Study of Quark Energy Loss Effect in p+A Collisions at Fermilab E906 Experiment

Benchmark Energy Loss Models with Drell-Yan

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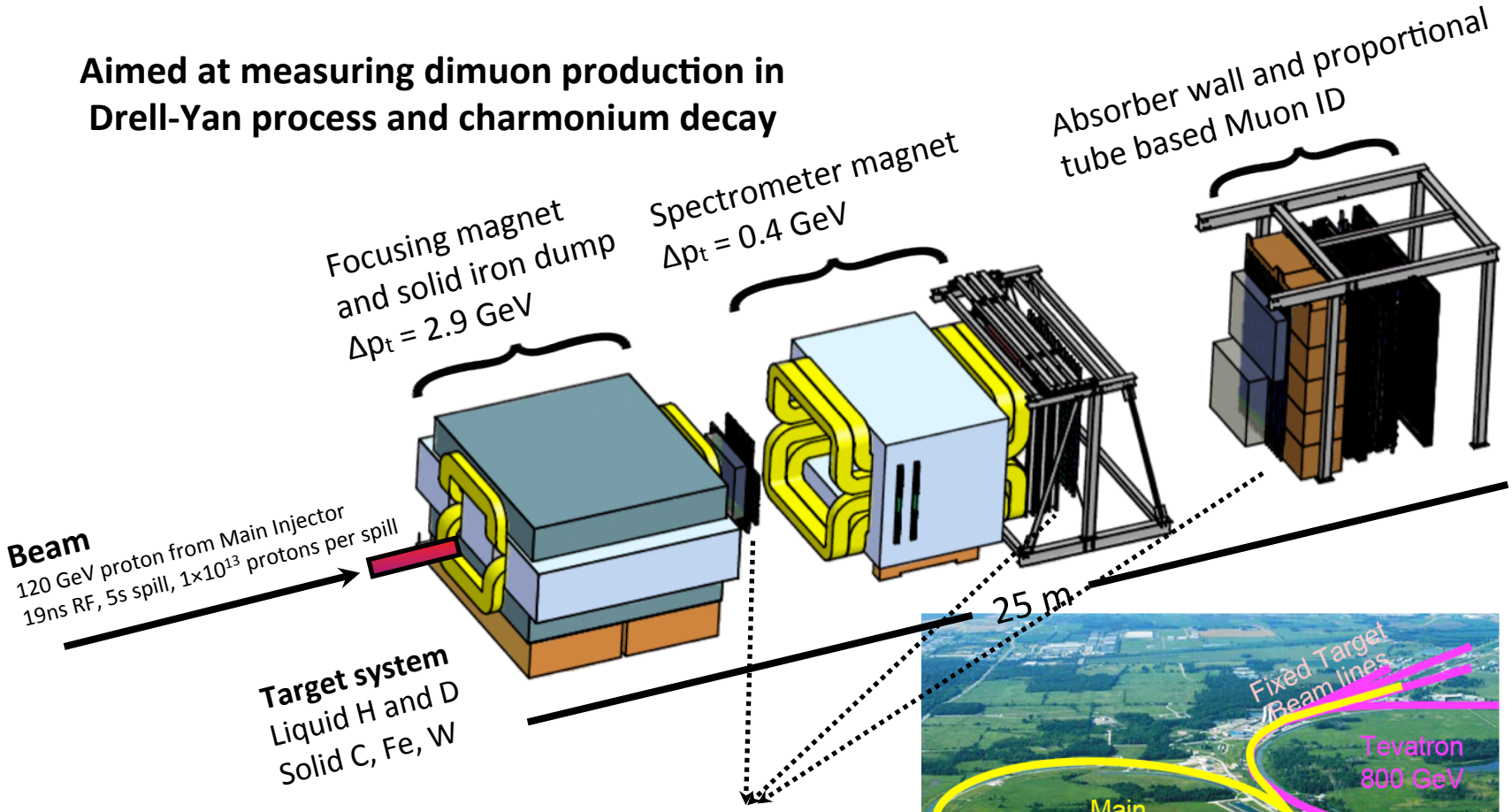
(Fermilab E906/SeaQuest Collaboration)

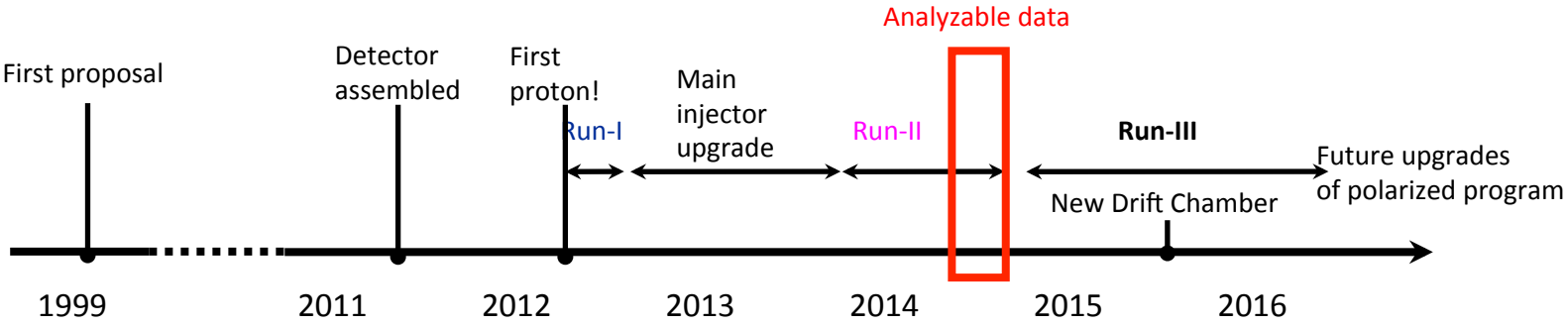
E906/SeaQuest Experiment at Fermilab

Aimed at measuring dimuon production in Drell-Yan process and charmonium decay

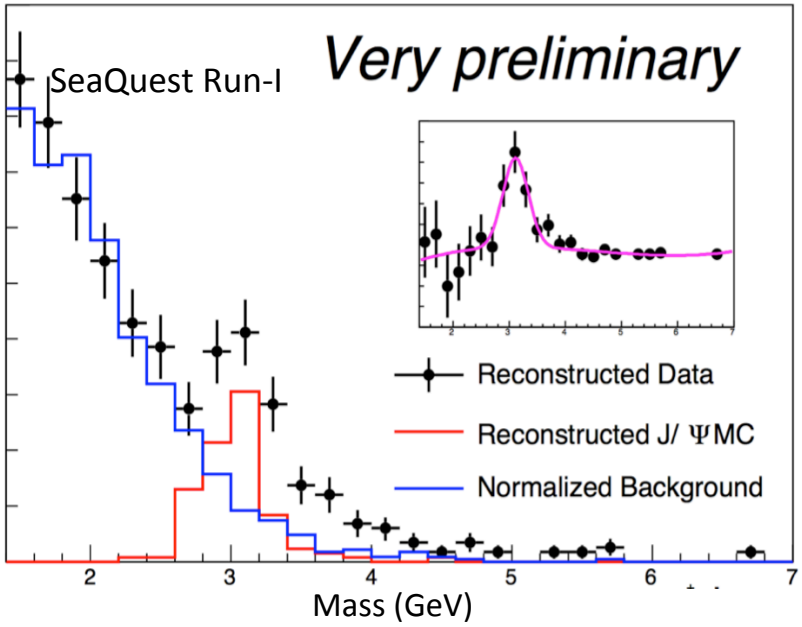


Tracking detectors
Drift chambers and hodoscope scintillators

Timeline and Milestones of SeaQuest



- Run-I: 2-month commissioning, first J/Psi signal
- Run-II, solved almost all the technical problems, last 2 months – physics
- Run-III, good quality beam:
  New station-1 DC will be installed soon to extend the x_2 coverage
- Polarized projects (target and/or beam) will take over E906 in summer 2016



E906/SeaQuest Collaboration

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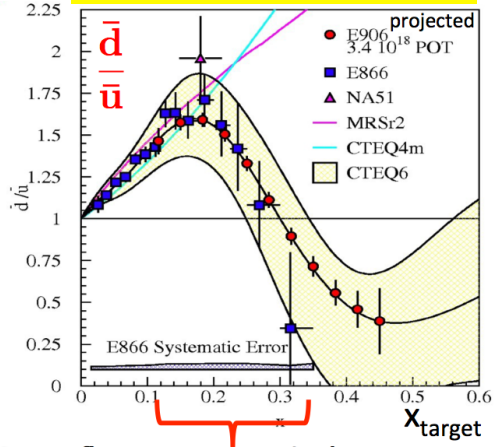
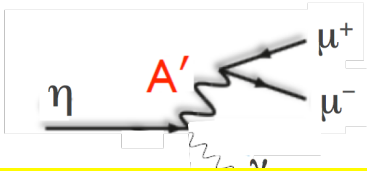
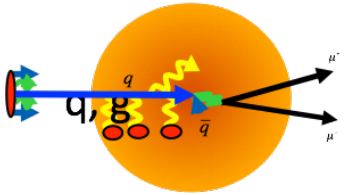
McClellan @PDF Sun. 8:25AM



Strong flavor asymmetry in the sea.





Sta. MD/PHE/PPHI @4PM

2009 @ Los Alamos

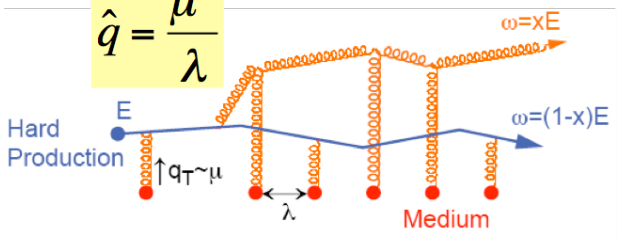
2013 @ Tokyo Tech

Do We Understand Jet Quenching at RHIC/LHC?

Energy loss of parton-jet created in hard scattering going through multiple-scatterings in the hot & dense medium

- nuclear modification factor $R_{AA} << 1$ at high p_T

$$\hat{q} = \frac{\mu^2}{\lambda}$$

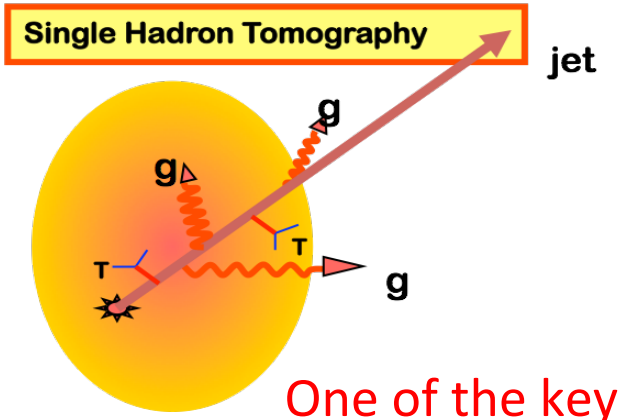


$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{\text{binary}} \rangle_{AA}}{\text{Yield}_{pp}} \sim 1 - \int \rho \otimes \frac{dE}{dx}$$

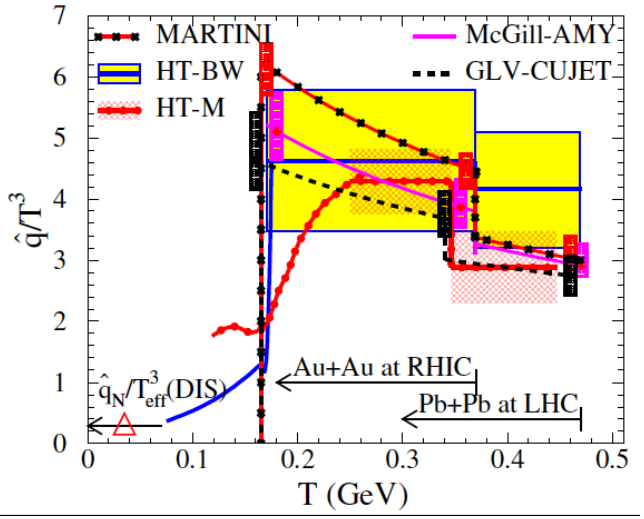
Access medium properties through statistical analysis:

-example: transport coefficient $\hat{q}$

-model dependent



One of the key questions in heavy ion physics

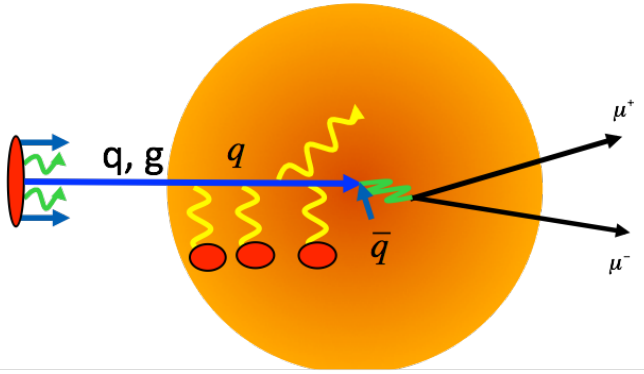


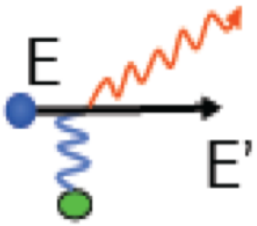
Recent JET collaboration progress (PRC 90, 014909 (2014)) for 10GeV quark:
qhat = 1.2 ± 0.3 GeV^2/fm (RHIC); 1.9 ± 0.7 GeV^2/fm (LHC)

Initial-state Energy Loss and Drell-Yan in p+A

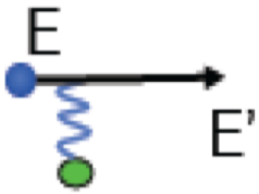
Benchmark quark energy loss models

- Minimal final-state interactions
- Know nuclear matter



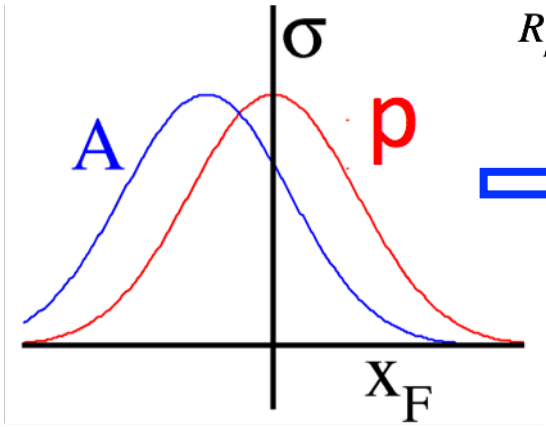


Radiative dE/dx

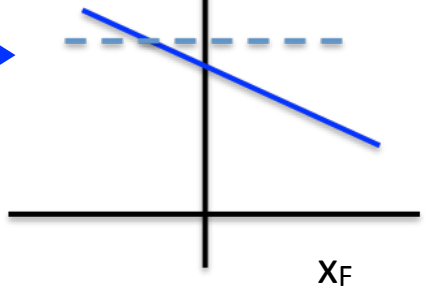


Collisional dE/dx

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$



$$R_{pA}(x_F) = \frac{\sigma^{pA}}{A \cdot \sigma^{pA}}$$



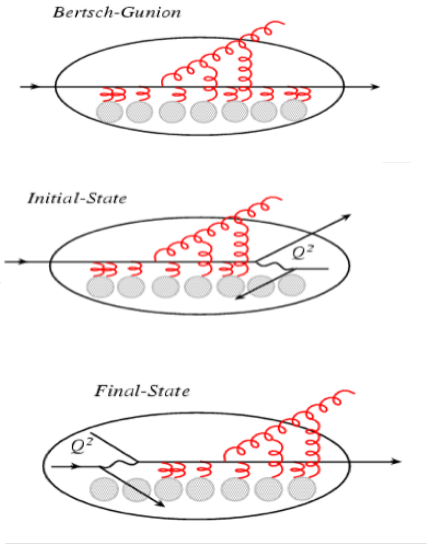
The Expectations

Think of the parton (quark) energy loss in the nuclear rest frame

Ideal QGP

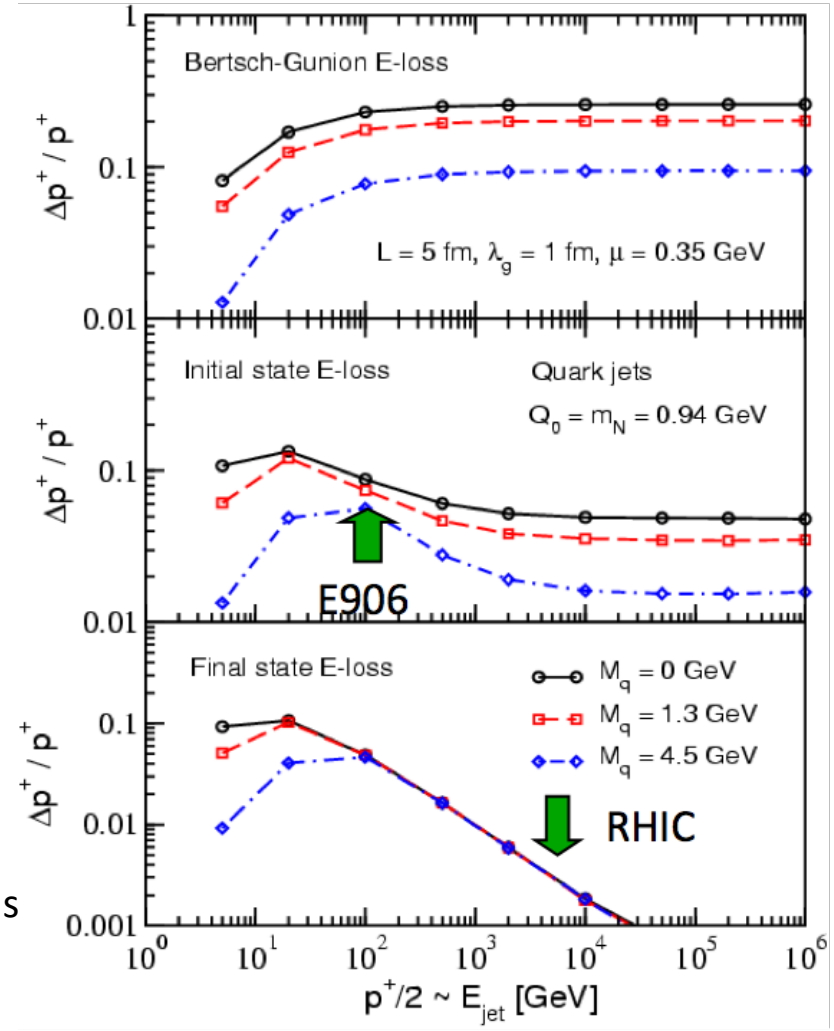
Drell-Yan: p+A

DIS:e+A



- Initial-state E-loss is large and much larger than final-state energy loss for cold nuclei
- In Drell-Yan we don't have final-state interactions

I. Vitev PRC 75, 064906 (2007)



Parton Energy Loss Measured in SIDIS

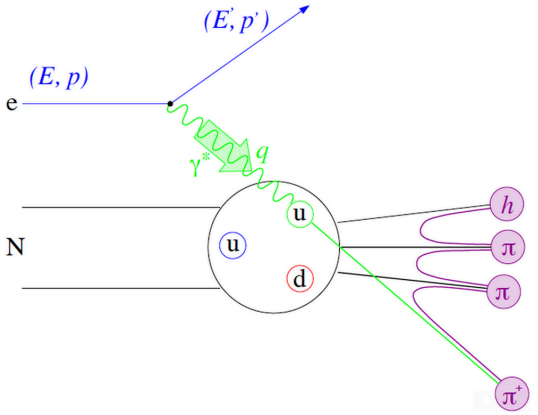
Wang & Wang, PRL 89 162301 (2002)
Z.-B. Kang et al, arXiv:1310.6759

- Out going quarks
  - HERMES A-dependent fragmentation functions
  - Must understand nuclear-dependent fragmentation
  - Wang & Wang (2002)
    - Assume all from quark energy loss

dE/dx ~ 0.5 GeV/fm

@ E = 10 GeV for Au.

Kang et al, NLO (2013)



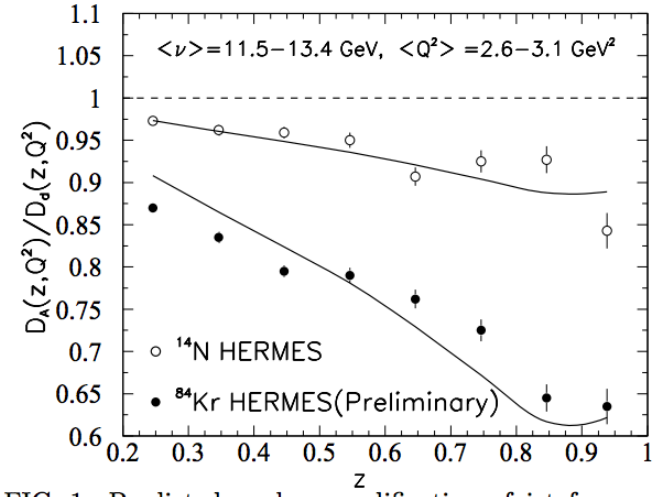
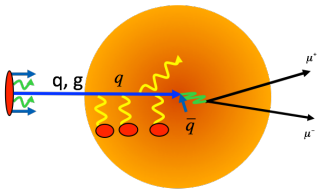


FIG. 1. Predicted nuclear modification of jet fragmentation function is compared to the HERMES data [10] on ratios of hadron distributions between A and D targets in DIS.

Early Data from E866 p+A @ Fermilab

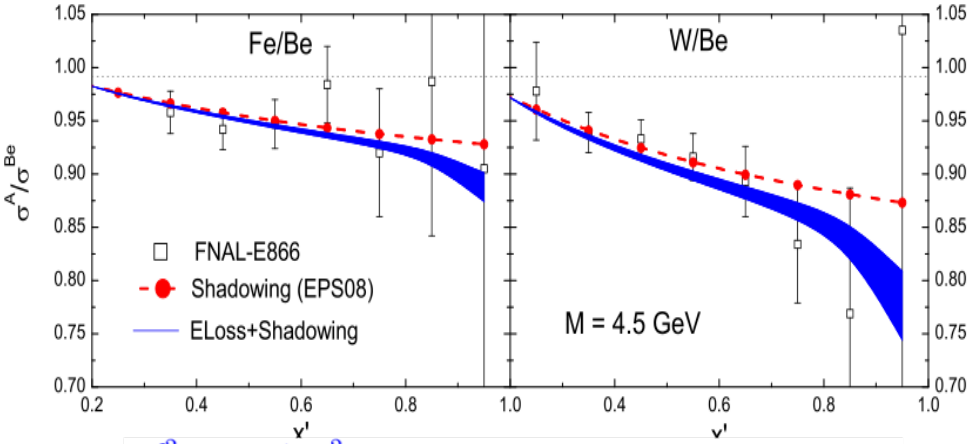


- Energy loss vs. shadowing
- Correction must be made for shadowing effects
  - Garvey & Peng PRL 90 (2003)
- NO partonic energy loss if all effects from shadowing
  - Vasiliev *et al.*, PRL 83 (1999)
- Significant parton energy loss,
  - ~1.2 GeV/fm if all from energy loss

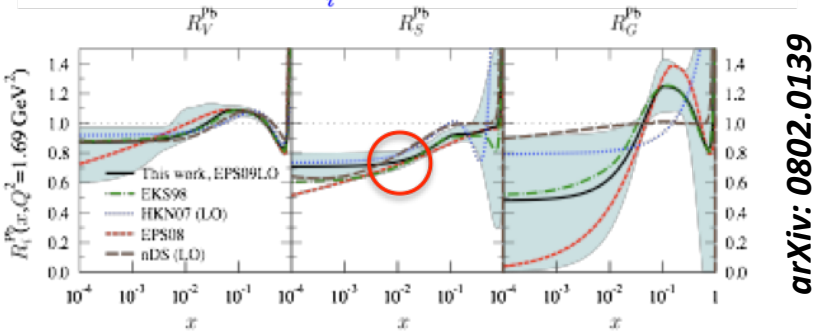
  Johnson *et al.*, PRC 65 025203 (2002)

Both yield 20~30% effects in R_{pA}

H. Xing et al Nucl. Phys. A 879 (2012)



$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$



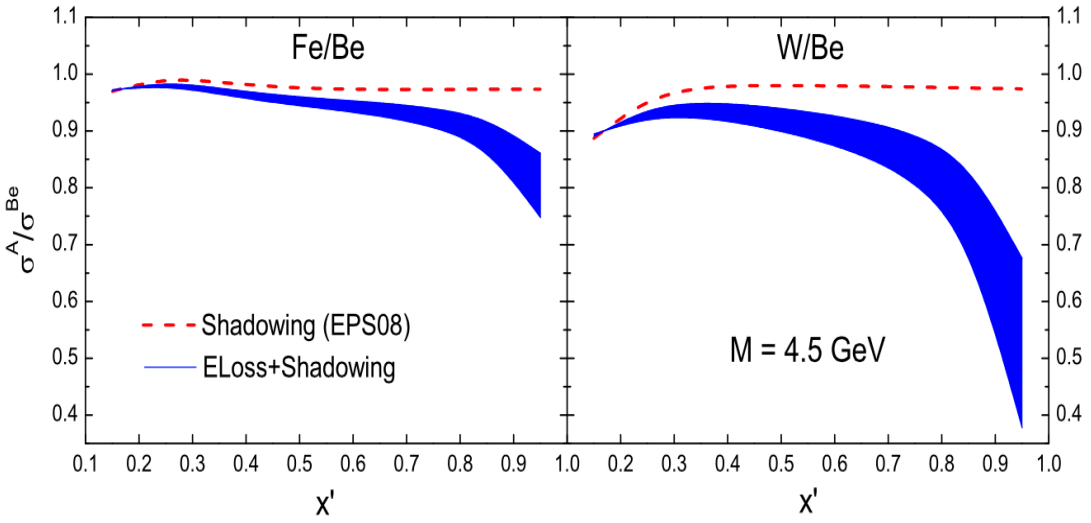
arXiv: 0802.0139

Figure 11: Comparison of the average valence and sea quark, and gluon modifications at $Q^2 = 1.69\,\mathrm{GeV}^2$ for Pb nucleus from LO global DGLAP analyses EKS98 [1, 2], EKPS [3], nDS [6], HKN07 [5], and this work EPS09LO.

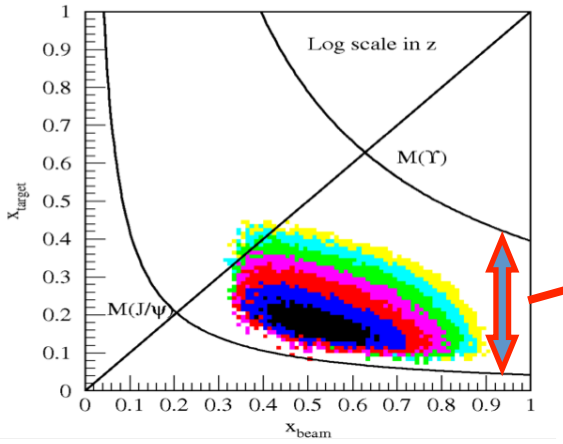
E906 Drell-Yan R_{pW} Predictions

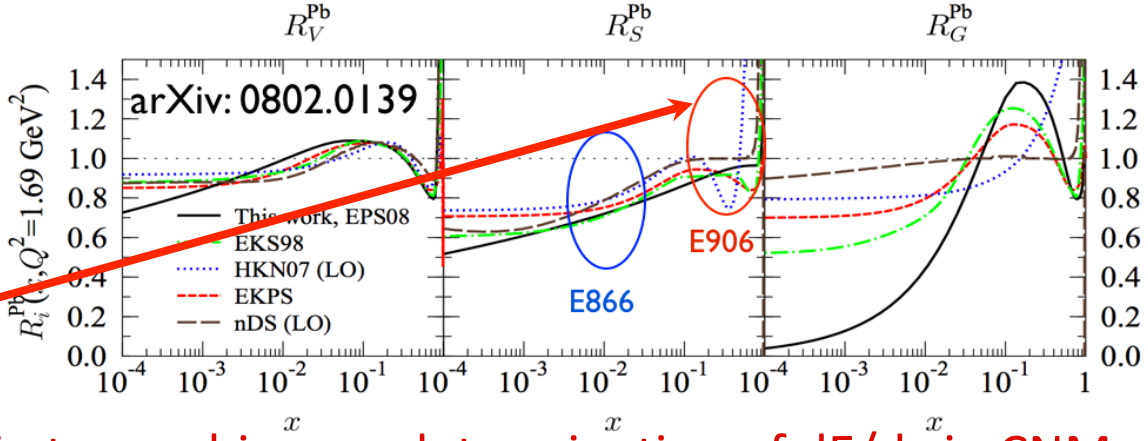
- Parton initial energy: 30 - 120 GeV (relevant to RHIC and LHC outgoing final state parton energy)
- Direct test on various models:
  - Gavin and Milana: $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer: $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al*: $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

H. Xing et al, Nucl. Phys. A 879 (2012)



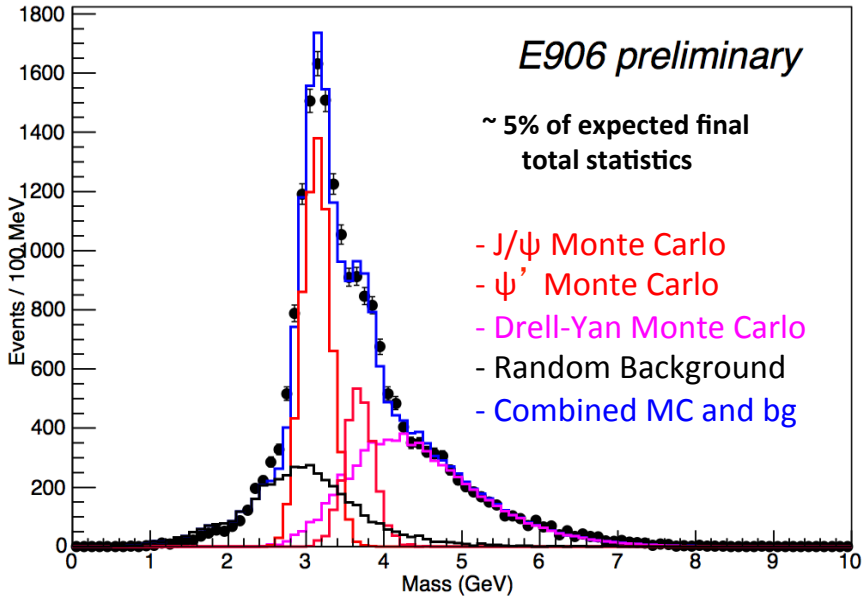
- Sea quark x = 0.1 ~ 0.3
- Minimal shadowing
- *1/s* enhanced dE/dx effect





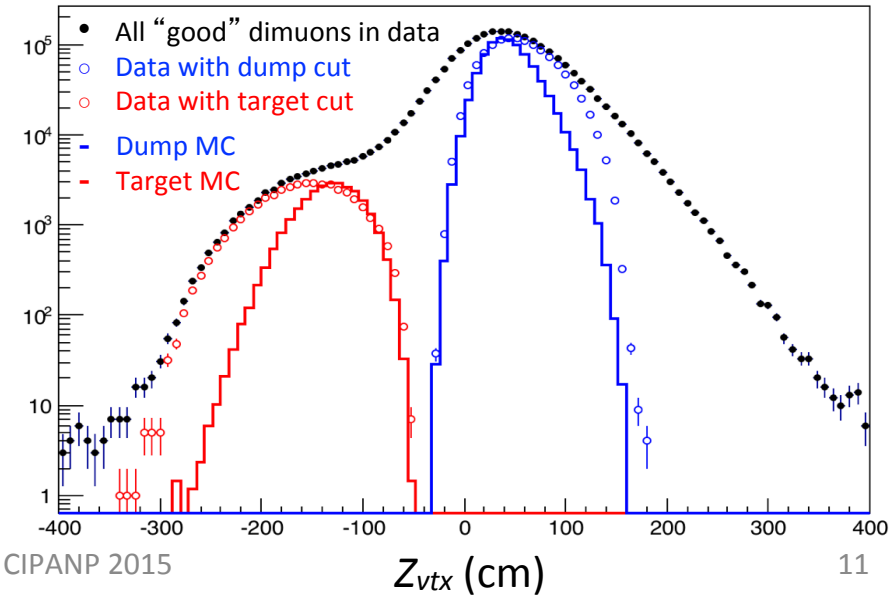
First unambiguous determination of dE/dx in CNM

Data from Run 2014 (Run-II)



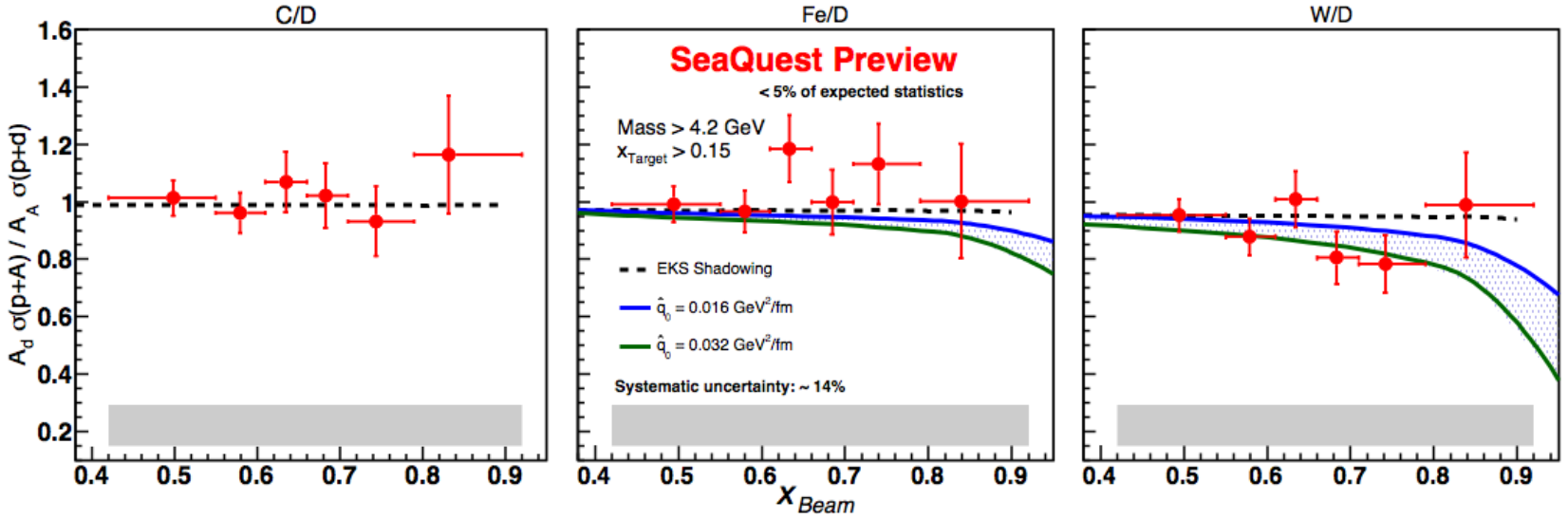
- Monte Carlo describe data well
  - $\sigma_M(J/\psi) \sim 180$ MeV, $\sigma_M(DY) \sim 220$ MeV
  - J/ψ ψ' separation
  - Cleaner DY sample
- Good target/beam dump separation

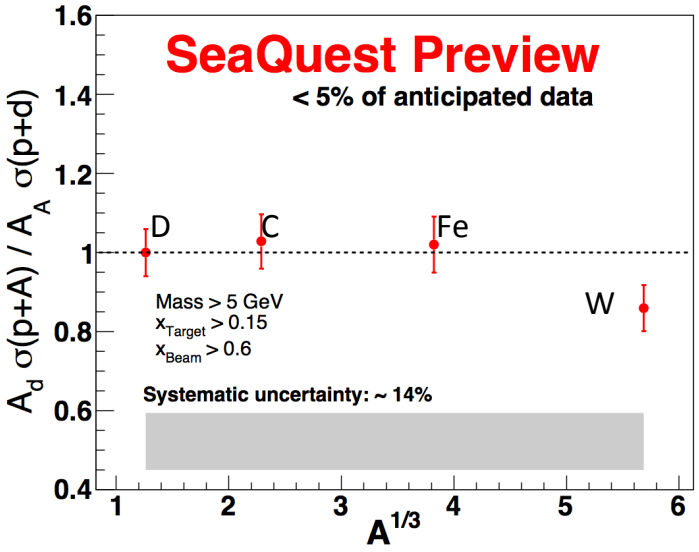
- Beam quality worse than expected (instantaneous rate much higher than average)
  - live time of spectrometer greatly reduced by the 'super' RF buckets
  - Reconstruction efficiency lower than expected because of the high detector occupancy



First Quark Energy Loss Study at E906

R.B. Neufeld et al, Phys. Lett. B 704 (2011)
Z.-B. Kang et al, Phys. Lett. B 740 (2015)





- Statistically limited to make firm conclusion
- Hits of negative slope beyond the shadowing in p+W data.
- With 20x more statistics, we will be able to clearly distinguish between:
  - ➢ $-dE \propto A^{1/3}$ (or $\propto L$)
  - ➢ $-dE \propto A^{2/3}$ (or $\propto L^2$)

Summary and Outlook

Run-II: 5% of total statistics:

- observed a negative slope 2σ beyond the extent of shadowing

Ongoing Run-III: ~20x of Run-II statistics

Other ongoing physics analysis:

- EMC effect in Drell-Yan
- Transverse momentum broadening
- Difference between J/ψ and ψ' suppression in pA
- Search for double J/ψ production
- Search for dark photons
- …