Hadronization in Cold Nuclear Matter

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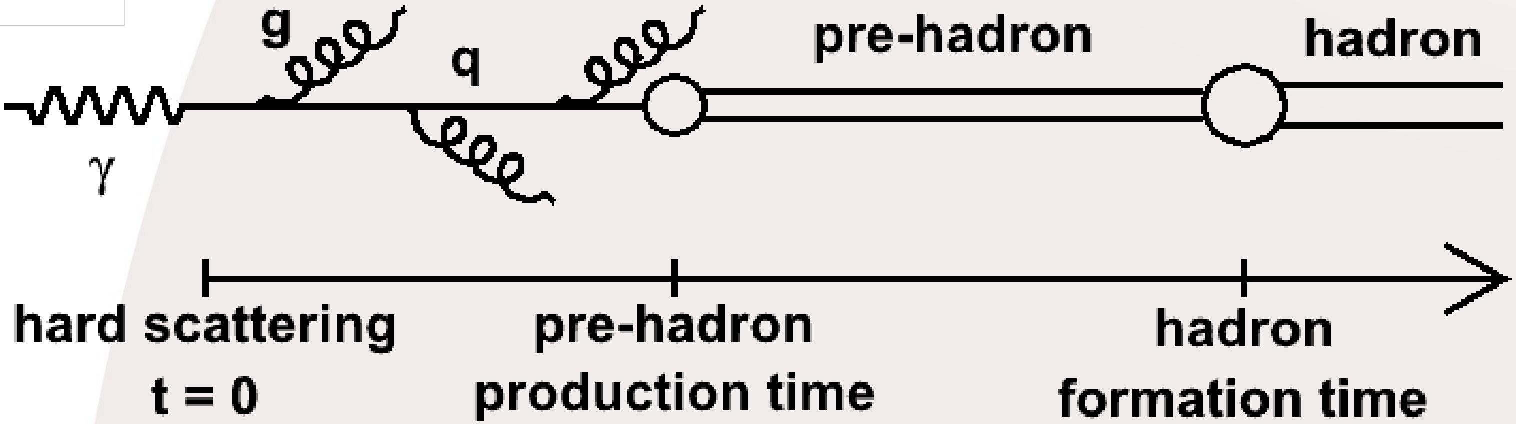
The Hadronization Process



- **Non perturbative QCD process**
  → Need models and data

- **Production time → propagation of the colored quark**

- **Formation time → propagation of the color neutral prehadron**

- **Very wide theoretical prediction ranges but no experimental quantification of these times !**

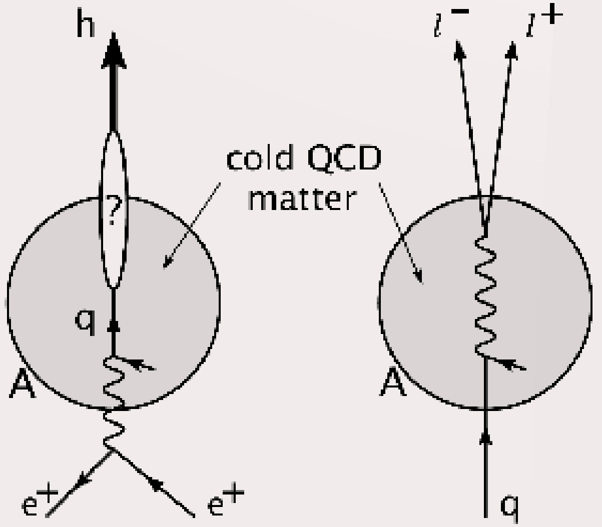
- **With nuclear targets of different size we can measure them!**
  → However the large model uncertainty leads to complicated interpretations
  → We need very precise data on a wide set of nuclei and a wide kinematic range

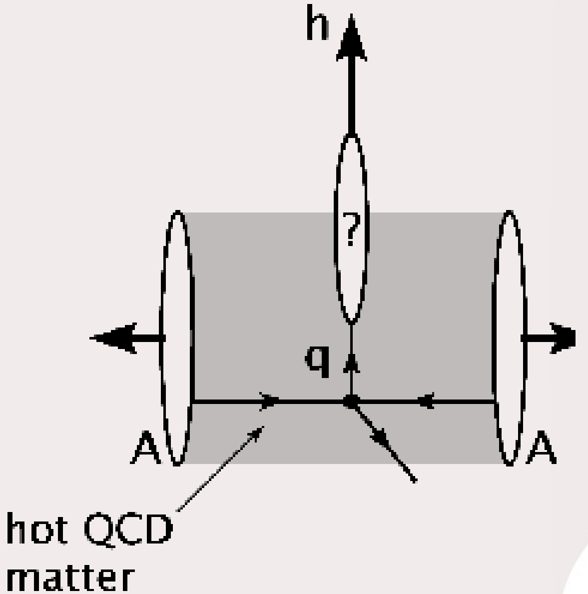
Motivations

- **Understand the hadronization process**
  - Measuring the characteristic times
  - Calculating parton energy loss in QCD medium
  - Understanding the pre-hadron structure

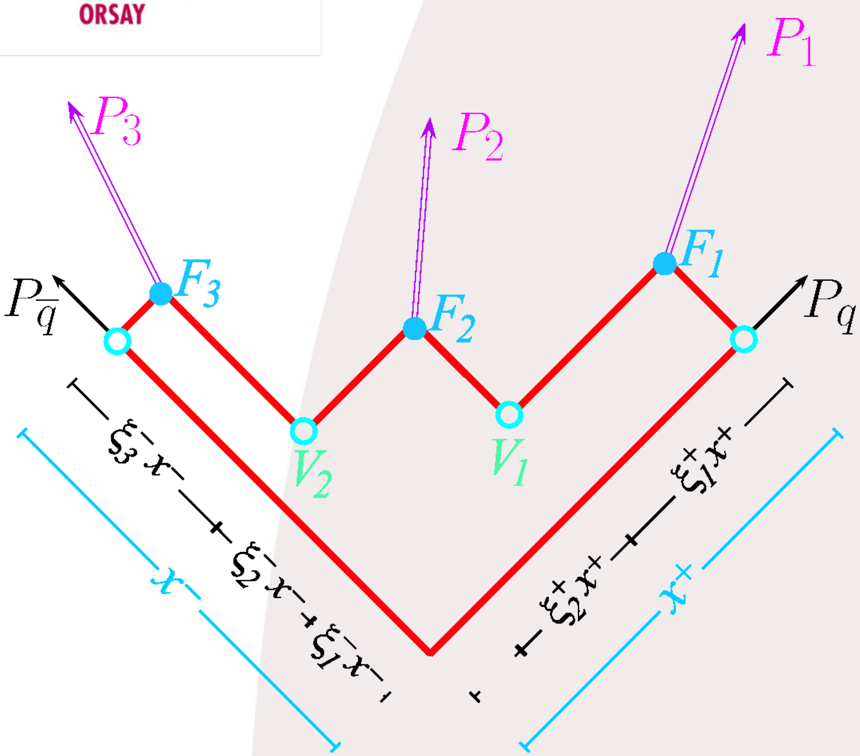
- **Characterization of the QCD medium**
  - Using parton energy loss
  - Compare cold to hot nuclear matter
  - Understand QCD evolution in medium

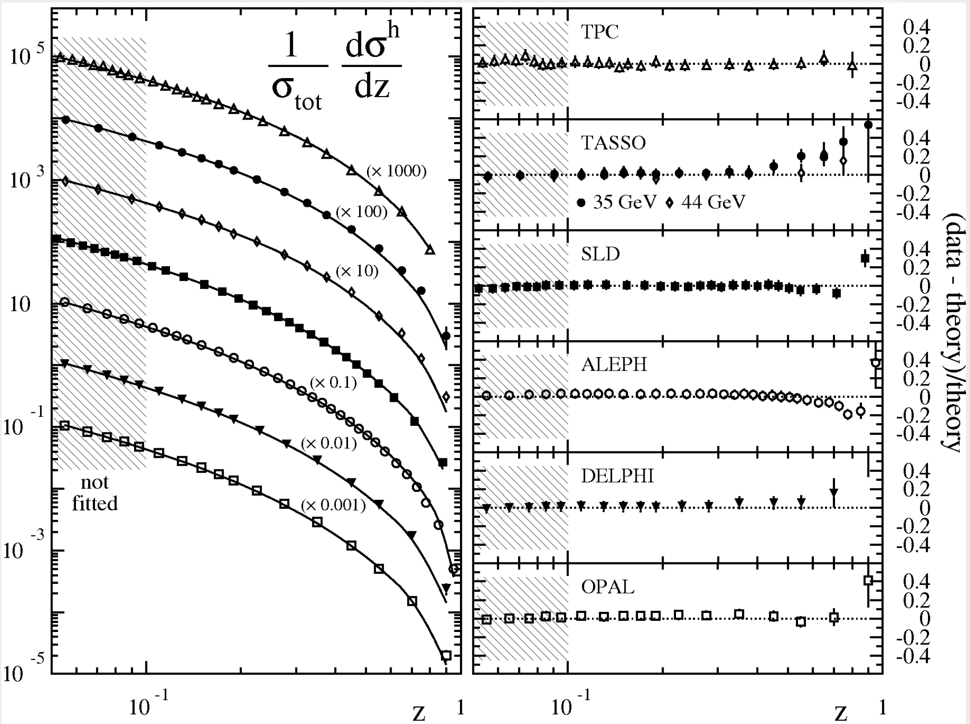
- **Reduce systematic effects on measurements where attenuation needs to be corrected**
  - Neutrino experiments
  - Nucleon structure in nuclei





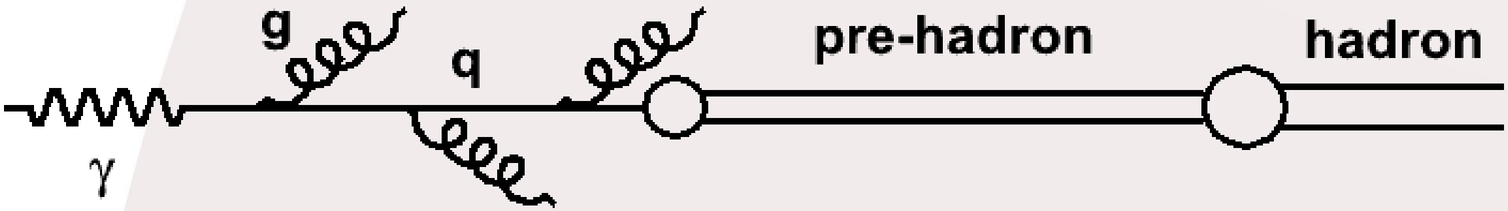
Fragmentation Functions





- **They parametrize the fragmentation in vacuum**
- **They focus is on the current region**
  - Fracture functions are used for the target region
- **They respects evolution predicted by perturbative QCD**
  - What about in medium ?
- **Yet, they are measured and cannot be predicted by QCD or models**

Theoretical Models



- **Three families of models**
  - Parton energy loss
  - Modified fragmentation functions
  - Hadron absorption

- **Parton energy loss or Hadron absorption ?**
  - Important debate on which dominates

- **Is there a significant modification of the evolution in medium ?**
  - Leads to a modification of fundamental fragmentation functions
  - Has a huge impact on heavy ion measurements

- **Many models exists with different answers to these questions**
  - Pure models (see parton energy loss calculations in this talk for example)
  - Mixed models (with all possible combinations represented in the litterature)

DIS Kinematics

- **4-Momentum squared of the photon**

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

- **Energy of the photon**

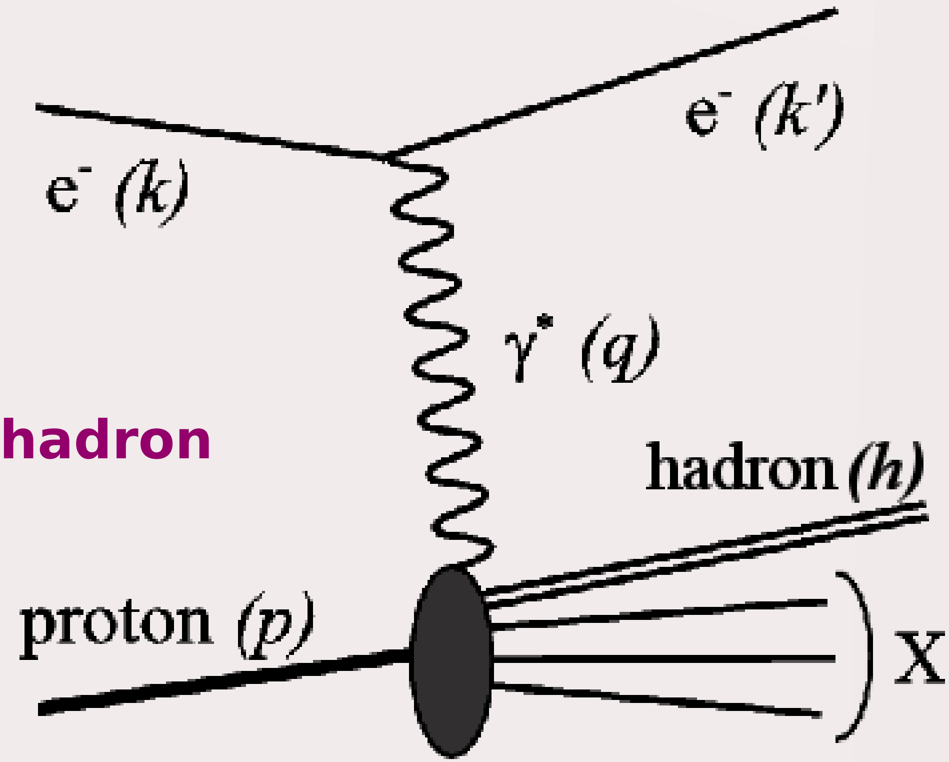
$$\nu = E_\gamma$$

- **Fraction of energy of the hadron**

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

- **Transverse momentum**

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



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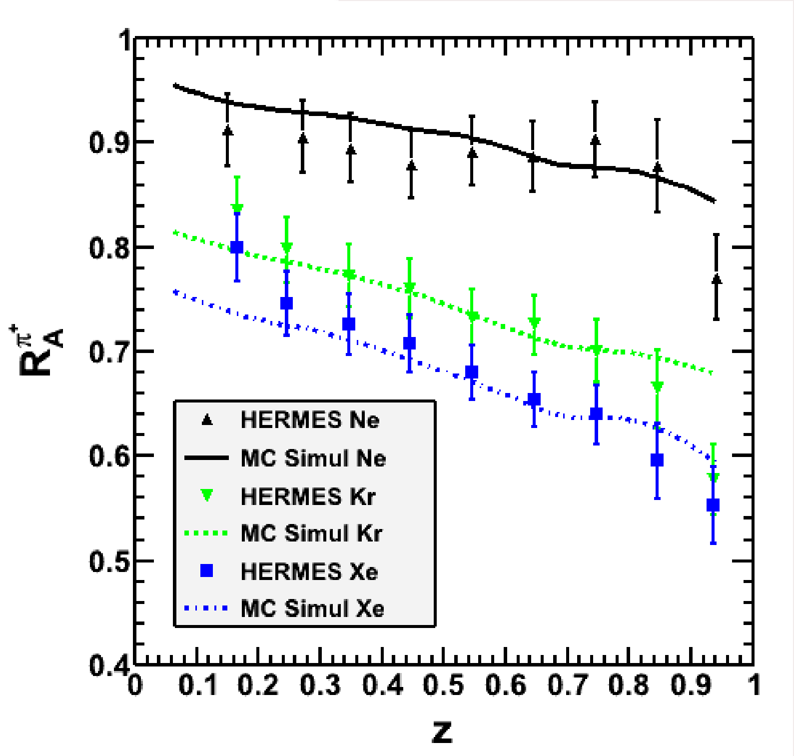
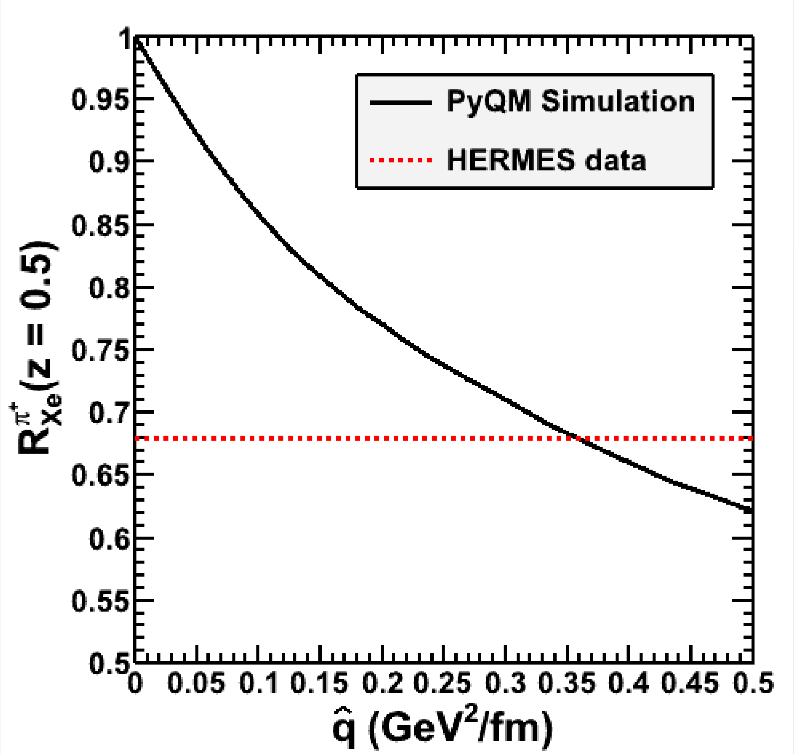
Energy Loss MC Simulation

- **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

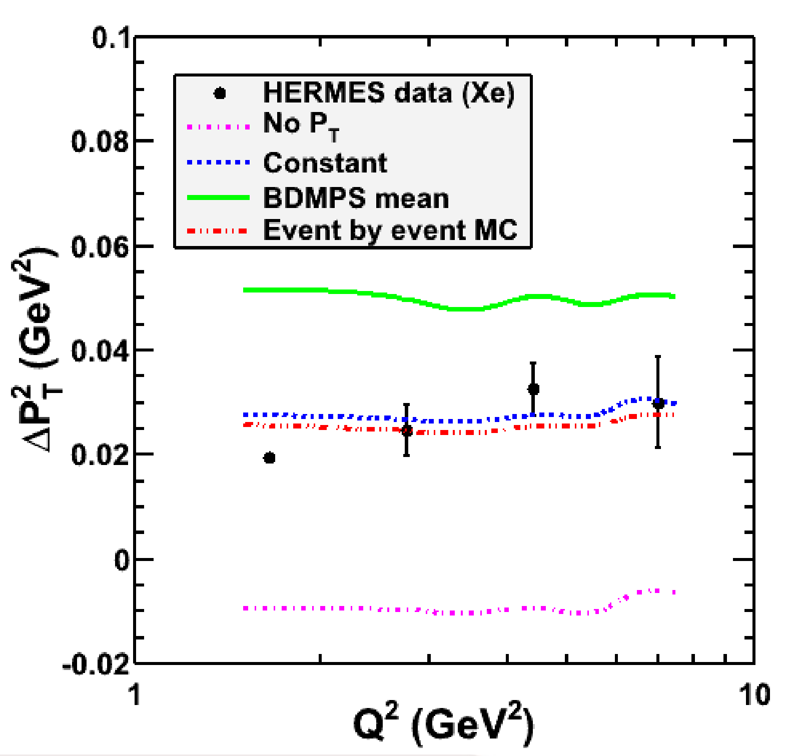


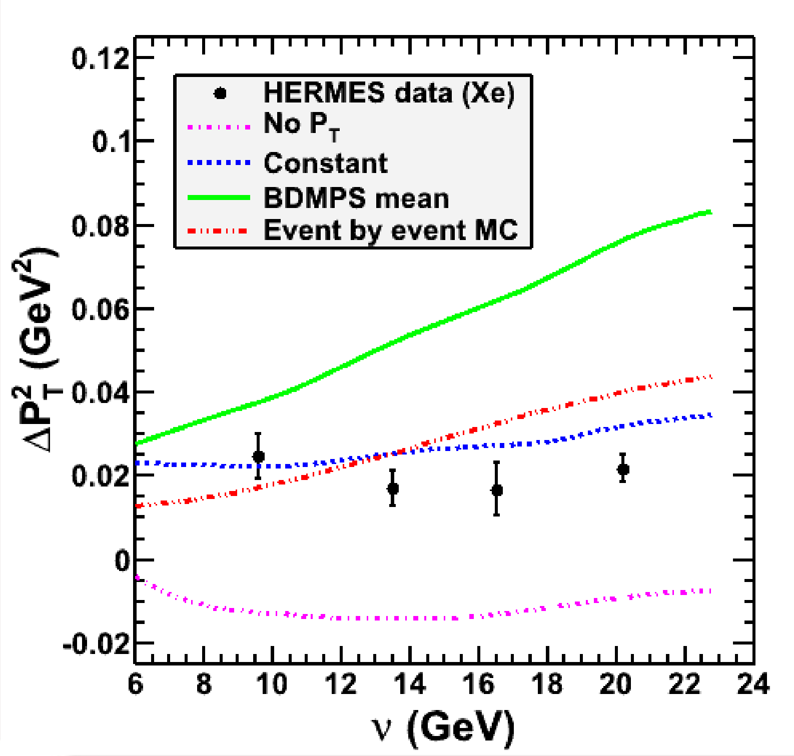


- **Good description with qhat = 0.36 GeV^2/fm**
  - Single parameter model !
  - Value is high but still in range to other calculation
- **Not consistent with observed transverse momentum?**

Transverse Momentum

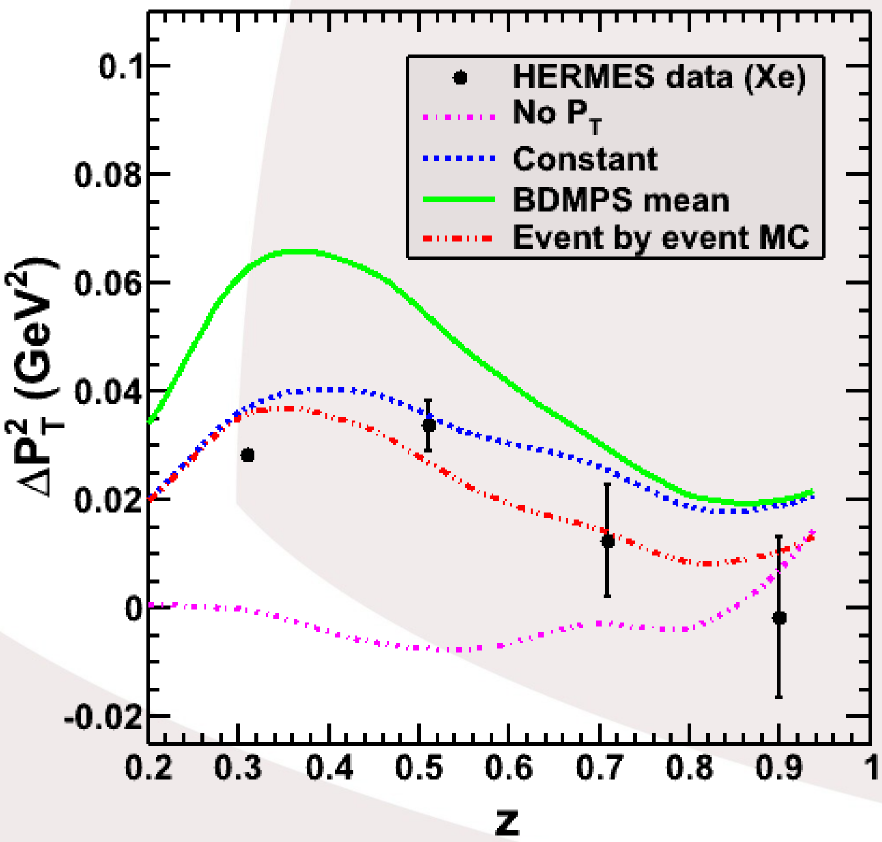
- **How do we got from Lx0.36 to ~0.03 ?**
  - Reduction by z square (~0.1)
  - Reduction due to lower parton energy
  - Reduction due to absorption
- **It matches data for all kinetic variables**

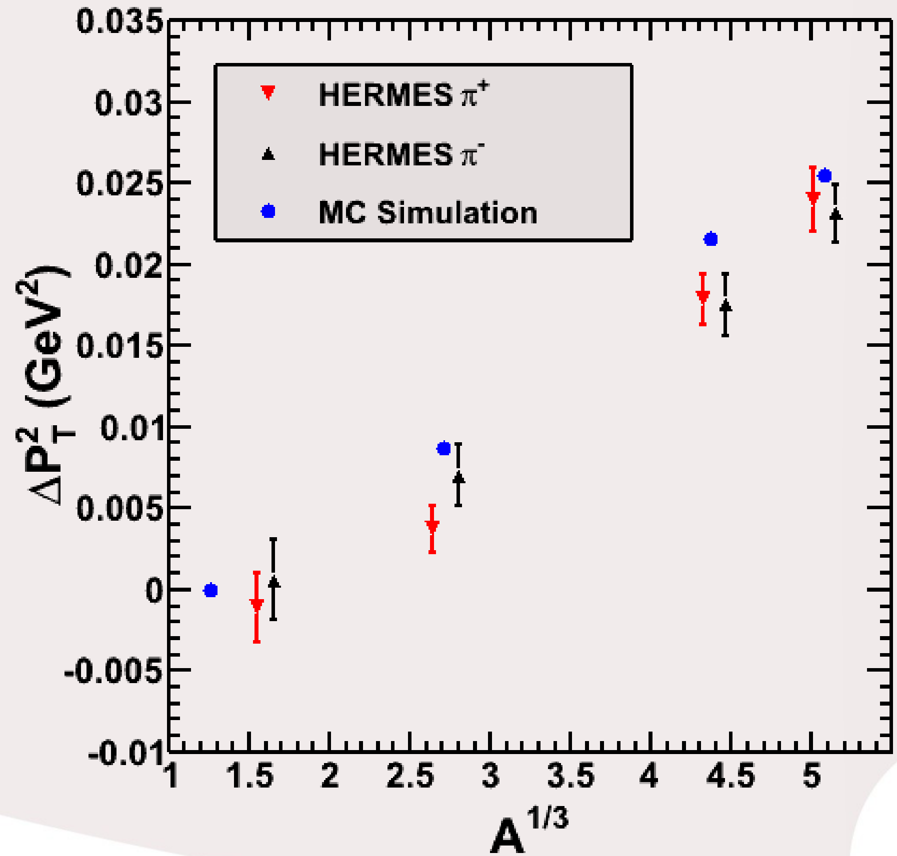




Transverse Momentum

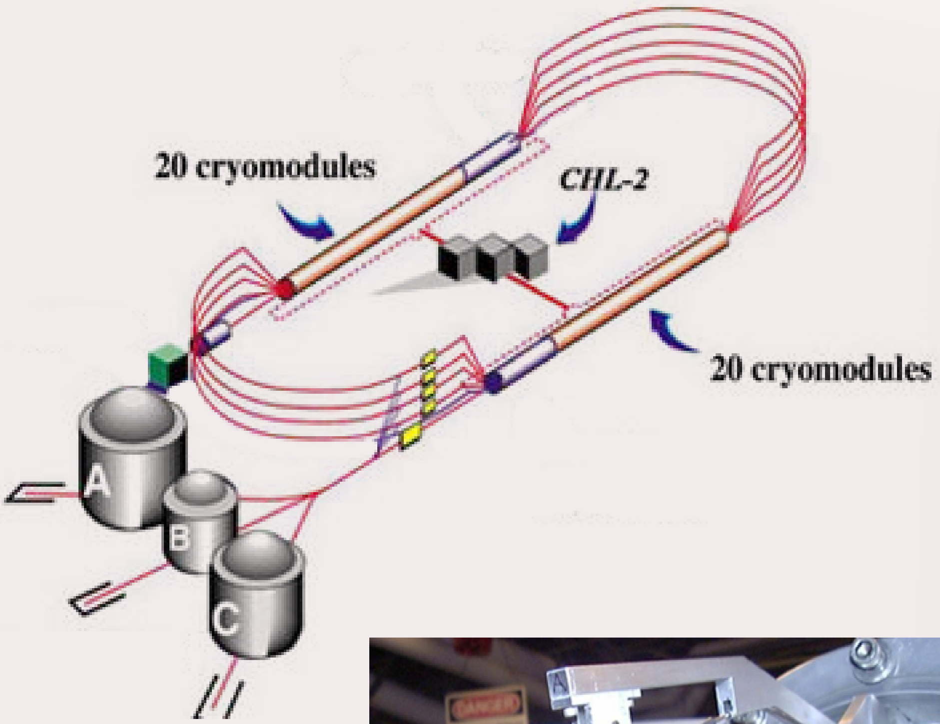
- **Can be implemented in many ways**
  - Here we test 4 options
  - Good shape with A (Event by event MC model)



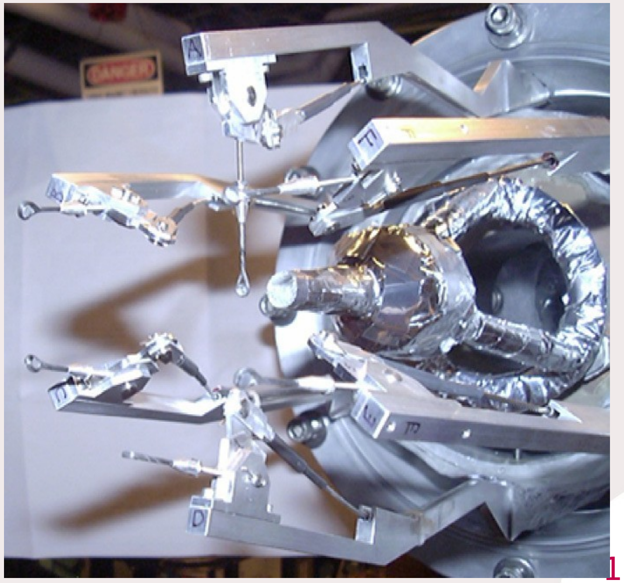


Jefferson Lab – EG2 exp

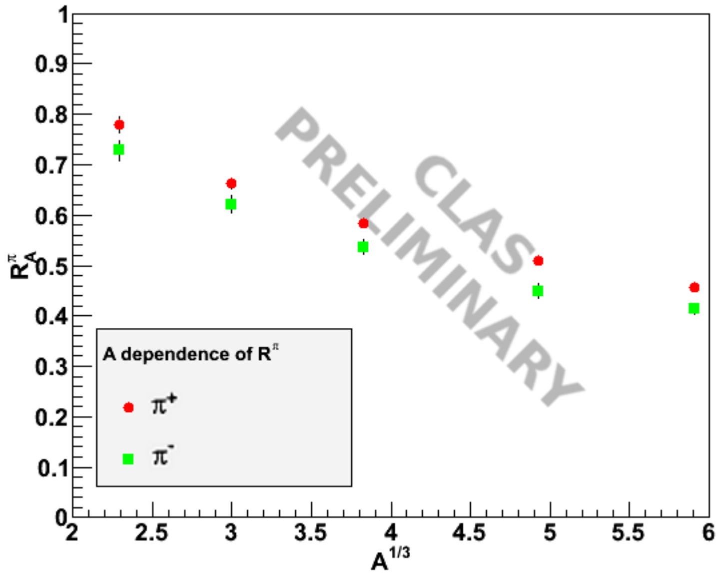
- **JLab continuous electron beam**
  - 5.012 GeV electrons
  - ~nA current
  - 2 cm long liquid deuterium target
  - 5 solid targets (C, Al, Fe, Sn and Pb)

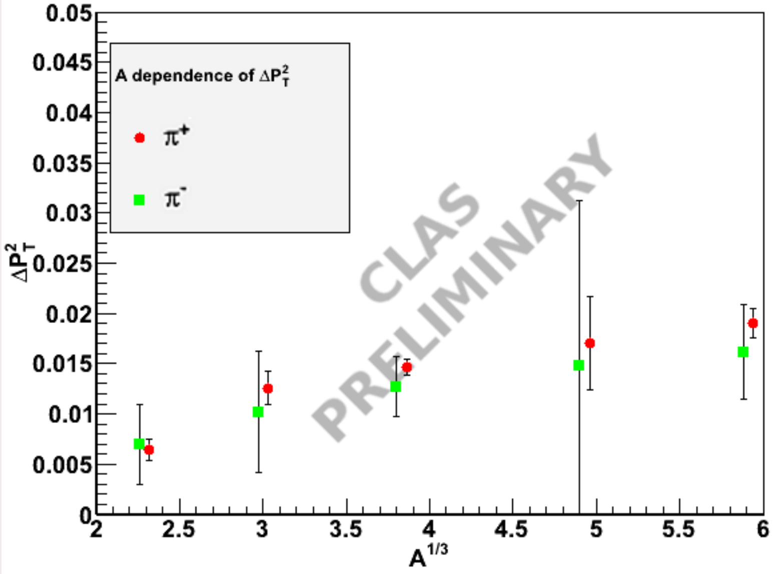


- **In the Hall-B**
  - CLAS Collaboration spectrometer
  - Detect and trigger on scattered electron (selected in DIS kine.)
  - Detect hadrons from ~15 to 160 degrees



CLAS Preliminary Results



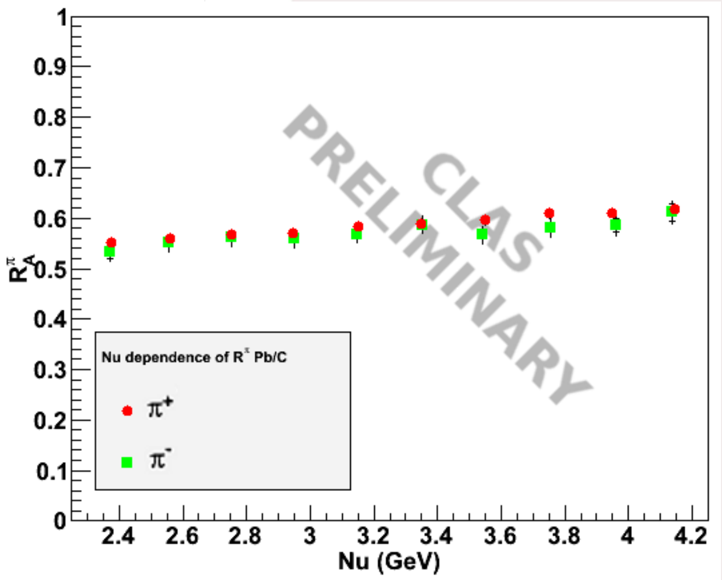


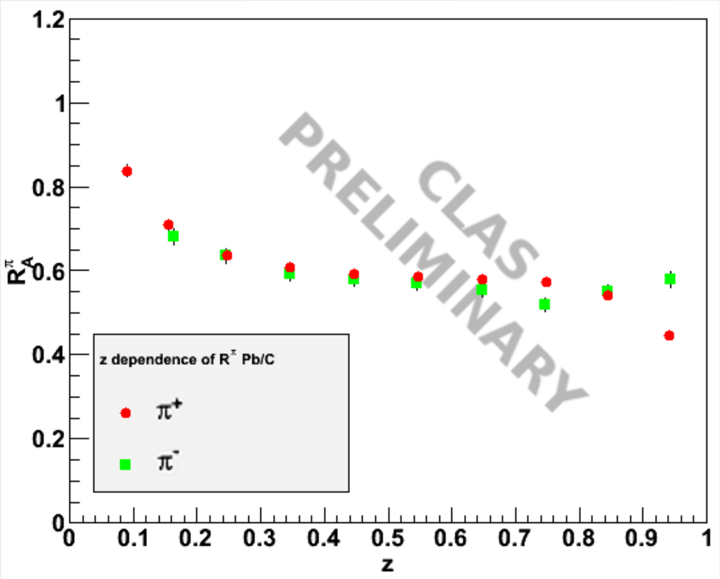
- **Nuclear effect saturates at high A and do not follow either $A^{1/3}$ nor $A^{2/3}$ trends**
  - First measurement with enough coverage to reveal such structure
  - Appears contradictory with hadron absorption models at first sight

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

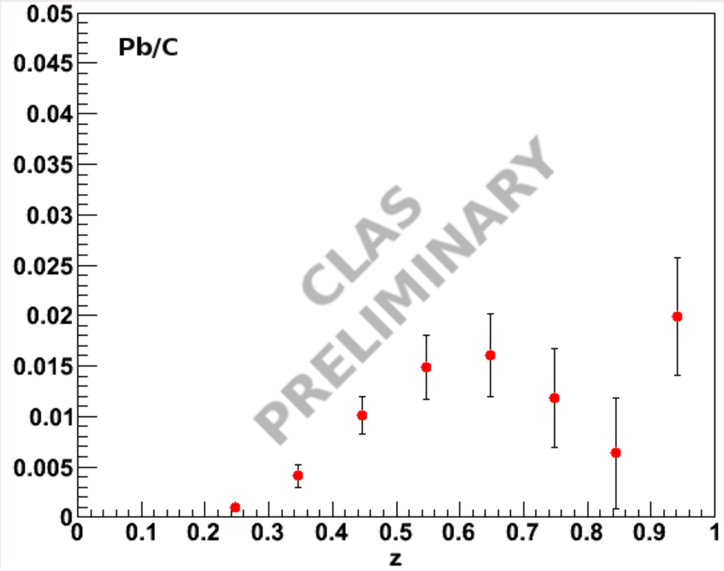
  → Do they originate from the same process or just a coincidence?

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

CLAS Preliminary Results

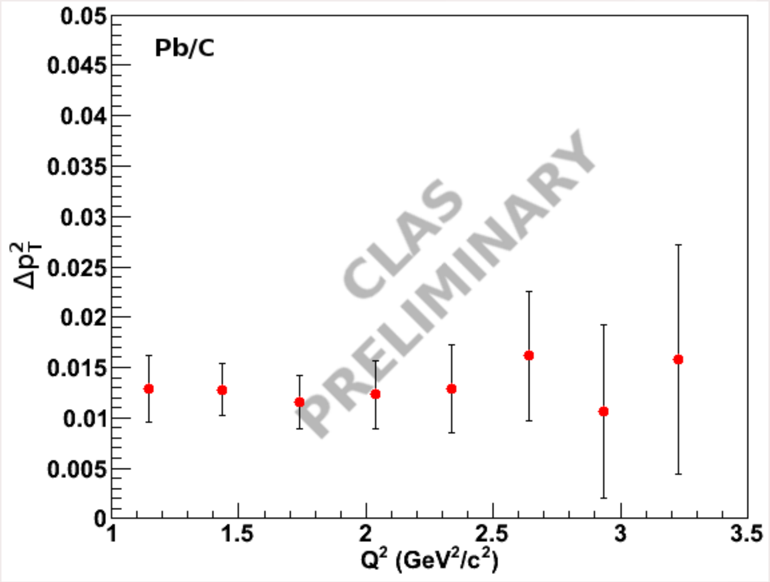
- **Some models have important predictions for the Q^2 trend**

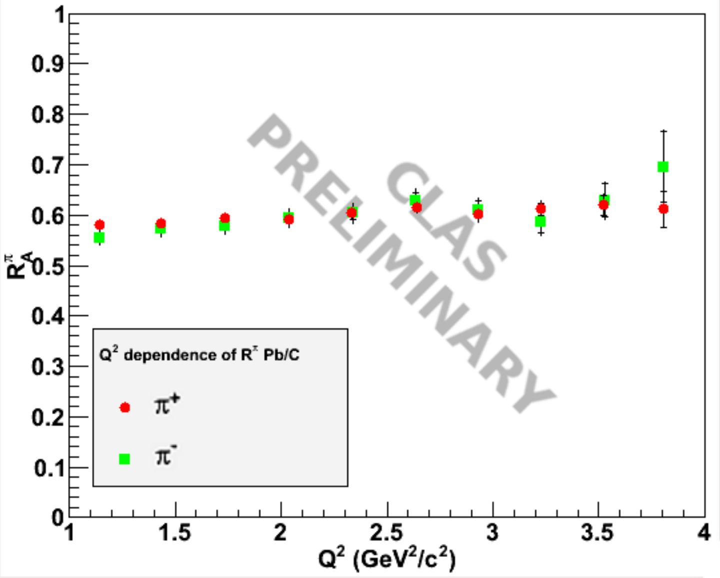
- **Yet, we see no effect with Δp_t^2**

  → to compare with expectations from theory

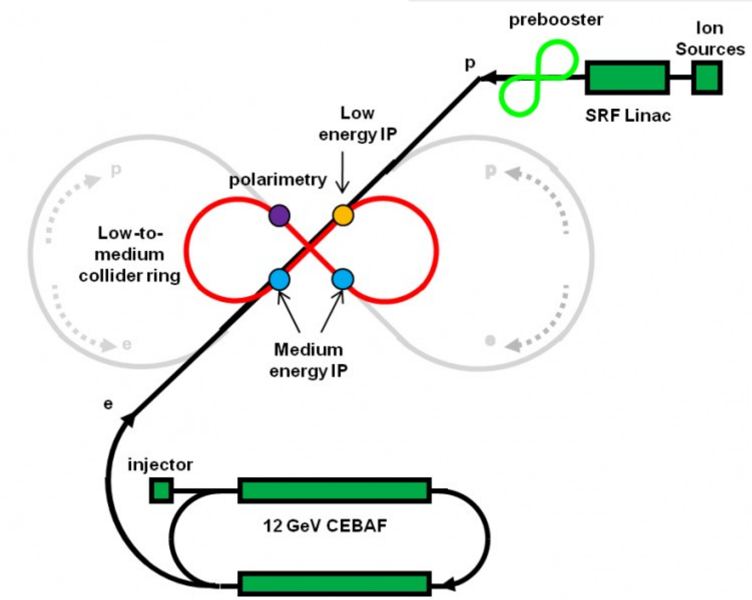
- **Small raise of the multiplicity ratio**
  - Same as HERMES
  - Not very conclusive

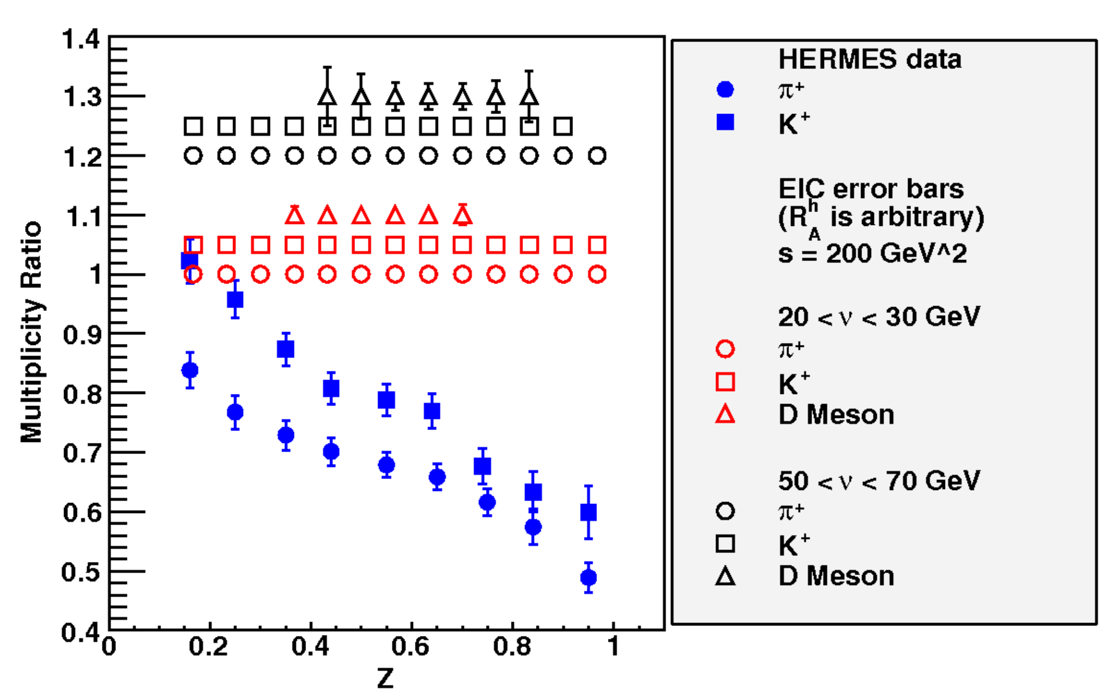
- **We have more precision but less coverage than HERMES**
  - More investigation is still needed to solve this question





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

- **Study of hadronization dynamics needs nuclei**
- **Hadronization in CNM is the best benchmark for energy loss models for heavy ion collisions**
- **Energy loss models can describe the HERMES attenuation with qhat~0.36 GeV2/fm**
- **Interpret transverse momentum of detected particles is biased!**
  - They have by nature experienced only limited interaction
  - We found good match between the results from attenuation and broadening
- **JLab results (CLAS coll.) provides for new high precision data to test models**
- **Future experiments are still necessary to have high enough energy as well as high enough statistics**