Quark Energy Loss – Experimental

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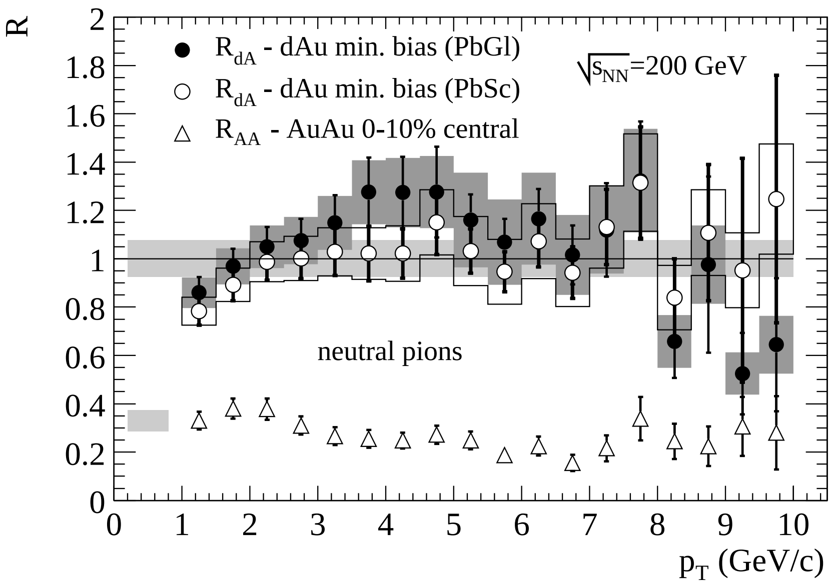
Outline

- Quark energy loss in the Drell-Yan experiments
  - Proton induced Drell-Yan ($pA \rightarrow \mu^+\mu^- X$)
  - Pion induced Drell-Yan ($\pi A \rightarrow \mu^+\mu^- X$)
- Quark energy loss in the semi-inclusive DIS
  - $eA \rightarrow e'hX$
- Quark energy loss in single hadron production
- Current status and future prospects

Quark Bremsstrahlung in Nuclear Medium

- Landau-Pomeranchuk-Migdal (LPM) effect of medium modification for electron bremsstralung has been observed
- LPM effect in QCD remains to be identified
- Quark energy loss dE/dx is predicted to be proportional to L
- Enhanced quark energy loss in traversing quark-gluon plasma

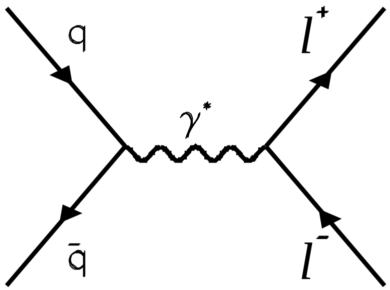


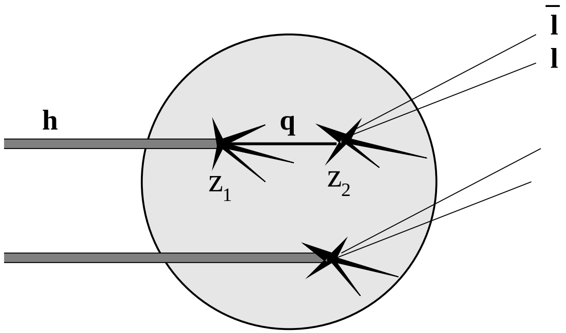
PHENIX Collaboration

(nucl-ex/0306021)

Quark energy loss in cold nuclei needs to be better measured

Quark energy loss in cold nuclei from the Drell-Yan process





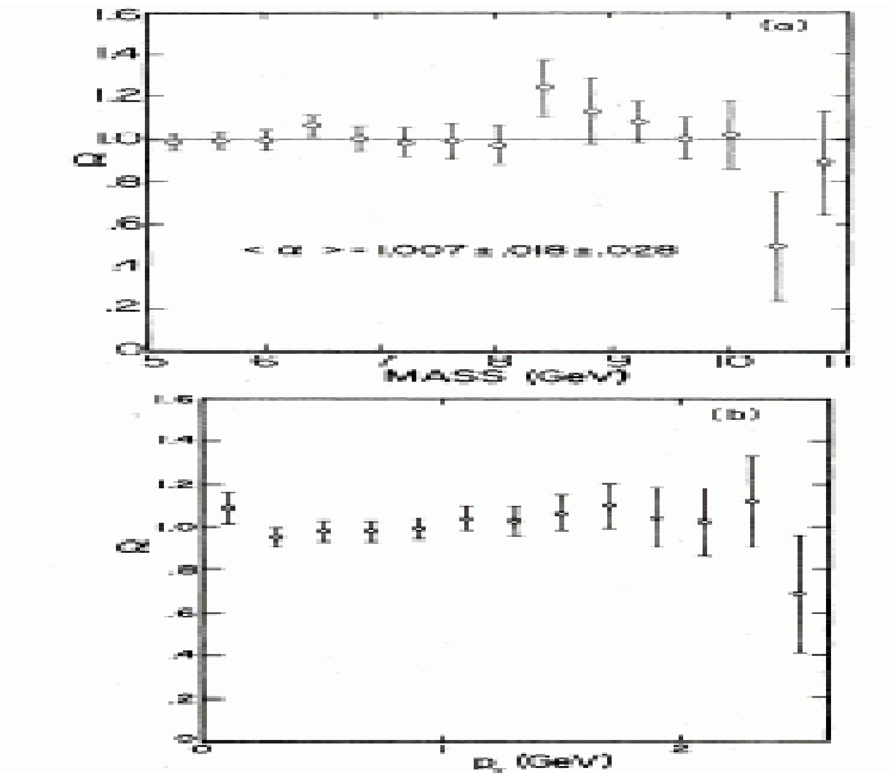
- Energy loss of the incident quark is reflected in the reduced longitudinal momentum and the increased transverse momentum of the lepton pair.
- Measure the amount of quark energy loss by varying the quark path-length, i.e., by varying the nuclear size, A.
- The challenge is to isolate the quark energy loss effect from other nuclear effects (shadowing, EMC effects, etc.)
- Advantage of D-Y is that lepton-pairs do not have final-state interactions.

Quark energy loss from proton-induced Drell-Yan

$$\sigma_{DY}(p+A) = A^{\alpha}\sigma_{DY}(p+p)$$

$pA \rightarrow \mu^{+}\mu^{-}x$

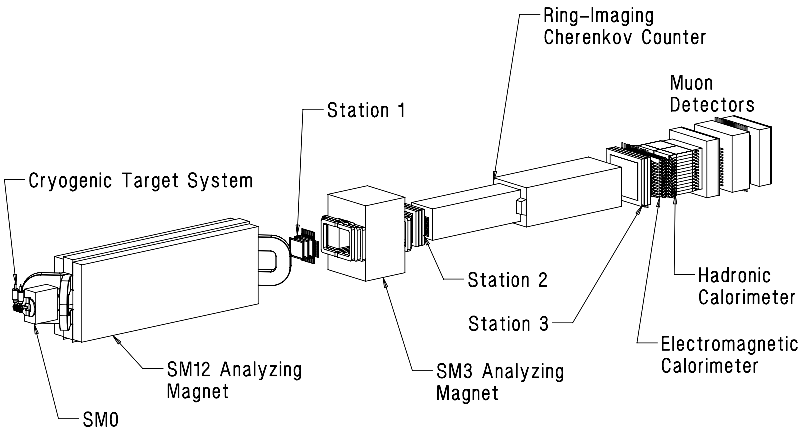
200, 300, 400 GeV



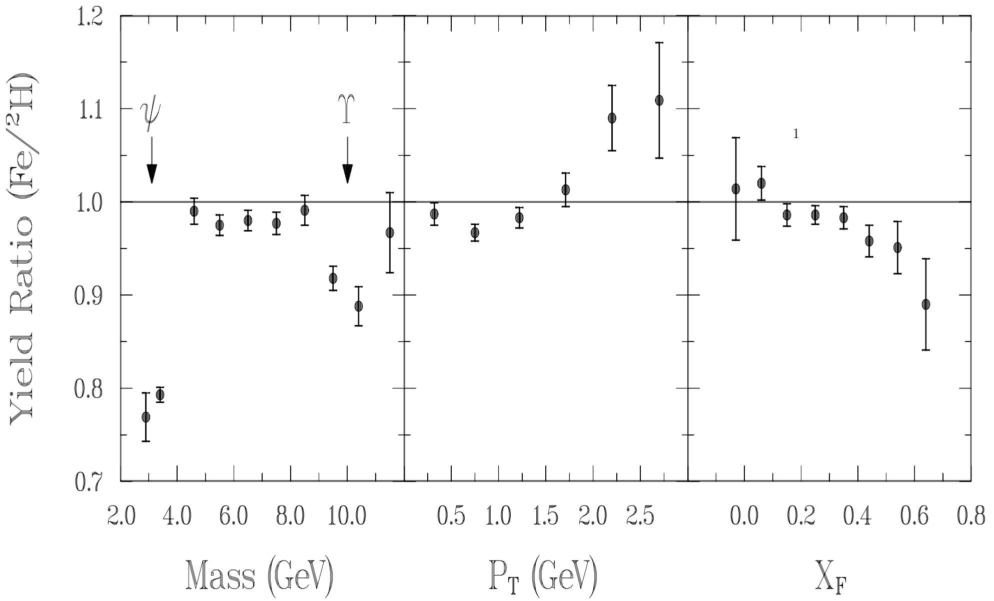
(Ito et al. PRD23 (1981) 604)

- α for integrated Drell-Yan cross section is consistent with 1.
- Need to measure α as a function of longitudinal momentum ($\alpha(x_1)$ or $\alpha(x_F)$) to identify quark energy loss effect.
- $\alpha(p_T)$ suggests that α increases gradually with p_T.

A-dependence of Drell-Yan from 800 GeV pA interaction at Fermilab (E772 + E866)

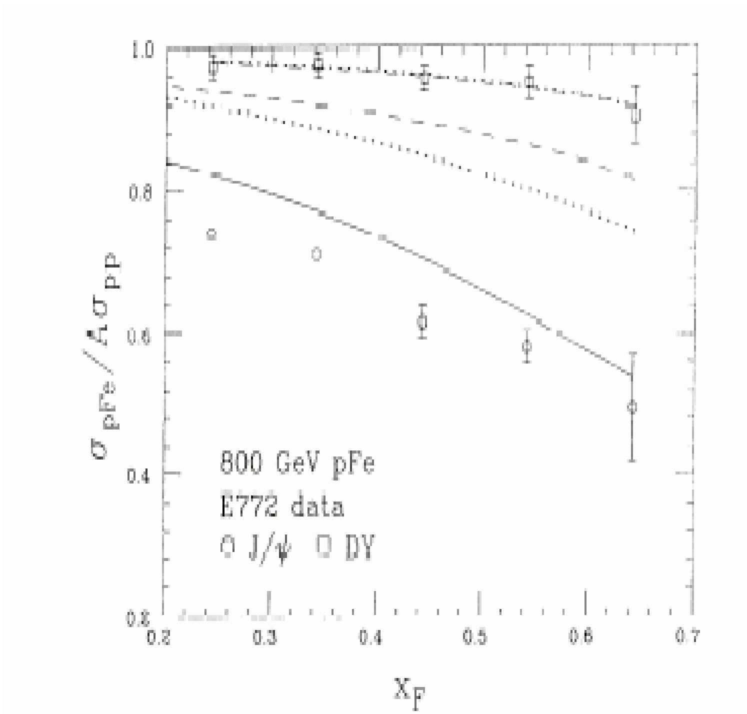


800 GeV/c p + A → $\mu^+\mu^-$ x

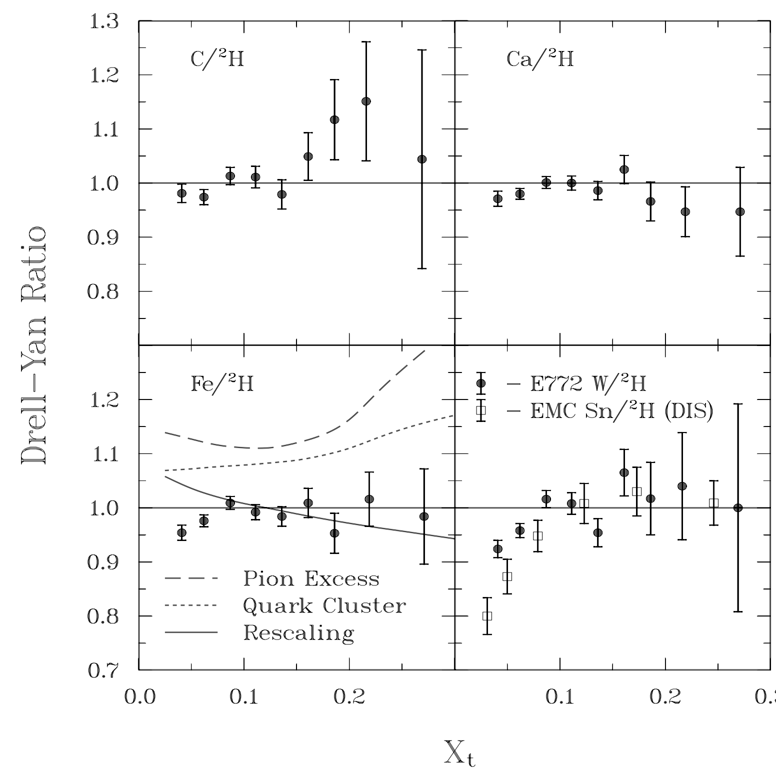


Clear X_F and P_T dependences

Quark energy loss deduced from Drell-Yan



Gavin and Milana, PRL 68 (1992) 1834



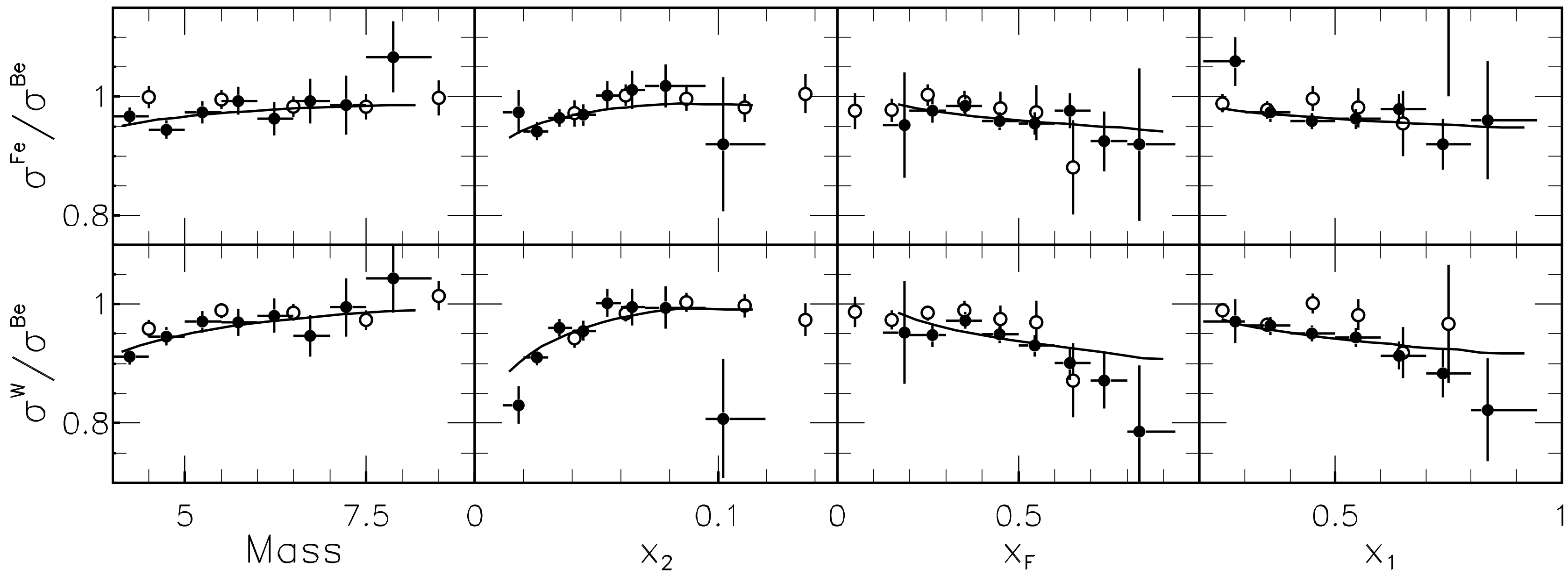
dE / dZ ~ 1.5 GeV/fm

Large x_F corresponds to large x_1 and small x_2 ($x_F=x_1-x_2$)

Is the observed A-dependence at large x_F due to quark energy loss or due to nuclear shadowing at small x_2?

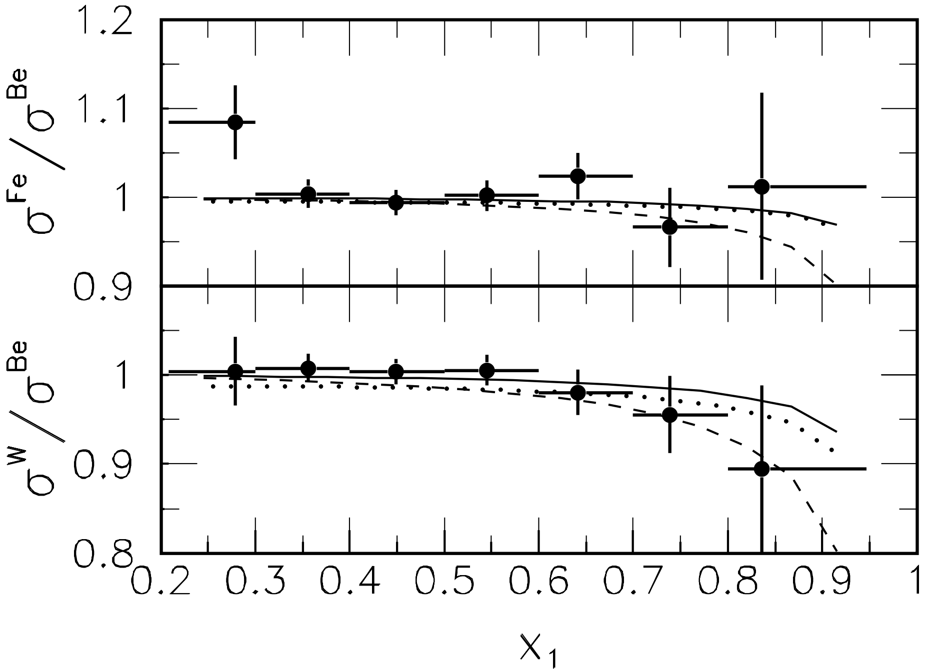
A-dependence Drell-Yan data from Fermilab E866

E866 measures Drell-Yan data for p+W, p+Fe, and p+Be, covering smaller x2 and larger x1 than E772



Solid curves use nuclear shadowing parametrization of EKS98 and no quark energy loss

Analysis of E866 A-dependence Drell-Yan



PRL 83 (1999) 2304

Three different curves correspond to

1) $\Delta x_1 = -\kappa_1 x A^{\frac{1}{3}}$

2) $\Delta x_1 = -\frac{\kappa_2}{s} x A^{\frac{1}{3}}$

3) $\Delta x_1 = -\frac{\kappa_3}{s} x A^{\frac{2}{3}}$

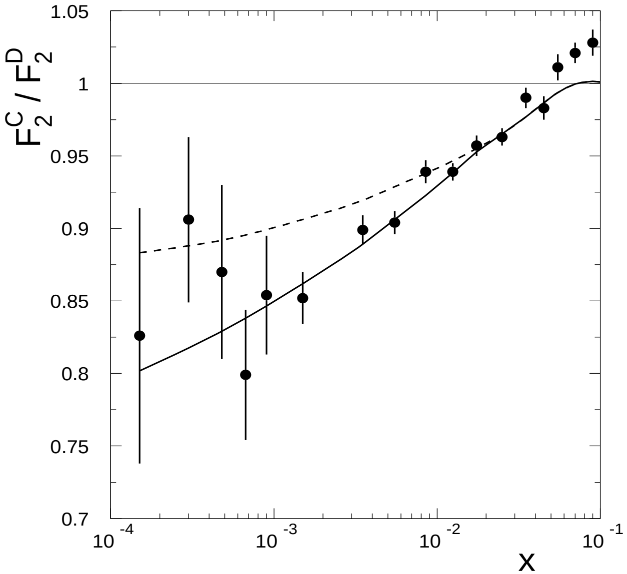
An upper limit of

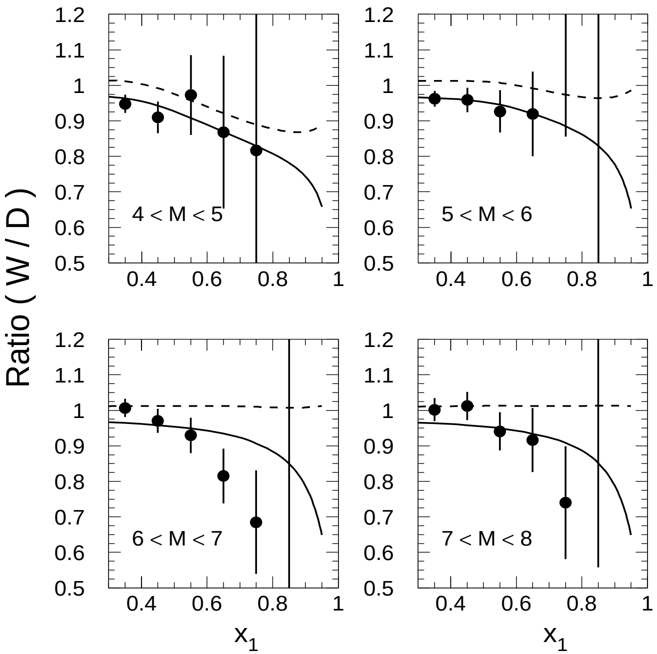
$\frac{dE}{dZ} < 0.44\,\mathrm{GeV/fm}$ is obtained

How reliable is the shadowing parametrization used in this analysis?

Is Nuclear Shadowing the same is Drell-Yan as in DIS?

Kopeliovich et al. predict different shadowing for DY and DIS using light-cone dipole epproach





DIS data can be well reproduced

- Shadowing alone can not explain the DY data
- Quark energy loss is required

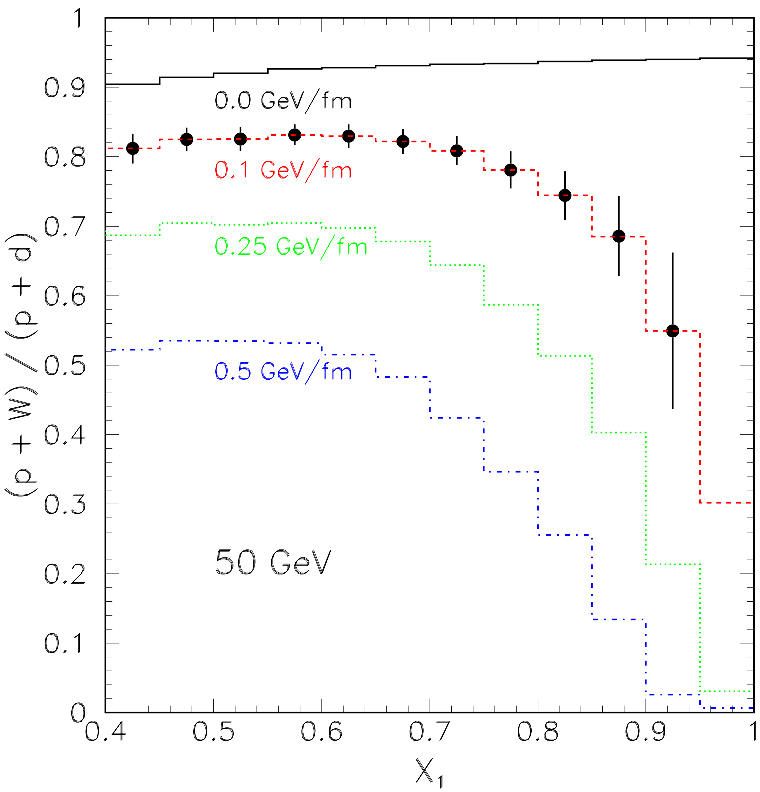
dE/dz = 2.73 ± 0.7GeV/fm

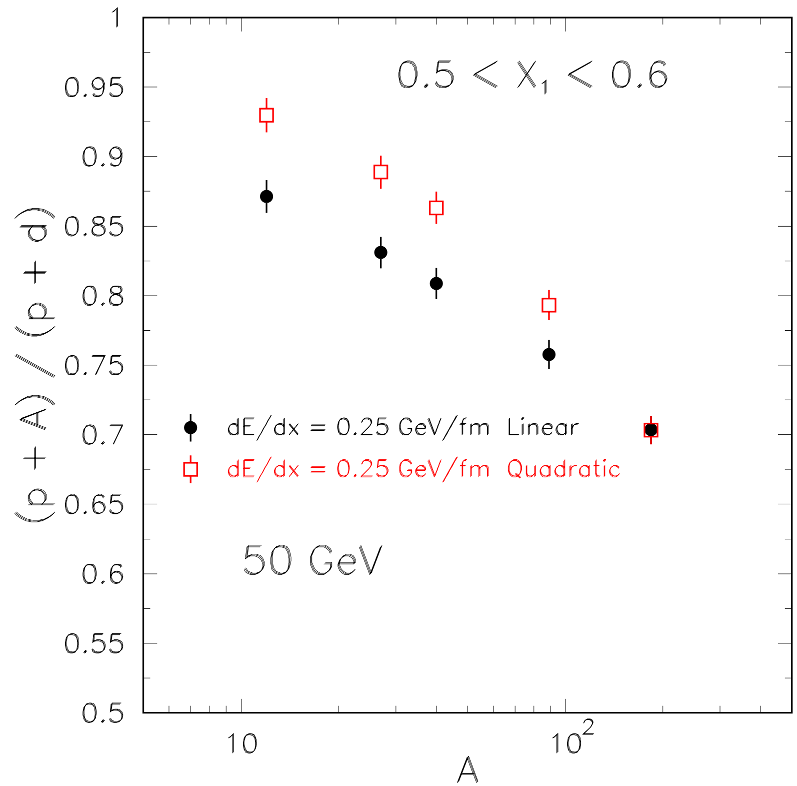
Quark Energy Loss with D-Y at Lower Energies

Correspond to larger x2, no nuclear shadowing

Fractional energy loss is larger at 50 GeV

Possible to test the LPM effect from the A-dependence





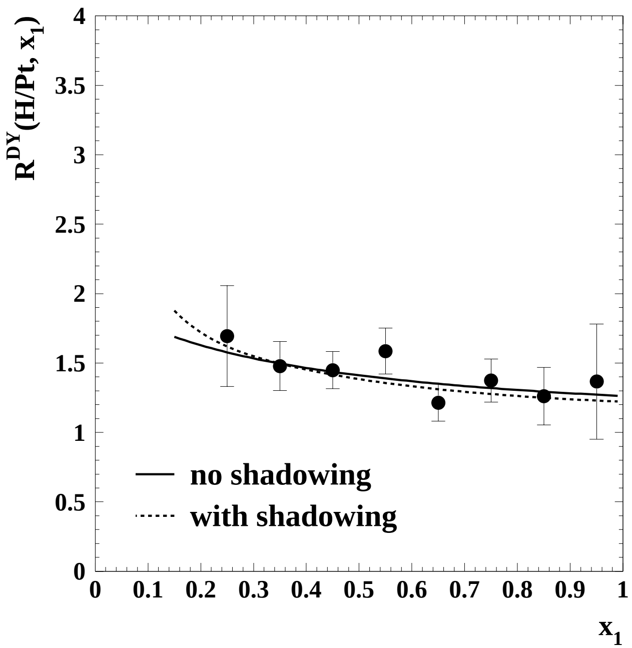
Garvey and Peng, PRL 90 (2003) 092302

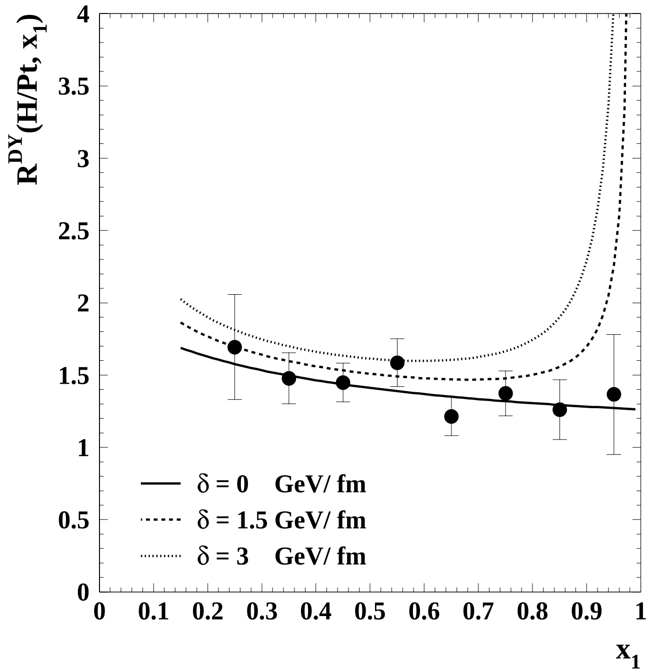
Fermilab E906 can study this at 120 GeV

Pion-induced Drell-Yan experiments

$$\sigma_{DY}(\pi^- + p)/\sigma_{DY}(\pi^- + Pt) \quad \text{at 150 GeV}$$

(NA 3 data)





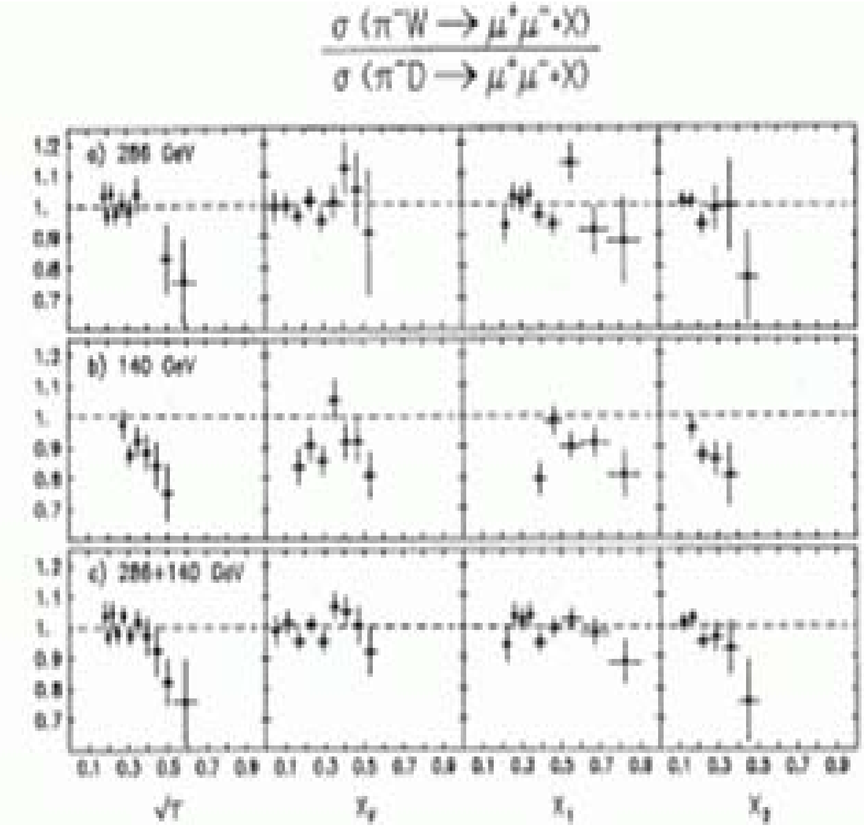
Arleo, Phys. Lett. B532 (2002) 231

- Relatively poor statistics (535 π + p DY events)
- Isospin correction required for σ (π⁻ + Pt) / σ (π⁻ + p)

Pion-induced Drell-Yan experiments

$\sigma_{DY}(\pi^- + W)/\sigma_{DY}(\pi^- + D)$ at 140 and 286 GeV

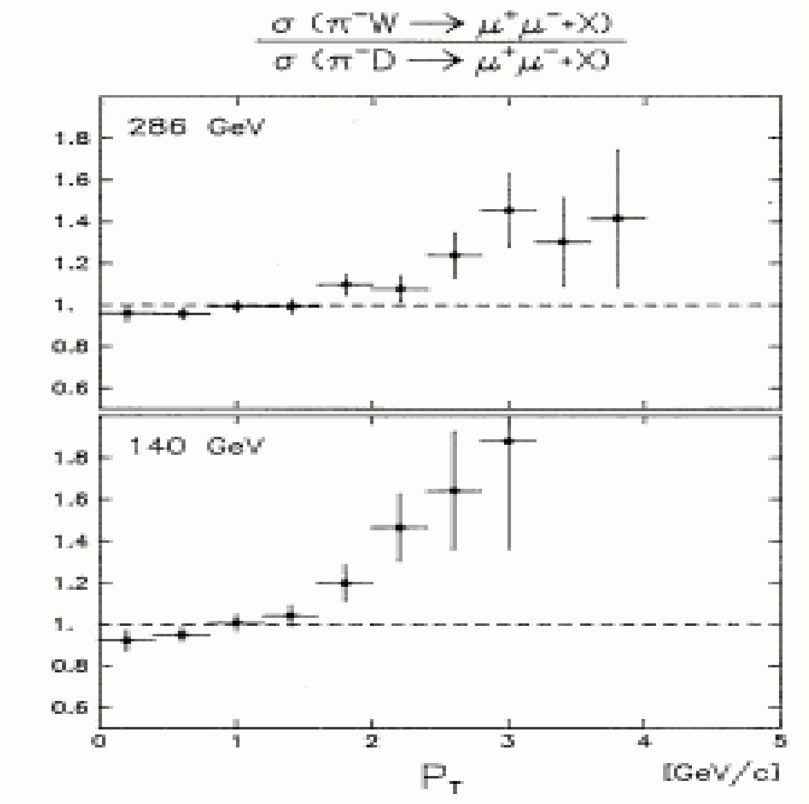
(NA 10 data, ~11,000 π + D D-Y events and ~ 80,000 π +W D-Y events)



- Clear suppression at large x1
- Would be interesting to analyse these data to deduce the quark energy loss

Phys. Lett. 193 (1987) 368

NA10 observes clear p_T dependence in π-A Drell-Yan



- Quark bremsstrahlung could contribute to pT-broadening
- Nuclear shadowing effect can not lead to pT broadening
- Another means to distinguish quark energy loss from shadowing

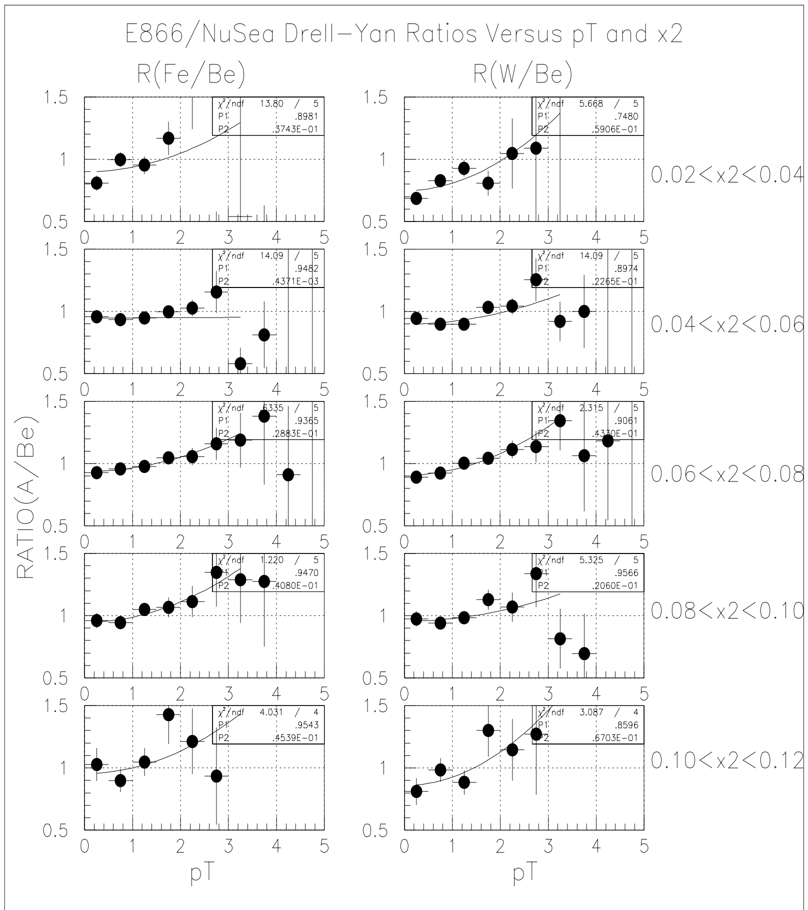
Phys Letts. 193 (1987) 373

$$< p_T^2 >_W - < p_T^2 >_D = 0.15 \pm 0.04 GeV^2/c^2 \text{ at 286 GeV}$$

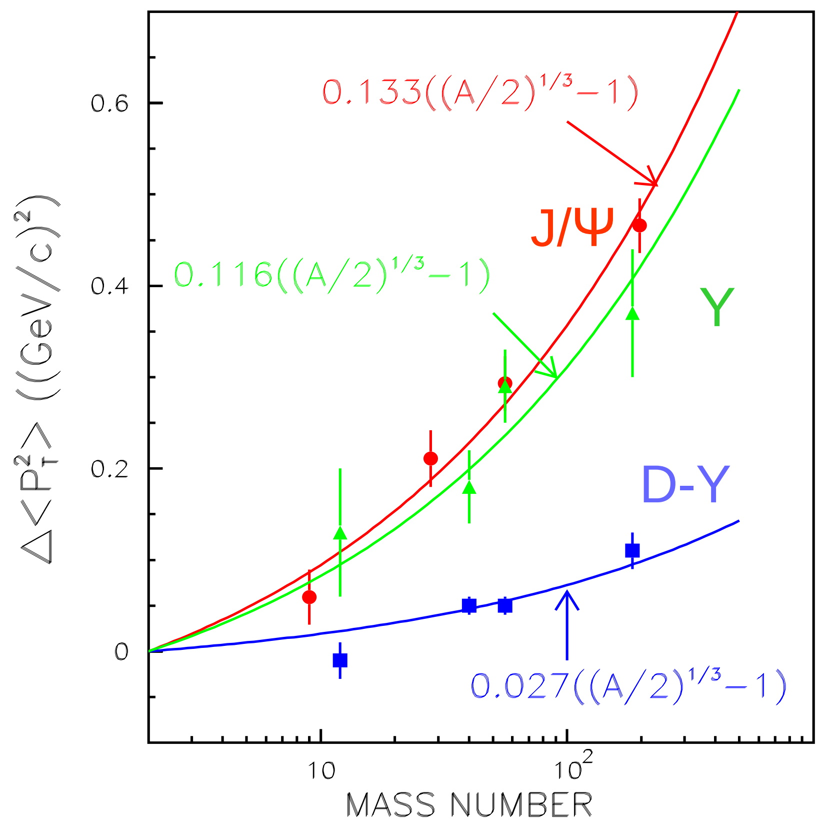
$$< p_T^2 >_W - < p_T^2 >_D = 0.16 \pm 0.04 GeV^2/c^2 \text{ at 140 GeV}$$

Similar p_T – dependence is also observed in p+A Drell-Yan

E866

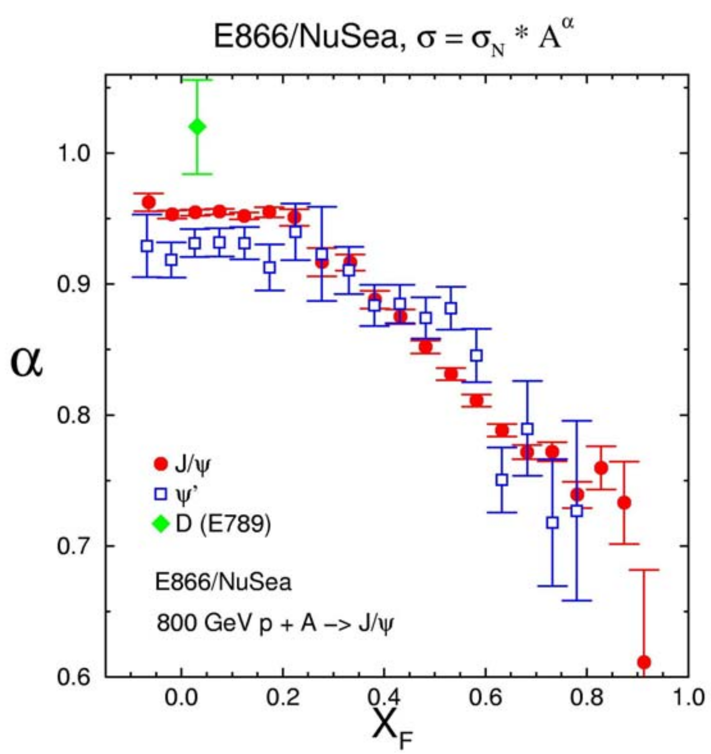


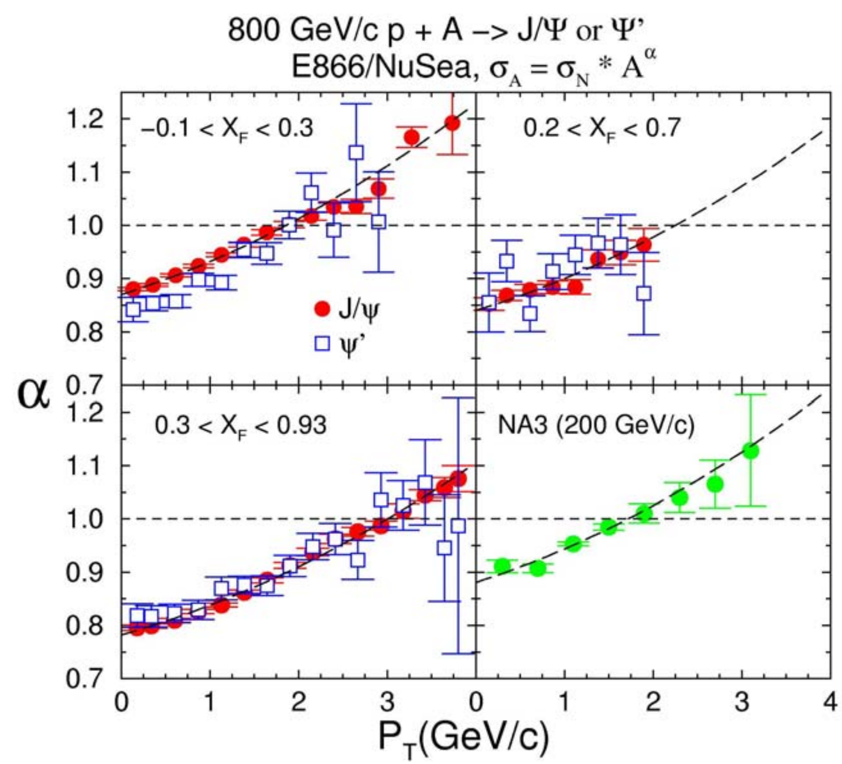
E772 + E866



Similar but much more pronounced effects for J/Ψ and Ψ' nuclear production

p + A → J/Ψ or Ψ' at $s^{1/2}$ = 38.8 GeV

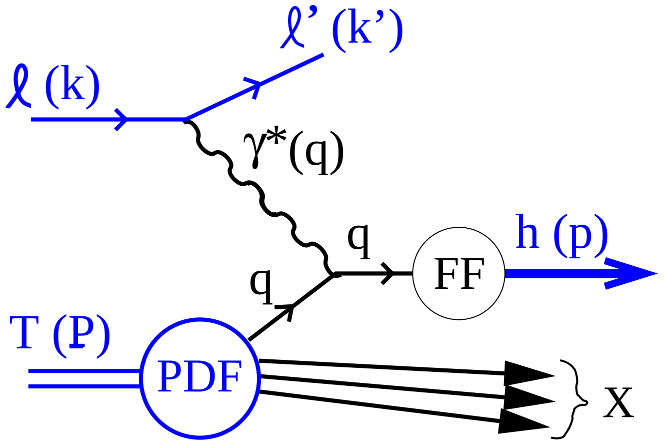


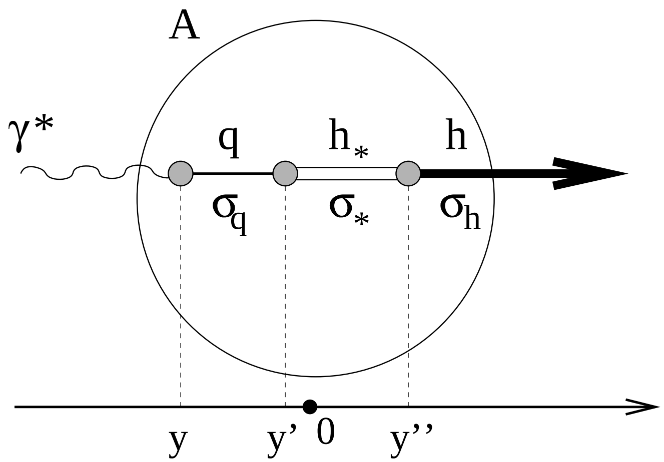


α(x_F) is largely the same for J/Ψ and Ψ' (except at x_F ~ 0 region)

'Universal' behavior for α(p_T) (similar for J/Ψ, Ψ'; weak $s^{1/2}$ dependence)

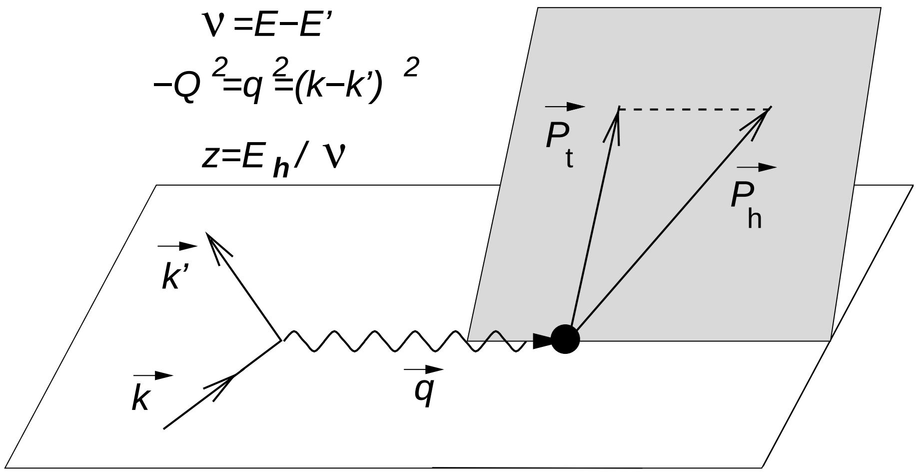
Quark energy loss from semi-inclusive DIS





- No initial-state interaction
- Energy loss of quarks and hadrons in nuclei
- Need to avoid the target fragmentation region
- Complementary to Drell-Yan

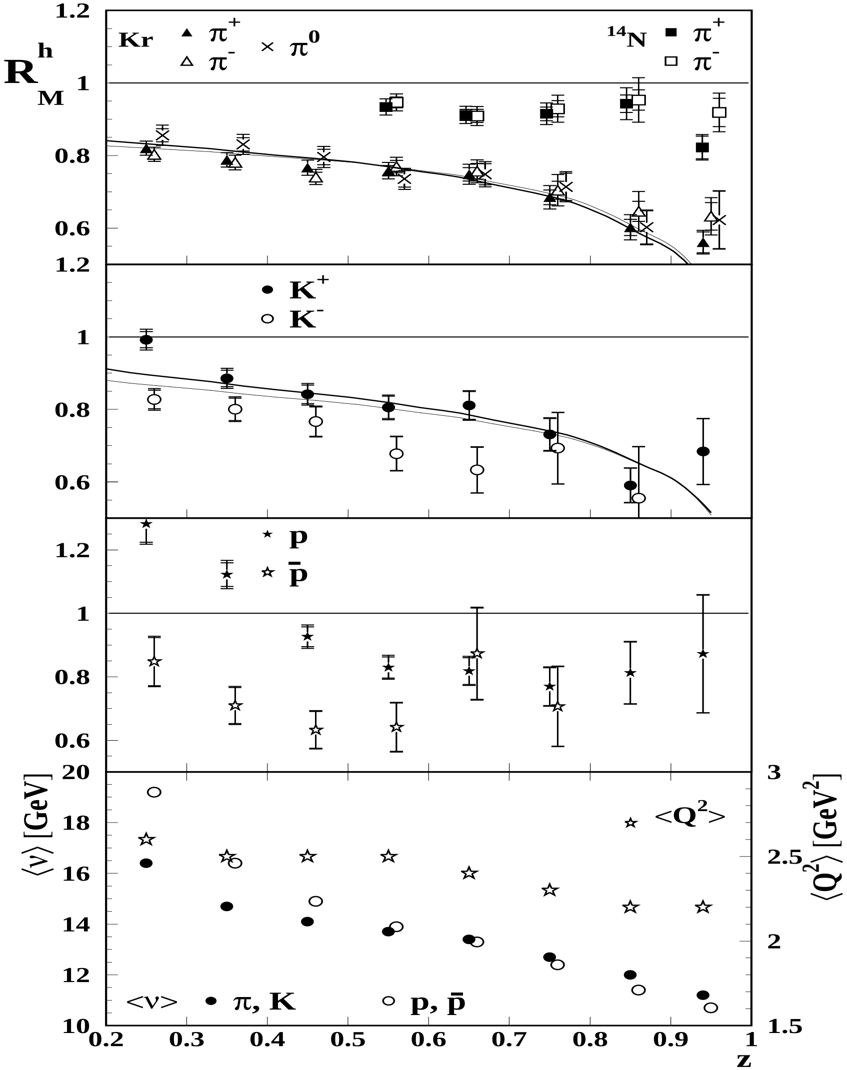
Kinematic variables in SIDIS



Rough correspondence between Drell-Yan and SIDIS

Drell-Yan	SIDIS
E_{beam}	ν
x_1	z
p_T	p_T

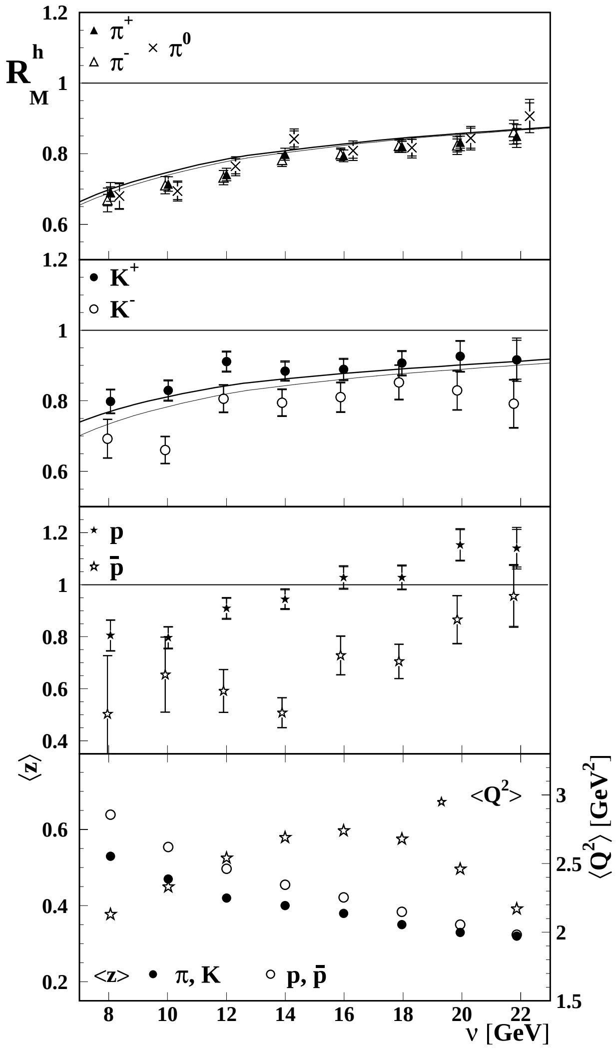
Dependence of SIDIS on *z*



Hermes Data

Similar to the X1-dependence in Drell-Yan !

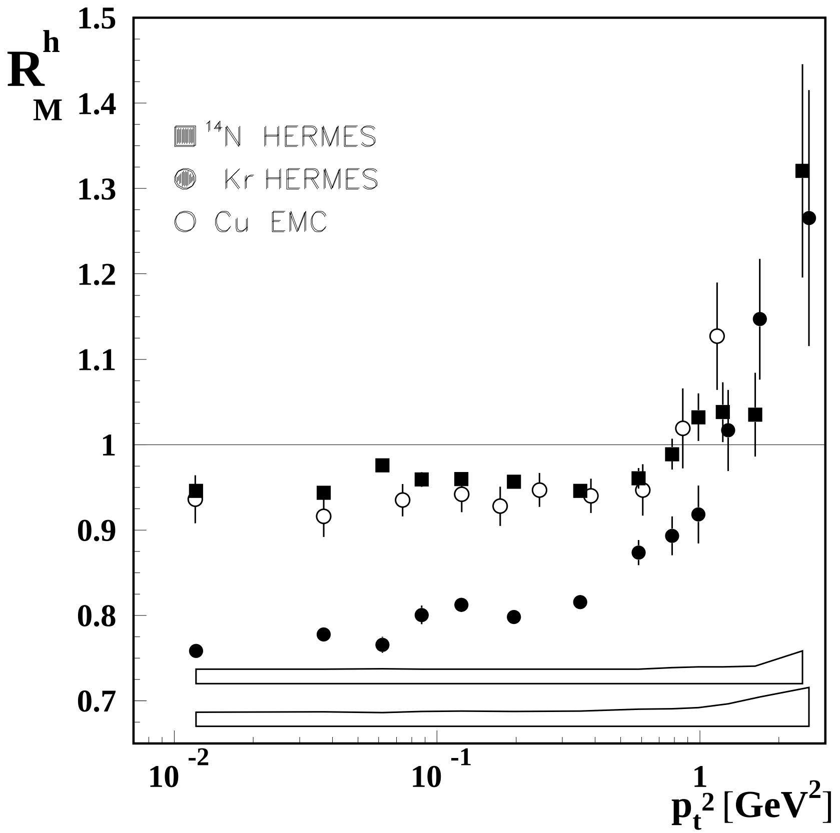
Dependence of SIDIS on ν



Larger suppression at lower ν

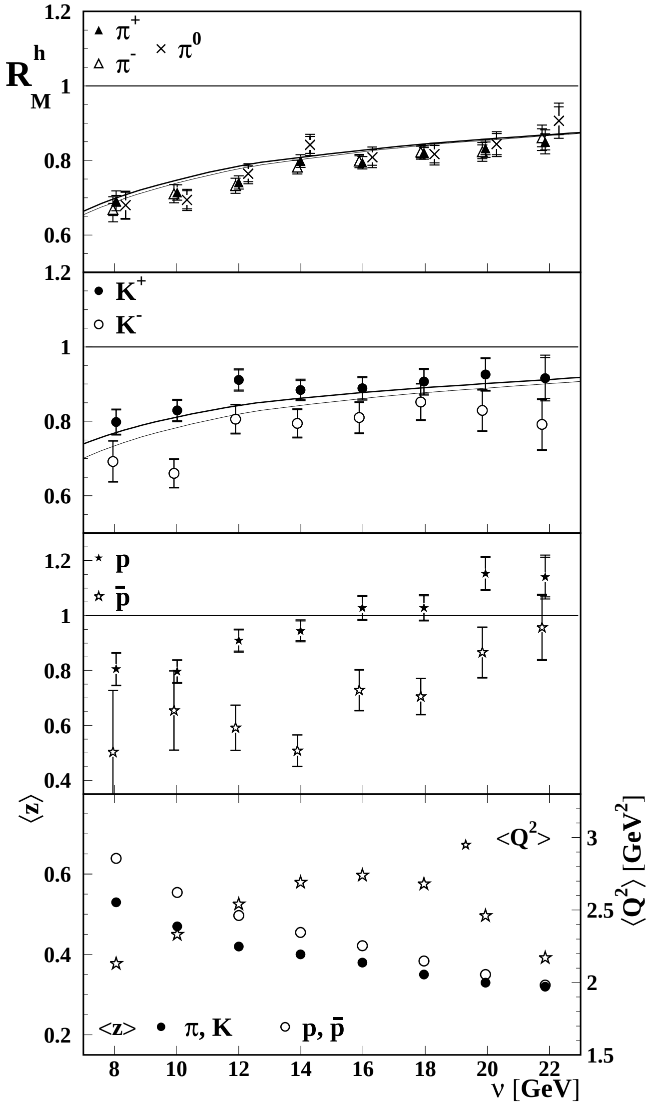
Similar to expected beam energy dependence in Drell-Yan?

P_T-dependence of SIDIS



Again, analogous to Drell-Yan p_T dependence!

Dependence on hadron species

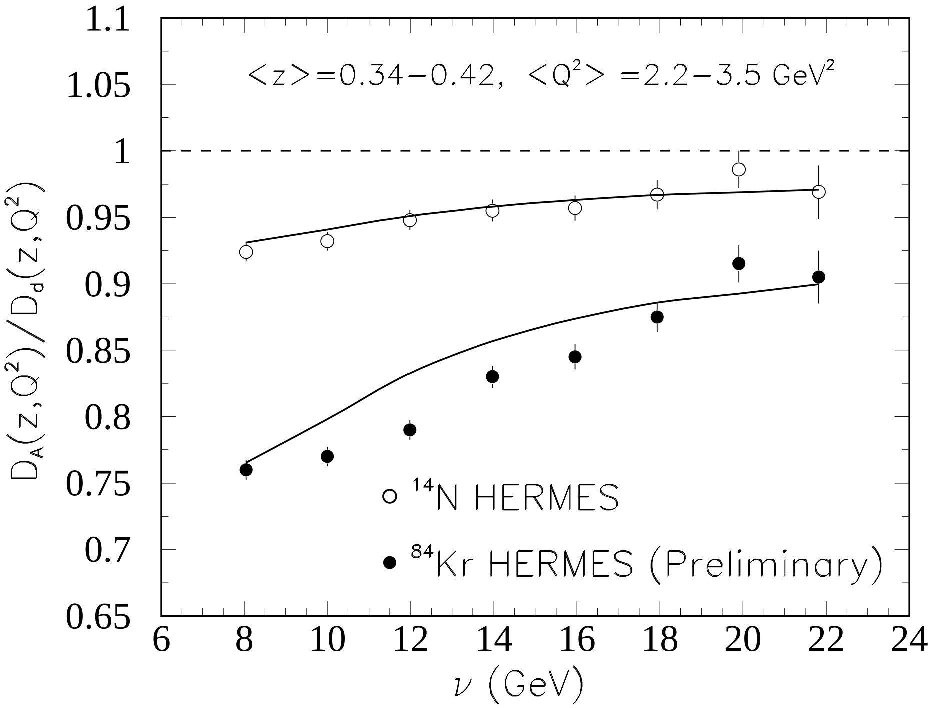


- Clearly show that both the quark and the hadron contribute to the energy loss
- Will pion-induced Drell-Yan be different from the proton-induced Drell-Yan?

Quark Energy Loss in Cold Nuclei

Semi-inclusive DIS

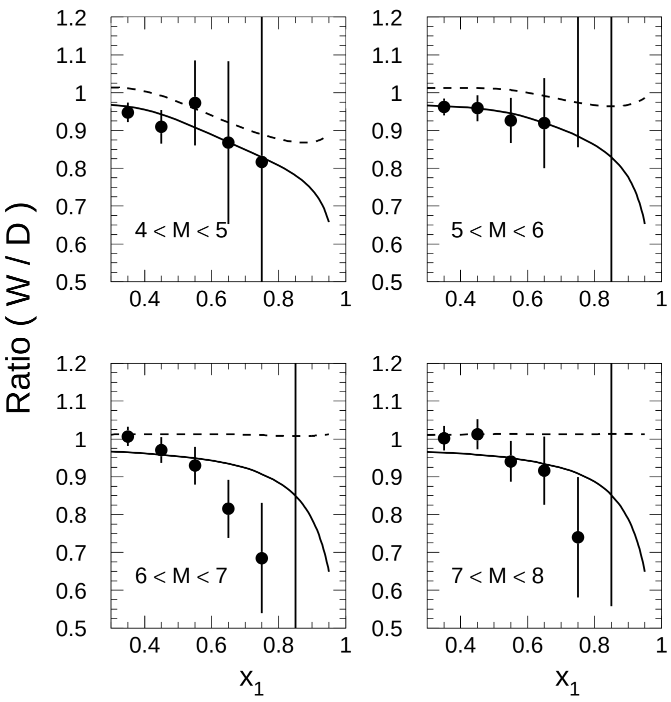
(PRL 89 (2002) 162301)



$$\frac{dE}{dx} \simeq 0.5 \text{ GeV/fm}$$

Drell-Yan

(PRL 86 (2001) 4483)



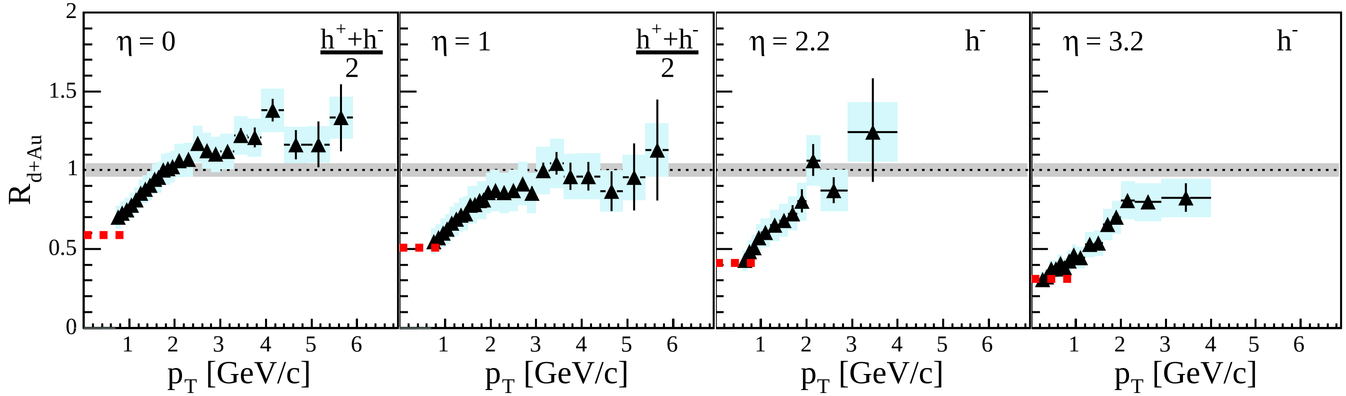
$$\frac{dE}{dx} \simeq 2.5 \pm 0.6 \text{ GeV/fm}$$

Opportunities of quark energy loss study at 12 GeV

- Study the dependence of ν
- Detailed A-dependence measurement to check $A^{1/3}$ or $A^{2/3}$ dependence.
- Centrality tagging

Studies of d-Au collisions at RHIC

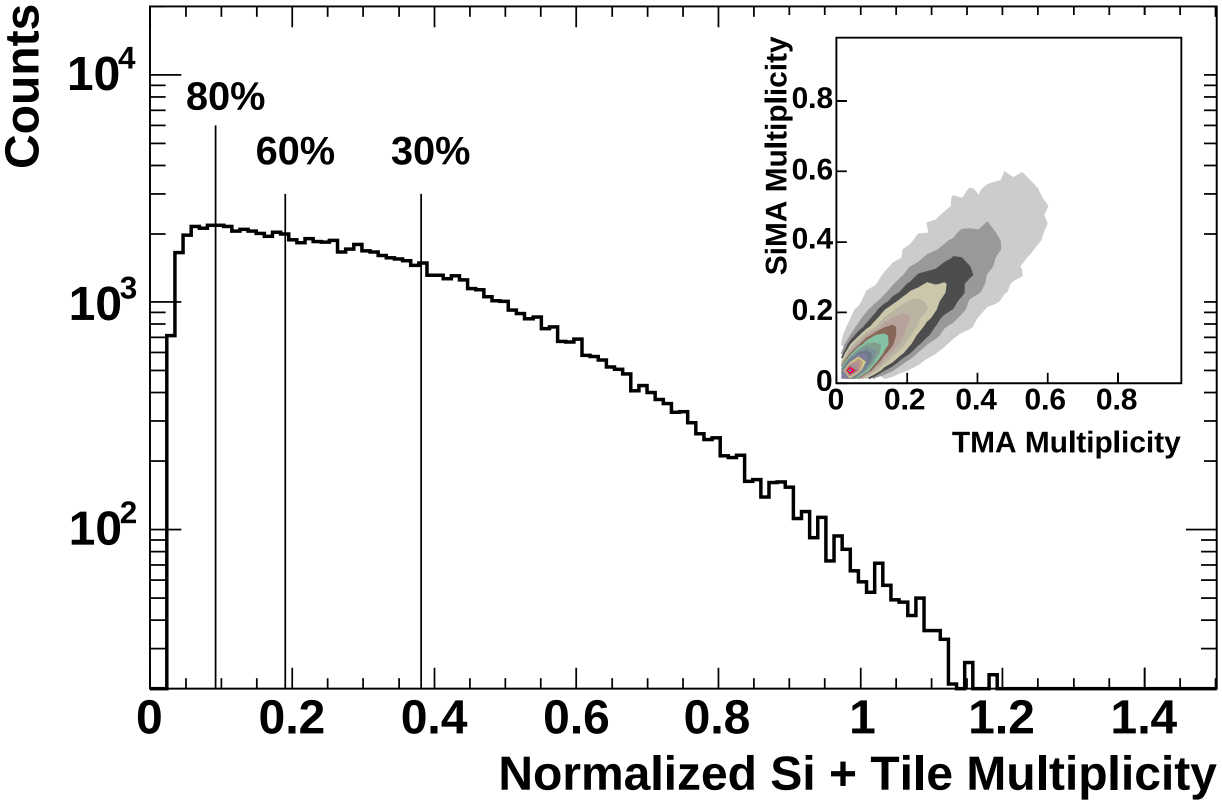
σ(d+Au) / σ(p+p) from BRAHMS at $s^{1/2}$=200 GeV



- Enhancement at large p_T
- Suppression at large rapidity

Very similar to what have been observed in Drell-Yan and SIDIS !

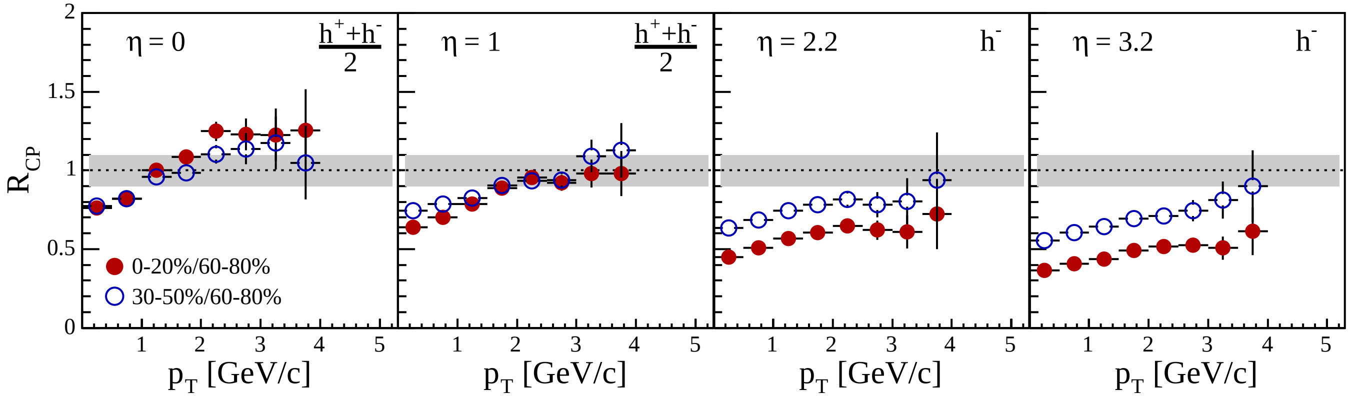
How to measure A-dependence without changing target (or beam)?



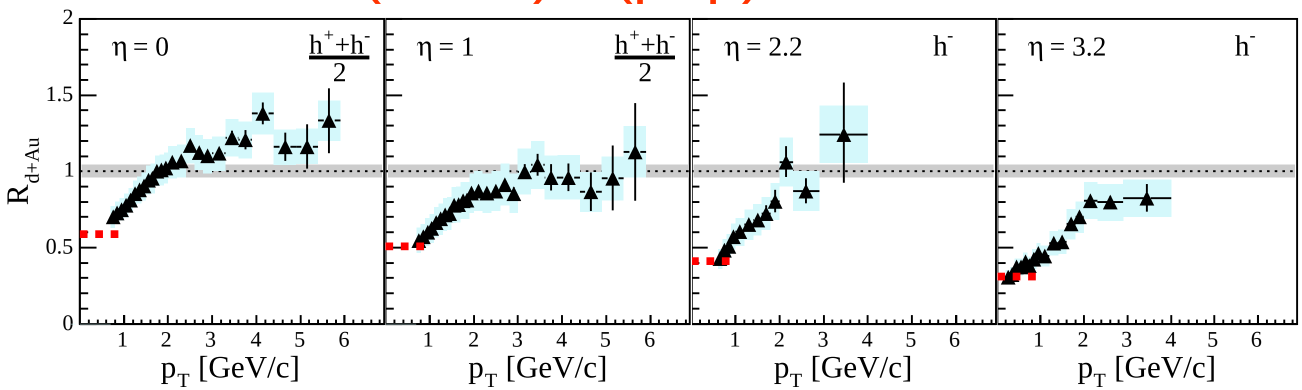
Determine the centrality of the d+Au collision using multiplicity information

Similarity of d+Au / p+p ratios and the R_{CP}

R_{CP} : Ratio of Central / Peripheral d+Au collision

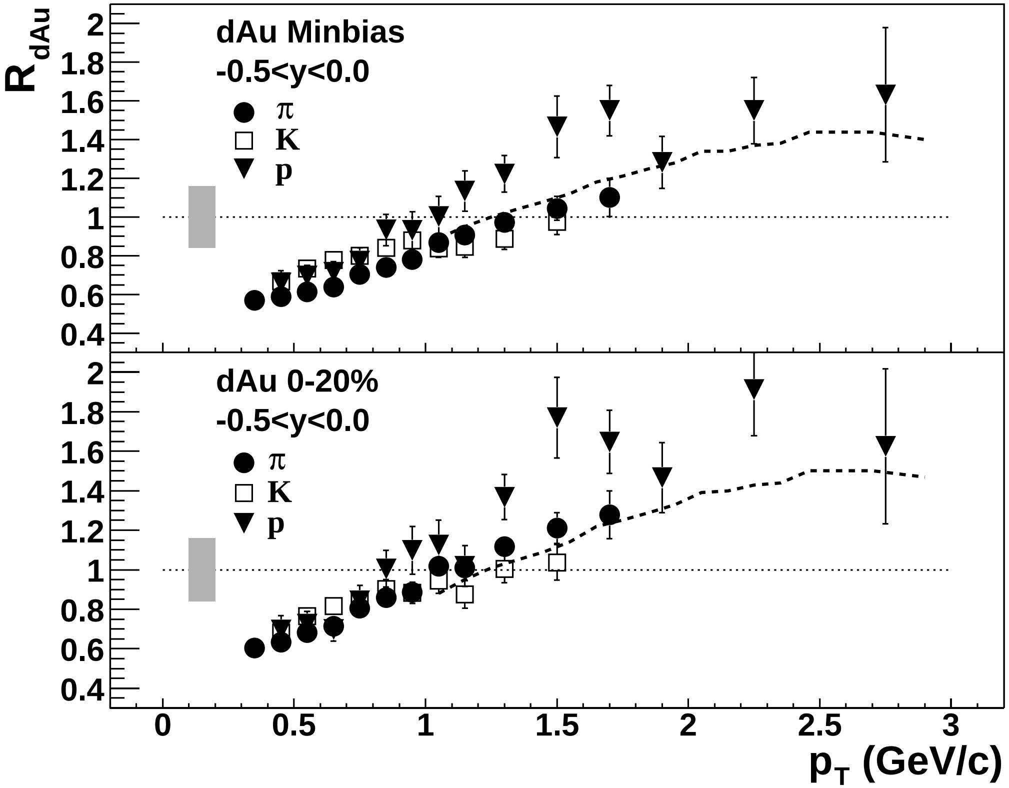


σ(d+Au)/σ(p+p) ratios



Centrality measurement can be done at CLAS using BONUS !

Did RHIC observe the hadron species dependence in d+Au collsion?



YES !

Summary

- A unified picture is starting to emerge from the study of quark energy loss in Drell-Yan, SIDIS, and hadron production in d+Au collision. The 12 GeV upgrade provides an opportunity to further study the SIDIS.
- Future Drell-Yan, SIDIS, and p-A data will provide quantitative information on the propagation and hadronization of quarks in cold and hot nuclear medium.