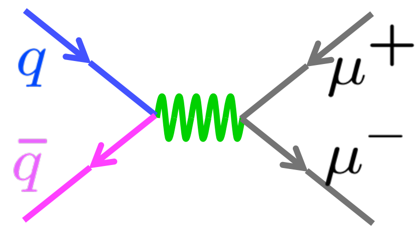
Fermilab E-906/SeaQuest: Measurements of pA Spin Independent Drell-Yan

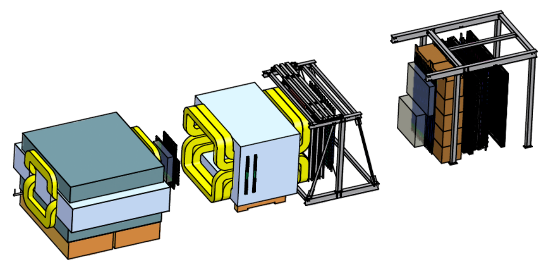
Paul E. Reimer

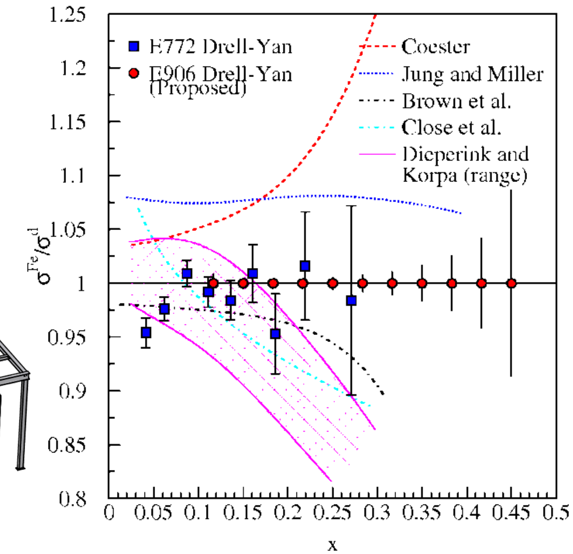
Physics Division

Argonne National Laboratory

7 January 2013







I. The Big Picutre--Drell-Yan
II. EMC effect
III. Partonic Energy Loss

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

The Big Picture

Early Muon Pair Data—soon to be called Drell-Yan

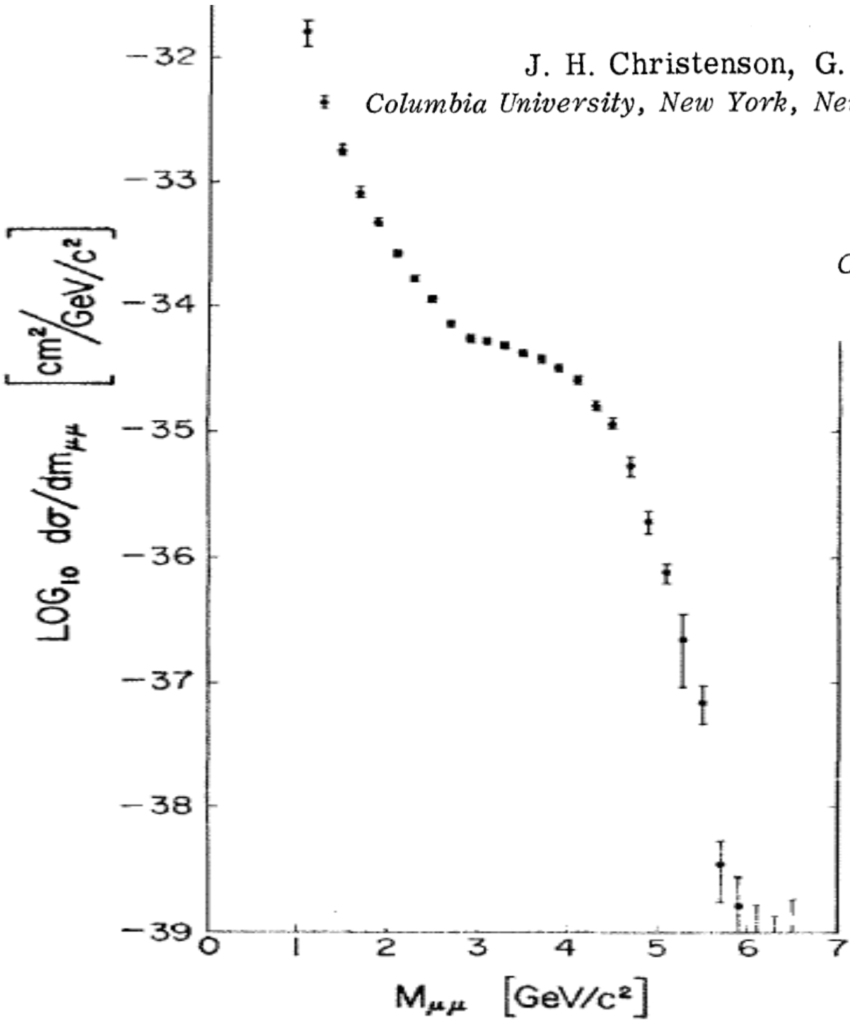
VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)



Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

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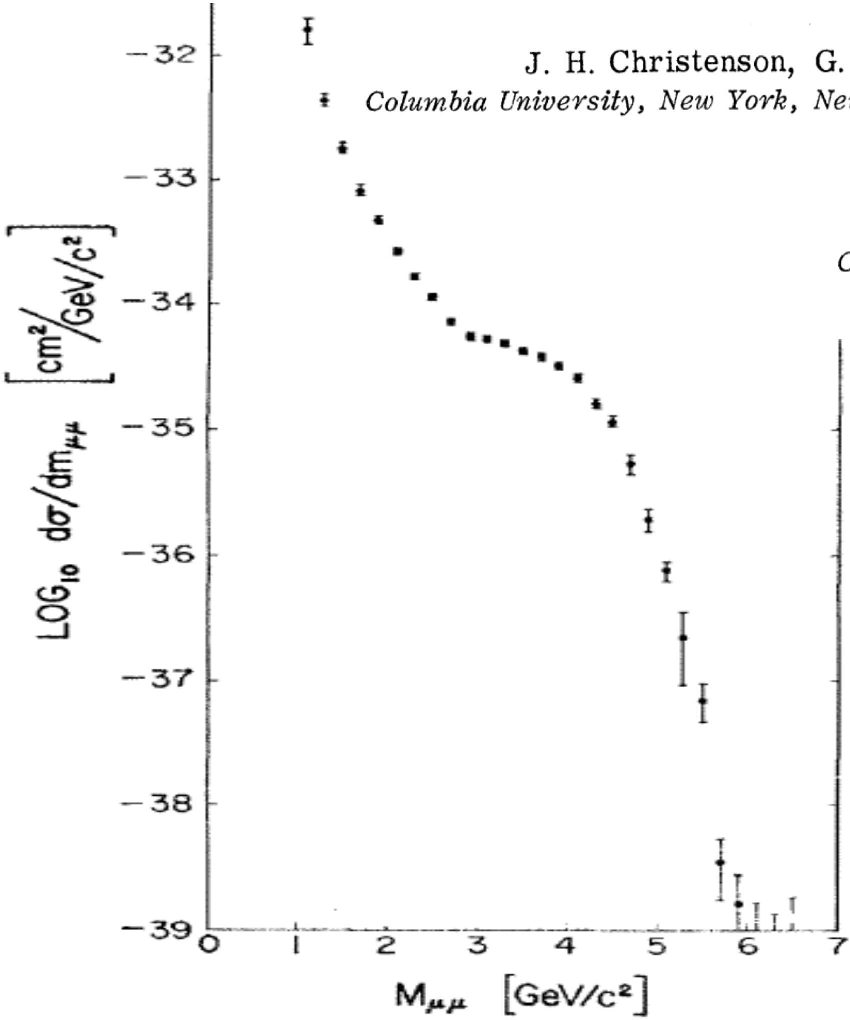
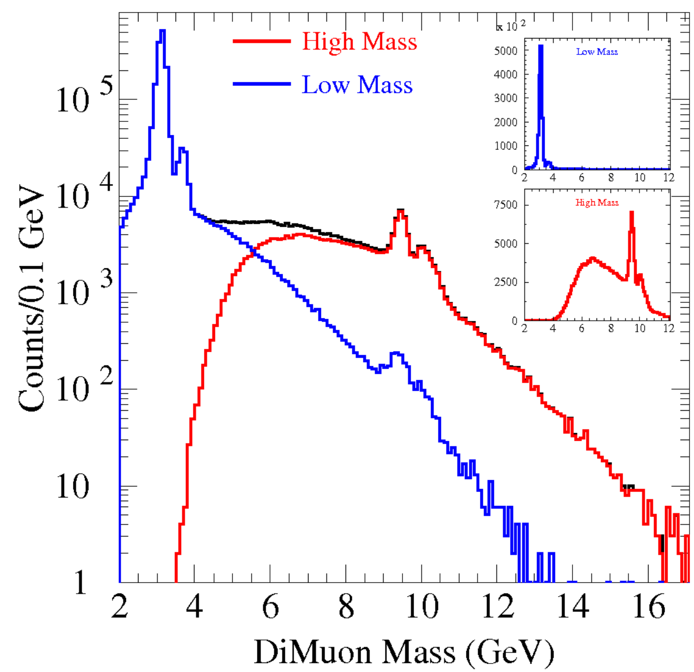




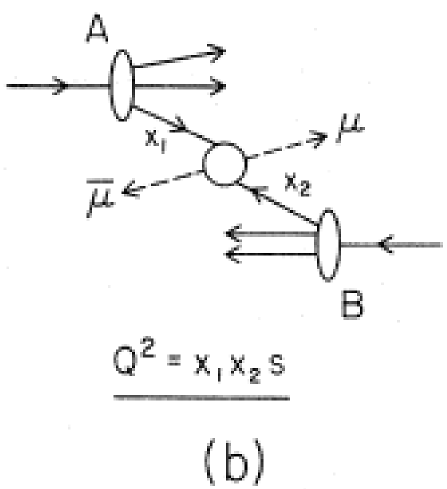
Drell and Yan's explanation

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s\to\infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



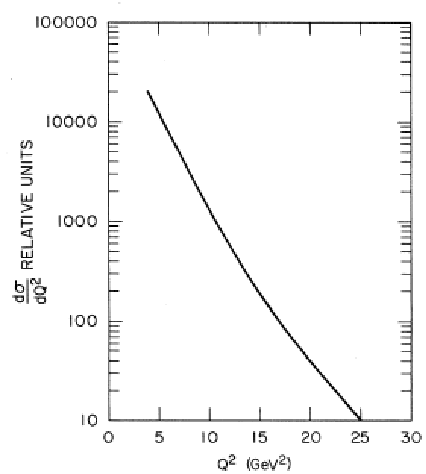
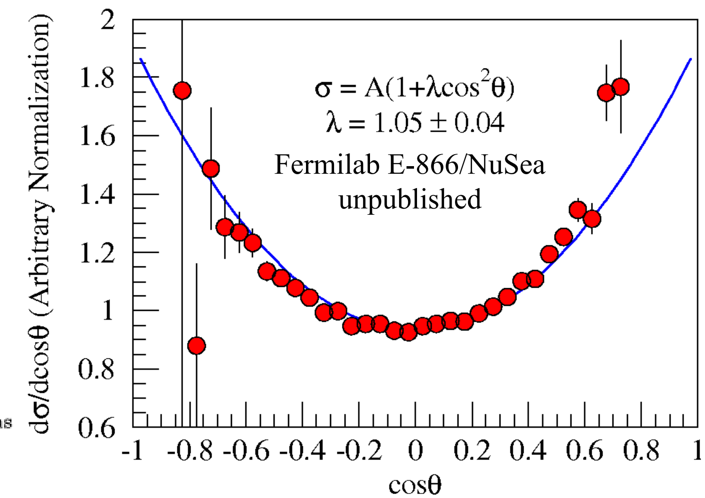


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

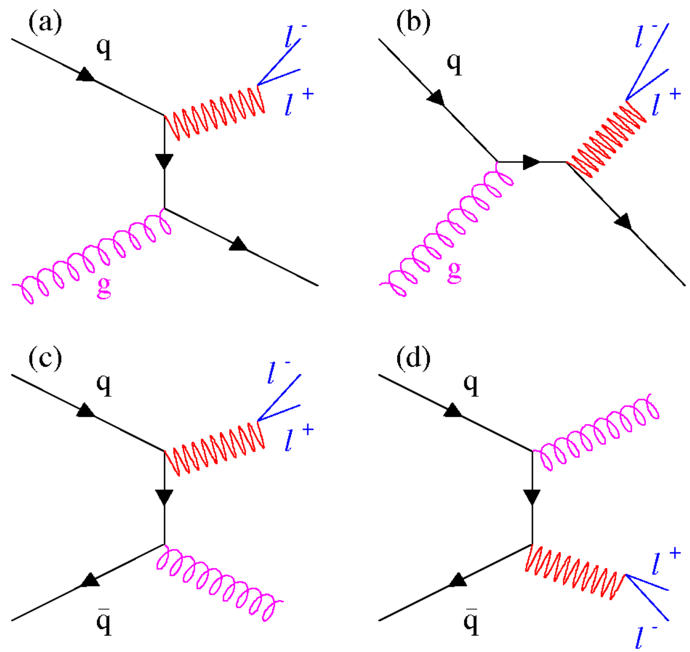
Also predicted
$\lambda(1+\cos^2\theta)$
angular distributions.



Drell-Yan Cross Section

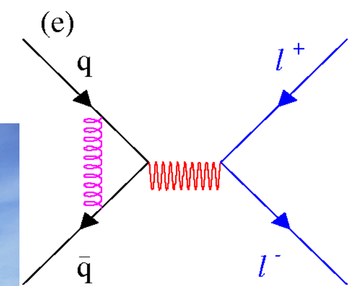
Next-to-Leading Order

- These diagrams are responsible for up to **50% of the measured cross section**
- **Parton distributions are Universal!**
- Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)
- **Soft gluon resummation at all orders**



Angular Distributions

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



Higher Twist??

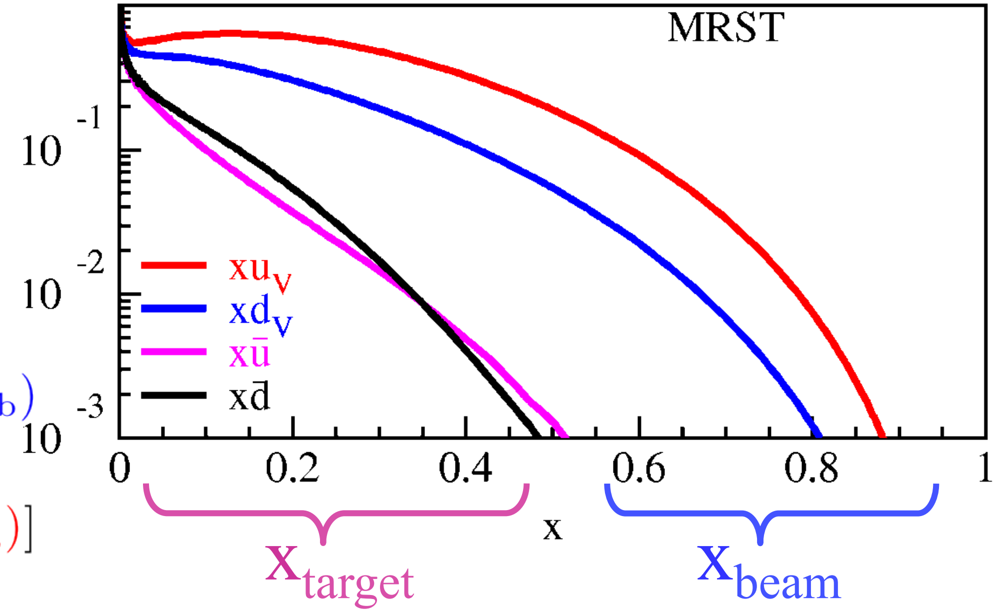
Drell-Yan Cross Section

- Measured cross section is a convolution of beam and target parton distributions
- **Proton Beam**
  - Target antiquarks and beam

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

- u-quark dominance

(2/3)² vs. (1/3)²



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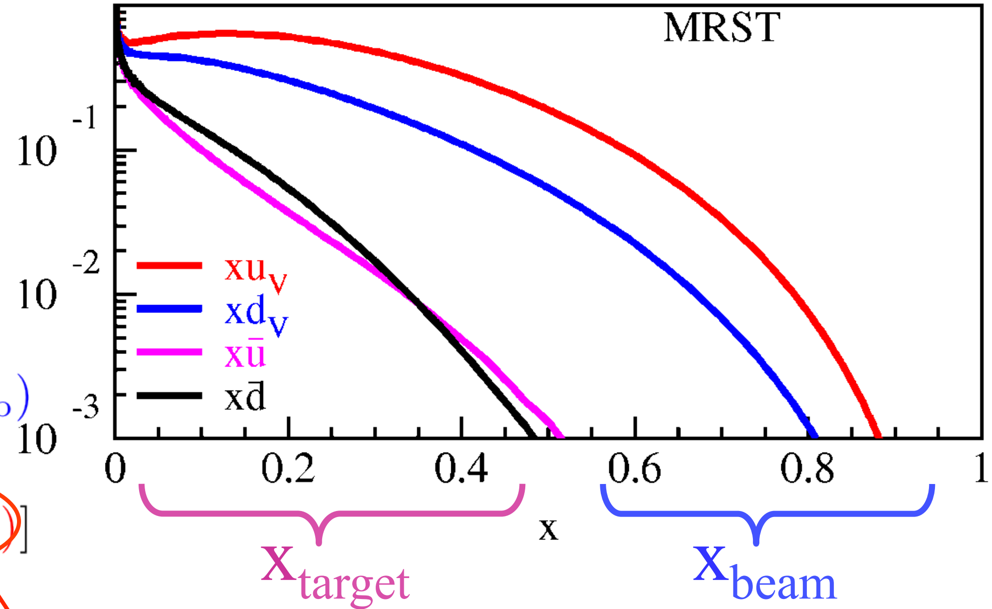
Acceptance limited

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



- **π^- beam**
  - Valence beam anti-u quark and u target quark

$$\left.\frac{d^2\sigma}{dx_\pi dx_N}\right|_{\pi^- N} = \frac{4\pi\alpha^2}{x_\pi x_N s}\left[\frac{4}{9}\bar{u}_\pi(x_\pi)u_N(x_N) + \frac{1}{9}d_\pi(x_\pi)\bar{d}_N(x_N) + \frac{4}{9}u_\pi(x_\pi)\bar{u}_N(x_N) + \frac{1}{9}\bar{d}_\pi(x_\pi)d_N(x_N)\right]$$

Valence × Valence

Valence-sea ×¼

Sea-Sea

Beam	Target	Experiment
Hadron	Beam valence quarks target antiquarks	Fermilab E-906, RHIC (forward acpt.) J-PARC
Anti-Hadron	Beam val. antiquarks Target valence quarks	GSI-FAIR Fermilab Collider
Meson	Beam val. antiquarks Target valence quarks	COMPASS

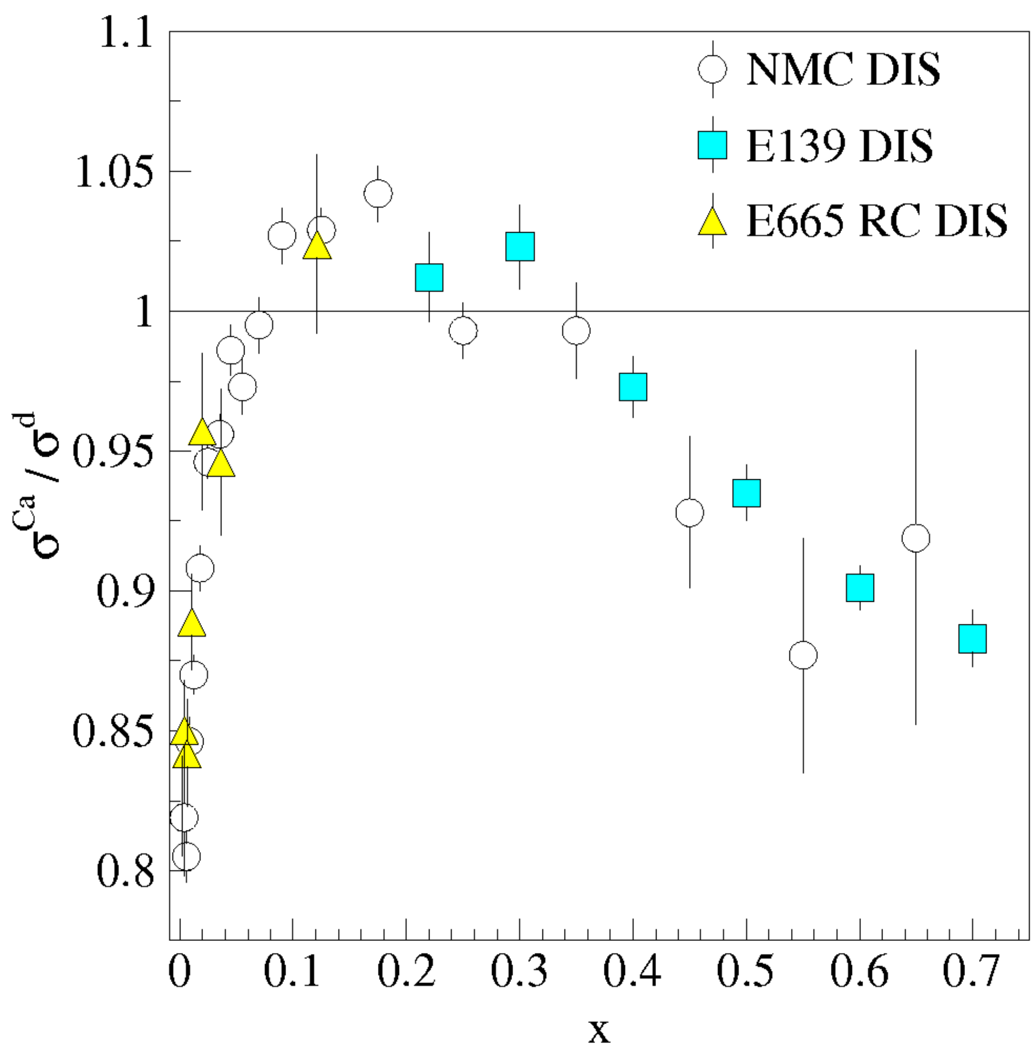
What can Drell-Yan tell us about the EMC effect?

Structure of nucleonic matter: The EMC effect

Comparison with
Deep Inelastic Scattering (DIS)

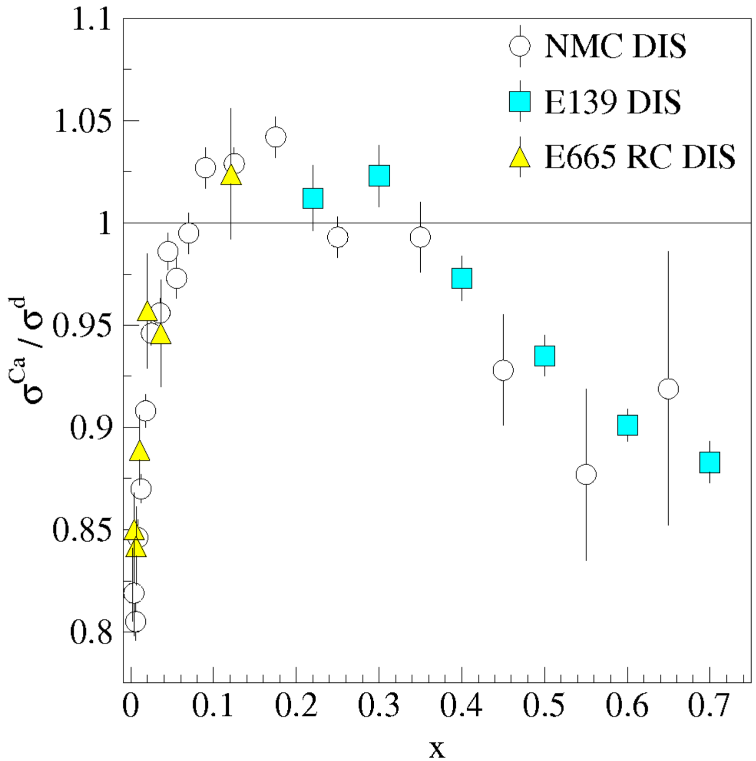
- EMC: Parton distributions of bound and free nucleons are different.

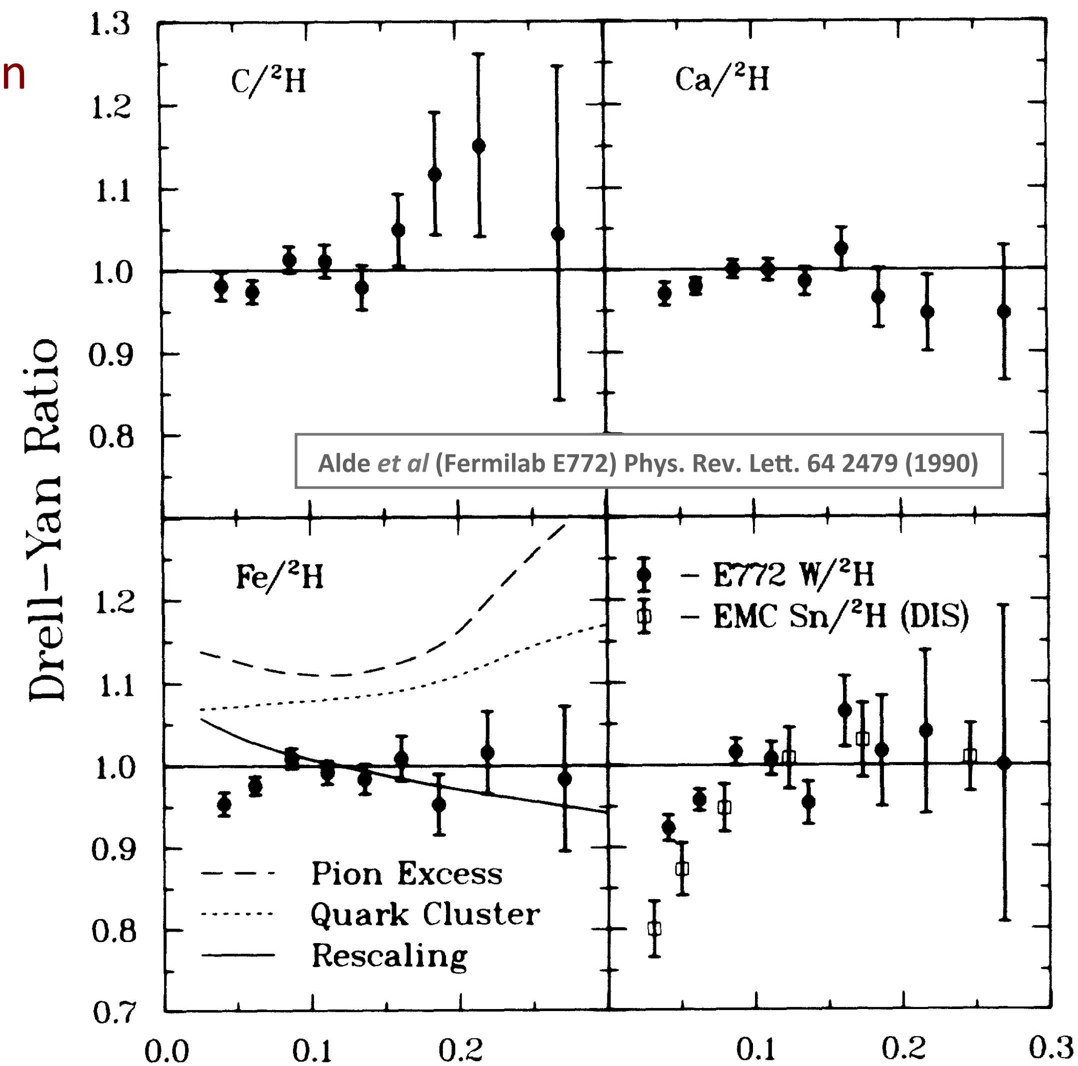
- Nuclear binding effects distributions of quarks within the nucleons



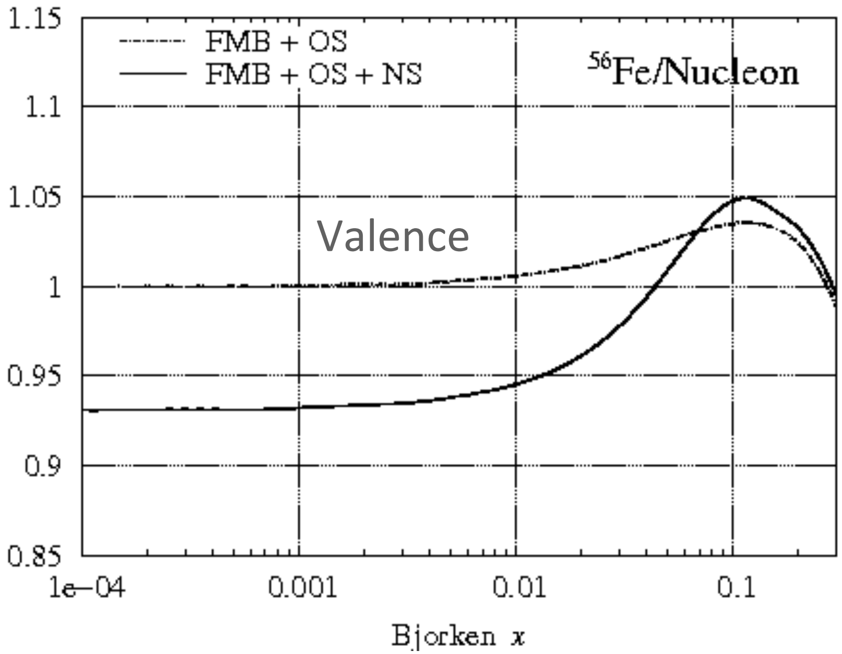
Structure of nucleonic matter: How do DIS and Drell-Yan data compare?

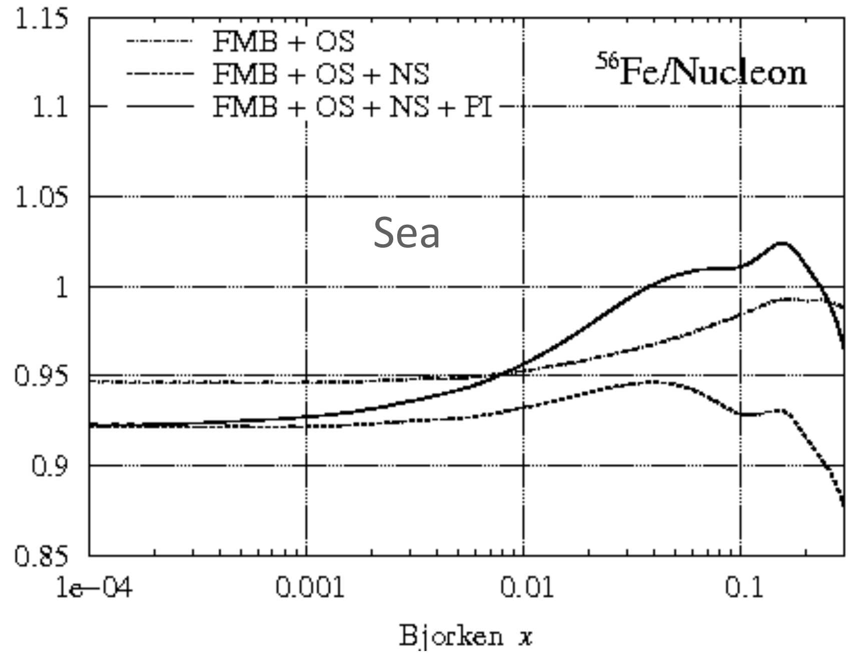
- Shadowing present in Drell-Yan
- Antishadowing not seen in Drell-Yan
  —Valence only effect





Kulagin and Petti sea vs. valence nuclear effects

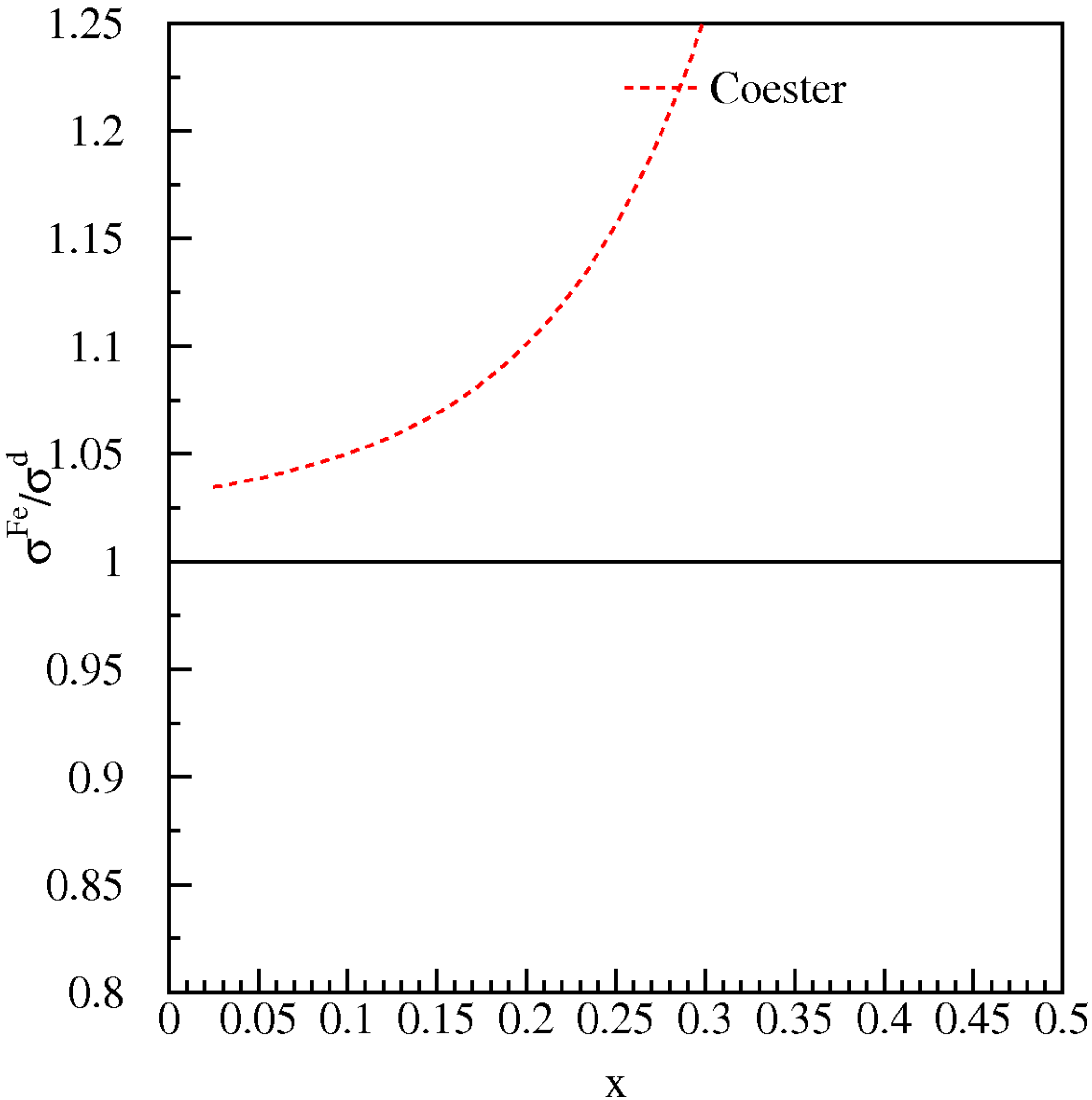




Nuclear Physics A 765 (2006) 126–187

Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.



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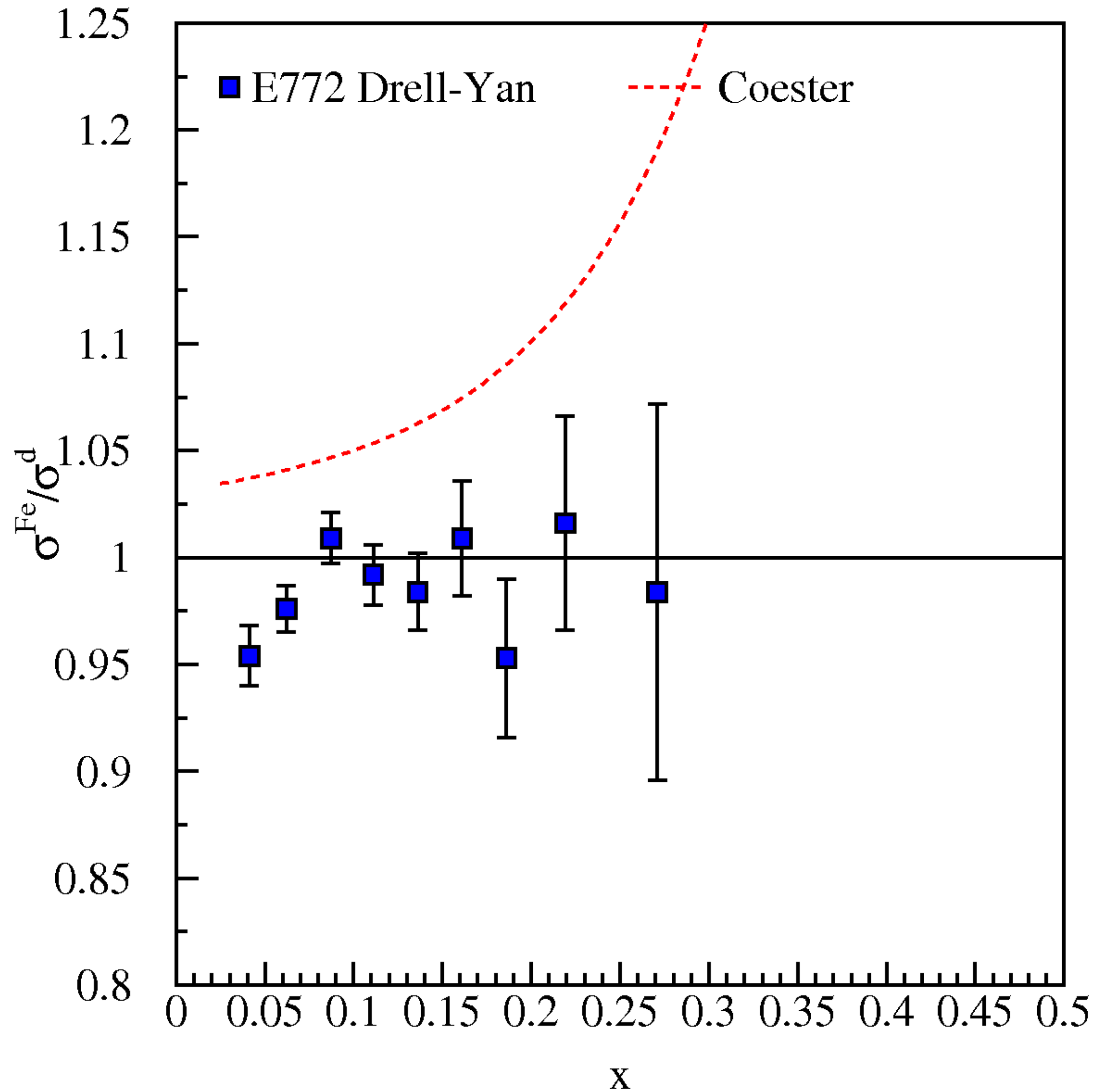
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.



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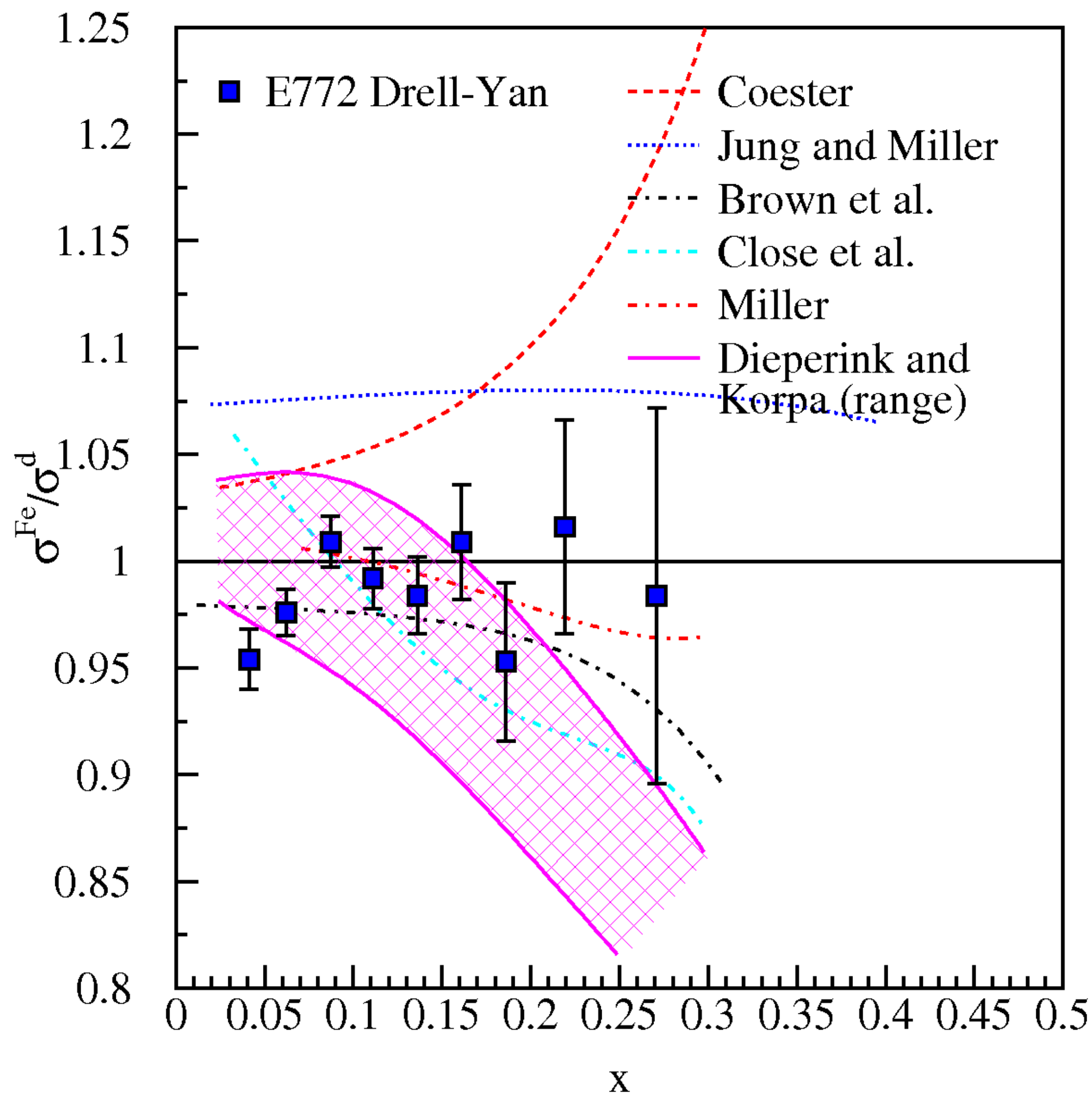
- Contemporary models predict large effects to antiquark distributions as x increases.
- **Models must explain both DIS-EMC effect and Drell-Yan**



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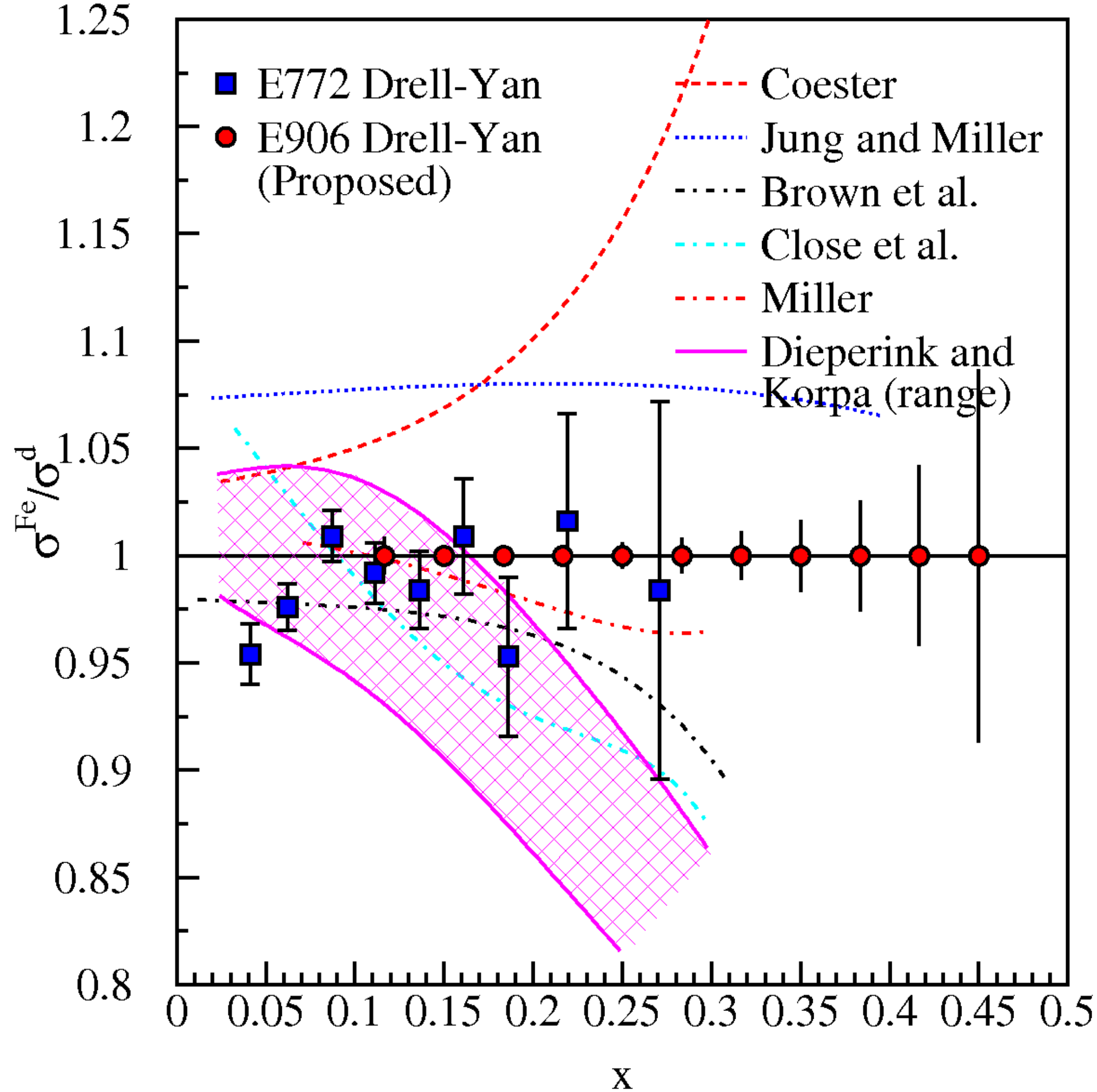
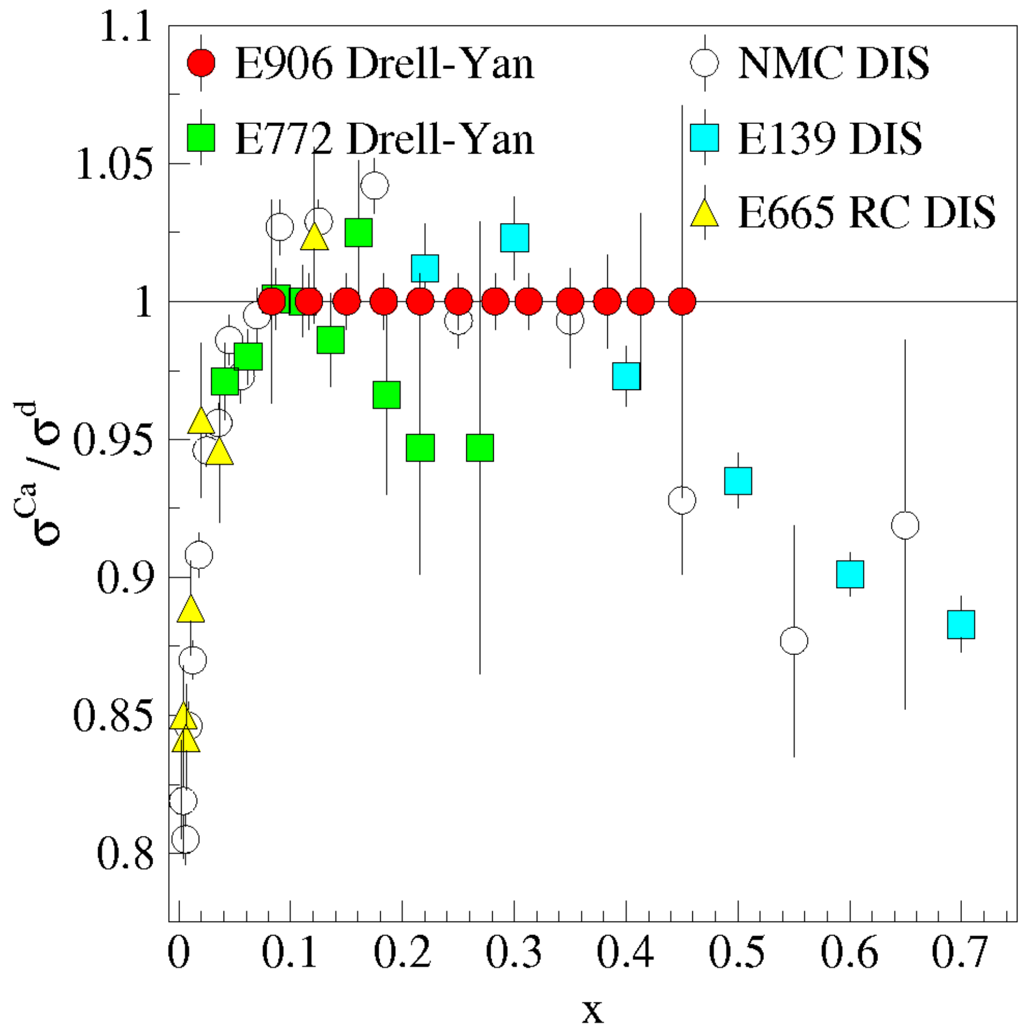


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Intermediate-*x* *sea* PDF's

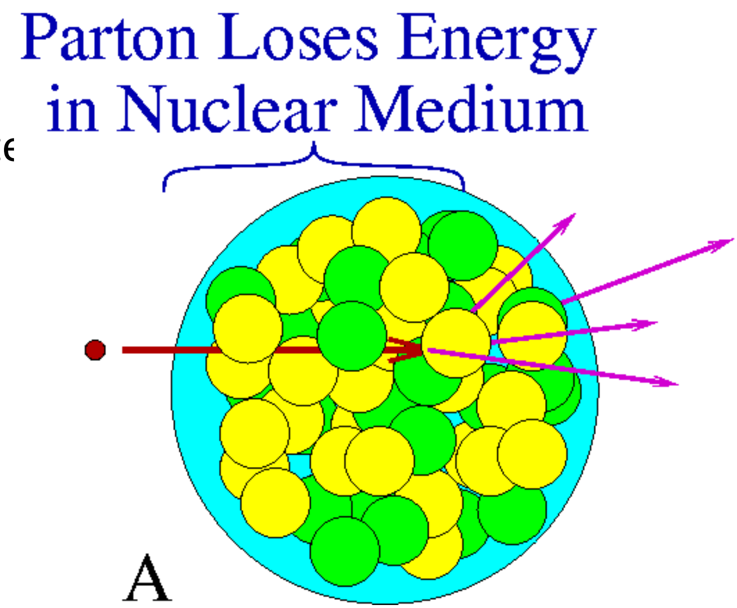
- ν-DIS on iron—Are nuclear effects with the weak interaction the same as electromagnetic?
- Are nuclear effects the same for sea and valence distributions

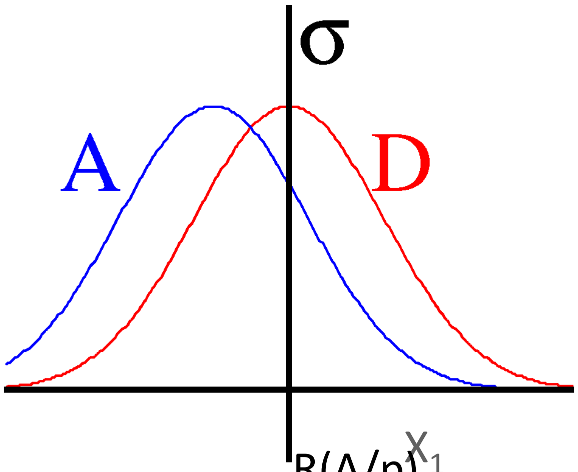


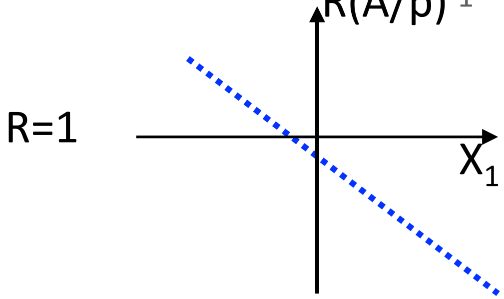
Partonic energy loss in Cold Nuclear Matter

Partonic Energy Loss

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

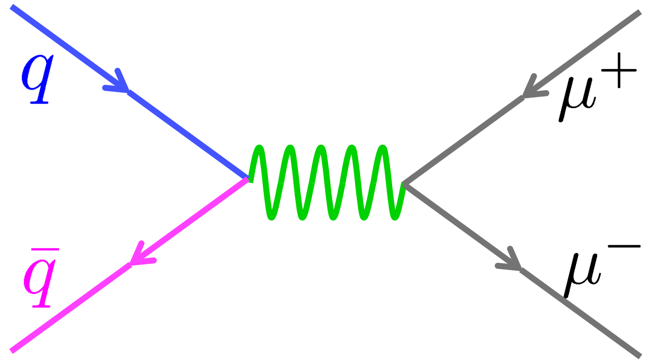






- Models:
  - Galvin and Milana $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

Event Reconstruction



- We measure
  1. Direction of particles
  2. Absolute momentum of particles
- We assume
  3. Particles are muons

(Items 1–2: momentum vector; items 1–3: Relativistic energy-momentum vector ***P***)

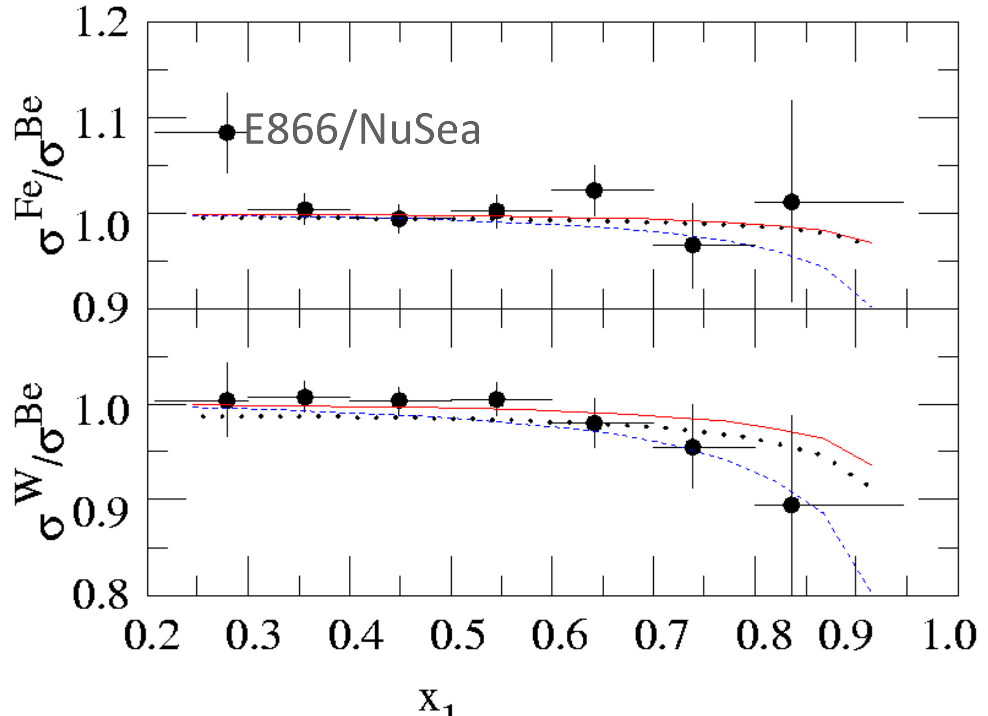
$$\vec{P}^2 \equiv m_\gamma^2 = x_t x_b s$$

$$\frac{p_l}{p_l^{\text{max.}}} = x_{\text{Feymann}} = x_b - x_t$$

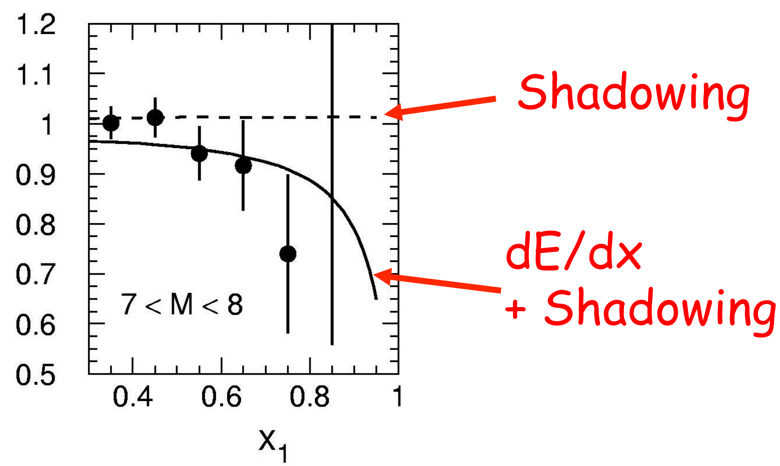
- Add 4-vectors of muons to get 4-vectors of virtual photon ***P***
  – Now we know everything

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
  - Analysis of our p-A Drell-Yan data using the Kopeliovich model.
  - **dE/dx = 2.32 ± 0.52 ± 0.5 GeV/fm**
  - 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

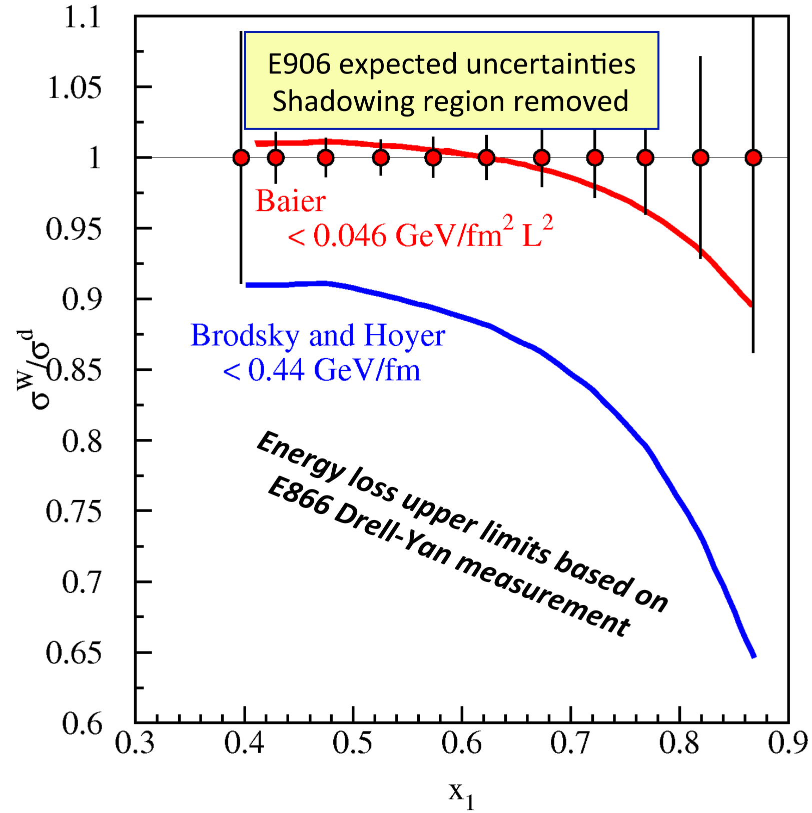


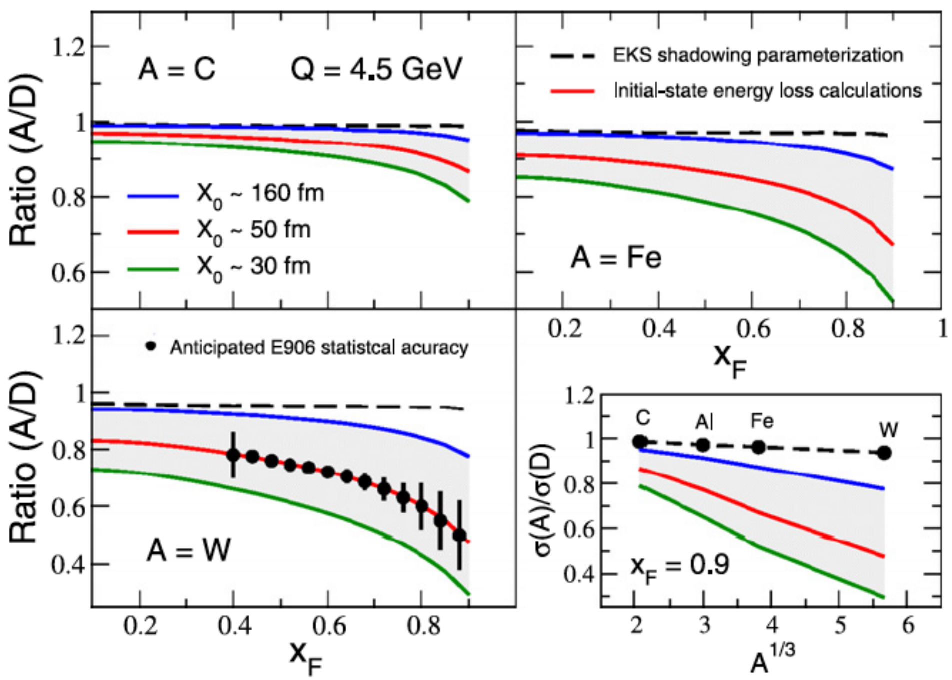
Johnson, Kopeliovich et al., PRL 86, 4483 (2001)



Parton Energy Loss

- Shift in Δx / 1/s
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits
- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample





- Shadowing vs. initial state energy loss
  R.B. Neufeld *et al.* Physics Letters B 704 (2011) 590–595

- Possible to distinguish between $A^{1/3}$ (collisional) and $A^{2/3}$ (radiative) dependence?

- Would like data at different **s**

Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^1H, ^2H, and nuclear targets
- 800 GeV proton beam

The future:

Fermilab E906

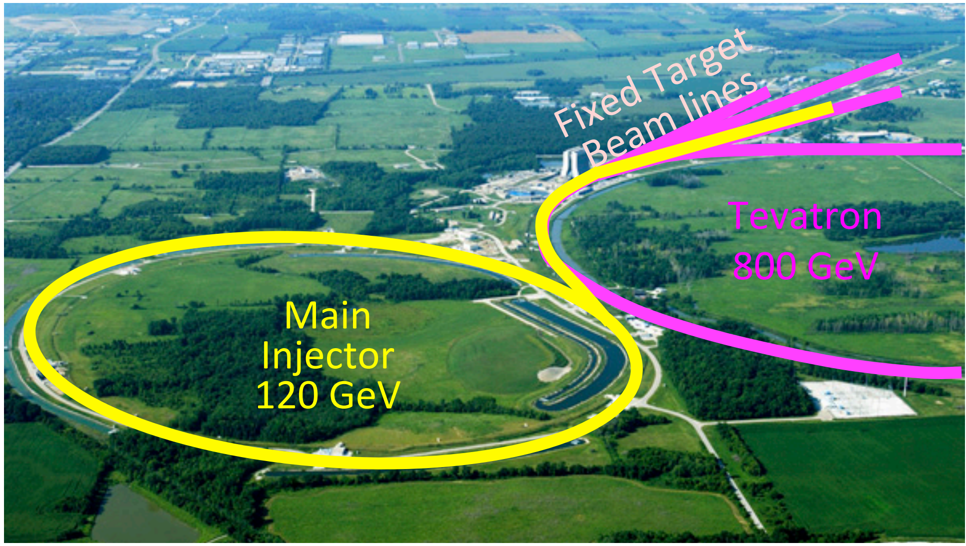
- First test run in 2011
- ^1H, ^2H, and nuclear targets
- 120 GeV proton Beam

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

- Cross section scales as 1/s
  - *7× that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7× Luminosity for same detector rate as 800 GeV beam*

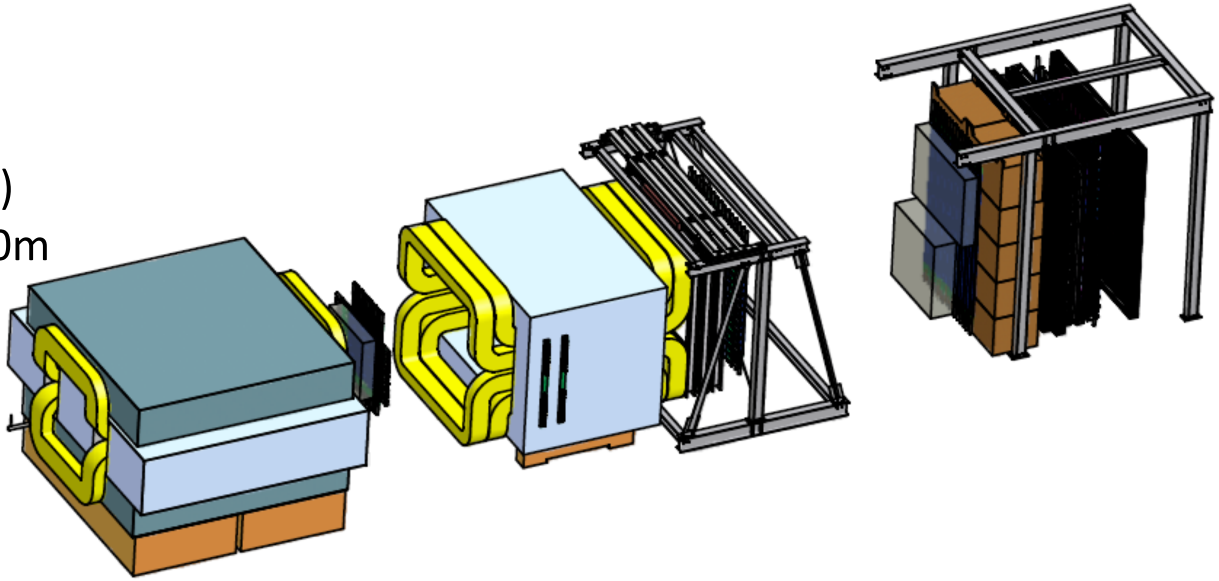
50× statistics!!

at the same x_t, x_b



Drell-Yan Spectrometer Guiding Principles

- Follow basic design of MEast spectrometer (don't reinvent the wheel):
  - Two magnet spectrometer
  - Beam dump within first magnet
  - Hadron absorber within first magnet
  - Muon-ID wall before final elements
- Where possible and practical, reuse elements of the E866 spectrometer.
  - Tracking chamber electronics
  - Hadron absorber, beam dump, muon ID walls
  - Station 2 and 3 tracking chambers
  - Hodoscope array PMT's
  - SM3 Magnet
- New Elements
  - 1^{st} magnet (different boost)
    Experiment shrinks from 60m to 26m
  - Sta. 1 tracking (rates)
  - Scintillator (age)
  - Trigger (flexibility)



Fermilab E906/Drell-Yan Collaboration

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Academia Sinica
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KEK
Shin'ya Sawada

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Gerry Garvey, Mike Leitch, Han Liu, Ming Liu, Pat McGaughey, Joel Moss, Andrew Puckett

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Betsy Beise, Kazutaka Nakahara

University of Michigan
Christine Aidala, Wolfgang Lorenzon, Richard Raymond, Josh Rubin, Michael Stewart

National Kaohsiung Normal University
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RIKEN
Yoshinori Fukao, Yuji Goto, Atsushi Taketani, Manabu Togawa

Rutgers University
Lamiaa El Fassi, Ron Gilman, Ron Ransome, Brian Tice, Ryan Thorpe, Yawei Zhang

Tokyo Tech
Shou Miyaska, Ken-ichi Nakano, Florian Sanftl, Toshi-Aki Shibata

Yamagata University
Yoshiyuki Miyachi

*Co-Spokespersons

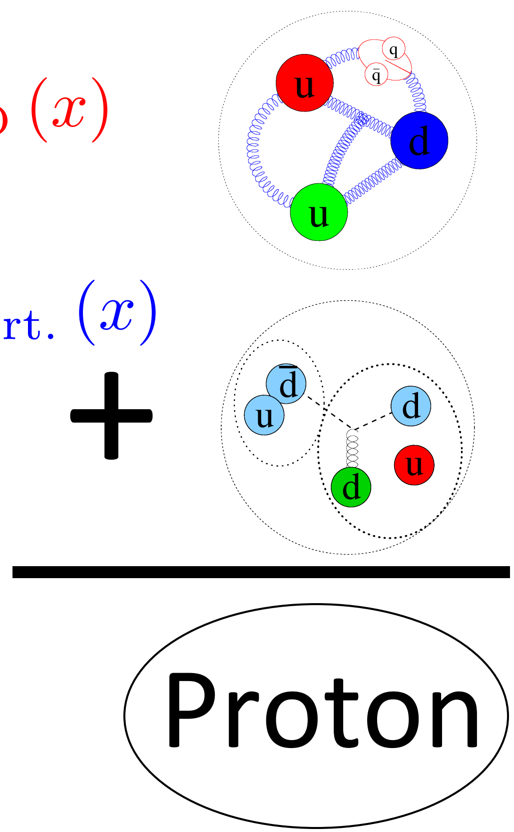
SeaQuest E-906 pp and pD physics

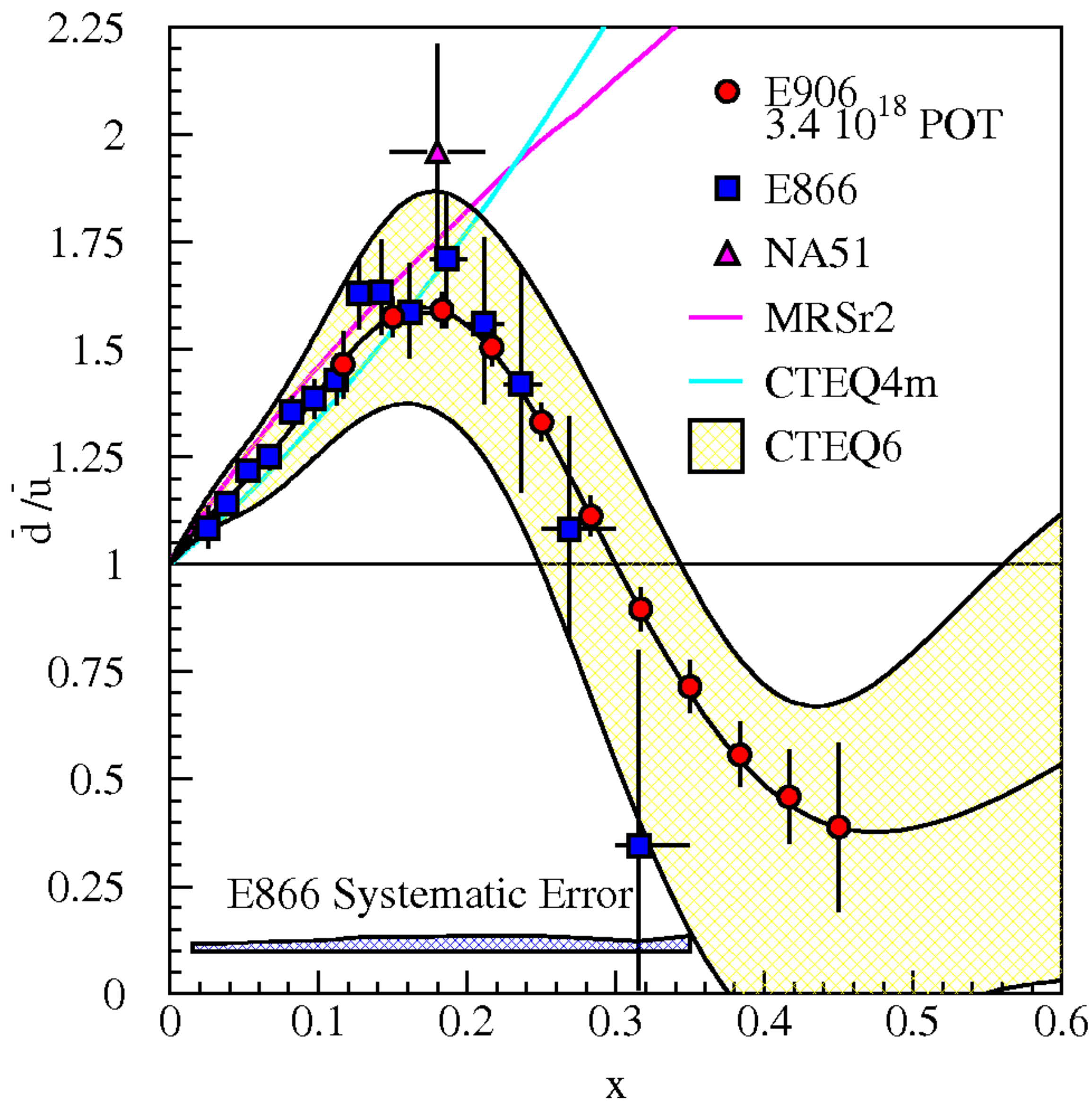
- Non perturbative QCD models can explain excess d-bar quarks, but no return to symmetry or deficit of d-bar quarks

$\bar{q}_{\text{pQCD}}(x)$

$\bar{q}_{\text{NonPert.}}(x)$

+



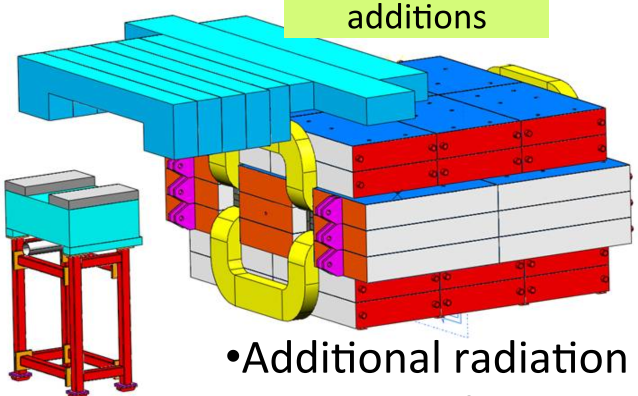


Time Line

1999 — Proposed to Fermilab
2000
2001 — Approved w/ conditions
2002 2003 2004 2005
2006 — Fermilab PAC reaffirms approval
2007
2008 — Funding Approval

2008 — Funding Approval
2009
2010
2011
2012 — Run 1 / Comission
Fermilab upgrade
2013 — Main Run

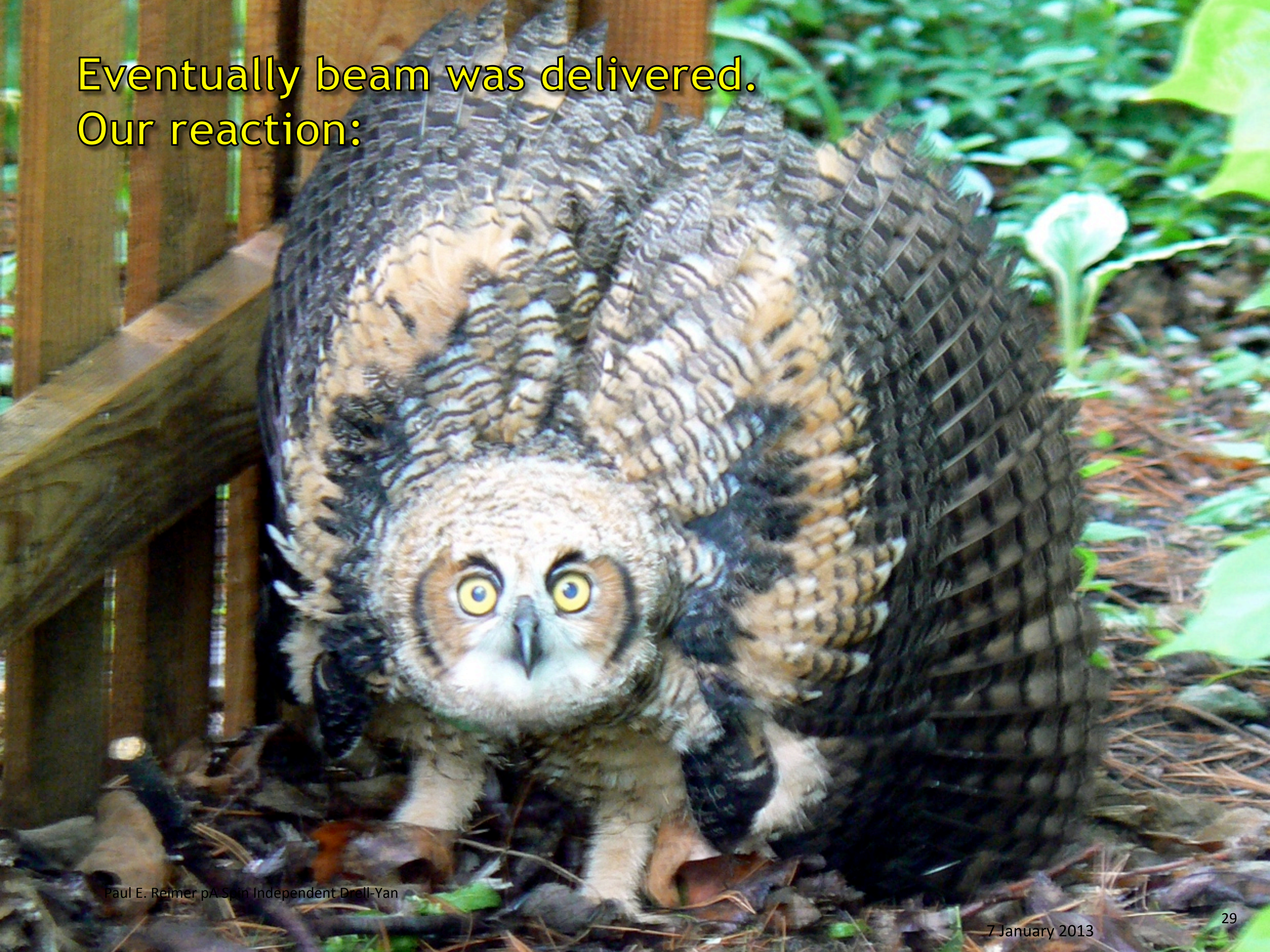
Spectrometer construction
upgrades
Beam Line Problems
Vacuum Leak
Filled w/ concrete
Repairs
more repairs
Shielding additions



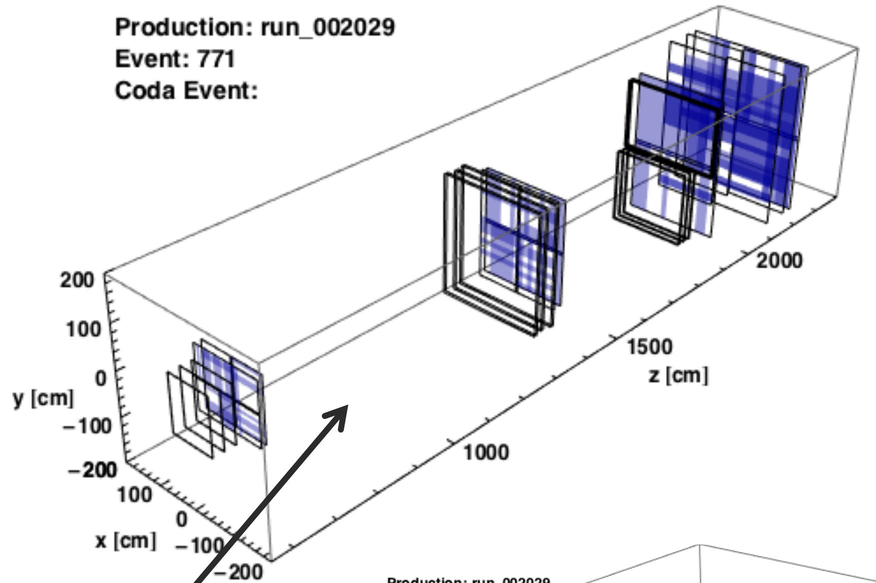
- Additional radiation shielding required
- 500 tons of concrete and steel
- 14 tons of steel on movable cart

Eventually beam was delivered. Our reaction:

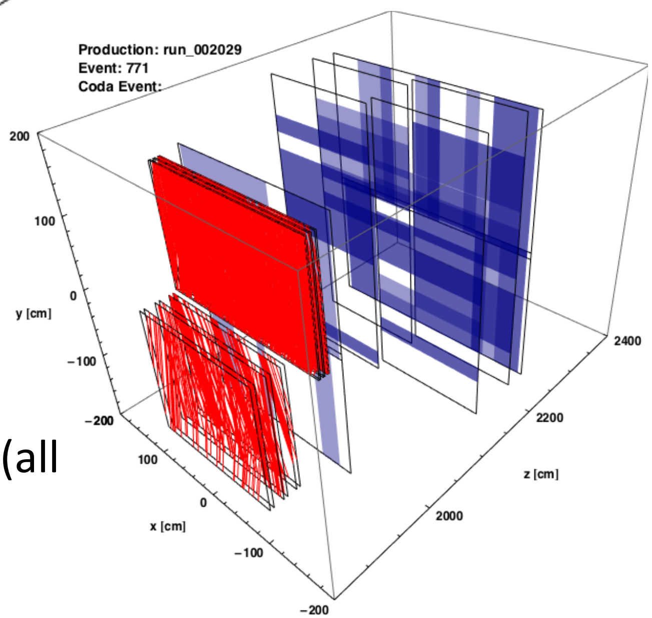
Eventually beam was delivered.
Our reaction:



“Splat” Events



full detector (hodoscope hits)



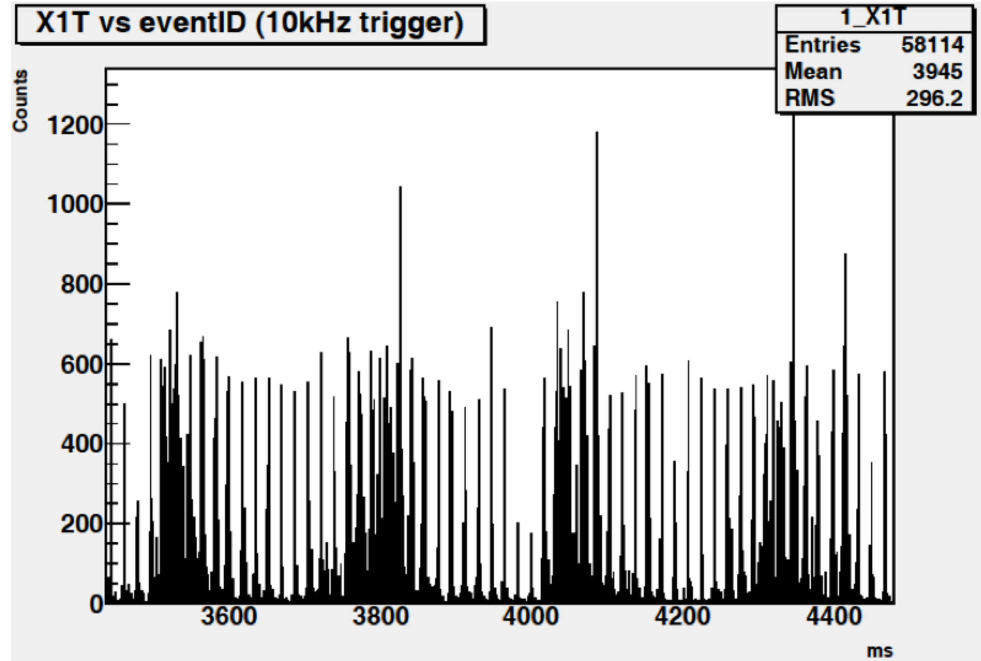
Stations 3+4 (all hits)

Symptoms and Clues:

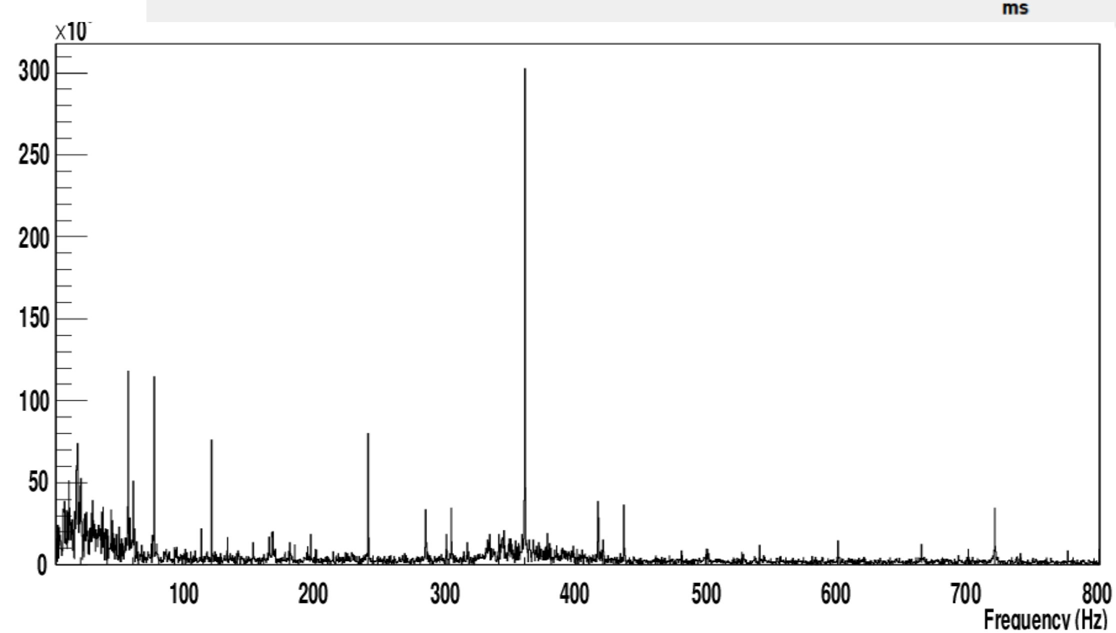
- Very large hit multiplicity for dimuon trigger events for both matrix and simple NIM triggers
- All systems: hodoscopes, chambers, and prop. tubes swamped
- *Average* intensity normal, measured by beamline instrumentation

from Josh Rubin, U. Michigan

Understanding the Beam

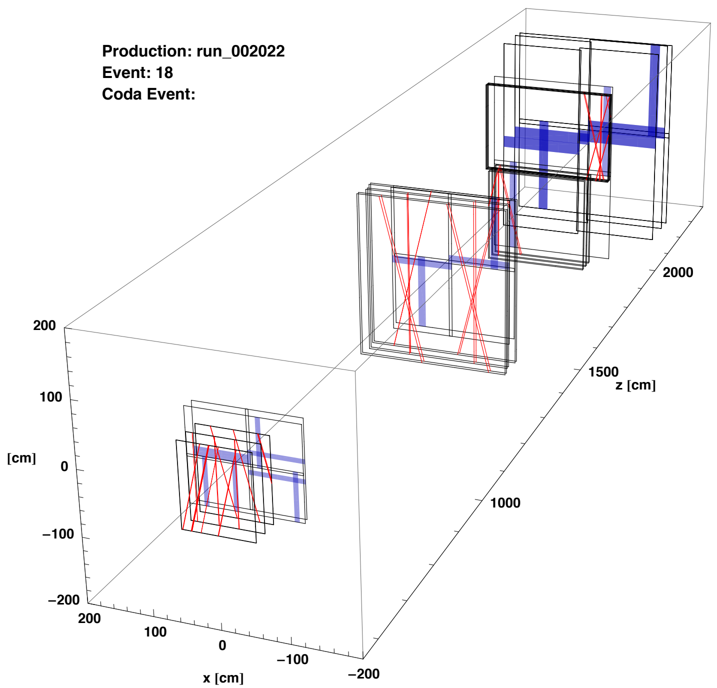


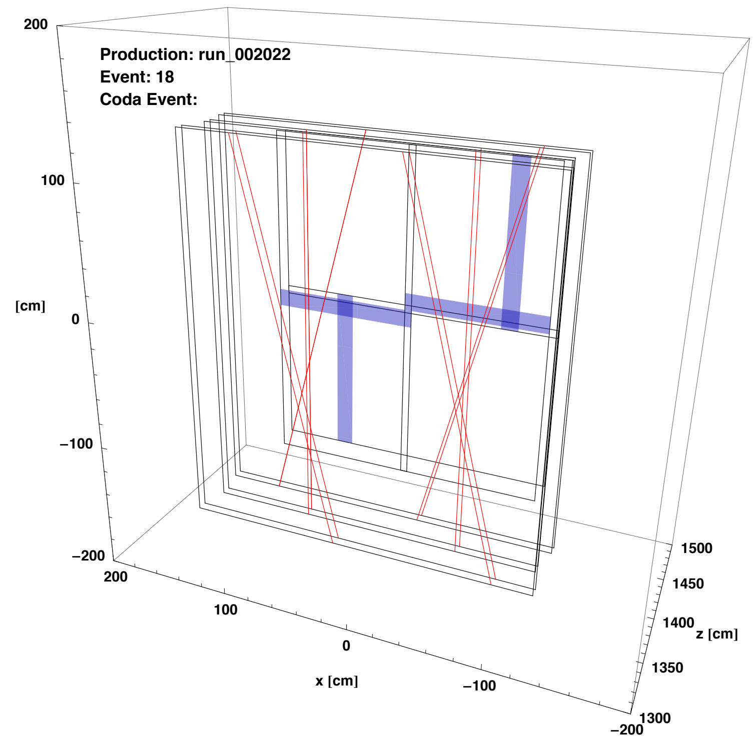
- Independent 10kHz pulsed DAQ read out raw hodoscope rates
- Bins are integrated counts over 100μs (≈5000 RF buckets)
- Large variation in Instantaneous intensity, duty factor very low.
- Periodic structure
- Frequency phase locked to AC line 60 Hz



The Splat-Block Card

- A card was developed to keep a running average of the multiplicity over a 160 ns window (8 RF buckets).
- If average multiplicity above threshold, raises a trigger veto
- Luminosity greatly reduced, but trigger suppresses windows of time with large beam intensities.





from Josh Rubin, U. Michigan

Commissioning (beam line and spectrometer) Run (~two months)

- First protons arrived March 8, 2012, Run ended April 30, 2012
- **All systems worked!**
  - Typical issues with mapping and timing resolved quickly
  - Some challenges with TDC microcode – modules rolled-back to a prior software version, zero-suppression moved to VME CPUs→relatively long dead-times
- Unexpectedly large hit multiplicities with dimuon trigger – termed **"splat events"**

Where do we go from here?

- **Better Beam Quality**
  - Fermilab is has gotten this message
  - mistuned 720 Hz harmonic suppression (was suppressing 680)
  - Better 60 Hz AC filtering on all power supplies
  - Completely revamped control and feedback system
  - Other improvements

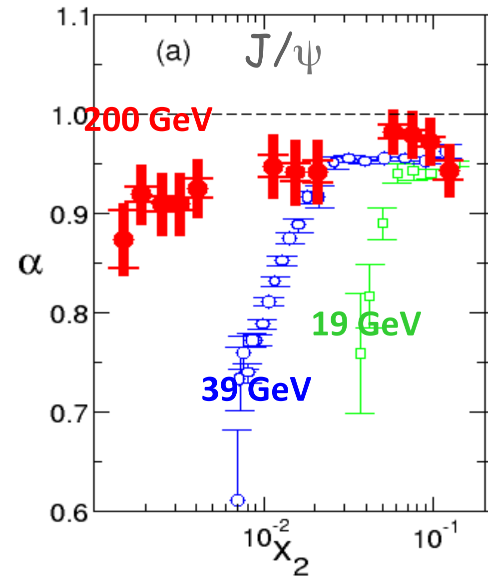
- **Experimental Improvements**
  - TDC Micro code improvements—less dead time, pipelining?
  - Cherenkov Beam monitor for better splat block
  - New St. 1 and St. 3- for better rate capabilities
  - Phototube bases optimized for rate rather than linearity

pA Drell-Yan at RHIC?

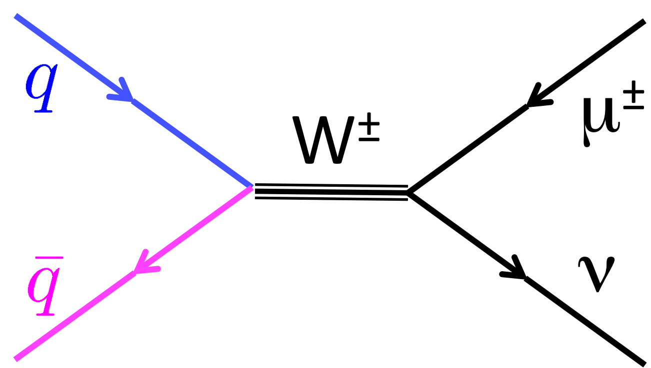
- What about the J/ψ and ψ'?
  - **See talk by Mike Leitch in 1st session**
  - E906/SeaQuest does not have sufficient resolution to see the ψ'
- Possibly easier to select kinematical regions to emphasize quarks or antiquarks in proton or Nucleus.
- di-leptons may be hard to see/separate from background
- Use $W^{\pm}$ or Z^{0} instead of γ^{*}
  - Easy to identify
  - Necessarily correlates x_1 x_2:

$$s x_1 x_2 \equiv M_W^2$$

  - For $W^{\pm}$–difficult to reconstruct x_1 x_2 since ν is unseen

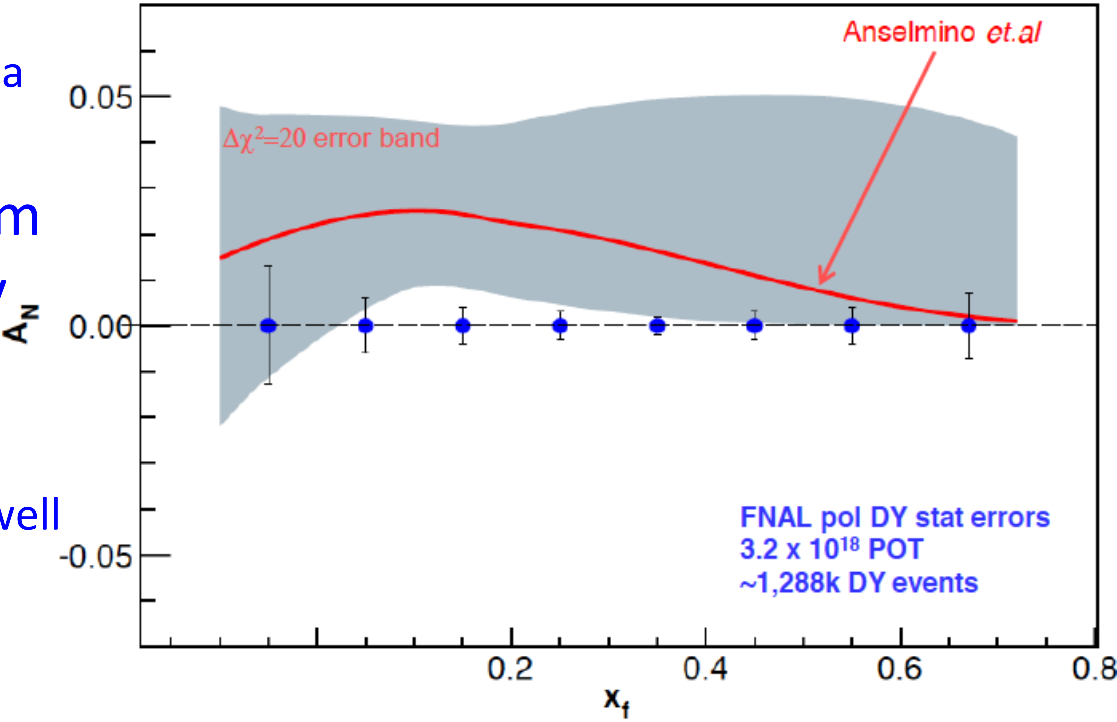


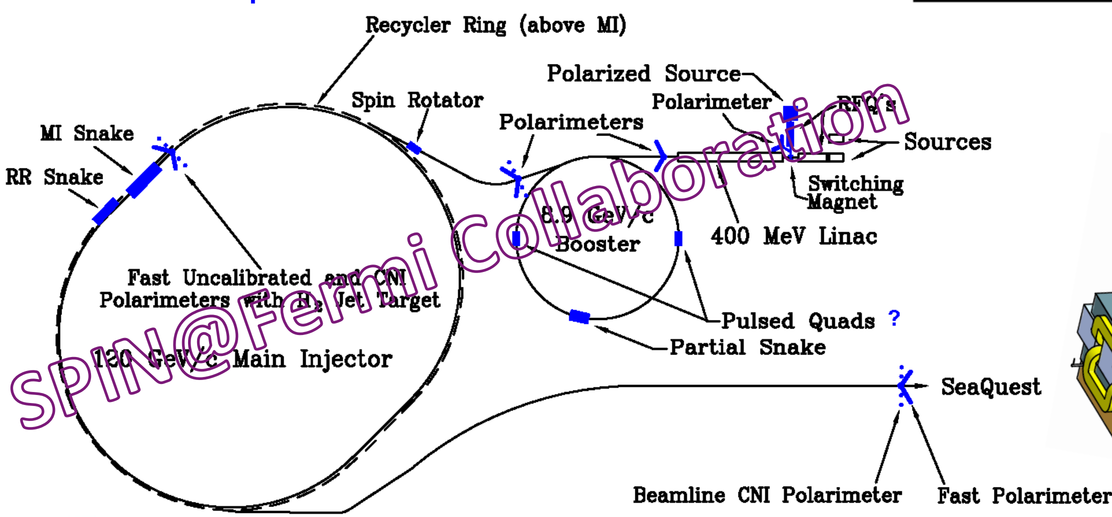
J/ψ suppression doesn't scale like shadowing



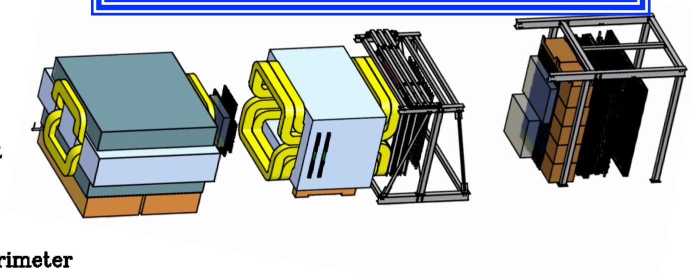
Polarized Drell-Yan@Fermilab Main Injector

- Polarized beam
  - Major advantage—the beam is a blow torch—Luminosity
  - Major disadvantage—the beam polarization is presently ***virtual***—only a proposal
- Spectrometer:
  - By 2014, spectrometer will be well understood, including angular acceptance





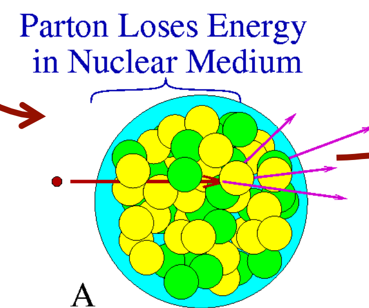
Exploring polarized target
- sea quark Sivers'

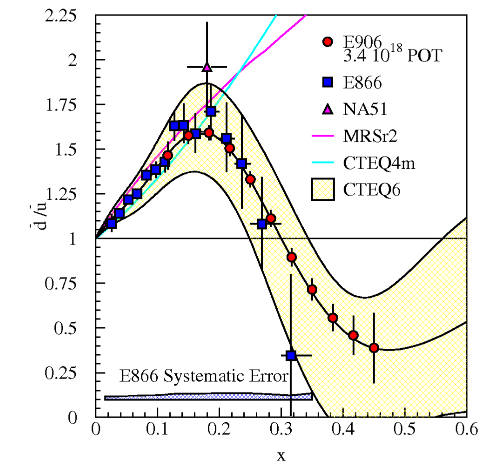


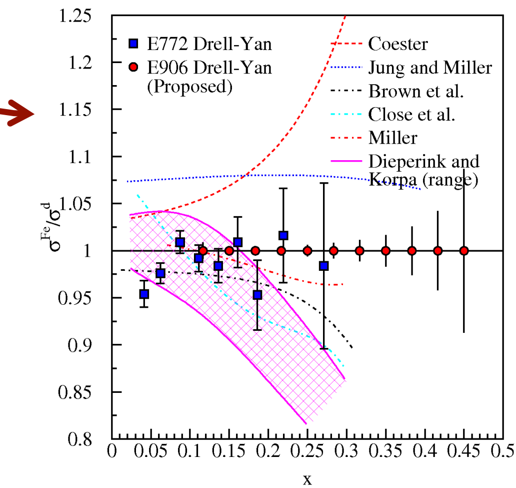
Conclusion—not yet

Unpolarized pA collisions can offer unique insight into

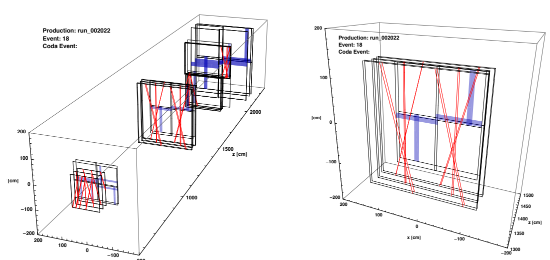
- EMC Effect
- Partonic Energy Loss







Fermilab E-906/SeaQuest spectrometer works, waiting for beam



Fermilab may also provide laboratory for pA physics