AN ASYMMETRY IN THE ANTI-MATTER OF THE PROTON: EXPLORING THE SEA

PAUL E REIMER
Argonne National Laboratory
18 March 2021

Argonne NATIONAL LABORATORY

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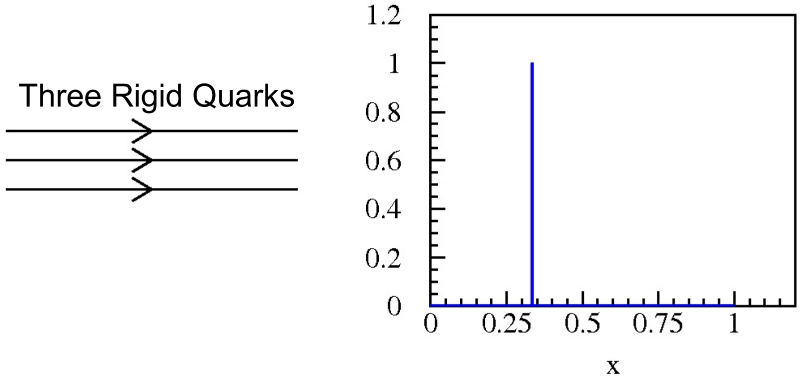
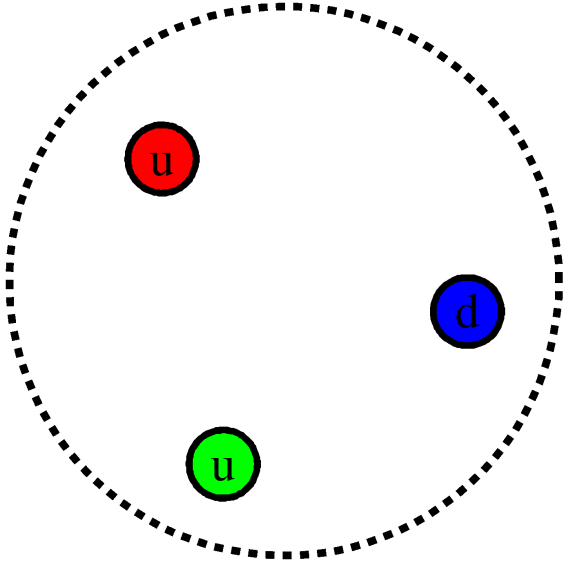
U.S. DEPARTMENT OF ENERGY

From Constituent Quarks to Partonic Quarks

- 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





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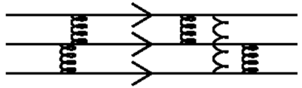
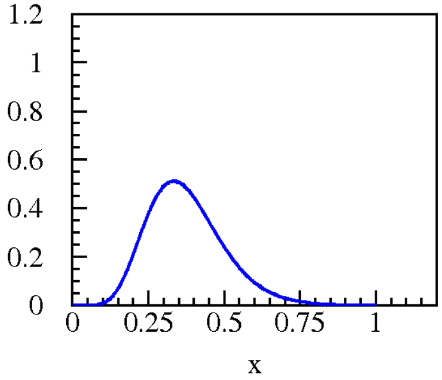
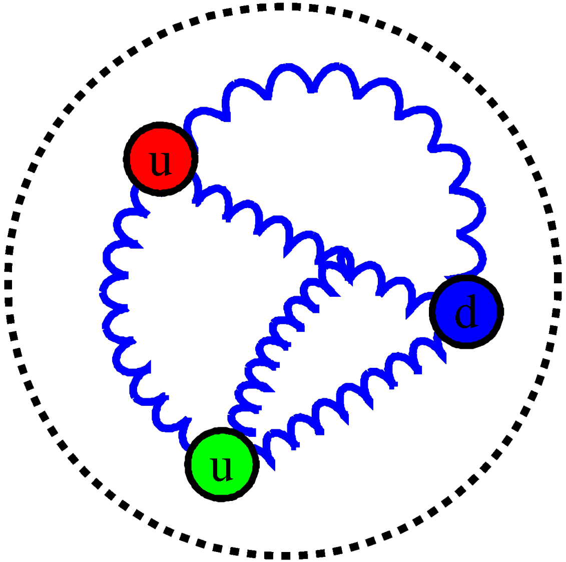
Three interacting Quarks







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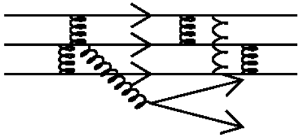
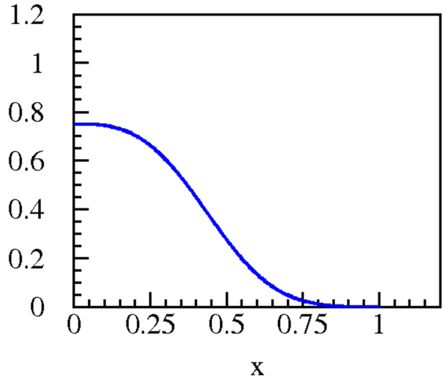
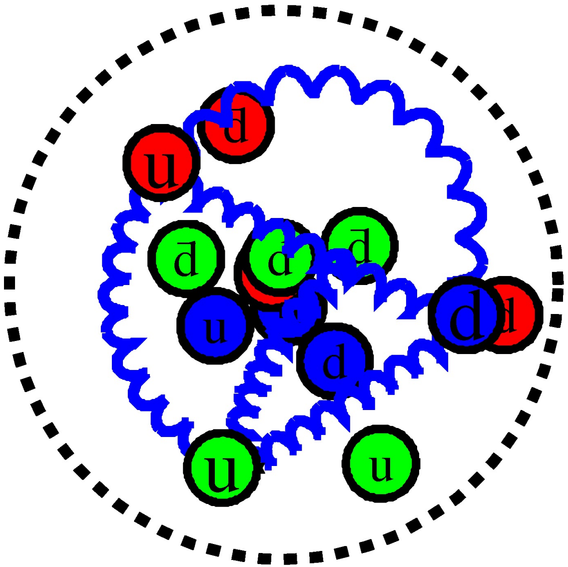






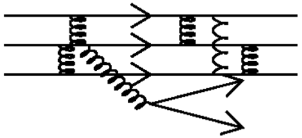
From Constituent Quarks to Partonic Quarks

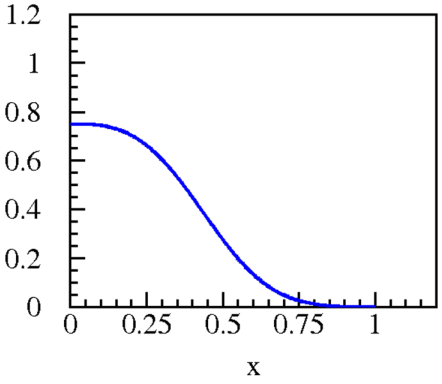
- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Radiatively generate sea and glue. Gluck, Vogt, ZPC 53, 127 (1992)

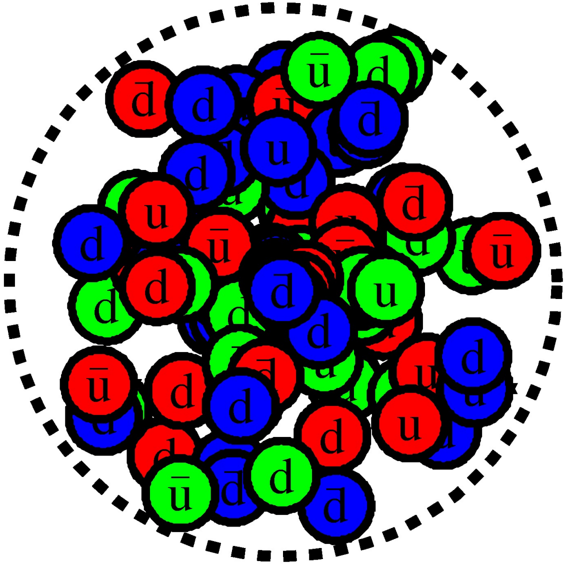
What does valence mean?

$$\int_0^1 [u(x) - \bar{u}(x)]\, dx = 2$$

$$\int_0^1 [d(x) - \bar{d}(x)]\, dx = 1$$







VOLUME 23, NUMBER 24 PHYSICAL REVIEW LETTERS 15 DECEMBER 1969

VERY HIGH-ENERGY COLLISIONS OF HADRONS

Richard P. Feynman
California Institute of Technology, Pasadena, California
(Received 20 October 1969)

Proposals are made predicting the character of longitudinal-momentum distributions in hadron collisions of extreme energies.

. . . I have difficulty in writing this note because it is not in the nature of a deductive paper, but is the result of induction. I am more sure of the conclusions than of any single argument which suggested them to me for they have an internal consistency which surprises me and exceeds the consistency of my deductive arguments which hinted at there existence.

Only the barest indications of the logical bases of these suggestions will be indicated here. Perhaps in a future publication I can be more detailed.[2]

The Sea is a Fundamental Part of the Proton

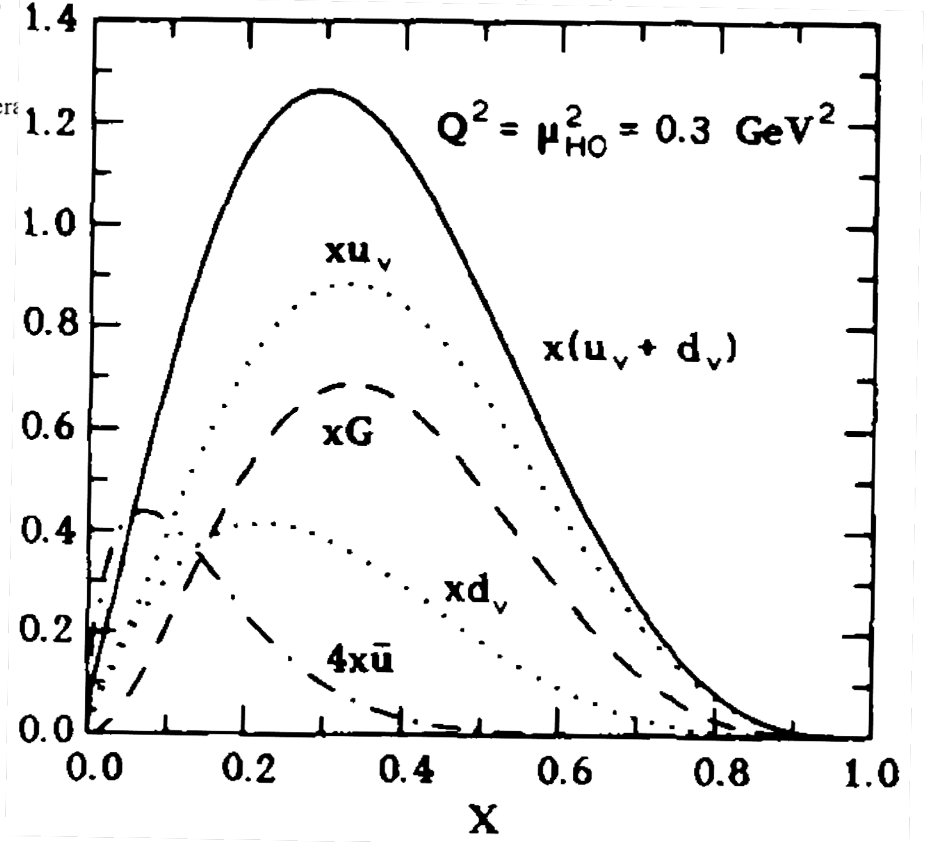
Parton distributions for high energy collisions

M. Glück, E. Reya, A. Vogt
Institut für Physik, Universität Dortmund, Postfach 500500, W-4600 Dortmund 50, Federa

Received 10 June 1991

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 . . . .

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



Light Antiquark Flavor Asymmetry: Brief History

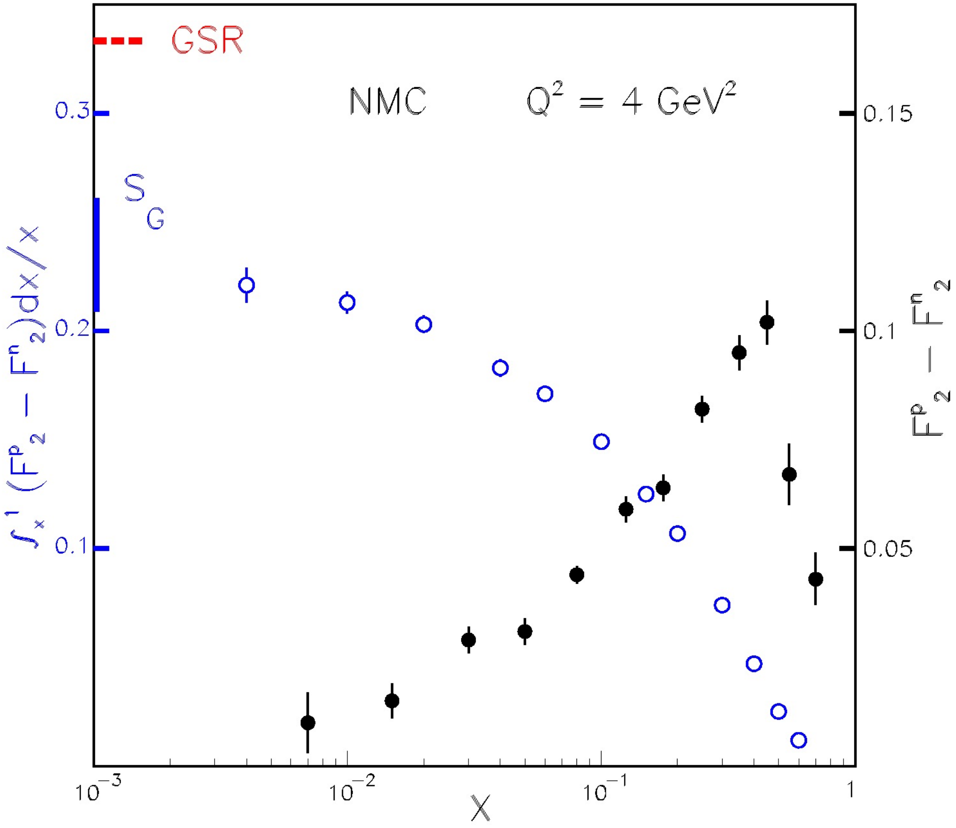
- Naïve Assumption:

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

- NMC (Gottfried Sum Rule)

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

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



Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

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

- NMC (Gottfried Sum Rule)

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

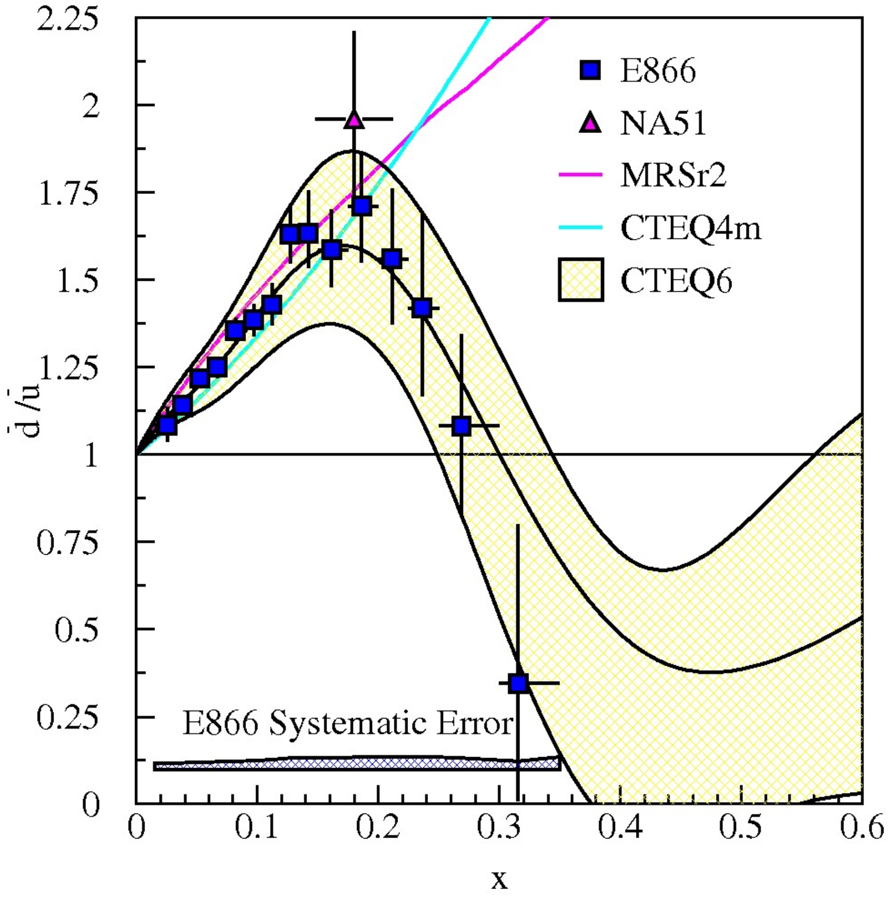
- CERN NA51 (Drell-Yan):

  $$\bar{d}(0.18) \approx 2\times\bar{u}(0.18)$$

- Fermilab E866/NuSea:

  $\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.035$

- Knowledge of sea dist. are data driven
- Non-pQCD allow $\bar{d}(x) > \bar{u}(x)$



NON-PERTURBATIVE MODELS: PION CLOUD

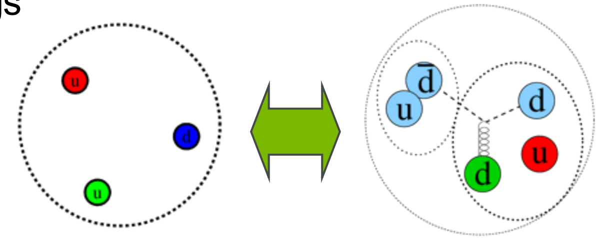
- Meson Cloud in the nucleon Sullivan process in DIS

$$|p\rangle = (1 - \sum a_i)|p_0\rangle + a_{|N\pi\rangle}|N\pi\rangle + a_{|\Delta\pi\rangle}|\Delta\pi\rangle + a_{|\Lambda K\rangle}|\Lambda K\rangle + \cdots$$

- In its simplest form, Clebsch-Gordon Coefficients and πN, $\pi\Lambda$ couplings

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

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



Predicts

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

Cannot have

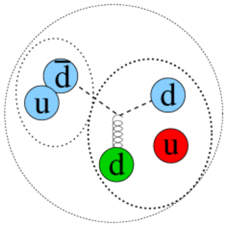
$\bar{d} < \bar{u}$

Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS

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

Antiquarks in spin 0 object → No net spin



- Chiral Quark models—effective Lagrangians

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

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

- Instantons

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

- Statistical Parton Distributions

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

How is the Sea Created?

- pQCD does create a Sea

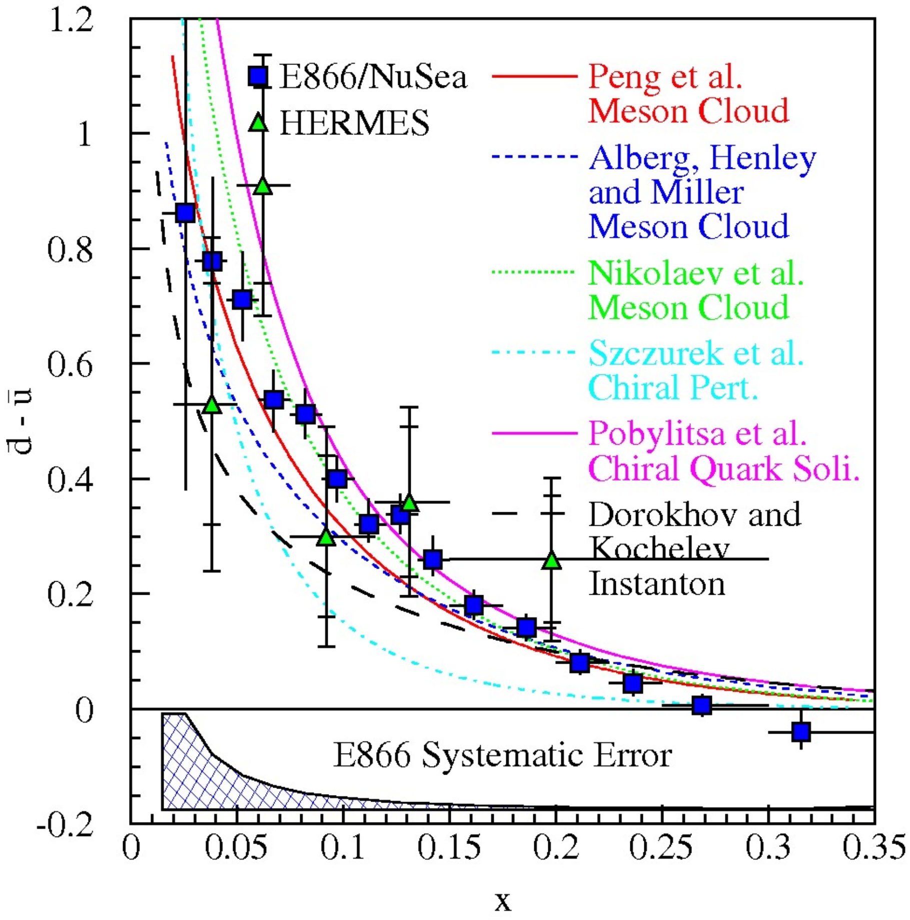
$$\bar{d}(x) = \bar{d}_{pQCD}(x) + \bar{d}_{meson}(x)$$
$$\bar{u}(x) = \bar{u}_{pQCD}(x) + \bar{u}_{meson}(x)$$

- Gluon splitting component is symmetric

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

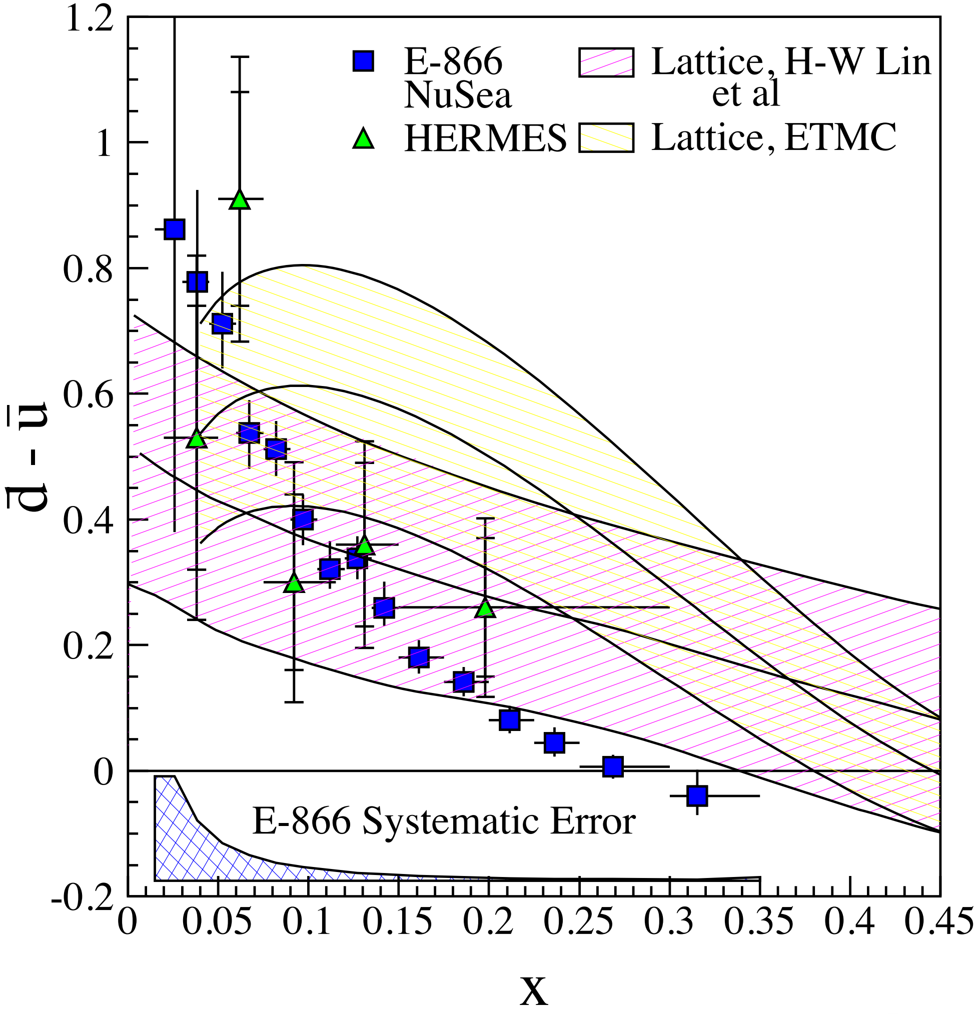
$$\bar{d}(x) - \bar{u}(x) = \bar{d}_{meson}(x) - \bar{u}_{meson}(x)$$

- Symmetric sea via subtracts away
- No Gluon contribution at 1st order in α_s
- Non-pQCD models compare to difference

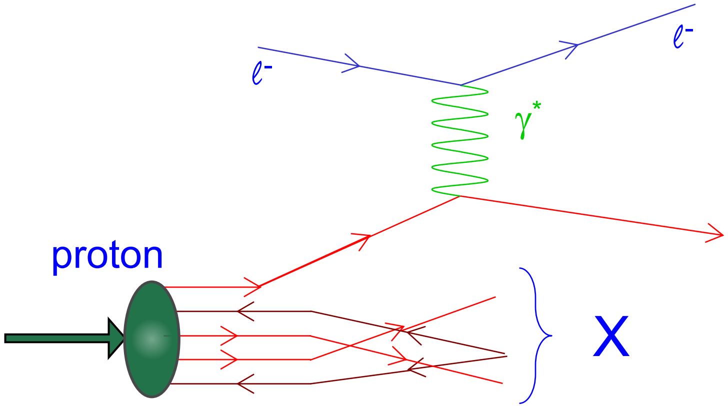


How is the Sea Created?

- Lattice weighs in!!



VOYAGE INTO THE SEA



$$F_2^{\mu p}(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x \left[q(x,Q^2) - \bar{q}(x,Q^2)\right]$$

$$N^{\pi^\pm} \propto \sum_{q\in\{u,d,\dots\}} \left[q(x,Q^2)D^{\pi^\pm} + \bar{q}(x,Q^2)D^{\pi^\pm}\right]$$

How can we measure the sea distributions?

Need a process that can isolate sea contributions:

- SIDIS
  - K/π identification
  - Knowledge of fragmentation functions (D^π)
  - HERMES, COMPASS, JLab 12 GeV

$$F_2^{\mu p}(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$F_2^{\nu p}(x)+F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2)-\bar{q}(x,Q^2)\right]$$

$$N^{\pi^\pm} \propto \sum_{q\in\{u,d,\dots\}} \left[q(x,Q^2)D^{\pi^\pm}+\bar{q}(x,Q^2)D^{\pi^\pm}\right]$$

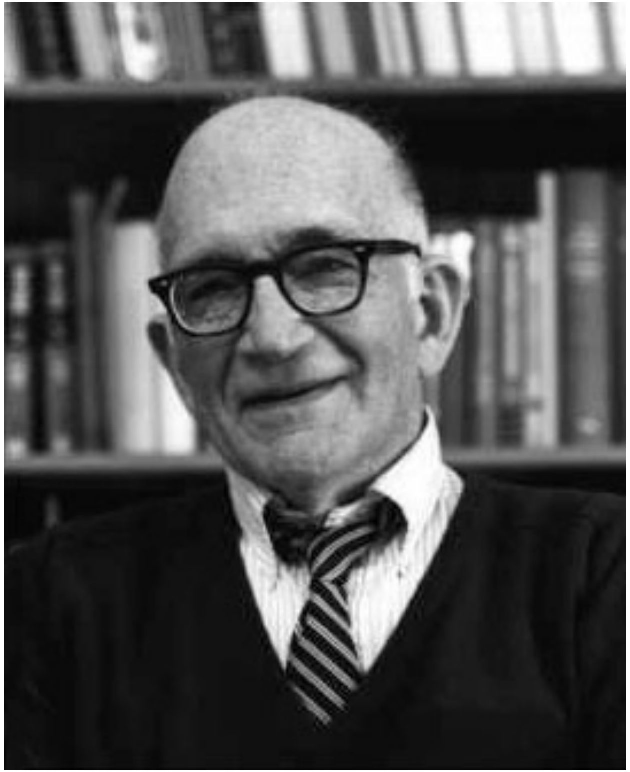
- Collider W production
  - Fermilab Tevatron, CERN LHC, BNL RHIC

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

- Drell-Yan
  - Rest of talk

$$\frac{d\sigma}{dx_1 dx_2} \propto \sum_{q\in\{u,d,\dots\}} e_q^2\left[q(x_1)\bar{q}(x_2)+\bar{q}(x_1)q(x_2)\right]$$

The Drell-Yan Process



Early Muon Pair Data

Volume 25, Number 21 PHYSICAL REVIEW LETTERS 23 November 1970

Observation of Massive Muon Pairs in Hadron Collisions*

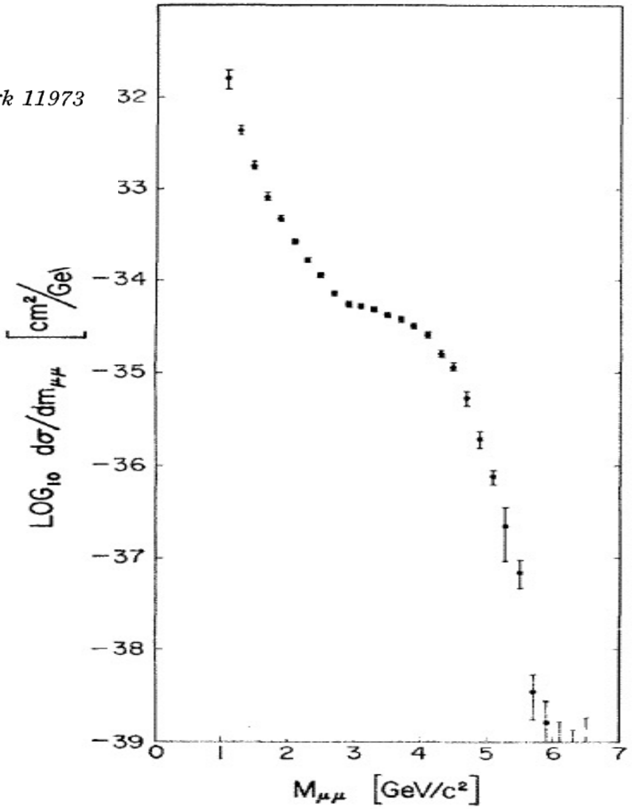
J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)

Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

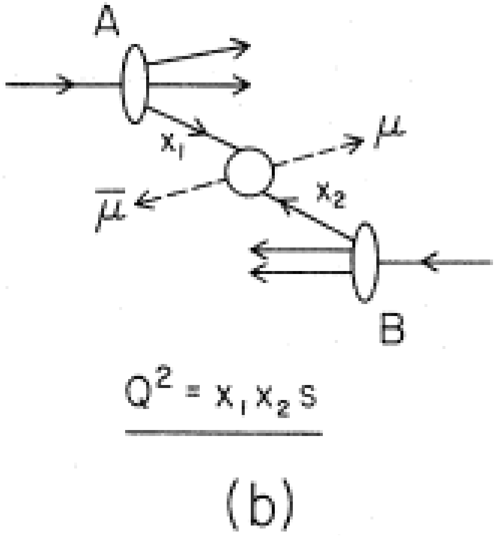


DRELL AND YAN'S EXPLANATION

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)



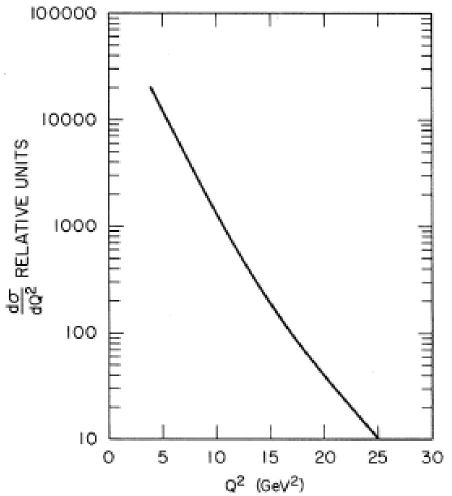
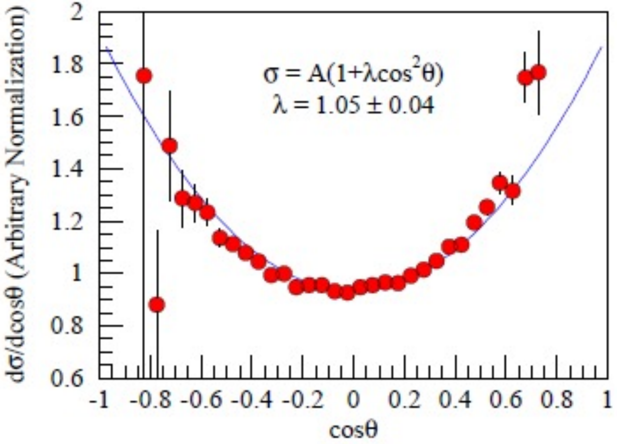


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributic and with relative normalization.

Also predicted $\lambda(1+\cos^2\theta)$ angular distributions



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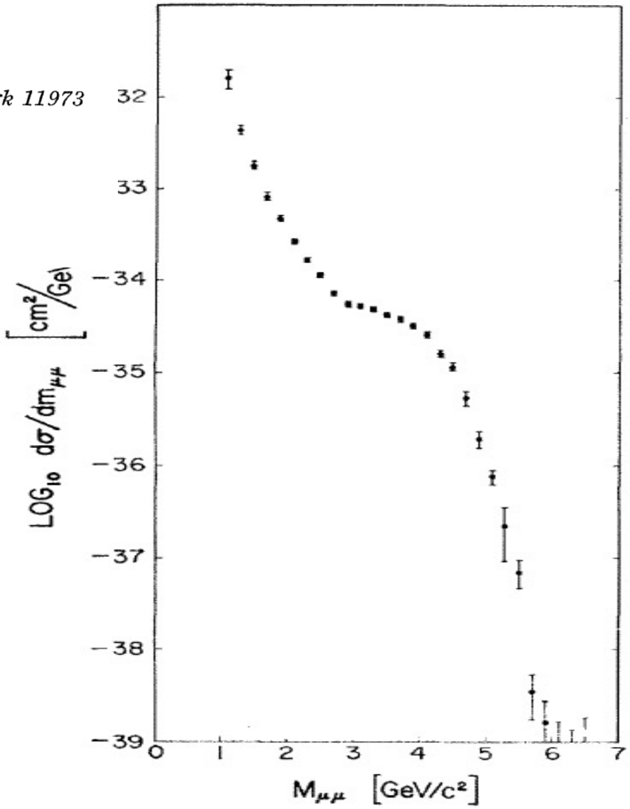
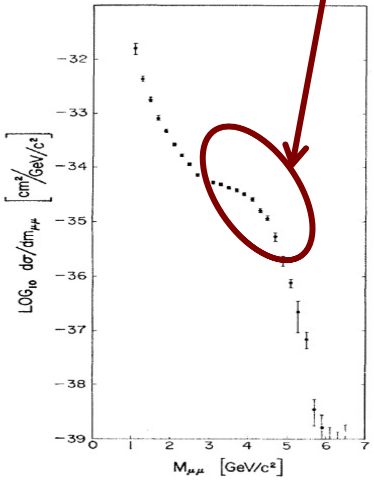
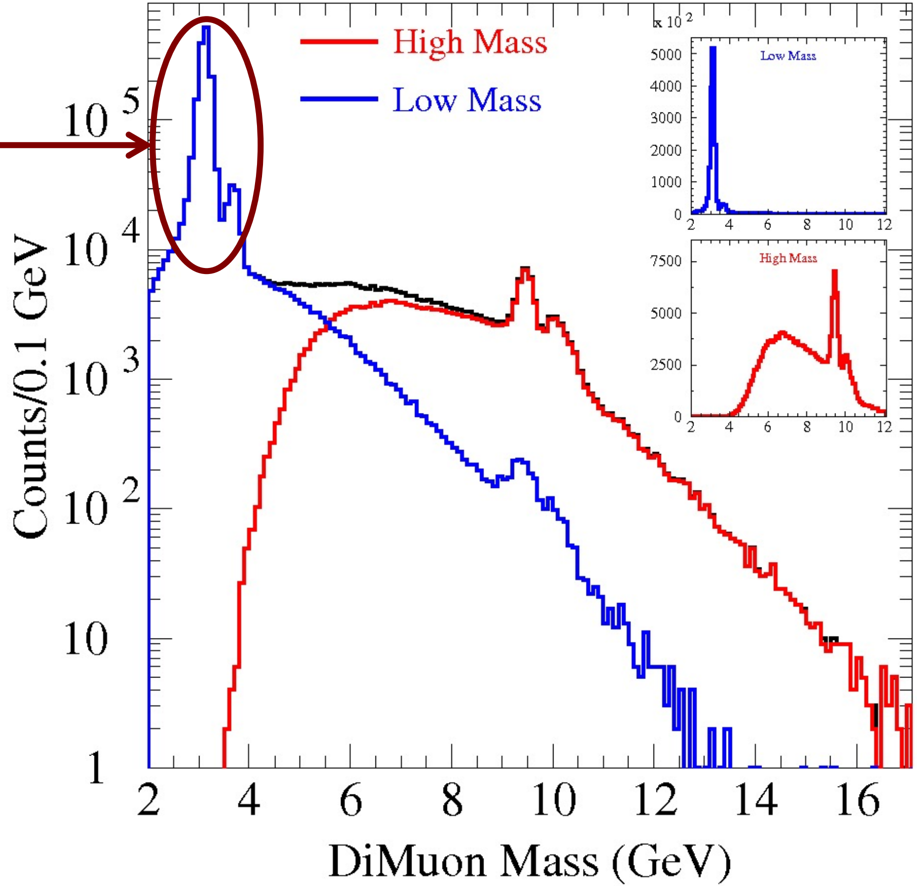


Drell-Yan Mass Spectra

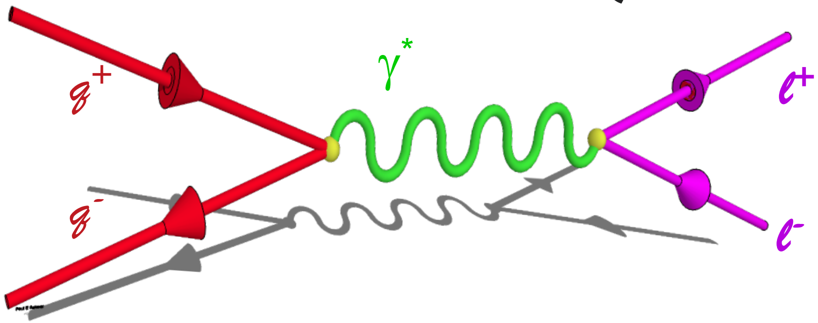
- What they could have seen if they had sufficient resolution
- The Nobel Prize was awarded to Sam Ting and Burton Richter for the discovery of the J/Ψ

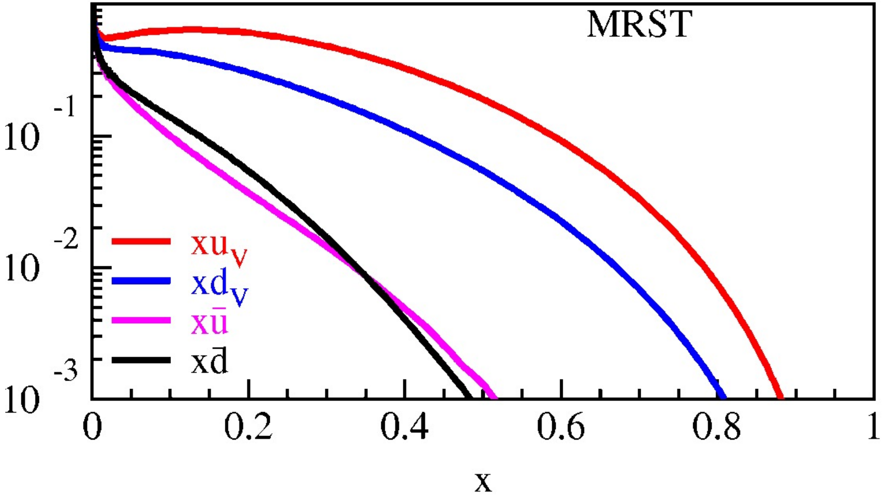




Data from Fermilab E-866/NuSea

Drell-Yan Cross Section—Sensitivity to Sea Quarks



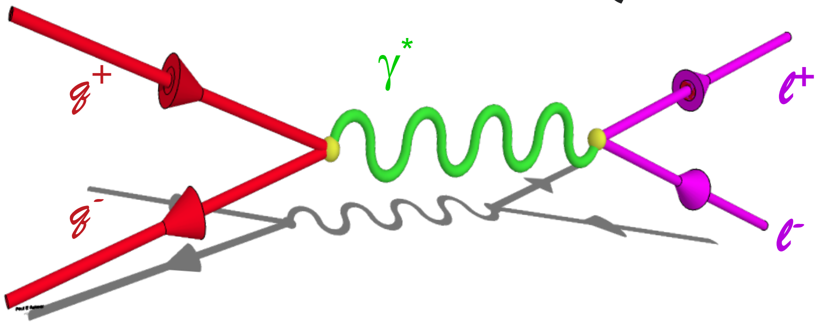


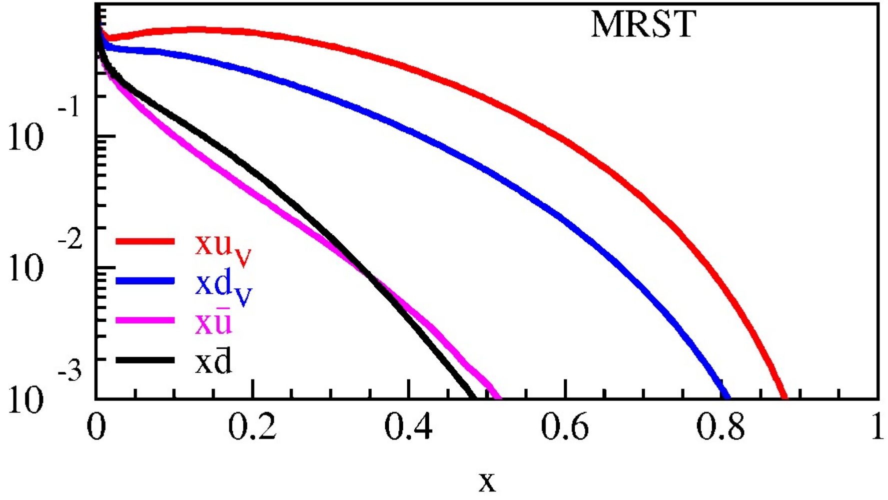
Cross Section

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

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

DRELL-YAN CROSS SECTION— SENSITIVITY TO SEA QUARKS





Cross Section

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

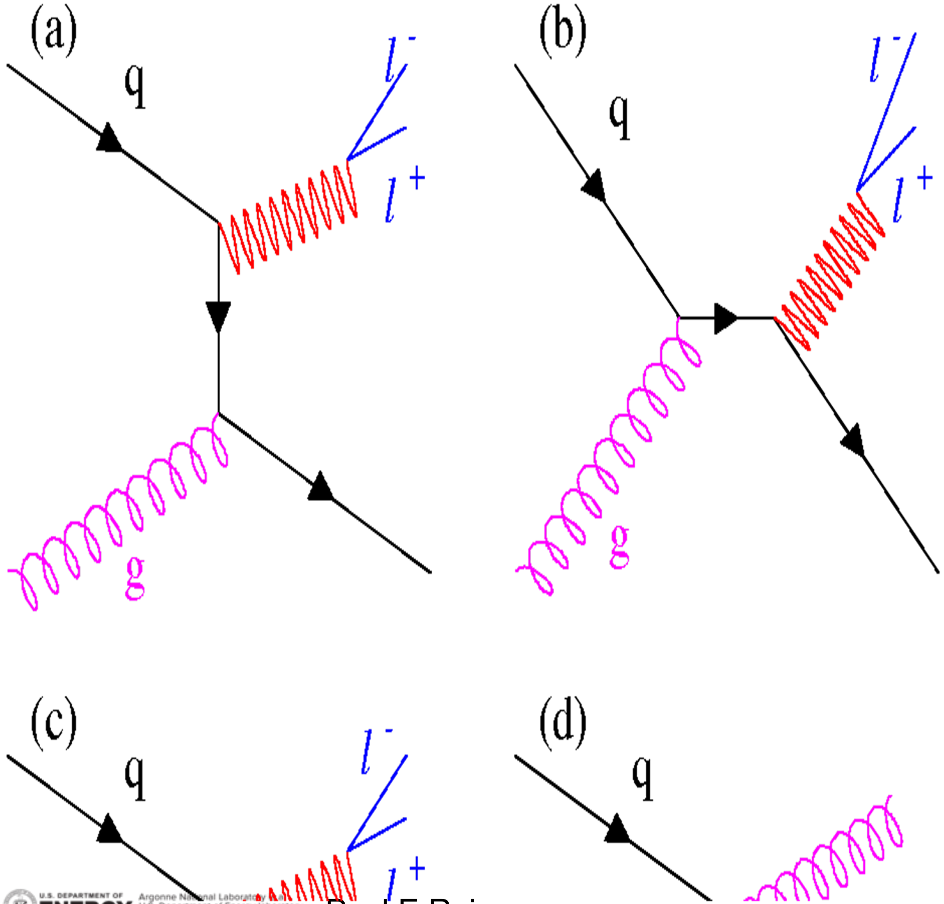
$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

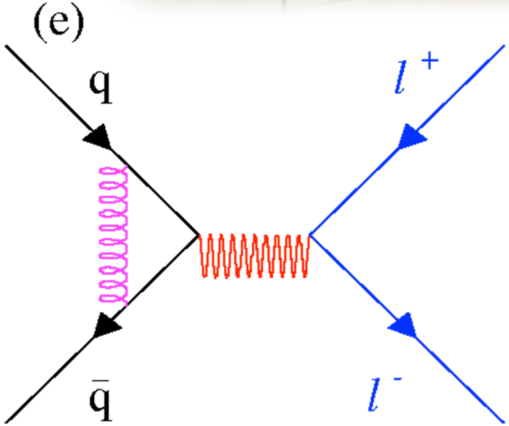
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

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

Acceptance limited
(Fixed Target, Hadron Beam)

NEXT-TO-LEADING ORDER IN α_S

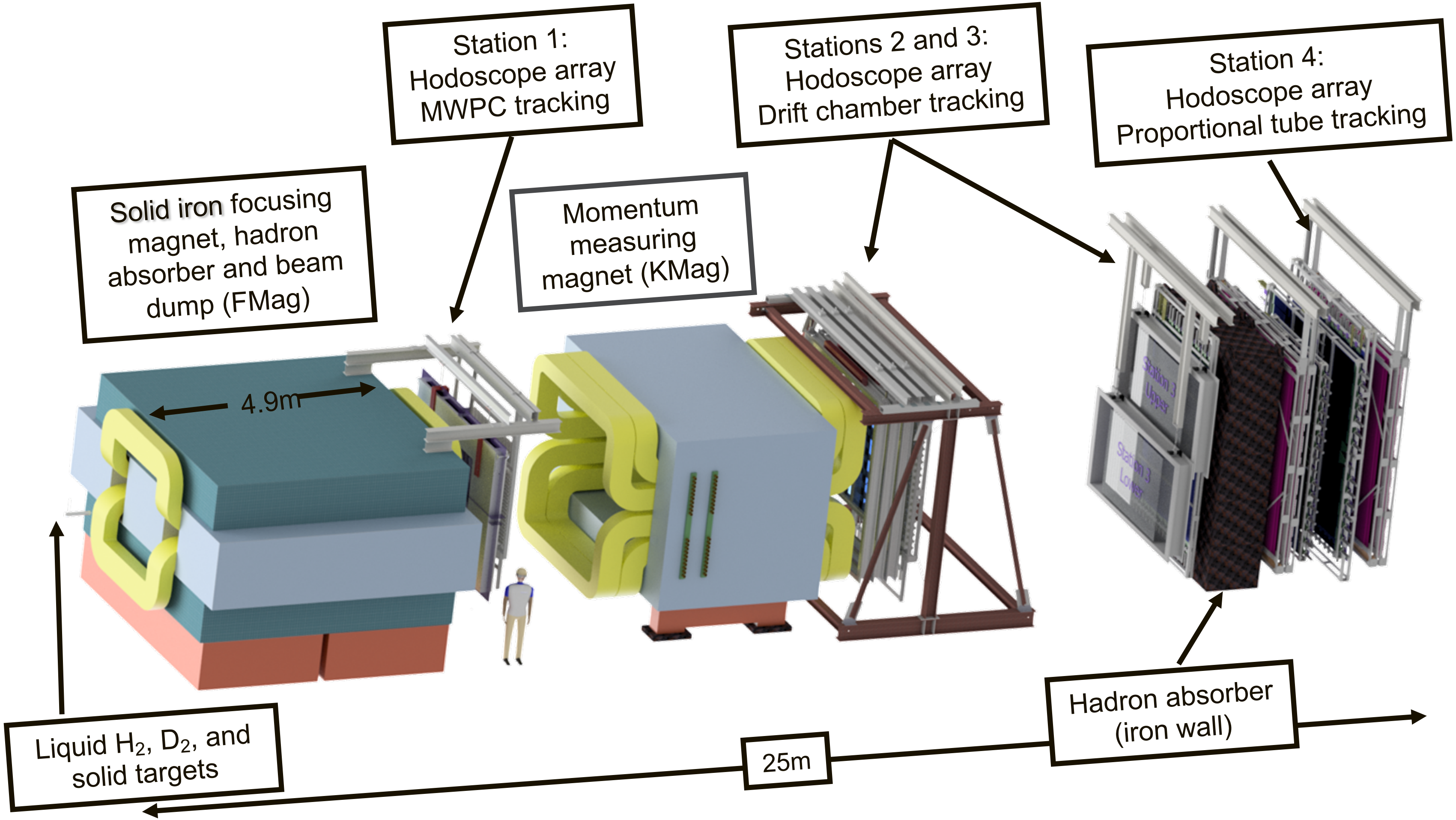


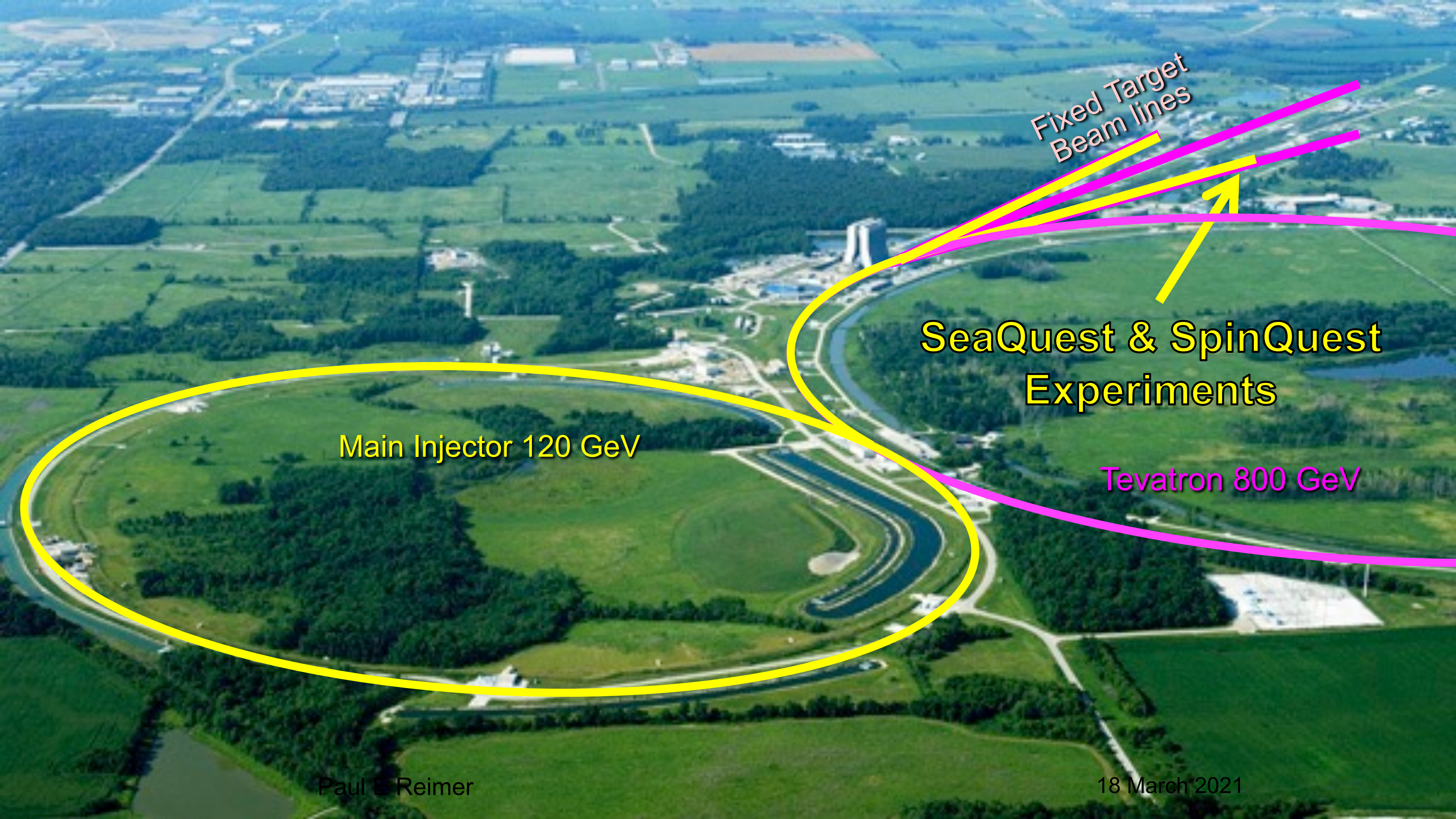


The SeaQuest Detector

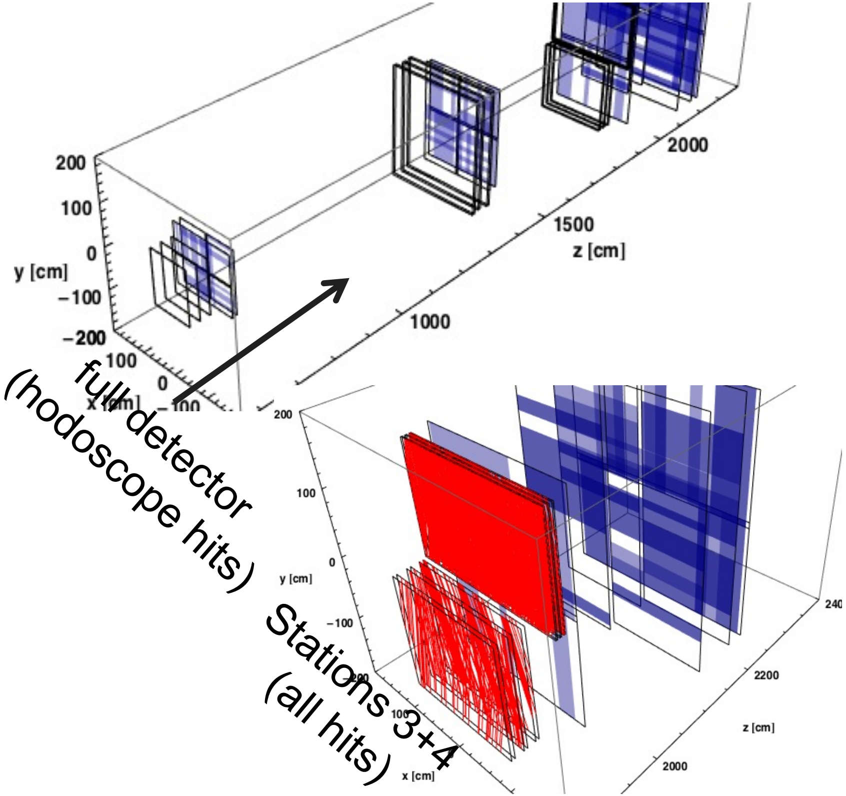
Paul E Reimer

18 March 2021


Station 1:
Hodoscope array
MWPC tracking
Stations 2 and 3:
Hodoscope array
Drift chamber tracking
Station 4:
Hodoscope array
Proportional tube tracking
Solid iron focusing magnet, hadron absorber and beam dump (FMag)
Momentum measuring magnet (KMag)
4.9m
Liquid H_2, D_2, and solid targets
25m
Hadron absorber (iron wall)


Fixed Target
Beam lines
SeaQuest & SpinQuest
Experiments
Main Injector 120 GeV
Tevatron 800 GeV

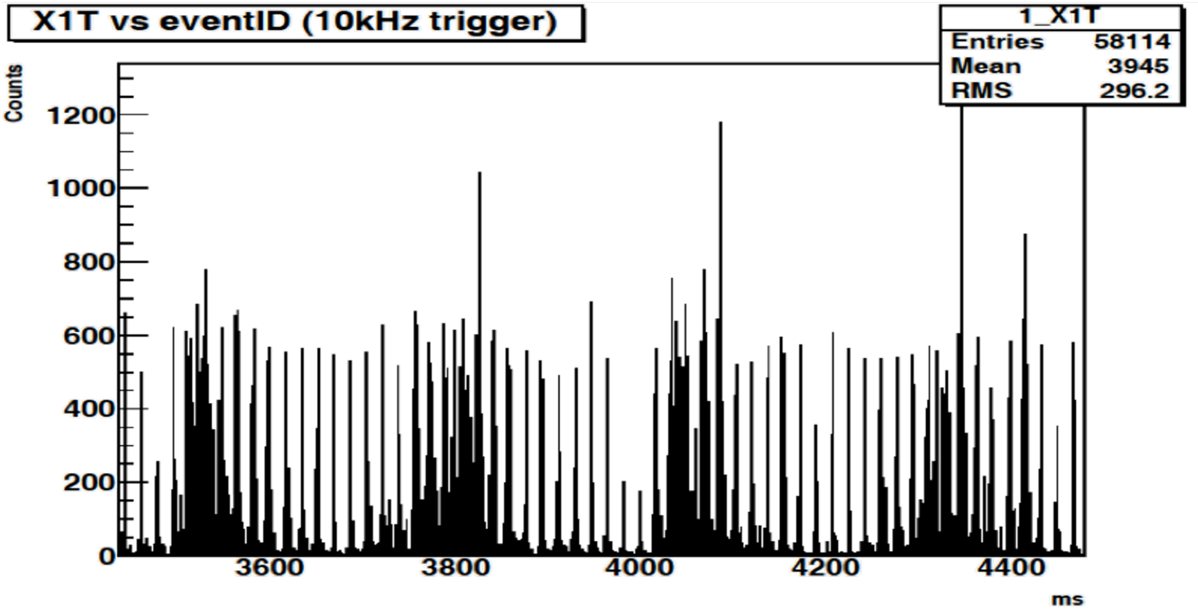
THE BEAM WAS DELIVERED



“SPLAT” EVENTS – UNDERSTANDING THE BEAM

Beam Structure

- Macroscopic:
  - 4s every 60s
- Microscopic
  - “bucket” every 19 ns
- Independent 10kHz pulsed DAQ read out raw hodoscope rates
  - Long time compared to accelerator frequency of 53MHz
  - Phase locked to 60 Hz AC

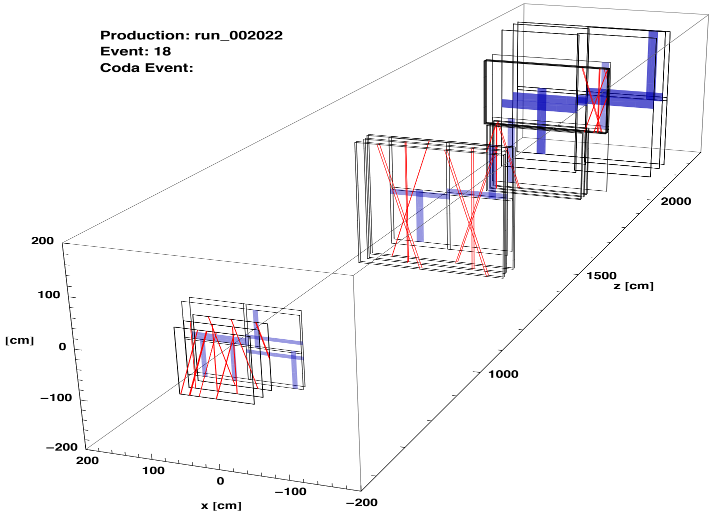


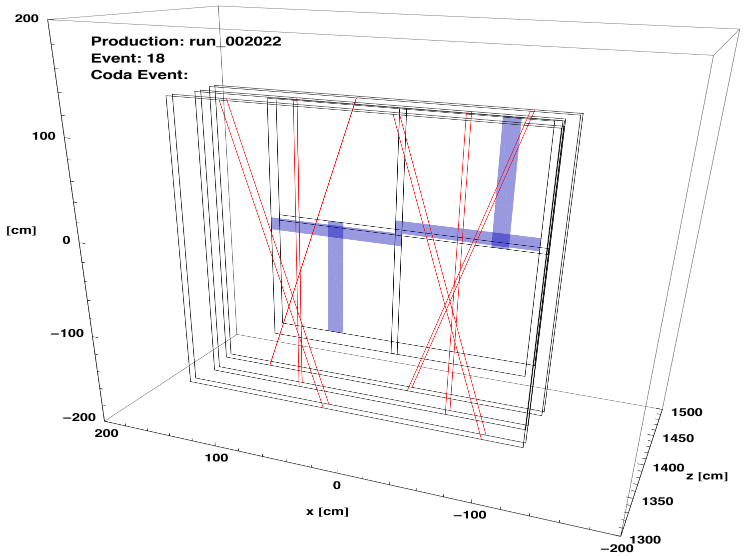
- Average intensity normal, measured by beamline instrumentation

THE SPLAT-BLOCK CARD

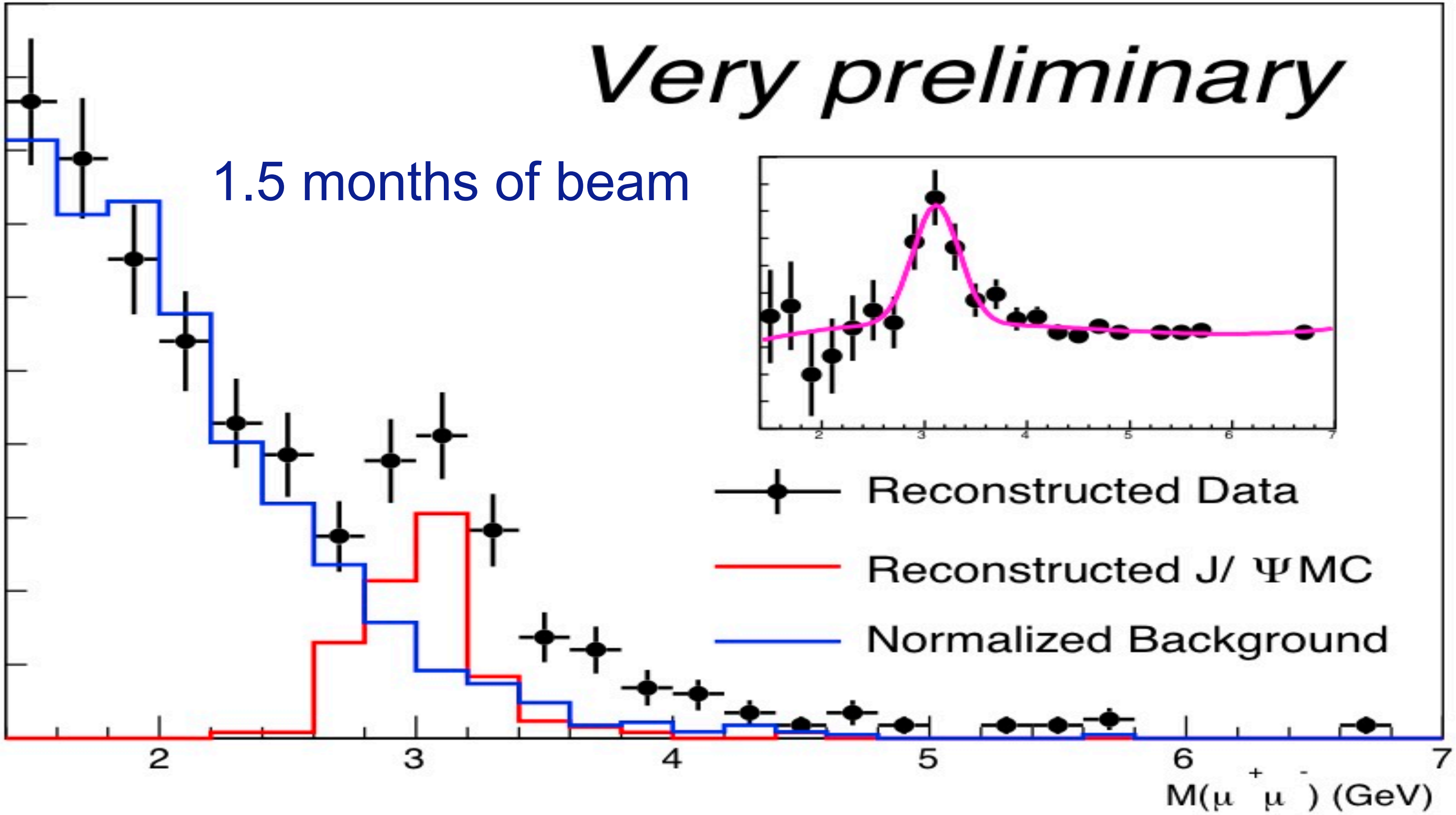
Trigger veto:

- Electronic running average of the multiplicity over a 160 ns window (8 RF buckets).
- If average multiplicity above threshold, raises a trigger veto
- Luminosity greatly reduced, but trigger suppresses windows of time with large beam intensities.



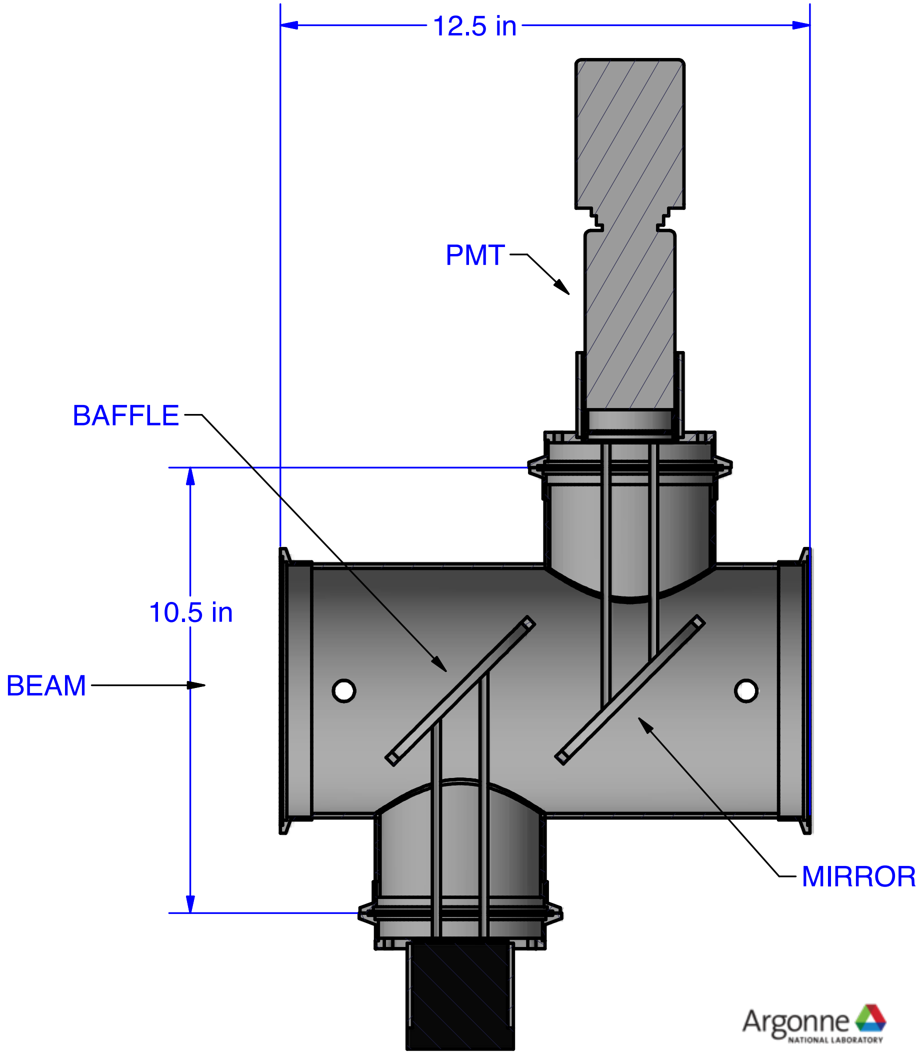


COMMISSIONING RUN

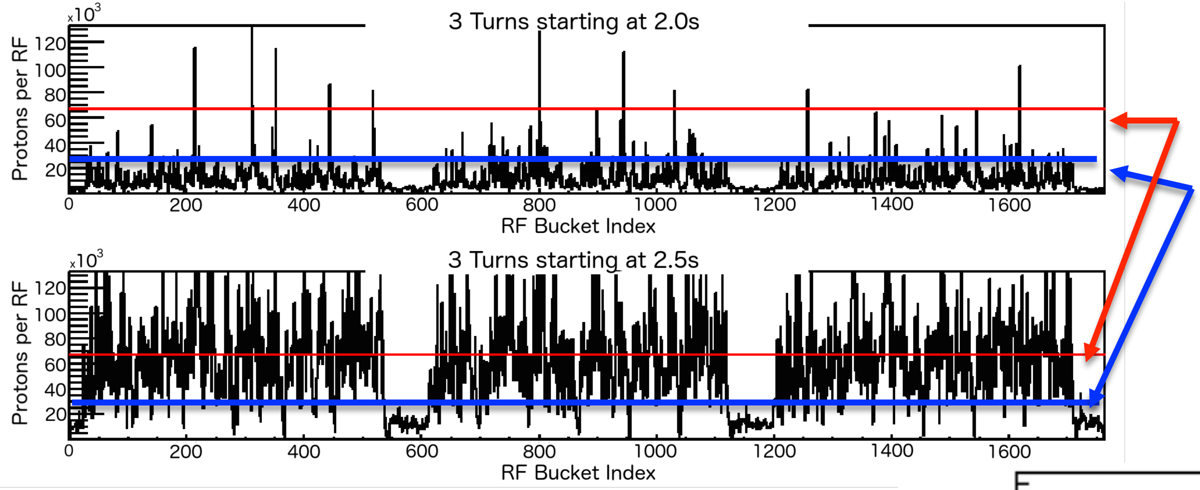


Beam Cherenkov

- <16 ns time resolution
- Approx. 30 to 3×10^{16} protons/RF cycle
- Calibrated every minute against beam line SEM

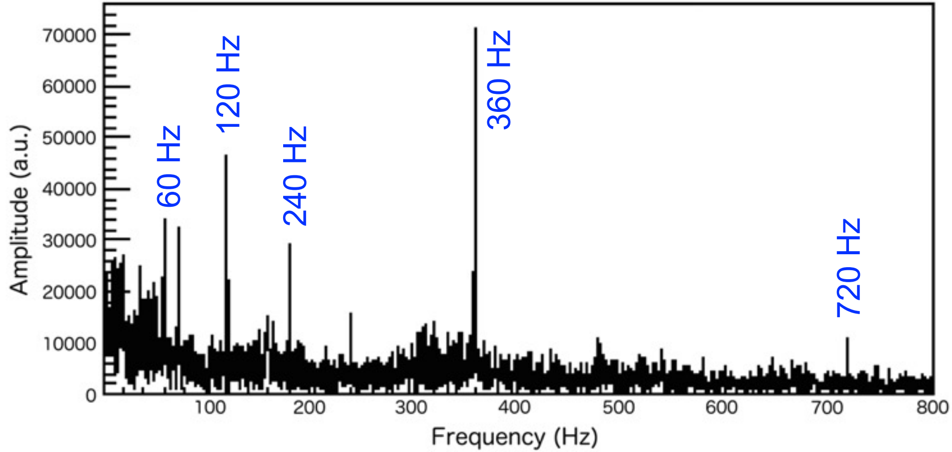


Randomly Chosen Beam Intensity Profile

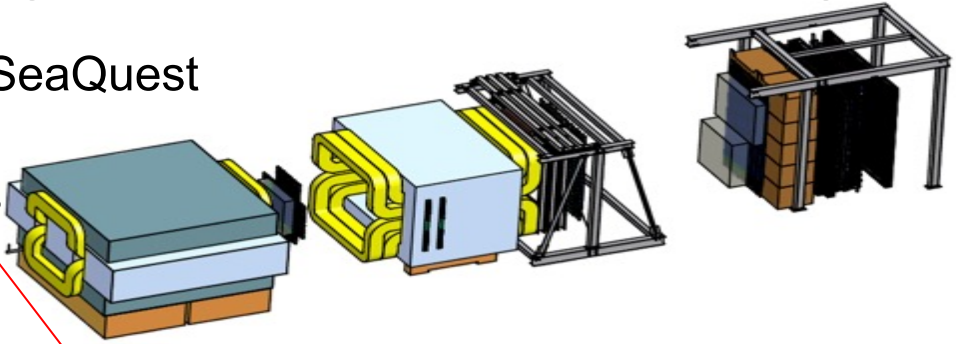


- **Each bin is 19 ns**
- Veto Level
- Even beam distribution

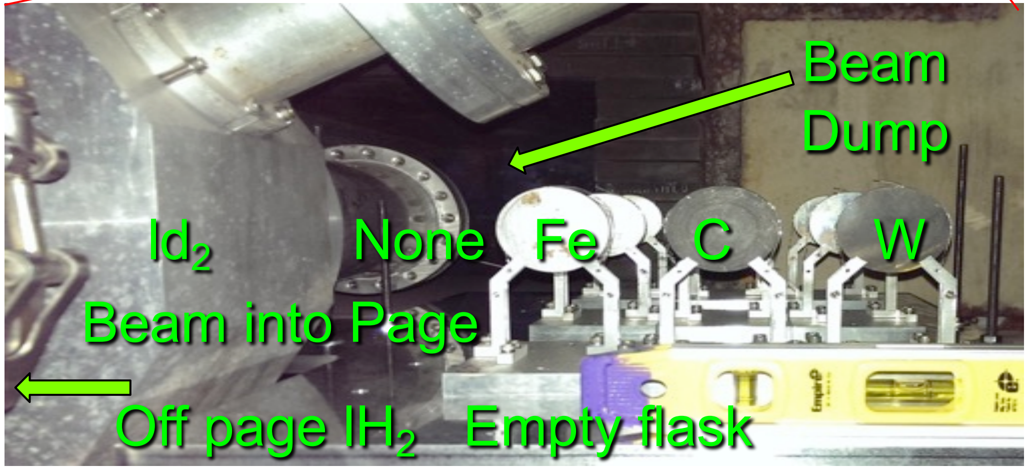
Fourier Transform

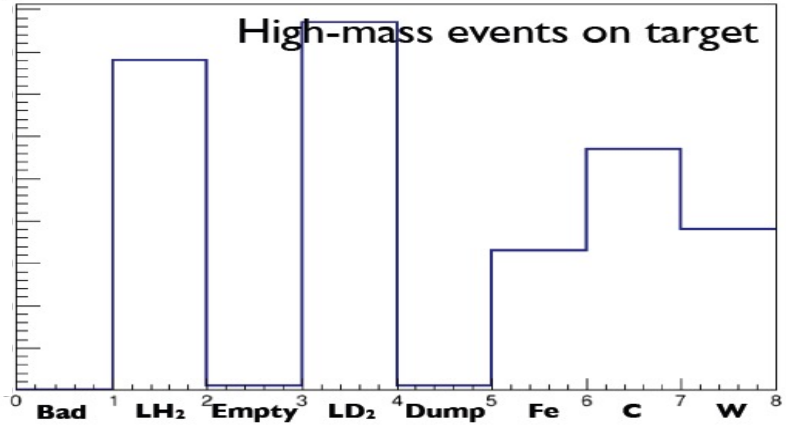


Do We Reconstruct Events When there are Events?

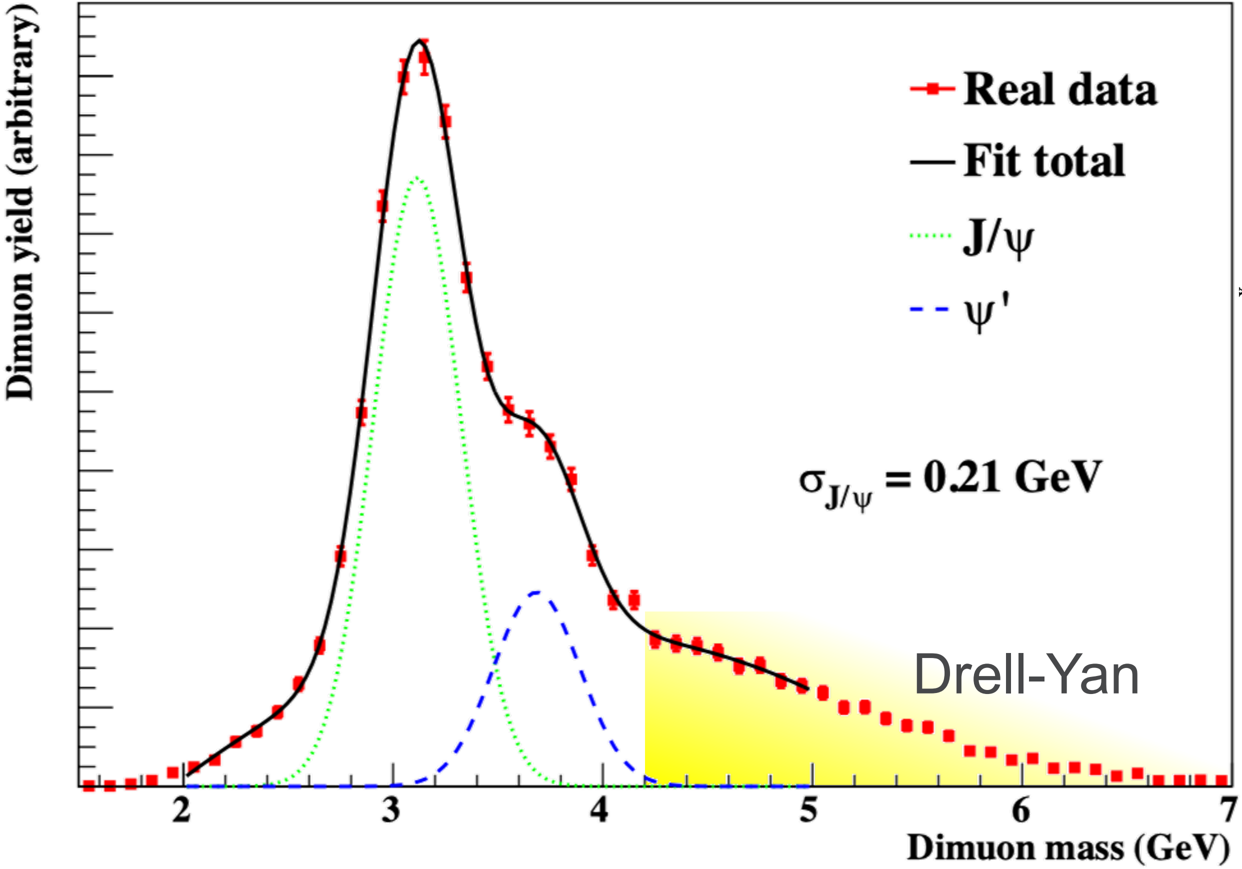


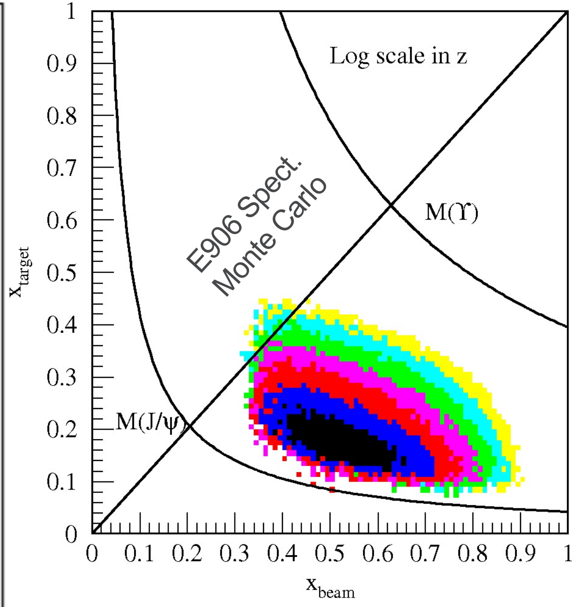
- Entire beam interacts upstream of first SeaQuest Spectrometer tracking chamber
- Spatial resolution poor along beam axis
- Resolve target vs beam dump





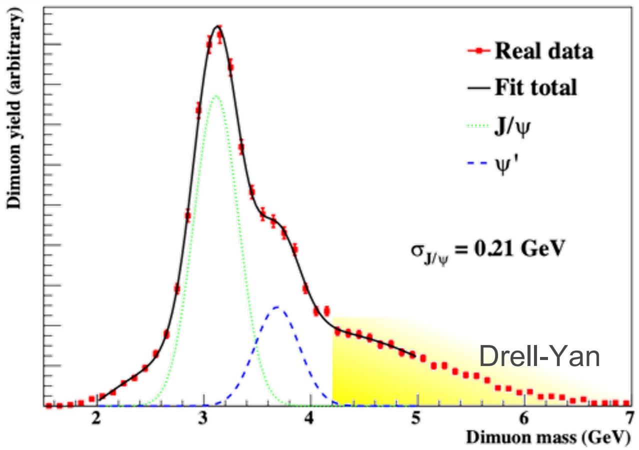
E906 Mass Spectrum

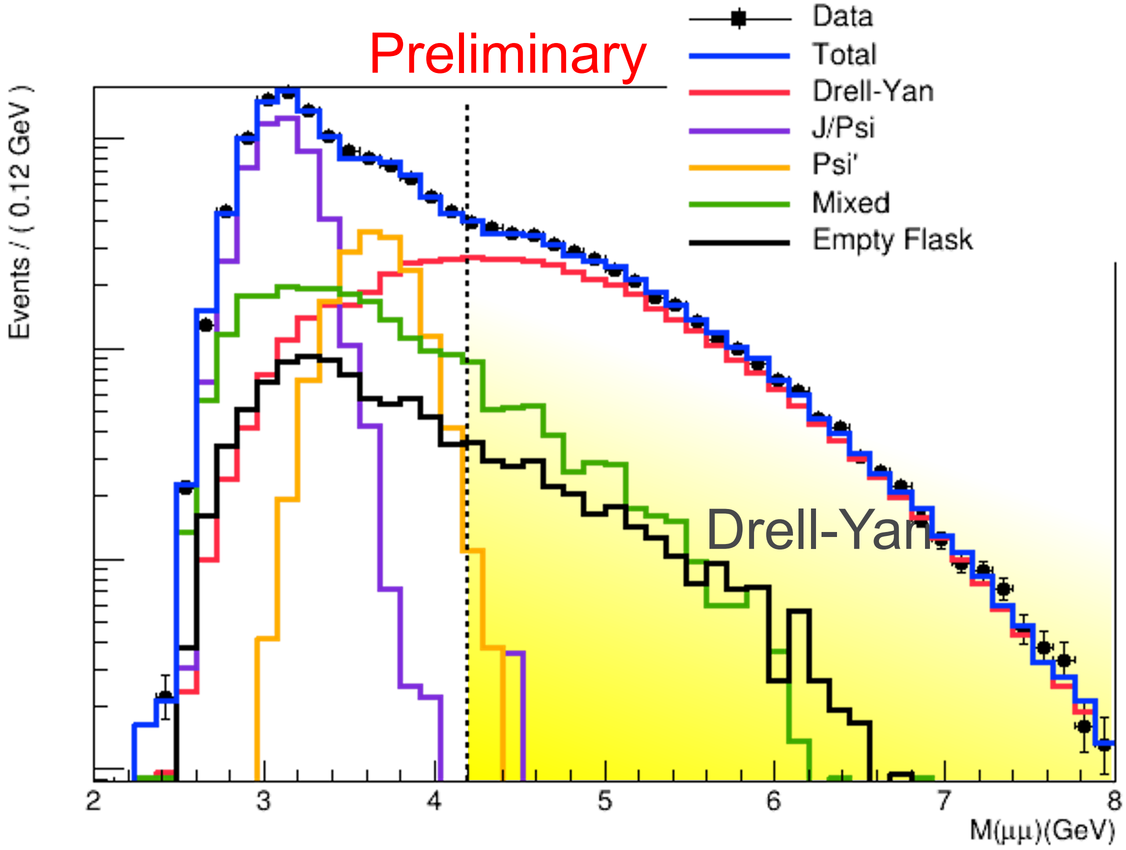




CROSS CHECK OF RATE DEPENDENCE

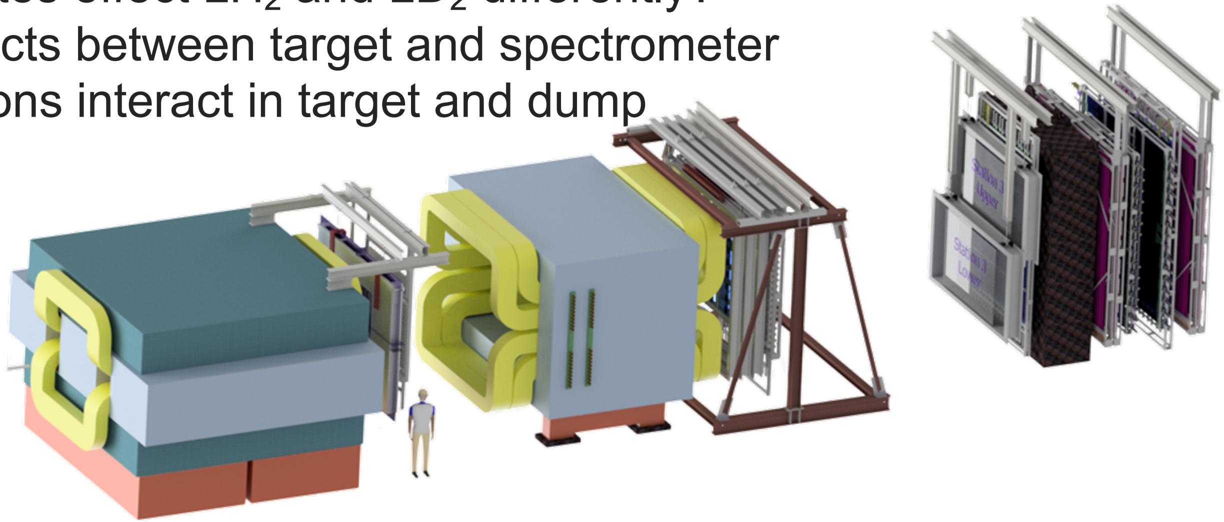
- Multi-component mass fit
- Combinatorial background "mixed" and reconstruction efficiency





Rate Dependent Effects

- We were expecting these effects and had handled them in E866/NuSea
- Overall question: Do the rates effect LH_2 and LD_2 differently?
  - 1st order, all beam interacts between target and spectrometer
  - 2nd order, different fractions interact in target and dump



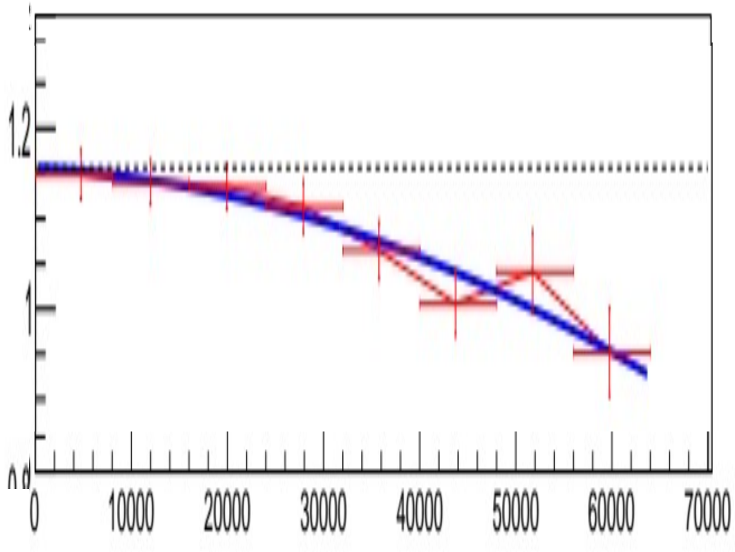
- Primary problem:
  - Background from two uncorrelated muons
  - Different distribution from target and dump

Is There Still an Intensity Dependence?

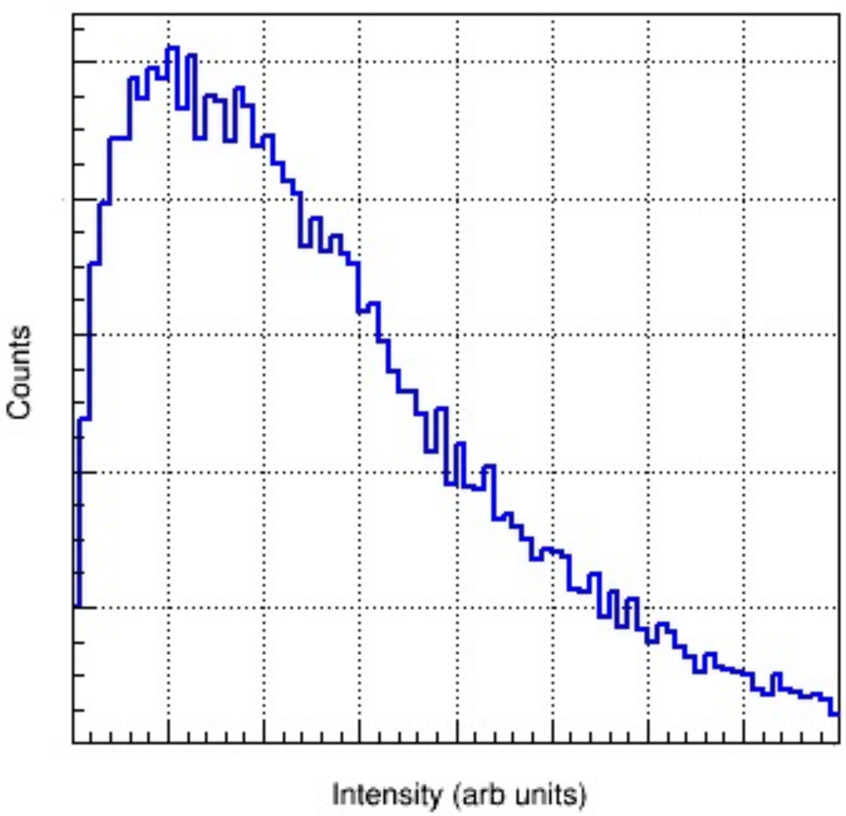
Plot $^{\sigma_D}/_{2\sigma_H}$ as a function of the # of protons in the triggered bucket

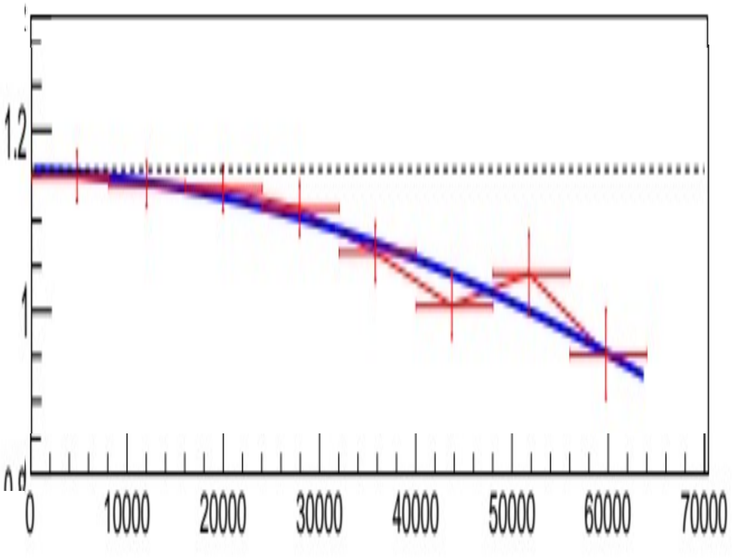
Possible sources:

- Trigger inefficiency at high rates
- Increased triggering on noise events
- Reconstruction inefficiency at high occupancy
- . . . .
- Cut on beam intensity
  - Lose statistical power of the data
- Model-based corrections
  - Fit data w/model of source
  - Monte Carlo to verify
  - Used by E866/NuSea
  - Becomes difficult with multiple effects



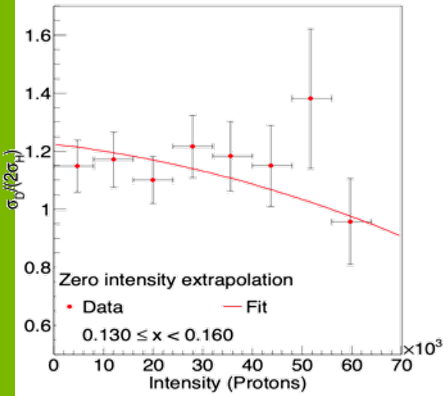
Intensity Dependence

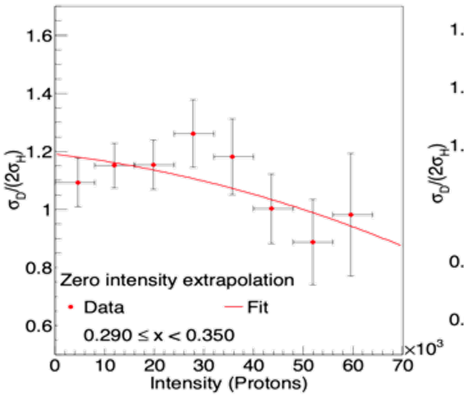


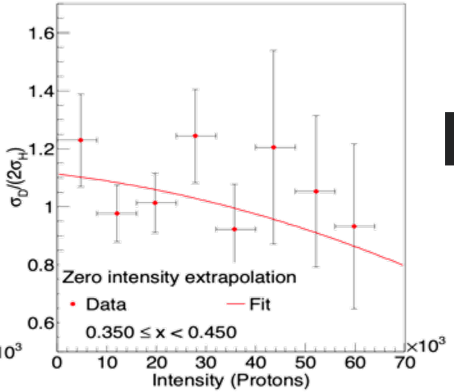


- Extract intercept at 0 which is free from accidental background and rate dependence!

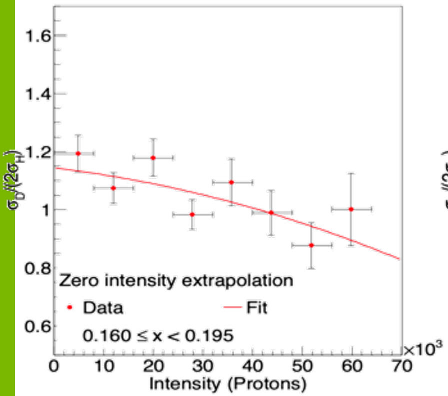
Intensity Extrapolation

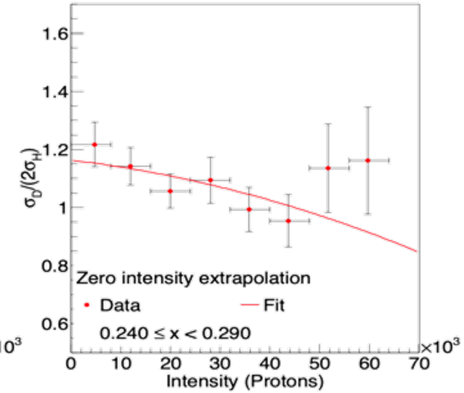


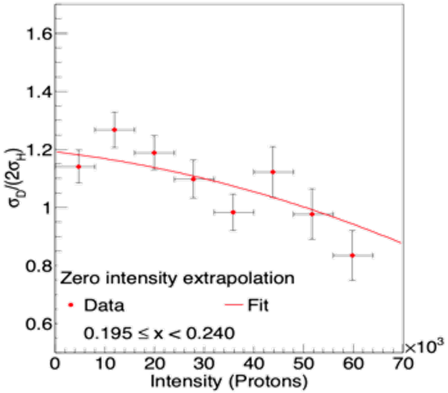




$$\frac{Y_D(x_t, I)}{2Y_H(x_t, I)} = R_{x_t} + a\,I + b\,I^2$$

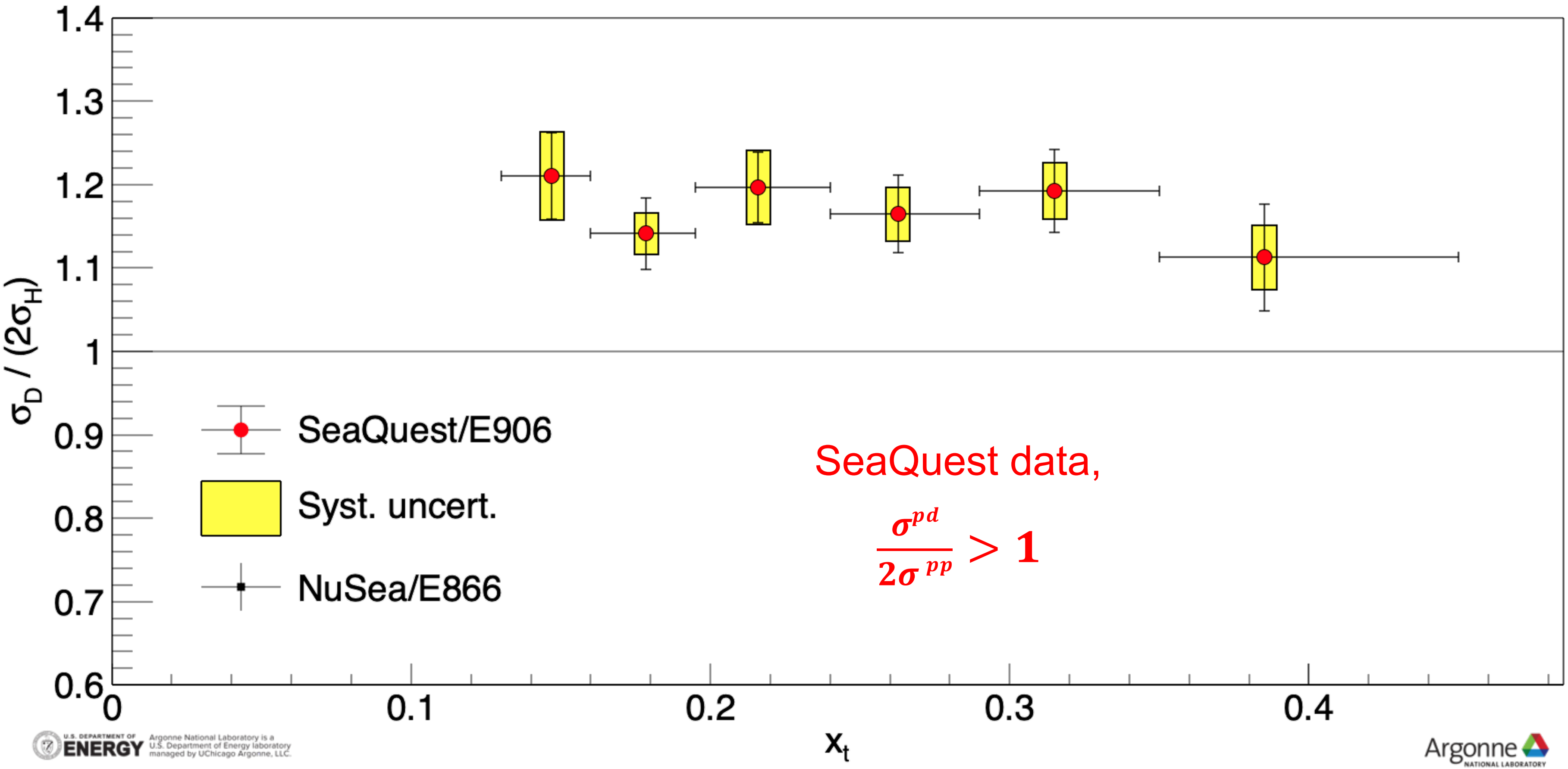






Intensity = 0 intercept from simultaneous fits gives ${}^{\sigma_d}/_{2\sigma_p}$ for different x_T bins

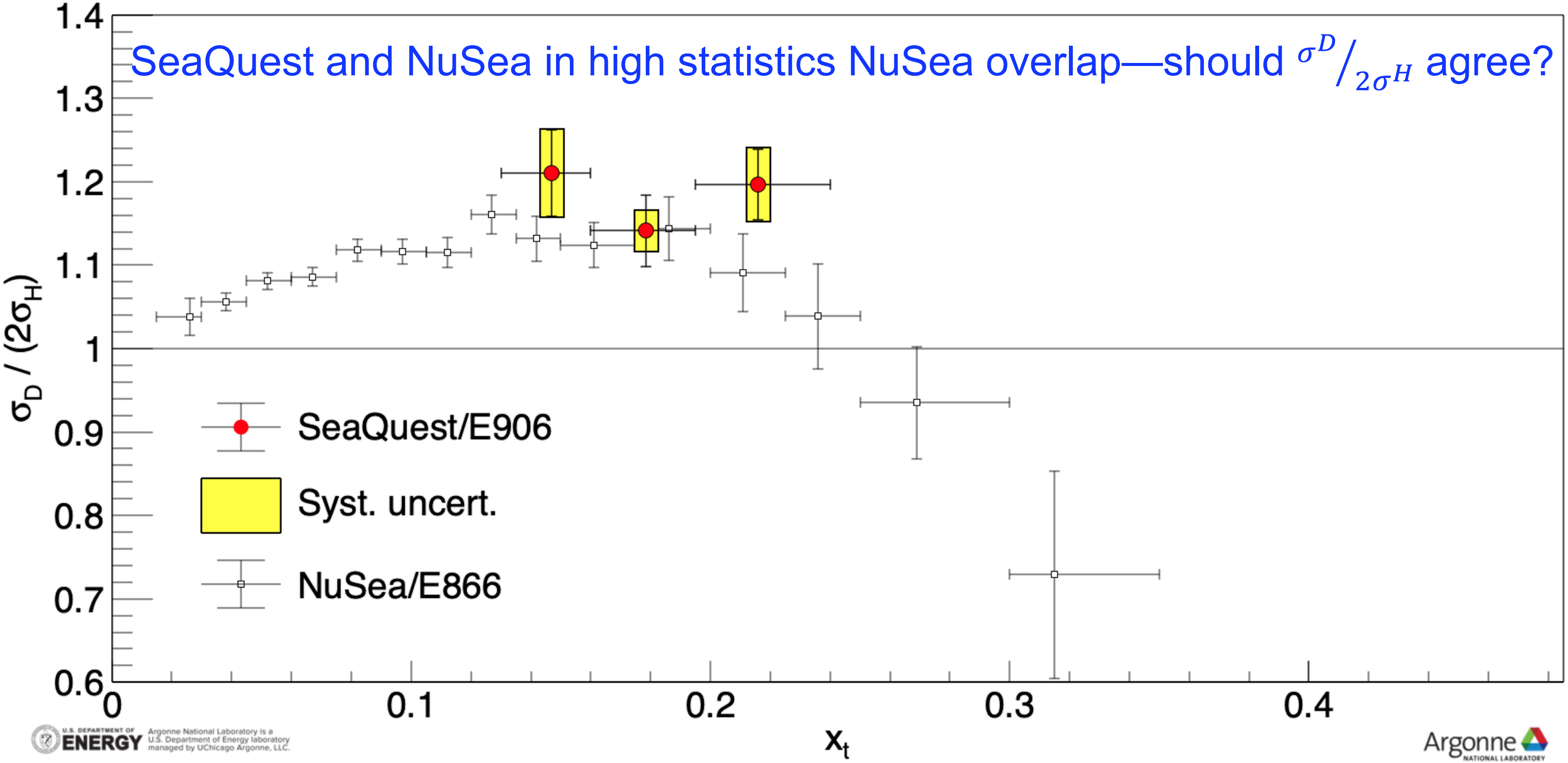
SeaQuest



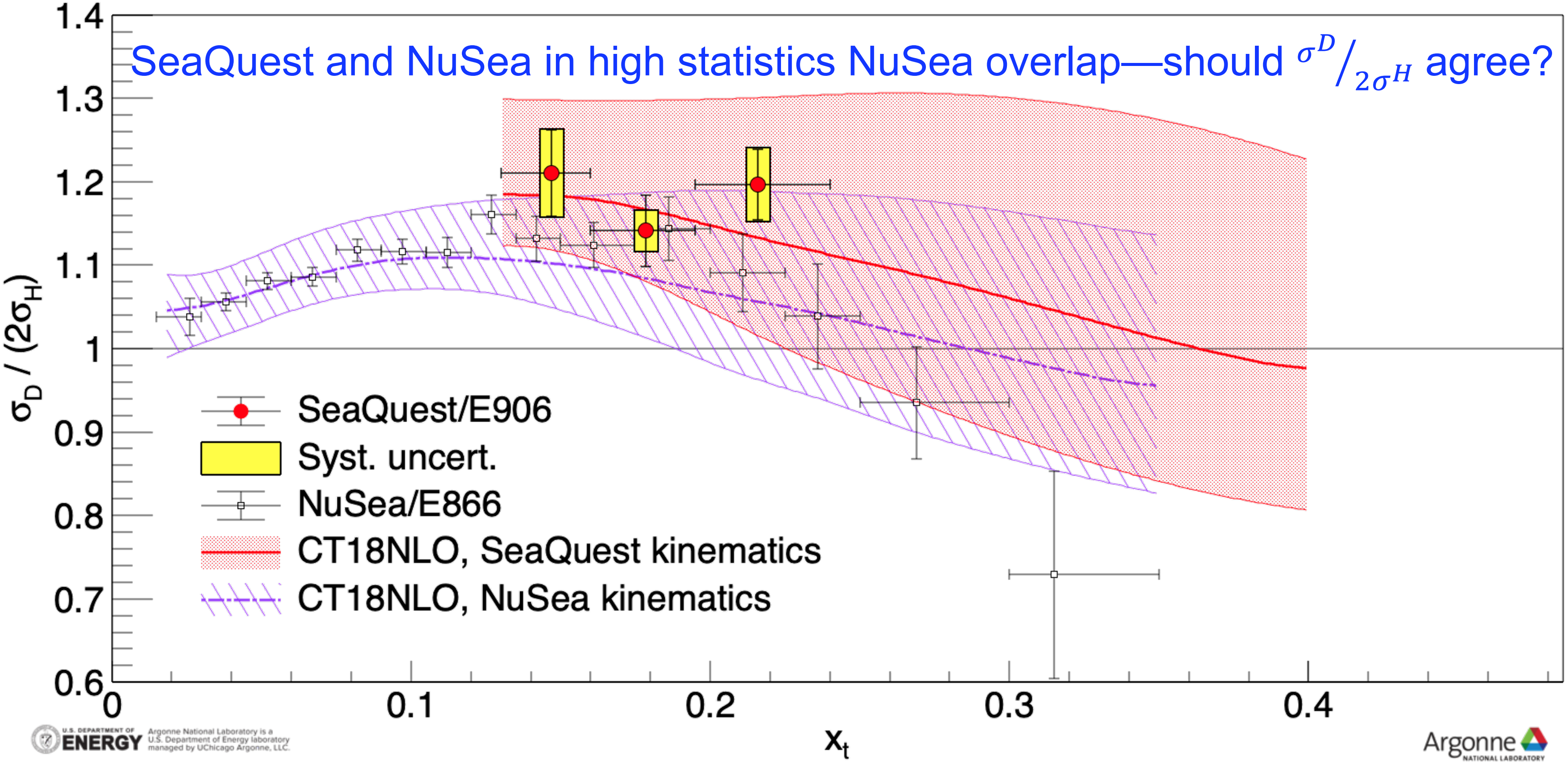
SeaQuest data,

$$\frac{\sigma^{pd}}{2\sigma^{pp}} > 1$$

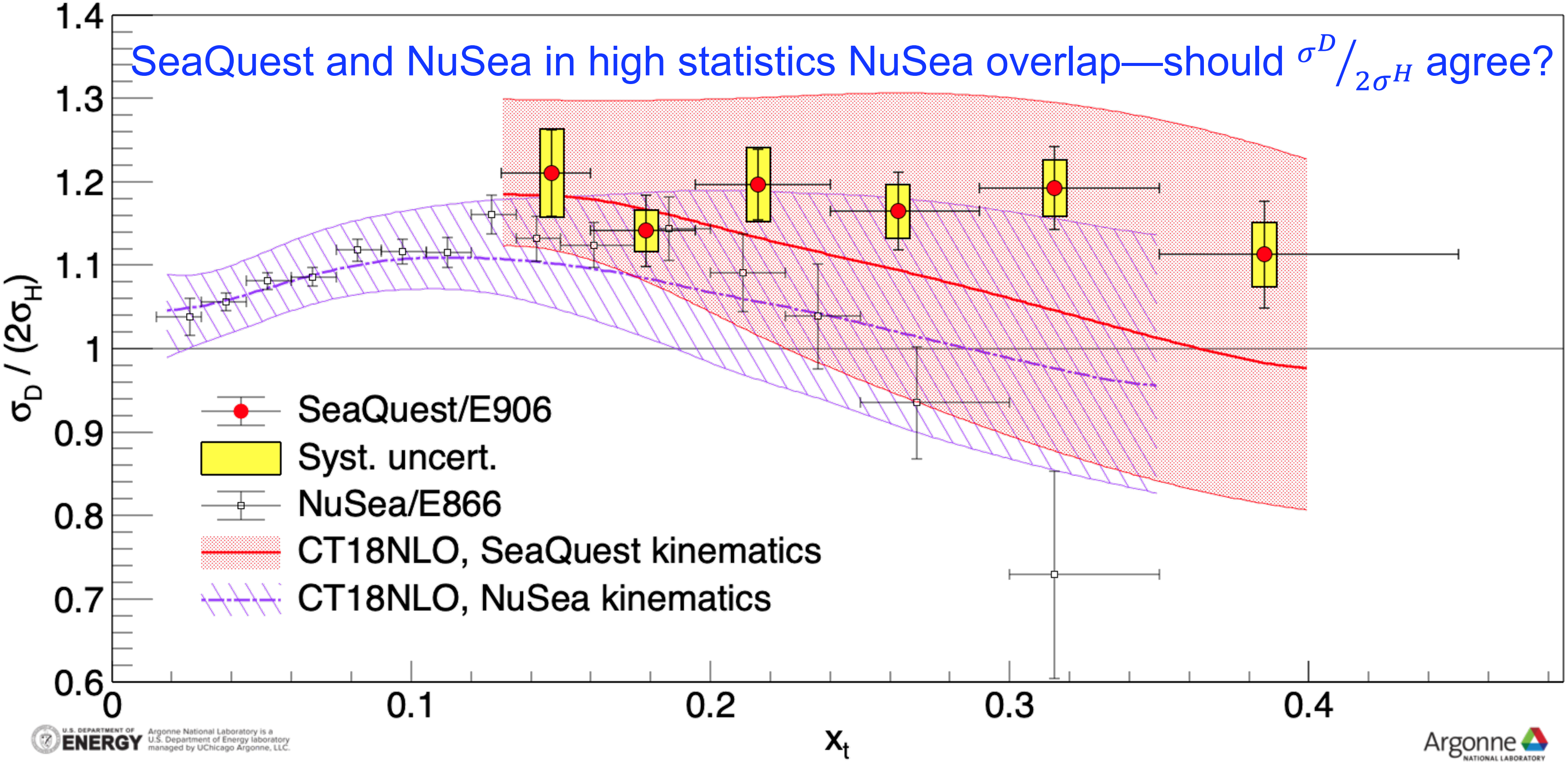
SEAQUEST AND E866



SEAQUEST AND E866



SeaQuest and E866



SeaQuest's $\bar{d}/\bar{u}$ Extraction

$$\frac{\sigma^D}{2\,\sigma^H} = \frac{1}{2}\left[1 + \frac{\bar{d}}{\bar{u}}\right]$$

Correct way to extract quark distributions is within the context of a global fit.

What we did instead:

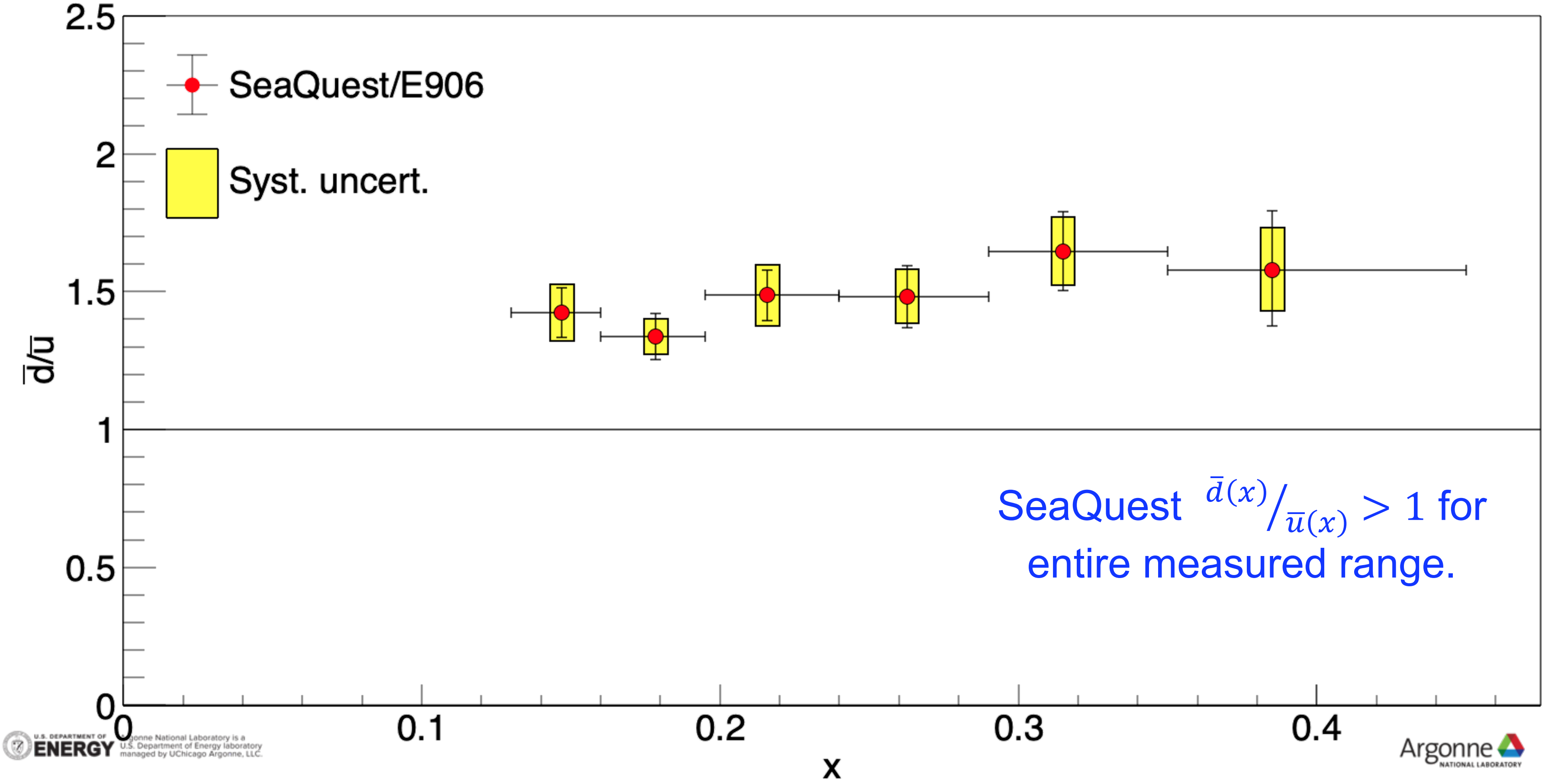
- Assume the current global fits are omnipotent except for $\bar{d}/\bar{u}$
- Compute

$$\frac{\sigma^D}{2\sigma^H} = \frac{\iint \frac{d\sigma^D_{NLO}}{dx_1 dx_2} dx_1\, dx_2}{2\iint \frac{d\sigma^H_{NLO}}{dx_1 dx_2} dx_1\, dx_2} \text{ with } \bar{d}/\bar{u}\,\Big]_i$$

  and the integrals are over the experimental acceptance

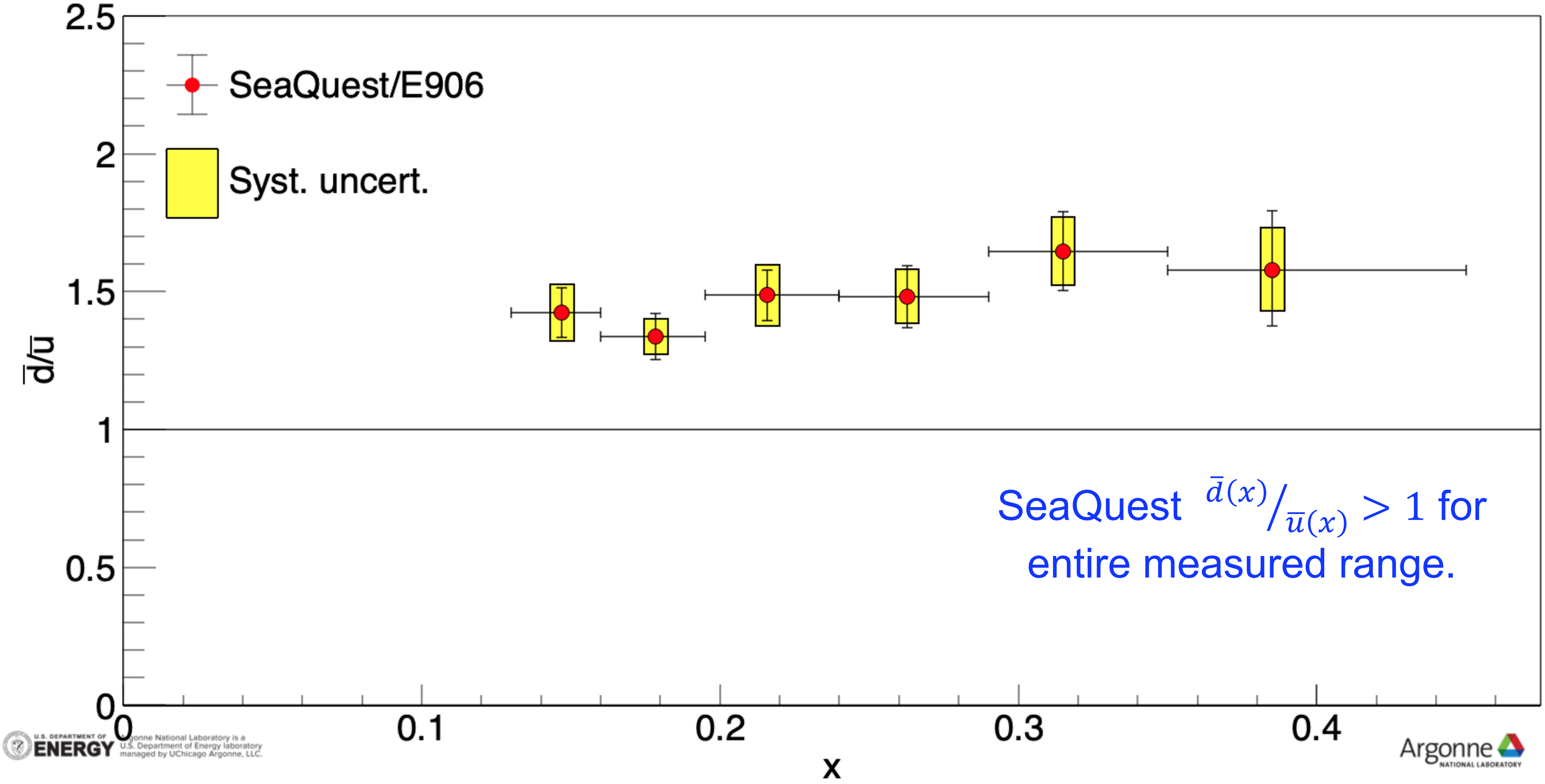
- Compare with measured $\frac{\sigma^D}{2\sigma^H}$, and iterate on $\bar{d}/\bar{u}\,\Big]_{i+1}$

SeaQuest and E866



SeaQuest $\bar{d}(x)/\bar{u}(x) > 1$ for entire measured range.

SeaQuest and E866



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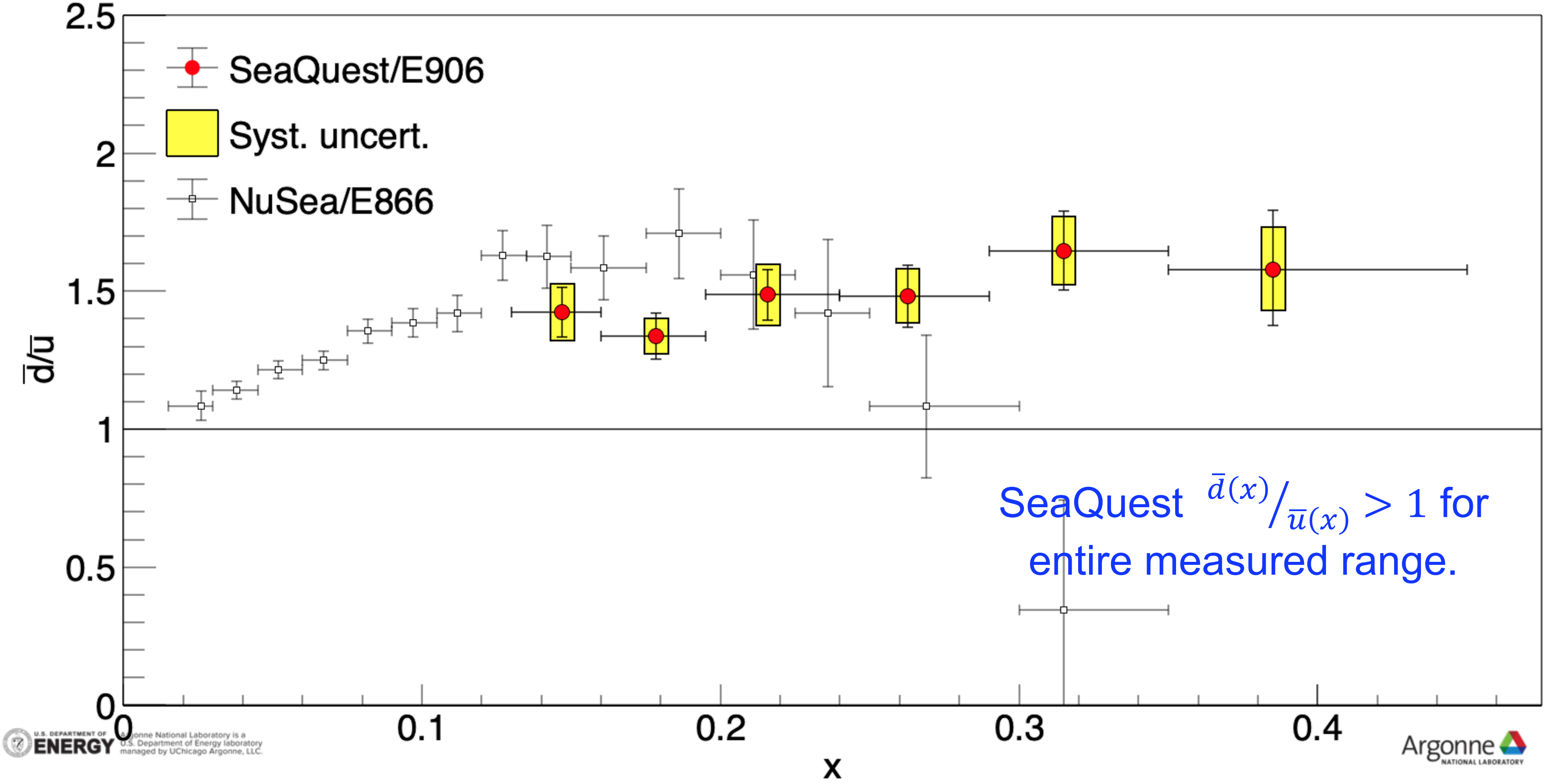

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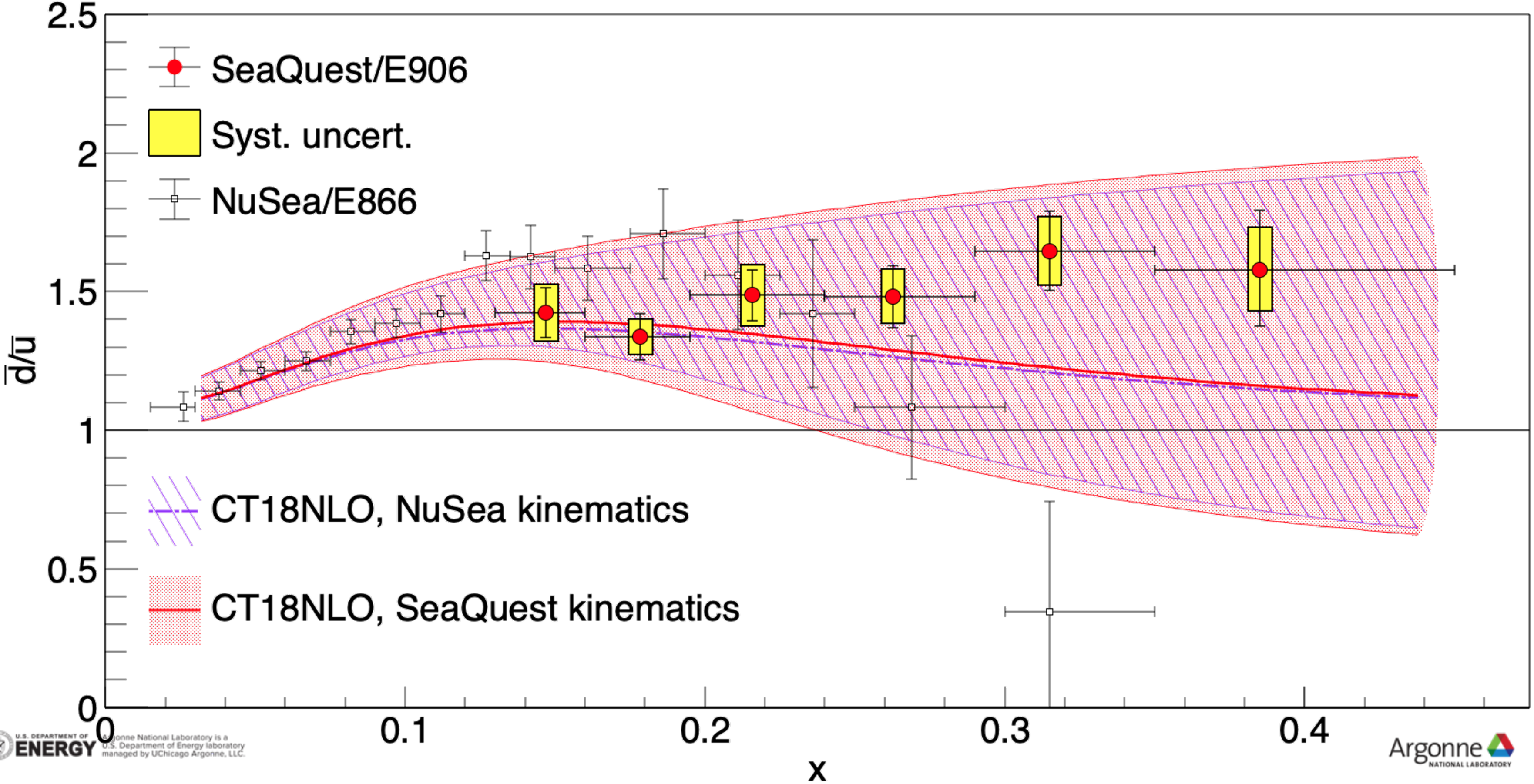
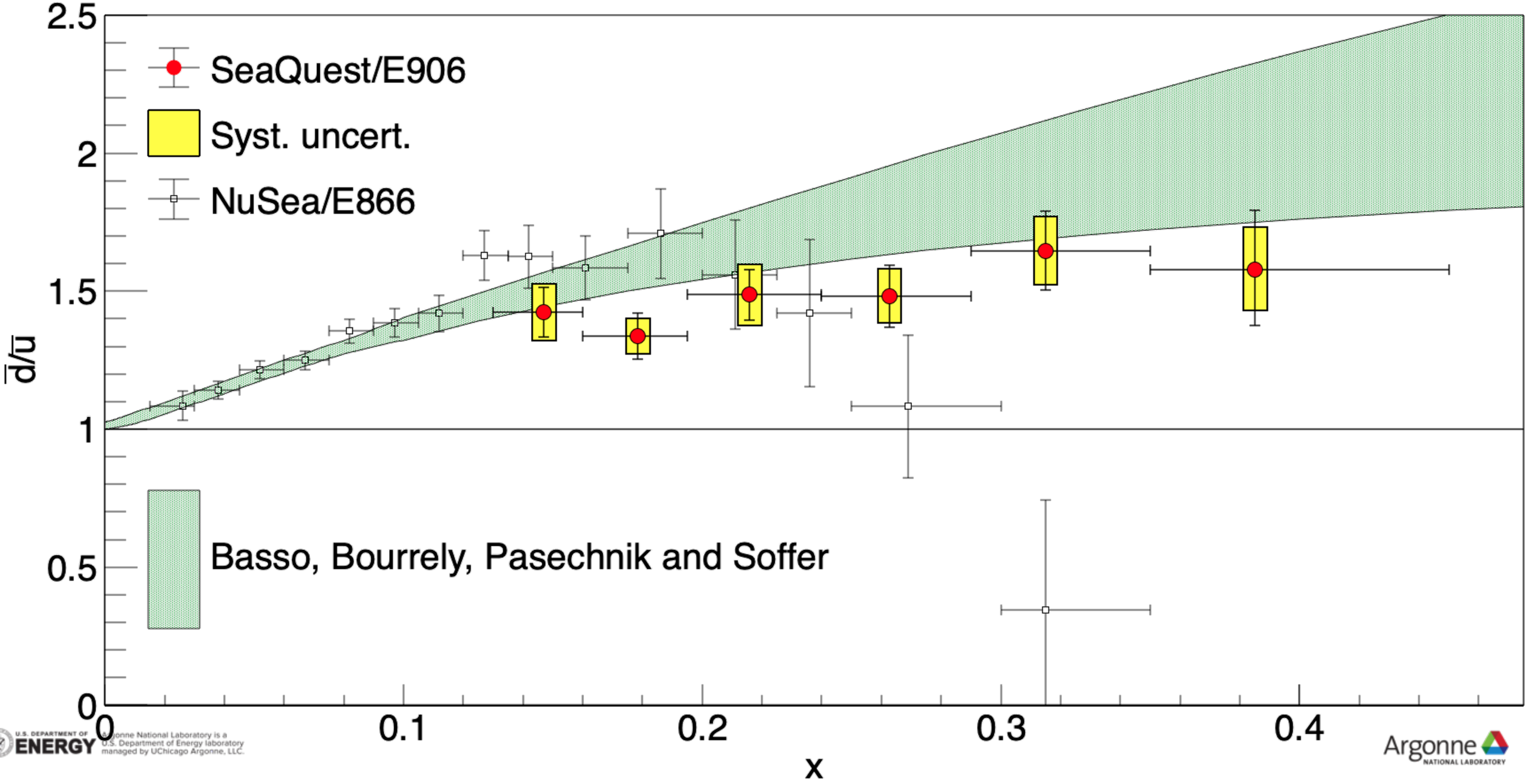
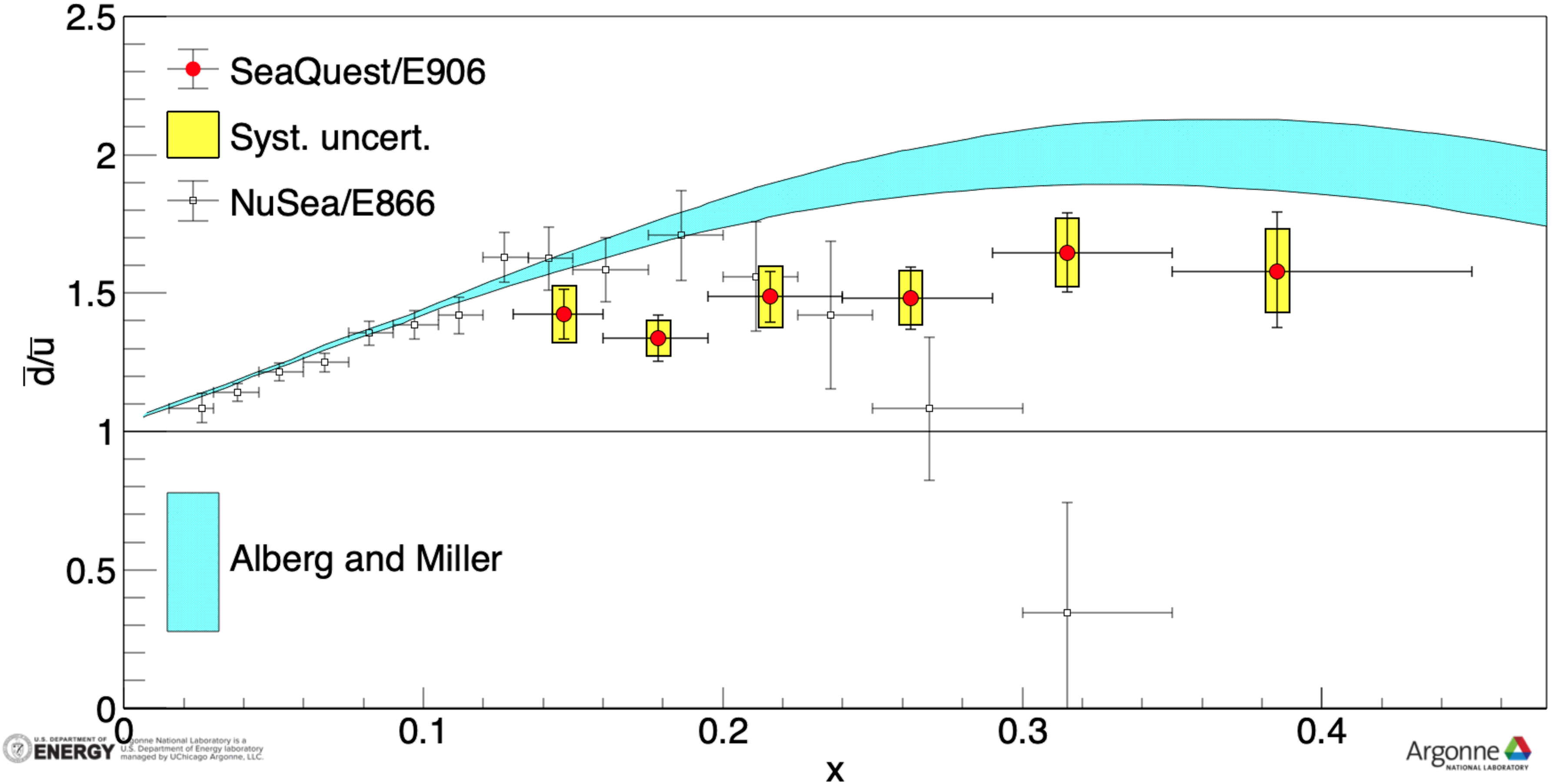
SeaQuest compared with Global Fits



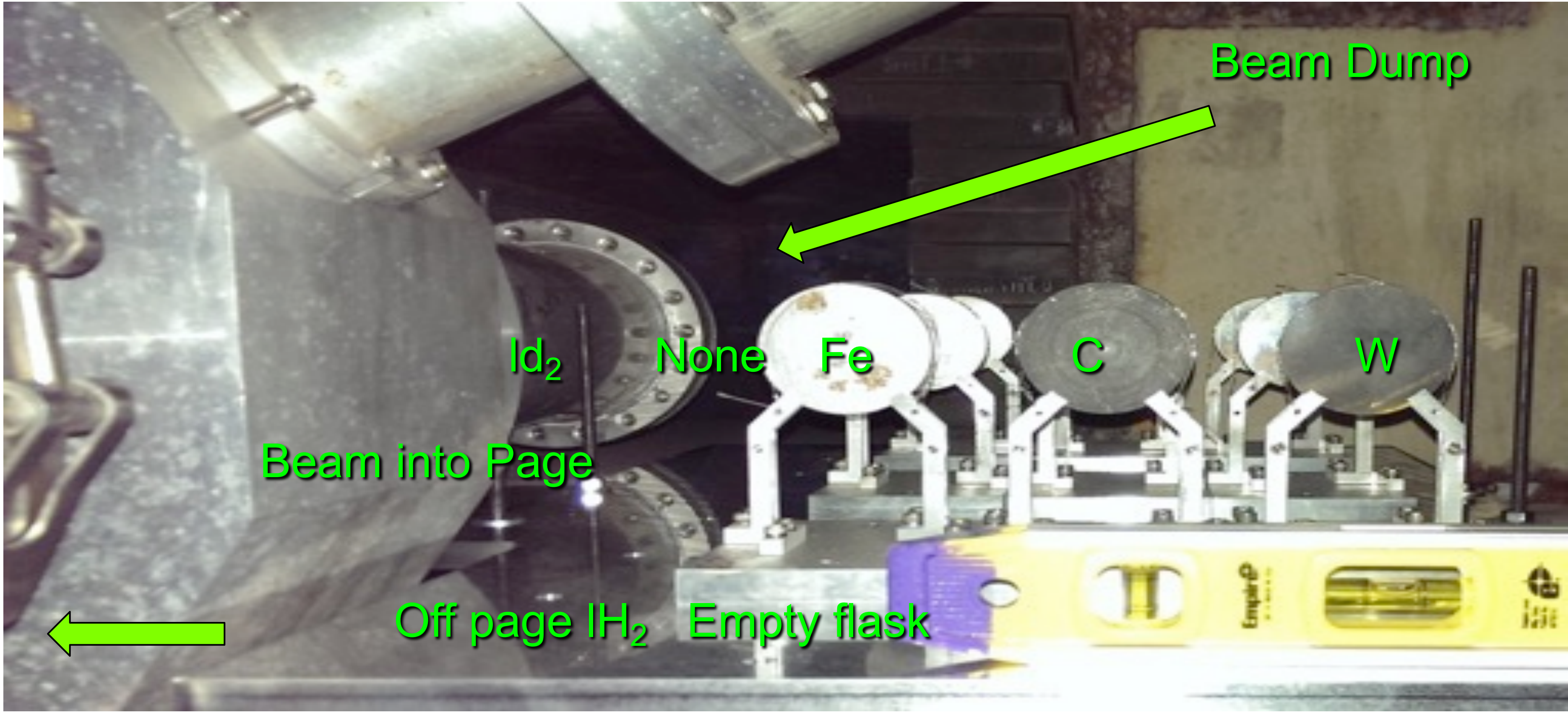
SeaQuest compared with Models



SEAQUEST COMPARED WITH MODELS



What about the Solid Targets?



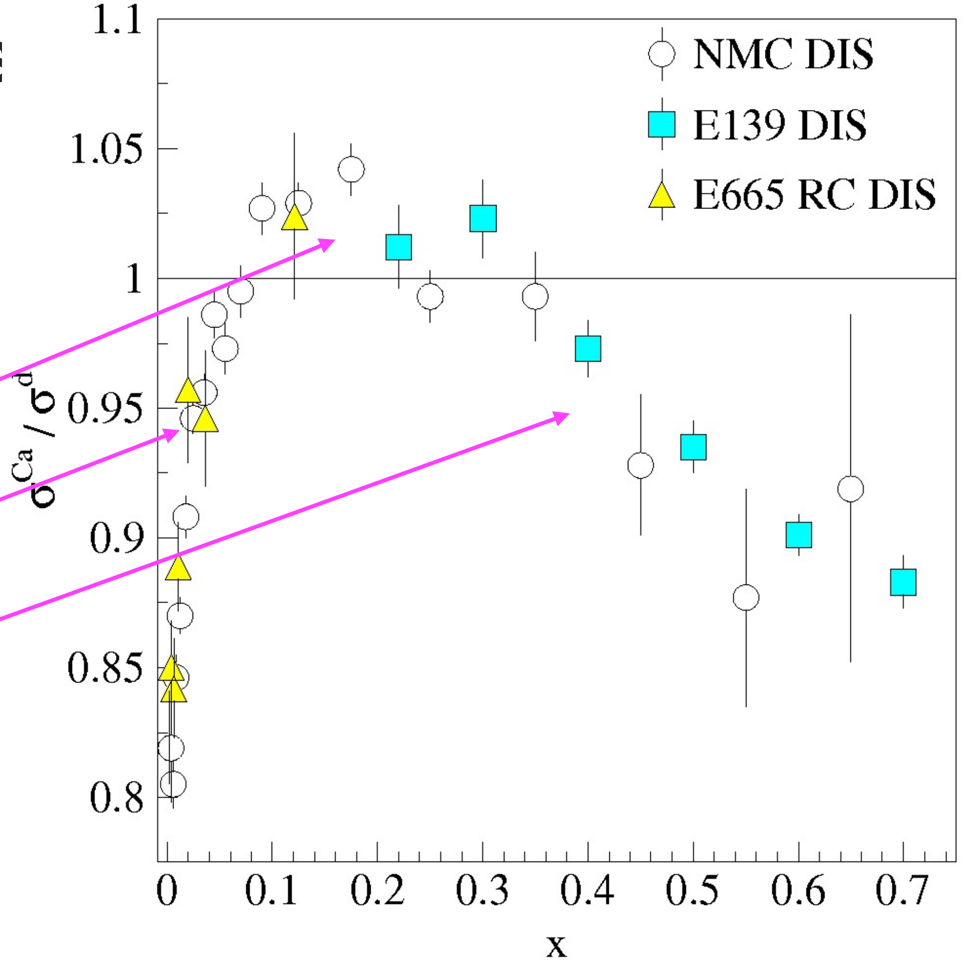
EMC Effect in Anti Quarks

- DIS results establish nuclear dependence of quark distributions.
- Expectations of large antiquark effects

Anti-Shadowing

Shadowing

EMC Effect



EMC Effect With Anti Quarks?

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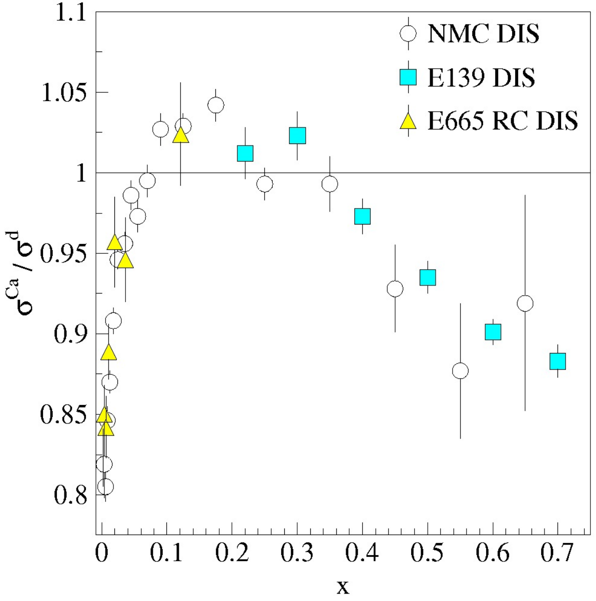
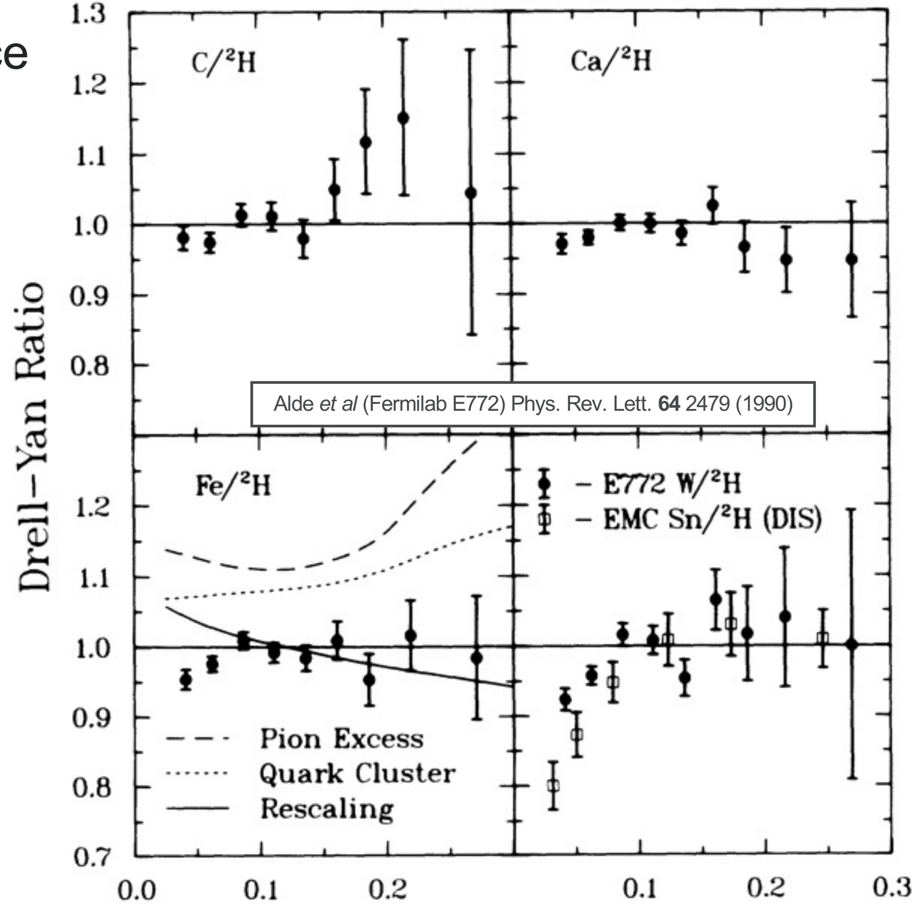
- **No effects were seen in Drell-Yan**





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

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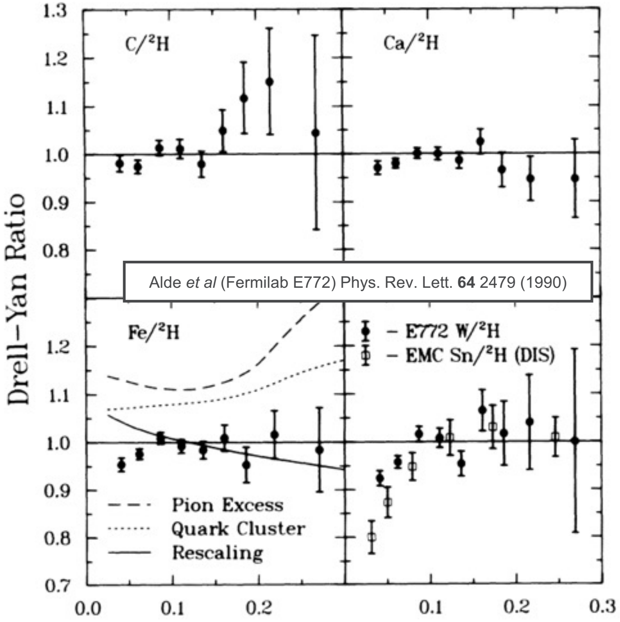

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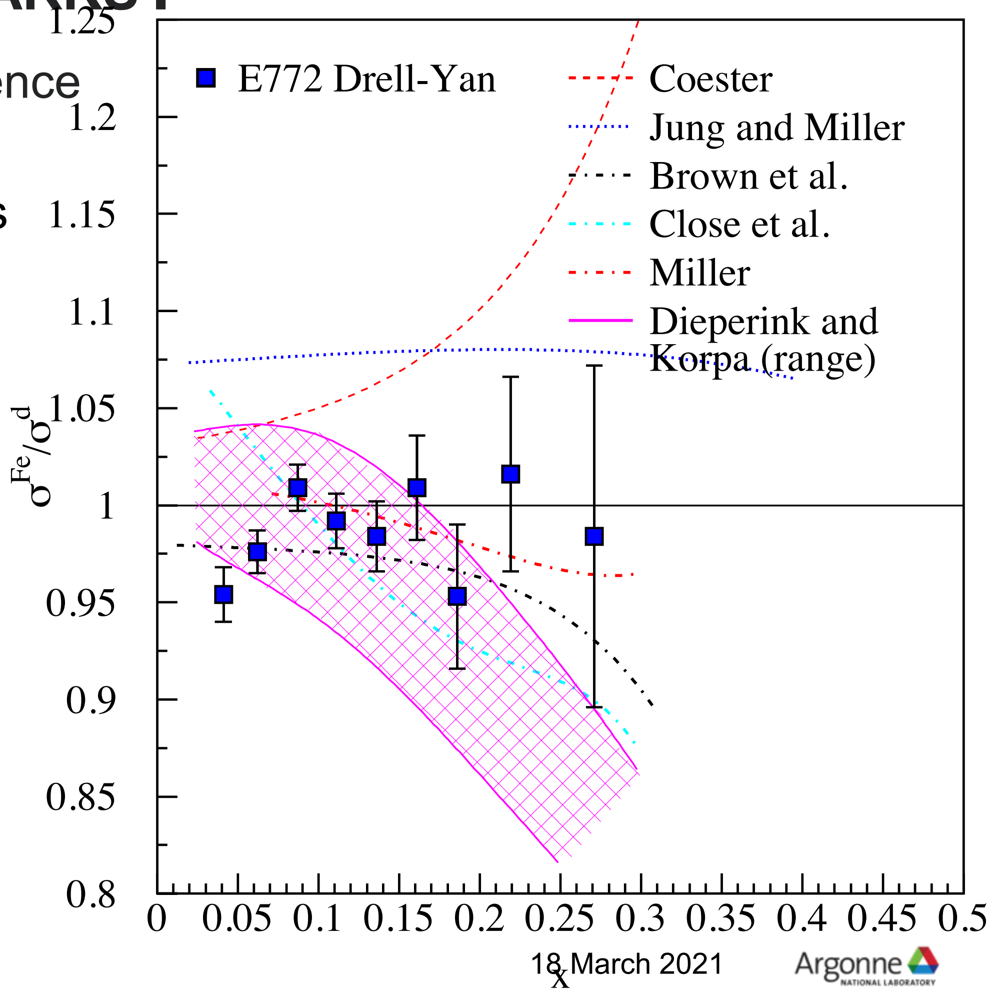
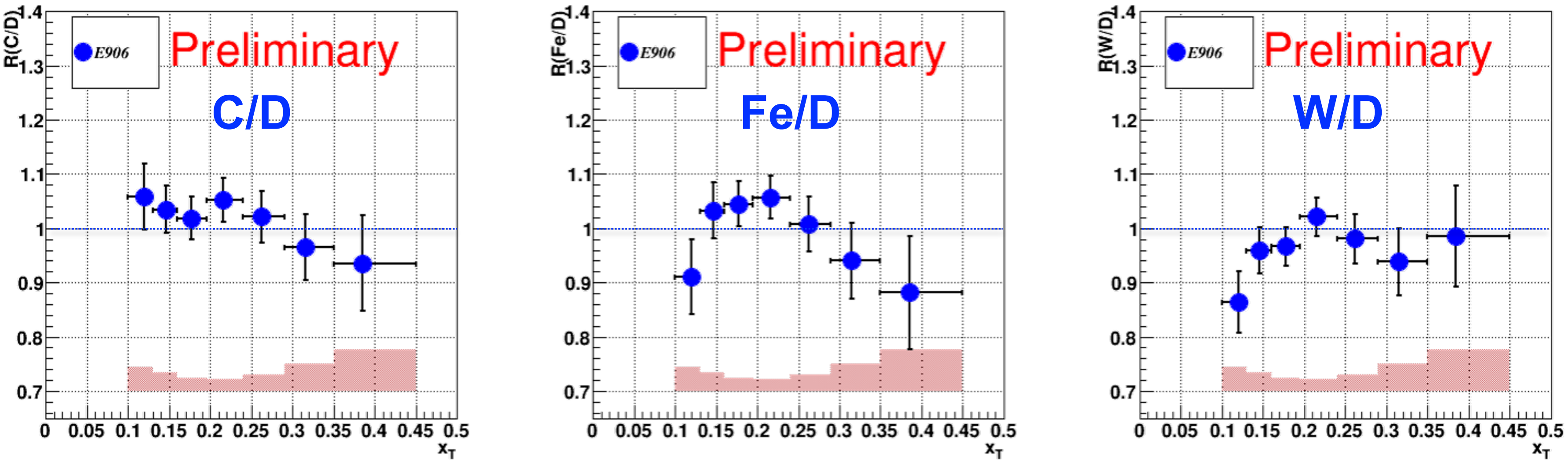
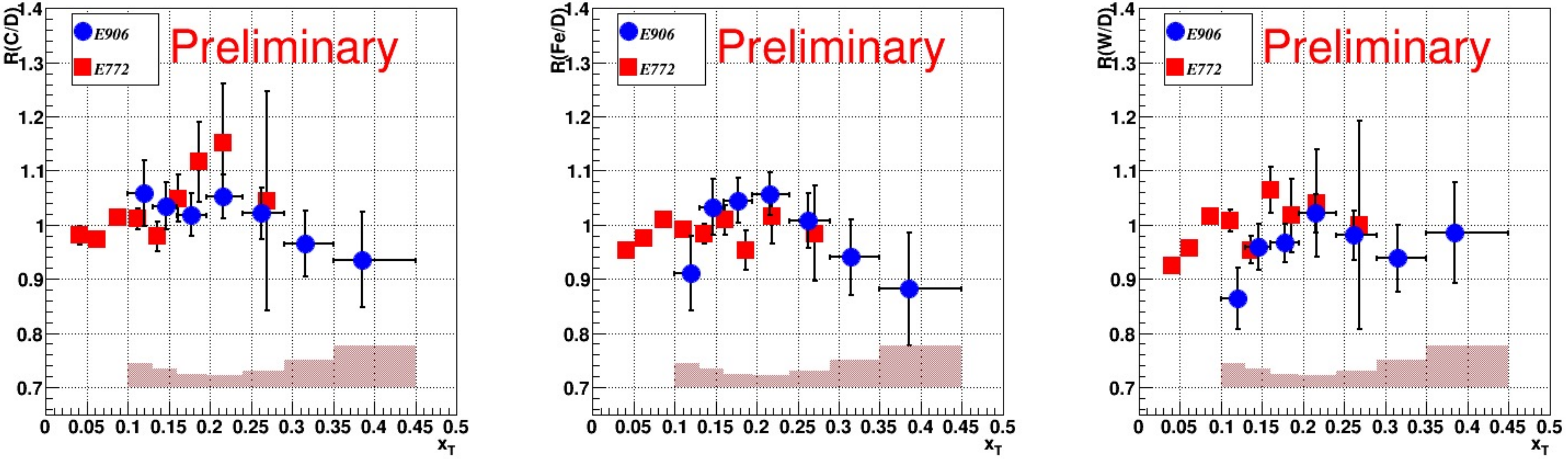


SeaQuest EMC Nuclear Dependence



- No enhancement seen as in the case of a pion excess model
- Caveat—**partionic energy loss is important**

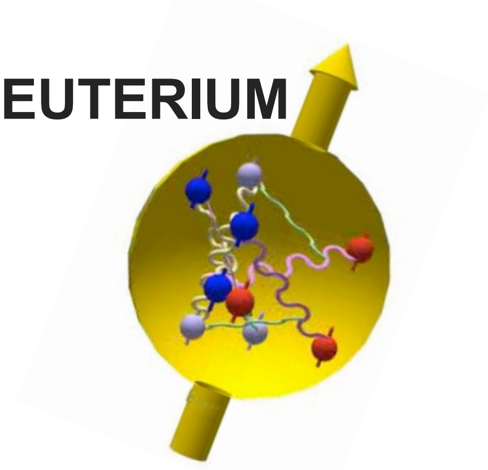
SeaQuest EMC Nuclear Dependence



- No enhancement seen as in the case of a pion excess model!
- Caveat—**partionic energy loss is important**
- In agreement with E772 results in the overlap region

QUARK MOTION IN THE SEA

SpinQuest—Polarized Hydrogen and Deuterium



Where is the spin of the proton?

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

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

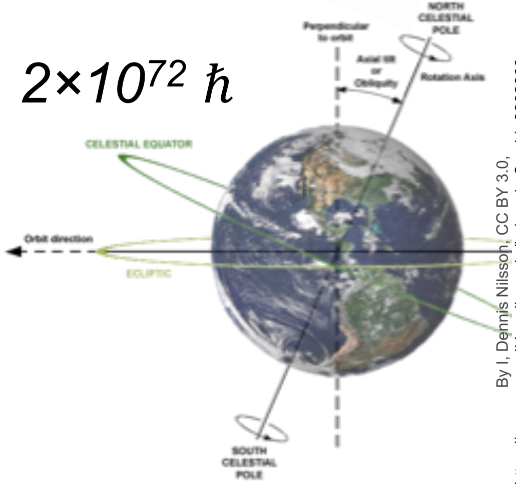
$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

SMC, HERMES, COMPASS

STAR, PHENIX

$$L \Leftrightarrow \text{unmeasured}$$

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



Spin decomposition

1. It's all in the quark spin (u and d).

2. It's in the strange quarks

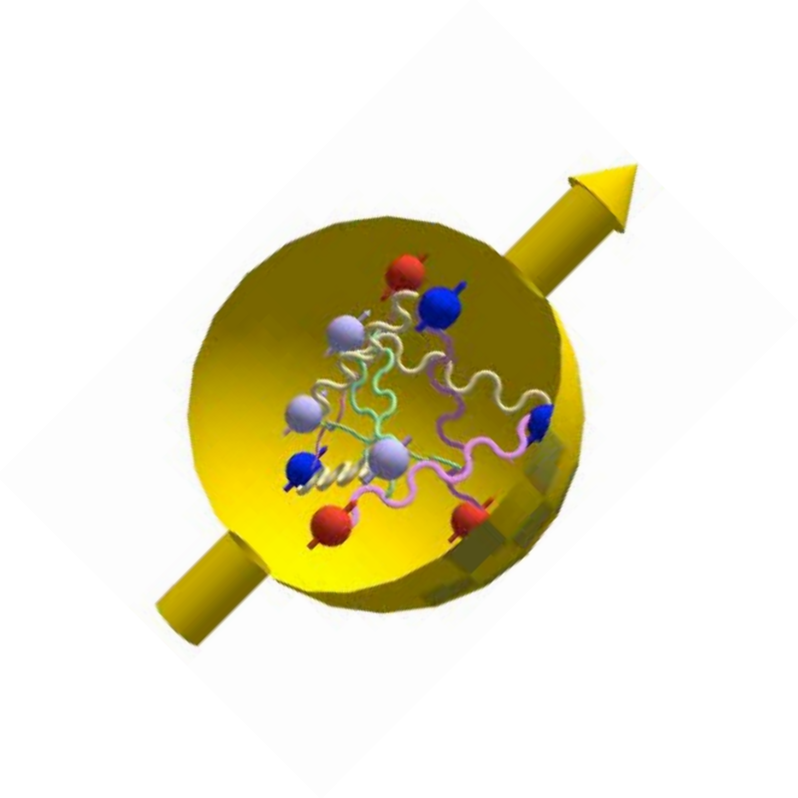
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma \neq \frac{1}{2} \times 0.18$$

3. It's in the glue

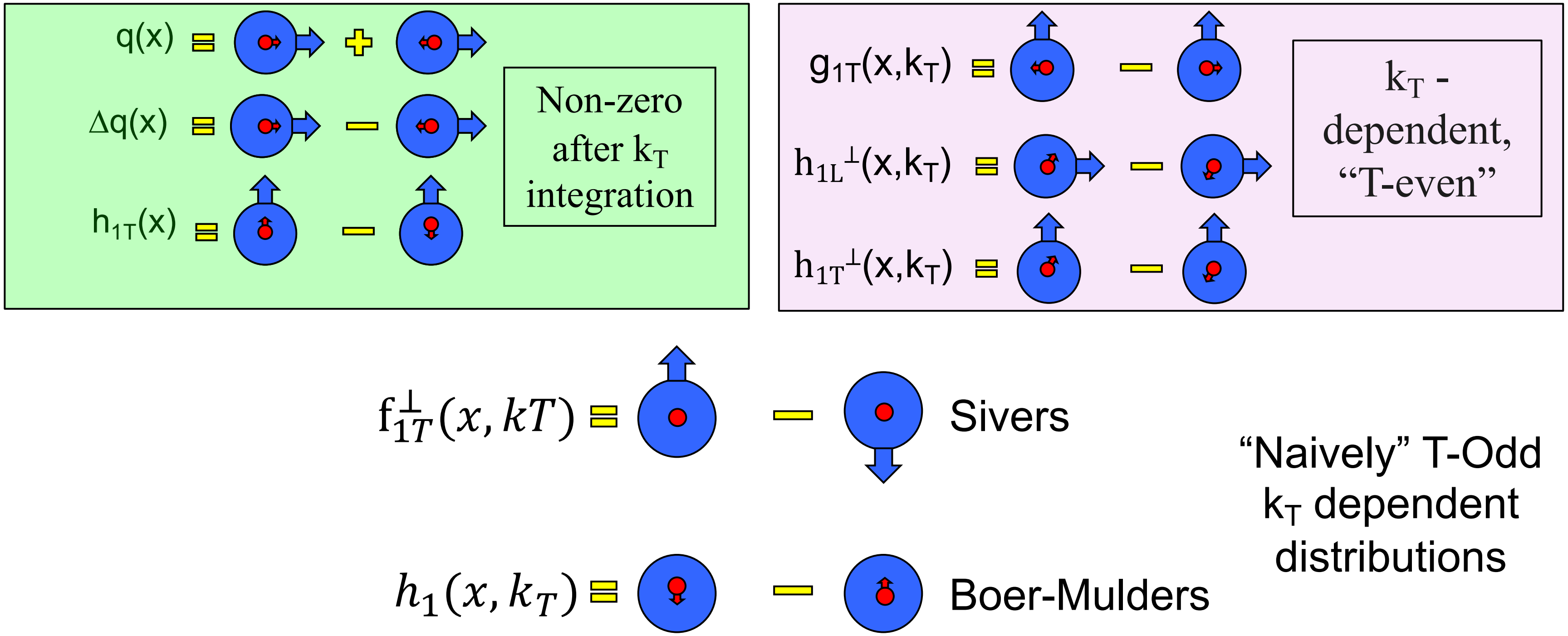
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

1. It's in Orbital Angular Momentum???

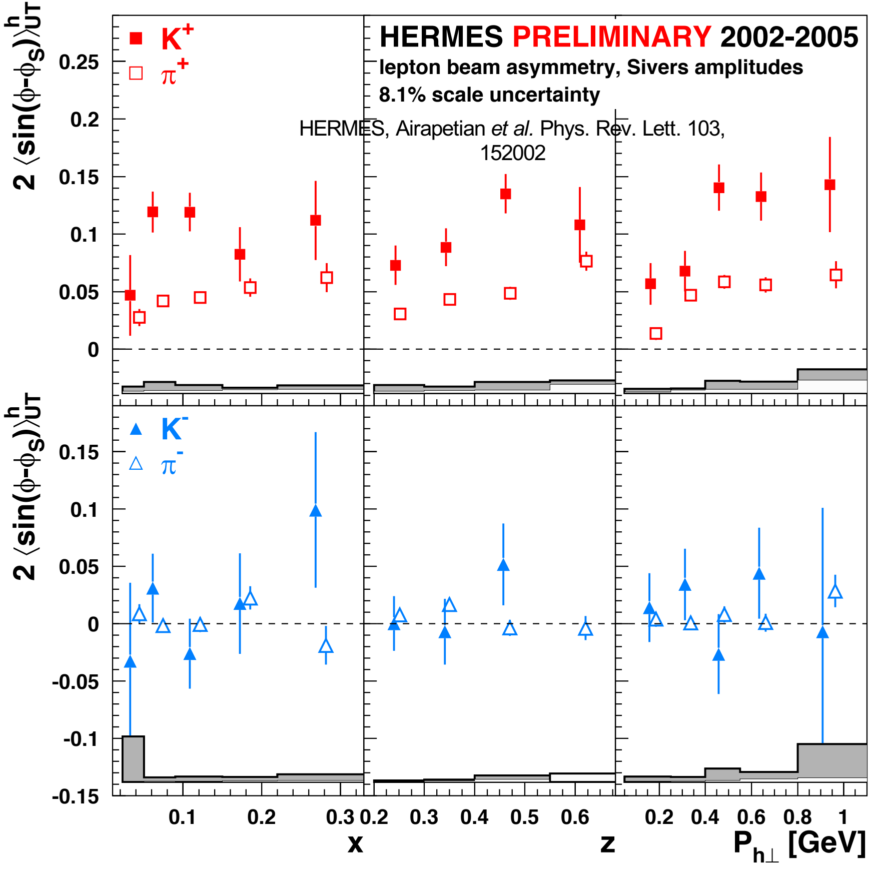
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$



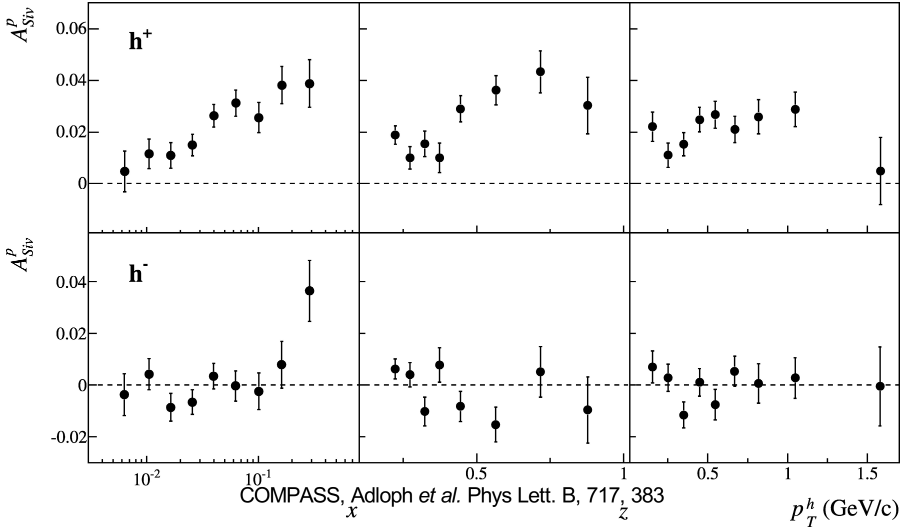
How to Measure Orbital Angular Momentum?



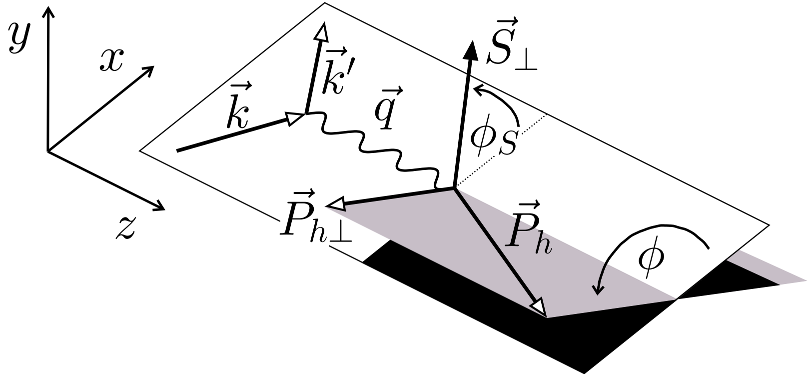
SIDIS Sivers Measurements



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



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



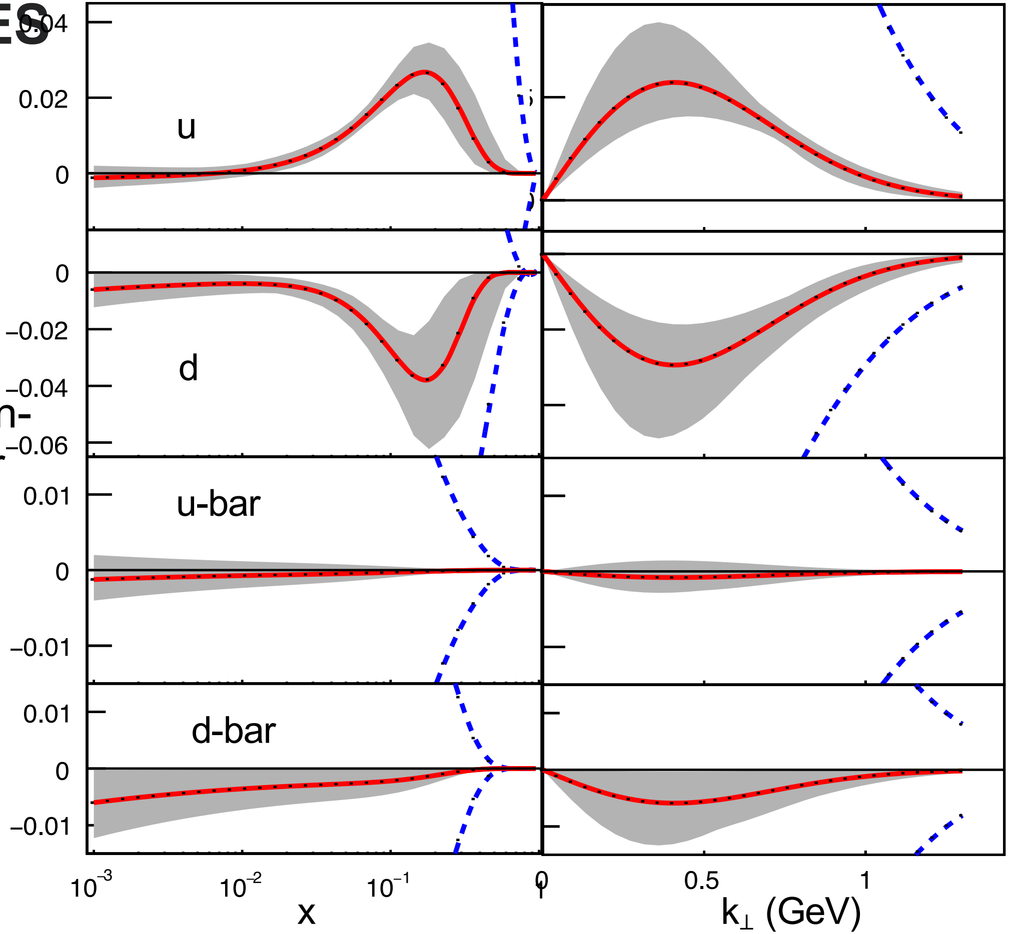
Anselmino et al, JHEP 1704 (2017) 046

FITS OF SIVERS ASYMMETRIES

- Data fit to extract Sivers distributions
- Shown at left are the 1st moments
- But . . .

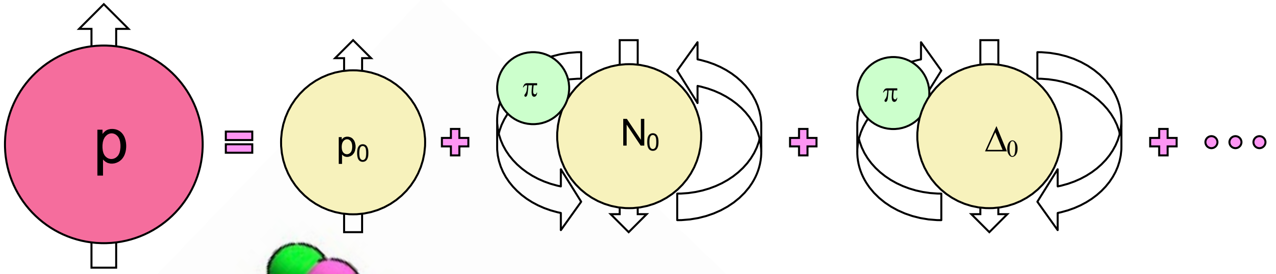
  While it can be shown rigorously that a non-zero Sivers function implies orbital angular momentum

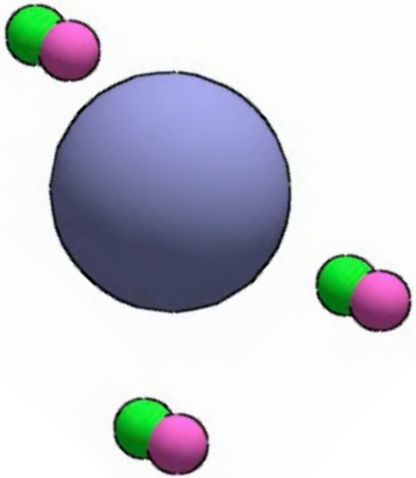
  There is not yet a rigorous method to quantitatively extract L_q from $F_{1T}^{\perp}$



Pion Cloud and OAM

Consider a nucleonic pion cloud $|p\rangle = (1 - a - b)|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle + \cdots$

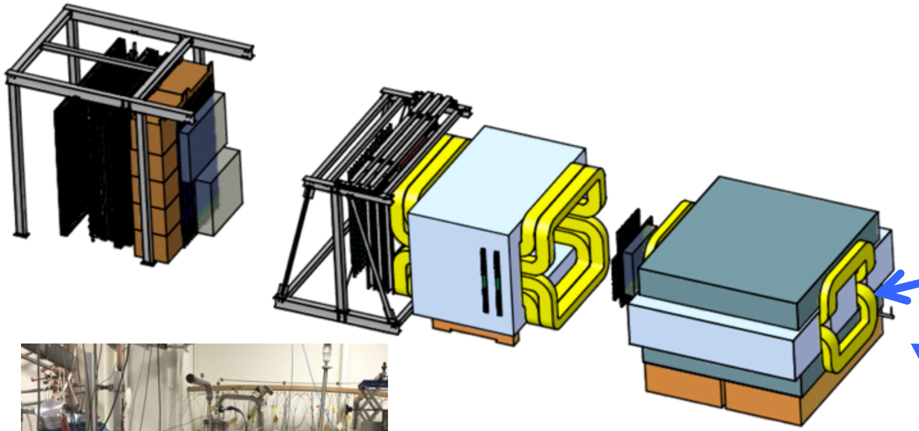


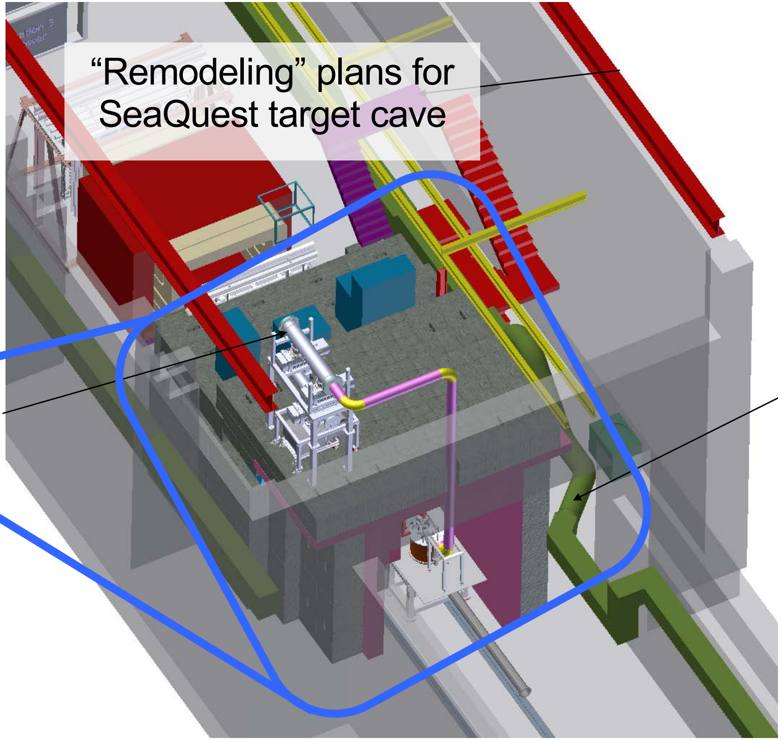


Pion $J^p=0^-$ Negative Parity

Need L=1 to get proton's $J^p=½^+$

SeaQuest E1039 Status

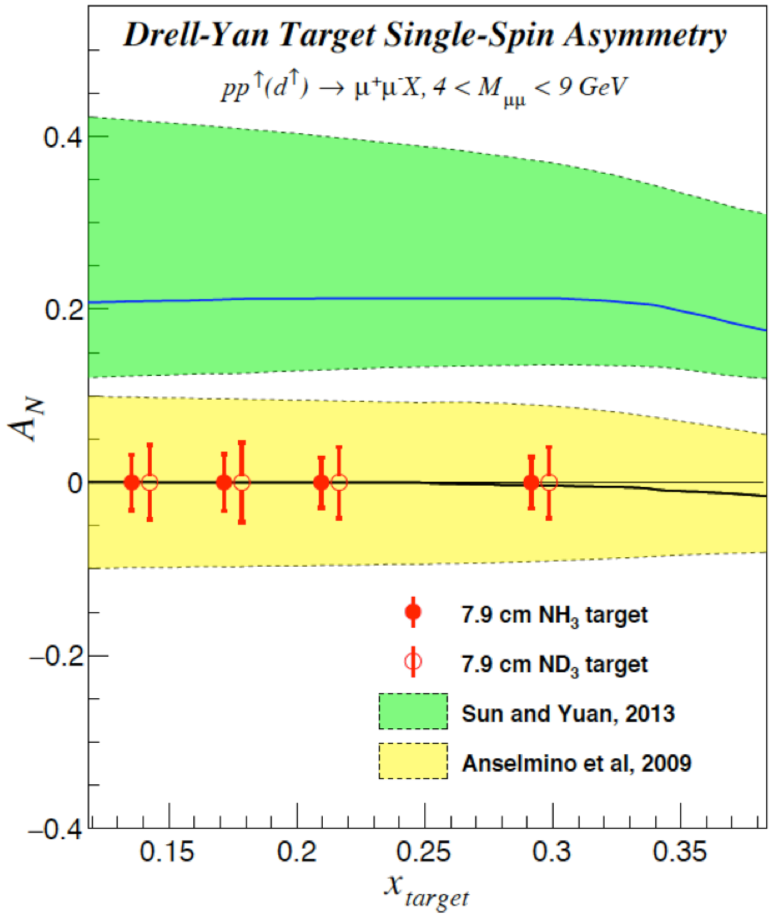




E1039 SpinQuest Statistics

- 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

- Spring 2020—Commissioning run
- Fall 2020-Summer 2022—Data production runs



Media

NATURE PODCAST · 24 FEBRUARY 2021

The quark of the matter: what's really inside a proton?

EurekAlert! AAAS

NEWS RELEASE 24-FEB-2021

Nature's funhouse mirror: understanding asymmetry in the proton

DOE/ARGONNE NATIONAL LABORATORY

Quanta magazine

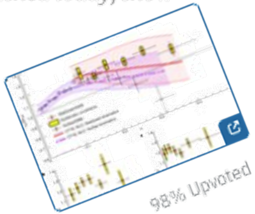
QUANTUM PHYSICS

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

27

Twenty years ago, physicists set out to investigate a mysterious asymmetry in the proton's interior. Their results, published today, show how antimatter helps stabilize every atom's core.

Google News



98% Upvoted

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Posted by u/m3prx 18 days ago

487 The asymmetry of antimatter in the proton

nature.com/articl...

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WIRED

ScienceNews

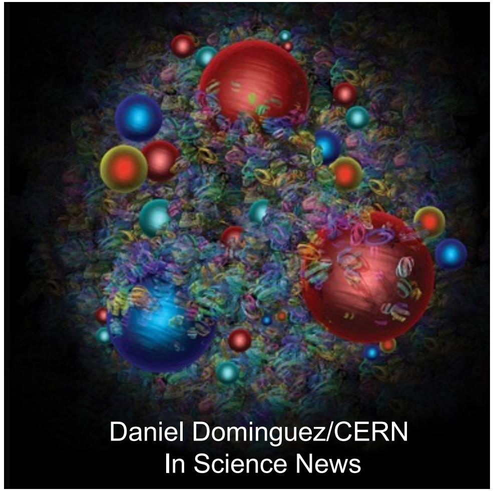
INDEPENDENT JOURNALISM SINCE 1921

NEWS PARTICLE PHYSICS

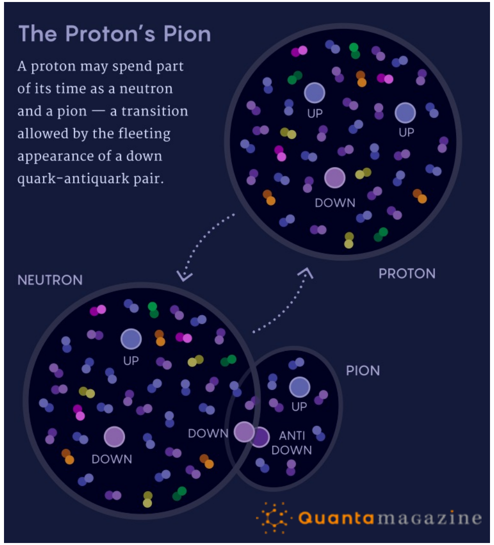
Protons' antimatter is even more lopsided than we thought

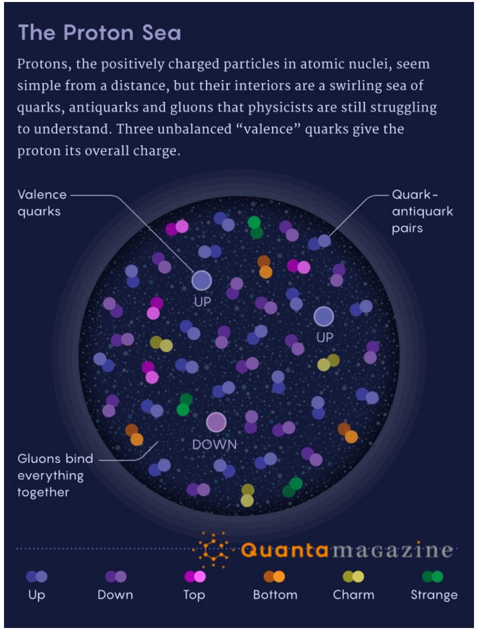
In the sloshing sea of particles within a proton, down antiquarks outnumber up antiquarks

Graphic Art from Media!



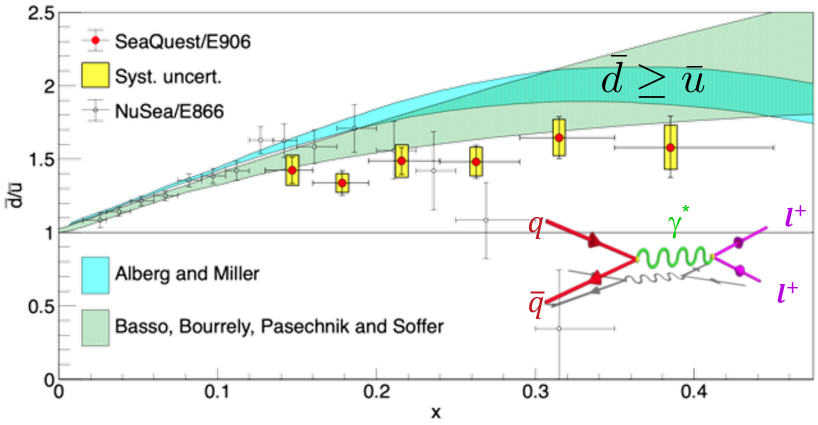
Daniel Dominguez/CERN
In Science News

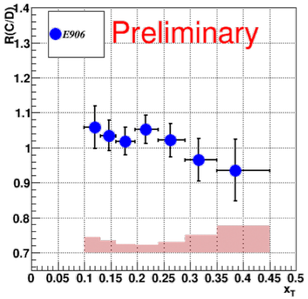


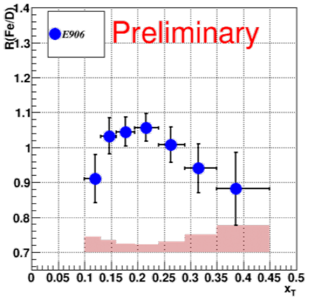


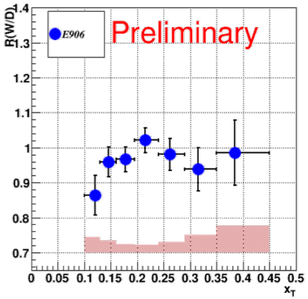
Epilogue

- Feynman made it all look easy.
- Drell-Yan provides access to antiquark dist.
- For x_{Bj} < 0.45, $\sigma^{pd} / \sigma^{pp} \geq 1$
- SeaQuest has measured the nuclear dependence of the Drell-Yan reaction









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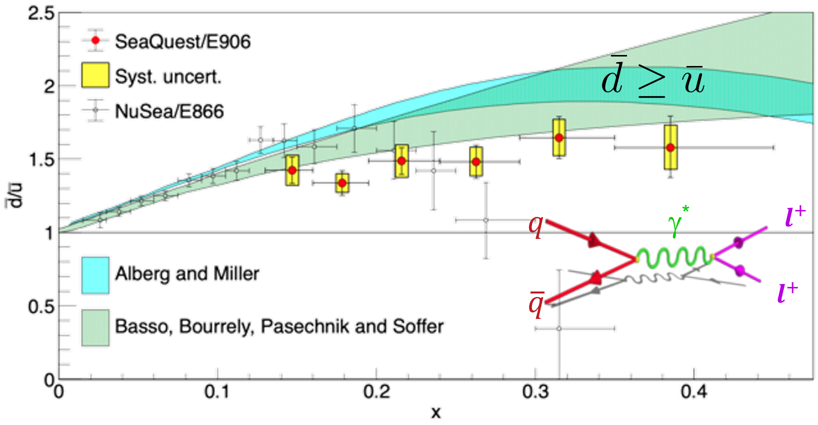
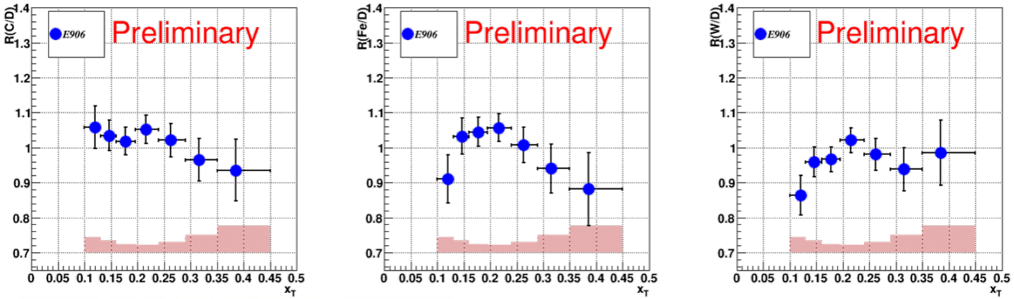
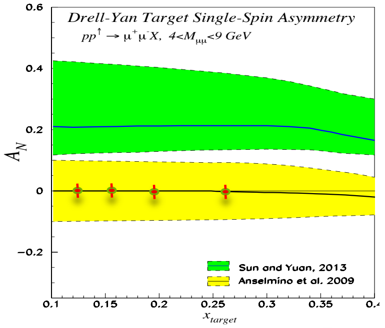




- SpinQuest will measure the Drell-Yan Sivers Function and probe sea quark orbital angular momentum with a polarized target.



Argonne NATIONAL LABORATORY