Argonne NATIONAL LABORATORY

HOW SHOULD WE VIEW THE SEA: THREATENING OR CALM?

PAUL E REIMER
Physicist
Argonne Argonne National Laboratory

11 September 2018
Trento, IT

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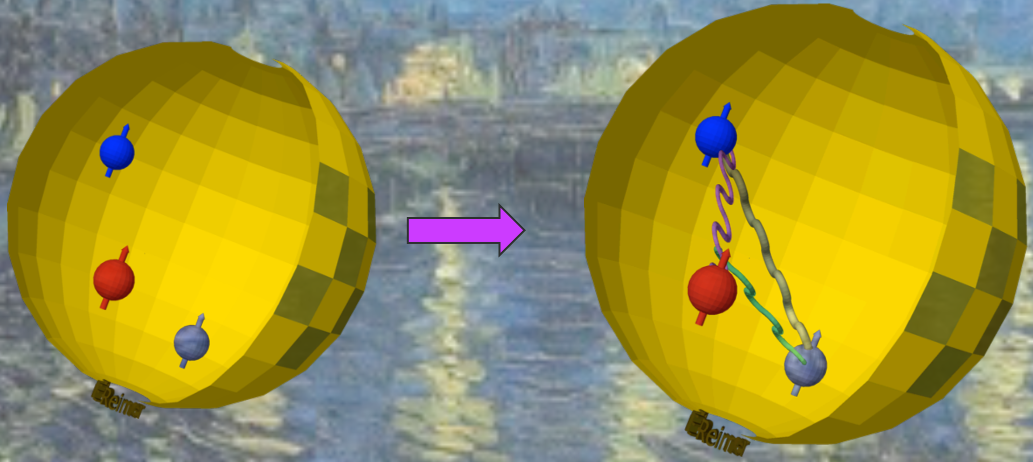
U.S. DEPARTMENT OF ENERGY

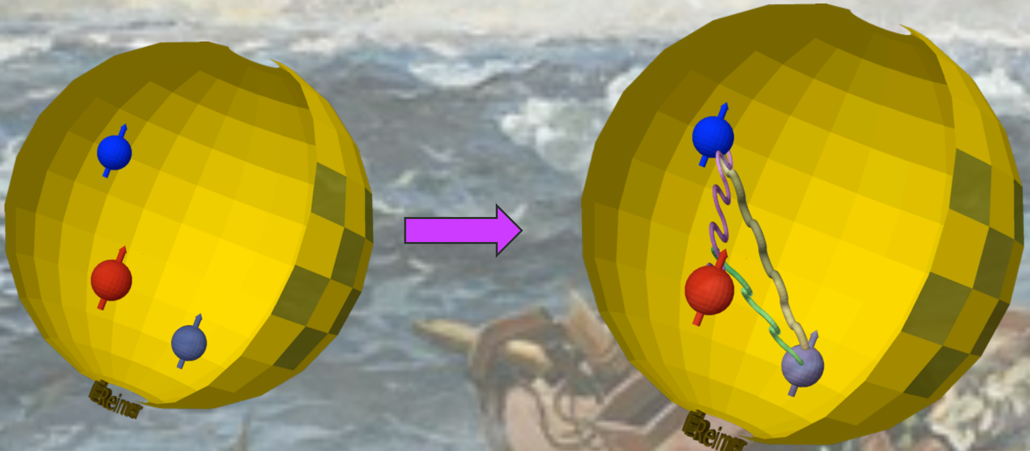
SAILING THE PROTON SEA

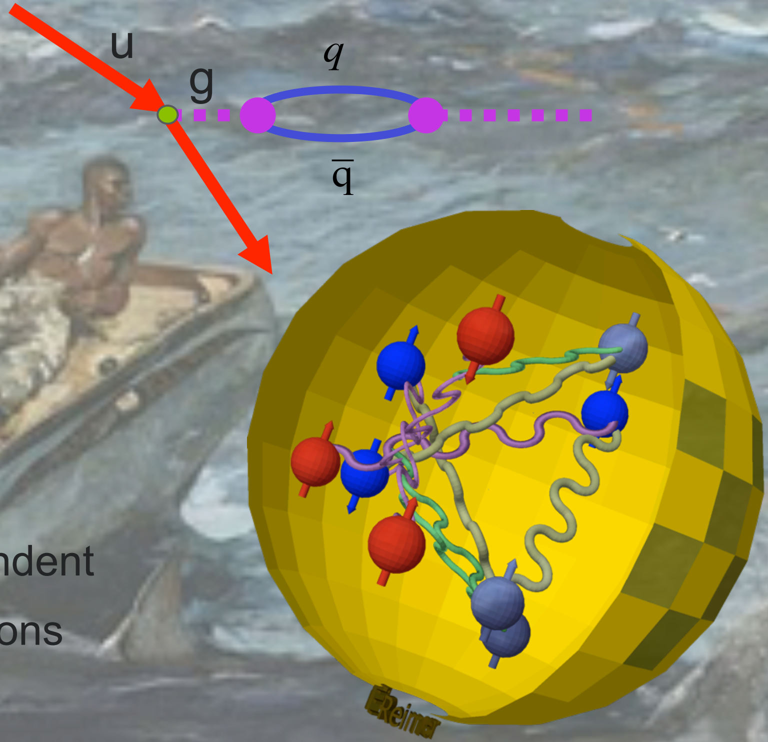


Conventional thought:

- Gluon splitting leads to sea
- Sea is flavor symmetric since splitting is flavor independent
- Unfortunately this picture doesn’t agree with observations

SAILING THE PROTON SEA





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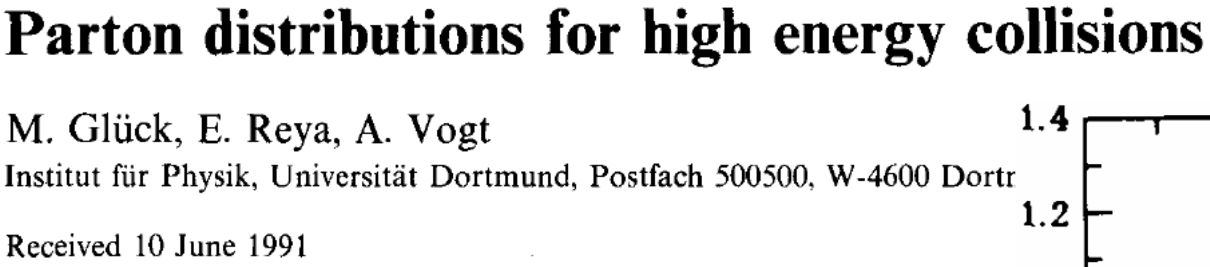
EVIDENCE FOR A TURBULENT SEA (I).

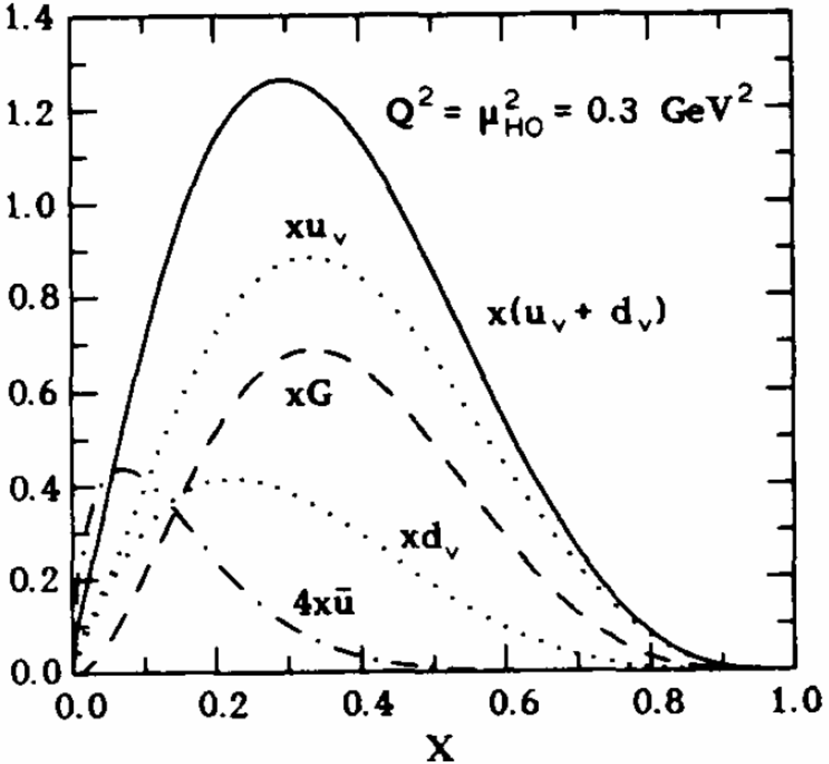


Parton distributions for high energy collisions

M. Glück, E. Reya, A. Vogt

Institut für Physik, Universität Dortmund, Postfach 500500, W-4600 Dortr

Received 10 June 1991



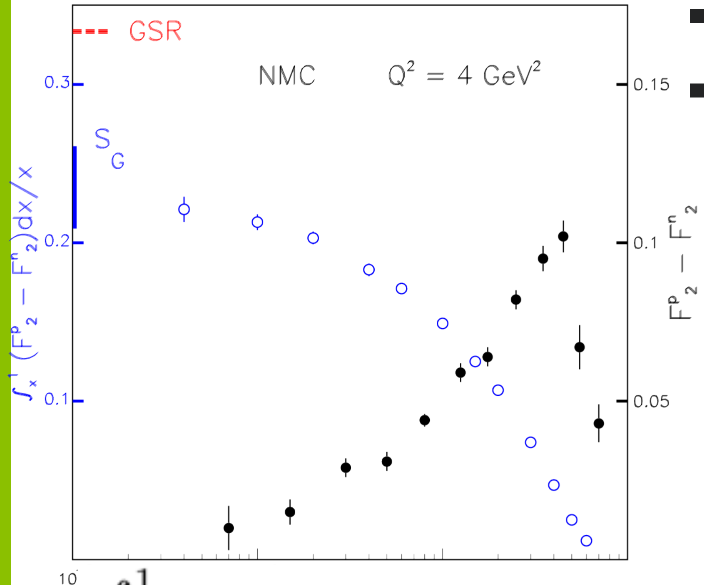
Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3\ GeV^2$. *The predicted extrapolations are uniquely determined by the requirement of a valence-like structure of all parton distributions at some low resolution scale . . . .* *[emphasis mine]*

EVIDENCE FOR A TURBULENT SEA (II).

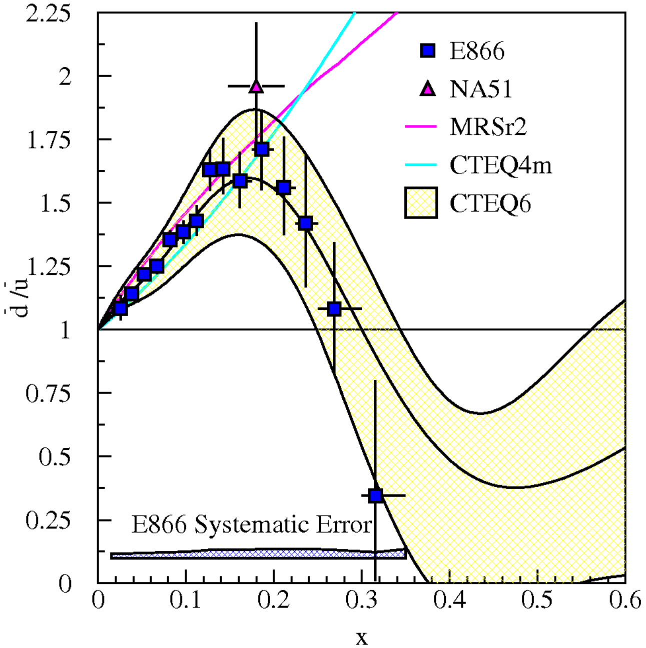
$$\int_0^1 \left[F_2^p(x) - F_2^n(x)\right] dx = \frac{1}{3}$$

Gottfried Sum Rule

- NMC 1994
- Integral over all x

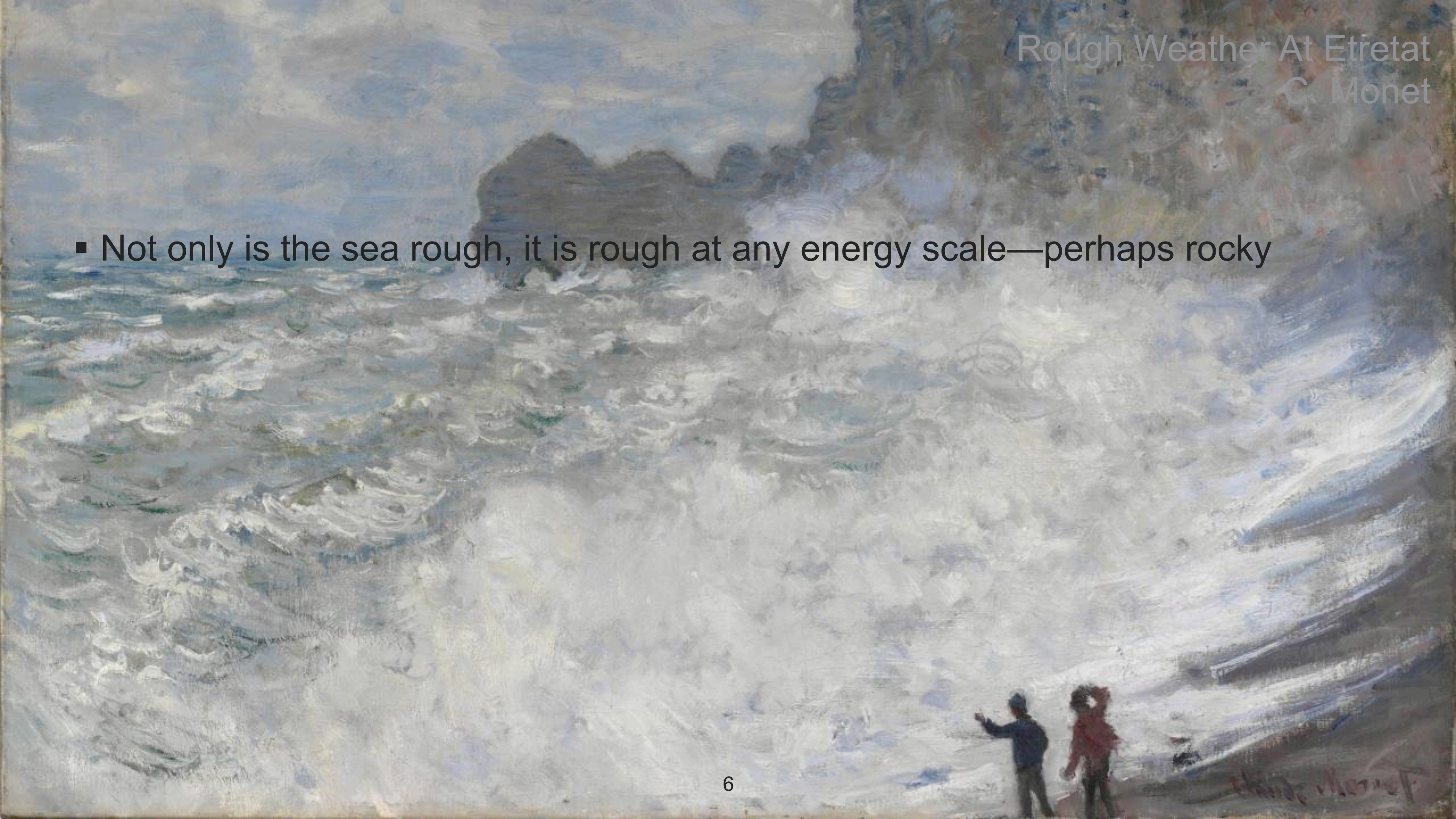


$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$



Drell-Yan

- CERN NA51
- Fermilab E866
- $\bar{d}(x) \neq \bar{u}(x)$



Rough Weather At Etretat
C. Monet

- Not only is the sea rough, it is rough at any energy scale—perhaps rocky

FROM WHENCE THE SEA CREATED?

- Gluon splitting component is symmetric
  - DGLAP

$$\bar{d}(x) = \bar{d}_{\rm pQCD}(x) + \bar{d}_{\pi}(x)$$

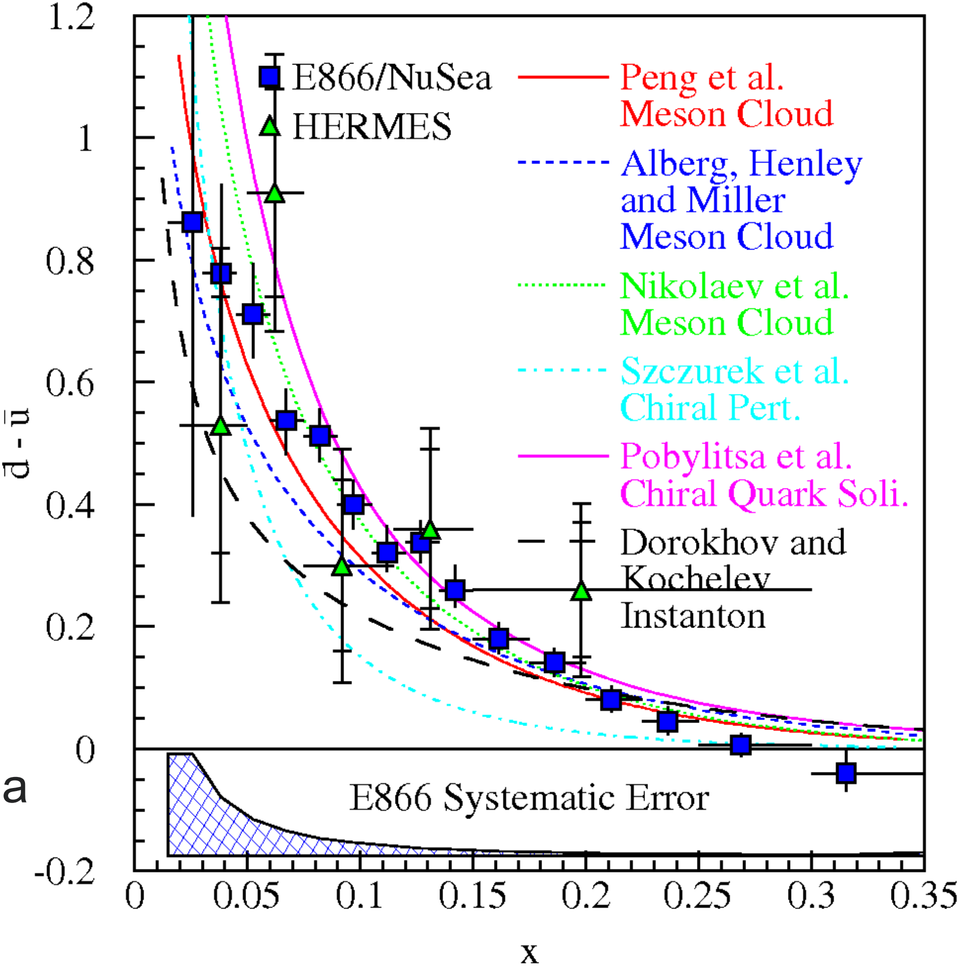
$$\bar{u}(x) = \bar{u}_{\rm pQCD}(x) + \bar{u}_{\pi}(x)$$

$$\bar{q}_{\rm pQCD}(x) = \bar{d}_{\rm pQCD}(x)$$

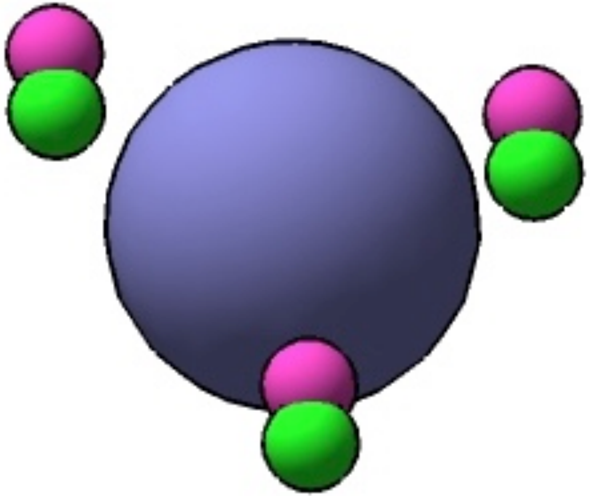
$$= \bar{u}_{\rm pQCD}(x)$$

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

  - Non-perturbative component of the sea



MODELS RELATE ANTIQUARK FLAVOR ASYMMETRY AND SPIN



- Meson Cloud in the nucleon—Sullivan process in DIS

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

Antiquarks in spin 0 object → No net spin

- Statistical Parton Distributions

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

- Chiral Quark models—effective Lagrangians

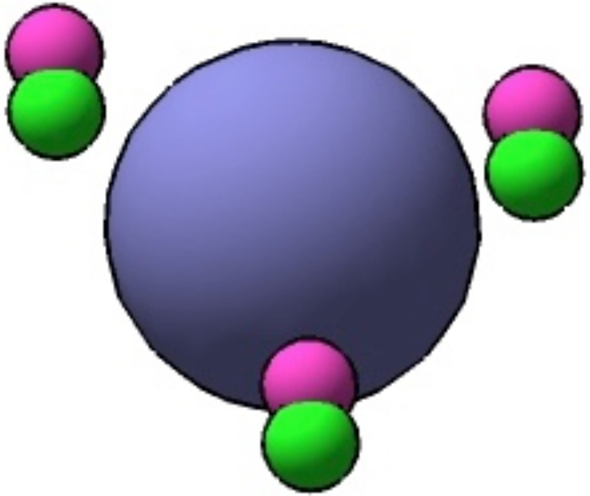
$$\langle q|\bar{q}\rangle = \left[1 - \frac{3a}{2}\right]\langle q|\bar{q}\rangle + \frac{3a}{2}\langle q\pi|\bar{q}\pi\rangle$$

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

- Instantons

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

MESON CLOUDS AND SULLIVAN PROCESS

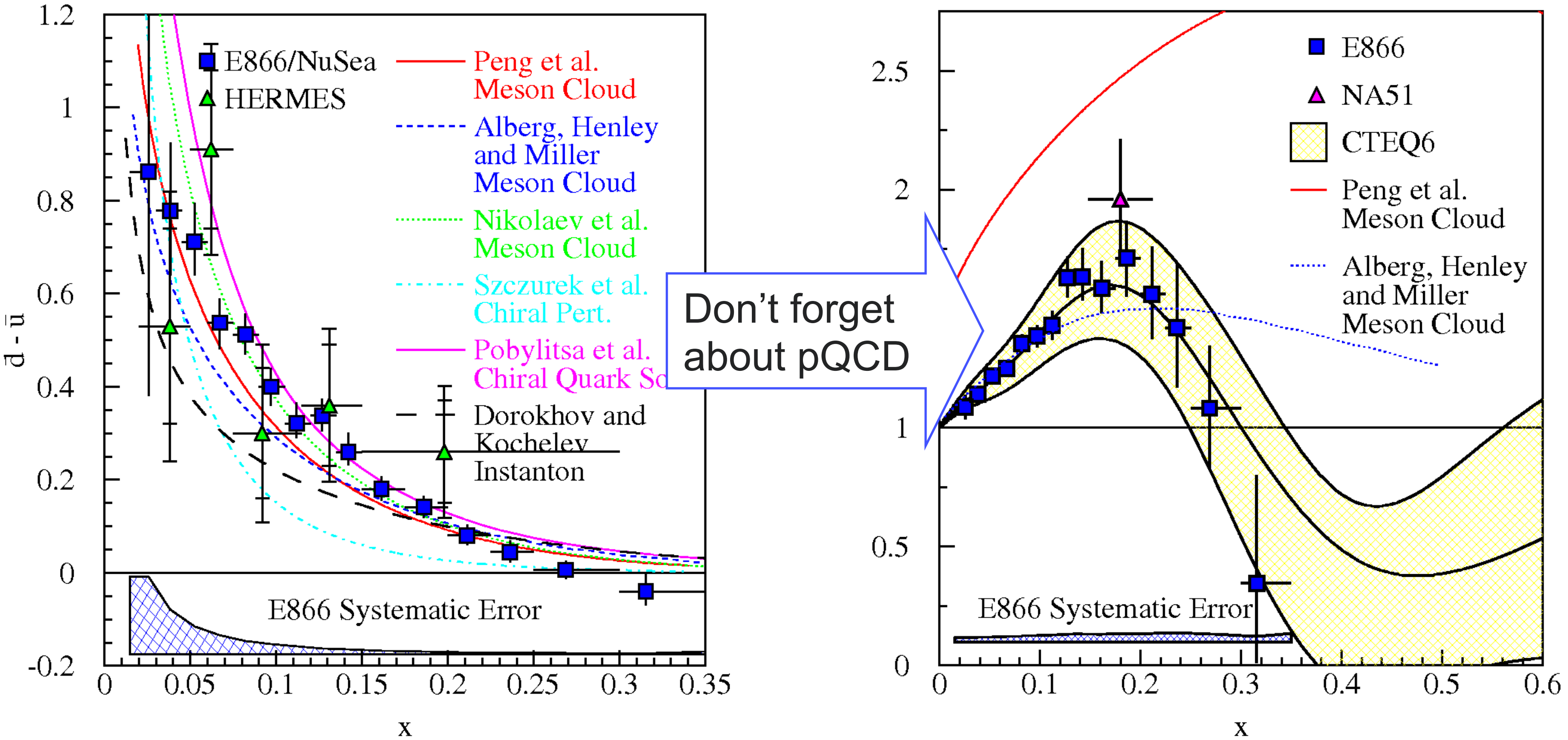


$$|p\rangle = |p_0\rangle + \alpha|N\pi\rangle + \beta|\Delta\pi\rangle + \gamma|\Lambda K\rangle + \ldots$$

- In its simplest form, Clebsch-Gordon coefficients and πN, πΛ couplings

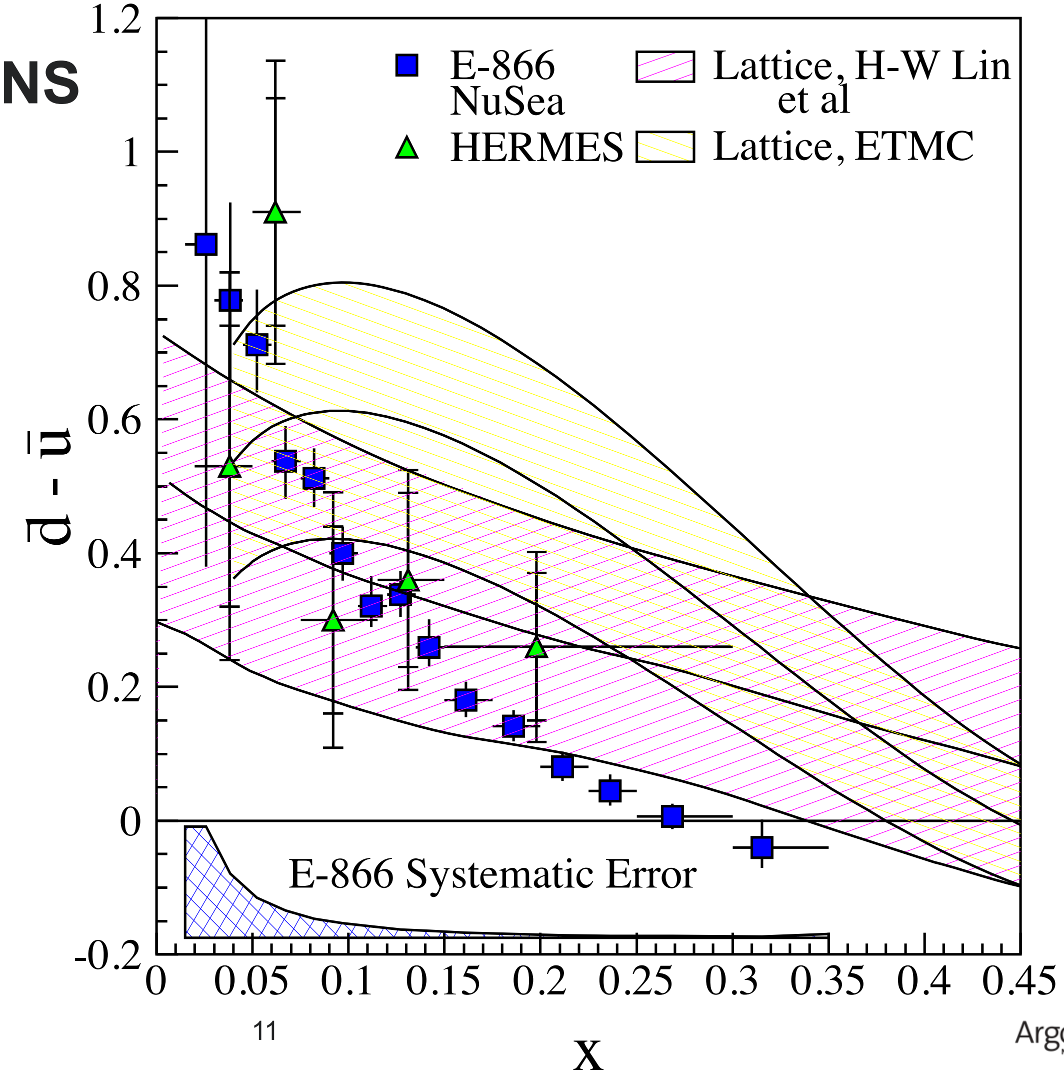
$$\bullet\ \alpha: \quad |N\pi\rangle = \begin{cases} |p,\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |n,\pi^+\rangle & u\bar{d} & \sqrt{\frac{2}{3}} \end{cases}$$

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



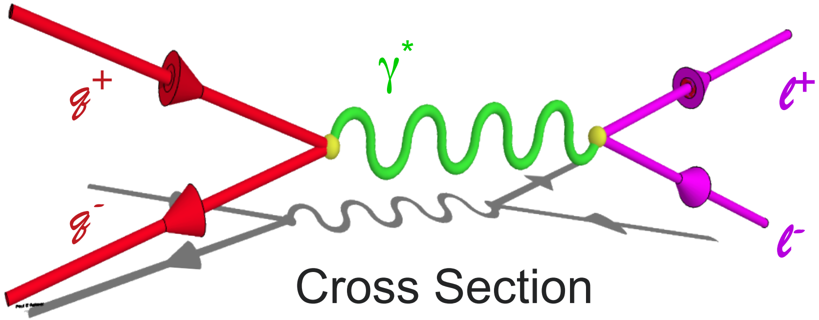
Don’t forget about pQCD

LATTICE COMPUTATIONS OF THE SEA



EXPLORING THE SEA => DRELL YAN

DRELL-YAN CROSS SECTION—SENSITIVITY TO SEA QUARKS



Cross Section

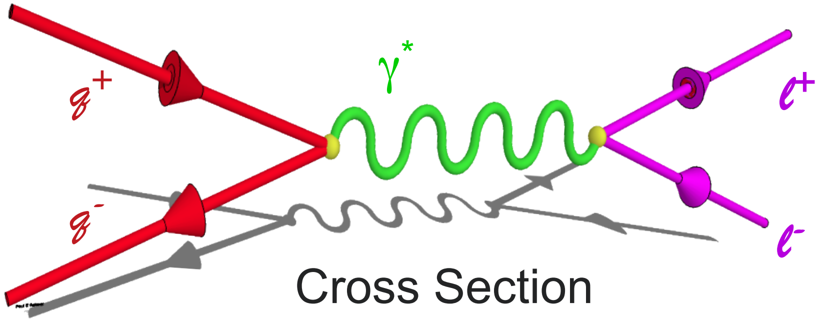
- Point-like scattering of spin-1/2 particles
- Convolute beam and target parton distributions

$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\ldots\}} \boxed{e_q^2} \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

u-quark dominance

$(2/3)^2$ vs. $(1/3)^2$

DRELL-YAN CROSS SECTION—SENSITIVITY TO SEA QUARKS



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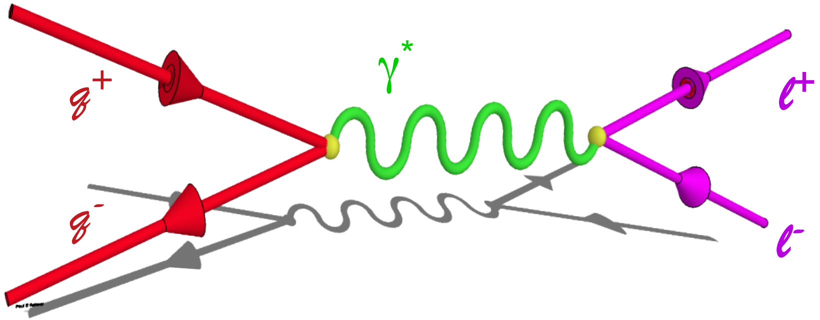
u-quark dominance

$(2/3)^2$ vs. $(1/3)^2$

- Point-like scattering of spin-1/2 particles
- Convolute beam and target parton distributions

Beam	**Sensitivity**	**Experiment**
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	**COMPASS**, J-PARC

DRELL-YAN CROSS SECTION—SENSITIVITY TO SEA QUARKS



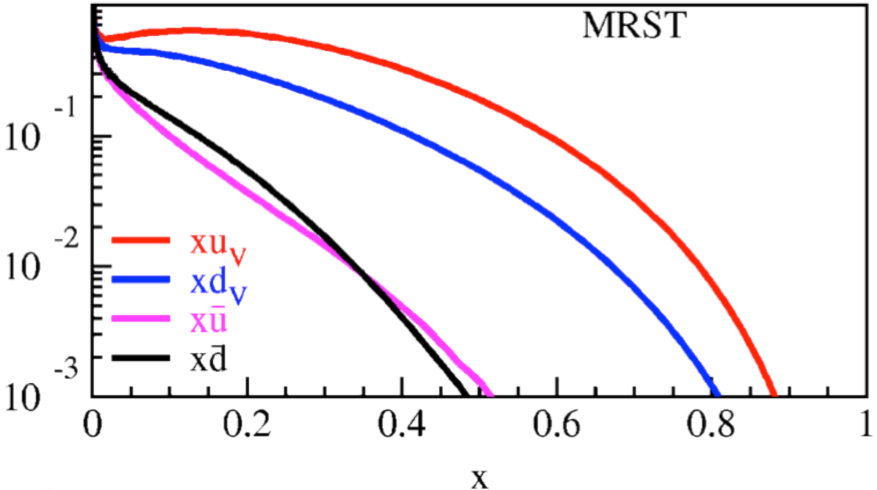
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} \boxed{e_q^2} \left[\bar{q}_t(x_t) q_b(x_b) + \cancel{\bar{q}_b(x_b) q_t(x_t)}\right]$$

u-quark dominance

$(2/3)^2$ vs. $(1/3)^2$

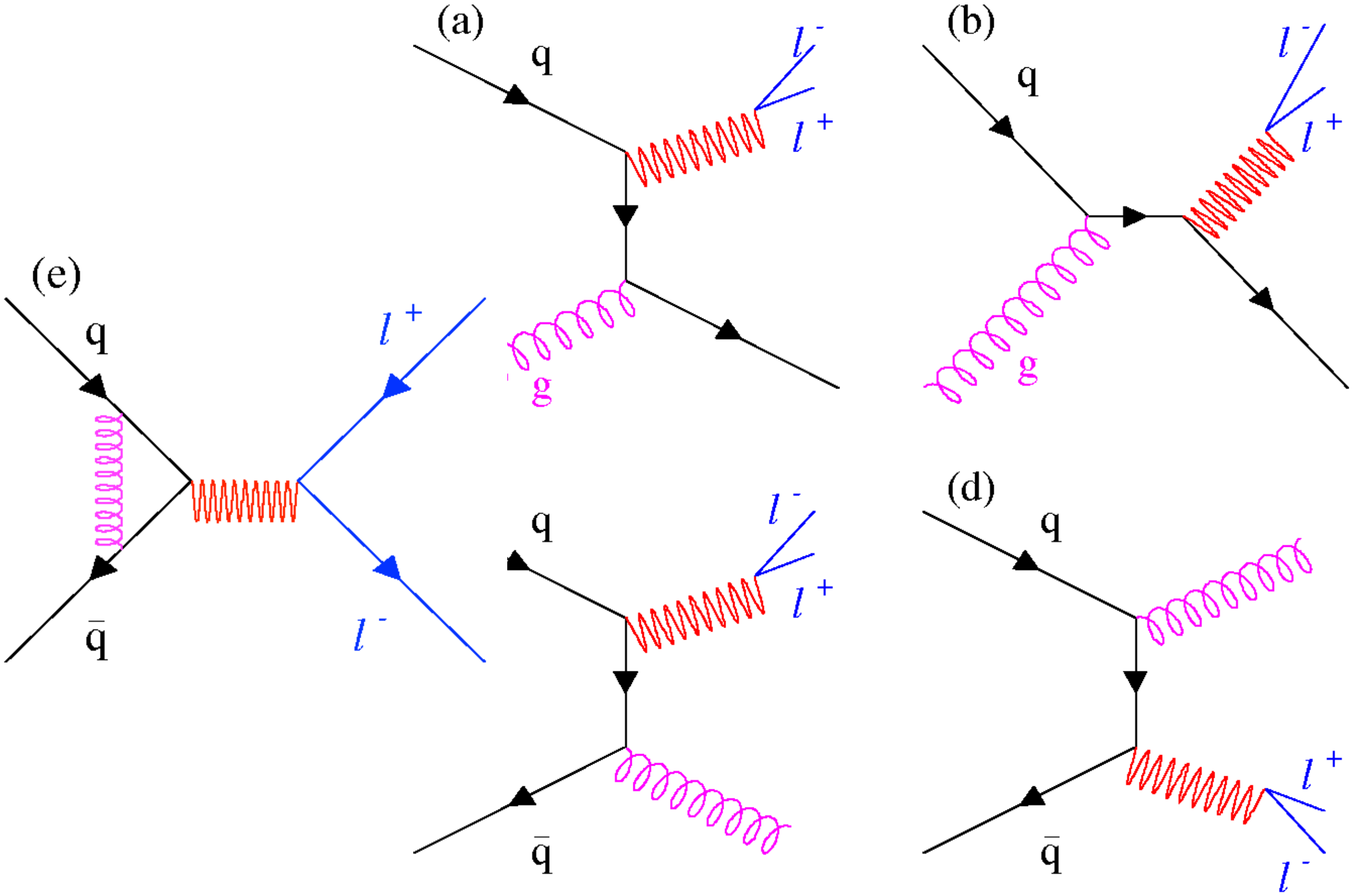
Acceptance limited at large x_T

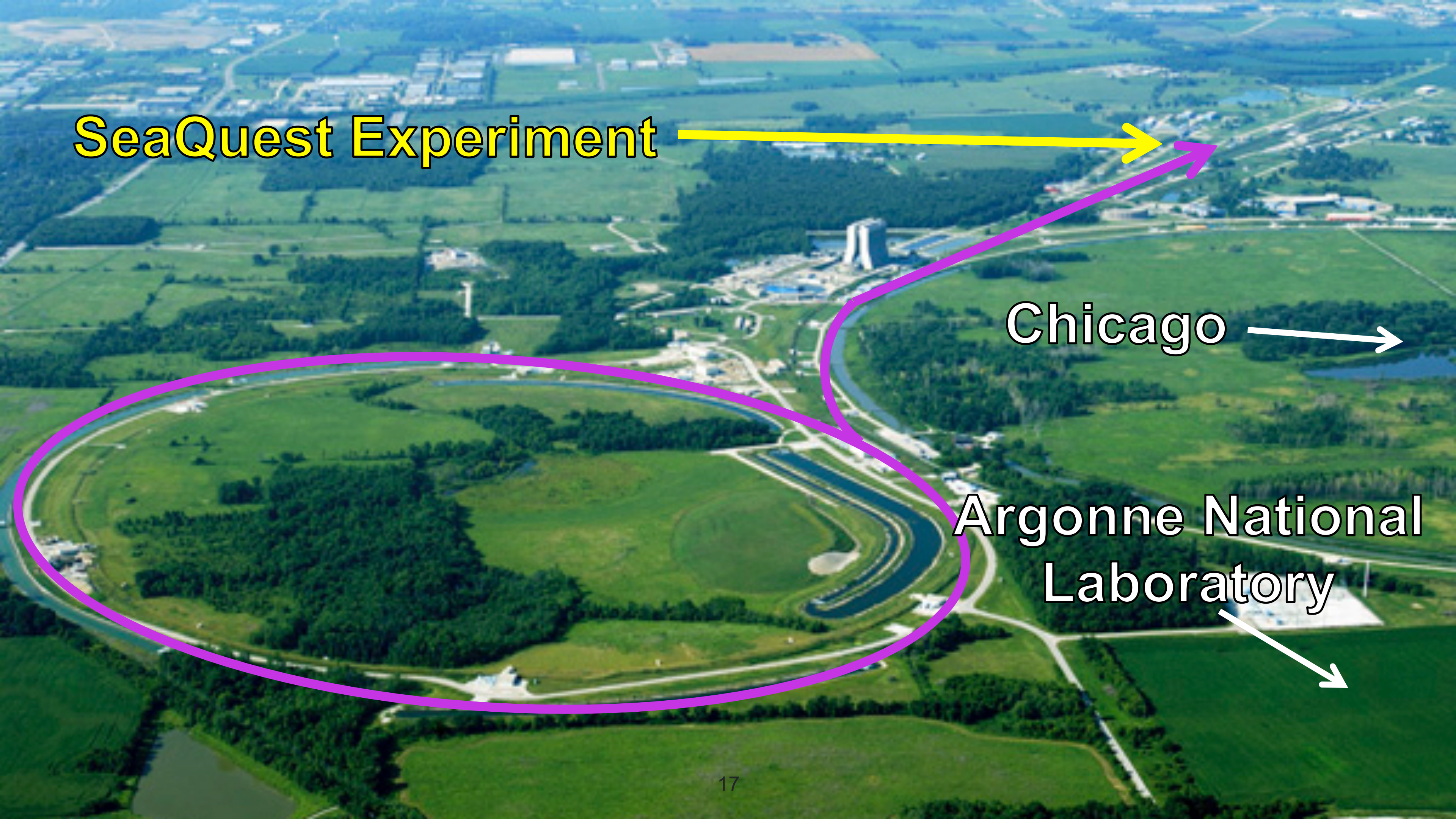
(Fixed Target, Hadron Beam)

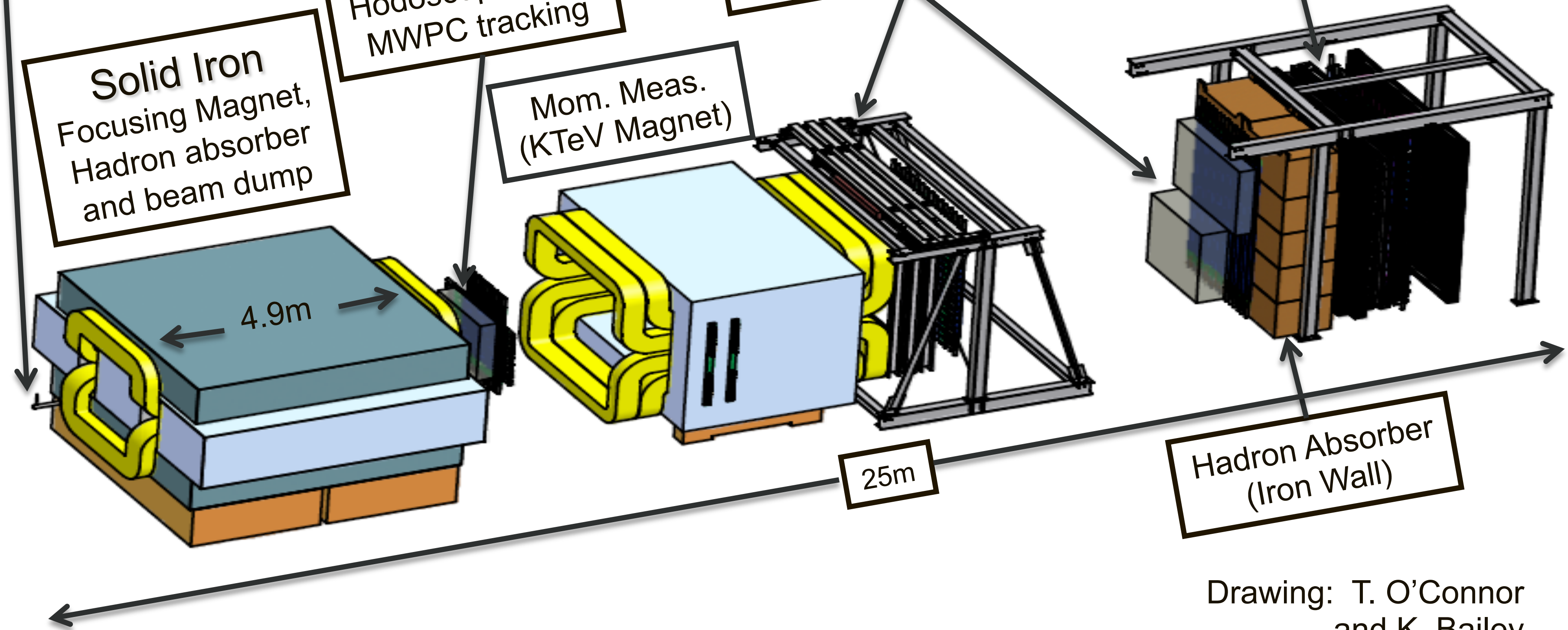


$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

NEXT-TO-LEADING ORDER IN α_s




SeaQuest Experiment
Chicago
Argonne National Laboratory



Liquid H_2, d_2, and solid targets (Fe, C, W)

Station 1:
Hodoscope array
MWPC tracking

Station 2 and 3:
Hodoscope array
Drift Chamber tracking

Station 4:
Hodoscope array
Prop tube tracking

Solid Iron
Focusing Magnet,
Hadron absorber
and beam dump

Mom. Meas.
(KTeV Magnet)

4.9m

25m

Hadron Absorber
(Iron Wall)

Drawing: T. O'Connor
and K. Bailey

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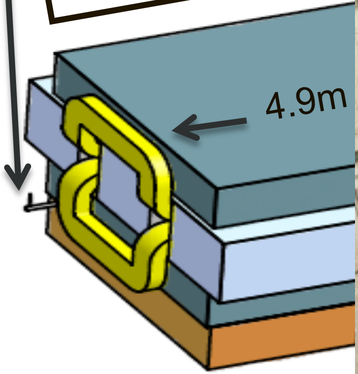

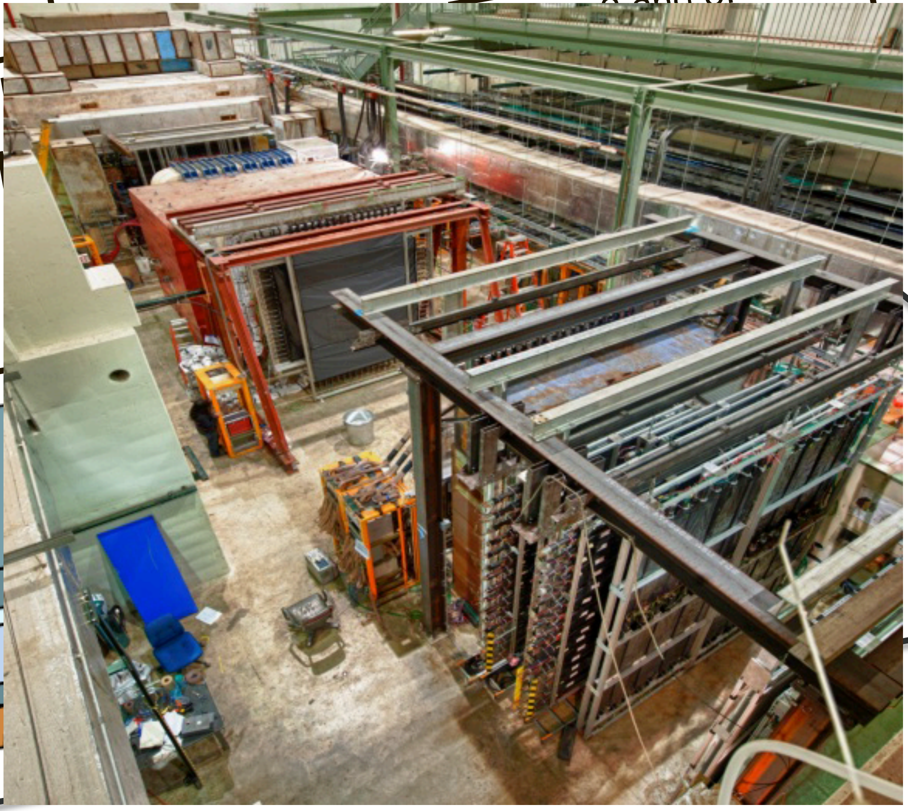

and 3:

Station 4:
Hodoscope array
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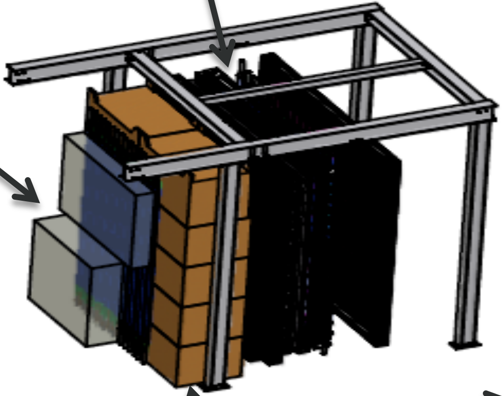

Hadron Absorber
(Iron Wall)

Drawing: T. O'Connor
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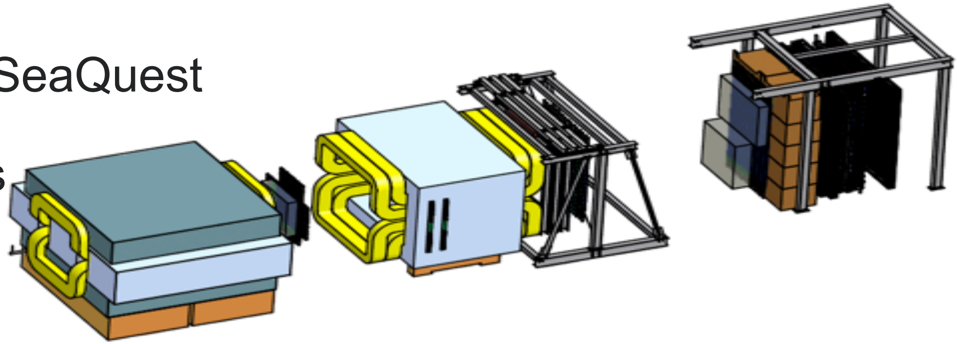
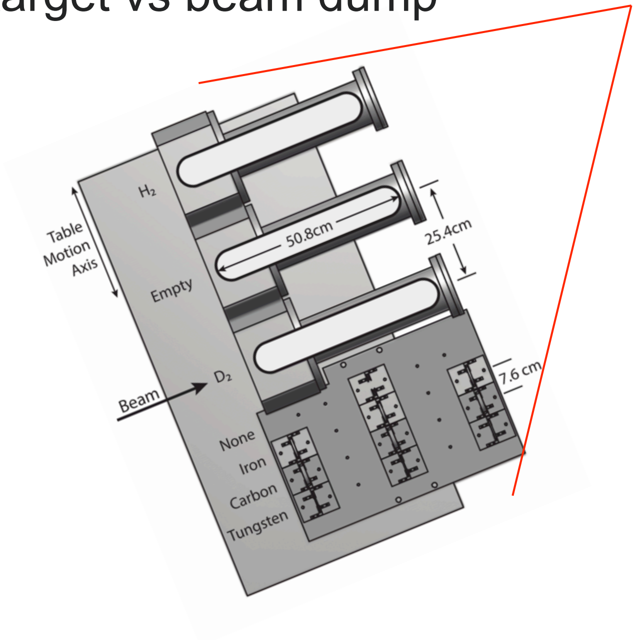
DATA FROM FY2014—TARGET-DUMP SEPARATION

- Entire beam interacts upstream of first SeaQuest Spectrometer tracking chamber
- Spatial resolution poor along beam axis
- Resolve target vs beam dump





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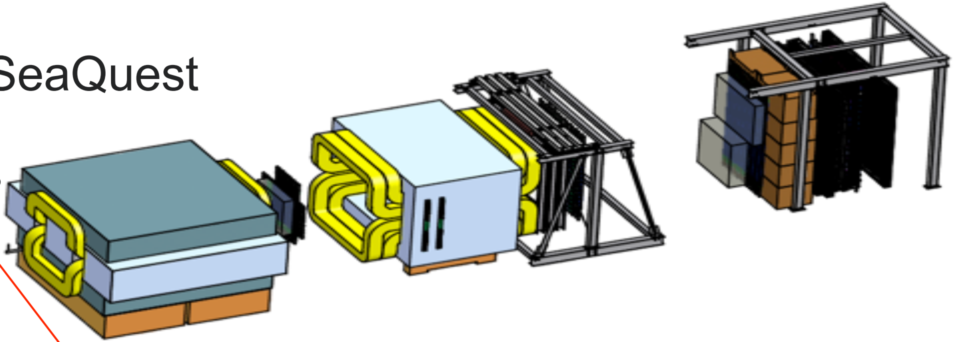
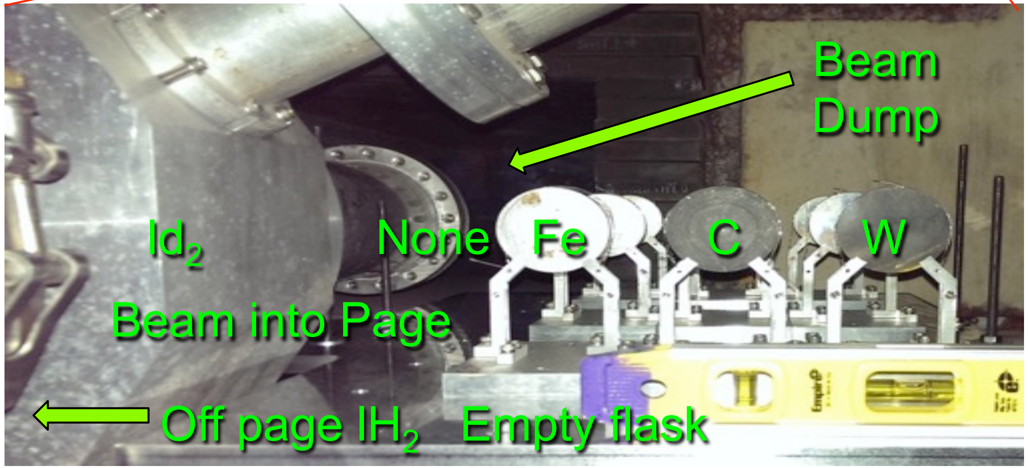
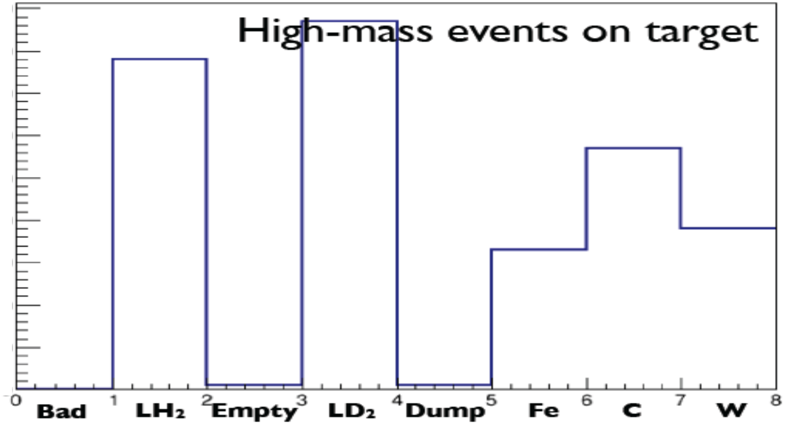






DRELL-YAN MASS SPECTRA

Mass spectrum components:

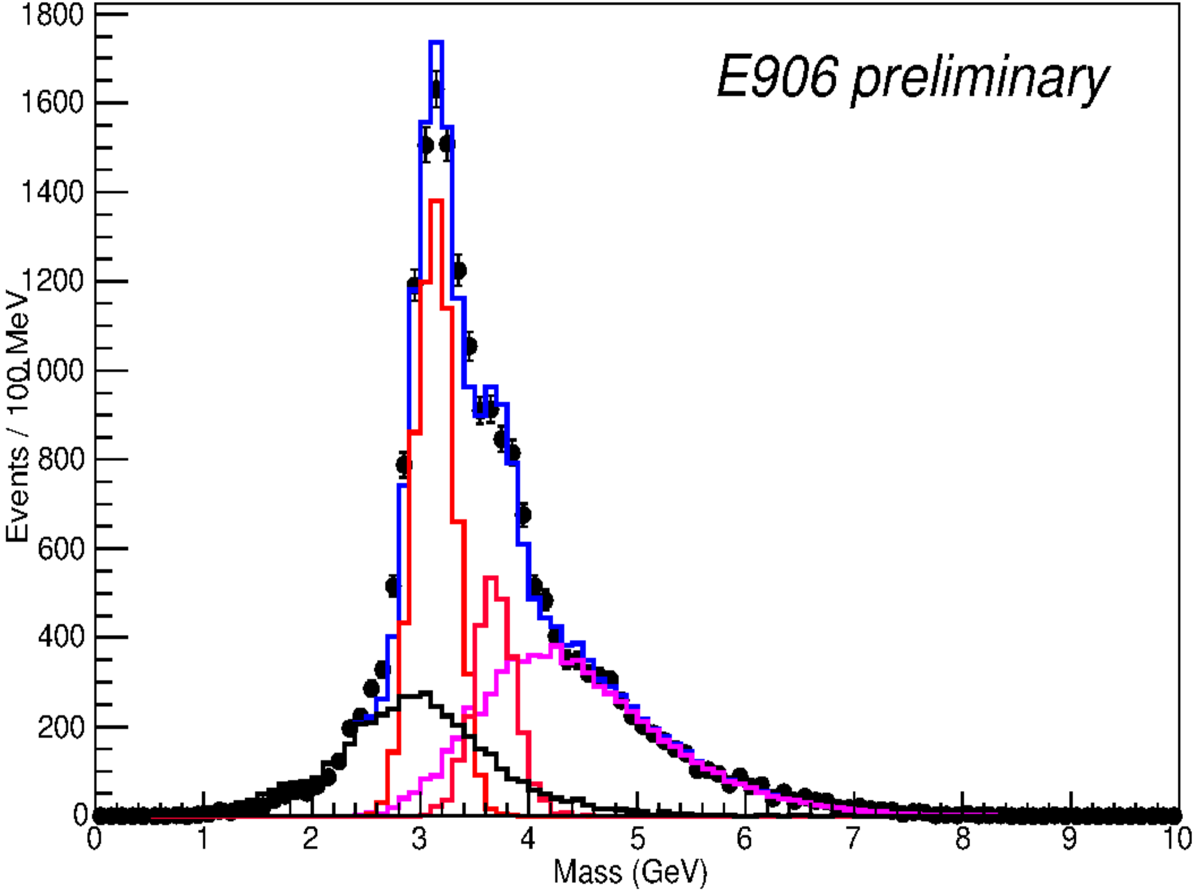
- J/ψ Monte Carlo
- ψ' Monte Carlo
- Drell-Yan Monte Carlo
- Random Background
- Combined MC and bkg

Resolution

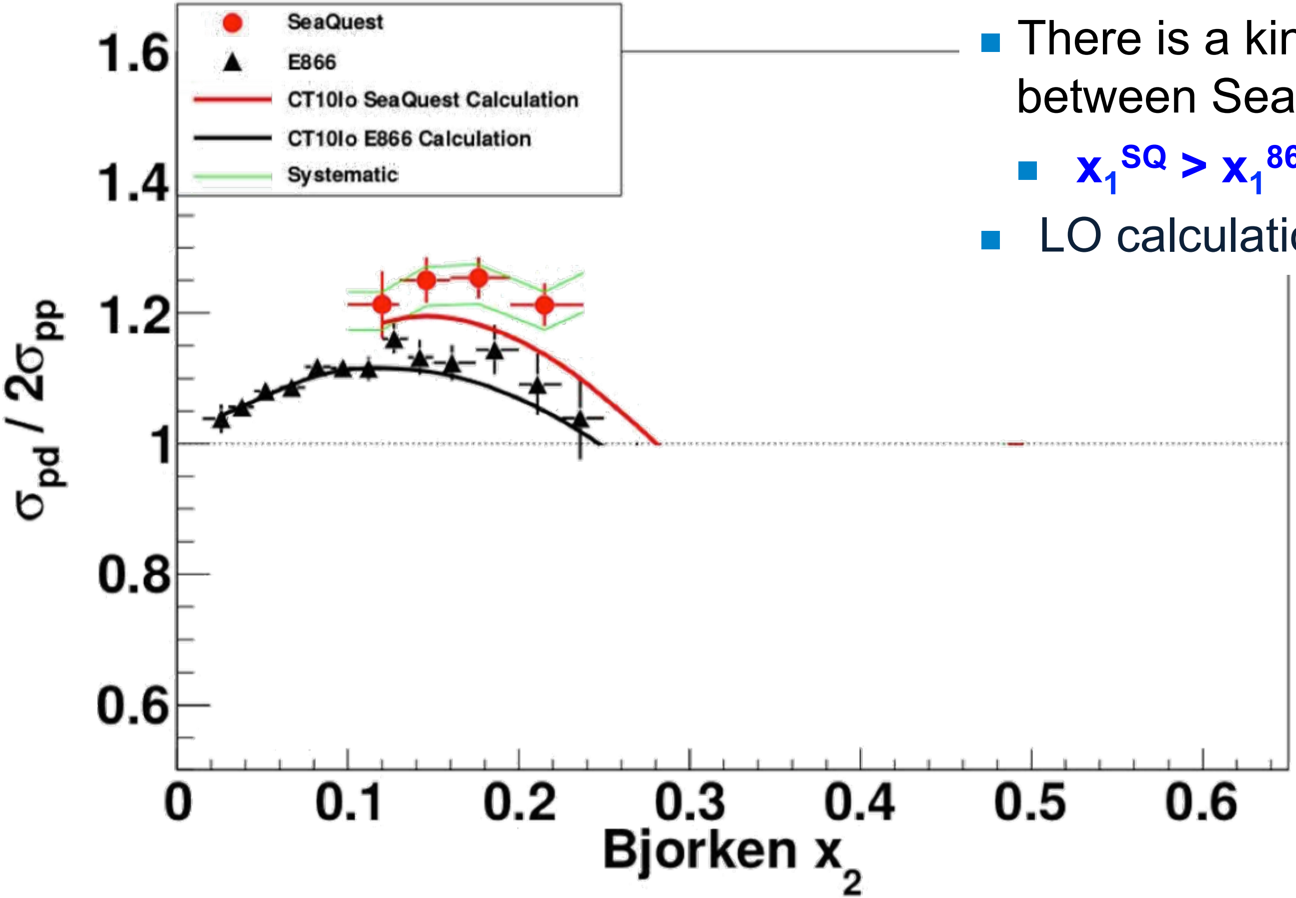
- σ_M(J/ψ) ~180 MeV
- σ_M(D-Y) ~220 MeV
- J/ψ ψ' separation

Ongoing Issues

- Spectrometer rate dep. and background est.



CROSS SECTION RATIO



- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
  - $x_1^{SQ} > x_1^{866}$
- LO calculations still slightly low

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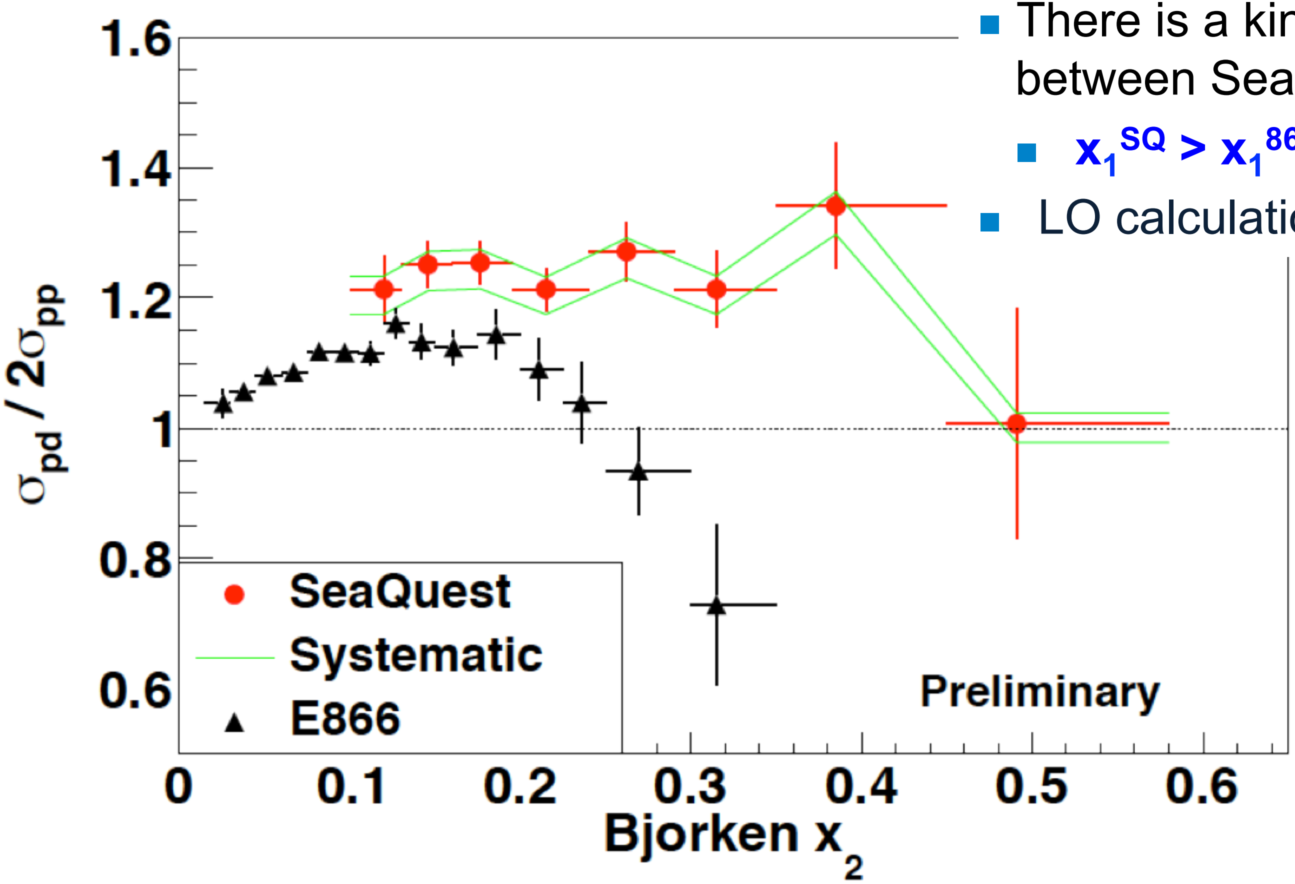

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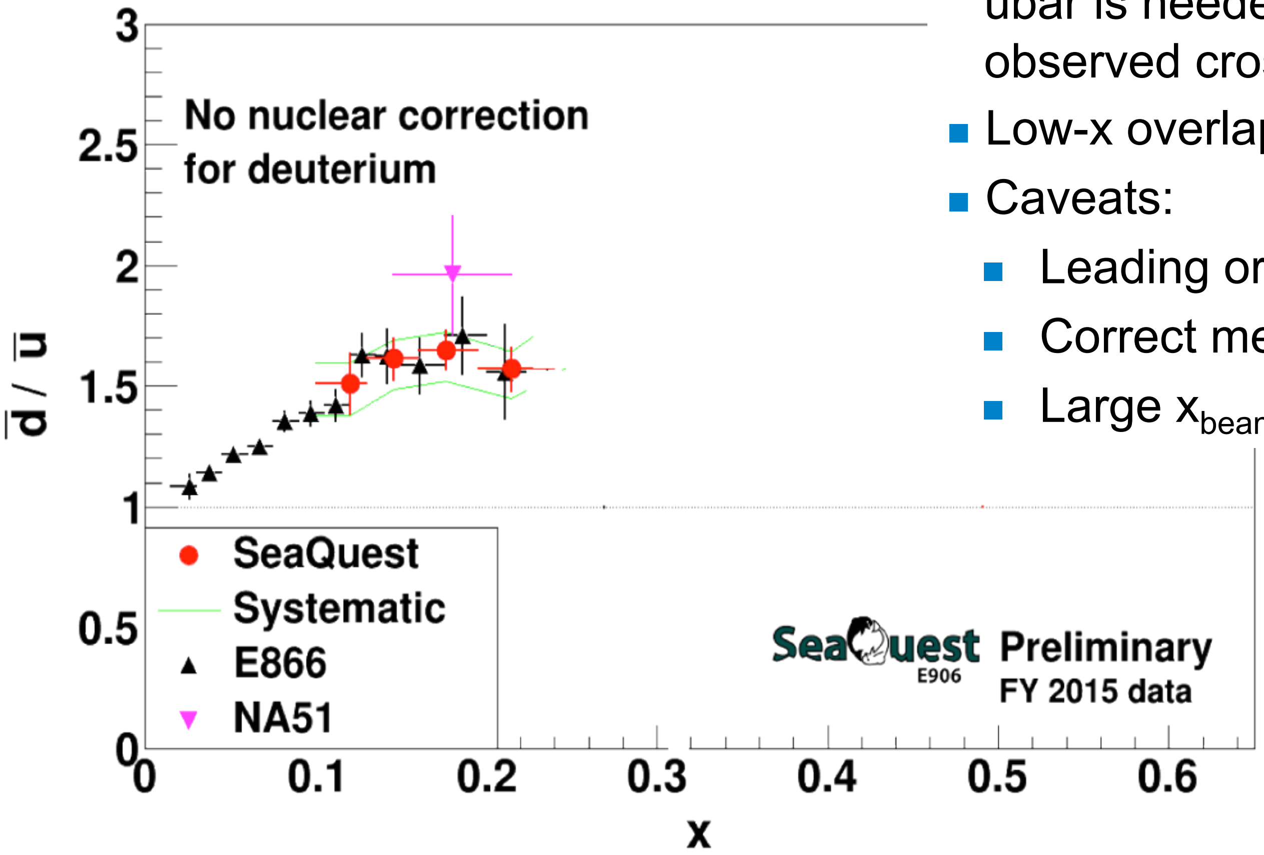
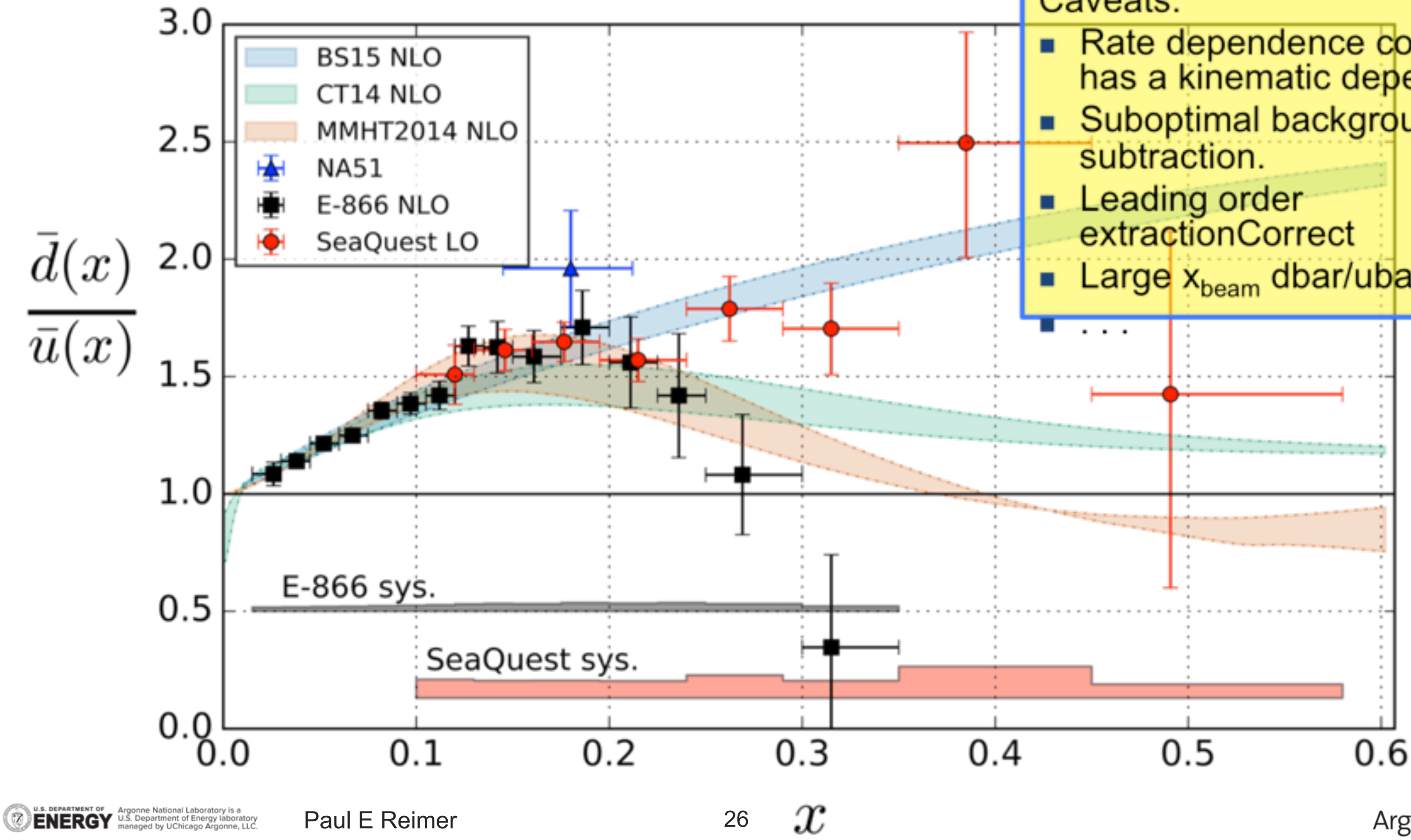
dbar/ubar

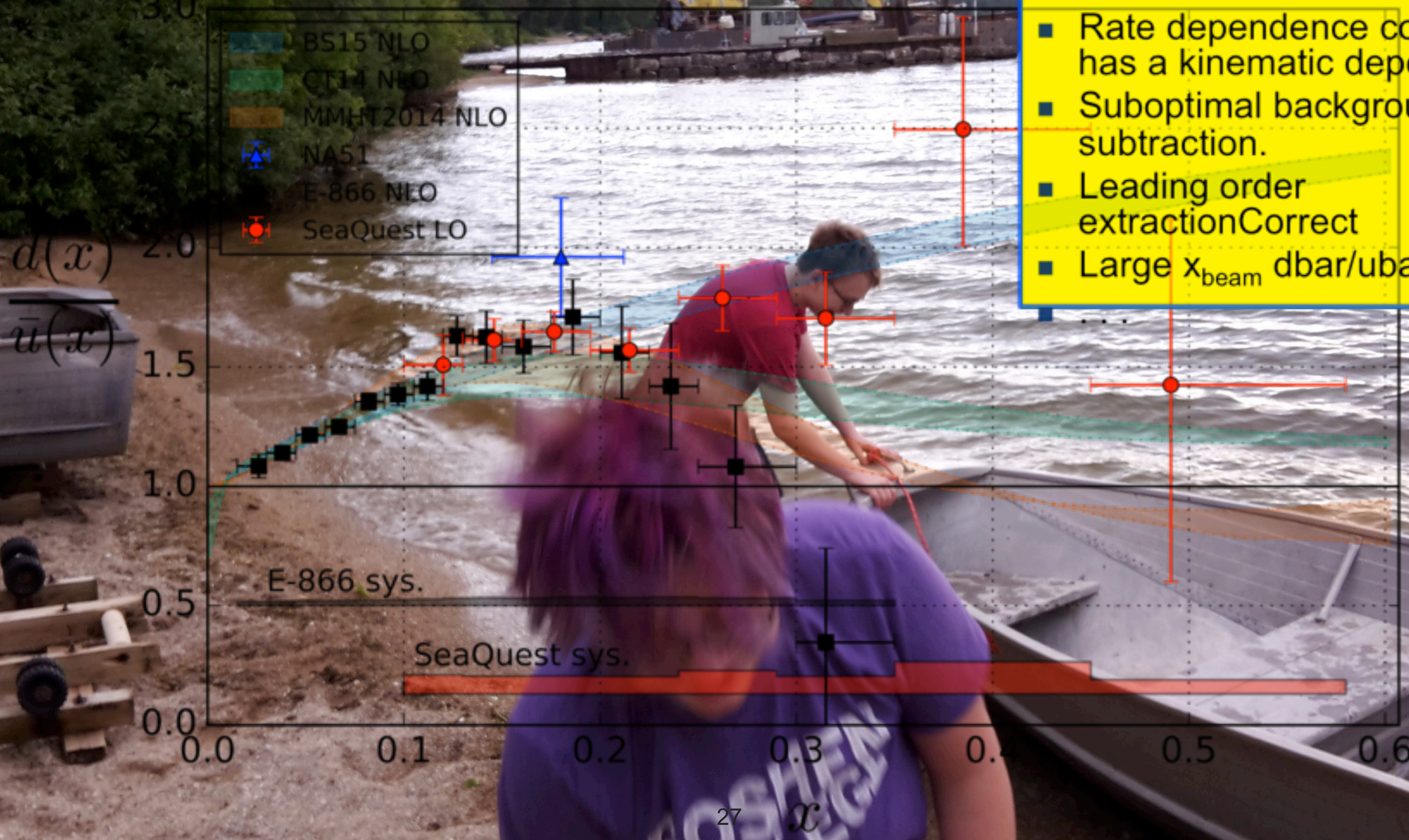


- Iteratively ask, “What ratio of dbar/ubar is needed to reproduce the observed cross section ratio?”
- Low-x overlap region consistency ✔
- Caveats:
  - Leading order only—so far
  - Correct method -> global fit
  - Large x_{beam} dbar/ubar



Caveats:

- Rate dependence correction has a kinematic dependence
- Suboptimal background subtraction.
- Leading order extractionCorrect
- Large x_{beam} dbar/ubar
- …



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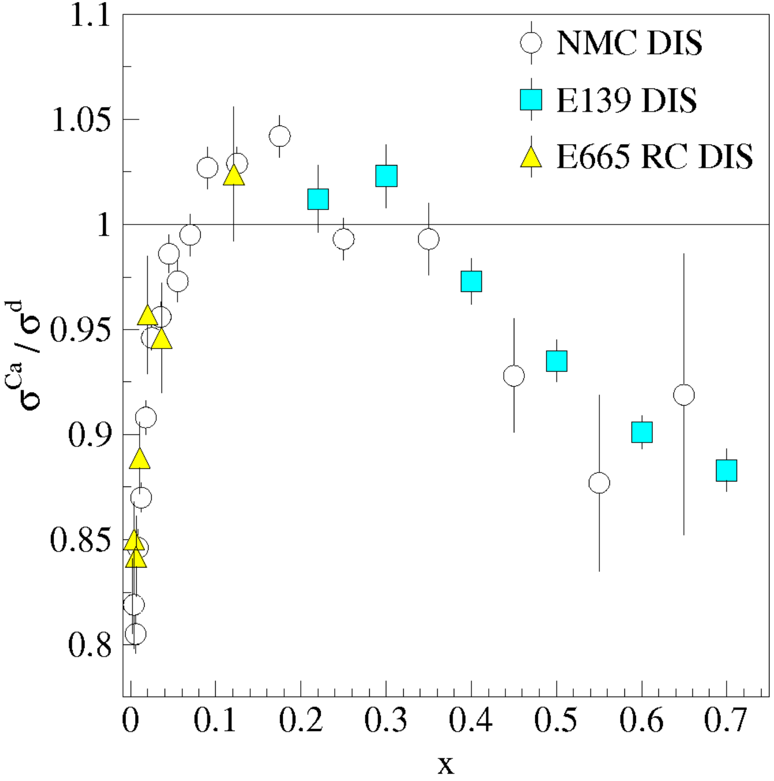
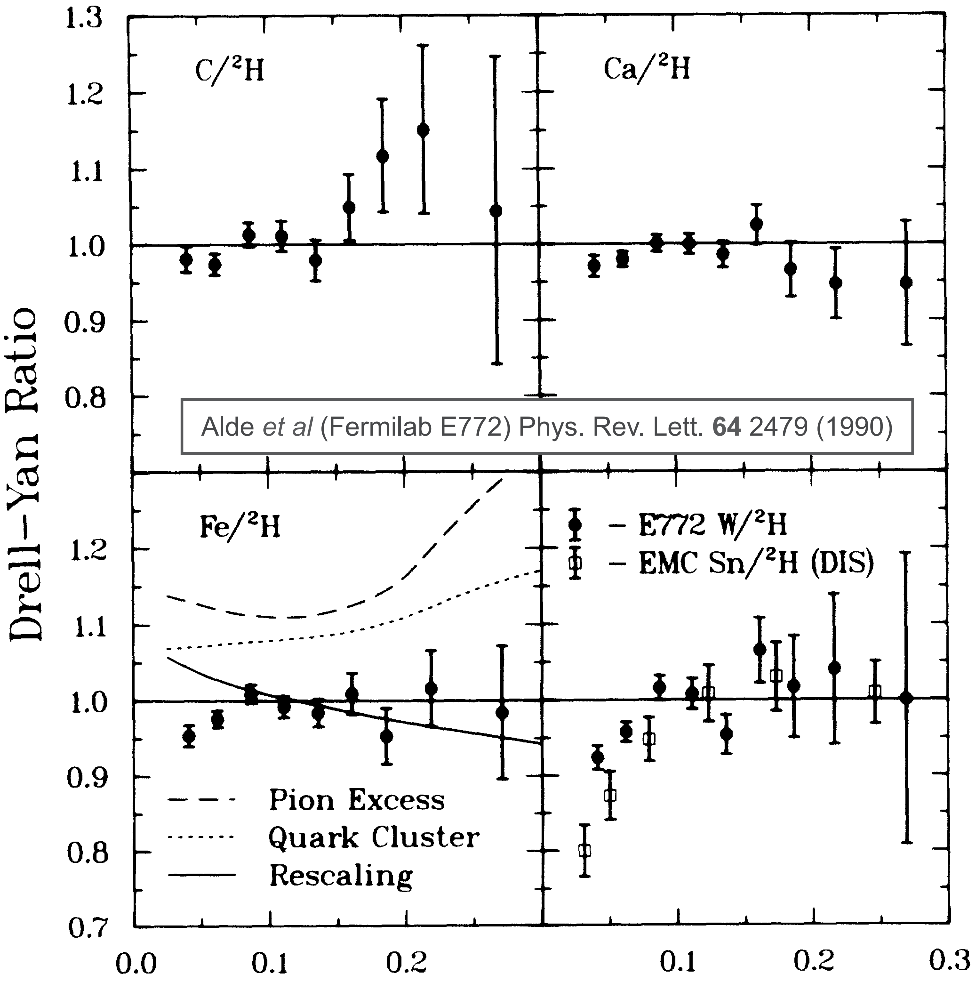
NUCLEAR SEA QUARK DISTRIBUTIONS

- No clear EMC effect in Drell-Yan





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

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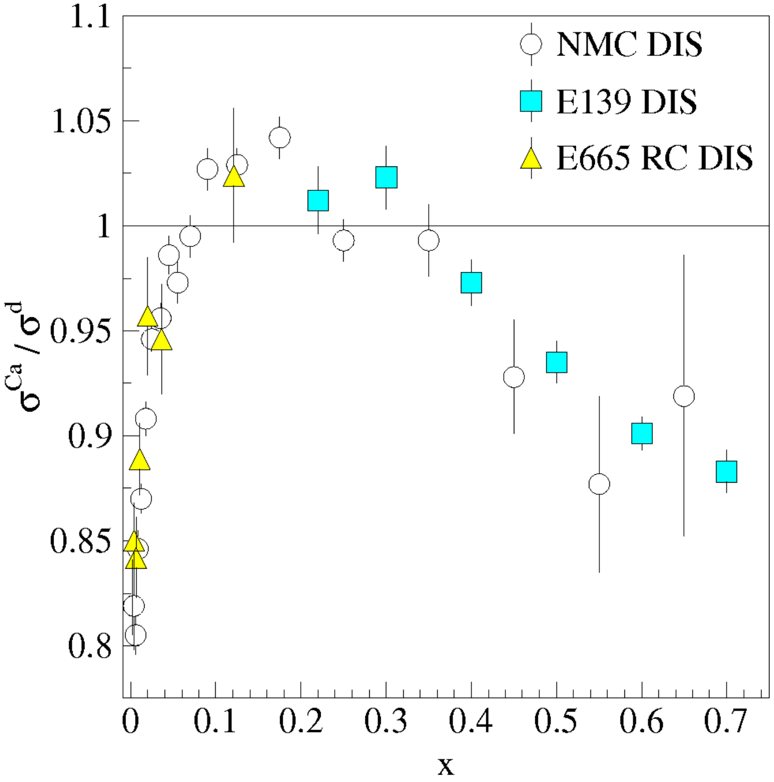

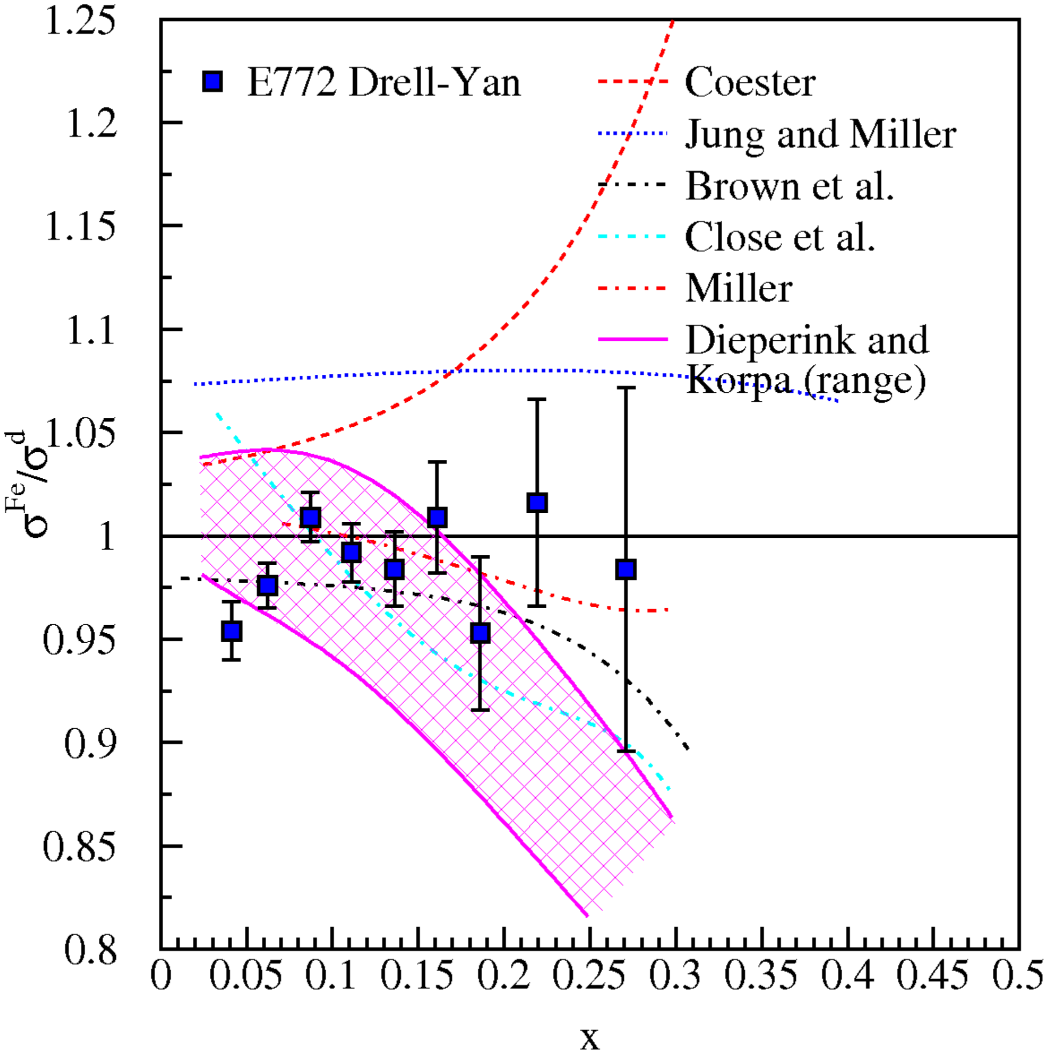

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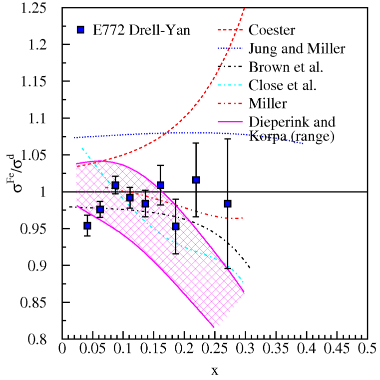
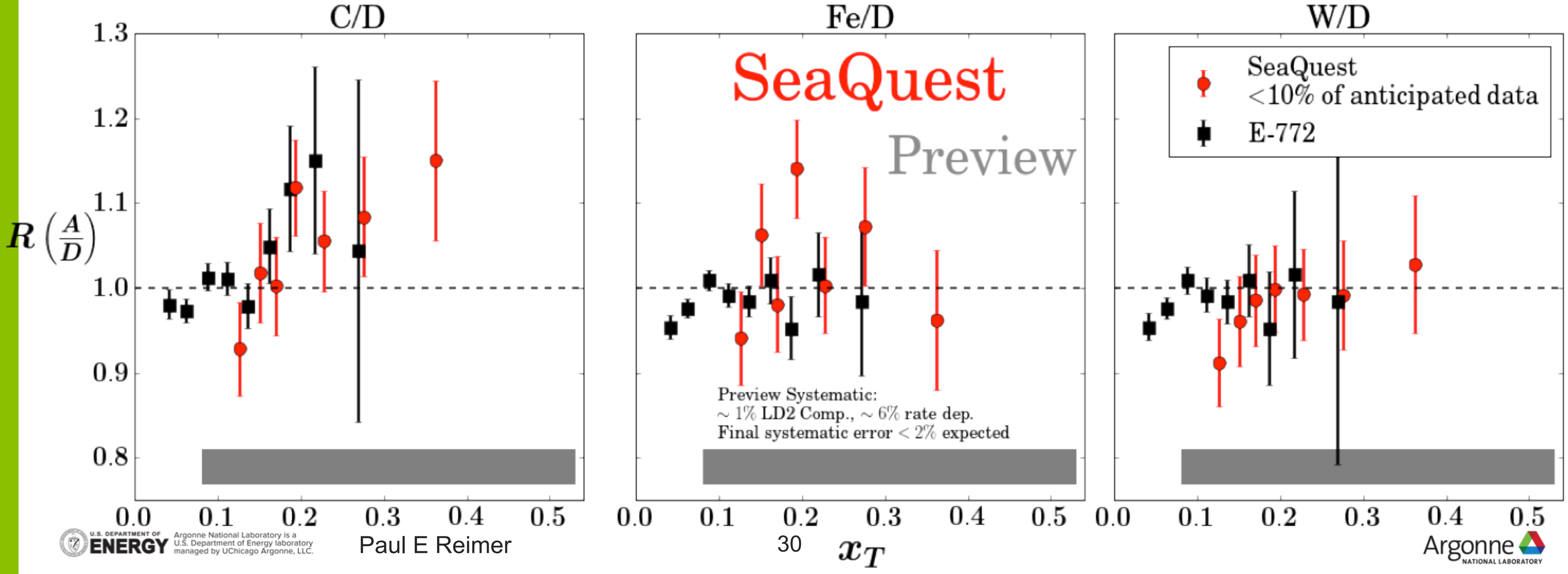


- No antiquark enhancement apparent.
- Increased detector acceptance at large-x to come.



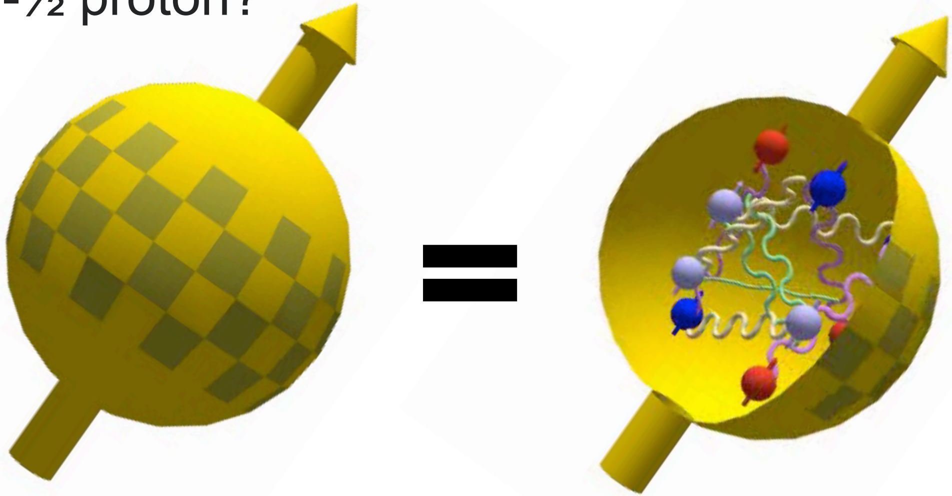
Preview Systematic:
~ 1% LD2 Comp., ~ 6% rate dep.
Final systematic error < 2% expected

POLARIZED DRELL-YAN

- v

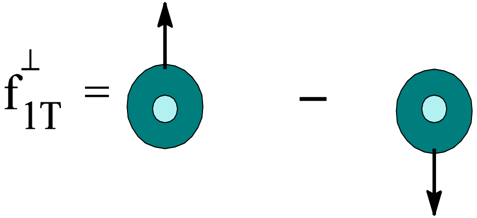
THE PROTON'S SPIN

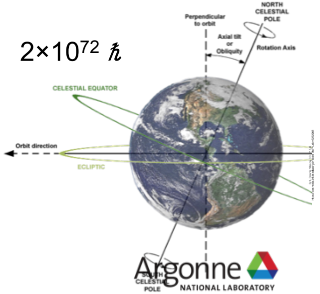
How do the quarks' and gluons' spin and angular momentum add to form a spin-½ proton?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

Key may be orbital angular momentum and the Sivers function





$2\times10^{72}\ \hbar$

SIVERS FUNCTION & ORBITAL ANGULAR MOMENTUM

Forward limit

$$J^q = \frac{1}{2}\int_0^1 dx\, x\left[H^q(x,0,0) + E^q(x,0,0)\right]$$

Ji Sum Rule

from: Anselmino

Usual pdf q(x)

$$-L(x)E^q(x,0,0,Q^2) = \int d^2k_\perp \hat{f}_{1T}^{\perp a}(x,k_\perp,q^2)$$

L(x) = lensing function (unknown, can be computed in models)

Measured Sivers

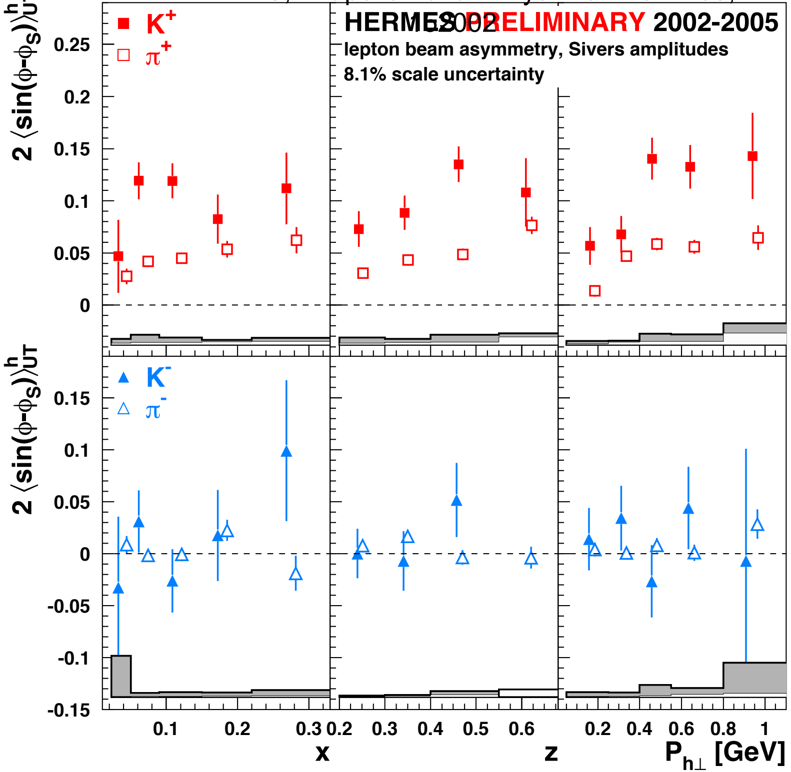
results at $Q^2 = 4$ GeV^2: $J^u \approx 0.23$, $J^{q\neq u} \approx 0$

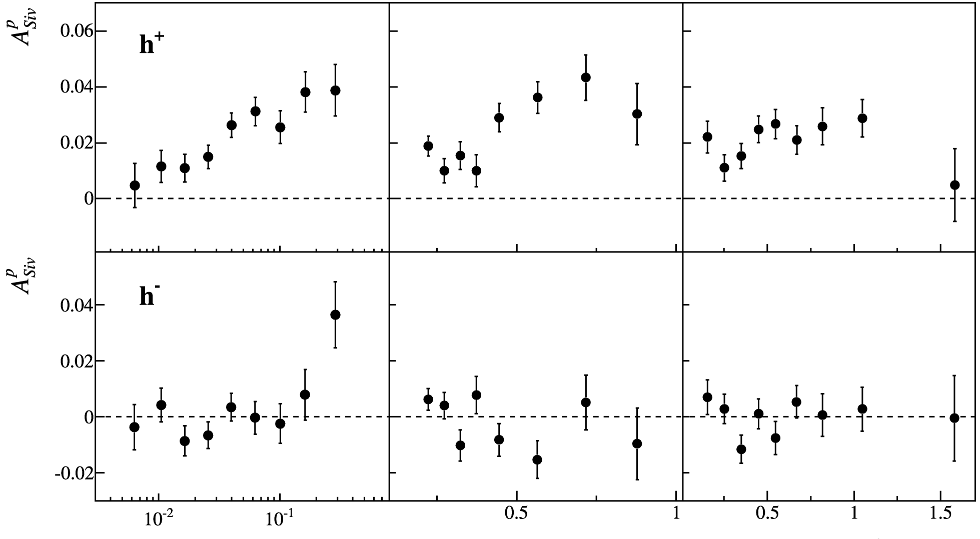
Bacchetta, Radici, PRL 107 (2011) 212001

Can OAM be decomposed into Valence and Sea?

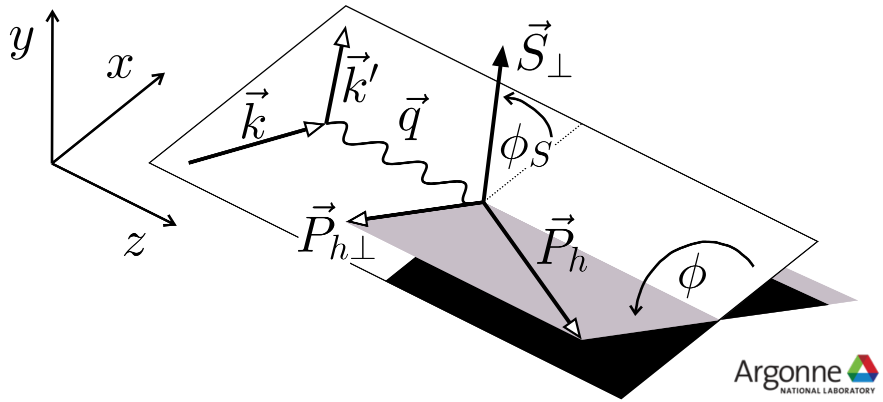
SIDIS SIVERS MEASUREMENTS

HERMES, Airapetian *et al.* Phys. Rev. Lett. 103, 152002



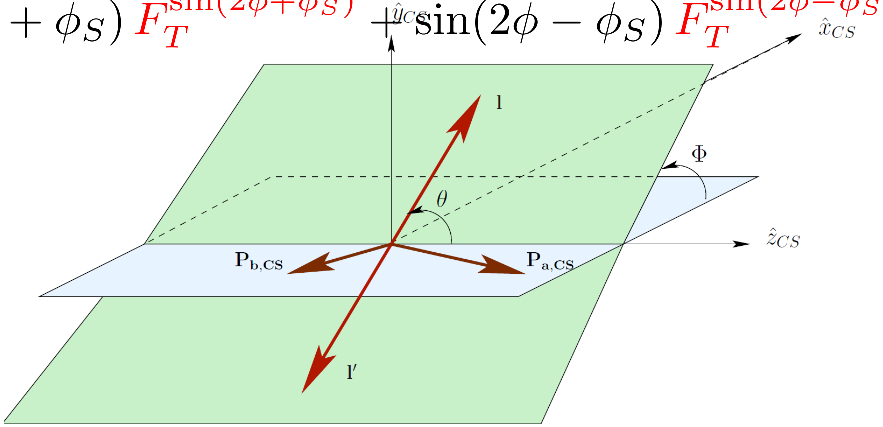


COMPASS, Adloph *et al.* Phys Lett. B, 717, 383



L-O SINGLE SPIN DRELL-YAN CROSS SECTION

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\Omega} = \frac{\alpha^2}{\Phi\, q^2}\Big\{ & (1+\cos^2\theta)\, F_U^1 + (1-\cos^2\theta)\, F_U^2 + \sin 2\theta \cos\phi\, F_U^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_U^{\cos 2\phi} \\
& + S_L \left(\sin 2\theta \sin\phi\, F_L^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_L^{\sin 2\phi}\right) \\
& + S_T \Big[\left(F_T^{\sin\phi_S} + cos^2\theta\, \tilde{F}_T^{\sin\phi_S}\right)\sin\phi_S + \sin 2\theta \Big(\sin(\phi+\phi_S)\, F_T^{\sin(\phi+\phi_S)} \\
& \qquad + \sin(\phi-\phi_S)\, F_T^{\sin(\phi-\phi_S)}\Big) \\
& + \sin^2\theta \left(\sin(2\phi+\phi_S)\, F_T^{\sin(2\phi+\phi_S)} + \sin(2\phi-\phi_S)\, F_T^{\sin(2\phi-\phi_S)}\right)\Big]\Big\}
\end{aligned}
$$



Anselmino

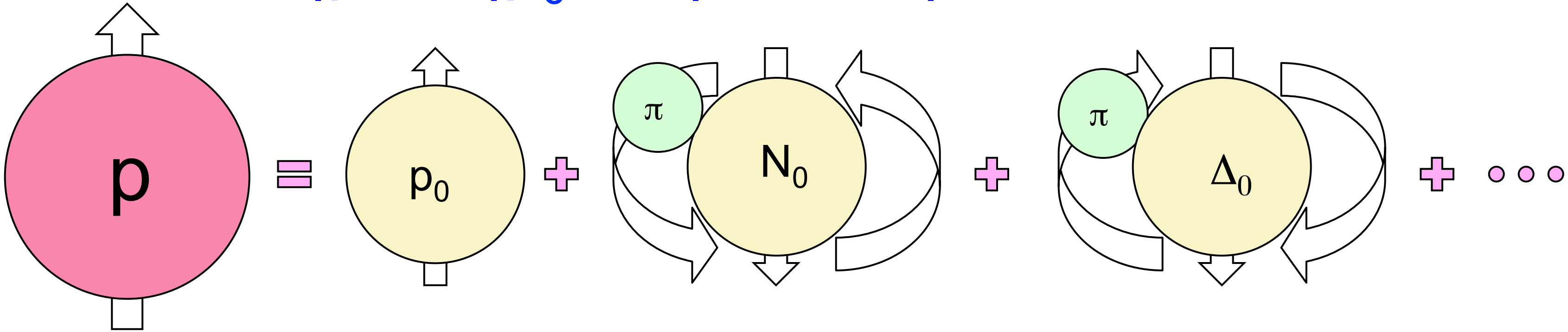
Sivers

Boer-Mulders

PION CLOUD AND ORBITAL ANGULAR MOMENTUM

Consider a nucleonic pion cloud

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

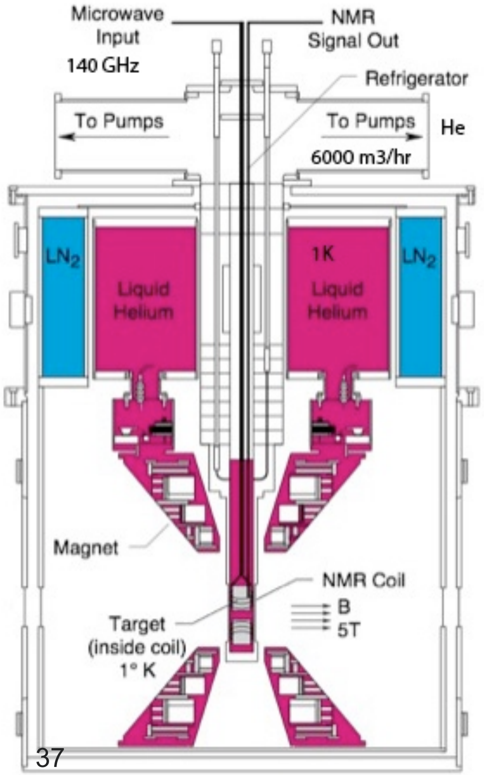


Pion $J^p=0^-$ Negative Parity

Need L=1 to get proton's $J^p=½^+$

SEAQUEST E1039—POLARIZED TARGET

- Los Alamos and UVa provide refurbished polarized target (LANL LDRD money)
- Fermilab (DOE/NP money)
  - Installs infrastructure for target
  - Refurbishes beam line
  - Upgrades radiation shielding
- Work started in spring 2018

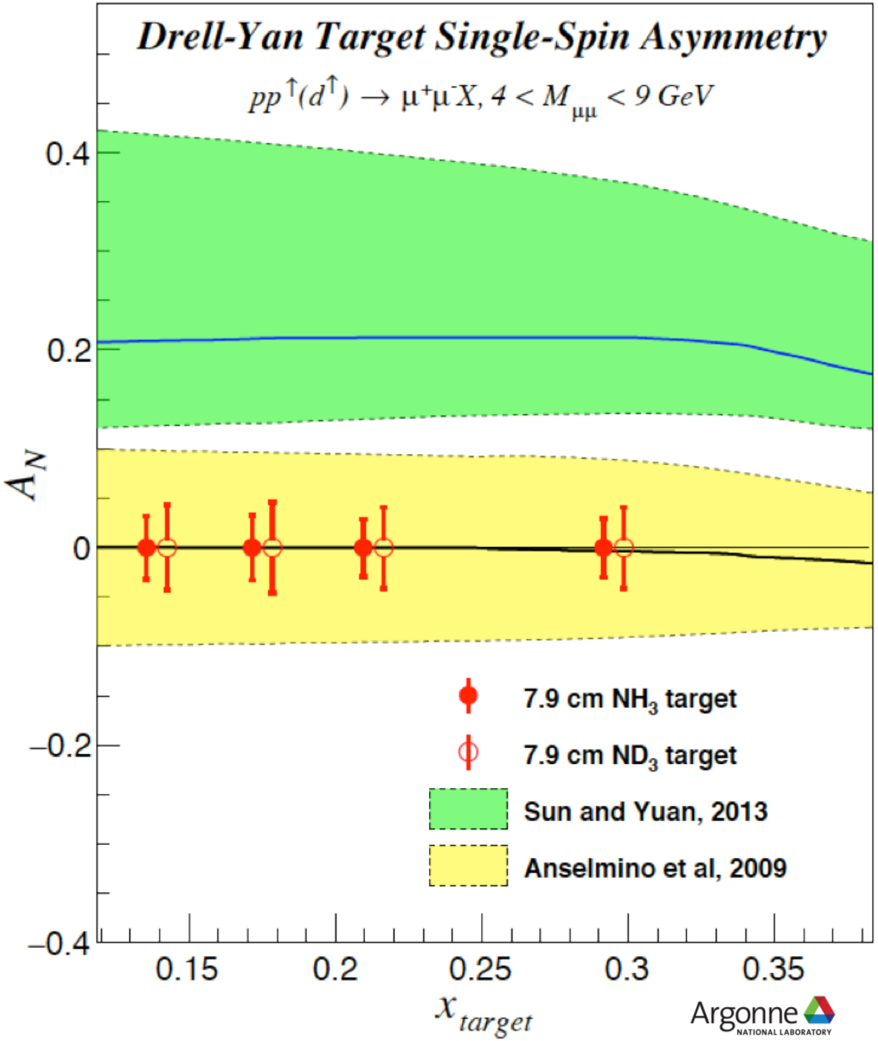


SEAQUEST E1039 EXPECTED RESULTS

- Statistics precision shown for two calendar years of running:
  - Integrated Protons on target 2.7 × 10^{18}
  - $\mathcal{L} = 7.2 \times 10^{42}$ /cm^2

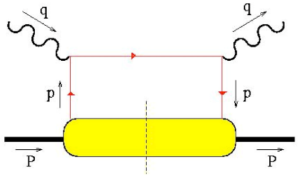
Status

- Install Target & Shielding—Ongoing
- Commissioning—Winter/Spring 2019
- Production data—Fall 2019

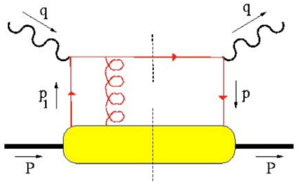


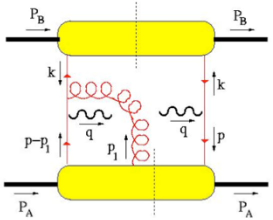
“NAÏVE” T-ODD OBSERVABLES

- Naïve T-odd effect ($F_{1T}^{\perp q}$) must arise from interference between spin-flip and non-flip amplitudes w/different phases



can interfere with





- soft gluons “gauge links” required for color gauge invariance
- soft gluon re-interactions are final (or initial) state interactions … and may be process dependent!

Spacelike (DIS) vs. Timelike (Drell-Yan) virtual photon

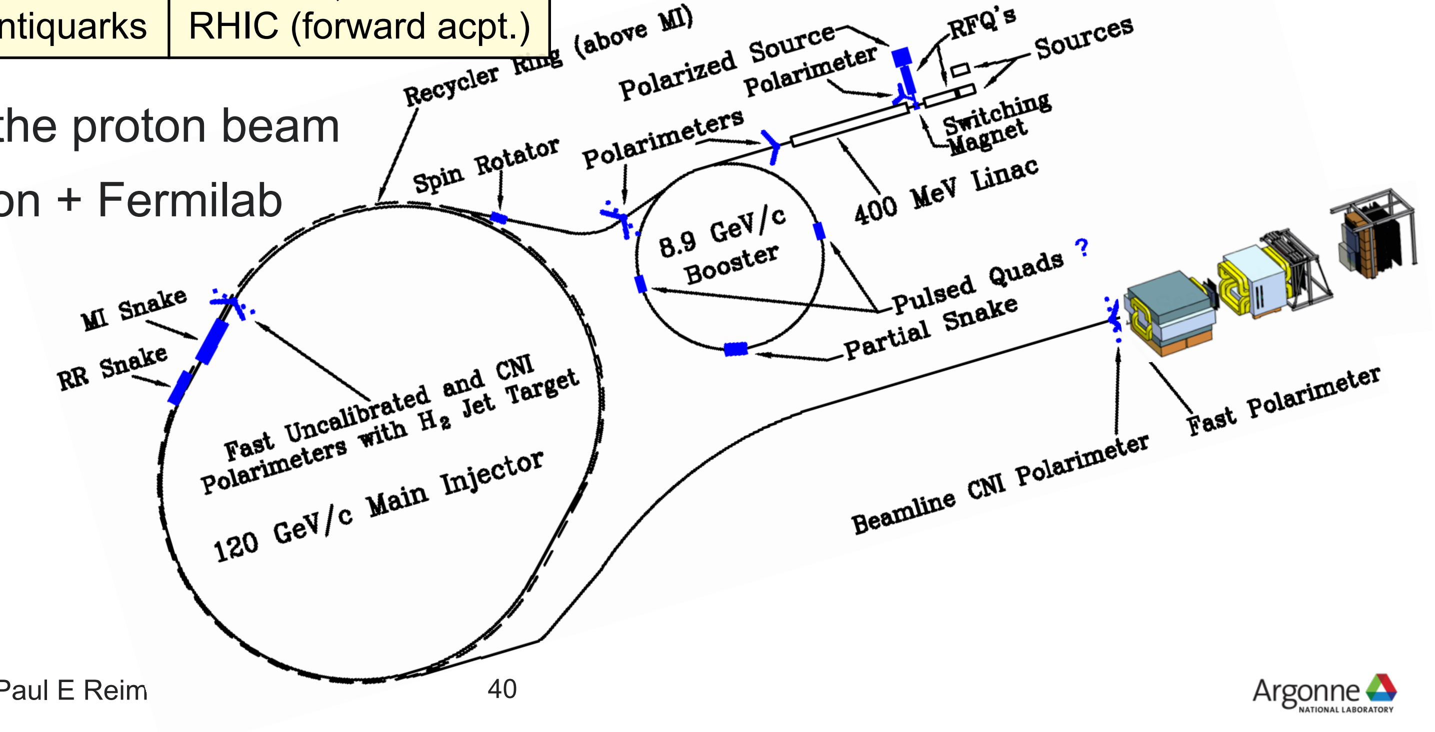
$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = -\,f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

SEAQUEST E1027—POLARIZED BEAM

- Access to Valence Sivers function

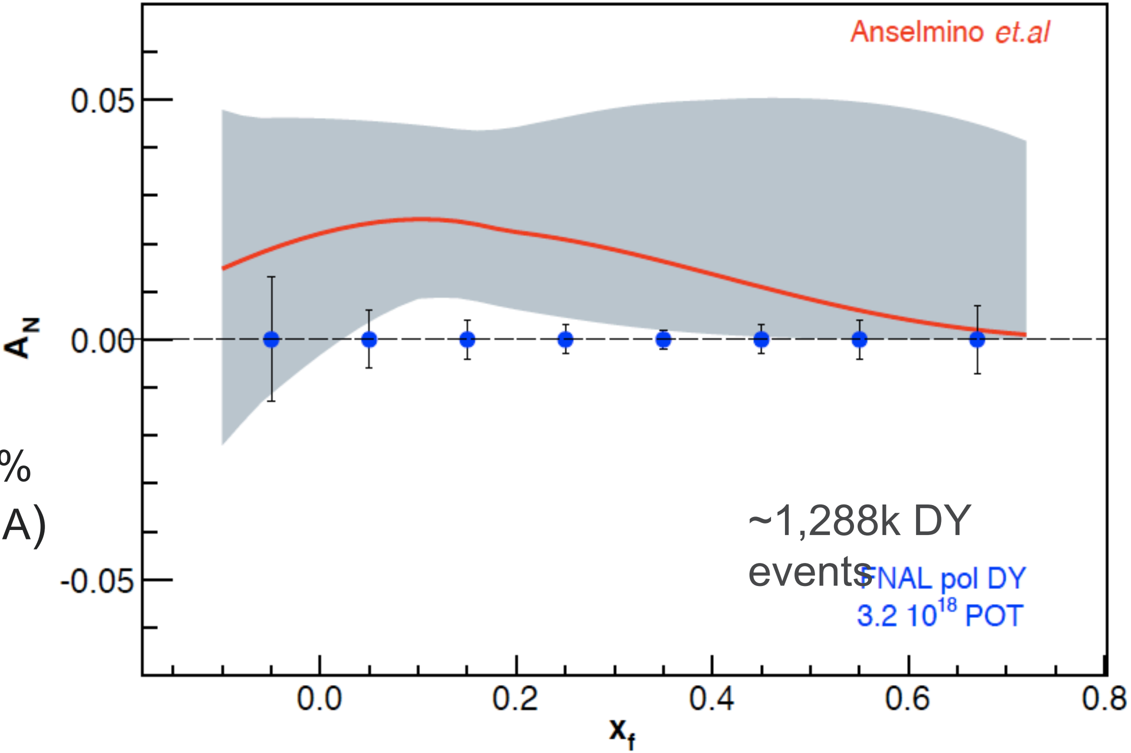
Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)

- Need to polarize the proton beam
- $\mathcal{O}$(\$10M) + inflation + Fermilab



SEAQUEST E1027 POLARIZED BEAM EXPECTED RESULTS

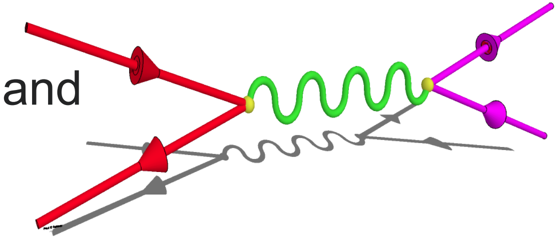
- Experimental Conditions
  - Same as SeaQuest
  - Luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: $I_{av} = 15$ nA)
  - 3.2×10^{18} total protons for 5×10^5 min: (= 2 yrs at 50% efficiency) with $P_b = 70\%$

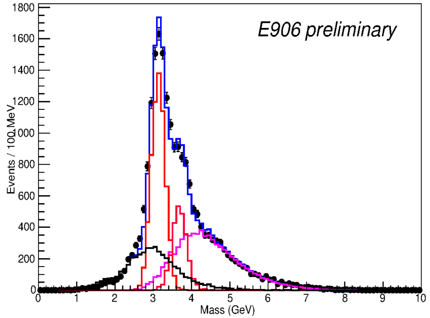


Can measure not only sign, but also the size & maybe shape of the Sivers function!

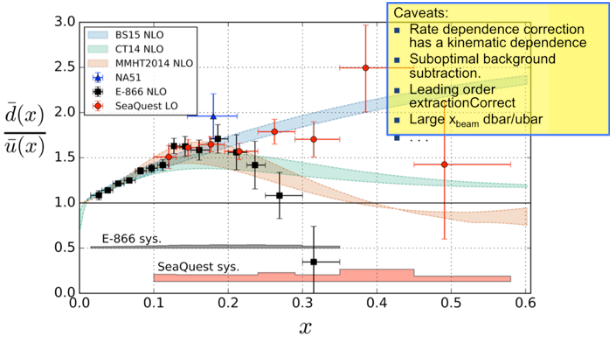
TAKE AWAY

- The sea is interesting, turbulent, and a fundamental part of the proton!
- The boat I'm sailing is Drell-Yan.

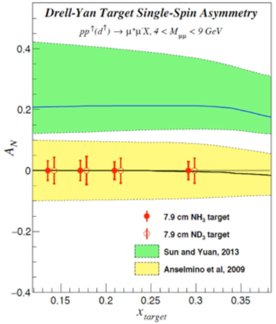




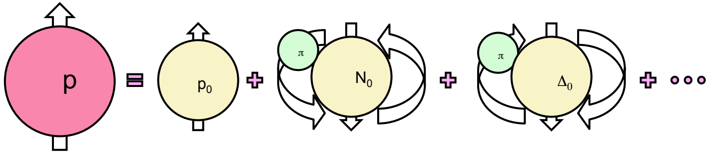
- Preliminary results look good, final results take time.
- Other SeaQuest topics:
  - SeaQuark EMC
  - Partonic energy loss



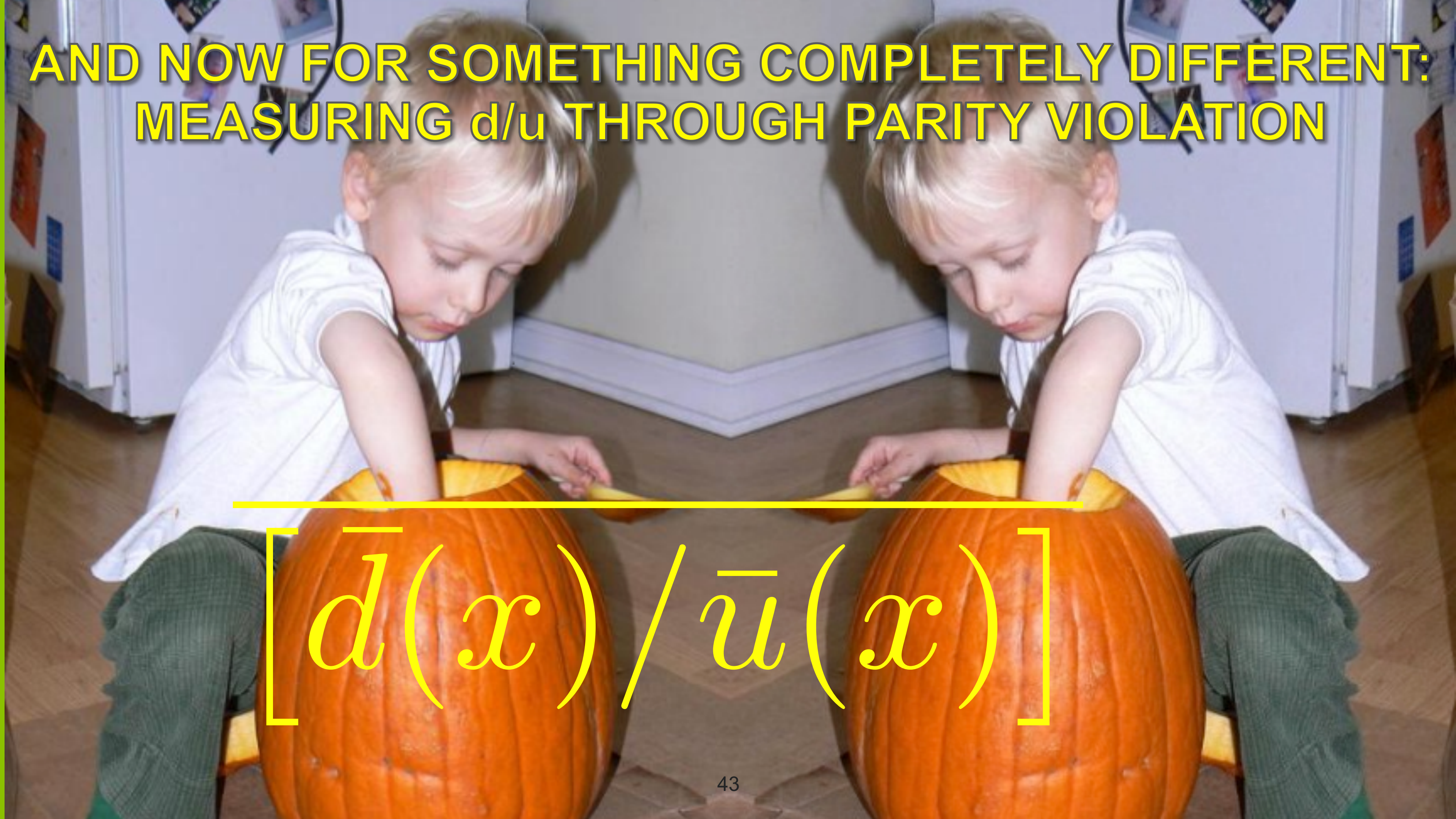
Caveats:
- Rate dependence correction has a kinematic dependence
- Suboptimal background subtraction.
- Leading order extractionCorrect
- Large x_{beam} dbar/ubar
- . . .



- SeaQuest 1039—Polarized *target* Drell-Yan
  - Do sea quarks carry orbital angular momentum?

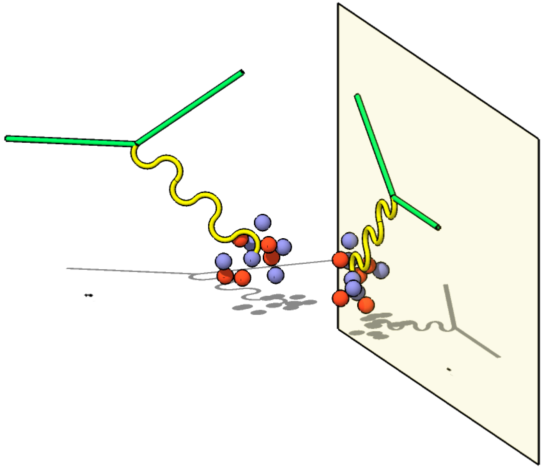


AND NOW FOR SOMETHING COMPLETELY DIFFERENT: MEASURING d/u THROUGH PARITY VIOLATION

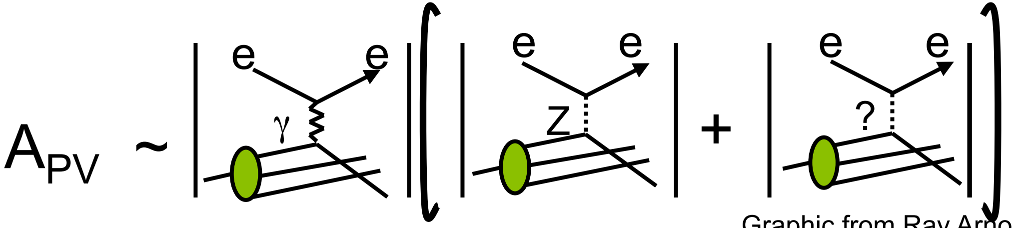


$$\overline{\left[\bar{d}(x)/\bar{u}(x)\right]}$$

MEASURING D/U THROUGH PARITY VIOLATION



- PV gives access to the weak interaction at low energy (well below the mass of the Z^0).



Graphic from Ray Arnold

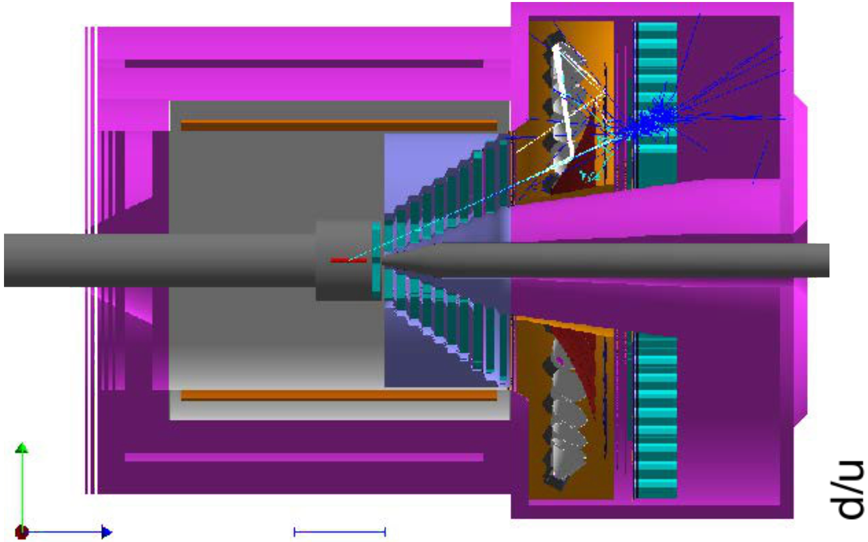
$$\sigma^l \propto \left|\mathcal{M}_\gamma + \mathcal{M}^l_{Z^0}\right|^2 \qquad \sigma^r \propto \left|\underbrace{\mathcal{M}_\gamma}_{\text{large}} + \underbrace{\mathcal{M}^r_{Z^0}}_{\text{Tiny}}\right|^2$$

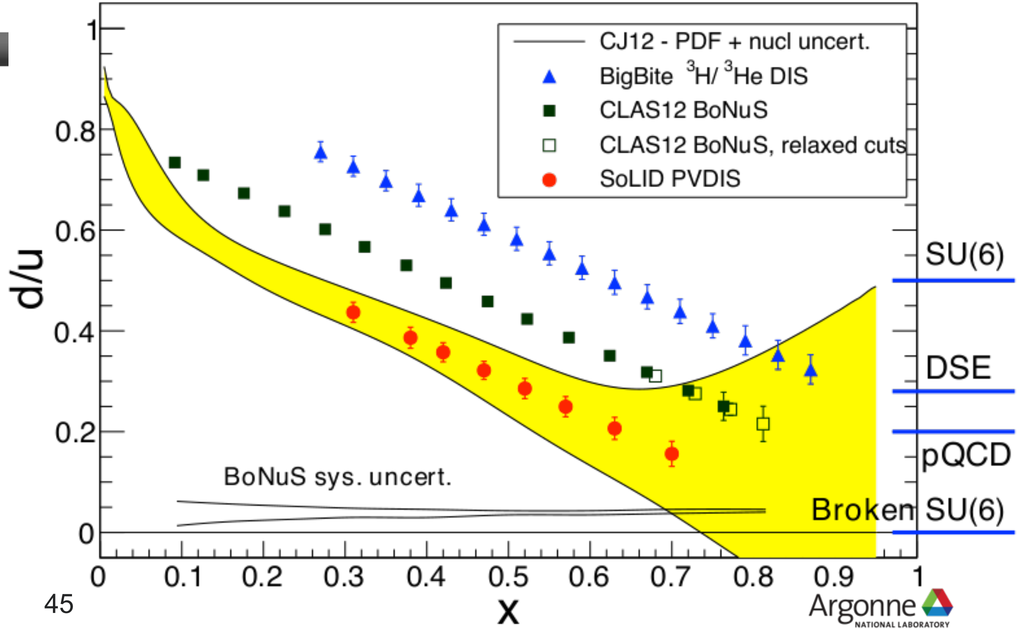
$$A_{\mathrm{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{Z^0} - \mathcal{M}^r_{Z^0}}{\mathcal{M}_\gamma}$$

PVDIS ON ^{1}H WITH SoLID

$$a(x) \approx \frac{3}{4}\left[\frac{6C_{1u}u(x) - 3C_{1d}d(x)}{u(x)+\frac{1}{4}d(x)}\right]$$

$$\approx \left[\frac{u(x)+0.912d(x)}{u(x)+0.25d(x)}\right]$$





- Only SoLID uses only ^{1}H
- No ^{3}H, ^{2}H or ^{3}He

TAKE AWAY

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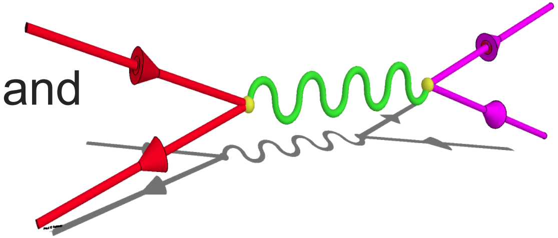

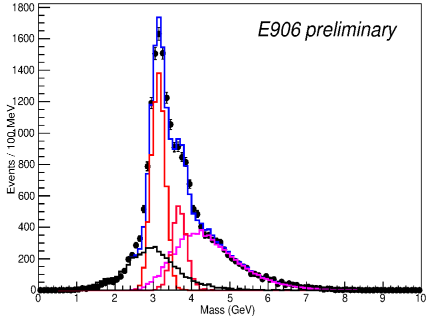

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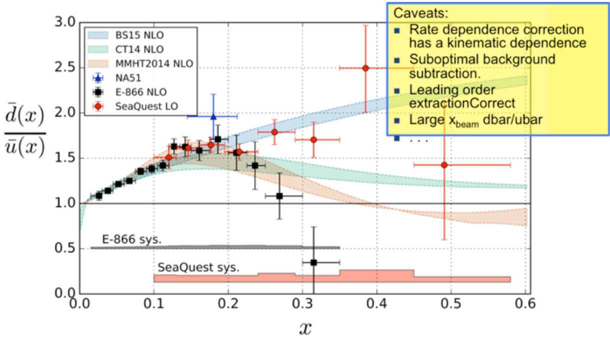

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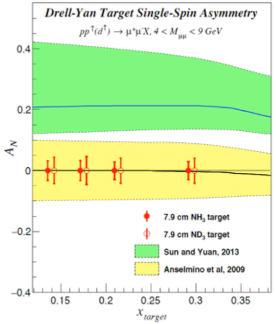

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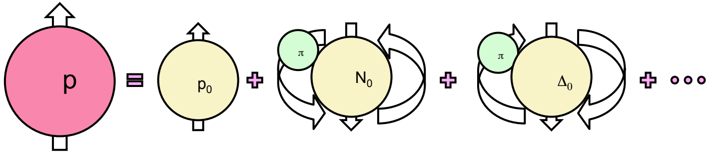

FERMILAB E906/SEAQUEST COLLABORATION

Abilene Christian University
Ryan Castillo, Michael Daugherty, Donald Isenhower, Noah Kitts, Lacey Medlock, Noah Shutty, Rusty Towell, Shon Watson, Ziao Jai Xi

Academia Sinica
Wen-Chen Chang, Shiu Shiuan-Hao

Argonne National Laboratory
John Arrington, Don Geesaman*, Kawtar Hafidi, Roy Holt, Harold Jackson, Michelle Mesquita de Medeiros, Bardia Nadim, Paul E. Reimer*

University of Colorado
Ed Kinney, Po-Ju Lin

Fermi National Accelerator Laboratory
Chuck Brown, Dave Christian, Gabriele Garzoglio, Su-Yin (Grass) Wang, Jin-Yuan Wu

University of Illinois
Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Hao Li, Naomi C.R Makins, Dhyaanesh Mullagur R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo, Mariusz Witek, Yangqiu Yin

KEK
Shin'ya Sawada

Los Alamos National Laboratory
Gerry Garvey, Xiaodong Jiang, Andreas Klein, David Kleinjan, Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey

University of Maryland
Betsy Beise, Andrew (Yen-Chu) Chen

University of Michigan
Christine Aidala, McKenzie Barber, Catherine Culkin, Vera Loggins, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh Rubin, Matt Wood

Mississippi State University
Lamiaa El Fassi

RIKEN
Yuji Goto

Rutgers, The State University of New Jersey
Ron Gilman, Ron Ransome, Arun Tadepalli

Tokyo Tech
Shou Miyaska, Kei Nagai, Kenichi Nakano, Shigeki Obata, Toshi-Aki Shibata

Yamagata University
Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara

*Co-Spokespersons

POLARIZED DRELL-YAN COLLABORATING INSTITUTES

Polarized Target:

Argonne National Laboratory
Fermi National Accelerator Laboratory
Institute of Physics, Academia Sinica
KEK
Ling-Tung University
Los Alamos National Laboratory
University of Maryland
University of Michigan
Mississippi State University
University of New Hampshire
National Kaohsiung Normal University
RIKEN
Rutgers University
Thomas Jefferson National Accelerator Facility
Tokyo Tech
University of Virginia

Kun Liu and Dustin Keller
Co-Spokespersons

Polarized Beam:

Abilene Christian University
Argonne National Laboratory
University of Basque Country
University of Colorado
Fermi National Accelerator Laboratory
University of Illinois
KEK
Los Alamos National Laboratory
University of Maryland
University of Michigan
Mississippi State University
RIKEN
Rutgers
Tokyo Tech
Yamagata University

Wolfgang Lorenzon and Paul E Reimer
Co-Spokespersons