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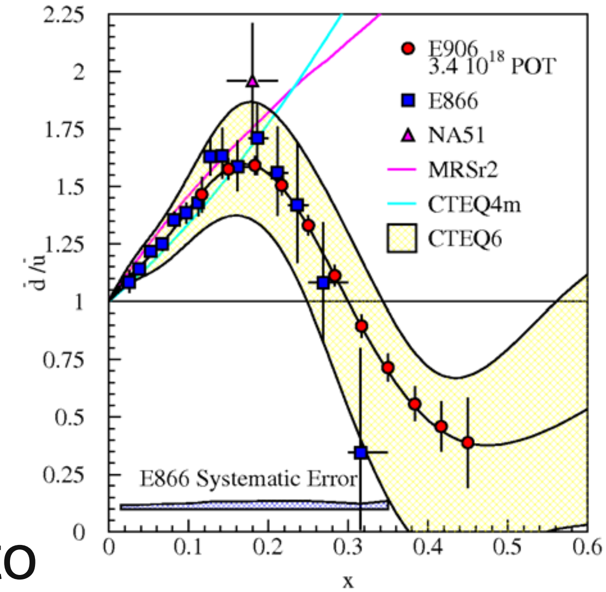
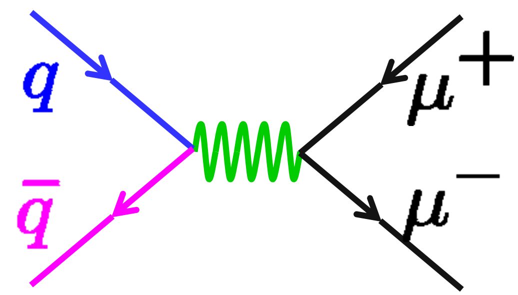
Exploring the Antiquark Structure of Matter with Drell-Yan Scattering

Paul E. Reimer

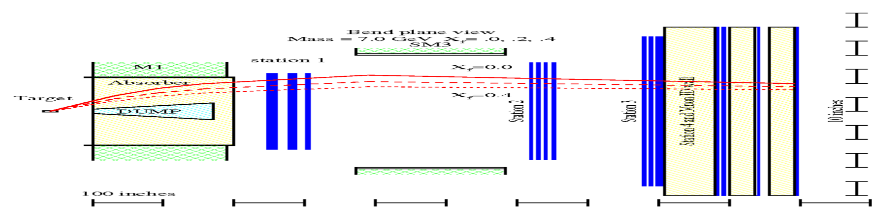
17 March 2008



- Internal proton structure
  - *Femto scale physics*
- Drell-Yan and its relation to anitquarks



- E906/Drell-Yan experiment



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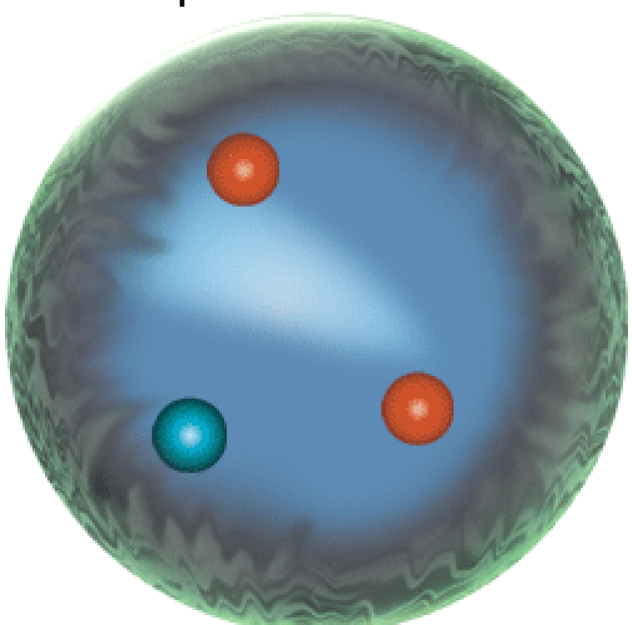
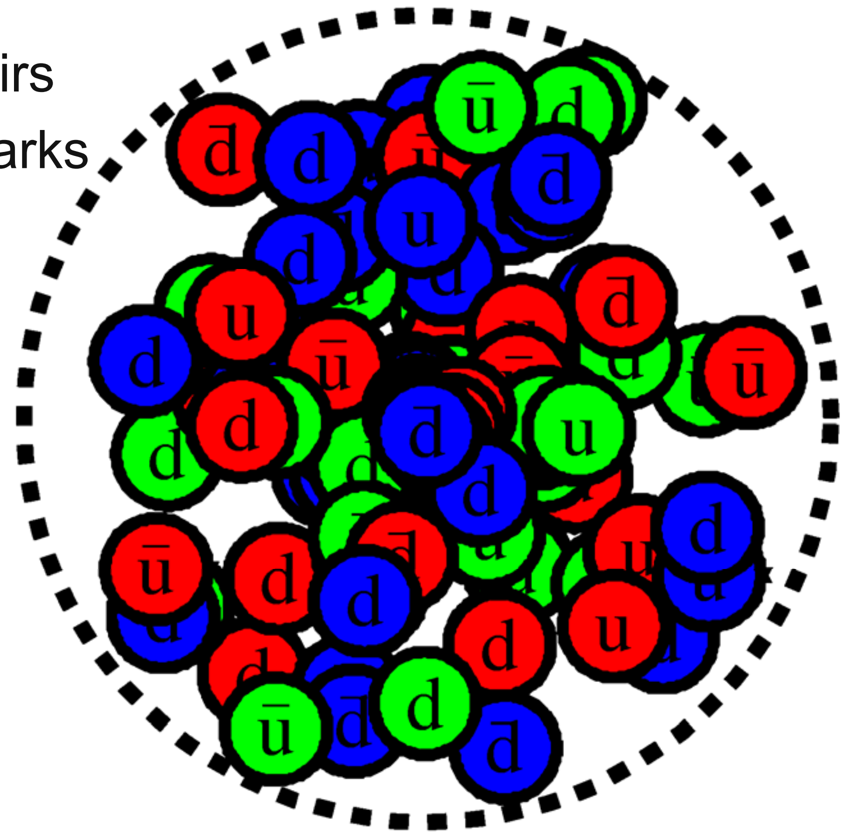
What is in the Proton?

- Three "Valence" quarks
  - 2 "up" quarks
  - 1 "down" quark
- Bound together by gluons
- Gluons can split into quark-antiquark pairs
- Forms large "sea" of low momentum quarks and antiquarks





How do we probe the quarks in the proton?

- Deep Inelastic Scattering

$$F_2^{\mu N}(x) \propto \sum e^2 x\,[q(x)+\bar{q}(x)]$$
$$F_2^{\nu p}(x)+F_2^{\nu n}(x) \propto \sum x\,[q(x)+\bar{q}(x)]$$
$$xF_3^{\nu N}(x) \propto \sum x\,[q(x)-\bar{q}(x)]$$
$$\text{(Valence Dist.)}$$

- Semi-Inclusive DIS (HERMES)—Spin/Flavor

$$N^{\pi^\pm} \propto \sum^{2}\left[q(x)D^{\pi^\pm}+\bar{q}(x)D^{\pi^\pm}\right]$$

- W Production Asymmetry

$$A_W(y) \propto \frac{u(x_1)d(x_2)-d(x_1)u(x_2)}{u(x_1)d(x_2)-d(x_1)u(x_2)}$$

- Drell-Yan Scattering (D-Y)

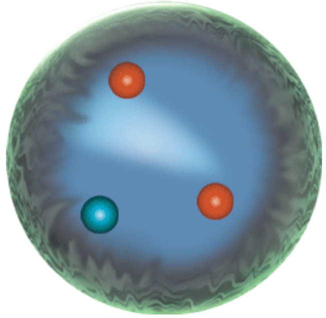
$$\sigma^{\mathrm{D-Y}} \propto \sum e^2\,[q_b(x)\bar{q}_t(x) + \bar{q}_b(x)q_t(x)]$$

  - Unique access to sea distributions

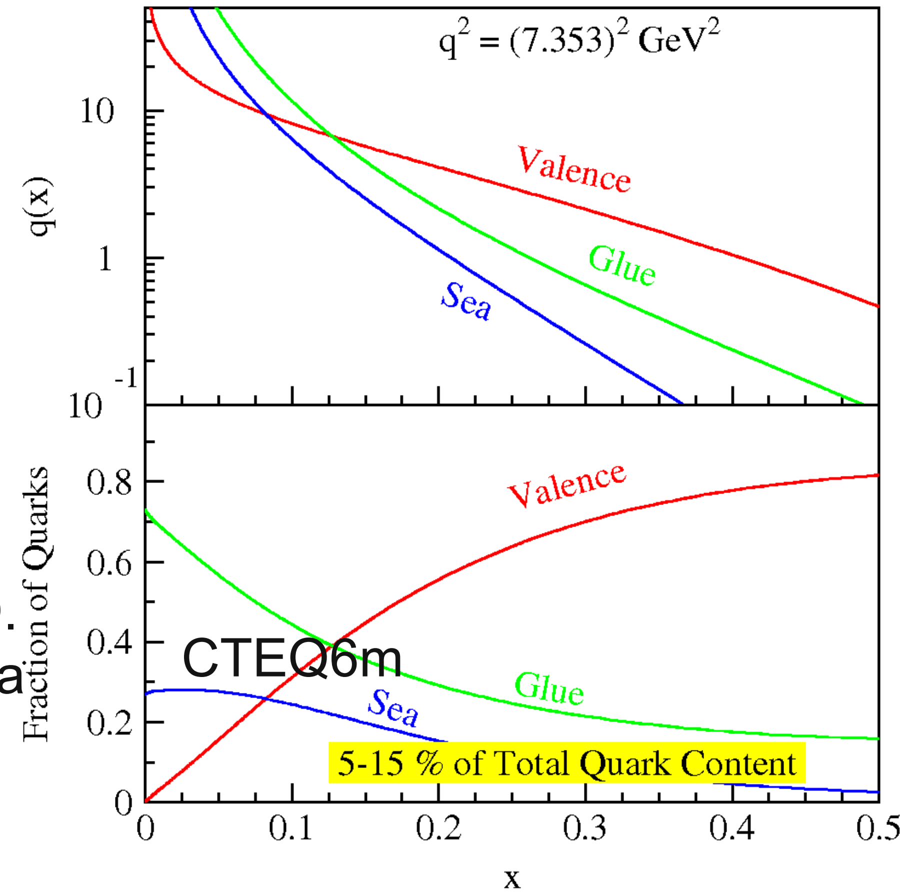
- Distributions extracted with phenomenological fits to worlds data set.
  - MRST, Eur. Phys. J **C23** 73 (2002)
  - CTEQ, JHEP **07** 012 (2002)

What is the distribution of sea quarks?

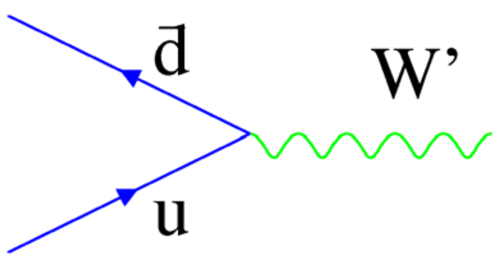
In the nucleon:



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



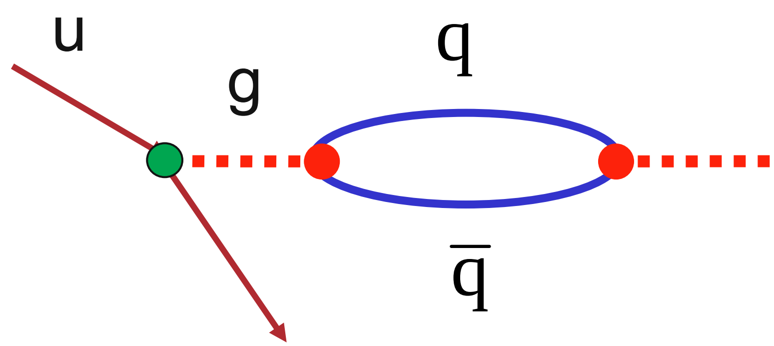
- Not just three valence quarks and QCD. Shown by E866/NuSea d-bar/u-bar data
- What are the origins of the sea?
- Significant part of LHC beam.



In nuclei:

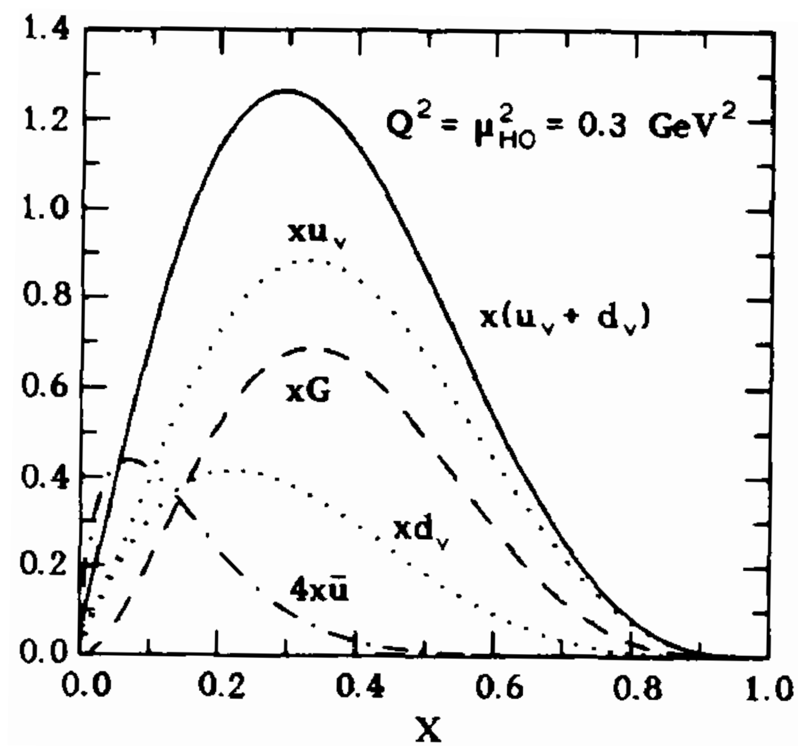
- The nucleus is not just protons and neutrons
- What is the difference?
  - Bound system
  - Virtual mesons affects antiquarks distributions

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



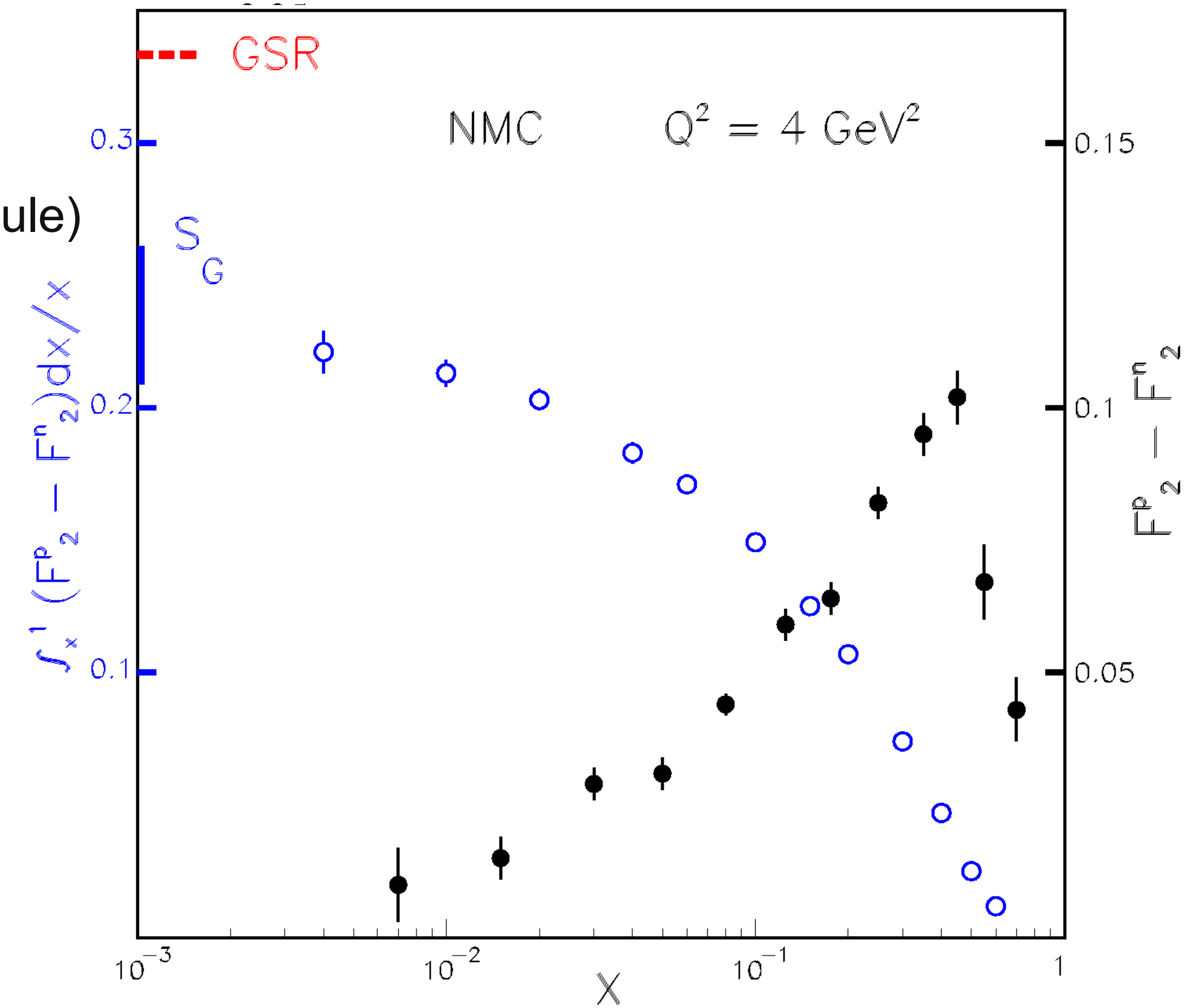
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

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

- NMC (Gottfried Sum Rule)

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



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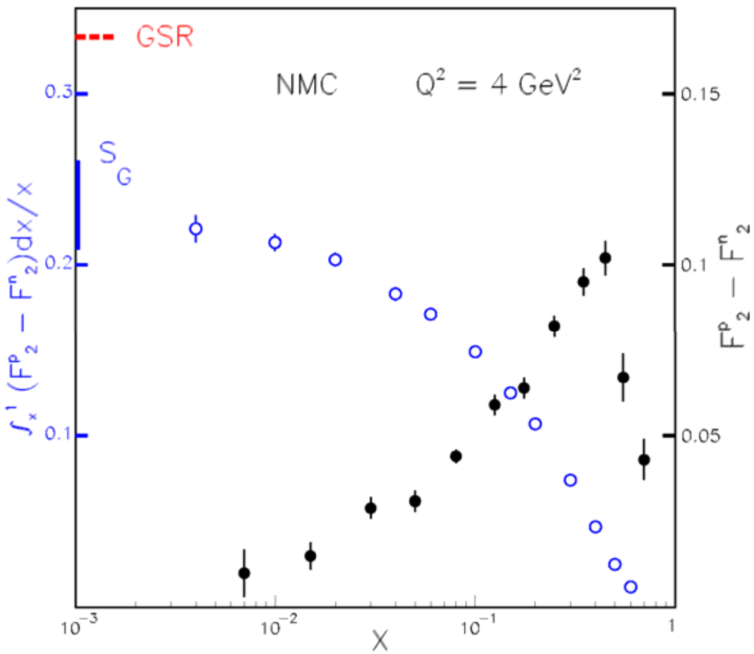

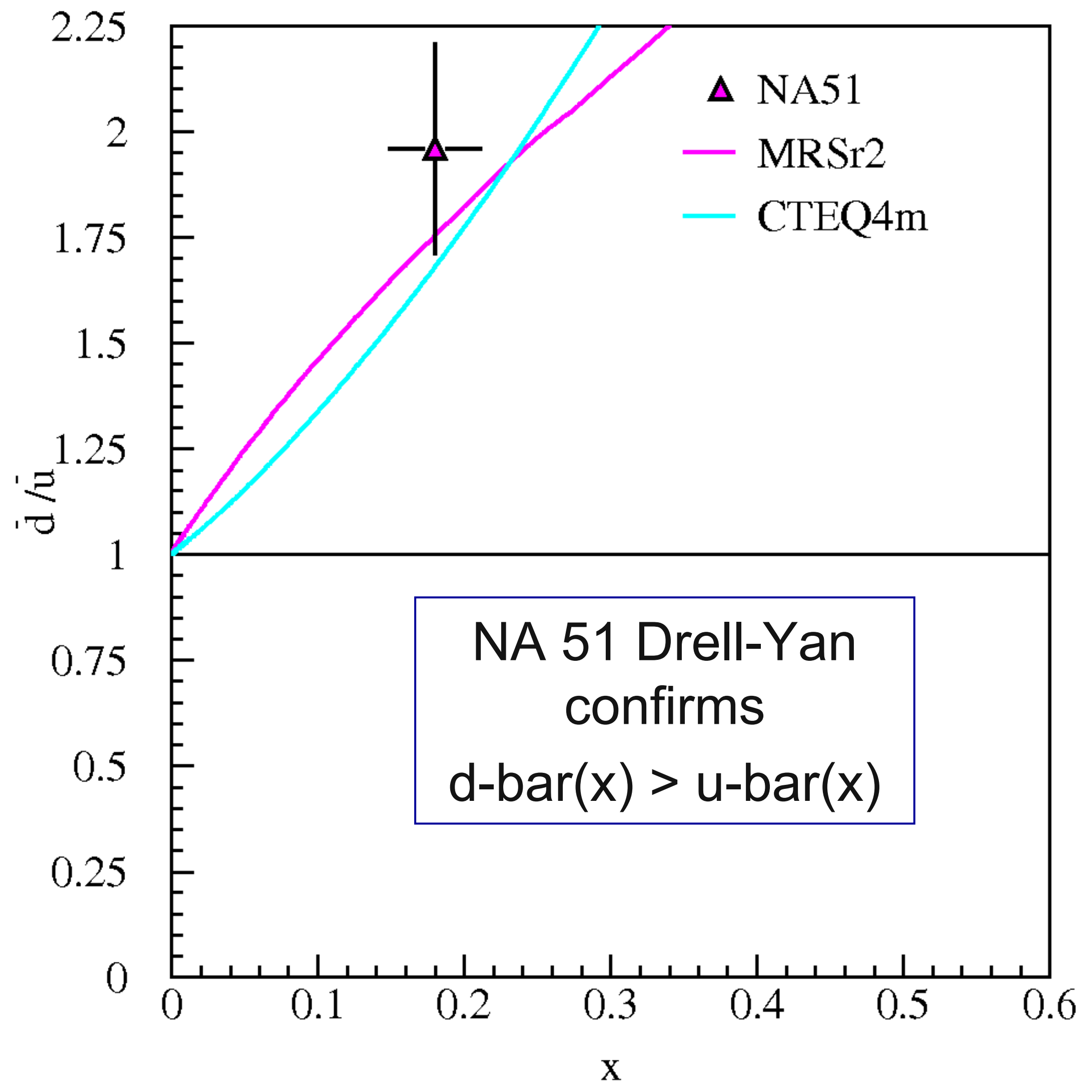

Light Antiquark Flavor Asymmetry: Brief History

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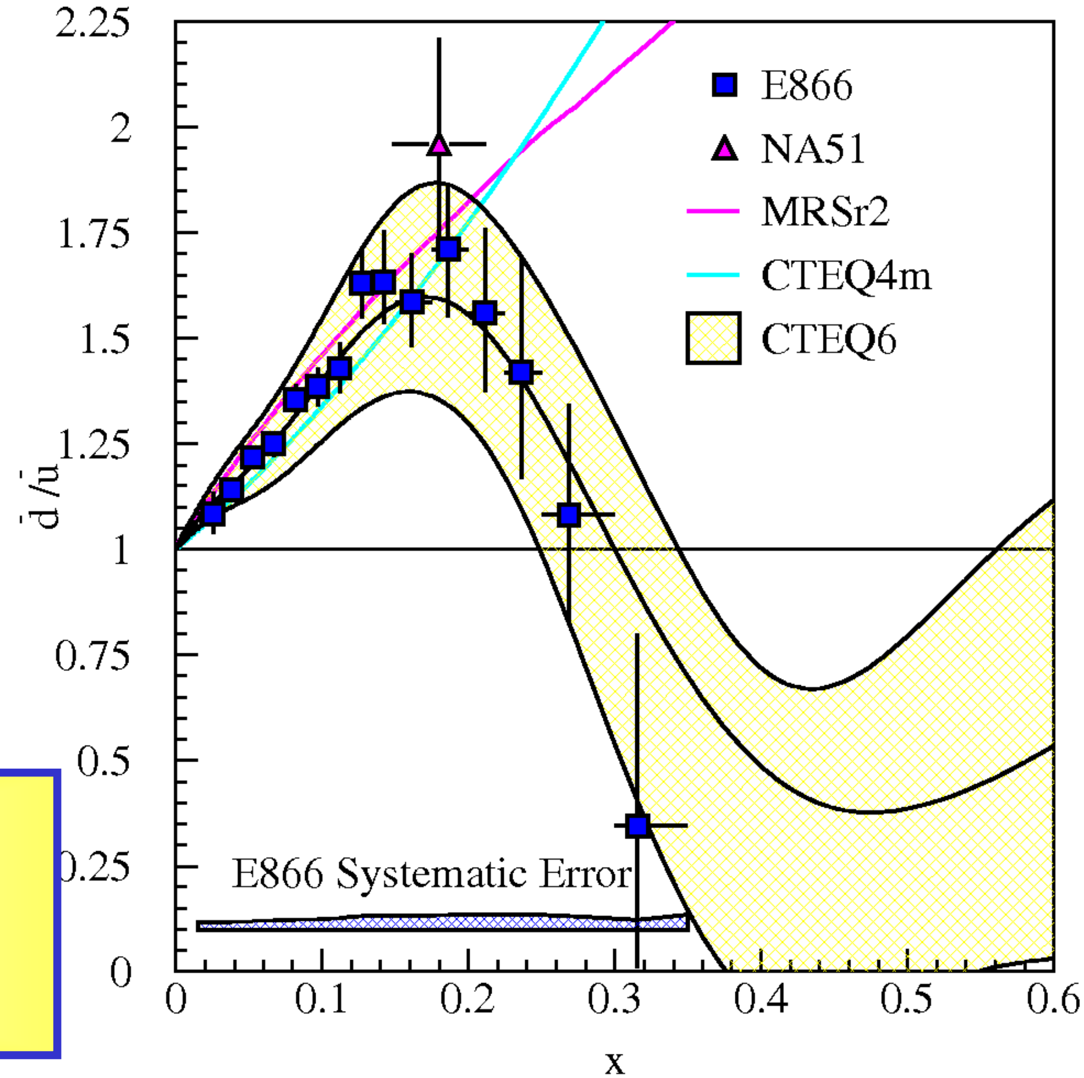
  $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule)
  $$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$
- NA51 (Drell-Yan)
  $\bar{d} > \bar{u}$ at $x = 0.18$
- E866/NuSea (Drell-Yan)
  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



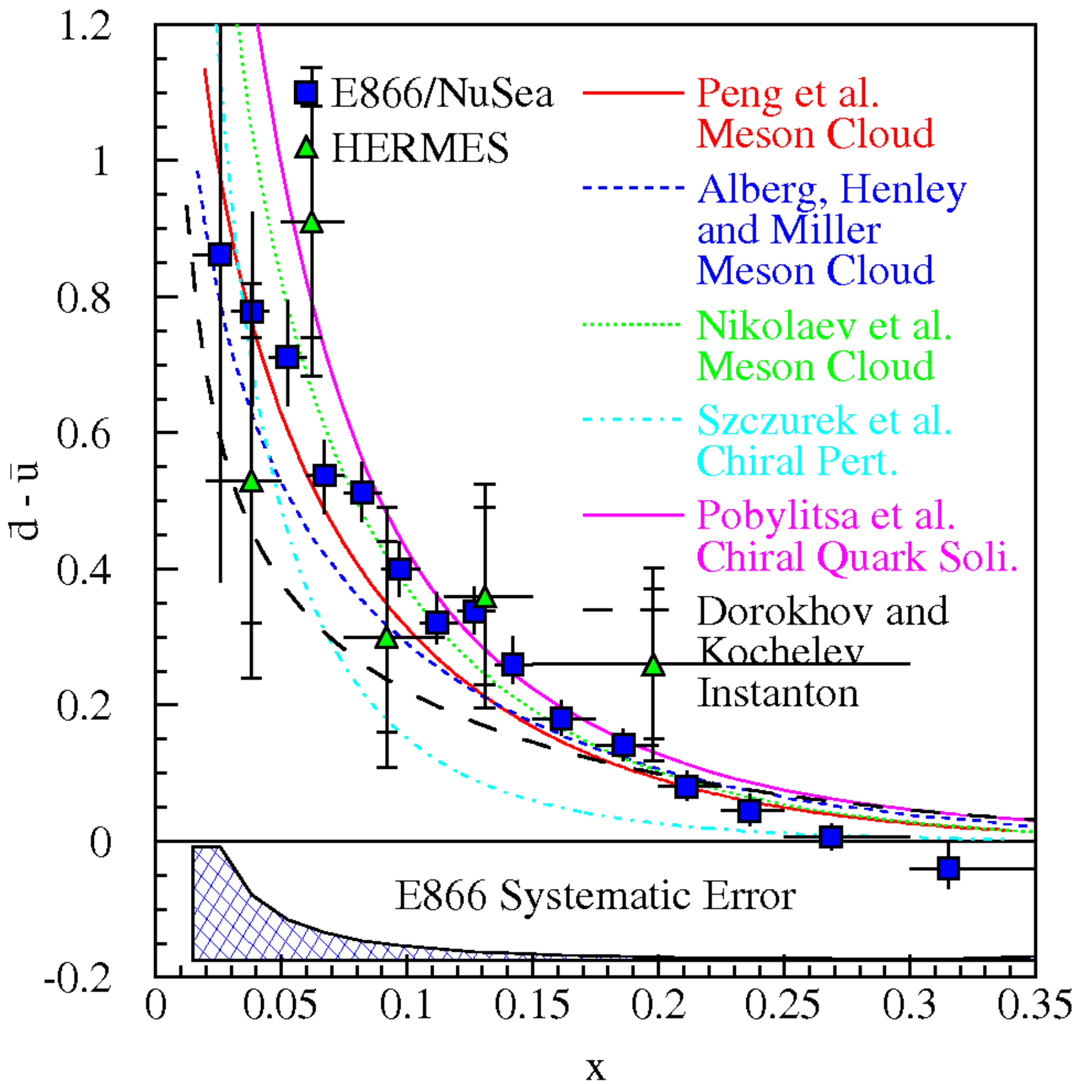
- Knowledge of distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

Proton Structure: By What Process Is the Sea Created?

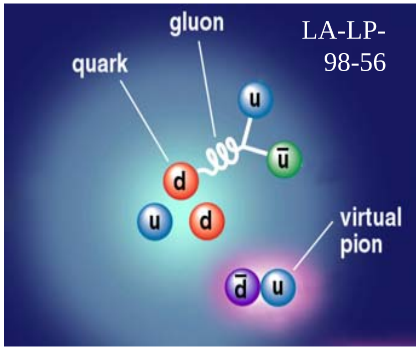
- There is a gluon splitting component which is symmetric

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

- $\bar{d} - \bar{u}$
  - 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!!



Models Relate Antiquark Flavor Asymmetry and Spin

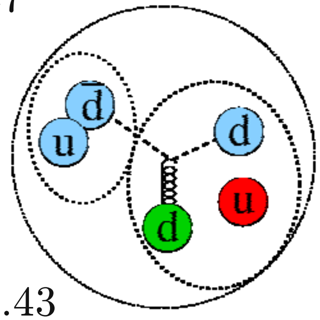


- Meson Cloud in the nucleon—Sullivan process in DIS

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

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

- Chiral Quark models—effective Lagrangians



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

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

- Instantons

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

- Statistical Parton Distributions

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

Related issue – What carries the spin of the nucleon?

HERMES PRD 71, 012003 (05)
Quarks carry 0.347+/-0.024+/-0.066 of nucleons spin

QUARK HELICITY DISTRIBUTIONS IN THE NUCLEON ...

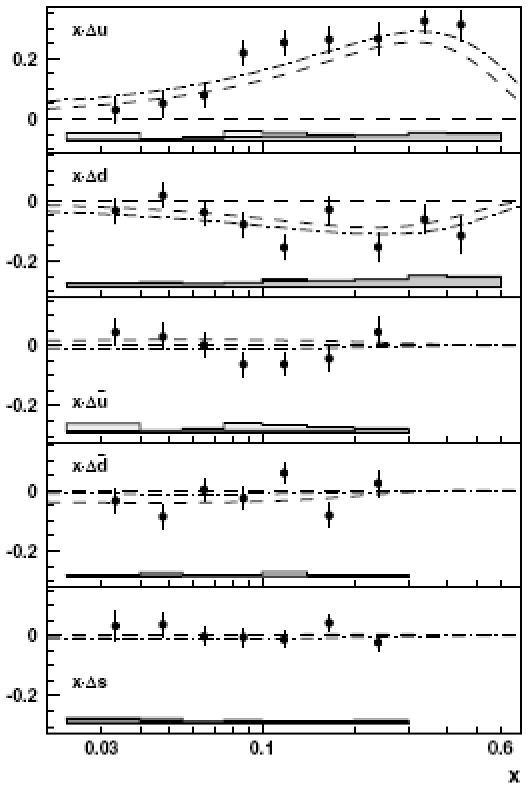


FIG. 20. The quark helicity distributions $x\Delta q(x, Q_0^2)$ evaluated at a common value of $Q_0^2 = 2.5\,\mathrm{GeV}^2$ as a function of x. The dashed line is the GRSV2000 parametrization (LO, valence scenario) [18] scaled with $1/(1+R)$ and the dash-dotted line is the Blümlein-Böttcher (BB) parametrization (LO, scenario 1) [67]. See Fig. 19 for explanations of the uncertainties shown.

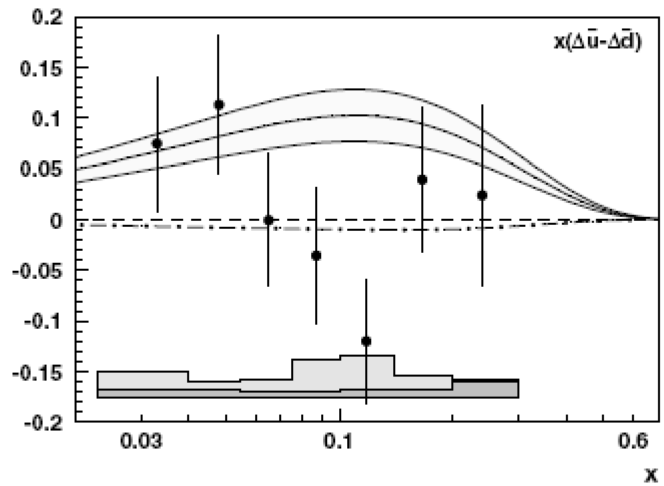


FIG. 21. The flavor asymmetry in the helicity densities of the light sea evaluated at $Q_0^2 = 2.5\,\mathrm{GeV}^2$. The data are compared with predictions in the χQSM [74] and a meson cloud model [81]. The solid line with the surrounding shaded band show the χQSM prediction together with its $\pm 1\sigma$ uncertainties while the dash-dotted line shows the prediction in the meson cloud model. The uncertainties in the data are presented as in Fig. 19.

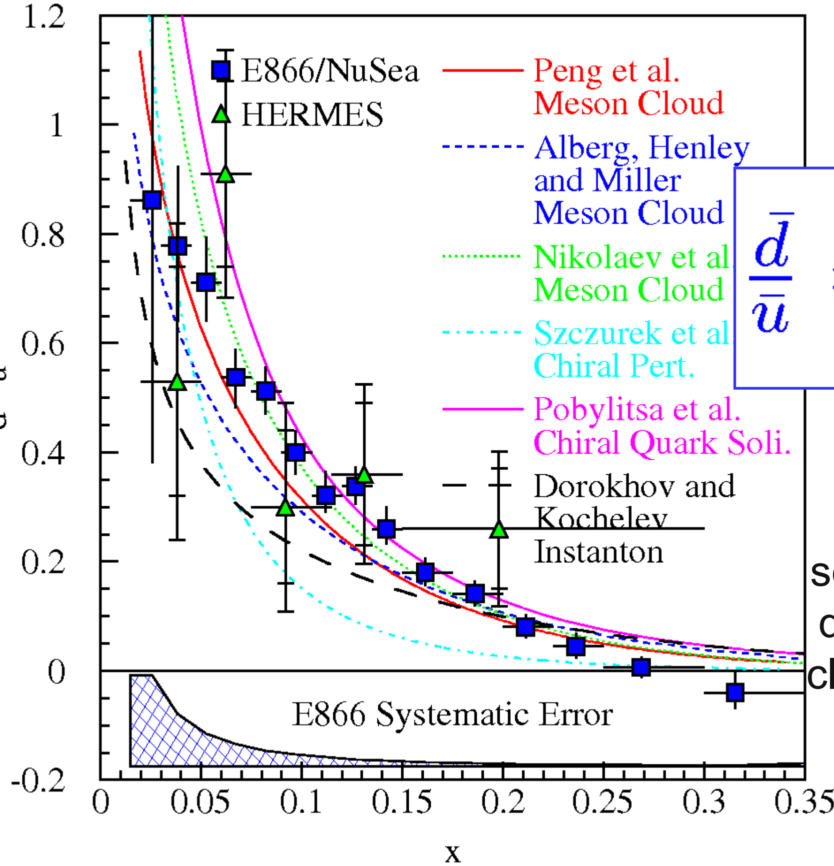
Proton Structure: By What Process Is the Sea Created?

- Meson Cloud in the nucleon

  Sullivan process in DIS
  $|p\rangle = |p_0\rangle + \alpha\,|N\pi\rangle + \beta|\Delta\pi\rangle + \ldots$

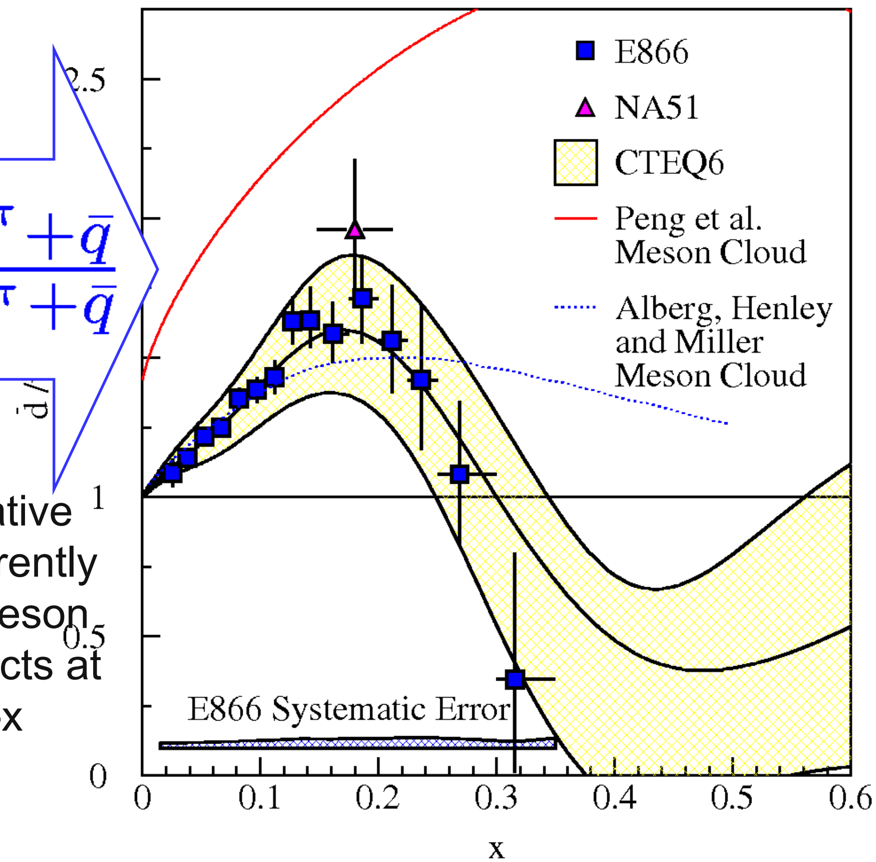
- Chiral Models

  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



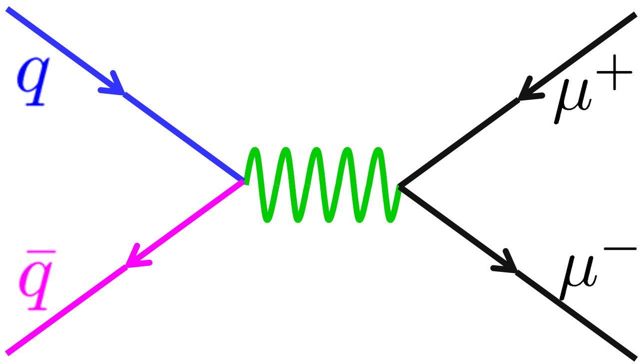
Something is missing

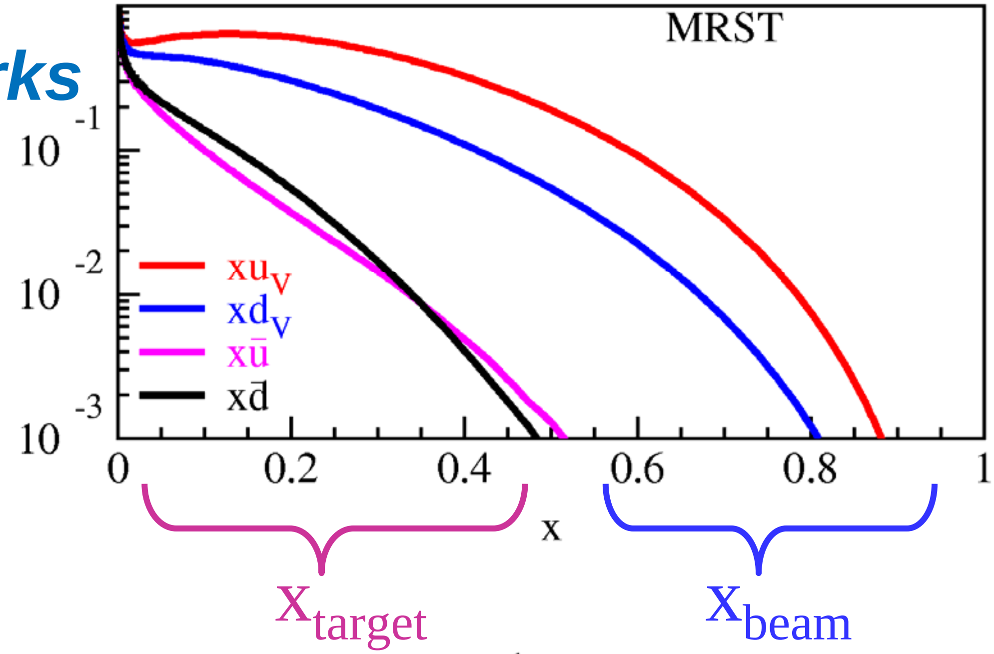
- All non-perturbative models predict large asymmetries at high x.

- Are there more gluons and therefore symmetric anti-quarks at higher x?

- Does some mechanism like instantons have an unexpected x dependence? (What is the expected x dependence for instantons in the first place?)

Drell-Yan scattering:
A laboratory for sea quarks

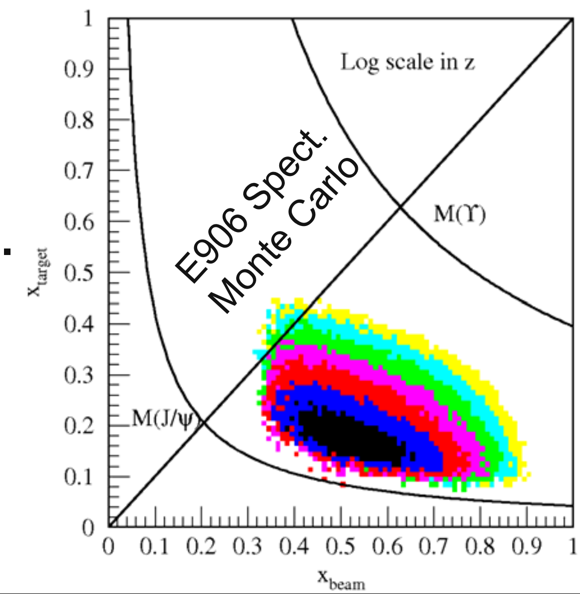




$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2 \left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

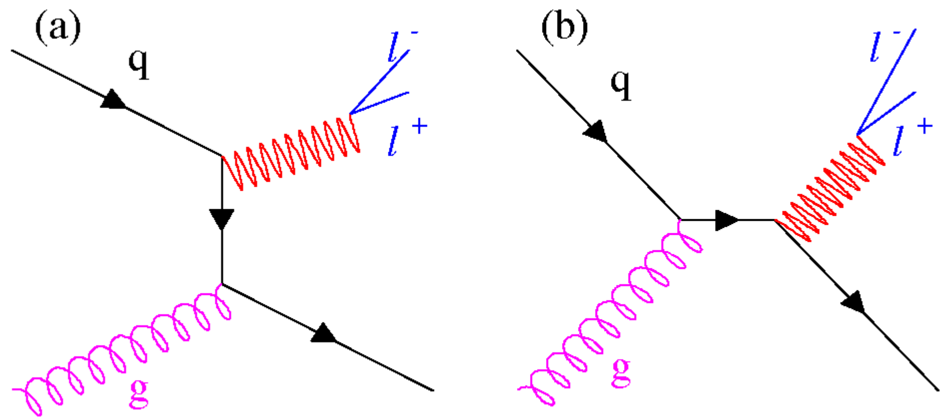
Detector acceptance chooses x_{target} and x_{beam}.

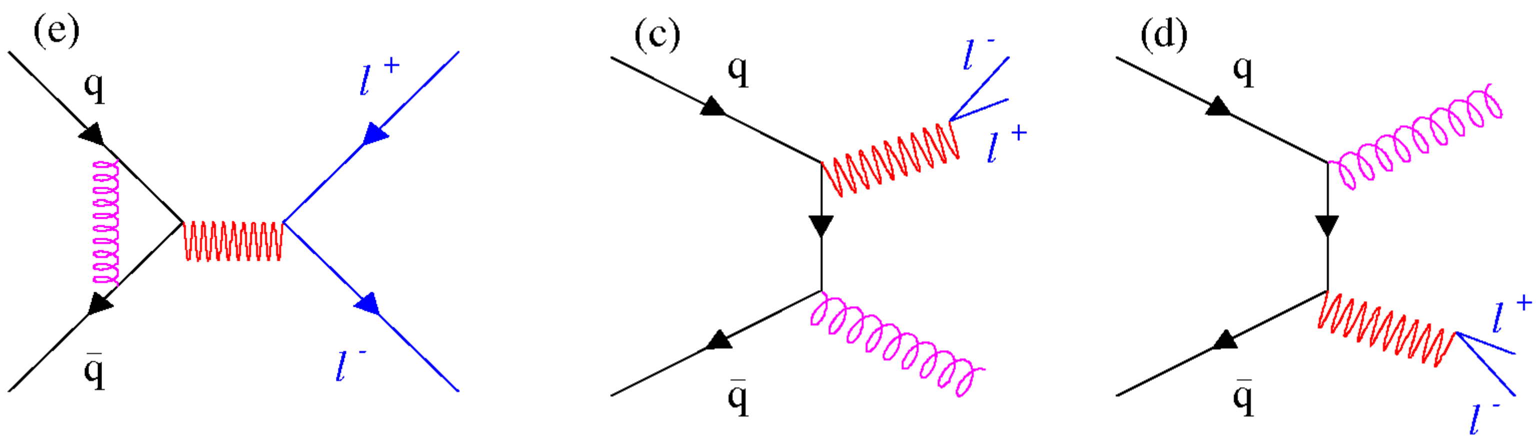
- Fixed target ⇒ high $x_F = x_{beam} - x_{target}$
- Valence Beam quarks at high-x.
- Sea Target quarks at low/intermediate-x.



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, $\lambda > 0.8$)





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:

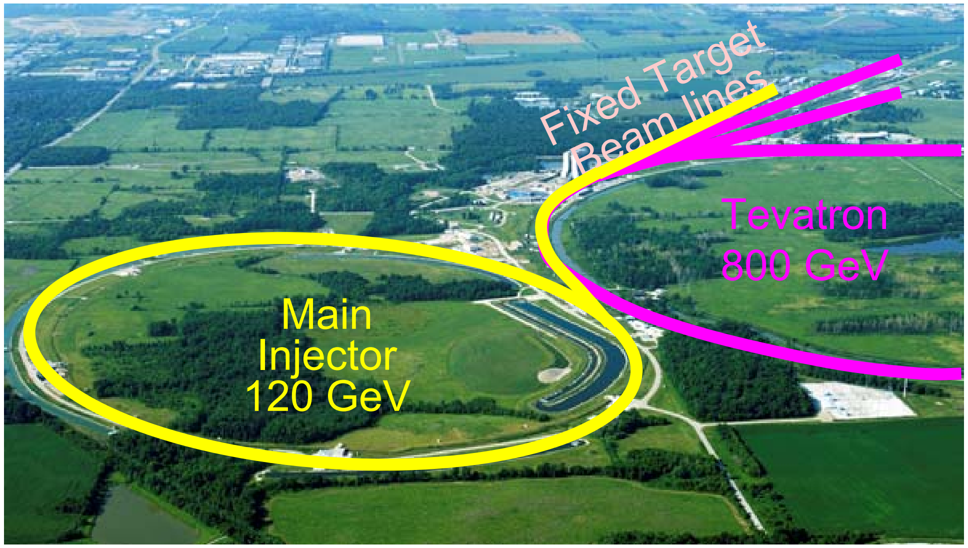
Fermilab E906

- Data in 2009
- ^1H, ^2H, and nuclear targets
- 120 GeV proton Beam

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

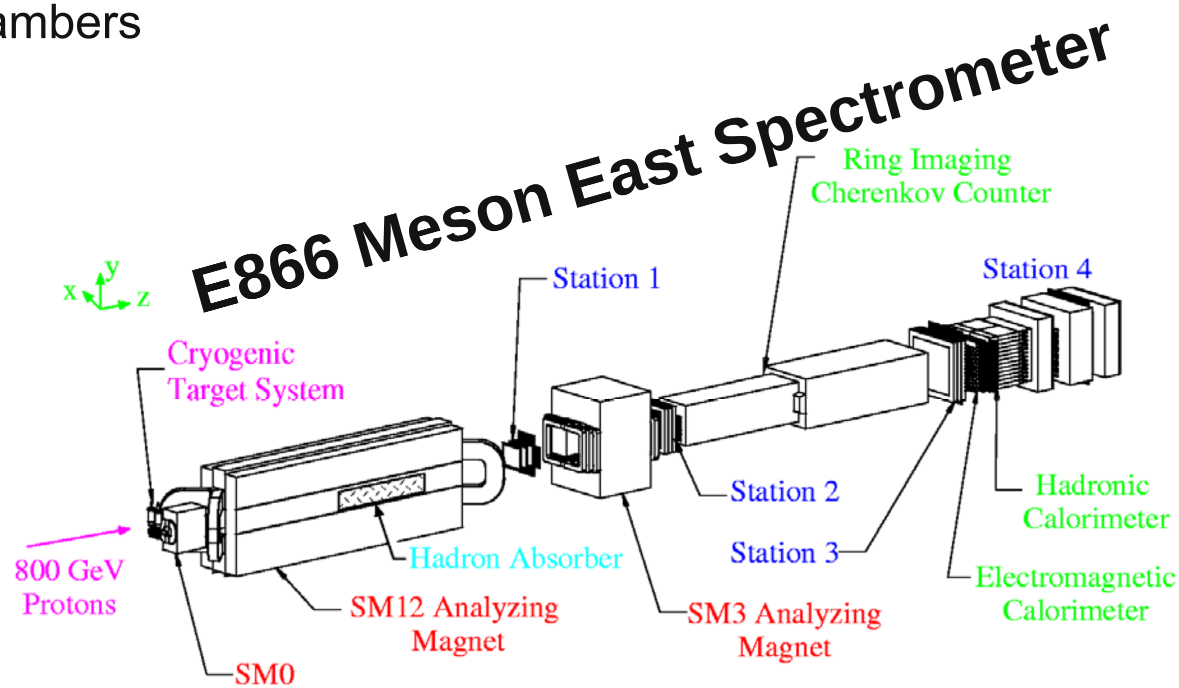
- Cross section scales as 1/s
  - *7× that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7× Luminosity for same detector rate as 800 GeV beam*

50× statistics!!

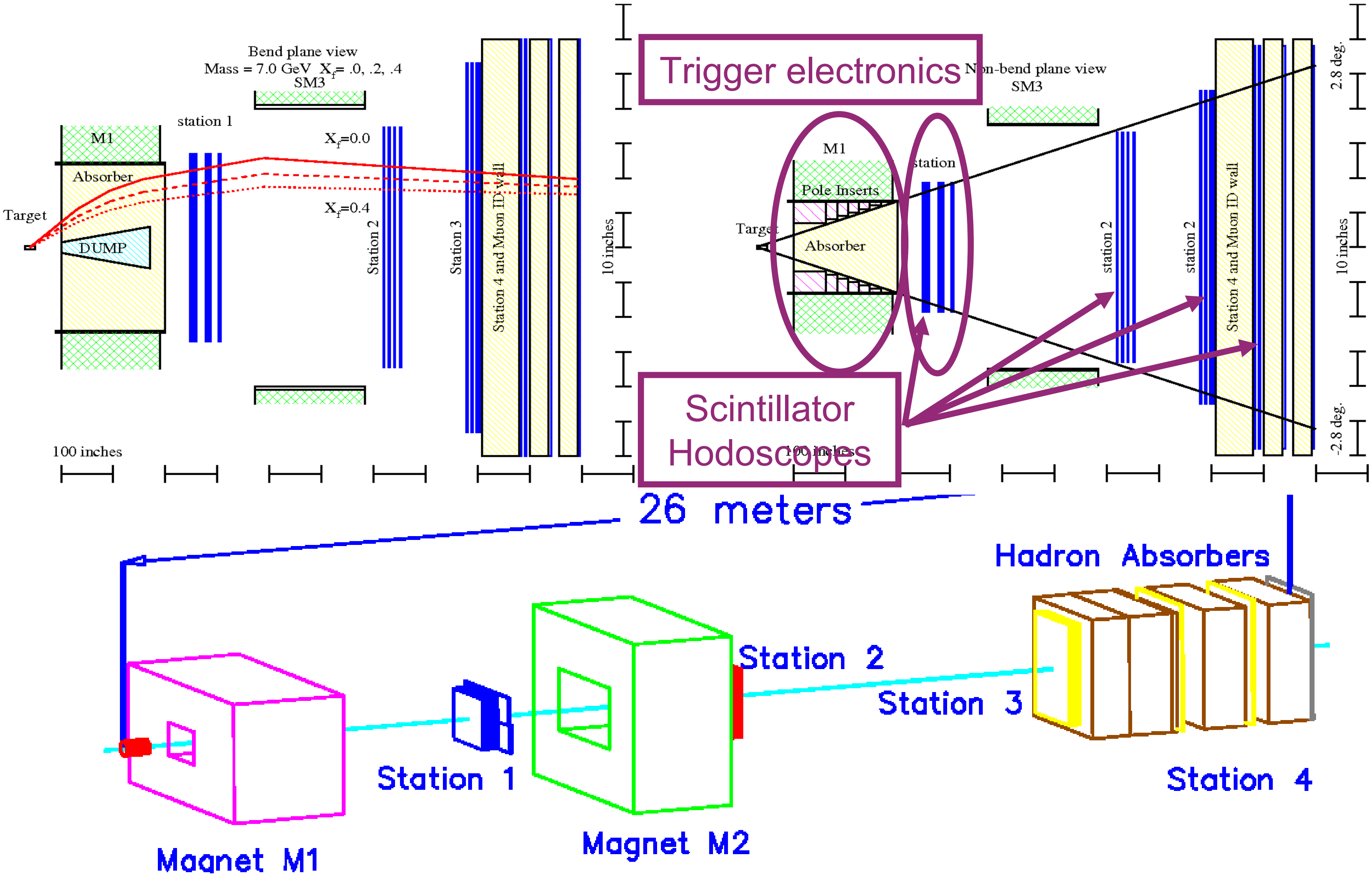


Drell-Yan Spectrometer Guiding Principles

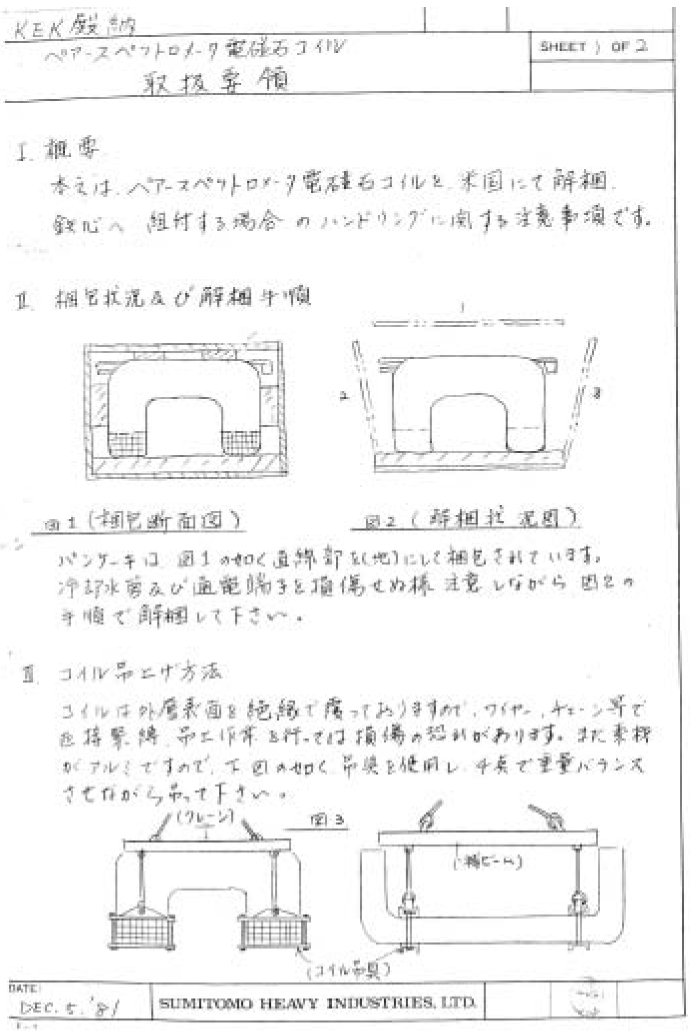
- Follow basic design of MEast spectrometer (don't reinvent the wheel):
  - Two magnet spectrometer
  - Hadron absorber within first magnet
  - Beam dump within first Magnet
  - Muon-ID wall before final elements
- Where possible and practical, reuse elements of the E866 spectrometer.
  - Tracking chamber electronics (and electronics from E871)
  - Hadron absorber, beam dump, muon ID walls
  - Station 2 and 3 tracking chambers
  - Hodoscope array PMT's
  - SM3 Magnet
- New Elements
  - 1st magnet (different boost) Experiment shrinks from 60m to 26m
  - Sta. 1 tracking (rates)
  - Scintillator (age)
  - Trigger (flexibility)



E906 Detector



Spectrometer will use SM3 coils--constructed in 1981 for E605 by Sumitomo and supervised by KEK and Kyoto



KEK殿納
ペアースペクトロメータ電磁石コイル
取扱要領

SHEET 1 OF 2

I. 概要
本文は、ペアースペクトロメータ電磁石コイルを米国にて解梱、鉄心へ組付する場合のハンドリングに関する注意事項です。

II. 梱包状況及び解梱手順

図1（梱包断面図）　図2（解梱状況図）

パンケーキは図1の如く直線部を(地)にして梱包されています。冷却水管及び通電端子を損傷せぬ様注意しながら図2の手順で解梱して下さい。

III. コイル吊上げ方法
コイルは外層表面を絶縁で覆っておりますので、ワイヤー、チェーン等で直接緊縛、吊上作業を行っては損傷の恐れがあります。また素材がアルミですので、下図の如く吊具を使用し、中央で重量バランスさせながら吊って下さい。

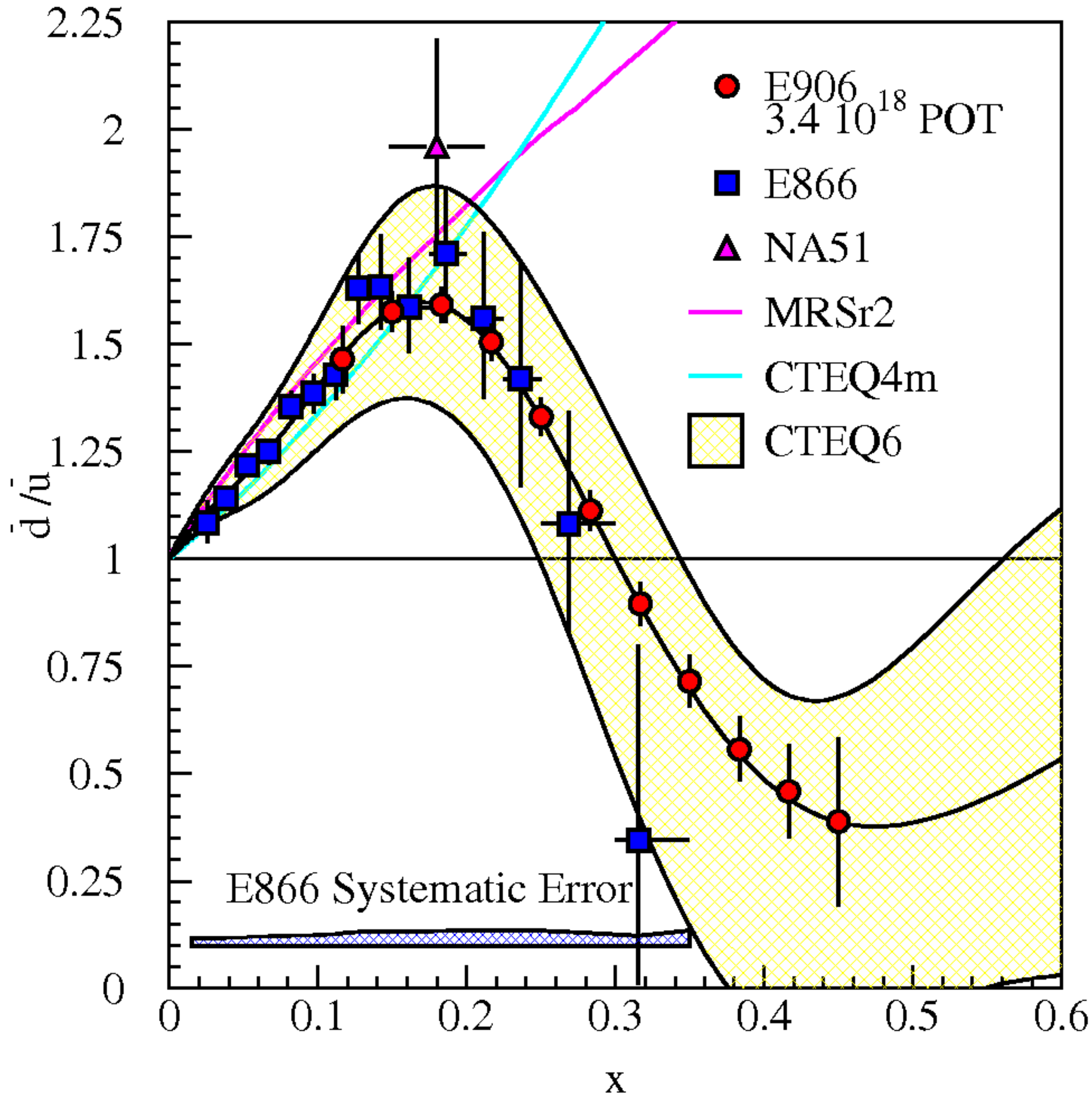
(クレーン)　図3　(コイル吊具)

DATE: DEC. 5. '81　SUMITOMO HEAVY INDUSTRIES, LTD.

Supervised by Prof. Miyake and Dr. Maki and Dr. Sakai

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

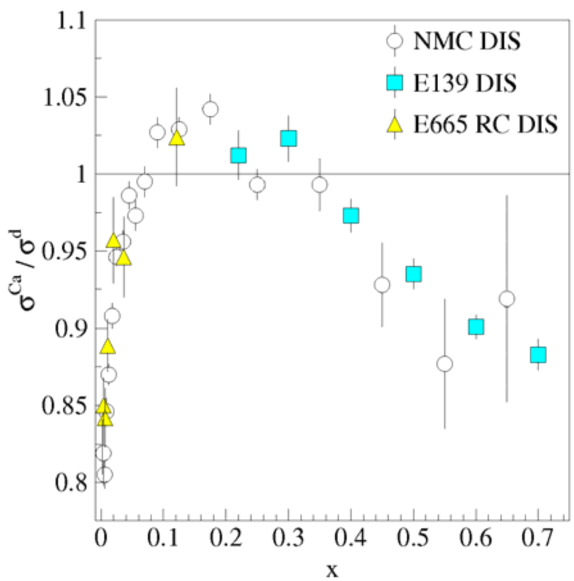
- E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.

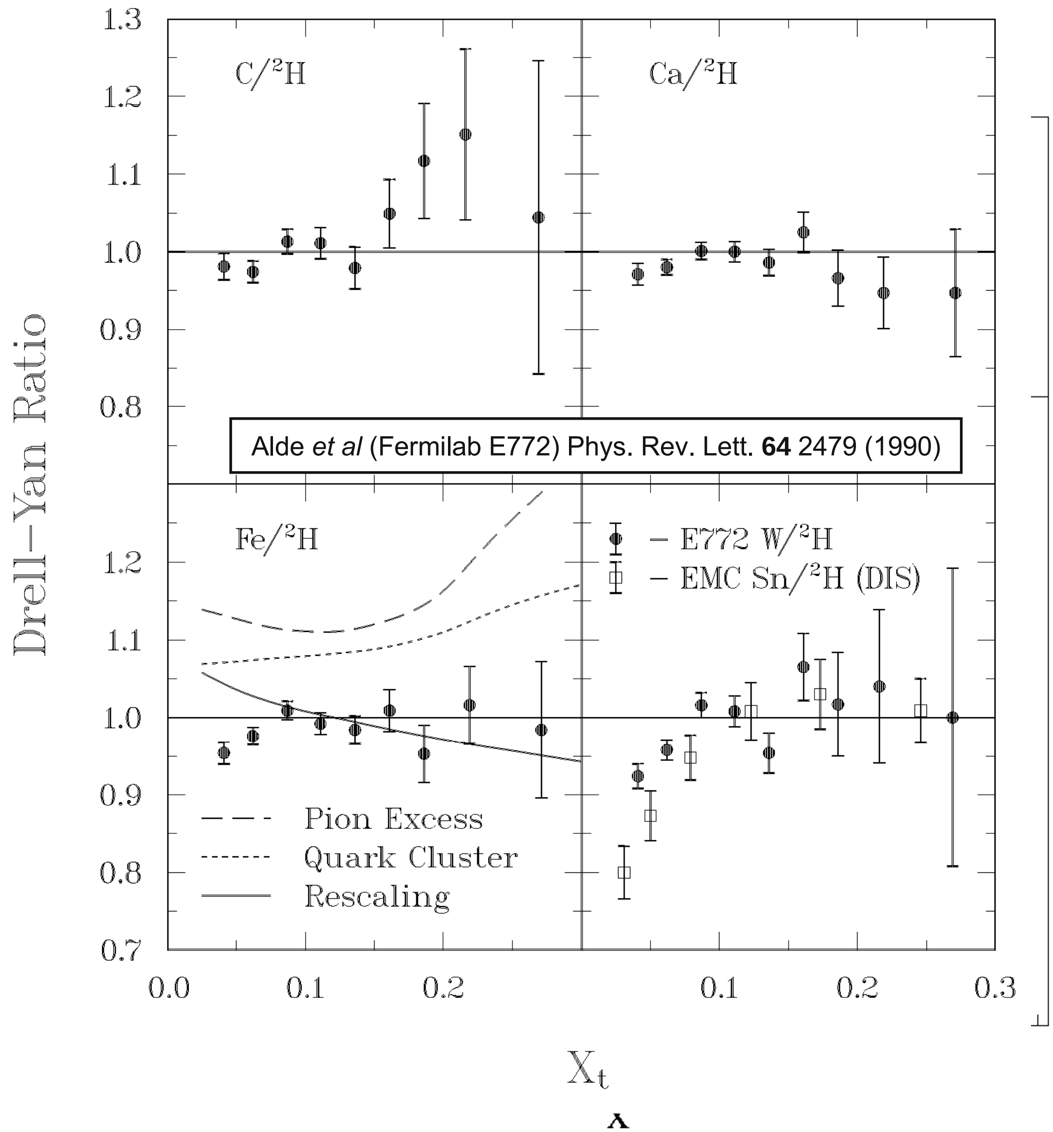


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Comparison with Deep Inelastic Scattering (DIS)

- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell Yan—Valence only effect

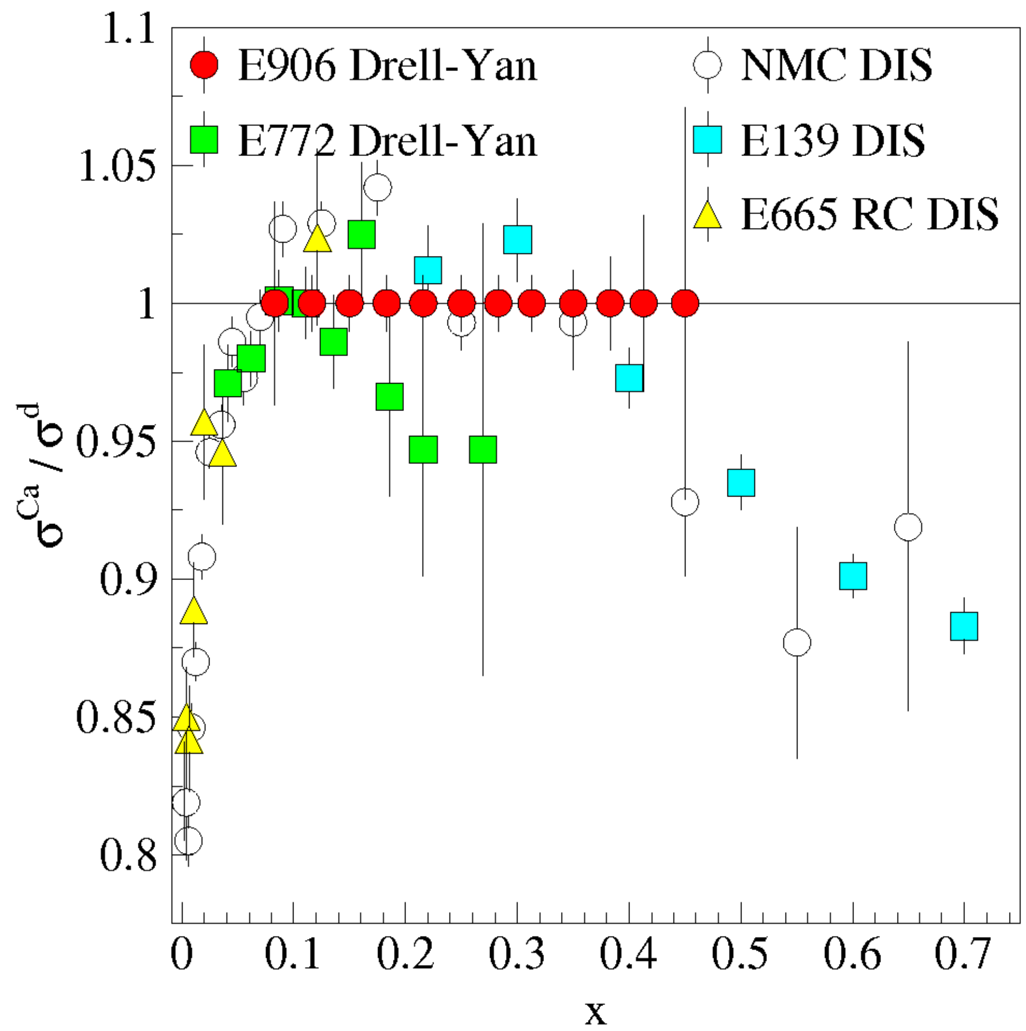




Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

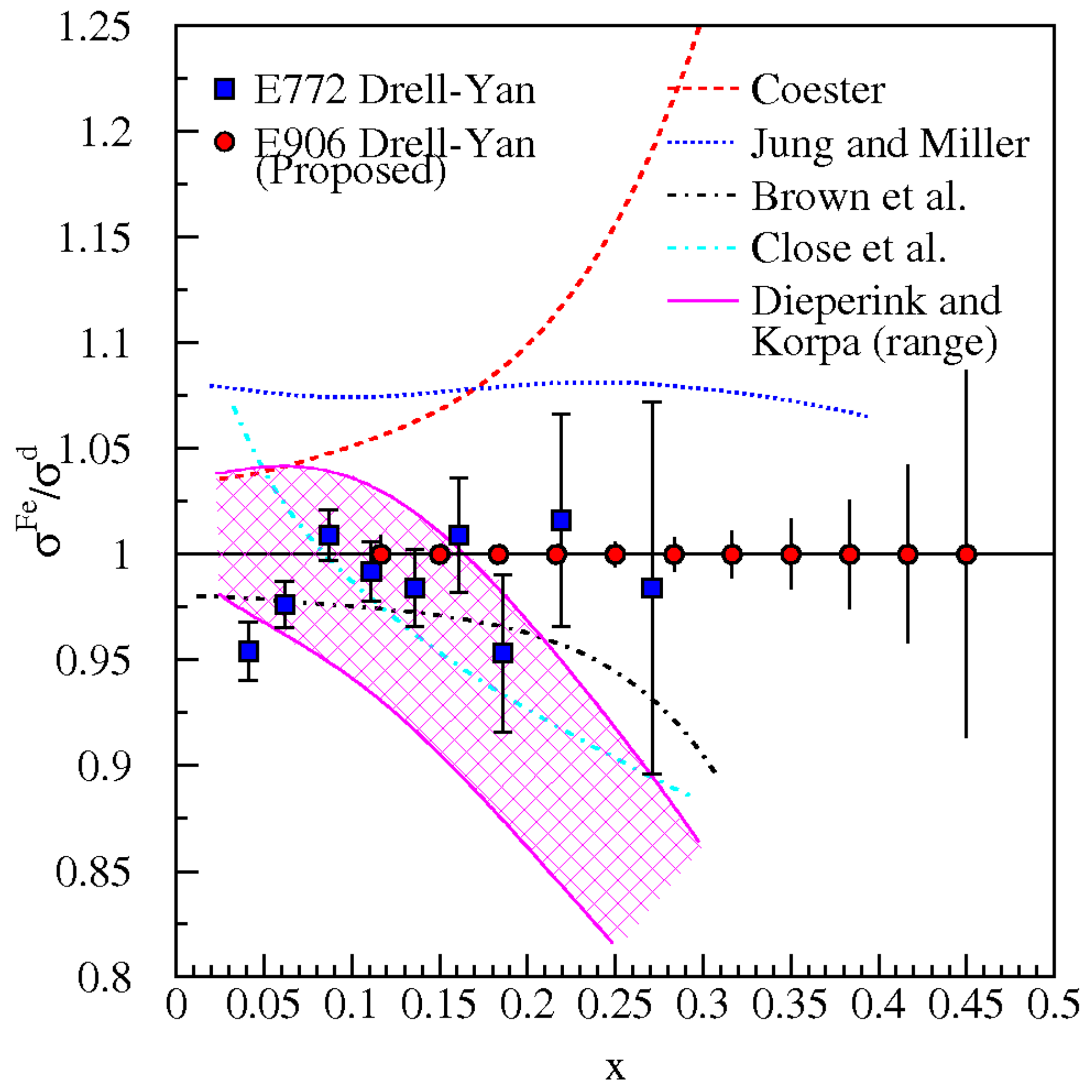
Intermediate-*x* *sea* PDF's

- 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
- 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



FNAL E866/NuSea Collaboration

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Fermi National Accelerator Laboratory
Chuck Brown, Bill Cooper

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Gus Petitt, Xiao-chun He, **Bill Lee**

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Mike Beddo, **Ting Chang**, Gary Kyle, Vassilios Papavassiliou, J. Seldon, **Jason Webb**

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Academia Sinica
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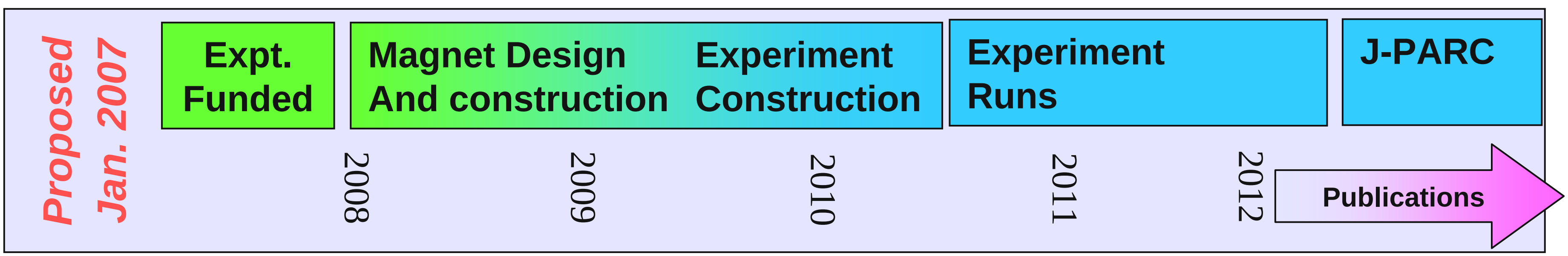
E906/Drell-Yan timeline

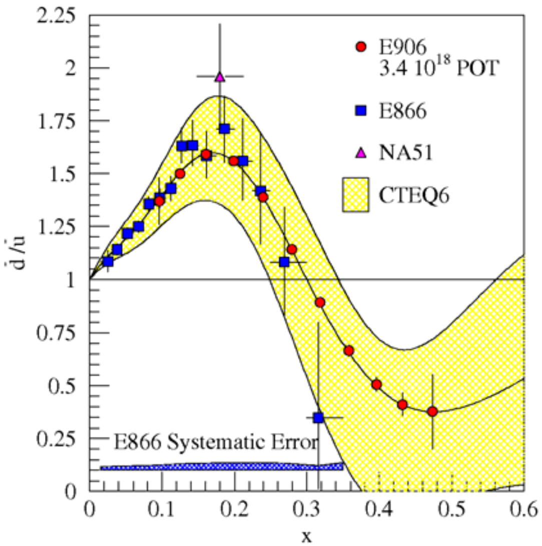
- Fermilab PAC approved the experiment in 2001, but experiment was not scheduled due to concerns about “proton economics”
- Spectrometer upgrade funded by DOE/Office of Nuclear Physics (already received $538k in FY07)
- Fermilab PAC reaffirms earlier decision in Fall 2006
- Scheduled to run in 2010 for 2 years of data collection

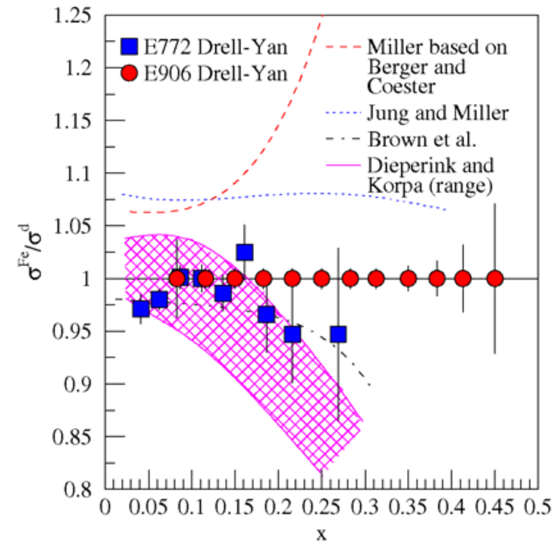
- Apparatus available for future program at J-PARC
  - Significant interest from collaboration for continued program here



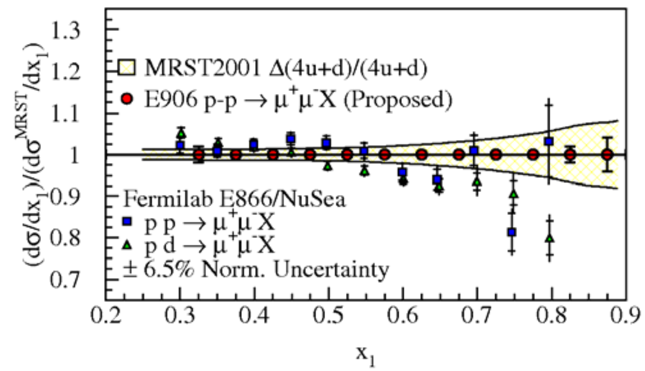
Drell-Yan at Fermilab

- **What is the structure of the nucleon?**
  - What is d-bar/u-bar?
  - What are the origins of the sea quarks?
  - *What is the high-x structure of the proton?*

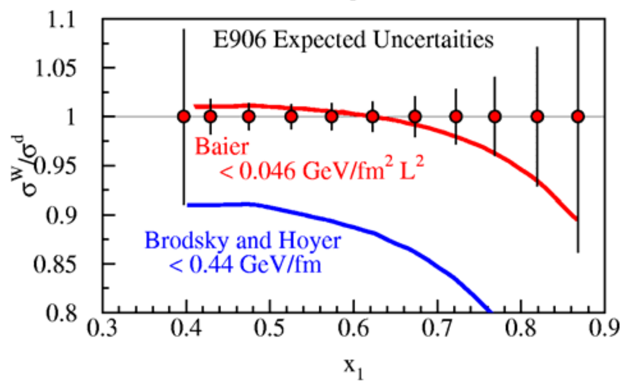




- **What is the structure of nucleonic matter?**
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
- ***Do colored partons lose energy in cold nuclear matter?***



- **Answers from Fermilab E906/Drell-Yan**
  - Significant increase in physics reach over previous Drell-Yan experiments
  - DOE/ONP funded spectrometer

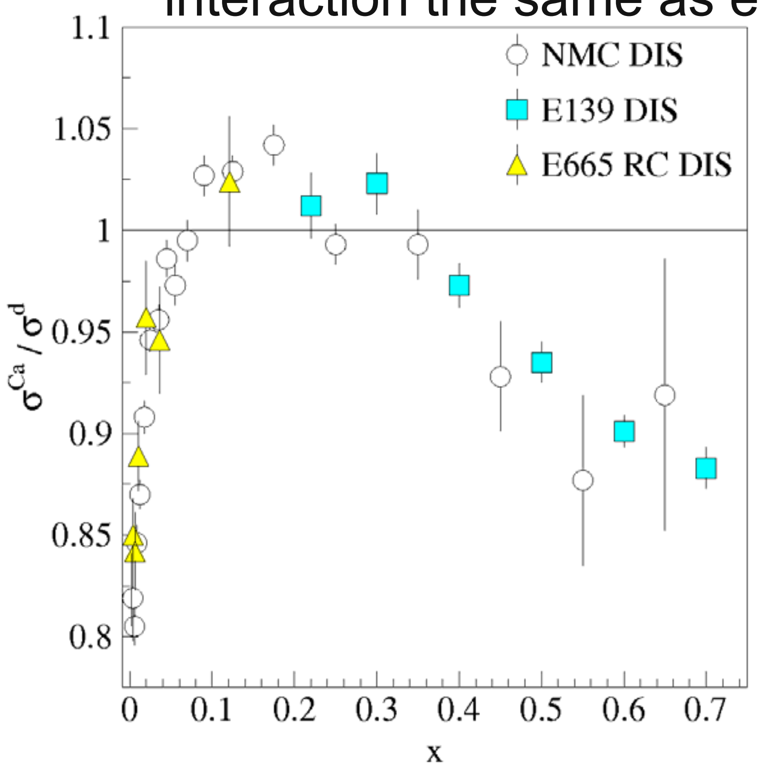


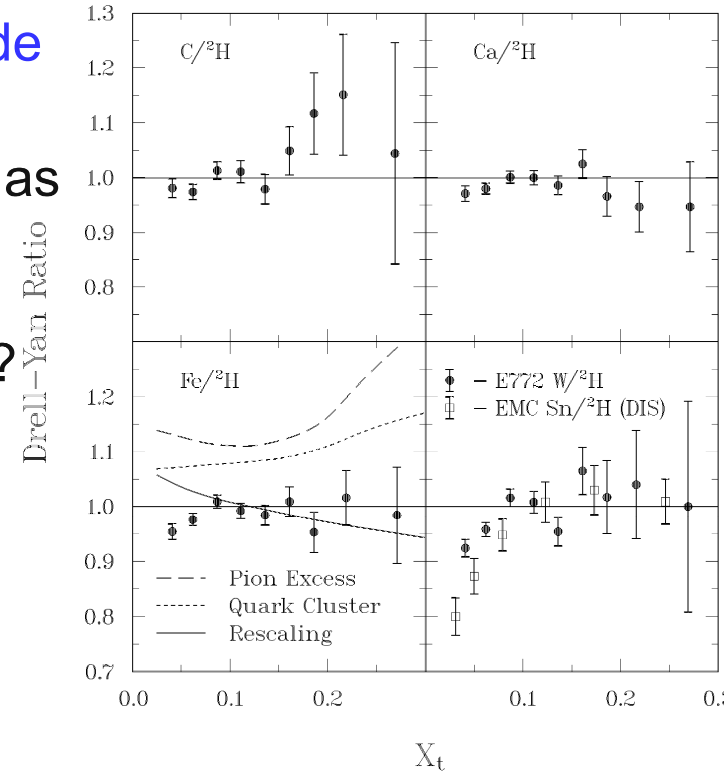
- **Future possibilities at J-PARC**

Additional Material

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?

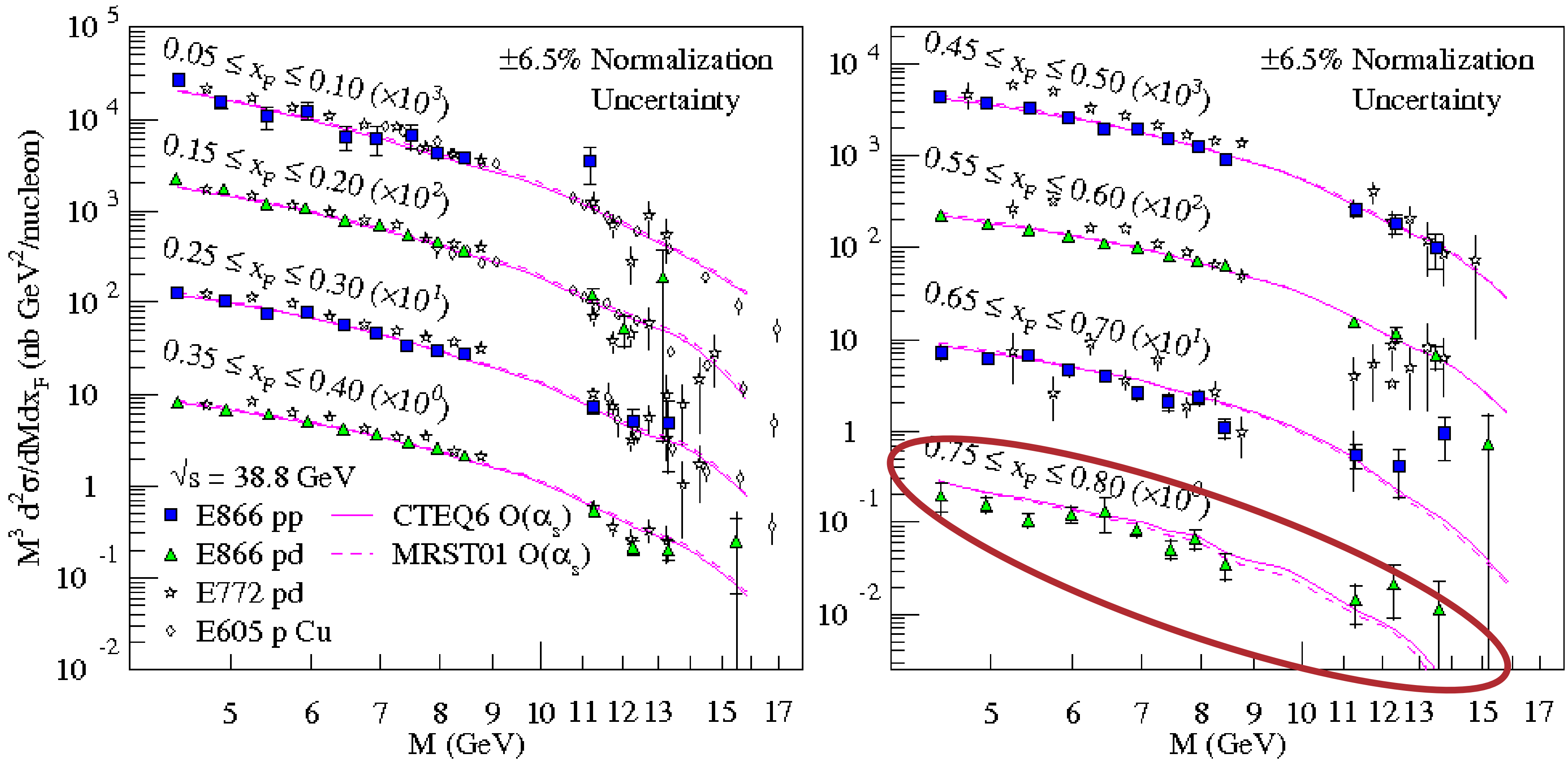




Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

- 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?

Drell-Yan Absolute Cross Sections



- ¼ of data represented in plot (alternate decades, alternate targets)
- Last few x_F bins show PDF's "over predict" NLO cross section

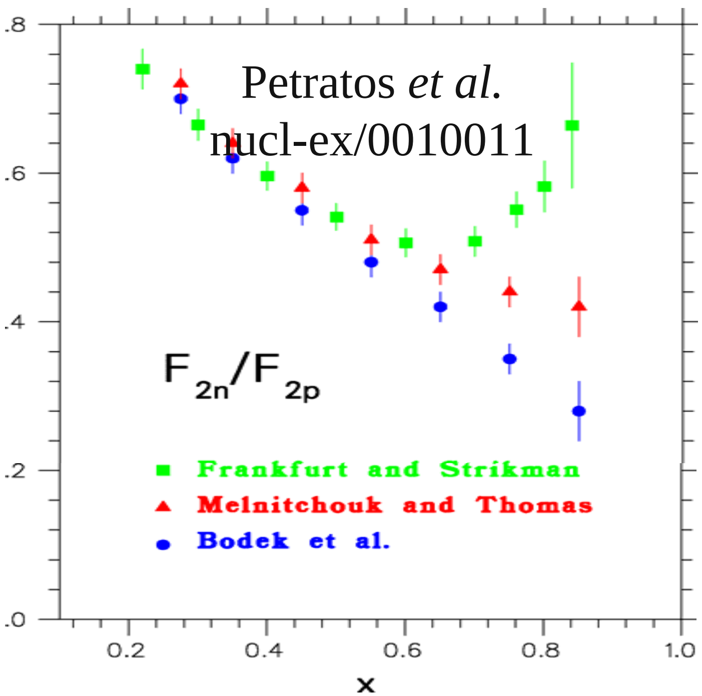
Proton Valence Structure: Unknown as $x \rightarrow 1$

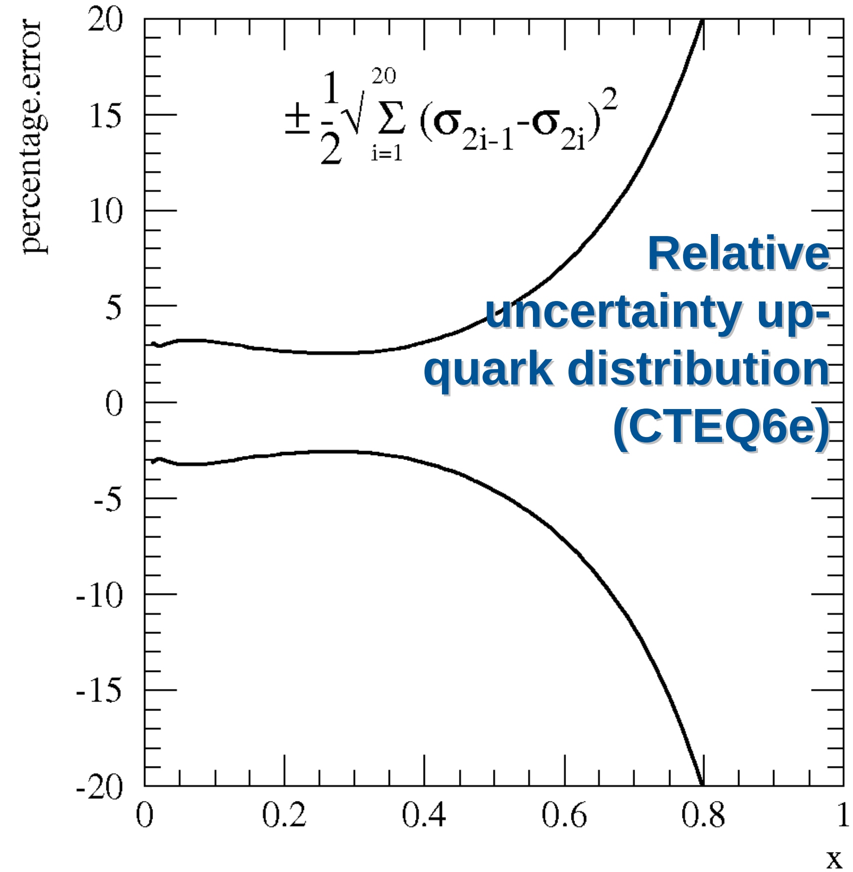
Theory

- Exact SU(6): $d/u \rightarrow 1/2$
- Diquark S=0 dom.: $d/u \rightarrow 0$
- pQCD: $d/u \rightarrow 3/7$

Data

- Binding/Fermi Motion effects in deuterium—choice of treatments.
- ***Proton data is needed.***

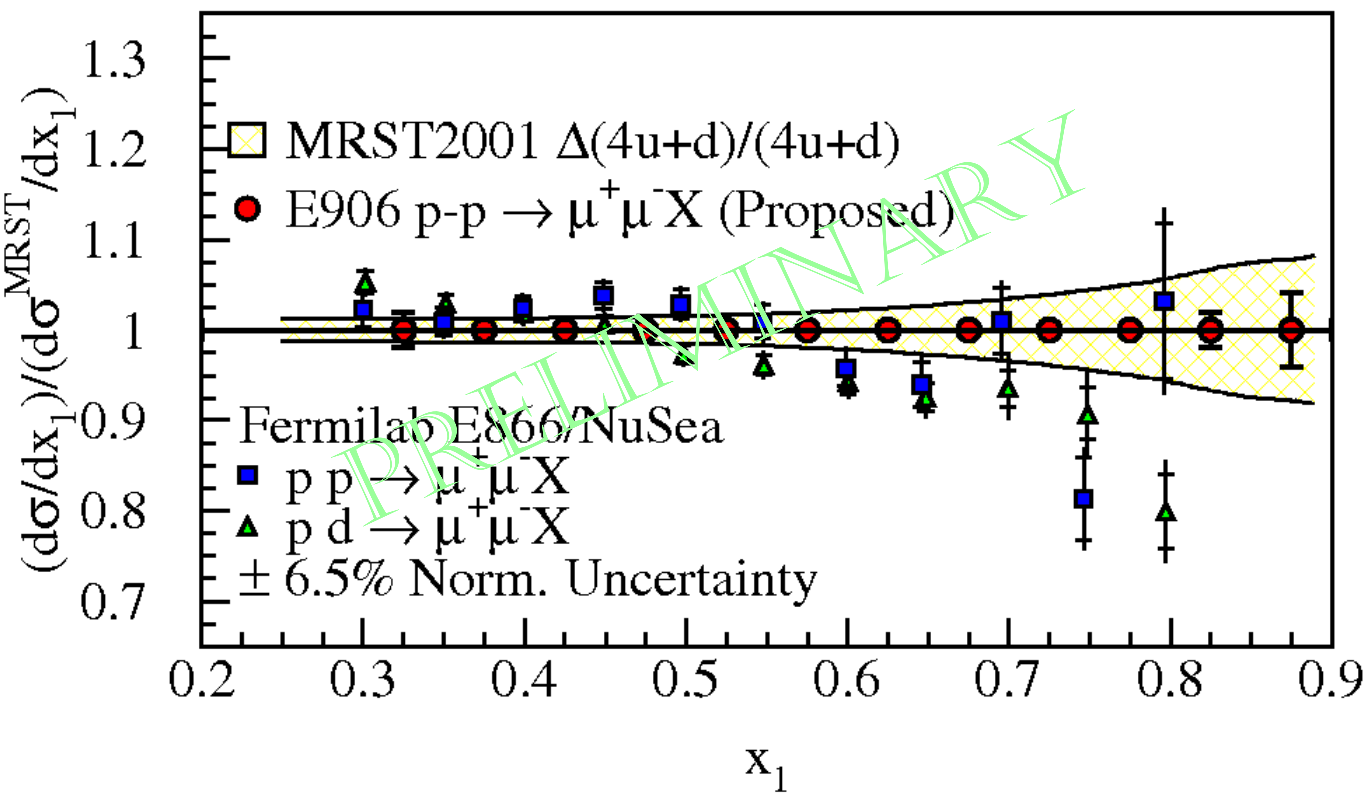




Reality:
We don't even know the u or d quark distributions—there really is very little high-x proton data

Drell-Yan Absolute Cross Sections: x_{target}

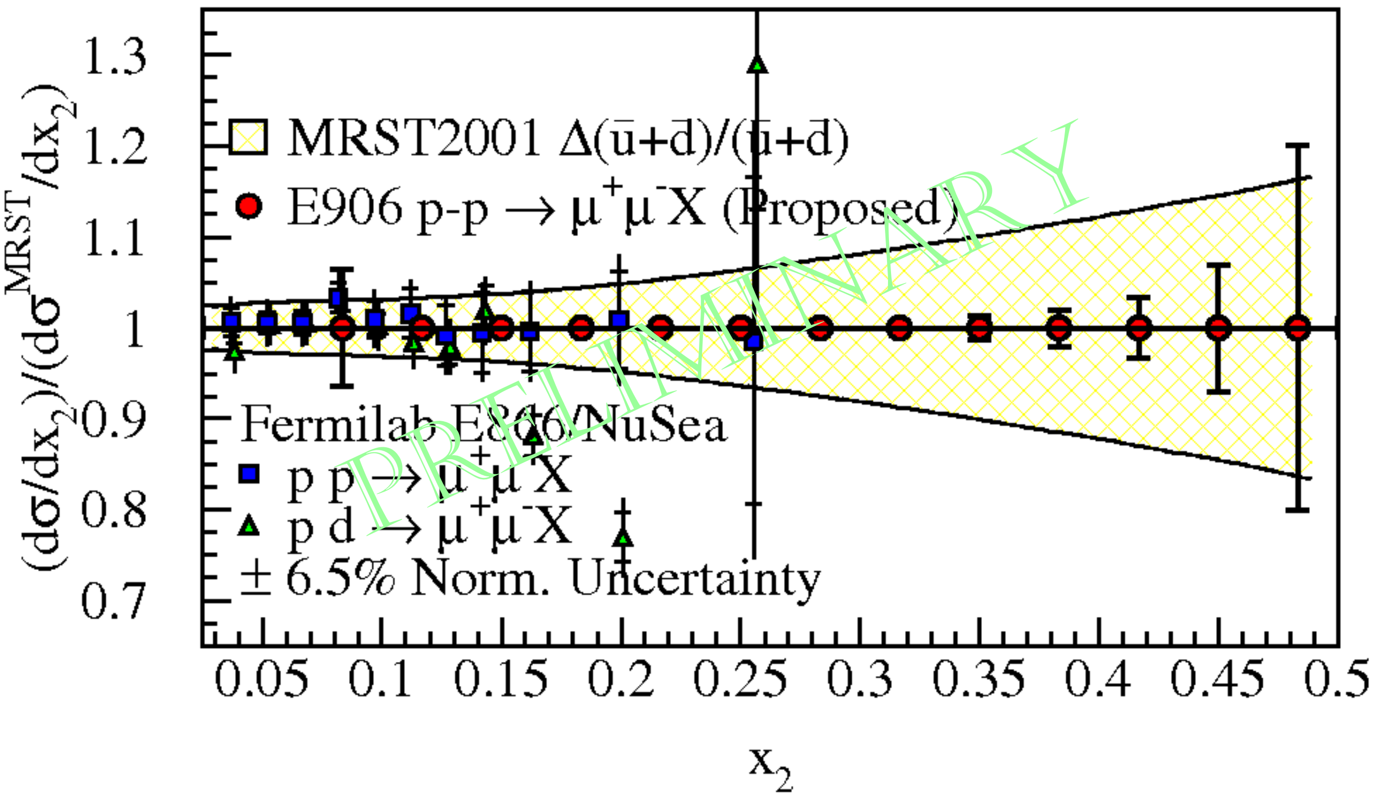
- Reach high-x through *beam proton*—Large $x_F \Rightarrow$ large x_{beam}.
- High-x distributions poorly understood
  - Nuclear corrections are large, even for deuterium
  - Lack of proton data
- Proton-Proton—no nuclear corrections—*4u(x) + d(x)*



Drell-Yan Absolute Cross Sections: x_{target}

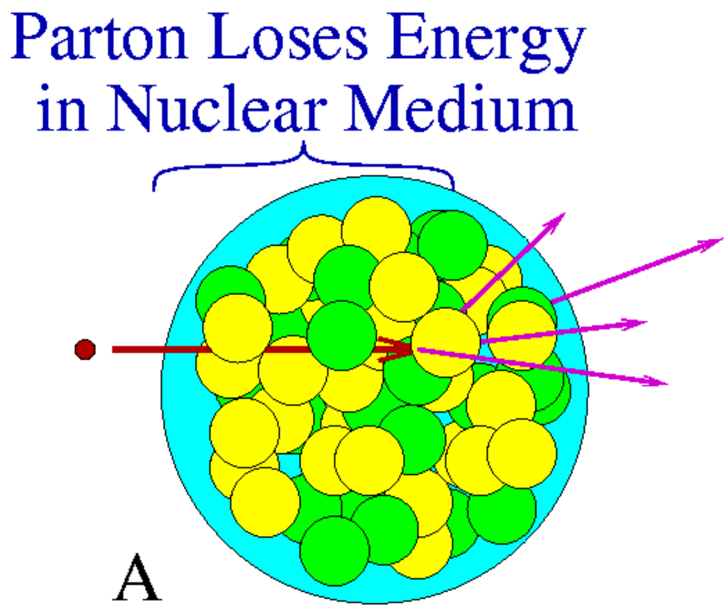
Measures a convolution of beam and target PDF

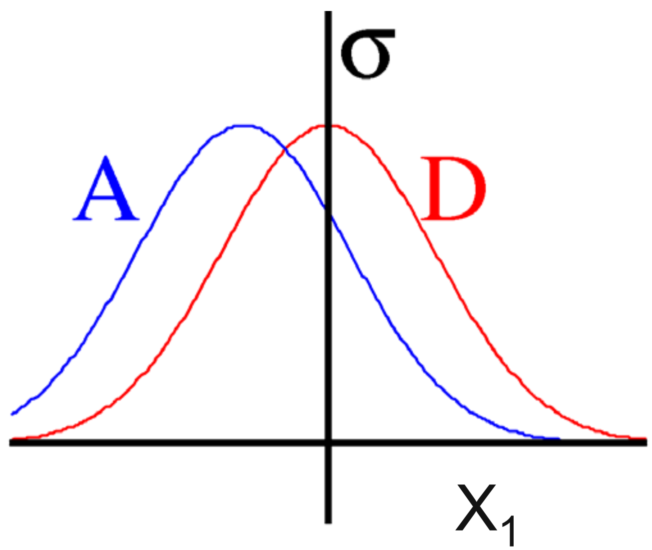
- absolute magnitude of high-x valence beam distributions
- absolute magnitude of the sea in the target
  - *Currently determined by ν–Fe DIS*



Partonic Energy Loss

- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values (x_1 or x_F) is shifted
- Fit shift in x_1 relative to deuterium

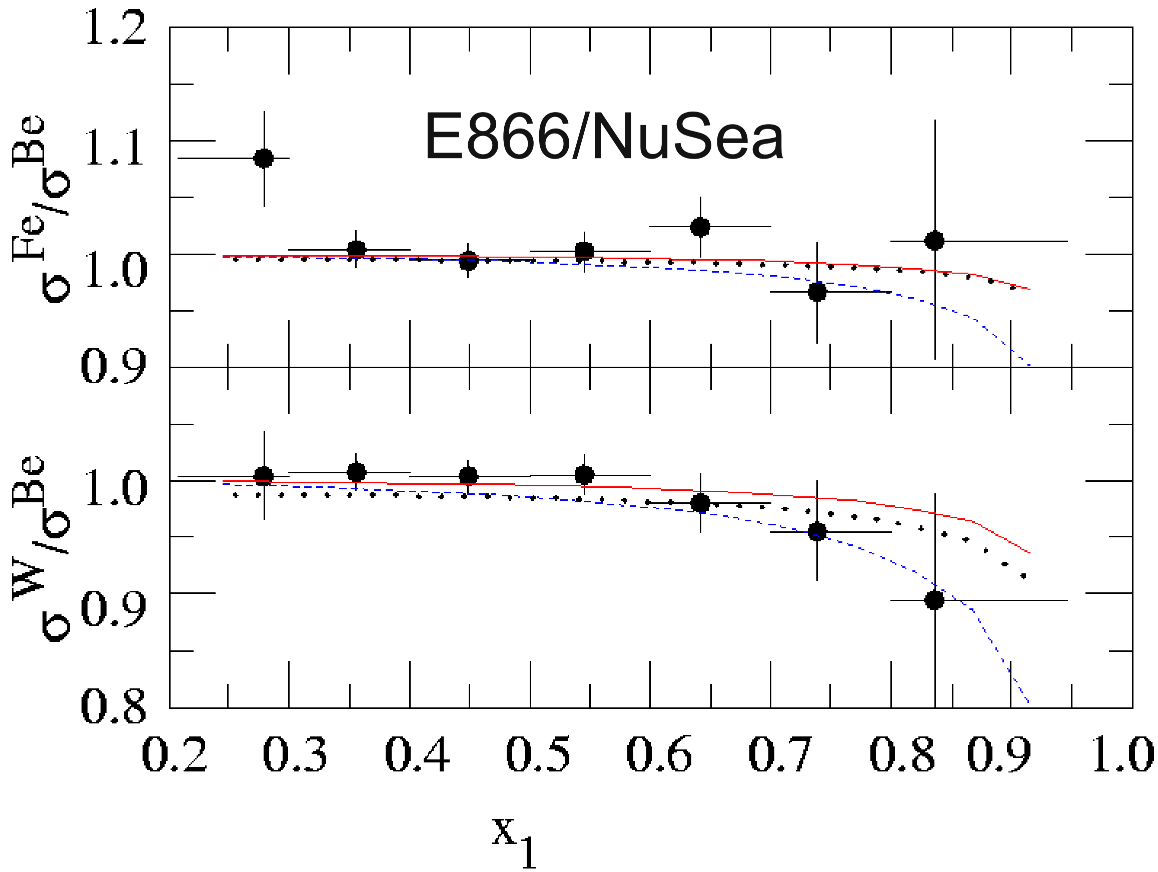




- Models:
  - Galvin and Milana $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

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*.

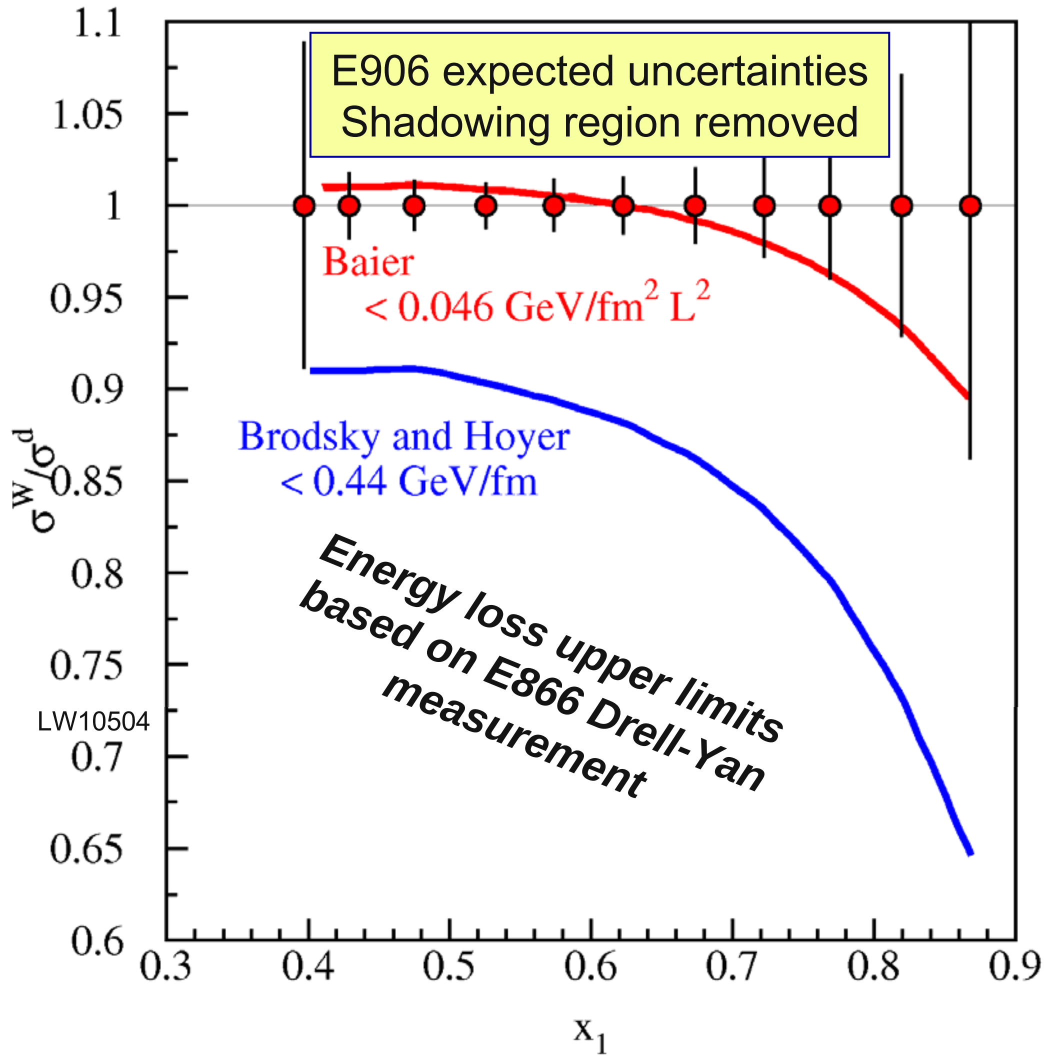


- Treatment of parton propagation length and shadowing are critical
  - Johnson *et al.* find 2.7 GeV/fm (≈1.7 GeV/fm after QCD vacuum effects)
  - Same data with different shadowing correction and propagation length
- **Better data outside of shadowing region are necessary.**

- Drell-Yan p_T broadening also will yield information

Parton Energy Loss

- Shift in $\Delta x \propto 1/s$
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits



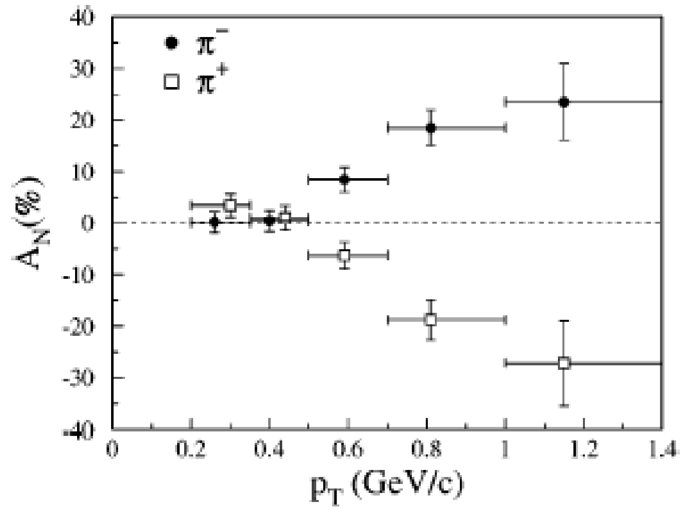
- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample

Other Possibilities: Transversely Polarized Target

Sivers' distribution $f^{\perp}_{1T}(x, k_T)$

- Single spin asymmetry

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



Fermilab E704, Phys. Rev. Lett. **77**, 2626 (1996)

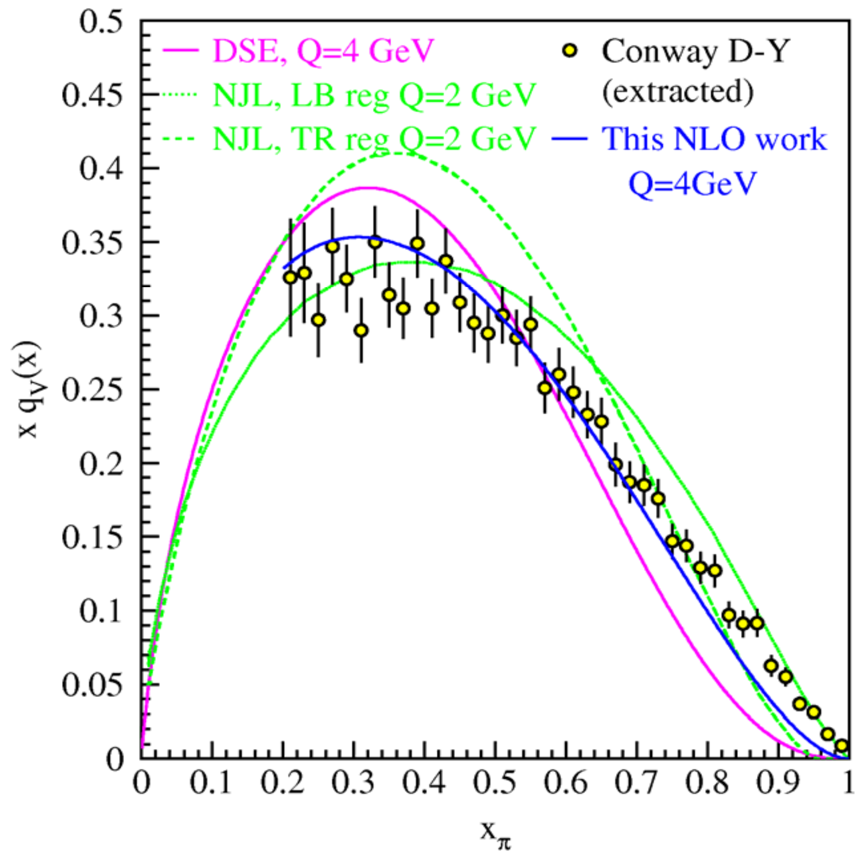
FIG. 2. A_N data as a function of p_T for π^- (full circles) and π^+ (open squares) in the x_F range of 0.2–0.9. For clarity, the first two π^- (π^+) data points are offset by −0.02 (+0.02) GeV/c.

- Possibly explanation for E704 data
- Collins Fragmentation function could also produce such an asymmetry

- HERMES has observed both effects in SIDIS
- With Drell-Yan: $f^{\perp}_{1T}(x, k_T)|_{DIS} = - f^{\perp}_{1T}(x, k_T)|_{D\text{-}Y}$
- With transversely polarized target one measures sea quarks
- Sea quark effects might be small
- Transversely polarized beam at J-PARC????

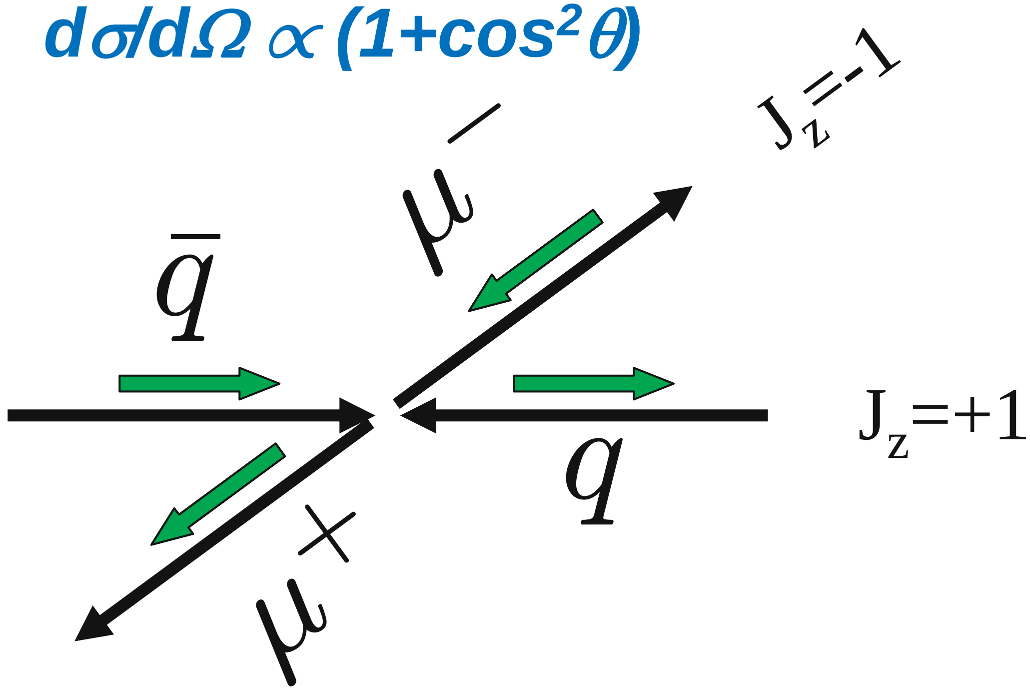
Other Possibilities: Pionic Drell-Yan

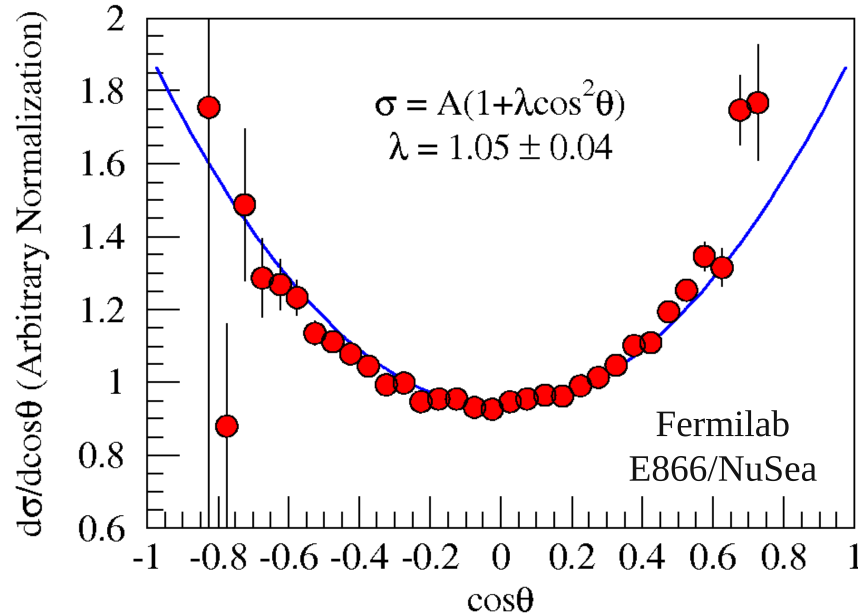
- High-x pionic parton distributions
  - High-x from of $(1-x)^{\alpha}$
  - Specific predictions for α from Dyson-Schwinger, pQCD and Nambu-Jona-Lasinio models
  - Data fall between predictions, but may have poor x_{π} resolution and other systematic effects



- Charge symmetry violation
  - π^{+}/π^{-} comparison on deuterium target
  - Difficulty producing pure π^{+} beam

Leading Order Drell-Yan Angular Distributions: $d\sigma/d\Omega \propto (1+\cos^2\theta)$





$$\mathcal{M} \propto d^j_{\lambda'\lambda}(\theta) = \langle j\lambda'|e^{-i\theta J_y}|j\lambda\rangle$$

$$\frac{d\sigma}{d\Omega} \propto \overline{\mathcal{M}^2} \propto (1+\cos^2\theta)$$

$$d^1_{11} = d^1_{-1-1} = \frac{1}{2}(1+\cos\theta)$$

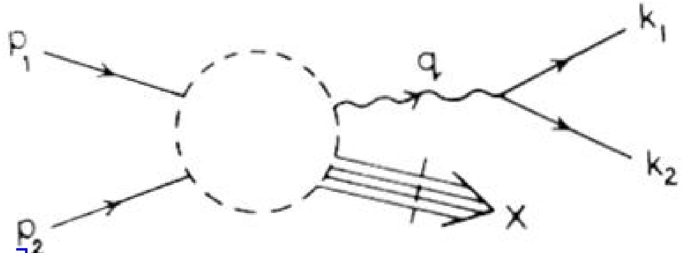
$$d^1_{-11} = d^1_{1-1} = \frac{1}{2}(1-\cos\theta)$$

Helped to validate the Drell-Yan picture of quark-antiquark annihilation for lepton pair production

Generalized Angular Distributions

Chi-Sing Lam and Wu-Ki Tung—basic formula for lepton pair production angular distributions PRD **18** 2447 (1978)

$$\frac{d\sigma}{d^4q\ d\Omega_k^*} = \frac{1}{2}\frac{1}{(2\pi)^4}\frac{\alpha^2}{(Ms)^2}\left[W_T\left(1+\cos^2\theta\right) + W_L\left(1-\cos^2\theta\right) + W_\Delta \sin 2\theta\cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi\right]$$



- Lam-Tung Relation $W_L = 2W_{\Delta\Delta}$

  Direct analogy to the Callan-Gross relation in DIS

  Normally written as $1-\lambda = 2\nu$

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

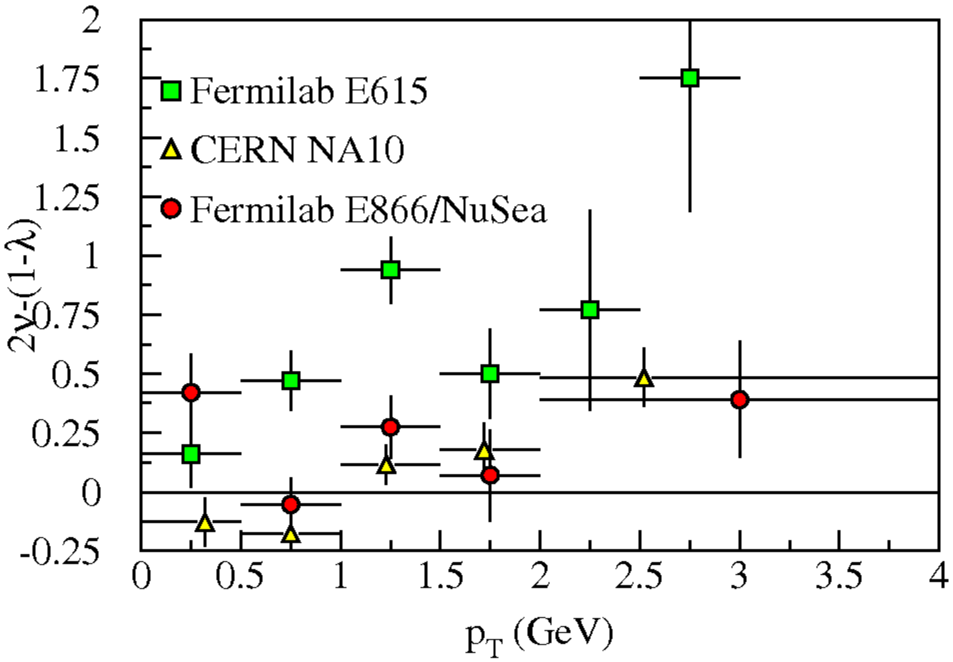
- Unaffected by $O(\alpha_s)$ (NLO) corrections
- NNLO [$O(\alpha_s^2)$] corrections also small Mirkes and Ohnemus, PRD **51** 4891 (1995)

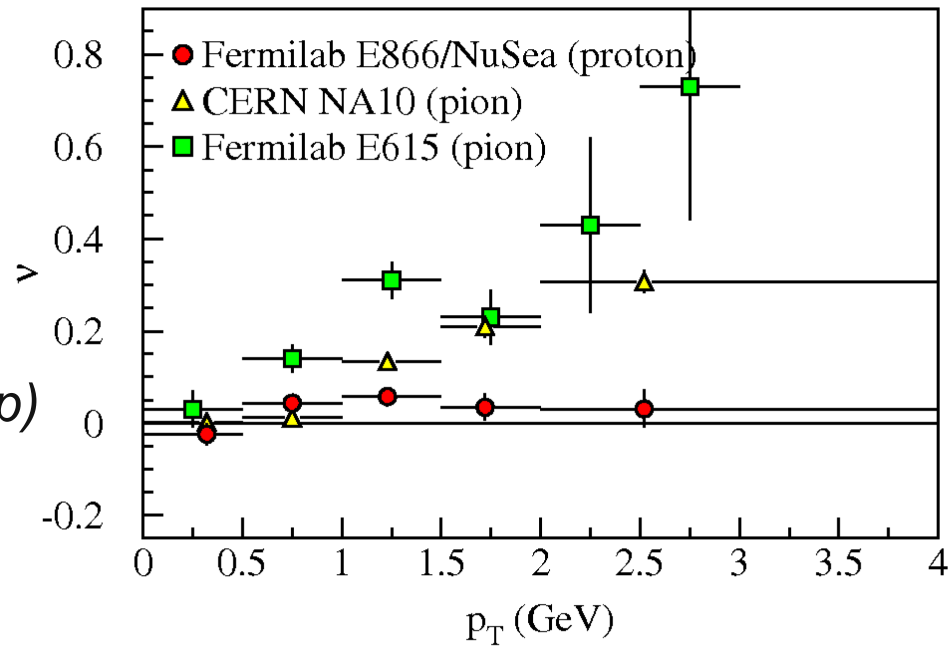
Lam-Tung Relation

- π^- Drell-Yan
  - Violates L-T relation
  - Large ν ($\cos 2\phi$) dependence
  - Strong with p_T
- Proton Drell-Yan
  - **Consistent** with L-T relation
  - **No** ν ($\cos 2\phi$) dependence
  - **No** p_T dependence
- With Boer-Mulders function $h1^{\perp}$:
  - $\nu(\pi^- W \rightarrow \mu^+\mu^- X)$

    *valence $h1^{\perp}(\pi)$ * valence $h1^{\perp}(p)$*
  - $\nu(pd \rightarrow \mu^+\mu^- X)$

    *valence $h1^{\perp}(p)$ * sea $h1^{\perp}(p)$*

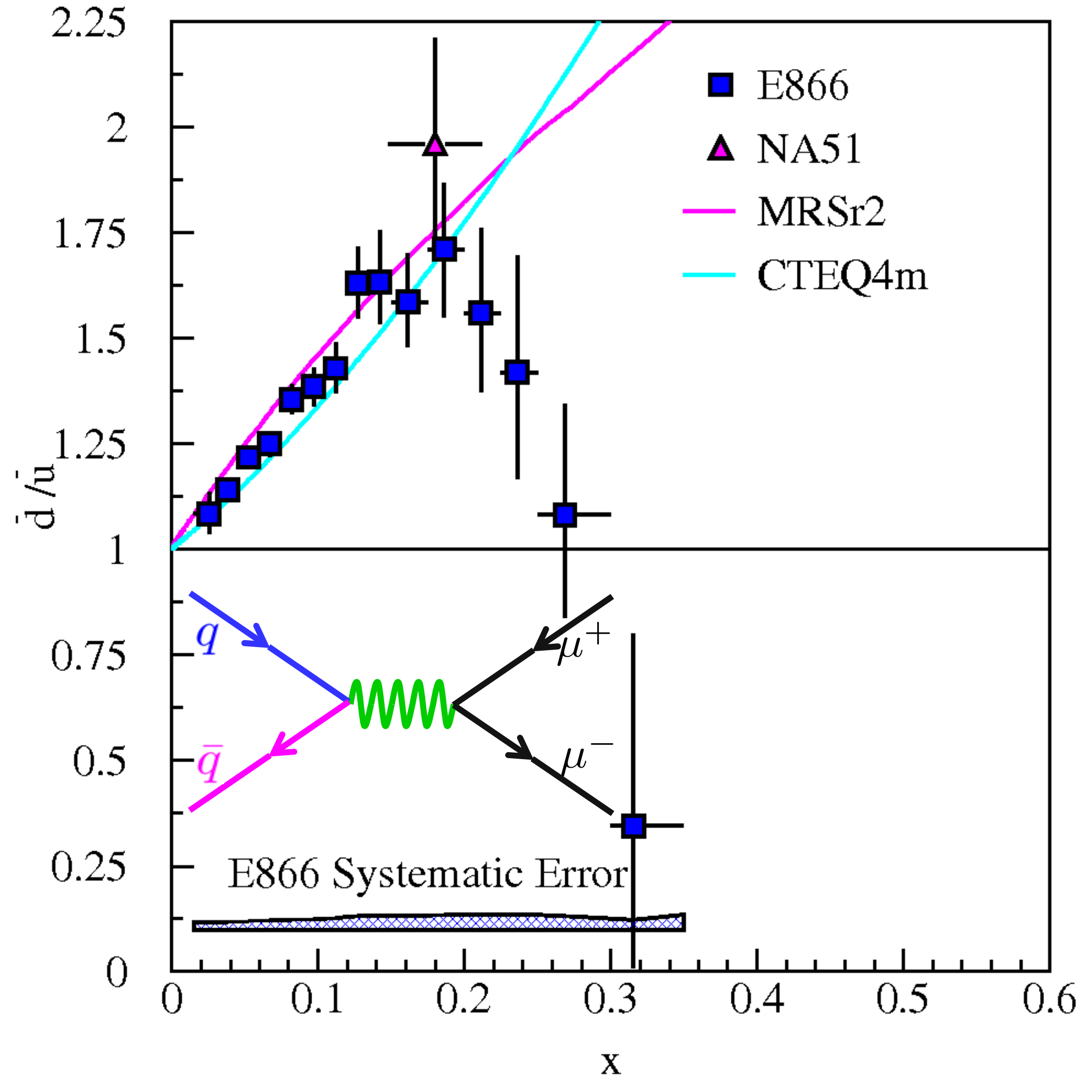




Drell-Yan Scattering: What we really measure

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

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



Drell-Yan Mass Spectra