The Quest for the Origin of the Proton's Sea

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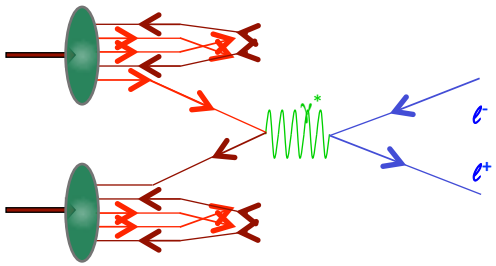
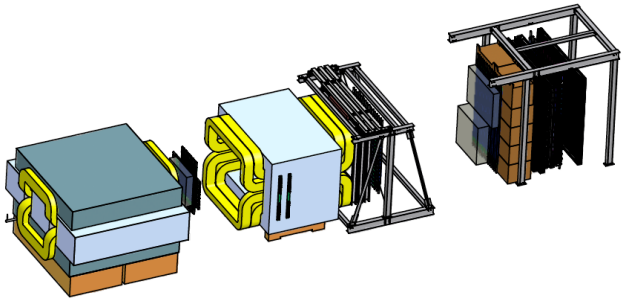
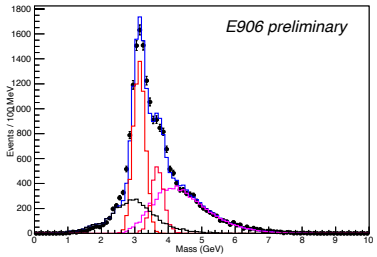
Physics Division
Argonne National Laboratory
4 September 2016





I. AntiQuarks and Proton Structure
II. Proton and Nucleon Structure
III. Drell-Yan and Spin

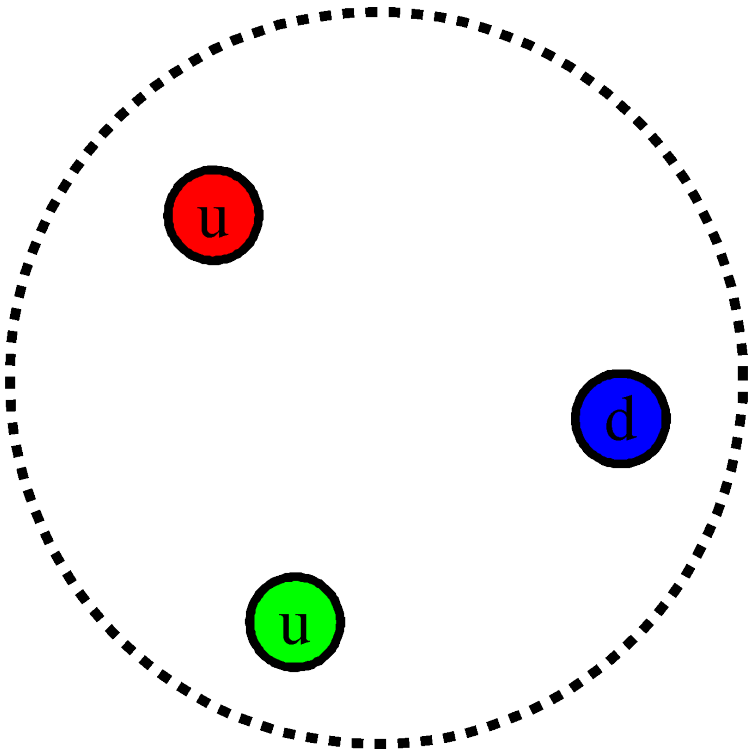


$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

What are the origins of the Sea?

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



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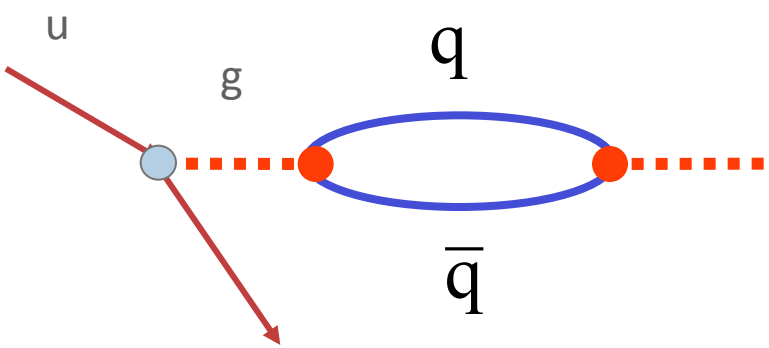
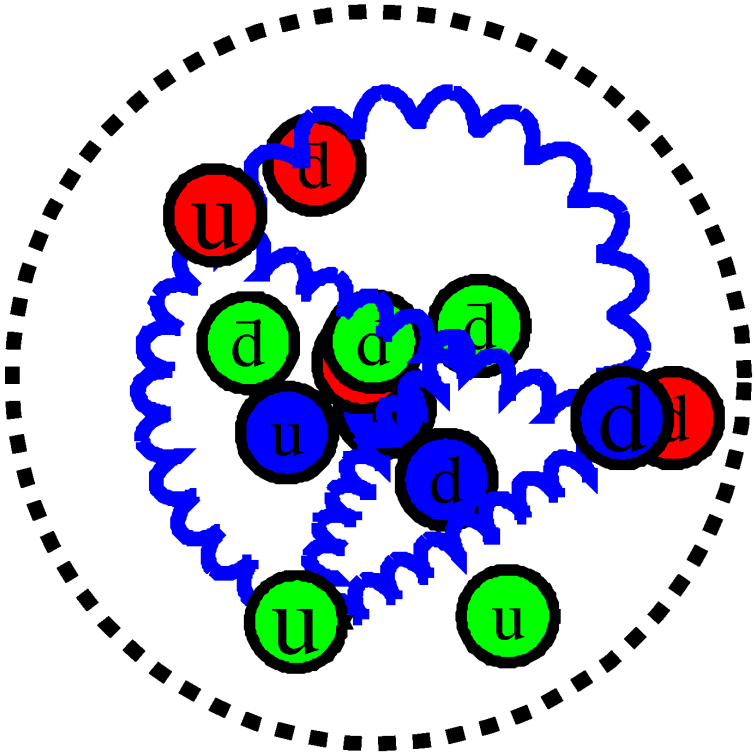
Great idea but it didn't agree with the data





Sea is a fundamental part of the proton

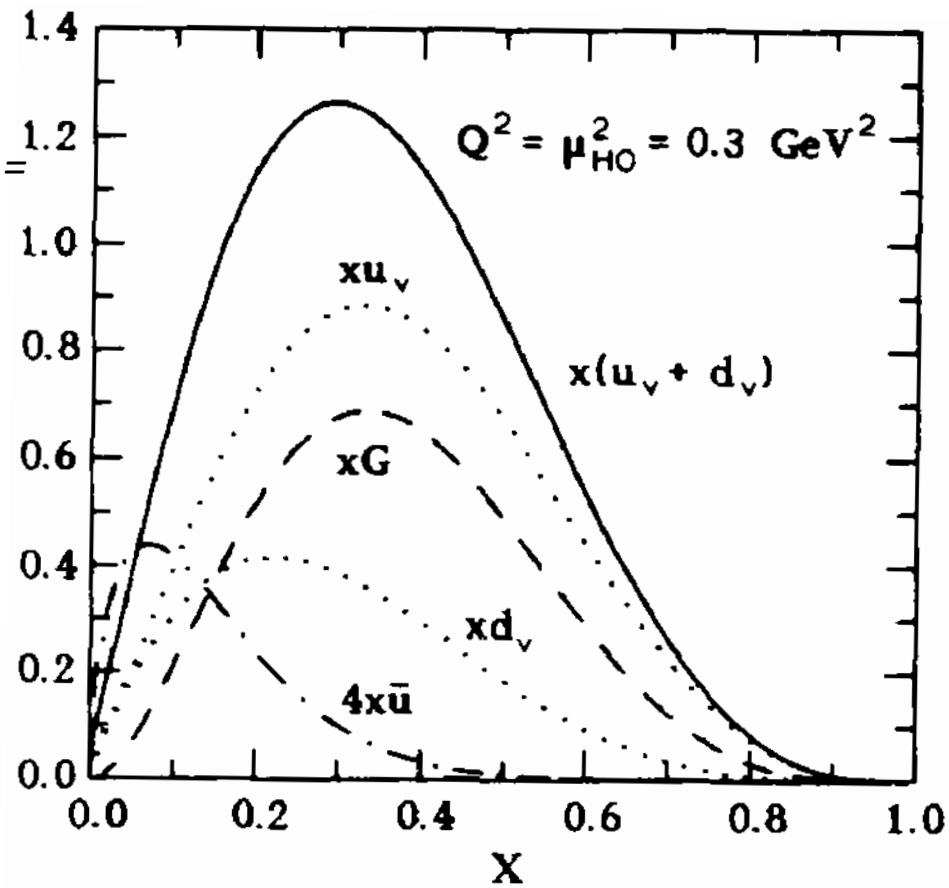
Parton distributions for high energy collisions

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

M. Glück, E. Reya, A. Vogt
Institut für Physik, Universität Dortmund, Postfach 500500, W-4600 Dortmund 50, Federal Republic of Germany

Received 10 June 1991

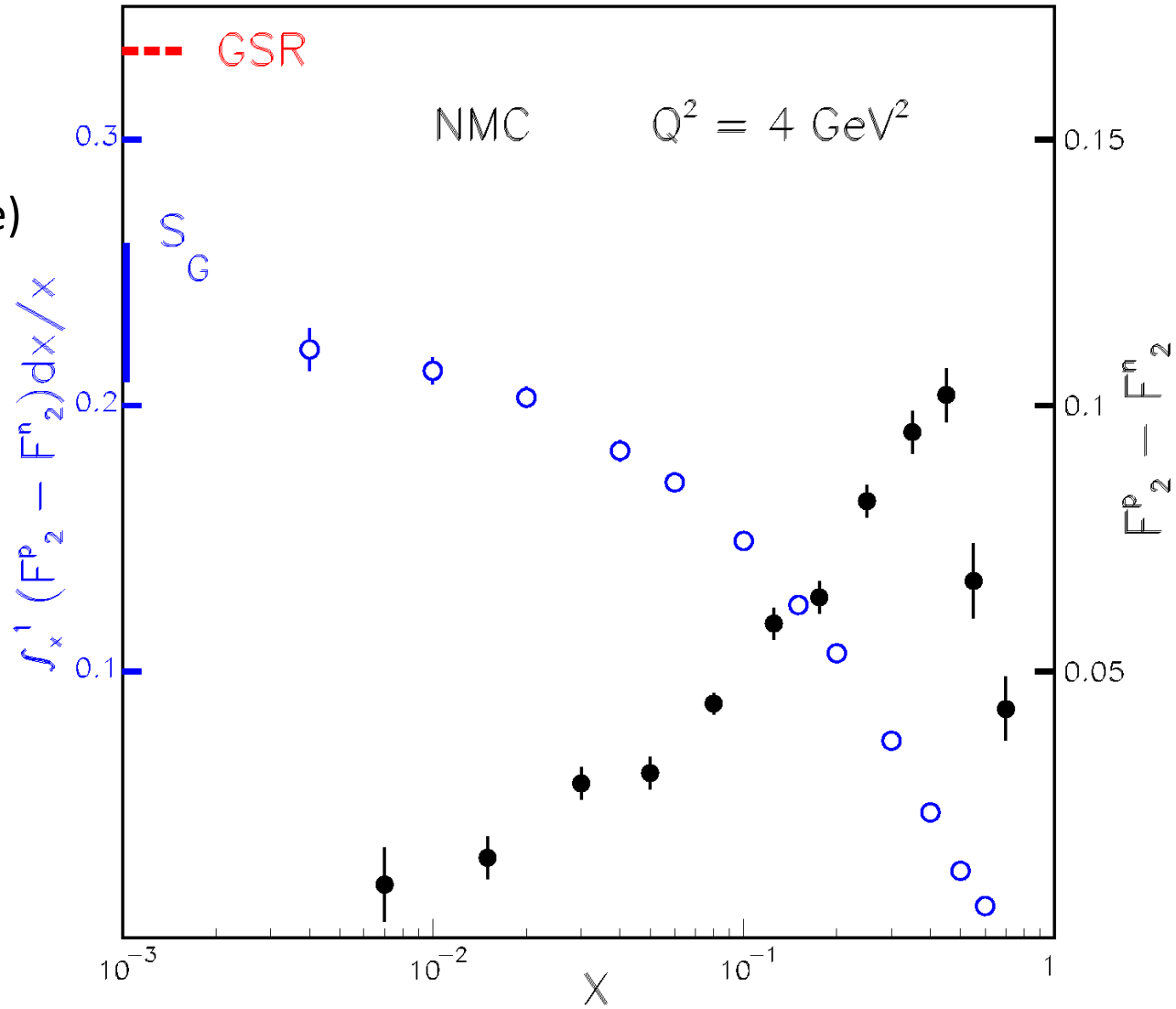
Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3\ GeV^2$. **The predicted extrapolations are uniquely determined by the requirement of a *valence*-like structure of *all* parton distributions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



Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:
  $\bar{d}(x) = \bar{u}(x)$
- NMC (Gottfried Sum Rule)

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



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

- NA51 (Drell-Yan)

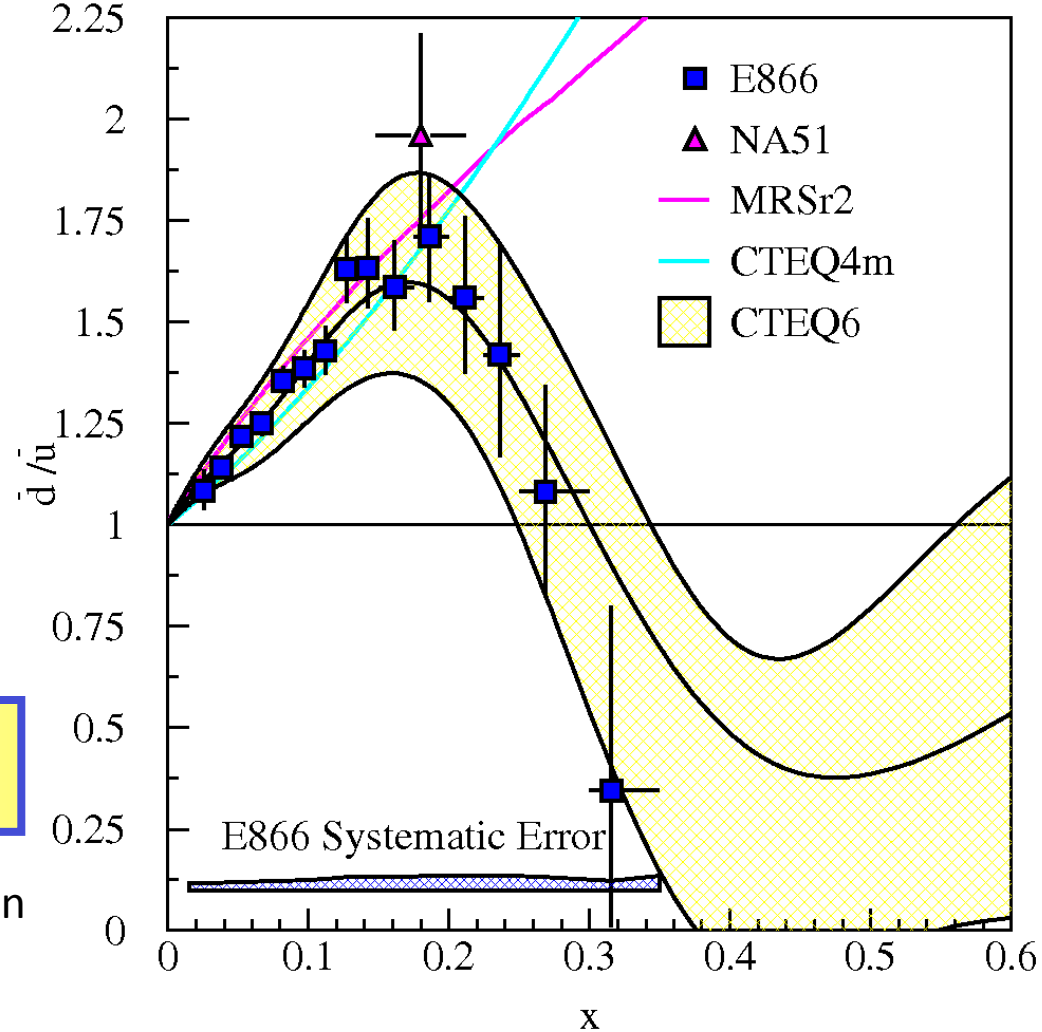
$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- E866/NuSea (Drell-Yan)

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

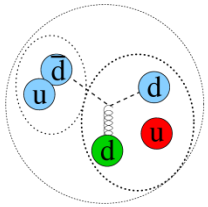
- Knowledge of sea dist. are data driven
  - Sea quark distributions are difficult for Lattice QCD

- Non perturbative QCD models can explain excess d-bar quarks, but not return to symmetry or deficit of d-bar quarks



Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS



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

Antiquarks in spin 0 object → No net spin

- Chiral Quark models—effective Lagrangians

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

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

- Instantons

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

- Statistical Parton Distributions

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

Proton Structure: By What Process Is the Sea Created?

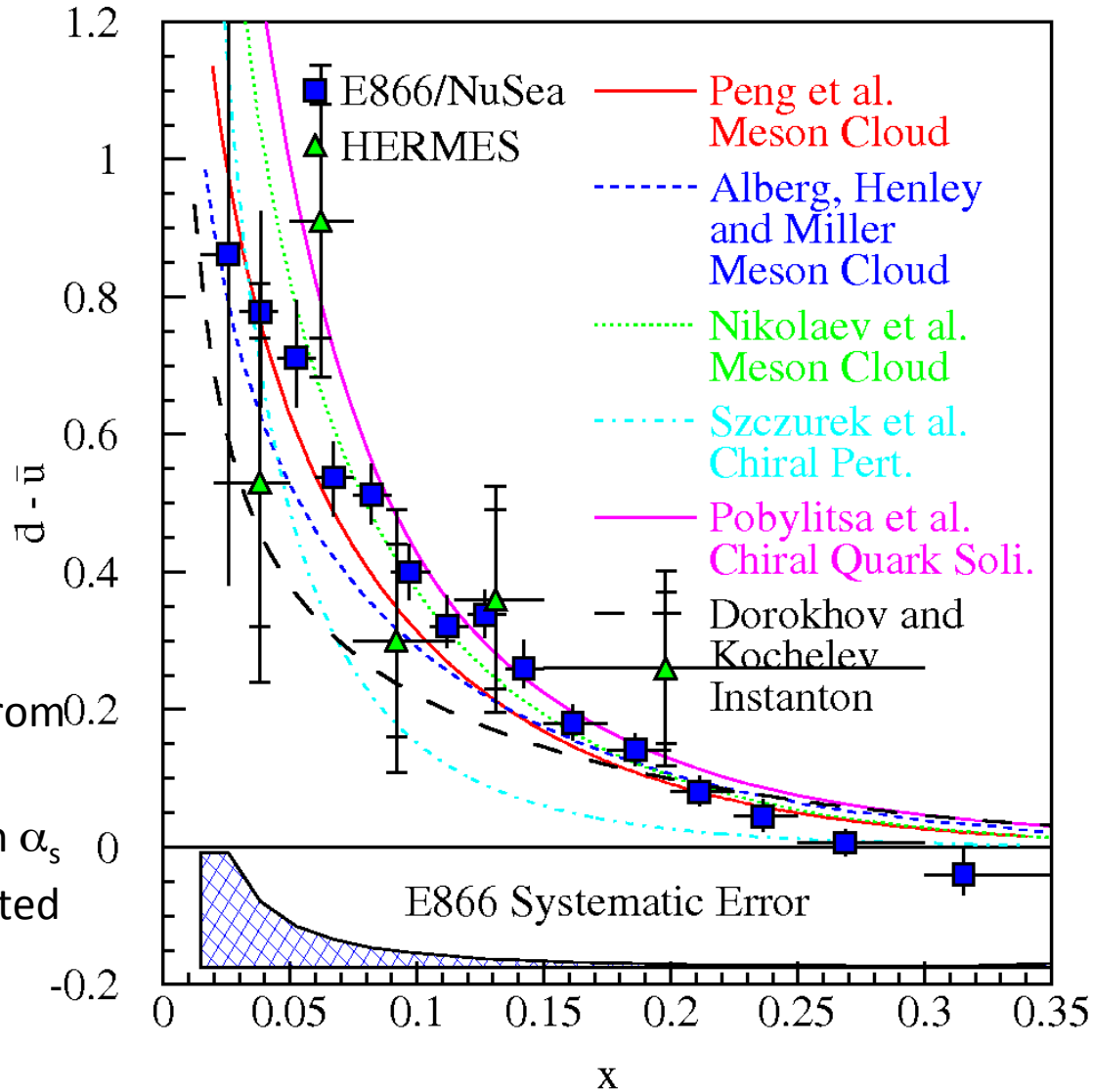
- There is a gluon splitting component which is symmetric

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

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

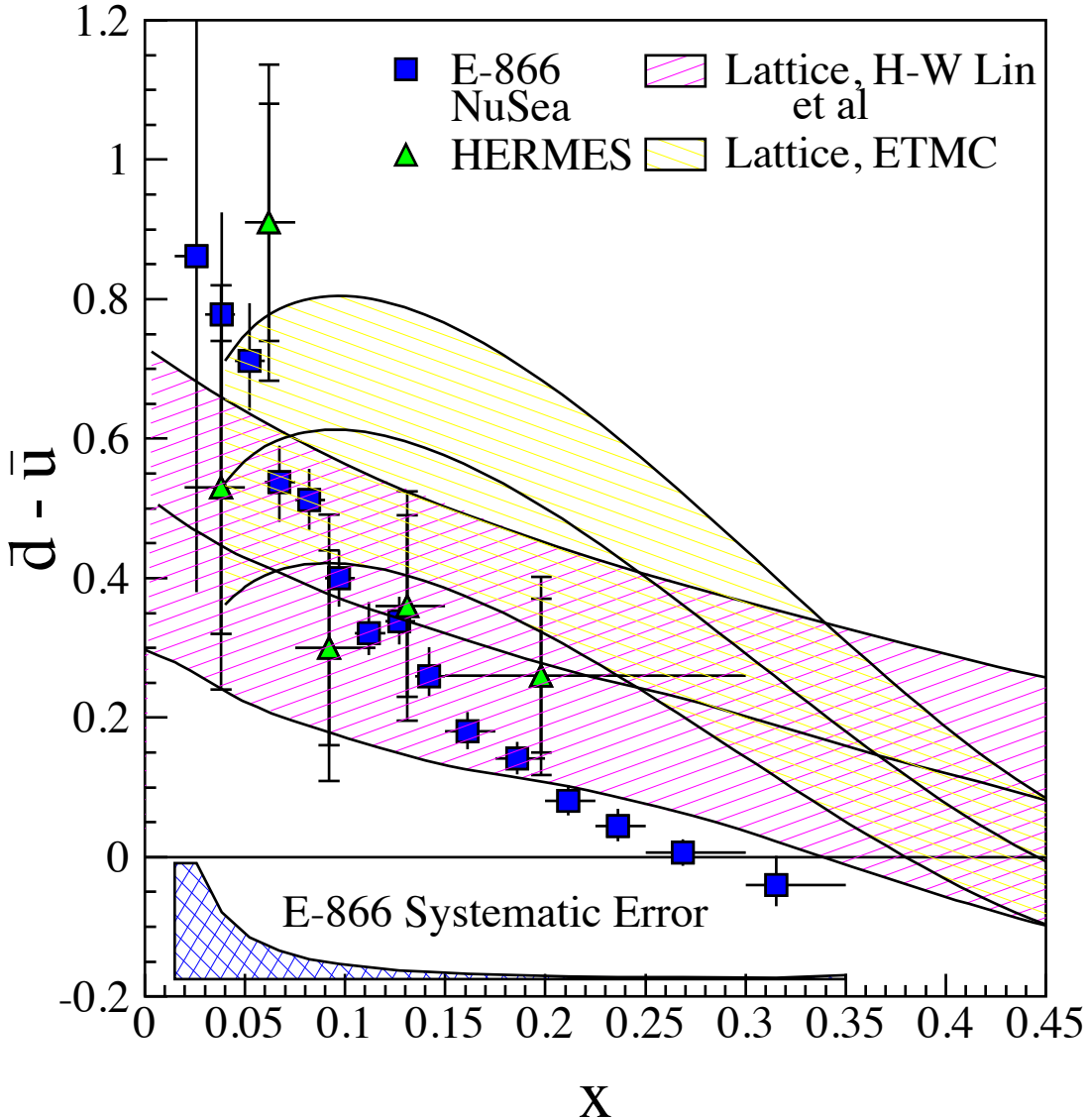
$$\bar{q}_{\mathrm{pQCD}}(x) = \bar{d}_{\mathrm{pQCD}}(x) = \bar{u}_{\mathrm{pQCD}}(x)$$

- $\bar{d}(x) - \bar{u}(x)$
  - Symmetric sea via pair production from gluons subtracts away
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference



Proton Structure: By What Process Is the Sea Created?

- Lattice weighs in!!



How can we measure the sea distributions?

Need a process that can isolate sea contributions:

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

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

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

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

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

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

How can we measure the sea distributions?

Need a process that can isolate sea contributions:

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

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

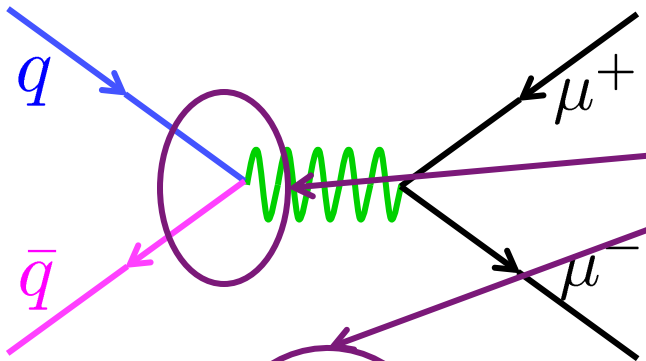
- Collider W production
  - Fermilab Tevatron, CERN LHC, **RHIC**

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

- Drell-Yan
  - Fermilab, COMPASS, RHIC

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

The Drell-Yan reaction:

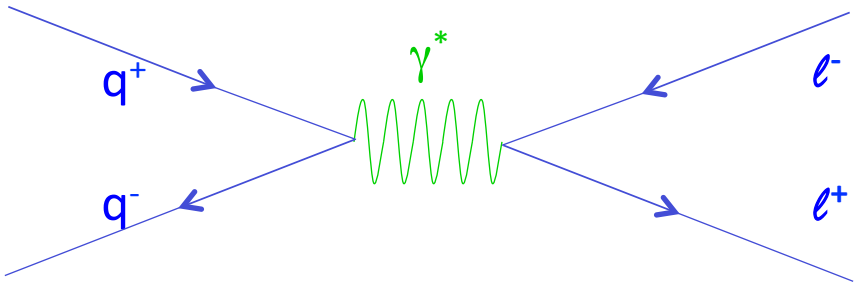


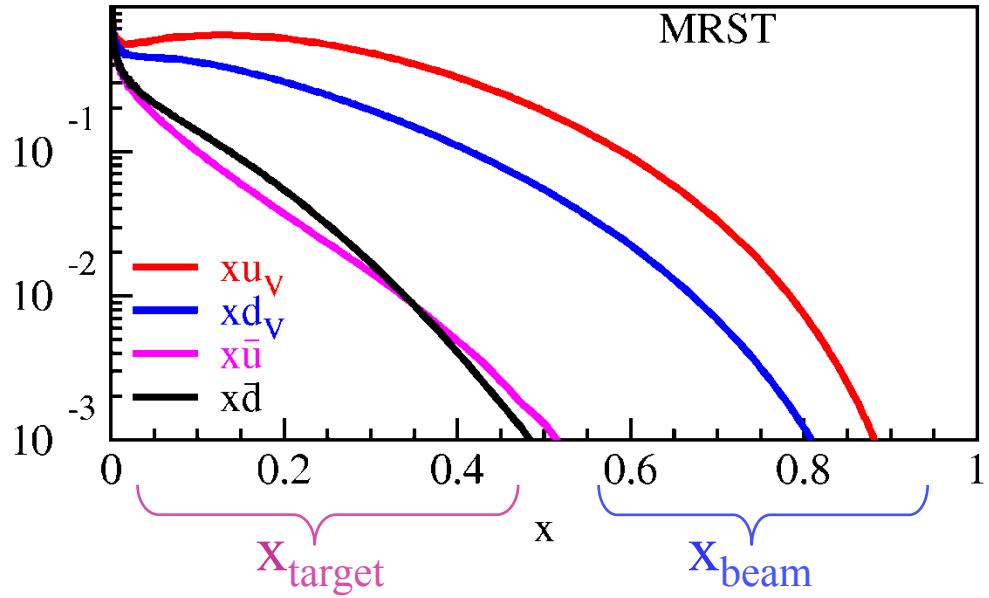
Start with point cross section for two annihilating Fermions (See Halzen and Martin or Perkins)

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

Calculate the probability of finding two quarks with momentum in the range $[x_t, x_t+dx_t]$ and $[x_b, x_b+dx_b]$

Drell-Yan Cross Section





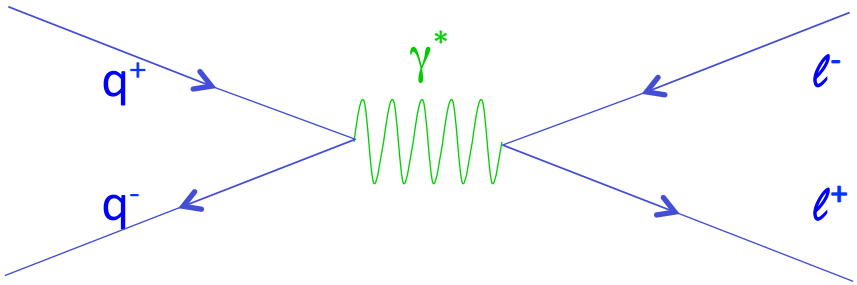
- Cross section is a convolution of beam and target parton distributions

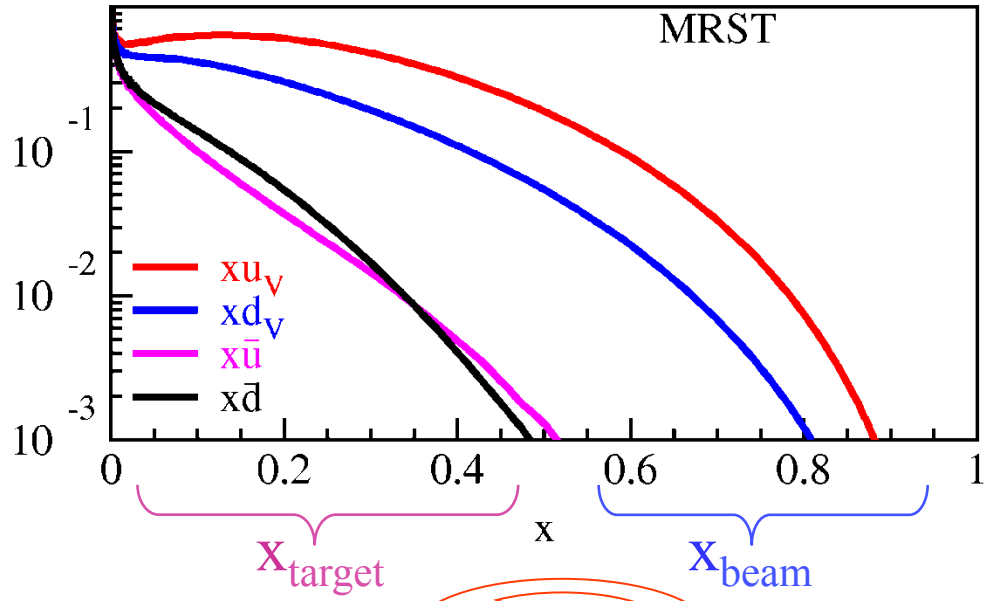
$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

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

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





- Cross section is a convolution of beam and target parton distributions

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Acceptance limited

(Fixed Target, Hadron Beam)

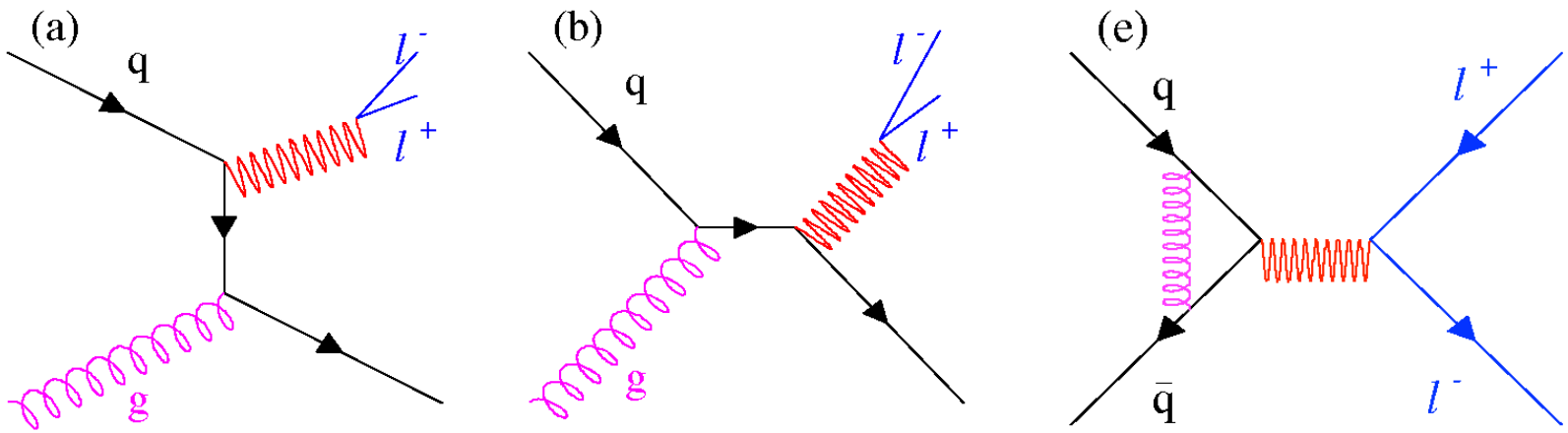
- u-quark dominance

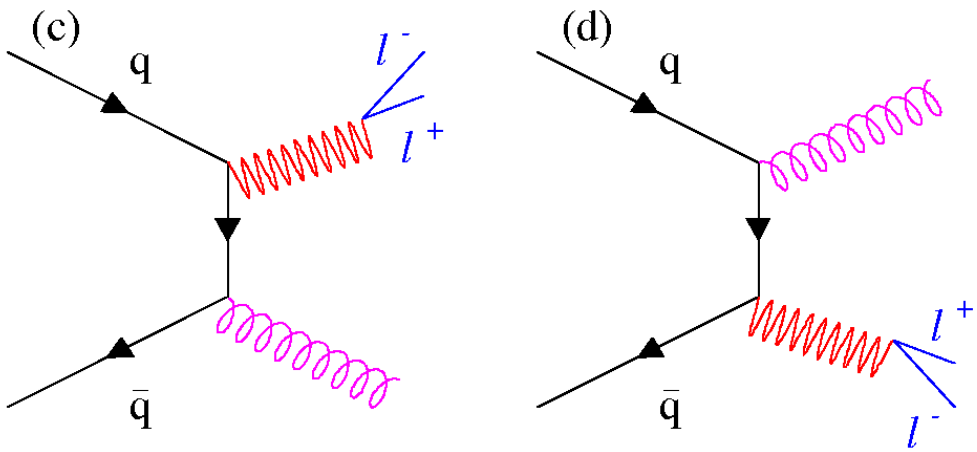
  $(2/3)^2$ vs. $(1/3)^2$

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

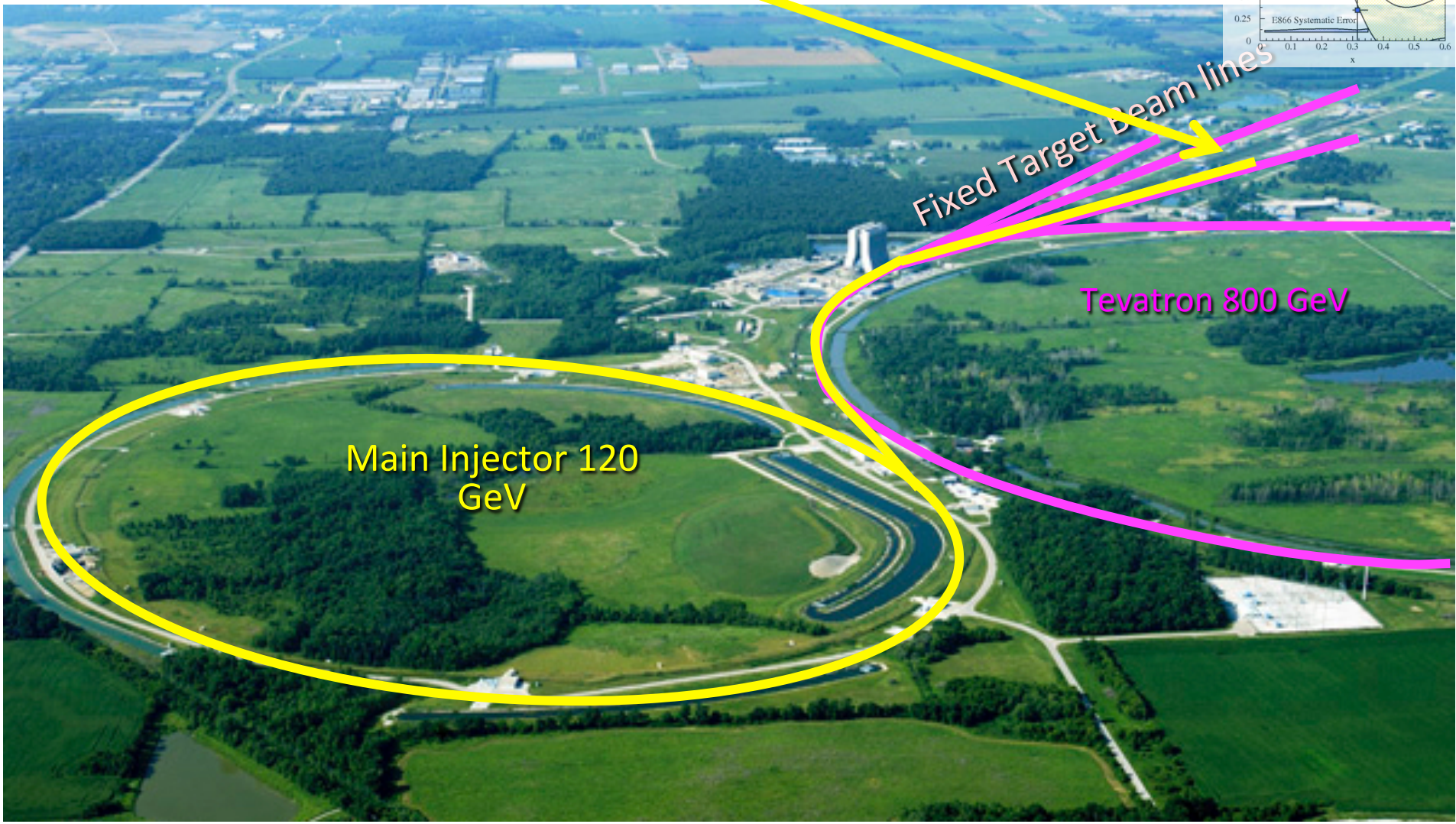
Drell-Yan Cross Section—Next-to-leading order α_s

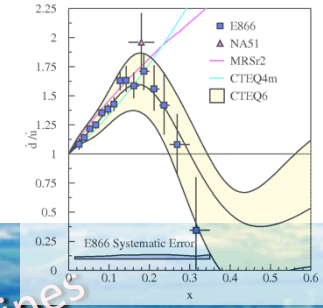
- These diagrams are responsible for approximately 50% of the measured cross section

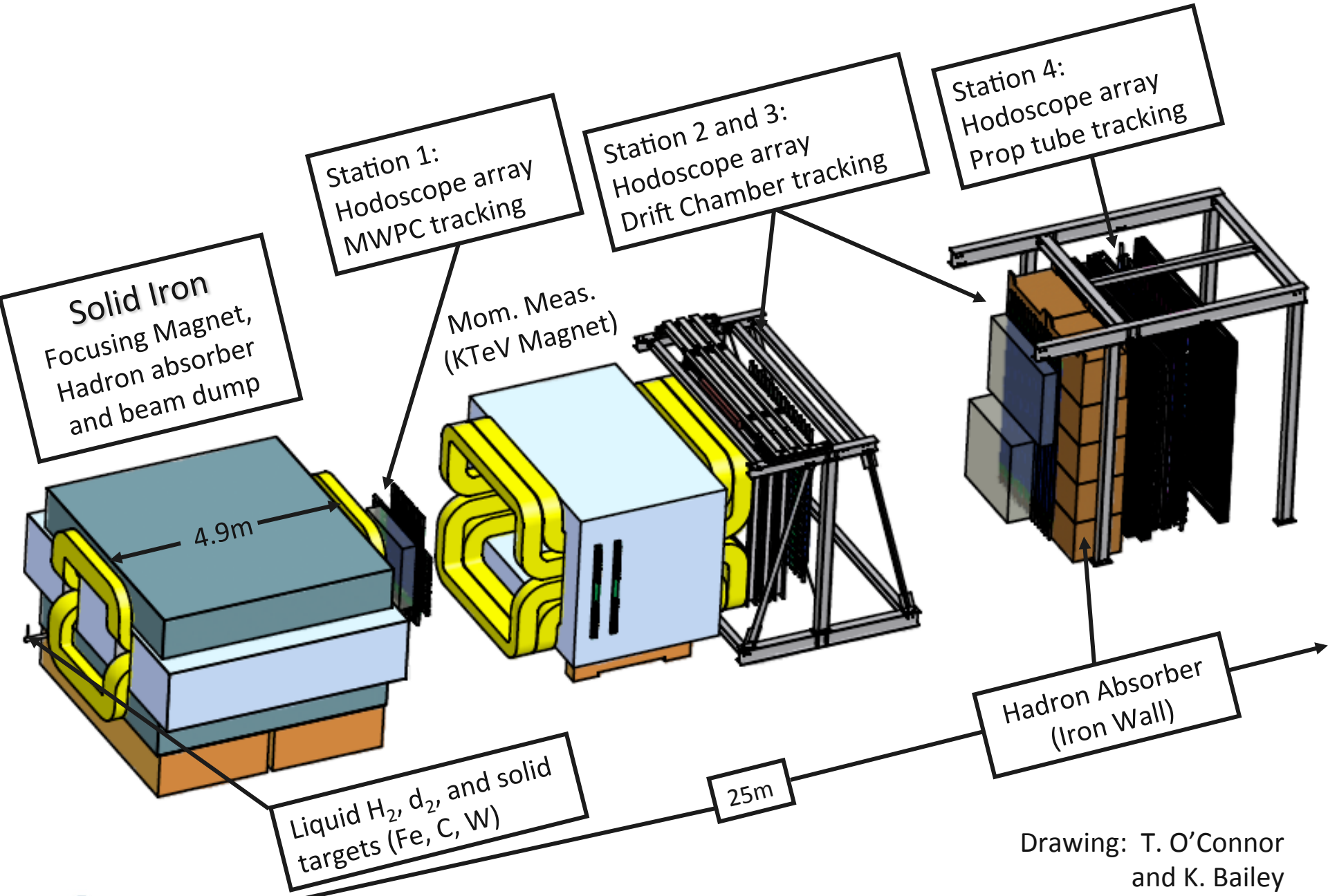




SeaQuest Experiment



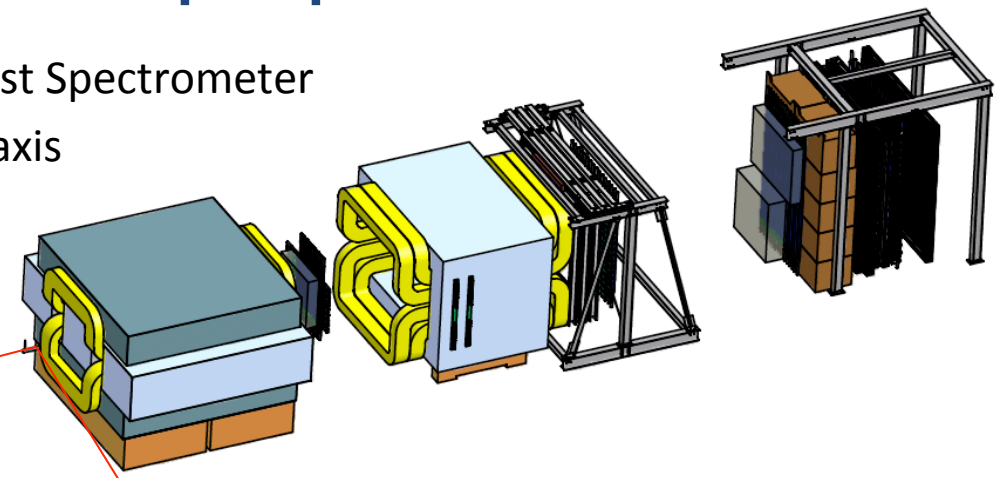


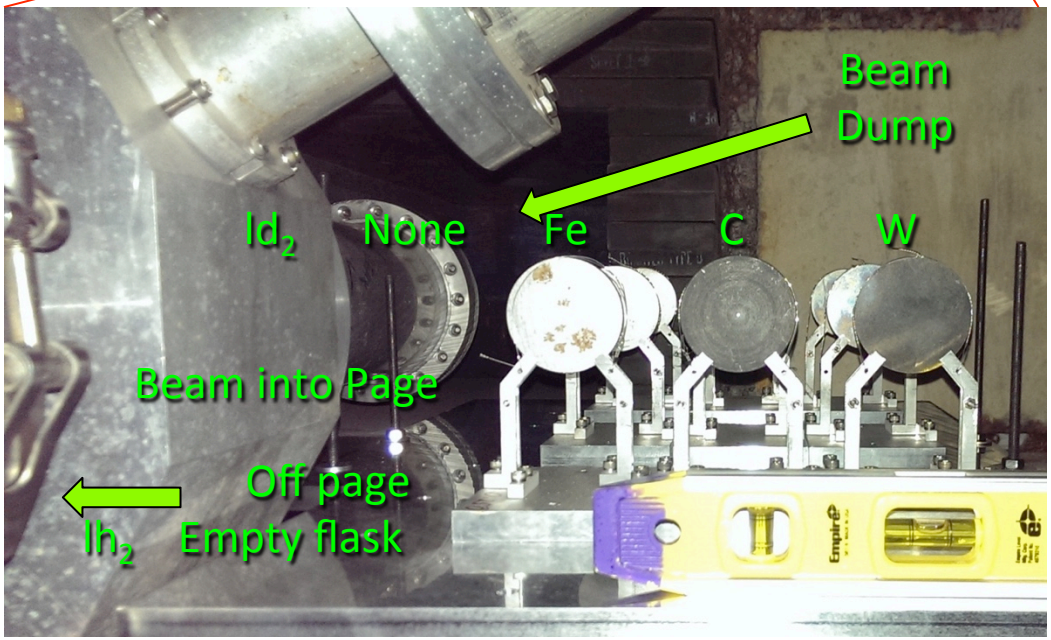


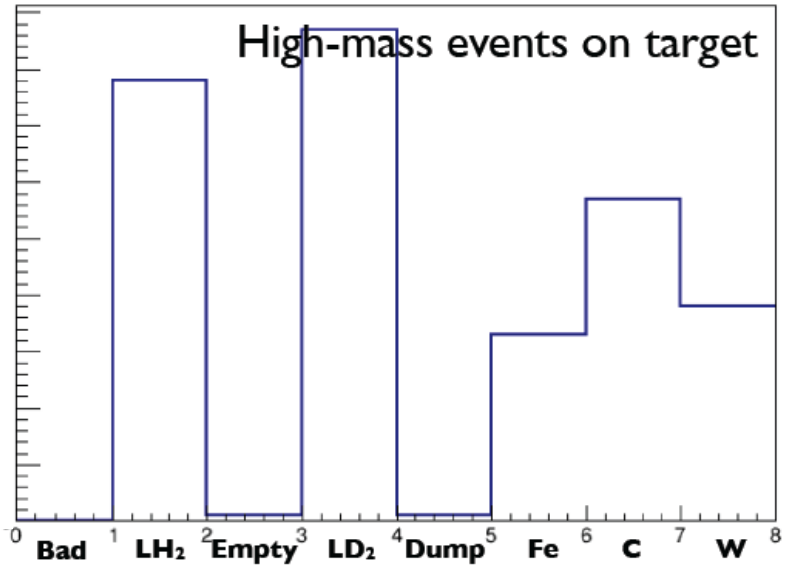
Drawing: T. O'Connor
and K. Bailey

Data From FY2014—target-dump separation

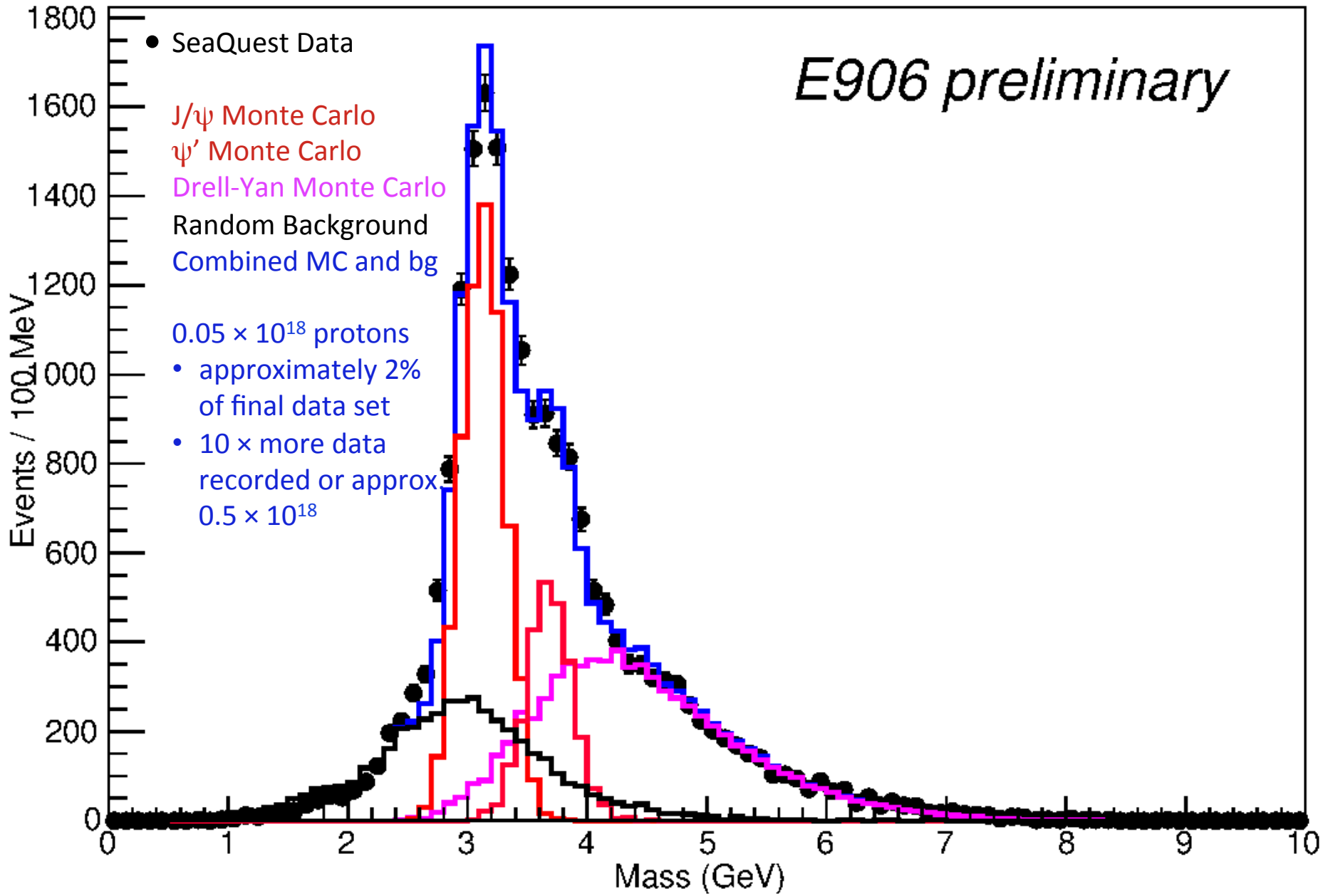
- Entire beam interacts upstream of SeaQuest Spectrometer
- Pointing resolution very poor along beam axis







Data From FY2014



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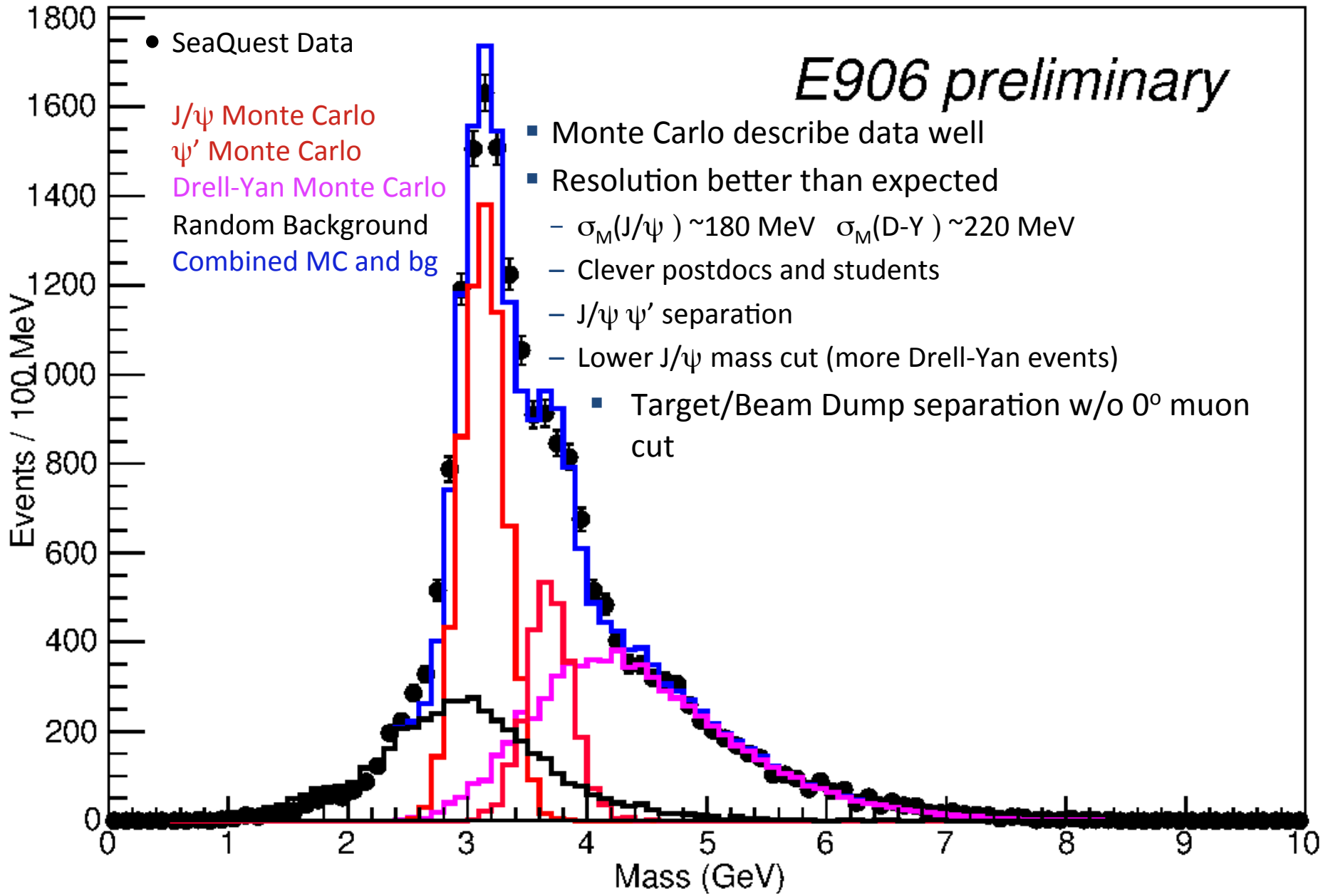

- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi)$ ~180 MeV σ_M(D-Y) ~220 MeV
  - Clever postdocs and students
  - J/ψ ψ' separation
  - Lower J/ψ mass cut (more Drell-Yan events)
    - Target/Beam Dump separation w/o 0° muon cut

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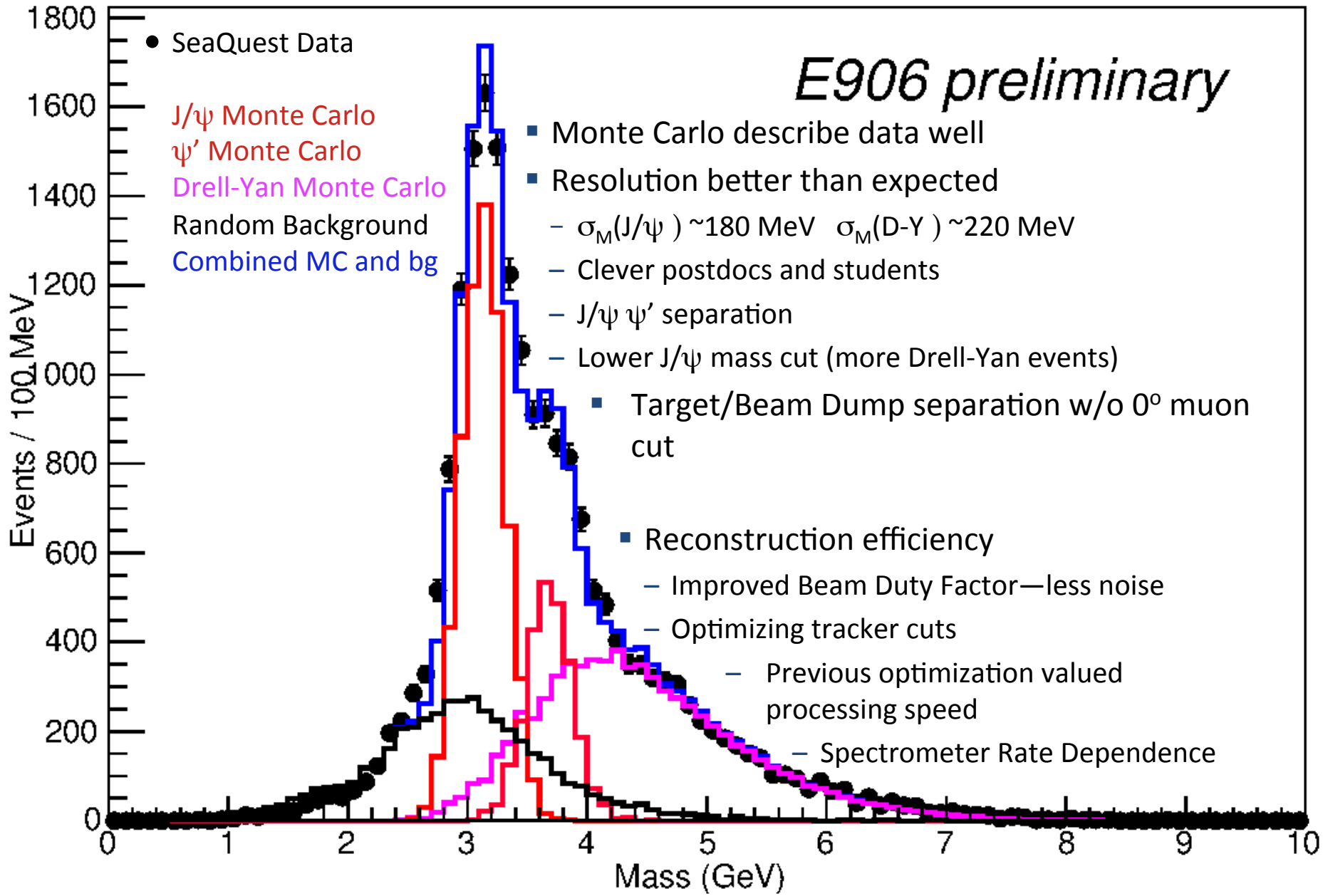

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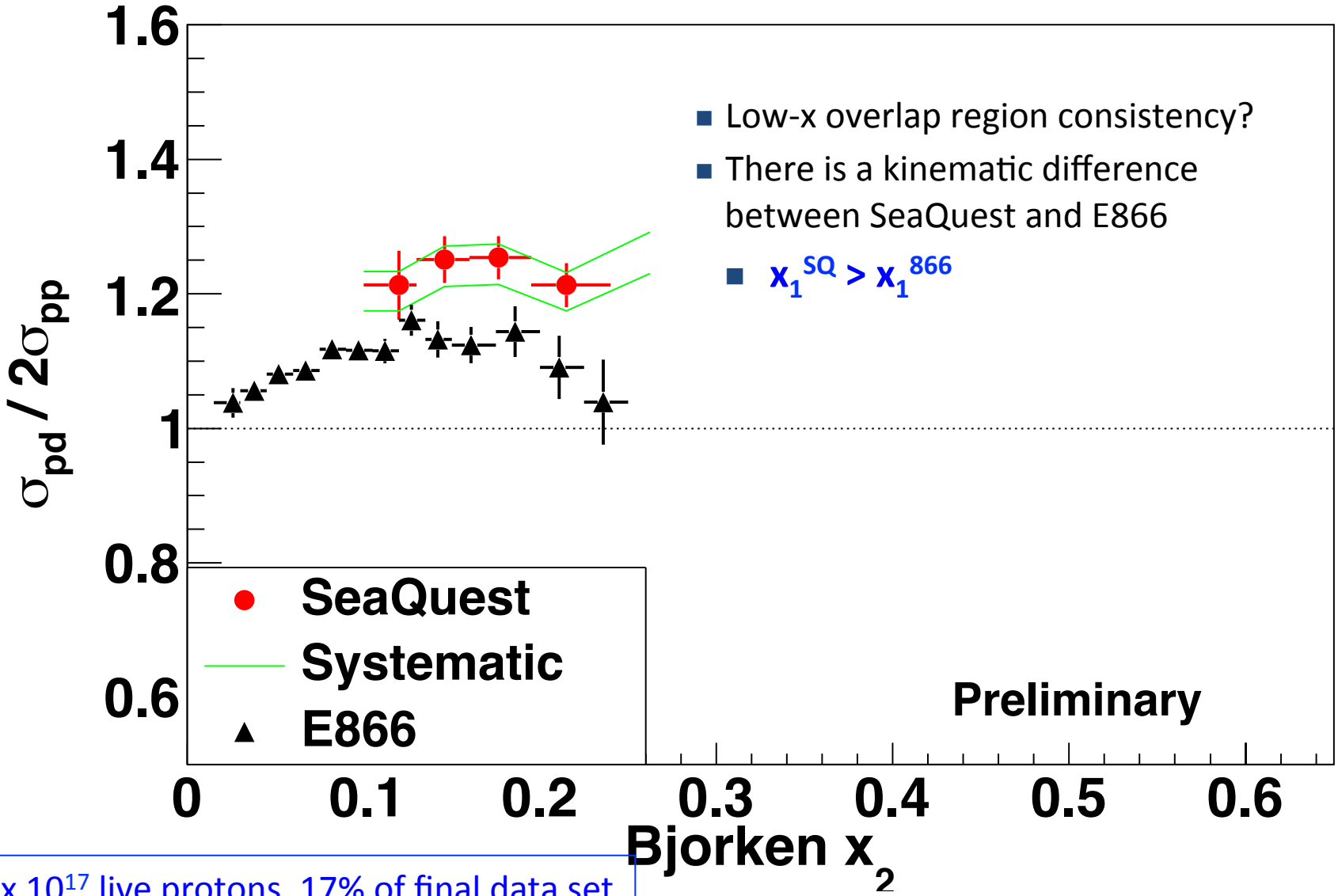
- Target/Beam Dump separation w/o 0° muon cut
- Reconstruction efficiency
  - Improved Beam Duty Factor—less noise
  - Optimizing tracker cuts
    - Previous optimization valued processing speed
    - Spectrometer Rate Dependence

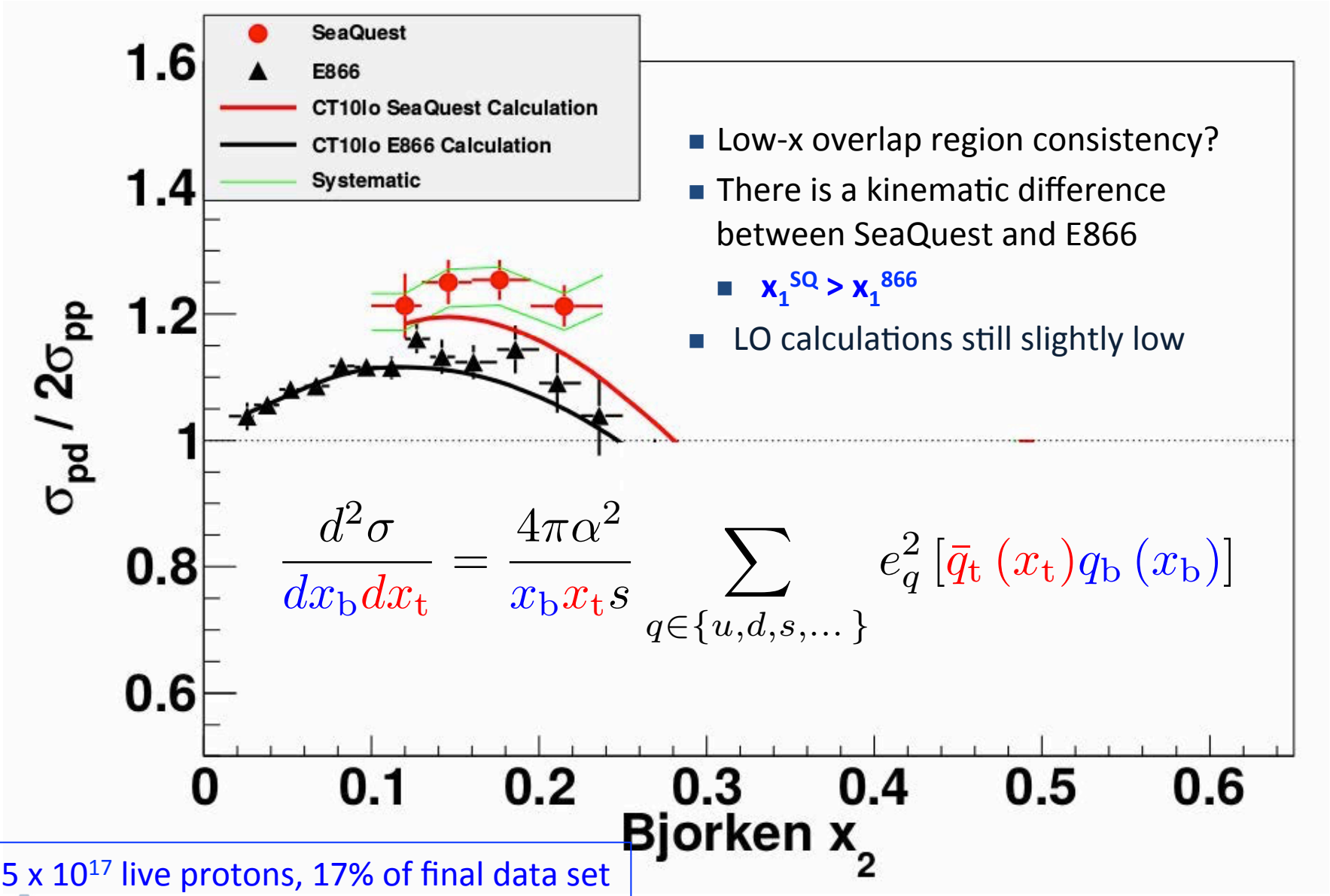
SeaQuest Cross Section Ratio



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

3.5 x 10^{17} live protons, 17% of final data set

SeaQuest Cross Section Ratio

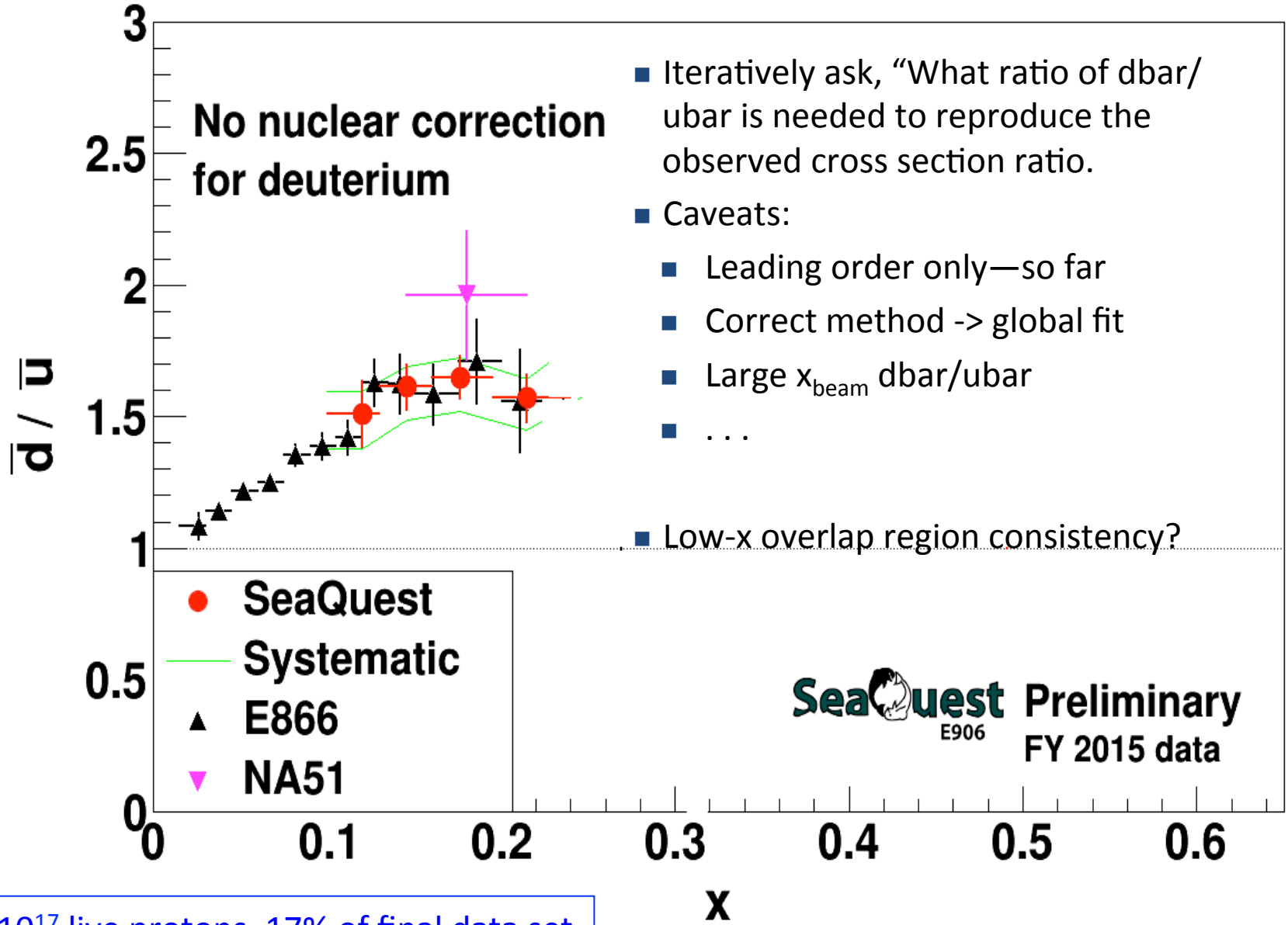


- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
  - $x_1^{SQ} > x_1^{866}$
- LO calculations still slightly low

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

3.5 x 10^{17} live protons, 17% of final data set

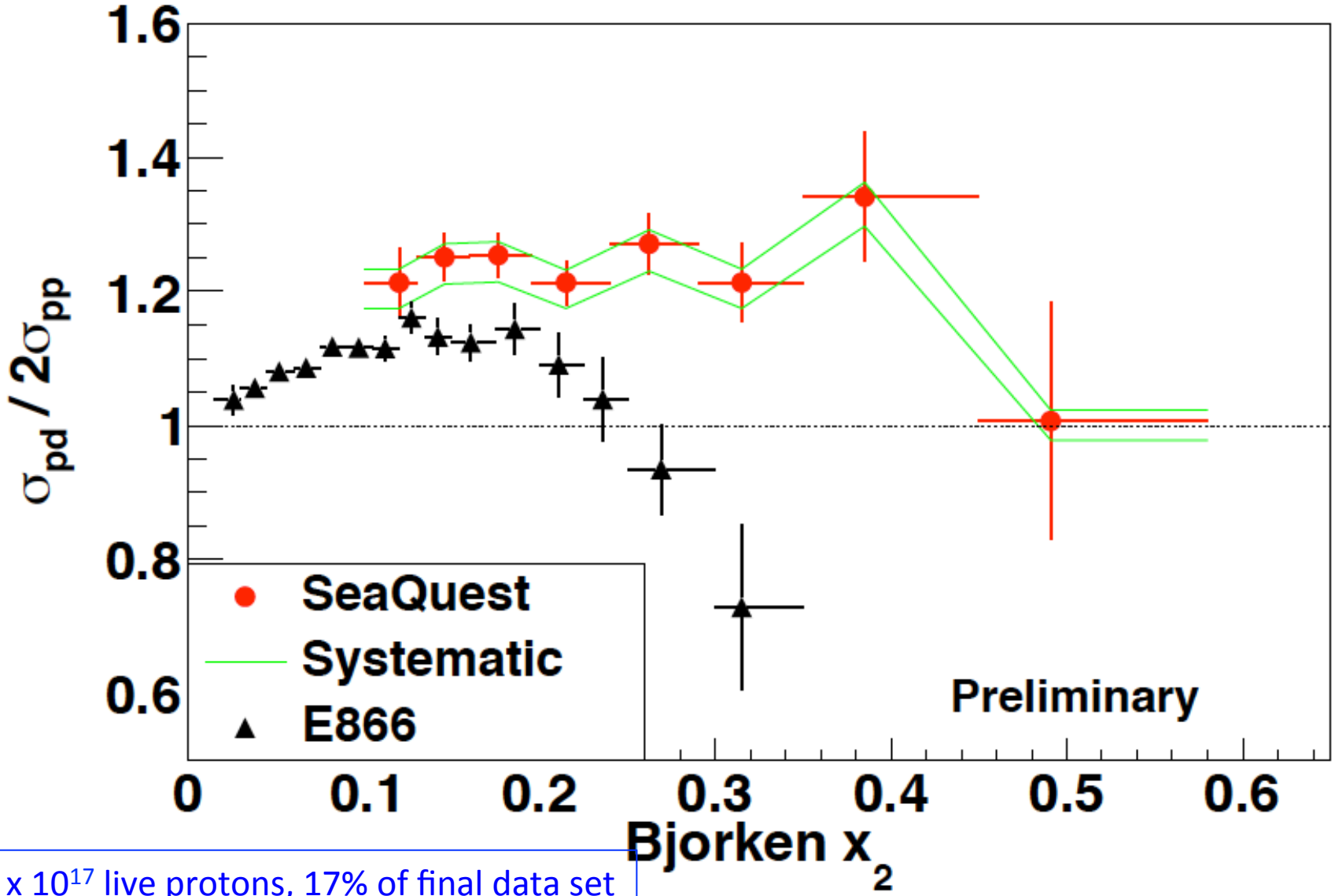
SeaQuest LO dbar/ubar extraction



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

3.5 x 10^{17} live protons, 17% of final data set

SeaQuest Cross Section Ratio

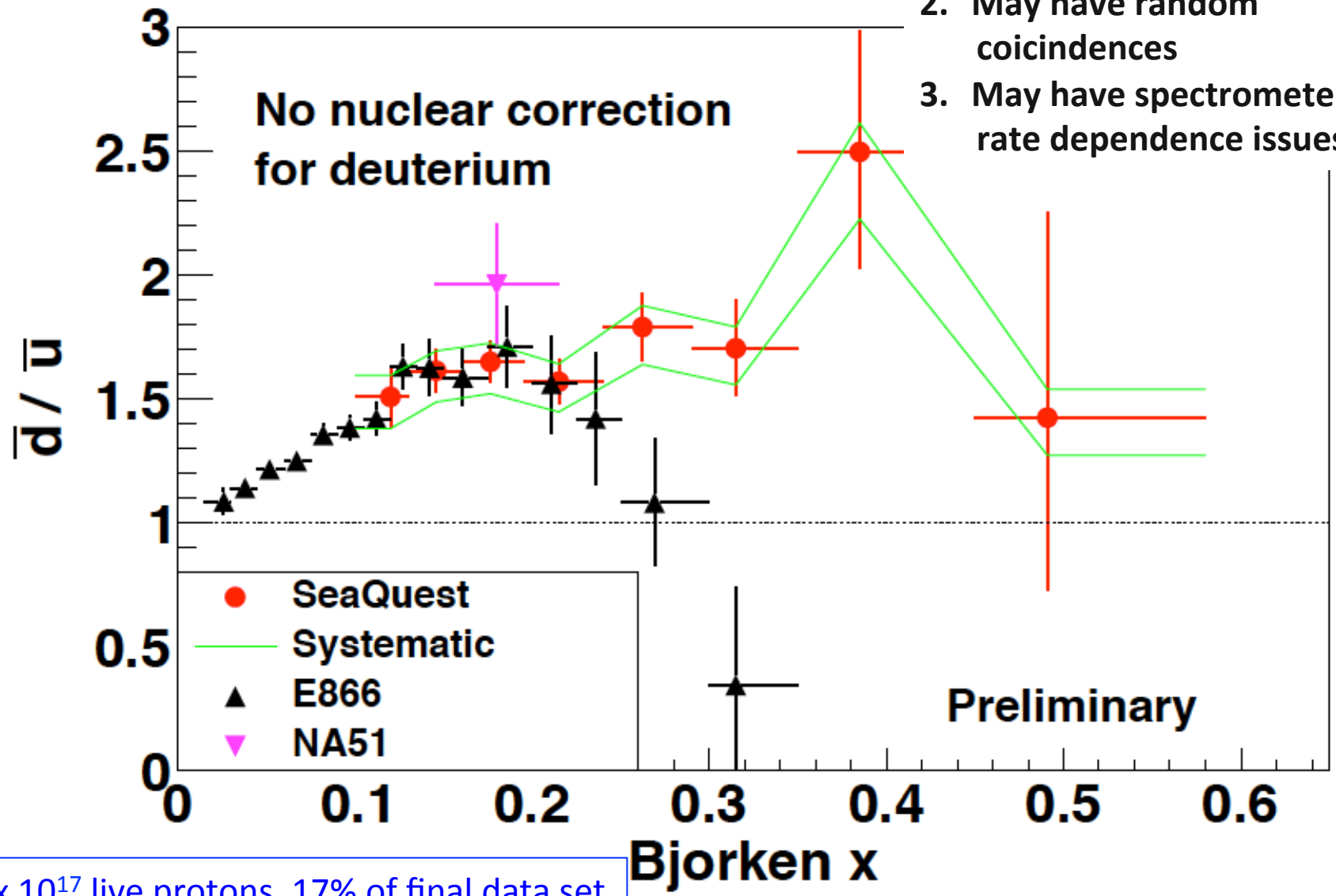


3.5 x 10^{17} live protons, 17% of final data set

SeaQuest Cross Section Ratio

Caveat emptor:

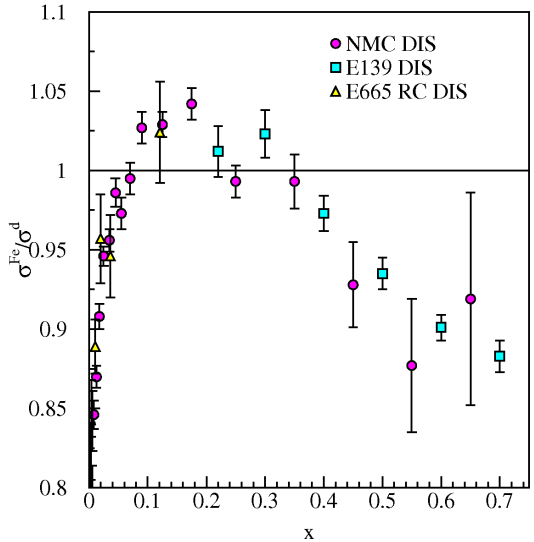
1. **These data are preliminary**
2. **May have random coicindences**
3. **May have spectrometer rate dependence issues**

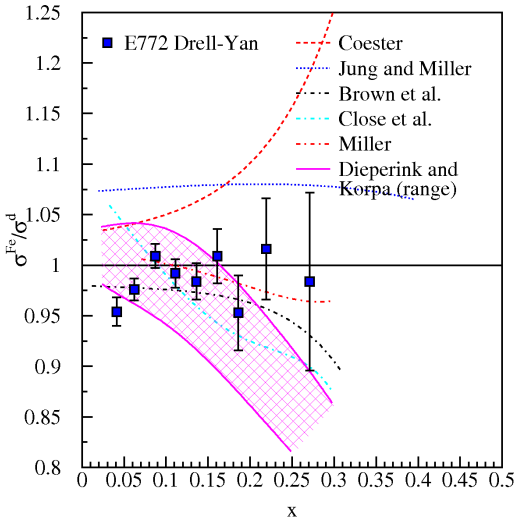


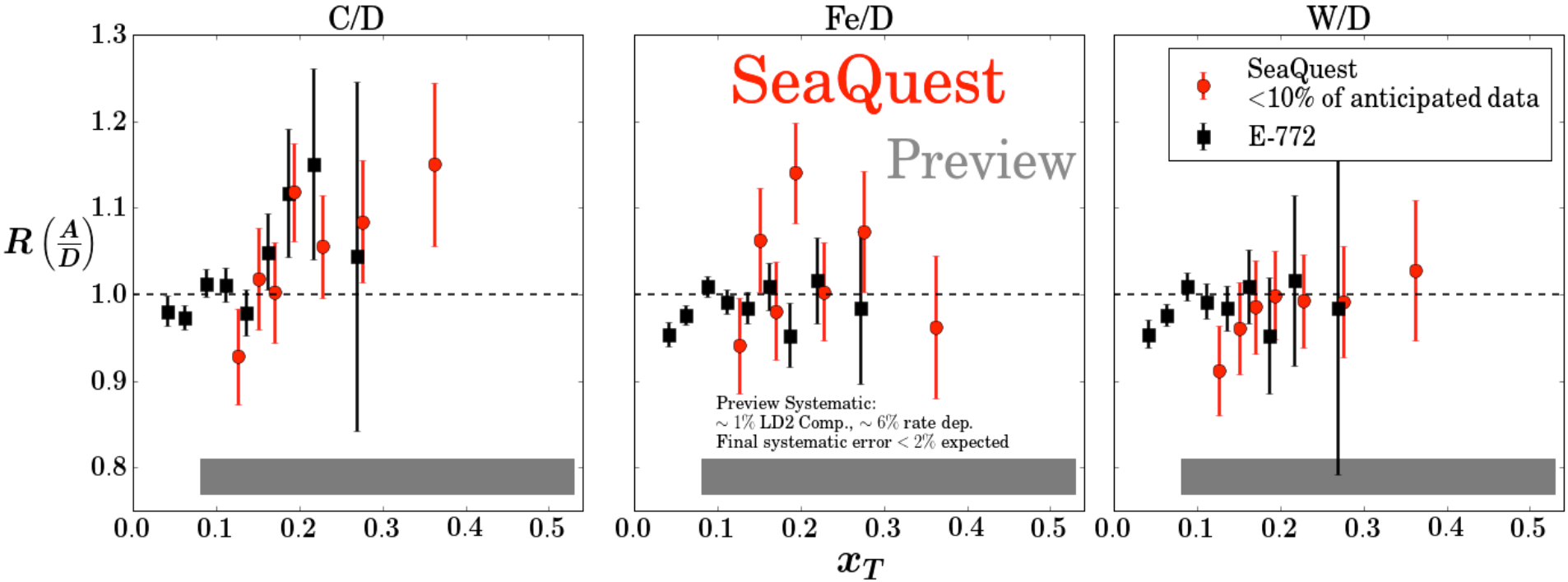
3.5 x 10^{17} live protons, 17% of final data set

SeaQuest Seaquark EMC Effect

- 10% of anticipated statistical precision
- Increased detector acceptance at large-x to come.
- No antiquark modification apparent.





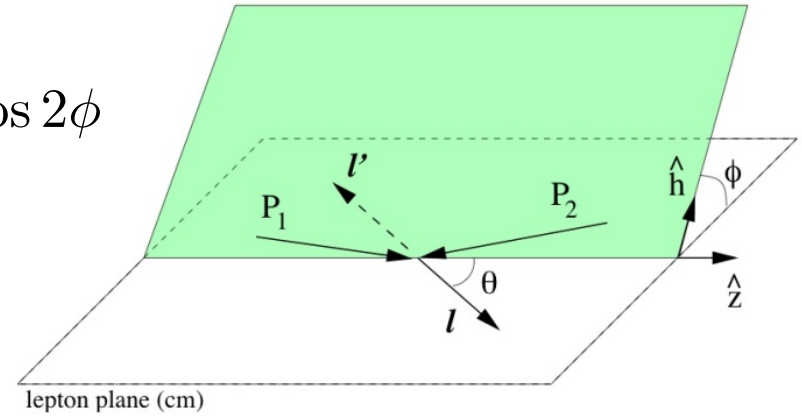


Now add Spin

- Dynamics make things messy
- . . . Or more interesting?

Leading order Single Spin Drell-Yan Cross Section

$$\frac{d\sigma^{\mathrm{LO}}}{d^4q d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_{\mathrm{U}}^{\mathrm{LO}}\Big[1 + D^{\mathrm{LO}}_{\sin^2\theta} A_{\mathrm{U}}^{\cos 2\phi}\cos 2\phi$$
$$+ S_{\mathrm{L}} D^{\mathrm{LO}}_{\sin^2\theta} A_{\mathrm{L}}^{\sin 2\phi}\sin 2\phi$$
$$+ \left|\vec{S}_{\mathrm{T}}\right| A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}\sin\phi_{\mathrm{S}}$$
$$+ \left|\vec{S}_{\mathrm{T}}\right| D^{\mathrm{LO}}_{\sin^2\theta} A_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})}\sin(2\phi+\phi_{\mathrm{S}})$$
$$+ \left|\vec{S}_{\mathrm{T}}\right| D^{\mathrm{LO}}_{\sin^2\theta} A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})}\sin(2\phi-\phi_{\mathrm{S}})\Big]$$



Formula: from Aram Kotzinian
Slide: content from Oleg Denisov

$A_{\mathrm{U}}^{\cos 2\phi}$ Boer-Mulders of target hadron

$A_{\mathrm{T}}^{\sin\phi_S}$ Sivers for beam nucleon

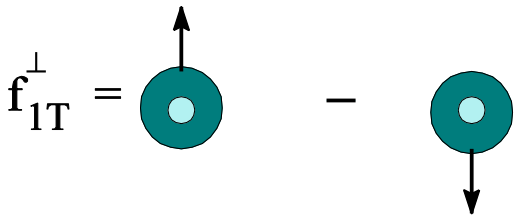
$A_{\mathrm{T}}^{\sin(2\phi+\phi_S)}$ Boer-Mulders of target and $h_1^{\perp}$ and pretzelosity of beam

$A_{\mathrm{T}}^{\sin(2\phi-\phi_S)}$ Boer-Mulders of target and h_1 and transversity of beam

(with polarized beam and unpolarized target)

Sivers Function and the Spin Crisis

- Correlation between unpolarized quarks and a nucleon's transverse polarization



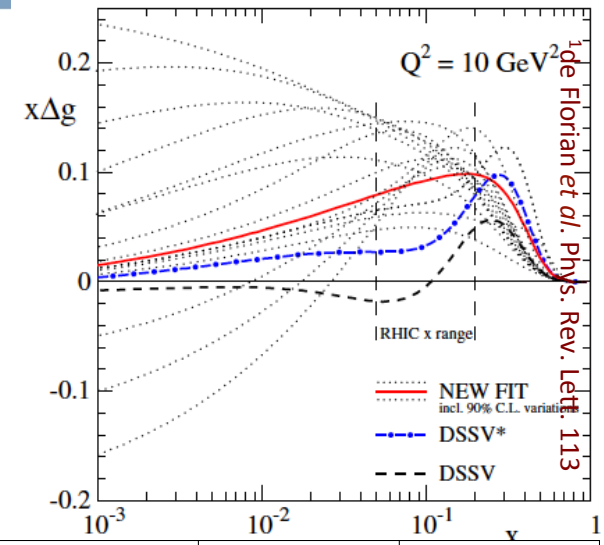
- Non-zero Sivers distribution ⇨ non-zero quark orbital momentum

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

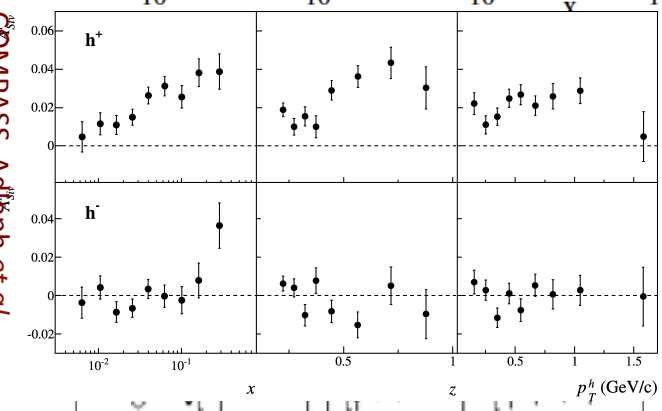
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

½ ΔΣ ≈ 25% ΔG ≈ 0-15%[1]

L ≈ unmeasured

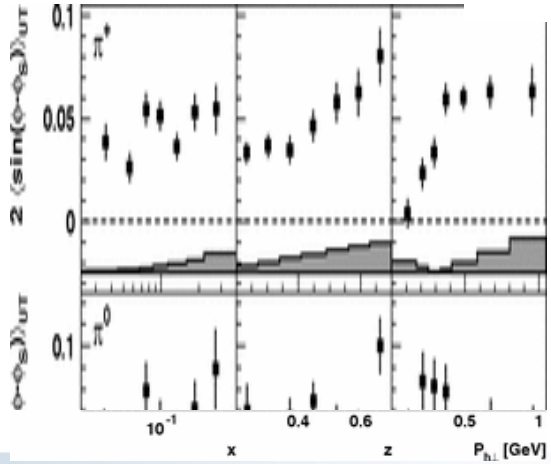


[1]de Florian *et al.* Phys. Rev. Lett. 113

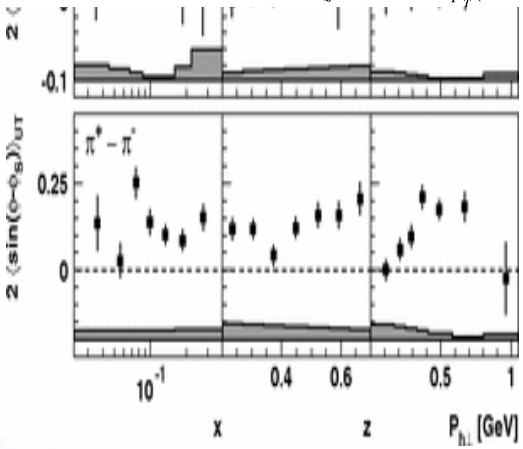


COMPASS, Adolph *et al.* Phys Lett. B, 717, 383

- SeaQuest will measure antiquark Sivers
  - Orbital angular momentum of sea quarks
  - Or pionic cloud

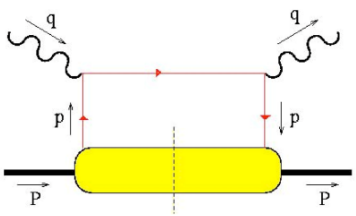


HERMES, Airapetian *et al.* Phys. Rev. Lett. 103, 152002

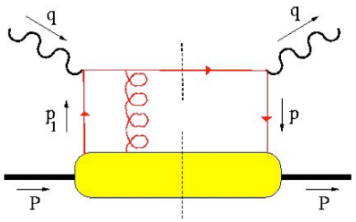


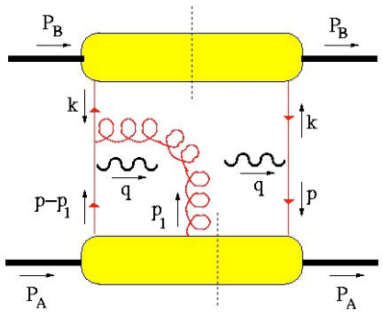
“Naïve” T-odd observables

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

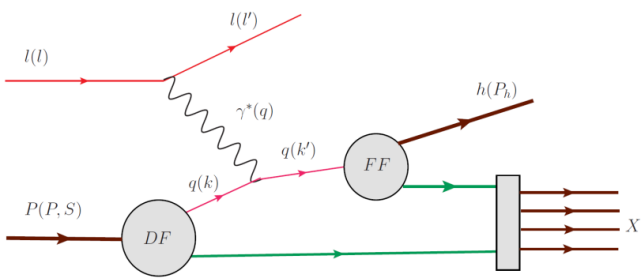


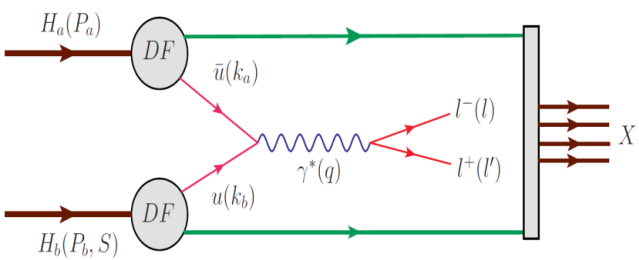
can interfere with





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



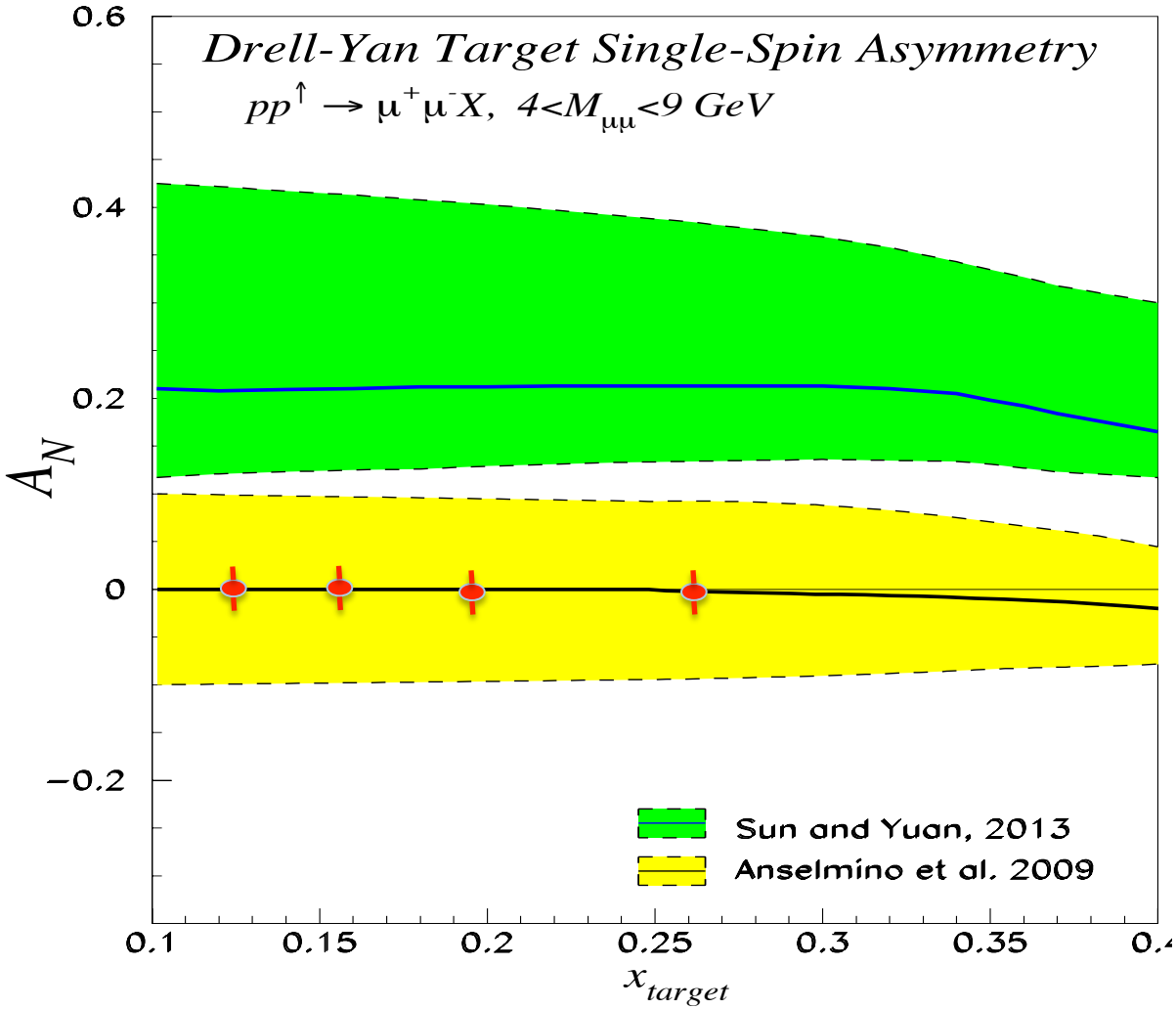


spacelike (DIS) **vs.** **Timelike (Drell-Yan)** **virtual photon**

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

A. Kotzinian, DY workshop, B. CERN, 4/10

Projected Statistical Precision with a Polarized Target at SeaQuest



Polarized target

- Installation in Summer 2017
- Supported with Los Alamos LDRD funds
- Operation funds expected from DOE HEP & NP

Statistics precision shown for two calendar years of running :

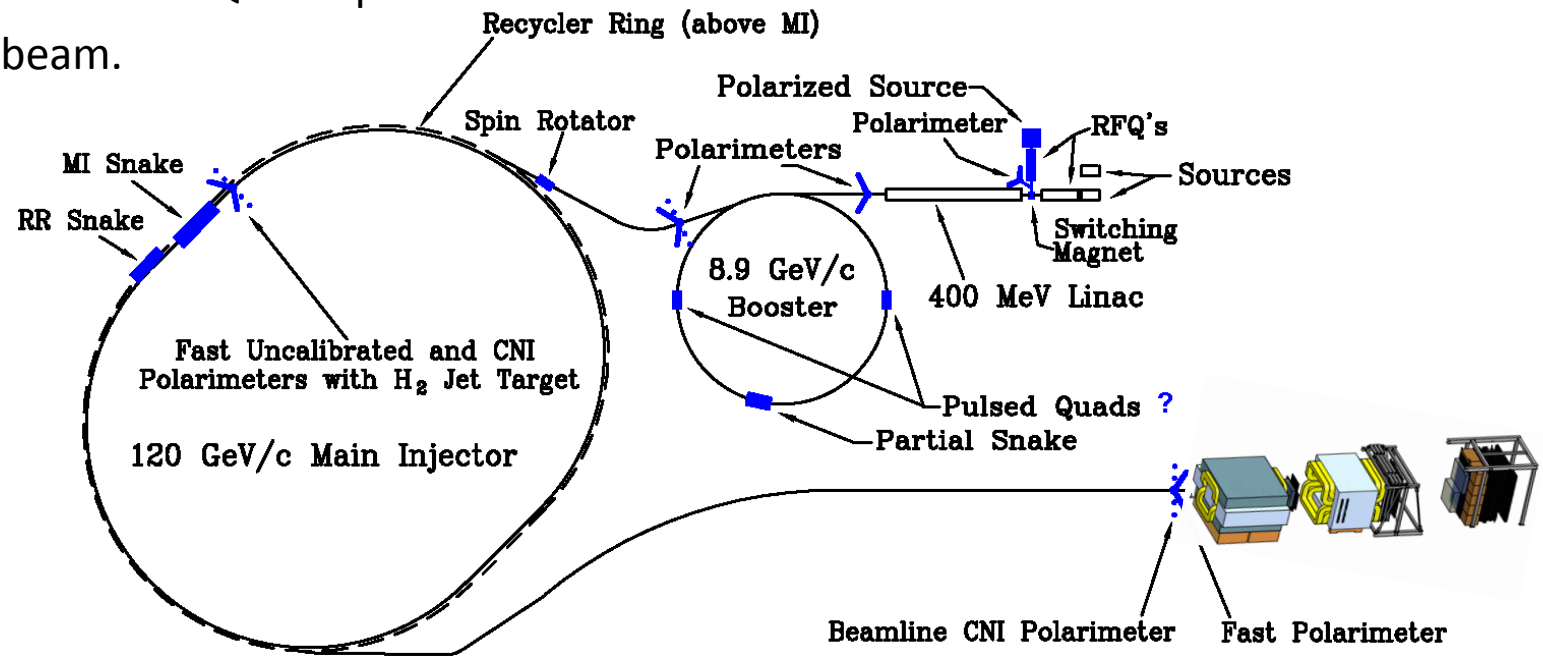
Protons on target = 2.7×10^{18}

$\mathcal{L} = 7.2 \times 10^{42}\ /cm^2$

Polarized Beam Drell-Yan at Fermilab

The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam.



Polarized Beam Drell-Yan at Fermilab

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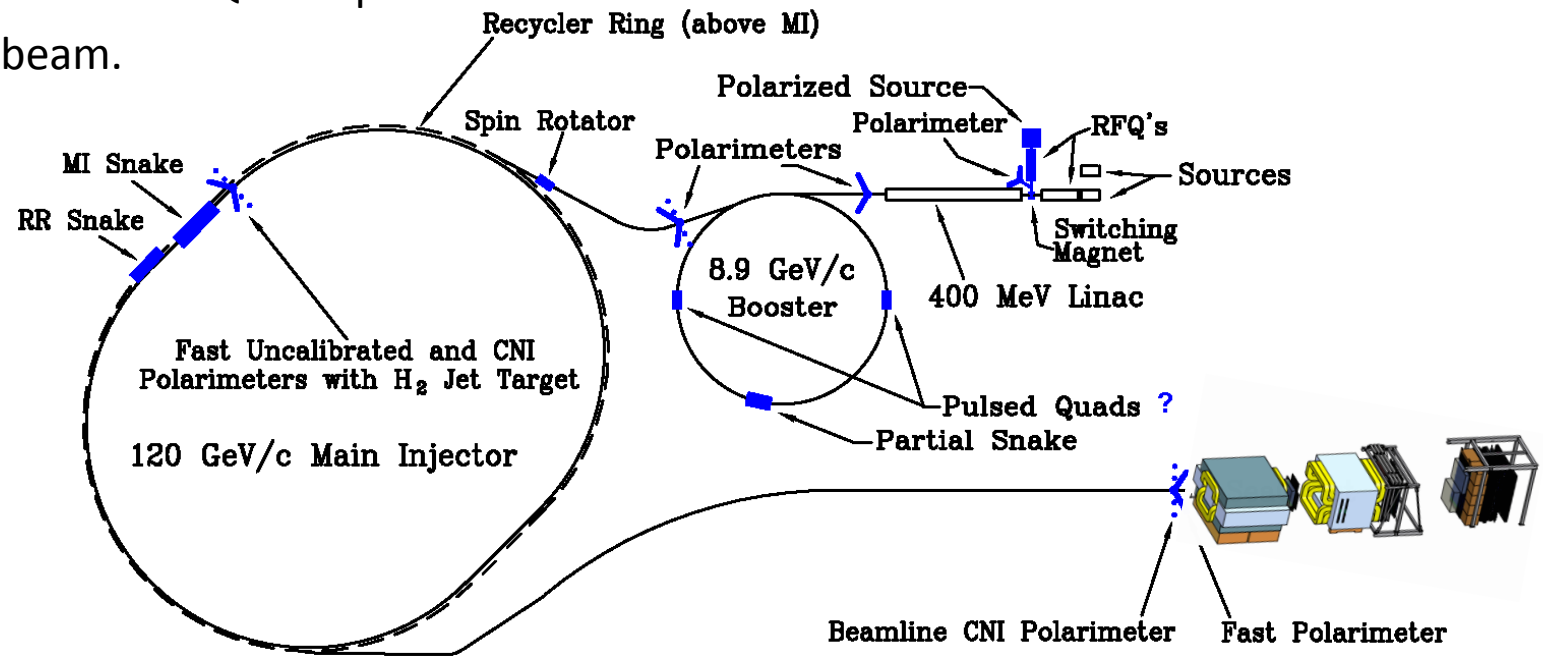


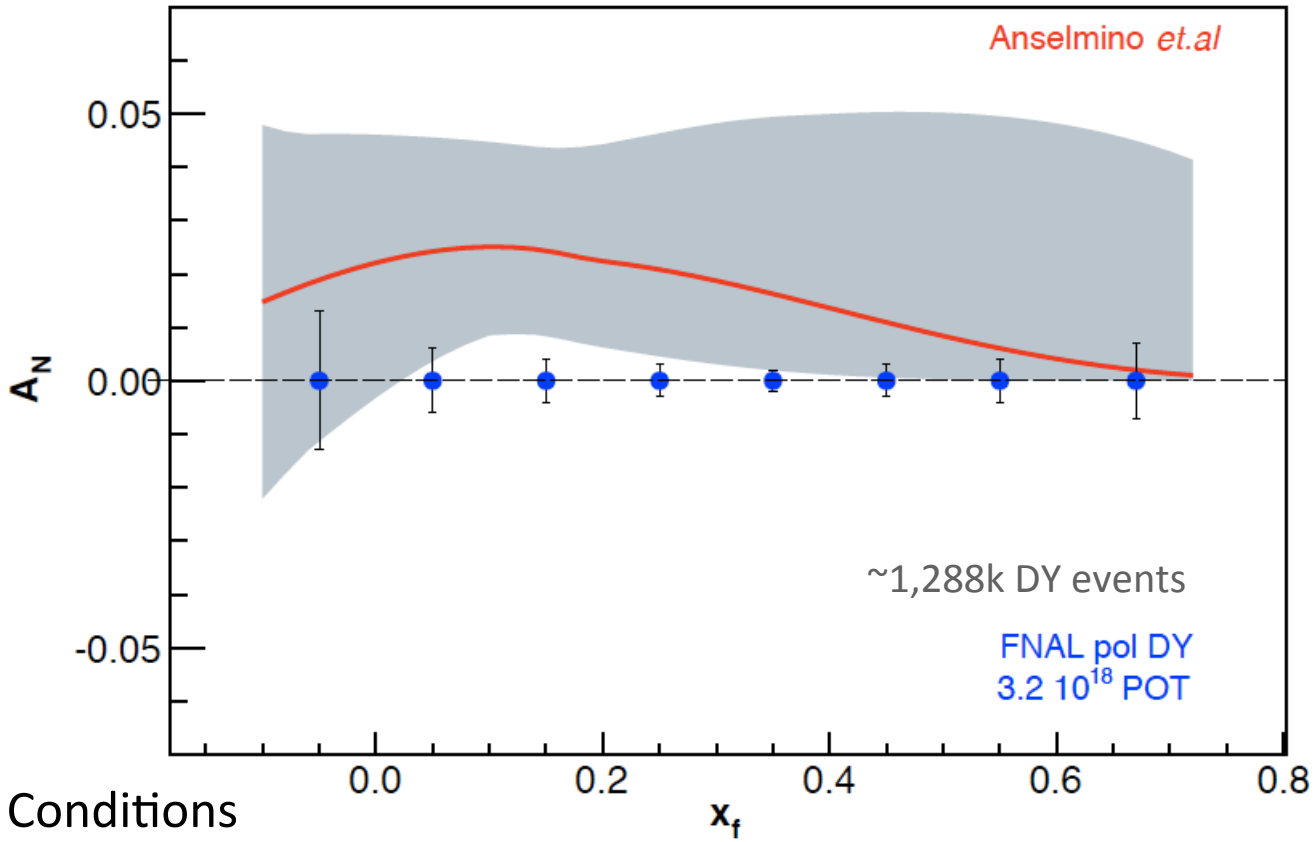
Polarized Target:

- Installation costs $1.9M

Polarized Main Injector:

- Cost Est.: $6M +$4M Contingency & Management = $10M (in 2013)

Expected Precision from E-1027 at Fermilab



- Experimental Conditions
  - Same as SeaQuest
  - luminosity: L_{av} = 2 x 10^{35} (10% of available beam time: I_{av} = 15 nA)
  - 3.2 X 10^{18} total protons for 5 x 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!

Drell-Yan Physics Program

Sea Quarks of the Target

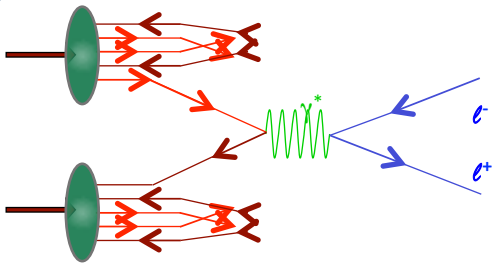
- dbar/ubar
- Sea quark EMC effect

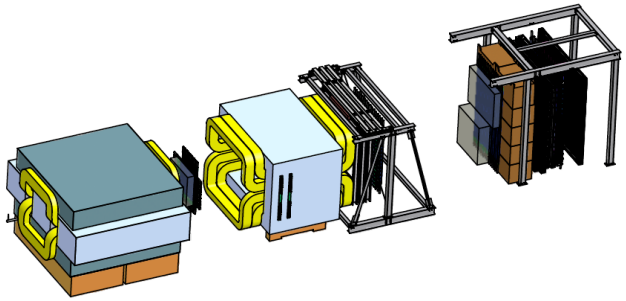
Transverse Spin Physics

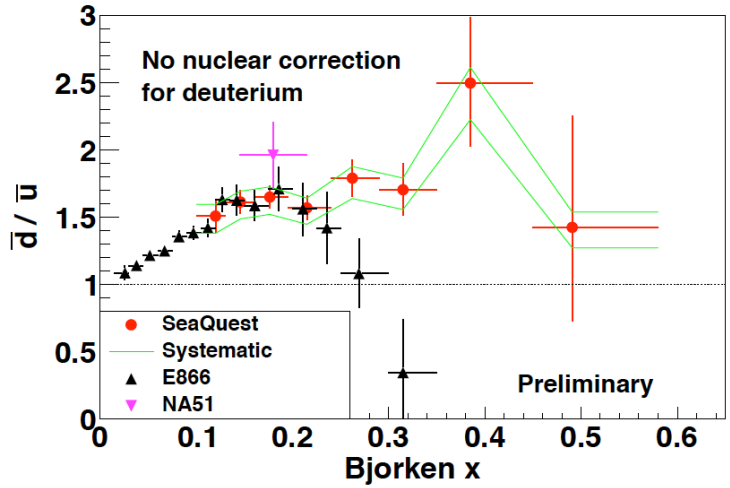
- Sivers and OAM of Sea Quarks
- Sivers and QCD on Valence Quarks (COMPASS and SeaQuest

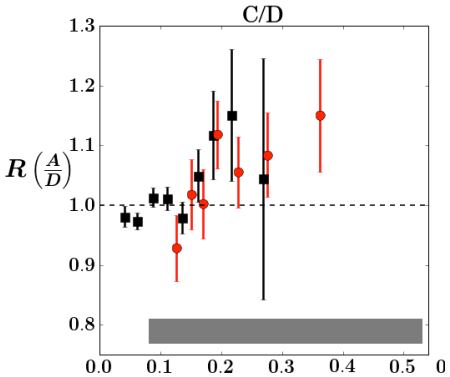
Not discussed:

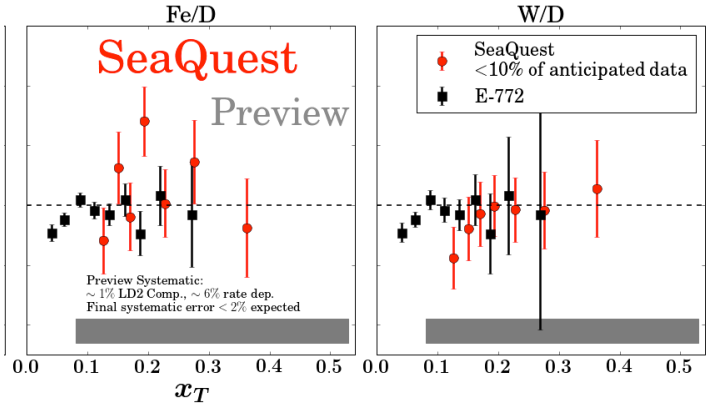
- Boer Mulders from un-polarized D-Y
- Quark sea absolute magnitude
- Partonic Energy Loss
- J/ψ Nuclear Dependence
- Dark Photons







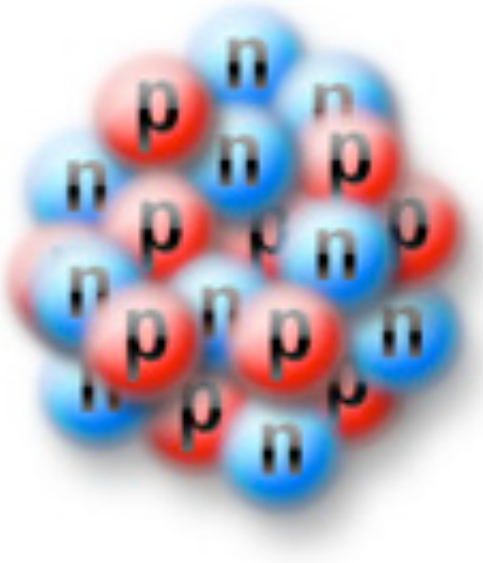




Sea Quark EMC Effect

Guggenheim, Bilbao, Spain

The European Muon Collaboration (EMC) Effect



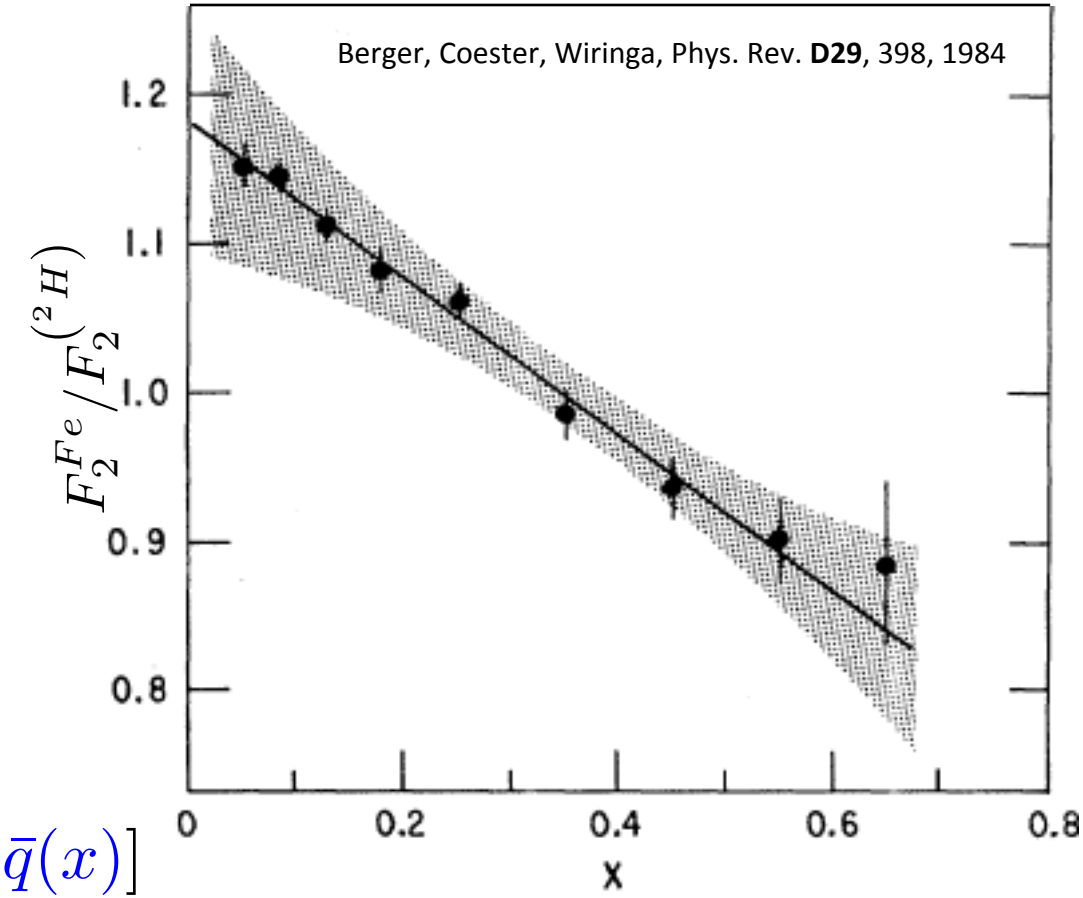
Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Is there a difference between hitting a proton in a nucleus and a free proton?
- Hard scattering makes an implicit assumption that the interaction is energetic enough so that the binding of quarks in a proton is small so surely, the binding of protons in the nucleus is also small?
- Do the quarks change configuration?

The European Muon Collaboration (EMC) Effect

Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Experimentally—No
- EMC measured the DIS F_2 ratio for Iron to Deuterium



$$F_2(x) = \sum_{q \in \{u,d\ldots\}} e_q^2 \left[q(x) + \bar{q}(x)\right]$$

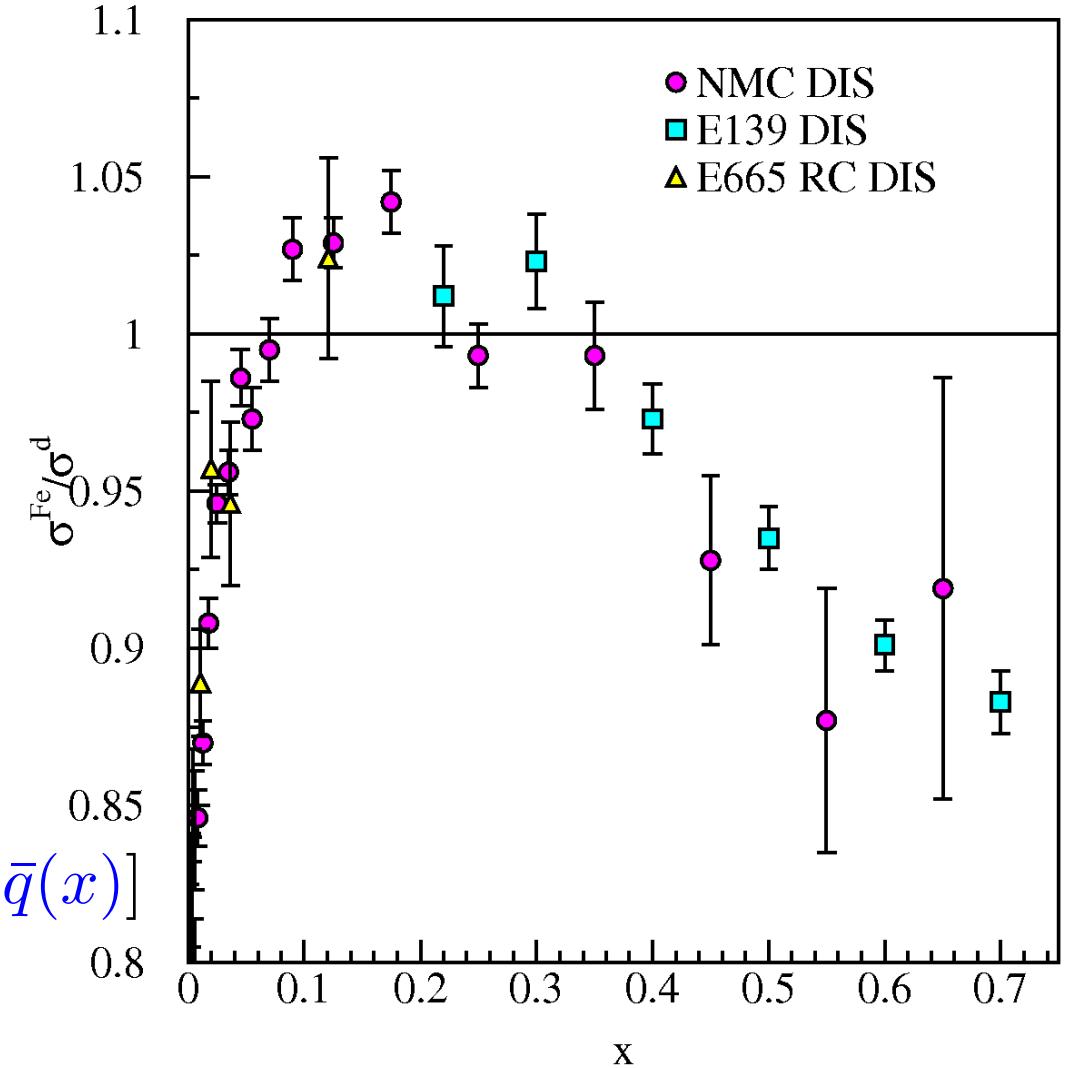
Why?

- Shadowing
- Nuclear binding effects

The European Muon Collaboration (EMC) Effect

Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Experimentally—No
- EMC measured the DIS F_2 ratio for Iron to Deuterium



$$F_2(x) = \sum_{q \in \{u,d\ldots\}} e_q^2 \left[q(x) + \bar{q}(x)\right]$$

Why?

- Shadowing
- Nuclear binding effects

Do quarks and antiquarks experience the same modifications?

Aside: Problem for PDF fits

- Many experiments used nuclear targets

- Does this data need to be thrown out now?
  - Information of d-quark distributions comes from Deuterium and isospin symmetry

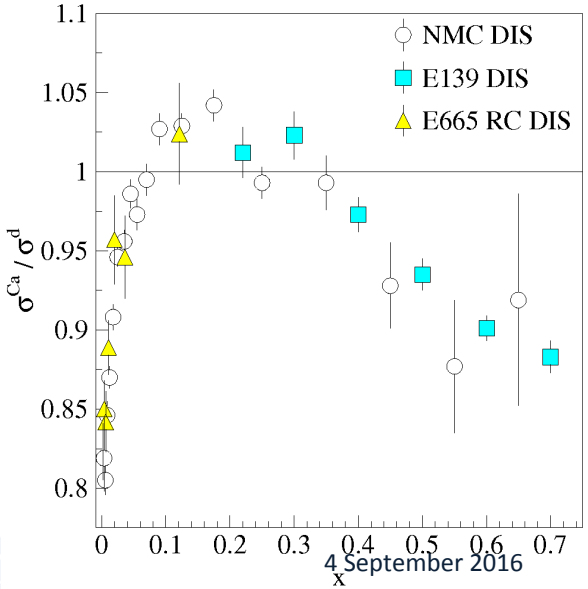
$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q \in \{u,d,\ldots\}} x\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

  - Neutrino DIS data?
    - Old H_2 bubble chamber data OK
    - Modern experiments use iron target
    - Magnitude of Sea Quark distributions dominated by neutrino data

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

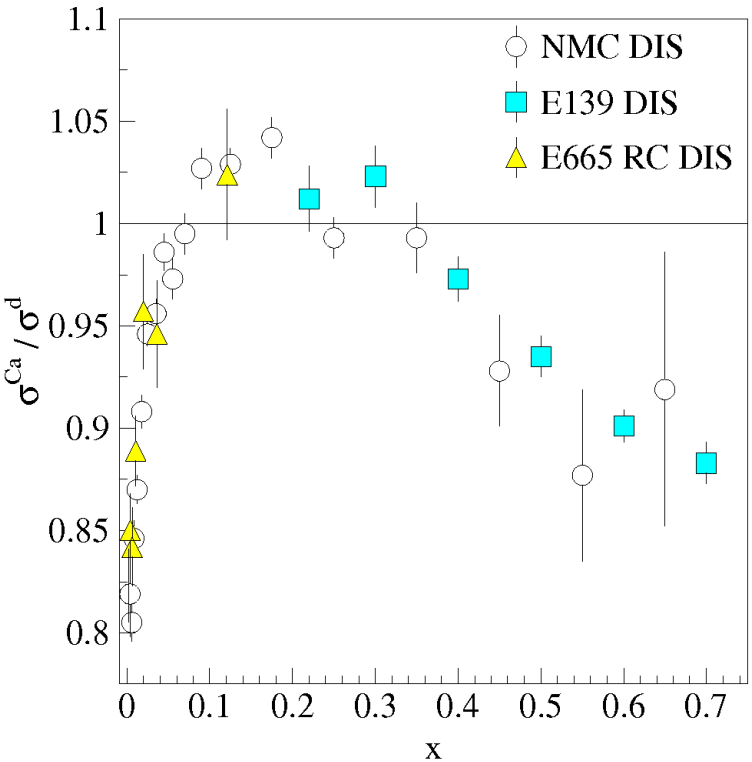
- Parameterize measurements?

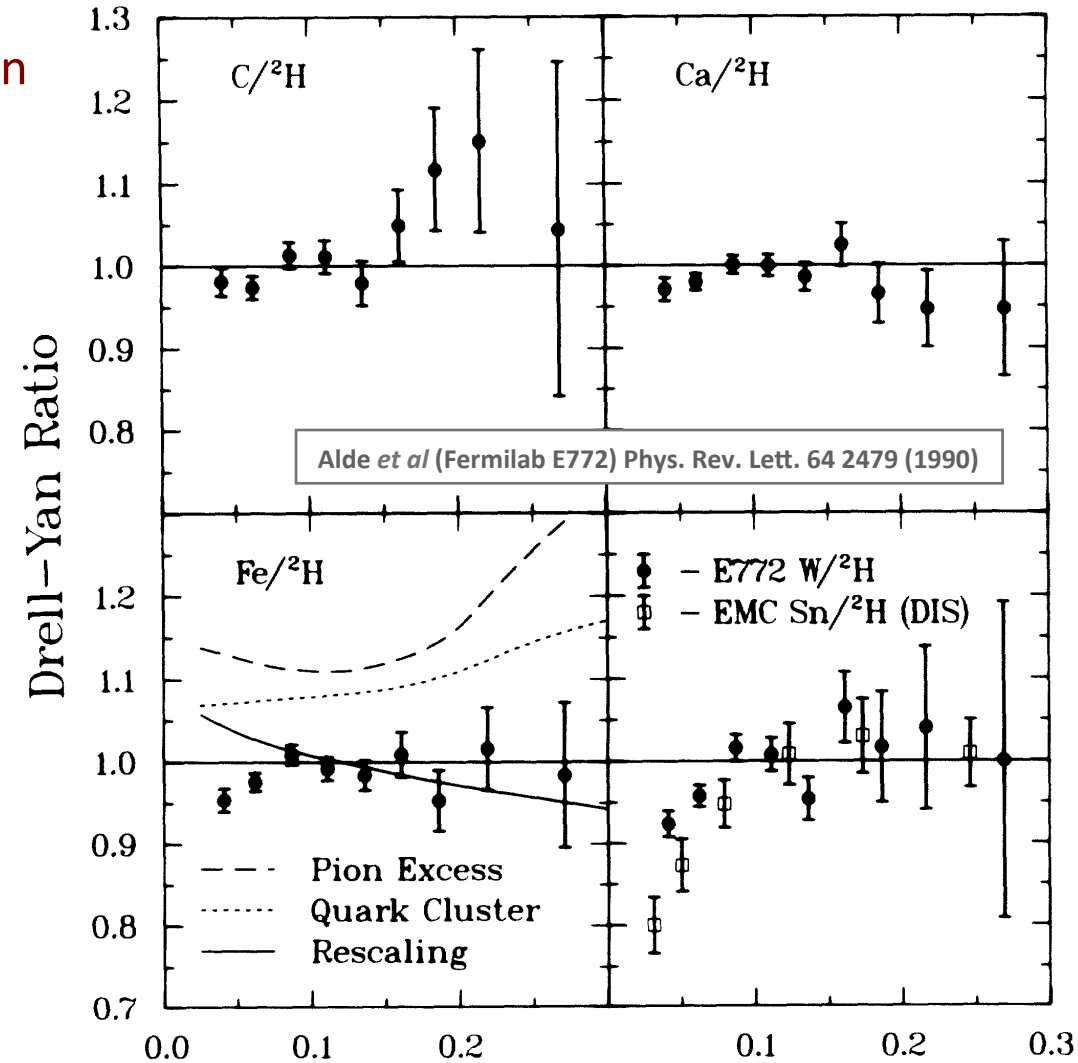
  K. J. Eskola, V. J. Kolhinen, and P. V. Ruuskanen, Nucl. Phys. B535, 351 (1998);



Structure of nucleonic matter: How do DIS and Drell-Yan data compare?

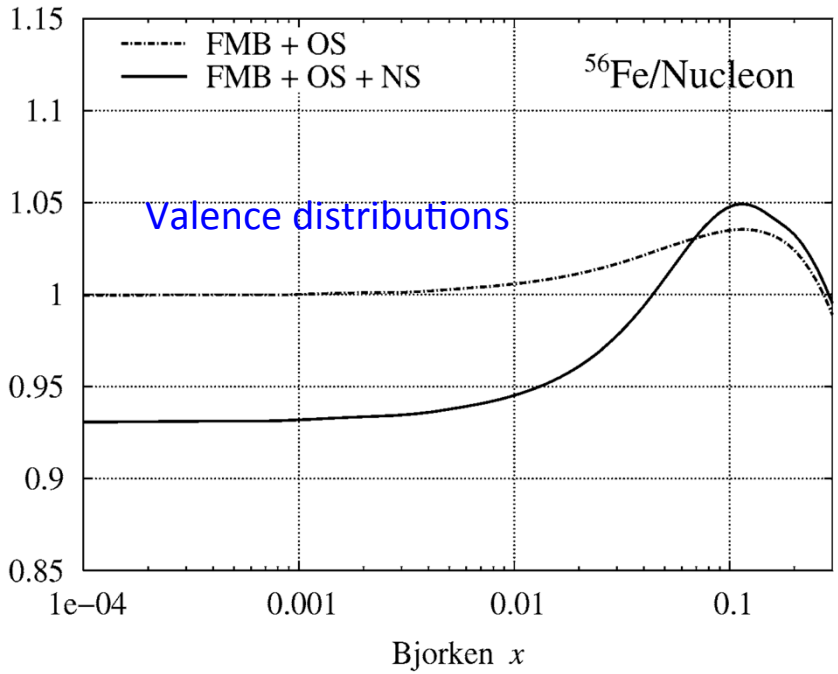
- Shadowing present in Drell-Yan
- Antishadowing not seen in Drell-Yan
  —Valence only effect

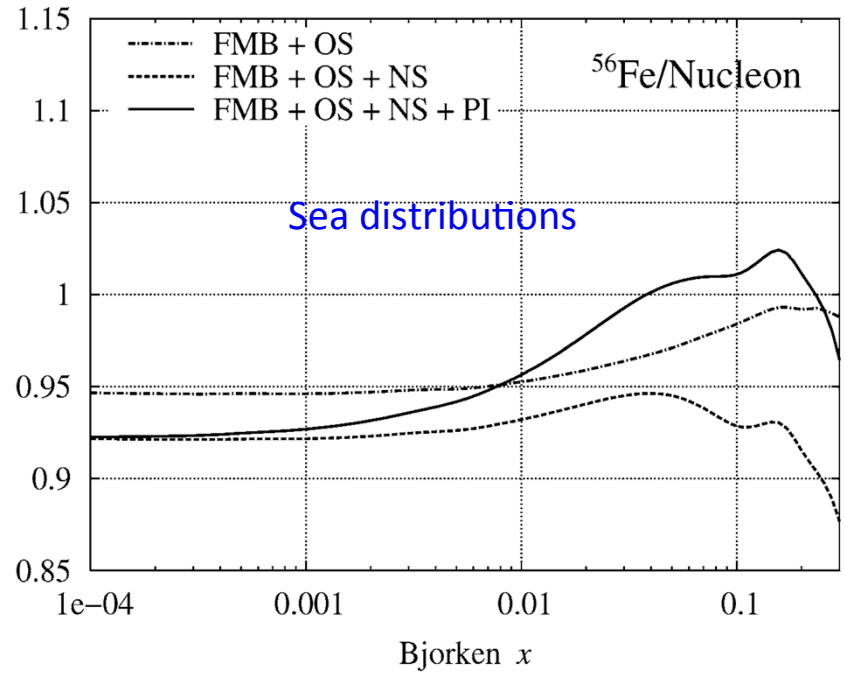




Alde *et al* (Fermilab E772) Phys. Rev. Lett. 64 2479 (1990)

Kulagin and Petti sea vs. valence nuclear effects



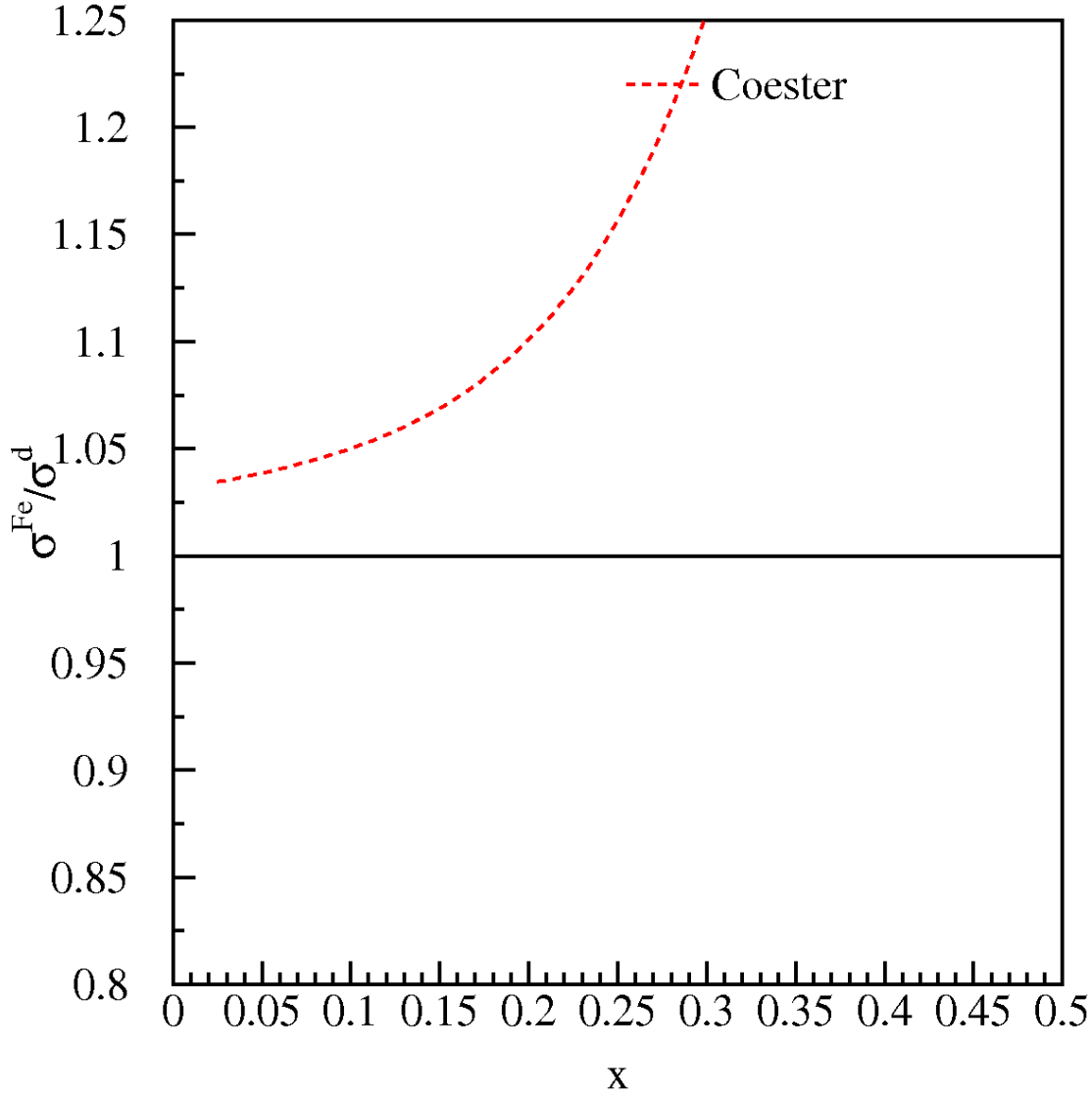


Nuclear Physics A 765 (2006) 126–187

FMB—Fermi Motion and Nuclear Binding
OS—Off shell effects
NS—nuclear shadowing
PI—nuclear pions

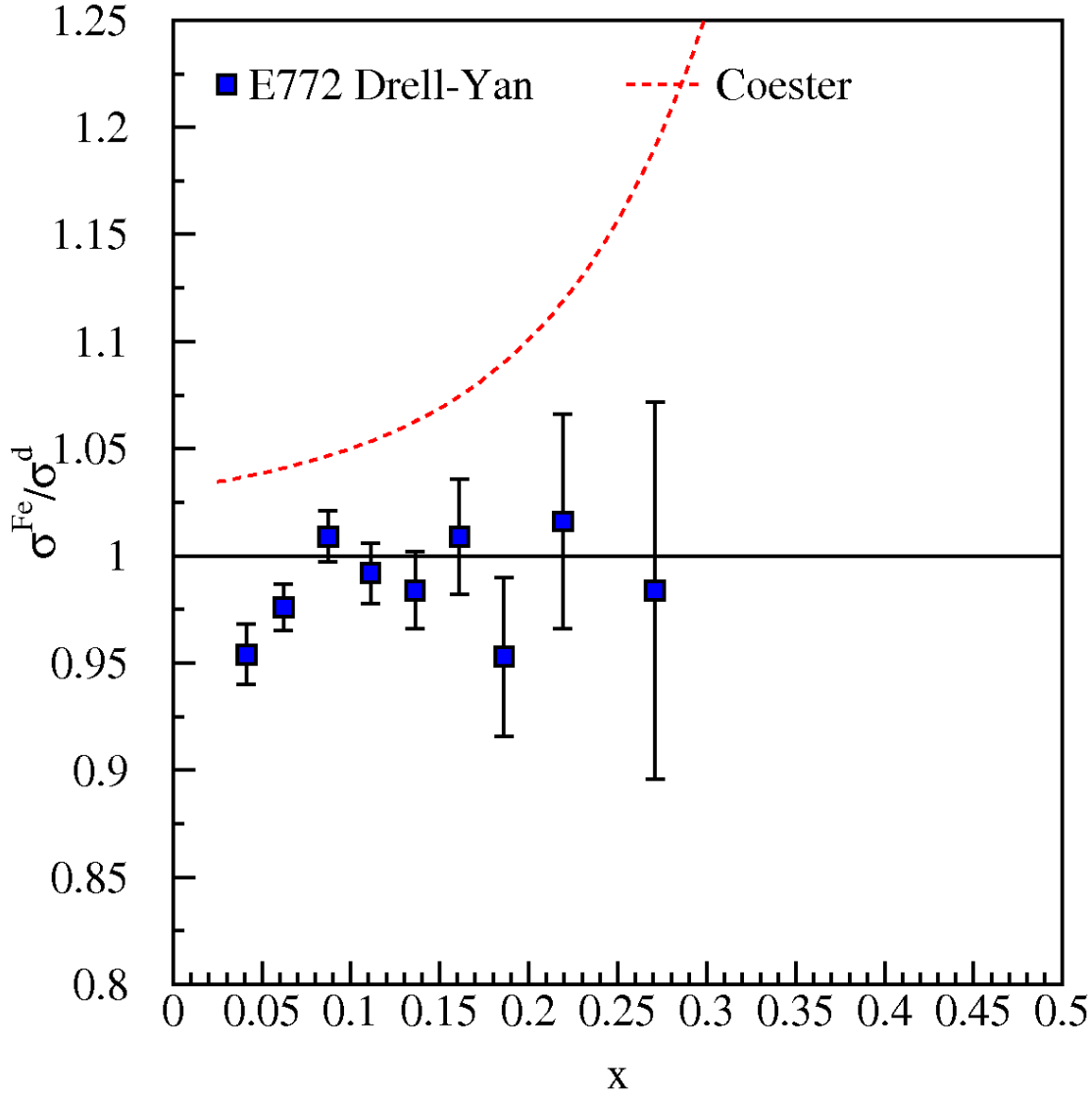
Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.



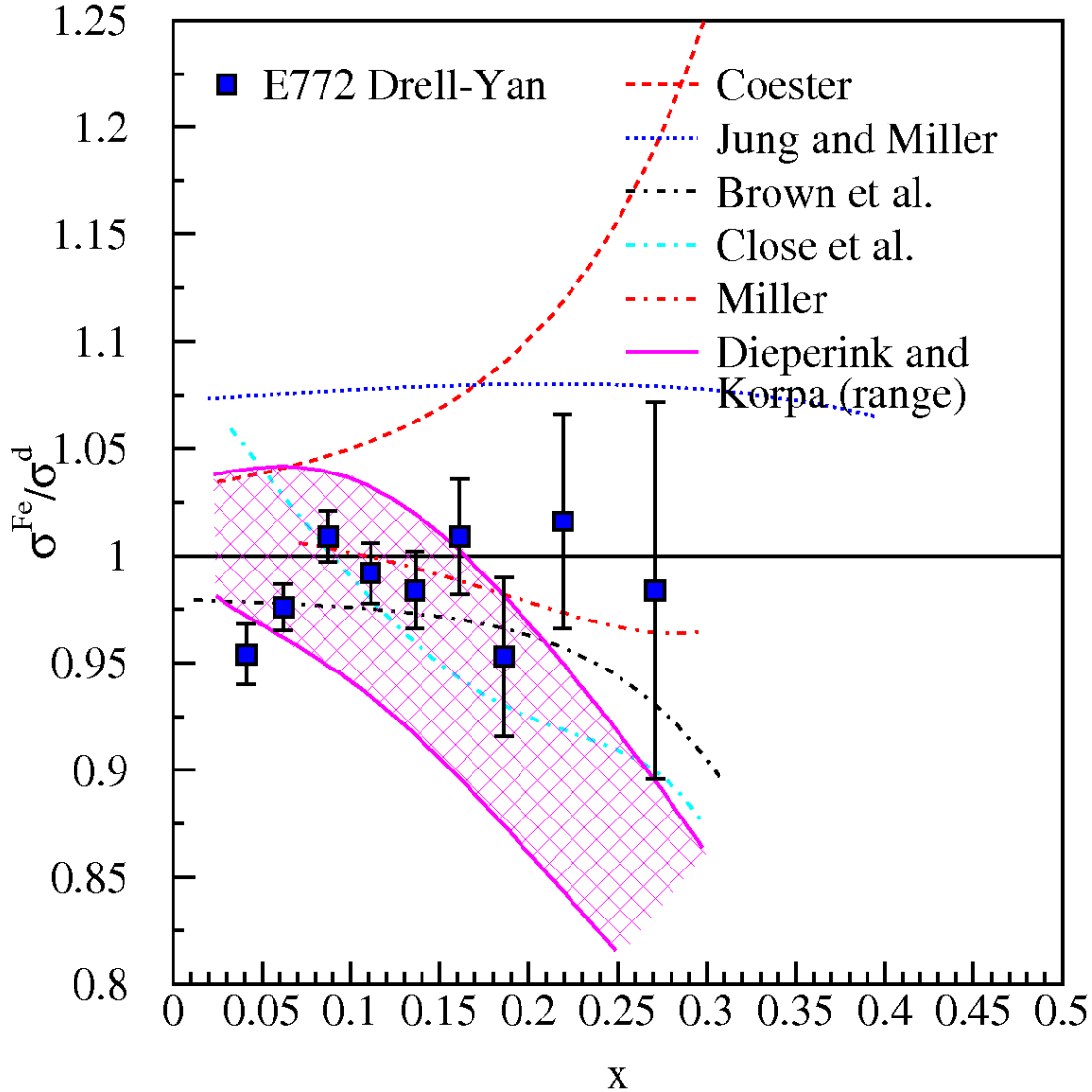
Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.



Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- **Models must explain both DIS-EMC effect and Drell-Yan**



Fermilab E906/SeaQuest Collaboration

Abilene Christian University
Ryan Castillo, Michael Daugherity, 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
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KEK
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Christine Aidala, McKenzie Barber, Catherine Culkin, Vera Loggins, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh Rubin, Matt Wood

National Kaohsiung Normal University
Rurngsheng Guo

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

Fermilab 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
University of New Hampshire
National Kaohsiung Normal University
RIKEN
Rutgers University
Thomas Jefferson National Accelerator Facility
Tokyo Tech
University of Virginia

Andi Klein and Xiaodong Jiang
Co-Spokespersons

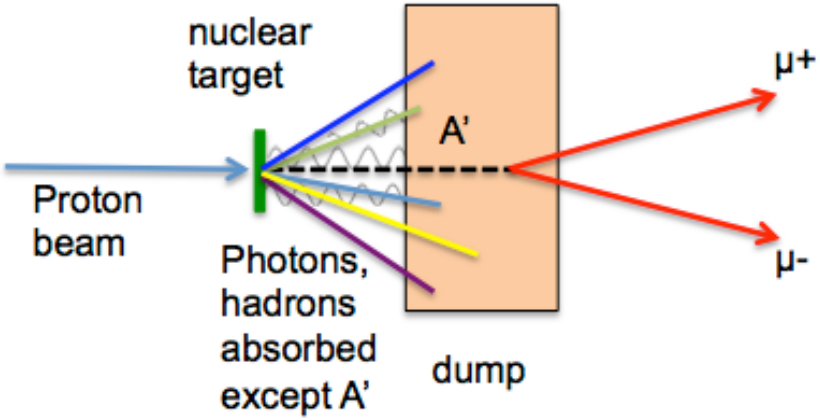
Polarized Beam:

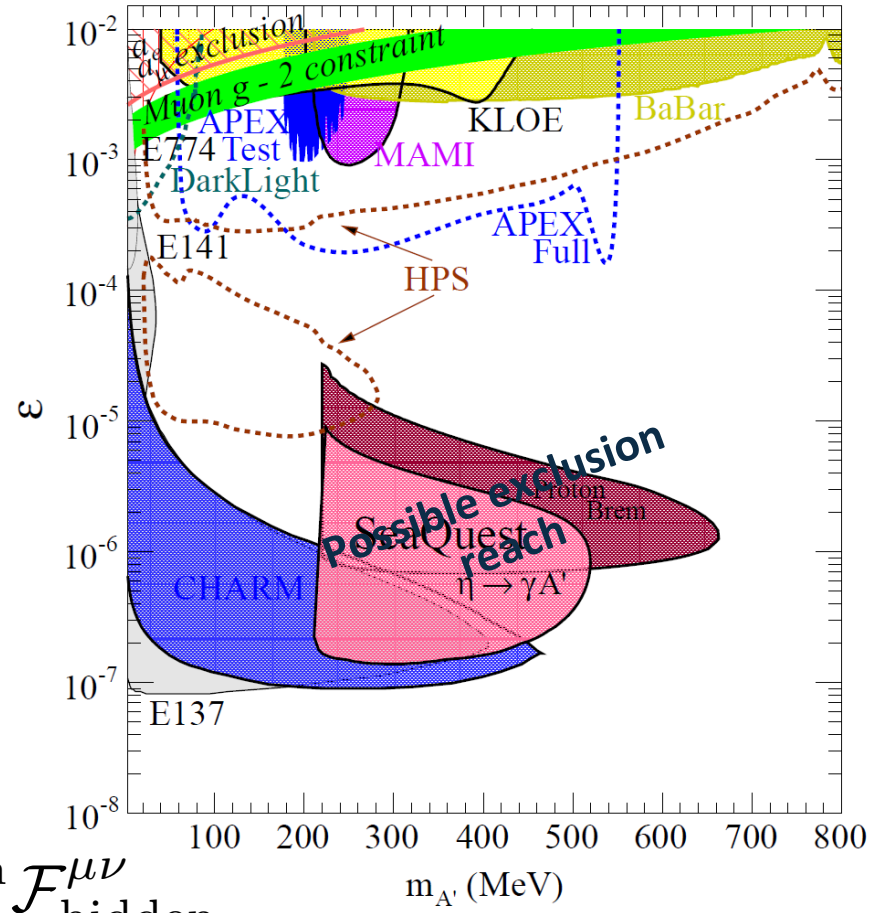
Abilene Christian University
Argonne National Laboratory
University of Basque Country
University of Colorado
Fermi National Accelerator Laboratory
University of Illinois
KEK
Los Alamos National Laboratory
University of Maryland
University of Michigan
RIKEN
Rutgers
Tokyo Tech
Yamagata University

Wolfgang Lorenzon and Paul E Reimer
Co-Spokespersons

Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment

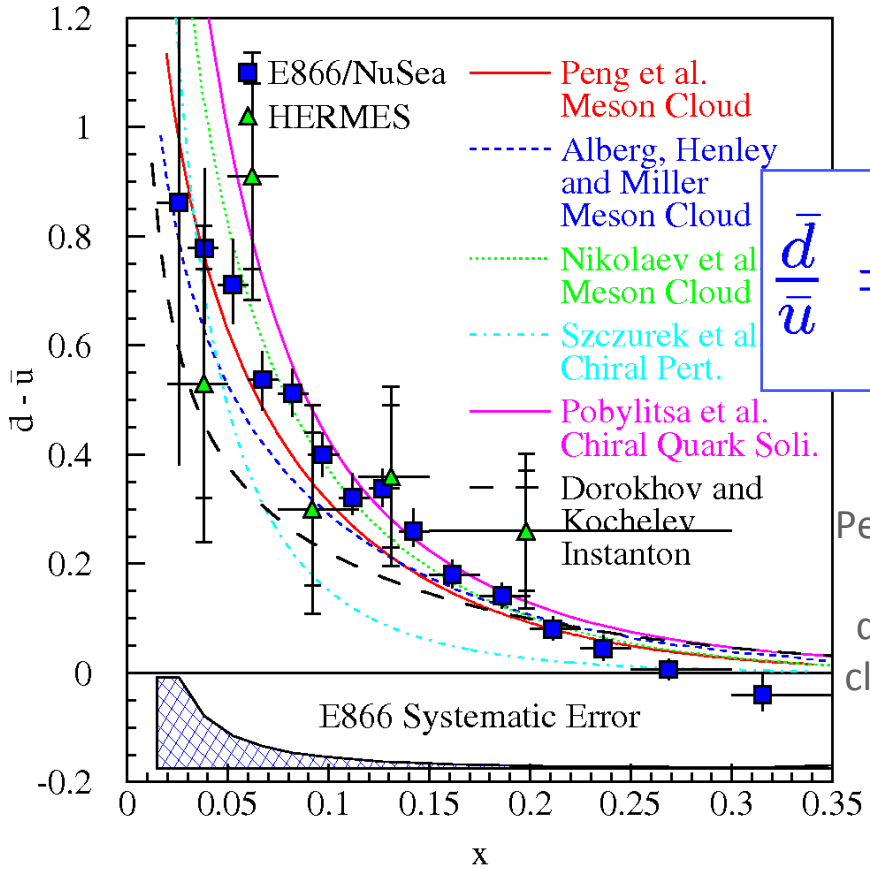




- Minimal impact on Drell-Yan program

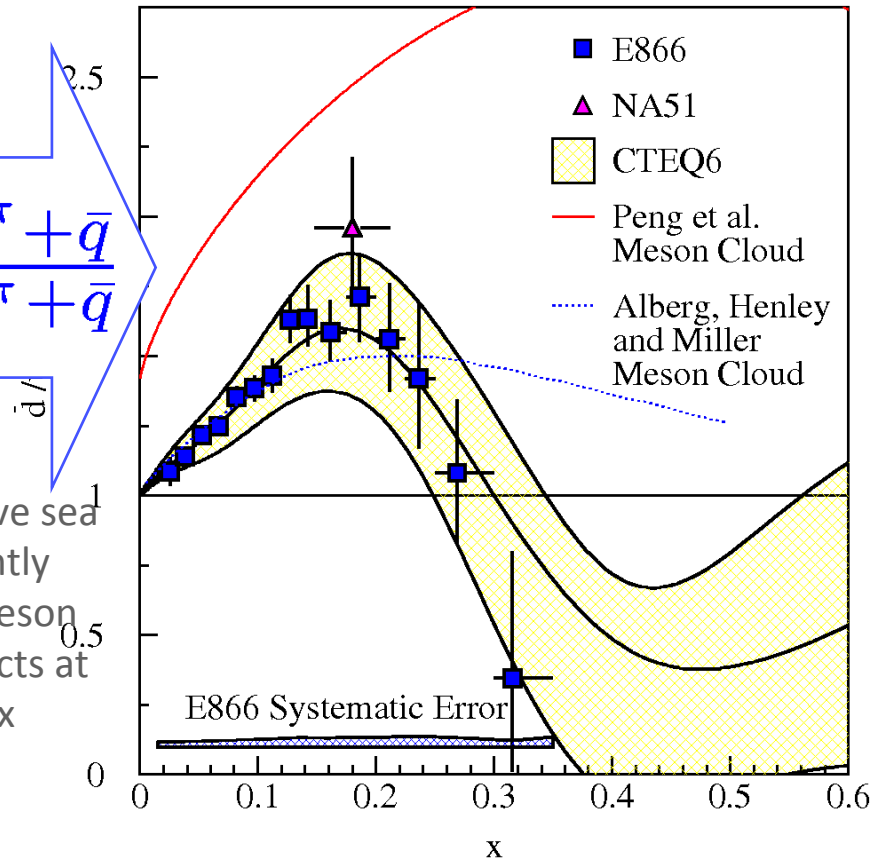
$$\mathcal{L} \propto -\frac{1}{4}\mathcal{F}^{\mathrm{SM}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\mathrm{SM}} - \frac{1}{4}\mathcal{F}^{\mathrm{hidden}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\mathrm{hidden}} + \frac{1}{2}\epsilon\mathcal{F}^{\mathrm{SM}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\mathrm{hidden}} + m^2_{A'}A^{\mathrm{hidden}}_{\mu}A^{\mu}_{\mathrm{hidden}}$$

Proton Structure: By What Process Is the Sea Created?



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

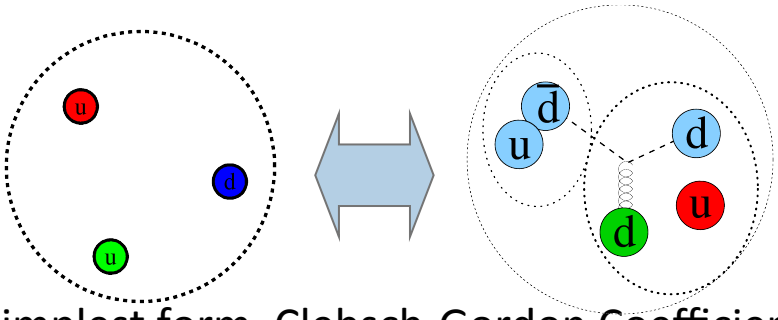
Perturbative sea apparently dilutes meson cloud effects at large-x



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, πΛ 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

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