Reaching for higher x_{Bj} structure with Drell-Yan interactions at Fermilab

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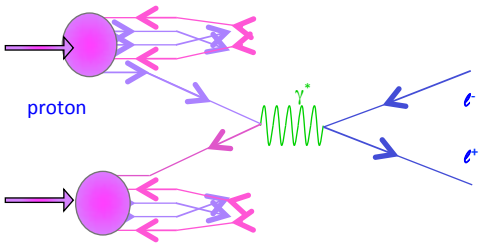
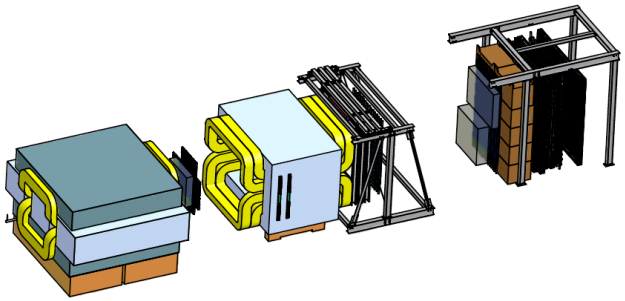
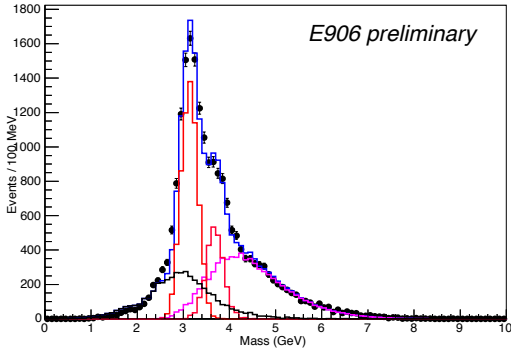
20 November 2014

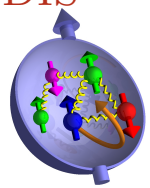




I. Tool: Drell-Yan interaction
II. Uses for the tool
III. Progress with SeaQuest at Fermilab
IV. Polarized Drell-Yan at Fermilab

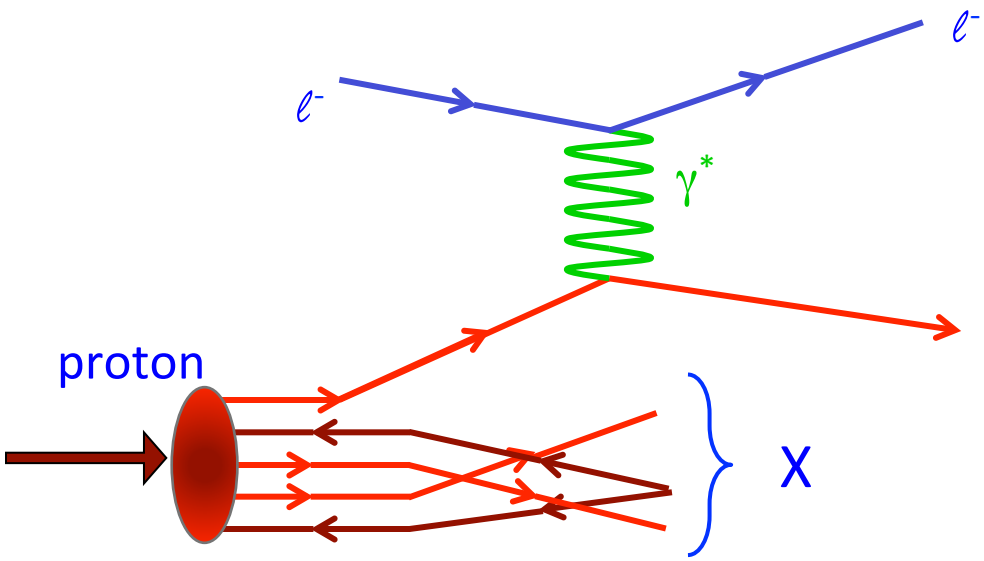


$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$



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

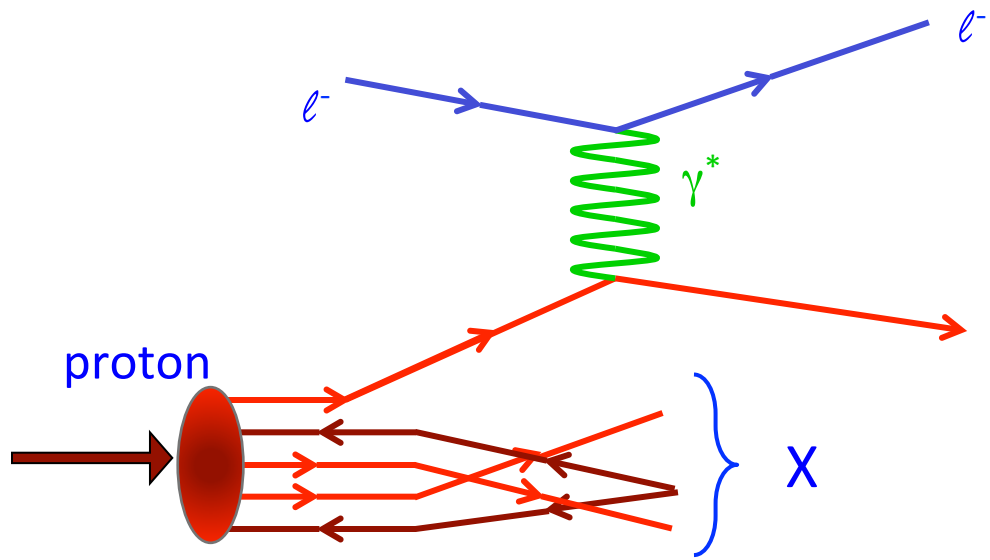
Probes of proton structure



Deep Inelastic Scattering

- Archetype probe of proton structure
  - Relatively simple to measure and
  - Relatively easy to calculate
  - Charge-weighted flavor sensitivity
  - No quark-antiquark selectively
    - SIDIS & fragmentation functions

Probes of proton structure



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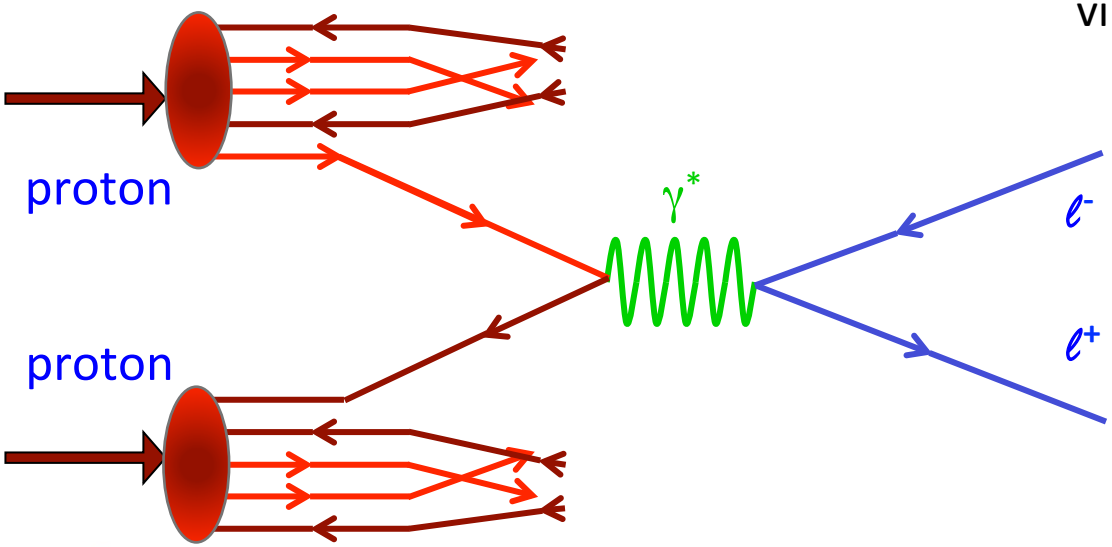
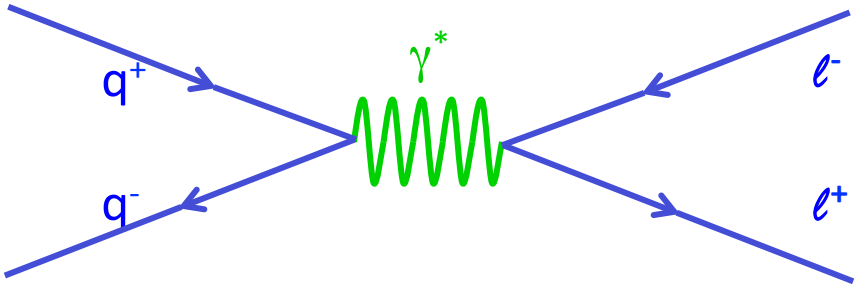
Drell-Yan interaction

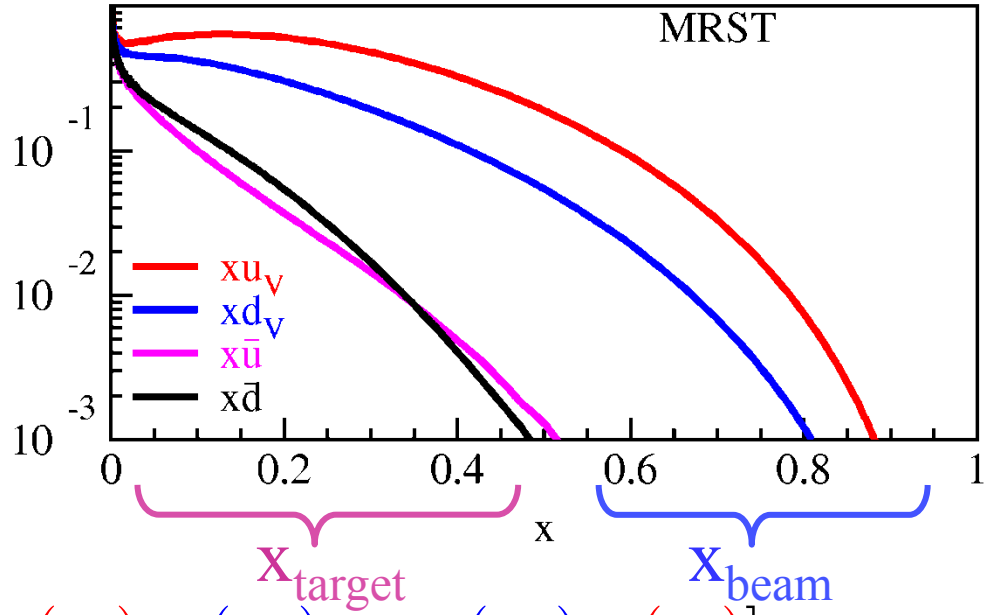
- Timelike (Drell-Yan) vs. spacelike (DIS) virtual photon.



- Hadron beam and convolution of parton distributions (Drell-Yan)
- Requires antiquark
- No Strong Final State Interactions

Drell-Yan Cross Section





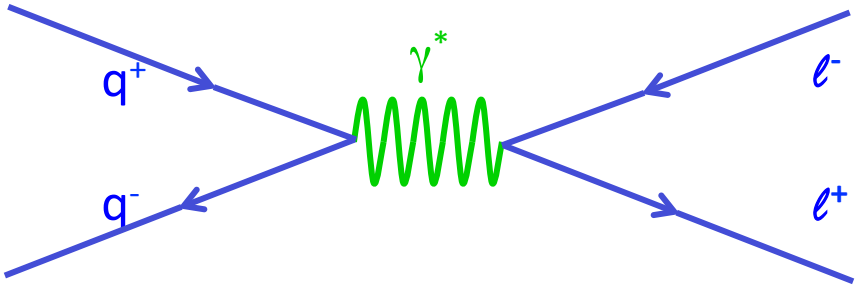
- Cross section is a convolution of beam and target parton distributions

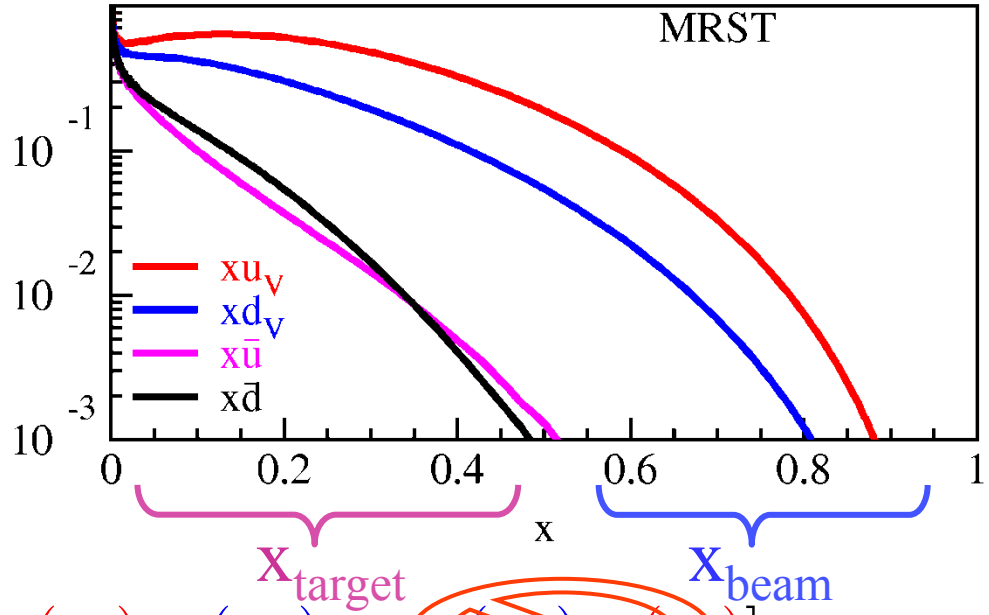
$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

- u-quark dominance

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

Drell-Yan Cross Section





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Acceptance limited
(Fixed Target)

- 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	GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	COMPASS

Drell-Yan Cross Section
Not quite that simple

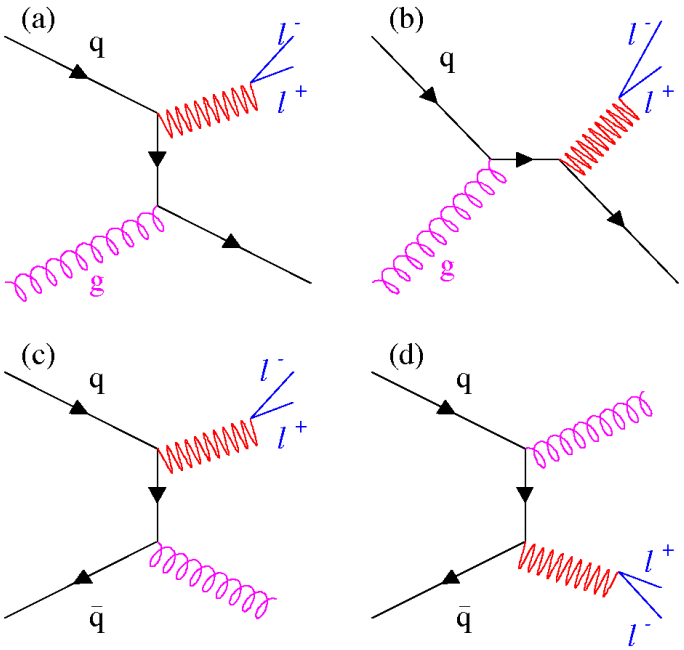
Guggenheim, Bilbao, Spain

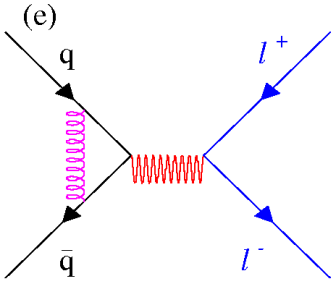
Drell-Yan Cross Section

- These diagrams are responsible for up to 50% of the measured cross section
- Intrinsic transverse momentum of quarks (although a small effect, λ > 0.8)
- Soft gluon resummation at all orders
- Angular Distributions

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

- Higher Twist





SeaQuest Physics Program (Unpolarized)

SeaQuarks of the target

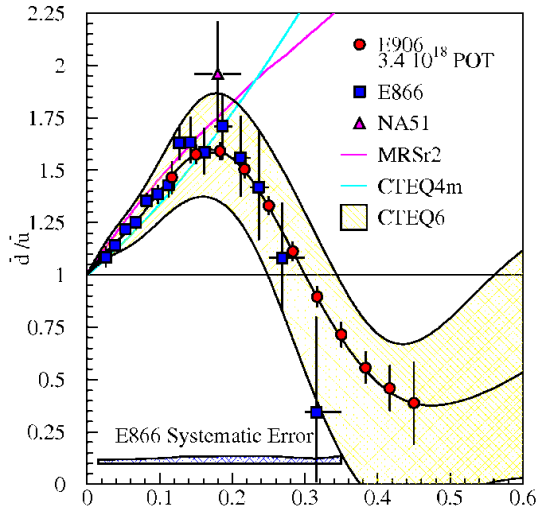
- dbar/ubar
- Sea quark EMC effect
- Quark sea absolute magnitude

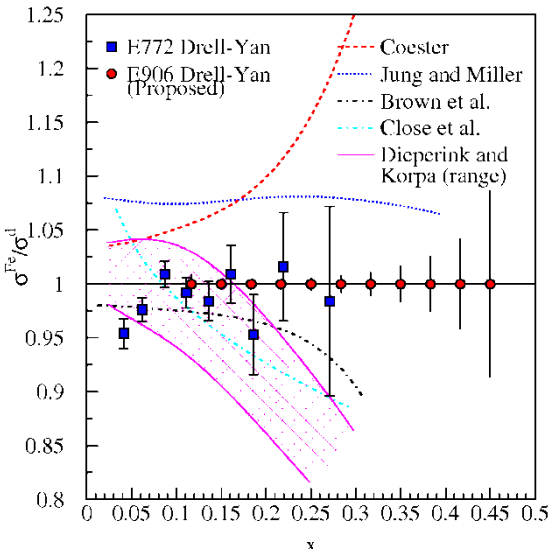
Large-x_{Bj} quarks of the beam

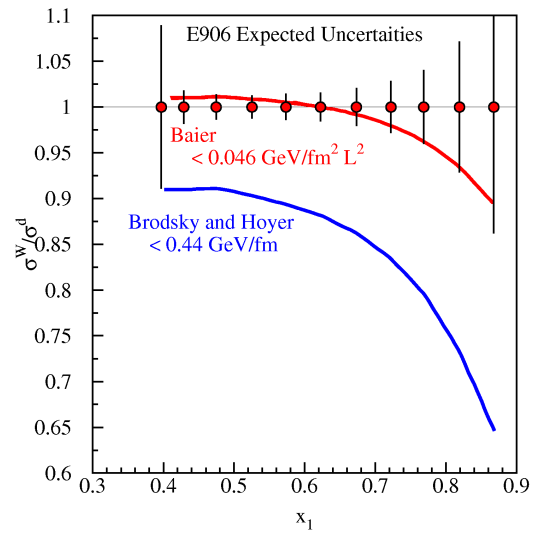
- Partonic Energy Loss

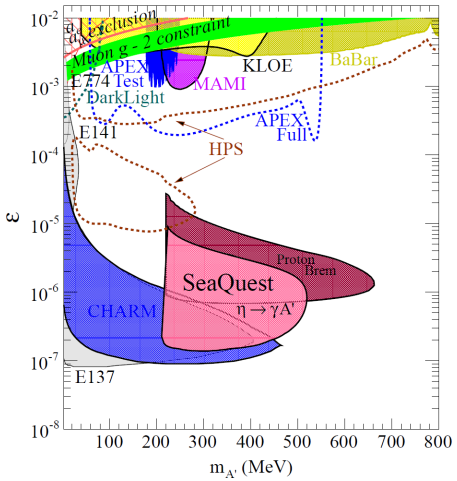
J/ψ Nuclear Dependence

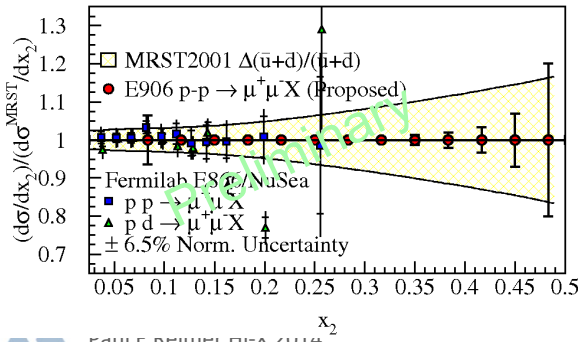
Dark Photons?



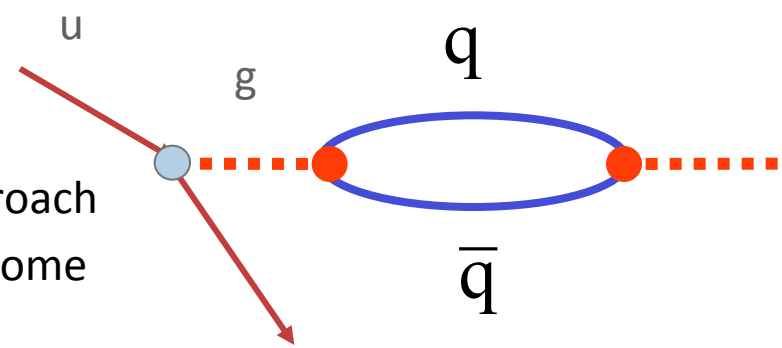






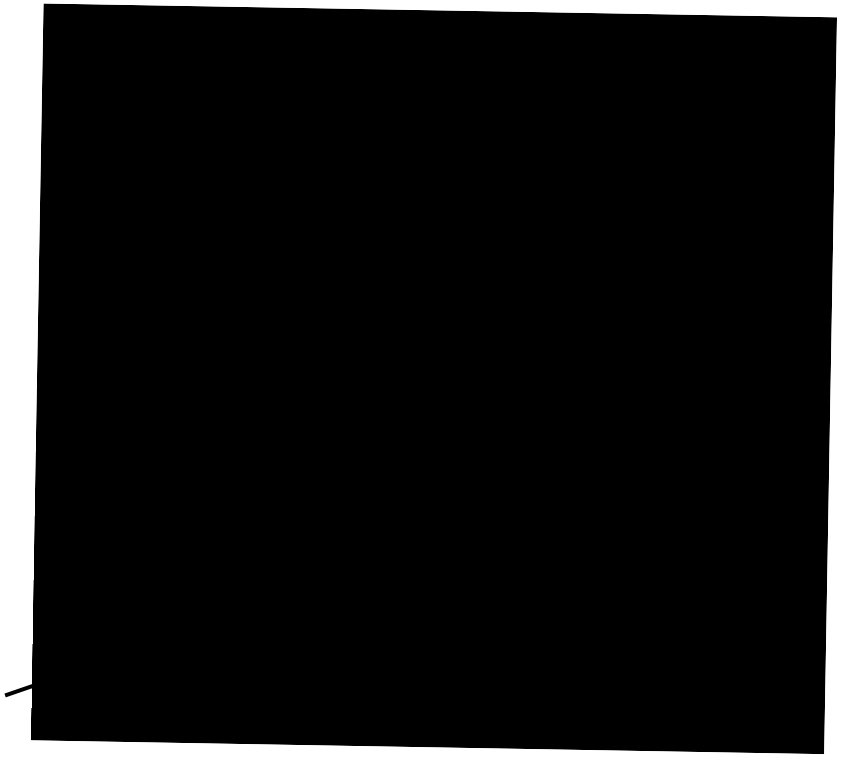


Simple view of parton distributions: A historic approach



- 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)

- It was quickly realized that some valence-like (primordial) sea was needed. Gluck, Reya, Vogt, ZPC 53, 127 (1992)
  - Driven by BCDMS and EMC data
  - Assumption of symmetric sea remained



Intrinsic light antiquark sea

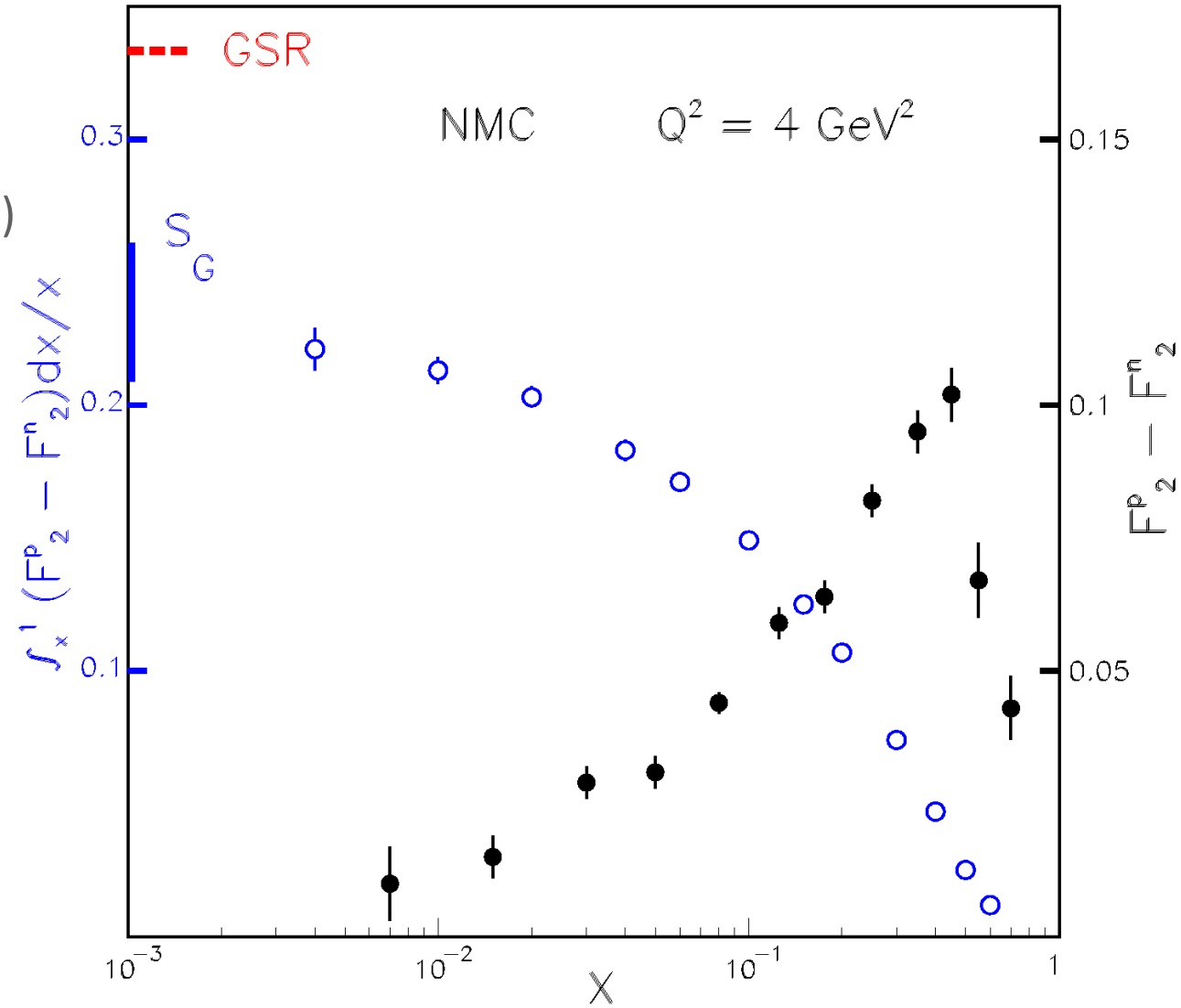
Light Antiquark Flavor Asymmetry: Brief History

- 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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- NA51 (Drell-Yan)

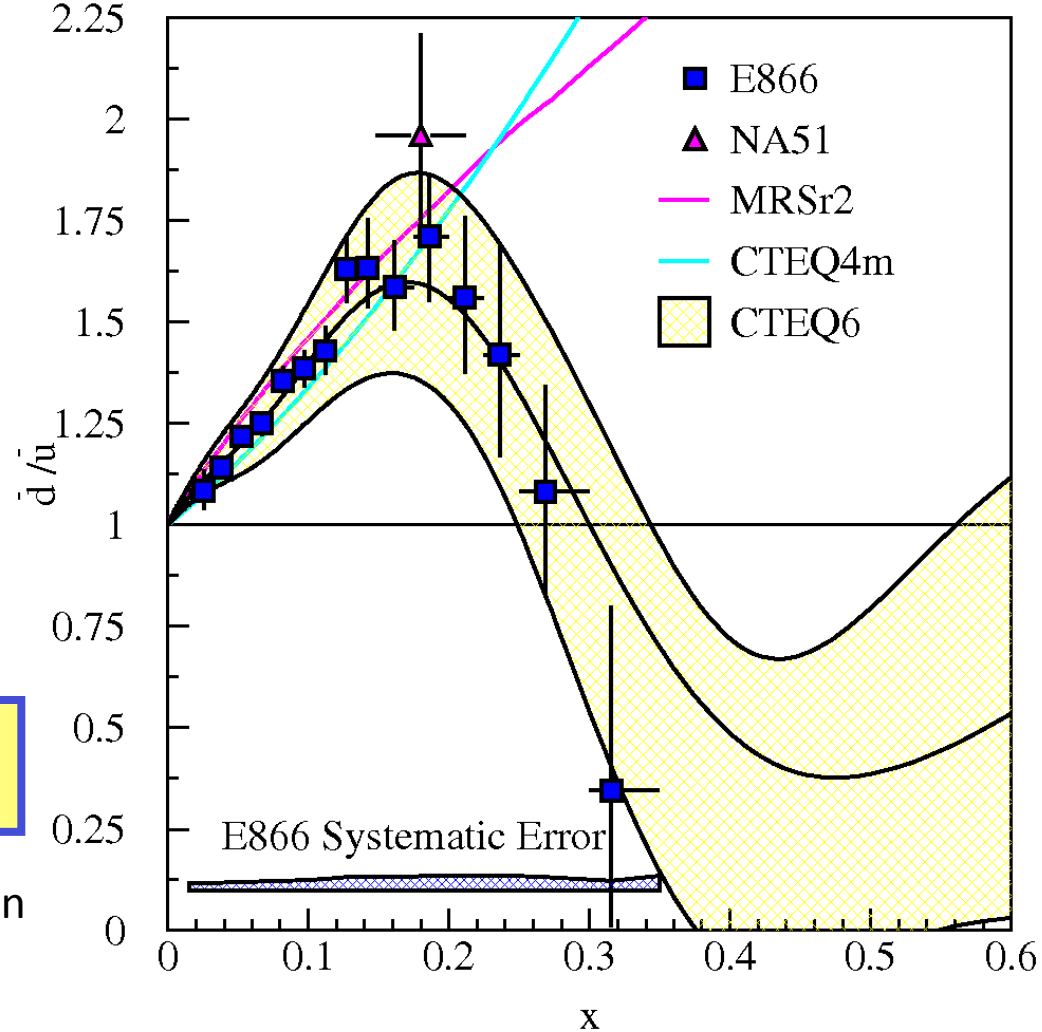
$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- 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

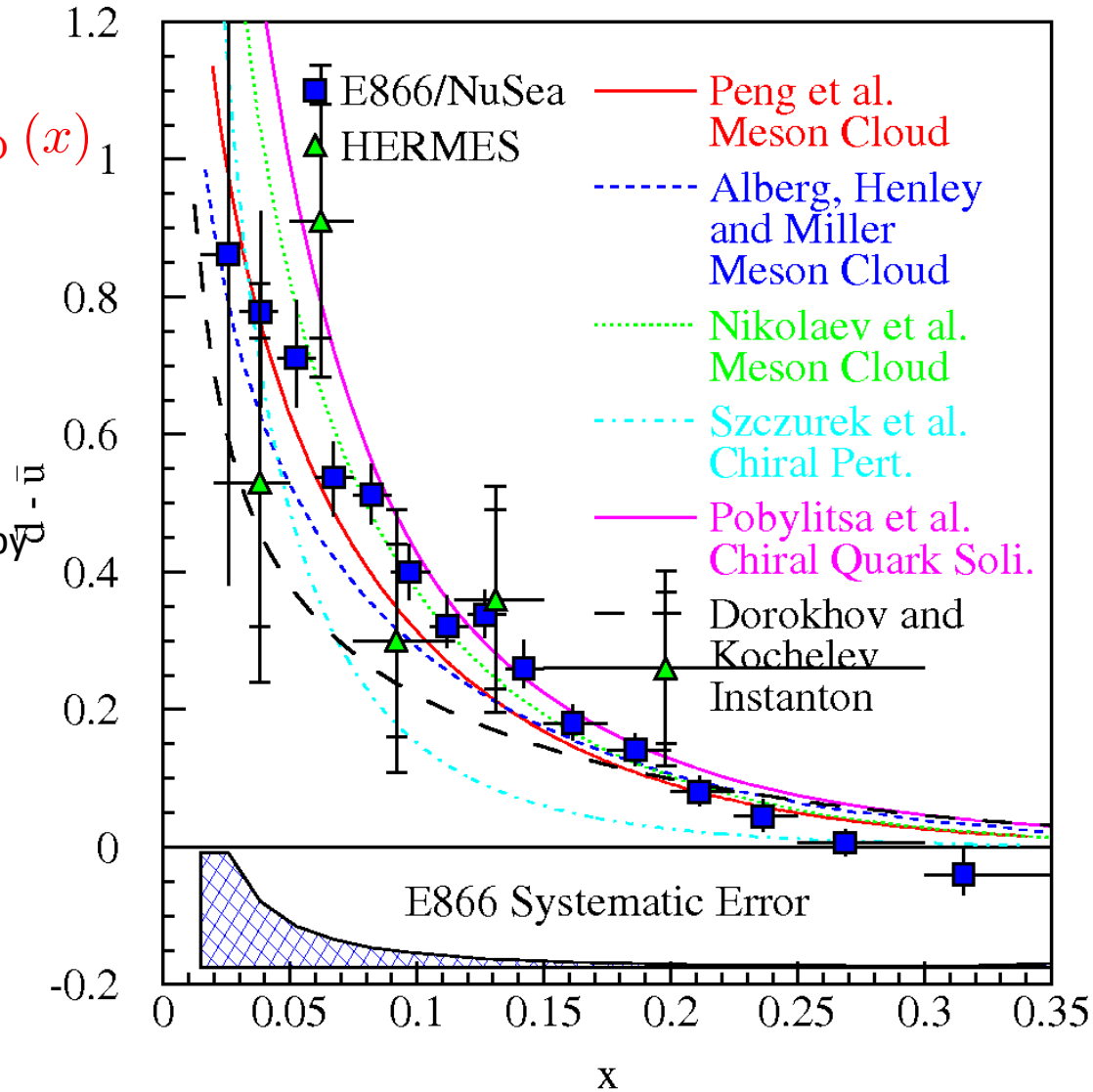


Proton Structure: By What Process Is the Sea Created?

- There is a gluon splitting component which is symmetric

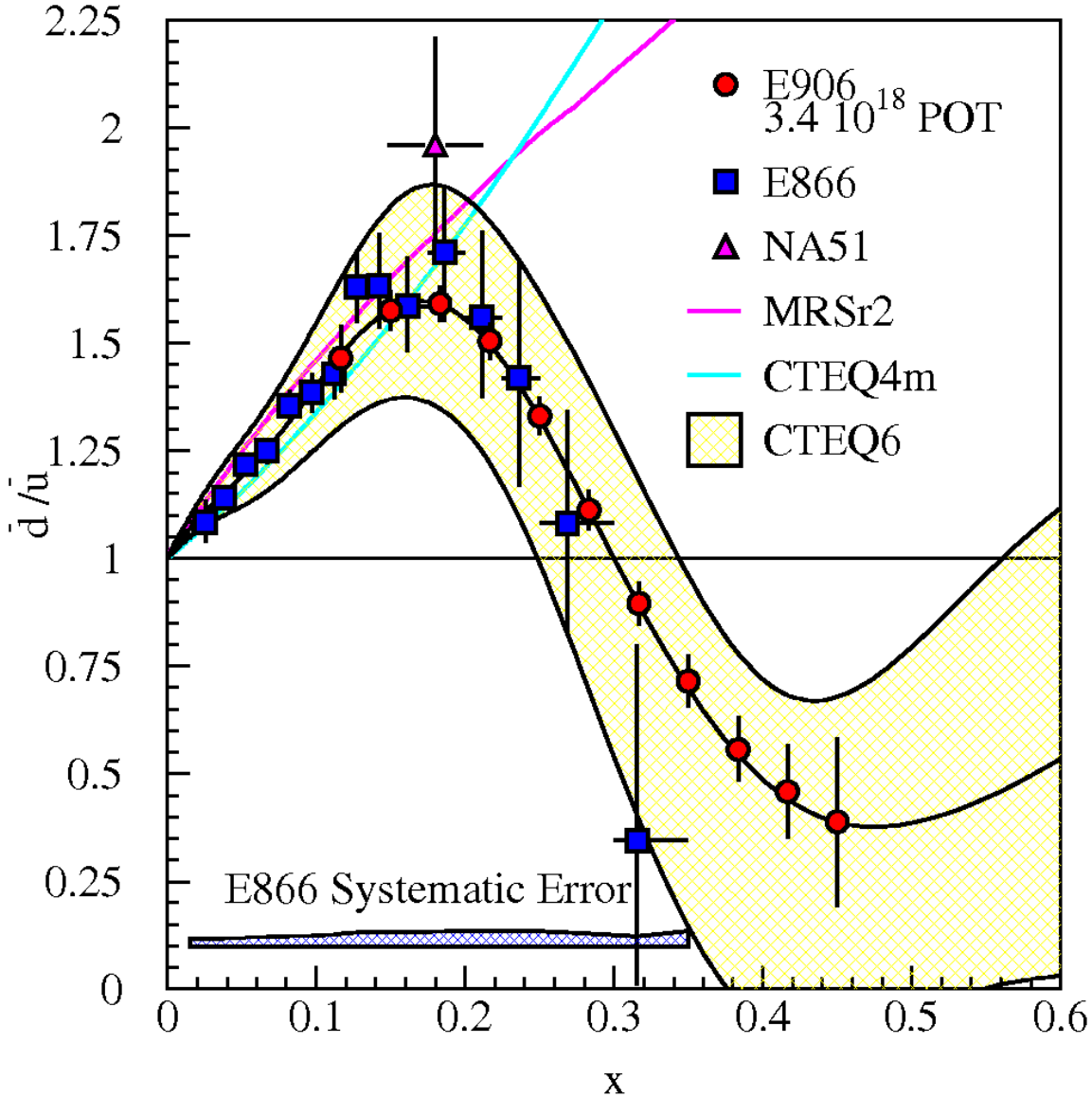
$$\bar{d}_{\mathrm{pQCD}}(x) \equiv \bar{u}_{\mathrm{pQCD}}(x) \equiv \bar{q}_{\mathrm{pQCD}}(x)$$

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



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

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



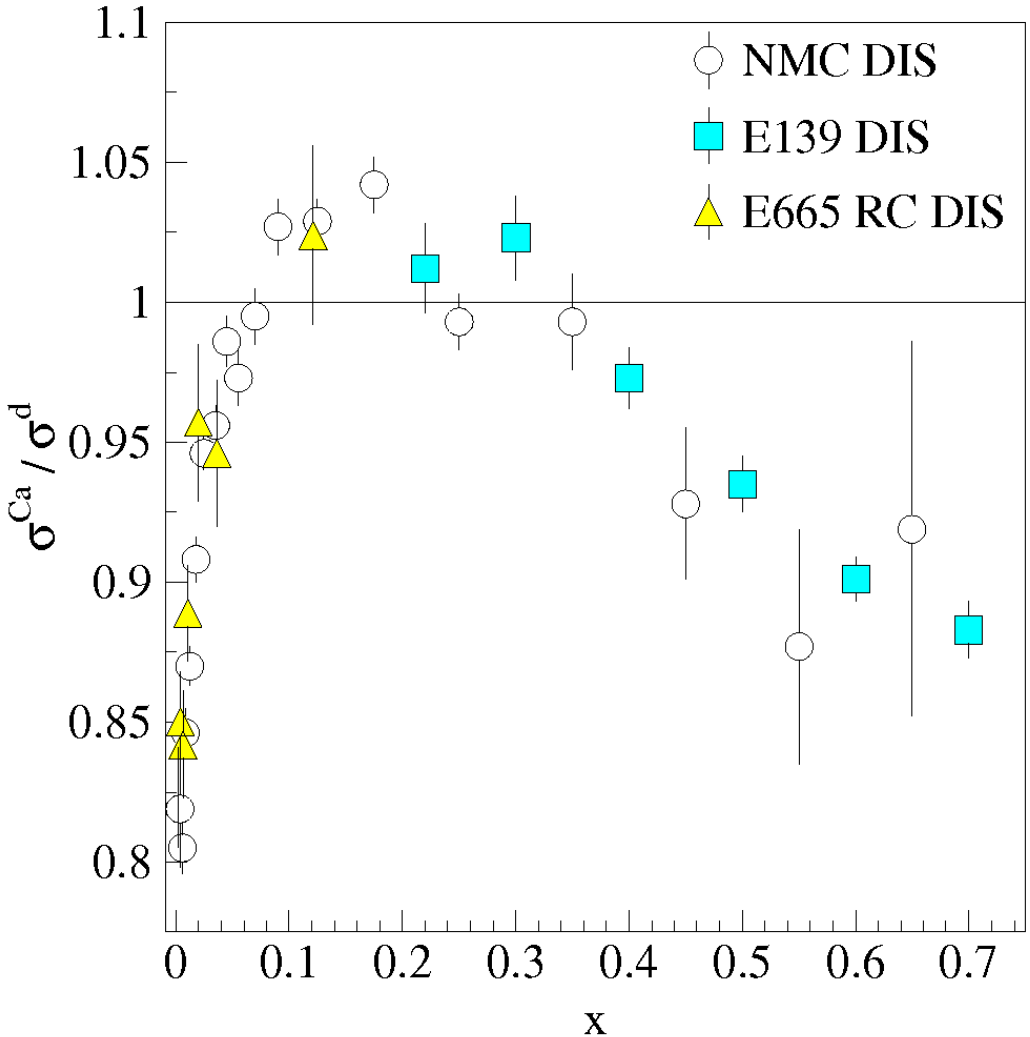
Sea Quark EMC Effect

Guggenheim, Bilbao, Spain

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

Comparison with
Deep Inelastic Scattering (DIS)

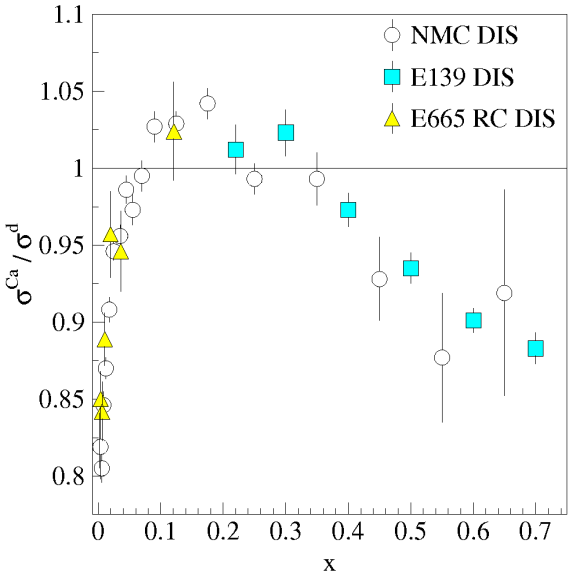
- EMC: Parton distributions of bound and free nucleons are different.

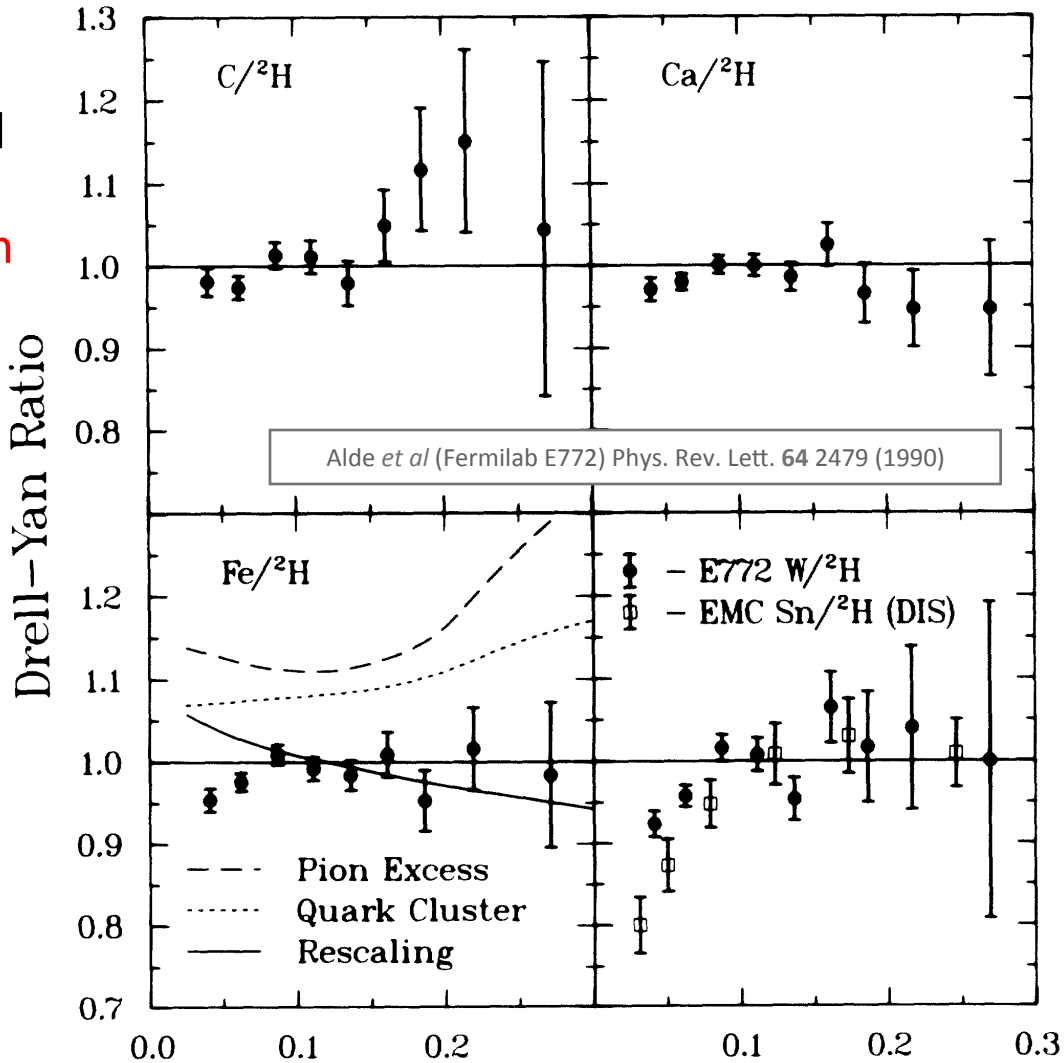


Structure of nucleonic matter: How do sea quark distributions differ in a nucleus?

Comparison with
Deep Inelastic Scattering (DIS)

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

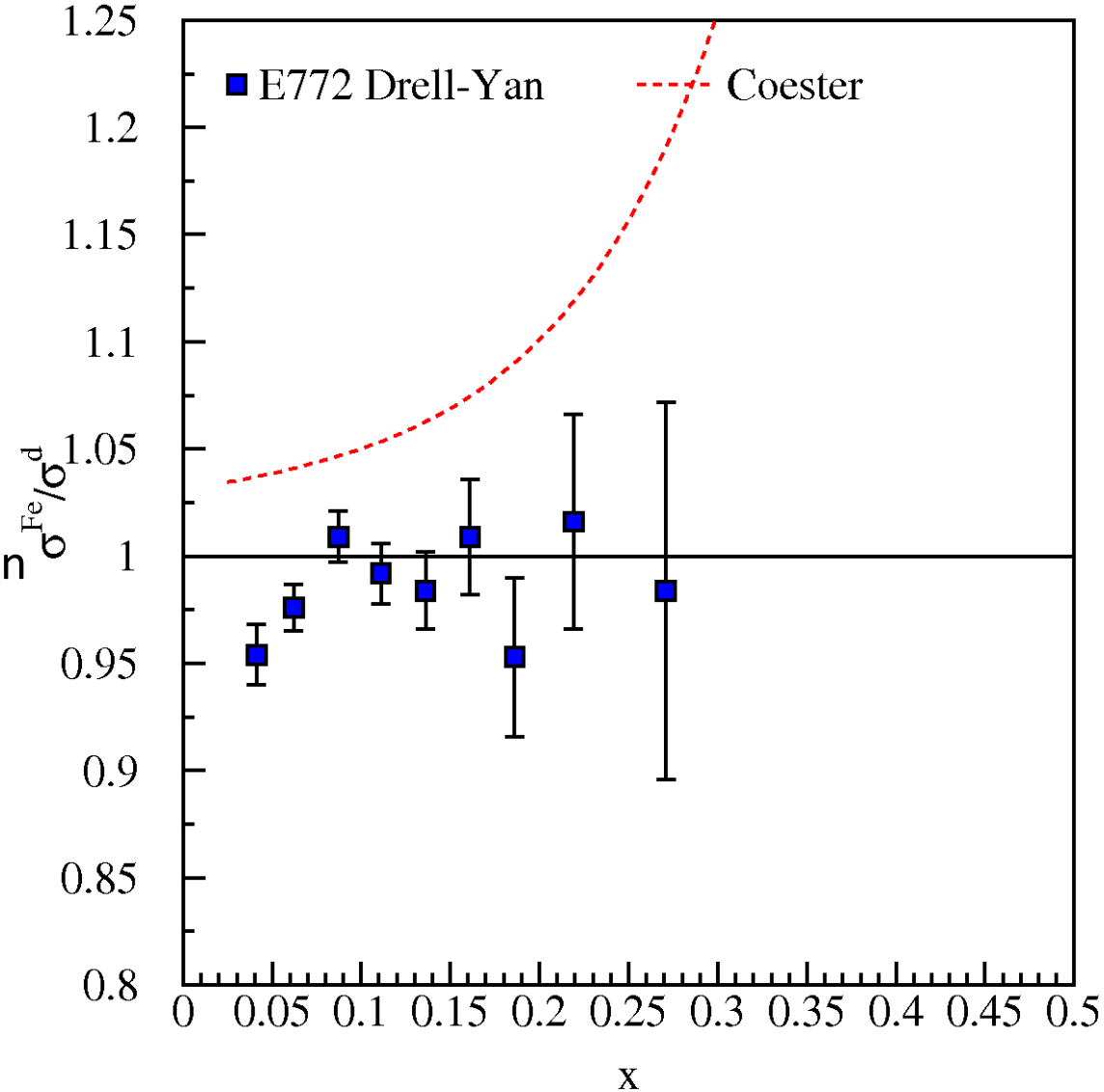




Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

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.



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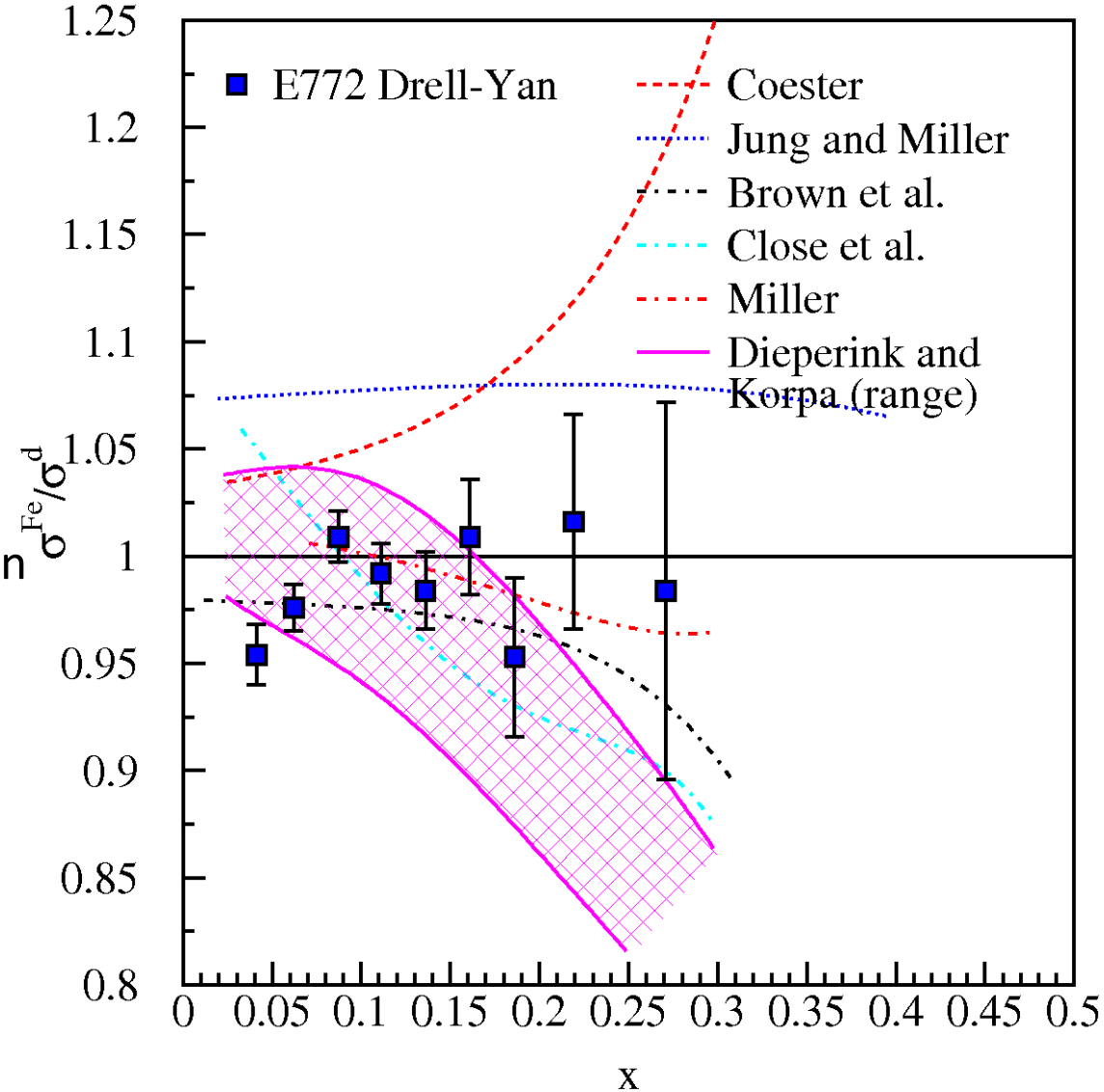
- Models must explain both DIS-EMC effect and Drell-Yan



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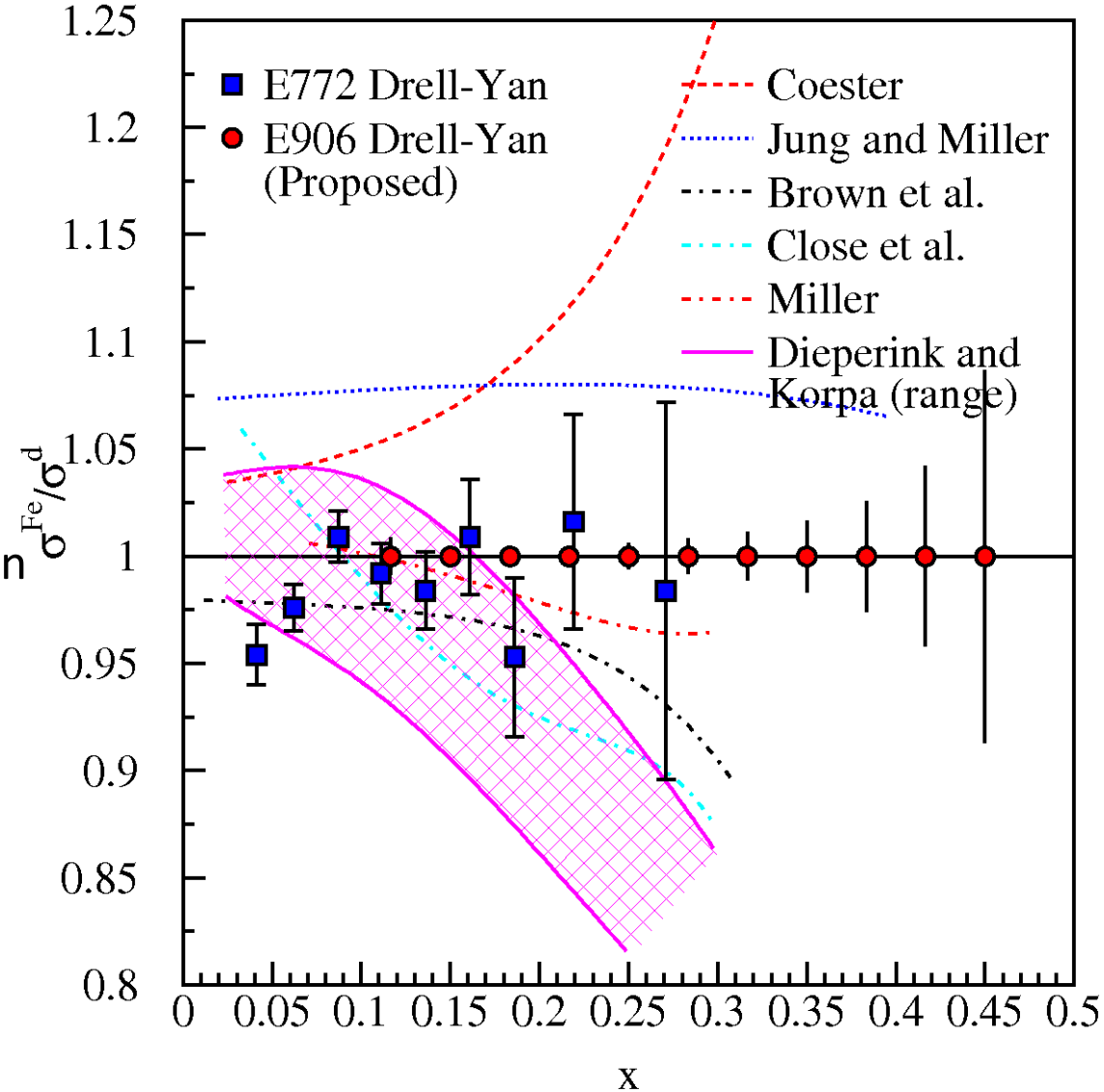
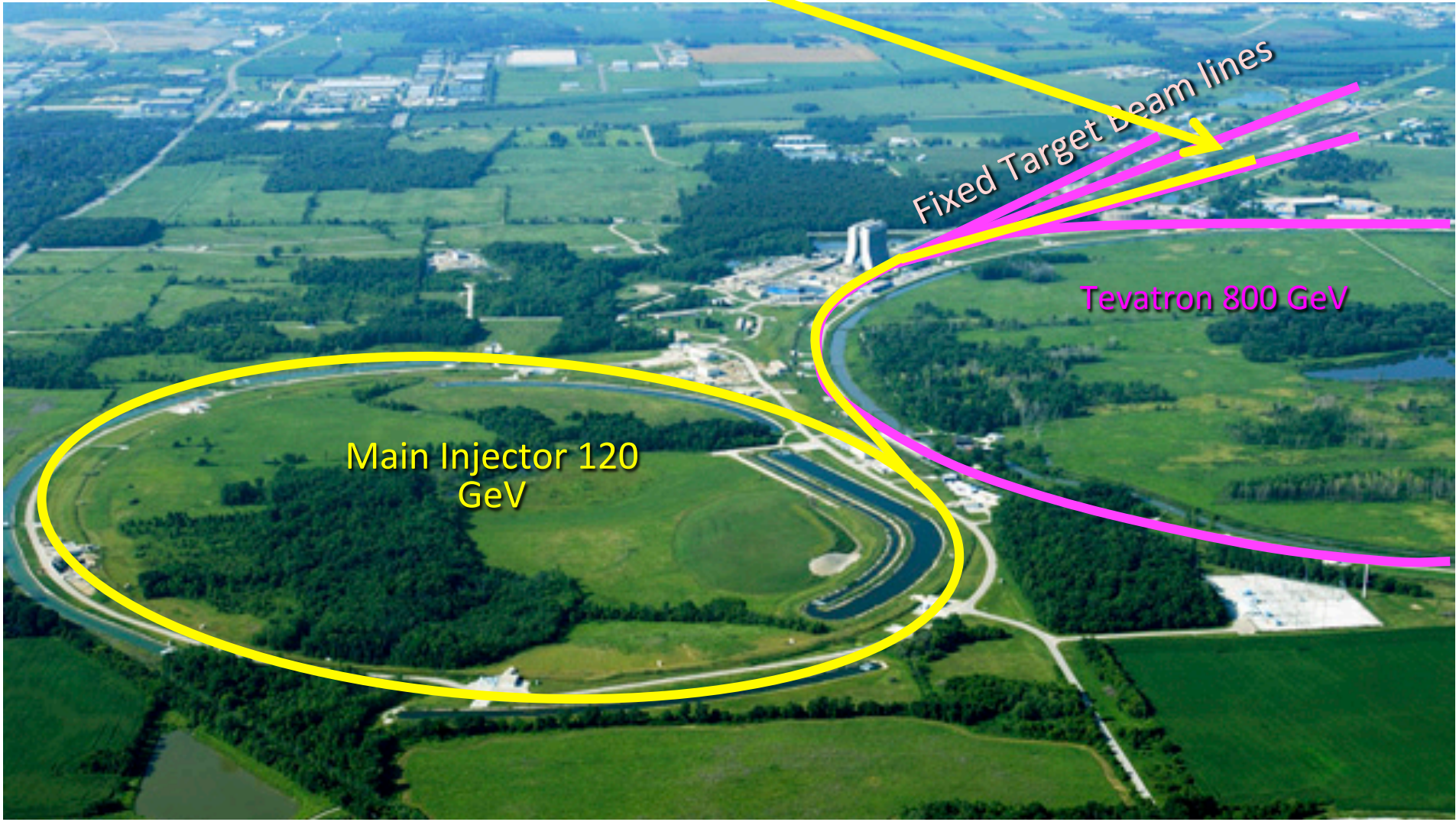
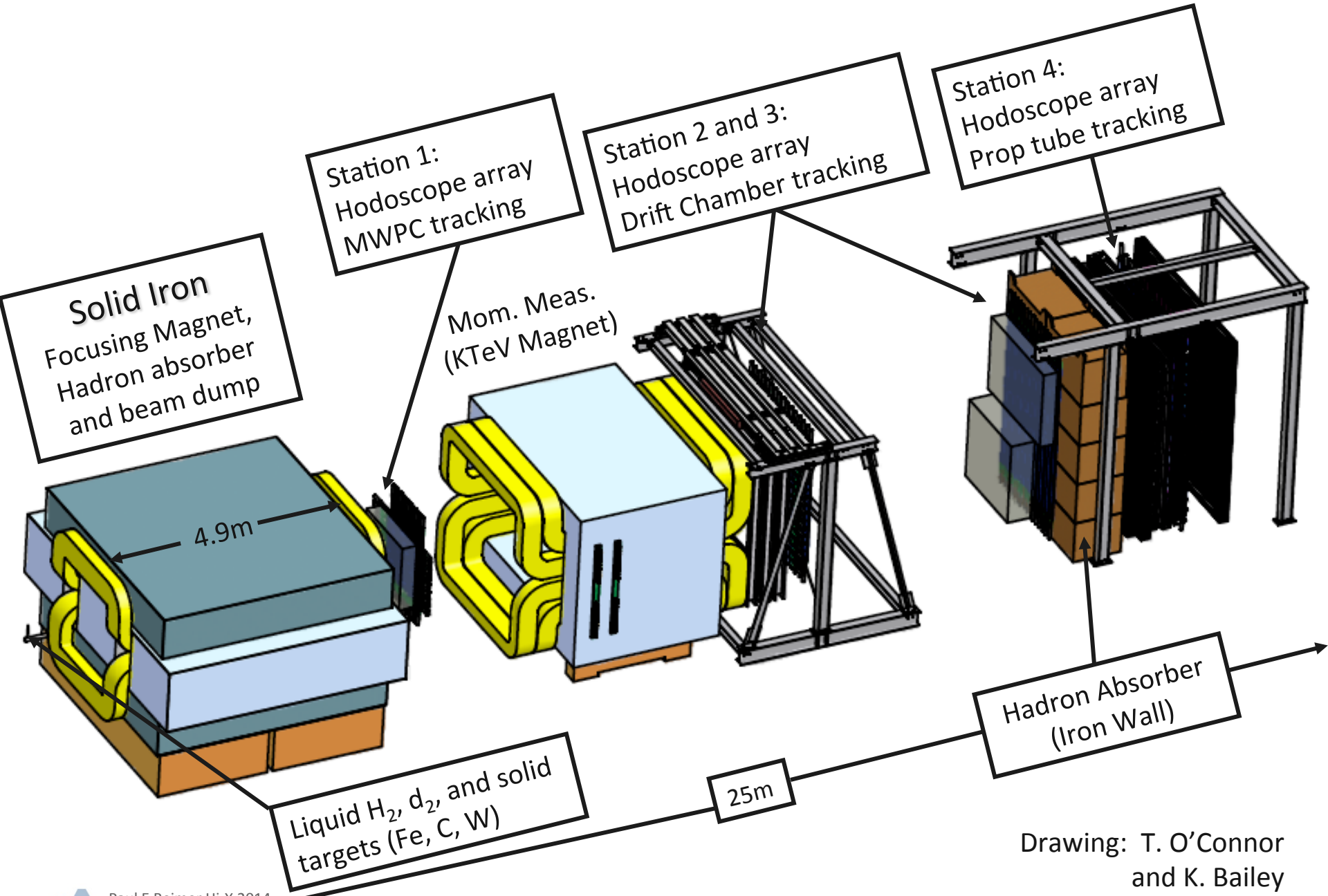


SeaQuest Experiment





Drawing: T. O'Connor
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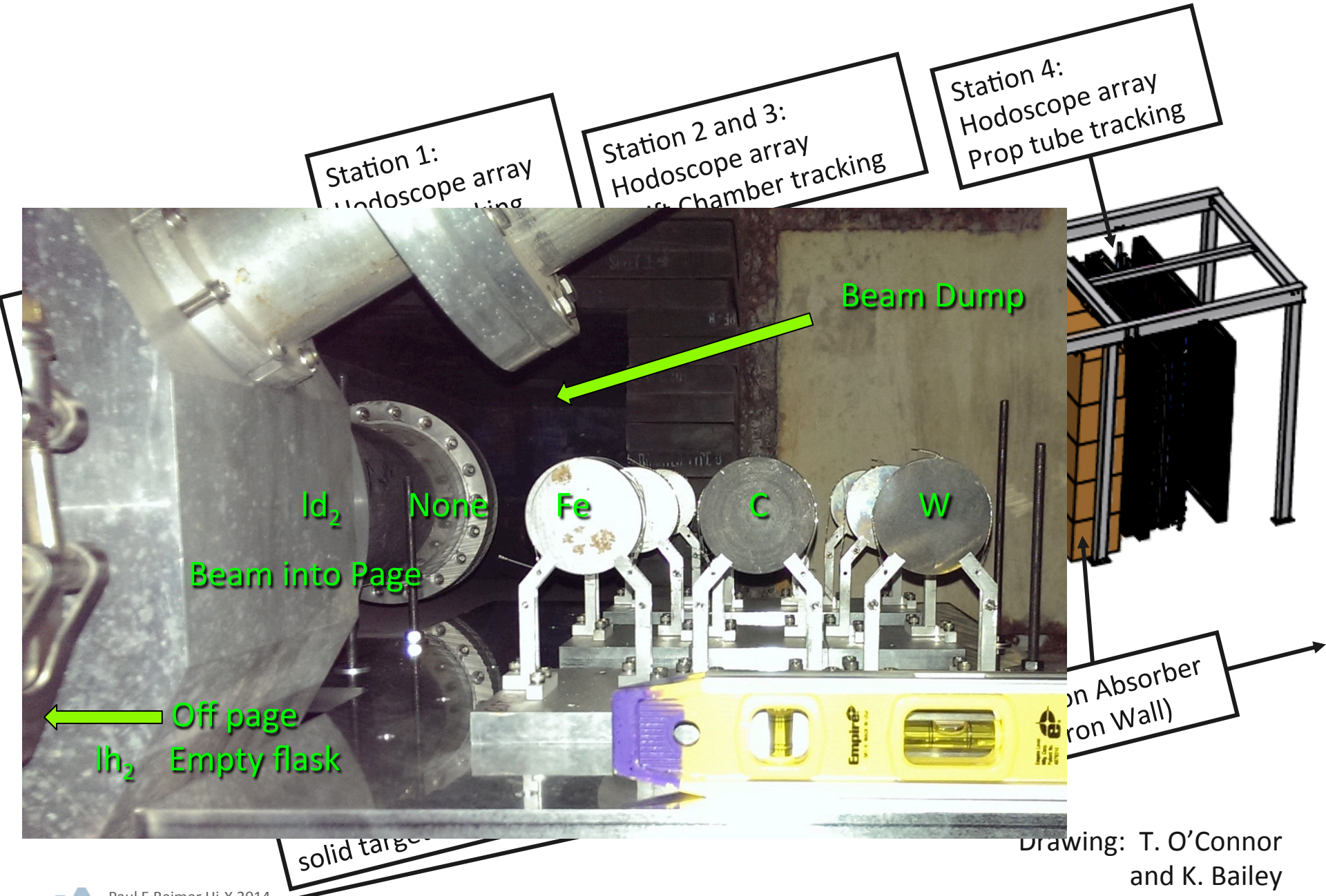

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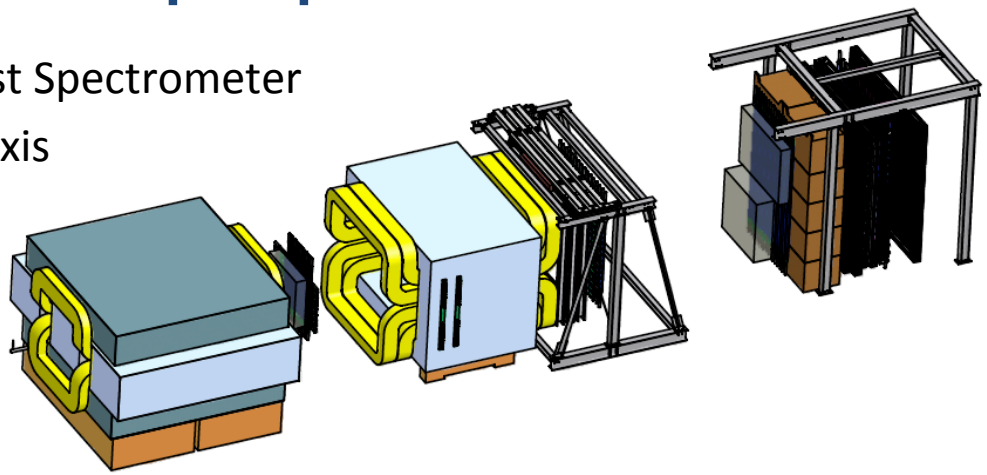
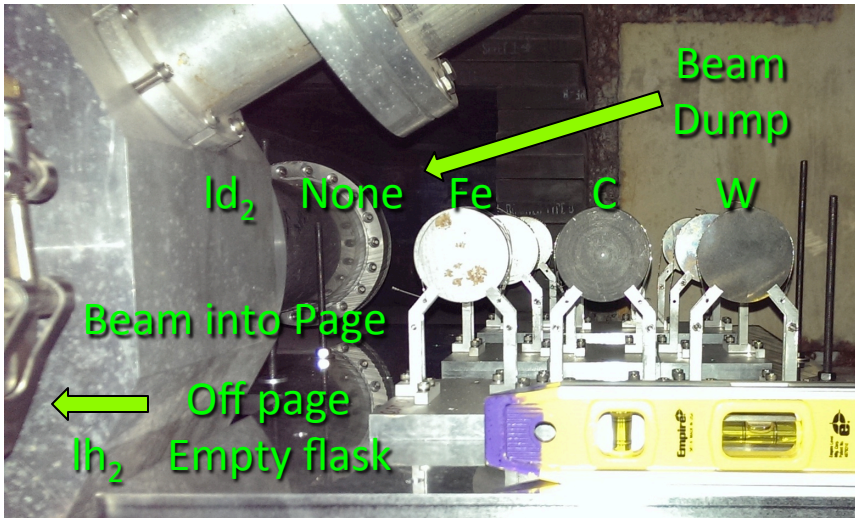
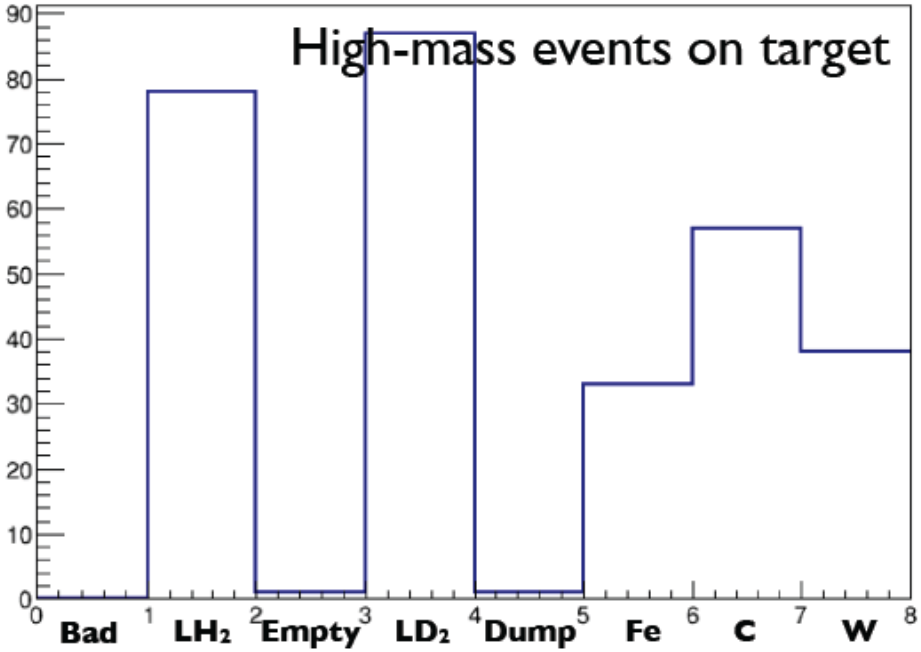
Data From FY2014—target-dump separation

- Entire beam interacts upstream of SeaQuest Spectrometer
- Pointing resolution very poor along beam axis
- Dominated by random coincidences







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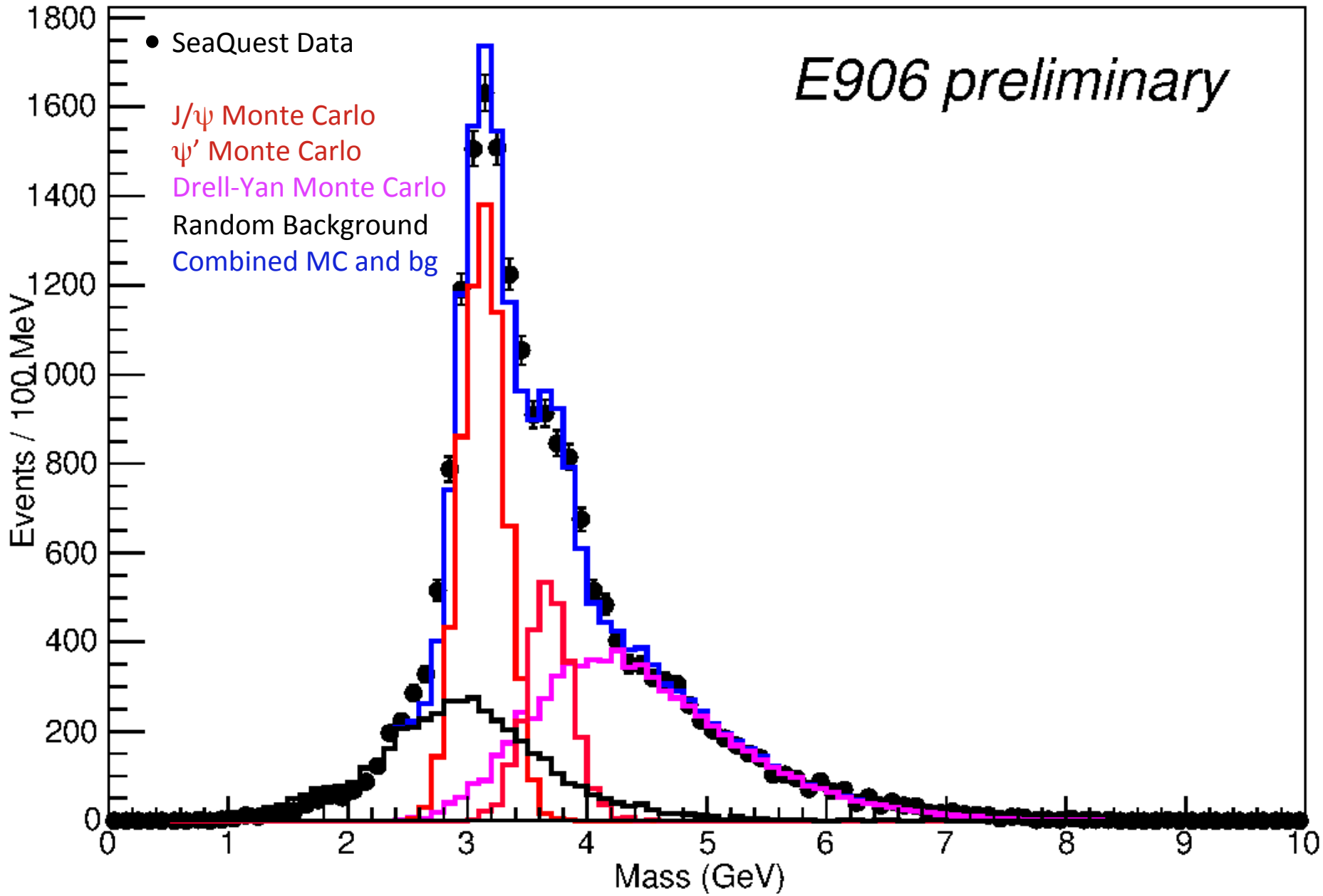

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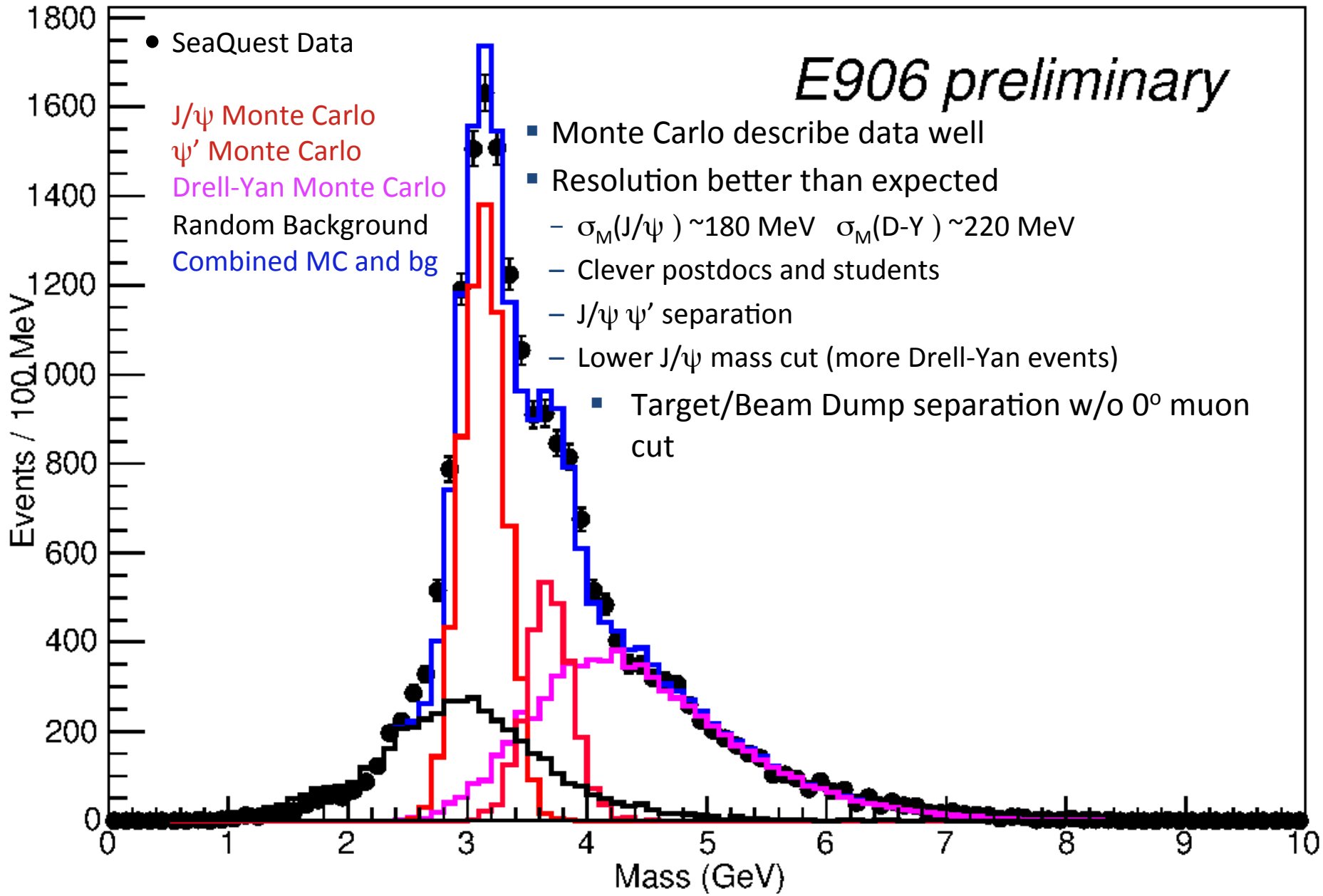

- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi)$ ~180 MeV σ_M(D-Y) ~220 MeV
  - Clever postdocs and students
  - J/ψ ψ' separation
  - Lower J/ψ mass cut (more Drell-Yan events)
    - Target/Beam Dump separation w/o 0° muon cut

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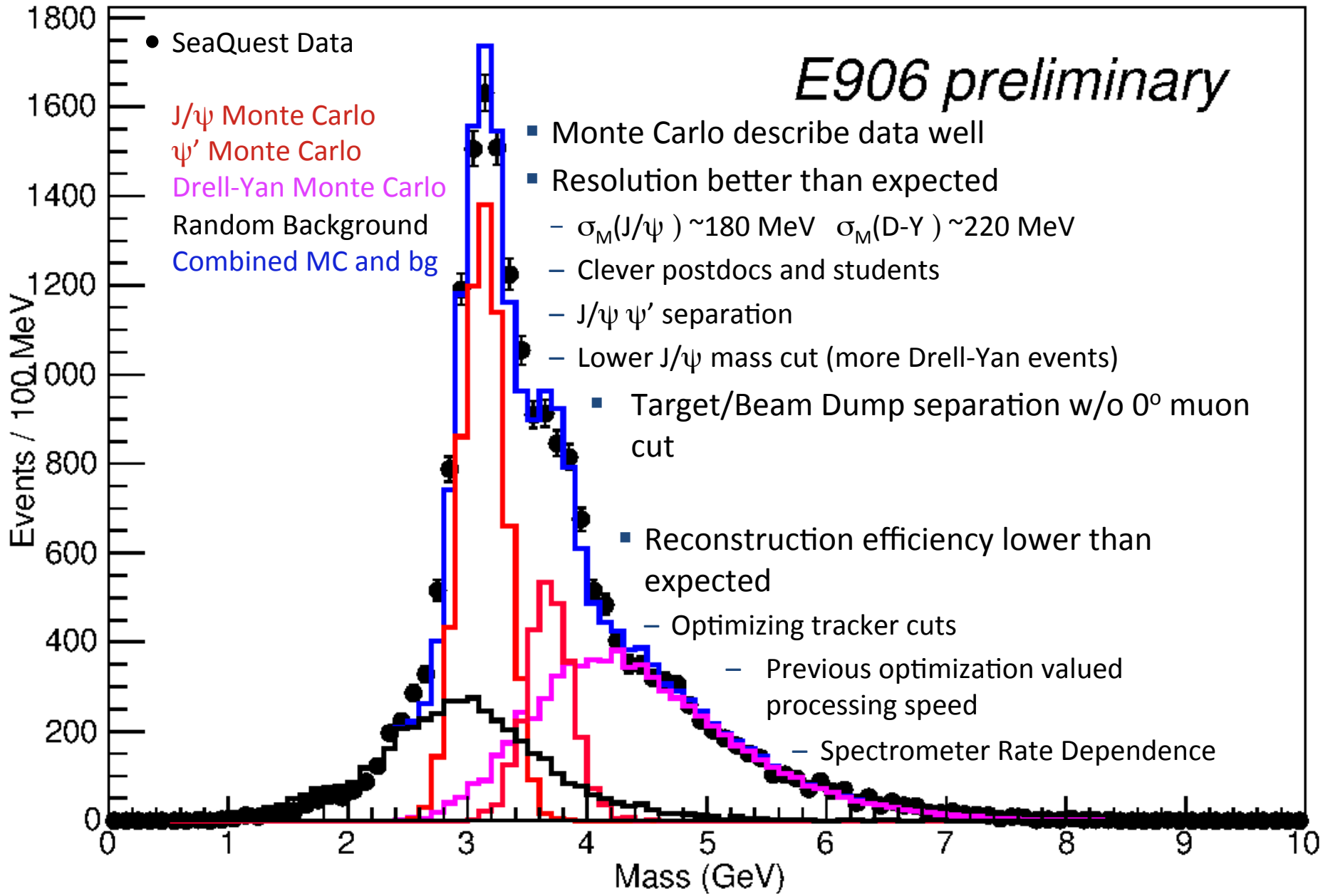

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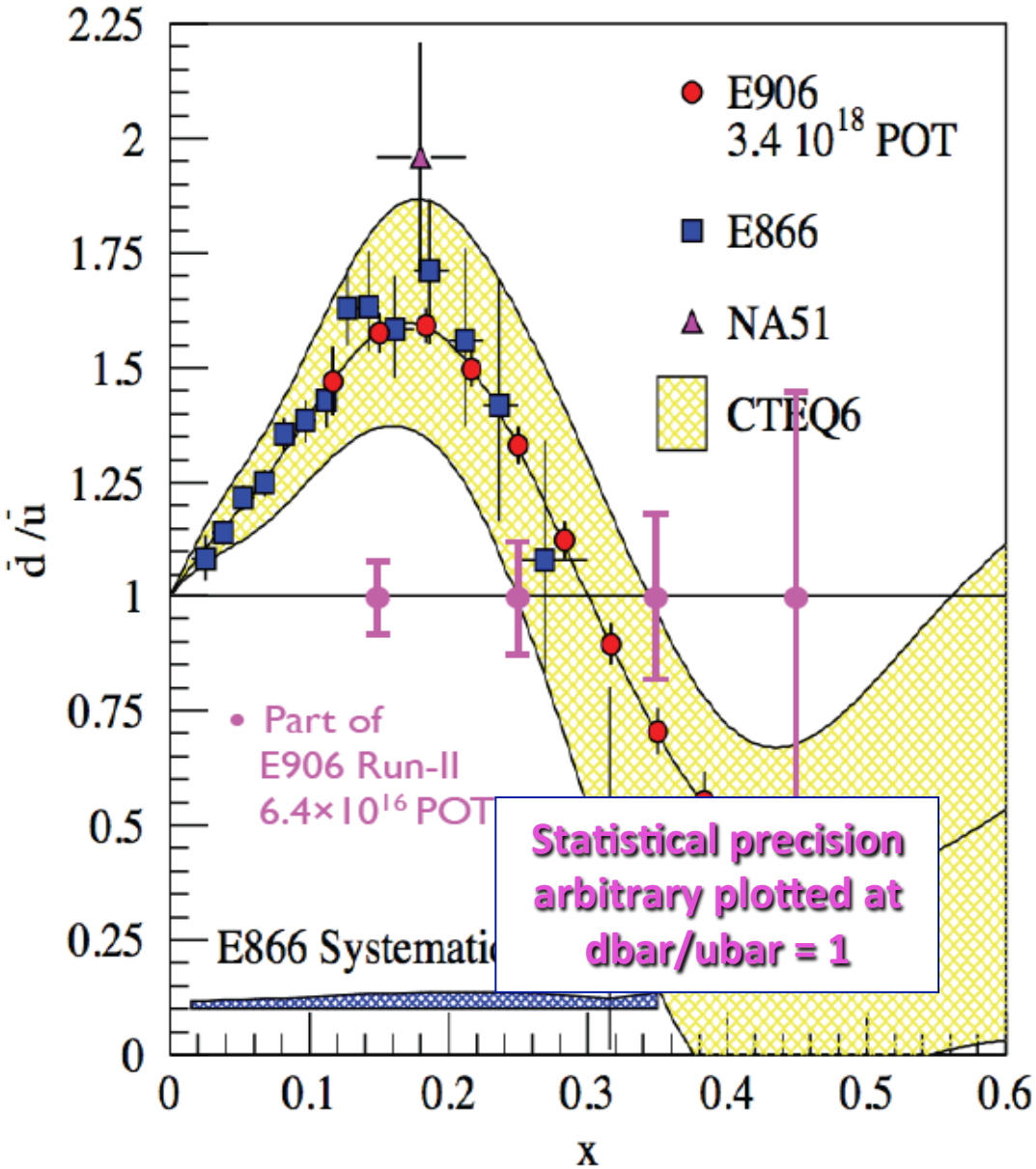
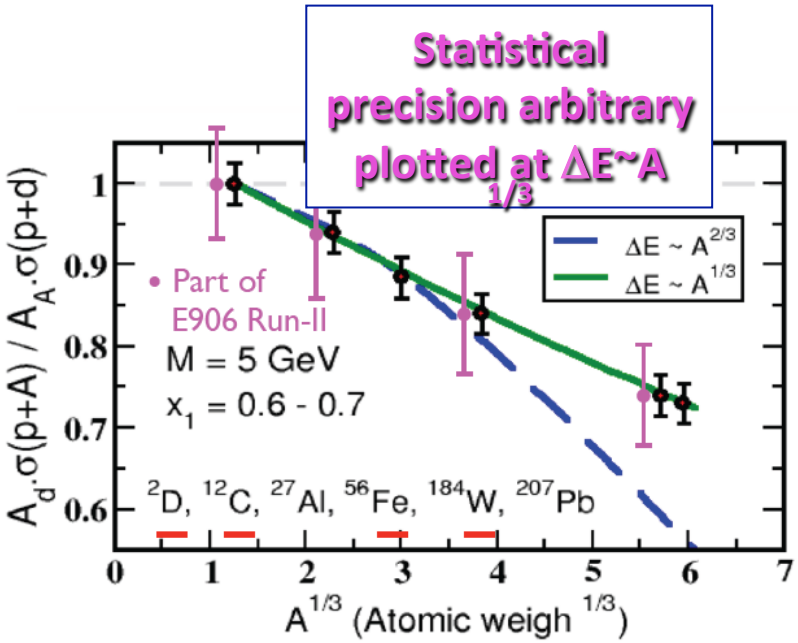
- Target/Beam Dump separation w/o 0° muon cut
- Reconstruction efficiency lower than expected
  - Optimizing tracker cuts
    - Previous optimization valued processing speed
    - Spectrometer Rate Dependence

SeaQuest Recorded Data



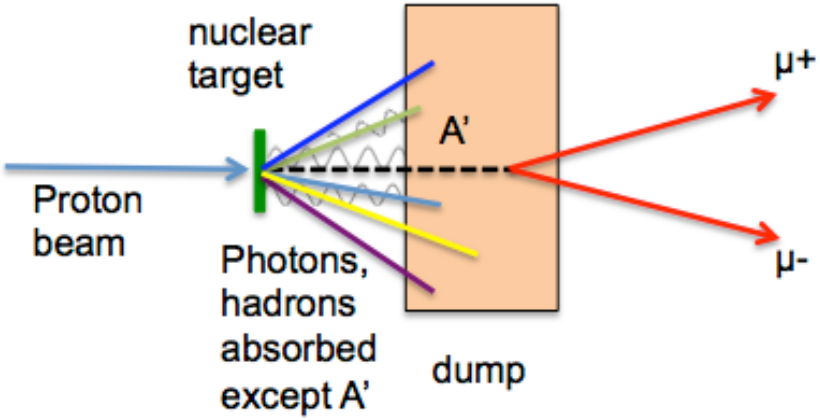
June-September 2014

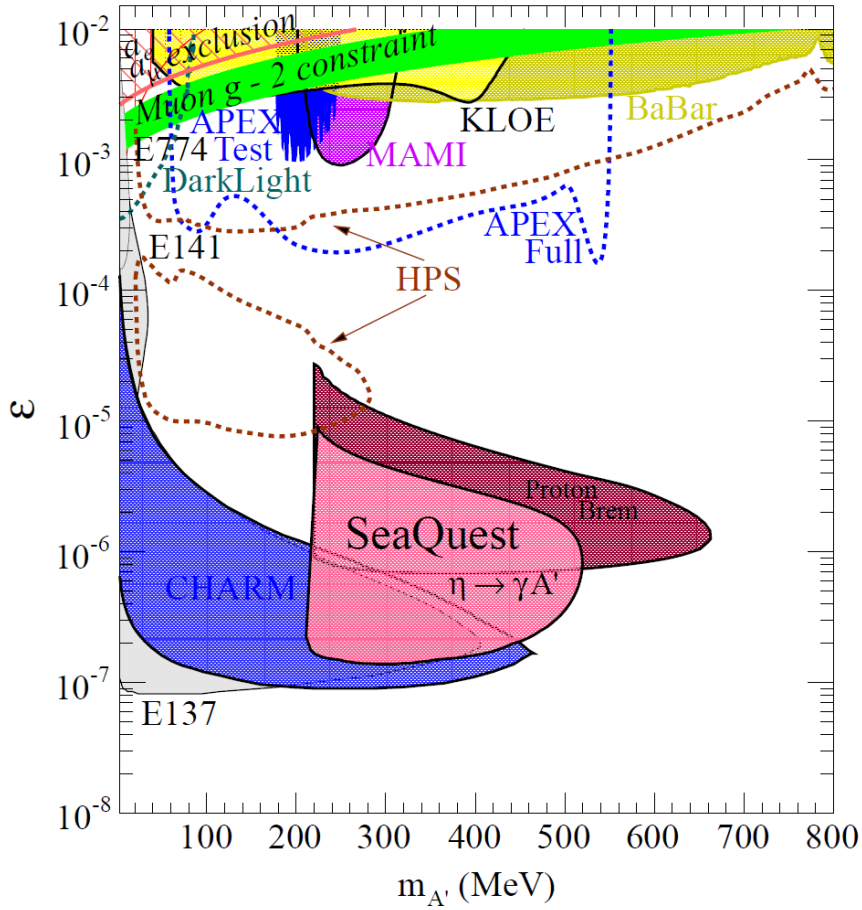
- 50% of recorded protons
- 2.5% of expected final data set (summer 2016)
- Optimizing event reconstruction for high background environment



Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment





- Minimal impact on Drell-Yan program

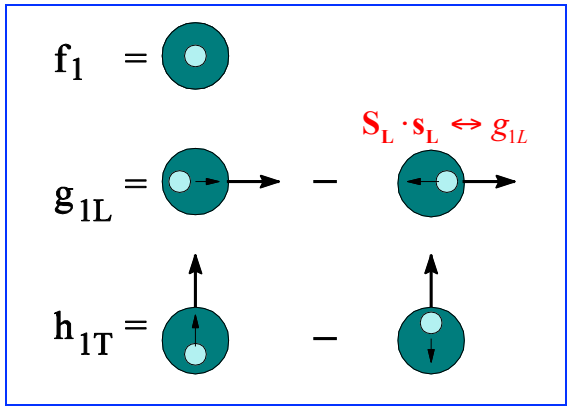
$$L \sim -\frac{1}{4}F^{SM}_{\mu\nu}F^{\mu\nu}_{SM} - \frac{1}{4}F^{hidden}_{\mu\nu}F^{\mu\nu}_{hidden} + \frac{1}{2}\epsilon F^{SM}_{\mu\nu}F^{\mu\nu}_{hidden} + m^2_{A'}A^{hidden}_{\mu}A^{\mu}_{hidden}$$

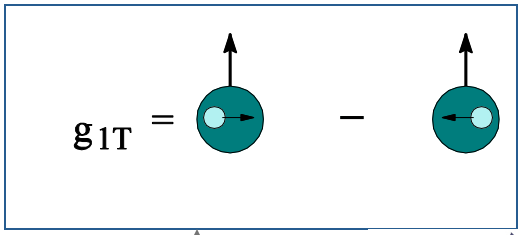
Now add Spin

Petroglyph in Wakiloa Hawai'i

Transverse Momentum Distributions: Introduction

Survive k_T integration

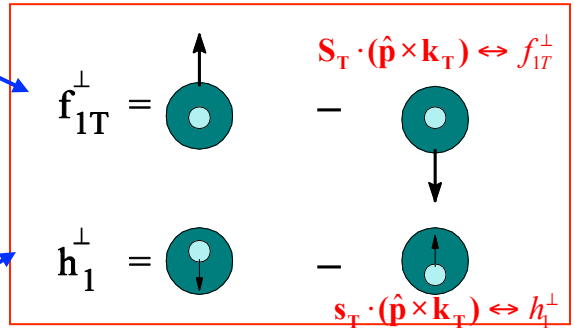




Sivers Function

k_T - dependent,

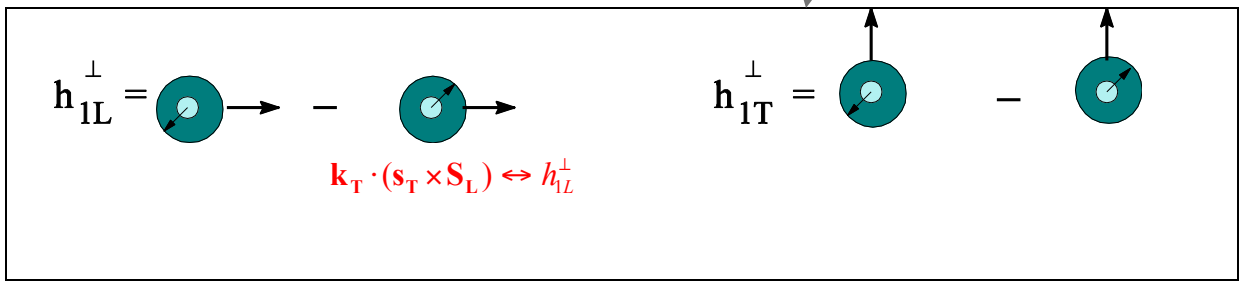
"NaiveT-odd"



k_T - dependent,

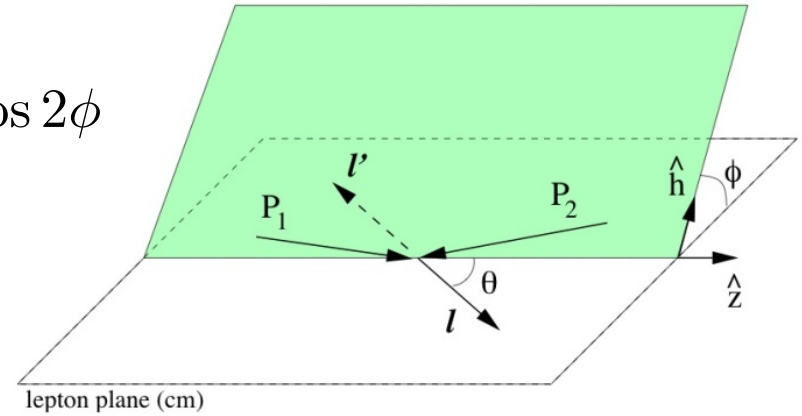
T-even

Boer-Mulders Function



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)*

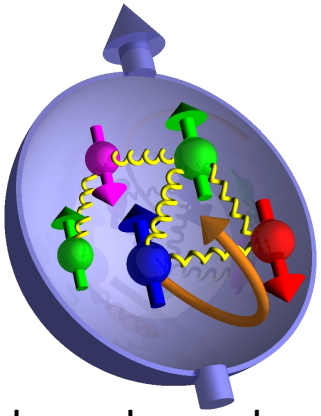
Sivers Function and the Spin Crisis

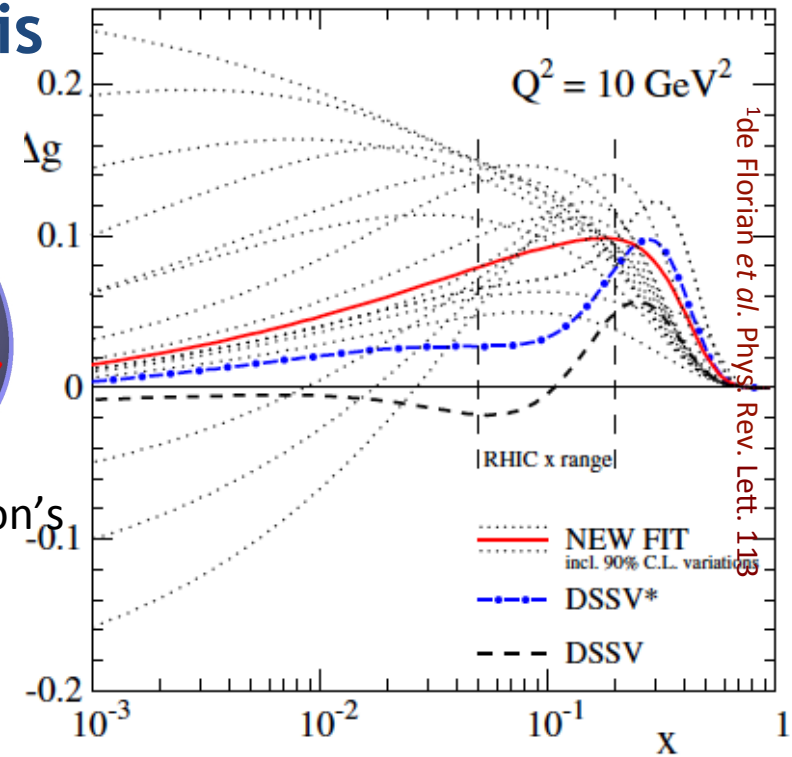
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

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

½ ΔΣ ≈ 25% ΔG ≈ 15%[1]

L ≈ unmeasured

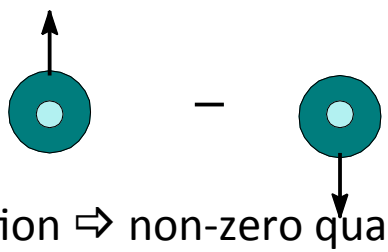




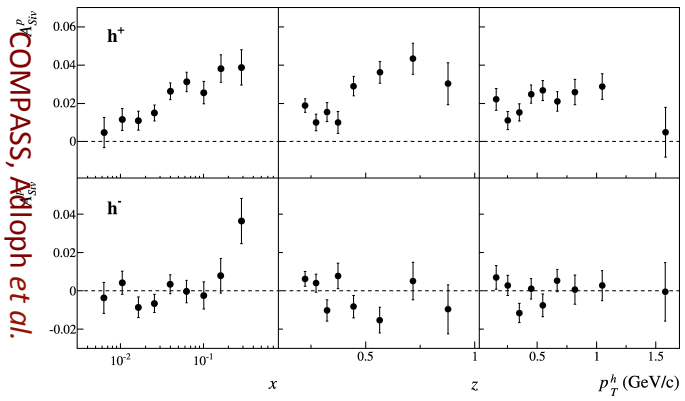
[1]de Florian *et al.* Phys. Rev. Lett. 113

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

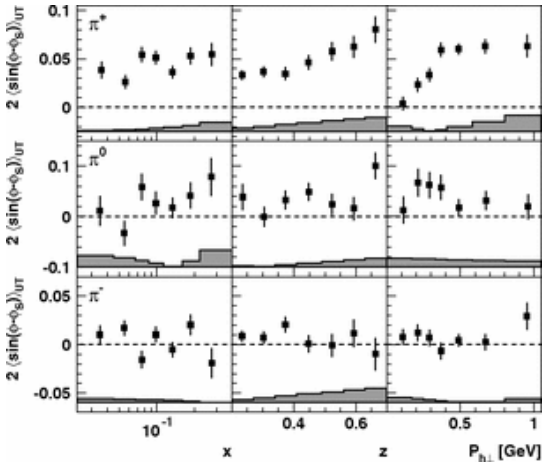
$$f_{1T}^{\perp} =$$

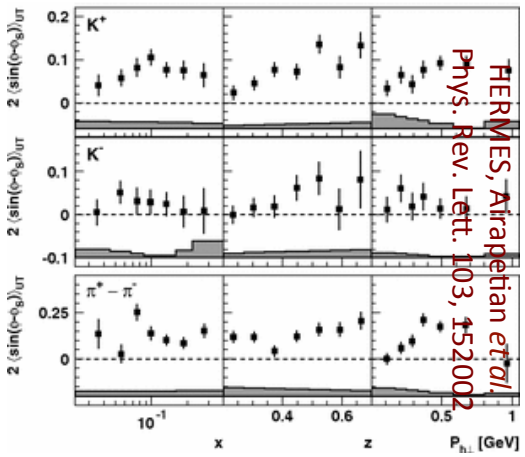


- Non-zero Sivers distribution ⇨ non-zero quark orbital momentum



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

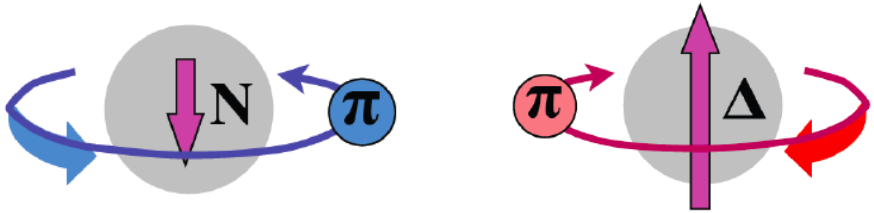




HERMES, Airapetian *et al.* Phys. Rev. Lett. 103, 152002

Pion Cloud and OAM

- Consider a nucleonic pion cloud
  $|p\rangle = p + N\pi + \Delta\pi + \ldots$



Pions $J^p=0^-$ Negative Parity
Need **L=1** to get proton's $J^p=½^+$

Sea quarks should carry orbital angular momentum.

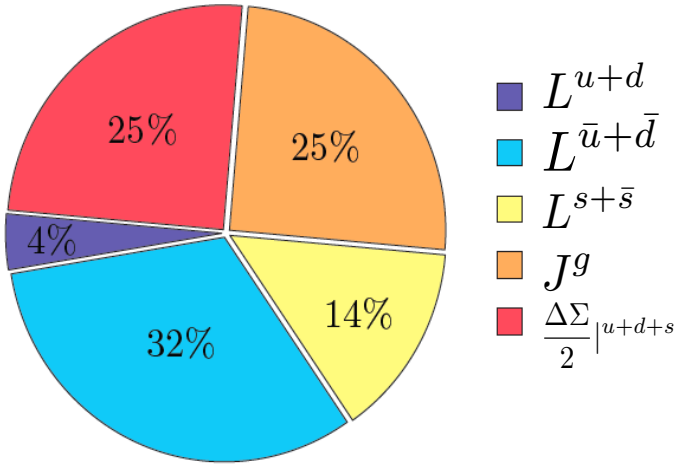
How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD Transverse Momentum Distribution

$$A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \neq 0$$

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

Lattice QCD:



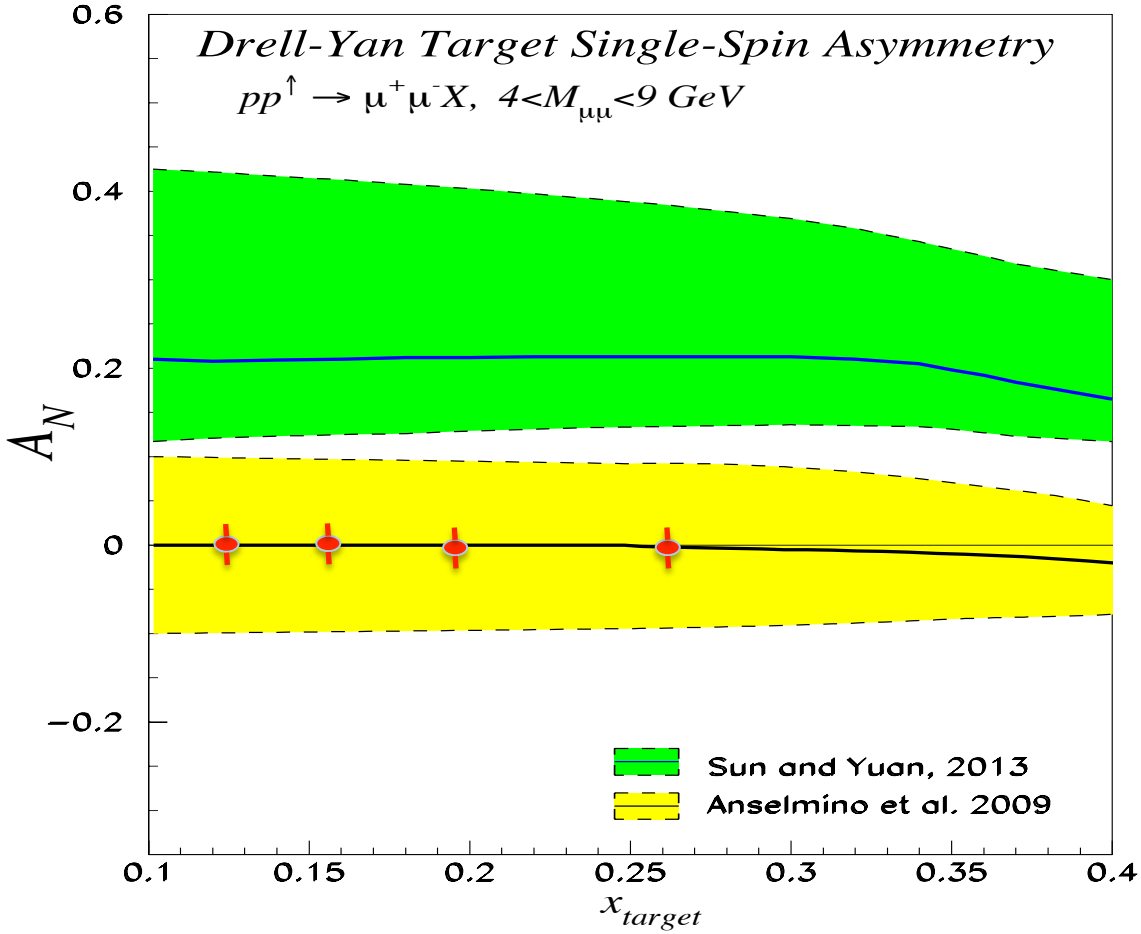
$\Delta\Sigma_q \approx 25\%$

$2\,L_q \approx 46\%$ (0%(valence)+46%(sea))

$2\,J_g \approx 25\%$

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

Projected Statistical Precision with a Polarized Target at SeaQuest



- First Sea Quark Sivers Measurement
- Determine sign and value of ubar Sivers distribution

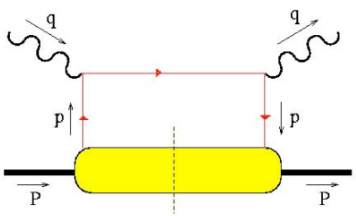
Statistics shown for one calendar year of running :

$\mathcal{L}$ = 7.2 *10^{42} /cm^2 ←→ POT = 2.7*10^{18}

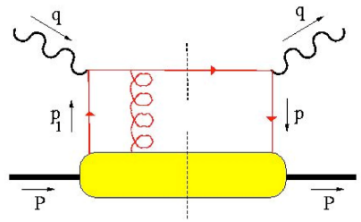
Running will be two calendar years of beam time

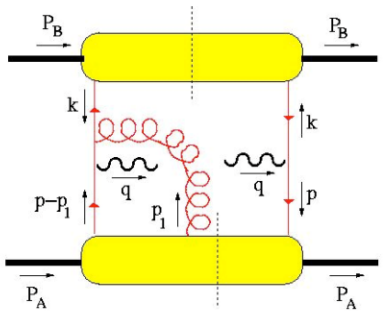
“Naïve” T-odd observables

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

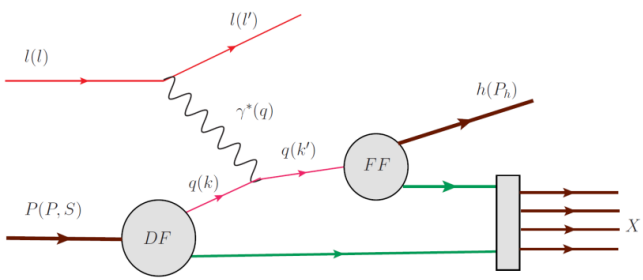


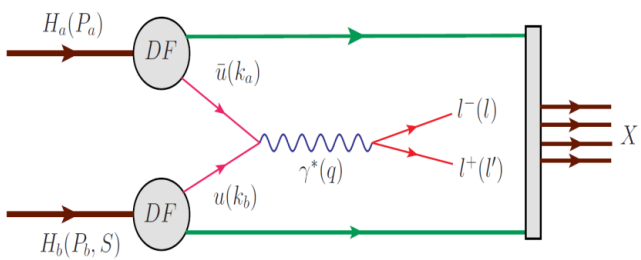
can interfere with





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





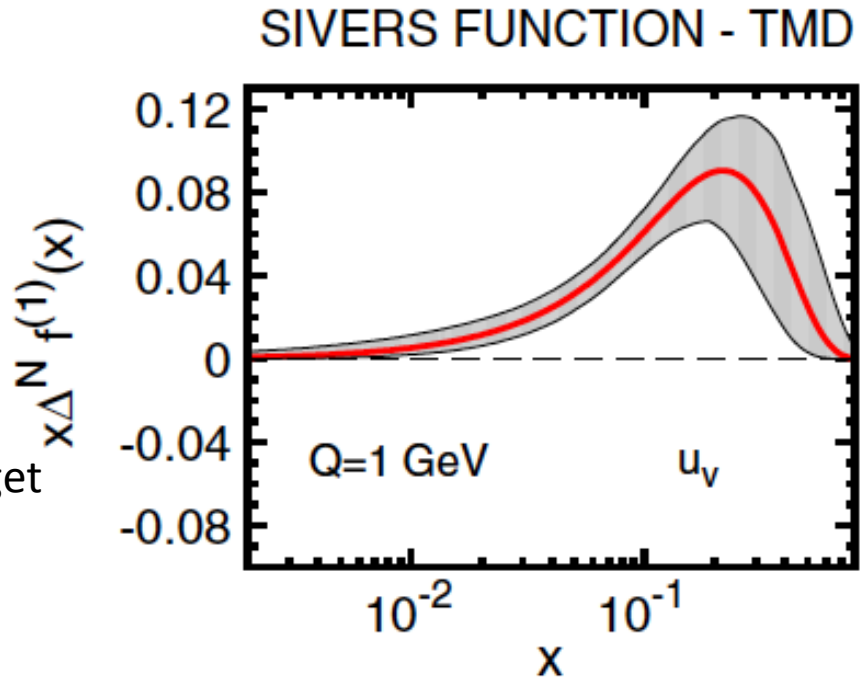
spacelike (DIS) **vs.** **Timelike (Drell-Yan)** **virtual photon**

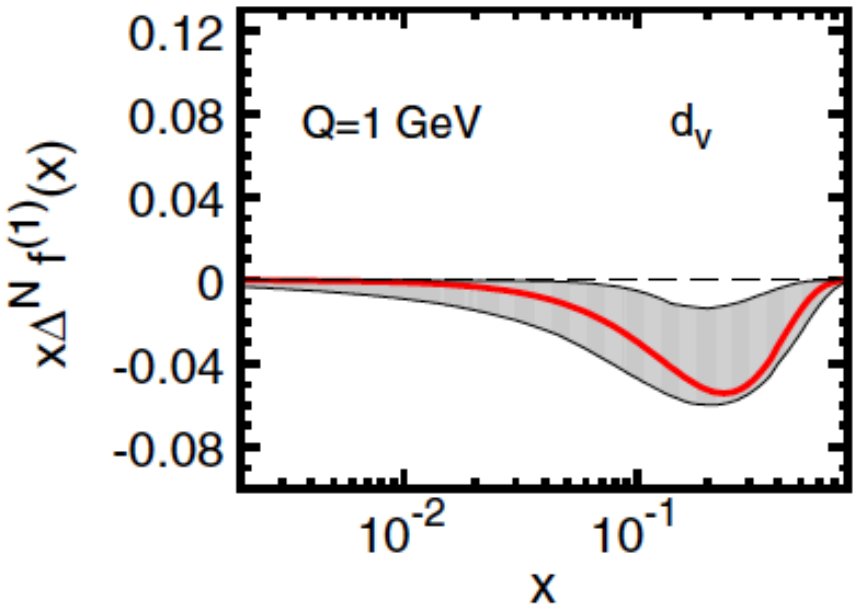
$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

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

Why Polarized-Beam D-Y?

- Existing Sivers SIDIS data better constrain valence distributions
- Some fits of sea distributions show much smaller effect.
- COMPASS will reach this with polarized target and pion beam

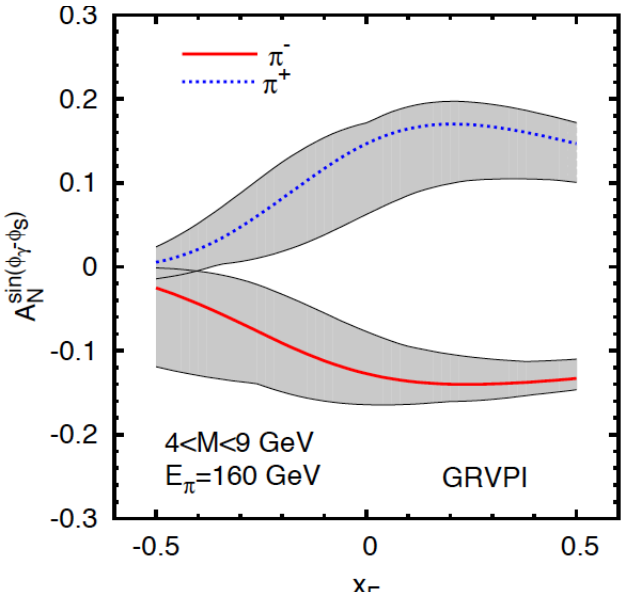




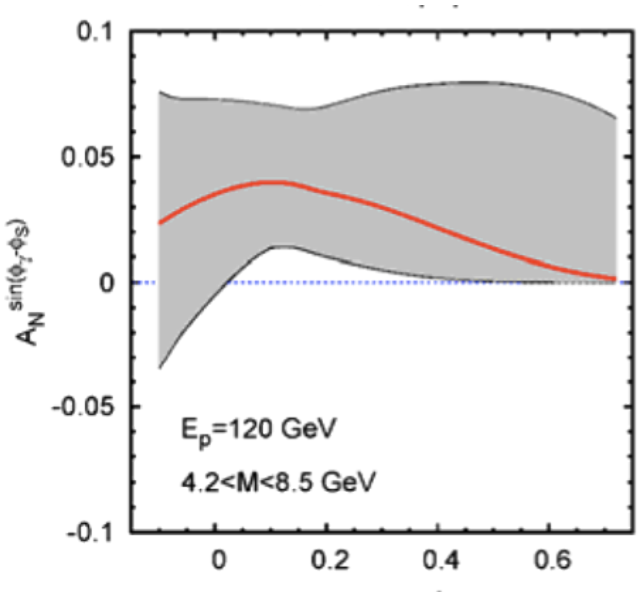
Anselmino *et al.* Phys. Rev. D 86 014028 (2012)

Experiment	Particles	Lumin. (cm-2 s^{-1})
COMPASS	$\pi^{\pm} + p^{\uparrow}$	2×10^{32}
GSI	$p^{\uparrow}$+ p-bar	few $\times 10^{32}$
NICA	$p^{\uparrow}$+ p	1×10^{31}
RHIC	$p^{\uparrow}+p^{\uparrow}$	few $\times 10^{32}$
E-1027	$p^{\uparrow}$+p	**2×10^{35}**

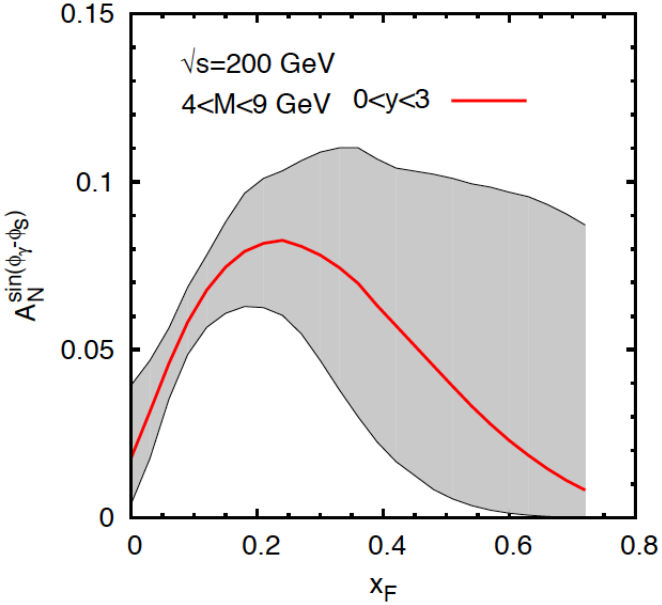
$A_N^{\sin(\varphi_\gamma-\varphi_s)}$ prediction Anselmino *et al*



COMPASS



Fermilab



RHIC

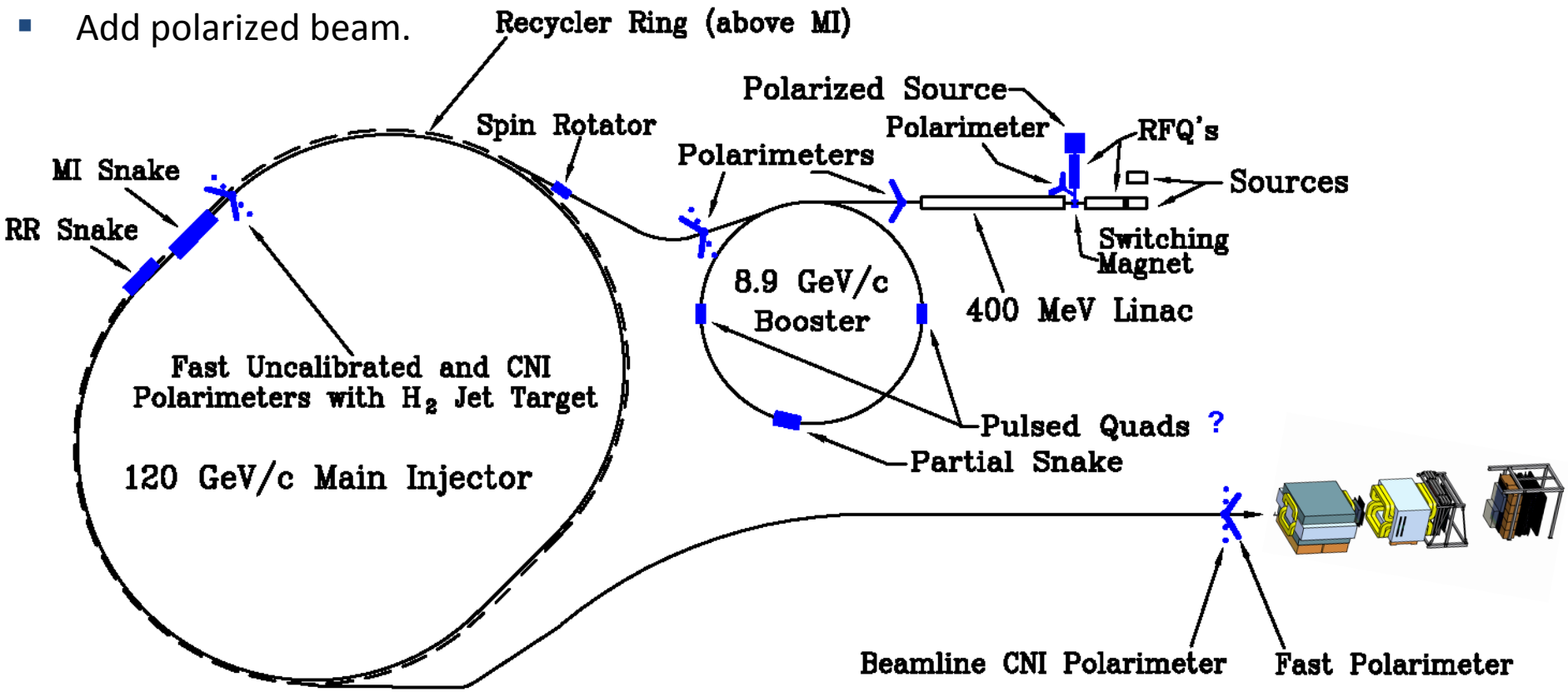
Anselmino, *et al* Phys. Rev. D79 (2009) 054010 and private communication (for Fermilab)

- Uncertainties in predictions dominated by uncertainties in SIDIS data
- Also predictions for GSI PAX, GSI PANDA, J-PARC, JINR NCIA, IHEP SPASCHARM

Polarized Beam Drell-Yan at Fermilab

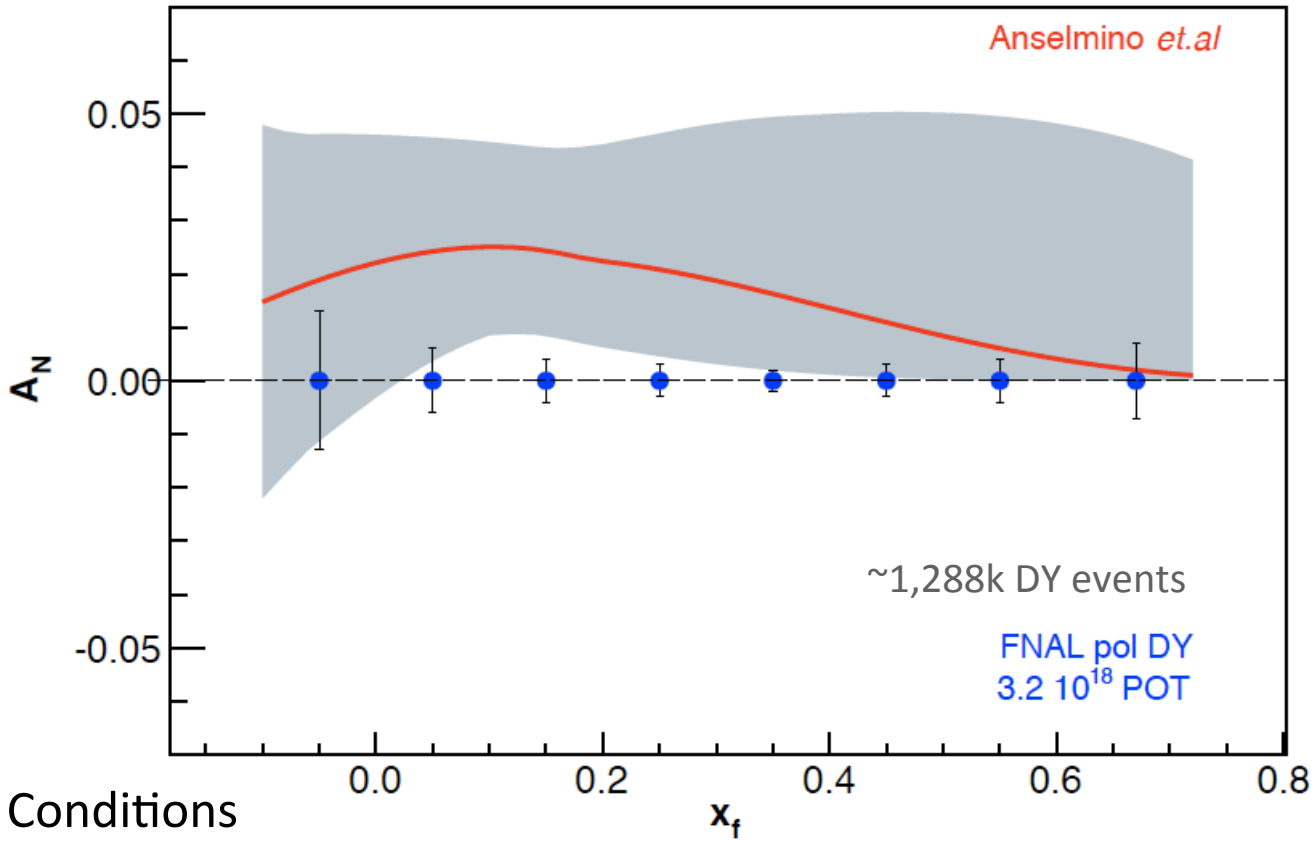
The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam.



- **Cost Est.: $6M +$4M Contingency & Management = $10M**
- based on earlier 2 snake estimate

Expected Precision from E-1027 at Fermilab

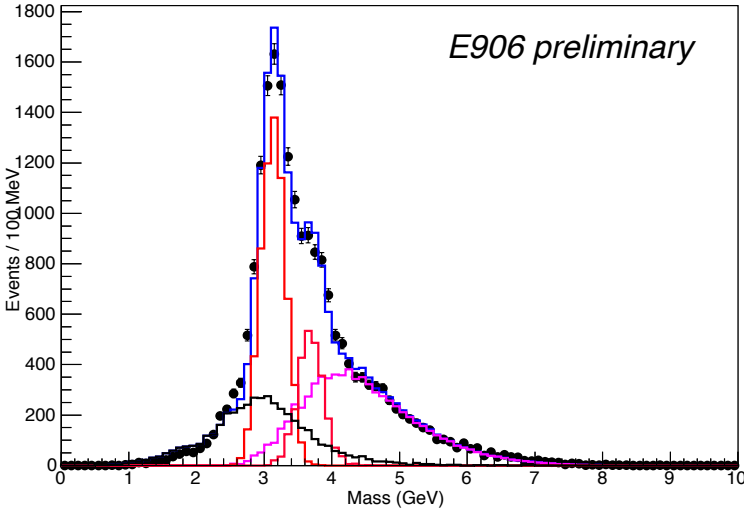


- Experimental Conditions
  - Same as SeaQuest
  - luminosity: L_{av} = 2 x 10^{35} (10% of available beam time: I_{av} = 15 nA)
  - 3.2 X 10^{18} total protons for 5 x 10^5 min: (= 2 yrs at 50% efficiency) with P_b = 70%

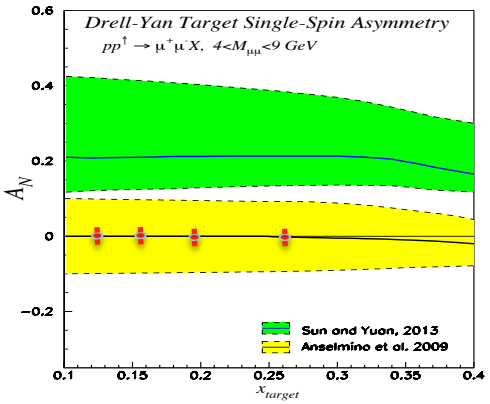
Can measure not only sign, but also the size & maybe shape of the Sivers function!

Summary

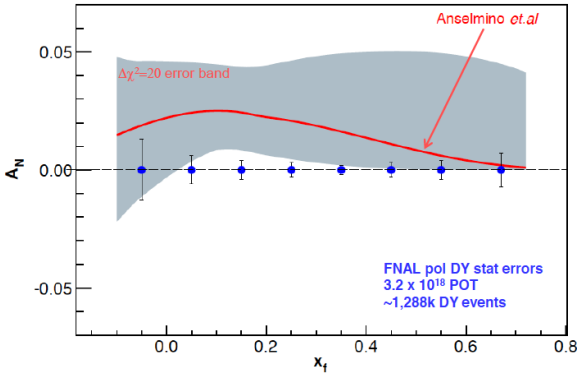
- The Drell-Yan interaction probes antiquark distributions

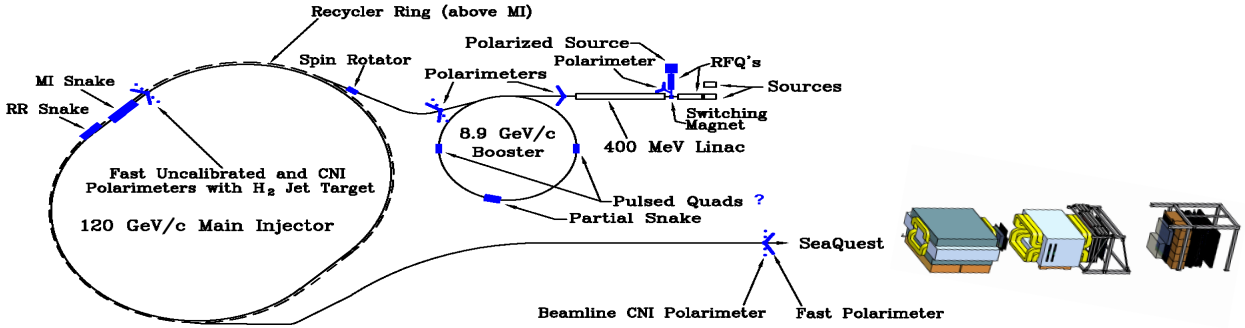


- Fermilab E906/SeaQuest
  - dbar/ubar, antiquark EMC, partonic energy loss,
  - Spectrometer works as predicted by Monte Carlo



- The Sivers distribution contains unique information on
  - QCD gauge invariance and factorization
  - Angular momentum
- The Sivers distribution must be measured with Drell-Yan
  - Valence-Sea separation





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Students and postdocs
*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

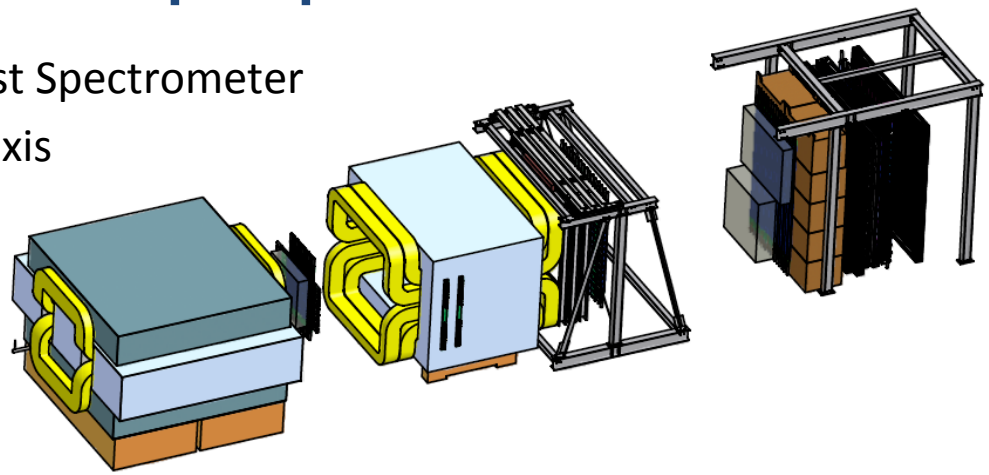
Polarized Beam:

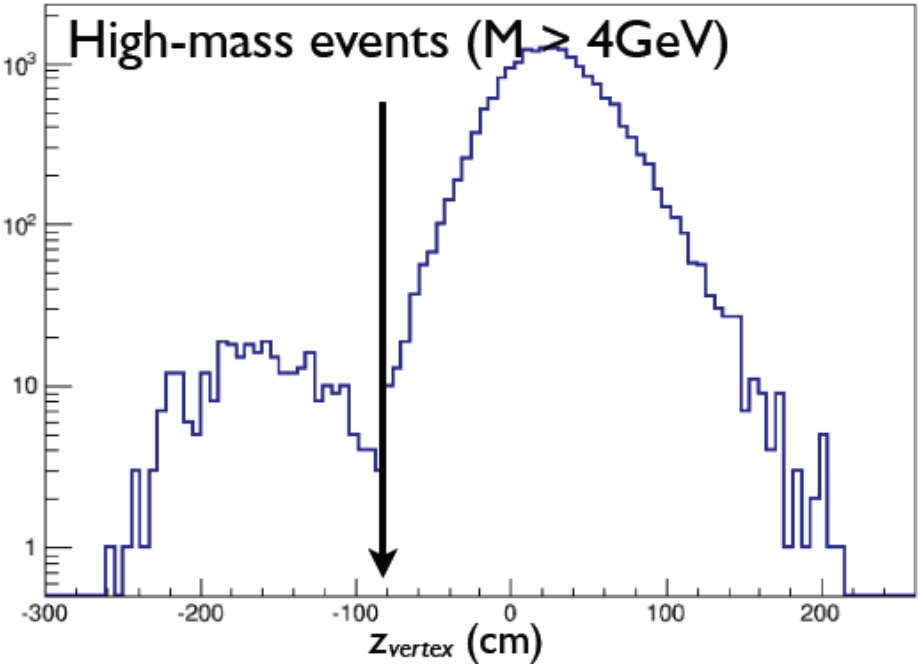
Abilene Christian University
Argonne National Laboratory
University of Basque Country
University of Colorado
Fermi National Accelerator Laboratory
University of Illinois
KEK
Los Alamos National Laboratory
University of Maryland
University of Michigan
RIKEN
Rutgers
Tokyo Tech
Yamagata University

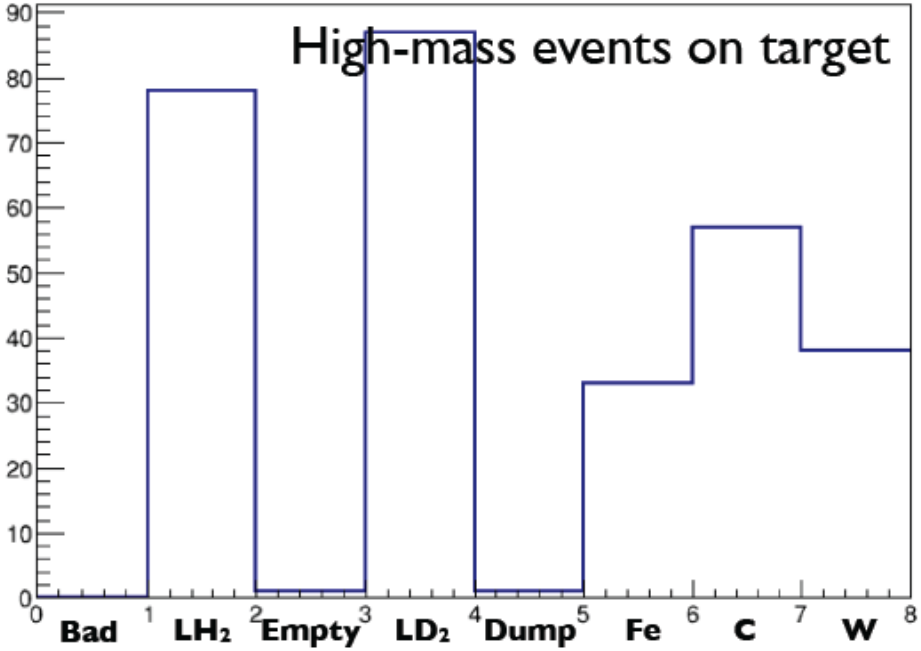
Wolfgang Lorenzon and Paul E Reimer
Co-Spokespersons

Data From FY2014—target-dump separation

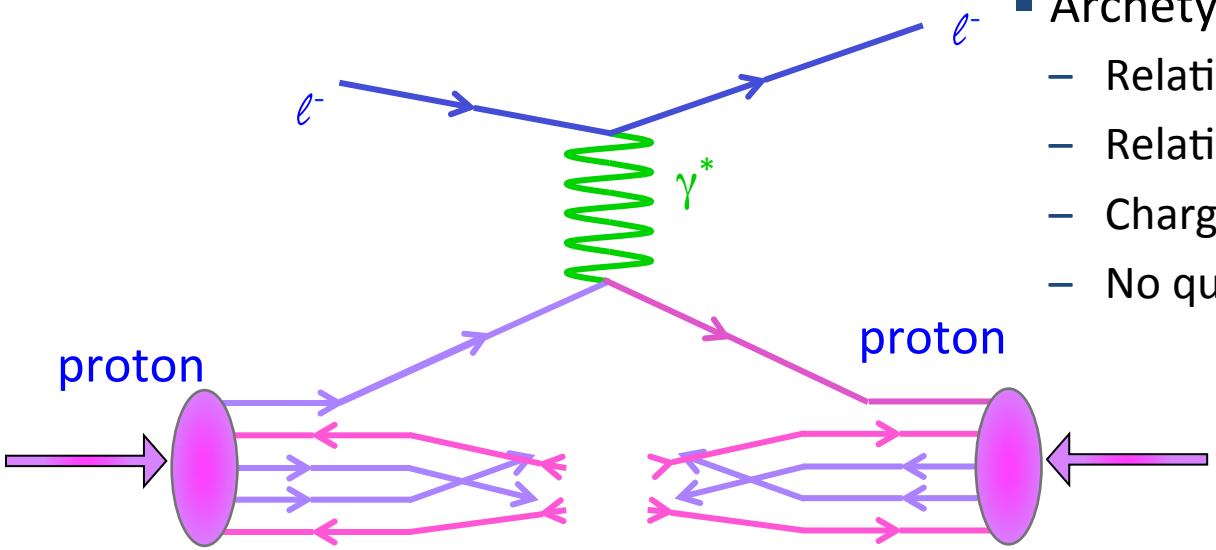
- Entire beam interacts upstream of SeaQuest Spectrometer
- Pointing resolution very poor along beam axis
- Dominated by random coincidences







Probes of proton structure

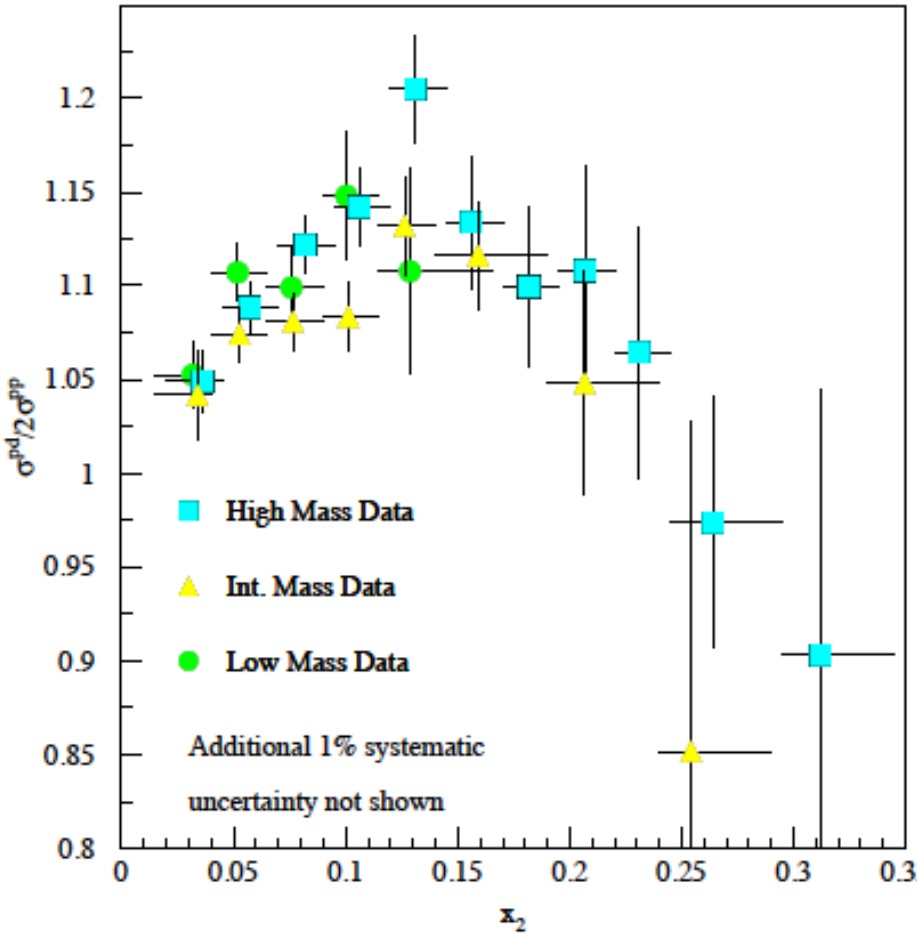


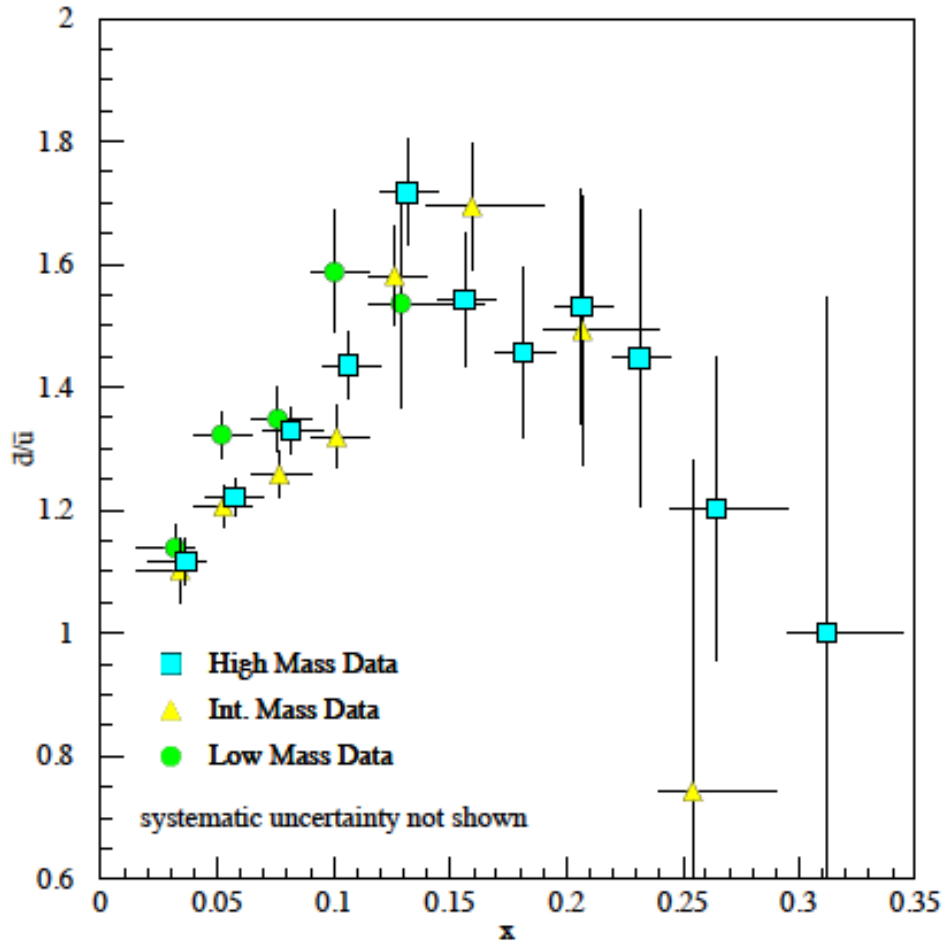
Deep Inelastic Scattering

- Archetype probe of proton structure
  - Relatively simple to measure and
  - Relatively easy to calculate
  - Charge-weighted flavor sensitivity
  - No quark-antiquark selectively

- Differences
  - Timelike (Drell-Yan) vs. spacelike (DIS) virtual photon.
  - Hadron beam and convolution of parton distributions (Drell-Yan)
  - Factorazion/Hadronization (SI-DIS)

E866/NuSea comparison of data sets





Rusty Towell, PhD Thesis