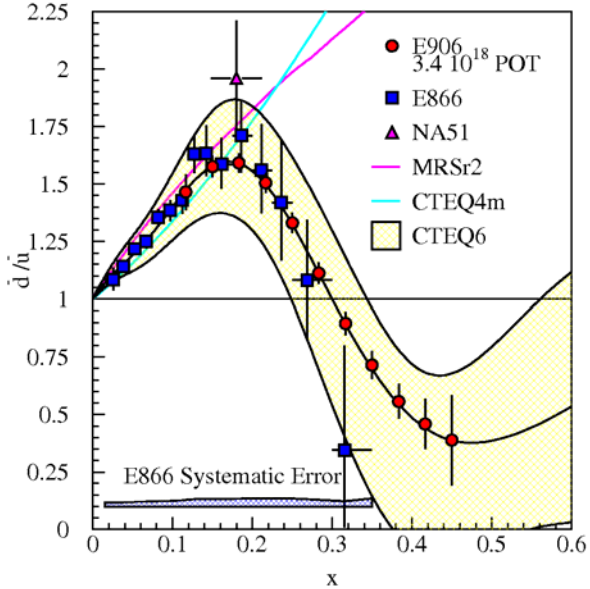
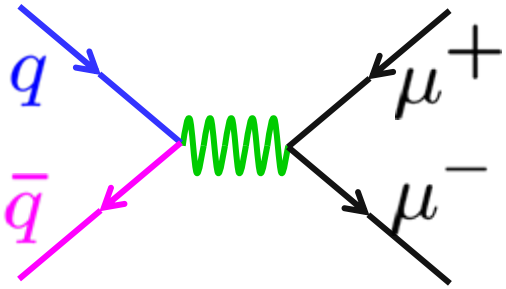
Exploring the Antiquark Structure of Matter with Drell-Yan Scattering

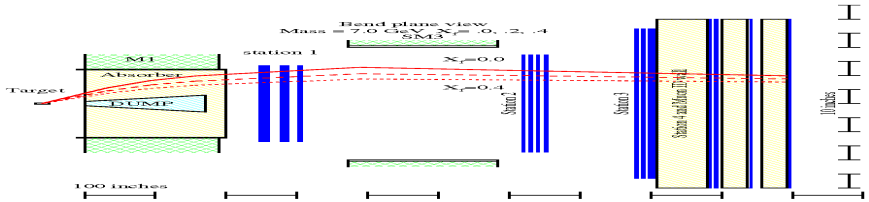
Paul E. Reimer

17 March 2008



- What will we learn?
  - Sea of the proton and of nuclei
  - High-*x* valence distributions
  - Partonic energy loss in cold nuclear matter
- What will we measure?
- How will we measure it?
  - Spectrometer upgrade





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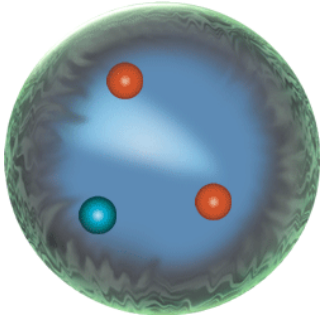
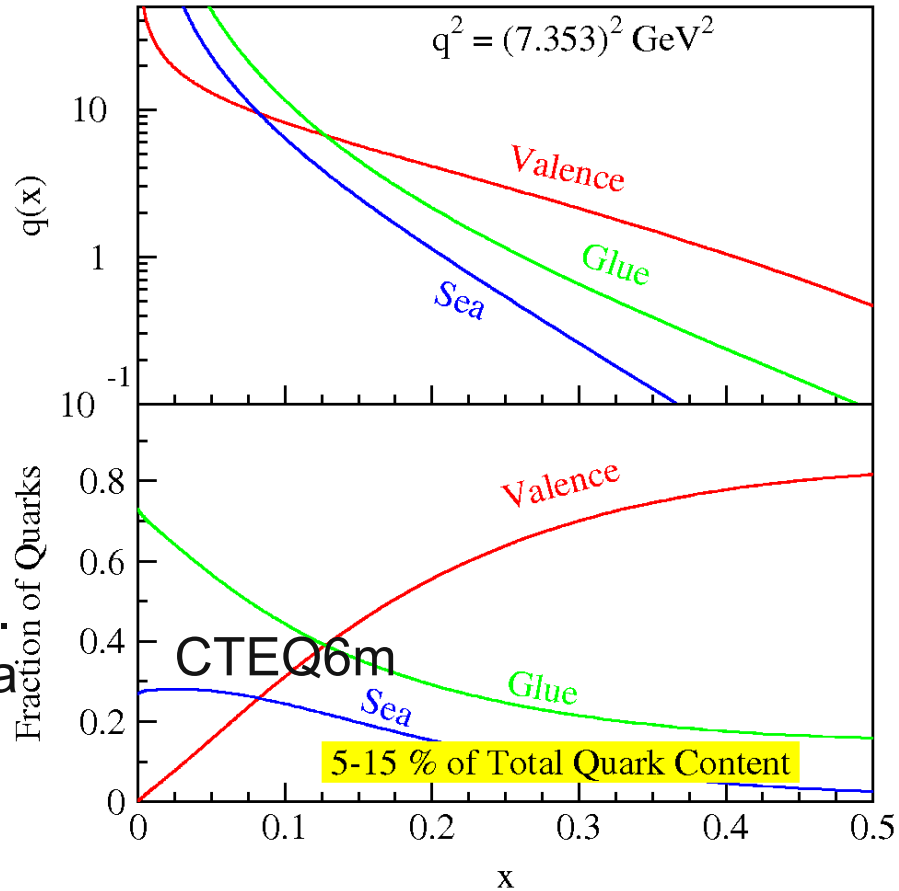
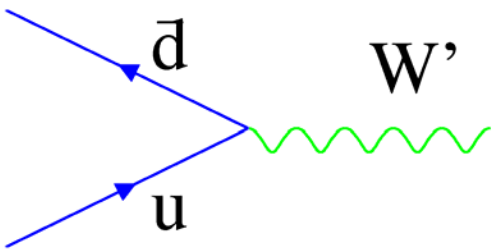
What is the distribution of sea quarks?

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.

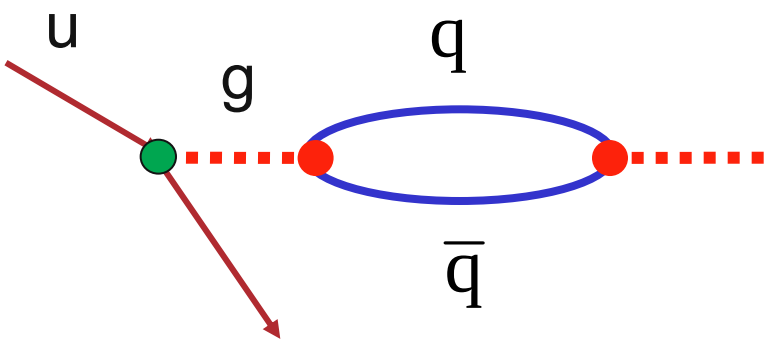




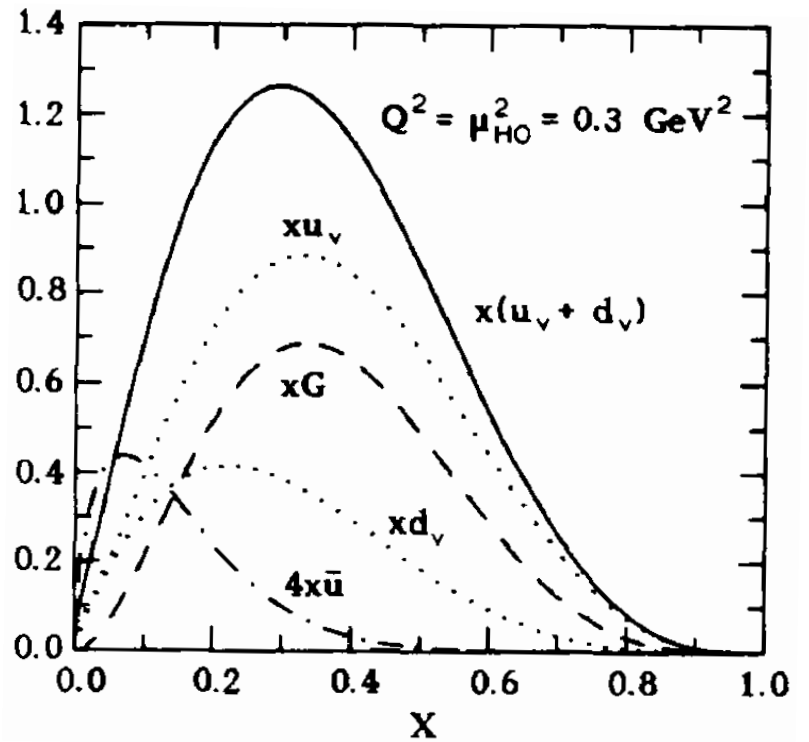
In nuclei:

- 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



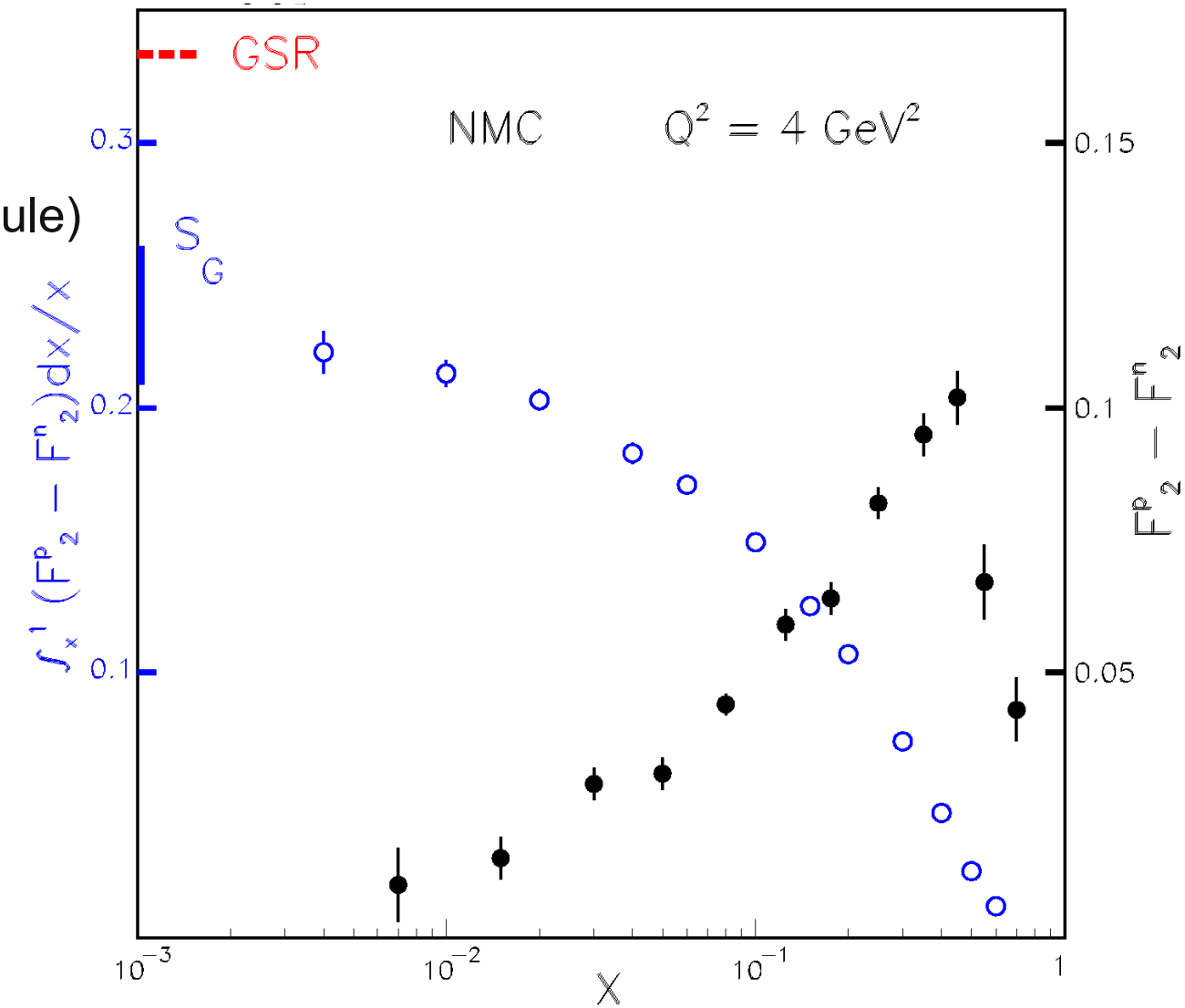
- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Radiatively generate sea and glue. Gluck, Godbole, Reya, ZPC **41** 667 (1989)
- It was quickly realized that some valence-like (primordial)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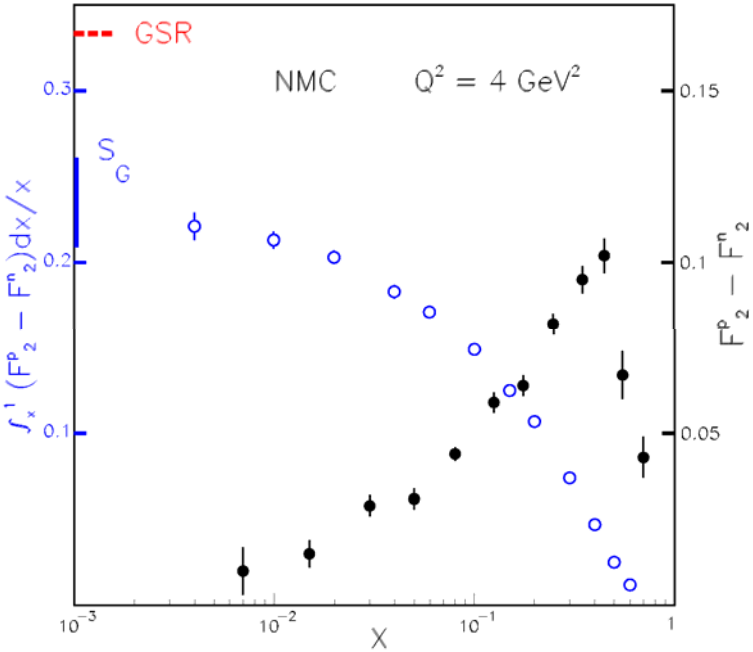
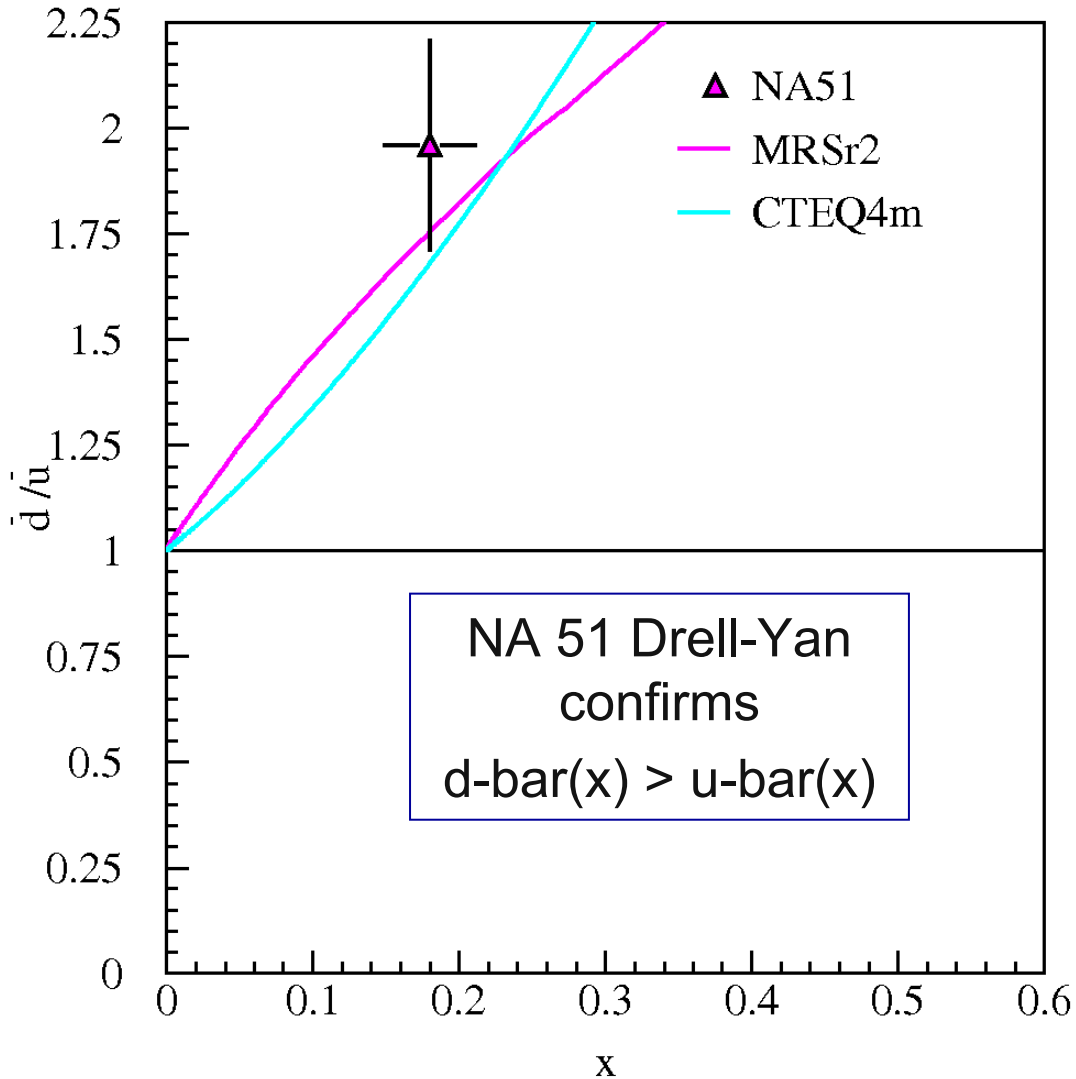




NA 51 Drell-Yan confirms d-bar(x) > u-bar(x)

Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

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

- NMC (Gottfried Sum Rule)

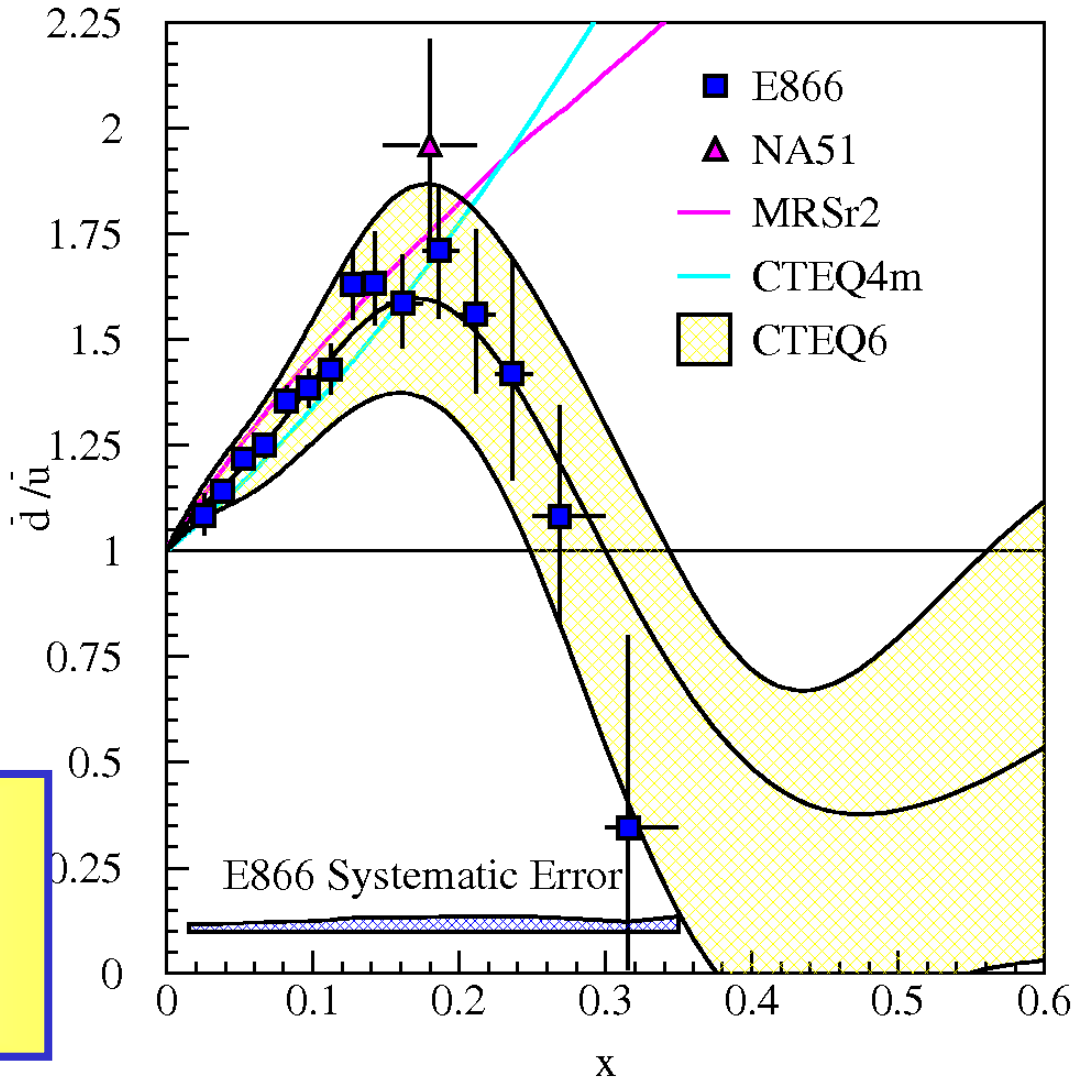
$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan)

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

- E866/NuSea (Drell-Yan)

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



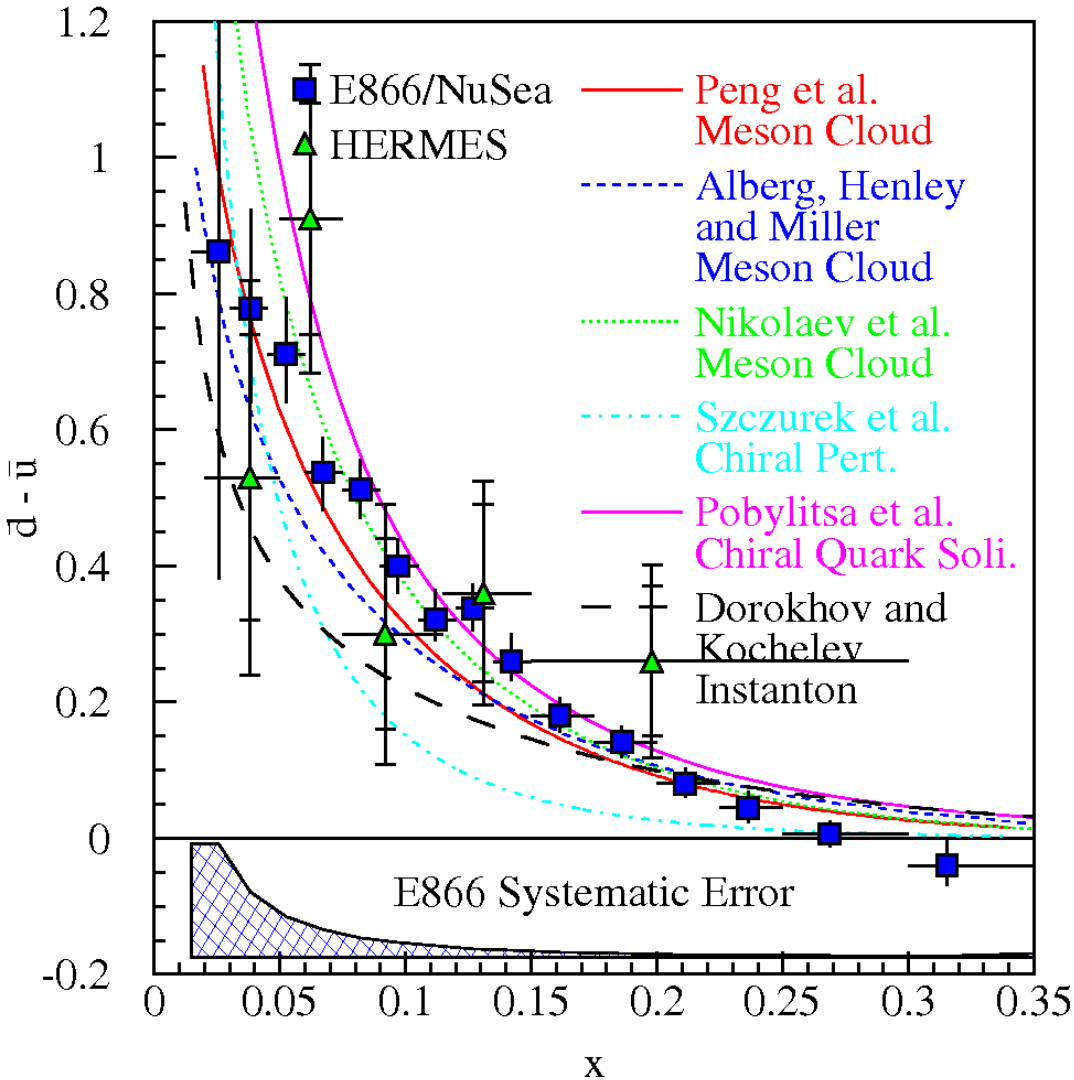
- Knowledge of distributions is data driven
  - Sea quark distributions are difficult for Lattice QCD

Proton Structure: By What Process Is the Sea Created?

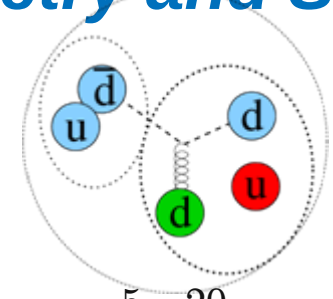
- There is a gluon splitting component which is symmetric

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

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

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

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

- 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

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

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?)

Proton Structure: By What Process Is the Sea Created?

- Meson Cloud in the nucleon

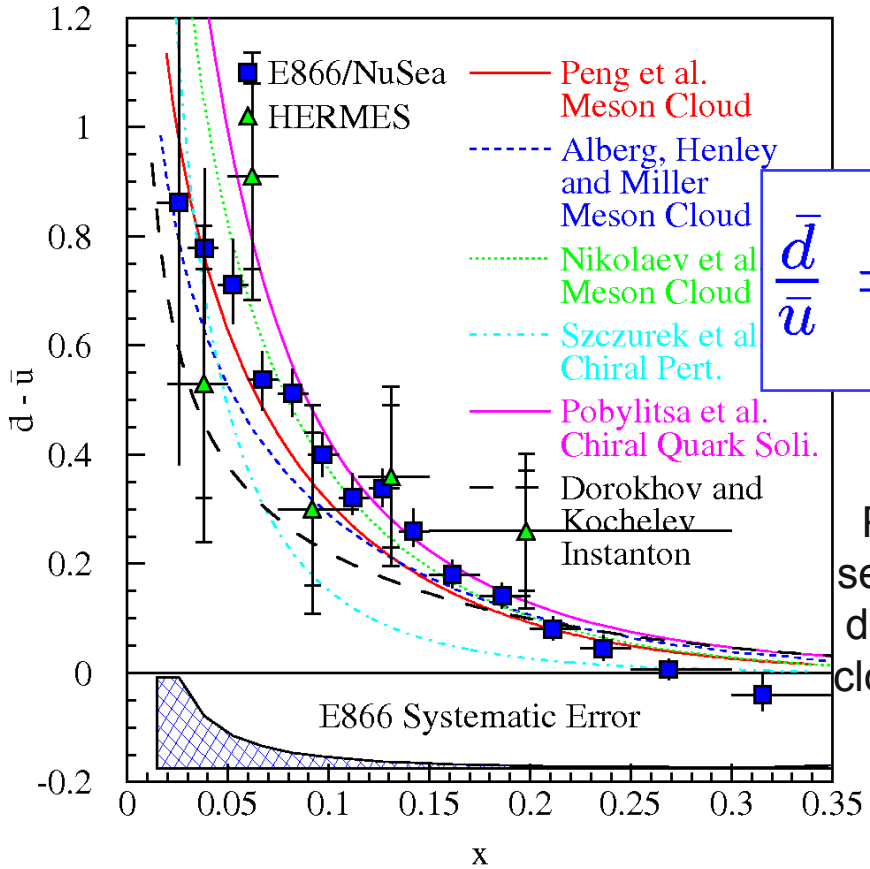
  Sullivan process in DIS

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

- Chiral Models

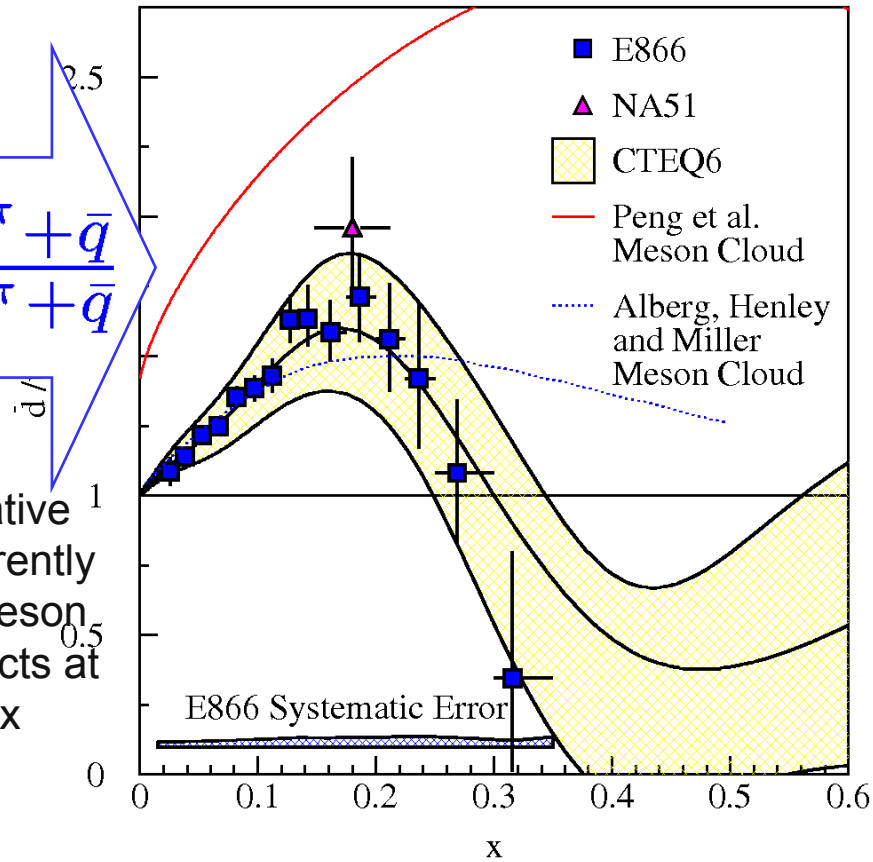
  Interaction between Goldstone Bosons and valence quarks

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

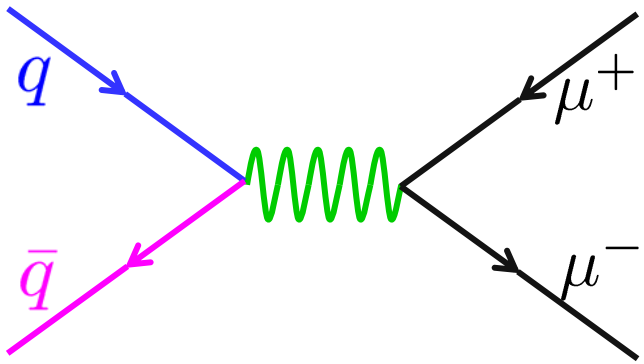


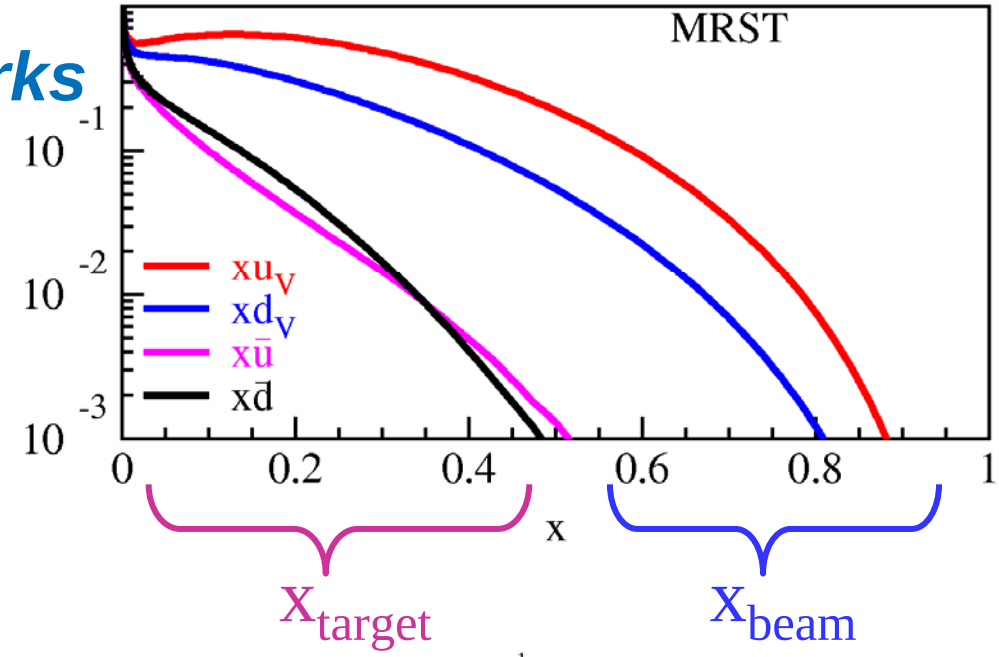
$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$

Perturbative sea apparently dilutes meson cloud effects at large-x

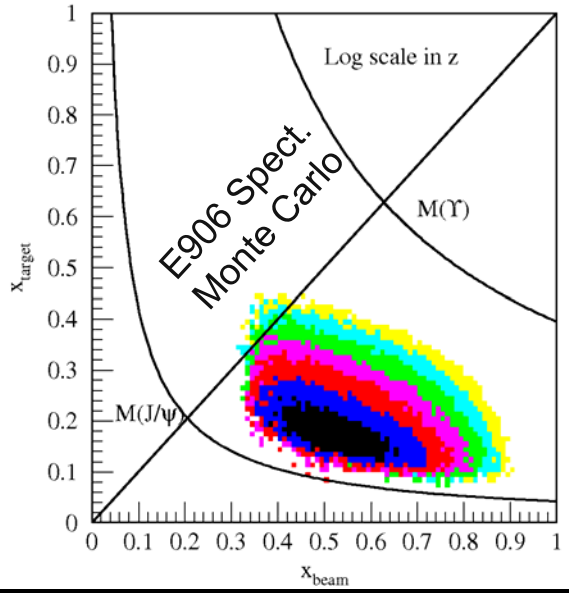


Drell-Yan scattering:
A laboratory for sea quarks





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



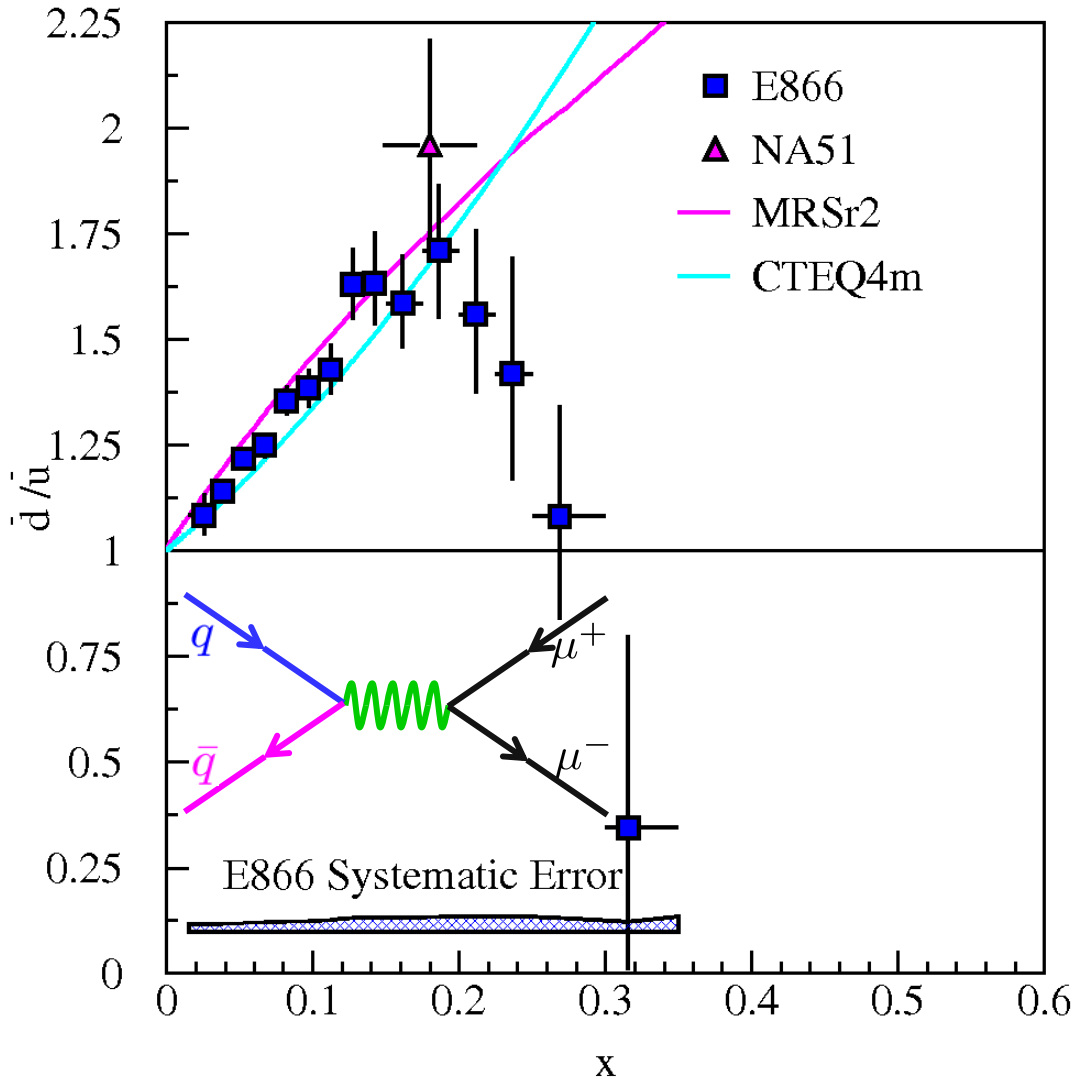
Detector acceptance chooses x_{target} and x_{beam}.

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

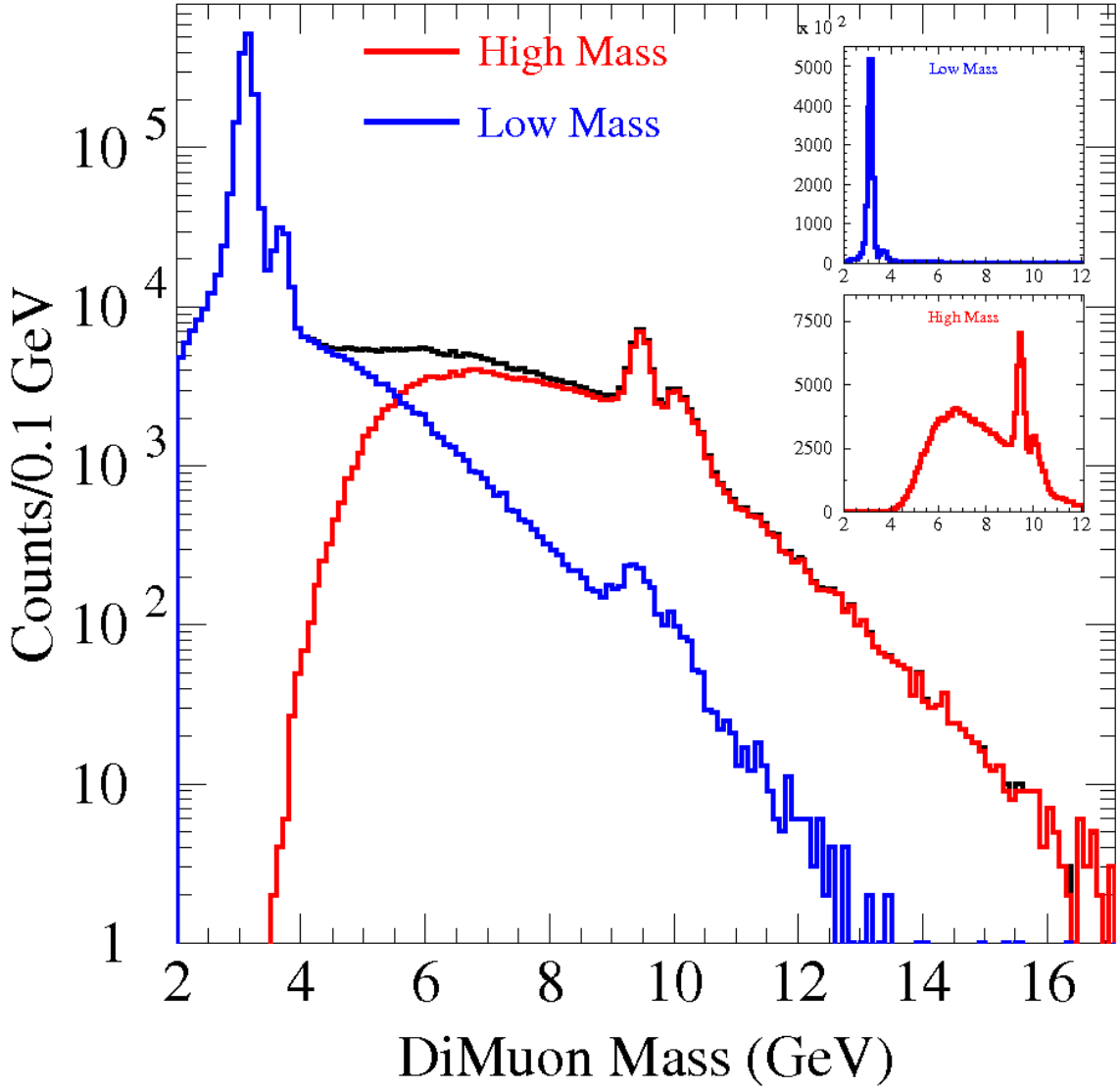
Drell-Yan Scattering: What we really measure

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

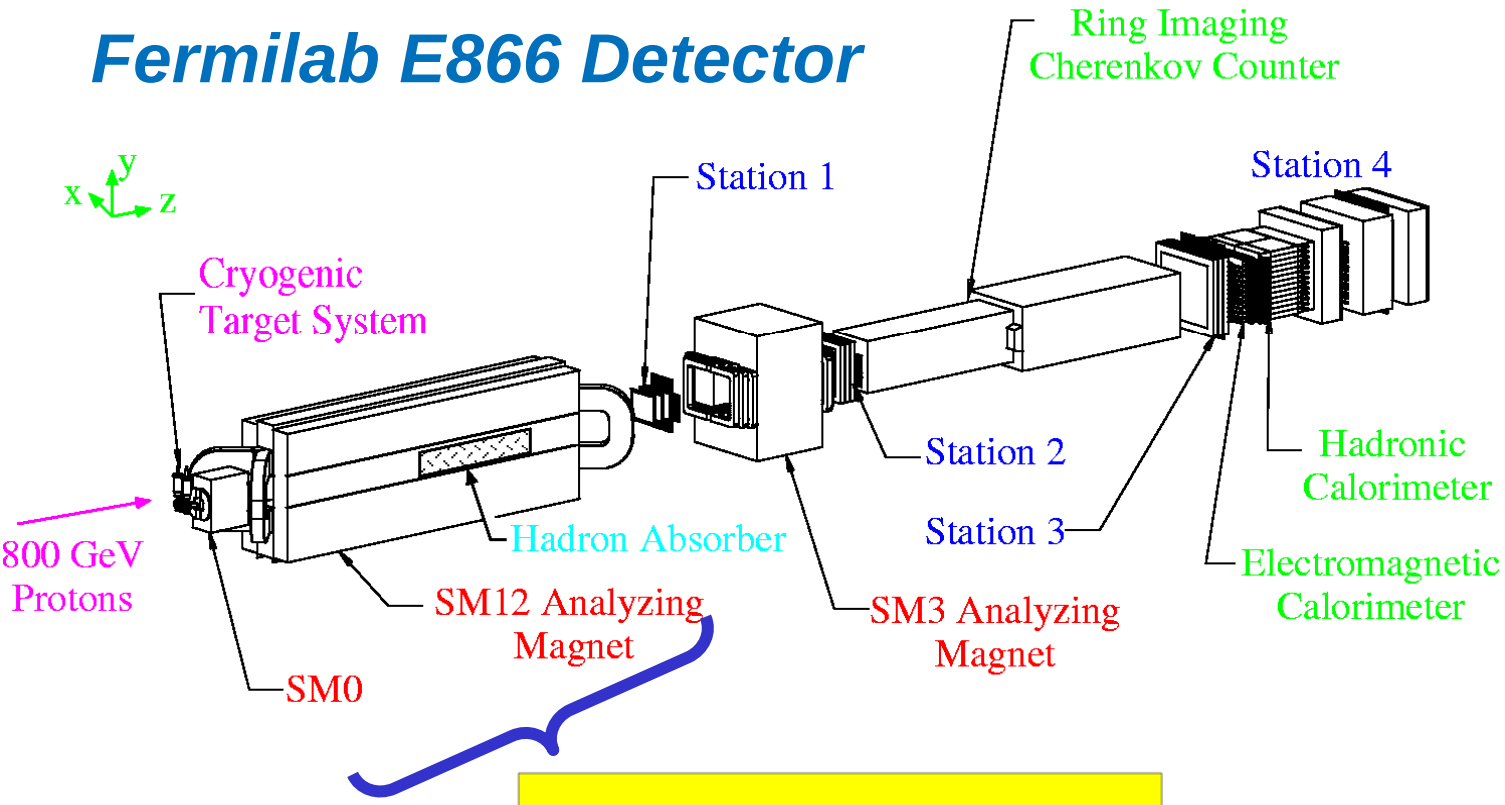
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

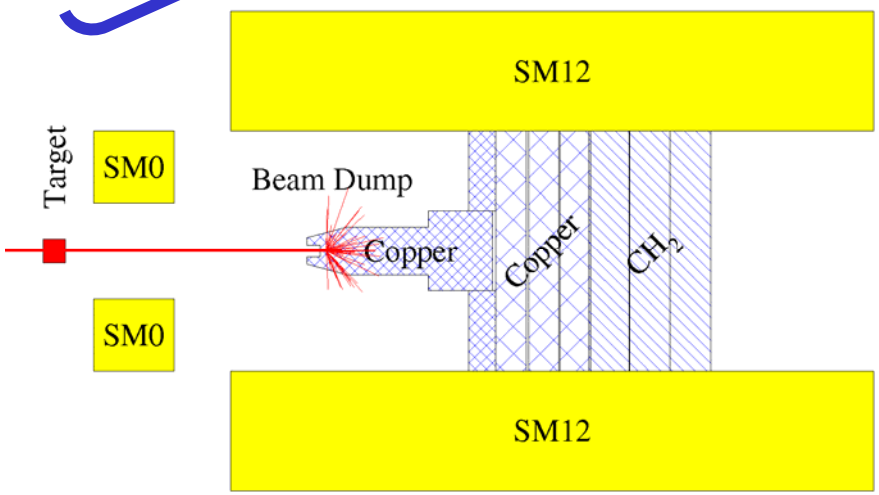


Drell-Yan Mass Spectra



Fermilab E866 Detector





FNAL E866/NuSea Collaboration

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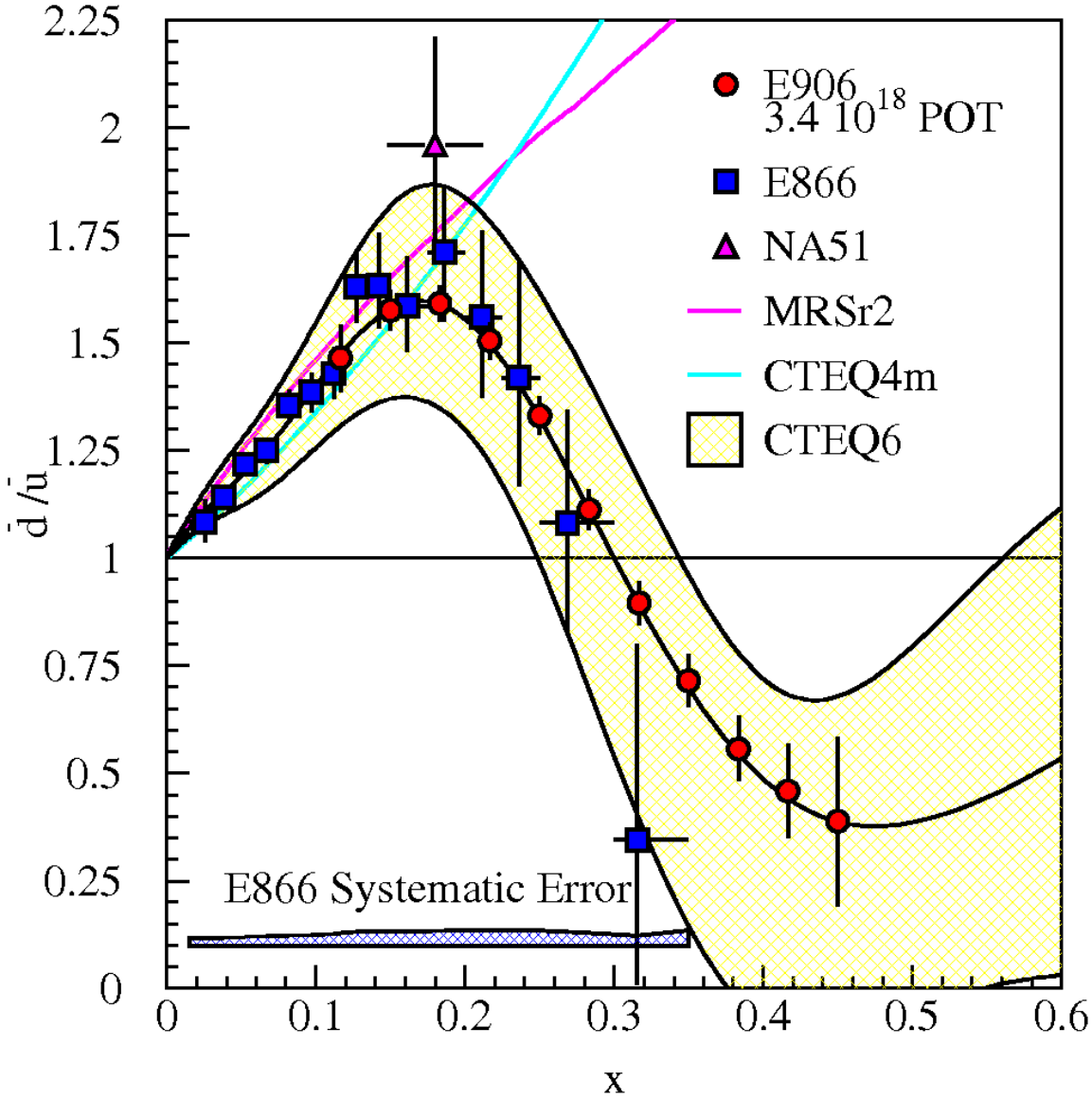
Valparaiso University
Don Koetke, Paul Nord

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.



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:

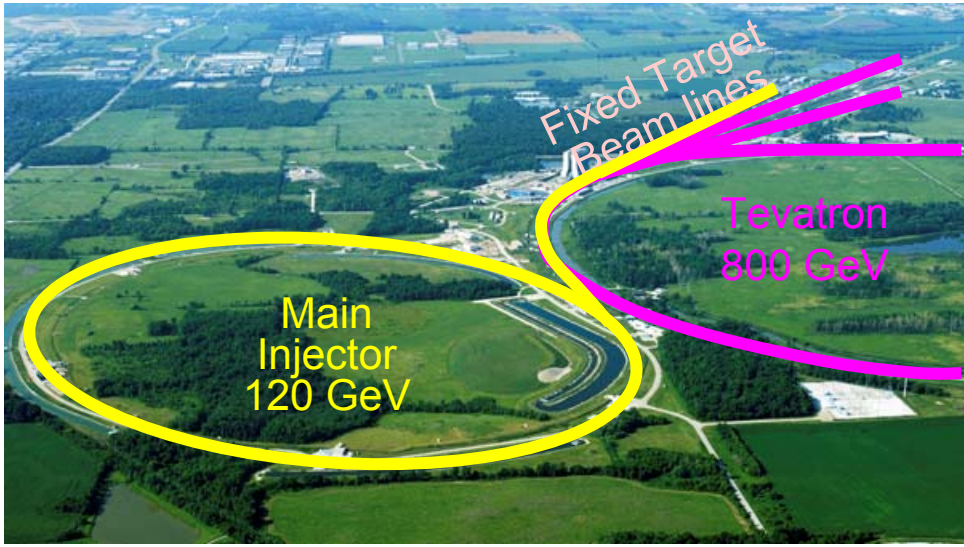
Fermilab E906

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

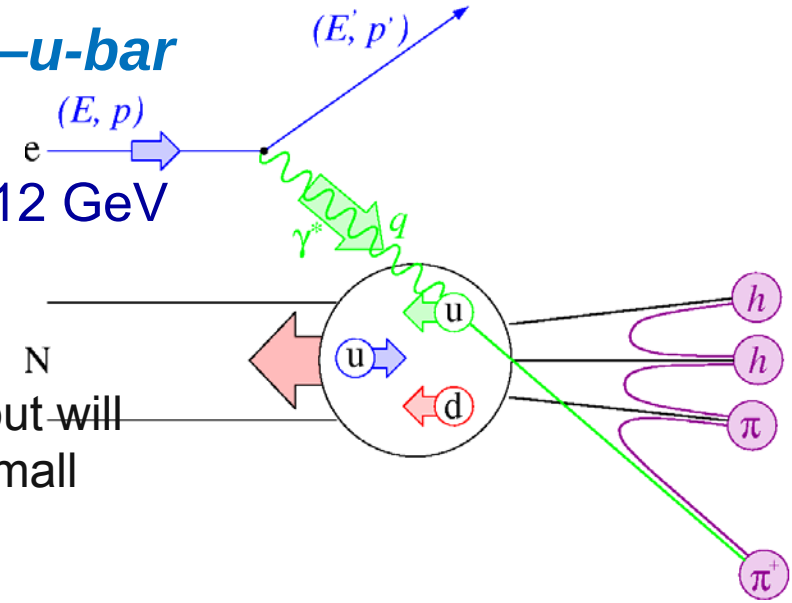
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- 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!!



Other Possible Measurements of d-bar—u-bar asymmetry

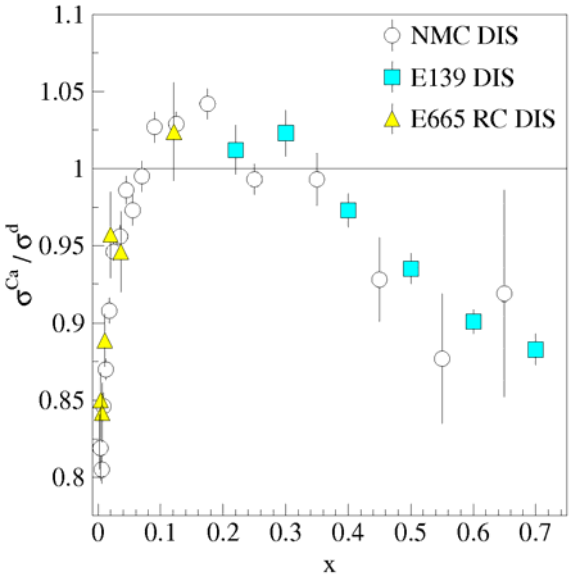


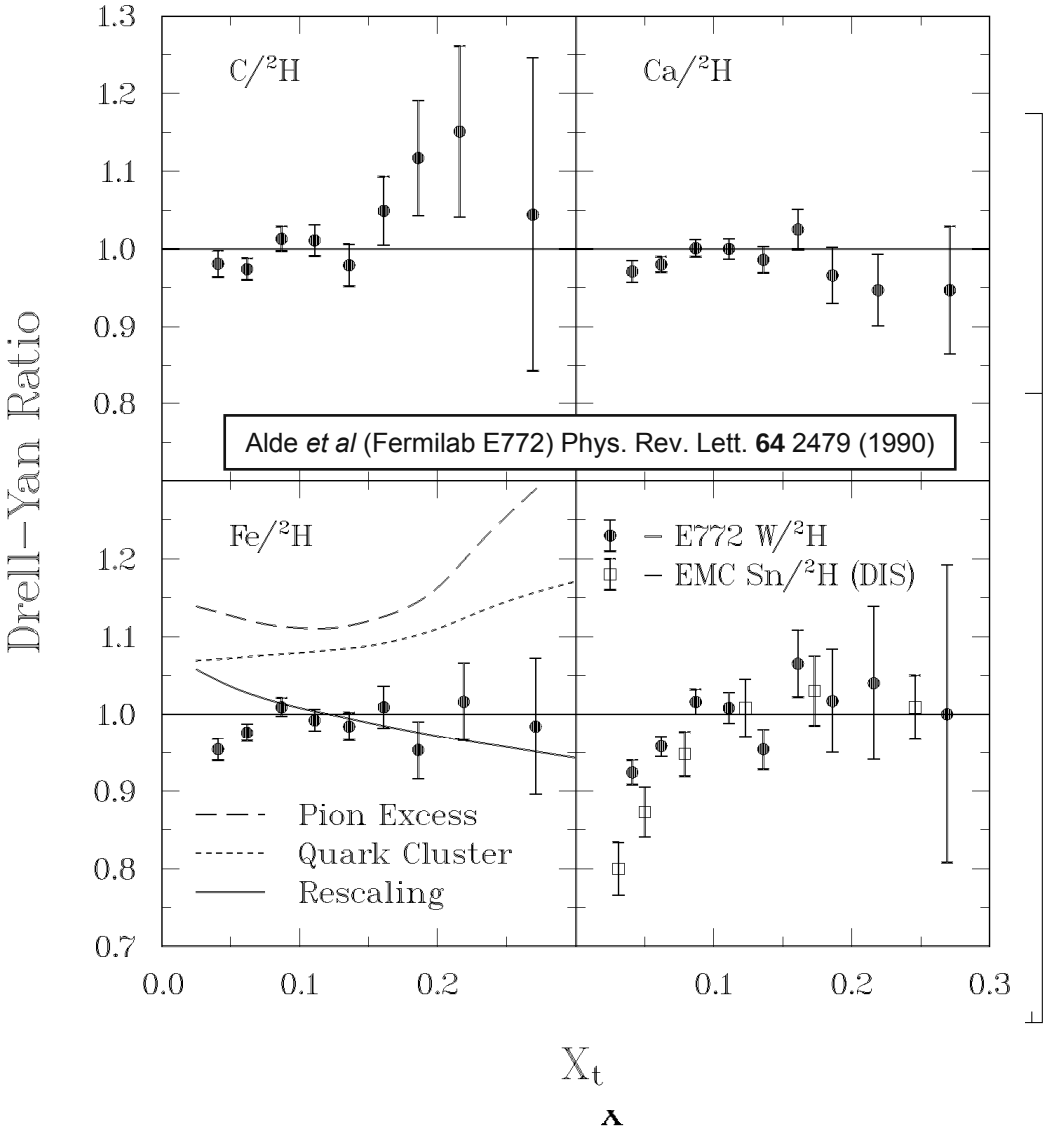
- Semi-Inclusive DIS—HERMES, JLab, JLab 12 GeV
  - Tag struck quark through leading hadron
  - Must understand fragmentation
  - HERMES may reduce statistical uncertainty but will still have significant systematic uncertainty (small differences between large numbers)
- Drell-Yan—JPARC
  - Initial phase of JPARC is 30 GeV—sufficient only for J/ψ studies, no Drell-Yan (no phase space for events above J/ψ)
  - JPARC Phase II—50 GeV
    - great possibilities for polarized Drell-Yan
    - Berger criteria for nuclear targets—insufficient energy for heavy A
    - No partonic energy loss studies—x_{beam}-x_{target} correlations
    - Experimental issues: p_T acceptance, $\pi^{\pm}$ decay in flight background
  - **Physics Program cannot be reached by 30 GeV machine (physics program strongly endorsed)**

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

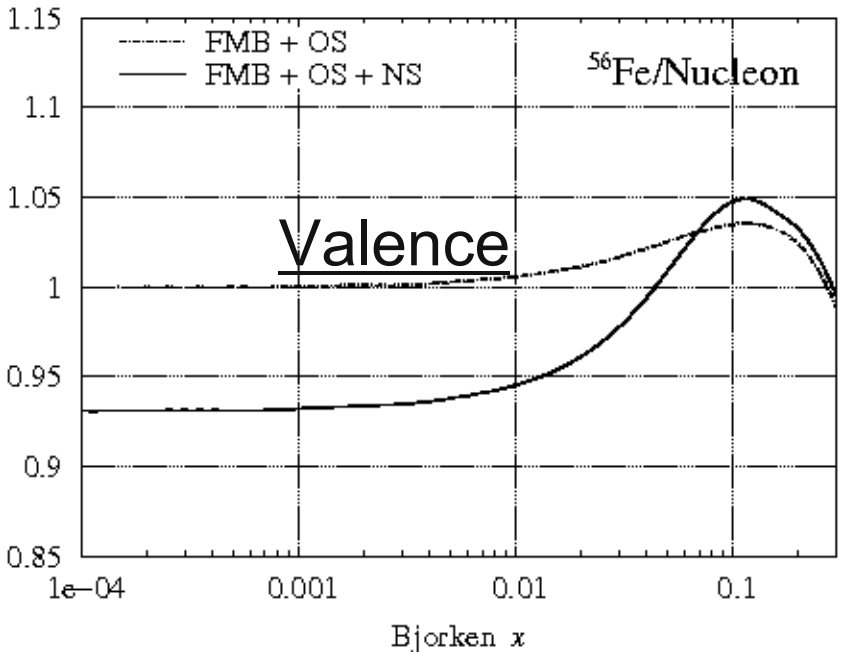
Comparison with
Deep Inelastic Scattering (DIS)

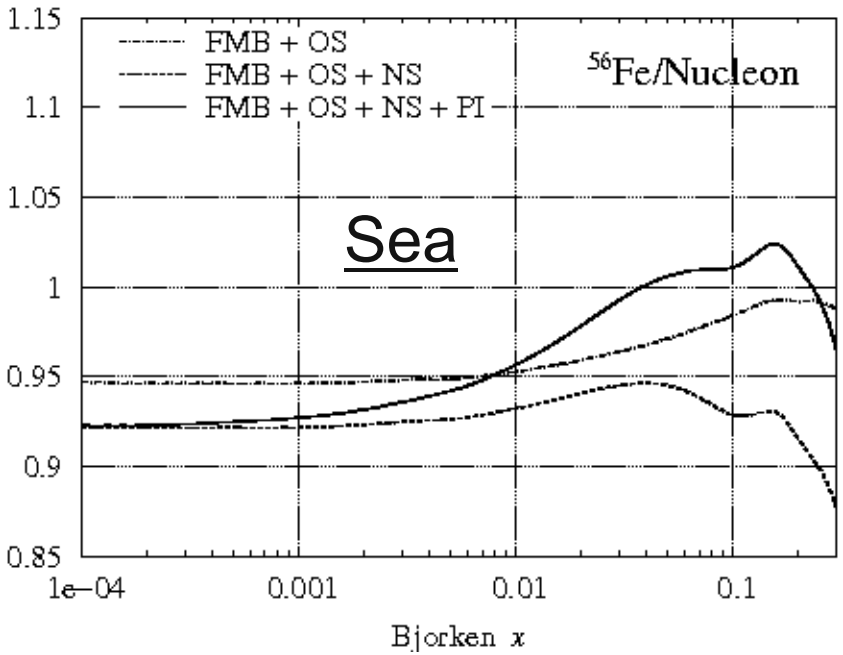
- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell Yan—Valence only effect





Kulagin and Petti sea vs. valence nuclear effects



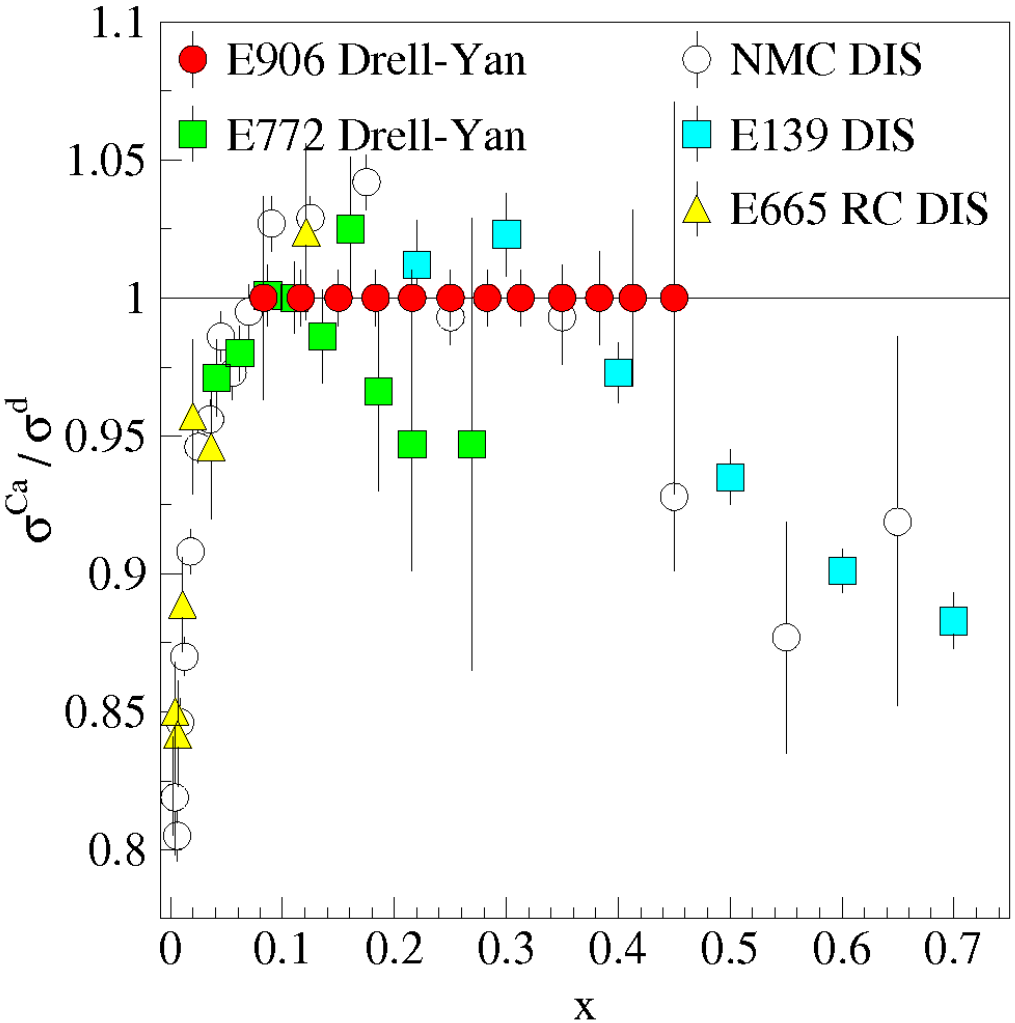


Nuclear Physics A 765 (2006) 126–187

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

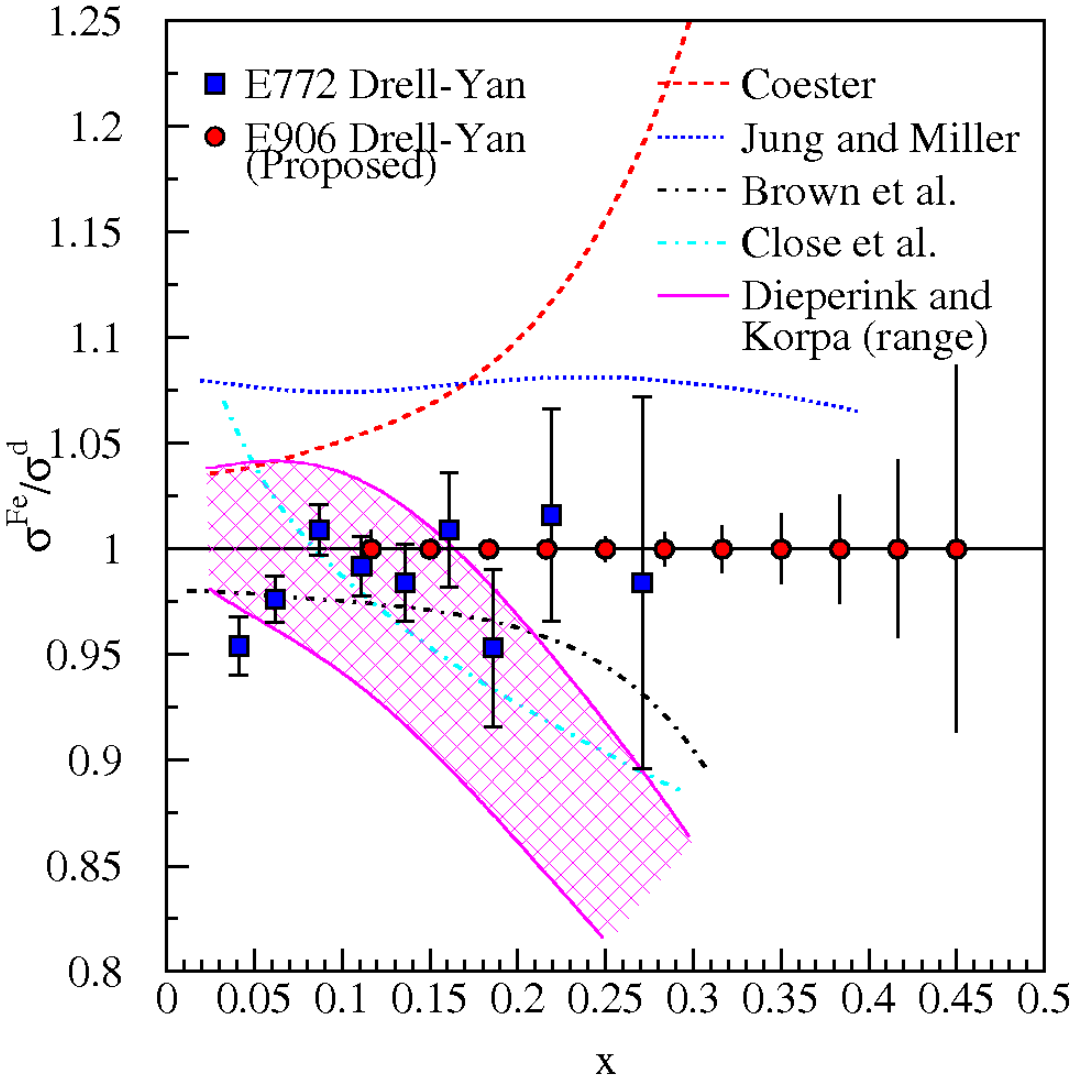
Intermediate-*x* *sea* PDF's

- 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?



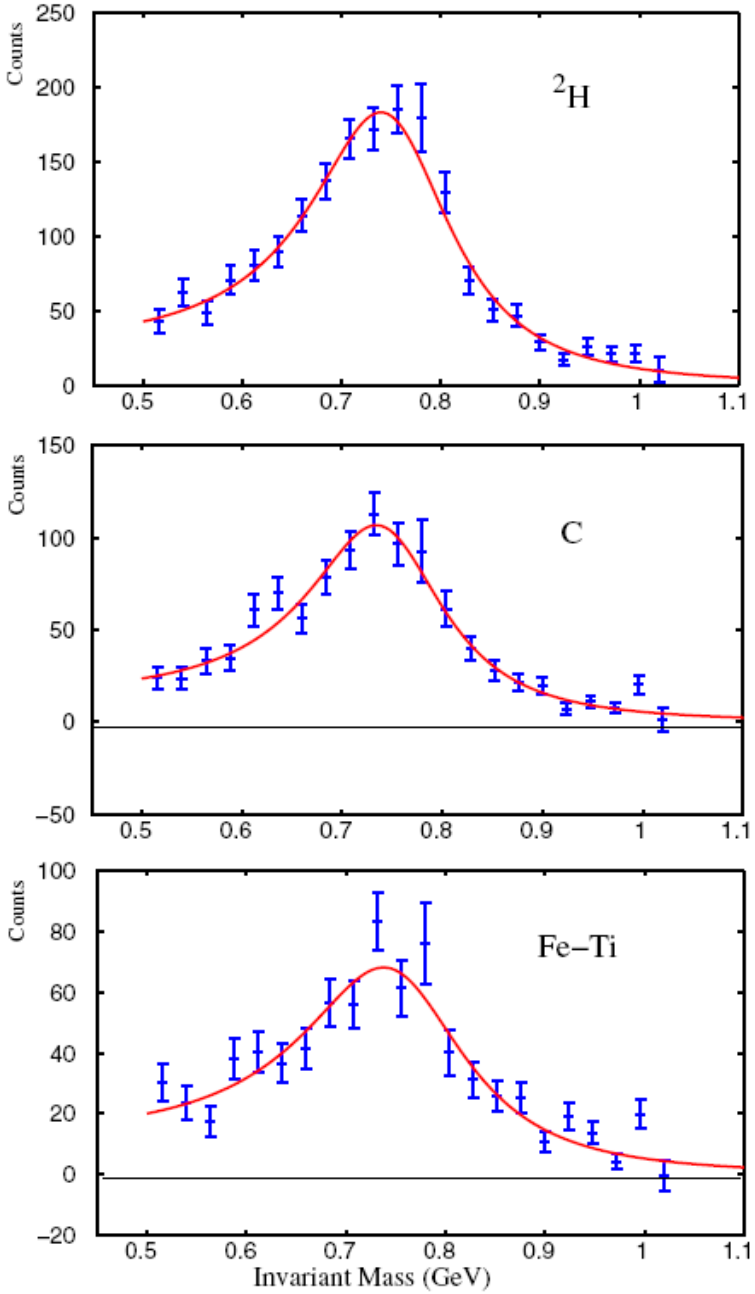
Structure of nucleonic matter: Where are the nuclear pions?

- 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

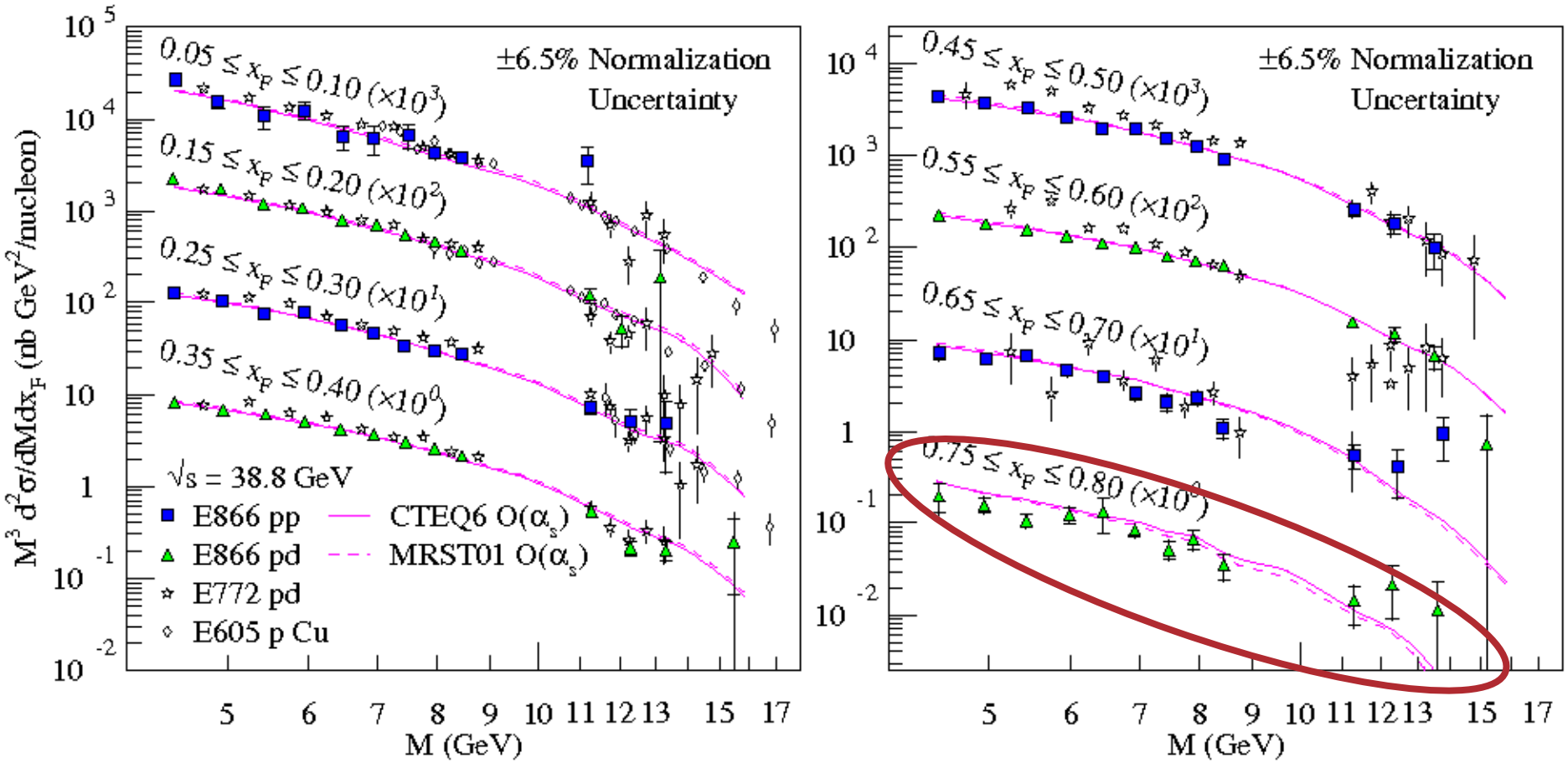


Aside: Rescaling Models in Trouble?

- Prediction of ρ mass/width modification not seen in JLab/CLAS data Nasseripour *et al.* (CLAS) PRL 99, 262302 (2007)



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

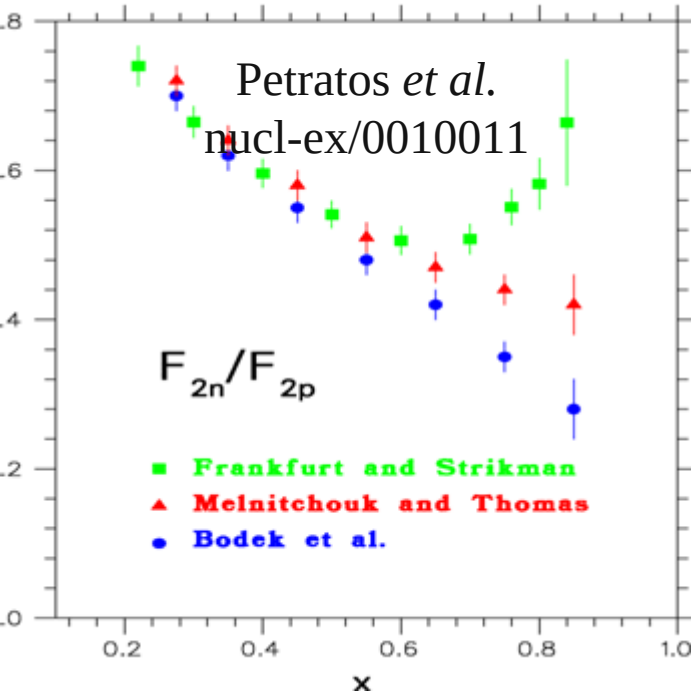
Proton Valence Structure: Unknown as $x \to 1$

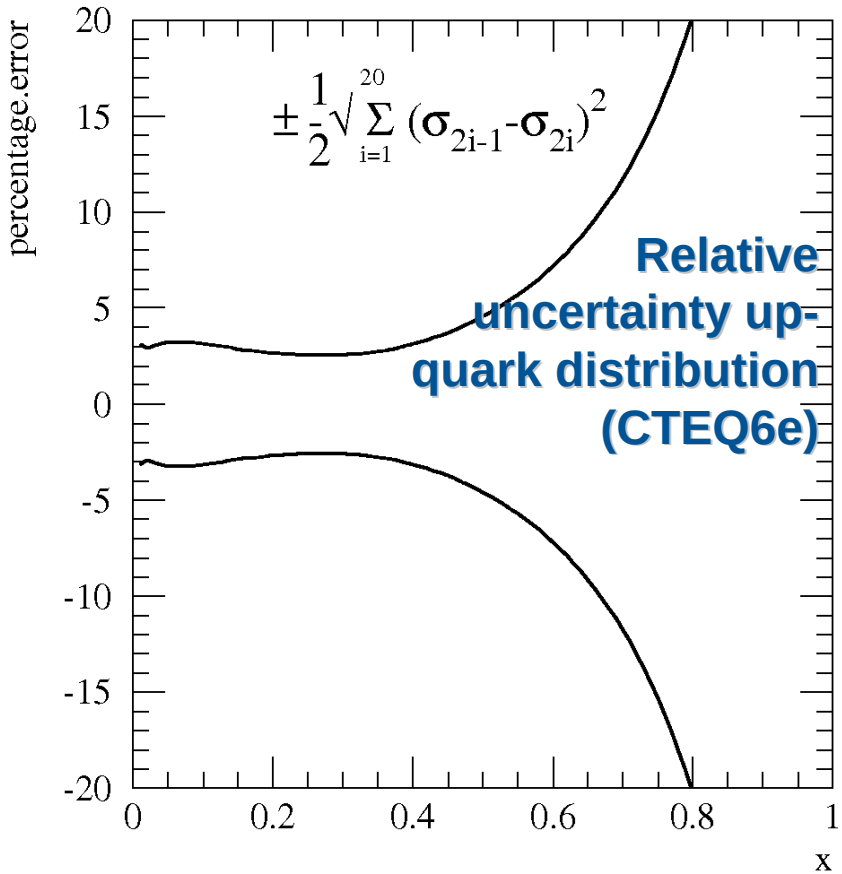
Theory

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

Data

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

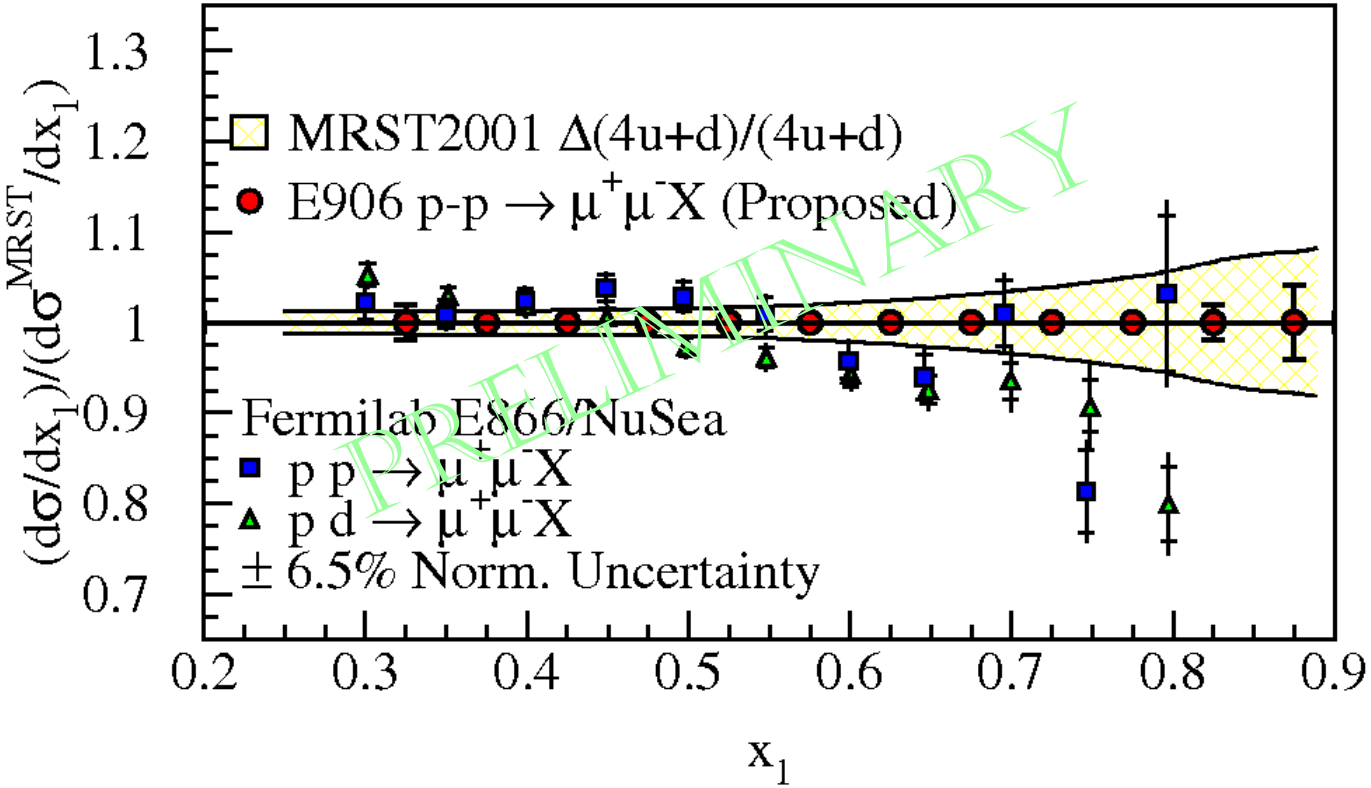




Reality:
We don't even know the u or d quark distributions—there really is very little high-x proton data

Drell-Yan Absolute Cross Sections: x_{target}

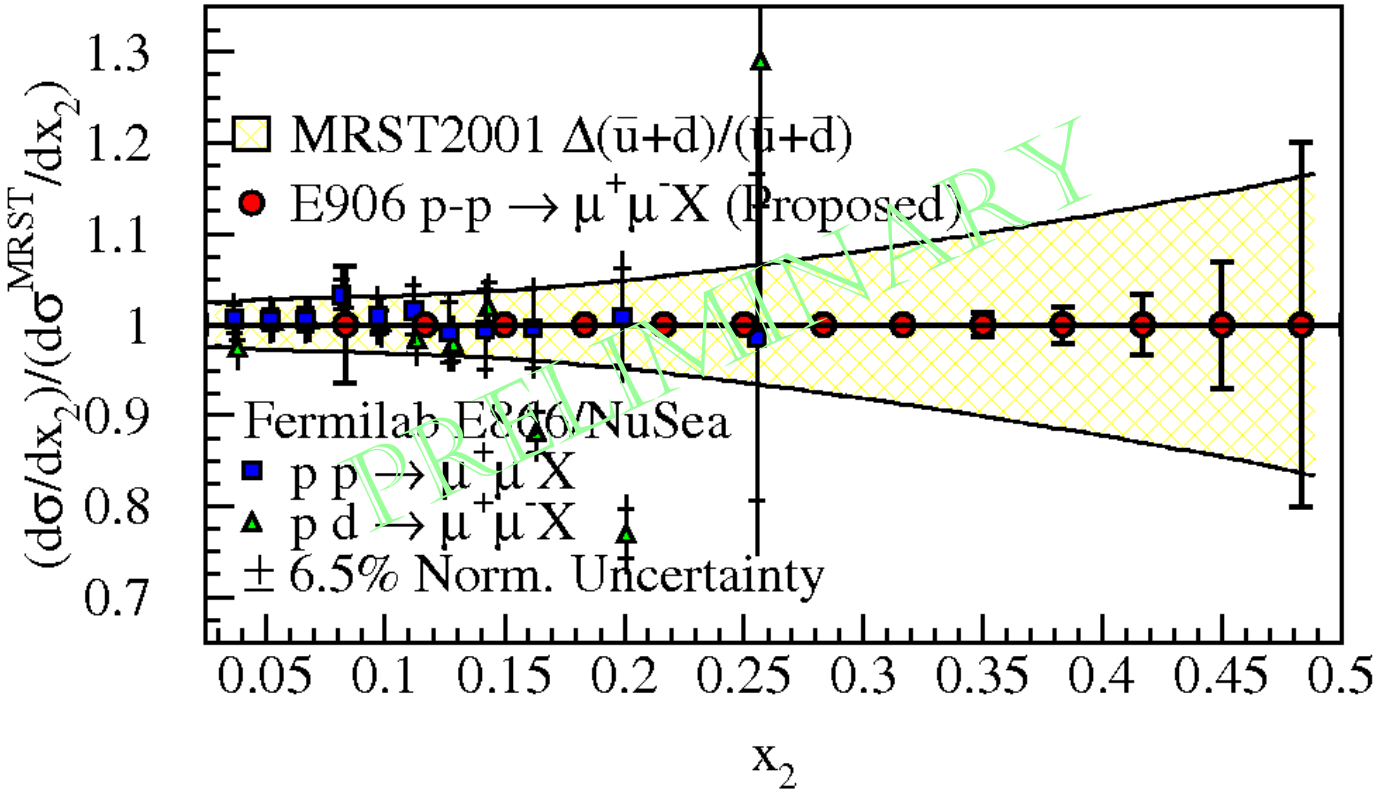
- Reach high-x through *beam proton*—Large $x_F \Rightarrow$ large x_{beam}.
- High-x distributions poorly understood
  - Nuclear corrections are large, even for deuterium
  - Lack of proton data
- Proton-Proton—no nuclear corrections—*4u(x) + d(x)*



Drell-Yan Absolute Cross Sections: x_{target}

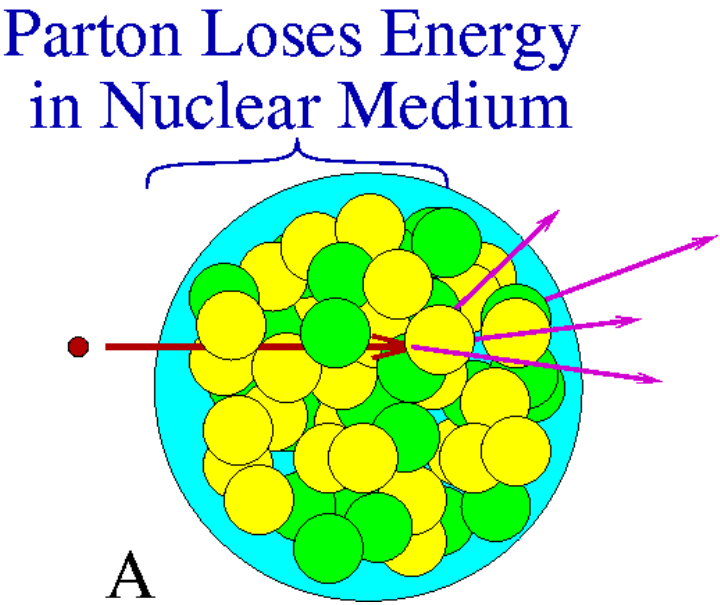
Measures a convolution of beam and target PDF

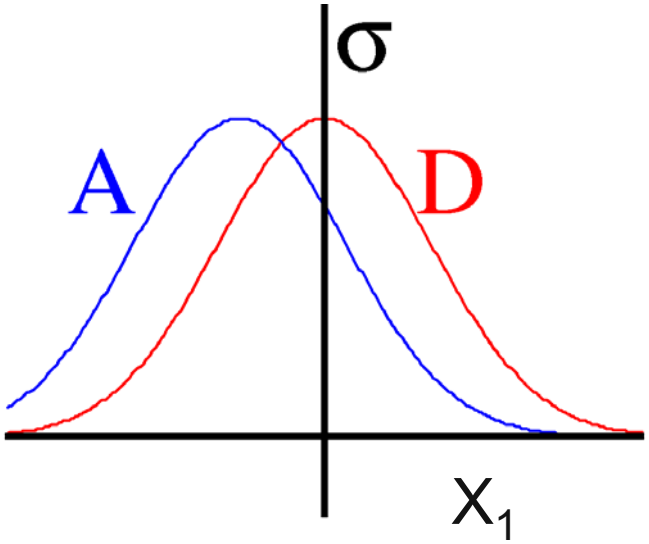
- absolute magnitude of high-x valence beam distributions
- absolute magnitude of the sea in the target
  - *Currently determined by ν–Fe DIS*



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

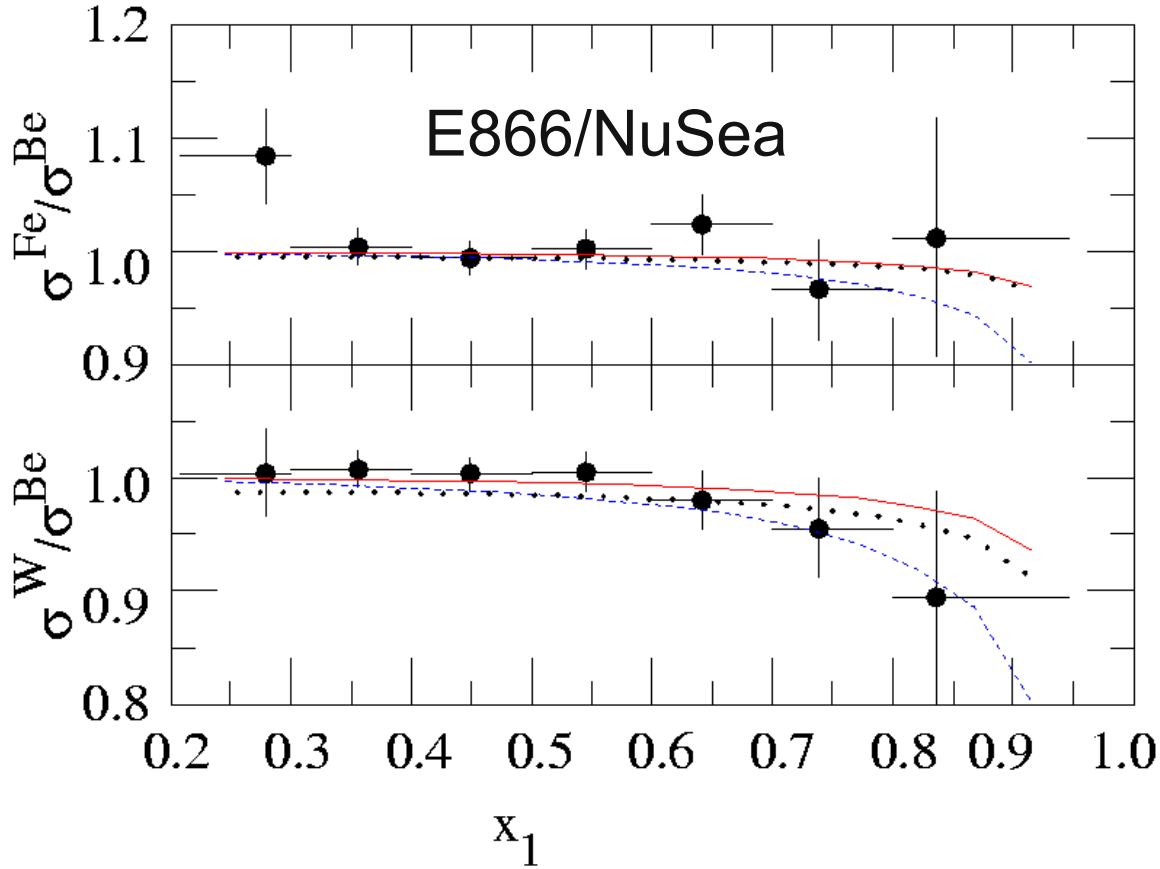




- Models:
  - Galvin and Milana $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

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*.

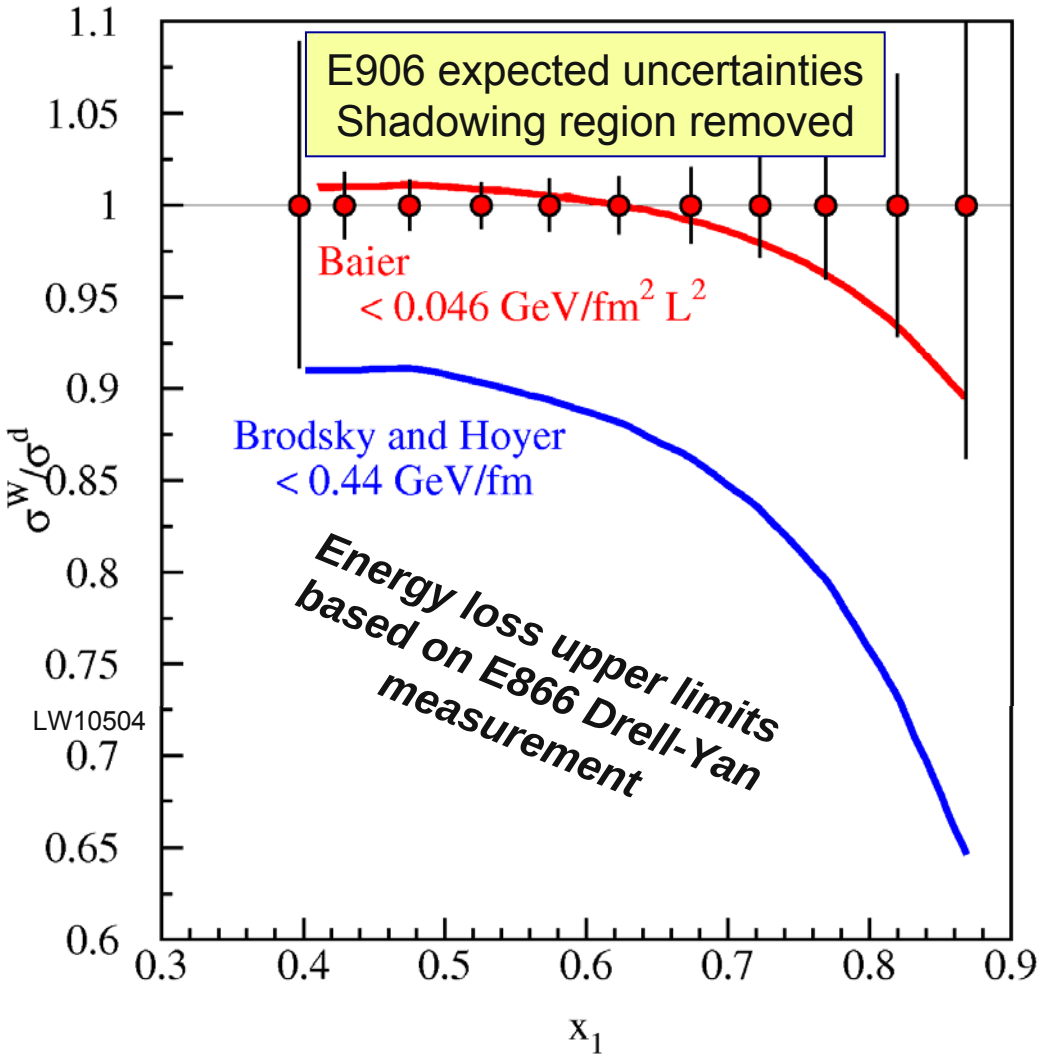


- Treatment of parton propagation length and shadowing are critical
  - Johnson *et al.* find 2.7 GeV/fm (≈1.7 GeV/fm after QCD vacuum effects)
  - Same data with different shadowing correction and propagation length
- **Better data outside of shadowing region are necessary.**

- 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

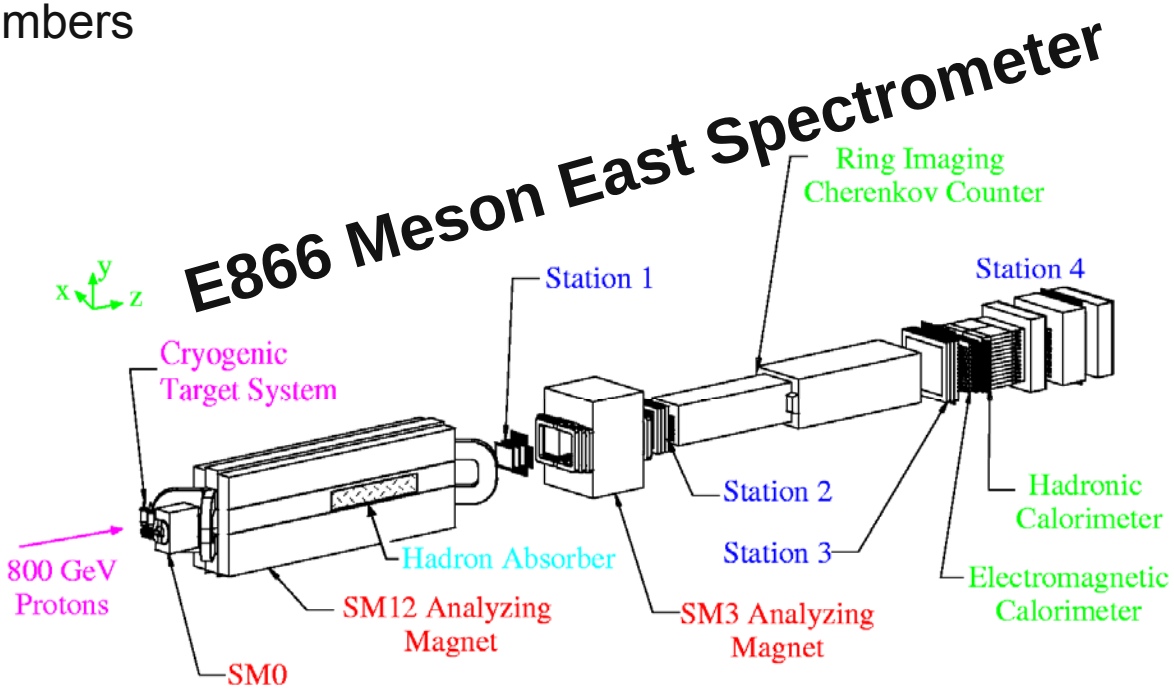


LW10504

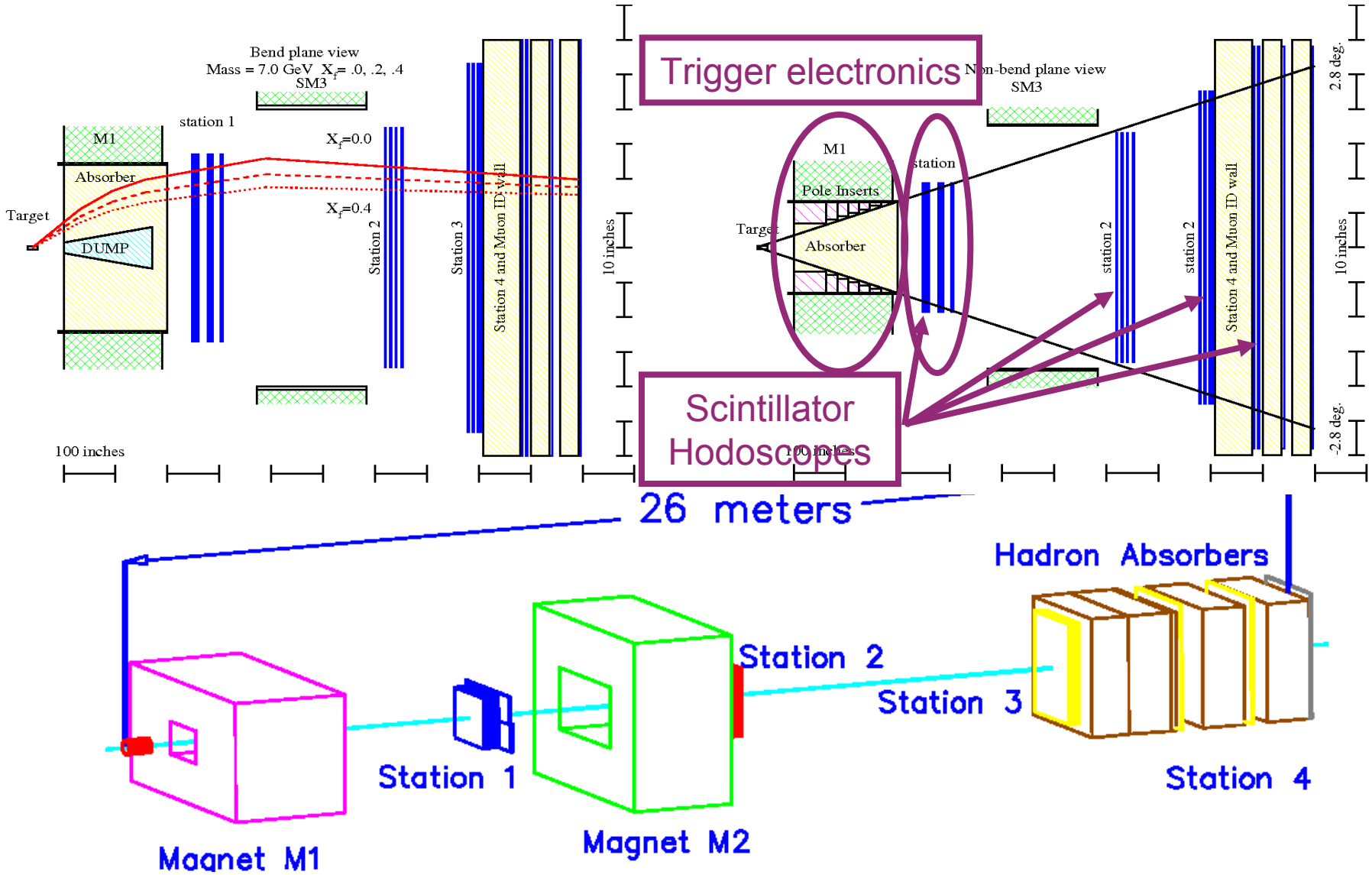
- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample

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 (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)

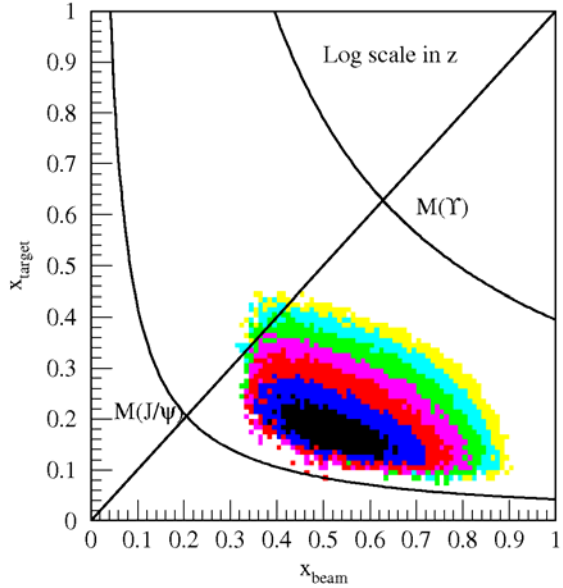


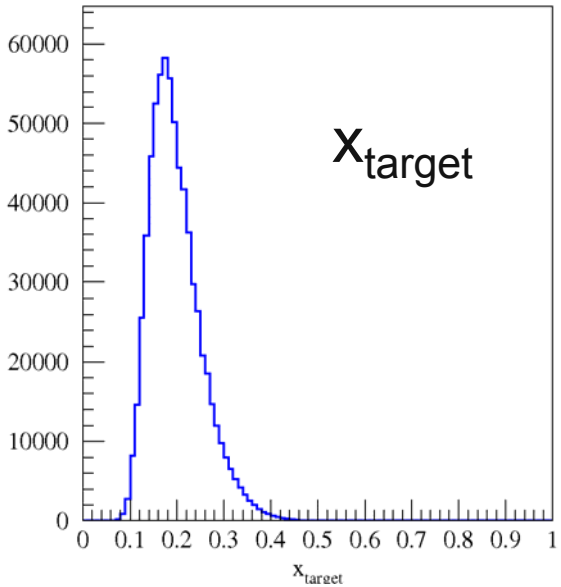
E906 Detector

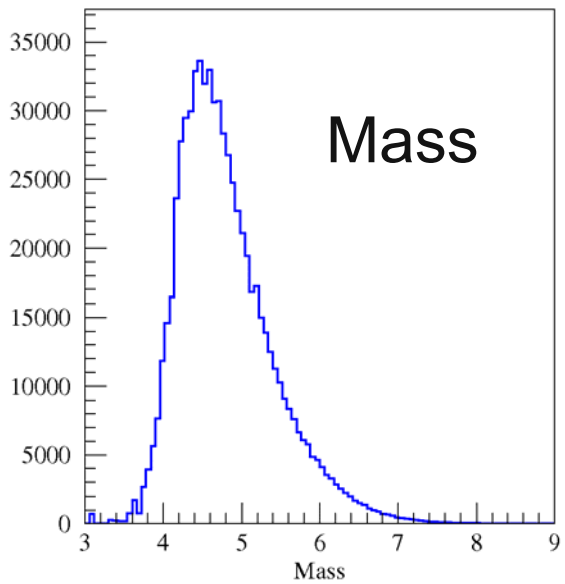


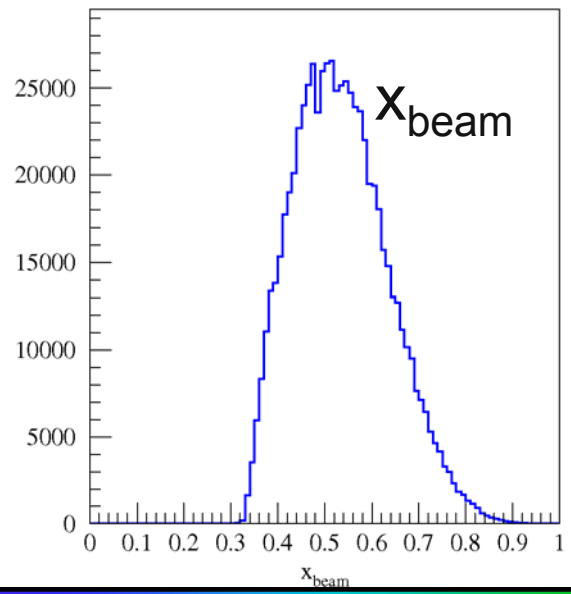
Drell-Yan Acceptance

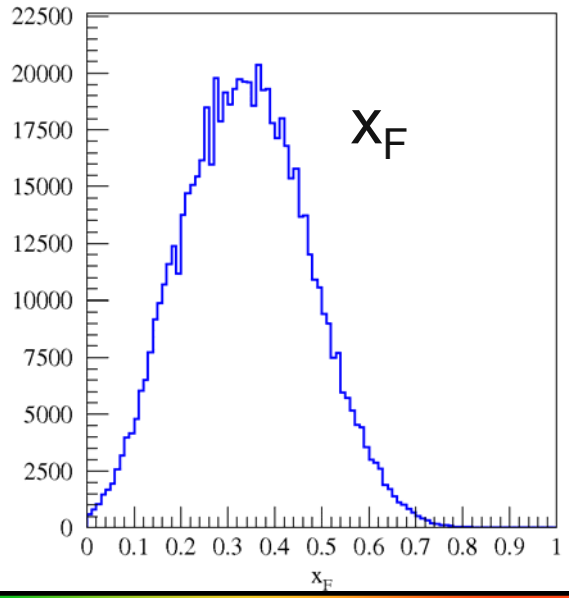
- Programmable trigger removes likely J/ψ events
- Transverse momentum acceptance to above 2 GeV
- Spectrometer could also be used for J/ψ, ψ′ studies



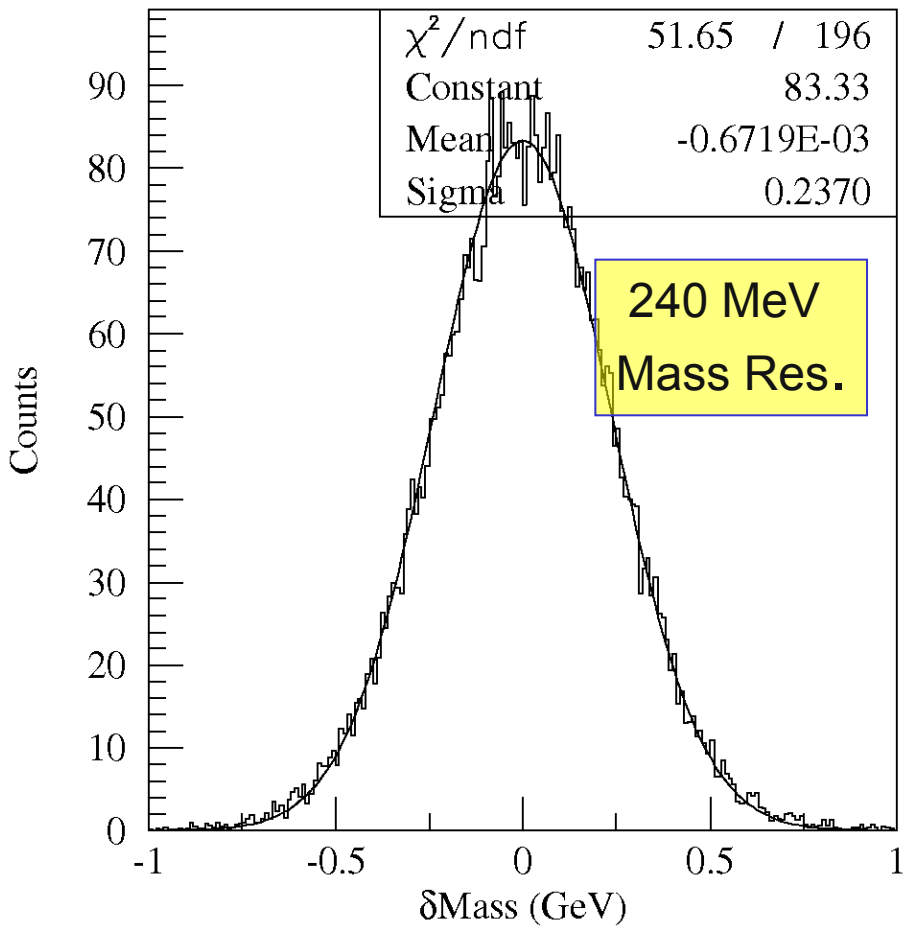


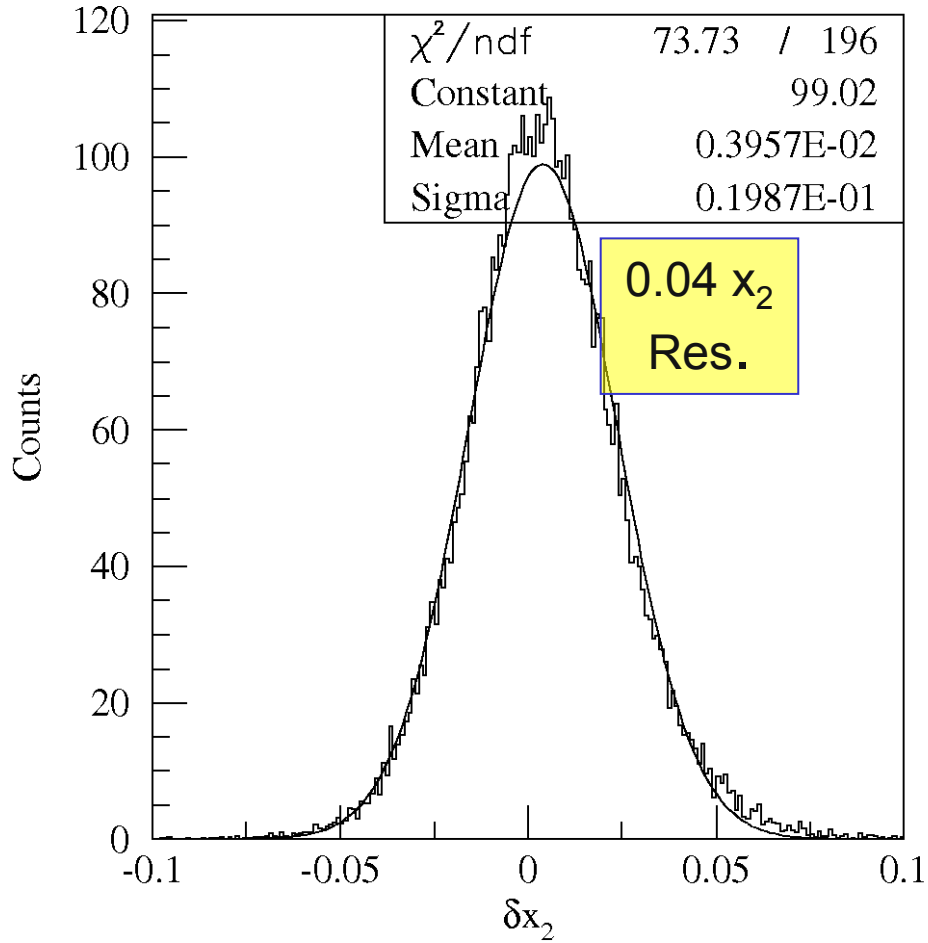






Detector Resolution





- Triggered Drell-Yan events

Fermilab E906/Drell-Yan Collaboration

Abilene Christian University
Donald Isenhower, Mike Sadler, Rusty Towell

Institute of Physics, Academia Sinica
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John Arrington, Don Geesaman*, Kawtar Hafidi, Roy Holt, Harold Jackson, David Potterveld, Paul E. Reimer*, Patricia Solvignon

University of Colorado
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*Co-Spokespersons

Institutions under negotiation

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Kyoto

KenIchi Imai, Tomofumi Nagae

RIKEN

Yuji Goto, Atsushi Taketani, Yoshinori Fukao, Manabu Togawa

Tokyo Tech

Toshi-Aki Shibata, Yoshiyuki Miyachi

People with underline are included also in P04 and/or P24 at J-PARC.

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Ting-Hua Chang

Los Alamos National Laboratory
Gerry Garvey, Mike Leitch, Pat McGaughey, Joel Moss

Maryland
Betsy Beise

Rutgers University
Ron Gilman, Charles Glashausser, Xiaodong Jiang, Elena Kuchina, Ron Ransome, Elaine Schulte

Texas A & M University
Carl Gagliardi, Robert Tribble

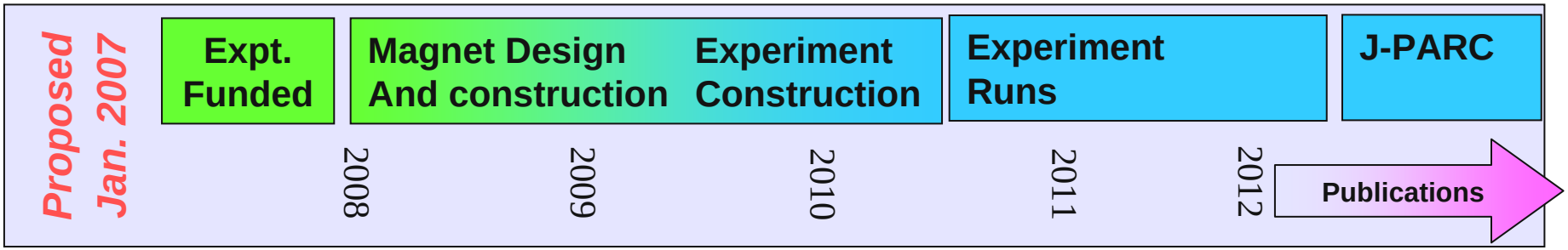
Thomas Jefferson National Accelerator Facility
Dave Gaskell

Valparaiso University
Don Koetke, Jason Webb

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



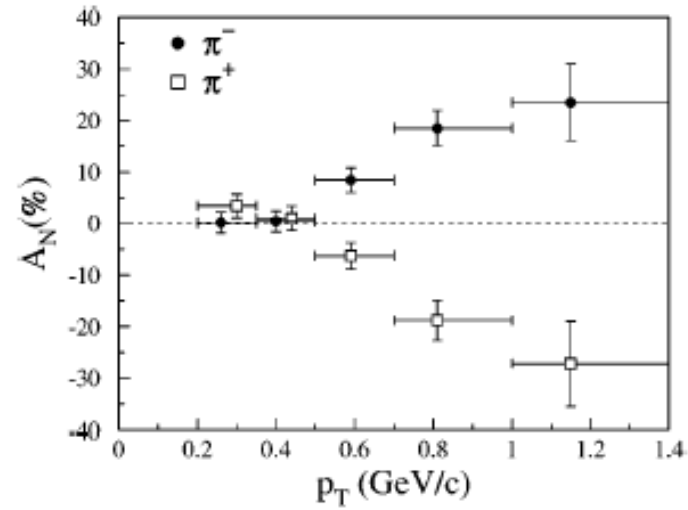
Other Possibilities: Transversely Polarized Target

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

- Single spin asymmetry

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

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



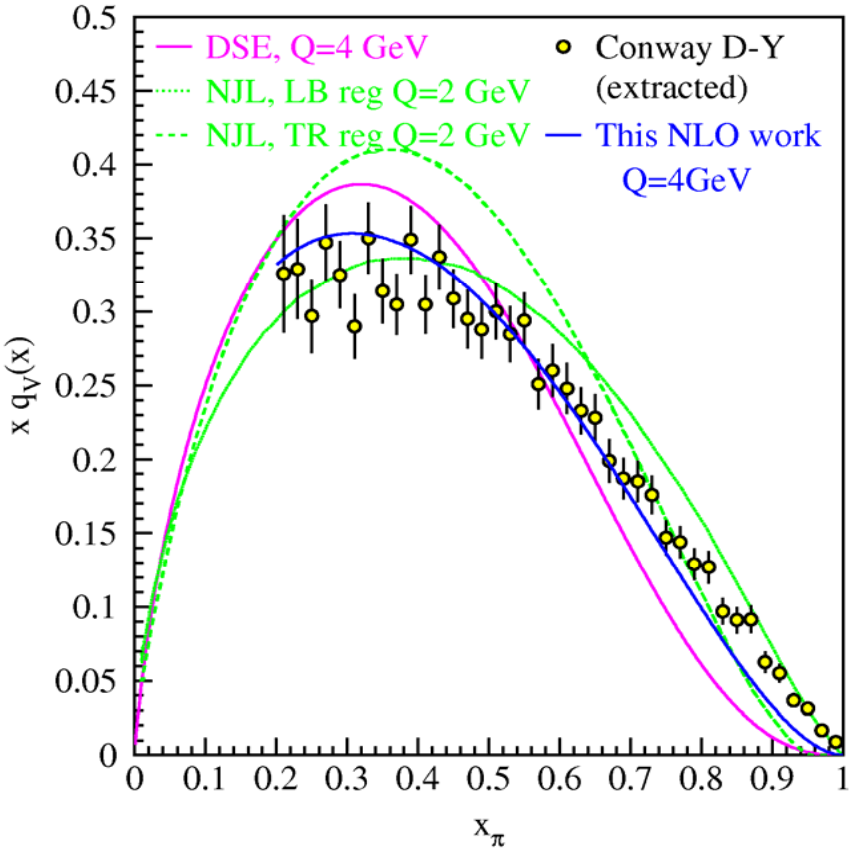
Fermilab E704, Phys. Rev. Lett. **77**, 2626 (1996)

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.

- 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????

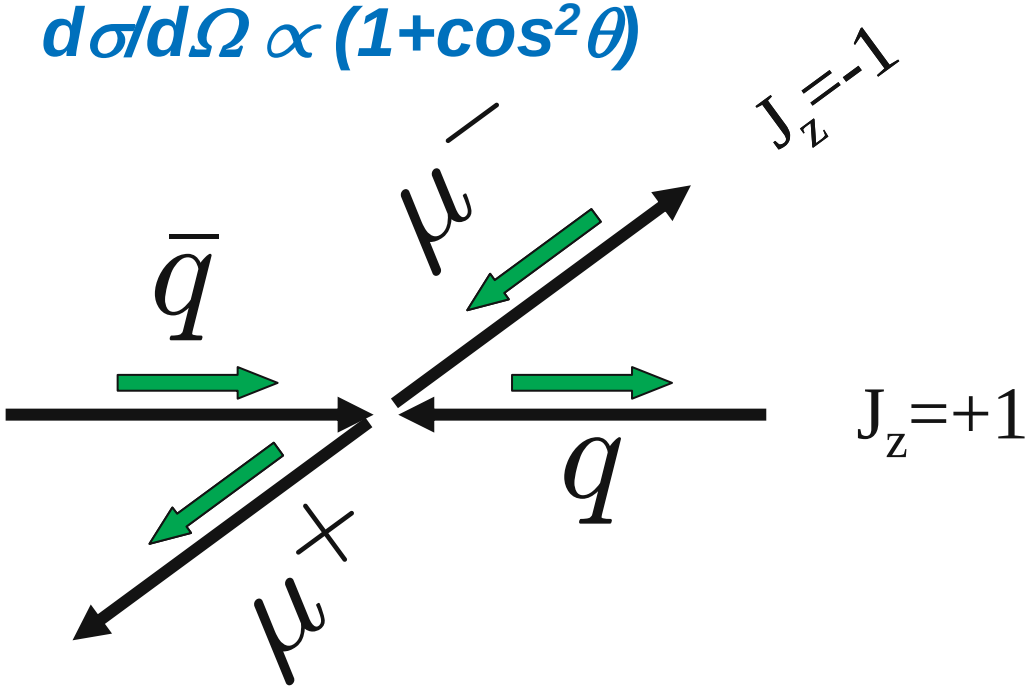
Other Possibilities: Pionic Drell-Yan

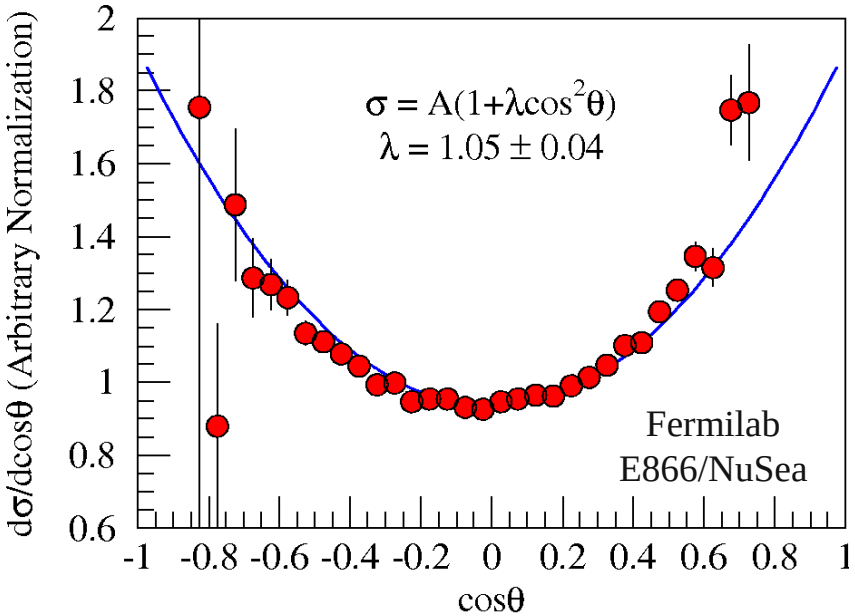
- High-x pionic parton distributions
  - High-x from of $(1-x)^{\alpha}$
  - Specific predictions for α from Dyson-Schwinger, pQCD and Nambu-Jona-Lasinio models
  - Data fall between predictions, but may have poor x_{π} resolution and other systematic effects



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

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





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

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

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

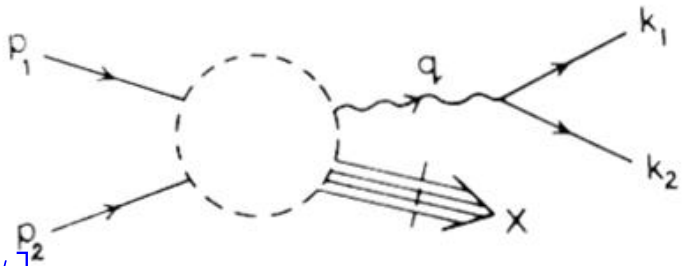
$$d^1_{-11} = d^1_{1-1} = \tfrac{1}{2}\left(1-\cos\theta\right)$$

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)

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



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

  Direct analogy to the Callan-Gross relation in DIS

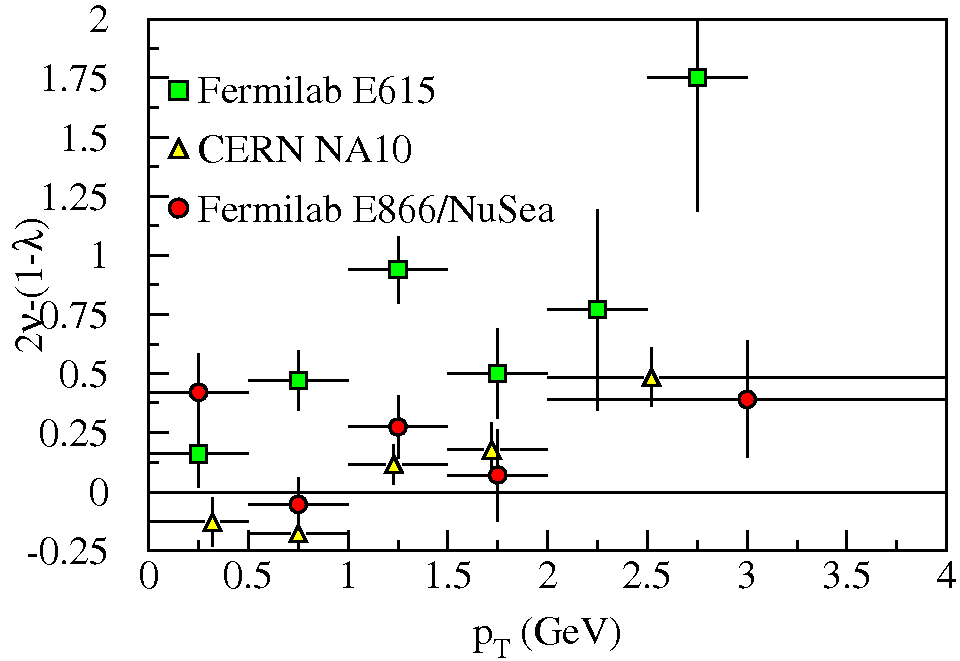
  Normally written as $1 - \lambda = 2\nu$

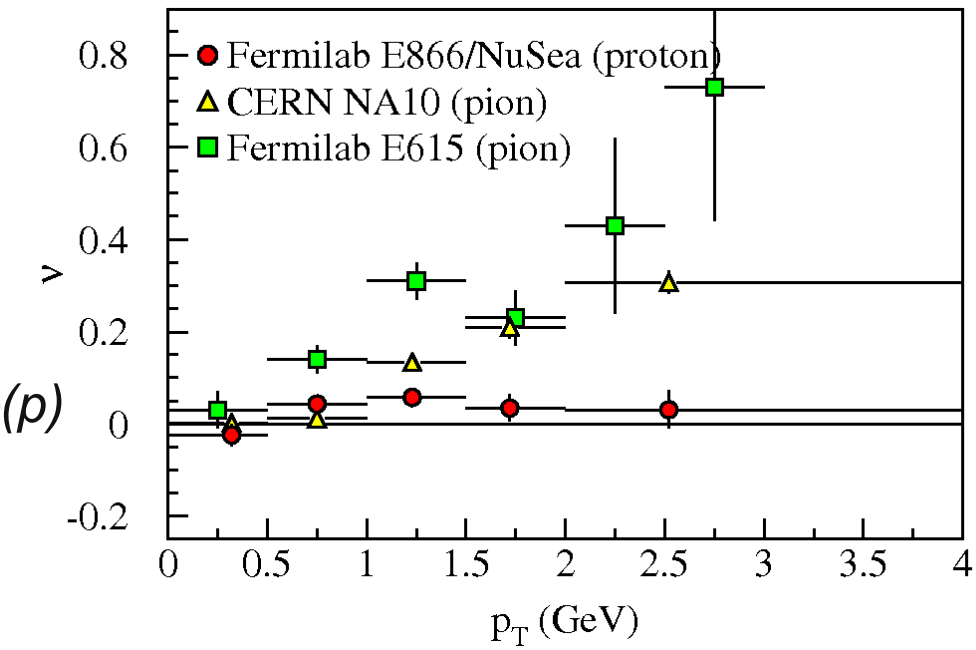
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

- 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

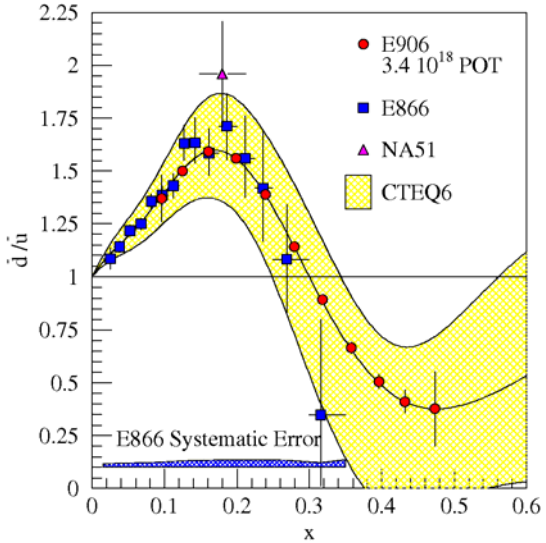
- π^- Drell-Yan
  - Violates L-T relation
  - Large ν ($\cos 2\phi$) dependence
  - Strong with p_T
- Proton Drell-Yan
  - **Consistent** with L-T relation
  - **No** ν ($\cos 2\phi$) dependence
  - **No** p_T dependence
- With Boer-Mulders function $h1^{\perp}$:
  - $\nu(\pi\text{-}W \rightarrow \mu+\mu\text{-}X)$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

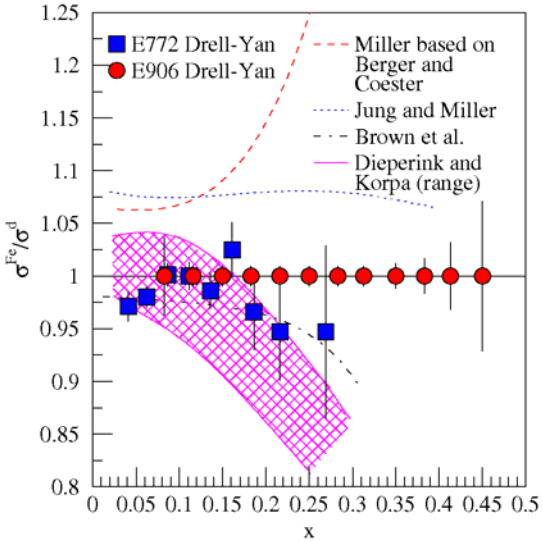




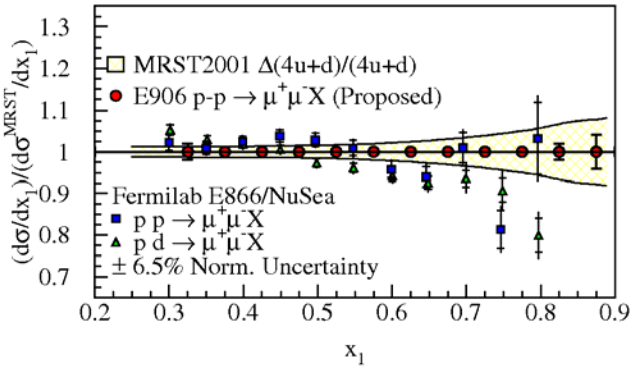
Drell-Yan at Fermilab

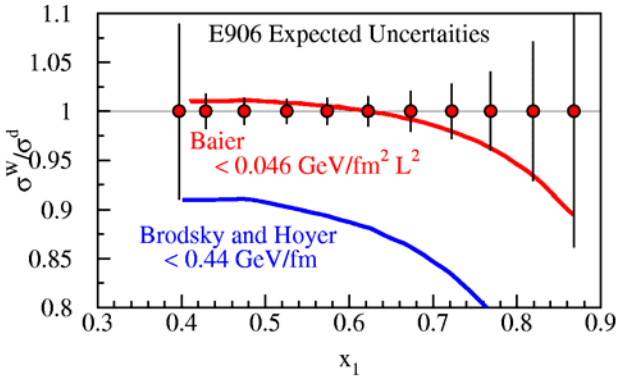
- **What is the structure of the nucleon?**
  - What is d-bar/u-bar?
  - What are the origins of the sea quarks?
  - What is the high-x structure of the proton?





- **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

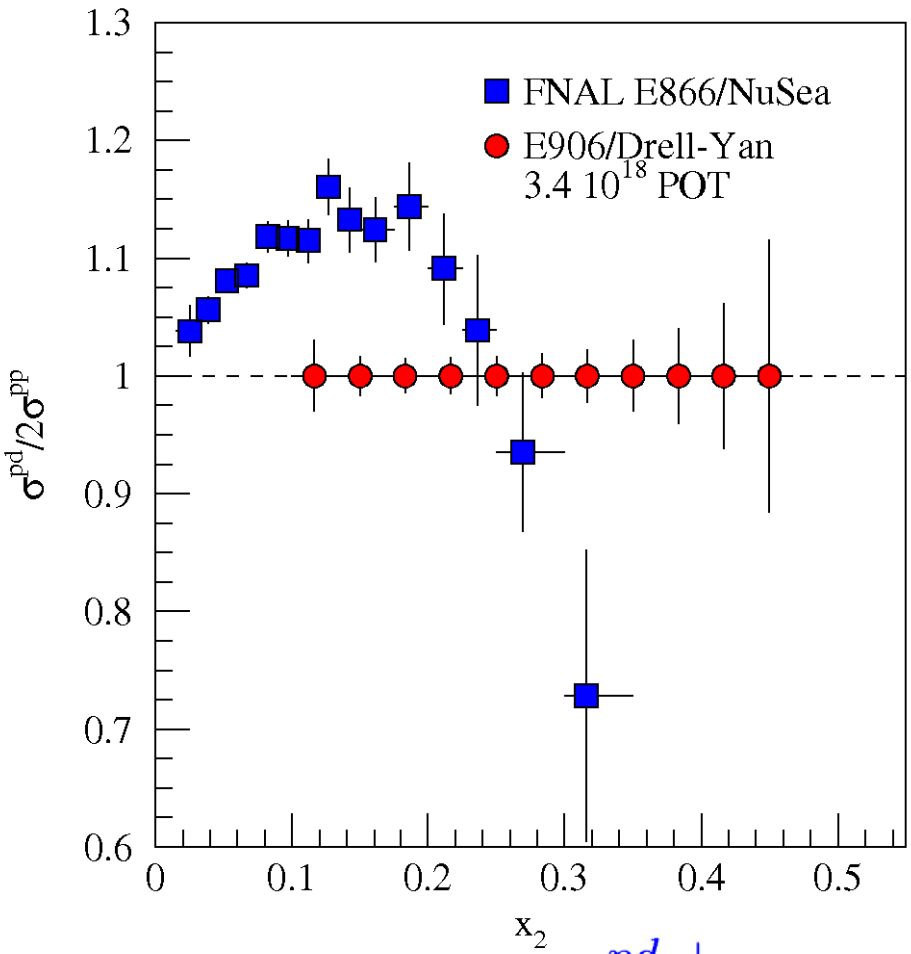


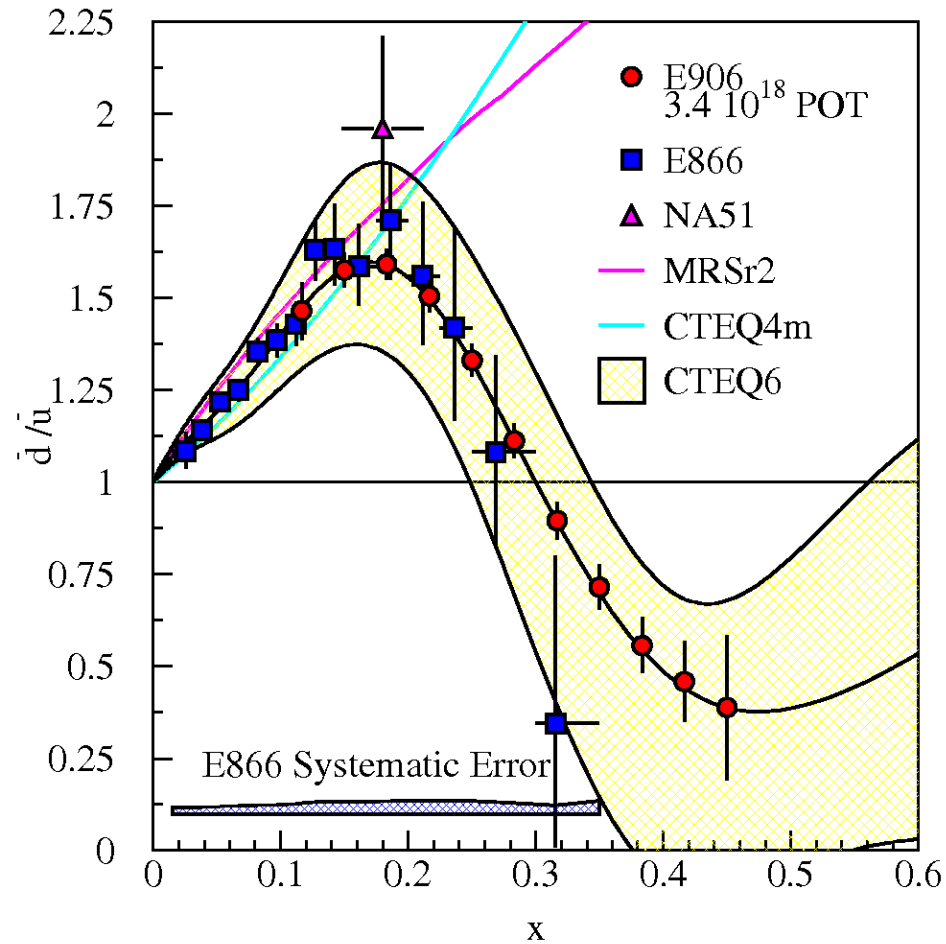


- **Future possibilities at J-PARC**

Additional Material

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





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

Proton Economics

- Total of 5.2×10^{18} protons (over 2 years)

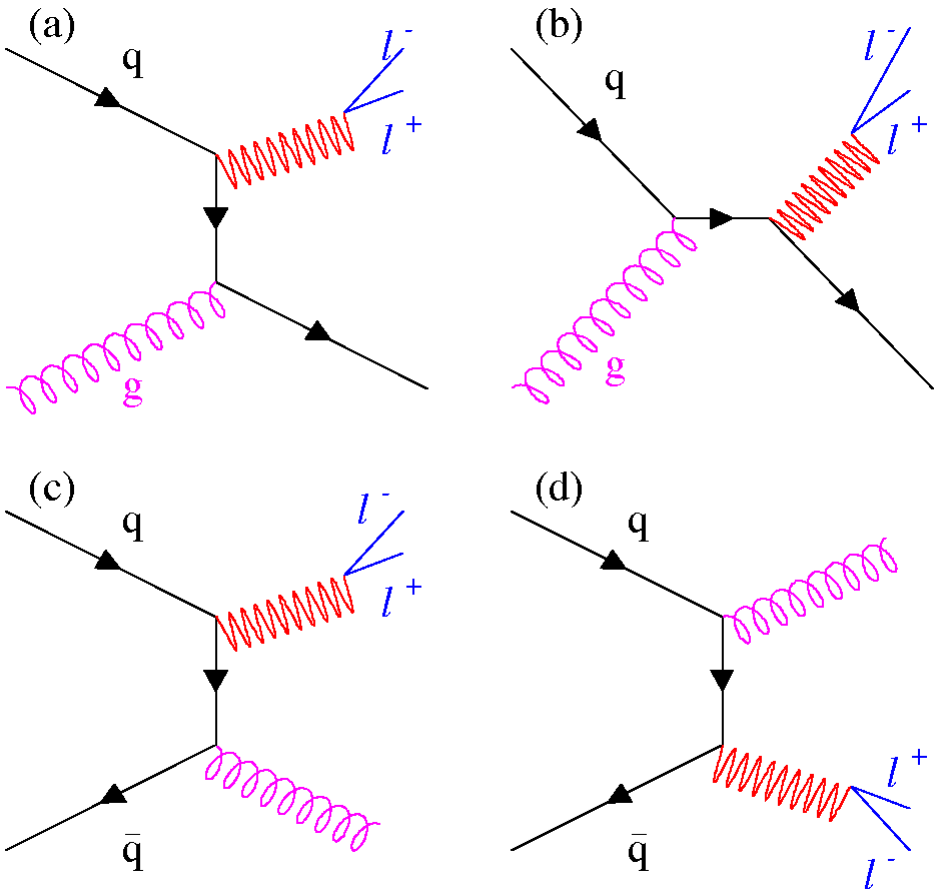
- Maximum instantaneous rate of 2×10^{12} proton/sec
  - Based on E866 experience with target related rate dependence—balance systematic and statistical uncertainties
  - Station 1 chamber rates.

- Possible delivery scenario:
  - 5 sec spill of 1×10^{13} protons each minute
  - Longer spill (5 sec) desirable over 5-1 sec spills

Detector Rates

	LH_2 Target		$LD2$ Target		Copper Beam Dump	
	μ's	Trks.	μ's	Trks.	μ's	Trks.
π^+ decay-in-flight	81 k	12 k	195 k	29 k	153 k	13 k
π^- decay-in-flight	35 k	8 k	84 k	20 k	76 k	20 k
K^+ decay-in-flight	63 k	13 k	151 k	31 k	139 k	20 k
K^- decay-in-flight	6 k	3 k	15 k	6 k	18 k	8 k
Total μ^+	144 k	25 k	346 k	60 k	292 k	33 k
Total μ^-	41 k	11 k	99 k	26 k	94 k	28 k

Expected single muon rates per 2×10^{12} protons from decay-in-flight mesons which pass through the detector (μ's) and satisfy trigger matrix tracking requirements (Trks.) from liquid hydrogen and deuterium targets and the copper beam dump.

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, $\lambda > 0.8$)