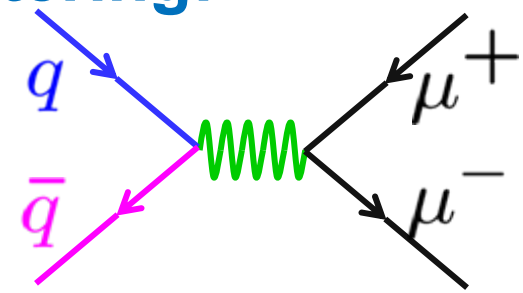
Argonne NATIONAL LABORATORY

... for a brighter future

Exploring the Antiquark Structure of Matter with Drell-Yan Scattering: Fermilab E-906/Drell-Yan

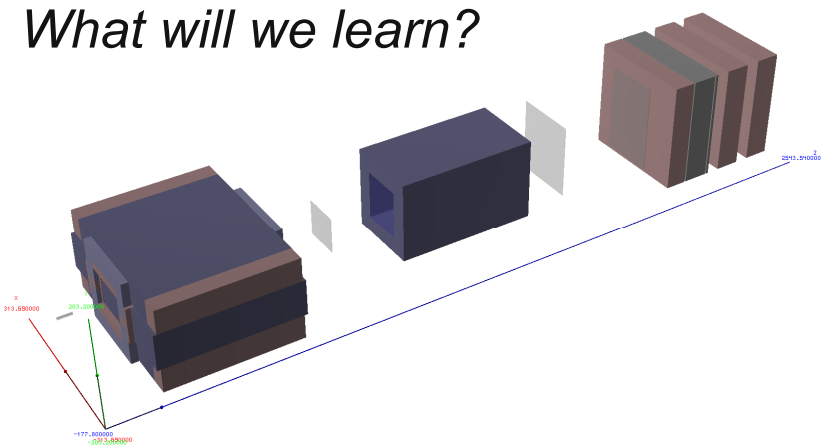


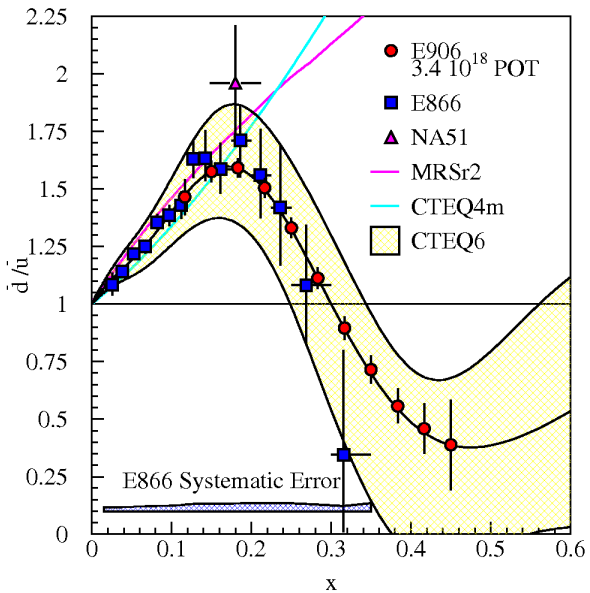
Paul E. Reimer
Argonne National Laboratory
Representing the Fermilab E-906/Drell-Yan collaboration

Why Drell-Yan?

Where will we measure it?

What will we learn?





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

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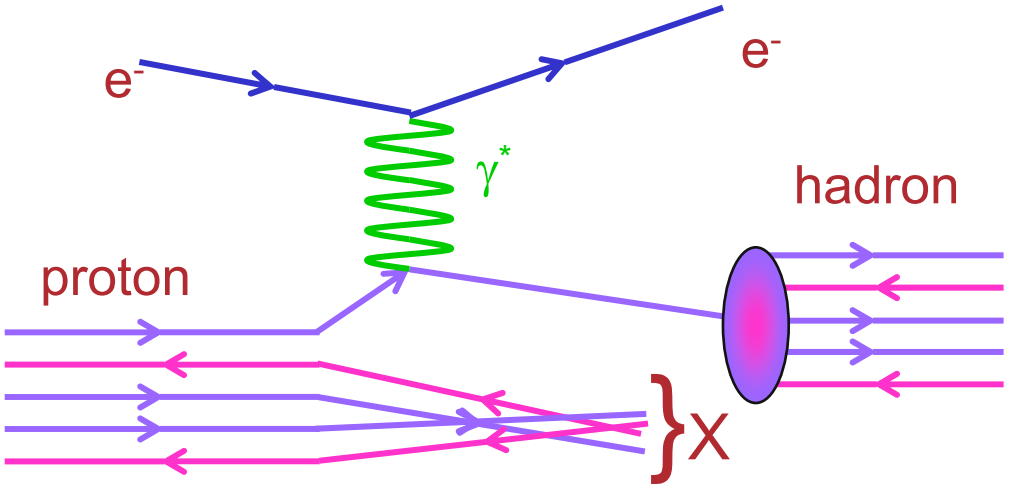
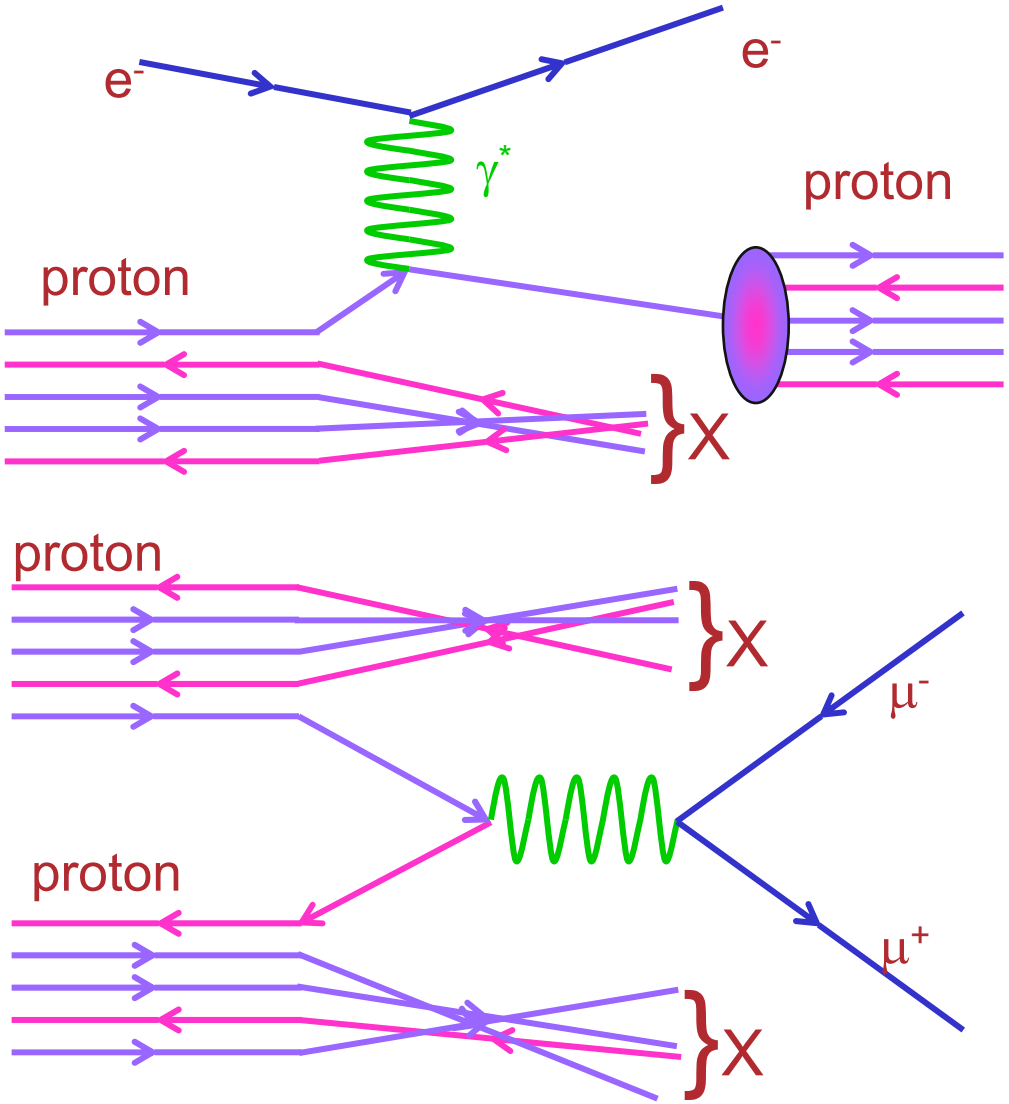
Why talk about Drell-Yan at JLab?



- Similar Physics Goals
  - Parton level understanding of nucleon
  - Electromagnetic probe

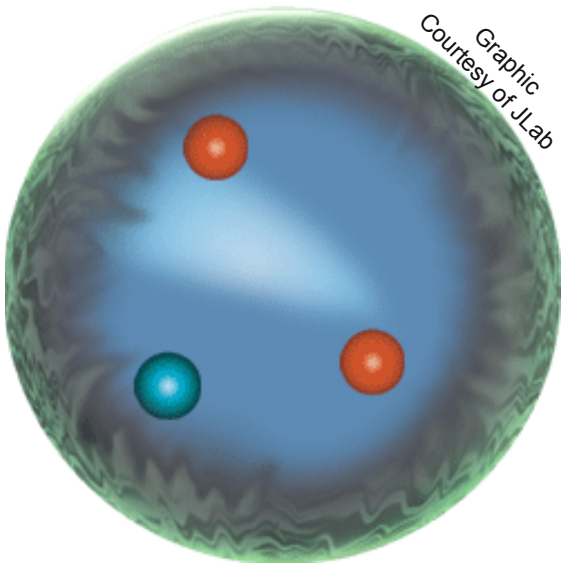
Why talk about Drell-Yan at JLab?



- Similar Physics Goals
  - Parton level understanding of nucleon
  - Electromagnetic probe
- Differences
  - Timelike (Drell-Yan) vs. spacelike (DIS) virtual photon.
  - Hadron beam and convolution of parton distributions (Drell-Yan)
  - Factorazion/Hadronization (SI-DIS)
  - Ability to select sea quark distributions

What's in the proton?

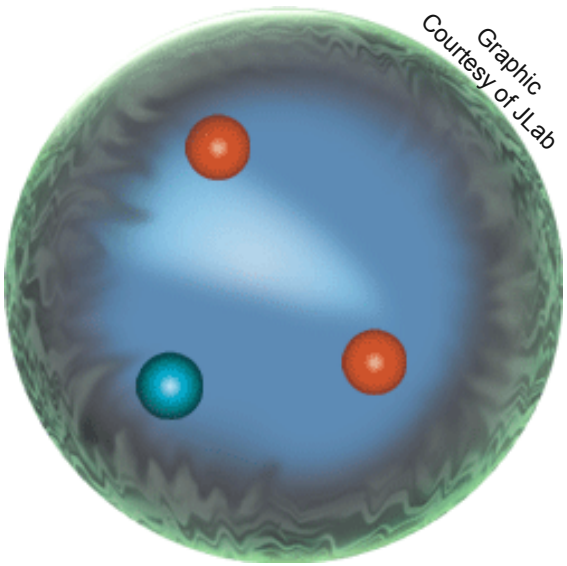
http://www.sciencecartoonsplus.com/index.htm



Graphic Courtesy of JLab

- Just three valence quarks?

What's in the proton?



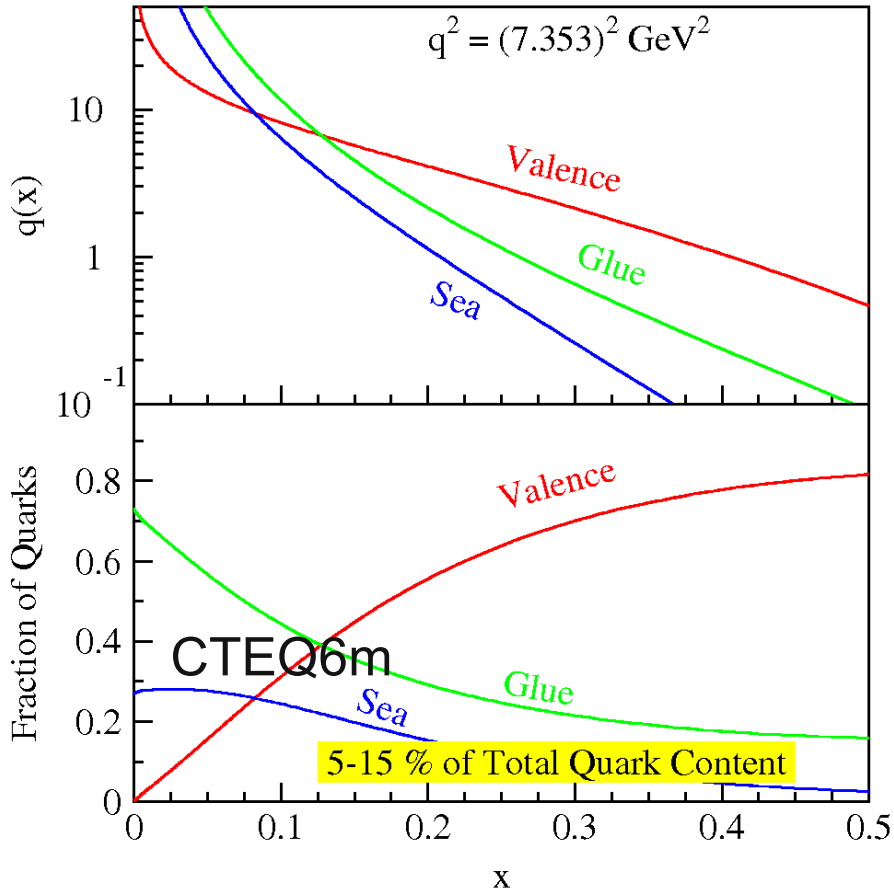
http://www.sciencecartoonsplus.com/index.htm

- Just three valence quarks?
- NO!!
- And quark distributions change in a nucleus

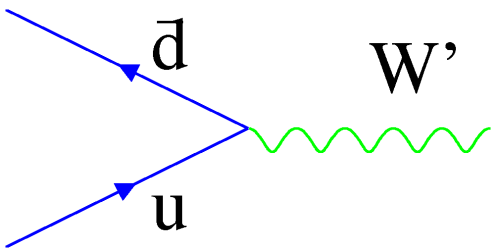
What is the distribution of sea quarks?

In the nucleon:

- Sea and gluons are important:
  - 98% of mass; 60% of momentum at $Q^2 = 2\ GeV^2$



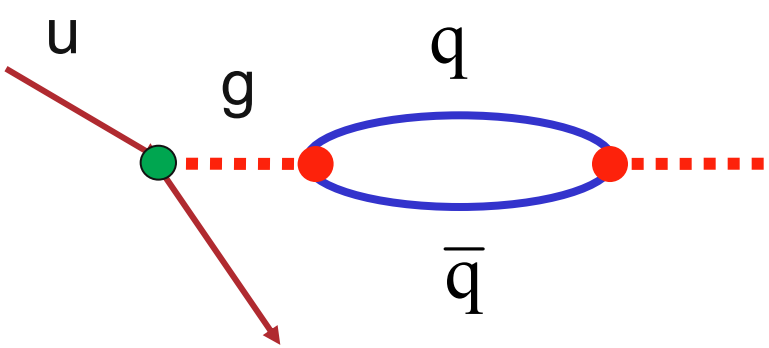
- Not just three valence quarks and QCD. Shown by E866/NuSea d-bar/u-bar data
- What are the origins of the sea?
- Significant part of LHC beam.



In nuclei:

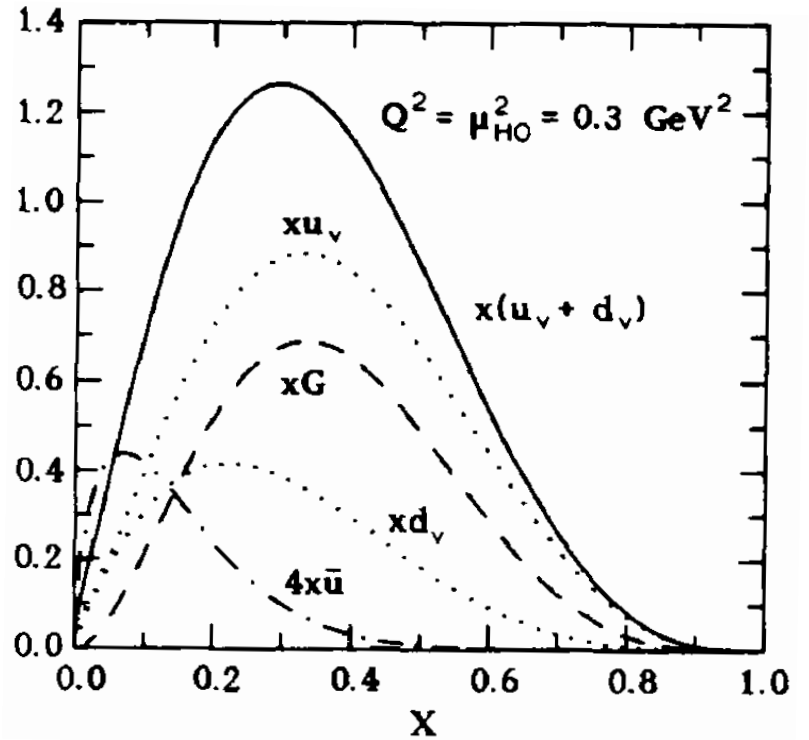
- The nucleus is not just protons and neutrons
- What is the difference?
  - Bound system
  - Virtual mesons affects antiquarks distributions

Simple view of parton distributions: A historic approach



- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Radiatively generate sea and glue. Gluck, Godbole, Reya, ZPC **41** 667 (1989)

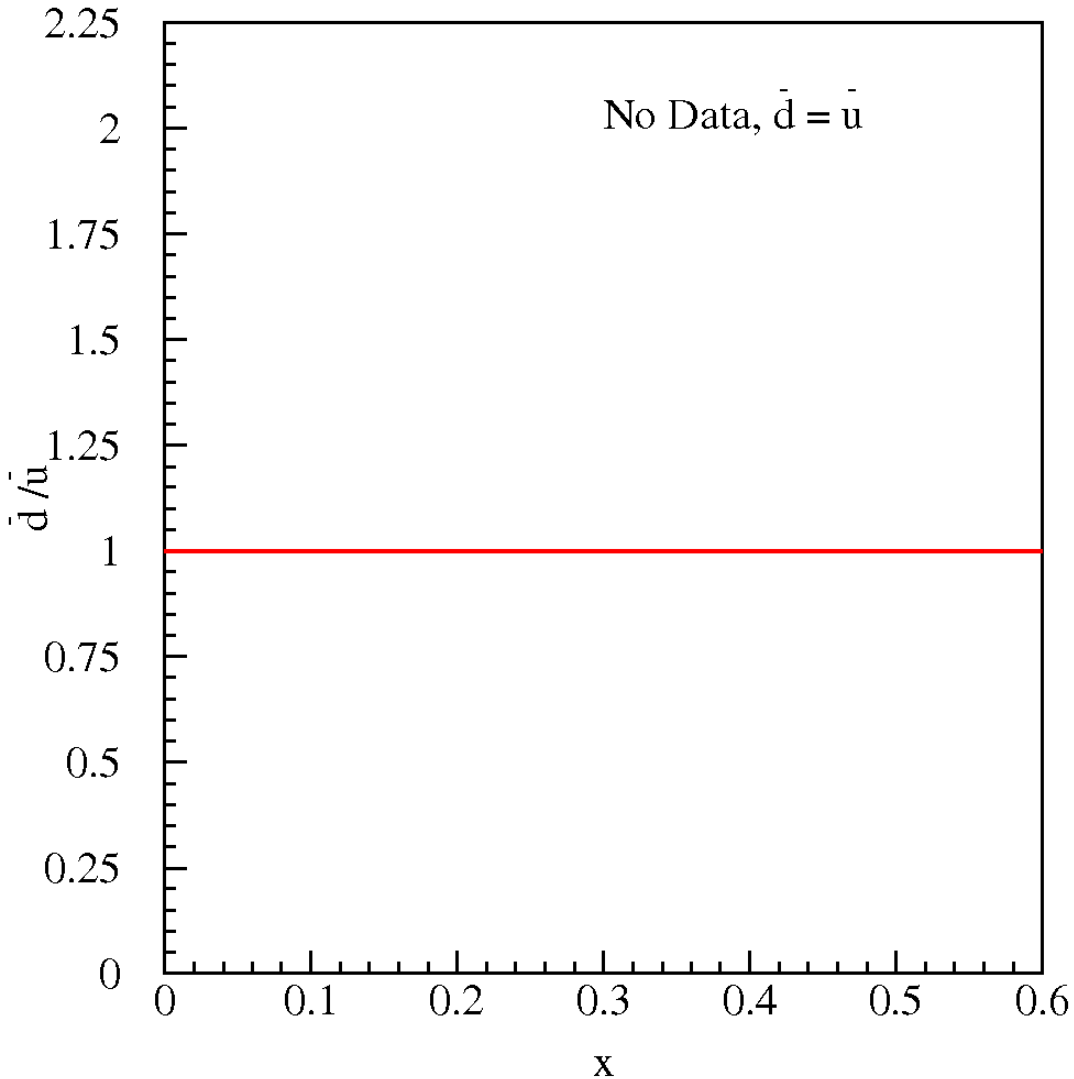
- It was quickly realized that some valence-like (primordial) sea was needed. Gluck, Reya, Vogt, ZPC 53, 127 (1992)
  - Driven by need to agree with BCDMS and EMC data
  - Assumption of symmetric sea remained



Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$



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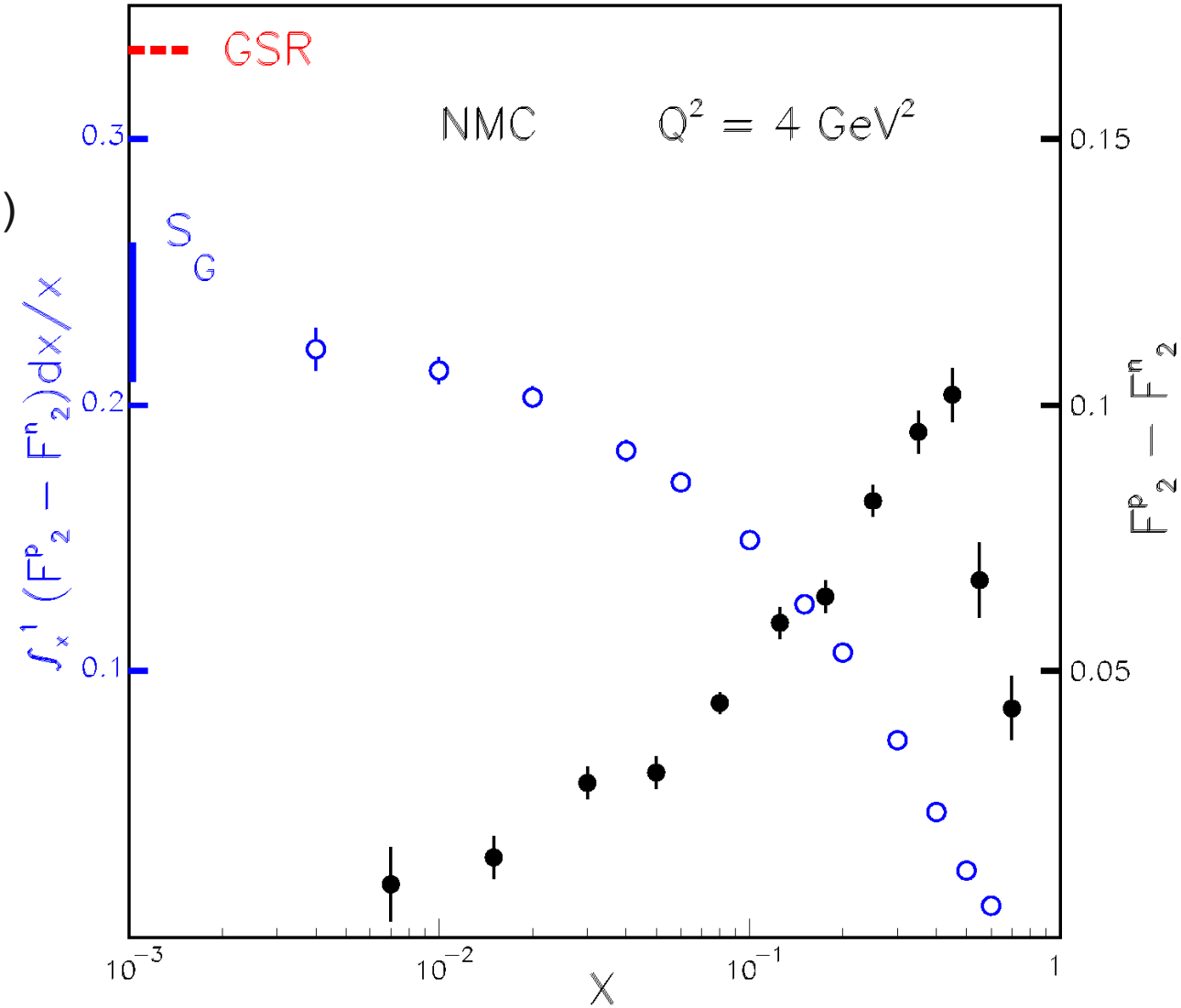
$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$



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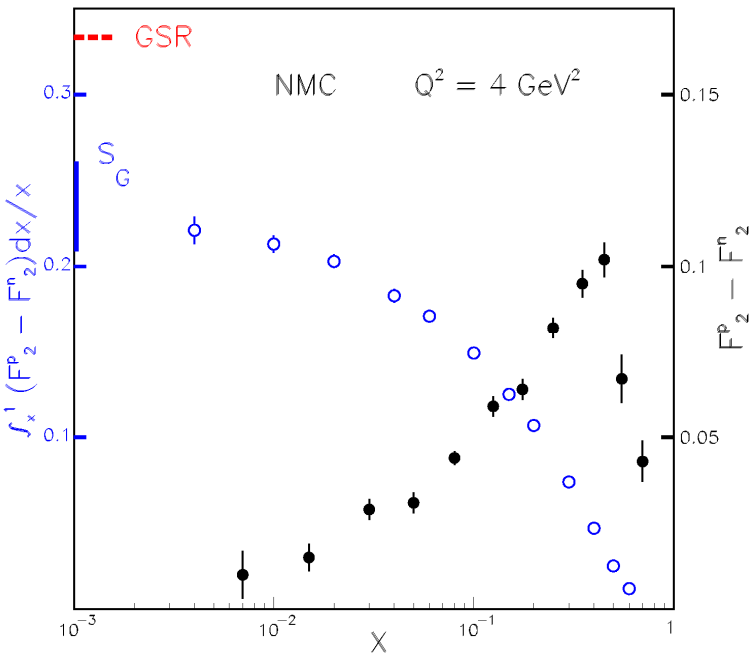

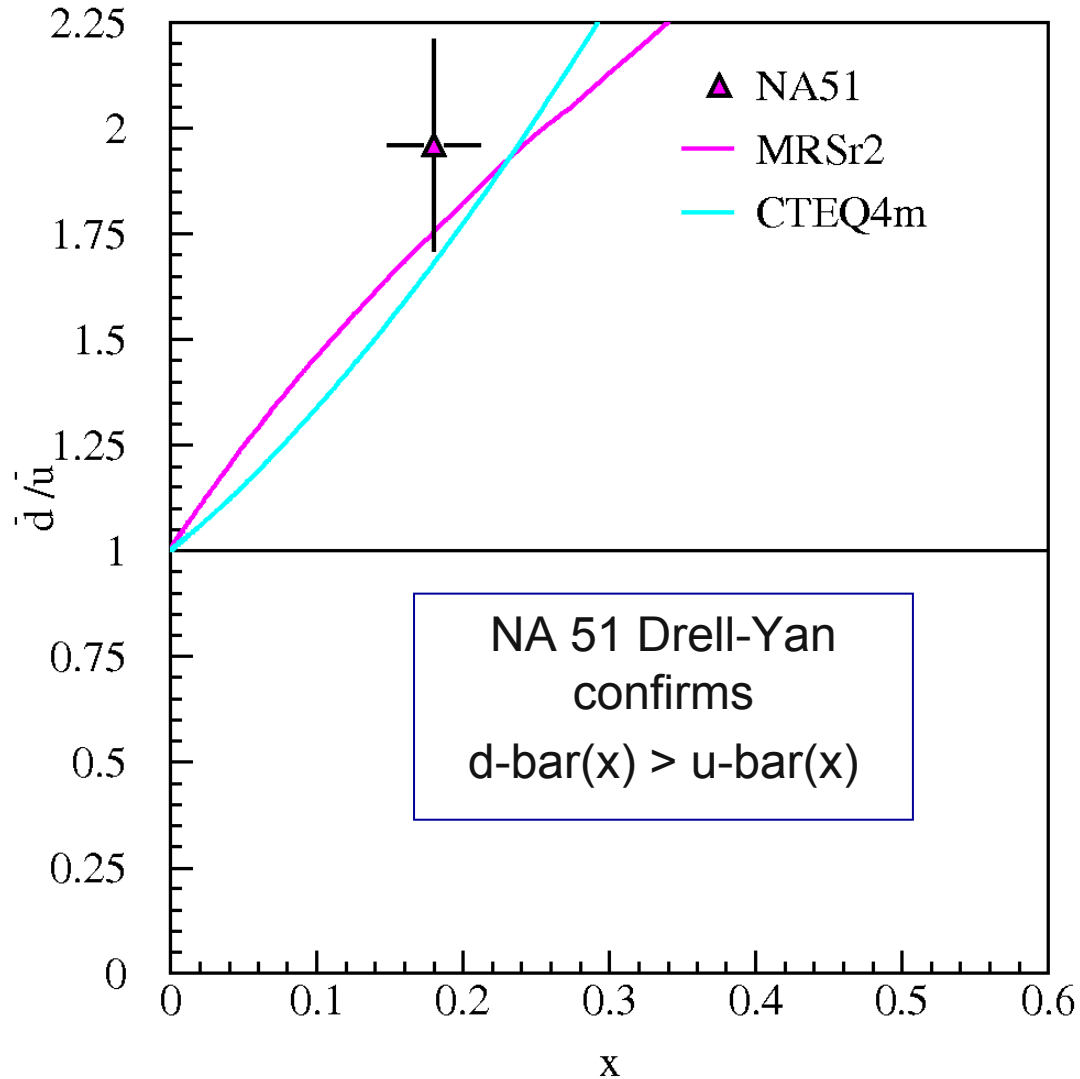

NA 51 Drell-Yan confirms d-bar(x) > u-bar(x)

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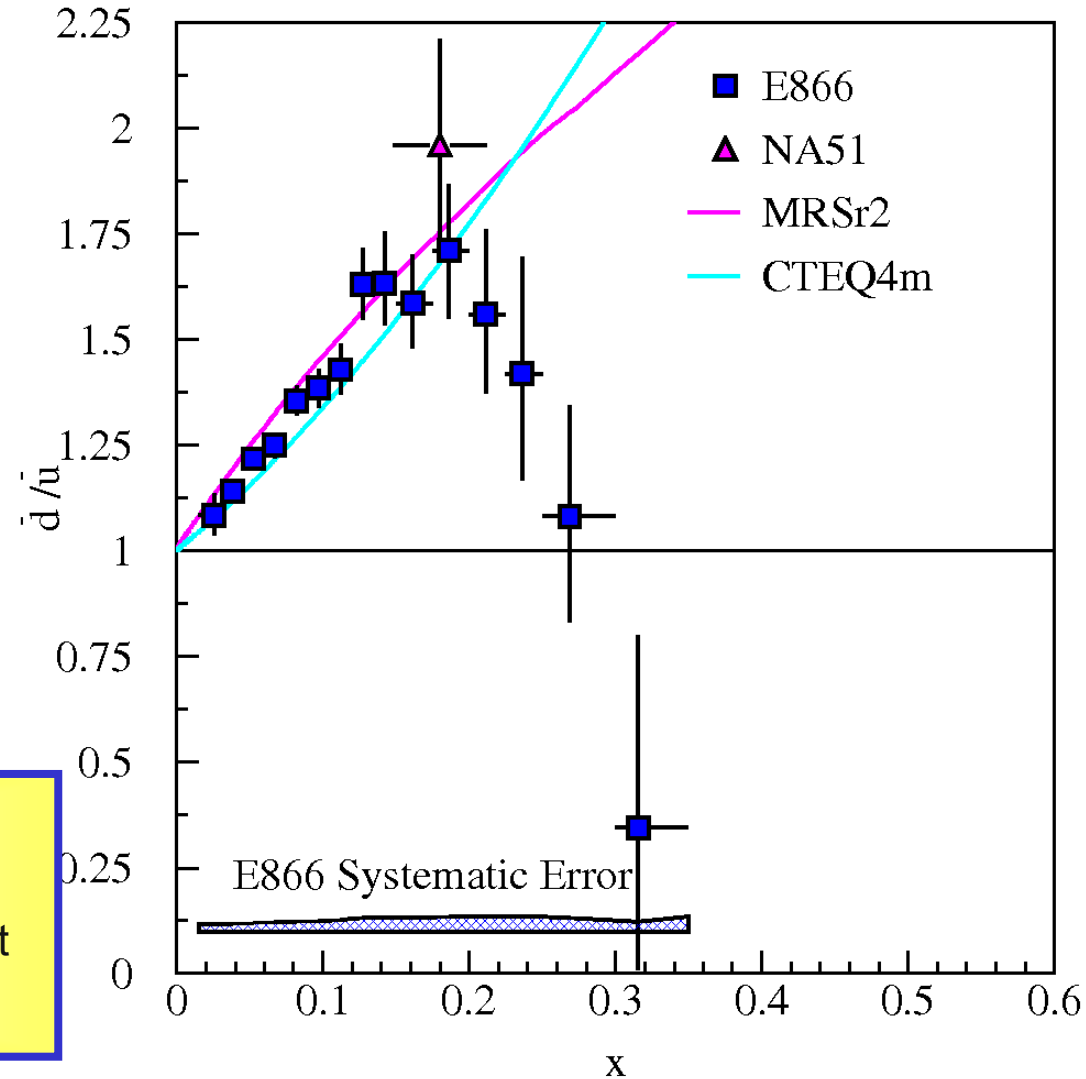
- NA51 (Drell-Yan)

$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- E866/NuSea (Drell-Yan)

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$



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  - Sea quark distributions are difficult for Lattice QCD

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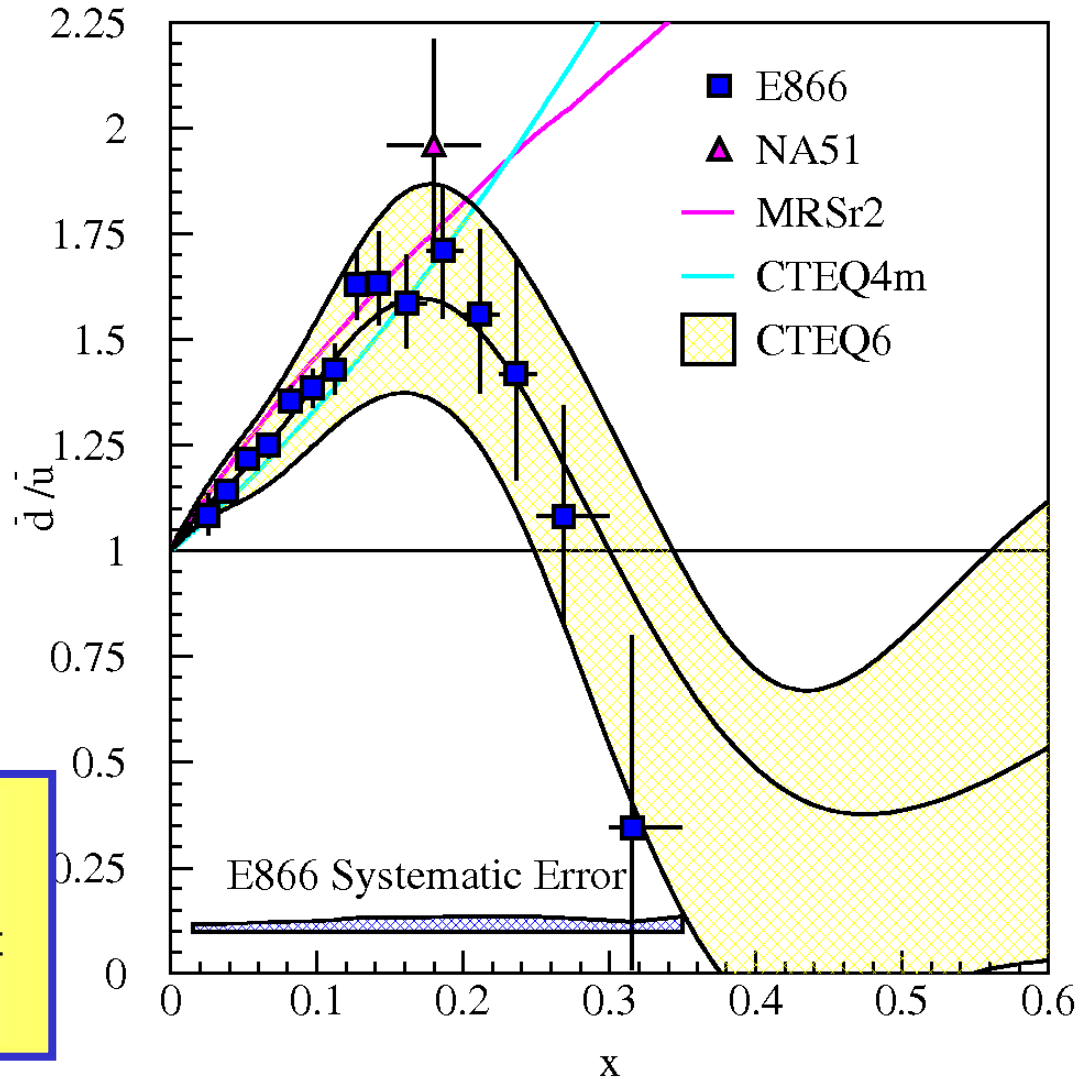

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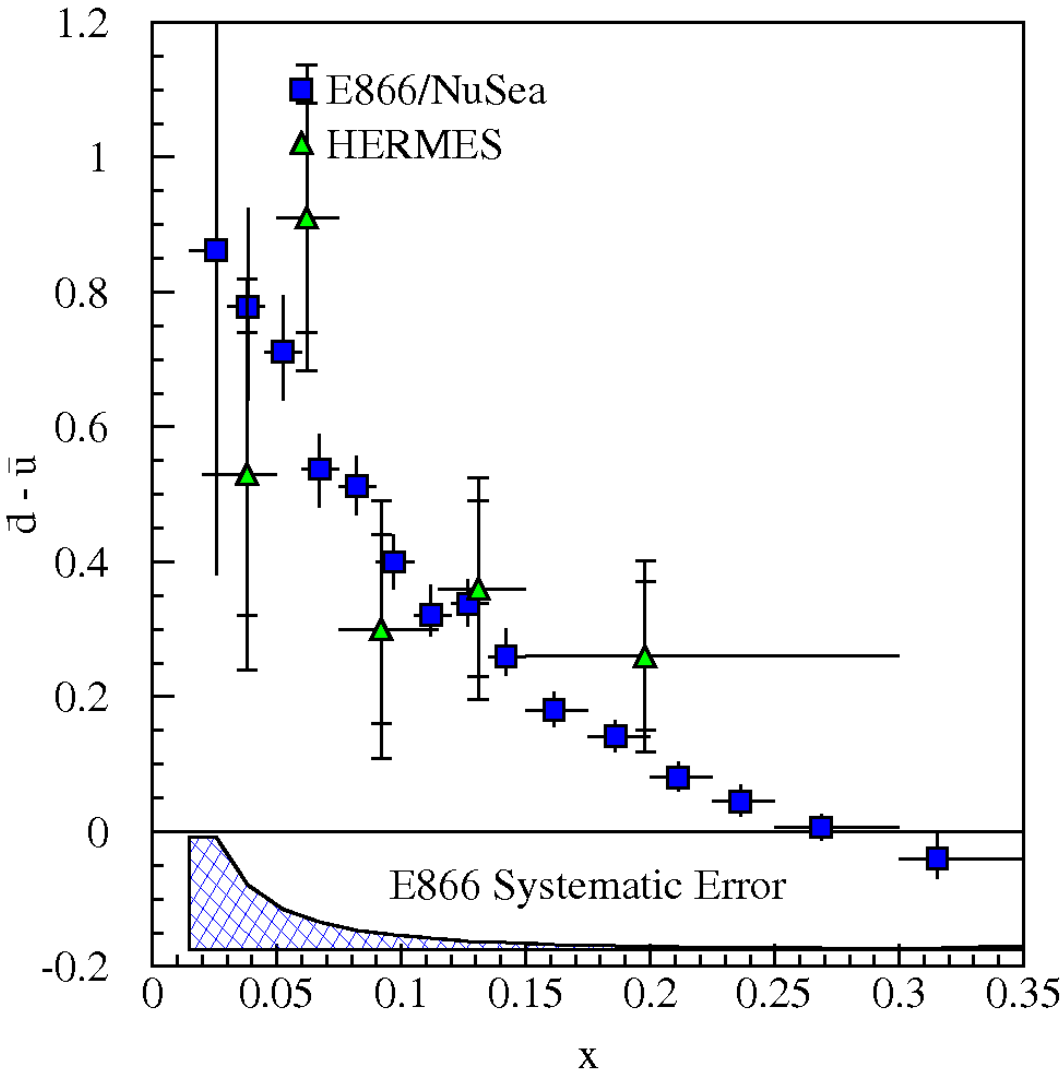
Proton Structure: By What Process Is the Sea Created?

- There is a gluon splitting component which is symmetric

$$\bar{d}(x) = \bar{u}(x) = \bar{q}(x)$$

- $\bar{d} - \bar{u}$
  - Symmetric sea via pair production from gluons subtracts off
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference
- A proton with 3 valence quarks plus glue cannot be right at any scale!!



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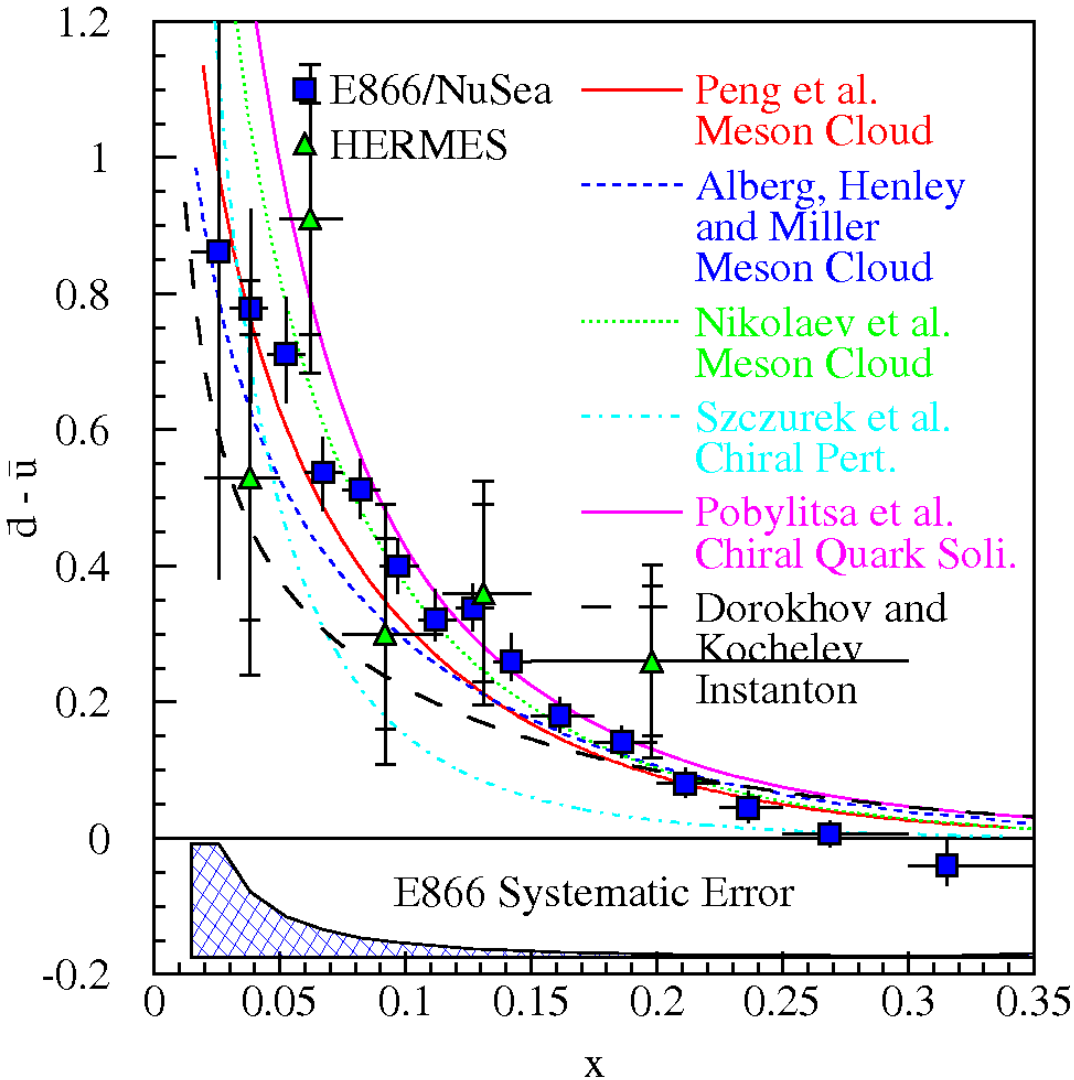
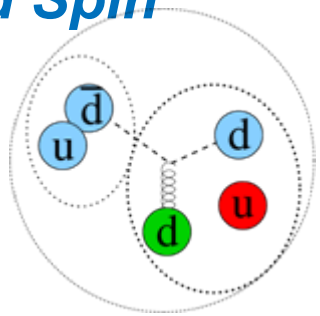


Models Relate Antiquark Flavor Asymmetry and Spin



- Meson Cloud in the nucleon—Sullivan process in DIS

$$\langle P|P\rangle = (1-a-b)\,\langle P_0|P_0\rangle + a\langle N_0\pi|N_0\pi\rangle + b\langle \Delta_0\pi|\Delta_0\pi\rangle \ldots$$

- Chiral Quark models—effective Lagrangians

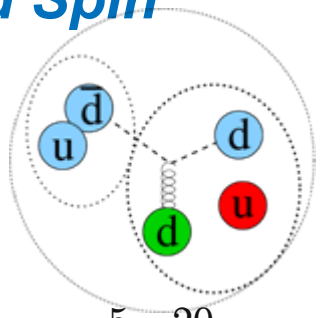
$$\langle q|q\rangle = \left[1-\frac{3a}{2}\right]\langle q|q\rangle + \frac{3a}{2}\langle q\pi|q\pi\rangle$$

- Instantons

$$\mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R$$

- Statistical Parton Distributions

Models Relate Antiquark Flavor Asymmetry and Spin



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$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] = \frac{2a-b}{3} = 0.10 \rightarrow a = 0.2 = 2b \qquad g_A = \int_0^1 \left[\Delta u - \Delta d\right] dx = \frac{5}{3} - \frac{20}{27}\sqrt{2ab} \rightarrow 1.5$$

- Chiral Quark models—effective Lagrangians

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$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] = \frac{2a}{3} = 0.10 \rightarrow a = 0.14 \qquad g_A = \int_0^1 \left[\Delta u - \Delta d\right] dx = \frac{5}{3}3a \rightarrow 1.43$$

- Instantons

$$\mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R \qquad \bar{d}_I(x) - \bar{u}_I(x) = \frac{3}{5}\left[\Delta u_I(x) - \Delta d_I(x)\right]$$

- Statistical Parton Distributions

$$\bar{d}(x) - \bar{u}(x) \approx \Delta\bar{u}(x) - \Delta\bar{d}(x)$$

Proton Structure: By What Process Is the Sea Created?

- Meson Cloud in the nucleon

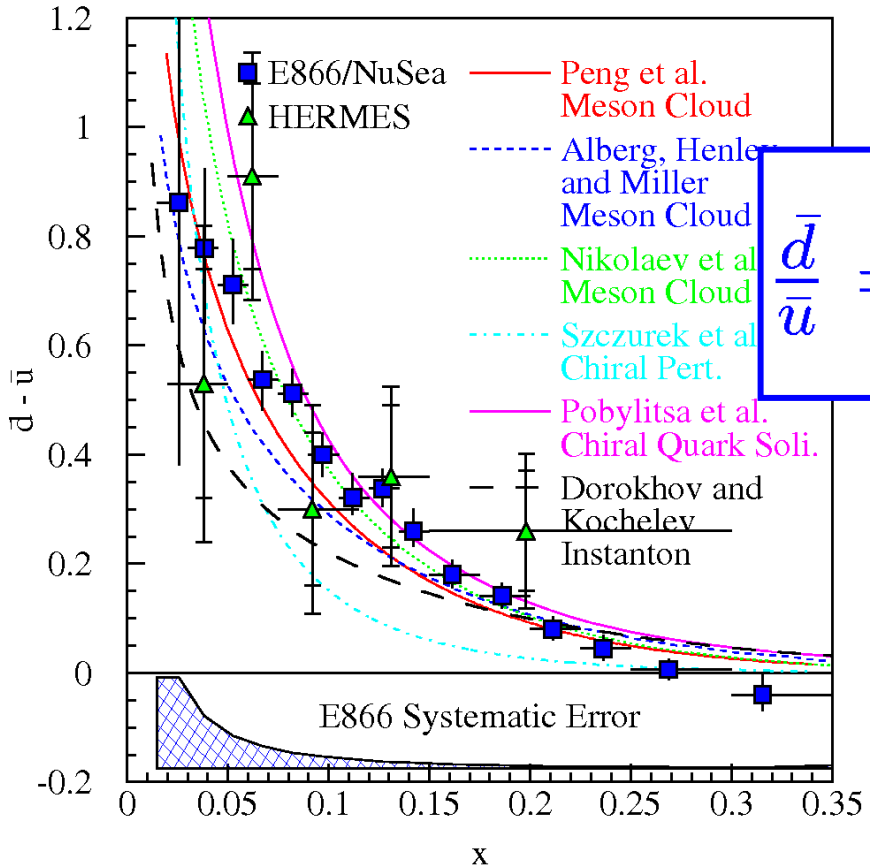
  Sullivan process in DIS

  $|p\rangle = |p_0\rangle + \alpha\,|N\pi\rangle + \beta|\Delta\pi\rangle + \ldots$

- Chiral Models

  Interaction between Goldstone Bosons and valence quarks

  $|u\rangle \rightarrow |d\pi^+\rangle$ and $|d\rangle \rightarrow |u\pi^-\rangle$



$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$

Perturbative sea apparently dilutes meson cloud effects at large-x, *but this requires large-x gluons*

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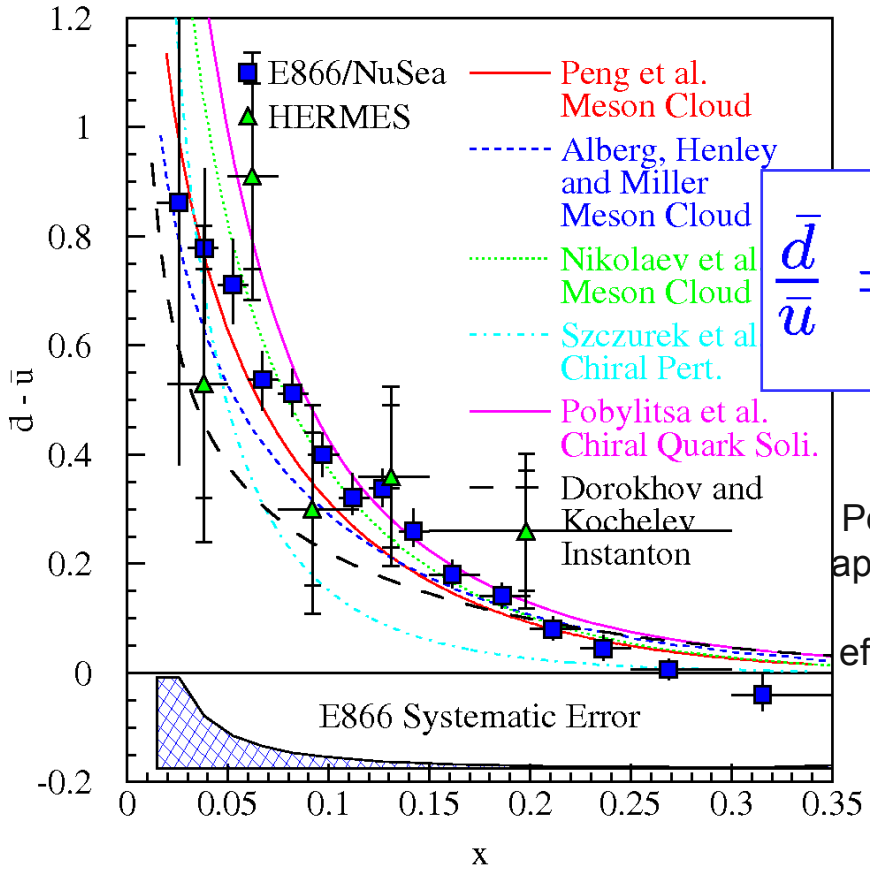

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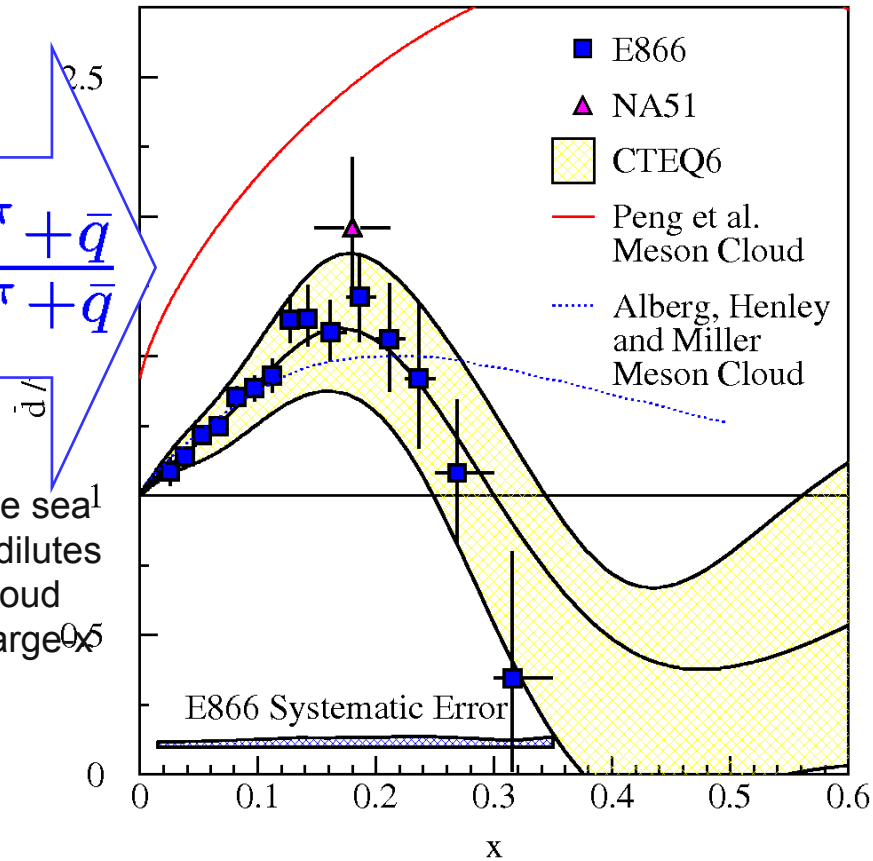
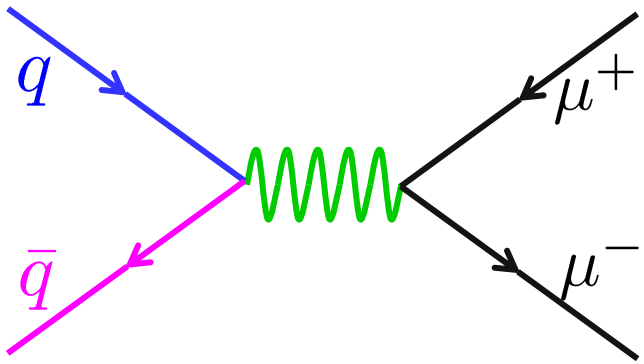


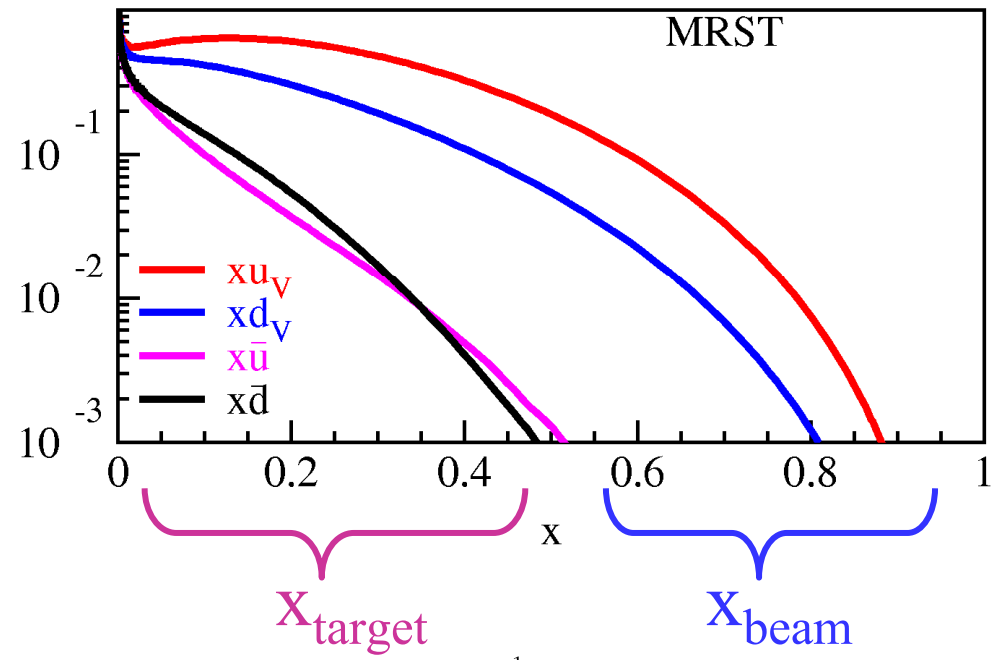
Why talk about Drell-Yan at JLab?

- Other possible answer

  Make Mont feel at home?

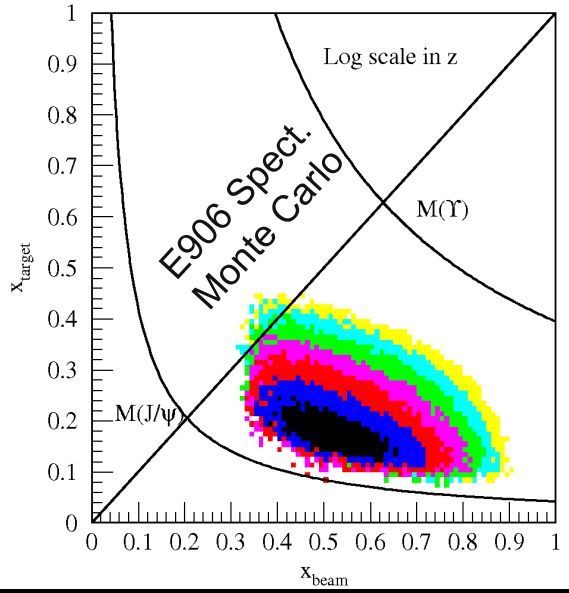
Drell-Yan scattering: A laboratory for sea quarks





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

Detector acceptance chooses x_{target} and x_{beam}.



- **Fixed target** ⇒ high $x_F = x_{beam} - x_{target}$
- Valence Beam quarks at high-x.
- Sea-target quarks at low/intermediate-x.

Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

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

The future:

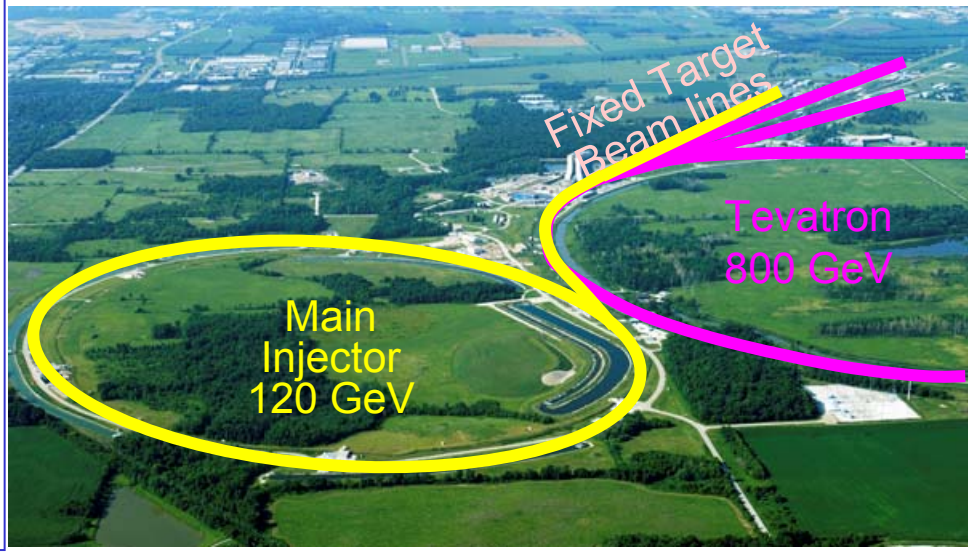
Fermilab E906

- Data in 2010
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam

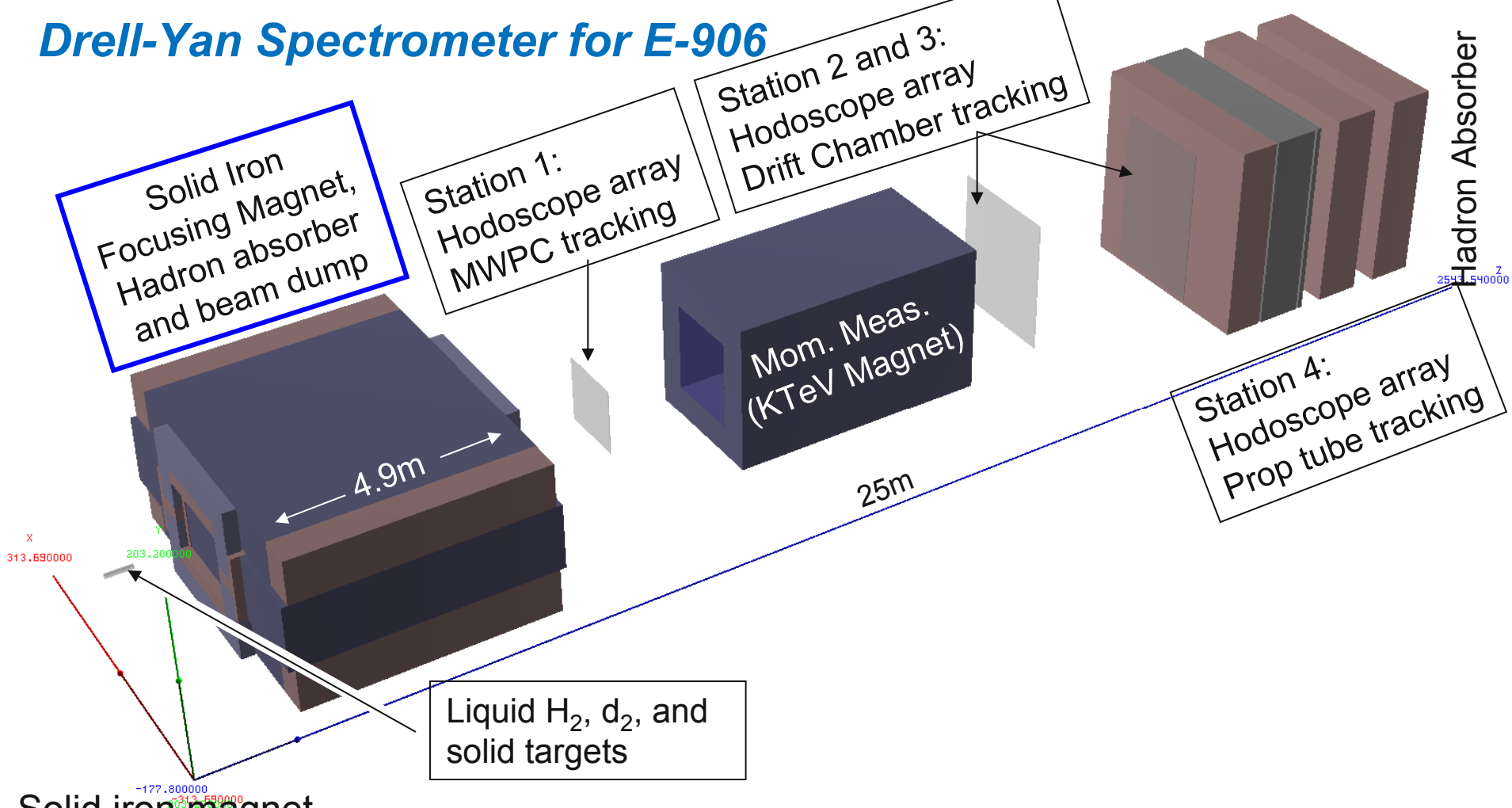
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- 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!!
- Limited Phase Space



Drell-Yan Spectrometer for E-906

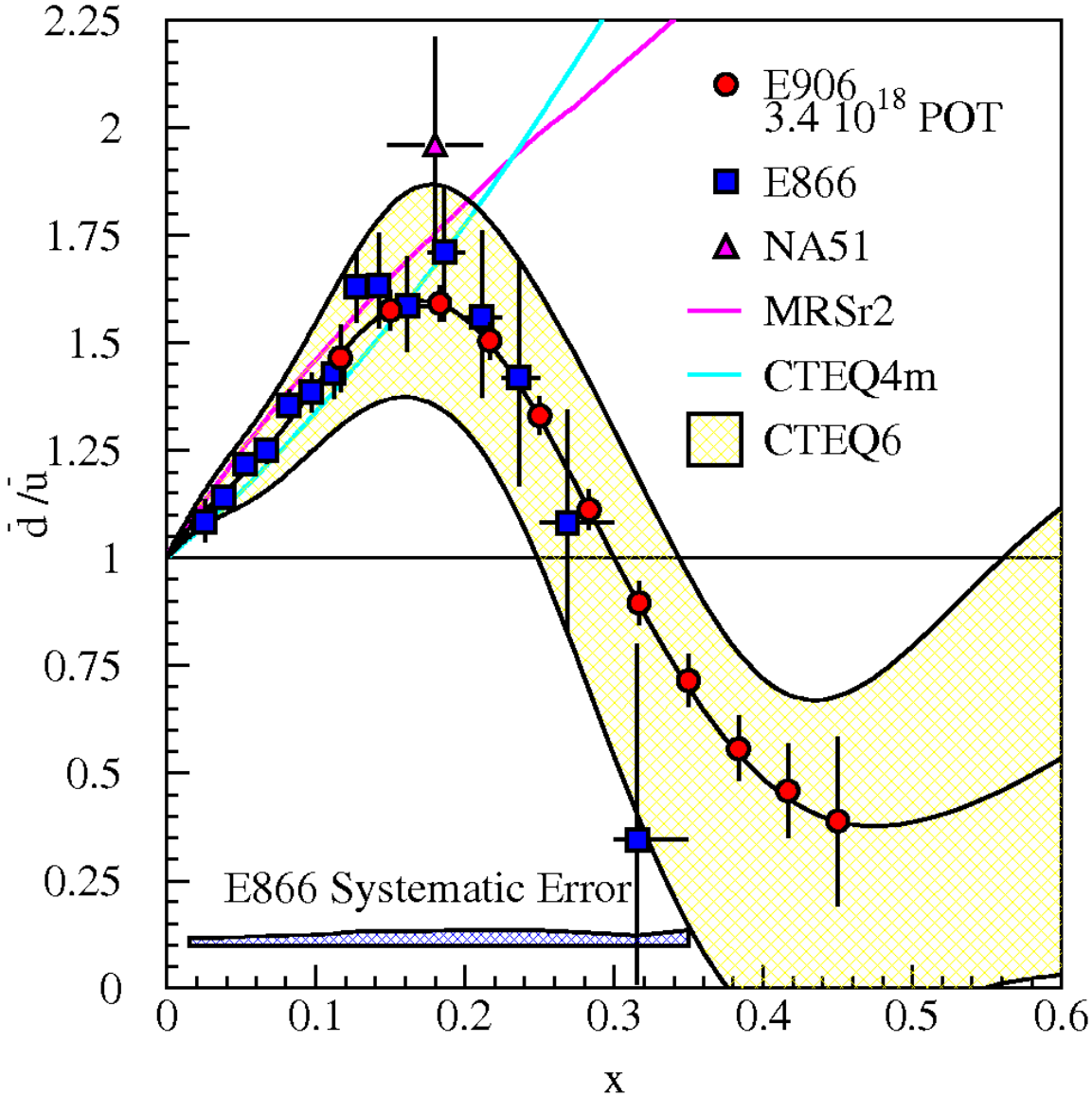


Solid iron magnet

- Reuse SM3 magnet coils
- Sufficient Field with reasonable coils (amp-turns)
- Beam dumped within magnet

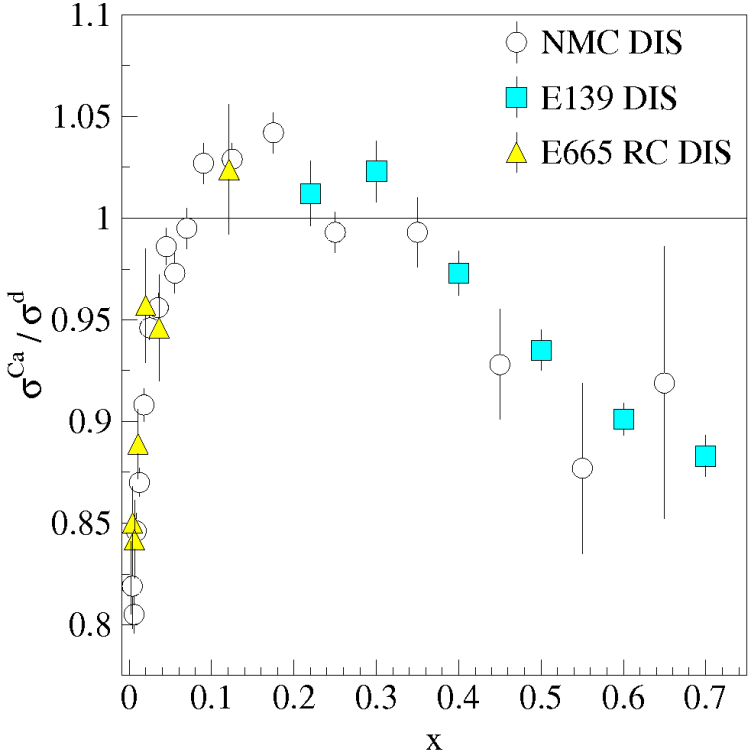
Extracting d-bar/-ubar From Drell-Yan Scattering

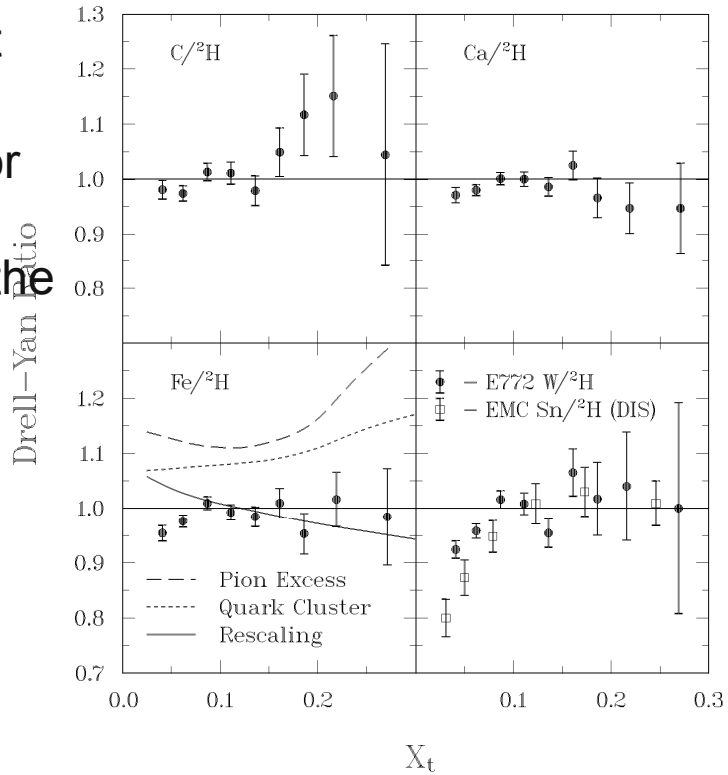
- E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.



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

- Intermediate-*x* *sea* PDF's absolute magnitude set by ν-DIS on iron.
  - Are nuclear effects the same for the sea as for valence?
  - Are nuclear effects with the weak interaction the same as electromagnetic?





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

- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell-Yan—Valence only effect
- What can the sea parton distributions tell us about the effects of nuclear binding?

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

Comparison with
Deep Inelastic Scattering (DIS)

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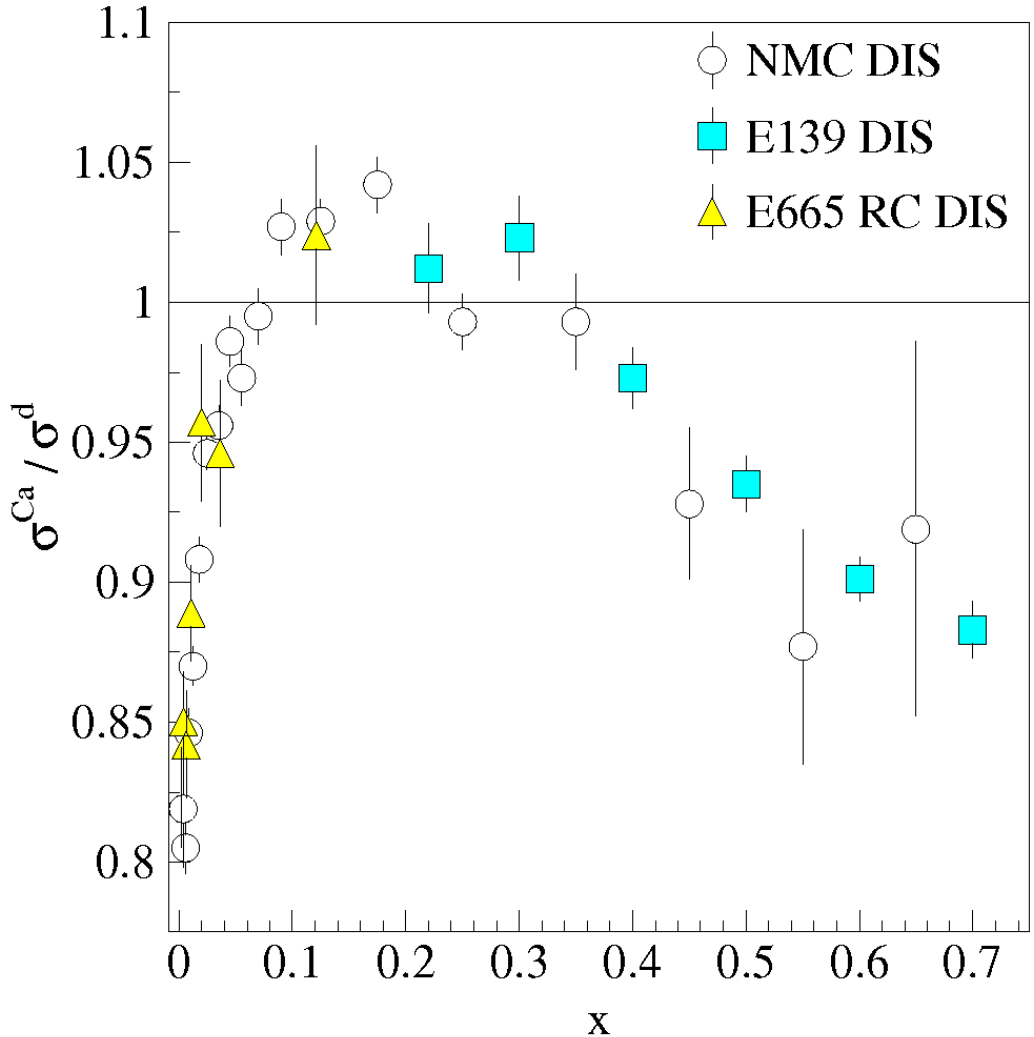

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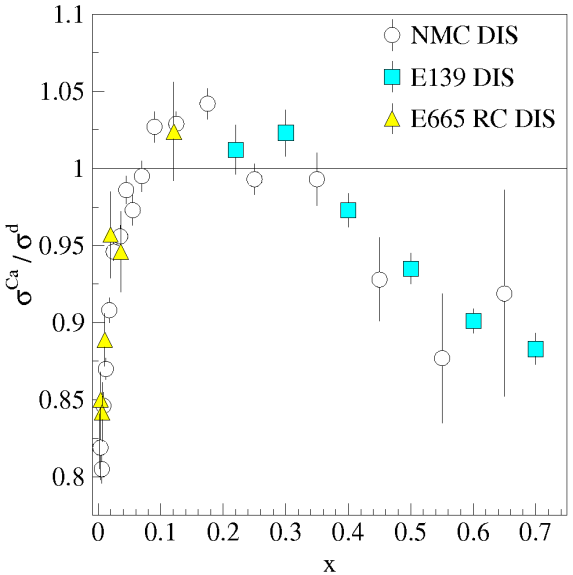
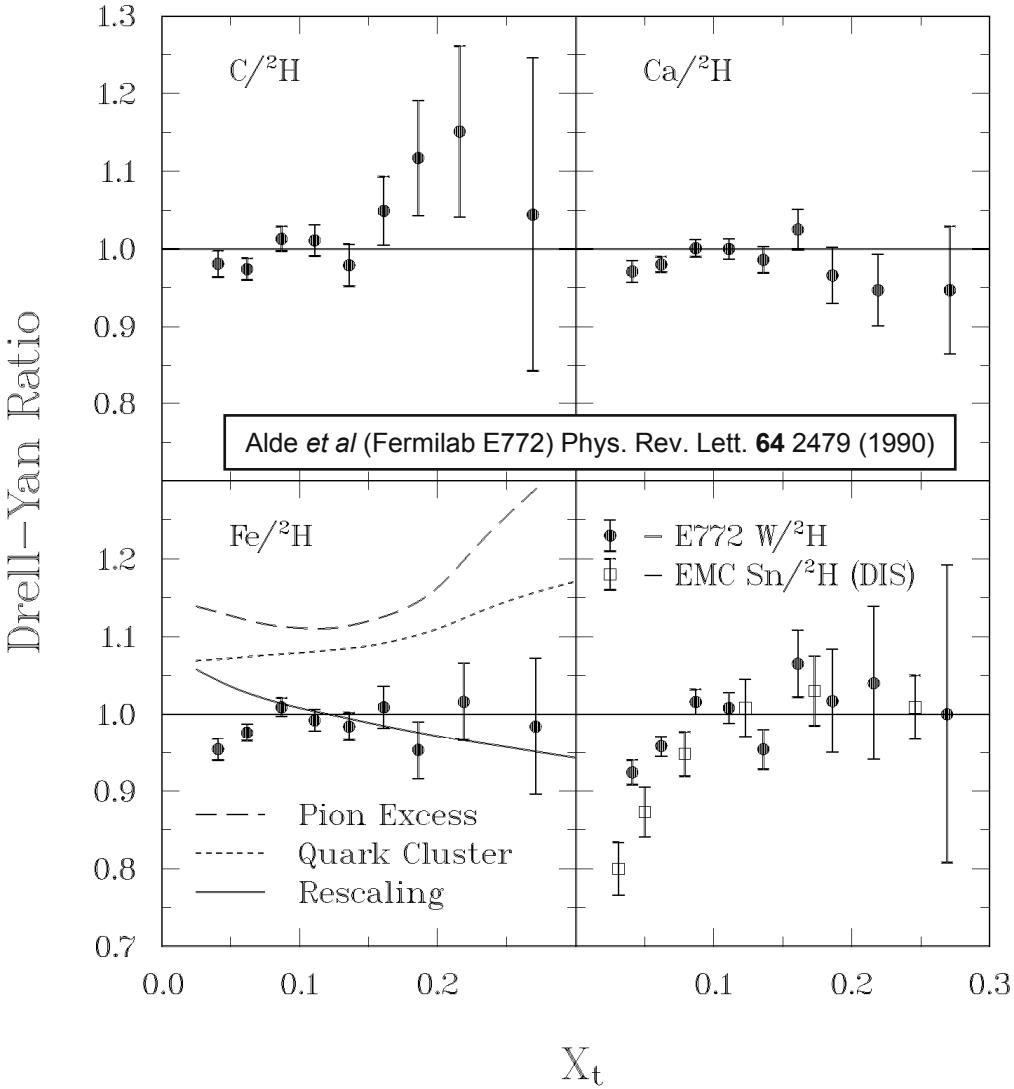
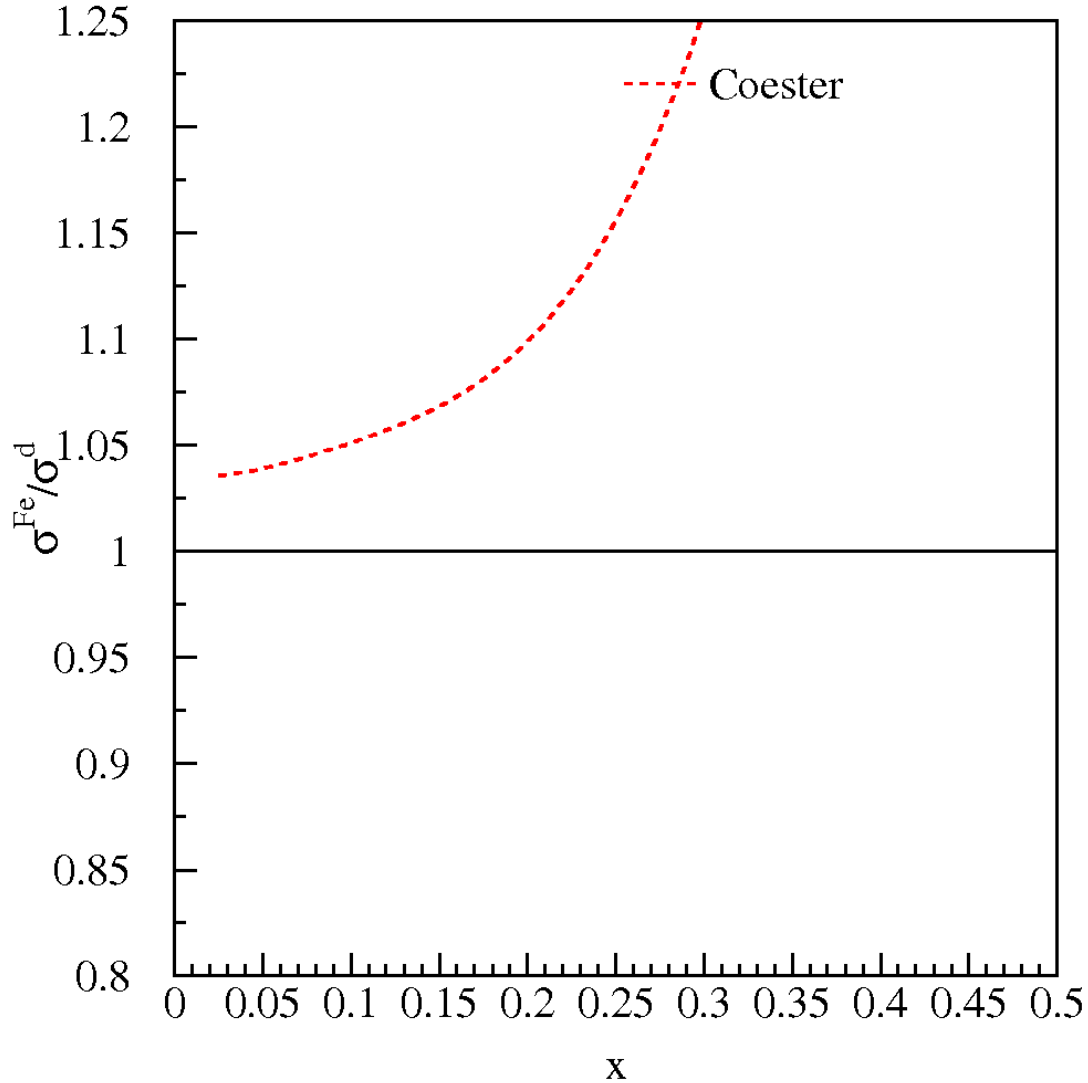




Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect and Drell-Yan



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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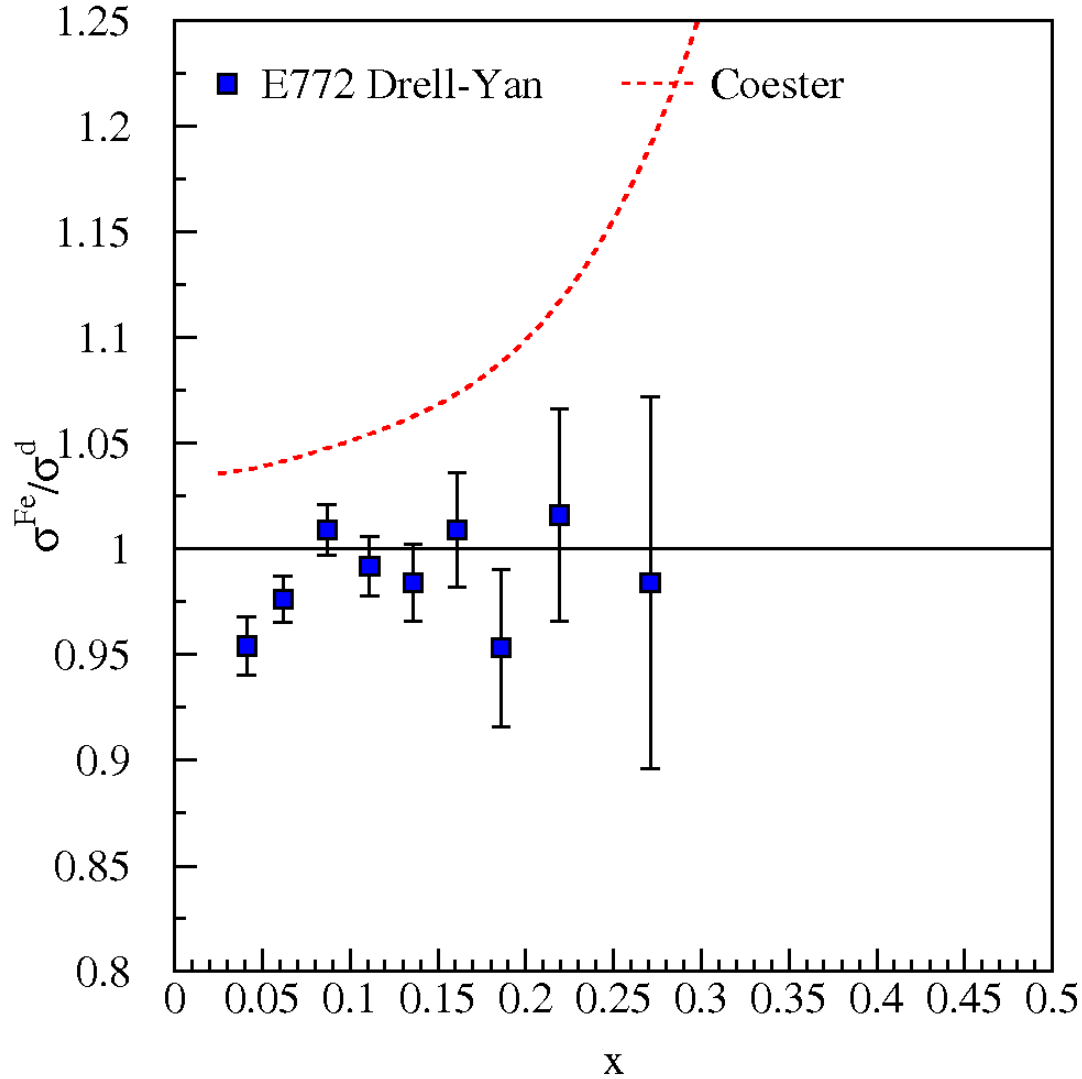

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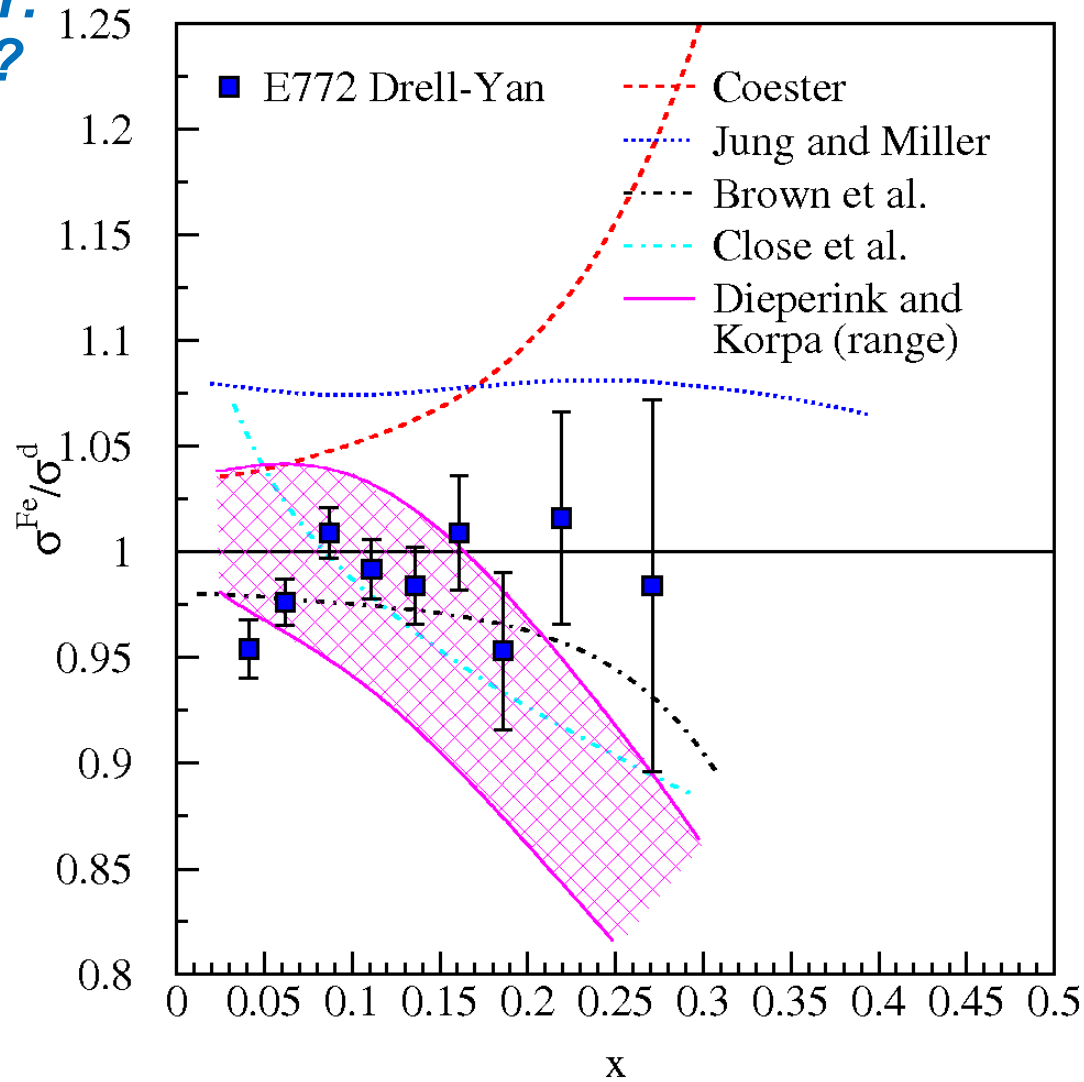

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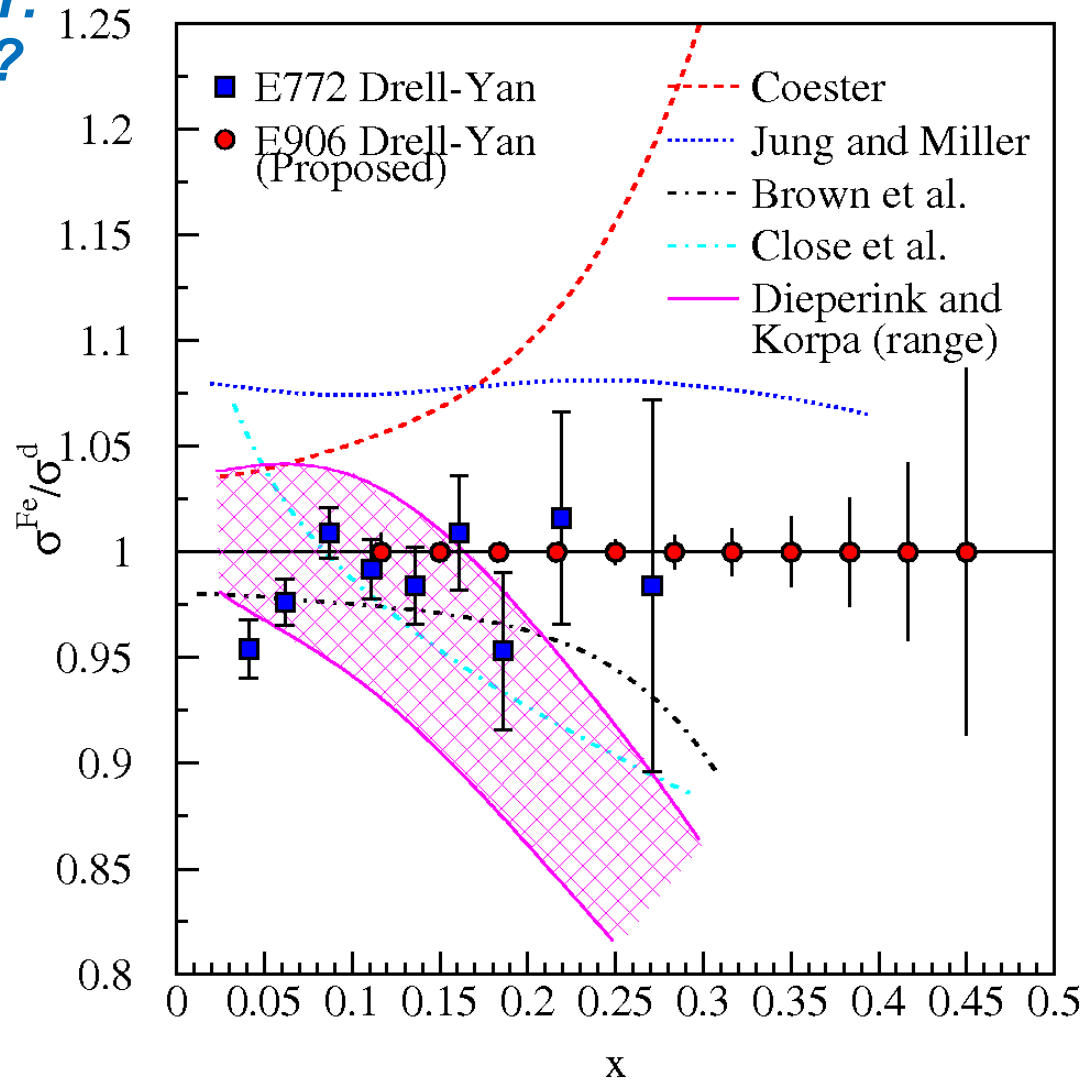
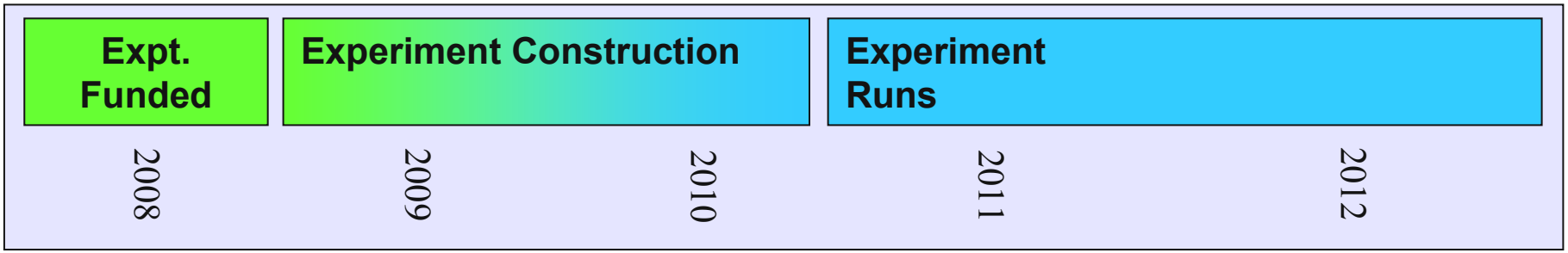


E906/Drell-Yan timeline

- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about "proton economics"
- Spectrometer upgrade funded by DOE/Office of Nuclear Physics (already received $700k by FY09)
- Fermilab PAC reaffirms earlier decision in Fall 2006
- Scheduled to run in 2010 for 2 years of data collection

- Apparatus available for future programs at, *e.g.* Fermilab, J-PARC or RHIC
  - Significant interest from collaboration for continued program



FNAL E866/NuSea Collaboration

Abilene Christian University
Donald Isenhower, Mike Sadler, Rusty Towell, Josh Bush, Josh Willis, Derek Wise

Argonne National Laboratory
Don Geesaman, Sheldon Kaufman, Naomi Makins, Bryon Mueller, Paul E. Reimer

Fermi National Accelerator Laboratory
Chuck Brown, Bill Cooper

Georgia State University
Gus Petitt, Xiao-chun He, **Bill Lee**

Illinois Institute of Technology
Dan Kaplan

Los Alamos National Laboratory
Melynda Brooks, Tom Carey, Gerry Garvey, Dave Lee, Mike Leitch, Pat McGaughey, Joel Moss, Brent Park, Jen-Chieh Peng, Andrea Palounek, Walt Sondheim, Neil Thompson

Louisiana State University
Paul Kirk, Ying-Chao Wang, Zhi-Fu Wang

New Mexico State University
Mike Beddo, **Ting Chang**, Gary Kyle, Vassilios Papavassiliou, J. Seldon, **Jason Webb**

Oak Ridge National Laboratory
Terry Awes, Paul Stankus, Glenn Young

Texas A & M University
Carl Gagliardi, Bob Tribble, **Eric Hawker**, Maxim Vasiliev

Valparaiso University
Don Koetke, Paul Nord

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Academia Sinica
Wen-Chen Chang, Yen-Chu Chen, Da-Shung Su

Argonne National Laboratory
John Arrington, Don Geesaman*, Kawtar Hafidi, Roy Holt, Harold Jackson, David Potterveld, Paul E. Reimer*, Patricia Solvignon

University of Colorado
Ed Kinney

Fermi National Accelerator Laboratory
Chuck Brown, Dave Christian

University of Illinois
Naomi C.R Makins, Jen-Chieh Peng

KEK
Shin'ya Sawada

Kyoto University
KenIchi Imai, Tomo Nagae

*Co-Spokespersons

Ling-Tung University
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University of Maryland
Prabin Adhikari, Betsy Beise, Kazutaka Nakahara

University of Michigan
Wolfgang Lorenzon, Richard Raymond

RIKEN
Yuji Goto, Atsushi Taketani, Yoshinori Fukao, Manabu Togawa

Rutgers University
Lamiaa El Fassi, Ron Gilman, Charles Glashausser, Elena Kuchina, Ron Ransome, Elaine Schulte

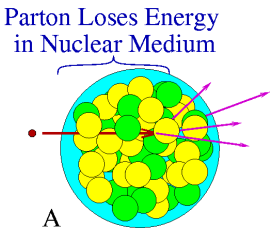
Texas A & M University
Carl Gagliardi, Robert Tribble

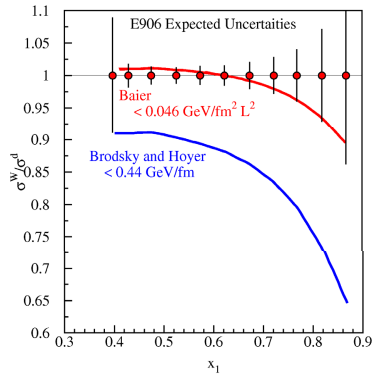
Thomas Jefferson National Accelerator Facility
Dave Gaskell

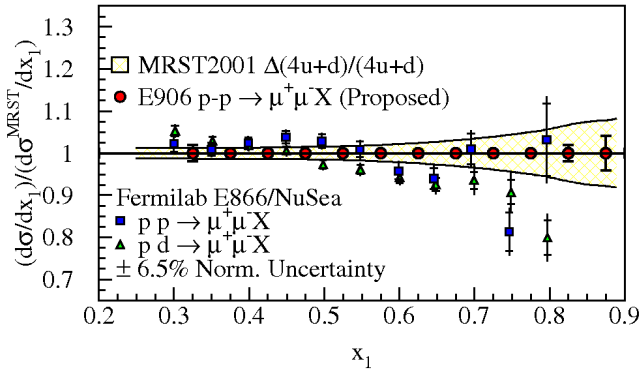
Tokyo Institute of Technology
Toshi-Aki Shibata, Yoshiyuki Miyachi

Additional Physics from beam parton distributions

- High-x_{Bj} Valence quark distributions
- Partonic energy loss in cold nuclear matter





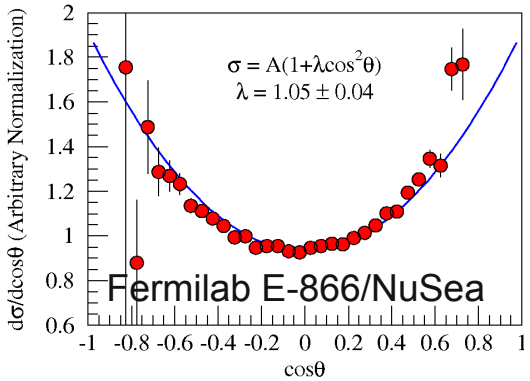


Unpolarized Angular distributions

- Lam-Tung Relation

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

- Boer-Mulders Distributions

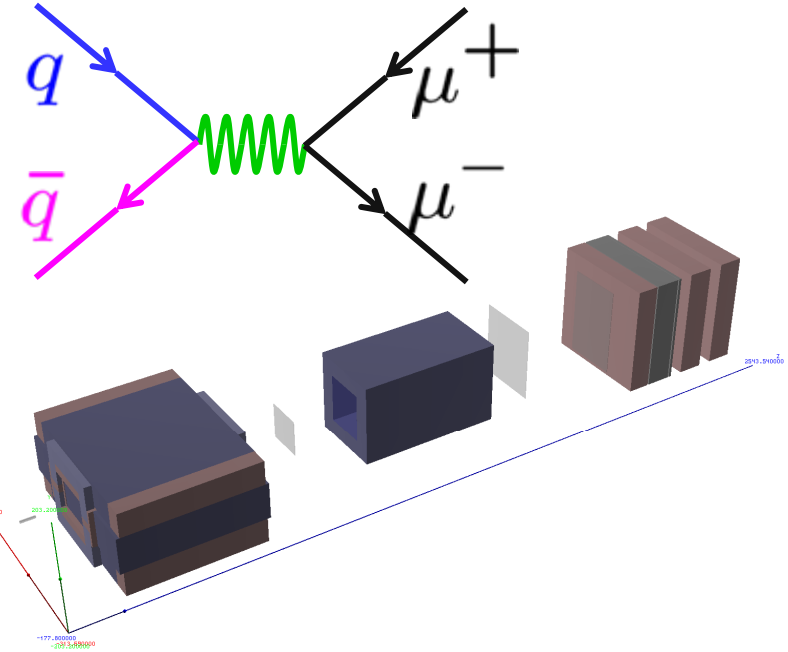


Possible future programs

- Polarized target of beam
- Pionic Drell-Yan

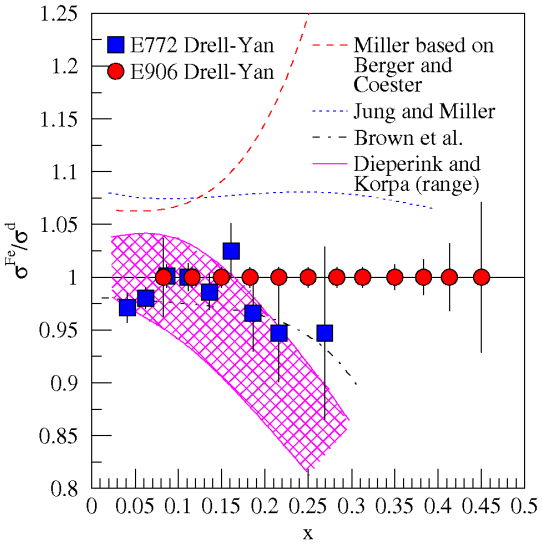
Drell-Yan at Fermilab

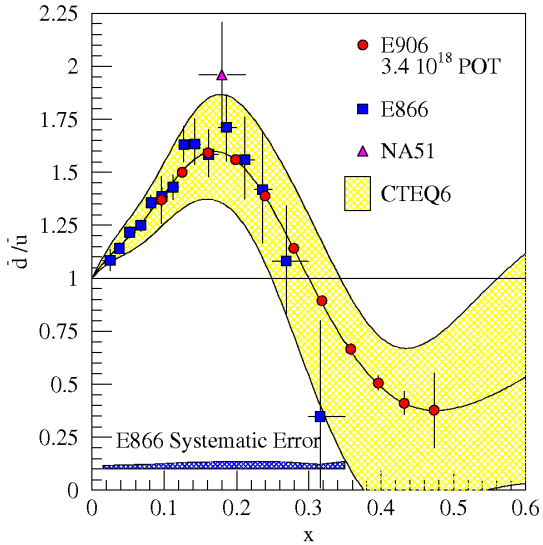
- Drell-Yan scattering is uniquely sensitive to the antiquark distributions of the target.



- The E-906/Drell-Yan Collaboration is constructing a facility to measure Drell-Yan Scattering.

- E-906/Drell-Yan will use this to measure
  - the ration of anti-d to anti-u distributions in the proton,
  - The modifications to the quark sea in a nucleus, and
  - Many more interesting topics

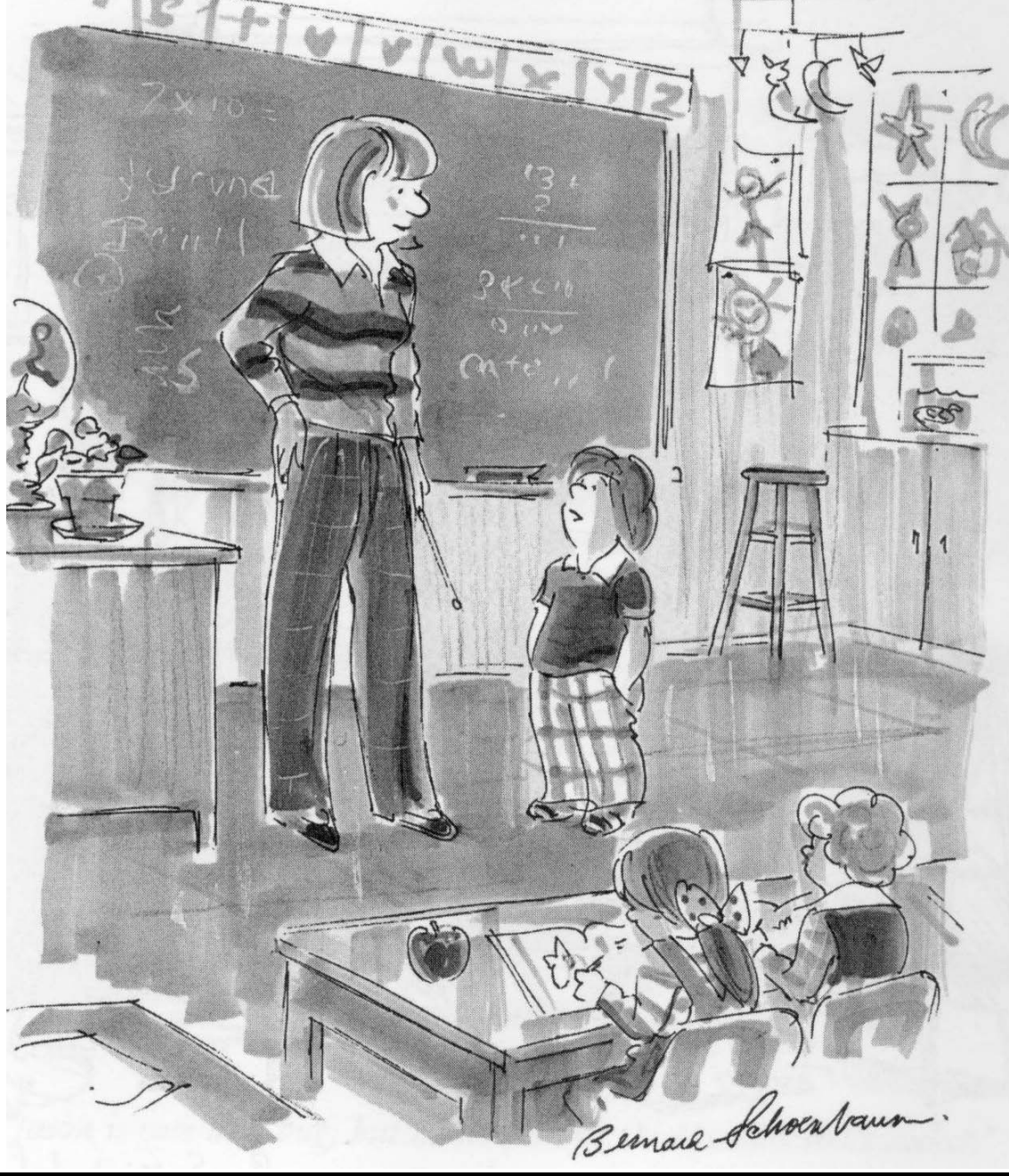




This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

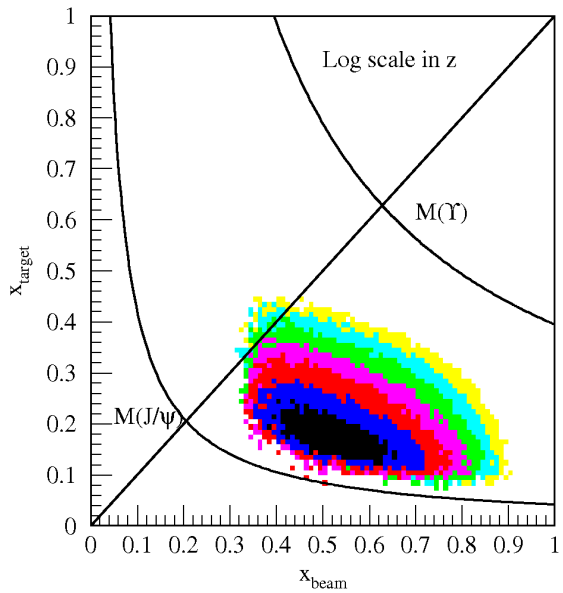
Additional Material

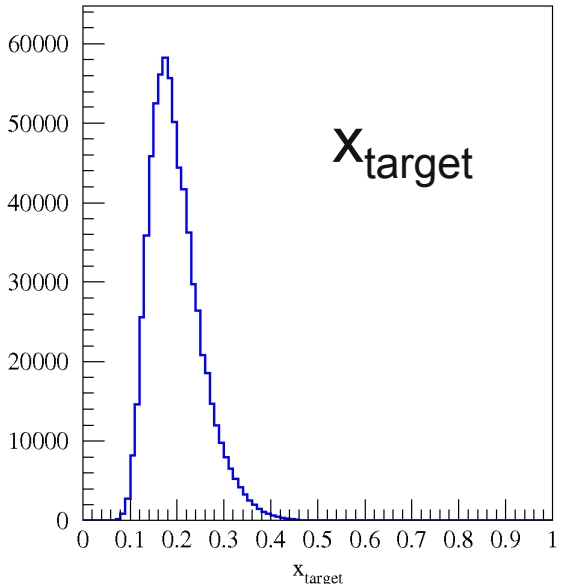
I don't have an answer, but you've sure given me a lot to think about

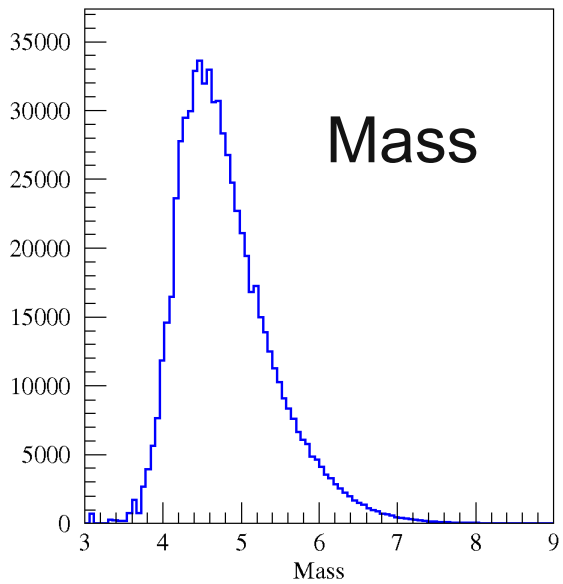


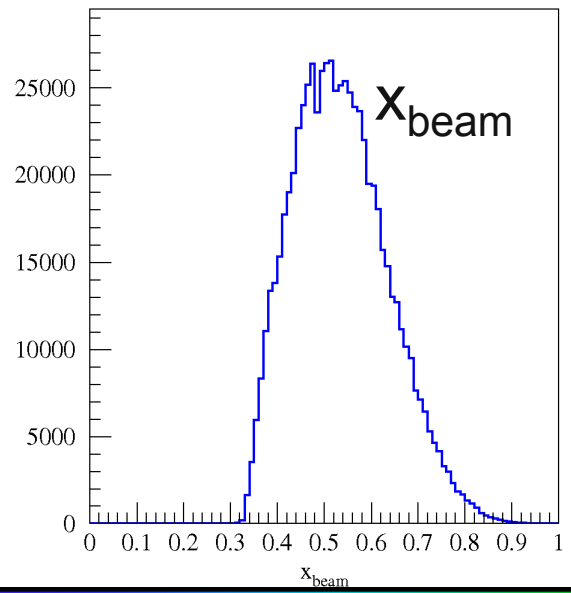
Drell-Yan Acceptance

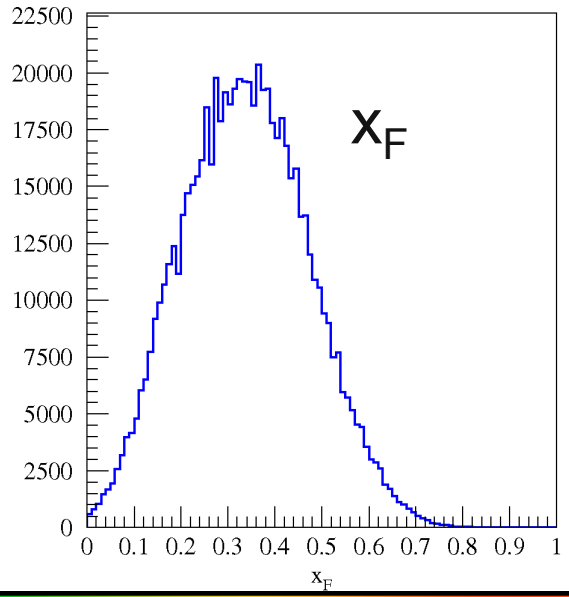
- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ′ studies



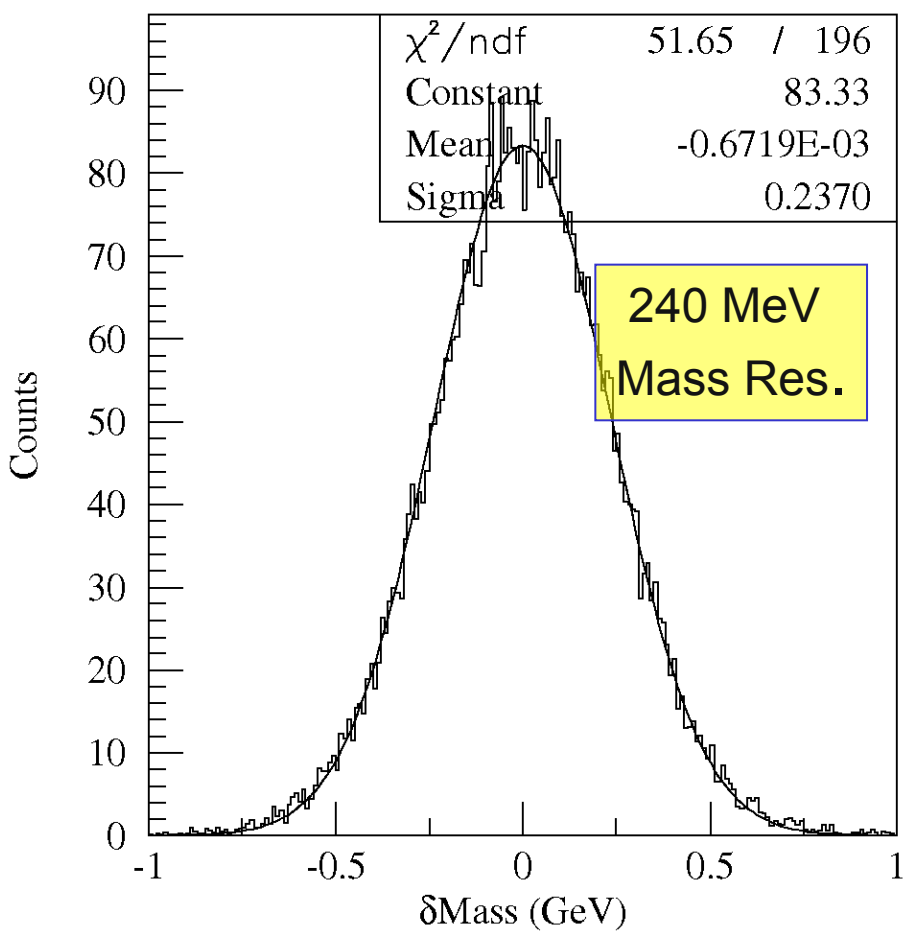


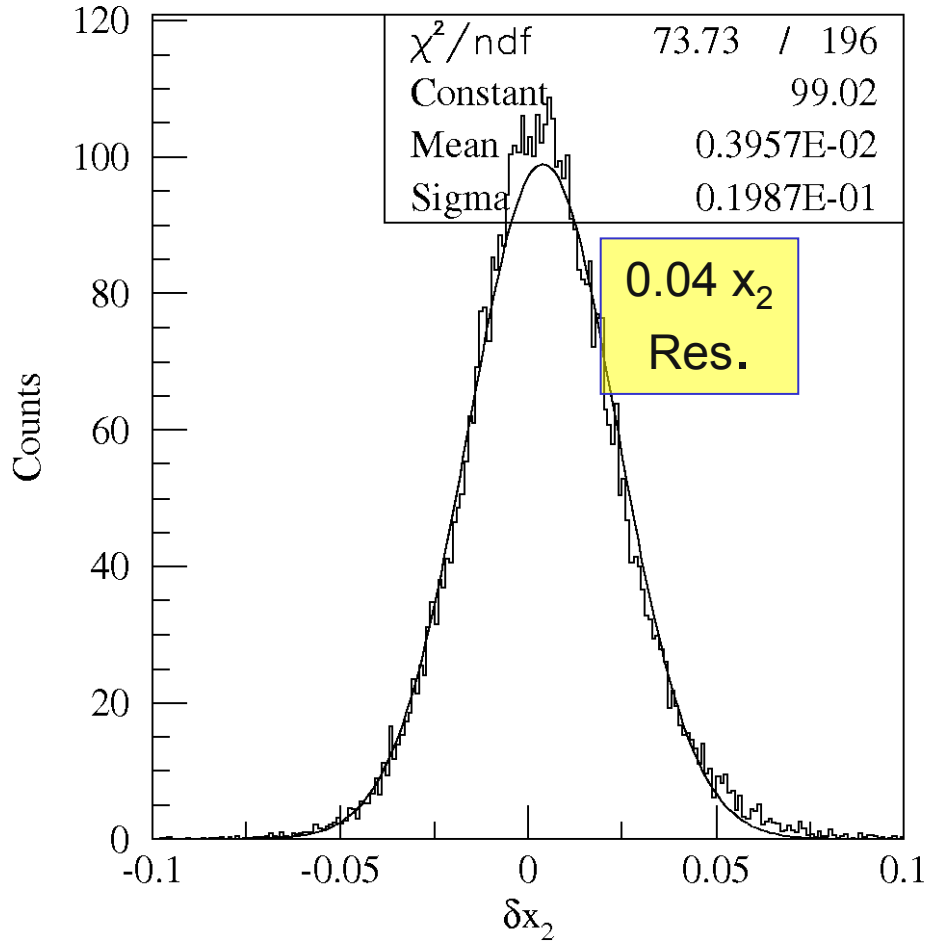






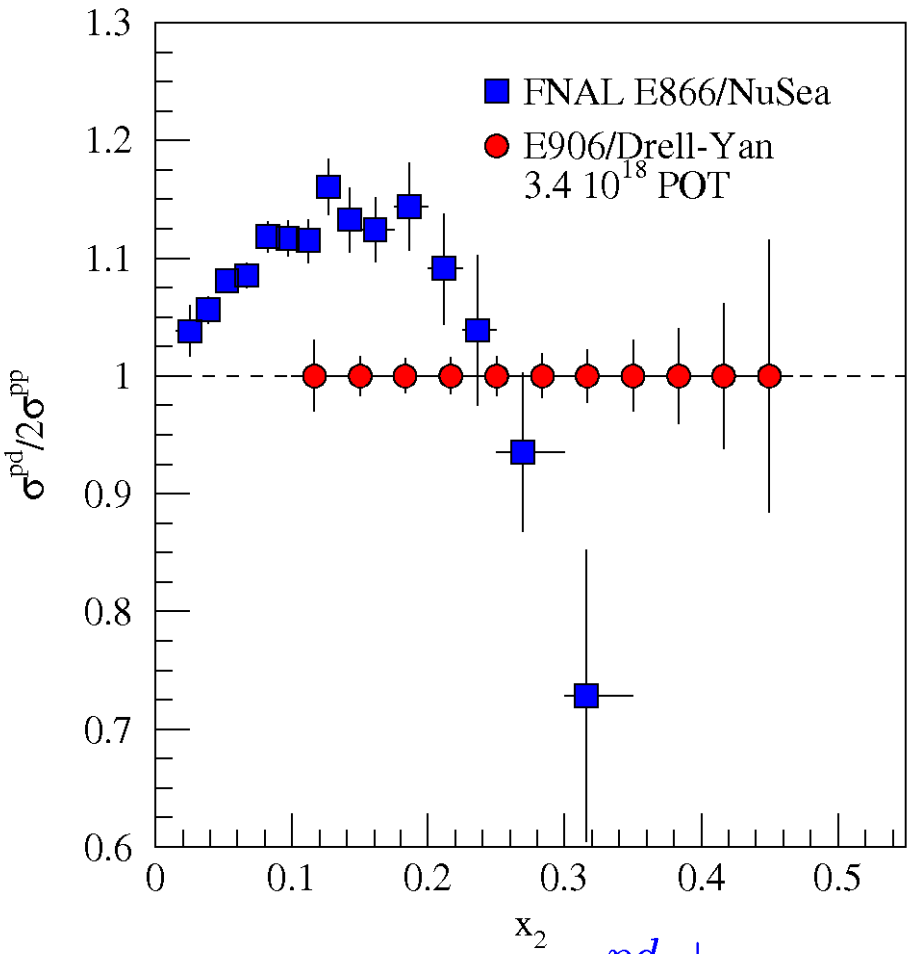
Detector Resolution

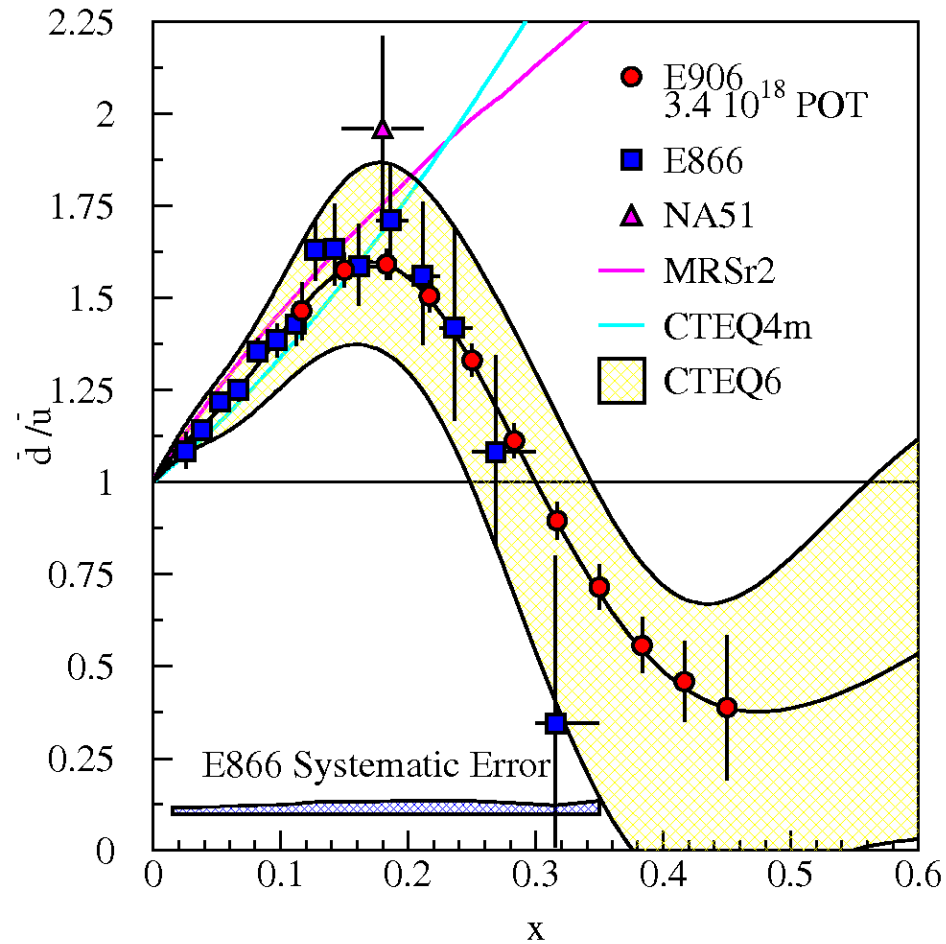




- Triggered Drell-Yan events

Drell-Yan Cross Section Ratio and d-bar/u-bar





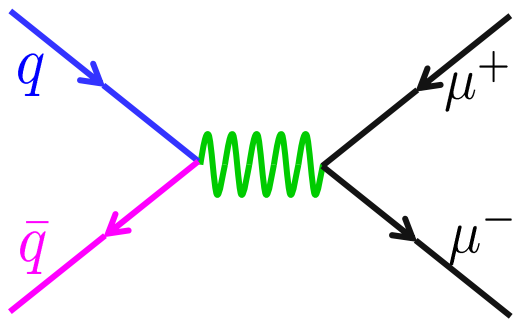
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Drell-Yan Scattering: What we really measure

- Measure yields of $\mu^+\mu^-$ pairs from different targets
- For each event measure 3-momentum of each μ
- Assume that it is a muon to get 4-momentum

- Reconstruct M^2_γ, p_T^γ, $p_{||}^\gamma$
- $M^2_\gamma = x_1 x_2 s$,
- $x_F = 2p_{||}^\gamma/s^{1/2} \approx x_1 - x_2$

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



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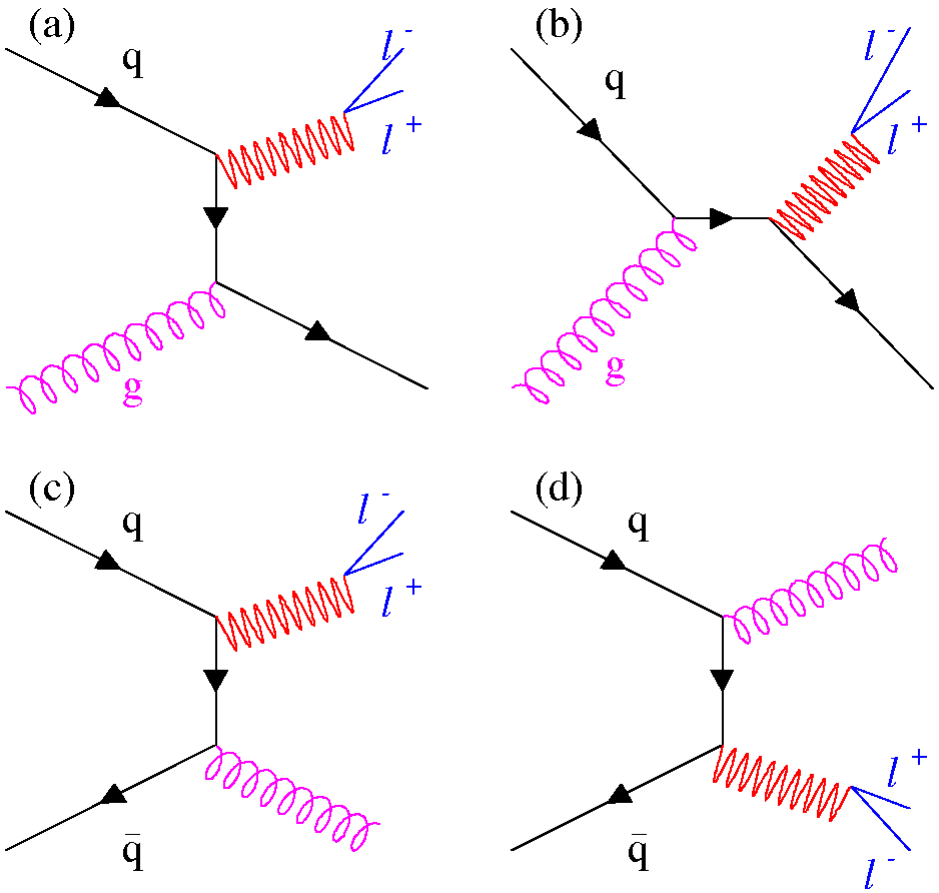
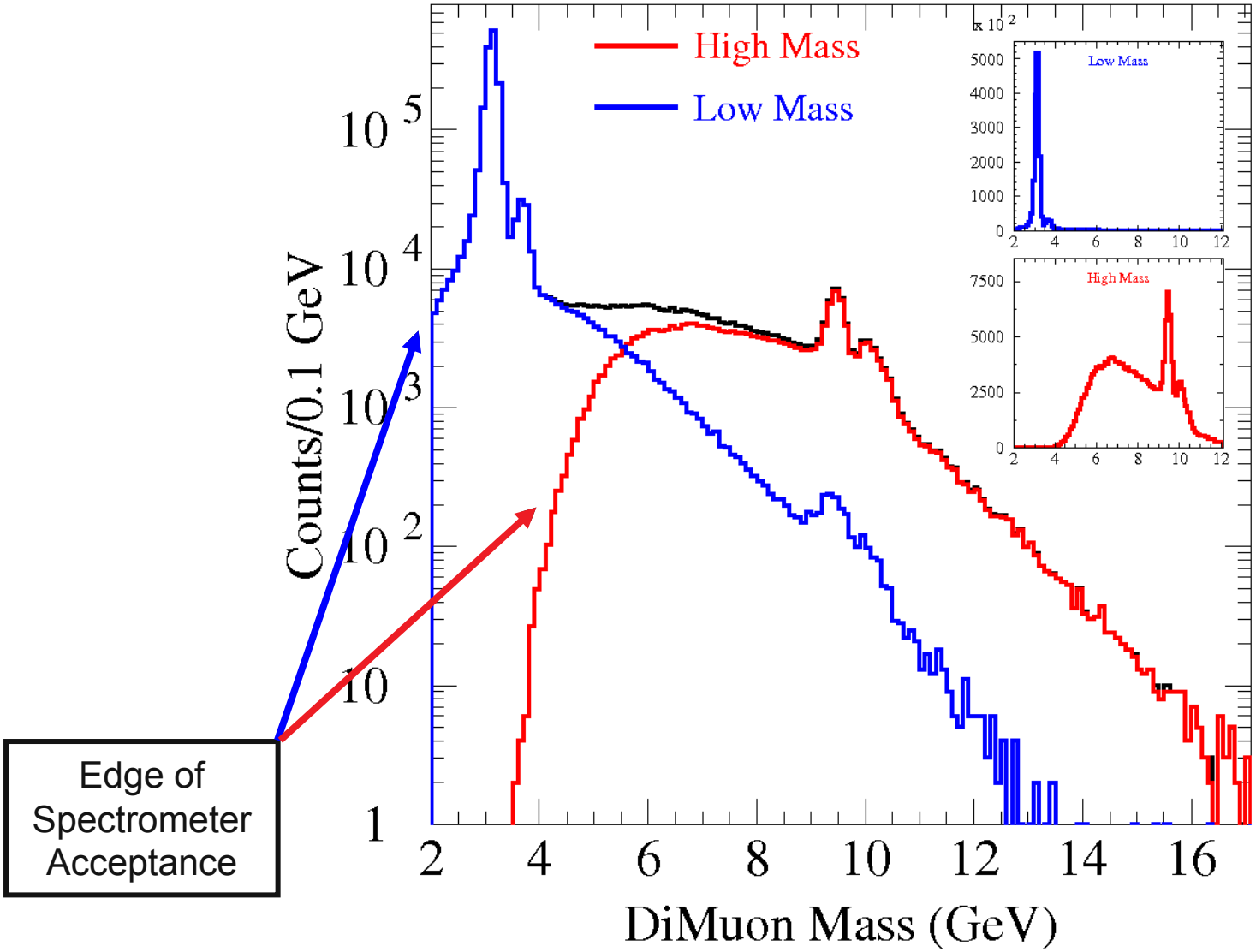
Next-to-Leading Order Drell-Yan

- Next-to-leading order diagrams complicate the picture
- These diagrams are responsible for **50% of the measured cross section**
- Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)



Drell-Yan Mass Spectra



Data From Fermilab E-866/NuSea
800 GeV proton beam on hydrogen target