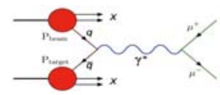
Polarized Drell-Yan at Fermilab

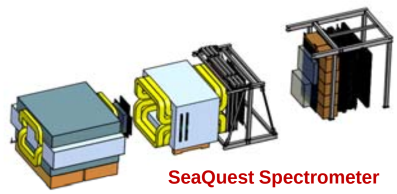
Wolfgang Lorenzon
University of Michigan
(18-February-2014)
Los Alamos



- 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 (E1027) or Target (E1039)
- Main Injector Polarization Scheme
  - ➡ present status & plans



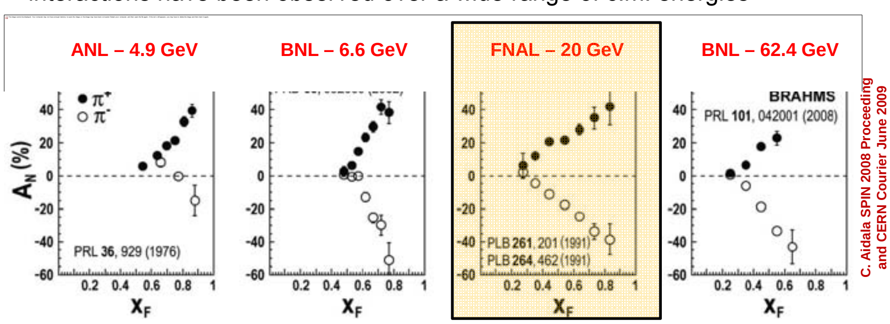
SeaQuest Spectrometer

This work is supported by

1

Transverse Single Spin Asymmetries (SSA)

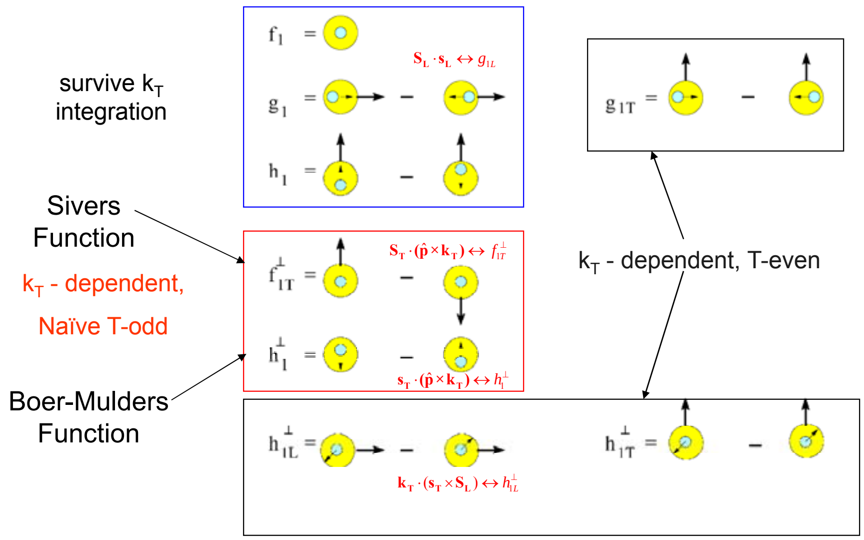
- (huge) single spin asymmetries for forward meson production in hadron-hadron interactions have been observed over a wide range of c.m. energies



- "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

2

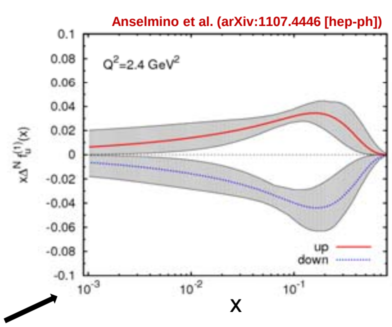
Transverse Momentum Distributions (Introduction)



3

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



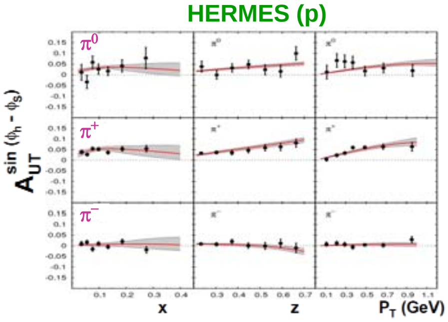
First moment of Sivers functions:

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

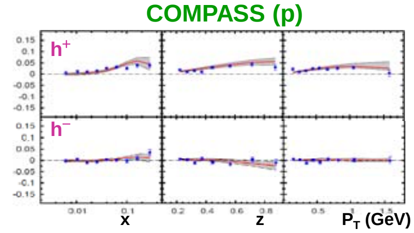
4

Sivers Asymmetry in SIDIS

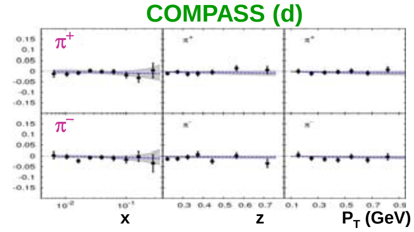
HERMES (p)



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

5

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 ⊗ 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 ⊗ anti-quark for pp collisions)
    - – anti-quark transversity might be very small

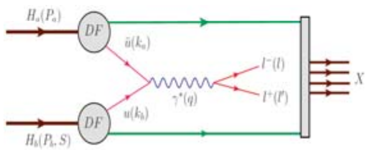
6

Drell Yan Process

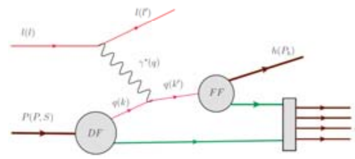
- Similar Physics Reach as SIDIS:
  - ➡ parton level understanding of nucleon
  - ➡ electromagnetic probe

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
- Assuming factorization valid in QCD: allows direct production of two transverse momentum-dependent distribution (TMD) functions (Sivers, Boer-Mulders, etc)
- Assuming universality valid in QCD: DF in DY and SIDIS are identical

7

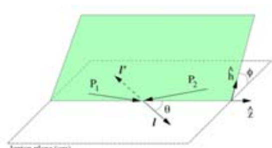
Leading order DY Cross Section

- DY cross section at LO:

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

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

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



Sivers Mechanism

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

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:

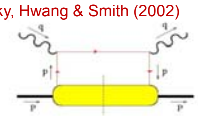
$$A_{TU}^{\sin\phi_b} = \frac{F_{TU}^1}{F_{UU}^1}$$

8

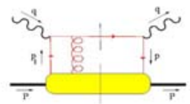
Sivers Function

- T-odd observables
  - ➡ SSA observable ~ $\vec{J}\cdot(\vec{p}_1\times\vec{p}_2)$ 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)

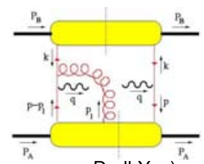


can interfere with



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

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



e.g. Drell-Yan)

9

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

10

Hadronic Physics Milestone #13

Report to NSAC, 11-Aug-2008 (by subcommittee on performance measures):

Table 11: New, Updated and Continuing Milestones for Hadronic Physics

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

New Milestone HP13 reflects the intense activity and theoretical breakthroughs of recent years in understanding the parton distribution functions accessed in spin asymmetries for hard-scattering reactions involving a transversely polarized proton. This leads to new experimental opportunities to test all our concepts for analyzing hard scattering with perturbative QCD.

11

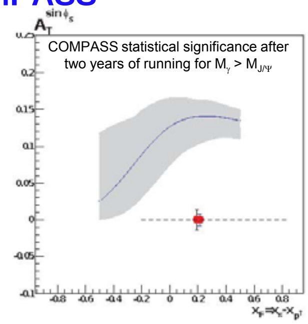
Planned Polarized Drell-Yan Experiments

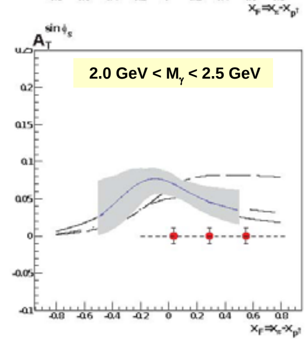
experiment	particles	energy	x_b or x_t	Luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	$x_t = 0.2 – 0.3$	2×10^{33} cm^{-2} s^{-1}	2014, 2018
PAX (GSI)	$p^{\uparrow} + p_{bar}$	collider $\sqrt{s}$ = 14 GeV	$x_b = 0.1 – 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (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}	>2018
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
Pol tgt DY‡ (E1039) (FNAL)	$p + p^{\uparrow}$	120 GeV $\sqrt{s}$ = 15 GeV	$x_t = 0.1 – 0.45$	3.4×10^{35} cm^{-2} s^{-1}	2016
Pol beam DY§ (E1027) (FNAL)	$p^{\uparrow} + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_b = 0.35 – 0.85$	2×10^{35} cm^{-2} s^{-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)*				

12

Main Competition: COMPASS

- approved for **one year** run at LHC restart
  - ➡ 2^{nd} 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

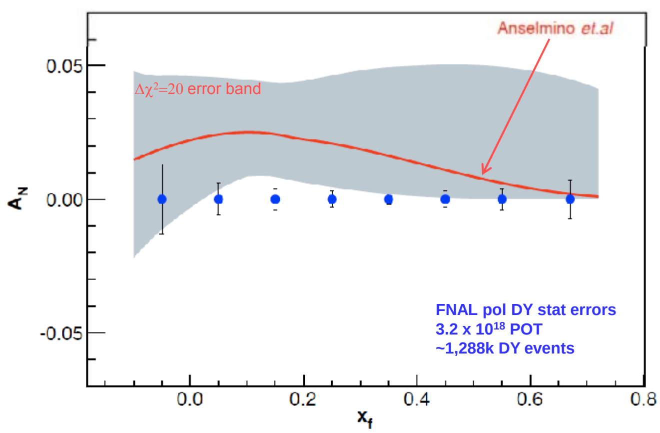




13

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:

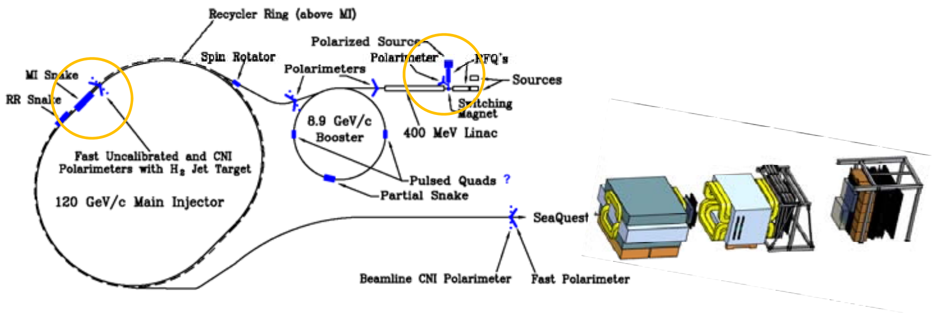
$$A_N = \frac{2}{\pi} A_{TU}^{\sin\phi_b}$$

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

14

Polarized Drell-Yan at Fermilab Main Injector

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



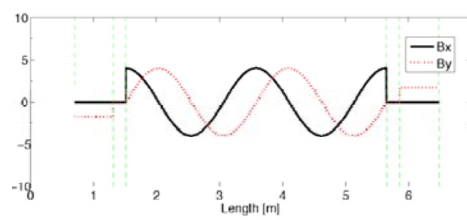
- SeaQuest di-muon Spectrometer
  - ➡ fixed target experiment, optimized for Drell-Yan
  - ➡ luminosity: L_{av} = 3.4 x 10^{35} /cm²/s
    - ⟶ I_{av} = 1.6 x 10^{11} p/s (=26 nA) / N_p= 2.1 x 10^{24} /cm²
  - ➡ approved for 2-3 years of running: 3.4 x 10^{18} pot
  - ➡ by 2016: fully understood, ready to take pol. beam

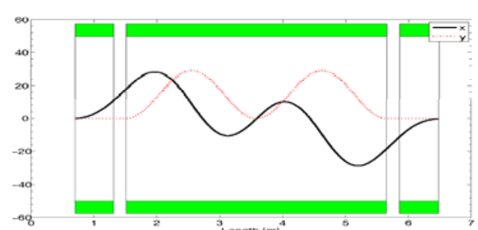
15

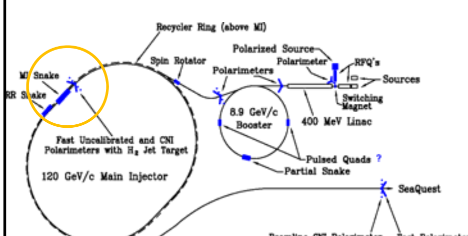
A Novel Siberian Snake for the Main Injector

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



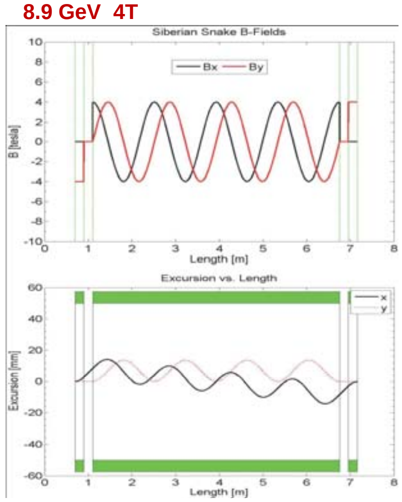




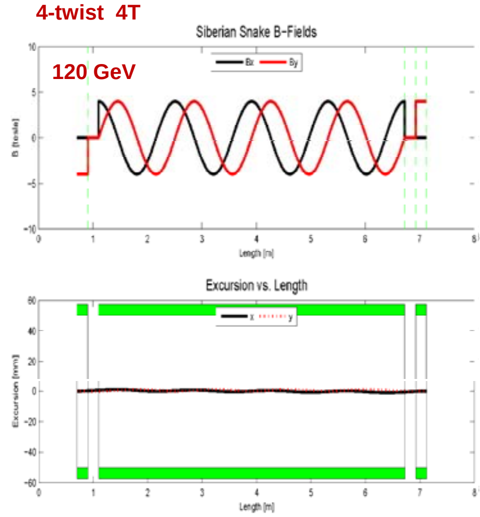
16

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

17

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

18

The Path to a polarized Main Injector

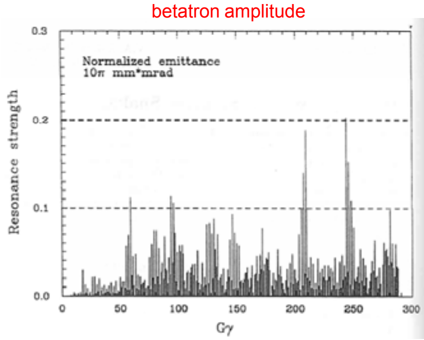
Stage 1 approval from Fermilab: 14-November-2012

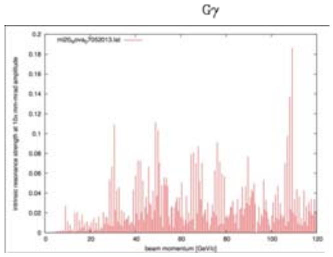
- Detailed machine design and costing using 1 snake in MI
  - ➡ E-1027 collaboration provide design
    - ⟶ get latest lattice for NOVA:
      - › translate “mad8” optics file to spin tracking code (“zgoubi”)
    - ⟶ determine intrinsic resonance strength from depolarization calculations
    - ⟶ do single 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

19

Intrinsic Resonance Strength in Main Injector

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

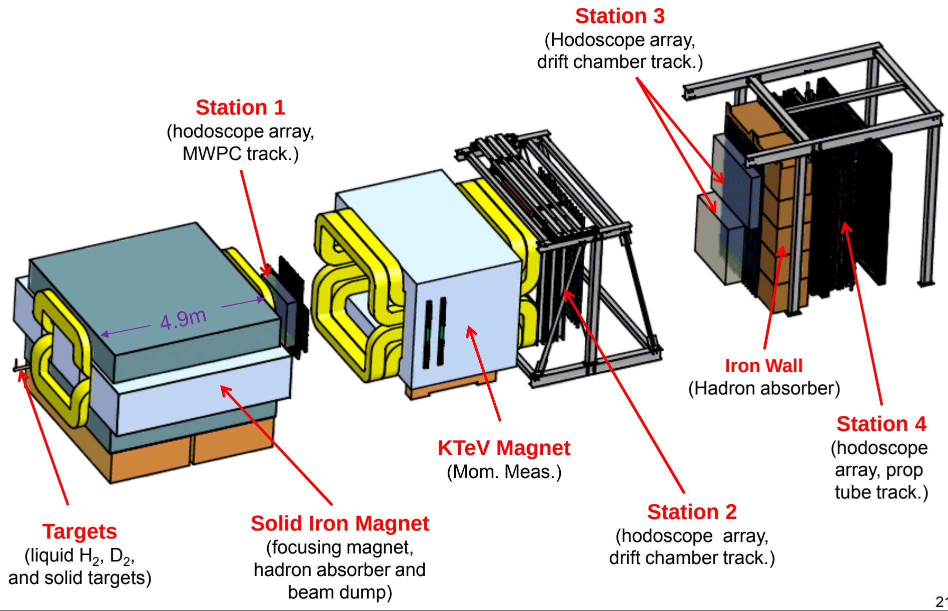




- 1995 Spin@Fermi report
  - ➡ before MI was built
- using NOVA lattice (July 2013)
- very similar: largest resonance strength just below 0.2
  - → one snake sufficient (E. Courant rule of thumb)

20

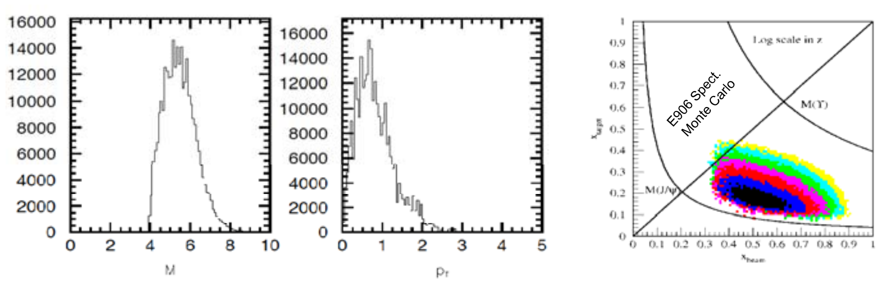
Drell-Yan Spectrometer for SeaQuest
(25m long)



21

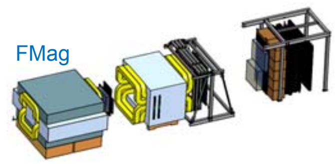
Acceptance for Polarized Drell-Yan

- 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



22

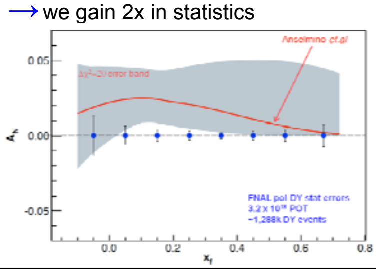
Measurement at Fermilab Main Injector

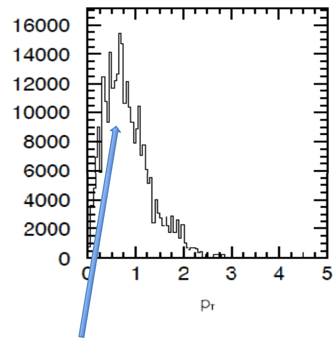


- Retune 1st spectrometer magnet (FMag):
  - ➡ focuses high p_T muons and over focuses low p_T muons
    - ⟶ we loose low p_T muons when field is high!
    - ⟶ SeaQuest is all about going to the largest x_t quarks, requiring high-p_T muons
  - ➡ lowering FMag field
    - ⟶ we get back the low p_T muons
    - ⟶ we loose the high p_T muons

    BUT

    - ⟶ we gain 2x in statistics





p_T spectrum peaks at low p_T

23

E-1027 Collaboration (Feb 2014)

Abilene Christian University
Donald Isenhower, Tyler Hague, Rusty Towell, Shon Watson

Academia Sinica
Wen-Chen Chang, Yen-Chu Chen, Shiu Shiuan-Hal, Da-Shung Su

Argonne
John Arrington, Don Geesaman Kawtar Hafidi, Roy Holt, Harold Jackson, Paul E. Reimer*

University of Basque Country†
Gunar Schnell

University of Colorado
Ed Kinney

Fermilab
Chuck Brown, David Christian, Jin-Yuan Wu

University of Illinois
Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Naomi C.R Makins, R. Evan McClellan

KEK
Shinya Sawada

Los Alamos National Laboratory
Ming Liu, Xiang Jiang, A. Klein, Pat McGaughey, J. Huang

University of Maryland
Betsy Beise, Kaz Nakahara

University of Michigan
Christine Aidala, Wolfgang Lorenzon*, Joe Osborn, Bryan Ramson, Richard Raymond, Joshua Rubin

National Kaohsiung Normal University
Rurngsheng Guo, Su-Yin Wang

RIKEN
Yuji Goto

Rutgers University
Ron Gilman, Ron Ransome, A. Tadepalli

Tokyo Institute of Technology
Shou Miyasaka, Ken-ichi Nakano, Florian Saftl, Toshi-Aki Shibata

University of Virginia‡
Don Crabb, D. Day, Oscar Rondon, Dustin Keller

Yamagata University
Yoshiyuki Miyachi

*Co-Spokespeople
†new group (Aug'12)
‡new group (Jan '13)

Collaboration contains most of the SeaQuest groups and two new groups (total 17 groups as of Feb 2014)
E-1027 collaborates with A. Krisch (SPIN@FERMI), M. Syphers (MSU), M. Bai (BNL)

24

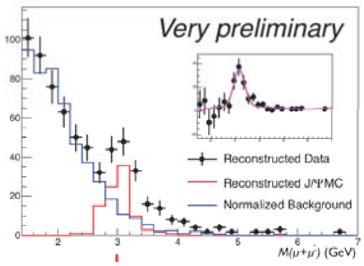
SeaQuest: from Commissioning to Science

- Commissioning Run I (late Feb. 2012 – April 30th, 2012)
- First beam in E906 on March 8th, 2012
- Extensive beam tuning by the Fermilab accelerator group
  - ➡ 1 x10^{12} protons/s (5 s spill/min)
  - ➡ 120 GeV/c
- All the detector subsystems worked
- Main Injector shut down began on May 1st , 2012
- Reconstructable dimuon events seen:

  $M_{J/\Psi}$ = 3.12 ± 0.05 GeV

  σ = 0.23 ± 0.07 GeV

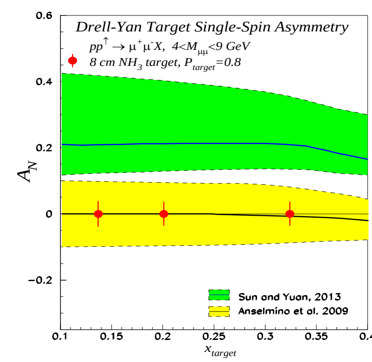
  A successful commissioning run



- Commissioning Run II (Nov. 2013 – today)
- Science Run start: tomorrow (for 2 years)

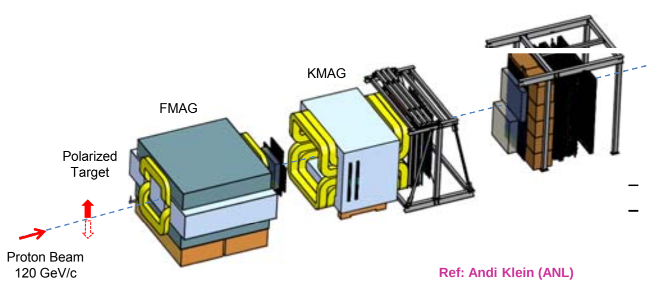
25

Another Way to Add Polarization: E1039



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: Andi Klein (ANL)

26

Reliability of predictions for the SSA in Drell-Yan

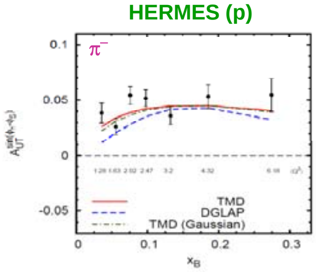
- Workshop: *Opportunities of Polarized Physics at Fermilab* (20 – 22 May, 2013)
  (J. Collins, U. D'Alesio, J. Qiu, D. Sivers, F. Yuan)
  - ➡ J. Collins conclusions
    - ⟶ issues with quantitative predictions, especially about dilution of Sivers asymmetry by evolution to higher Q
    - ⟶ A_N (DY) reduced substantially compared to HERMES
    - ⟶ predictions by Aybat-Prokudin-Rogers probably too pessimistic
    - ⟶ predictions by Sun-Yuan probably too optimistic (don't allow for known physics issues)

  ➡ substantial theoretical work needed to produce reliable predictions for DY

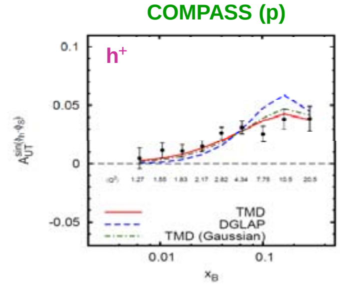
27

QCD Evolution of Sivers Function

HERMES (p)

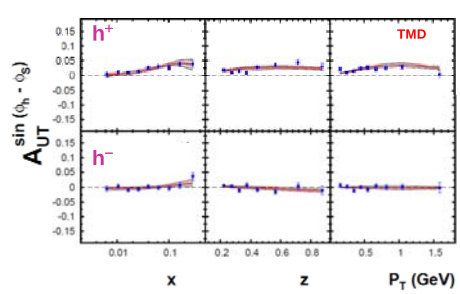


COMPASS (p)



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



28

E1039 Physics Summary

- We know almost nothing about sea quarks' angular momentum.
- Quark orbital angular momentum leads to quark Sivers distribution.
- Identifying a non-vanishing sea quark Sivers distribution could lead to a major breakthrough in nucleon structure.
- Polarized target D-Y at Fermilab's SeaQuest provides an unique opportunity to pin down sea quark's angular momentum.

Does Drell-Yan yield depend on target's spin direction?

$$A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \overset{?}{\neq} 0 \qquad A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}$$

$(A_N \equiv 0 \text{ if } L_{\bar{u}} = 0)$

- Sea quarks' orbital angular momentum could be a major part of the "missing spin".

Ref: Xiaodong Jiang (ANL)

29

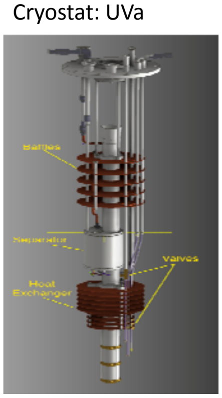
The Polarized Target System

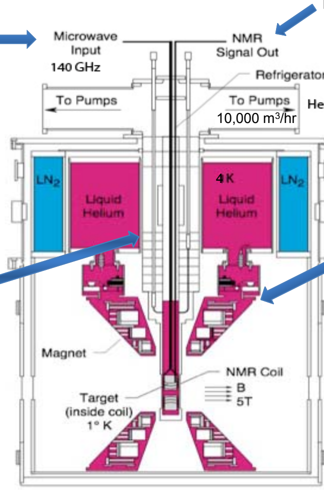
Magnet from LANL

Measure polarization

Microwave: Induces electron spin flips
- Tube + Power equip:

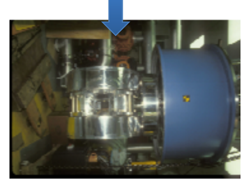
Cryostat: UVa





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)

30

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

	Beam Pol.	Target Pol.	Favored Quarks	Physics Goal
COMPASS $\pi^- p^\uparrow \to \mu^+\mu^- X$	✗	✔	Valence quark	**Sign** change and size of Sivers distribution for **valence** quark
E-1027 $p^\uparrow p \to \mu^+\mu^- X$	✔	✗	Valence quark	**Sign** change, size and shape of Sivers distribution for **valence** quark
E-1039 $pp^\uparrow \to \mu^+\mu^- X$	✗	✔	Sea quark	Size and sign of Sivers distribution for **sea** quarks, if DY $A_N \neq 0$.
E-XXXX	✔	✔	Sea & valence quark	many

Ref: Xiaodong Jiang (ANL)

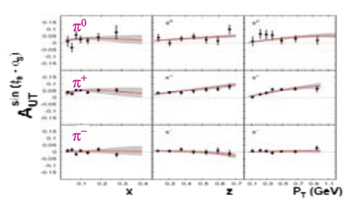
31

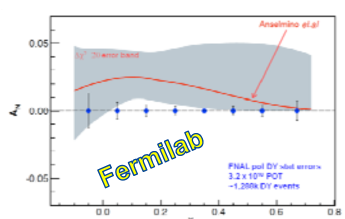
Summary

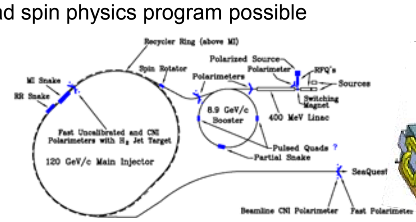
- A non-zero Sivers asymmetry has been measured both at HERMES and COMPASS
- QCD (and factorization) require sign change

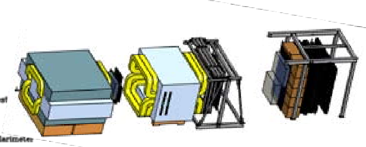
$$f_{1T}^{\perp}\Big|_{SIDIS} = - f_{1T}^{\perp}\Big|_{DY}$$

- Fermilab is arguably best place to do this measurement
  - ⟶ high luminosity, large x-coverage, high-intensity polarized beam
  - ⟶ 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









32

Thank You

33

Backup Slides

34

Project costs - I

	June '12		Oct '12	
Preaccelerator		$2.0 M		$1.9 M
Polarized H- ion source	$0.6 M		$0.6 M	
35 keV polarimeter	$0.3 M		$0.2 M	
RFQ and power supply (35 keV to 750 keV)	$0.3 M		$0.3 M	
Beam lines, switching magnets & vacuum system	$0.5 M		$0.5 M	
Building Modification	$0.1 M		$0.1 M	
Installation (~4wks)	$0.2 M		$0.2 M	
400 MeV LINAC		$0.3 M		$0.3 M
400 MeV polarimeter	$0.1 M		$0.1 M	
Installation (~4wks)	$0.2 M		$0.2 M	
8.9 GeV/c Booster		$3.4 M		$1.1 M
Solenoid and Partial Siberian snake (ramped warm)	$2.0 M		**$0.4 M**	
Two 3 μsec pulsed quadrupoles with power supplies	$0.1 M		$0.1 M	
8.9 GeV/c polarimeter	$0.9 M		$0.2 M	
8.9 GeV/c transfer line spin rotator	$0.1 M		$0.1 M	
Installation (~6wks)	$0.3 M		$0.3 M	
	2-snake BNL type design		1-snake new design	

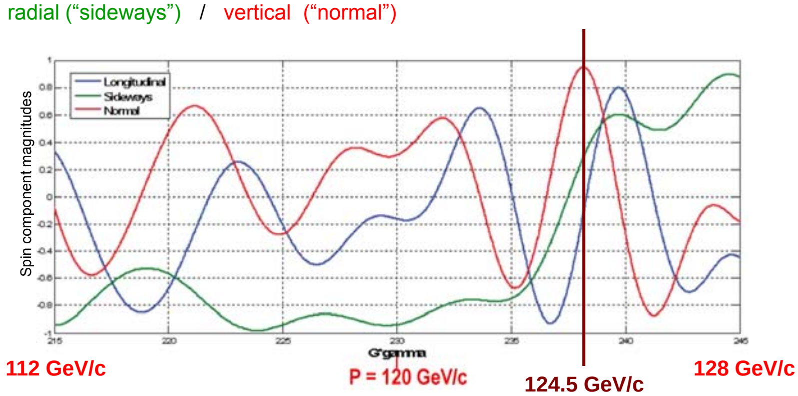
Project costs - II

	June '12		Oct '12	
Recycler Ring		$0.0 M		$0.4 M
one superconducting solenoidal Siberian Snake			$0.1 M	
8.9 GeV/c polarimeter			$0.2 M	
Installation (~2wks)			$0.1 M	
Main Injector		$8.57 M		$1.3 M
Two/**One** superconducting helical Siberian Snake(s)	$4.27 M		**$0.5 M**	
Power supply for snake	$0.7 M		**$0.1 M**	
120 GeV/c polarimeters (CNI & Inclusive)	$0.6 M		$0.4 M	
Cryogenics (2 Buildings@1.06M, Equip: 0.3 M)	$2.7 M		-------	
Installation (~6wks)	$0.3 M		$0.3 M	
120-150 GeV/c Transfer Line		$2.8 M		$0.5 M
120-150 GeV/c polarimeters (CNI & Inclusive)	$0.6 M		$0.4 M	
120-150 GeV/c transfer line spin rotator	$2.0 M		-------	
Installation (~4/2wks)	$0.2 M		$0.1 M	
Miscellaneous		$0.6 M		$0.6 M
Computers, control modules, cables, and interface	$0.3 M		$0.3 M	
Transport, reconfiguration, technical (guess estimate)	$0.3 M		$0.3 M	
Subtotals		$17.67 M		$6.1 M
Project Management estimate (15% of subtotal)	$2.65 M		$0.9 M	
Contingency (~50%)	$10.16 M		$3.5 M	
PROJECT TOTAL		**~$30.485 M**		**~$10.5 M**

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”)



37

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%

38