Nuclear Hadronization Studies at JLab: Present and Future

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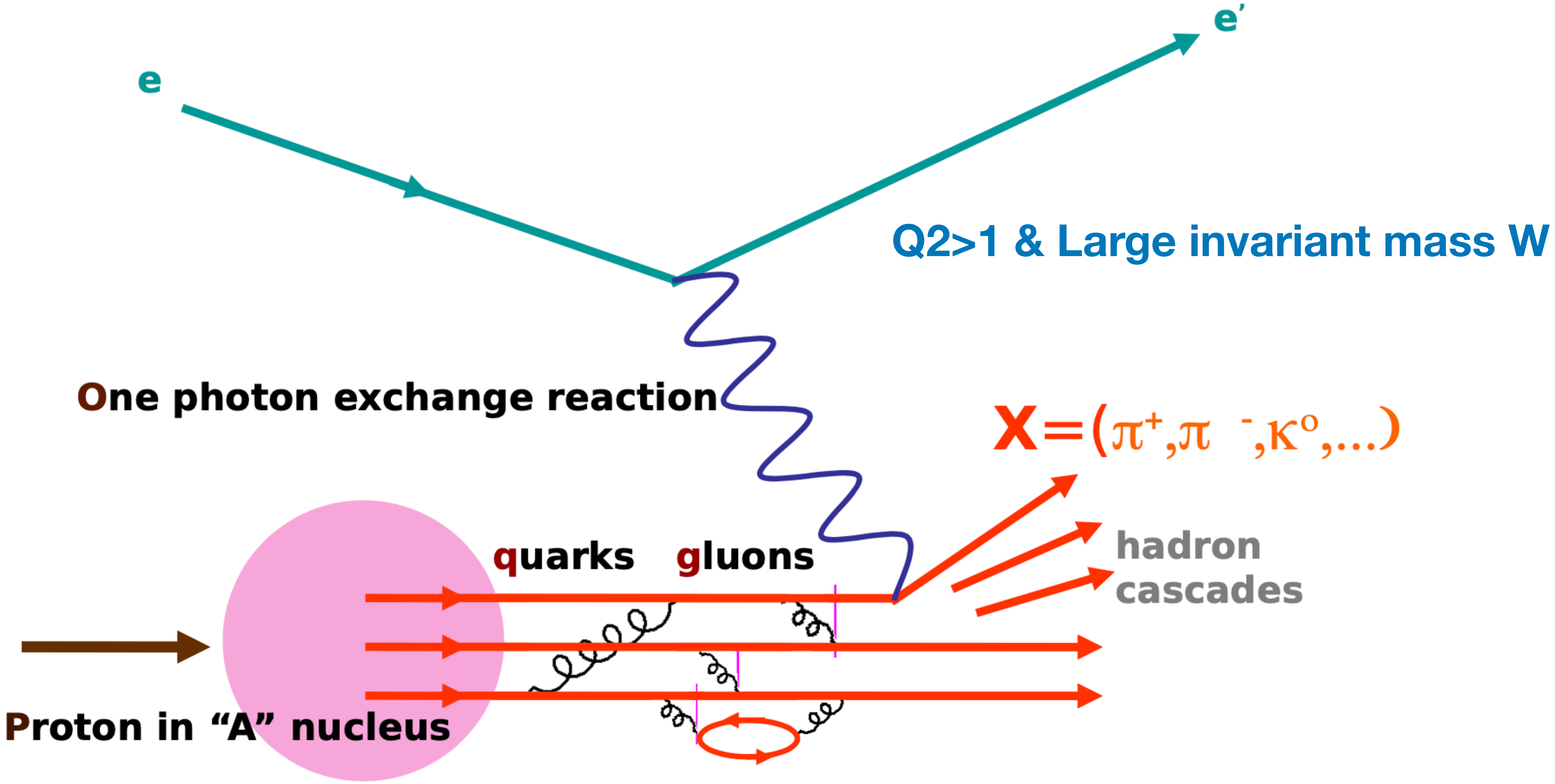
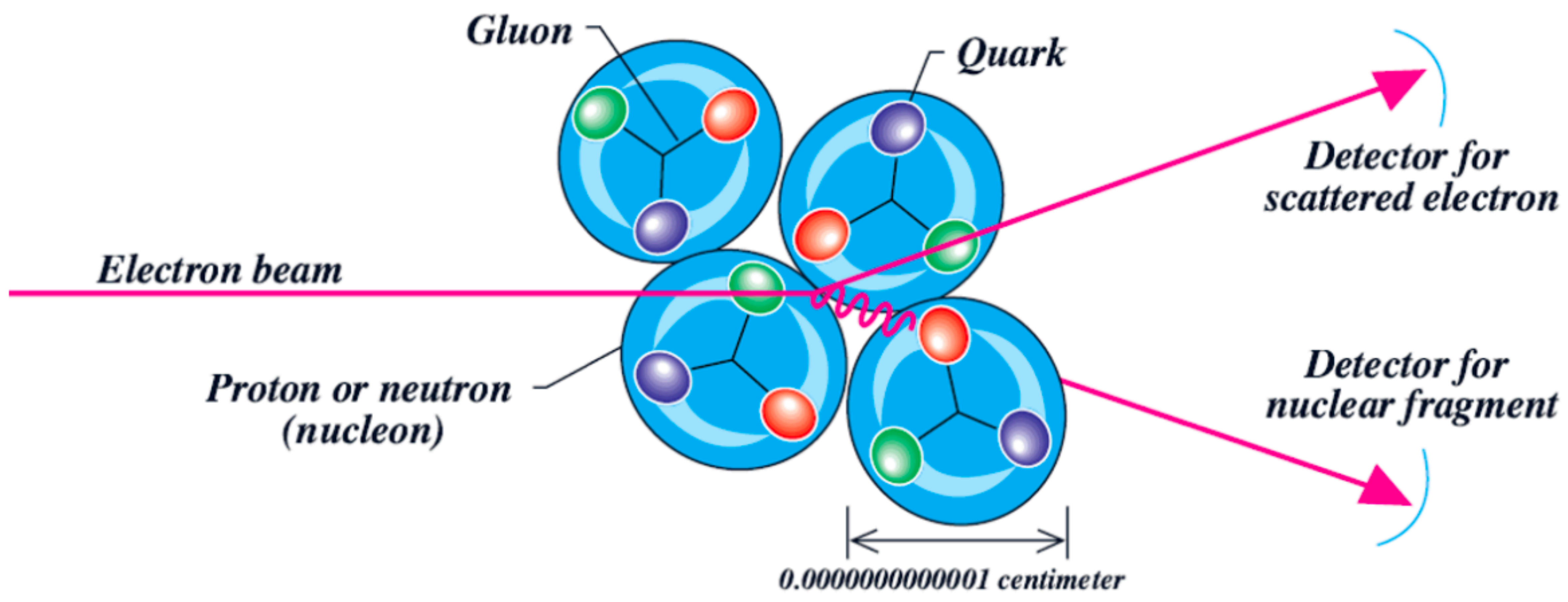
Old Dominion University, March 2024

Schematic diagram describing semi-inclusive Deep Inelastic Scattering of a lepton off a nucleon





To conduct a thorough investigation into how the nuclear medium influences quark hadronization, it is essential to perform a multidimensional cinematical analysis on a range of different hadrons. This approach not only uncovers the color properties inherent to the nuclear medium but also provides a comprehensive understanding of the phenomenon.

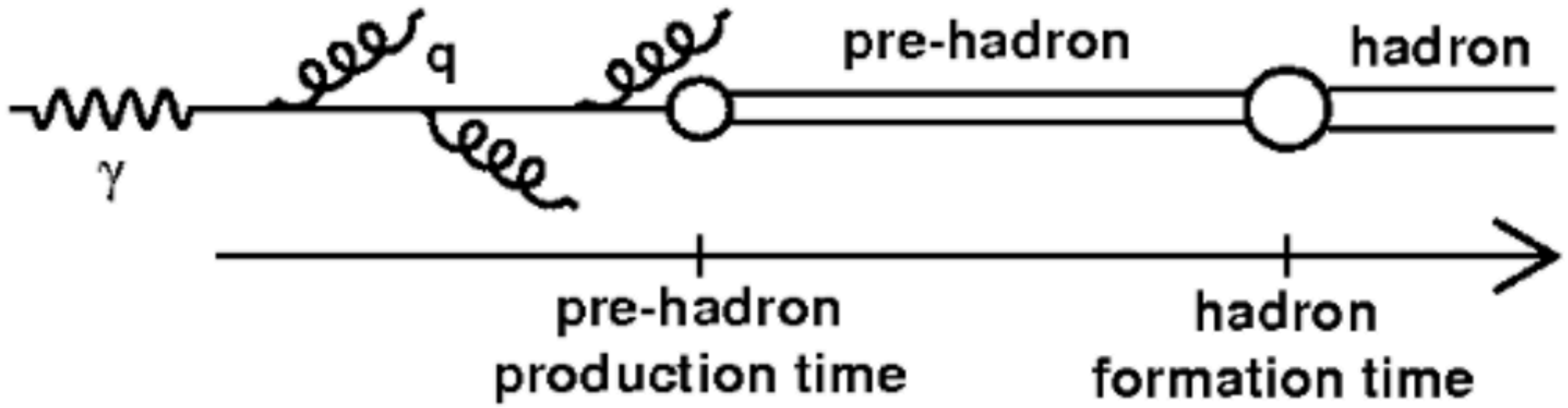
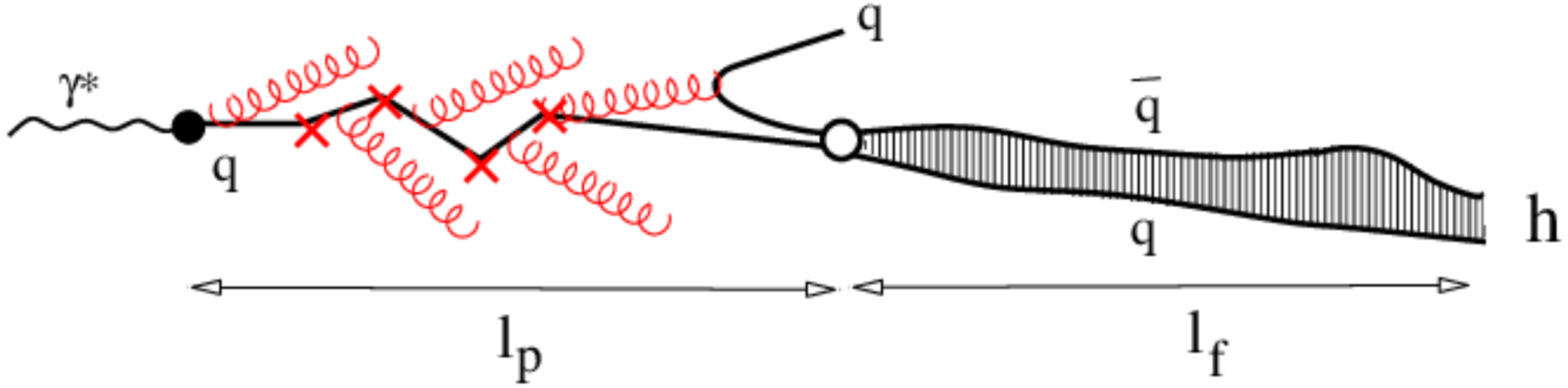
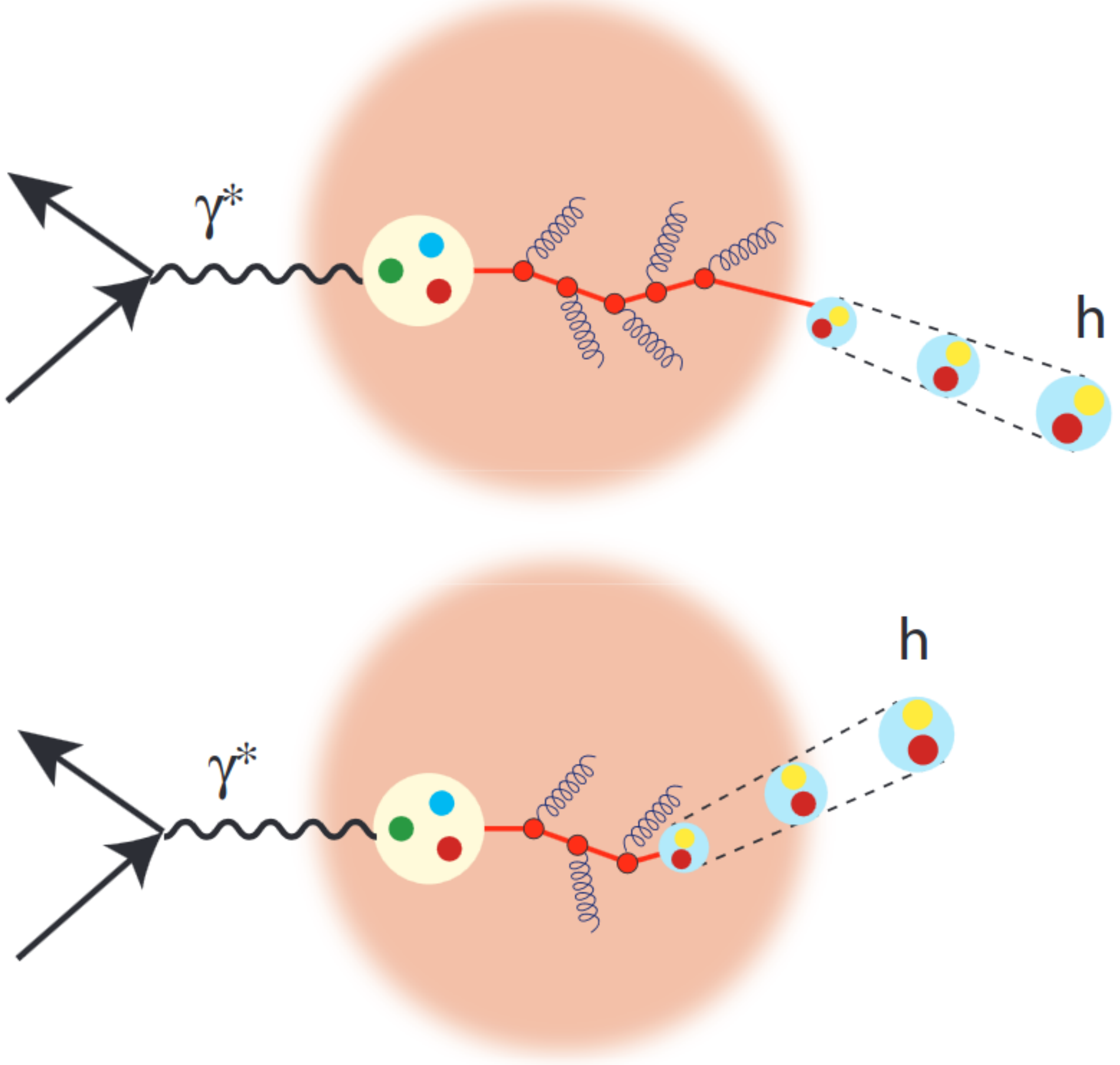


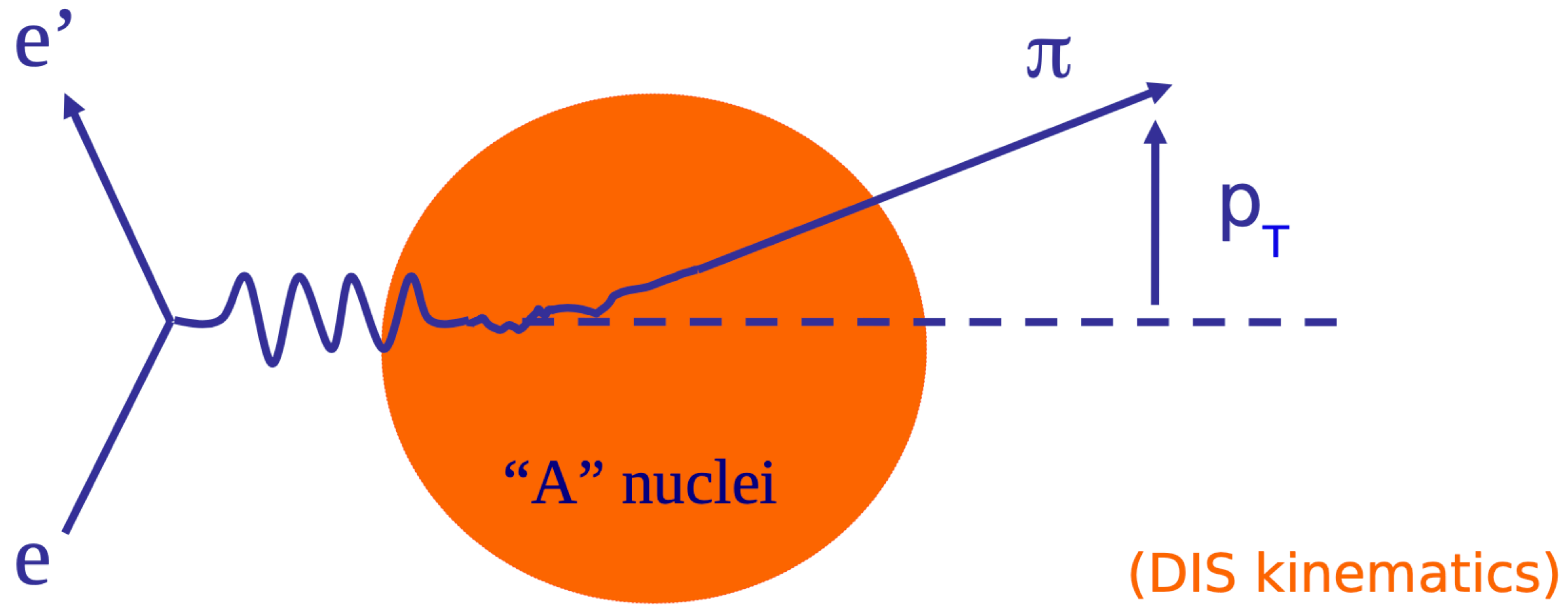
Illustration of a parton moving through nuclear media. At the top the prehadron is formed outside the nuclei and at the bottom it is formed inside.





Experimental observables

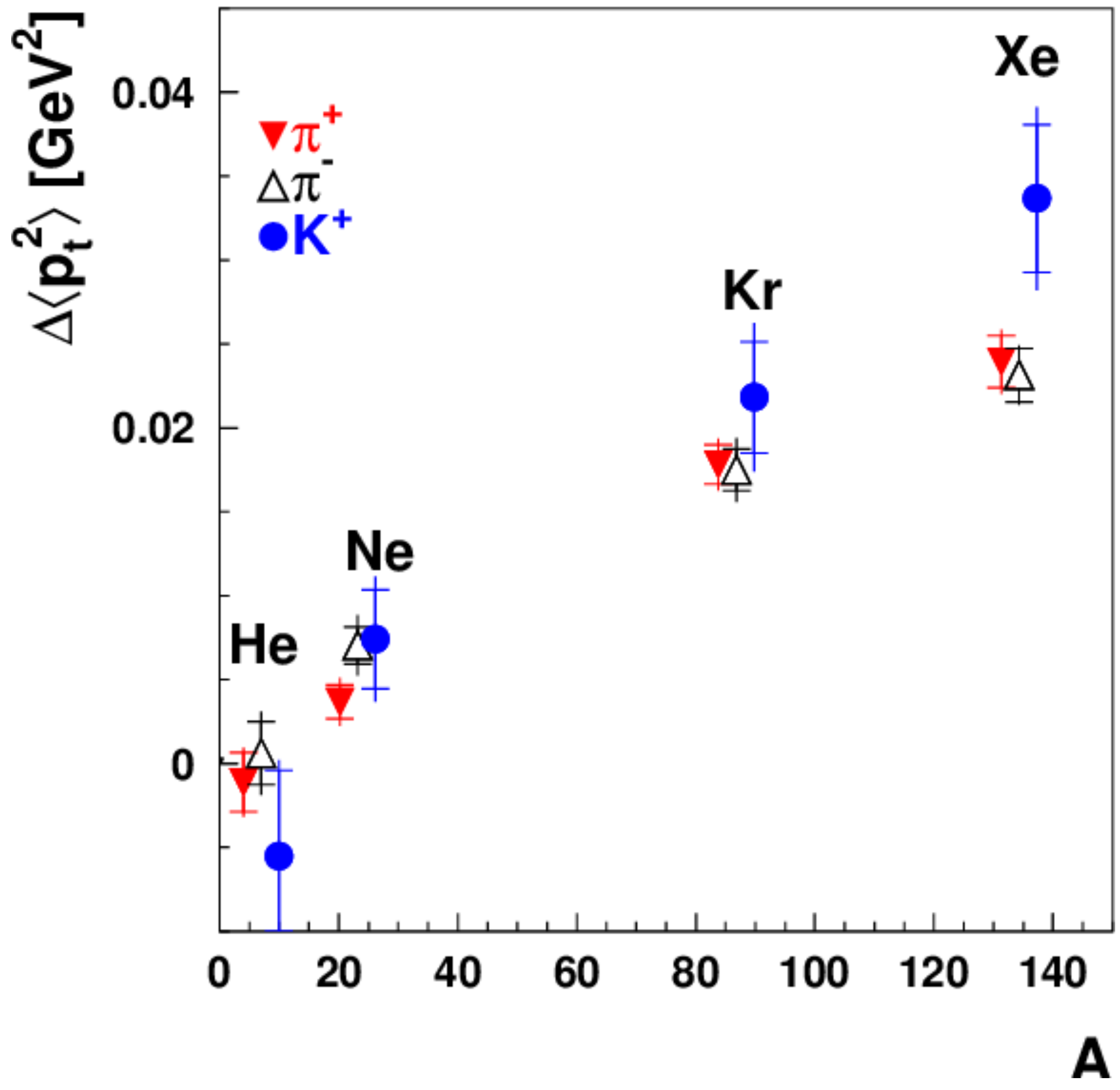
Transverse momentum broadening: $\Delta p_T^2 = p_T^2(A) - p_T^2(^2H)$

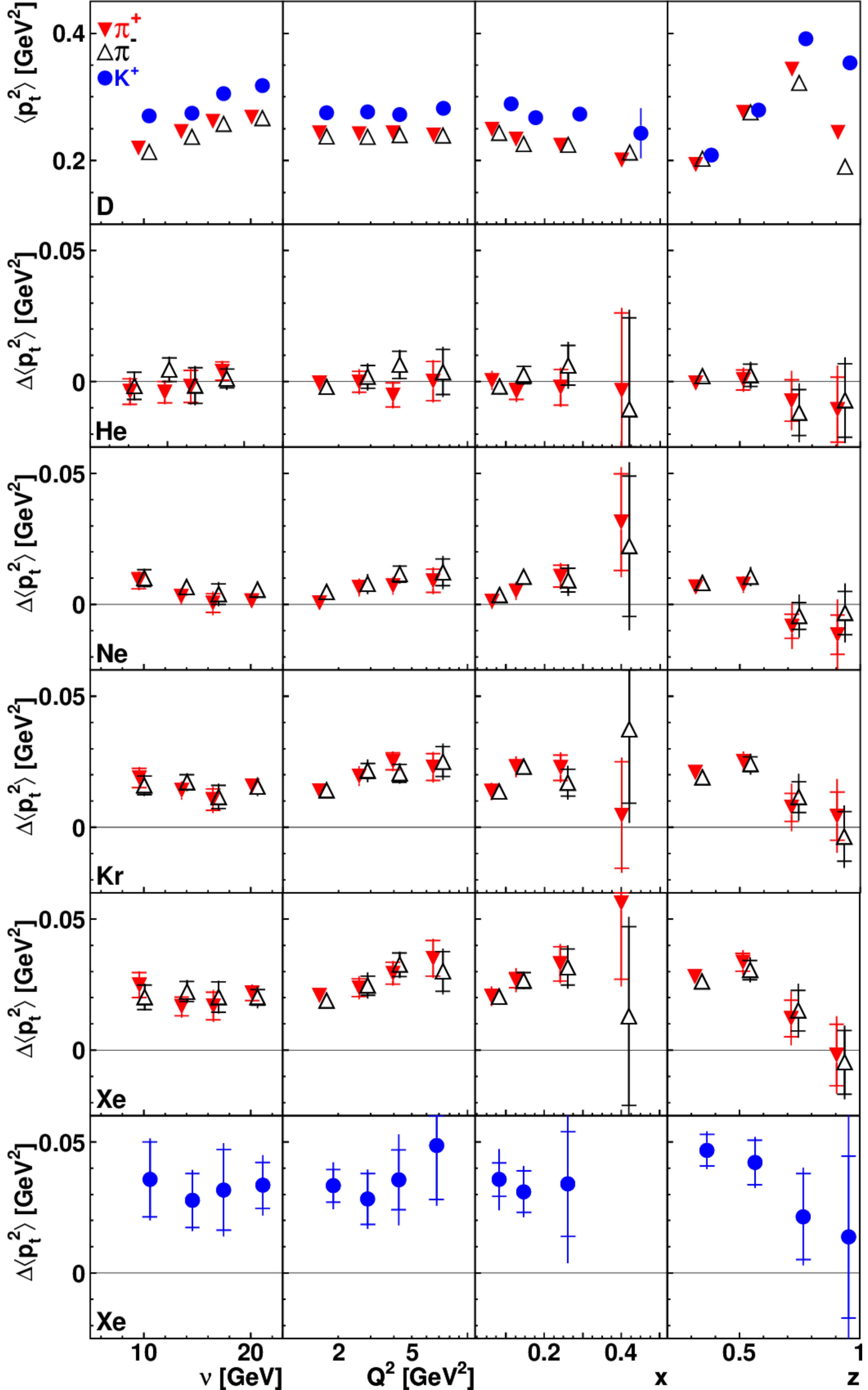


Hadronic multiplicity ratio:

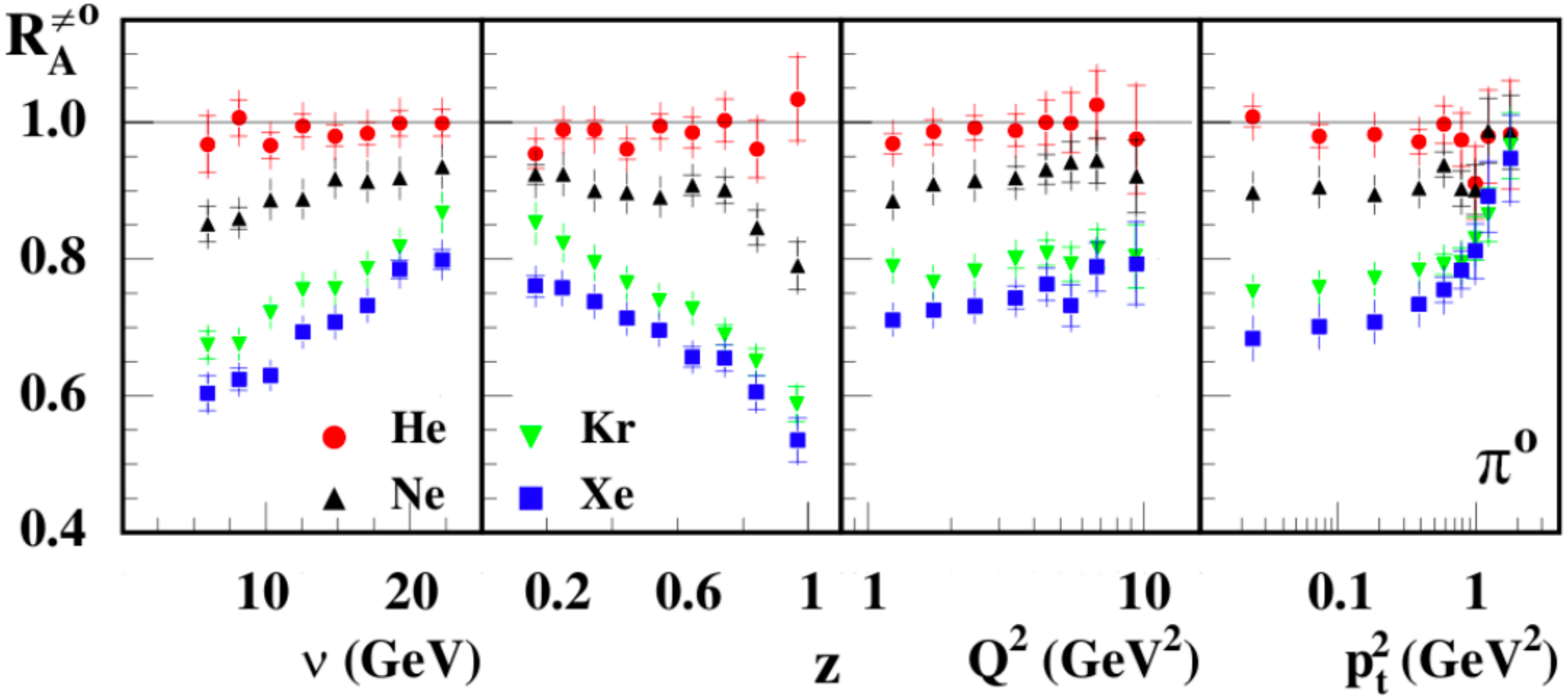
$$R_M^h(z,\nu,p_T^2,Q^2,\phi) = \frac{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_A}{\left\{\frac{N_h^{DIS}(z,\nu,p_T^2,Q^2,\phi)}{N_e^{DIS}(\nu,Q^2)}\right\}_D}$$

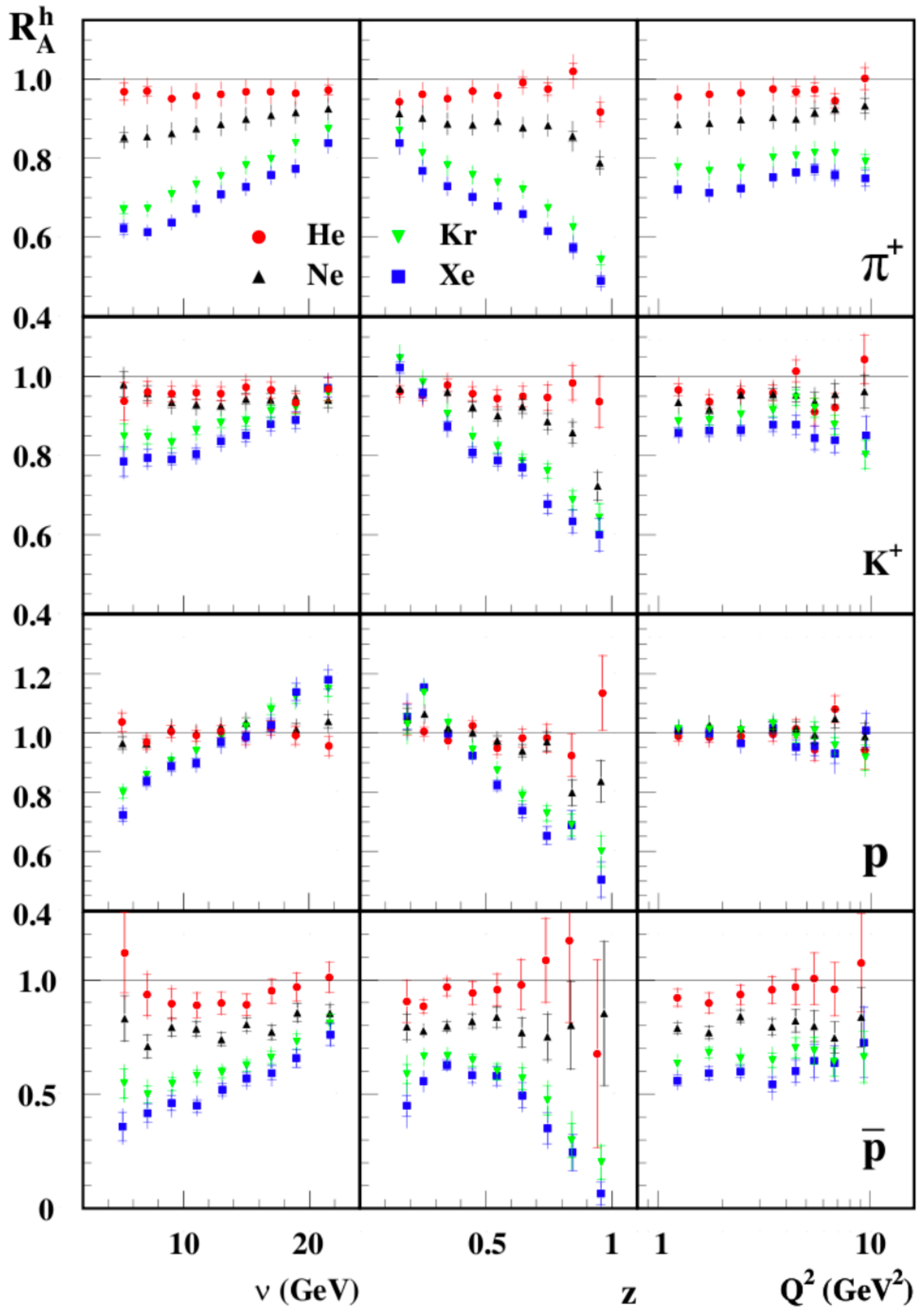
Studies with HERMES on He, Ne, Kr, Xe



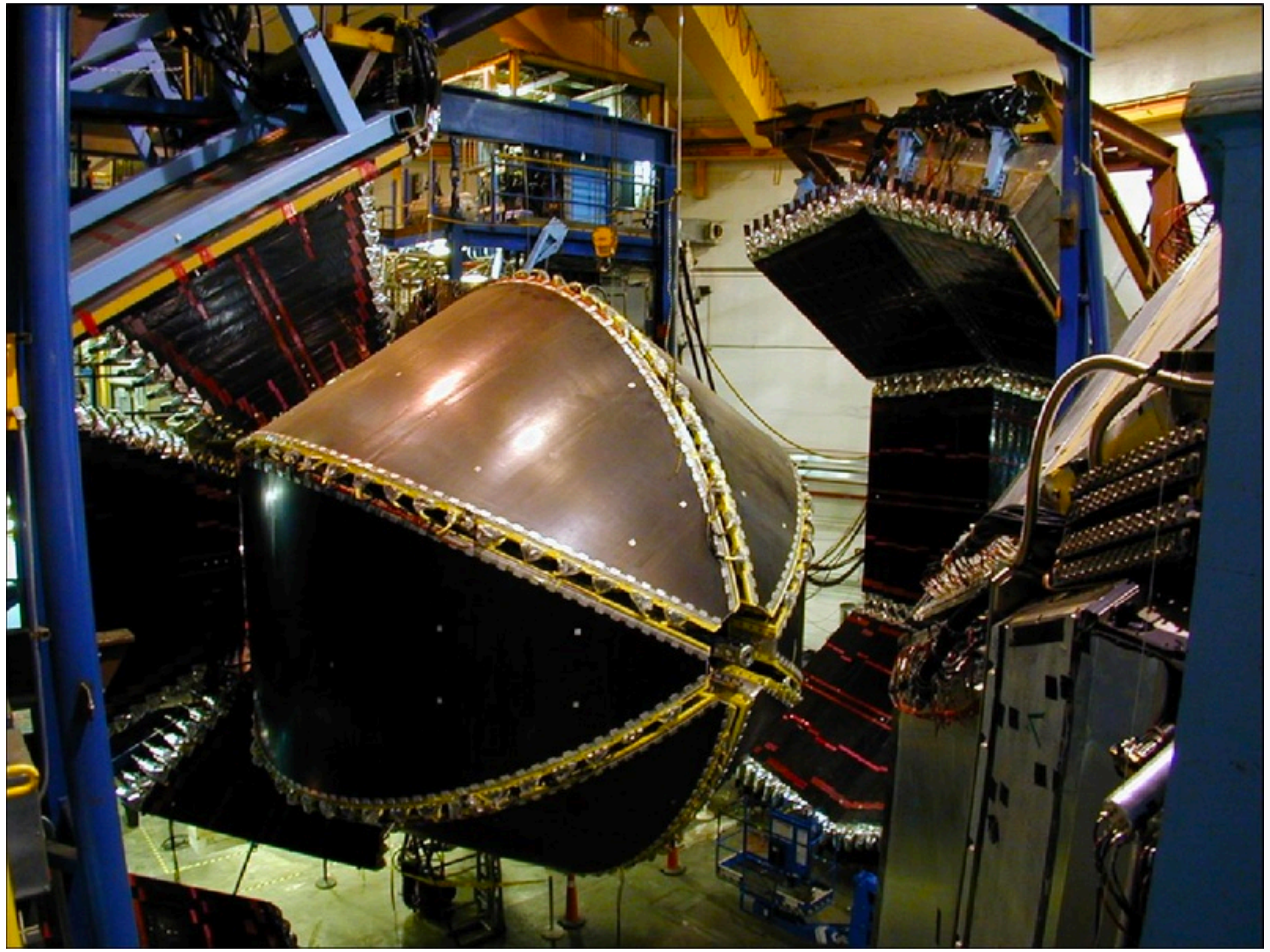


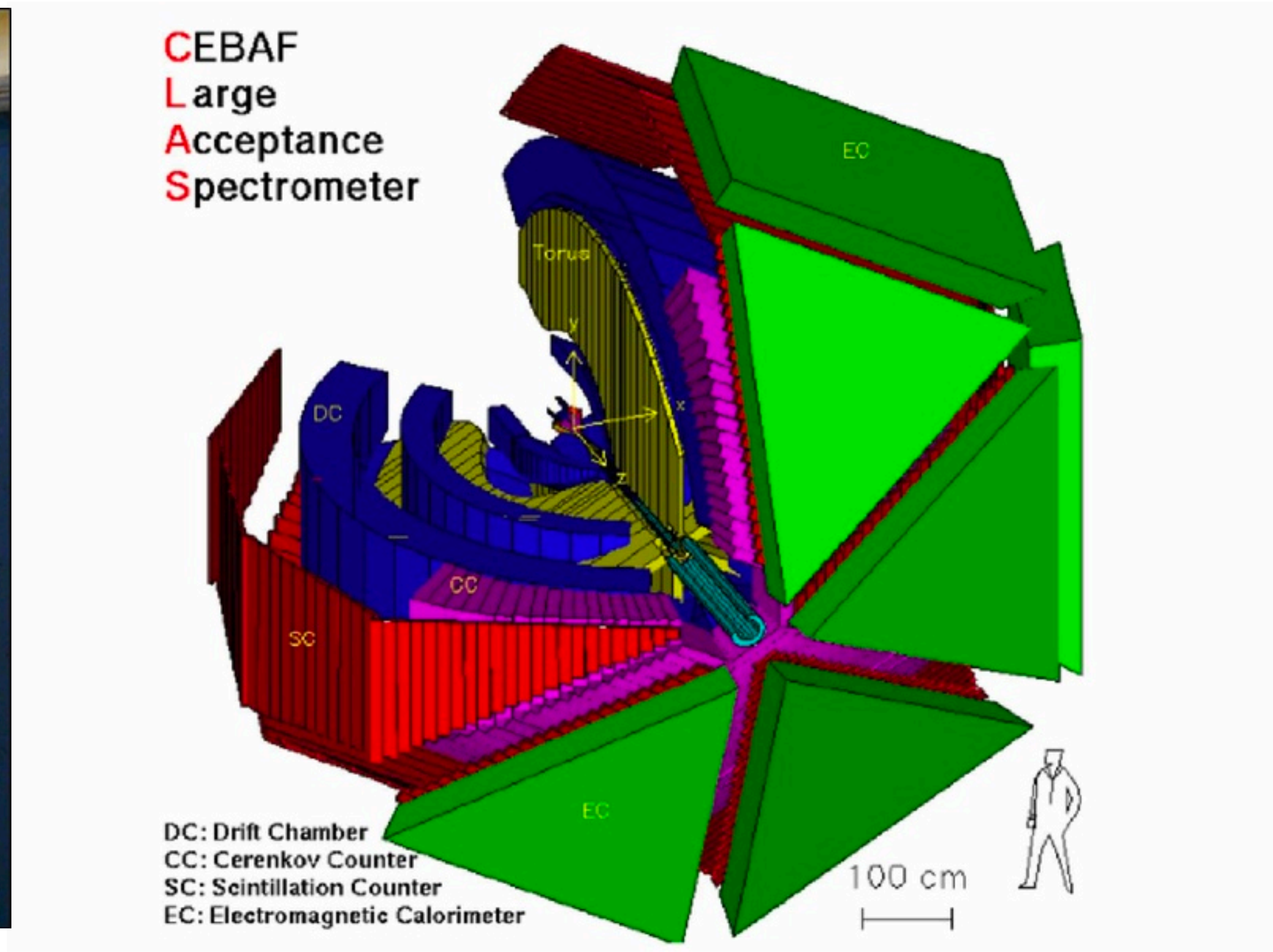
Studies with HERMES on He, Ne, Kr, Xe



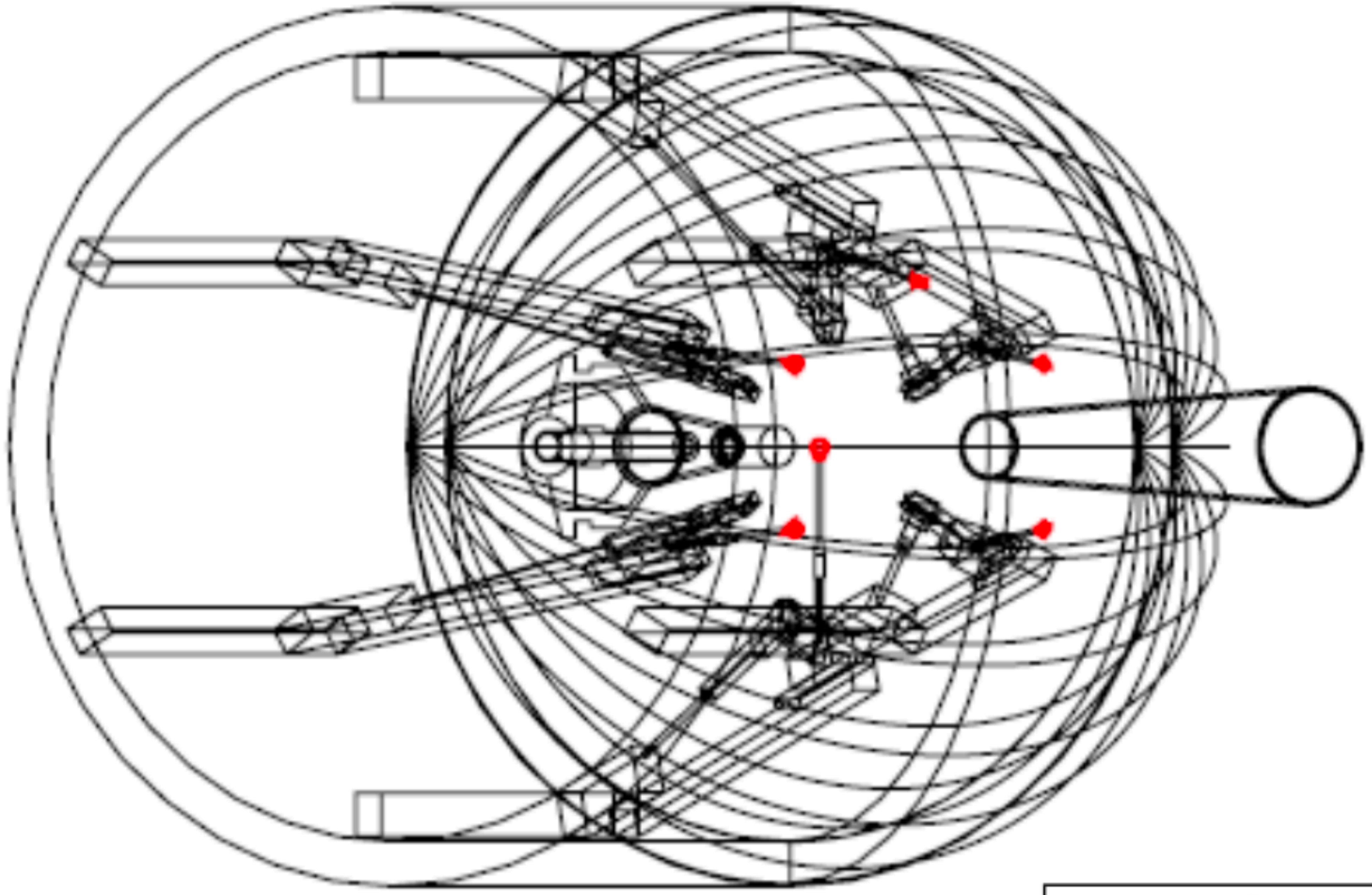


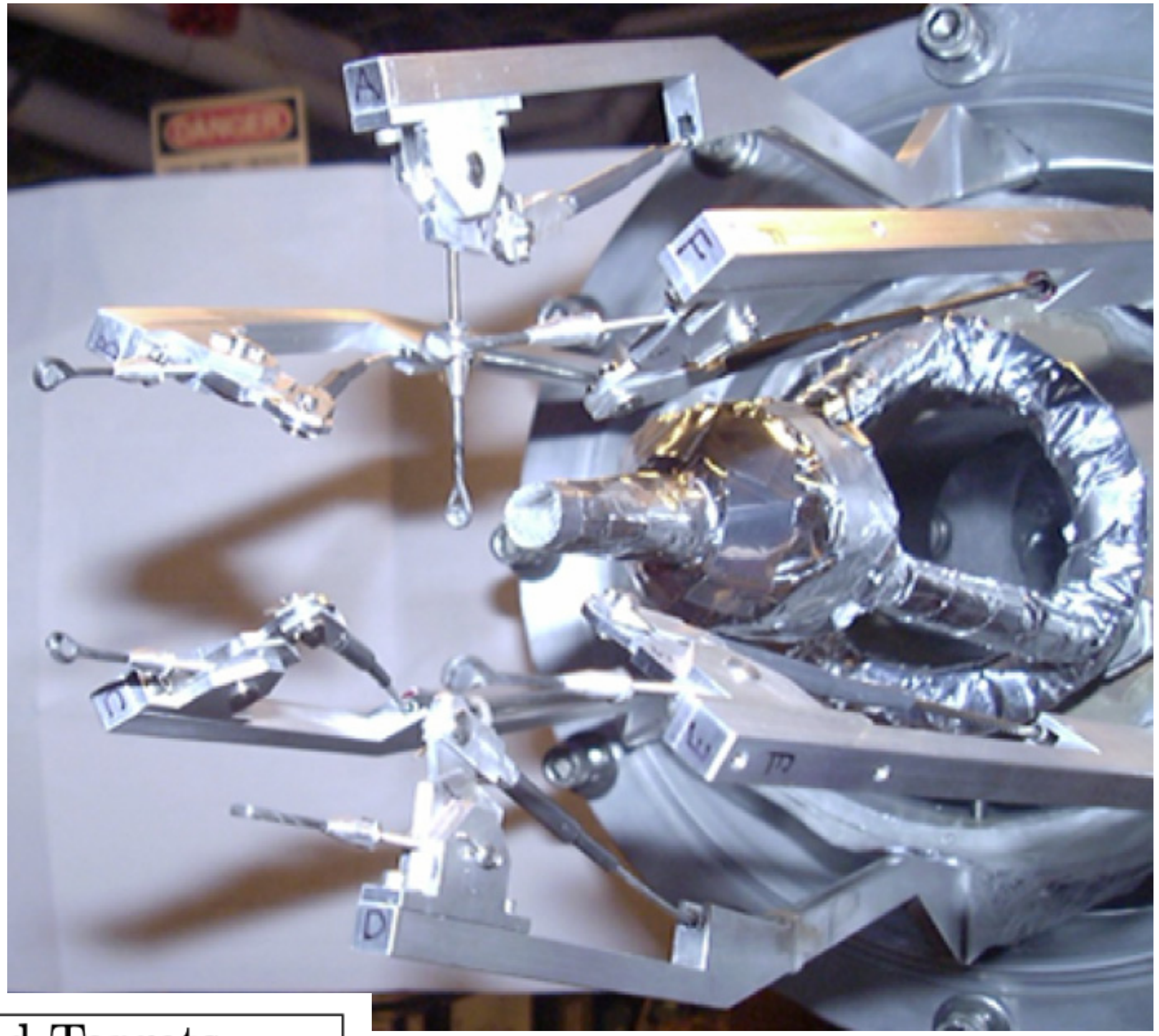
Past CLAS Spectrometer at JLab





Eg2 Double-Target





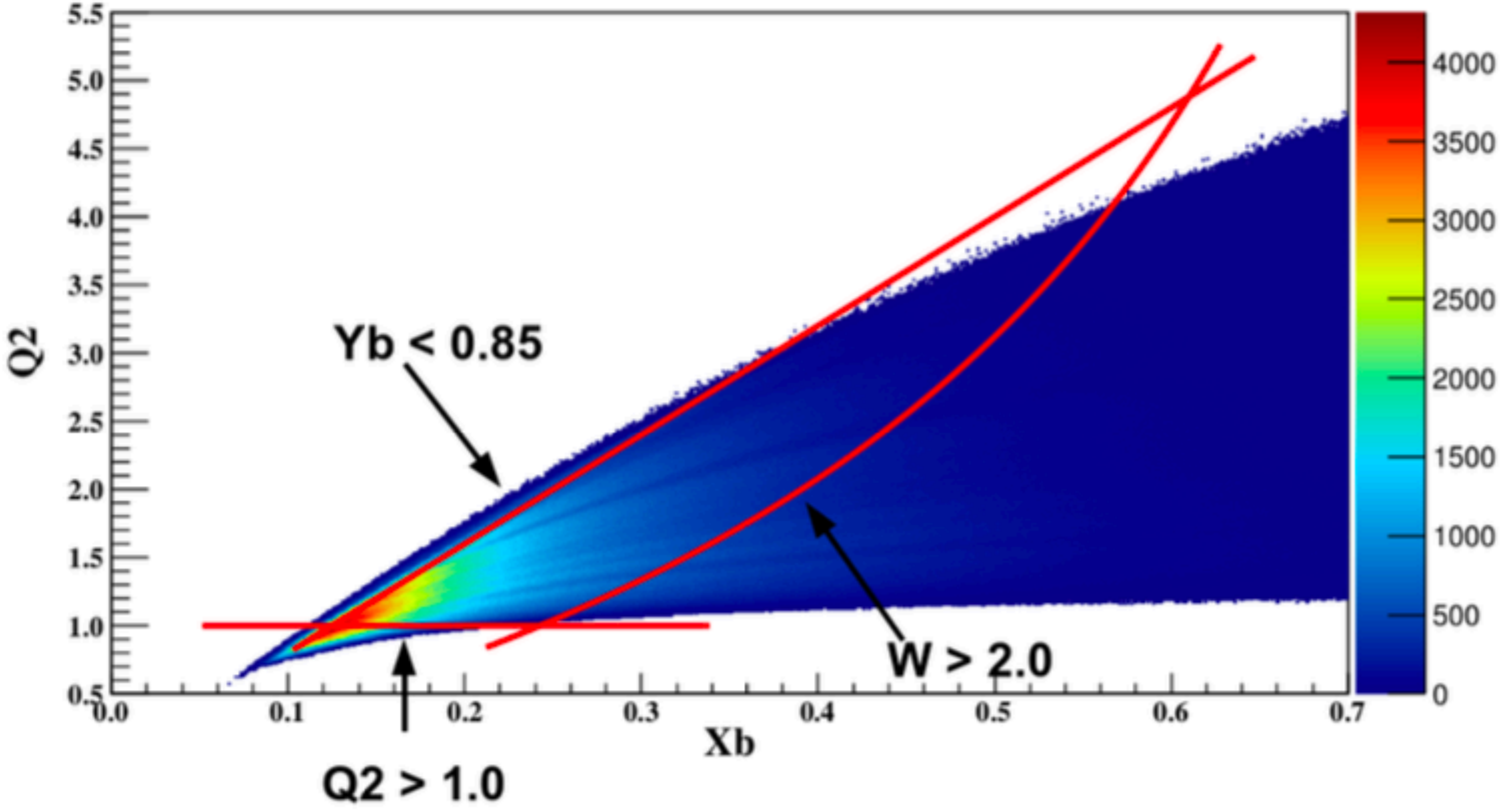
Thickness of Solid Targets		
Target	Thickness (cm)	ρ_A/ρ_D
C	0.17	0.894
Fe	0.04	0.949
Pb	0.014	0.478

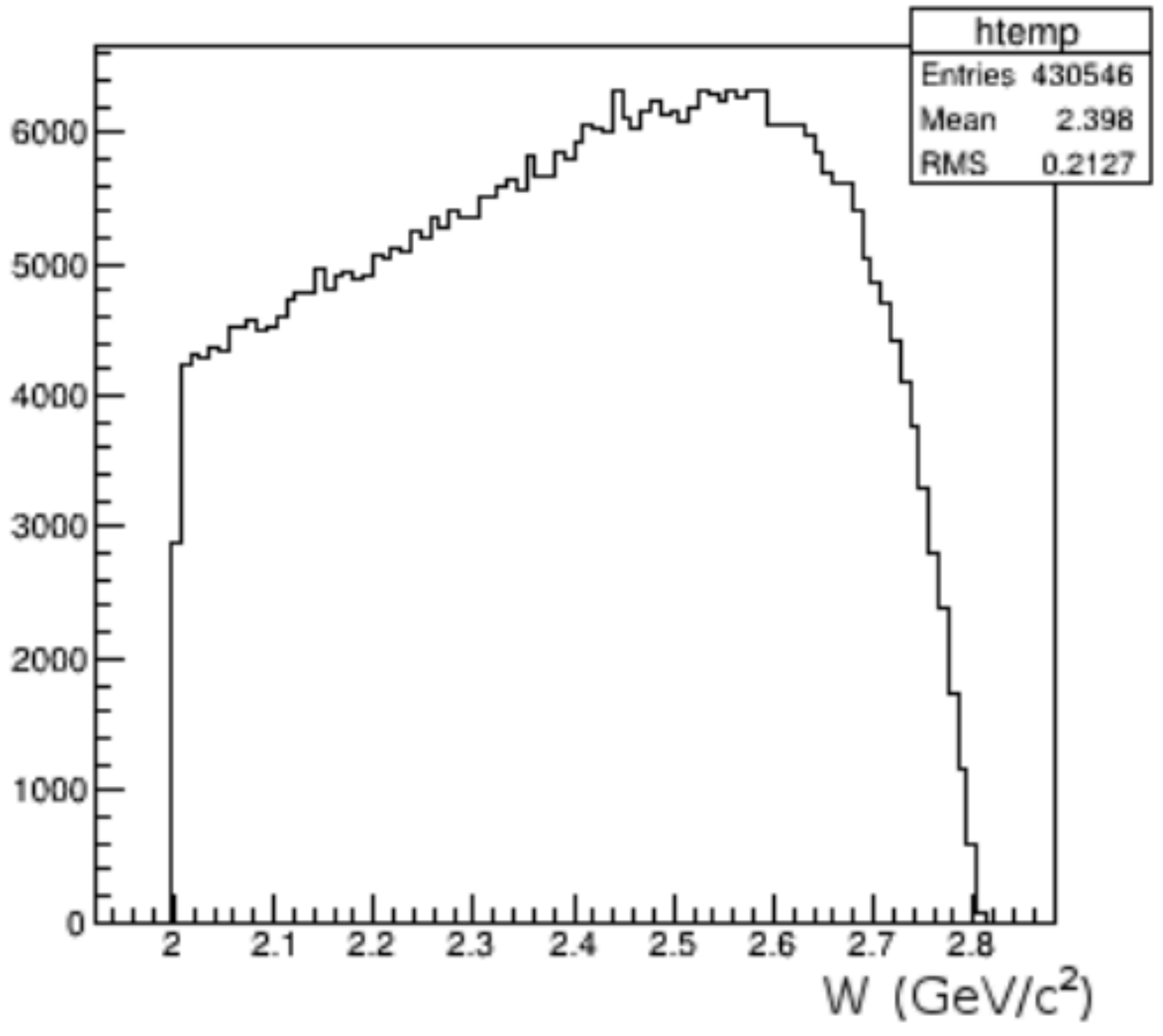
H. Hakobyan, W. Brooks et al, Nucl. Instrum. and Meth. A592:218-223, 2008.

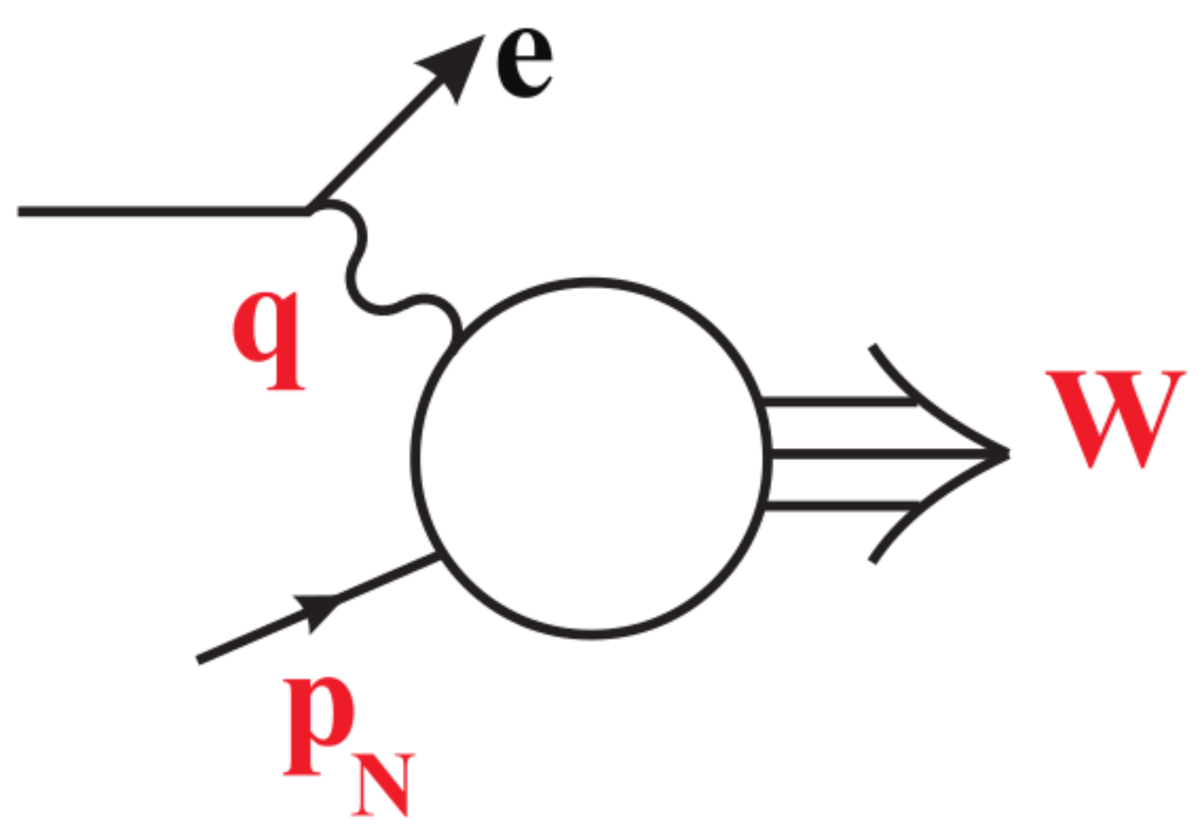
Studies performed with EG2 data

- Hadronization studies in nuclear medium
- Color transparency
- Short-Range Nuclear correlations
- Two-pion BEC correlations
- Dihadron supresión
- Etc.

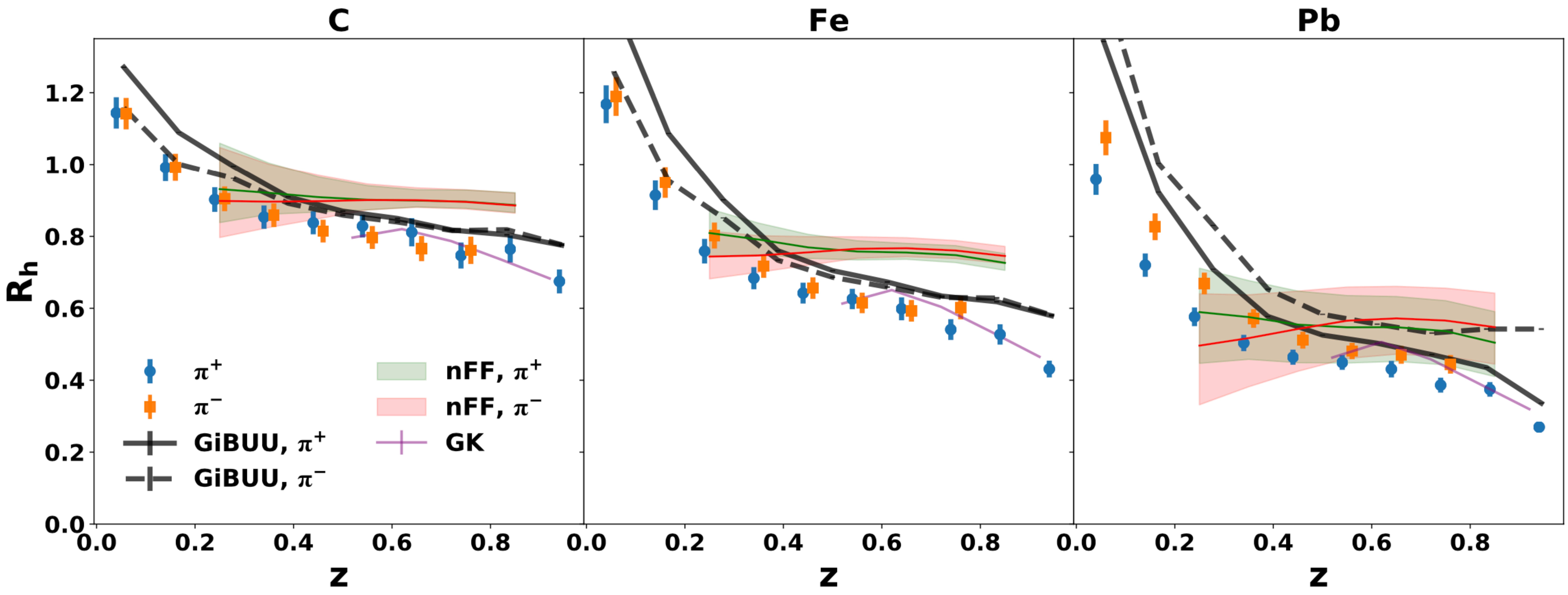
DIS cinematics on CLAS6





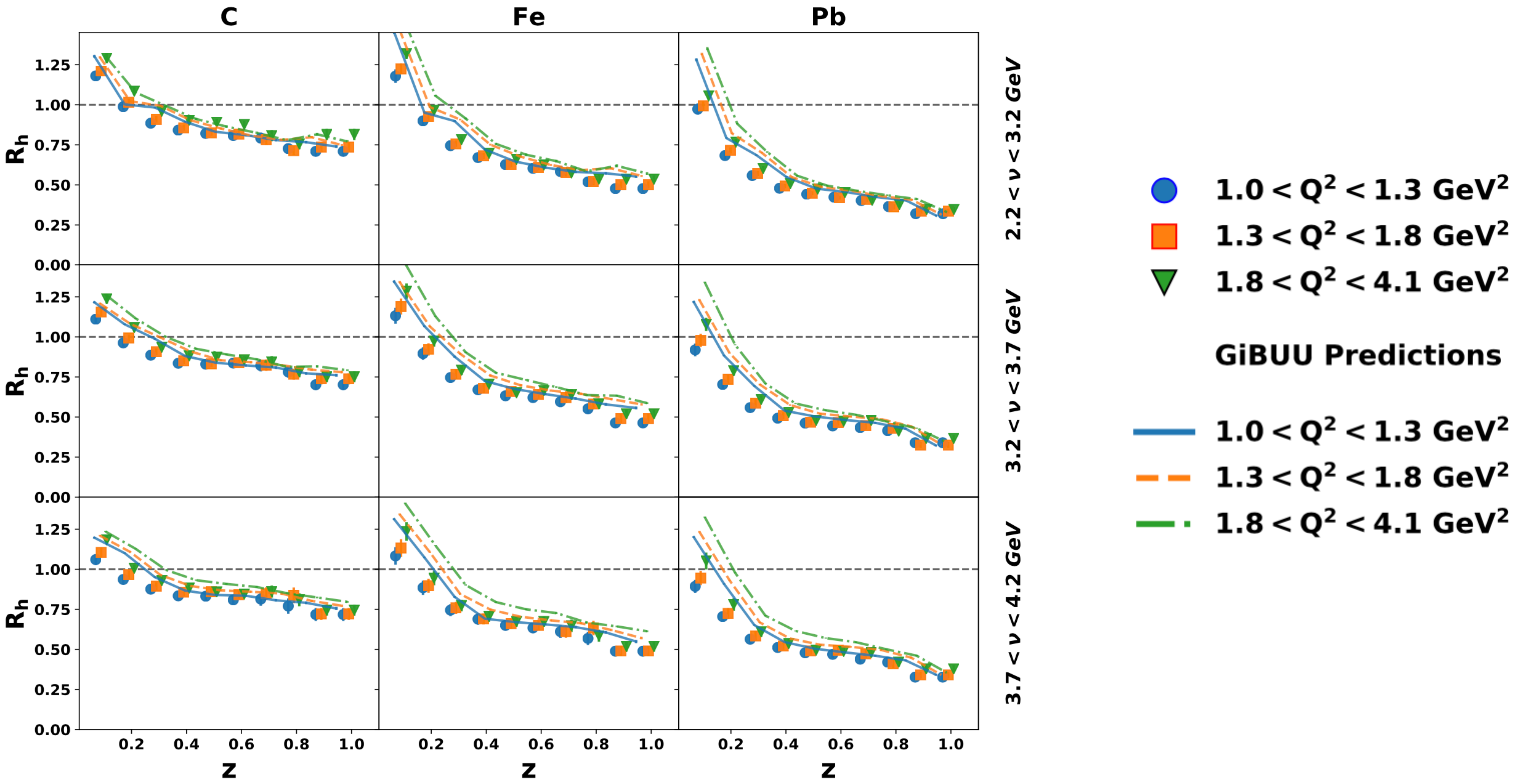


Charged pions - multiplicity ratio



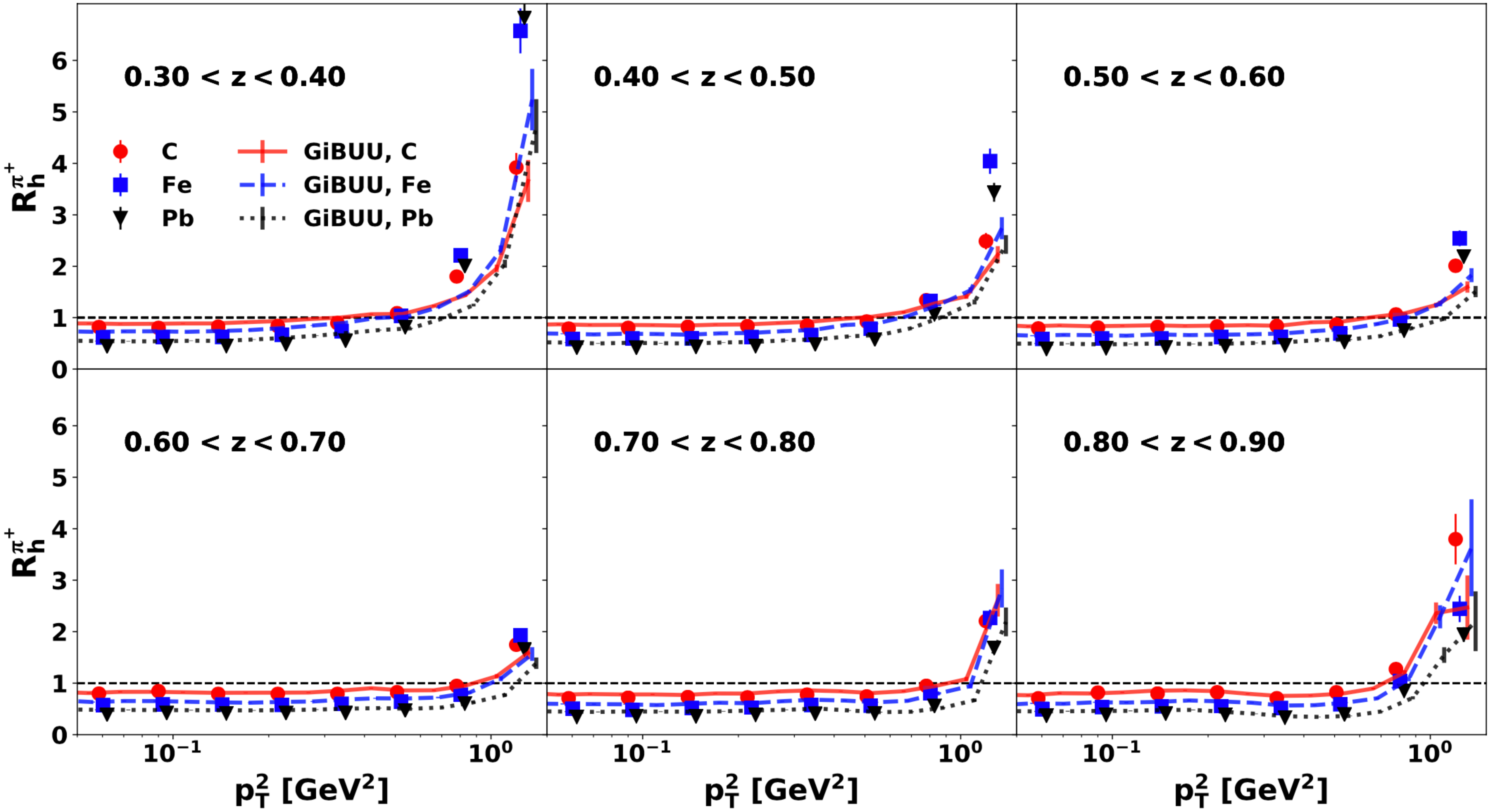
S. Moran, et al. (CLAS collaboration). Phys. Rev. C **105**, 015201 – January, 2022

Charged pions - multiplicity ratio - multidimensional



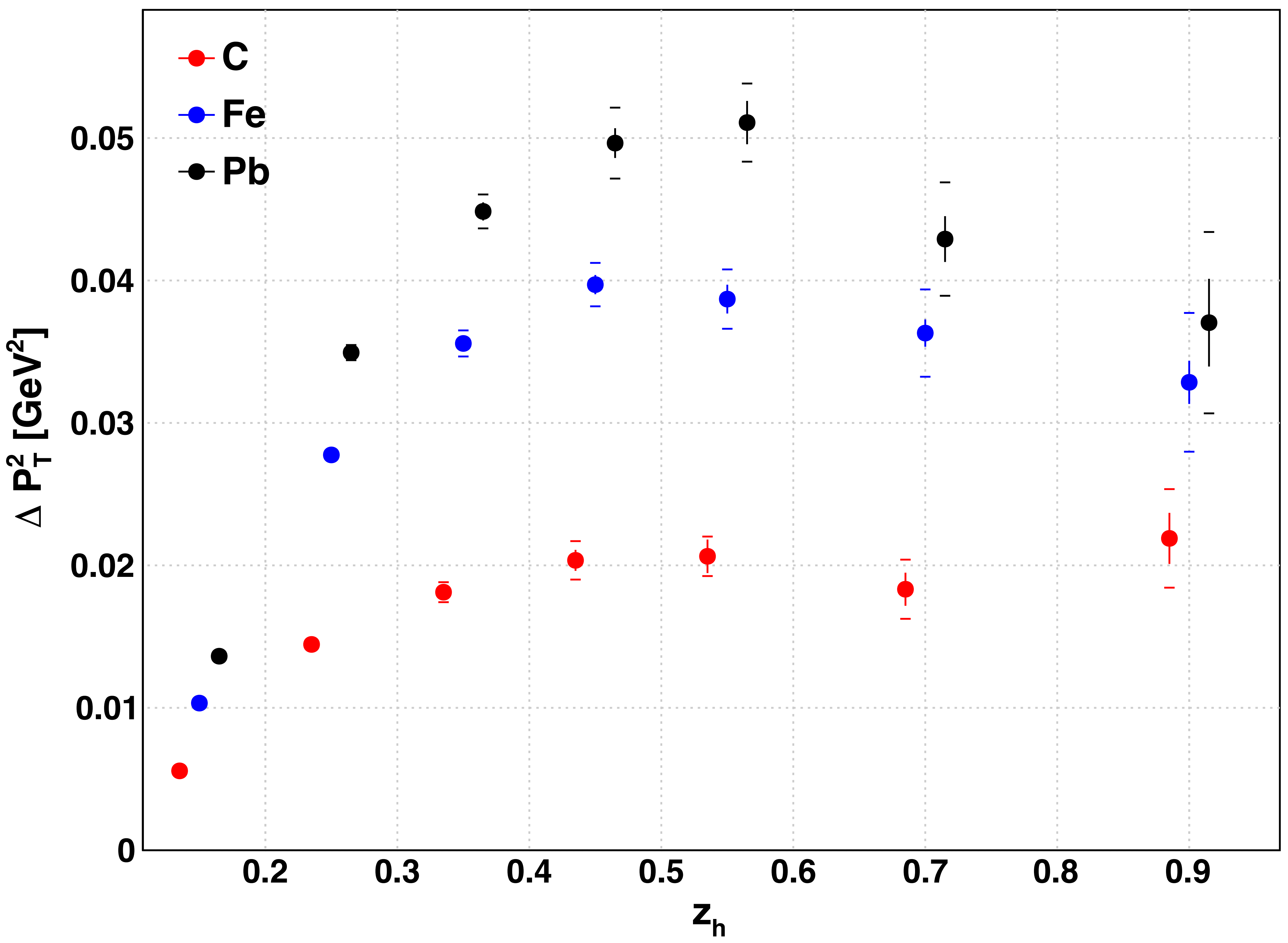
S. Moran, et al. (CLAS collaboration). Phys. Rev. C **105**, 015201 – January, 2022

Charged pions - ‘Cronin Effect’ - positive pions

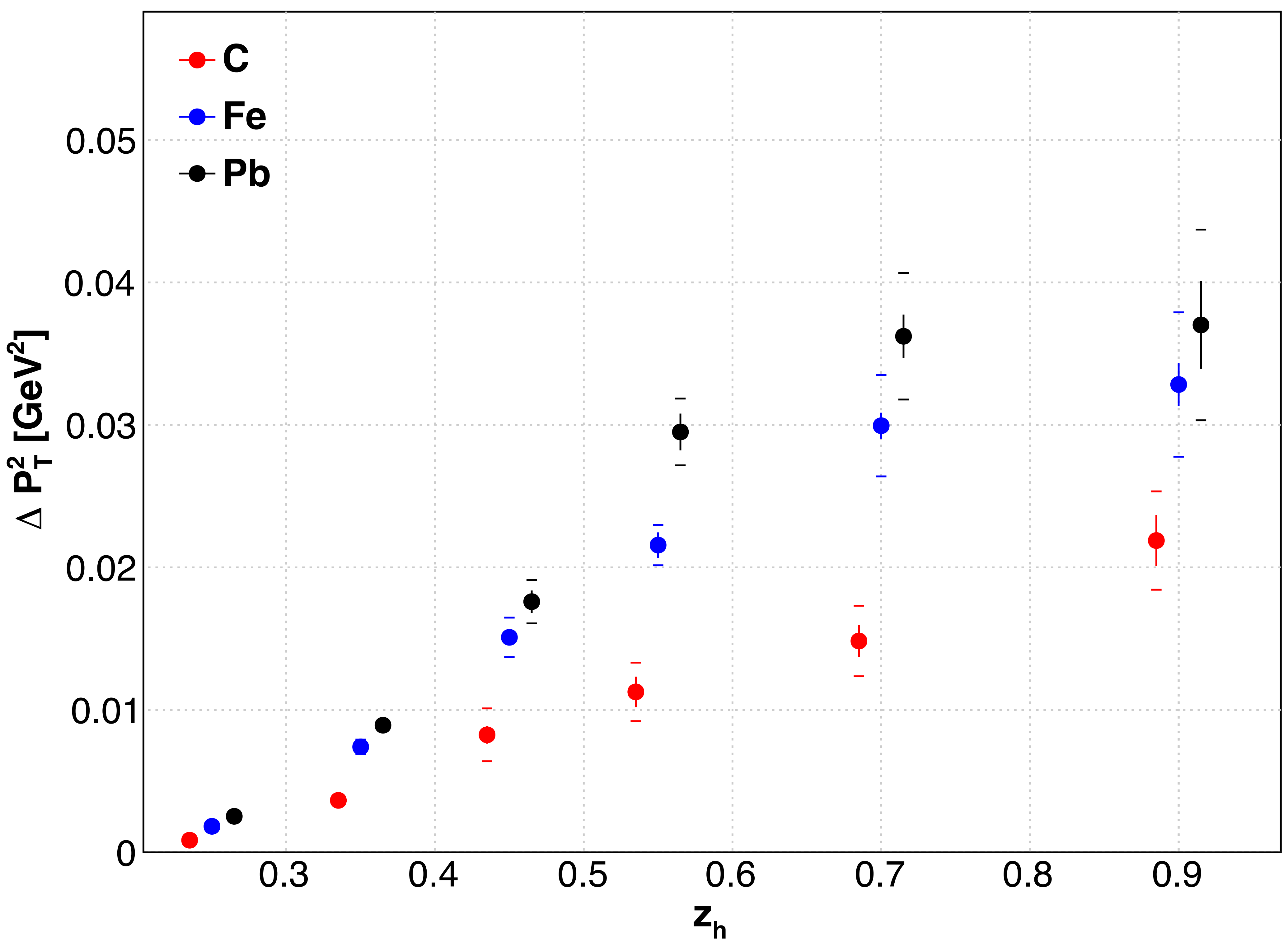


S. Moran, et al. (CLAS collaboration). Phys. Rev. C **105**, 015201 – January, 2022

Transverse momentum broadening Zh dependence for positive pions - integrated (CLAS PRELIMINARY)



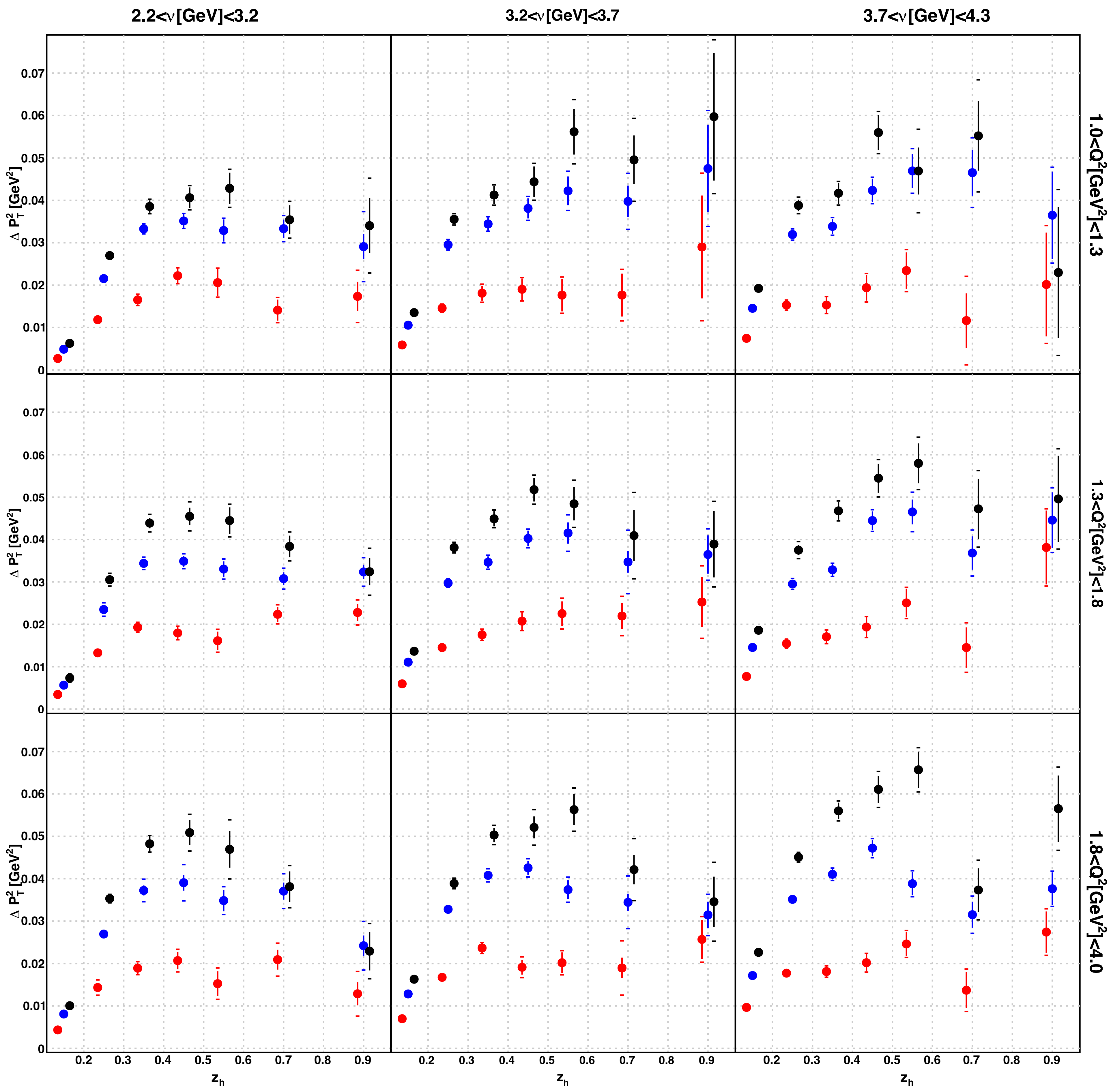
without Xf cut



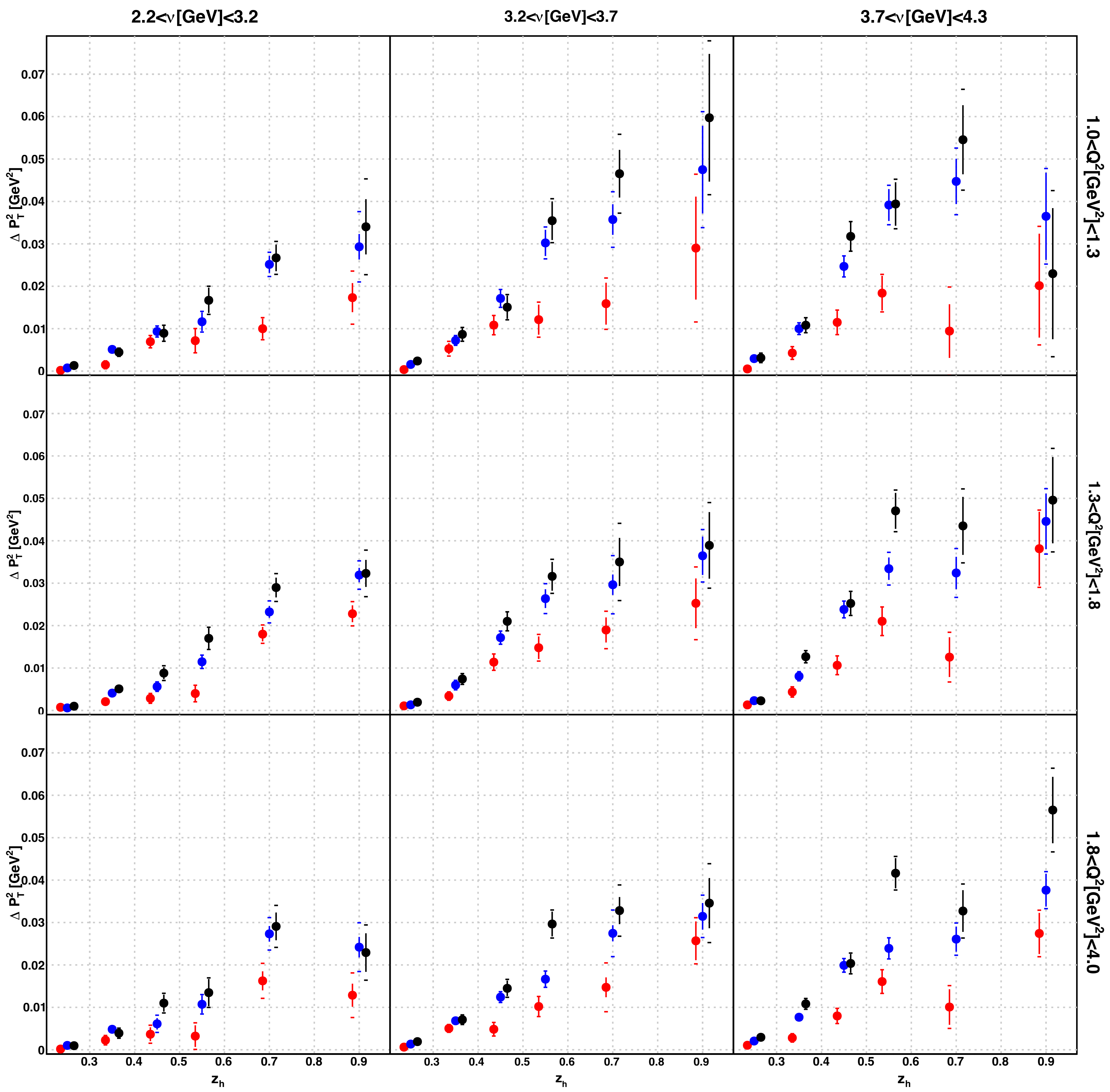
without Xf>0 cut

Esteban Molina et al.

Transverse momentum broadening Zh dependence for positive pions- differential (CLAS PRELIMINARY)

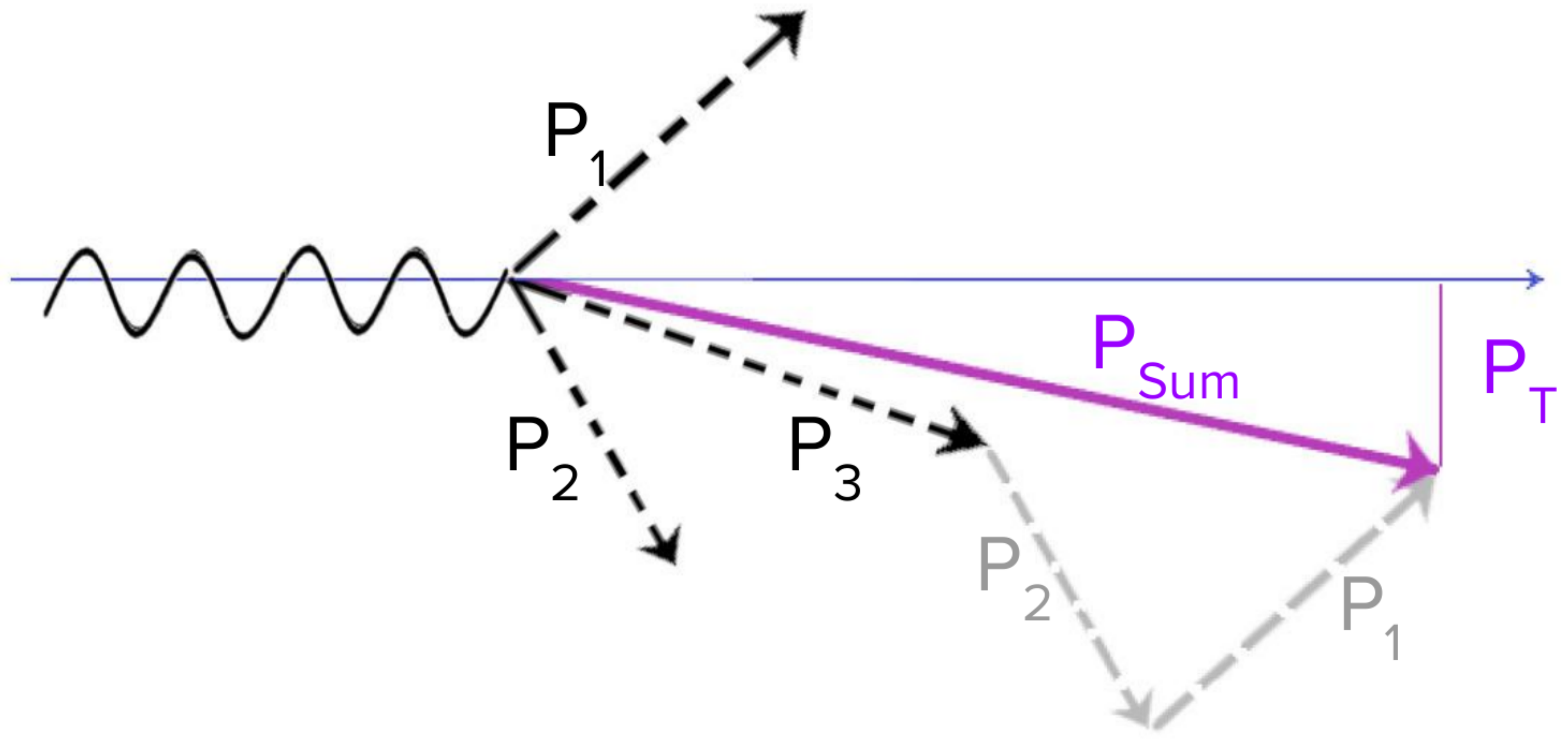


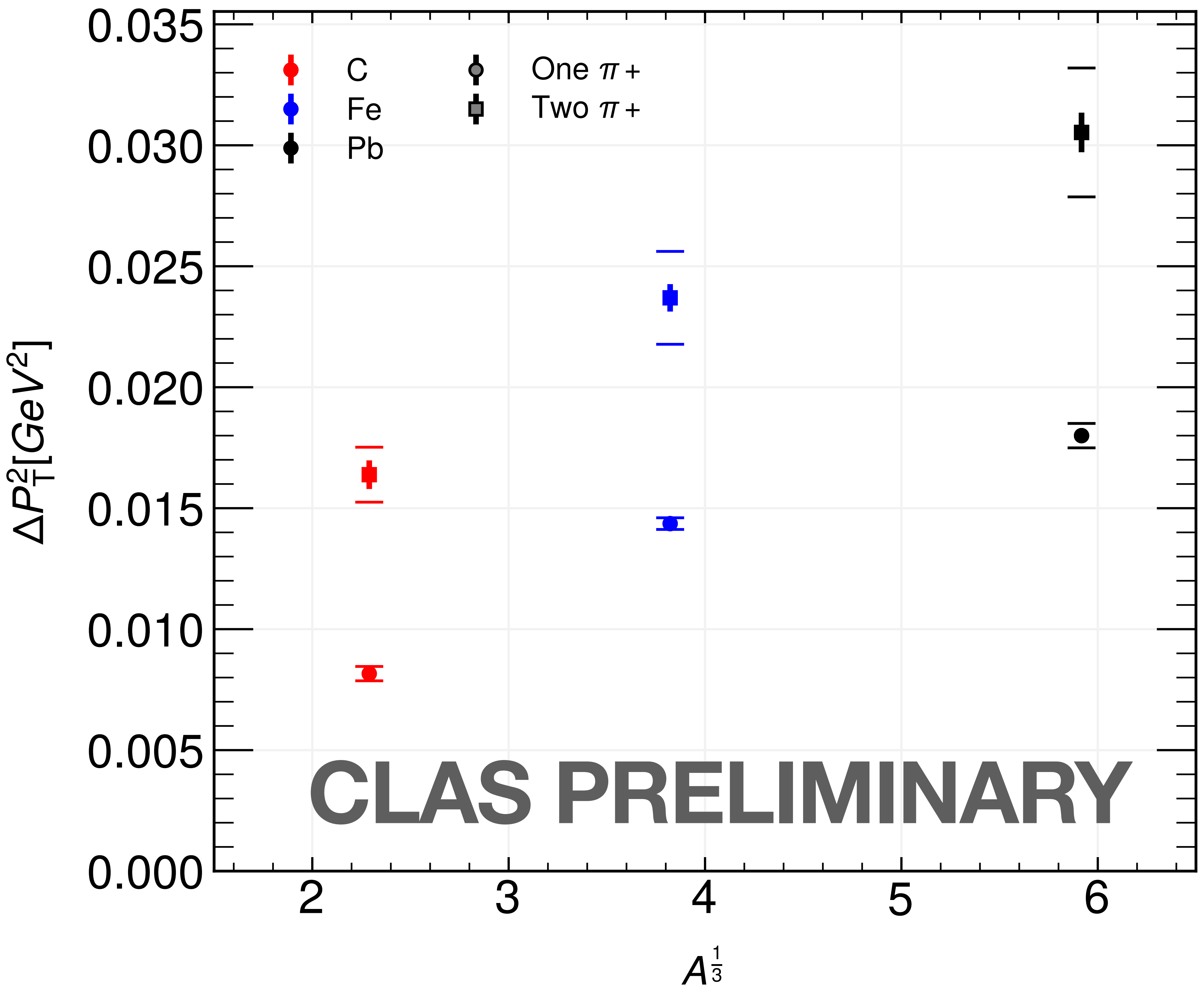
without Xf cut



without Xf>0 cut

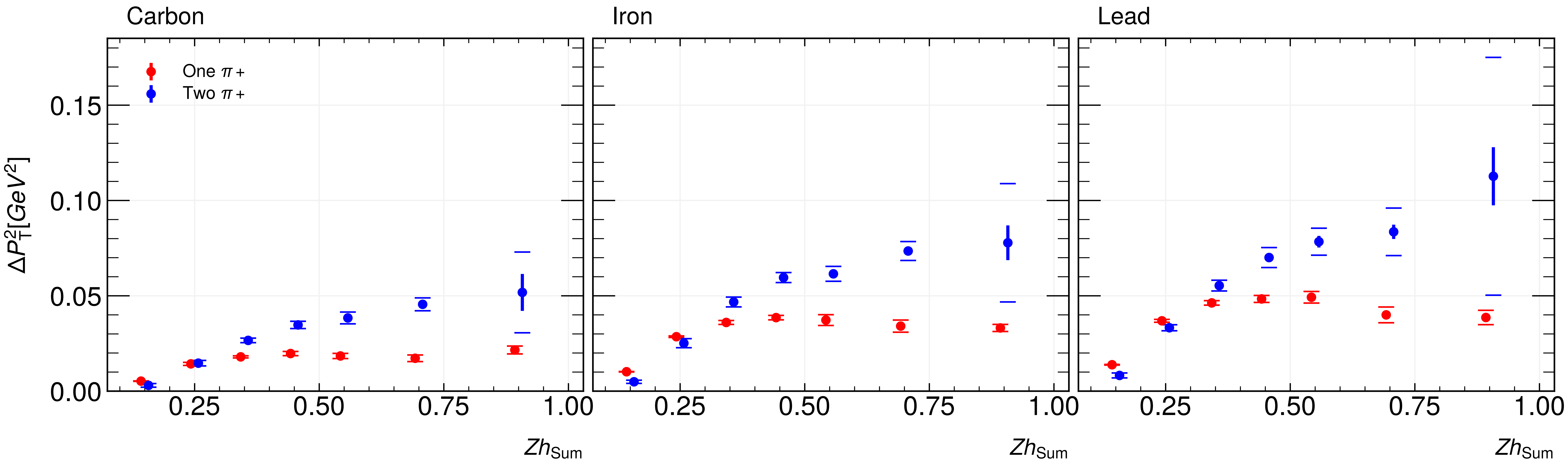
Schematic representation of the momentum vector sum in an event with multiple-pions in the final state.





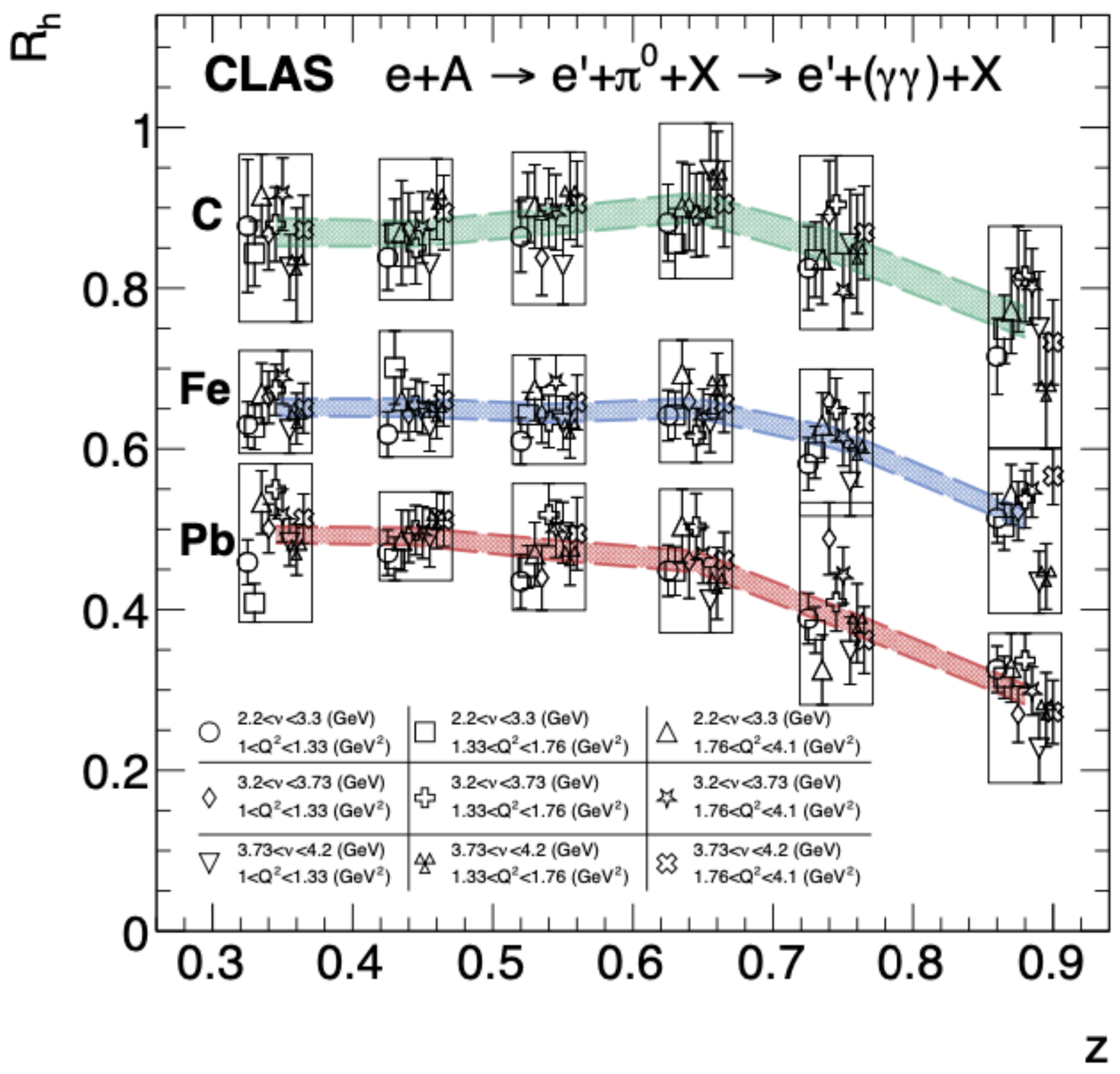
Transverse momentum broadening in function of A1/3, with all the other variables integrated. The circles are single-pion events, and the squares are two-pion events.

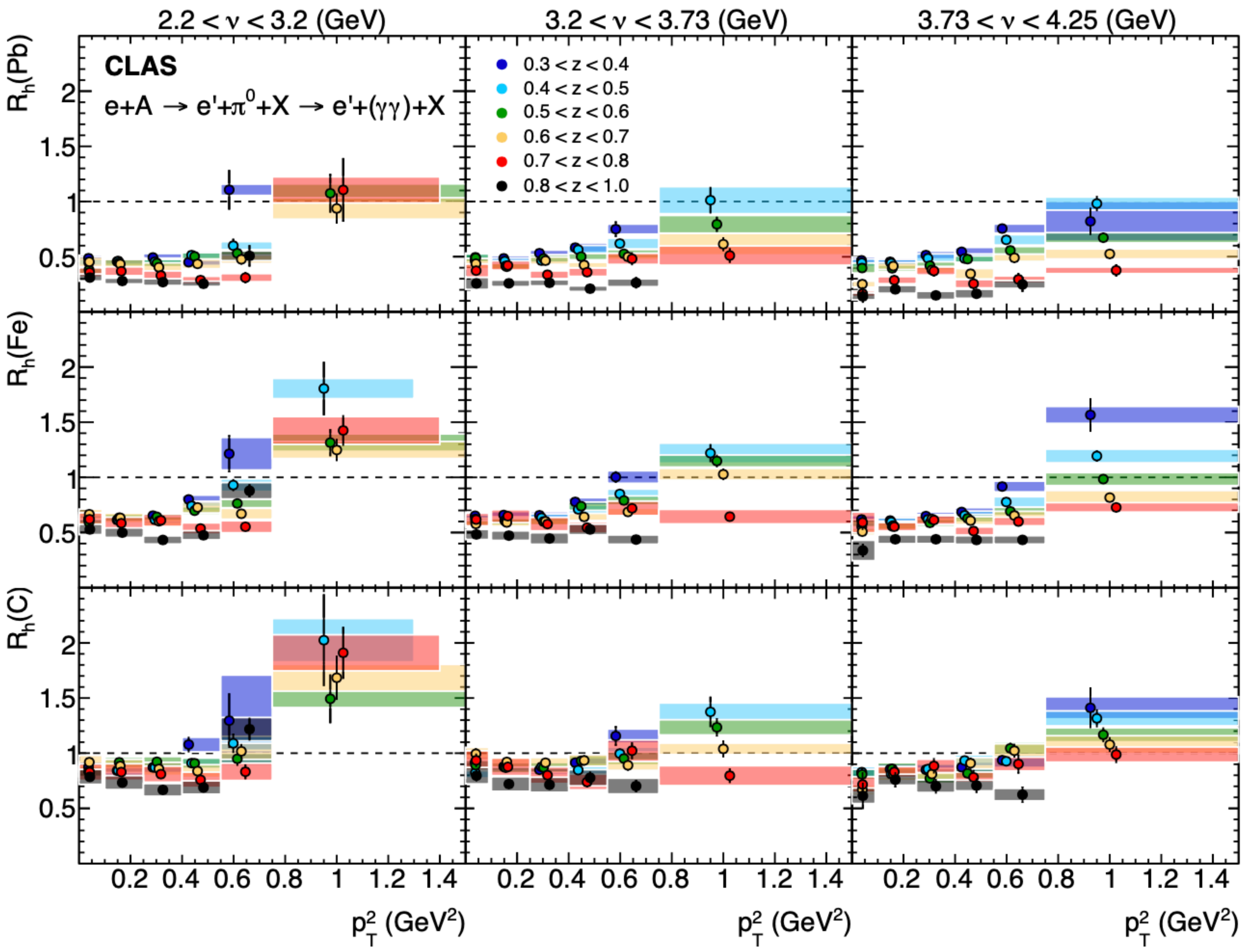
Transverse momentum broadening is shown as a function of the sum of Zh (with all other variables integrated), with each box representing a different target. Single-pion events are depicted in red, and two-pion events are depicted in blue.



Matias Barria et al. (CLAS PRELIMINARY)

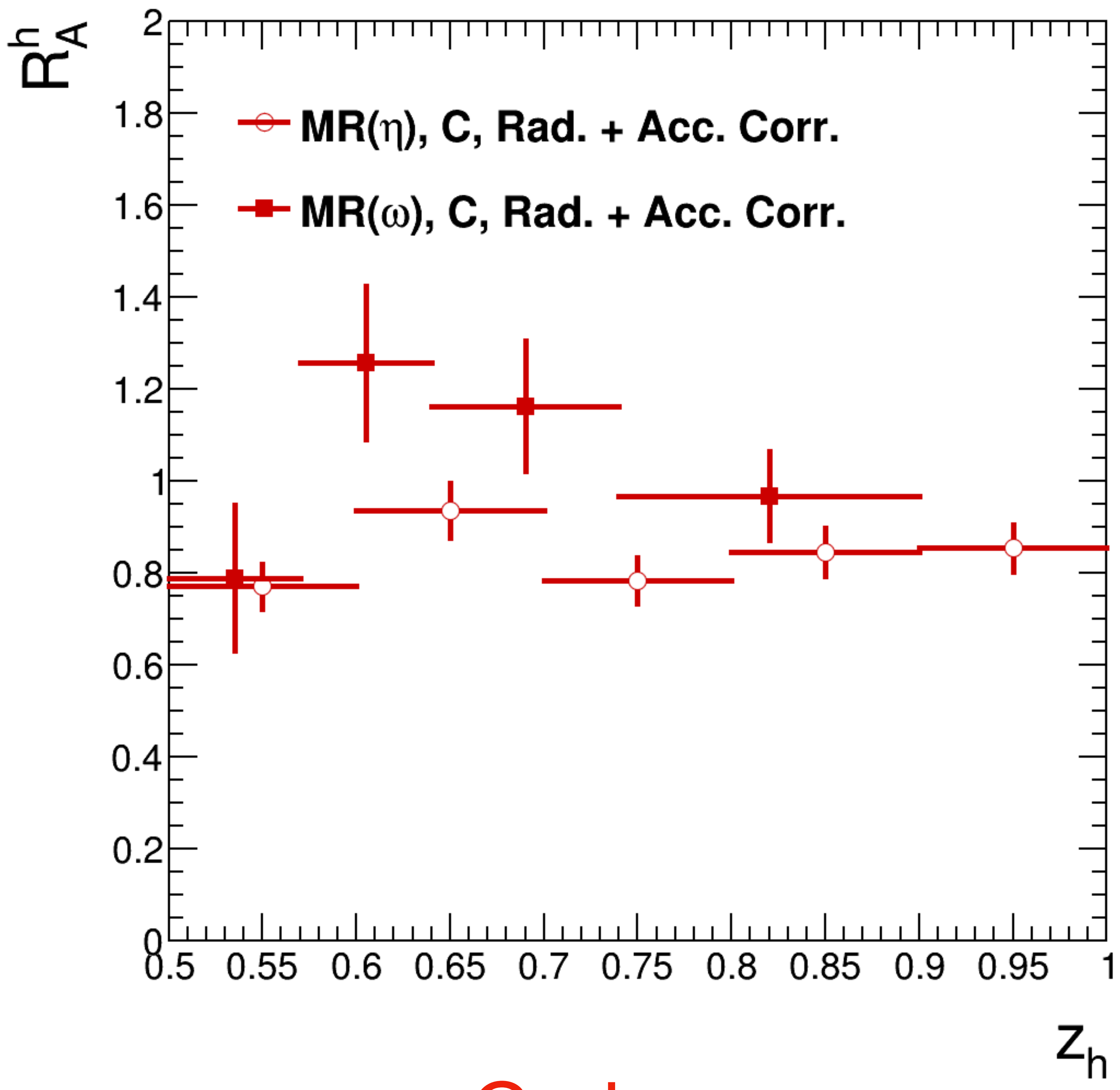
Neutral Pions



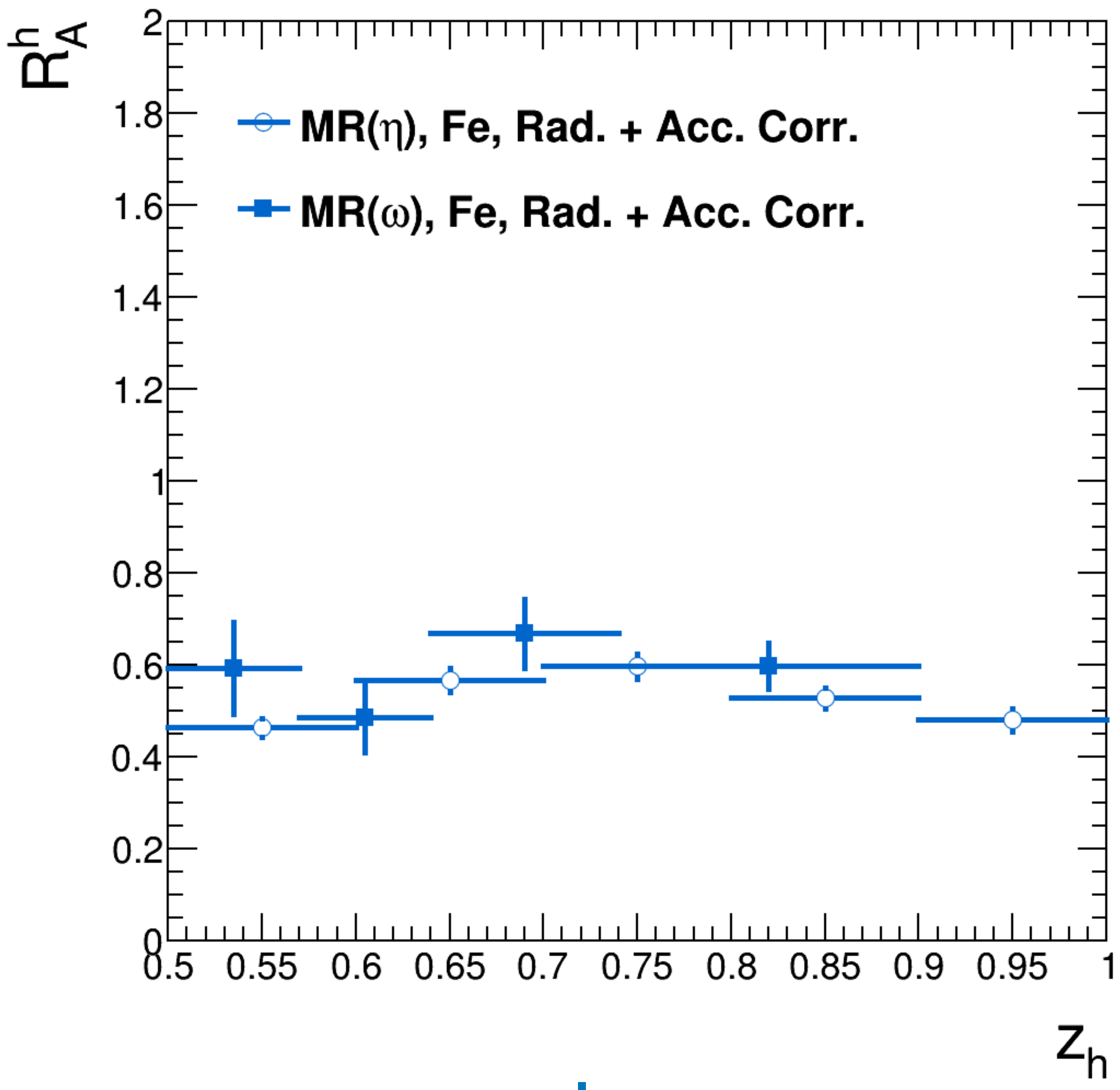


Tayisia Mineeva et al. approved CLAS analysis note.

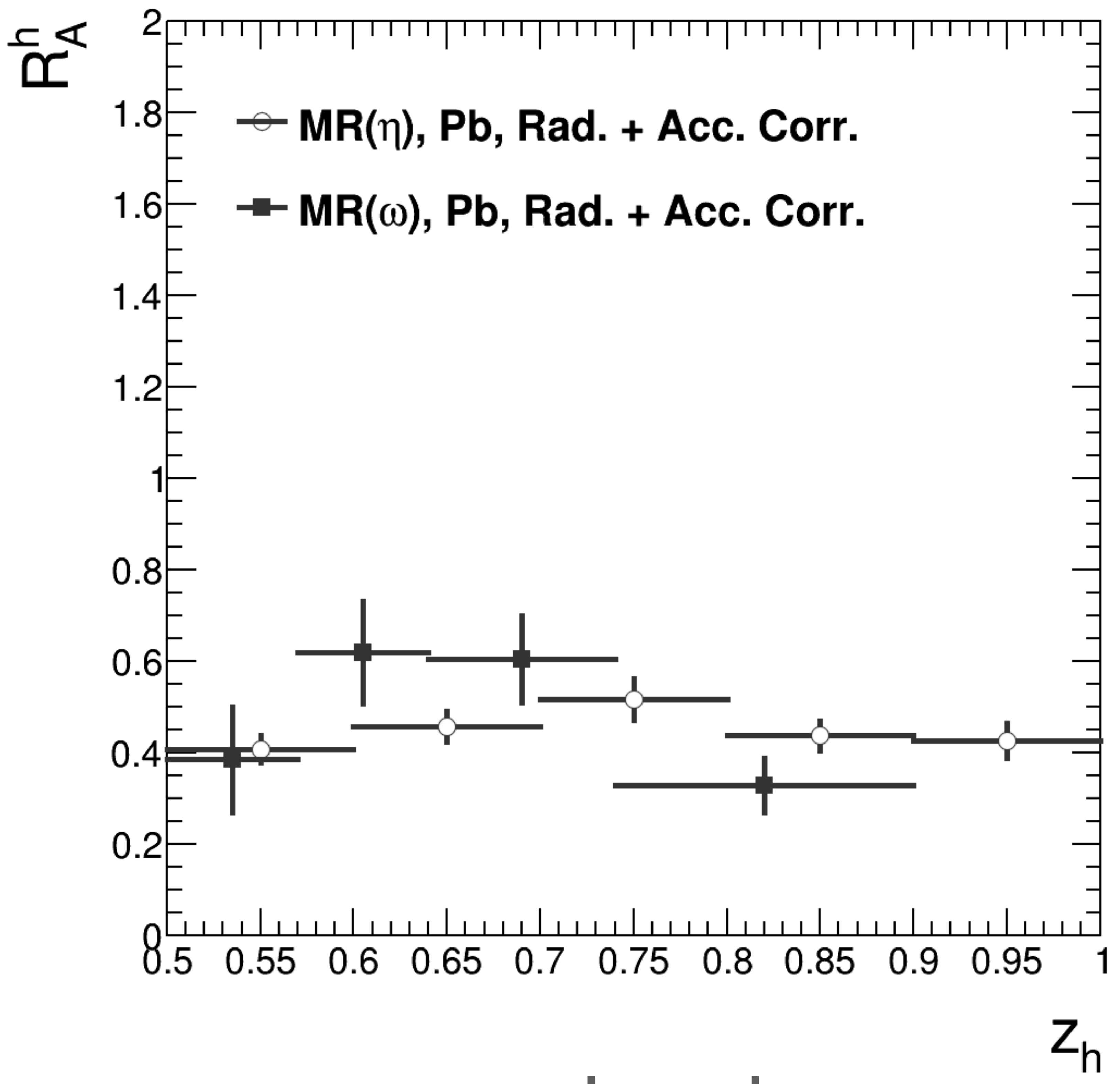
Etas and Omegas



Carbon



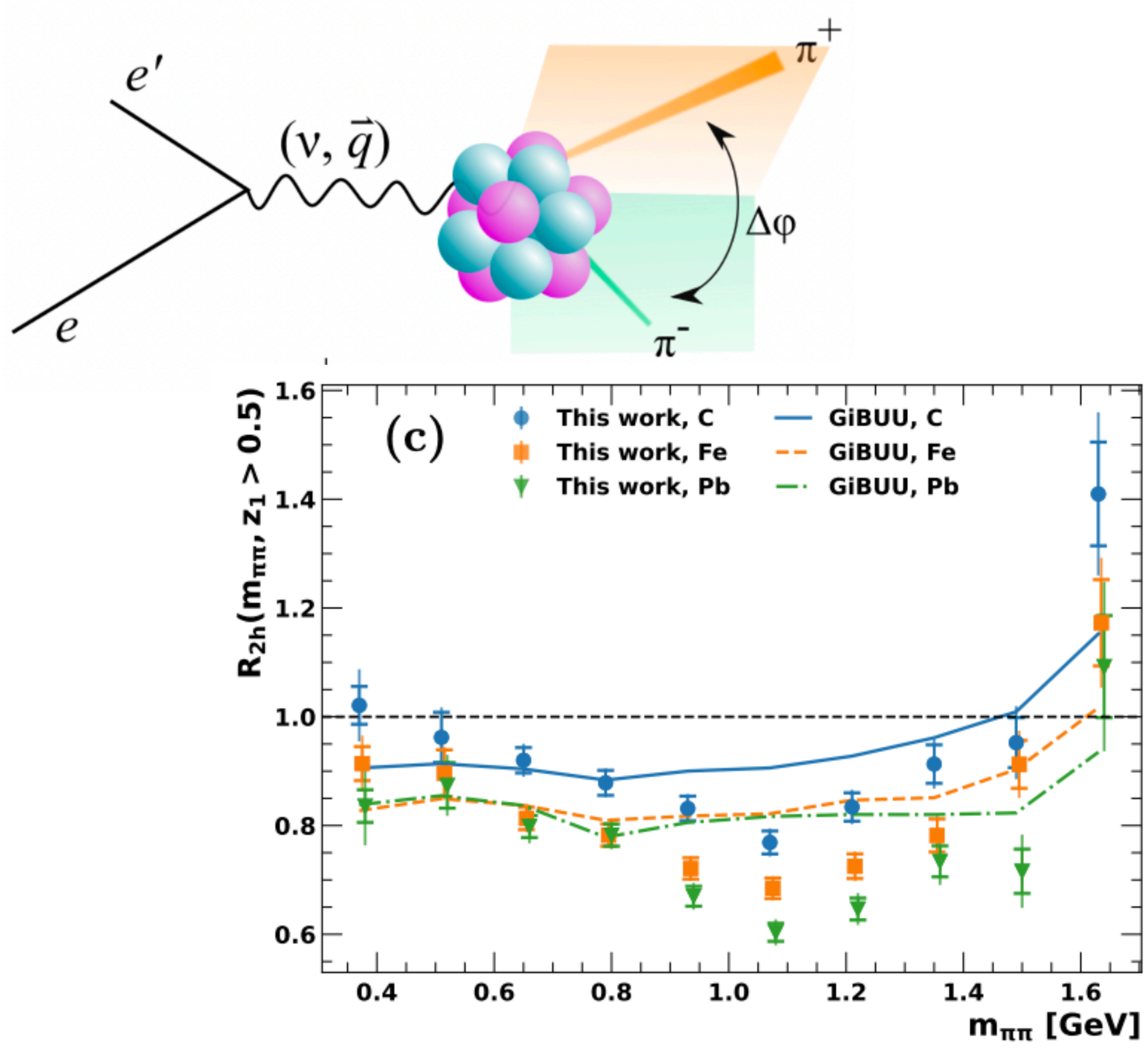
Iron

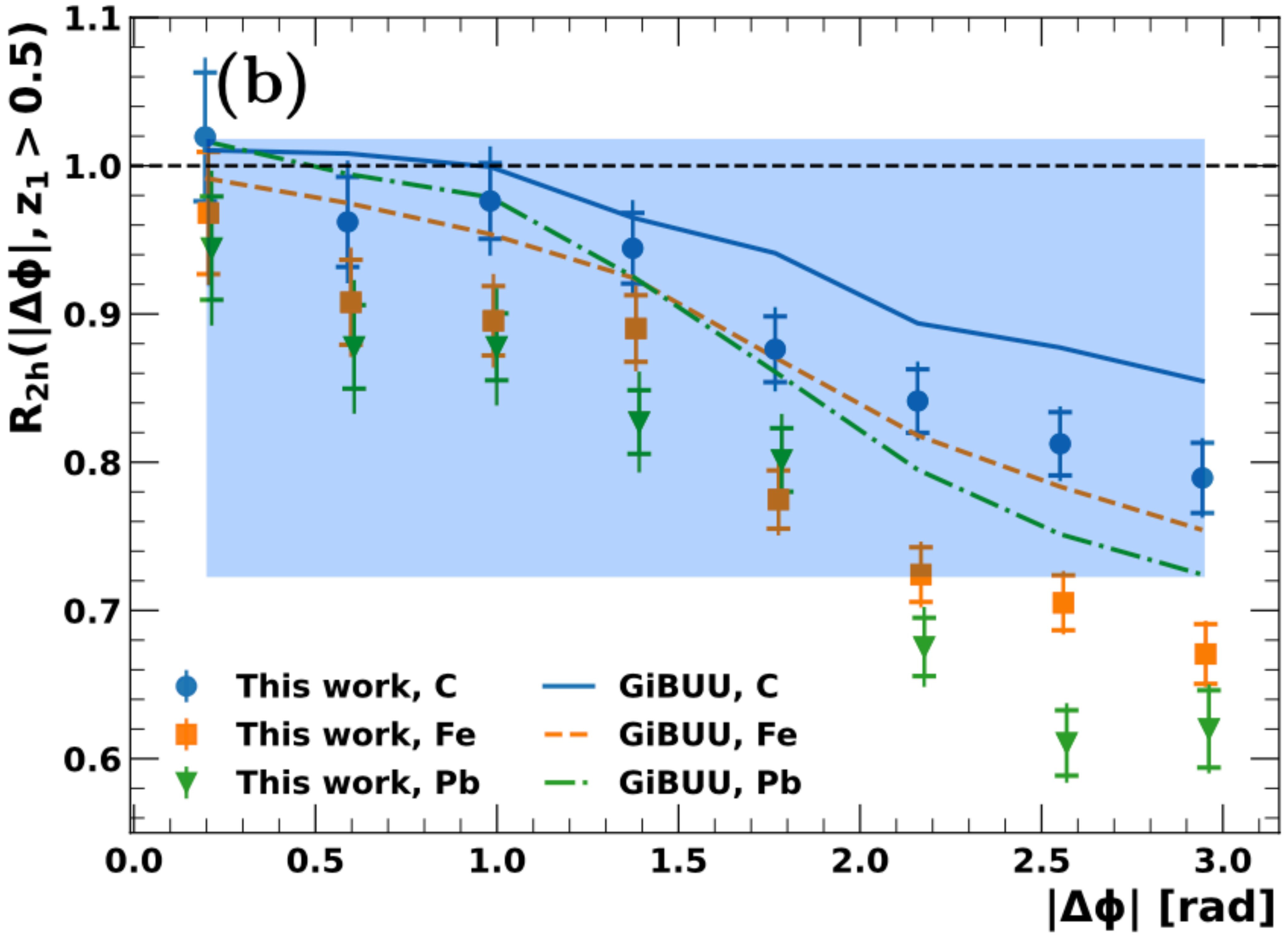


Lead

Andres Borquez, Orlando Soto et al. (CLAS PRELIMINARY).

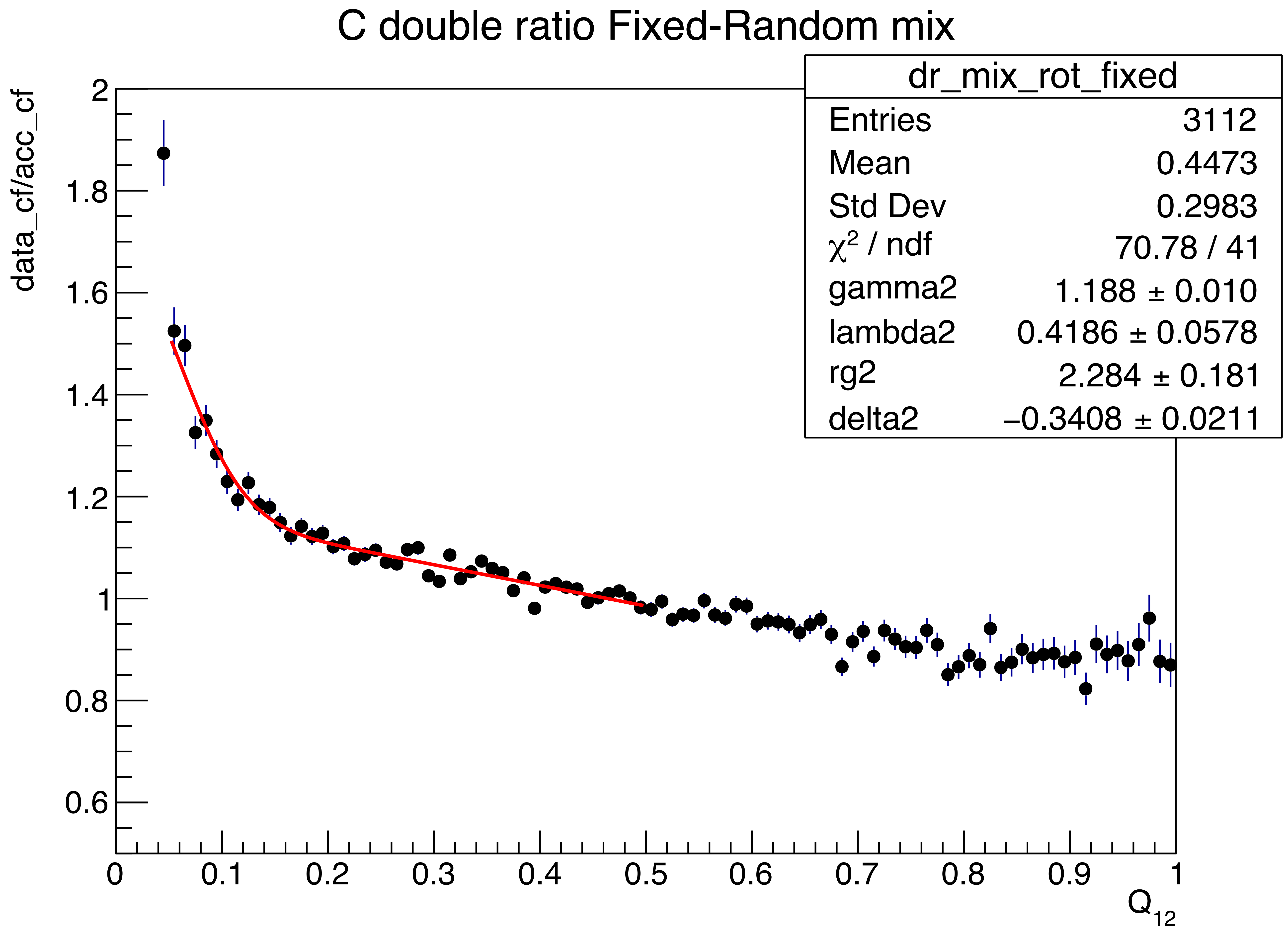
Multihadron events studies: Two-hadron azimuthal correlations





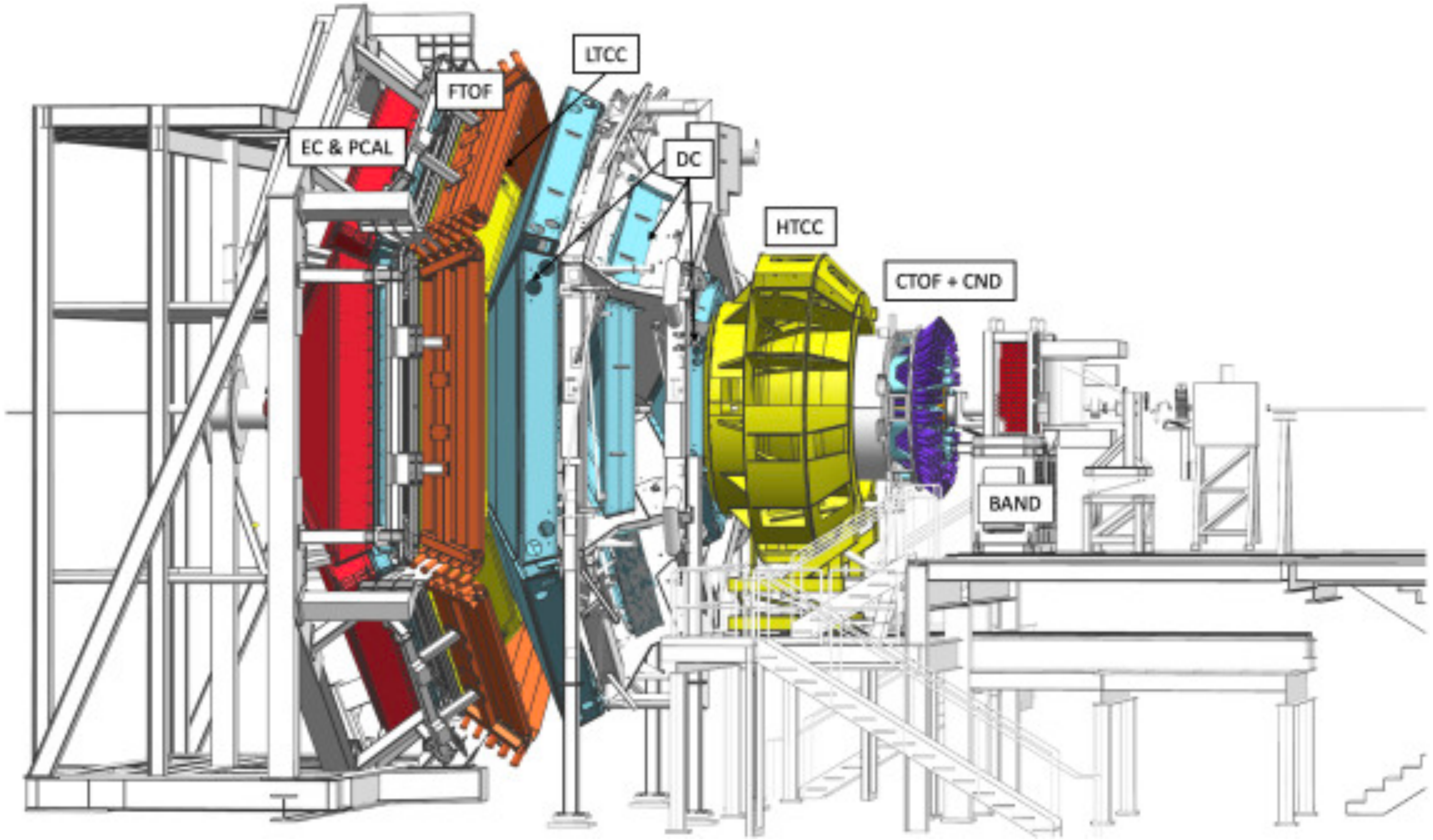
S.J. Paul, et al. (CLAS collaboration). Phys. Rev. Lett. **129**, 182501 – October, 2022

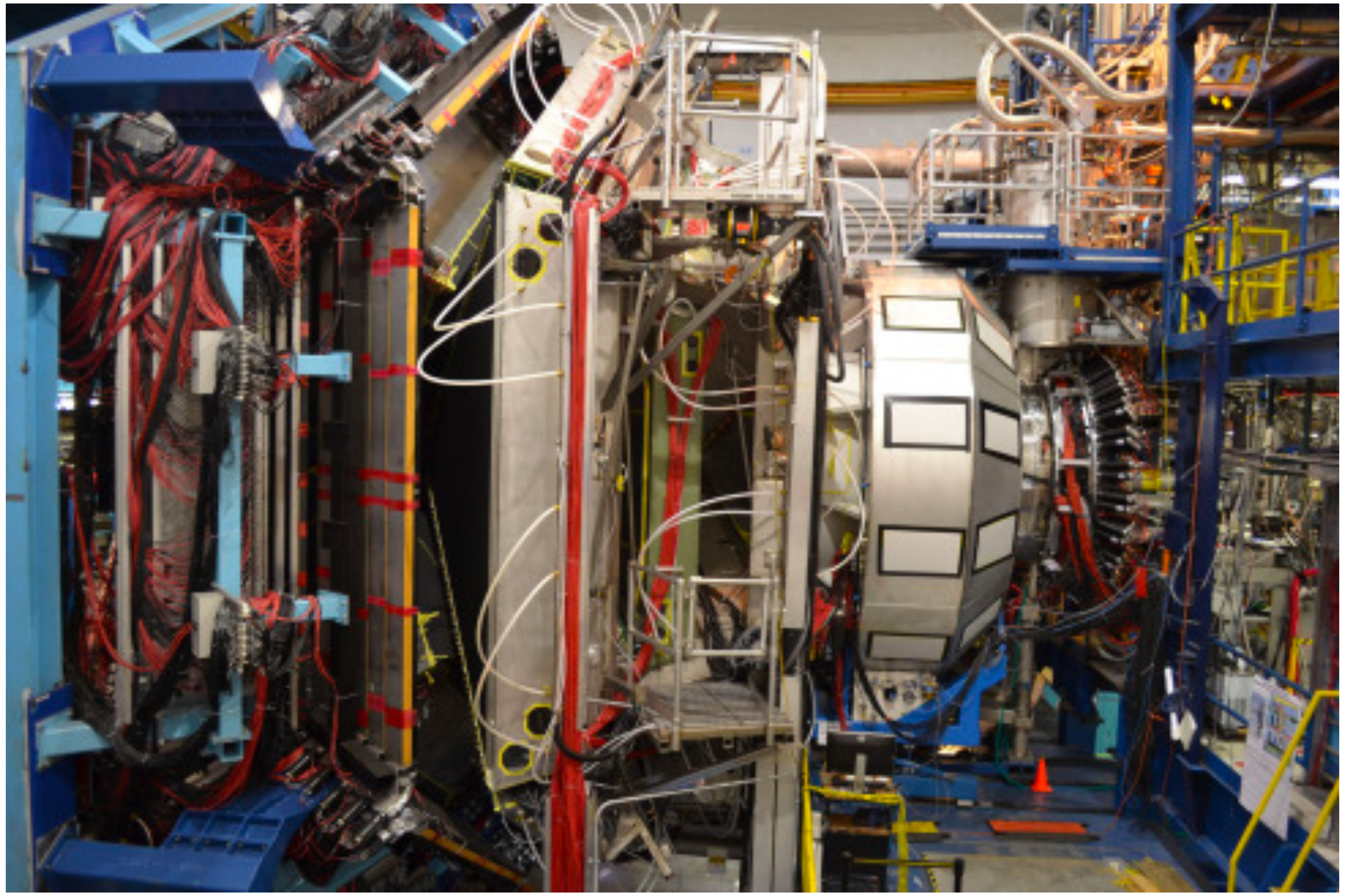
Multihadron events studies: Two-pion BEC correlations



Antonio Radic et al. (CLAS PRELIMINARY)

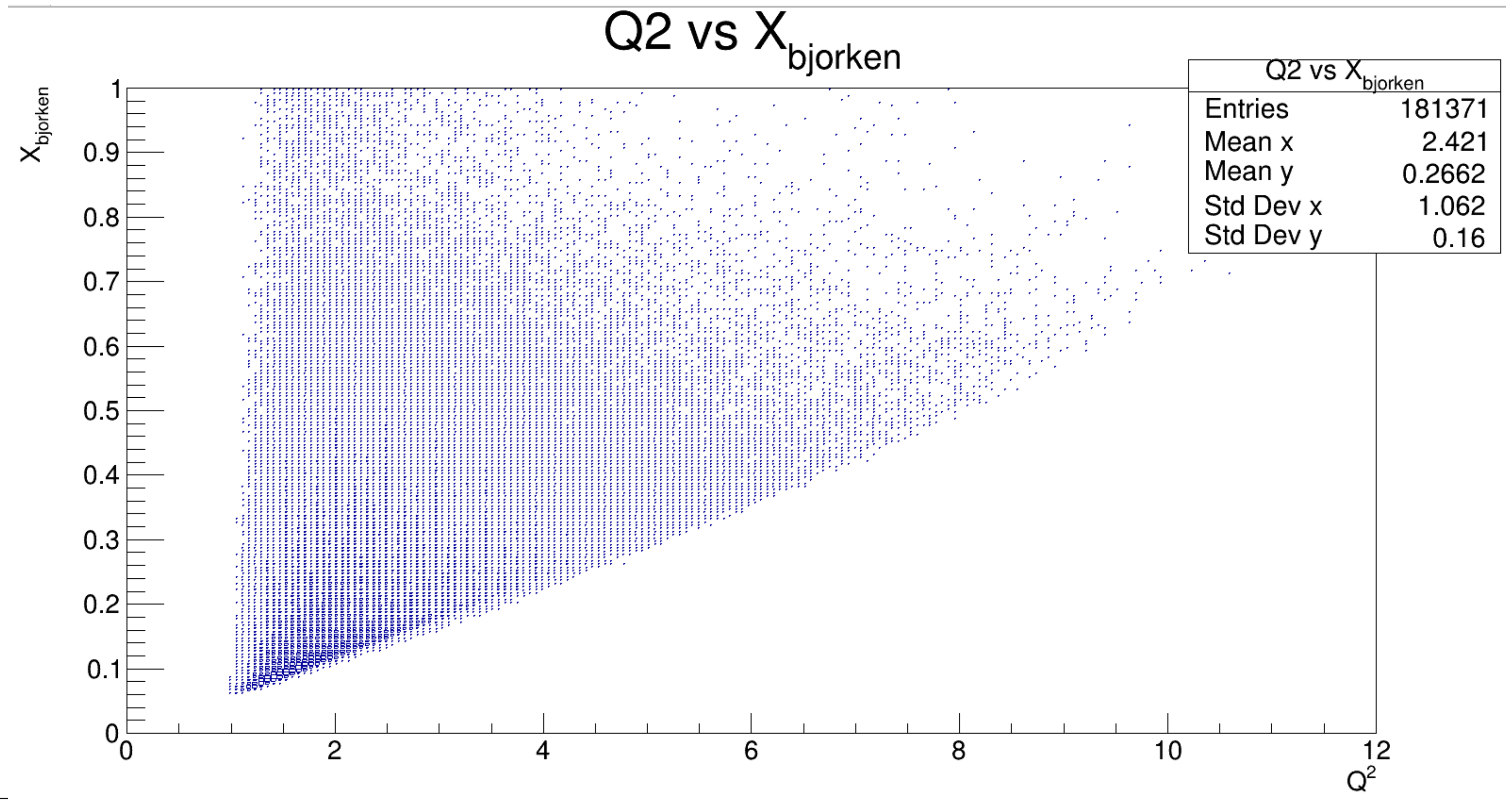
CLAS12 Spectrometer at JLab

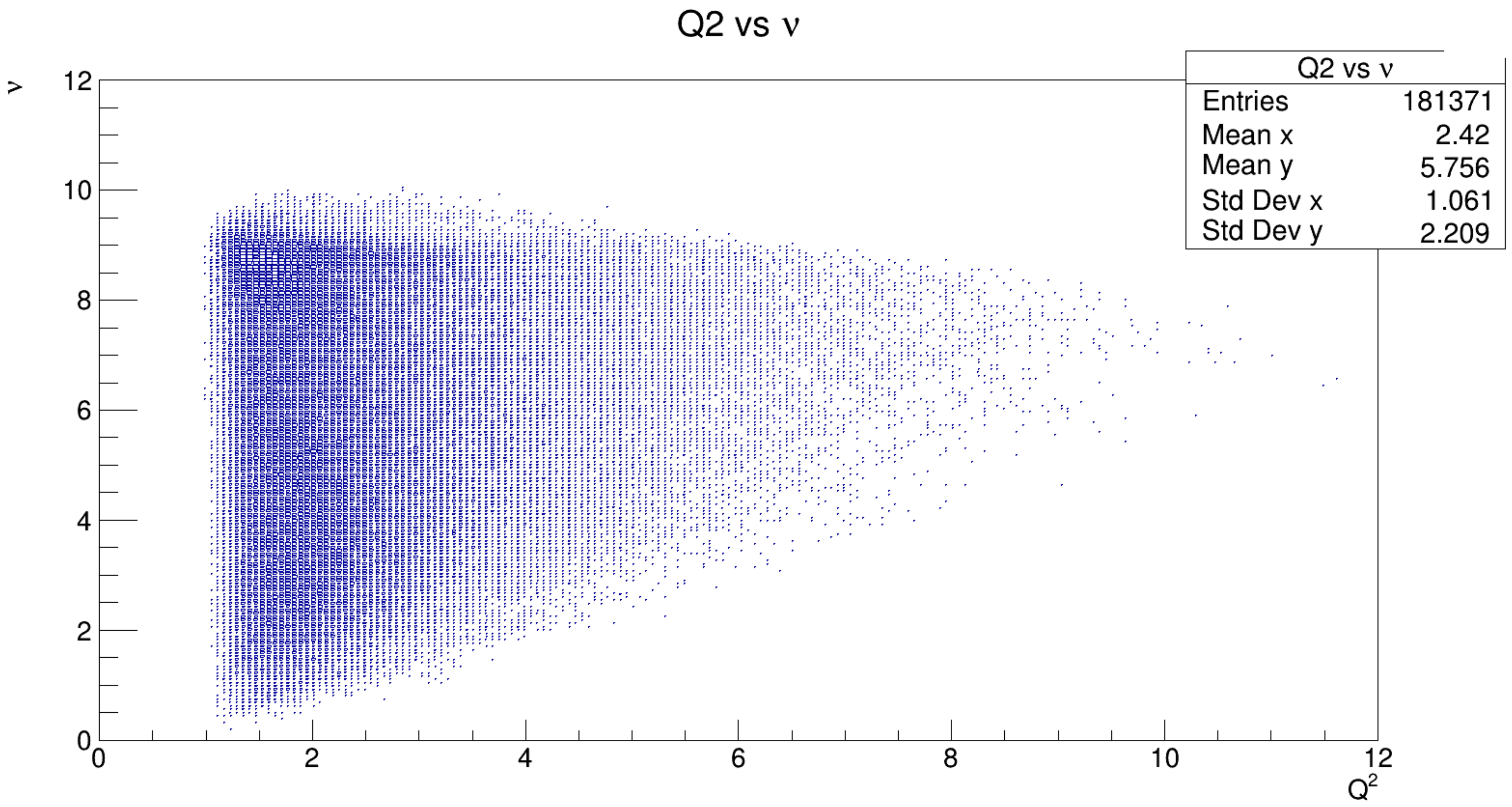


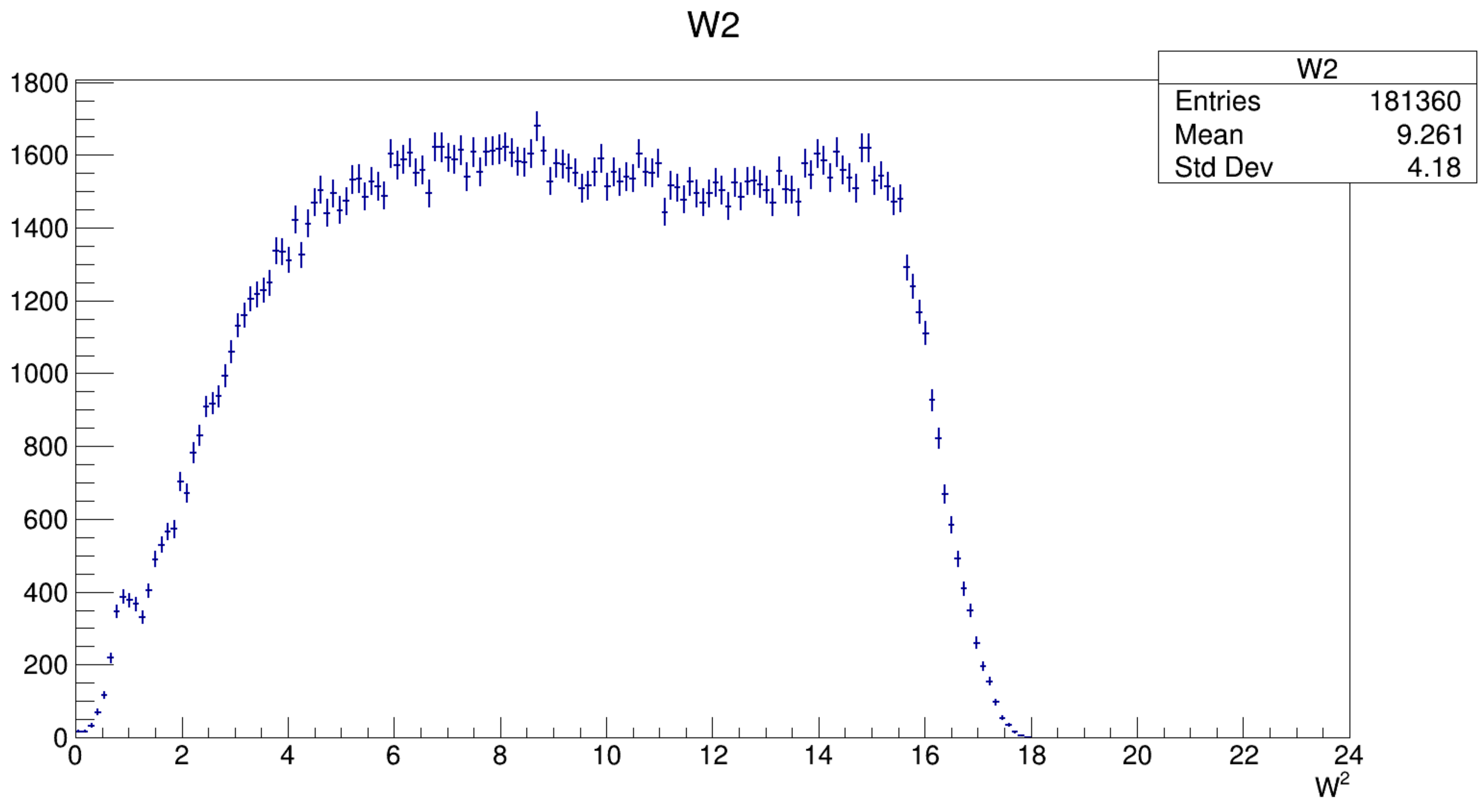


12 GeV cinematics

Data from RGF experiment







Hadrons in CLAS12

hadron	$c\tau$	mass (GeV)	flavor content	detection channel	Production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
$f1$	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	$\pi\pi\pi\pi$	-
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42
p	stable	0.94	ud	direct	530
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	-
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ξ^-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

With new double-target, designed and built in UTFSM

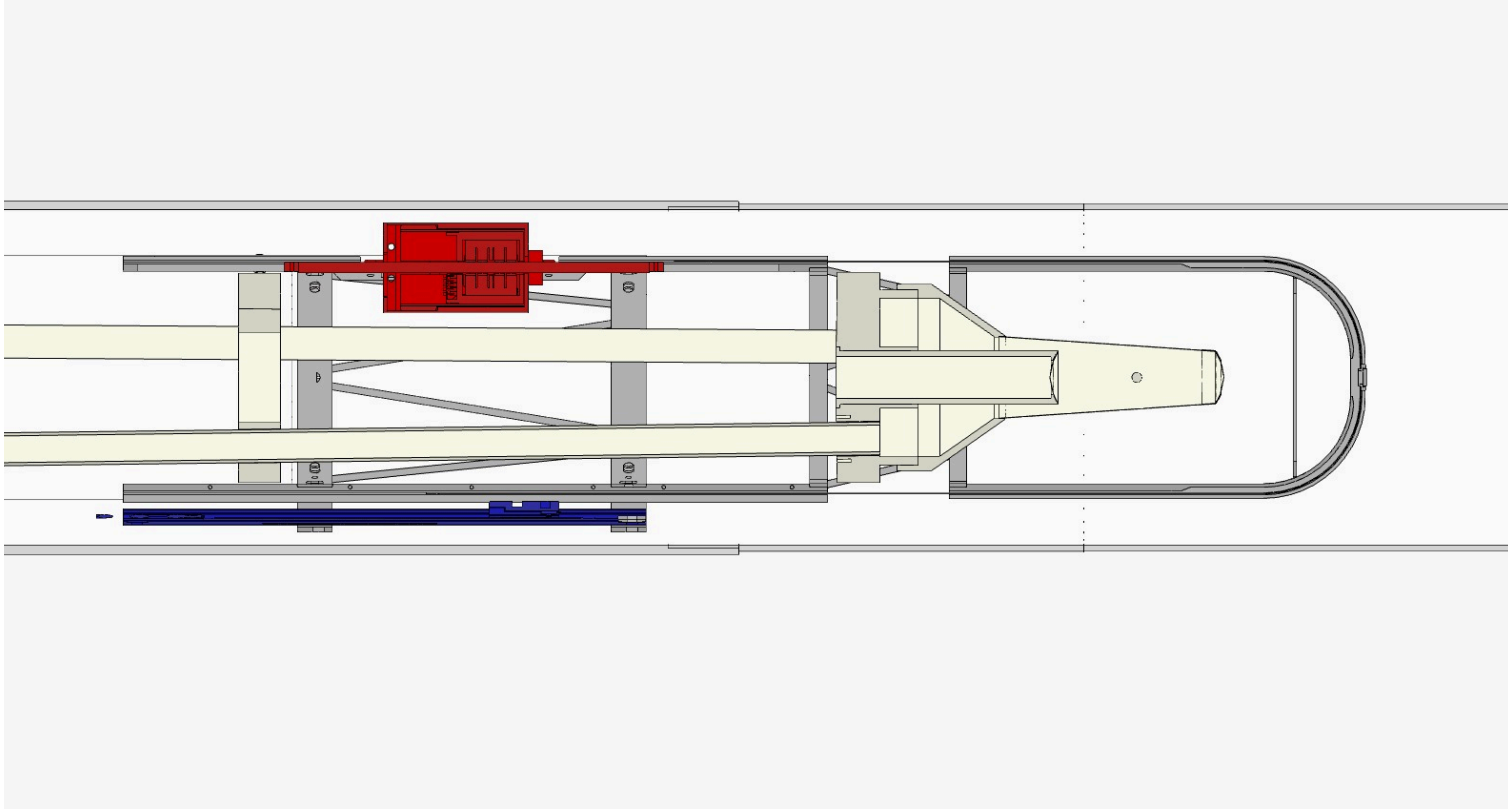
CCTVal

Experiment Context: CLAS12 Conditions

1. Reduced Space in Beamline, 85mm
2. High Vacuum, 10-6 mbar
3. Strong Magnetic Field, 5 Tesla
4. Cryogenic Temperatures, 22 Kelvin cryo-cell
5. 11 GeV Beam energy

- Interchangeable solid targets system in high vacuum
- Remote control system
- Resistant to high radiation
- Non-magnetic materials
- High vacuum resistant materials (no out-gassing)
- Fit in a 85mm diameter, cylindrical room
- Estimation of temperature in targets and devices

RGE Experiment Double Target System



Double Target for RG-E


DO NOT PULL
WITH RING—
USE HANDLES
CAUTION
MAGNETIC FIELD
HELIUM
UN 1963
REFRIGERATED LIQUID

Target configuration with 70 nA beam current

	Solid target thickness in mm	Liquid target Luminosity	Solid target Luminosity	Total Luminosity	Number of Days to Run	Days: inbending/ outbending
2cm LD2 + C	1.48	8.56E+34	8.79E+34	1.74E+35	9	8/1
2cm LD2 + Al	1.20	“”	8.53E+34	1.71E+35	9	8/1
2cm LD2 + Cu	0.36	“”	8.50E+34	1.71E+35	9	8/1
2cm LD2 + Sn	0.30	“”	5.78E+34	1.43E+35	14	12/2
2cm LD2 + Pb	0.14	“”	4.18E+34	1.27E+35	19	17/2

Integrated luminosity for each solid target is: 6.81E+40

Run Plan

	Inbending	Number of PAC Days to Run
1.	2cm LD2 + C	4
2.	2cm LD2 + Pb	8.5
3.	2cm LD2 + Cu	4
4.	2cm LD2 + Sn	6
5.	2cm LD2 + Al	4

	Outbending	Number of PAC Days to Run
6.	2cm LD2 + C	0.5
7.	2cm LD2 + Pb	1
8.	2cm LD2 + Cu	0.5
9.	2cm LD2 + Sn	1
10.	2cm LD2 + Al	0.5

Solid targets characterization measurements

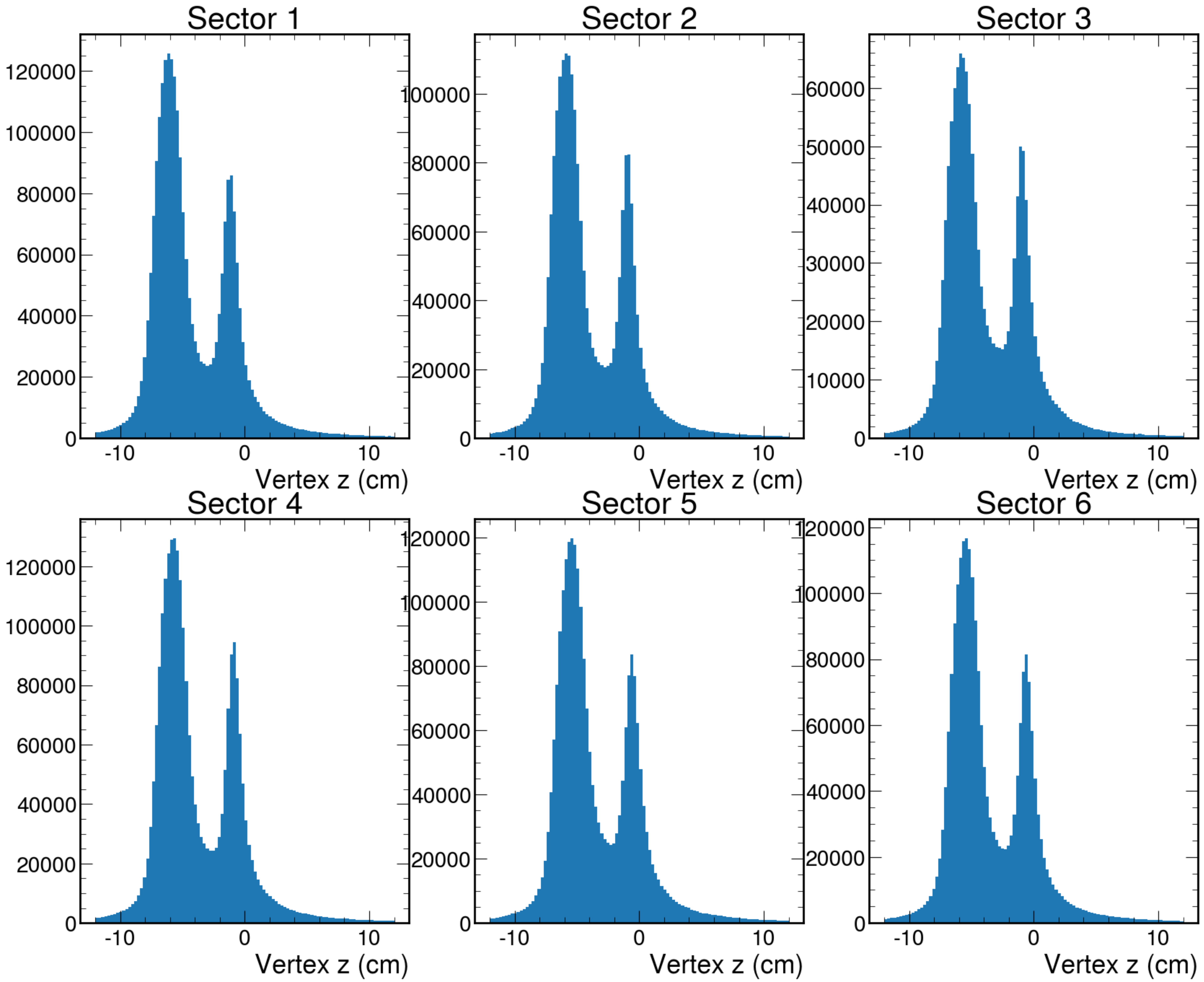
Target	thickness (cm)	width (cm)	lenght (cm)	V (cm3)	weight (min) (g)	weight (max)	Density (min)	Density (max)
Carbon	0.151	0.524	0.524	0.04146098	0.07	0.071	1.688	1.712
Aluminium*	0.121	0.525	0.525	0.03335063	0.086	0.088	2.579	2.639
Copper*	0.0335	0.524	0.525	0.00921585	0.076	0.077	8.247	8.355
Tin*	0.0289	0.525	0.525	0.00796556	0.056	0.058	7.030	7.281
Lead*	0.0143	0.525	0.525	0.00394144	0.041	0.043	10.402	10.910

Luminosities from calculations for 50 nA:
Lead: 2.99E34
Carbon: 4.64
Deuterium: 6.11E34

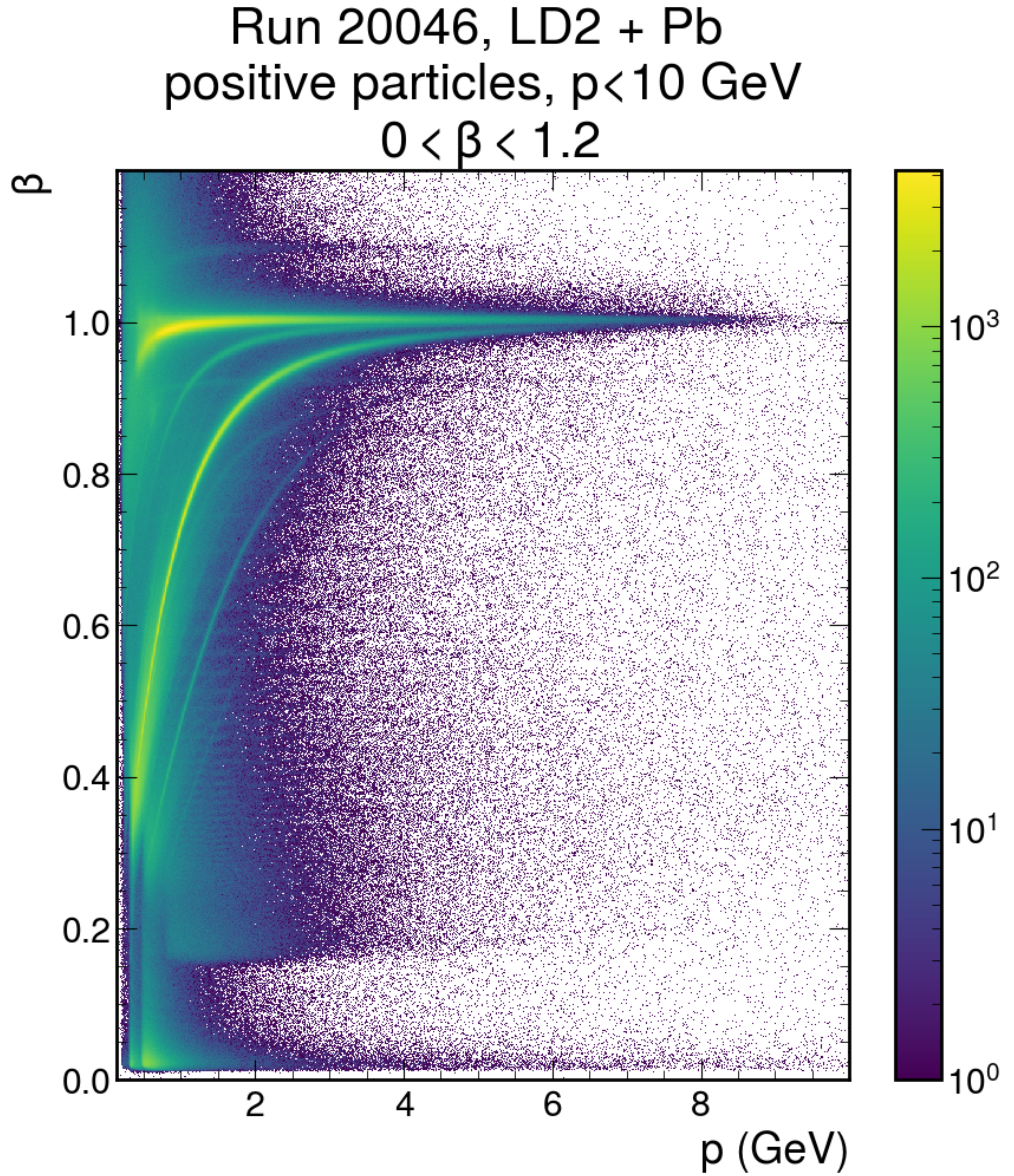
Ratios from the calculations:
Deuterium/Lead: 2.05
Deuterium/Carbon: 1.32

Ratios from RG-E experimental data (50 nA):
Deuterium/Lead: 2.17
Deuterium/Carbon: 1.40

First Preliminary RG-E measurements

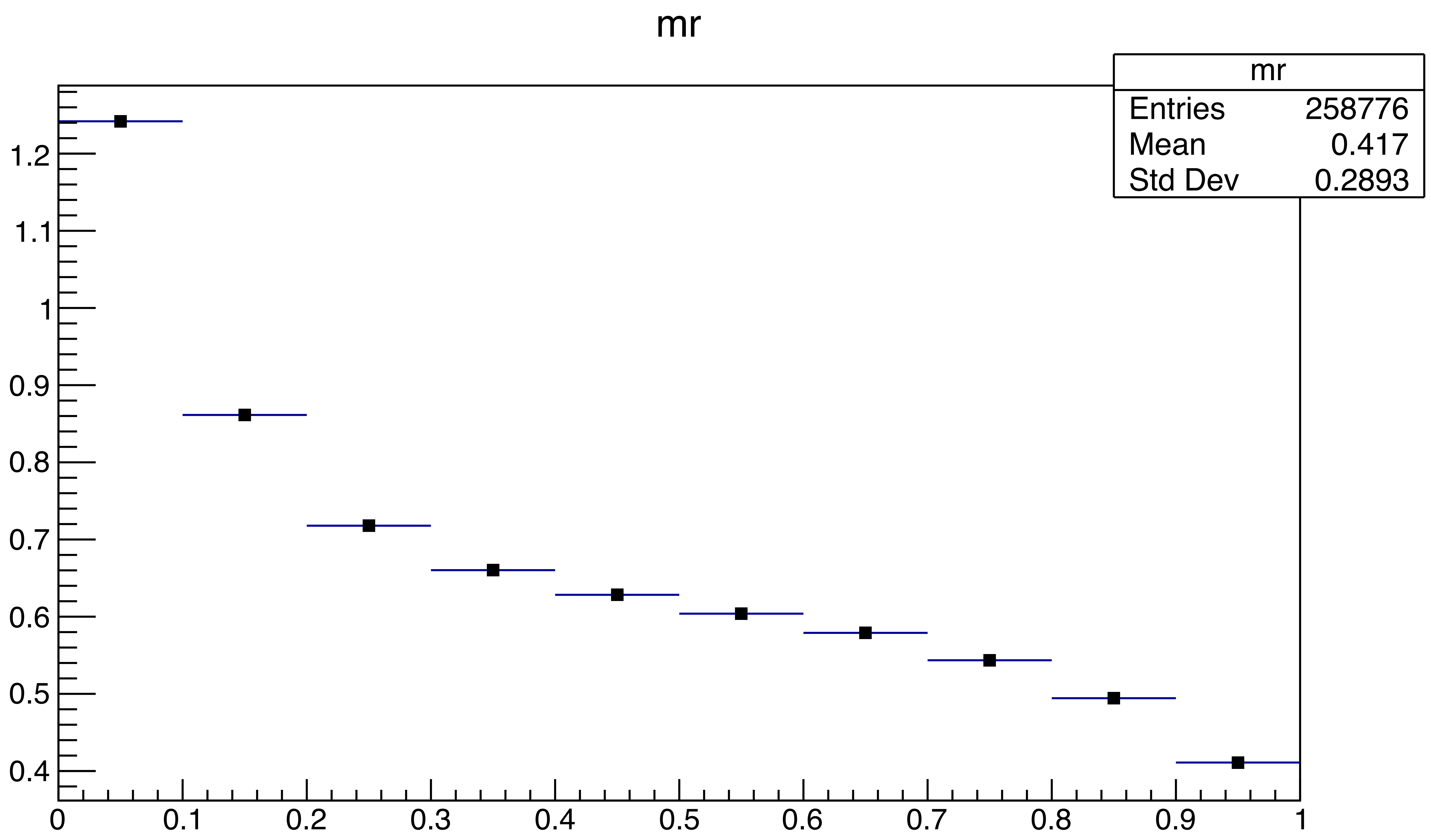


Quick analysis performed by Ryan Milton, Antonio Radic, Milan Ungerer, Sebouh Paul, Sebastian Moran



Quick analysis performed by Ryan Milton, Antonio Radic, Milan Ungerer, Sebouh Paul, Sebastian Moran

First Preliminary RG-E measurements
Multiplicity Ratio vs Z for LD2+Pb with DIS cuts



Quick analysis performed by Ryan Milton, Antonio Radic, Milan Ungerer, Sebouh Paul, Sebastian Moran

Conclusions:

- The CLAS-EG2 experiment, conducted on various types of nuclear targets, has provided a unique opportunity to measure a wide range of nuclear medium variables, such as hadronic multiplicity ratios, transverse momentum broadening, and correlation functions. These measurements offer a valuable opportunity to gain a comprehensive understanding of the hadronization phenomena within the nuclear medium.

- A new CLAS12-RGE experiment, scheduled for 2024 and 2025, aims to build upon the previous results by extending the study to a wider kinematic range and increasing the range of hadron species with higher statistical significance.

Remark:

- The program will benefit significantly from the future EIC and also from the potential JLab upgrade to 20 GeV.