Opportunities with polarized Drell-Yan at Fermilab

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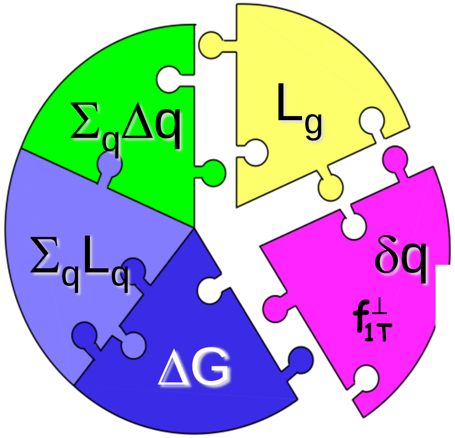
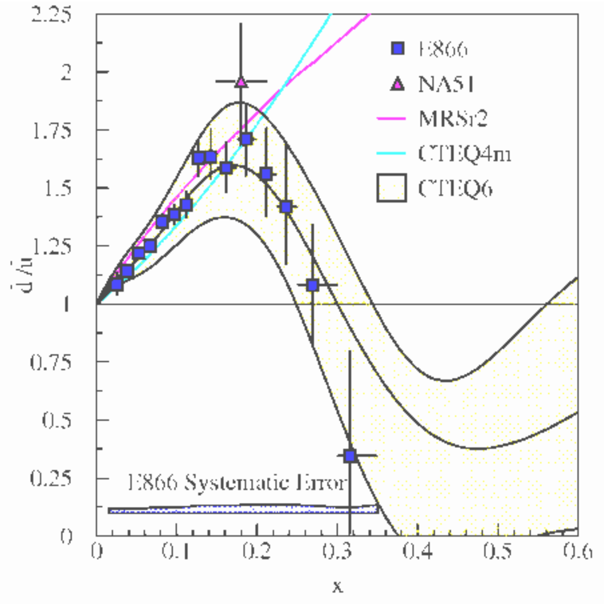
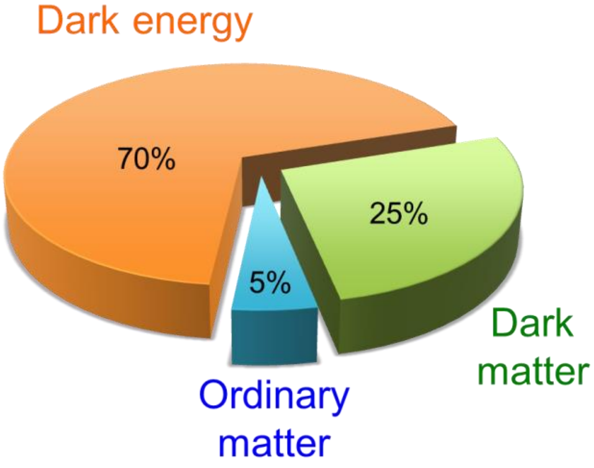
COMPASS Beyond 2020
(21-March-2016)



SeaQuest





$$\boxed{f_{1T}^{\perp}\Big|_{DIS} = - f_{1T}^{\perp}\Big|_{DY}}$$

This work is supported by

Current and Future D-Y Program at FNAL

Unpolarized Beam and Target w/ SeaQuest detector

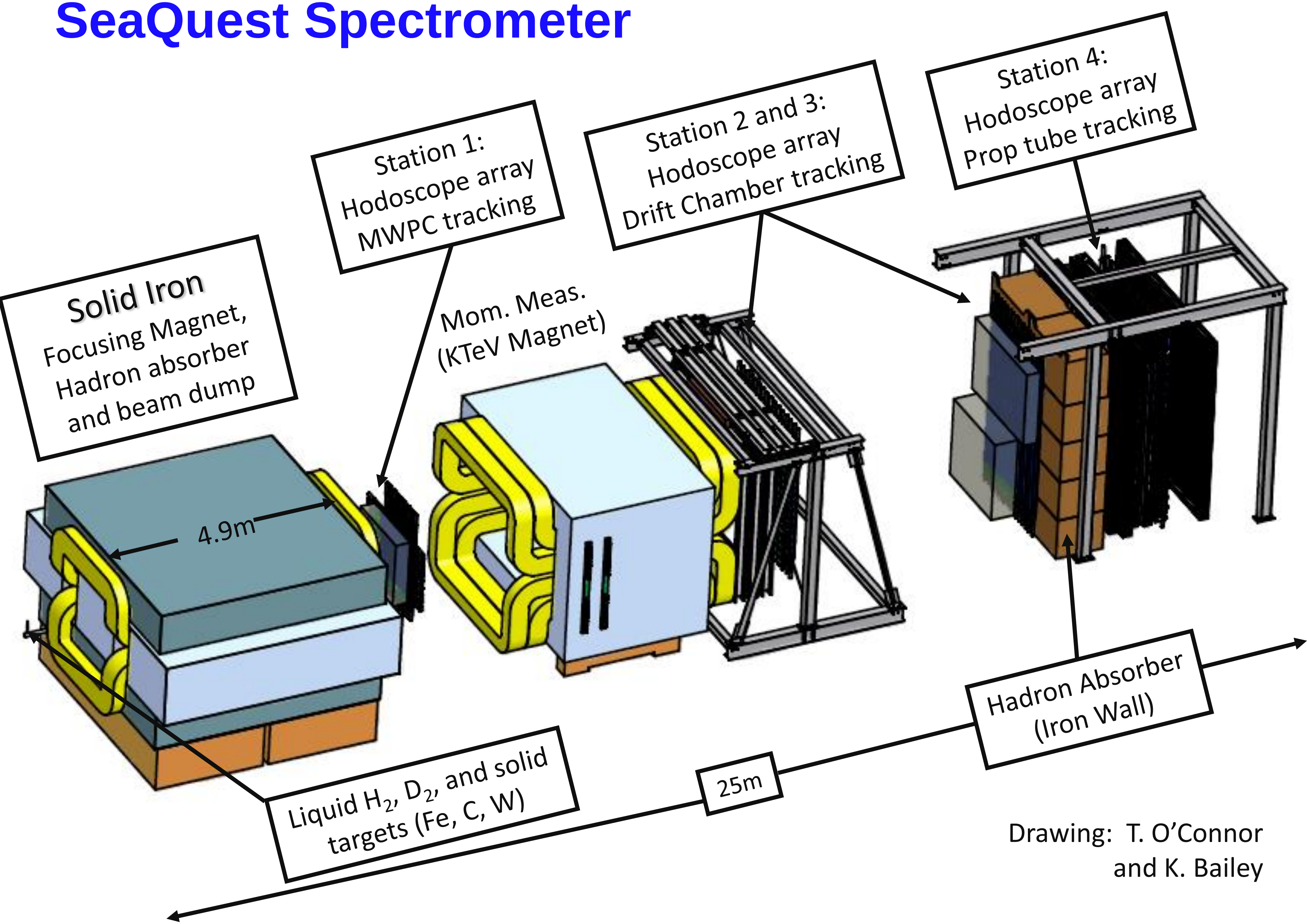
- **E-906**: 120 GeV p from Main Injector on LH_2,LD_2, C,Fe,W targets → **high-x Drell-Yan**
- Science data started in March 2014
  - ➡ run for 3 yrs
  - ➡ preview

Polarized Beam and/or Target w/ SeaQuest detector

→ **high-luminosity** facility for **polarized Drell-Yan**

- **E-1039**: SeaQuest w/ pol NH_3 target (2018-2019)
  - ➡ probe sea quark distributions
- **E-1027**: pol p beam on (un)pol tgt (2020-2021?)
  - ➡ **Sivers sign change** (valence quark)

SeaQuest Spectrometer



Solid Iron
Focusing Magnet,
Hadron absorber
and beam dump

Station 1:
Hodoscope array
MWPC tracking

Mom. Meas.
(KTeV Magnet)

Station 2 and 3:
Hodoscope array
Drift Chamber tracking

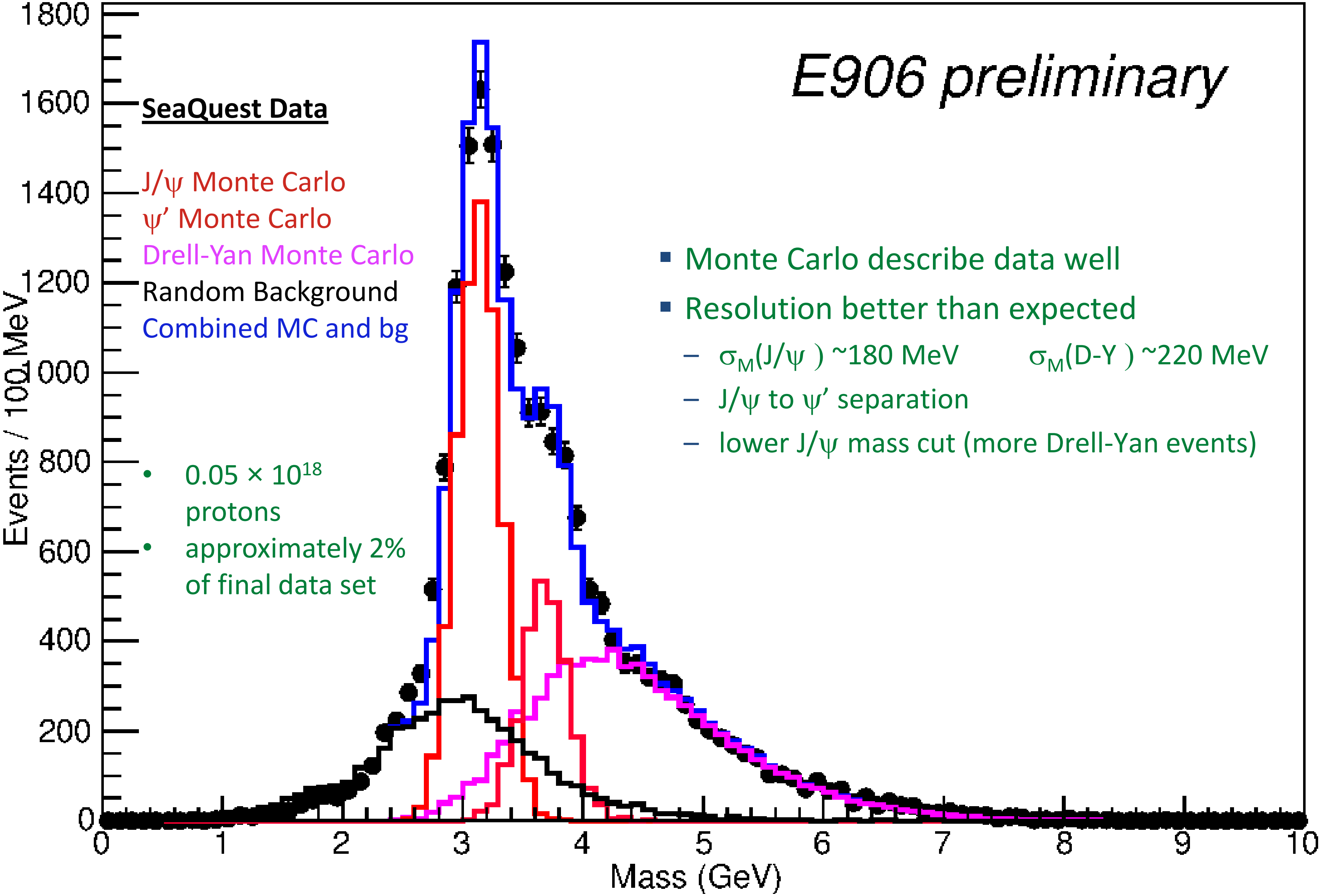
Station 4:
Hodoscope array
Prop tube tracking

Hadron Absorber
(Iron Wall)

Liquid H_2, D_2, and solid
targets (Fe, C, W)

Drawing: T. O'Connor
and K. Bailey

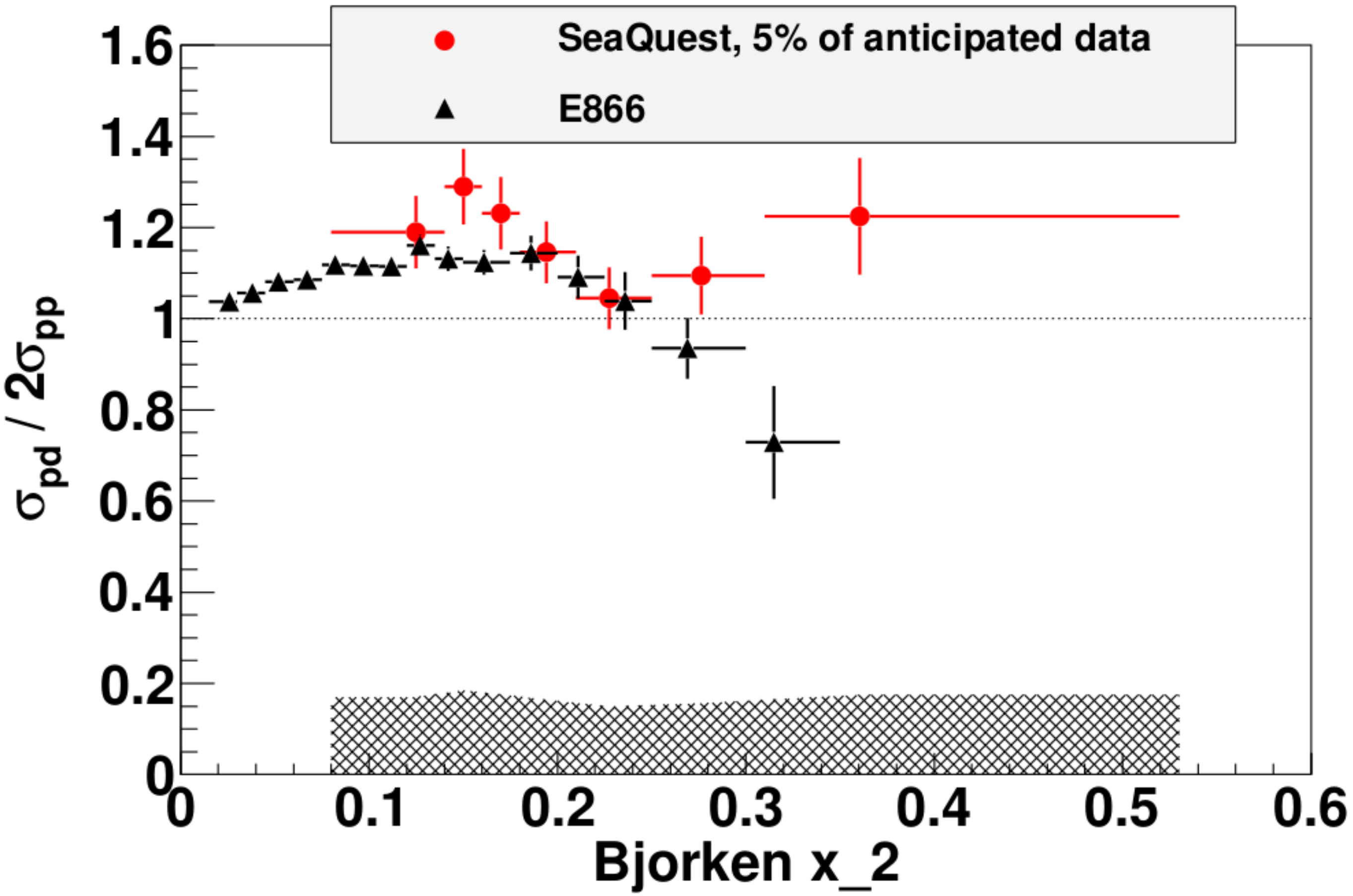
Data From FY2014



- Monte Carlo describe data well
- Resolution better than expected
  - $\sigma_M(J/\psi)$ ~180 MeV $\sigma_M(D\text{-}Y)$ ~220 MeV
  - J/ψ to ψ’ separation
  - lower J/ψ mass cut (more Drell-Yan events)

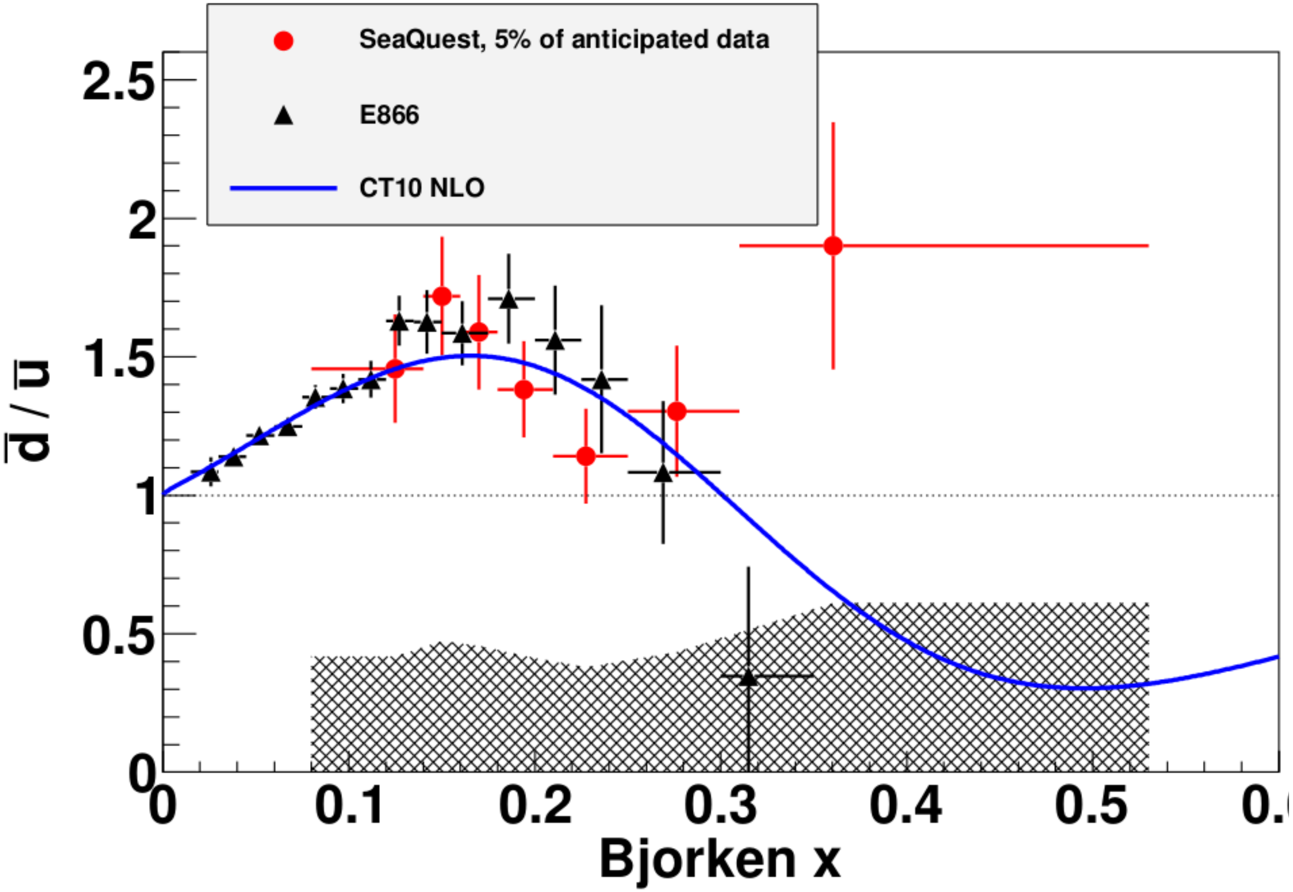
- 0.05×10^{18} protons
- approximately 2% of final data set

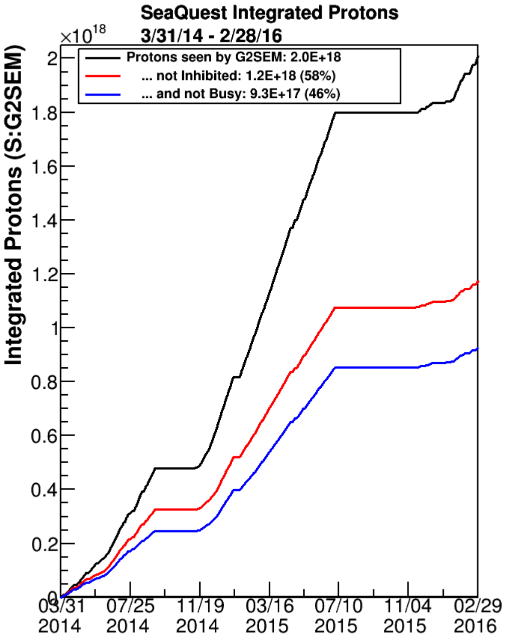
SeaQuest Cross Section Ratio (Preview)



- data presented by Bryan Kerns at April 2015 APS
- **Caution**: rate-dependence not included (still being studied)

SeaQuest Leading Order extraction (Preview)

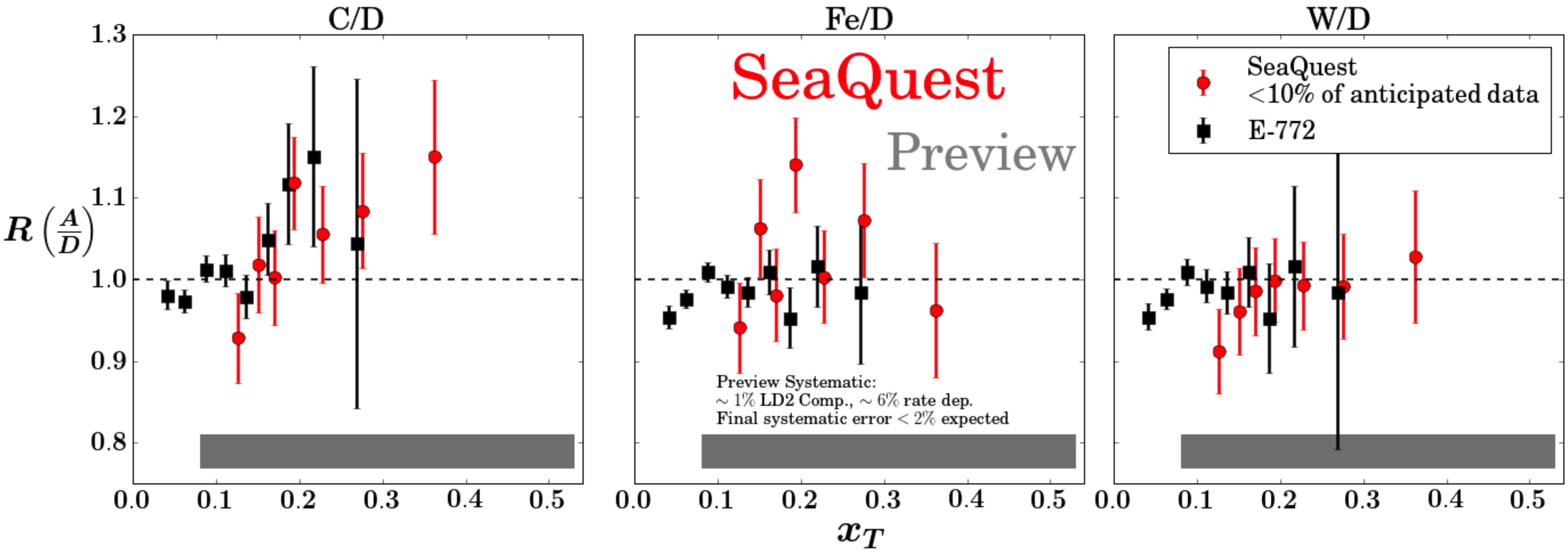




- plot based on fewer than 0.1 × 10^{18} protons (live)
- 20x more data recorded (1 × 10^{18}) so far
- anticipate total of 1.4 × 10^{18} protons by July 2016
- approved for 5 × 10^{18} pot

SeaQuest Nuclear Dependence (Preview)

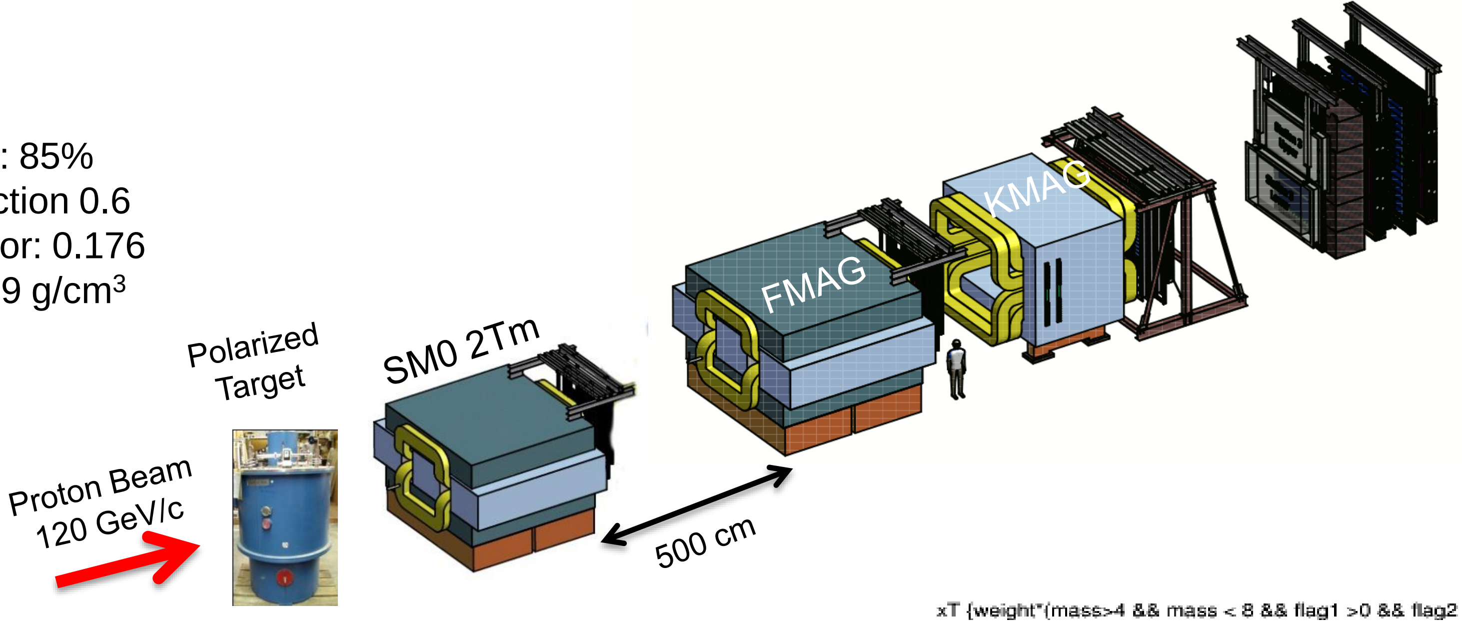
- data Presented by Bryan Dannowitz at April 2015 APS
- no antiquark enhancement apparent
- 10% of anticipated statistical precision
- increased detector acceptance at large-x_T to come (new D1 chamber)



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

Let’s Add a Polarized Target (E-1039)

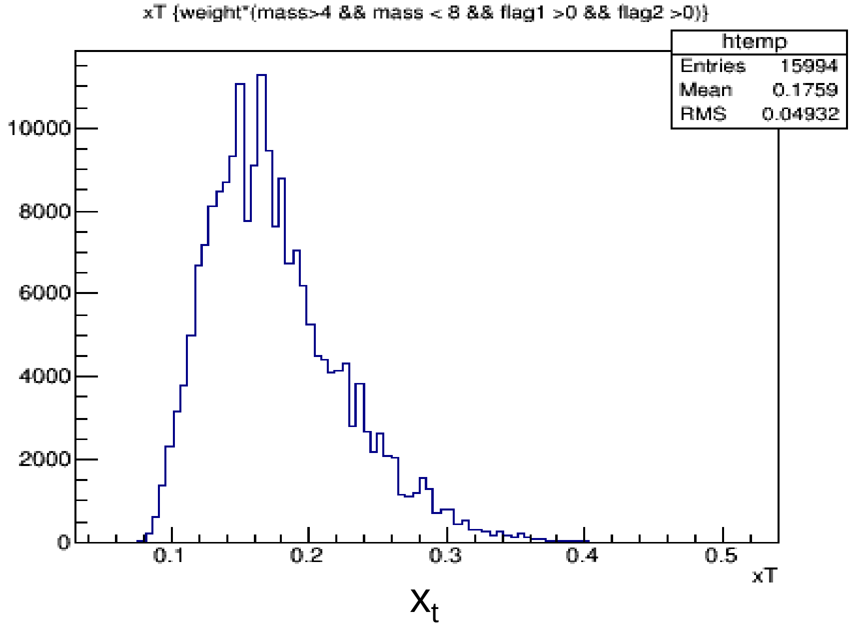
Target
Polarization: 85%
Packing fraction 0.6
Dilution factor: 0.176
Density: 0.89 g/cm^3



- use current SeaQuest setup, a polarized proton target, unpolarized beam
- add third magnet SM0 ~5m upstream

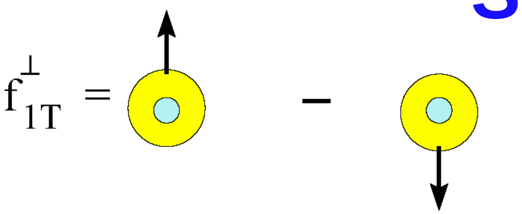
- improves dump-target separation
- moves $\langle x_t \rangle$ from 0.21 to 0.176
- reduces overall acceptance
- additional shielding

- installation in summer 2017
- supported with Los Alamos LDRD funds



Ref: Andi Klein (LANL)

Sivers Function and Spin Crisis



cannot exist w/o quark **OAM**

- describes transverse-momentum distribution of unpolarized quarks inside transversely polarized proton
- captures non-perturbative spin-orbit coupling effects inside a polarized proton

$$\boxed{\begin{array}{l}\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L \\ \Delta\Sigma = \Delta u + \Delta d + \Delta s\end{array}}$$

$$^{1}\!/_{2}\,\Delta\Sigma \approx 25\%; \quad \Delta G \approx 20\%$$

$$\mathrm{L} \approx \text{ unmeasured}$$

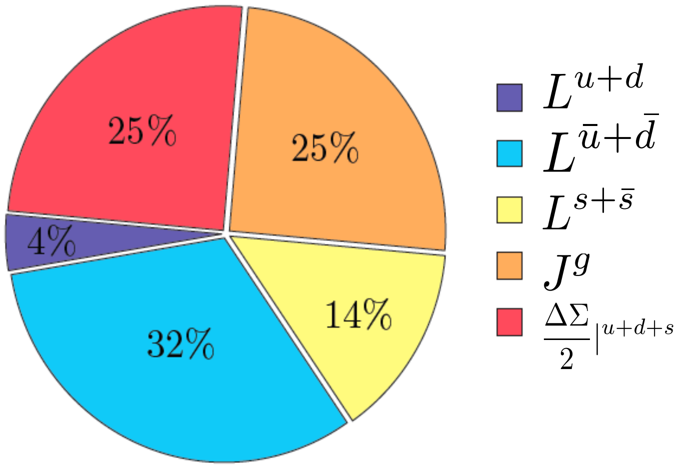
How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD: Transverse Momentum Distribution

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

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

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

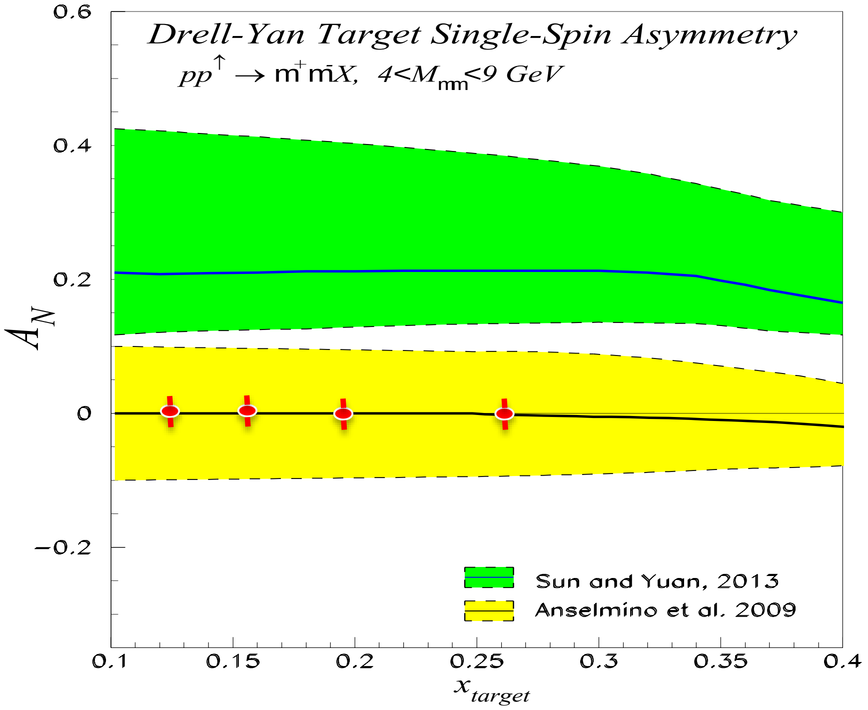
$2\,L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\,J_g \approx 25\%$

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

Projected Statistical Precision with a Polarized Target at (E-1039)

- Probe **Sea-quark Sivers Asymmetry**
  with a polarized proton target at SeaQuest



Statistics shown for two calendar years of running:
- L = 7.2 $*10^{42}$ /cm^2 ↔ POT = 2.8$*10^{18}$
- P = 85%

– existing SIDIS data poorly constrain sea-quark Sivers function (Anselmino)

– significant Sivers asymmetry expected from meson-cloud model (Sun & Yuan)

– **first Sea Quark Sivers Measurement**

– **determine sign and value of $\bar{u}$ Sivers distribution**

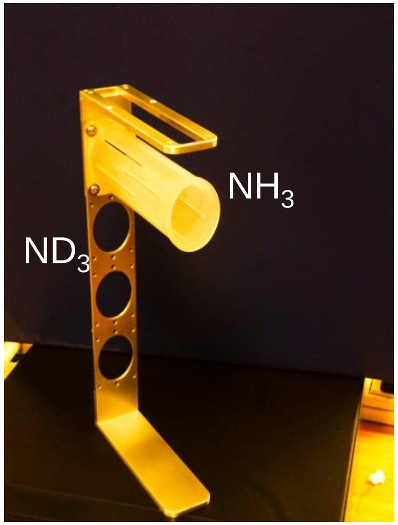
If $A_N \neq 0$, **major discovery**:
“Smoking Gun” evidence for $L_{\bar{u}} \neq 0$

Ref: Andi Klein (LANL)

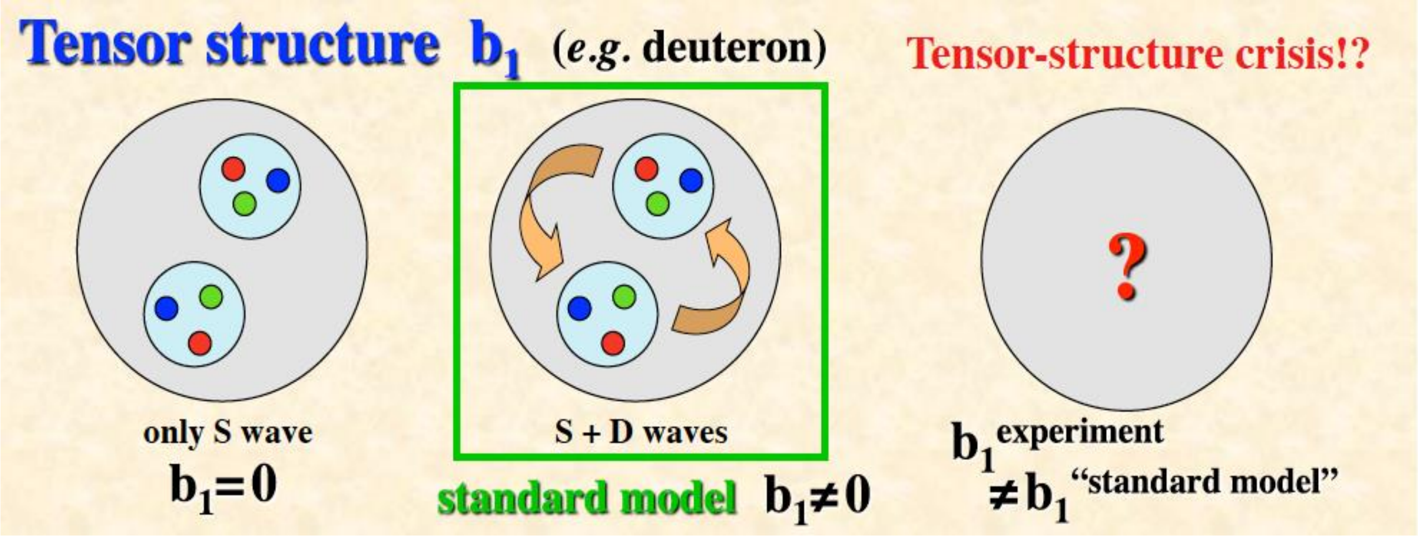
Further Plans with Polarized Targets (E-1039’)

- Probe $\bar{d}$ **Sivers Asymmetry** with a polarized ND_3 target at SeaQuest
  - SeaQuest only place to measure d-bar (explore during E1039)
  - measure Sivers asymmetry for pp and pD and take ratio
    - requires measuring p and “n” in parallel to control systematics
    - microwave irradiates both targets at the same time
    - one cell NH_3, the other ND_3

Target holder



- Probe **Tensor** Polarization Deuteron (40% - 50%)

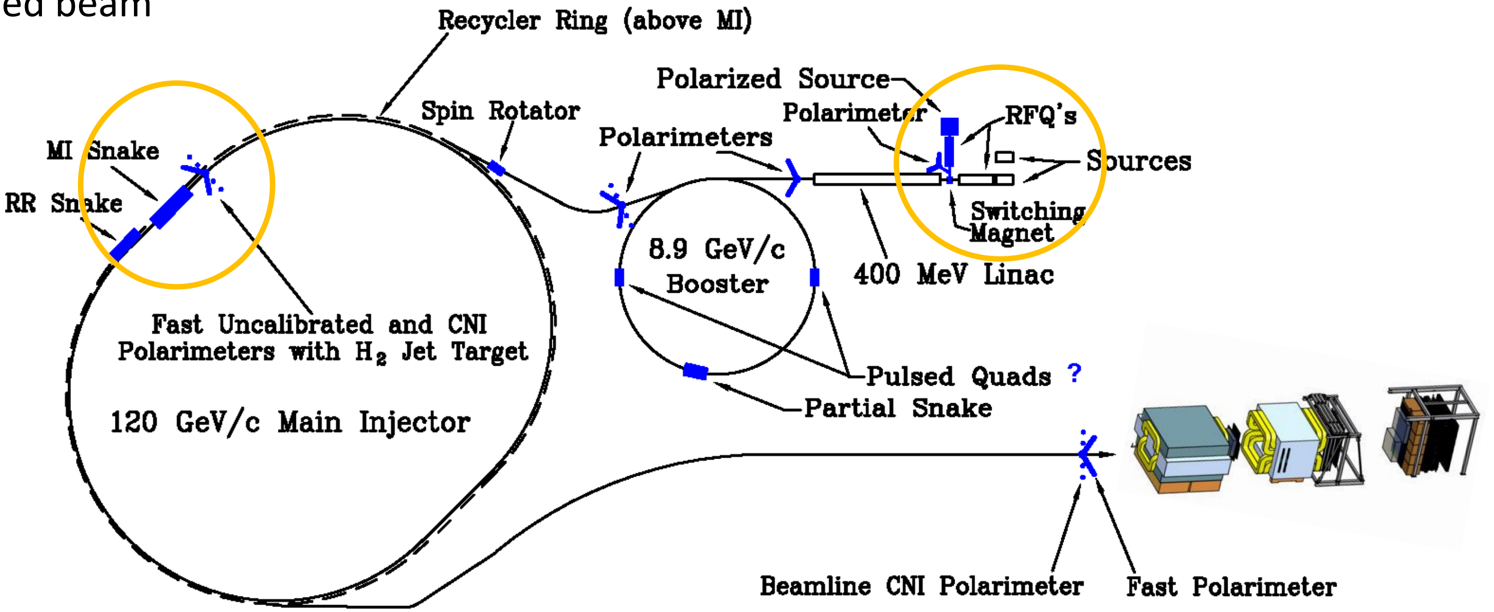


Ref: Andi Klein (LANL)

Let's Polarize the Beam at Fermilab (E-1027)

The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam



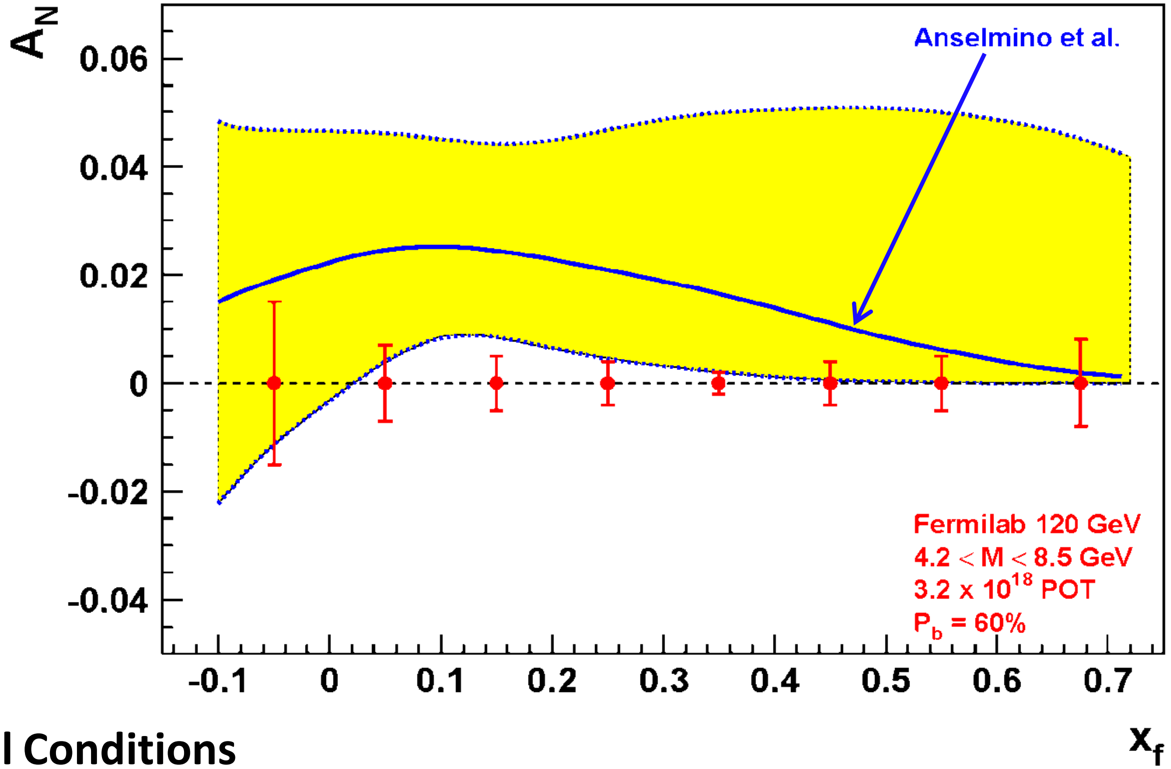
- **Measure sign-change in Sivers Function:**
  - ⟶ QCD (and factorization) require sign change
  - ⟶ major milestone in hadronic physics (HP13)

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

- **Fermilab (best place for polarized DY):**
  - ⟶ very high luminosity, large x-coverage, primary beam
- **Cost Est.: $6M +$4M Contingency & Management = $10M** (in 2013)

Expected Precision from E-1027 at Fermilab

- Probe **Valence-quark Sivers Asymmetry** with a polarized proton beam at SeaQuest



1.3 Mio DY events

- **Experimental Conditions**
  - same as SeaQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (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 = 60%

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

Planned(/running) Polarized Drell-Yan Experiments

Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\ s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 – 0.3$	2×10^{33}	0.14	$P_t = 90\%$ $f = 0.22$	1.1×10^{-3}	2015-2016, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$	$x_t = 0.2 – 0.4$	2×10^{32}	0.07	$P_t = 90\%$ $f = 0.22$	1.1×10^{-4}	>2018
PAX (GSI)	$p^{\uparrow} + \bar{p}$	collider $\sqrt{s} = 14$	$x_b = 0.1 – 0.9$	2×10^{30}	0.06	$P_b = 90\%$	2.3×10^{-5}	>2020?
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s} = 26$	$x_b = 0.1 – 0.8$	1×10^{31}	0.04	$P_b = 70\%$	6.8×10^{-5}	>2018
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider $\sqrt{s} = 510$	$x_b = 0.05 – 0.1$	2×10^{32}	0.08	$P_b = 60\%$	1.0×10^{-3}	>2018
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	$\sqrt{s} = 200$ $\sqrt{s} = 510$	$x_b = 0.1 – 0.5$ $x_b = 0.05 – 0.6$	8×10^{31} 6×10^{32}	0.08	$P_b = 60\%$ $P_b = 50\%$	4.0×10^{-4} 2.1×10^{-3}	>2021
SeaQuest (FNAL: E-906)	$p + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$ $x_t = 0.1 – 0.45$	3.4×10^{35}	---	---	---	2012 - 2017
Pol tgt DY‡ (FNAL: E-1039)	$p + p^{\uparrow}$	120 GeV $\sqrt{s} = 15$	$x_t = 0.1 – 0.45$	4.4×10^{35}	0 – 0.2*	$P_t = 85\%$ $f = 0.176$	0.15	2018-2019
Pol beam DY§ (FNAL: E-1027)	$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$	$x_b = 0.35 – 0.9$	2×10^{35}	0.04	$P_b = 60\%$	1	2020

‡ 8 cm NH_3 target / § L= 1×10^{36} $cm^{-2}\ s^{-1}$ (LH_2 tgt limited) / L= 2×10^{35} $cm^{-2}\ s^{-1}$ (10% of MI beam limited)

***not constrained by SIDIS data** / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

W. Lorenzon (U-Michigan) 3/2016

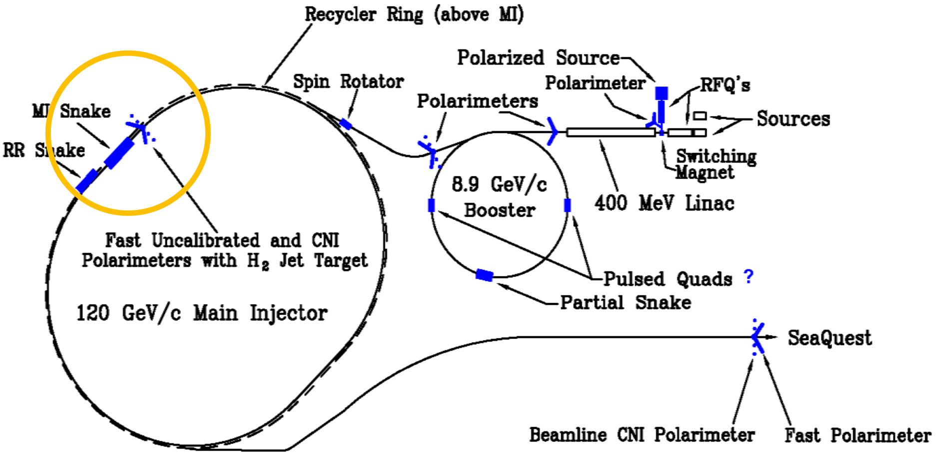
A Novel, Compact Siberian Snake for the Main Injector

Single snake design (6.4m long):

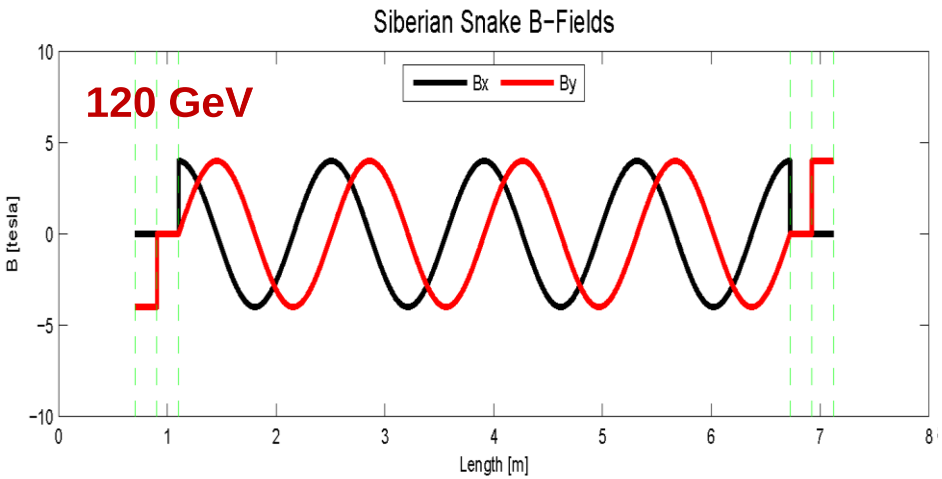
- 1 helical dipole + 2 conv. dipoles
  - helix: 4T / 5.6 m / 4” ID
  - dipoles: 4T / 0.2 m / 4” ID

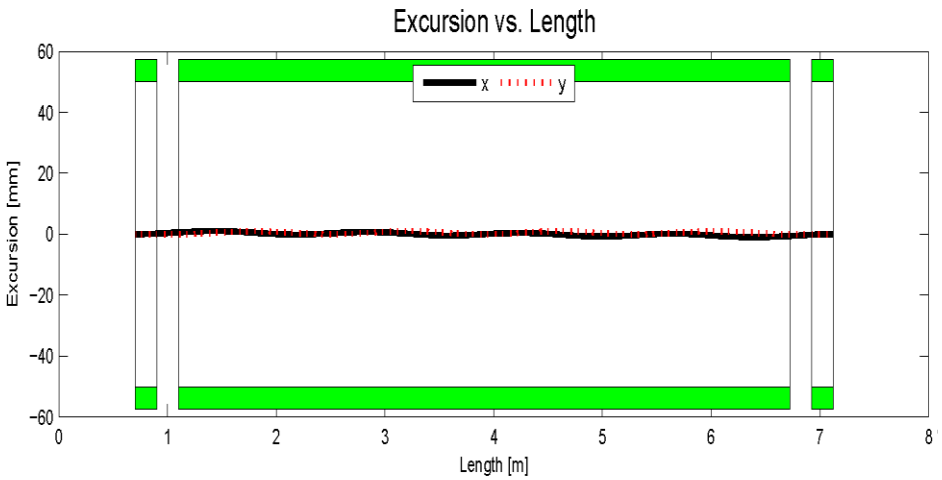
- use 4-twist magnets
  - 8π rotation of B field

- never done before in a high energy ring
  - RHIC uses snake pairs
  - 4 single-twist magnets (2π rotation)



initial design studies

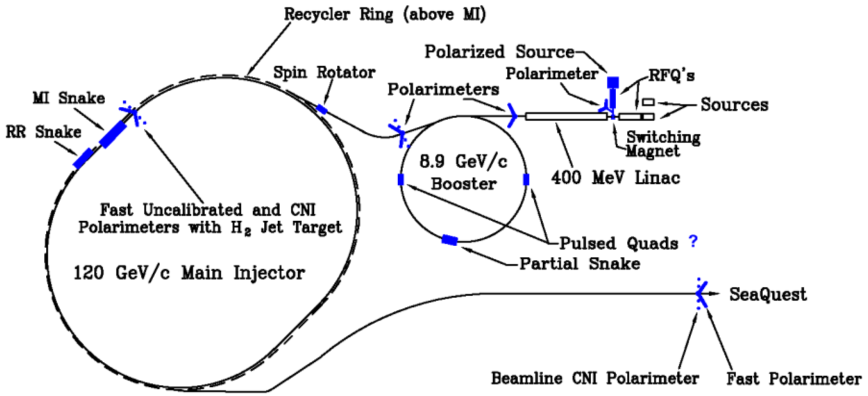


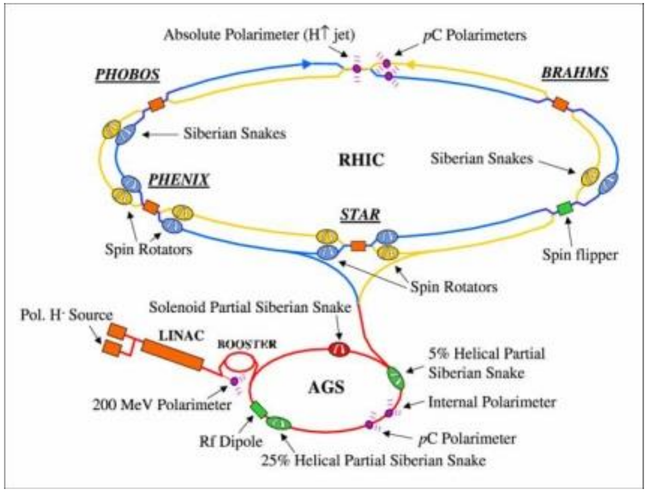


beam excursions shrink w/ beam energy

Differences compared to RHIC

- **Most significant difference**:
  Ramp time of **Main Injector < 0.7 s**, at **RHIC 1-2 min**
  - ➞ **warm magnets** at MI vs. superconducting at RHIC
    - → pass through all depolarizing resonances much more quickly
- Beam remains in **MI ~2 s**, in **RHIC ~8 hours**
  - ➞ **extracted beam** vs. **storage ring**
  - ➞ much **less** time for **cumulative depolarization**
- **Disadvantage** compared to RHIC — no **institutional history** of accelerating polarized proton beams
  - ➞ Fermilab E704 had polarized beams through hyperon decays



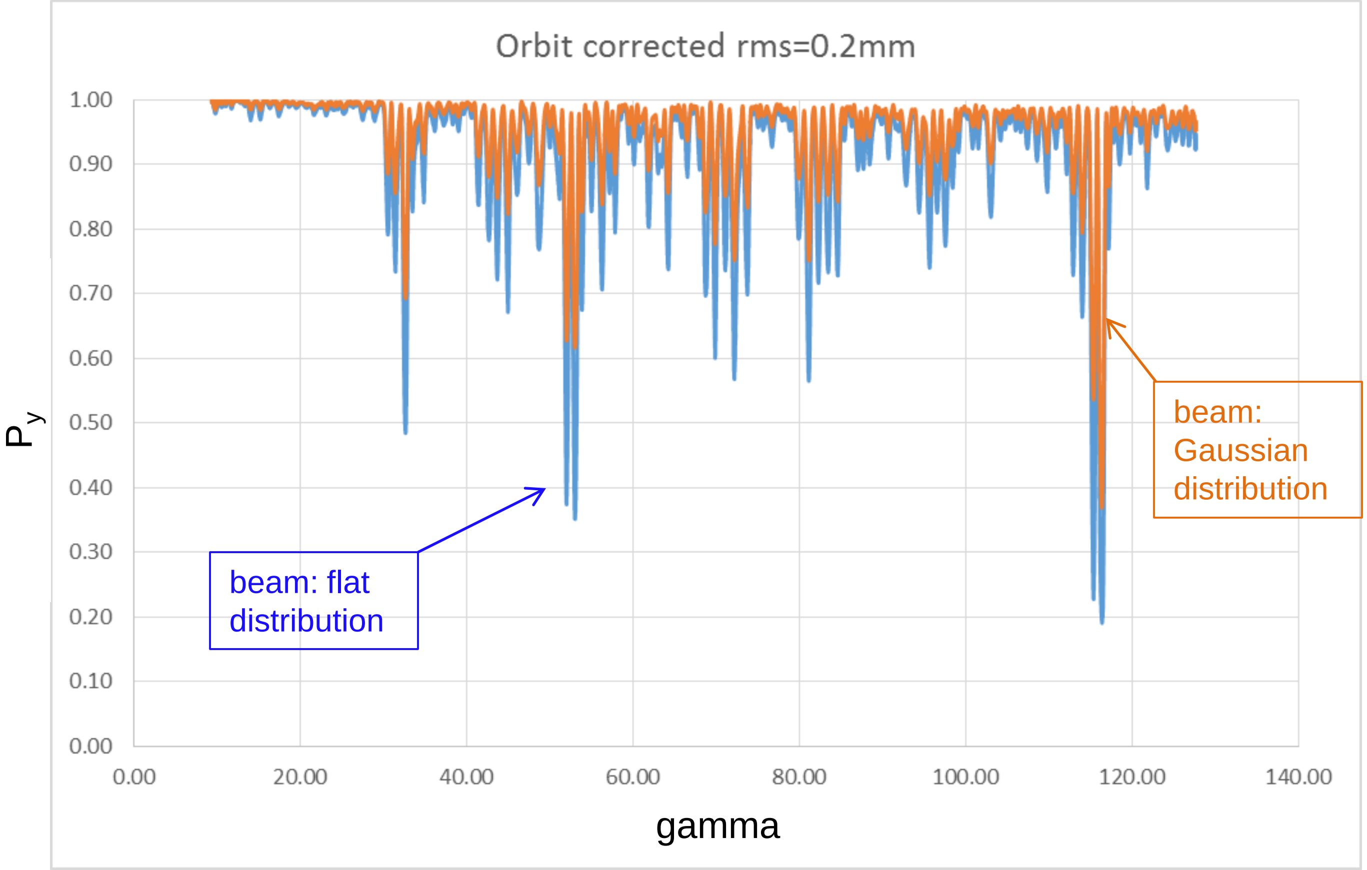


The Path to a polarized Main Injector

Stage 1 approval from Fermilab: 14-November-2012

- PAC request: detailed machine design and costing using 1 snake in MI
- Collaboration with A.S. Belov at INR and Dubna to develop polarized source
- During 2013 - 2014:
  - ➡ set up Zgoubi spin-tracking package (M. Bai, F. Meot, BNL)
    - ⟶ single particle tracking, emittance, momentum spread of particles
    - ⟶ conceptual design that works *at least for a perfect machine* — perfect magnet alignment, perfect orbits, no momentum spread, etc
    - ⟶ but slow and limited support:
difficulties implementing orbit errors, quadrupole mis-alignments/rolls, ramp rates
- Fermilab AD support: 2015-2016
  - ➡ Meiqin Xiao from AD set up PTC (Etienne Forest, KEK)
    - ⟶ repeated Zgoubi work in 1 month
    - ⟶ “easy” to include orbit errors, quadrupole mis-alignments/rolls, ramp rates
  - ➡ support for one year
    - ⟶ plan to complete simulations
    - ⟶ go back to PAC

Simulation of final polarization as function of Energy



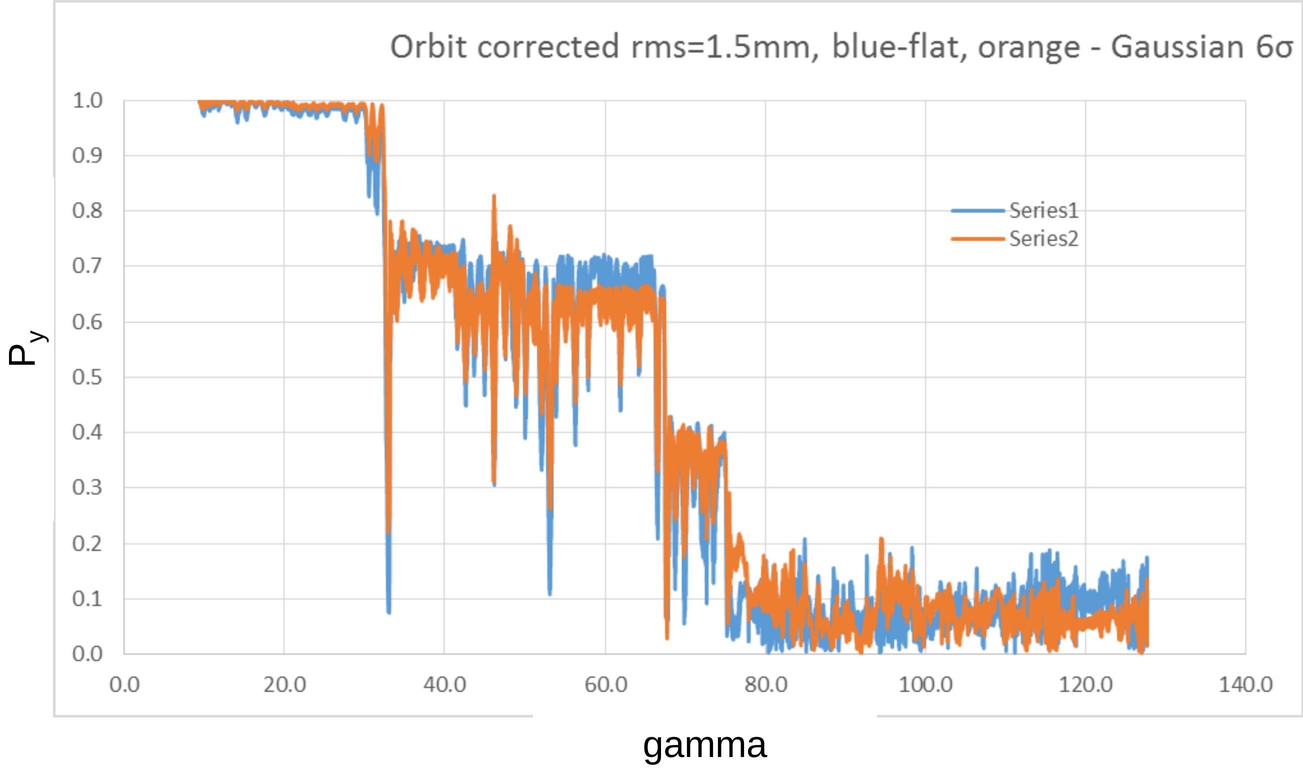
Point-like snake in correct location, actual ramp rate for acceleration.

Polarizations with magnet field error and misalignment, corrected

Final polarization: > 90%

ε_{max} = 20 π mm.mrad in y plane and $\Delta p = 1.25*10^{-3}$ in longitudinal plane

Simulation of final polarization as function of Energy



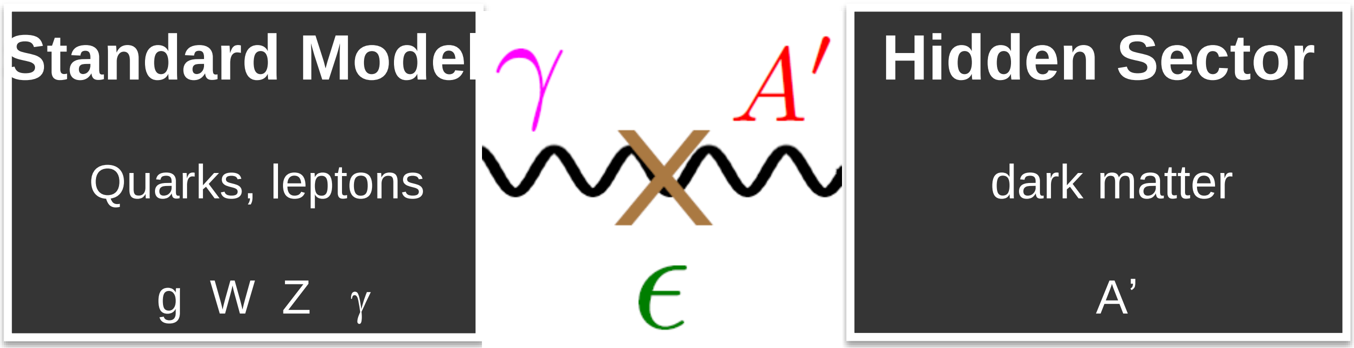
Point-like snake in correct location, actual ramp rate for acceleration.

Polarizations with magnet field error and misalignment, partially corrected

Final polarization: < 10%

ε_{max} = 20 π mm.mrad in y plane and $\Delta p = 1.25*10^{-3}$ in longitudinal plane

Exploring the Dark Side of the Universe



Standard Model

Quarks, leptons

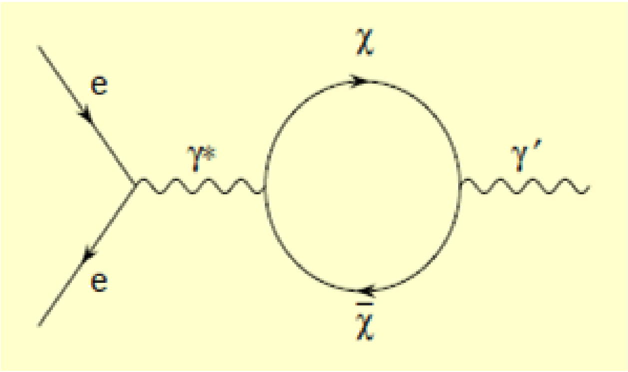
g W Z γ

Hidden Sector

dark matter

A’

- Dark sector could interact with the standard model sector via a hidden gauge boson (A’ or “dark photon” or “para photon” or “hidden photon”)
- Dark photons can provide a portal into the dark sector
- Dark photons could couple to standard model matter with $\alpha' = \alpha\varepsilon^2$



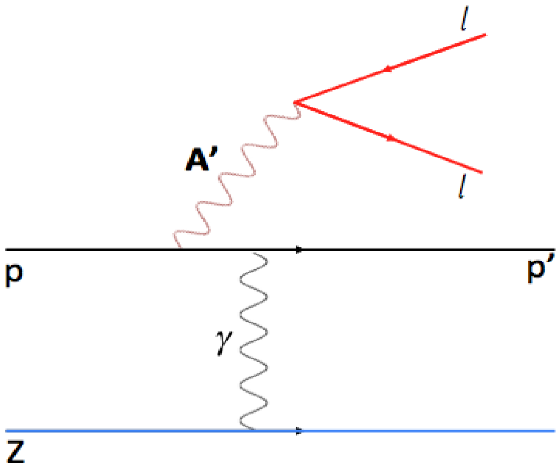
A’ produced via a loop mechanism

B. Holdom, PLB **166** (1986) 196
J. D. Bjorken et al, PRD **80** (2009) 075018

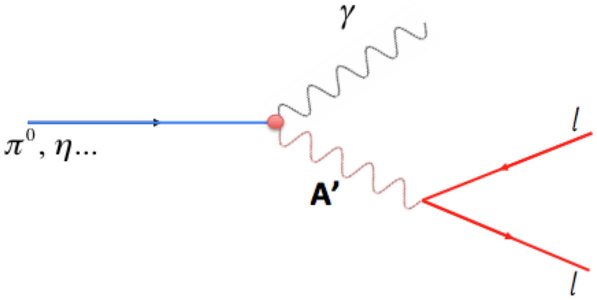
$\varepsilon \sim 10^{-2}$ to 10^{-8} from loops of heavy particles

Possible Mechanisms for producing A’ at SeaQuest

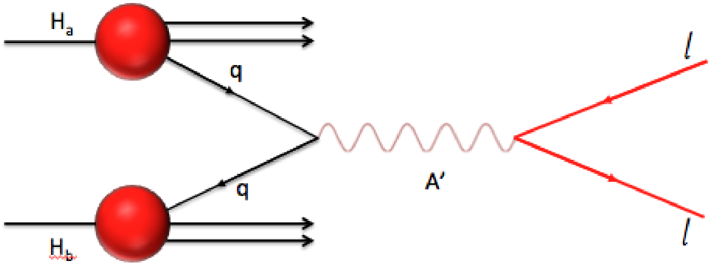
- Proton Bremsstrahlung



- η … decay

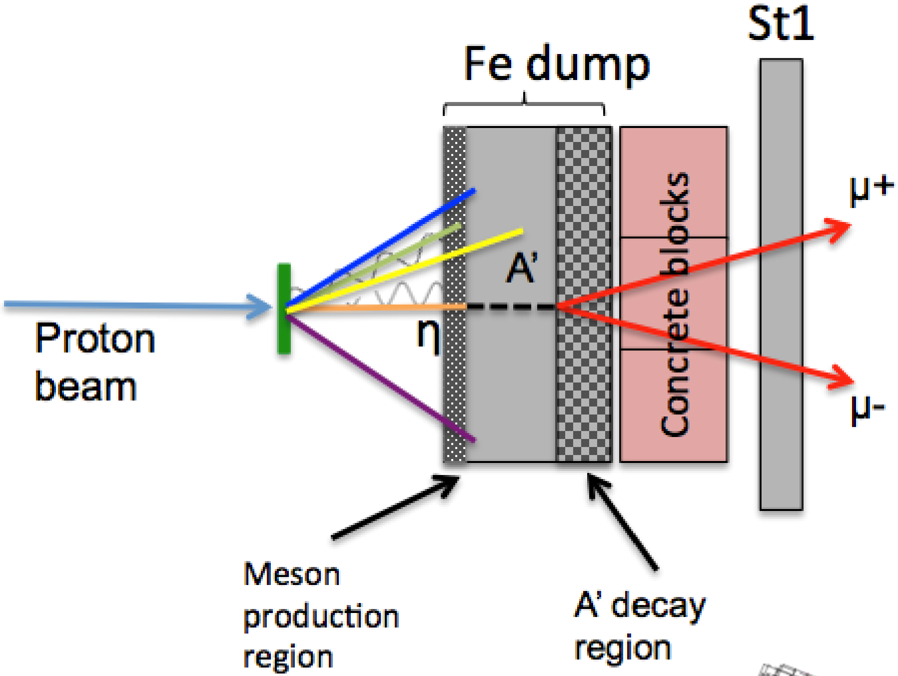


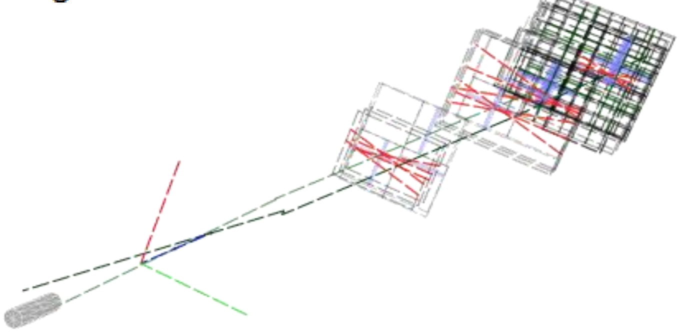
- Drell-Yan process



SeaQuest A’ search strategy

- Classic Beam Dump Experiment
  - ➞ A’ generated by η decay and/or proton Bremsstrahlung in the Iron beam dump
  - ➞ A’ could travel a distance l_0 without interacting
  - ➞ A’ decays into di-leptons
  - ➞ Reconstructed di-lepton vertex is **displaced**, downstream of the target in the beam dump
- Minimal impact on Drell-Yan program
  - ➞ run parasitically during E906



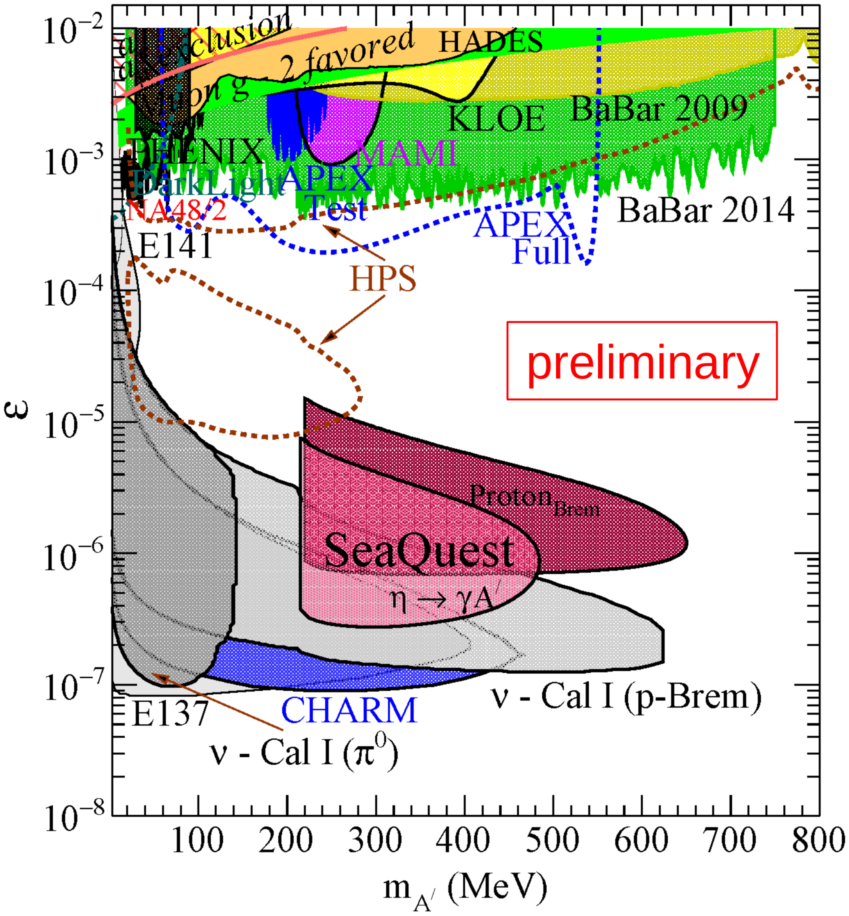


A’ sensitivity region for SeaQuest

$$l_o \approx \frac{0.8\,cm}{N_{eff}} \left(\frac{E_o}{10\,GeV}\right) \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\,MeV}{m_{A'}}\right)^2$$

J. D. Bjorken et al, PRD **80** (2009) 075018

- E_0 = energy of the A’
    - ➡ E_0 = 5 - 20 GeV for η decay
    - ➡ E_0 = 5 - 110 GeV for Proton Bremsstrahlung
- N_{eff} = no. of available decay products
    - ➡ N_{eff} = 2
- l_0 = distance that A’ travels before decaying
    - ➡ l_0 = 0.17m – 5.95m
- ε = coupling constant between standard model and dark sector
- $m_{A'}$ = mass of A’



η decay: limited to A’ mass less than the meson mass

Polarized Proton Beams and Searches for Dark Forces

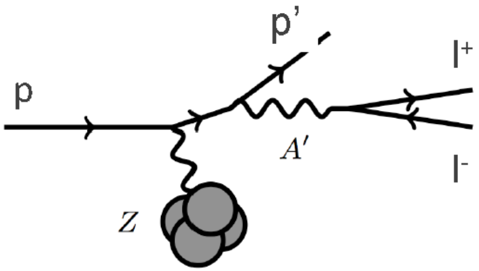
Searches for a dark photon also limit other possibilities

Parity violation studies could prove key

$$\mathcal{L}_{\rm darkZ} = -(\varepsilon e J^{\mu}_{\rm em} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{\rm NC}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

If the A' is a dark Z, then ...



The dilepton yield can change
with proton polarization:
the asymmetry
can be O(1)!

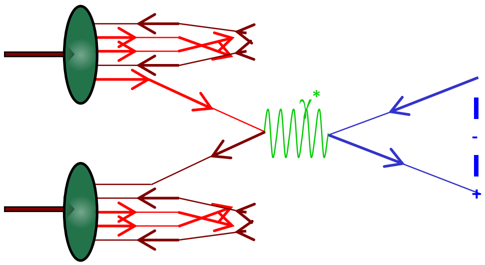
E-1027, E-1039 (and Beyond)

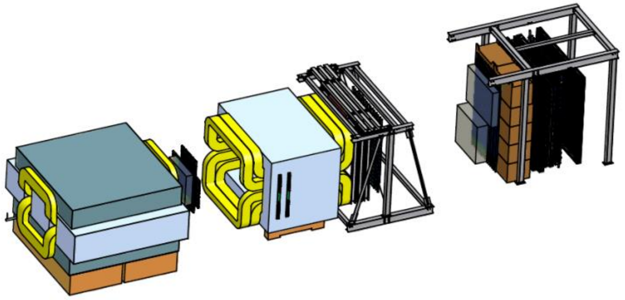
	Beam Pol.	Target Pol.	Favored Quarks	Physics Goals				
				(Sivers Function)			L_{sea}	A', Z_d
				sign change	size	shape		
E-1027 $p^{\uparrow} p \rightarrow \mu^{+} \mu^{-} X$	✓	✗	valence	✓	✓	✓	✗	✓
E-1039 $p\, p^{\uparrow} \rightarrow \mu^{+} \mu^{-} X$	✗	✓	sea	✗	✓	(✓)	✓	✓
E-10XX $p^{\uparrow} p^{\uparrow} \rightarrow \mu^{+} \mu^{-} X$ $\vec{p}\, \vec{p} \rightarrow \mu^{+} \mu^{-} X$	✓	✓	sea & valence	Transversity, Helicity, Other TMDs …				

Double-Spin Drell-Yan

→ rich, high-lumi spin-physics: complementary to RHIC and JLab

Drell-Yan Physics Program at Fermilab



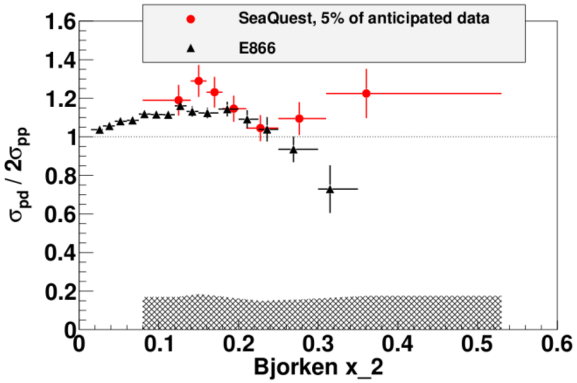


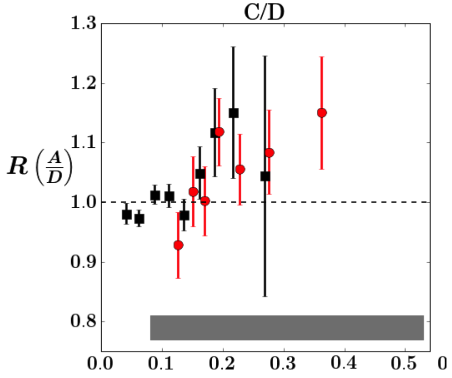
Sea Quarks of the Target

- dbar/ubar
- Sea quark EMC effect

Not discussed:

- Quark sea absolute magnitude
- Partonic Energy Loss
- J/ψ Nuclear Dependence

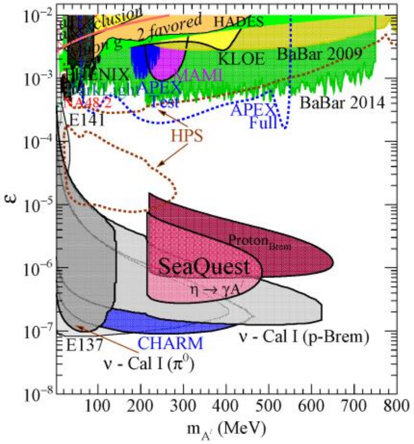


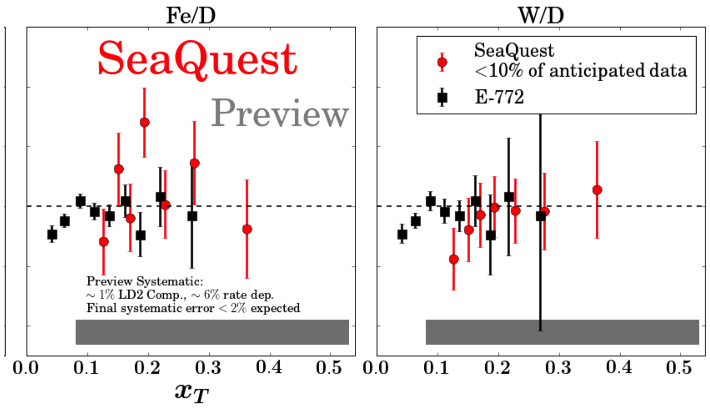


Transverse Spin Physics

- Sivers and OAM of Sea Quarks
- Sivers and QCD on Valence Quarks (sign change))

Dark Photons?





Thank You

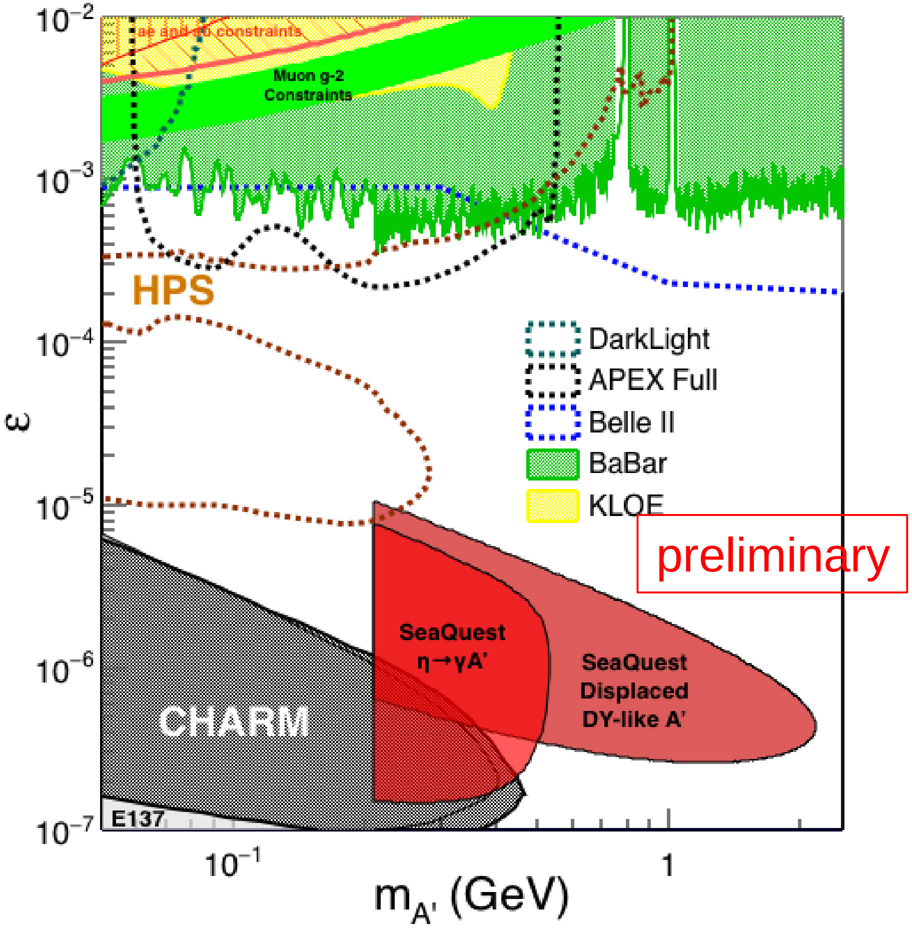
Backup Slides

A’ sensitivity region for SeaQuest

$$l_o \approx \frac{0.8\,cm}{N_{eff}} \left(\frac{E_o}{10\,GeV} \right) \left(\frac{10^{-4}}{e} \right)^2 \left(\frac{100\,MeV}{m_{A'}} \right)^2$$

J. D. Bjorken et al, PRD **80** (2009) 075018

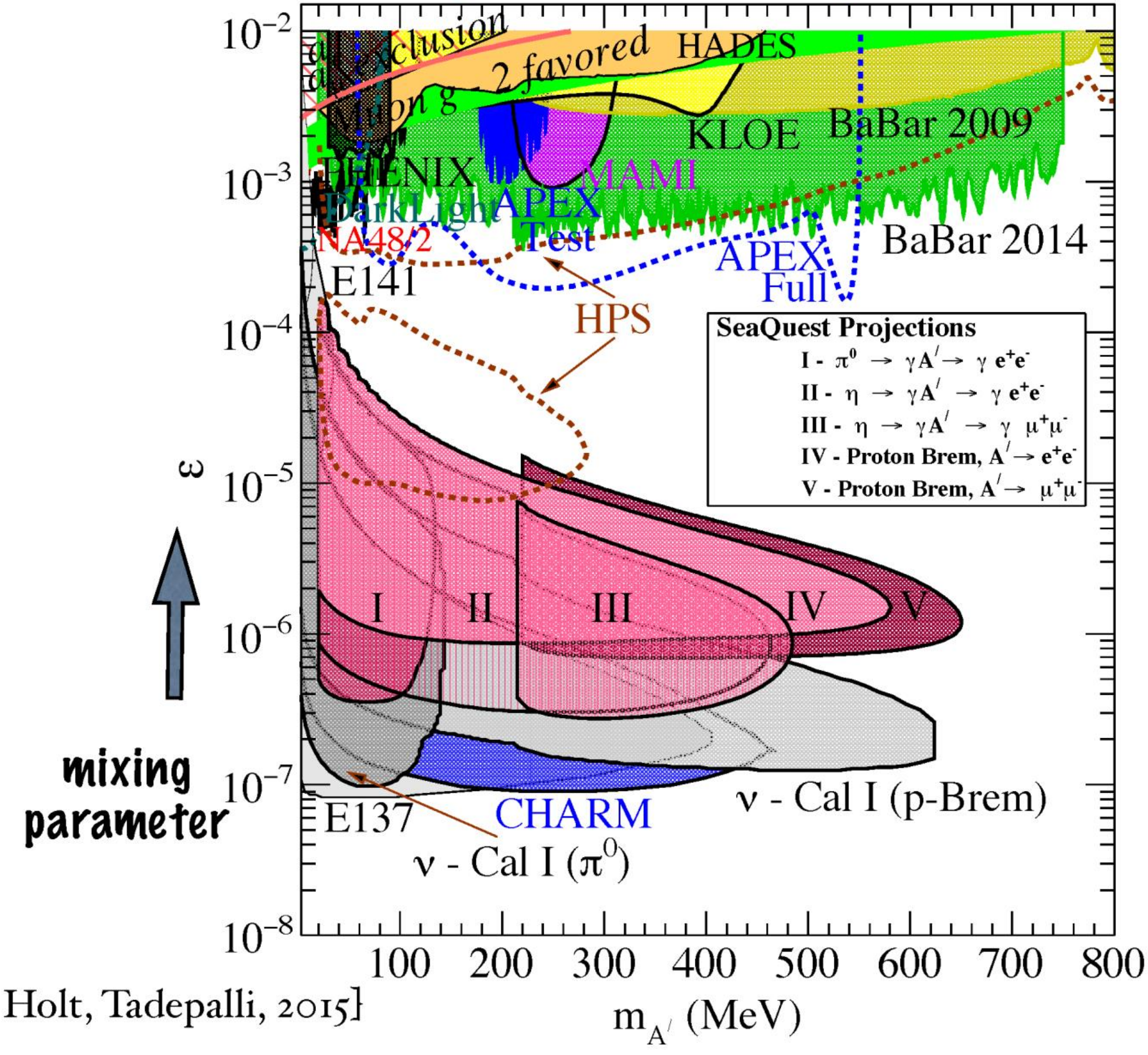
- E_0 = energy of the A’
  - ➡ E_0 = 5 - 20 GeV for η decay
  - ➡ E_0 = 5 - 110 GeV for Proton Bremsstrahlung
- N_{eff} = no. of available decay products
  - ➡ $N_{eff} = 2$
- l_0 = distance that A’ travels before decaying
  - ➡ l_0 = 0.17m – 5.95m
- ε = coupling constant between standard model and dark sector
- $m_{A'}$ = mass of A’



DY-like: can access A’ with larger mass

Dark Photons at SeaQuest (FNAL)

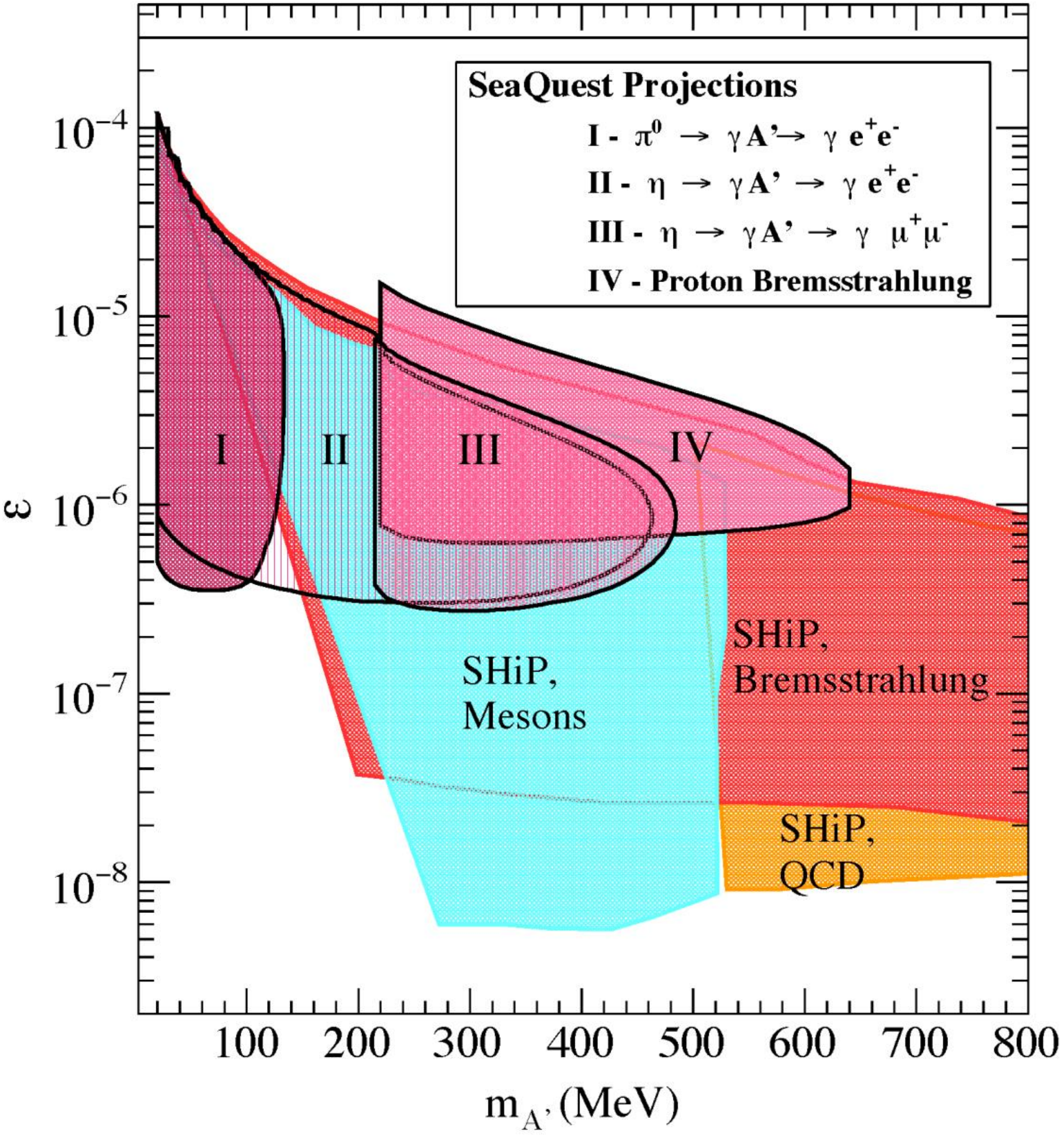
SeaQuest Projections are competitive with SHiP



[SG, Holt, Tadepalli, 2015]

Dark Photons: SeaQuest vs. SHiPS

"apples & oranges"

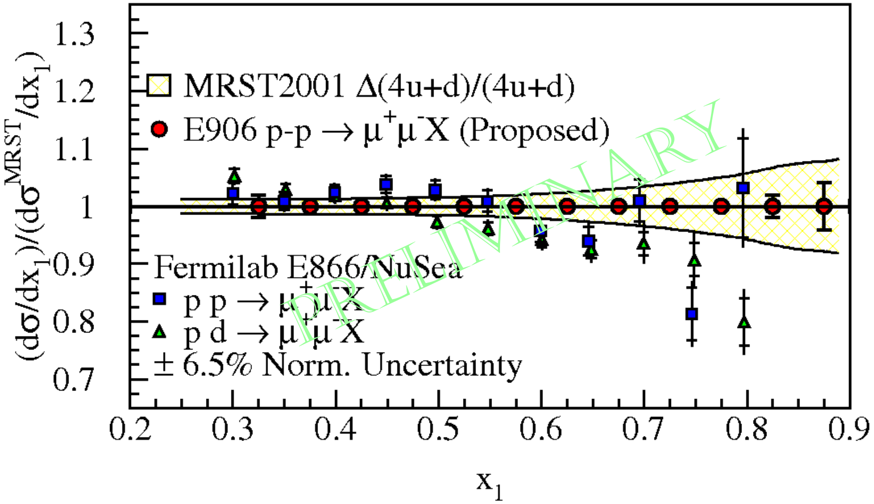


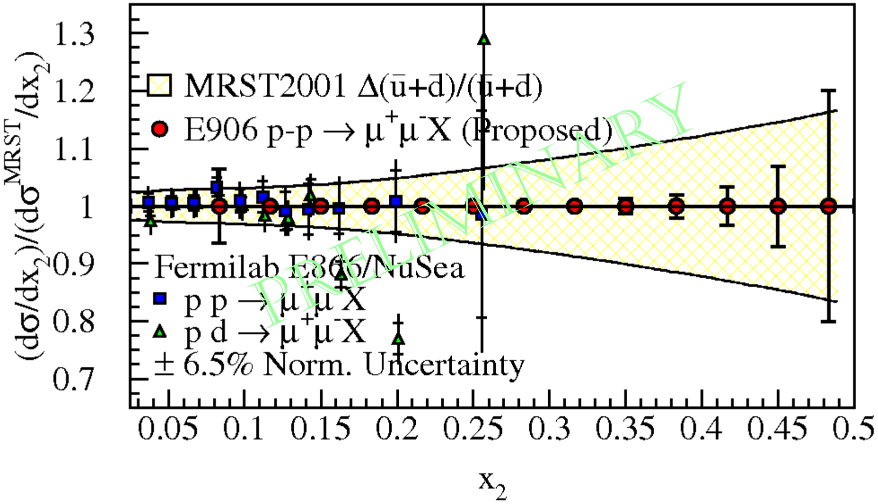
5 yr exposure
400 GeV beam
opt. detectors
vs.
1 yr exposure
120 GeV beam
SeaQuest spect.

Sharper constraints are possible!

SeaQuest Projections for absolute cross sections

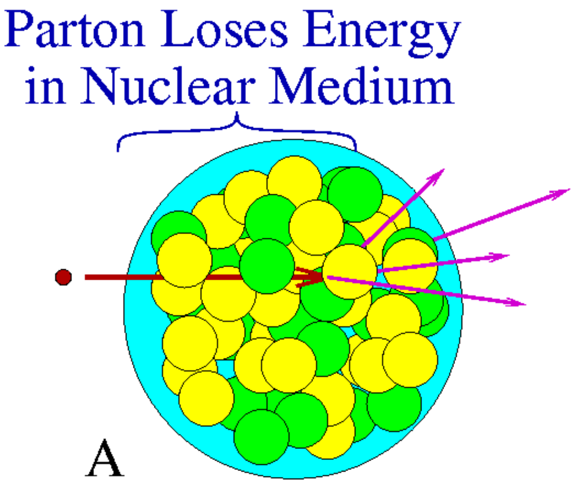
- Measure high x structure of beam proton
  - large x_F gives large x_{beam}
- High x distributions poorly understood
  - nuclear corrections are large, even for deuterium
  - lack of proton data
- In *pp* cross section, no nuclear corrections
- Measure convolution of beam and target PDF
  - absolute magnitude of high x valence distributions ($4u+d$)
  - absolute magnitude of the sea in target $(\bar{d}+\bar{u})$ (currently determined by ν-*Fe* DIS)



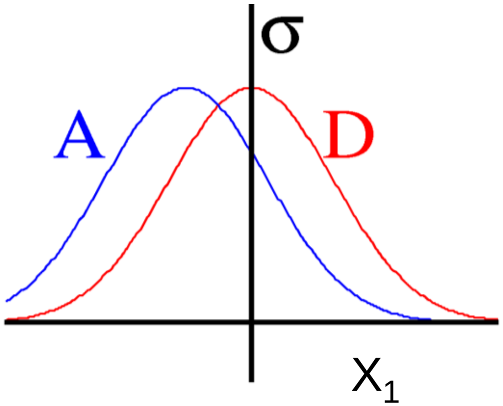


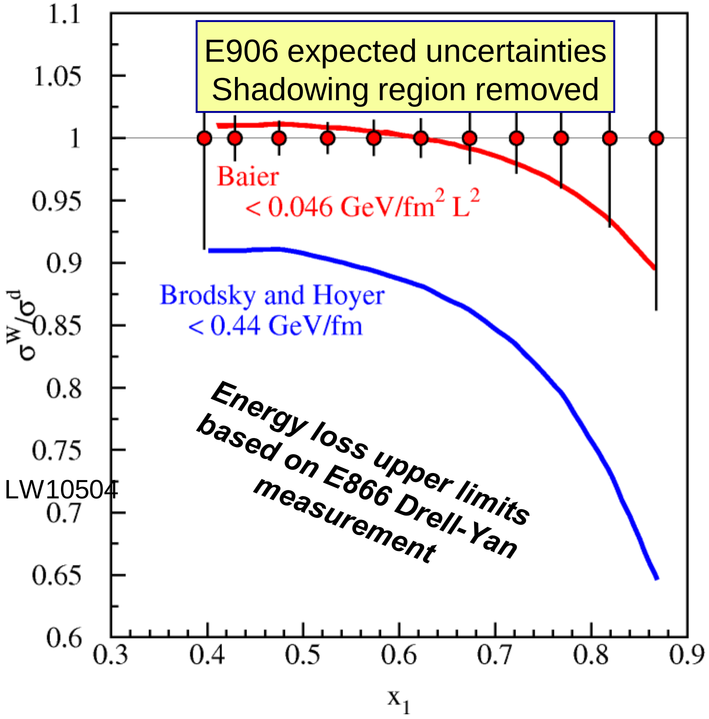
Partonic Energy Loss in Cold Nuclear Matter

- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic value (x_1 or x_F) is shifted



- Fit shift in x_1 relative to deuterium
    - ➡ shift in $\Delta x_1 \propto 1/s$ (larger at 120 GeV)





- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample

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Fermilab Polarized Drell-Yan Collaborating Institutes

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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

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