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Using Slow Protons in e-A at an EIC

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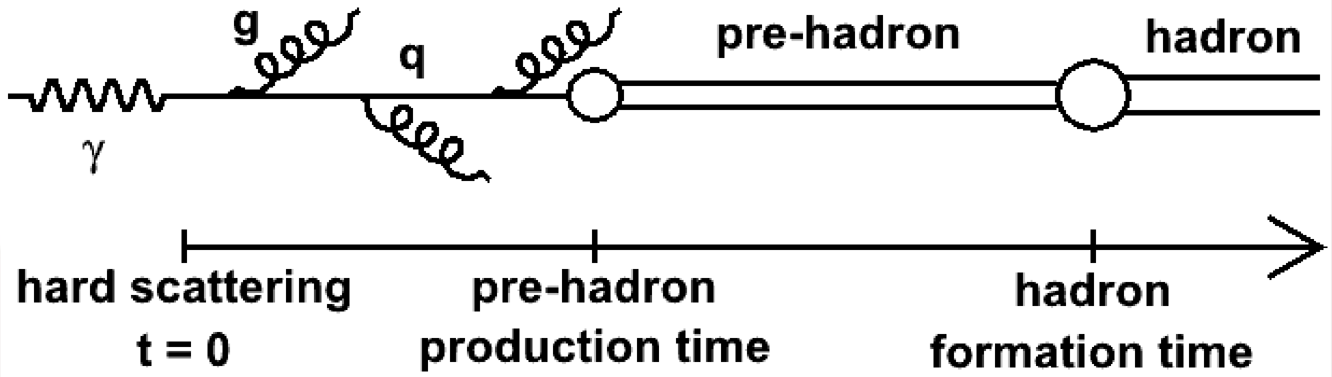
Overview

- ➔ How to study hadronization at an EIC ?
  - ➔ What can we measure in EIC?
- ➔Can we use total charge measured like in RHIC/LHC to determine centrality ?
- ➔ Can we find other similar method applicable to lepton scattering ?
  - ➔ How the nuclei is breaking up?
- ➔ Implications for measurement of other nuclear effects
  - ➔ Because this can be used for many nuclear effects

The Hadronization Process



- ➔ **Non perturbative QCD process**
  - ➔ **Need Models**
- ➔ **Production time → propagation of the colored quark**
- ➔ **Formation time → propagation of the color neutral prehadron**
- ➔ **No experimental quantification of these times !**
  - ➔ **Models indicate few fm level**
- ➔ **Nuclear targets of different size will help to measure them**
  - ➔ **Leads to more complicated models**

Observables

→**Multiplicity ratio**

- → **Characterizes the attenuation (1- R)**

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

→**Transverse momentum broadening**

- → **Characterizes the modification of the Pt spectrum**

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

Motivations

→ **Understand the hadronization process by**

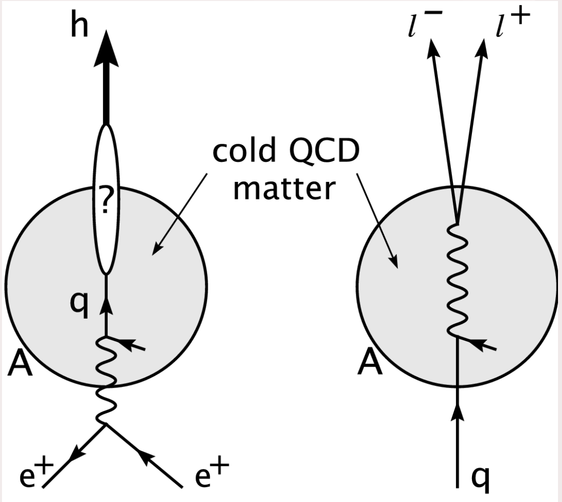
- → **Measuring the characteristic times**
- → **Calculating parton energy loss in QCD medium**
- → **Understanding the pre-hadron structure**

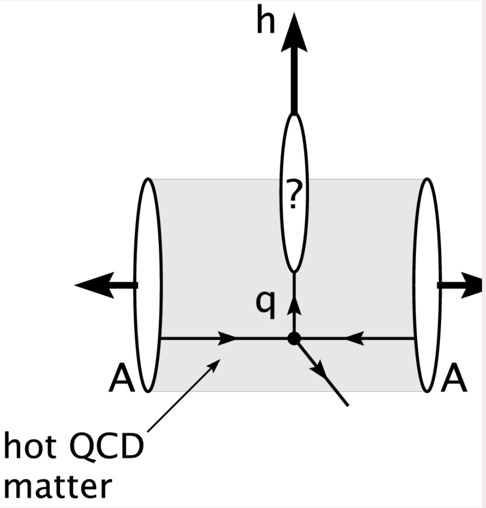
→ **Characterization of the QCD medium**

- → **Using parton energy loss**
- → **Comparing cold and hot nuclear matter**
- → **QCD evolution in medium**

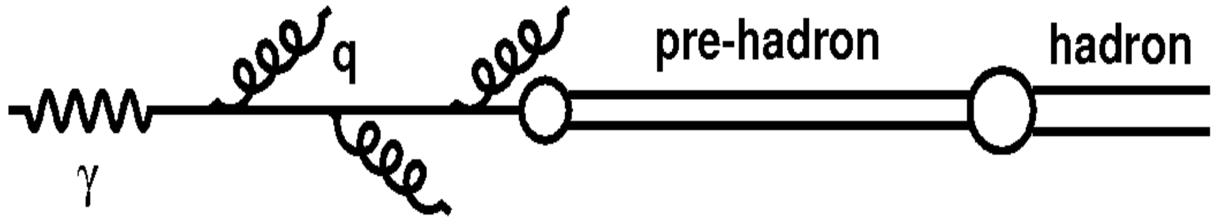
→ **Reduce systematic effects when attenuation needs to be corrected**

- → **Neutrino experiments especially**





Theoretical Models in Nuclear Medium



→Parton energy loss or Hadron absorption ?

→Modification of the evolution ?

- → Leads to a modification of fundamental fragmentation functions

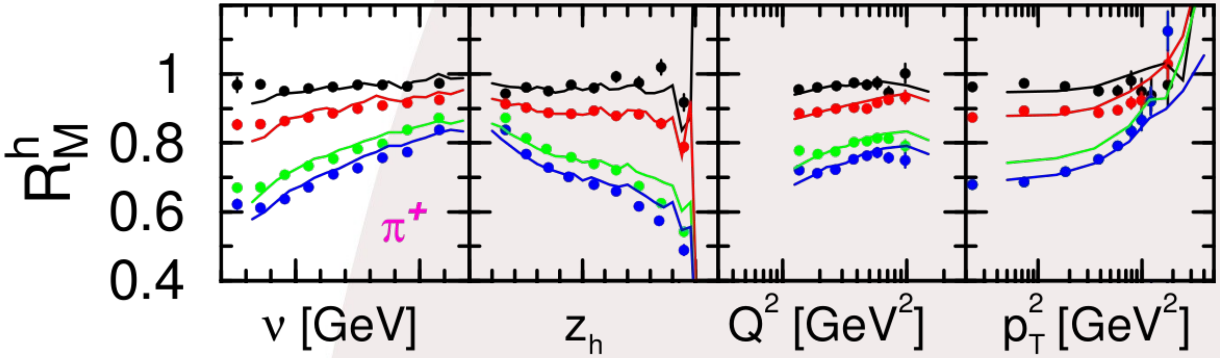
→Many models exists with different answers to these questions

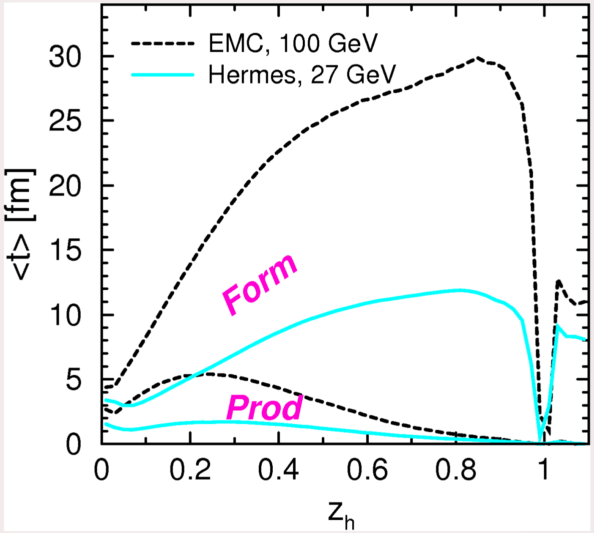
- → Pure parton energy loss or hadron absorption models
- → Mixed models (with all the possible combinations represented)

Summary of Experiments

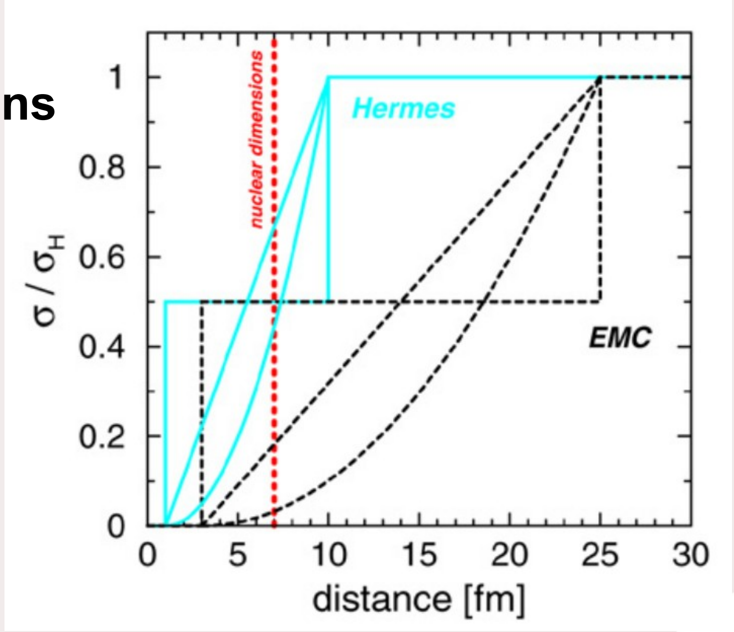
- **SLAC experiment**
  - First experiment, rough measurement of ratios
- **EMC experiment (CERN)**
  - Measure ratios at higher energy with a little more precision
- **E665 experiment (Fermi Lab)**
  - Ratios measured relatively to the number of slow protons
  - Enlighten the difference between target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

HERMES Results : The Pion Ratios

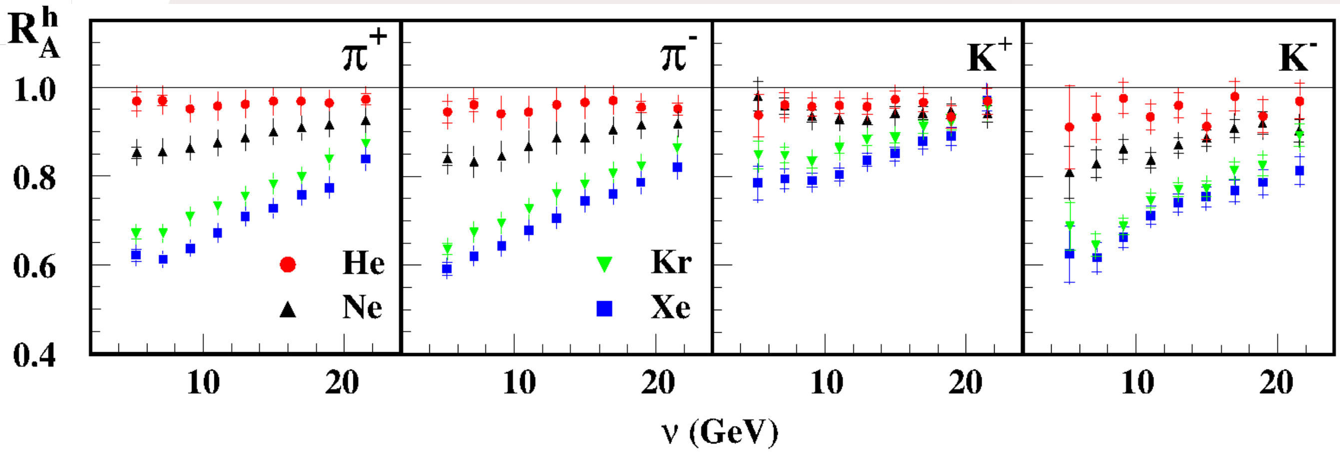




- ➔**Pion behavior coherent with all previous results for hadrons**
  - ➔ **no differences are observed with the 3 pions**
- ➔**GiBUU model based on prehadron absorption can describe these data**
  - ➔ **no quark energy loss**
  - ➔ **production and formation times extracted from PYTHIA**
  - ➔ **Prehadron cross section growing linearly with time**



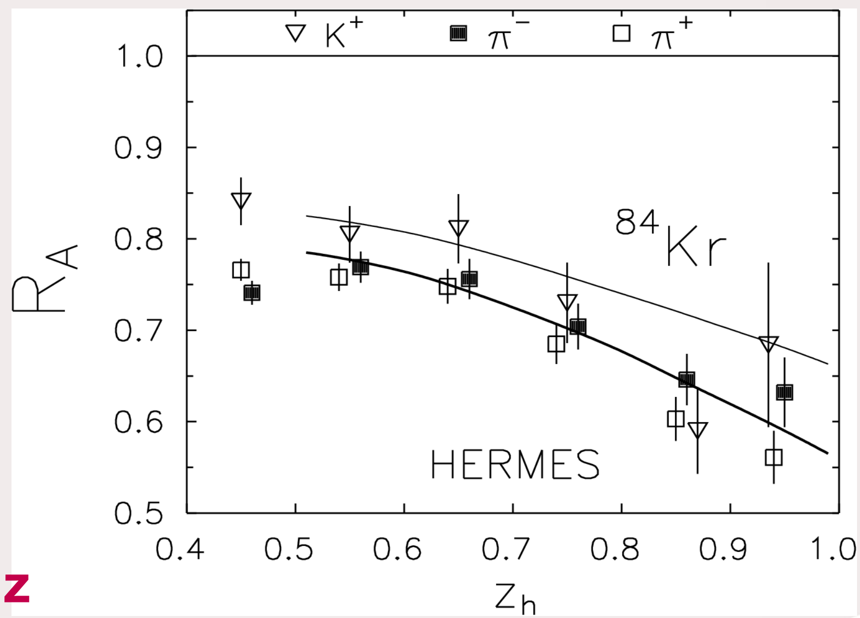
HERMES Results : The Pion-Kaon Discrepancy



➔Can be explained by

- ➔ the smaller cross section of K+
  - ➔ Success in GiBUU but miss K-
- ➔ the different behavior of the FF
  - ➔ Not enough as seen in Monte-Carlo simulation (Accardi & RD)
- ➔ contamination from $\pi + p \rightarrow \Lambda + K$

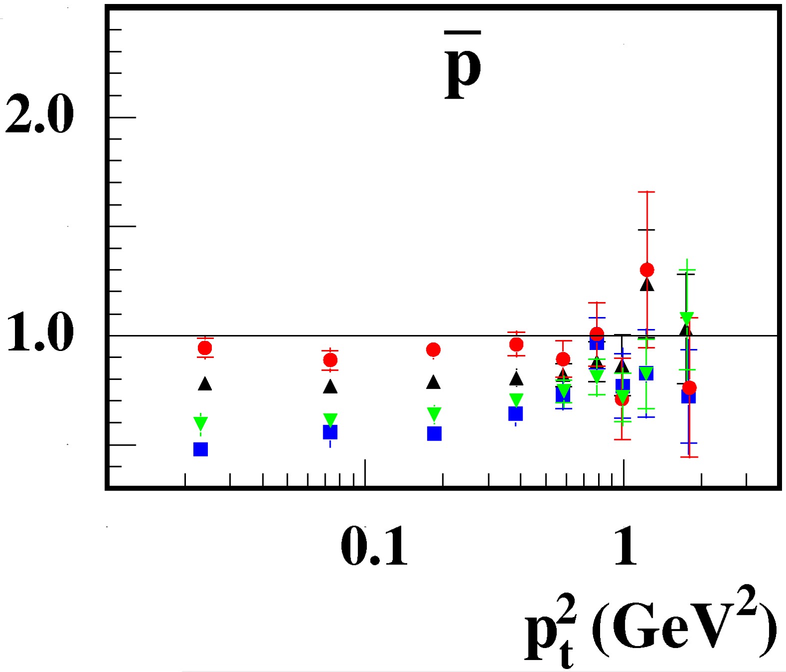
  (Kopeliovich et al.)

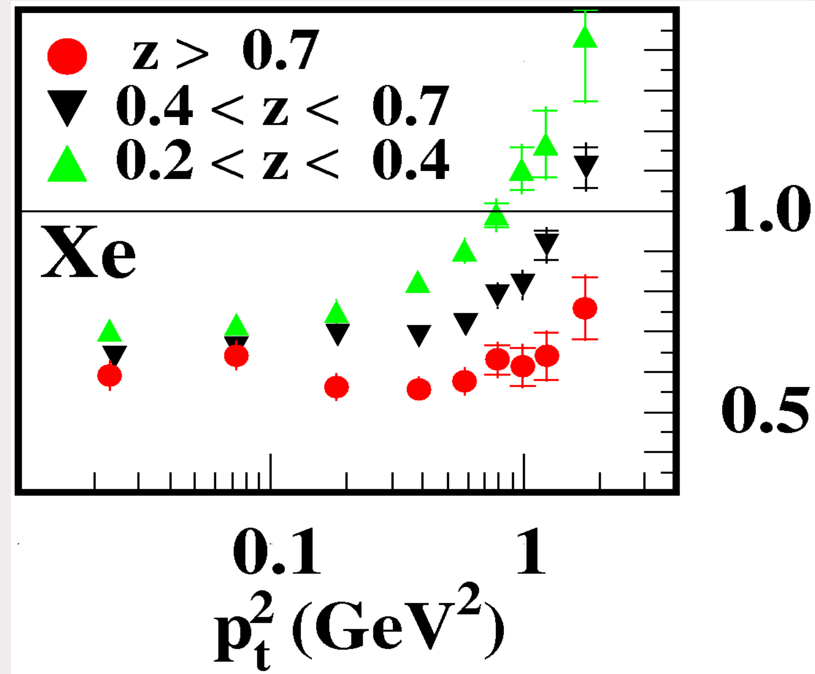


➔Can be resolved by selecting higher z

- ➔ Less target fragmentation

HERMES Results : The Cronin Effect



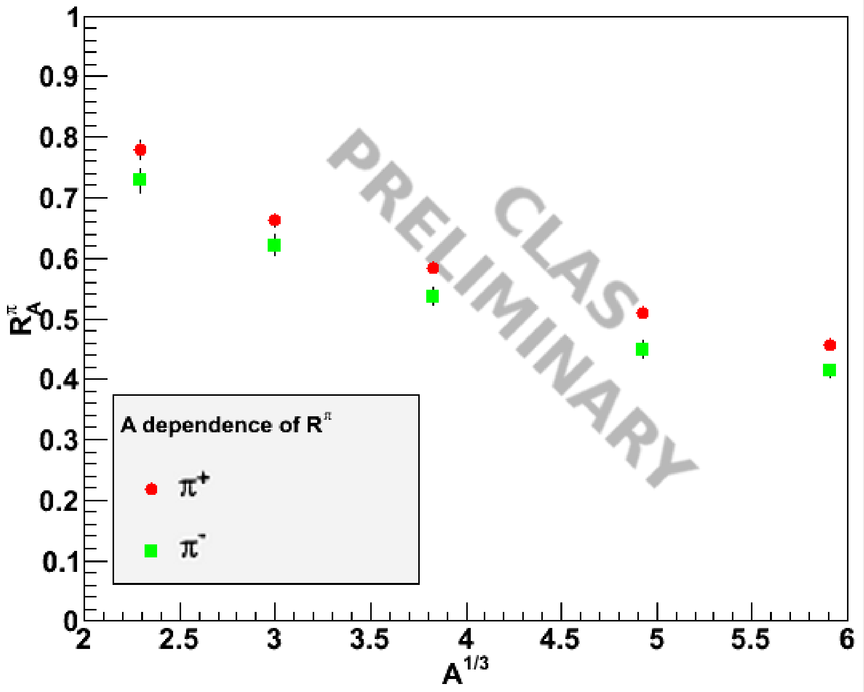


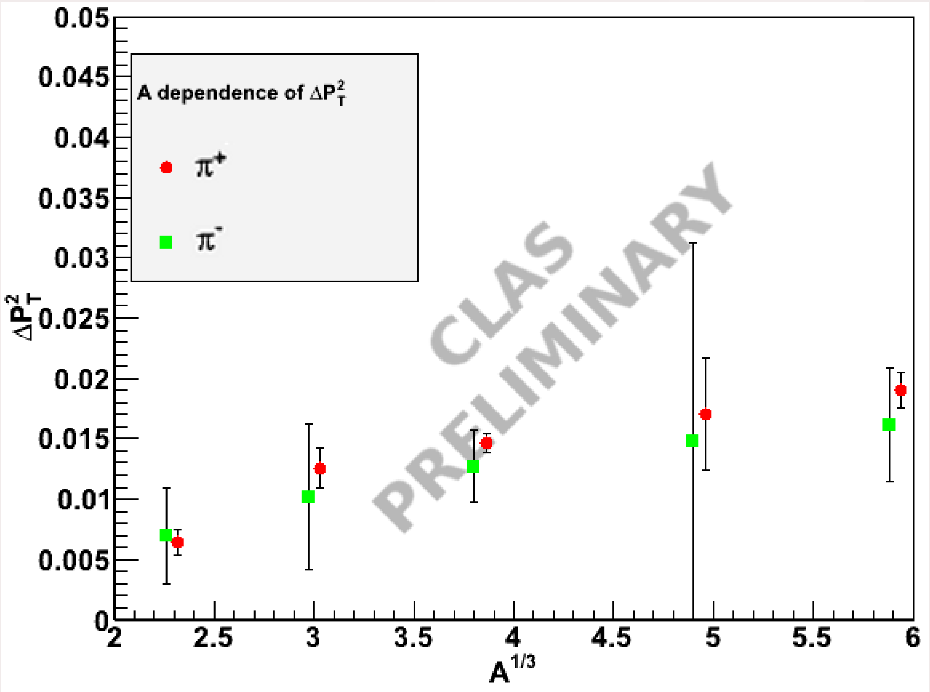
➔Cronin effect is limited in the case of anti-protons

➔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

CLAS Preliminary Results : A Dependence





→Nuclear effect saturates at high A – Does not follow A1/3 or A2/3

- → Can be resolved within parton energy loss picture with small production time

→Multiplicity ratio and Pt broadening follow the same trend

- → Do they originate from the same process ?

HERMES Results : Two Pions Ratio

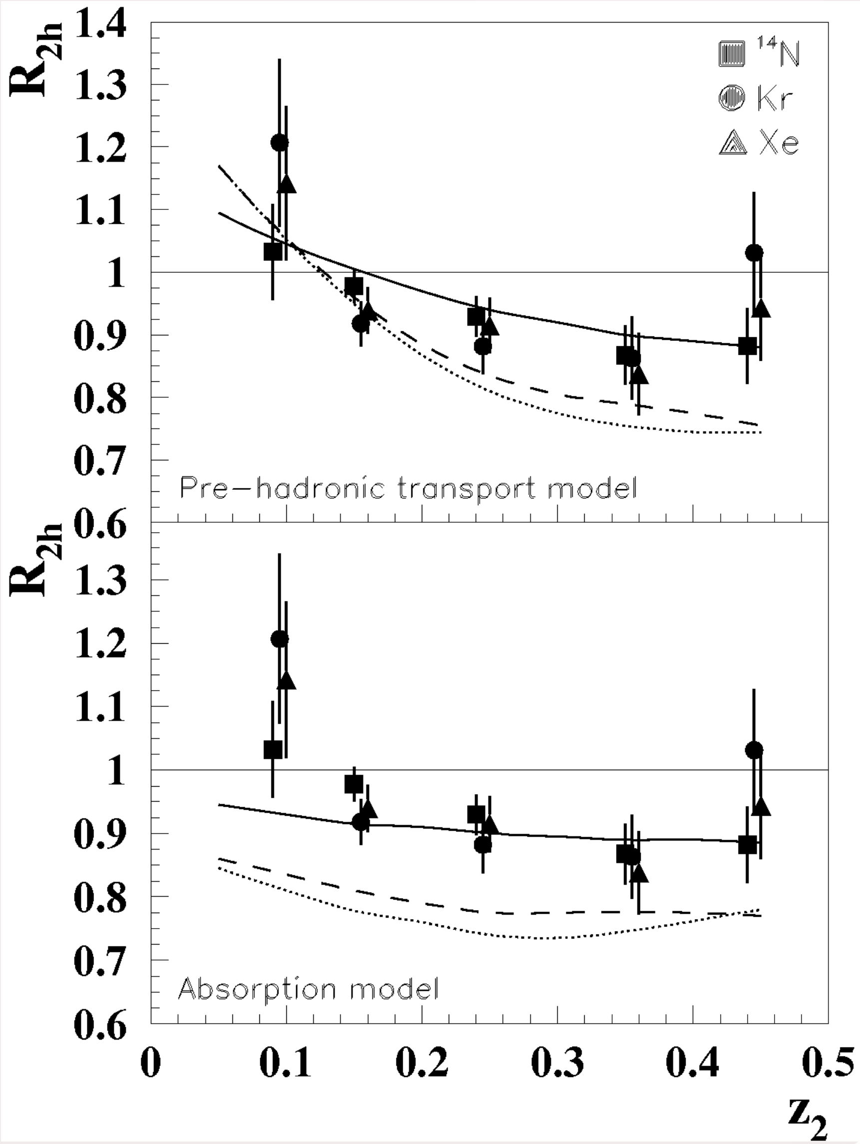
➔**Multiplicity ratio of two hadrons production**

➔**The A scaling disappears**

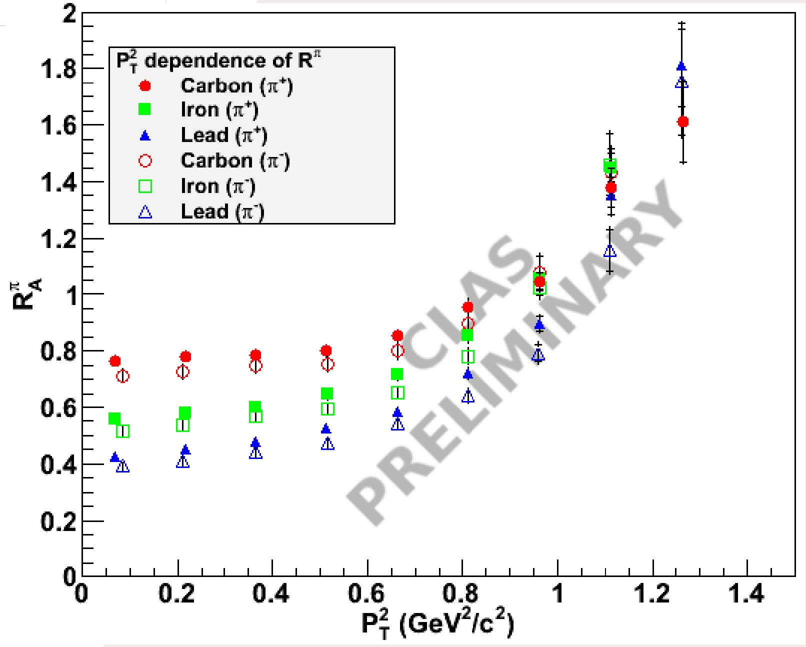
- ➔ in contradiction with all models
- ➔ most model ignore these data

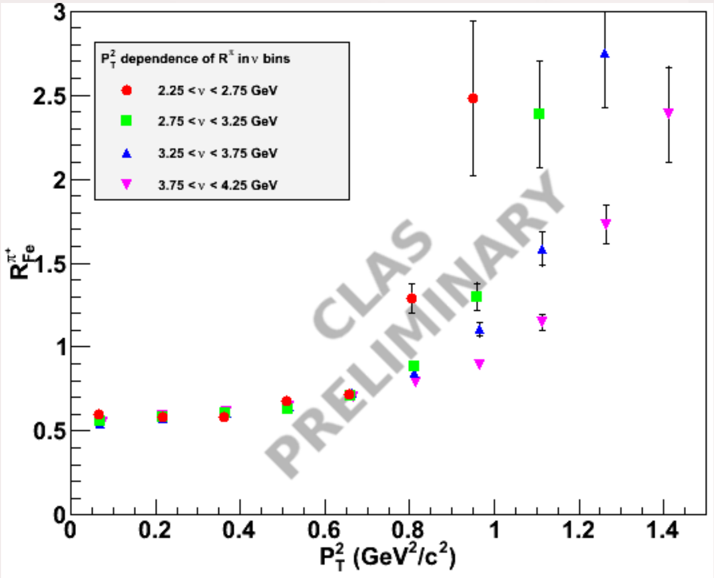
➔**Explanation based on a modification of the FF ?**

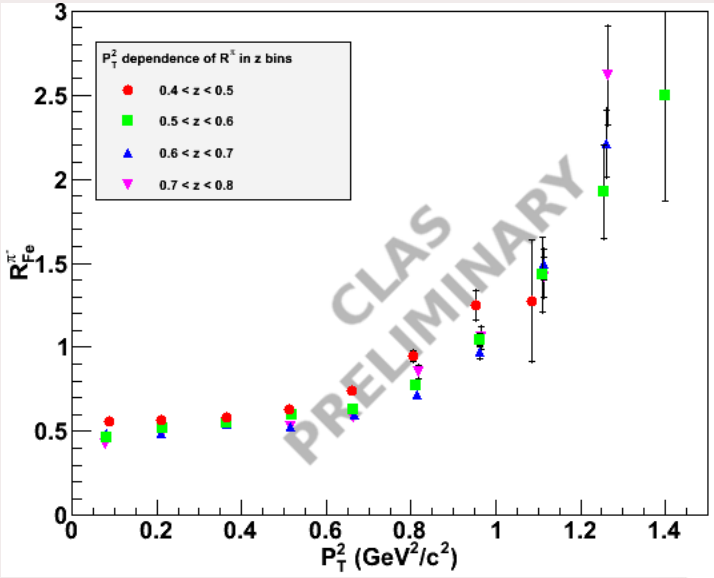
- ➔ Part of the energy lost by the leading hadron goes to the sub-leading hadrons ?



CLAS Preliminary Results: Pt broadening





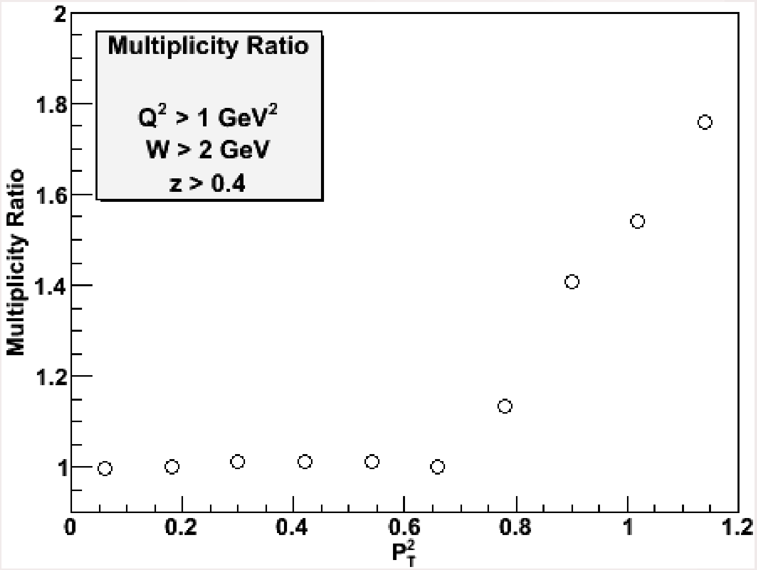


- ➔Cronin effect
  - ➔ stronger than for HERMES
  - ➔ vary with ν not z unlike HERMES
- ➔Higher z cut reduce the effect from target fragmentation
- ➔Replaced by a Fermi motion effect?

CLAS Preliminary Results: Pt broadening

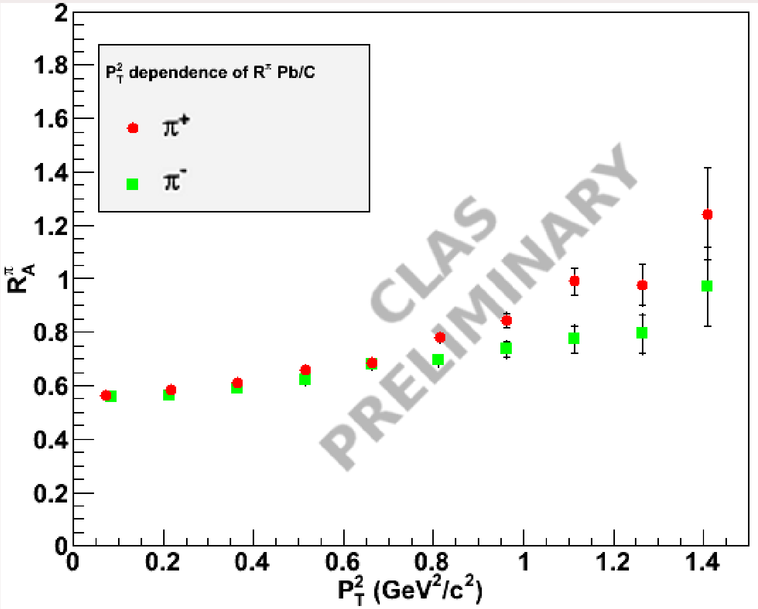
➔Monte-Carlo simulation shows a strong effect to be expected from Fermi motion

- ➔ Dilute the signal observed from hadronization
- ➔ Can be reduced by using carbon as reference nuclei

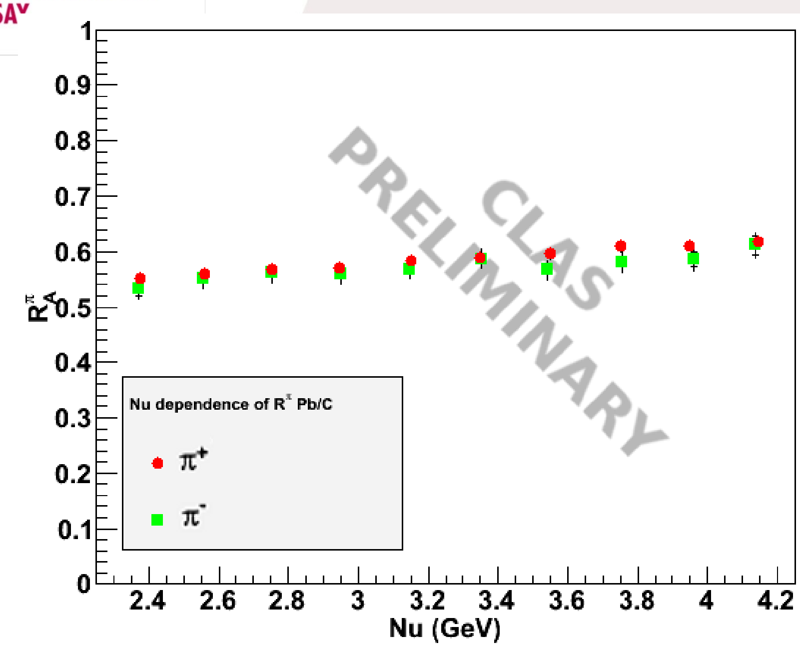


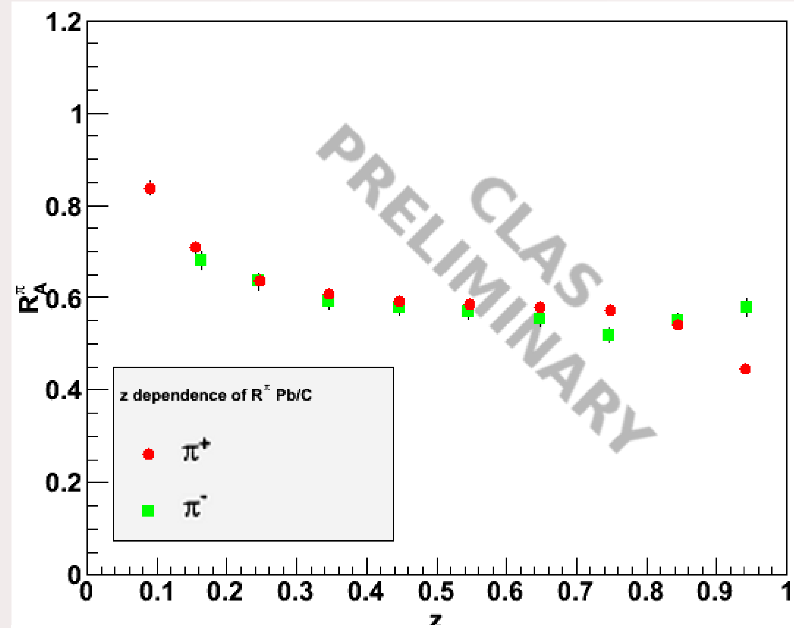
➔Moderated Cronin effect observed for C/Pb confirms the MC expectation

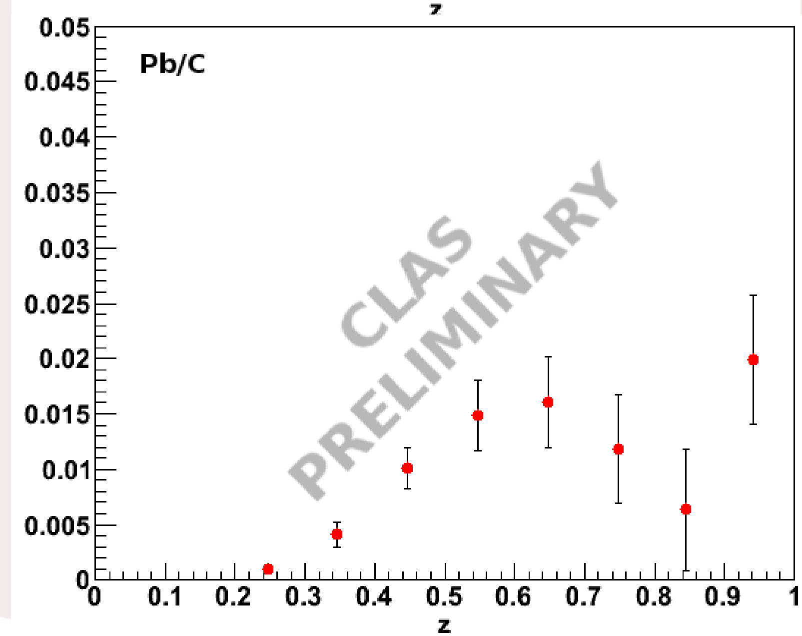
- ➔ The method should be generalized at CLAS energy to reduce FM effects



CLAS Preliminary Results: Pb/C







- ➔ Reproduce the ratios of HERMES
  - ➔ Slope in ν similar to HERMES
  - ➔ Slope in z not as pronounced as in HERMES (?)
- ➔ Results for Δpt2 coherent with HERMES

CLAS Preliminary Results: Q2 evolution

➔Smaller coverage than HERMES

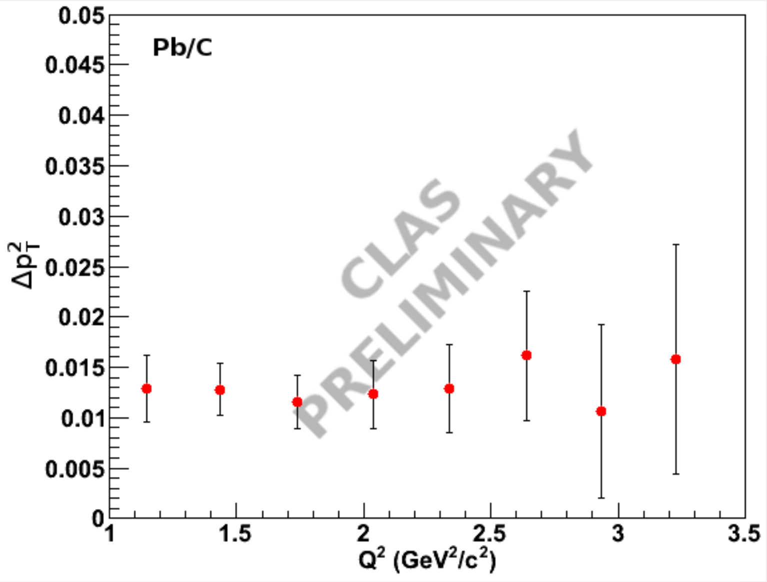
➔No effect with Δpt2

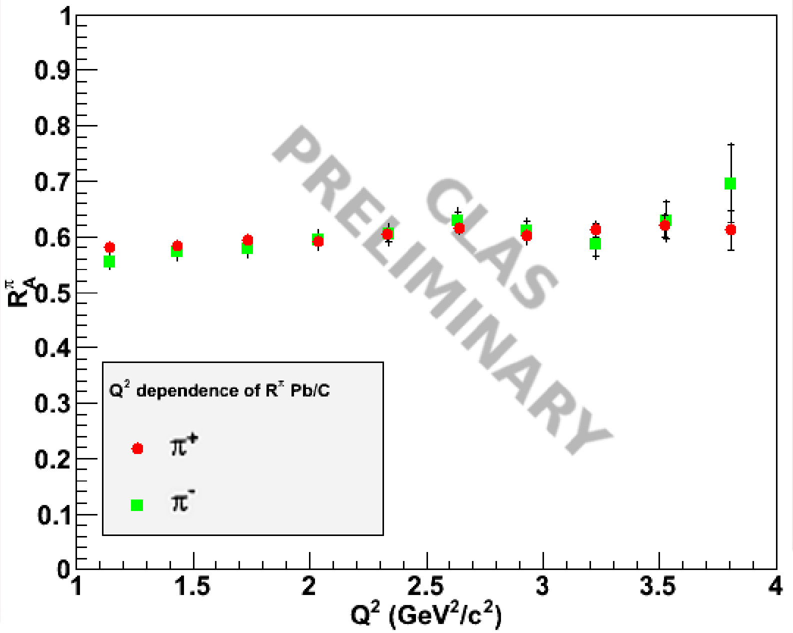
- ➔ to be compared with expectations from theory

➔Small raise of the multiplicity ratio

- ➔ Same as HERMES
- ➔ But here binned in nu!

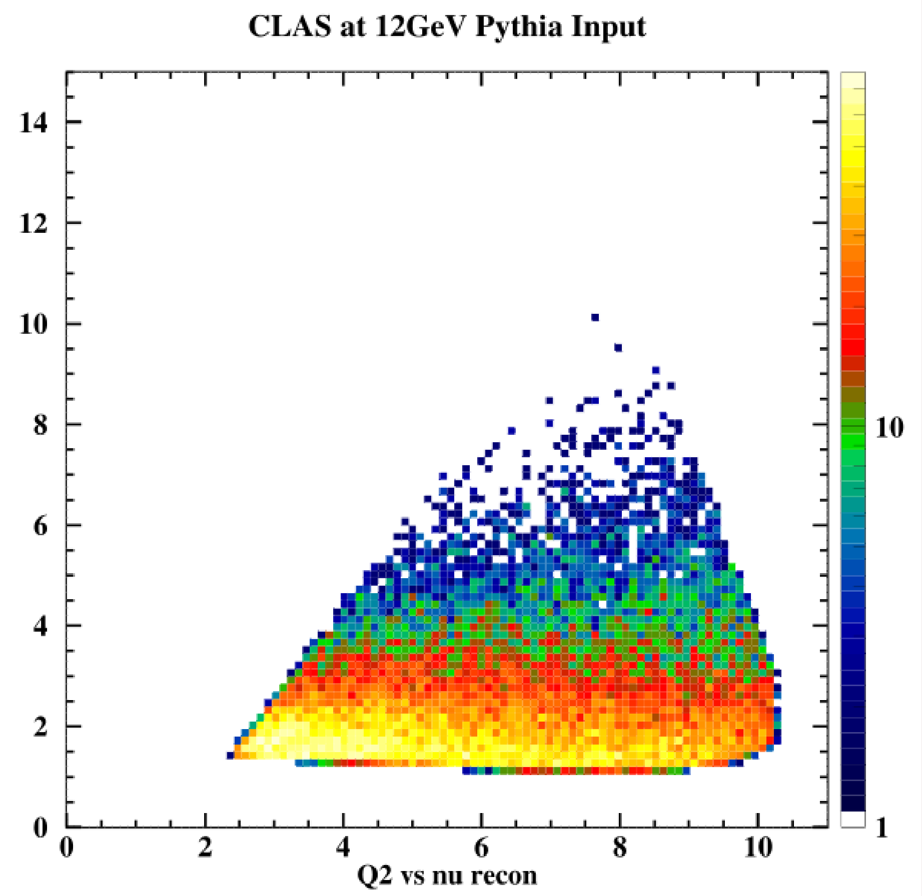
➔More leverage is needed to solve this question → EIC



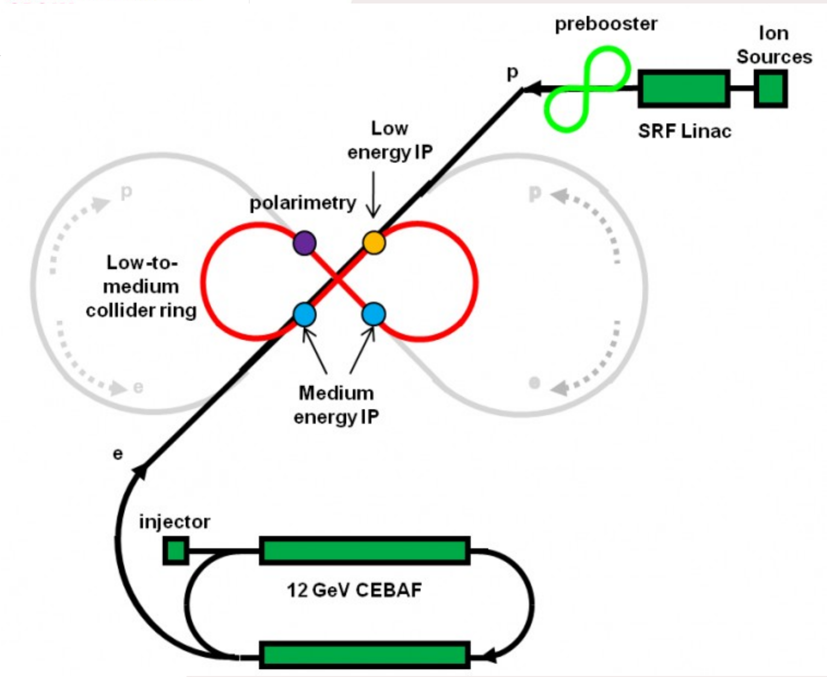


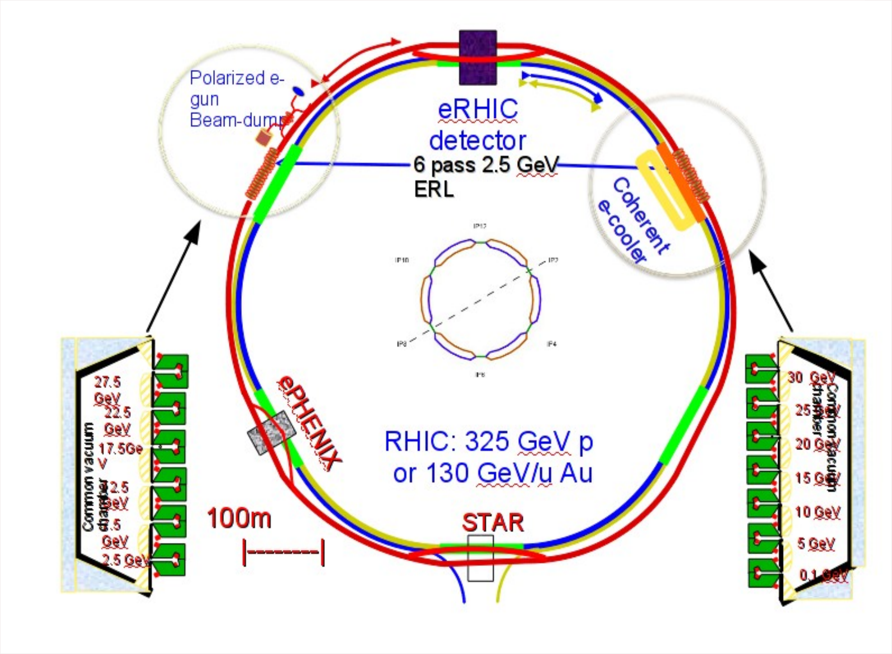
Experiment at CLAS12

- **Proposal by K. Hafidi, W. Brooks 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
  - Larger luminosity than CLAS (x10) and HERMES (x1000)



The Electron Ion Collider (EIC)





- **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**

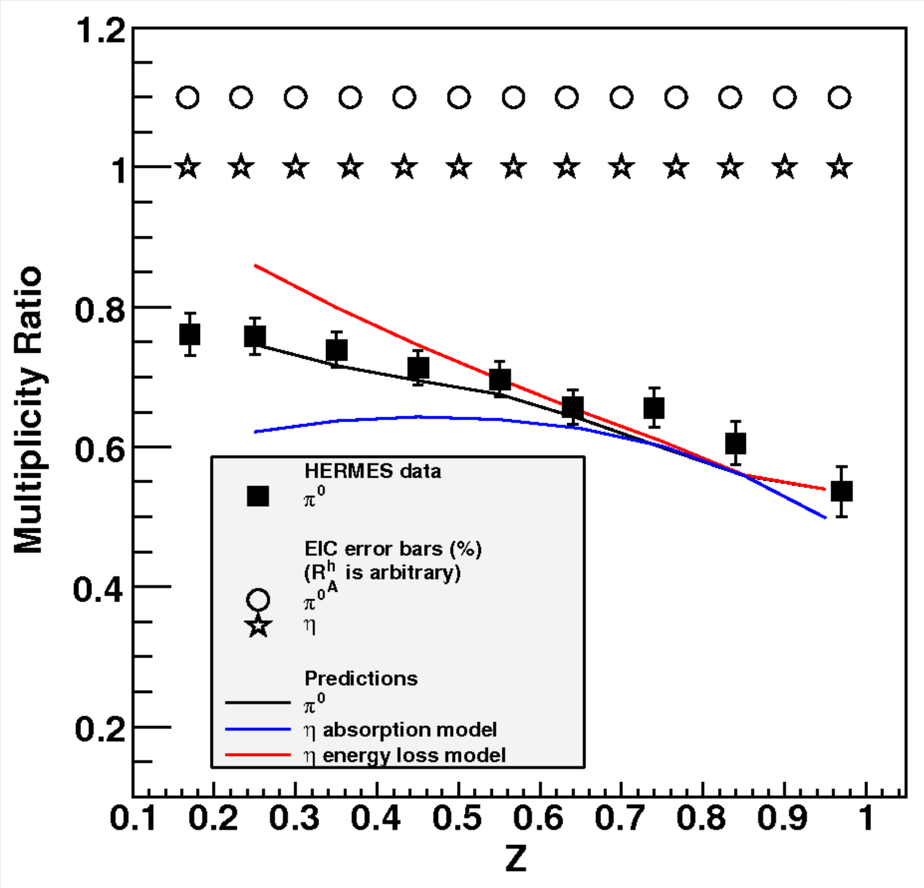
Simulation Parameters

- **Luminosity: 200 fb-1**
  - or 115 days at 2.10^34 cm-2s-1 per target
- **Use two energies**
  - s = 200 GeV2
  - s = 1000 GeV2
- **Cuts to select DIS on a single quark**
  - Q2 > 1 GeV2 & W > 4 GeV
  - XBj > 0.1 (permit to suppress di-quark production)
- **Cut to select leading hadrons**
  - z > 0.4
- **Experimental limits**
  - 0.1 < y < 0.85
- **Acceptance assumed**
  - π, K and η A = 50%
  - D and B A = 2%

Understanding the Dynamic of η Production In-Medium (s=200 GeV2)

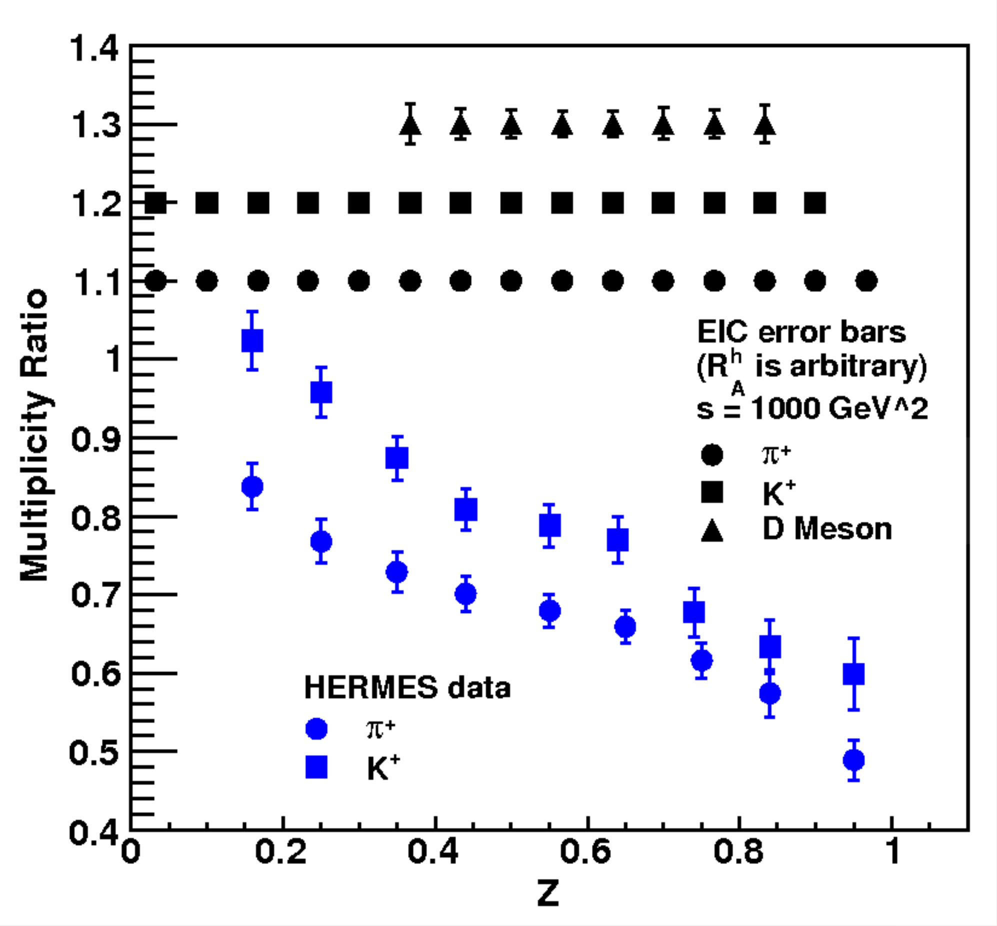
➔ Difference between π0 and η will permit to find which process is dominant, hadron absorption or parton energy loss (A. Accardi)

➔ For 20 < ν < 30 GeV



Ratio at s = 1000 GeV2 & 100 < ν <130 GeV

- →High precision measurement of attenuation as a function of ν and z for π, K and D mesons.
- →Will permit to understand the behavior of heavy quarks observed at RHIC/LHC



Ratio at s = 200 GeV2

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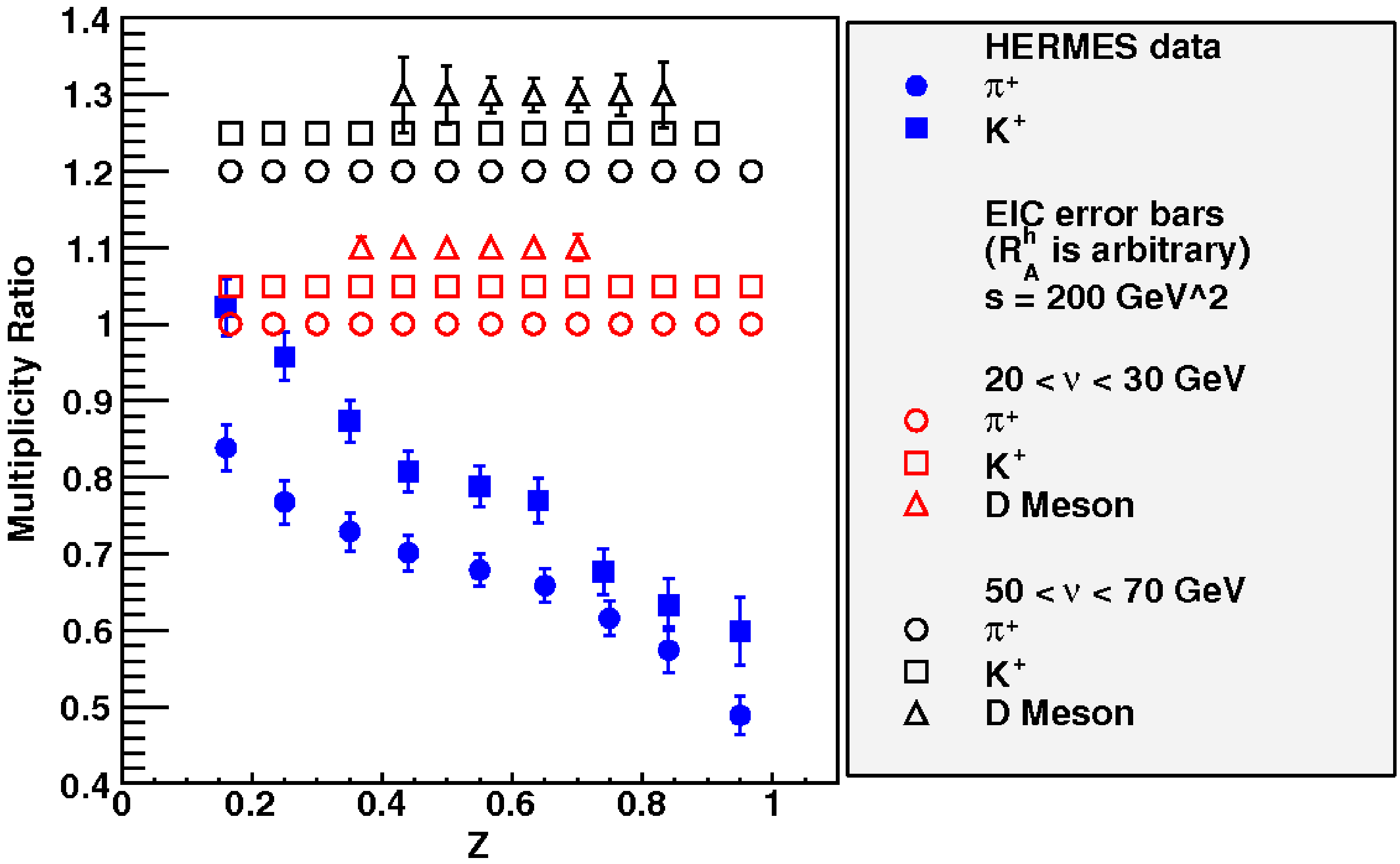
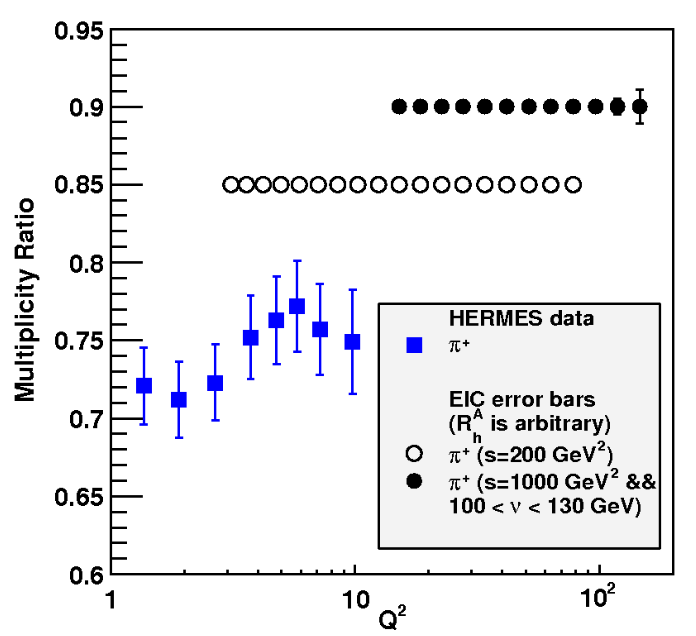
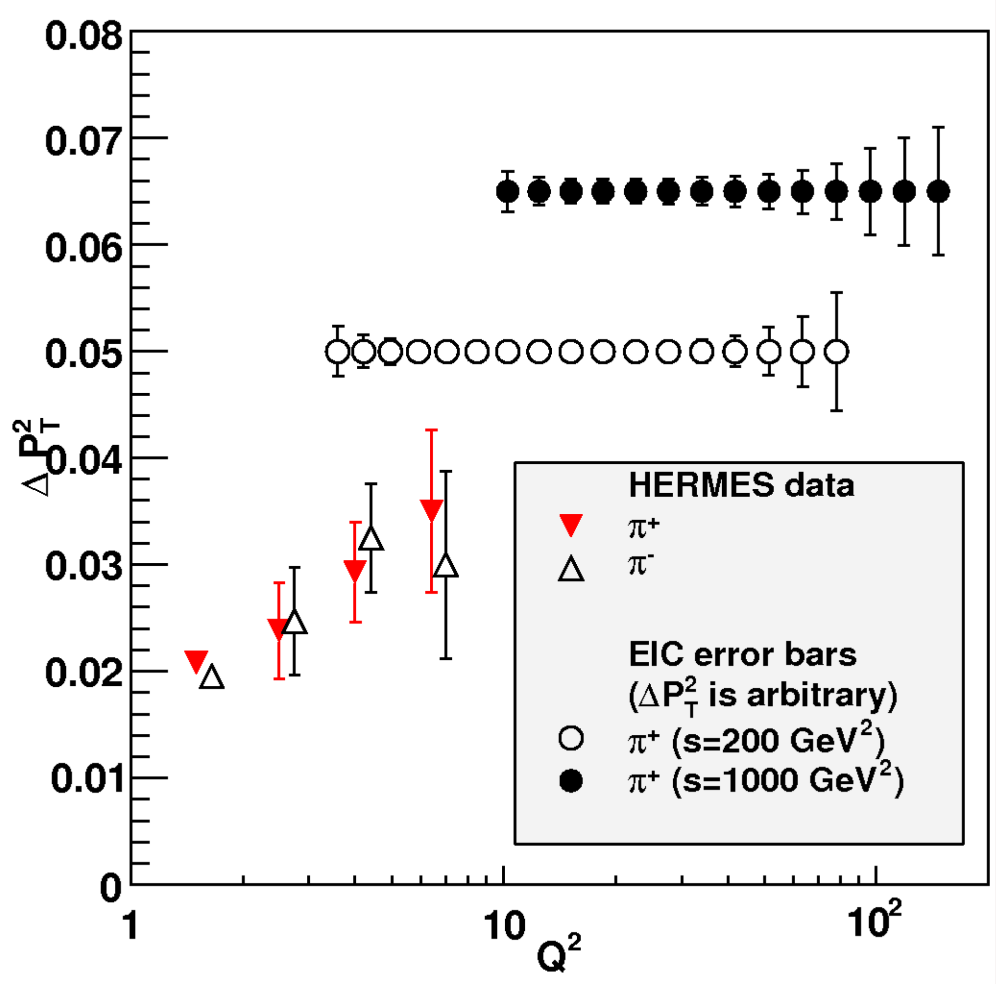


Q2 evolution

- ➔The Q2 dependence permit to measure any modification of the DGLAP evolution in medium
- ➔The Q2 variation is a very important tool to constrain energy loss calculations.



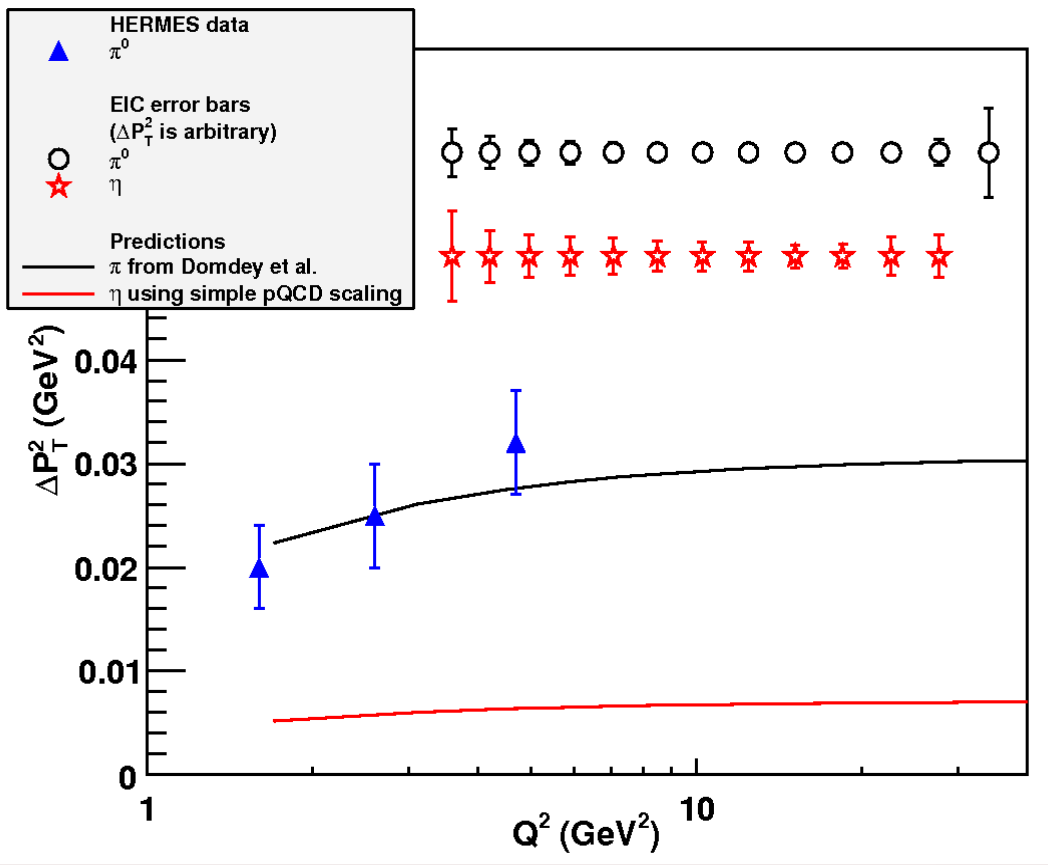


Flavor scaling of ΔPT2 (s=200 GeV2)

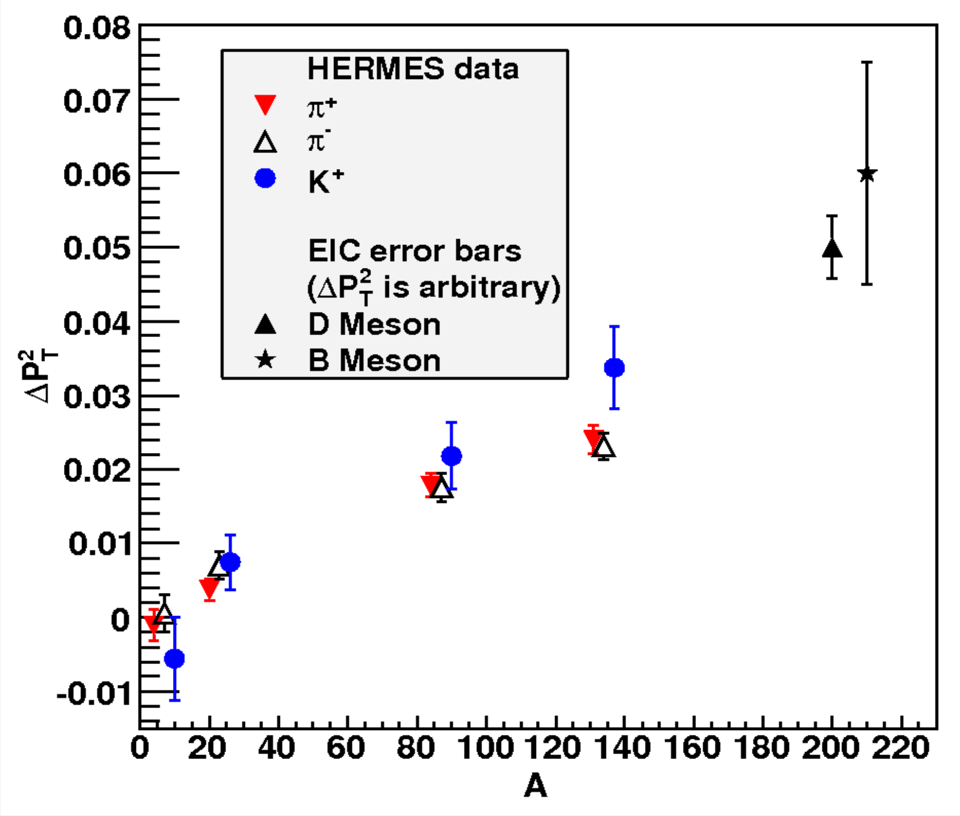
➔Work from Domdey et al. leads to a simple scaling of pQCD in-medium energy loss between quark flavors

➔Can be easily measured at any EIC energy

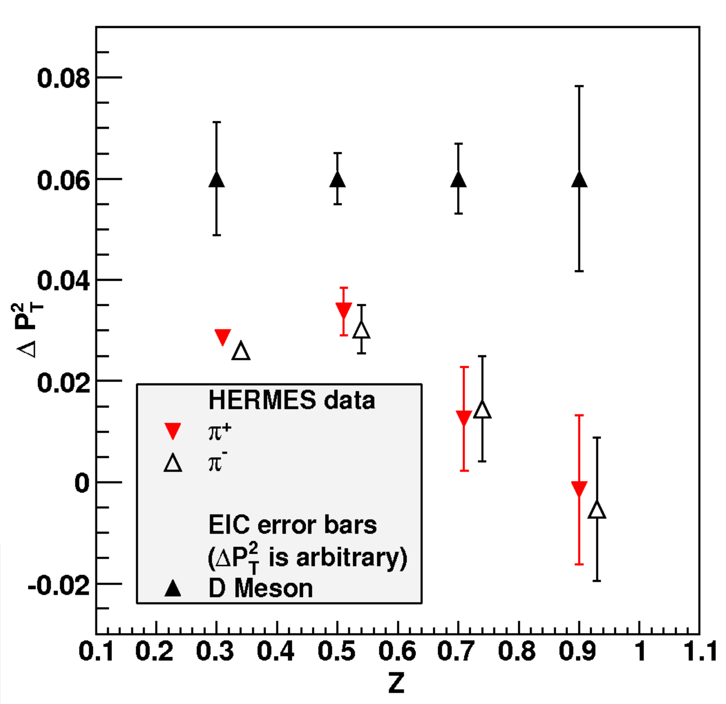
(here 20 < ν < 30 GeV)



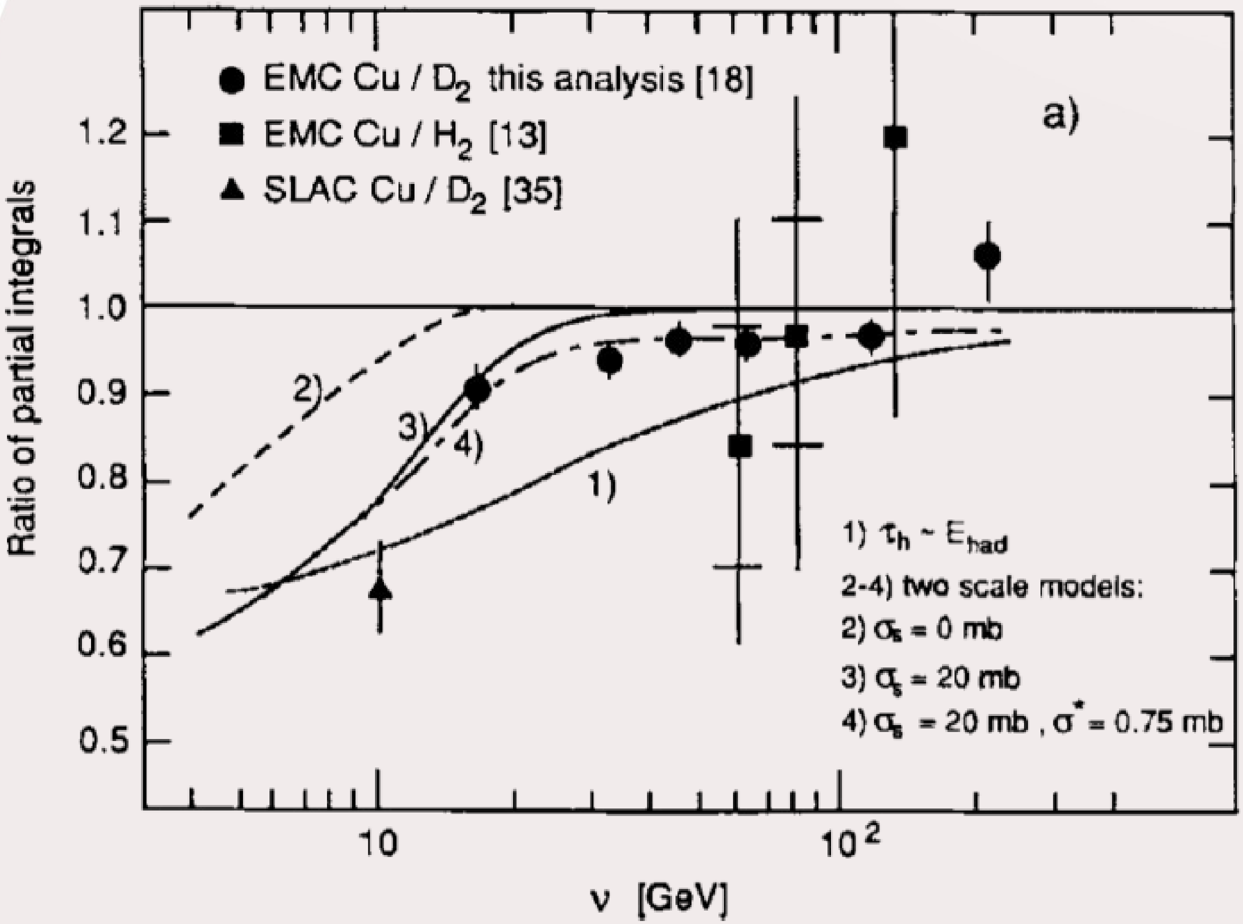
Heavy Quarks Energy Loss (s=1000 GeV2)



- ➔ΔPT2 dependence in A and z gives indication about the nature of parton energy loss.
- ➔Is the pattern similar for heavy and light quarks?



What happens at high energy ?



Hadronization effect gets smaller at higher energy. How to deal with that ?

Existing Data at EIC like Energy

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ORSAY

- ➔ **There is some data to explore this question !**
  - ➔ **E665 experiment at Fermi Lab**
  - ➔ **μ-D (6000 events) and μ-Xe (2000 events)**
  - ➔ **490 GeV beam energy**

Z. Phys. C 65, 225–244 (1995)

ZEITSCHRIFT FÜR PHYSIK C

Nuclear shadowing, diffractive scattering and low momentum protons in μXe interactions at 490 GeV

E665 Collaboration

M.R. Adams[6], M. Aderholz[11], S.Aïd[9,a], P.L. Anthony[10,b], M.D. Baker[10], J. Bartlett[4], A.A. Bhatti[13,c], H.M. Braun[14], W. Busza[10], T.J. Carroll[11], J.M. Conrad[5], G. Coutrakon[4,d], R. Davisson[13], I. Derado[11], S.K. Dhawan[15], W. Dougherty[13], T. Dreyer[1], K. Dziunikowska[8], V. Eckardt[11], U. Ecker[14,a], M. Erdmann[1,e], A. Eskreys[7], J. Figiel[7], H.J. Gebauer[11], D.F. Geesaman[2], R. Gilman[2,f], M.C. Green[2,g], J. Haas[1], C. Halliwell[6], J. Hanlon[4], D. Hantke[11], V.W. Hughes[15], H.E. Jackson[2], D.E. Jaffe[6,h], G. Jancso[11], D.M. Jansen[13,i], K. Kadija[11,†], S. Kaufman[2], R.D. Kennedy[3], T. Kirk[4,j], H.G.E. Kobrak[3], S. Krzywdzinski[4], S. Kunori[9], J.J. Lord[13], H.J. Lubatti[13], D. McLeod[6], S. Magill[6,j], P. Malecki[7], A. Manz[11], H. Melanson[4], D.G. Michael[5,k], W. Mohr[1], H.E. Montgomery[4], J.G. Morfin[4], R.B. Nickerson[5,l], S. O'Day[9,m], K. Olkiewicz[7], L. Osborne[10], V. Papavassiliou[15,j], B. Pawlik[7], F.M. Pipkin[5,*], E.J. Ramberg[9,m], A. Röser[14,o], J.J. Ryan[10], C.W. Salgado[4], A. Salvarani[3,p], H. Schellman[12], M. Schmitt[5,q], N. Schmitz[11], K.P. Schüler[15,r], H.J. Seyerlein[11], A. Skuja[9], G.A. Snow[9], S. Söldner-Rembold[11,s], P.H. Steinberg[9,*], H.E. Stier[1,*], P. Stopa[7], R.A. Swanson[3], R. Talaga[9,j], S. Tentindo-Repond[2,t], H.-J. Trost[2,u], H. Venkataramania[15], M. Wilhelm[1], J. Wilkes[13], Richard Wilson[5], W. Wittek[11], S.A. Wolbers[4], T. Zhao[13]

[1] Albert-Ludwigs-Universität Freiburg i. Br., Germany
[2] Argonne National Laboratory, Argonne, IL USA
[3] University of California, San Diego, CA USA
[4] Fermi National Accelerator Laboratory, Batavia, IL USA

Existing Data

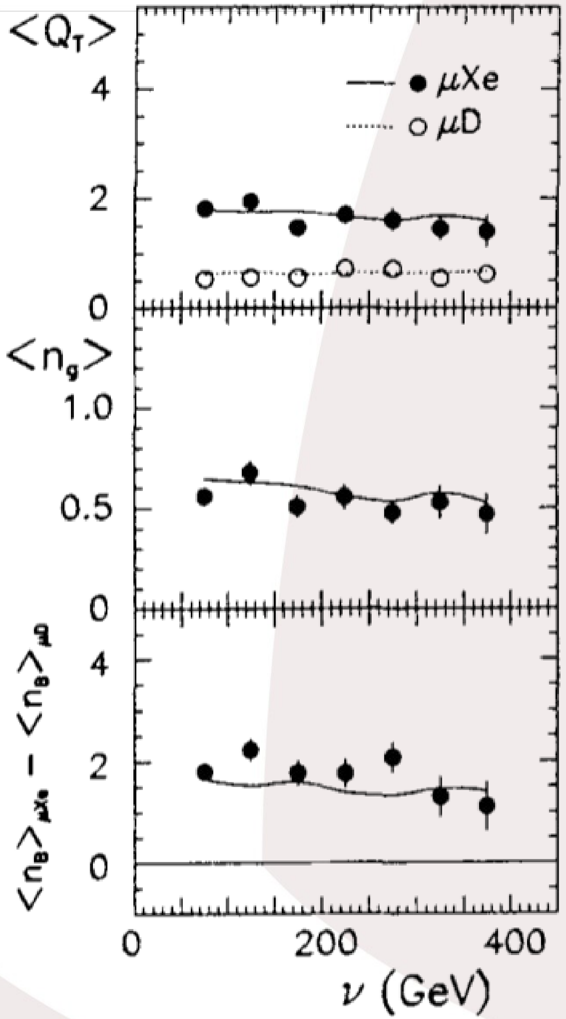

Fig. 2. Average total hadronic net charge $\langle Q_T \rangle$, average number of grey tracks $\langle n_g \rangle$ and difference of average charged backward multiplicities $\langle n_B \rangle_{\mu Xe} - \langle n_B \rangle_{\mu D}$ in μXe and μD scattering as a function of the leptonic energy transfer ν. The lines represent the predictions of the VENUS model

- **Kinematics**
  - Low x (0.002 → 0.1)
  - $Q^2 > 1$ GeV^2 / W > 8 GeV
  - Hadrons measured from p > 200 MeV/c
- **Grey Tracks (n_g)**
  - Energy deposit significantly higher than MIP
  - 200 < p < 600 MeV
- **Total hadronic net charge (Q_T)**

Which observable is most relevant?

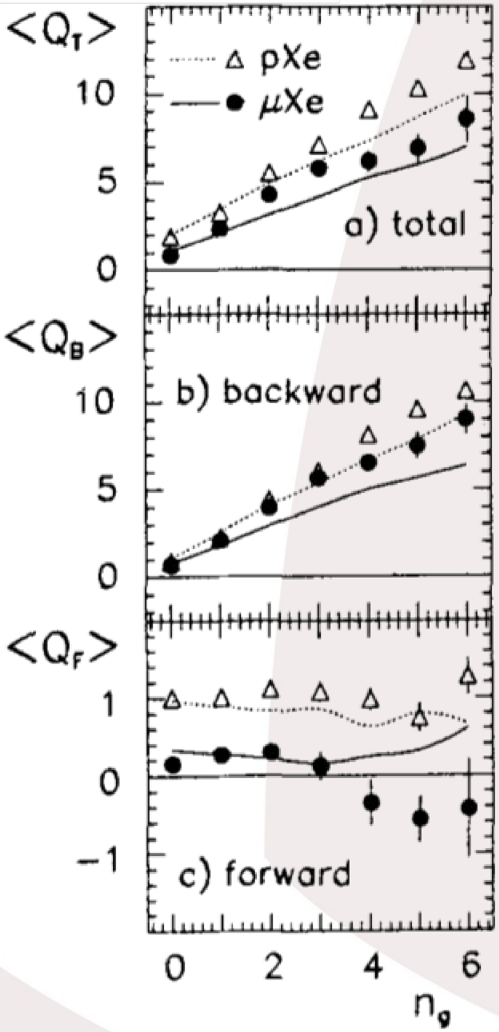

Fig. 6. Average hadronic net charge as a function of the number n_g of grey tracks for μXe and pXe scattering, in the total rapidity region ($\langle Q_T \rangle$) and in the backward ($\langle Q_B \rangle$) and forward ($\langle Q_F \rangle$) hemispheres. The lines represent the predictions of the VENUS model

- ➔ **Three correlated observables :**
  - ➔ **Total charge**
  - ➔ **Backward charge**
  - ➔ **Grey tracks**
- ➔ **Which should we use ?**
- ➔ **Which can we measure best in a collider ?**

Grey Tracks

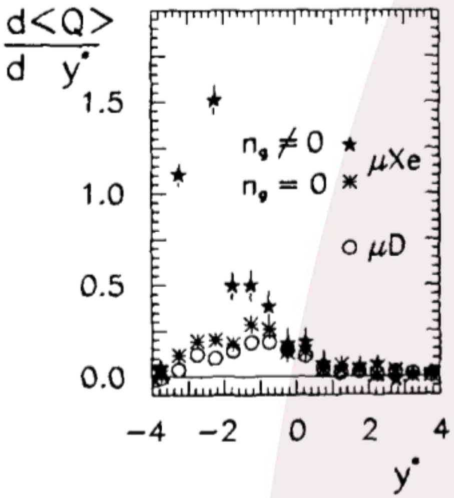

Fig. 3. Average hadronic net charge $d\langle Q\rangle/dy^*$ as a function of y^*, in μD events and in μXe events with ($n_g \neq 0$) and without ($n_g = 0$) grey tracks

➔**Xe similar to deuterium when no Grey tracks are observed (with 75% efficiency) !**

- ➔ **We are close to the spectator case**

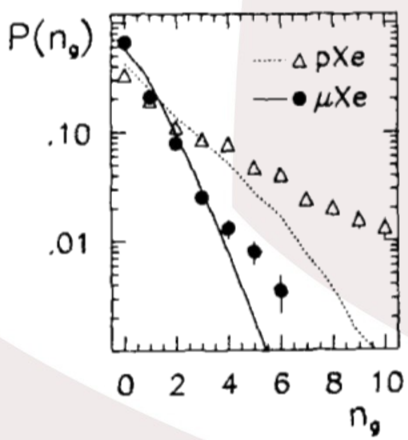

Fig. 5. Multiplicity distribution $P(n_g)$ of grey tracks for μXe and pXe scattering. The lines represent the predictions of the VENUS model

➔ **Number of Grey tracks to be expected**

- ➔ **0 and 1 Grey tracks represent 90% of the events → Luminosity at EIC will allow to go further**

Enhancement of Nuclear Effects

➔ **Requesting Grey tracks enhance the nuclear effects !**

➔ **Example for hadronization studies:**

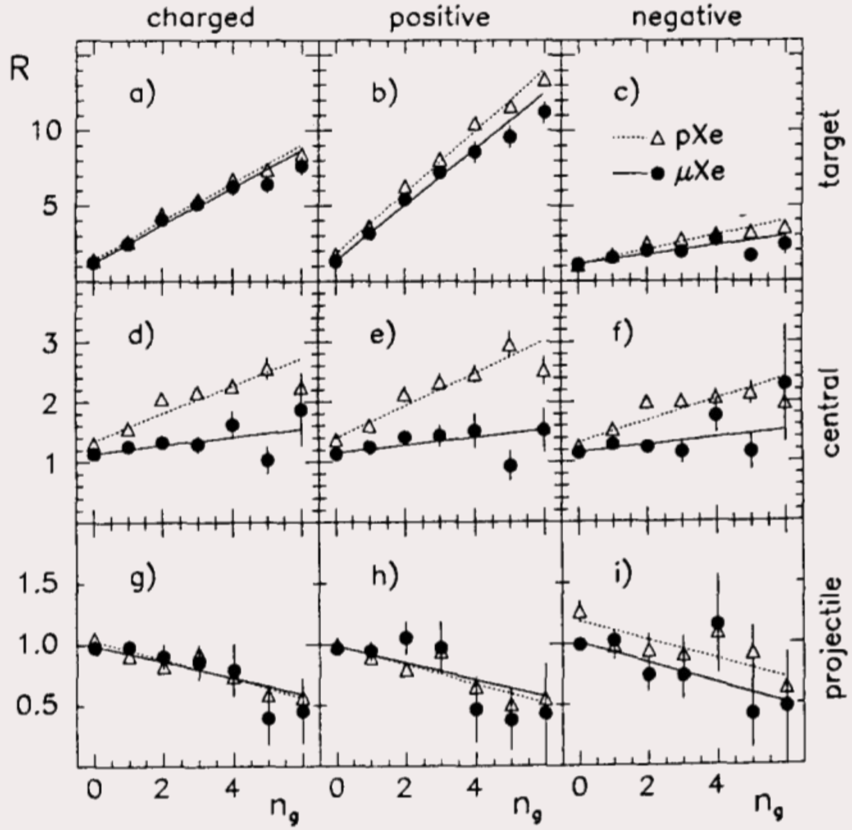

Fig. 10. Multiplicity ratio $R(n_g)_{\mu\mathrm{Xe}}$ (full circles) and $R(n_g)_{\mathrm{pXe}}$ (open triangles) as a function of the number n_g of grey tracks. The plots are for all charged, for positive and negative hadrons, and for three rapidity intervals (target, central, projectile). The lines are the results of straight-line fits to the data points

Shadowing Effect

- **Studied as function of net charge !**
  - **Results showed the importance of diffractive processes**

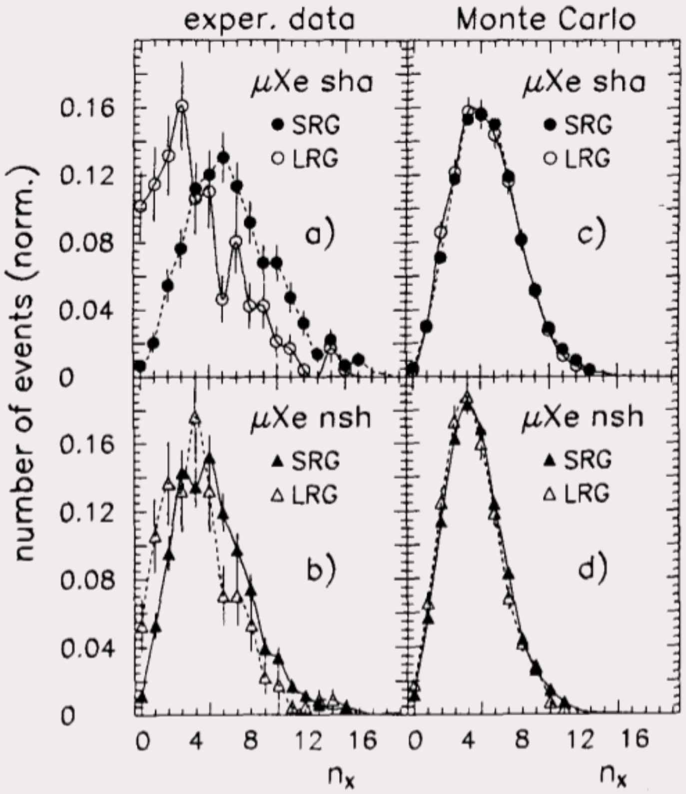

Fig. 25. Distribution of the charged hadron multiplicity n_X of the 'diffractive system', in the shadowing (sha, **a**) and **c**)) and non-shadowing (nsh, **b**) and **d**)) region of μXe scattering. In each subfigure the SRG event sample is compared with the LRG event sample. **a**) and **b**) are for the experimental data, **c**) and **d**) for the VENUS Monte Carlo data. The lines are drawn to guide the eye

Detection Issues

- ➔ **Total charge / Backward charge**
  - ➔ **Similar to HIC**
  - ➔ **Subject to fluctuations relatively large in regard to the limited total multiplicity**

- ➔ **Grey tracks**
  - ➔ **Correspond to angles up to 0.7 degrees (for 10x50)**

- ➔ **Beyond?**
  - ➔ **Neutrons**
  - ➔ **Other baryons**
  - ➔ **Nuclear fragments?**

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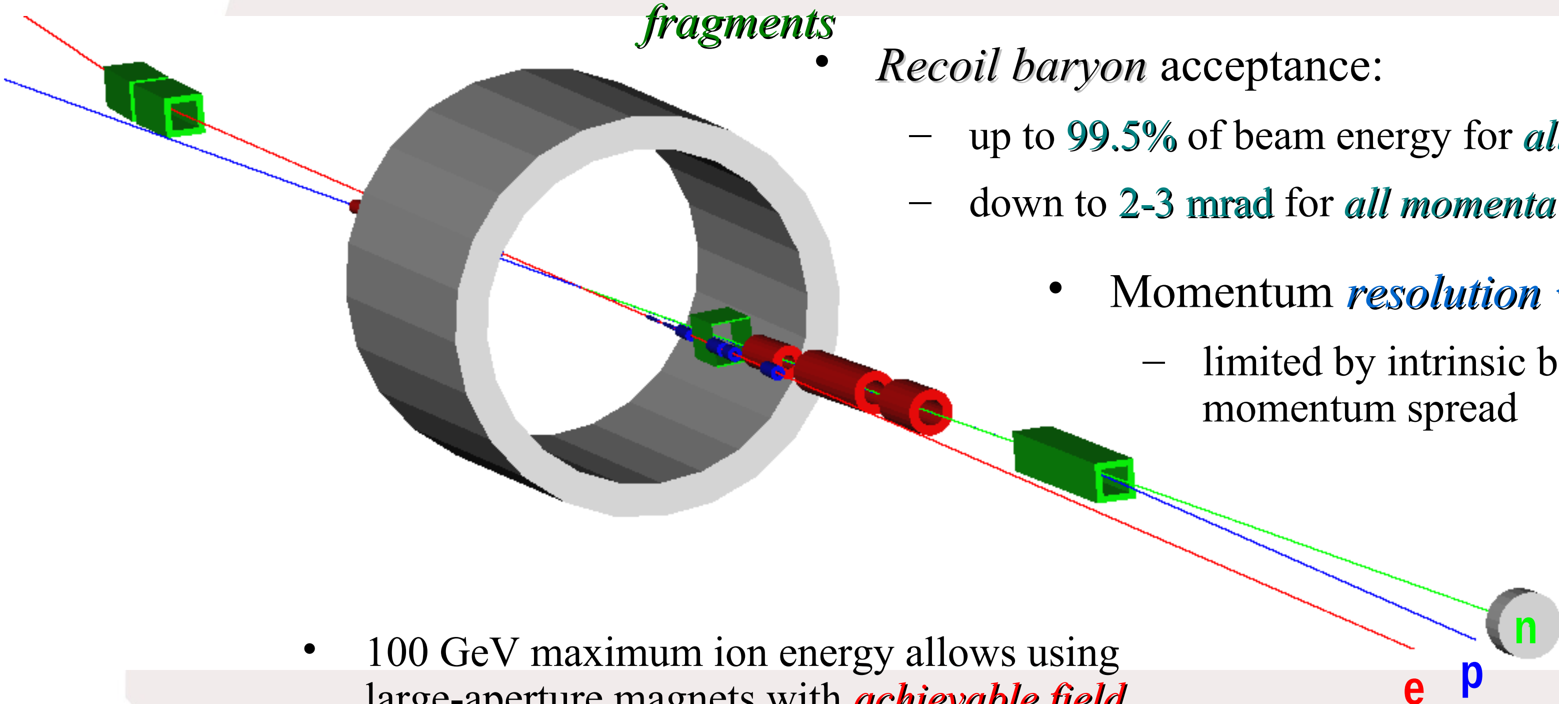
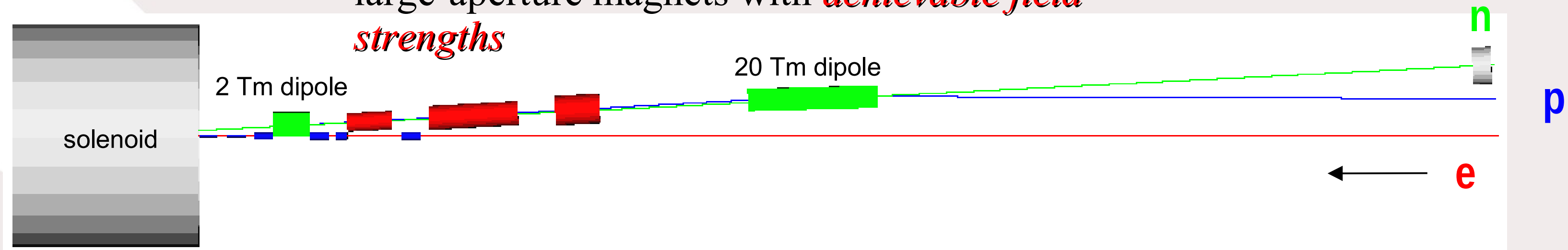
Ultra-forward hadron detection

- *Neutron* detection in a 25 mrad cone ***down to zero degrees***
- Excellent acceptance for ***all ion fragments***
- *Recoil baryon* acceptance:
  - up to **99.5%** of beam energy for ***all angles***
  - down to **2-3 mrad** for ***all momenta***
- Momentum ***resolution < 3x10^-4***
  - limited by intrinsic beam momentum spread



- 100 GeV maximum ion energy allows using large-aperture magnets with ***achievable field strengths***



Applicability to EIC

- **Grey tracks are useful to study nuclear effects**
  - Enhancement of hadronization effects by selecting long paths in nuclei → Sizable ratios & increased transverse momentum broadening
- **EIC can do better than E665 in this domain**
  - Can detect protons from energy 0 Mev to few hundreds MeV easily
  - Can detect neutrons too
  - And other heavier fragments?
- **Other physics topics available:**
  - Position information for effect such as shadowing or EMC
  -
  - Others ?

Physics Outlook

- **Hadronization at EIC**
  - **Large kinematic coverage**
  - **Clean access to parton energy loss**
  - **Observation of heavy quarks in CNM**
- **Grey Tracks at EIC**
  - **Access larger number of Grey tracks using the high luminosity**
  - **Access also to neutrons**
  - **Possibility to see heavier fragments**
- **New tool for all nuclear effects study**