Argonne NATIONAL LABORATORY

Avast! SeaQuest Charts the Nucleon Sea

New Perspectives 2015

Fermilab

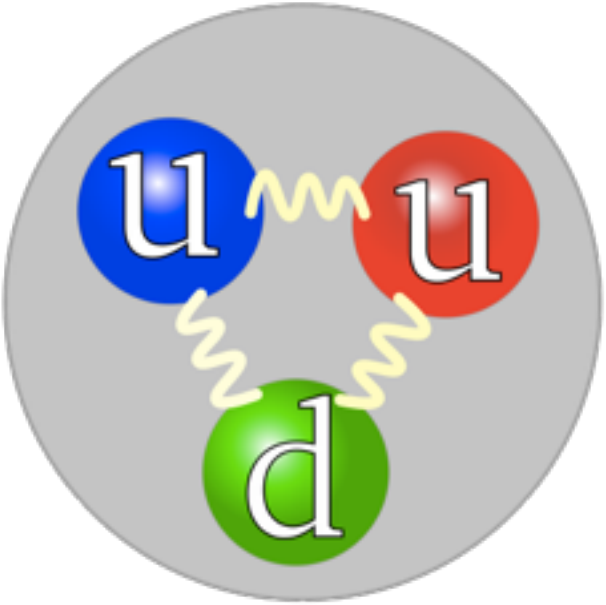
June 8, 2015

Brian G. Tice - Argonne National Laboratory - Physics Division

U.S. DEPARTMENT OF ENERGY

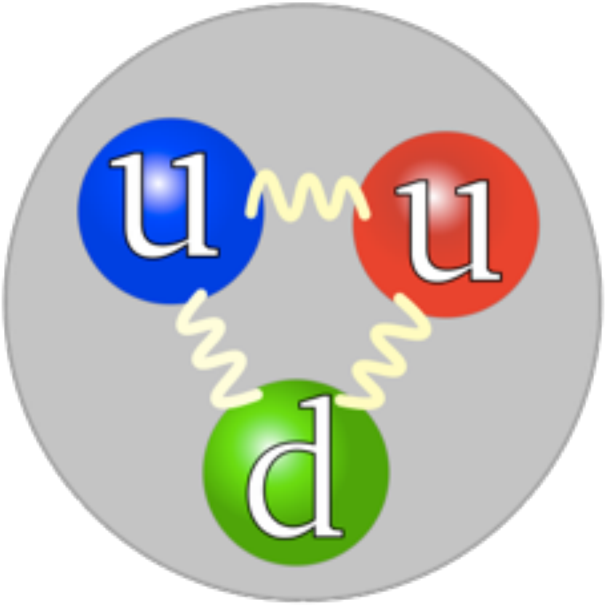
This Is Not a Proton

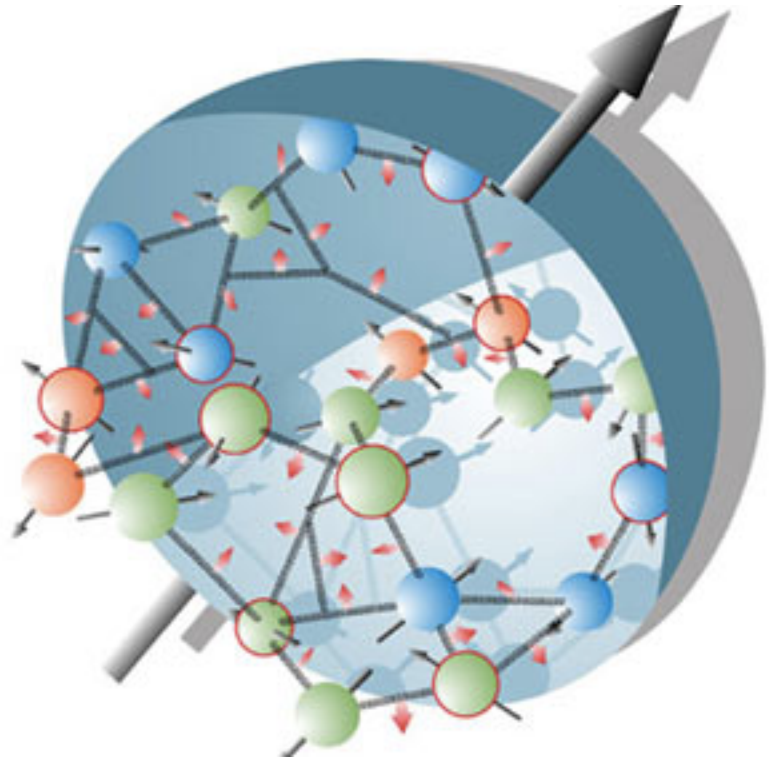
- “The proton is made of 3 quarks”



What Is a Proton?

- ~~"The proton is made of 3 quarks"~~
- "The proton is made of many interacting quarks and antiquarks"
  - Excess of 3 quarks, called **valence quarks**
  - All the rest are **sea quarks**





Describing Quarks in the Proton

- Proton as a sum of quarks: $P = q_u^1 + q_u^2 + q_d^3 + \sum_i q_s^i \bar{q}_s^i$

  valence — sea

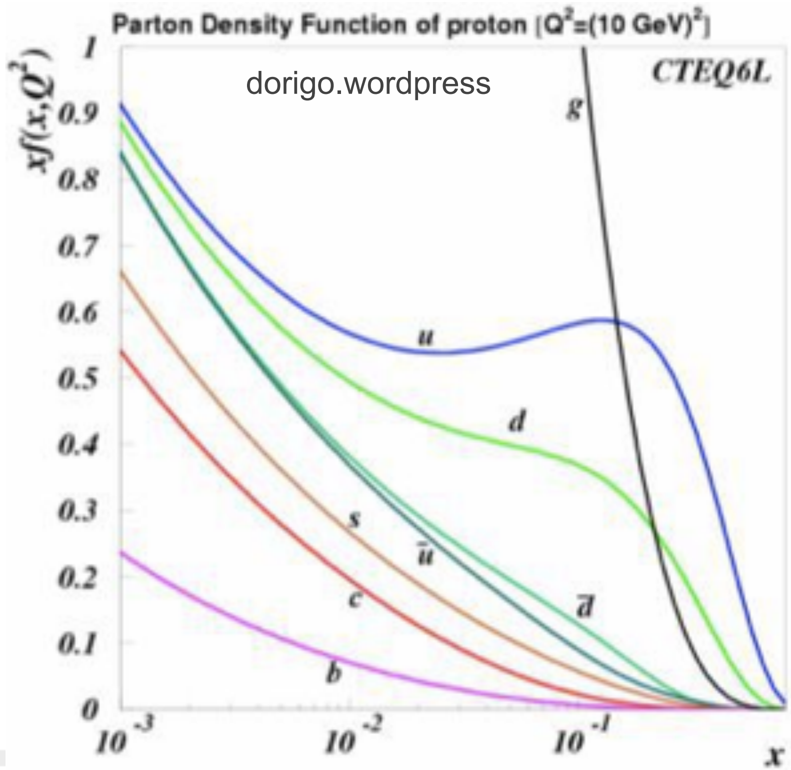
- Quark momentum distributions described by structure functions
  - Charged lepton DIS:

$$F_2^{l^\pm} \; \alpha \sum e^2 x \left(q(x) + \bar{q}(x)\right)$$

  - Neutrino DIS:

$$F_2^{\nu} \; \alpha \sum x \left(q(x) + \bar{q}(x)\right)$$

$$F_3^{\nu} \; \alpha \sum x \left(q(x) - \bar{q}(x)\right)$$



Structure in the Nucleon Sea

- Proton as a sum of quarks:

$$P = q_u^1 + q_u^2 + q_d^3 + \sum_i q_s^i \bar{q}_s^i$$

valence   sea

- Separate sea from valence

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)]\, dx$$

- If nucleon sea is flavor symmetric:

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

Gottfried Sum Rule

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

- **Until measured, nucleon sea was assumed to be symmetric**
  - Not required by symmetry but what else would you assume?

Light Antiquark Flavor Asymmetry

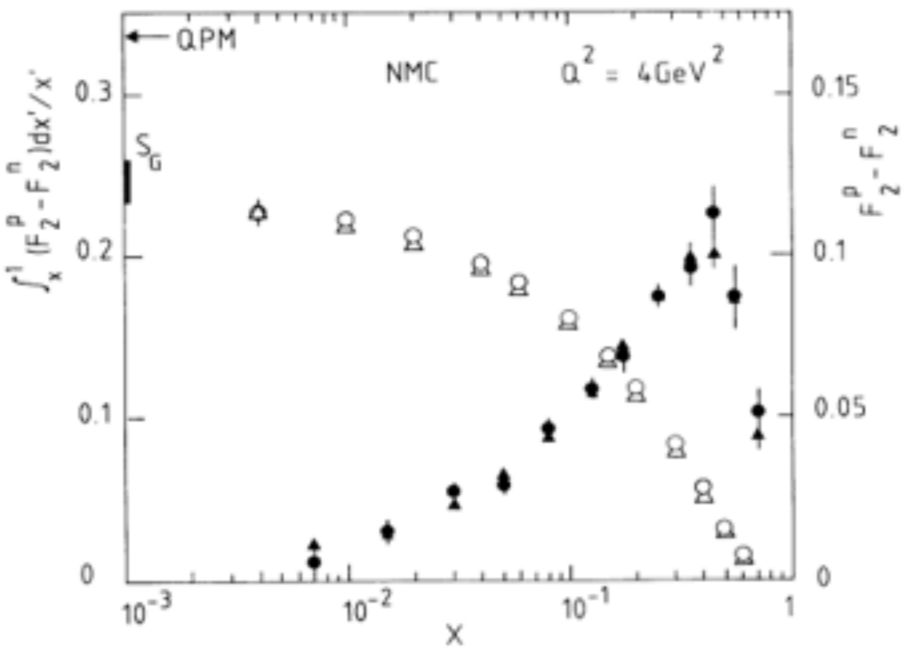
Muon DIS

NMC

P. Amaudruz et al., PRL 66, 2712 (1991)

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

$$\int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = 0.235 \pm 0.026$$

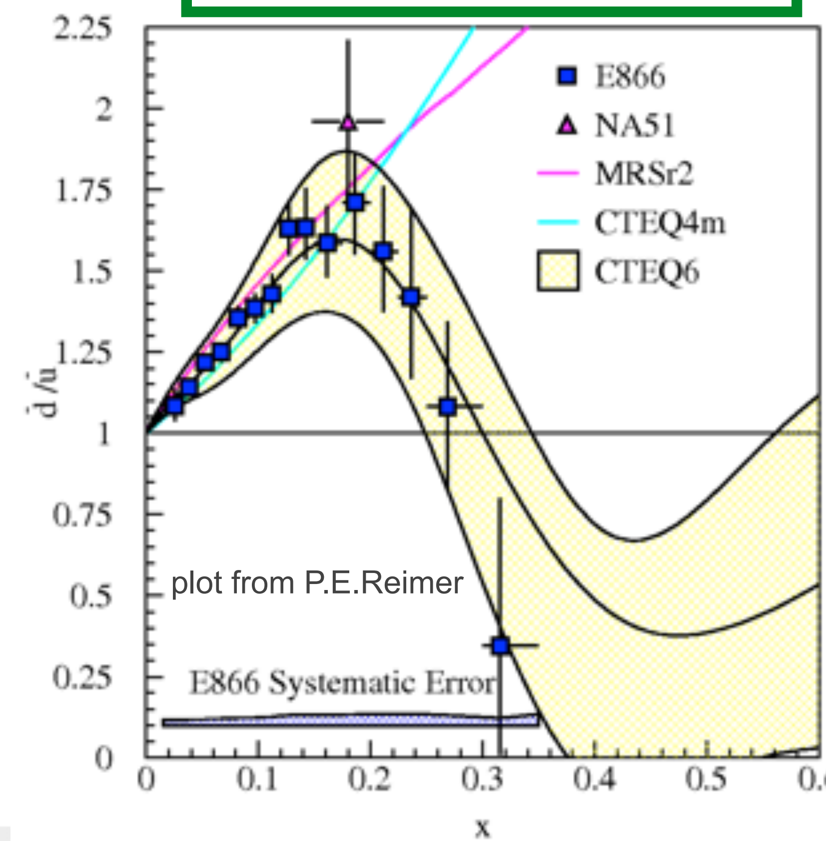


Drell-Yan

Fermilab E866/NuSea

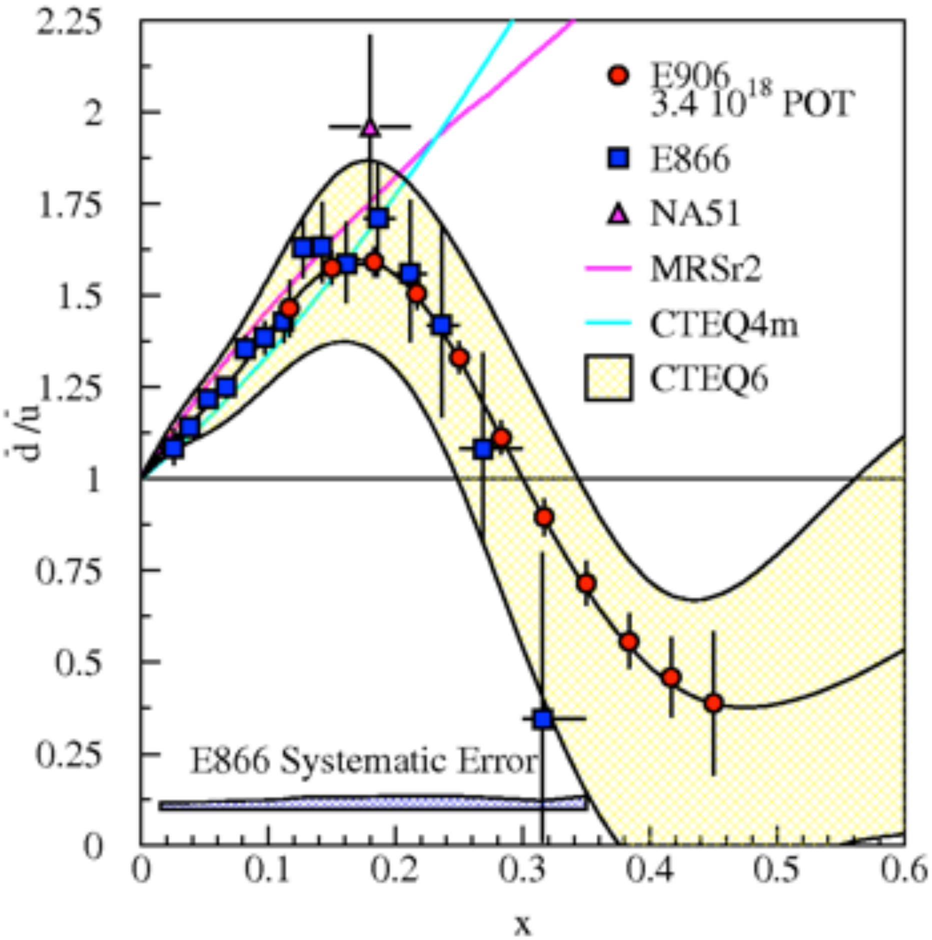
E.A.Hawker et al., PRL 80, 17 (1998)

Antiquark flavor asymmetry decreases at higher x



Enter SeaQuest

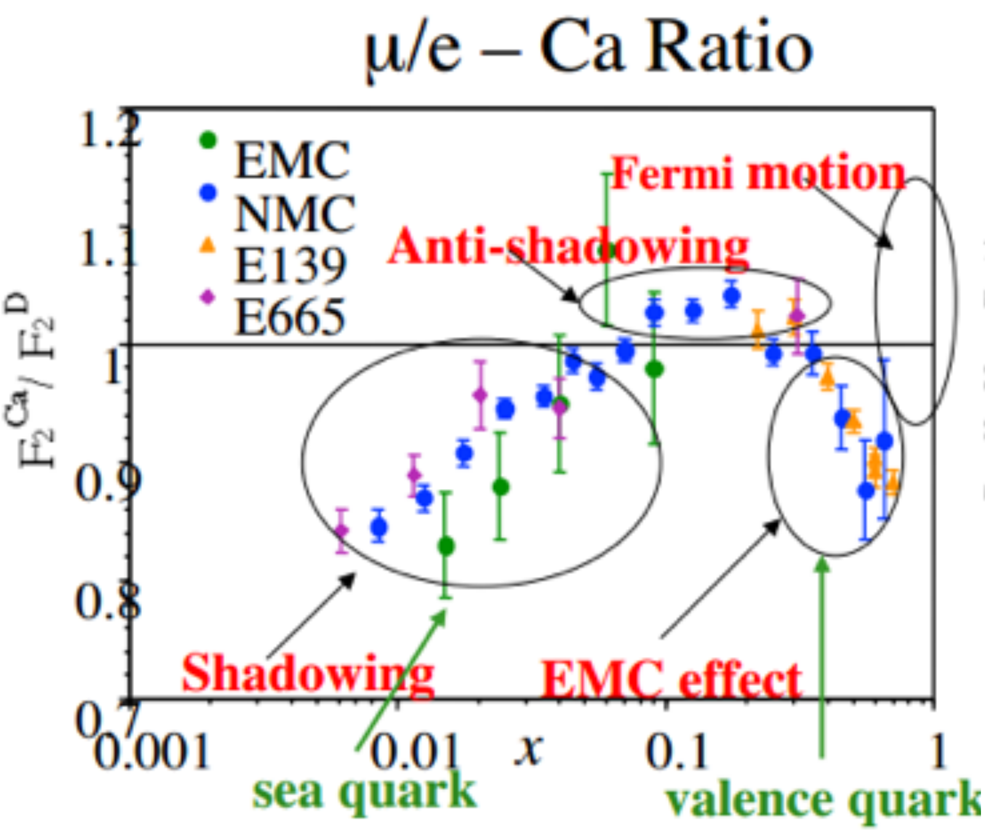
- Increase stats 50x over E866
- Higher reach in x
- Provide data in unconstrained region at x>0.3

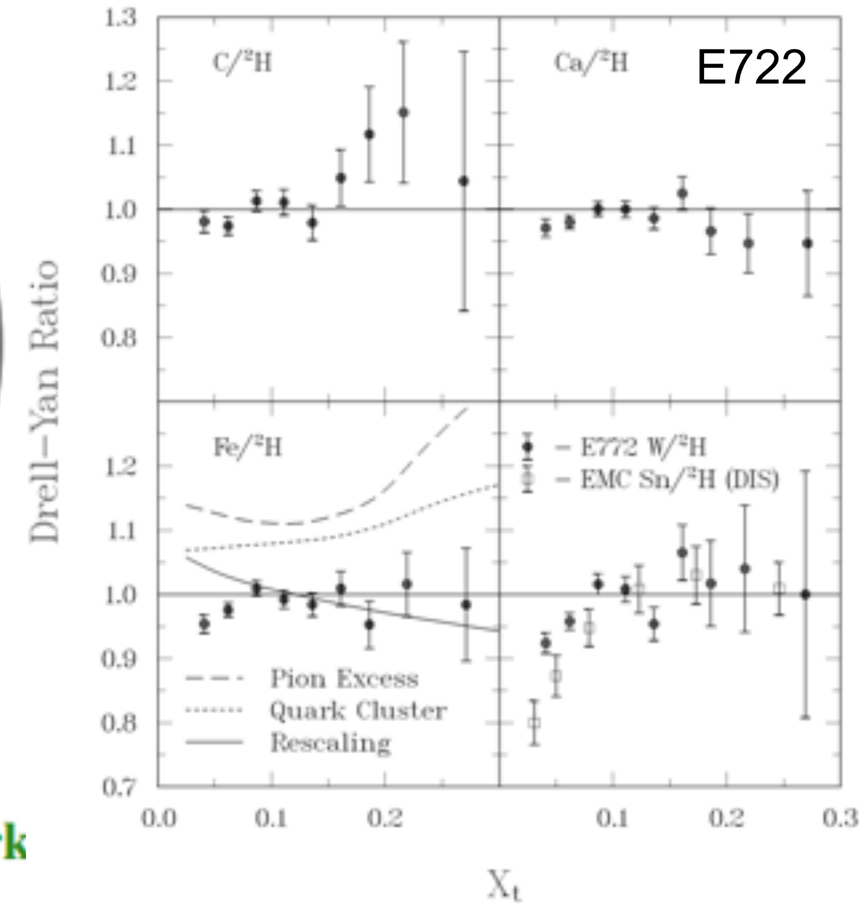


Nuclear Effects

- Charged lepton DIS shows structure function F2 effectively changed in nucleus

- Puzzle after 30+ years
- Perhaps different for sea and valence?
- No antishadowing for sea quarks?



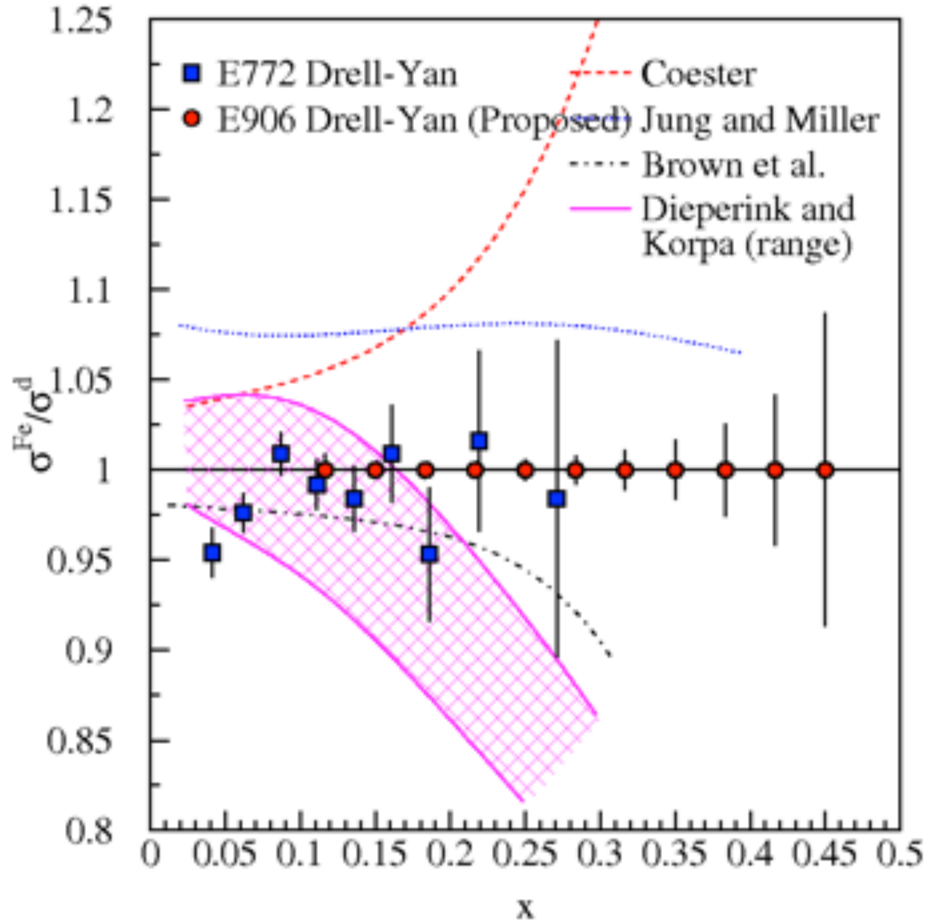


Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

Enter SeaQuest

- Nuclear targets C, Fe, W
- High stats in “antishadowing” zone
- Reach into EMC region

- Models must explain DIS and Drell-Yan
  - And neutrino DIS!



SeaQuest Collaboration

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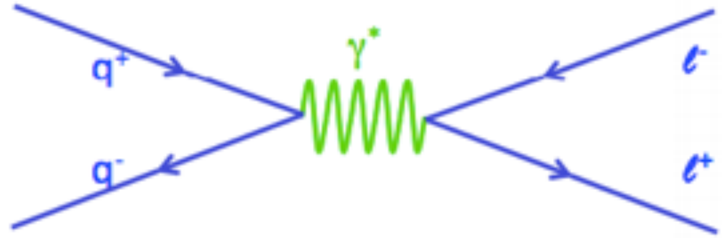
SeaQuest's Home: Fermilab NM4 enclosure

- 120 GeV protons from Main Injector slow-extracted for 4s spill every 60s
  - protons come in 19ns buckets (53MHz)

Proton-Induced Drell-Yan



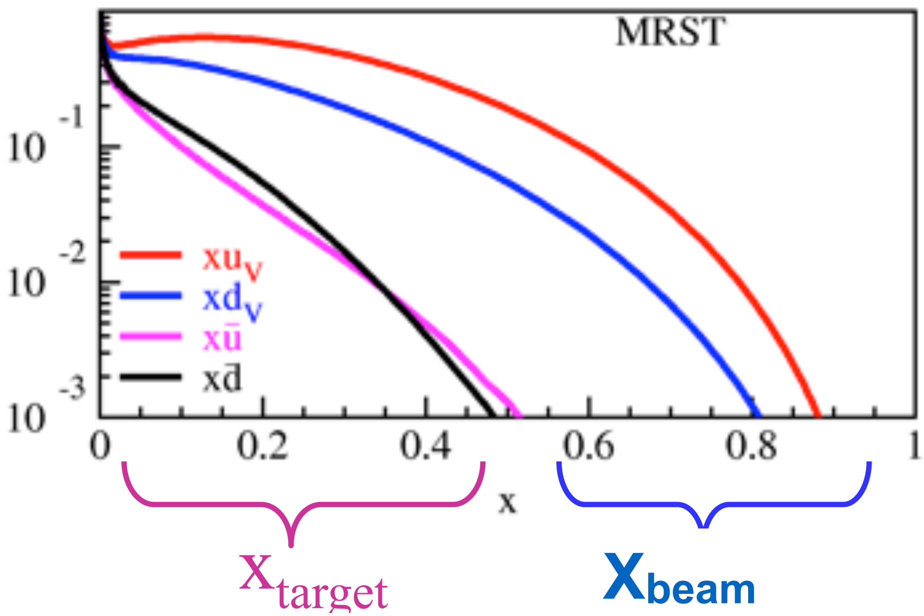
- 120 GeV protons from Main Injector slow-extracted for 4s spill every 60s

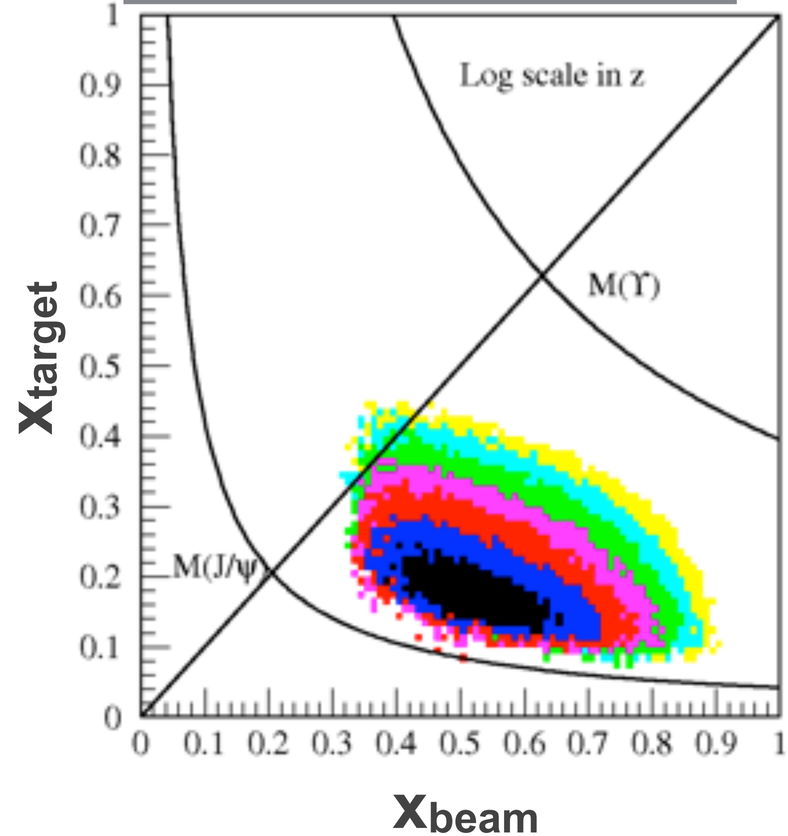
- E866 used 800 GeV protons from Tevatron
  - DY cross section scales as **1/s**
  - Backgrounds (charmonium production) scale as **s**
- **SeaQuest statistics enhanced over E866 by factor of 50**

- DY directly probes antiquarks of target and has simple final state

$$\frac{d^2\sigma^{DY}}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

Dimuon Acceptance



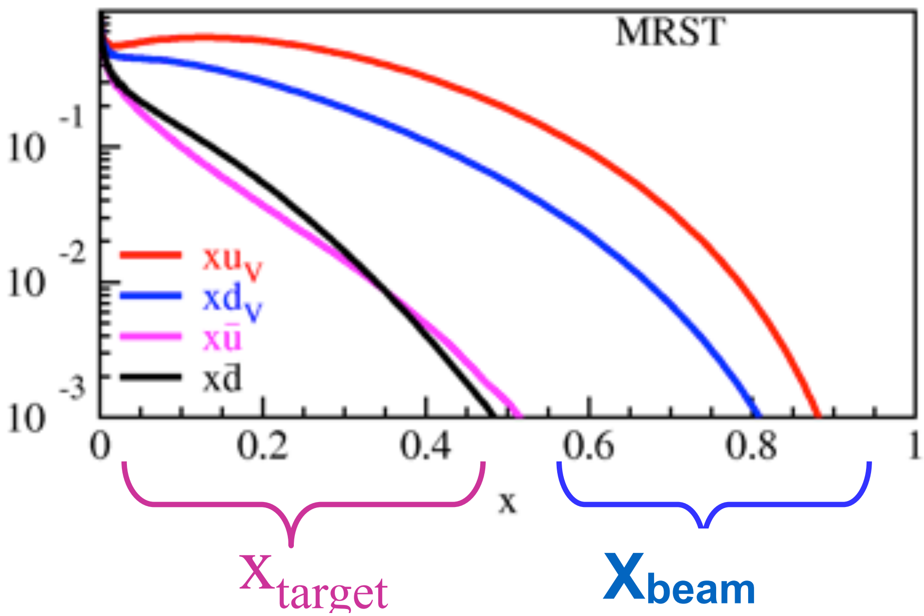


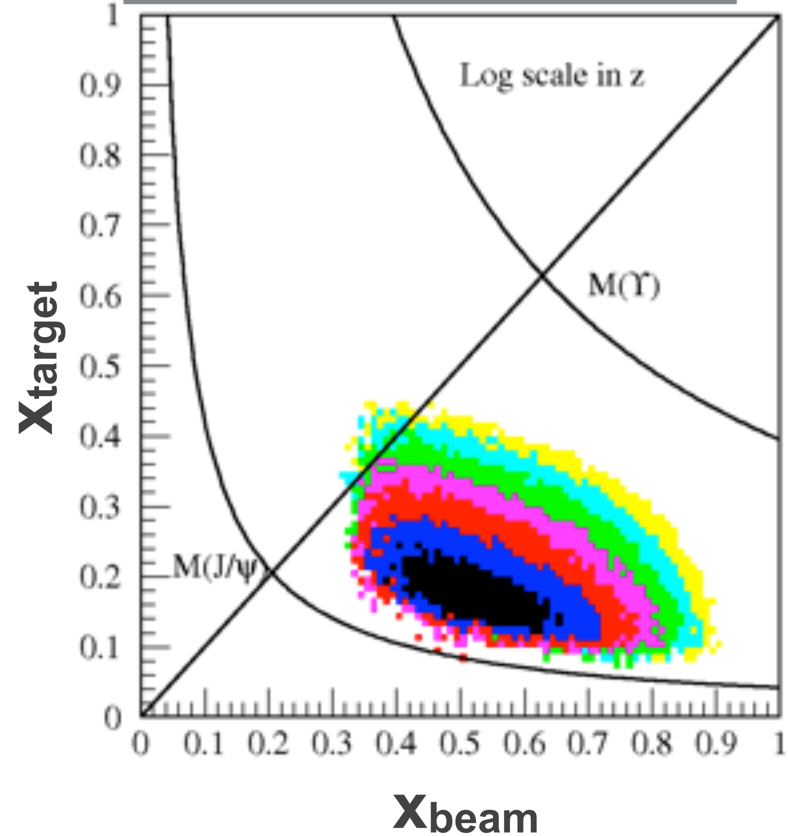
- DY directly probes antiquarks of target an

$$\frac{d^2\sigma^{DY}}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b}\frac{1}{s} \times \sum_i e_i^2 \left[\cancel{q_{ti}(x_t)\bar{q}_{bi}(x_b)} + \bar{q}_{ti}(x_t) q_{bi}(x_b)\right]$$

- Detector acceptance for fixed-target favors $x_b > x_t$

Dimuon Acceptance





- DY directly probes antiquarks of target an

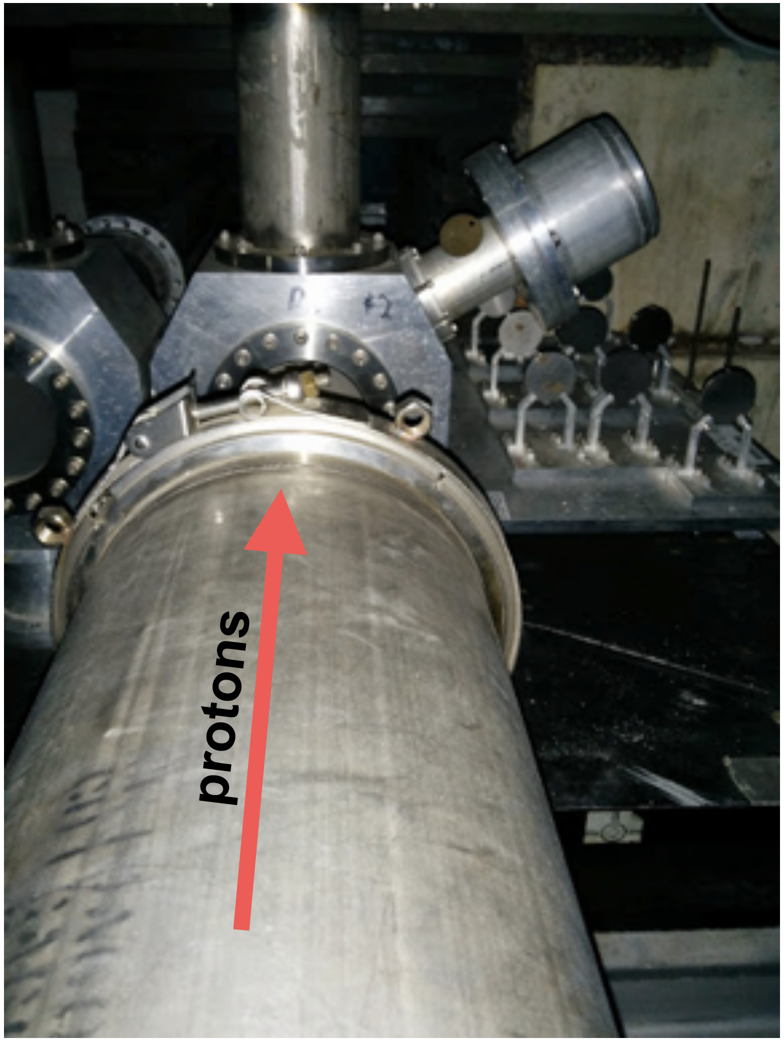
Beam quark strikes **target antiquark**

- Detector acceptance for fixed-target favors $x_b > x_t$

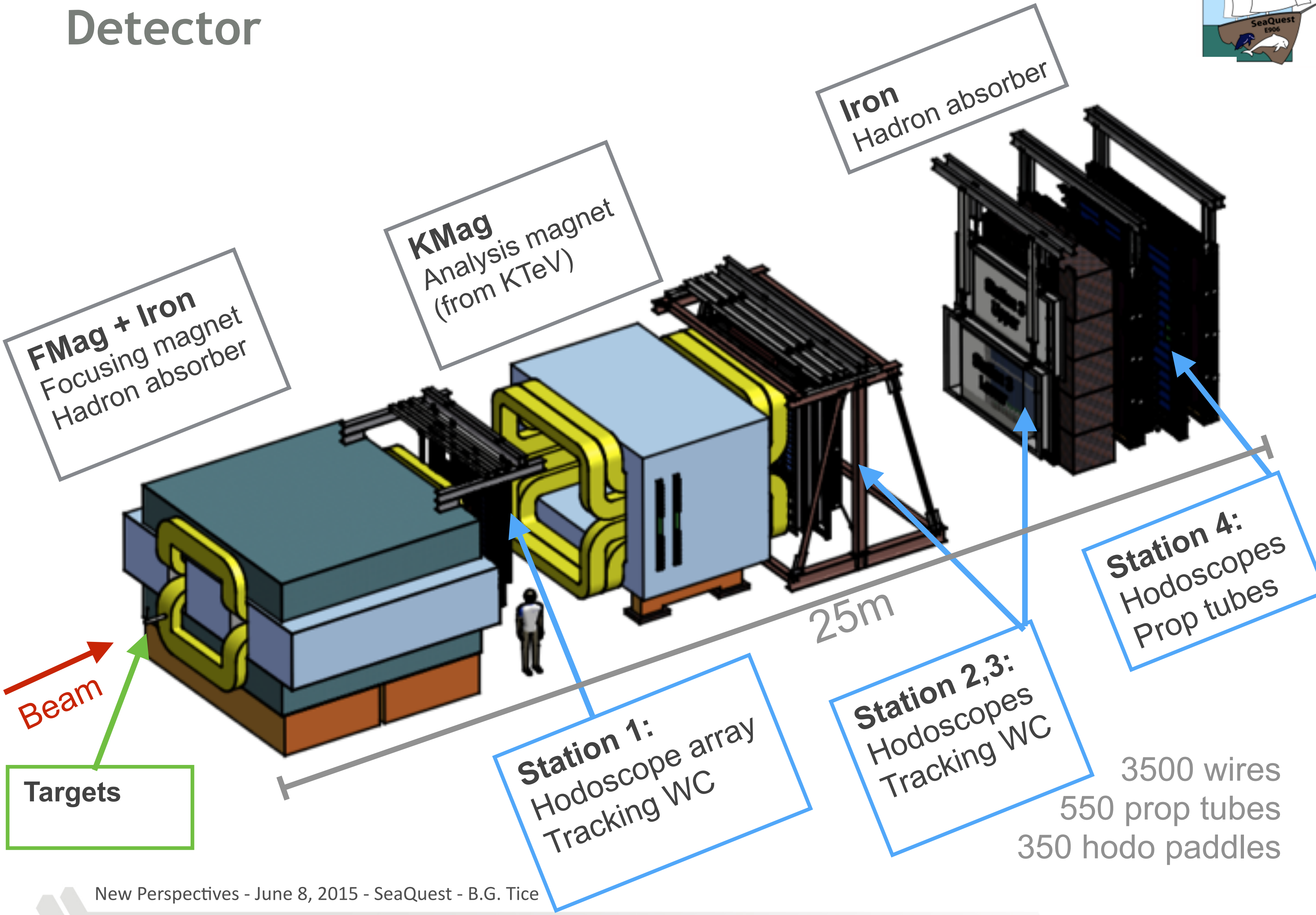
$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Targets

- 2 liquid targets: **hydrogen** and **deuterium**
  - 20” long, 3” diameter
- 3 solid targets: **carbon**, **iron**, **tungsten**
- Background subtraction: empty flask, nothing
- All targets <15% interaction length
- Beam time split roughly:
  - LH2 - 44%
  - LD2 - 22%
  - C, Fe, W - 17%
  - Special background - 17%

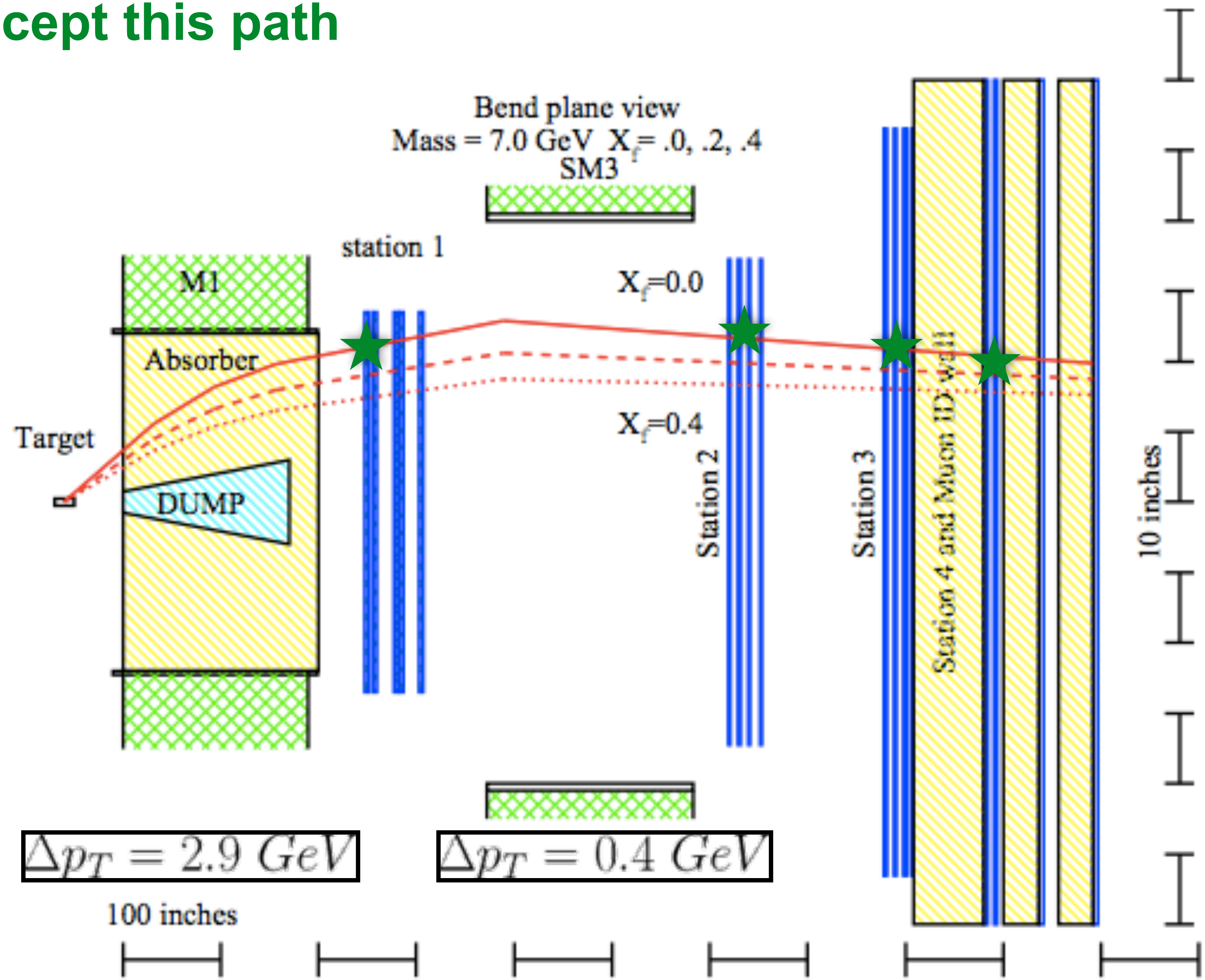


Detector

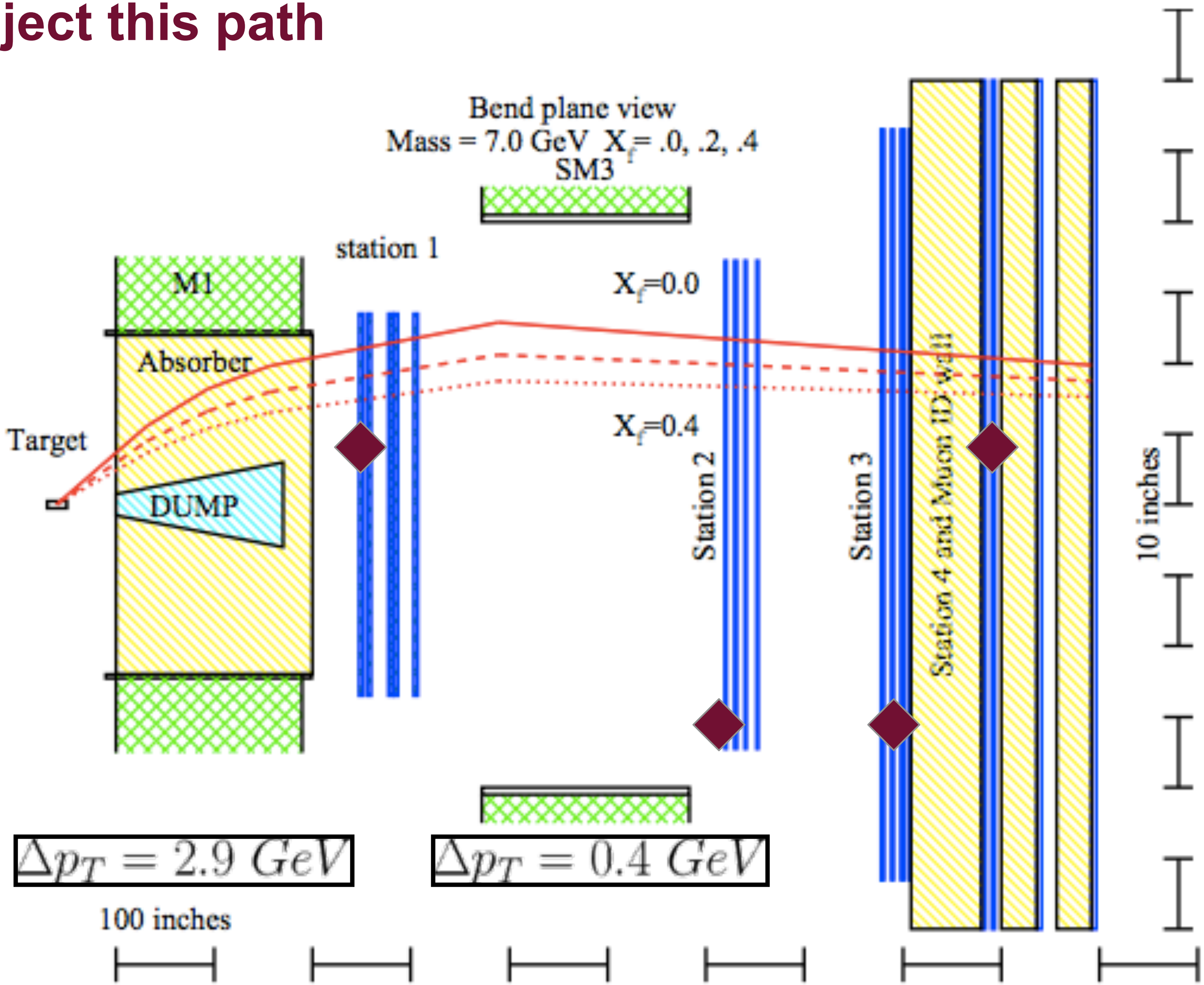


3500 wires
550 prop tubes
350 hodo paddles

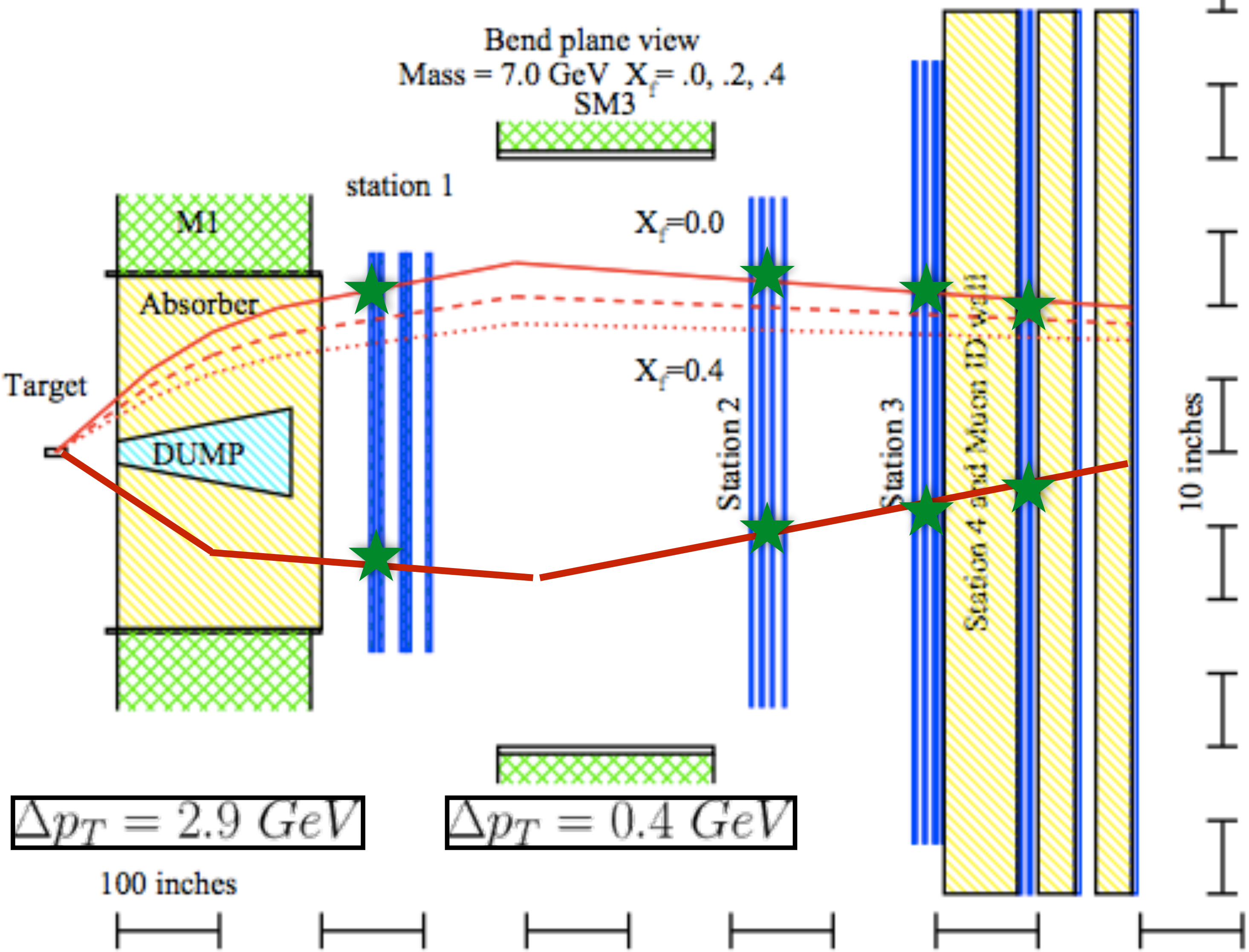
Accept this path



Reject this path



Signal is coincidence of + and - paths

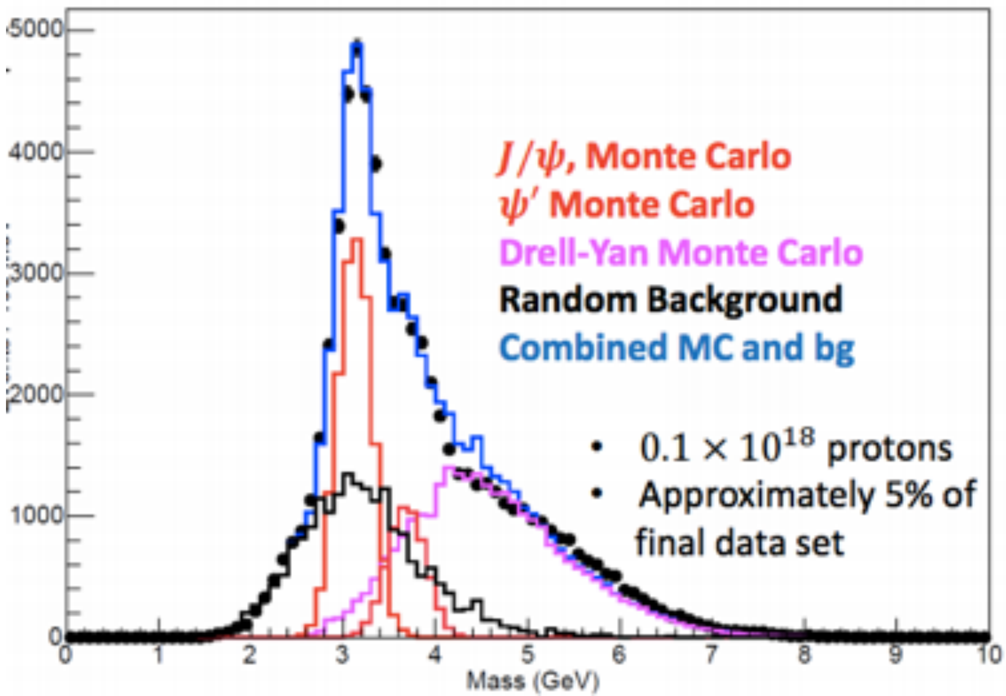


Run Plan

- Run I - Commissioning run Spring 2012
  - Discovered instantaneous beam problems, developed Cerenkov monitor
- Run II - Nov 2013 - August 2014
  - Continued commissioning through Feb 2014, then analyzable-quality data
  - **Collected ~2.5E17 analyzable protons!**
- Run III - Nov 2014 - present
  - Collect more analyzable quality data, beam quality improves
  - **Collected ~3.3E17 analyzable protons!**
  - New upgraded Station 1 wire chamber to be installed in coming months
  - Ends July 2015 for accelerator maintenance
- Run IV - future (Summer 2016?)
  - Continue to 2.5E18 protons (50% of proposed goal but enough)

Mass Distribution

- Background channels estimated with Geant, template fit to set absolute scale



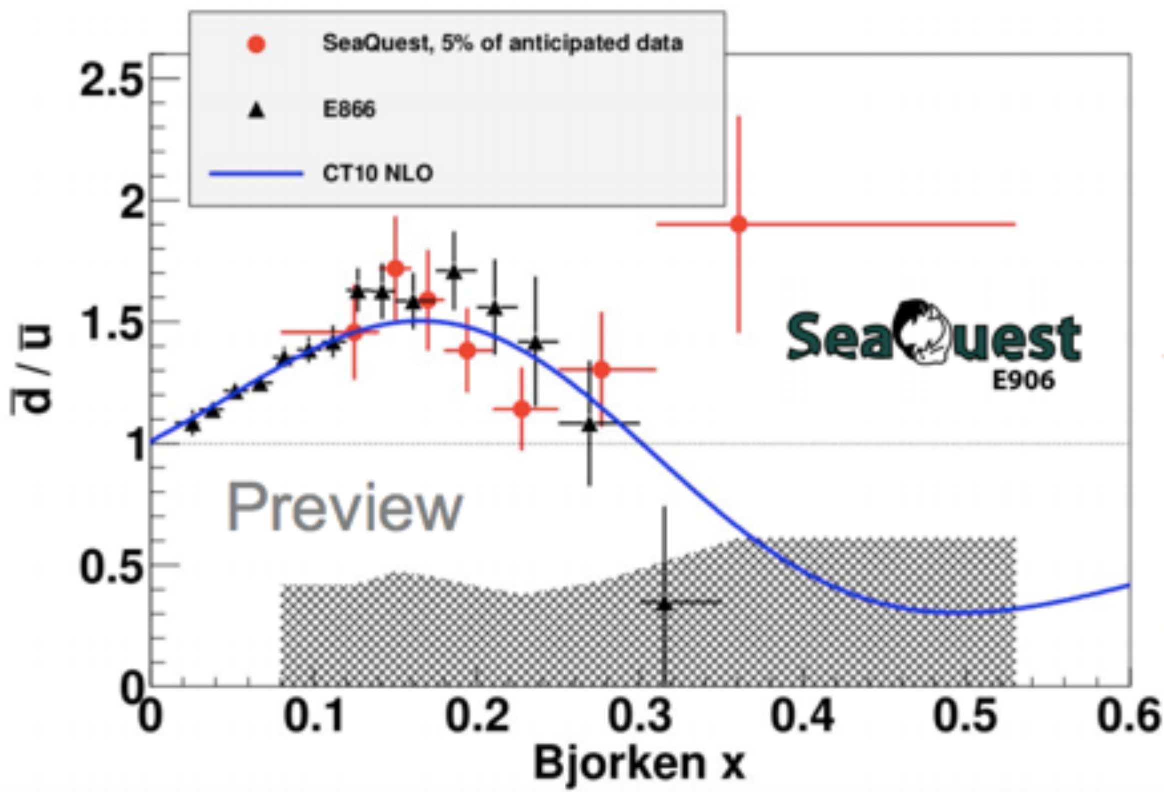
- Mass resolution ~180 MeV
- Can separate $J/\psi, \psi'$

- MC reproduces data
- Experiment works!

Preview of Flagship Measurement
Light Antiquark Flavor Asymmetry

$$\frac{\bar{d}(x_t)}{\bar{u}(x_t)}$$

- Includes 5% of expected statistics
- Know we are "in the ball park"
- Students working feverishly to include full dataset, reduce systematics
  - Eventually < 2% systematics

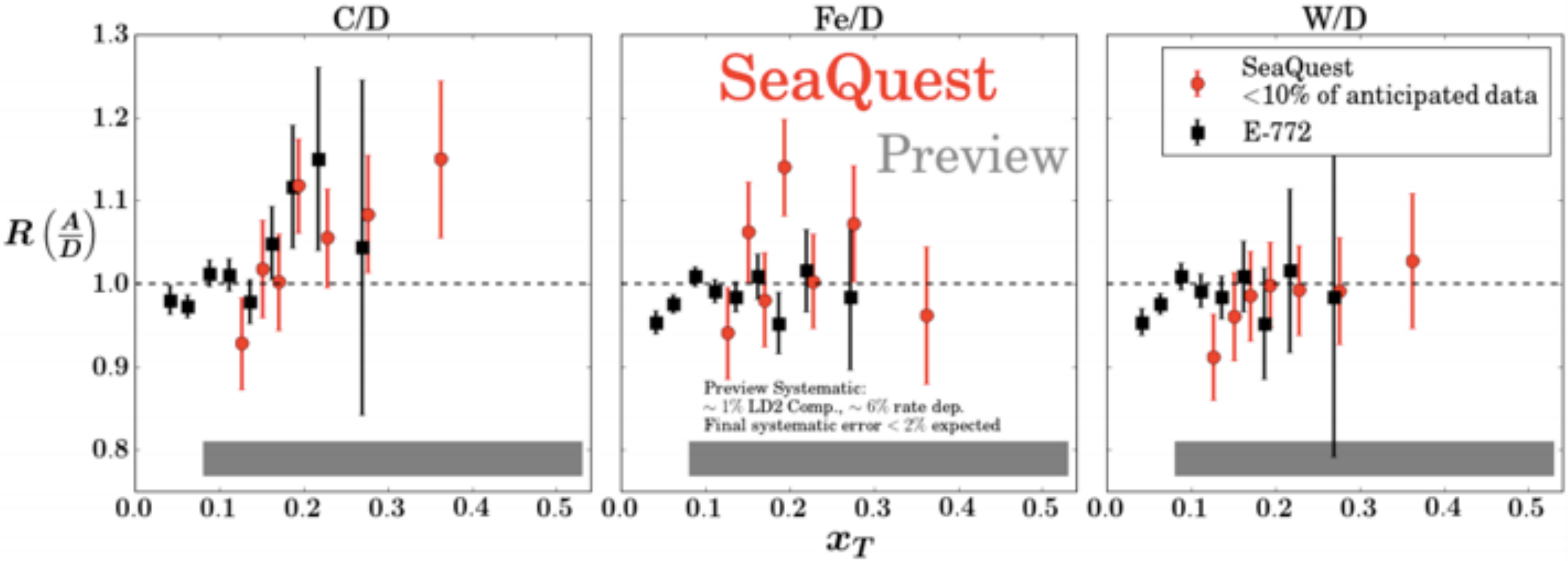


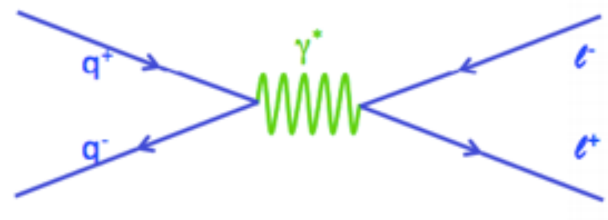
$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Preview of Flagship Measurement
Nuclear Dependence of Nucleon Sea

$$\frac{\sigma^C(x)}{\sigma^D(x)}, \frac{\sigma^{Fe}(x)}{\sigma^D(x)}, \frac{\sigma^W(x)}{\sigma^D(x)}$$

- Ratios of Drell-Yan cross section
- Uses <10% of expected statistics - already competitive with existing data





Conclusions

- SeaQuest is a running Fermilab experiment measure nucleon structure
- 120 GeV protons induce Drell-Yan on targets of H2, D2, C, Fe, W

- Physics goals include
  - Measure antiquark flavor asymmetry in nucleon sea
  - Measure nuclear dependence of antiquark distributions
  - …and much more!

$$\frac{\bar{d}(x_t)}{\bar{u}(x_t)}$$

$$\frac{\sigma^C(x)}{\sigma^D(x)}, \frac{\sigma^{Fe}(x)}{\sigma^D(x)}, \frac{\sigma^W(x)}{\sigma^D(x)}$$

- 5% of data for $\frac{\bar{d}(x_t)}{\bar{u}(x_t)}$ analysis made public
- Planning for preliminary results this year

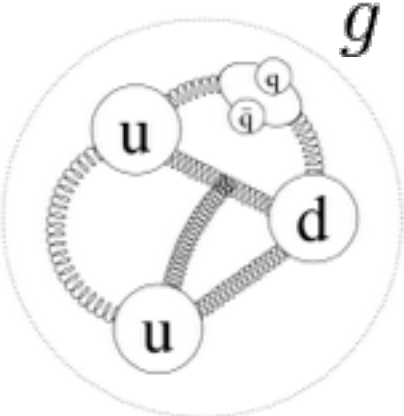
- Successor experiments add spin:
  - E1039: Drell-Yan with polarized target
  - E1027: Drell-Yan with polarized Main Injector

Backup

Explanations for Origin of Nucleon Sea

Gluon Splitting

$$g \rightarrow q\bar{q}$$

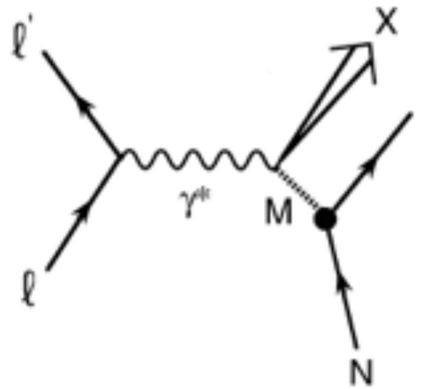


R.S. Towell - FERMILAB-THESIS-1999-26

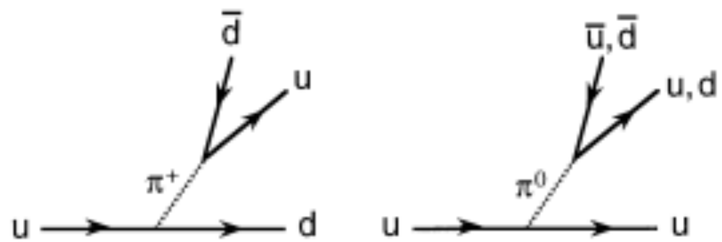
Meson Cloud

i.e. Sullivan Process in DIS

$$p \rightarrow \pi^{+} + n, \pi^{0} + p, \pi^{-} + \Delta^{++}, \ldots$$



Chiral Models



Diagrams: S.Kumano

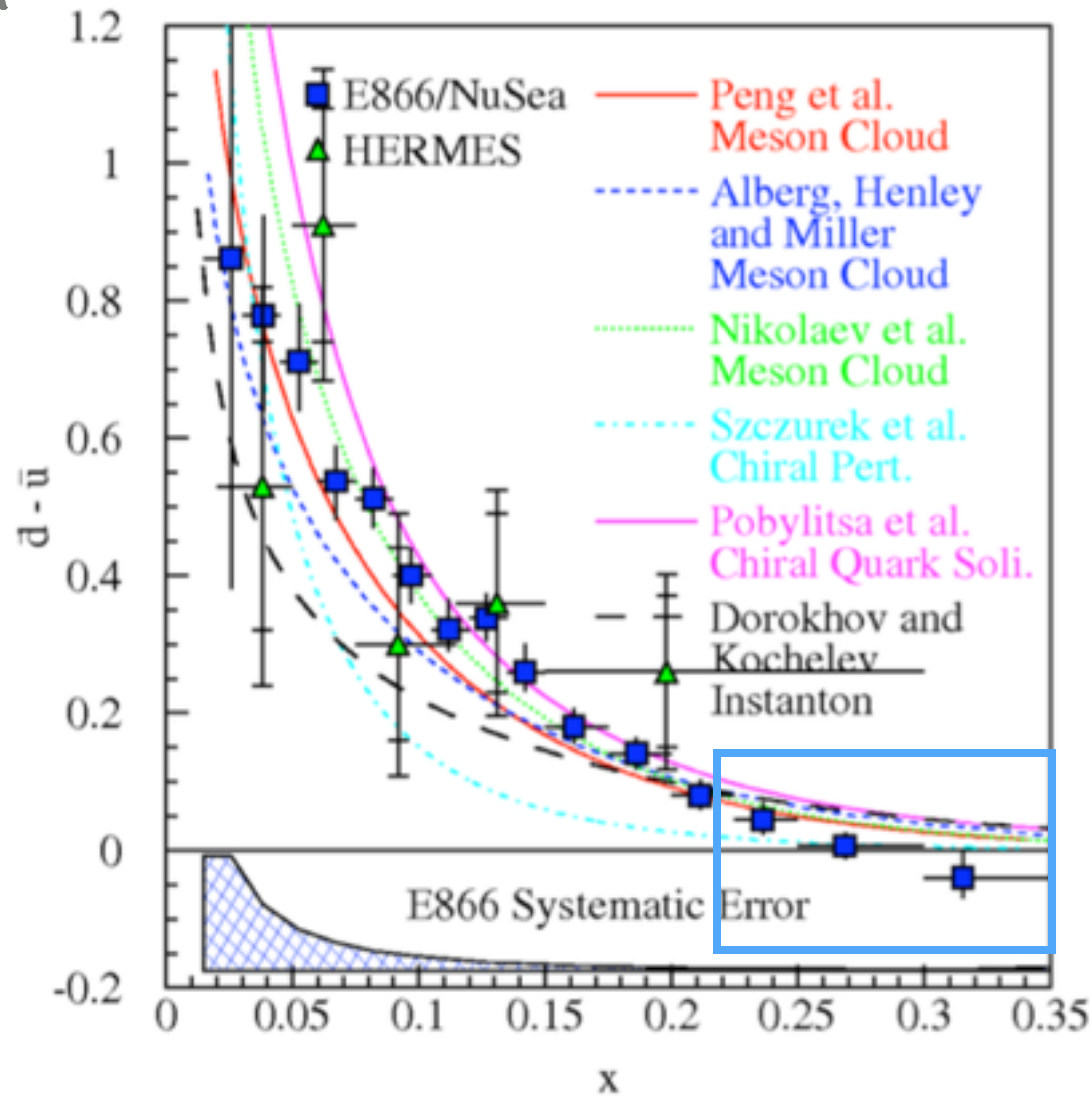
Fermilab E866/NuSea

- Similar Drell-Yan experiment

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

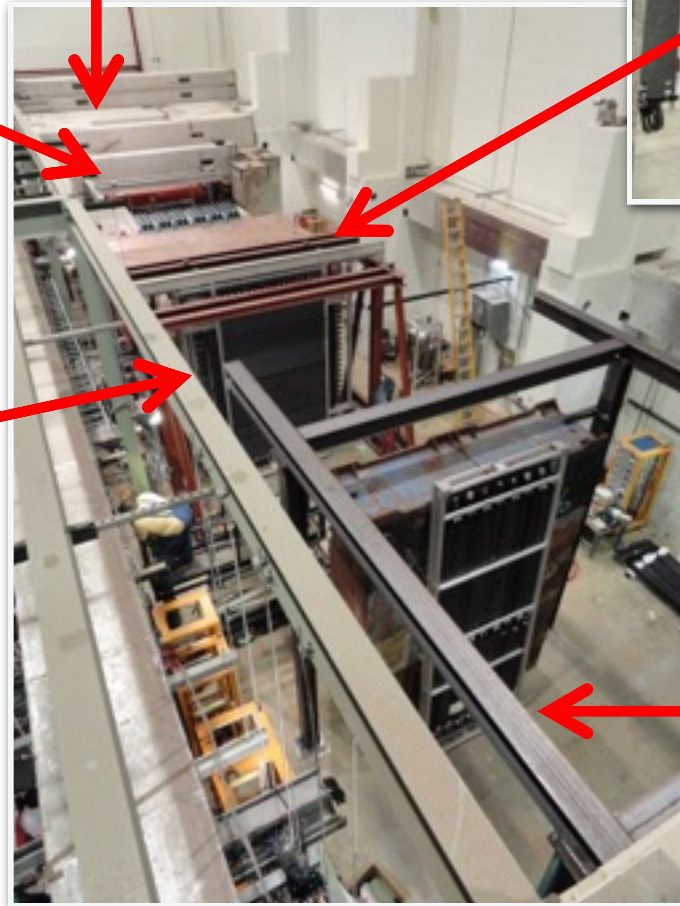
Antiquark flavor asymmetry decreases at higher x

E.A.Hawker et al., PRL 80, 17 (1998)

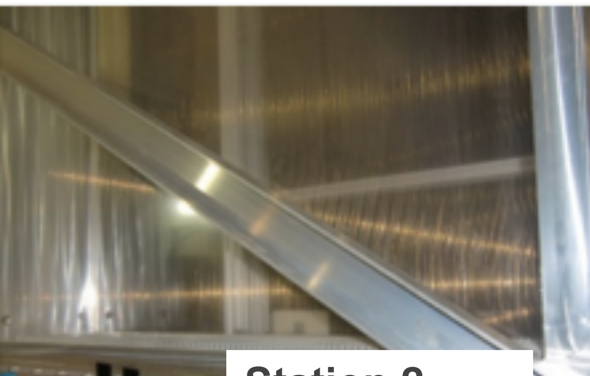


Beam comes from here

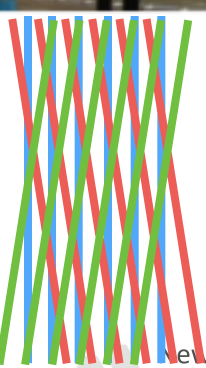
Station 1
FMag
Beam Dump
Hodoscopes



KMag
(KTev)

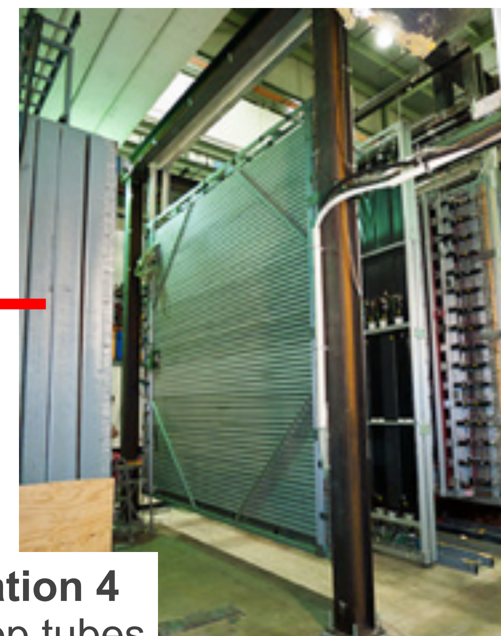


Station 2
Wire Chamber



resolution < 0.4 mm

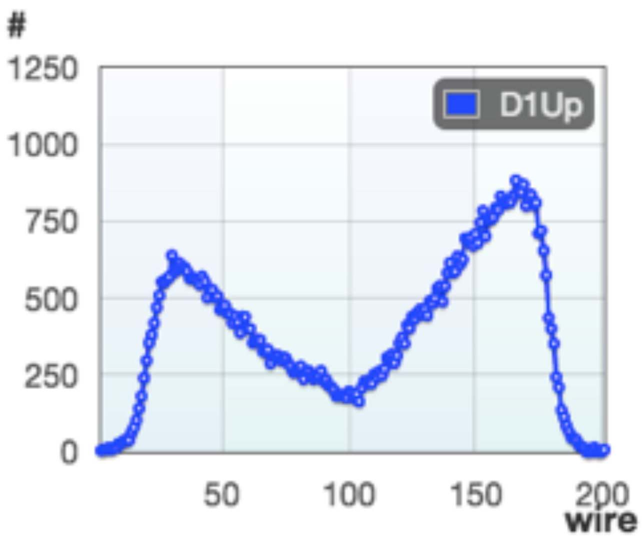
note: pictures taken during construction



Station 4
Prop tubes

Web Monitoring

- Online decoding and web monitoring provide hit distributions with ~10s delay, viewable from home

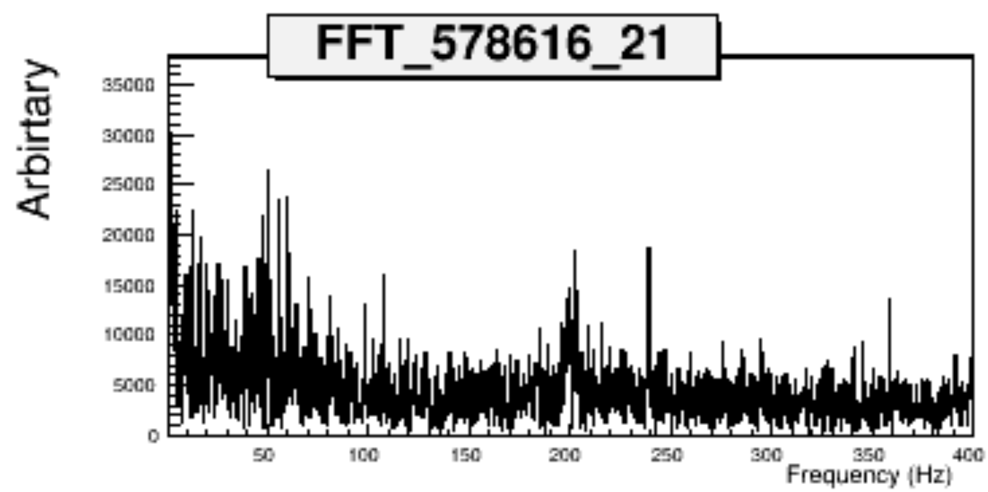


MainDAQ Status

Last Updated: 2015-04-06 10:40:03

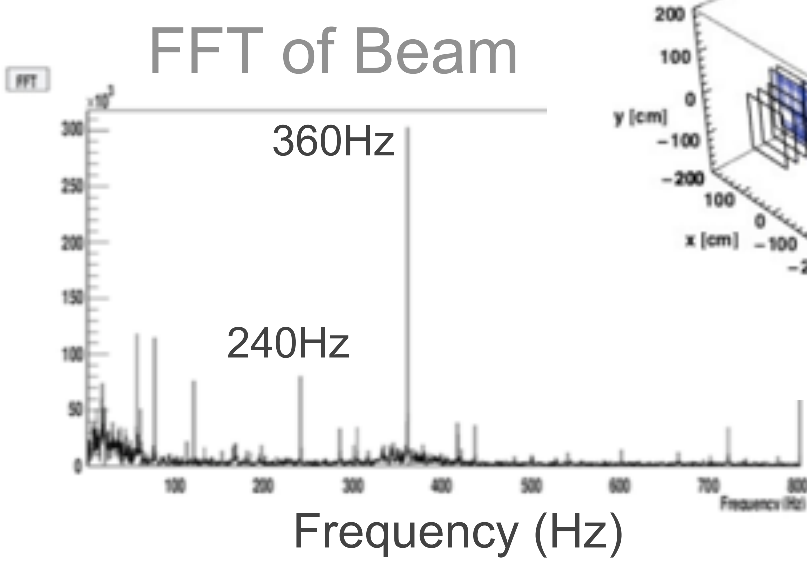
Coda EventBuilder Alive?	Yes
Coda EventReader Alive?	Yes
Run Number	14320
Run Started	10:23:28
Run Ended	0
Run State	active
All components OK?	Yes
File Size (GB)	0.30

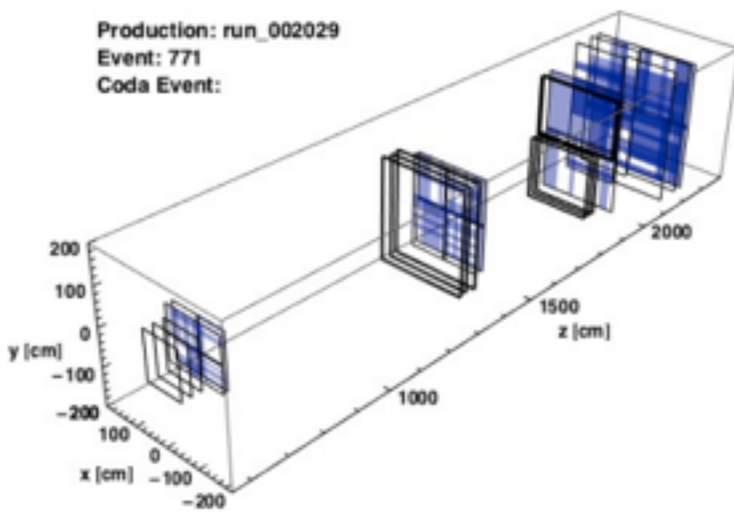
- Critical Beam and DAQ properties displayed on web page

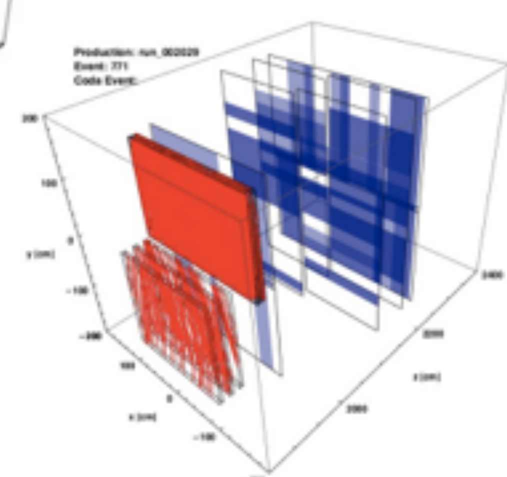


Early Beam Difficulty

- Large variations in instantaneous beam intensity during commissioning (2013)
- Far too many channels register hits -> backgrounds dominate

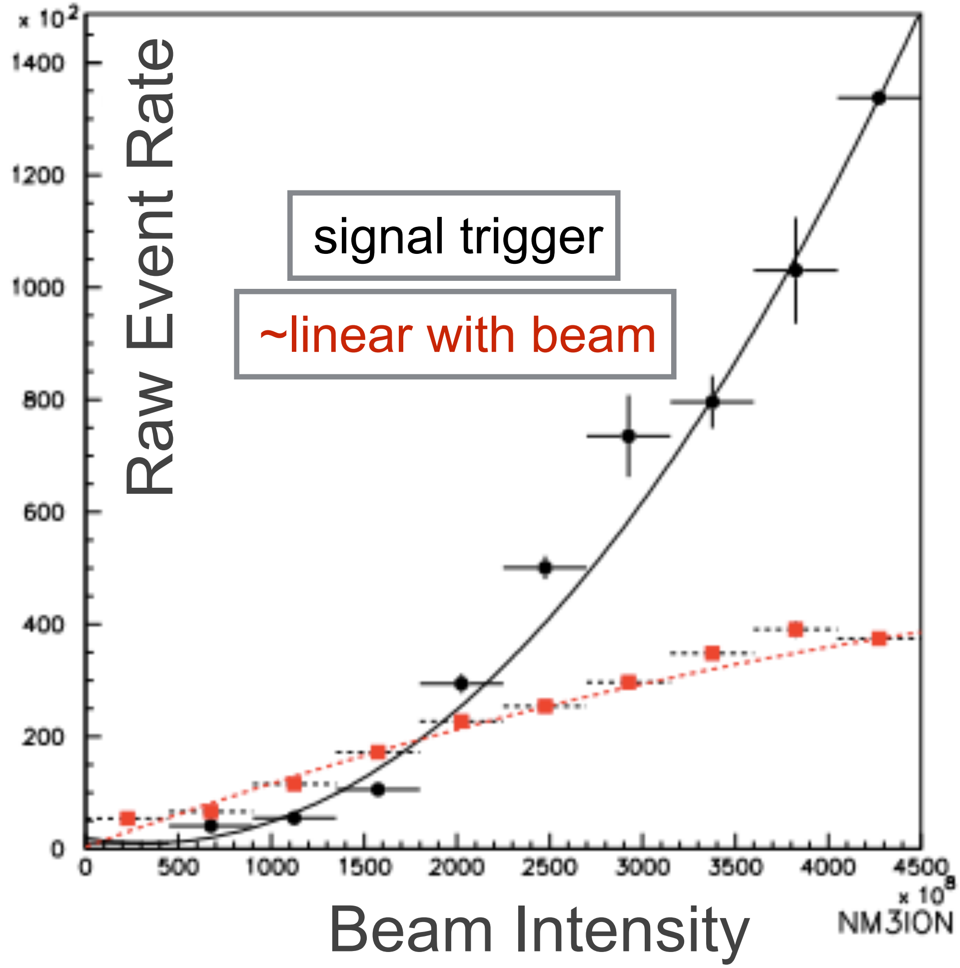






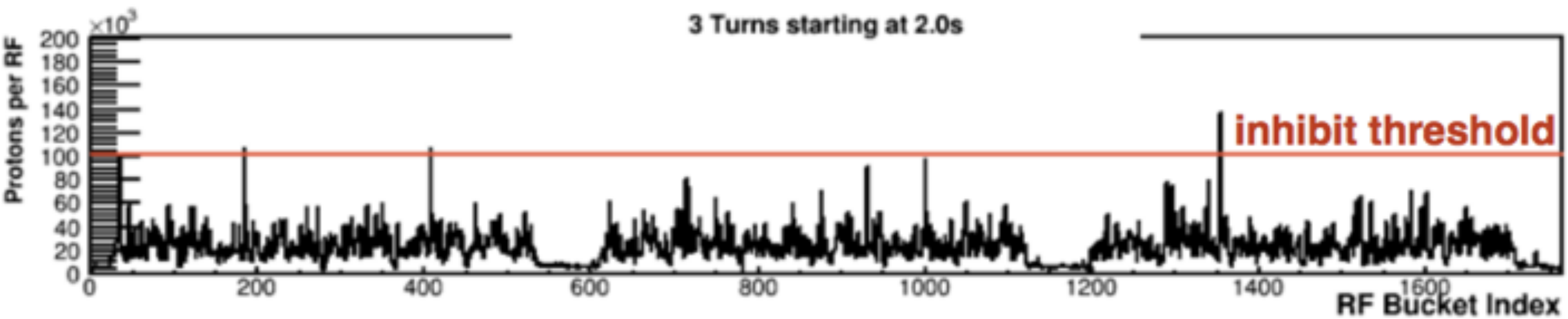
Intensity-Dependent Event Rate

- Large "combinatorial" background
  - So many single muons that trigger for signal dimuon is satisfied
- This background is very sensitive to rate
- In addition, tracking algorithms don't scale well to high occupancy



Beam line Cherenkov Monitor
Beam Inhibit

- Monitor 53MHz structure of beam with Cherenkov detector in beam line
- Signal:Background is reasonable up to ~100,000 protons per bucket
- If rf bucket has more than this -> Inhibit trigger
  - Typically **~40% of beam is inhibited** for being near very high bucket
- Monitor directly measures number of protons for which trigger was live



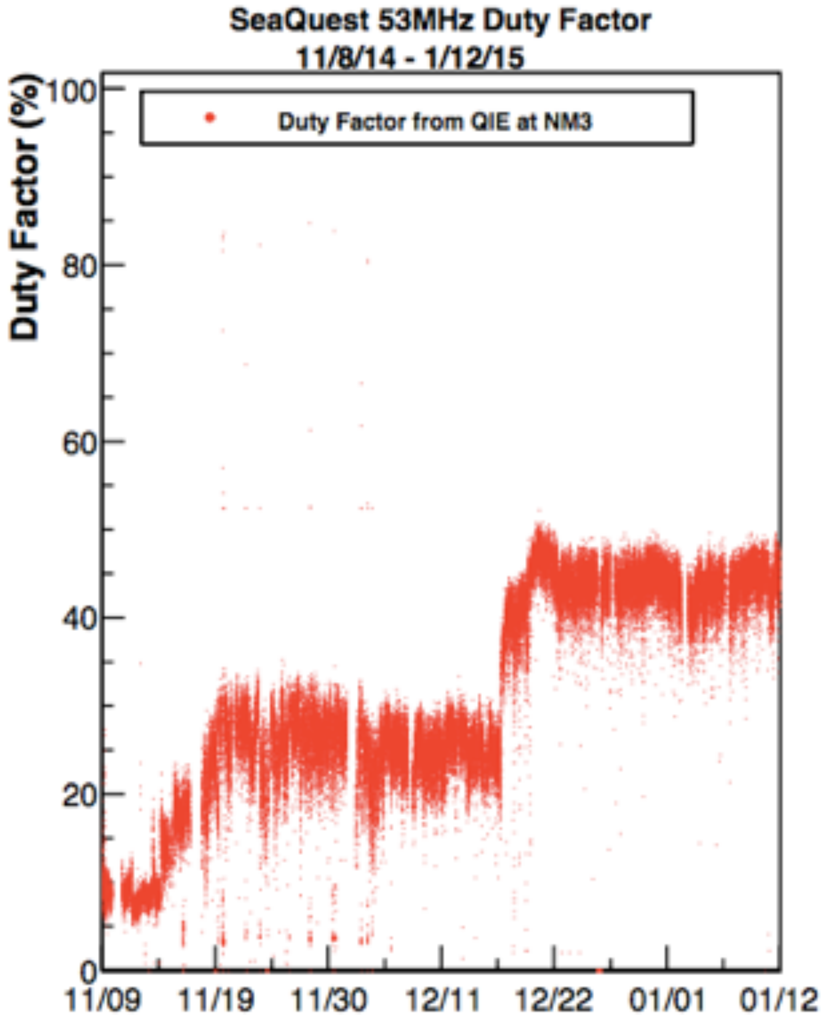
Beam Improvements

- Duty factor is measure of consistency in intensity per 53MHz rf bucket

$$\frac{<I>^2}{<I^2>}$$

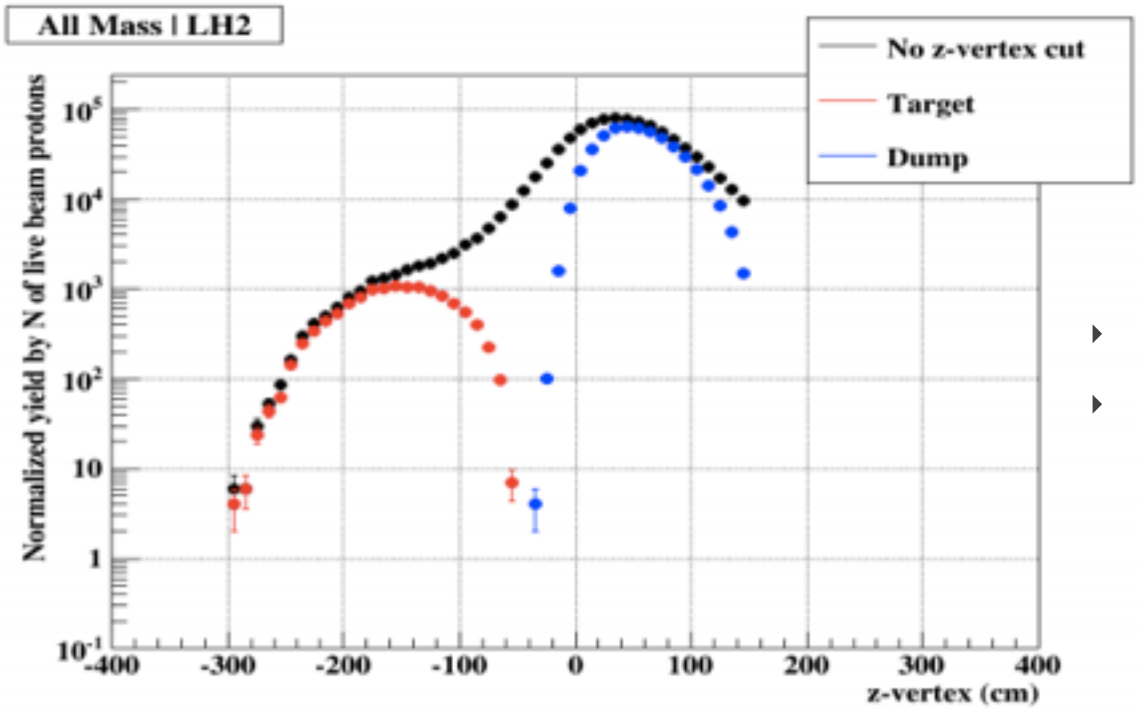
- The greater the intensity varies within a spill, the lower the duty factor
- Perfect is 86% since small some rf buckets are intentionally empty

- Dec 2014: increase from 27% -> 44%
  - “Wildman” parameter was adjusted
- Greatly improves signal/background



Separating Target from Beam Dump

- About 85% of protons interact in the beam dump, not the targets
- Rely on trigger system to minimize contribution from dump backgrounds
- Use vertex position to assign event to target or dump

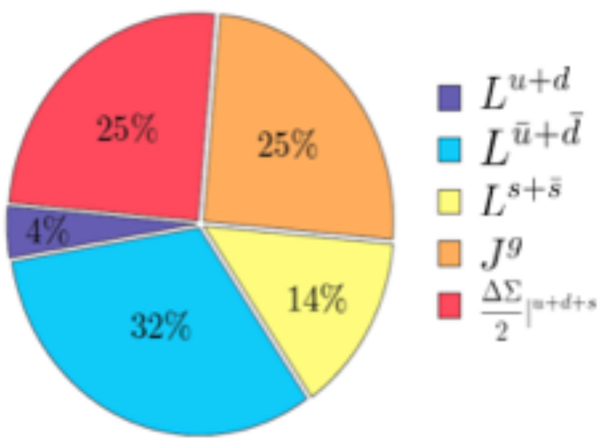


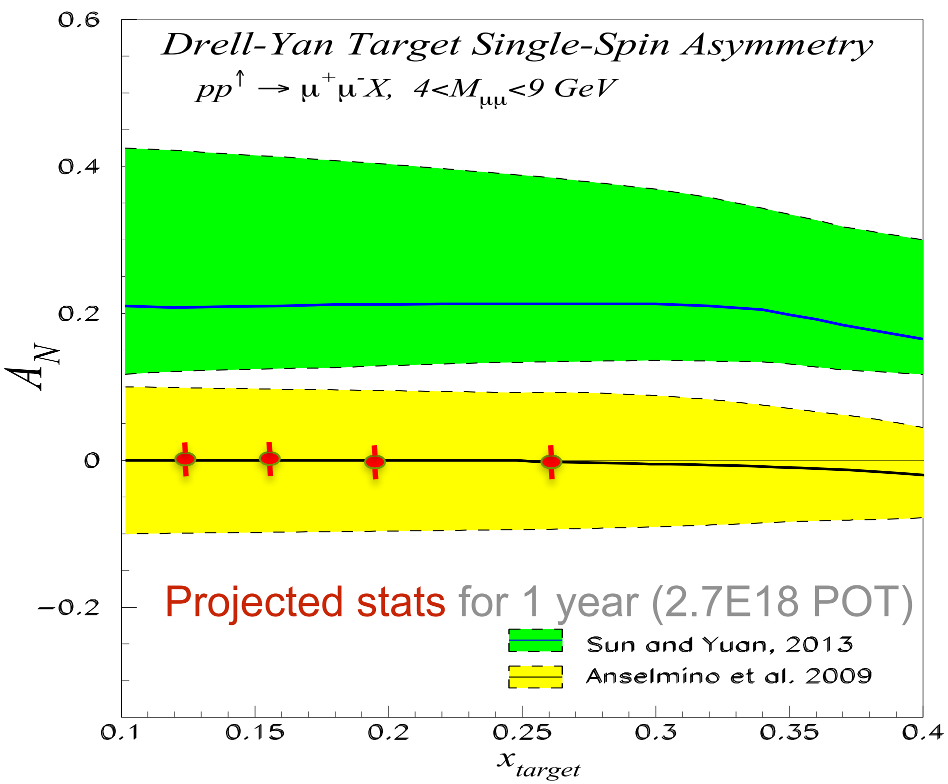
- If dump events are in target sample
- Subtract measured event rate in:
  - empty flask (for H2, D2)
  - no target (for C, Fe, W)

Future: E1039 - Drell-Yan with Polarized Target

- Where does the proton get its spin?
  - Large contribution of orbital angular momentum from nucleon sea

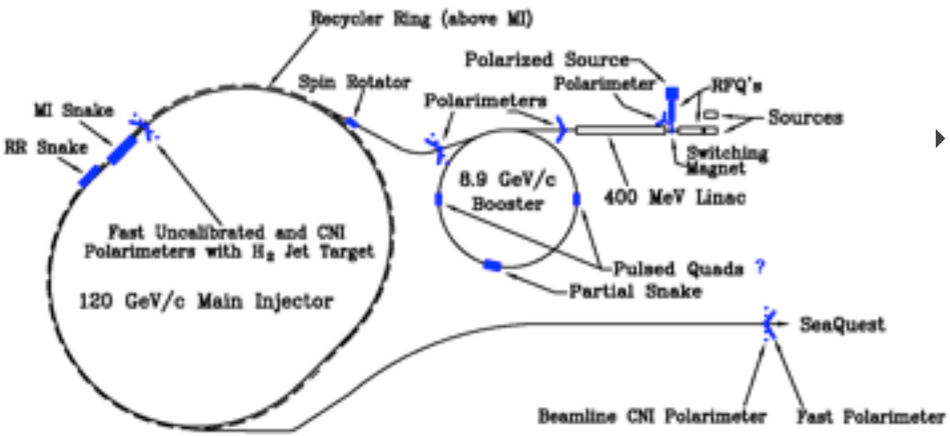
Lattice QCD: K.-F. Liu *et al* arXiv:1203.6388



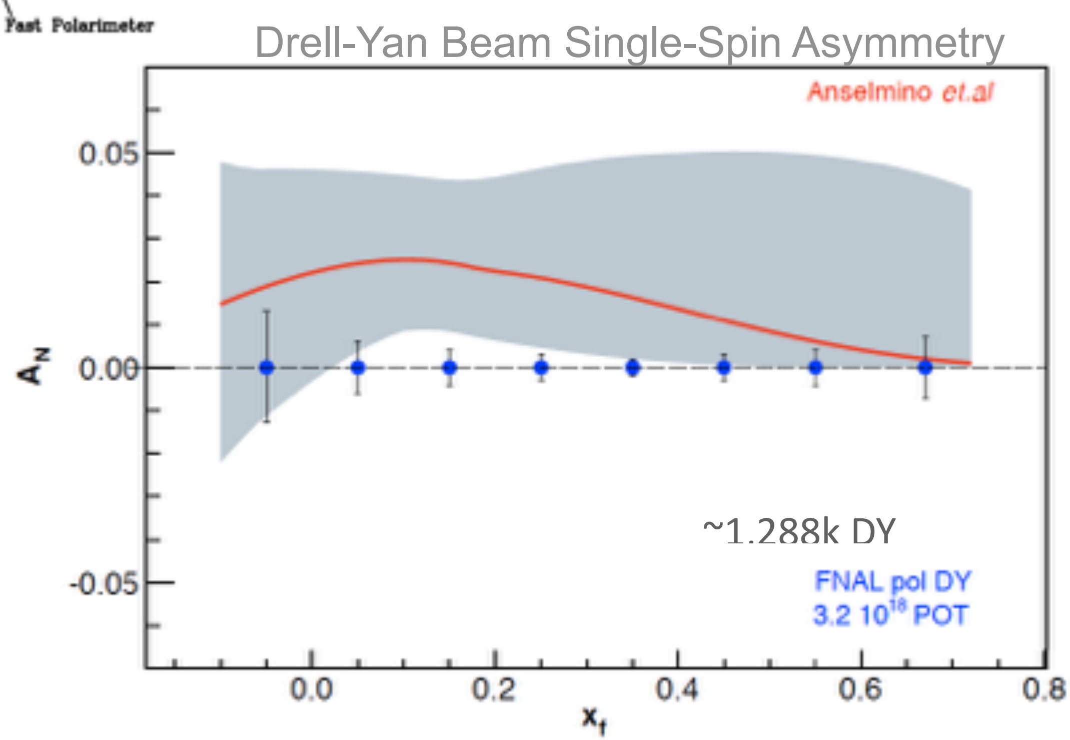


- "Repeat" SeaQuest with **polarized NH_3**
- First sea quark Sivers measurement

Future: E1027 - Drell-Yan with Polarized Beam



- Polarize Main Injector and "repeat" SeaQuest to measure valence contribution to orbital angular momentum



- Similar measurements with SIDIS from HERMES, COMPASS
- SIDIS vs Drell-Yan is strong test of QCD gauge formulation and factorization
- Fundamental prediction is:

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