Sea Quark Sivers Asymmetry at Fermilab's E1039 Experiment

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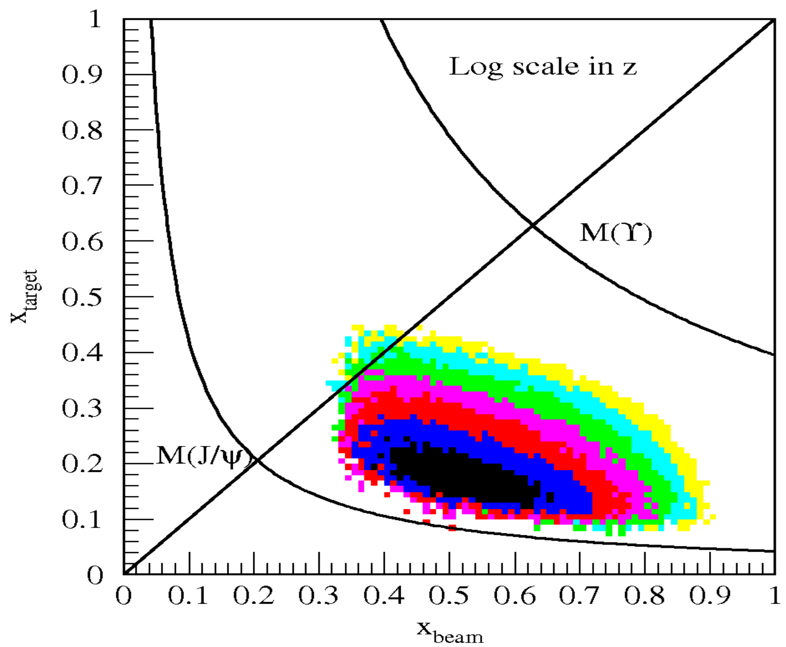
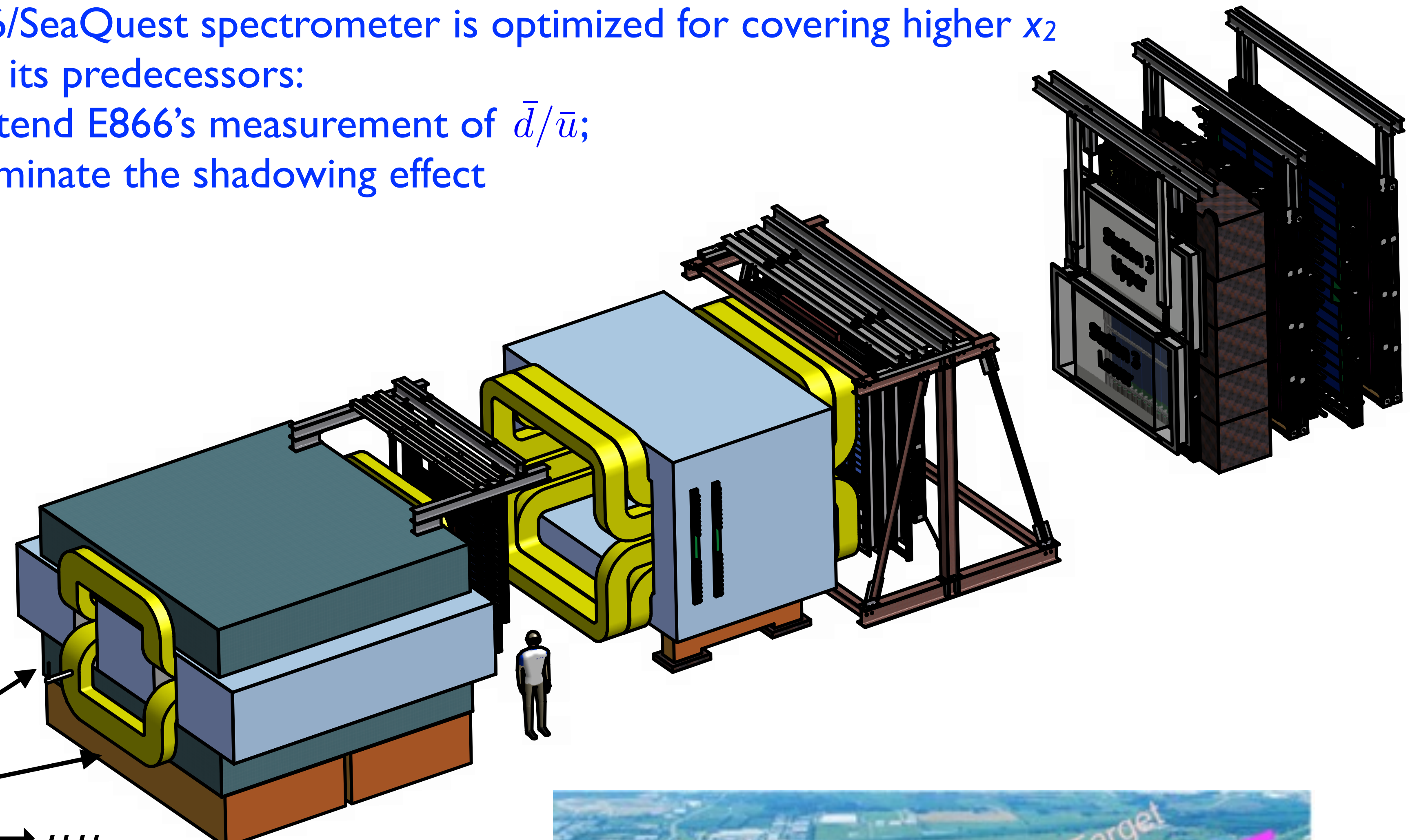
INT-17-68W Workshop, Seattle, WA
October 5, 2017

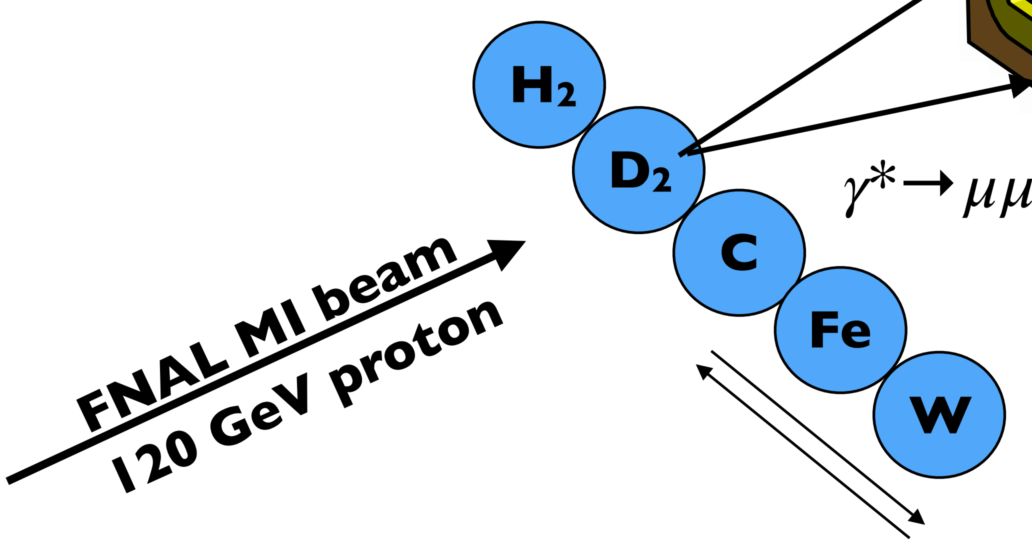
E906 SeaQuest experiment

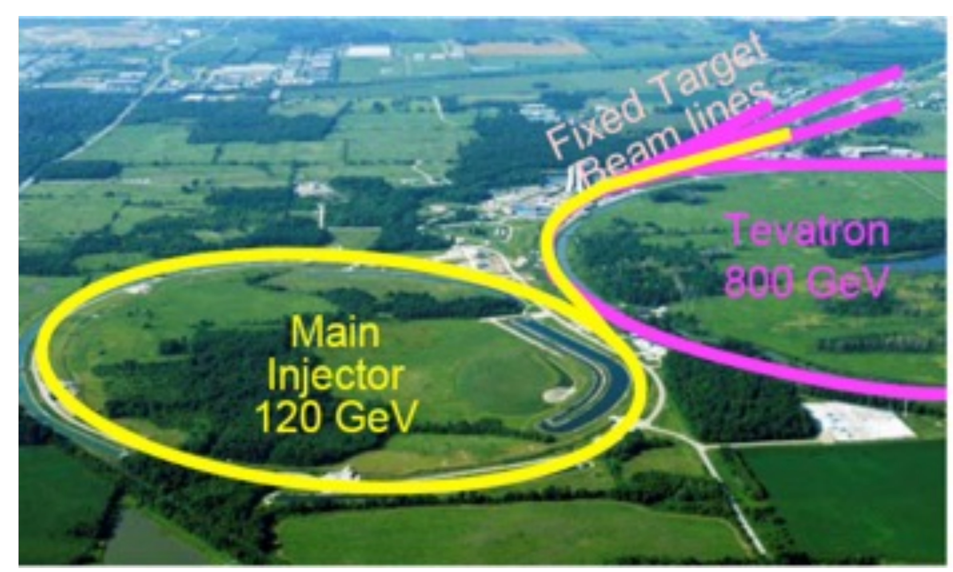


E906/SeaQuest spectrometer is optimized for covering higher x_2 than its predecessors:

- extend E866's measurement of $\bar{d}/\bar{u}$;
- eliminate the shadowing effect







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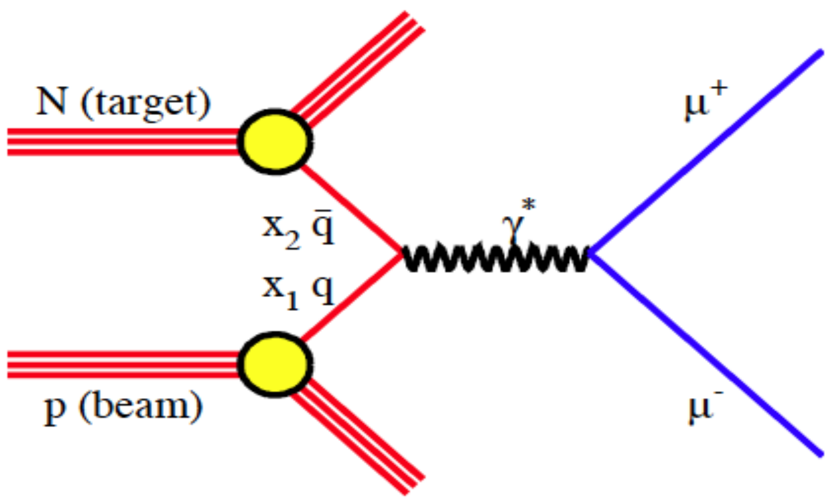
SeaQuest kinematic coverage

The Drell-Yan process:



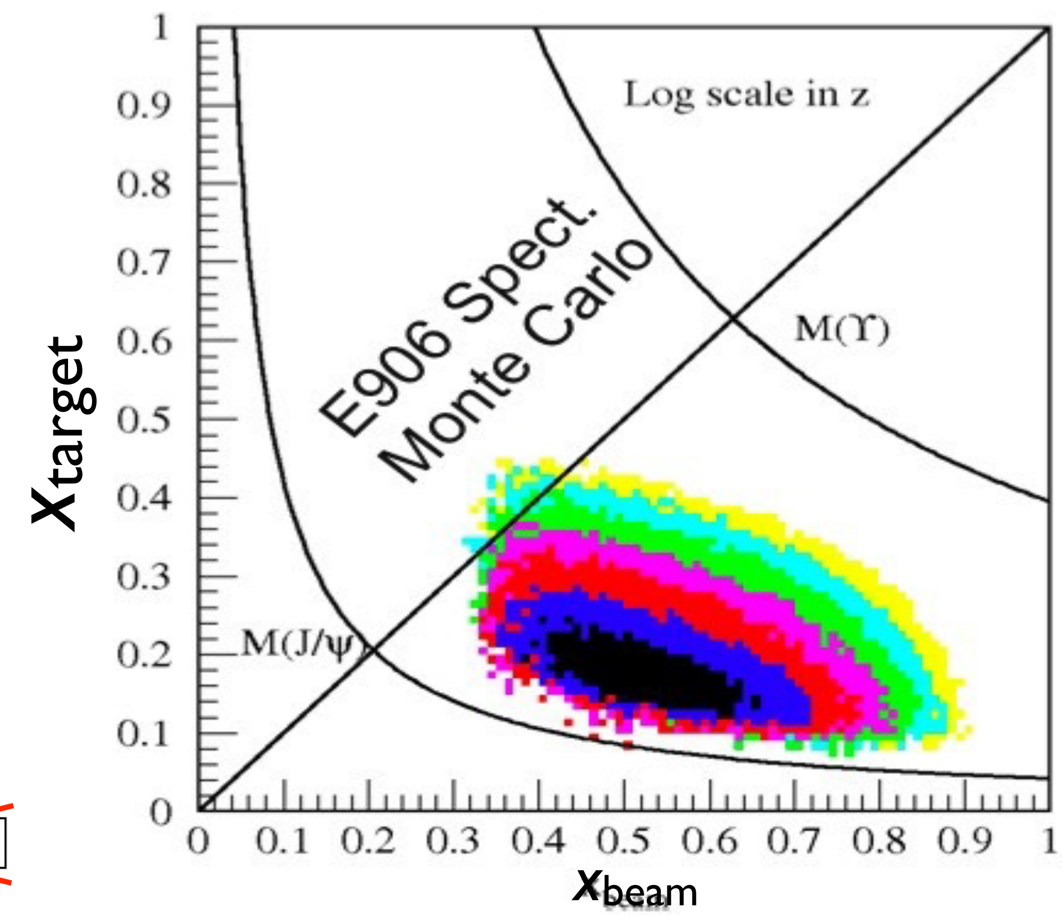
$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\pi\alpha^2}{9x_b\,x_t}\frac{1}{s}\sum_q e_q^2\left[\bar{q}_t(x_t)q_b(x_b) + \cancel{q_t(x_t)\bar{q}_b(x_b)}\right]$$

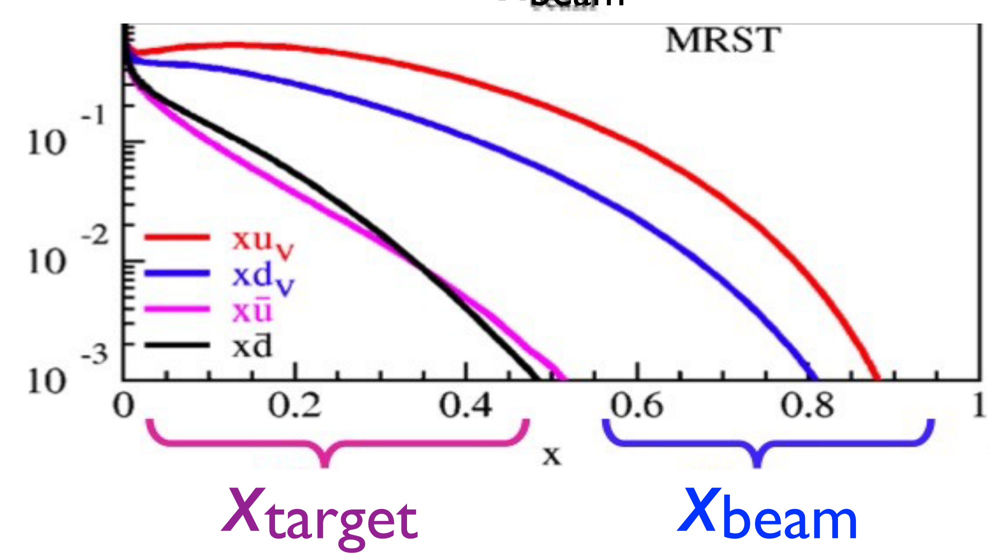
small

Unique sensitivity to target sea quarks!

$\bar{q}_t(x_t)$: target sea quark at low/intermediate x

$q_b(x_b)$: beam valence quark at high x





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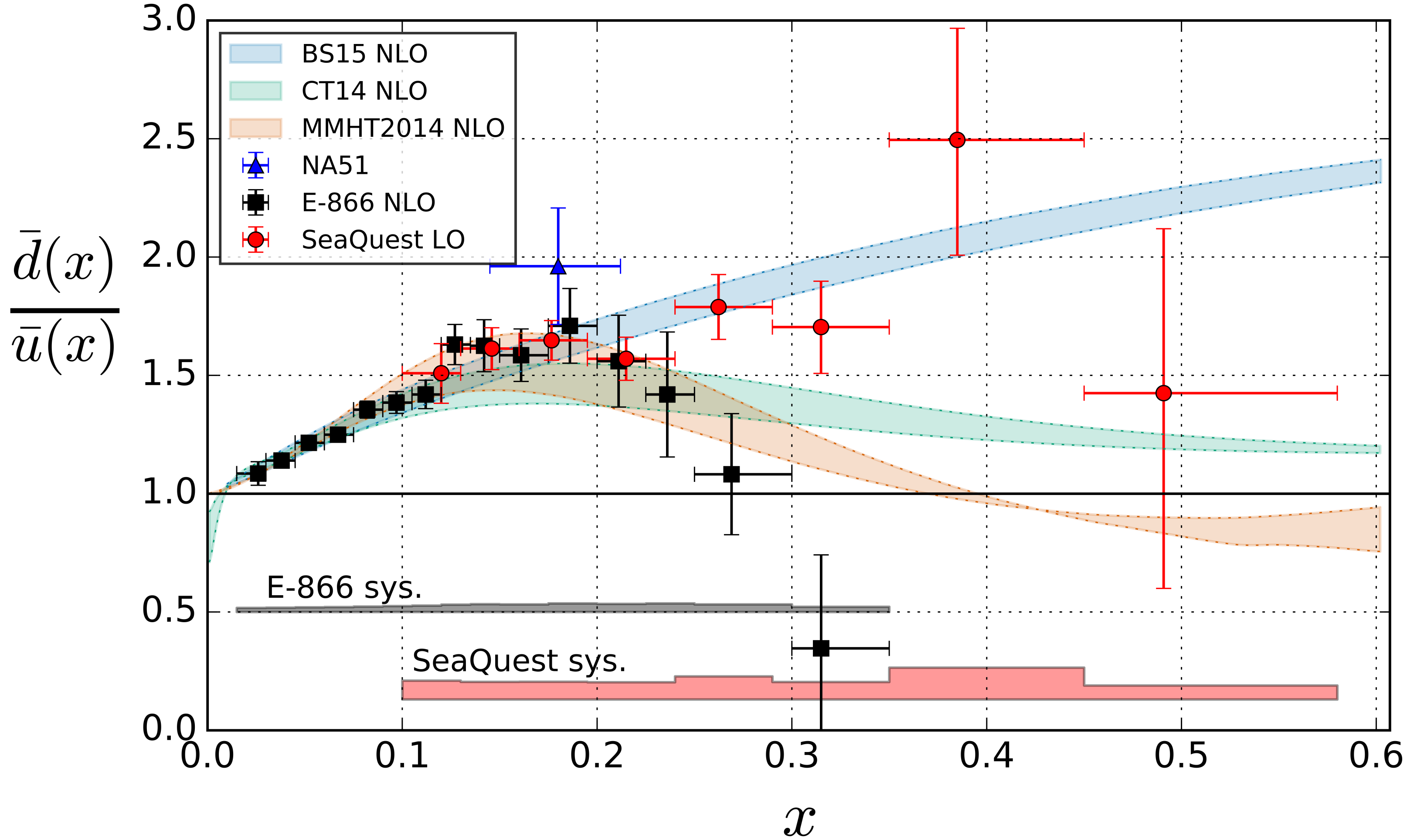
E906: Flavor asymmetry in the sea



- Assuming charge symmetry, ignoring nuclear effects of deuterium and heavy quark contributions:

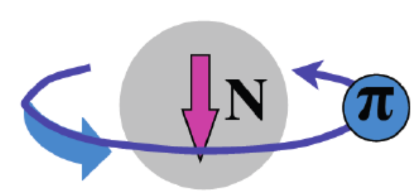
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right].$$

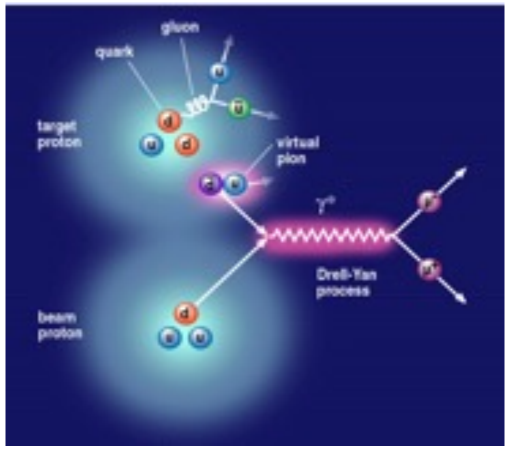
- Naively we would expect flavor symmetry between ubar and dbar
- NA51 and E866/NuSea experiment reveals a striking asymmetry in the sea distributions at moderate x

- Potential disagreement between E906 and E866
  - ➢ Very different Q^2, 54 GeV^2 for E866 and ~29 GeV^2 for E906
  - ➢ Nuclear effects in deuterium

- New analysis underway with 2x more statistics

- Caused by virtual pions?





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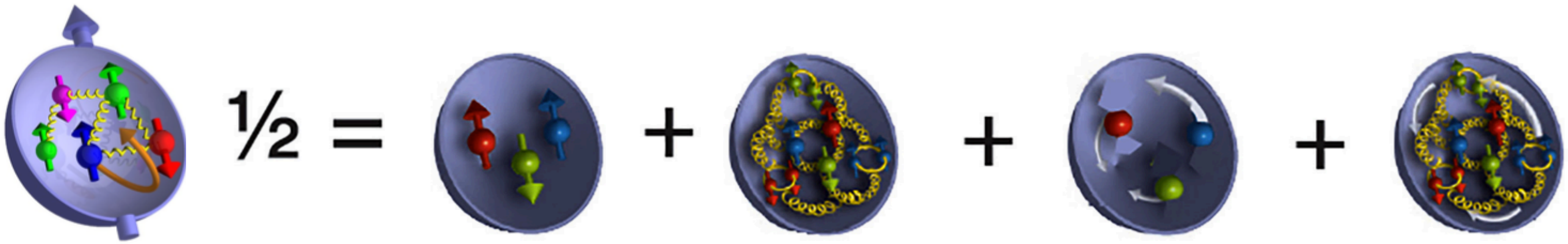
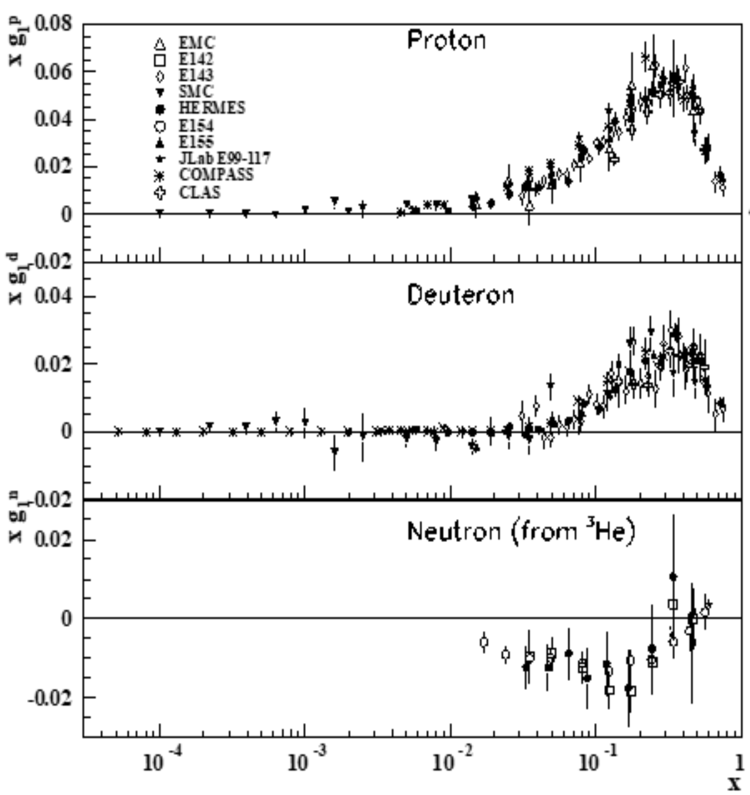
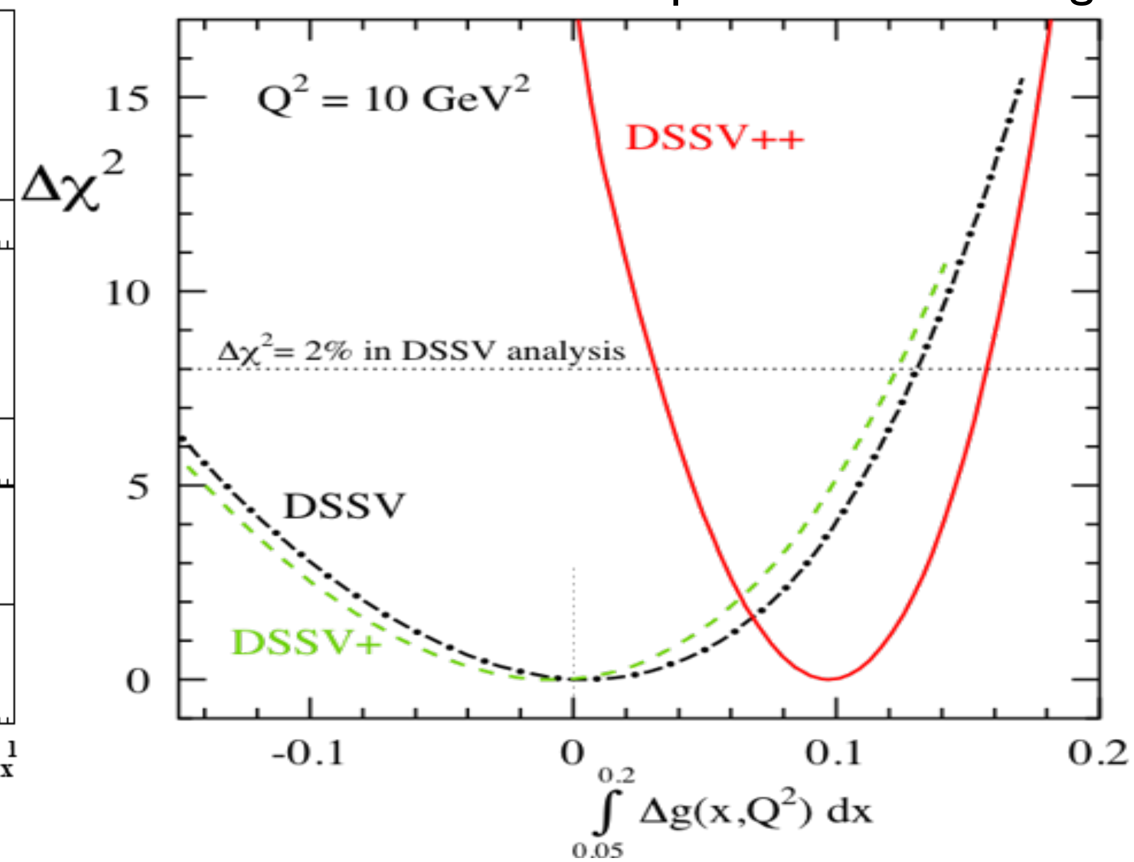
E1039: Nucleon spin puzzle

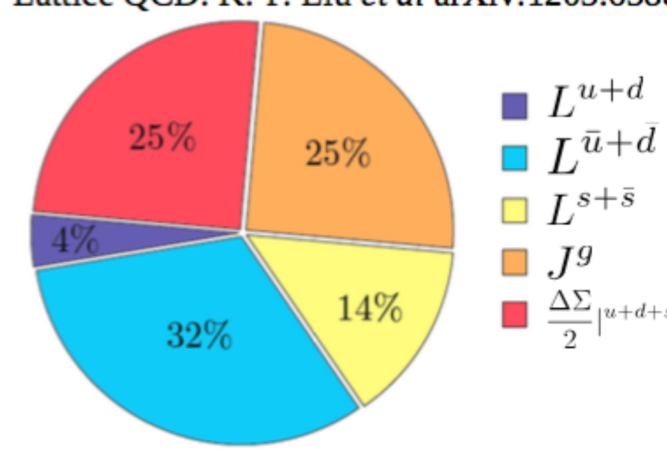


Spin of quarks | Spin of gluons | Orbital angular momentum of quarks | Orbital angular momentum of gluons





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



$\Delta\Sigma \sim 25\%,$

$2L_q \sim 46\%[0\%(L_{\text{valence}}) + 46\%(L_{\text{sea}})],$

$2J_g \sim 25\%$

$$\Delta\Sigma \sim 0.25 \pm \ldots$$

$$\int_{0.05}^{0.2} dx \Delta g(x) = 0.2 \pm 0.06$$

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Leading twist TMDs

Nucleon \ Parton	U	L	T
U	Unpolarized $f_1(x)$		Boer-Mulders $h_1^{\perp}(x, k_T)$
L		Helicity $g_{1L}(x)$	Worm-Gear $h_{1L}^{\perp}(x, k_T)$
T	Sivers $f_{1T}^{\perp}(x, k_T)$	Worm-Gear $g_{1T}^{\perp}(x, k_T)$	Transversity $h_{1T}(x)$; Pretzelosity $h_{1T}^{\perp}(x, k_T)$

Access through the angular distribution of unpolarized DY at E906

Access through L-R asymmetry in polarized DY at E1039

Non-zero Sivers ⇆ Non-zero OAM

- Both TMDs lack experimental measurement in DY
- Compared with SIDIS, DY provides unique probe to sea quarks
- Both TMDs are naive T-odd, leading to a sign change between DY and SIDIS

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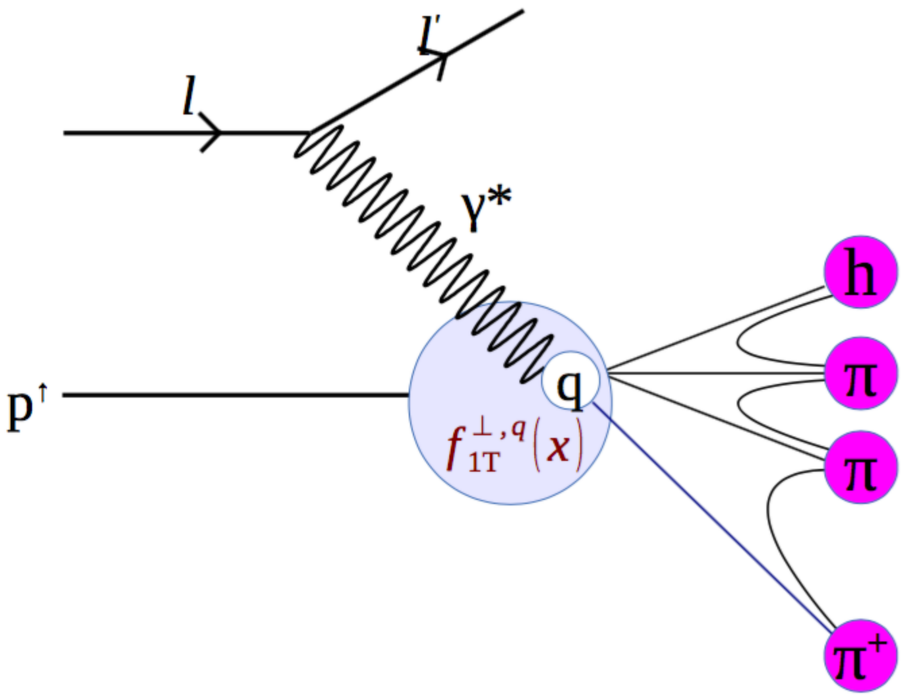
Accessing Quark Sivers function

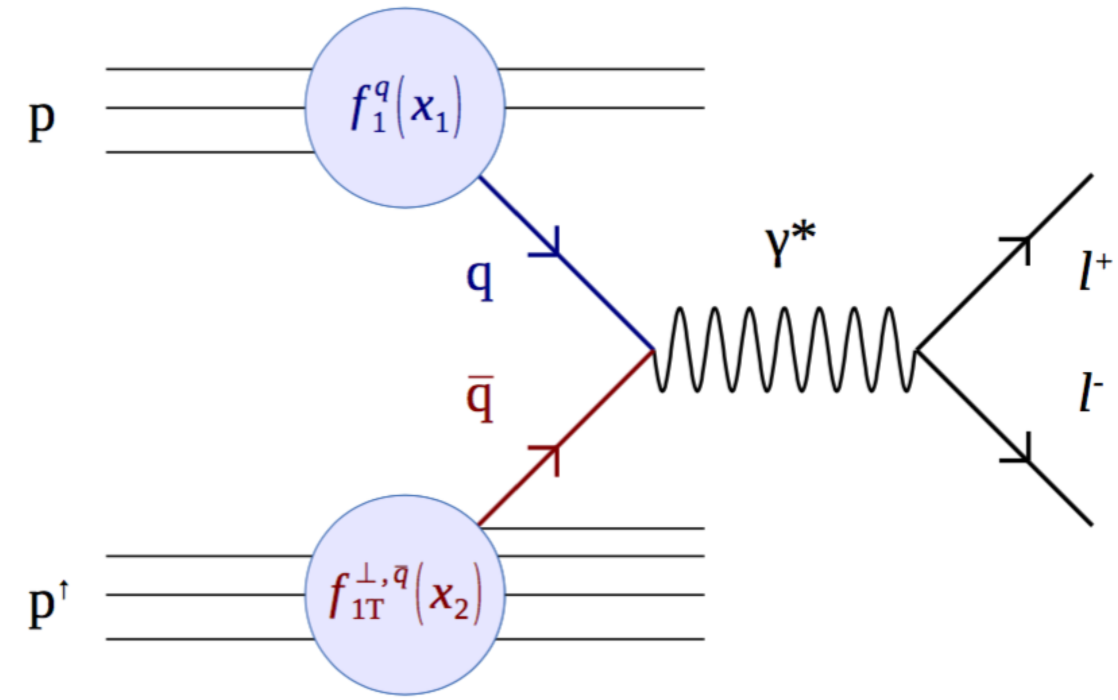
Polarized Semi-Inclusive DIS



$$A_{UT}^{SIDIS} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \otimes D_1^q(z)}$$

- L-R asymmetry in hadron production
- Quark to hadron fragmentation function
- Valence-sea quark: mixed

Polarized Drell-Yan



$$A_N^{DY} \propto \frac{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}{\sum_q e_q^2 \left[f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2 \right]}$$

- L-R asymmetry in Drell-Yan production
- **No fragmentation function involved**
- Valence-sea quark: **isolated**

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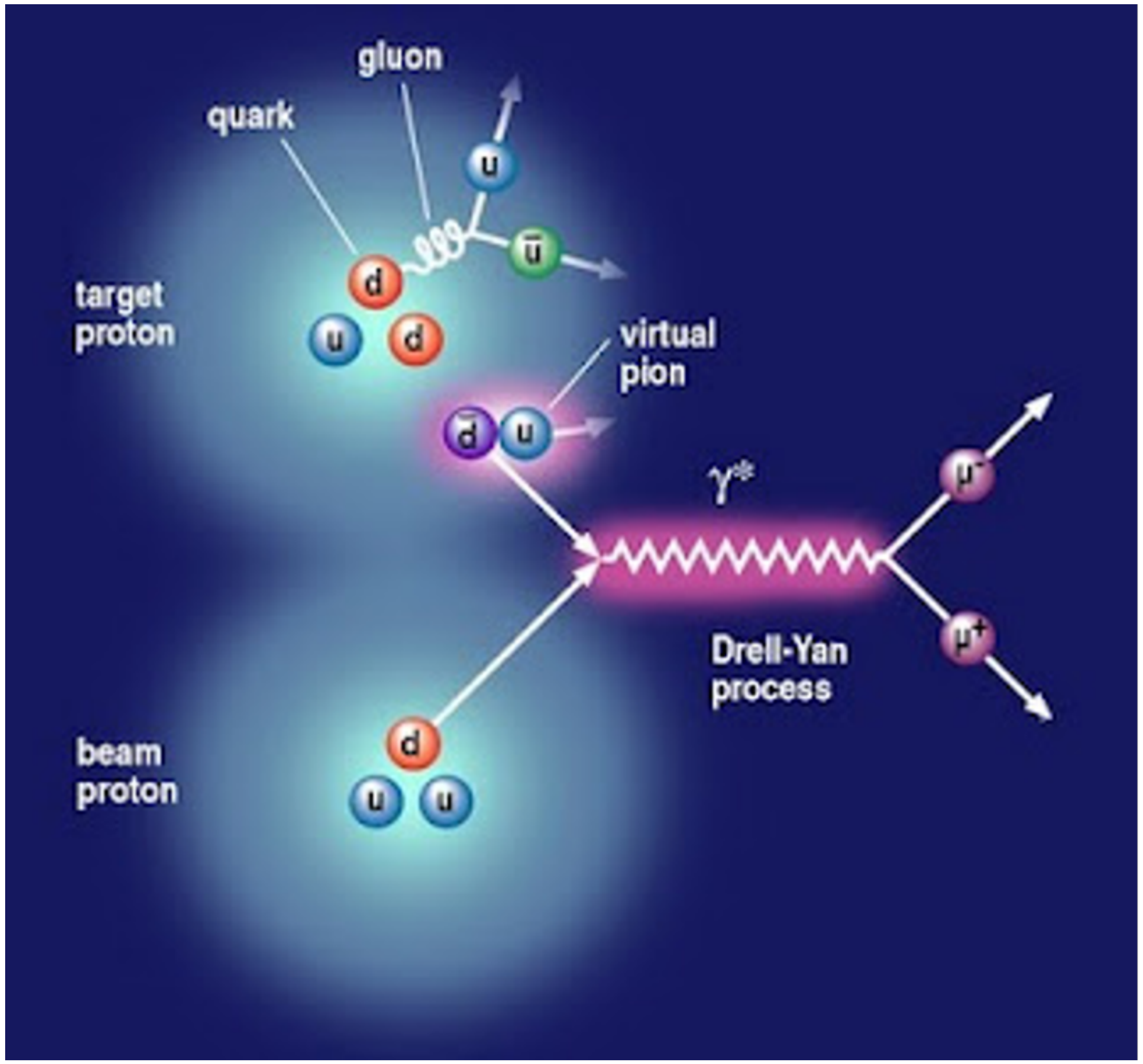
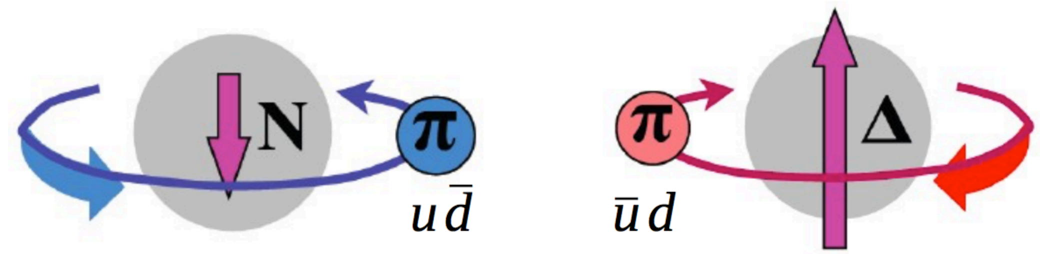
Flavor dependent Sivers function





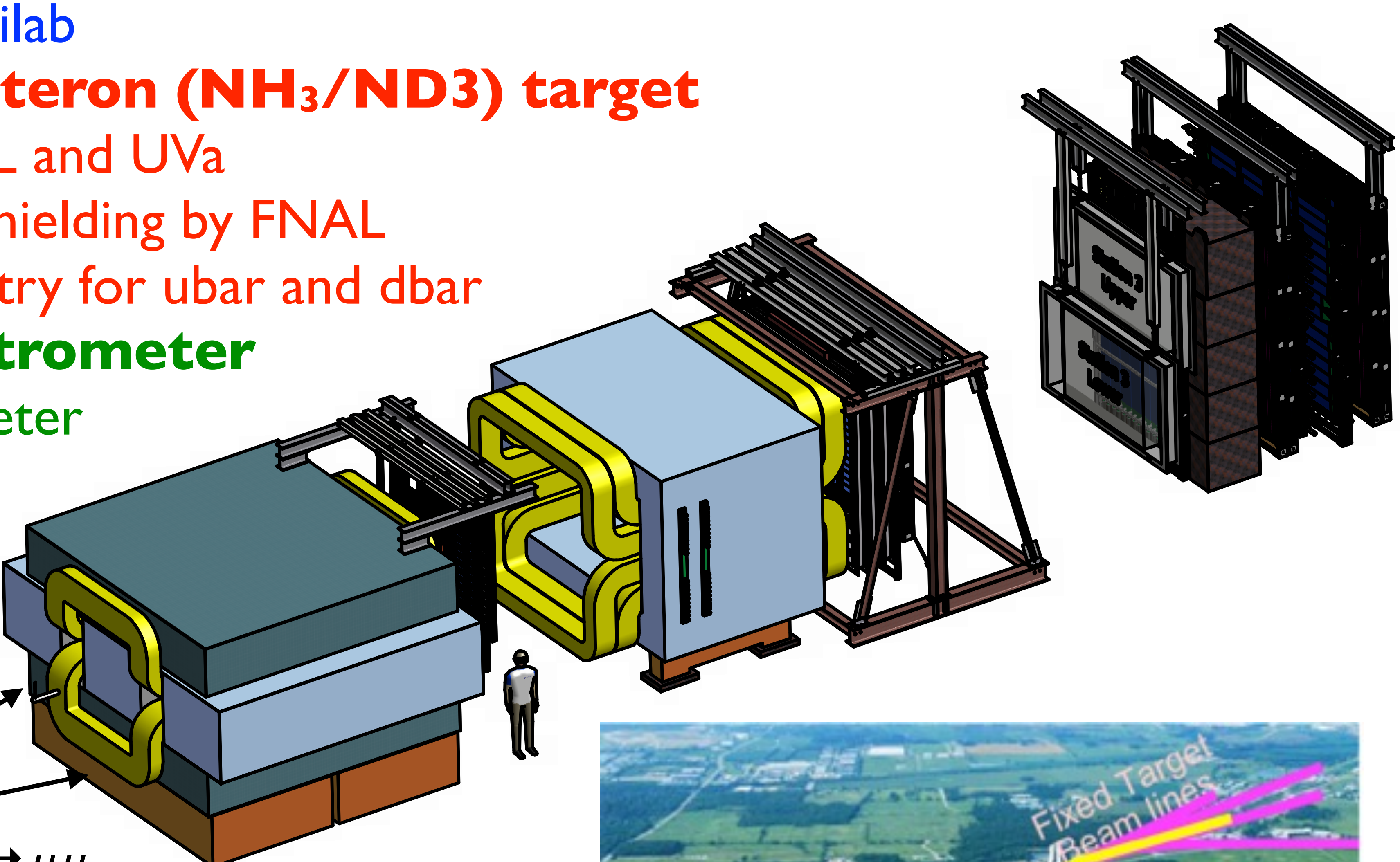
$$|p\rangle = |p\rangle + |N^0\pi^+\rangle + |\Delta^{++}\pi^-\rangle + \ldots$$

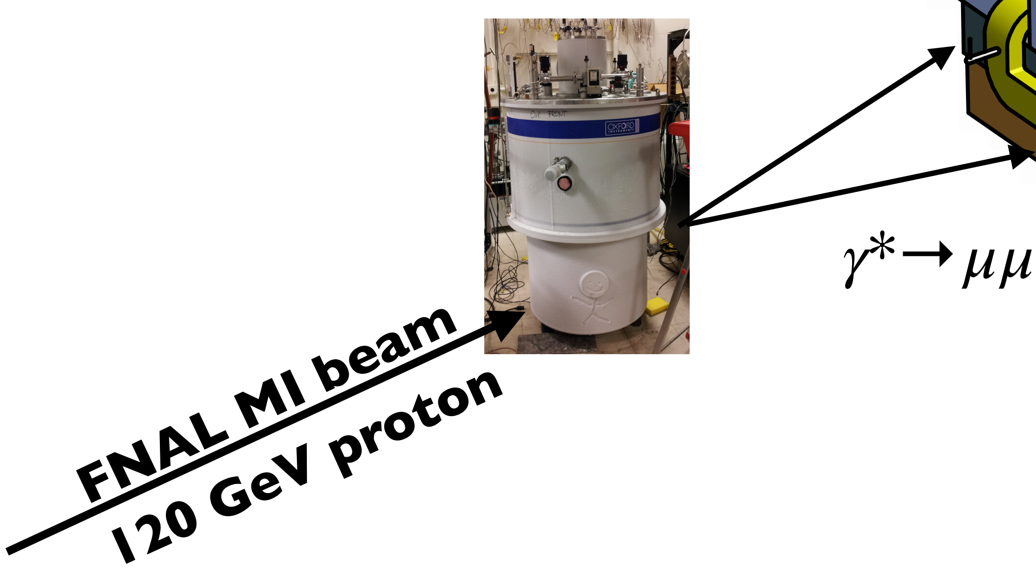
A complete picture needs to measure the Sivers function of both ubar and dbar

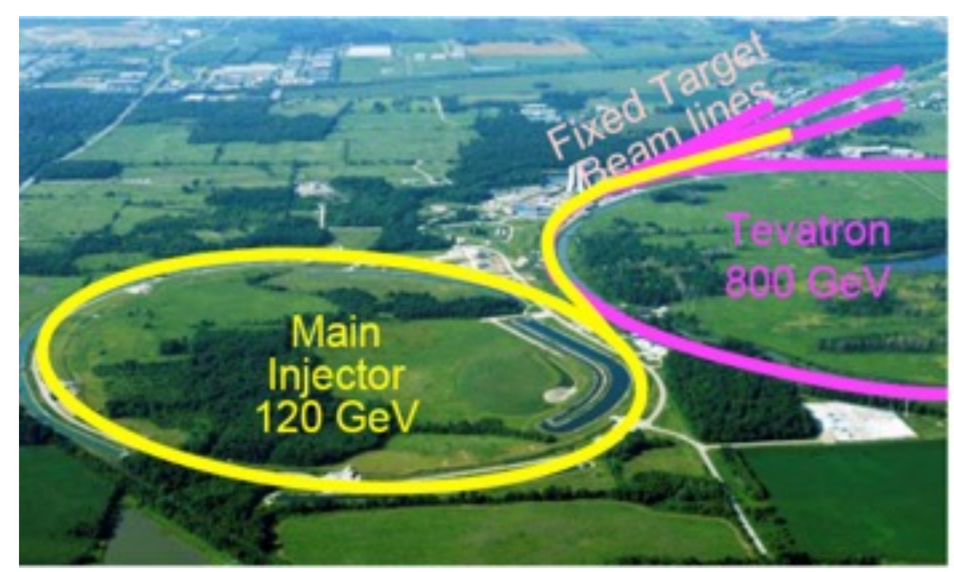
- Indirect measurement with polarized D
- Requires measuring p and "n" in parallel to control systematics
- E1039 target perfectly suited:
  - ➢ NH_3 and ND_3 in separated cells

E1039 experiment with polarized target

- **120 GeV proton beam from Main Injector**
  - ➢ Improved focusing
  - ➢ In development at Fermilab
- **Polarized proton/deuteron (NH_3/ND3) target**
  - ➢ In development at LANL and UVa
  - ➢ Modification to target shielding by FNAL
  - ➢ Measure Sivers asymmetry for ubar and dbar
- **Existing dimuon spectrometer**
  - ➢ Existing E906 spectrometer
- **Collaboration**





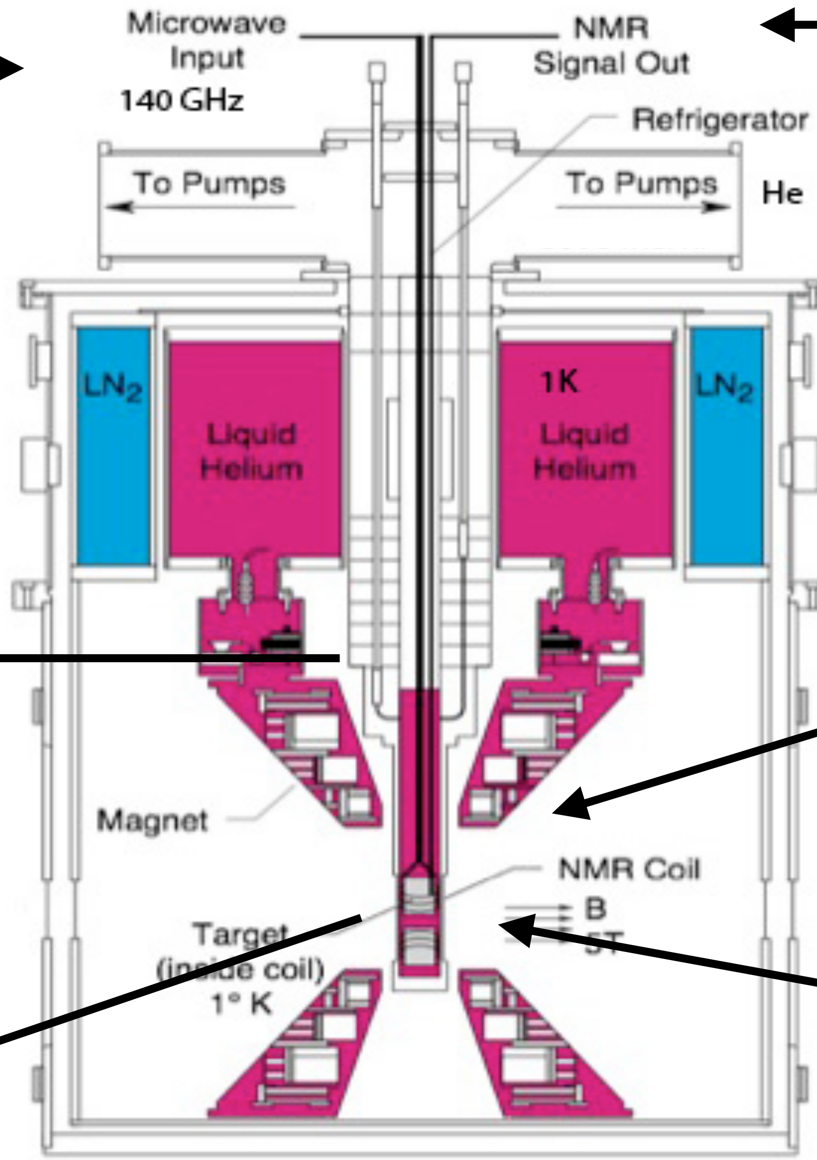


Polarized target in a nutshell

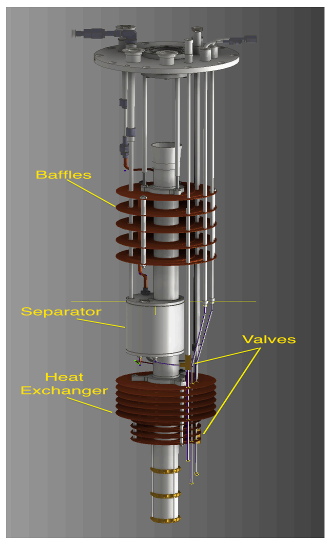
Dynamic Nuclear Polarization (DNP) Microwave signal
ν = 140 ± 0.256 GHz

NMR Polarization Measurement

Roots pump system to pump on liquid ^4He evaporation to reach 1K, power15,000 m^3/hr

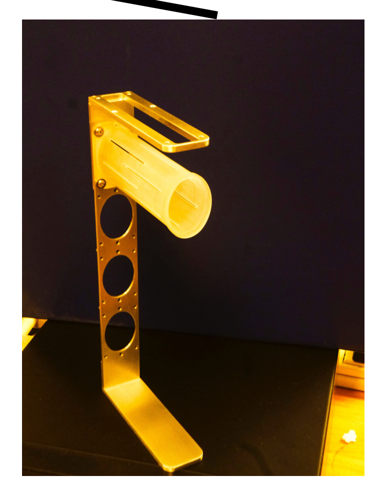


Cryostat



Superconductor Coils
5T magnetic field

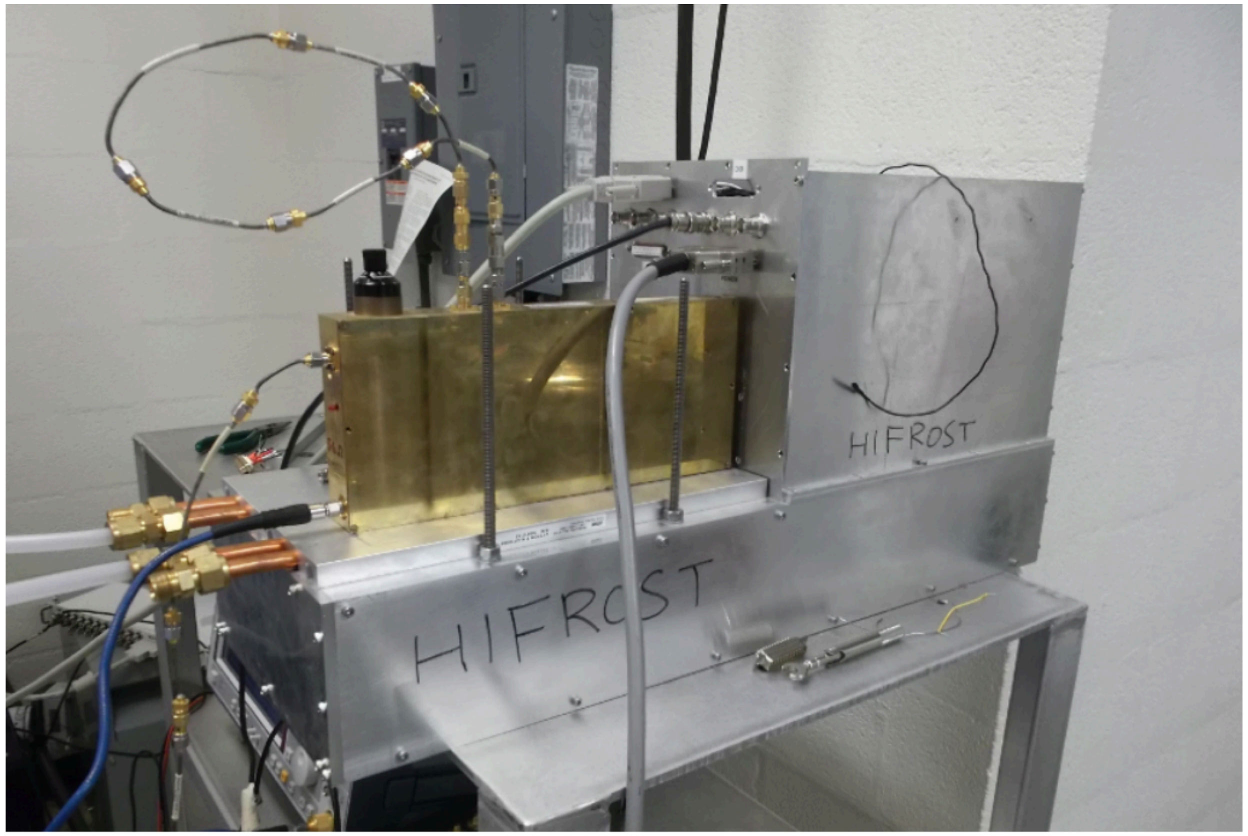
Irradiated NH_3 at NIST or Fermilab



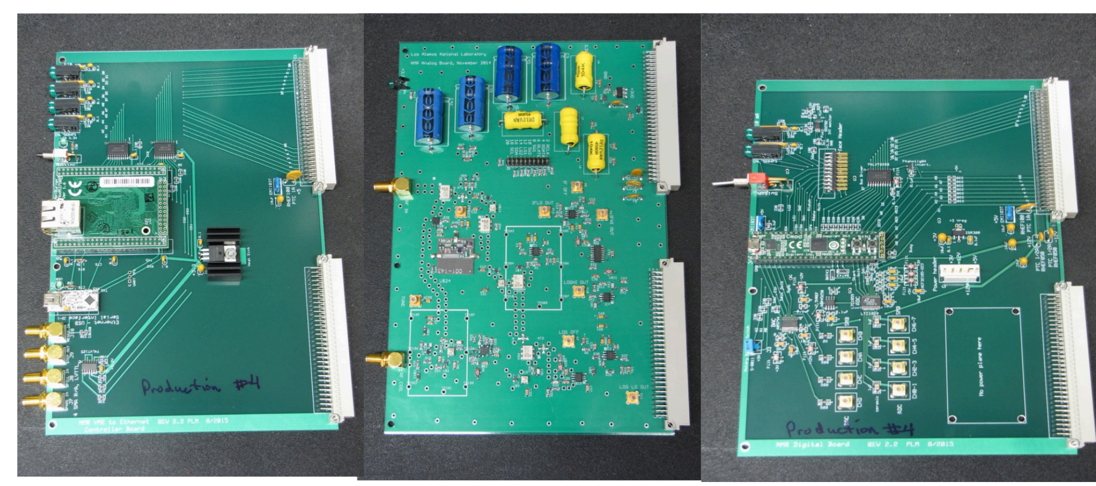
E1039 target tube

- Full system tested at UVa
- Expect installation at Fermilab in early 2018
- Data taking expected to start in Fall 2018

Brand new NMR system



- The inductance of the coil is modified by the NH_3/ND_3 emitting or absorbing RF energy
- The amount of energy is proportional to the polarization
- Redesigned the 30-year-old Liverpool Q-meter
  - ➢ Using VME form factor
  - ➢ Replaced with modern electronic parts
  - ➢ Get rid of all mechanical controls



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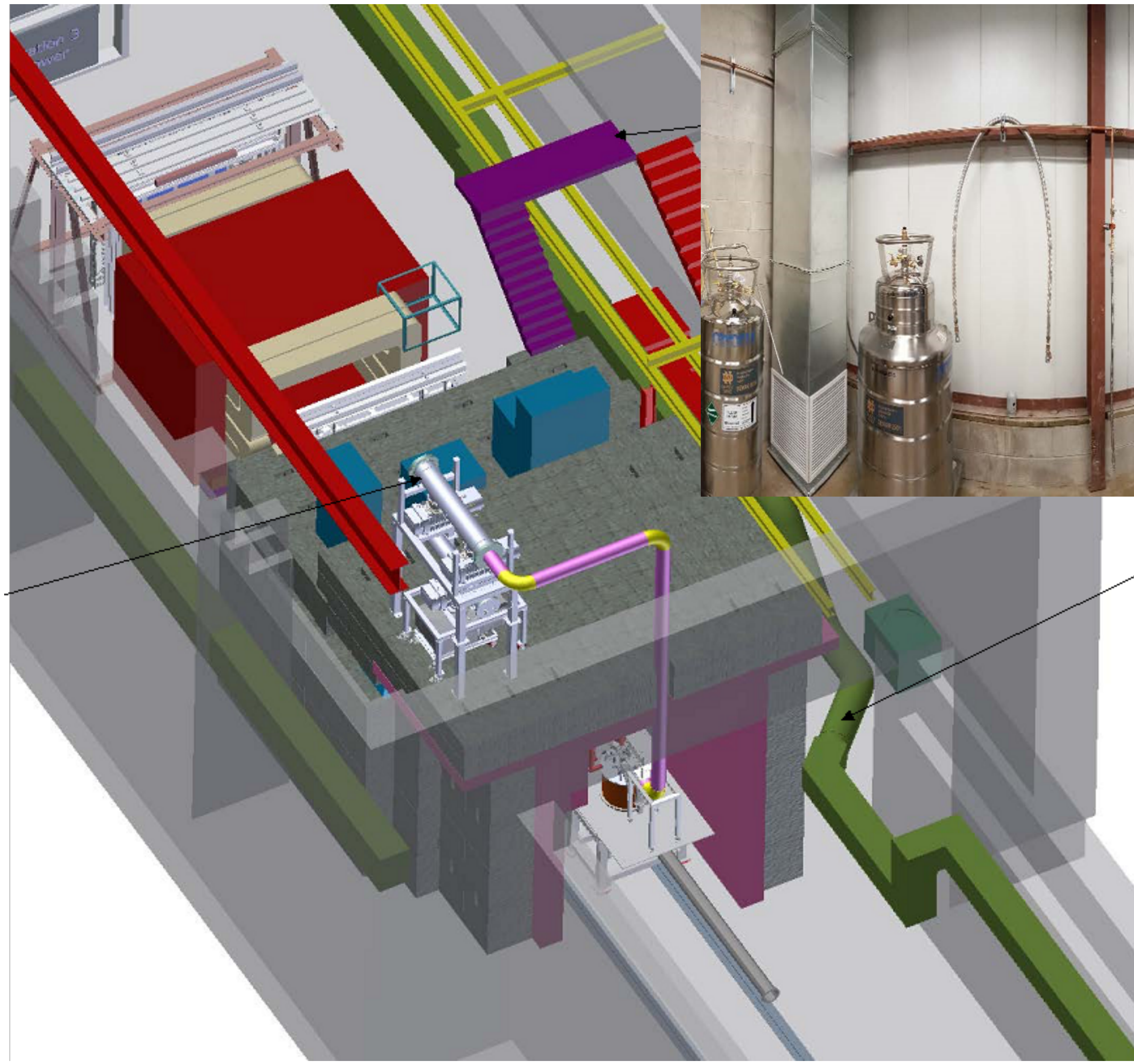
Target cave and beam line upgrades



- Compared with E906, E1039 has its target further upstream
  - ➢ Better target/dump separation
  - ➢ Better low-x acceptance
- Redesigned shielding to handle the new target position and instruments on top
- Redesigned the beam line to assure the systematic error be less than 1%

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Unprecedented luminosity and sensitivity

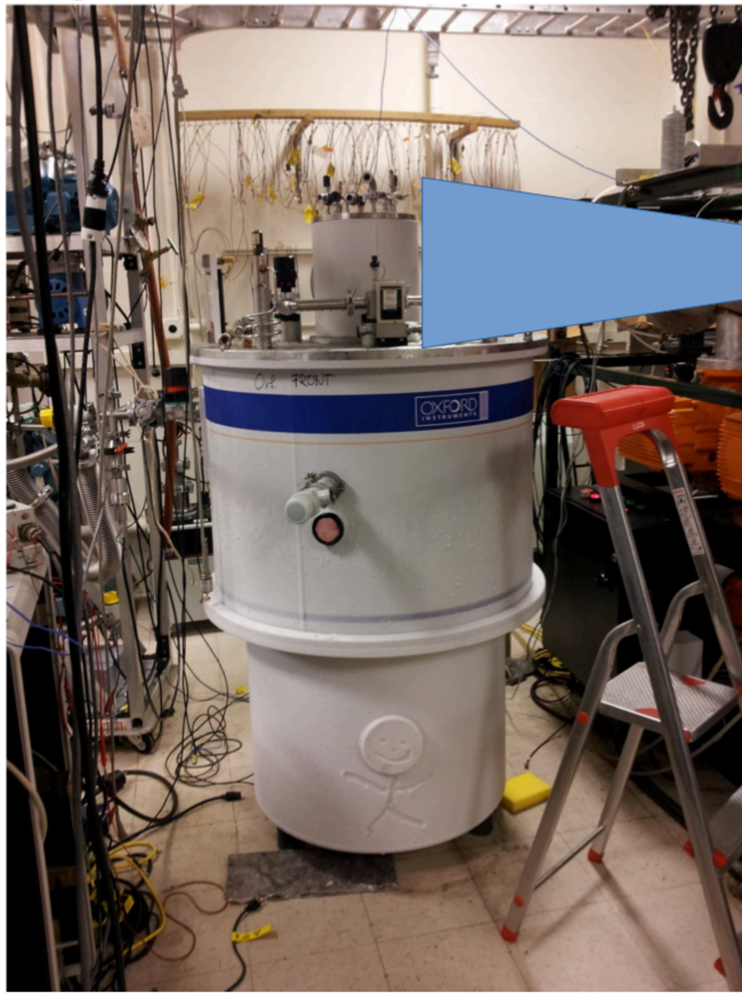
Experiment	Particles	Energy (GeV)	x_b or x_t	Luminosity ($cm^{-2}\,s^{-1}$)	$A_T^{\sin\phi_S}$	P_b or P_t (f)	rFOM#	Timeline
COMPASS (CERN)	$\pi^- + p^\uparrow$	160 GeV $\sqrt{s} = 17$	$x_t = 0.1 - 0.3$	2×10^{33}	0.14	$P_t = 90\%$ f = 0.22	1.1×10^{-3}	2015-2016, 2018
PANDA (GSI)	$\bar{p} + p^\uparrow$	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}	>2020?
J-PARC (high-p beam line)	$\pi^- + p$	10-20 GeV $\sqrt{s} = 4.4$-6.2	$x_b = 0.2 - 0.97$ $x_t = 0.06 - 0.6$	2×10^{31}	---	---	---	>2019? under discussion
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
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

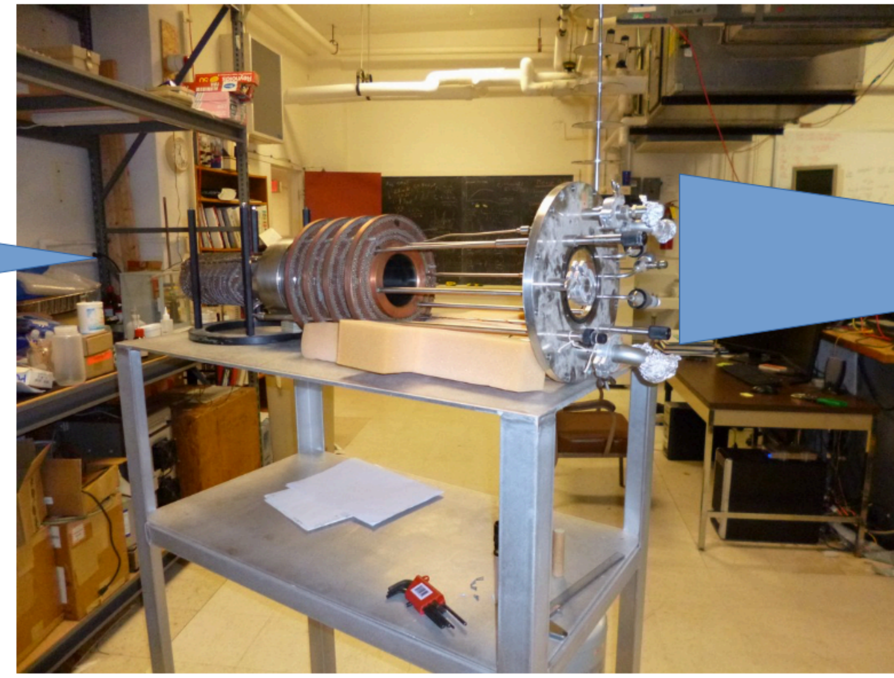
‡ 8 cm NH_3 target / § L= 1 x 10^{36} $cm^{-2}\,s^{-1}$ (LH_2 tgt limited) / L= 2 x 10^{35} $cm^{-2}\,s^{-1}$ (10% of MI beam limited)

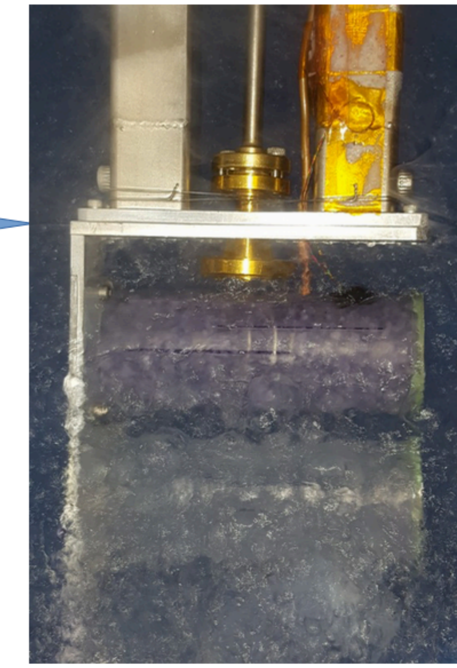
**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

From Wolfgang Lorenzo's talk on Monday

April 2016 UVa full system test

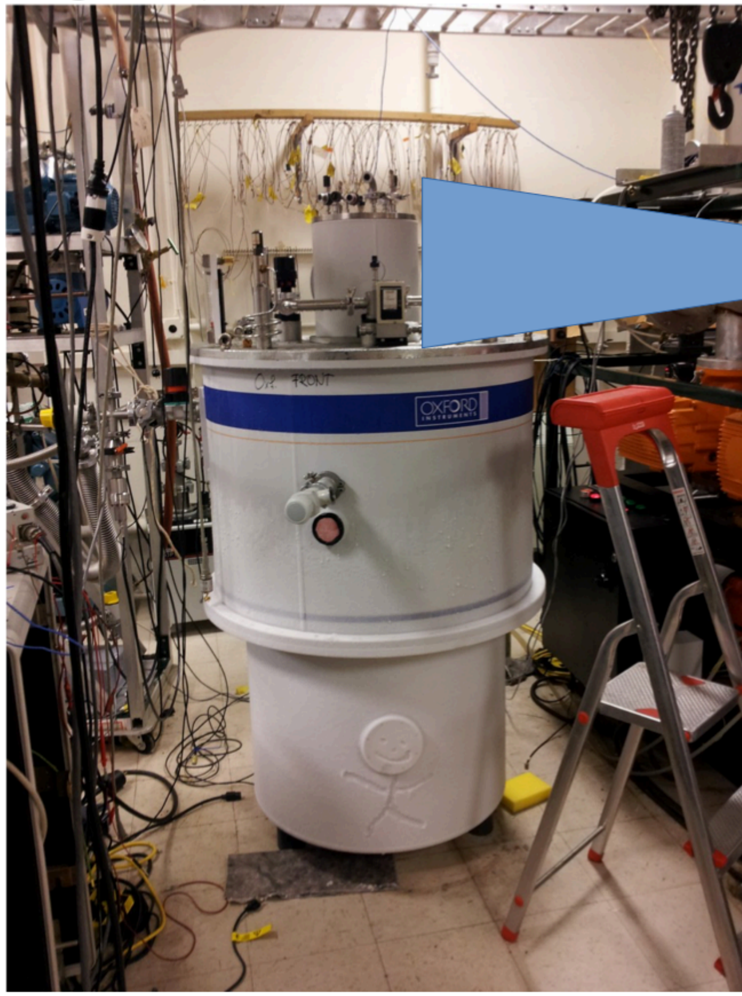


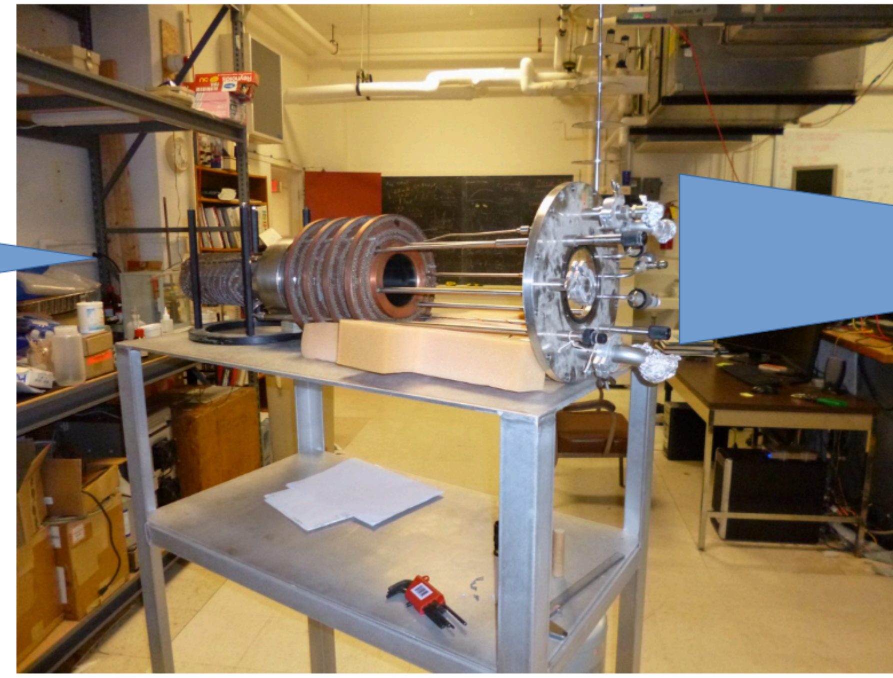


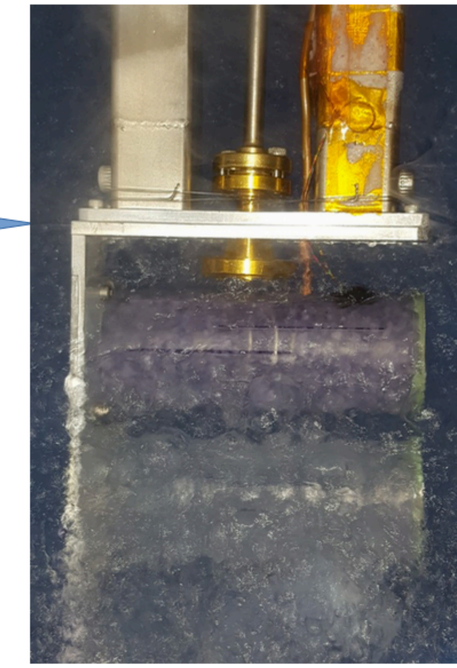


- Cool down to 4K, Magnet at 5 Tesla
- Inserted the refrigerator and target, brought down to 1K by pumping on vapor pressure

April 2016 UVa full system test

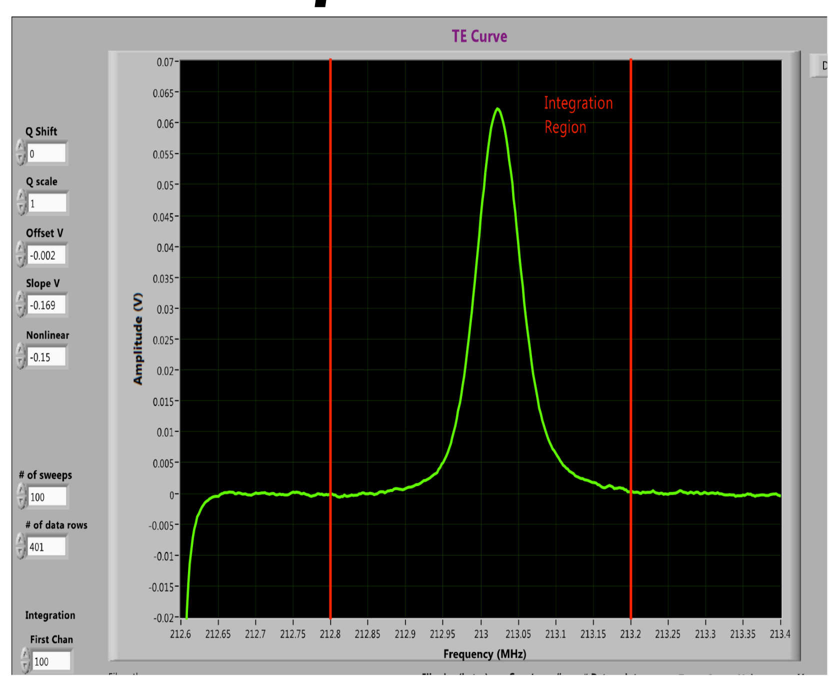






- Cool down to 4K, Magnet at 5 Tesla
- Inserted the refrigerator and target, brought down to 1K by pumping on vapor pressure
- Very clean TE signal is measured once the target is 1K

Termal Equilibrium



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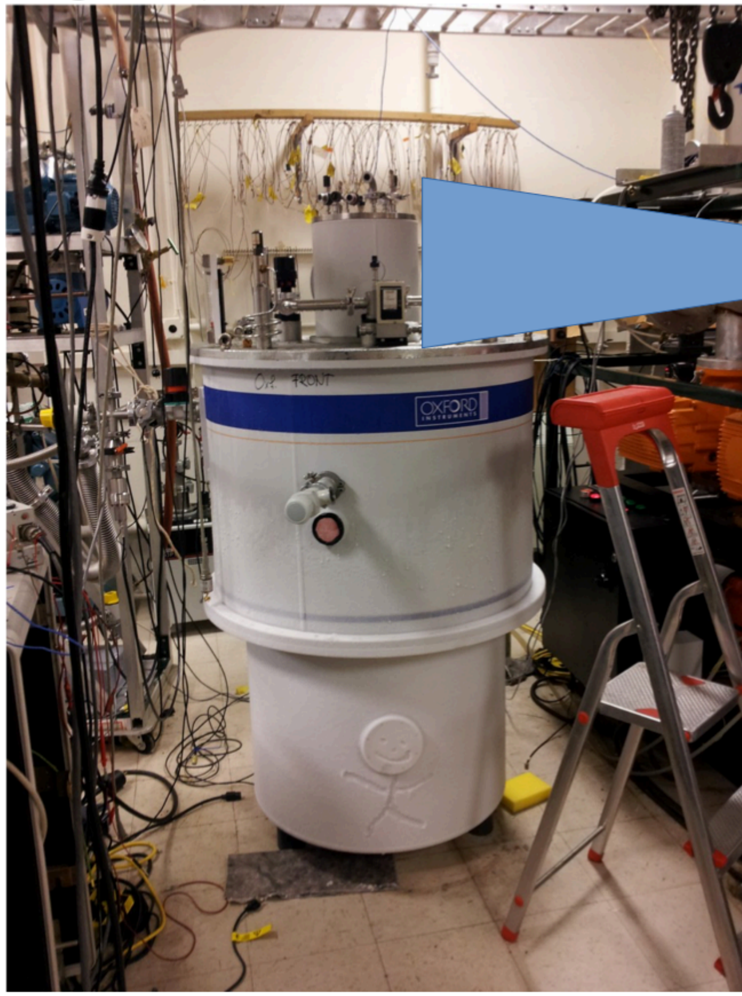
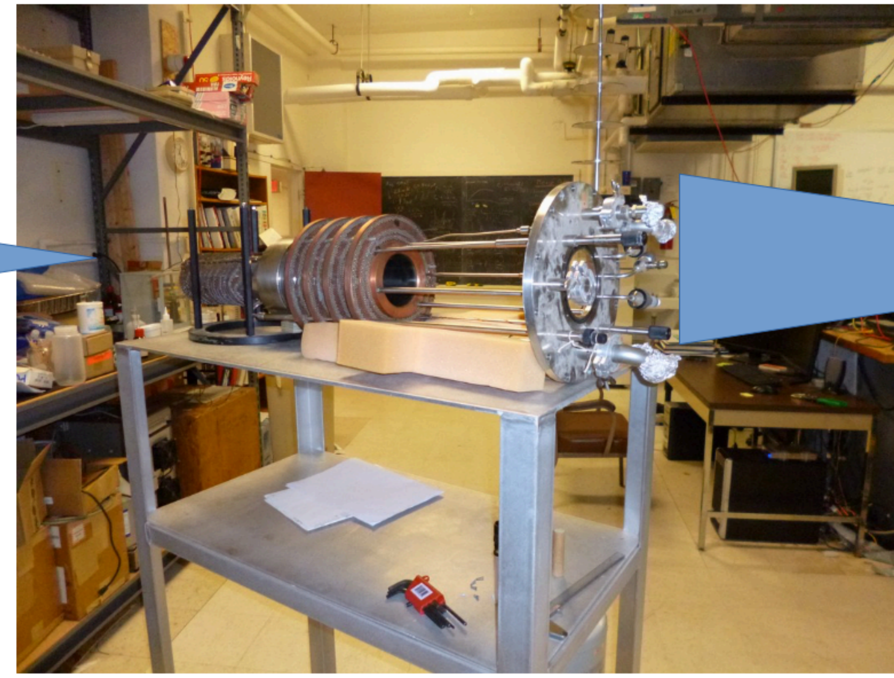
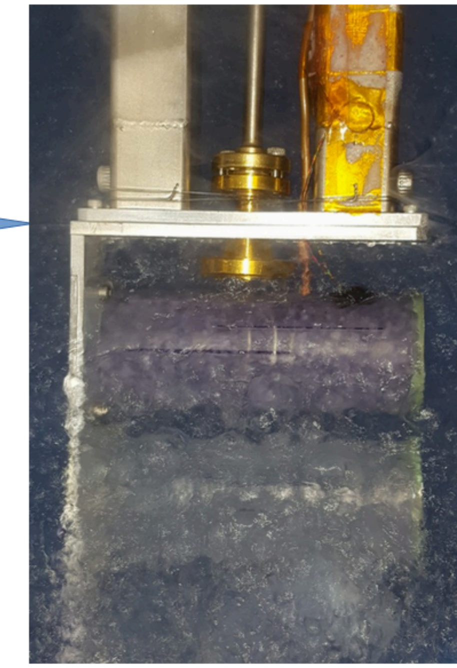
April 2016 UVa full system test

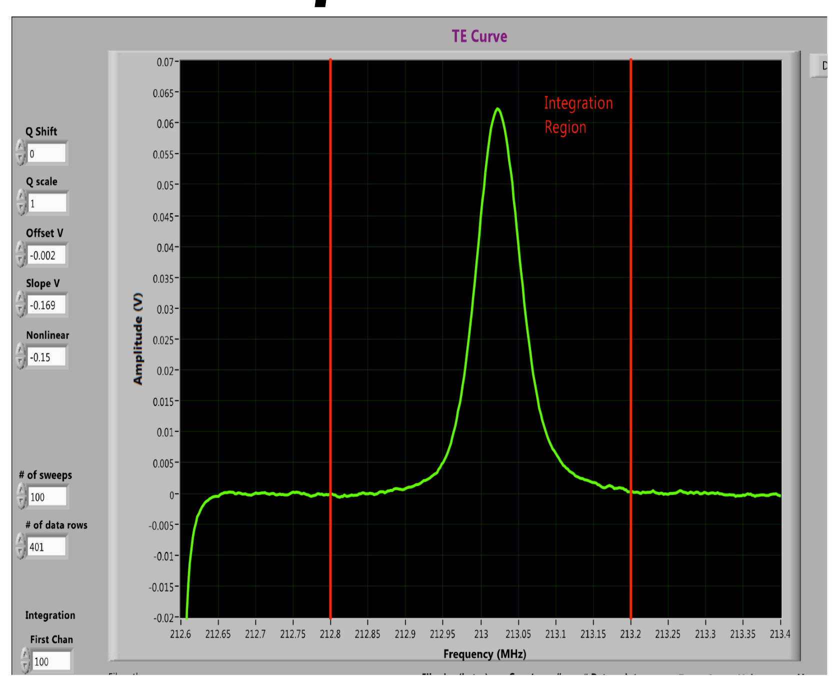




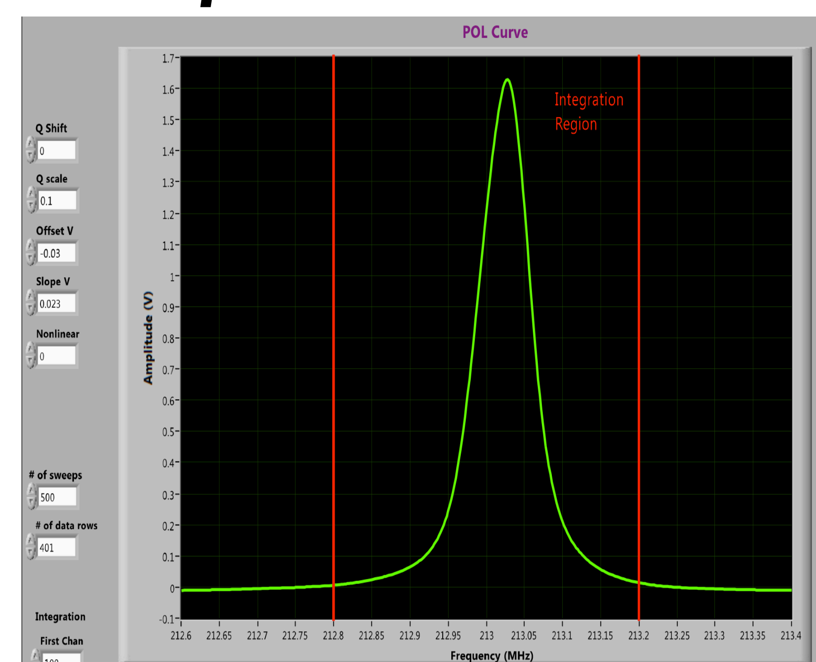


- Cool down to 4K, Magnet at 5 Tesla
- Inserted the refrigerator and target, brought down to 1K by pumping on vapor pressure
- Very clean TE signal is measured once the target is 1K
- Also measured polarization when microwave is applied, **Est. P = 95%**

Termal Equilibrium



95% polarization



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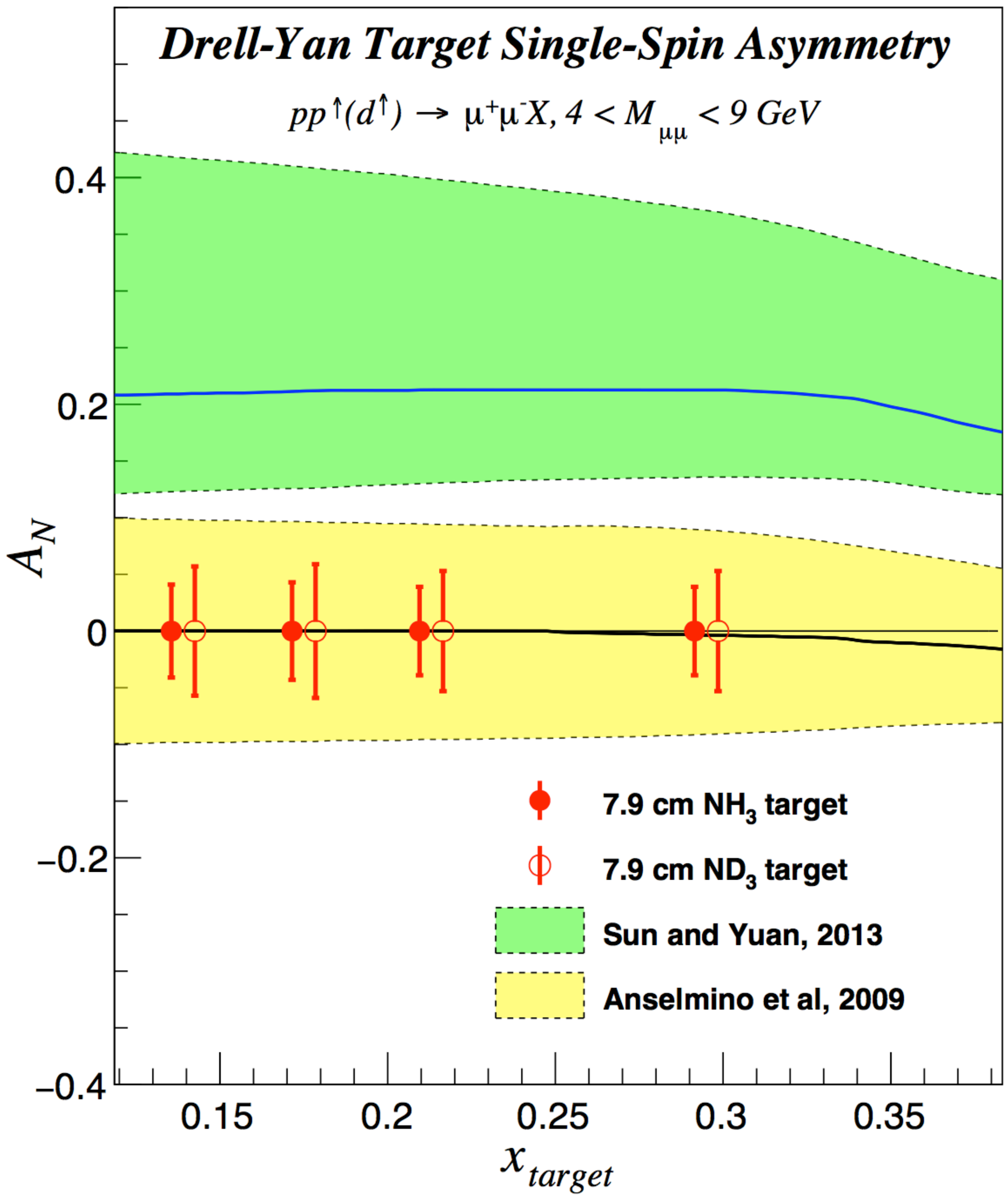
A working target

Projected precision with a polarized target at E1039



Statistics shown for 2 calendar years of running

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

Existing data do not put enough constraints on the sea quark Sivers distribution, neither sign nor value.

If $A_N \neq 0$, major discovery:

- "Smoking gun" evidence for $L_{sea} \neq 0$
- Determine sign and value for sea quark Sivers distribution
- Confirm Lattice QCD and Meson Cloud Model expectations

If $A_N = 0$:

- $L_{sea} = 0$, spin puzzle more dramatic ?
- Sea flavor asymmetry hard to explain
- In contradiction to Lattice QCD and Meson Cloud Model expectations

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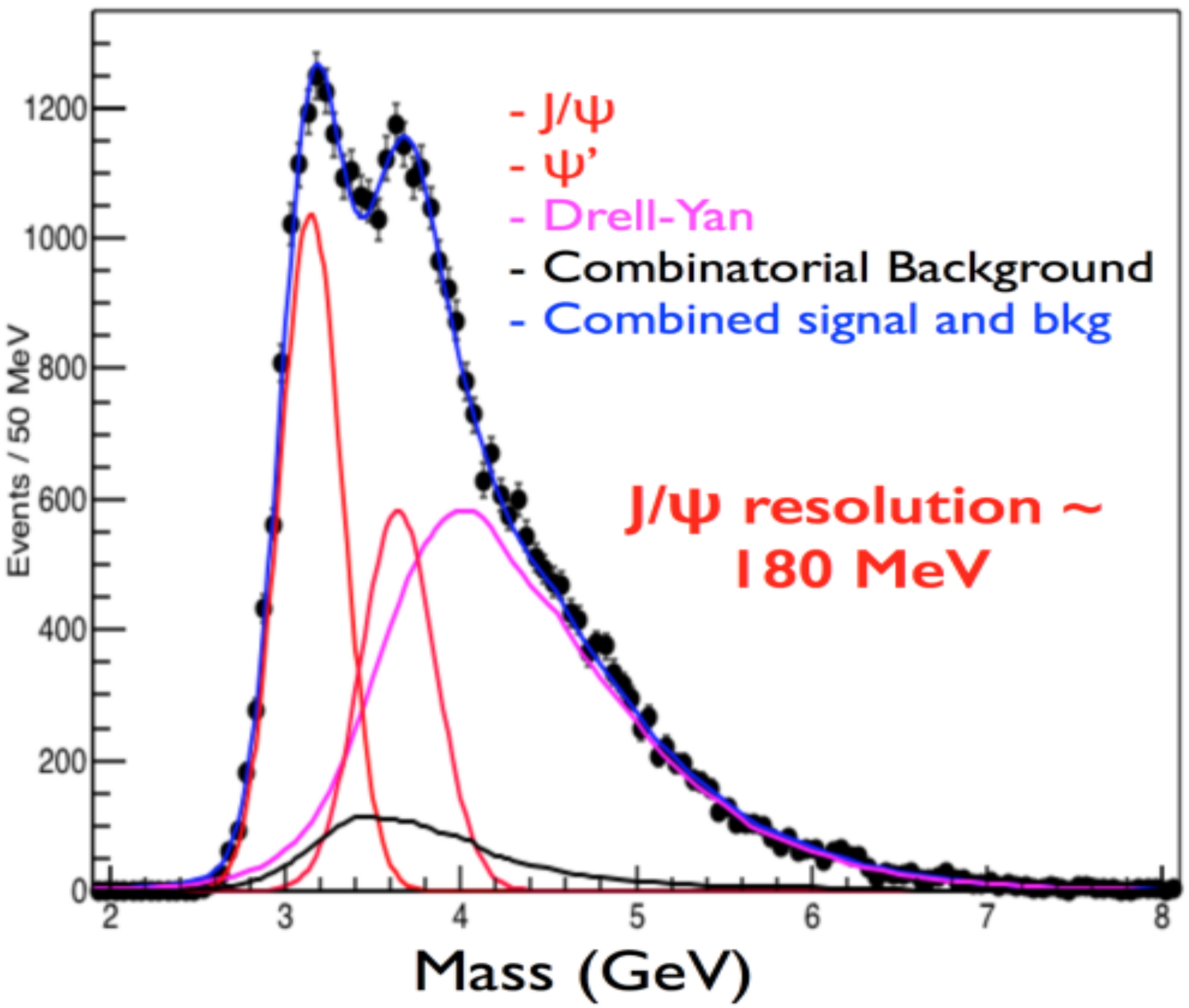
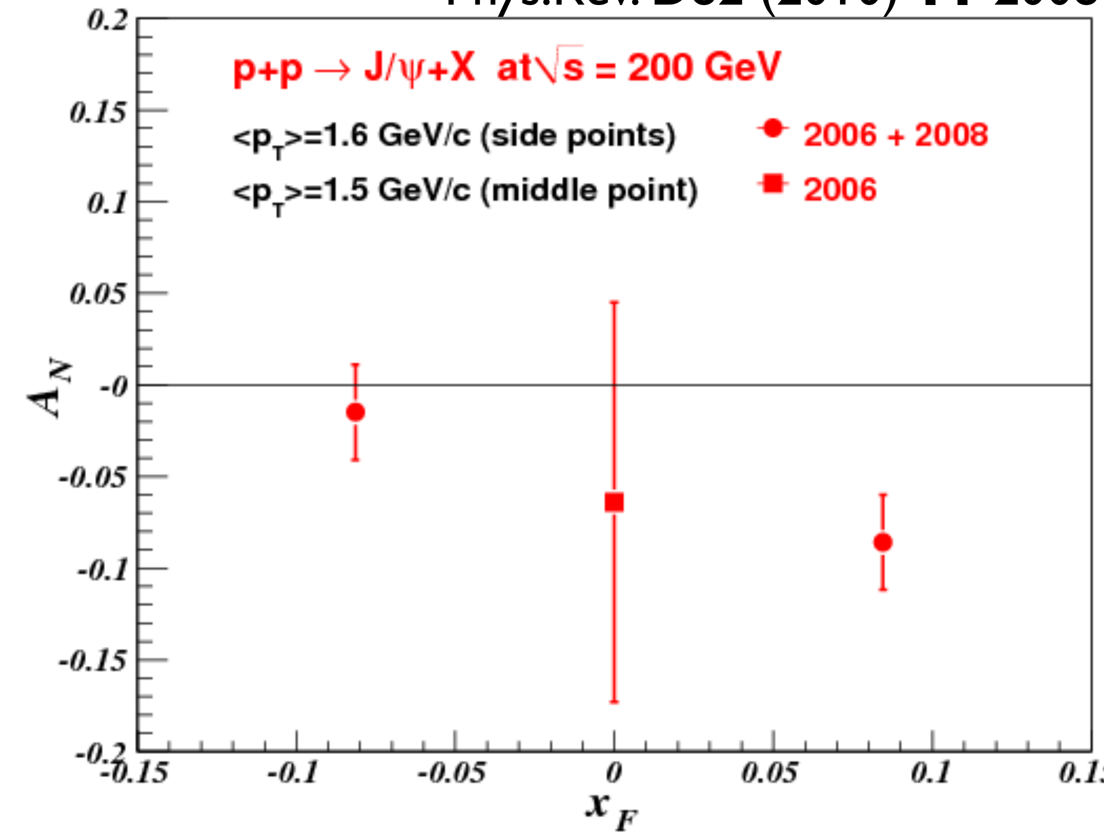
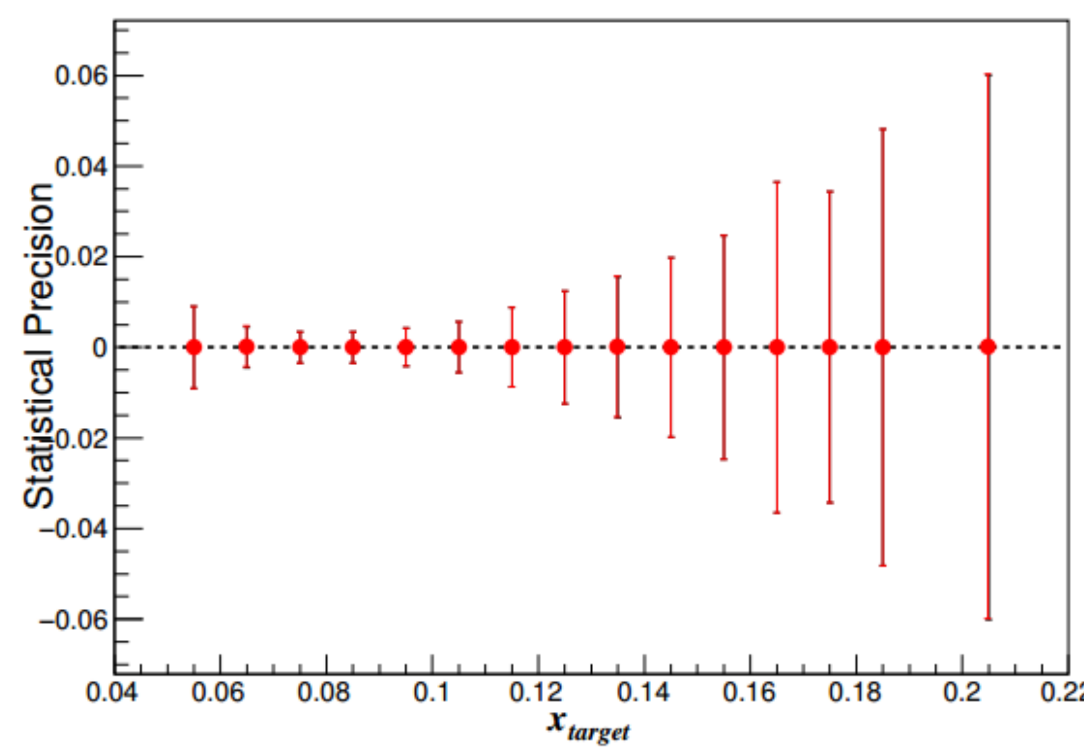
Bonus: gluon Sivers function through J/ψ production



Phys.Rev. D82 (2010) ▌▌ 2008





- Large amount of J/ψ is produced at $0.1 < x_B < 0.2$
- Based on E906 data, J/ψ is still dominantly produced by gg fusion
- Measurement of J/ψ TSSA to extract gluon Sivers function, especially at high x

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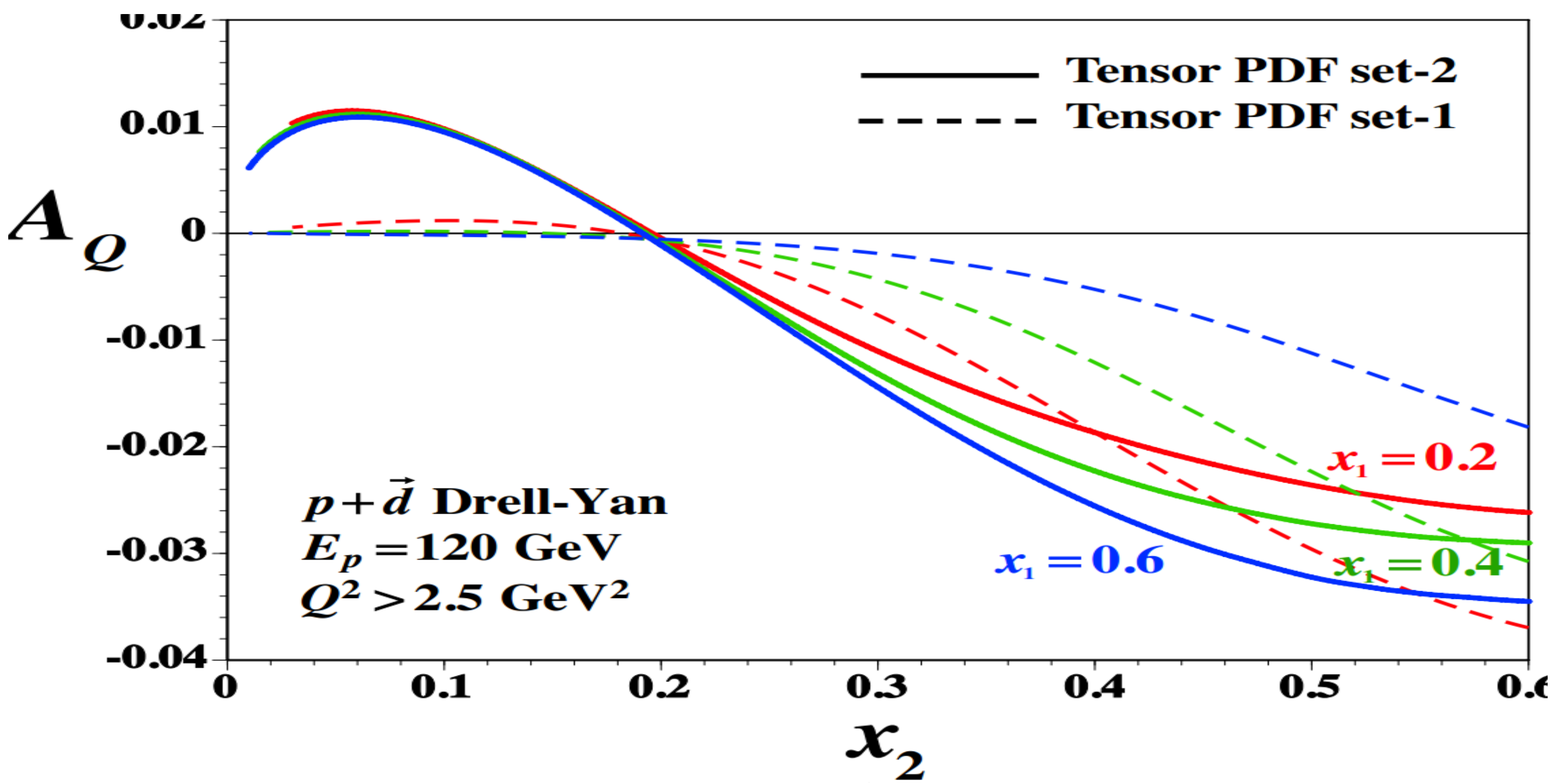
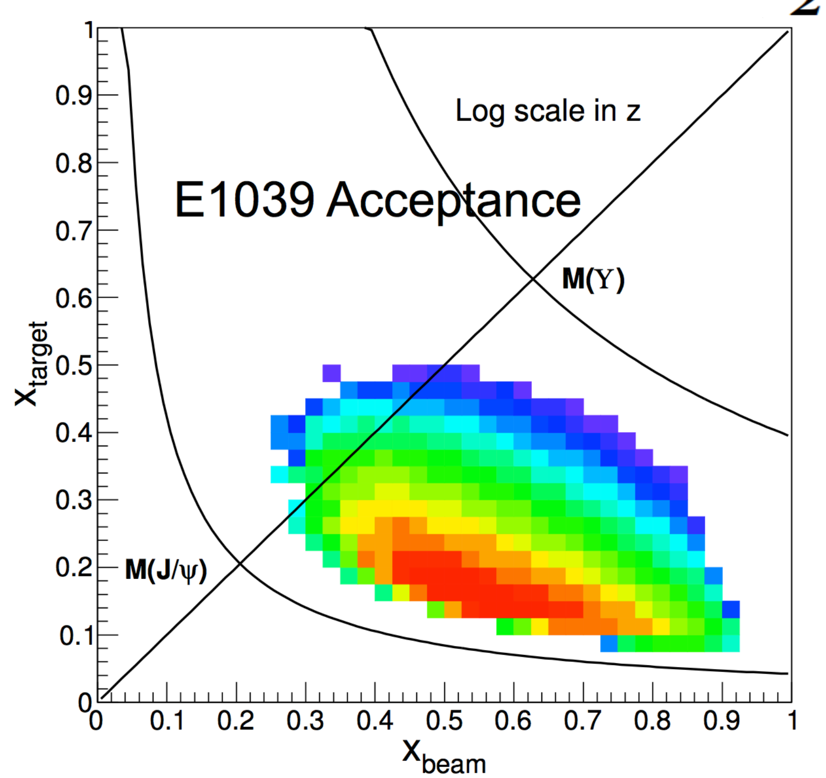
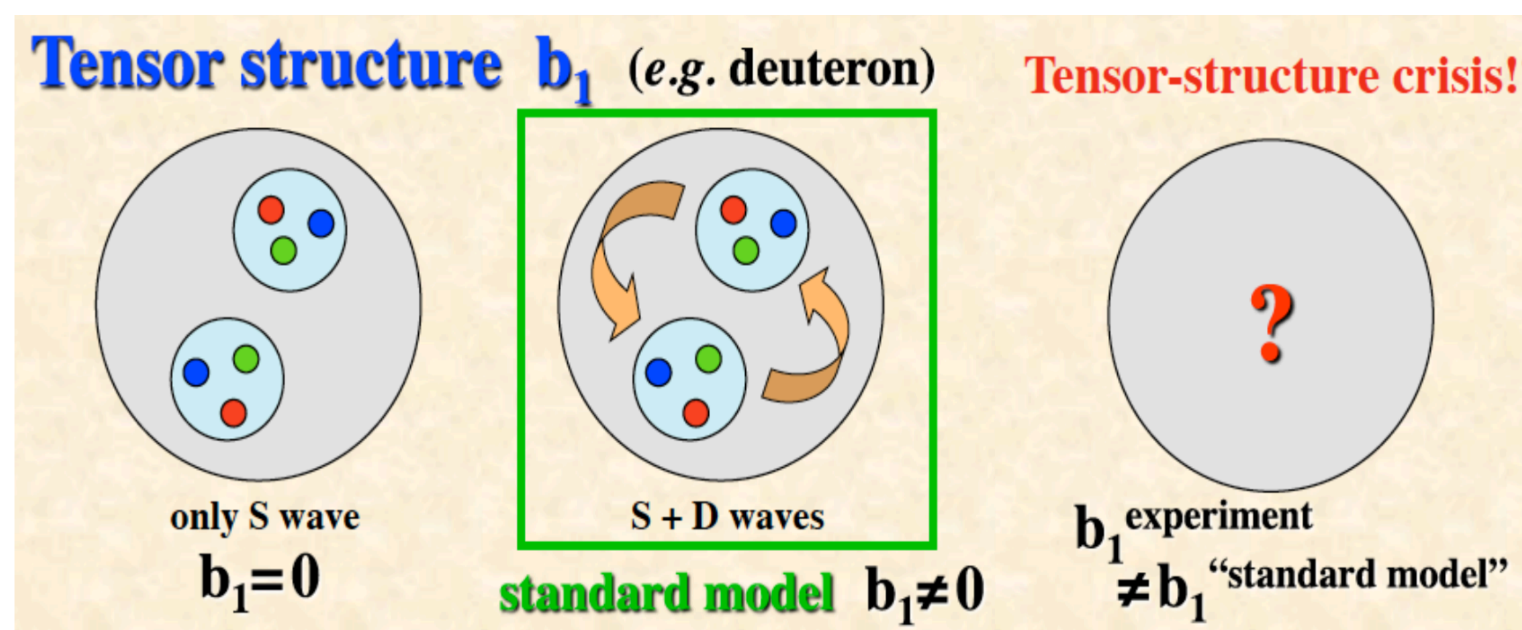
Bonus: tensor polarization of deuteron



- d is a spin-1 particle, in a B-field it could be tensor polarized, allows us to probe the tensor structure function b_1
- HERMES first observed significantly non-zero b_1
- An interplay between properties of nucleon and nucleus
- UVa has achieved 40% tensor polarization on ND_3





From S. Kumano's talk on Monday

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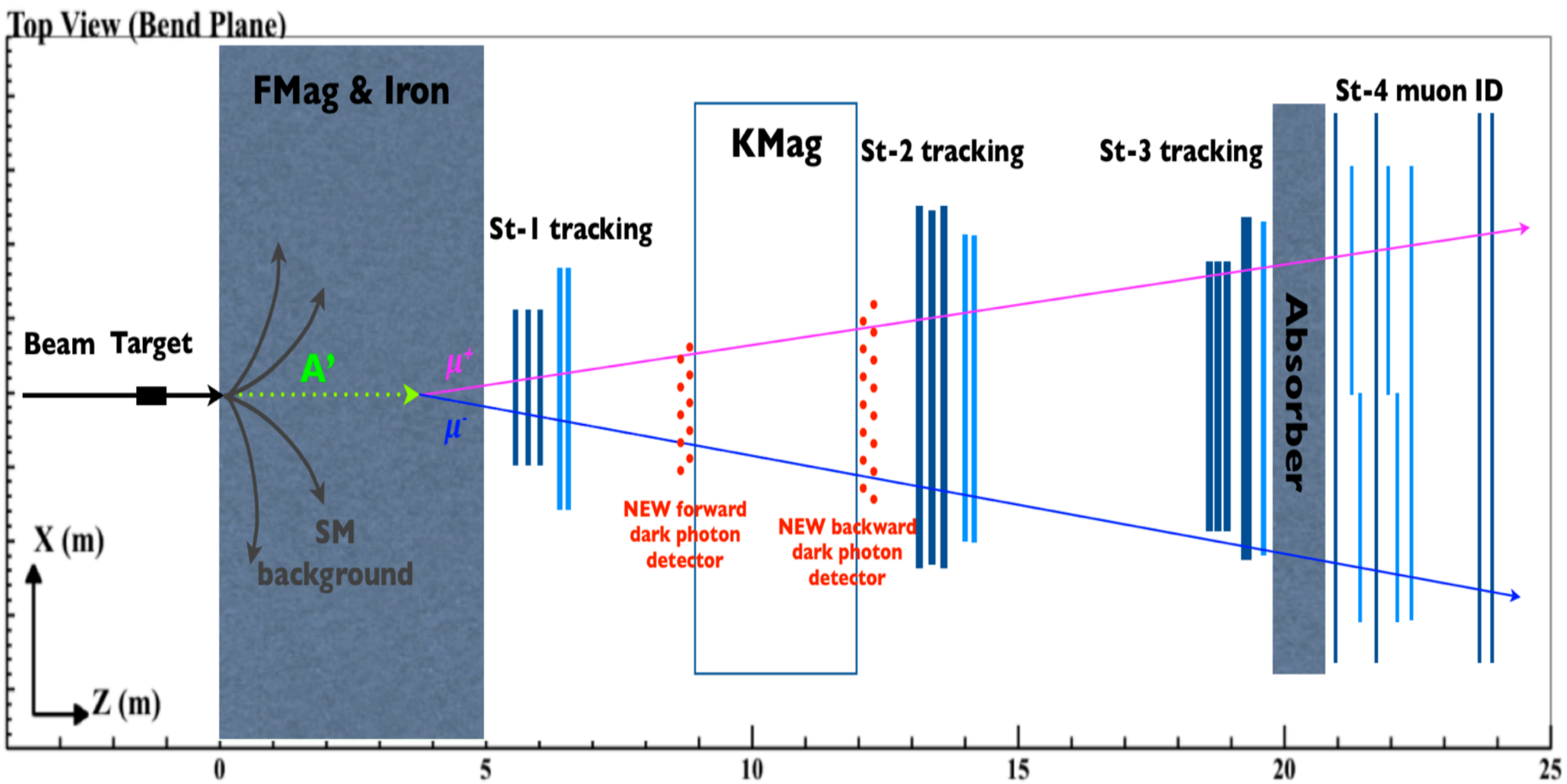
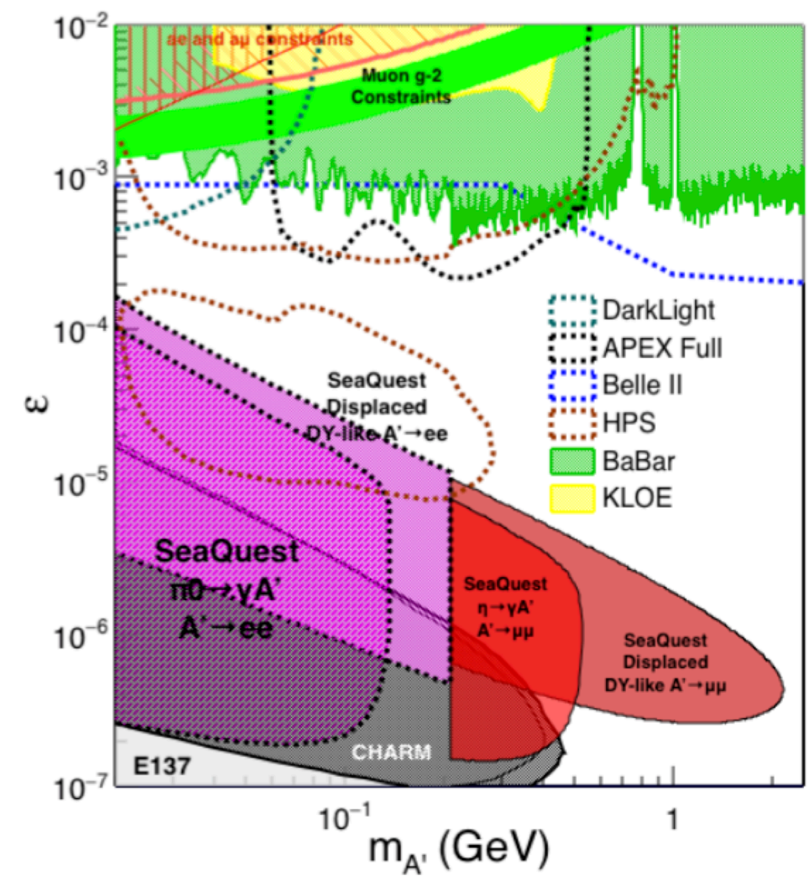
Bonus: dark photon search





Phase-I:

- Addition of new displaced dimuon trigger to tag long-lived downstream decayed dark photon/higgs (**completed in 2017**)
- Runs ***parasitically*** with E1039 and any future upgrades
- The experiment E-1067 was endorsed by Fermilab PAC

Phase-II:

- Dedicated beam time if phase-I is successful, with EMCal upgrades for $e^{+/-}$ and $h^{+/-}$ capabilities
- Two sectors of PHENIX EMCal are secured and prepared for shipping
- Cover full parameter phase space allowed by beam energy and luminosity
- An open lab for all possible target physics

"… recognizes the exciting opportunity brought by P1067 to search directly for a dark photon and dark Higgs in high-energy proton-nucleus collisions using existing SeaQuest Spectrometer."

"The PAC believes P1067 offers exciting prospects and recommends the Laboratory to grant these modest requests"

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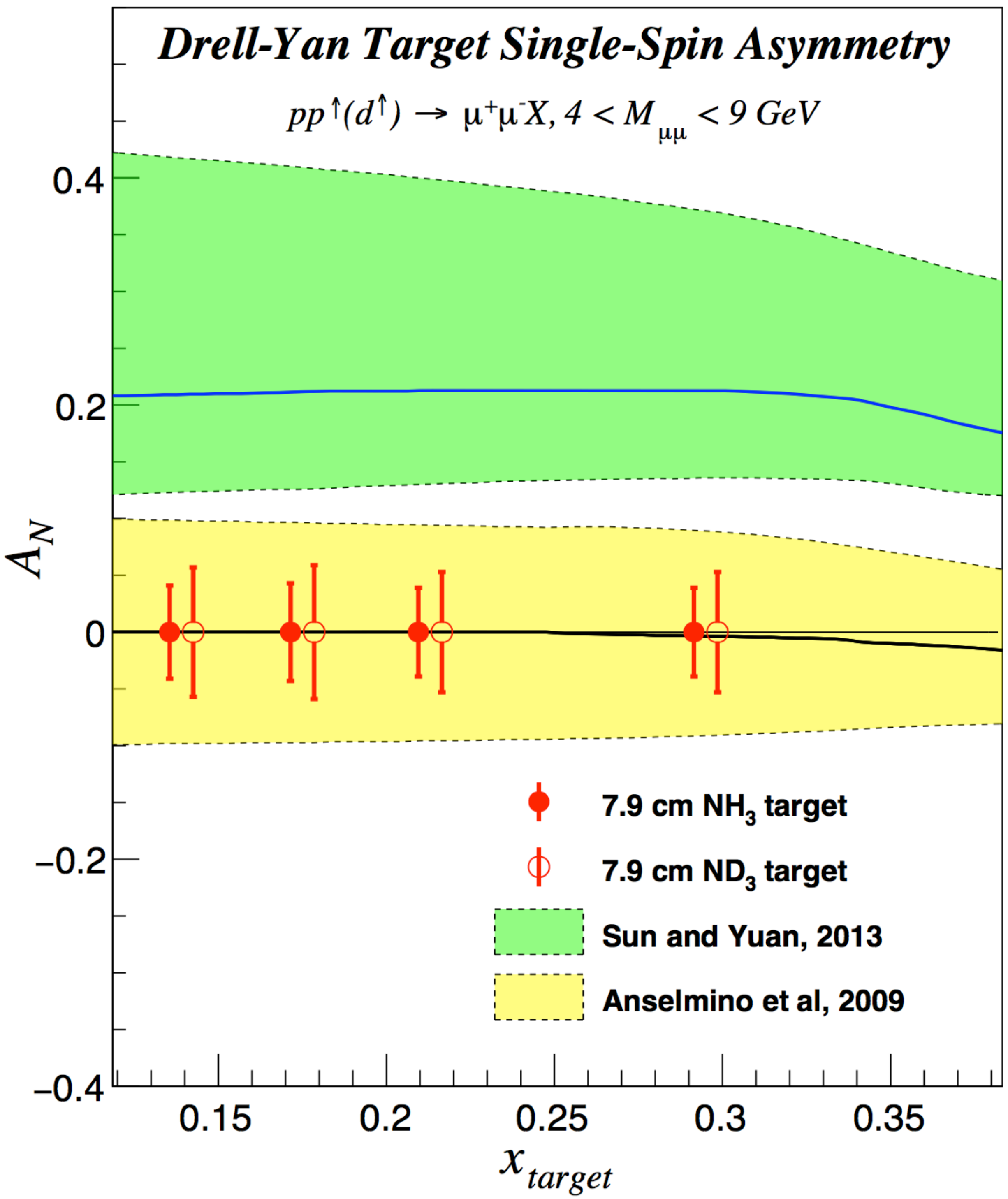
Summary and timeline



- E1039 provides unique sensitivity to the Sivers function of both ubar and dbar and shed light on understanding the nucleon spin

- Many other interesting program in addition to sea quark Sivers
  - ➢ Tensor polarization of deuteron
  - ➢ Gluon Sivers function via J/ψ production
  - ➢ Parasitic dark matter search

- **Project timeline:**
  - ➢ Funded by DOE/NP
  - ➢ E906 starts decommissioning in Nov. 2017
  - ➢ E1039 start target installation in early 2018
  - ➢ Target and beam line commission in May 2018
  - ➢ Short spectrometer commission after Summer shutdown
  - ➢ 2 years of production data taking

Looking for collaborators!

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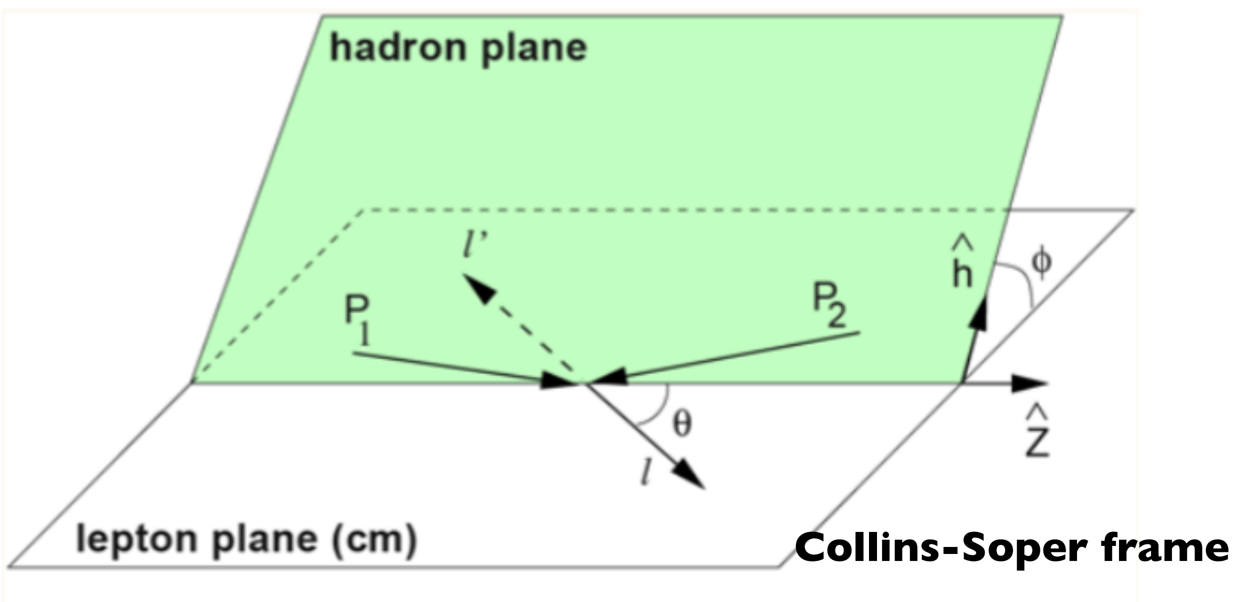
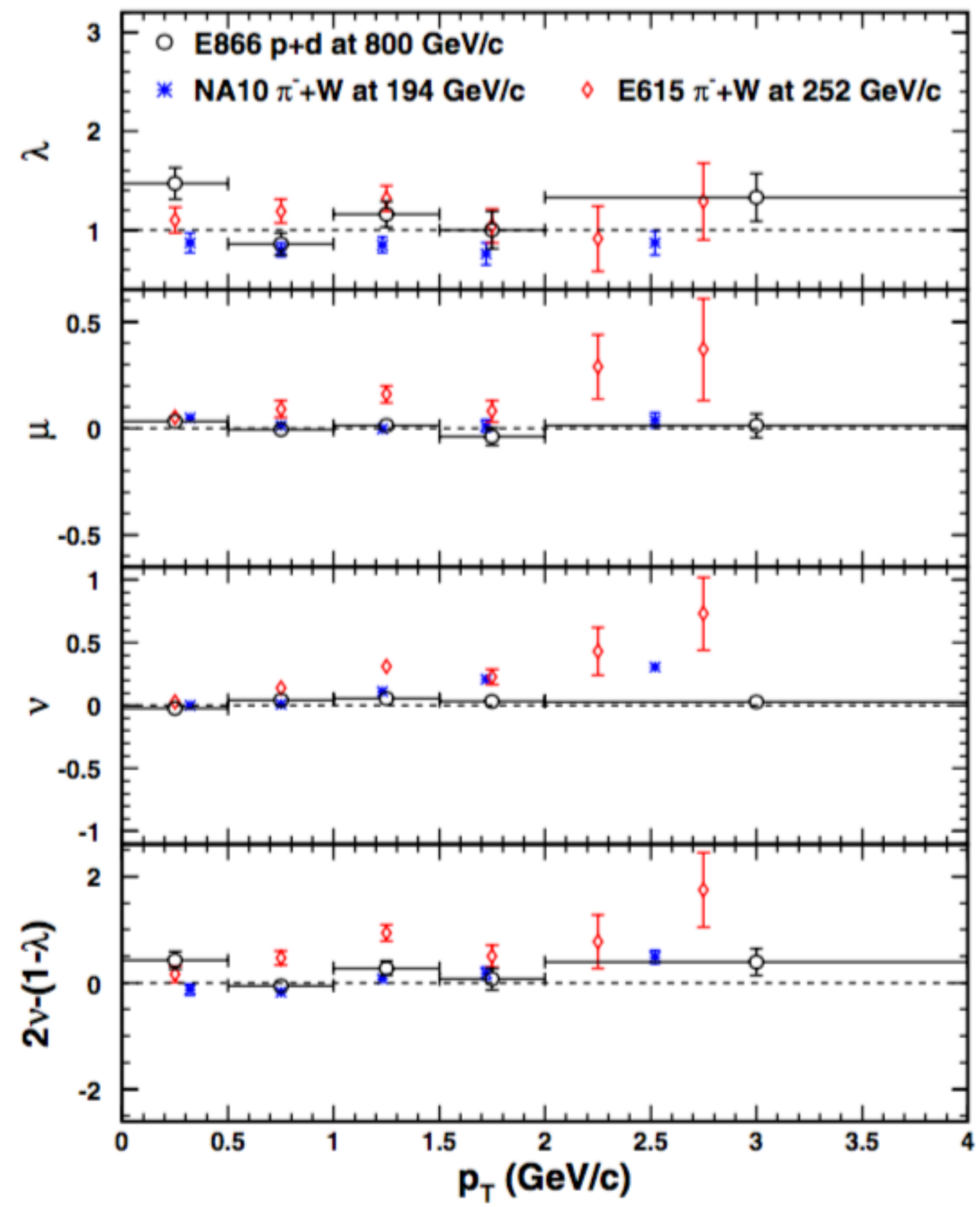
Thanks!

Backup

Accessing Boer-Mulders (BM) function in unpolarized DY

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





- Lam-Tung violation: $1 - \lambda \neq 2\nu$
- ν can be decomposed to the convolution of two BM functions: $\nu \propto [h_1^\perp \text{ of } \bar{q}] \times [h_1^\perp \text{ of } q]$
- Measurement of BM in proton-induced DY using pp and pd data:
  - ➢ identify the source of Lam-Tung violation
  - ➢ test the flavor dependence prediction

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Expected precision of E906

- Significant improvement in precision compared with previous experiments
- Very challenging analysis
- Both p+p and p+d data available