SIDIS Production in Nuclei

Dr. Sebouh J. Paul, UC Riverside

1/25/2023

Science at the Luminosity Frontier:
Jefferson Lab at 22 GeV workshop

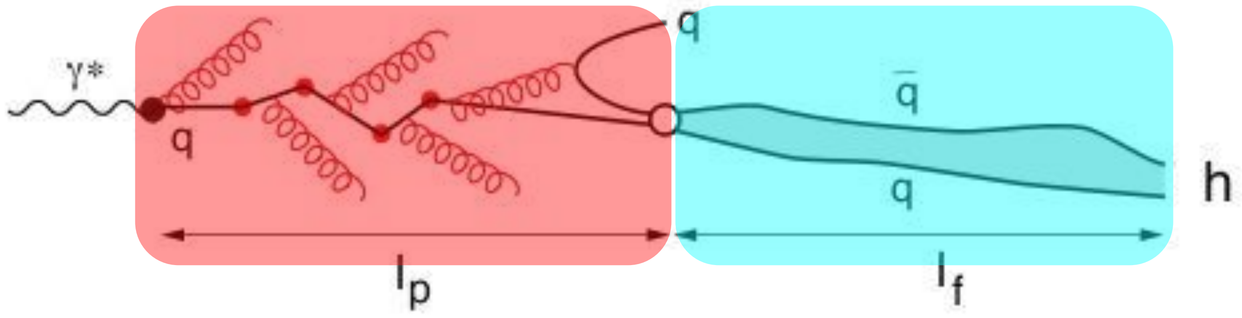
In collaboration with A. El Alaoui, H. Avakian, L. El Fassi

Hadronization Process I

Hadronization is the process responsible for transforming quarks produced from hard scattering reactions into hadrons. Studying hadronization helps us to understand the properties of quark propagation and fragmentation.

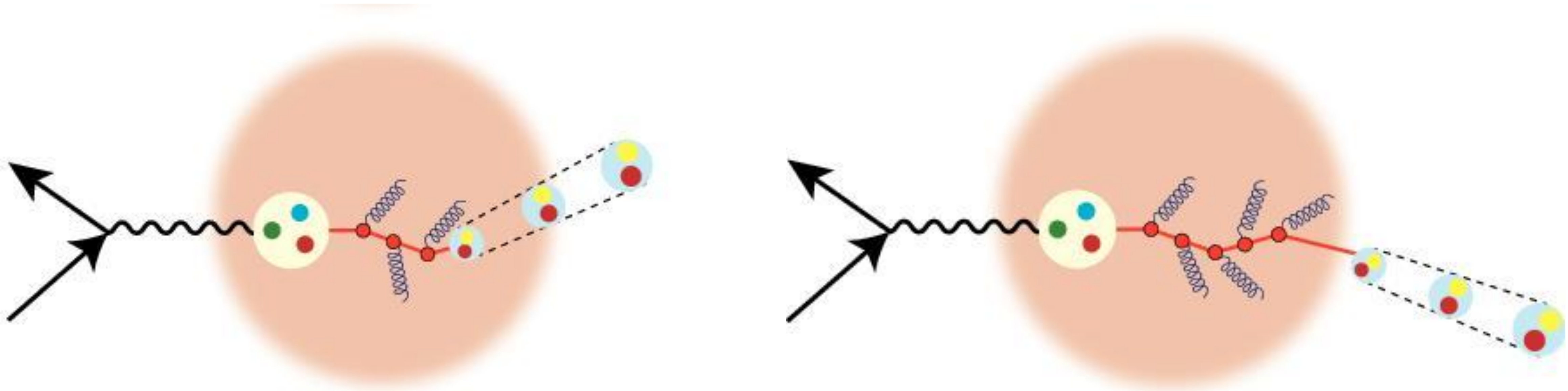
Hadronization in nuclei is characterized by two mechanisms :

- **Quark energy loss** : related to the hadron production length (l_p) and can be accessed experimentally by measuring the transverse momentum of hadrons in various nuclei.
- **Hadron absorption** : related to the hadron formation length (l_f). It can be inferred from the ratio of number of observed hadrons produced in various nuclei.



Hadronization Process II

Depending on nucleus size, hadron formation can take place inside or outside the nucleus.



Provides a test for the existing theoretical models

- Which process dominates? Parton energy loss or Hadron absorption?
- How long does it take to form the colorless object (prehadron) and the color field of a hadron ?
- How are fragmentation functions modified in the presence of nuclear medium?

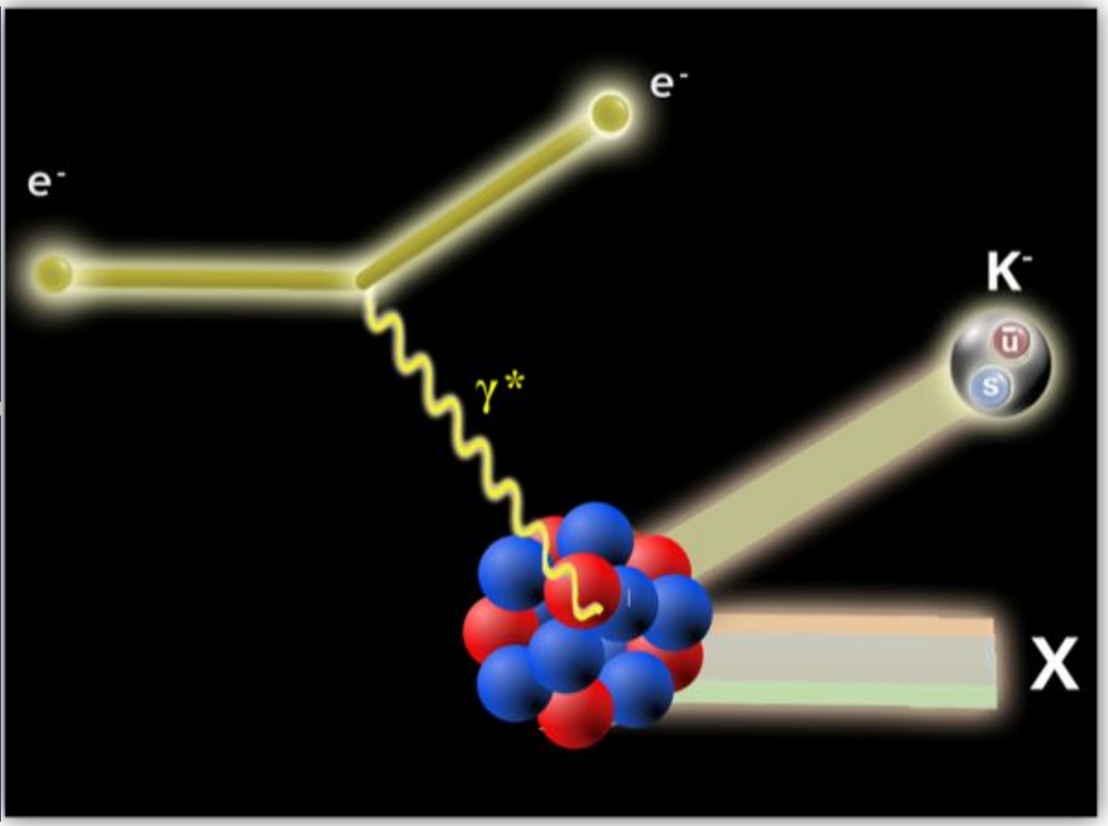
Experimental Observables

Single hadron Multiplicity Ratio:

$$R_A^h(x_B, Q^2, z, p_T^2, \varphi_{\gamma^* h}) = \frac{\left.\frac{N^h(x_B, Q^2, z, p_T^2, \varphi_{\gamma^* h})}{N_{e-}(x_B, Q^2)}\right|_A}{\left.\frac{N^h(x_B, Q^2, z, p_T^2, \varphi_{\gamma^* h})}{N_{e-}(x_B, Q^2)}\right|_D}$$

di-hadron Multiplicity Ratio:

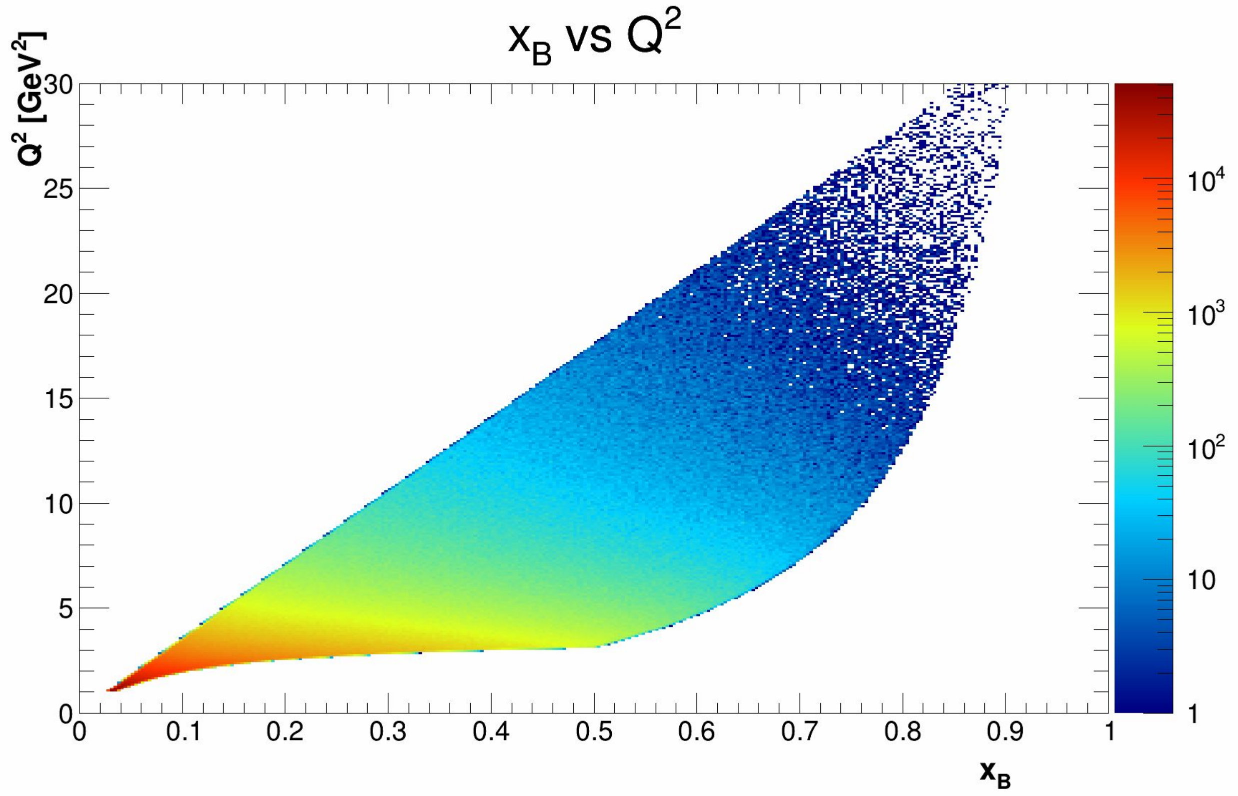
$$R_{2h}(x_B, Q^2, z_2) = \frac{\left.\frac{(dN^{z_1>0.5}(x_B, Q^2, z_2)/dz_2)}{N^{z_1>0.5}}\right|_A}{\left.\frac{(dN^{z_1>0.5}(x_B, Q^2, z_2)/dz_2)}{N^{z_1>0.5}}\right|_D}$$

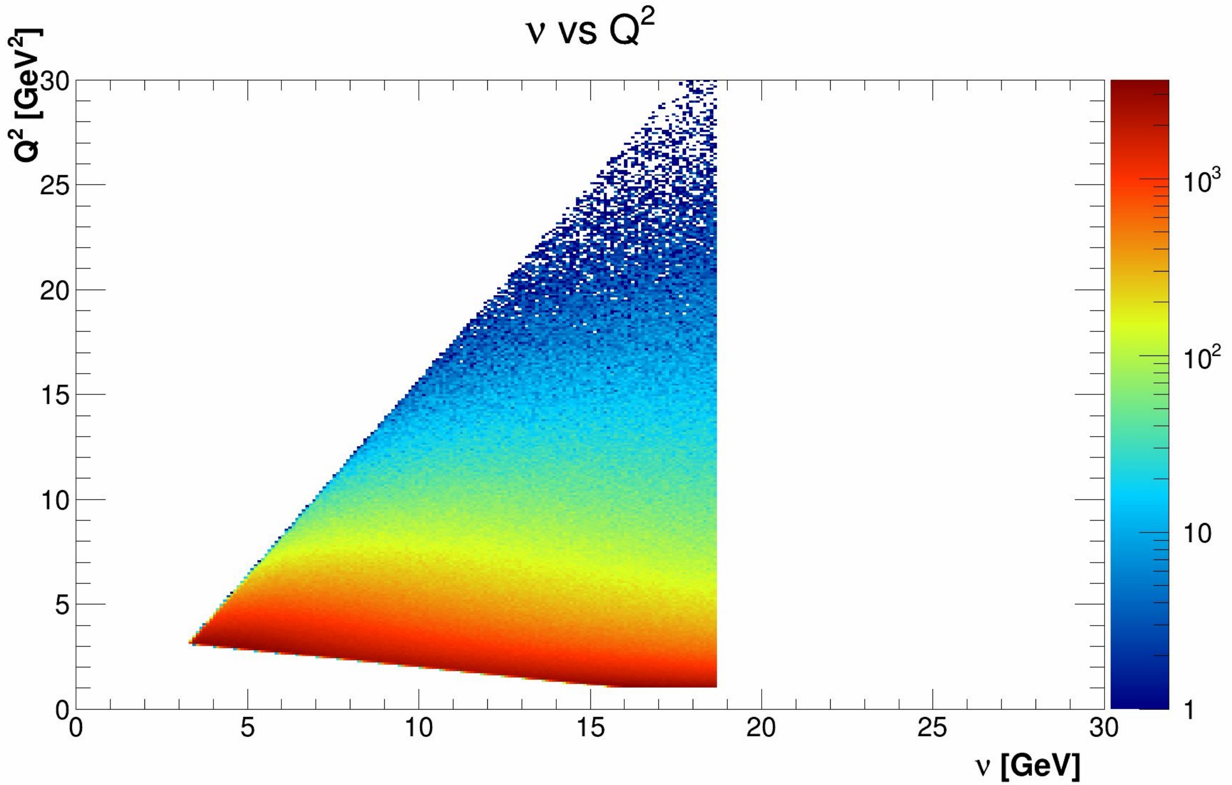


PT-Broadening:

$$\Delta P_T^2(x_B, Q^2, z, \varphi_{\gamma^* h})\Big|_A^h = \left(\langle P_T^2\rangle_A^h - \langle P_T^2\rangle_D^h\right)(x_B, Q^2, z, \varphi_{\gamma^* h})$$

Phase Space





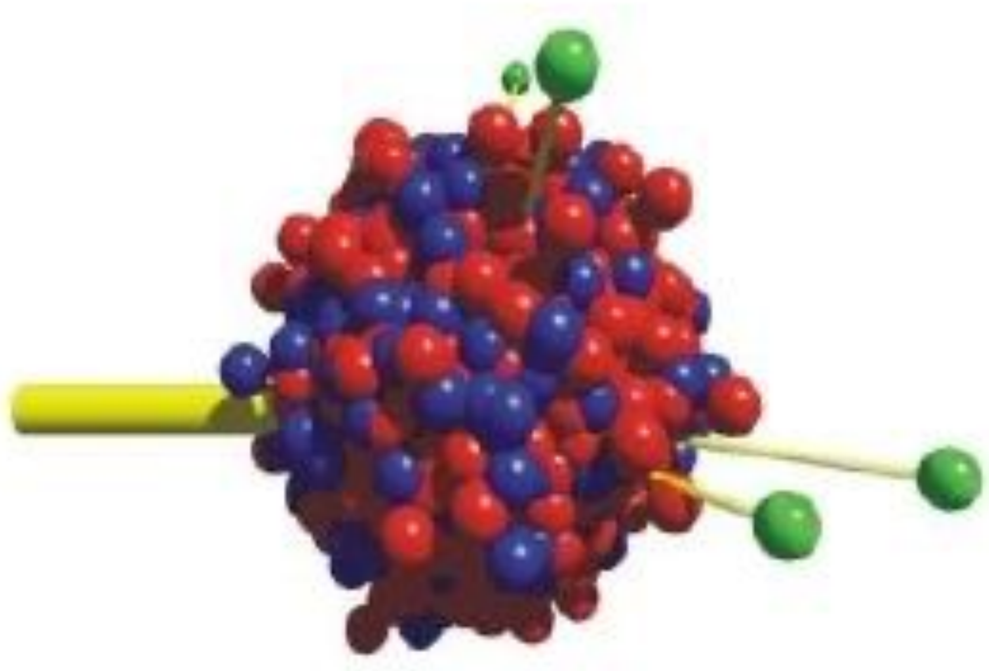
A. El Alaoui, "SIDIS Production in Nuclei", ECT Workshop, Trento Italy, September 29th 2022

GiBUU model for MC:

- Interactions between nuclear medium and hadrons
- Includes pre-hadronic degrees of freedom, Fermi motion, Pauli blocking, and nuclear shadowing

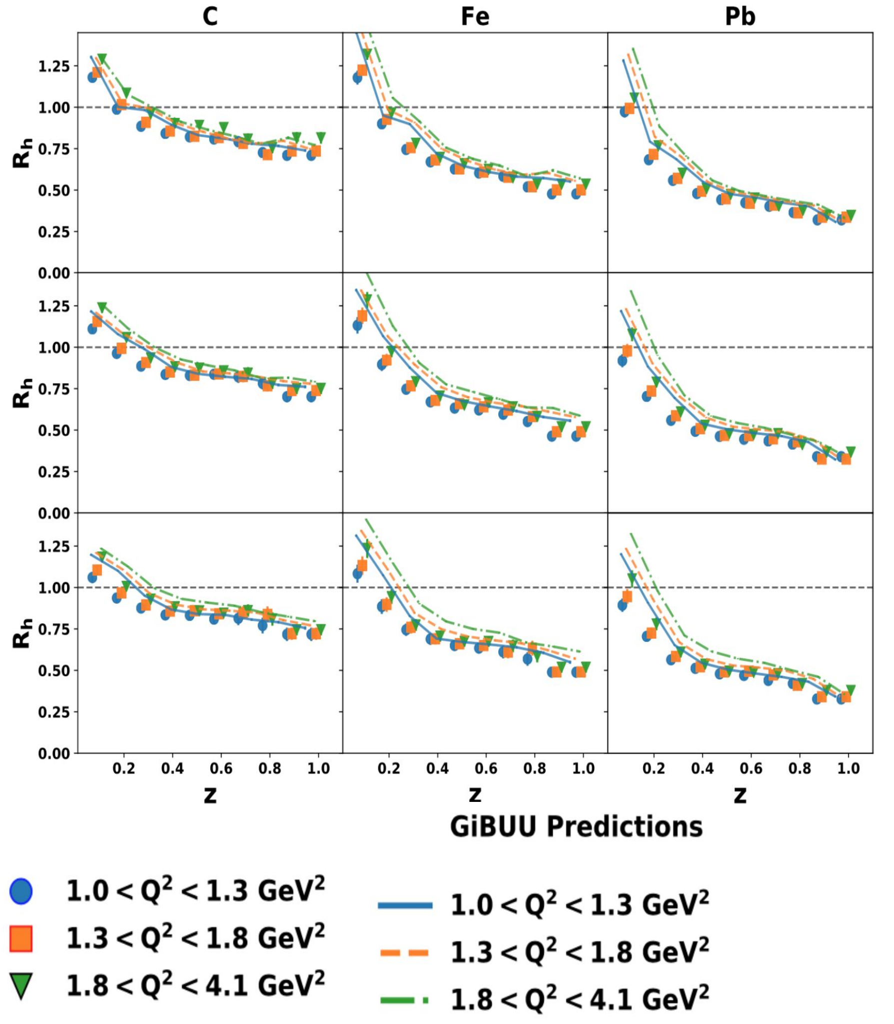
Run conditions:

- ~10M events generated for C and D targets (very small fraction of planned experiment)
- Estimated cross-sections are 260 and 34 μb respectively
- Statistical precision is scaled to reflect 100 PAC days with $L=10^{35}$ $cm^{-2}s^{-1}$ or 1 PAC day at $L=10^{37}$ $cm^{-2}s^{-1}$
  - 6-7 orders of magnitude larger than generated sample

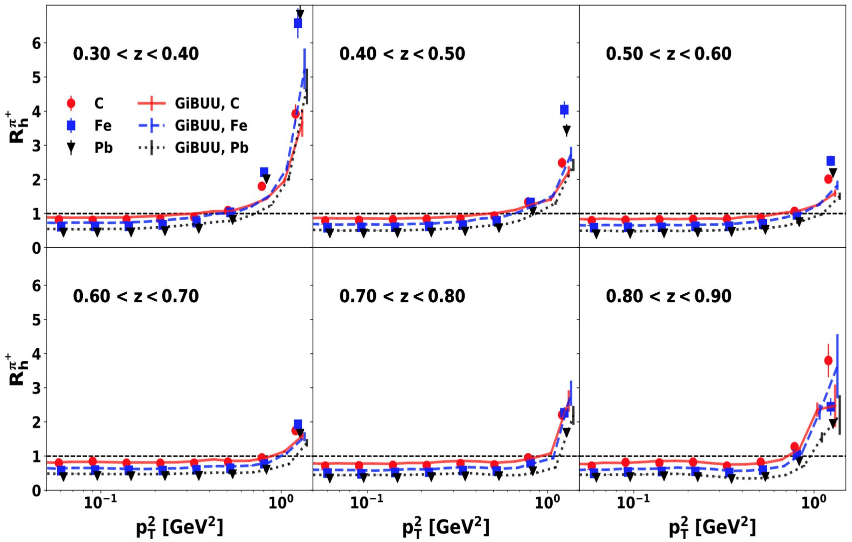


GiBUU

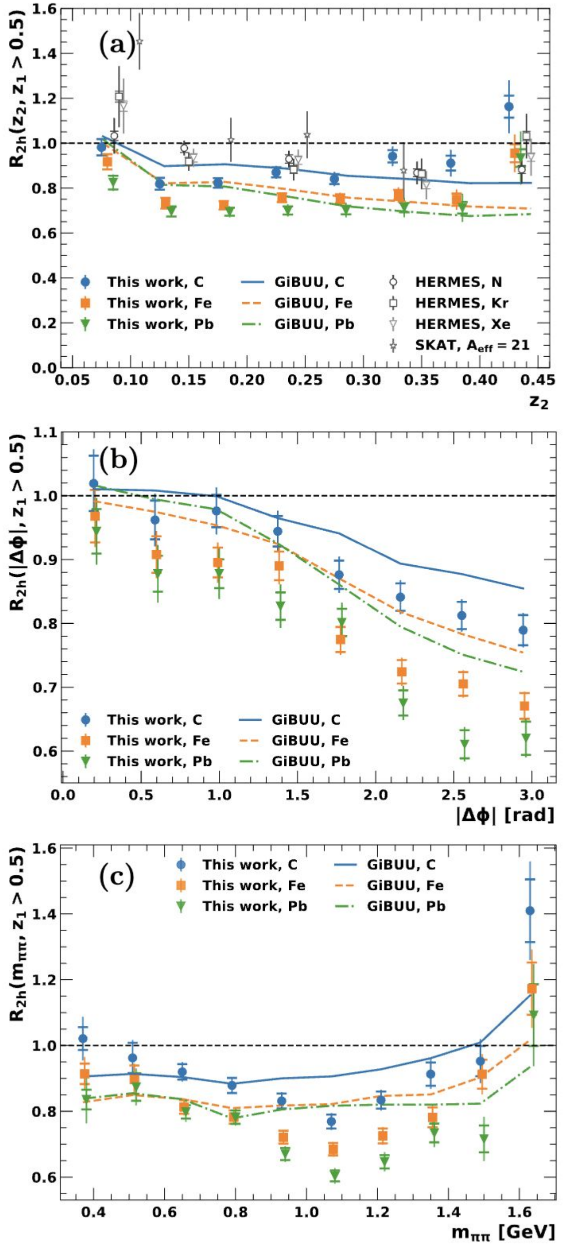
Why the GiBUU model? Compares well with CLAS data (EG2)



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



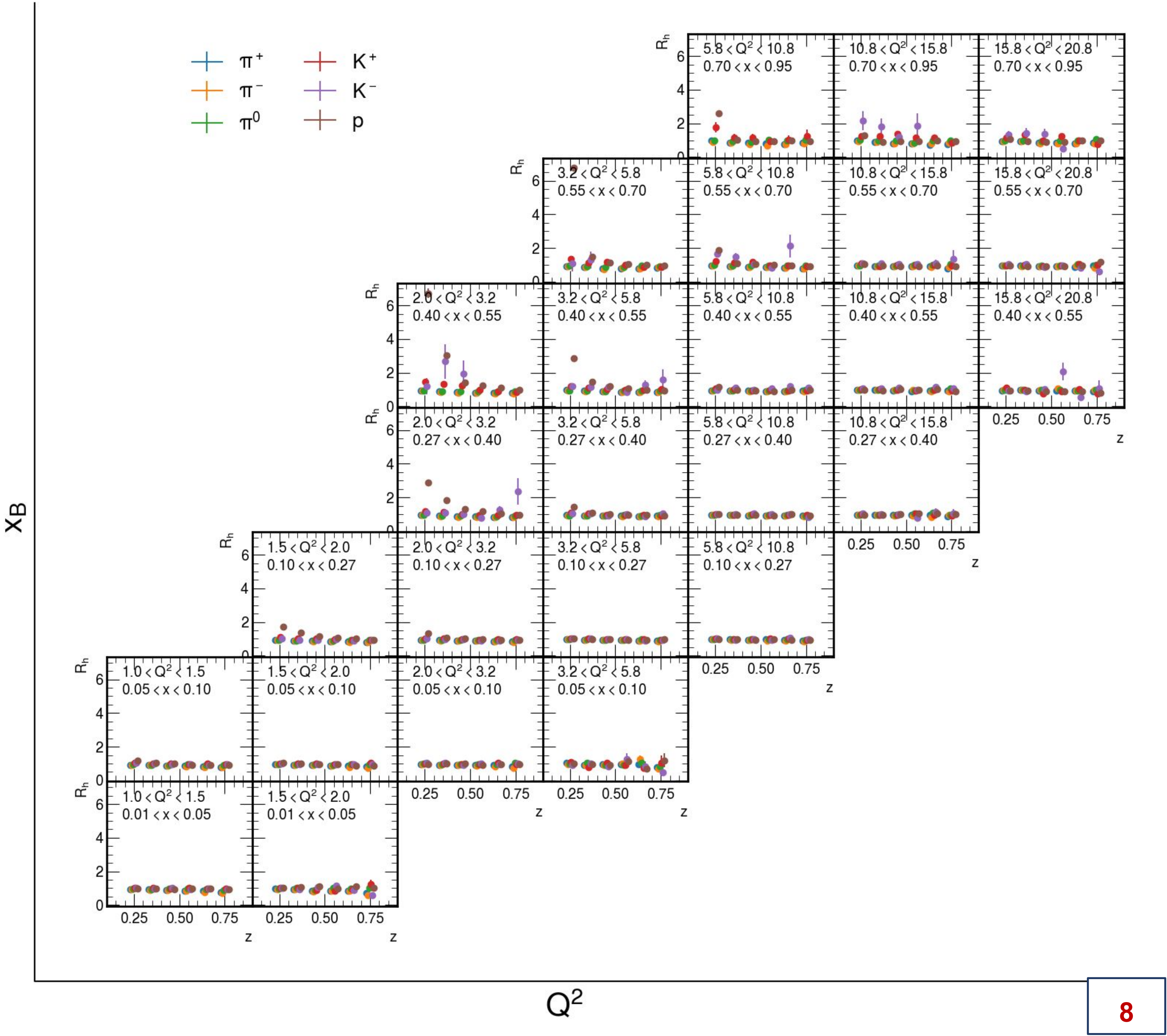
S. Moran et al, (CLAS Collab.)
Phys. Rev. C 105 (2022), 015201



S.J Paul et al (CLAS Collab)
PRL 129 (2022) 182501

Single-hadron multiplicity ratios: Predicted values

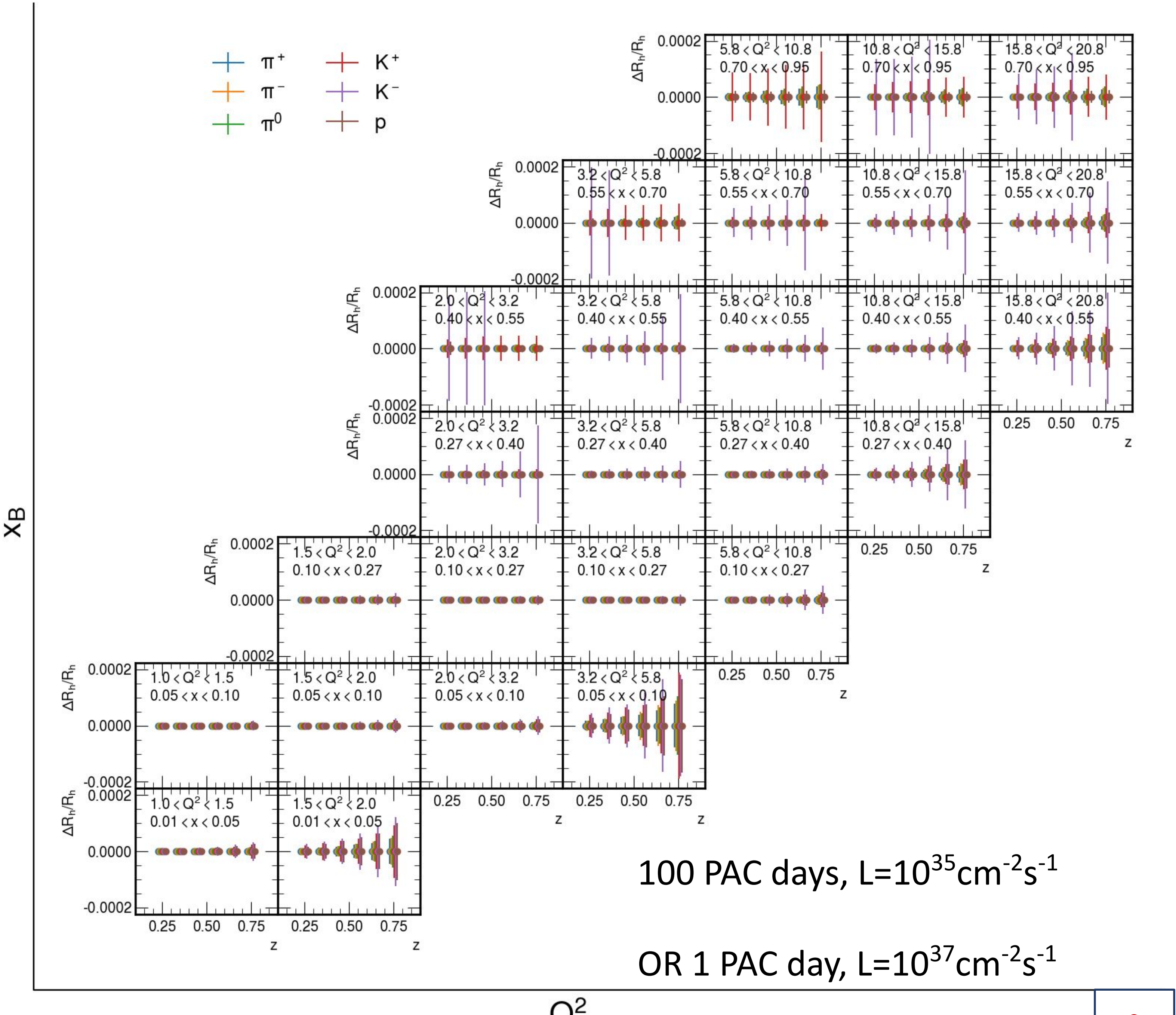
- Values of multiplicity ratios can depend on the
  - species of hadron
  - the kinematic variables
- Previously measured at CLAS (5 GeV) and HERMES:
  - S. Moran et al, (CLAS Collab.) Phys. Rev. C 105 (2022), 015201
  - A Airapetian et al (HERMES Collab.) Eur. Phys. J A47 (2011) 113



Single-hadron multiplicity ratios: Statistical precision

- Predicted relative statistical errors for most bins are $O(10^{-5})$ to $O(10^{-4})$ for pions, kaons and protons
    - Could be somewhat larger than shown here due to acceptance and efficiency, but still same order of magnitude

- Multidimensional binning could include other variables (φ_h, p_T, etc), and still have sub-percent statistical precision

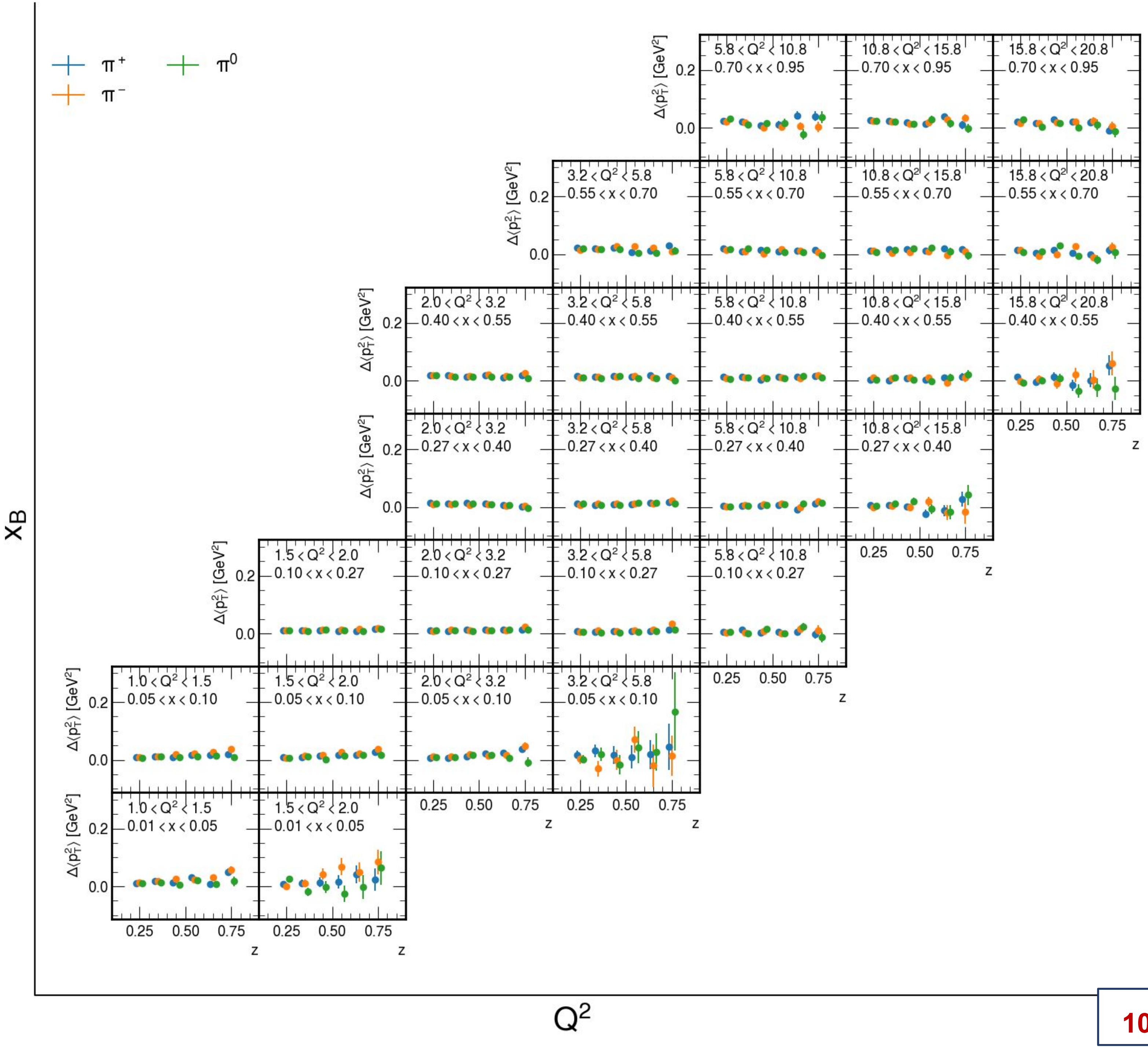


100 PAC days, $L=10^{35}cm^{-2}s^{-1}$

OR 1 PAC day, $L=10^{37}cm^{-2}s^{-1}$

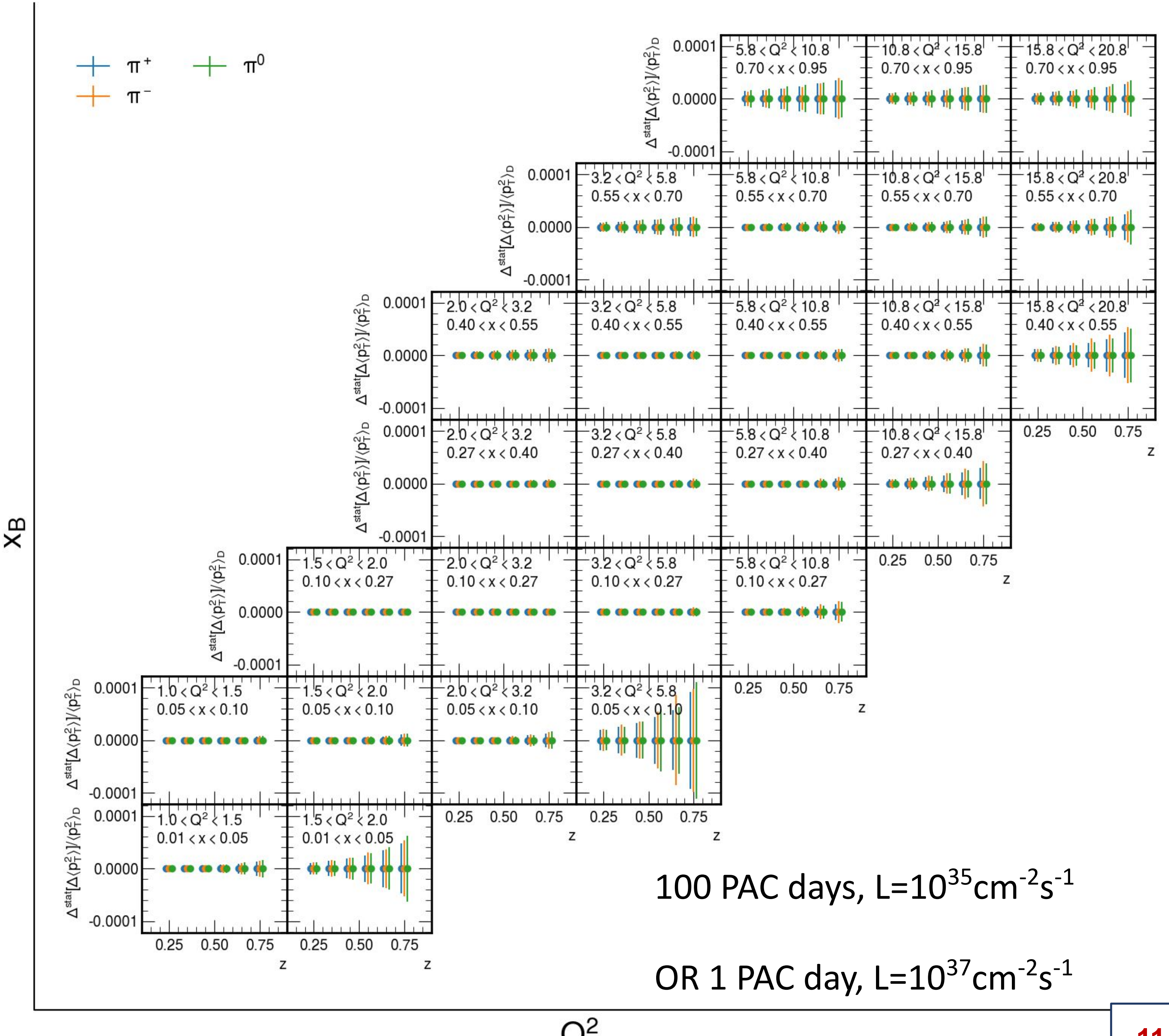
Single-hadron pT broadening: Predicted values

- Previously measured at HERMES
    - A. Airapetian et al (HERMES Collaboration) Phys. Lett. B684 (2010) 114-118



pT broadening:
Statistical precision

- Predicted statistical errors at are at the level of O(10^{-5}) to O(10^{-4}) times $\langle p_T^2 \rangle$.
- Multidimensional binning could include φ_h as an additional variable and still have sub-percent statistical precision

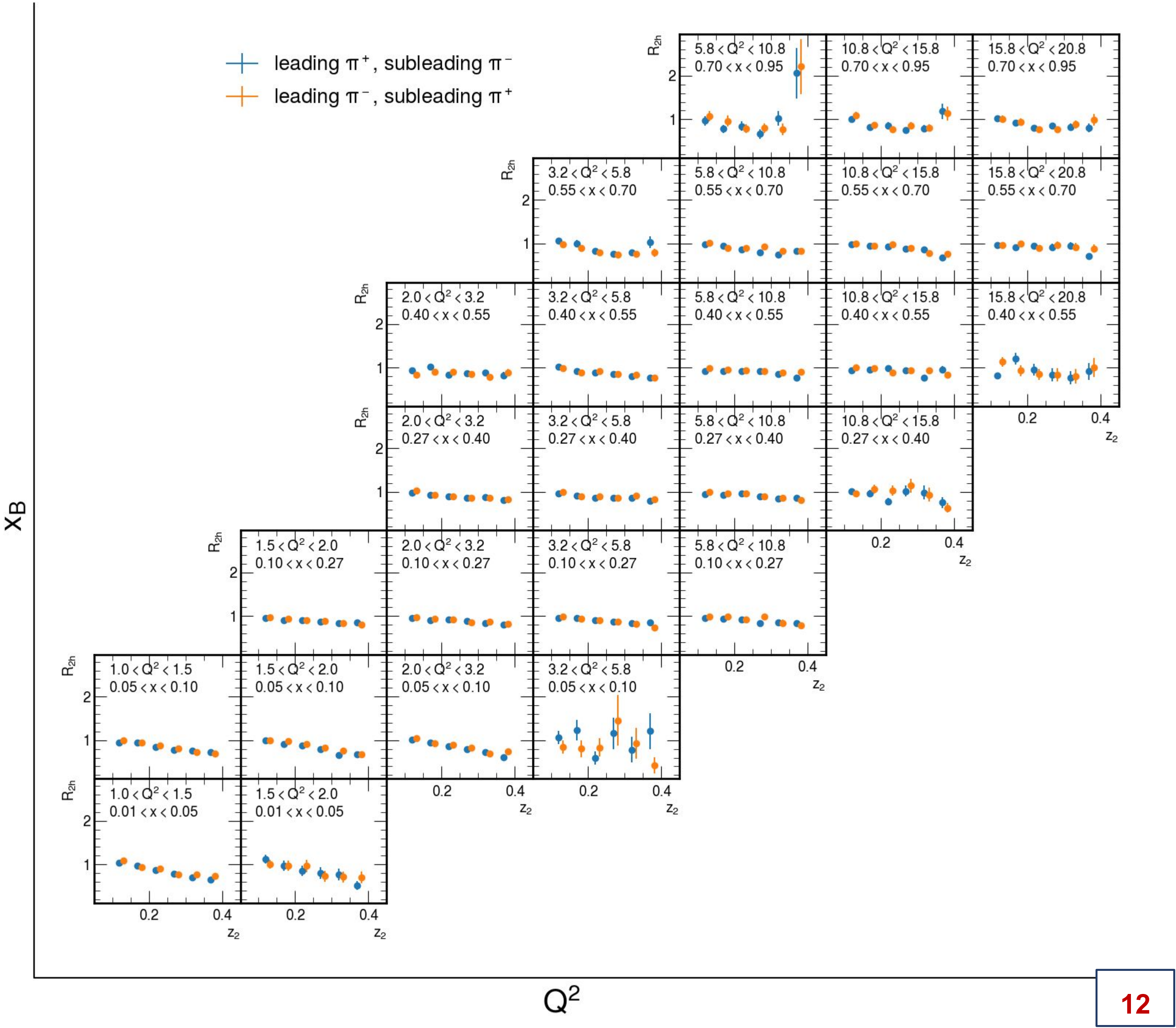


100 PAC days, L=10^{35}cm^{-2}s^{-1}

OR 1 PAC day, L=10^{37}cm^{-2}s^{-1}

Di-hadron multiplicity ratios: Predicted values

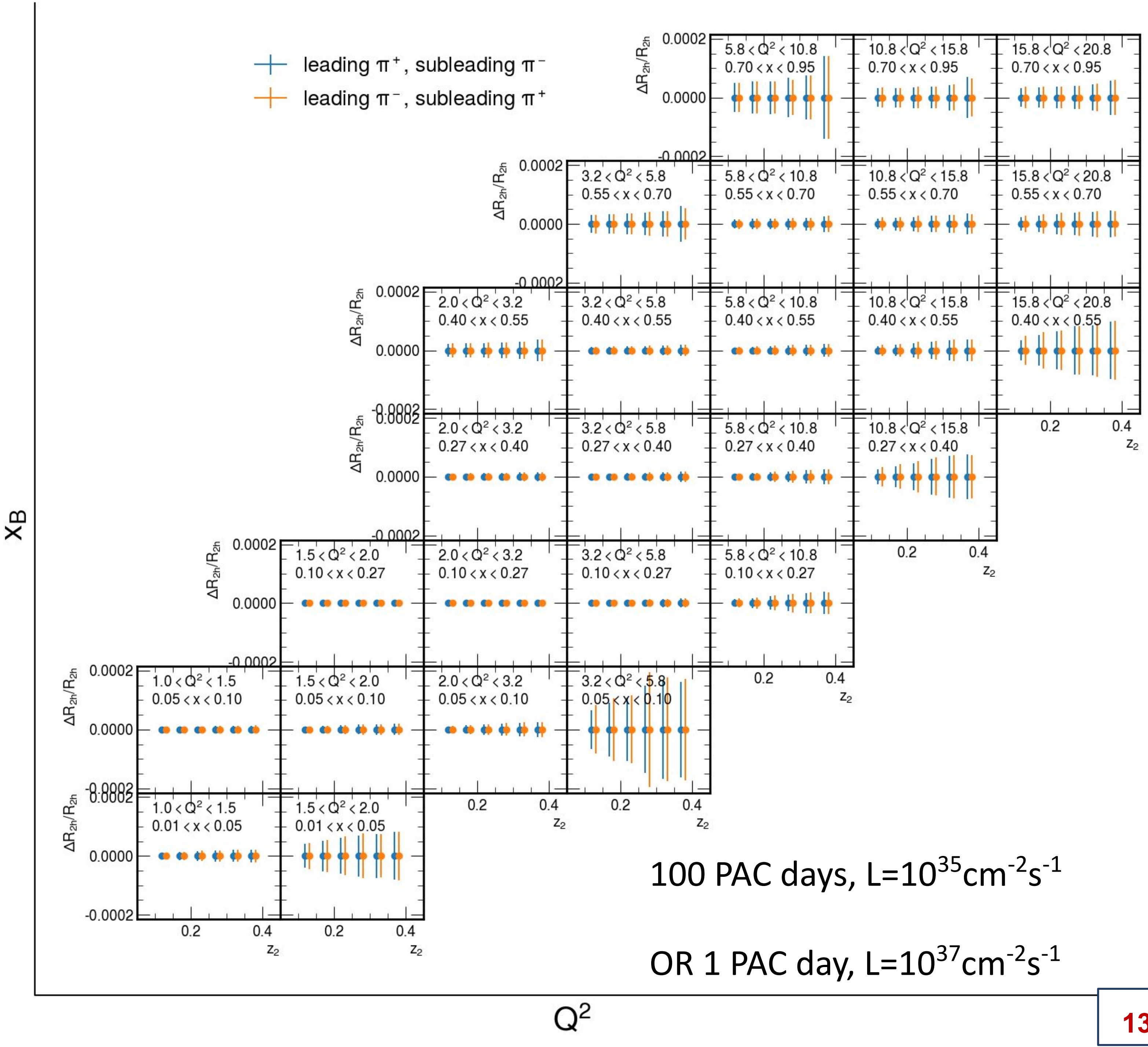
- Close to 1 at low z, drops off at higher z.
- Little variation predicted with respect to Q^2 and x_B
- Other combinations of hadrons can be measured besides $\pi^+\pi^-$
- Previous measurements at CLAS (5 GeV) and HERMES:
  - S.J. Paul et al (CLAS Collab) PRL 129 (2022) 182501
  - A. Airapetian et al. (HERMES Collab.), Phys. Rev. Lett. 96, 162301 (2006).



Di-hadron multiplicity ratios: Statistical precision

- Predicted statistical errors for all bins are less than 0.02% for all bins; most are O(0.001%)

- Multidimensional binning could include other variables (pair mass, Δφ, etc)



100 PAC days, L=10^{35}cm^{-2}s^{-1}

OR 1 PAC day, L=10^{37}cm^{-2}s^{-1}

Other Hadron types

- Rates of production for fast-decaying hadrons were estimated using Pythia+RADGEN*
- Even for less-common hadron production such as φ, we can expect at least O(10^{11}) of them.

Count Rates @ 22 GeV (per 3M SIDIS Events)

Particle	Decay mode/detection mode	Rates
π^+	direct	1,978,446
π^-	direct	1,283,912
K^+	direct	254754
K^-	direct	111,496
p	direct	1,666,891
π^0	2γ (98.82%)	2,696,633
K_s^0	$\pi^0\pi^0(30.7\%),\ \pi^+\pi^-(69.2\%)$	209,971
η	$2\gamma(39.41\%), 3\pi^0(32.7\%)$ $\pi^+\pi^-\pi^0(22.9\%), \pi^+\pi^-\gamma(4.22\%)$	145,739
ρ^0	$\pi^+\pi^-(\sim 100\%)$	671,091
ω	$\pi^+\pi^-\pi^0(89.3\%), \pi^0\gamma(8.4\%)$	851,882
Λ	$p\pi^-(63.9\%)$	35,198
ϕ	K^+K^- (49.2%)	15,606

A. El Alaoui, “SIDIS Production in Nuclei”, ECT Workshop, Trento Italy, September 29th 2022

Summary

- JLab @ 22 GeV will offer an opportunity to study hadronization processes with greater detail.

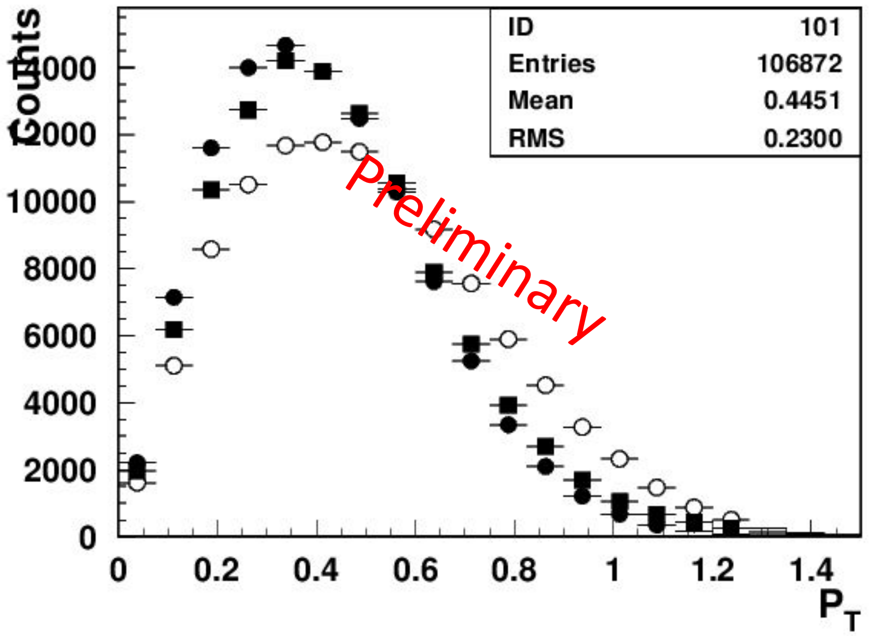
- The high luminosity and beam energy will allow for multidimensional analyses involving many hadron species and multiple observables including

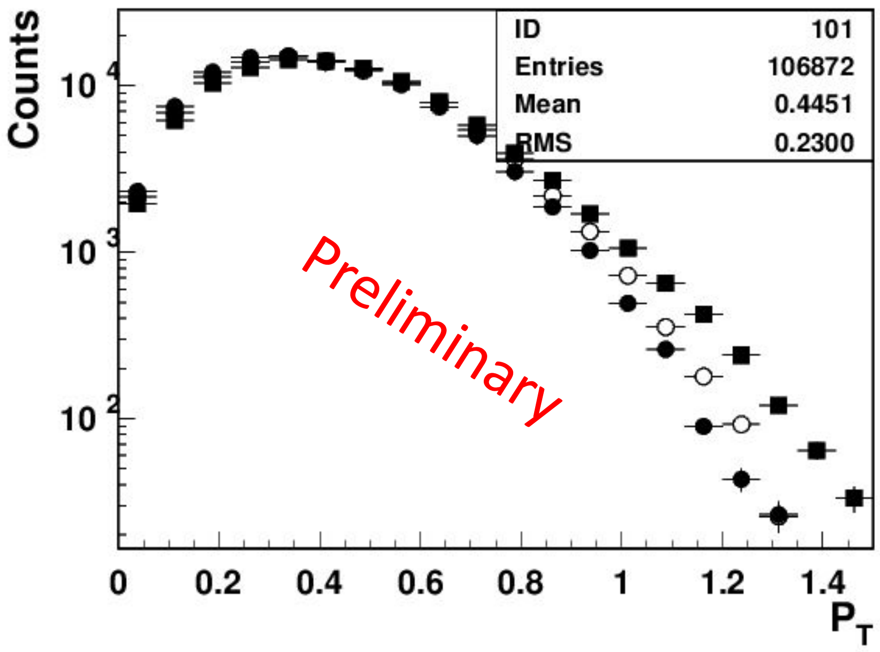
  - Single-hadron multiplicity ratios
  - pT broadening
  - Di-hadron multiplicity ratios (R_{2h})

- The data will provide a way to test several theoretical models and calculations.

Backup slides

P_T Distribution RGC Data vs Pythia*



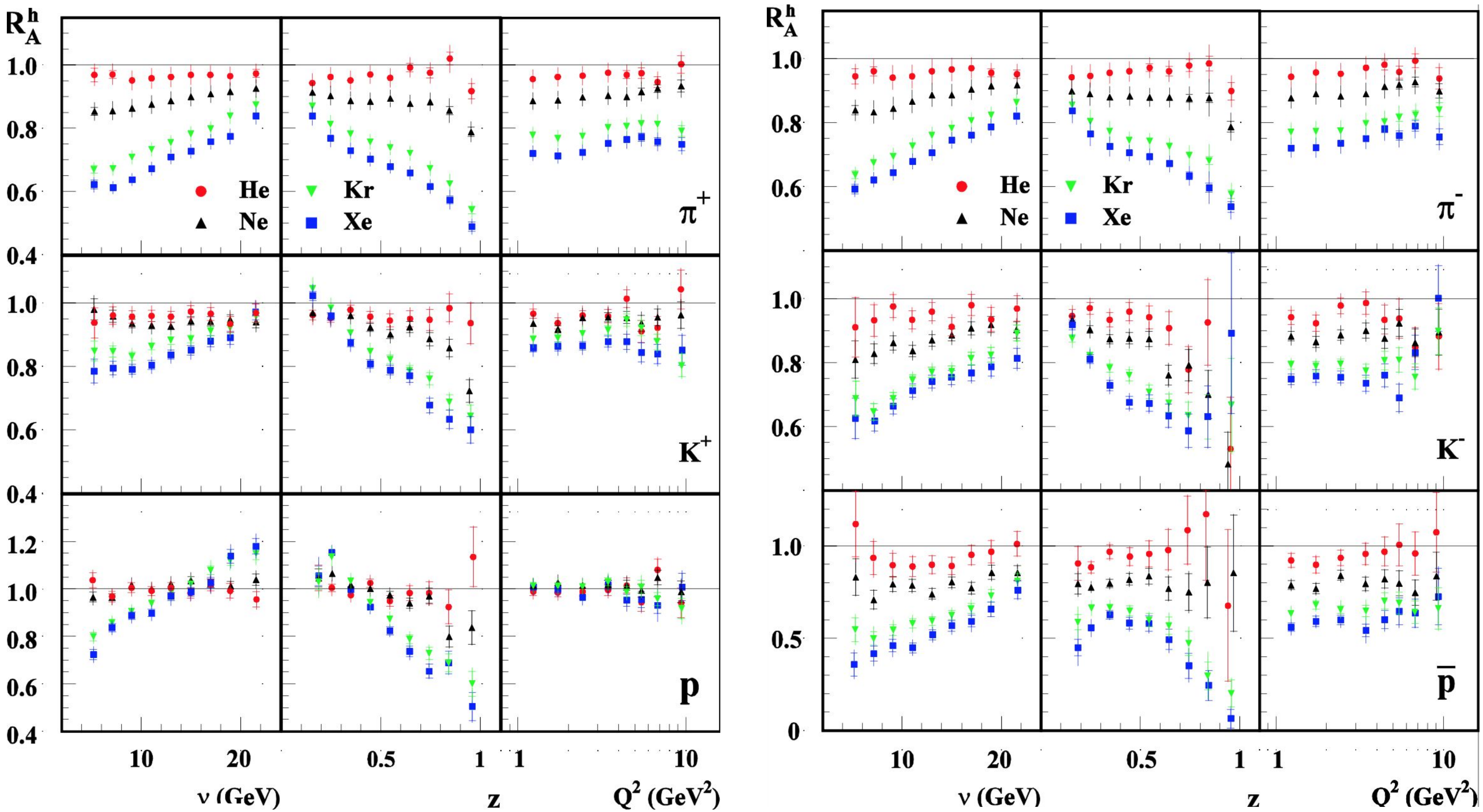


Full square RGC data
Open circle pythia (Tune 1)
Full circle pythia (Tune 4)

Full square RGC data
Full circle pythia (Tune 4)
Open circle pythia (Tune 5)

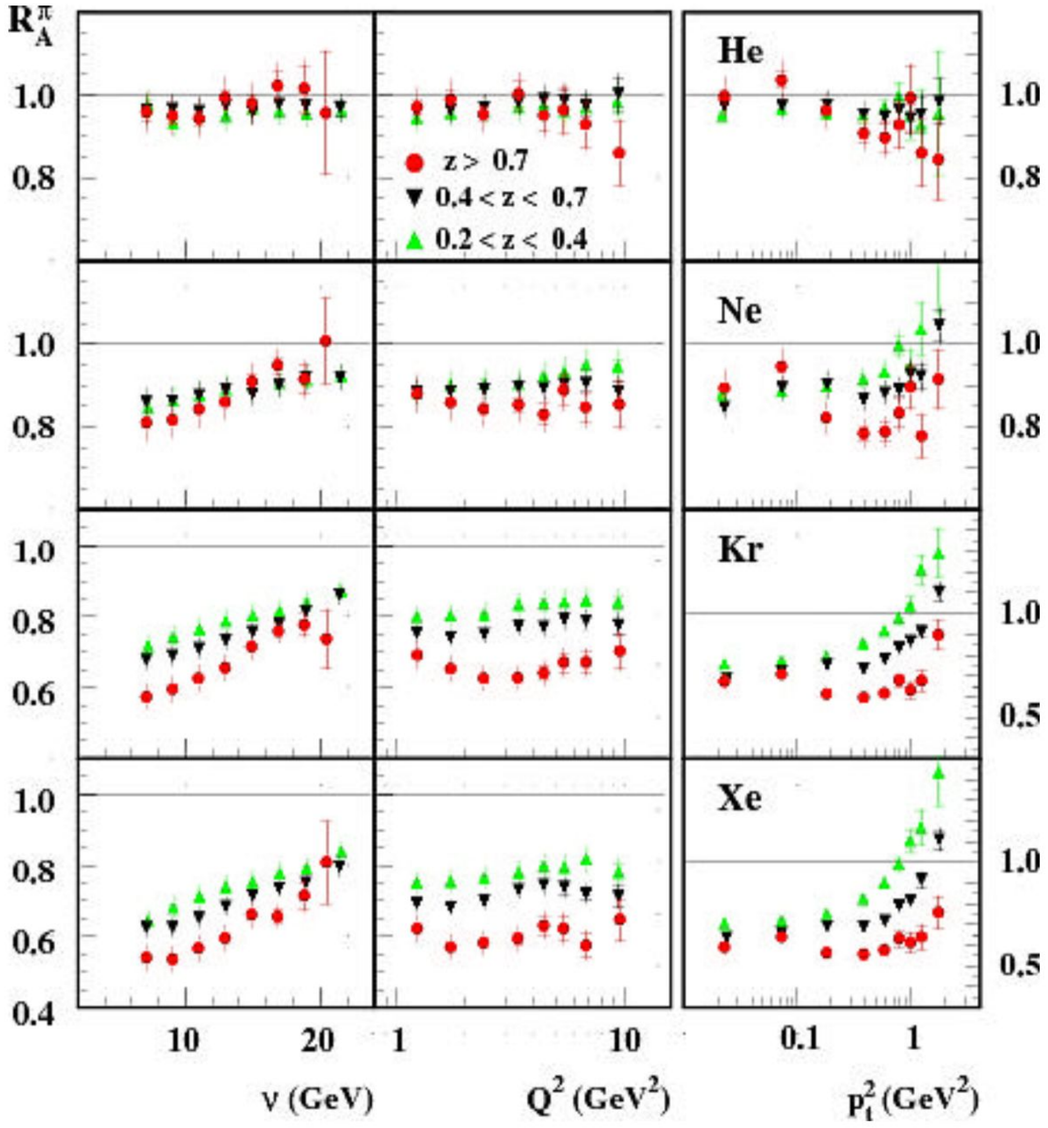
A. El Alaoui, "SIDIS Production in Nuclei", ECT Workshop, Trento Italy, September 29th 2022

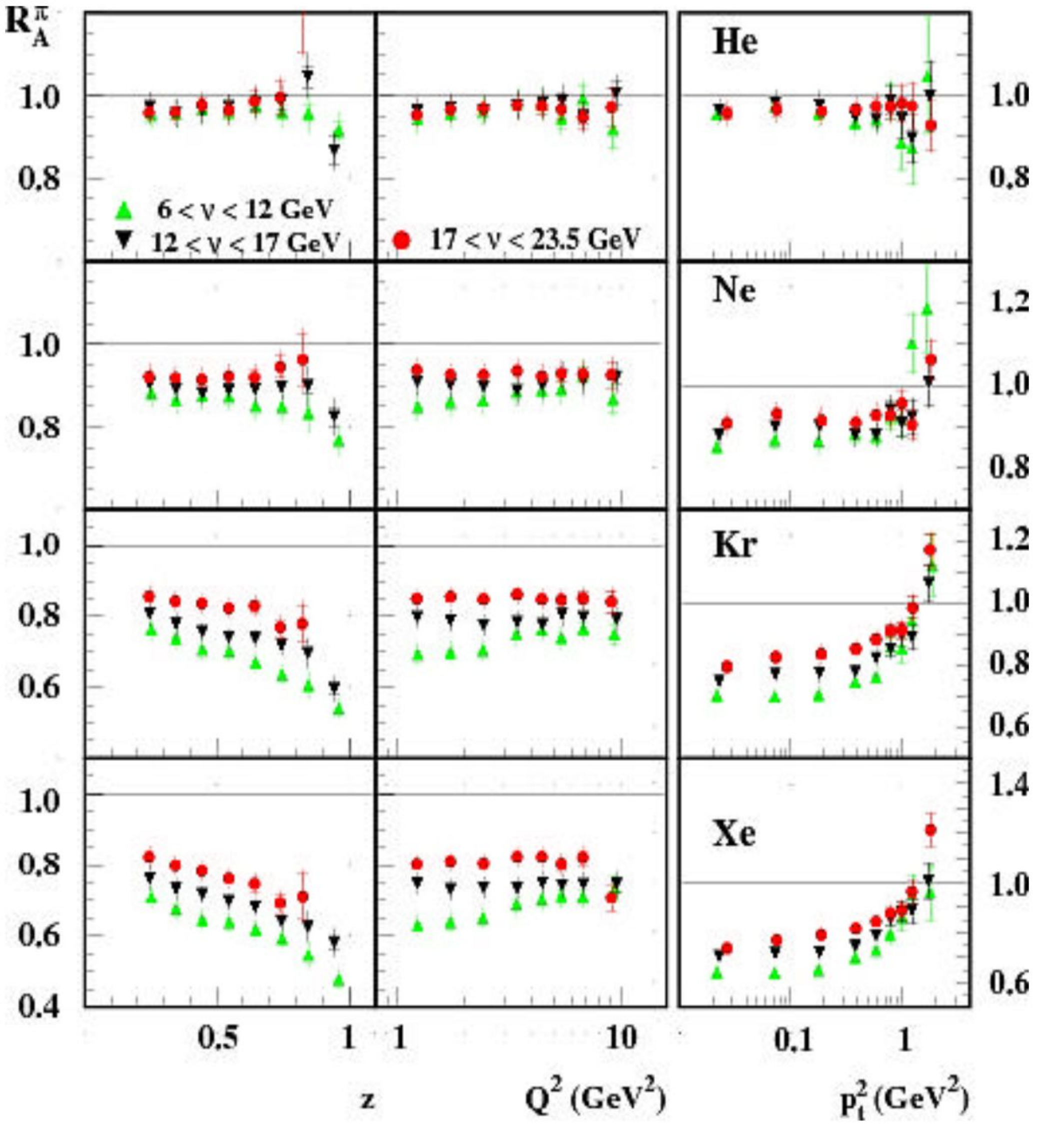
Multiplicity Ratio (HERMES)



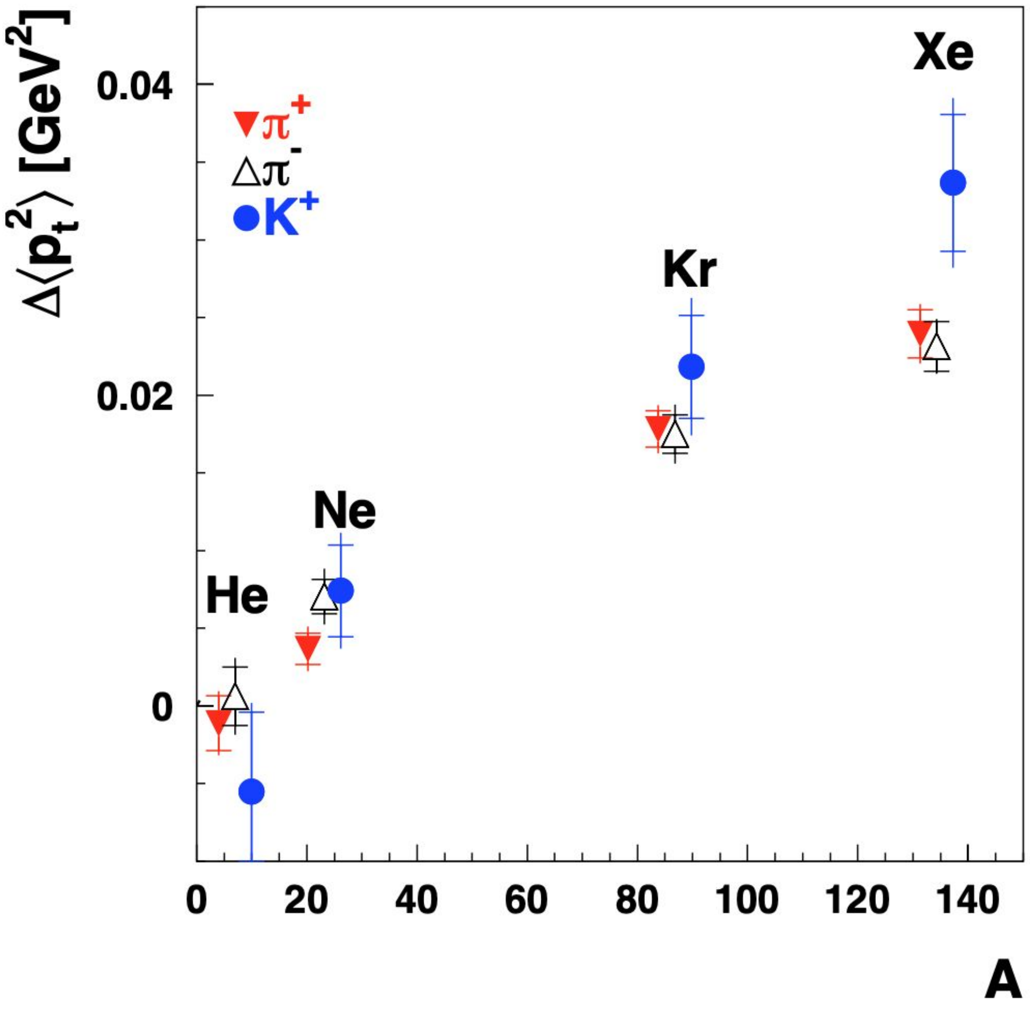
UC RIVERSIDE UNIVERSITY OF CALIFORNIA

2D MR Pions (HERMES)



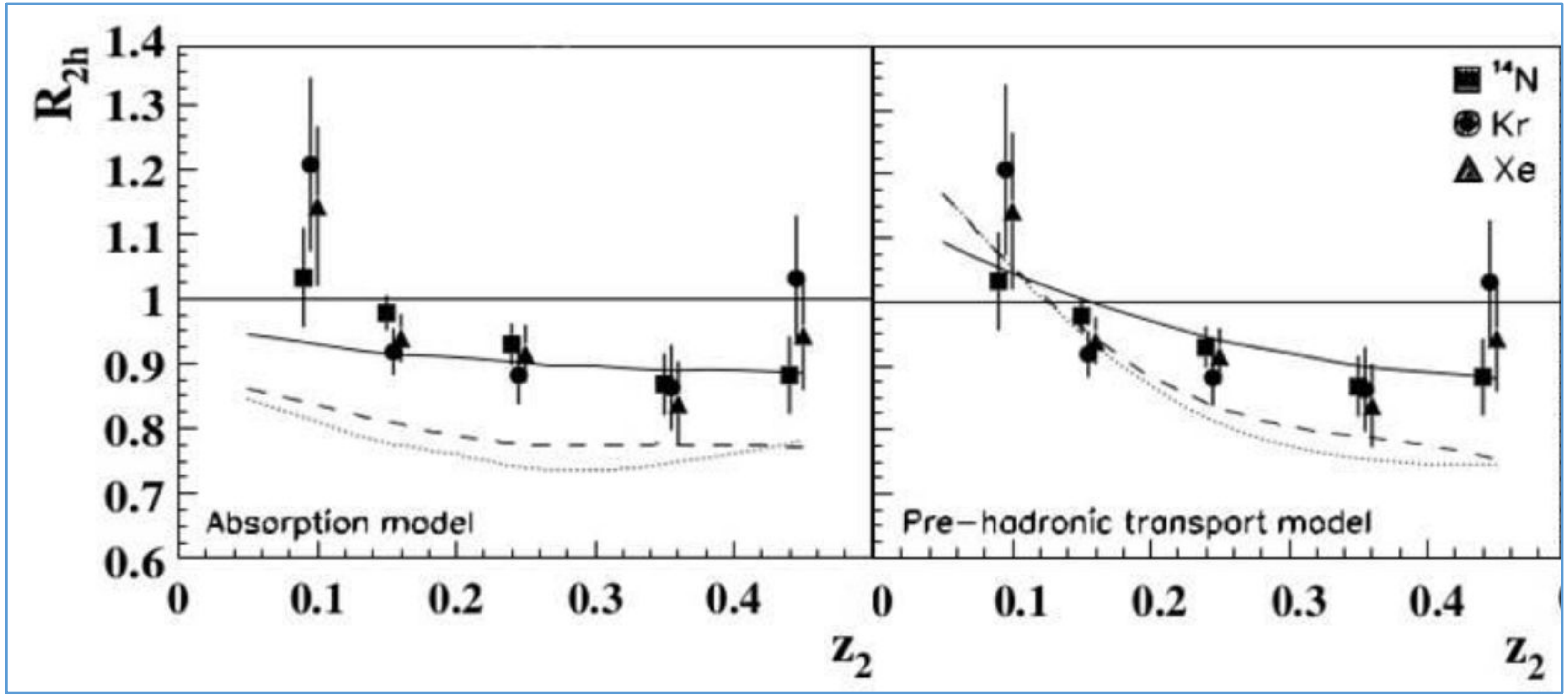


P_T-Broadening (HERMES)



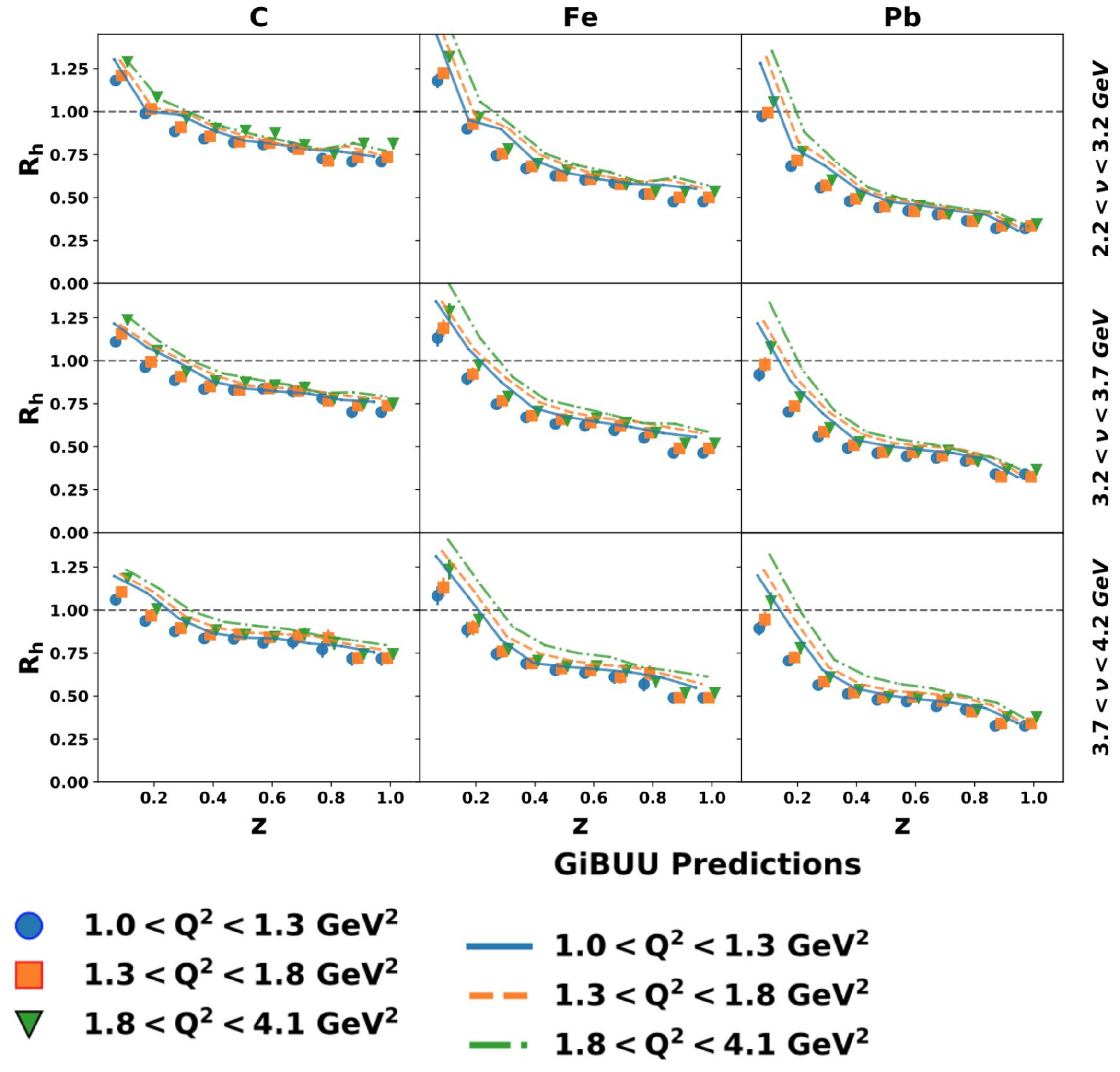
- Broadening increases with mass number A
- Similar effect for pions
- Broadening seems to be slightly different for K^+.

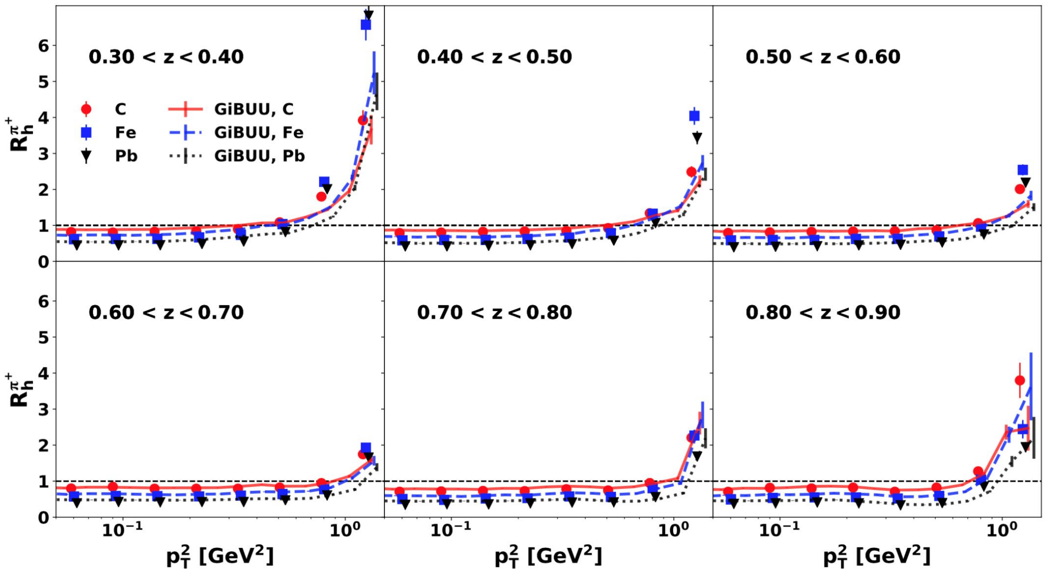
Di-hadron (HERMES)



- Di-hadron electroproduction offers an additional way to study hadronization.
- If partonic energy loss is the only mechanism involved, then, the absorption should not depend on the number of produced hadrons.
- Di-hadron to single hadron ratio vary slightly with A.

CLAS Results (EG2 experiment)





Results involving more hadron species, π^0, Λ, proton, di-hadrons to be pulished in the near future

Pythia Tune*

Parameter	Default	Tune 1	Tune 2	Tune 3	Tune 4	Tune 5
$q\bar{q}_{supp}$	0.10	0.10	0.02	0.03	0.025	0.029
q^s_{supp}	0.30	0.16	0.20	0.20625	0.120	0.283
$q^s q^s_{supp}$	0.40	0.40	0.40	0.25	0.25	0.40
$BM\bar{B}/B\bar{B}$	0.50	0.50	0.50	0.0	0.0	0.50
$s\bar{s}/BM\bar{B}$	0.50	0.50	0.50	0.0	0.0	0.50
$M_s/BM\bar{B}$	0.50	0.50	0.50	0.0	0.0	0.50
VM_{supp}	0.50	0.50	0.20	0.25	0.25	0.50
VM^s_{supp}	0.60	0.60	0.60	0.30	0.30	0.60
σ	0.36	0.33	0.37	0.382	0.382	0.381
f	0.01	0.01	0.03	0.03	0.03	0.01
P_T^f	2.00	2.00	2.50	2.50	2.50	2.00
E_0	0.80	0.80	0.80	0.20	0.20	0.80
a	0.30	0.89	1.74	1.1266	1.13	1.940
b	0.58	0.24	0.23	0.3672	0.37	0.544
a_{qq}	0.50	0.50	0.50	0.80	0.80	1.05

A. El Alaoui, “SIDIS Production in Nuclei”, ECT Workshop, Trento Italy, September 29th 2022

Some Theoretical Models*

- Quark Energy loss models Gluon radiation induced by multiple soft quark interactions with the medium is considered as the main source of quark energy loss. It can be evaluated from calculations based on pQCD.
- Twist-4 pQCD (X.-N. Wang, E. Wang, X. Guo, J. Osborne): Medium-induced gluon radiation only. Neglects hadron absorption because it assumes that hadron is formed outside the nucleus.
- Rescaling (A. Accardi, H. Pirner, V. Muccifora): Inspired by many deconfinement models originally developed to provide an explanation for the observed EMC effect. Introduce a scaling factor in the nuclear pdfs to account for the fact that the quark confinement scale in a bound nucleon is larger than the one in a free nucleon. Most of these models were extended to study the hadronization in nuclear environment by introducing a similar Q^2 rescaling factor in the medium-modified fragmentation functions.
- Quantitative Models shift in the quark energy (ΔE), introduced by the emission of gluons, results in a rescaling of the hadron energy fraction . In this context, the medium modified FF, is used to calculate the hadron multiplicity ratio. The calculations are used to provide a quantitative global fit to the quark energy loss.
- GIBUU (Gallmeister Boltzmann-Uehling- Uhlenbeck): MC generator that uses PYTHIA/JETSET to simulate the hard scattering and the production of hadrons. Interactions of the prehadron with the surrounding nuclear medium are included according to a semiclassical transport description which allows for elastic and inelastic rescattering through coupled-channel effects. This approach allows for hadron absorption as well as hadron recreation. Nuclear effects such as Fermi motion Pauli blocking and nuclear shadowing are taken into account.
- …

A. El Alaoui, “SIDIS Production in Nuclei”, ECT Workshop, Trento Italy, September 29th 2022