A new way to study hadron production with nuclear DIS

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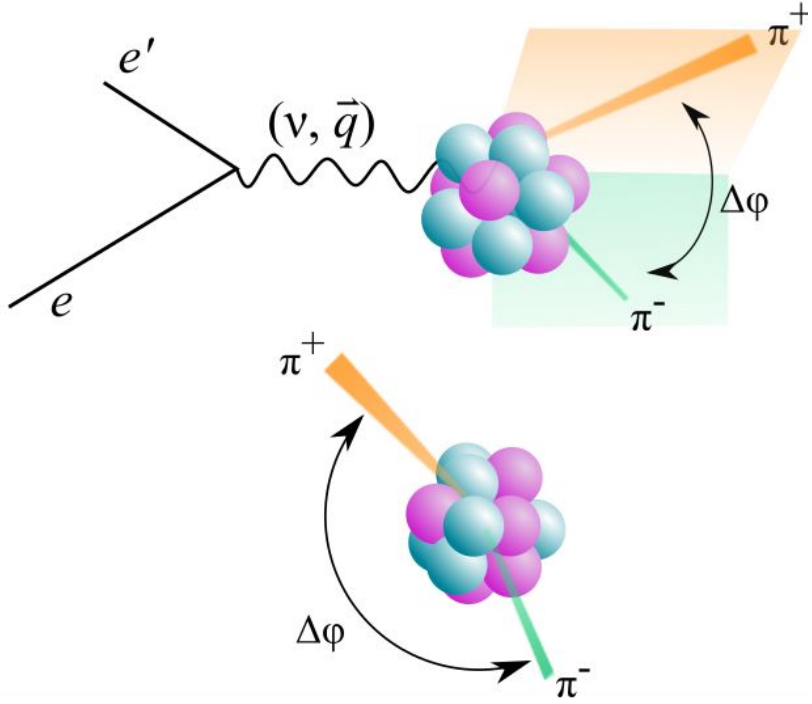


How does the nucleus react to a fast moving quark?

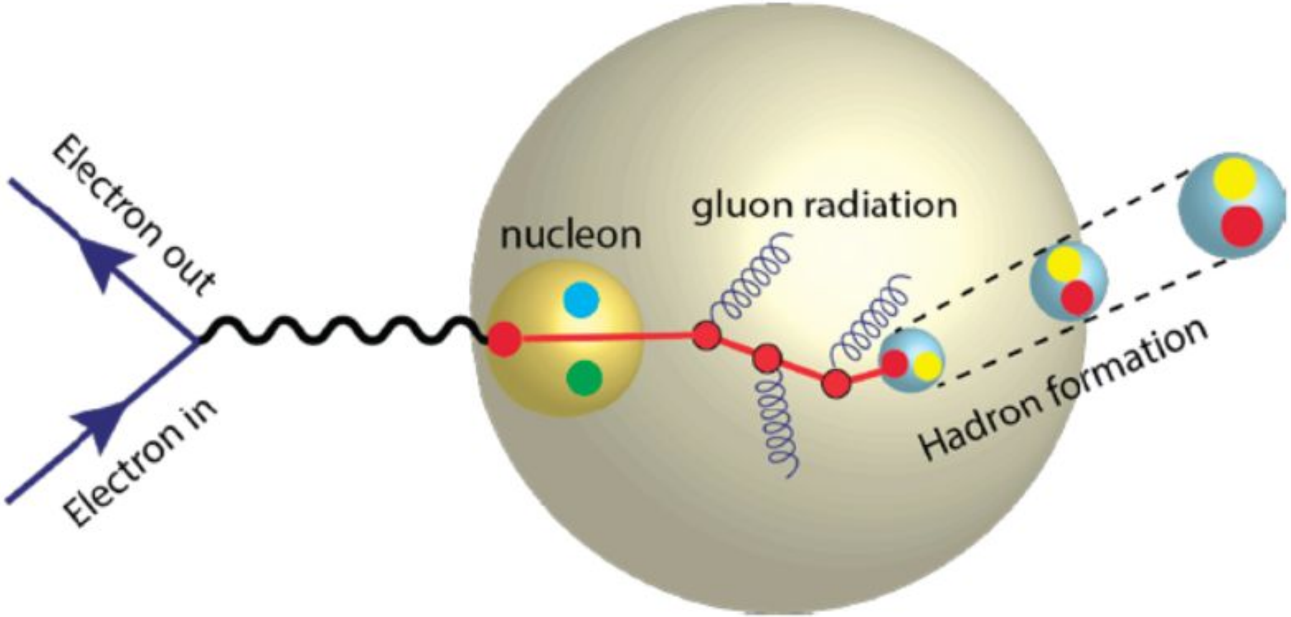
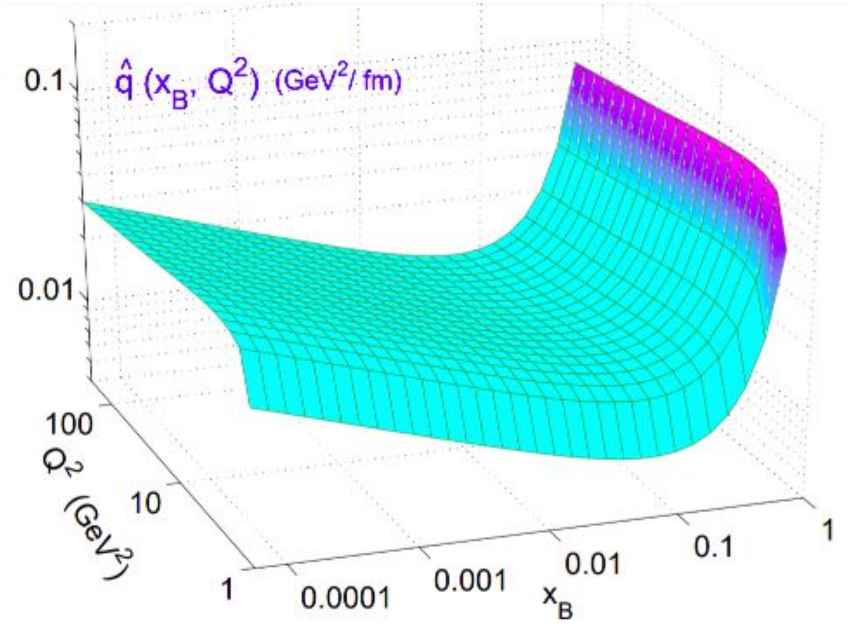
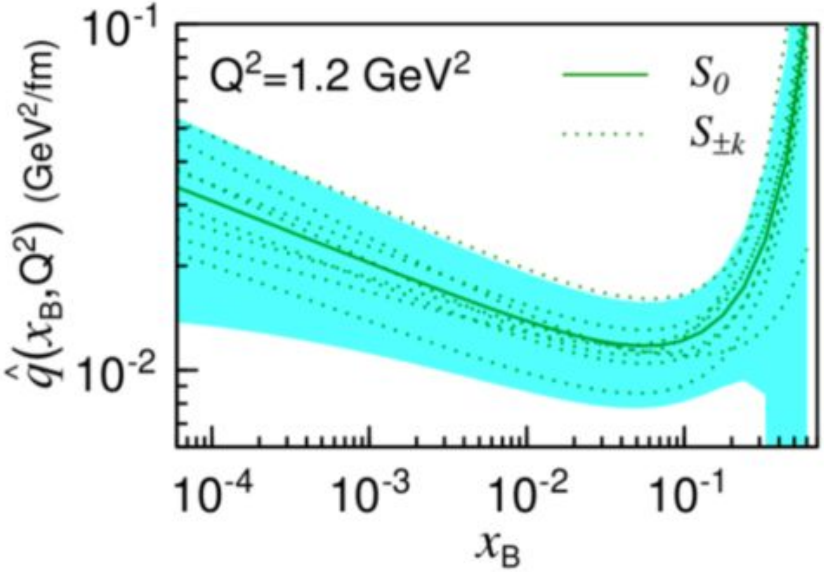


Figure from EIC NAS

Quark transport in nuclei

Result of global analysis on hadron production with nuclear targets
Ru et al. PRD 103, 031901 (2021)





Timescales of hadronization?

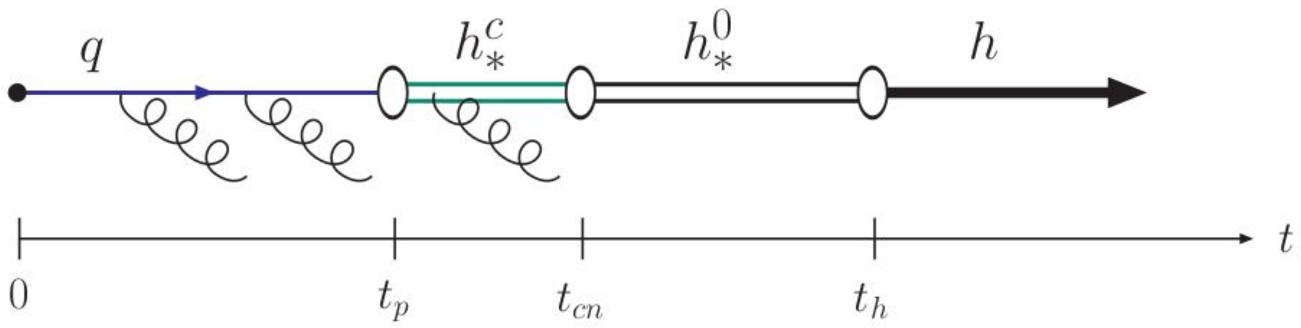
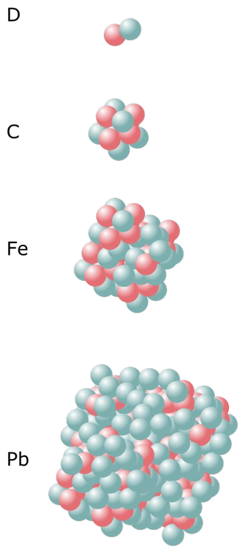


Fig. 7. – Sketch of the time evolution of the hadronisation process with definition of various time scales. A quark q created at time 0 in a hard collision turns into a coloured prehadron h_*^c, which subsequently neutralises its colour, h_*^0, and collapses on the wave function of the observed hadron h. Gluon radiation lasts until colour neutralisation.

Figure from Acardi et al. Riv.Nuovo Cim. 32 (2009) 9-10, 439-554

Hadron formation times vs kinematics in Lund model

https://arxiv.org/abs/2202.12804



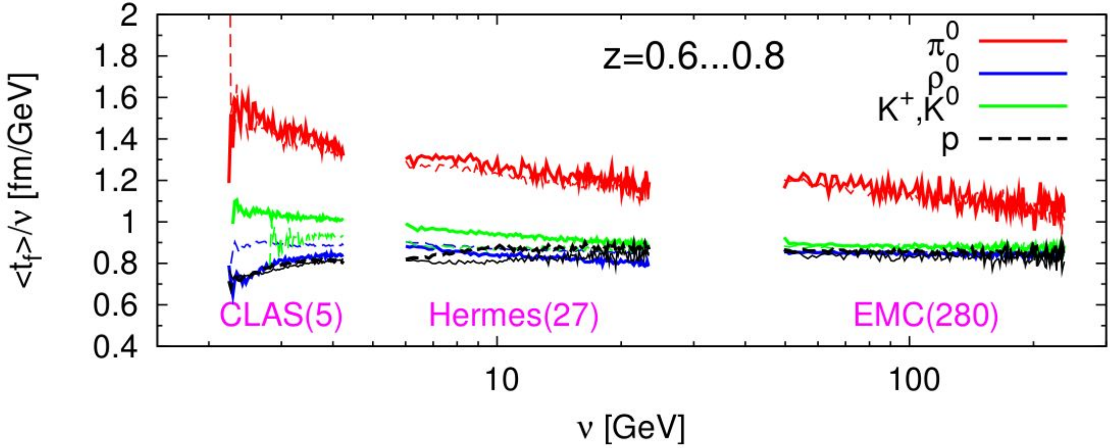
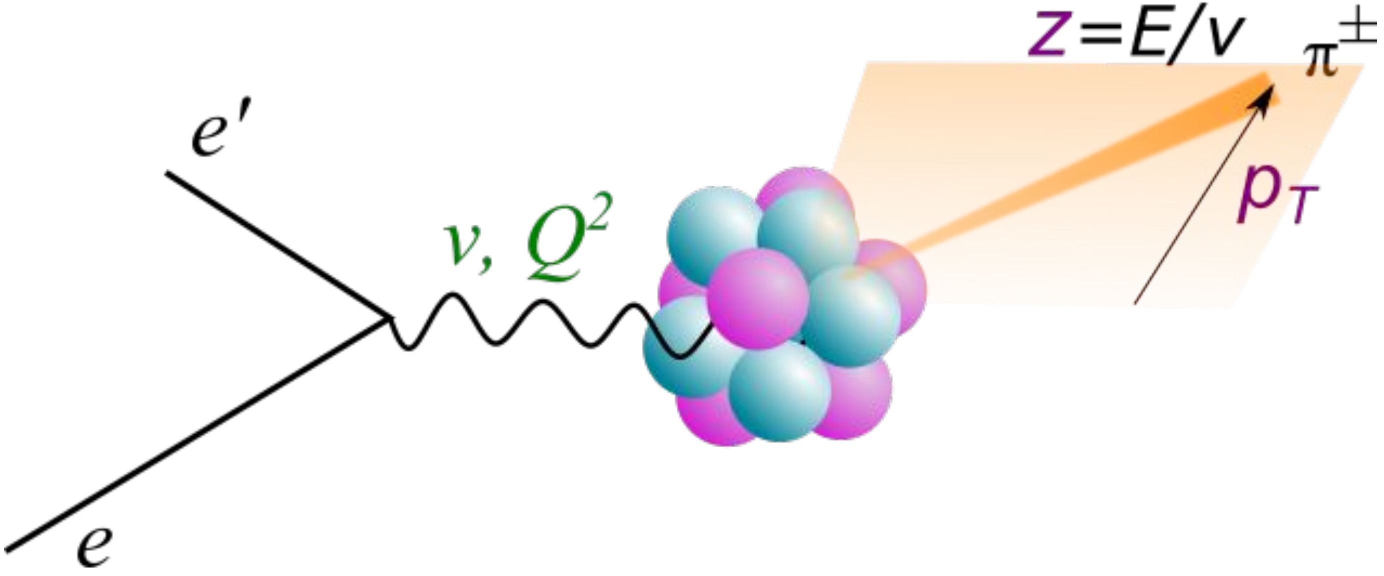


FIG. 1. Average formation times in the lab frame as a function of energy transfer ν for an intermediate $z = E_h/\nu = 0.6..0.8$ in three kinematical regimes for some hadrons.

CLAS and CLAS12 cover region where formation length is comparable to nuclear size

Lepton variables

Hadron variables



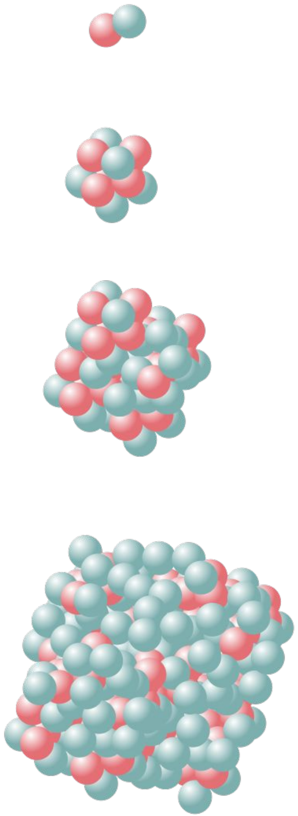
CLAS data: 5 GeV electron beam on nuclear targets

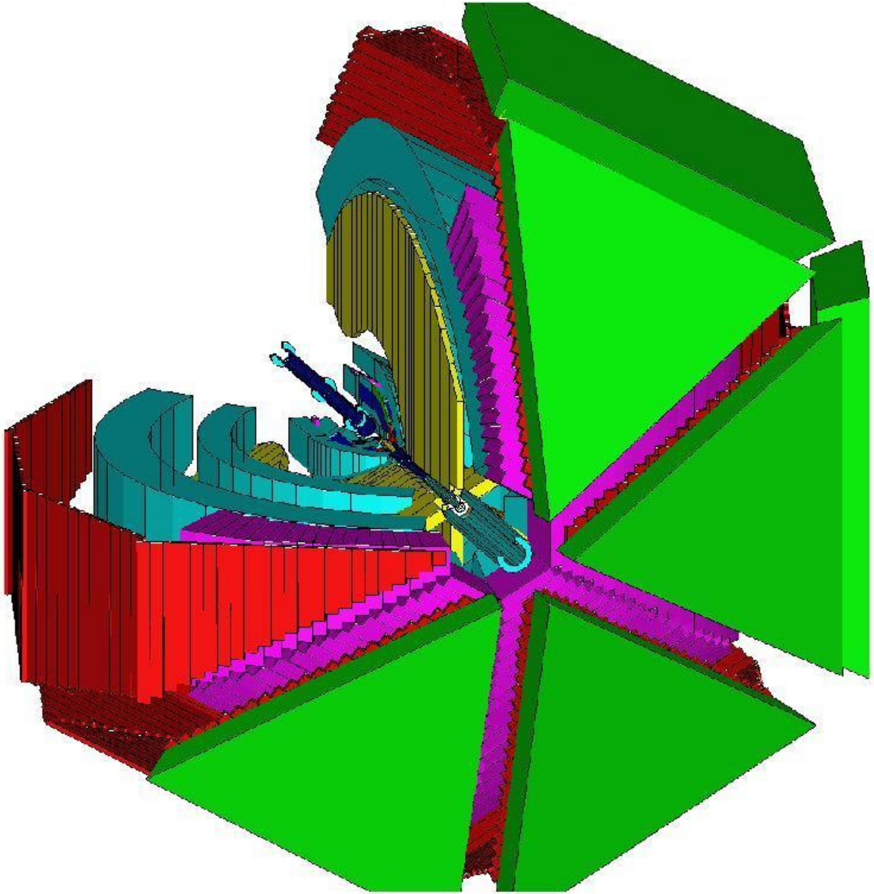
D

C

Fe

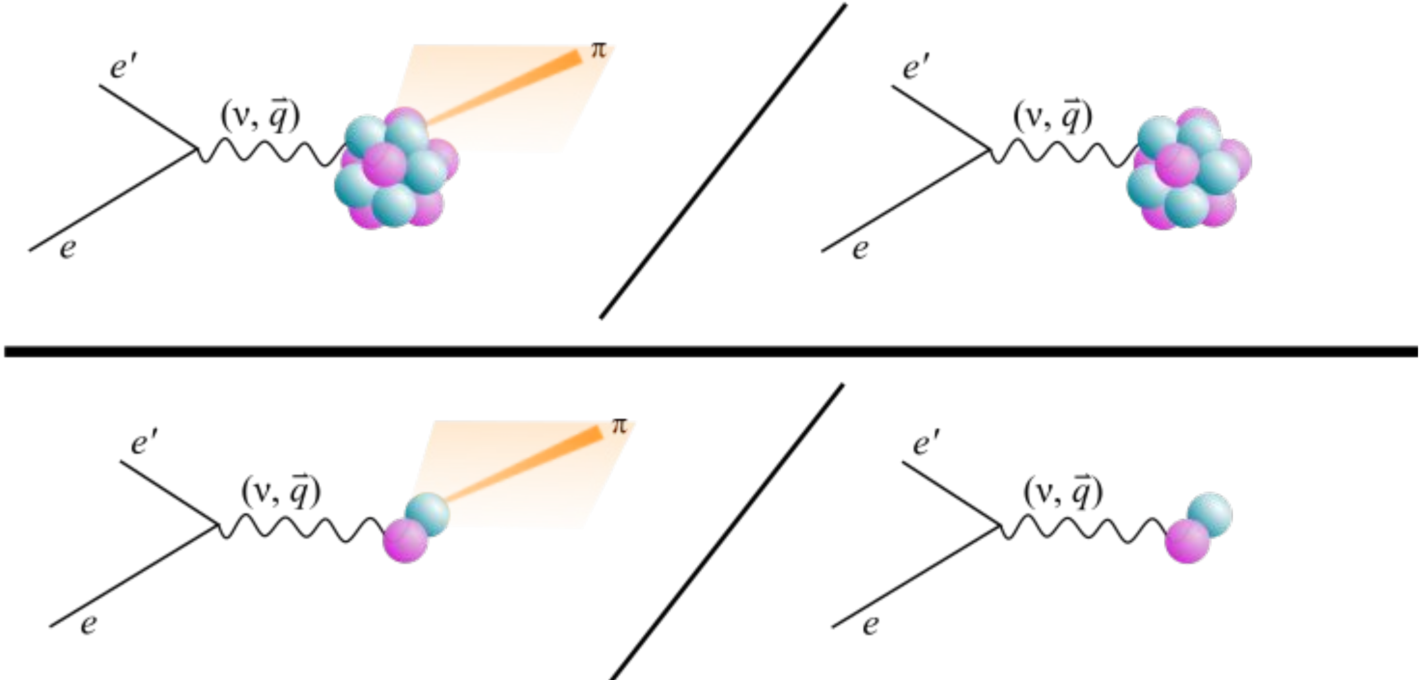
Pb





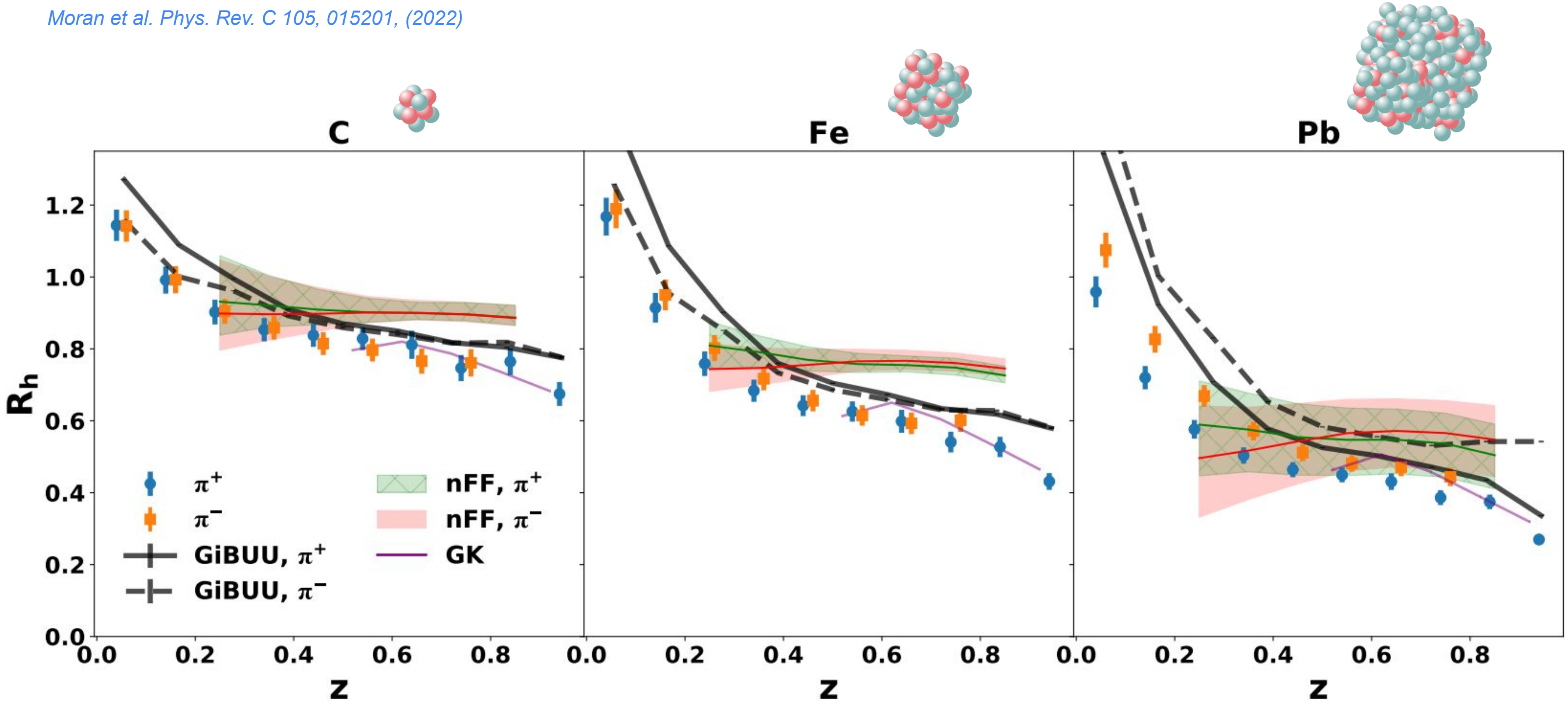
Single hadron production ratio:

$$R_h(\nu, Q^2, z, p_T^2) = \frac{N_h^A(\nu, Q^2, z, p_T^2)/N_e^A(\nu, Q^2)}{N_h^D(\nu, Q^2, z, p_T^2)/N_e^D(\nu, Q^2)}.$$



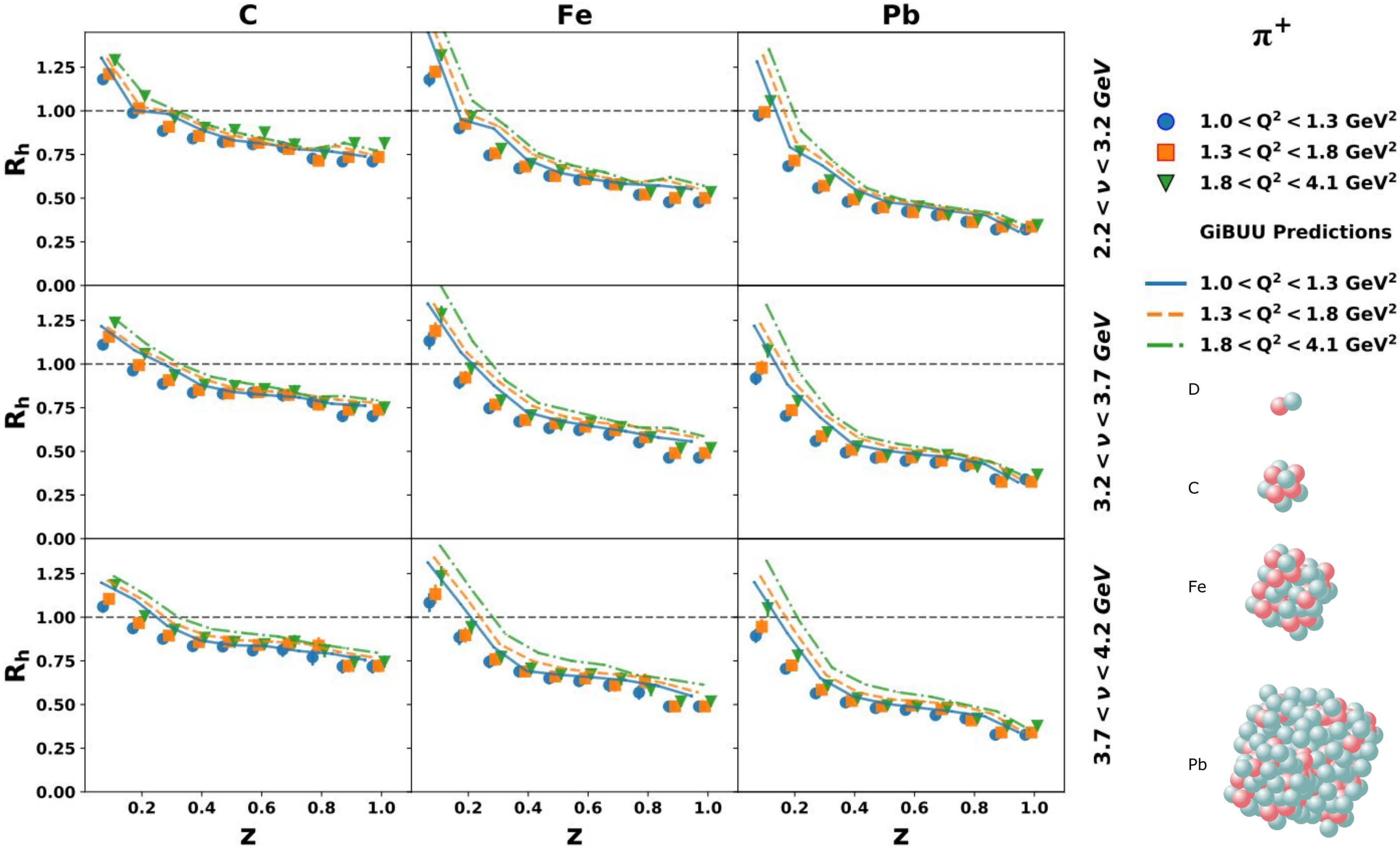
Single-hadron multiplicity ratio

Moran et al. Phys. Rev. C 105, 015201, (2022)

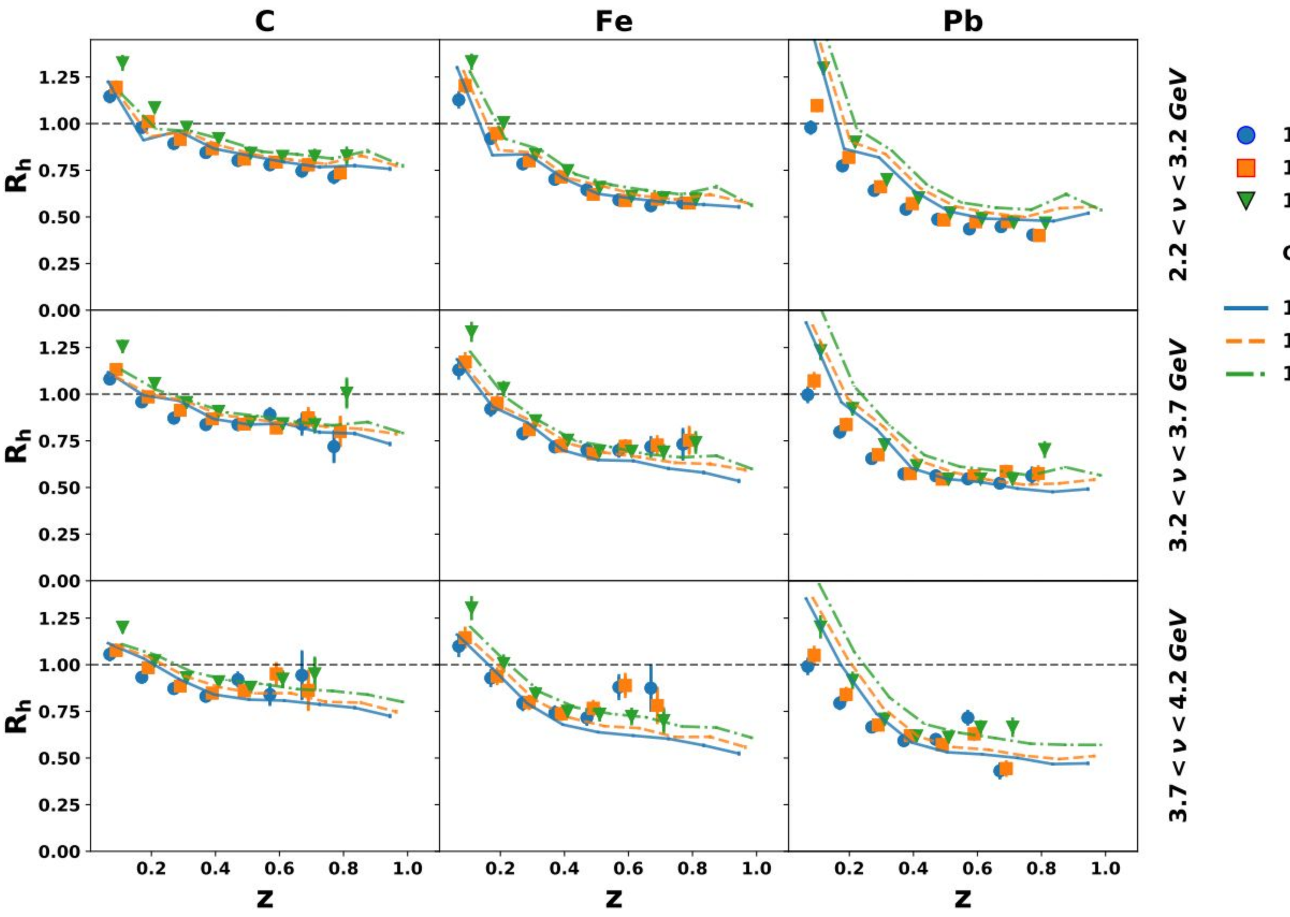


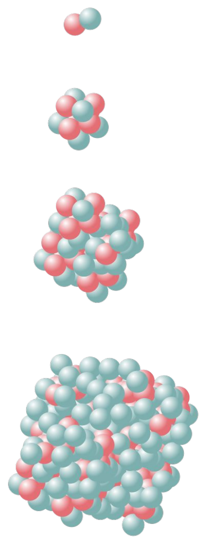
High-precision, multidimensional charged-pion data

Moran et al. Phys. Rev. C 105, 015201, (2022)



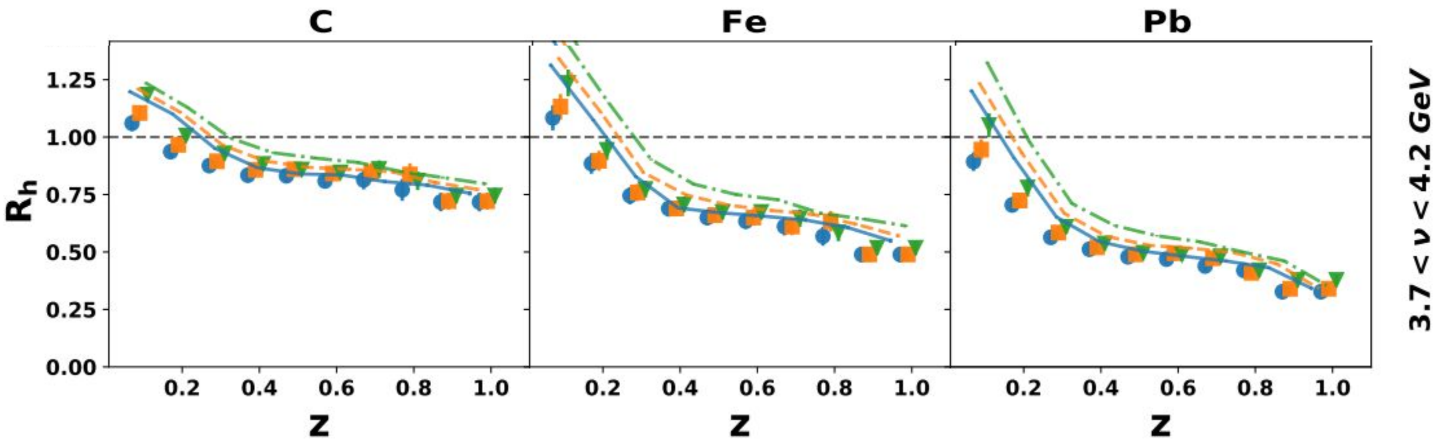
Negative pion too





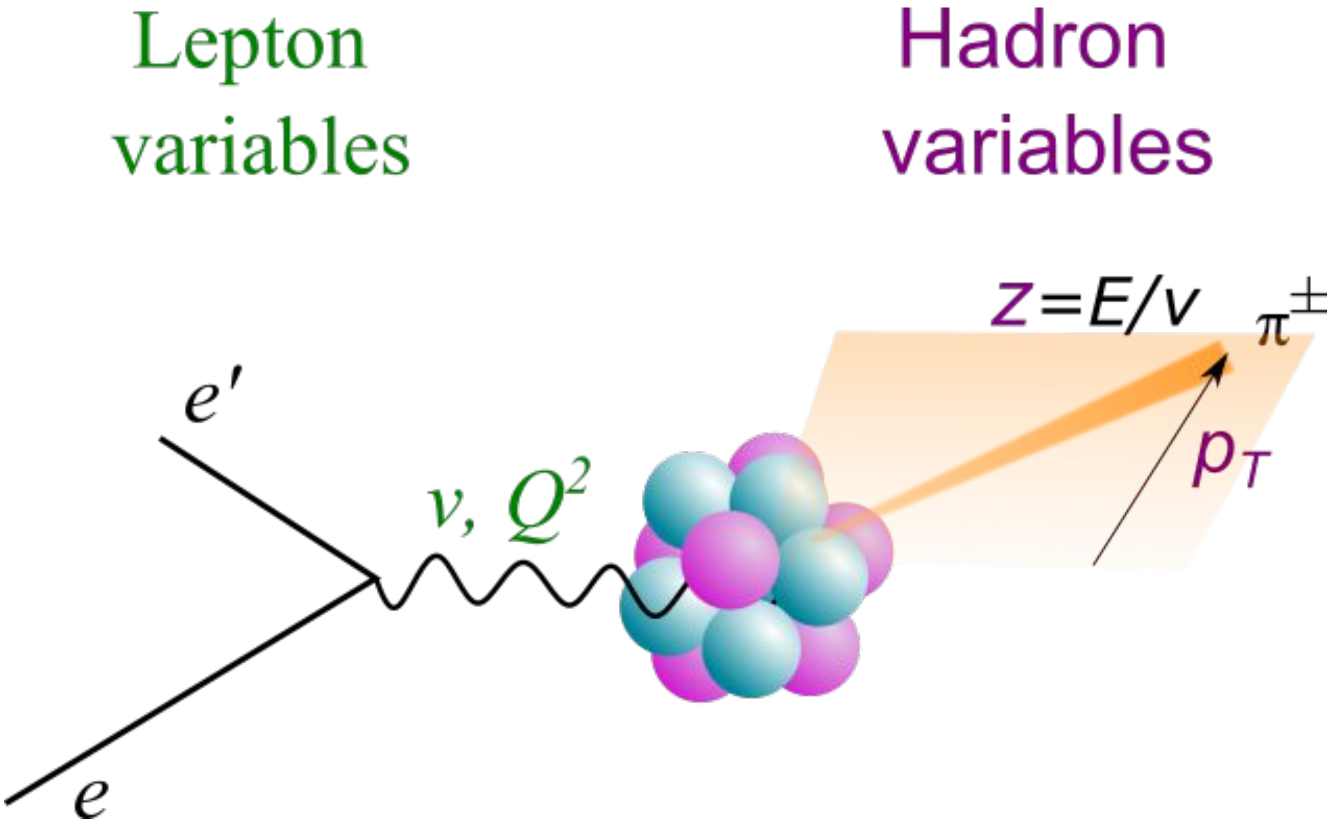
What causes the excess of slow hadrons?

It has been long argued that this is "medium response"



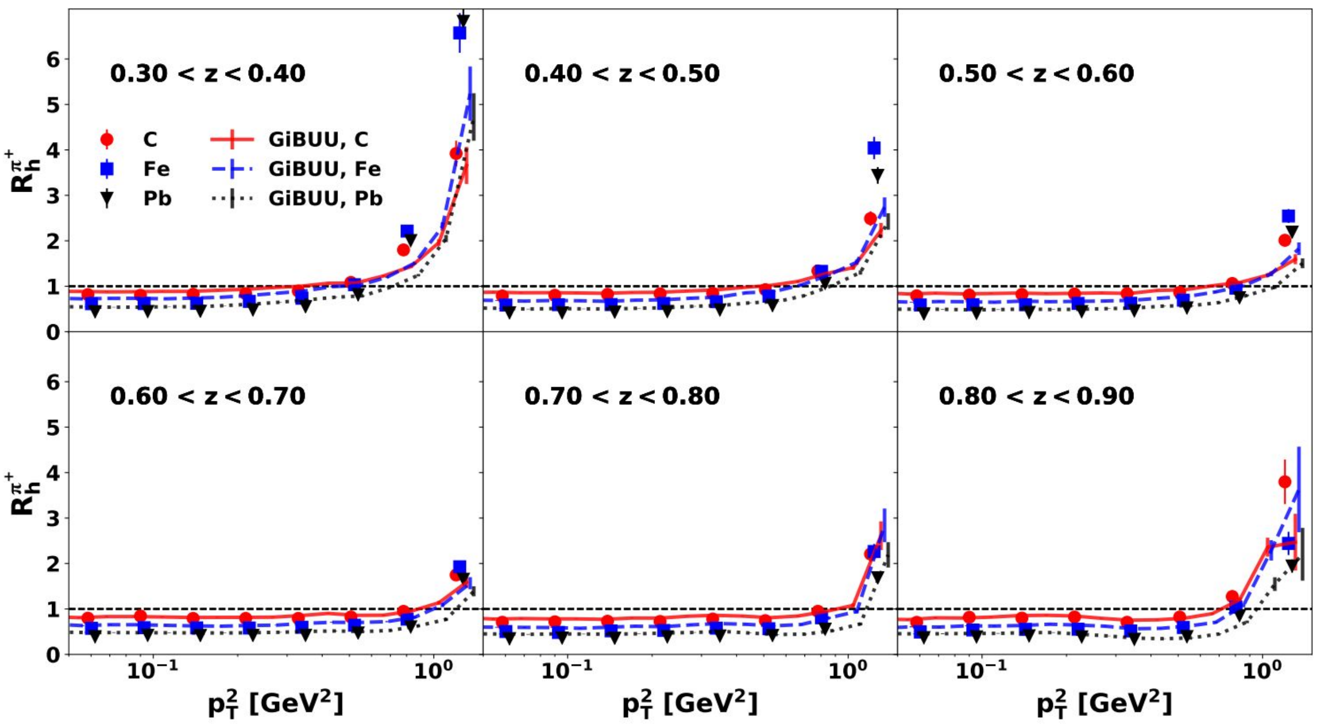
What causes the excess of slow hadrons?

We must investigate simultaneously in energy and transverse momentum



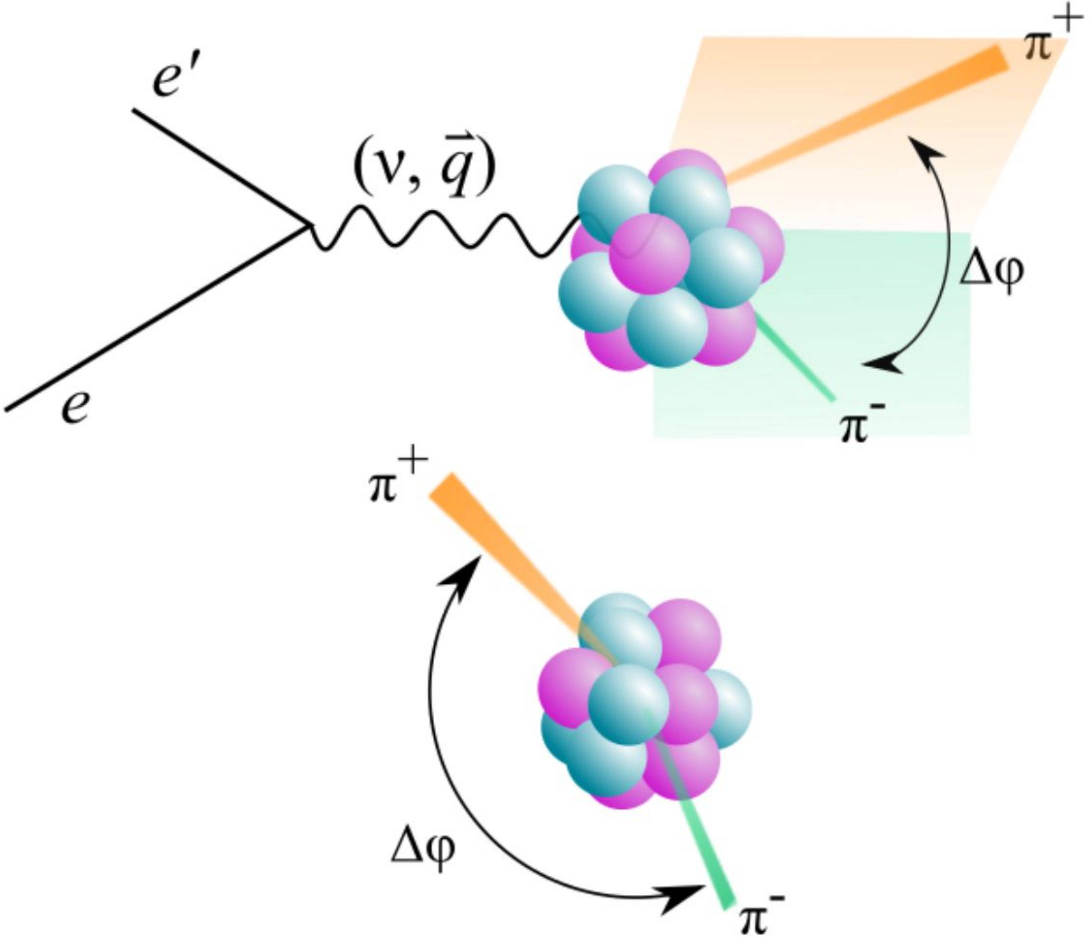
Modification ratio differential in energy and transverse momentum

Moran et al. Phys. Rev. C 105, 015201, (2022)

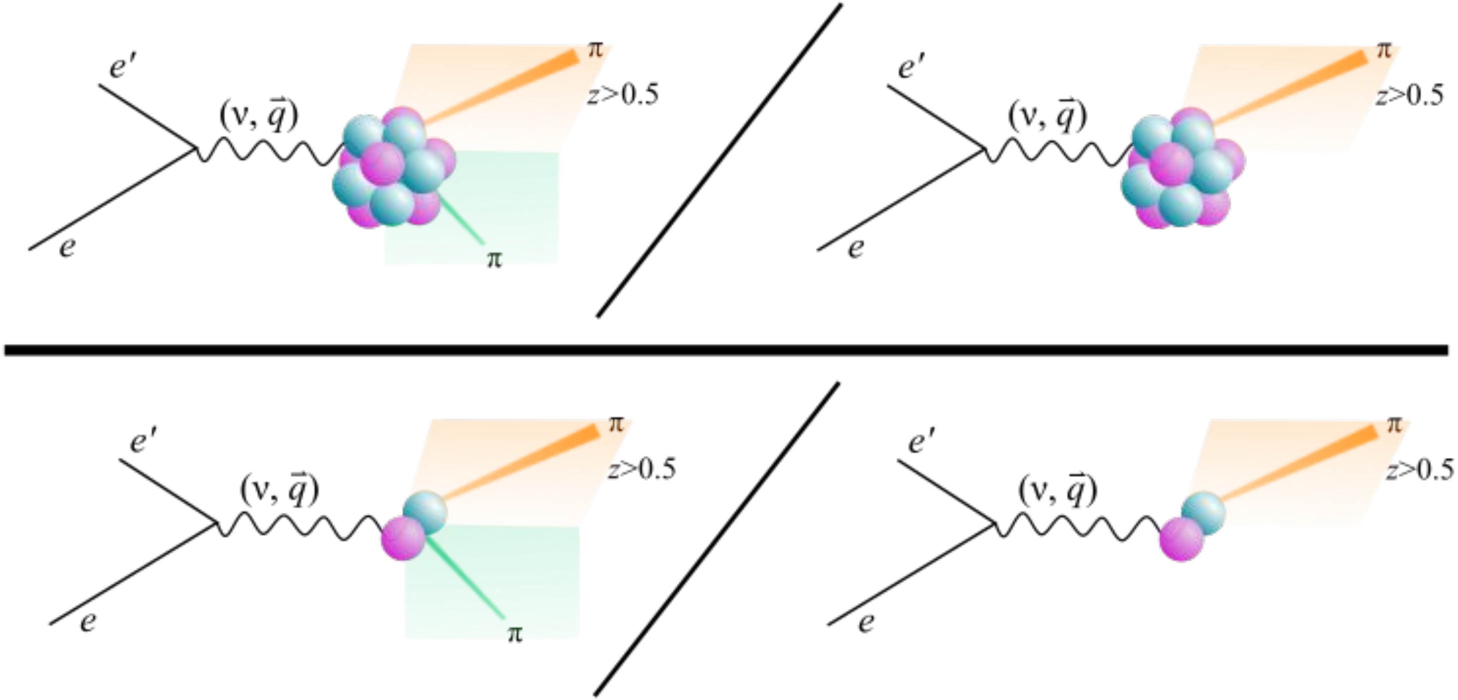


- Excess at low energy and high pT
- Magnitude decreases with Increasing z, but then increases again at high z

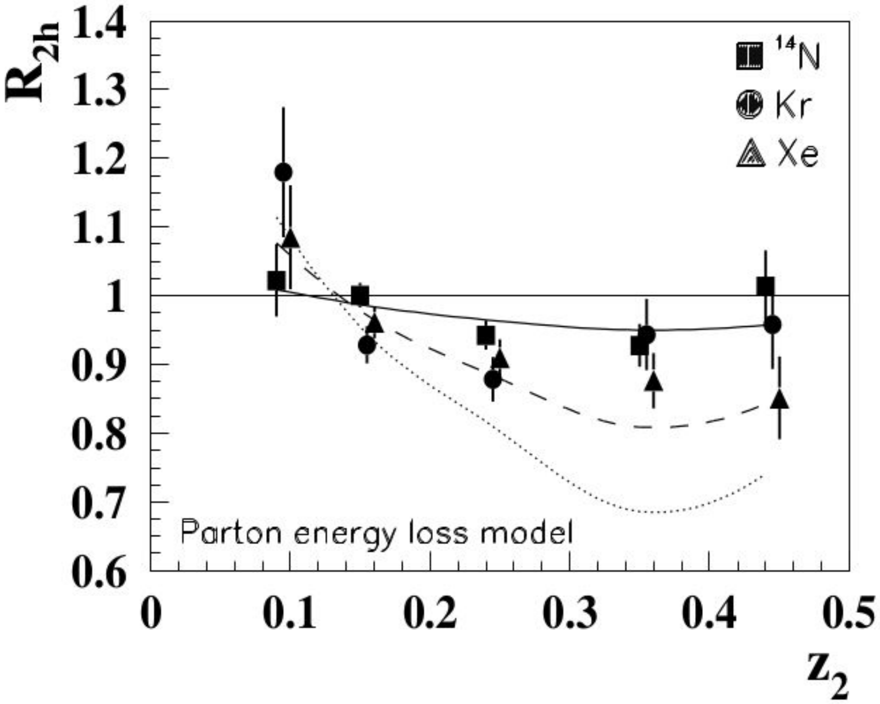
Enter di-hadron angular correlations

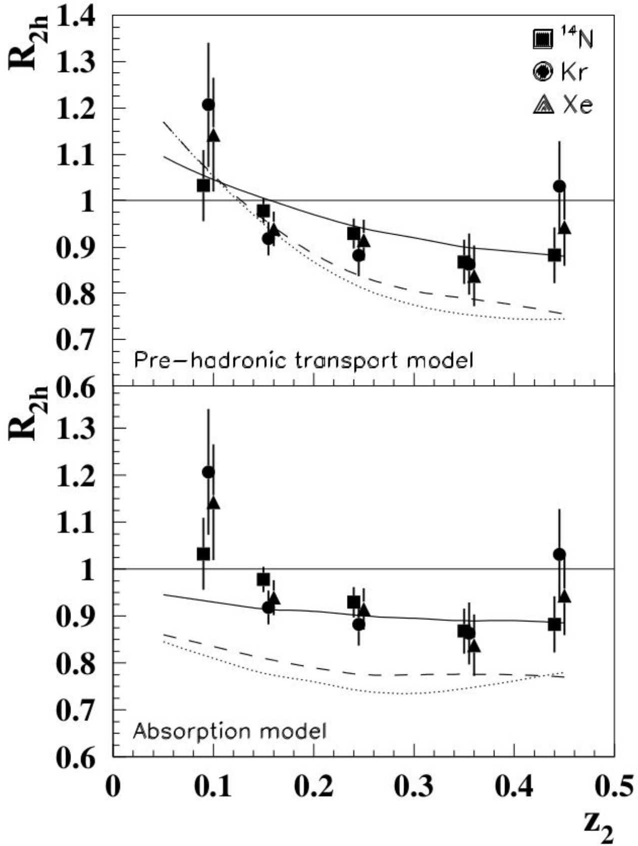


Double hadron production ratio

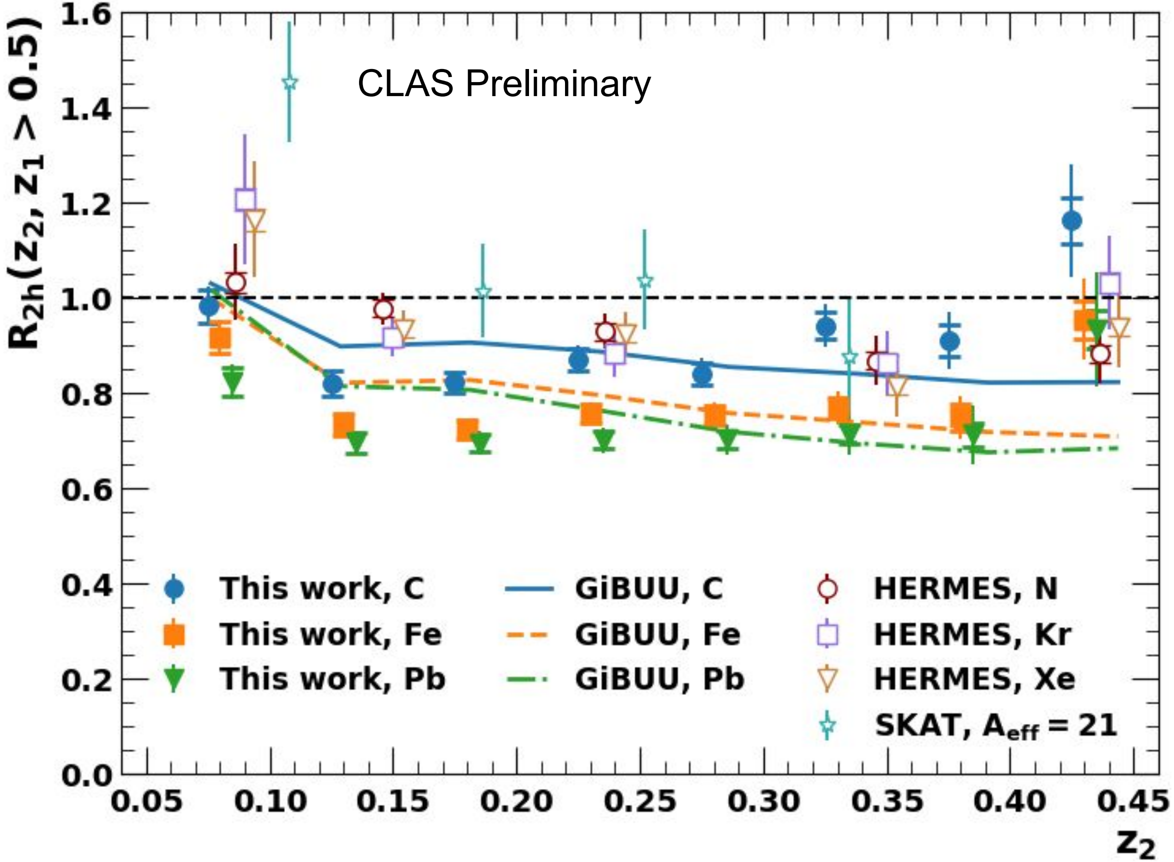


HERMES measured this observable, which carries large discriminating power PRL 96:162301,2006

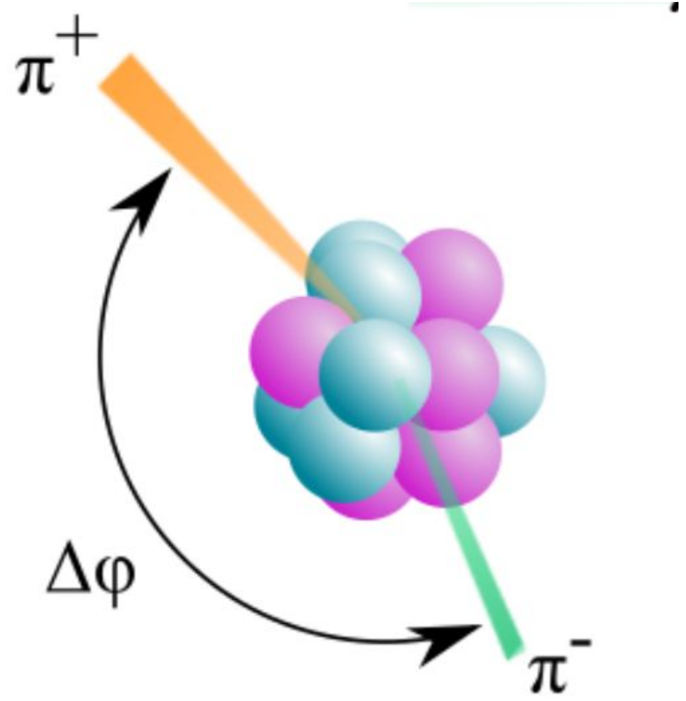




Double hadron production ratio

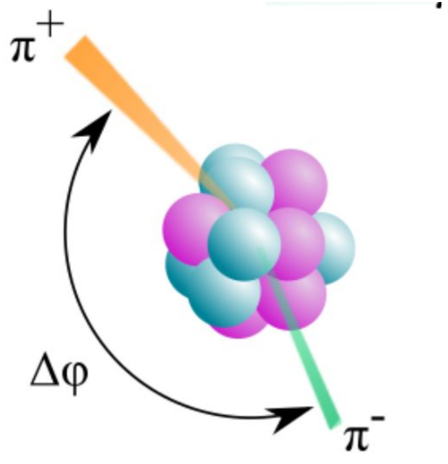


- Small A dependence
- Flat trend with z2
- Significant difference with HERMES reveals strong kinematic dependence

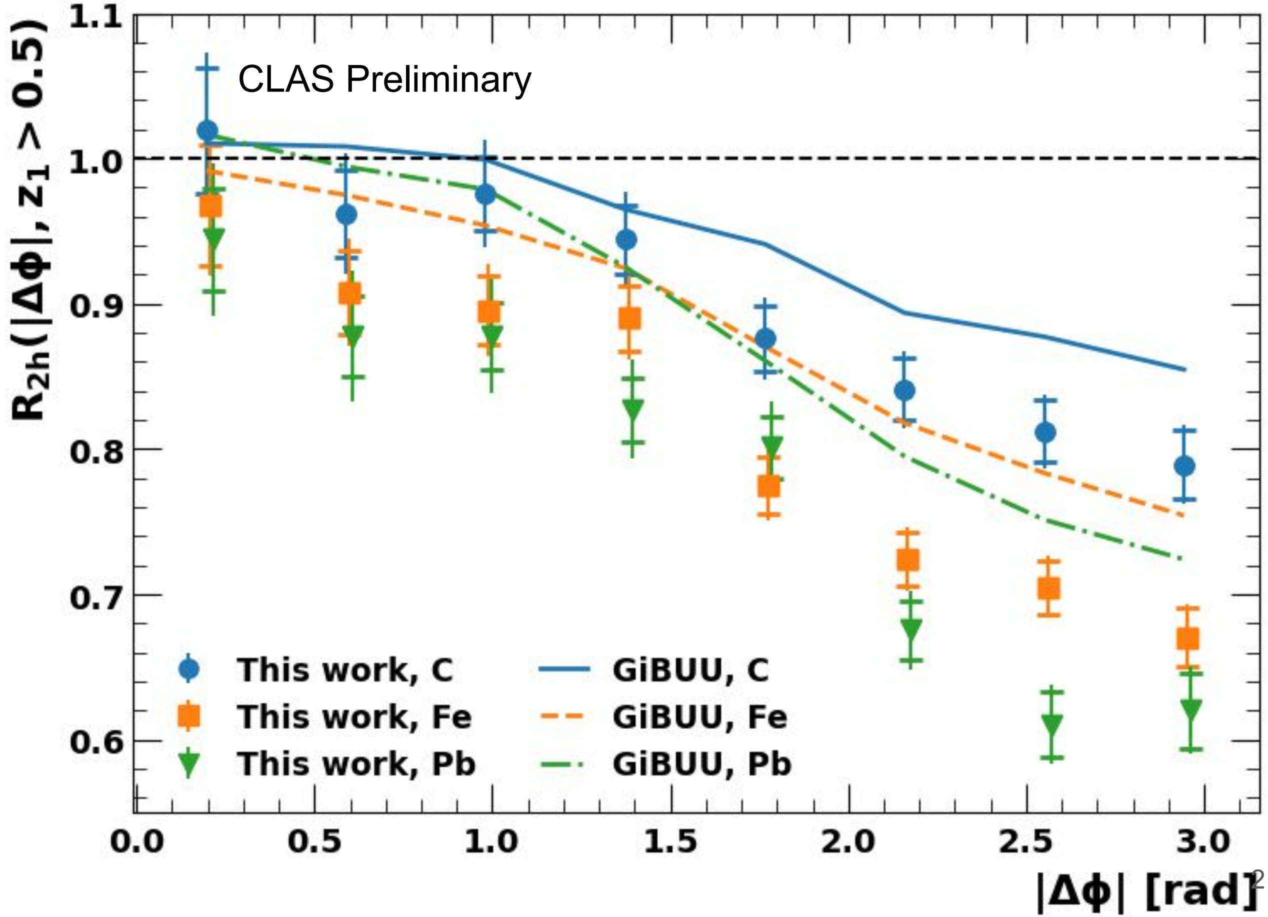


We can go beyond HERMES by measuring angular correlations

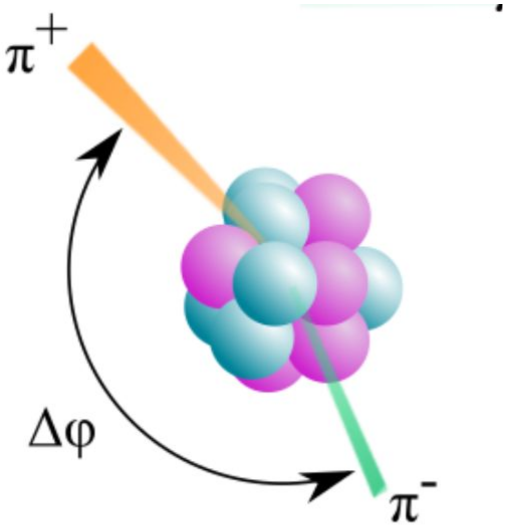
First-ever measurement of azimuthal correlation in eA

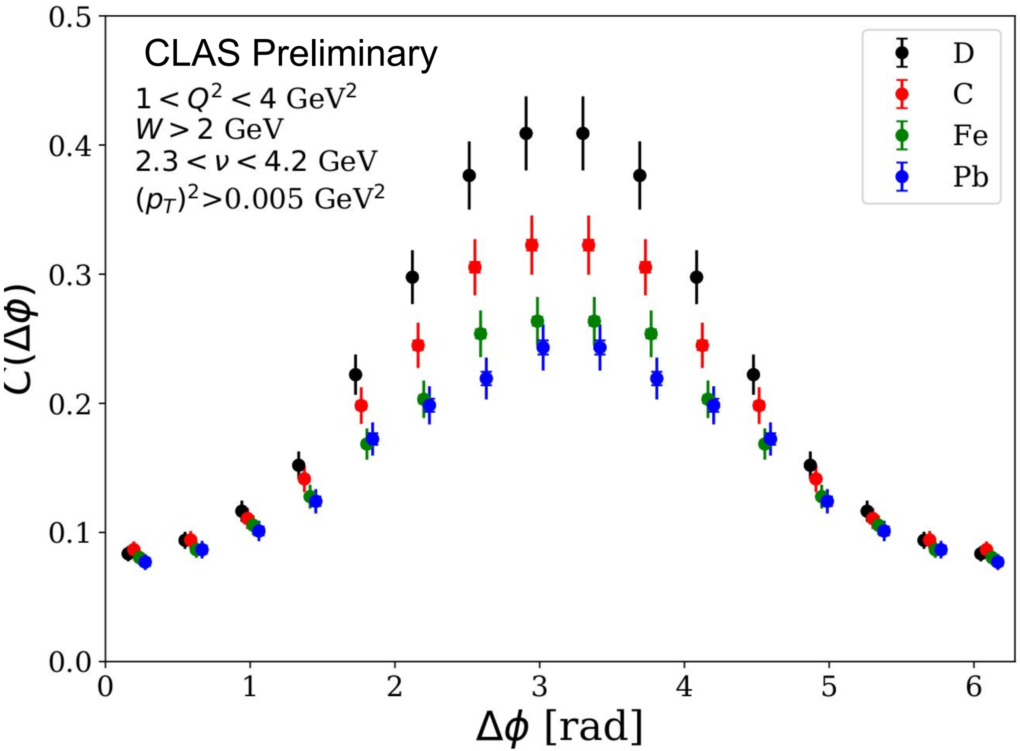


"Dipion quenching"



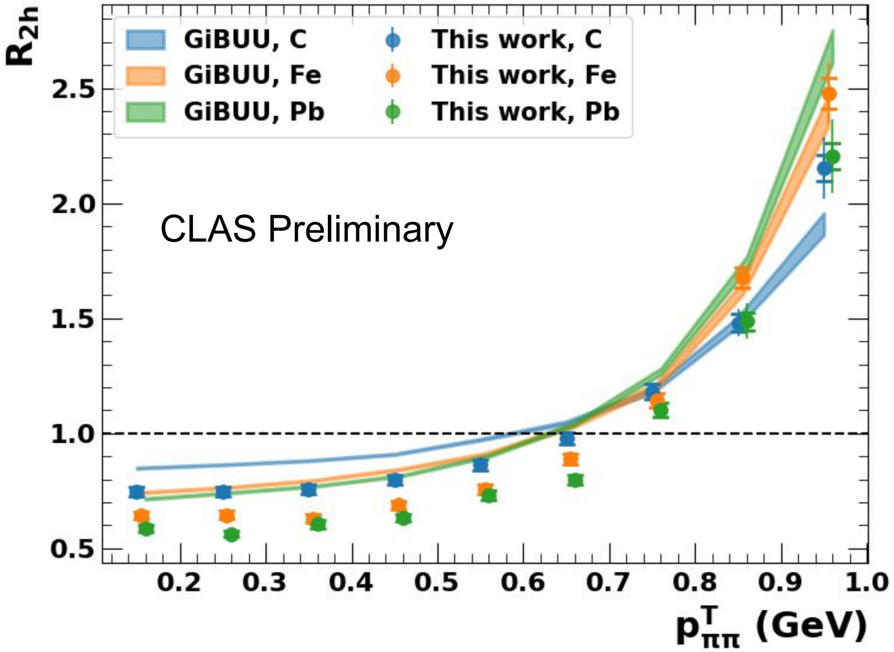
Broadening and suppression of correlation function in e-A DIS

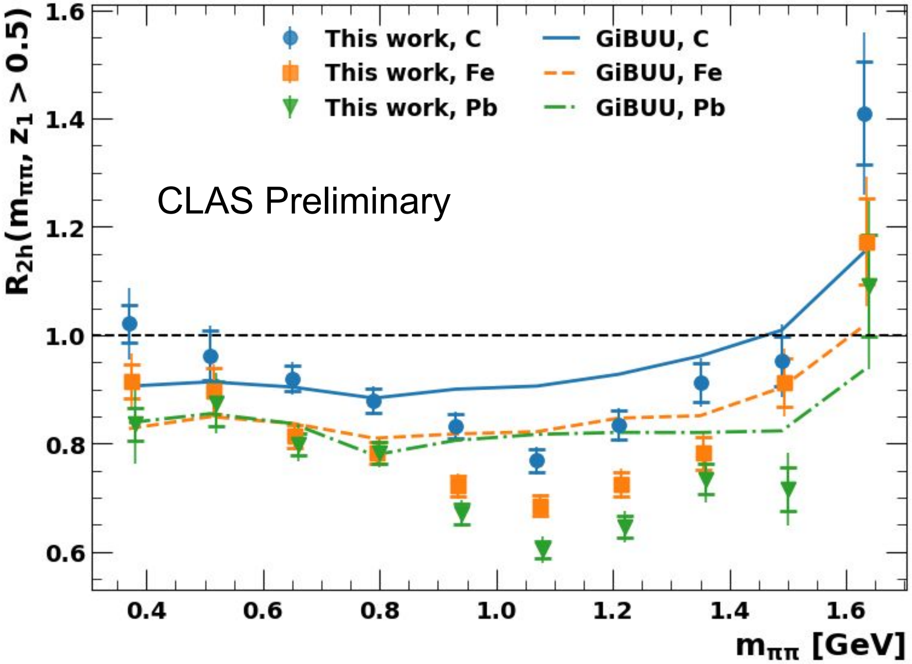




"Dipion quenching"

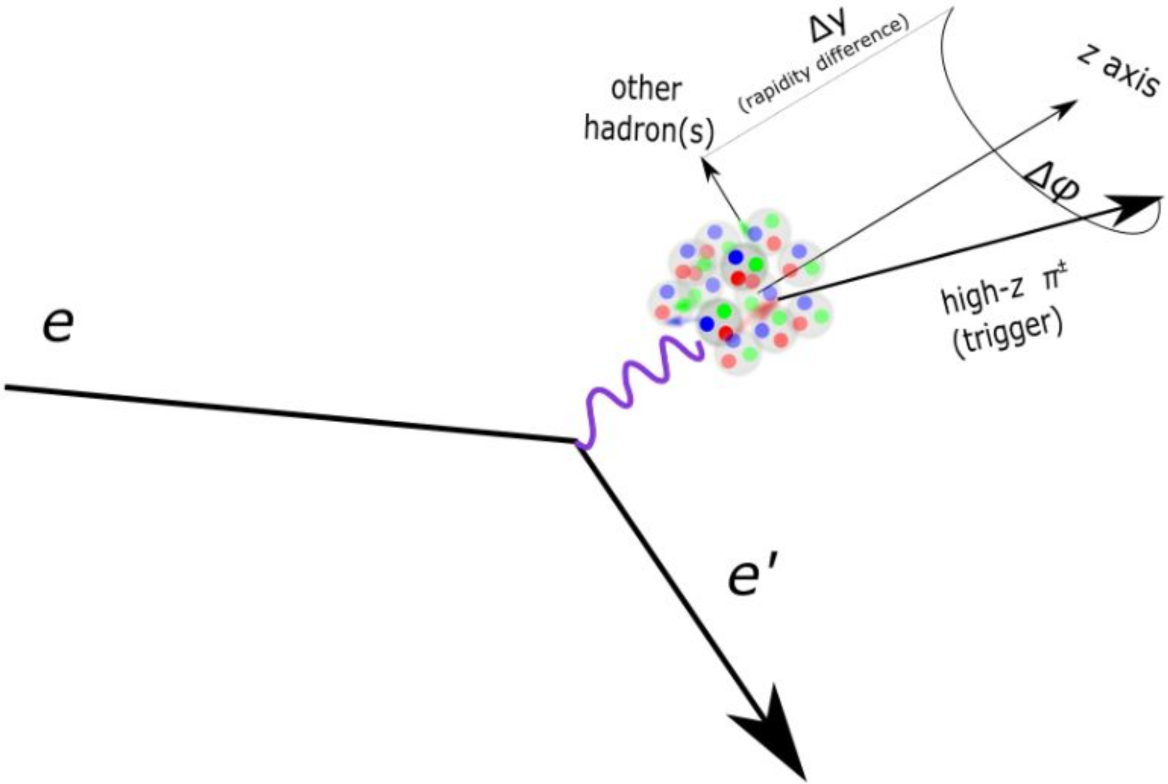
Dependence on dipion transverse momentum and mass



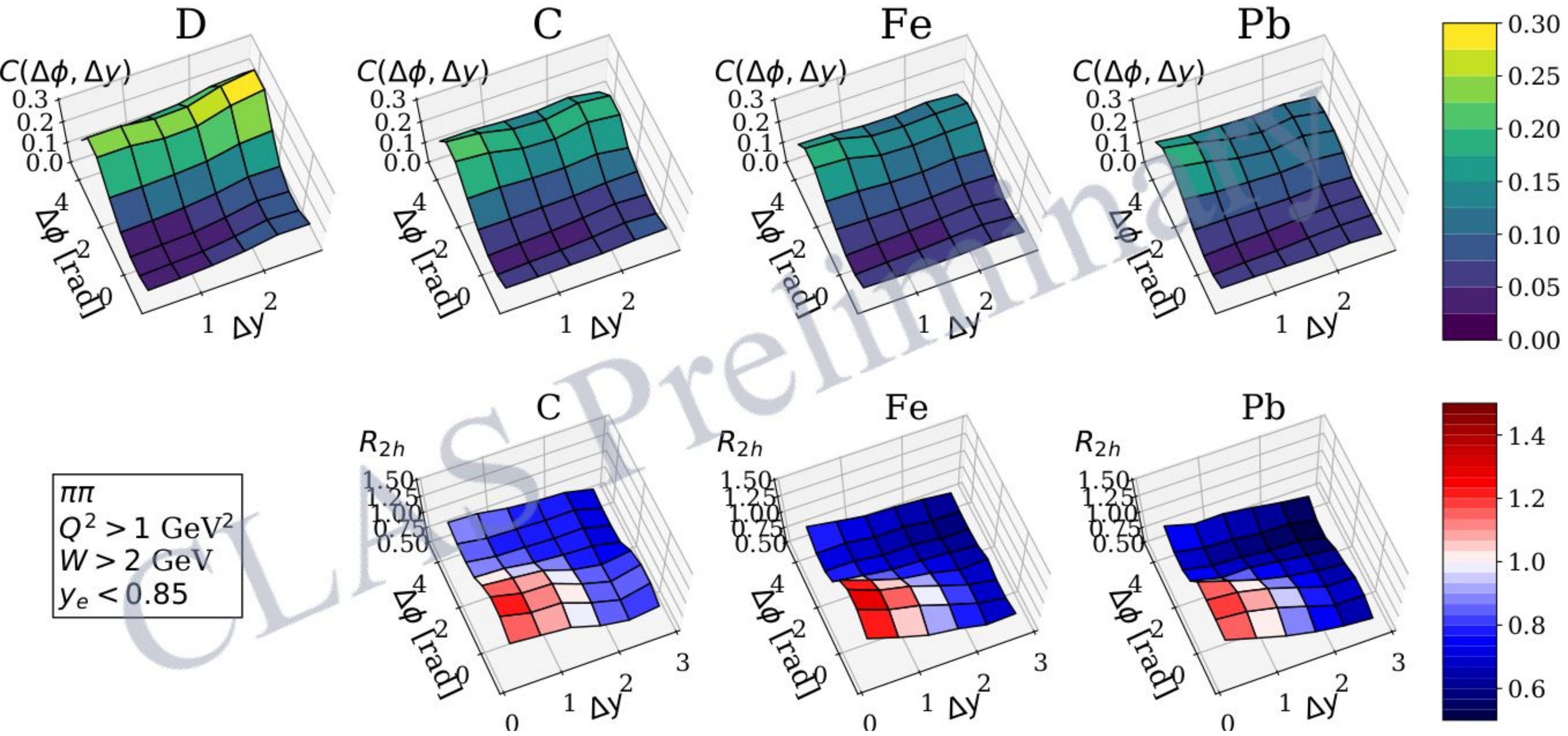


Uptick at large values, weak dependence at small values. Similar to single hadron

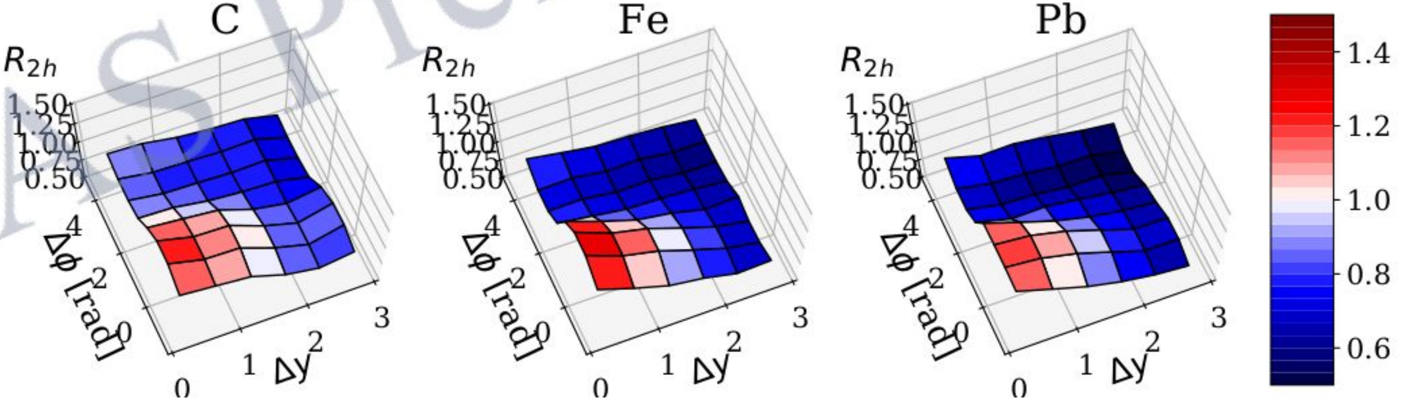
Azimuthal & rapidity correlations



Azimuthal & rapidity correlations



$\pi\pi$
$Q^2 > 1$ GeV^2
$W > 2$ GeV
$y_e < 0.85$



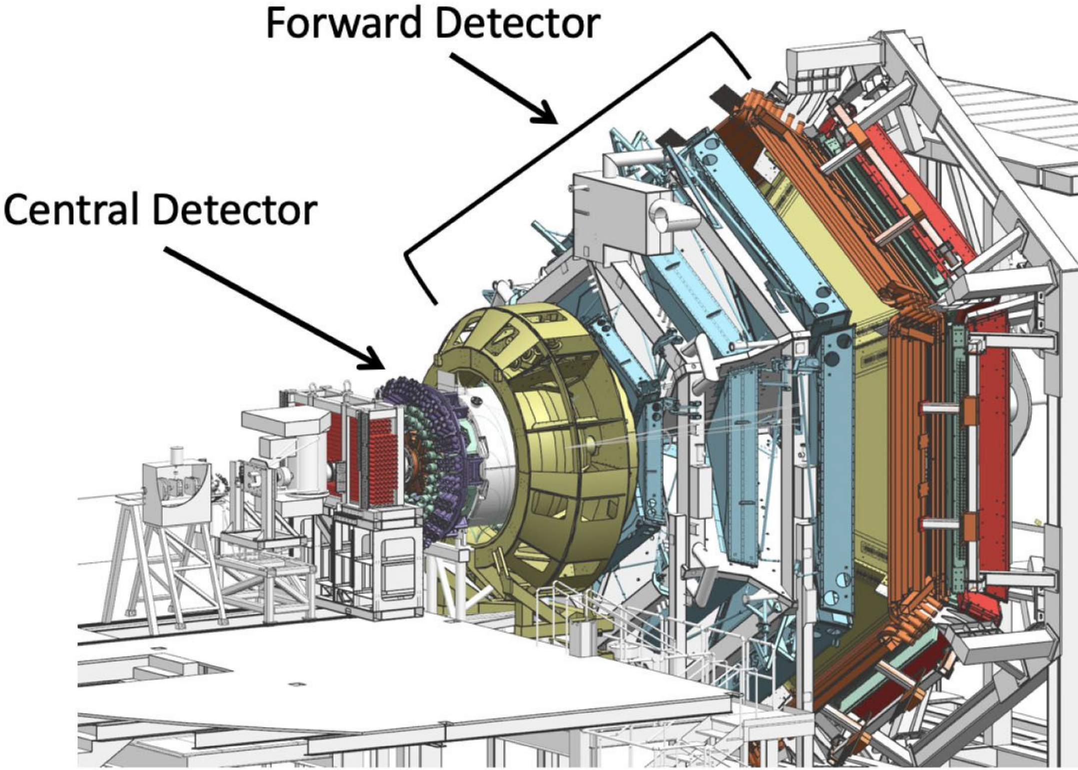
CLAS12 set to bring an exciting future for nuclear DIS

- *"Quark propagation and hadron formation experiment"* with 11 GeV beam to run in near future

- 10 times more statistics.
- Larger kinematic range
- Better tracking, PID.

- **Expect a decade worth of SIDIS studies in nuclear DIS with general purpose detector.**
  A gateway to the EIC.

- **We need new challenges…**



Taking inspiration from HERMES [charm upgrade]() (proposal circa ~97)

Muon detectors (RPCs) proposed
Along with RICH to go after open charm production with various decay channels involving kaons, muons, e.g:

Table 2: Anticipated counts at 80 pb^{-1}, for RICH only

decay mode	N_{sig}	N_{back}	Significance	Total Significance
$\overline{D^0} \to K^+ \pi^-$	77	250	$4.3\ \sigma$	$4.8\ \sigma$
$D^0 \to K^- \pi^+$	27	110	$2.3\ \sigma$	

Table 3: Anticipated counts at 80 pb^{-1}, for RICH + muon detection

decay modes	N_{sig}	N_{back}	Significance
$\overline{D^0} \to K^+ \mu^- X$ $D^0 \to K^- \mu^+ X$	267	3011	$4.7\ \sigma$

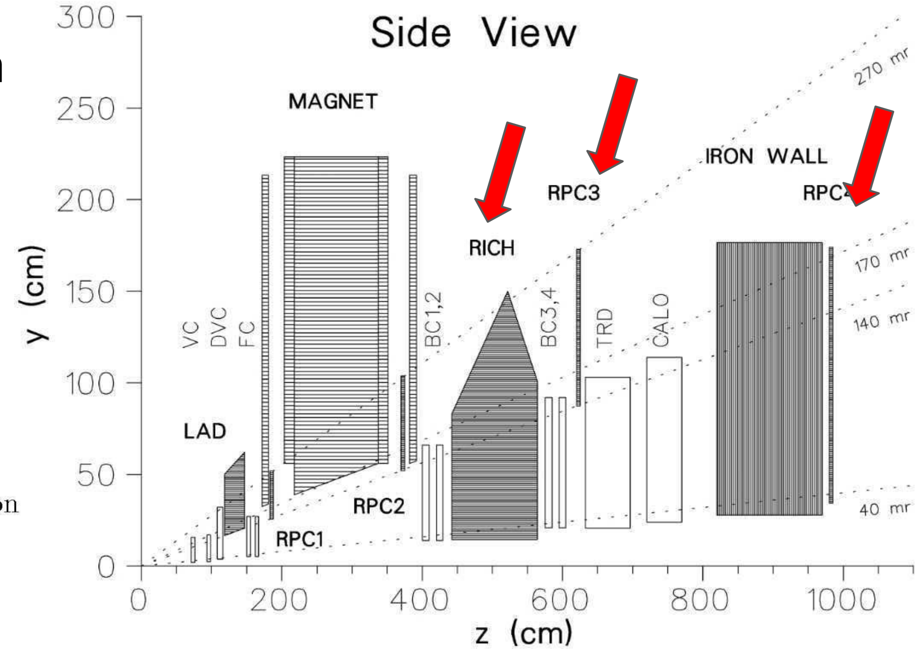


Figure 2: Schematic diagram indicating the location of the proposed new detectors.

Some model predictions, e.g

CHARM PRODUCTION IN NN AND γN COLLISIONS

Egle Tomasi-Gustafsson[†]

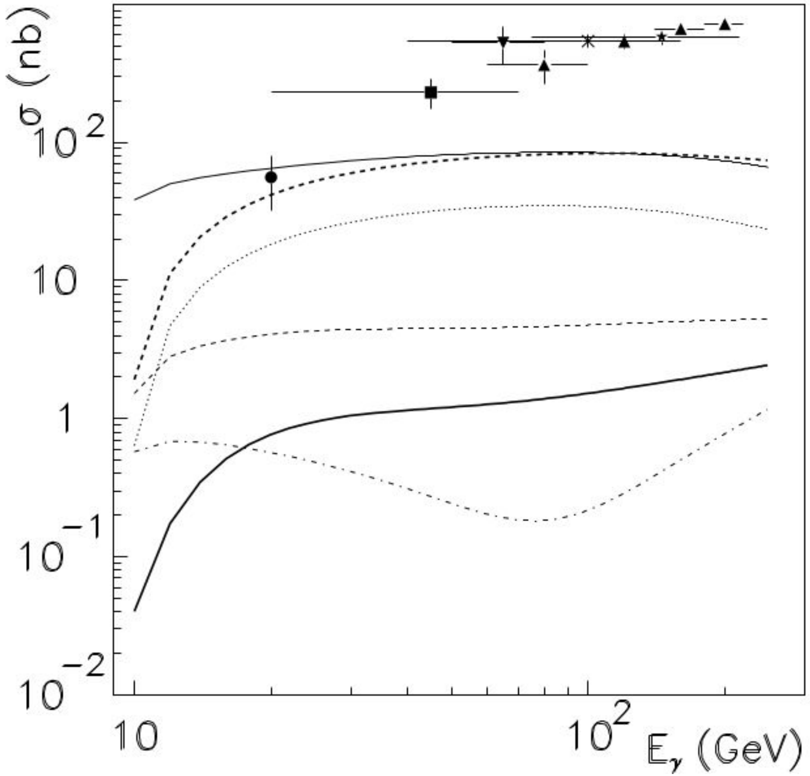
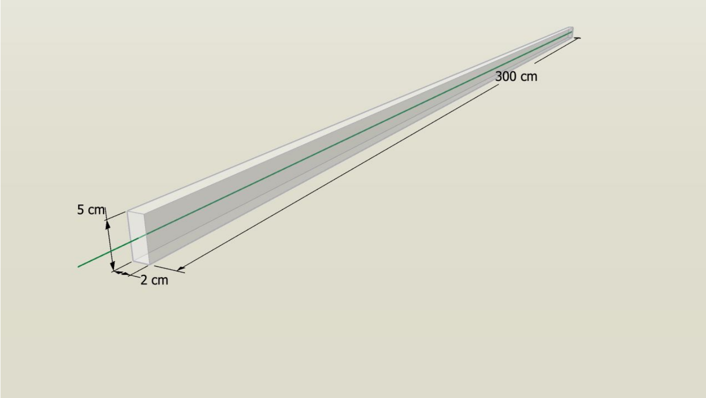
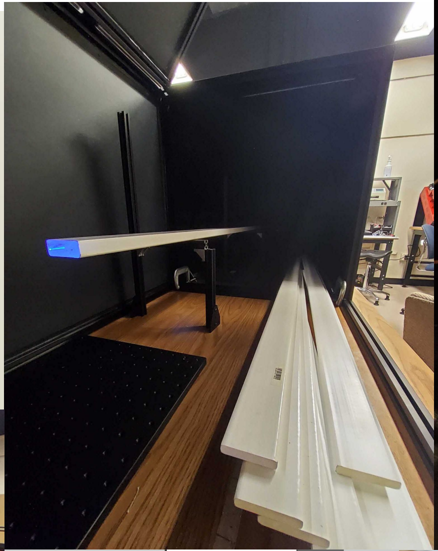


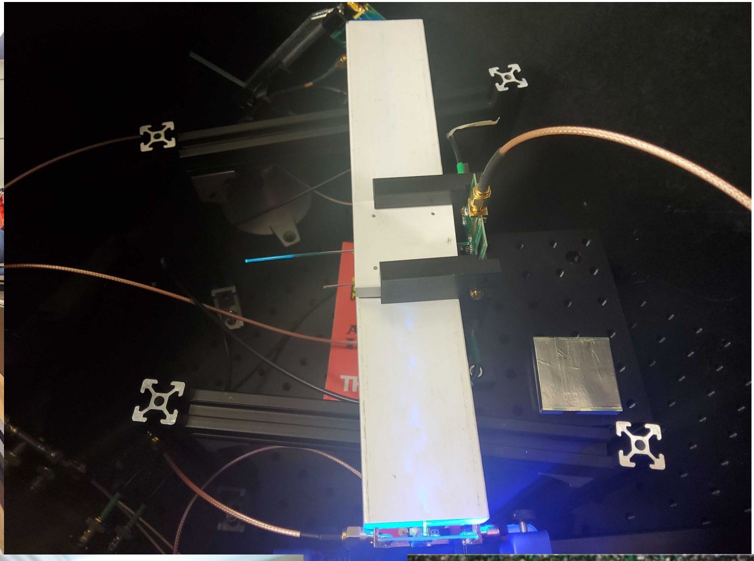
Fig. 3 E_γ-dependence of the total cross section for photoproduction of charmed particles for model I. The curves correspond to different reactions: $\gamma + p \to \Lambda_c^+ + \overline{D}^0$ (solid line), $\gamma + p \to \Sigma_c^{++} + D^-$ (dashed line), $\gamma + p \to \Sigma_c^+ + \overline{D}^0$ (dotted line), $\gamma + n \to \Lambda_c^+ + D^-$ (dot-dashed line), $\gamma + n \to \Sigma_c^+ + D^-$ (thick solid line), $\gamma + n \to \Sigma_c^0 + \overline{D}^0$ (thick dashed line). The data correspond to the total charm photoproduction cross section ([4] and refs. herein)

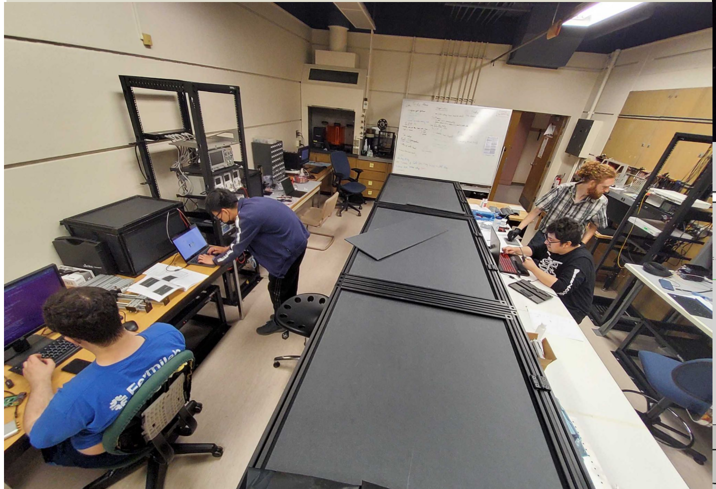
New muon detector for CLAS12 required to tag charm

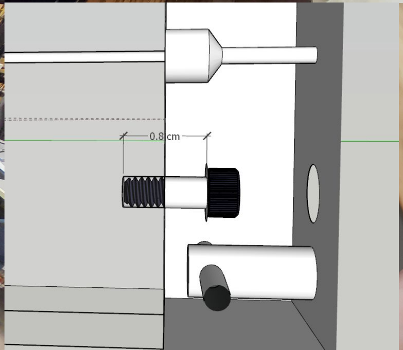
We can do it effectively and cheaply with plastic bars, WLS fiber, and SiPMs

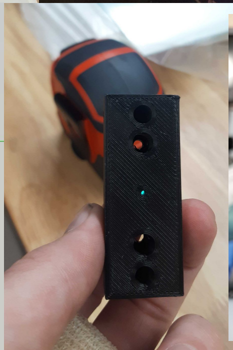


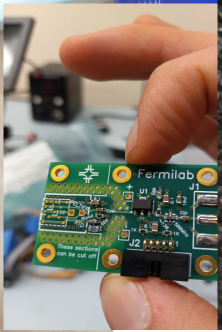


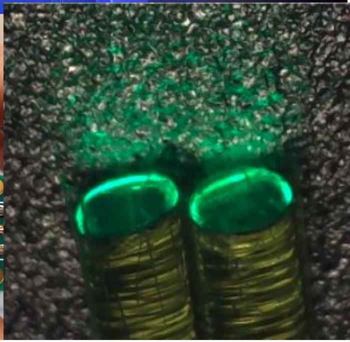












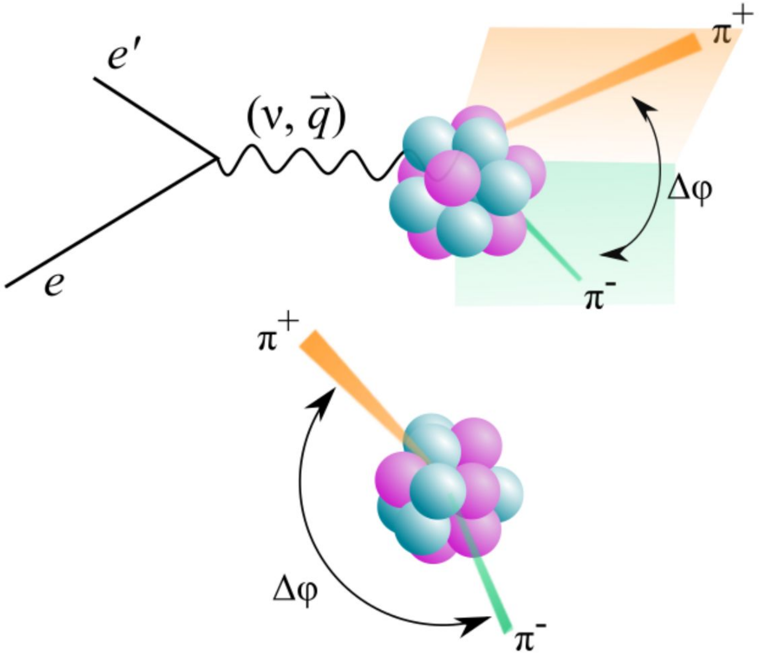
Summary

- Large acceptance, high statistics data from CLAS@JLab allow us to do novel studies in nuclear DIS with **angular correlation techniques.**

- First indications show interesting patterns, which might **reveal interplay between struck quark/ leading hadron interactions and nuclear response.**

- **New MC generators (GiBUU, eHIJING, etc) will be crucial to interpret data** and extract transport parameters, possibly hadronization timescales

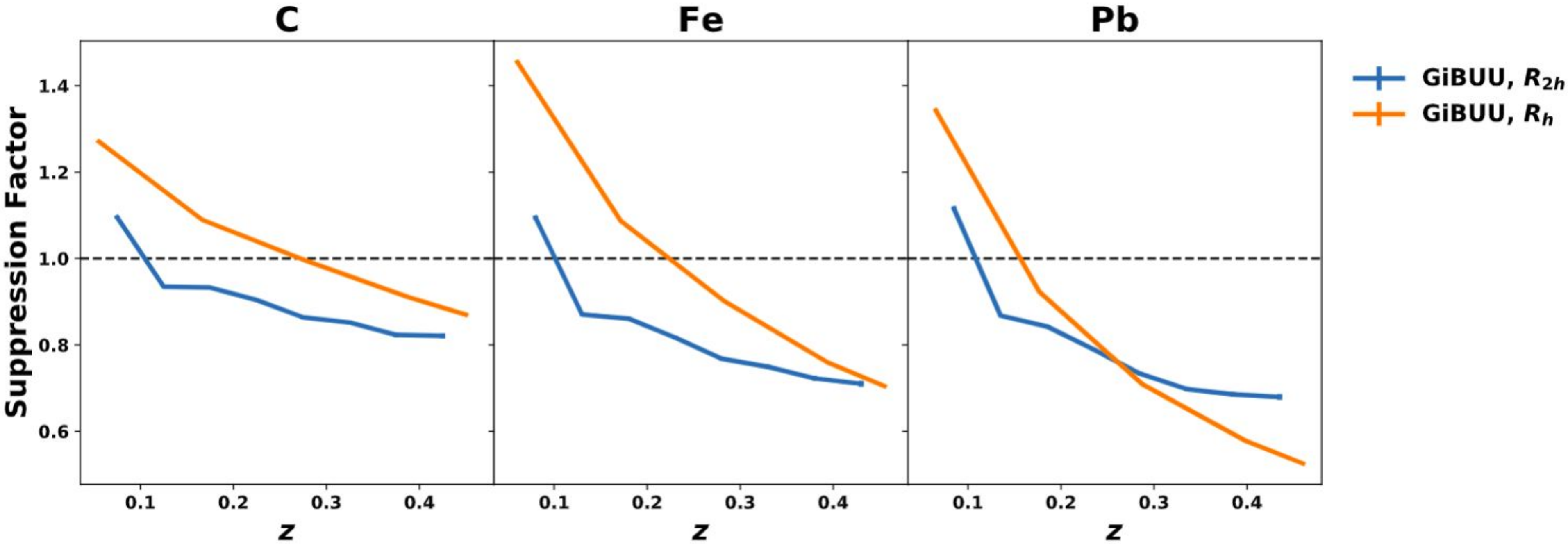
- Future looks great with upcoming 11 GeV data and the future EIC



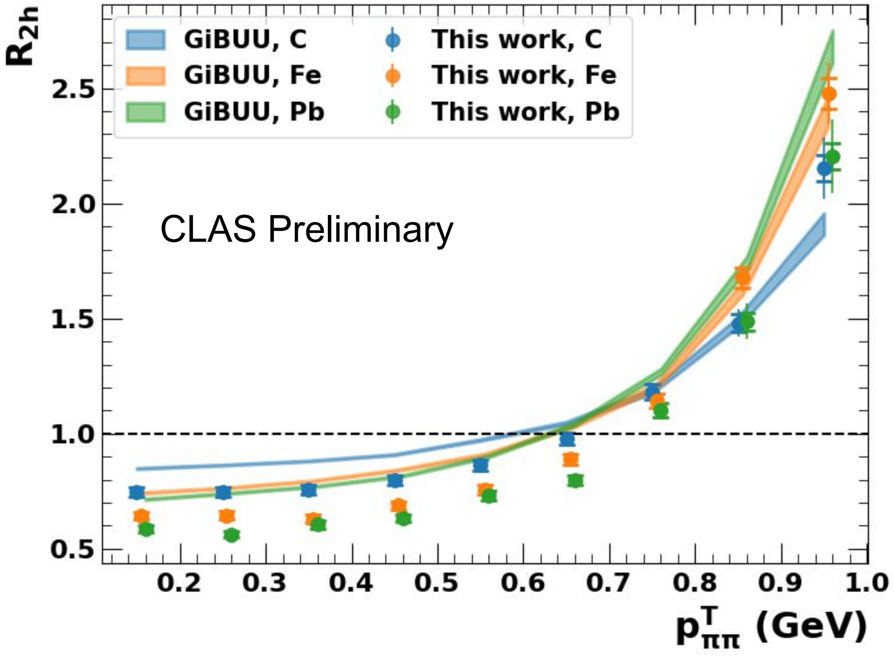
Backup

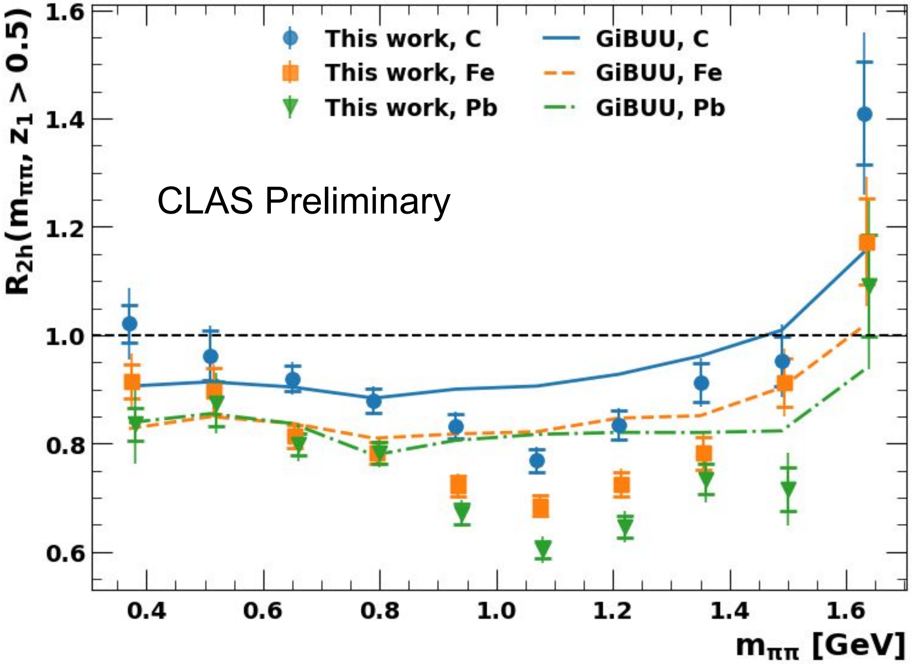
GiBUU calculations for CLAS 5 GeV data

Double-hadron vs single-hadron suppression factors



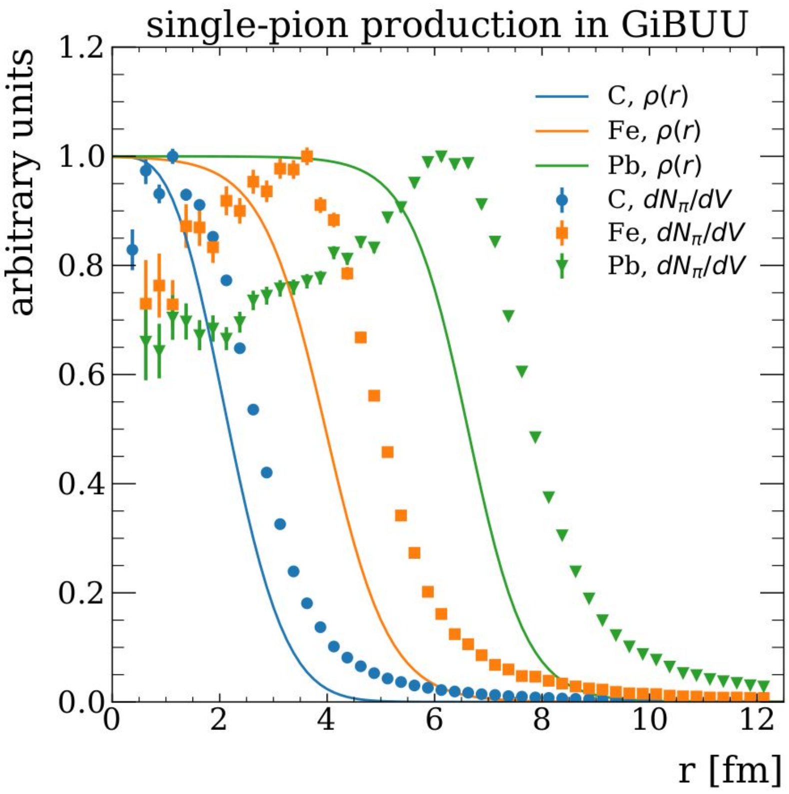
Dependence on dipion transverse momentum and mass

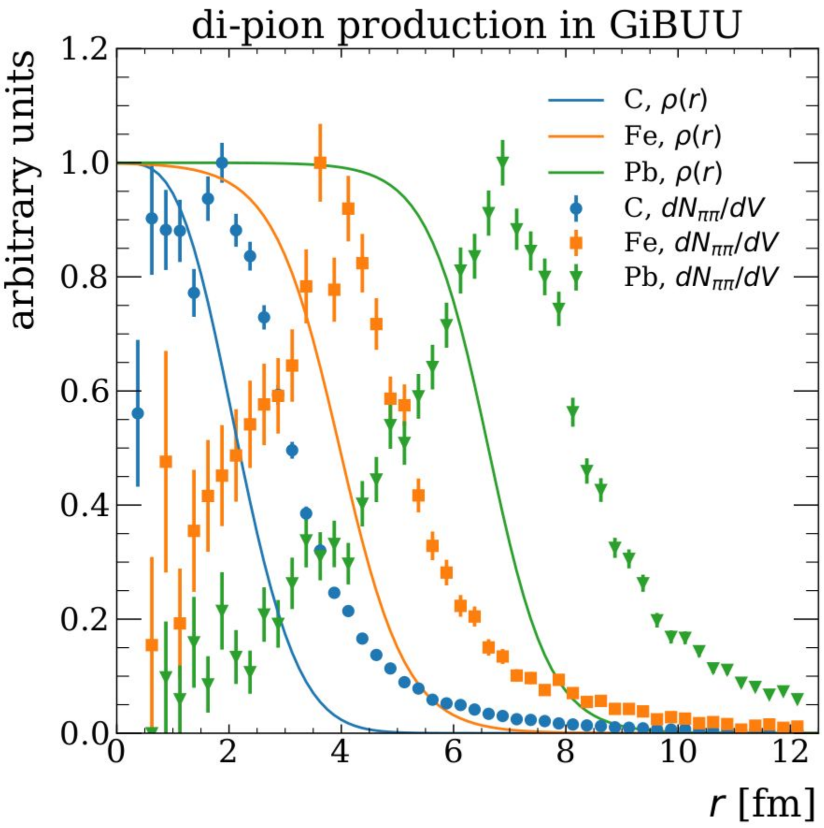




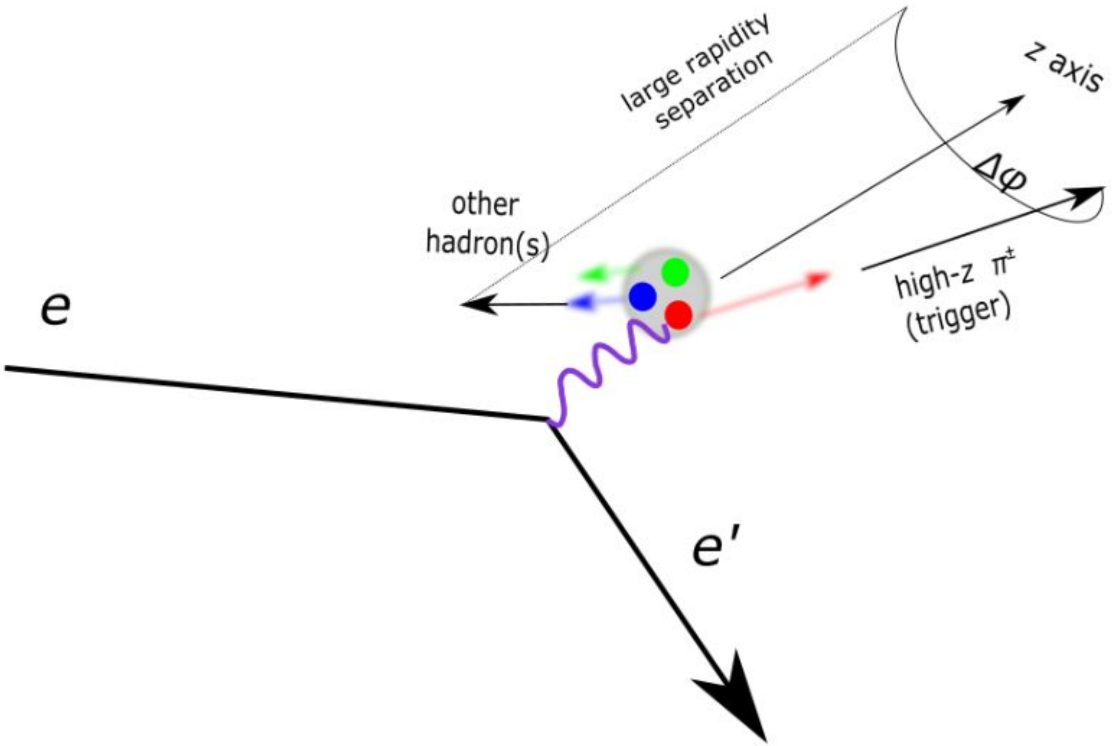
Uptick at large values, weak dependence at small values. Similar to single hadron

Geometrical effects within GiBUU model





Meanwhile, we can explore proton target data

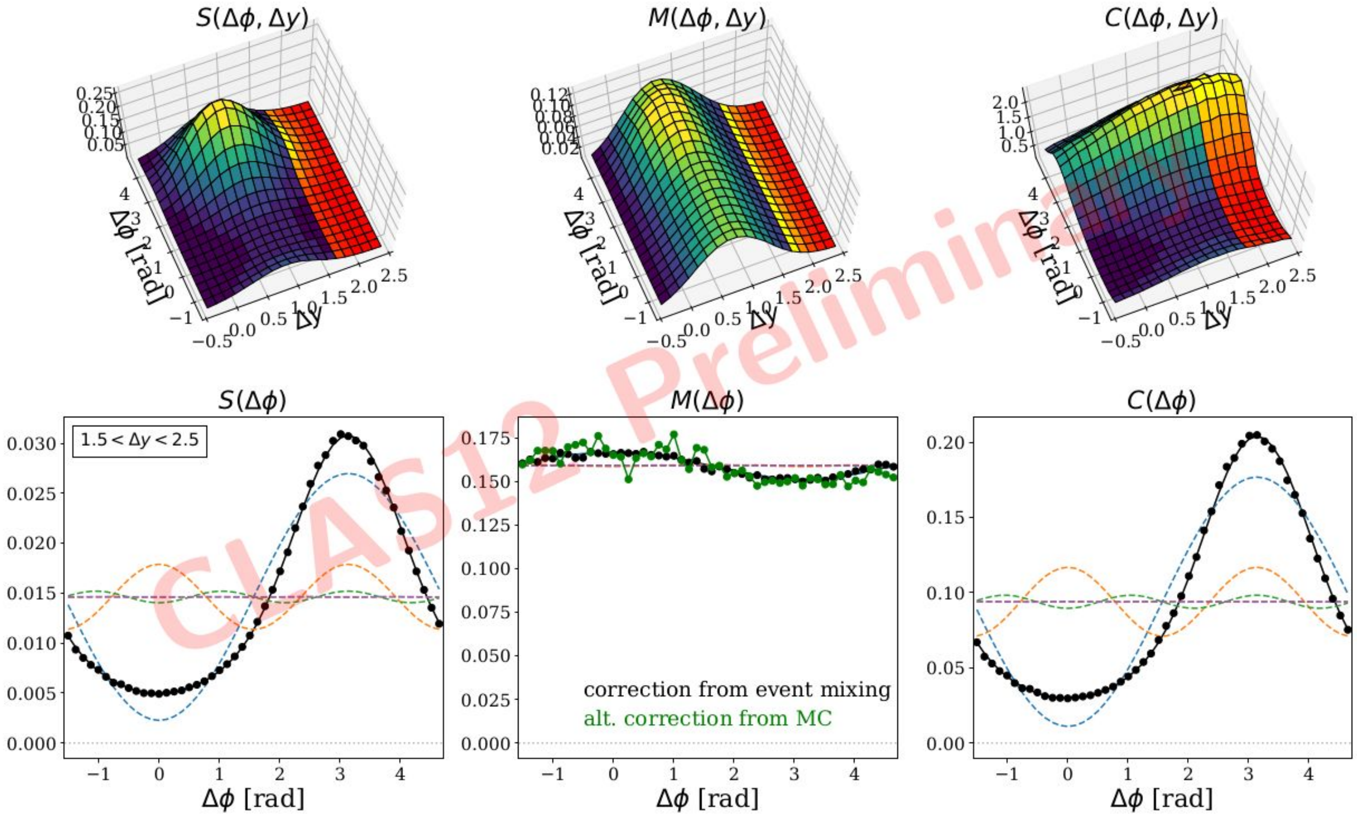


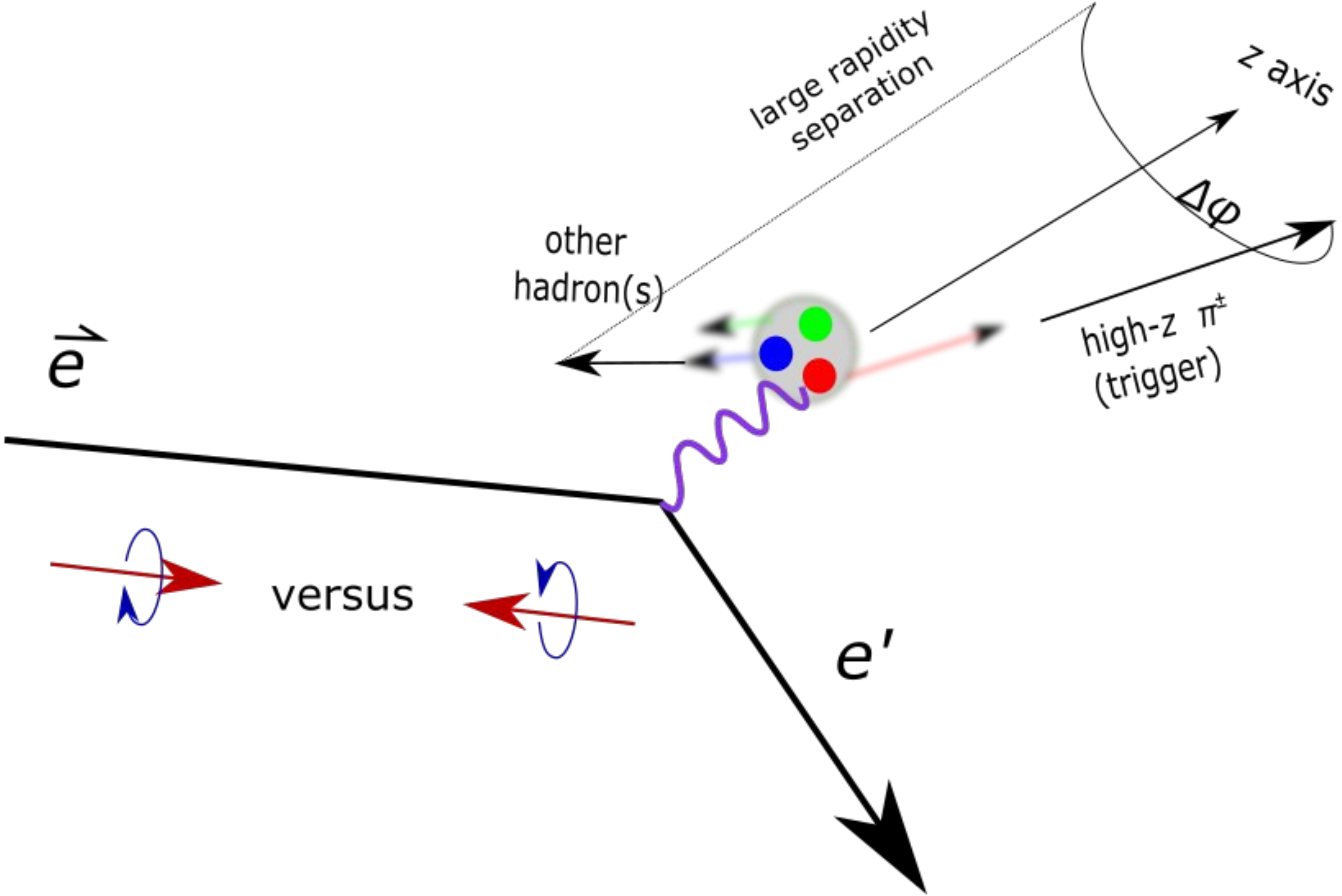
- Correlations between struck quark and diquark remnant?

- Spin-observables being explored in CLAS12 revealing so-far-ignored phenomena

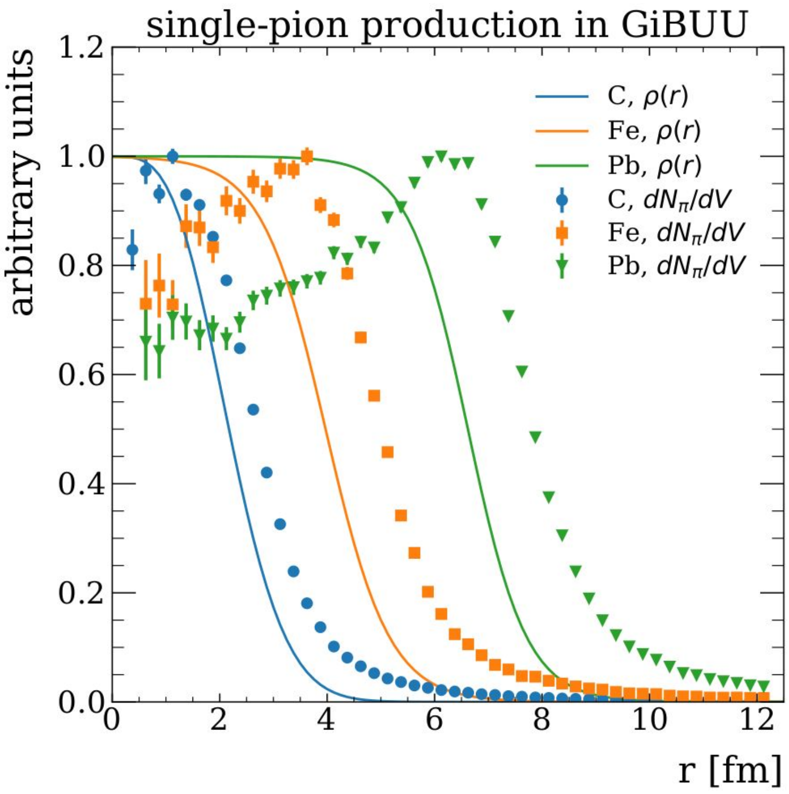
A glimpse into CLAS12 capabilities

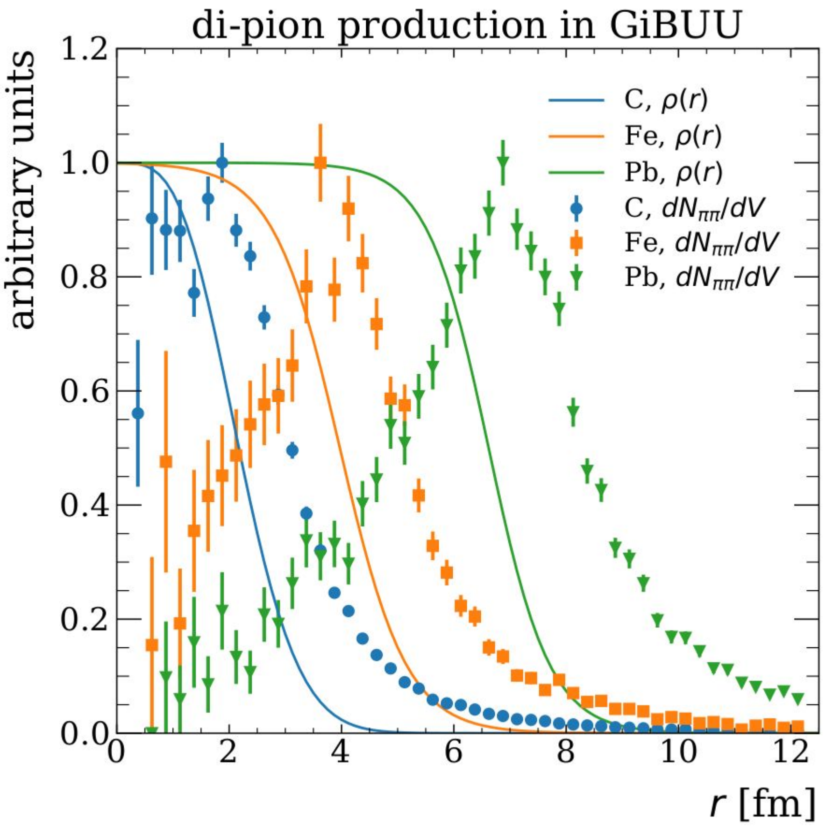
$\pi\pi$
$p_T > 0.3$ GeV
$Q^2 > 1$ GeV^2
$W > 2$ GeV
$y_e < 0.85$
$z_1 > 0.4$
$p_T > 0.3$ GeV



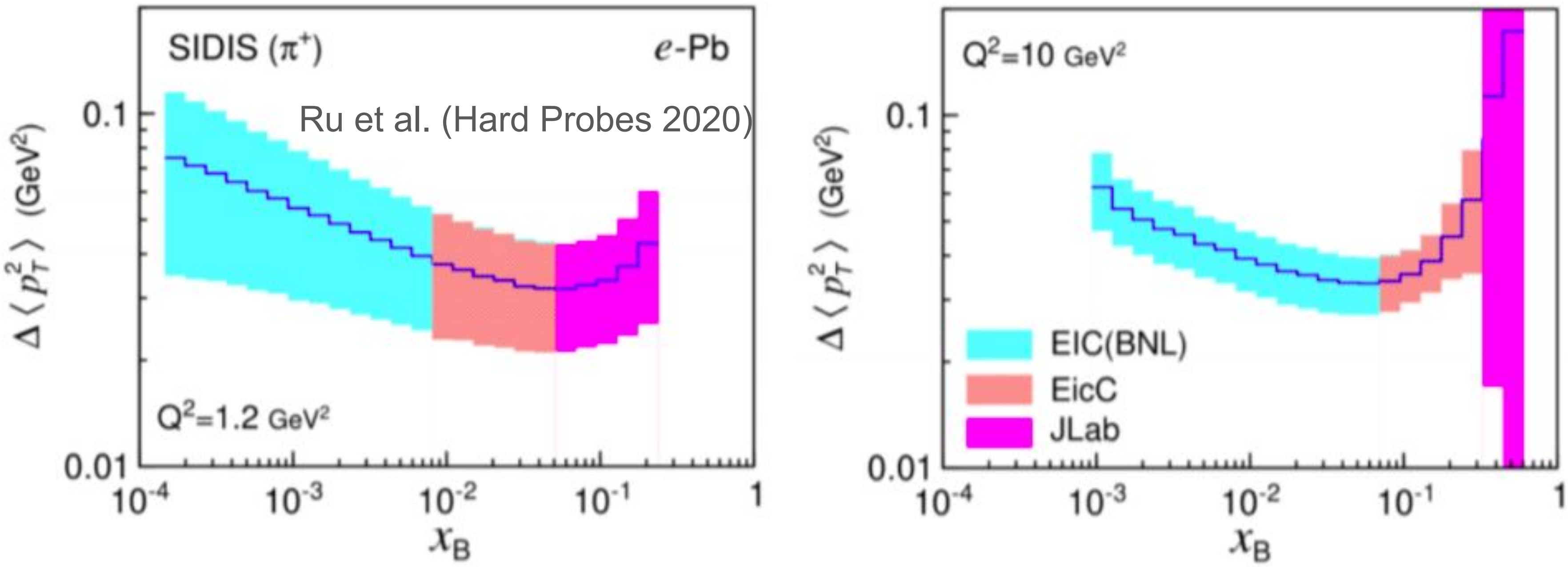

large rapidity
separation
z axis
other
hadron(s)
Δφ
high-z $\pi^{\pm}$
(trigger)
$\vec{e}$
versus
e'

Geometrical effects within GiBUU model





CLAS and CLAS12 coverage will complement and provide crucial baseline for future measurements at EIC



Cross-sections for open charm