Polarized Protons in the Fermilab Main Injector

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- Sivers Function in Polarized Drell-Yan
  - ➡ fundamental QCD prediction:

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

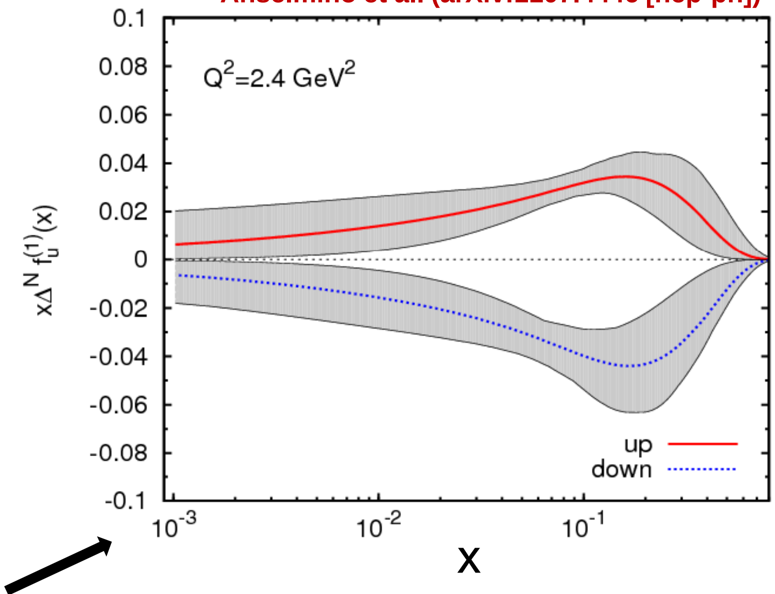
- Polarized Drell-Yan at Fermilab
  - ➡ polarized Beam (E-1027) or Target (E-1039)
- Main Injector Polarization Scheme
  - ➡ present status & plans

This work is supported by

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

Polarized Drell-Yan Experiment

NOT YET DONE!

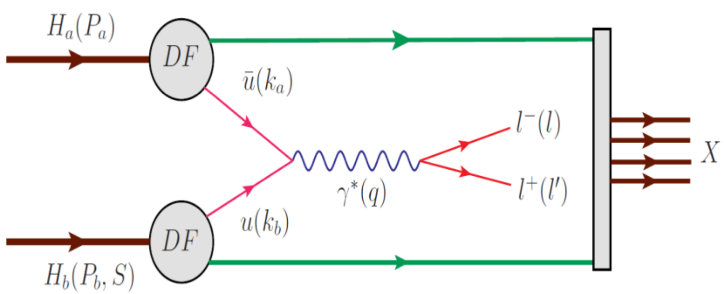
- Access to transverse-momentum dependent distribution (TMD) functions
  - ⟶ Sivers, Boer-Mulders, etc
- Transversely Polarized Beam or Target
  - ⟶ Sivers function in single-transverse spin asymmetries (sea quarks or valence quarks)
    - – valence quarks constrain SIDIS data much more than sea quarks
    - – 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

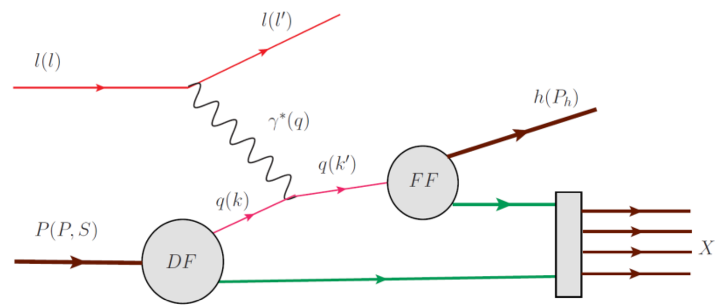
- Similar Physics Goals as SIDIS:
  - ➡ parton level understanding of nucleon
  - ➡ electromagnetic probe

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 sensitivity of transverse momentum-dependent distribution (TMD) functions (Sivers, Boer-Mulders, etc)

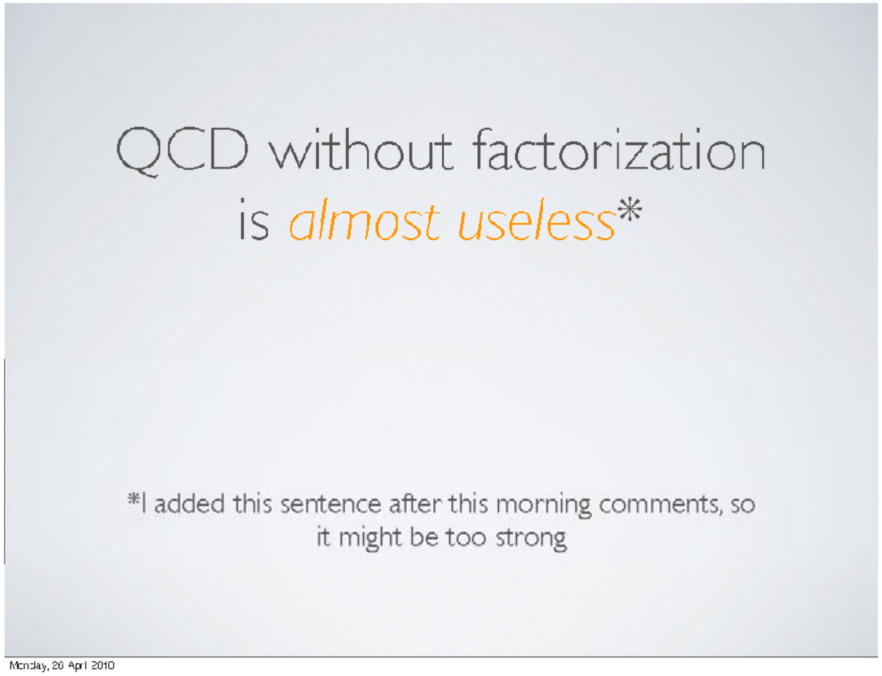
Sivers in Drell-Yan vs SIDIS: The Sign Change

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

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

- Polarized Drell-Yan:
  - ➡ major milestone in hadronic physics (HP13)

- Importance of factorization in QCD:



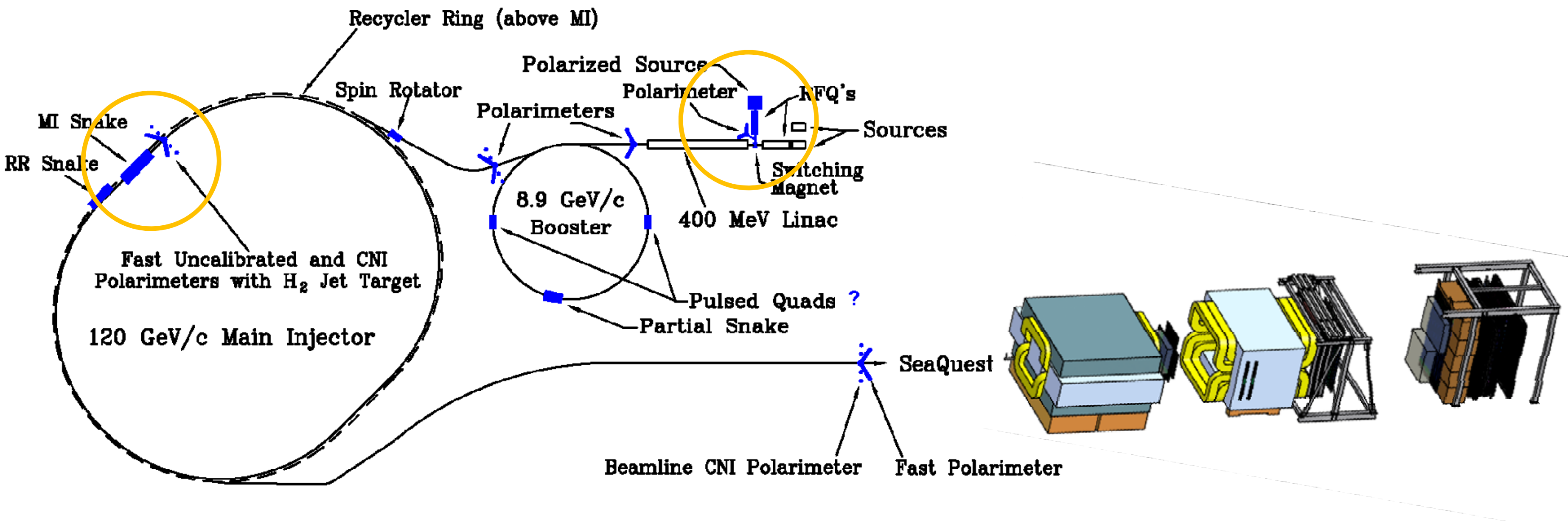
A. Bacchetta , DY workshop, CERN, 4/10

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	$x_t = 0.2 - 0.3$	$2 \times 10^{33}\ cm^{-2}\ s^{-1}$	2014, 2018
PAX (GSI)	$p^{\uparrow} + p_{bar}$	collider $\sqrt{s}$ = 14 GeV	$x_b = 0.1 - 0.9$	$2 \times 10^{30}\ cm^{-2}\ s^{-1}$	>2017
PANDA (GSI)	$p_{bar} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	$x_t = 0.2 - 0.4$	$2 \times 10^{32}\ cm^{-2}\ s^{-1}$	>2016
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	$x_b = 0.1 - 0.8$	$1 \times 10^{30}\ cm^{-2}\ s^{-1}$	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	$x_b = 0.05 - 0.1$	$2 \times 10^{32}\ cm^{-2}\ s^{-1}$	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_b = 0.25 - 0.4$	$2 \times 10^{33}\ cm^{-2}\ s^{-1}$	
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_b = 0.25 - 0.4$	$6 \times 10^{34}\ cm^{-2}\ s^{-1}$	
SeaQuest (unpol.) (FNAL)	$p + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_b = 0.35 - 0.85$ $x_t = 0.1 - 0.45$	$3.4 \times 10^{35}\ cm^{-2}\ s^{-1}$	2012 - 2015
polDY§ (FNAL)	$p^{\uparrow} + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_b = 0.35 - 0.85$	$2 \times 10^{35}\ cm^{-2}\ s^{-1}$	>2016
	§ $L = 1 \times 10^{36}\ cm^{-2}\ s^{-1}$ (LH_2 tgt limited) / $L = 2 \times 10^{35}\ cm^{-2}\ s^{-1}$ (10% of MI beam limited)				

Polarized Drell-Yan at Fermilab Main Injector

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

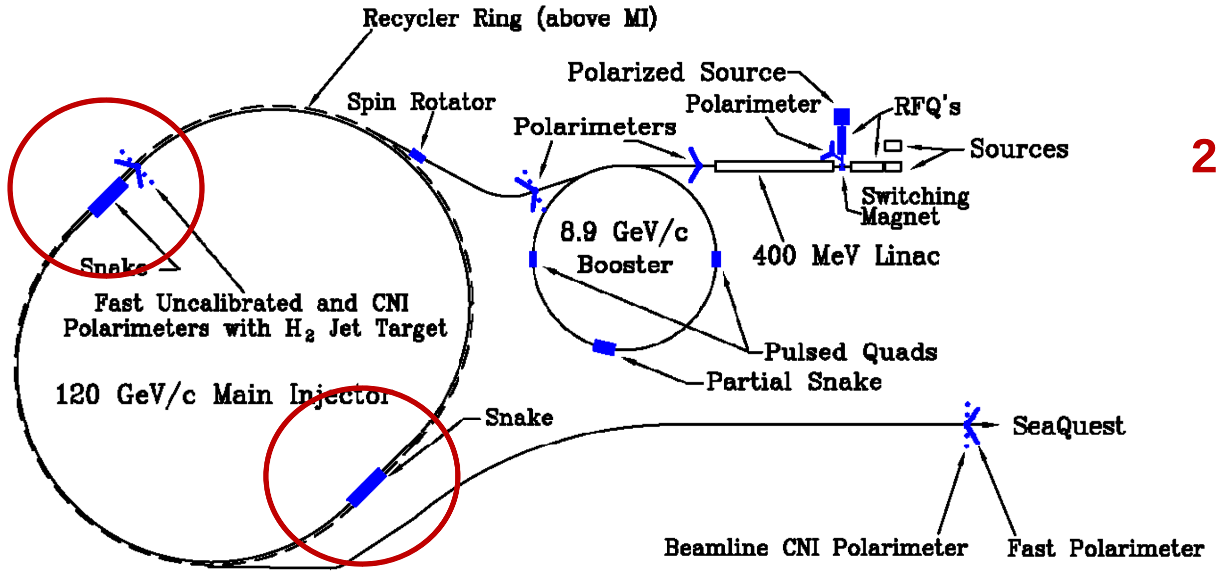


- SeaQuest di-muon Spectrometer
  - ➡ fixed target experiment, optimized for Drell-Yan
  - ➡ luminosity: L_{av} = 3.4 x 10^{35} /cm^2/s
    - ⟶ I_{av} = 1.6 x 10^{11} p/s (=26 nA) / N_p= 2.1 x 10^{24} /cm^2
  - ➡ approved for 2-3 years of running: 3.4 x 10^{18} pot
  - ➡ by 2015: fully understood, ready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

Polarized Drell-Yan at Fermilab Main Injector - II

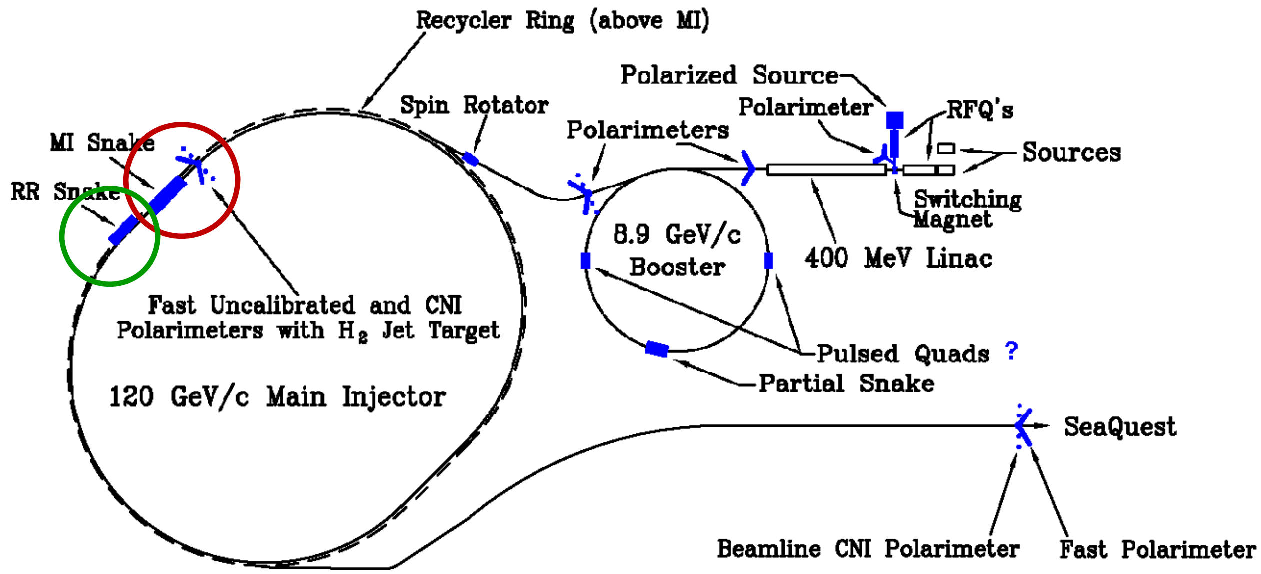
- Polarized Beam in Main Injector
  - ➡ use SeaQuest target
    - ✓ liquid H_2 target can take about $I_{av} = 5 \times 10^{11}$ p/s (=80 nA)
  - ➡ 1 mA at polarized source can deliver about $I_{av} = 1 \times 10^{12}$ p/s (=150 nA) for 100% of available beam time *(A. Krisch: Spin@Fermi report in (Aug 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)
  - ➡ Luminosity considerations:
    - ✓ $L_{av} = 2.0 \times 10^{35}$ /cm^2/s (beam-time limited)
    - ✓ $L_{av} = 1 \times 10^{36}$ /cm^2/s (target heating limited)

From 2 Siberian Snakes to 1 Snake



2 Siberian Snakes in MI

(not enough space)



1 Siberian Snake in MI

(fits well)

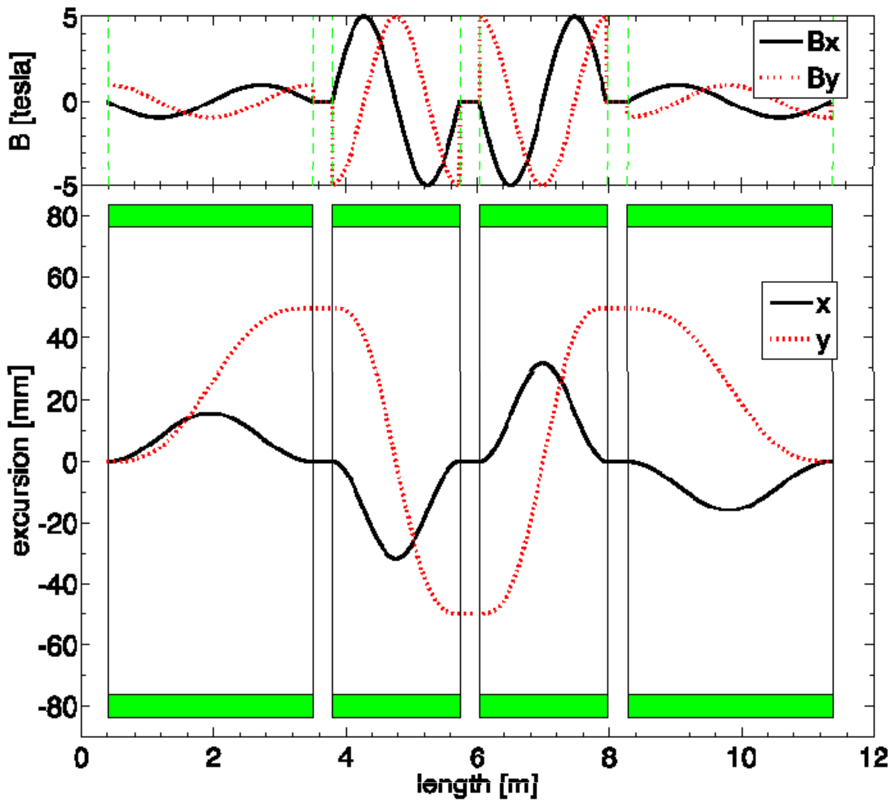
plus 1 solenoid snake in RR

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**)

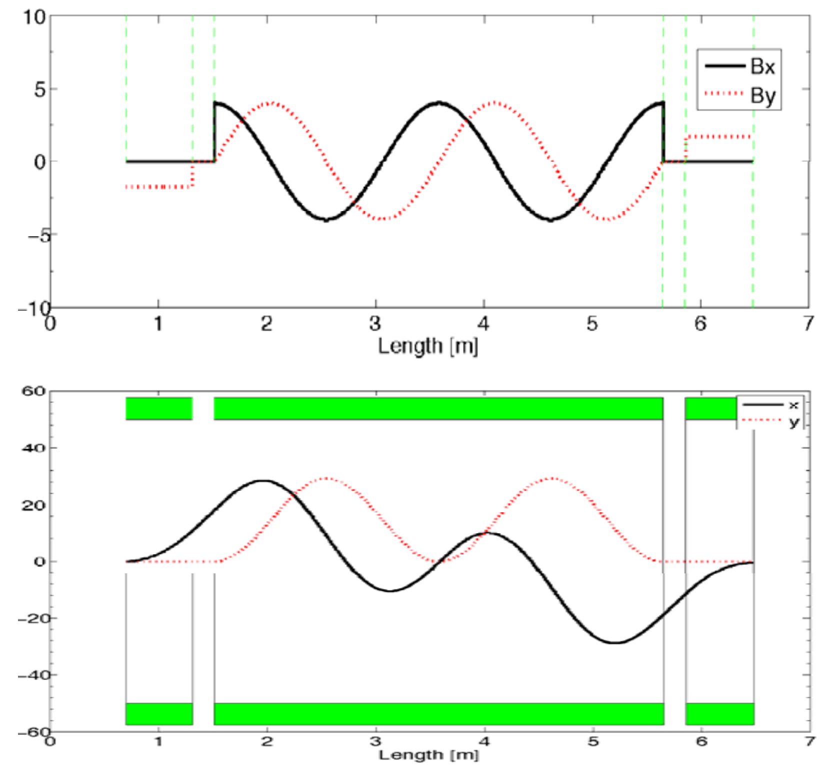
does not fit



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**)

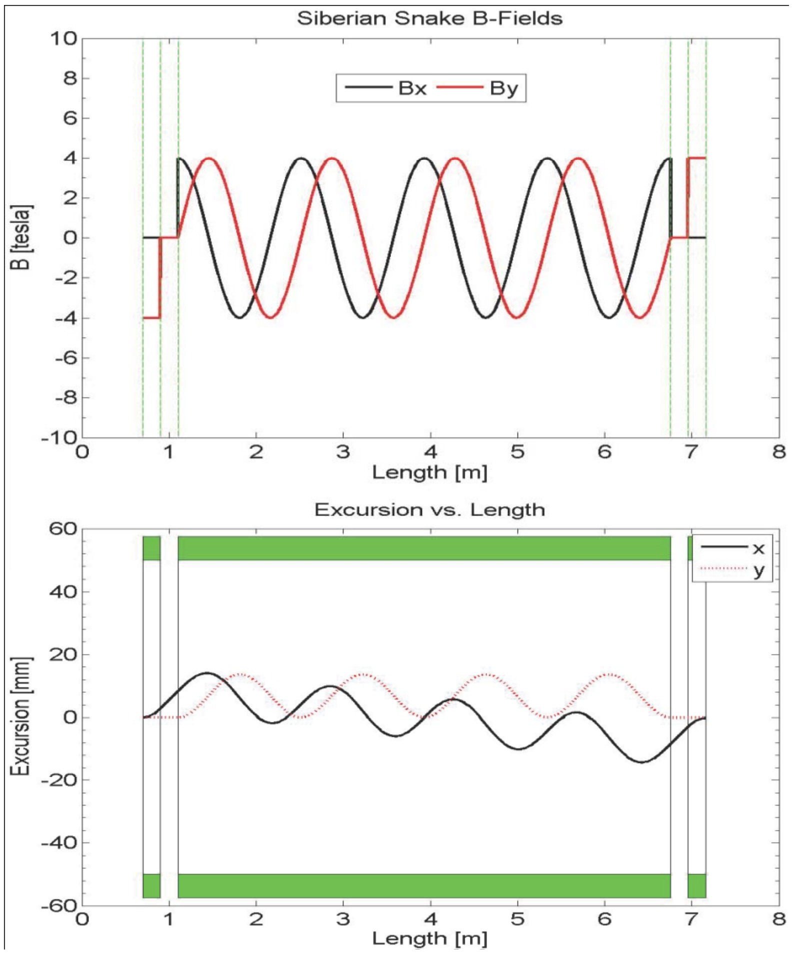
fits well



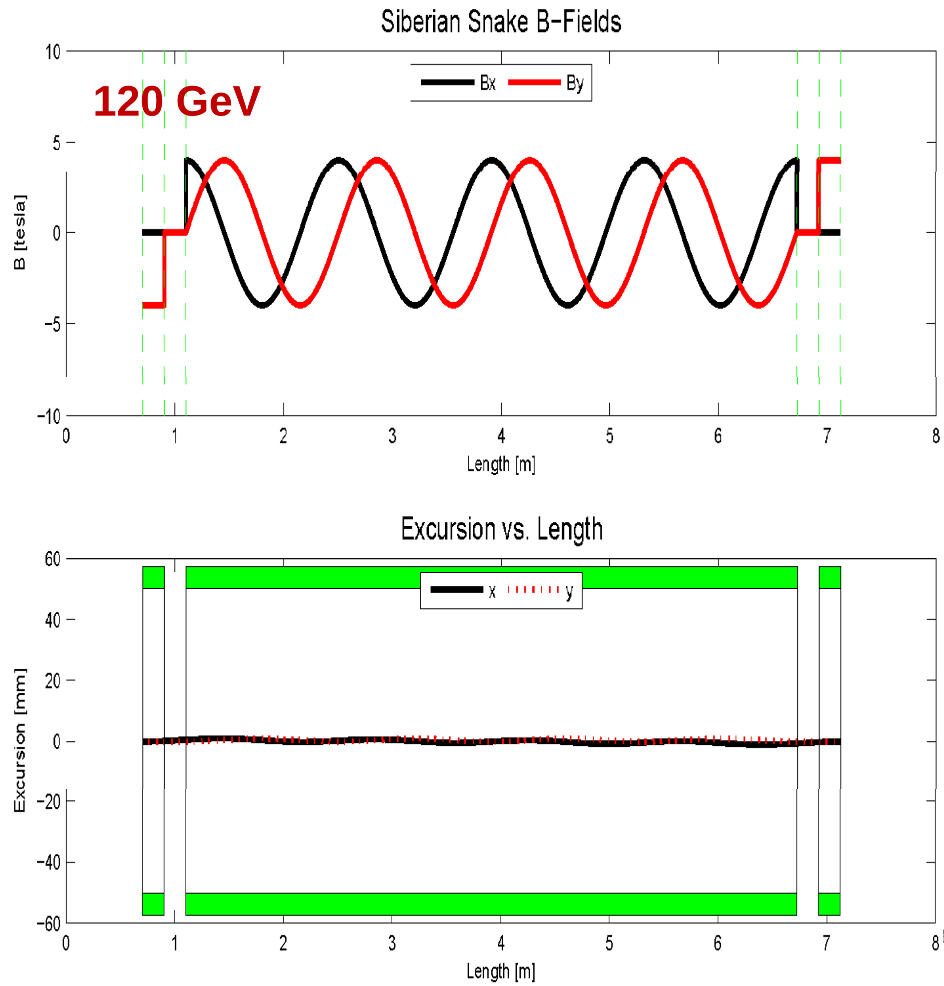
T. Roser (BNL): - test snakes/rotators up to 5.4T
- operation not above 4T

Steady Improvements to 1 Snakes solution - I

8.9 GeV 4T



4-twist 4T

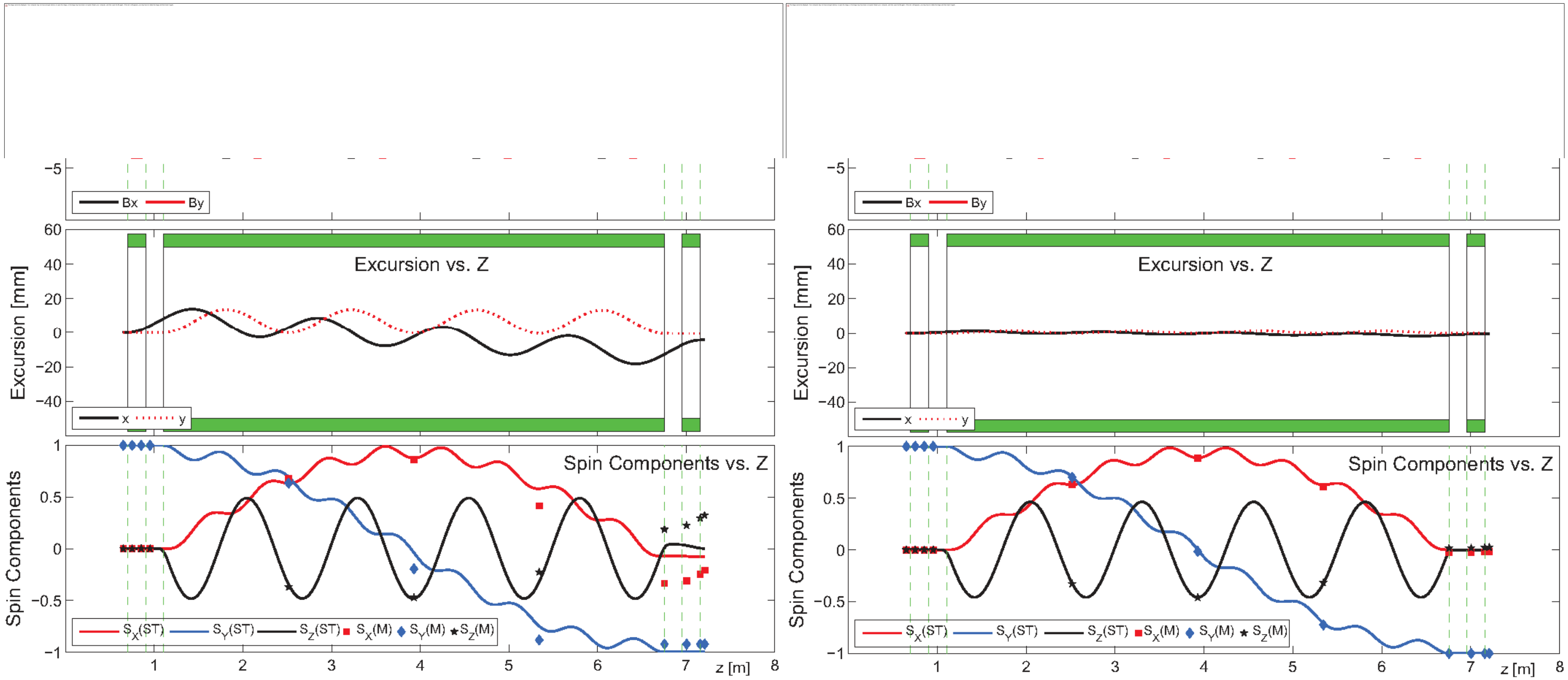


beam excursions shrink w/ number of twists

beam excursions shrink w/ beam energy

Steady Improvements to 1 Snakes solution - II

Including fringe fields



x, y, z spin components vs distance

♦ transport matrix formalism (E.D. Courant): fringe field not included, β = 1 (fixed)

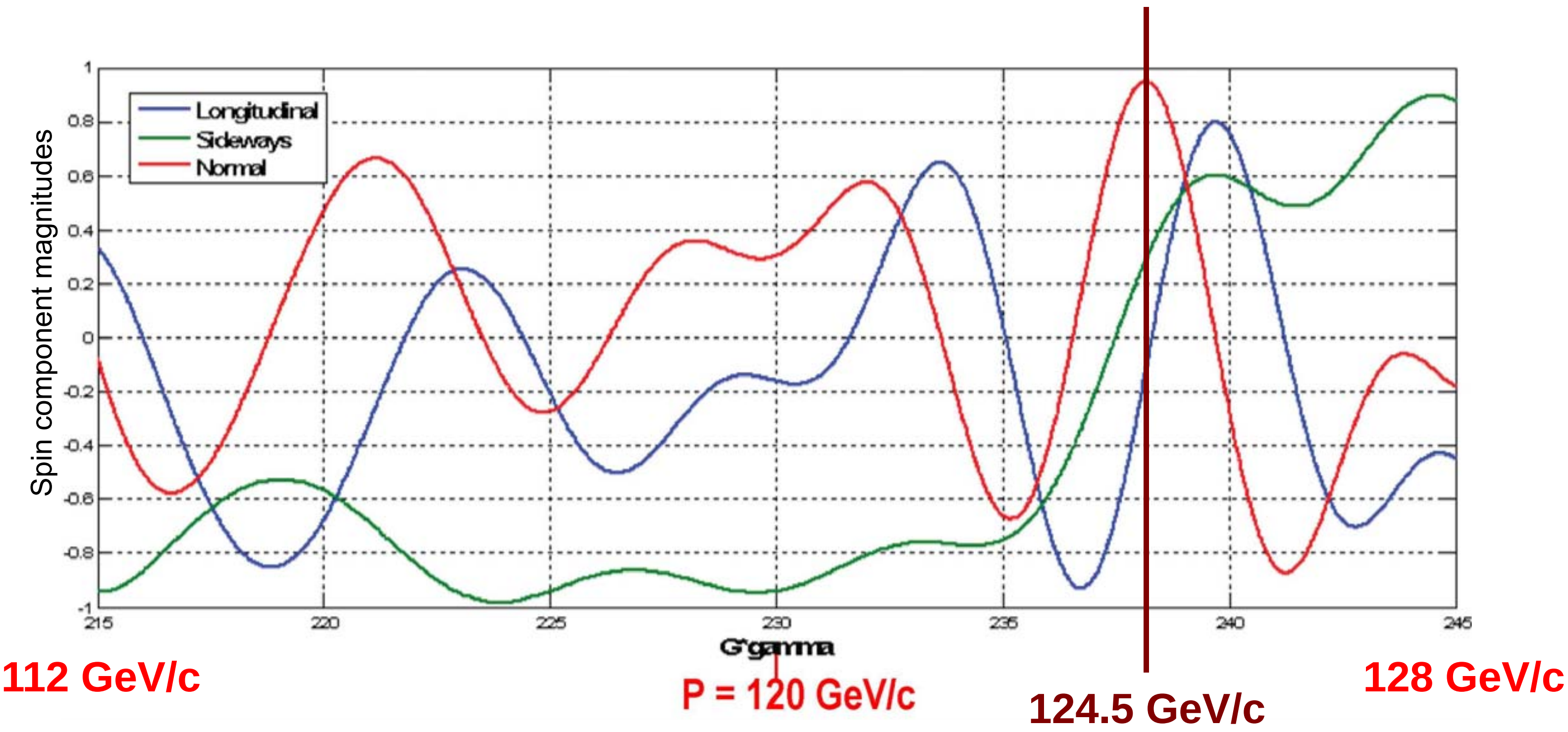
– spin tracking formalism (Thomas-BMT): fringe field included, β varibale

fringe fields have <0.5% effect at 8.9 GeV and <<0.1% effect at 100 GeV [arXiv: 1309.1063]

Spin direction control for extracted beam

- Spin rotators used to control spin direction at BNL
- Spin@Fermi collaboration recent studies (to save $$)
  ➡ rotate beam at experiment by changing proton beam energy around nominal 120 GeV

radial ("sideways") / vertical ("normal")



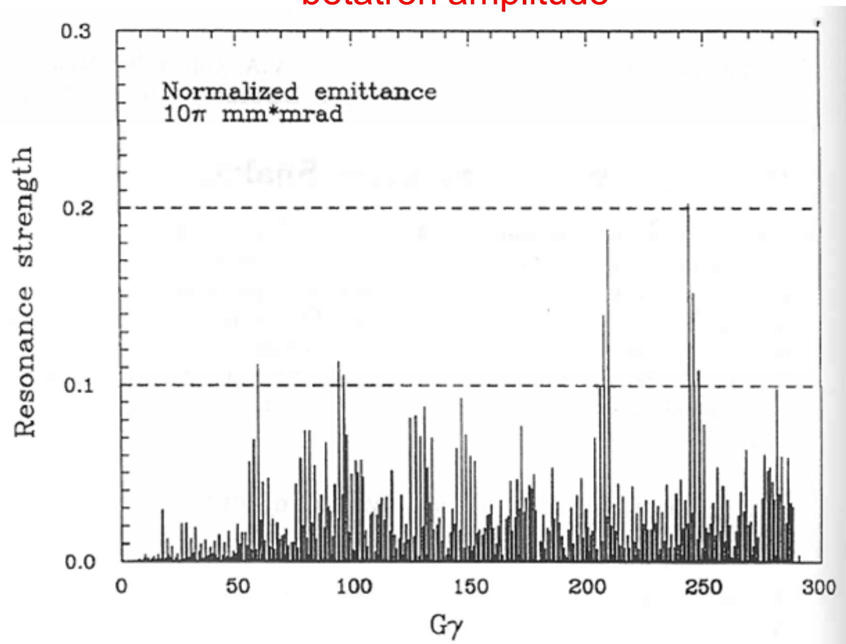
The Path to a polarized Main Injector

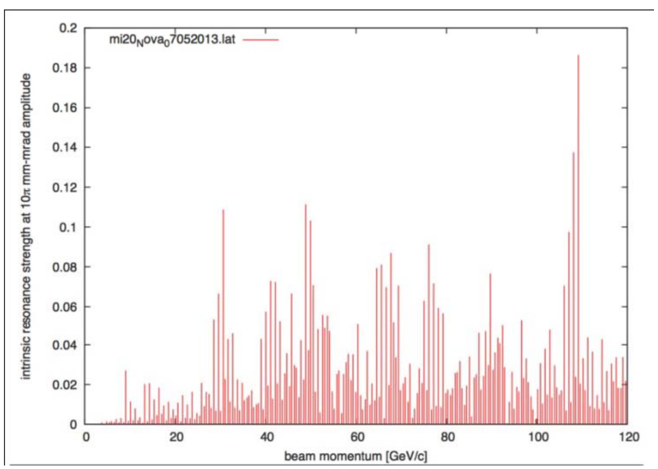
Stage 1 approval from Fermilab: 14-November-2012

- Collaboration with A.S. Belov at INR and Dubna to develop polarized source
- Detailed machine design and costing using 1 snake in MI
  - ➡ Spin@Fermi collaboration provide design
    - ⟶ get latest lattice for NOVA:
      - › translate “mad8” optics file to spin tracking code (“zgoubi”)
    - ⟶ determine intrinsic resonance strength from depolarization calculations
    - ⟶ do single particle tracking with “zgoubi” with novel single-snake
    - ⟶ set up mechanism for adding errors into the lattice:
      - › orbit errors, quadrupole mis-alignments/rolls, etc.
    - ⟶ perform systematic spin tracking
      - › explore tolerances on beam emittance
      - › explore tolerances on various imperfections: orbit / snake / etc
  - ➡ Fermilab (AD) does verification & costing

Intrinsic Resonance Strength in Main Injector

Depol calculations: single particle at 10π mm-mrad betatron amplitude



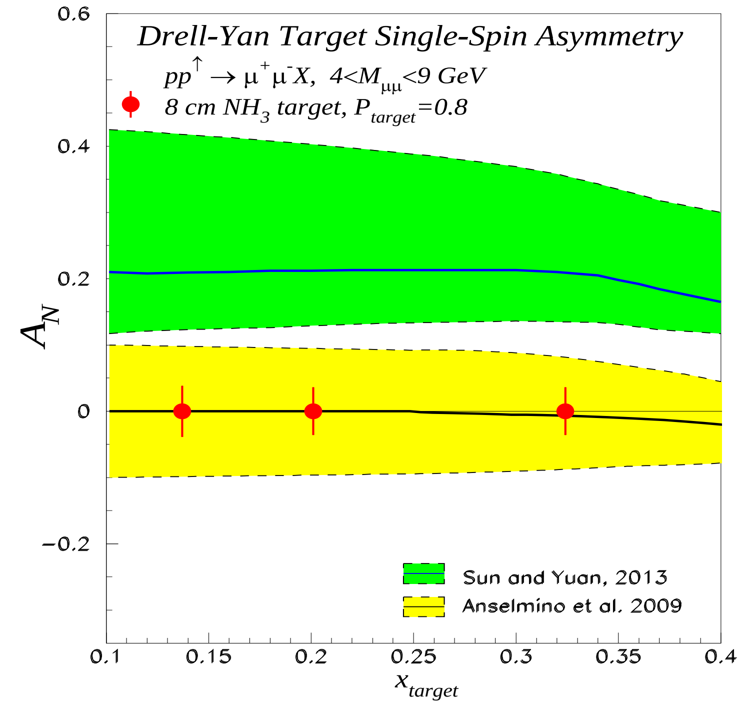


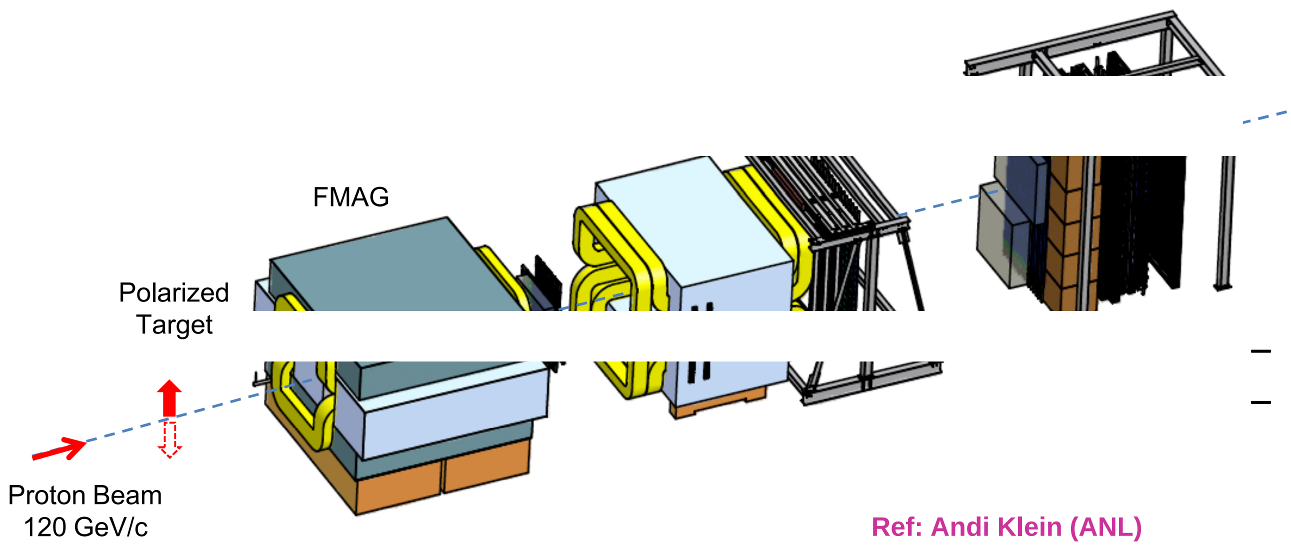
- 1995 Spin@Fermi report
  - ➡ before MI was built
- using NOVA lattice (July 2013)
- very similar: largest resonance strength just below 0.2
  - – one snake sufficient (E. Courant rule of.thumb)

Polarized Target at Fermilab (E-1039)

- 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





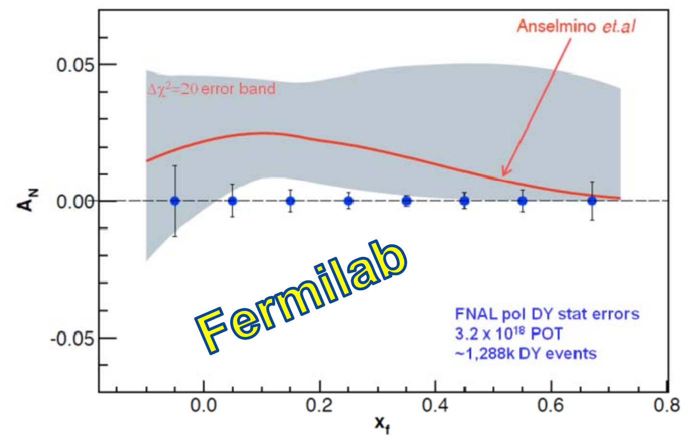
- use current SeaQuest setup
- a polarized proton target, unpolarized beam

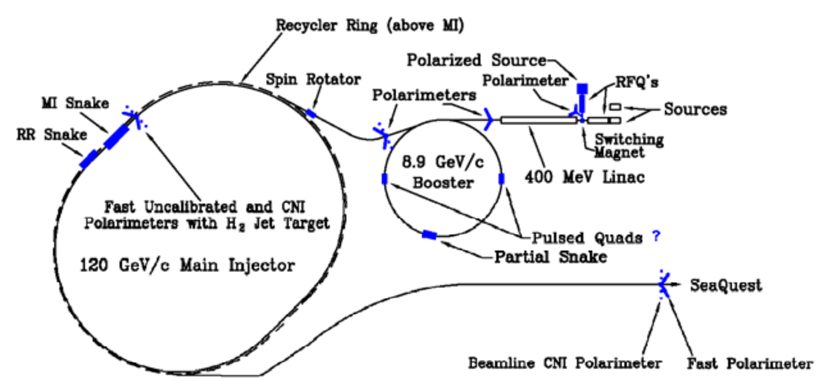
Ref: Andi Klein (ANL)

Summary

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

- QCD (and factorization) require sign change
- Fermilab is arguably best place to do this measurement
  - ⟶ high luminosity, large x-coverage
  - ⟶ spectrometer already setup and running
- Run alongside neutrino program (10% of beam needed)
- Measure DY with both Beam or/and Target polarized
  - ⟶ broad spin physics program possible
- Path to polarized proton beam at Main Injector
  - ⟶ perform detailed machine design and costing studies
    - › proof that single-snake concept works
    - › applications for JPARC, NICA, ….
  - ⟶ Secure funding

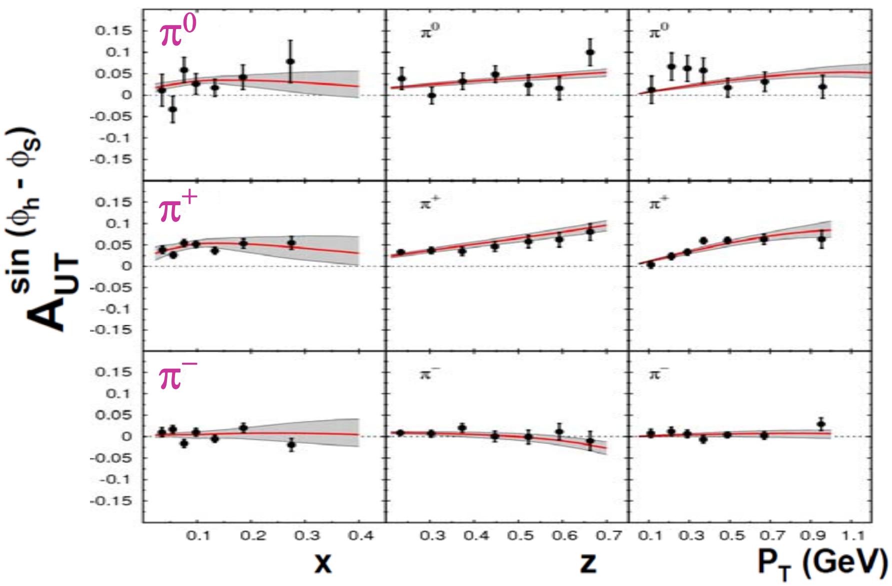




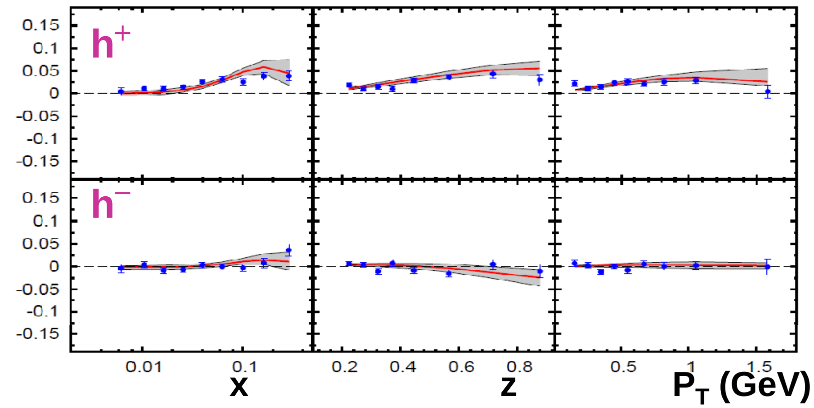
The END

Sivers Asymmetry in SIDIS

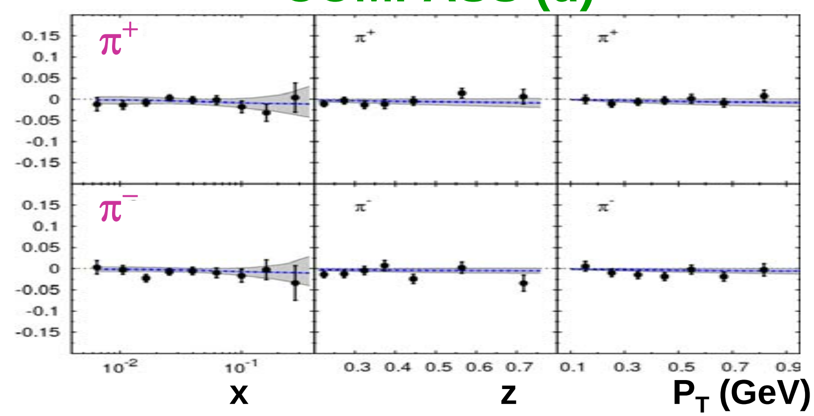
HERMES (p)



COMPASS (p)



COMPASS (d)

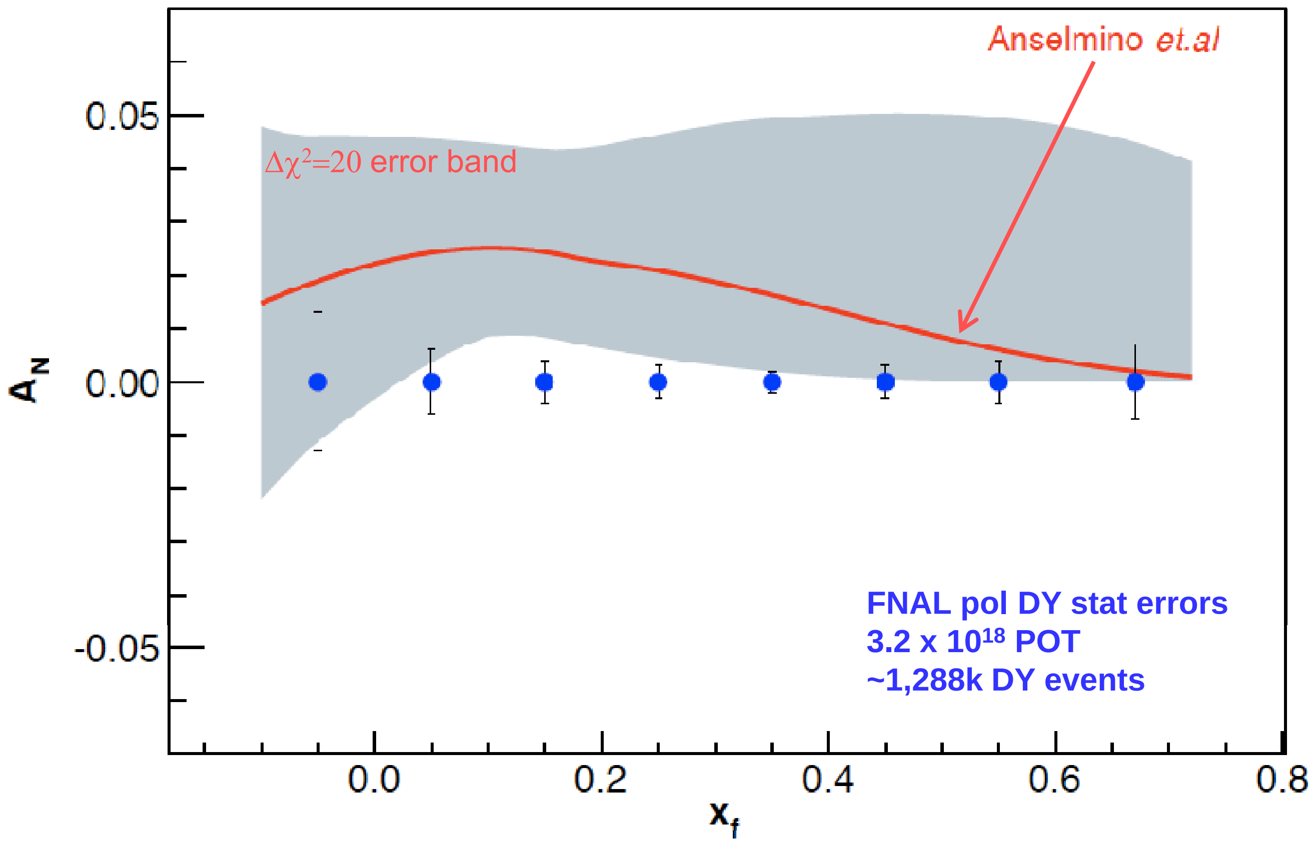


- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS (HERMES (p), COMPASS (p), COMPASS (d))

Comparable measurements needed in Drell-Yan process

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 !

Main Competition: COMPASS

- approved for **one year** run at LHC restart
  - ➡ 2nd year after 2 years of Primakoff measurements

- for comparison of Sivers function need to measure entire function
  - ➡ must evolve to same Q^2
  - ➡ cannot do QCD evolution on a point

- for $M_\gamma < M_{J/\Psi}$ significant contamination from many sources
  - ➡ charm decays that appear to reconstruct to low mass
  - ➡ combinatorial background