Argonne NATIONAL LABORATORY

… for a brighter future

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

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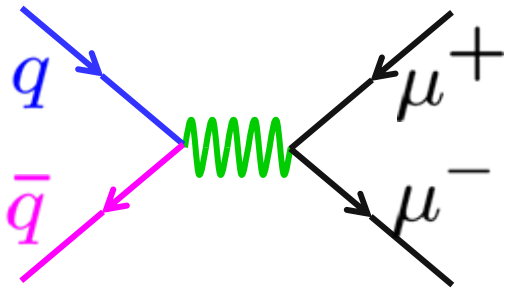
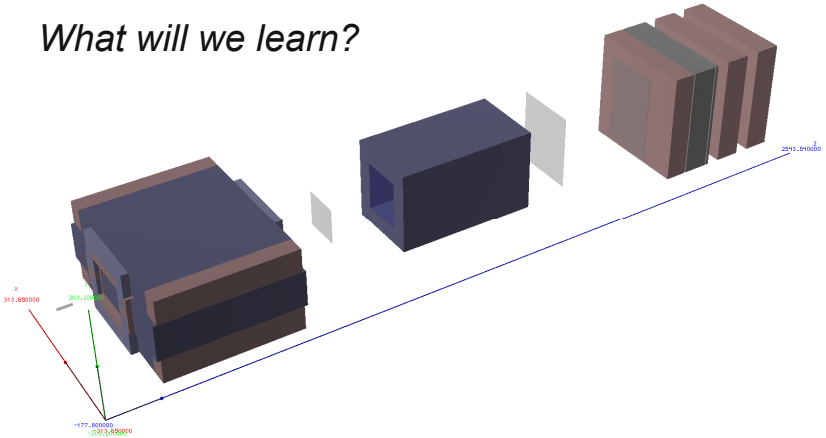
Argonne National Laboratory
Representing the Fermilab
E-906/Drell-Yan collaboration
29 April 2009

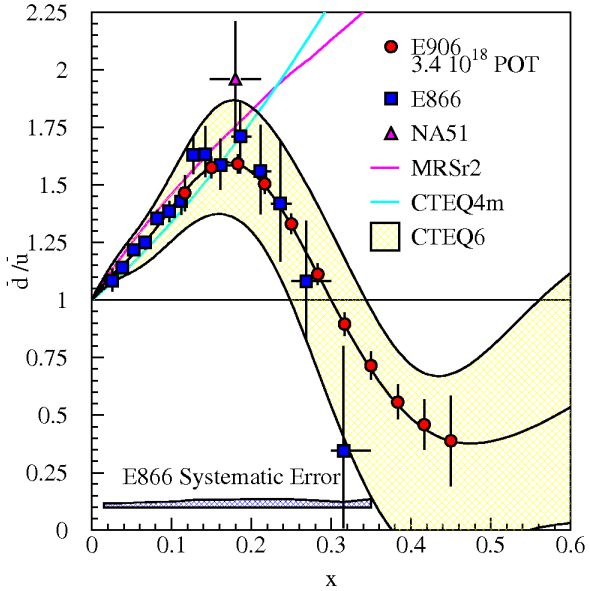


Why Drell-Yan?

Where will we measure it?

What will we learn?





U.S. Department of Energy

UChicago Argonne LLC

Office of Science
U.S. DEPARTMENT OF ENERGY

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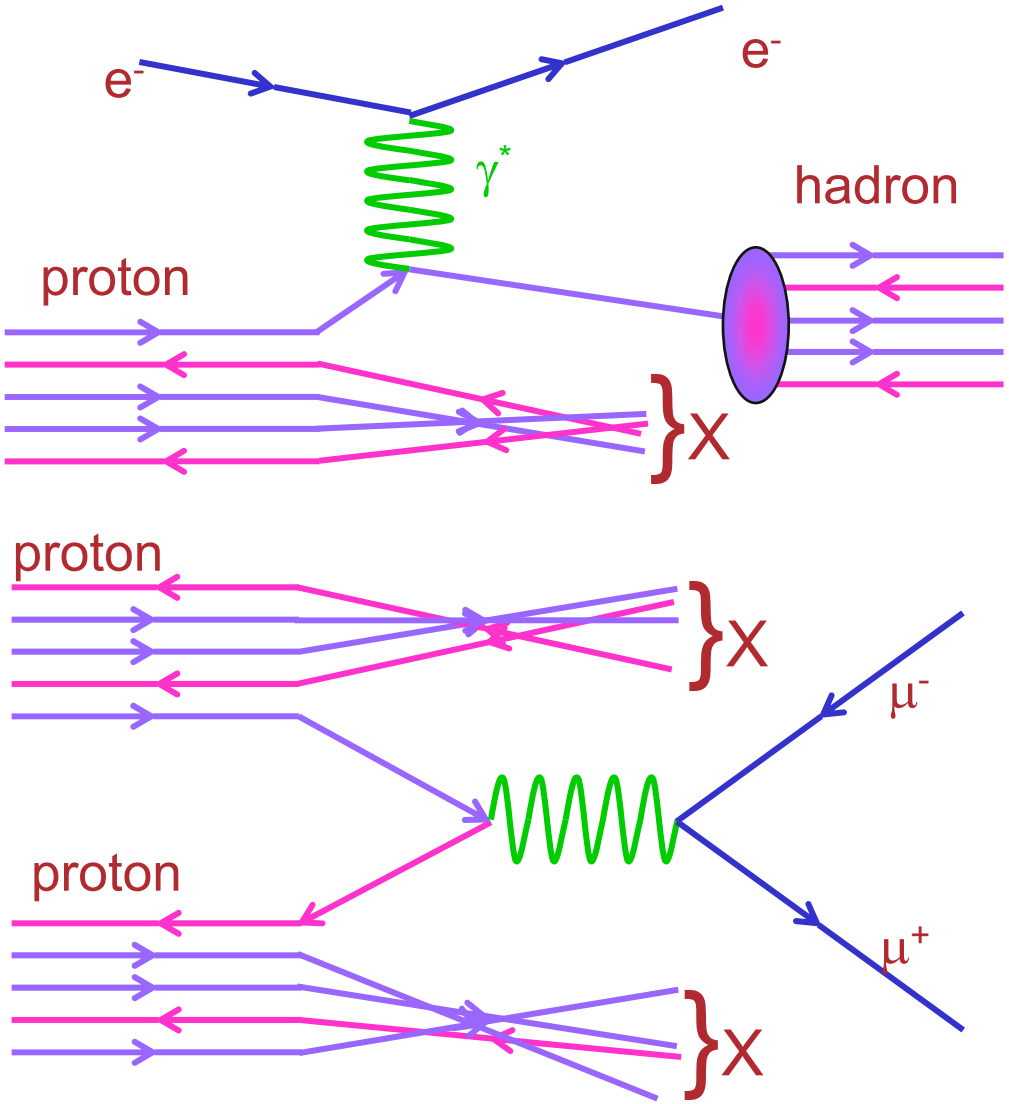
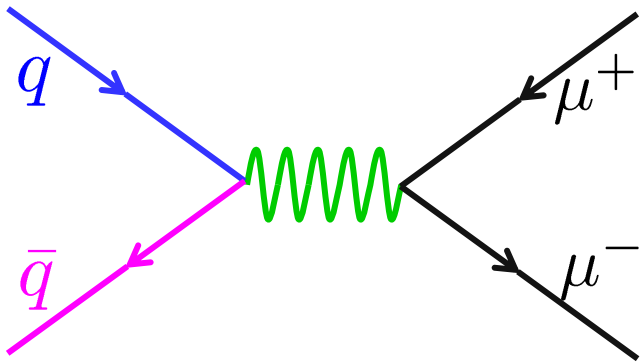
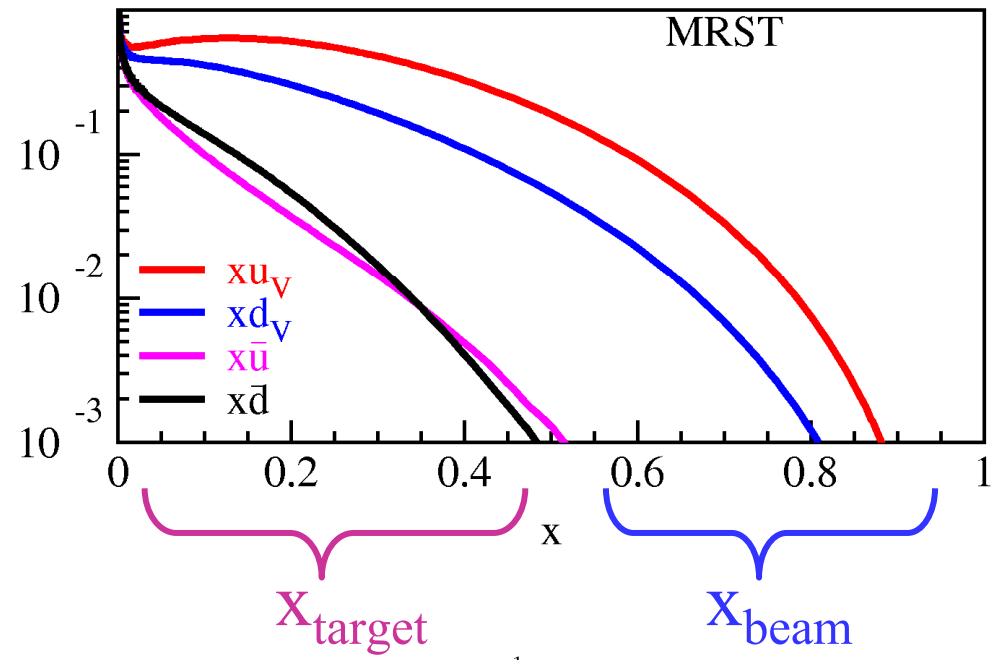
Why talk about Drell-Yan at DIS 2009?



- 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

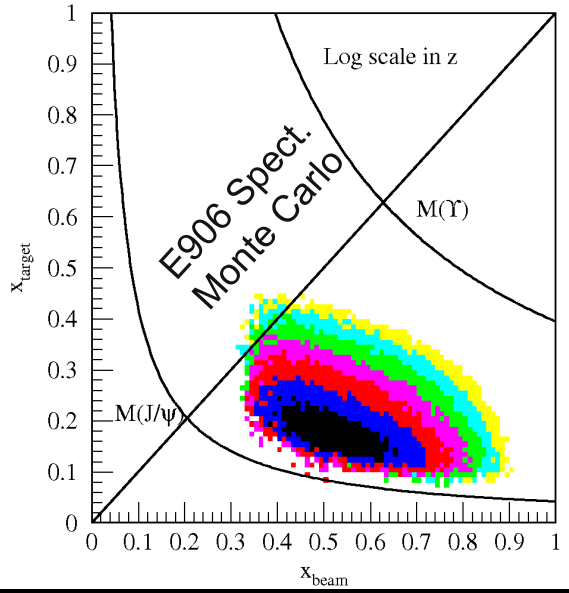
Drell-Yan scattering: A laboratory for sea quarks





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

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:

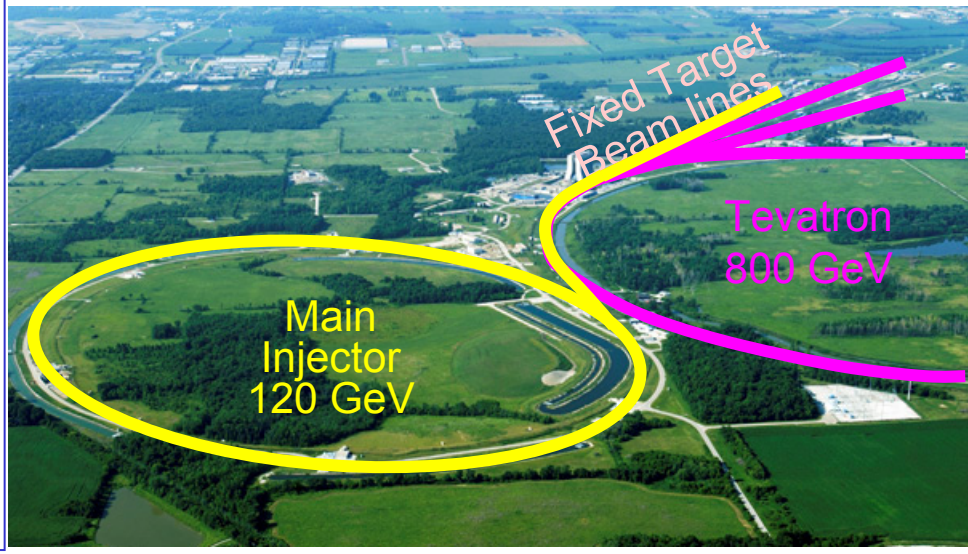
Fermilab E906

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

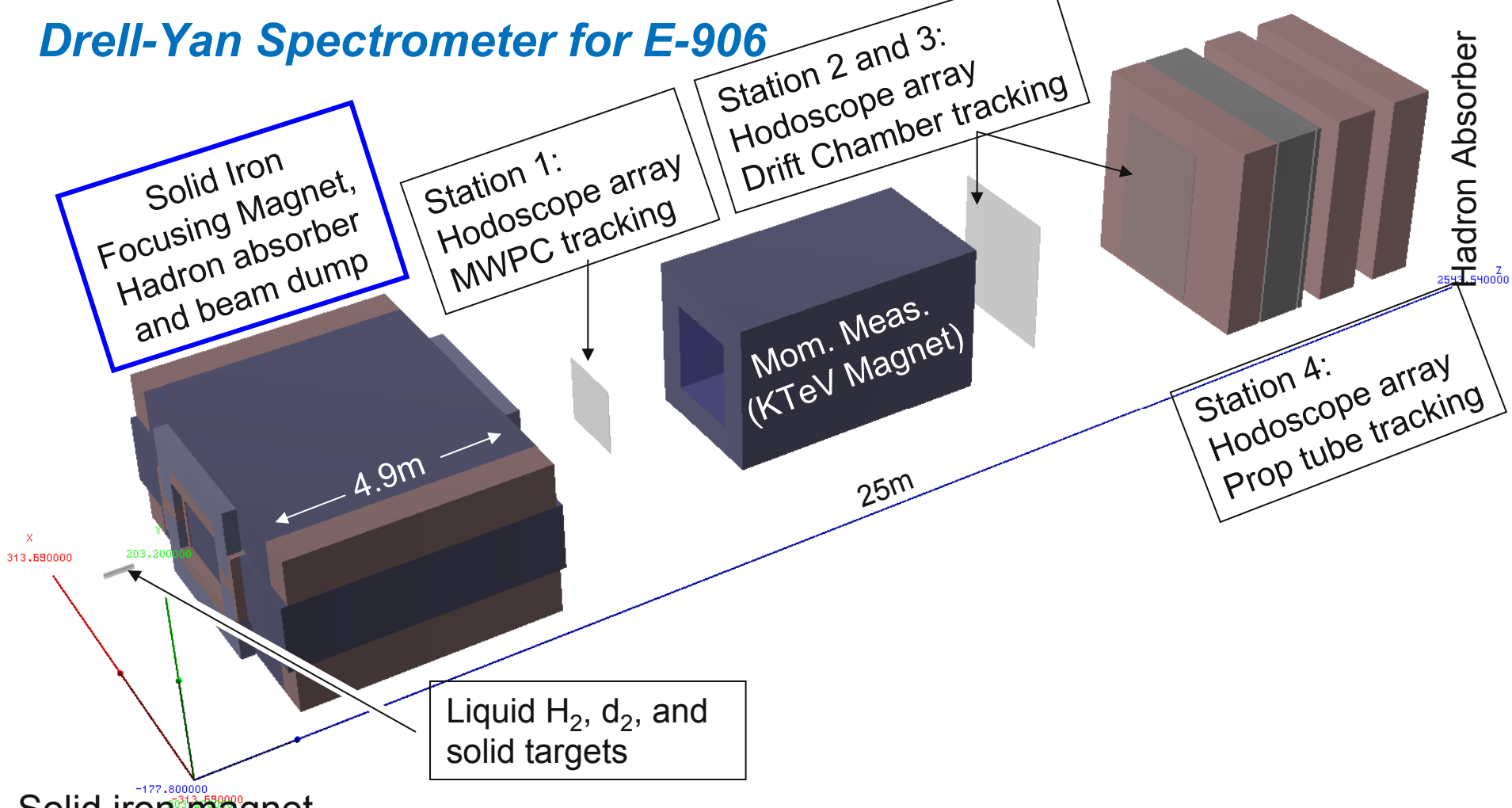
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- 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



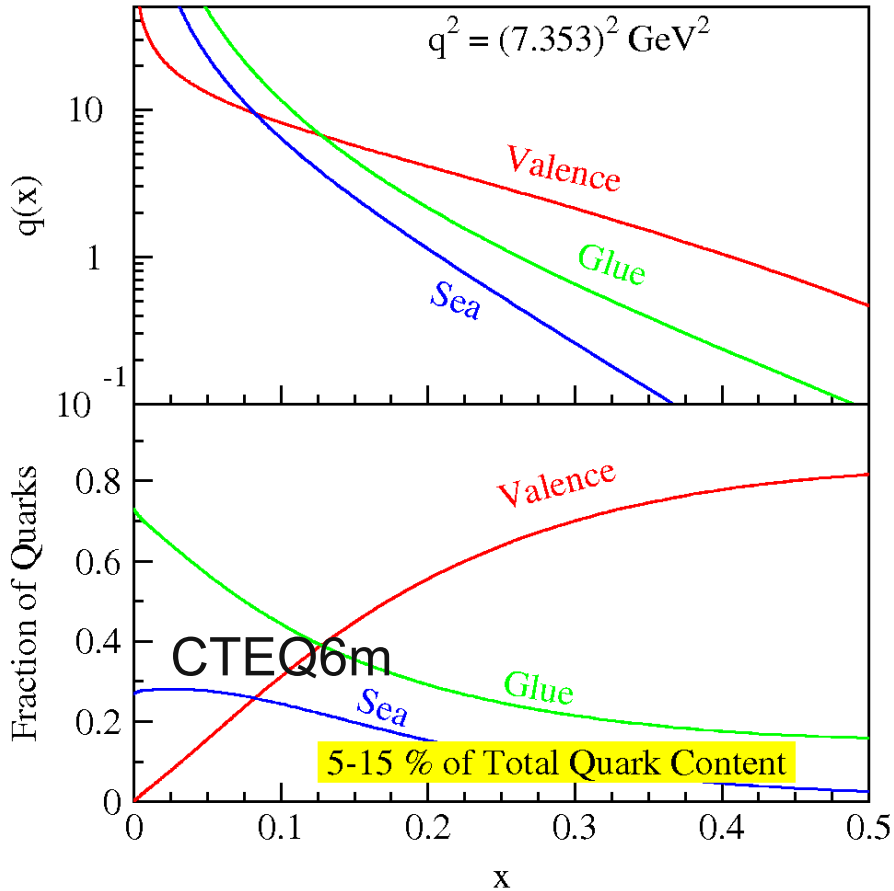
Solid iron magnet

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

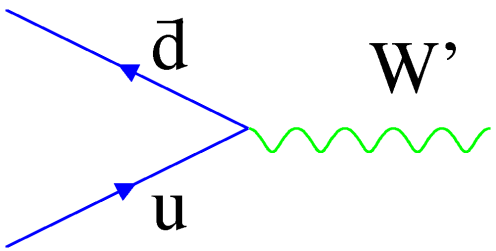
What is the distribution of sea quarks?

In the nucleon:

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



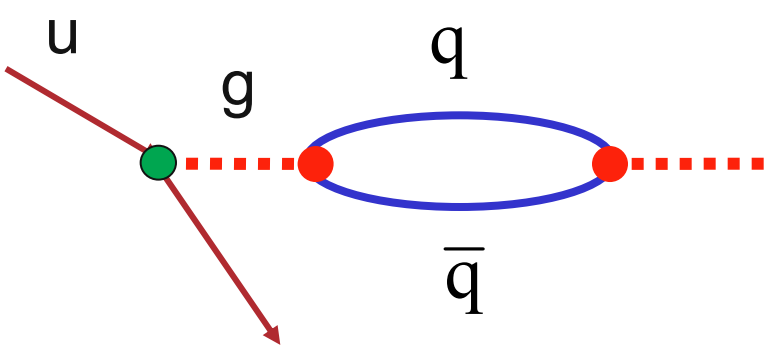
- Not just three valence quarks and QCD. Shown by E866/NuSea d-bar/u-bar data
- What are the origins of the sea?
- Significant part of LHC beam.



In nuclei:

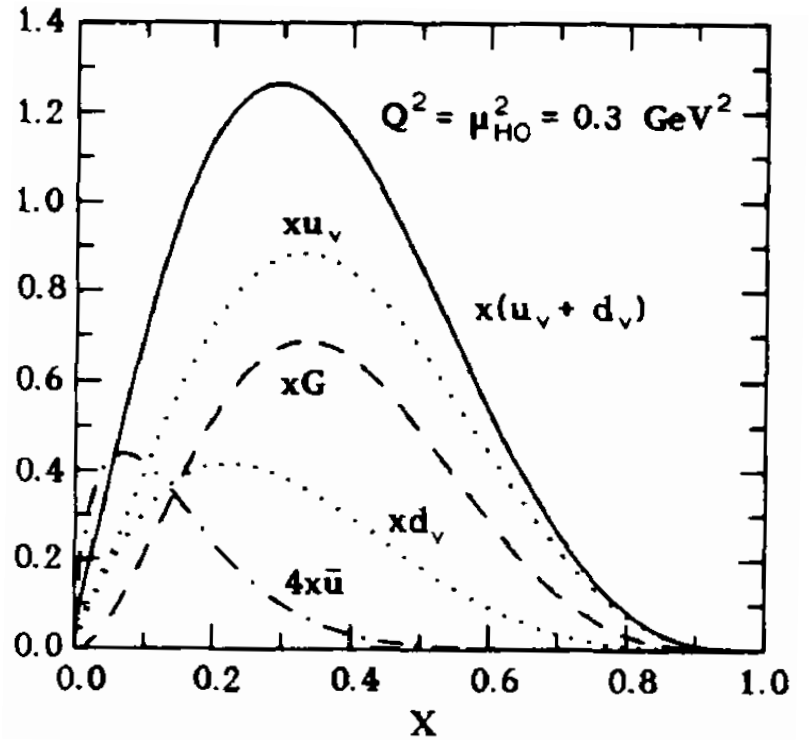
- The nucleus is not just protons and neutrons
- What is the difference?
  - Bound system
  - Virtual mesons affects antiquarks distributions

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



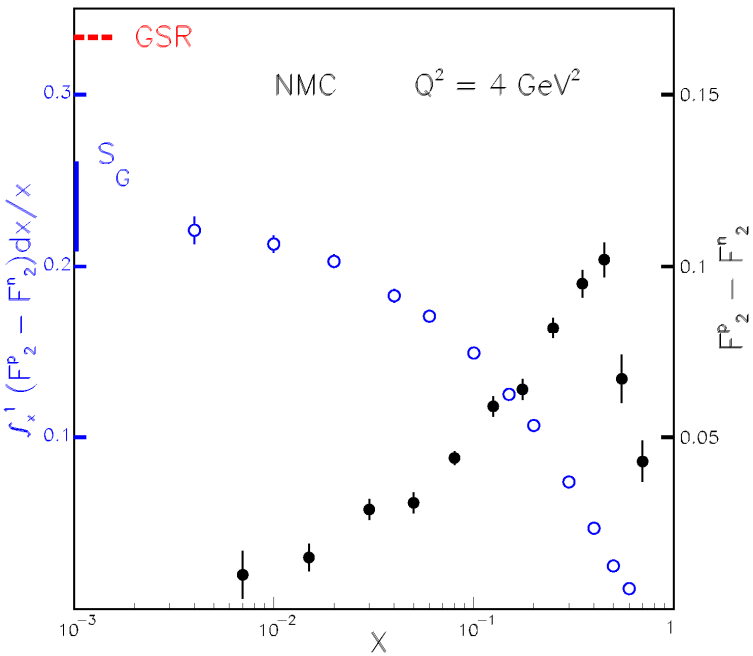
Light Antiquark Flavor Asymmetry: Brief History

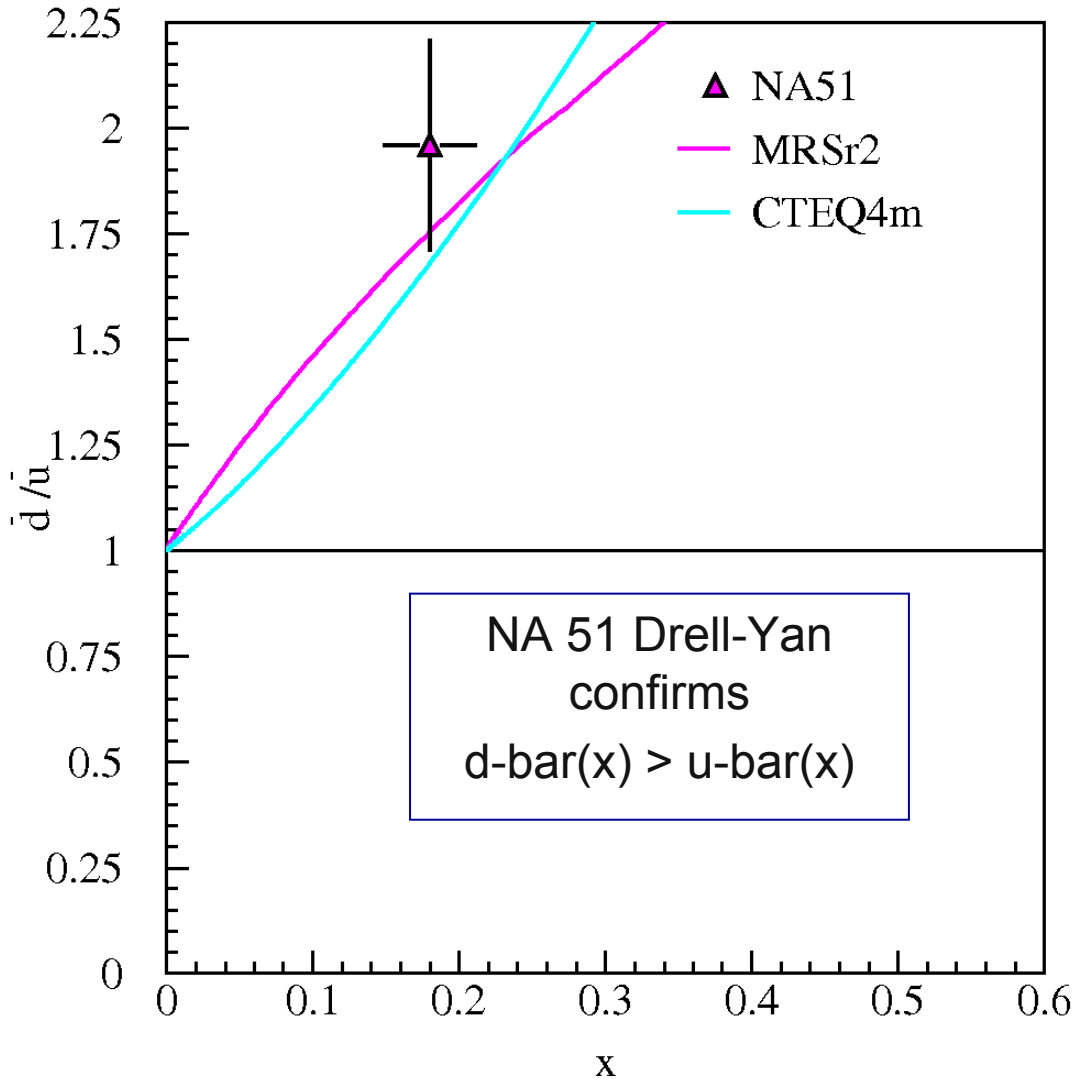
- Naïve Assumption:

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

- NMC (Gottfried Sum Rule)

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





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

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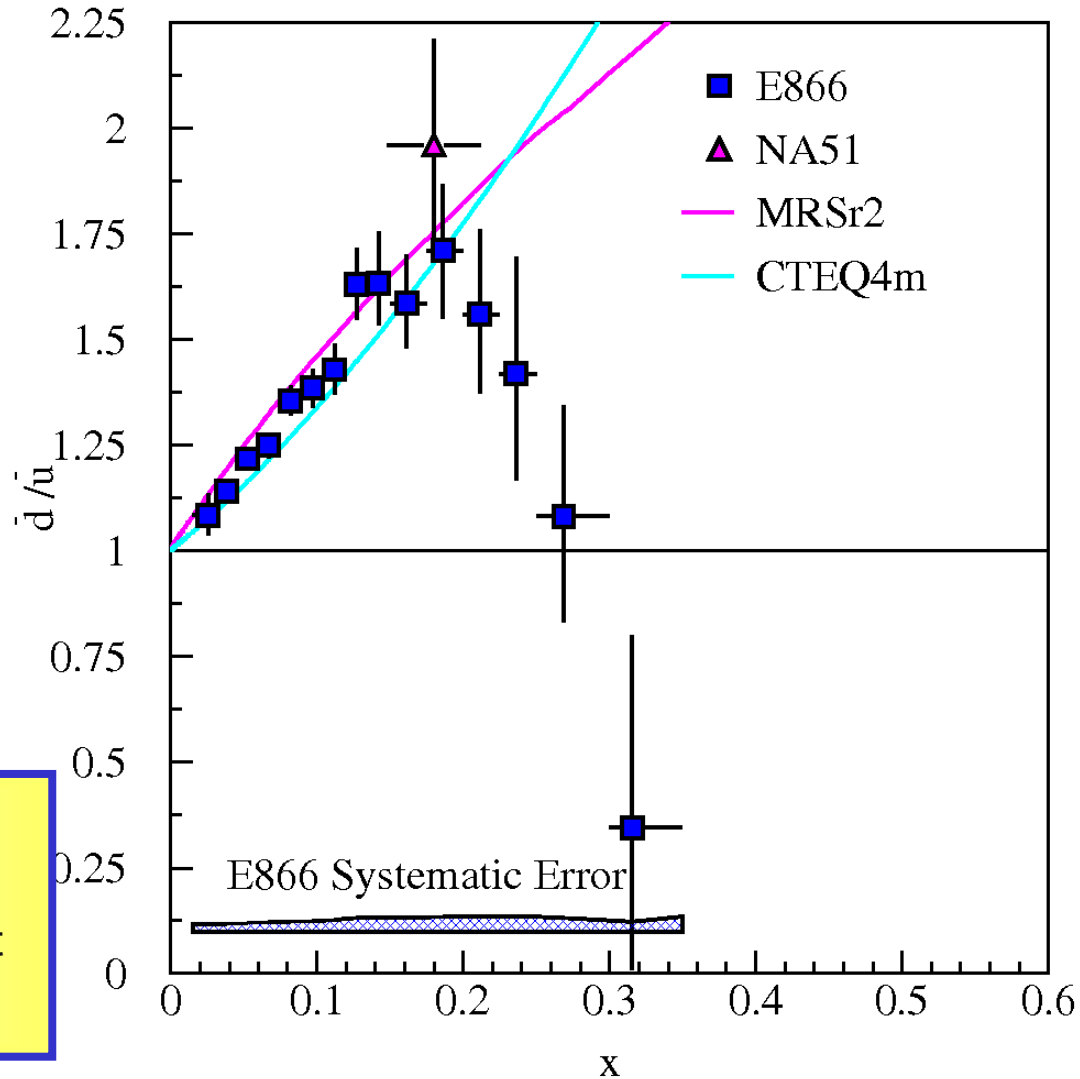
- NA51 (Drell-Yan)

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

- E866/NuSea (Drell-Yan)

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



- Knowledge of distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

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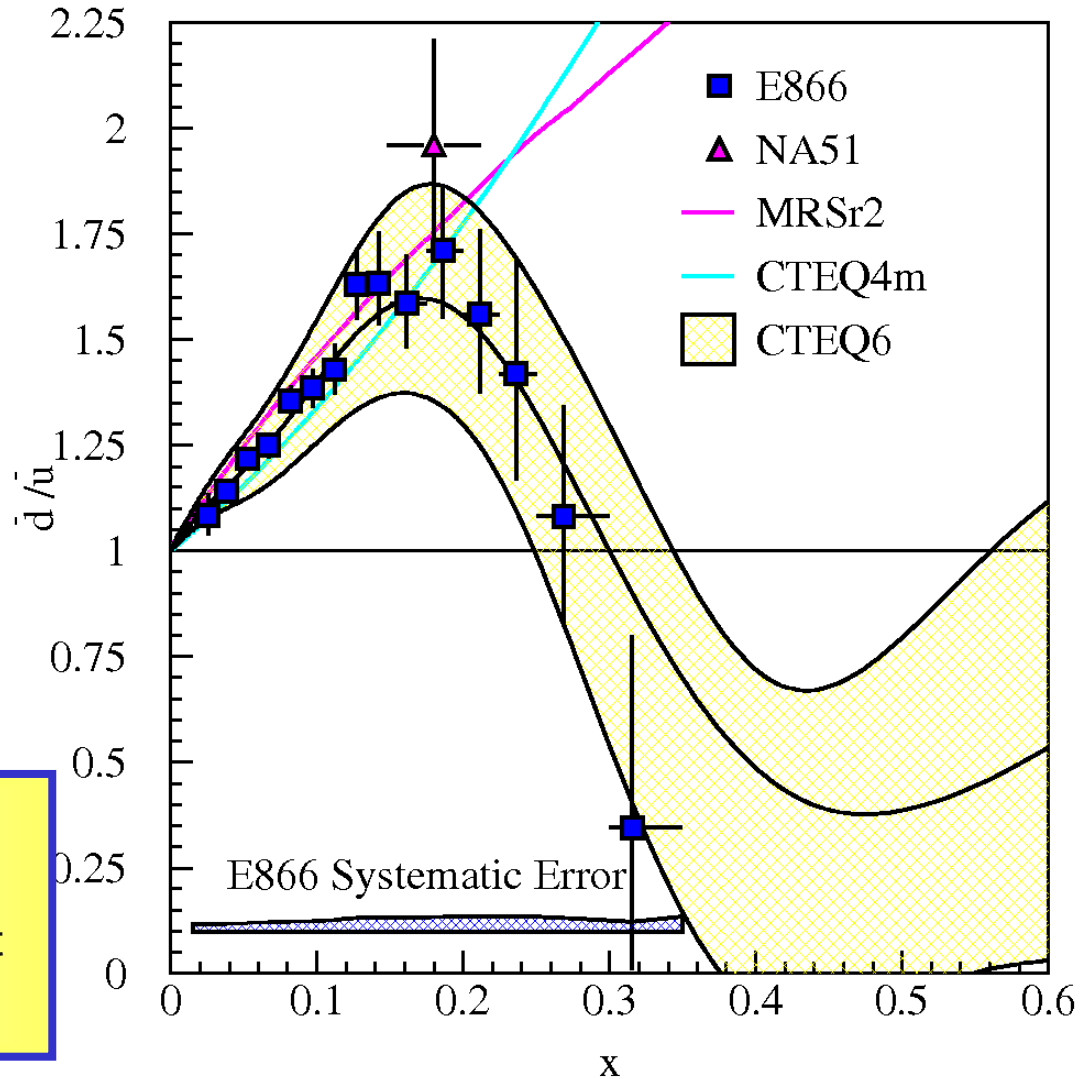

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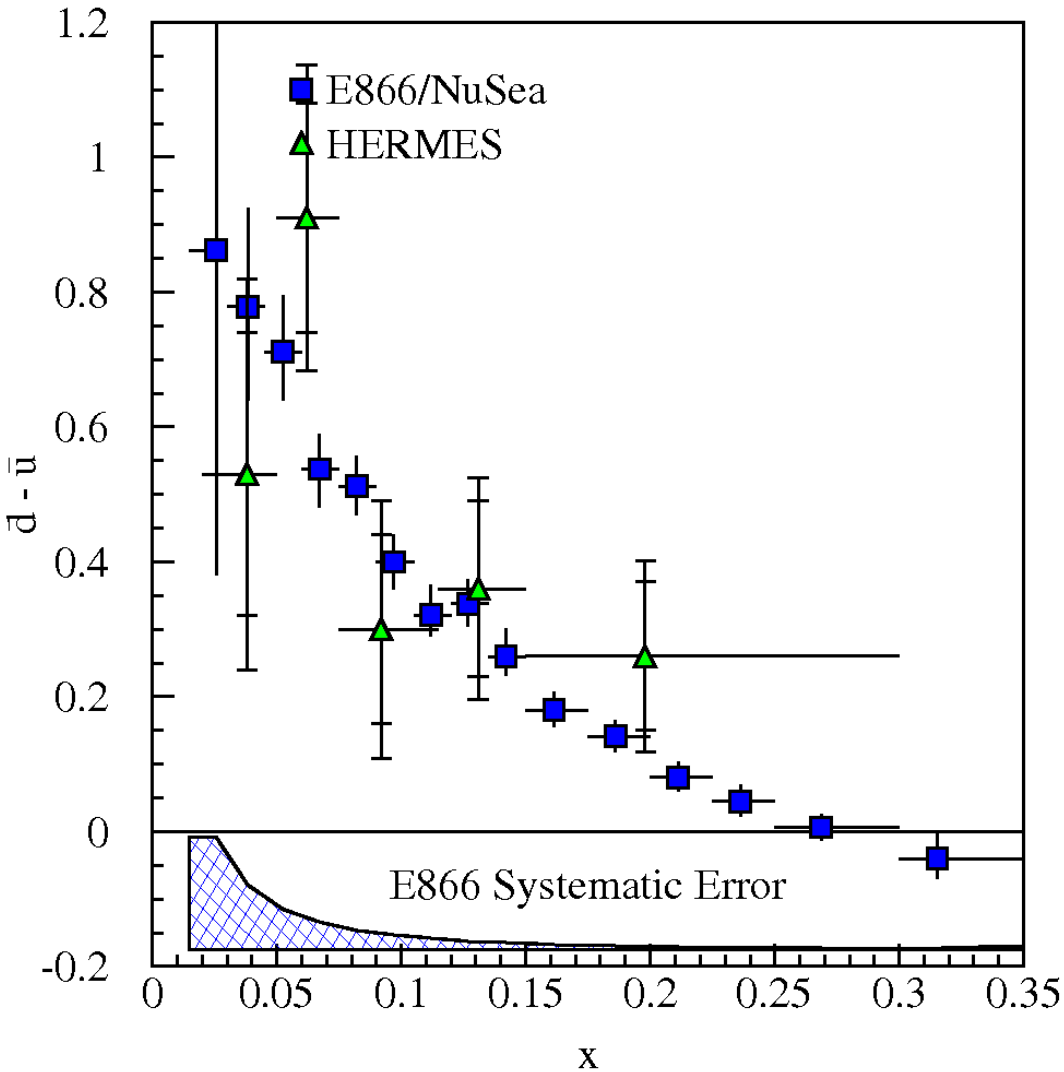
Proton Structure: By What Process Is the Sea Created?

- 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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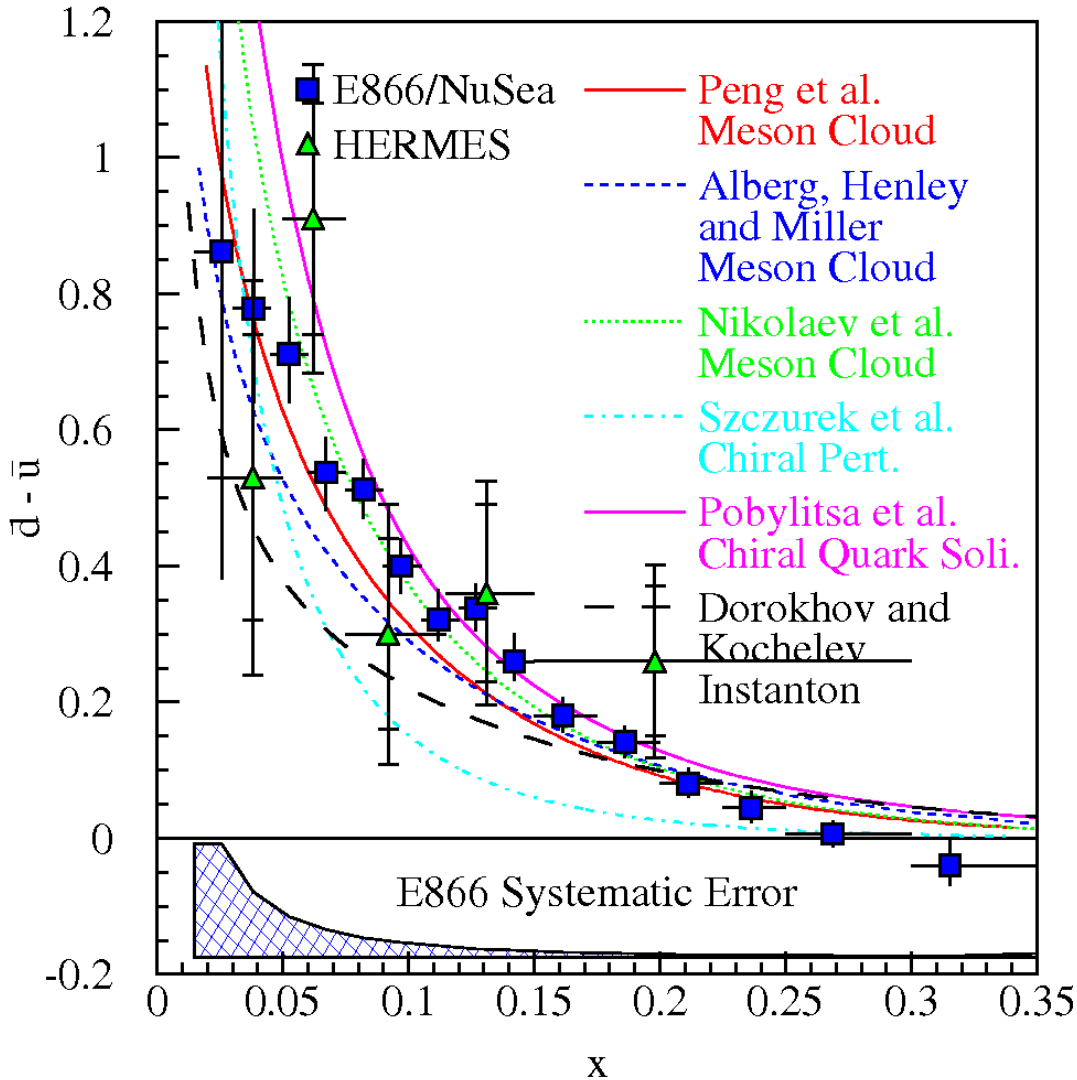
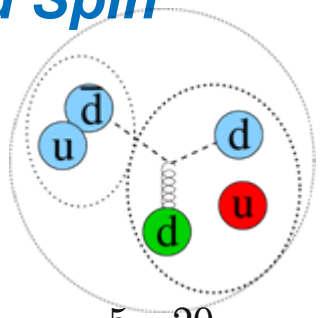


Models Relate Antiquark Flavor Asymmetry and Spin



- Meson Cloud in the nucleon—Sullivan process in DIS

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

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

- Chiral Quark models—effective Lagrangians

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

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

- Instantons

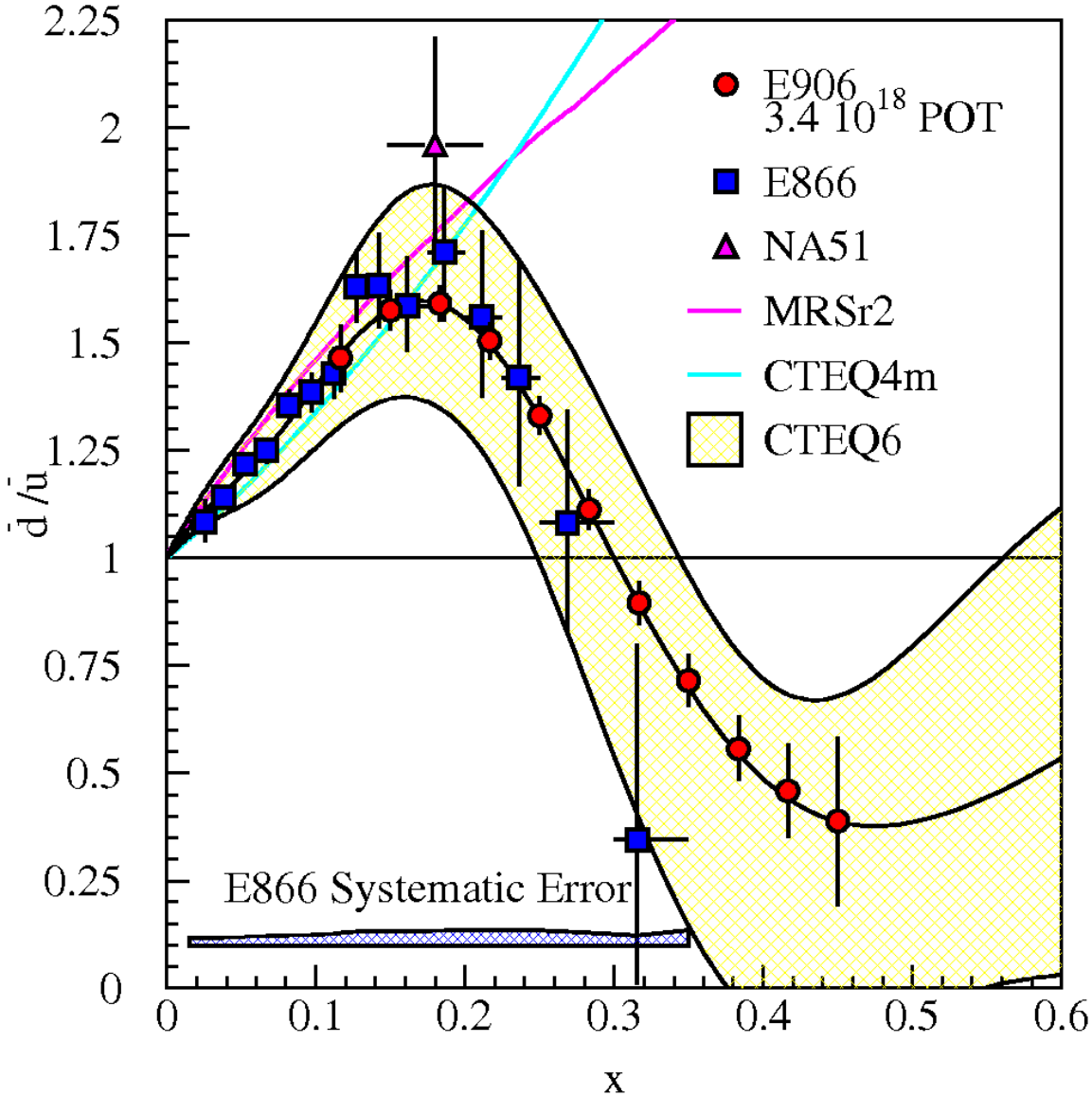
$$\mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R \qquad \bar{d}_I(x) - \bar{u}_I(x) = \frac{3}{5}\left[\Delta u_I(x) - \Delta d_I(x)\right]$$

- Statistical Parton Distributions

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

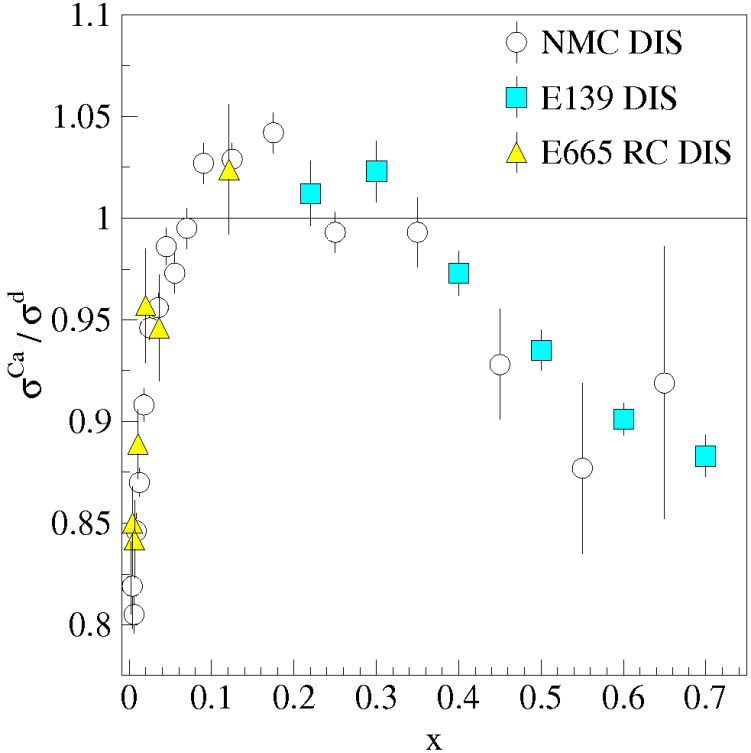
Extracting d-bar/-ubar From Drell-Yan Scattering

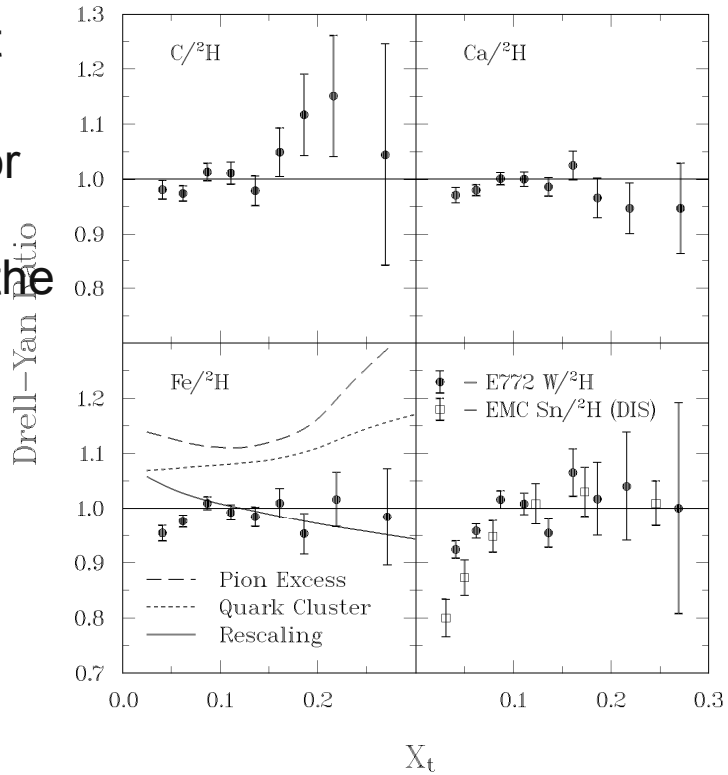
- E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.



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?



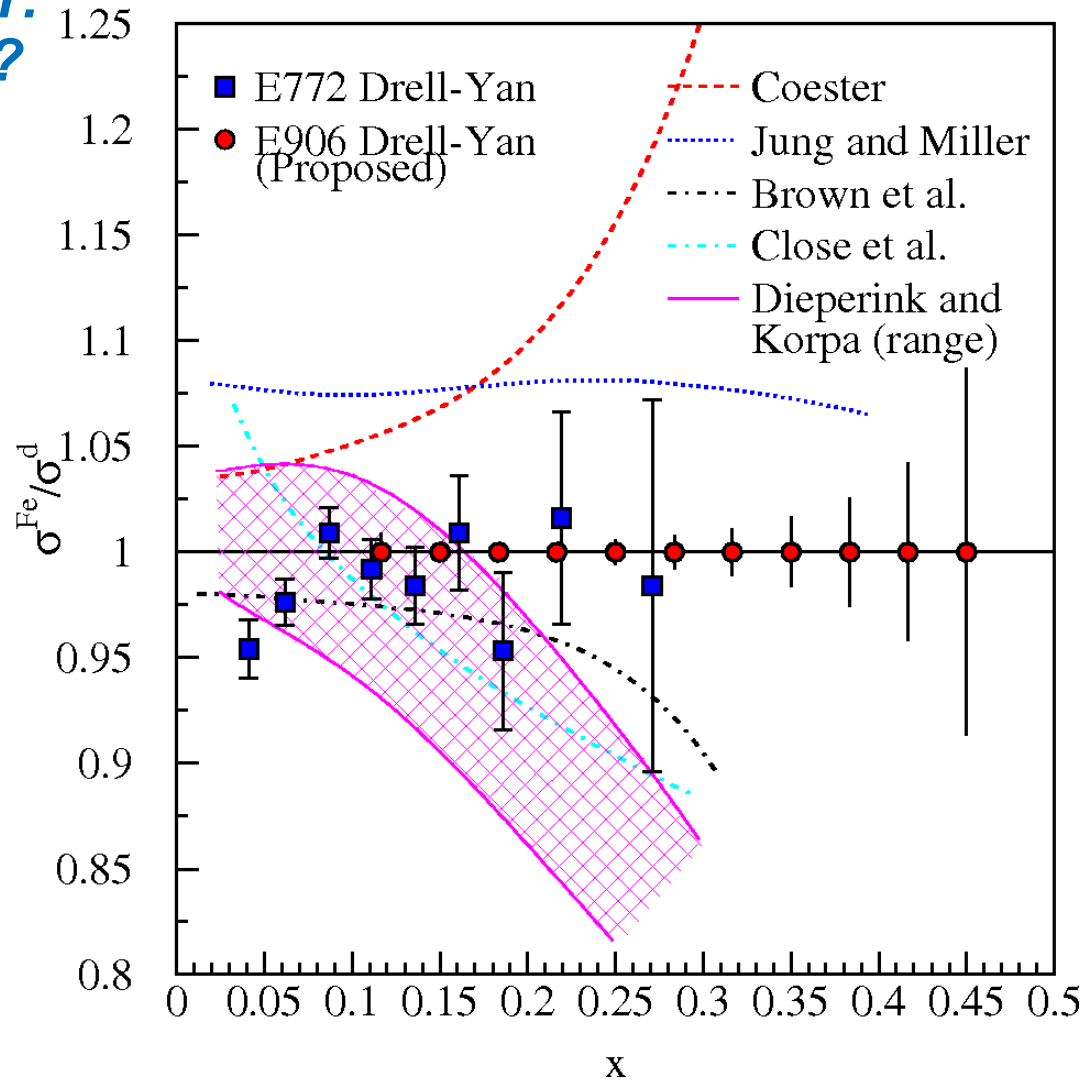


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

- 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: Where are the nuclear pions?

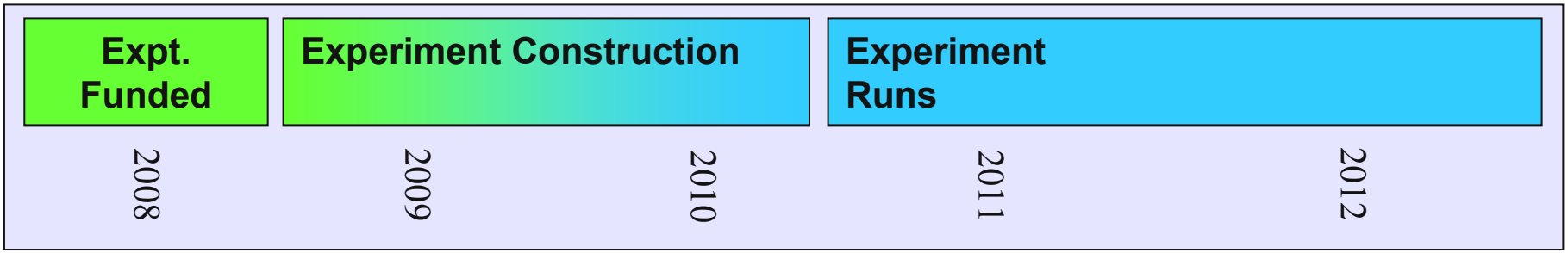
- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect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



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



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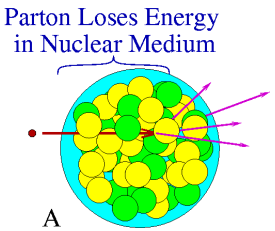
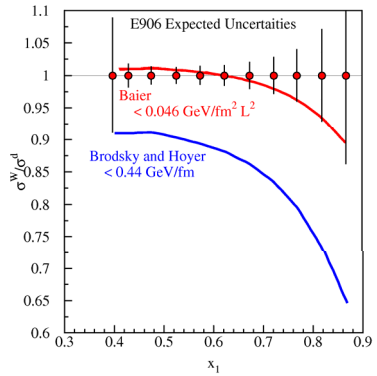
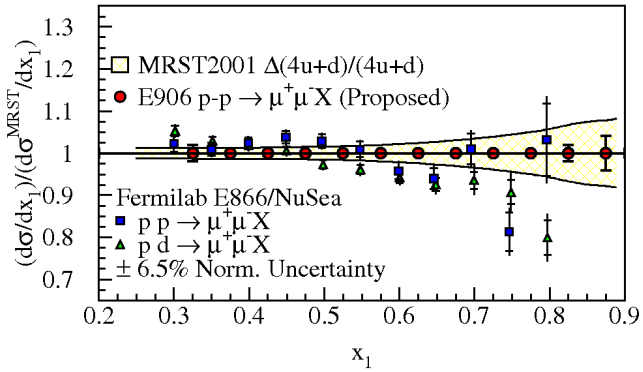
Additional Physics from beam parton distributions

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





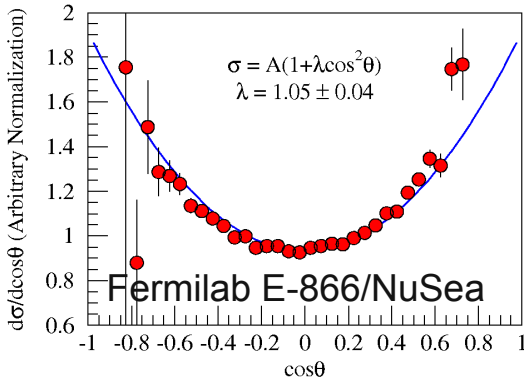


Unpolarized Angular distributions

- 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

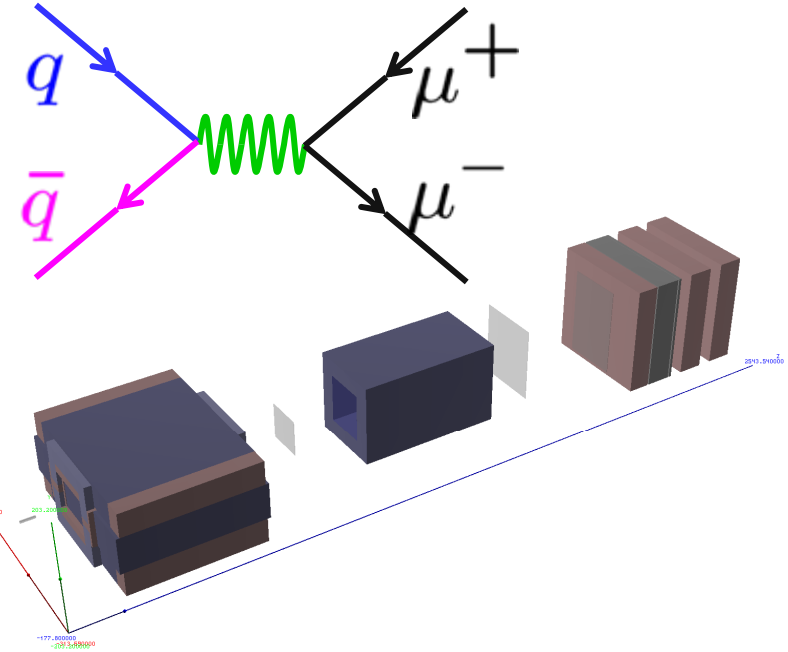


Possible future programs

- Polarized target of beam
- Pionic Drell-Yan

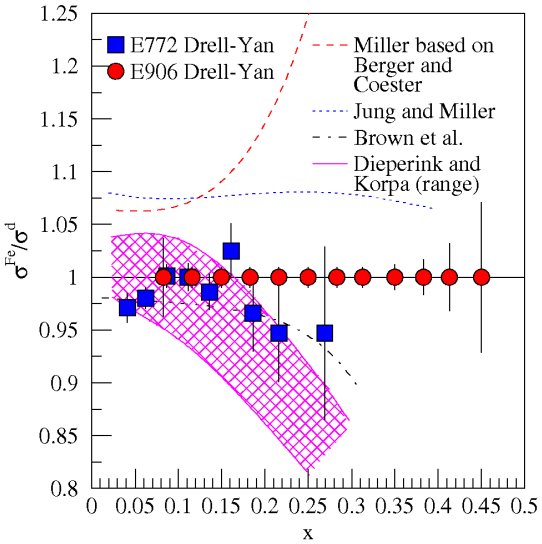
Drell-Yan at Fermilab

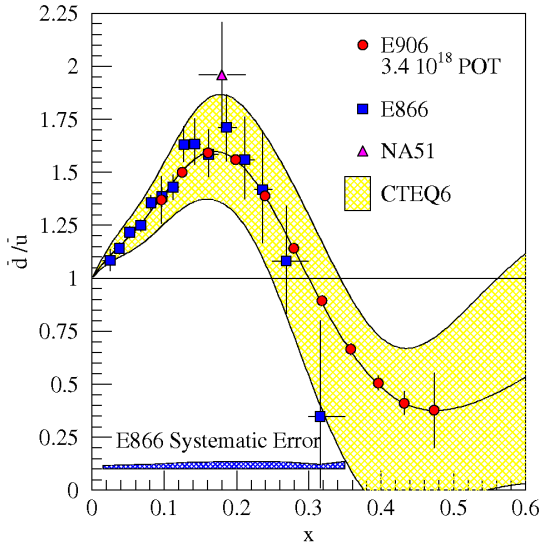
- Drell-Yan scattering is uniquely sensitive to the antiquark distributions of the target.



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

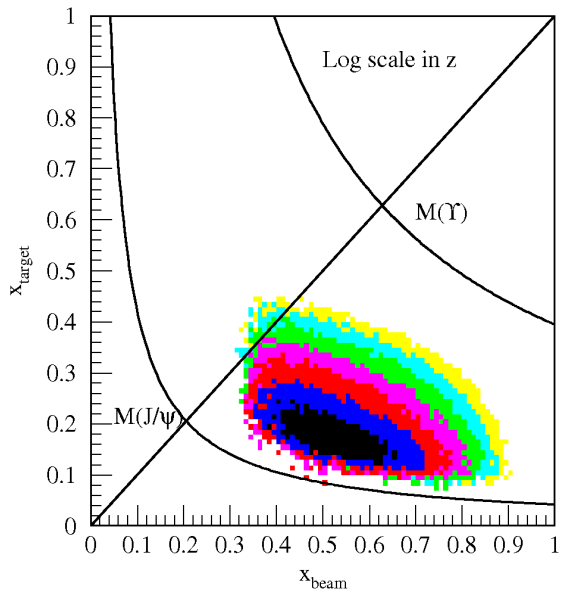
- E-906/Drell-Yan will use this to measure
  - the ration of anti-d to anti-u distributions in the proton,
  - The modifications to the quark sea in a nucleus, and
  - Many more interesting topics

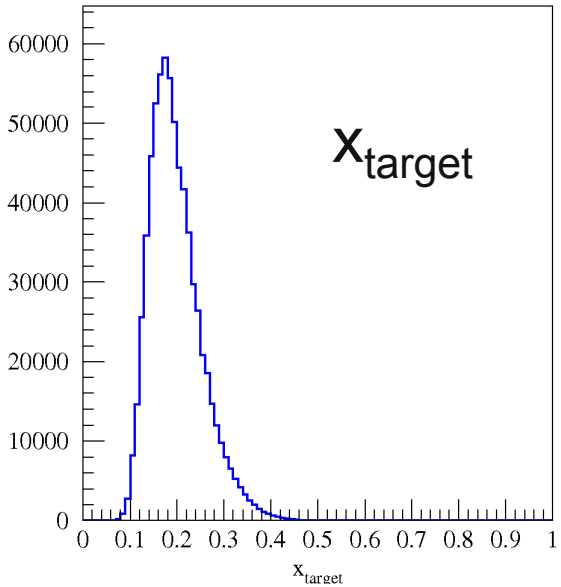


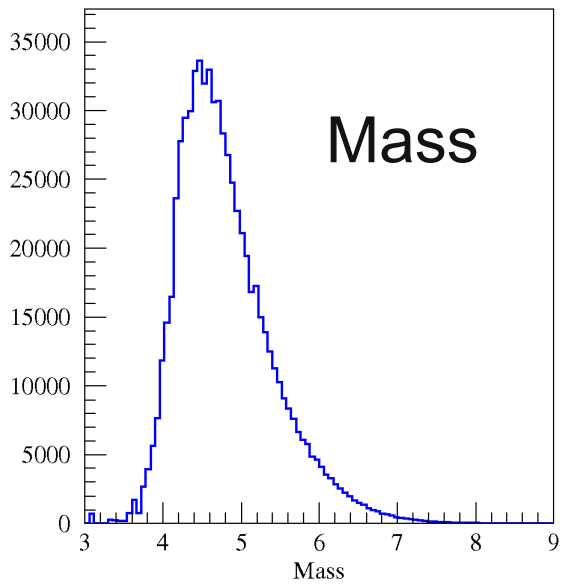


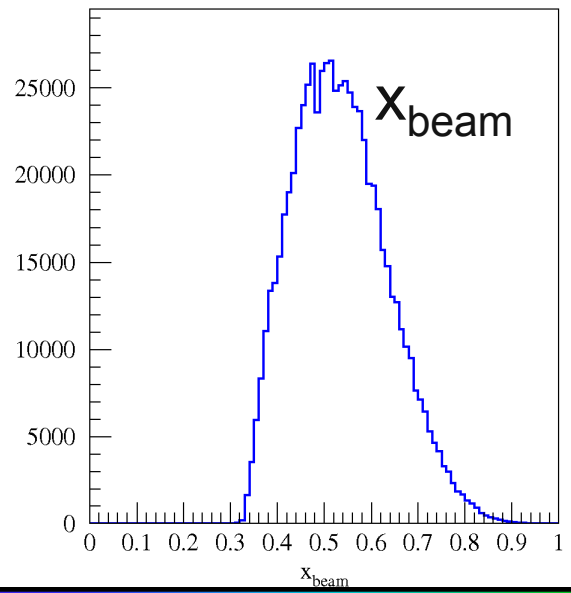
Drell-Yan Acceptance

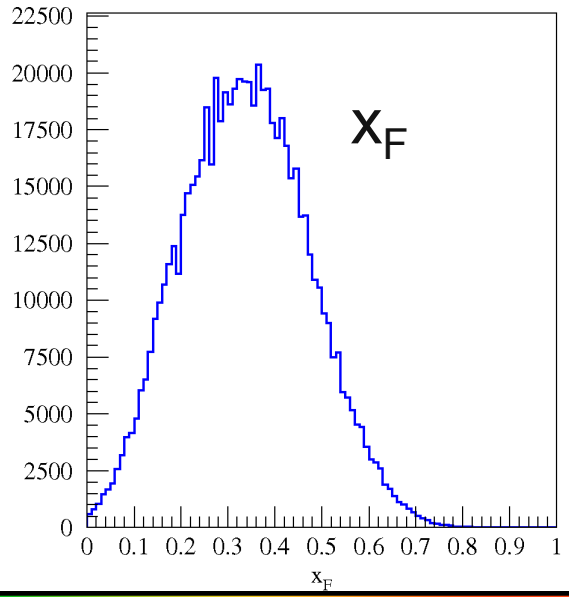
- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ′ studies



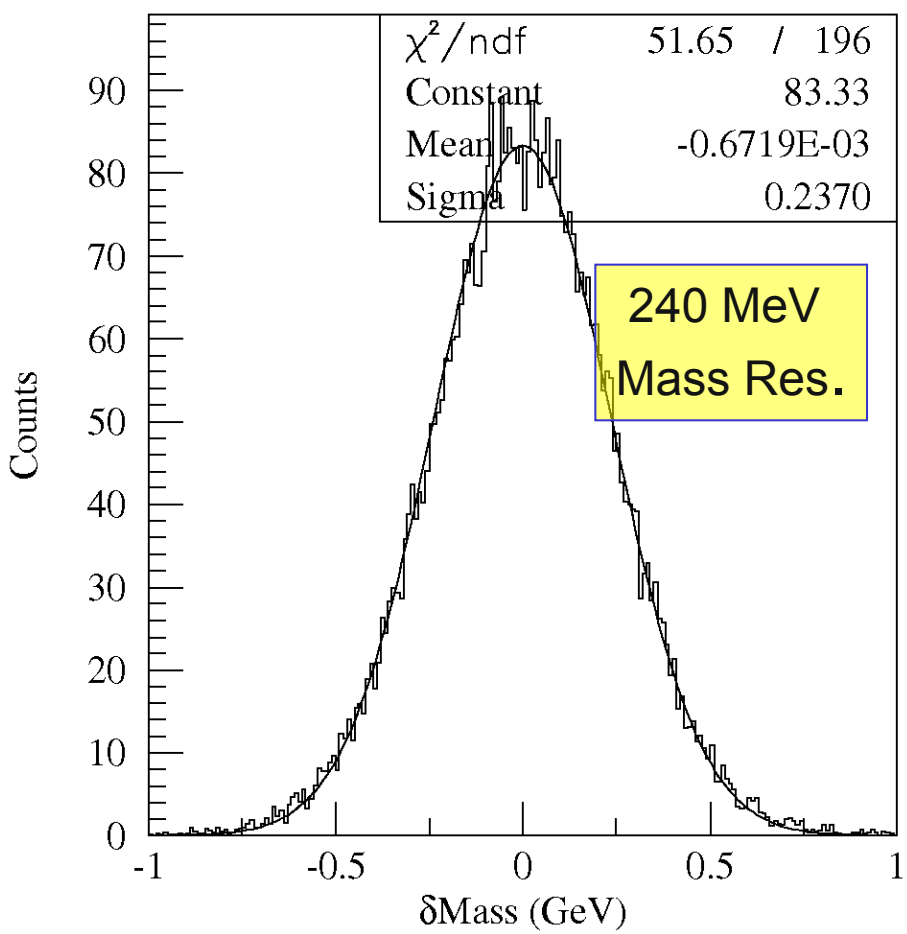


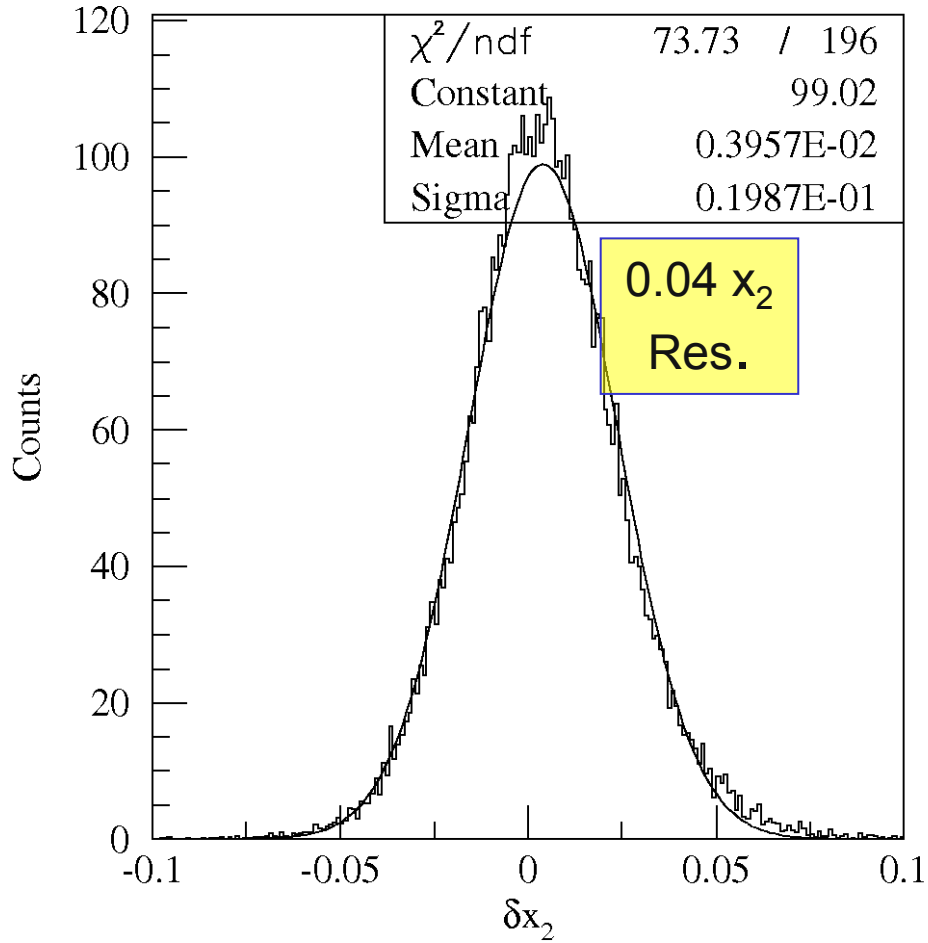






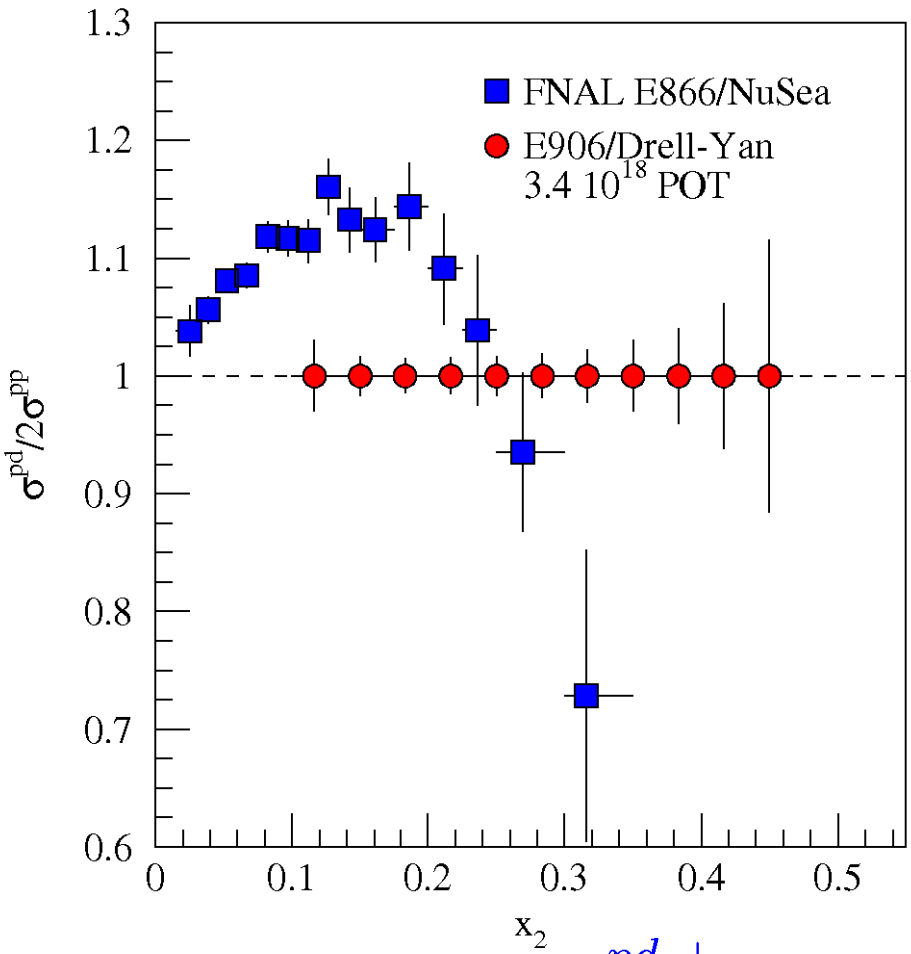
Detector Resolution

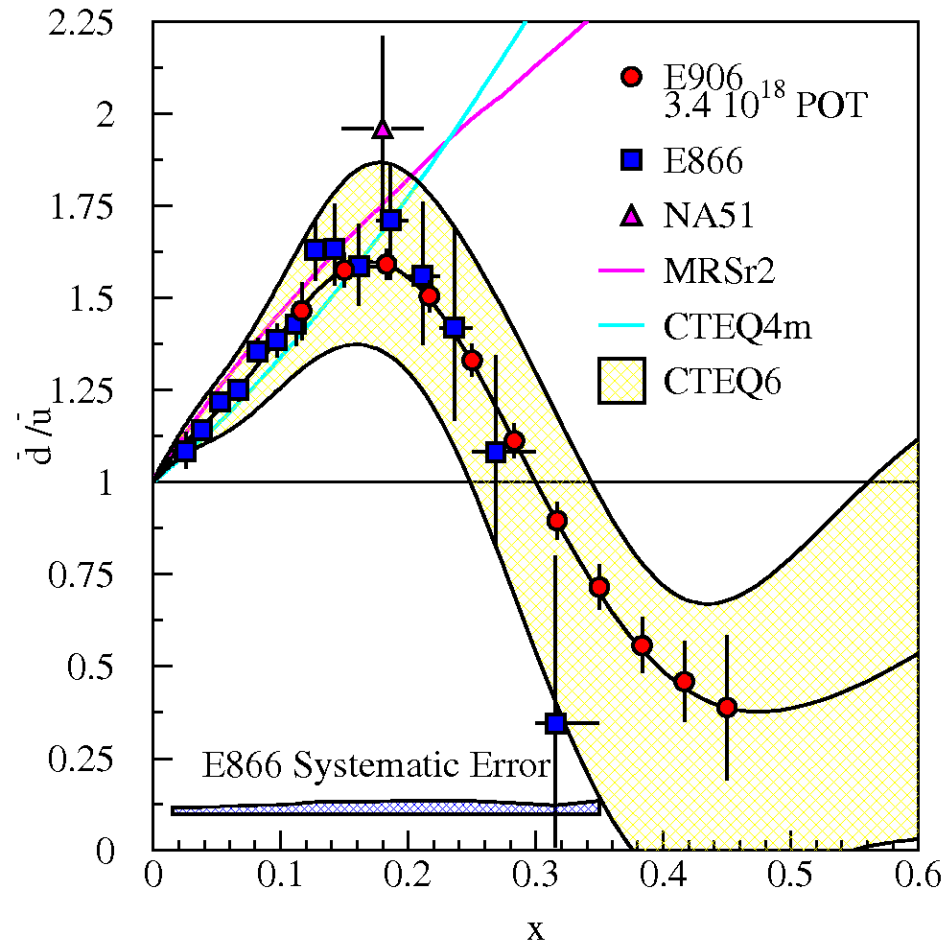




- Triggered Drell-Yan events

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





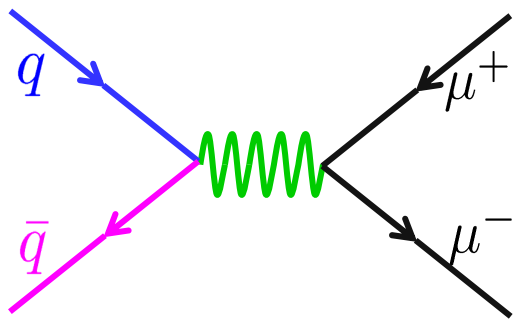
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

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

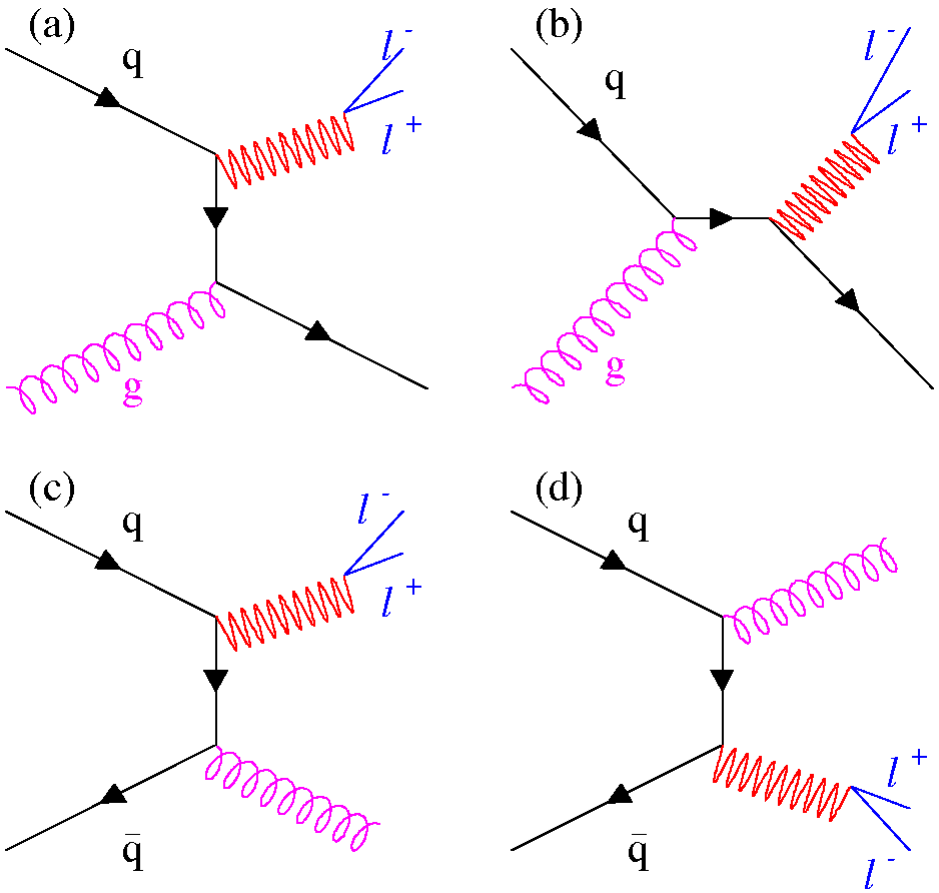
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$



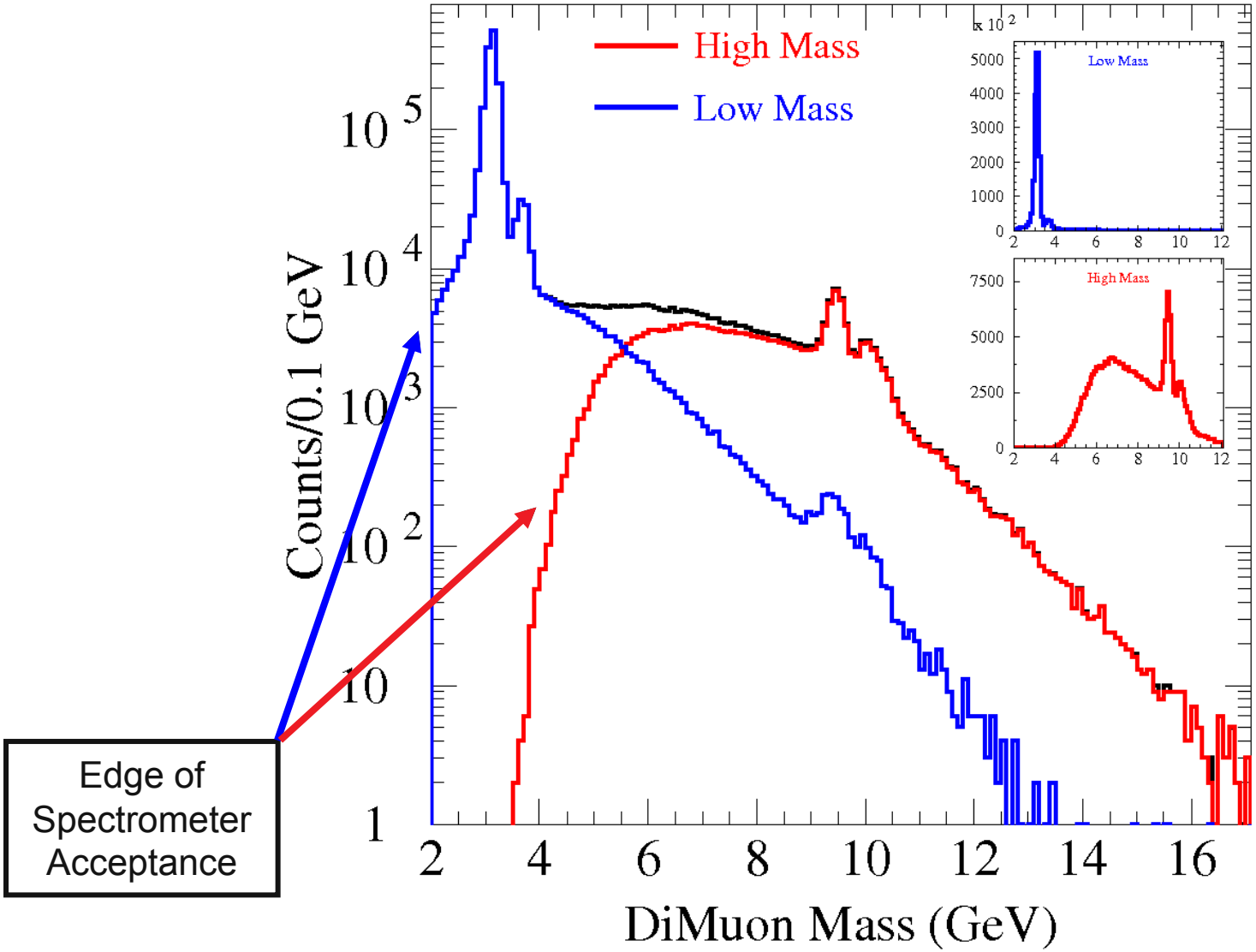
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

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