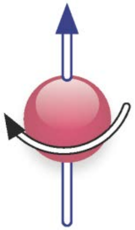
The Asymmetry of Antimatter in the Proton



Wolfgang Lorenzon

(8-Mar-2021)

U-M: HEP Seminar

Nature 590, 561 (2021)

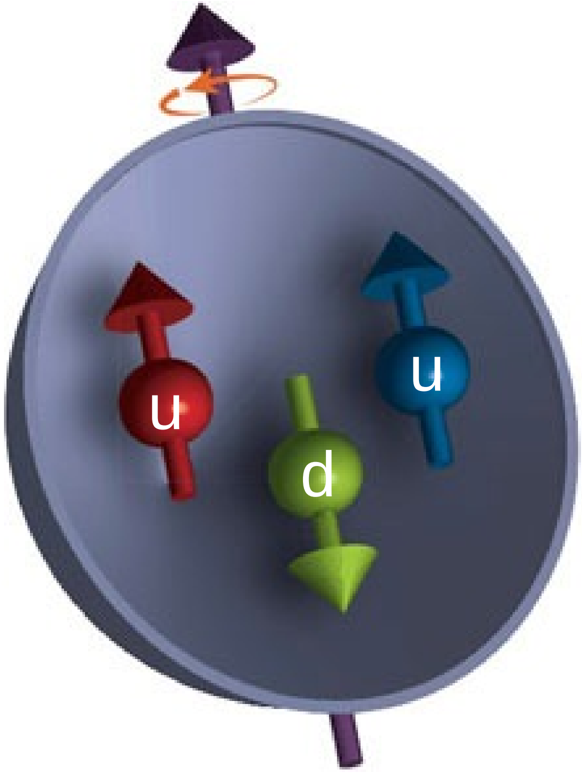
article by SeaQuest collaboration

Michigan collaborators:

C.A. Aidala, C. Ayuso, A. Chen, W. Lorenzon, I. Mooney, D.H. Morton, B.J. Ramson, J.G. Rubin, T. Sawada, M.B.C. Scott

This work is supported by

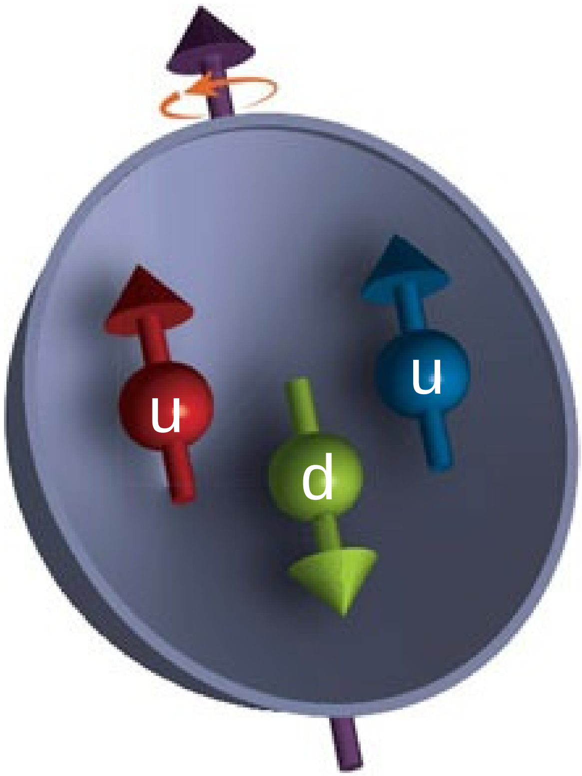
The Proton



- proton discovered in 1917
  - $^{14}N + \alpha \rightarrow {}^{17}O + p$
  - extensively studied, but still puzzling
    - size? spin? mass?
- future Electron-Ion Collider (>2030)
  - how does the mass of the nucleon arise?
  - how does the spin of the nucleon arise?

The Proton

size: (~1 fm)



Quark Model
(1964)

electric charge

$$+1 = \frac{2}{3} + \frac{2}{3} - \frac{1}{3}$$

magnetic moment

QM pred. $$\frac{\mu_n}{\mu_p} = -\frac{2}{3}$$

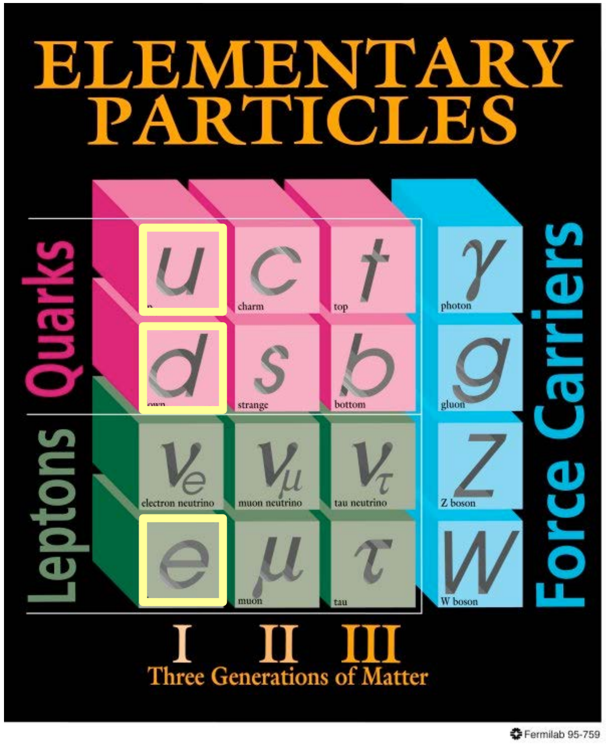
experiment –0.685

spin

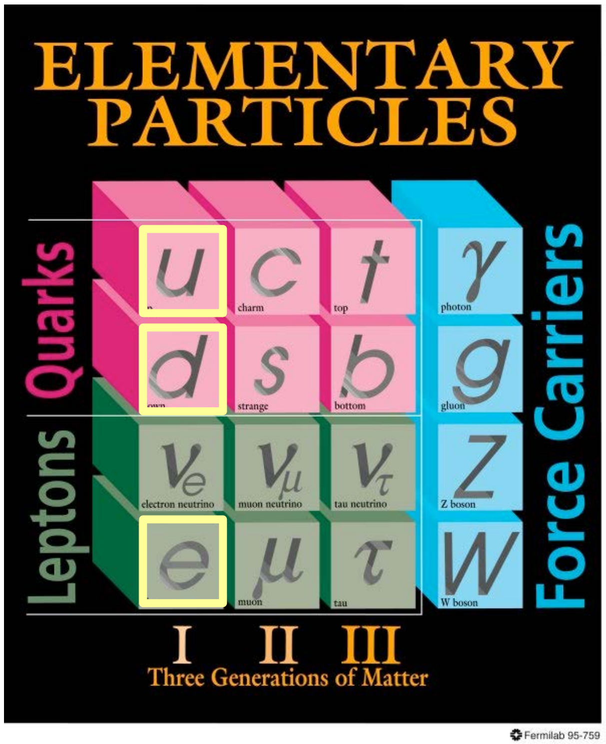
$$+\frac{1}{2} = \frac{1}{1} \oplus \frac{1}{1} \oplus \frac{1}{1}$$

- proton is spin-1/2 particle
- proton is not pointlike
  (made of three constituents, called quarks)

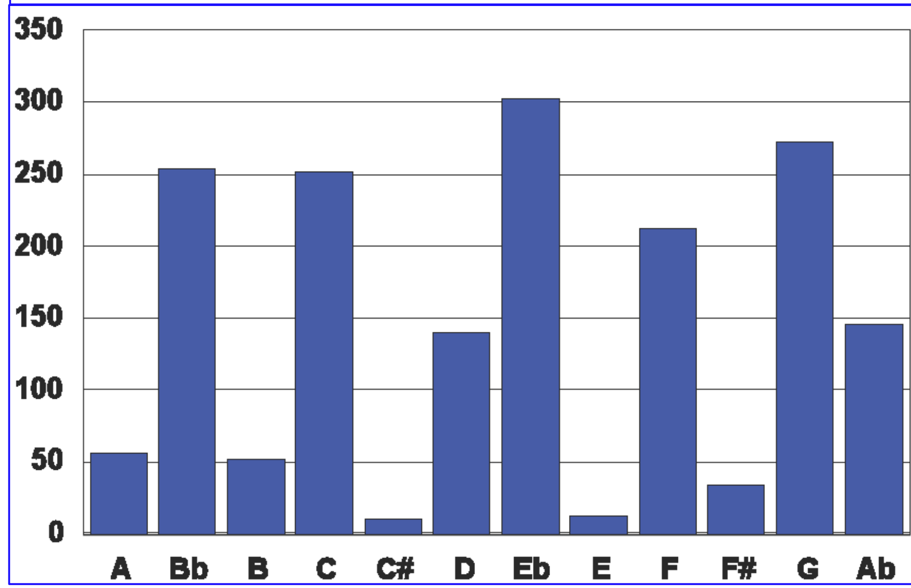
The Proton – is it boring?



Proton - more than just constituents



Histogram of notes used in Beethoven's 5th symphony



Both plots focus on constituents rather than interactions

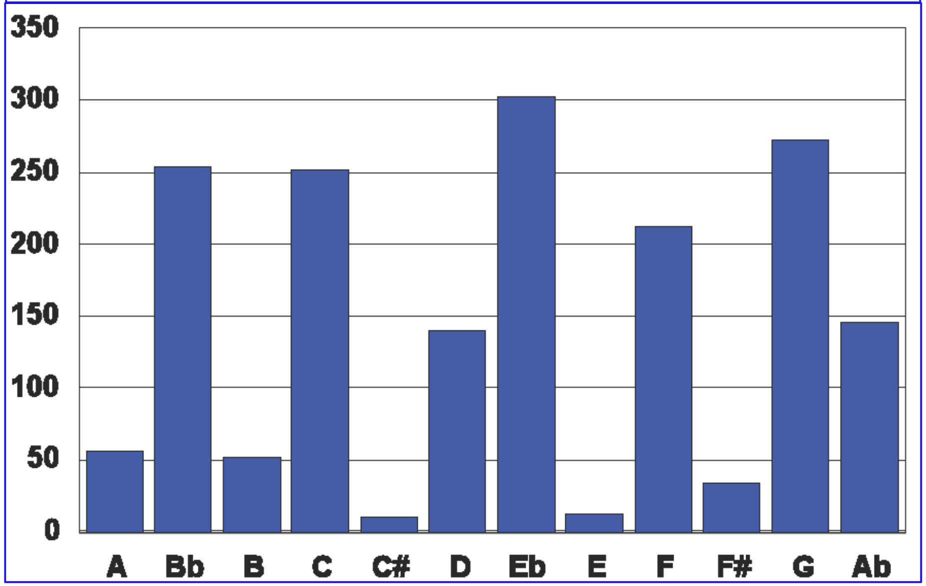
Interactions are important - they create the dynamics

Plot inspired by J. Arrington (ANL)

Proton - more than just constituents

- the 1st four notes
- adding rhythmic variation
- with full dynamics

Histogram of notes used in Beethoven's 5th symphony



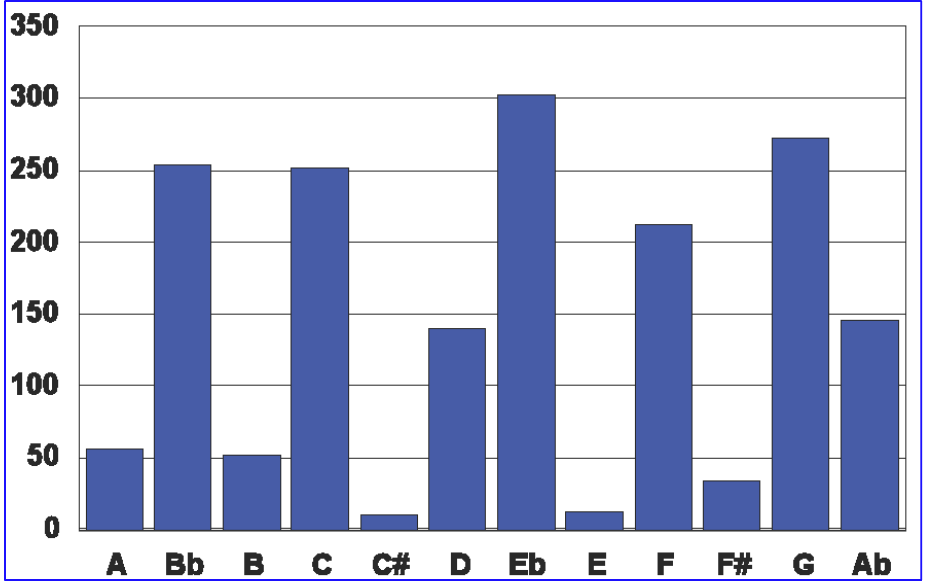
Interactions are important - they create the dynamics

Plot inspired by J. Arrington (ANL)

Proton - more than just constituents

- the 1st four notes (G, E, F, D)
- adding rhythmic variation
- with full dynamics

Histogram of notes used in Beethoven's 5th symphony



Interactions are important - they create the dynamics

Plot inspired by J. Arrington (ANL)

The Proton

- quarks are held together by strong nuclear force, which arises when quarks exchange gluons
- complex internal structure generated by interactions between pointlike constituents (quarks/partons).
- Uncertainty Principle dictates: quarks must be in motion - at close to speed of light:

  $p \geq \frac{\hbar}{x}$: for M_q = 350 MeV, x = 1 fm

  $\rightarrow v \geq 0.6\ c$

  → proton is a strongly-coupled, relativistic, infinite-body system

Source: PIXELPARTICLE/SHUTTERSTOCK

In the News

QUANTUM PHYSICS

Decades-Long Quest Reveals Details of the Proton's Inner Antimatter

In the News

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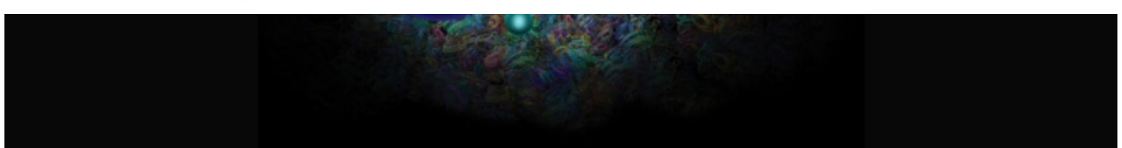
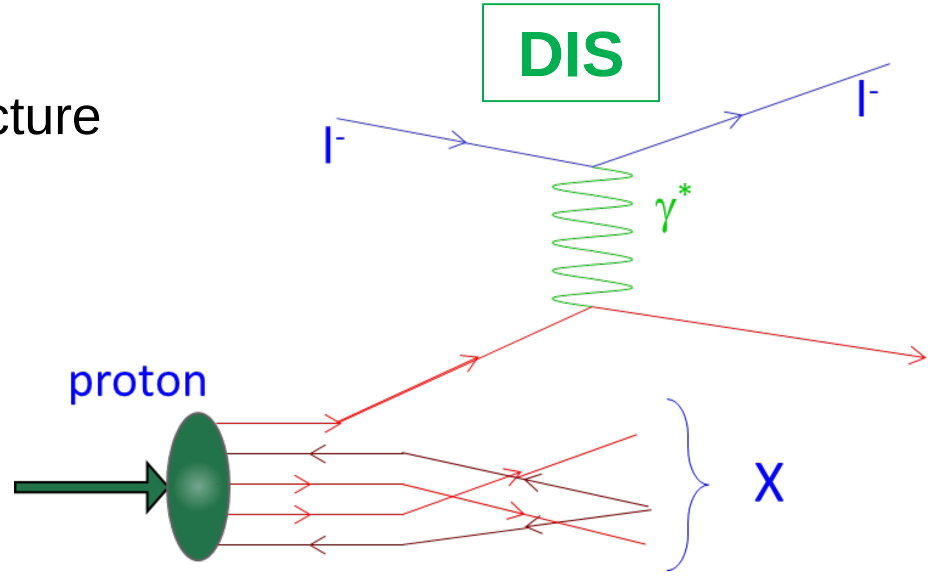


Protons are messy on the inside. Made of three main quarks (illustrated with large spheres), the particles also harbor a constantly shifting collection of transient quarks and antiquarks (smaller spheres) and gluons (squiggles) that bind the quarks together.

Probing the inner Structure of the Proton



Quintessential probe of hadron structure

- relatively simple to measure
- relatively easy to calculate
- charge-weighted flavor sensitivity
- **no quark-antiquark selectivity**

cross-section measurements

↓ **decomposed**

Structure Functions — process dependent

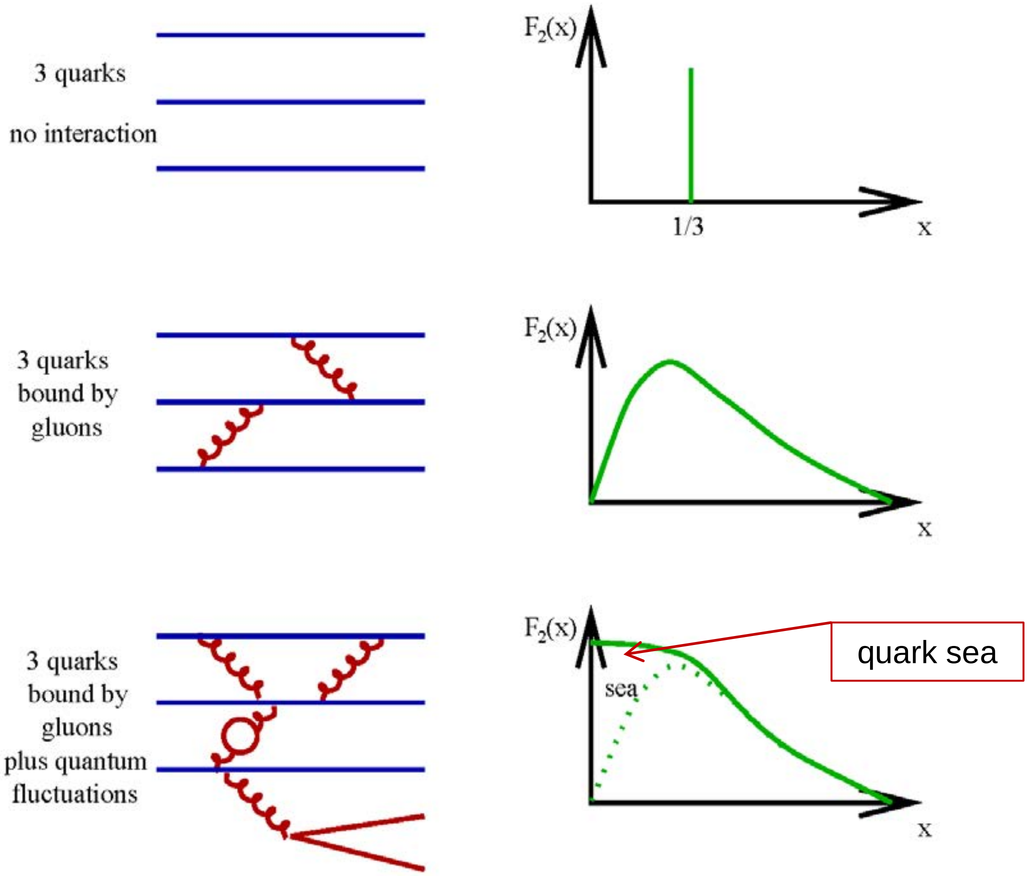
↓ **interpreted**

Parton Distribution Functions — universal

J. Qiu: "Structure functions and parton distributions"
https://arxiv.org/abs/nucl-th/02110

Structure Functions

QCD effects on structure functions

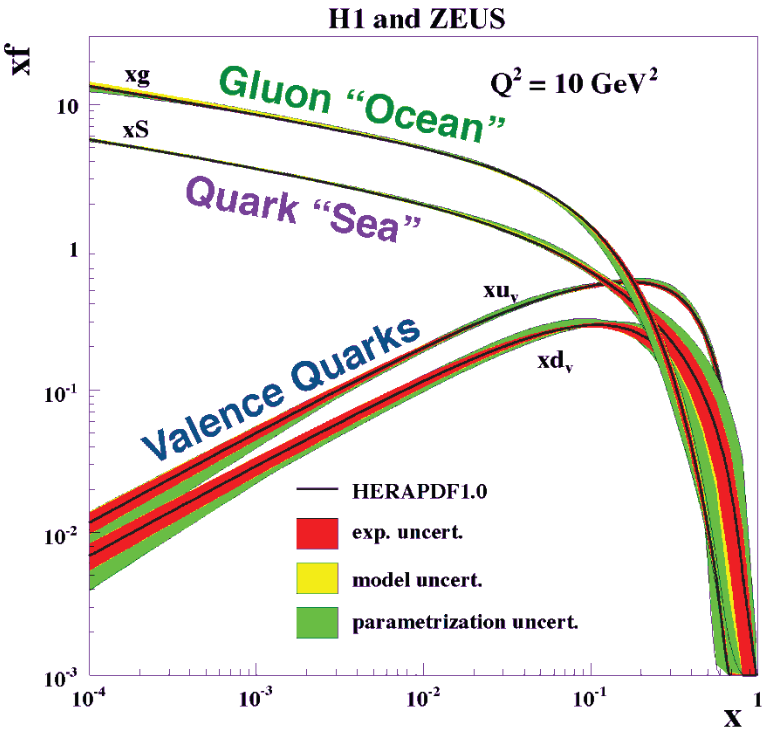


Example:

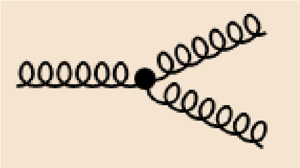
$$F_2(x) = \sum_f e_f^2 x q_f(x)$$

represents quark momentum distribution inside nucleon

Parton Distribution Functions



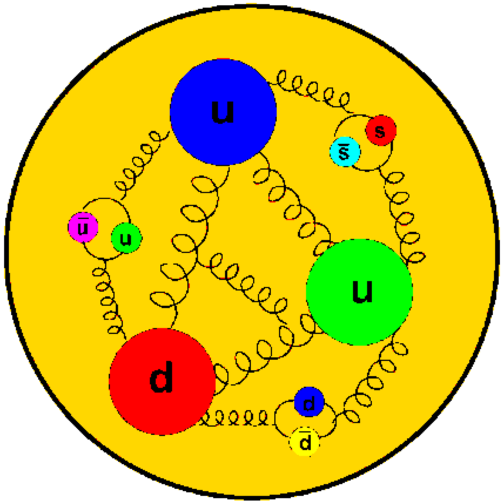
- Dramatic rise in gluon distribution discovered at HERA in 1990's.

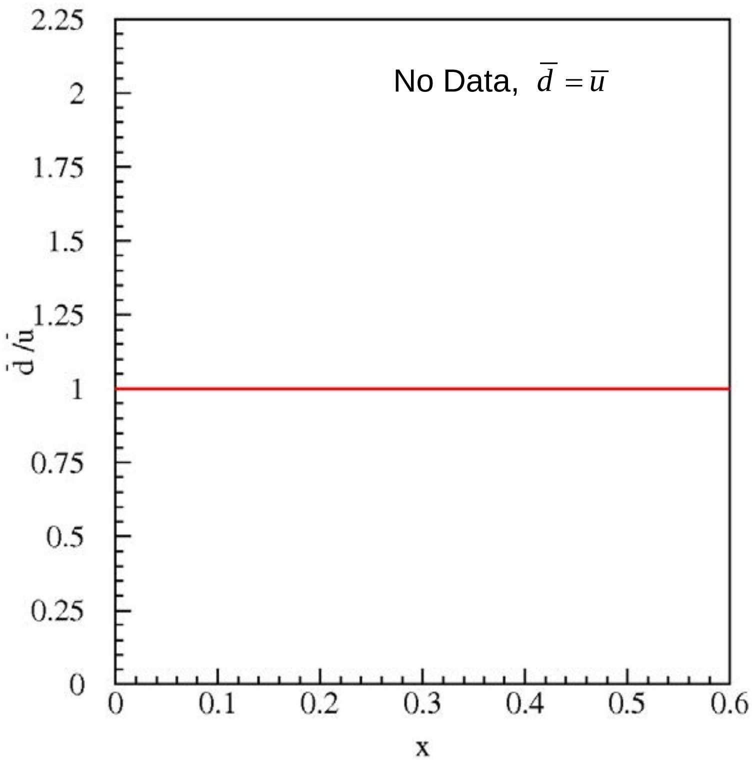


- The Quark "Sea" derives from the Gluon "Ocean" by gluon splitting into a quark-antiquark pair

- Gluon splitting drives the dynamics at $x<0.1$

Flavor Structure of the Proton





- **Constituent Quark Model**
  Pure valence description: proton = 2u + d
- **Perturbative Sea**
  sea quark pairs from $g \rightarrow q\bar{q}$
  should be flavor symmetric: $\bar{d} = \bar{u}$
- What does the data tell us?

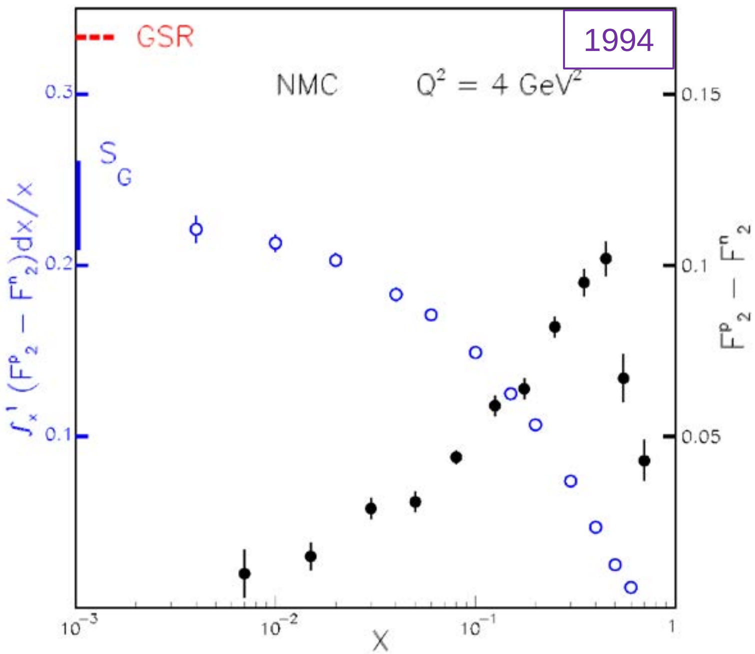
Flavor Structure of the Proton: Brief History

- Perturbative Sea

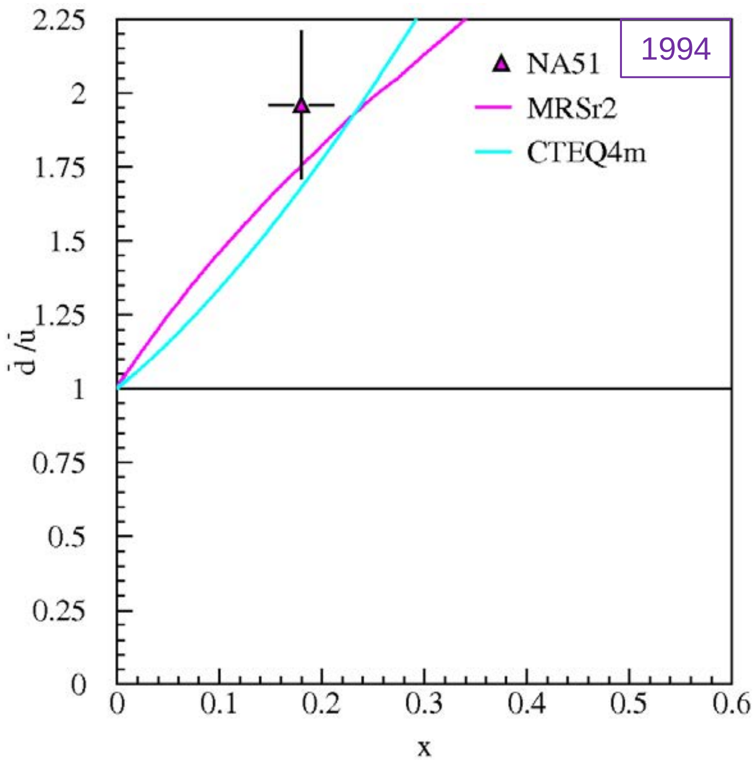
$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

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



NA51: $\bar{d} > \bar{u}$



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

Flavor Structure of the Proton: Brief History

- Perturbative Sea

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

- NMC (inclusive DIS)

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

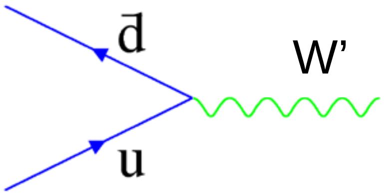
- NA51 (Drell-Yan)

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

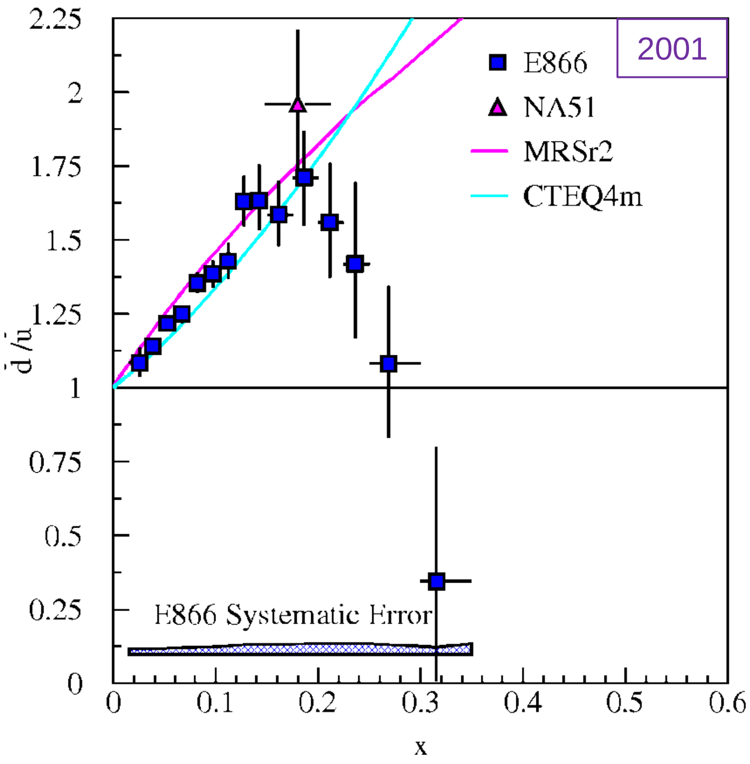
- E866/NuSea (Drell-Yan)

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

- What is the origin of the sea?
- Significant part of the LHC beam



E866: $\bar{d} > \bar{u}$

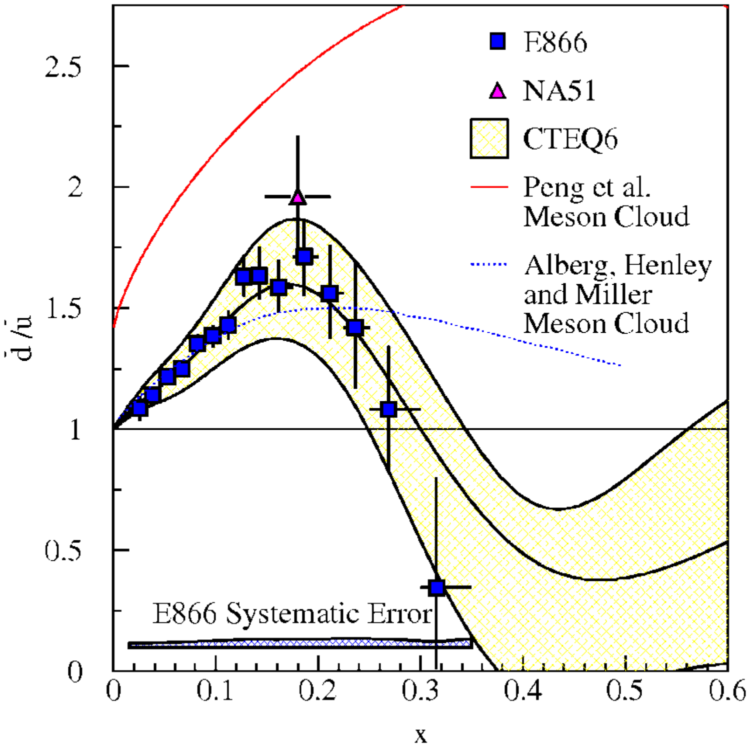


Flavor Structure of the Proton: Brief History

- Perturbative Sea

E866: $\bar{d} > \bar{u}$

- NMC (inclusive DIS)
- NA51 (Drell-Yan)
- E866/NuSea (Drell-Yan)
  - are there more gluons and thus symmetric anti-quarks at higher x?
  - unknown other mechanisms with unexpected x-dependence?
  - non-perturbative QCD models can explain excess d-bar quarks, but not return to symmetry or deficit of d-bar quarks

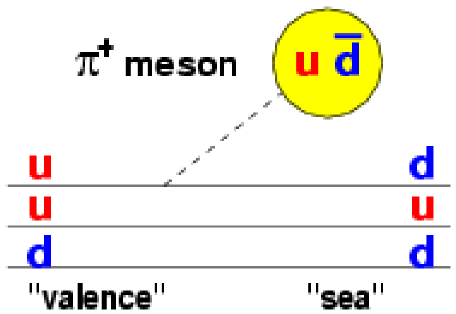


- parton distributions is data driven
  - global fits by CTEQ6 incl E866 data

Flavor Structure of the Proton: Models

Non-perturbative models: alternate d.o.f.

Meson Cloud Models



Quark sea from cloud of 0^- mesons:

$\rightarrow$ $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model

- quark d.o.f. in a pion mean-field: $u \rightarrow d + \pi^+$
- nucleon = chiral soliton
- one parameter: dynamically generated quark mass
- expand in $1/N_c$:

$\rightarrow$ $\bar{d} > \bar{u}$

Statistical Model

- nucleon = gas of massless partons
- few parameters: generate parton distribution functions
- input: QCD: chiral structure DIS: u(x) and d(x)

$\rightarrow$ $\bar{d} > \bar{u}$

$\Rightarrow$ important constraints on flavor asymmetry for polarization of light sea

$\Delta\bar{q} = 0$

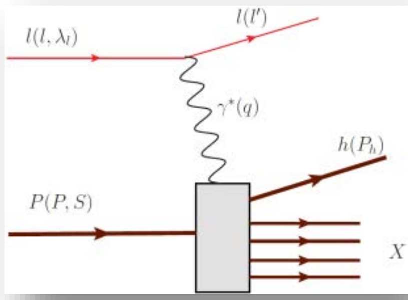
$\Delta\bar{u} \cong -\Delta\bar{d} > 0$

$\Delta\bar{d} < 0, \Delta\bar{u} > 0$

Probing the inner Structure of the Proton

- SIDIS and Drell-Yan have similar physics reach:
  - ➞ tools to probe quark and antiquark structure of nucleon
  - ➞ electromagnetic probes

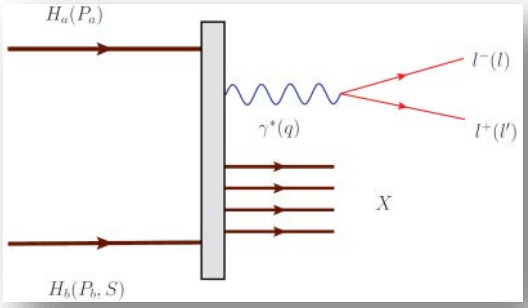
SIDIS (spacelike)



Quintessential probe of hadron structure:

- ➞ relatively simple to measure and calculate
- ➞ charge-weighted flavor sensitivity
- ➞ QCD final state effects
- ➞ fragmentation process
- ➞ **no quark-antiquark selectivity**

Drell-Yan (timelike) virtual photon

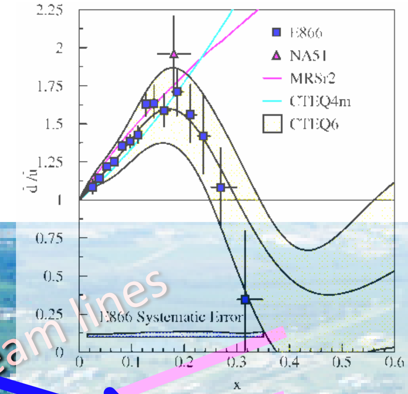


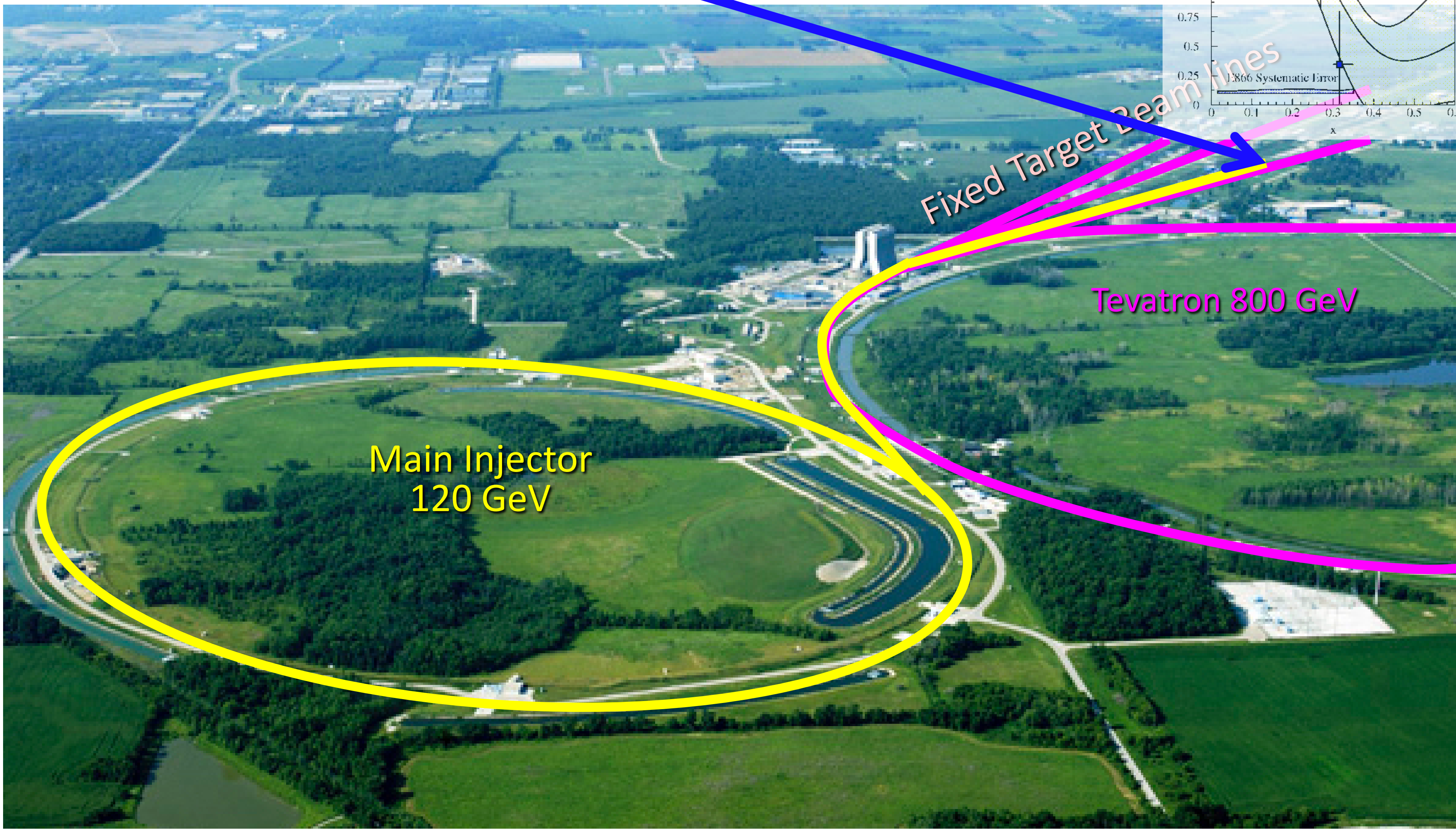
credit: A. Kotzinian

Cleanest probe to study hadron structure:

- ➞ no QCD final state effects
- ➞ no fragmentation process
- ➞ production of two TMD parton distribution functions
- ➞ **ability to select sea quark distribution**
- ➞ hadron beam: σ(DY) / σ(nuclear) ≈ 10^{-7}

SeaQuest Experiment

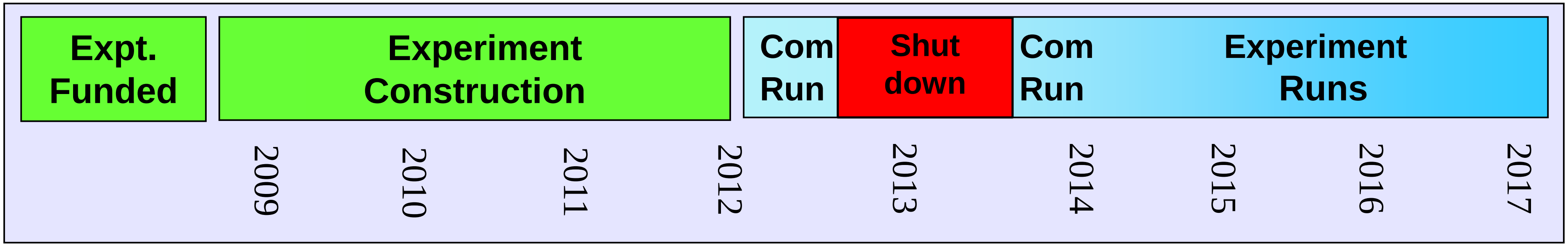




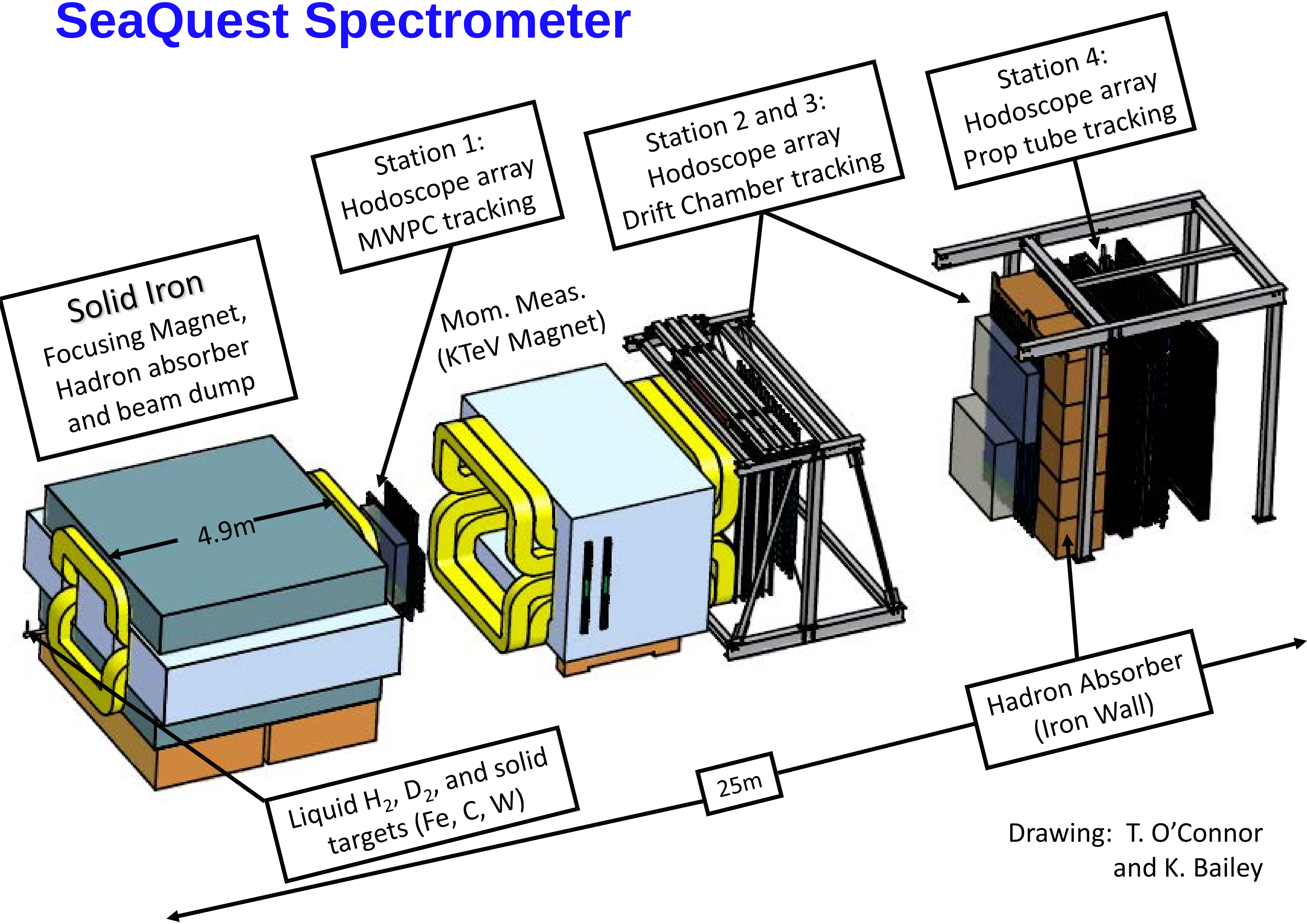
10% of available beam to SeaQuest / 90% to neutrino program

The long Path towards the Science

- Stage I approval in 2001
- Stage II approval in Dec 2008
  - U-M group joined experiment
- Commissioning Runs (Apr 2012 – Feb 2014, w/ interruptions)
- Data Collection (Feb 2014 – Jul 2017)

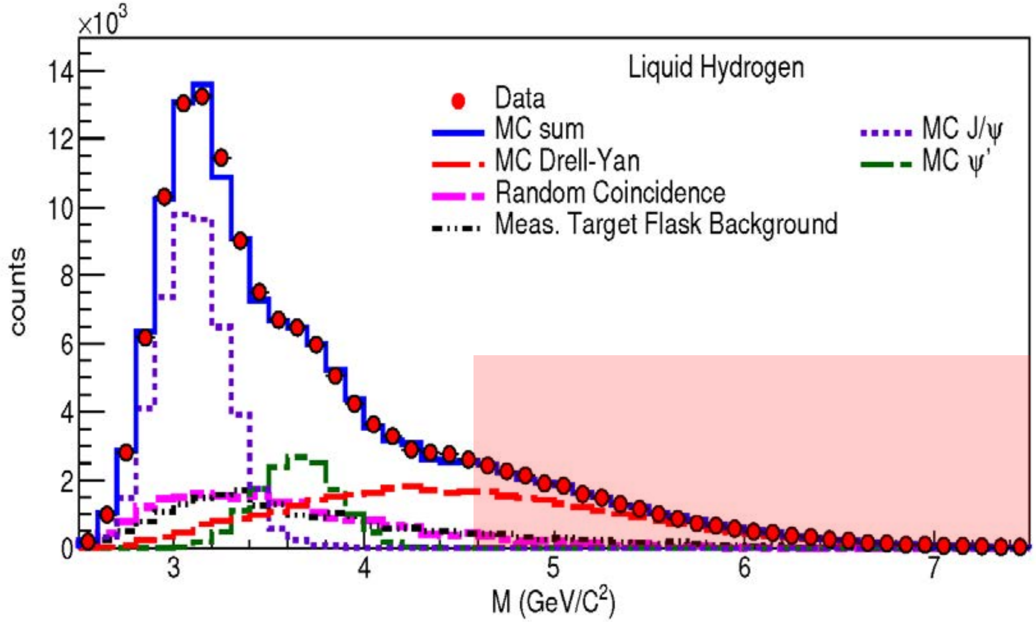


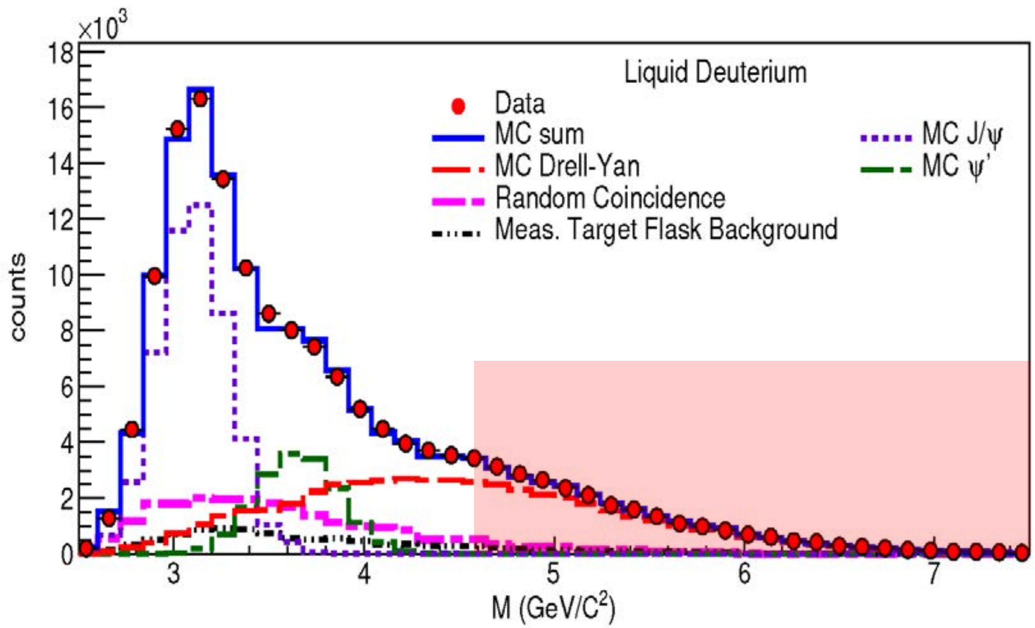
SeaQuest Spectrometer



Drawing: T. O'Connor
and K. Bailey

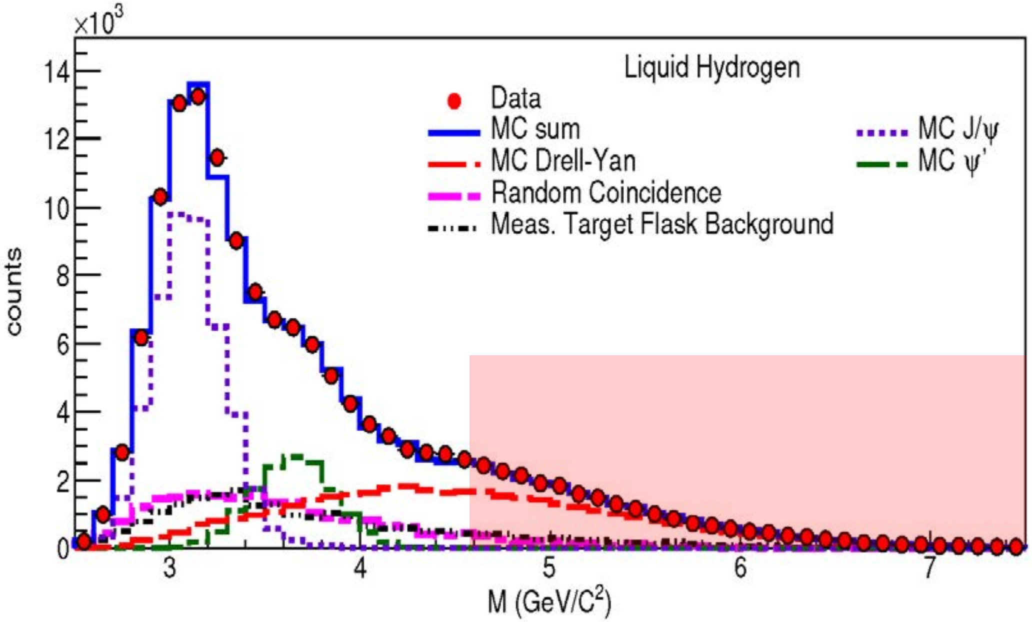
Invariant Mass Reconstruction





- Monte Carlo sims describe data well
- Resolution as expected
  - $\sigma_M(J/\psi) = 210$ MeV/c^2
  - J/ψ to ψ' separation
- Drell-Yan mass region: > 4.5 GeV/c^2
- Invariant mass spectra for LH_2 and DH_2 look very similar

Event Selection & Reconstruction



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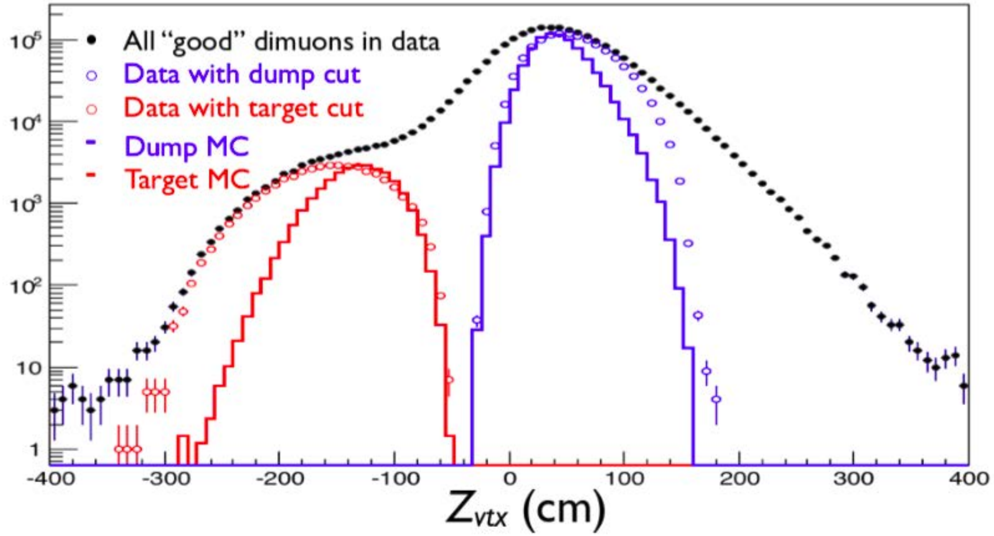
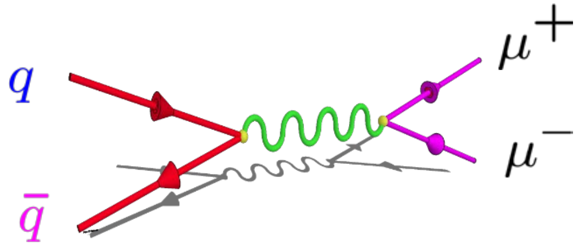
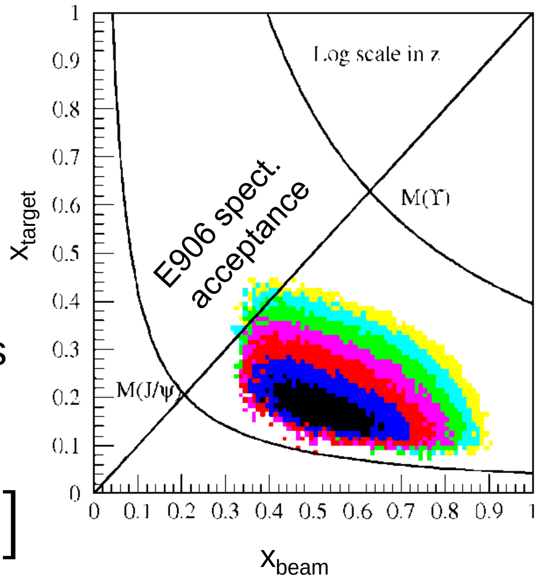


- good Target/Dump separation
- pointing resolution poor along beam axis
- dominated by random coincidences

Fixed Target Drell-Yan: Sensitivity to sea quarks





- Cross section: convolution of beam and target parton distributions

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

u-quark dominance
$(2/3)^2$ vs. $(1/3)^2$

acceptance limited
(Fixed Target, Hadron Beam)

beam: valence quarks at high x

target: sea quarks at low/intermediate x

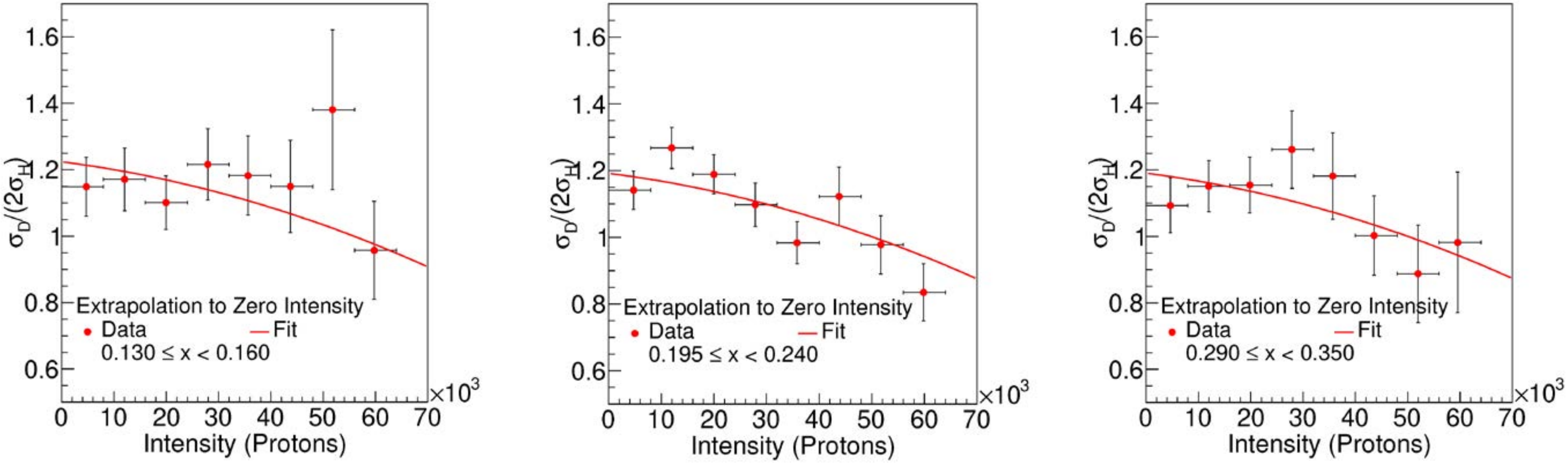
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Analysis Challenge

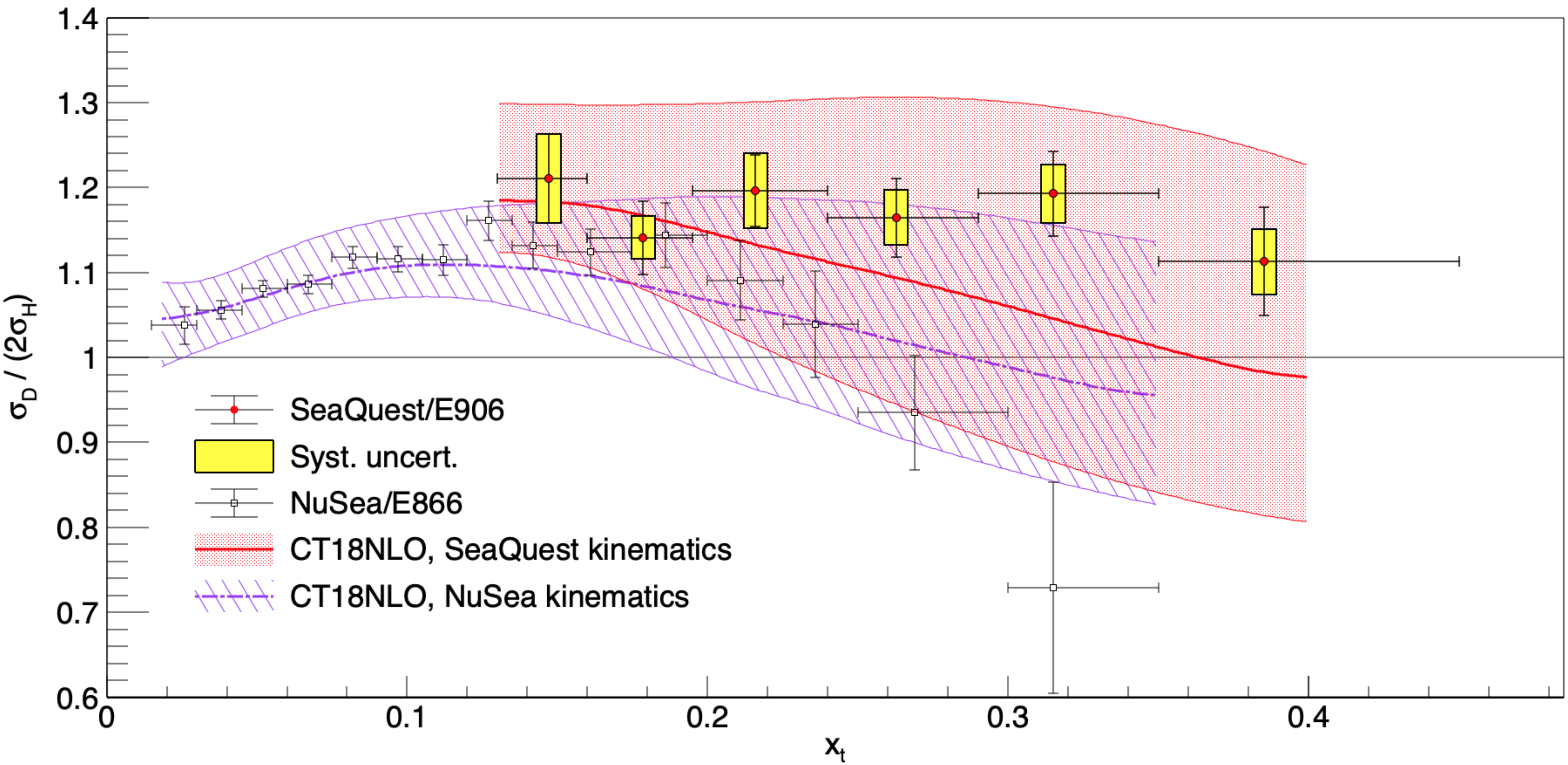
- Neutrino program extracts full beam from Main Injector in ~ 1 ms
- SeaQuest uses slow-spill extraction for 4 s every 60 s
- **Primary challenge**: large fluctuations in the bunch beam intensity
  - variation in track reconstruction efficiency
  - change in rate of accidental coincidences
- Remedy options:
  - reject all events above a certain (low) threshold (absorb remainder into syst. error)
    - large impact on stat. error
  - model each effect in MC, parametrize effect, and apply to data
    - syst. effect of model and any still unknown effects grows too large?
  - fit ratio of final (ie. lumi-corrected) yields on LH_2(x,I) and LD_2(x,I) to a functional form -> extrapolate to zero intensity
    - retain full statistical power of the data, w/o need to model every effect

Analysis Challenge

- Neutrino program extracts full beam from Main Injector in ~ 1 ms
- SeaQuest uses slow-spill extraction for 4 s every 60 s
- **Primary challenge**: large fluctuations in the bunch beam intensity
  - variation in track reconstruction efficiency
  - change in rate of accidental coincidences
- Remedy:
  - fit ratio of final (ie. lumi-corrected) yields on $LH_2(x,I)$ and $LD_2(x,I)$ to a functional form -> extrapolate to zero intensity
    - data alone are being used to measure and correct for the intensity dependence
    - χ^2 / dof = 38.7 / 40 for the simultaneous fit of all five x_t bins

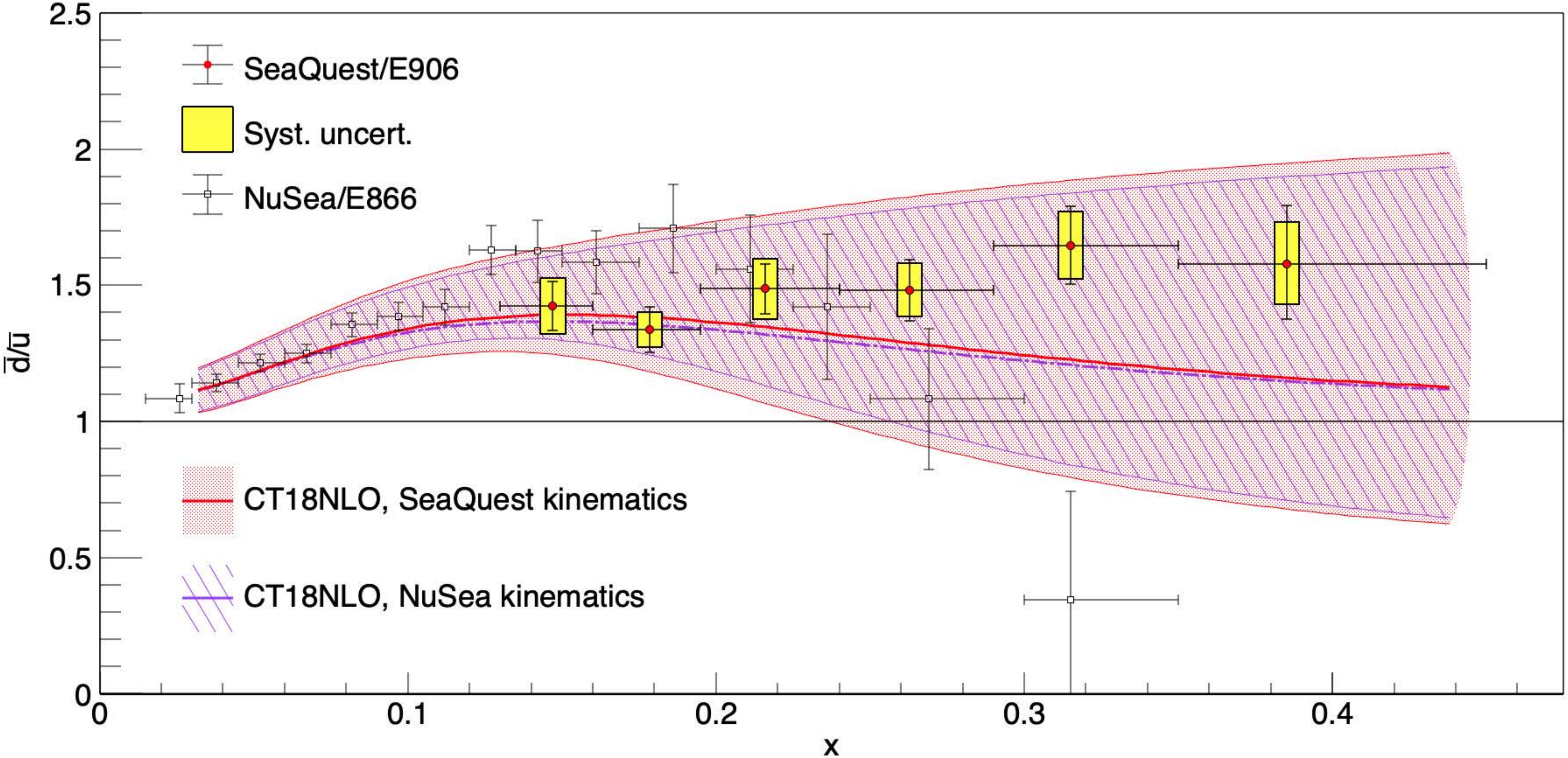


SeaQuest Cross Section Ratio



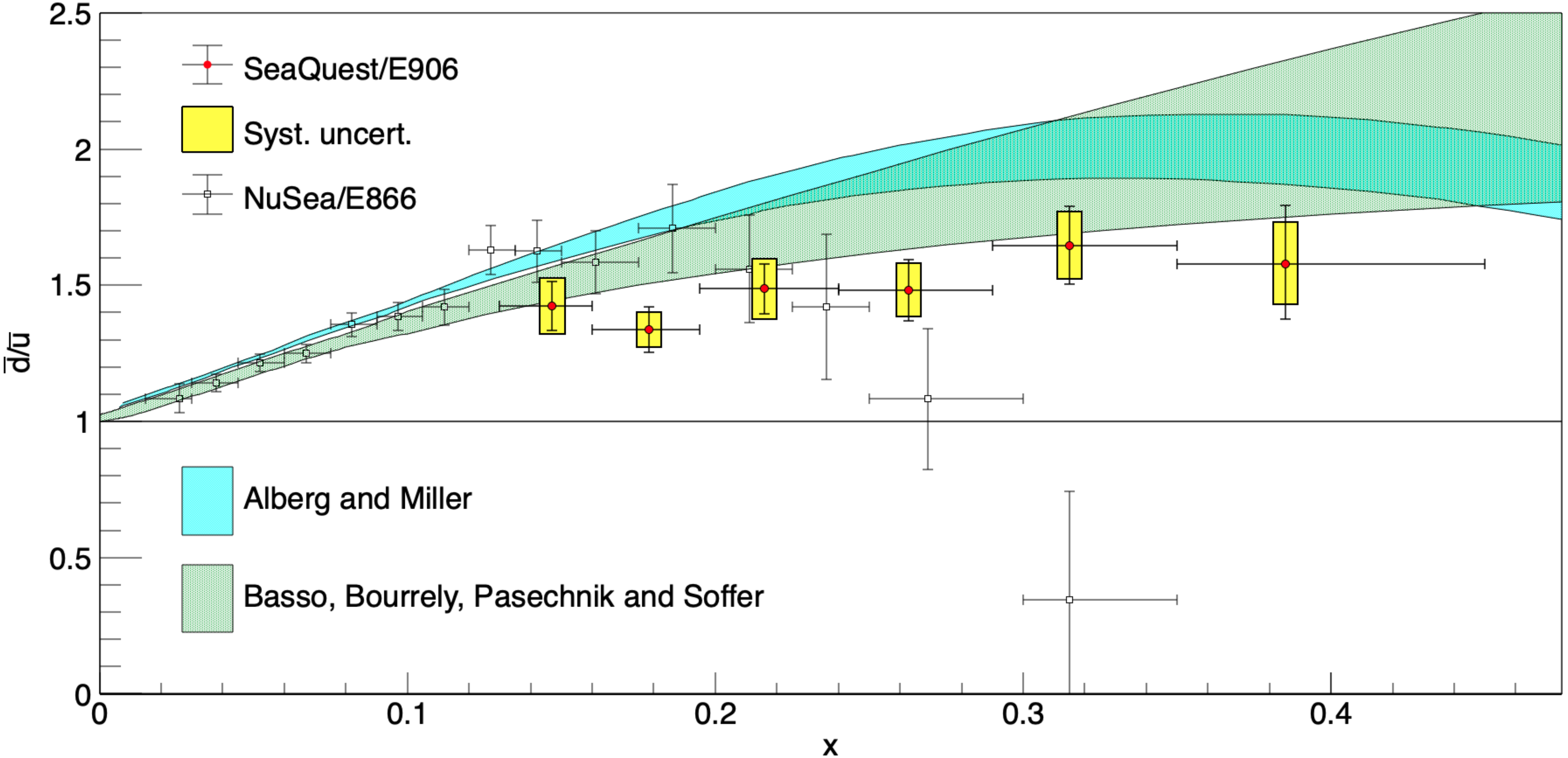
- different kinematics and Q^2 for E866 & SeaQuest data sets
  - E866 data at Q^2 = 54 GeV^2
  - SeaQuest data at $Q^2 \approx 29$ GeV^2
  - different beam energies & acceptances -> slightly different x_b distributions
- cross section ratios calculated in NLO with CT18 parton distribution

SeaQuest d_bar / u_bar extraction



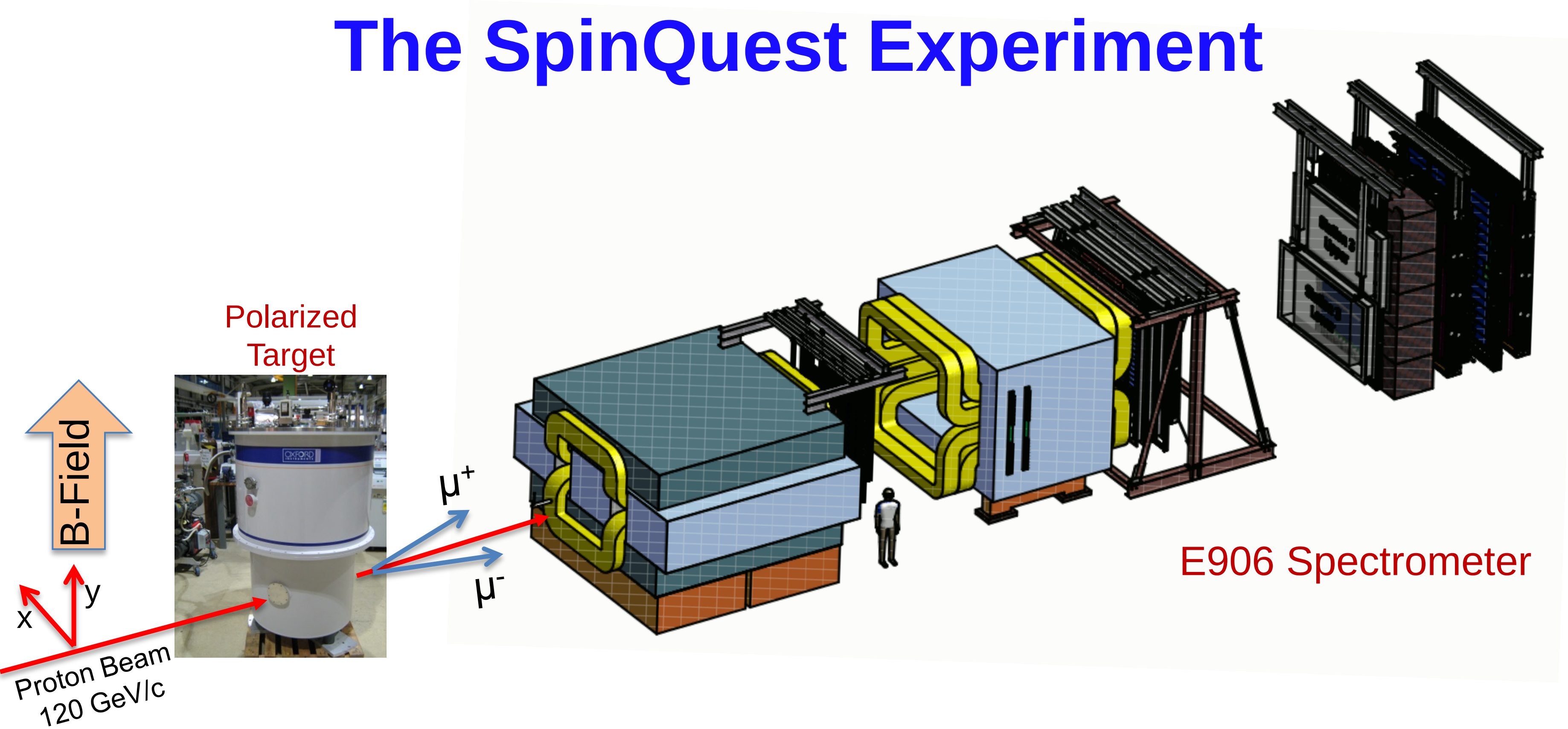
- Different Q^2 for E866 and SeaQuest
  - difference should be insignificant
- why is there disagreement at high x?
  - no explanation found yet

SeaQuest d_bar / u_bar extraction



- SeaQuest data reasonably well described by meson-baryon model & statistical model
  - those predictions do NOT support the drop seen at high x for E866 data
- data will ultimately be compared to Lattice QCD calculations

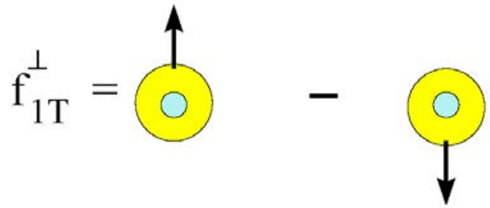
The SpinQuest Experiment



- replace unpolarized E906 target w/ polarized target
  → LANL and UVA effort
- move polarized target ~3m upstream
  → improves target-dump separation
  → moves acceptance to lower x_2

L_{int} = 1.82 *10^{42}/cm^2 NH_3 / 2.11 *10^{42}/cm^2 ND_3 for 2 years

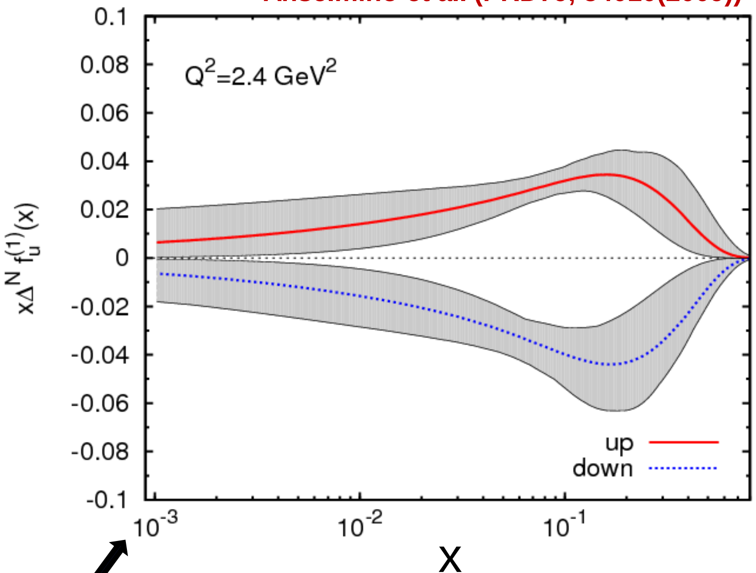
Sivers Function



operator structure: horizontal direction is that of the virtual boson probing the distribution

- **The main physics focus for SpinQuest is on the Sivers Function**
- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- Sivers function is odd under “naïve time-reversal”
  - ➡ operation that reverses all vectors and pseudo-vectors but does not exchange initial and final states
- leads to
  - ➡ $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS
  - ➡ $\sin\phi_b$ asymmetry in Drell-Yan
- measured in SIDIS (HERMES, COMPASS, Jlab)

Anselmino et al. (PRD79, 54010(2009))

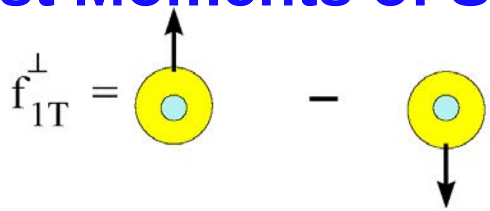


First moment of Sivers functions:

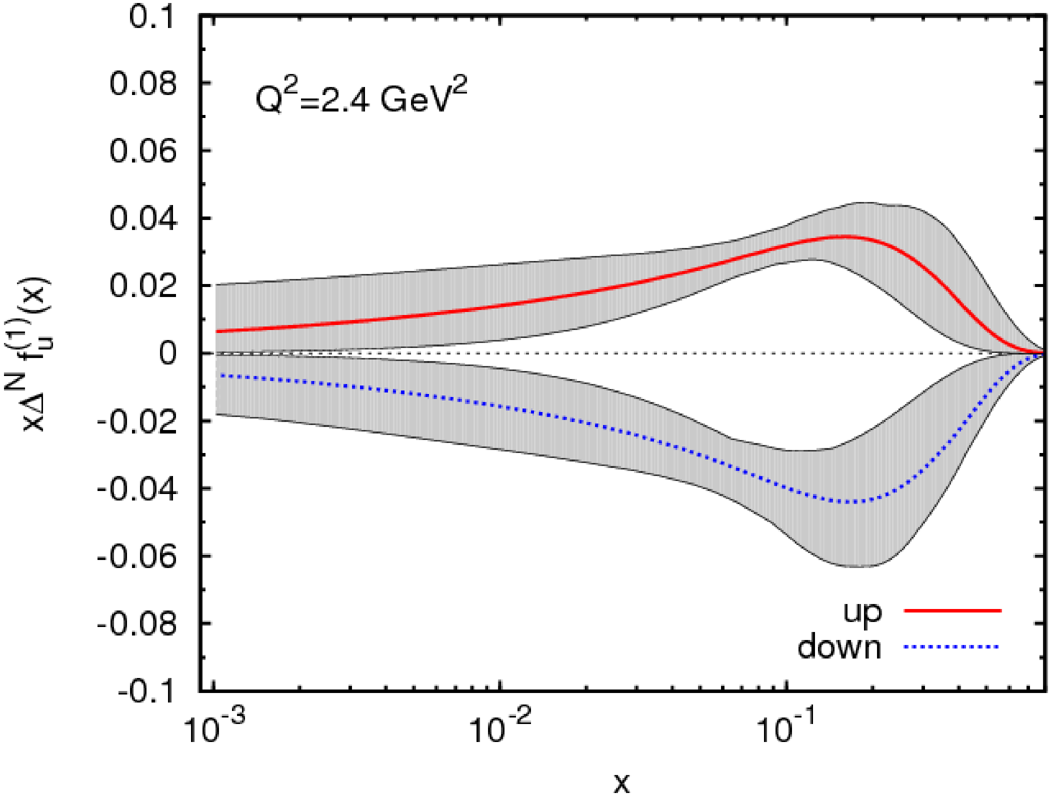
➡ u- and d-Sivers have opposite signs, of roughly equal magnitude

➡ u-Sivers slightly smaller than d-Sivers

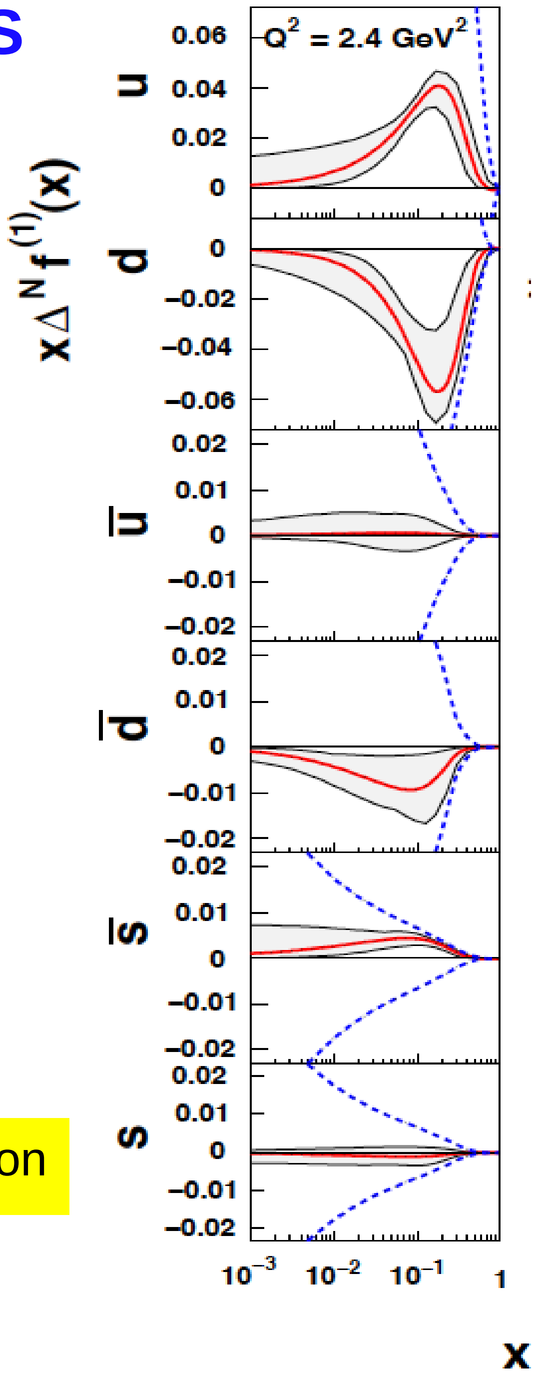
First Moments of Sivers Function from SIDIS



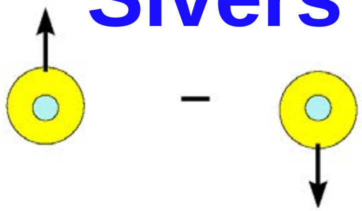
Anselmino et al. (PRD79, 54010(2009))



existing SIDIS data poorly constrain sea-quark Sivers function



Sivers Function and Spin Crisis

$f_{1T}^{\perp} =$ 

cannot exist w/o quark **OAM**

But: connection b/w Sivers function and OAM is yet model-dependent

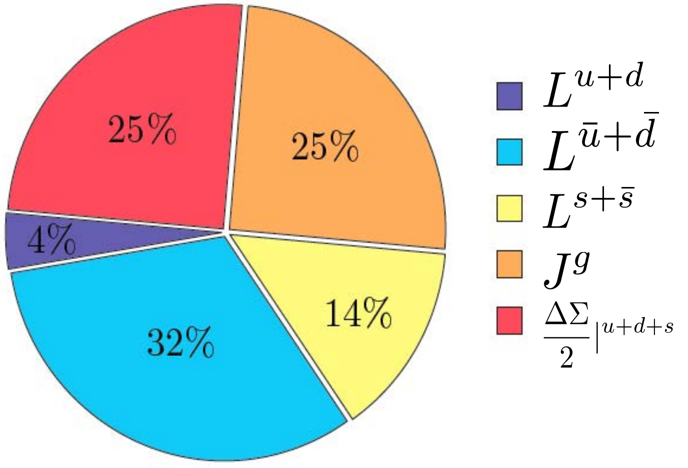
What does data tell us?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$$\tfrac{1}{2}\Delta\Sigma \approx 25\%; \quad \Delta G \approx 20\%$$

$$L \approx \text{ unmeasured}$$

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

$2\ L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\ J_g \approx 25\%$

K.-F. Liu *et al* arXiv:1203.6388

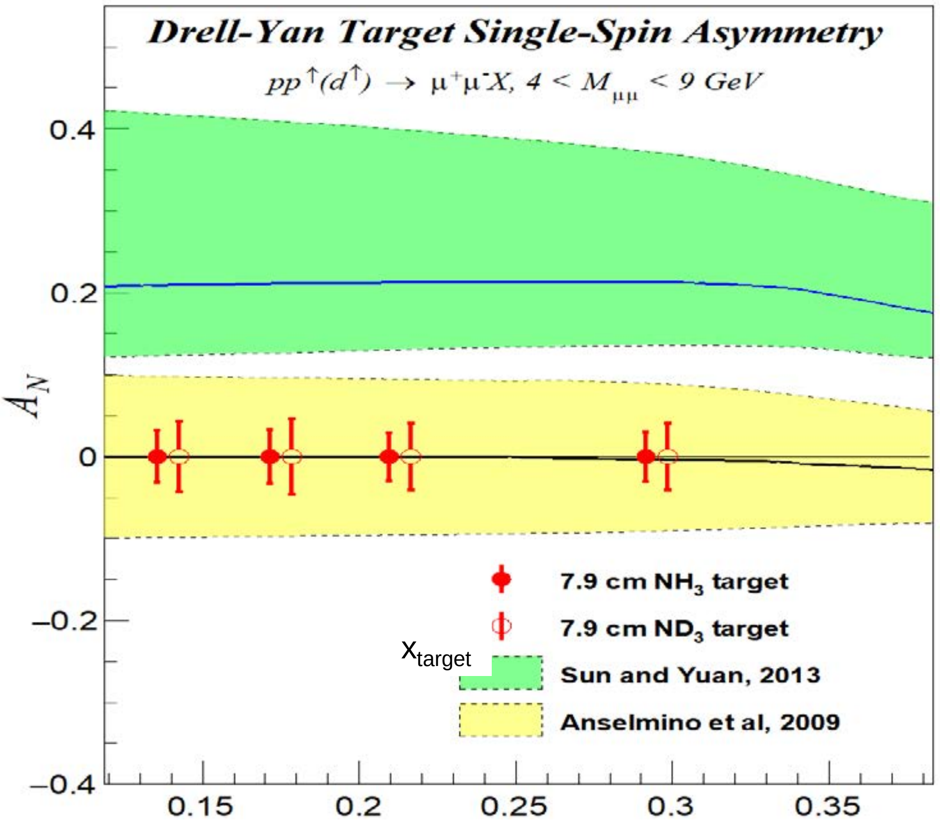
How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD: Transverse Momentum Distribution

$$A_N^{DY} \propto \frac{u(x_b)\cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b)\cdot \bar{u}(x_t)}$$

Projected DY Transverse Single Spin Asymmetry

E1039 proposal



- existing SIDIS data poorly constrain sea-quark Sivers function (Anselmino)
- significant Sivers asymmetry expected from meson-cloud model (Sun & Yuan)

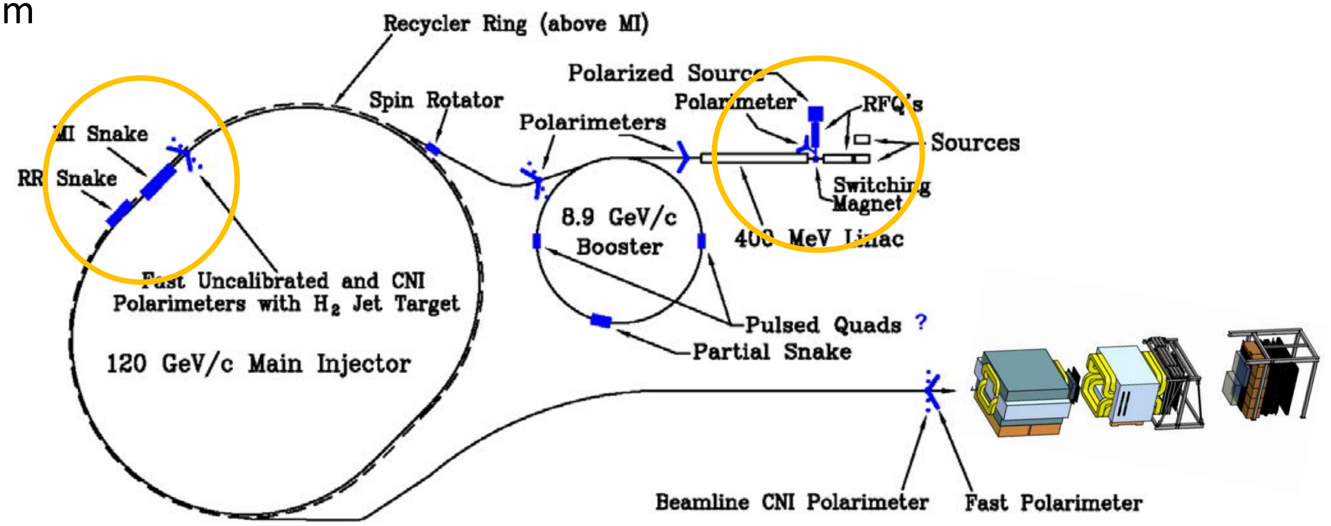
- **determine sign and value of sea quark Sivers asymmetry**
- **measure sea quark Sivers flavor dependence (H & D targets)**

If $A_N \neq 0$, **major discovery**:
"Smoking Gun" evidence for $L_{\bar{u},\bar{d}} \neq 0$

Let's Polarize the Beam at Fermilab (E-1027)

The Plan:

- Use SpinQuest Spectrometer
- Add polarized beam



- **Fermilab (best place for polarized DY):**

  $\longrightarrow$ very high luminosity, large x-coverage (primary beam, fixed target)

- **Measure sign-change in Sivers Function:**

  $\longrightarrow$ sign, size and shape of Sivers function

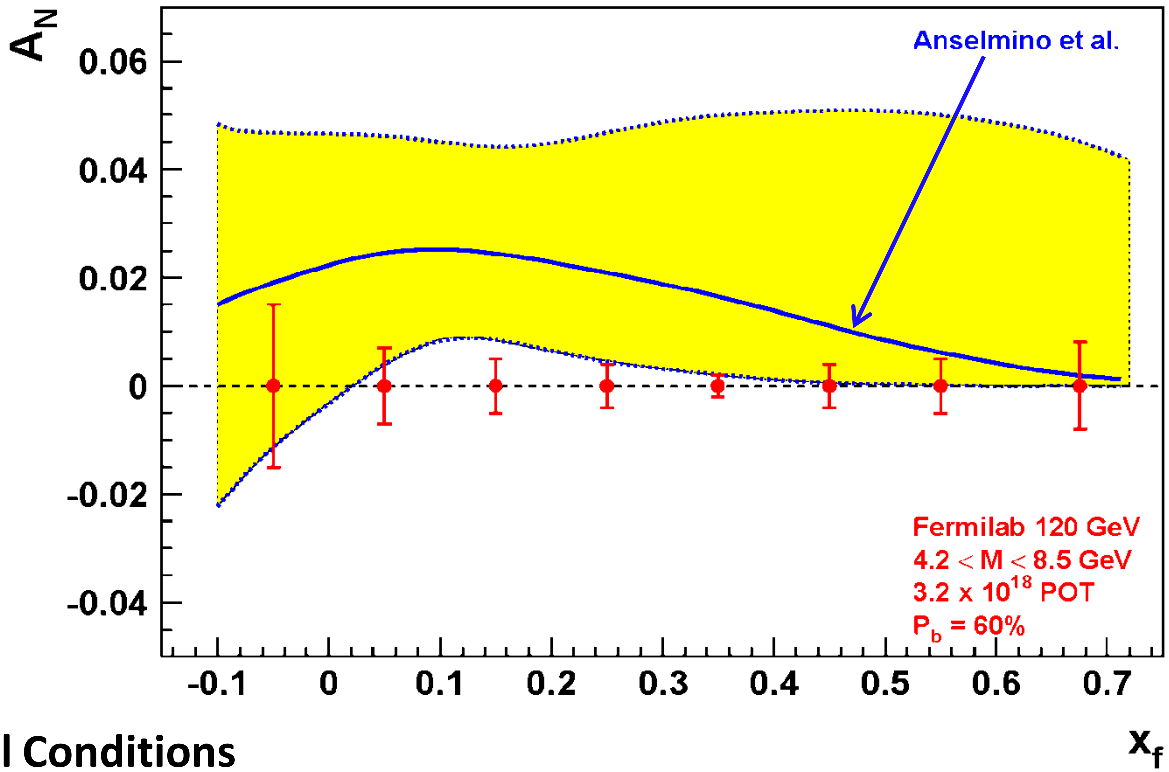
  $\longrightarrow$ and TMD evolution

$$f_{1T}^{\perp}\Big|_{SIDIS} = - f_{1T}^{\perp}\Big|_{DY}$$

- **Access to valence quarks**

Expected Precision from E-1027 at Fermilab

- Probe **Valence Quark Sivers Asymmetry** with a polarized proton beam at SeaQuest



1.3 Mio DY events with no dilution

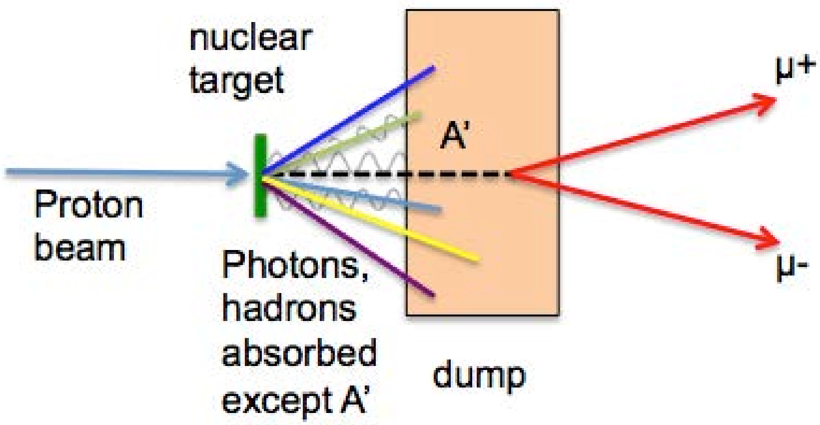
- **Experimental Conditions**
  - same as SpinQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: I_{av} = 15 nA)
  - 3.2×10^{18} total protons for 5×10^5 min: (= 2 yrs at 50% efficiency) with P_b = 60%

Can measure not only sign, but also the size & probably shape of the Sivers function!

as well as TMD evolution!

Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment

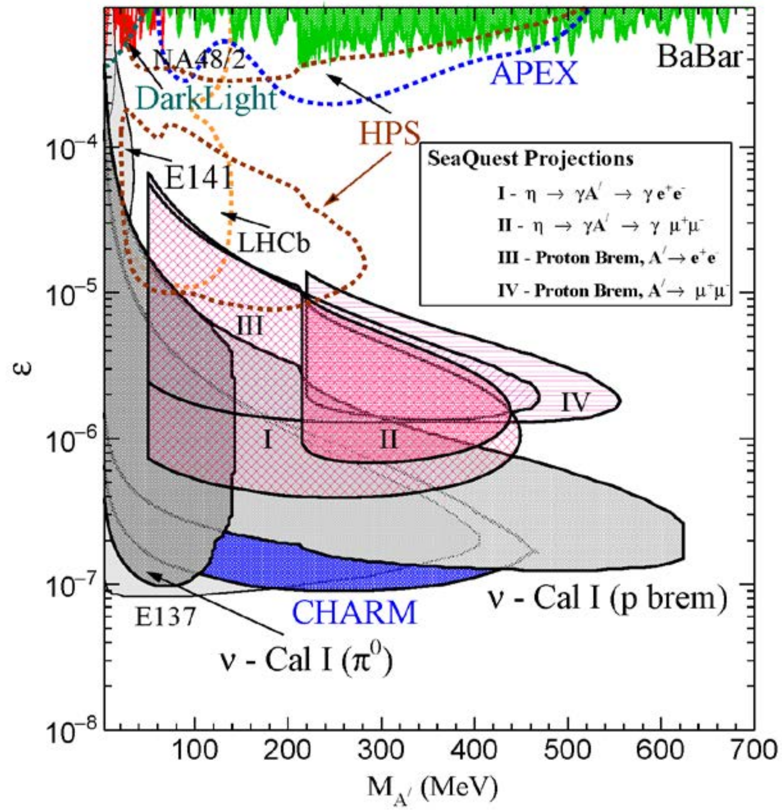


- Minimal impact on Drell-Yan program

  → run parasitically during E906/E1039

$$l_o \approx \frac{0.8\,cm}{N_{eff}}\left(\frac{E_o}{10\,GeV}\right)\left(\frac{10^{-4}}{\varepsilon}\right)^2\left(\frac{100\,MeV}{m_{A'}}\right)^2$$

J. D. Bjorken et al, PRD **80** (2009) 075018



SeaQuest experimental parameters:

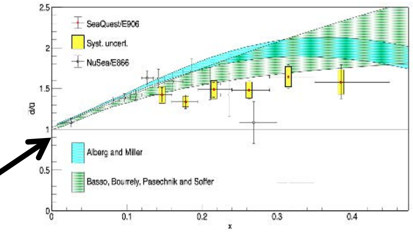
→ E_0 = 5 - 110 GeV for Proton Bremsstrahlung

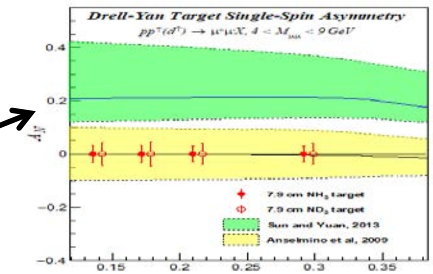
→ N_{eff} = 2

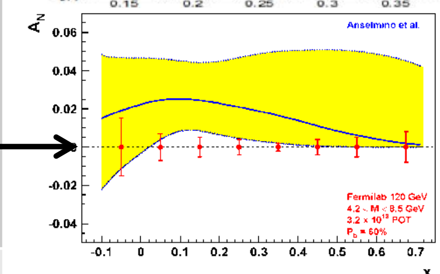
→ l_0 = 0.17m – 5.95m

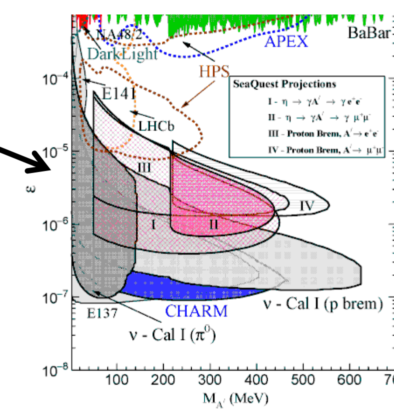
Fermilab - Summary and Outlook

Experiments	Timeline	Interactions	Physics
E906 (SeaQuest)	2014 - 2017	p + LH_2 / LD_2 p + C, Fe, W	dbar/ubar, nucl dep quark dE/dx
E1039 (SpinQuest)	2021 – 2023+	p + pol NH_3 p + pol ND_3	sea-quark Sivers, TMD
E1027	(?)	pol p + LH_2 or pol p + pol NH_3	valence quark Sivers, sign change, TMDs
E1067 (DarkQuest)	2016 - 2023+ (para.) 2023+ (dedicated?)	p + any target	dark photon, dark Higgs, dark Z, …









Summary & Outlook

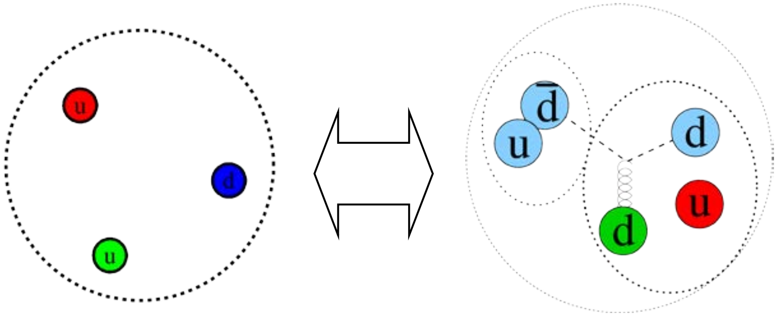
- SeaQuest confirms that nature prefers anti-down to anti-up quarks in proton
  - ⟶ preference for anti-down quarks persists even in previously unmeasured domains
  - ⟶ in fact, measurements show that there are more anti-down than anti-up quarks up to the quarks' fractional momenta of almost 0.5
- However, inconsistency between SeaQuest and E866 above $x > 0.3$ is unresolved and requires further study
  - ⟶ future experiments need precision at least comparable to that of Seaquest
  - ⟶ nevertheless, precision of current results has potential implications for collider experiments that are searching for physics BSM of particle physics
- Origin of the observed antimatter asymmetry remains elusive though
  - ⟶ will ultimately be compared to Lattice QCD calculations
  - ⟶ be a good test for QCD
- Exciting future opportunities at Fermilab for fundamental study of proton
  - ⟶ what role do sea quarks play in resolving the spin puzzle?
  - ⟶ is there significant orbital angular momentum?
  - ⟶ does TMD formalism work? Does Sivers function change sign (but keep shape /size)?
- Expand SpinQuest physics reach to Dark Photon search?

Thank You

Non-perturbative Models: Pion Cloud

- Meson Cloud in the nucleon Sullivan process in DIS

$$|p\rangle = |p_0\rangle + \alpha|N\pi\rangle + \beta|\Delta\pi\rangle + \gamma|\Lambda K\rangle + \ldots$$



- In its simplest form, Clebsch-Gordon Coefficients and πN, πΔ couplings

- $\alpha: \quad |N\pi\rangle = \begin{cases} |p,\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |n,\pi^+\rangle & u\bar{d} & \sqrt{\frac{2}{3}} \end{cases}$

- $\beta: \quad |\Delta\pi\rangle = \begin{cases} |\Delta^{++},\pi^-\rangle & d\bar{u} & \sqrt{\frac{1}{2}} \\ |\Delta^{+},\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |\Delta^{0},\pi^+\rangle & u\bar{d} & \sqrt{\frac{1}{6}} \end{cases}$

- predicts

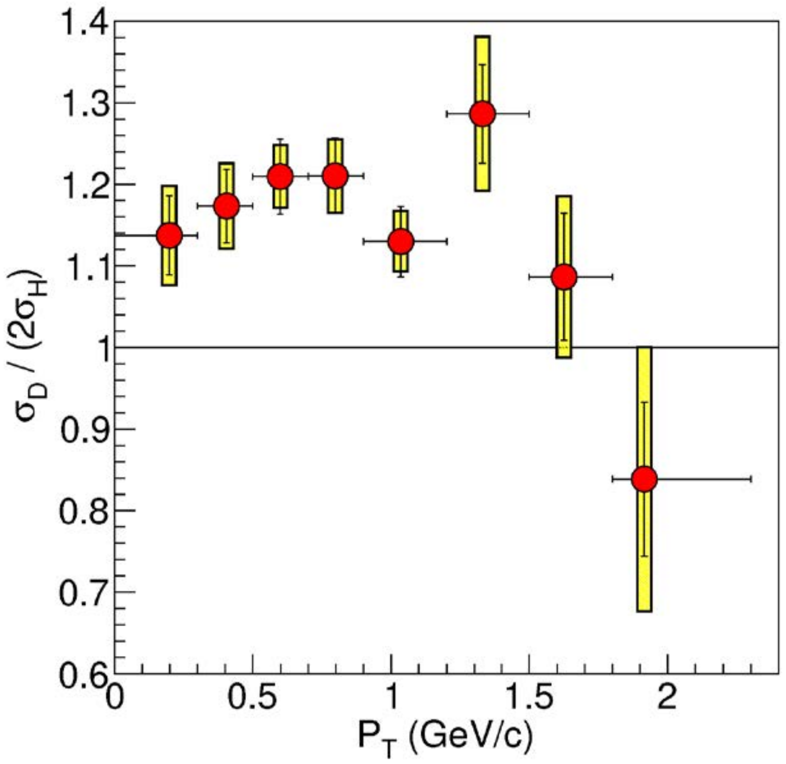
$$\bar{d} \geq \bar{u}$$

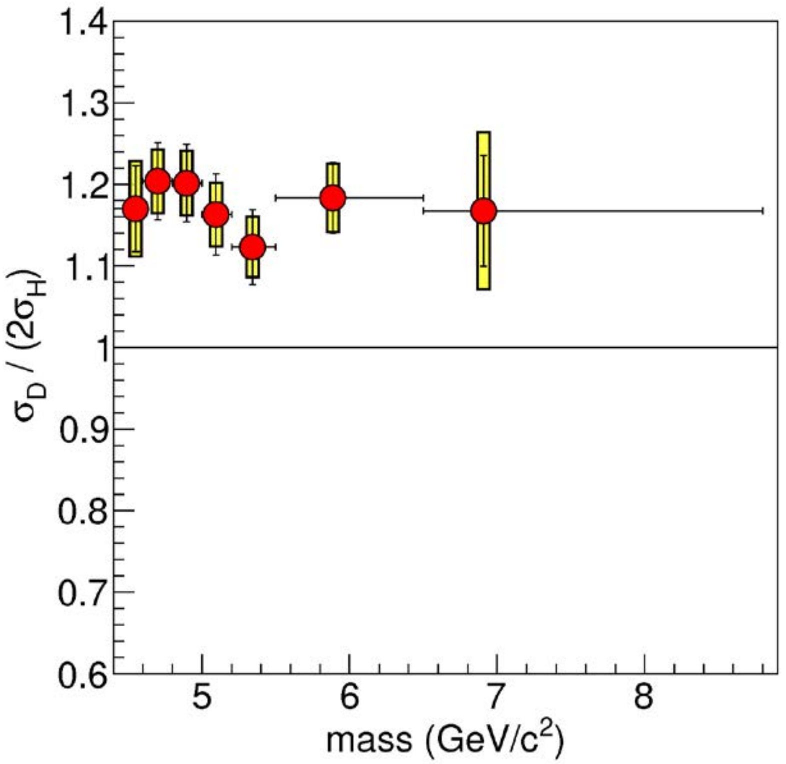
- cannot have

$$\bar{d} \leq \bar{u}$$

Acceptance

- **Acceptance is very similar for LH_2 and LD_2 targets**
  - both M and P_T (for all but the very highest P_T bins) distributions have same shapes

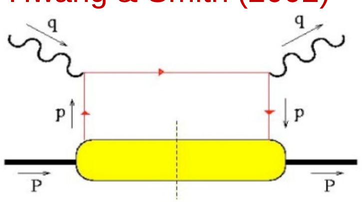




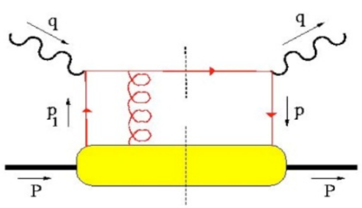
Sivers Function

- T-odd observables
  - ➡ SSA observable $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$ odd under naïve Time-Reversal
  - ➡ since QCD amplitudes are T-even, must arise from interference (between spin-flip and non-flip amplitudes with different phases)
- should all be completely suppressed in perturb hard scattering subprocess xsec
- A T-odd function like $f_{1T}^{\perp}$ must arise from interference (How?)

Brodsky, Hwang & Smith (2002)

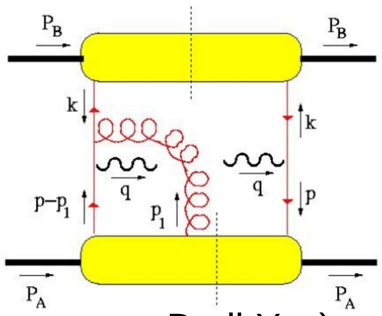


can interfere with



and produce a T-odd effect!
(also need $L_z \neq 0$)

- ➡ soft gluons: “gauge links” required for color gauge invariance
- ➡ such soft gluon re-interactions with the soft wavefunction are final (or initial) state interactions … and maybe process dependent!
- ➡ leads to sign change: $f_{1T}^{\perp}\Big|_{SIDIS} = -\, f_{1T}^{\perp}\Big|_{DY}$



e.g. Drell-Yan)