Opportunities with Drell-Yan Scattering at Fermilab

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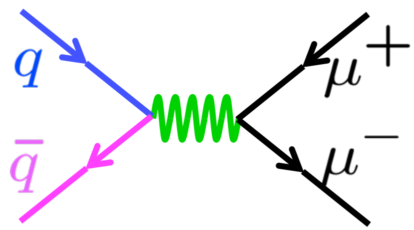
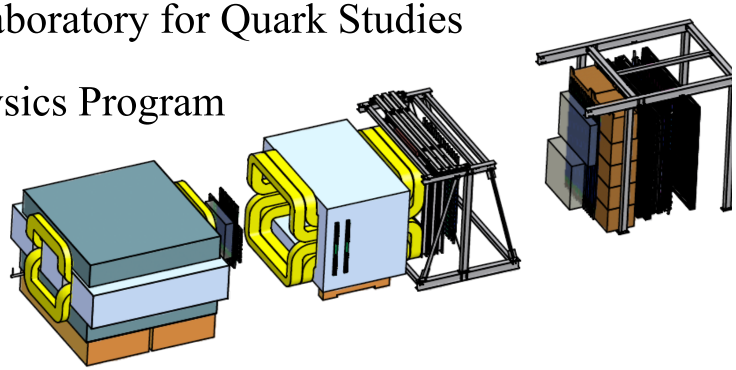
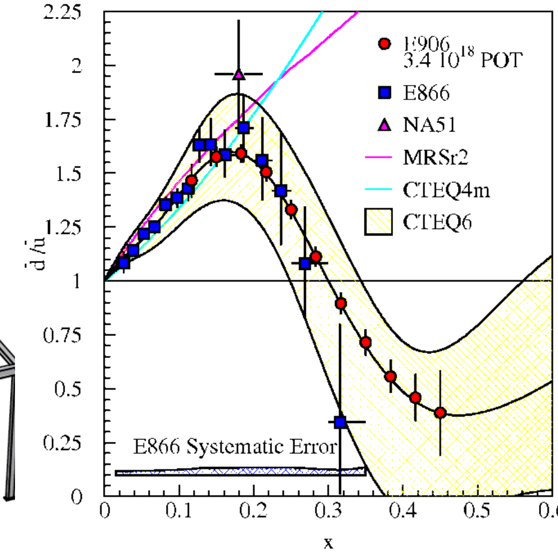
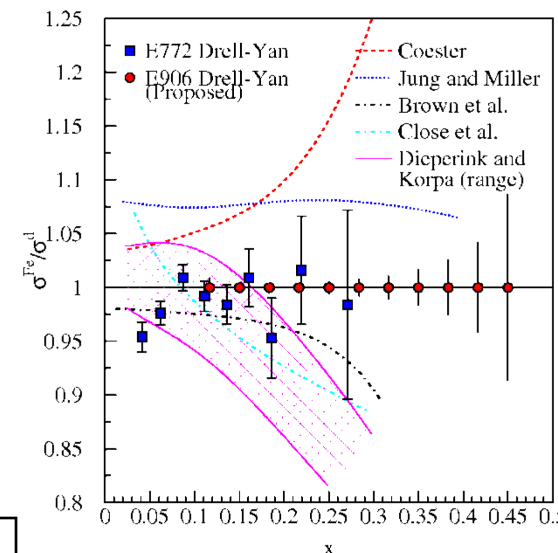


1. The Drell-Yan Process—A Laboratory for Quark Studies
2. Fermilab E-906/SeaQuest Physics Program
   - Sea quark in the proton
   - Sea quarks in the nucleus
   - Angular distributions
3. What can the future hold? Polarized targets or beams?







$$f_{1T}^{\perp}(x,k_T)\big|_{DIS} = -\, f_{1T}^{\perp}(x,k_T)\big|_{DY}$$


HERMES
U. Elschenbroich

With help from Chiranjib Dutta, Wolfgang Lorenzon, U. Michigan and Yuji Goto, RIKEN

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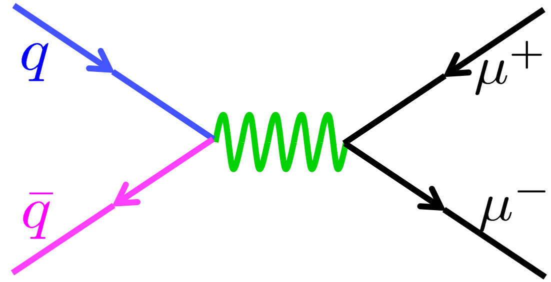
U.S. DEPARTMENT OF ENERGY

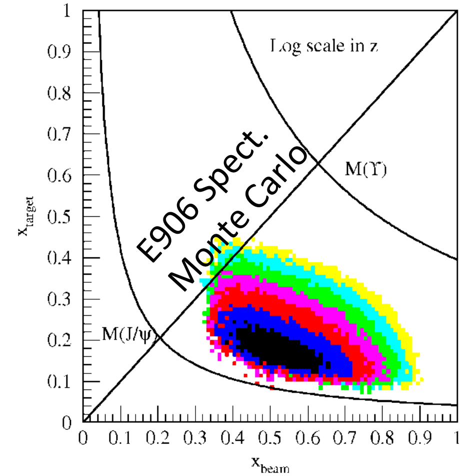
Drell-Yan cross section (what we all know already)



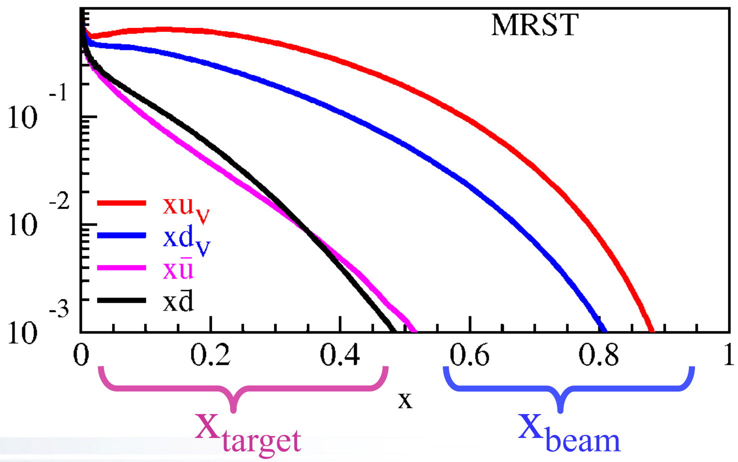
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

- Fixed target—detector acceptance chooses large x_b and small x_t
  - (or to a lesser extent single arm collider experiment)
- Don't forget quark charge

$$e_u^2 = 4e_d^2$$

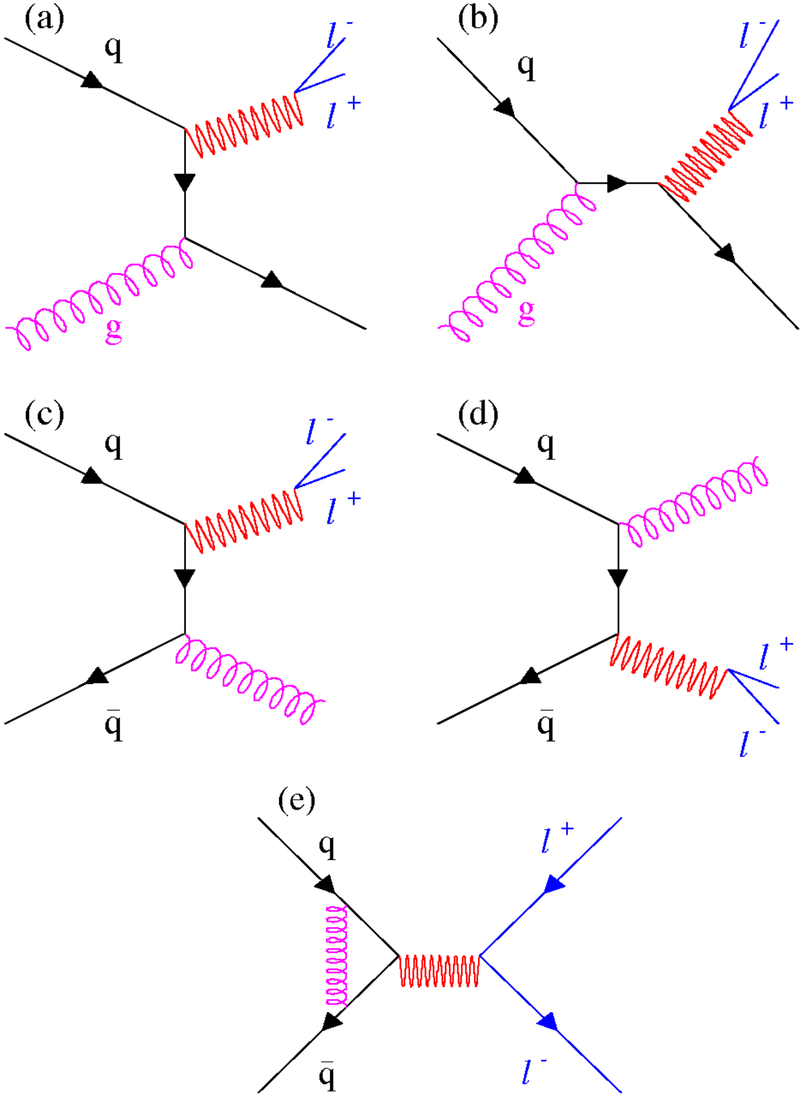


Beam	Target	
Hadron	Beam valence quarks target antiquarks	Fermilab E-906, RHIC (forward acpt.) J-PARC
Anti-Hadron	Beam valence antiquarks Target valence quarks	GSI-FAIR Fermilab Collider
Meson	Beam valence antiquarks Target valence quarks	COMPASS

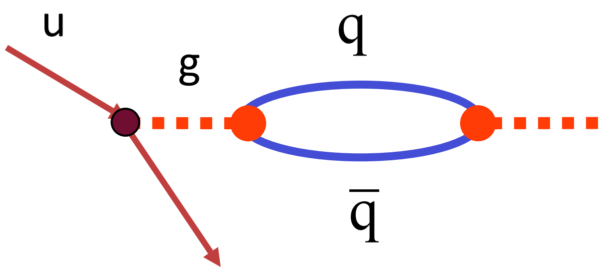


Next-to-Leading Order Drell-Yan

- 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, $\lambda > 0.8$)
- Actual data analysis used full Next-to-Leading Order calculation



Generation of the Proton's sea



- Constituent Quark/Bag Model motivated valence approach

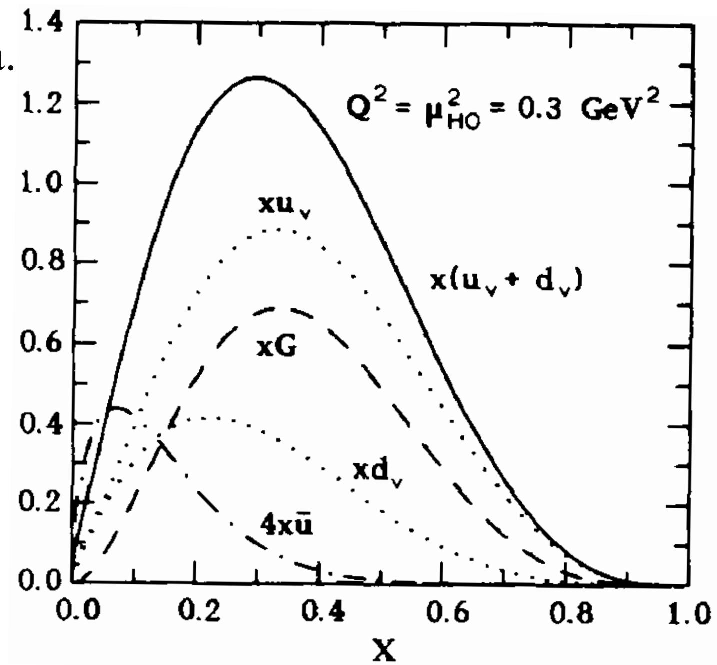
  Gluck, Godbole, Reya, ZPC **41** 667 (1989)

  – Use valence quark distributions at some very low energy scale Q^2
  – Radiatively generate sea and glue

- Quickly realized need for valence-like (primordial) sea.

  Gluck, Reya, Vogt, ZPC 53, 127 (1992)

  – Driven by need to agree with BCDMS and EMC data
  – Assumption of $\bar{d}(x) \equiv \bar{u}(x)$ remained



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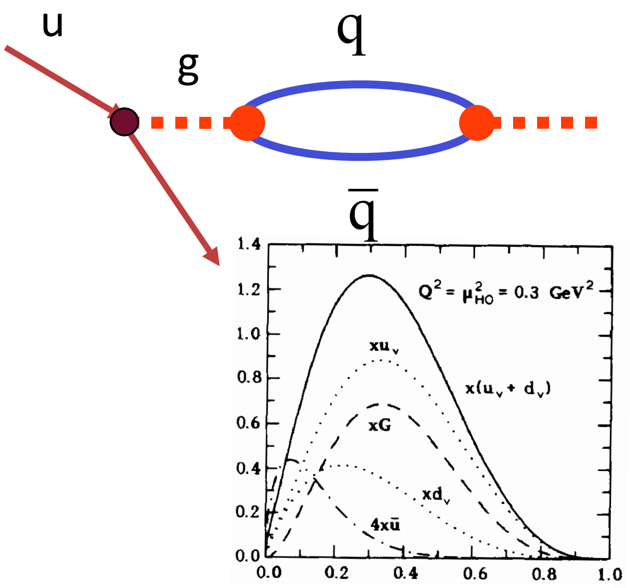
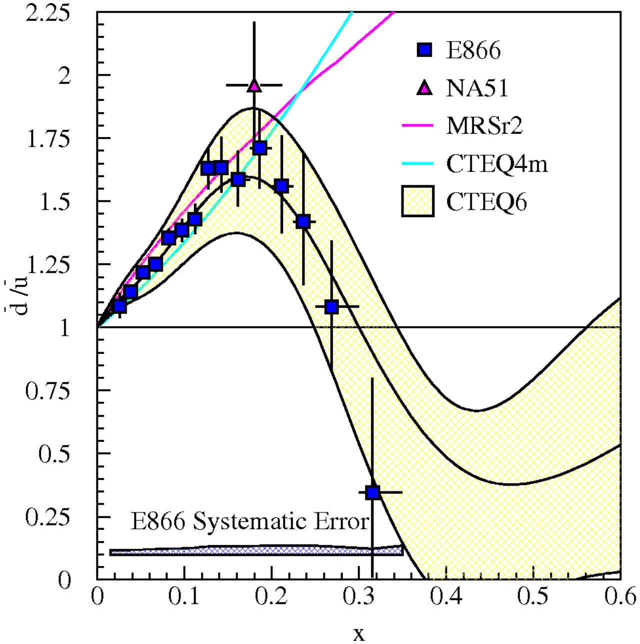
  – Driven by need to agree with BCDMS and EMC data
  – Assumption of $\bar{d}(x) \equiv \bar{u}(x)$ remained
- NMC (Gottfried Sum Rule)

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

- CERN NA51 and Fermilab E-866/NuSea
  – Drell-Yan Scattering on hydrogen and deuterium



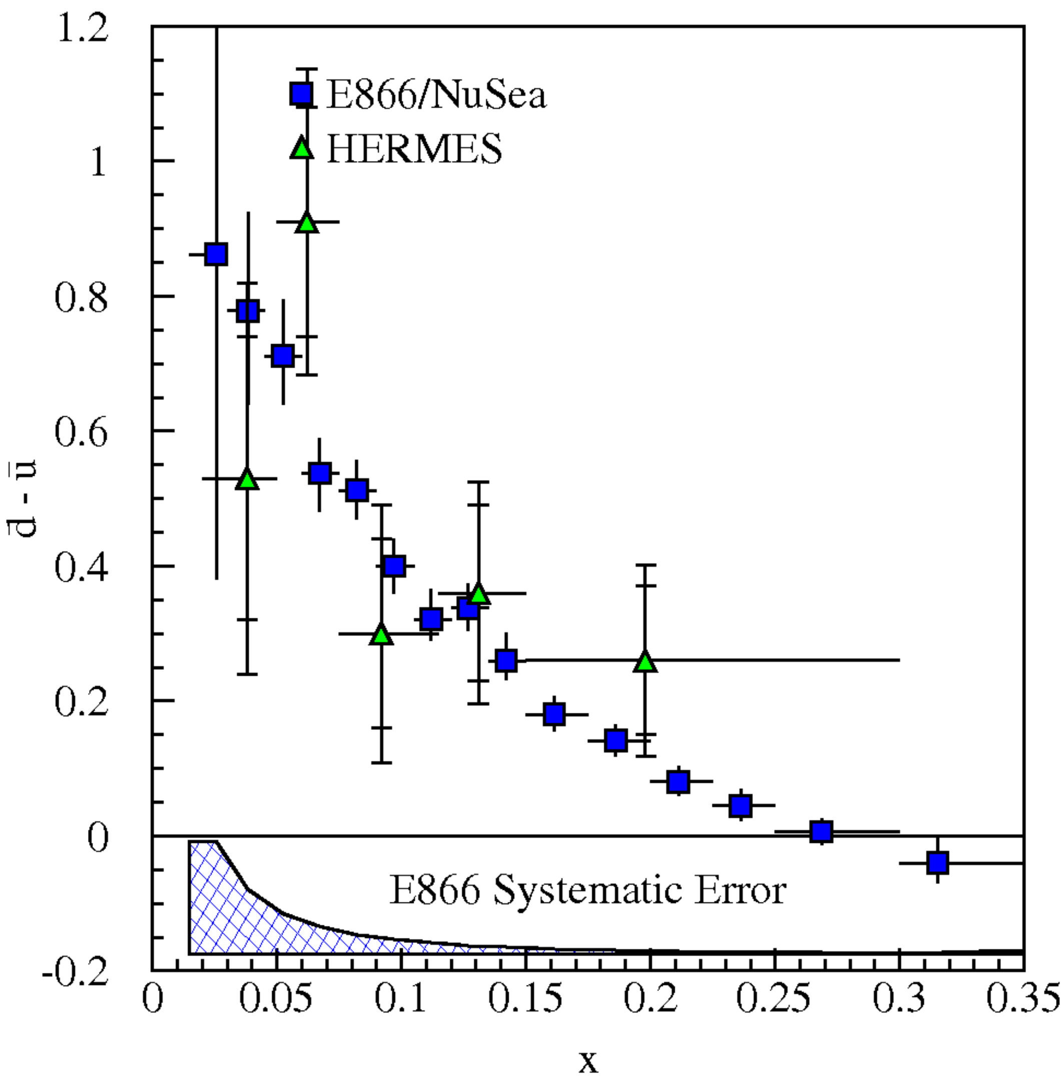


Proton Structure: By What Process Is the Sea Created?

- There is a gluon splitting component which is symmetric

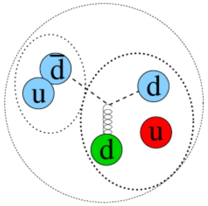
$$\bar{d}_{\text{split}}(x) = \bar{u}_{\text{split}}(x) = \bar{q}_{\text{split}}(x)$$

- $\bar{d}(x) - \bar{u}(x)$
  - Symmetric sea via pair production from gluons subtracts away
  - 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



$$|p\rangle = (1 - a - b)\,|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + \ldots$$

- Chiral Quark models—effective Lagrangians

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

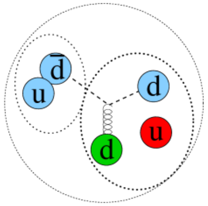
- Instantons

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

- Statistical Parton Distributions

Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS



$$|p\rangle = (1 - a - b)\,|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + \ldots$$

Antiquarks in spin 0 object ⟶ No net spin

- Chiral Quark models—effective Lagrangians

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

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

- Instantons

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

- Statistical Parton Distributions

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

Proton Structure: By What Process Is the Sea Created?

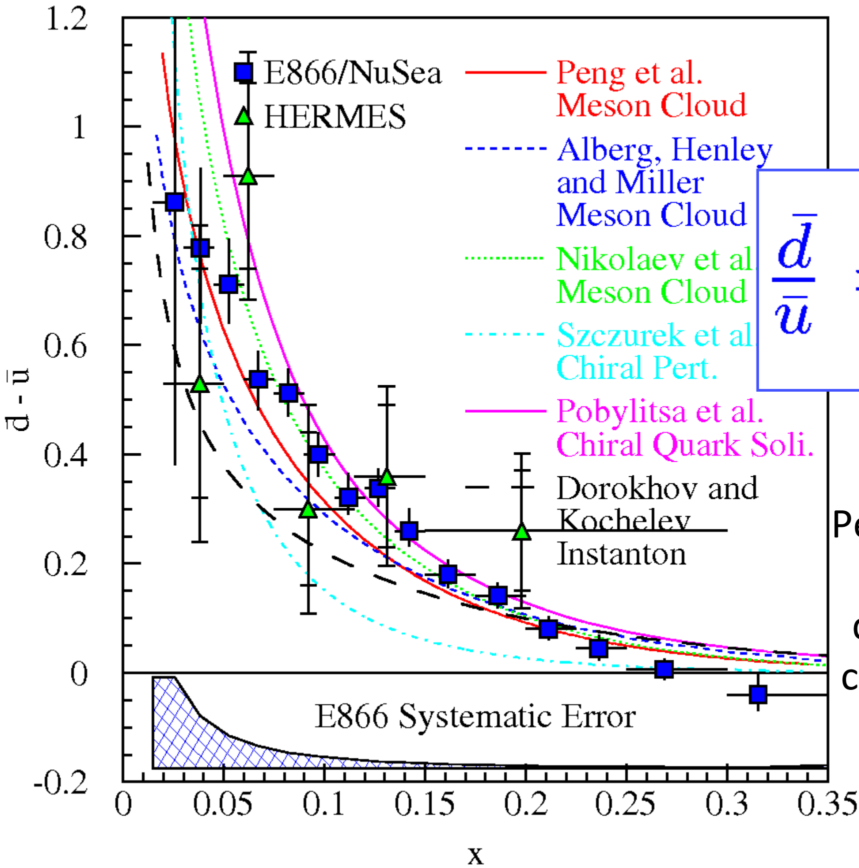
- Meson Cloud in the nucleon

  Sullivan process in DIS

  |p> = |p> + α |Nπ> + β|Δπ> + . . .

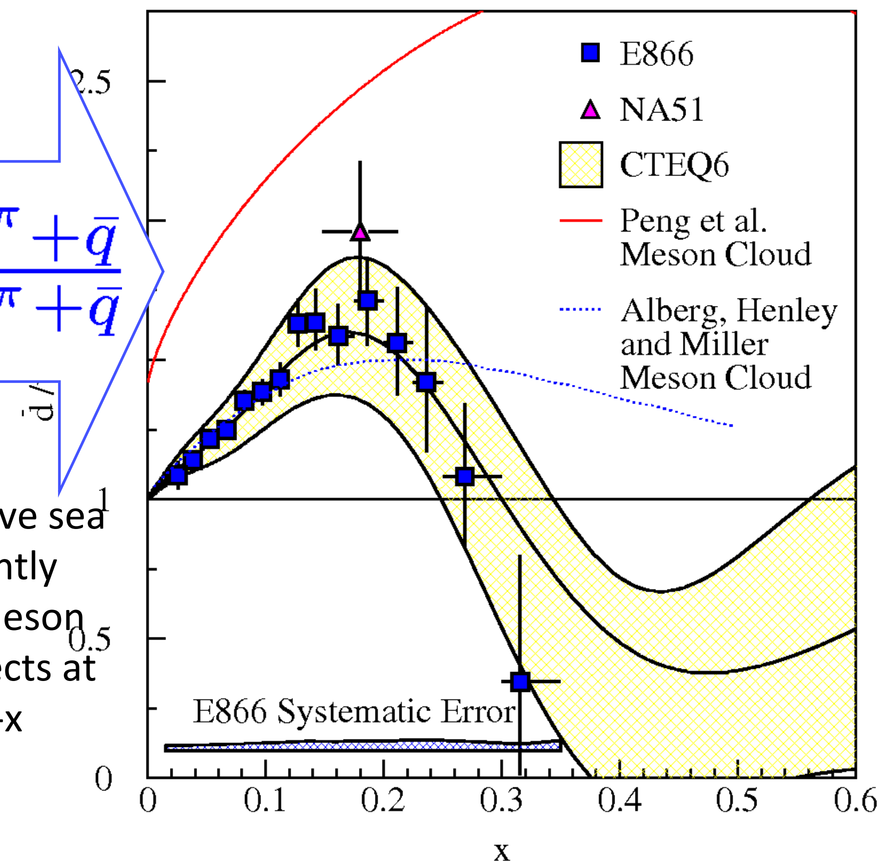
- Chiral Models

  Interaction between Goldstone Bosons and valence quarks



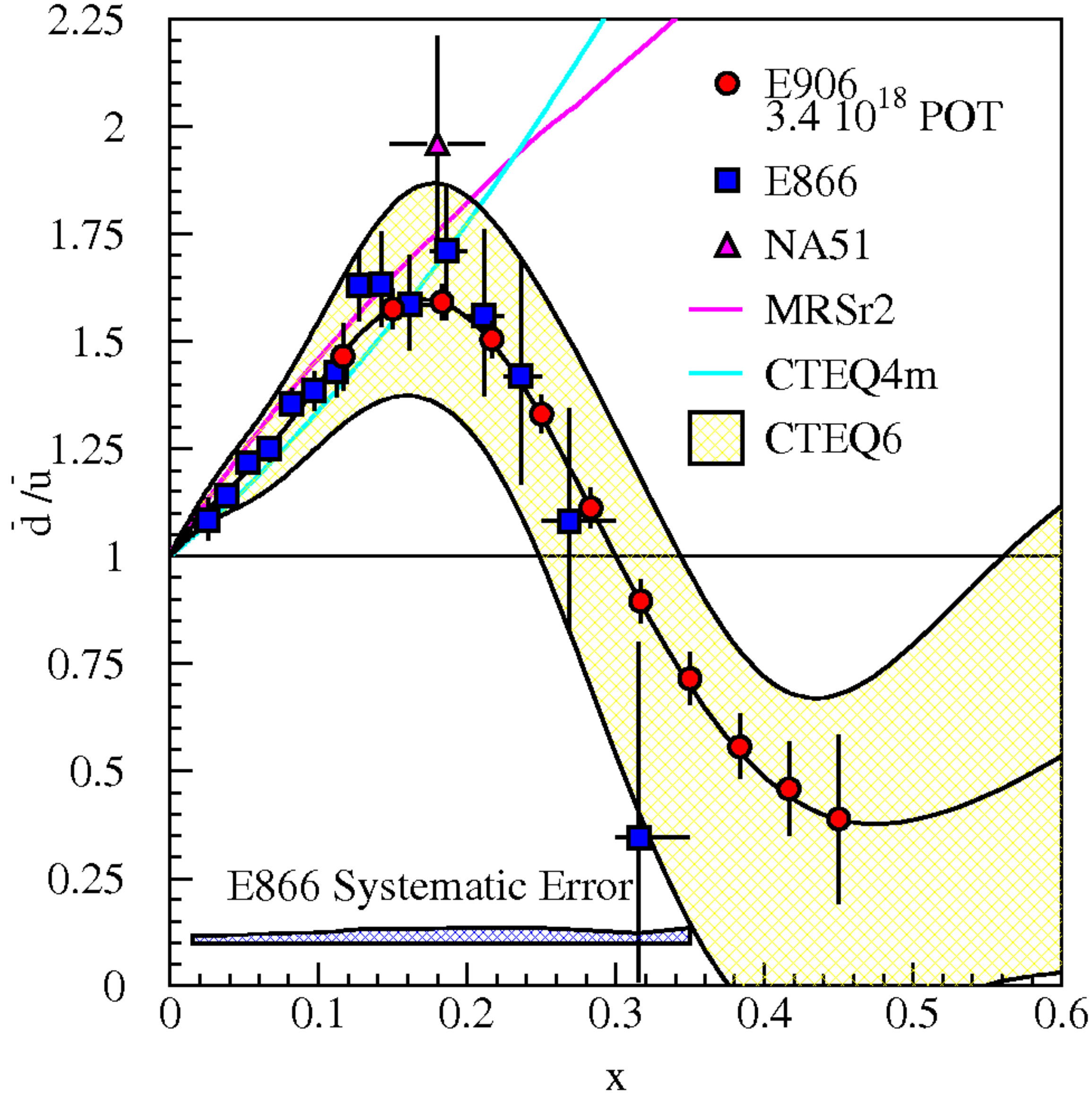
$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$

Perturbative sea apparently dilutes meson cloud effects at large-x



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

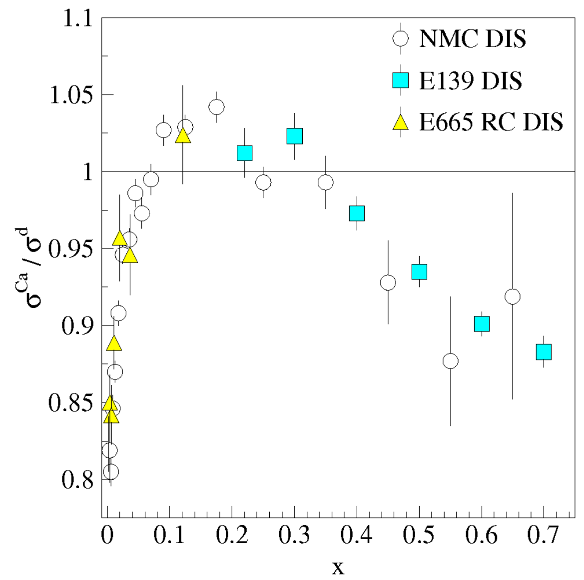
- E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.

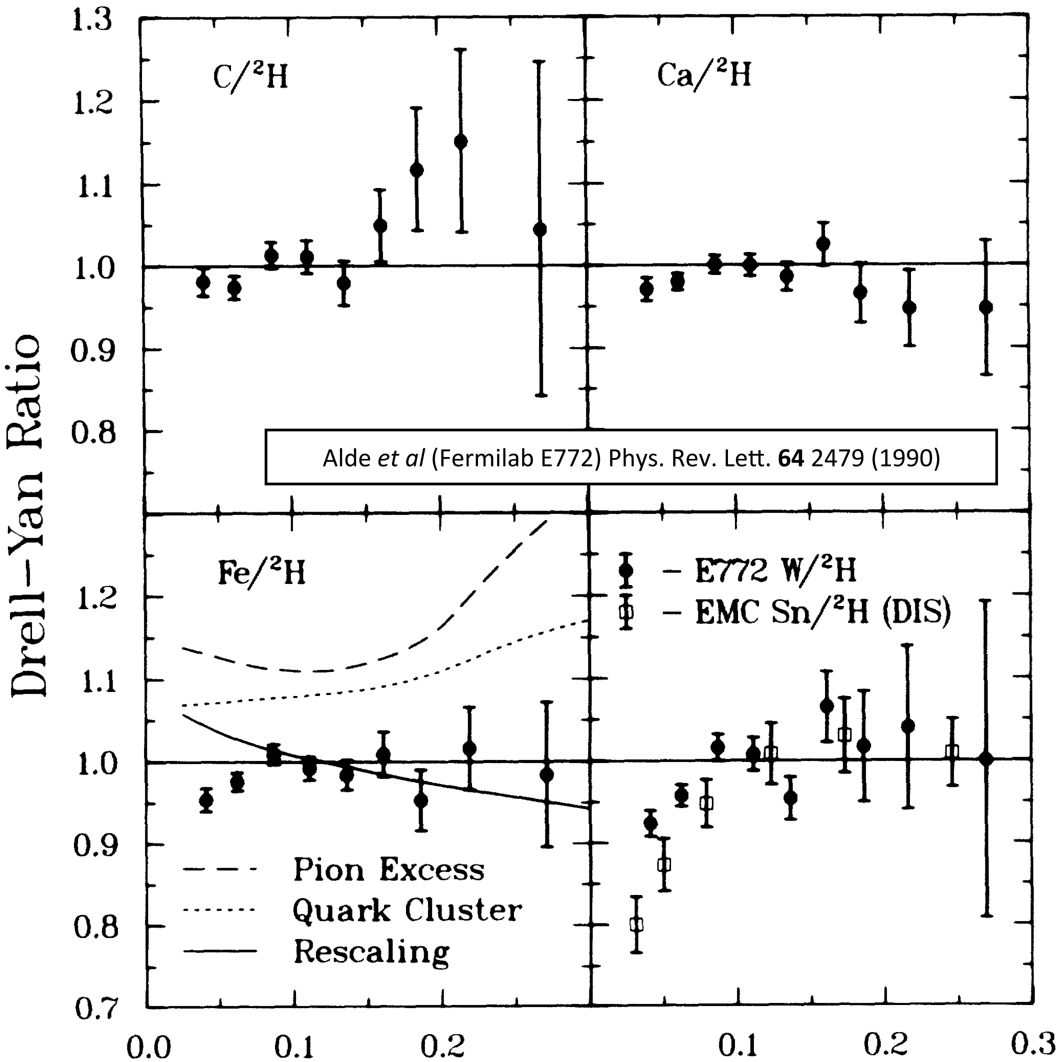


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Comparison with
Deep Inelastic Scattering (DIS)

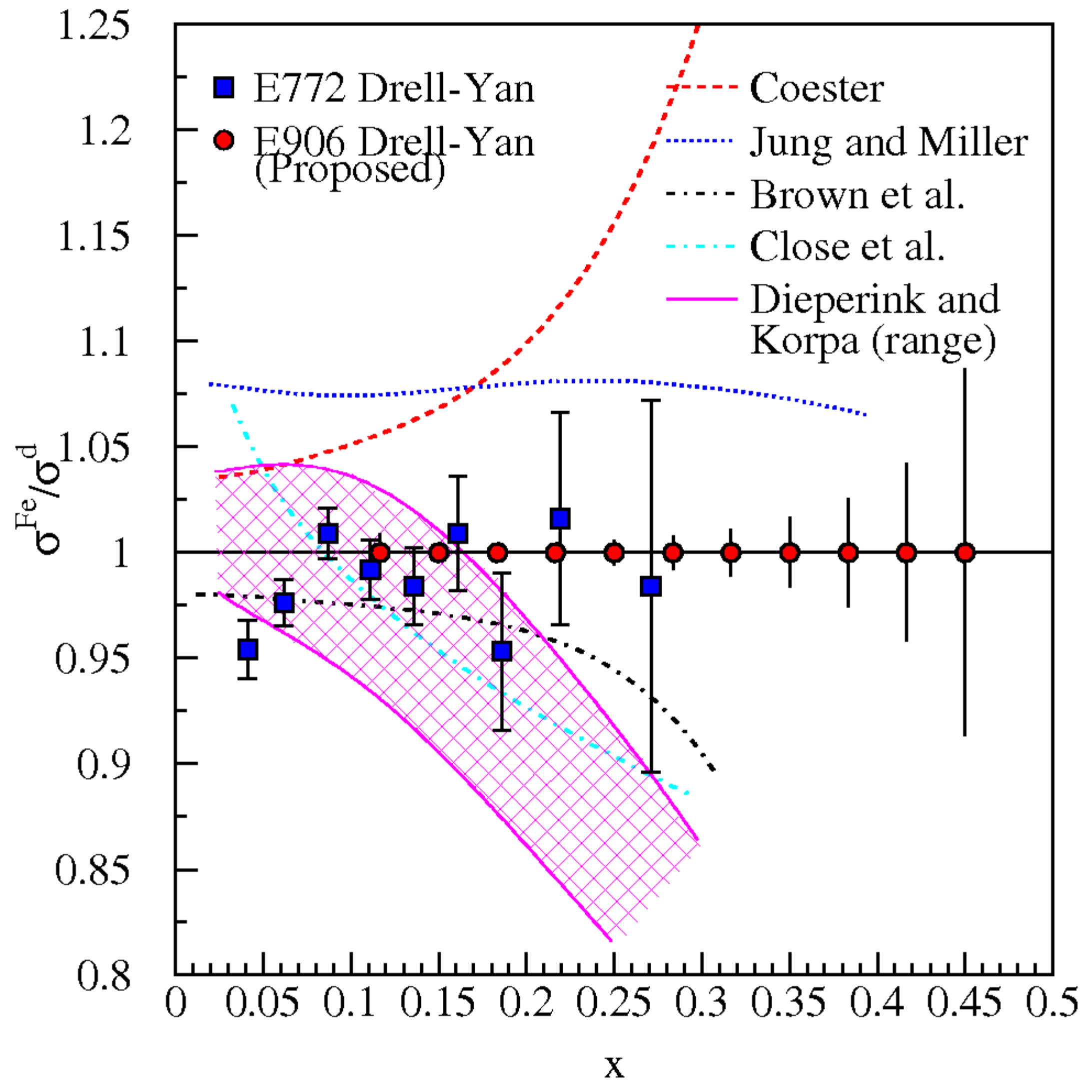
- EMC: Parton distributions of bound and free nucleons are different.
- Antishadowing not seen in Drell-Yan—Valence only effect





Structure of nucleonic matter: 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



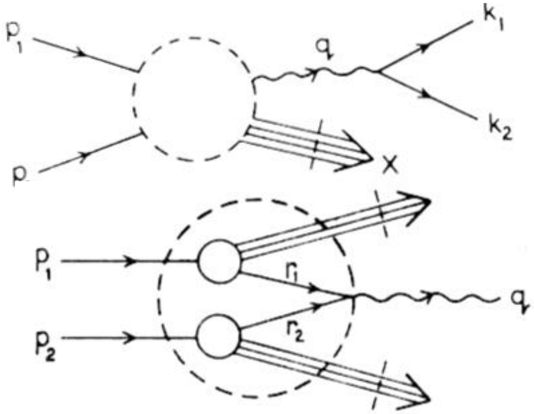
Generalized Angular Distributions & Lam Tung relation

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

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

Structure function formalism

- Derived in analogy to DIS
- Independent of Drell-Yan and parton "models"
- Showed same relations follow as a general consequence of the quark-parton model



Lam-Tung relation

- Derived in analogy to Colin-Gross relation of DIS
- Unaffected by $O(\alpha_s)$ (NLO) corrections
- NNLO $[O(\alpha_s^2)]$ corrections also small Mirkes and Ohnemus, PRD **51** 4891 (1995)

$$W_L = W_{\Delta\Delta}$$

Generalized Angular Distributions & Lam Tung relation

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

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

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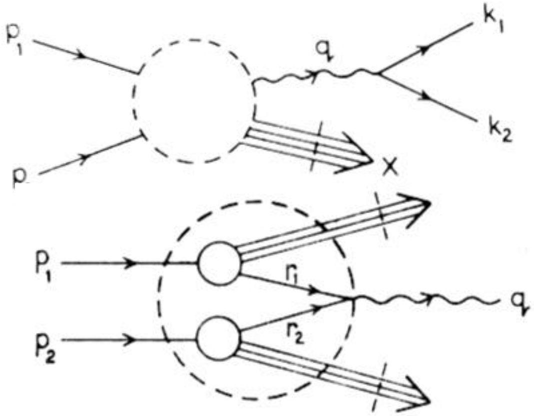

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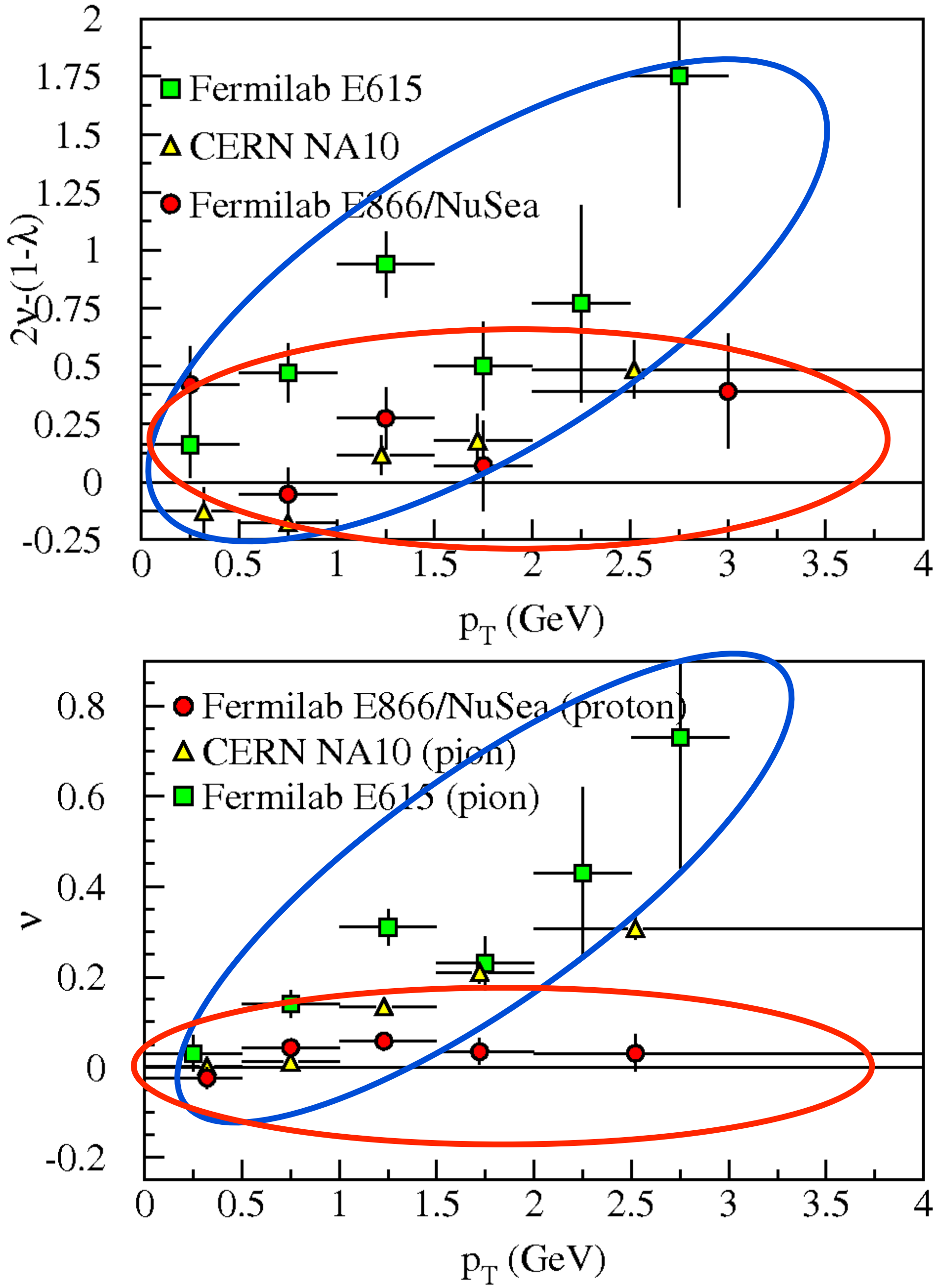
$$1 - \lambda = 2\nu$$

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



Lam-Tung Relation

- π^- Drell-Yan
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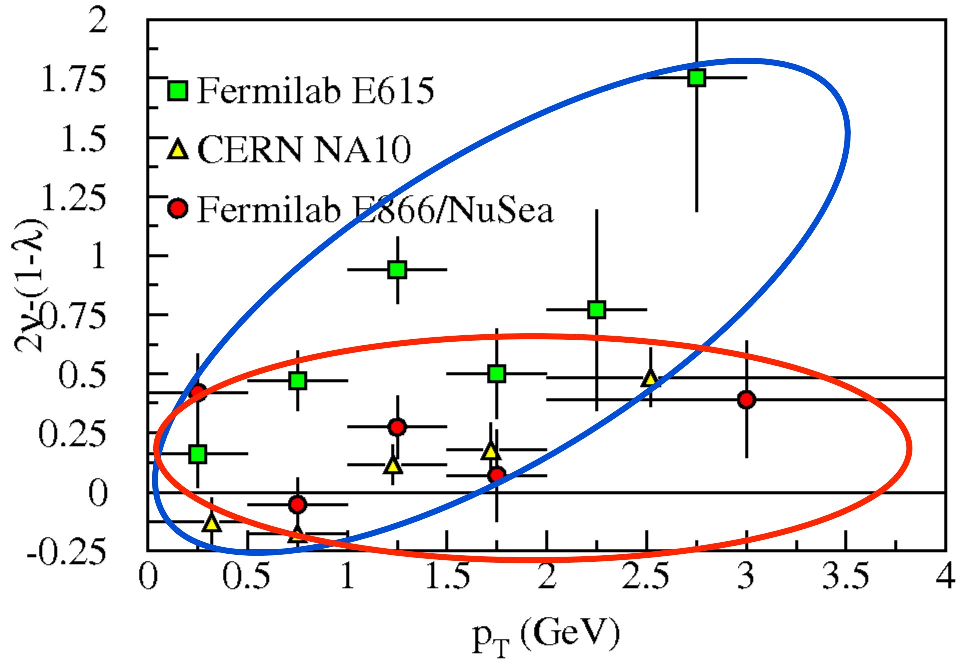
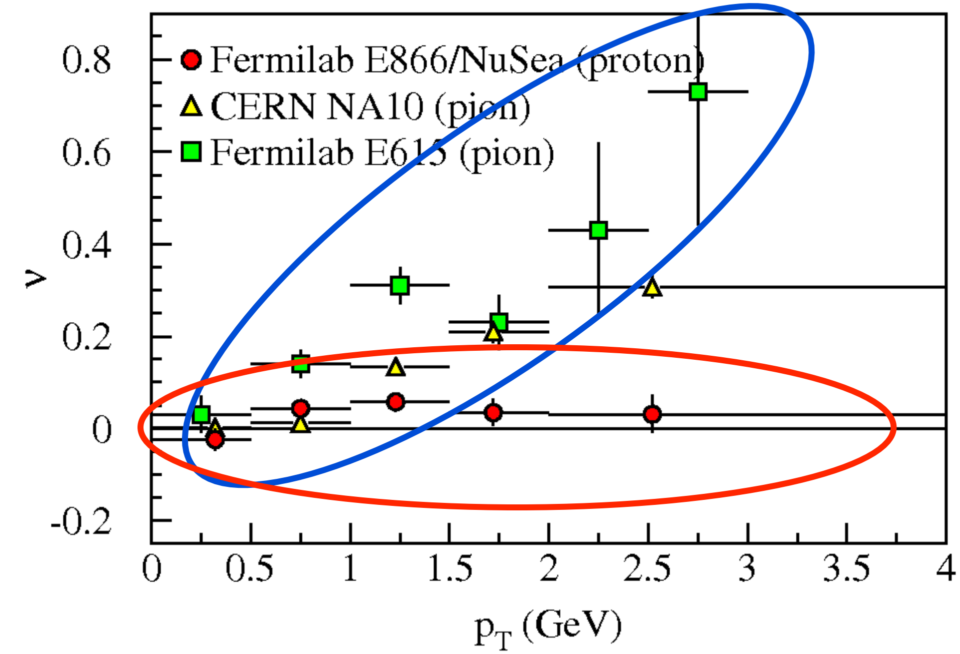
- Proton Drell-Yan
  - **Consistent** with L-T relation
  - **No** ν ($\cos 2\phi$) dependence
  - **No** p_T dependence
- With Boer-Mulders function $h_1^{\perp}$:
  - $\nu(\pi\text{-}W \rightarrow \mu^+\mu^- X)$

    valence $h_1^{\perp}(\pi)$ * *valence* $h_1^{\perp}(p)$
  - $\nu(pd \rightarrow \mu^+\mu^- X)$

    valence $h_1^{\perp}(p)$ * *sea* $h_1^{\perp}(p)$
- E-906/SeaQuest will have
  - Higher statistics
  - Poorer resolution





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:

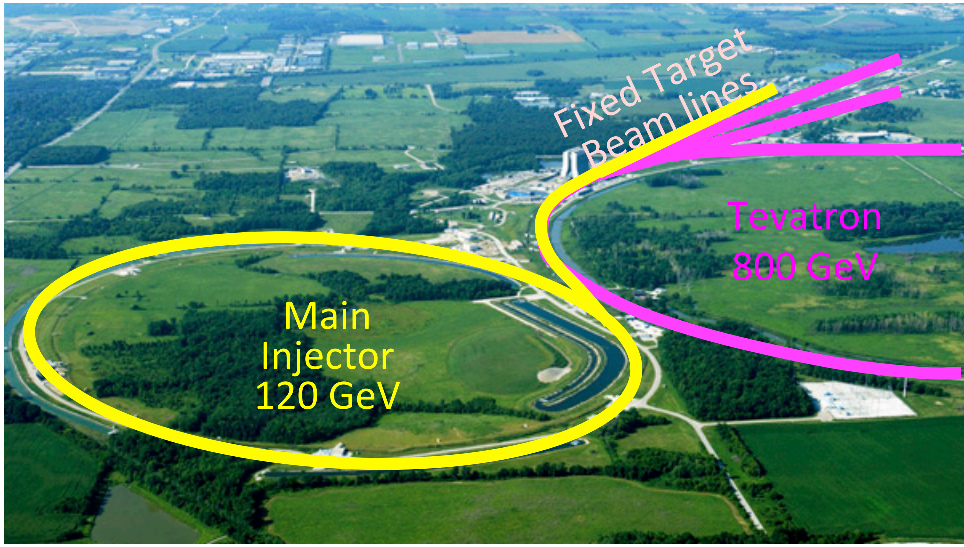
Fermilab E906

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

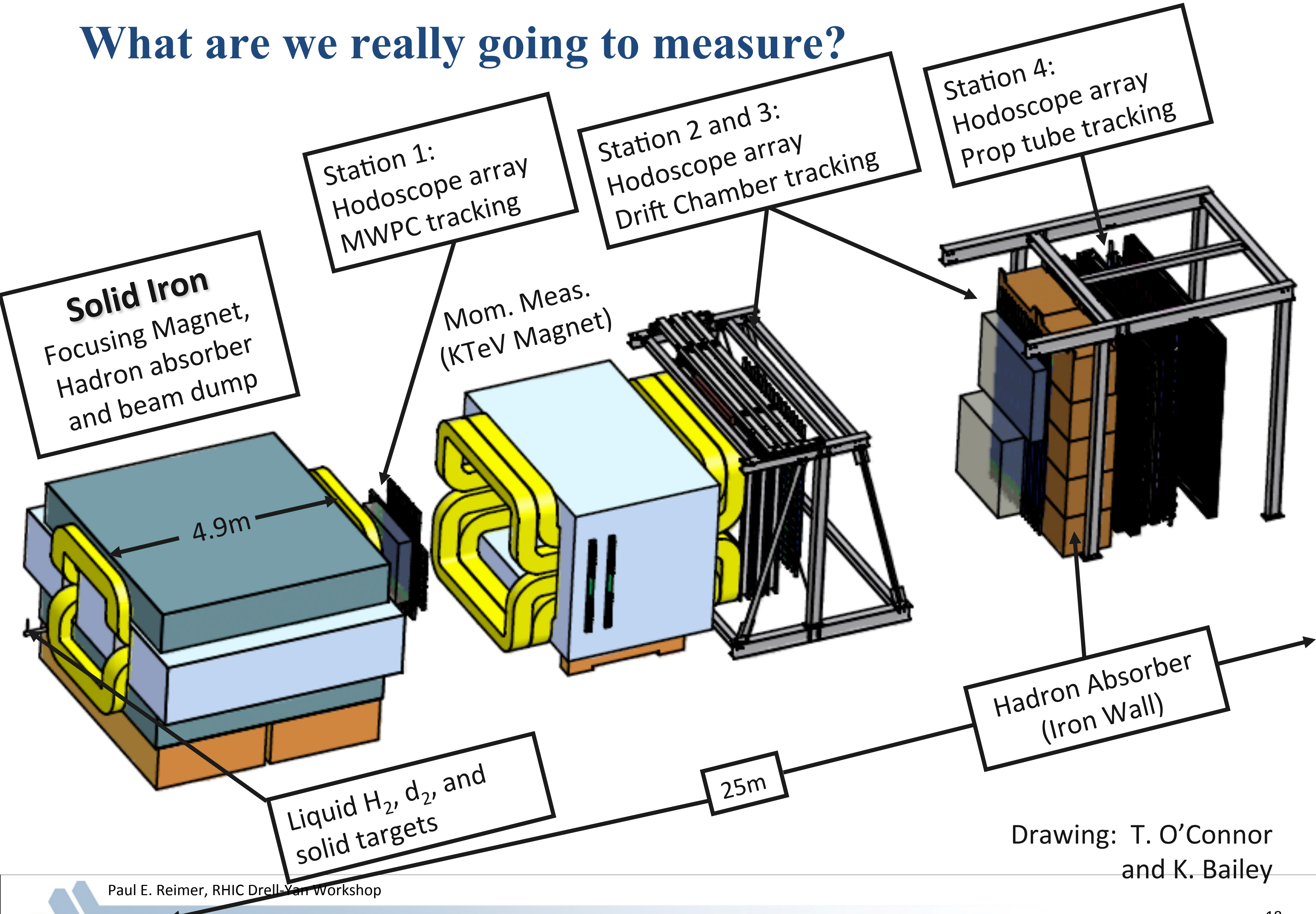
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

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

50× statistics!!



What are we really going to measure?

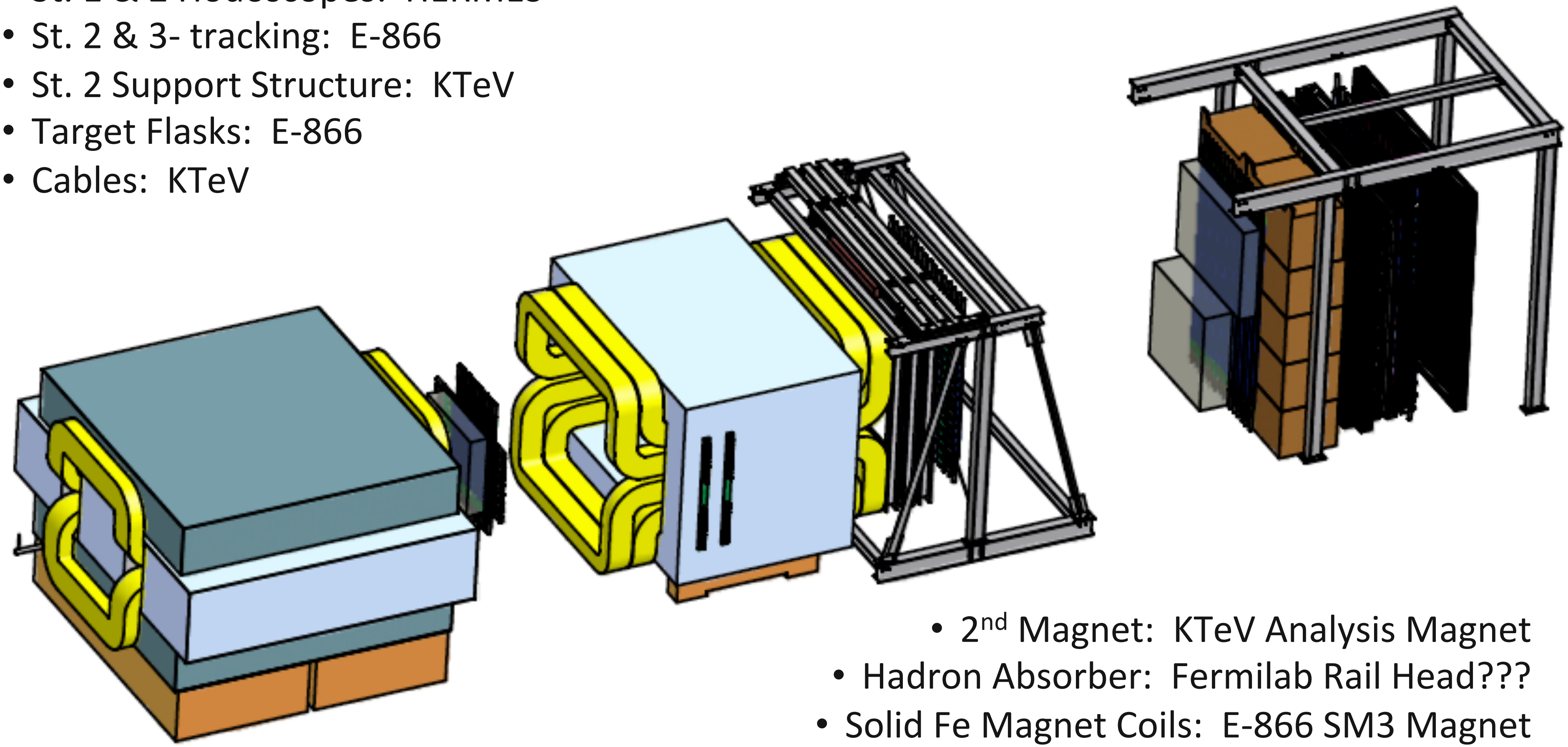


Drawing: T. O'Connor
and K. Bailey

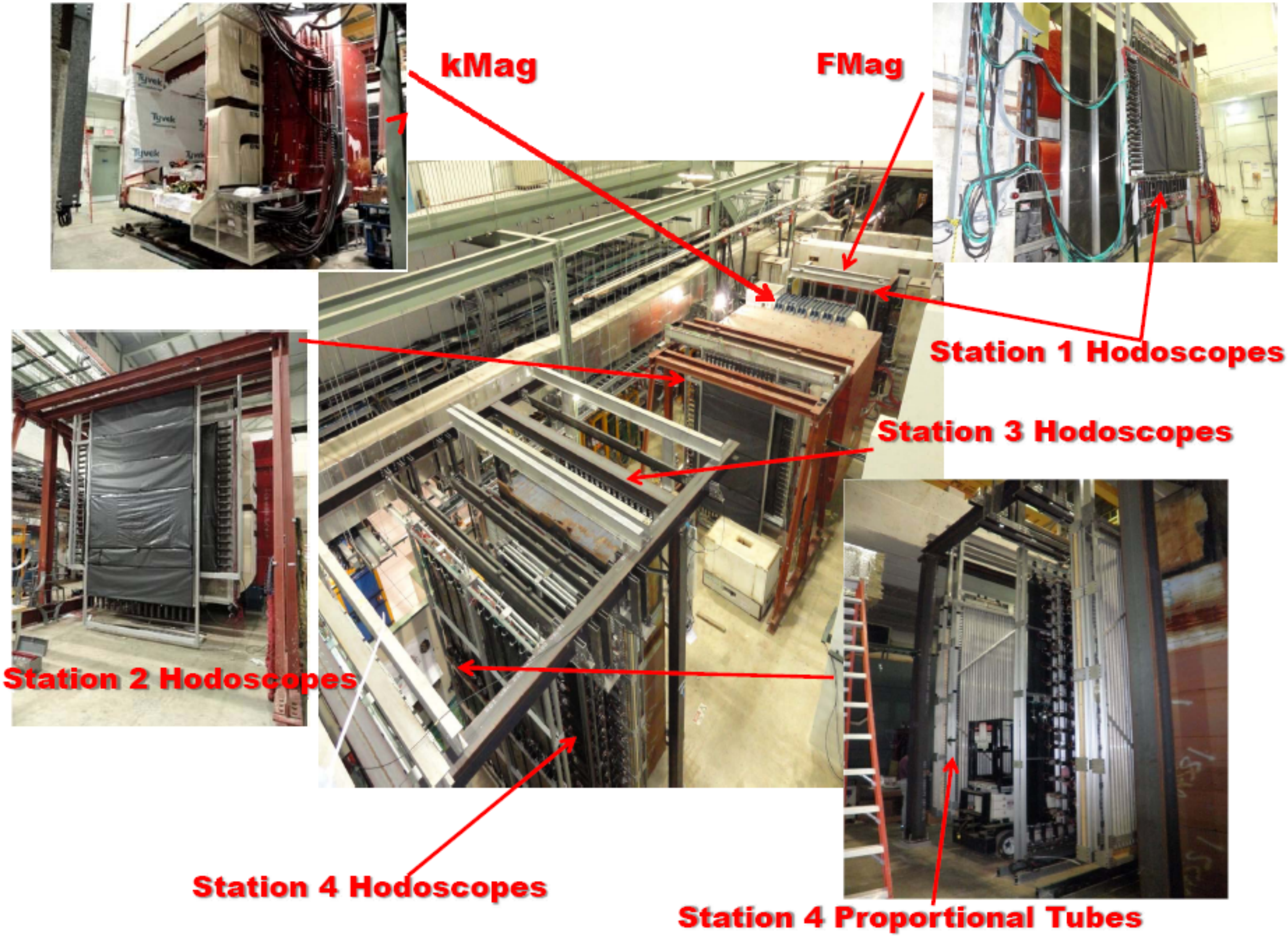
Reduce, Reuse, Recycle

Expect to start collecting data June 2011

- St. 4 Prop Tubes: Homeland Security via Los Alamos
- St. 3 & 4 Hodo PMT's: E-866, HERMES, KTeV
- St. 1 & 2 Hodoscopes: HERMES
- St. 2 & 3- tracking: E-866
- St. 2 Support Structure: KTeV
- Target Flasks: E-866
- Cables: KTeV



- 2^{nd} Magnet: KTeV Analysis Magnet
- Hadron Absorber: Fermilab Rail Head???
- Solid Fe Magnet Coils: E-866 SM3 Magnet
- Shielding blocks from old beam line (Fermilab Today)
- Solid Fe Magnet Flux Return Iron: E-866 SM12 Magnet


kMag
FMag
Station 1 Hodoscopes
Station 3 Hodoscopes
Station 2 Hodoscopes
Station 4 Hodoscopes
Station 4 Proportional Tubes

Fermilab E906/Drell-Yan Collaboration

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Fermilab E906/Drell-Yan Collaboration

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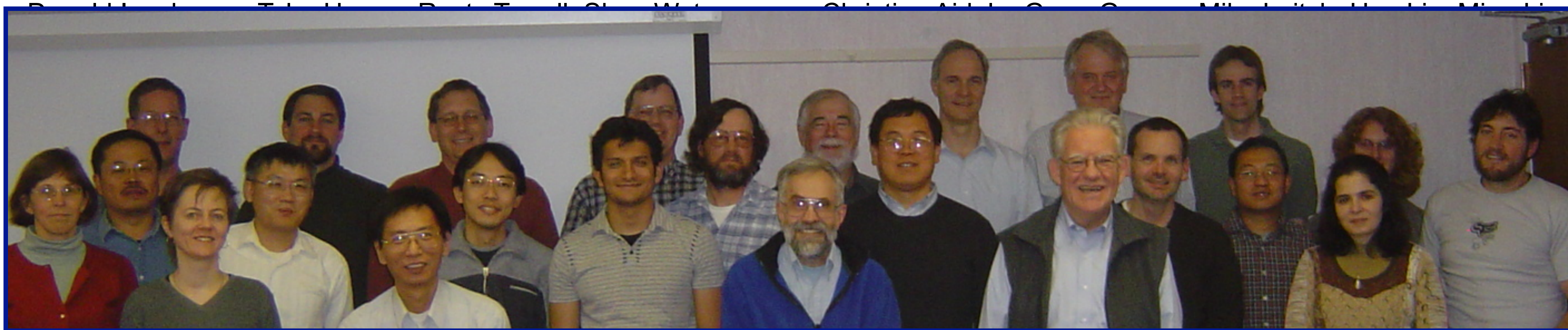
Los Alamos National Laboratory



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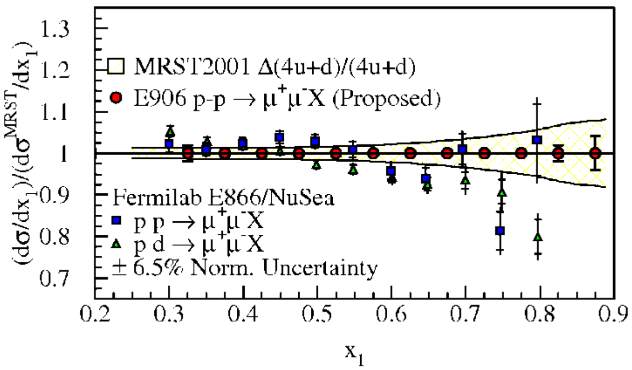
Shou Miyaska, Ken-ichi Nakano, Florian Sanftl, Toshi-Aki Shibata

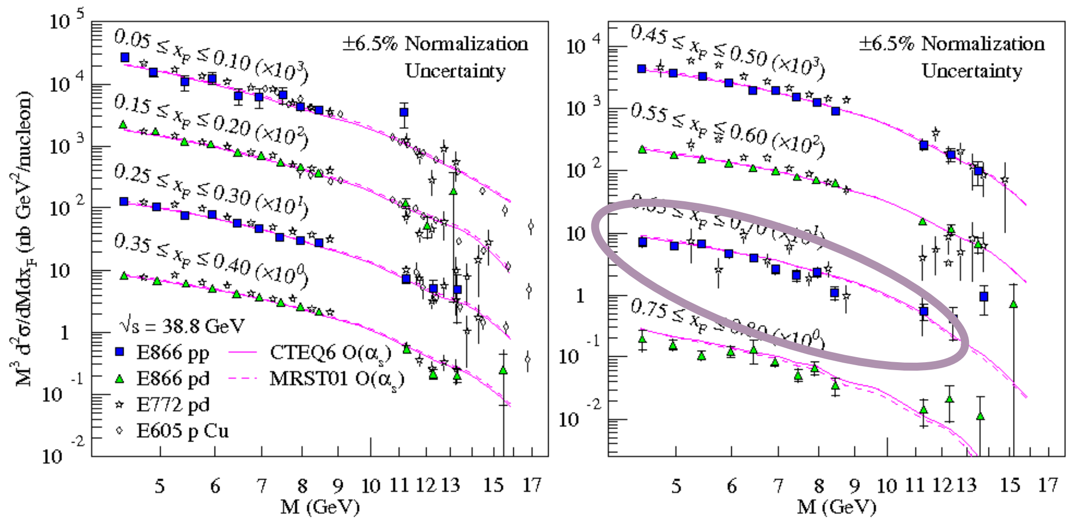
Yamagata University
Yoshiyuki Miyachi

*Co-Spokespersons

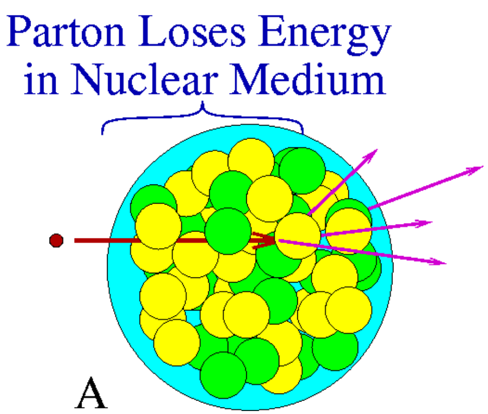
Other Physics from E-906/SeaQuest

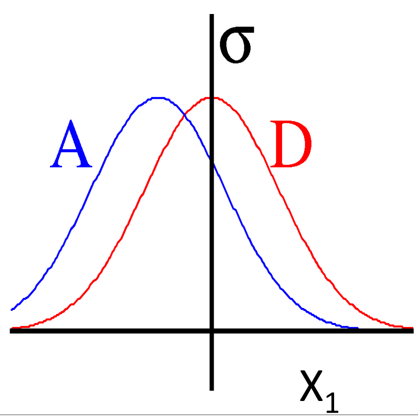
- Absolute High-x_{Bj} Parton Distributions

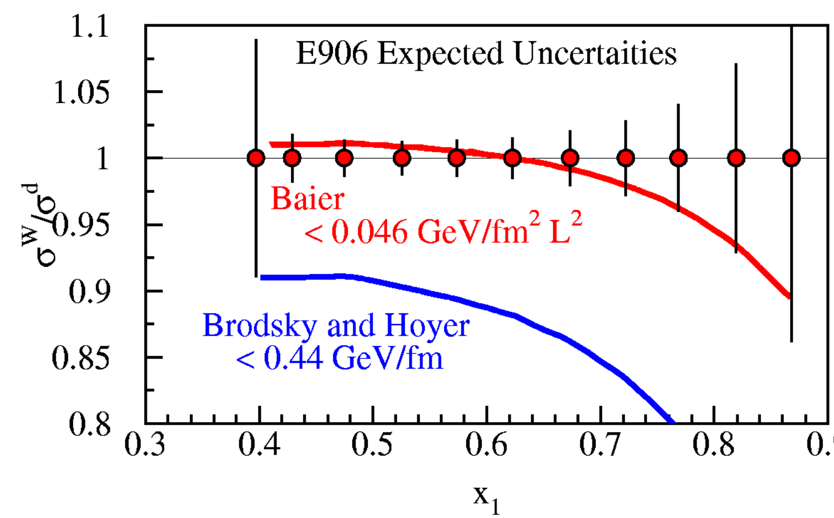




- Partonic Energy Loss in Cold Nuclear Matter

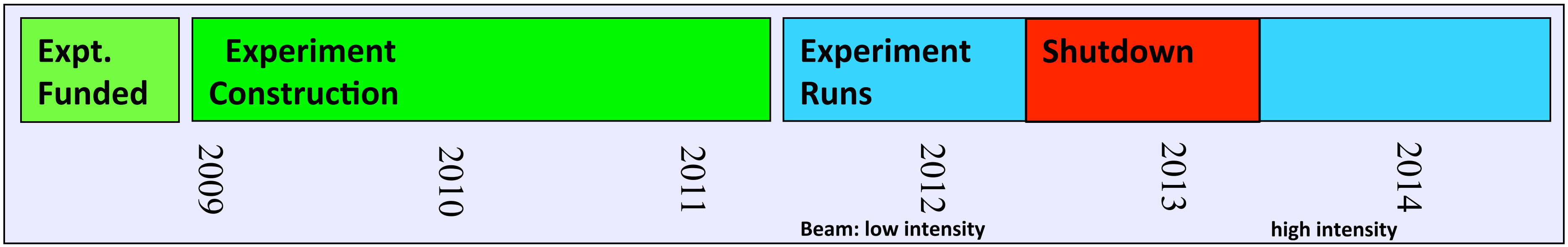






E-906/SeaQuest timeline and plans

- Fermilab PAC approved the experiment in 2001—but experiment was not scheduled due to concerns about "proton economics"
- Fermilab Stage-II Approval granted on 24 December 2008
- Expected first beam in late June 2011



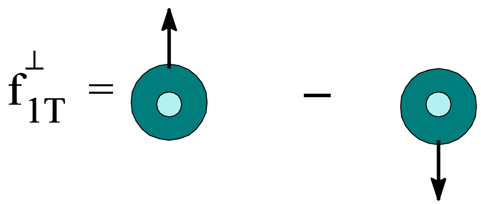
Apparatus available for future programs at, *e.g.* Fermilab, J-PARC or RHIC

- Collaboration has a significant interest in a continued program

Polarized Fermilab Main Injector
Polarized Target at Fermilab
Move apparatus to an existing polarized beam

Beyond E-906/SeaQuest: Transversely Polarized Target or Beam

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

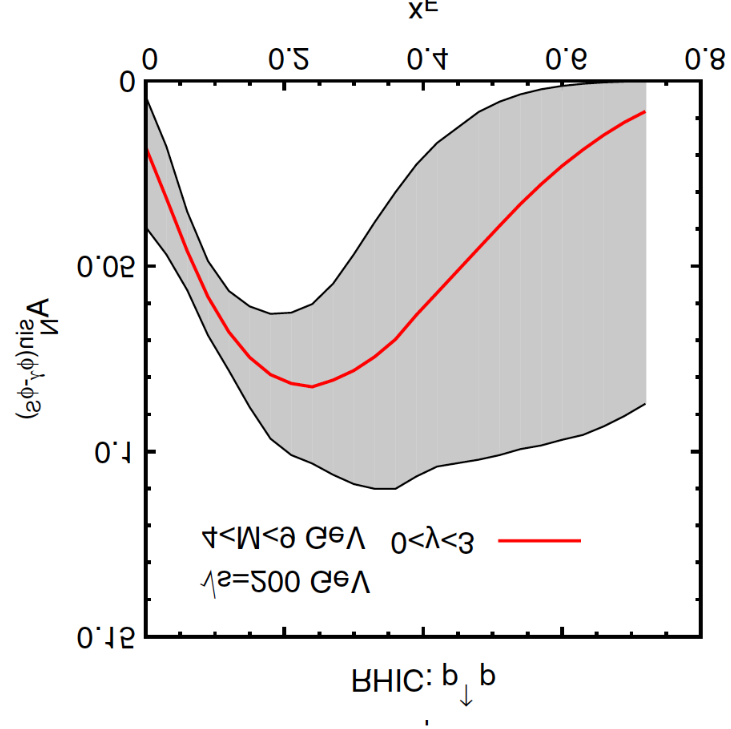


$$f_{1T}^{\perp}(x, k_T)\big|_{\mathrm{DIS}} = -\, f_{1T}^{\perp}(x, k_T)\big|_{\mathrm{DY}}$$

- Single spin asymmetry

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

Beam	Target	
Hadron	Beam valence quarks Target Antiquarks	Fermilab, RHIC (forward acpt.) J-PARC
Anti-Hadron	Beam valence antiquarks Target valence quarks	GSI-FAIR
Meson	Beam valence antiquarks Target valence quarks	COMPASS



Anselmino *et al.* PRD 79, 054010 (2009)

What if

$$|f_{1T}^{\perp}|_{\mathrm{DIS}} \times |f_{1T}^{\perp}|_{\mathrm{DY}} < 0$$

but

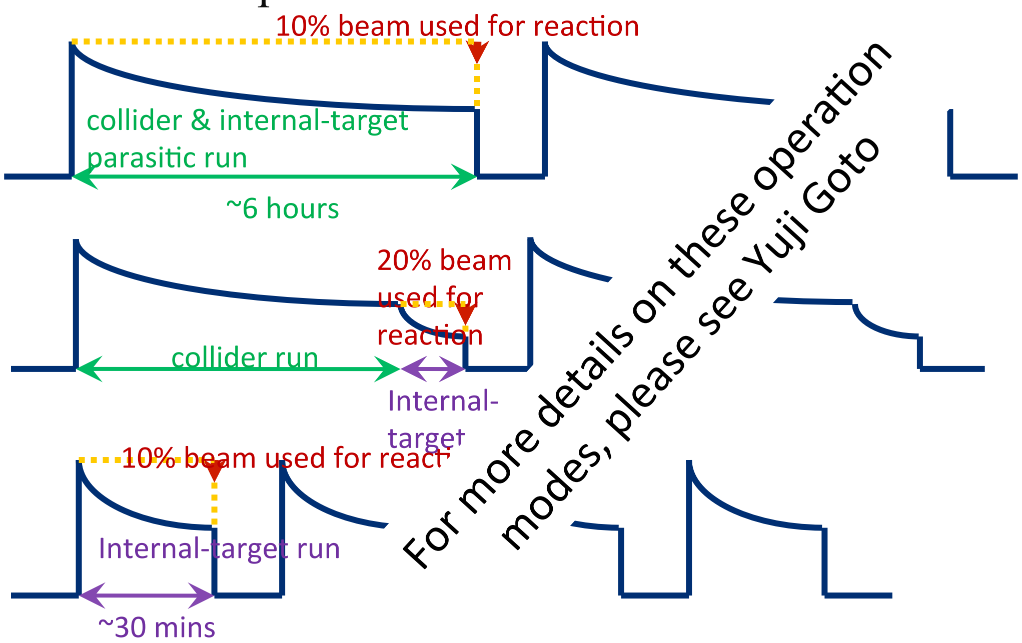
$$|f_{1T}^{\perp}|_{\mathrm{DIS}} \neq |f_{1T}^{\perp}|_{\mathrm{DY}}$$

?

Move to Polarized Beam

At RHIC?

- Internal Cluster-jet or pellet target 10^{15}atoms/cm^2
  – 50 times thinner than RHIC CNI carbon target
- Operational modes—effect on STAR & PHENIX Operations
  – Parasitic
  – End-of-fill (HERMES)
  – Dedicated (in-and-out strike)



- Other questions/obstacles
  – Competition for interaction region (AnDY, EIC)
  – Beam compensation for double dipole spectrometer
  – Beam pipe through spectrometer?

Experimental sensitivities for fixed target at RHIC

Phase-1 (parasitic operation)

- $\mathcal{L} = 2\times10^{33}$ cm^{-2}s^{-1}
- 10,000 pb^{-1} with 5×10^6 s ~ 8 weeks, or 3 years (10 weeks×3) of beam

Phase-2 (dedicated operation)

- $\mathcal{L} = 3\times10^{34}$ cm^{-2}s^{-1}
- 30,000 pb^{-1} with 10^6 s ~ 2 weeks, or 8 weeks of beam

Measure not only the sign of the Sivers but also ***the shape*** of the function

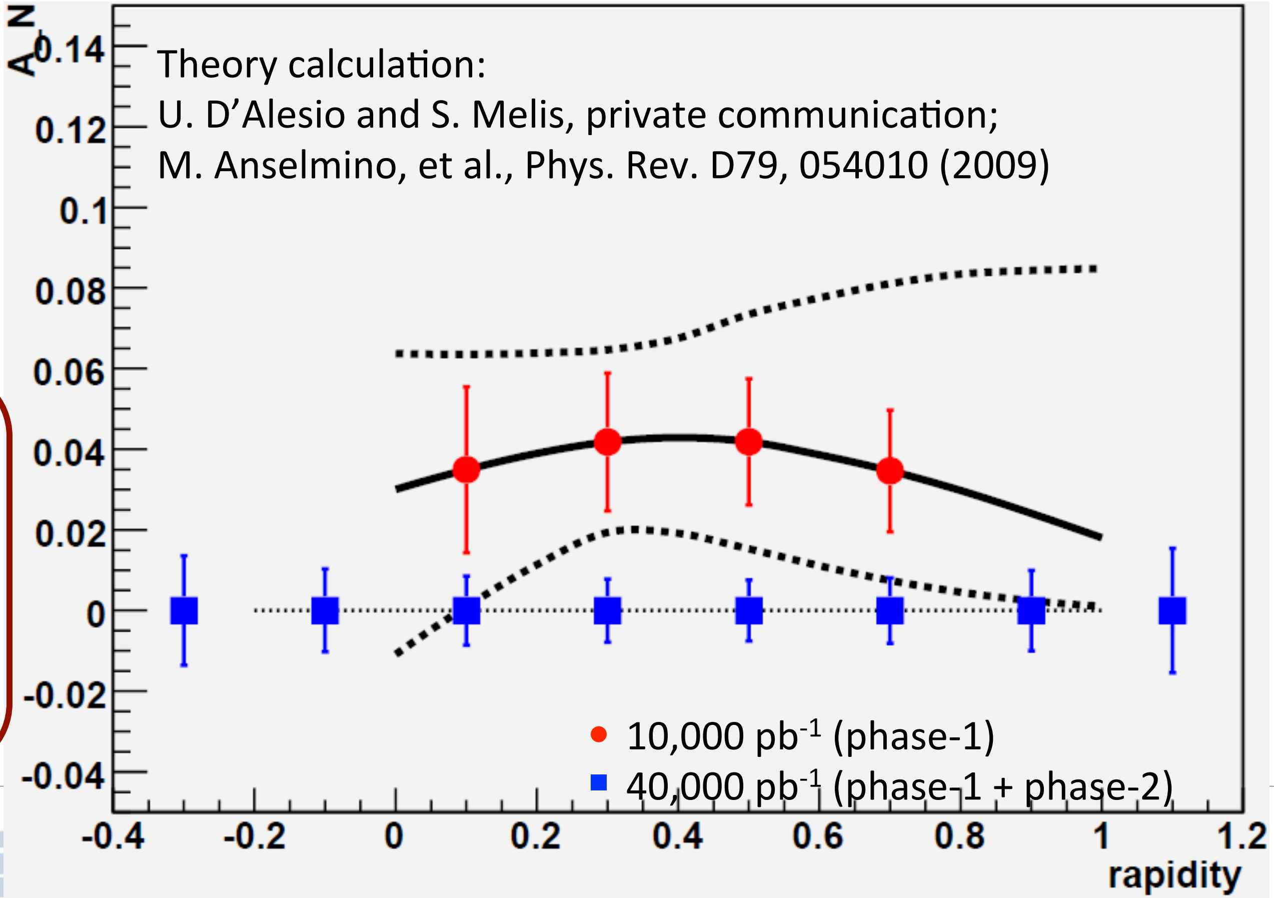
What if

$$|f_{1T}^{\perp}|_{DIS} \times |f_{1T}^{\perp}|_{DY} < 0$$

but

$$|f_{1T}^{\perp}|_{DIS} \neq |f_{1T}^{\perp}|_{DY}$$

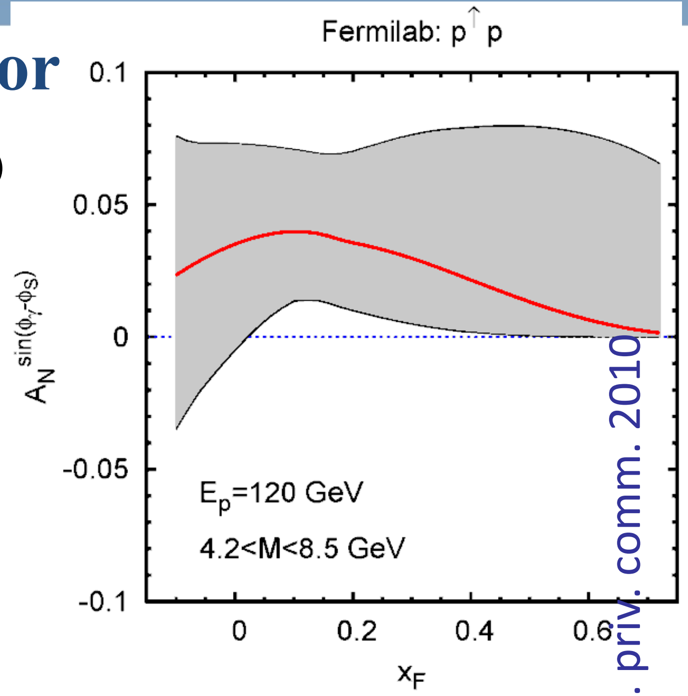
?

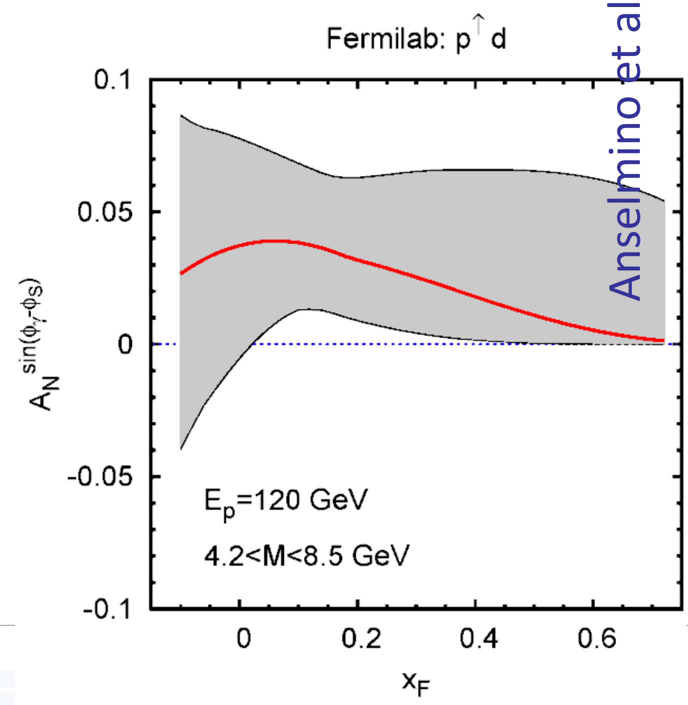


Polarized beam at Fermilab Main Injector

Polarized beam at Fermilab Main Injector

- 1 mA at polarized source delivers 8.1 x 10^{11} p/s (=130 nA)
  - A. Krisch: Spin@Fermi study in 1995
  - Fermilab Main Injector can be polarized (not Tevatron)
  - Revisit study to re-evaluate cost (done in early fall 2011)
  - Feasibility depends on cost (both in $$ and down time of MI)
- Scenarios:
  - SeaQuest liquid H_2 target can take ~5 x 10^{11} p/s (=80 nA)
  - **$\mathcal{L}$ = 1 x 10^{36} /cm²/s** (60% of beam delivered to experiment)
  - **$\mathcal{L}$ = 2 x 10^{35} /cm²/s** (10% of beam delivered to experiment)
- *x*-range:
  - x_1 0.3 – 0.9 (valence quarks)
  - x_2 0.1 – 0.5 (sea quarks)
- Unpolarized SeaQuest
  - luminosity: $\mathcal{L}$ = 3.4 x 10^{35} /cm²/s
  - I_{av} = 1.6 x 10^{11} p/s (=26 nA)
  - N_p = 2.1 x 10^{24} /cm²
  - 2-3 years of running: 3.4 x 10^{18} pot



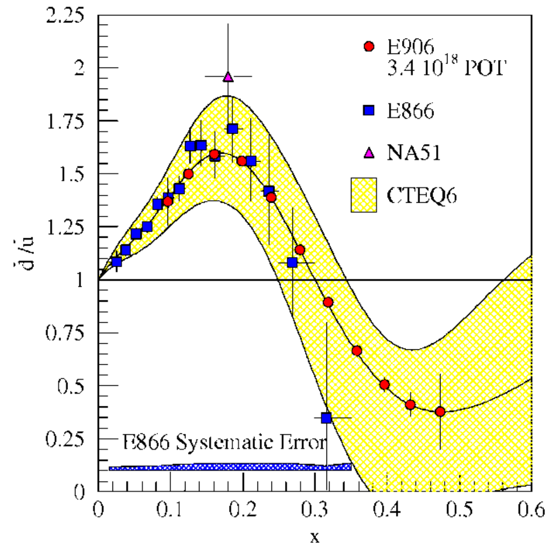


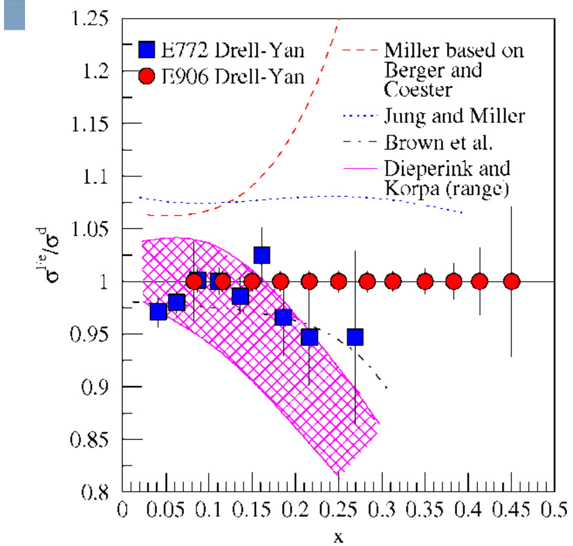
Anselmino et al. priv. comm. 2010

experiment	particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	$x_2 = 0.2 - 0.3$ $x_2 \sim 0.05$ (low mass)	2×10^{33} cm^{-2} s^{-1}	>2012
PAX (GSI)	$p^{\uparrow} + p_{par}$	collider $\sqrt{s}$ = 14 GeV	$x_1 = 0.1 - 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$p_{par} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	$x_2 = 0.2 - 0.4$	2×10^{32} cm^{-2} s^{-1}	>2016
J-PARC	$p^{\uparrow} + p$	50 GeV $\sqrt{s}$ = 10 GeV	$x_1 = 0.5 - 0.9$	1×10^{35} cm^{-2} s^{-1}	>2015 ??
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	$x_1 = 0.1 - 0.8$	1×10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	$x_1 = 0.05 - 0.1$	2×10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 - 0.4$	2×10^{33} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 - 0.4$	6×10^{34} cm^{-2} s^{-1}	>2018
A_nDY RHIC (IP-2)	$p^{\uparrow} + p$	500 GeV $\sqrt{s}$ = 32 GeV	x_1 = ??	?? cm^{-2} s^{-1}	>2015
SeaQuest (unpol.) (FNAL)	$p + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_1 = 0.3 - 0.9$	3.4×10^{35} cm^{-2} s^{-1}	>2010
pol. SeaQuest (FNAL)	**$p^{\uparrow} + p$**	**120 GeV $\sqrt{s}$ = 15 GeV**	**$x_1 = 0.3 - 0.9$**	**1×10^{36} cm^{-2} s^{-1}**	**>??**

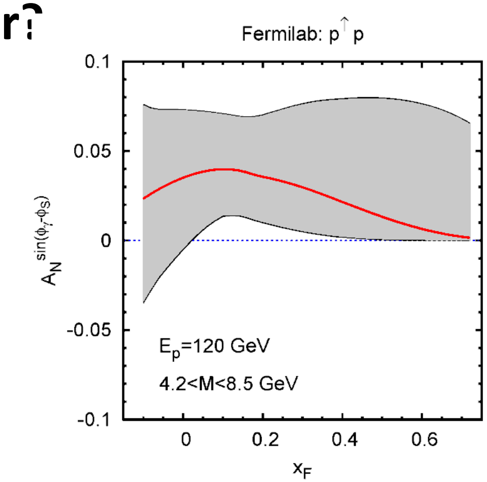
Drell-Yan at Fermilab

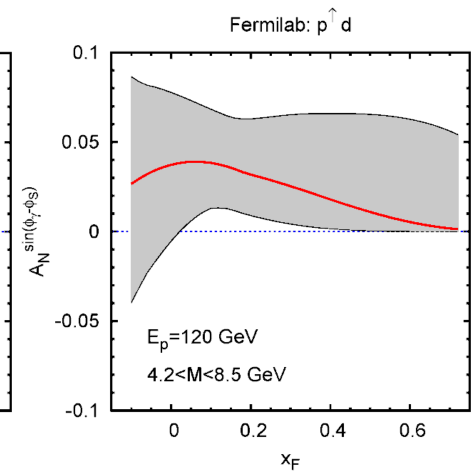
- **What is the structure of the nucleon?**
  - What is d-bar/u-bar?
  - What are the origins of the sea quarks?
  - What is the high-x structure of the proton?

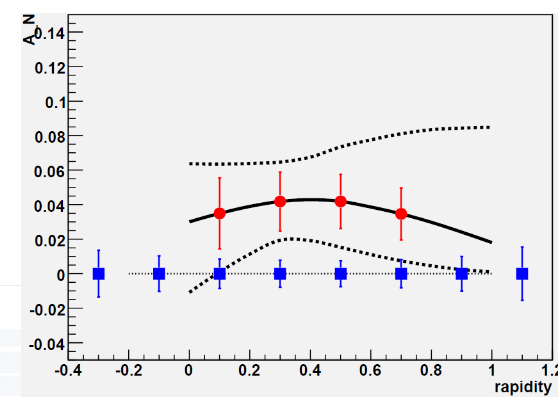




- **What is the structure of nucleonic matter?**
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
- **What is the transverse Structure of the proton?**
  - Polarized beam at Fermilab Main Injector
  - Move apparatus to RHIC or J_PARC







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