Opportunities with polarized protons at Fermilab

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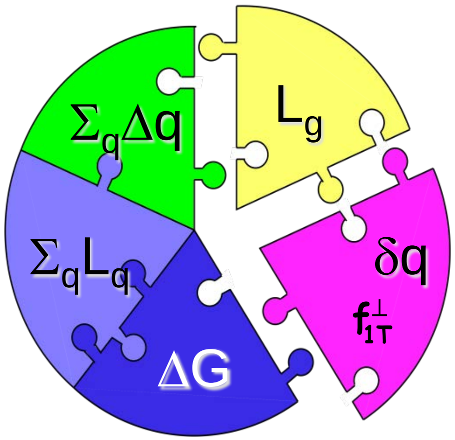
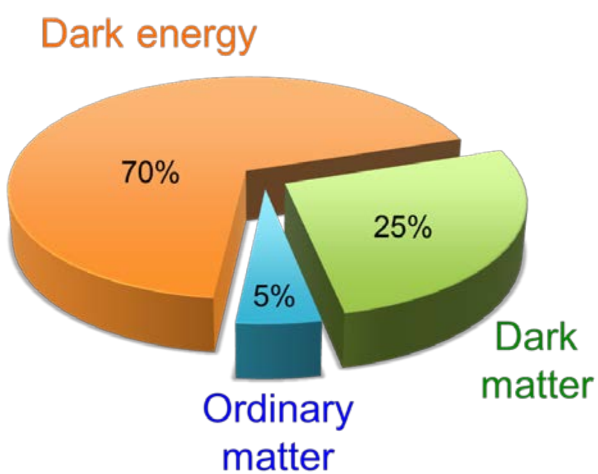
University of Michigan

PacSPIN2015
(8-October-2015)



E906 SeaQuest

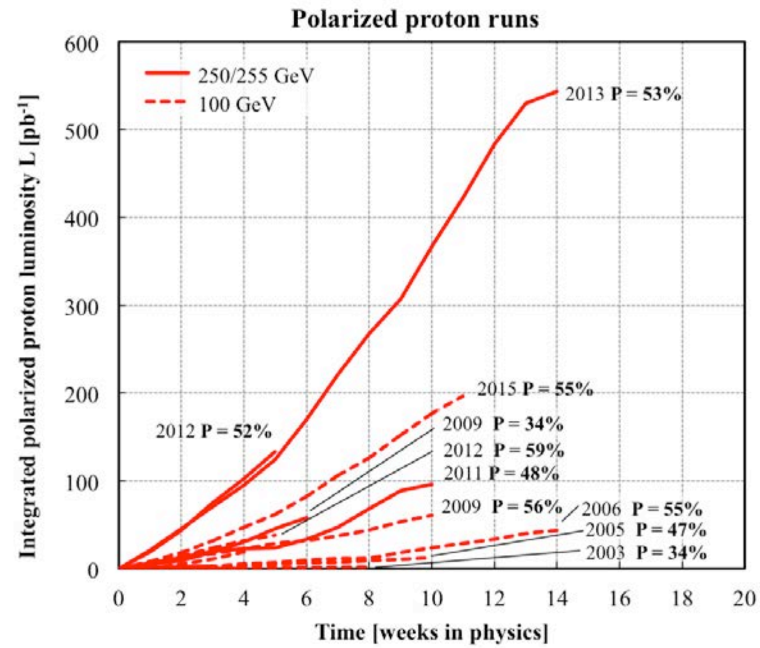
$$f_{1T}^{\perp}\Big|_{DIS} = - f_{1T}^{\perp}\Big|_{DY}$$



This work is supported by

Current Facilities

- T & L polarized p beams ($\sqrt{s}$ = 200, 500 GeV)
- L program:
  - ➞ $A_{LL}^{\pi^0}$ (PHENIX) & A_{LL}^{jet} (STAR) → **Δg(x)**
    - first significant non-zero results on **Δg(x)**
  - ➞ $A_L^{W^\pm}$ at $\sqrt{s}$ = 500 GeV → **Δq**$_{bar}$**(x)**
    - surprise: $\Delta\bar{u} - \Delta\bar{d} > 0$
- T program:
  - ➞ $A_N^{\pi^0,\eta,jet,...}$ → Sivers/Collins/Twist-3



E906 SeaQuest

- 120 GeV p from Main Injector on LH_2,LD_2, C,Ca,W targets → **high-x Drell-Yan**
- Science data started in March 2014
  - ➞ run for 2 yrs

COMPASS-II

- 190 GeV π^- beam on T-pol H target → **polarized Drell-Yan**
- Data collection started in May 2015
  - ➞ run for 100 days

Future Spin Measurements

New instrumentation in forward direction

→ **higher η**: higher x_{beam} , lower x_{target}

- STAR Forward Calorimeter System: EMCal + HCal
- fsPHENIX: forward spectometer w/ EMCal, HCal, RICH, tracking

➞ planned spin program in **$\Delta g(x,Q^2)$ at low-x** (longitudinal) as well as Jets**, Drell-Yan** (transverse), ...

Polarized Beam and/or Target w/ SeaQuest detector

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

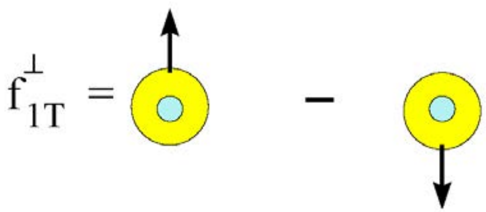
- E-1039: SeaQuest w/ pol NH_3 target

➞ probe sea quark distributions

- E-1027: pol p beam on unpol tgt

➞ **Sivers sign change** (valence quark)

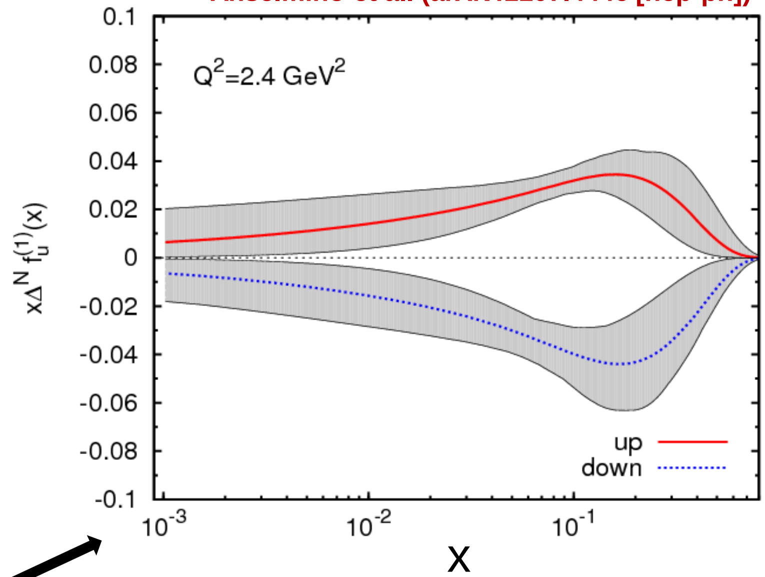
TMDs: Sivers Function



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
- Sivers function is naïve time-reversal odd
- leads to
  - ➡ $\sin(\phi - \phi_S)$ asymmetry in SIDIS
  - ➡ $\sin\phi_b$ asymmetry in Drell-Yan
- measured in SIDIS (HERMES, COMPASS)
- future measurements at Jlab@12 GeV planned

Anselmino et al. (arXiv:1107.4446 [hep-ph])

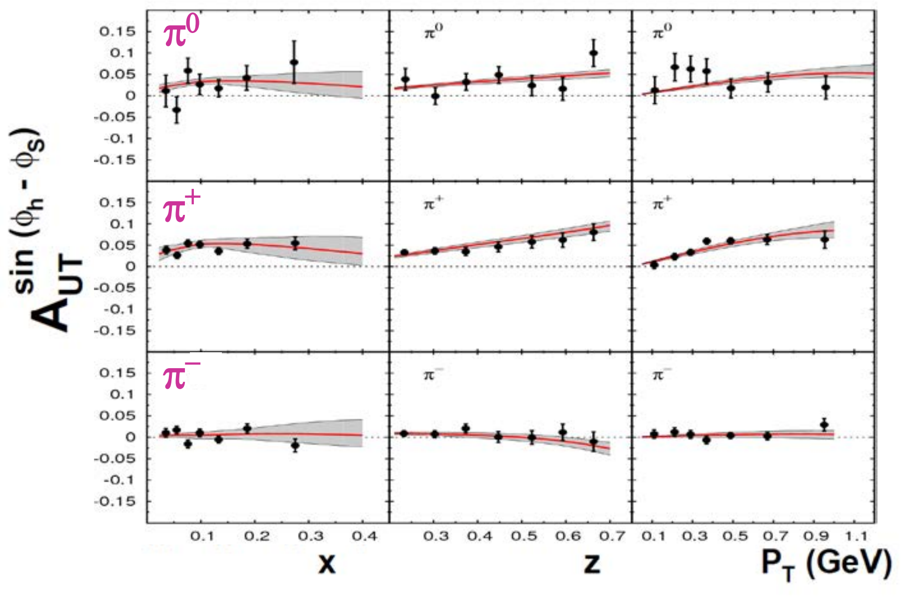


First moment of Sivers functions:

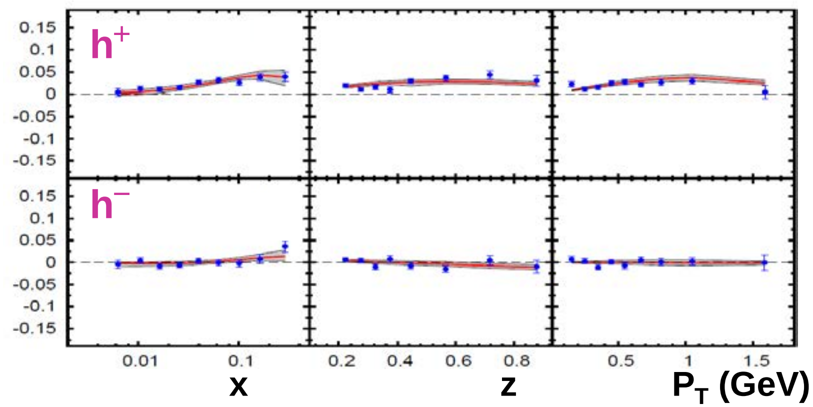
➡ u- and d- Sivers have opposite signs, of roughly equal magnitude

Sivers Asymmetry in SIDIS

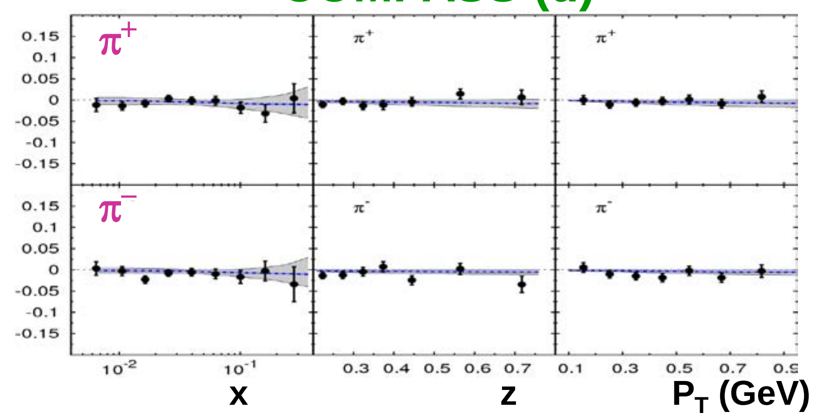
HERMES (p)



COMPASS (p)



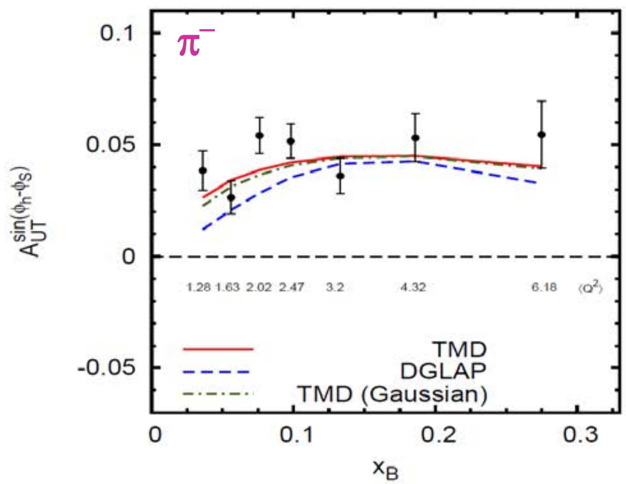
COMPASS (d)



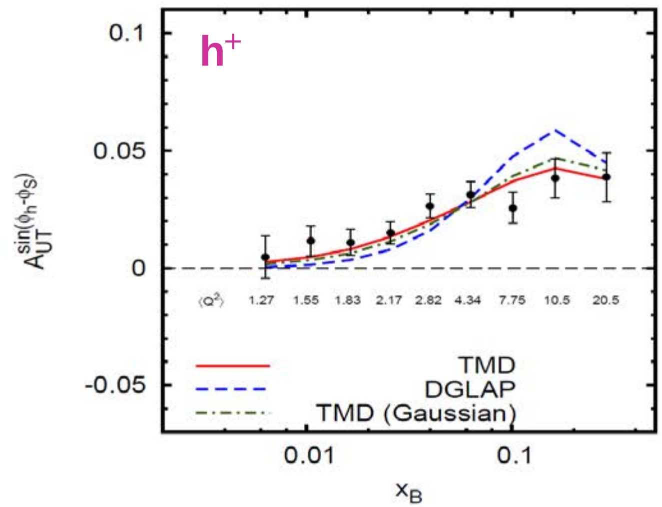
- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES (p), COMPASS (p), COMPASS (d))

QCD Evolution of Sivers Function

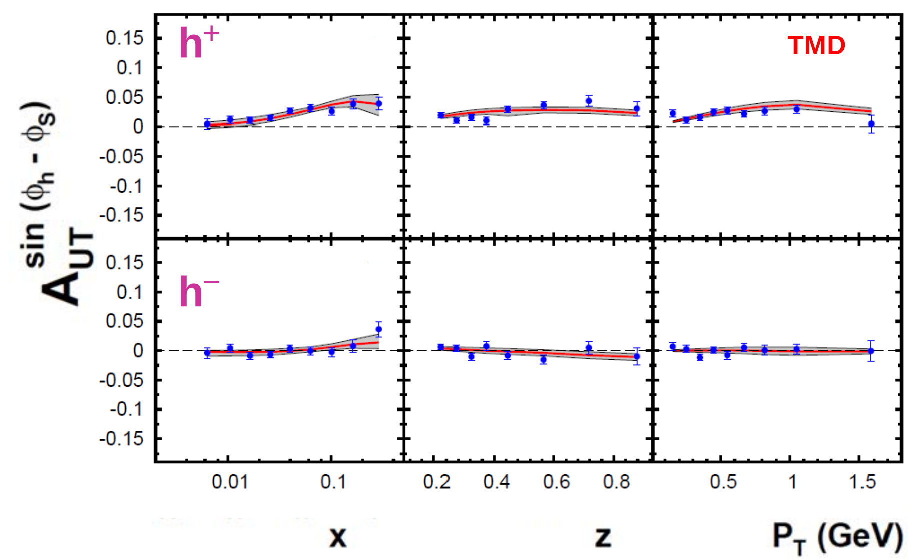
HERMES (p)



COMPASS (p)



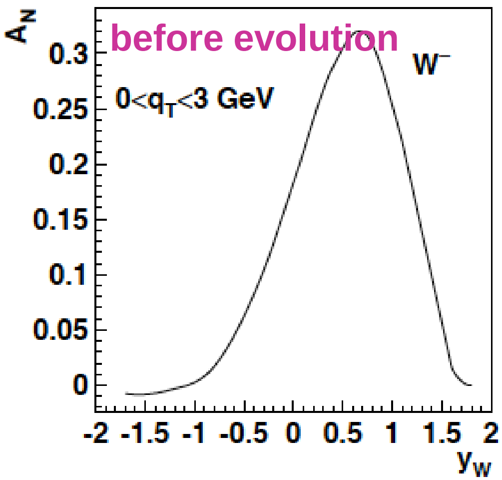
Anselmino et al.
(arXiv:1209.1541 [hep-ph])



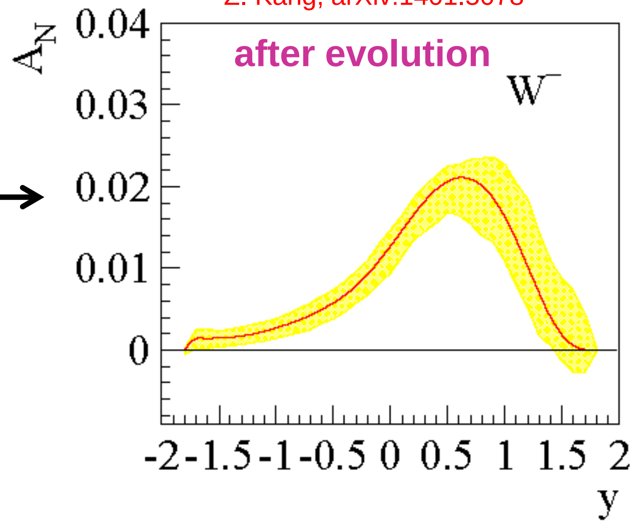
- Initial global fits by Anselmino group included DGLAP evolution only in collinear part of TMDs (not entirely correct for TMD-factorization)
- Using TMD Q^2 evolution:
  → agreement with data improves

TMD Evolution of Sivers Asymmetry (W^-)

Z. Kang, arXiv:0903.3629



Z. Kang, arXiv:1401.5078



- much stronger than any other known evolution effects
- but needs input from data to constrain non-pertubative part in evolution
- **Can only be done at RHIC (**plans for 2% measurement in 2016**)**

A_N(**DY**)	Q^2: 16 – 80 GeV^2	<p_t>: 1-2 GeV
A_N(**$W^\pm$,Z^0**)	Q^2: **6,400** GeV^2	<p_t>: 3-4 GeV

$$A_N \propto \frac{1}{Q^{0.7}}$$

Comparison of extracted TMD (Sivers) will provide strong constraint on TMD evolution

The Sign Change

$$f_{1T}^{\perp}(x,k_T)\Big|_{SIDIS} = -\, f_{1T}^{\perp}(x,k_T)\Big|_{DY,\,W}$$

- fundamental prediction of QCD (in non-perturbative regime)
  → goes to heart of gauge formulation of field theory

- "Smoking gun" prediction of **TMD formalism**

- **Universality test includes not only the sign-reversal character of the TMDs but also the comparison of the amplitude as well as the shape of the corresponding TMDs**

- **NSAC** Milestone HP13 (2015):
  "Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering"

Planned Polarized Drell-Yan Experiments

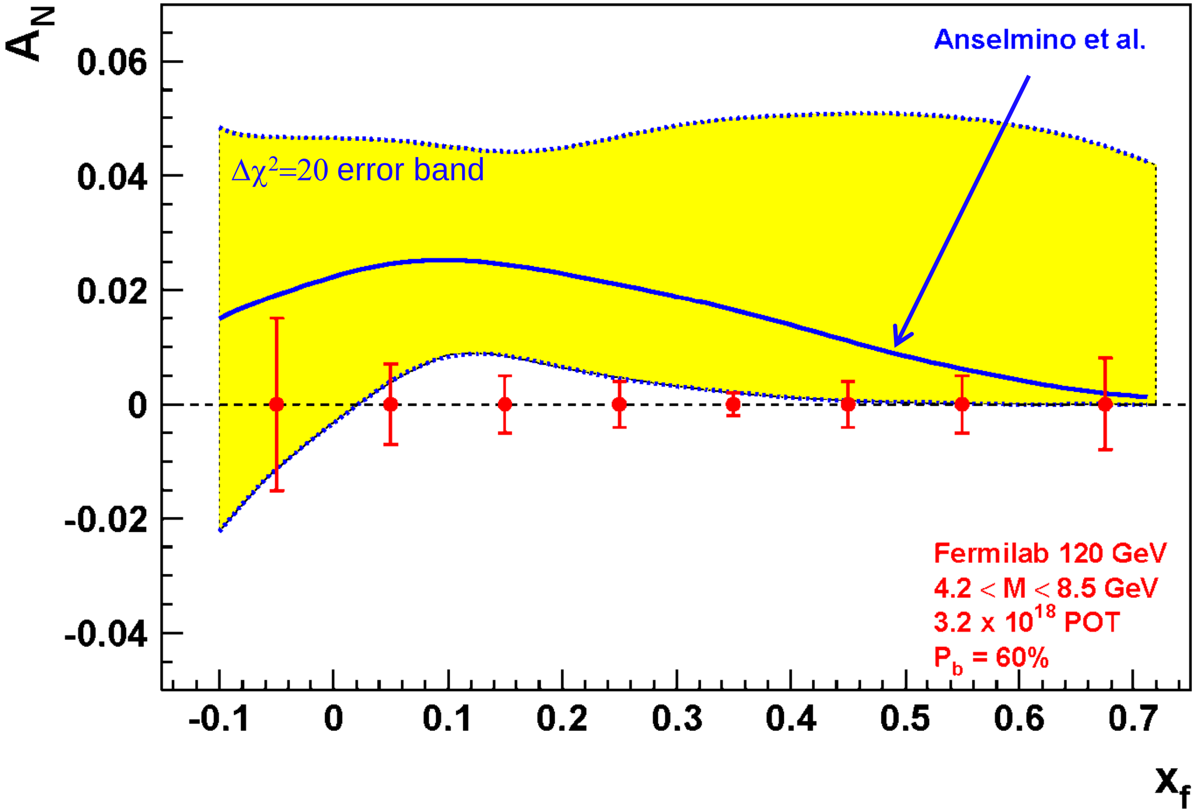
Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\ s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2015, 2018
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	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 - 2016
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	2017-2018
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	>2018

‡ *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) 10/2015

Sivers Asymmetry at Fermilab Main Injector

- Experimental Sensitivity
  - ➡ 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 $P_b = 60\%$



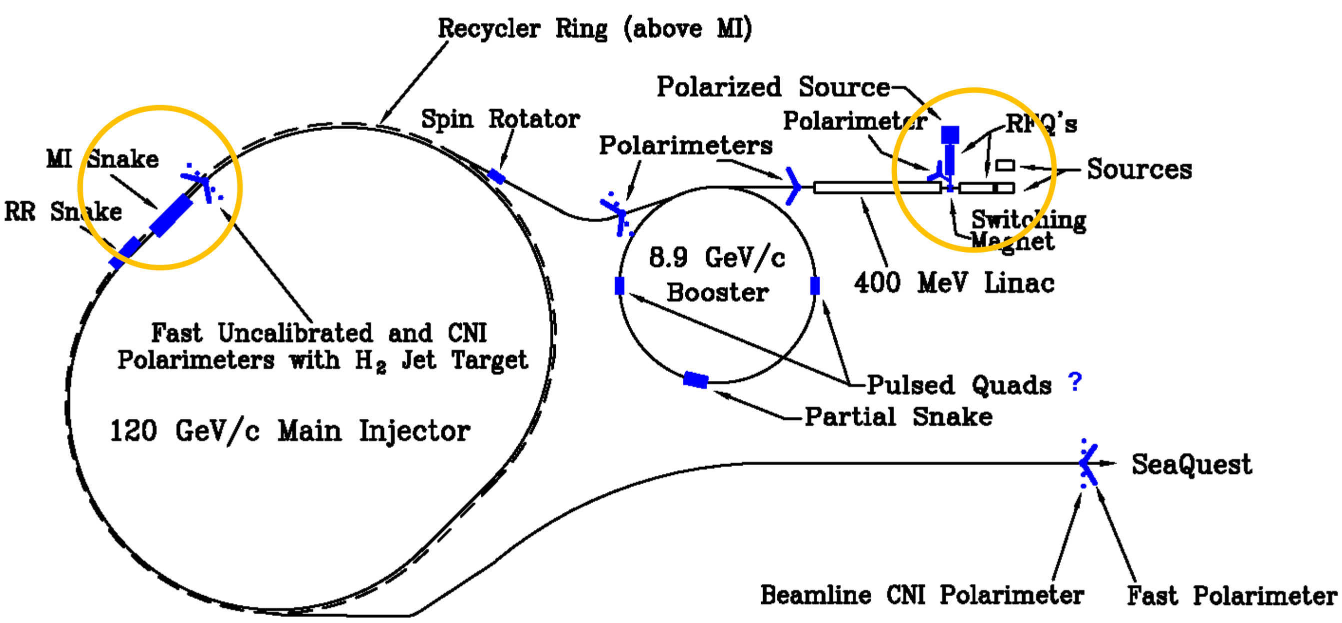
Note:

$$A_N = \frac{2}{\pi} A^{\sin\phi_b}_{TU}$$

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

Polarized Beam Drell-Yan at Fermilab (E-1027)

- Extraordinary opportunity at Fermilab (best place for polarized DY) :
  - ⟶ high luminosity, large x-coverage
  - ⟶ (SeaQuest) spectrometer already setup and running
  - ⟶ run alongside neutrino program (w/ 10% of beam)
  - ⟶ experimental sensitivity:
    - › 2 yrs at 50% eff, P_b = 60%, I_{av} = 15 nA
    - › luminosity: $L_{av} = 2 \times 10^{35}$ /cm^2/s
    - › measure sign, size & shape of Sivers function



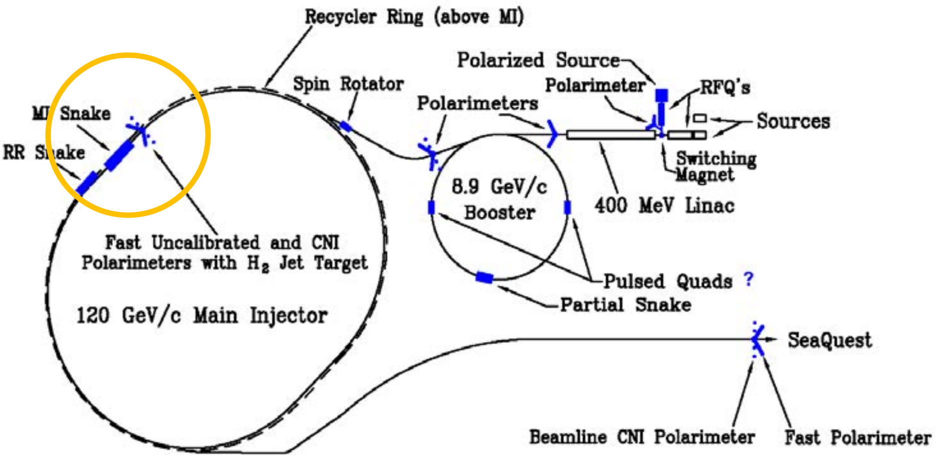
A Novel, Compact Siberian Snake for the Main Injector

Single snake design (6.4m long):

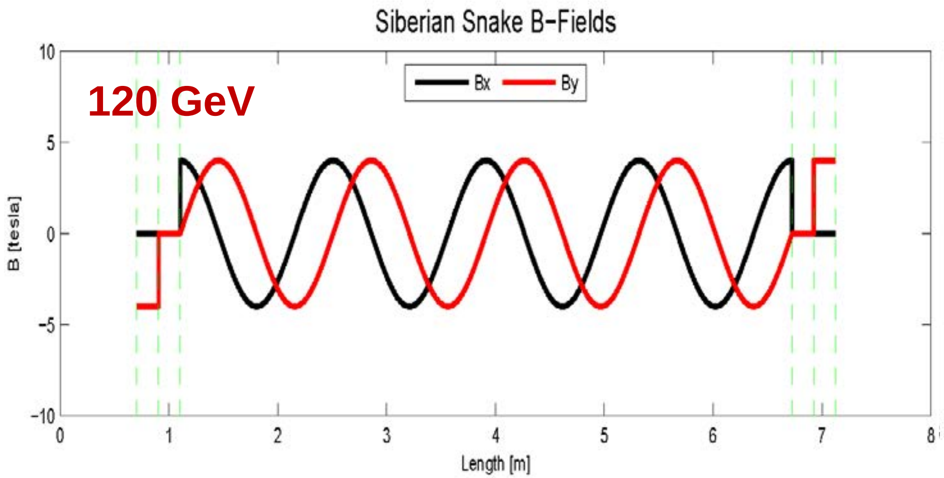
- 1 helical dipole + 2 conv. dipoles
  - helix: 4T / 5.6 m / 4” ID
  - dipoles: 4T / 0.2 m / 4” ID

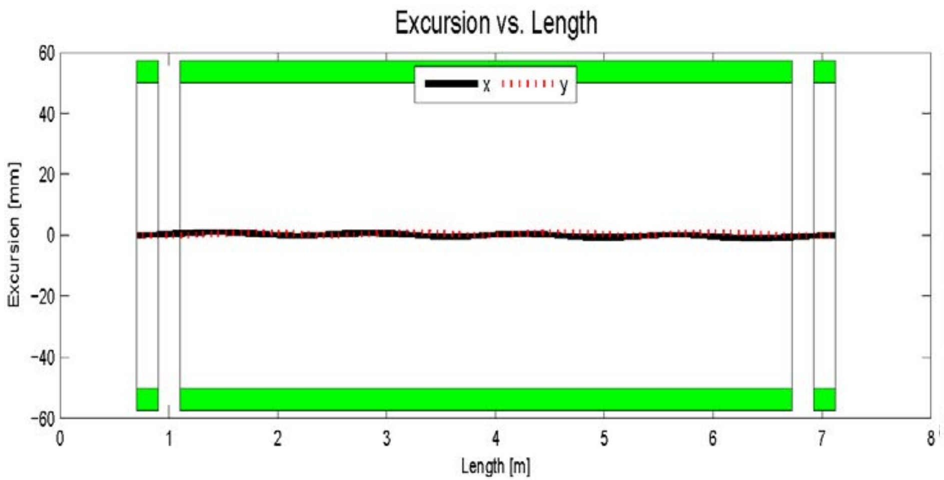
- use 4-twist magnets
  - 8π rotation of B field

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



initial design studies

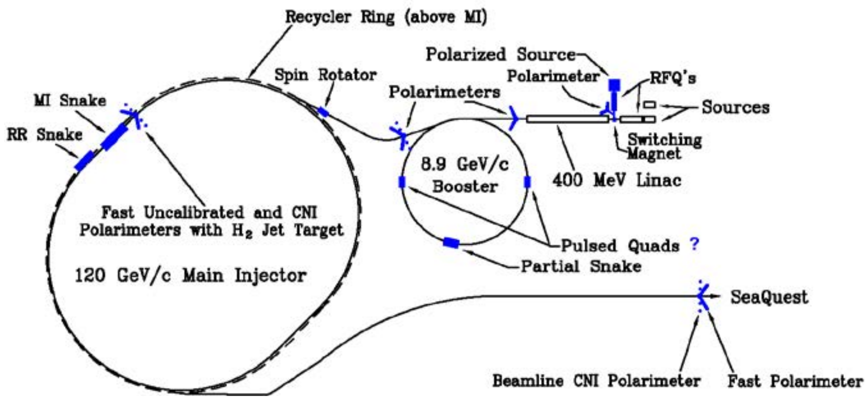


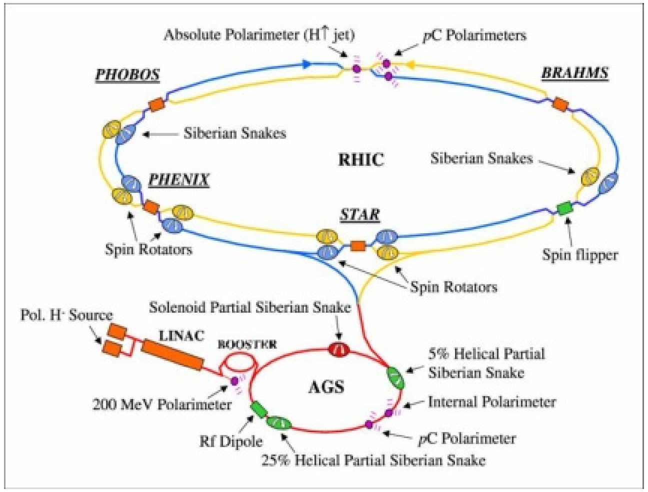


beam excursions shrink w/ beam energy

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 ~5 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



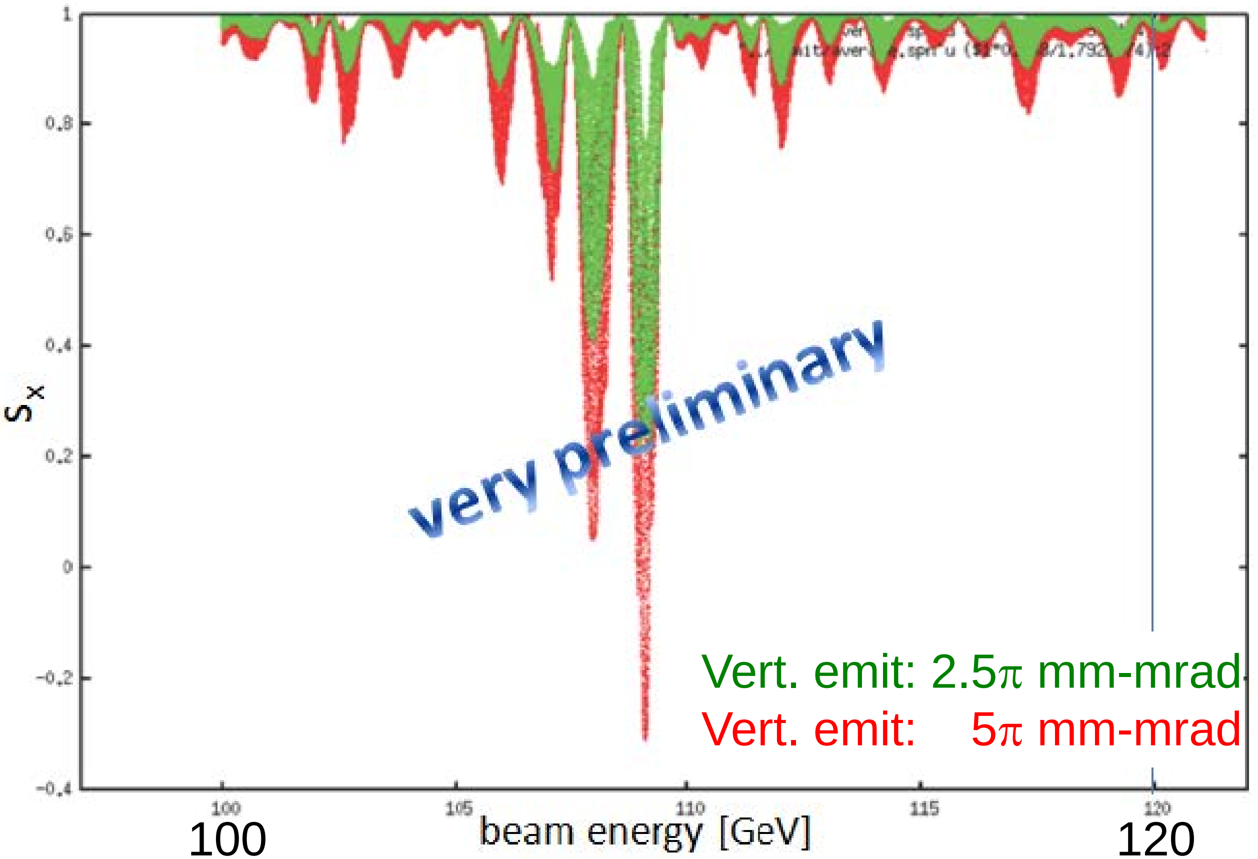


The Path to a polarized Main Injector

Stage 1 approval from Fermilab: 14-November-2012

- PAC request: detailed machine design and costing using 1 snake in MI
  - ➡ Spin@Fermi collaboration provide design
  - ➡ Fermilab (AD) does verification & costing
- Collaboration with A.S. Belov at INR and Dubna to develop polarized source
- Initial simulations in 2013 - 2014:
  - ➡ set up Zgoubi spin-tracking package (M. Bai, F. Meot, BNL, M. Syphers, MSU)
    - ⟶ 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

Effect of emittance on final polarization vs Energy



Point-like snake in correct location, perfect orbit, no momentum smearing.

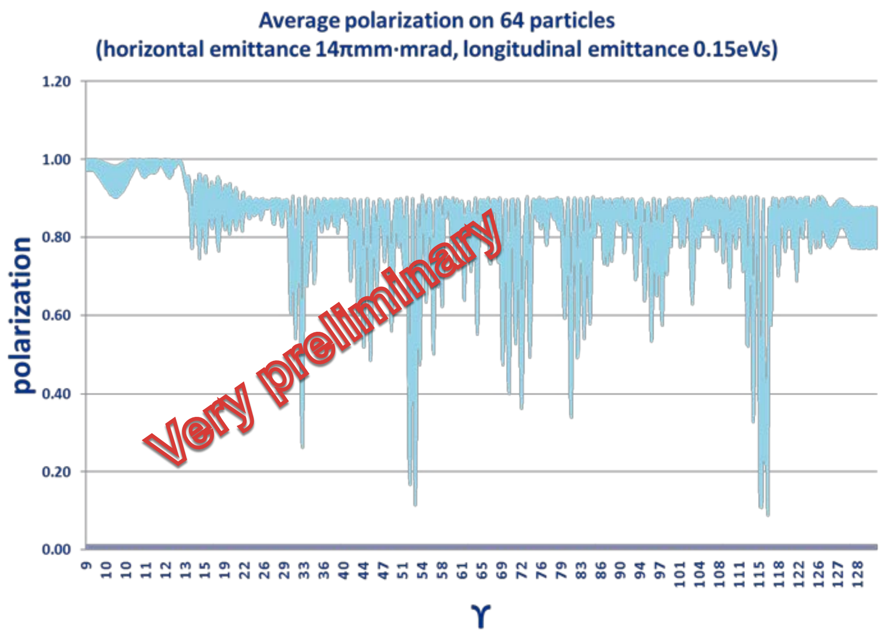
Average polarization for 8 particles

Only small difference seen at final energy of 120 GeV

The Path to a polarized Main Injector - II

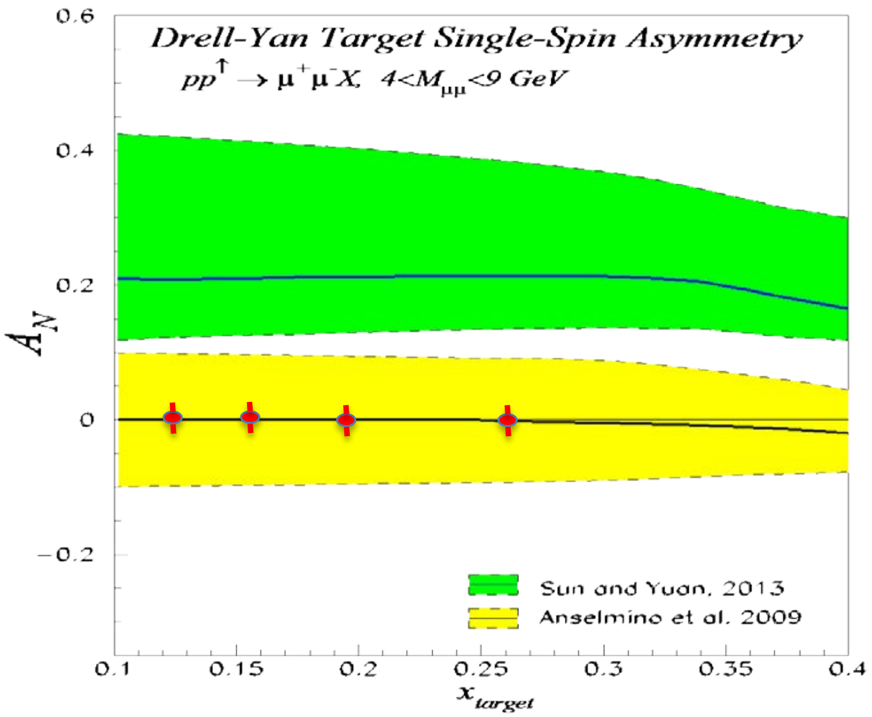
Breakthrough: AD support from Fermilab: July-2015

- Fermilab AD support in 2015
  - ➞ S. Nagaitsev pledges support for simulations (April 2015)
  - ➞ 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



Polarized Traget Drell-Yan at Fermilab (E-1039)

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



- Statistics shown for one calendar year of running:
- L = 7.2 *10^{42} /cm^2 ↔ POT = 2.8*10^{18}
- Running will be two calendar years of beam time

– existing SIDIS data poorly constrain sea-quark Sivers function

– significant Sivers asymmetry expected from meson-cloud model

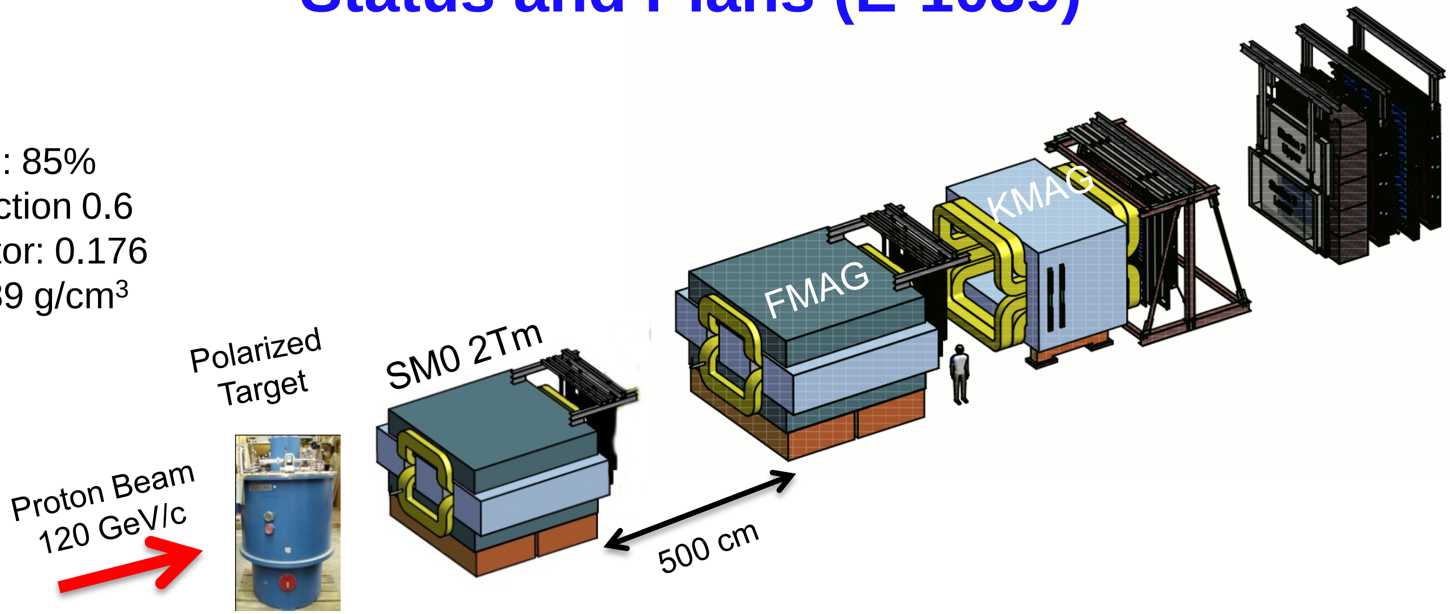
– **first Sea Quark Sivers Measurement**

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

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

Status and Plans (E-1039)

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



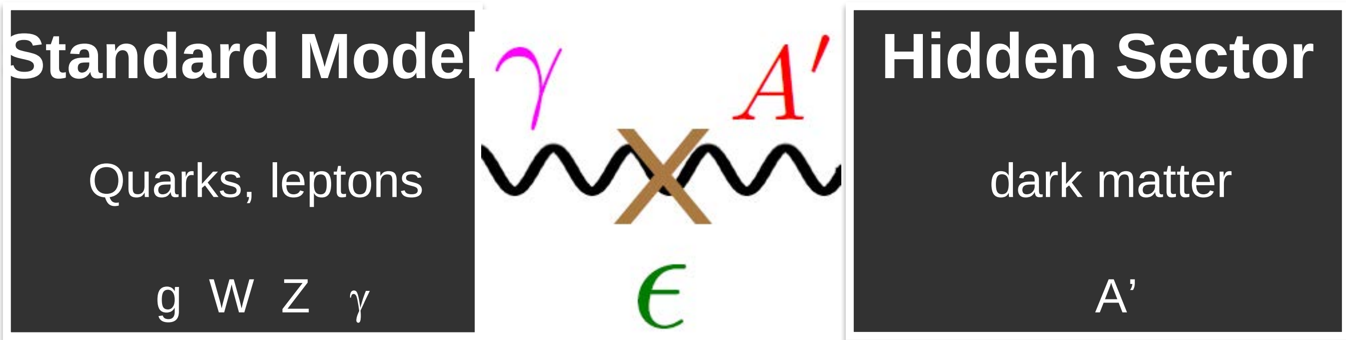
- use current SeaQuest setup, a polarized proton target, unpolarized beam
- add third magnet SM0 ~5m upstream
  → improves dump-target separation
  → reduces overall acceptance

- Current status
  - magnet system is finished and working
  - refrigerator is finished and tested (at 1K)
  - NMR system reached final design
  - mechanical design laid out

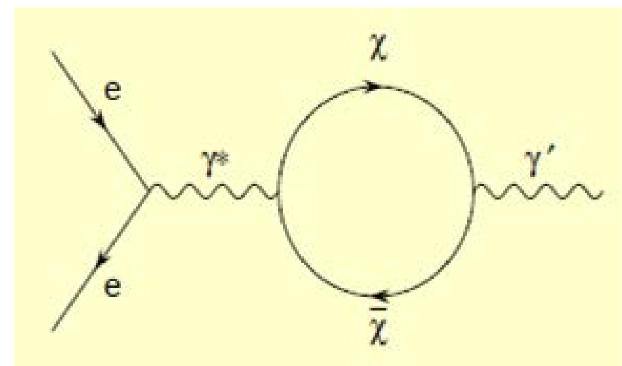
  } ahead of schedule, ready for installation in Fall 2016

Ref: Andi Klein (LANL)

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



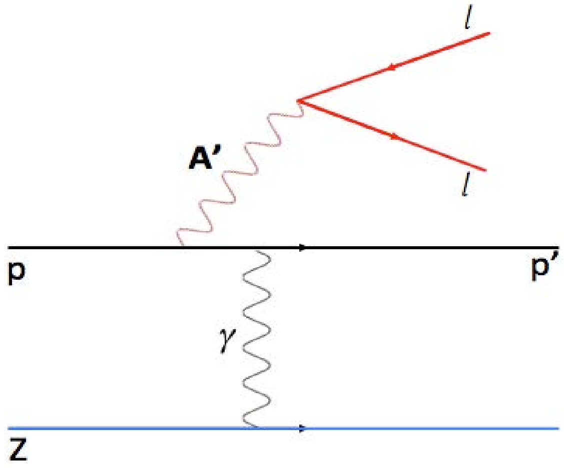
A’ produced via a loop mechanism

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

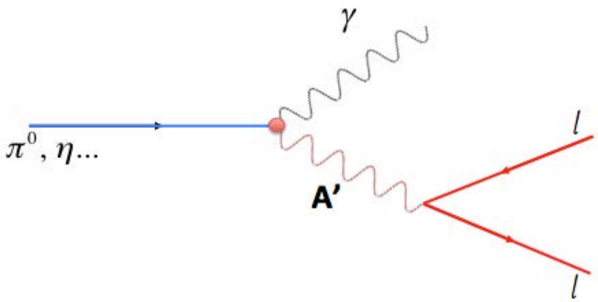
$\varepsilon \sim 10^{-2}$ to 10^{-8} from loops of heavy particles

Possible Mechanisms for producing A' at SeaQuest

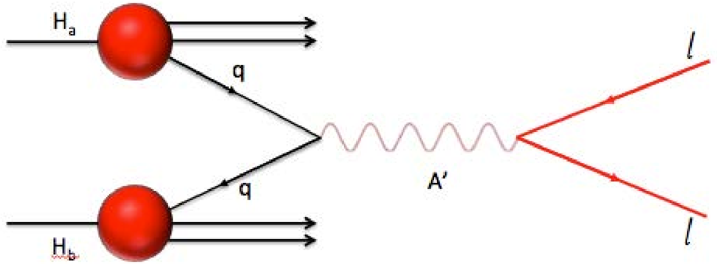
- Proton Bremsstrahlung



- π^0, η … decay

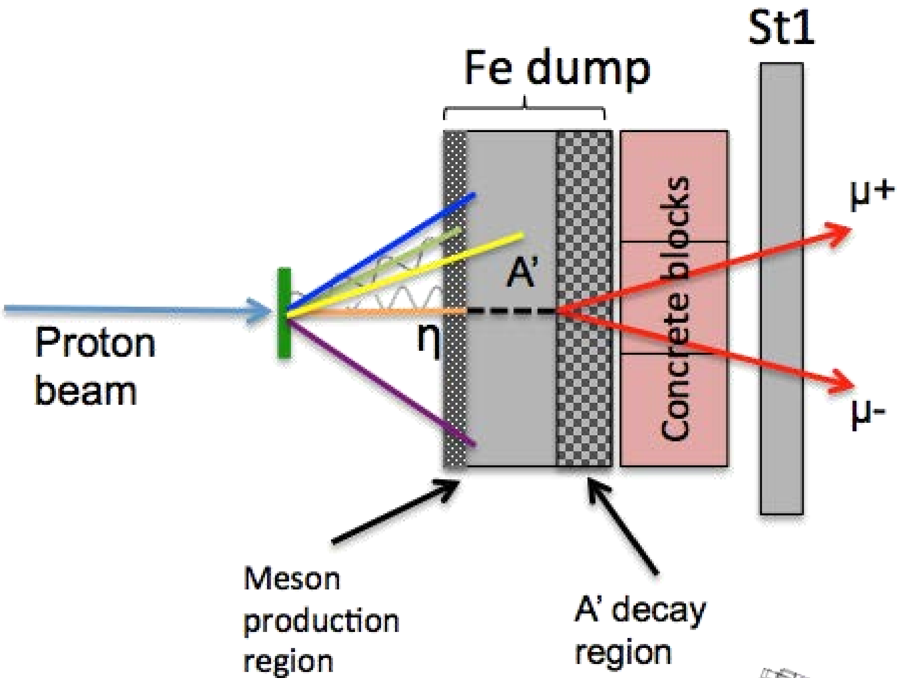


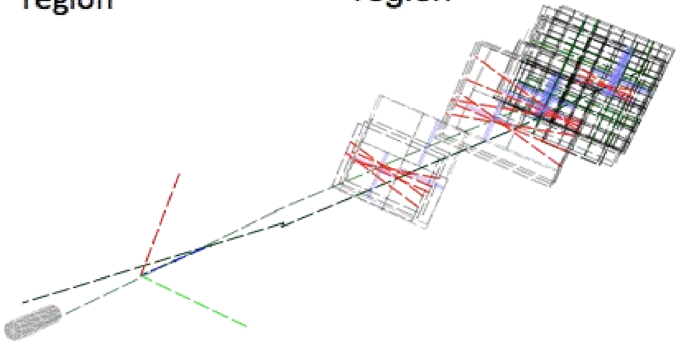
- Drell-Yan process



SeaQuest A' search strategy

- 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



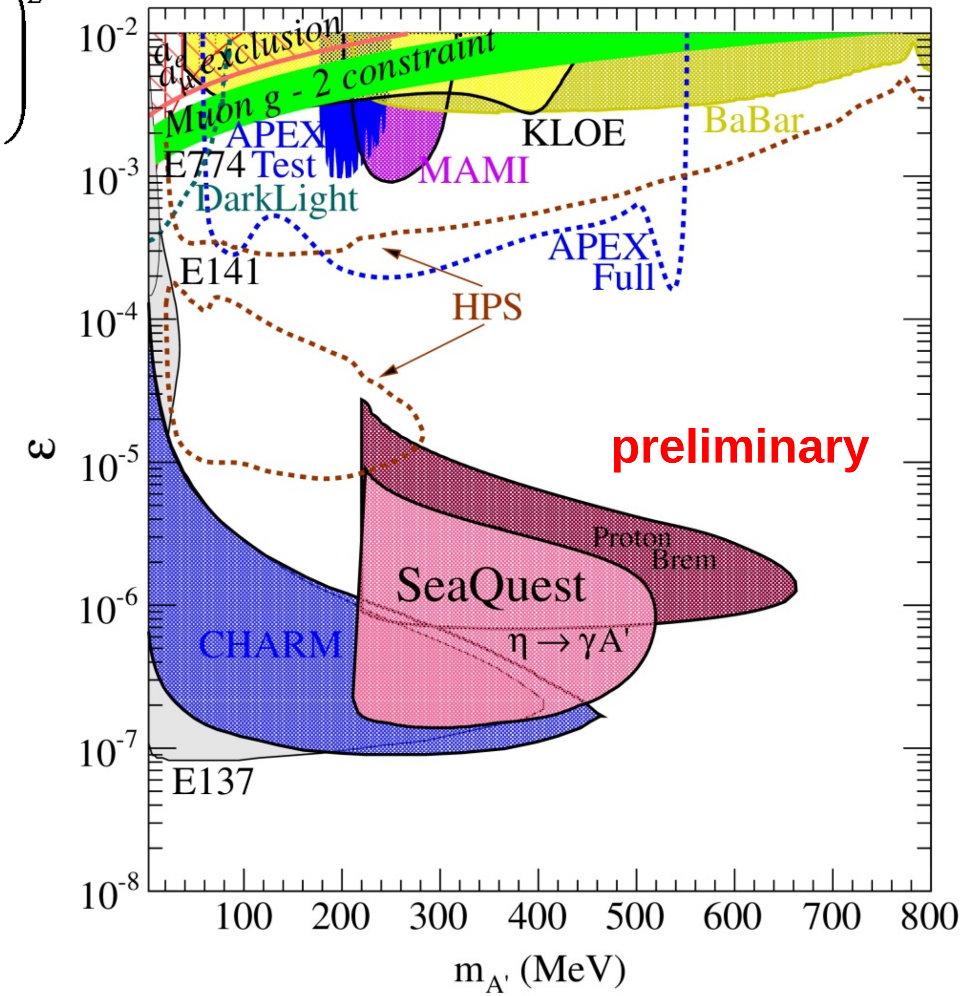


A' sensitivity region for SeaQuest

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

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 p bremsstrahlung
- N_{eff} = no. of avail. 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

A’ sensitivity region for SeaQuest

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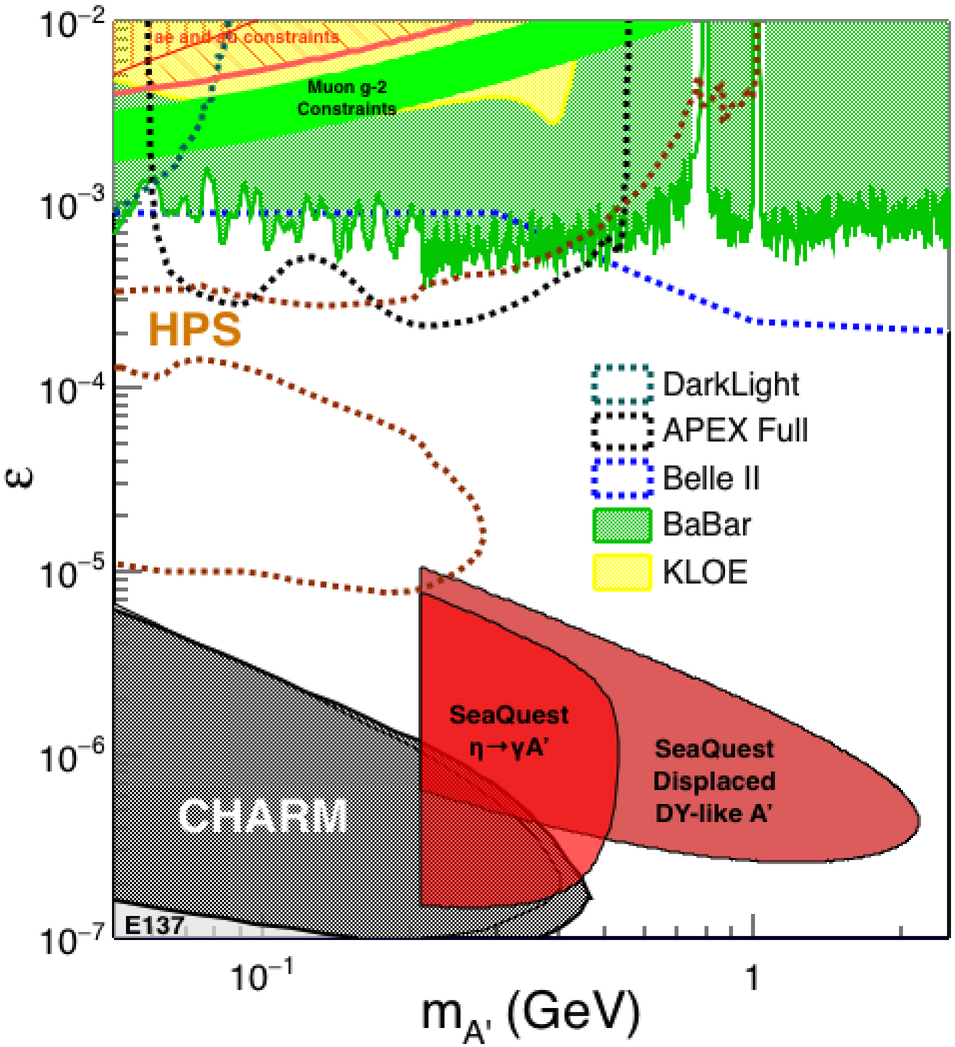


DY-like: can access A’ with larger mass

Polarized Proton Beams and Searches for Dark Forces

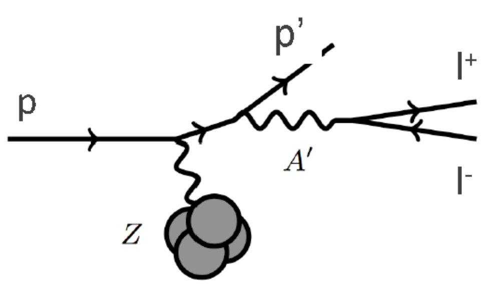
Searches for a dark photon also limit other possibilities

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)!

[SG, Holt, Tadepalli, 2015]

Summary

- There are many exiting opportunities with polarized hadron beams in the coming decade
- RHIC, Fermilab, COMPASS offer complementary probes and processes to study hadronic landscape

  $\longrightarrow$ a complete spin program requires multiple hadron species
- Hope to answer some of the burning questions

  $\longrightarrow$ how much do the gluons contribute to the nucleon spin?

  $\longrightarrow$ is there significant orbital angular momentum?

  $\longrightarrow$ does TMD formalism work? Does Sivers function change sign?
- Explore the Dark Sector

  $\longrightarrow$ SeaQuest is nearly ideal beam-stop experiment

  $\longrightarrow$ underway for at least the next year

  $\longrightarrow$ probe not only dark photons, but also Z_d with a polarized beam

Thank You

COMPASS, 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		
COMPASS $\pi^- p^\uparrow \to \mu^+ \mu^- X$	✗	✓	valence	✓	✗	✗	✗	✗
E-1027 $p^\uparrow p \to \mu^+ \mu^- X$	✓	✗	valence	✓	✓	✓	✗	✓
E-1039 $p\, p^\uparrow \to \mu^+ \mu^- X$	✗	✓	sea	✗	✓	(✓)	✓	(✓)
E-10XX To help protect your privacy, PowerPoint has blocked automatic download of this picture. $\vec{p}\, \vec{p} \to \mu^+ \mu^- X$	✓	✓	sea & valence	**Transversity, Helicity, Other TMDs …**				

Polarized Beam at Fermilab Main Injector

- Polarized Beam in Main Injector

  ➡ use SeaQuest target

  ✓ liquid H_2 target can take about I_{av} = 5 x 10^{11} p/s (=80 nA)

  ➡ 1 mA at polarized source can deliver about I_{av} = 1 x 10^{12} p/s (=150 nA) for 100% of available beam time *(A. Krisch: Spin@Fermi report in (Aug 2011): arXiv:1110.3042 [physics.acc-ph])*

  ✓ 26 μs linac pulses, 15 Hz rep rate, 12 turn injection into booster, 6 booster pulses into Recycler Ring, followed by 6 more pulses using slip stacking in MI

  ✓ 1 MI pulse = 1.9 x 10^{12} p

  ✓ using three 2-sec cycles/min (~10% of beam time):
  → 2.8 x 10^{12} p/s (=450 nA) instantaneous beam current , and I_{av} = 0.95 x 10^{11} p/s (=15 nA)

  ➡ possible scenarios:

  ✓ L_{av} = 2.0 x 10^{35} /cm^2/s (10% of available beam time: I_{av} = 15 nA)

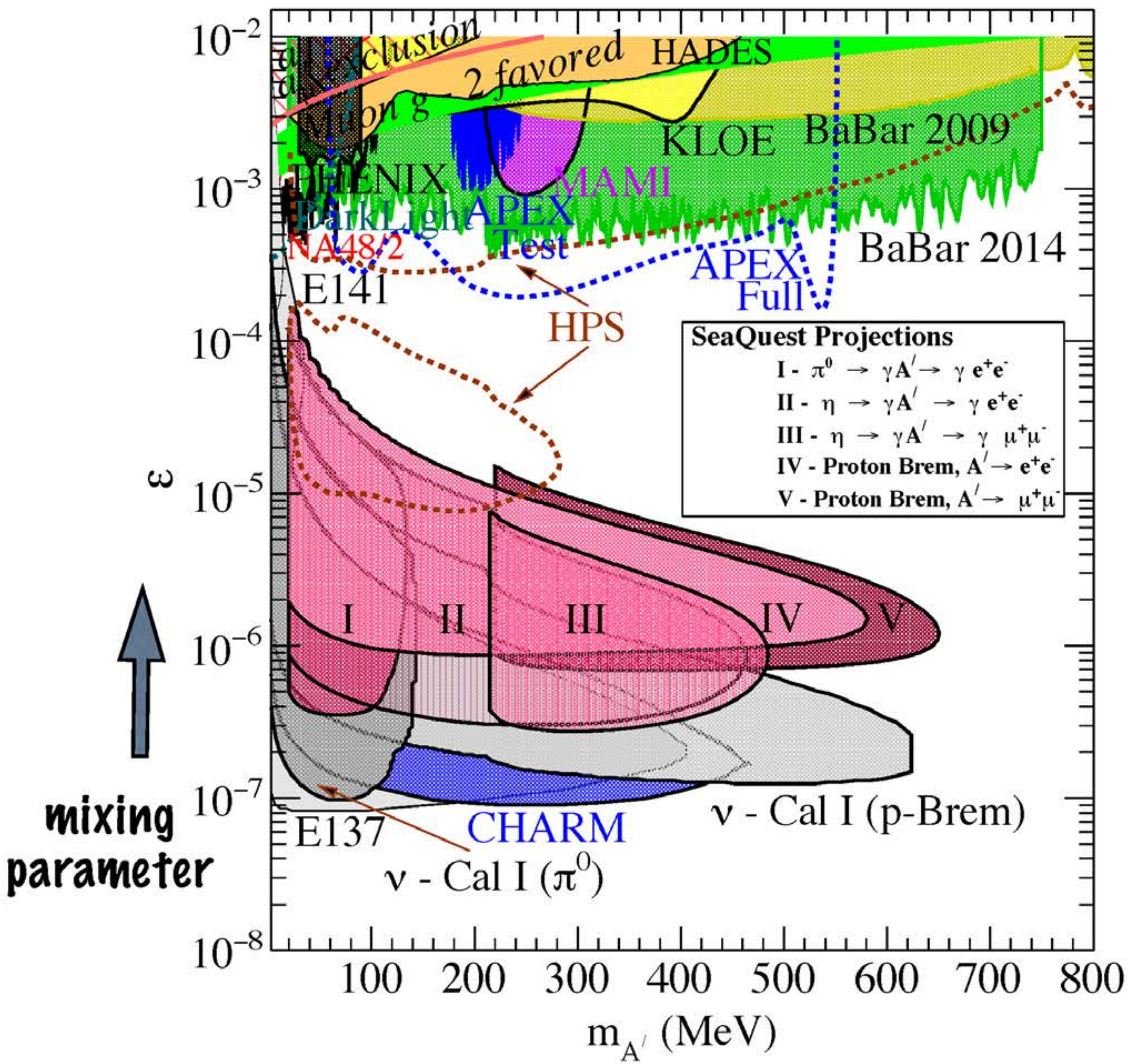
  ✓ L_{av} = 1 x 10^{36} /cm^2/s (50% of available beam time: I_{av} = 75 nA)

  ➡ Systematic uncertainty in beam polarization measurement (scale uncertainty)

$$\Delta P_b/P_b < 5\%$$

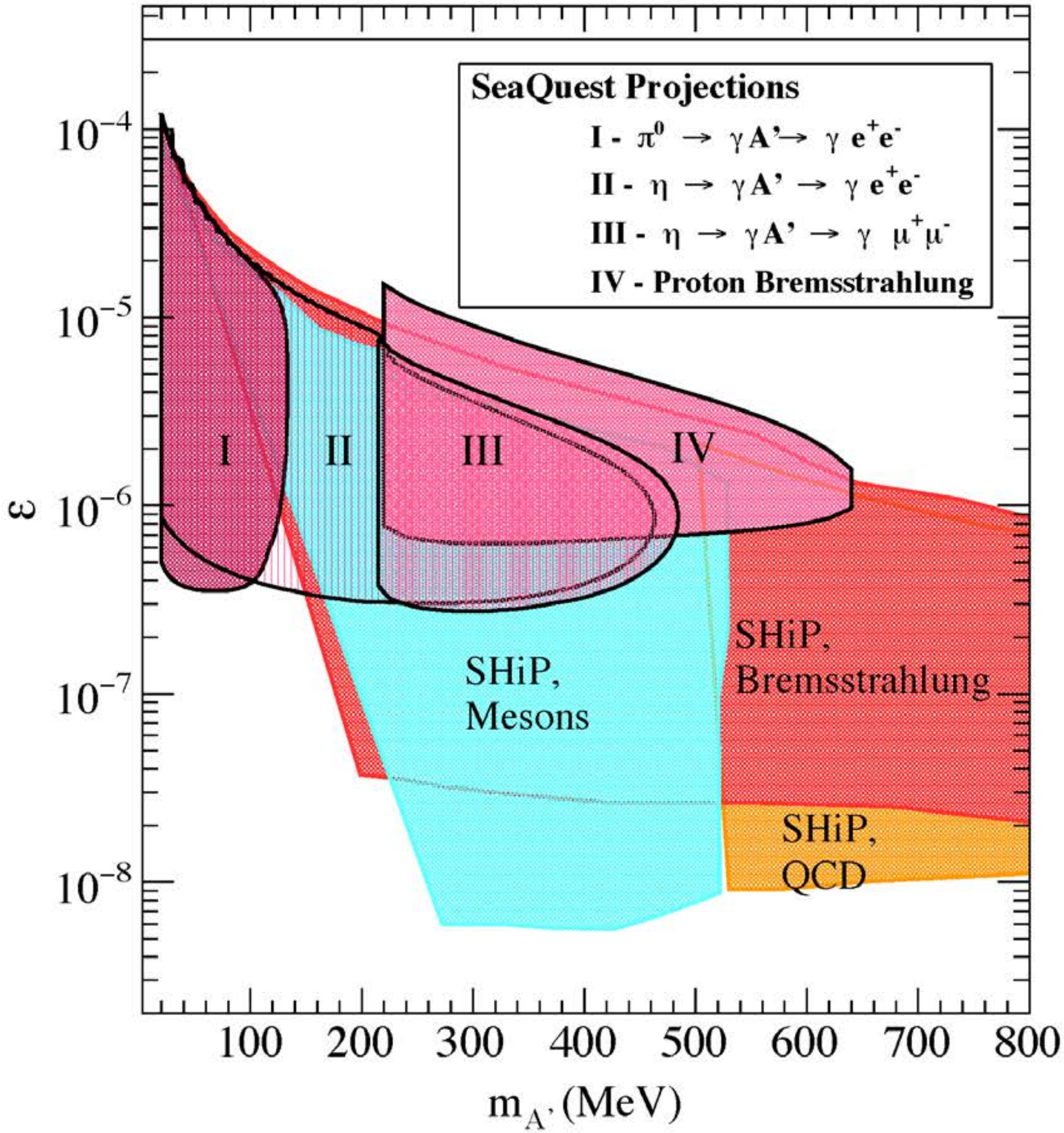
Dark Photons at SeaQuest (FNAL)

[SG, Holt, Tadepalli, arXiv:1509.00050]



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!