Argonne NATIONAL LABORATORY

Do antiquarks in the proton's sea look different in nuclei?

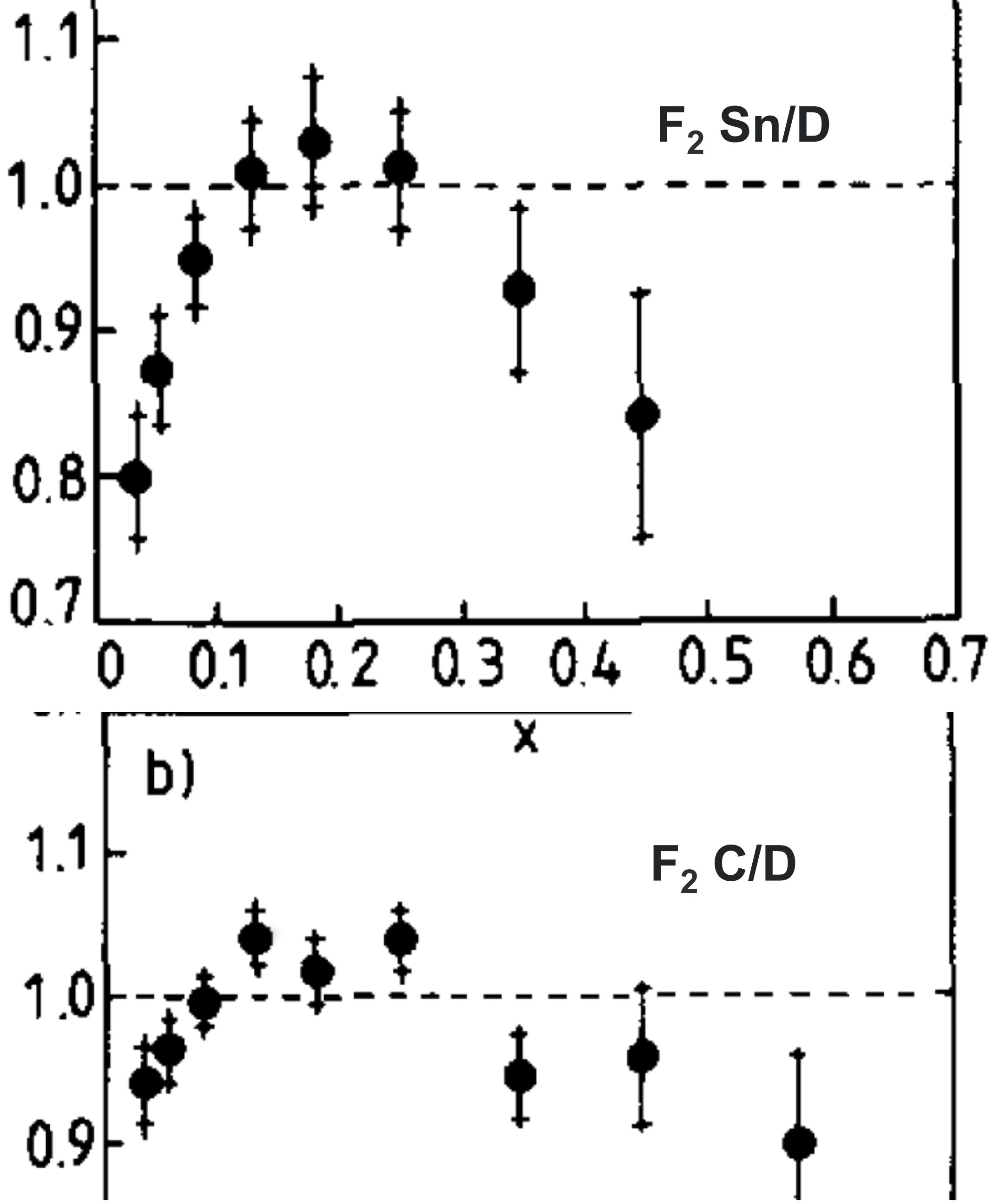
PAUL E REIMER
Physicist
Argonne National Laboratory

17 April 2018
Trento, Italy

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

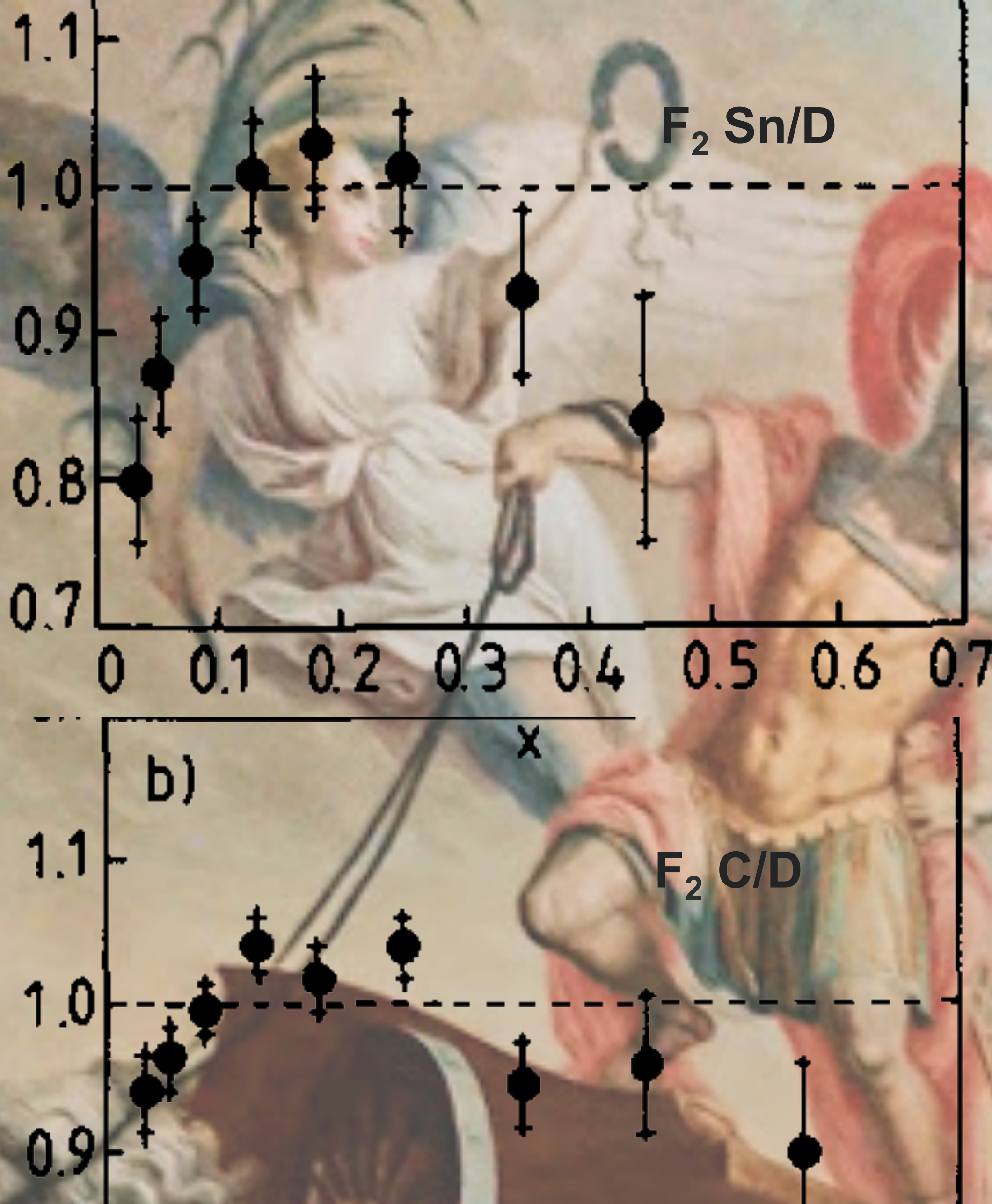
U.S. DEPARTMENT OF ENERGY

EMC Effect is NeoClassic



European Muon Collaboration discovered that quark and antiquark distributions are not the same in Heavy Nuclei as they are in Deuterium

$$F_2(x) = \sum_{q\in\{u,d\ldots\}} e_q^2 \left[q(x) + \bar{q}(x)\right]$$

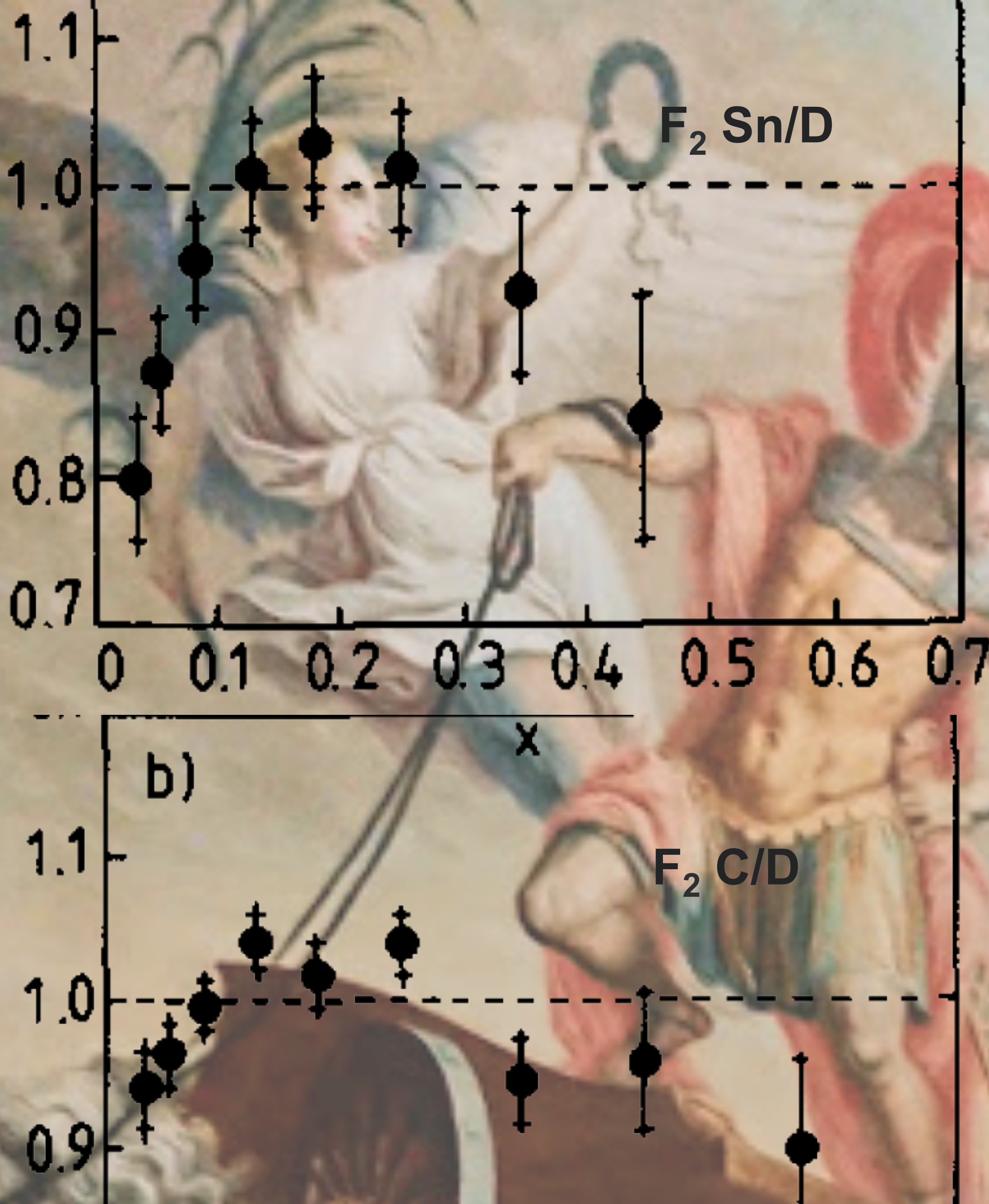


EMC Effect is NeoClassic

European Muon Collaboration discovered that quark and antiquark distributions are not the same in Heavy Nuclei as they are in Deuterium

$$F_2(x) = \sum_{q\in\{u,d\dots\}} e_q^2\left[q(x) + \bar{q}(x)\right]$$

EMC Effect is NeoClassic



European Muon Collaboration discovered that quark and antiquark distributions are not the same in Heavy Nuclei as they are in Deuterium

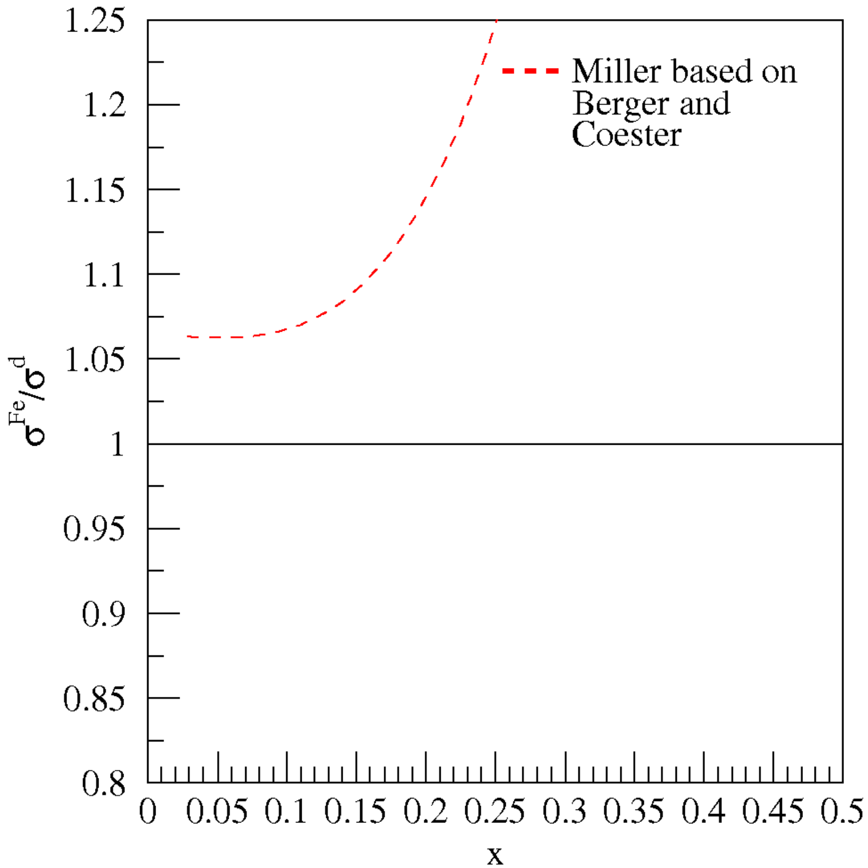
$$F_2(x) = \sum_{q\in\{u,d\dots\}} e_q^2\,[q(x) + \bar{q}(x)]$$

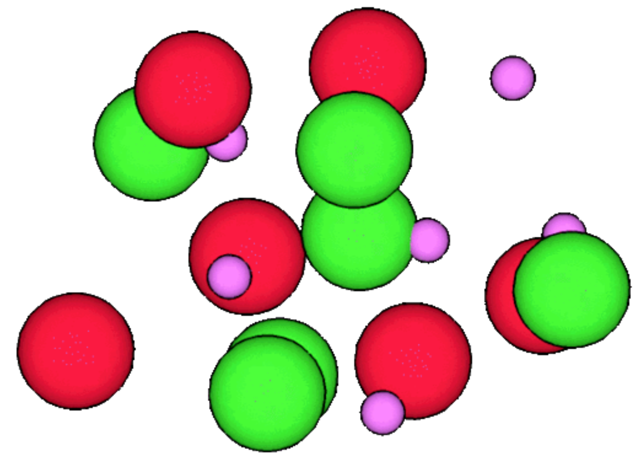
Is this valence? $[q(x) - \bar{q}(x)]$

Or sea? $2 \times \bar{q}(x)$

How can we reach the sea quark distributions in nuclei? Is the effect different?

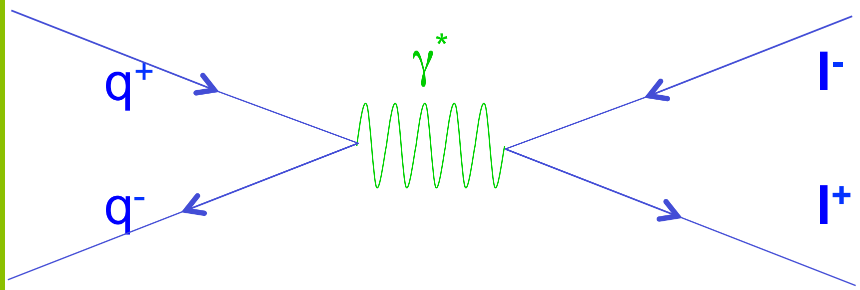
Nuclear Pions

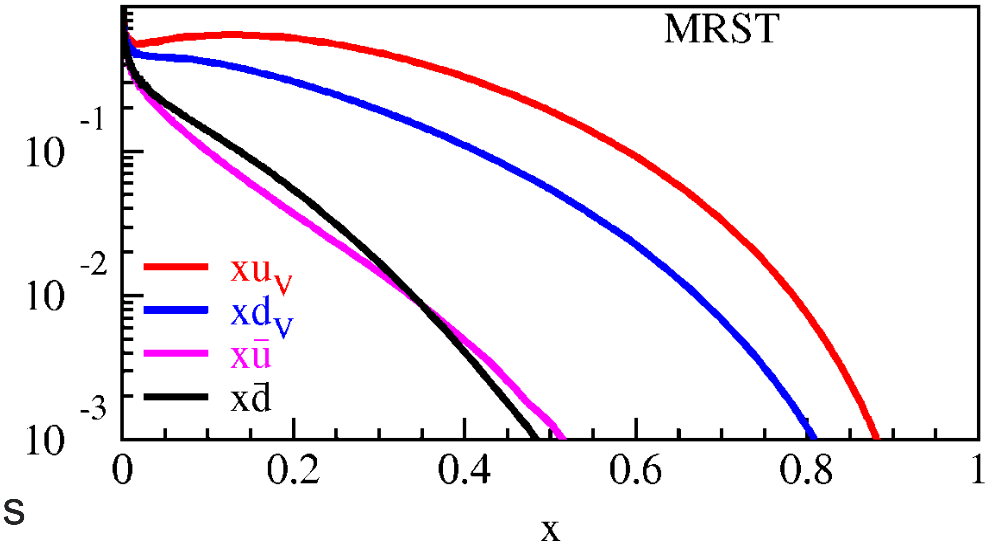




- Nuclear binding via Virtual Meson Exchange
  - Nuclear Pions
  - **Expect enhancement in antiquark distributions for tightly bound nuclei**

Drell-Yan Cross Section—Sensitivity to SeaQuarks



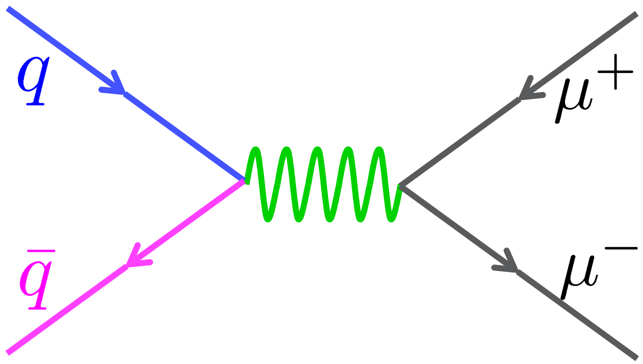


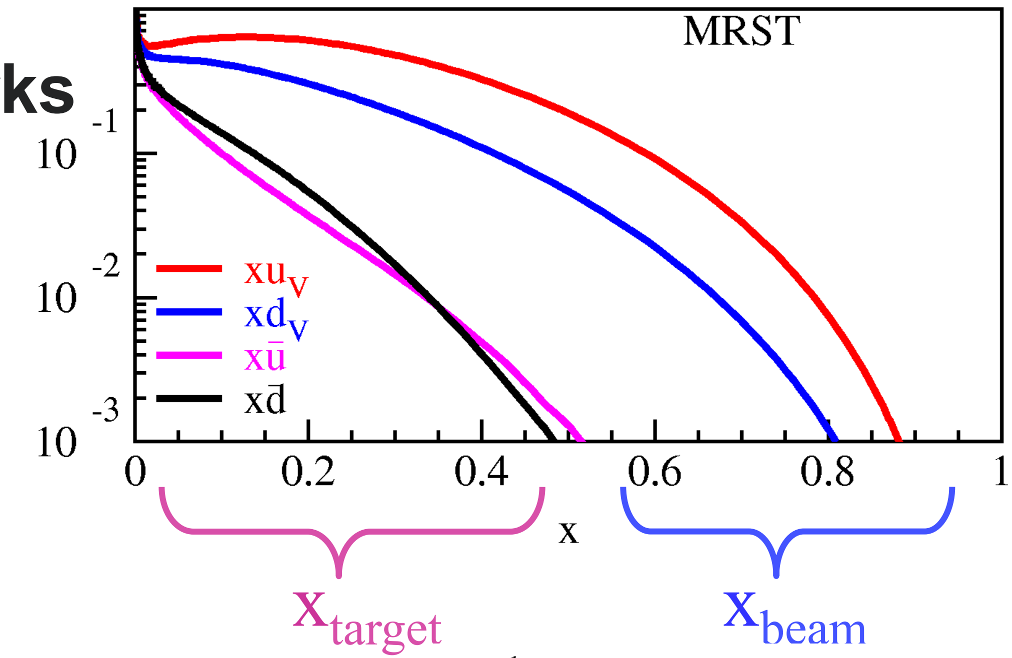
Cross Section

- Point-like scattering of spin-1/2 particles
- Convoluted of beam and target parton distributions

$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

Drell-Yan scattering:
A laboratory for sea quarks



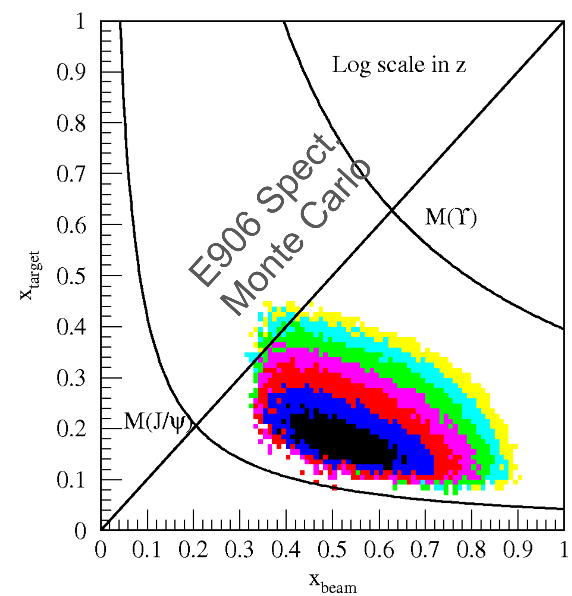


$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

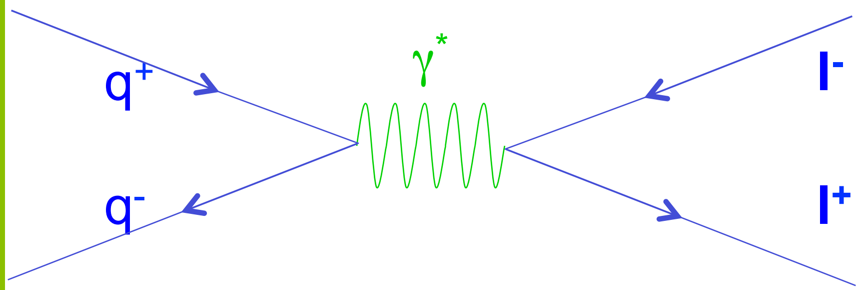
Use a proton beam: primarily u quarks at high x. Detec acceptance chooses x_{target} and x_{beam}.

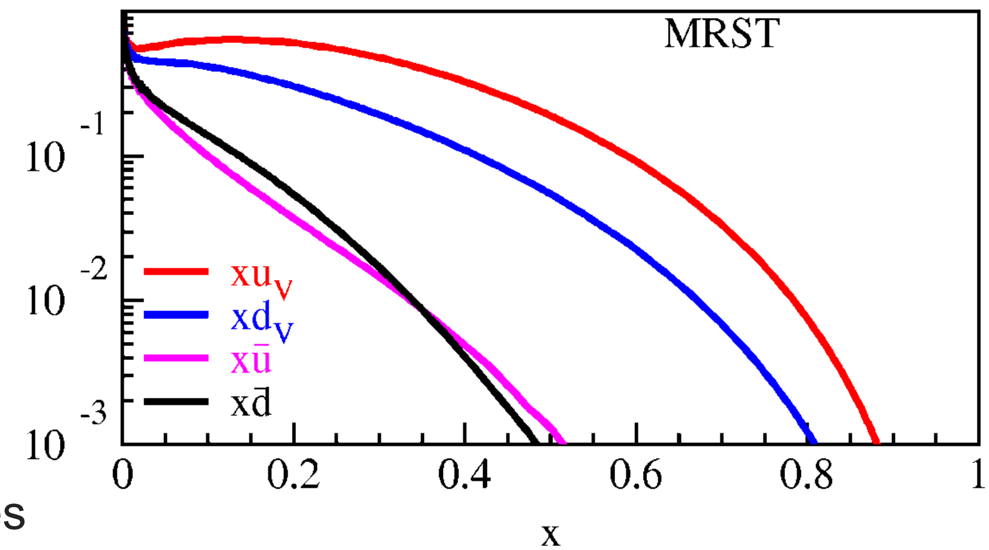
- Fixed target ⇒ high $x_F = x_{beam} - x_{target}$
- Valence beam quarks at high-x.

  $(e^2 u)/(e^2 d) > 8$ Dominated by u quarks
- Sea target quarks at low/intermediate-x.



Drell-Yan Cross Section—Sensitivity to SeaQuarks





Cross Section

- Point-like scattering of spin-1/2 particles
- Convoluted of beam and target parton distributions

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

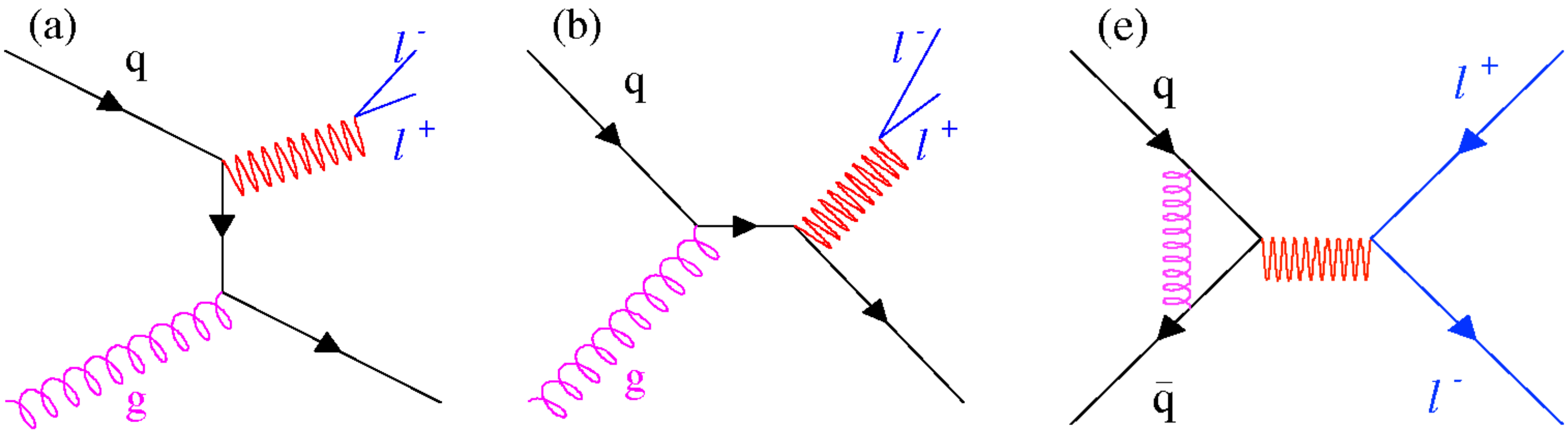
u-quark dominance
$(2/3)^2$ vs. $(1/3)^2$

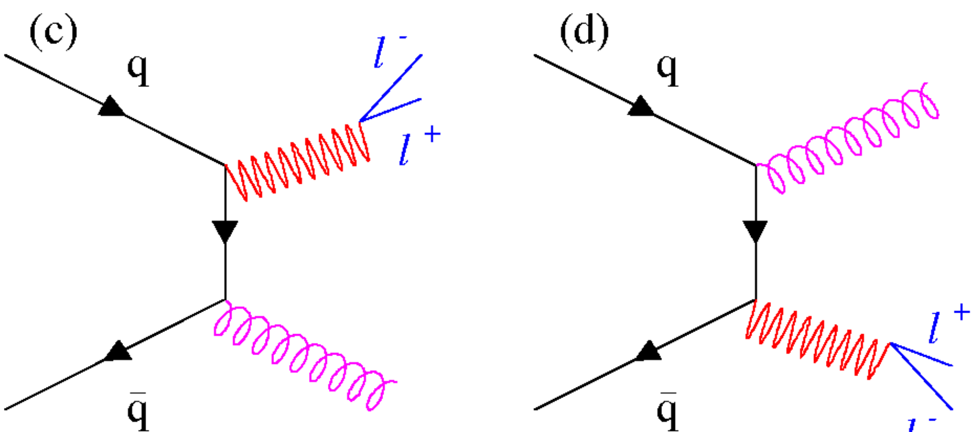
Acceptance limited
(Fixed Target,
Hadron Beam)

Beam	**Sensitivity**	**Experiment**
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	**COMPASS**, J-PARC

Drell-Yan Cross Section—Next-to-leading order α_s

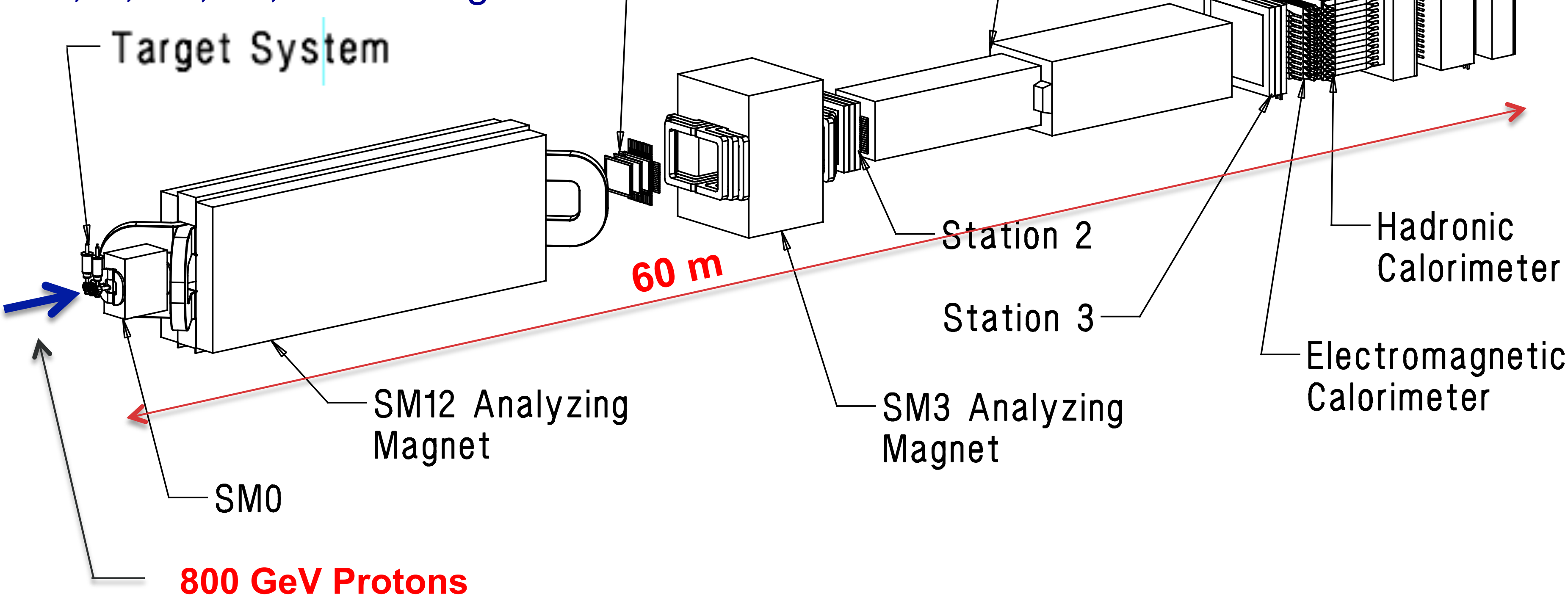
- Responsible for up to 50% of the cross section





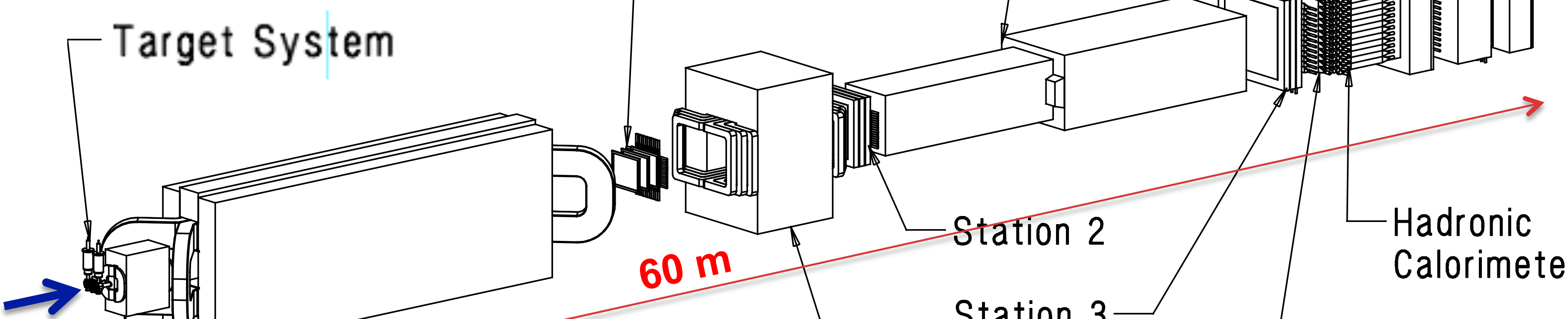
Fermilab E772

- Spect. initially built for E604 (400 GeV Hadron Prod)
  - Also used for E789, E866
  - With parts being used in E906 &E1039 (SeaQuest)
- Beam dump in SM12 Magnet
- ^{2}H, C, Ca, Fe, and W targets

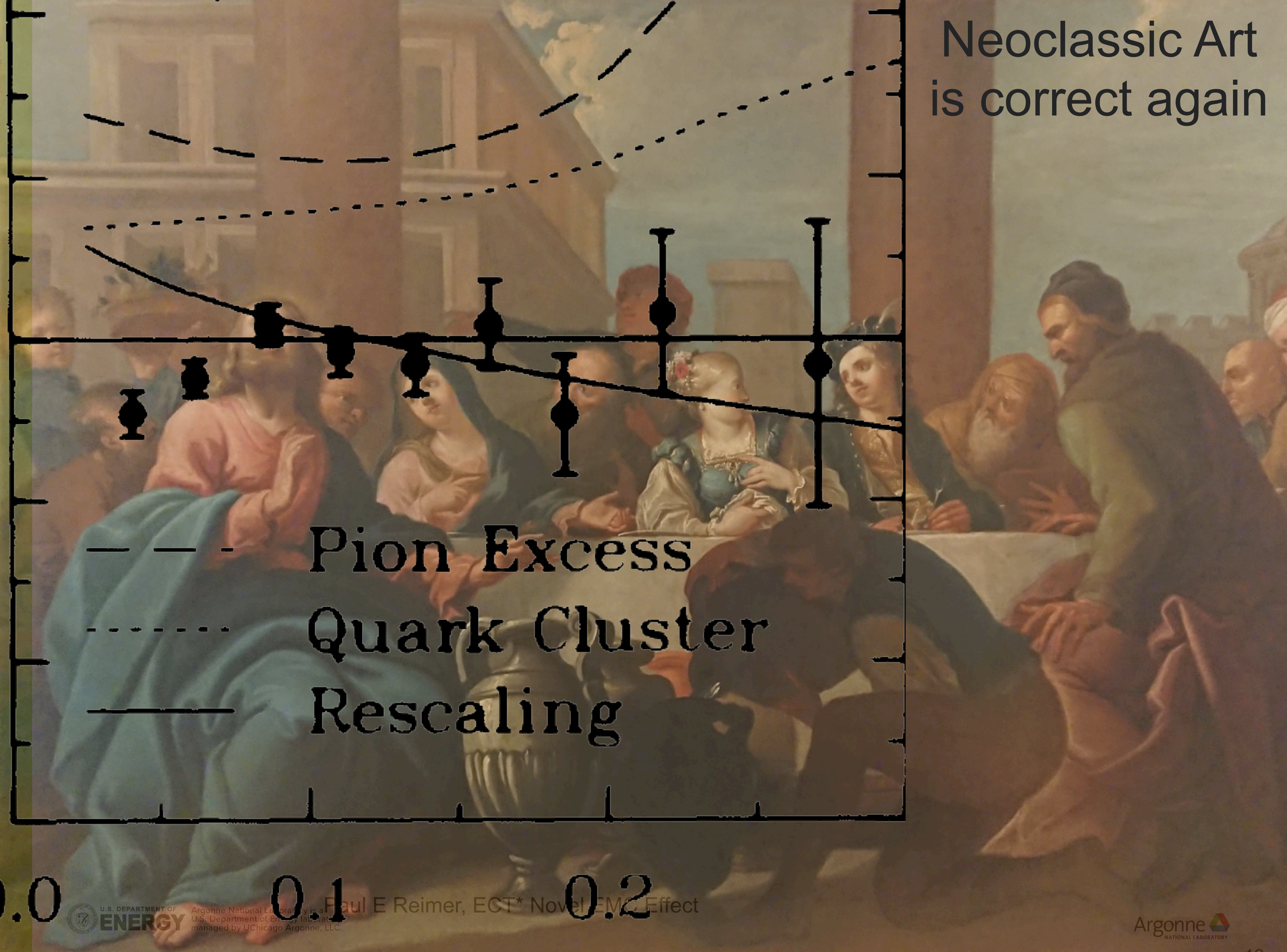


Fermilab E772

- Spect. initially built for E604 (400 GeV Hadron Prod)
  - Also used for E789, E866
  - With parts being used in E906 &E1039 (SeaQuest)
- Beam dump in SM12 Magnet
- ^{2}H, C, Ca, Fe, and W targets



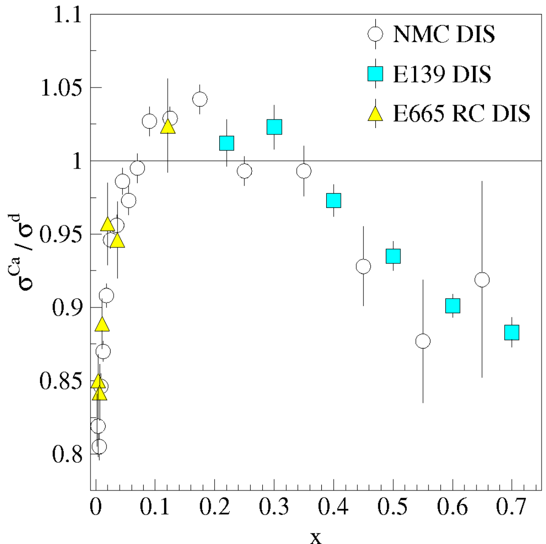
Neoclassic Art is correct again

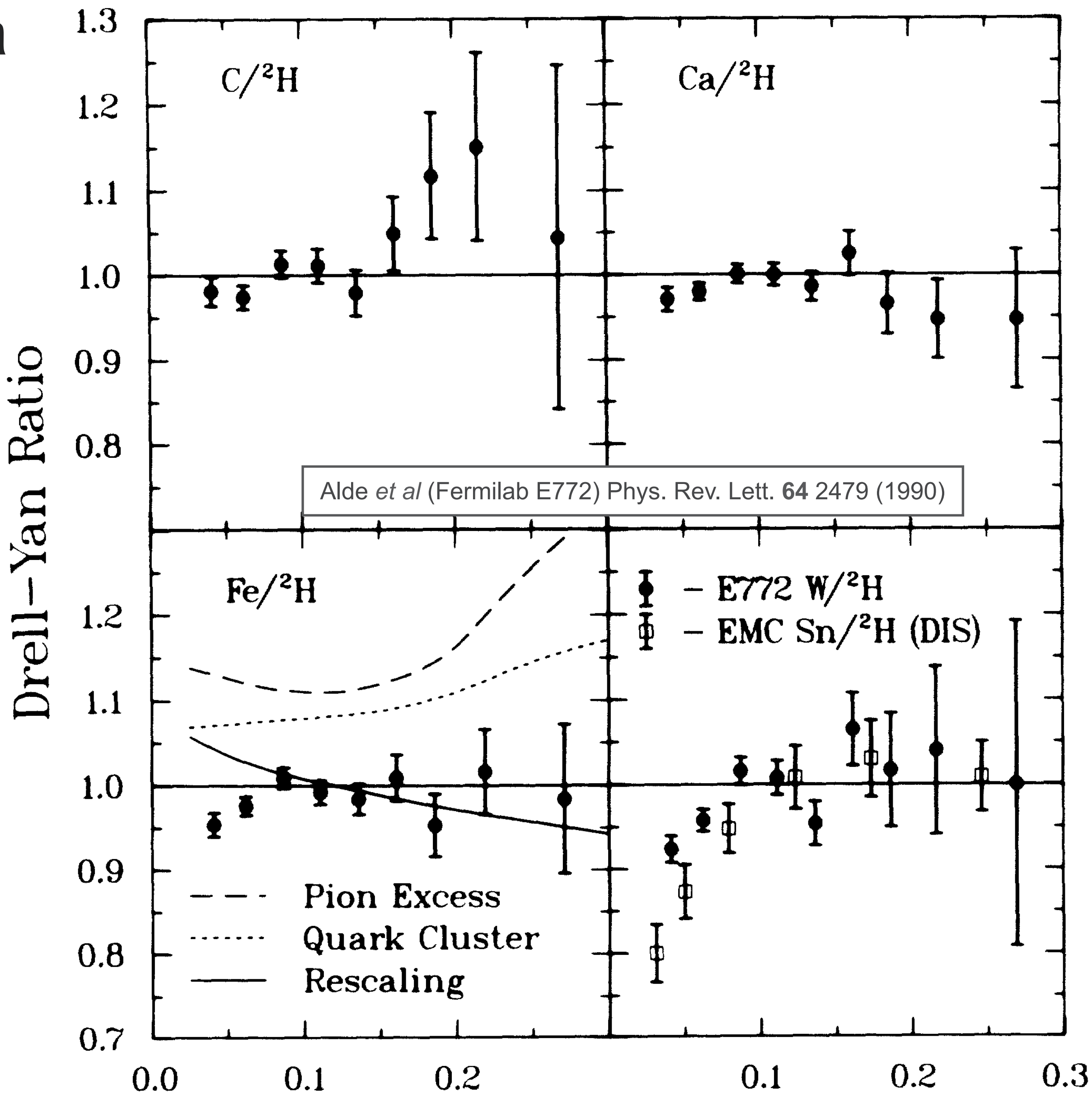


Fermilab E772 Data

- No clear EMC effect

- **No evidence for nuclear pion enhancement**





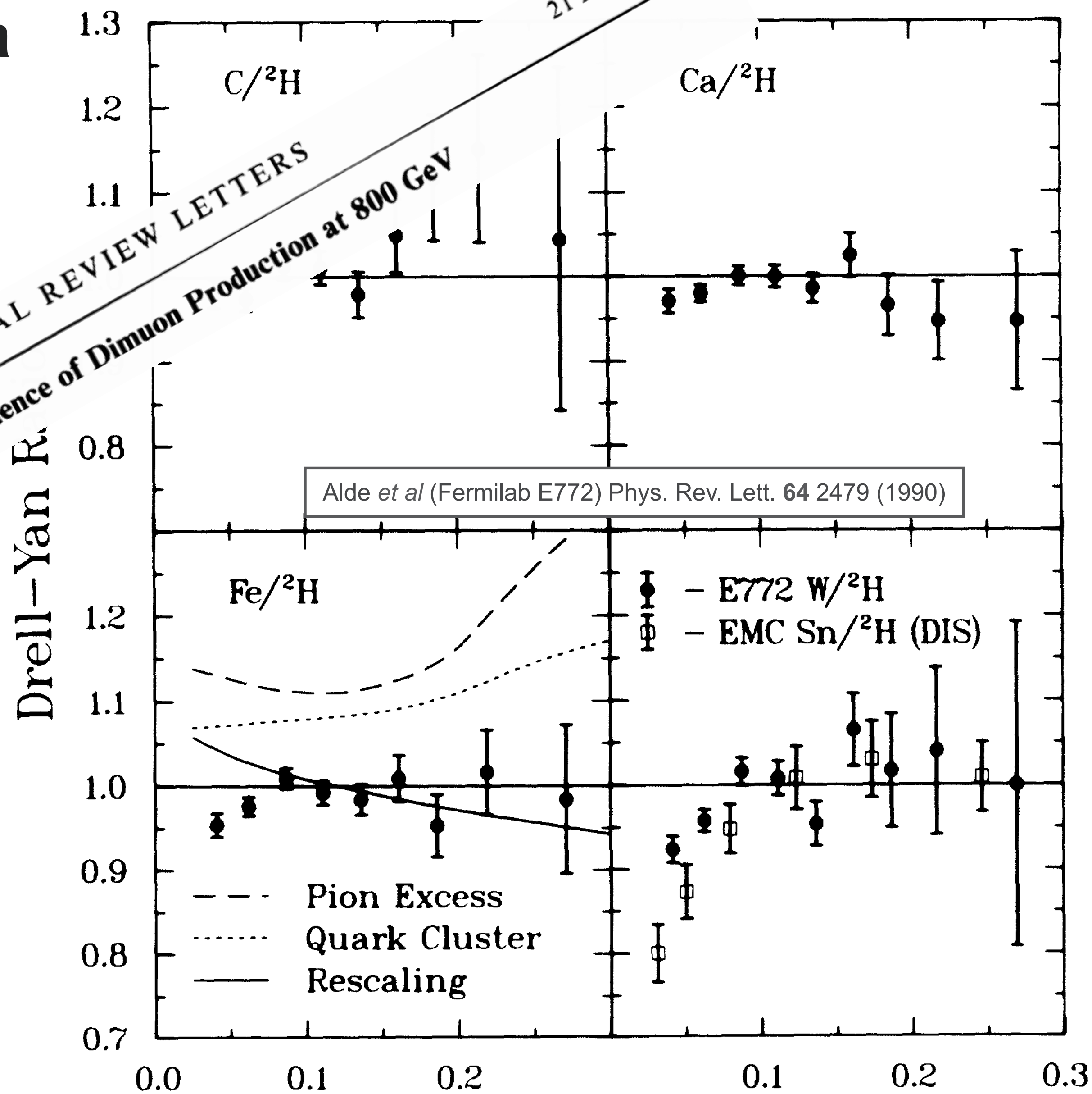
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

Paul E Reimer, ECT* Novel EMC Effect

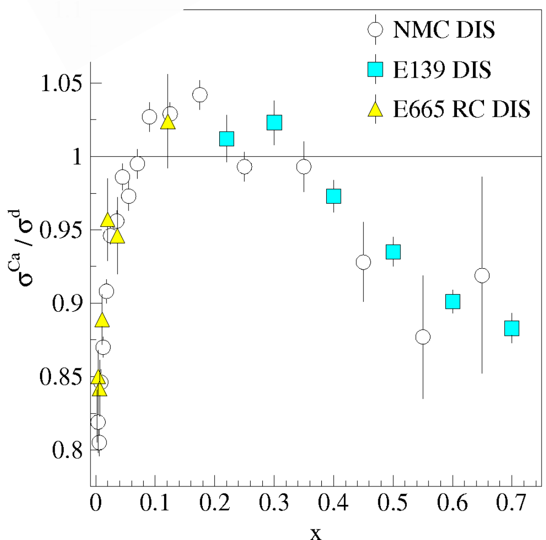
Fermilab E772 Data

- No clear EMC effect

- **No evidence for nuclear pion enhancement**



Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



Paul E Reimer, ECT* Novel EMC Effect

Fermilab E772 Data

- No clear EMC effect
- **No evidence for nuclear pion enhancement**

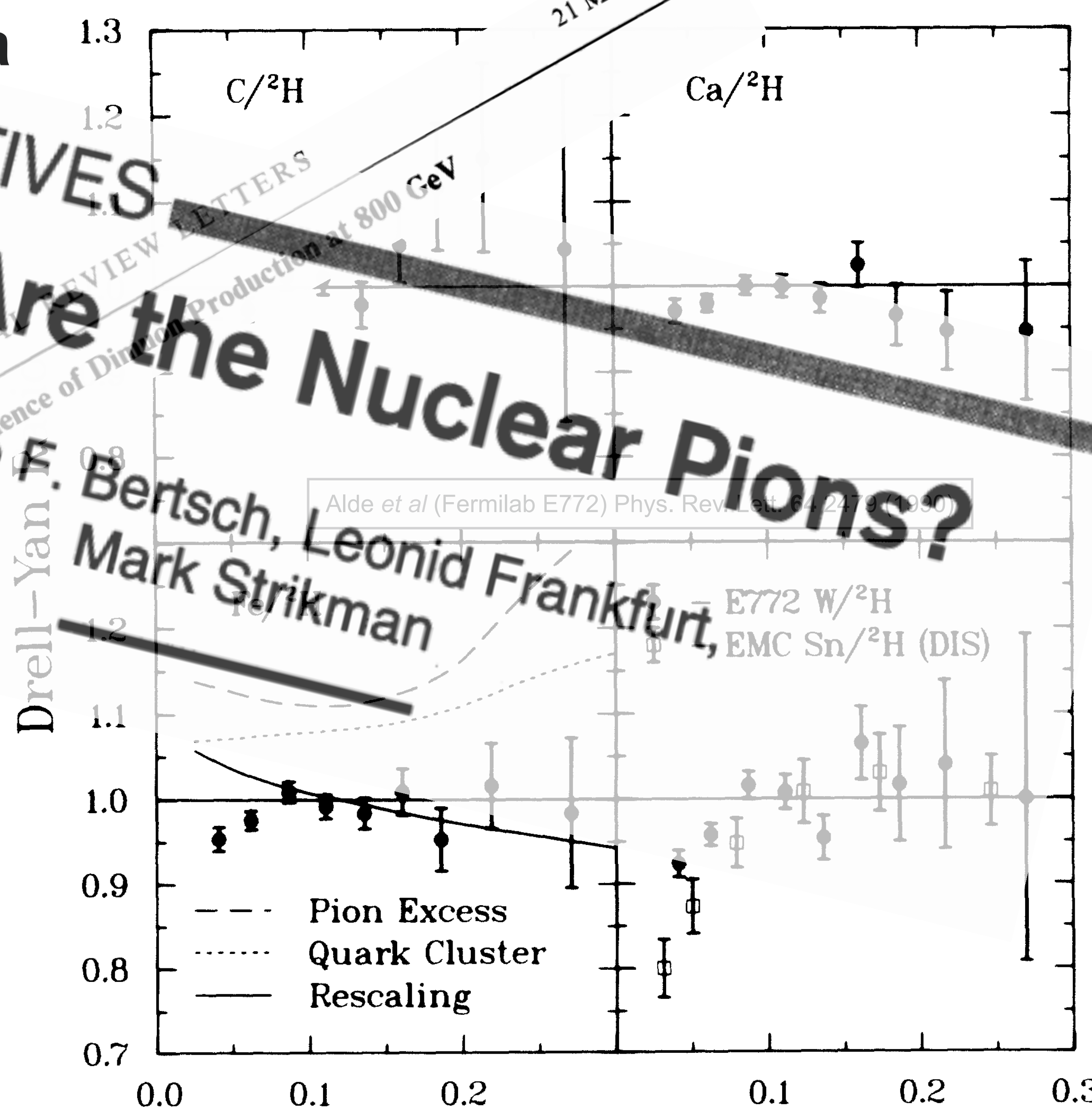
PERSPECTIVES

Where Are the Nuclear Pions?

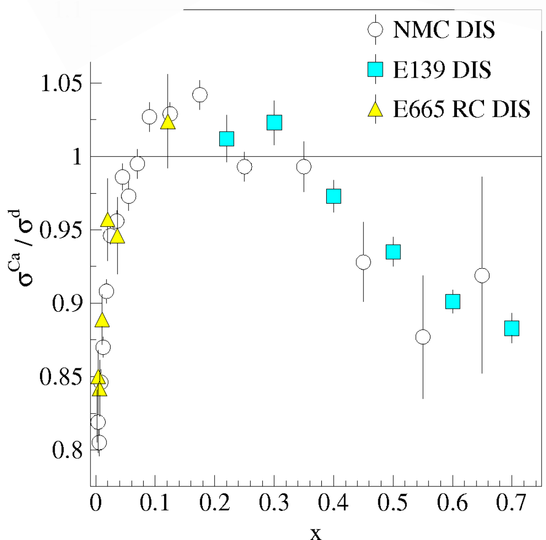
George F. Bertsch, Leonid Frankfurt, Mark Strikman

VOLUME 64, NUMBER 21 PHYSICAL REVIEW LETTERS 21 MAY 1990

Nuclear Dependence of Dimuon Production at 800 GeV



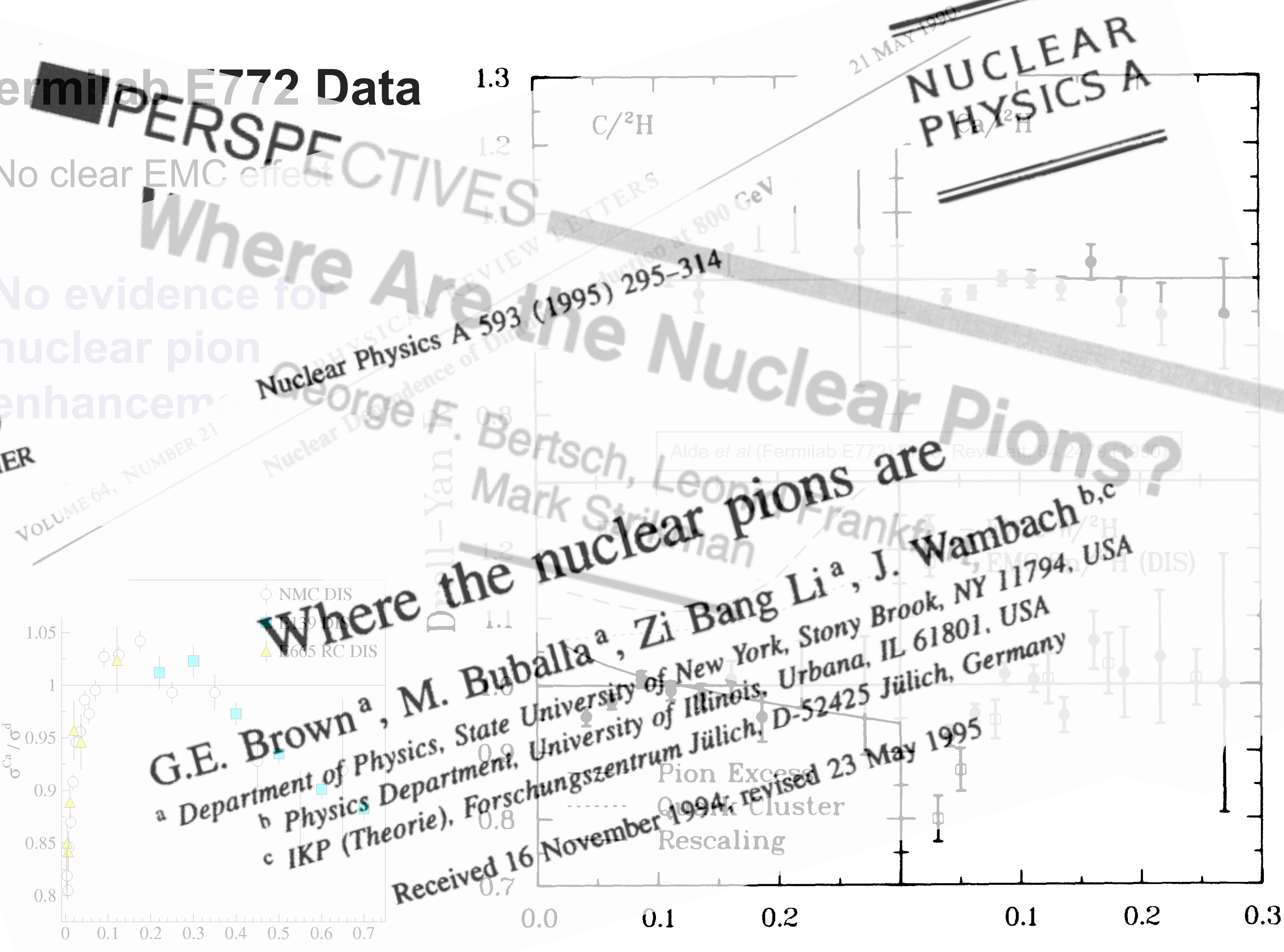
Alde *et al* (Fermilab E772) Phys. Rev. Lett. 64 2479 (1990)



Paul E Reimer, ECT* Novel EMC Effect

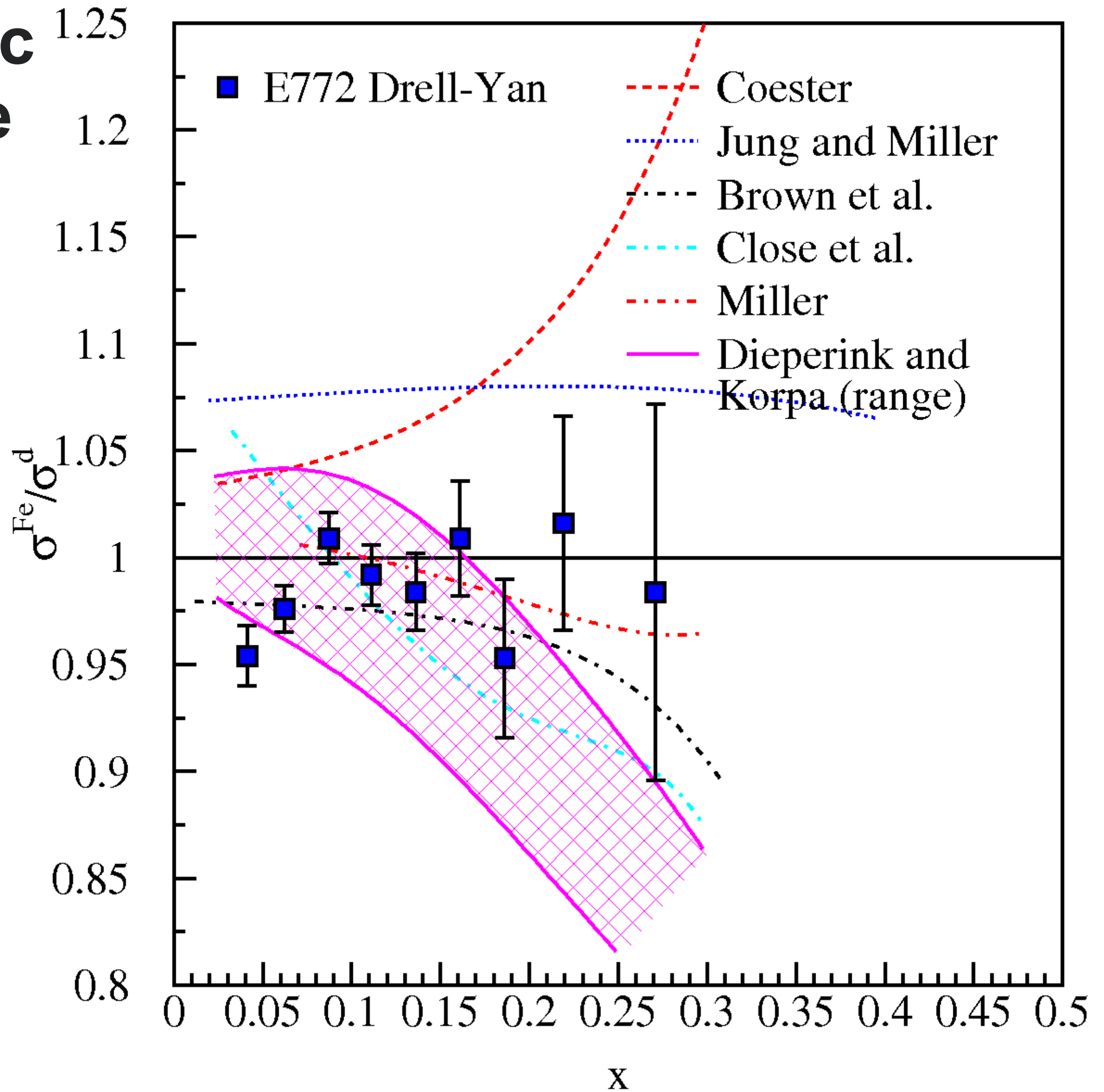
Fermilab E772 Data

- No clear EMC effect
- No evidence for nuclear pion enhancement

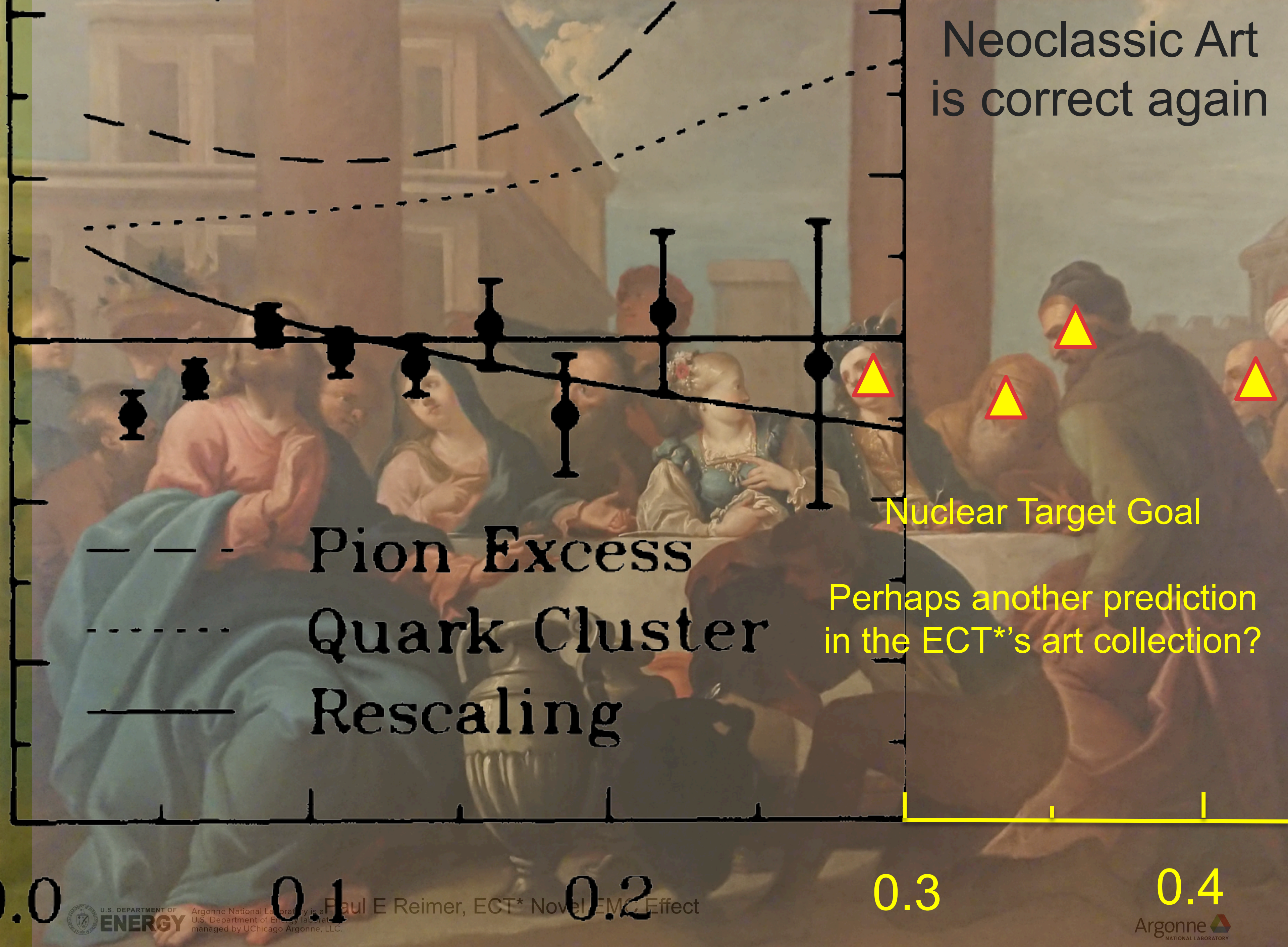


Structure of nucleonic matter: Where are the nuclear pions?

- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect and Drell-Yan



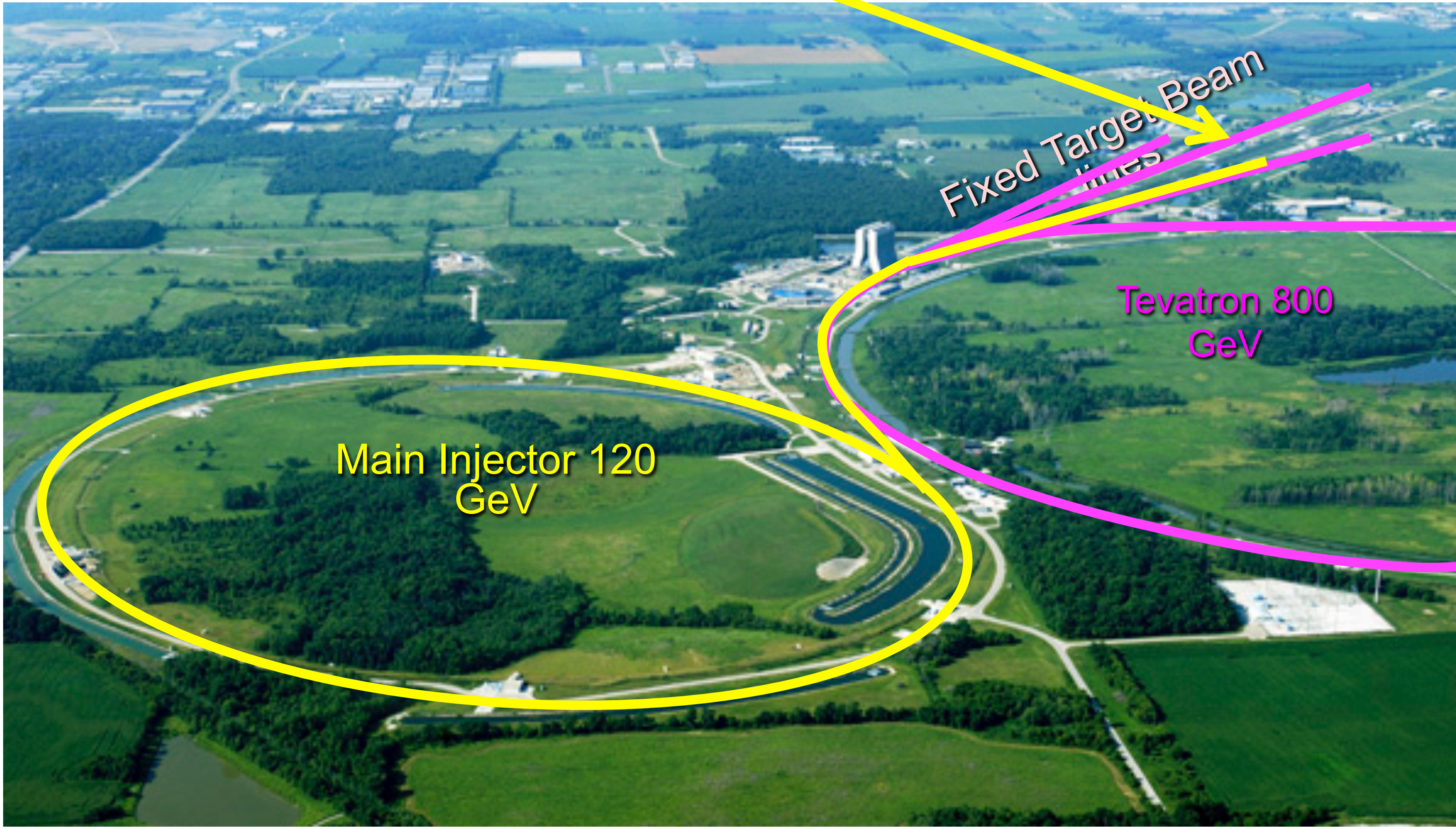
Neoclassic Art is correct again



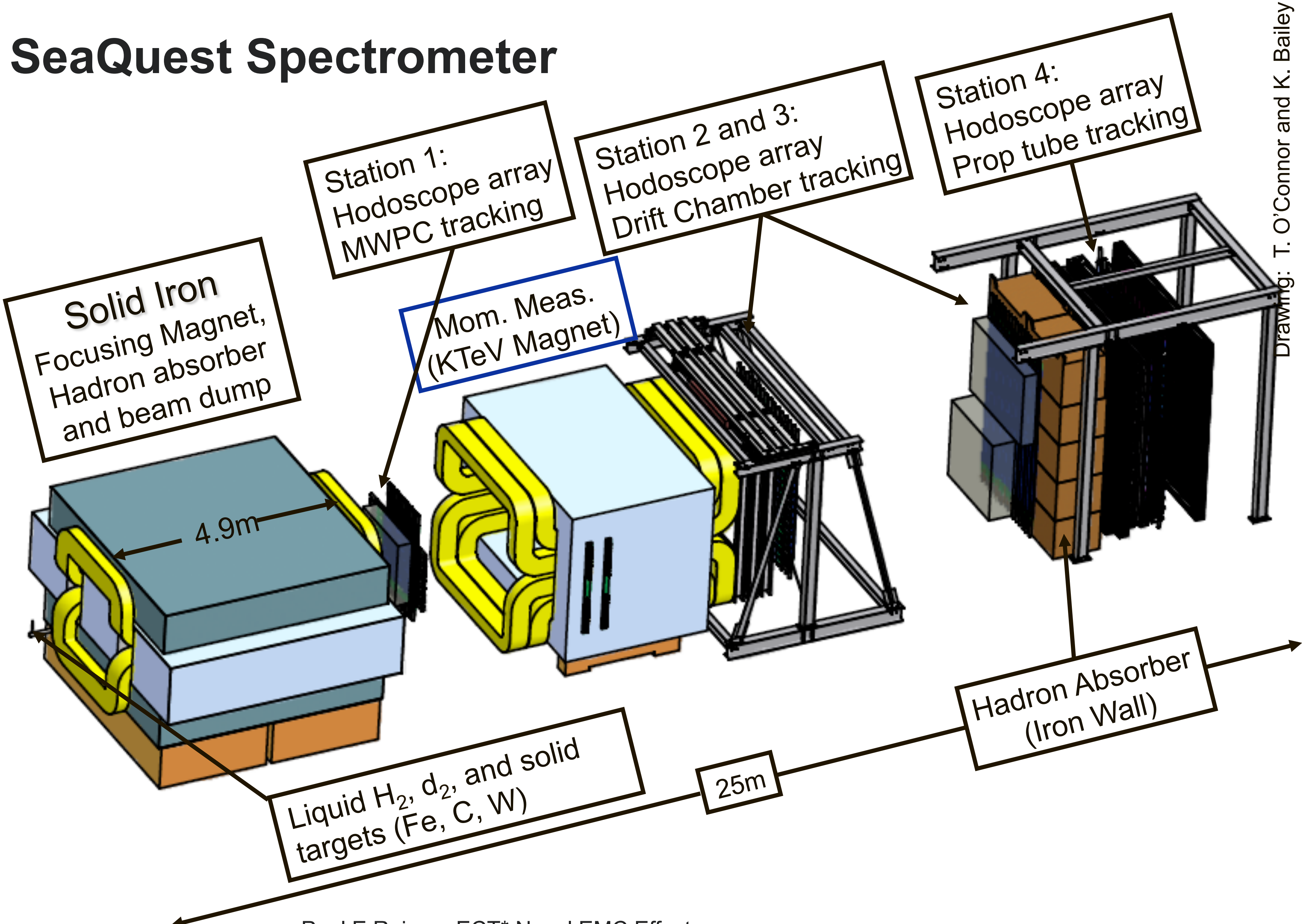
Nuclear Target Goal

Perhaps another prediction in the ECT*'s art collection?

SeaQuest Experiment

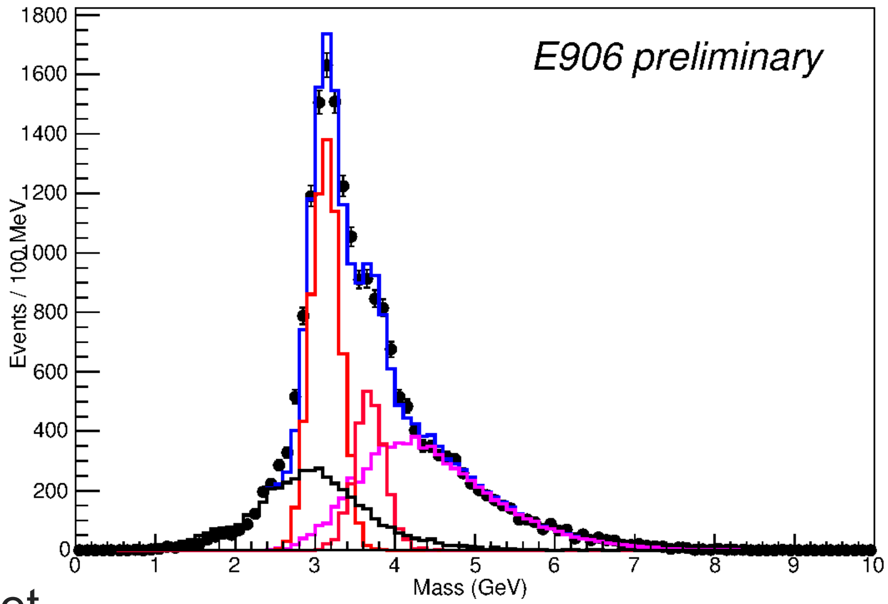


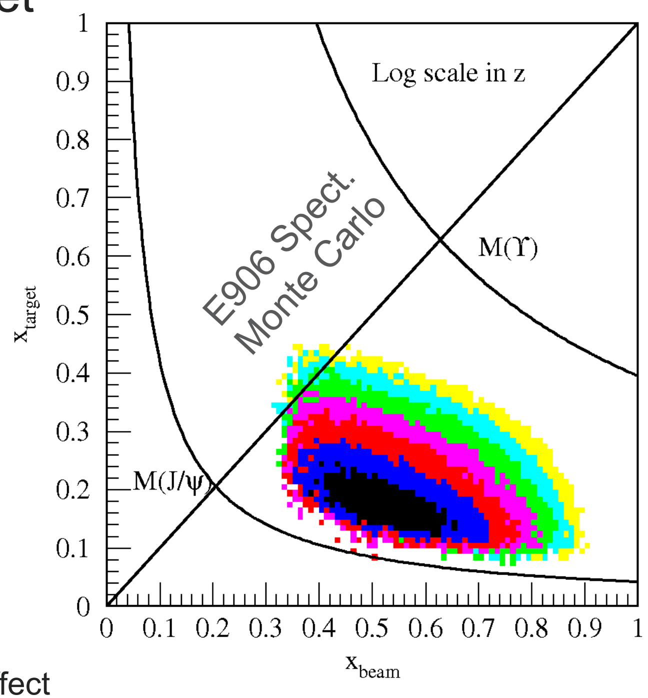
SeaQuest Spectrometer



E906/SeaQuest Status

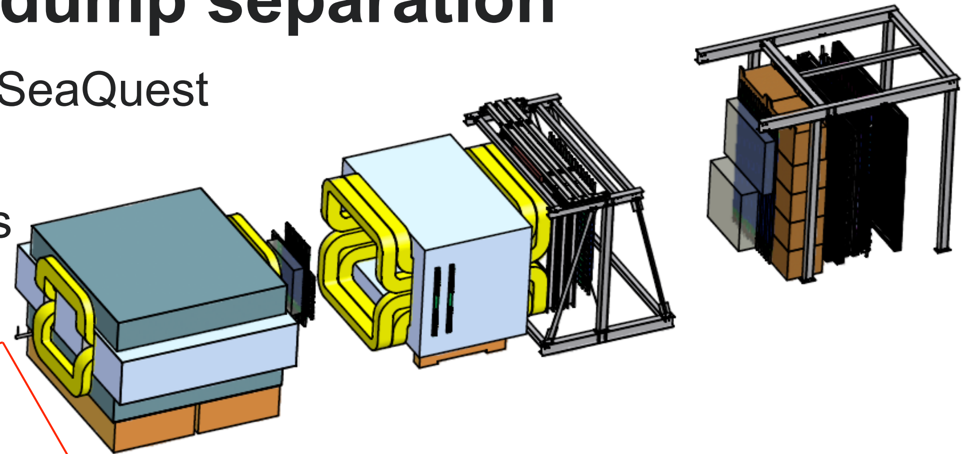
- Data with ^{1}H, ^{2}H, C, Fe and W targets
- Acceptance from below J/ψ to ≈8 GeV
- Completed data recording summer 2017
- Recorded 1.8×10^{18} "live" protons on target
  – 1/3 of requested integrated luminosity

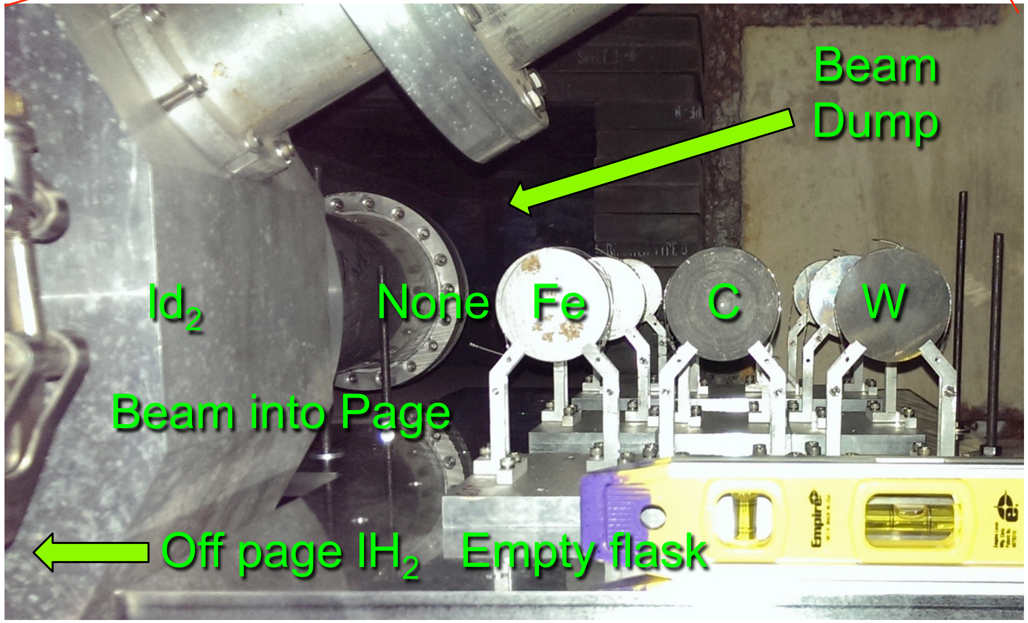


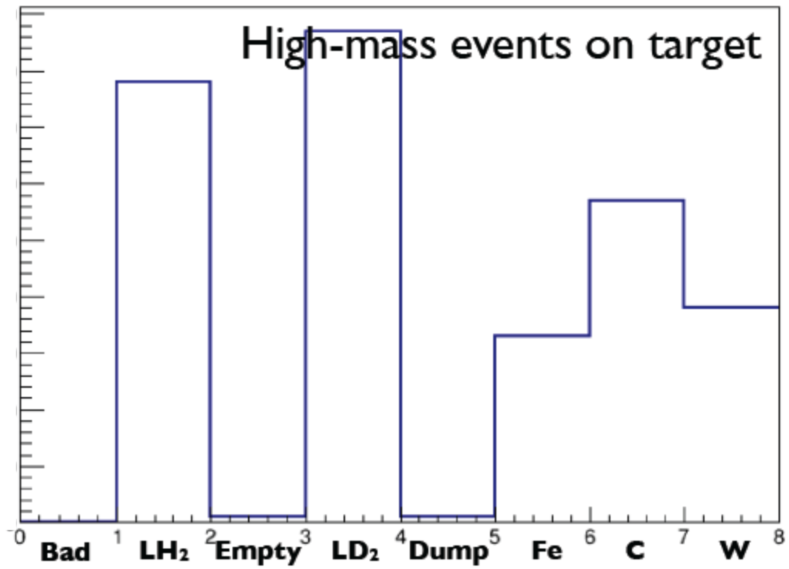


Data From FY2014—target-dump separation

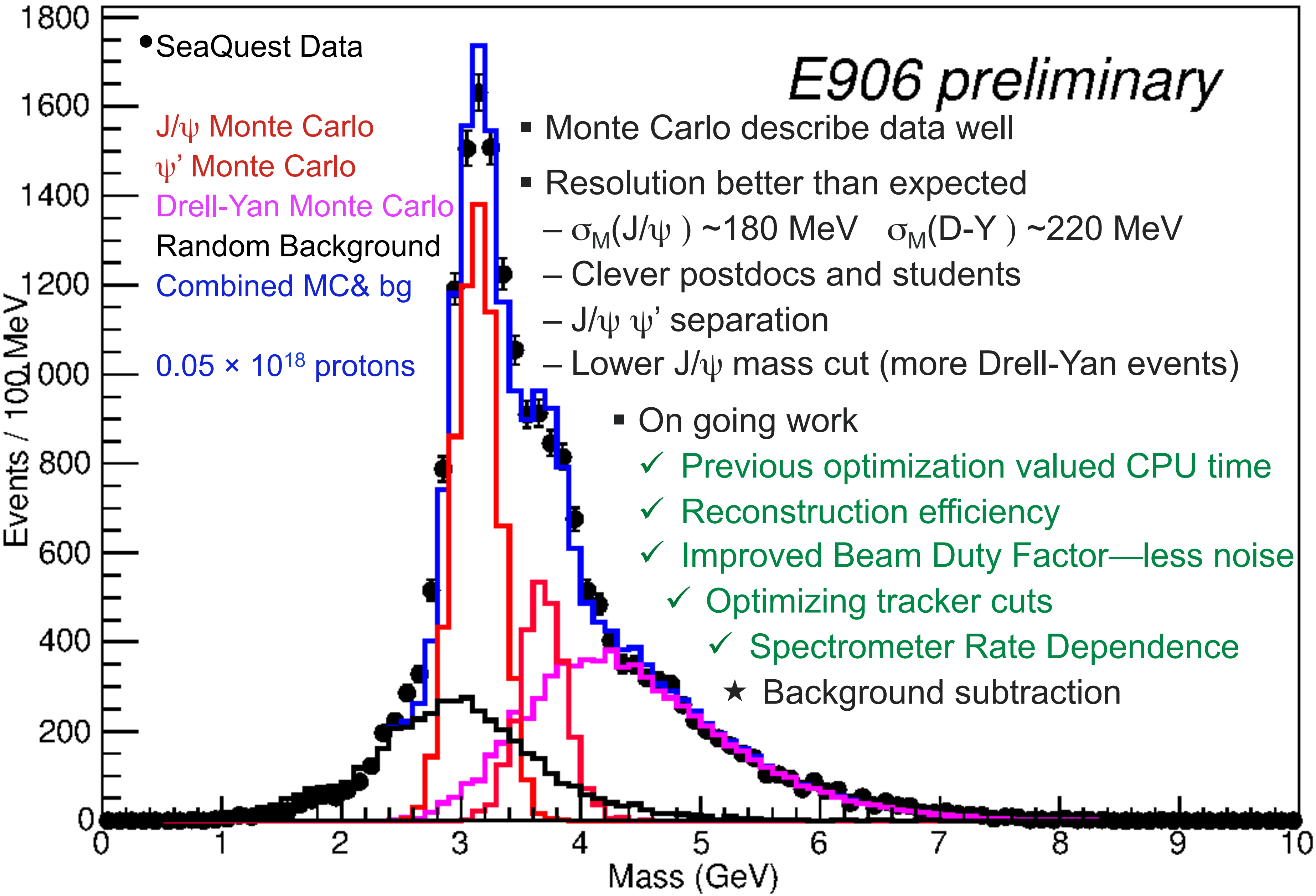
- Entire beam interacts upstream of first SeaQuest Spectrometer tracking chamber
- Spatial resolution poor along beam axis
- Resolve target vs beam dump





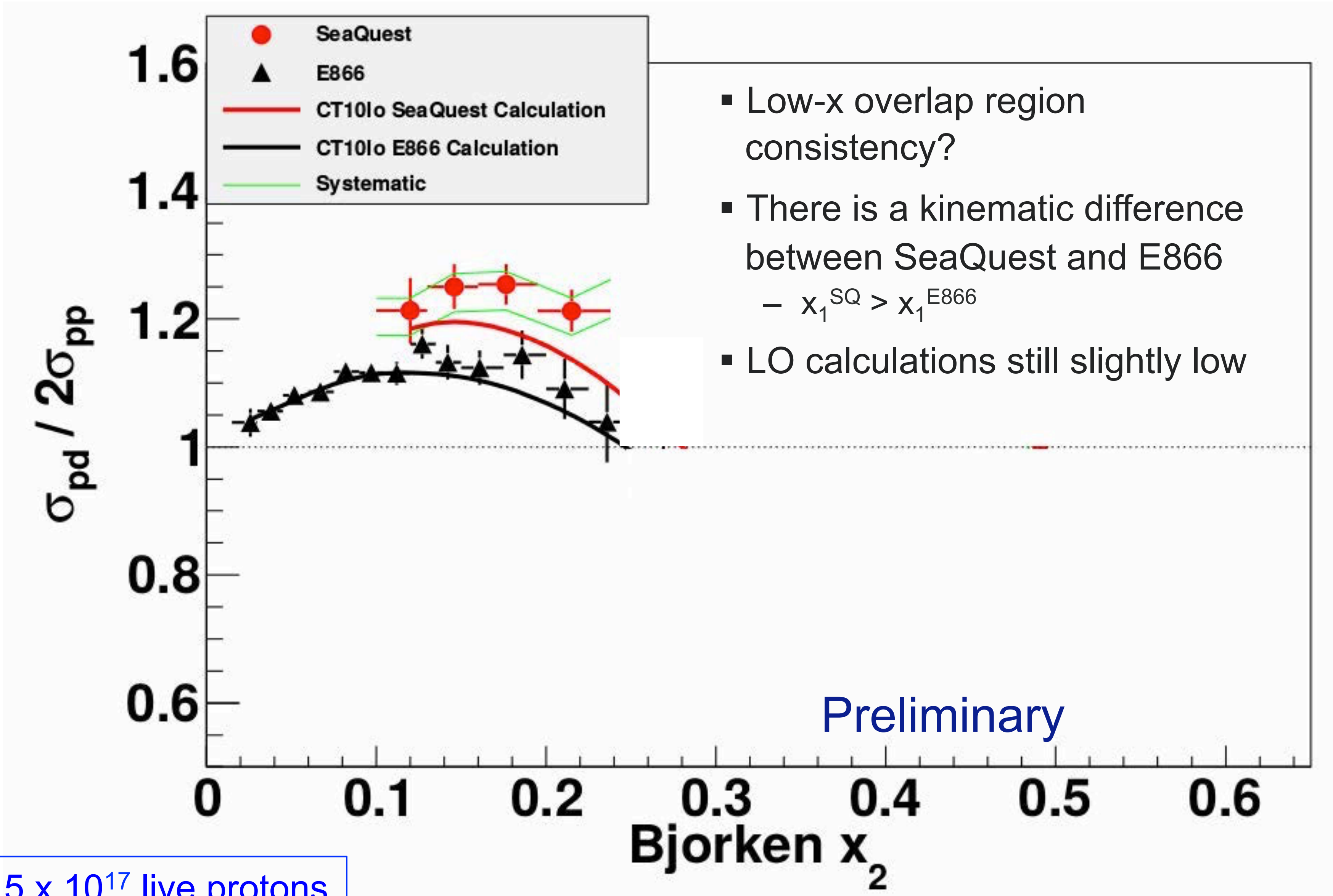


Data From FY2014



- Monte Carlo describe data well
- Resolution better than expected
  - σ_M(J/ψ) ~180 MeV σ_M(D-Y) ~220 MeV
  - Clever postdocs and students
  - J/ψ ψ' separation
  - Lower J/ψ mass cut (more Drell-Yan events)
- On going work
  - ✓ Previous optimization valued CPU time
  - ✓ Reconstruction efficiency
  - ✓ Improved Beam Duty Factor—less noise
  - ✓ Optimizing tracker cuts
  - ✓ Spectrometer Rate Dependence
  - ★ Background subtraction

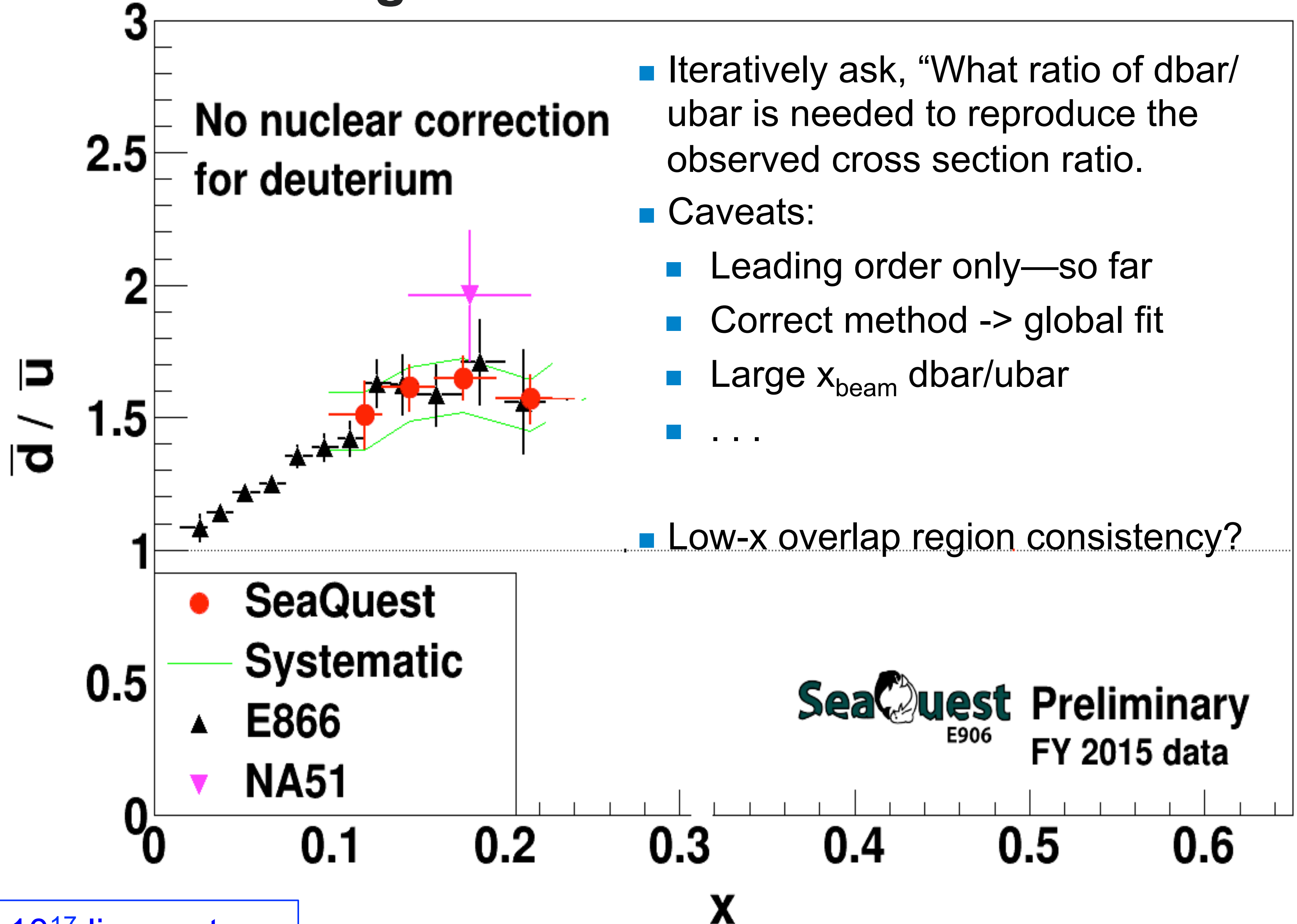
SeaQuest Cross Section Ratio



- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
  - $x_1^{SQ} > x_1^{E866}$
- LO calculations still slightly low

3.5 x 10^{17} live protons

SeaQuest Leading Order dbar/ubar

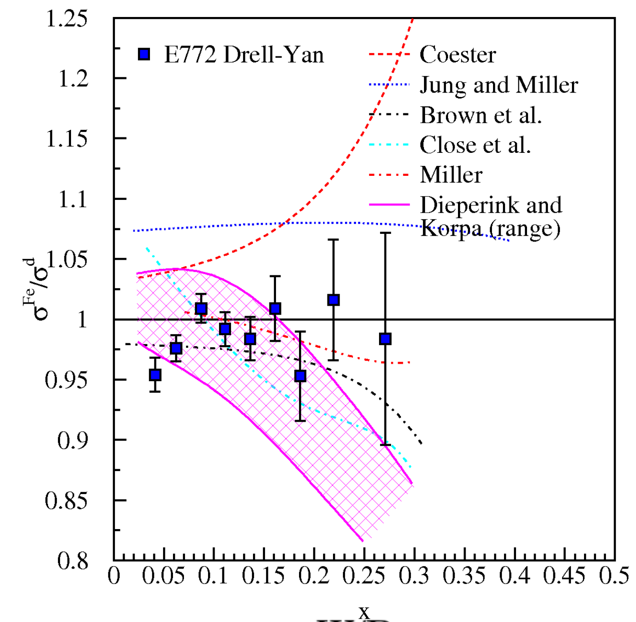


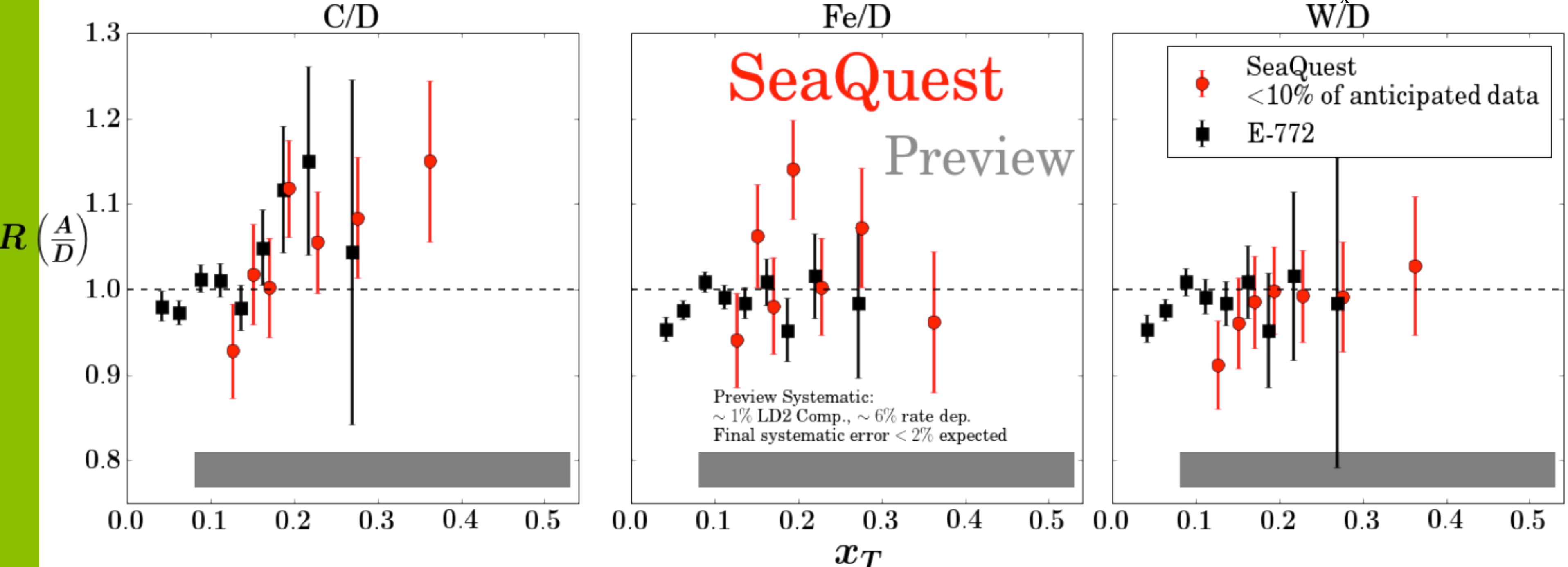
- Iteratively ask, "What ratio of dbar/ ubar is needed to reproduce the observed cross section ratio.
- Caveats:
  - Leading order only—so far
  - Correct method -> global fit
  - Large x_{beam} dbar/ubar
  - . . .
- Low-x overlap region consistency?

3.5 x 10^{17} live protons

SeaQuest Seaquark EMC Effect

- No antiquark enhancement apparent.
- 10% of anticipated statistical precision
- Increased detector acceptance at large-x to come.

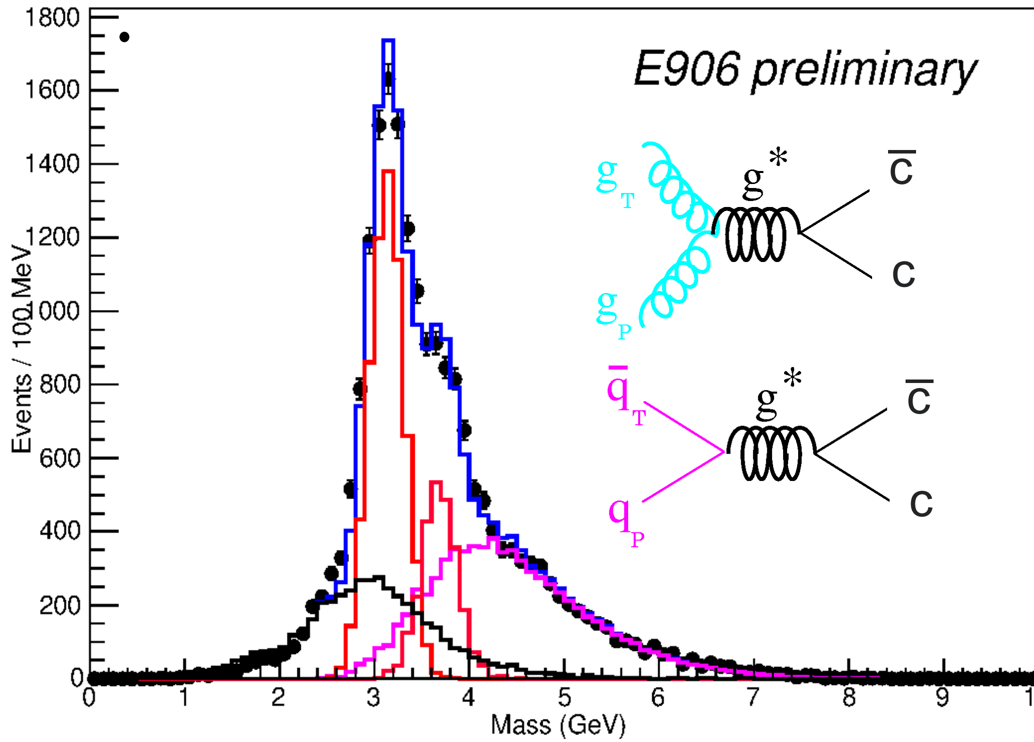




J/ψ production

EMC in gluons

- Majority of SeaQuest events are J/ψ
- Most J/ψ events produced in the decay of higher mass states:
  $\chi \rightarrow \gamma J/\psi$
- Not a problem with ψ’
- Sufficient resolution to fit line shape



Process:

– g-g or q-qbar fusion/annihilation?

– Octet or singlet formation?
  - Polarization observables

$$\lambda = \frac{\sigma - 3\sigma_L}{\sigma + \sigma_L} = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$

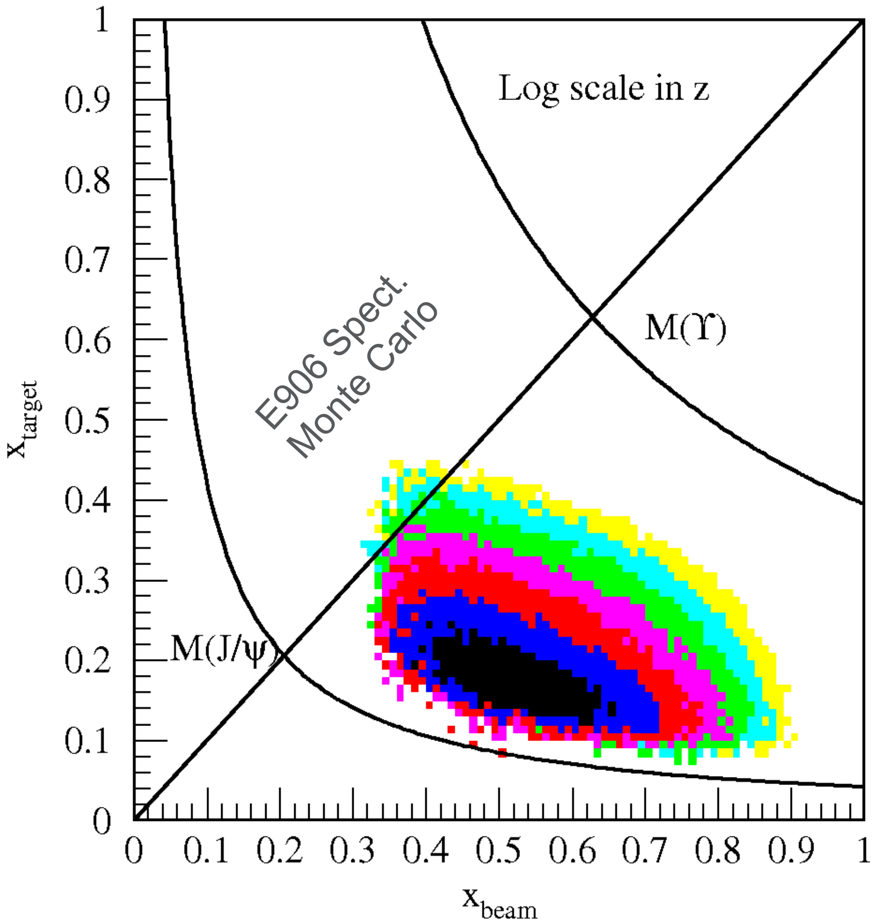
J/ψ production

EMC in gluons

Issue:

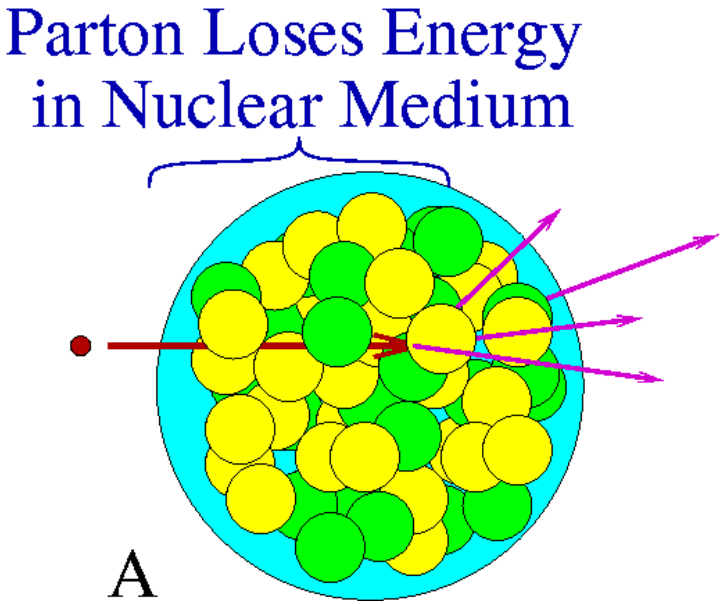
- Correlation between x_{beam} and x_{target}
  - $M_{J/\psi}^2 = s x_b x_t$

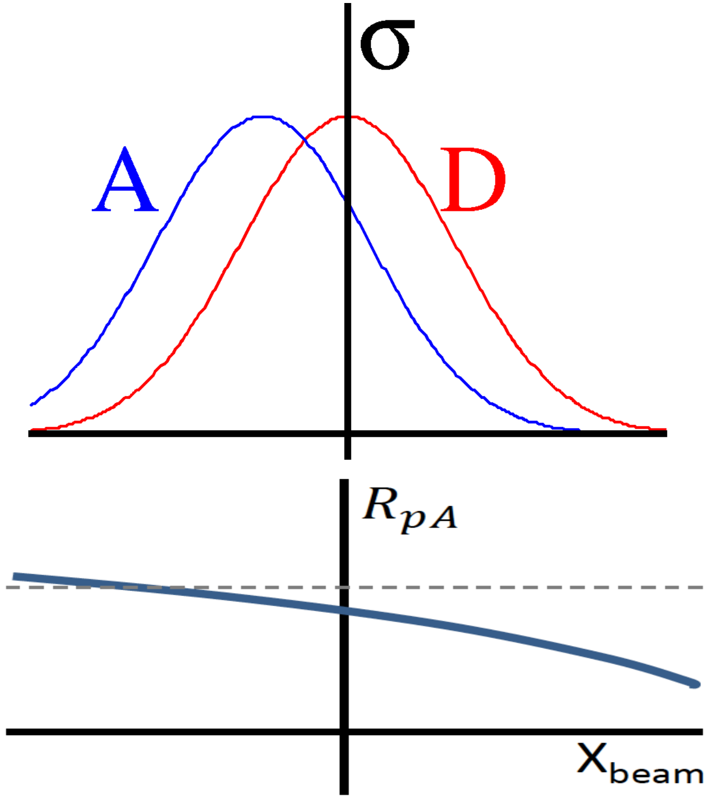
- Cannot integrate over hidden variable



Partonic Energy Loss

- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values (x_1 or x_F) are shifted
- Fit shift in x_1 relative to deuterium



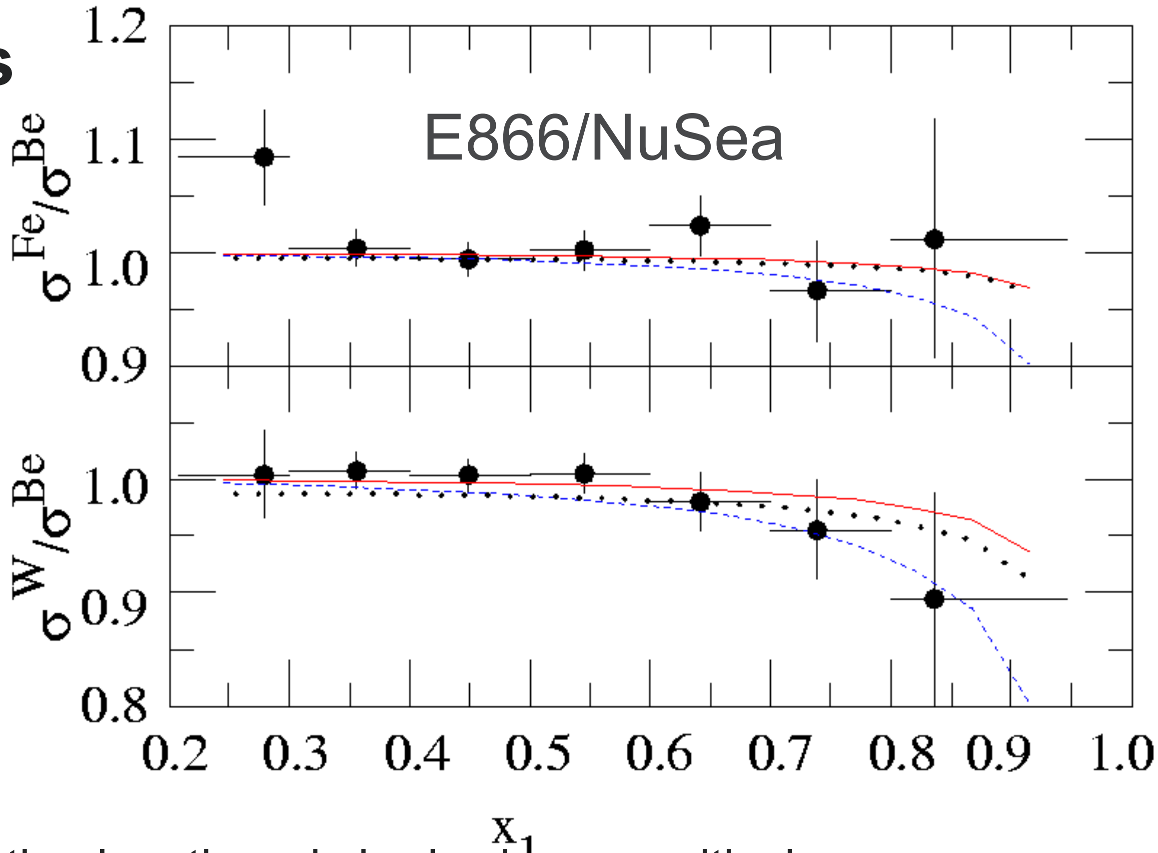


Models:

- Galvin 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.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

Partonic Energy Loss

- E866 data are consistent with NO partonic energy loss for all three models
- Caveat: A correction must be made for shadowing because of x_1—x_2 correlations
  - E866 used an empirical correction based on EKS fit do DIS and *Drell-Yan*.

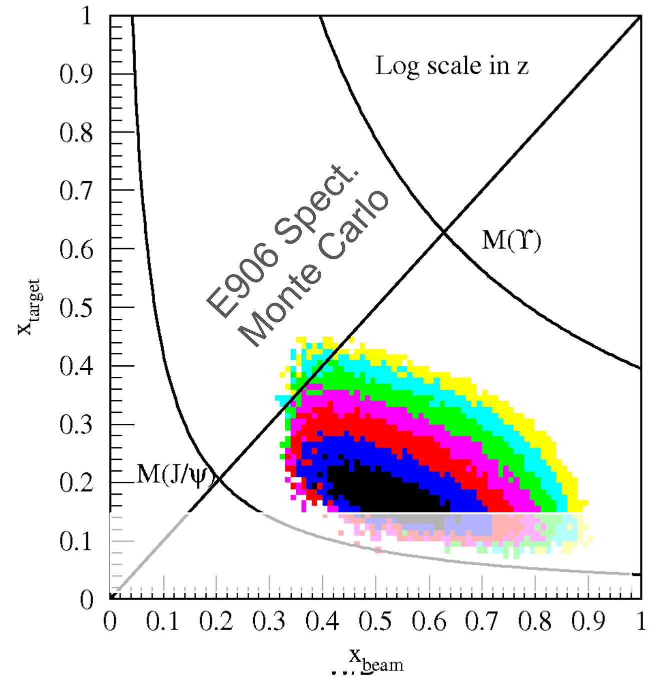


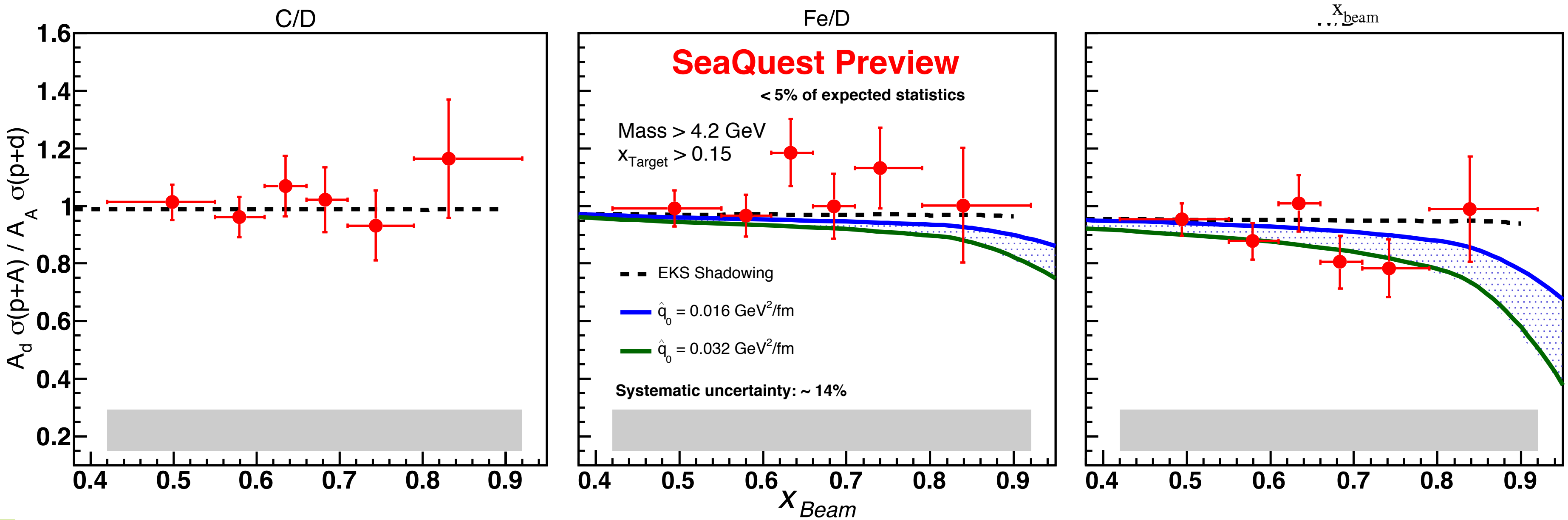
- Treatment of parton propagation length and shadowing are critical
  - Johnson *et al.* find 2.7 GeV/fm (≈1.7 GeV/fm after QCD vacuum effects)
  - Same data with different shadowing correction and propagation length
- **Better data outside of shadowing region are necessary.**

- Drell-Yan p_T broadening also will yield information

Partonic Energy Loss

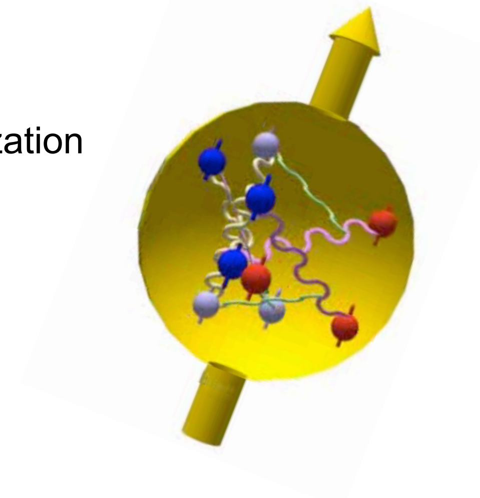
- Remove shadowing region $x_{target} > 0.15$
- Data show very little energy loss





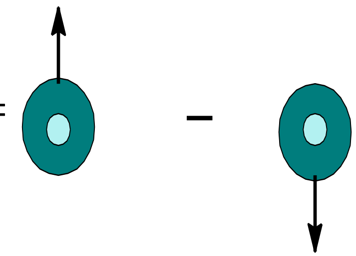
Future SeaQuest Physics

Drell-Yan Future: Polarized Target, Beam



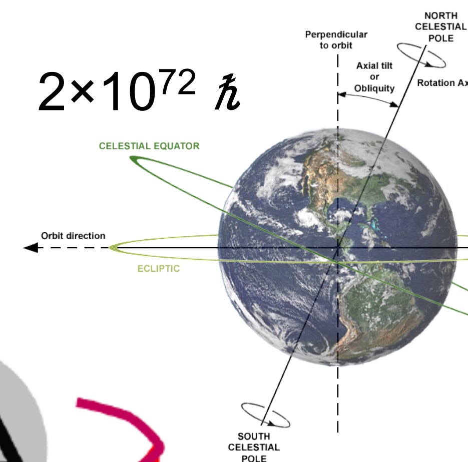
- E-1039: Correlation between unpolarized quarks and nucleon transverse polarization
- **Do sea quarks have orbital angular momentum?**
  - Non-zero Sivers distribution ⇨ non-zero quark orbital momentum:
- Requires Transversely polarized target

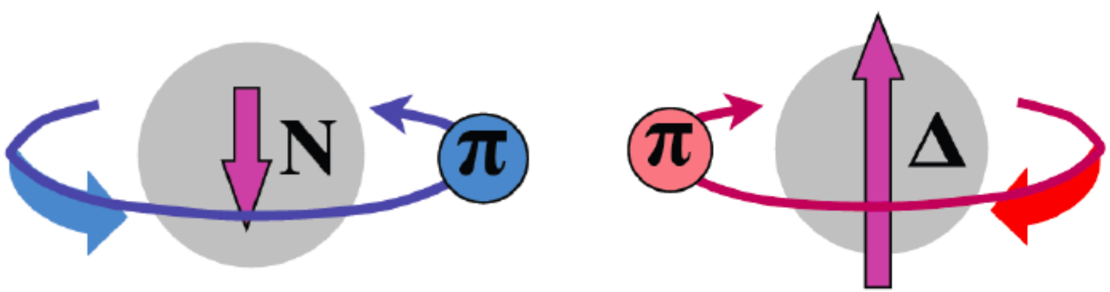
$f_{1T}^{\perp} =$



- Status
  - **Funding from DOE/Nuclear Physics with support from HEP**
  - **Installation beginning!!**
  - Commissioning fall 2018
  - Production data FY19-20.

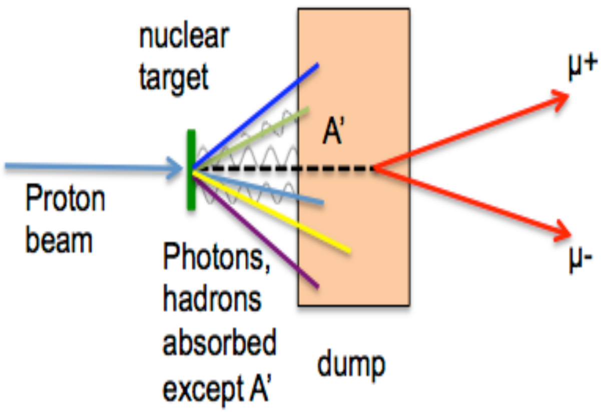
$2\times10^{72}\ \hbar$



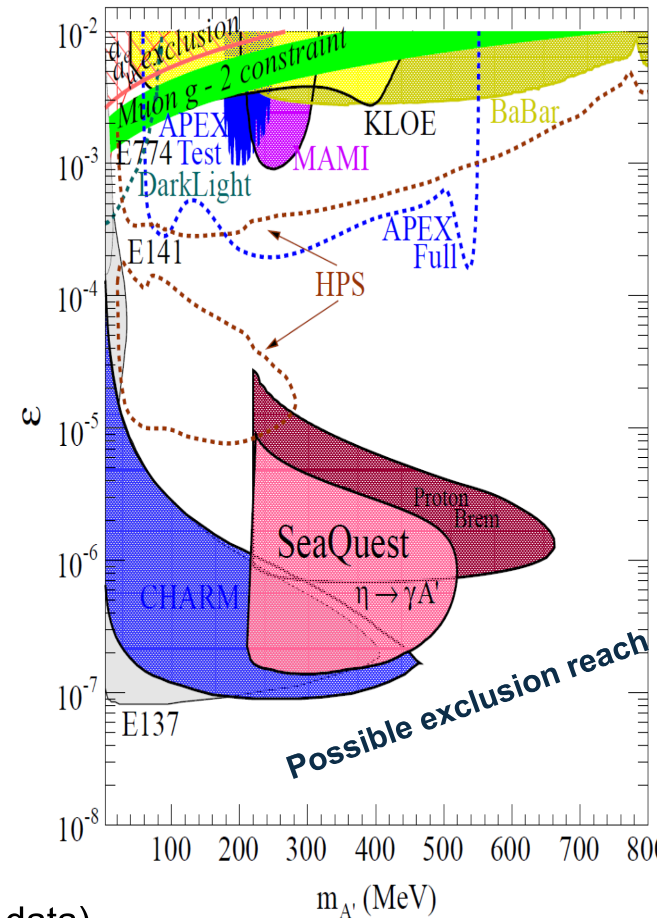


E906: Search for Dark Photons at SeaQuest

- SeaQuest is also a classic Beam Dump Experiment



$$\mathcal{L} \propto -\frac{1}{4}\mathcal{F}^{\text{SM}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\text{SM}} - \frac{1}{4}\mathcal{F}^{\text{hidden}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\text{hidden}} + \frac{1}{2}\epsilon\mathcal{F}^{\text{SM}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\text{hidden}} + m^2_{A'}A^{\text{hidden}}_{\mu}A^{\mu}_{\text{hidden}}$$



- Status:
  - Dark photon roads added to trigger (minimal impact on Drell-Yan data)
  - New Dark Photon trigger counters have been installed and commissioned
  - Will continue taking data through out polarized running
  - Possible extension of coverage with e^+e^- detection using PHENIX calorimeter

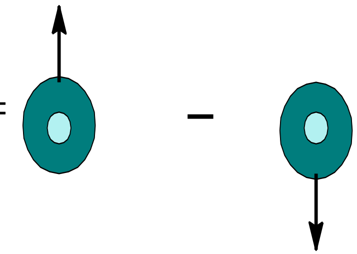
Drell-Yan Future: Polarized Target, Beam

- E-1027: Polarized beam and target (Reimer, Spokesperson)
- Measure **valence-quark Sivers distributions**
  - Look for predicted sign change from SIDIS [HP13]
  - Directly comparable to SIDIS measurements
  - SIDIS fits predict measureable D-Y asymmetry
  - \$6.5M + 65%(cont. and manage.) = \$10.5M (**2013 \$**)

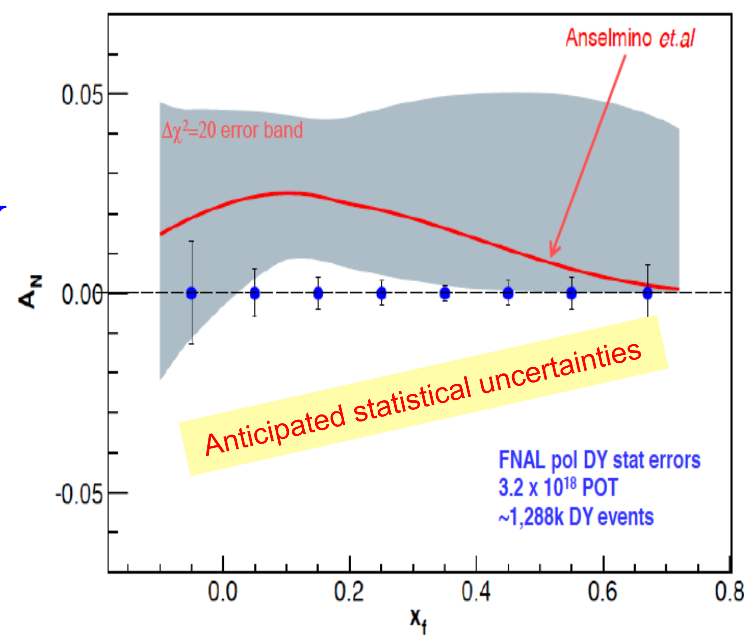
$$f_{1T}^{\perp,q}(x,k_T)\Big|_{\mathrm{DIS}} \stackrel{?}{=} -f_{1T}^{\perp,q}(x,k_T)\Big|_{\mathrm{DY}}$$

  - Is our understanding of Gauge Invariance in QCD correct?

$f_{1T}^{\perp} =$



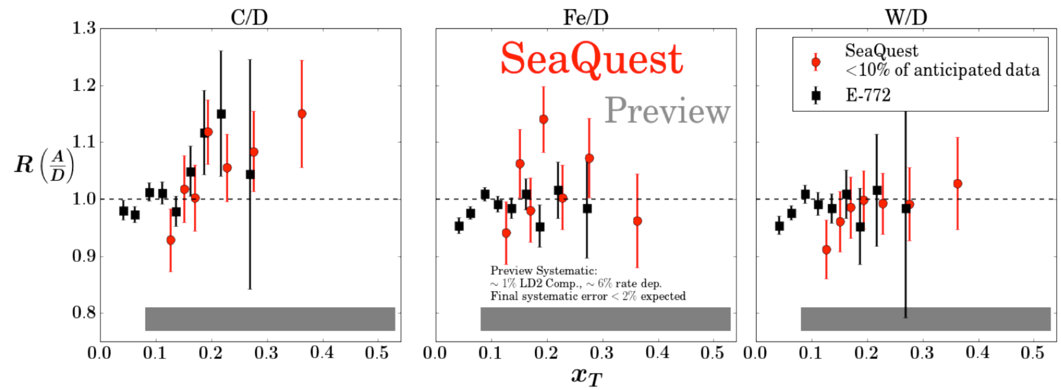
Polarized beam Valence Sivers distribution

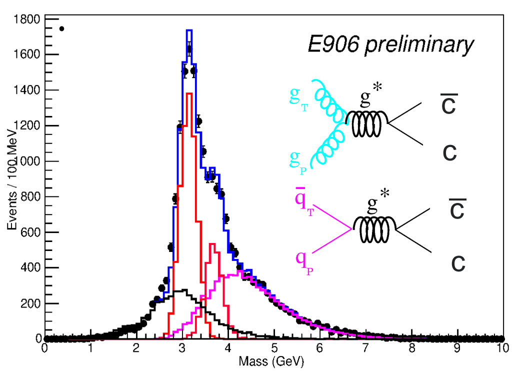


Drell-Yan & J/ψ dimuon production

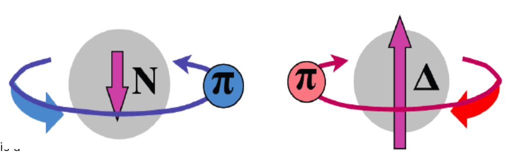
Take away messages

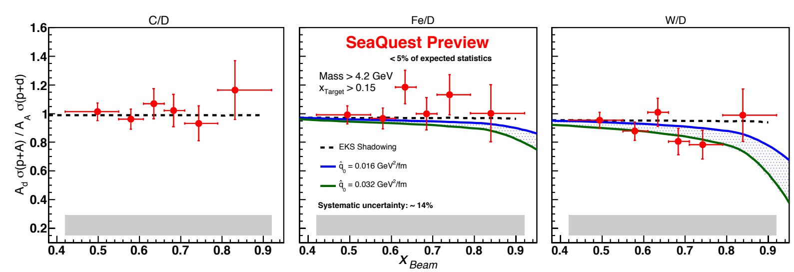
1. Drell-Yan and J/y dimuon production provides insight complementary to DIS
2. EMC effect does not appear to be strongly present in sea quarks
   - Observed by E772, extended by E906/SeaQuest
   - Must be addressed by any model addressing the EMC effect



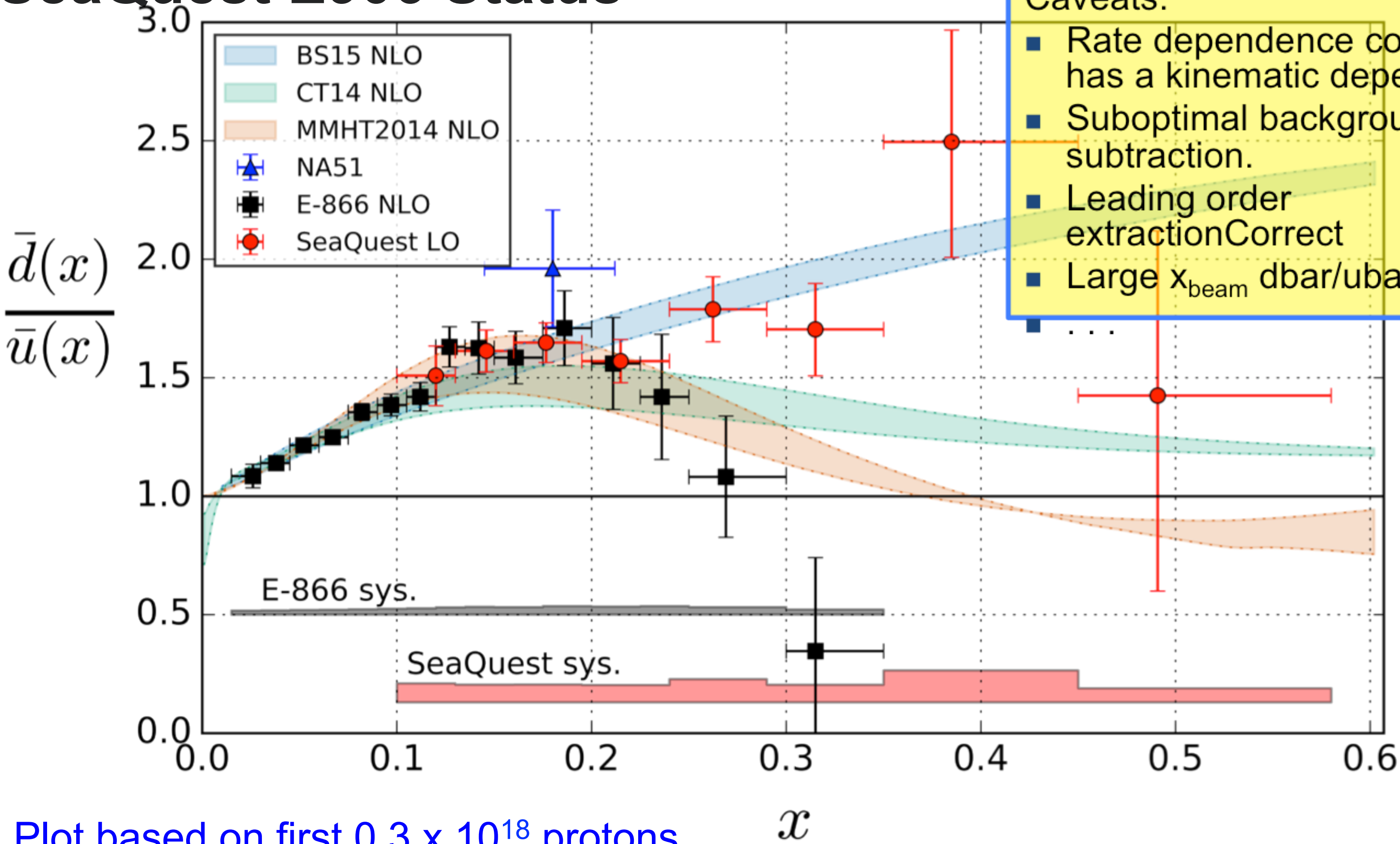


3. J/ψ production may yield information on the EMC effect for gluon distributions
4. Viewed from the incoming hadron's perspective, No partonic energy loss in cold QCD matter is apparent.
5. SeaQuest's future: polarized-target & sea quark Sivers distribution.
   - OAM





SeaQuest E906 Status



Caveats:

- Rate dependence correction has a kinematic dependence
- Suboptimal background subtraction.
- Leading order extractionCorrect
- Large x_{beam} dbar/ubar
- . . .

Plot based on first 0.3 x 10^{18} protons

SeaQuest has recorded 1.8 x 10^{18} protons

Acceptance improvements so later protons are “worth” more