Opportunities with polarized Hadron Beams

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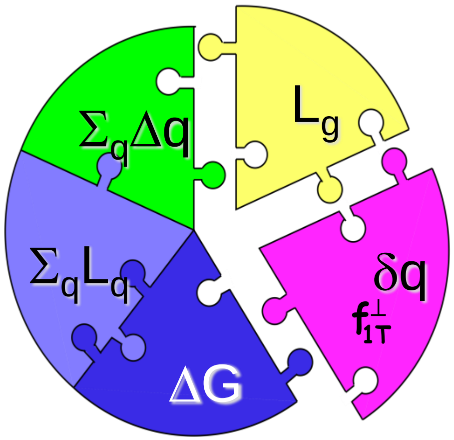
University of Michigan

Spin2014
Beijing, China
(24-October-2014)



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

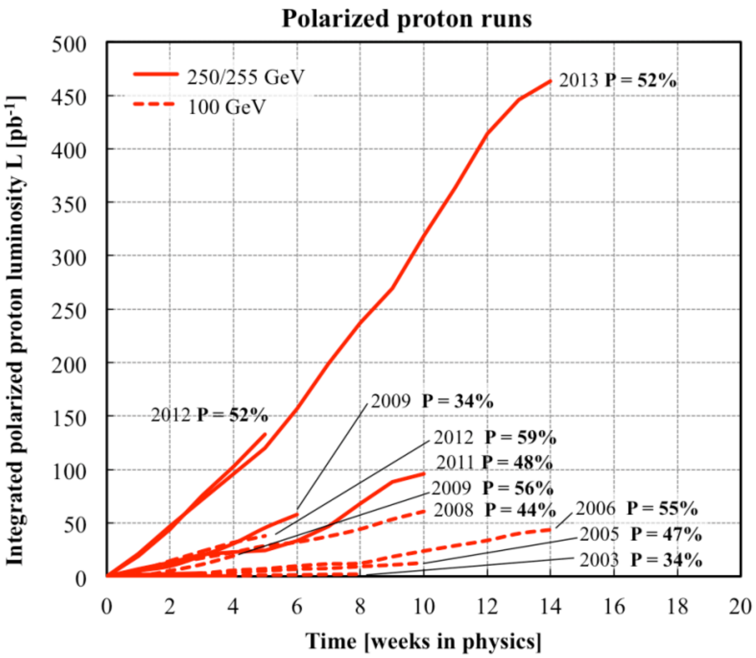
This work is supported by

Current Facilities

STAR

PHENIX

- T & L polarized p beams ($\sqrt{s}$ = 200, 500 GeV)
- L program:
  - ➡ $A_{LL}^{\pi 0}$ (PHENIX) & A_{LL}^{jet} (STAR) → **Δg(x)**
  - ➡ $A_L^{W\pm}$ at $\sqrt{s}$ = 500 GeV → **$\Delta q_{bar}(x)$**
- 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

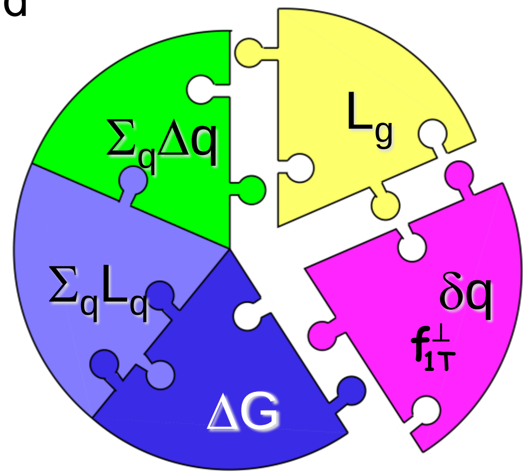
COMPASS

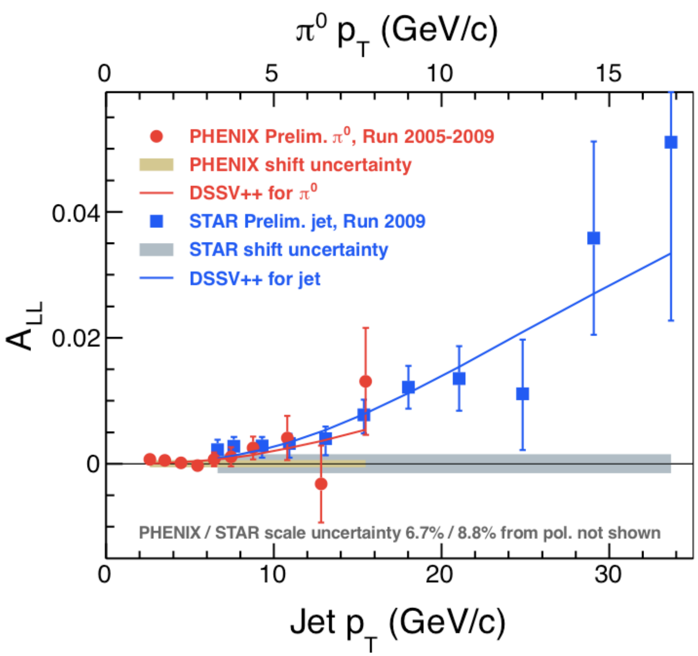
COMPASS-II

- 190 GeV π^- beam on T-pol H target → **polarized Drell-Yan**
- First π^- beam expected: Apr 2015
  - ➡ run 2 yrs total

How do we build the proton spin?

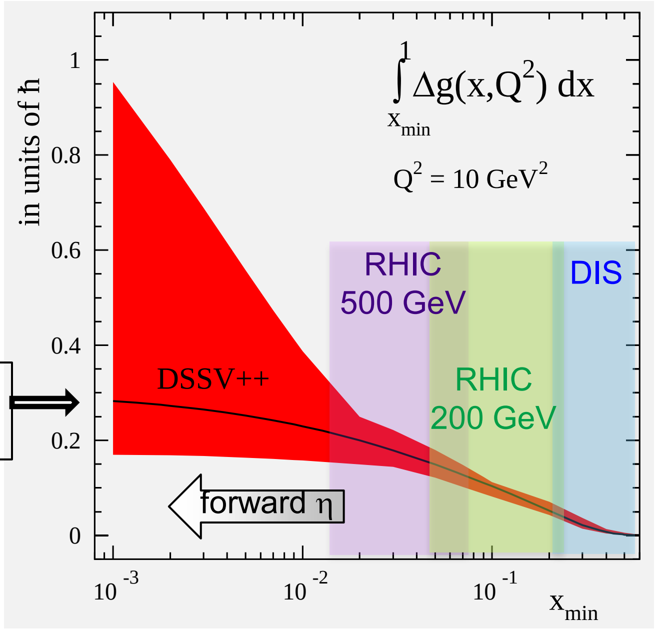
- The origin of nucleon spin and the distributions of quarks and gluons in nuclei remain mysteries after decades of study.
  - ➡ How much do the quarks and gluons contribute to the nucleon spin? Is there significant orbital angular momentum?
  - ➡ Polarized DIS: $\Delta\Sigma \approx 0.3$
  - ➡ Q^2 evolution in polarized DIS gives relatively weak constraints on Δg
  - ➡ **RHIC** Spin program: **map $\Delta g(x)$**





RHIC '09 prelim

~ 60% of proton spin?



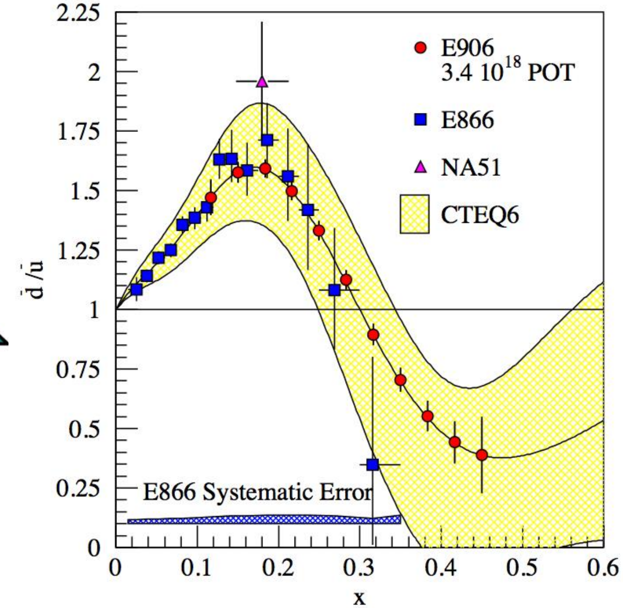
1st significant non-zero $\Delta g(x)$

What about the sea quarks?

- Understanding dynamics of sea-quark fluctuations
  - ➡ separation of quark flavors
  - ➡ flavor asymmetry in light sea quarks of proton

$$\bar{u} - \bar{d} < 0$$

E906 SeaQuest



- ➡ what about the polarized light quark sea?
- ➡ sea-quark polarizations critical for quark contribution to spin

Meson Cloud M. / Chiral-Quark Soliton M. / Statistical M.

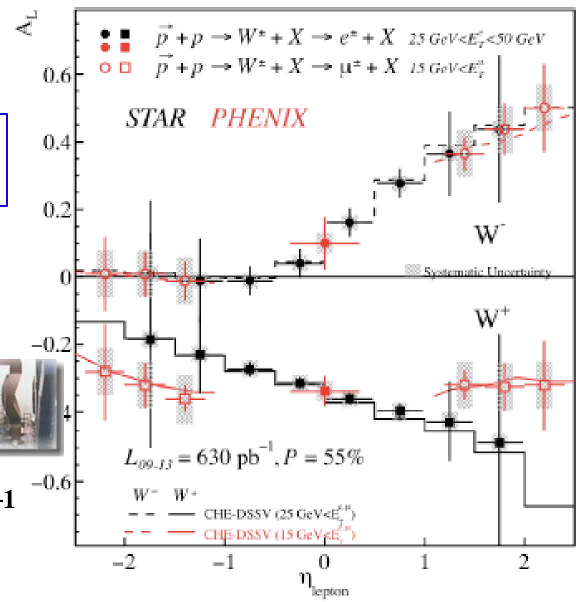
Meson Cloud M.	Chiral-Quark Soliton M.	Statistical M.
$\bar{d} > \bar{u}$	$\bar{d} > \bar{u}$	$\bar{d} > \bar{u}$
$\Delta\bar{q} = 0$	$\Delta\bar{u} \cong -\Delta\bar{d} > 0$	$\Delta\bar{d} < 0, \Delta\bar{u} > 0$

- ➡ surprise from RHIC

$$\Delta\bar{u} - \Delta\bar{d} > 0$$

STAR PHENIX

$$\int L_{deliv}^{2011+2012} = 140 \ \text{pb}^{-1}$$



Future Hadron Facilities

New instrumentation in forward direction

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

- STAR Forward Calorimeter System: EMCal + HCal
  - ➡ forward jets & e/h separation for Drell-Yan
- fsPHENIX: forward spectometer w/ EMCal, HCal, RICH, tracking
  - ➡ forward jets & identified hadrons and Drell-Yan

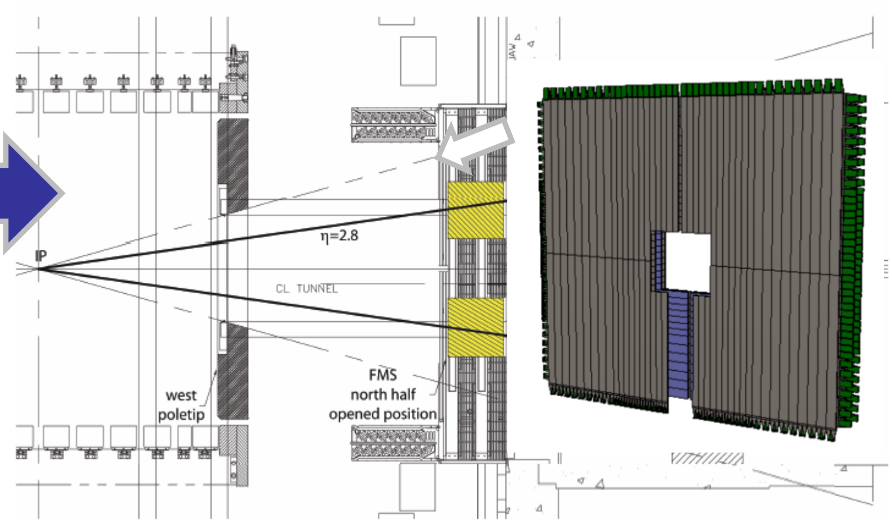
Polarized Beam and/or Target w/ SeaQuest detector

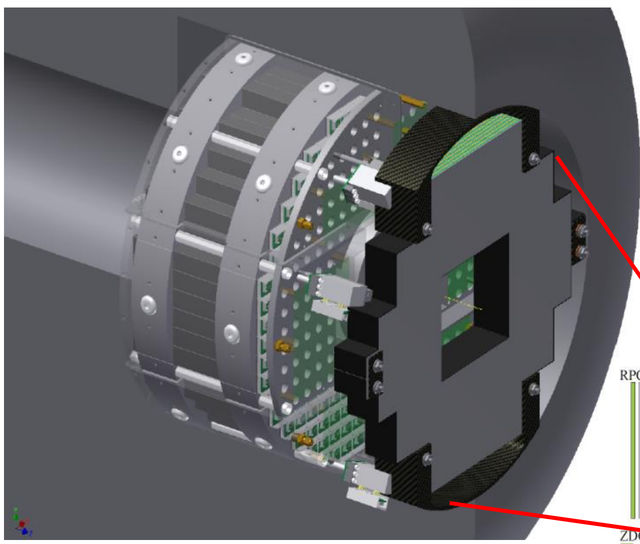
→ **high-luminosity** facility for **polarized Drell-Yan**

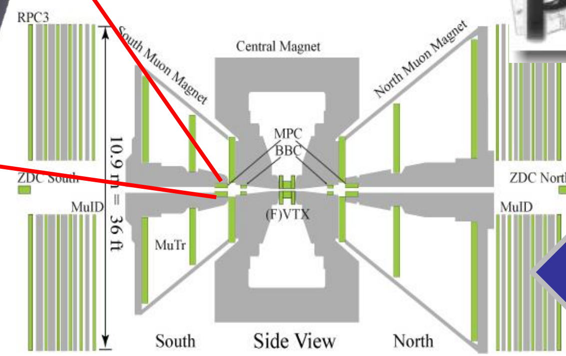
- E-1027: pol p beam on unpol tgt
  - ➡ **Sivers sign change** (valence quark)
- E-1039: SeaQuest w/ pol NH_3 target
  - ➡ probe sea quark distributions

RHIC Near Term Upgrades

STAR FPS Preshower Array



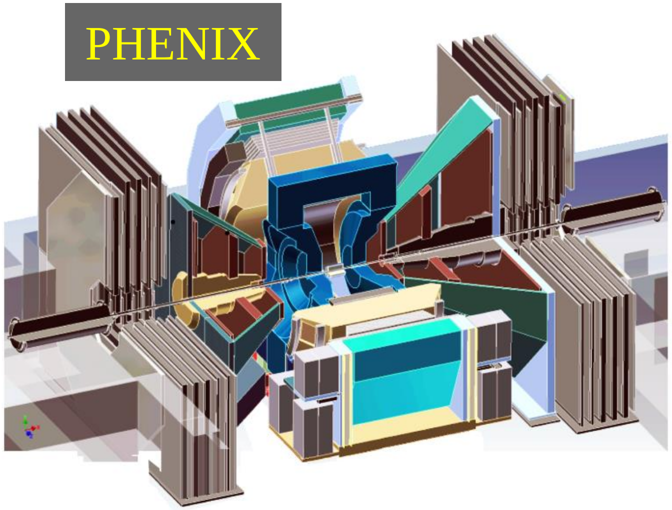




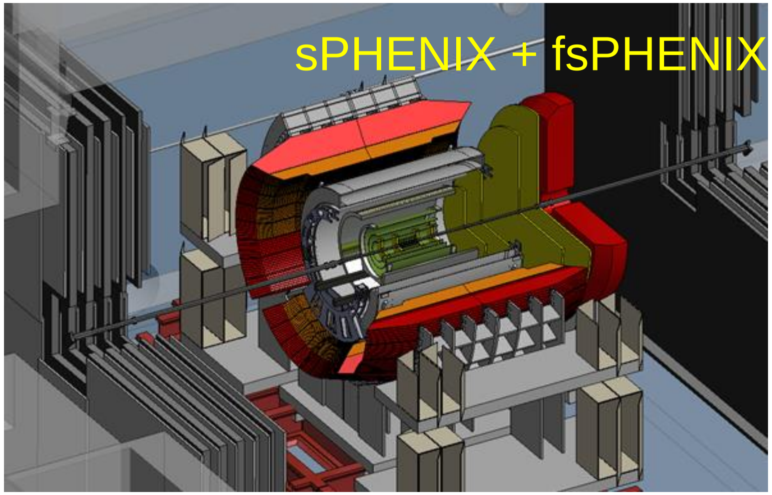
PHENIX MPC-EX Preshower

from John Lajoie

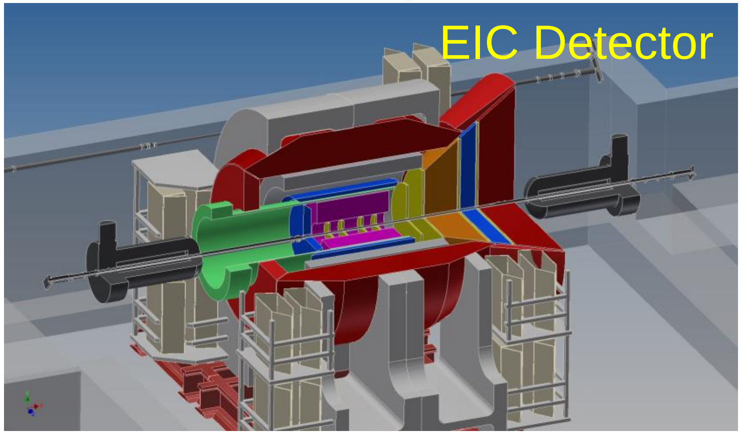
The PHENIX Detector Evolution



2021-22



~2025



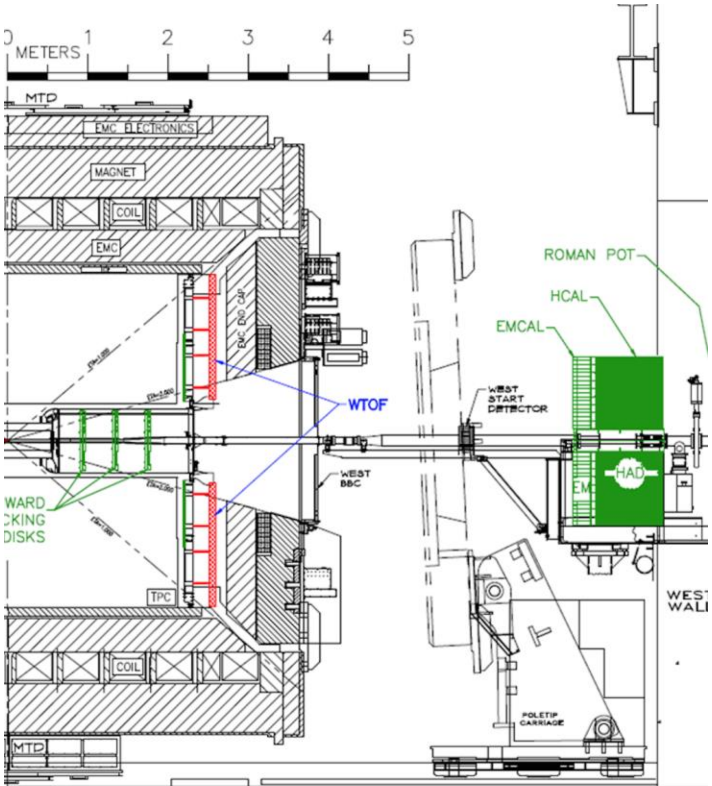
Evolve sPHENIX (HI detector) with forward instrumentation for p+p/p+A physics:

- GEM tracking chambers
- Hadronic Calorimetry
- Reconfigure existing FVTX and MuID

fsPHENIX forward instrumentation in common with evolution of sPHENIX into an EIC (eRHIC) detector.

from John Lajoie

STAR Forward Upgrades for 2021+



Forward Upgrades:

EMCal:

Tungsten-Powder-Scintillating-fiber
2.3 cm Moliere Radius, Tower-size: 2.5x2.5x17 cm^3, 23 X_o

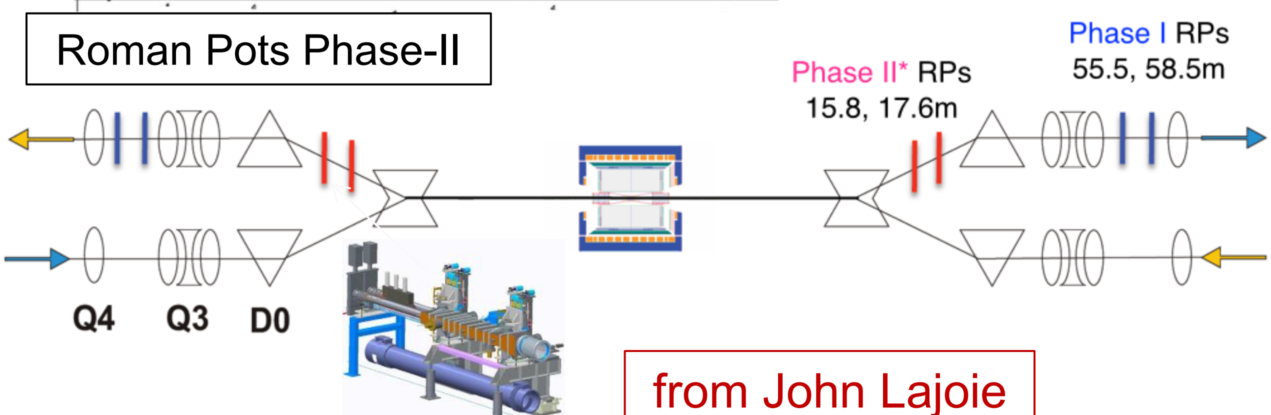
HCal:

Lead and Scintillator tiles, Tower size of 10x10x81 cm^3
4 interaction length

Tracking:

Silicon mini-strip detector 3-4 disks at z ~70 to 140 cm
Each disk has wedges covering full 2π range in ϕ
and 2.5-4 in η (other options still under study)

Roman Pots Phase-II



STAR is also pursuing a coordinated upgrade path that can lead to an EIC detector.

from John Lajoie

Future Spin Measurements @ RHIC

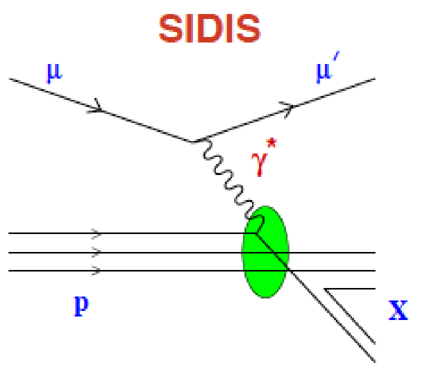
- **Near Term (2015-16):**
  - ➡ Prompt photon A_N in polarized p+p @ 200GeV
  - ➡ First exploration of SSA's in polarized p+A
  - ➡ *W* boson transverse SSA*
- **Longer Term (2021-22):**
  - ➡ Extensive forward upgrades for STAR, PHENIX
  - ➡ Long p+p (200/510 GeV) and p+A runs
  - ➡ Planned spin program in **$\Delta g(x,Q^2)$ at low-x** (longitudinal) as well as Jets**, Drell-Yan** (transverse), ...

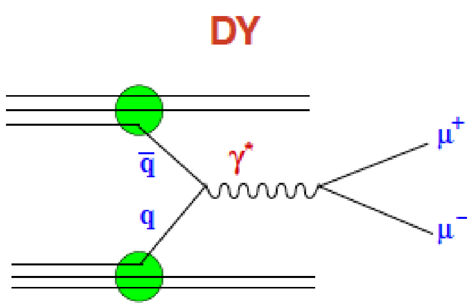
*Run plan for Run-16 not yet finalized.

from John Lajoie

The Missing Spin Program: Drell-Yan

In COMPASS @ CERN transverse momentum dependent PDFs (TMDs) can be accessed either from semi-inclusive DIS (SIDIS), or from Drell-Yan processes, using a transversely polarized target:





By measuring the Transverse Single Spin Asymmetries (TSSA) in these processes one can access the correlations between the partons k_T and the nucleon spin.

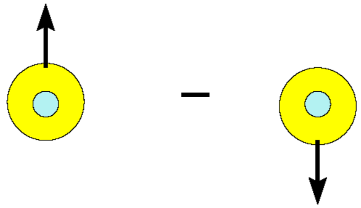
SIDIS: spin asymmetry proportional to TMD(quark) $\otimes$ FF(quark $\rightarrow$ hadron)

DY: spin asymmetry proportional to TMD(quark) $\otimes$ TMD(antiquark)

- Drell-Yan advantage:
  - ➡ no QCD final state effects & no fragmentation process
  - ➡ clean access to sea quarks
- Crucial test of **TMD formalism** $\rightarrow$ **sign change** of T-odd functions

from Oleg Denisov

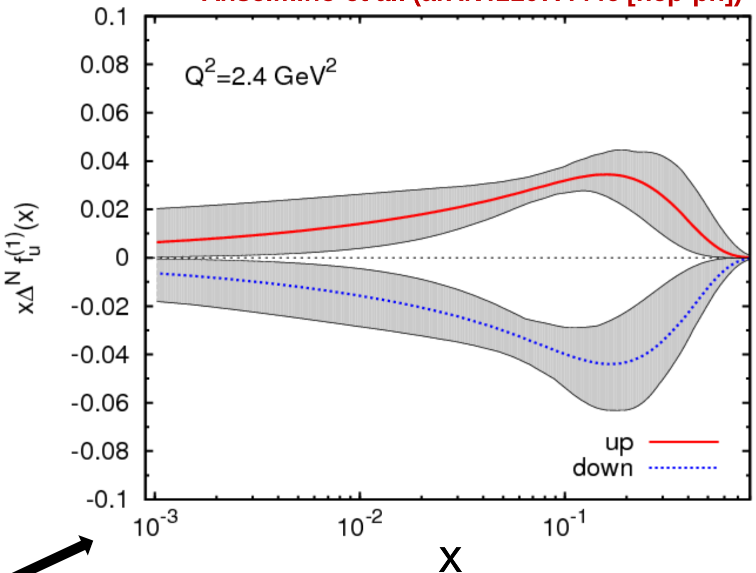
TMDs: Sivers Function

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

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
- 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])

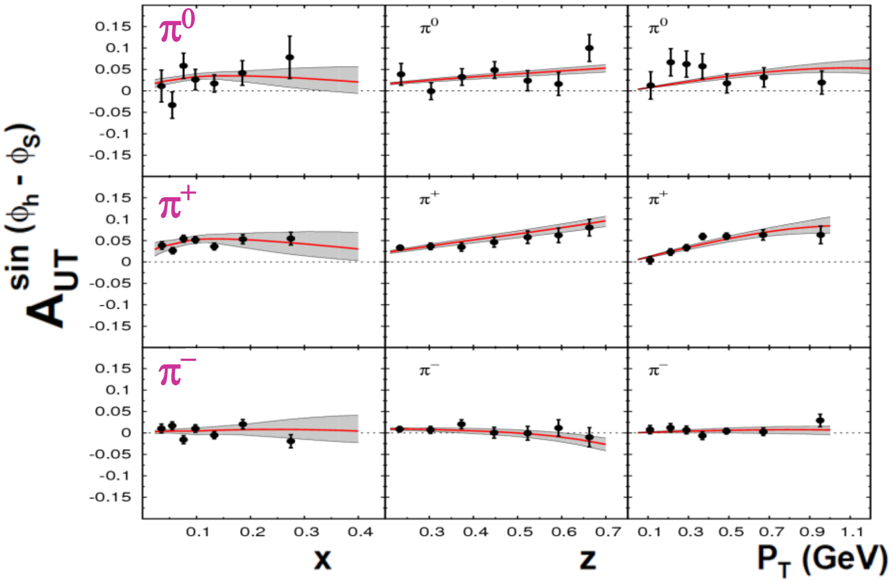


First moment of Sivers functions:

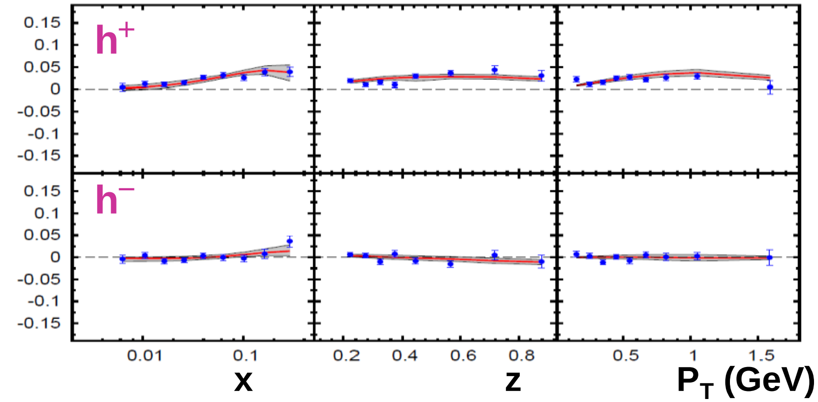
➡ u- and d- Sivers have opposite signs, of roughly equal magnitude

Sivers Asymmetry in SIDIS

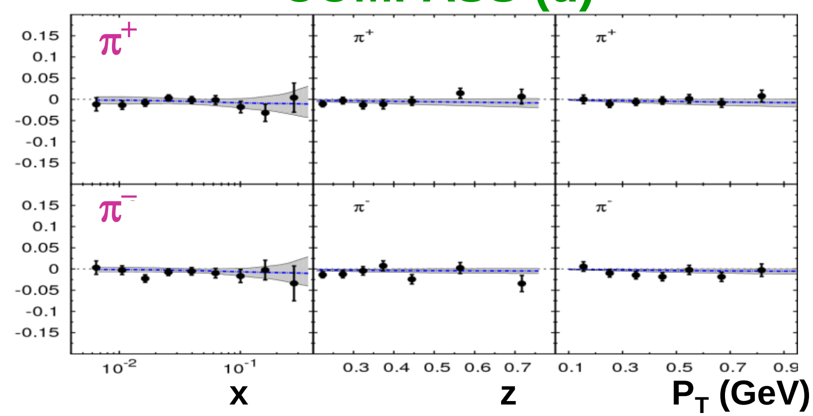
HERMES (p)



COMPASS (p)



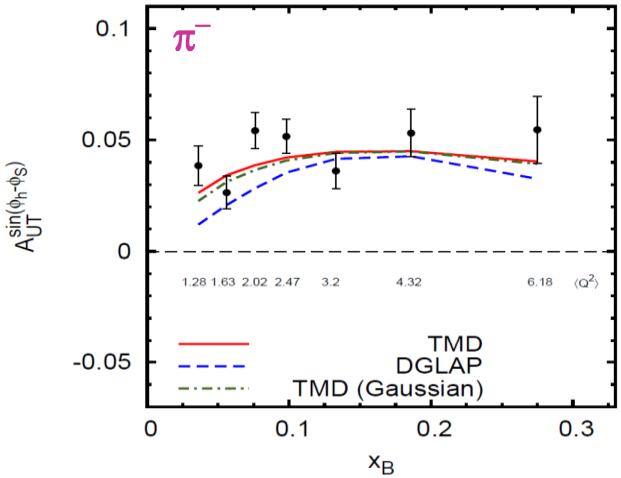
COMPASS (d)



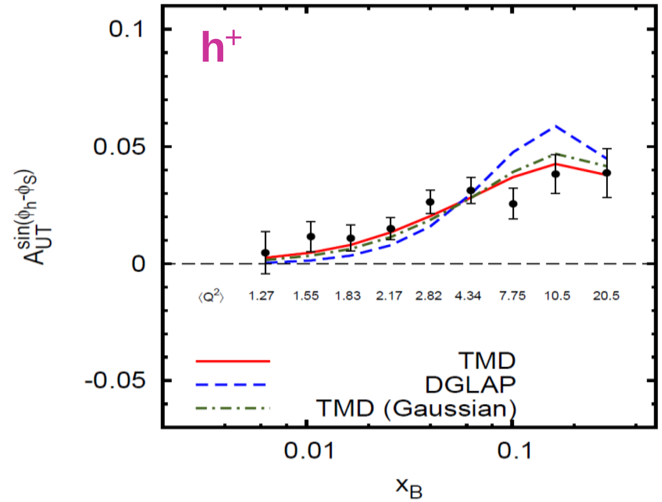
- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES (p), COMPASS (p), COMPASS (d))

QCD Evolution of Sivers Function

HERMES (p)



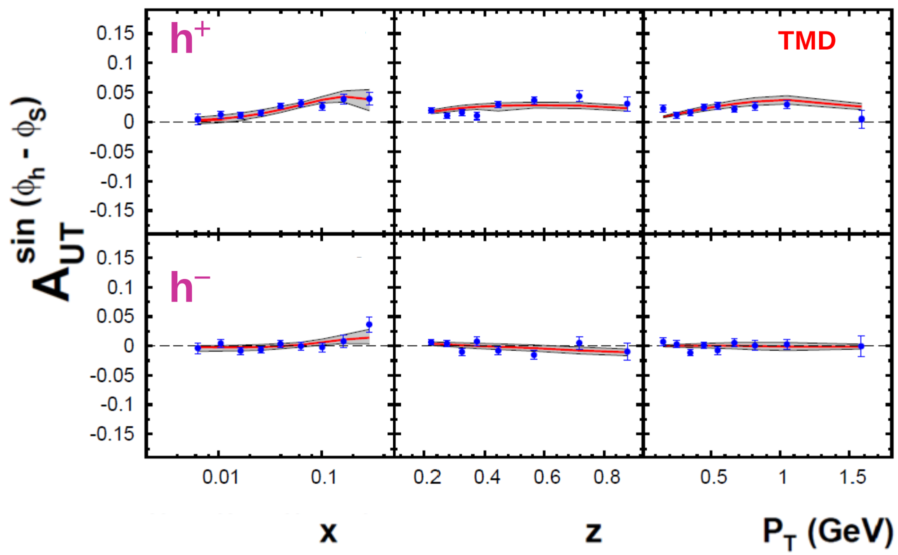
COMPASS (p)



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

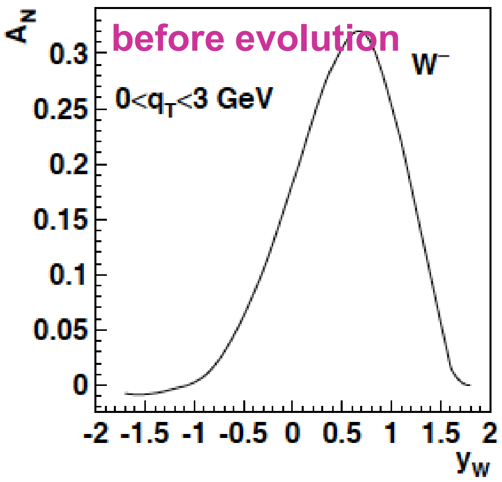
- Initial global fits by Anselmino group included DGLAP evolution only in collinear part of TMDs (not entirely correct for TMD-factorization)

- Using TMD Q^2 evolution:
  ⟶ agreement with data improves

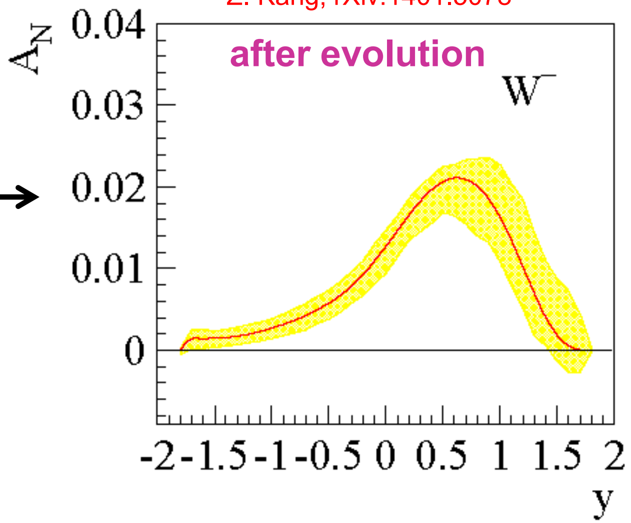


TMD Evolution of Sivers Asymmetry (W^-)

Z.-B. Kang, arXiv:0903.3629



Z. Kang, rXiv:1401.5078



- much stronger than any other known evolution effects
- needs input from data to constrain non-pertubative part in evolution
- **Can only be done at RHIC (**plans for 2% measurement in 2015**)**

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	2016
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= 1×10^{36} $cm^{-2} s^{-1}$ (LH_2 tgt limited) / L= 2×10^{35} $cm^{-2} s^{-1}$ (10% of MI beam limited)*

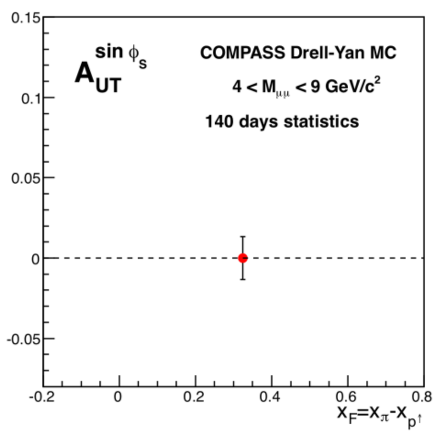
**not constrained by SIDIS data* / # rFOM = relative lumi * P^2 * f^2 wrt E-1027 (f=1 for pol p beams, f=0.22 for π^- beam on NH_3)

DY@COMPASS projections (NH_3)

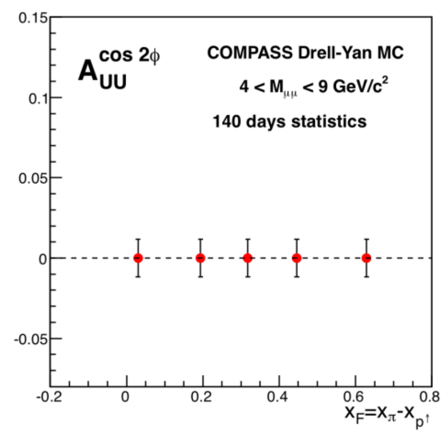
140 days of running with 10^8 pions per second

In the first two years we plan to collect ~600.000 DY events what would be factor of ~10 larger statistics compare to any other DY experiment performed so far

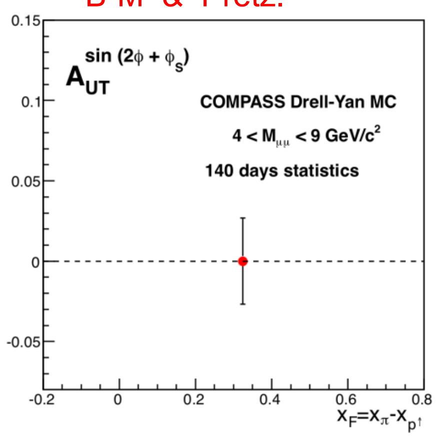
Sivers



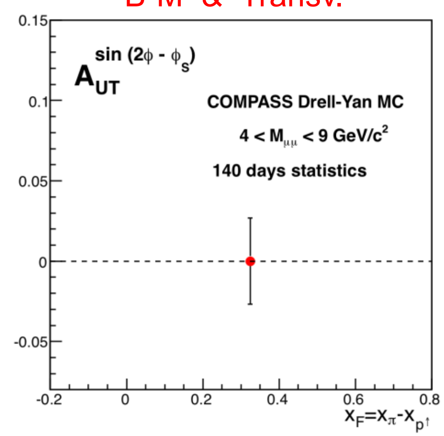
B-M

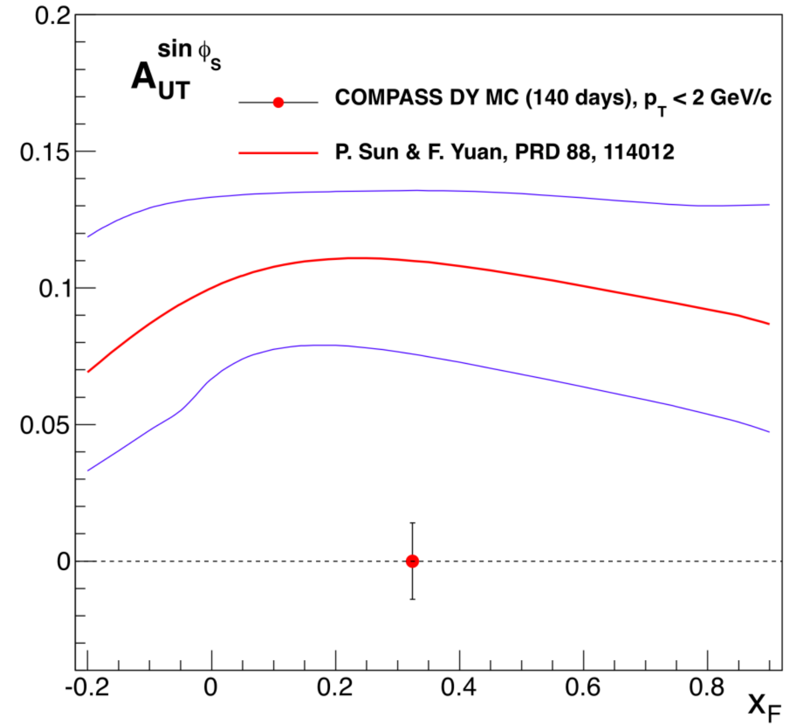


B-M & Pretz.



B-M & Transv.



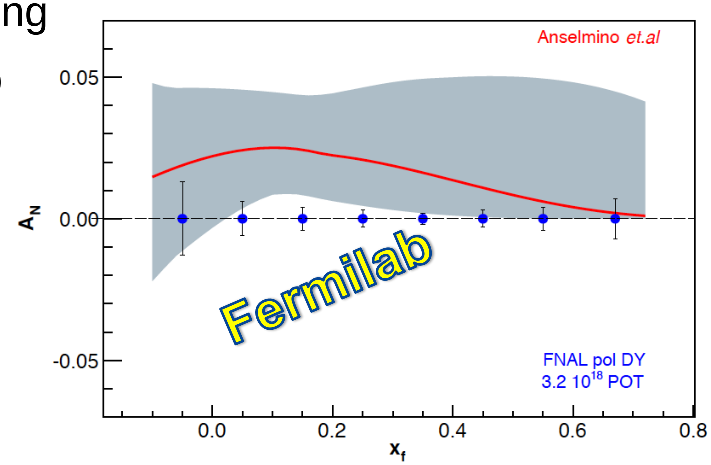


(HMR): $4. \le M_{\mu\mu} \le 9.$ GeV/c²

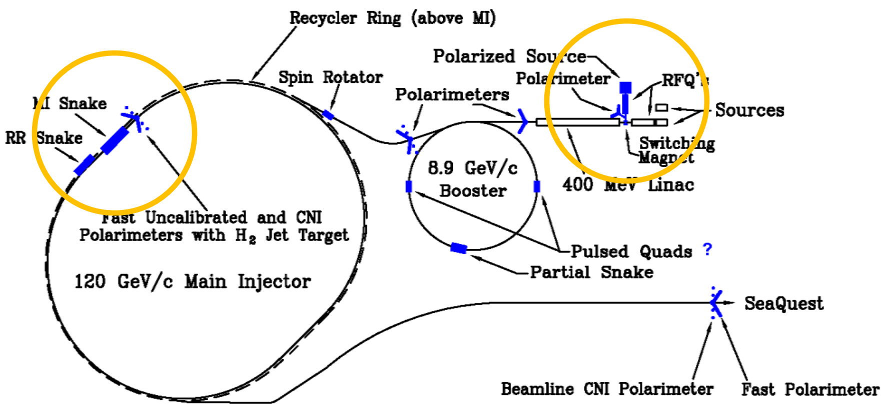
from Oleg Denisov

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



- Path to polarized proton beam at Main Injector
  - → perform detailed design studies
    - › proof that single-snake concept works
    - › applications for JPARC, NICA, ….
  - → community support
- Cost estimate to polarize Main Injector:
  - → $6M (M&S, labor), + $4M (project management & contingency)



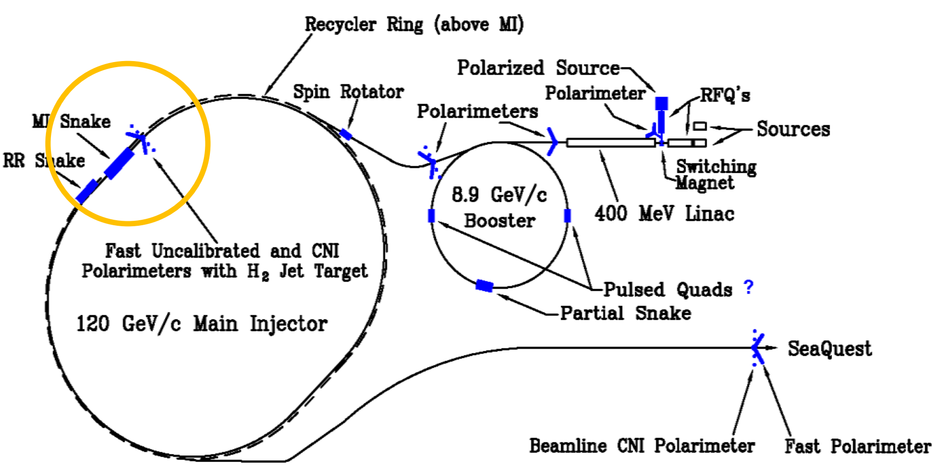
A Novel, Compact Siberian Snake for the Main Injector

Single snake design (5.8m long):

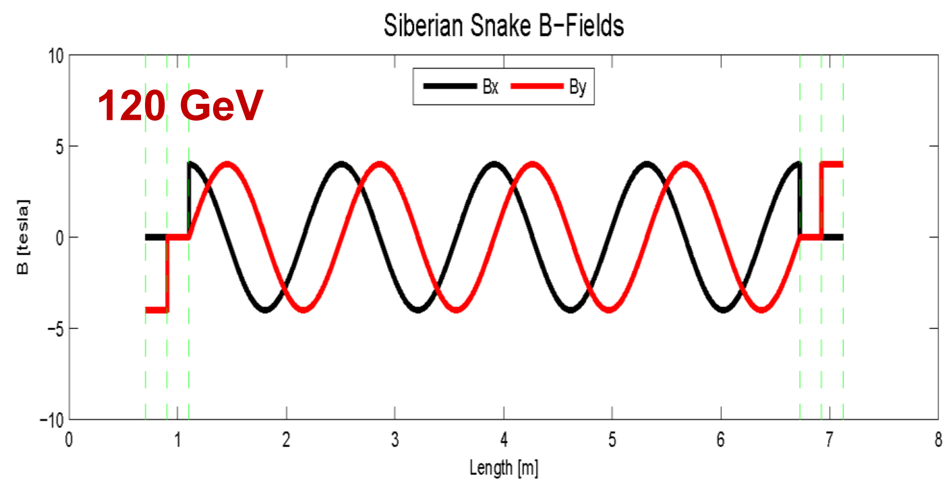
- 1 helical dipole + 2 conv. dipoles
    - helix: 4T / 4.2 m / 4” ID
    - dipoles: 4T / 0.62 m / 4” ID

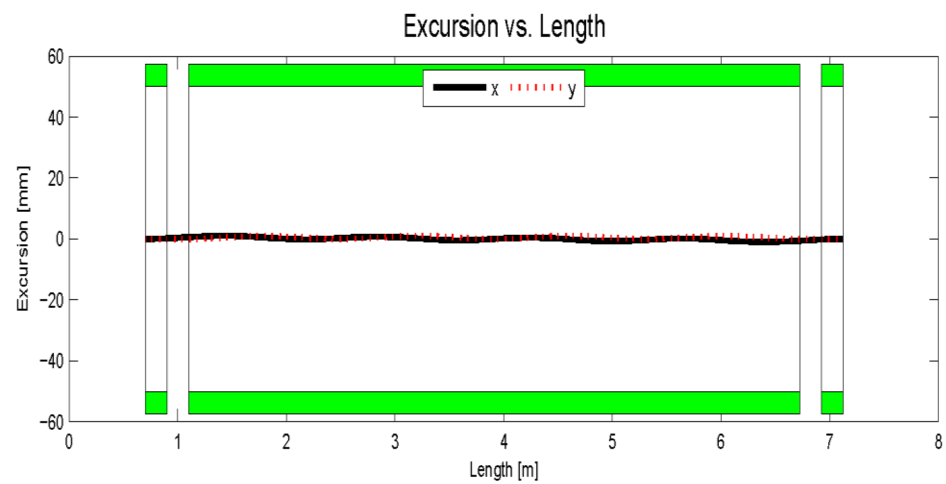
- use 4-twist magnets
    - 8π rotation of B field

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



initial design studies

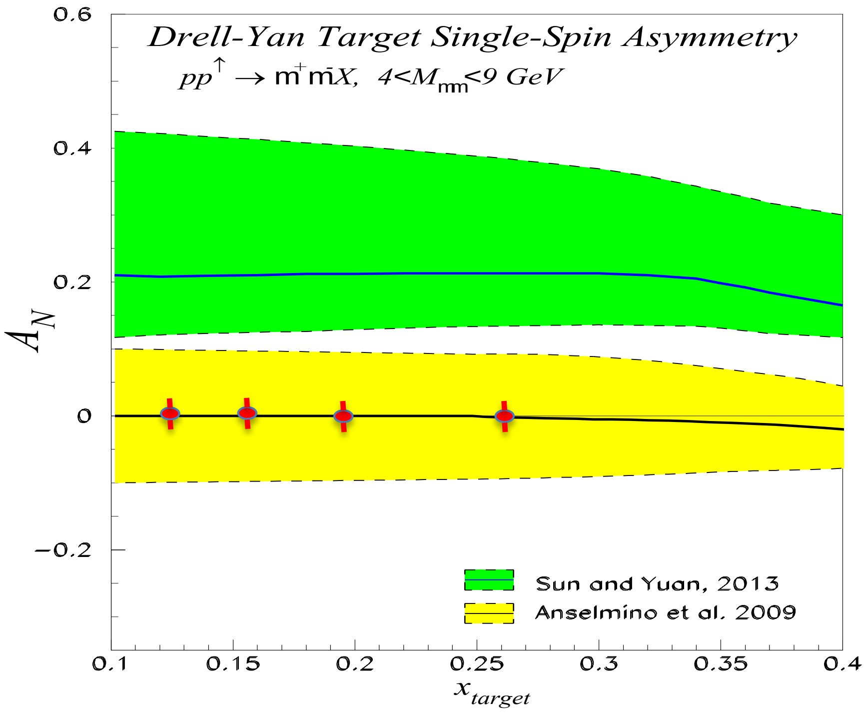




beam excursions shrink w/ beam energy

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

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



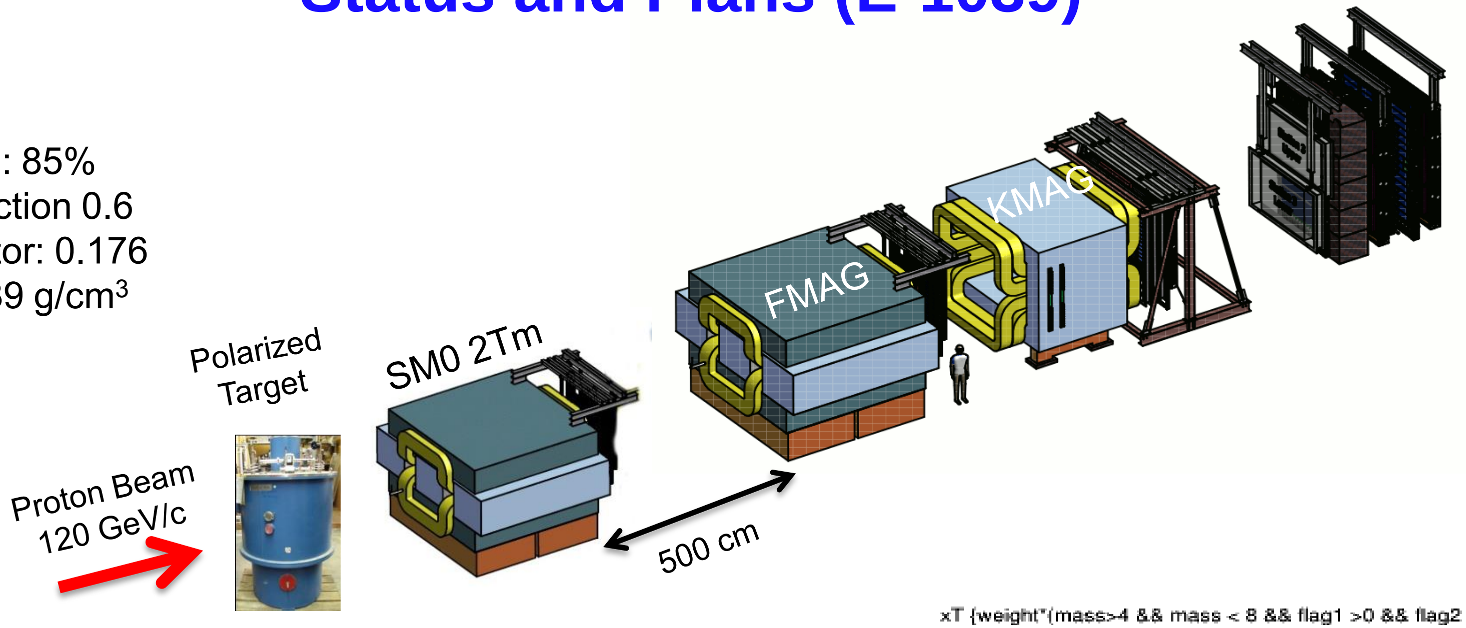
- Statistics shown for one calendar year of running:
- L = 7.2 *10^{42} /cm^2 ↔ POT = 2.8*10^{18}
- Running will be two calendar years of beam time

- 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**

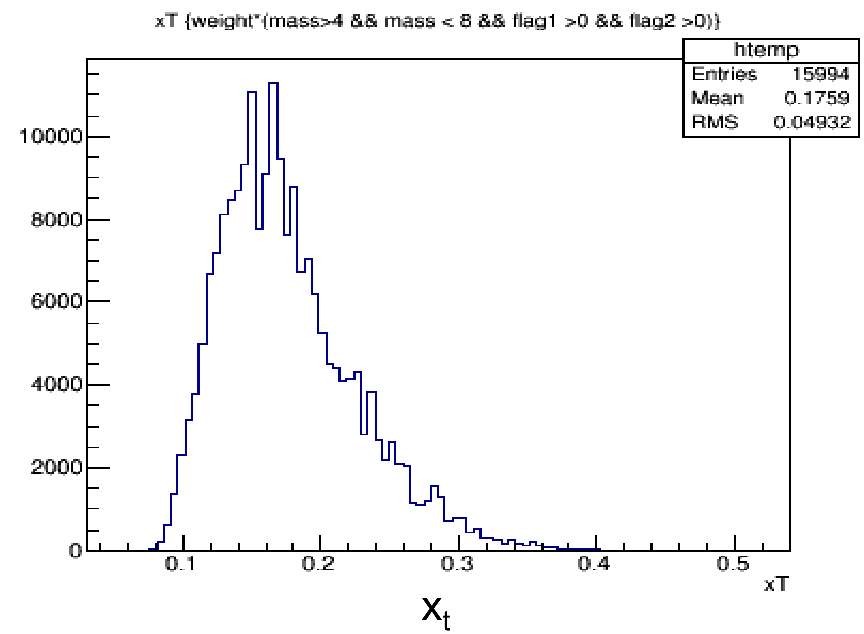
If $A_N \neq 0$, **major discovery**:
“Smoking Gun” evidence for $L_{\bar{u}} \neq 0$

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
- moves $\langle x_t \rangle$ from 0.21 to 0.176
- reduces overall acceptance
- adds shielding challenges



Ref: Andi Klein (LANL)

The Polarized Target System

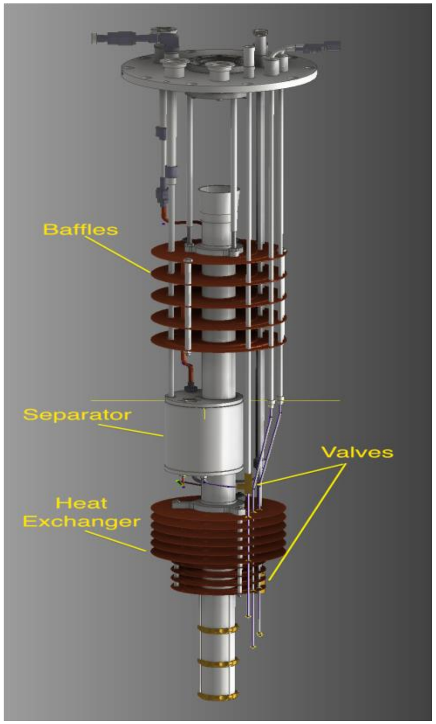
Magnet from LANL

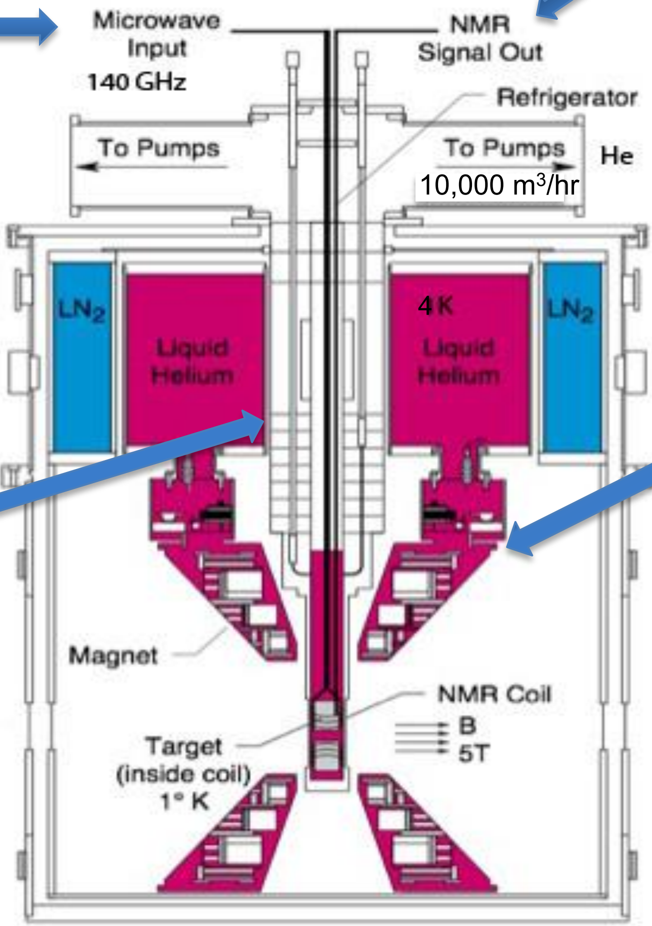
Measure polarization

Microwave: Induces electron spin flips

- Tube + Power equip:

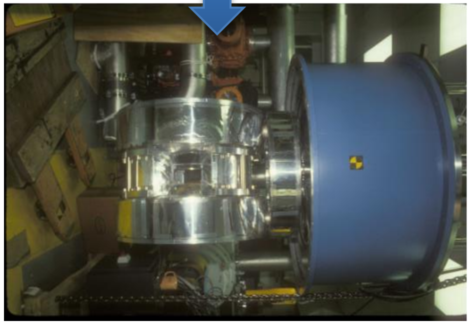
Cryostat: UVa





Roots pump system used to pump on ^{4}He vapor to reach 1K

Superconducting Coils for Magnet: 5T
Rotation needed



Target material: frozen NH_3
Irradiation @ NIST

Ref: Xiaodong Jiang (ANL)

New: compare to SIDIS unpolarised Drell-Yan with pions/kaons/antiprotons

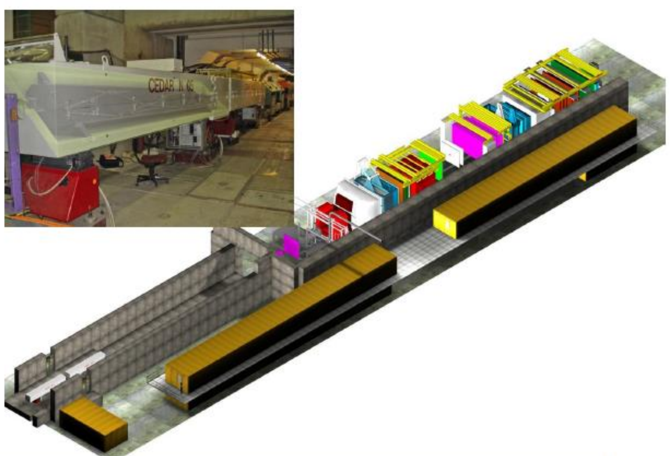
Drell-Yan gives unique additional opportunity to compare to SIDIS:

- ➡ study of unstable particle PDFs
- ➡ study of antiproton structure

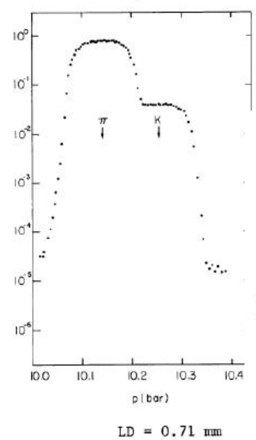
Beam PID:

CEDAR (Cerenkov Differential Counters with Achromatic Ring Focus)

π^- (96.5%), K^- (2.5%), Pbar(1%)



Improvement of CEDARs system performance for higher rate capability: "CEDARs for DY run", Ivan Gnesi in 2014 June COMPASS TB Meeting



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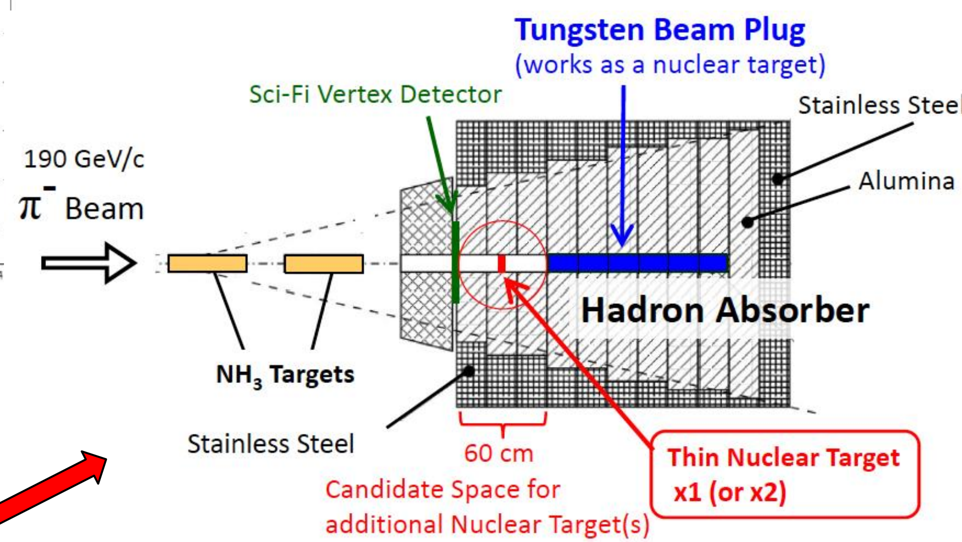


Tungsten → High Statistics
Tungsten + Thin targets → A-dependence

6

Additional nuclear target's:
- A-dependence
- Flavour separation

from Oleg Denisov

All targets: expected Drell-Yan events yields for all projectile types, comparison with the best statistics achieved so far

DY ($4 < M_{\mu\mu} < 9\ GeV/c^2$)
After 140 days data taking

Expected number of measurable DY

	NH_3	Al (7cm)	W	NA3	E537
π^- beam	285,000	55,100	549,000	21,220	
K^- beam	3,570	710	7,570	700	
$\bar{p}$ beam	2,570	450	3,640		387

COMPASS could improve the statistic of D-Y by one order of magnitude!

Beam-dependence study

$$\pi^-/K^-/\bar{p}\ \text{-}\ \mathrm{W}$$

$$\pi^-/K^-/\bar{p}\ \text{-}\ (\mathrm{W} + \mathrm{Al} + \mathrm{NH_3})$$

$$\pi^-/K^-/\bar{p}\ \text{-}\ \mathrm{NH_3}$$

Target-dependence study

$$\pi^-\ \text{-}\ \mathrm{W/Al/NH_3}$$

$$(\ K^-\ \text{-}\ \mathrm{W/NH_3}\ )$$

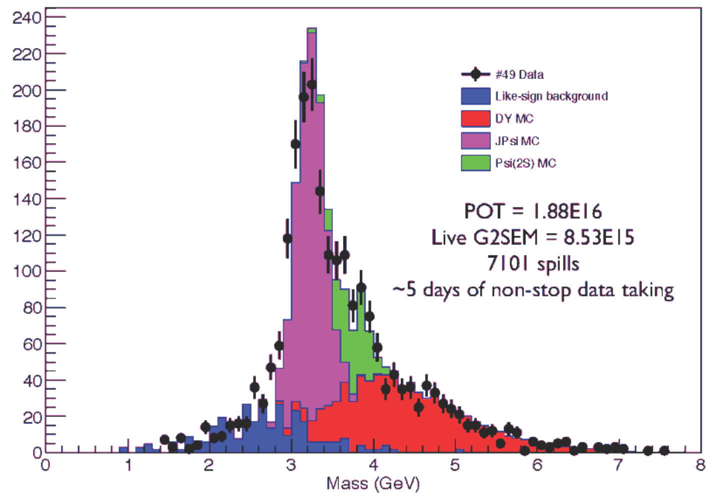
$$(\ \bar{p}\ \text{-}\ \mathrm{W/NH_3}\ )$$

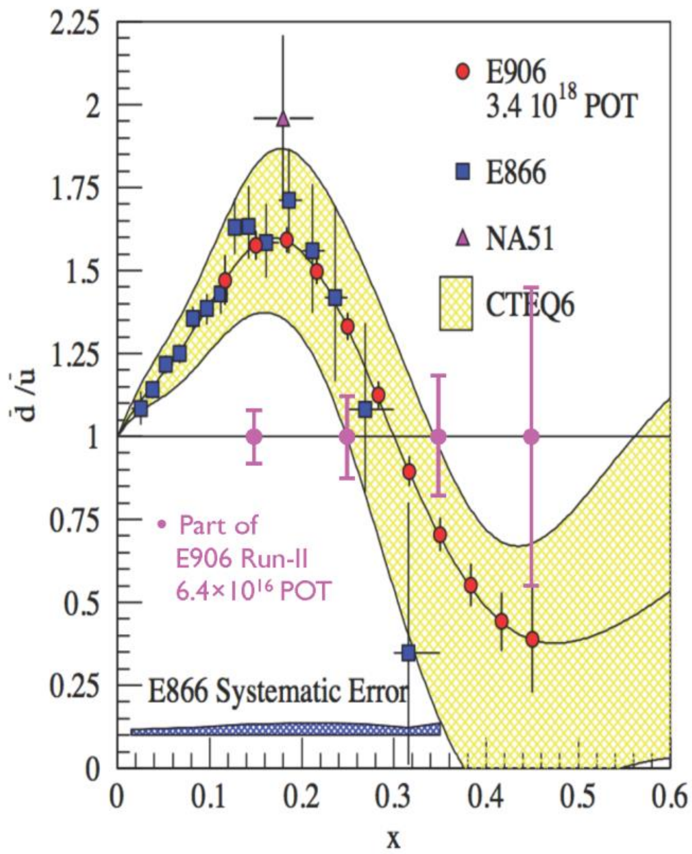
Blue Colors:
if NH_3 is possible to be treated as "nucleus"

from Oleg Denisov

SeaQuest: from Commissioning to Science

- Run I (Commissioning: late Feb. 2012 – April 30th, 2012)
- Main Injector Lumi Upgrade (16 months)
- Run II (Commissioning: Nov. ‘13 – Feb ‘14)
  (Science run: Mar ’14 – Sep ’14; 5% of POT)





- Run III: Nov ’14 – summer 2016:
- SeaQuest: expect 20x more statistics

- **Future: Polarized Drell-Yan** at Fermilab:

  ⟶ polarized **Target** [**E-1039**]: 2016 (for 2 yrs) **Stage 1 approval: July-2013**

  ⟶ polarized **Beam** [**E-1027**]: >2018 (for 2 yrs) **Stage 1 approval: Nov-2012**

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

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

  ⟶ How much do the quarks and gluons contribute to the nucleon spin?

  ⟶ Is there significant orbital angular momentum?

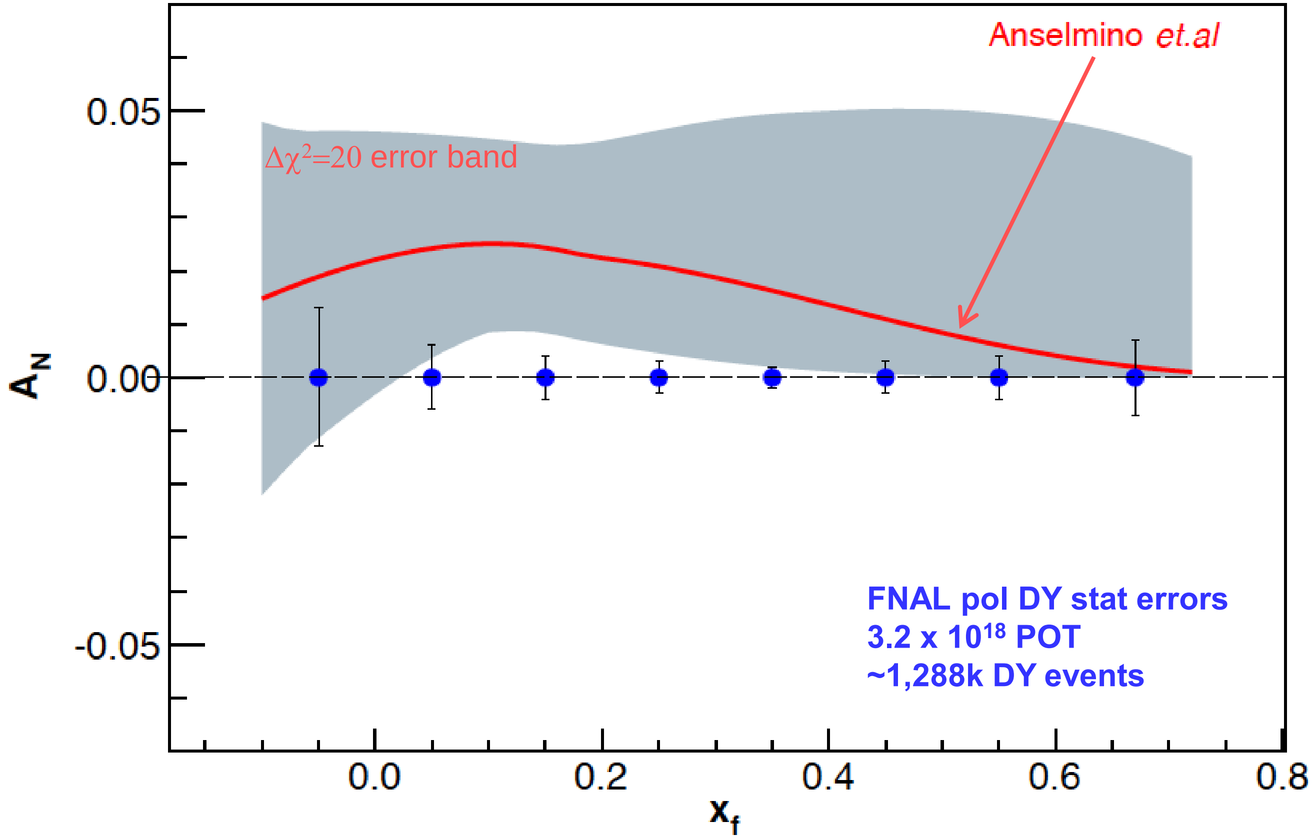
  ⟶ Does TMD formalism work? Does Sivers function change sign?

Many thanks to Oleg Denisov and John Lajoie who contributed slides

Thank You

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 at Fermilab Main Injector

- Polarized Beam in Main Injector
  - ➡ use SeaQuest target
    - ✓ liquid H_2 target can take about $I_{av} = 5 \times 10^{11}$ p/s (=80 nA)
  - ➡ 1 mA at polarized source can deliver about $I_{av} = 1 \times 10^{12}$ 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 = 1.9×10^{12} p
    - ✓ using three 2-sec cycles/min (~10% of beam time):
      → 2.8×10^{12} p/s (=450 nA) instantaneous beam current , and $I_{av} = 0.95 \times 10^{11}$ p/s (=15 nA)
  - ➡ possible scenarios:
    - ✓ $L_{av} = 2.0 \times 10^{35}$ /cm²/s (10% of available beam time: I_{av} = 15 nA)
    - ✓ $L_{av} = 1 \times 10^{36}$ /cm²/s (50% of available beam time: I_{av} = 75 nA)
  - ➡ Systematic uncertainty in beam polarization measurement (scale uncertainty)

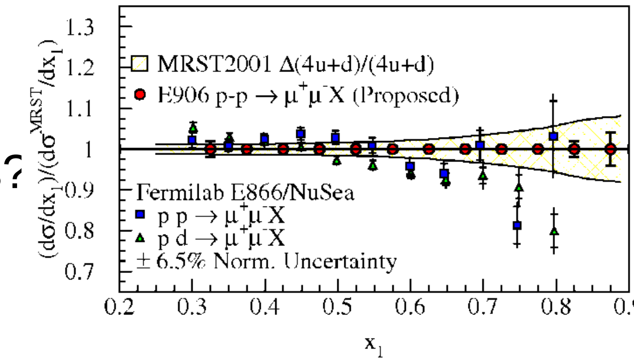
$$\Delta P_b/P_b < 5\%$$

COMPASS, E-1027, E-1039 (and Beyond)

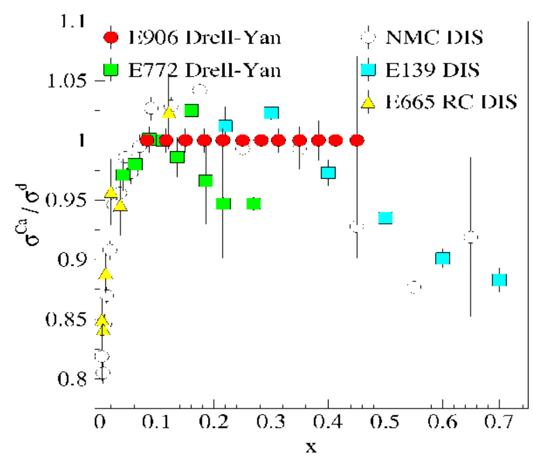
	Beam Pol.	Target Pol.	Favored Quarks	Physics Goals			
				(Sivers Function)			L_{sea}
				sign change	size	shape	
COMPASS $\pi^- p^\uparrow \to \mu^+\mu^- X$	✗	✓	**valence**	✓	✗	✗	✗
E-1027 $p^\uparrow p \to \mu^+\mu^- X$	✓	✗	**valence**	✓	✓	✓	✗
E-1039 $p\, p^\uparrow \to \mu^+\mu^- X$	✗	✓	**sea**	✗	✓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

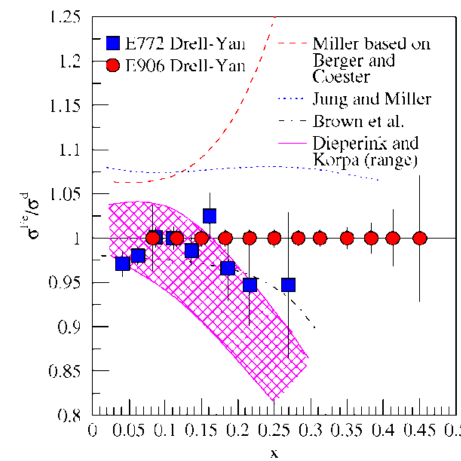
SeaQuest: what else …

- **What is the structure of the nucleon?**
  - What is $\bar{d}\,/\,\bar{u}$? What is the origin of the sea quarks?
  - What is the high x structure of the proton?



- **What is the structure of nucleonic matter?**
  - Is anti-shadowing a valence effect?
  - Where are the nuclear pions?





- ***Do colored partons lose energy in cold nuclear matter ?***
  - How large is energy loss of fast quarks in cold nuclear matter?