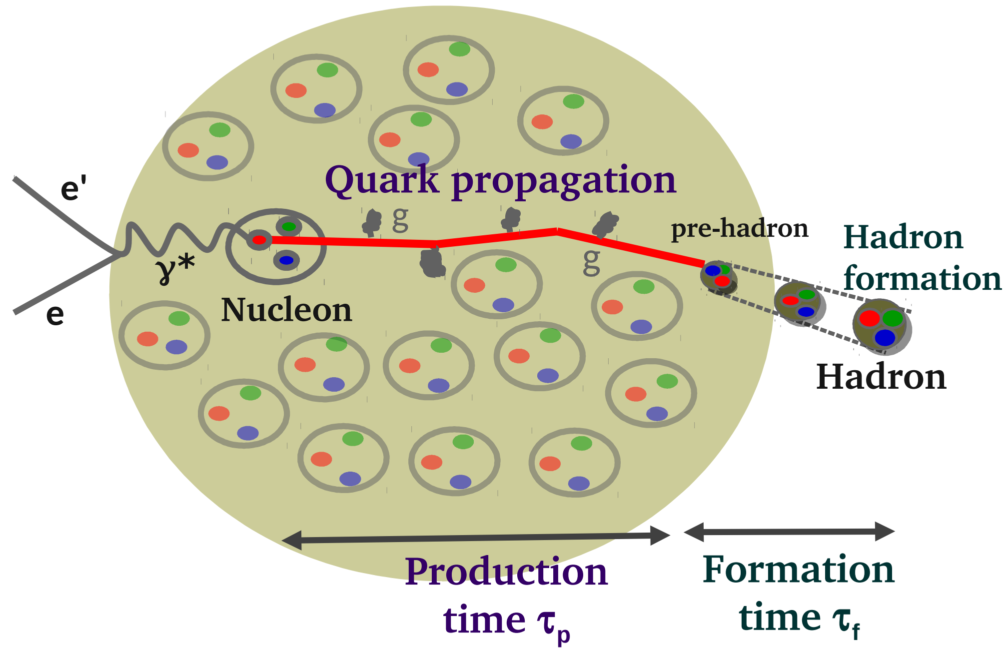
HIC

Probing 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

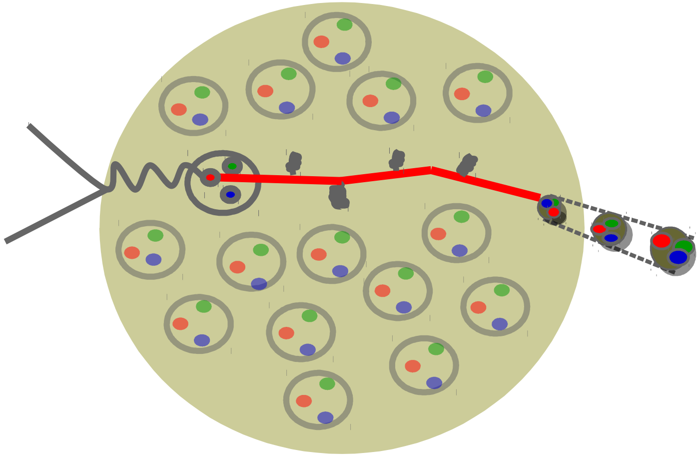


Hadron formation outside the nuclear medium dominates at high energies

Probe Hadronization Time-distance Scales

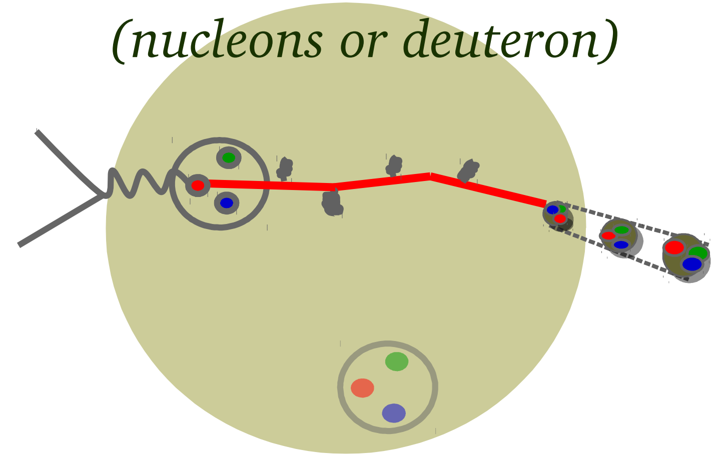
- Explore SIDIS production to access the hadronization time-distance scales
  ⟹ their extraction via a comparison of QCD dynamics in

Medium



Vacuum

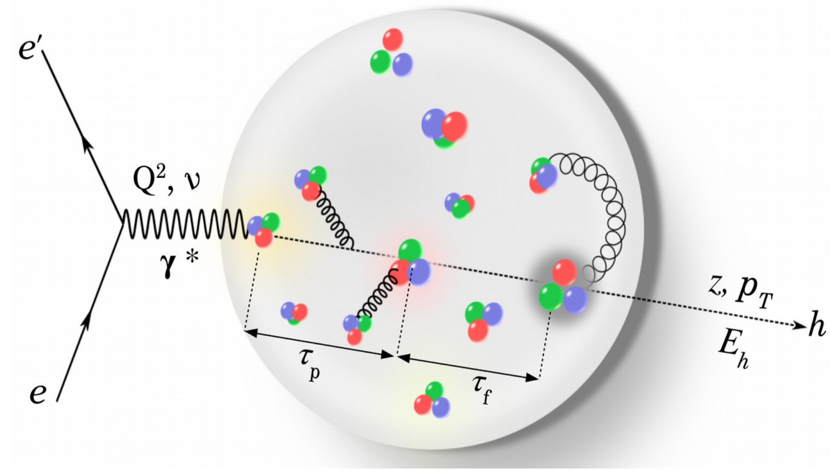
(nucleons or deuteron)



- **Production time τ_p**: time spent by a deconfined quark to neutralize its color charge
  ⟹ Transverse momentum broadening due to medium-stimulated parton energy loss via gluon bremsstrahlung

- **Formation time τ_f**: time required to form a regular hadron (h)
  ⟹ Hadron suppression in measured multiplicity ratios due to (pre)hadron elastic or inelastic scattering and/or energy loss of hadron-fragmented struck quark(s)

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;

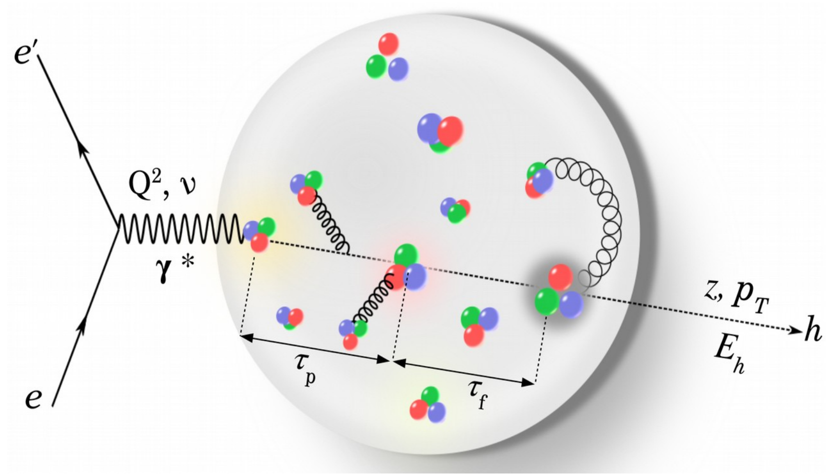
$W = \sqrt{M_n^2 + 2\nu M_n - Q^2}$: Total mass of the hadronic final state, where M_n is the nucleon mass

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



Drawing courtesy of T. Chetry (former postdoc)

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

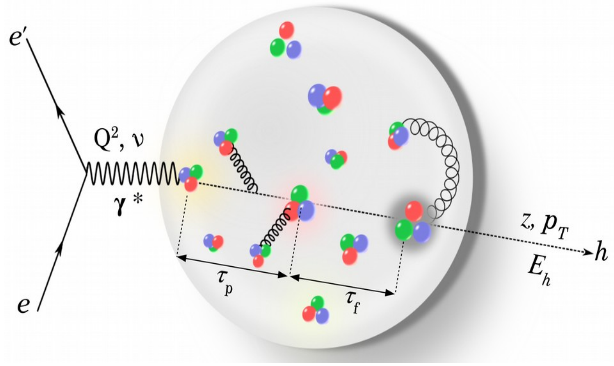
< 0, selects the backward (target) fragmentation region

Later discussion

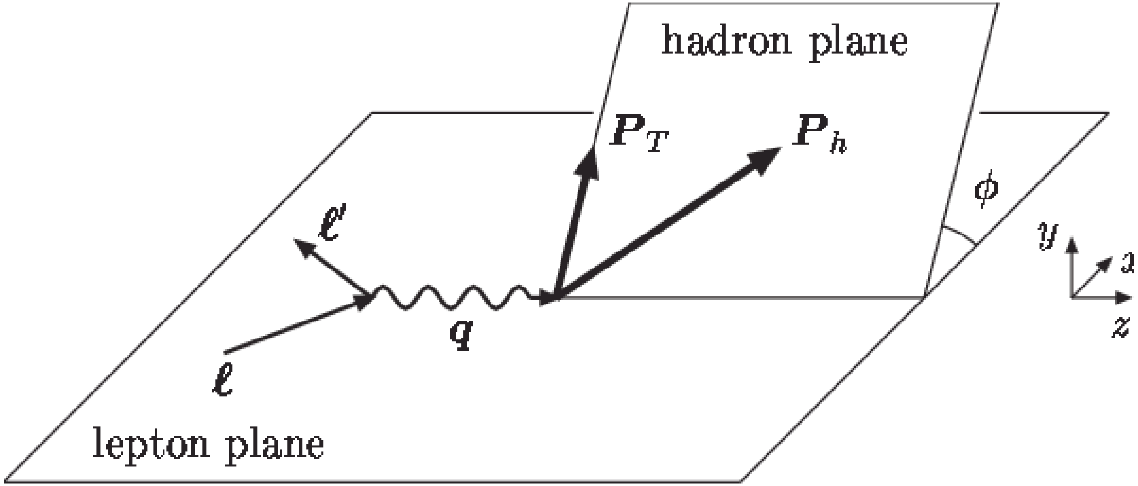
Experimental Observables

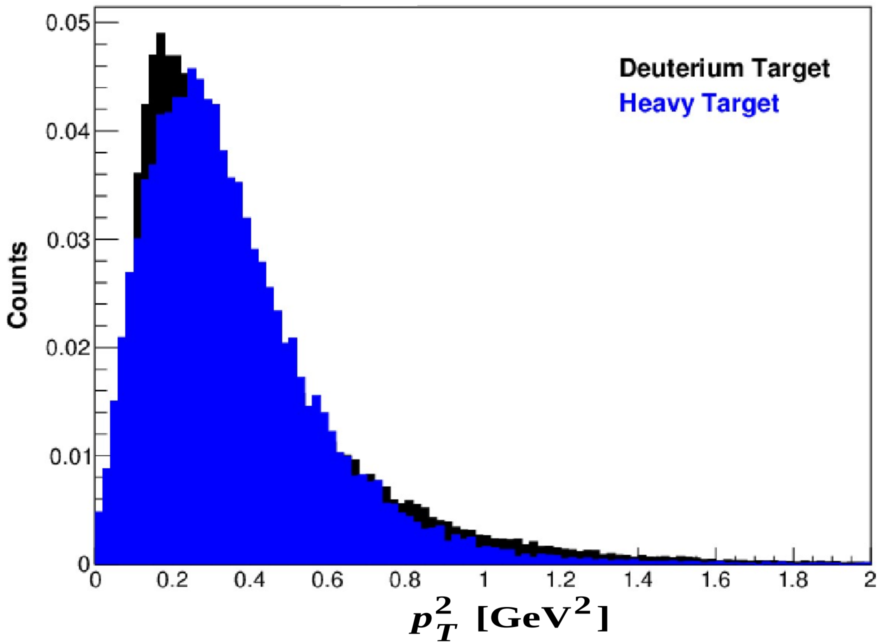
Transverse Momentum Broadening

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



Grant access to τ_p via production of different hadrons and quark flavors off various nuclei

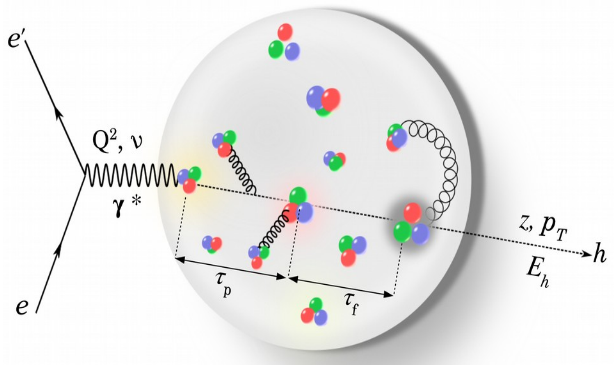




Experimental Observables

Transverse Momentum Broadening

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

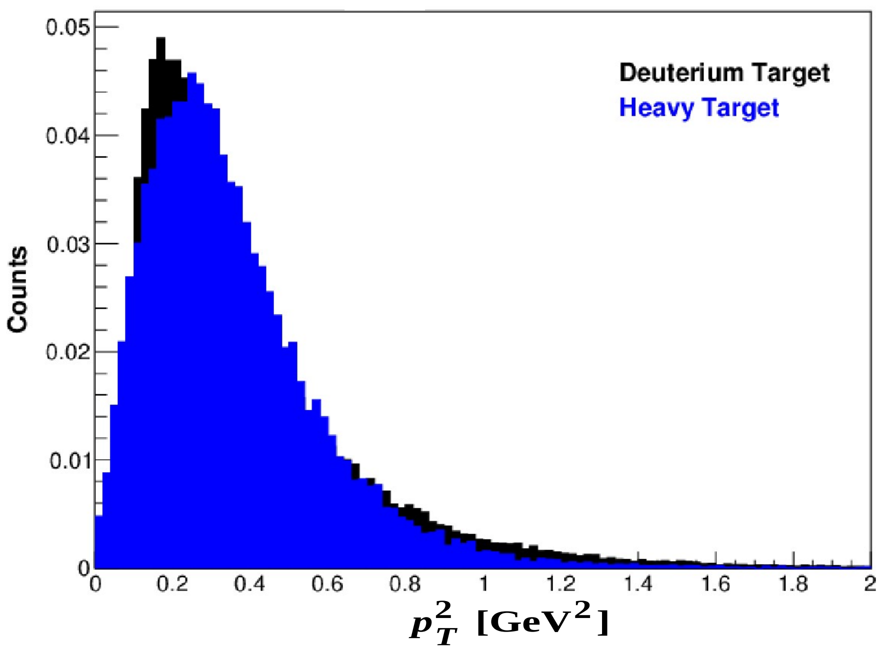


Grant access to τ_p via production of different hadrons and quark flavors off various nuclei

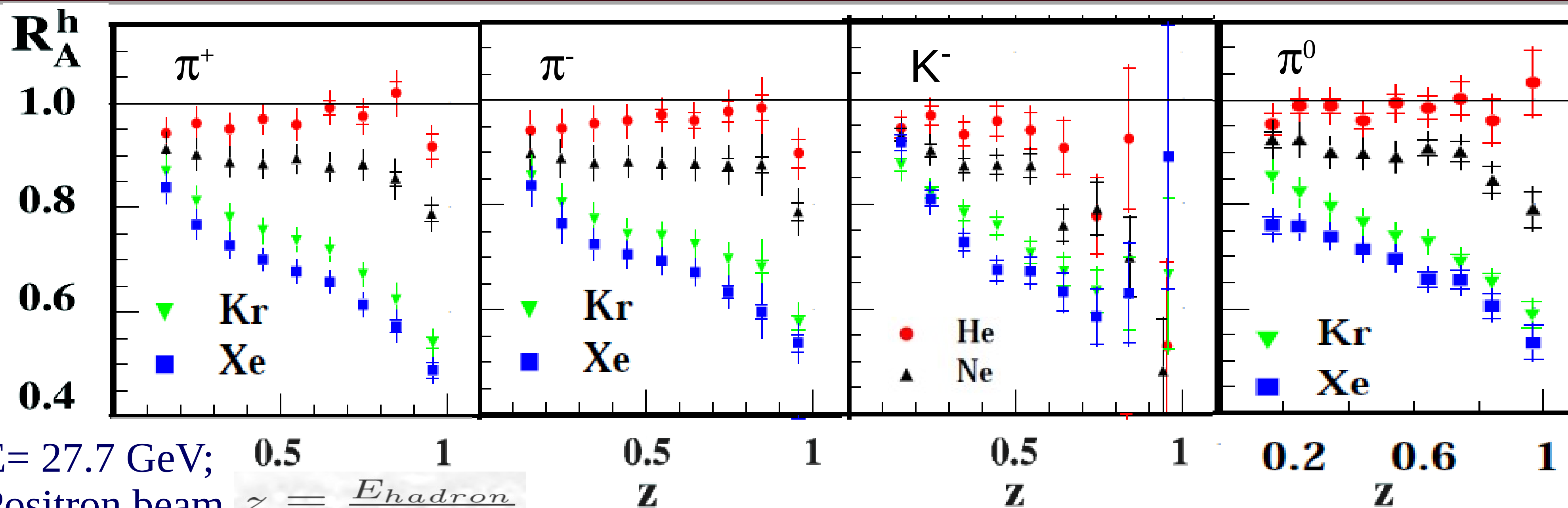
Hadron Multiplicity Ratio

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

Grant access to τ_f after the extraction of τ_p



Previous Study: HERMES Multiplicity Ratios

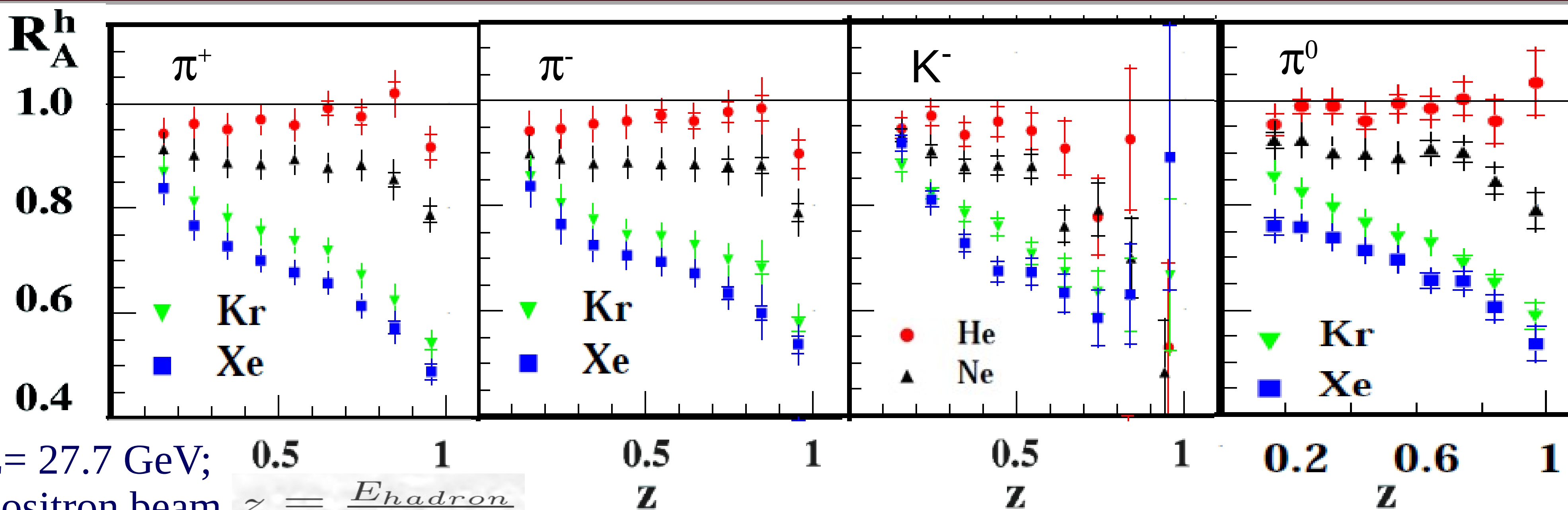


E= 27.7 GeV;
Positron beam $z \equiv \frac{E_{hadron}}{\nu}$

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

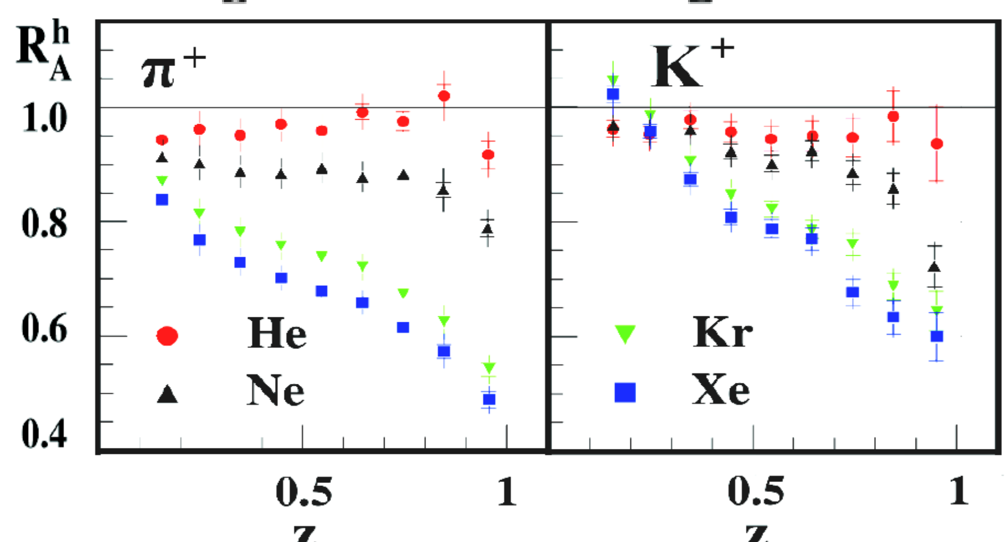
- Pions flavors and K^- experienced similar attenuation.

Previous Study: HERMES Multiplicity Ratios



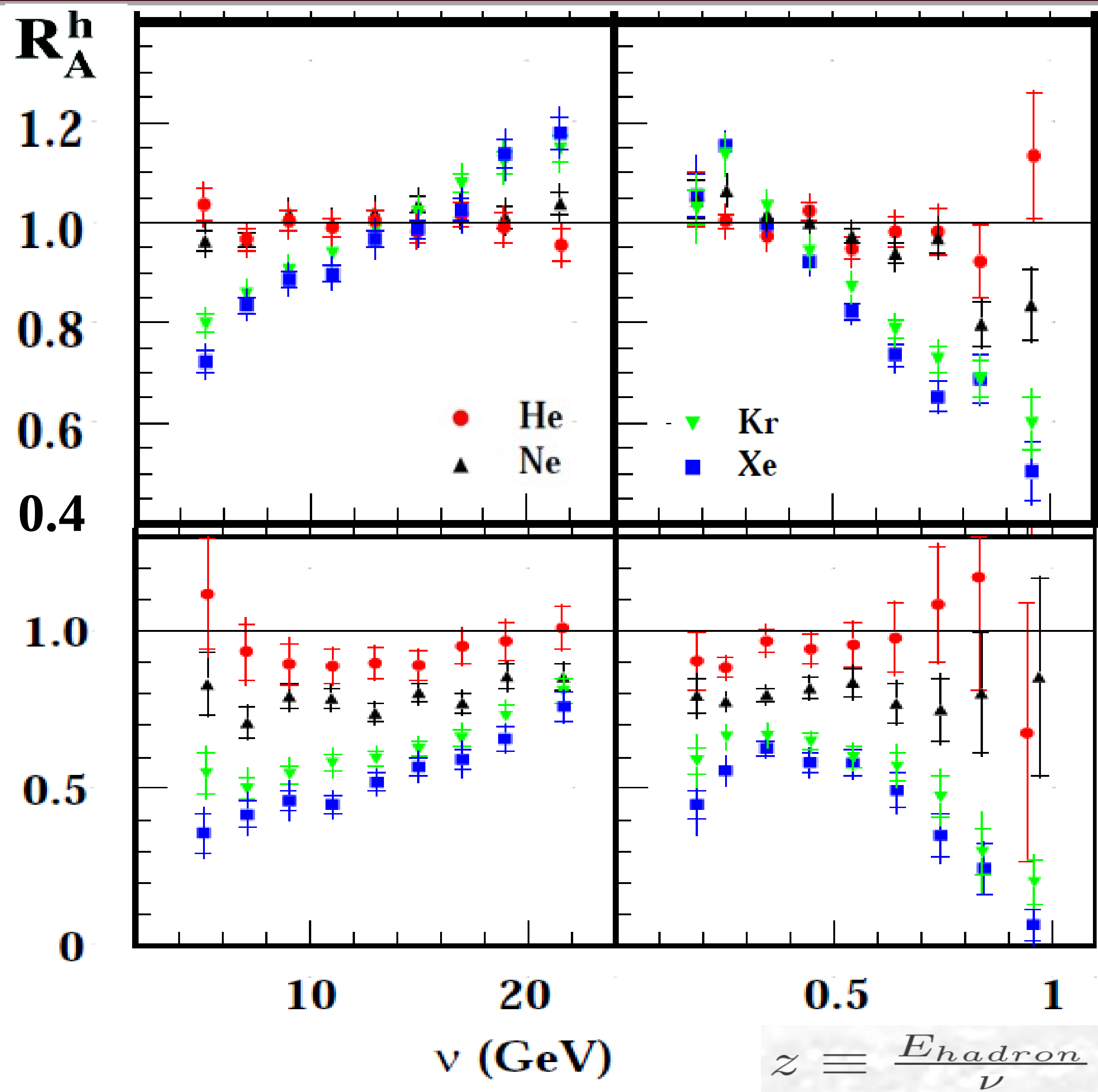
E= 27.7 GeV;
Positron beam $z \equiv \frac{E_{hadron}}{\nu}$

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



- 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 region.

Previous Study: HERMES Multiplicity Ratios



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

E= 27.7 GeV; Positron beam

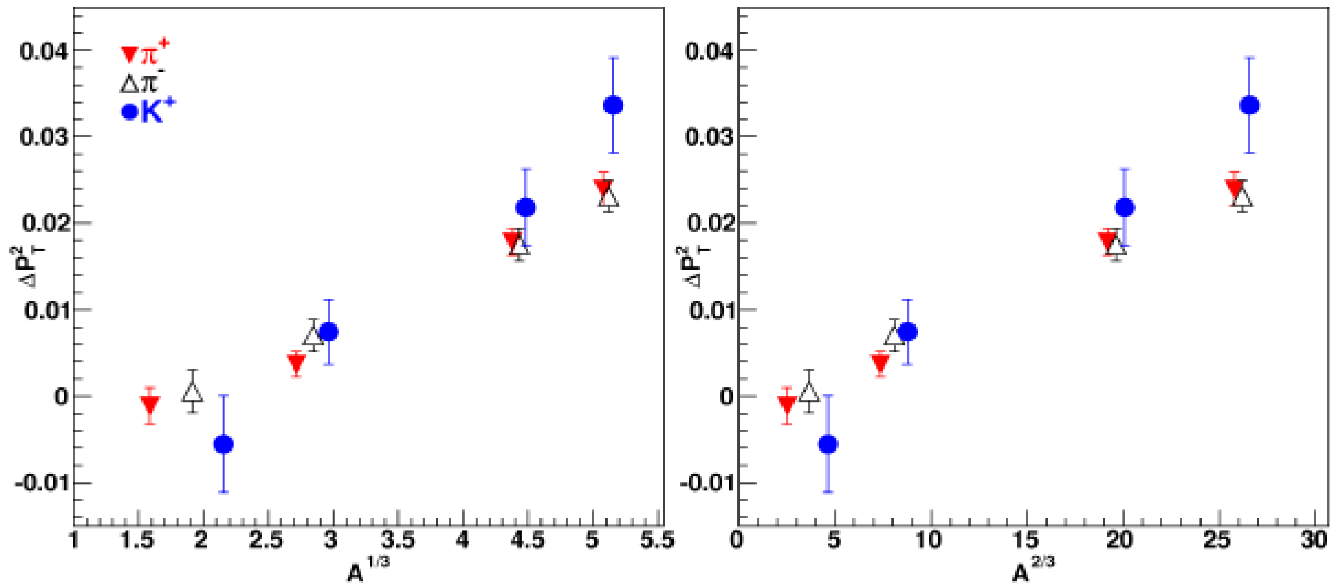
Protons

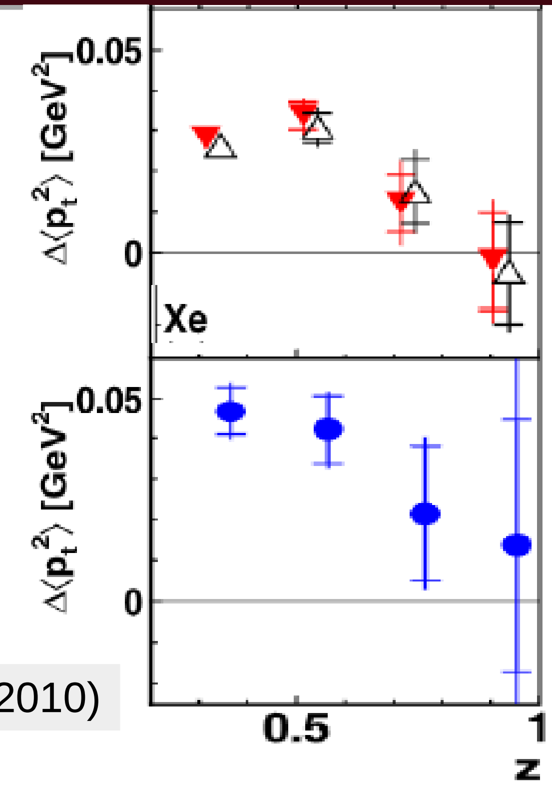
Antiprotons

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

Previous Study: HERMES p_T Broadening

E= 27.7 GeV; Positron beam



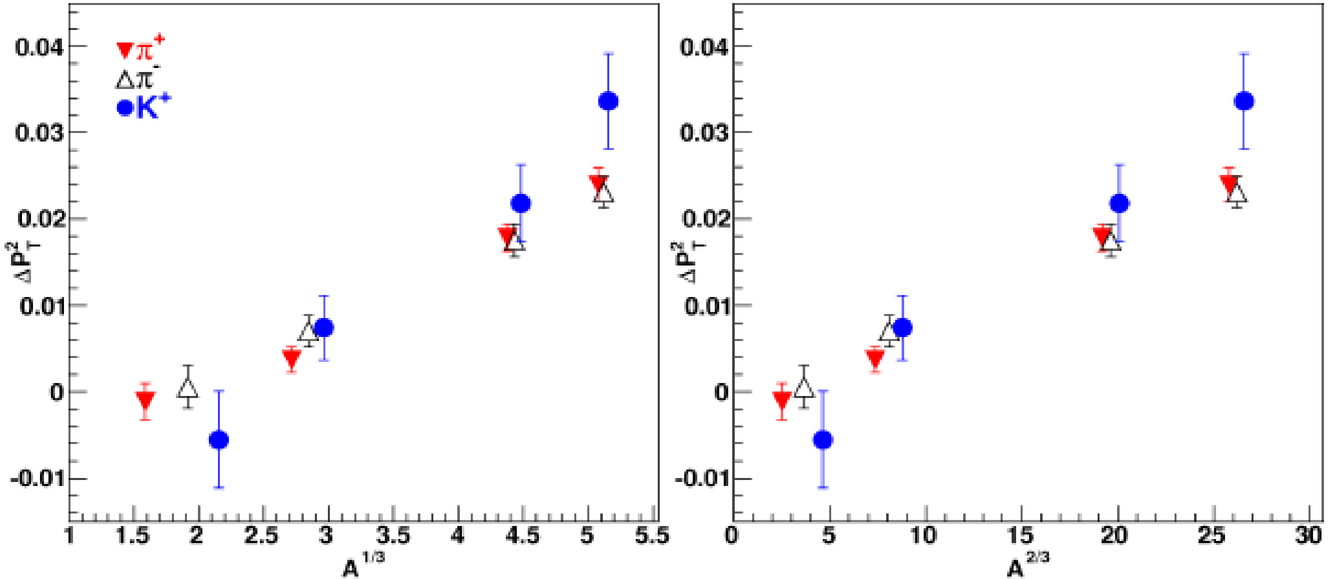


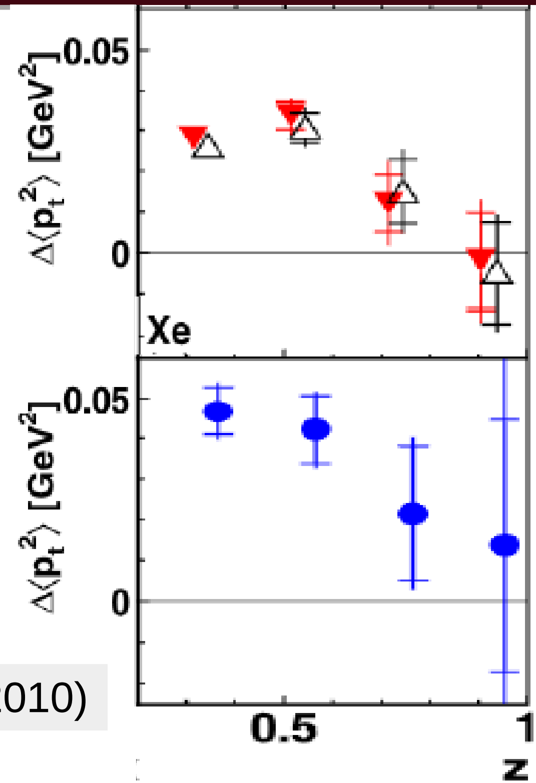
Phys. Lett. B **684**, 114 - 118 (2010)

- 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;

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:

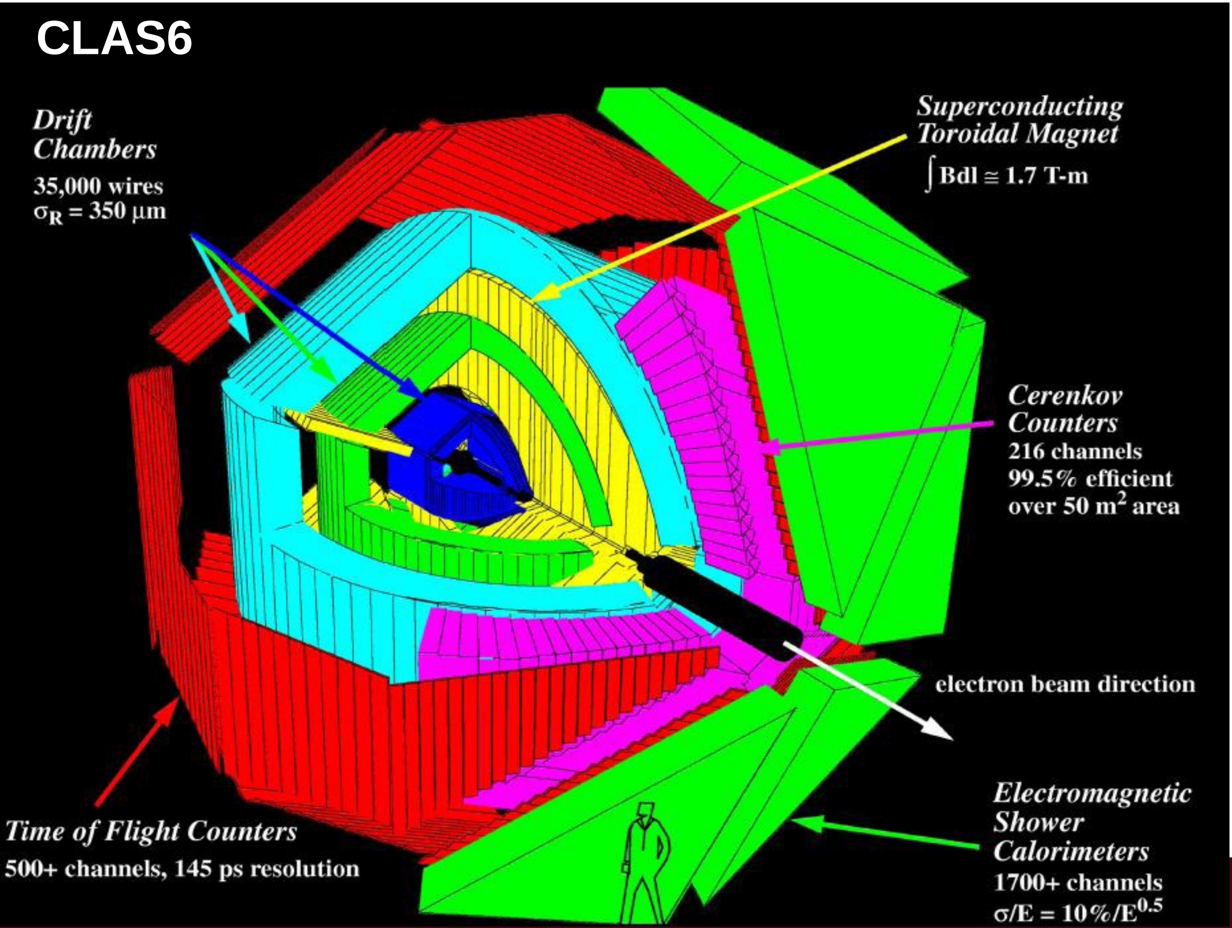
$$\Delta p_T^2 \propto \frac{\Delta E}{dx}, \text{ where}$$

$$\Delta p_T^2 \propto L \propto A^{1/3} \ \& \ \Delta E \propto L^2 \propto A^{2/3}$$

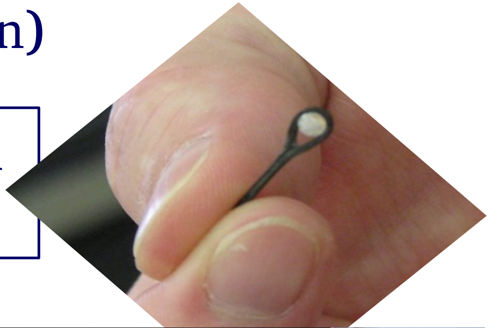
- Similar Δp_T^2 dependence on $A^{1/3}$ & $A^{2/3}$ $\Longrightarrow$ Motivation for JLab/CLAS studies!

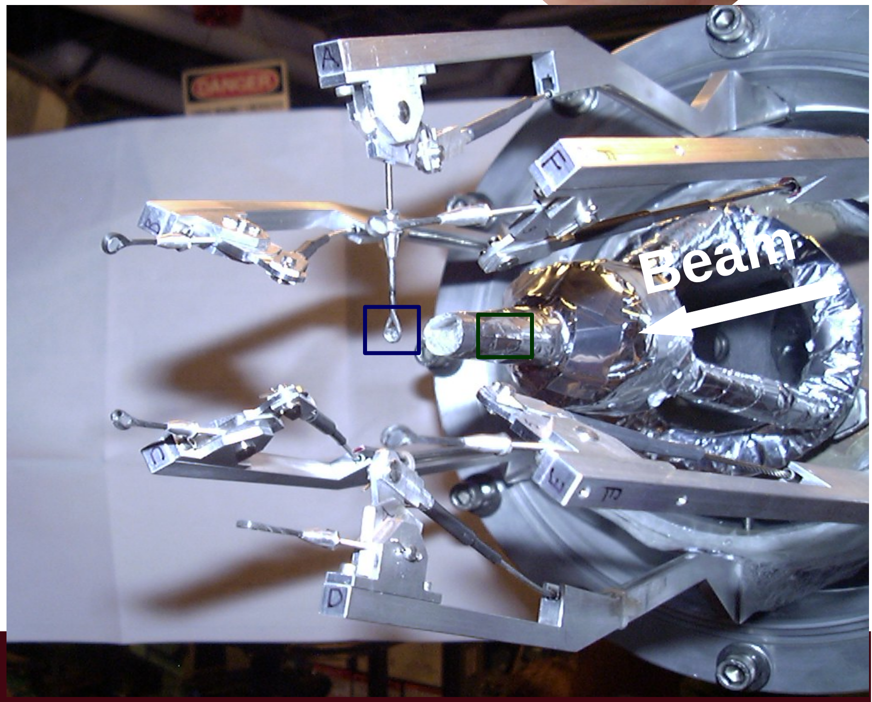
JLab 6 GeV CLAS (CLAS6) Experiment

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

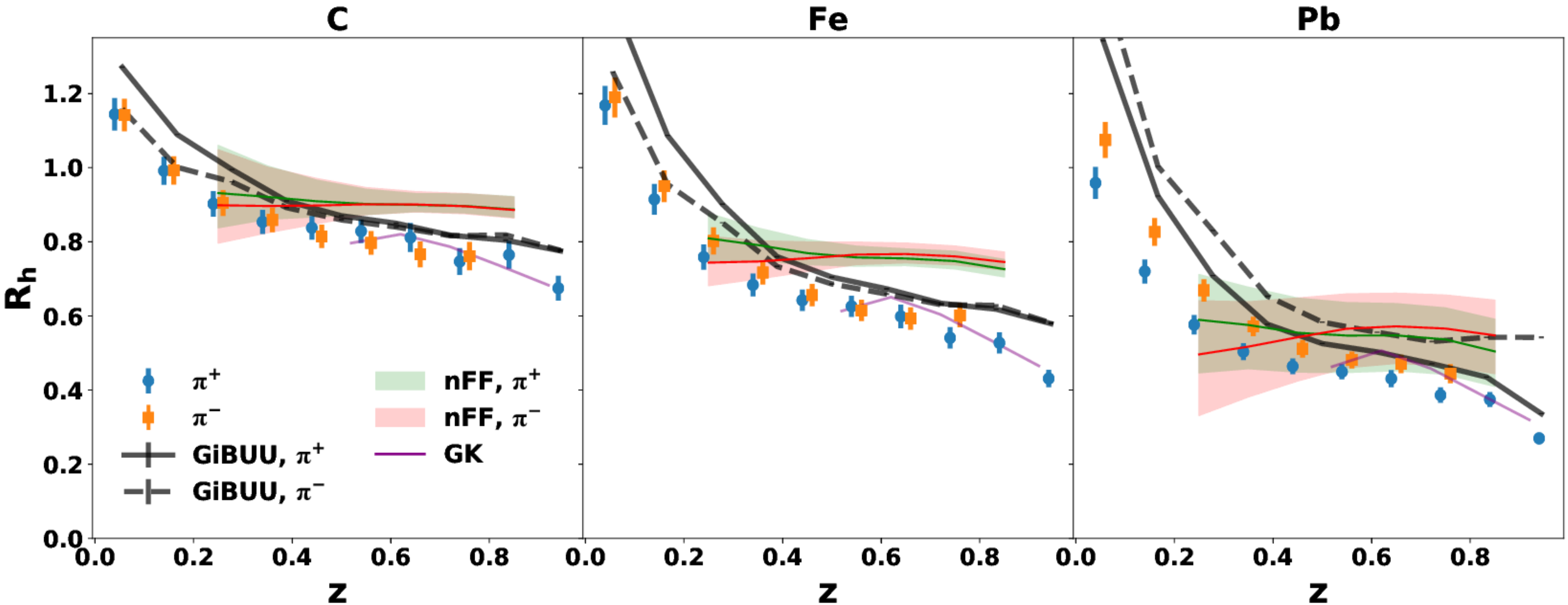


Solid disk





CLAS6 Hadronization Studies: Charged Pions



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

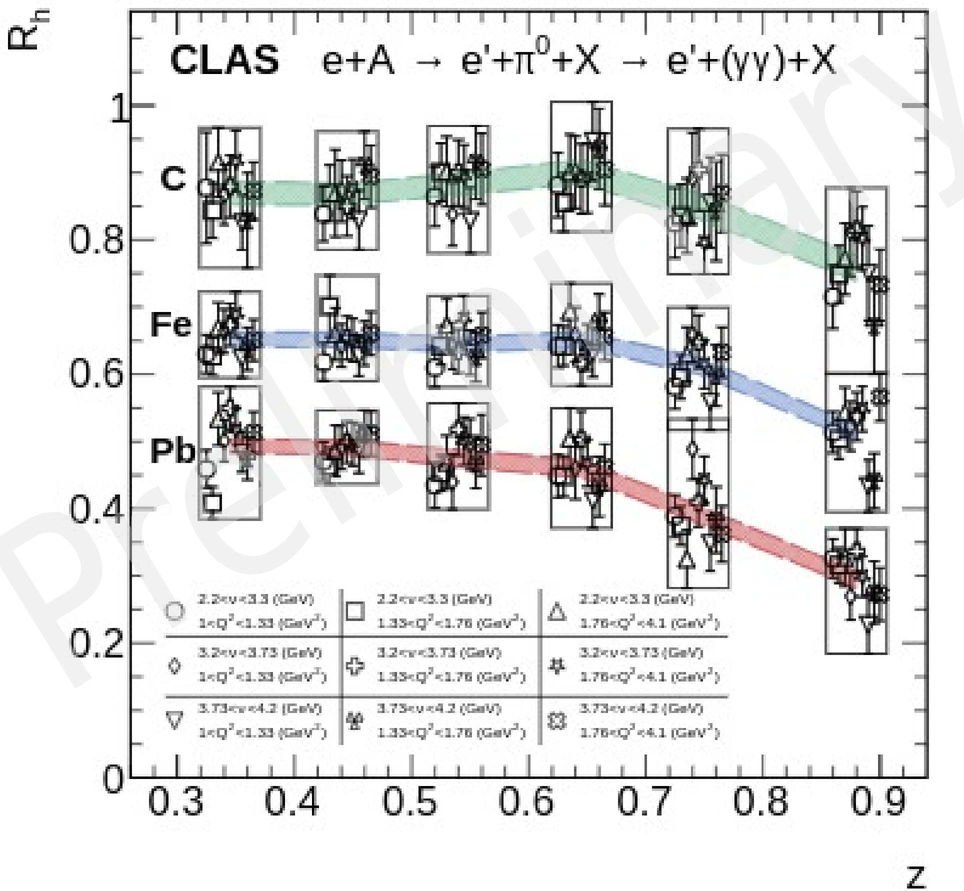
GiBUU (Giessen Boltzmann-Uehling-Uhlenbeck) uses hadronic degrees of freedom, it incorporates formation times, prehadron interactions, CT, and nuclear shadowing. Ingredients successfully used to describe nuclear modifications of DIS hadrons production in the HERMES and EMC experiments.

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*. (2024)



PRC-targeted paper; to-be-resubmitted soon!

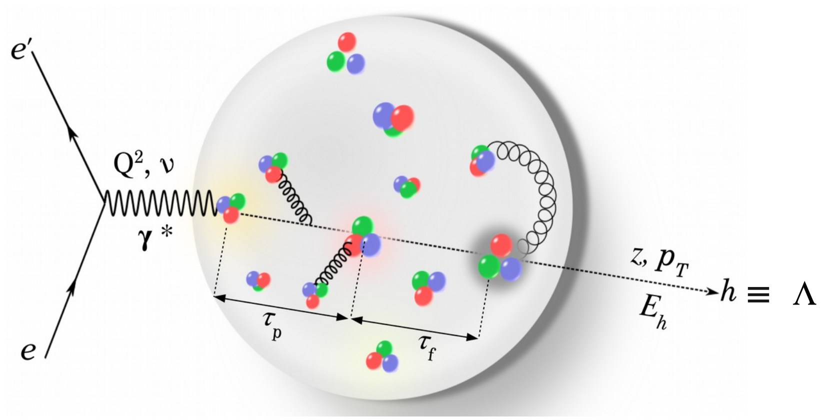
- Measured attenuation varies from a maximum of 25% on C to 75% on Pb
- No dependence on Q^2 and ν observed
- Results are quantitatively compatible with HERMES data

CLAS6 Hadronization Studies: Λ Baryon

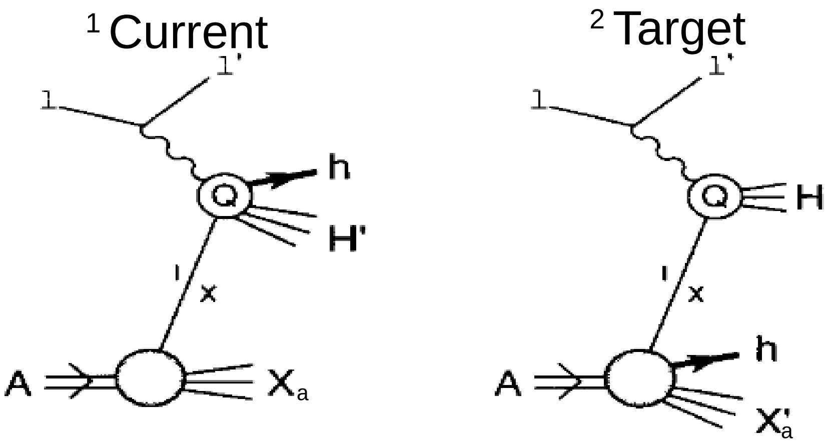
- First-ever study of Λ SIDIS production off C, Fe, and Pb nuclei in the forward[1] and backward[2] fragmentation regions

SIDIS Λ production:

e + A ⟶ e' + Λ + X



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

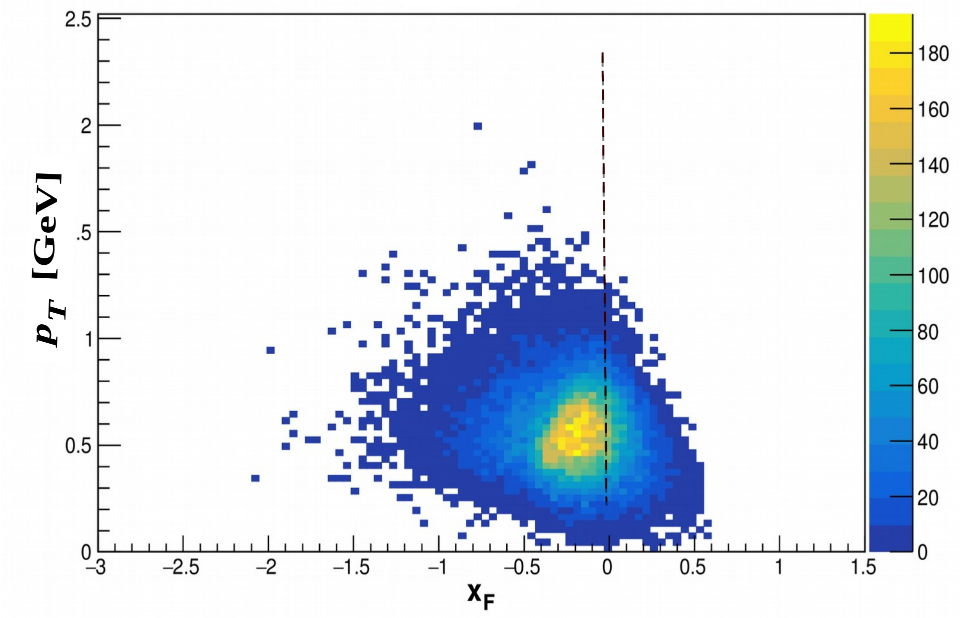


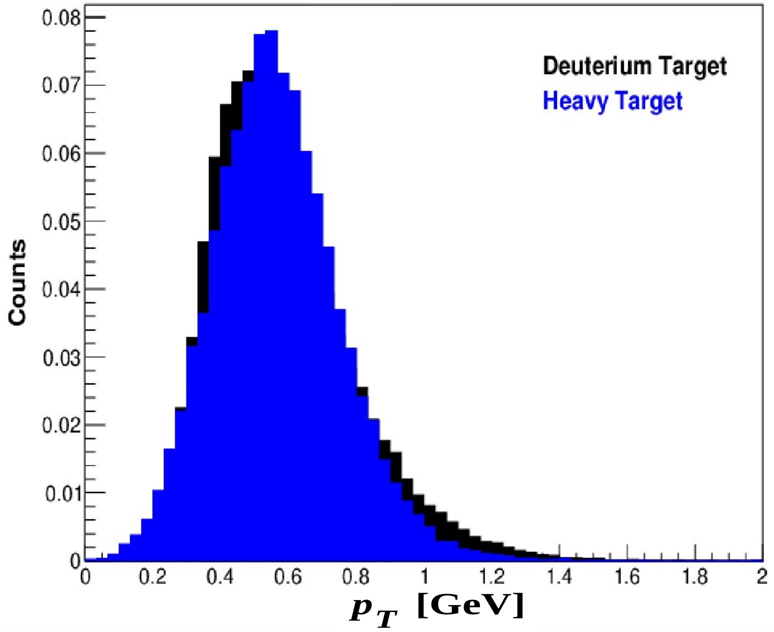
L. Trentadue & G. Veneziano, Phys. Lett. B **323**, 201-211 (1994)

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 since Λs show a significant leading particle effect 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)





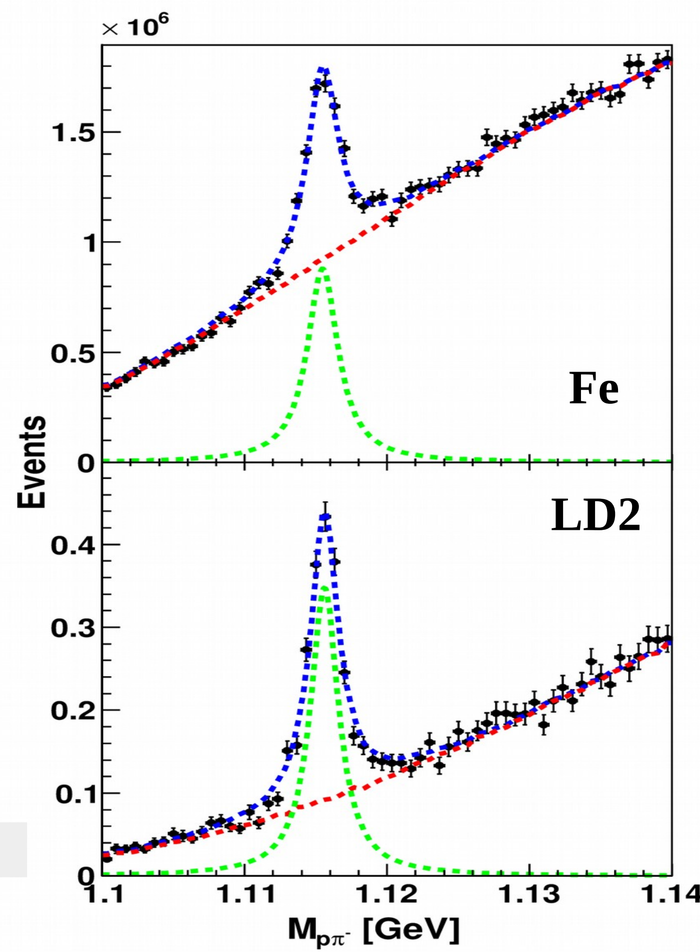
Phys. Rev. Lett. **130**, 142301 (2023)

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.

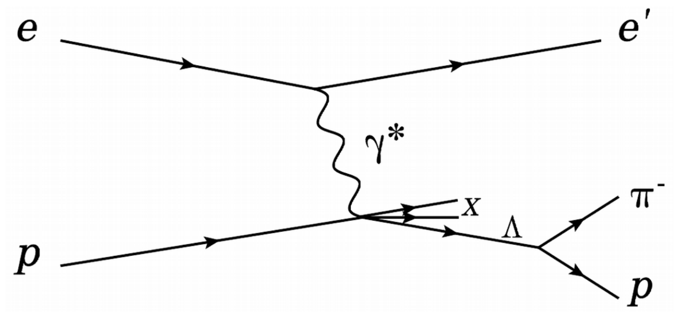
--------- Combinatorial background

Pure Λ signal



SIDIS Λ production:

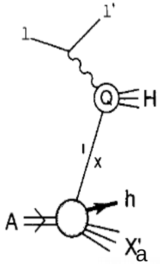
$e + p \longrightarrow e' + \Lambda + X$



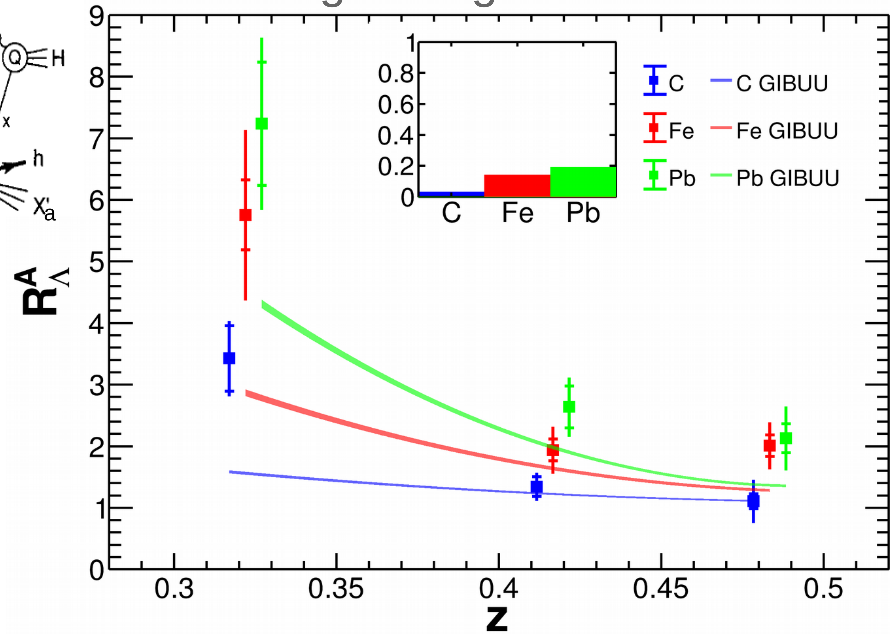
Phys. Rev. Lett. **130**, 142301 (2023)

Former Postdoc
Taya Chetry

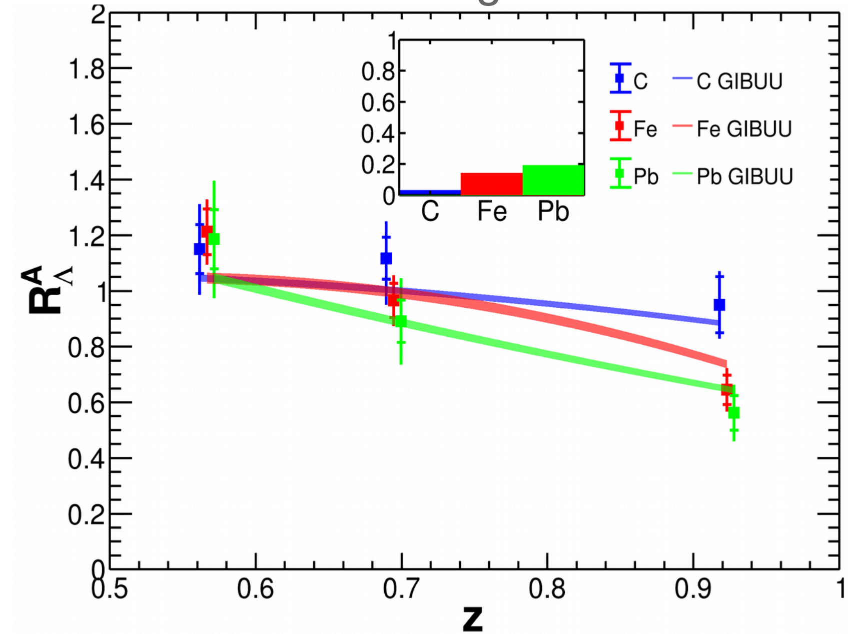
CLAS6 Λ Multiplicity Ratios

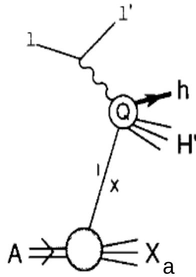


Target Fragmentation



Current Fragmentation



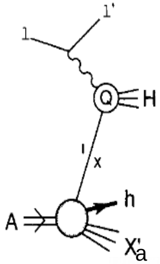


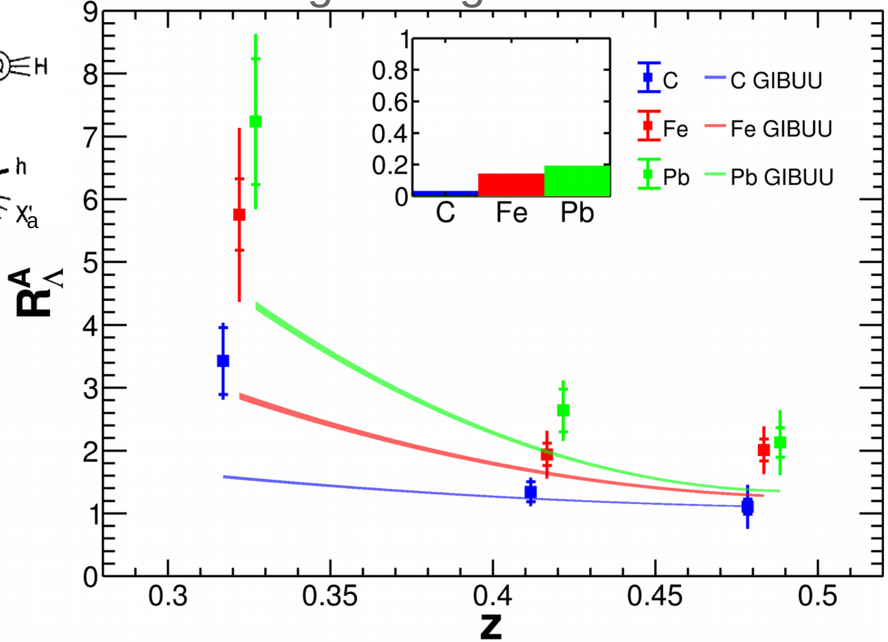
Phys. Rev. Lett. **130**, 142301 (2023)

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

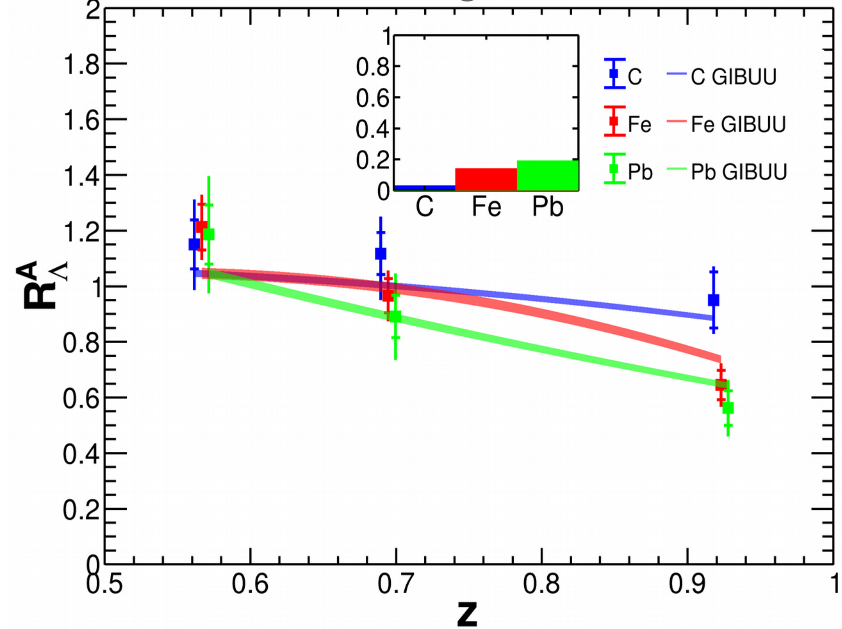
CLAS6 Λ Multiplicity Ratios

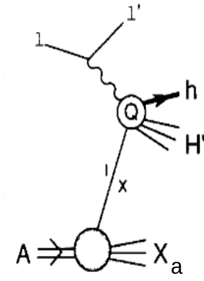
Target Fragmentation

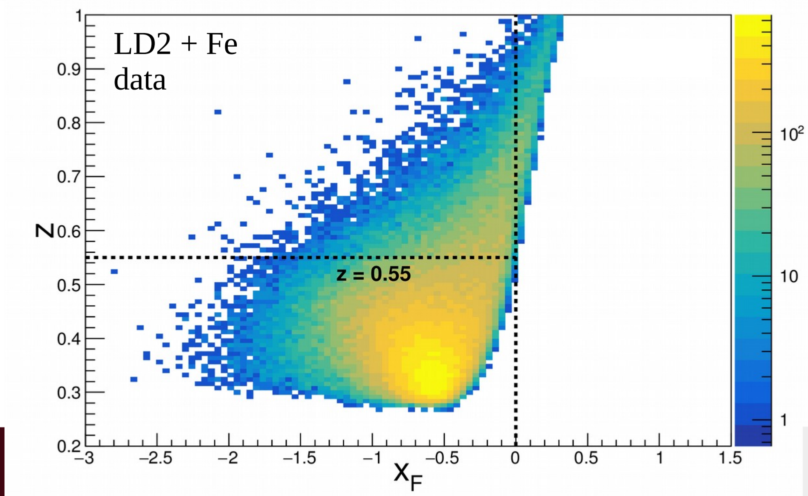




Current Fragmentation





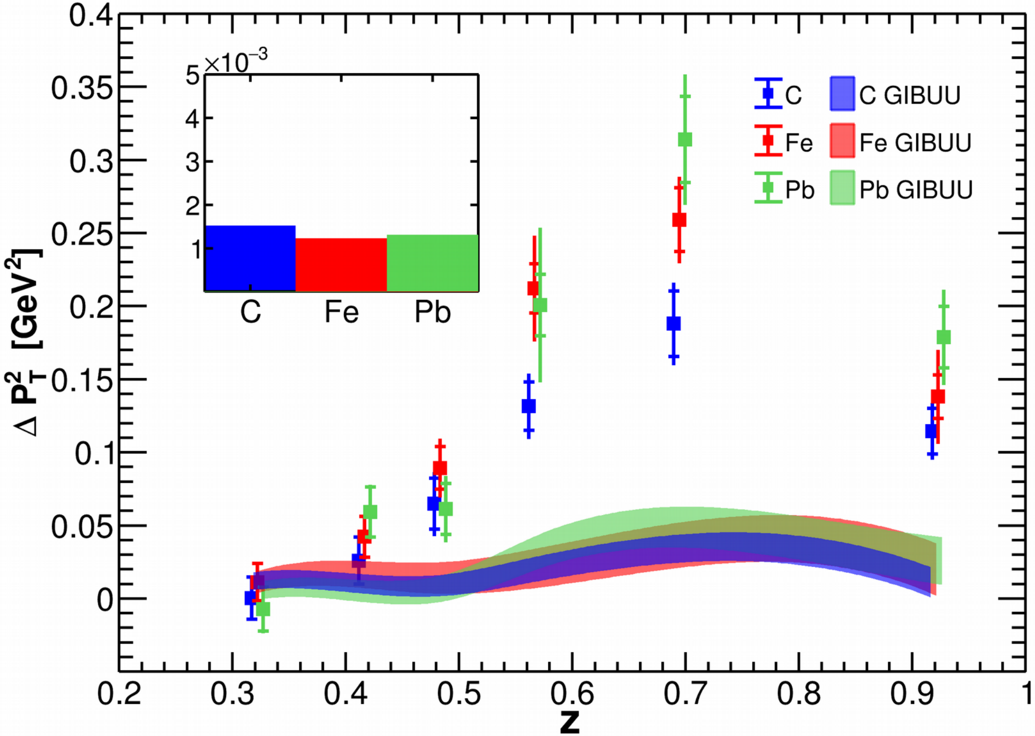


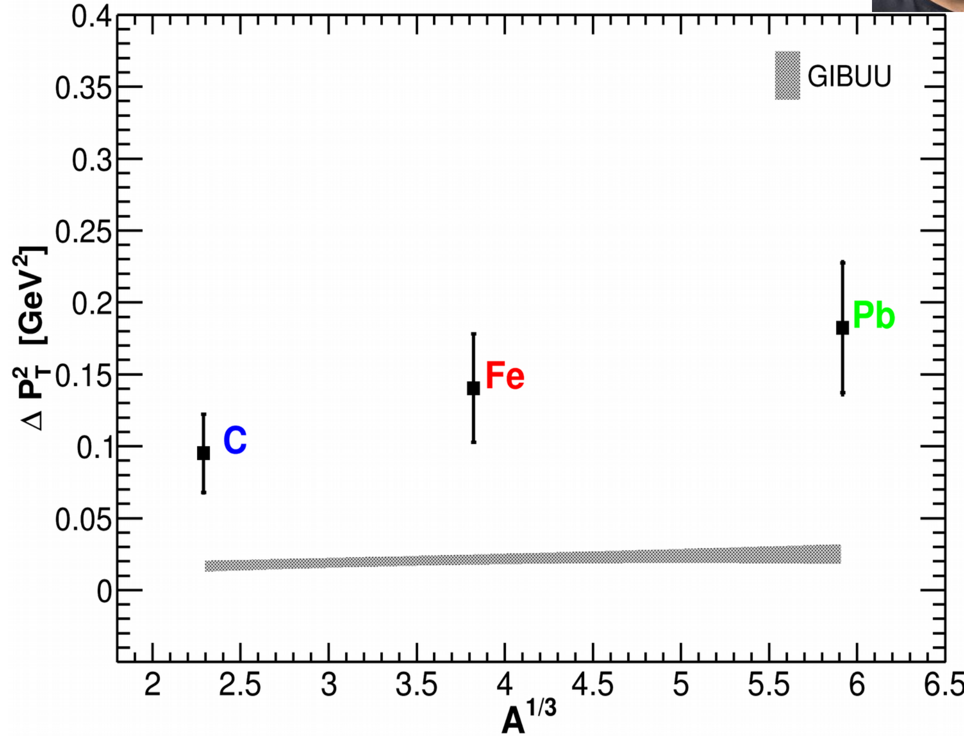
Phys. Rev. Lett. **130**, 142301 (2023)

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

See Supplemental Material

CLAS6 Λ Transverse Momentum Broadening Results

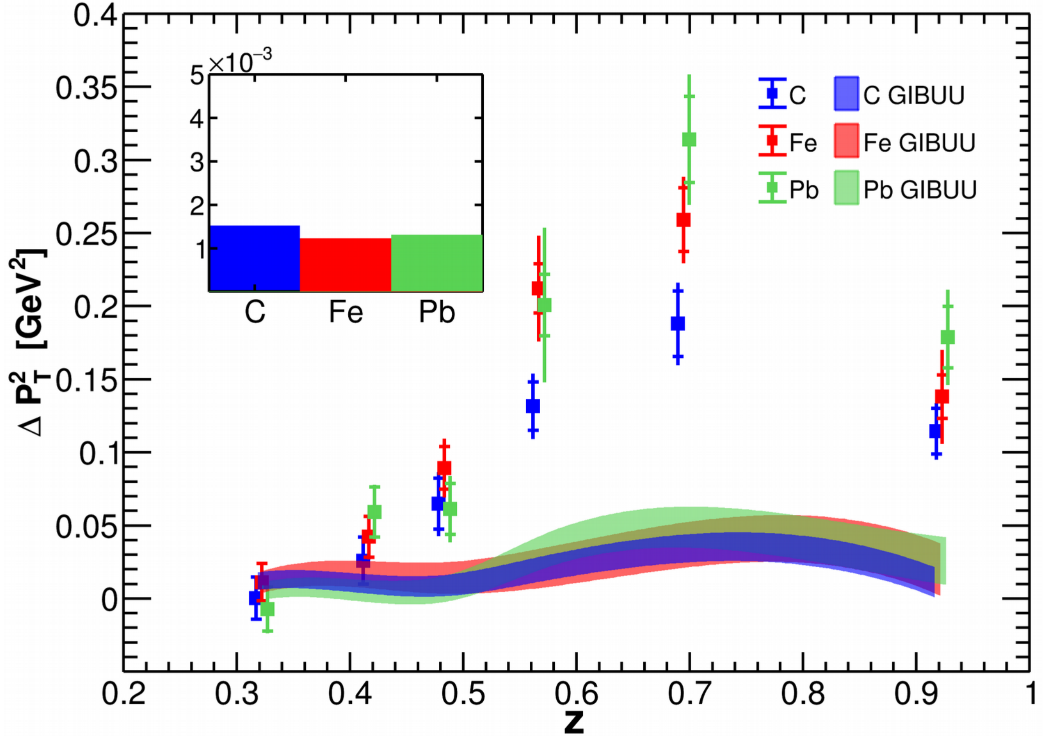




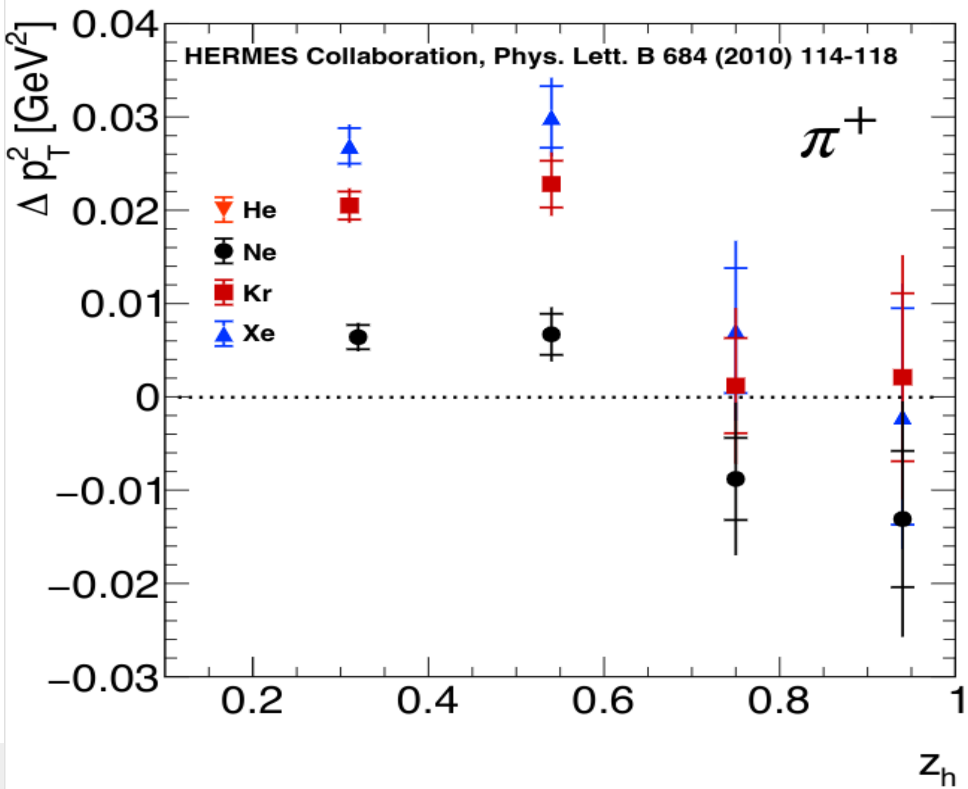
Phys. Rev. Lett. **130**, 142301 (2023)

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

CLAS6 Λ Transverse Momentum Broadening Results



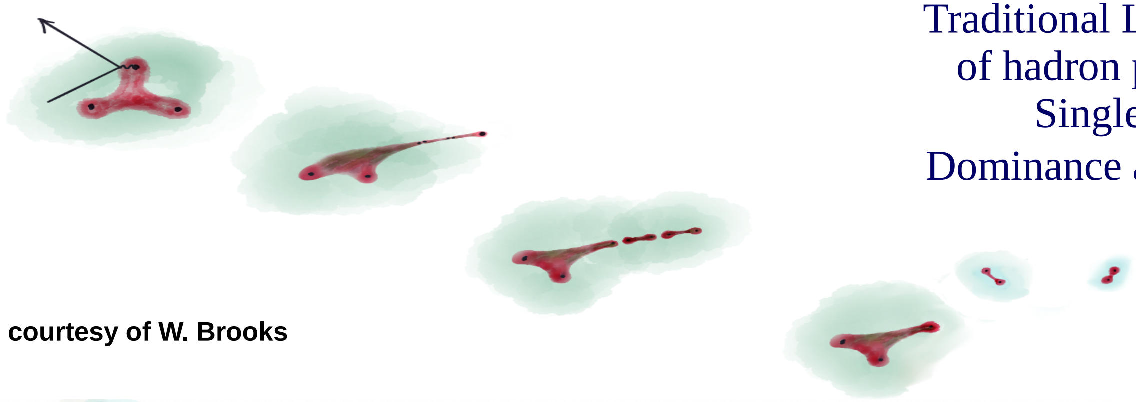
Phys. Rev. Lett. **130**, 142301 (2023)



- 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;

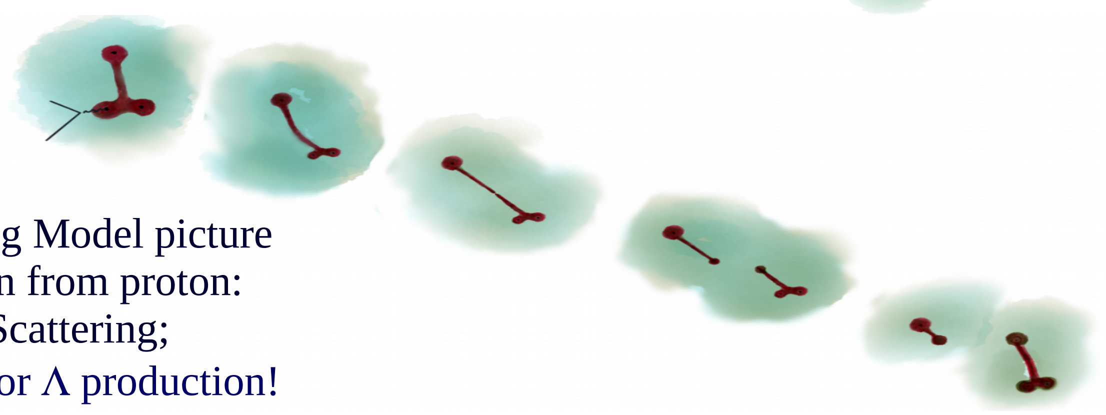
CLAS6 Λ Transverse Momentum Broadening Results

- 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)

CLAS6 Λ Results: Press Highlights

Jefferson Lab

TEASING STRANGE MATTER FROM THE ORDINARY

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

NEWPORT NEWS, VA – In a unique analysis of experimental data, nuclear physicists have made the first-ever observations of how lambda particles, so-called "strange matter," are produced by a specific process called semi-inclusive deep inelastic scattering (SIDIS). What's more, these data hint that the building blocks of protons, quarks and gluons, are capable of marching through the atomic nucleus in pairs called diquarks, at least part of the time. These results come from an experiment conducted at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility.

It's a result that has been decades in the making. The dataset was originally collected in 2004. Lamiaa El Fassi, now an associate professor of physics at Mississippi State University and principal investigator of the work, first analyzed these data during her thesis project to earn her graduate degree on a different topic.

Nearly a decade after completing her initial research with these data, El Fassi revisited the dataset and led her group through a careful analysis to yield these unprecedented measurements. The dataset comes from experiments in Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF), a DOE user facility. In the experiment, nuclear physicists tracked what happened when electrons from CEBAF scatter off the target nucleus and probe the confined quarks inside protons and neutrons. The results were recently published in *Physical Review Letters*.

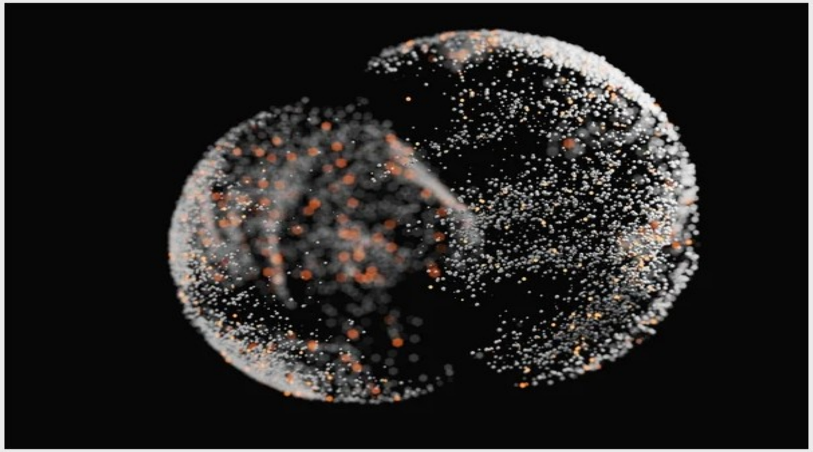
SCIENTIFIC AMERICAN

APRIL 27, 2023 | 4 MIN READ

Physicists See 'Strange Matter' Form inside Atomic Nuclei

New research attempts to discern how bizarre particles of strange matter form in the nuclei of atoms

BY STEPHANIE PAPPAS



koto_feja/Getty Images

Particle Physics

A new physics result two decades in the making has found a surprisingly complex path for the production of strange matter within atoms.

EurekAlert! AAAS

HOME NEWS RELEASES MULTIMEDIA MEETINGS

NEWS RELEASE 18-APR-2023

Teasing strange matter from the ordinary

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

Peer-Reviewed Publication

DOE/THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

CLAS6 Λ Results: Press Highlights

Jefferson Lab

TEASING STRANGE MATTER FROM THE ORDINARY

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

NEWPORT NEWS, VA – In a unique analysis of experimental data, nuclear physicists have made the first-ever observations of how lambda particles, so-called "strange matter," are produced by a specific process called semi-inclusive deep inelastic scattering (SIDIS). What's more, these data hint that the building blocks of protons, quarks and gluons, are capable of marching through the atomic nucleus in pairs called diquarks, at least part of the time. These results come from an experiment conducted at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility.

It's a result that has been decades in the making. The dataset was originally collected in 2004. Lamiaa El Fassi, now an associate professor of physics at Mississippi State University and principal investigator of the work, first analyzed these data during her thesis project to earn her graduate degree on a different topic.

Nearly a decade after completing her initial research with these data, El Fassi revisited the dataset and led her group through a careful analysis to yield these unprecedented measurements. The dataset comes from experiments in Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF), a DOE user facility. In the experiment, nuclear physicists tracked what happened when electrons from CEBAF scatter off the target nucleus and probe the confined quarks inside protons and neutrons. The results were recently published in *Physical Review Letters*.

EurekAlert! AAAS

HOME NEWS RELEASES MULTIMEDIA MEETINGS

NEWS RELEASE 18-APR-2023

Teasing strange matter from the ordinary

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

Peer-Reviewed Publication

DOE/THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

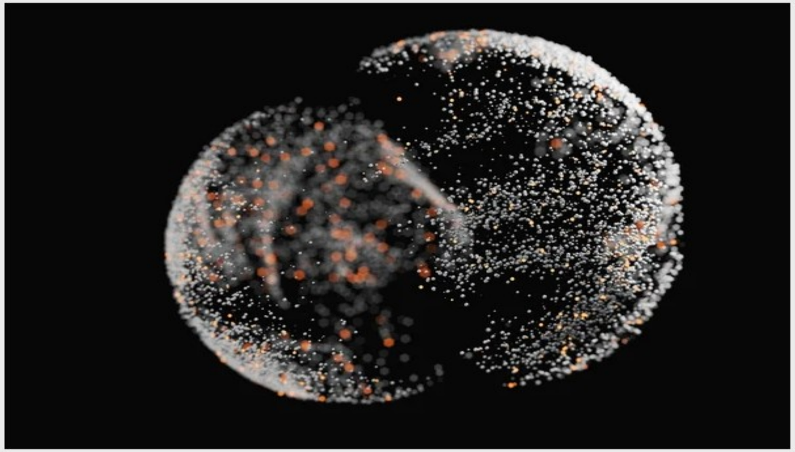
SCIENTIFIC AMERICAN

APRIL 27, 2023 | 4 MIN READ

Physicists See 'Strange Matter' Form inside Atomic Nuclei

New research attempts to discern how bizarre particles of strange matter form in the nuclei of atoms

BY STEPHANIE PAPPAS



koto_feja/Getty Images

physicsworld

particle and nuclear

PARTICLE AND NUCLEAR | RESEARCH UPDATE

Strange-matter observation points to existence of diquarks in baryons

15 May 2023

Surprising observation: evidence for lambda baryons and the involvement of diquarks in their production has been spotted in data taken at Jefferson Lab's CEBAF Large Acceptance Spectrometer. (Courtesy: DOE/Jefferson Lab)

CLAS6 Λ Results: Press Highlights

Jefferson Lab

TEASING STRANGE MATTER FROM THE ORDINARY

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

NEWPORT NEWS, VA – In a unique analysis of experimental data, nuclear physicists have made the first-ever observations of how lambda particles, so-called "strange matter," are produced by a specific process called semi-inclusive deep inelastic scattering (SIDIS). What's more, these data hint that the building blocks of protons, quarks and gluons, are capable of marching through the atomic nucleus in pairs called diquarks, at least part of the time. These results come from an experiment conducted at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility.

It's a result that has been decades in the making. The dataset was originally collected in 2004. Lamiaa El Fassi, now an associate professor of physics at Mississippi State University and principal investigator of the work, first analyzed these data during her thesis project to earn her graduate degree on a different topic.

Nearly a decade after completing her initial research with these data, El Fassi revisited the dataset and led her group through a careful analysis to yield these unprecedented measurements. The dataset comes from experiments in Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF), a DOE user facility. In the experiment, nuclear physicists tracked what happened when electrons from CEBAF scatter off the target nucleus and probe the confined quarks inside protons and neutrons. The results were recently published in *Physical Review Letters*.

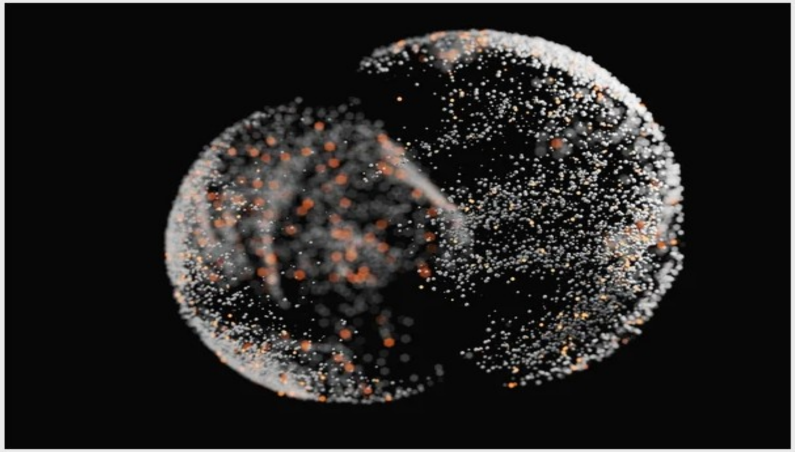
SCIENTIFIC AMERICAN

APRIL 27, 2023 | 4 MIN READ

Physicists See 'Strange Matter' Form inside Atomic Nuclei

New research attempts to discern how bizarre particles of strange matter form in the nuclei of atoms

BY STEPHANIE PAPPAS



koto_feja/Getty Images

EurekAlert! AAAS

HOME NEWS RELEASES MULTIMEDIA MEETINGS

NEWS RELEASE 18-APR-2023

Teasing strange matter from the ordinary

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

Peer-Reviewed Publication

DOE/THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

MISSISSIPPI STATE UNIVERSITY OFFICE OF PUBLIC AFFAIRS — MAROON MEMO

myState Calendars Contact Us | Search | A-Z Index Directories Maps News

Maroon MEMO: Employee News and Information — Week of June 19, 2023 | Archive

Physics and Astronomy's El Fassi first to observe formation of rare 'strange matter'

physicsworld

PARTICLE AND NUCLEAR | RESEARCH UPDATE

Strange-matter observation points to existence of diquarks in baryons

15 May 2023

Surprising observation: evidence for lambda baryons and the involvement of diquarks in their production has been spotted in data taken at Jefferson Lab's CEBAF Large Acceptance Spectrometer. (Courtesy: DOE/Jefferson Lab)

Daily Press

How nuclear physicists at Jefferson Lab found something 'strange' in the ordinary

Eliza Noe, Daily Press

April 25, 2023 · 2 min read

SciTechDaily

BIOLOGY CHEMISTRY EARTH HEALTH PHYSICS SCIENCE SPACE TECHNOLOG

HOT TOPICS NOVEMBER 5, 2023 | DECARBONIZING THE WORLD: MIT ENERGY INITIATIVE'S STRATEGIES FOR REDUCING GREENHOUSE GAS

HOME PHYSICS NEWS

"Extremely Surprising" – Nuclear Physicists Ha[…] Groundbreaking Observation of "Strange Matte[…]

TOPICS: DOE Electrons Matter Neutrons Particle Physics Popular Thomas Jefferson National Laboratory

By CHRIS PATRICK, THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY APRIL 20, 2023

MISSISSIPPI STATE UNIVERSITY

Our State Future Students Students Alumni Employees

HEADLINES ANNOUNCEMENTS CATEGORIES COLLEGES ARCHIVE DAILY DIGEST SUGGEST NEWS MED

Home / Newsroom / MSU physicist first to observe formation of rare 'strange matter'

MSU physicist first to observe formation of rare 'strange matter'

Contact: Sam Kealhofer

STARKVILLE, Miss.—A Mississippi State physicist and her colleagues are the first scientists to observe how subatomic particles—known as lambda particles—are formed, helping researchers learn more about their production and formation in atomic nuclei, deepening the overall understanding of the dynamics of subatomic structure that governs most of the visible matter in the universe.

CLAS6 Λ Results: Press Highlights

Jefferson Lab

TEASING STRANGE MATTER FROM THE ORDINARY

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

NEWPORT NEWS, VA – In a unique analysis of experimental data, nuclear physicists have made the first-ever observations of how lambda particles, so-called "strange matter," are produced by a specific process called semi-inclusive deep inelastic scattering (SIDIS). What's more, these data hint that the building blocks of protons, quarks and gluons, are capable of marching through the atomic nucleus in pairs called diquarks, at least part of the time. These results come from an experiment conducted at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility.

It's a result that has been decades in the making. The dataset was originally collected in 2004. Lamiaa El Fassi, now an associate professor of physics at Mississippi State University and principal investigator of the work, first analyzed these data during her thesis project to earn her graduate degree on a different topic.

Nearly a decade after completing her initial research with these data, El Fassi revisited the dataset and led her group through a careful analysis to yield these unprecedented measurements. The dataset comes from experiments in Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF), a DOE user facility. In the experiment, nuclear physicists tracked what happened when electrons from CEBAF scatter off the target nucleus and probe the confined quarks inside protons and neutrons. The results were recently published in *Physical Review Letters*.

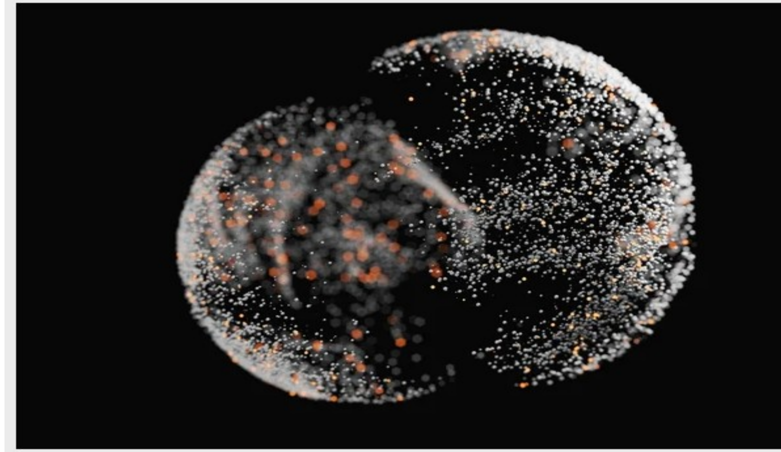
SCIENTIFIC AMERICAN

APRIL 27, 2023 | 4 MIN READ

Physicists See 'Strange Matter' Form inside Atomic Nuclei

New research attempts to discern how bizarre particles of strange matter form in the nuclei of atoms

BY STEPHANIE PAPPAS



koto_feja/Getty Images

physicsworld

particle and nuclear

Office of SCIENCE | ABOUT US | INITIATIVES | MISSION | SCIENCE & INNOVATION | FUNDING | RESOURCES

Office of Science

Digging Through Data to Investigate Strange Matter

NOVEMBER 30, 2023

Office of Science » Digging Through Data to Investigate Strange Matter

Office of SCIENCE | ABOUT US | INITIATIVES | MISSION | SCIENCE & INNOVATION | FUNDING | RESOURCES

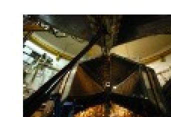
SCIENCE & INNOVATION

Science Highlights

March 18, 2024

Teasing Strange Matter from Ordinary

New insights reveal details of how strange matter forms.



MISSISSIPPI STATE UNIVERSITY™ OFFICE OF PUBLIC AFFAIRS

MAROON MEMO

myState Calendars Contact Us

Search

A-Z Index Directories Maps News

Maroon MEMO: Employee News and Information | Week of June 19, 2023 | Archive

Physics and Astronomy's El Fassi first to observe formation of rare 'strange matter'

MISSISSIPPI STATE UNIVERSITY

MSU physicist first to observe formation of rare 'strange matter'

Contact: Sam Kealhofer

STARKVILLE, Miss.—A Mississippi State physicist and her colleagues are the first scientists to observe how subatomic particles—known as lambda particles—are formed, helping researchers learn more about their production and formation in atomic nuclei, deepening the overall understanding of the dynamics of subatomic structure that governs most of the visible matter in the universe.

CLAS6 Λ Results: Press Highlights

Jefferson Lab

TEASING STRANGE MATTER FROM THE ORDINARY

New insights from Jefferson Lab reveal details of how strange matter forms in ordinary matter

NEWPORT NEWS, VA – In a unique analysis of experimental data, nuclear physicists have made the first-ever observations of how lambda particles, so-called "strange matter," are produced by a specific process called semi-inclusive deep inelastic scattering (SIDIS). What's more, these data hint that the building blocks of protons, quarks and gluons, are capable of marching through the atomic nucleus in pairs called diquarks, at least part of the time. These results come from an experiment conducted at the U.S. Departm... Energy's Thomas Jefferson National A...

It's a result that has been decades in the making. The dataset... professor of physics at Mississippi State U... project to earn her...

Nearly a d... analysis to... Beam Acce... from CEBA... published i...

Office of SCIENCE

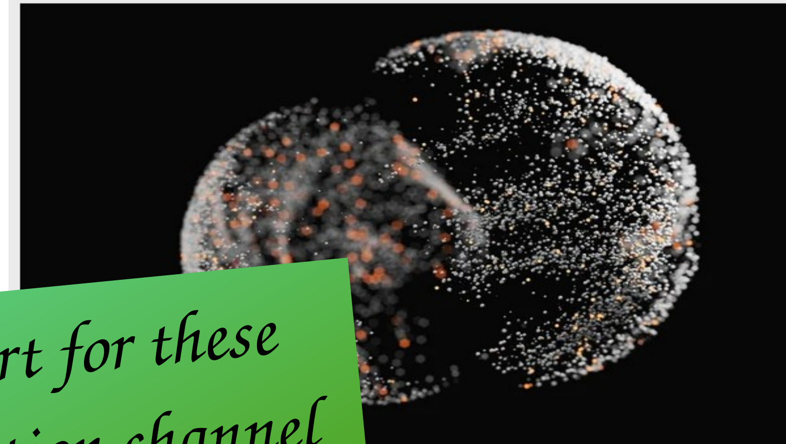
SCIENTIFIC AMERICAN

APRIL 27, 2023 | 4 MIN READ

Physicists See 'Strange Matter' Form inside Atomic Nuclei

New research attempts to discern how bizarre particles of strange matter form in the nuclei of atoms

BY STEPHANIE PAPPAS



Hope to stimulate some theoretical support for these hadronization studies as well as Λ production channel

physicsworld

particle and nuclear

Office of Science

Digging Through Data to Investigate Strange Matter

NOVEMBER 30, 2023

Office of Science » Digging Through Data to Investigate Strange Matter

Office of SCIENCE | ABOUT US | INITIATIVES | MISSION | SCIENCE & INNOVATION | FUNDING | RESOURCES

SCIENCE & INNOVATION

Science Highlights

MISSISSIPPI STATE UNIVERSITY OFFICE OF PUBLIC AFFAIRS

MAROON MEMO

myState Calendars Contact Us

Search

A-Z Index Directories Maps News

Maroon MEMO: Employee News and Information — Week of June 19, 2023 | Archive

Physics and Astronomy's El Fassi first to observe formation of rare 'strange matter'

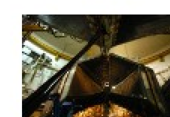
MISSISSIPPI STATE UNIVERSITY

MSU physicist first to observe formation of rare 'strange matter'

March 18, 2024

Teasing Strange Matter from Ordinary

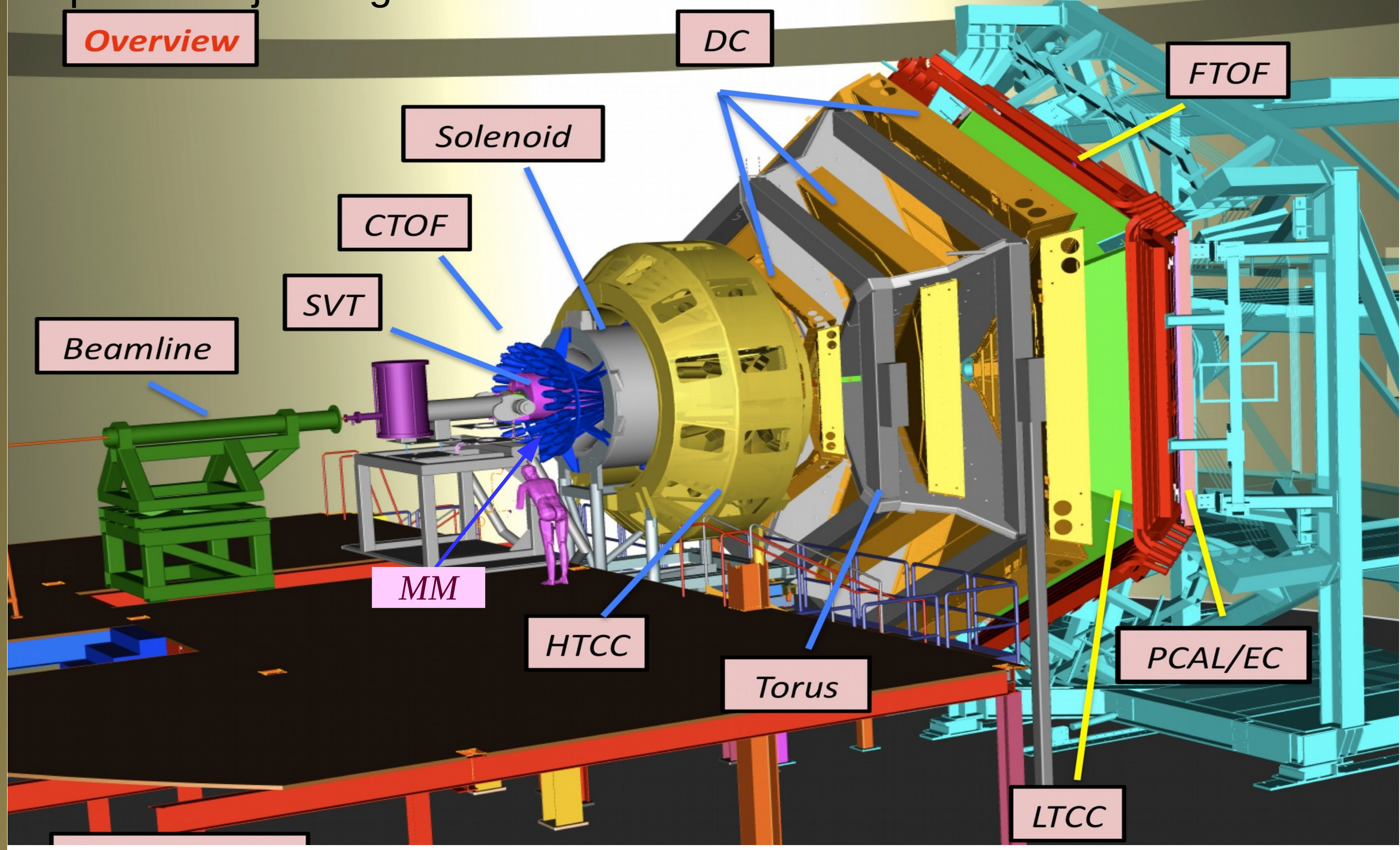
New insights reveal details of how strange matter forms.



nDIS Studies with CLAS12 @ JLab: Run Group E Experiments

- 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: **$2.5^o < \theta < 125^o$**
- Acceptance for all charged particles: **$5^o < \theta < 125^o$**
- Acceptance for neutrons: **$5^o < \theta < 120^o$**

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



~ 111832 readout channels

Central Detector

Forward Detector

nDIS Studies with CLAS12: RG-E Experiments

HERMES

CLAS6 *(done or ongoing)*

My group interest

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

nDIS Studies with CLAS12: RG-E Experiments

- 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
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

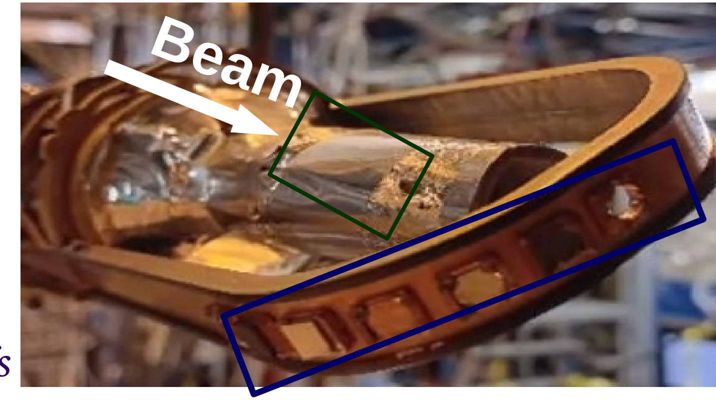
My group interest

HERMES

CLAS6 *(done or ongoing)*

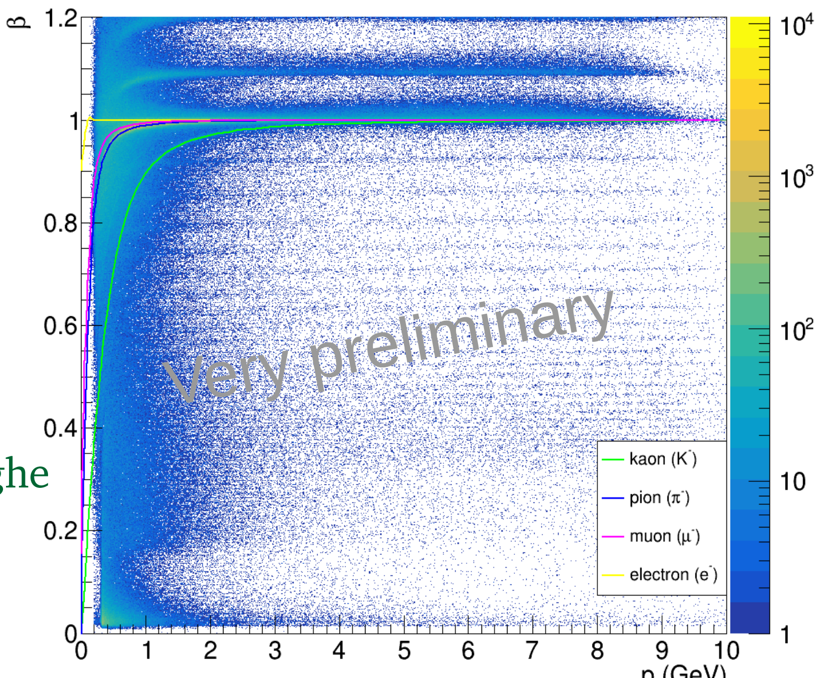
nDIS Studies with CLAS12: RG-E Experiments

- Spring 2024 data-taking using CLAS12 in its standard configuration and dual-target assembly: **LD2** + **solid foils (C or Cu or Pb or Al or Sn)**

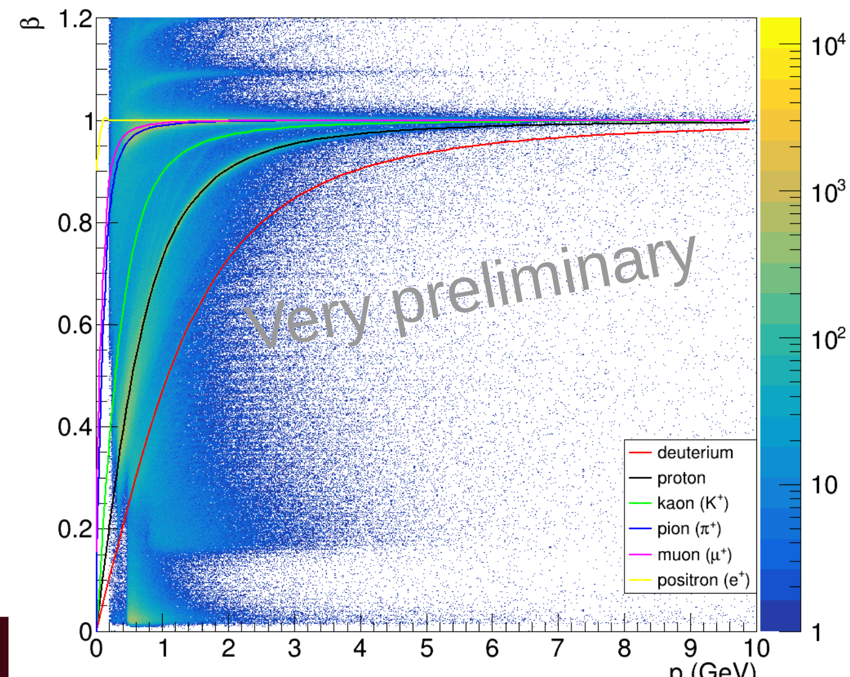


See Apr. 3rd JLab News Briefs

RG-E: LD2 + Pb - Negative Particles



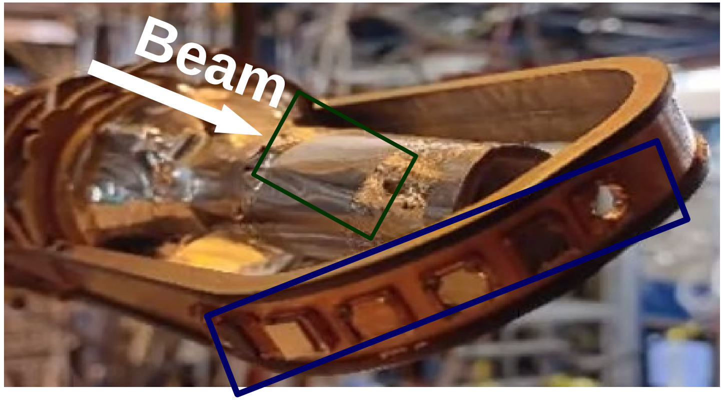
RG-E: LD2 + Pb - Positive Particles



Ph.D. student:
Uditha Weerasinghe

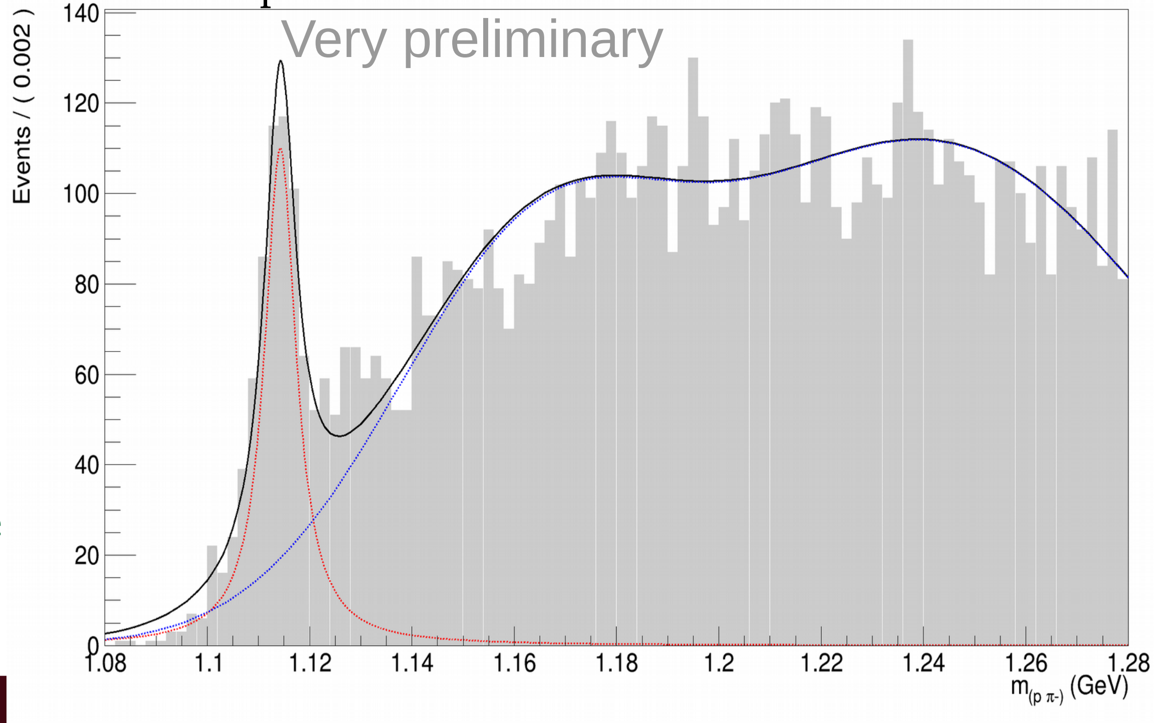
nDIS Studies with CLAS12: RG-E Experiments

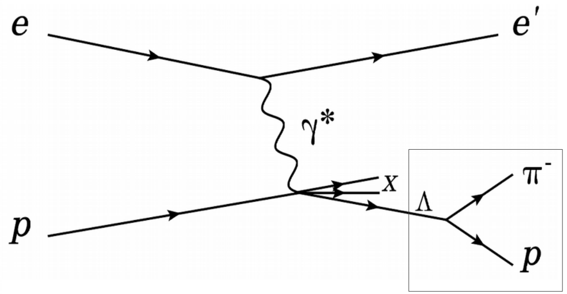
- Spring 2024 data-taking using CLAS12 in its standard configuration and dual-target assembly: **LD2** + **solid foils (C or Cu or Pb or Al or Sn)**



See Apr. 3rd JLab News Briefs

Example of RG-E Λ Invariant-mass Distribution





Λ detached vertex cuts are applied

Ph.D. student:
Uditha Weerasinghe

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 Λ 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 structure!
  - Further calibration of theoretical models is needed to describe these results.
- Ongoing CLAS12 RG-E studies will provide the multi-dimensional data needed to extract the hadronization production and formation time-distance 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 and (*strange*) baryon structure.

Thank you !

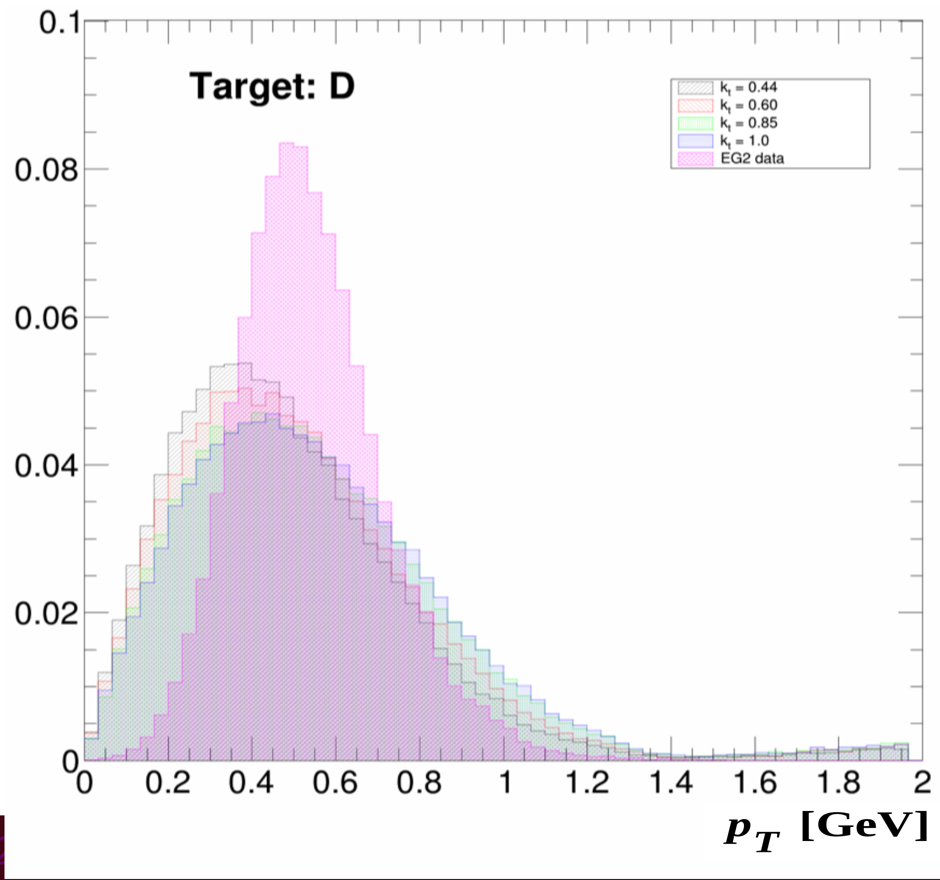
This work is supported in part by the U.S. DOE award #: DE-FG02-07ER41528

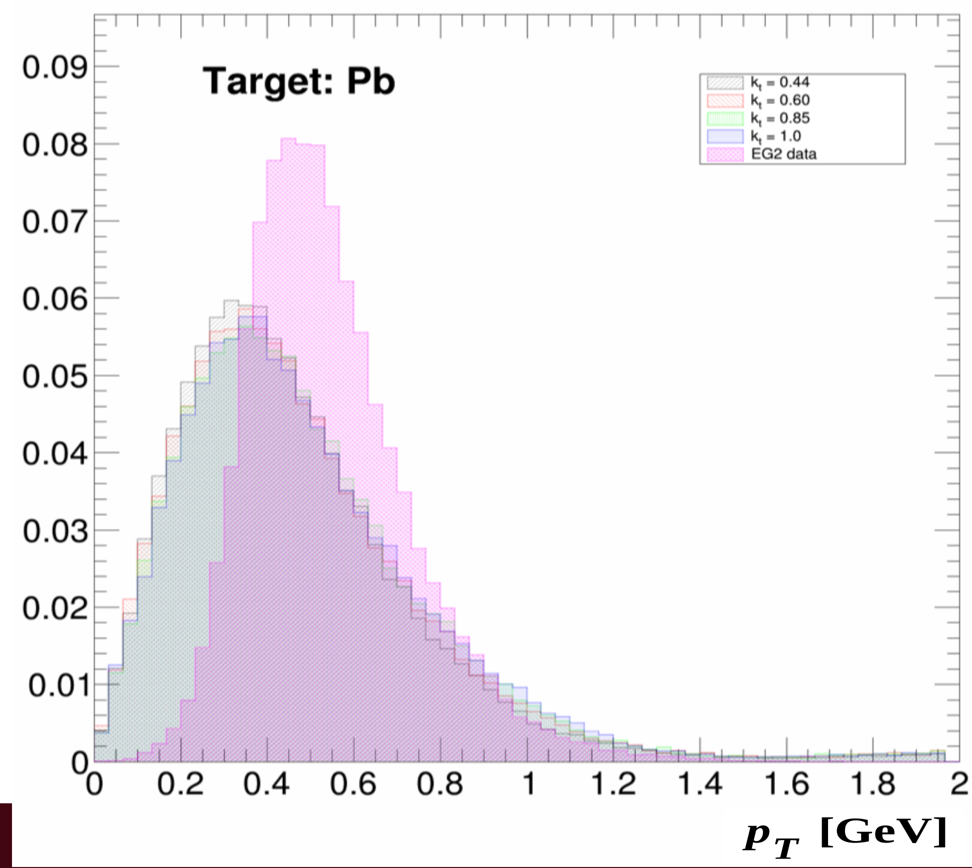
Backup Slides

GIBUU Predictions: Λ nDIS Production

- GIBUU underestimates Λ p_T broadening due to
  i. Inaccurate angular distributions 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 communications (2022)





Systematic Uncertainties for Λ nDIS Analysis

- Multiplicity Ratios budget:
  - Particle identification cuts
  - Symmetric mass range (9 σ)
  - Dual-target vertex corrections
  - Number of combinations of uncorrelated protons and pions pairs.
  - Different AC 6-D 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%**

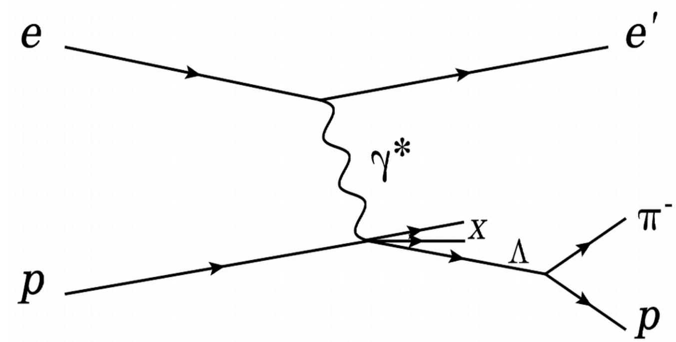
See Phys. Rev. Lett. **130**, 142301 (2023) and its Supplemental Material

Λ-analysis Cuts and Corrections

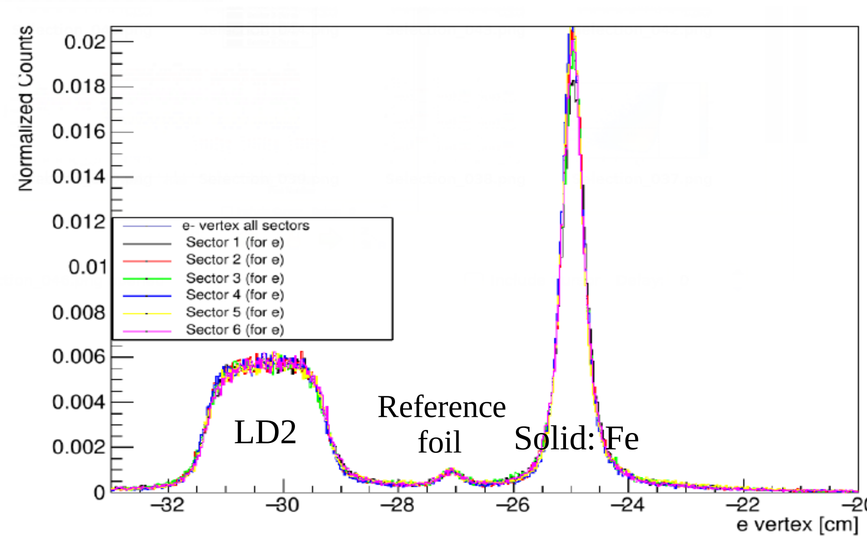
- Final-state Λ events: one e^-, and at least one π^- and proton to identify Λs.

SIDIS Λ production:

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



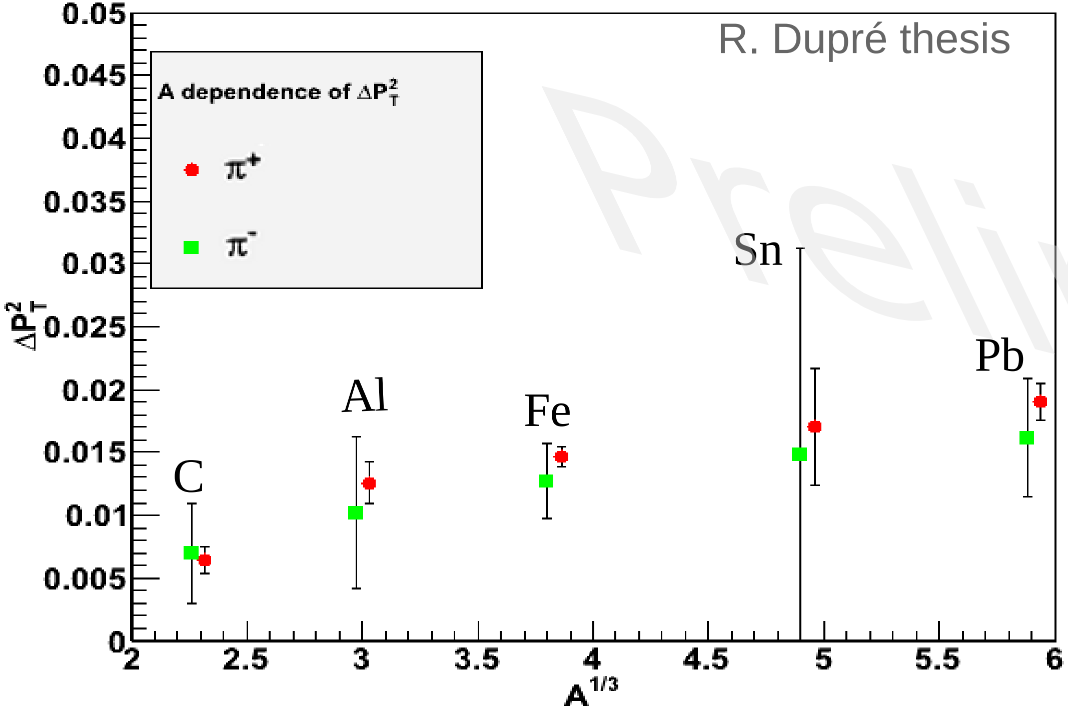
- Electron ID: Positive response in DC, CC, SC, and EC;
- Pion ID: Matching signal in DC and SC;
- Proton ID: Momentum time-dependent analysis using a ROOT's TSpline method;
- SIDIS cuts: $W > 2$ GeV, $Q^2 > 1$ GeV^2, and $y < 0.85$;
- Corrections:
  - Vertex corrections;
  - Proton energy loss and electron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



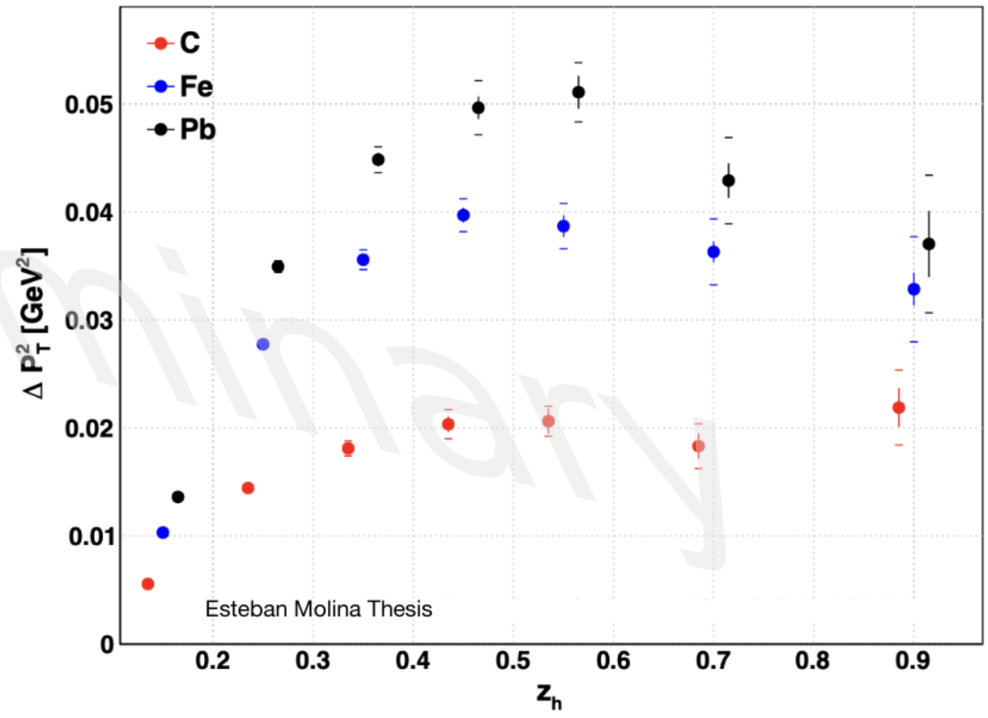
Corrected e^- z-vertex distributions for CLAS6 six sectors

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

Preliminary CLAS6 p_T Broadening: Charged Pions

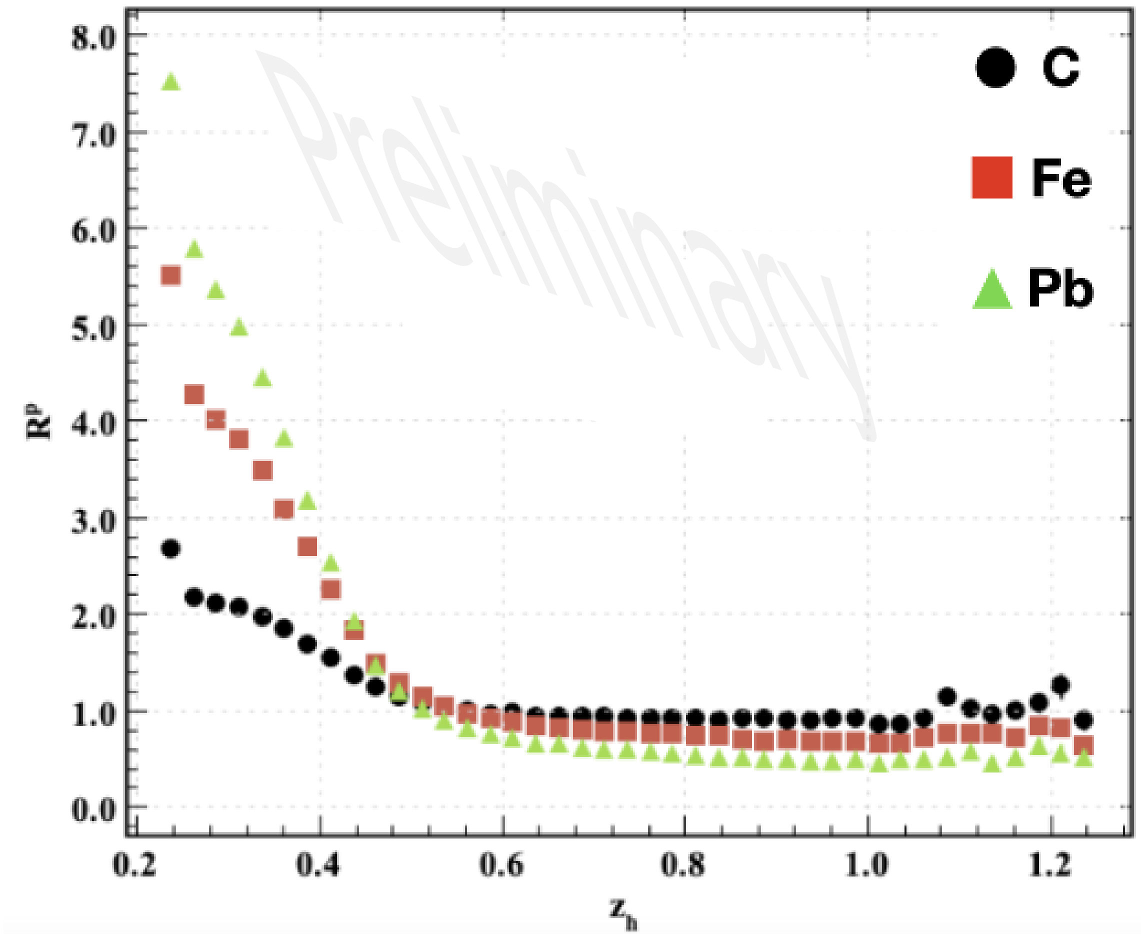


(Slight shift was added for clarity)



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

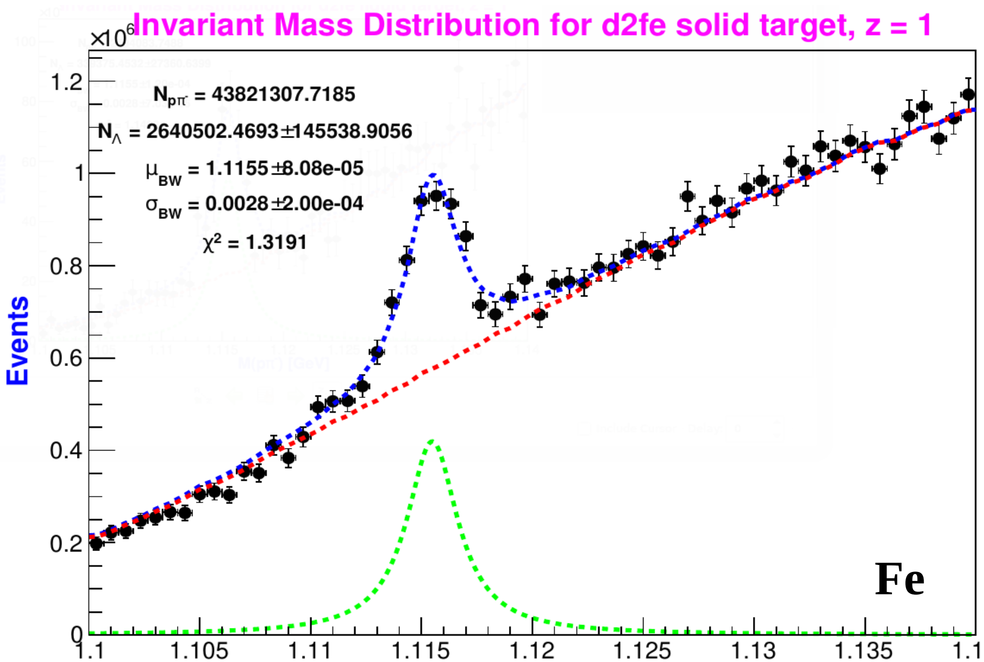
Preliminary CLAS6 Proton Multiplicity Ratios



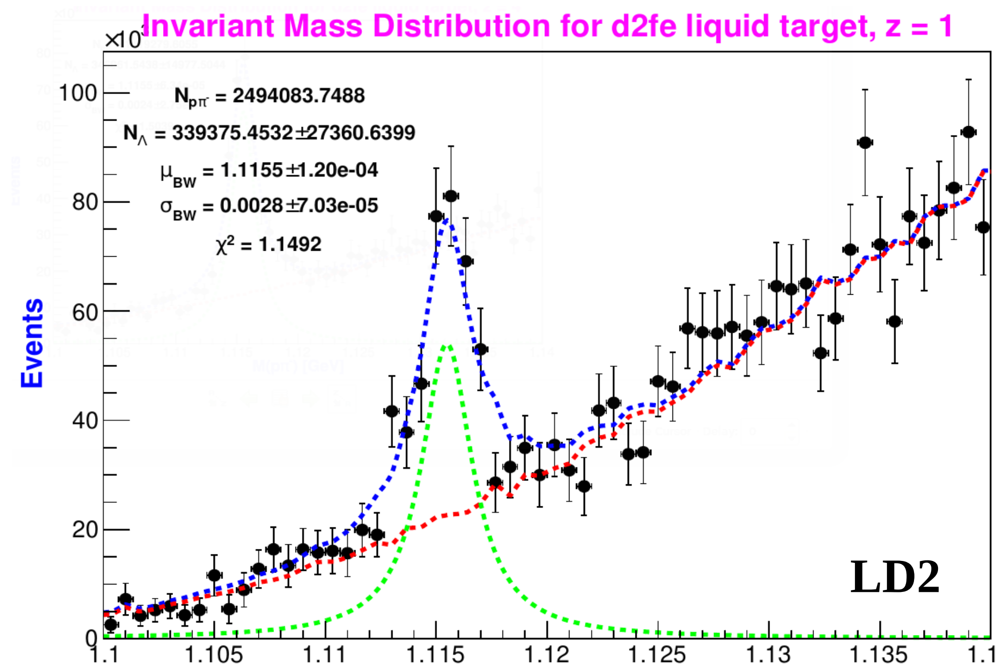
M. Wood, J.P. Garces *et al.* (2023)
(Under internal CLAS Collaboration review)

Λ Yield Extraction

- Identify Λ via its decay particles, π^- and proton;
- 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*).



$M_{\pi\text{-}p}$ [GeV]



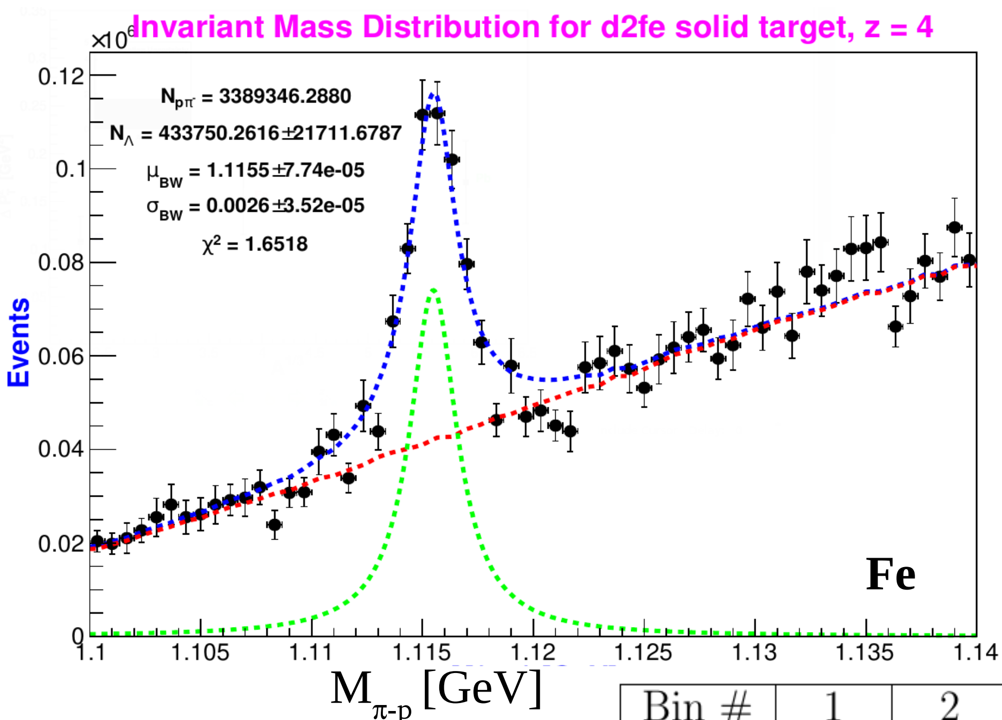
$M_{\pi\text{-}p}$ [GeV]

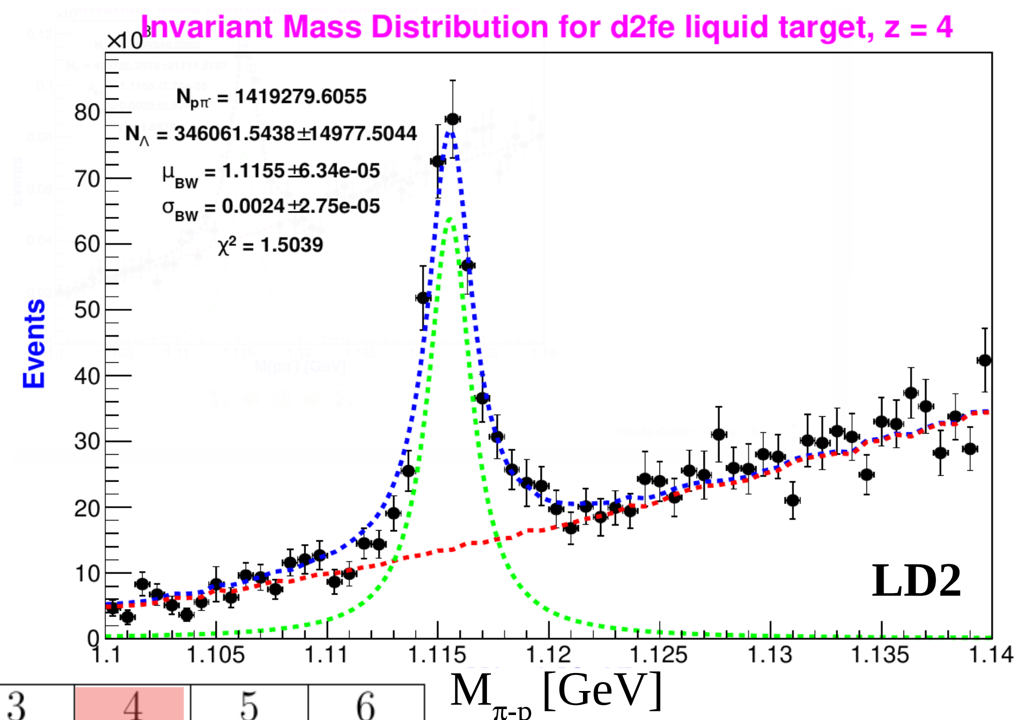
$z\ (= E_\Lambda / \nu)$

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

Λ Yield Extraction

- Identify Λ via its decay particles, π^- and proton;
- 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*).

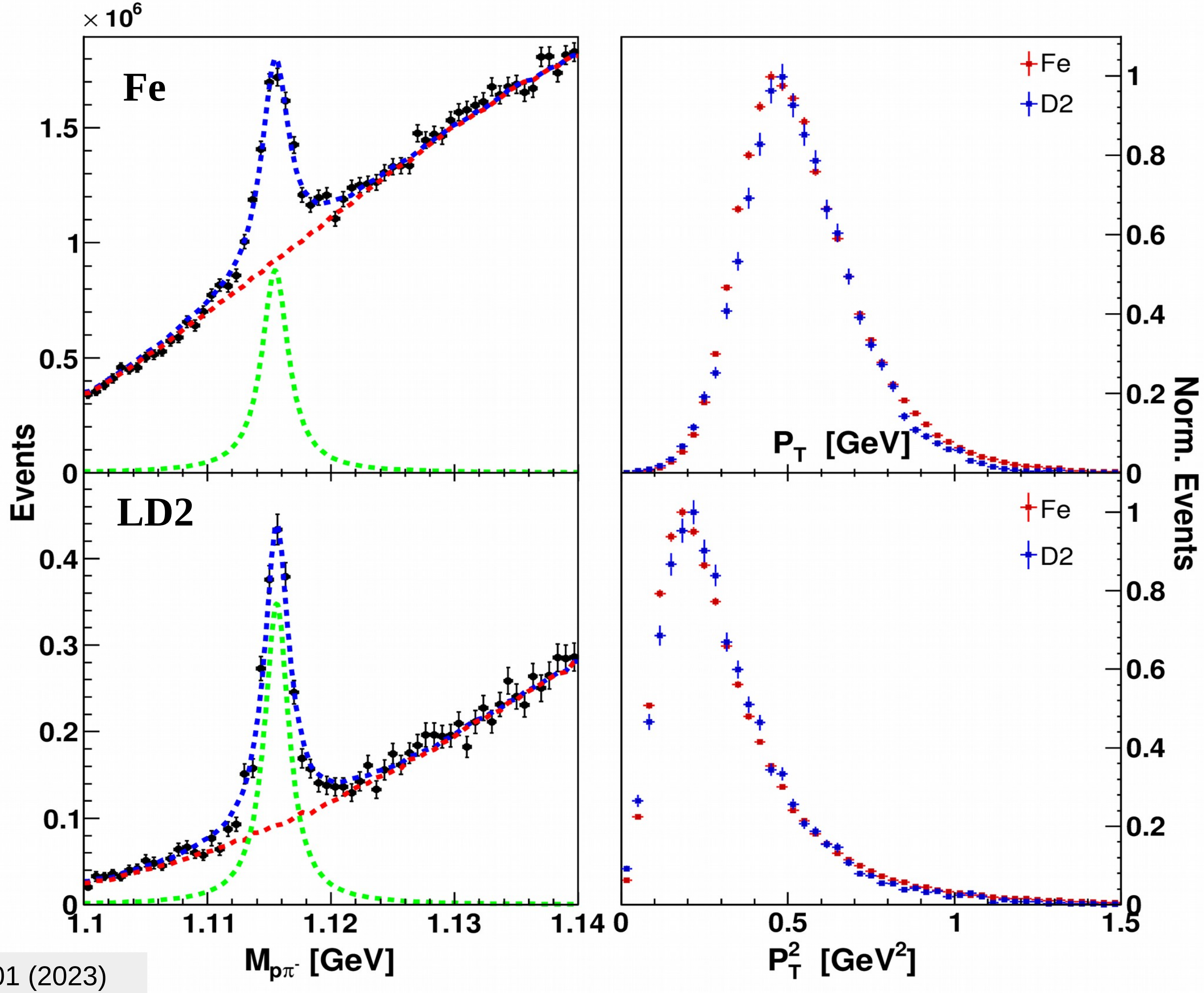




$z\ (= E_\Lambda / \nu)$

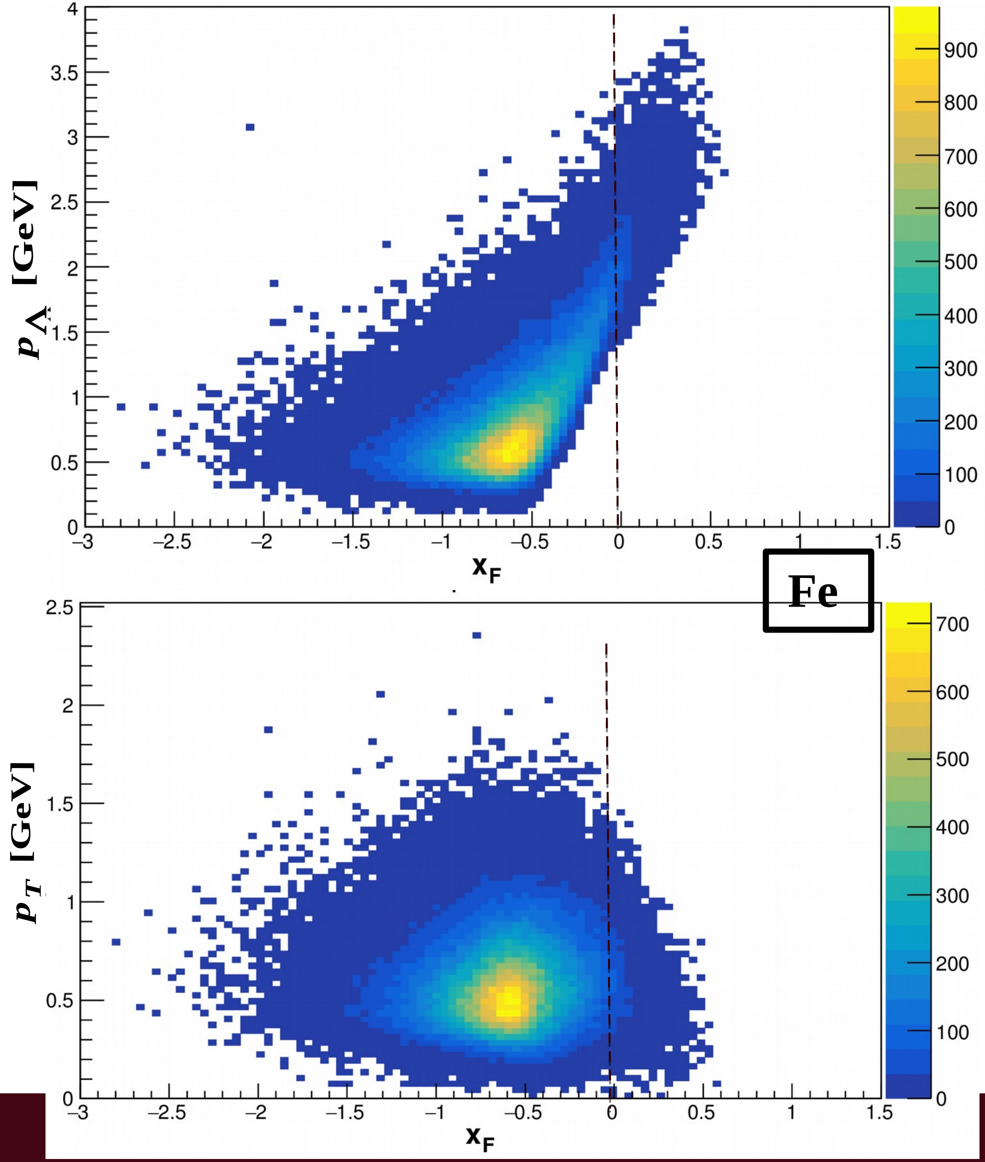
Bin #	1	2	3	4	5	6
z_{min}	0.28	0.38	0.44	0.51	0.60	0.75
z_{max}	0.38	0.44	0.51	0.60	0.75	1.00

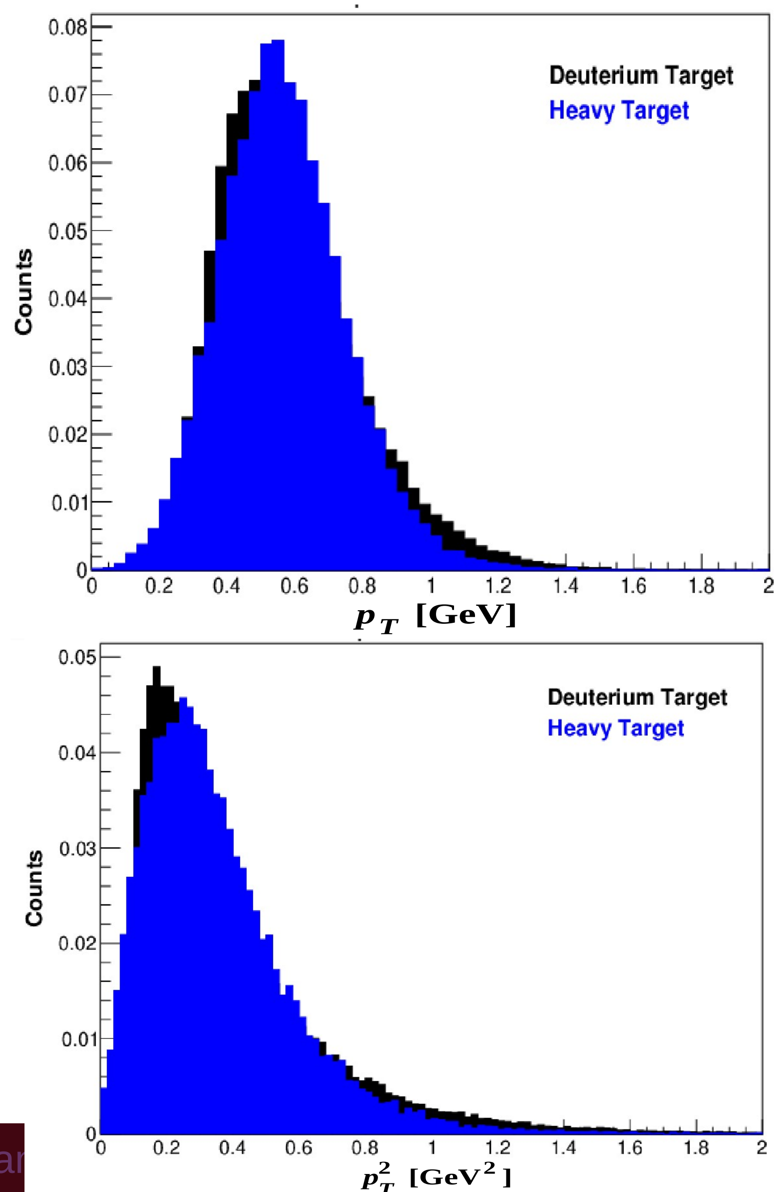
Λ Mass Distributions and Kinematics



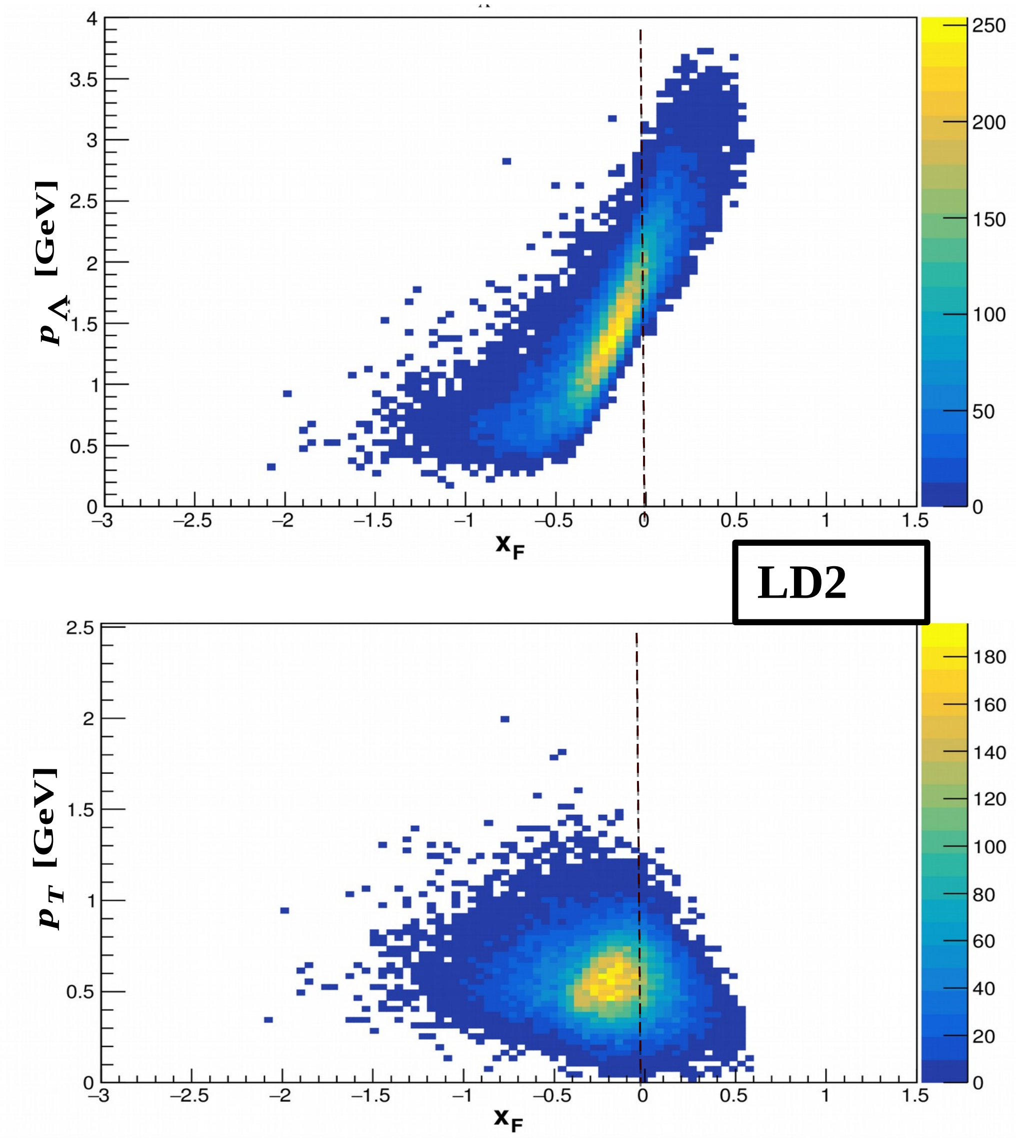
Phys. Rev. Lett. **130**, 142301 (2023)

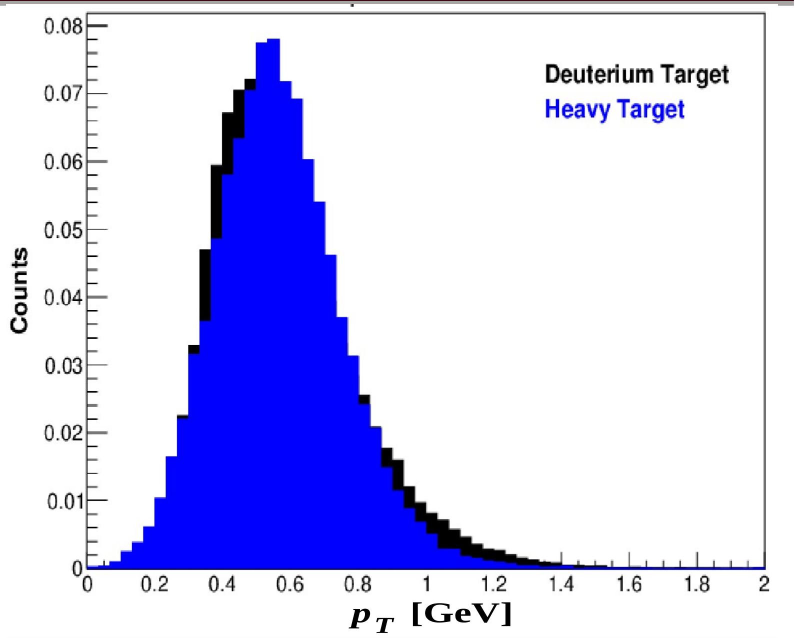
Λ Kinematics

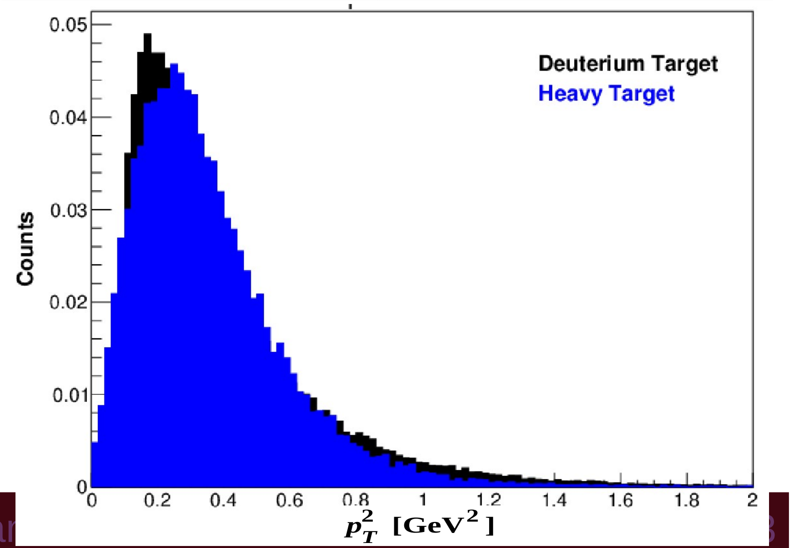




Λ Kinematics

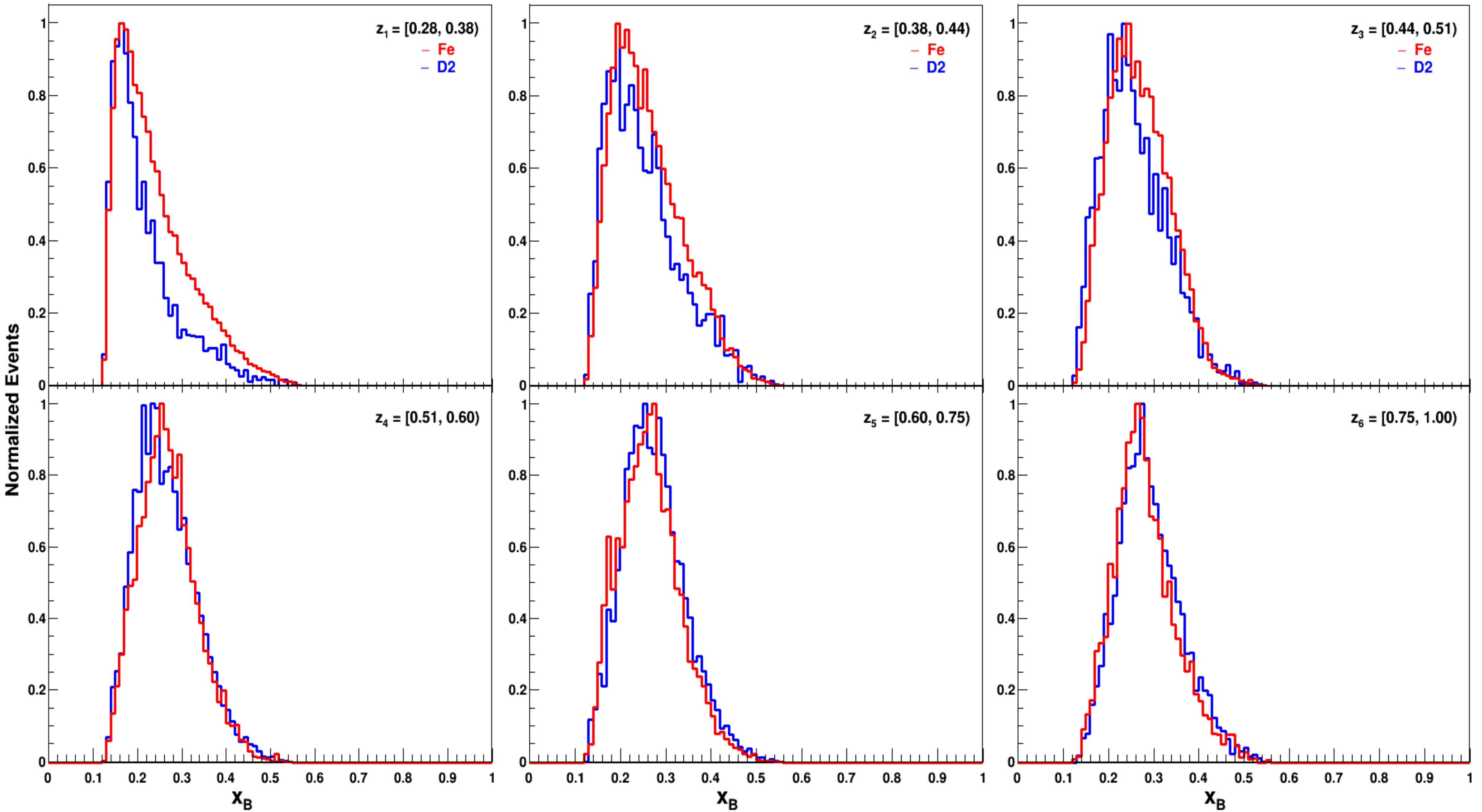






Λ Kinematics

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	$1.38\overline{3}$
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