Hadronization Studies

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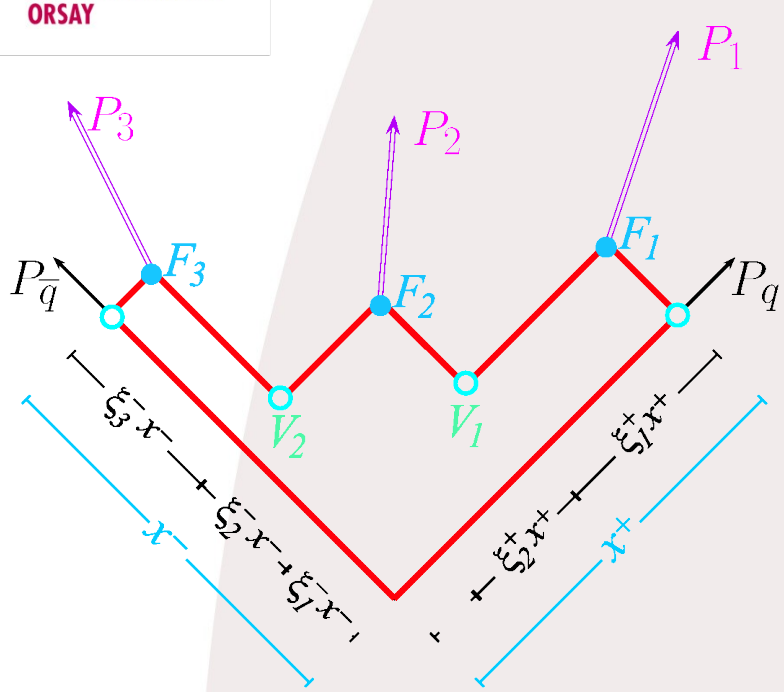
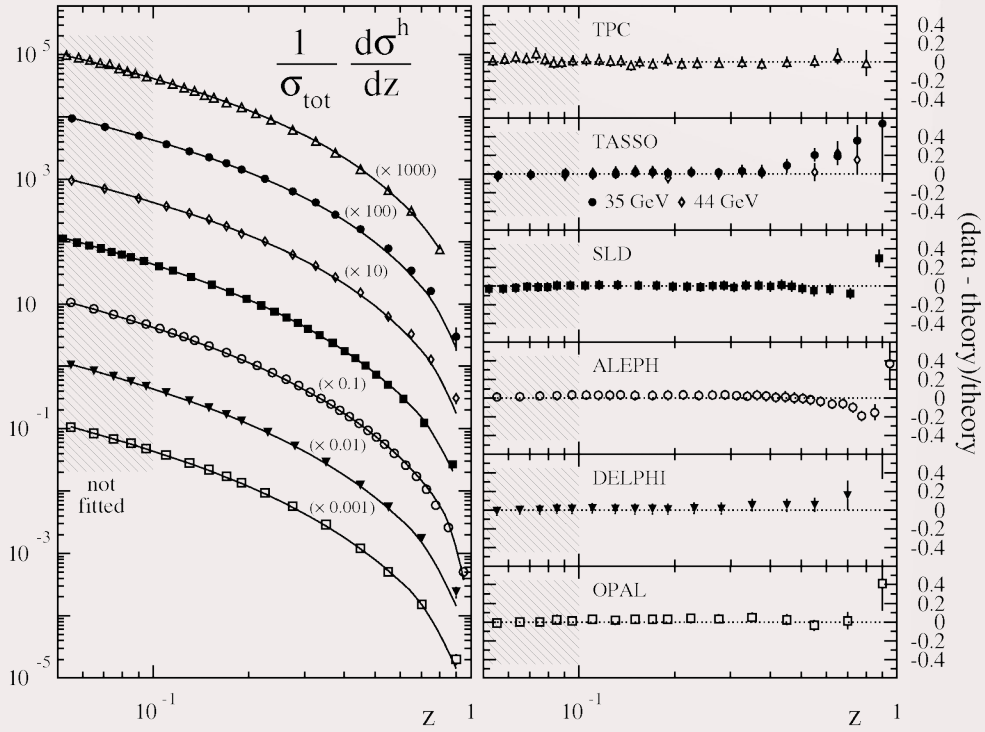
EMMI 14/10/2015

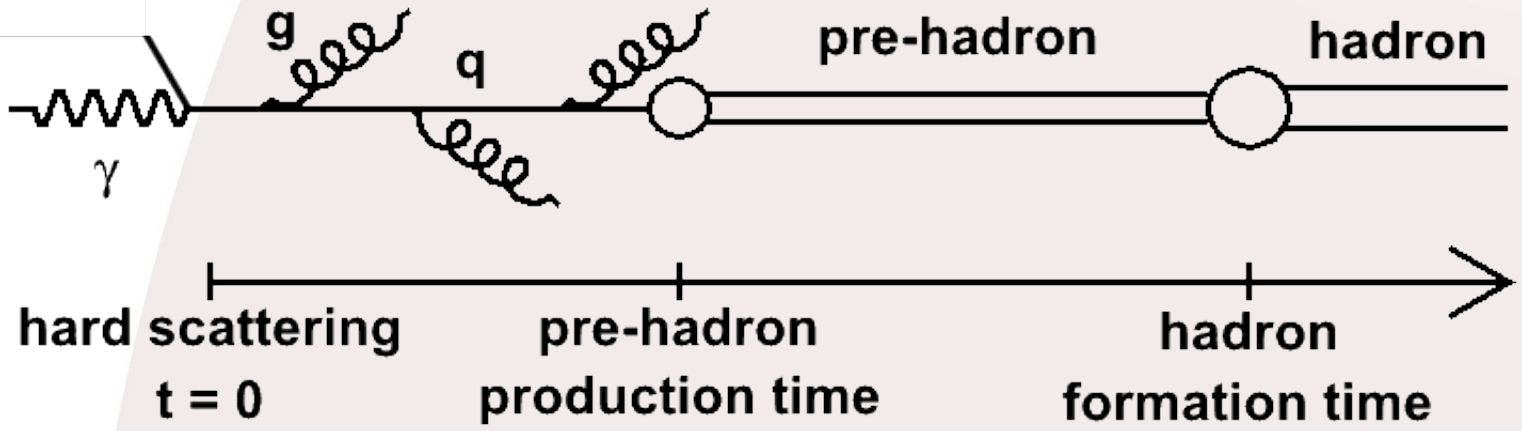
Fragmentation in Vacuum





- **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 is ignored**
  - We are unable to describe any of it from first principles

The Hadronization Process



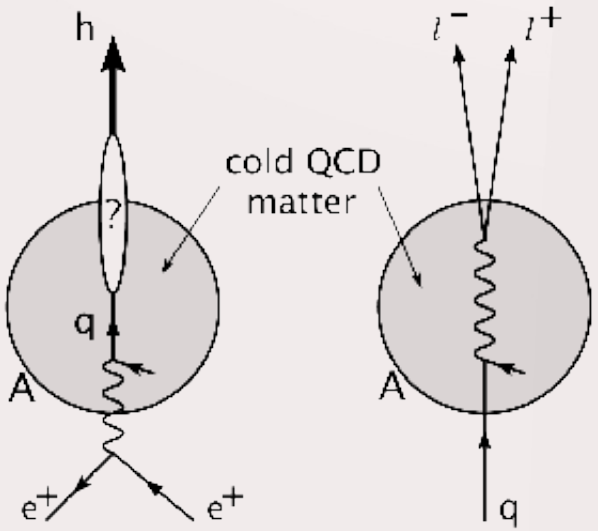
- **Process by which colored objects color neutralizes**
  - Mix Non perturbative and perturbative QCD
- **Most models separate the process in two parts**
  - Production time → propagation of the colored quark
  - Formation time → propagation of the color neutral prehadron
- **Some theoretical predictions but no experimental quantification of these times !**
- **With nuclear targets of different size we can measure them!**

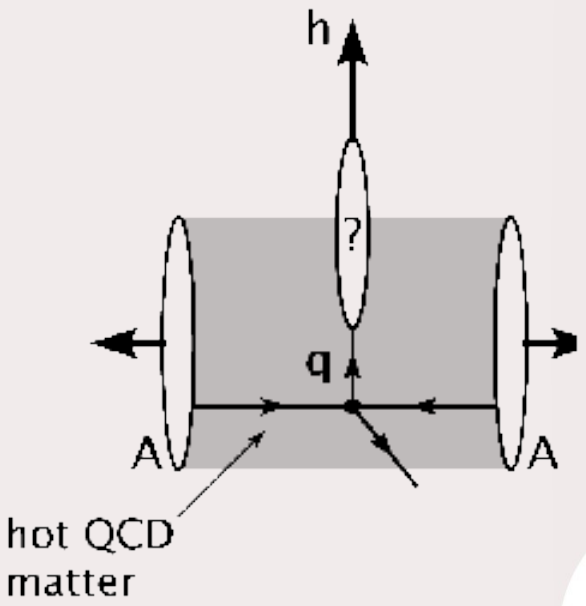
  → However the model uncertainty leads to complicated interpretations

  → We therefore need precise data on a wide set of nuclei and a wide kinematic range to measure these times

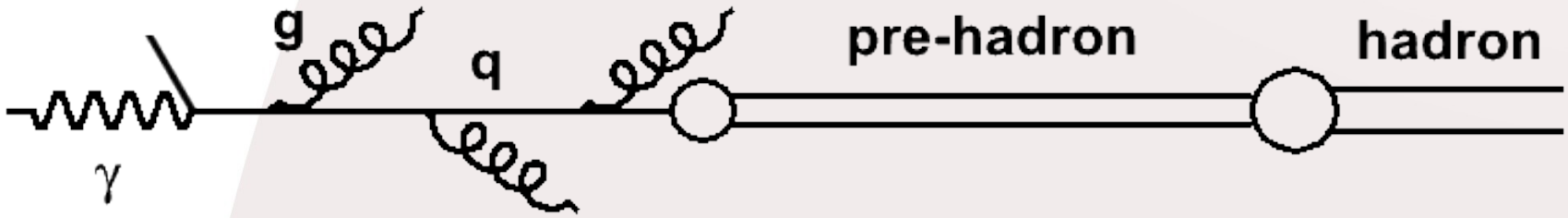
Motivations

- **Understand the hadronization process**
  - Measuring the characteristic times
  - Measuringparton energy loss in QCD medium
  - Understanding the pre-hadron structure
- **Characterization of the QCD medium**
  - Using parton energy loss
  - Characterize both cold and 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





Theoretical Models



- **Important modeling 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 or only seen in hot nuclear matter?

- **Many models exist with different hypothesis**
  - Some pure models (either parton energy loss or hadron absorption)
  - Mixed models (with all possible combinations represented in the literature)

Observables

- **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

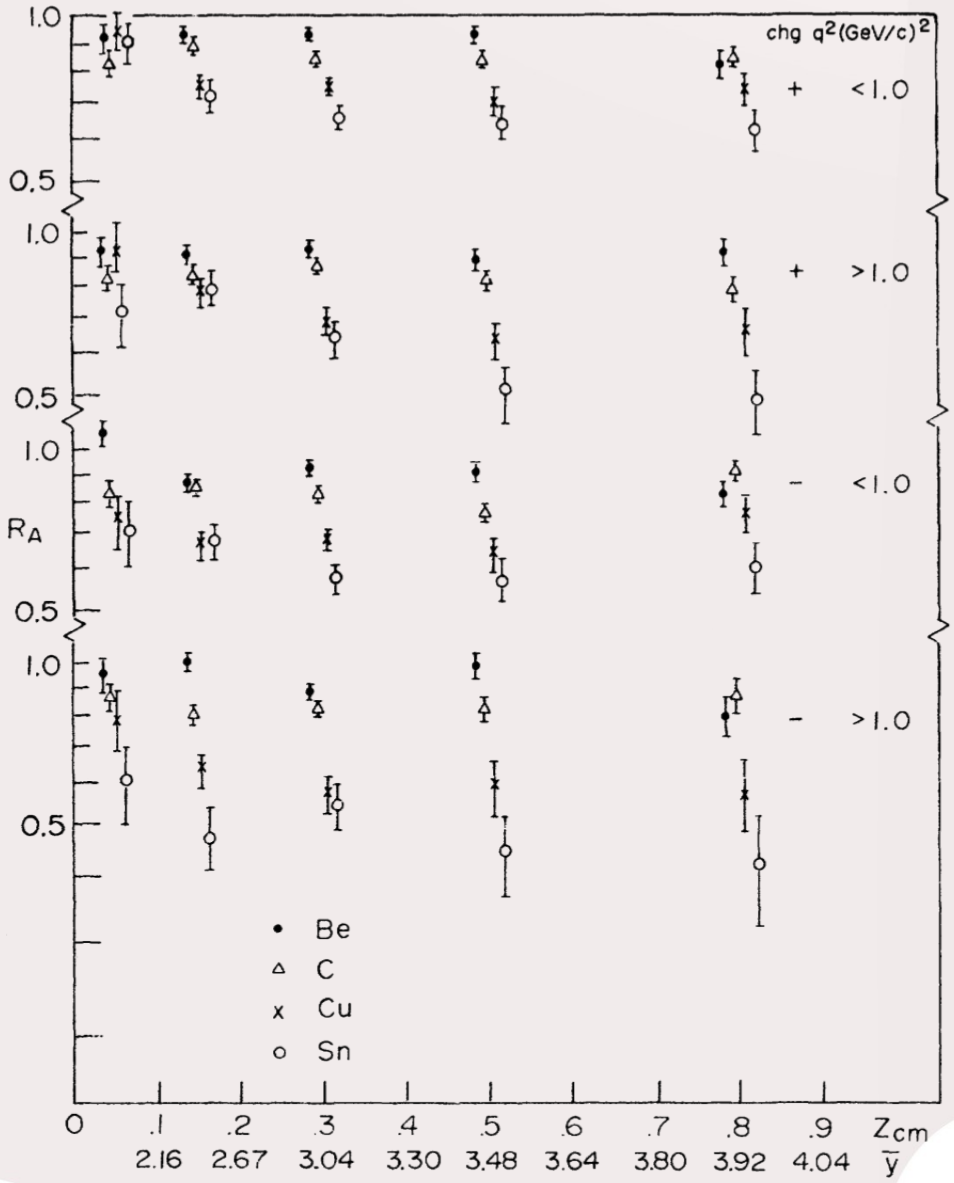
$$\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D$$

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

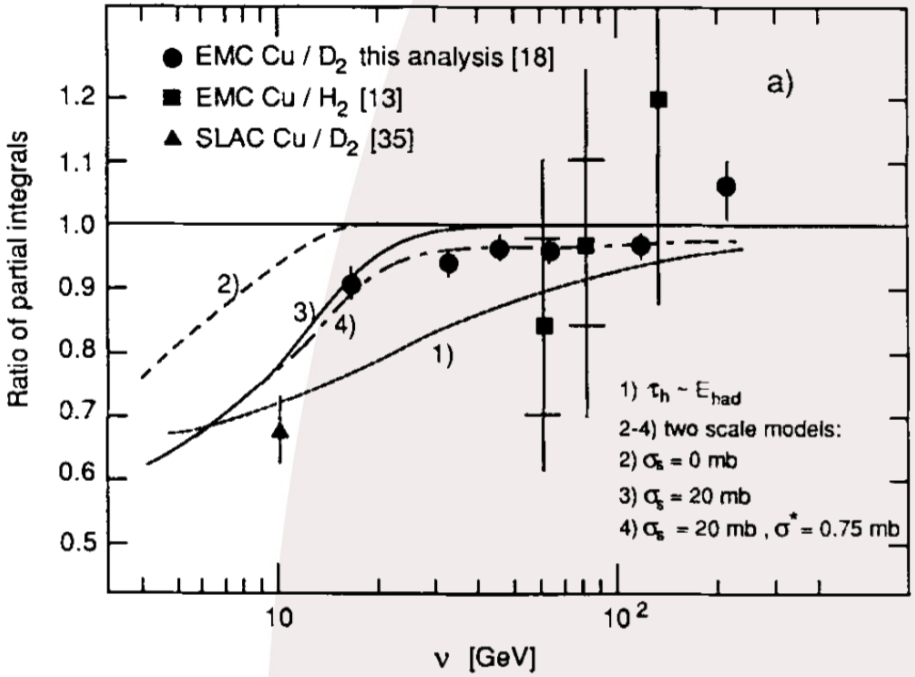
  → But other nuclei can be used for normalization

SLAC Results

- **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**

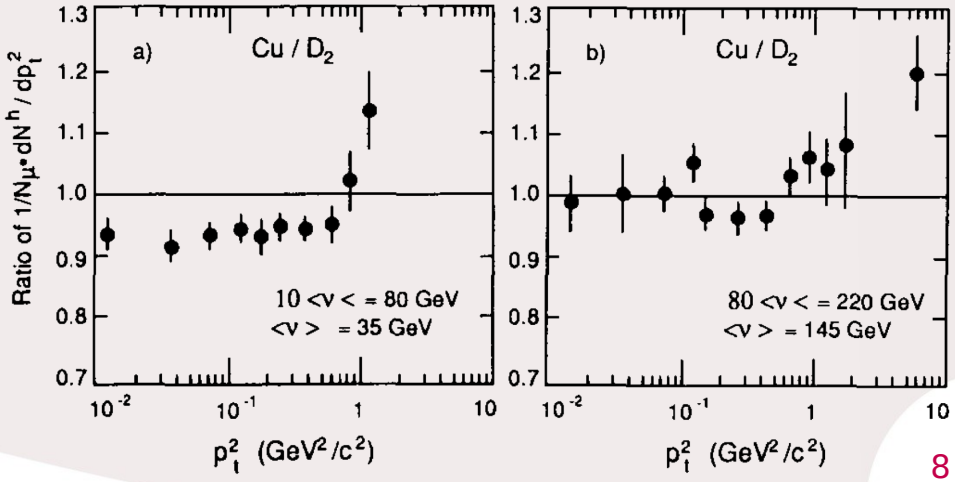


EMC Results



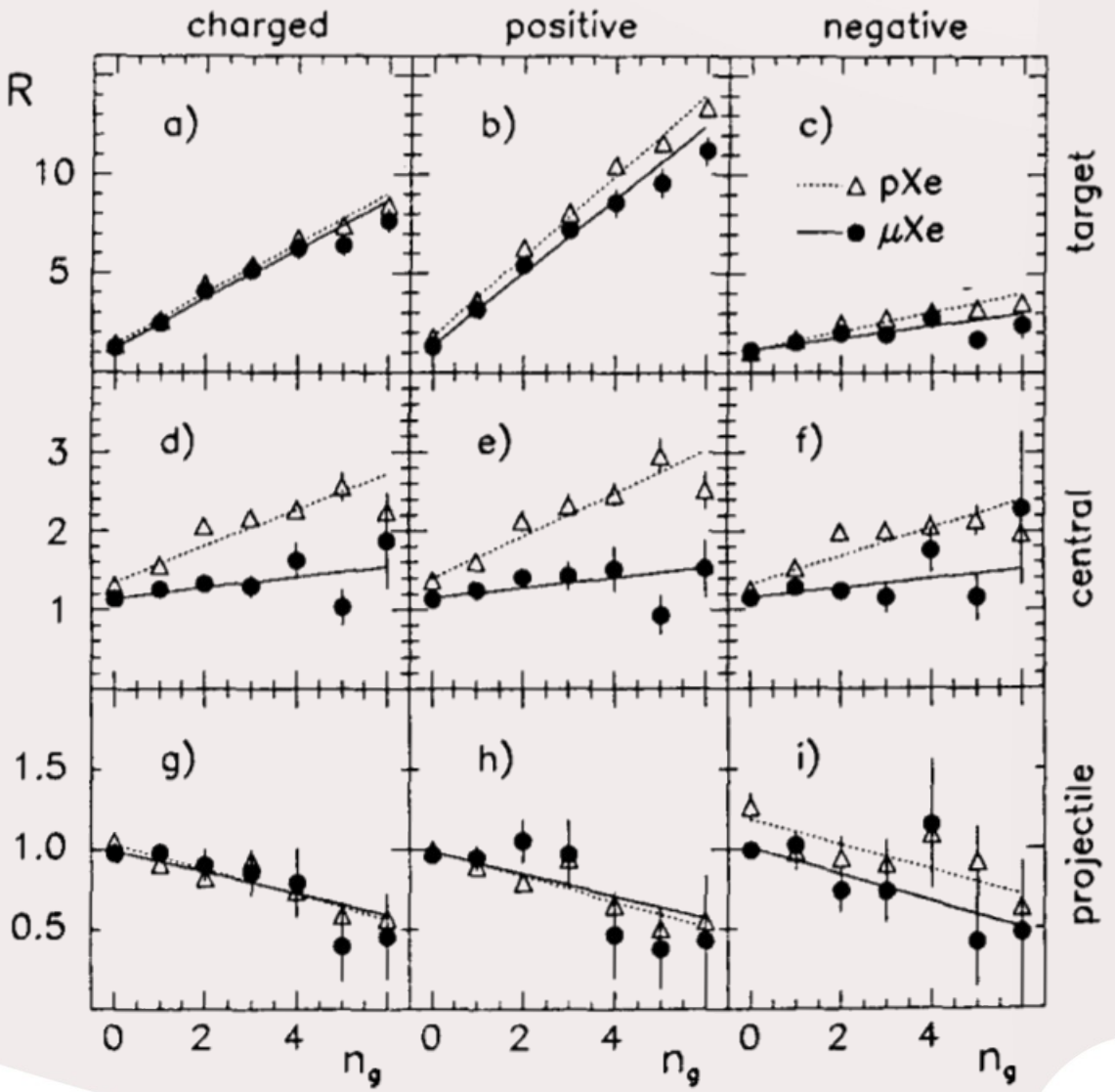
- **Together with SLAC data**
- **Attenuation appears reduced at higher ν**
  - Asymptotic < 1 ?
  - Explained by the Lorentz boost
- **Can help to explore hadronization dynamics but with low precision**

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

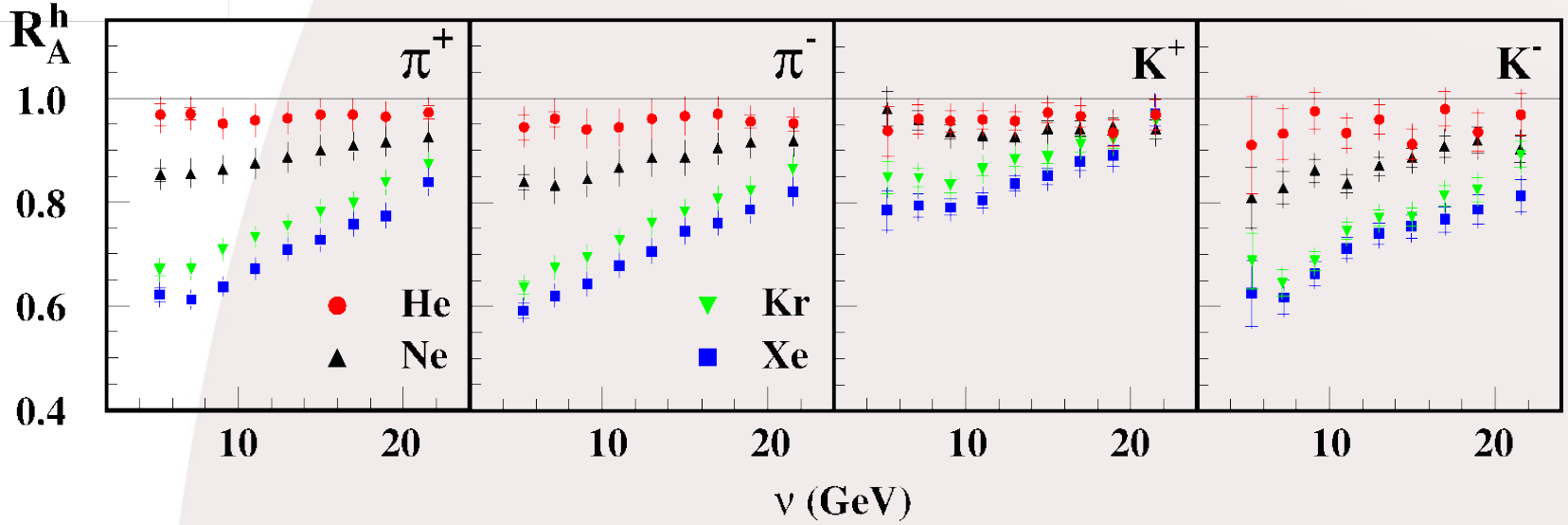


Fermi Lab E665 Results

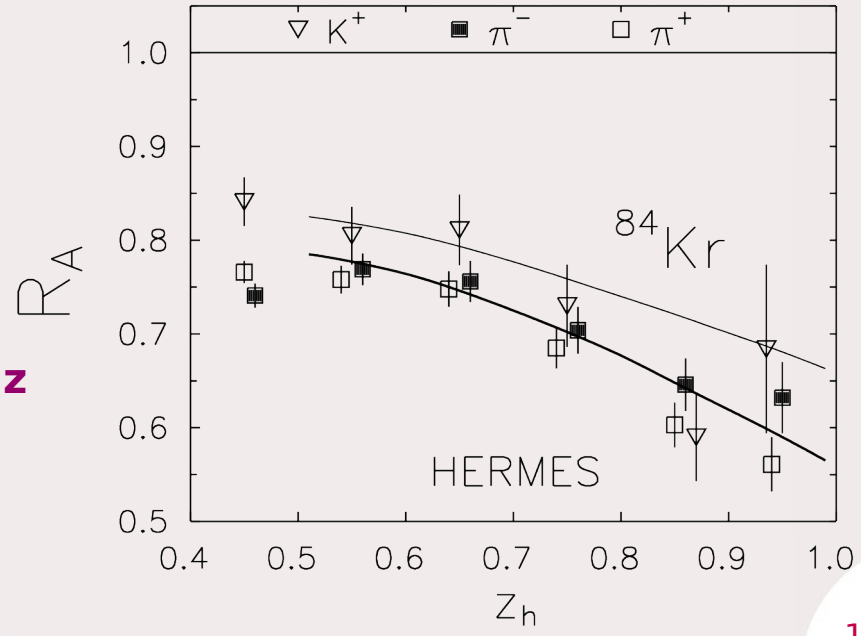
- **Use numbers of slow protons (n_g)**
  - n_g=0 → Xe behave like deuterium
  - the nuclear effect grows linearly with n_g
- **Study target and current regions**
  - the intermediate region follows the target region



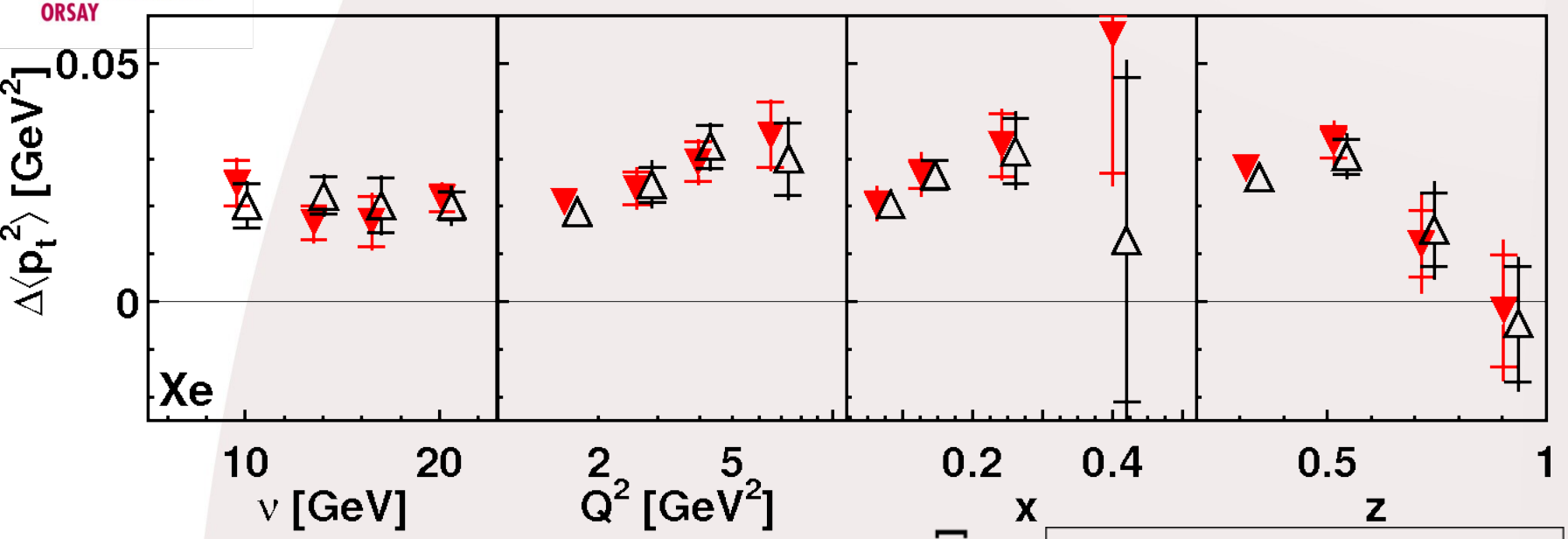
HERMES Results



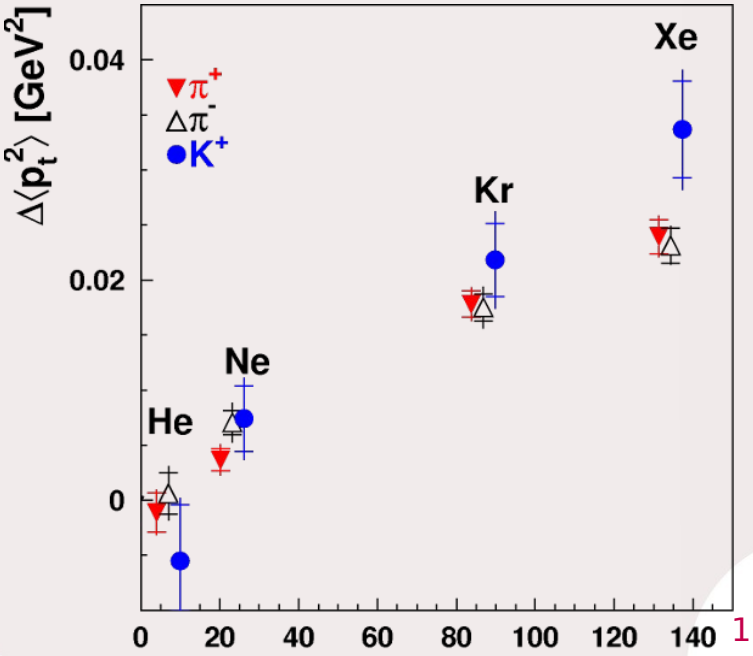
- **Explore all hadrons independently**
- **K- is less suppressed**
  - Due to the smaller cross section of K+?
  - The different behavior of the FF?
- **Not enough !**
  - contamination from $\pi + p \rightarrow \Lambda + K$?
- **Can be resolved by selecting higher z**
  - Less target fragmentation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



HERMES: ΔP_t^2

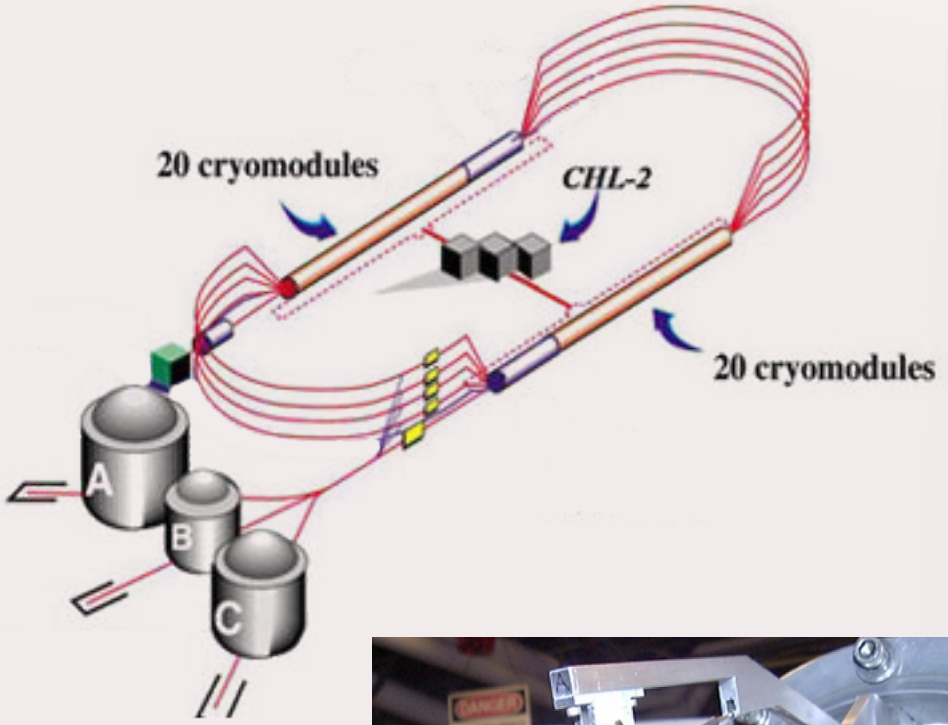


- **No broadening at high z**
  - Effect at the partonic level
- **Increase with Q^2**
  - Predicted in the framework of parton energy loss
- **Dependence in A not conclusive**
  - Compatible with $A^{1/3}$ and $A^{2/3}$
- **Gives access to q hat the transport coefficient of the medium**
  - A killer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

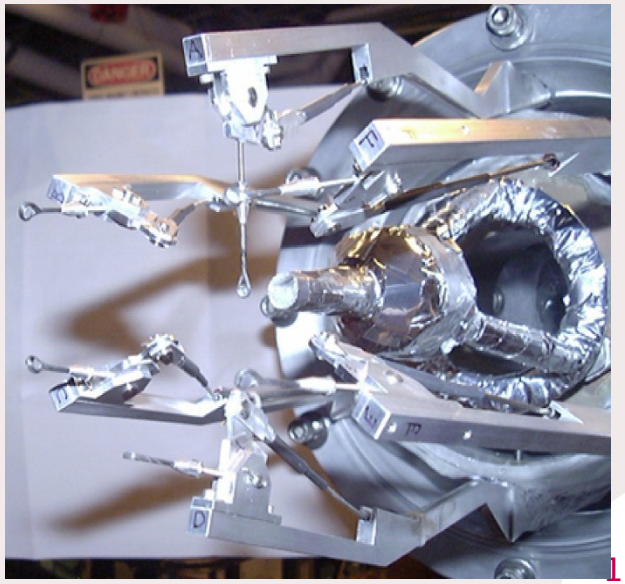


Jefferson Lab – EG2 exp

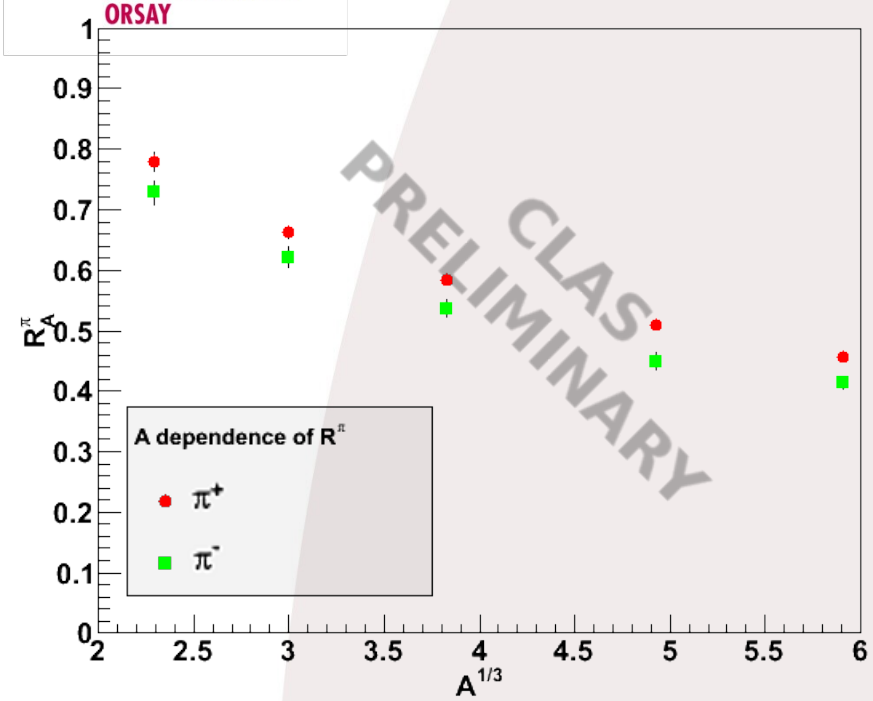
- **JLab continuous electron beam**
  - 5.012 GeV electrons
  - ~nA current
  - 2 cm long liquid deuterium target
  - 5 solid targets (C, Al, Fe, Sn and Pb)

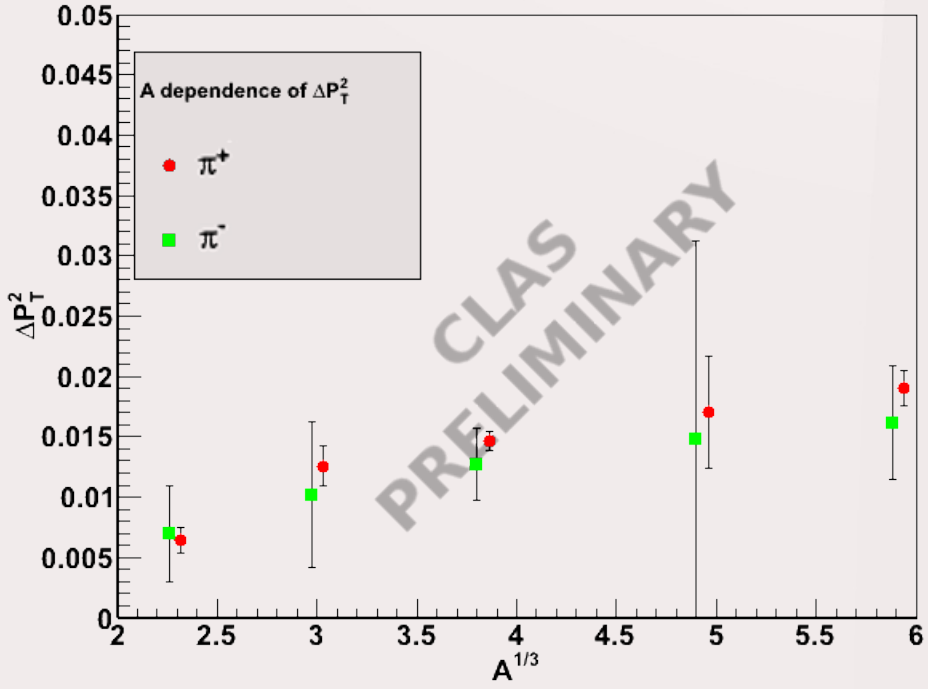


- **In the Hall-B**
  - CLAS Collaboration spectrometer
  - Detect and trigger on scattered electron (selected in DIS kine.)
  - Detect hadrons from ~15 to 160 degrees



CLAS Preliminary Results



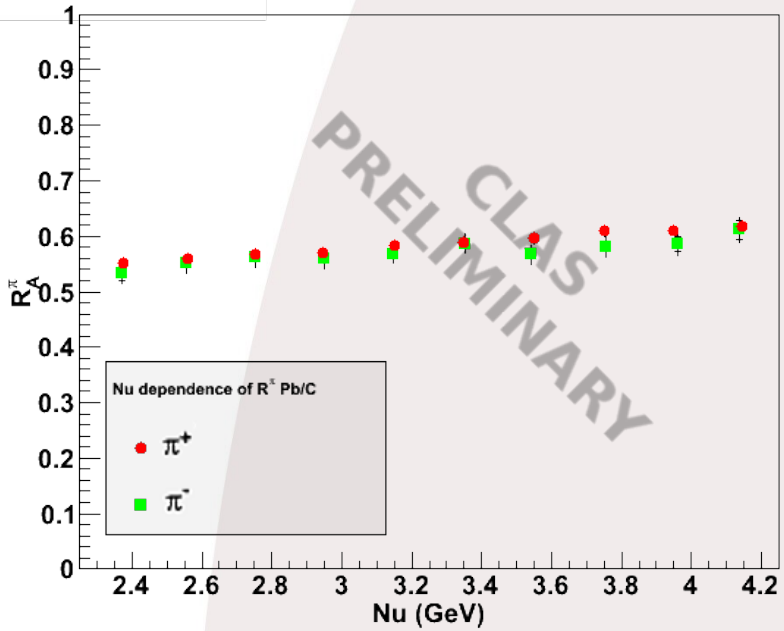


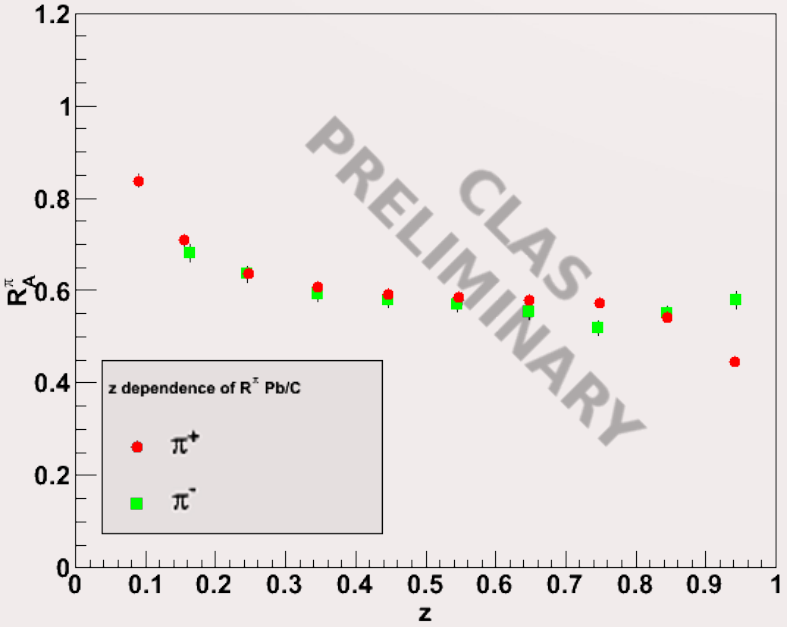
- **Nuclear effect saturates at high A and do not follow either $A^{1/3}$ nor $A^{2/3}$ trends**
  - First measurement with enough coverage to reveal such structure
  - Appears contradictory with hadron absorption models at first sight

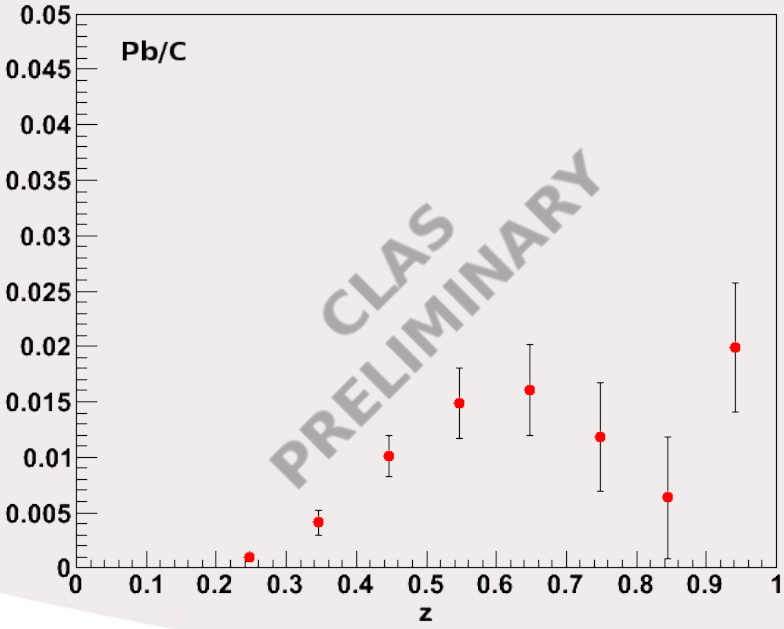
- **Multiplicity ratio and P_t broadening follow the same trend**

  → Do they originate from the same process or just a coincidence?

CLAS Preliminary Results

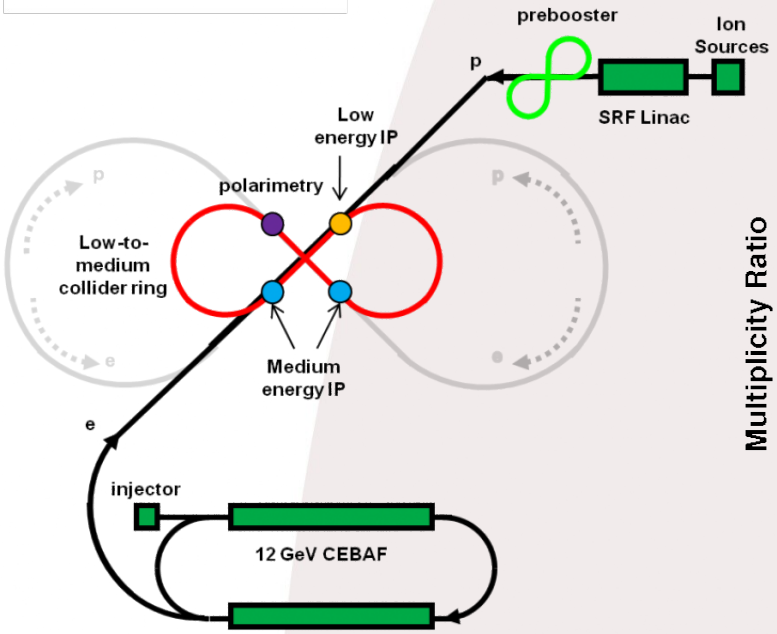


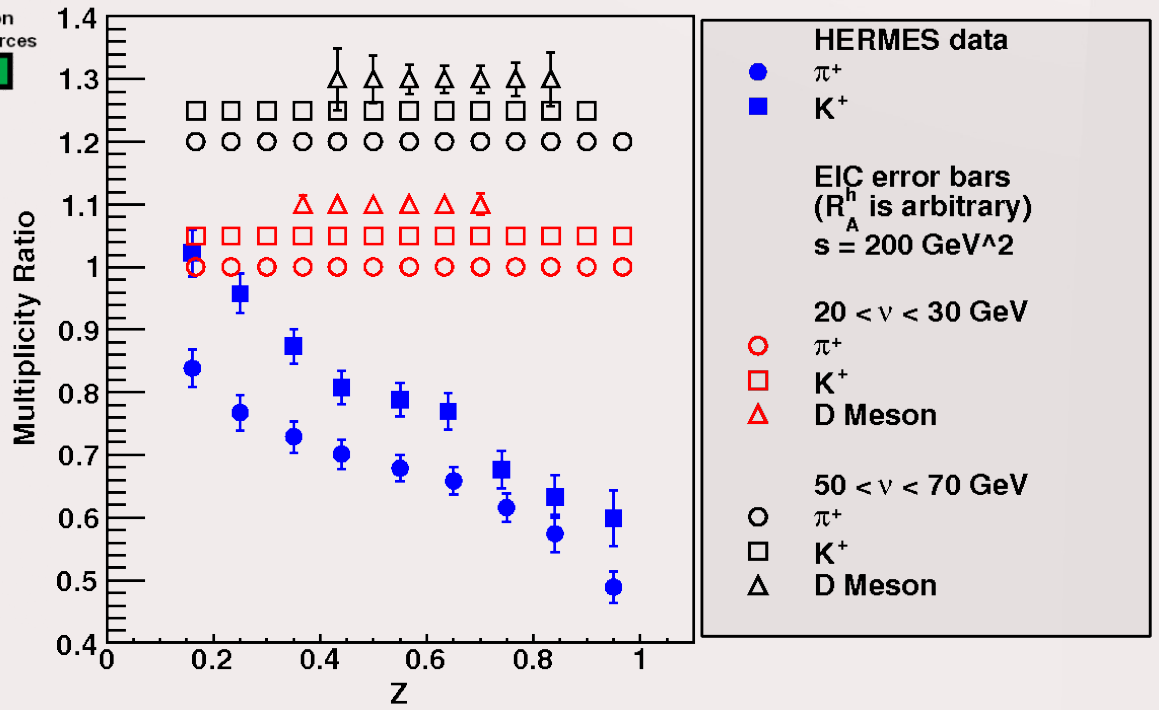




- **Nu and z dependence behave in the same way than expected**
  - → Slope in ν similar to HERMES
  - → However, the slope in *z* is not as pronounced as in HERMES (?)
- **Results for Δp_t^2 consistent with HERMES**
  - – Shows interesting trend

The Electron Ion Collider (EIC)





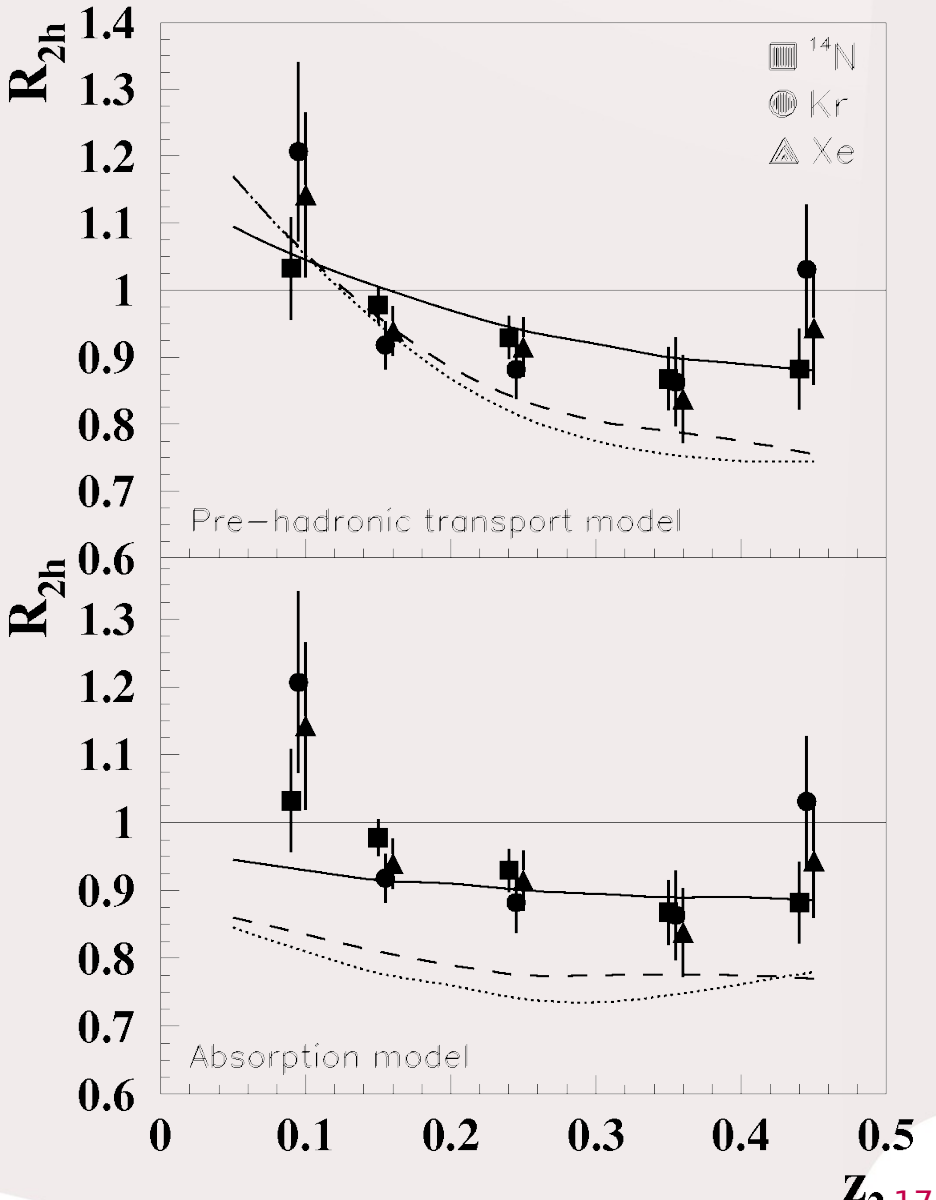
- **Project of electron ion collider (EIC)**
  - **JLab and RHIC projects s~1000 GeV^2 and more**
  - **Low to no attenuation region → centered on ΔP_T^2 measurement**
  - **Isolate energy loss effects and eventually modification of FF**
  - **Access to heavy flavor for comparison with Heavy Ion Collisions**

Summary

- **To study hadronization we need experiments on nuclei**
  - The use of lepton-nuclei SIDIS offers the best benchmark for models
  - Benchmarked model can be used to characterize heavy ion collisions
- **Hadronization in CNM has been progressing the last 30 years**
  - Most features observed in hadronization in nuclei are now understood
- **JLab results (CLAS coll.) provides for new high precision data**
  - Precision and multi-dimensional binning will allow better test of models
  - Should be also precise enough for first production time extraction
- **Future experiments are going to help achieve some important challenges**
  - CLAS12 with better coverage will allow both production and formation time extractions
  - EIC will give heavy mesons behavior to compare with recent RHIC and LHC data and large Q2 coverage to test in medium evolution

HERMES Two Pions Ratios

- **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 ?

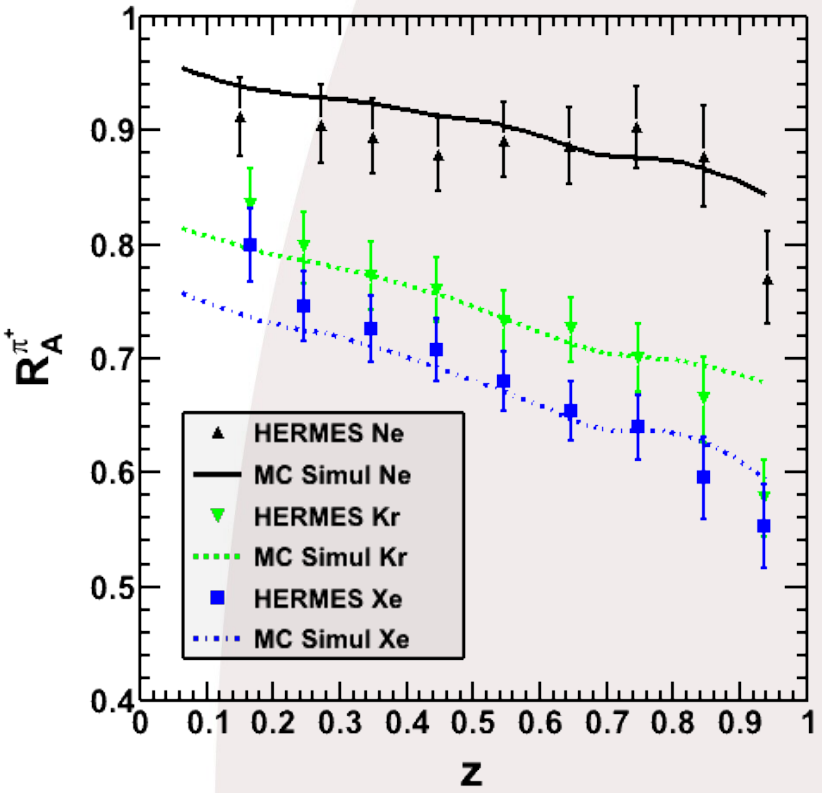


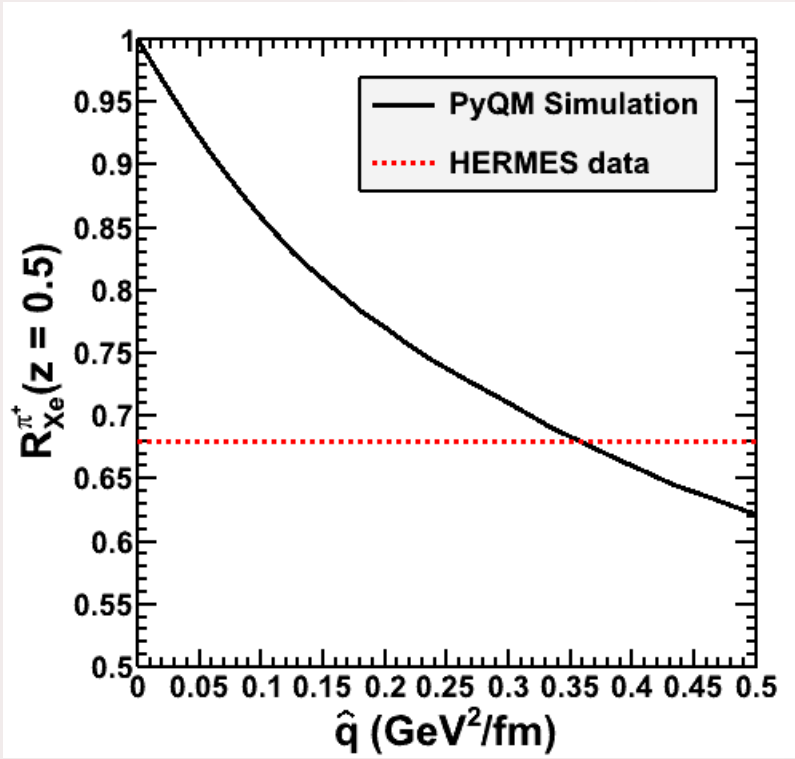
Energy Loss MC Simulation

- **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

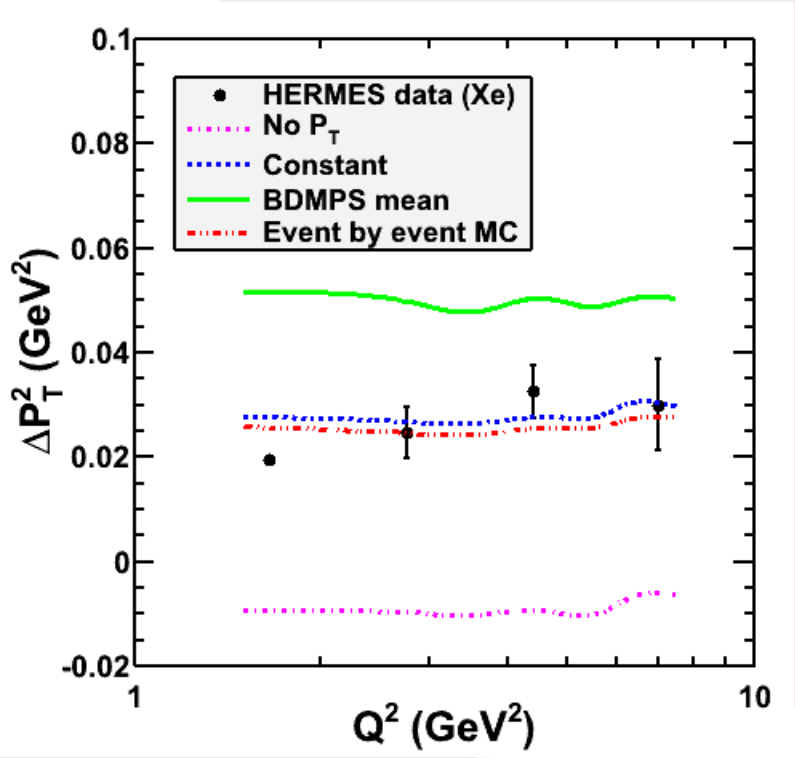


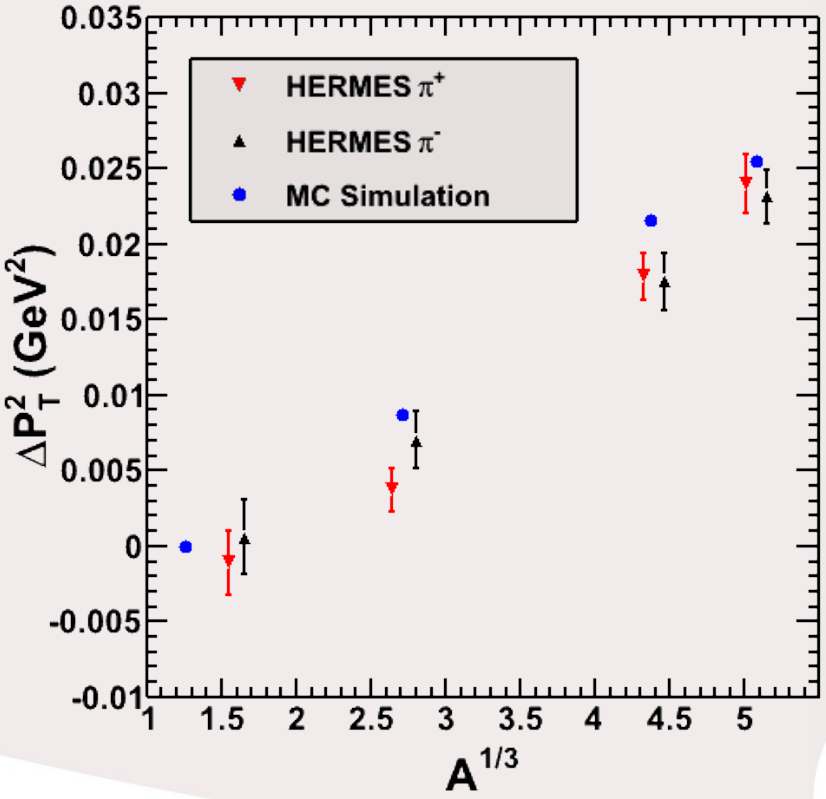


- **Good description with qhat = 0.36 GeV²/fm**
  - Single parameter model !
  - Value is high but still in range to other calculation
- **Not consistent with observed transverse momentum?**

Transverse Momentum

- **How do we got 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**

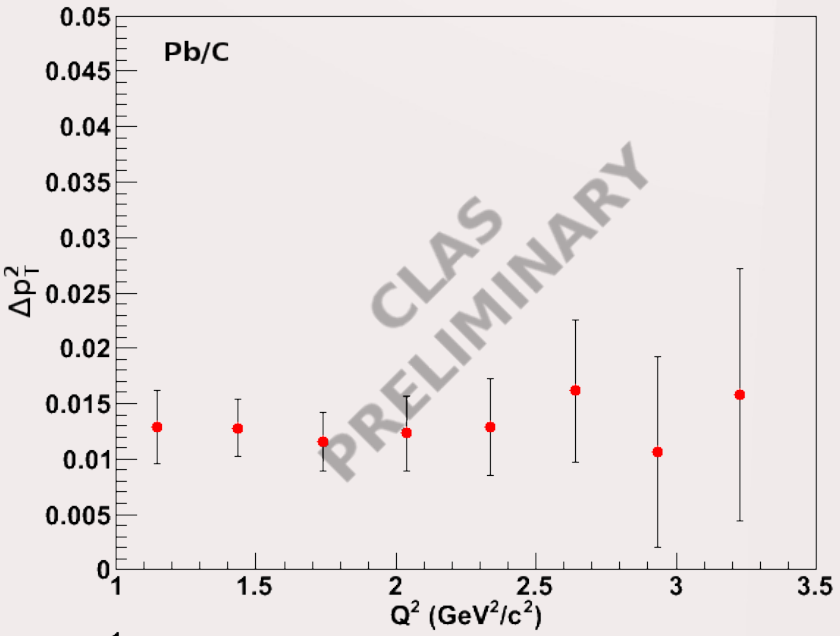


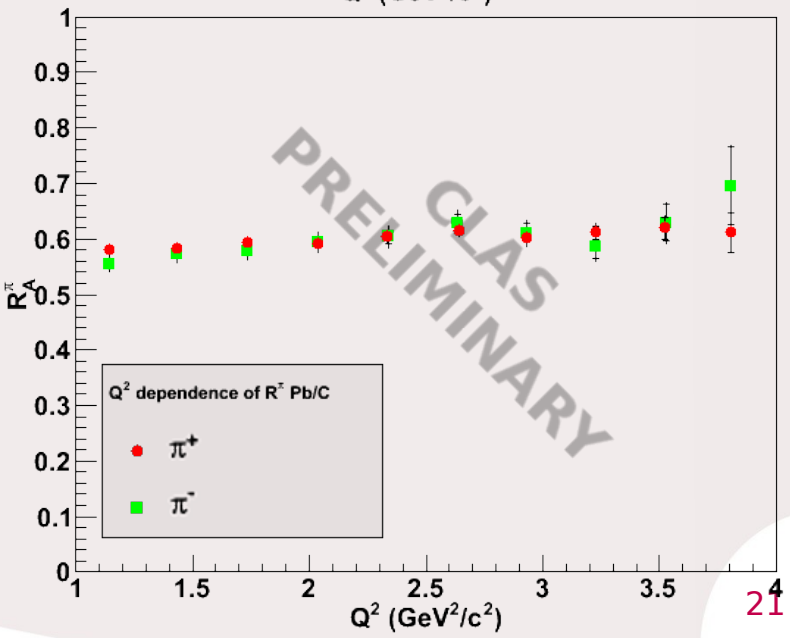


CLAS Preliminary Results

- **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





Experiment at CLAS12

- **Proposal by K. Hafidi et al.**

  "Quark Propagation and Hadron Formation"

- **Goals**
  - To explore both attenuation and ΔPT2
  - 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)