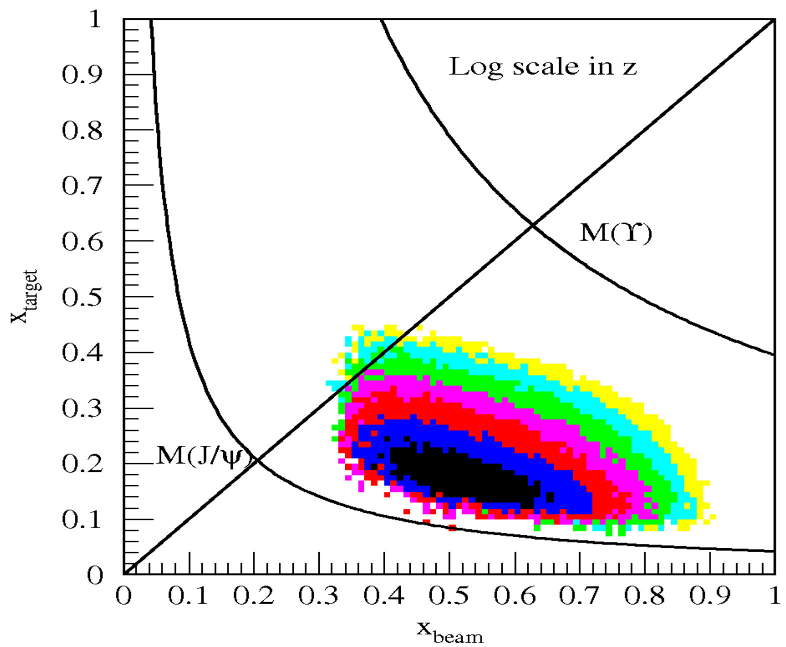
The E906/SeaQuest Fixed-Target Dimuon Experiment at Fermilab: Recent Results and Prospects

Kun Liu (on behalf of E906/SeaQuest collaboration)
Los Alamos National Laboratory

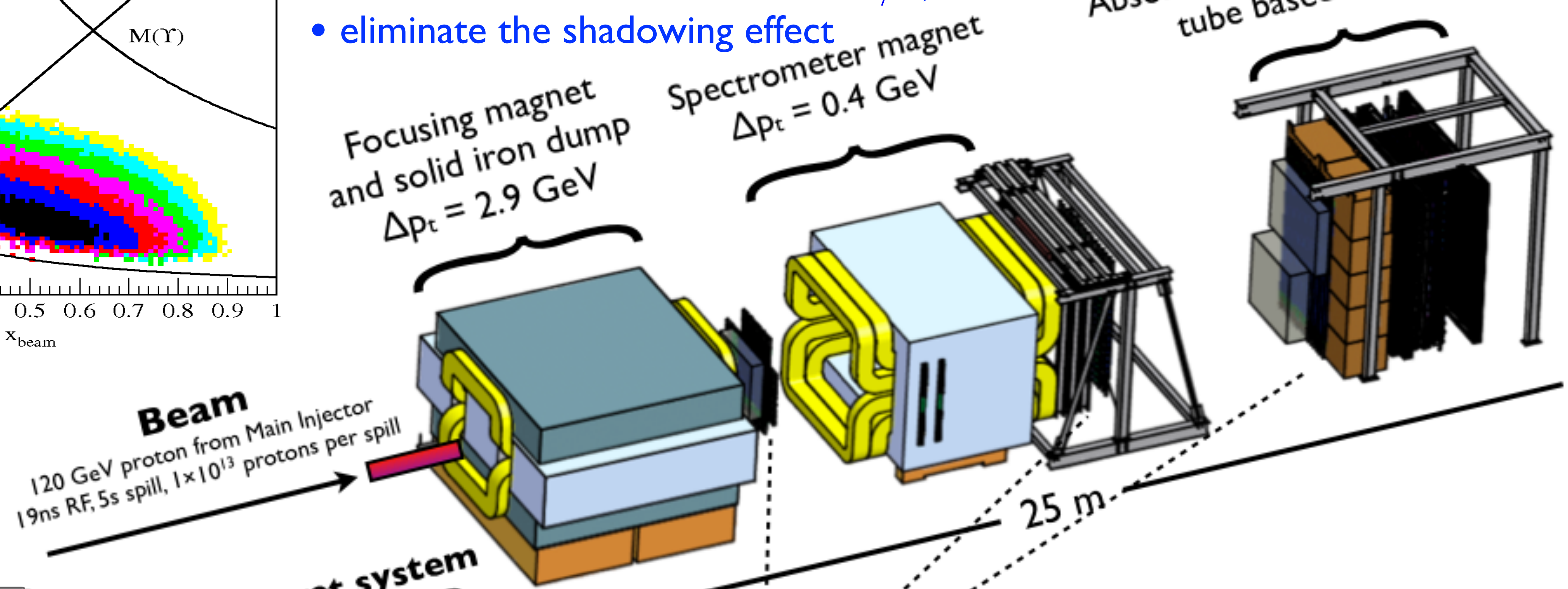
QCD Evolution 2018
Santa Fe, NM, May 20 - 24, 2018

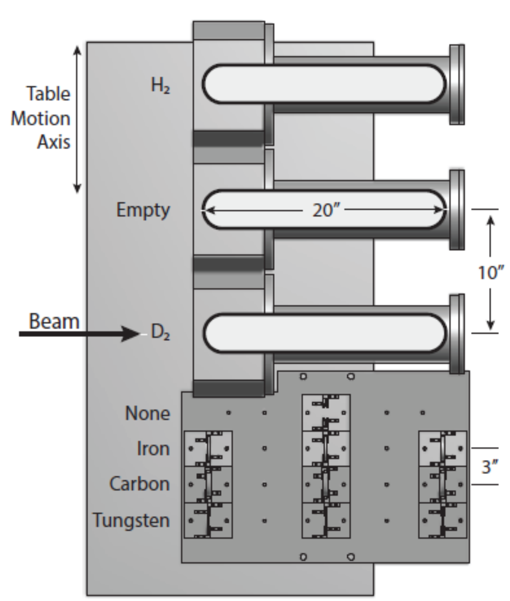
E906/SeaQuest experiment

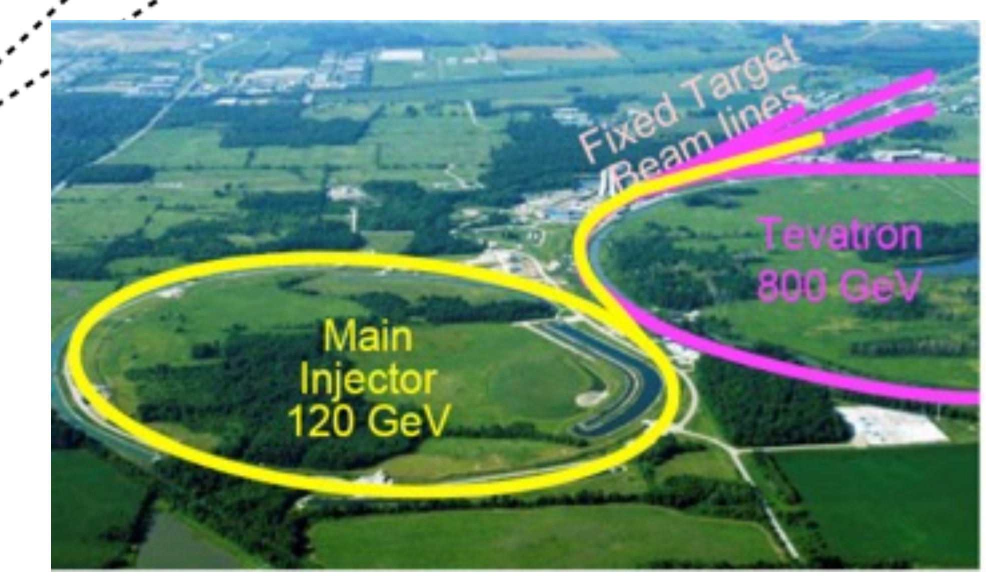


E906/SeaQuest spectrometer is optimized for covering higher x_2 than its predecessors:

- extend E866's measurement of $\bar{d}/\bar{u}$;
- eliminate the shadowing effect







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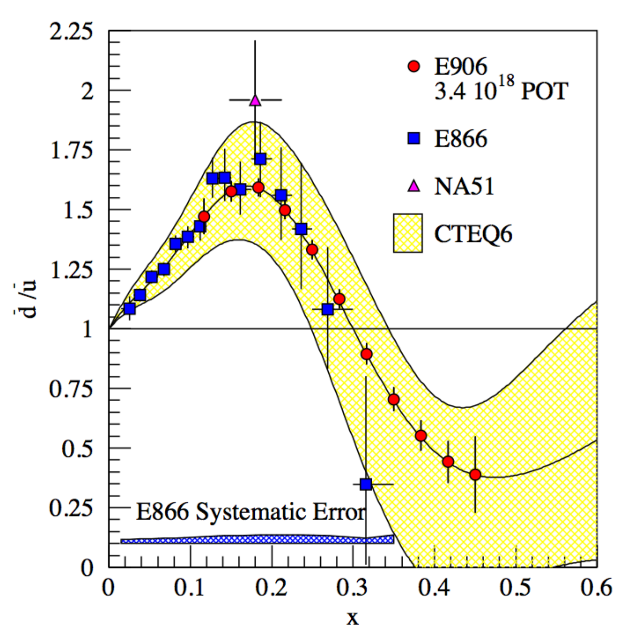
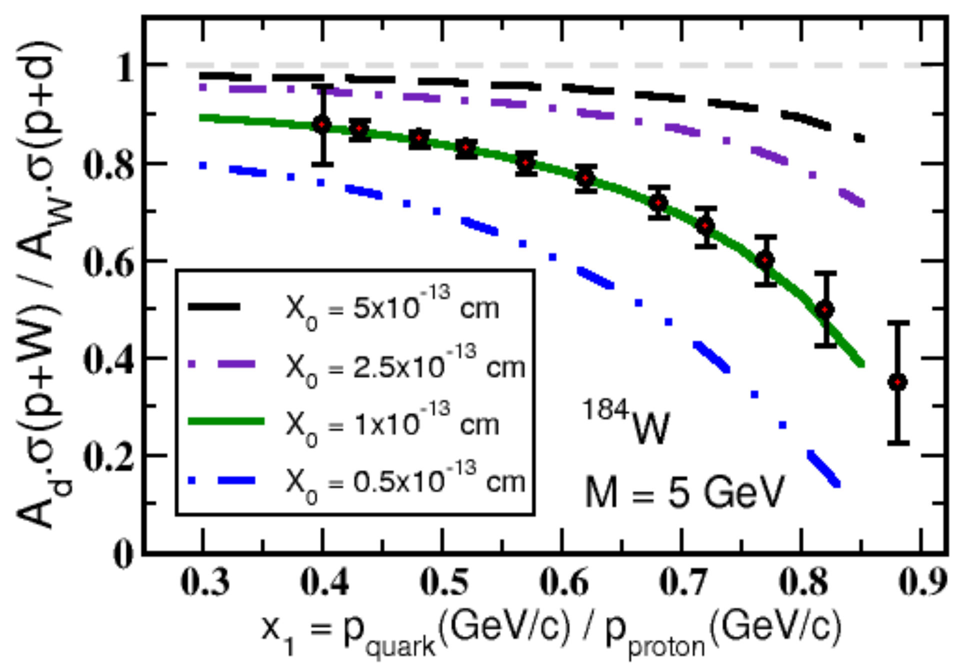
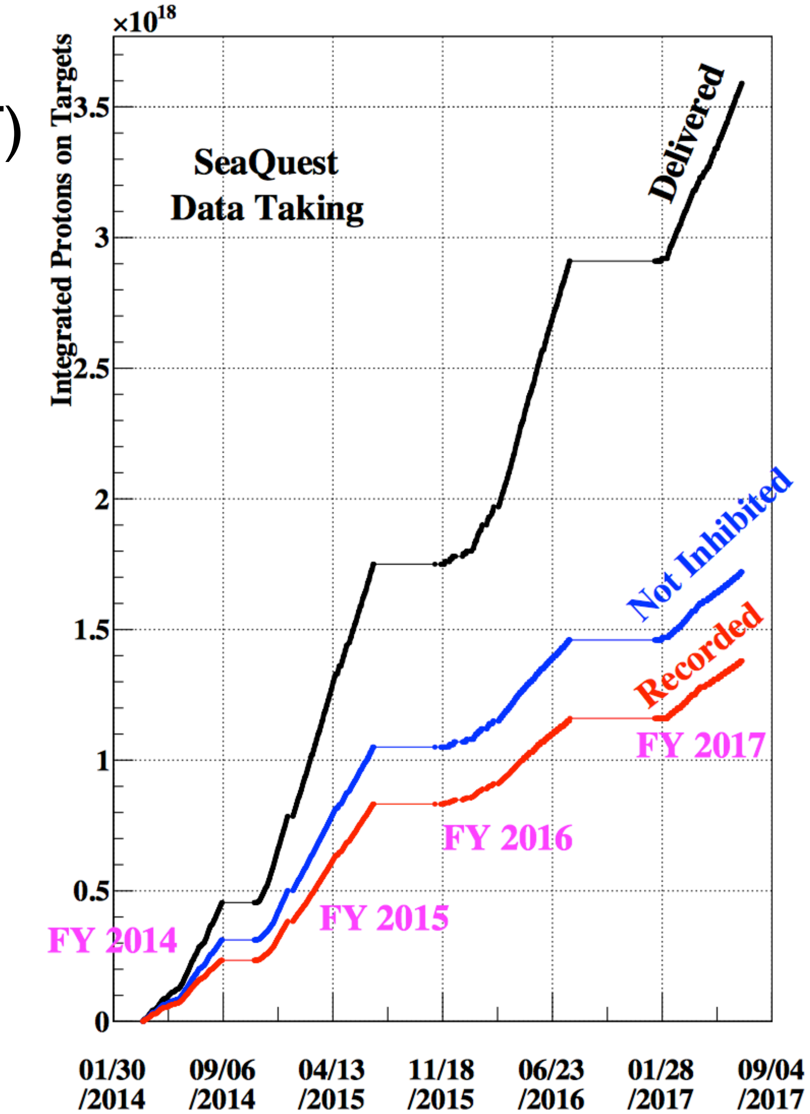
SeaQuest in a nutshell

- **Fixed-target dimuon experiment at Fermilab**
  - ➢ Physics data taking from 2013 to 2017 (**1.4E18** protons collected)
  - ➢ *Preliminary* results released based on FY14 and FY15 (**0.6E18** POT)
- **Understanding sea quark structure of proton:**
  - ➢ sea quark flavor asymmetry, *(eventually) absolute magnitude*
- **Nuclear effects:**
  - ➢ partonic energy loss, *EMC in sea quarks, J/ψ (ψ') nuclear dependence*







- **3 successor/parasitic experiments will follow:**
  - ➢ polarizing the target (**E1039**) - commissioning starts this fall (Xuan Li's talk tomorrow afternoon)
  - ➢ polarizing the beam (E1027) - hopefully after polarized target run
  - ➢ search for dark photon/higgs (**E1067**) - parasitic running with all future upgrades, with the potential for dedicated beam time

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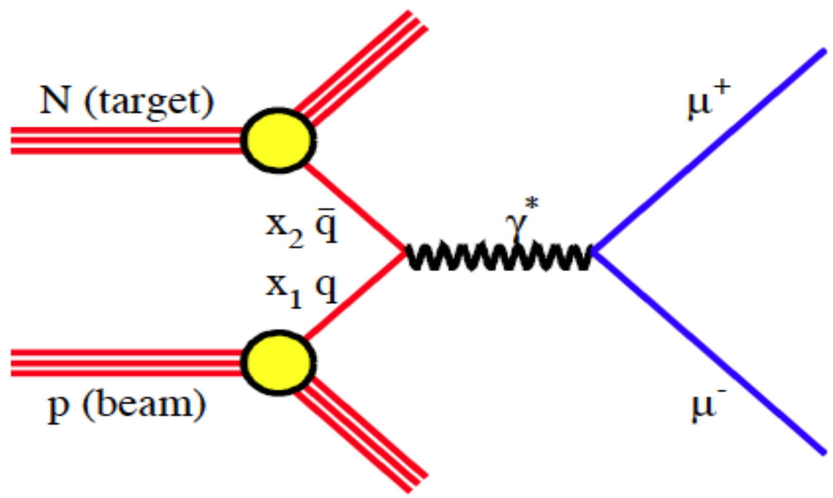
E906 kinematic coverage

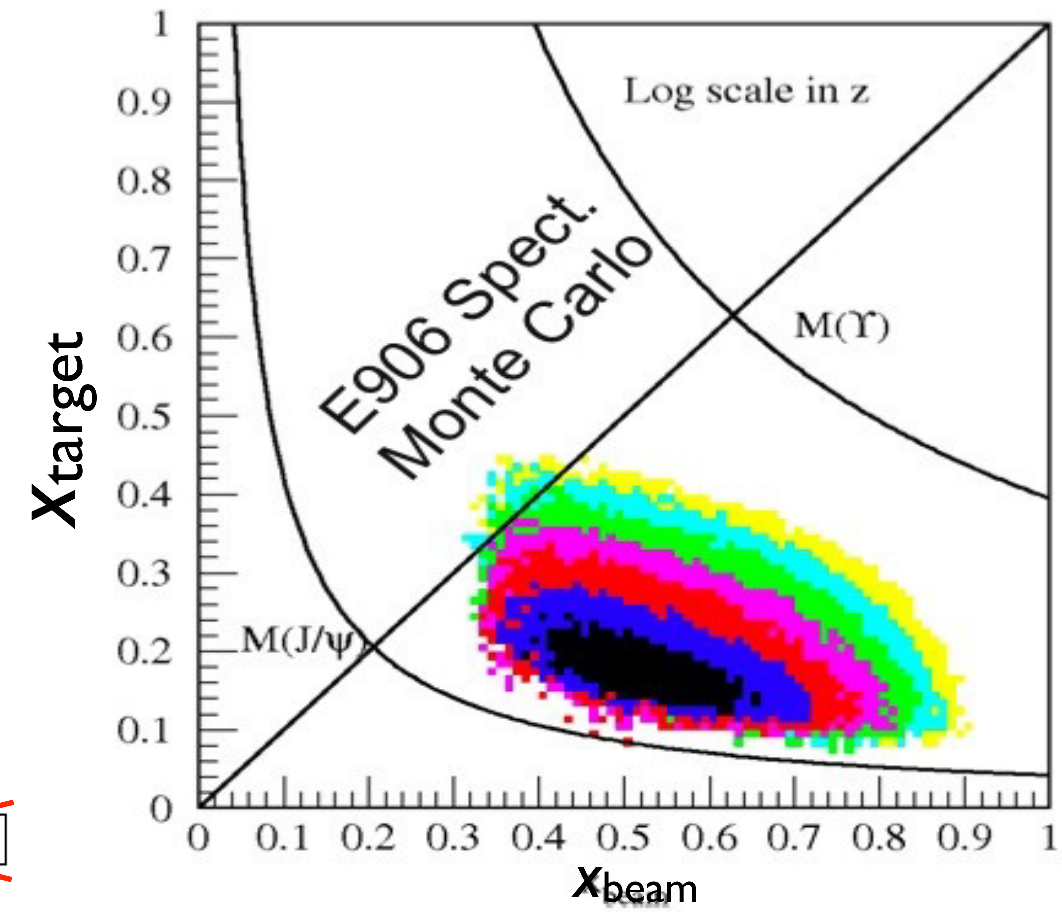
The Drell-Yan process:

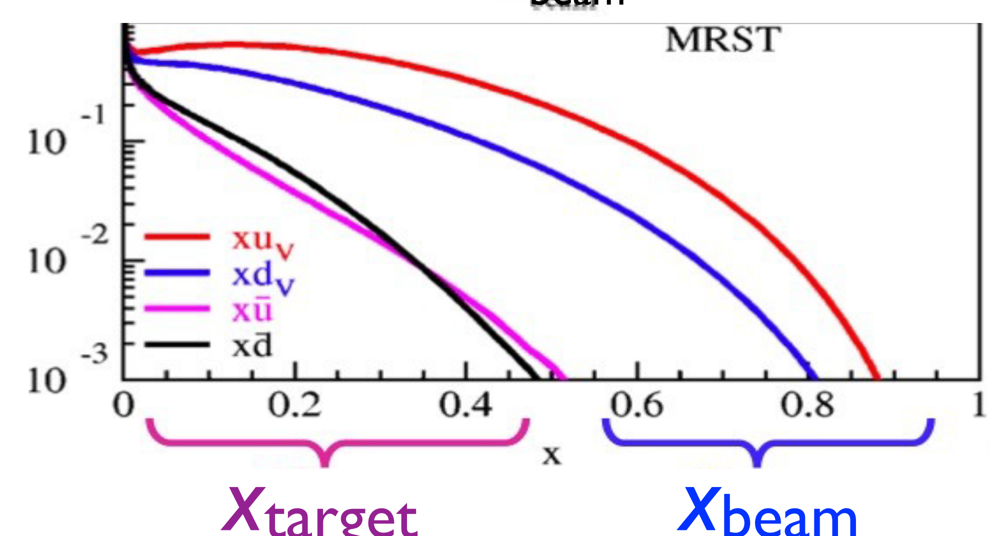


$$\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9 x_b\, x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t) q_b(x_b) + \underbrace{\cancel{q_t(x_t)\bar{q}_b(x_b)}}_{\text{small}}\right]$$

Unique sensitivity to sea quarks!

$\bar{q}_t(x_t)$: target sea quark at low/intermediate x
$q_b(x_b)$: beam valence quark at high x





Sea Quark Flavor Asymmetry

Looking into the light quark sea

- Proton as a sum of quarks: $P = q_u^1 + q_u^2 + q_d^3 + \sum_i q_{sea}^i \bar{q}_{sea}^i$
  Valence Sea

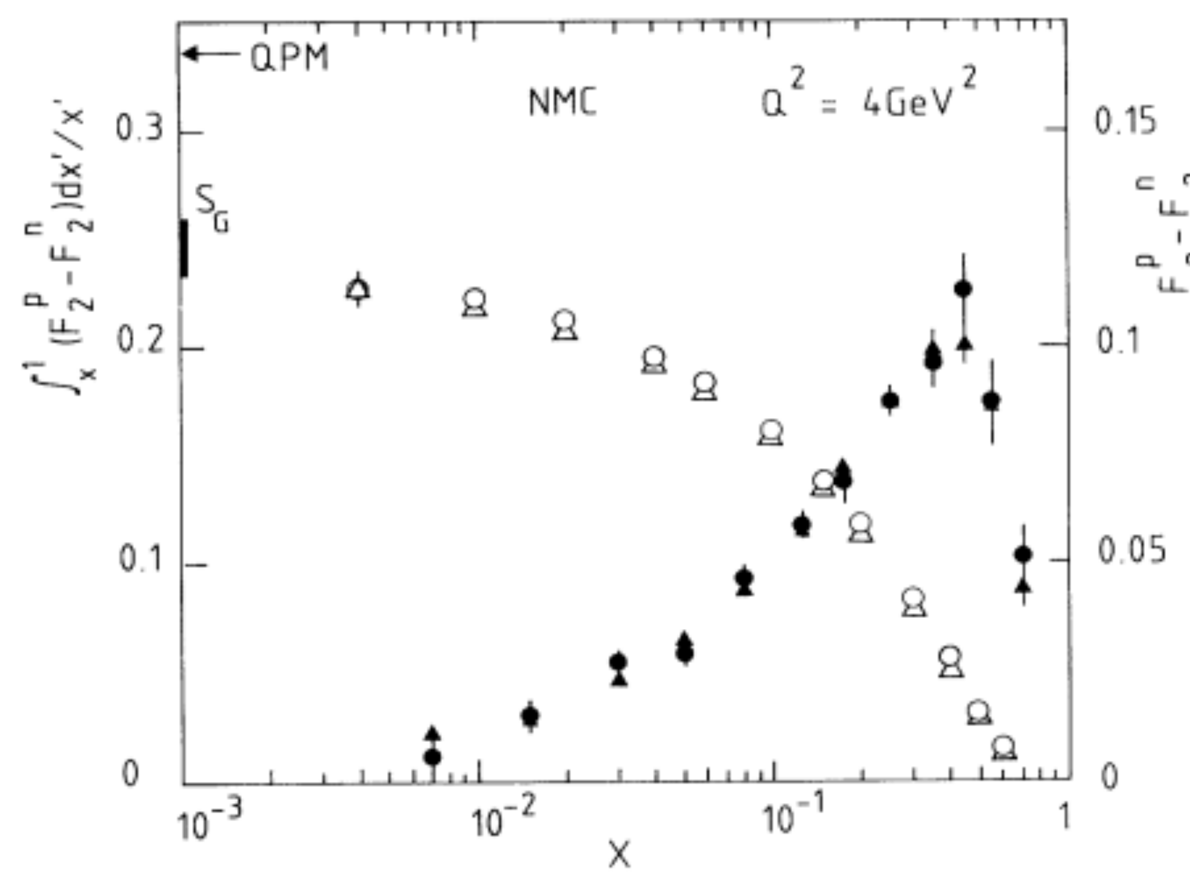
- Separate the sea from valence:

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)] dx$$

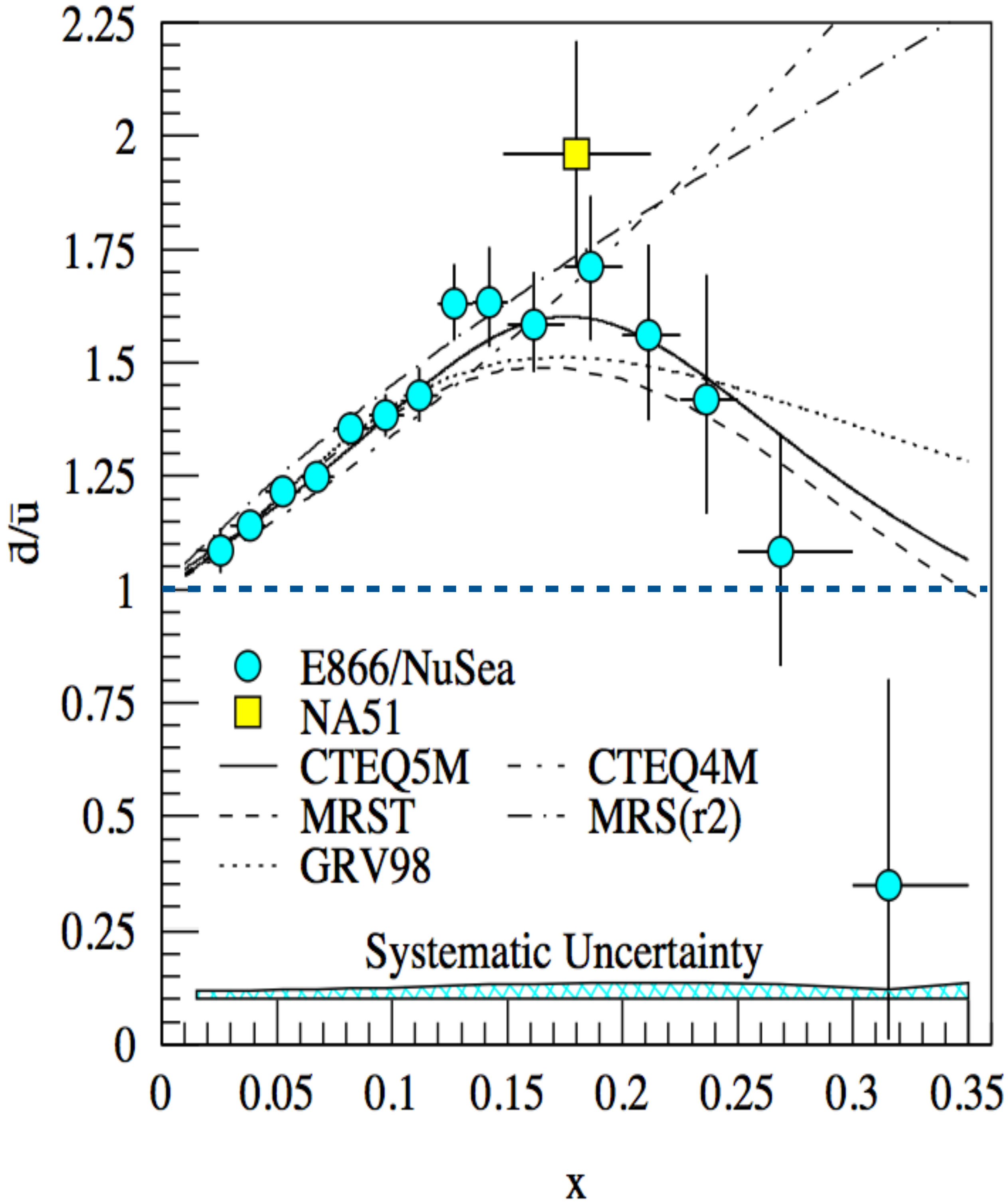
Gottfried Sum Rule

- NMC tested Gottfried Sum Rule by muon DIS on hydrogen and deuterium

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = 0.235 \pm 0.026$$



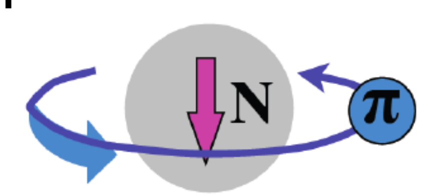
Flavor asymmetry in light quark sea

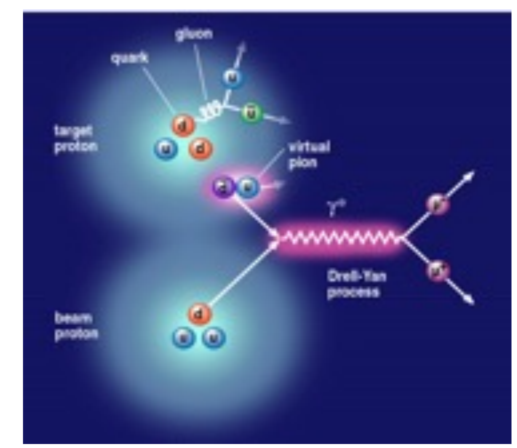


- Assuming charge symmetry, ignoring nuclear effects of deuterium and heavy quark contributions:

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right].$$

- Naively we would expect flavor symmetry between $\bar{u}$ and $\bar{d}$
- E866/NuSea experiment reveals a striking asymmetry in the sea distributions at moderate *x*
- Caused by virtual pions?

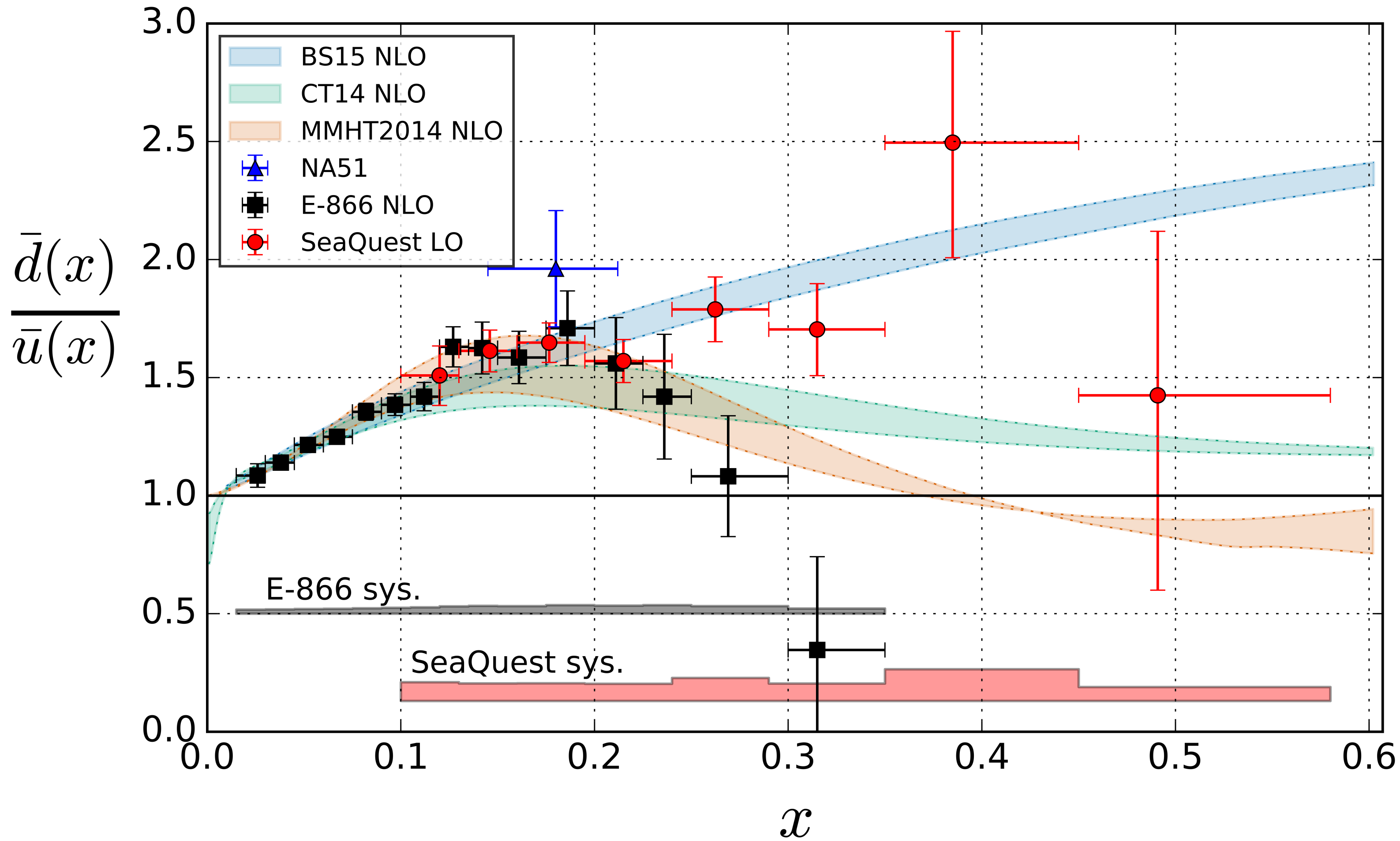




- Important constraints on light sea polarization

E906's *x* coverage: 0.1 - 0.45

Preliminary results



- ~40% of total statistics
- Major systematic uncertainties:
  - ➢ H contamination in LD2
  - ➢ Background
  - ➢ Beam intensity induced reconstruction inefficiencies
  - ➢ Uncertainty from CT10 PDF

- Potential disagreement between E906 and E866
  - ➢ Very different Q^2, 54 GeV^2 for E866 and ~29 GeV^2 for E906
  - ➢ Nuclear effects in deuterium

For final results, we could expect:

- ➢ *2.5x more statistics*
- ➢ *Better constraint on the systematic uncertainness*
- ➢ *NLO extraction*

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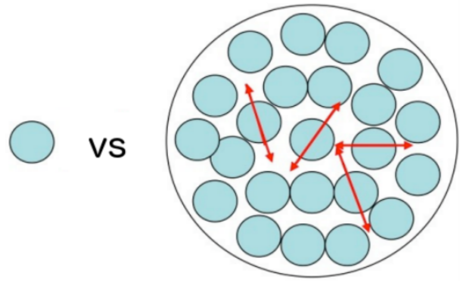
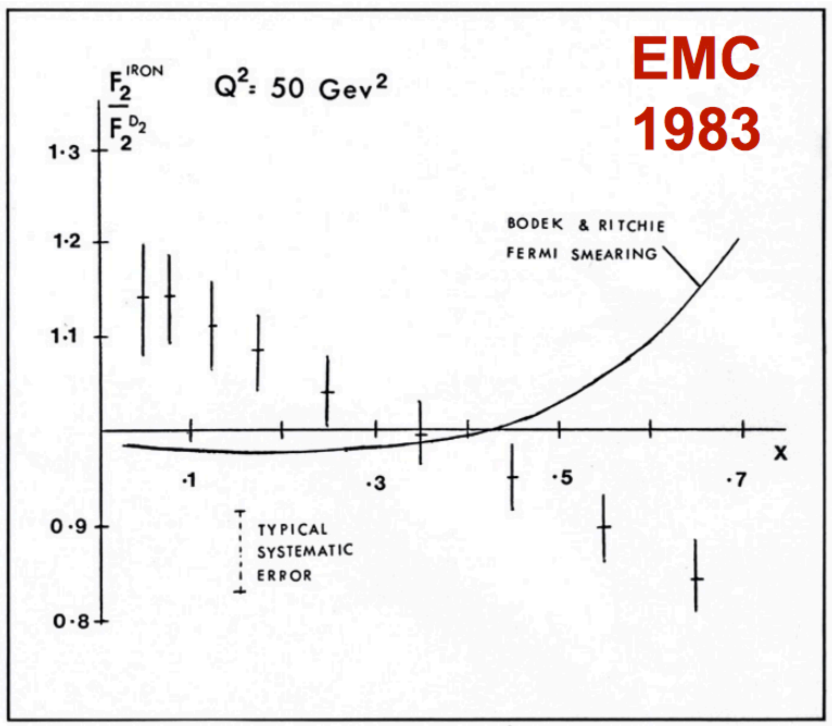
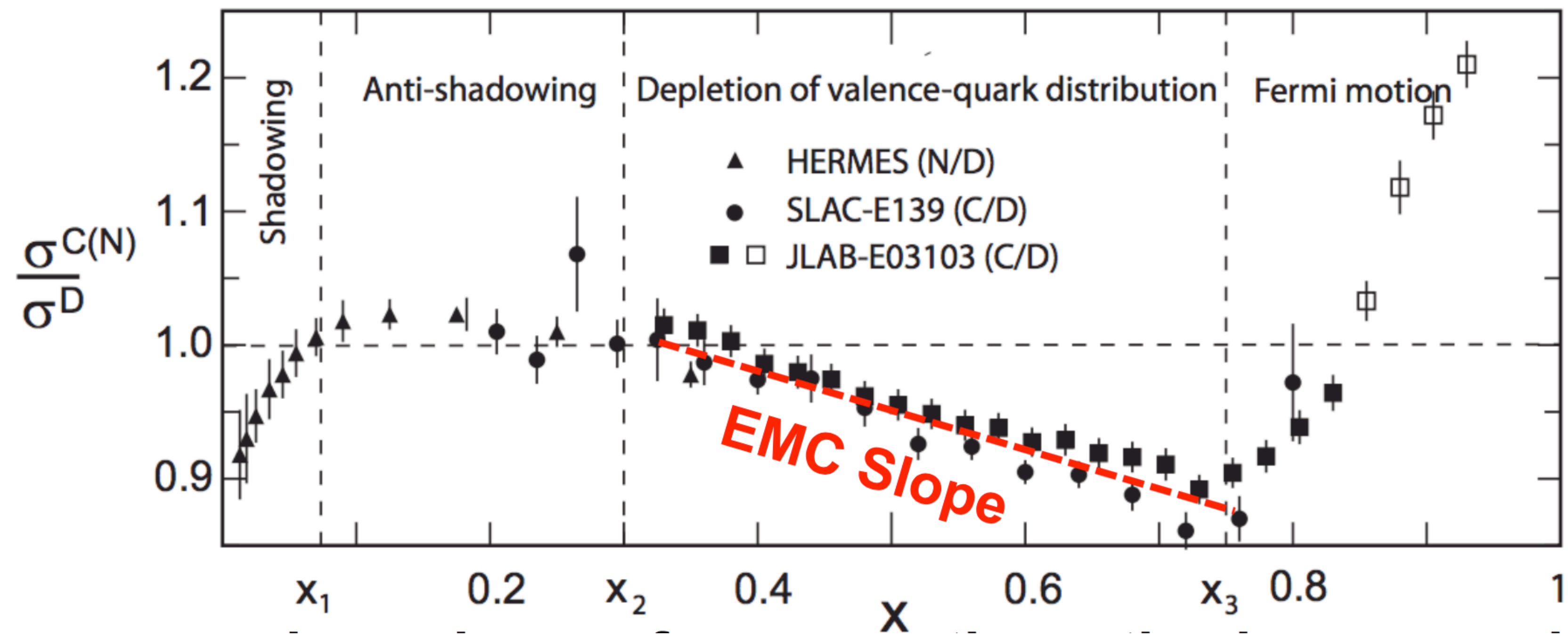
EMC Effect in Drell-Yan



Brief history of EMC effect in DIS





- First discovered by European Muon Collaboration in DIS process
- One natural explanation involves pion excess in the nuclear medium

  ⇒ results in sizable enhancement in the sea quark distribution

  ⇒ results in larger effect in DY process

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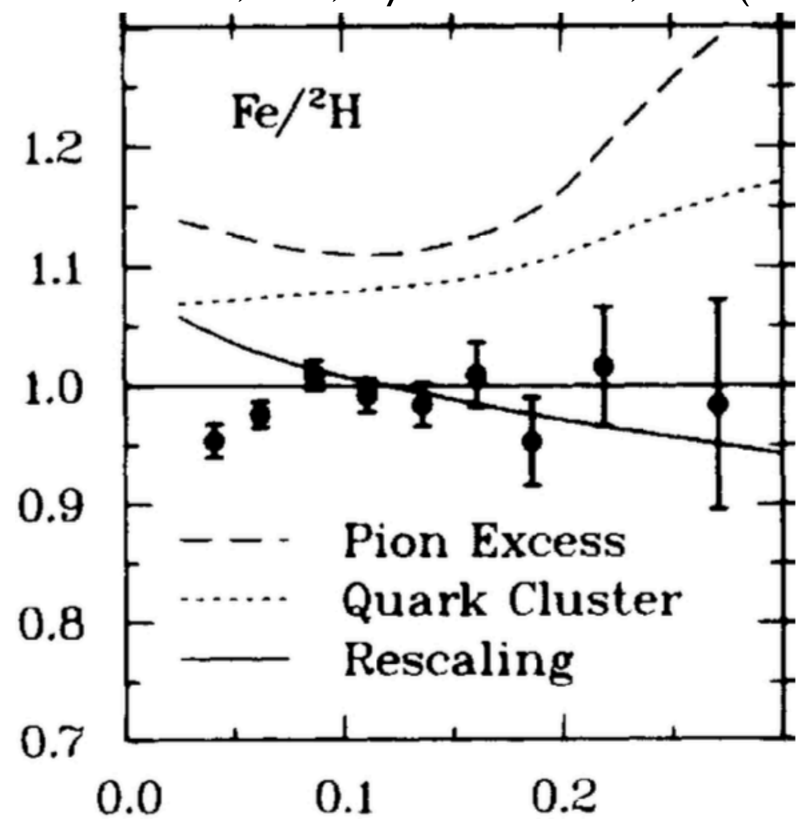
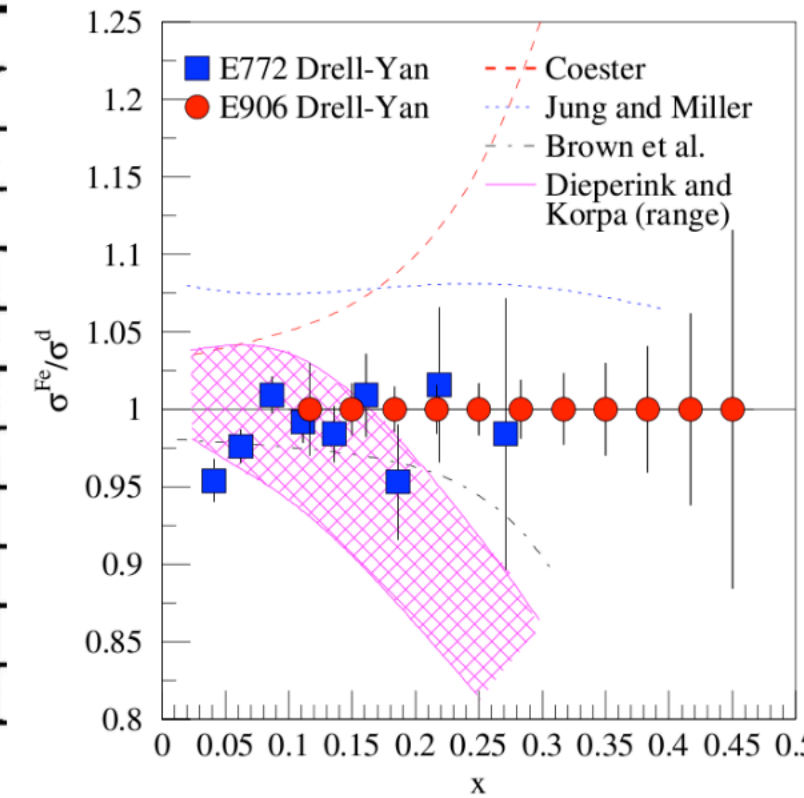
The EMC effect in DY

- E772 data found no anti-quark enhancement compared to the free nucleon
- Large theoretical discrepancy at high *x*. E906 will be able to provide enough sensitivity to differentiate between these models.

D. Alde, et al., Phys. Rev. Lett. 64, 2479 (1990)





PERSPECTIVES

Where Are the Nuclear Pions?

George F. Bertsch, Leonid Frankfurt, Mark Strikman

"Made a rather persuasive case that virtual pions with momenta created than about 400 MeV/c are not very important in a nucleus"

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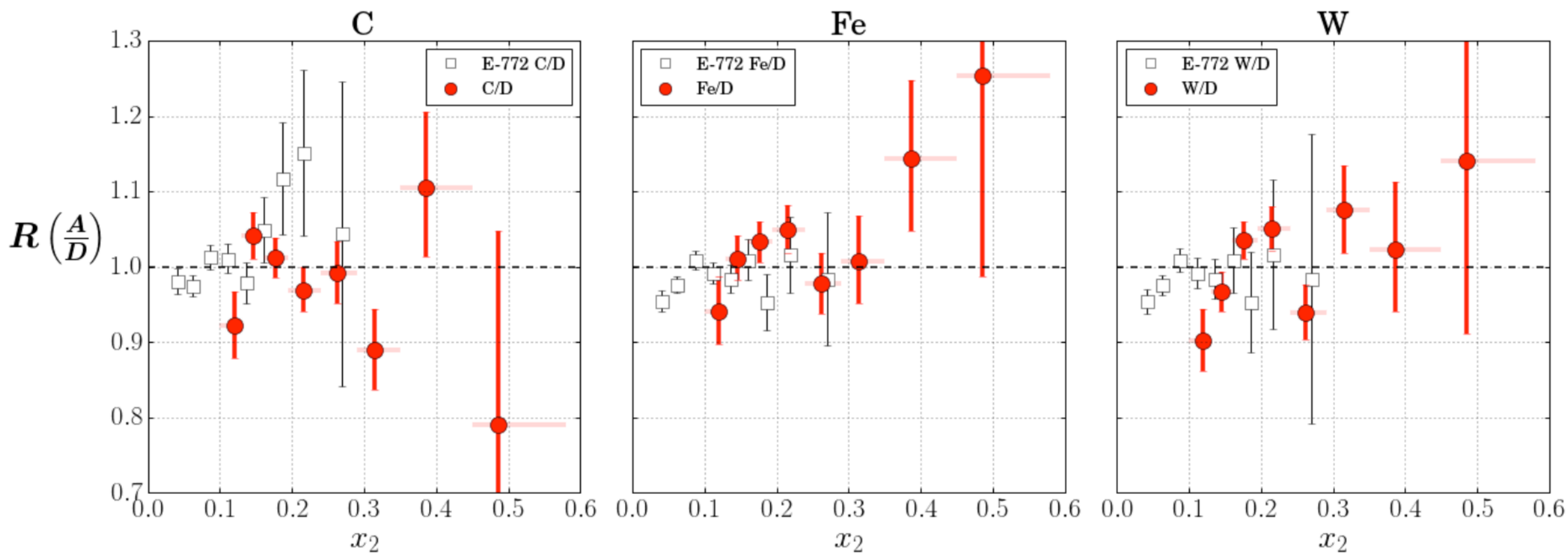
Preliminary results



From Bryan Dannowitz (UIUC) dissertation

- Includes ~40% of data
- ~3% of the systematic uncertainty not shown

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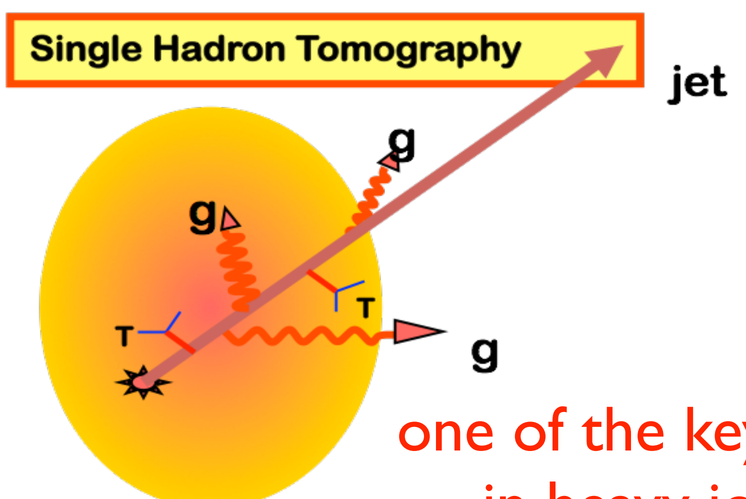
Partonic Energy Loss in Cold Nuclear Medium

Understanding Jet Quenching at RHIC/LHC

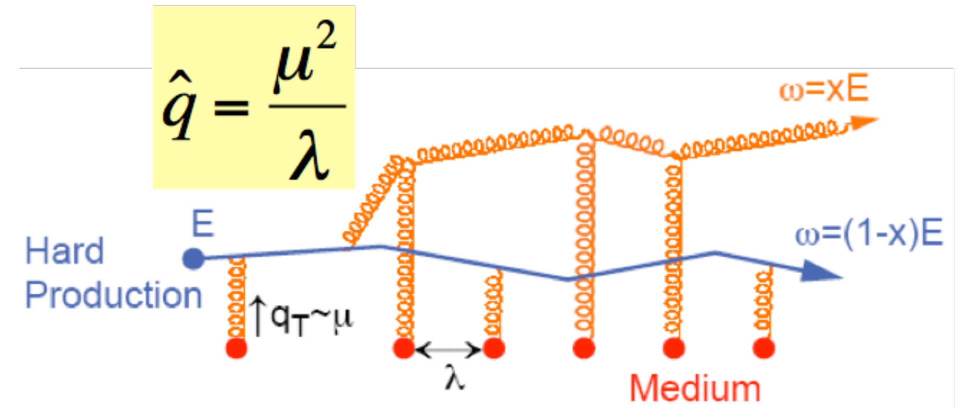
Energy loss of partons from hard scattering through re-scattering in the hot and dense medium (Quark Gluon Plasma)

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

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

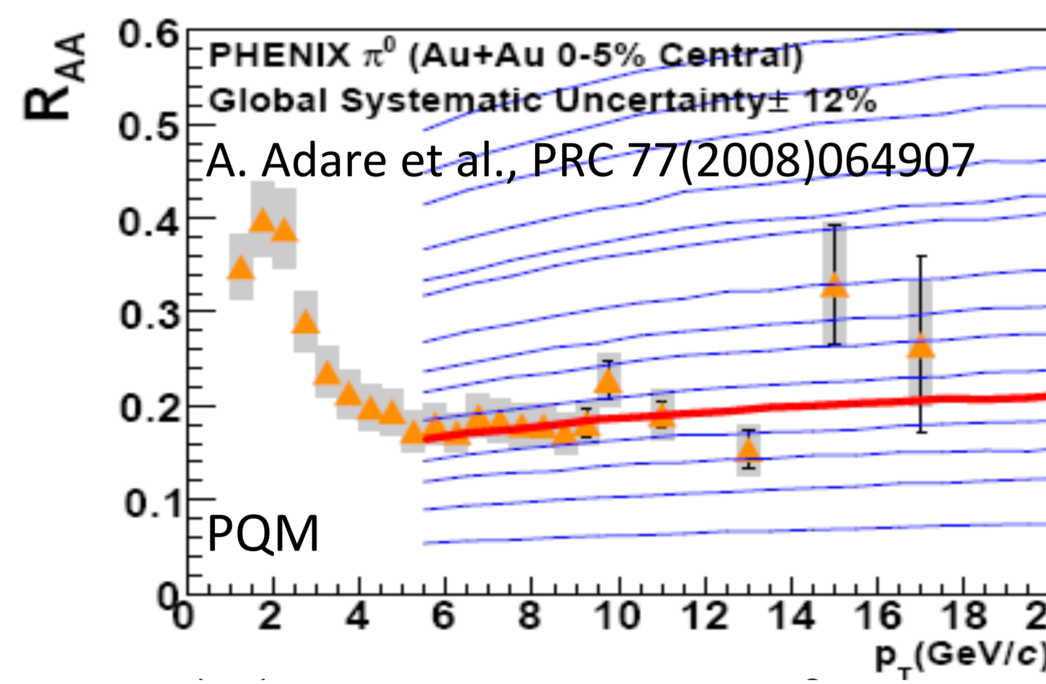


one of the key questions in heavy ion today



Access medium properties through statistical analysis:

- example: transport coefficient
- **model dependent**



Recent JET collaboration progress (PRC 90, 014909 (2014)) for 10 GeV quark:

- qhat = 1.2 ± 0.3 GeV²/fm for RHIC
- qhat = 1.9 ± 0.7 GeV²/fm for LHC

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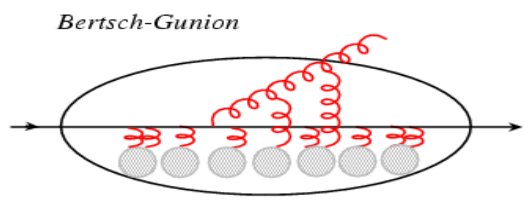
Measurement of Cold Nuclear Medium will help pin down the model uncertainty

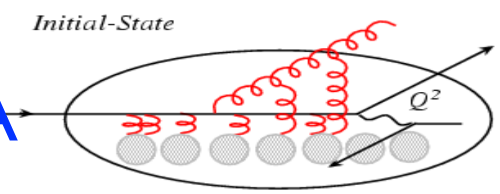
Theoretical expectations of the scale

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

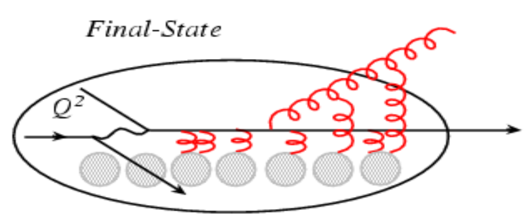
Ideal QGP



Drell-Yan: p+A

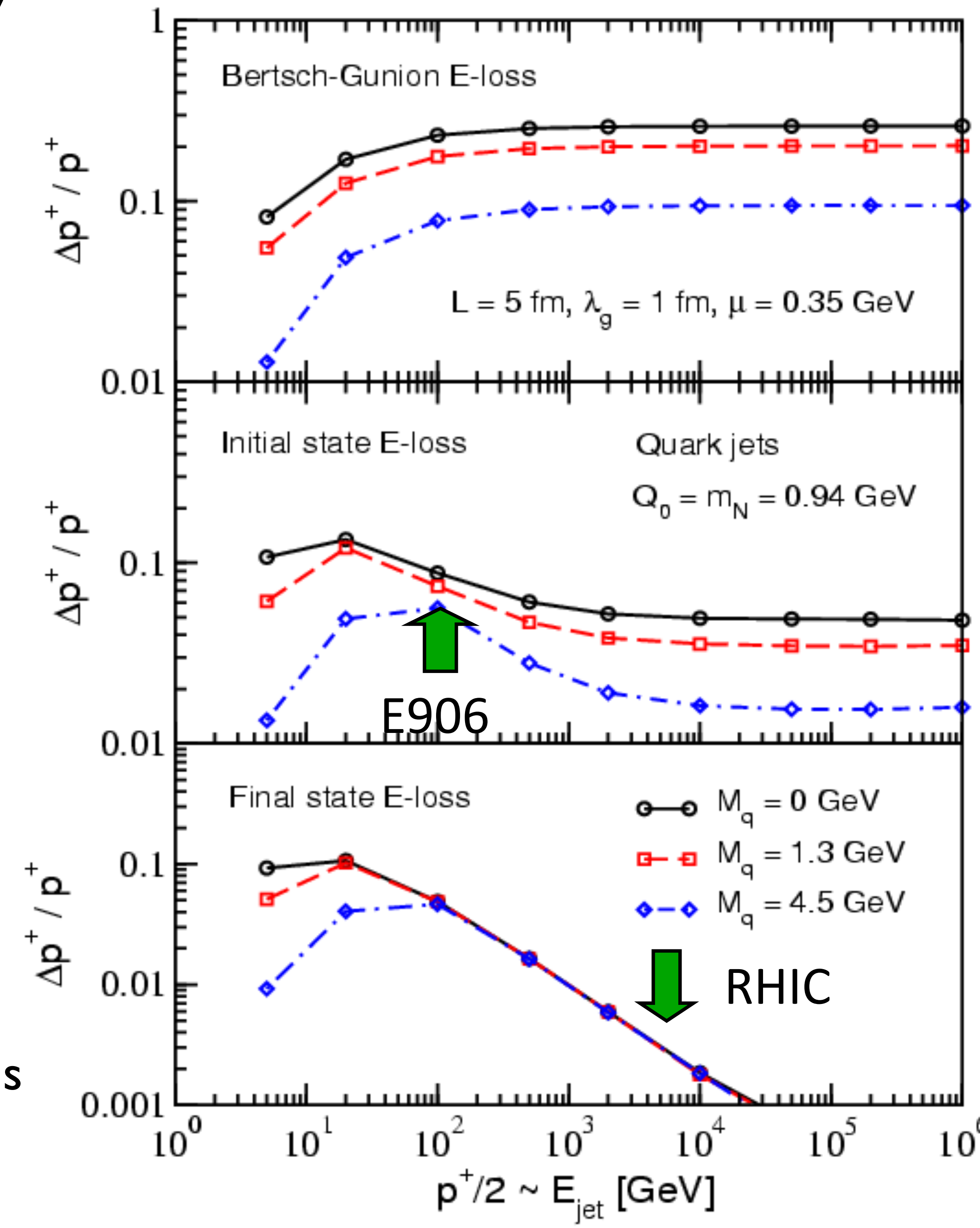


DIS:e+A



- 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)



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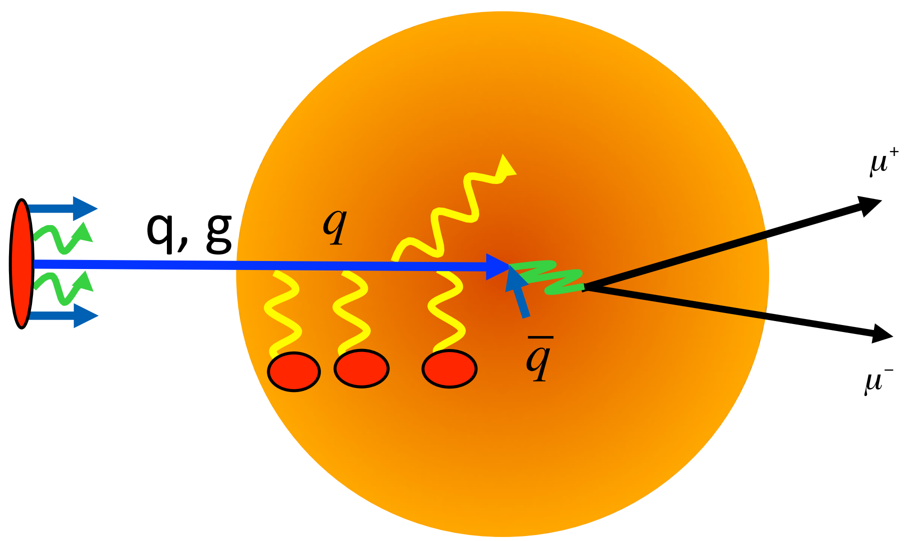
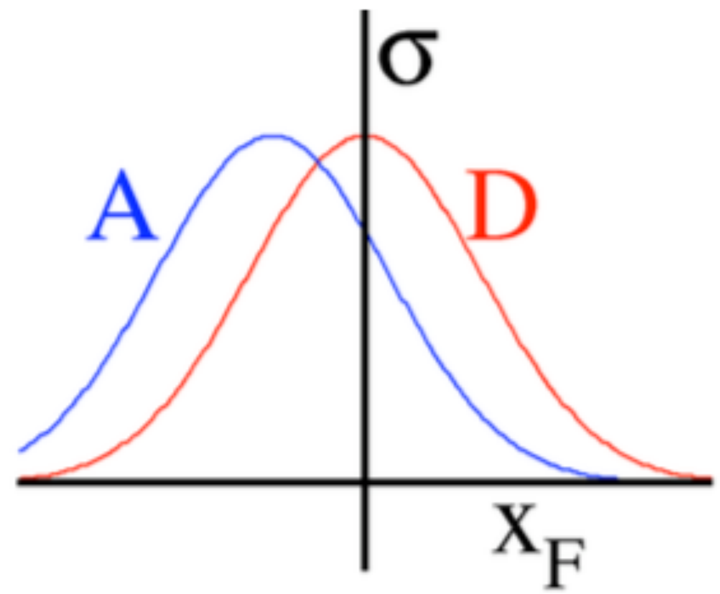
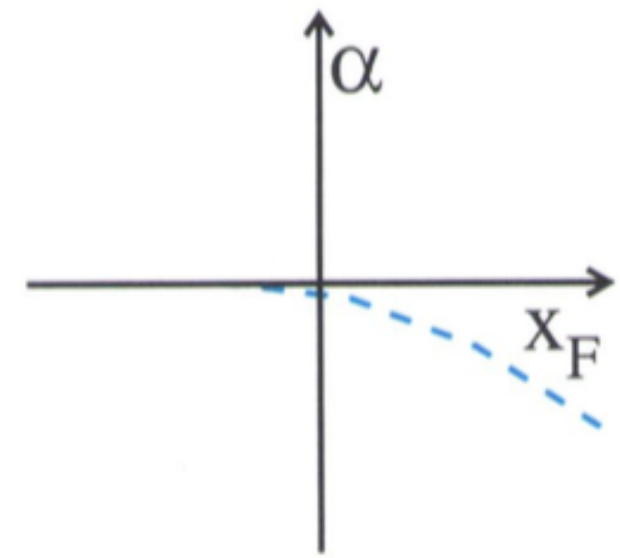
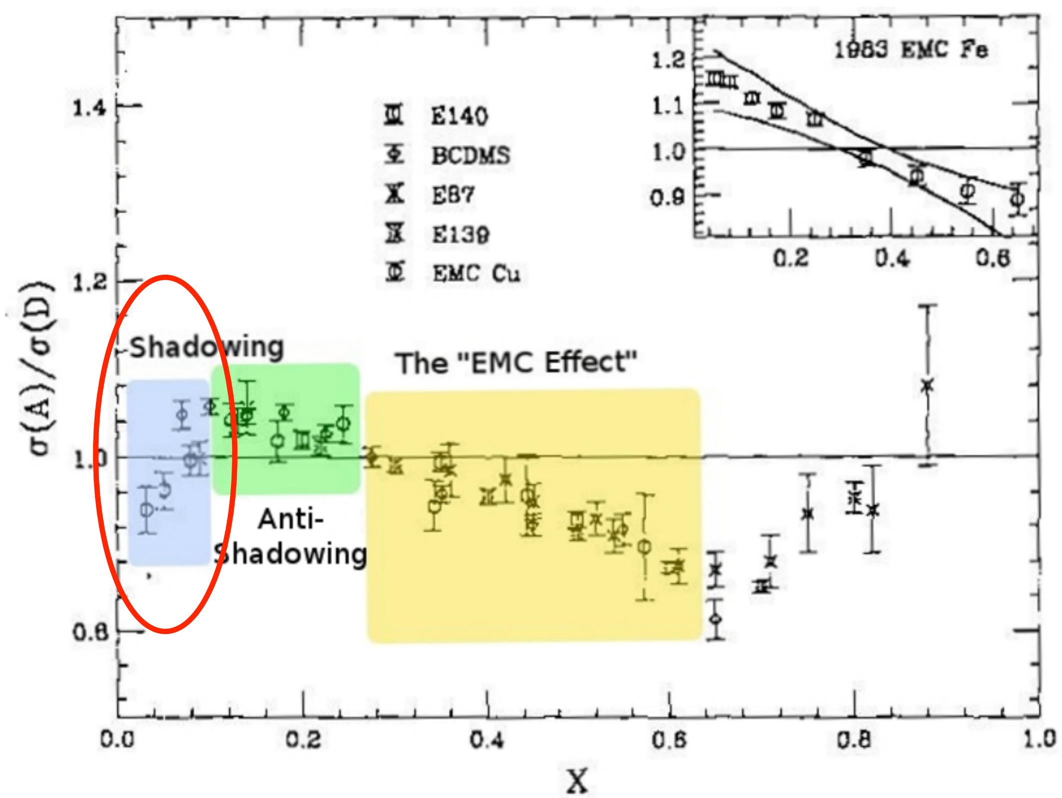
Initial-state energy loss and Drell-Yan in p+A





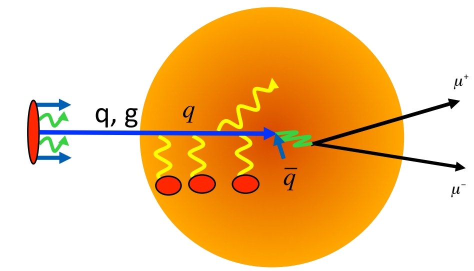




- Interaction would degrade the longitudinal momentum of the dimuons
- $d\sigma/dx_F$ would shift to more negative x_F for Drell-Yan on nuclei
- $R_{pA} = \sigma_{pA}/\sigma_{pD}$ would drop below *1* as x_F approaches *1*

Large x_F corresponds to small x_B
$\Rightarrow$ shadowing effect need to be considered

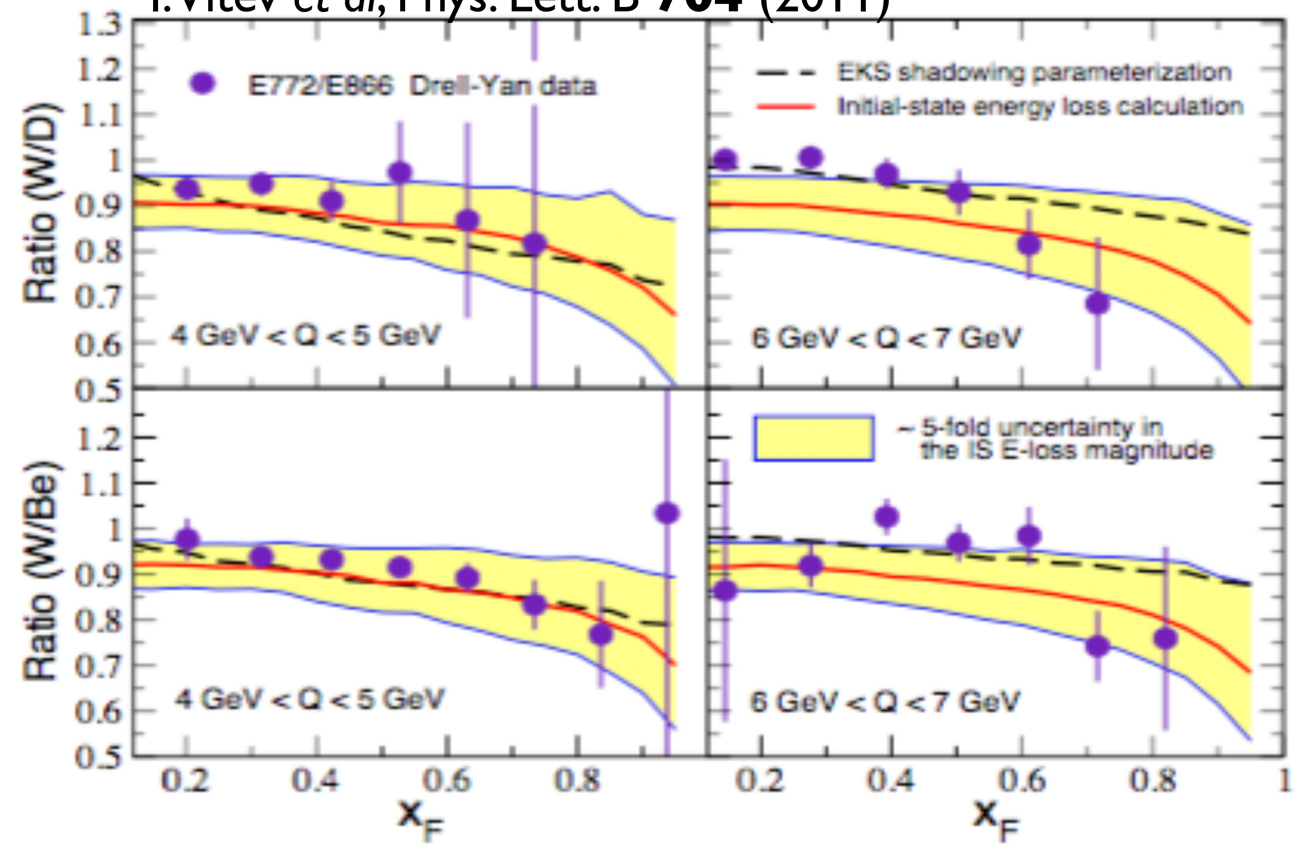
Early data from E866 @ Fermilab

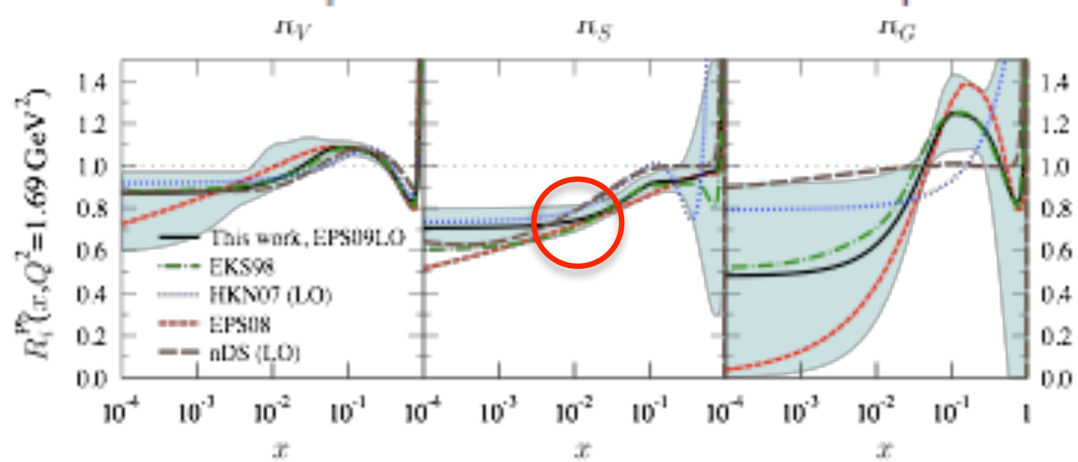


- Energy loss vs. shadowing
  - Correction must be made for shadowing effects
    - Garvey & Peng PRL 90 (2003)
  - NO partonic energy loss if all effects from shadowing
    - Vasiliev *et al.*, PRL 83 (1999)
  - Significant parton energy loss, ~1.2 GeV/fm if all from energy loss
    - Johnson *et al.*, PRC 65 025203 (2002)

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

I. Vitev *et al*, Phys. Lett. B **704** (2011)





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.

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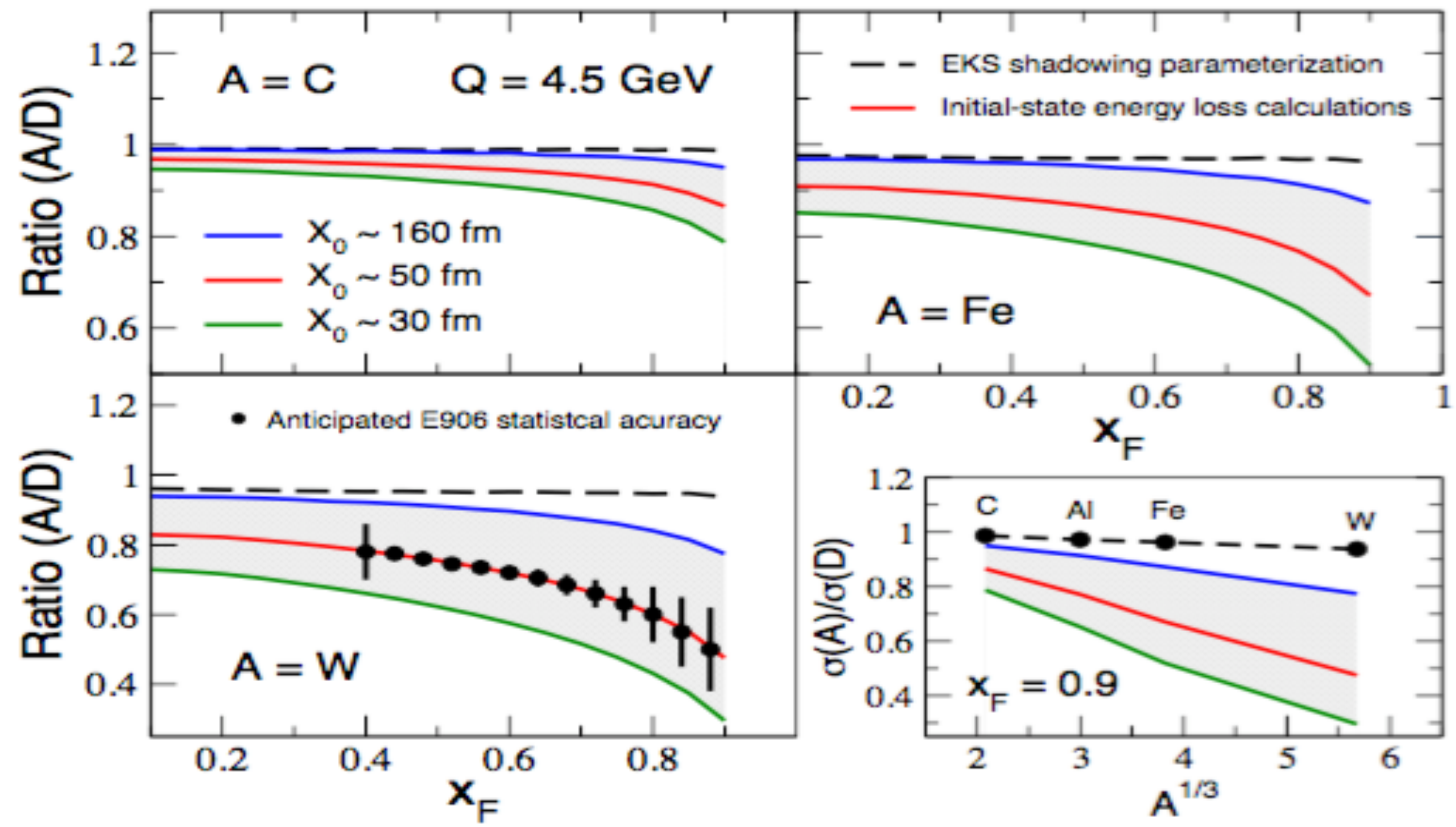
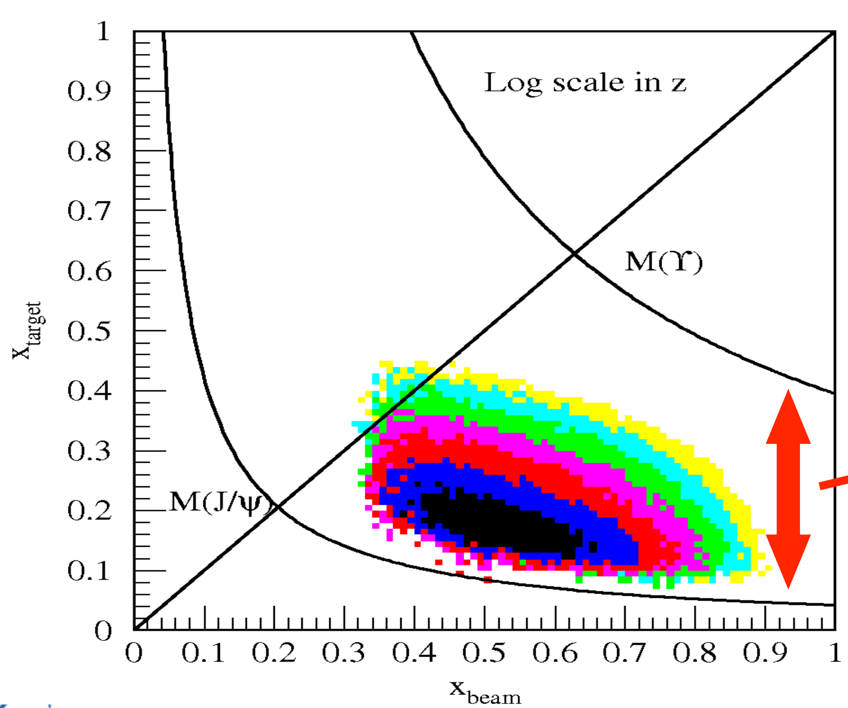
Quark energy loss at SeaQuest

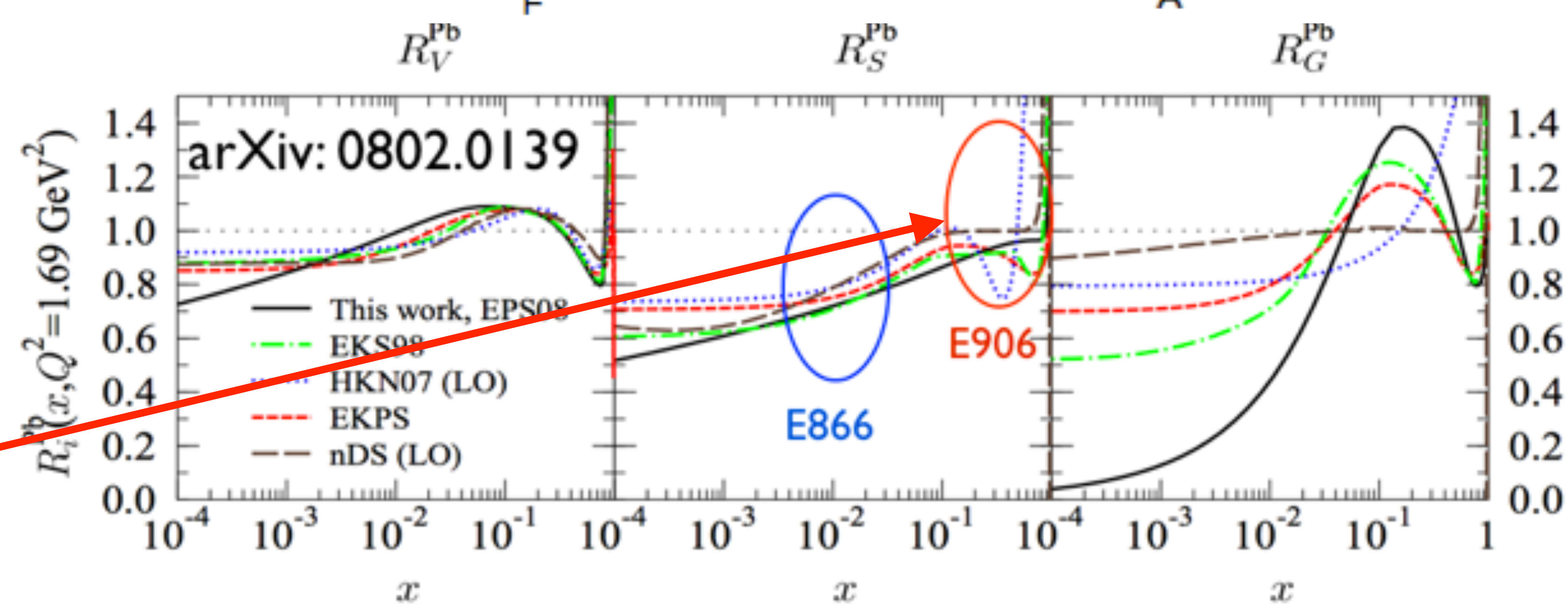
- Parton initial energy: 30 - 120 GeV (relevant to RHIC and LHC parton energy)
- Direct test on various models:
  - Gavin and Milana: $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer: $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al*: $\Delta x_1 = -\frac{\kappa_3}{s}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

- Sea quark x = 0.1 ~ 0.3
- Minimal shadowing
- *dE/dx* effect enhanced with lower beam energy (800 GeV to 120 GeV)

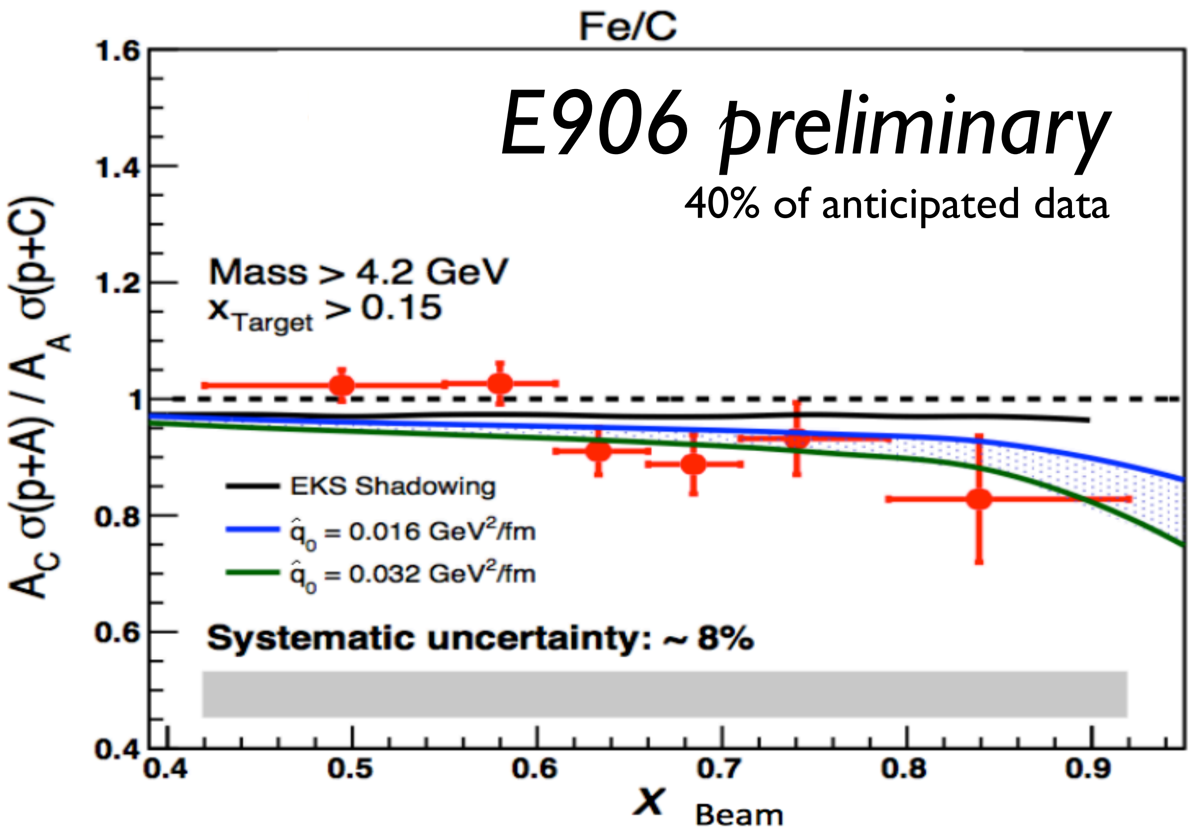
I. Vitev *et al*, Phys. Lett. B **704** (2011)

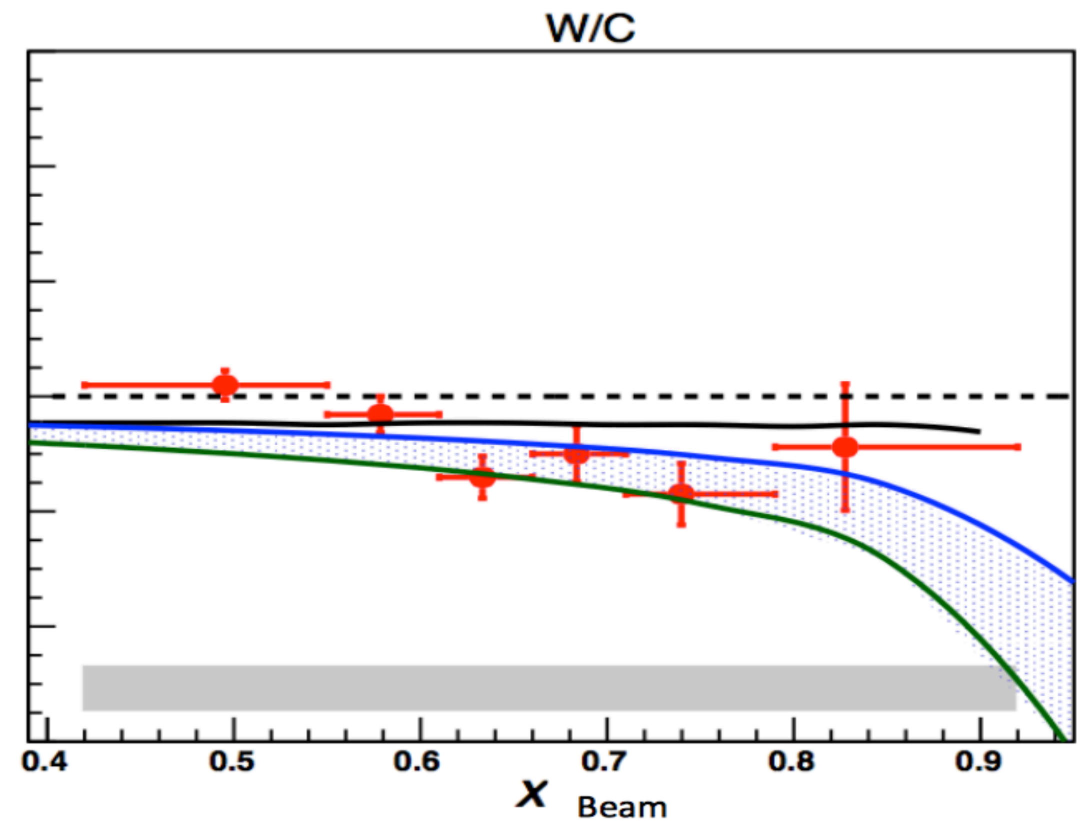


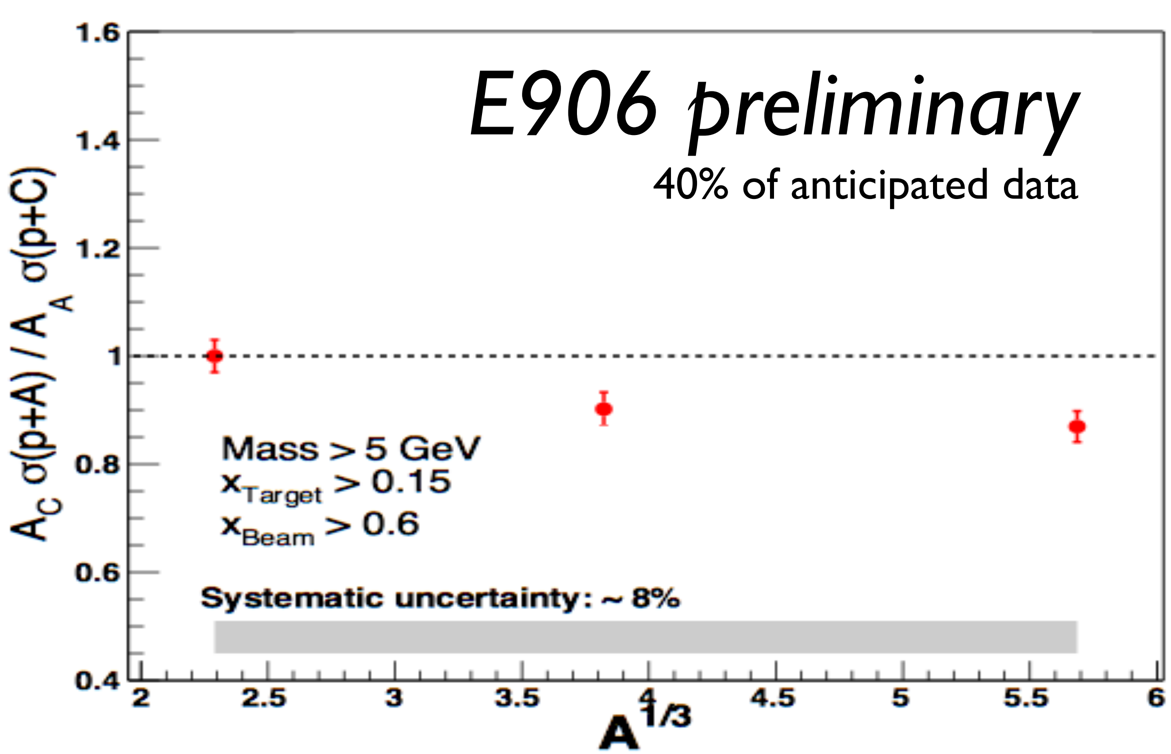




Preliminary results







- A clear indication of suppression beyond the shadowing strength is observed in p+Fe and p+W data
- E906's measurement in return proves the large suppression observed in E866 has a large shadowing contribution
- With the complete data set, 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

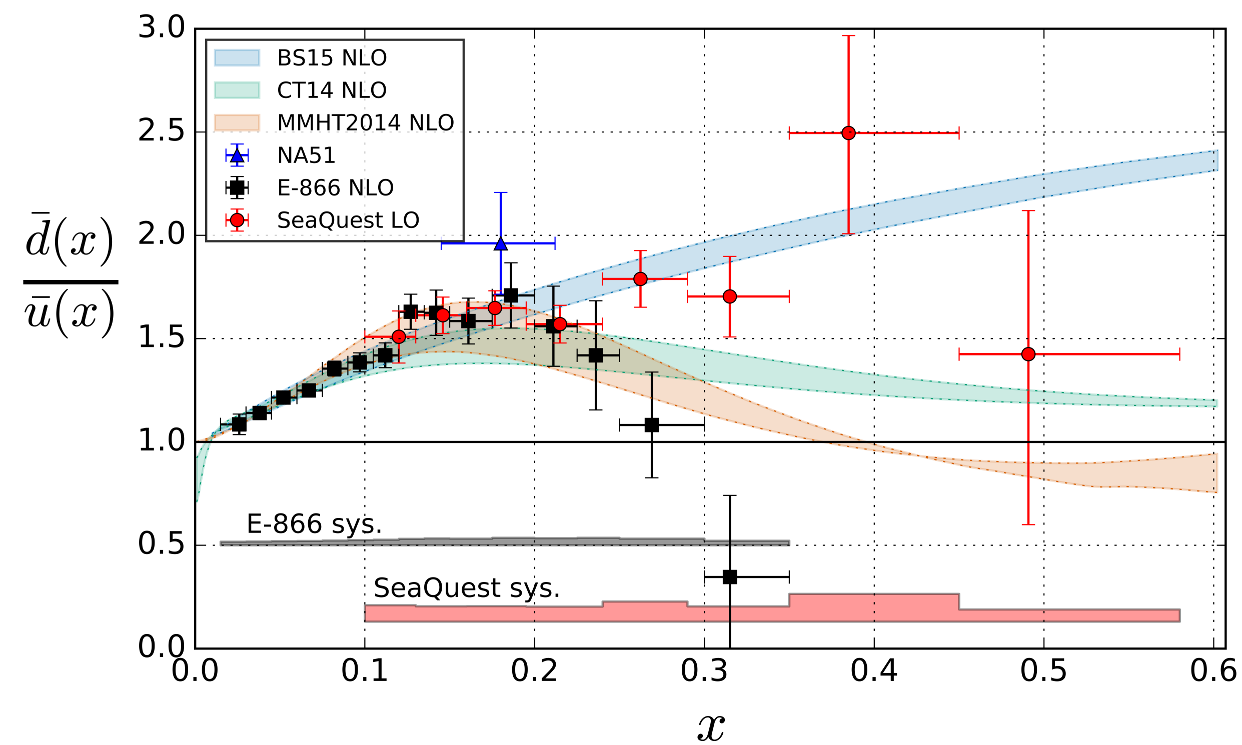
Exciting results: 40% of total statistics:

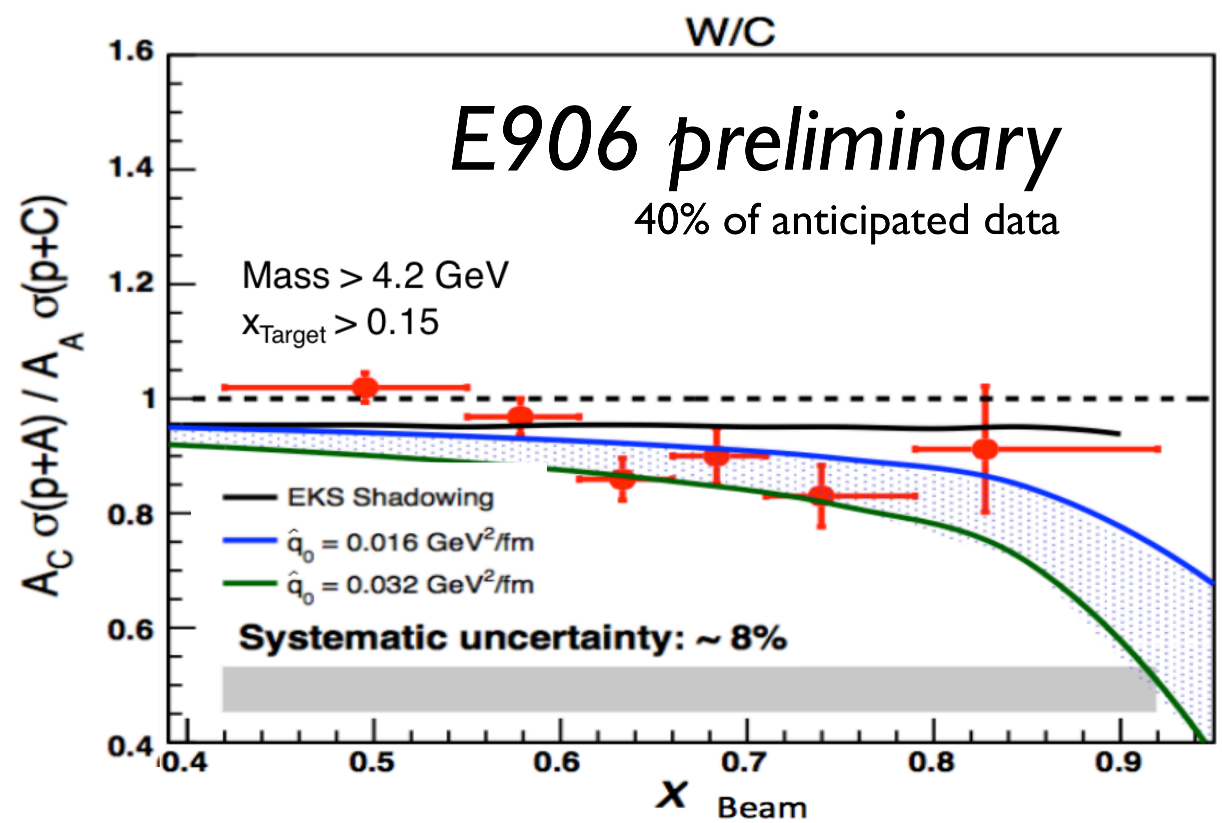
- confirmed the large light sea quark asymmetry at $x_2 \sim 0.15$, while the region beyond $x_2 > 0.3$ still needs to be understood
- observed consistent negative slope beyond the extent of shadowing

Ongoing analysis: 2.5x of statistics and better constrained systematics

Many other ongoing physics analysis:

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





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Backup slides

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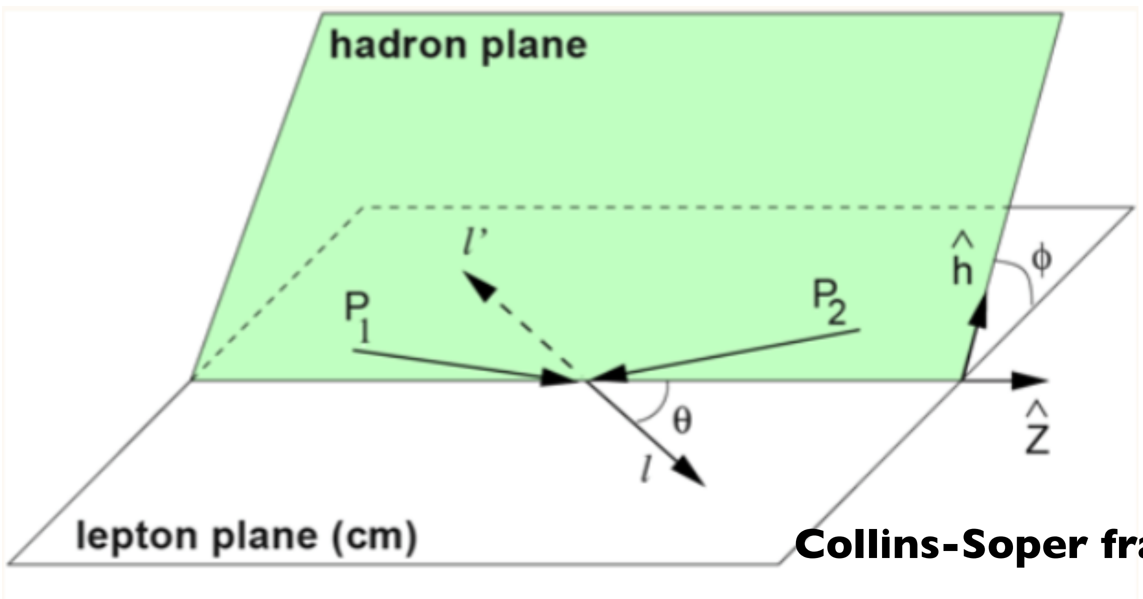
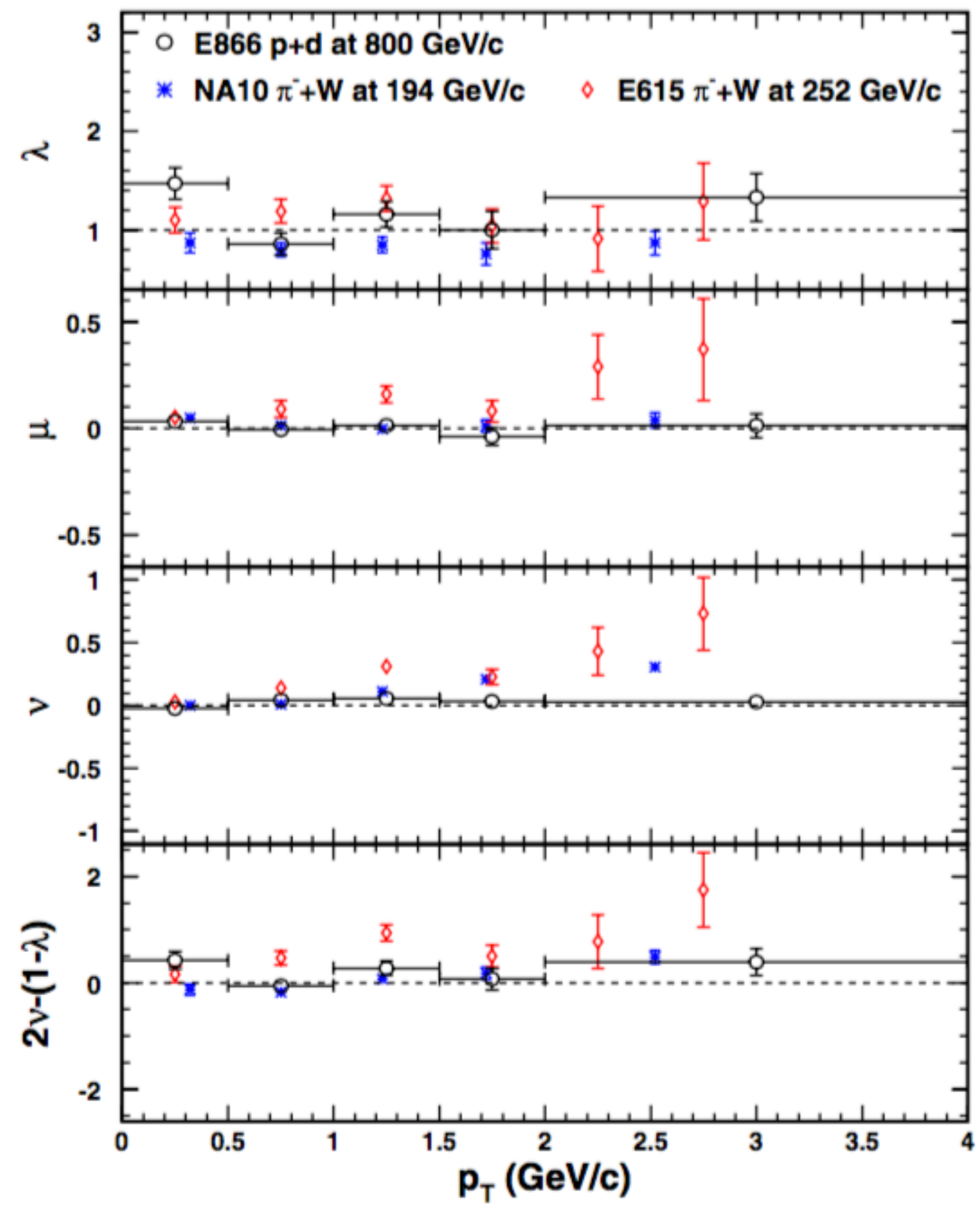
Accessing Boer-Mulders (BM) function in unpolarized DY

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



Collins-Soper frame



- Lam-Tung violation: $1 - \lambda \neq 2\nu$
- ν can be decomposed to the convolution of two BM functions: $\nu \propto [h_1^\perp \text{ of } \bar{q}] \times [h_1^\perp \text{ of } q]$
- Measurement of BM in proton-induced DY using pp and pd data:
  - ➢ identify the source of Lam-Tung violation
  - ➢ test the flavor dependence prediction

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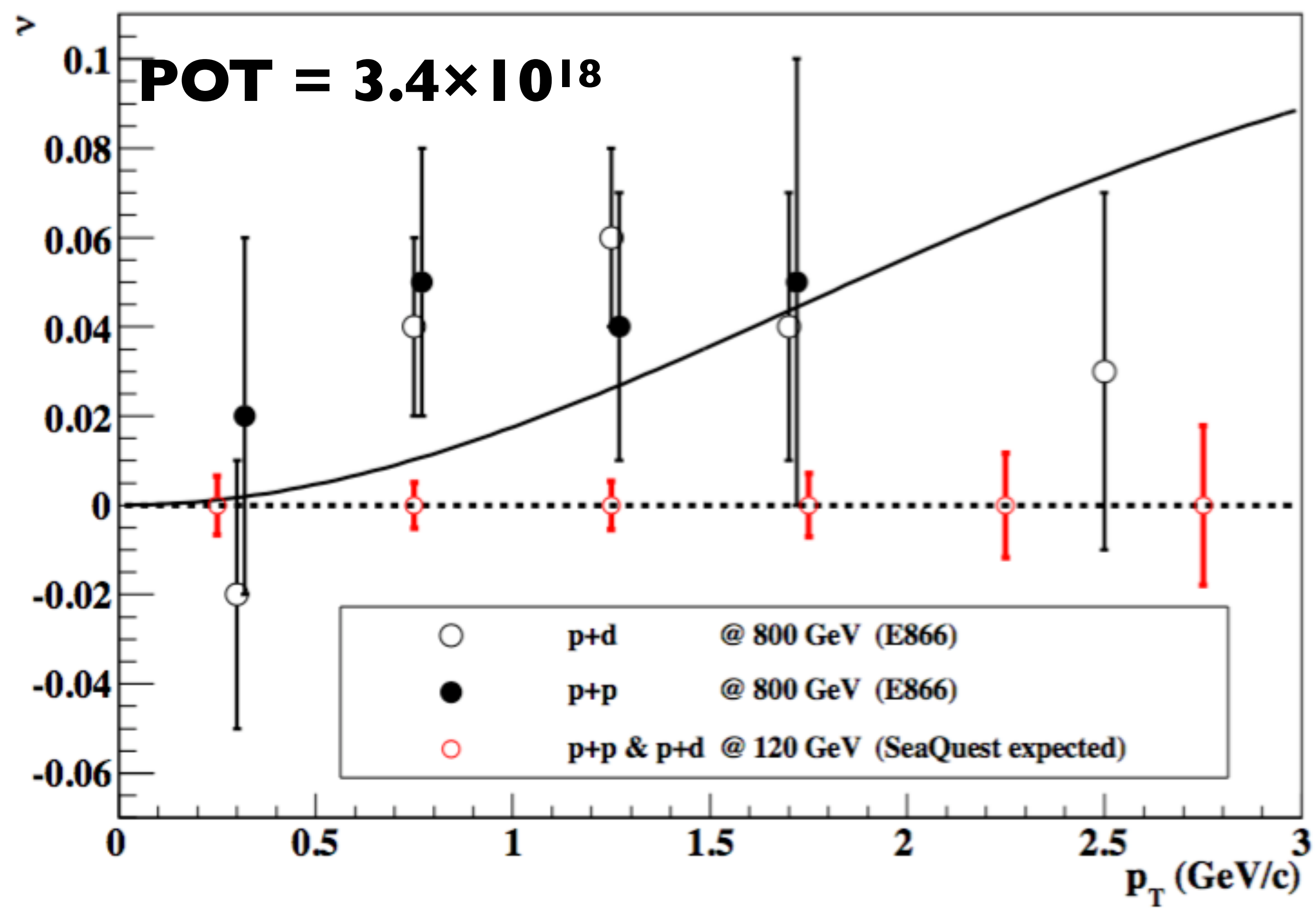
Expected precision of E906

- Significant improvement in precision compared with previous experiments
- Very challenging analysis
- Both p+p and p+d data available



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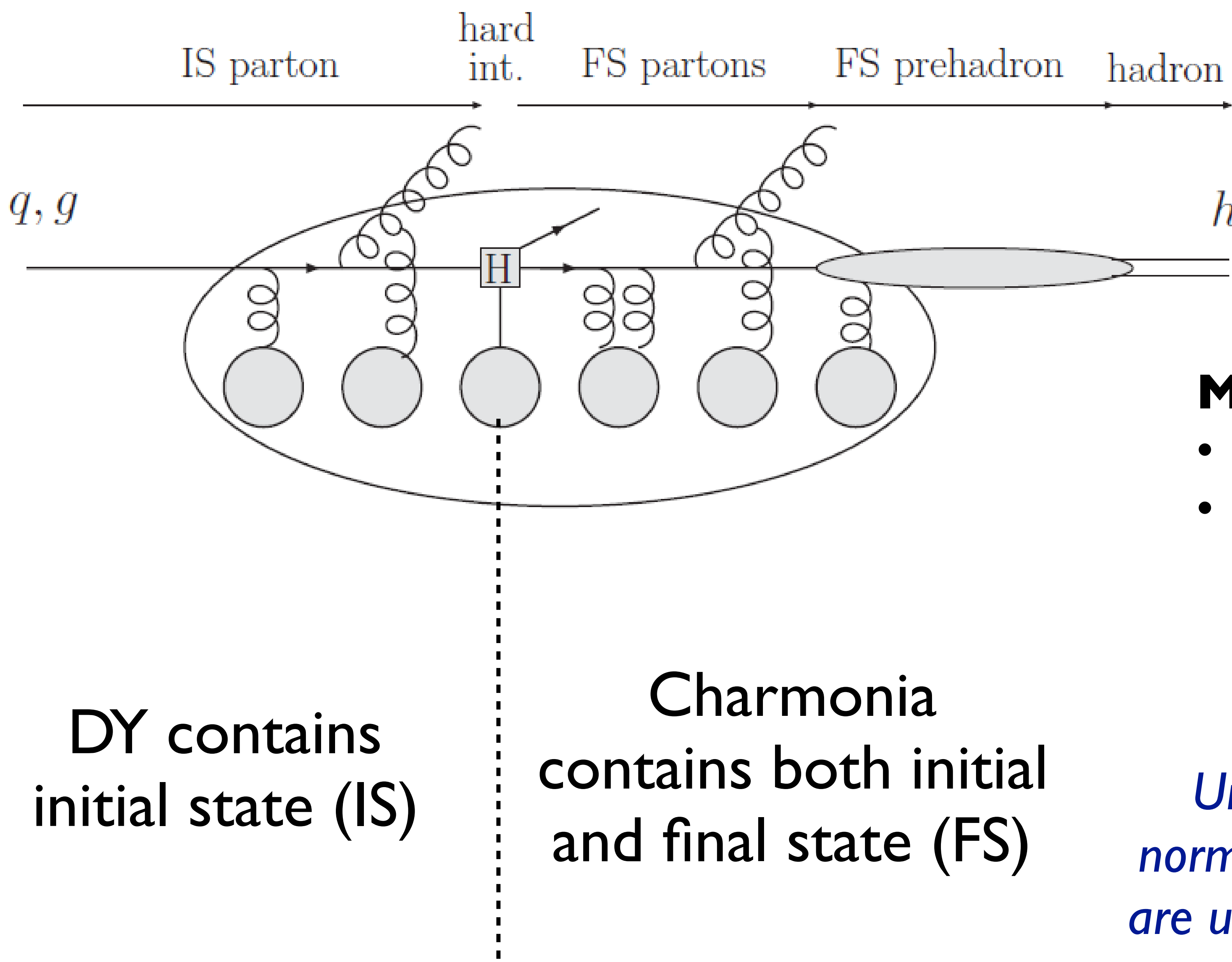
Understanding the p_T spectrum of DY and charmonia

Accord, PRC 76, 034902 (2007)



Origin of p_T spectrum

- intrinsic p_T of IS parton
- elastic scattering of IS parton
- gluon emission of IS parton
- can be isolated in DY process

Modification to p_T spectrum

- absorption of FS prehadron
- interaction of FS prehadron with nuclear medium

DY contains initial state (IS)

Charmonia contains both initial and final state (FS)

Understanding the suppression in normal nuclear matter is critical if they are used as a probe for hot high density matter (QGP) in heavy-ion collisions

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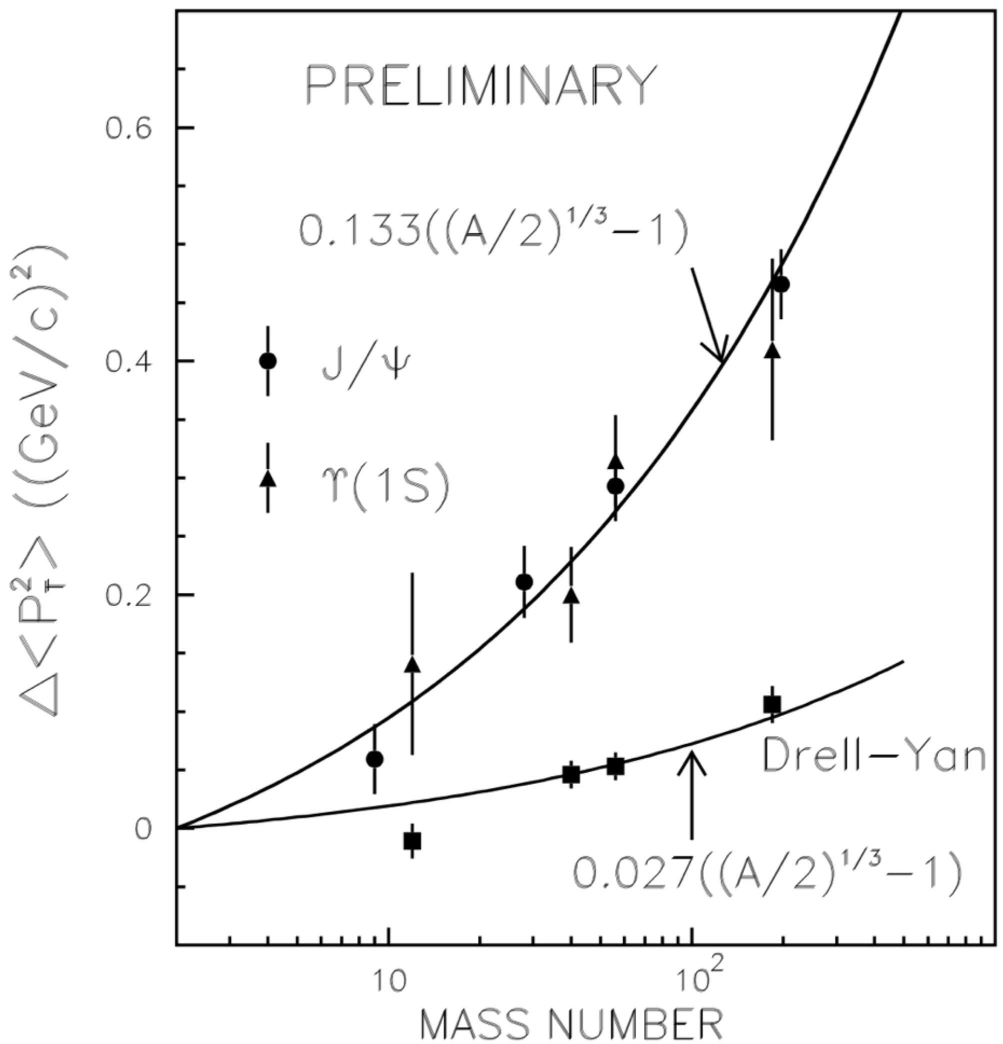
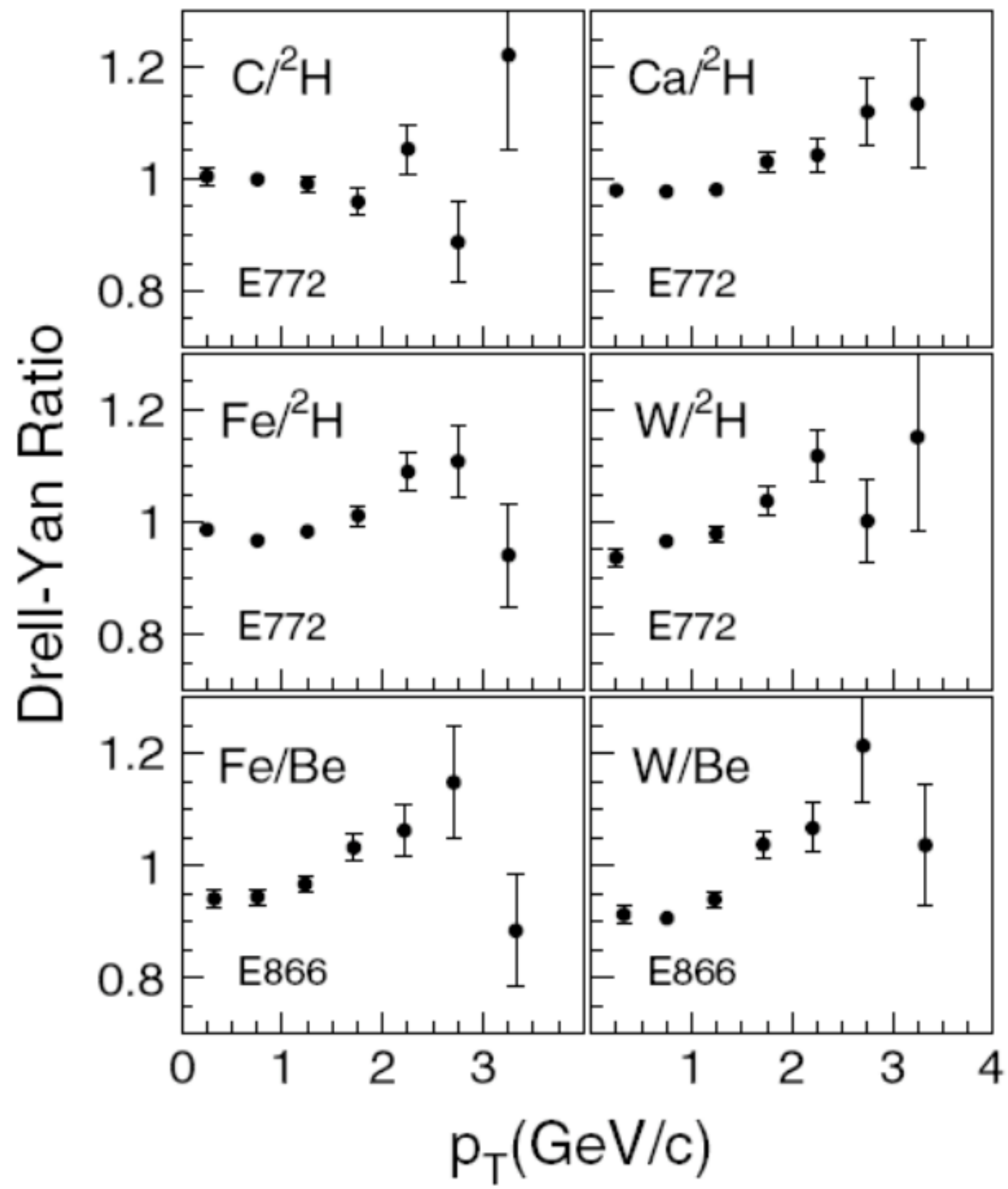
Transverse momentum broadening (Cronin effect)

P. L. McGaughey, J. M. Moss and J. C. Peng, Annu. Rev. Nucl. Part. Sci. 49, 217 (1999); J. C. Peng, arXiv:hep-ph/9912371.



E772/E866 p-A



A combined analysis of p_T-broadening and x_F degradation is needed to extract the initial-state interaction

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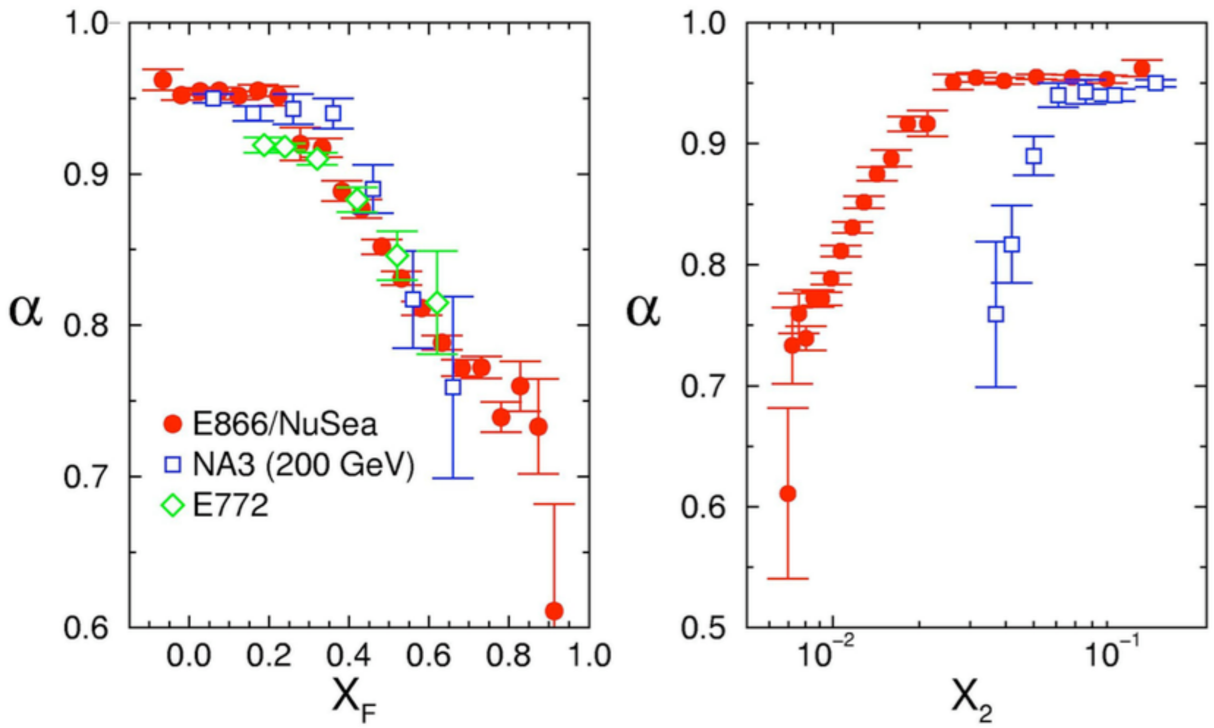
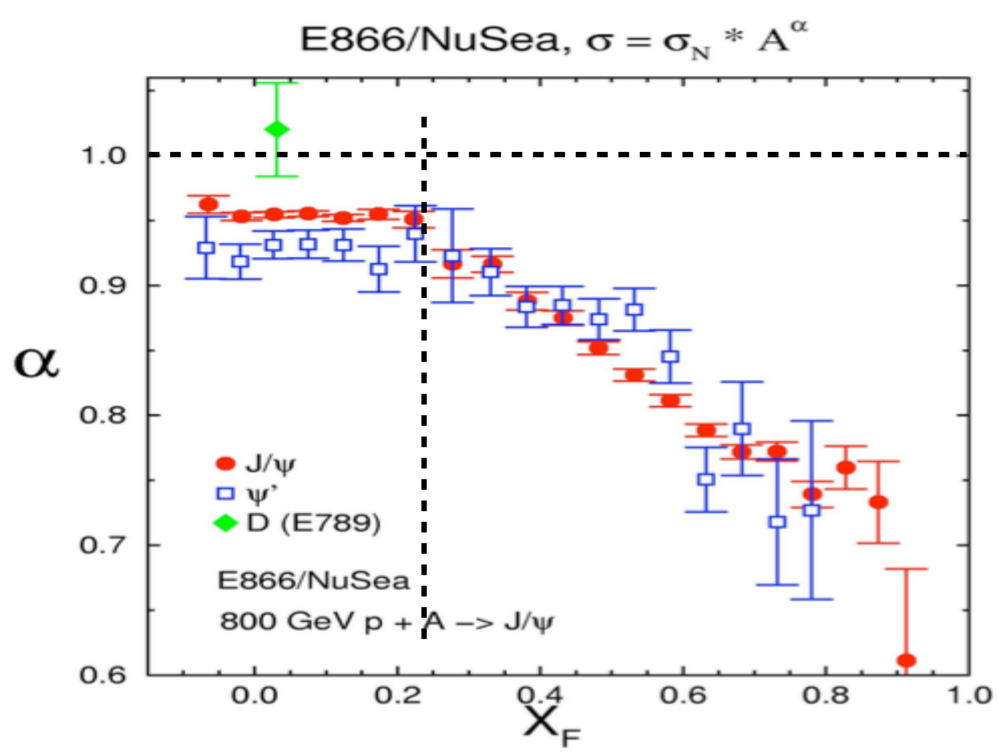
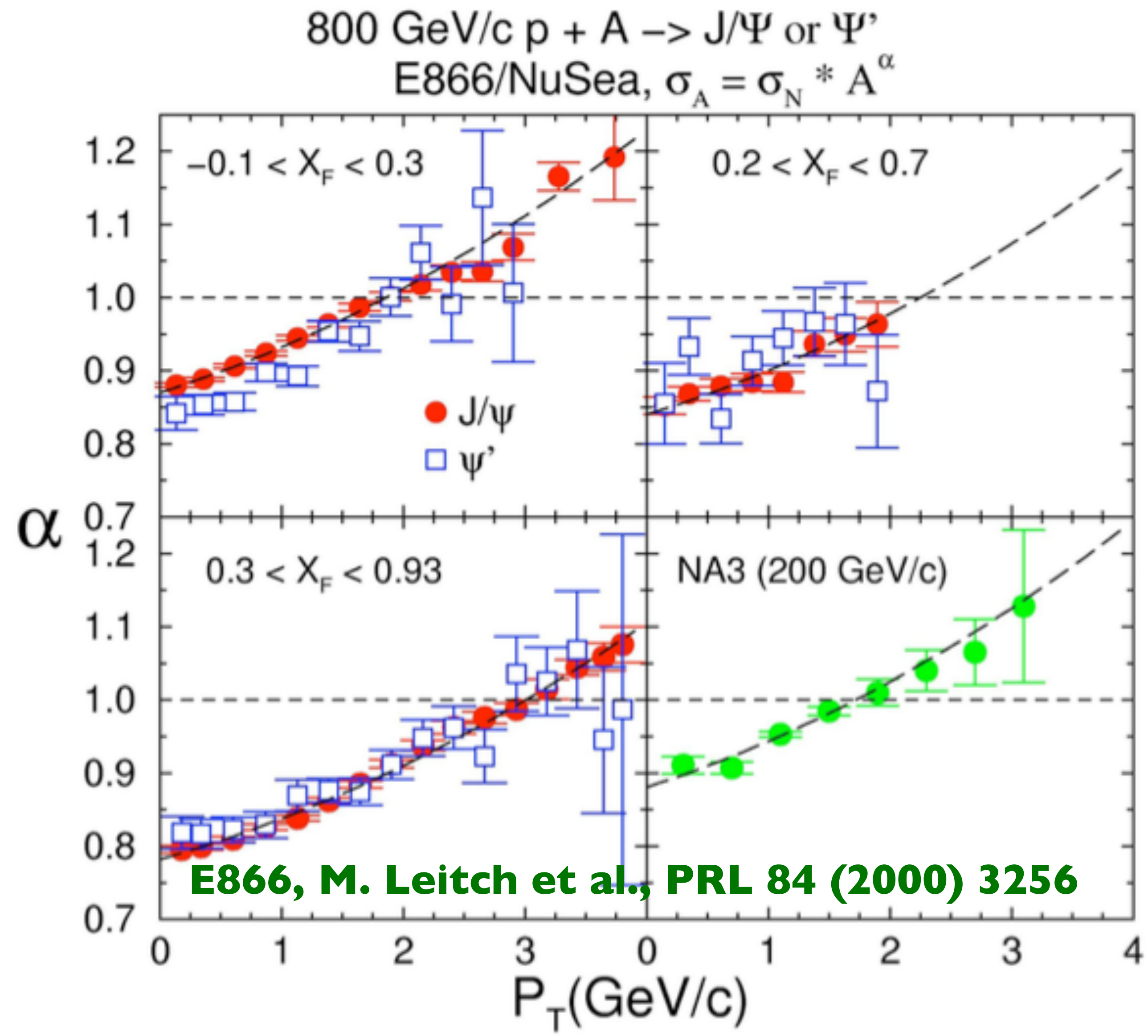
Nuclear effects in charmonia production







E866, M. Leitch et al., PRL 84 (2000) 3256

- Nuclear effects scale with x_F, but not x_T
- 'Universal' behavior for $\alpha(p_T)$ and $\alpha(x_F)$,
- E906 will probe this behavior at much lower energy
  - production mechanism changes with $\sqrt{s}$
  - formation time could also change

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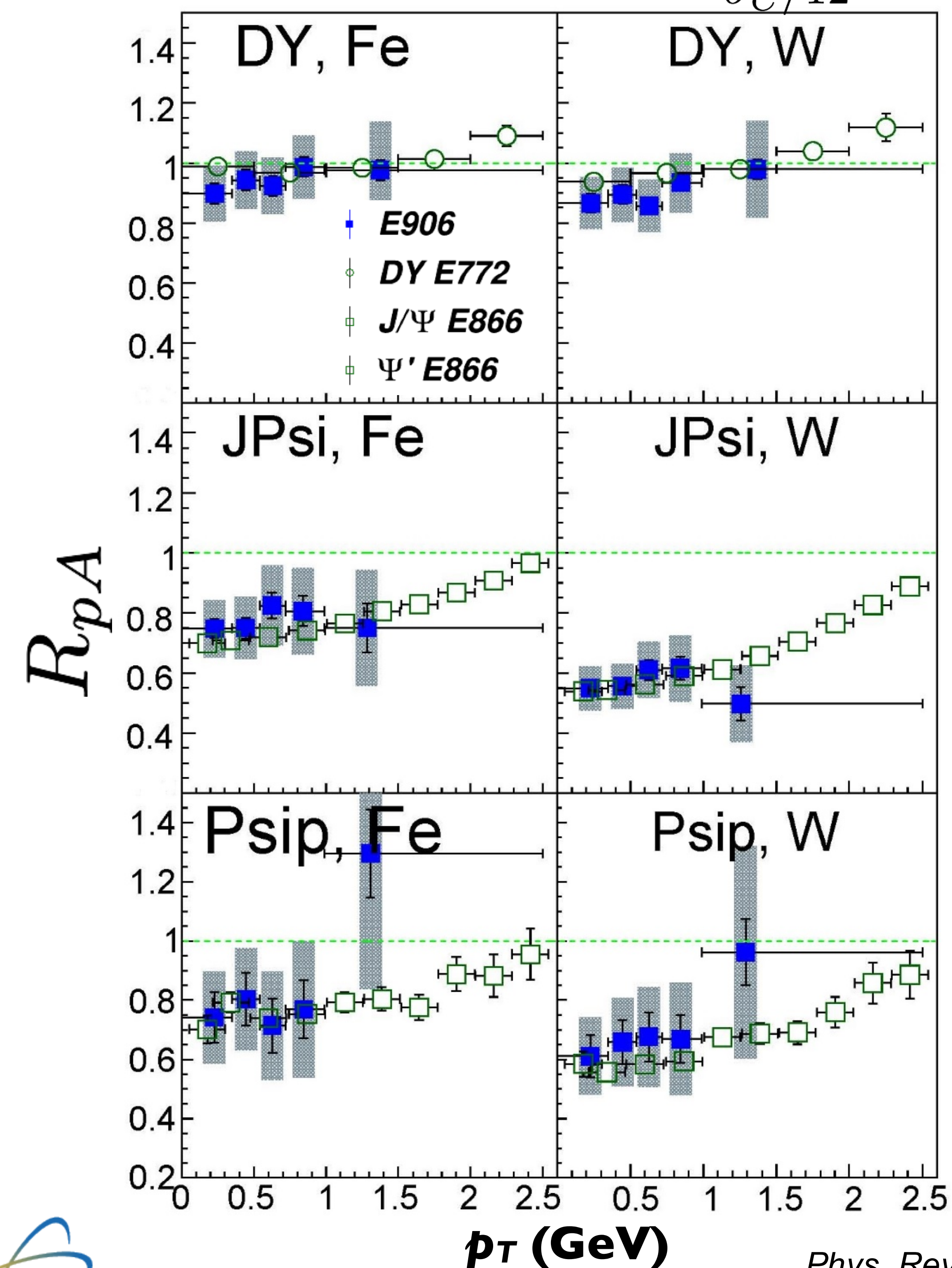
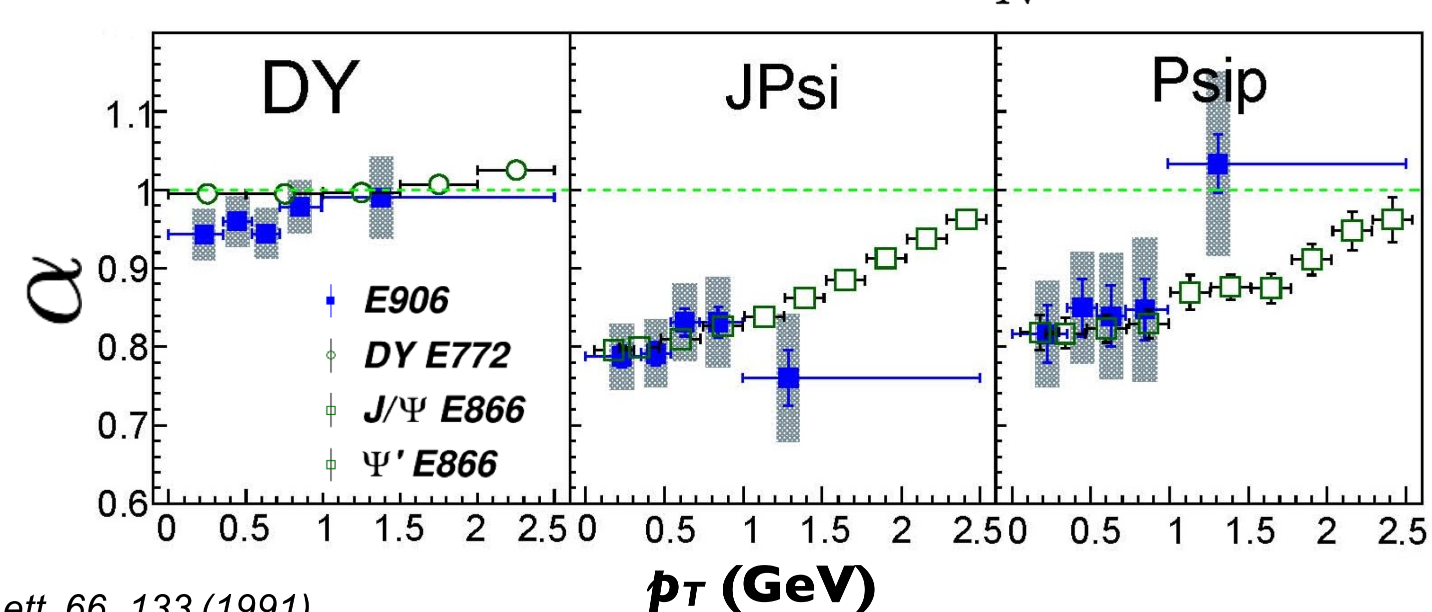
Preliminary p_T measurement at E906

E906 Preview $R_{pA} = \frac{\sigma_A/A}{\sigma_C/12}$



- Only 30% of final data set, and very conservative systematic error estimation
- Both DY and charmonia suppression shows very similar scale/shape compared to previous experiments with 800 GeV beam.
- J/ψ and ψ' shows very similar p_T dependence, where they both correspond to ccbar traversing the nucleus.

E906 Preview $\sigma = \sigma_N A^{\alpha}$



Phys. Rev. Lett. 66, 133 (1991)
Phys. Rev. D52, 4251 (1995)
Phys. Rev. Lett. 84, 3256-3260

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