Quark Fragmentation and Hadron Formation in Nuclear Matter

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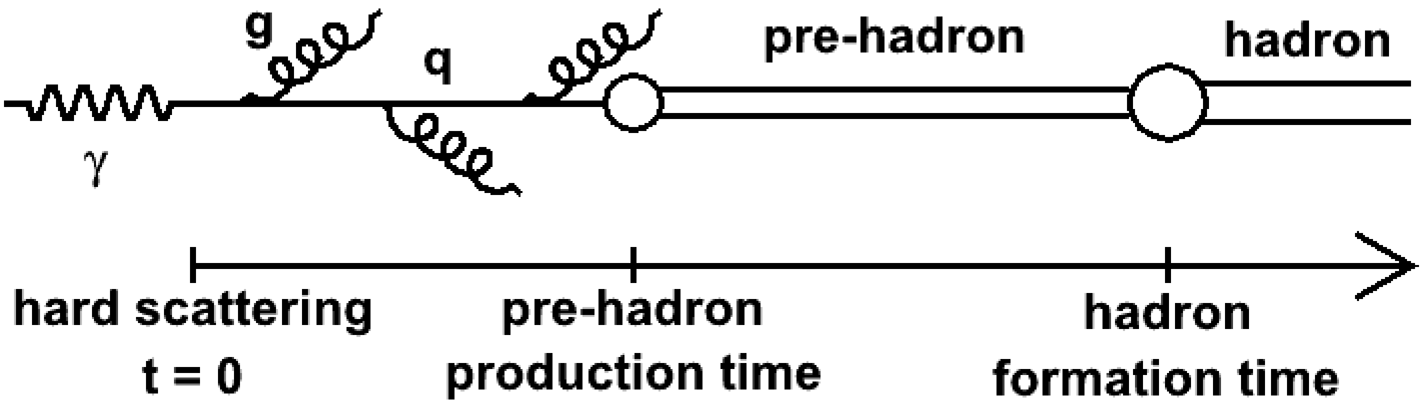
Hadronization

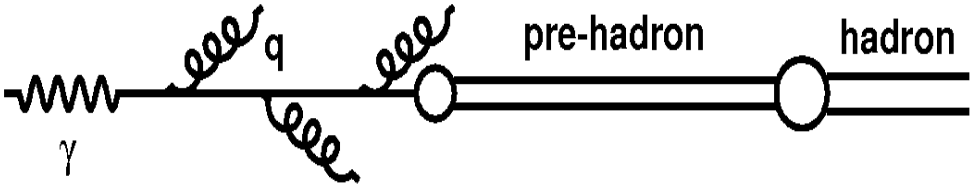


- Non perturbative process

  → cannot be exactly calculated

- Can be characterized by two times
  - Color neutralization at **production time**
  - At **formation time** hadronic properties are definitive

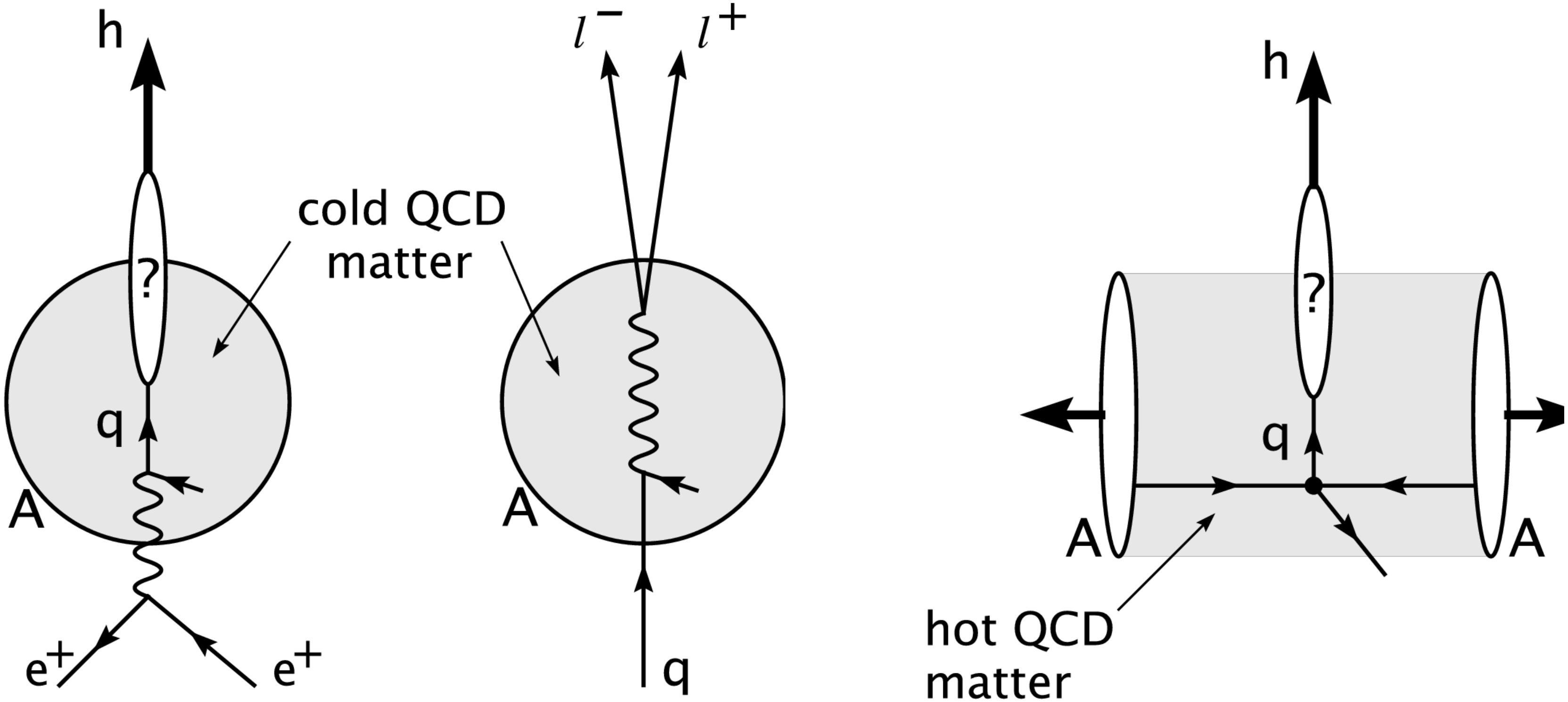
Motivations



- Understanding Hadronization Process
  - Measuring characteristic times
  - Being able to calculate parton energy loss
  - Understand the pre-hadron and the color transparency effects
- Characterization of cold nuclear matter
- Characterization of hot nuclear matter
- Reduce systematic effects in various experiments (such as νA and eA)

Processes Concerned

- Nuclear effects on hadronization important in
  - → Electron scattering
  - → Neutrino scattering
  - → Drell Yan
  - → Heavy Ion Collisions



Deep Inelastic Scattering

- Momentum transfer

$$Q^2 = -q^2$$

- Photon energy

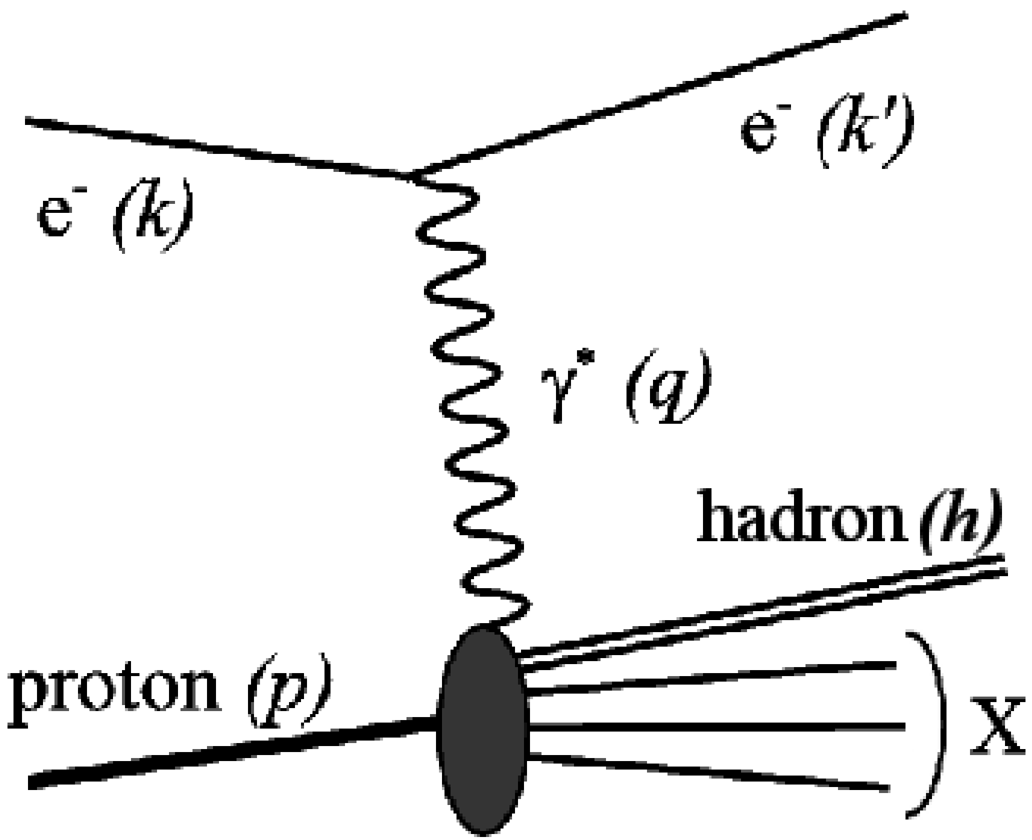
$$\nu = E_\gamma$$

- Fraction of the energy carried by the hadron

$$z = \frac{k.p}{q.p} = E_h / \nu$$

- Transverse momentum

$$\vec{P}_t = \vec{P}_h - \frac{\vec{P}_h . \vec{q}}{\|\vec{q}\|} \vec{q}$$



Observables in Nuclear DIS

- Transverse momentum broadening

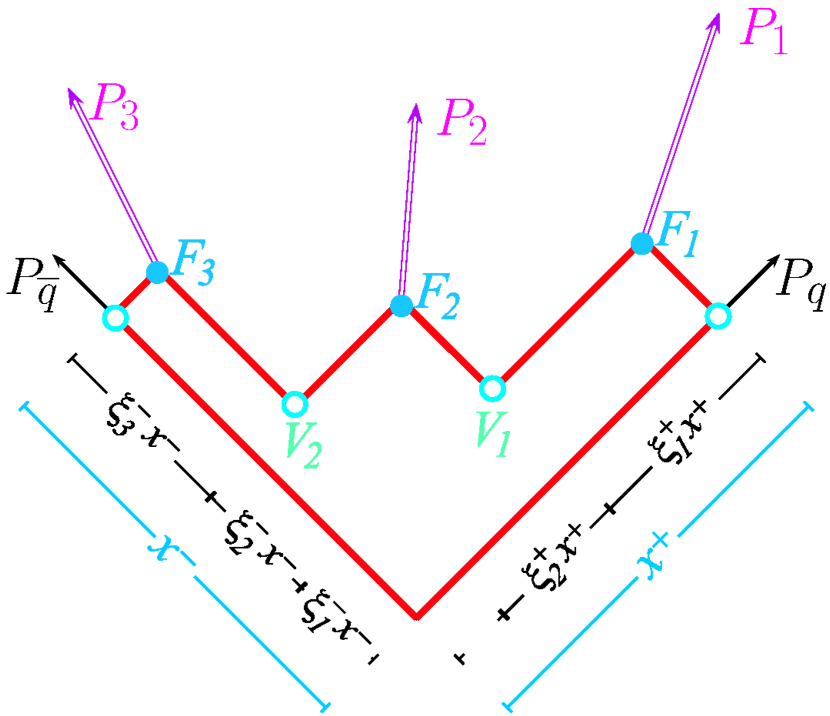
$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

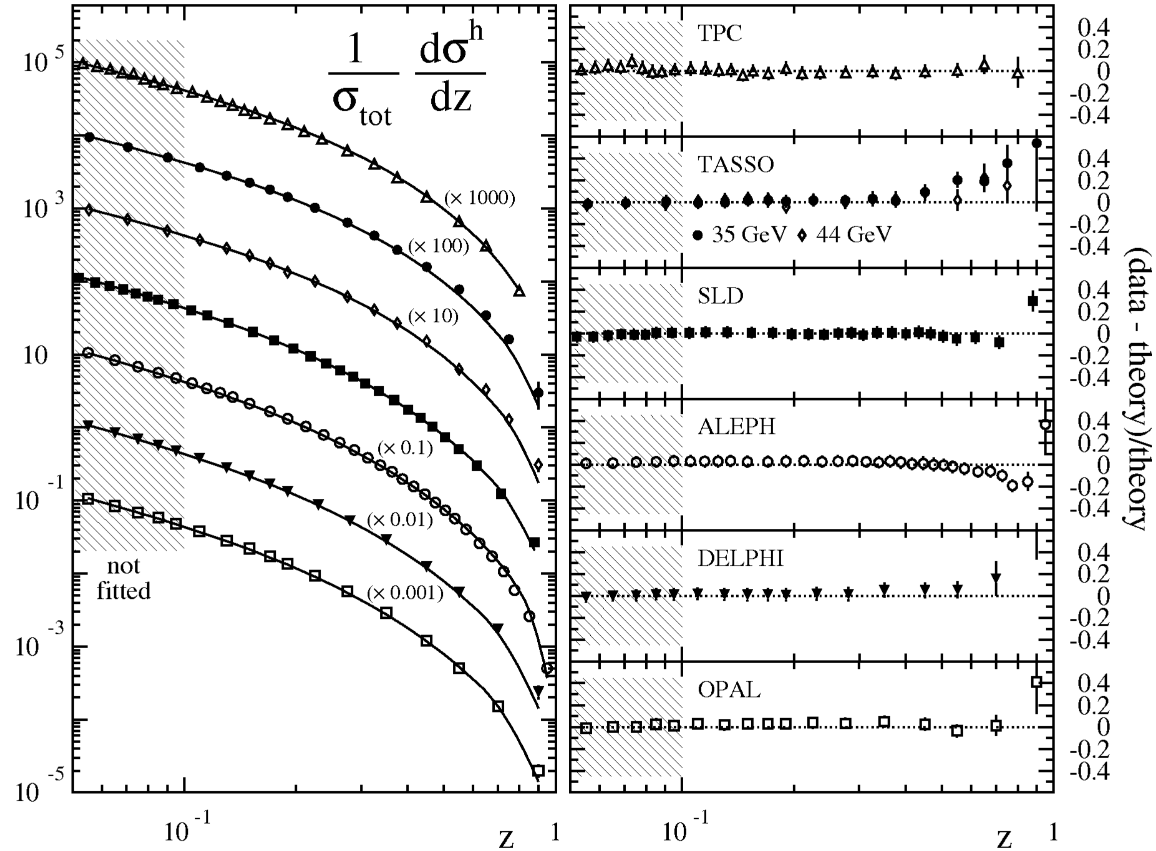
- Multiplicity ratio

$$R_A^h(Q^2, x_{Bj}, z, P_T) = \frac{N_A^h(Q^2, x_{Bj}, z, P_T) / N_A^e(Q^2, x_{Bj})}{N_D^h(Q^2, x_{Bj}, z, P_T) / N_D^e(Q^2, x_{Bj})}$$

The attenuation is 1-*R*

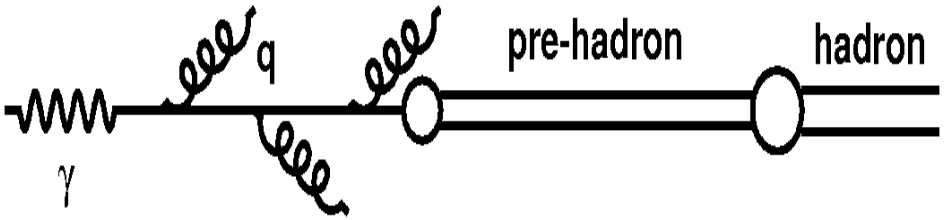
Fragmentation





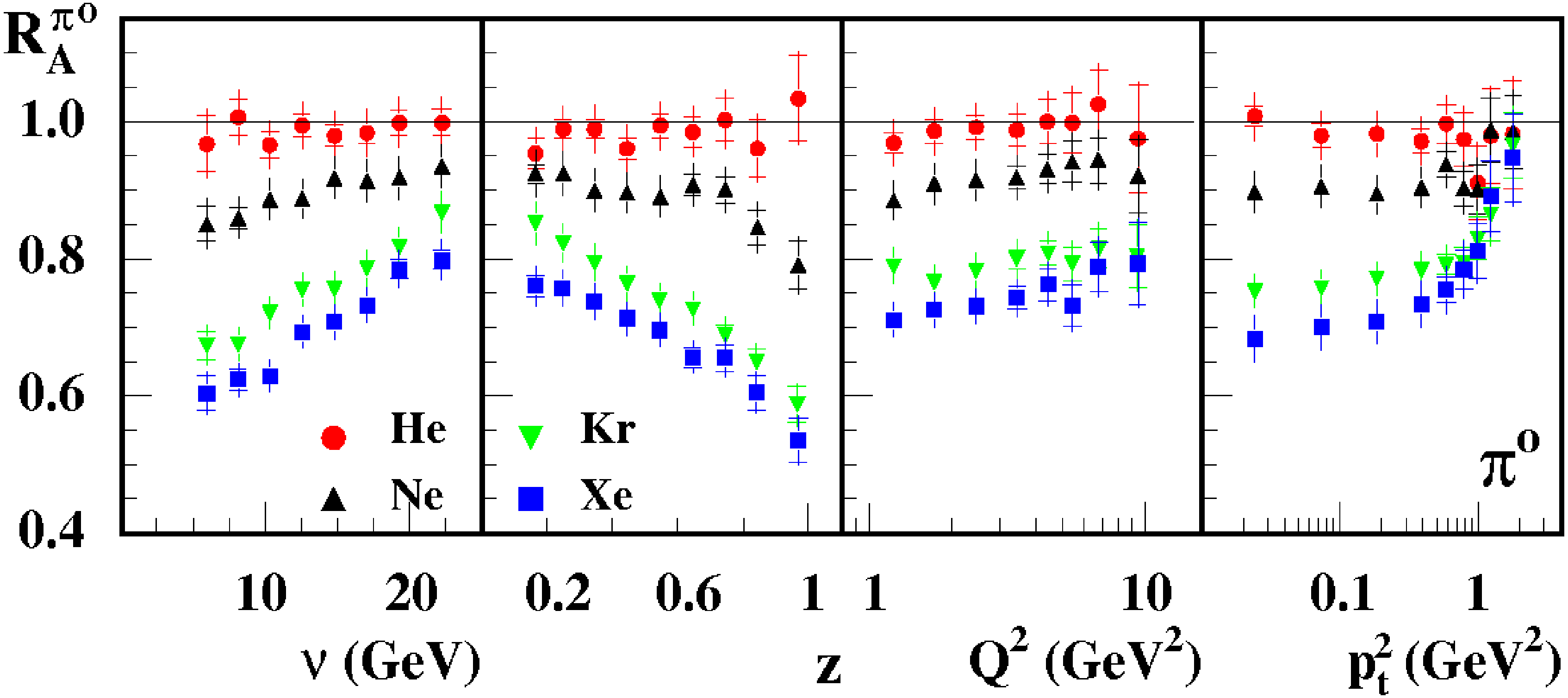
- Target and current fragmentation
- Fragmentation functions describe the current region

Theoretical Scenarios



- Parton energy loss
- (Pre-)Hadron absorption
- Medium modified fragmentation functions
- Models are either pure or combinations of several effects

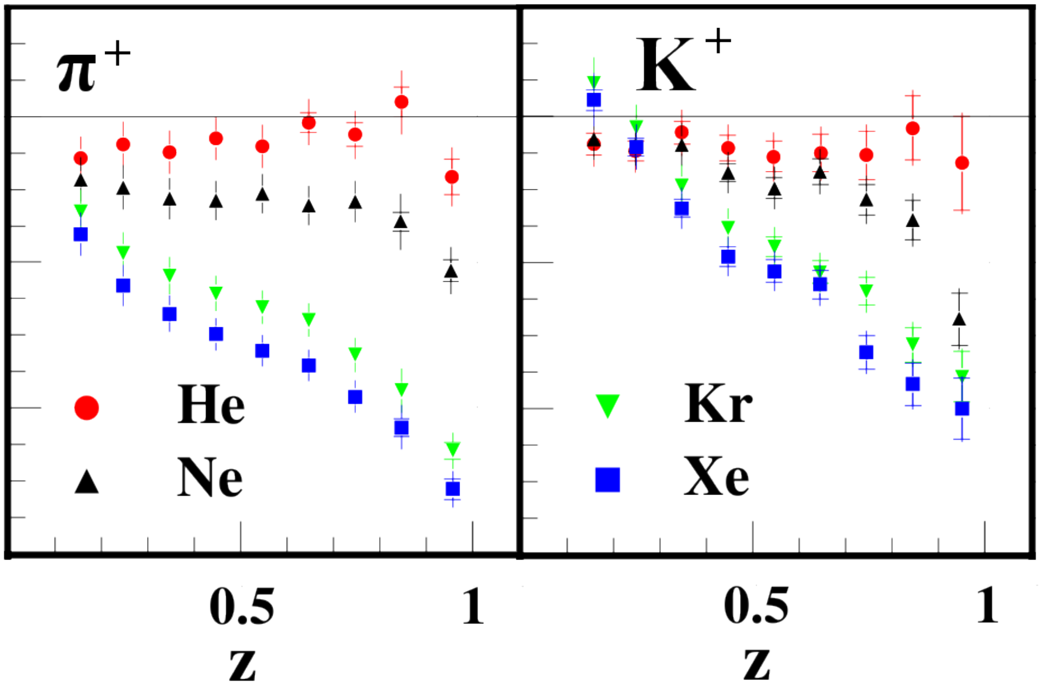
The General Picture



- Increase with ν
- Decrease with z
- Slight increase with Q^2
- Strong increase with P_T

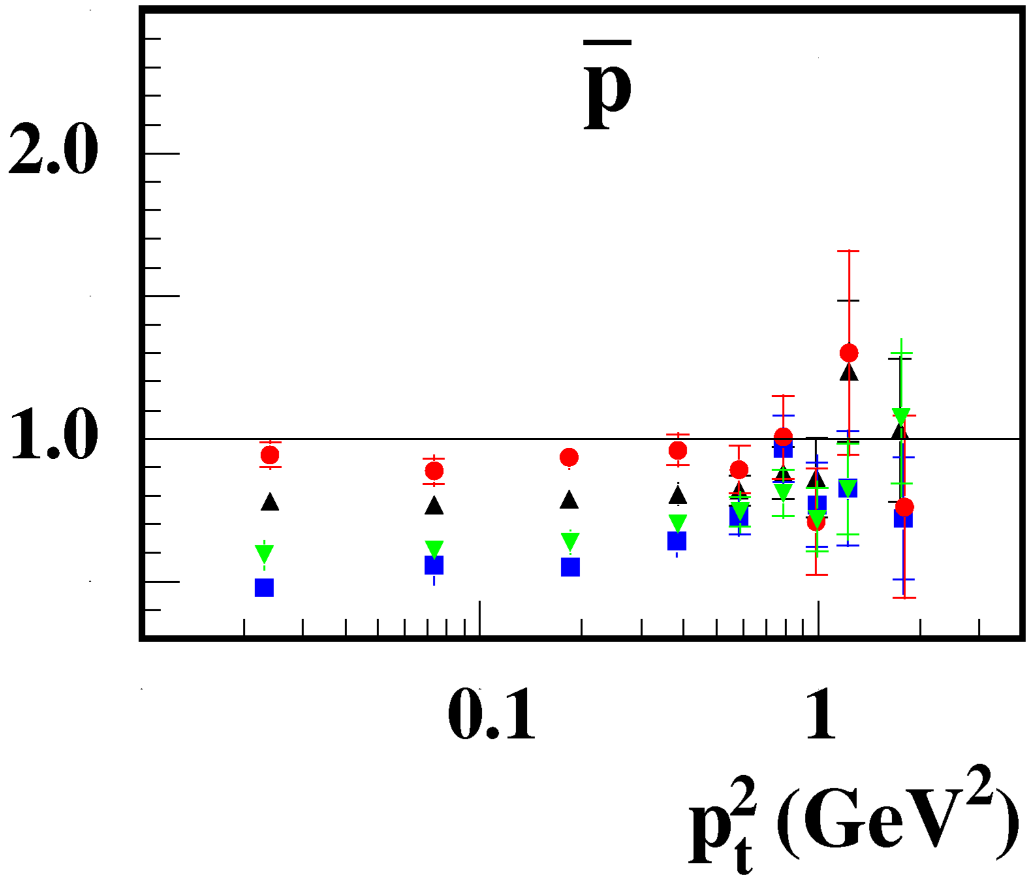
Some Open questions

- K^+ is less attenuated than pions or K^-
- Can be due to
  - lower cross section
  - Stronger FF fall
  - $\pi + p \rightarrow \Lambda + K$



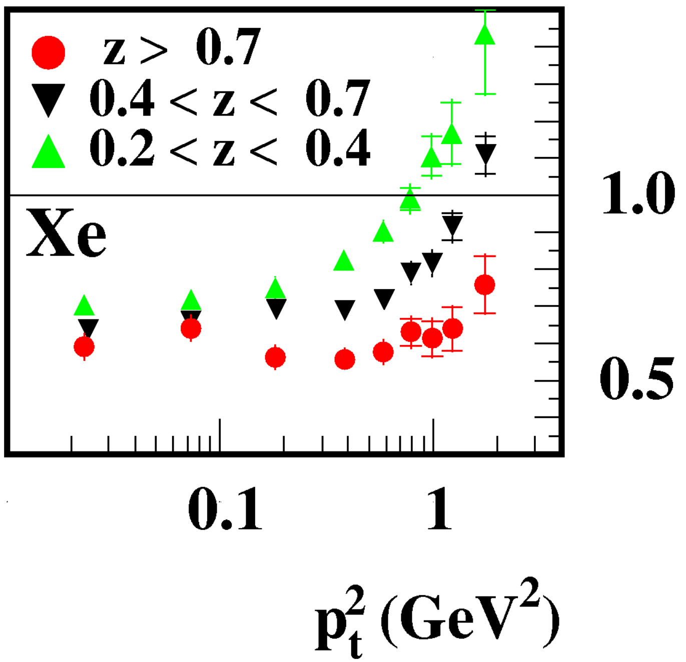
A. Airapetian *et al.* Nucl.Phys., B780 (2007) 1.

Some Open Questions



Cronin effect or target fragmentation?

- Effect is smaller at higher z
- Small effect for anti-p

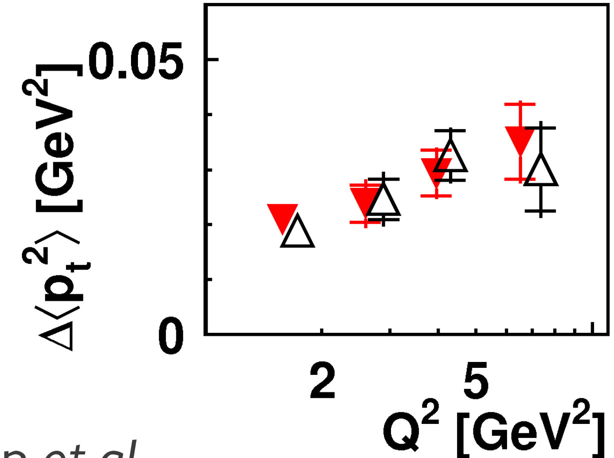


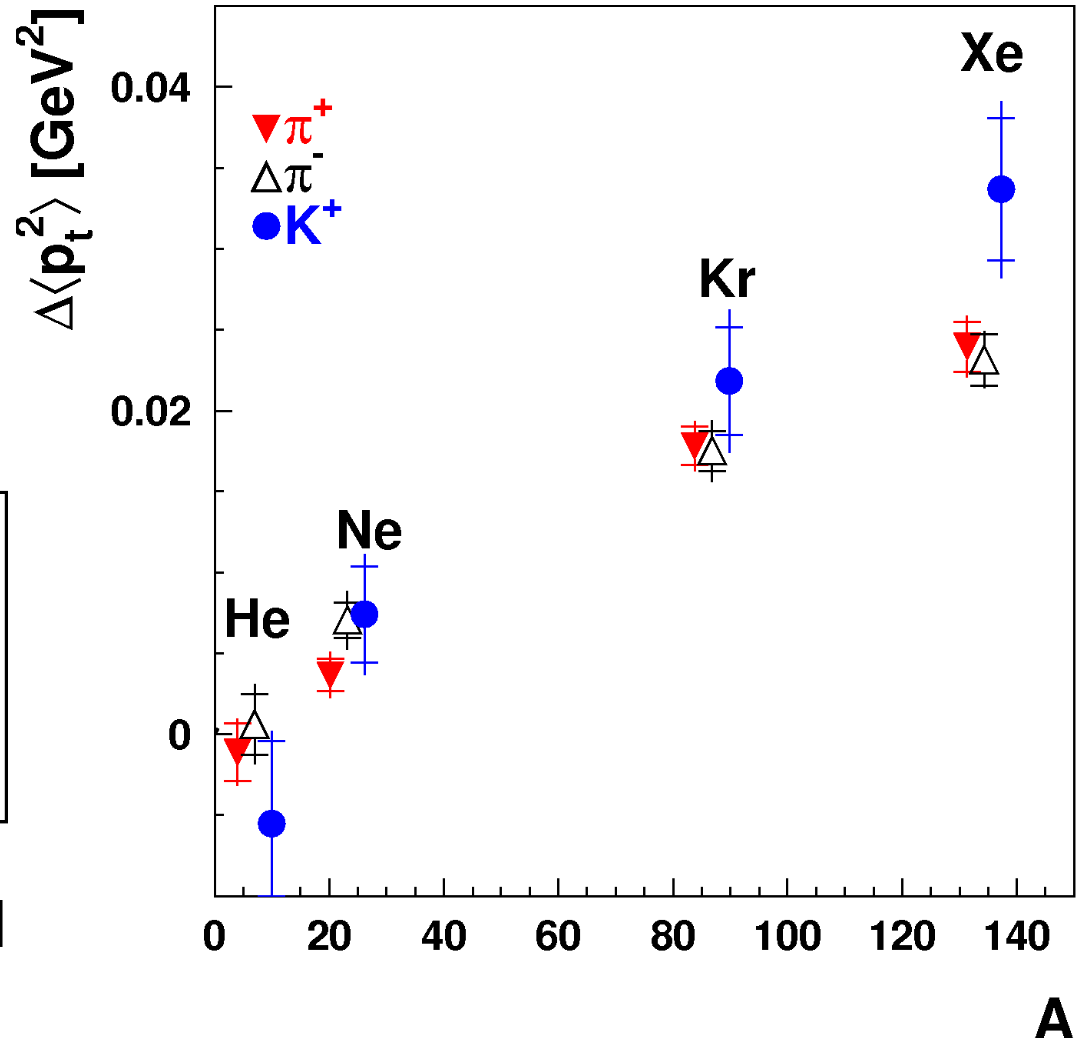
A. Airapetian *et al.*

Nucl.Phys., B780 (2007) 1.

Some Open Questions

- Pt broadening observed and measured
- Kaon behavior different ?
- Q^2 variation ?





A. Airapetian *et al.*

Phys.Lett., B684 (2010) 114.

Conclusions From HERMES

- Pions have similar behavior
- Demonstrated the raise with ν
- Provides interesting baryon measurement

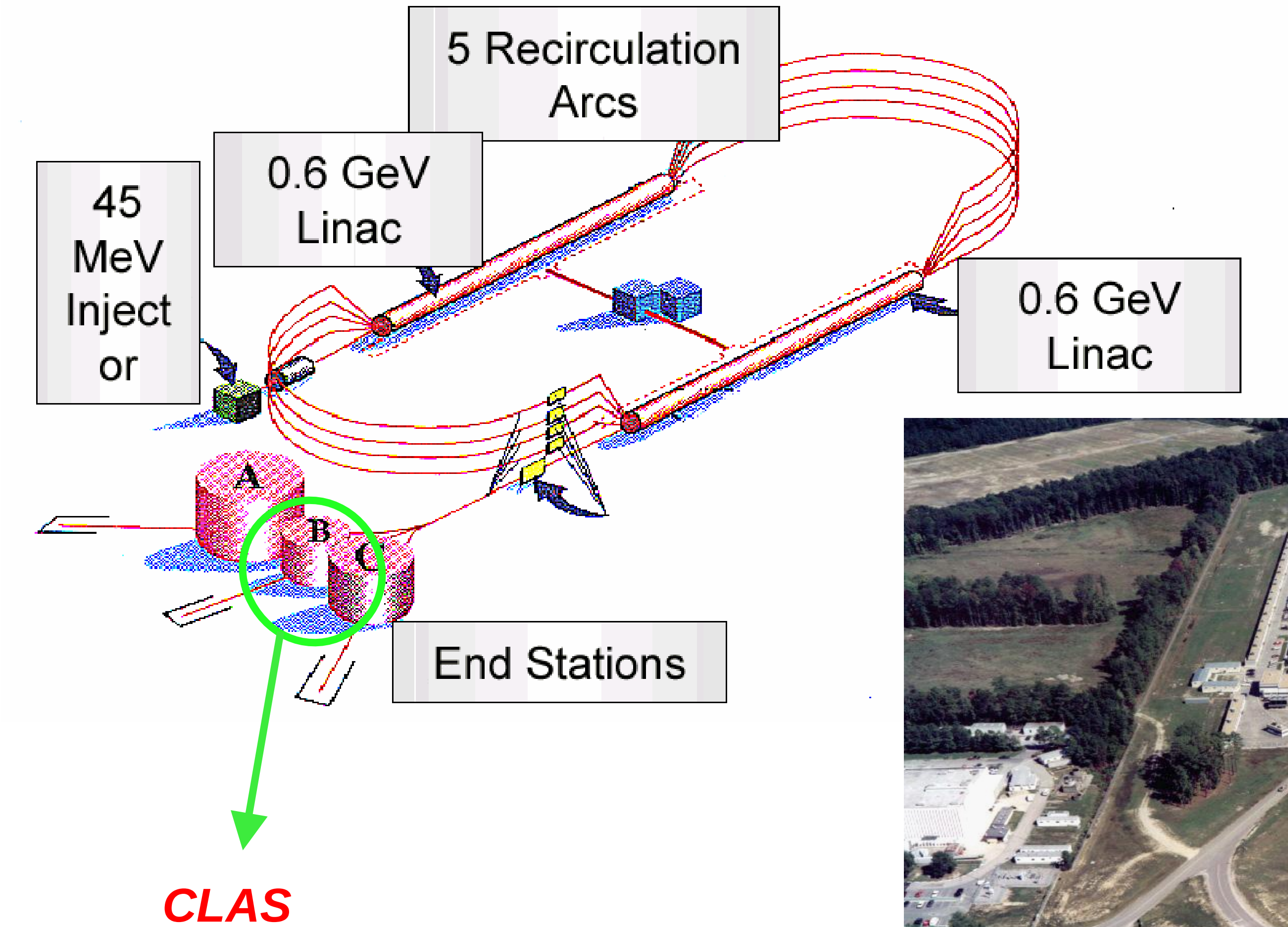
However

- Target fragmentation might be an issue
- All model types remain

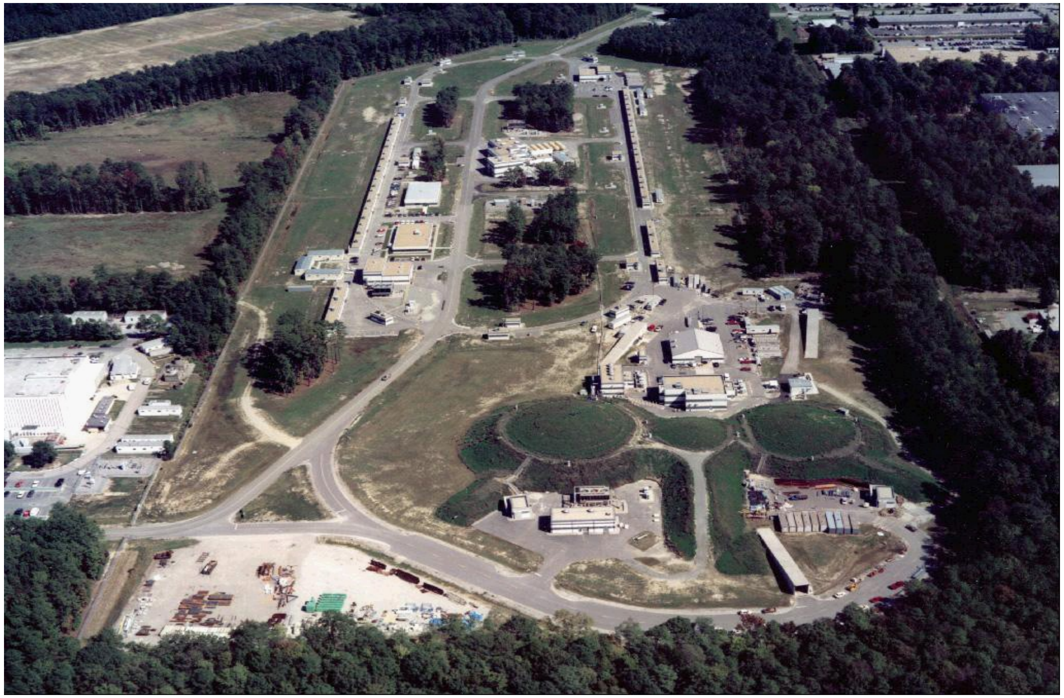
Still to be done

- Some multidimensional results are not confronted to models yet
- Interesting hints for a Q^2 and flavor effects need to be confirmed

Jefferson Laboratory (JLab)

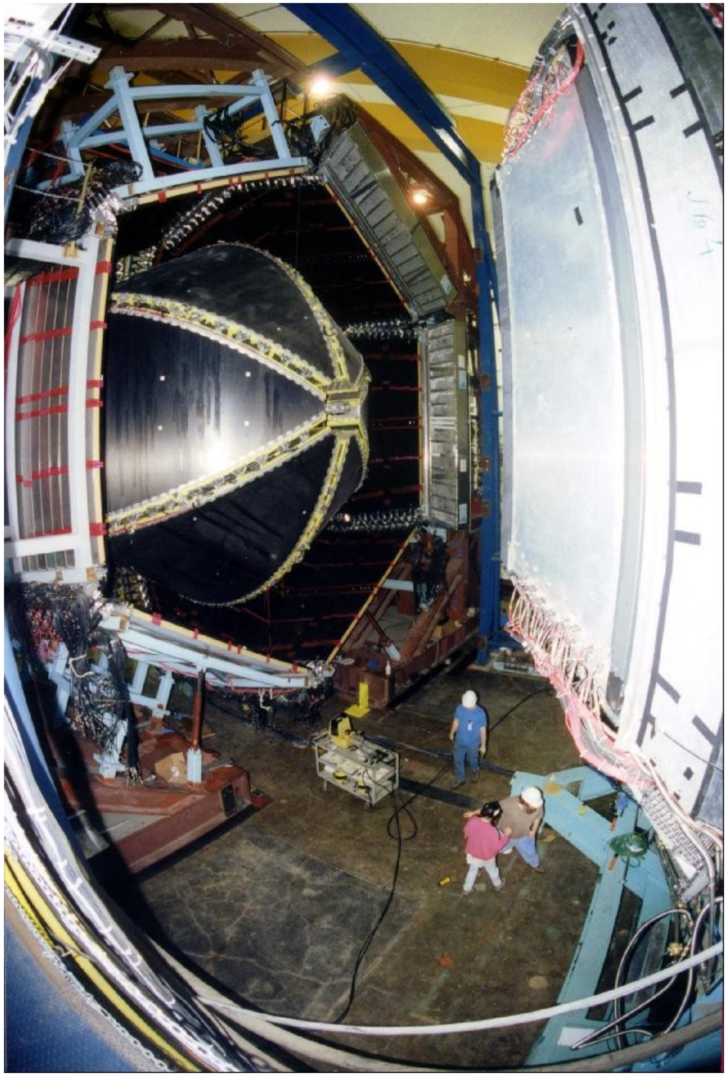


E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%



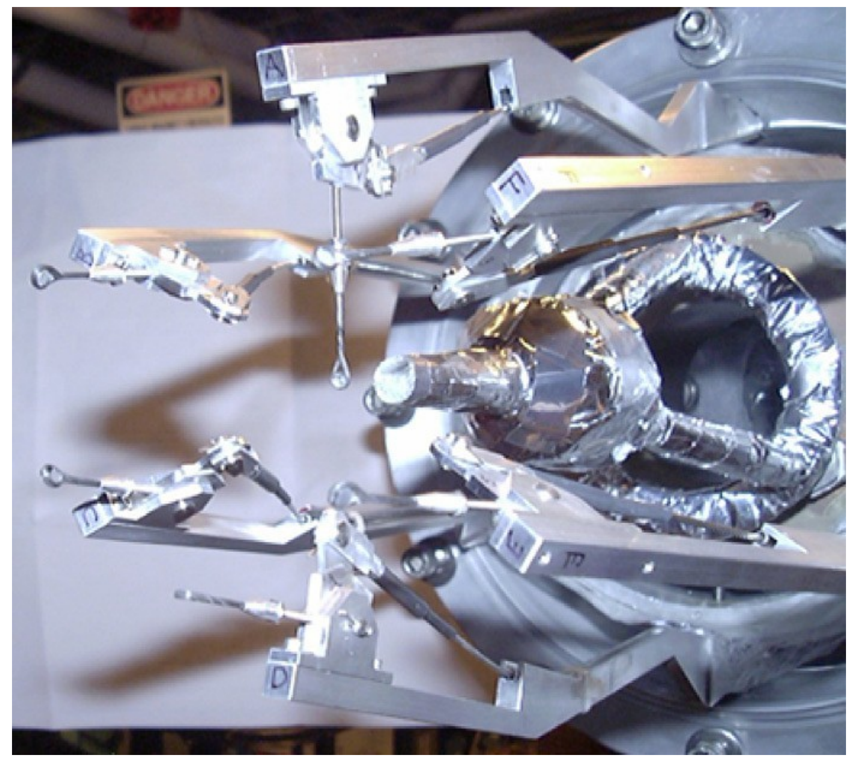
CLAS

- CEBAF Large Acceptance Spectrometer is composed of:
  - Torus magnet bending particle trajectories
  - Drift Chambers for momentum determination
  - Scintillators for time of flight measurement
    - Identification of pions and heavier particles
  - Cerenkov counters
    - Identification of electrons up to 2.5 GeV
  - Electromagnetic calorimeter
    - Identification of electrons



The eg2 run

- Proposed by W. Brooks et al. in "Quark Propagation Through Cold QCD Matter"
- Running 50 days in Hall B of JLab (CLAS Collaboration)
- 5 GeV electron beam
- Main goal is to obtain statistic for a multi-dimensional study
- Use 5 targets (**C**, Al, **Fe**, Sn, **Pb**)

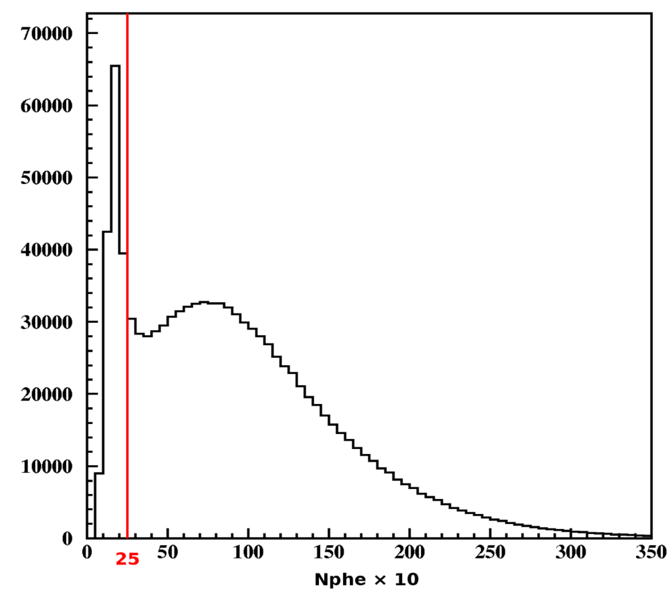


Analysis Status

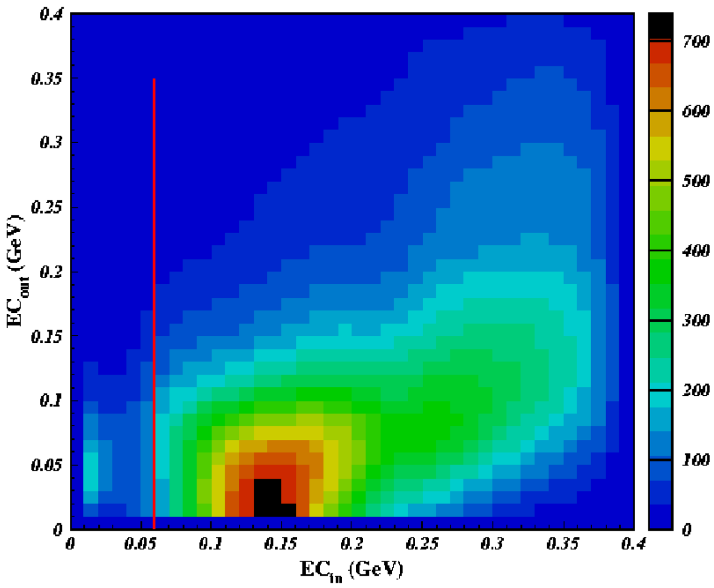
- Pion analyses, presented here, are close to completion with preliminary results available
- Analysis in parallel of several particles (all 3 pions, K^+, K^0, protons, Lambda…)

Electron Identification

- Use Cerenkov counter's photo-electrons

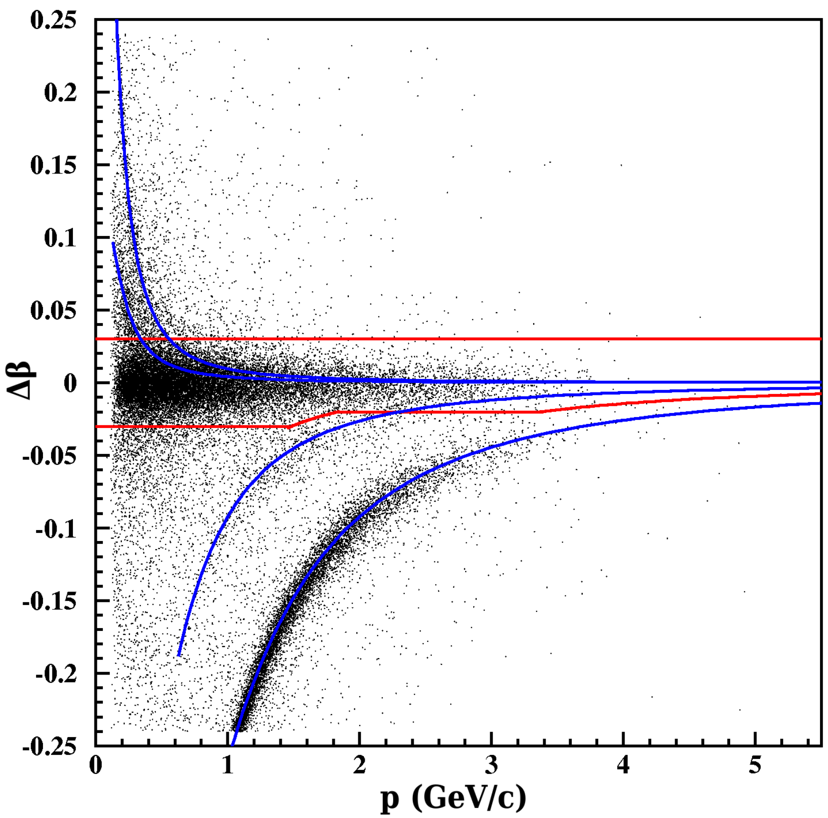


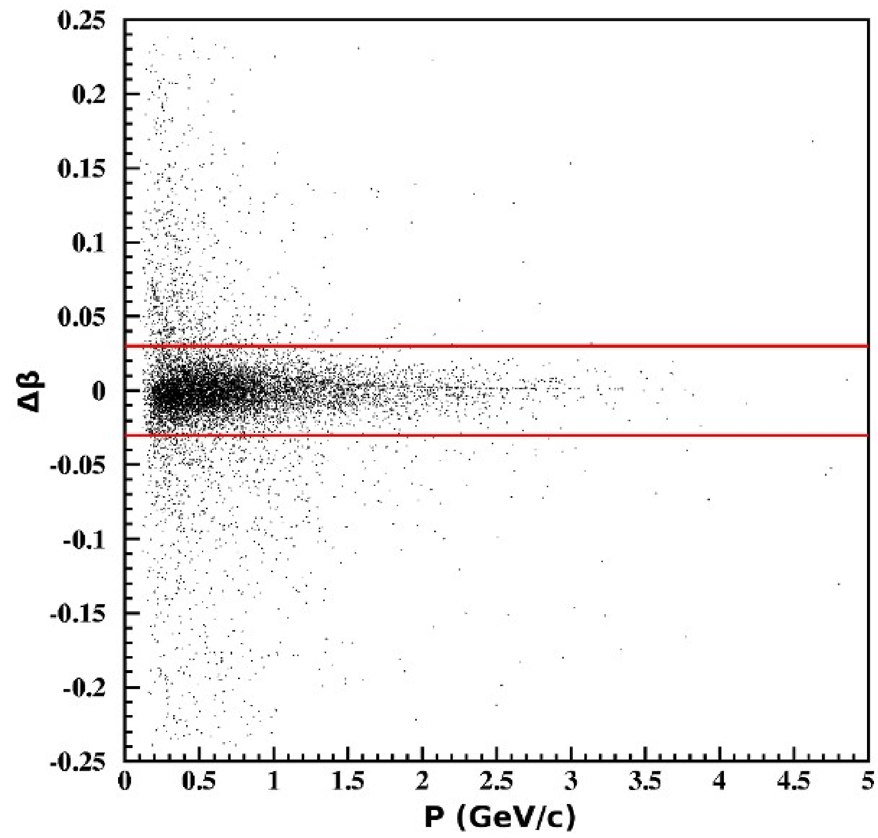
- Electromagnetic calorimeter energy deposit



Pion Identification

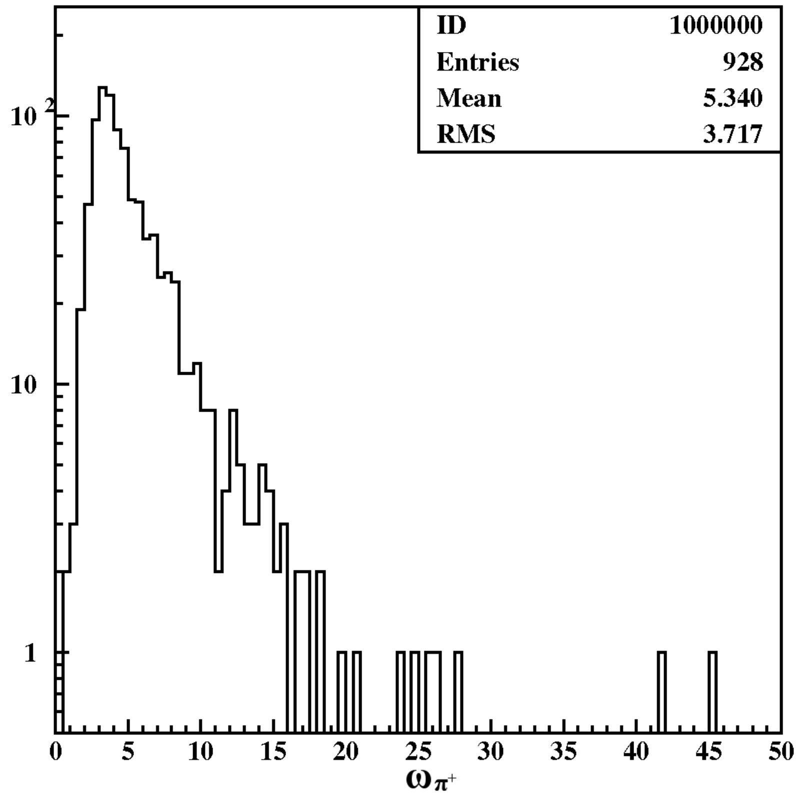
- Use time of flight difference between electron and pion

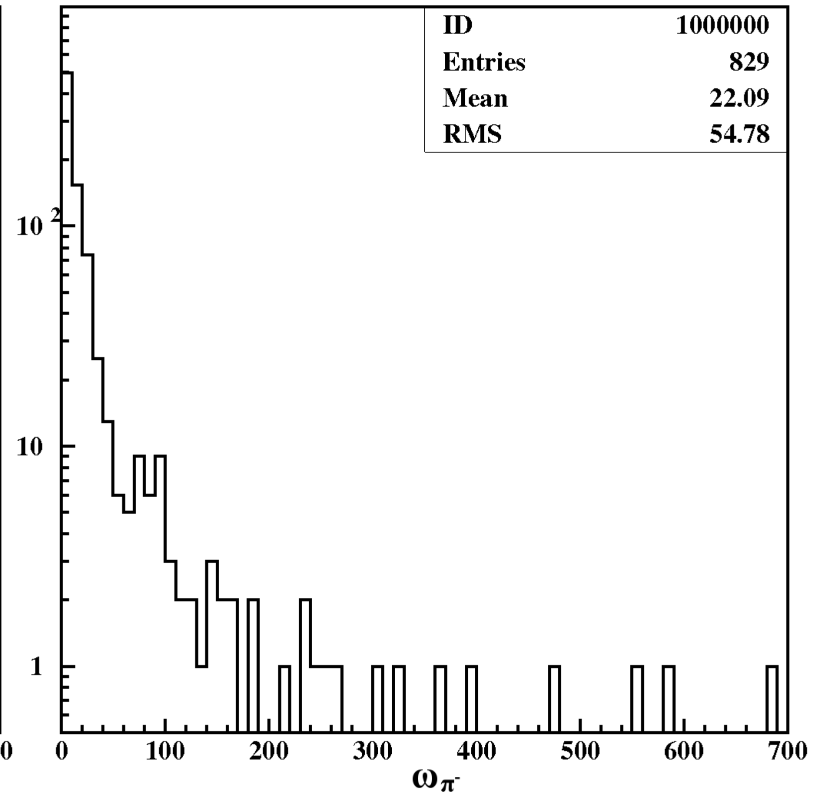




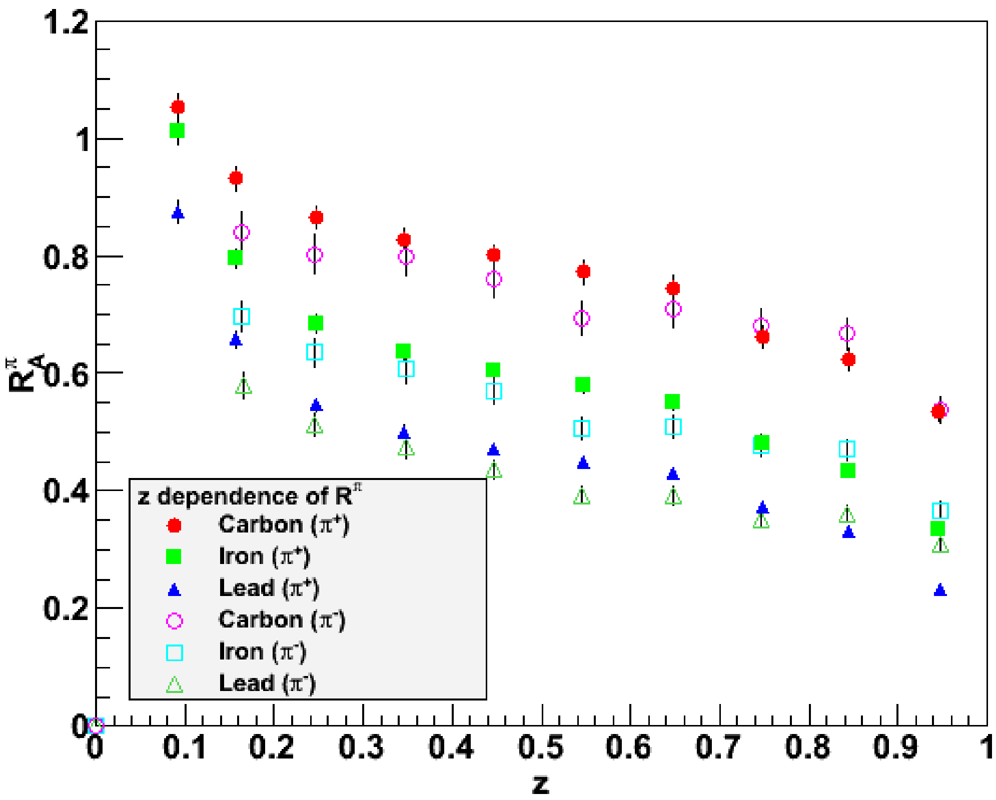
Acceptance Correction

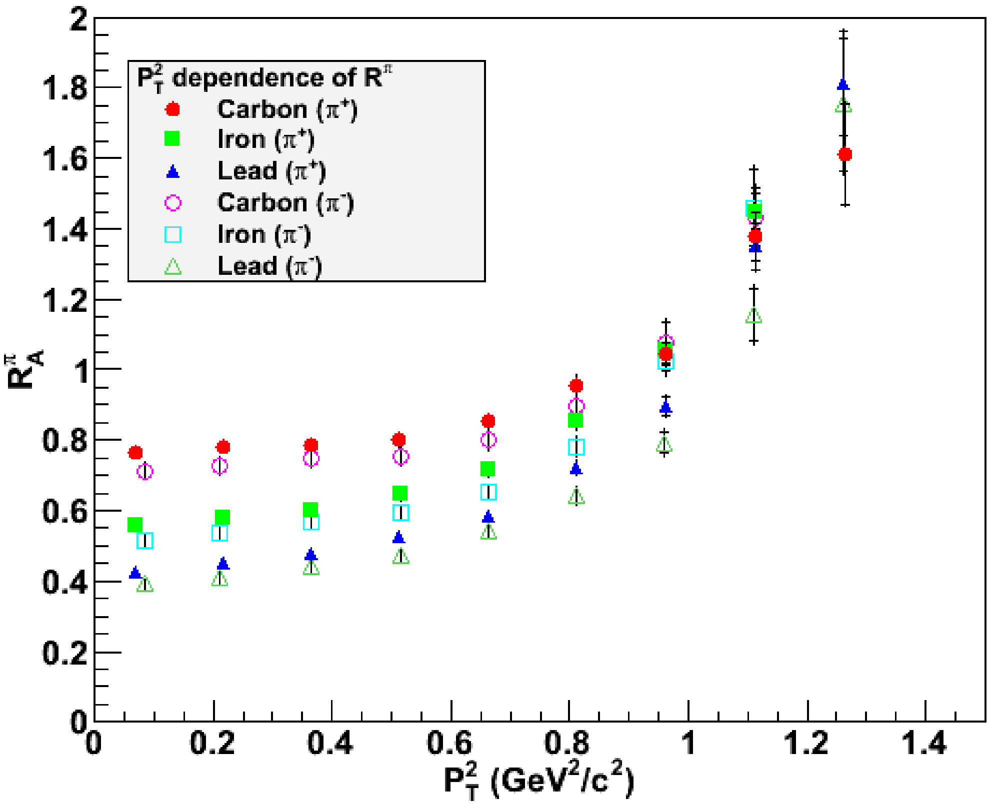
- Weights = generated / reconstructed
- Weights are applied to all events





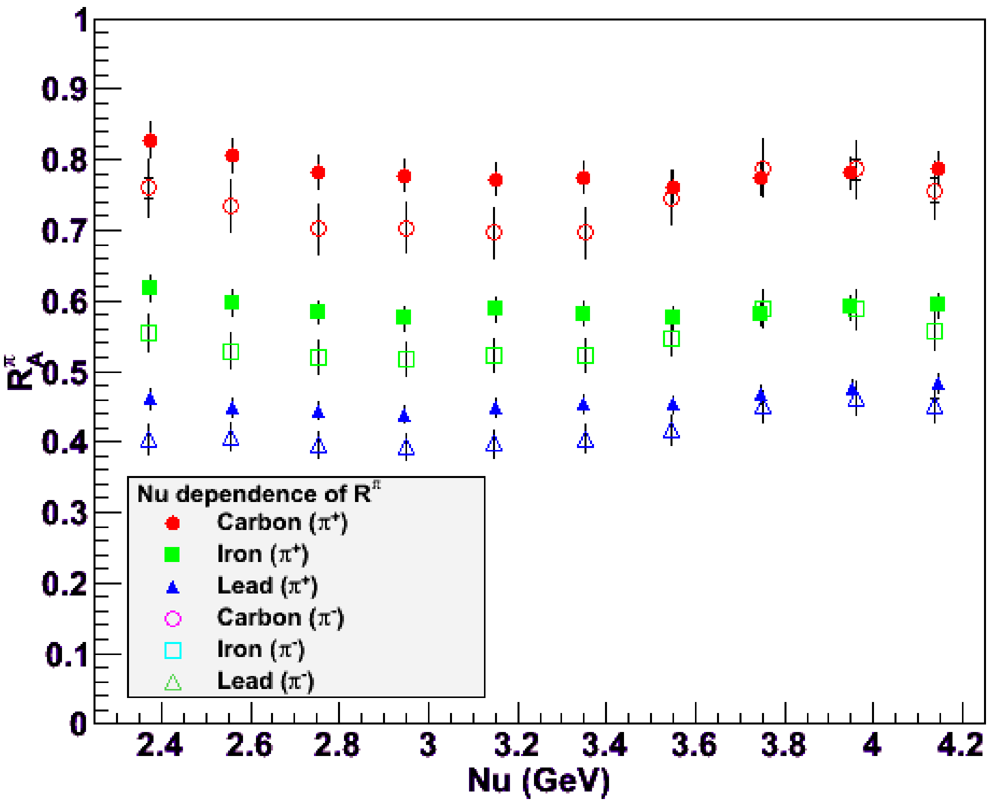
General Picture

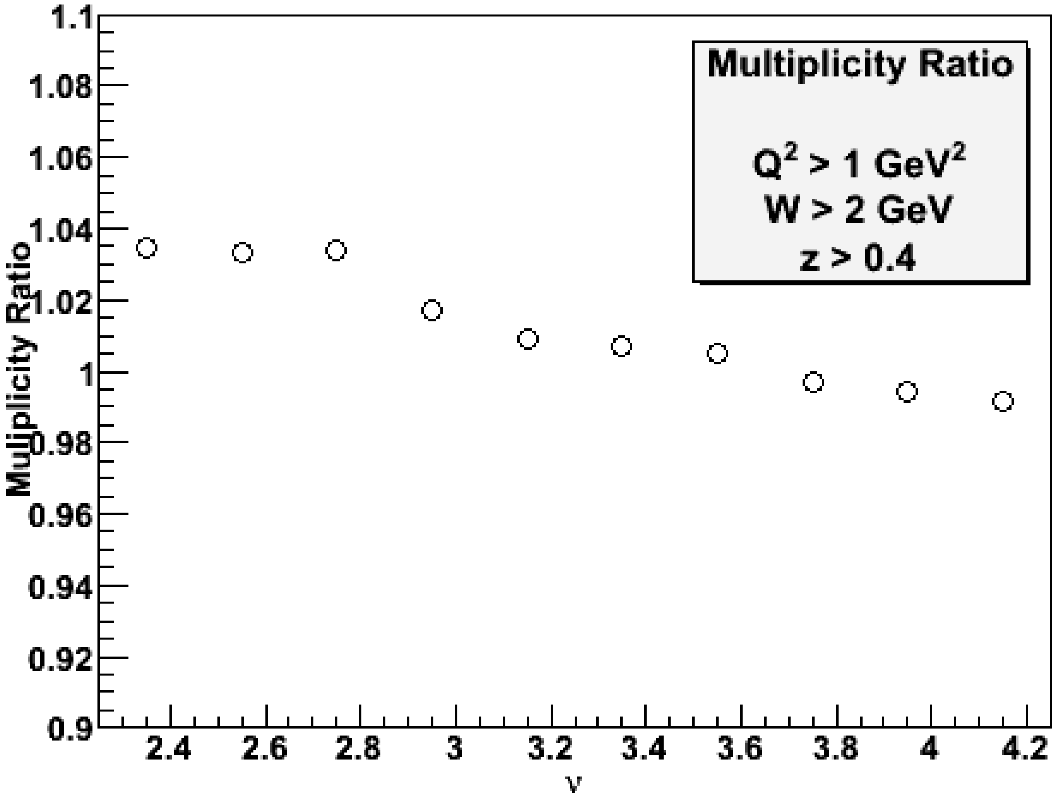




- Similar to HERMES in z and P_T

The ν dependence

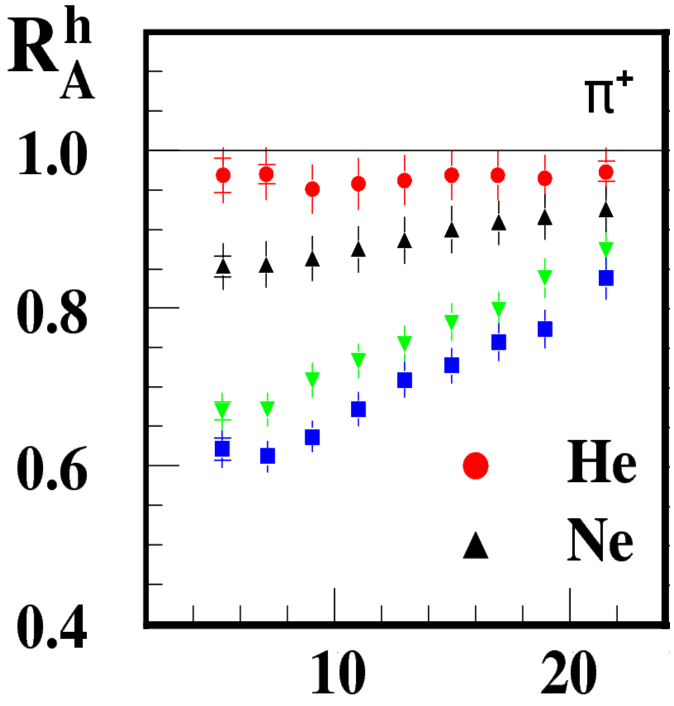


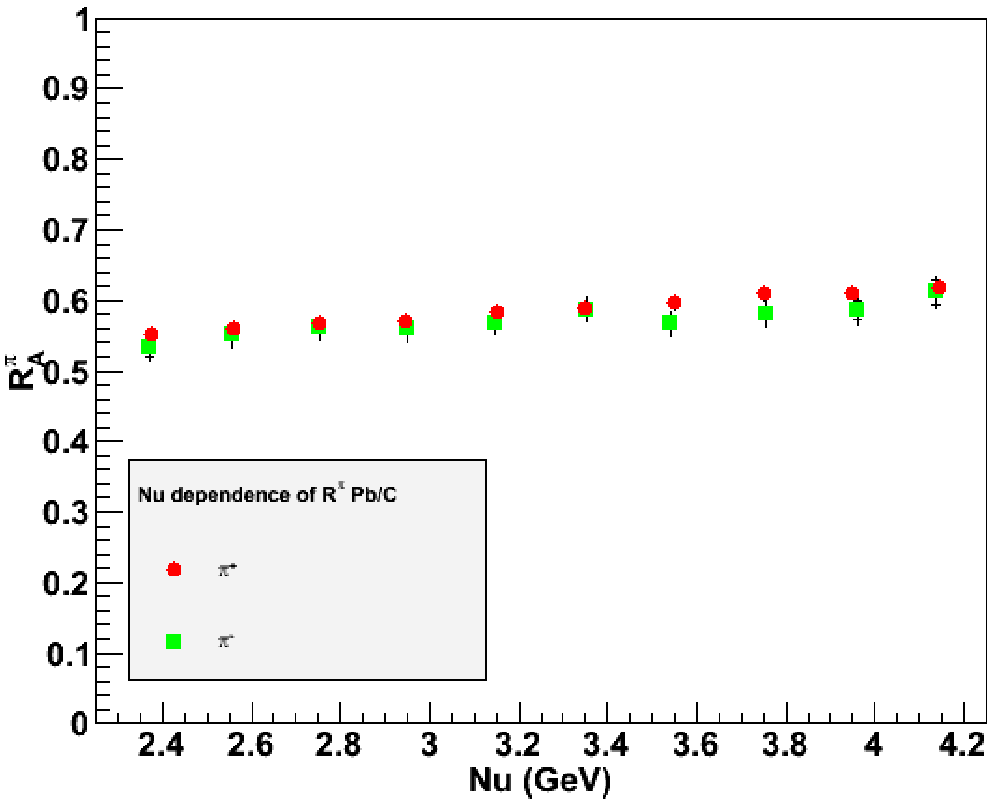


No clear ν dependence observed.

Not visible because of Fermi-motion?

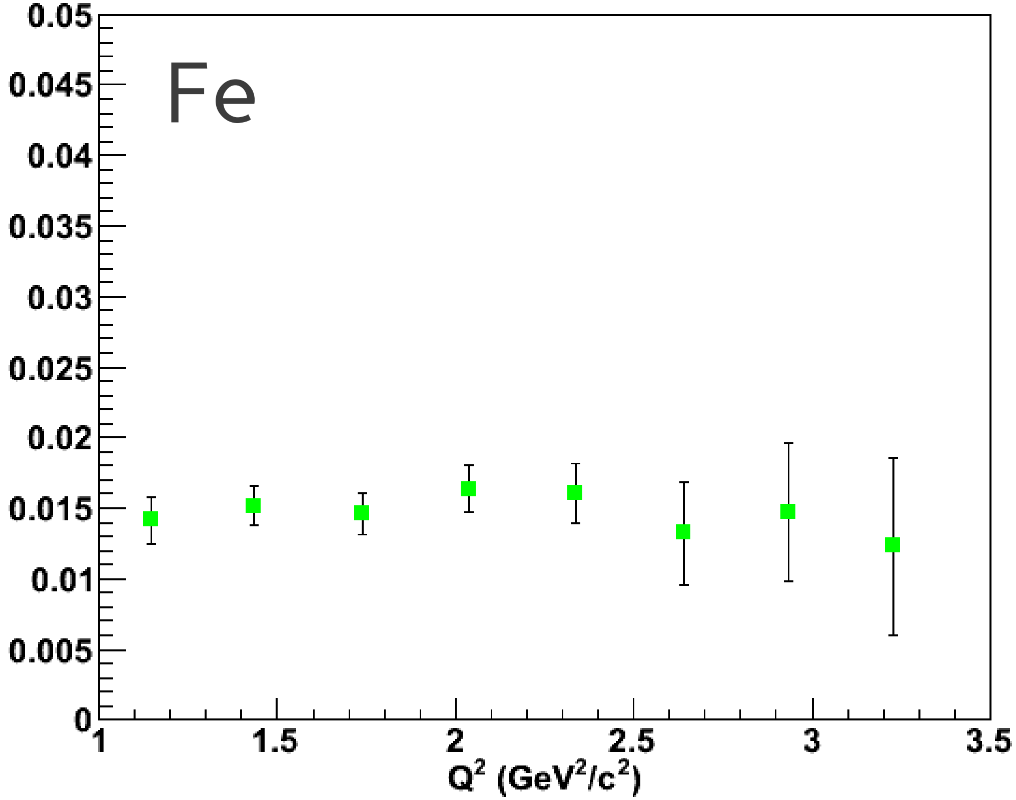
The ν dependence

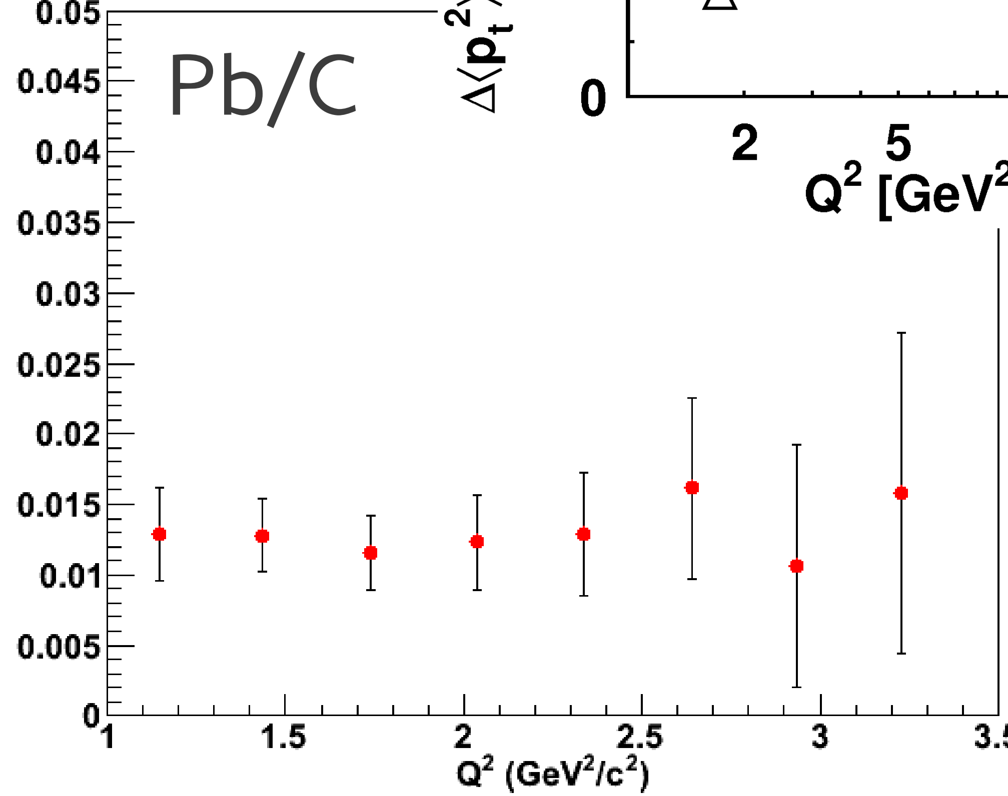


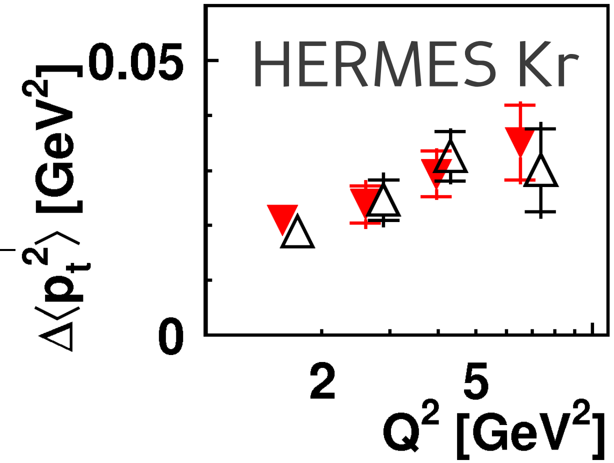


- According to HERMES not a big effect in CLAS
- Multiplicity ratio based on carbon → Expected effect visible

Q^2 effects?

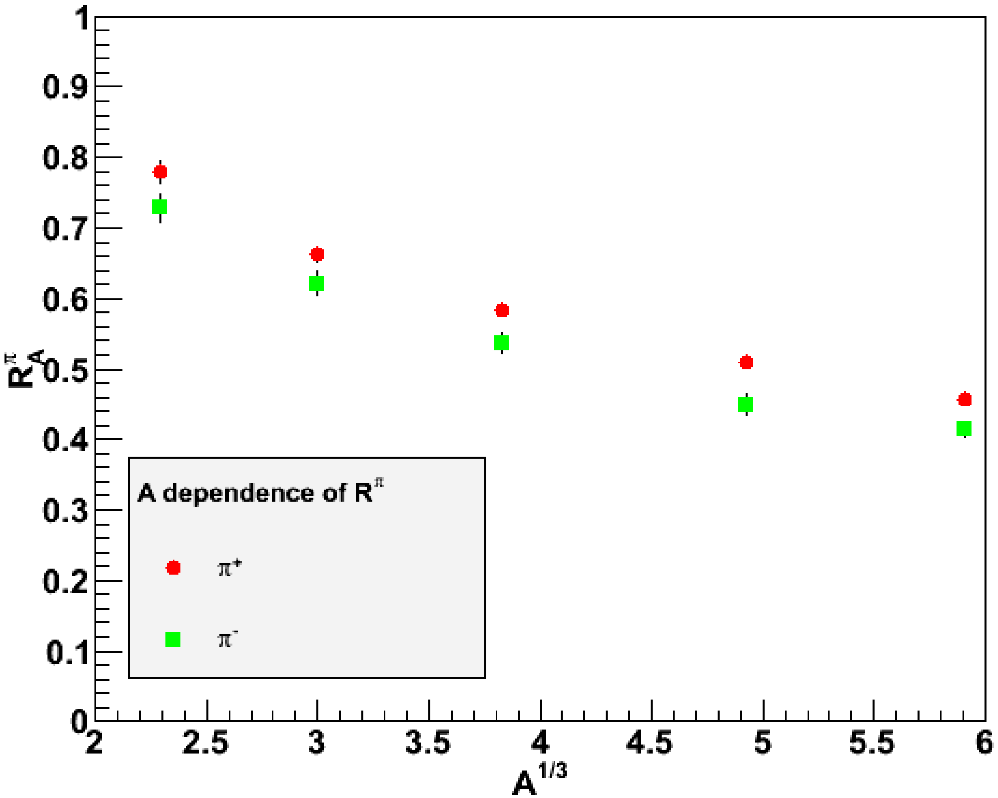


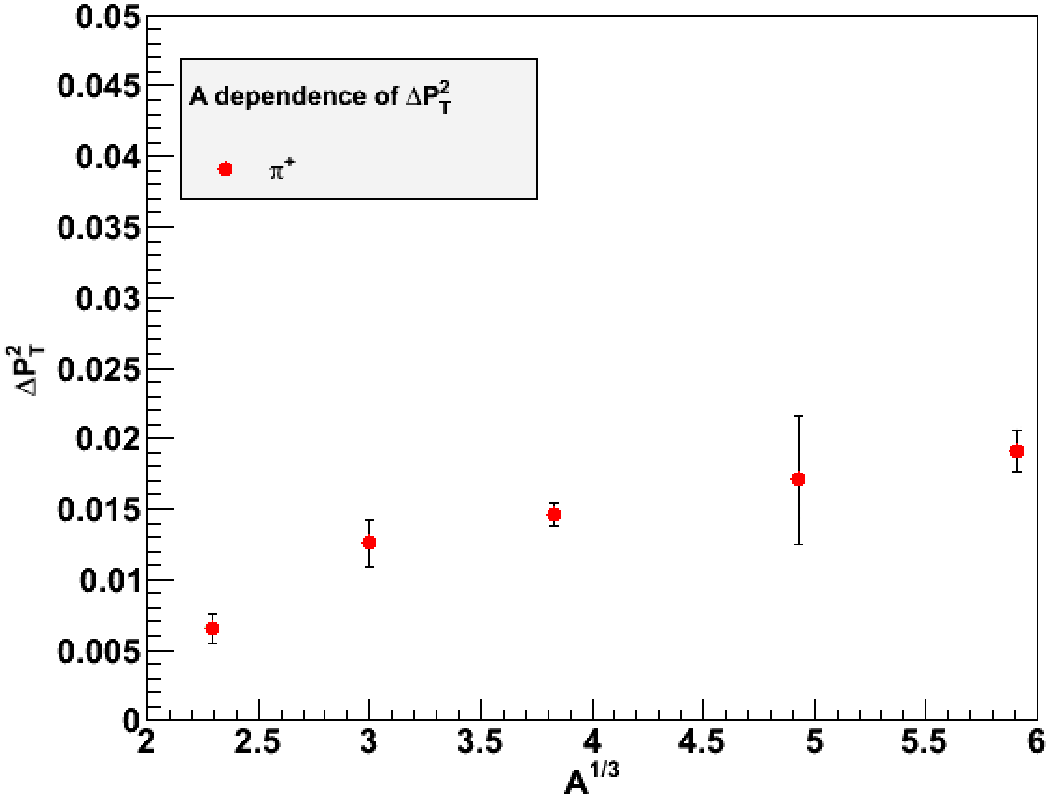




No modification of the transverse momentum broadening observed with Q^2

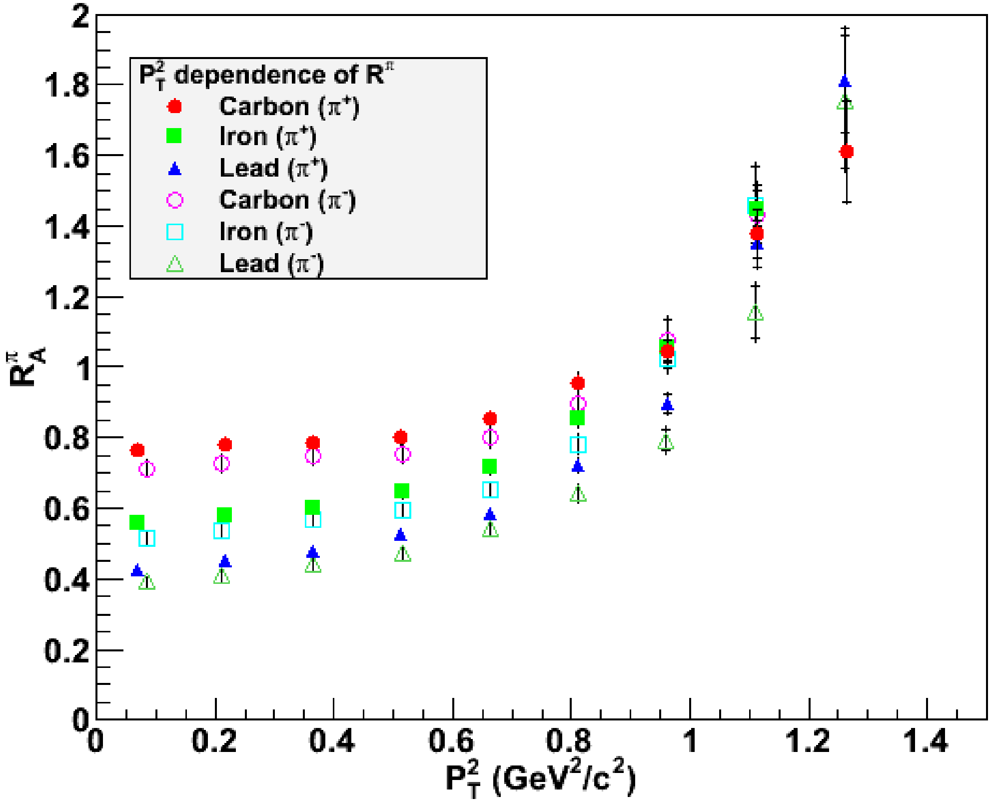
The A Dependence

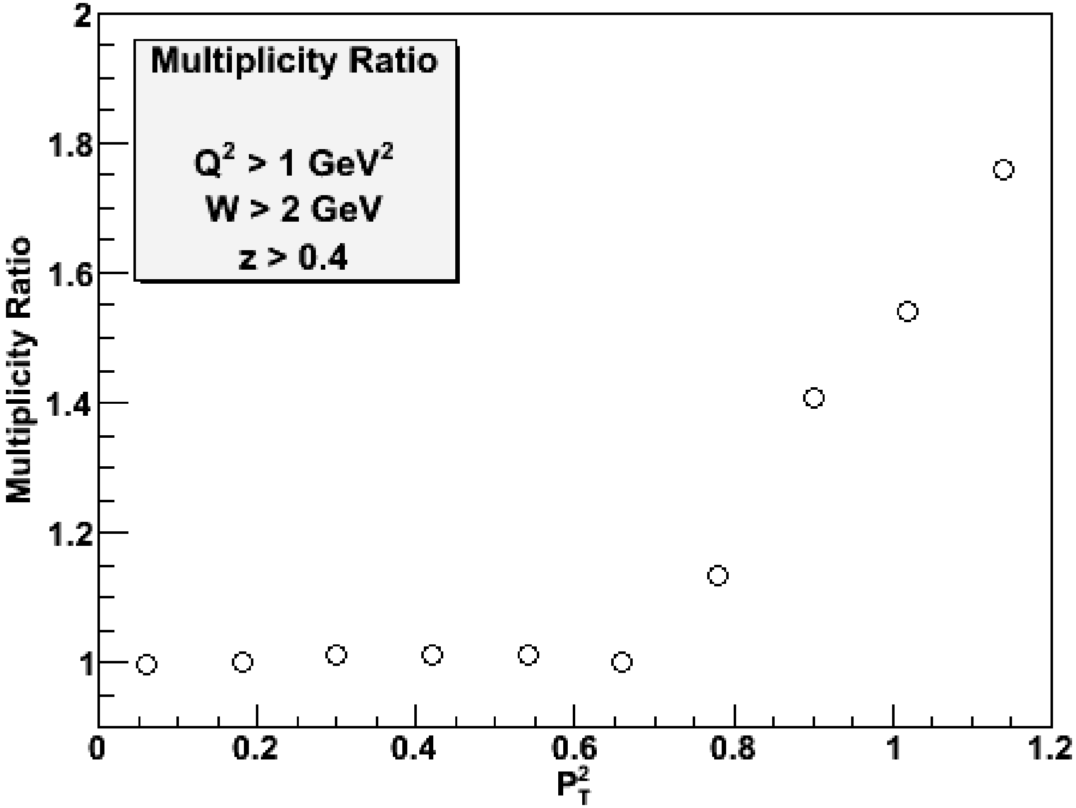




- Non-linear with $A^{1/3}$ neither $A^{2/3}$
- Nuclear effect seem to saturate

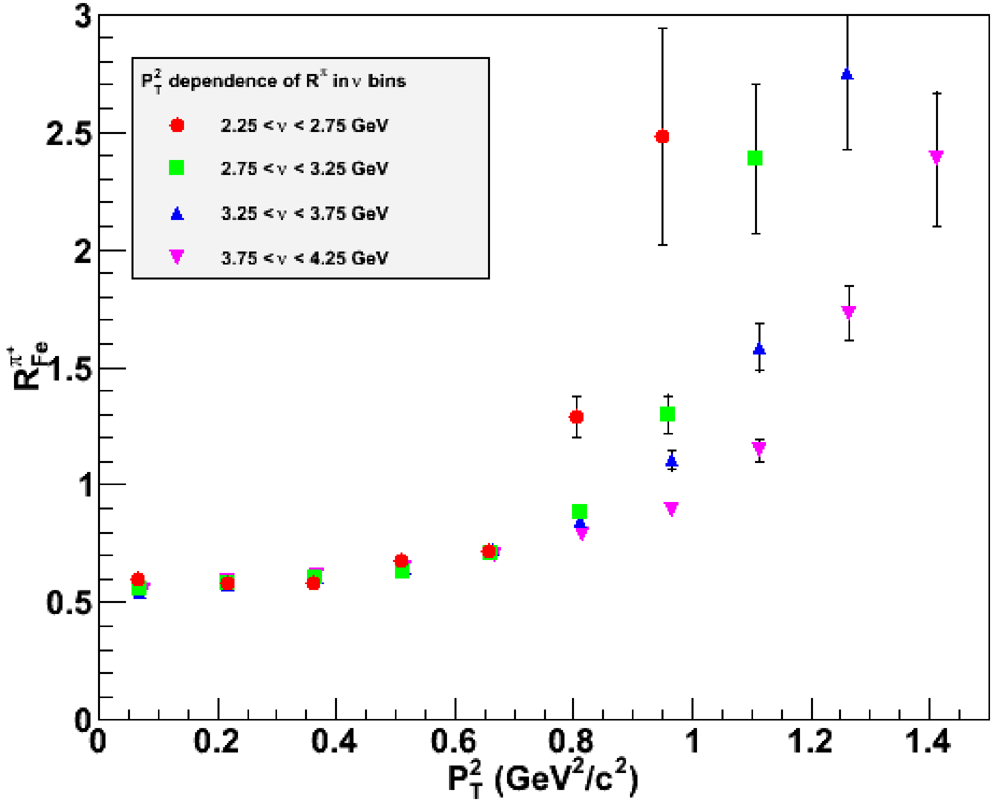
P_T Broadening

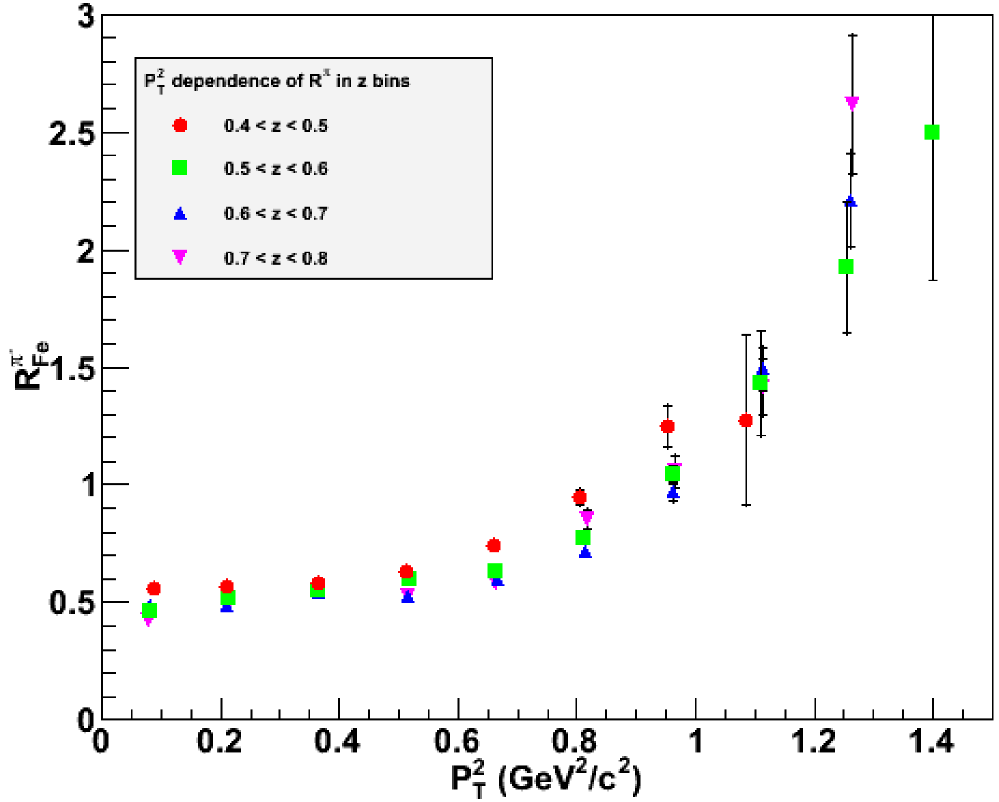




- Fermi-motion influence also in function of P_T

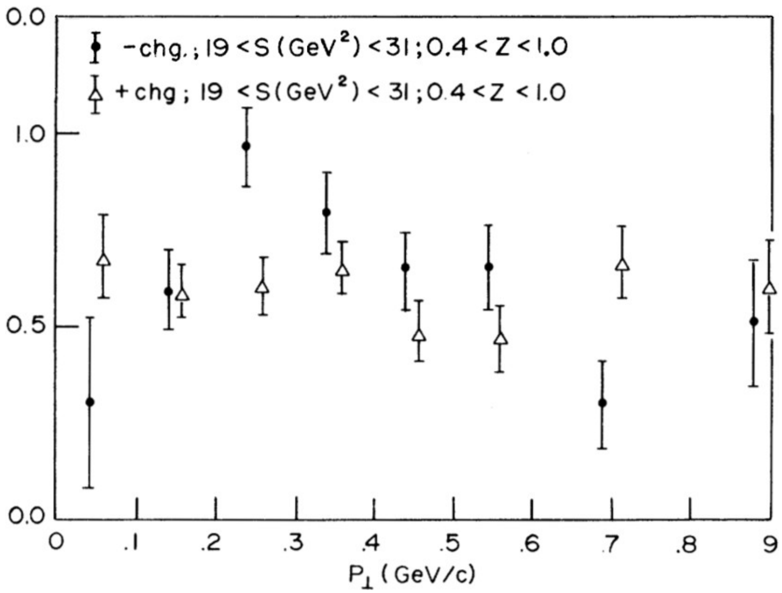
P_T Broadening





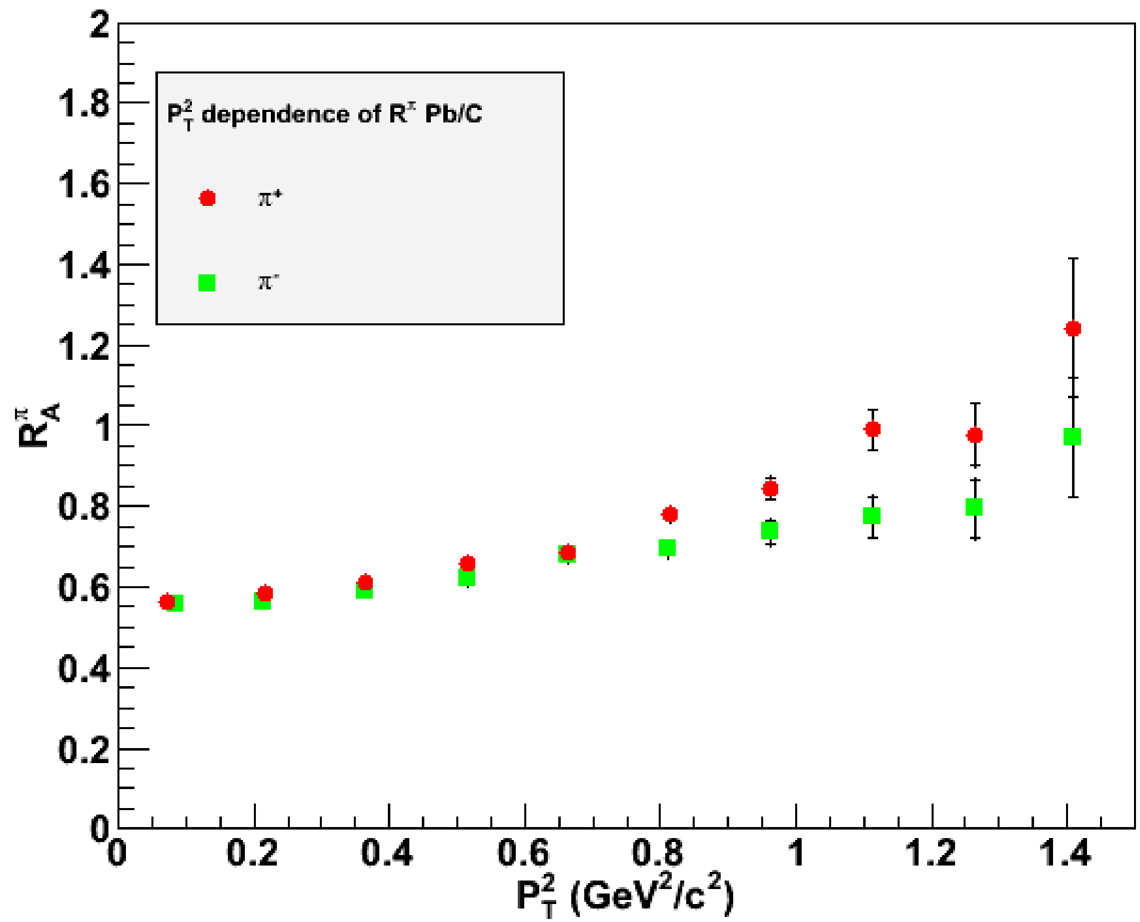
- Multi-dimensional bins give results opposite to HERMES
- Fermi-motion vs. Target fragmentation ?

P_T Broadening



SLAC Osborne et al.

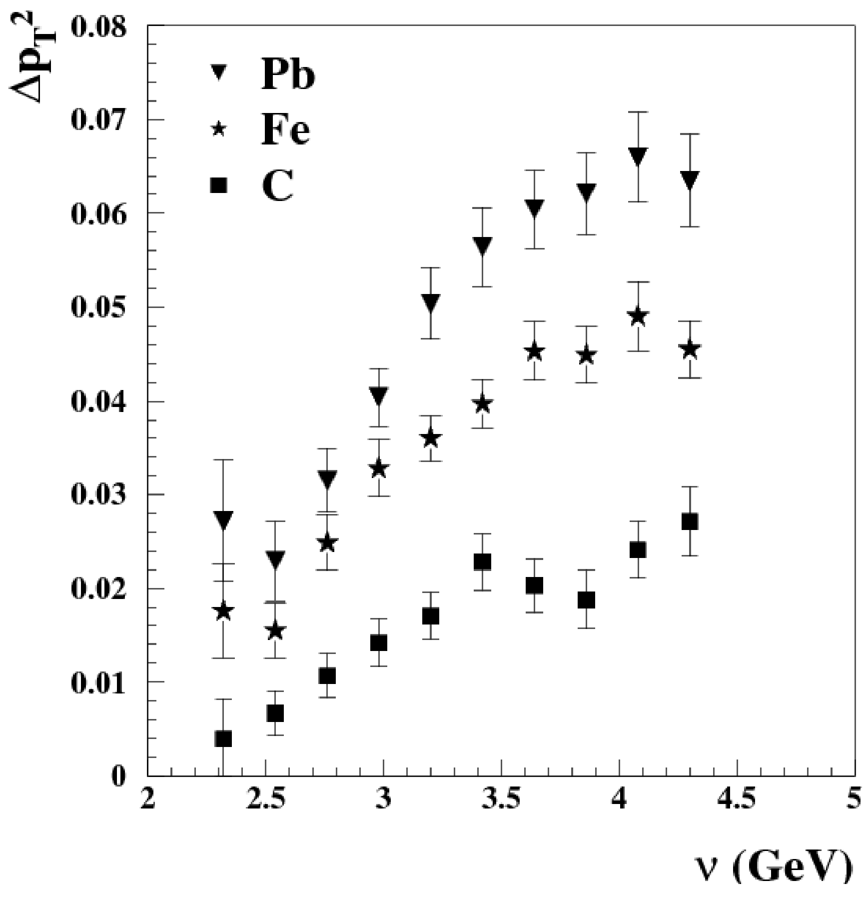
(PRL40 (1978) 1624)

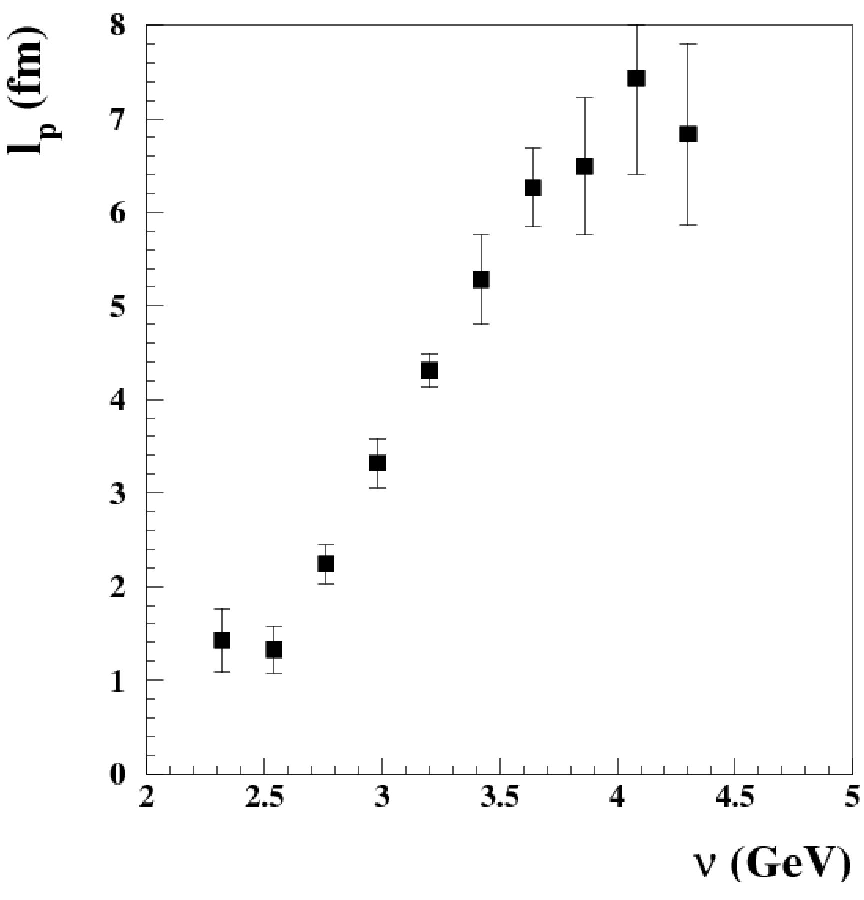


Relative to carbon → modest effect

(coherent with results from SLAC)

Possibilities with CLAS Data

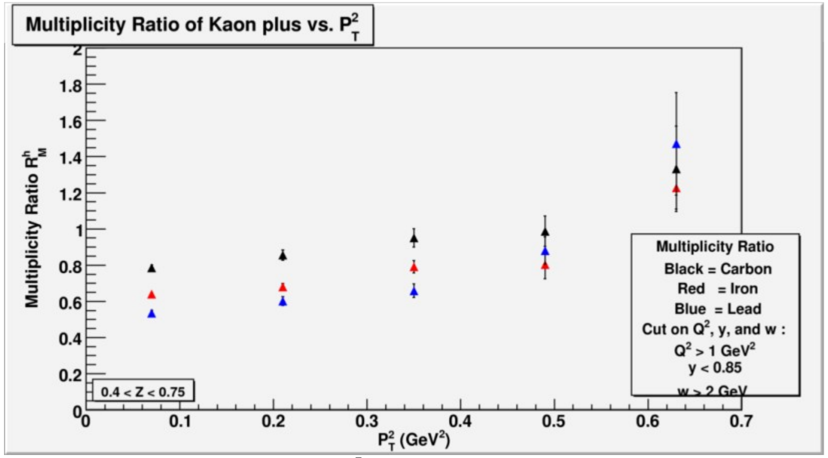




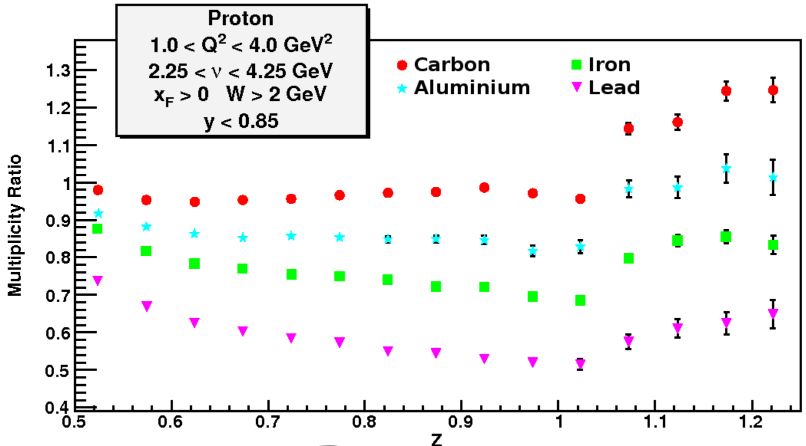
Extraction of the production time !

Kopeliovich *et al.* Nucl.Phys.A782:224-233,2007

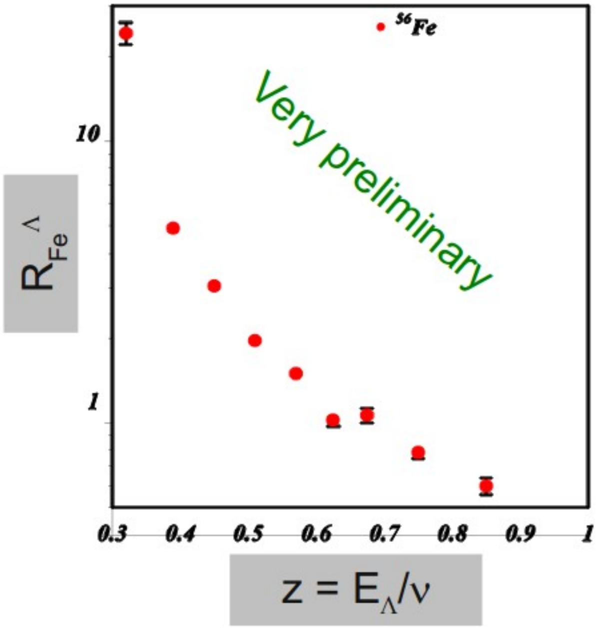
Other Possibilities with CLAS Data

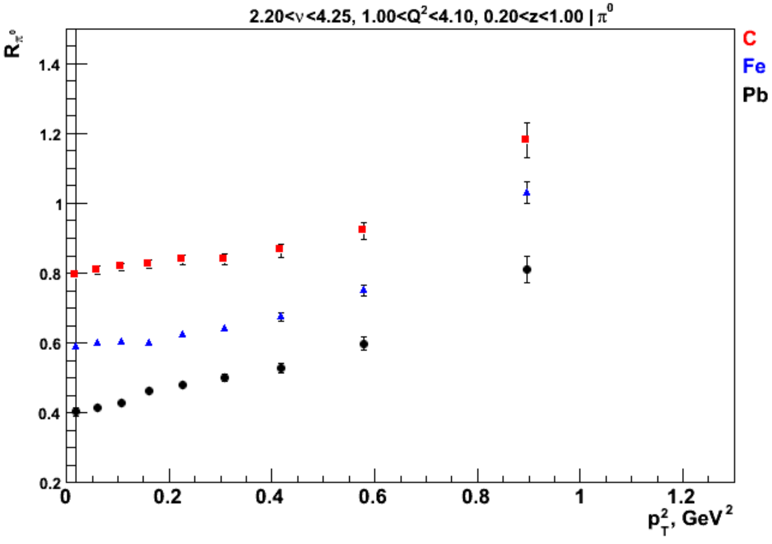


K+



Protons

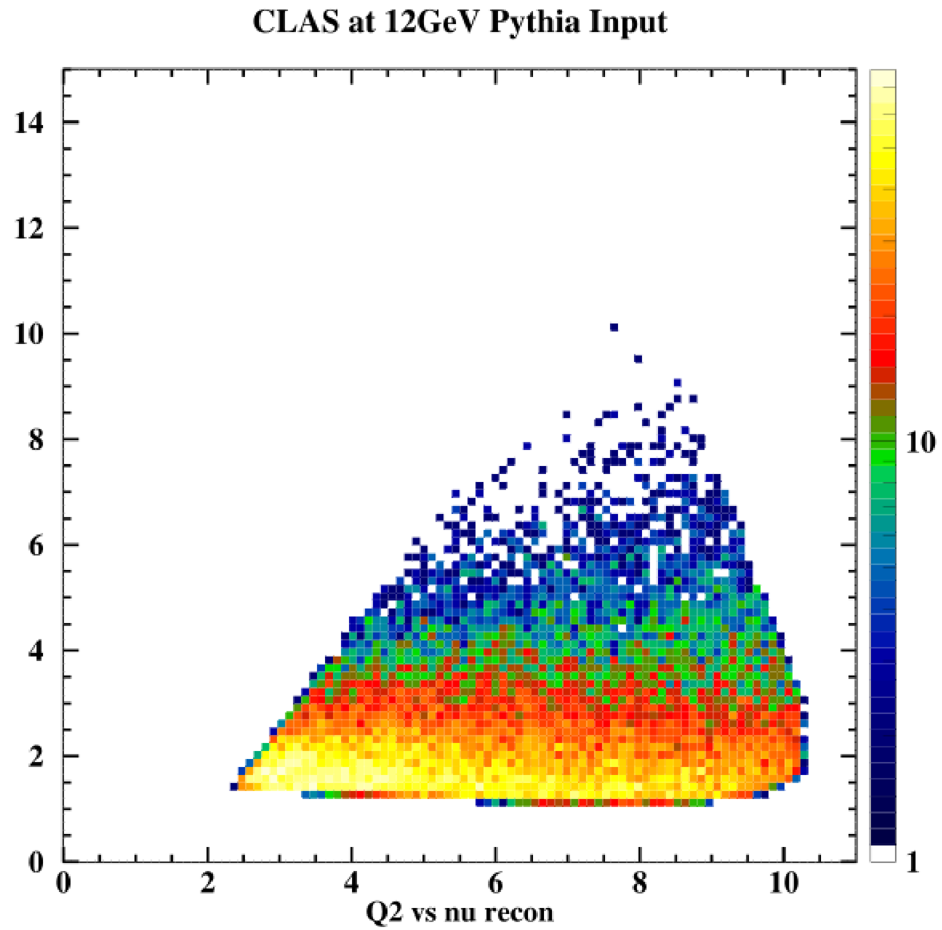




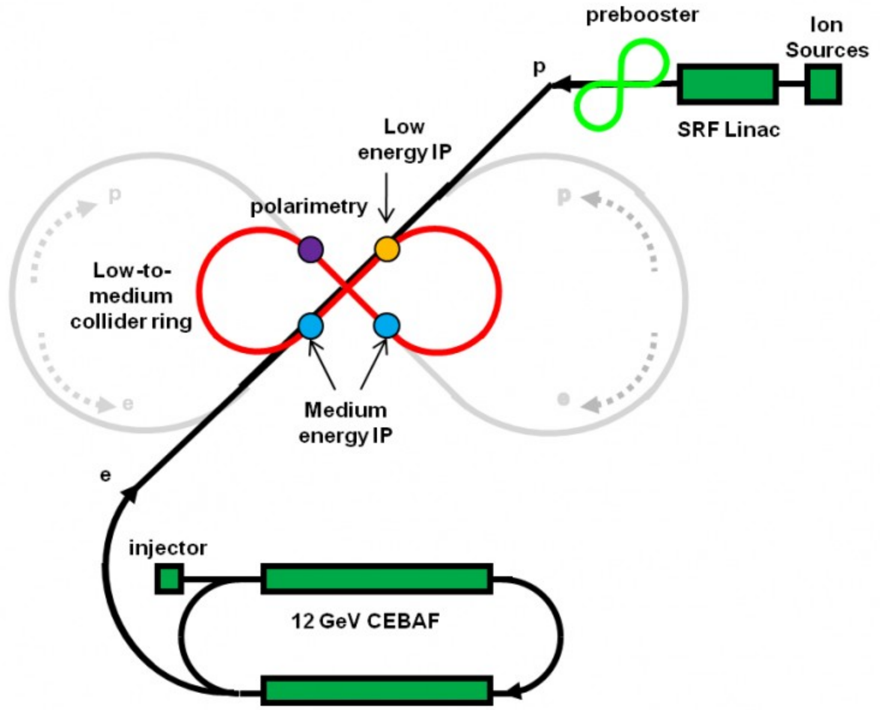
π^0

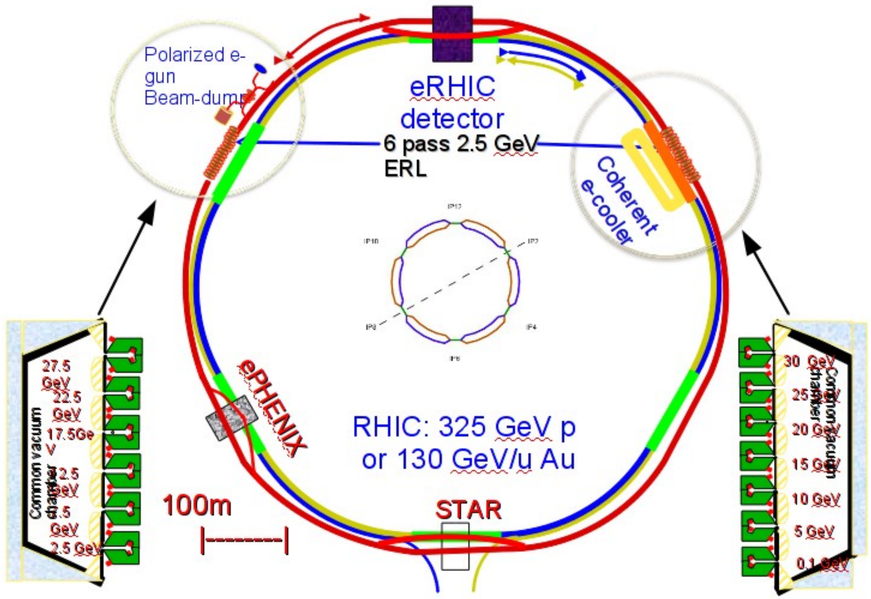
What's Next?

- Planned experiment at CLAS 12 (11 GeV beam)
  - "Quark Propagation and Hadron Formation" proposal, K. Hafidi et al.
  - To explore both attenuation and ΔP_T^2
  - Many particles available as in HERMES
  - Larger kinematic coverage than CLAS
  - Larger luminosity than CLAS (x10) and HERMES (x1000)



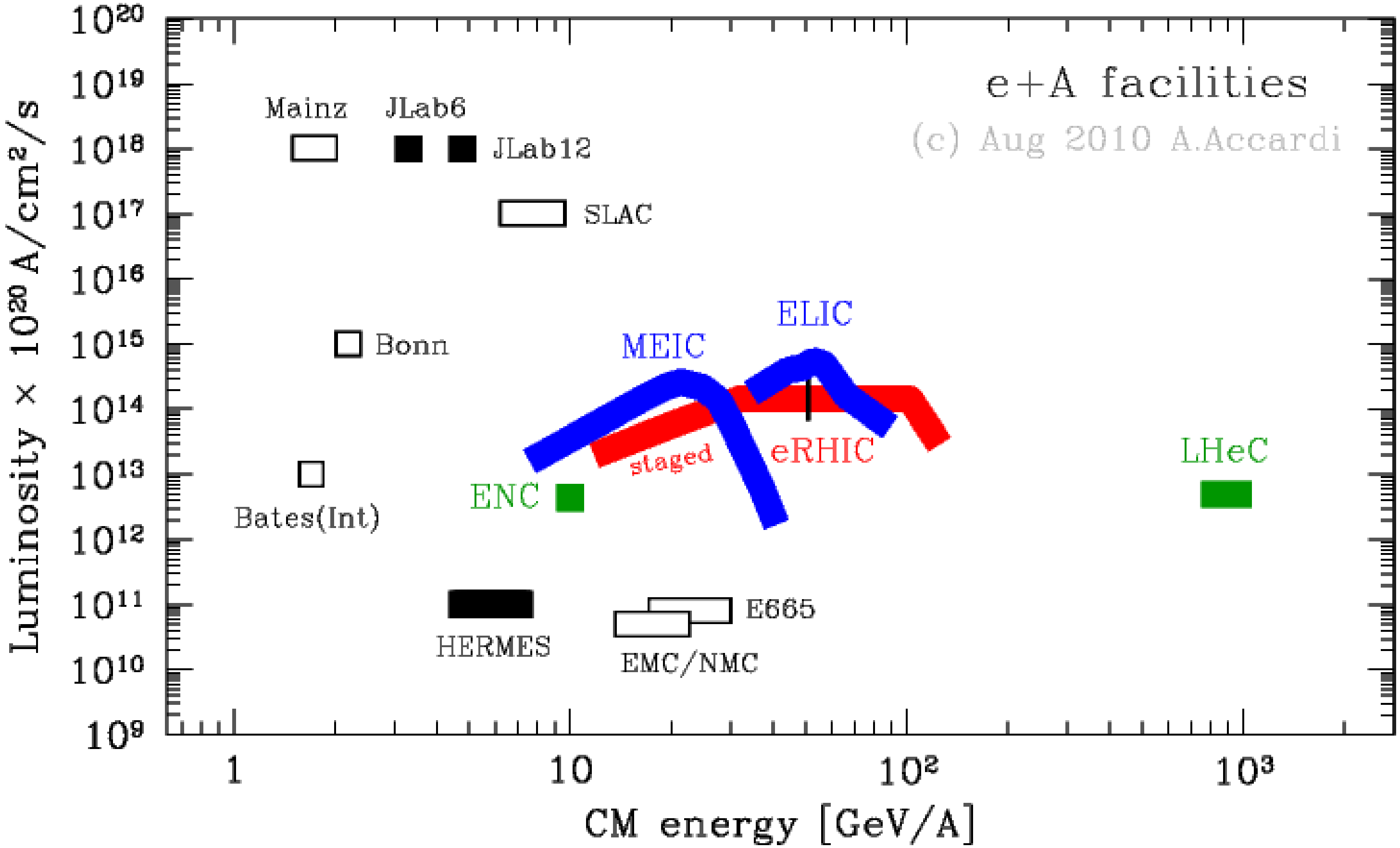
The EIC Projects (1)





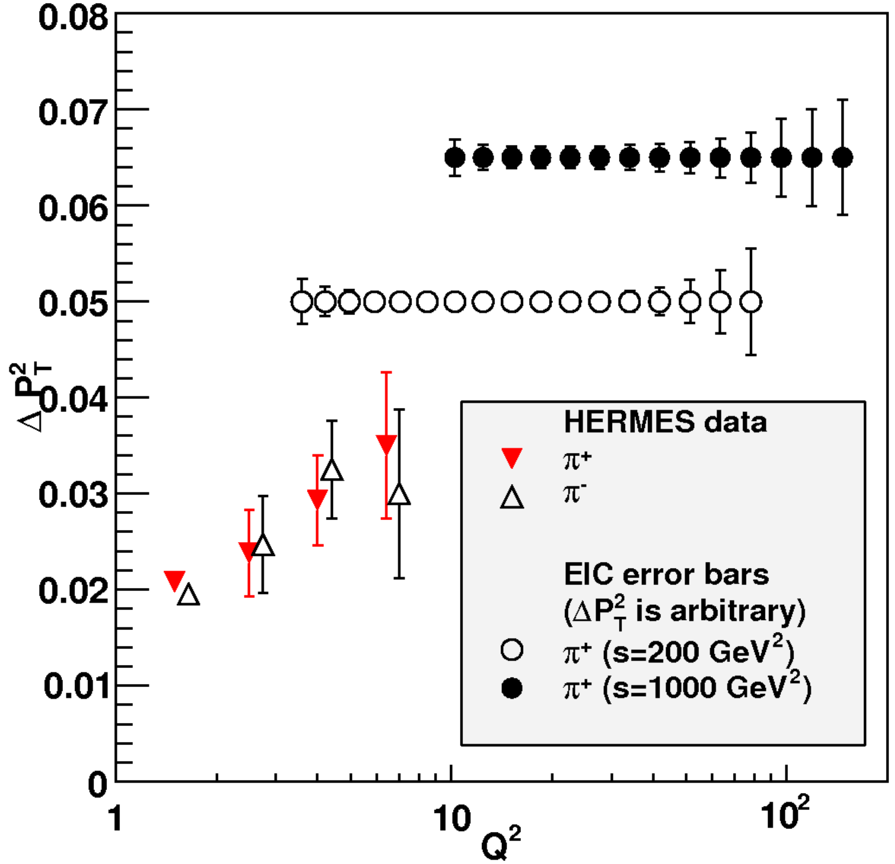
- Project of electron ion collider (EIC)
  - JLab and RHIC projects s~1000GeV^2 and more
  - Low to no attenuation region → centered on ΔP_T^2 measurement
  - Isolate energy loss effects and eventually modification of FF
  - Access to heavy flavor for comparison with Heavy Ion Collisions

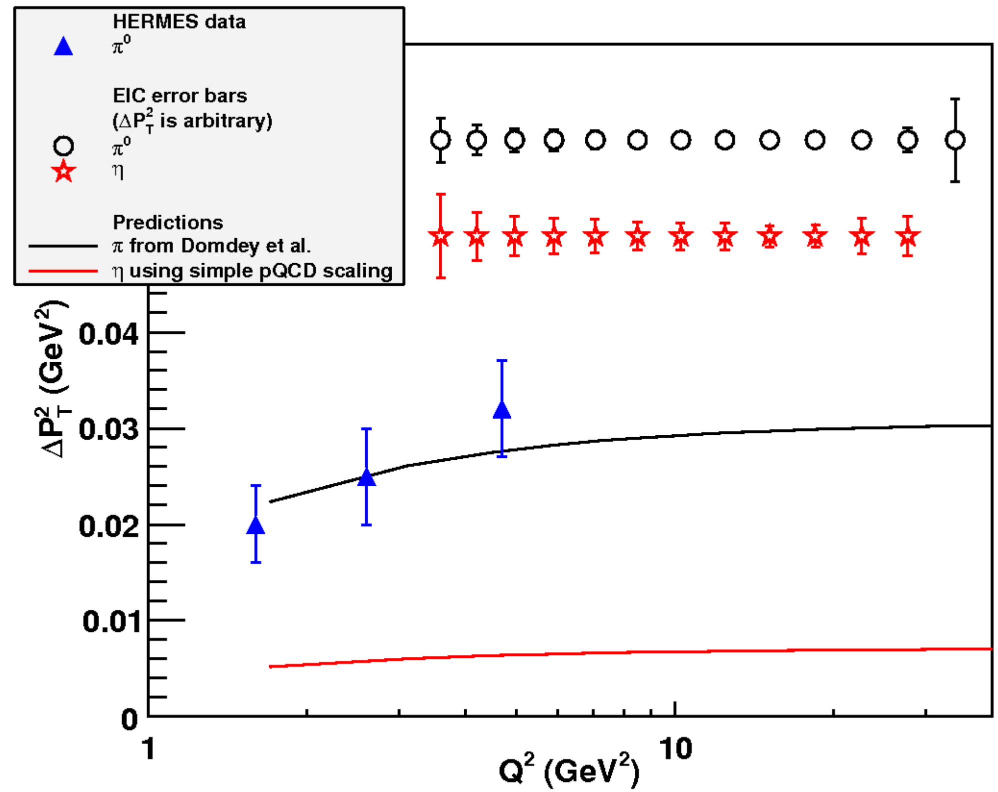
The EIC projects (2)



- Accelerator characteristics are still evolving
- Medium energy version for both
- Goals for both: high energy and high luminosity

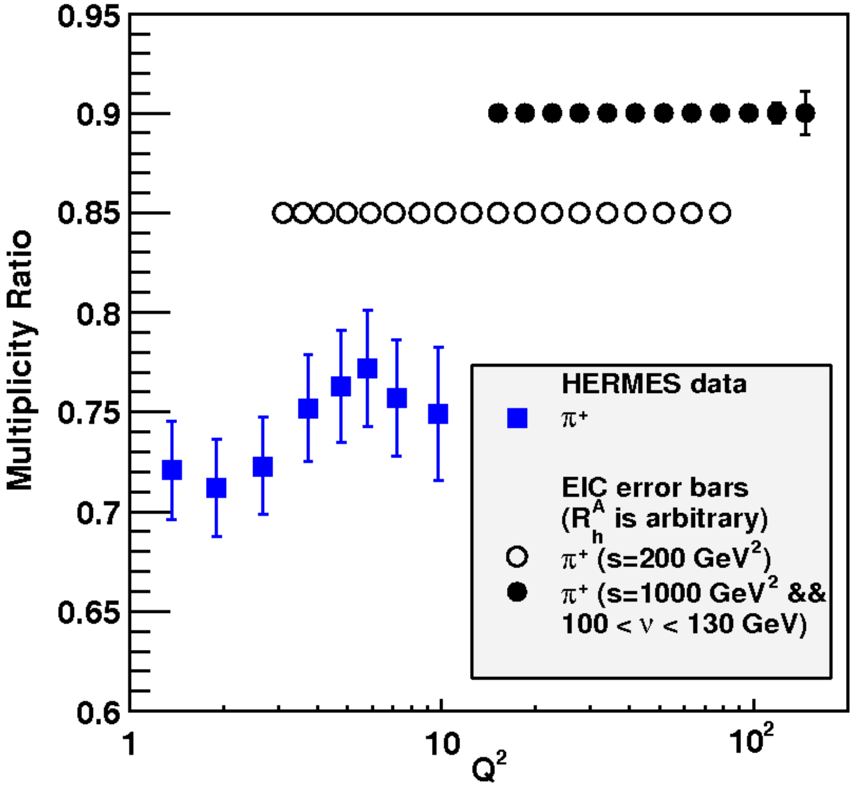
Exploring Pt Broadening





Large Q^2 coverage and many flavor available

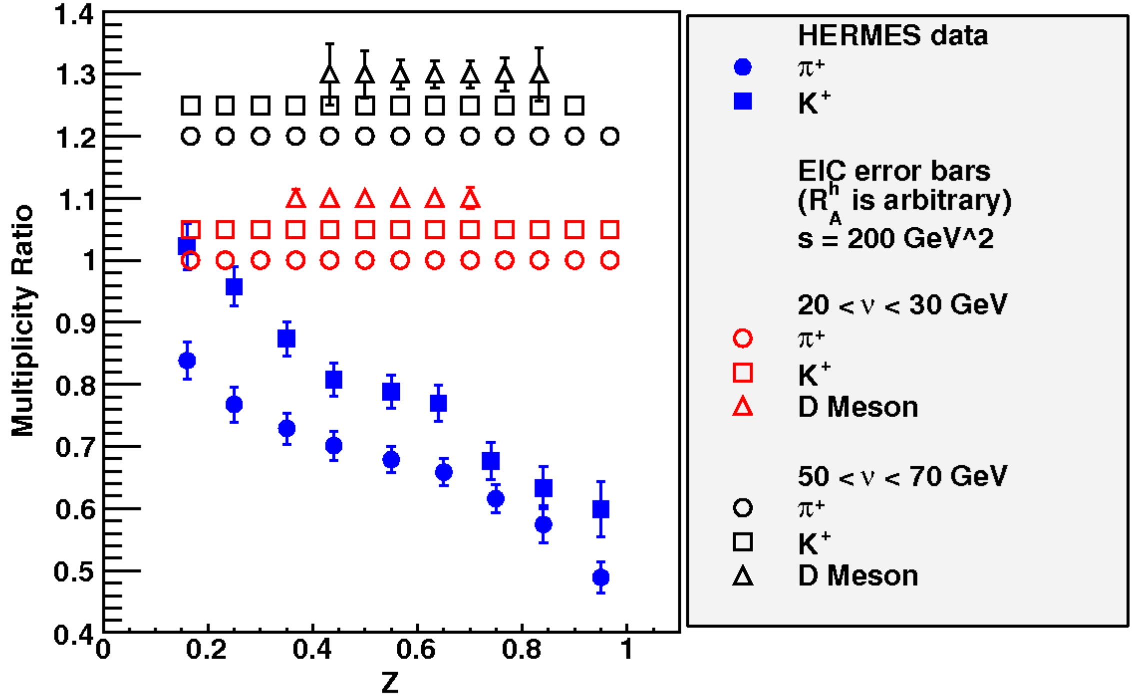
Large Q^2 Leverage

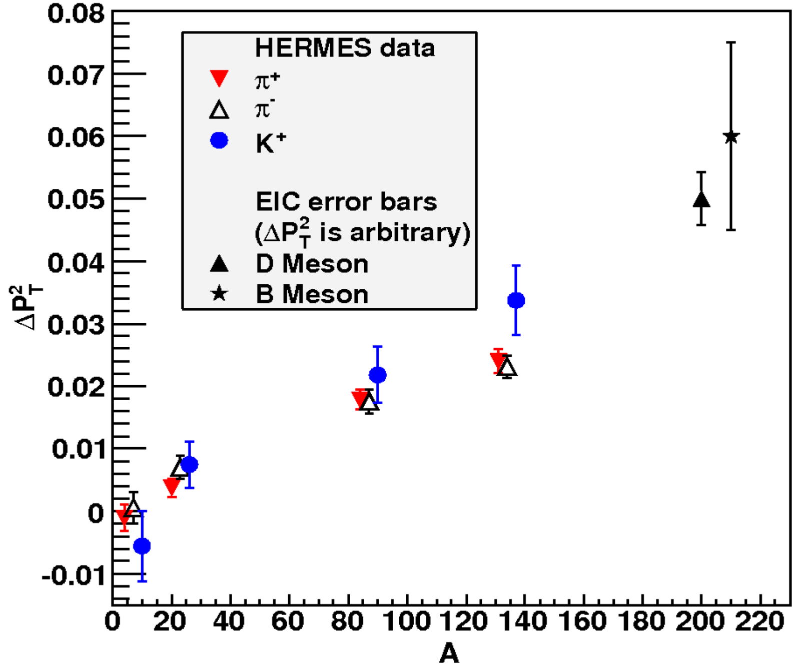


Also available for multiplicity ratio

using the medium energy setting

Precise Heavy Flavor Study





- Charm mesons available with high precision with 200 fb^{-1} (115 days per target)
- Bottom also available but need important luminosity or high reconstruction efficiency

Summary

- Great progress achieved by HERMES
  - But issues with target fragmentation
  - They raised new questions
- CLAS helps clarify some of these questions
  - No Q^2 evolution observed
  - Cronin Effect could be mimicked by other effects
- CLAS provides new results at low energy to test models
  - Saturation of the nuclear effects at high A
  - Clean measurement of ν, Q^2, z and P_T
- The Future
  - More results can be extracted from CLAS data
  - CLAS12 to improve the observations of HERMES and CLAS
  - EIC to explore parton energy loss and medium FF

Backup Slides

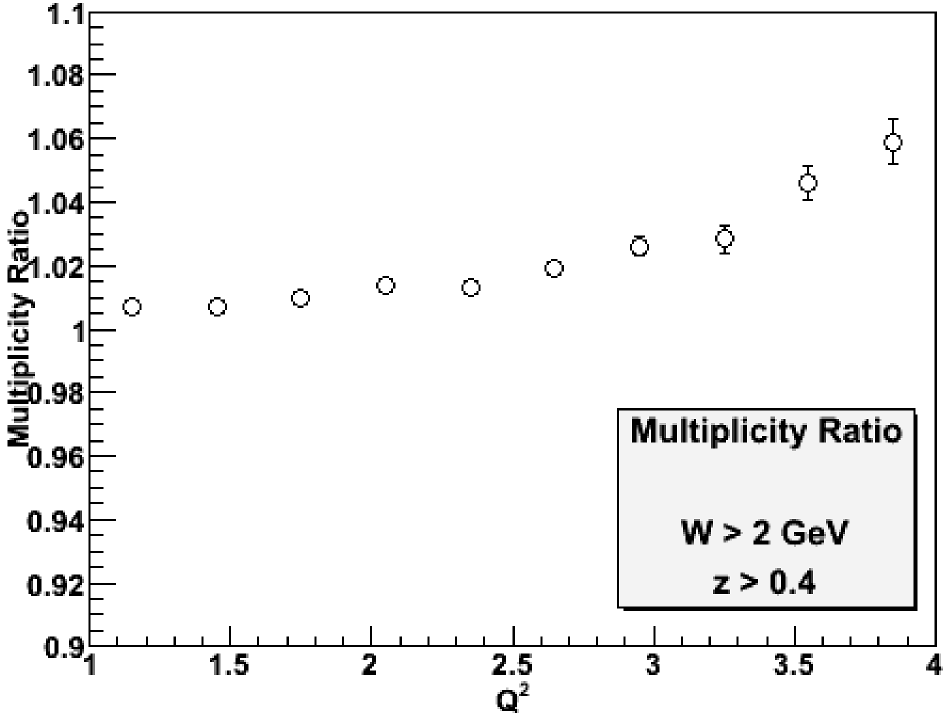
A Monte-Carlo generator to evaluate the Fermi-motion effects

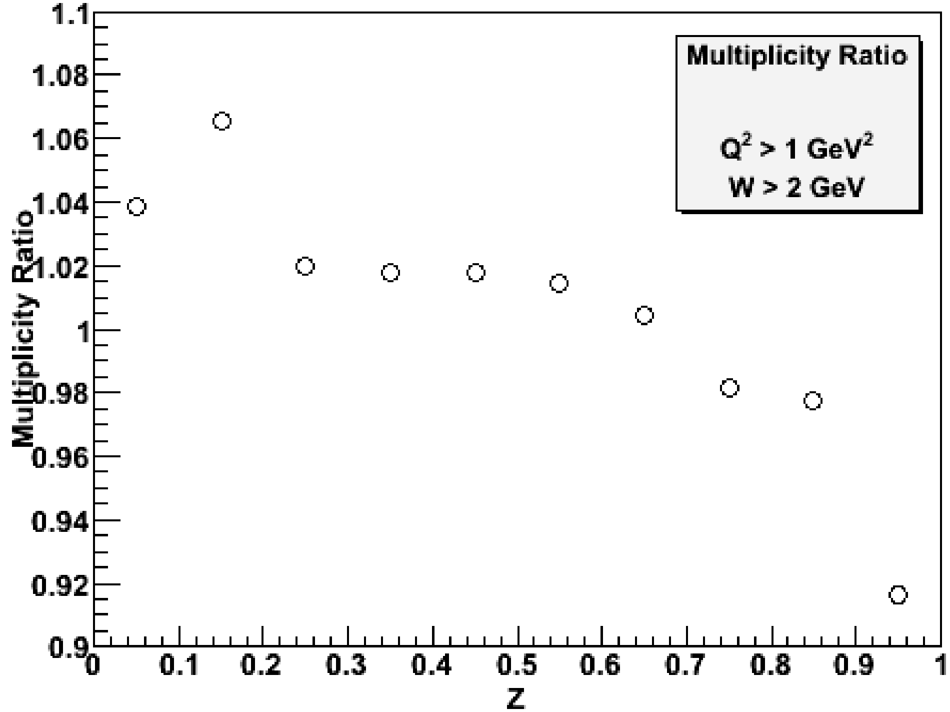
- Nuclear Fermi-motion of the nucleons

- PYTHIA Monte-Carlo
  - Simulation of the electron-nucleon scattering
  - Fragmentation of the products

- Basic acceptance cuts
  - Allows more precise comparison with data

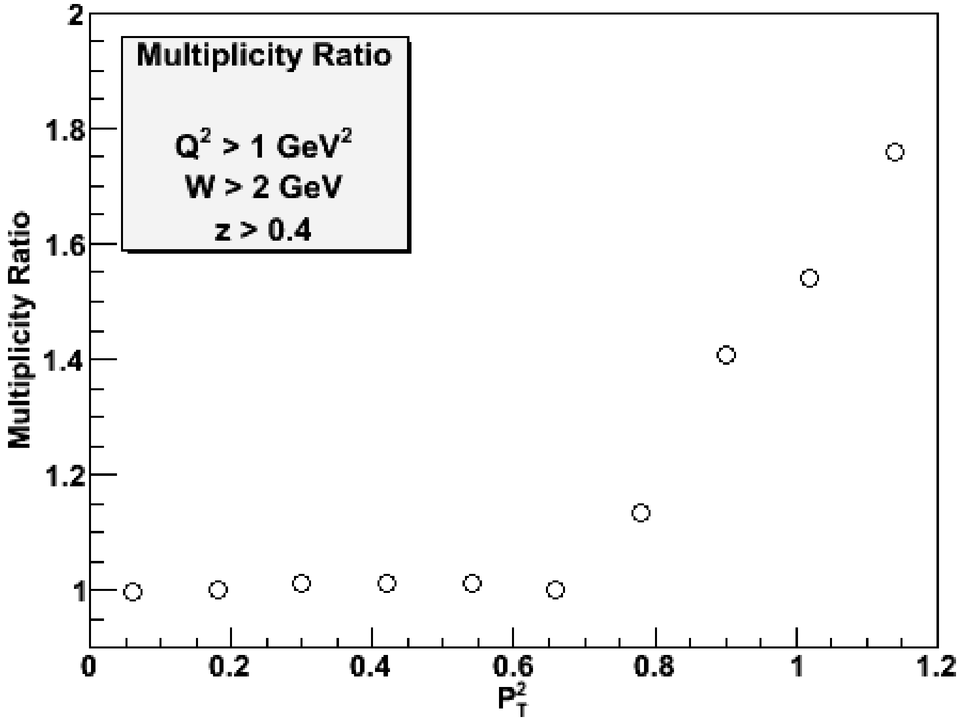
Fermi-motion effect on CLAS (1)

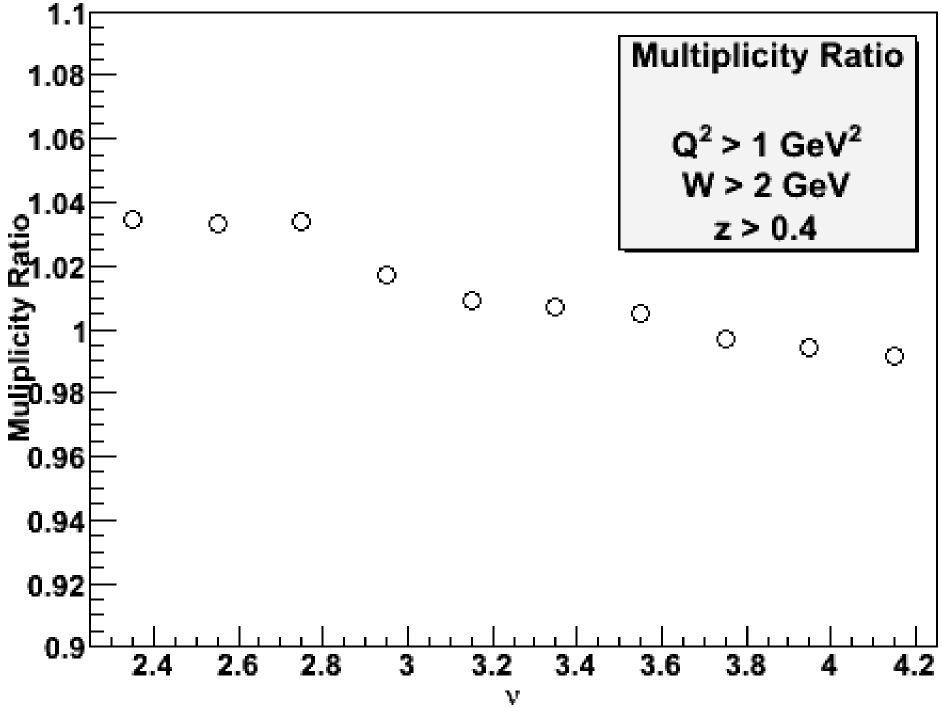




- Fermi-motion can mimic the expected effects!

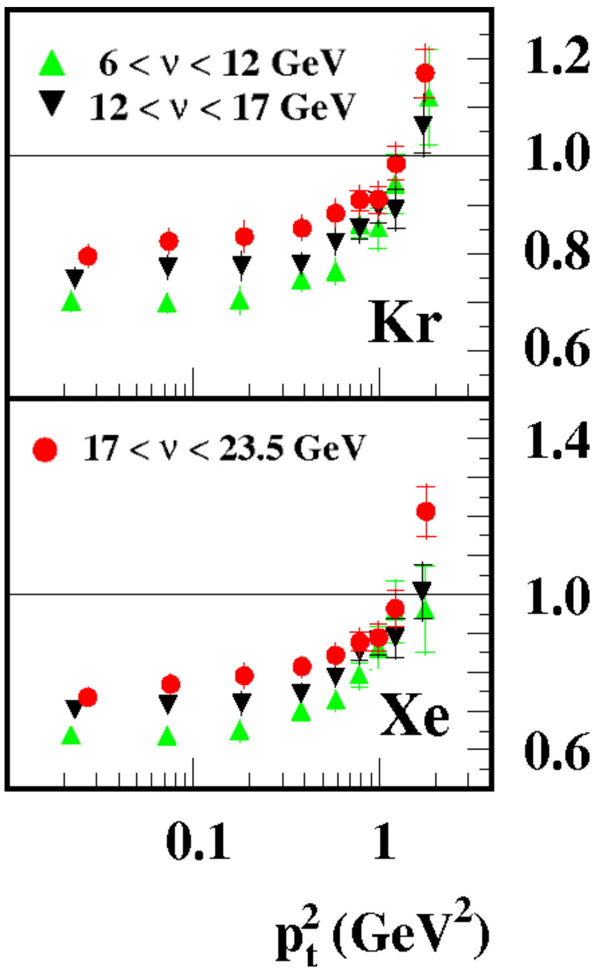
Fermi-motion effect on CLAS (2)





- Fermi-motion can mimic the expected effects again!
- But it can also cancel them!

HERMES


6 < ν < 12 GeV
12 < ν < 17 GeV
17 < ν < 23.5 GeV
Kr
Xe
1.2
1.0
0.8
0.6
1.4
1.0
0.6
0.1
1
p_t^2 (GeV^2)