

Color Propagation and Neutralization in Strongly Interacting Systems

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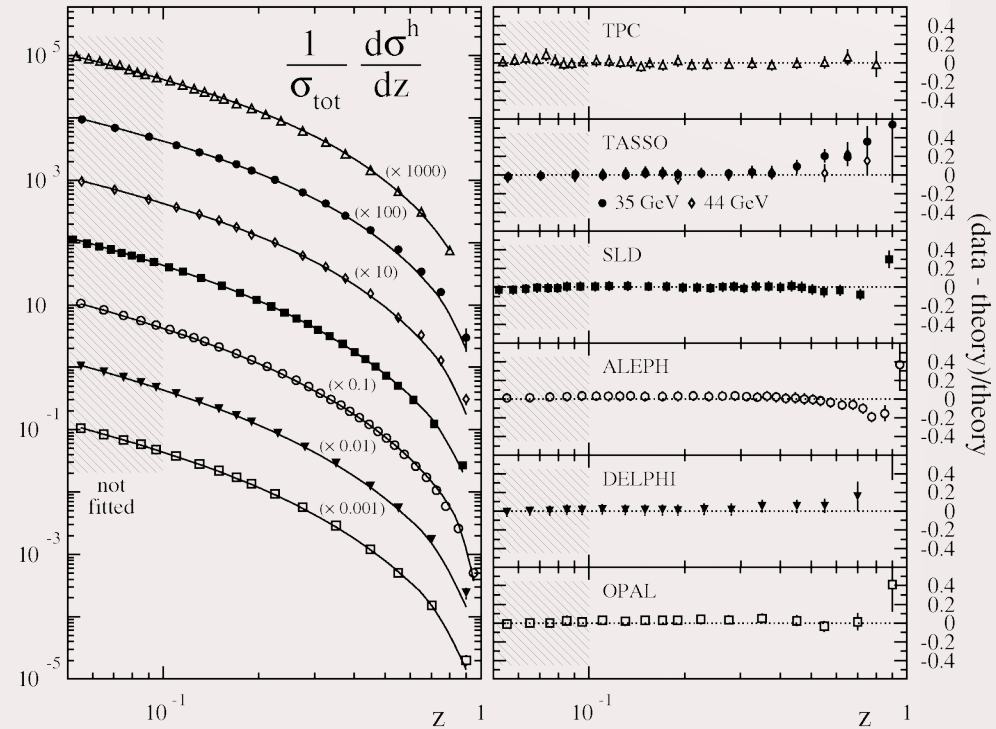
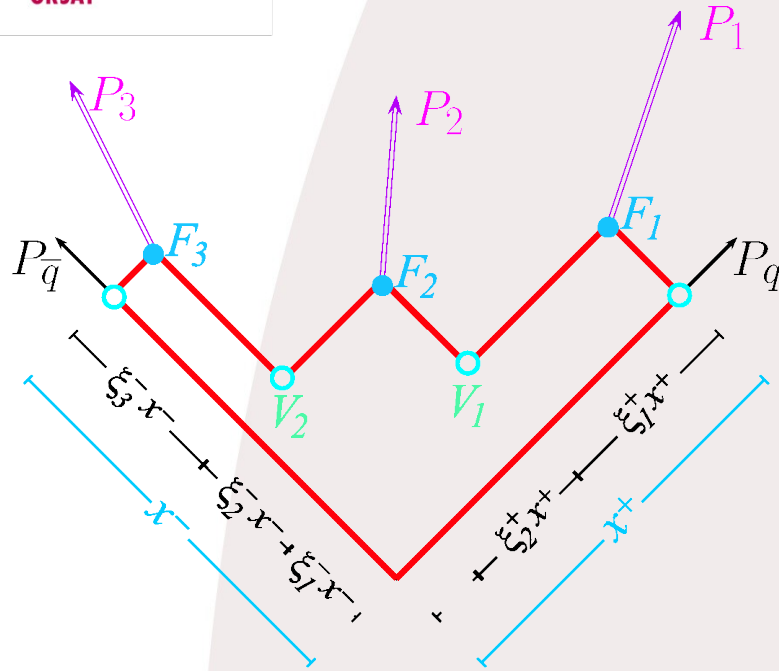
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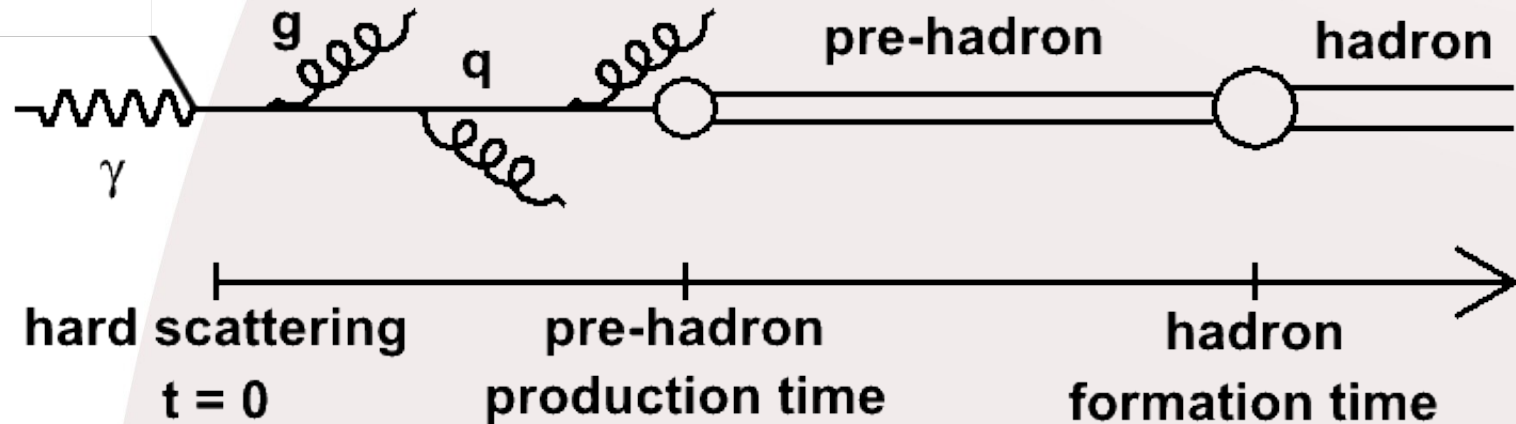
QNP 2015

Fragmentation in Vacuum



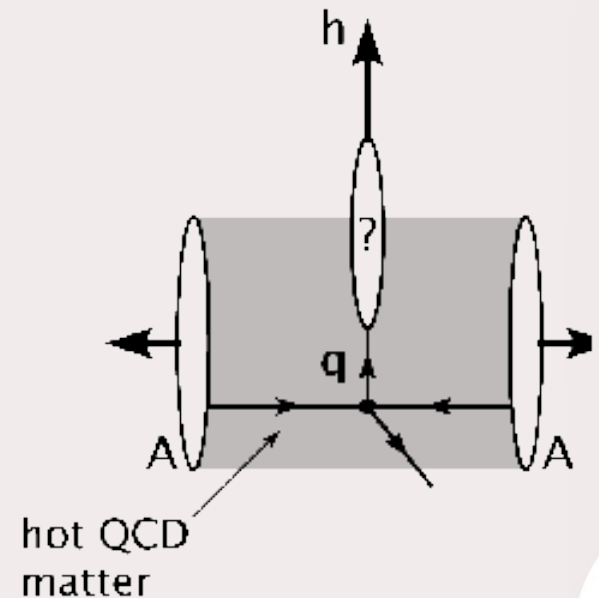
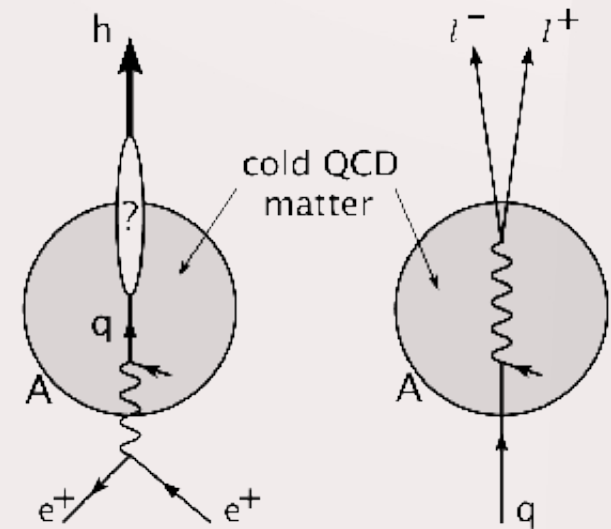
- **Fragmentation functions have been measured by many experiments**
 - They respect evolution equations of QCD
- **Modeled in different ways**
 - String or cluster models for example
- **The dynamic and the intermediate stages are ignored**

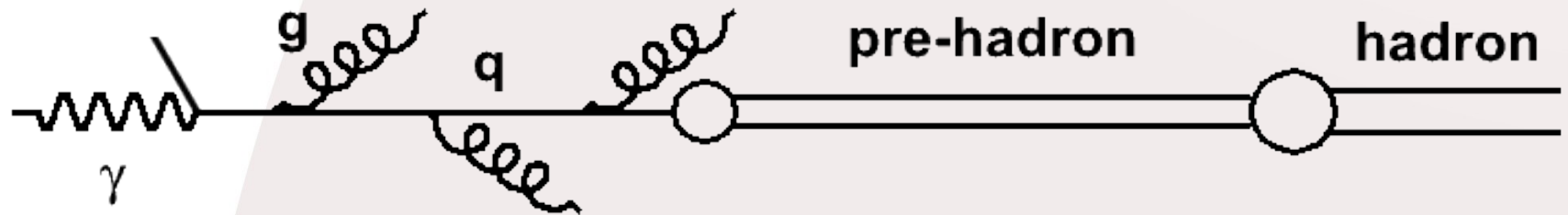
The Hadronization Process



- **Process by which colored objects color neutralizes**
 - Mix Non perturbative and perturbative QCD process
 - Need some modeling and data
- **We can separate the process in two parts**
 - Production time → propagation of the colored quark
 - Formation time → propagation of the color neutral prehadron
- **Some theoretical predictions but no experimental quantification of these times !**
- **With nuclear targets of different size we can measure them!**
 - However the model uncertainty leads to complicated interpretations
 - We therefore need precise data on a wide set of nuclei and a wide kinematic range to measure these times

- **Understand the hadronization process**
 - Measuring the characteristic times
 - Measuring parton energy loss in QCD medium
 - Understanding the pre-hadron structure
- **Characterization of the QCD medium**
 - Using parton energy loss
 - Compare cold to hot nuclear matter
 - Understand QCD evolution in medium
- **Reduce systematic effects on measurements where attenuation needs to be corrected**
 - Lepton scattering is a unique process for its control over the initial state
 - Neutrino experiments
 - Nucleon structure in nuclei





- **Models mostly differ on the nature of the dominating nuclear interaction**
 - Parton energy loss
 - Modified DGLAP evolution
 - Hadron absorption
- **Important questions are**
 - Absorption mainly due to parton energy loss or hadron absorption ?
 - Is there a modification of the evolution in medium ?
 - If yes, is it sizable in cold nuclear matter?
- **Many models exist with different answers to these questions**
 - Some pure models (see parton energy loss calculations in this talk for example)
 - Mixed models (with all possible combinations represented in the literature)

Experiment Summary

- **Experiments of lepton-nuclei Semi-Inclusive DIS**
- **SLAC experiment**
 - First experiment, rough measurement of multiplicity ratios
- **EMC experiment (CERN)**
 - Measure ratios at higher energy with a little more precision
- **E665 experiment (Fermi Lab)**
 - Ratios measured relatively to the number of slow protons
 - Enlighten the difference between target and current fragmentation
- **HERMES experiment (DESY)**
 - First precision measurement of multiplicity ratios
 - First measurement to differentiate the hadrons
 - First transverse momentum broadening measurement
- **Hall C experiment (JLab)**
 - Limited kinematic but very precise
- **CLAS experiment (JLab)**
 - Very important statistics and nuclei panel

- **Multiplicity ratio** → **Characterizes the attenuation**

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

- **Transverse momentum broadening**

→ Characterizes the modification of the Pt spectrum

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

- **These are normalized by deuterium to reduce isospin effects**

→ Other nuclei can be used for normalization

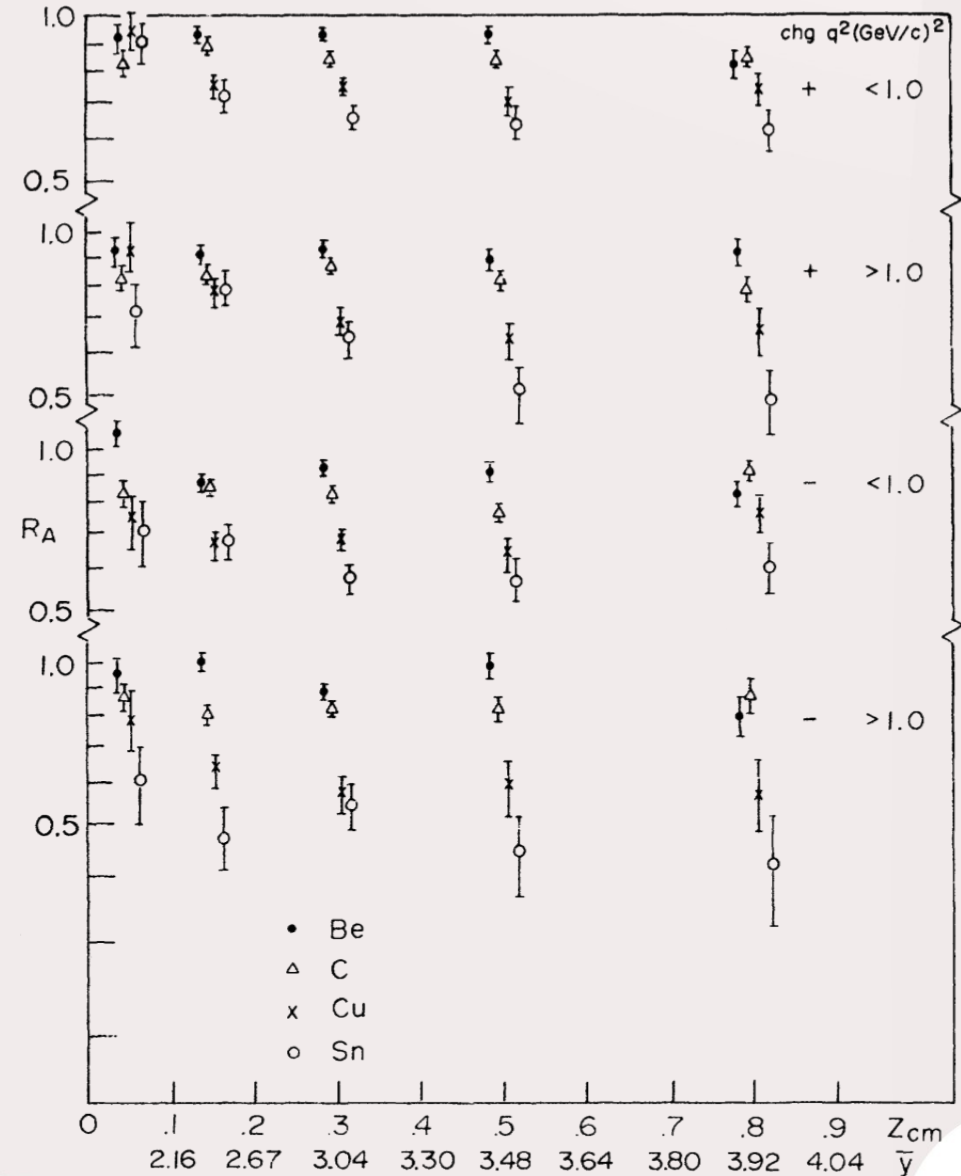
- **Early nuclear DIS (1978)**

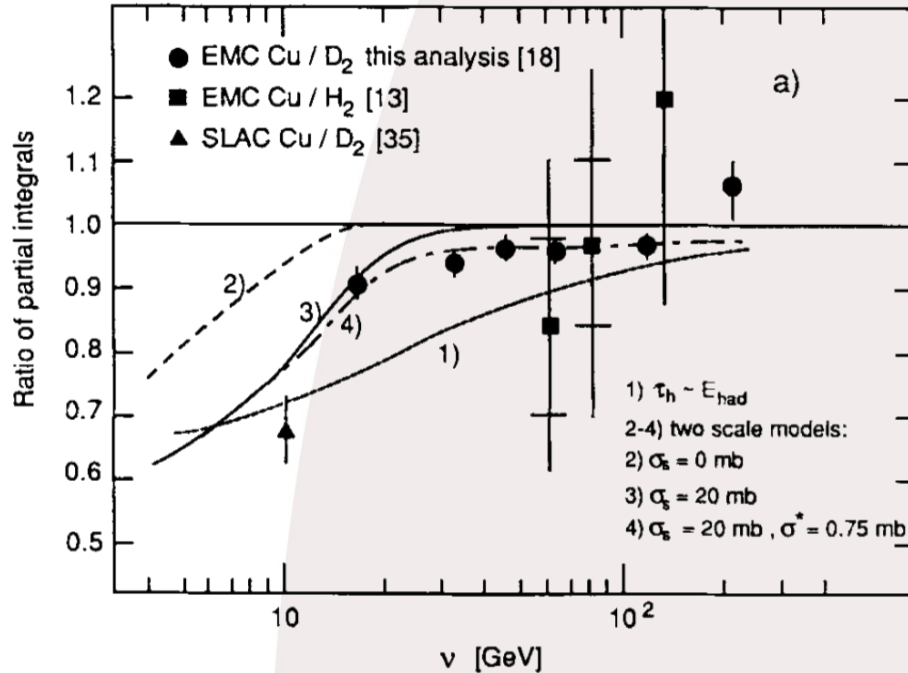
- Simple hadron ratios, not multiplicity ratios
- EMC effect not known yet

- **Attenuation is clearly observed**

- Logically enhanced when using heavier nuclei
- Decrease with z
 - Shorter production length ?
 - or Reduced parton energy loss ?

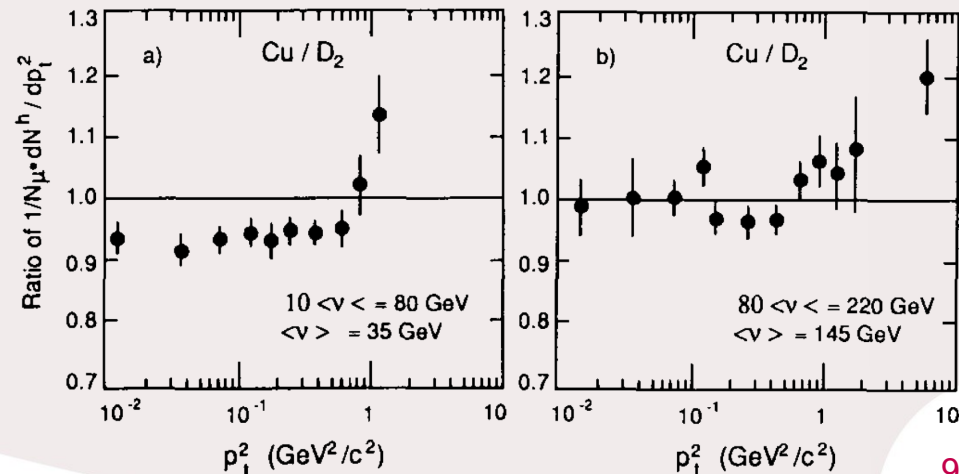
- **No effect is observed for the other variables**



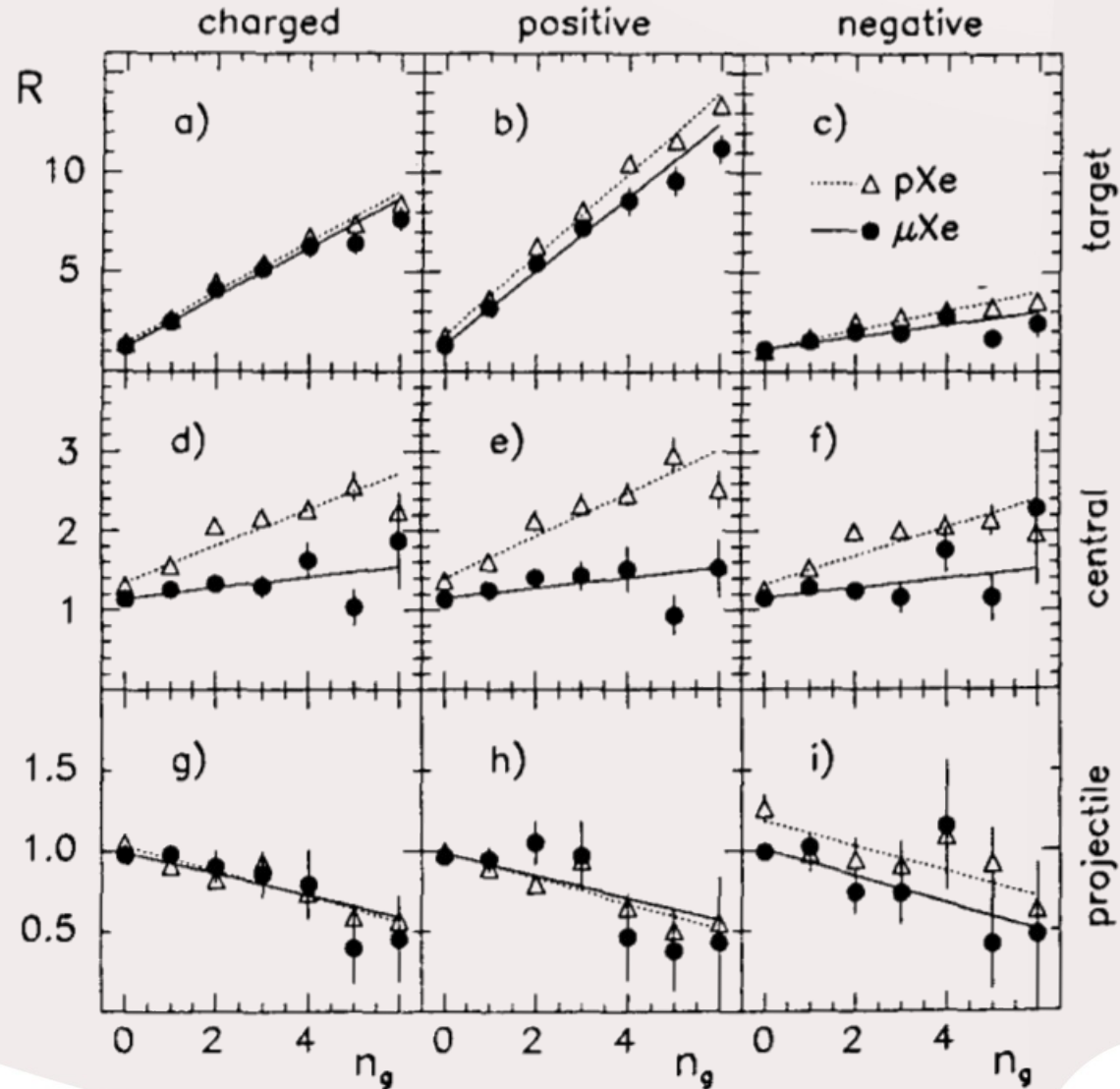


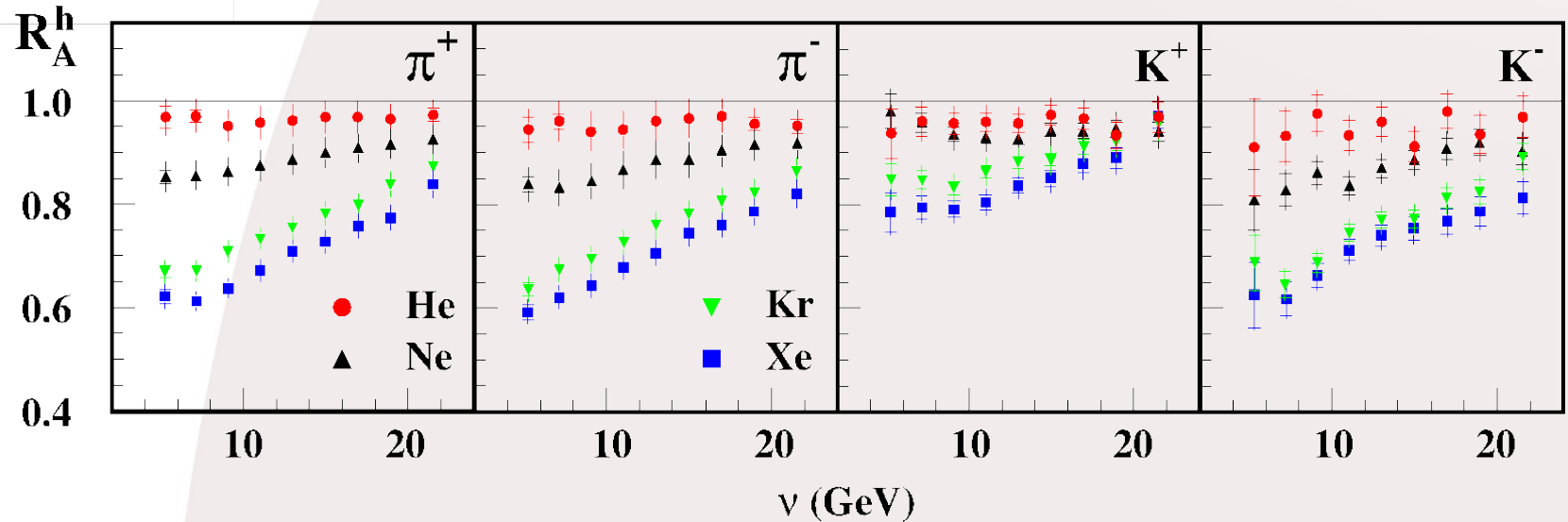
- Together with SLAC data
- Attenuation appears reduced at higher v
 - Asymptotic < 1 ?
 - Explained by the Lorentz boost
- Can help to explore hadronization dynamics but with low precision

- High transverse momentum have increased hadron production
 - Multiple soft scattering
 - Target fragmentation

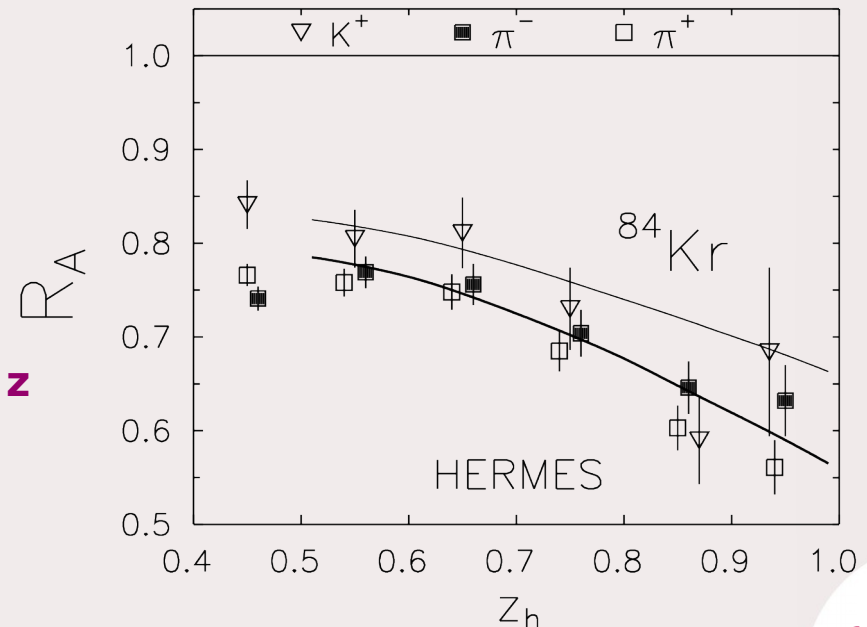


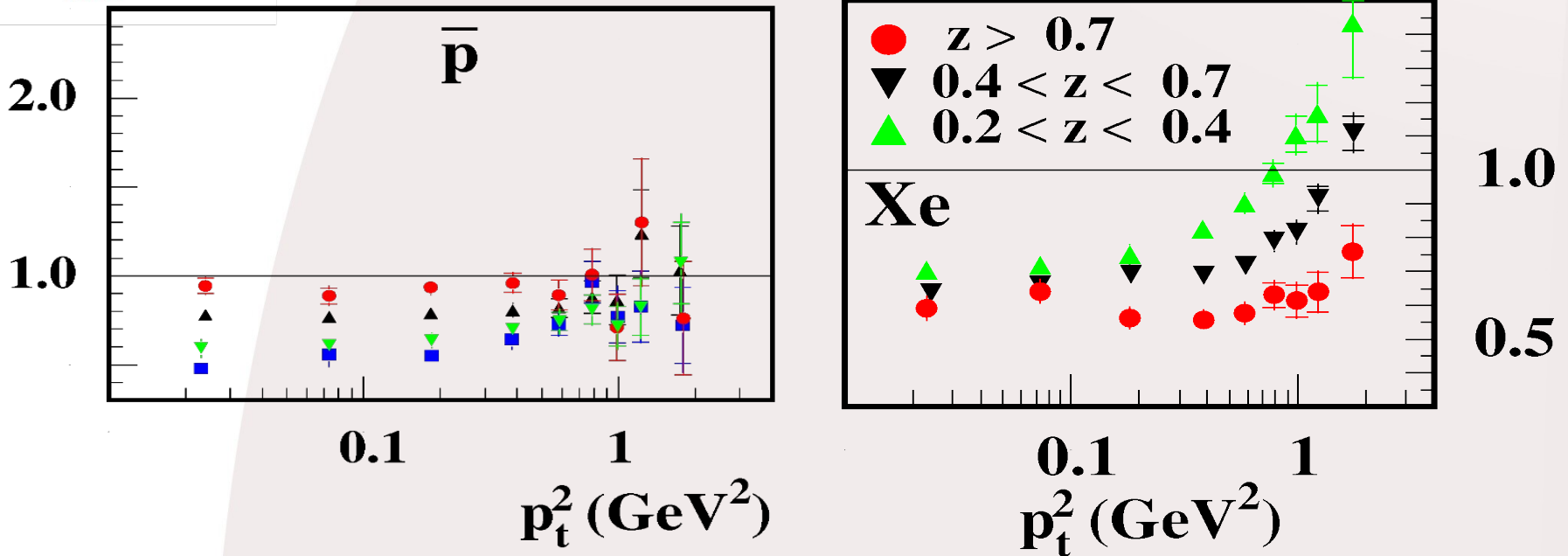
- **Use numbers of slow protons (n_g)**
 - $n_g=0 \rightarrow$ Xe behave like deuterium
 - the nuclear effect grows linearly with n_g
- **Study target and current regions**
 - the intermediate region follows the target region





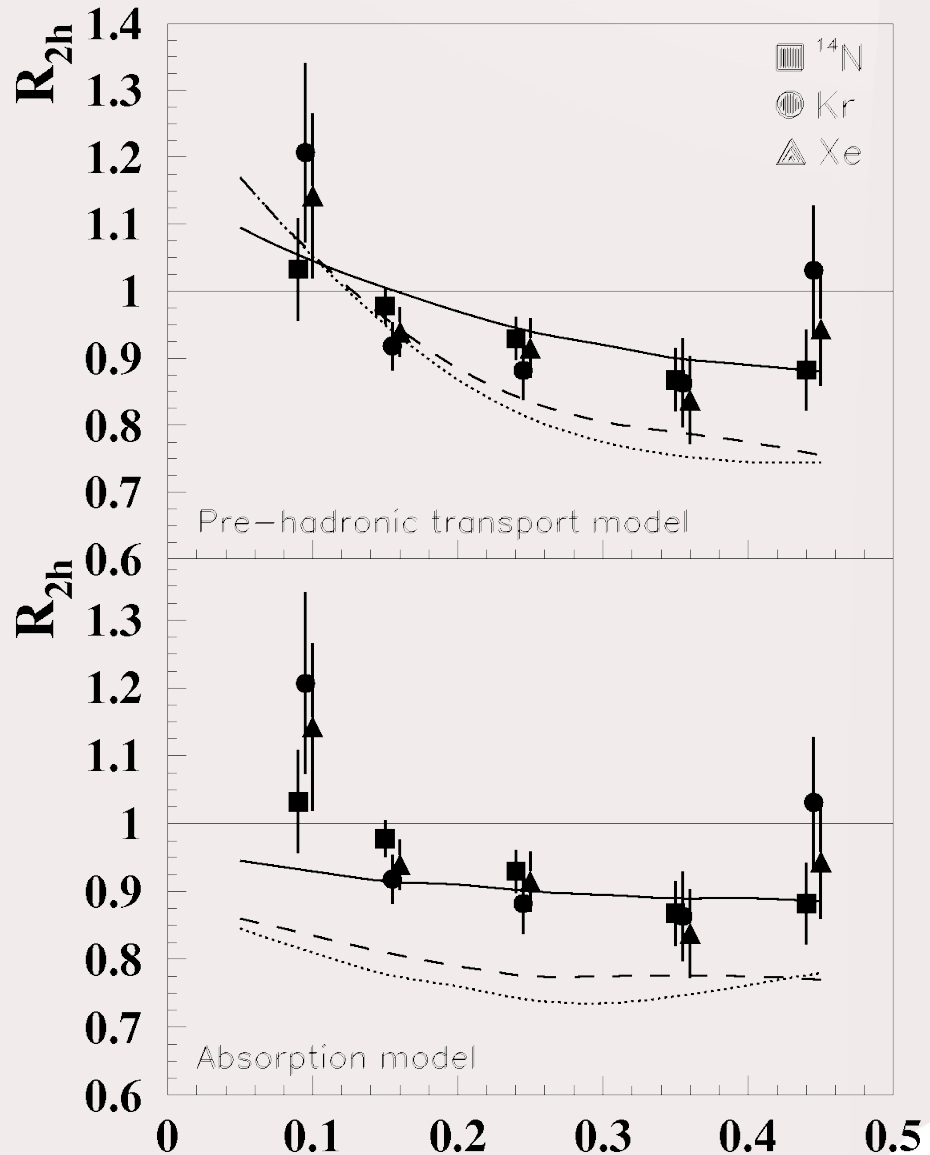
- **Explore all hadrons independently**
- **K- is less suppressed**
 - Due to the smaller cross section of K^+ ?
 - The different behavior of the FF?
- **Not enough !**
 - contamination from $\pi + p \rightarrow \Lambda + K$?
- **Can be resolved by selecting higher z**
 - Less target fragmentation
- **Cumulating all effects it can be described**
 - Kopeliovich et al. (2004)

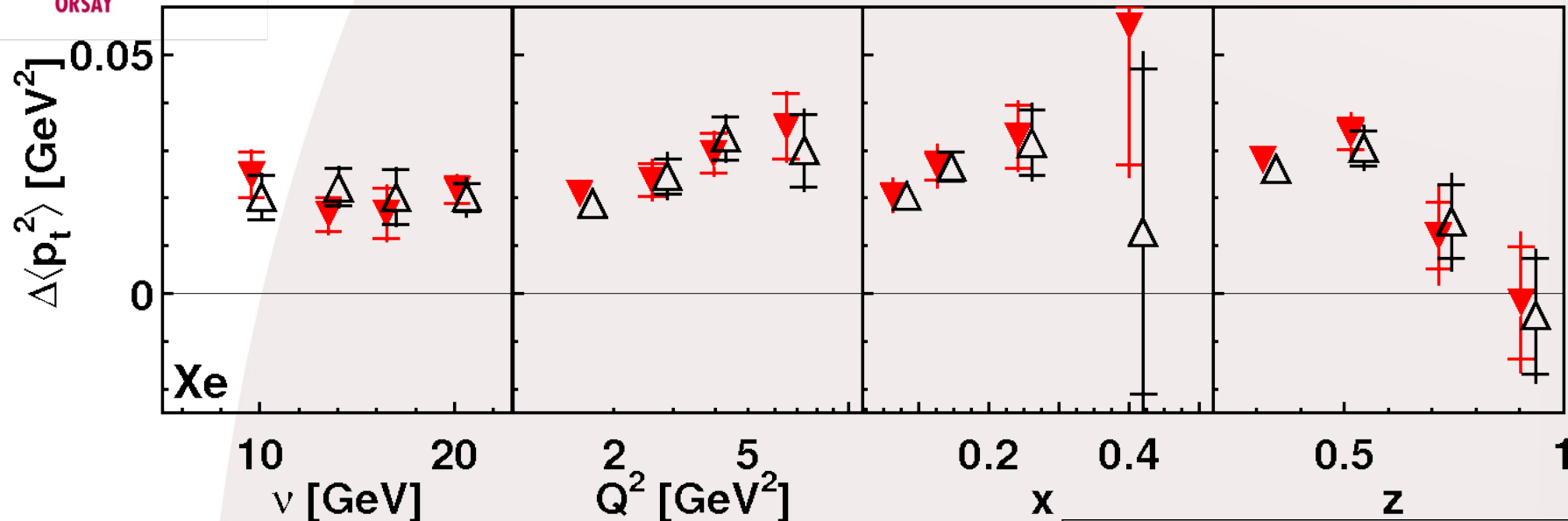




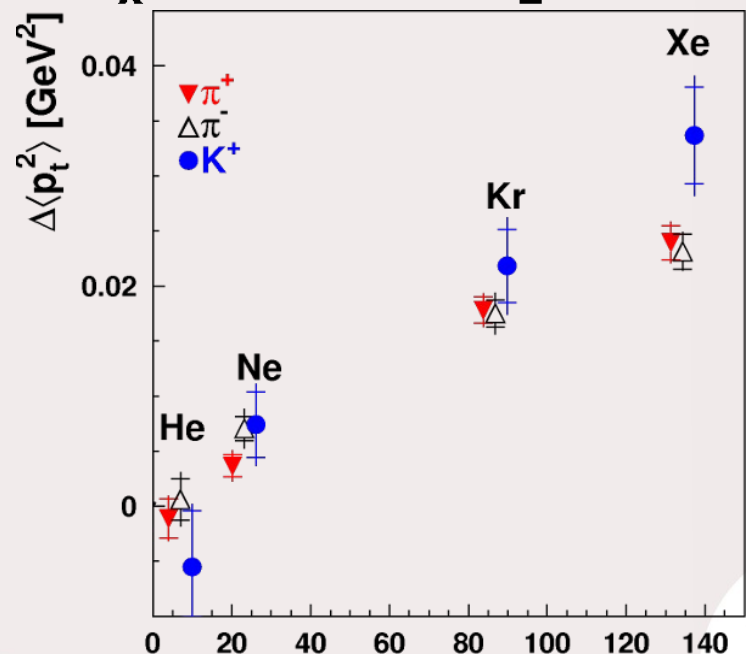
- **Cronin effect is limited in the case of anti-protons**
- **Cronin effect is stronger at low z**
 - Enhancement due to target fragmentation leaking in the sample
 - Interpretation of data in terms of hadronization requires careful selection of events

- **Multiplicity ratio of two hadrons production**
- **The A scaling disappears**
 - in contradiction with all the main models
 - most model ignore these data
- **Explanation based on a modification of the FF ?**
 - Part of the energy lost by the leading hadron goes to the sub-leading hadrons ?





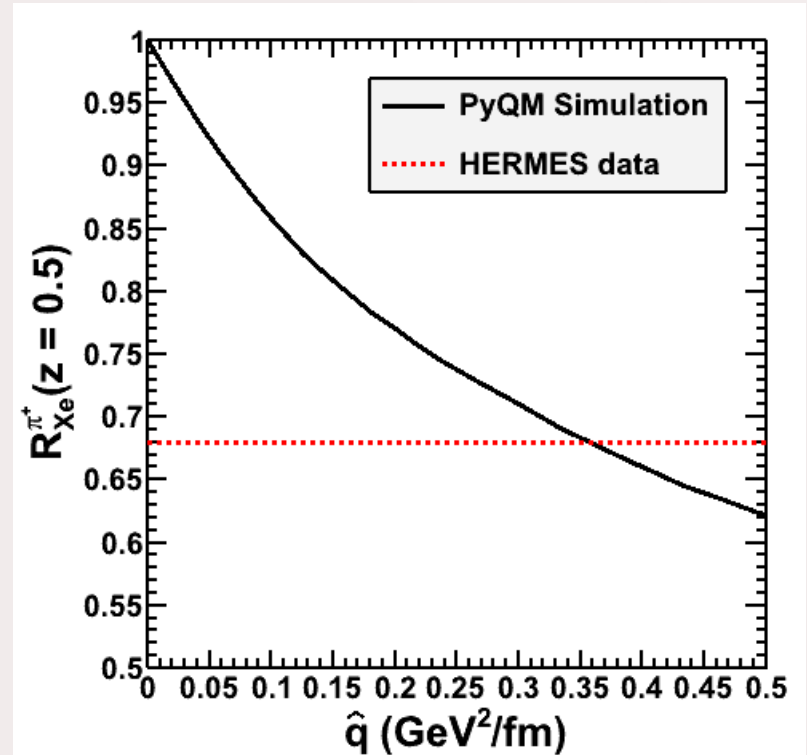
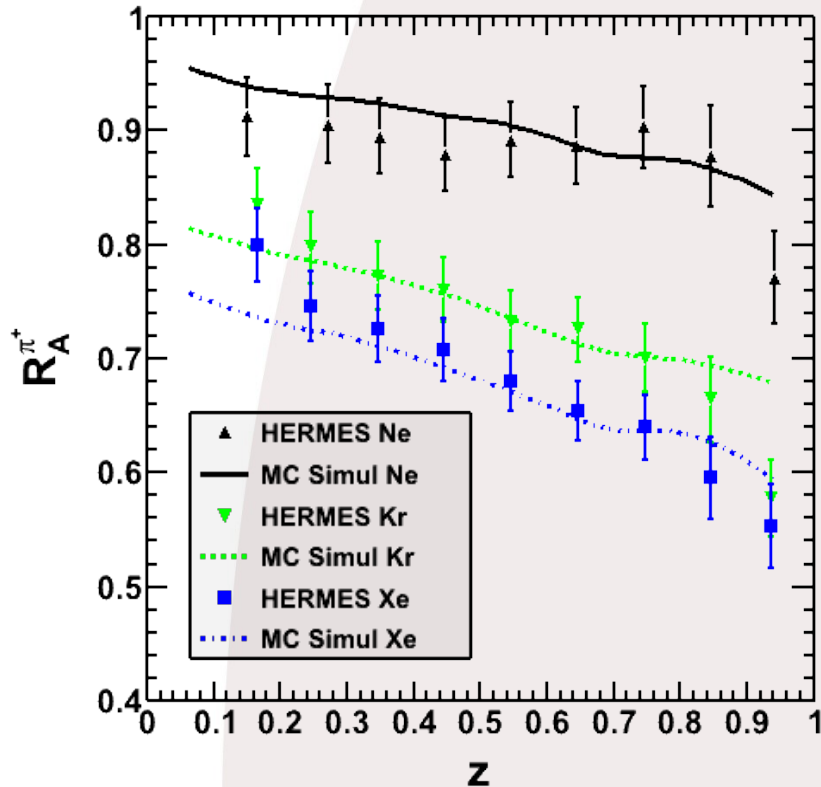
- **No broadening at high z**
 - Effect at the partonic level
- **Increase with Q^2**
 - Predicted in the framework of parton energy loss
- **Dependence in A not conclusive**
 - Compatible with $A^{1/3}$ and $A^{2/3}$
- **Gives access to q hat the transport coefficient of the medium**
 - A killer for parton energy loss models?



- **Nuclear Fermi-motion of the nucleons**
 - Relevant mostly for the lower energies
- **PYTHIA Monte-Carlo**
 - Simulation of the electron-nucleon scattering
- **Parton Energy Loss**
 - Based on Salgado&Wiedmann calculation (PRD68 014008, 2003)
 - Simulating nuclear material using realistic density profile
 - Assuming fragmentation will occur outside the nuclei → we cross all the nuclear material
- **Back to PYTHIA**
 - Fragmentation of the partons
- **Basic acceptance cuts**
 - Allows more precise comparison with data

Work with A. Accardi

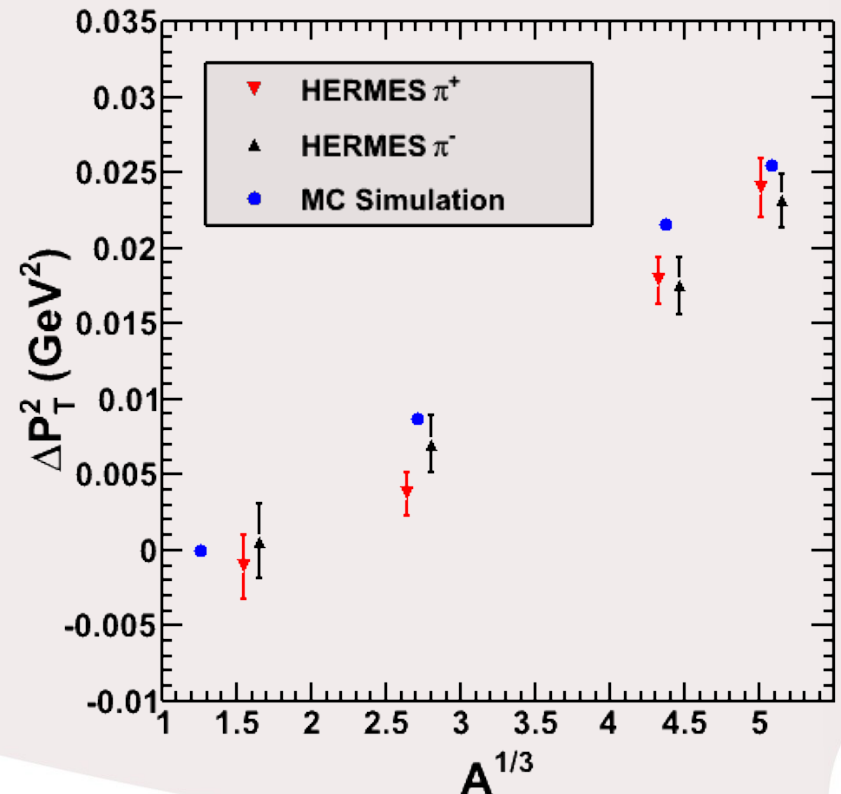
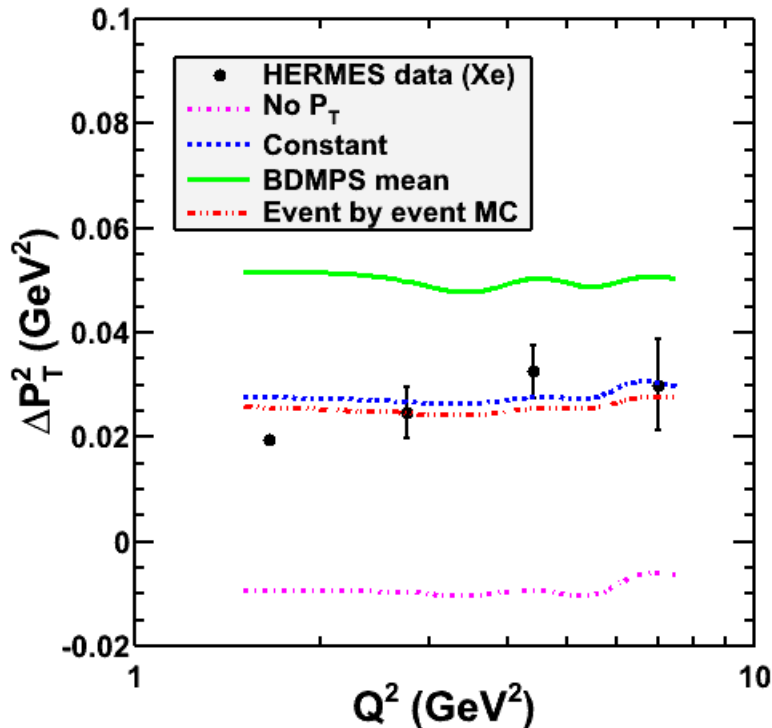
Attenuation from HERMES



- **Good description with $\hat{q} = 0.36 \text{ GeV}^2/\text{fm}$**
 - Single parameter model !
 - Value is high but still in range to other calculation
- **Not consistent with observed transverse momentum?**

Transverse Momentum

- **How do we get from $Lx0.36$ to ~ 0.03 ?**
 - Reduction by z square (~ 0.1)
 - Reduction due to lower parton energy
 - Reduction due to absorption
- **It gives good description of the transverse momentum together with the transverse momentum broadening**

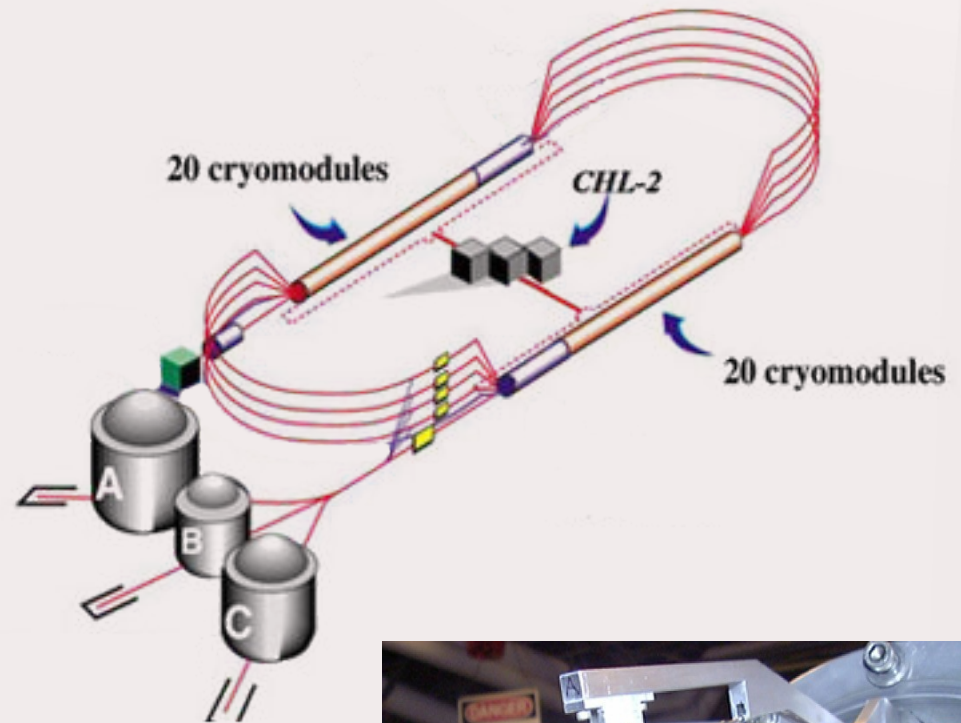


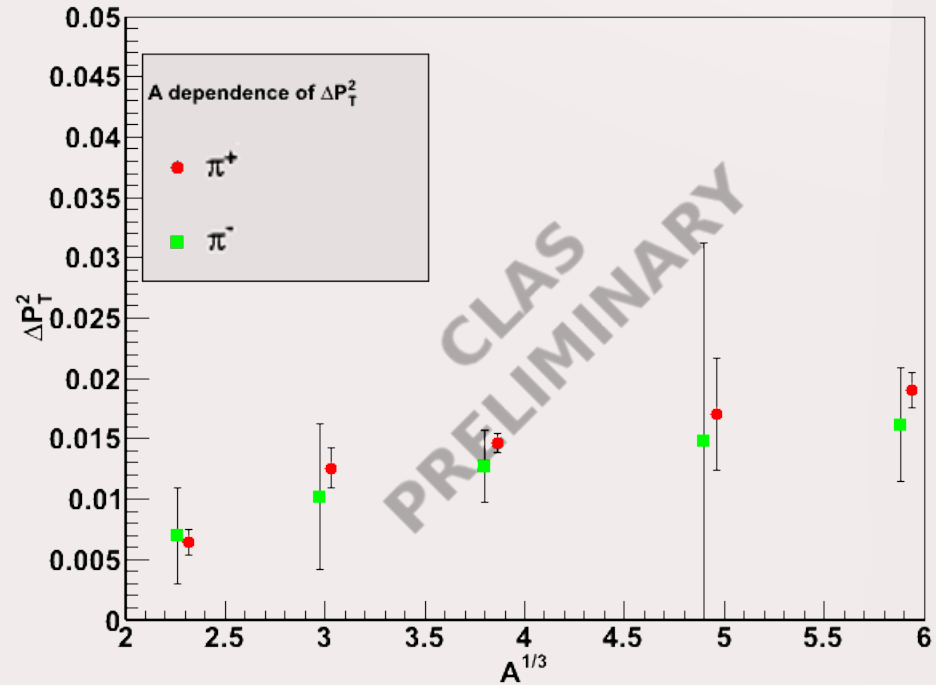
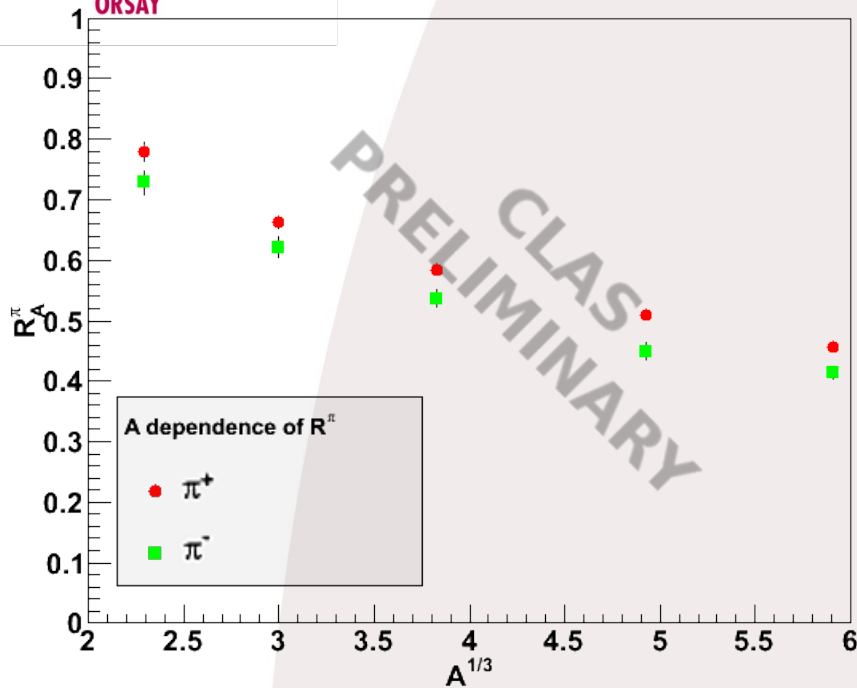
- **JLab continuous electron beam**

- 5.012 GeV electrons
- \sim nA current
- 2 cm long liquid deuterium target
- 5 solid targets (C, Al, Fe, Sn and Pb)

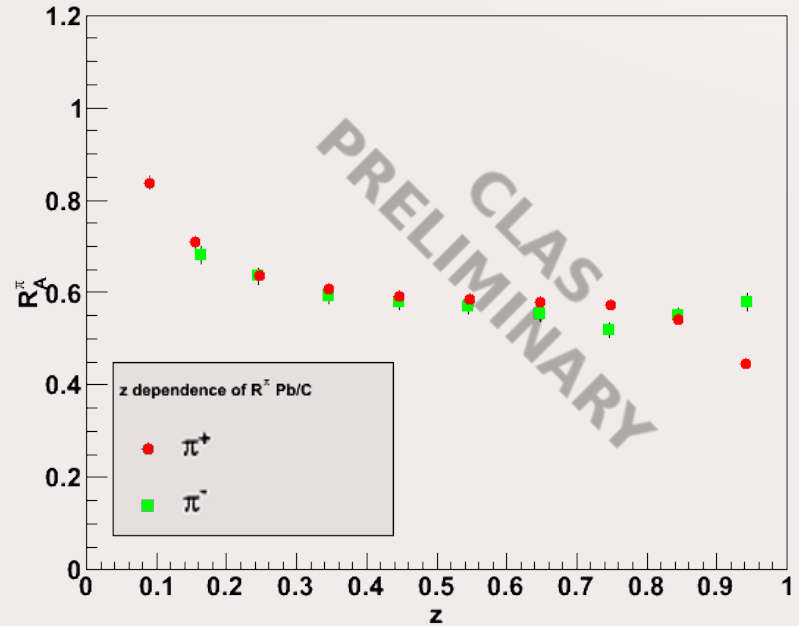
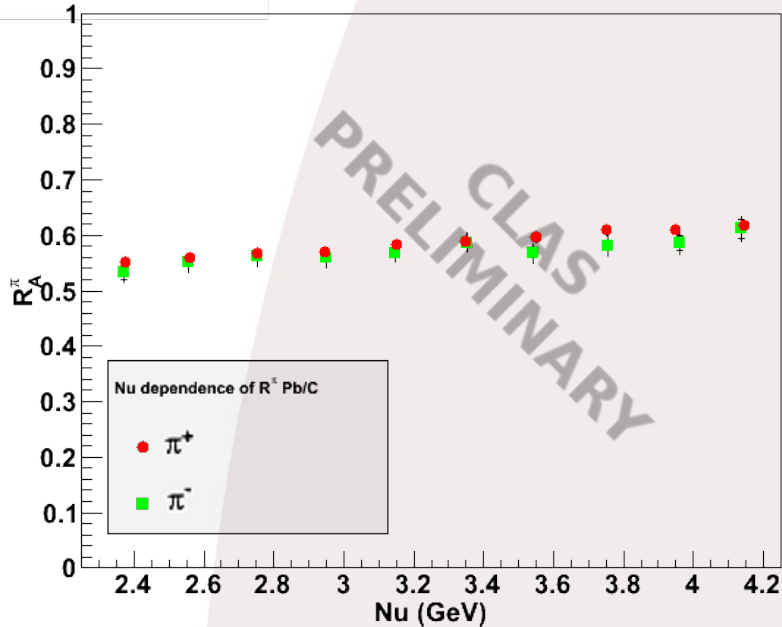
- **In the Hall-B**

- CLAS Collaboration spectrometer
- Detect and trigger on scattered electron (selected in DIS kine.)
- Detect hadrons from \sim 15 to 160 degrees

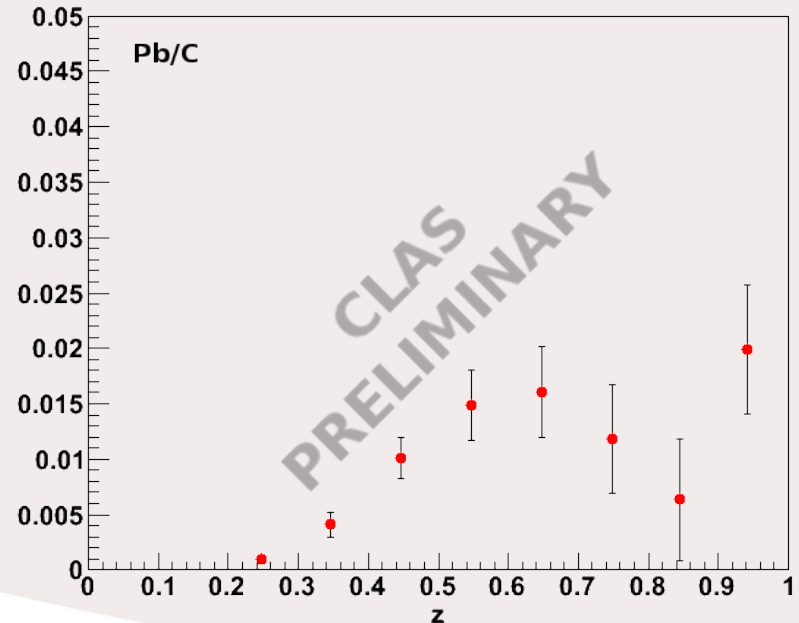




- **Nuclear effect saturates at high A and do not follow either $A^{1/3}$ nor $A^{2/3}$ trends**
 - First measurement with enough coverage to reveal such structure
 - Appears contradictory with hadron absorption models at first sight
- **Multiplicity ratio and P_t broadening follow the same trend**
 - Do they originate from the same process or just a coincidence?

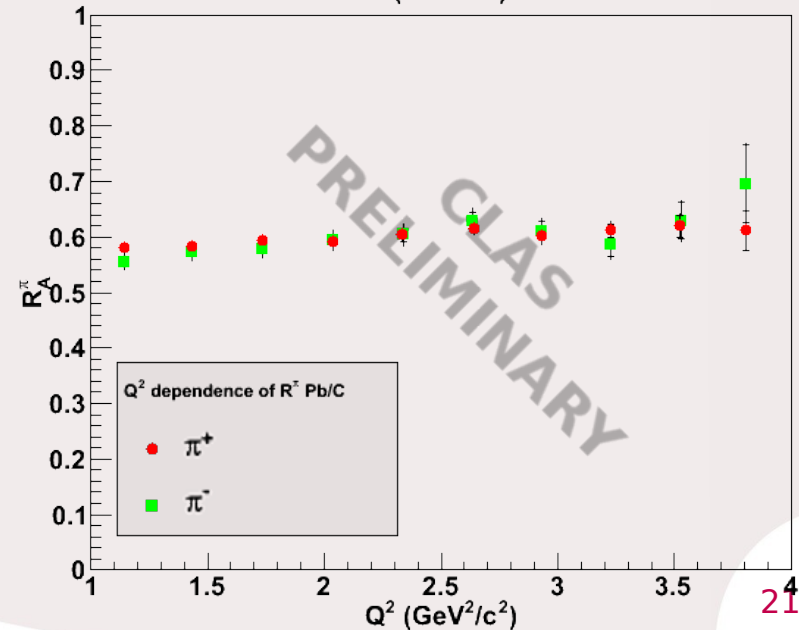
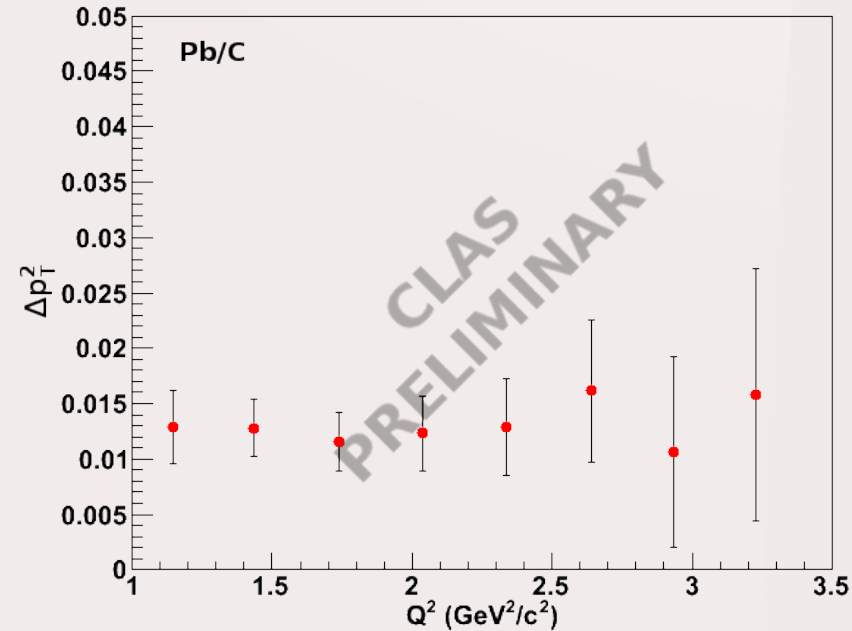


- **Nu and z dependence behave in the same way than expected**
 - Slope in ν similar to HERMES
 - However, the slope in z is not as pronounced as in HERMES (?)
- **Results for Δp_t^2 consistent with HERMES**
 - Shows interesting trend

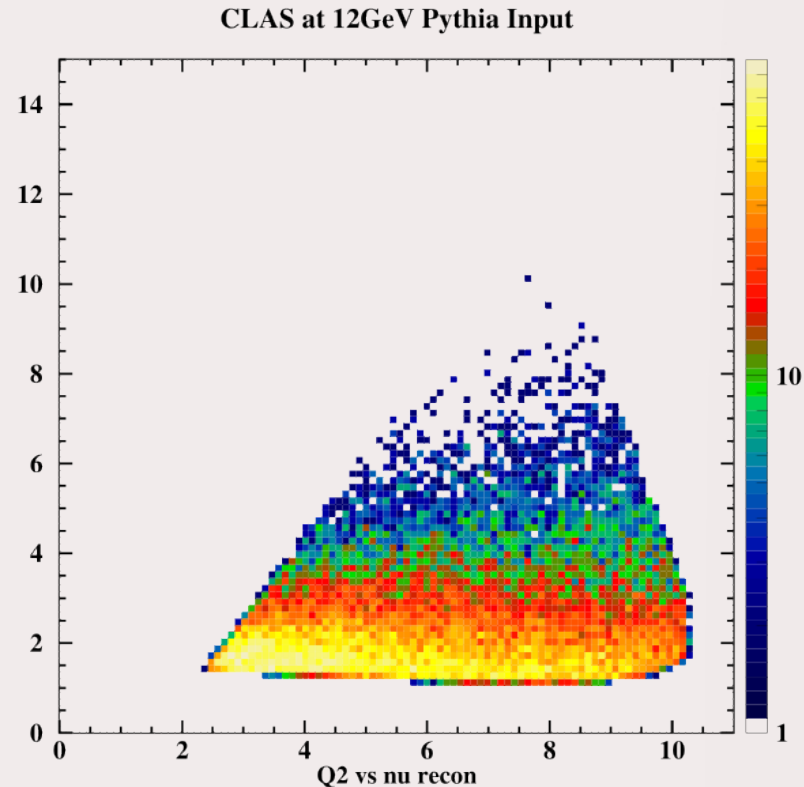


CLAS Preliminary Results

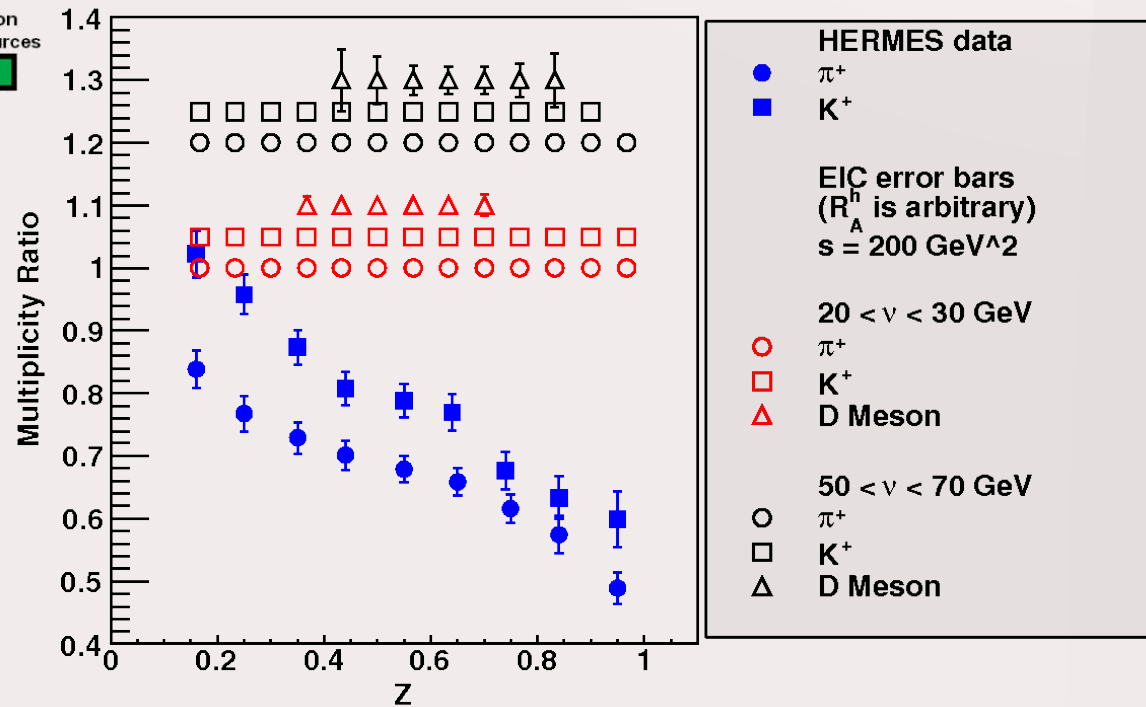
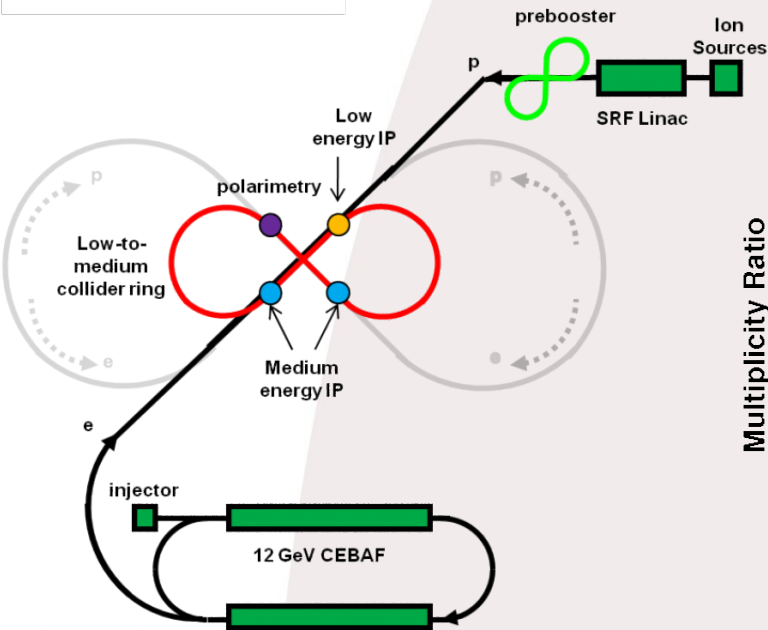
- **Some models have important predictions for the Q^2 trend**
- **Yet, we see no effect with Δp_t^2**
 - to compare with expectations from theory
- **Small raise of the multiplicity ratio**
 - Same as HERMES
 - Not conclusive
- **We have more precision but less coverage than HERMES**
 - More investigation is still needed to solve this question



- **Proposal by K. Hafidi et al.**
“Quark Propagation and Hadron Formation”
- **Goals**
 - To explore both attenuation and ΔPT^2
 - Many particles available as in HERMES
- **Advantages**
 - Larger kinematic coverage than CLAS
 - More hadron species than CLAS
 - Larger luminosity than CLAS (x10) and HERMES (x1000)



The Electron Ion Collider (EIC)



- **Project of electron ion collider (EIC)**
 - JLab and RHIC projects $s \sim 1000 \text{ GeV}^2$ 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

Summary

- **Experiments using nuclei need to understand hadronization - To study hadronization we need experiments on nuclei**
 - The use of lepton-nuclei SIDIS offers the best benchmark for models used in all sorts of experiments
- **Hadronization in CNM has been progressing the last 30 years**
 - Most features observed in hadronization in nuclei are now understood
- **Energy loss models can describe the HERMES attenuation**
 - Interpretation of transverse momentum of detected particles is tricky!
- **JLab results (CLAS coll.) provides for new high precision data to test models**
 - Precision and multi-dimensional binning will allow for first production time extraction
- **Future experiments are going to help achieve some important challenges**
 - CLAS12 with production and formation time extraction
 - EIC with heavy mesons behavior to compare with recent RHIC and LHC data