Polarized Drell-Yan at Fermilab

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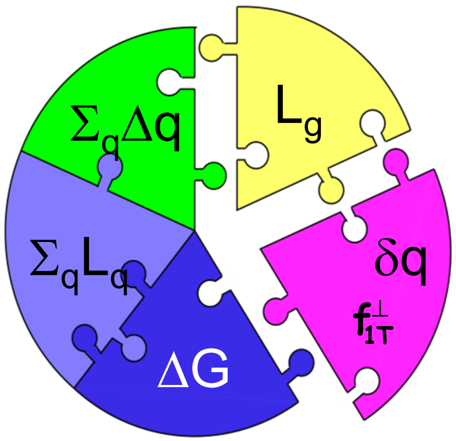
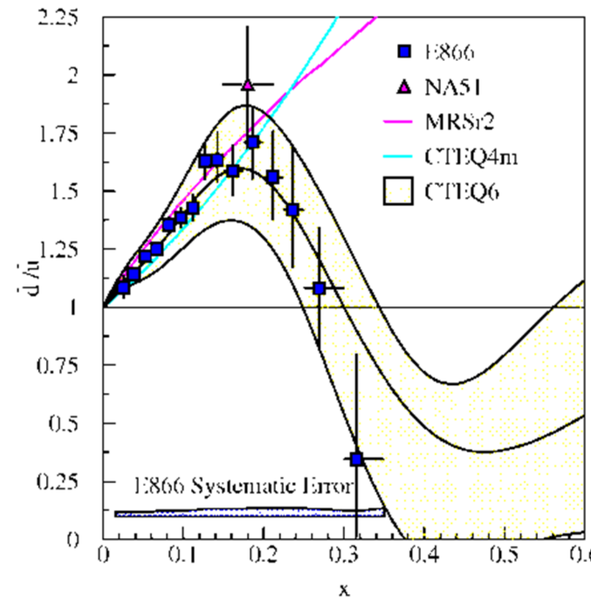
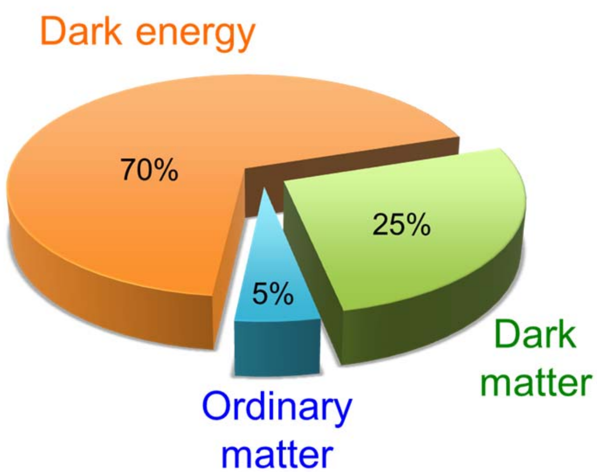
University of Michigan

TMD ECT* Workshop, Trento, Italy

(12-April-2016)







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

This work is supported by

Current and Future D-Y Program at FNAL

Unpolarized Beam and Target w/ SeaQuest detector

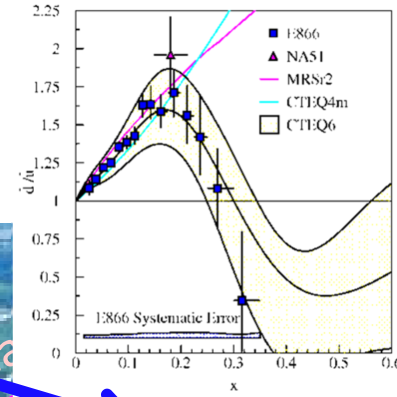
- **E-906**: 120 GeV p from Main Injector on LH_2,LD_2, C,Fe,W targets → **high-x Drell-Yan**
- Science data started in March 2014
  - ➡ run for 3 yrs
  - ➡ preview

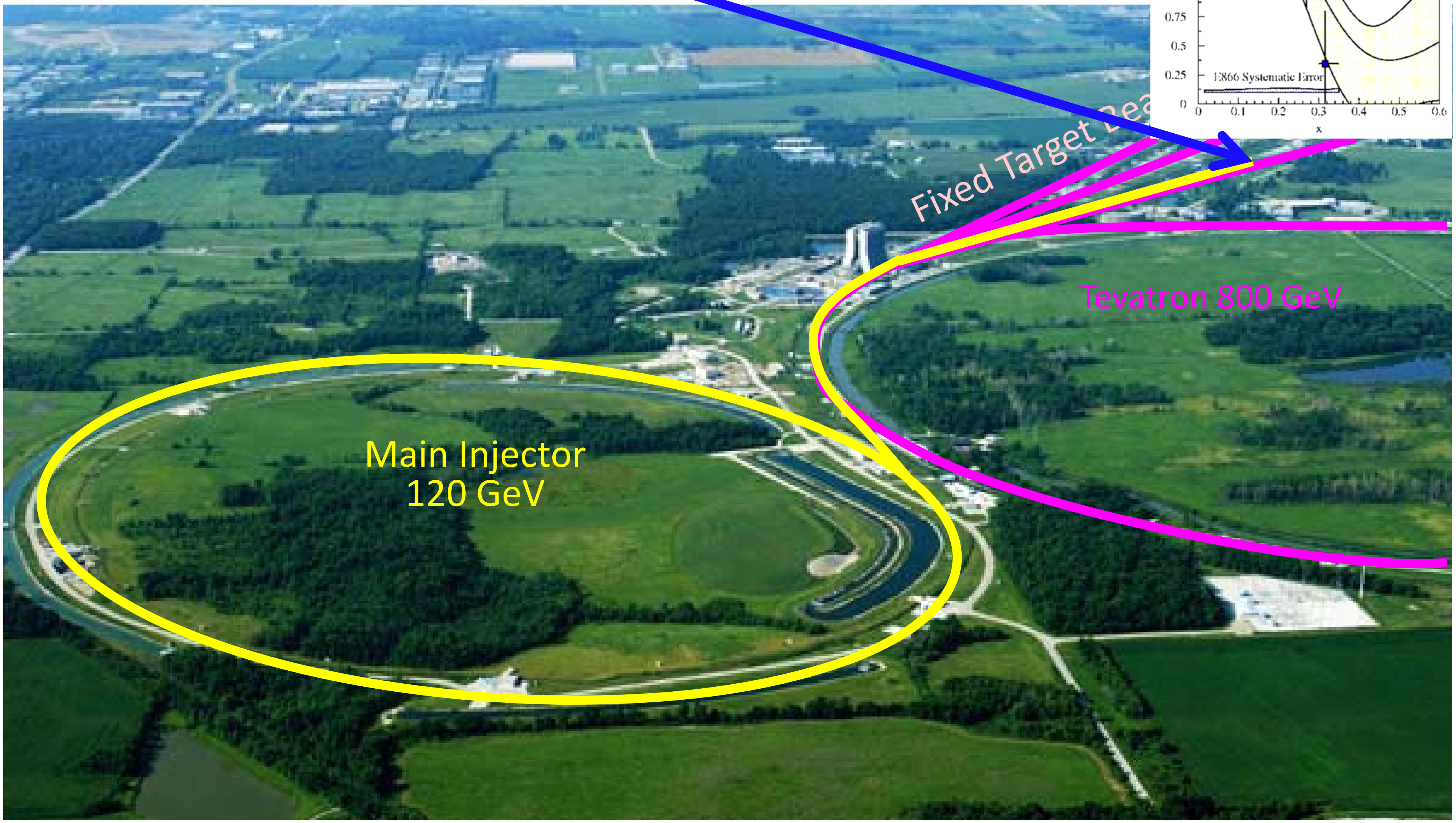
Polarized Beam and/or Target w/ SeaQuest detector

→ development of **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)

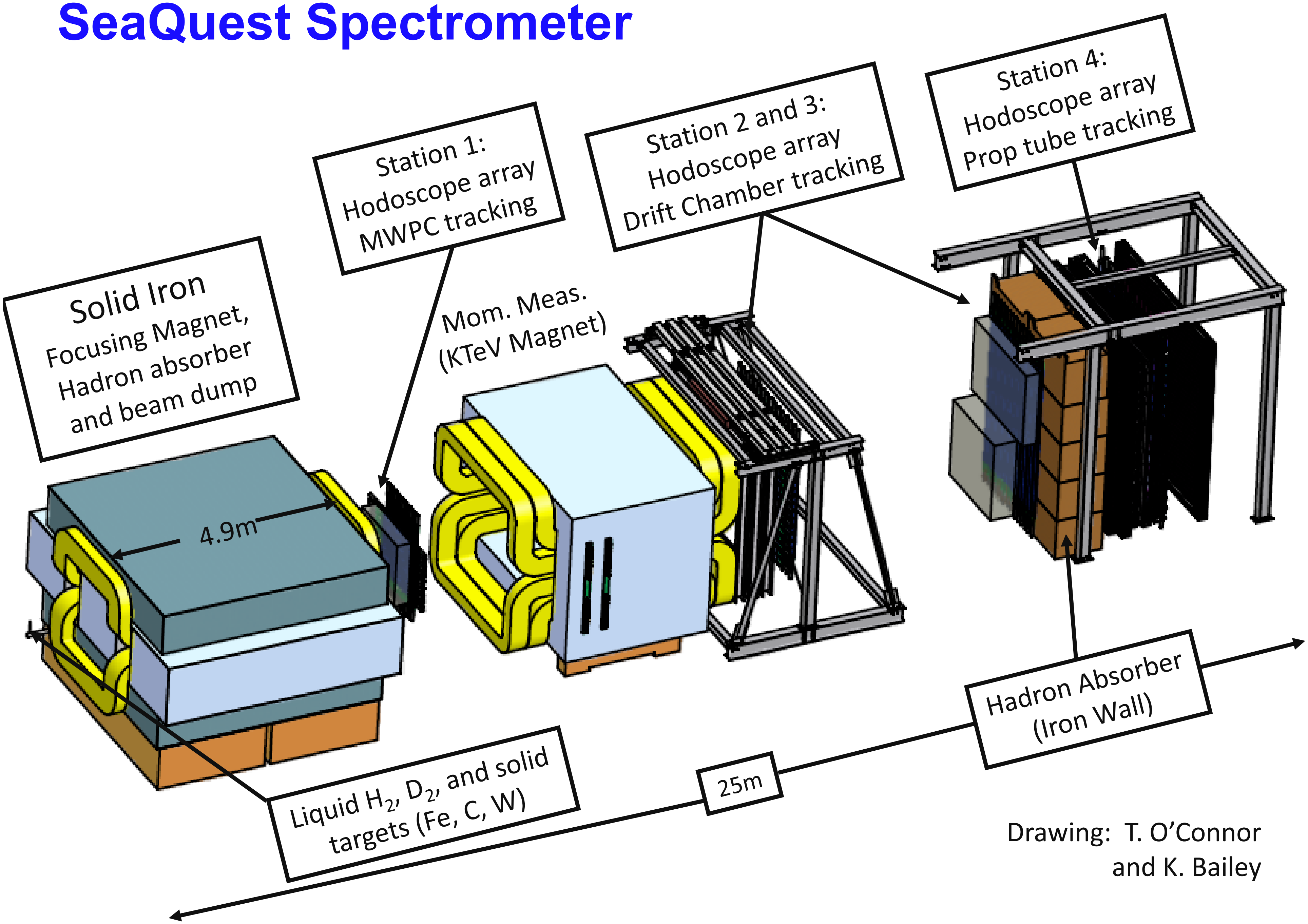
SeaQuest Experiment





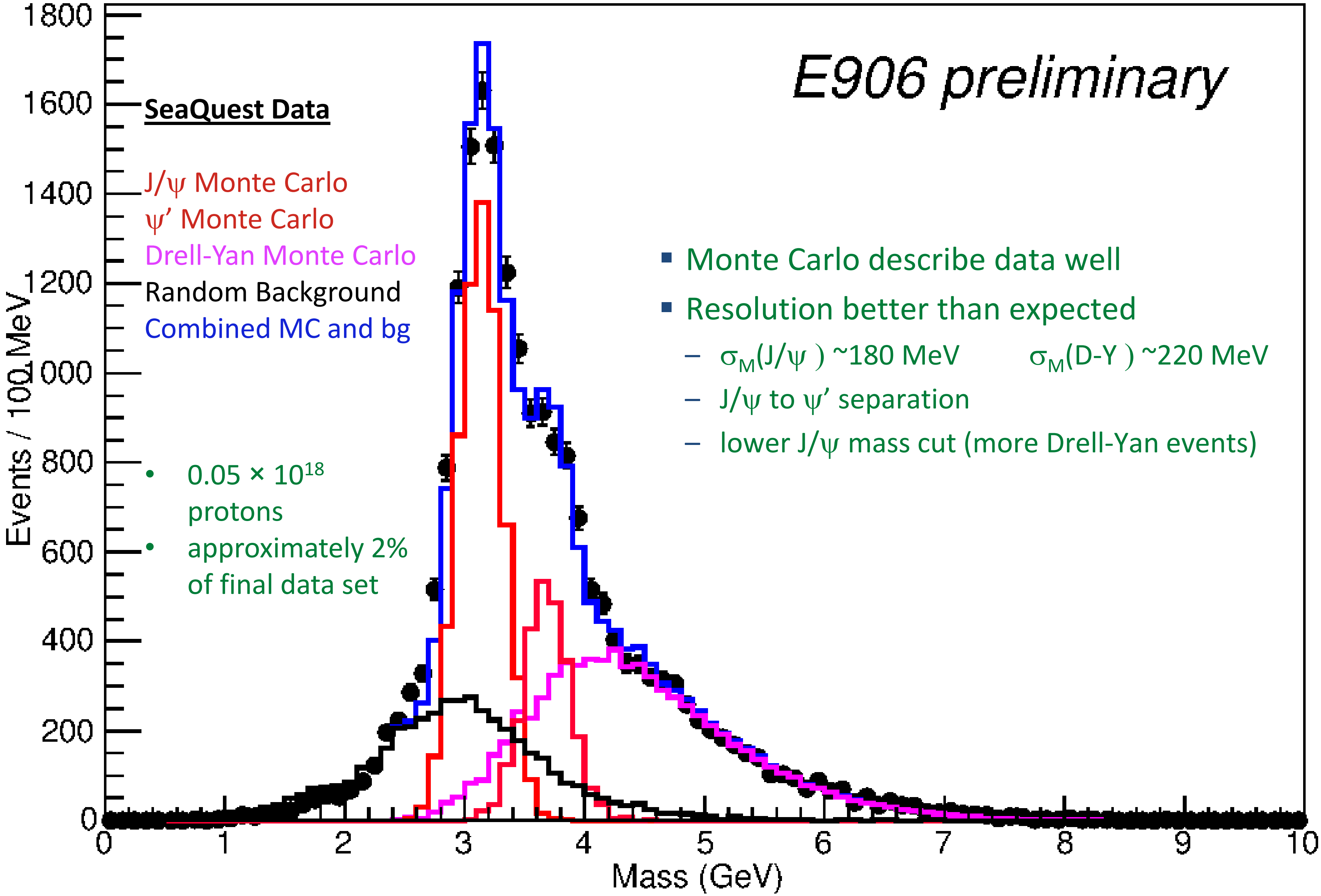
10% of available beam to SeaQuest / 90% to neutrino program

SeaQuest Spectrometer

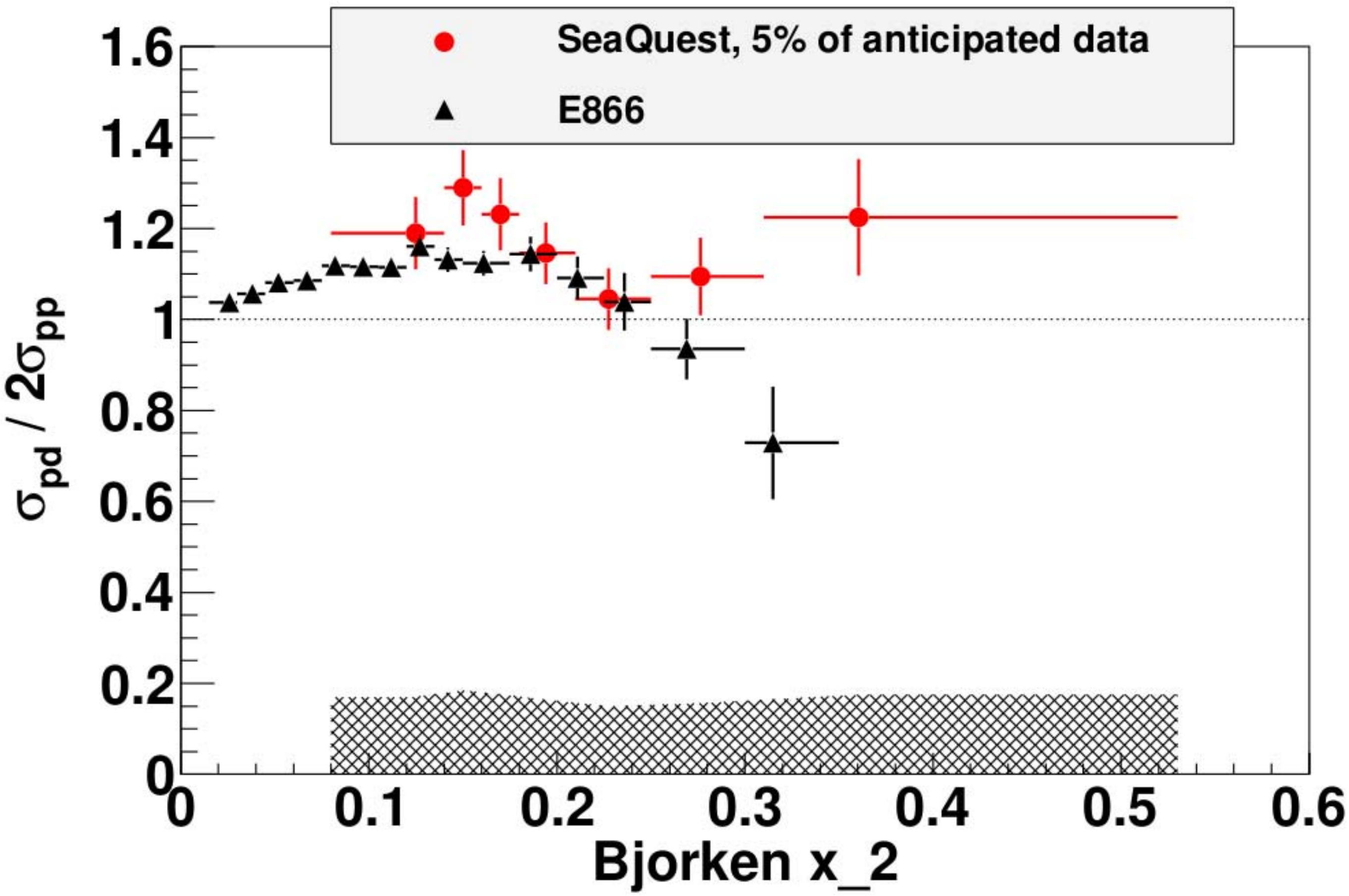


Drawing: T. O'Connor
and K. Bailey

Data From FY2014

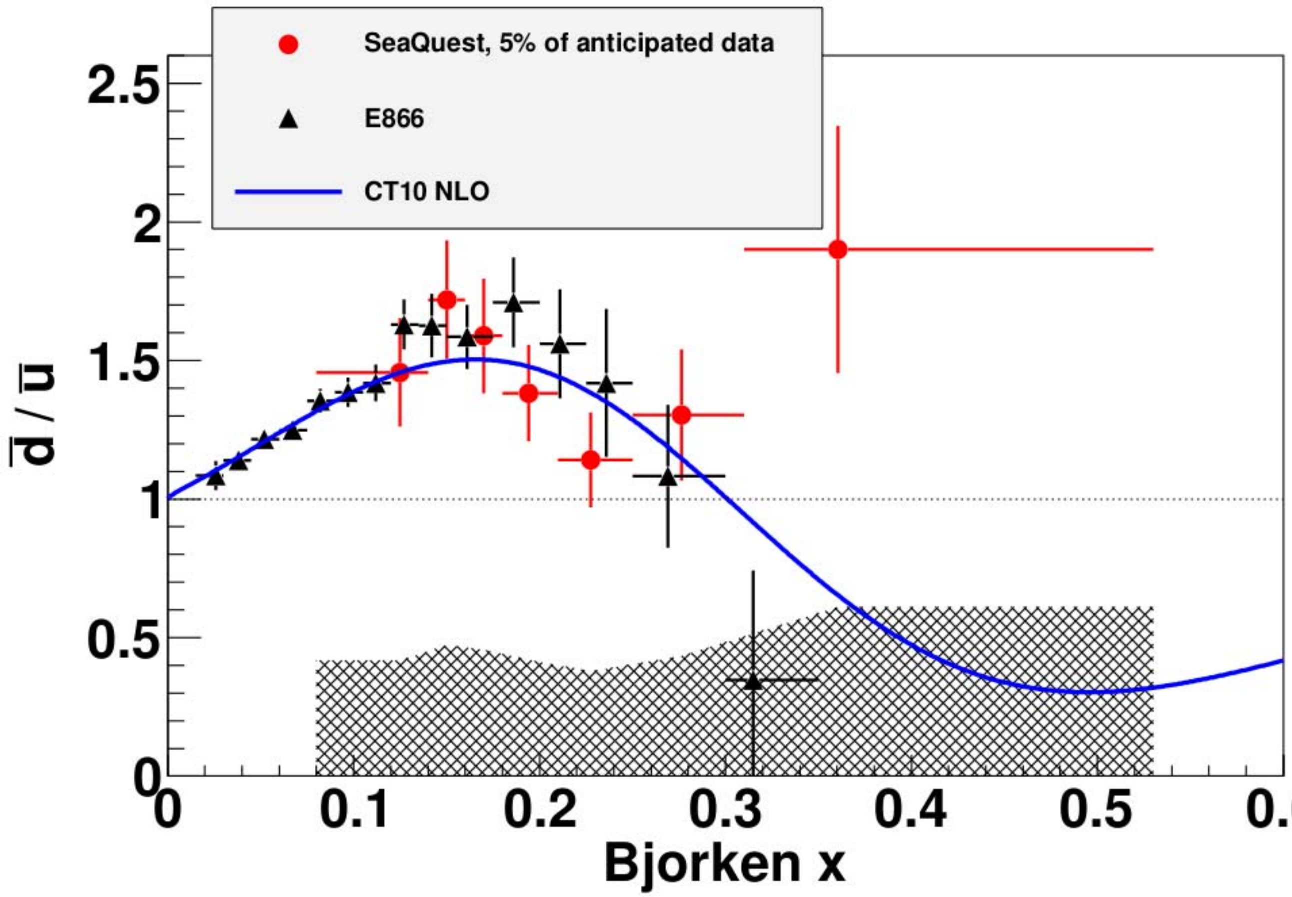


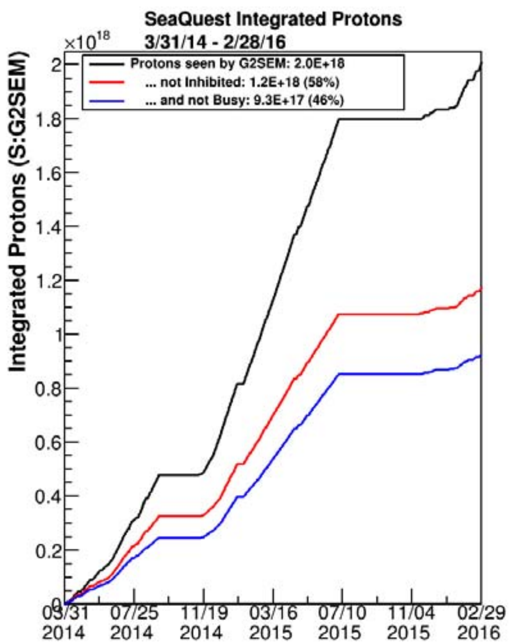
SeaQuest Cross Section Ratio (Preview)



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

SeaQuest Leading Order extraction (Preview)

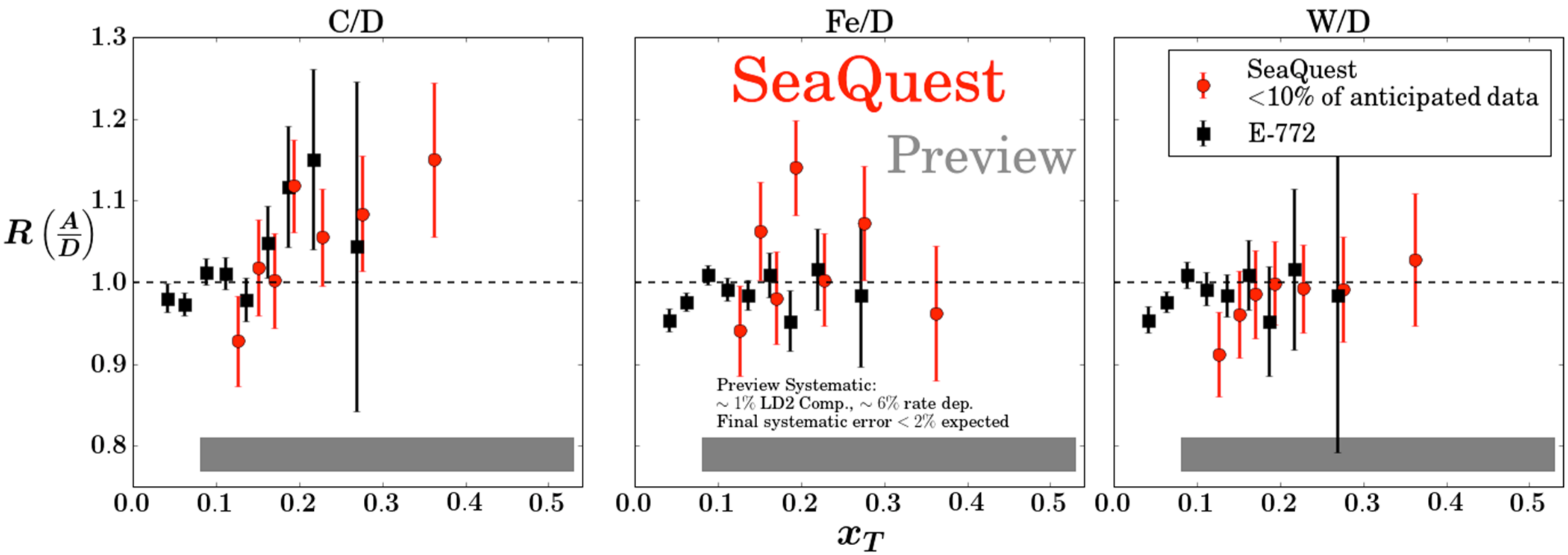




- plot based on fewer than 0.1×10^{18} protons (live)
- 20x more data recorded (1.2×10^{18}) so far
- anticipate total of 1.4×10^{18} protons by July 2016
- approved for 5×10^{18} pot

SeaQuest Nuclear Dependence (Preview)

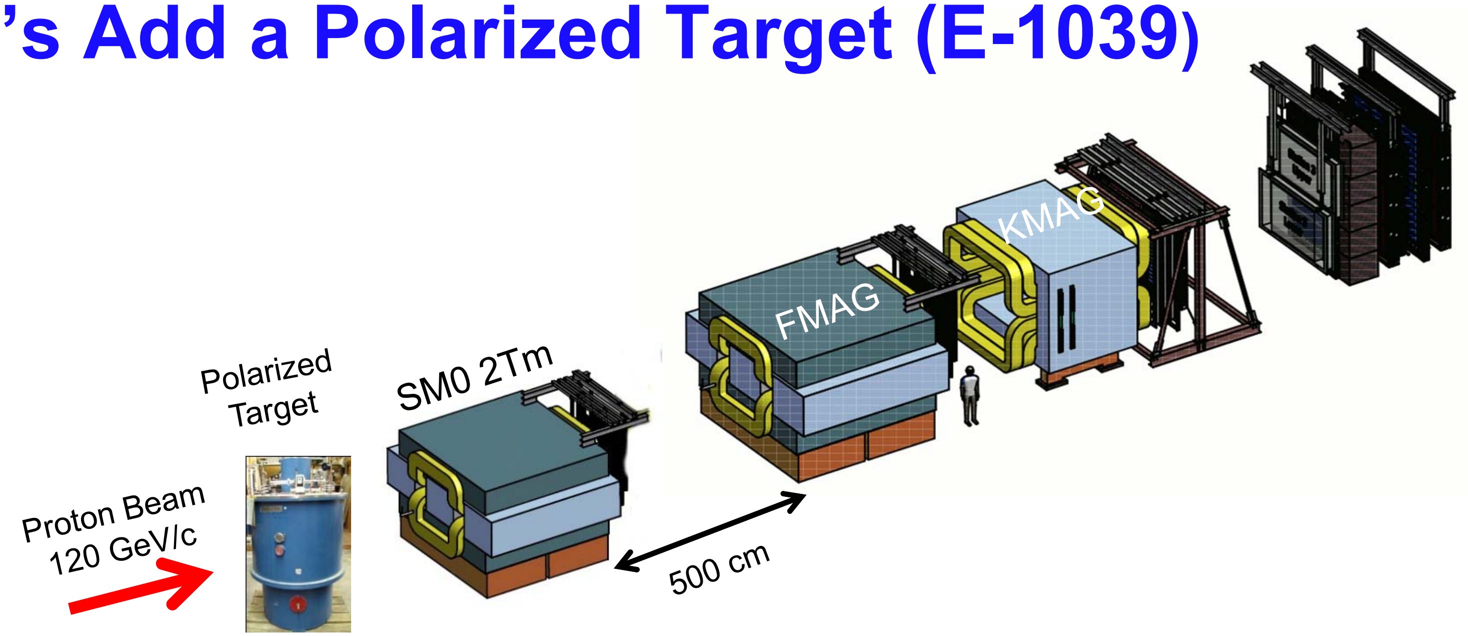
- data Presented by Bryan Dannowitz at April 2015 APS
- no antiquark enhancement apparent
- 10% of anticipated statistical precision
- increased detector acceptance at large-x_T to come (new D1 chamber)



- **Preliminary 2015 data set will be presented by Bryan Dannowitz at April 2016 APS – stay tuned**

Let's Add a Polarized Target (E-1039)

Target
Polarization: 85%
Packing fraction 0.6
Dilution factor: 0.176
Density: 0.82 g/cm^3



- use current SeaQuest setup, a polarized proton target, unpolarized beam
- add third magnet SM0 ~5m upstream
  → improves dump-target separation
  → reduces overall acceptance

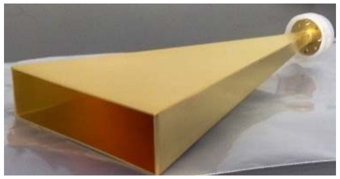
- Current status
  - magnet system is finished and working
  - refrigerator is finished and tested (at 1K)
  - NMR system is finished and working
  - mechanical design completed
  - Ammonia being irradiated at NIST

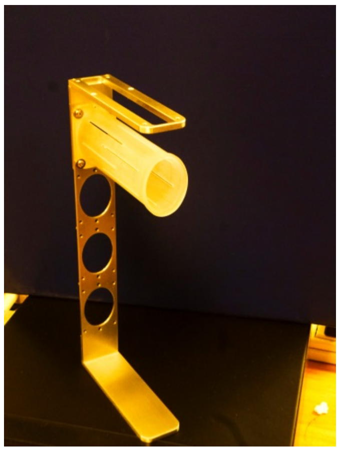
full systems test in April 11-22, 2016
installation in summer 2017

- supported with Los Alamos LDRD funds

Ref: Andi Klein (LANL)

E1039 Target and Running Conditions





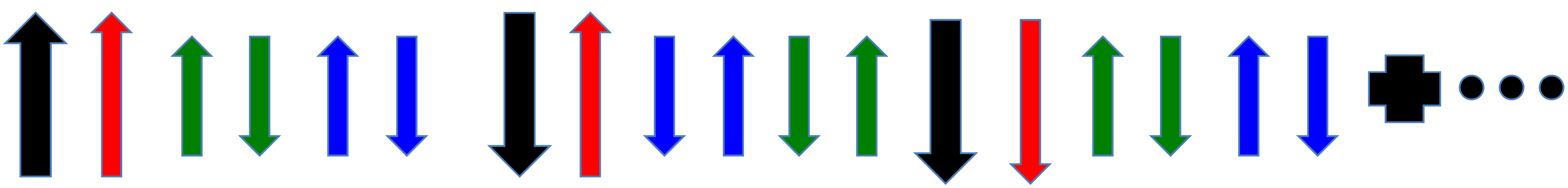
Target

- Field: 5T @ 1K
- Max Beam Current: $1*10^{13}$ p/spill ;120 GeV
  (might be limited by pump cycling)
- Elliptical shape: 1.9 cm x 2.1 cm (x,y), l:7.9cm (z)
- ρ= 0.82 g/cm^3 frozen NH_3
- Packing Fraction = 0.6
- Dilution Factor ~ 3/17 NH_3
- 5.1 g/cm^2 (NH_3) + 0.44 g/cm^2 He
- Polarization <80%>
- Horn irradiates 2 targets,
  plus one empty target, one C disk

Running Conditions: *(running length depends on rad damage)*

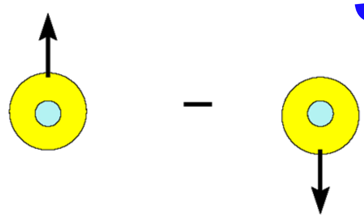
- Reverse Polarization through microwave ~8 hrs
- Reverse magnet field of FMAG and KMAG
- Reverse magnetic field of target

4 days



Ref: Andi Klein (LANL)

Sivers Function and Spin Crisis

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

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

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

$\frac{1}{2}\Delta\Sigma \approx 25\%; \quad \Delta G \approx 20\%$

L ≈ unmeasured

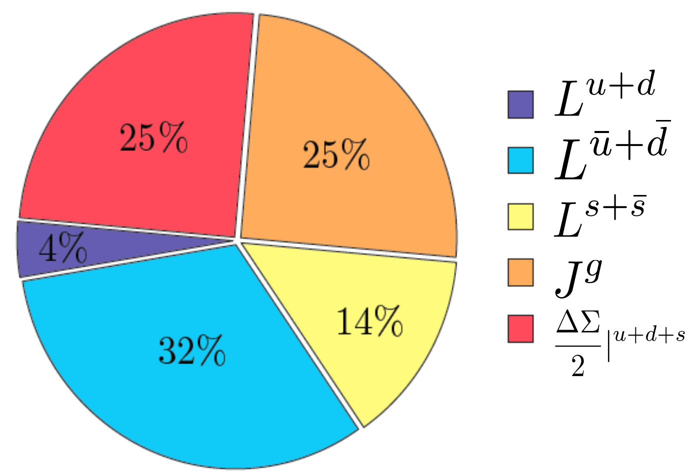
How measure quark OAM ?

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

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

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

Lattice QCD:



$\Delta\Sigma_q \approx 25\%$

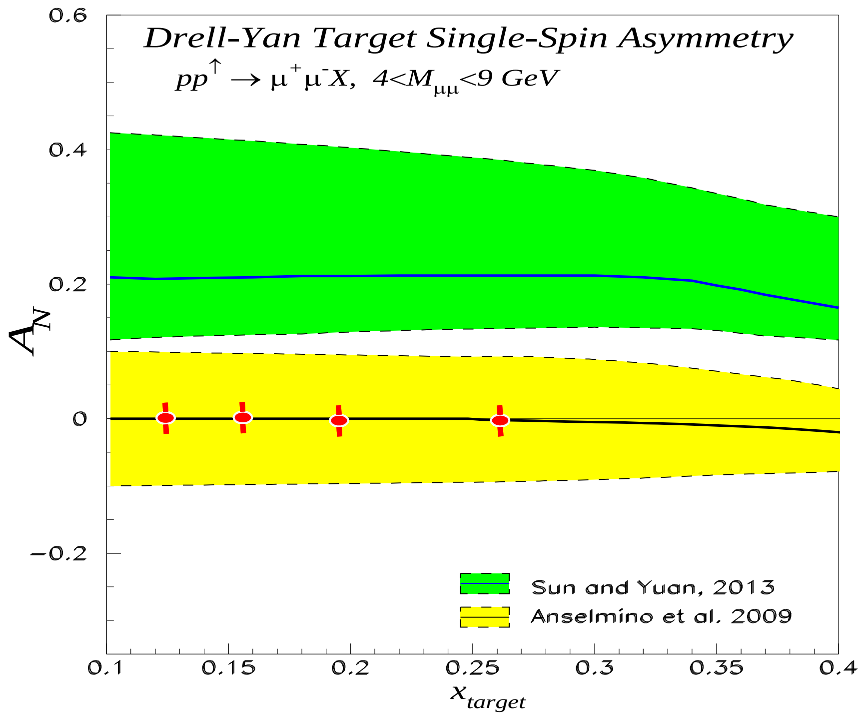
$2\ L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\ J_g \approx 25\%$

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**

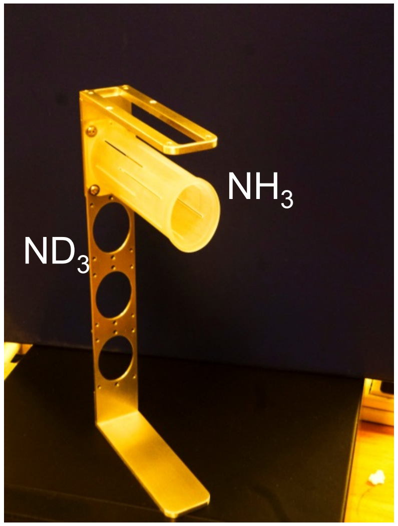
If $A_N \neq 0$, **major discovery**:
"Smoking Gun" evidence for $L_{\bar{u}} \neq 0$

Ref: Andi Klein (LANL)

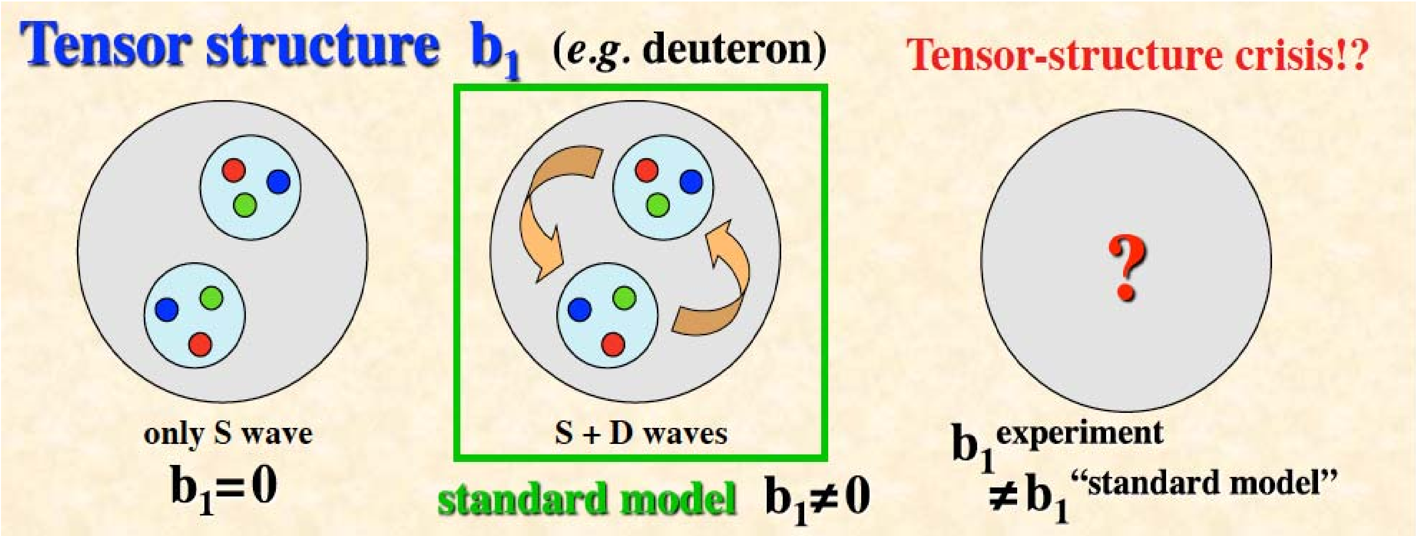
Further Plans with Polarized Targets (E-1039')

- 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 systematic errors
    - microwave irradiates both targets at the same time
    - one cell NH_3, the other ND_3

Target holder



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

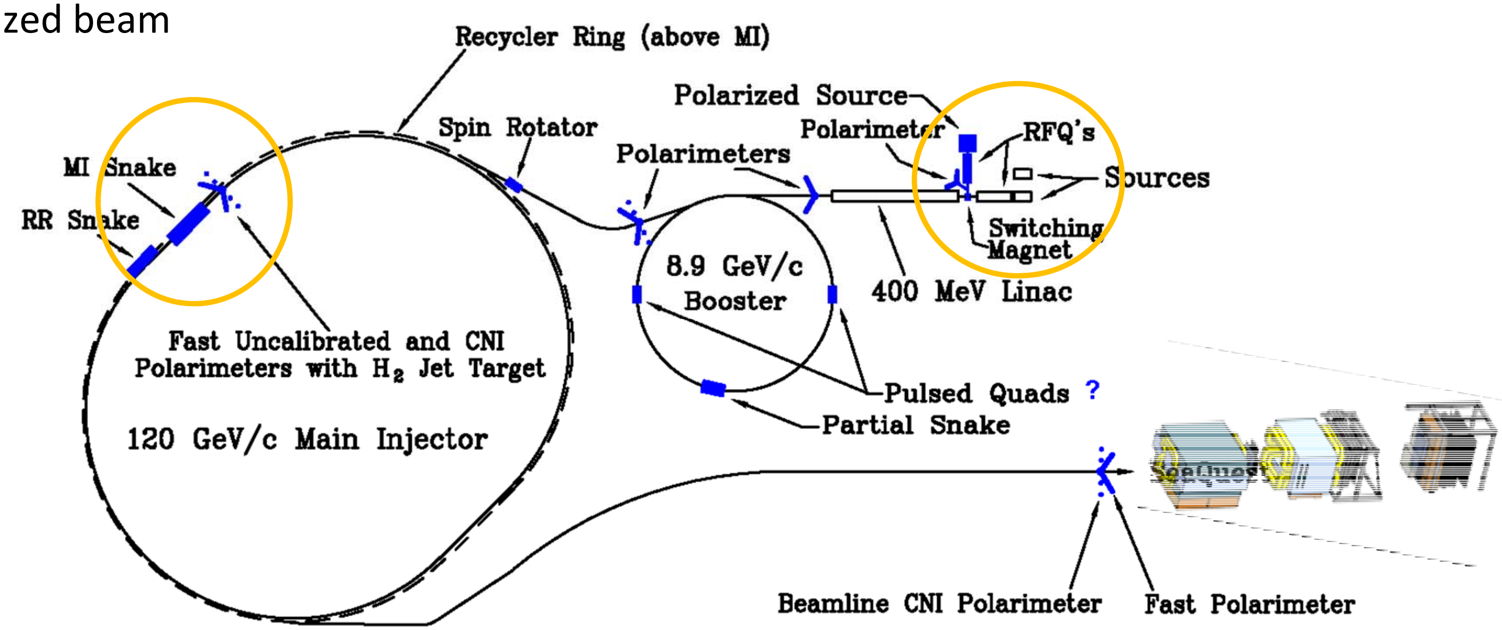


Ref: Andi Klein (LANL)

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

Planned(/running) Polarized Drell-Yan Experiments

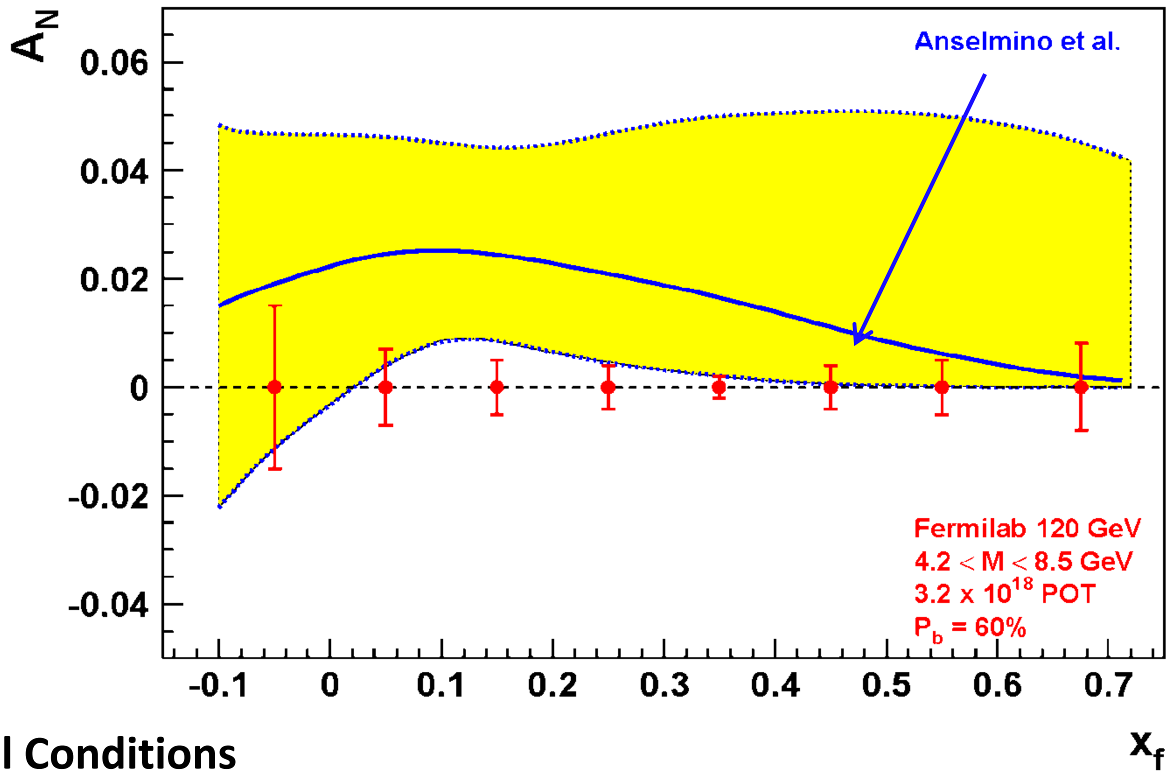
Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\,s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17	x_t = 0.1 – 0.3	2×10^{33}	0.14	P_t = 90% f = 0.22	1.1×10^{-3}	2015-2016, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	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= $1 \times 10^{36}\ cm^{-2}\ s^{-1}$ (LH_2 tgt limited)* / *L= $2 \times 10^{35}\ cm^{-2}\ s^{-1}$ (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

Expected Precision from E-1027 at Fermilab

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



1.3 Mio DY events with no dilution

- **Experimental Conditions**
  - same as SeaQuest
  - luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: I_{av} = 15 nA)
  - 3.2×10^{18} total protons for 5×10^5 min: (= 2 yrs at 50% efficiency) with P_b = 60%

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

as well as TMD evolution!

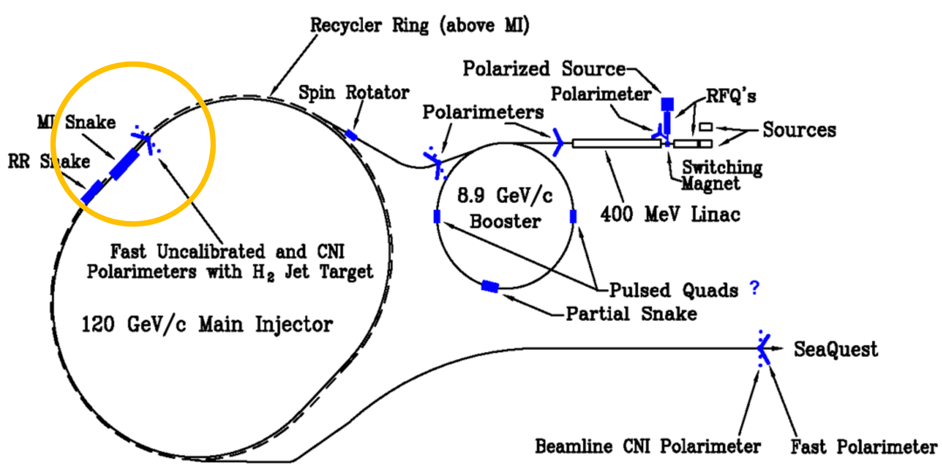
A Novel, Compact Siberian Snake for the Main Injector

Single snake design (6.4m long):

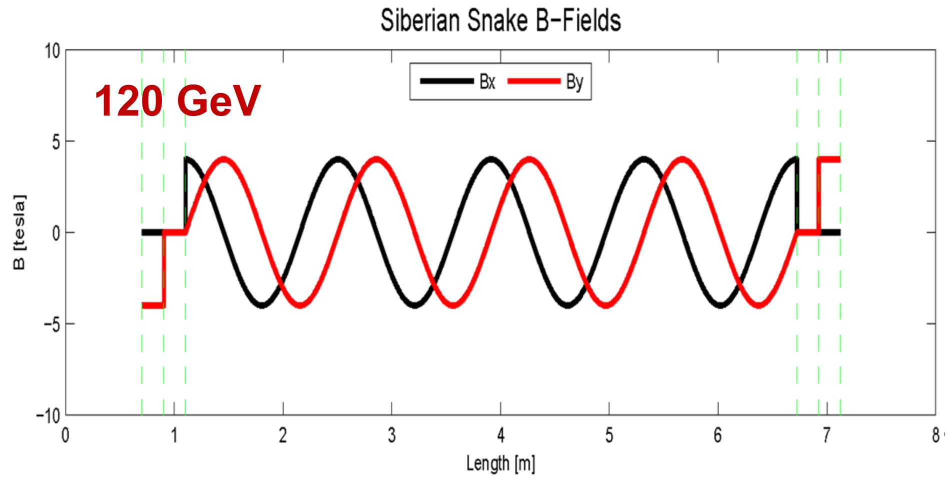
- 1 helical dipole + 2 conv. dipoles
    - helix: 4T / 5.6 m / 4” ID
    - dipoles: 4T / 0.2 m / 4” ID

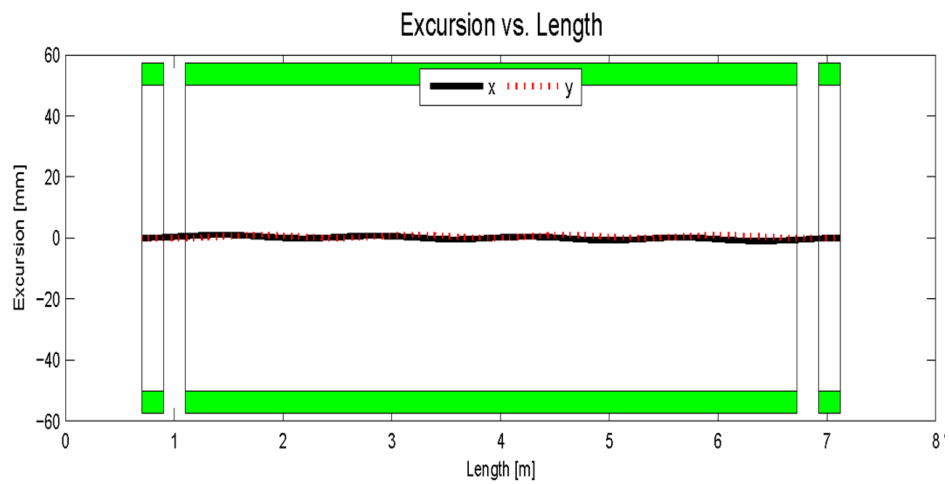
- use 4-twist magnets
    - 8π rotation of B field

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



initial design studies

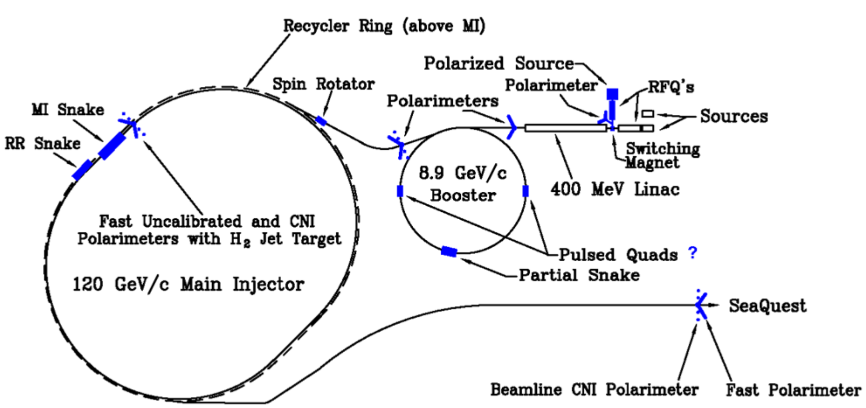


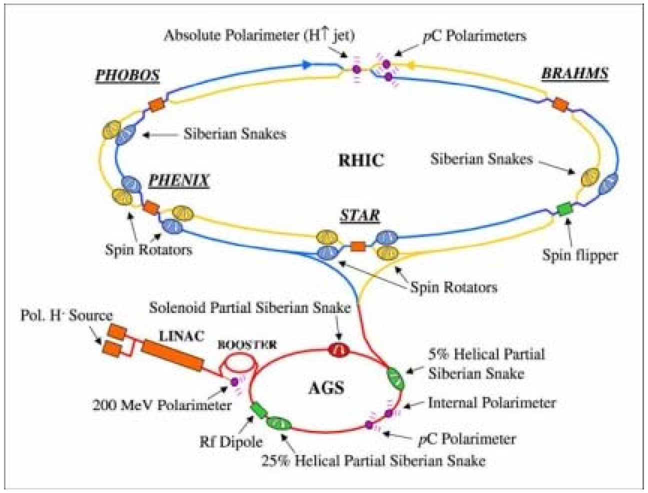


beam excursions shrink w/ beam energy

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



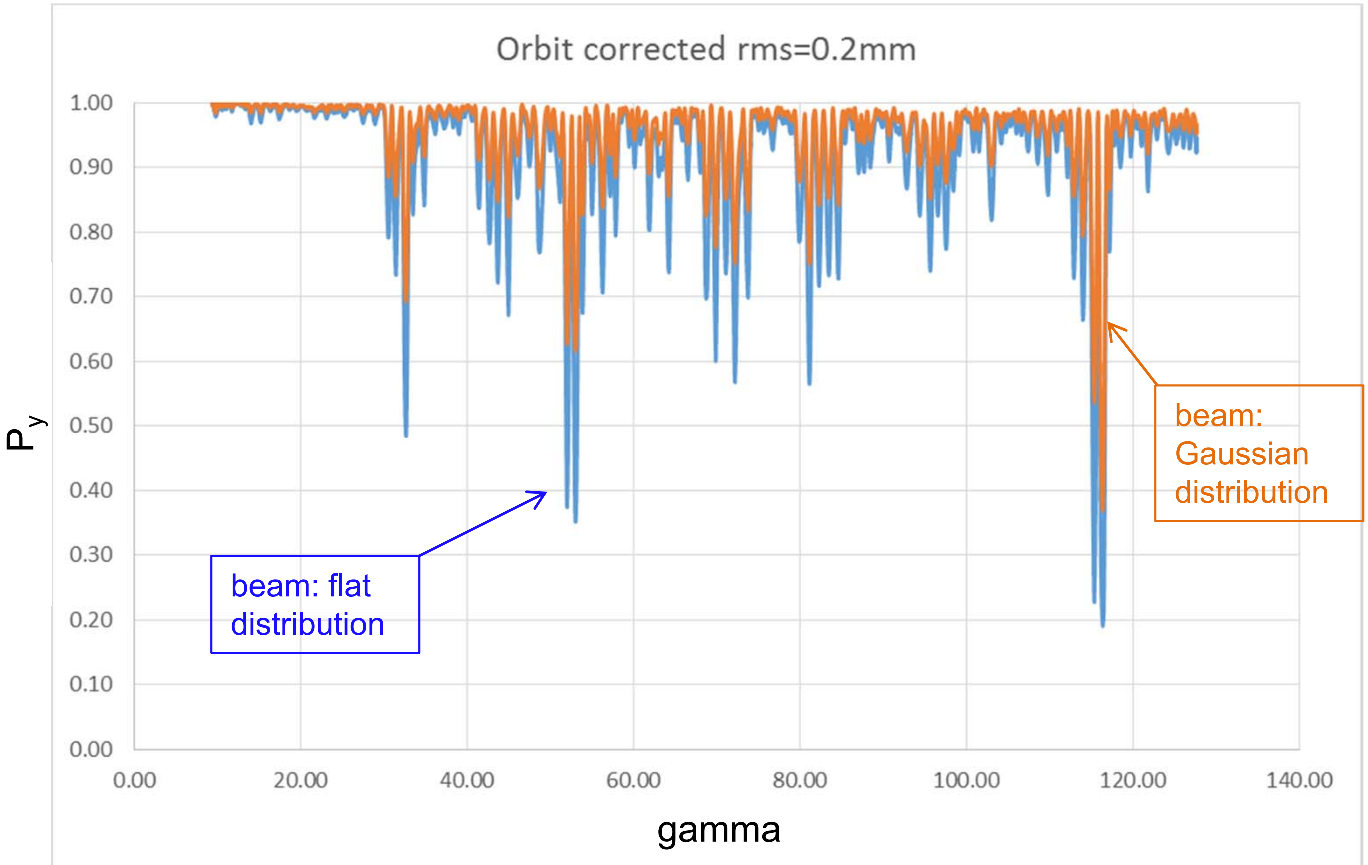


The Path to a polarized Main Injector

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



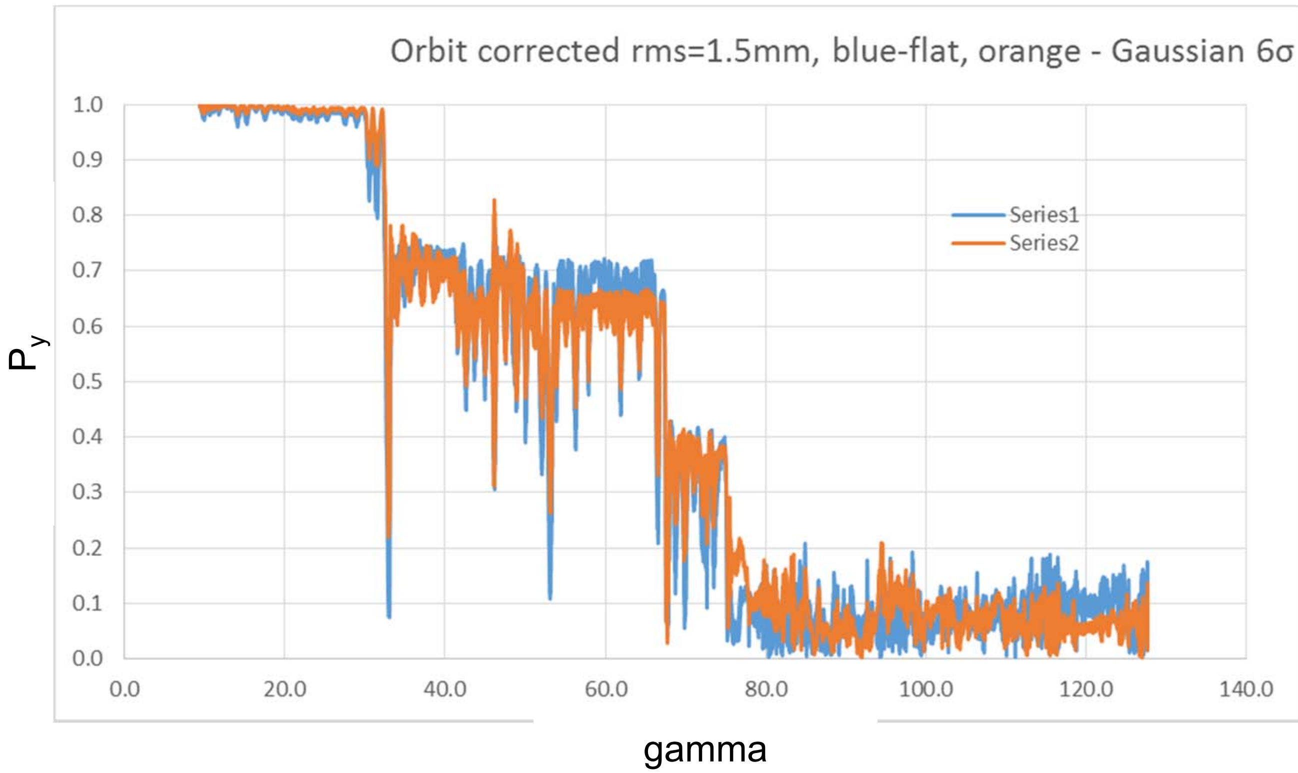
Point-like snake in correct location, actual ramp rate for acceleration.

Polarizations with magnet field error and misalignment (from magnet database and survey group), corrected (for SeaQuest running conditions)

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



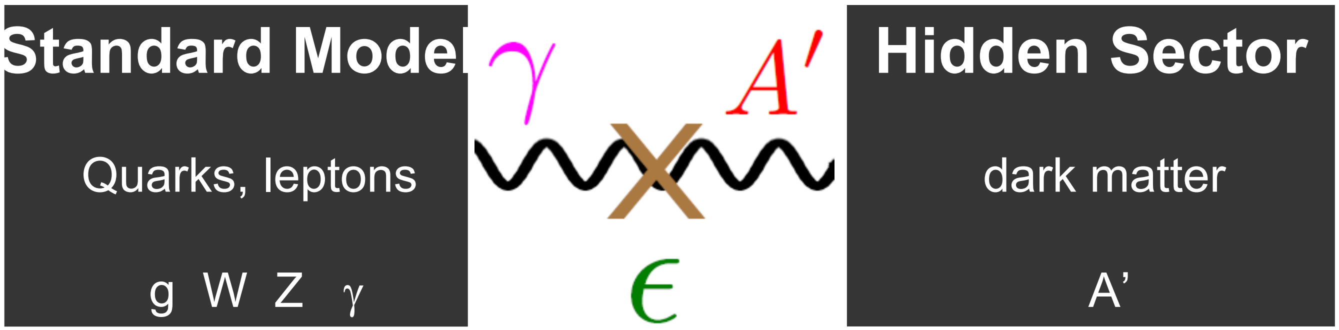
Point-like snake in correct location, actual ramp rate for acceleration.

Polarizations with magnet field error and misalignment, partially corrected

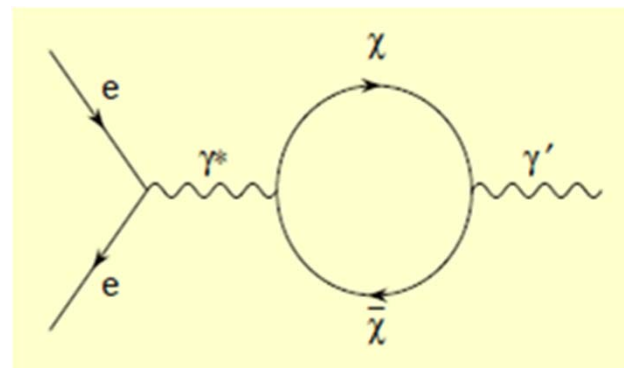
Final polarization: < 10%

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



- 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 $\alpha' = \alpha\varepsilon^2$



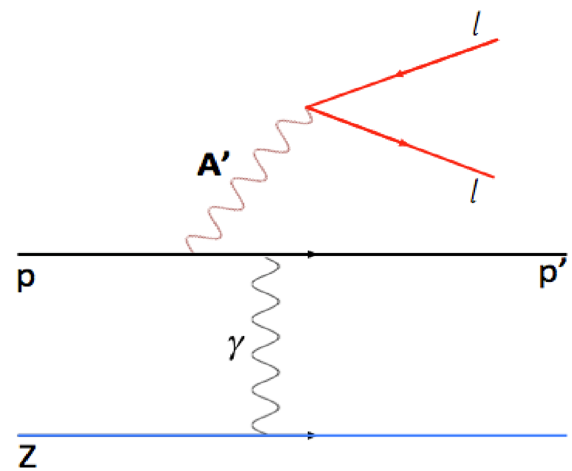
A’ produced via a loop mechanism

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

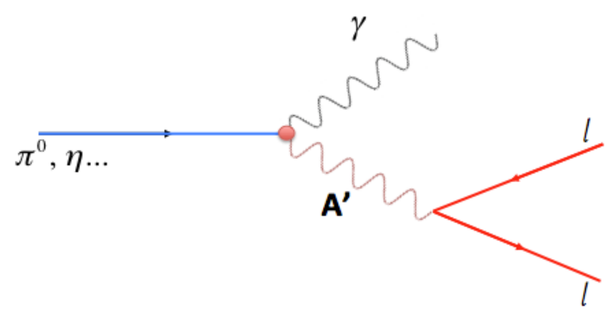
$\varepsilon \sim 10^{-2}$ to 10^{-8} from loops of heavy particles

Possible Mechanisms for producing A' at SeaQuest

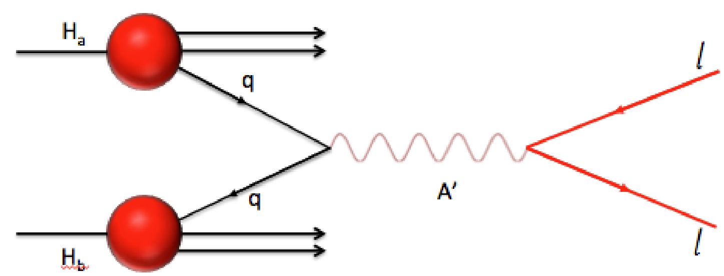
- Proton Bremsstrahlung



- η … decay

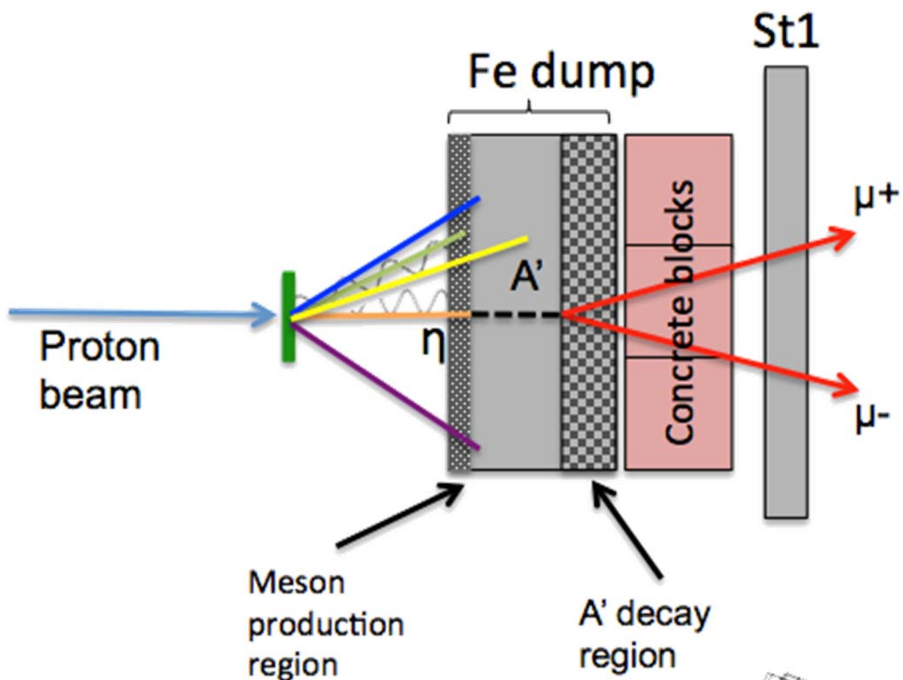


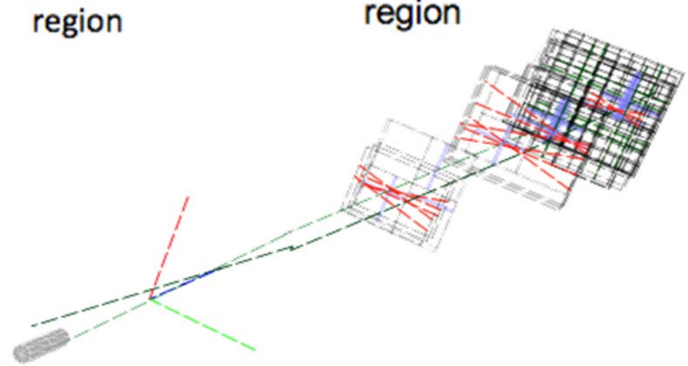
- Drell-Yan process



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



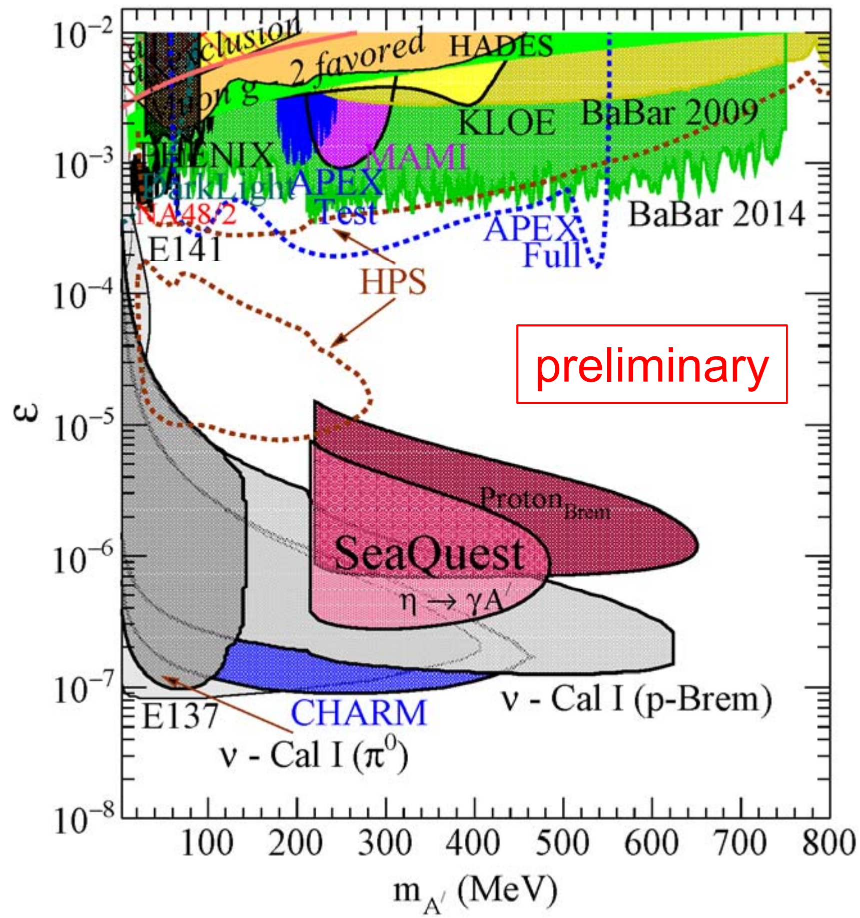


A’ sensitivity region for SeaQuest

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

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

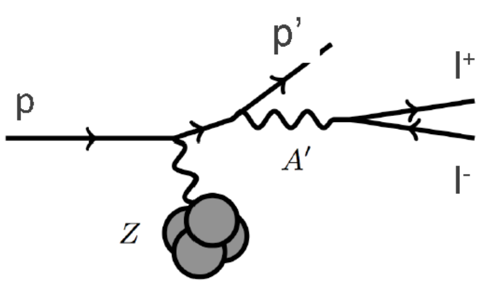
Searches for a dark photon also limit other possibilities

Parity violation studies could prove key

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

[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)!

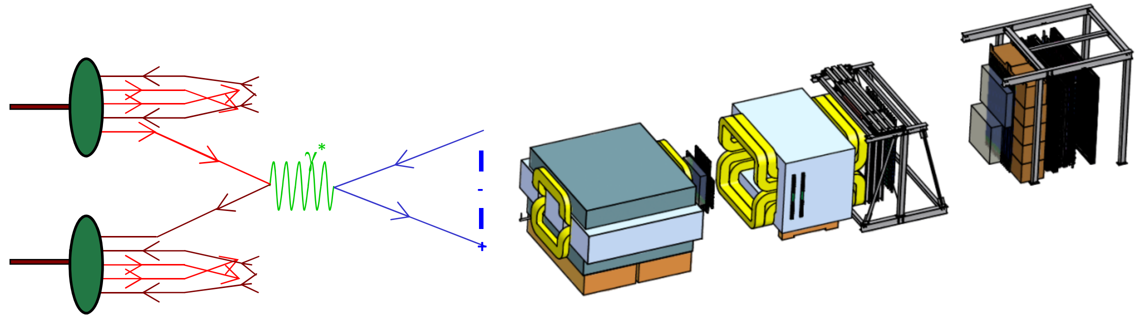
E-1027, E-1039 (and Beyond)

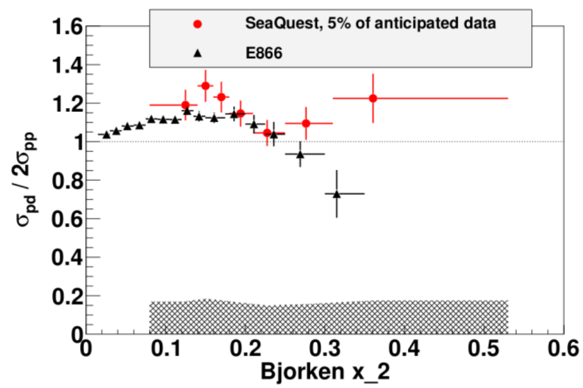
	Beam Pol.	Target Pol.	Favored Quarks	Physics Goals				
				(Sivers Function)			L_{sea}	A', Z_d
				sign change	size	shape		
E-1027 $p^{\uparrow} p \rightarrow \mu^{+}\mu^{-} X$	✔	✘	valence	✔	✔	✔	✘	✔
E-1039 $p\, p^{\uparrow} \rightarrow \mu^{+}\mu^{-} X$	✘	✔	sea	✘	✔	(✔)	✔	✔
E-10XX $p^{\uparrow} p^{\uparrow}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

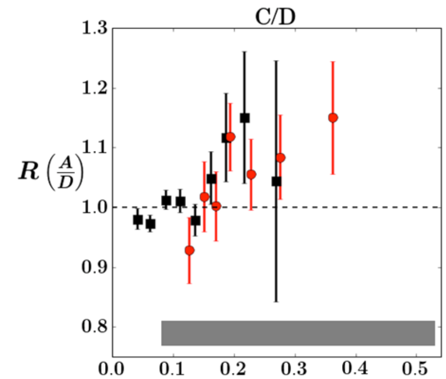
Double-Spin Drell-Yan

$\longrightarrow$ 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

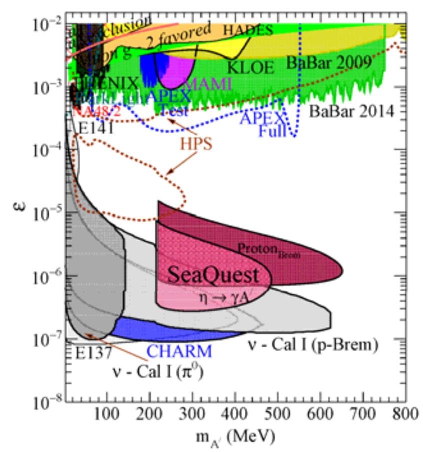
Not discussed:

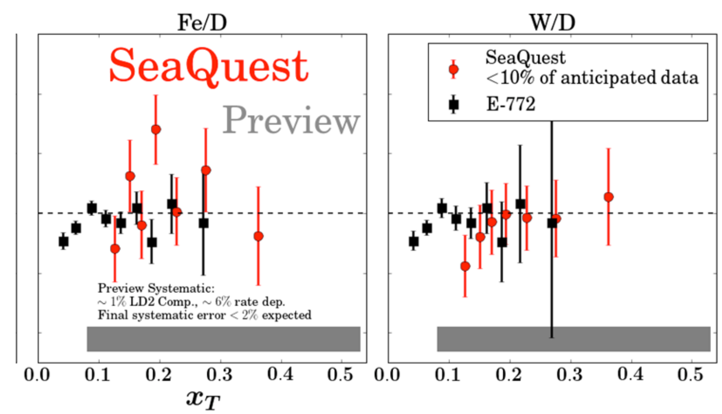
- Quark sea absolute magnitude
- Partonic Energy Loss
- J/ψ Nuclear Dependence

Transverse Spin Physics

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

Dark Photons?





Thank You