Polarized Drell-Yan at Fermilab

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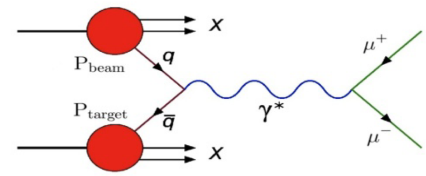
University of Michigan

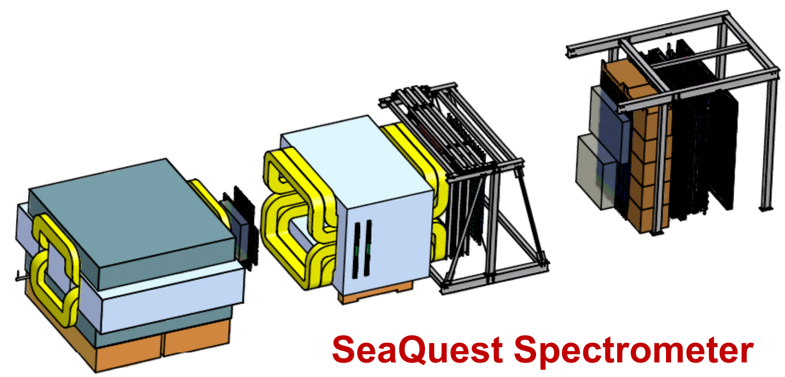
(20-May-2013)
Workshop on
Opportunities for Polarized Physics at Fermilab



- Single Spin Asymmetries and Sivers Function
- Sivers Function in Polarized Drell-Yan
  - ➡ fundamental QCD prediction:

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

- Polarized Drell-Yan at Fermilab
  - ➡ polarized Beam or Target
- Main Injector Polarization Scheme

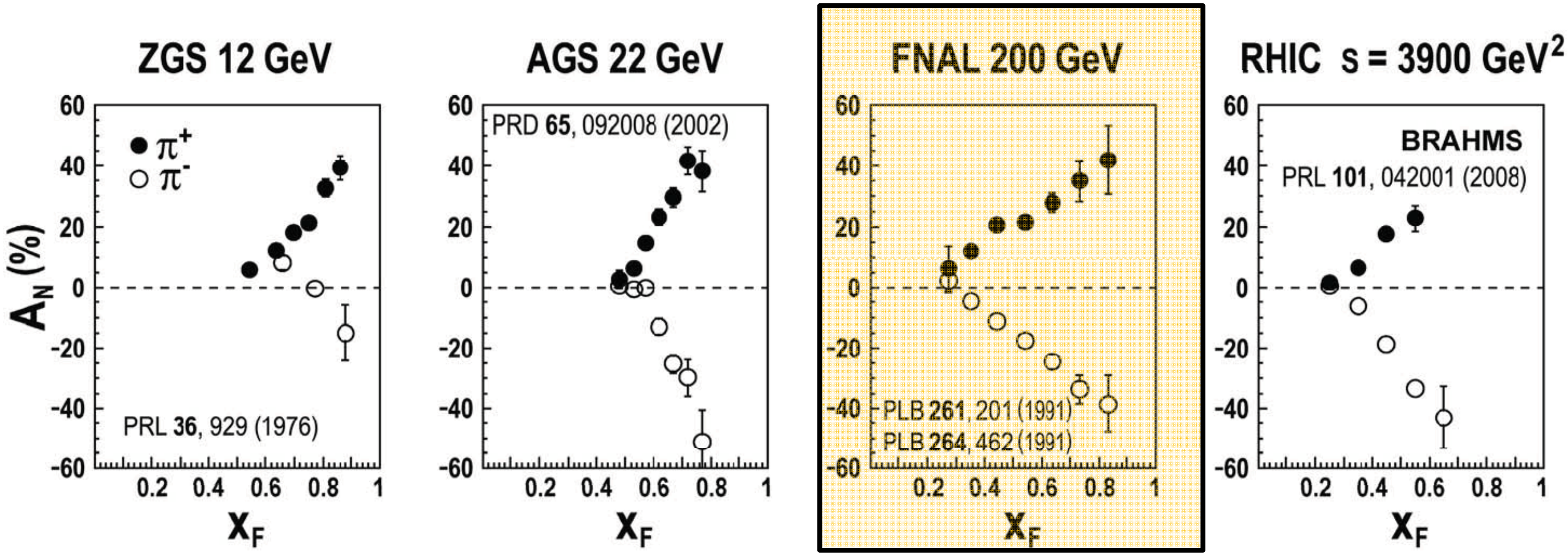


SeaQuest Spectrometer

This work is supported by

Single Spin Asymmetries in $p^{\uparrow}p \rightarrow \pi X$

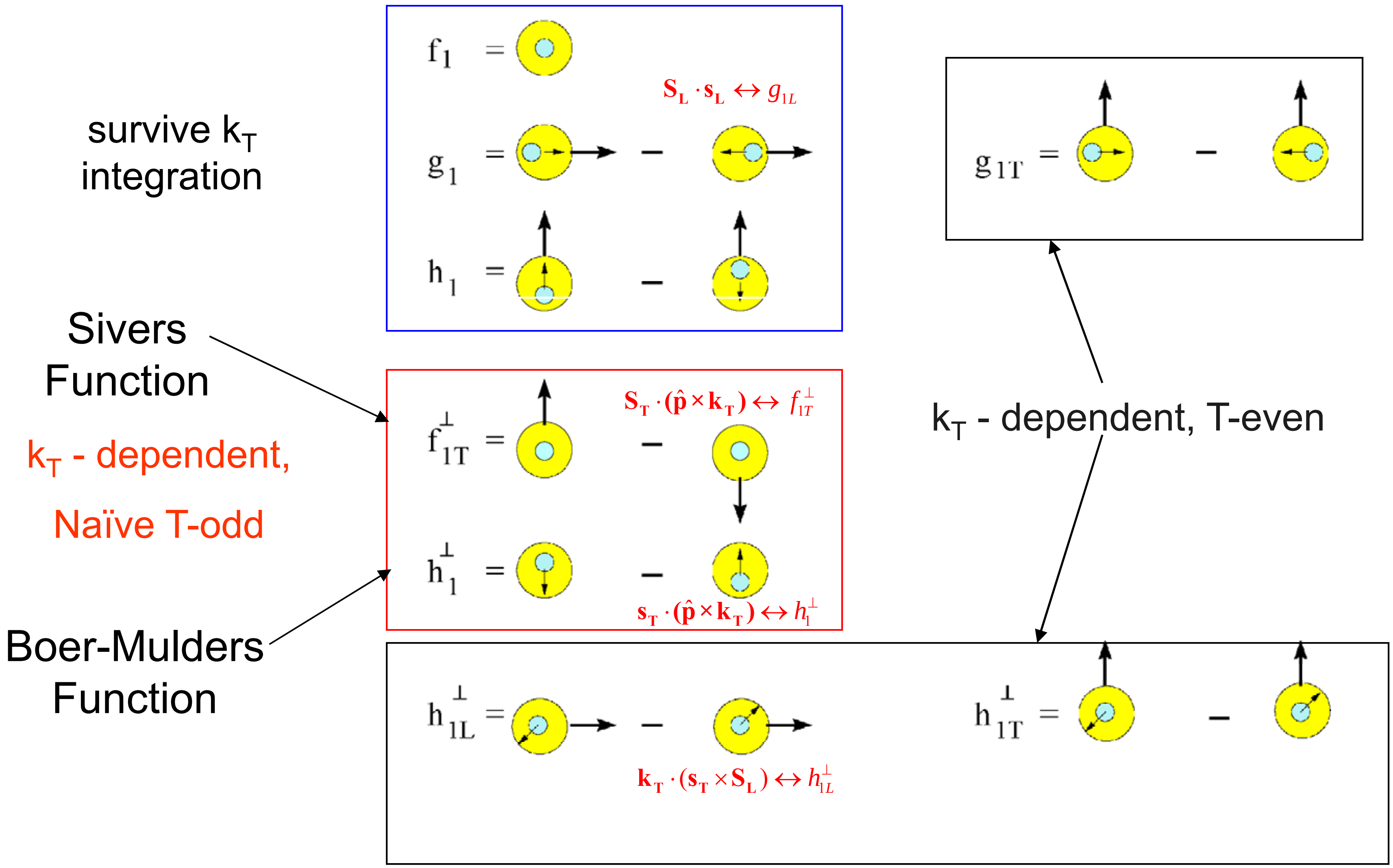
- (huge) single spin asymmetries for forward meson production in hadron-hadron interactions have been observed over a wide range of c.m. energies



C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009

- "E704 effect":
  - ➡ polarized beam at Fermilab (tertiary beam from production & decay of hyperons)
  - ➡ beam intensity too low for DY
- possible explanation for large inclusive asymmetries:
  - ➡ Sivers distribution function, or Collins fragmentation function

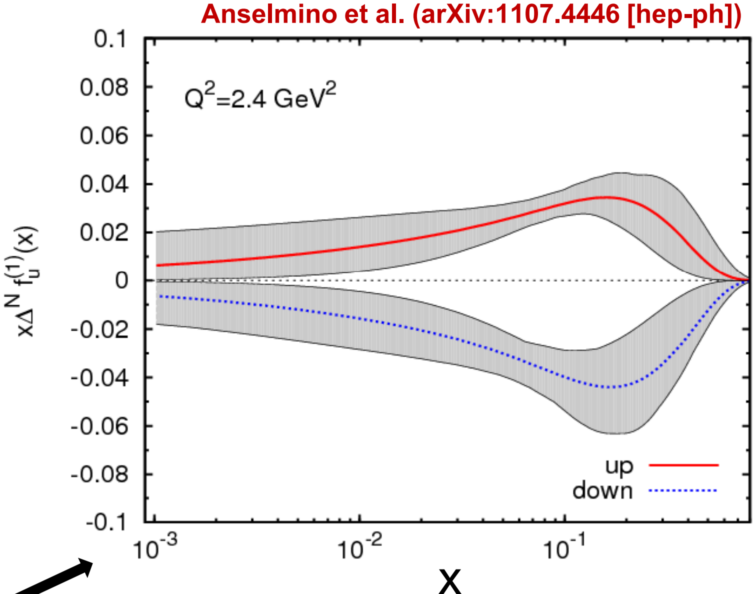
Transverse Momentum Distributions (Introduction)



Sivers Function

- 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])

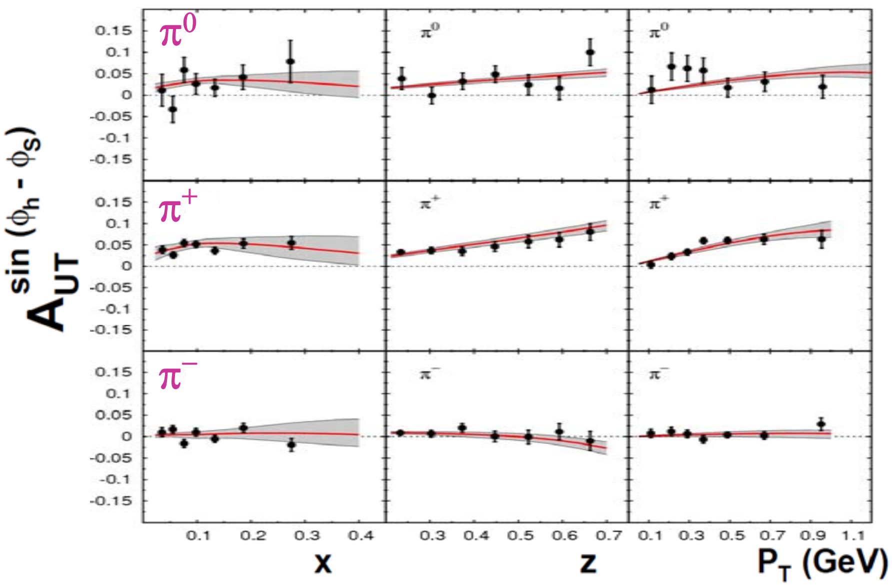


First moment of Sivers functions:

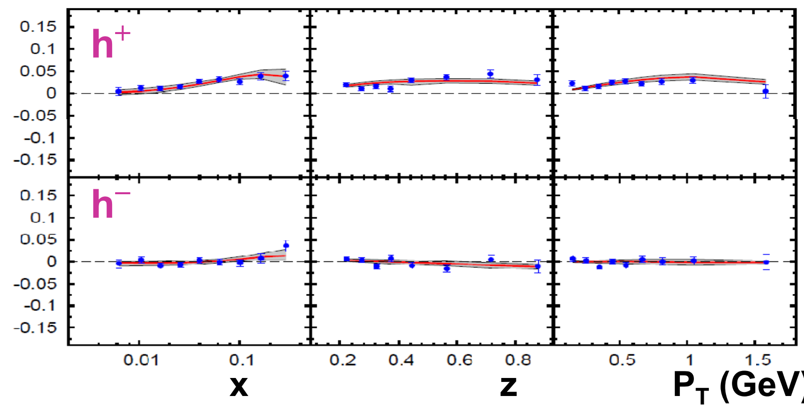
➡ u- and d- Sivers have opposite signs, of roughly equal magnitude

Sivers Asymmetry in SIDIS

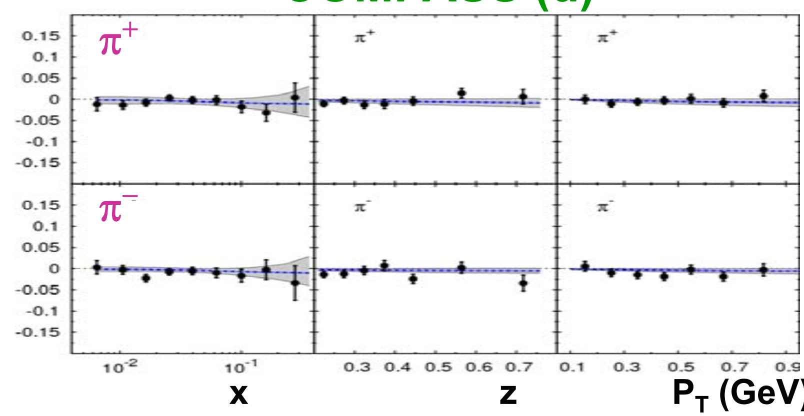
HERMES (p)



COMPASS (p)



COMPASS (d)



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

Comparable measurements needed in Drell-Yan process

Polarized Drell-Yan Experiment

NOT YET DONE!

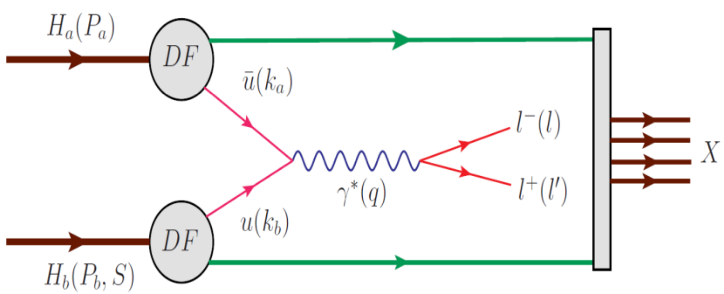
- Access to transverse-momentum dependent distribution (TMD) functions
  - → Sivers, Boer-Mulders, etc
- Transversely Polarized Beam or Target
  - → Sivers function in single-transverse spin asymmetries (sea quarks or valence quarks)
    - – valence quarks constrain SIDIS data much more than sea quarks
    - – global fits indicate that sea quark Sivers function is small
  - → transversity $\otimes$ Boer-Mulders function
  - → baryon production, incl. pseudoscalar and vector meson production, elastic scattering, two-particle correlations, J/ψ and charm production
- Beam and Target Transversely Polarized
  - → flavor asymmetry of sea-quark polarization
  - → transversity (quark $\otimes$ anti-quark for pp collisions)
    - – anti-quark transversity might be very small

Drell Yan Process

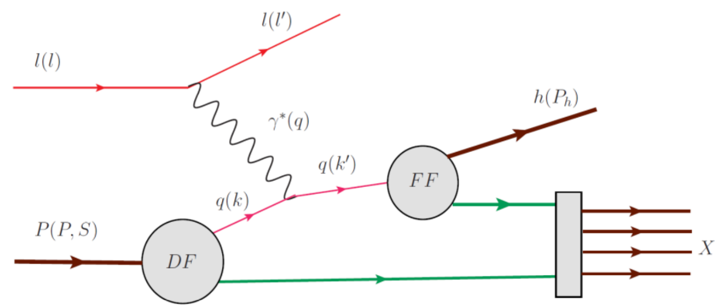
- Similar Physics Goals as SIDIS:
  - ➡ parton level understanding of nucleon
  - ➡ electromagnetic probe

    timelike (Drell-Yan) vs. spacelike (SIDIS) virtual photon

Drell-Yan



SIDIS



A. Kotzinian, DY workshop, CERN, 4/10

- Cleanest probe to study hadron structure:
  - ➡ hadron beam and convolution of parton distributions
  - ➡ no QCD final state effects
  - ➡ no fragmentation process
  - ➡ ability to select sea quark distribution
  - ➡ allows direct production of transverse momentum-dependent distribution (TMD) functions (Sivers, Boer-Mulders, etc)

Leading order DY Cross Section

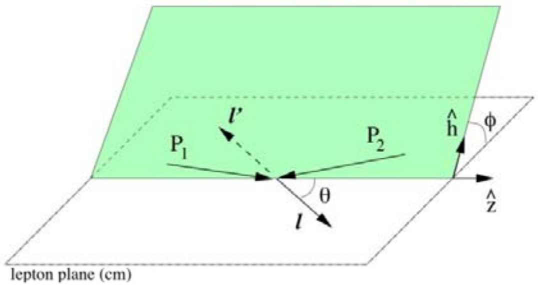
- DY cross section at LO:

$$\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha^2}{4q^2\sqrt{(P_b\cdot P_t)^2 - M_p^2}}$$

$$\Big\{ \Big[(1+\cos^2\theta)\,F_{UU}^1 + (1-\cos^2\theta)\,F_{UU}^2 + \sin 2\theta\cos\phi\,F_{UU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{UU}^{\cos 2\phi} \Big]$$

$$+\; S_L \Big[\sin 2\theta \sin\phi\,F_{LU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{LU}^{\sin 2\phi} \Big]$$

$$+\; S_T \Big[\sin\phi_b \Big((1+\cos^2\theta)\,F_{TU}^1 + (1-\cos^2\theta)\,F_{TU}^2 + \sin 2\theta\cos\phi\,F_{TU}^{\cos\phi} + \sin^2\theta\cos 2\phi\,F_{TU}^{\cos 2\phi} \Big) + \cos\phi_b \Big(\sin 2\theta\sin\phi\,F_{TU}^{\sin\phi} + \sin^2\theta\sin 2\phi\,F_{TU}^{\cos 2\phi} \Big) \Big] \Big\}$$



Sivers Mechanism

Sivers function

$$F_{TU}^1 = -\mathcal{C}\left[\frac{\mathbf{q}_T\cdot\mathbf{k}_{T,b}}{q_T M_p} f_{1T}^{\perp}(x_b,\mathbf{k}_{T,b}^2)\, \bar{f}_1(x_t,\mathbf{k}_{T,t}^2) \right]$$

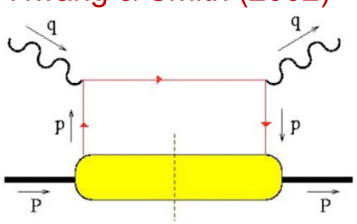
➡ with the asymmetry amplitude:

$$A_{TU}^{\sin\phi_b} = \frac{F_{TU}^1}{F_{UU}^1}$$

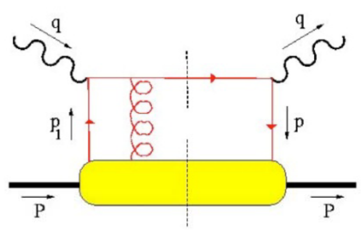
Sivers Function

- T-odd observables
  - ➡ SSA observable $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$ odd under naïve Time-Reversal
  - ➡ since QCD amplitudes are T-even, must arise from interference (between spin-flip and non-flip amplitudes with different phases)
- Cannot come from perturbative subprocess xsec at high energies:
  - ➡ q helicity flip suppressed by $m_q / \sqrt{s}$
  - ➡ need α_s suppressed loop-diagram to generate necessary phase
  - ➡ at hard (enough) scales, SSA's must arise from soft physics
- A T-odd function like $f_{1T}^{\perp}$ must arise from interference (How?)

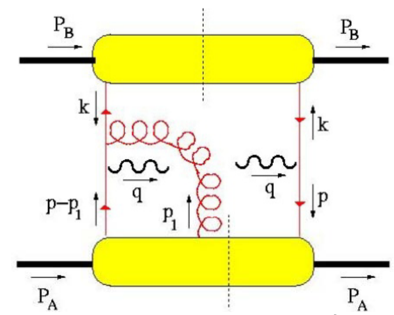
Brodsky, Hwang & Smith (2002)



can interfere with



and produce a T-odd effect!
(also need $L_z \neq 0$)



e.g. Drell-Yan)

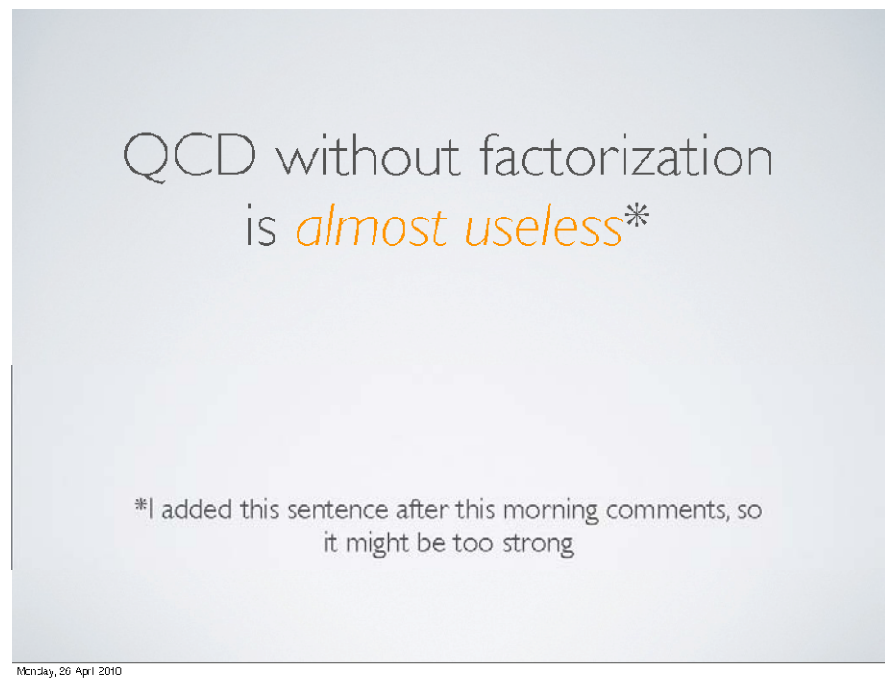
- ➡ soft gluons: "gauge links" required for color gauge invariance
- ➡ such soft gluon re-interactions with the soft wavefunction are final (or initial) state interactions … and maybe process dependent!
- ➡ leads to sign change: $f_{1T}^{\perp}\Big|_{SIDIS} = - f_{1T}^{\perp}\Big|_{DY}$

Sivers in Drell-Yan vs SIDIS: The Sign Change

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

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

- Importance of factorization in QCD:



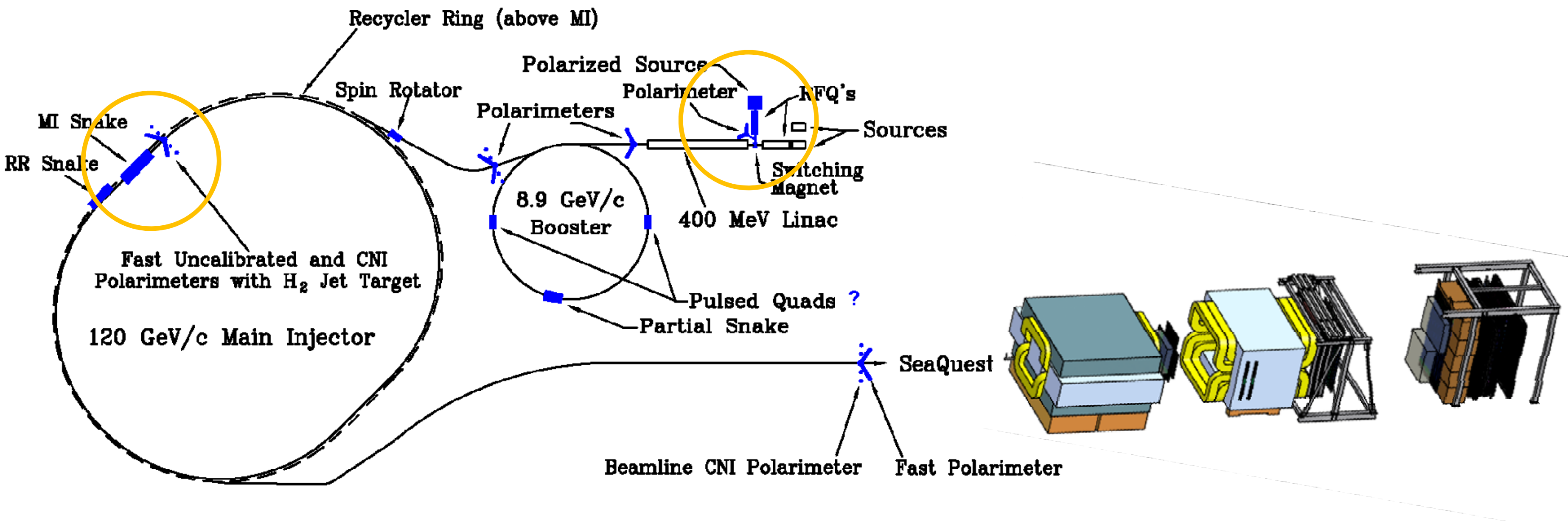
A. Bacchetta , DY workshop, CERN, 4/10

Planned Polarized Drell-Yan Experiments

experiment	particles	energy	x_b or x_t	Luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	x_t = 0.2 – 0.3	2×10^{33} cm^{-2} s^{-1}	2014, 2018
PAX (GSI)	$p^{\uparrow} + p_{bar}$	collider $\sqrt{s}$ = 14 GeV	x_b = 0.1 – 0.9	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$p_{bar} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	x_t = 0.2 – 0.4	2×10^{32} cm^{-2} s^{-1}	>2016
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	x_b = 0.1 – 0.8	1×10^{30} cm^{-2} s^{-1}	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	x_b = 0.05 – 0.1	2×10^{32} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	x_b = 0.25 – 0.4	2×10^{33} cm^{-2} s^{-1}	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	x_b = 0.25 – 0.4	6×10^{34} cm^{-2} s^{-1}	>2018
SeaQuest (unpol.) (FNAL)	$p + p$	120 GeV $\sqrt{s}$ = 15 GeV	x_b = 0.35 – 0.85 x_t = 0.1 – 0.45	3.4×10^{35} cm^{-2} s^{-1}	2012 - 2015
polDY§ (FNAL)	$p^{\uparrow} + p$	120 GeV $\sqrt{s}$ = 15 GeV	x_b = 0.35 – 0.85	2×10^{35} cm^{-2} s^{-1}	>2016
	§ 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)				

Polarized Drell-Yan at Fermilab Main Injector

- Polarize Beam in Main Injector & use SeaQuest di-muon spectrometer
  - ➡ measure Sivers asymmetry



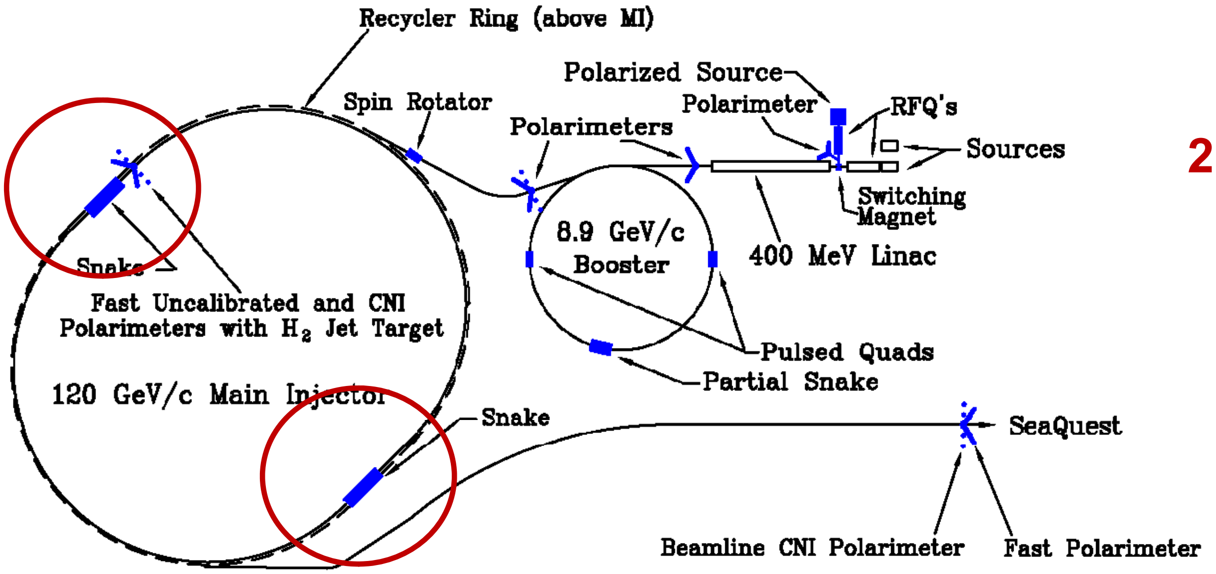
- SeaQuest di-muon Spectrometer
  - ➡ fixed target experiment, optimized for Drell-Yan
  - ➡ luminosity: $L_{av} = 3.4 \times 10^{35}$ /cm^2/s
    - ⟶ $I_{av} = 1.6 \times 10^{11}$ p/s (=26 nA) / $N_p = 2.1 \times 10^{24}$ /cm^2
  - ➡ approved for 2-3 years of running: 3.4×10^{18} pot
  - ➡ by 2015: fully understood, ready to take pol. beam

Polarized Drell-Yan at Fermilab Main Injector - II

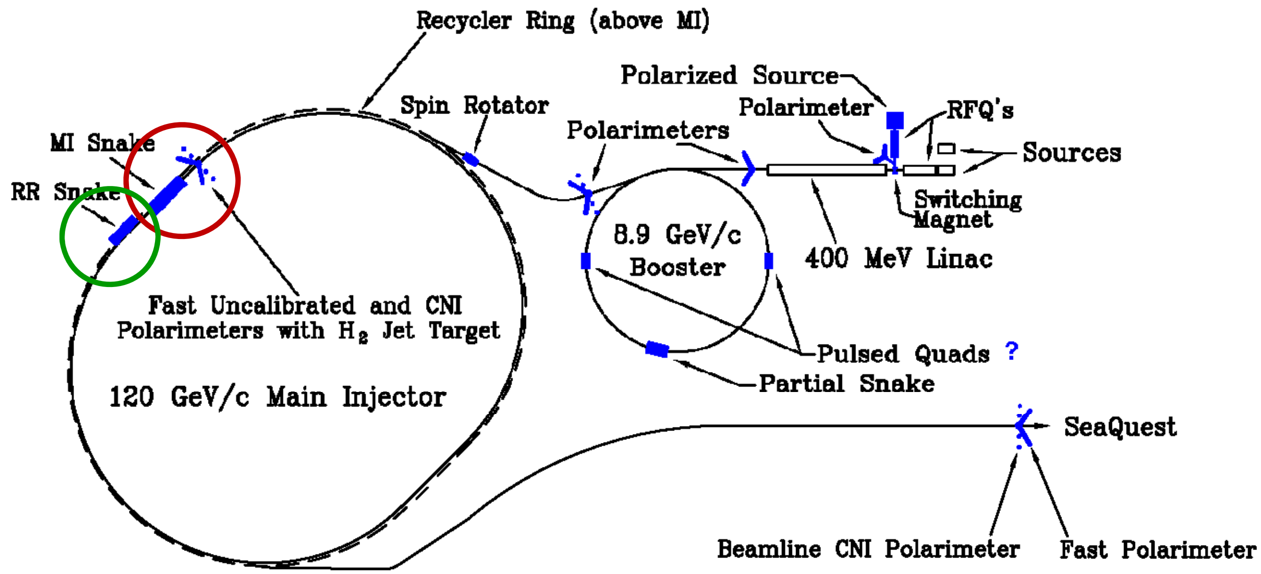
- Polarized Beam in Main Injector
  - ➡ use SeaQuest target
    - ✓ liquid H_2 target can take about I_{av} = 5 x 10^{11} p/s (=80 nA)
  - ➡ 1 mA at polarized source can deliver about I_{av} = 1 x 10^{12} p/s (=150 nA) for 100% of available beam time *(A. Krisch: Spin@Fermi report in (Aug 2011): arXiv:1110.3042 [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} /cm²/s (10% of available beam time: I_{av} = 15 nA)
    - ✓ L_{av} = 1 x 10^{36} /cm²/s (50% of available beam time: I_{av} = 75 nA)
  - ➡ Systematic uncertainty in beam polarization measurement (scale uncertainty)

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

From 2 Siberian Snakes to 1 Snake



2 Siberian Snakes in MI
(not enough space)



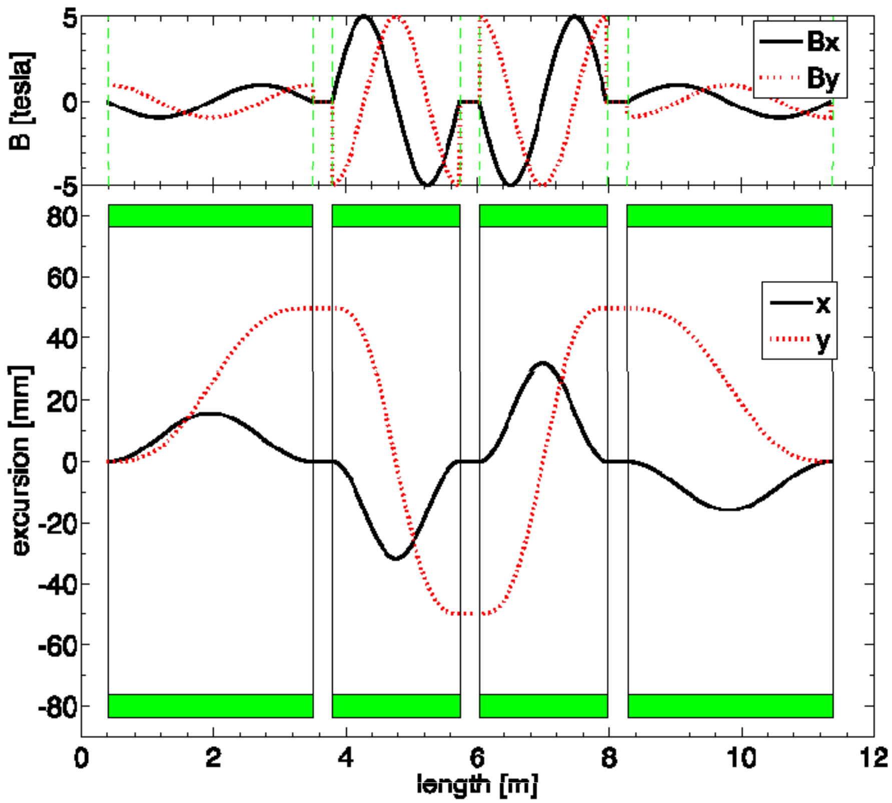
1 Siberian Snake in MI
(fits well)
plus 1 solenoid snake in RR

From 2 Siberian Snakes to 1 Snake - II

2-snake design (11m long):

- 4 helical dipoles / snake
  - 2 helices: 5T / 3.1m / 6” ID
  - 2 helices : 5T / 2.1m / 6” ID (**cold**)

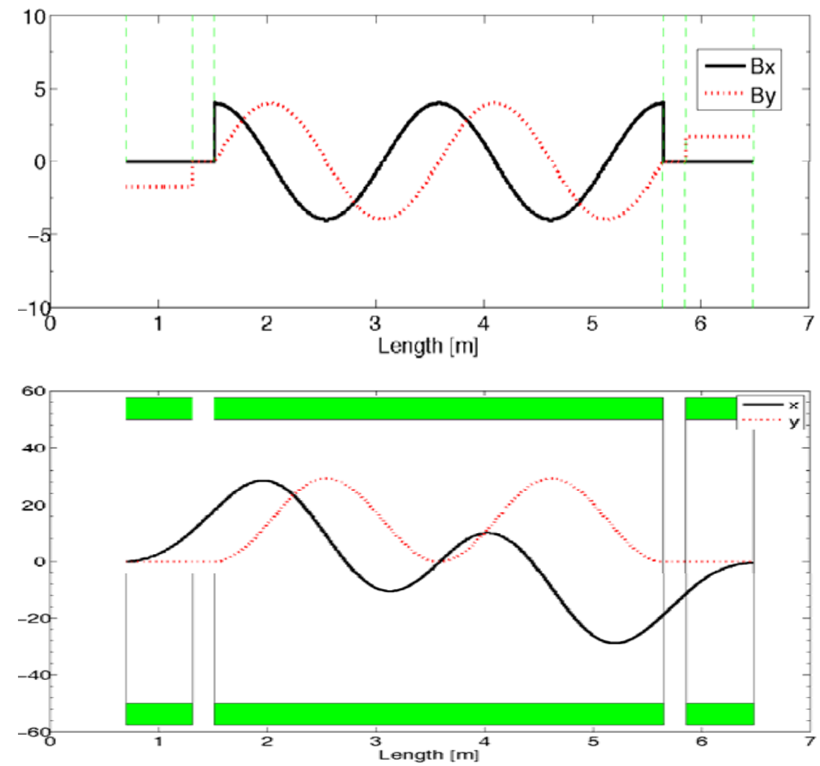
does not fit



1-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 (**warm**)

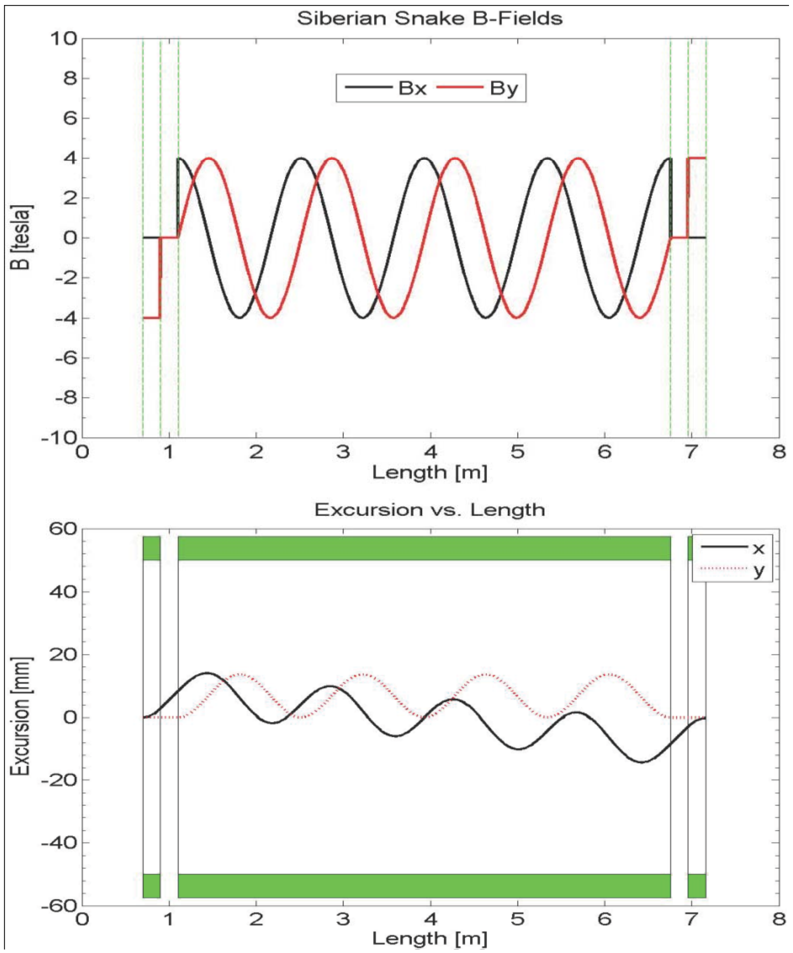
fits



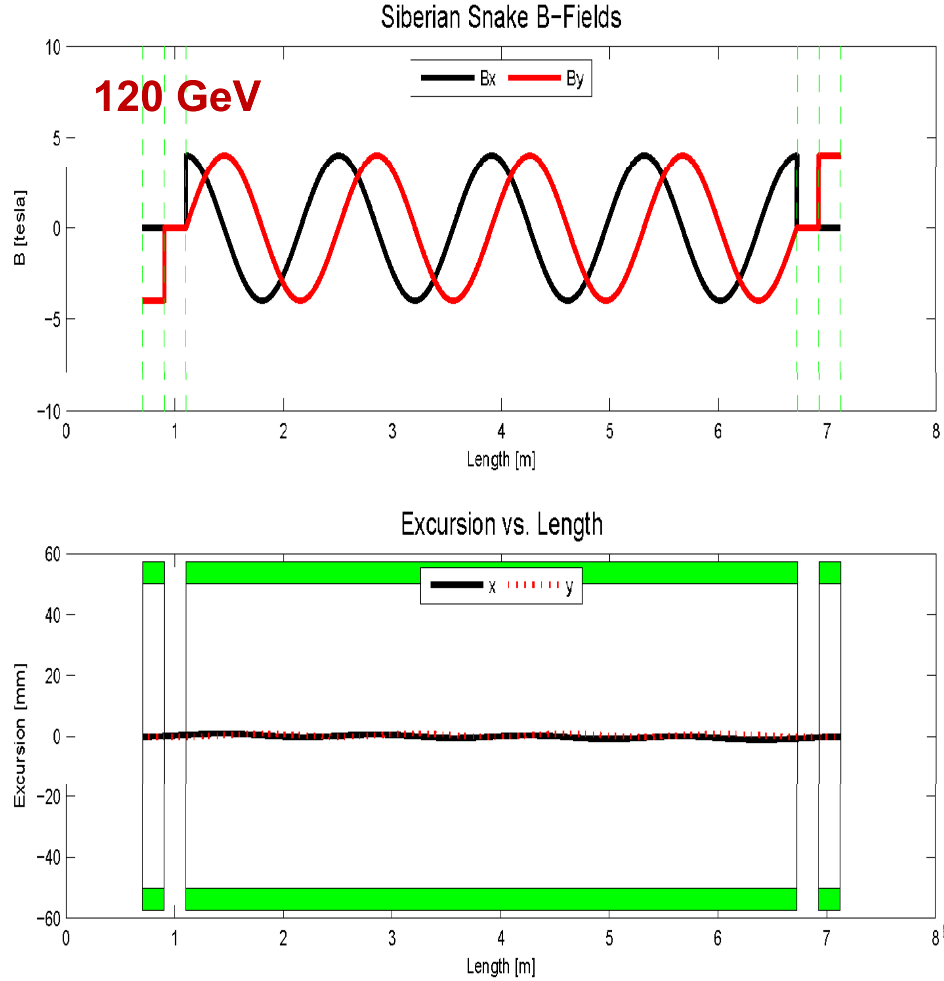
T. Roser (BNL):
- test snakes/rotators up to 5.4T
- operation not above 4T

Steady Improvements to 1 Snakes solution

8.9 GeV 4T



4-twist 4T

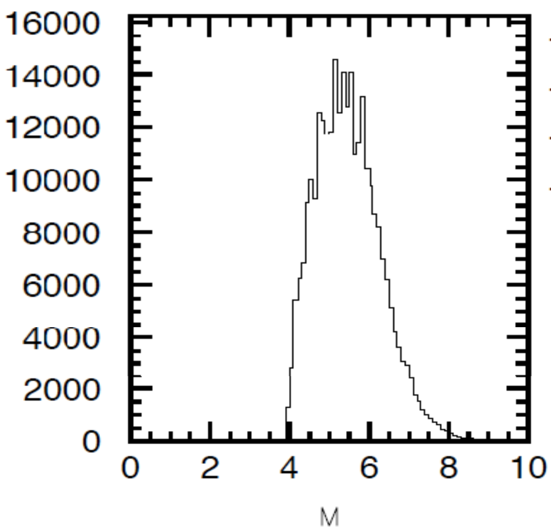


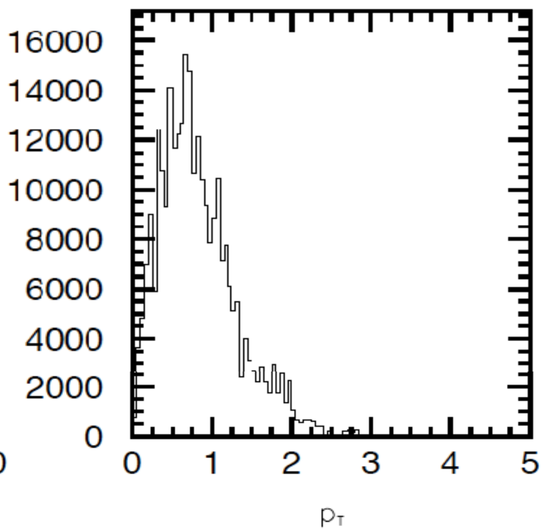
beam excursions shrink w/
number of twists

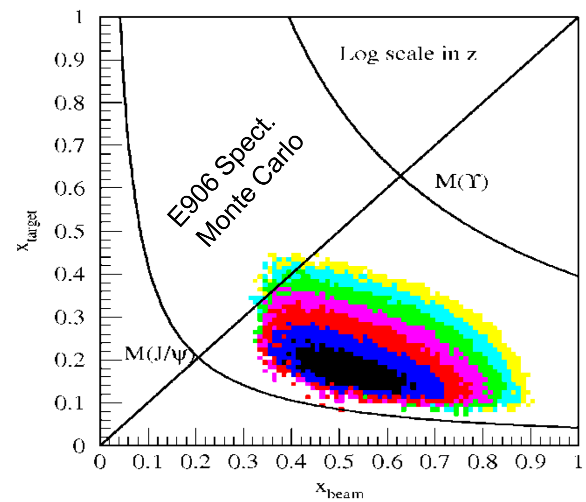
beam excursions shrink w/
beam energy

Acceptance for Polarized Drell-Yan - I

- x-range: x_b = 0.35 – 0.85 (valence quarks in proton beam)
  x_t = 0.1 – 0.45 (sea quarks in proton target)
- Invariant mass range: M = 4 – 8.5 GeV (avoid J/Ψ contamination)
- Transverse momentum: p_T = 0 – 3 GeV







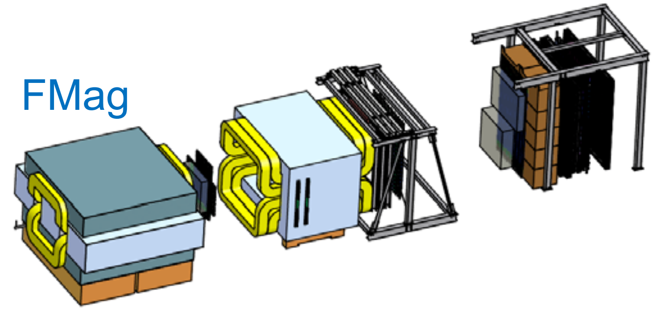
Measurement at Fermilab Main Injector

- Retune 1st spectrometer magnet (FMag):

➡ focuses high p_T muons and over focuses low p_T muons

⟶ we loose low p_T muons when field is high!

⟶ SeaQuest is all about going to the largest x_t quarks, requiring high-p_T muons



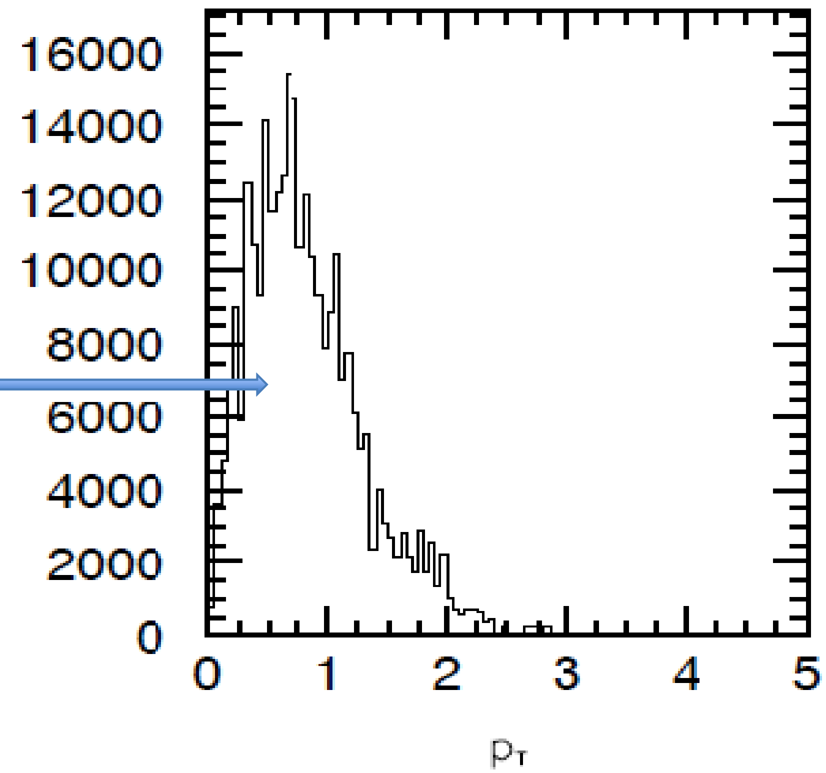
➡ Lowering FMag field

⟶ we get back the low p_T muons

⟶ we loose the high low p_T muons

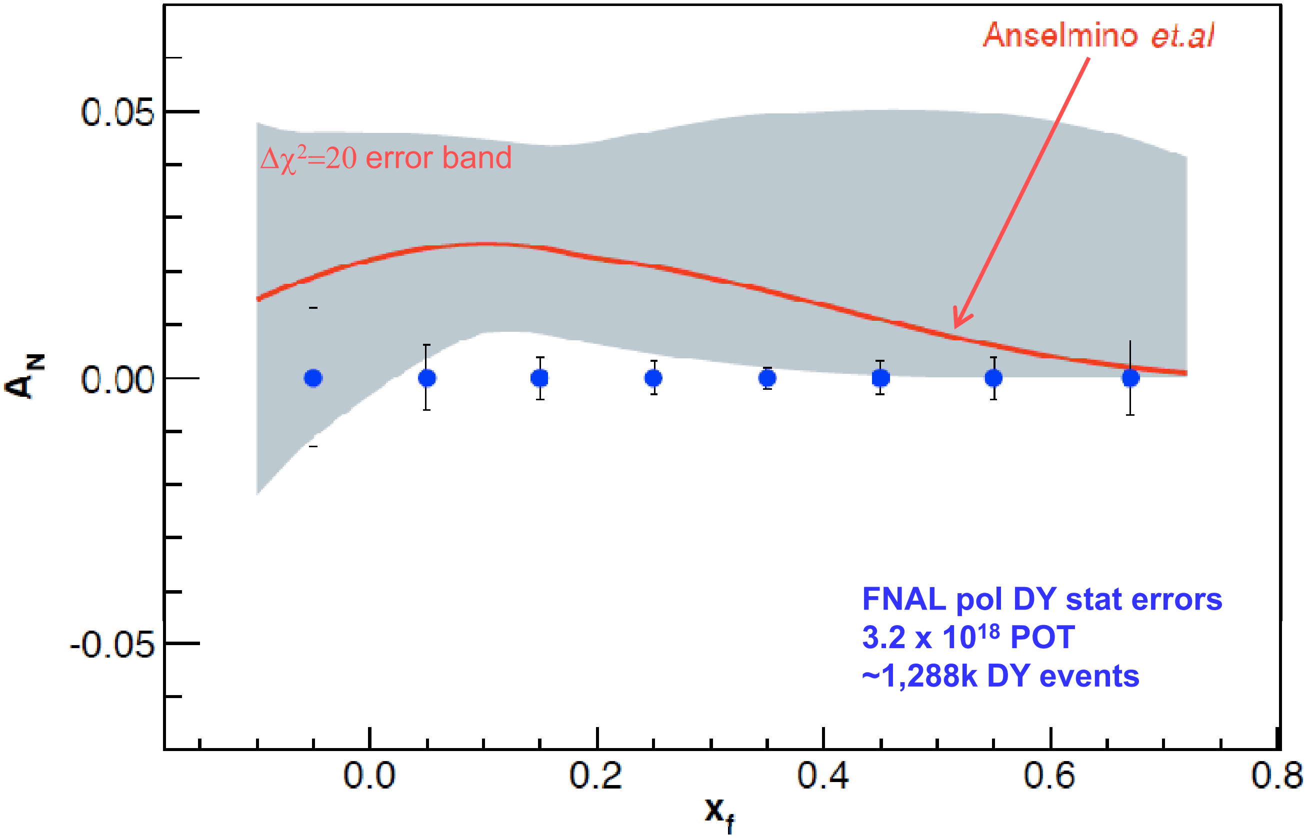
BUT

p_T spectrum peaks at low p_T



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 = 70%



Note:

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

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

E-1027 Collaboration (May 2013)

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Gunar Schnell

*Co-Spokespersons
†new group (Aug'12)

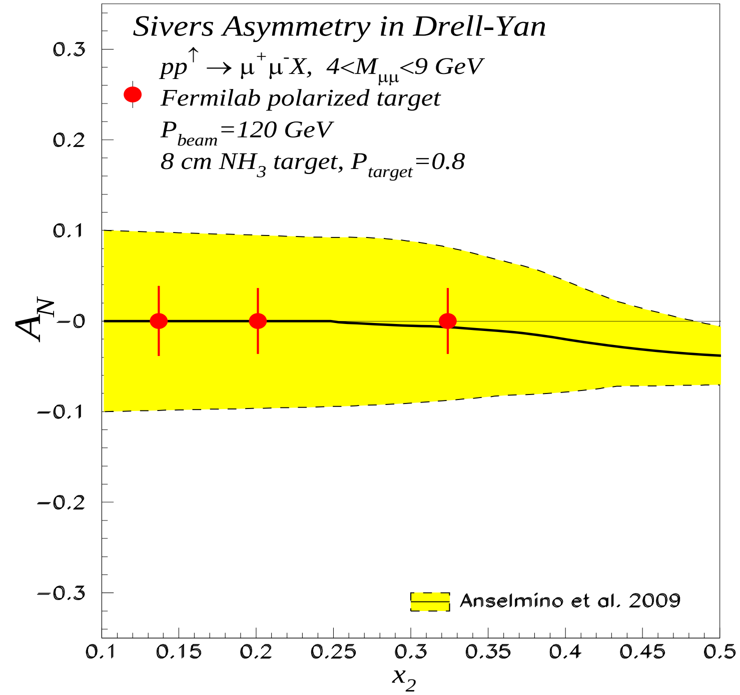
Collaboration contains most of the E-906/SeaQuest groups and one new group (total 16 groups as of May 2013)

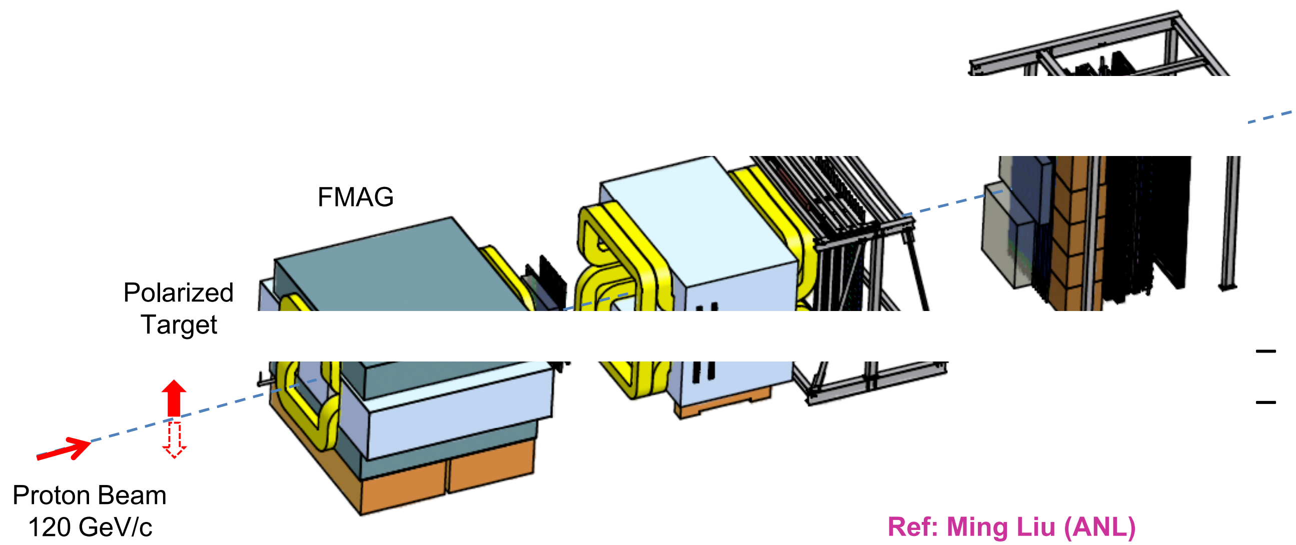
E-1027 collaboration working closely with SPIN@FERMI collaboration

Polarized Target at Fermilab

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

  – sea-quark Sivers function poorly known
  – significant Sivers asymmetry expected from meson-cloud model





– use current SeaQuest setup
– a polarized proton target, unpolarized beam

Ref: Ming Liu (ANL)

The Path to a polarized Main Injector

Stage 1 approval from Fermilab: 14-November-2012

- 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
- Develop proposal to DoE NP/HEP to polarize the Main Injector
  - ➡ Cost to polarize Main Injector $10M
    - ⟶ includes 15% project management & 50% contingency
  - ➡ secure funding to
    - ⟶ do detailed design: $200k/yr (short-term)
    - ⟶ implement modifications to MI: $10M (longer-term)
    - ⟶ conversations with DoE NP & HEP, NSF NP have started

Summary

- A non-zero Sivers asymmetry has been measured both at HERMES and COMPASS
- QCD (and factorization) require sign change

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

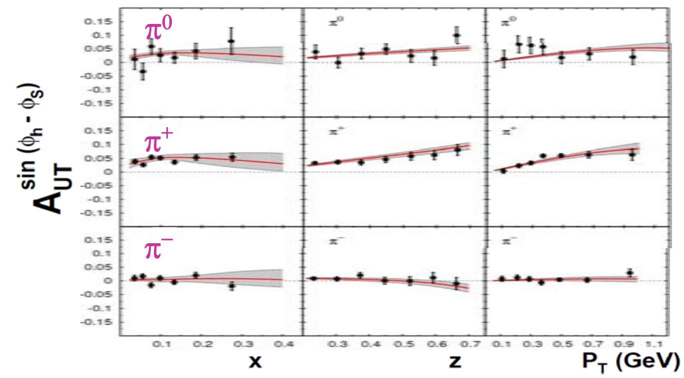
- Fermilab is arguably best place to do this measurement

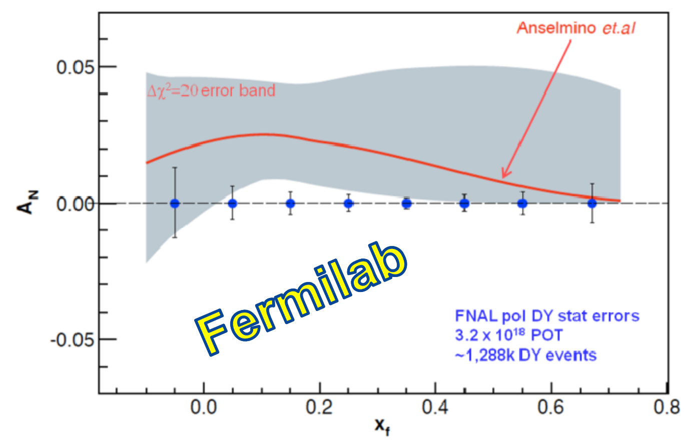
  $\longrightarrow$ high luminosity, large x-coverage, high-intensity polarized beam

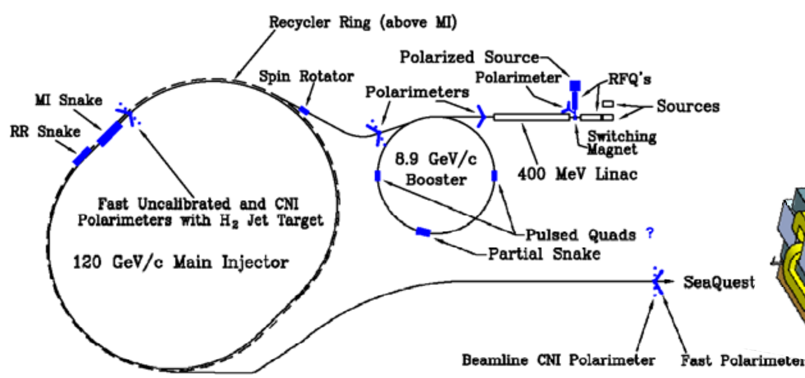
  $\longrightarrow$ spectrometer already setup and running

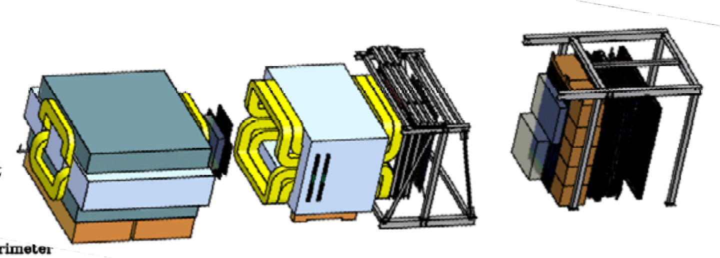
- Run alongside neutrino program (10% of beam needed)
- Measure DY with both Beam or/and Target polarized

  $\longrightarrow$ broad spin physics program possible







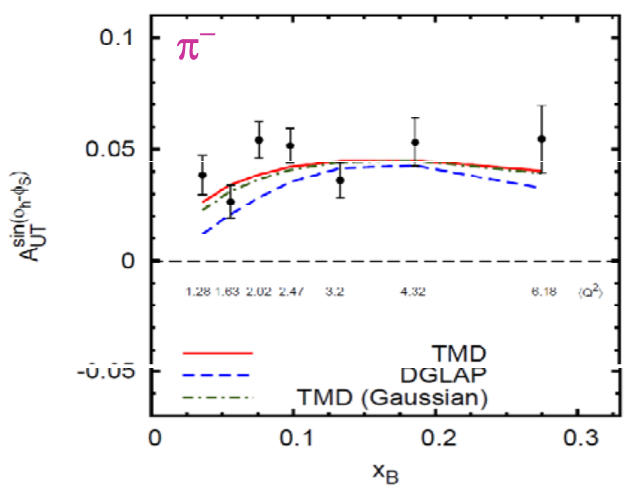


The END

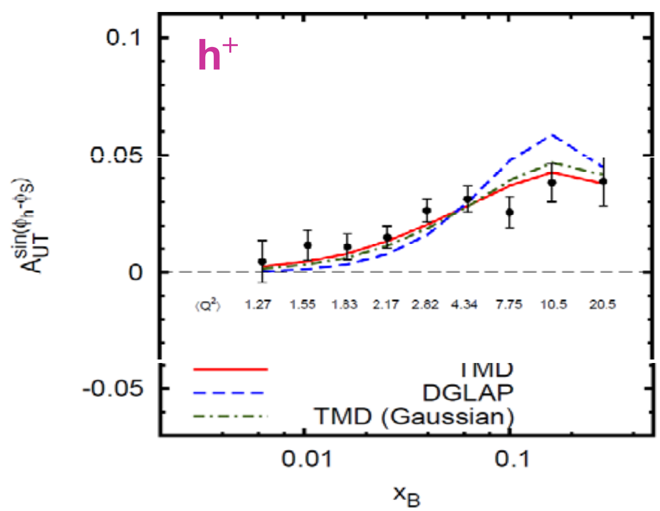
Backup Slides

QCD Evolution of Sivers Function

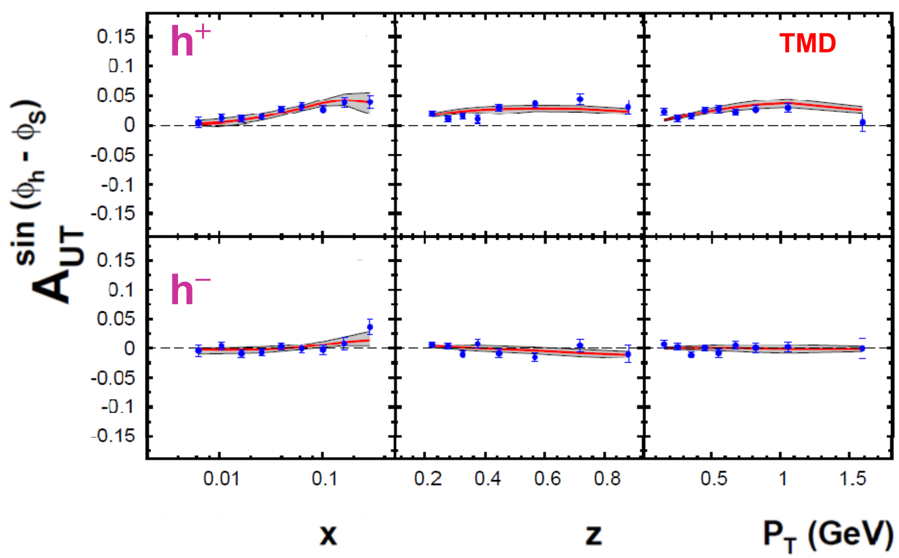
HERMES (p)



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

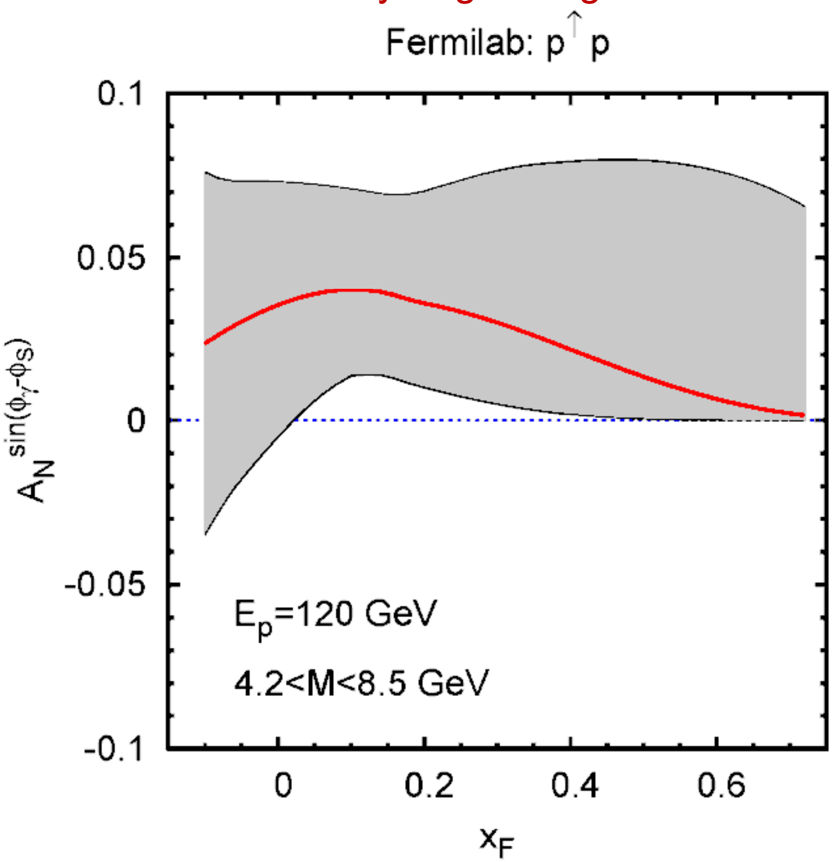
Polarized Drell-Yan at Fermilab

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

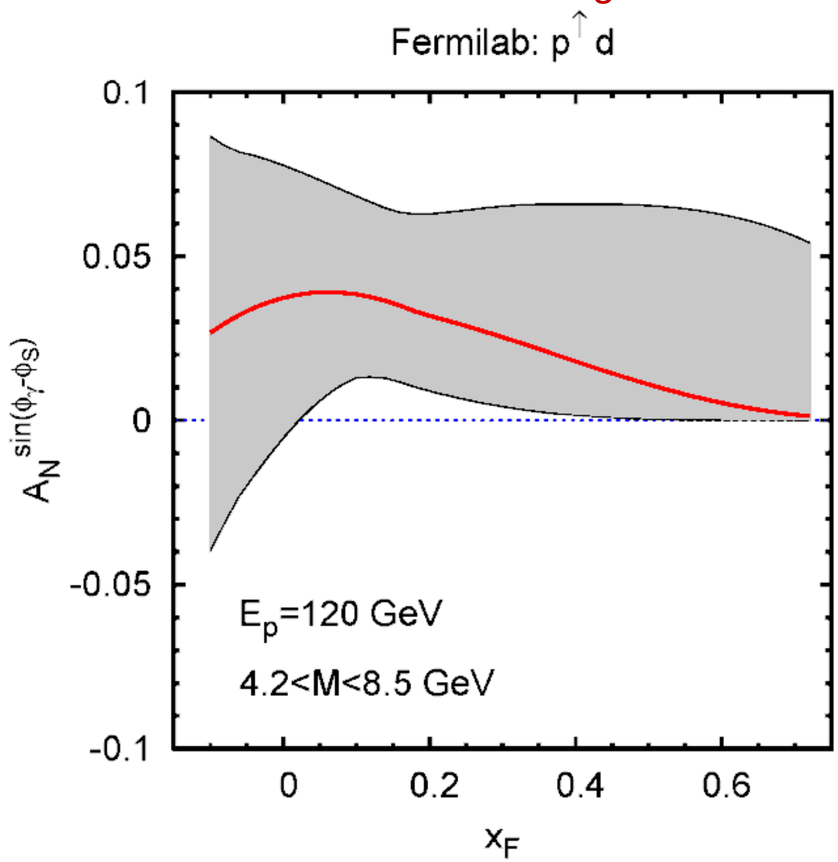
  → **Predictions** for Drell-Yan (gray error bands correspond to $\Delta\chi^2$ =20)

polarized beam: E_p=120 GeV **$\sqrt{s}$ ~ 15 GeV** **4.2 < M < 8.5 GeV**

hydrogen target



deuterium target



Anselmino et al. priv. comm. 2010