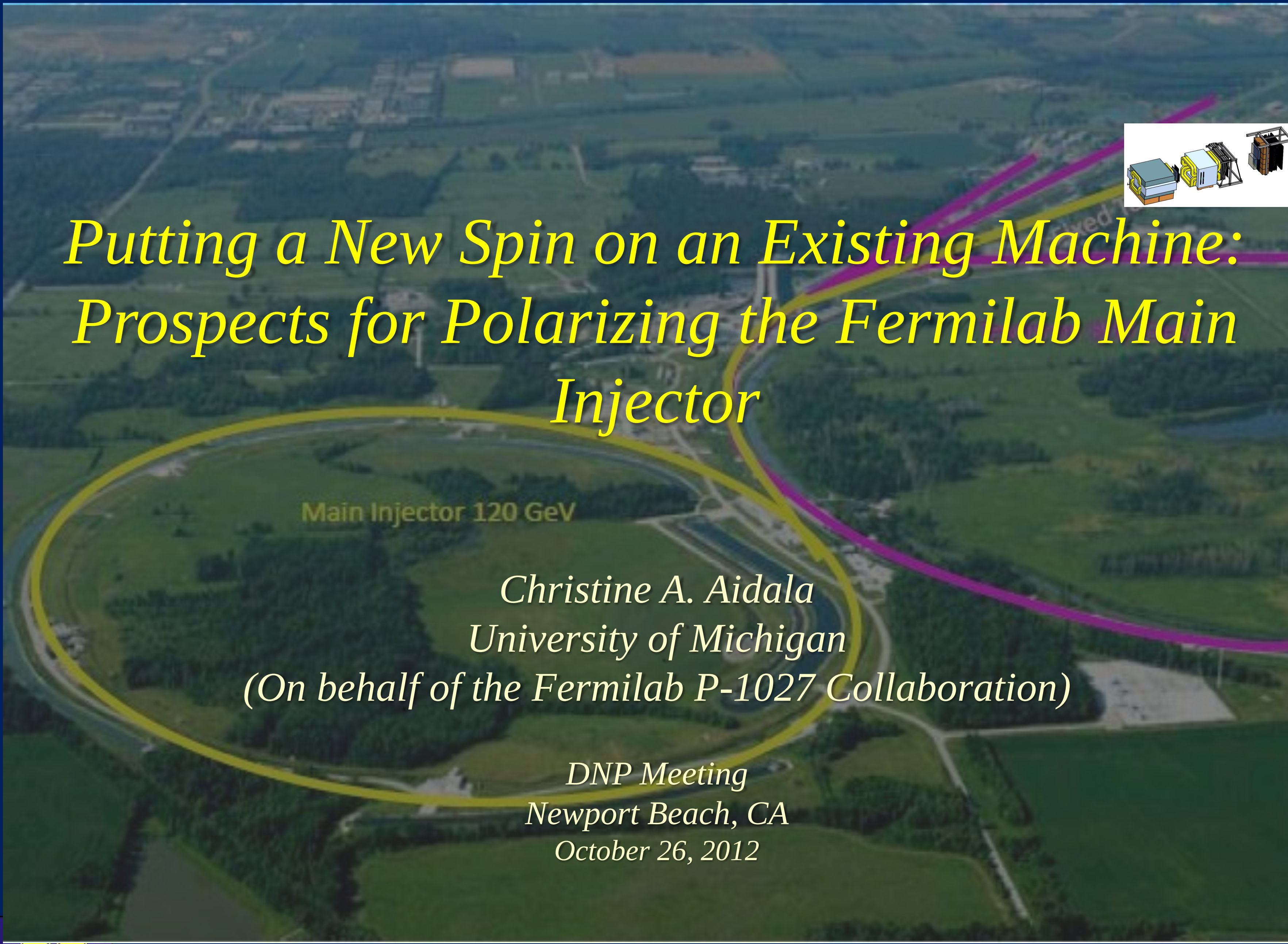


Putting a New Spin on an Existing Machine: Prospects for Polarizing the Fermilab Main Injector

Christine A. Aidala
University of Michigan
(On behalf of the Fermilab P-1027 Collaboration)

DNP Meeting
Newport Beach, CA
October 26, 2012

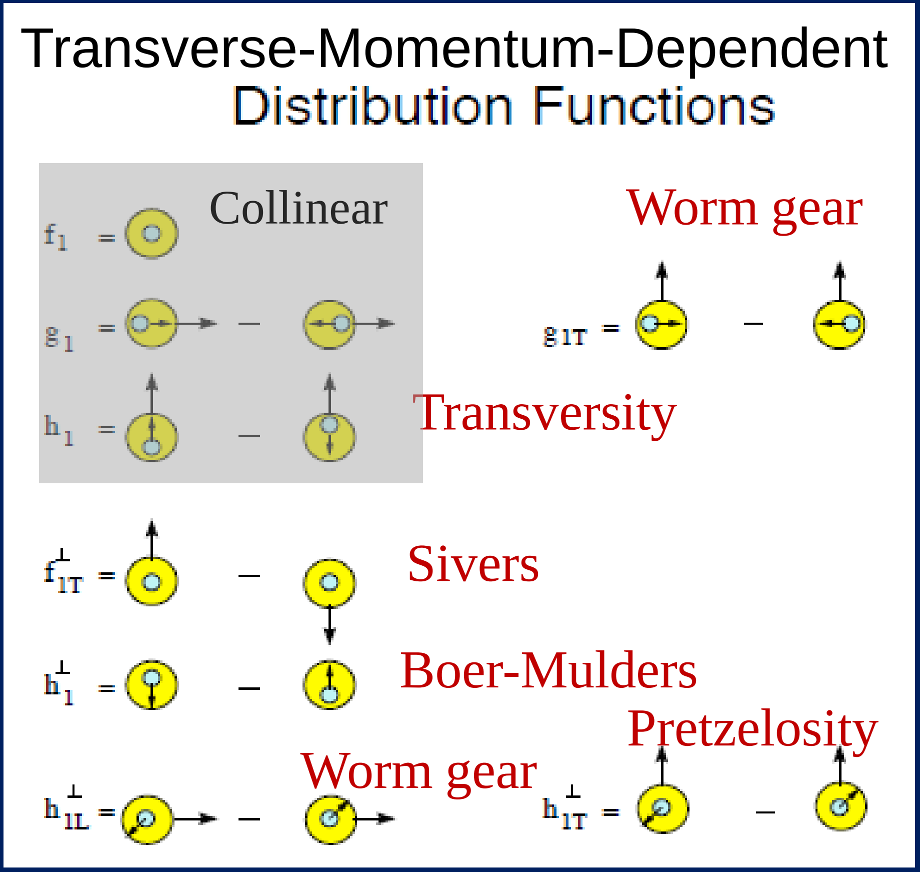
Why polarize the Main Injector?

- Opportunity to continue the several-decade-long, powerful Drell-Yan program at Fermilab with control over an additional d.o.f: spin!
  - Drell-Yan a "clean" process in hadronic interactions (electromagnetic final state)—excellent probe for testing QCD predictions

*In particular: Opportunity to test predicted **color** interactions in QCD via spin-momentum correlation measurements!*

QCD spin-momentum correlations: Transverse-momentum-dependent parton distributions

Mulders & Tangerman, NPB 461, 197 (1996)

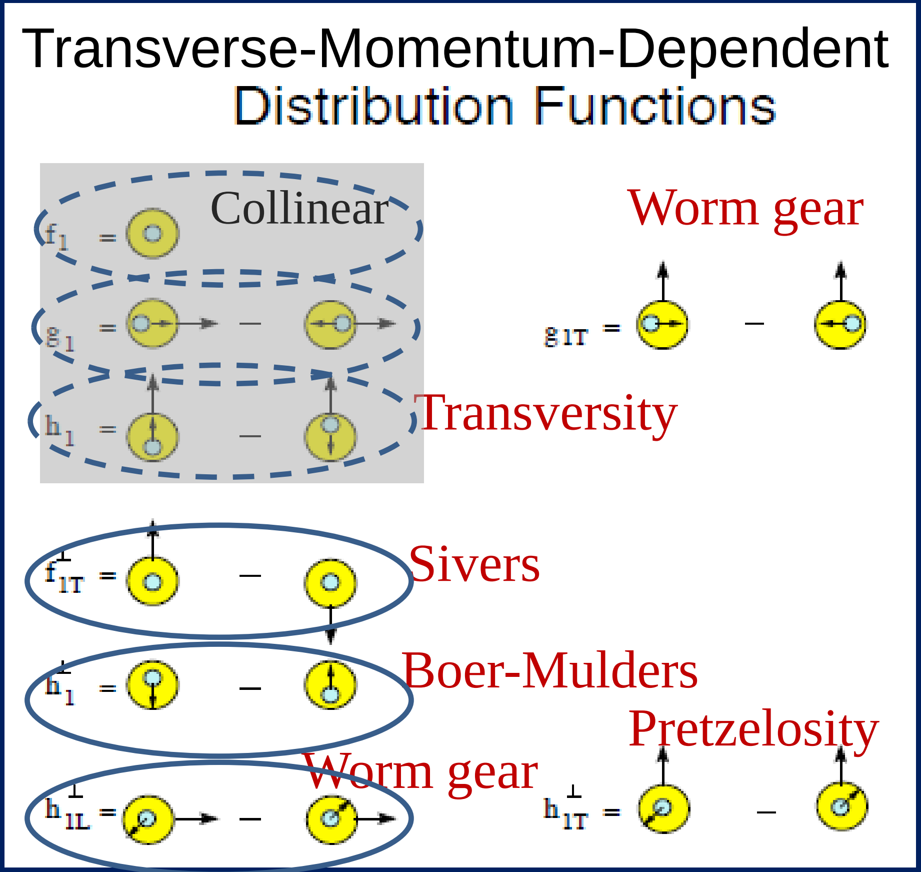


QCD spin-momentum correlations: Transverse-momentum-dependent parton distributions

Mulders & Tangerman, NPB 461, 197 (1996)

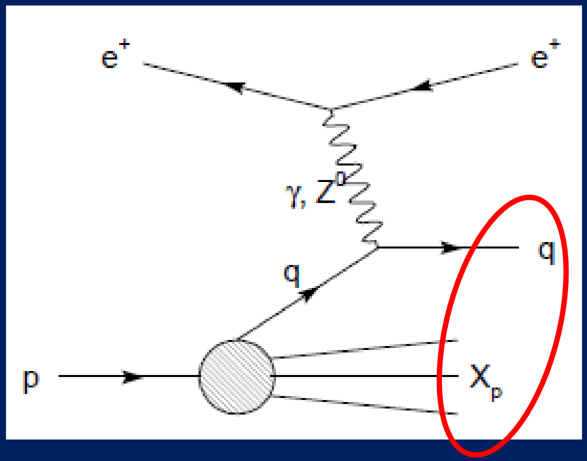
Evidence so far that several of these non-zero!

Transverse-momentum-dependent pdfs provide theoretical framework to describe spin-momentum correlations in nucleon, but difficult to disentangle contributions to inclusive hadron asymmetries
→ Turn to simpler processes: semi-inclusive deep-inelastic scattering and Drell-Yan!

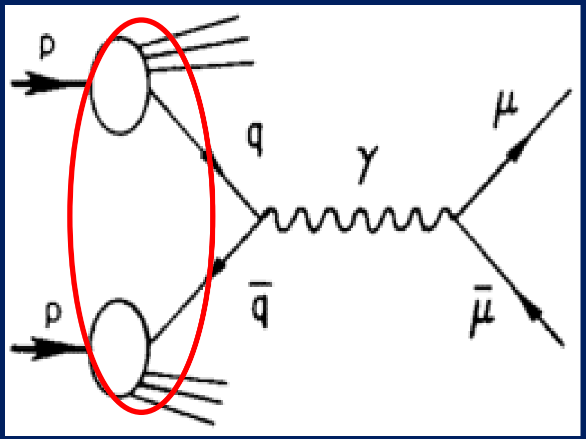


<u>Modified universality</u> of T-odd transverse-momentum-dependent distributions: Color in action!

DIS: attractive final-state interactions



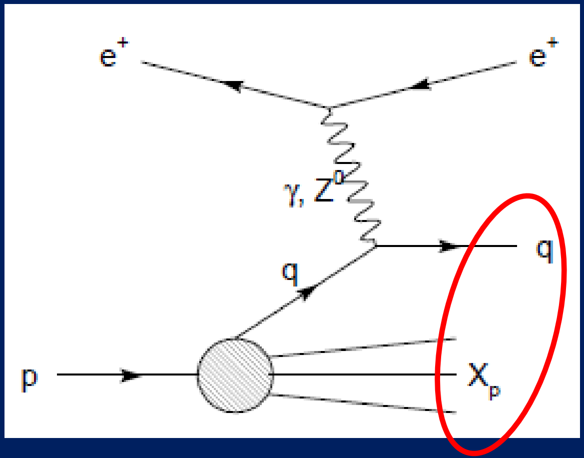
Drell-Yan: repulsive initial-state interactions



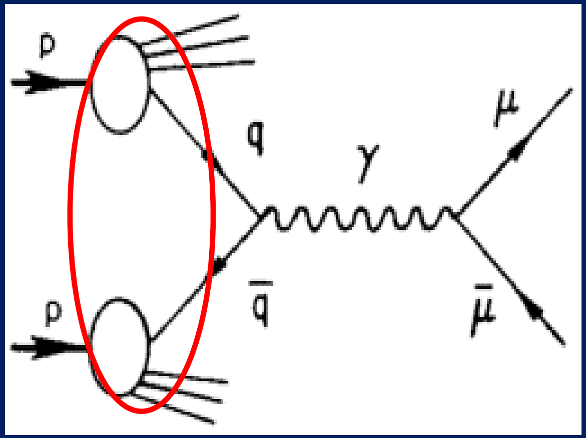
As a result: $\mathrm{Sivers}|_{\mathrm{DIS}} = -\mathrm{Sivers}|_{\mathrm{DY}}$

Modified universality of T-odd transverse-momentum-dependent distributions: Color in action!

DIS: attractive final-state interactions



Drell-Yan: repulsive initial-state interactions

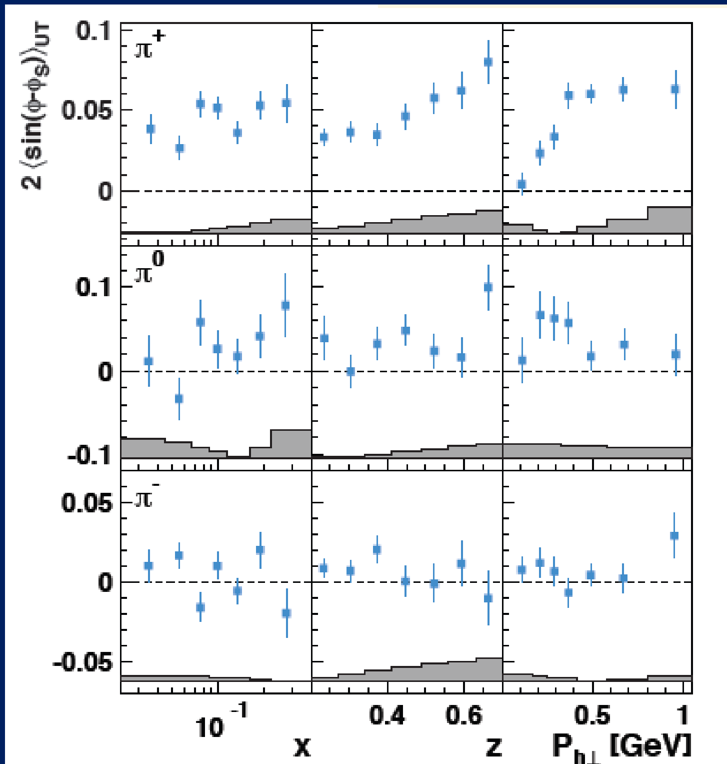


As :

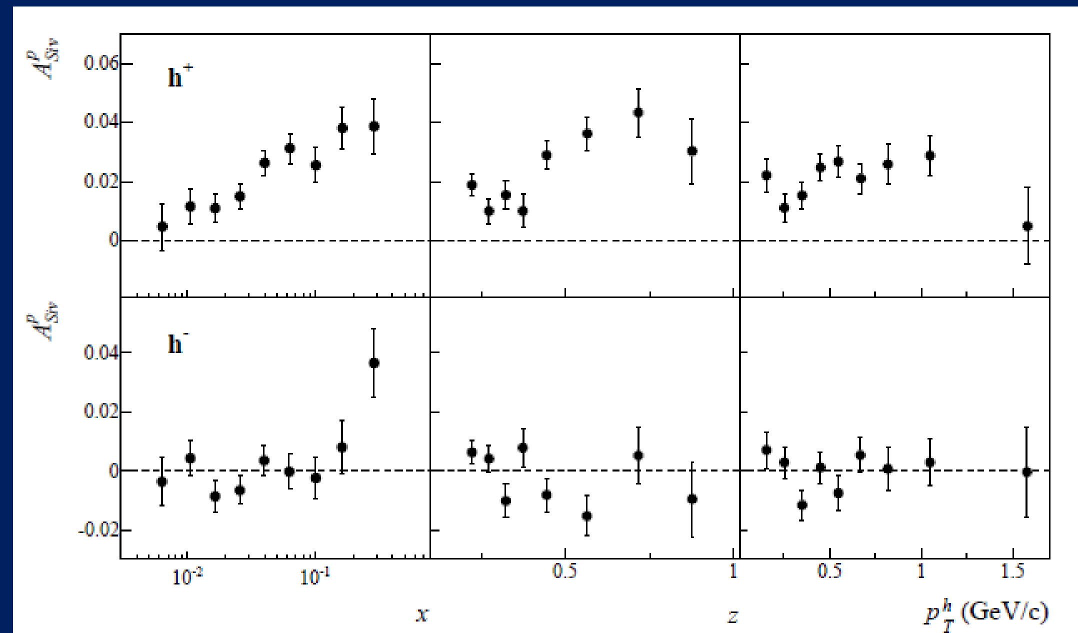
Crucial test of our understanding of QCD!
(NSAC Milestone HP13)

Sivers measurements in SIDIS

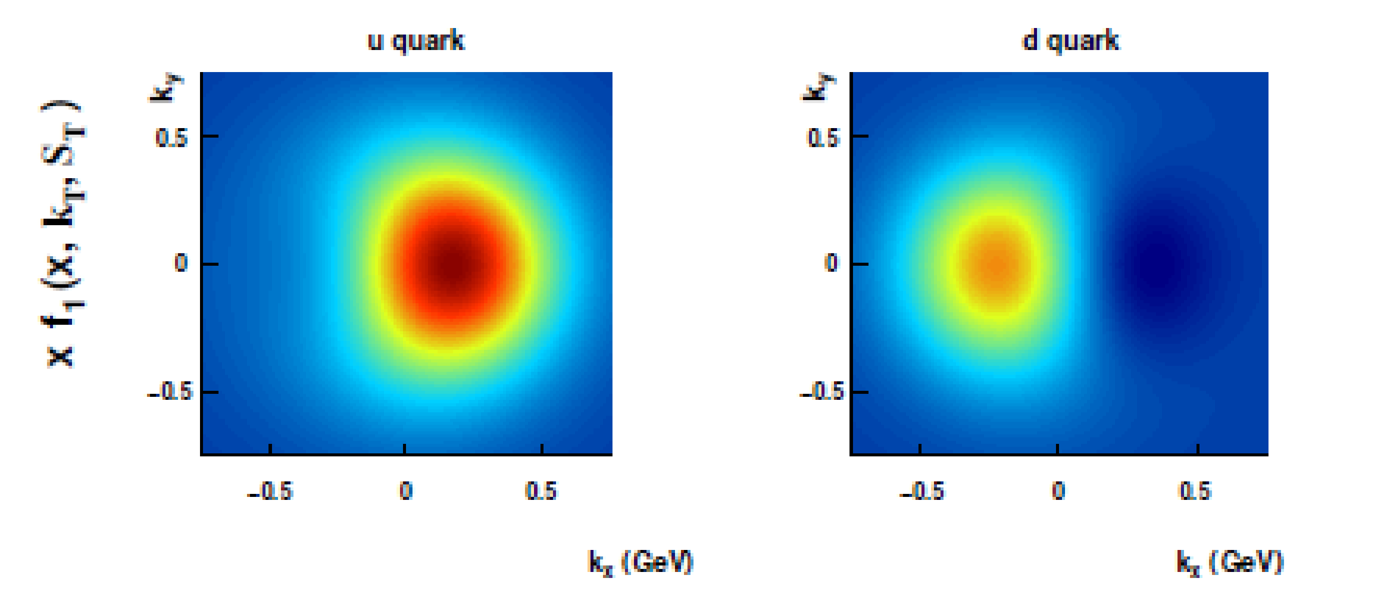
HERMES: PRL 103, 152002 (2009)



COMPASS: arXiv:1205.5122



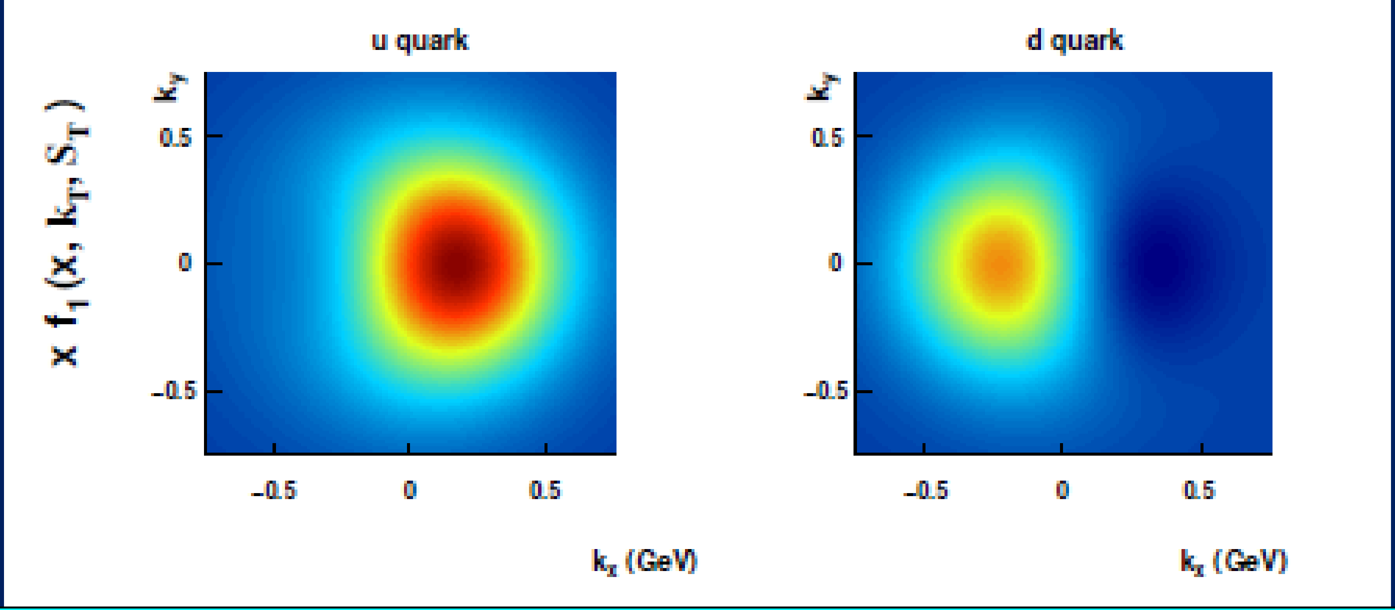
Sivers measurements in SIDIS



Fit to SIDIS data: quark densities in transverse momentum plane for a proton polarized in the +y direction. Up and down quarks orbiting in opposite directions??

Future measurements at JLab 12 GeV planned

Sivers measurements in SIDIS



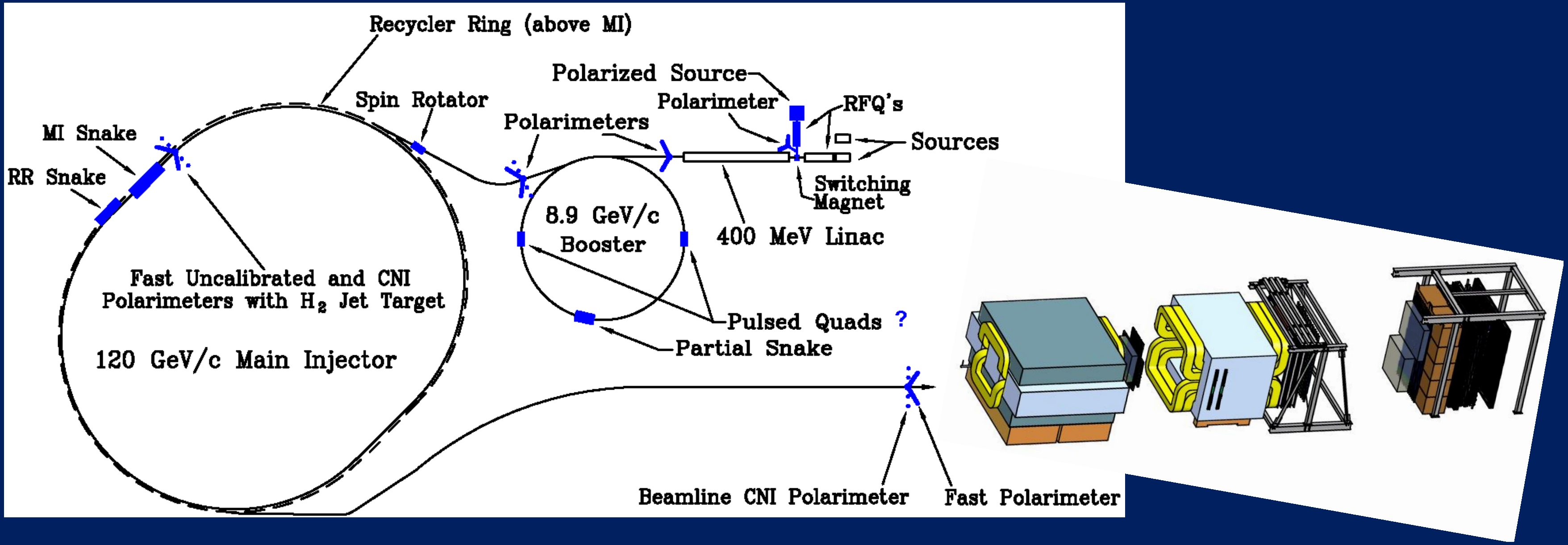
Comparable Drell-Yan measurements needed!

Future measurements at JLab 12 GeV planned

Polarized Drell-Yan at Fermilab Main Injector

- Polarize beam in Main Injector – Proposal submitted to Fermilab management September 2011

arXiv:1110.3042



- Use SeaQuest dimuon spectrometer and target
  - Approved for 2-3 years of running: 3.4 x 10^{18} protons on target
  - By 2015: fully understood, optimized for Drell-Yan, and ready to take pol. beam

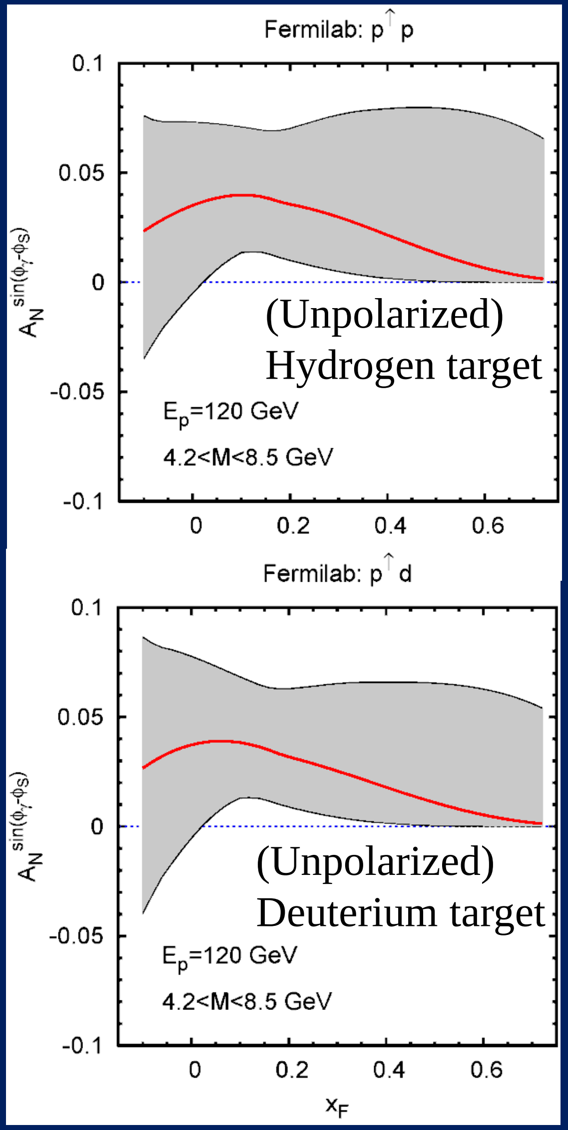
Facts and figures

- 120 GeV polarized proton beam on liquid hydrogen and deuterium targets
- x_{beam} 0.3-0.9, x_{target} 0.1-0.45
- L ~ 2.0 x 10^{35} cm^{-2} s^{-1}
  - 10% available beam time—minimal impact on neutrino program
  - Existing targets could handle 1.0 x 10^{36} cm^{-2} s^{-1}
- 70% polarization
- Run for ~2 years, starting after SeaQuest completed (2015)
- Could install all equipment in the two (already) scheduled 8-week shutdowns in 2014 and 2015
- Future polarized target could open up additional opportunities!
  - Studying antiquarks 0.1<x<0.45 in a polarized nucleon
  - Investigating double-spin asymmetries
  - See talk by Kwangbok Lee

Sivers asymmetry predictions

- Predictions from Anselmino et al. based on fit to SIDIS data
  - Gray error bands correspond to $\Delta\chi^2$=20
- Asymmetries expected to be several %
  - Similar for H and D (measuring Sivers function in polarized proton beam, not in target)

Anselmino et al. priv. comm. 2010

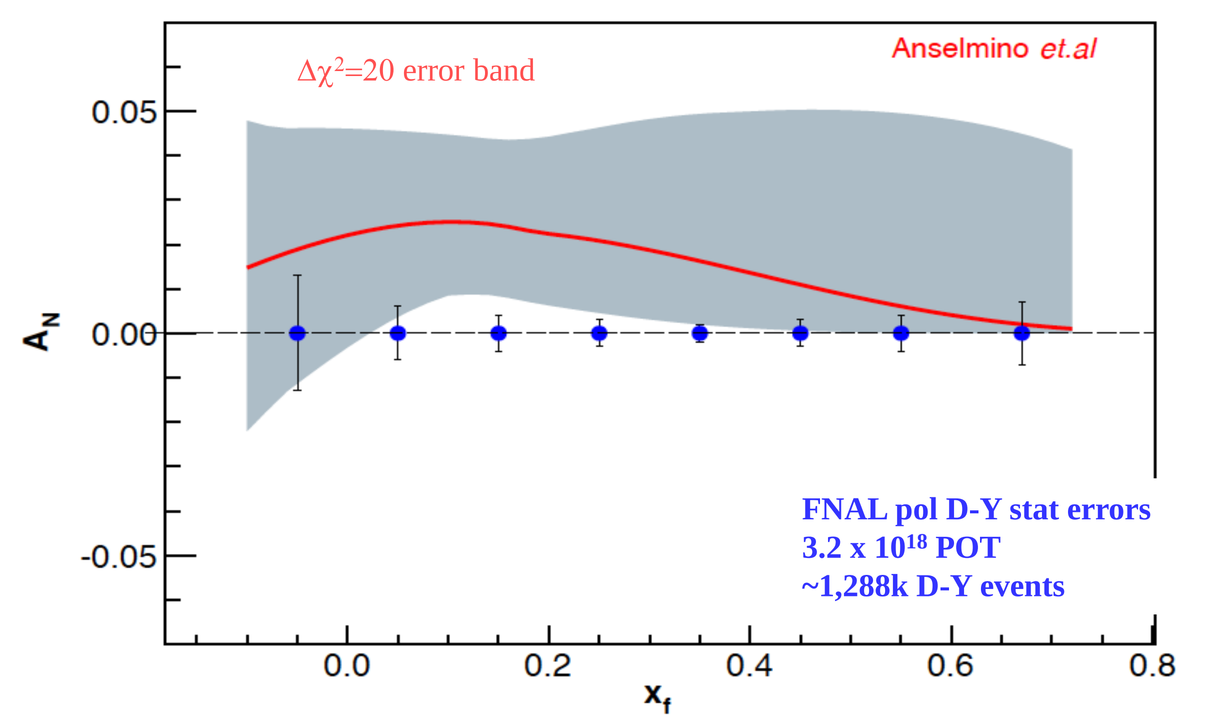


FNAL
120 GeV
polarized beam
$\sqrt{s}$ ~ 15 GeV

FNAL
120 GeV
polarized beam
$\sqrt{s}$ ~ 15 GeV

Experimental sensitivity to Sivers asymmetry

- Luminosity: $L_{av} = 2 \times 10^{35}$ (10% of available beam time: I_{av} = 15 nA)
- 3.2×10^{18} total protons (= 2 yrs at 50% efficiency) with P_b = 70%



Note:

$$A_N = \frac{2}{p} A_{TU}^{\sin f_b}$$

Experimental sensitivity to Sivers asymmetry

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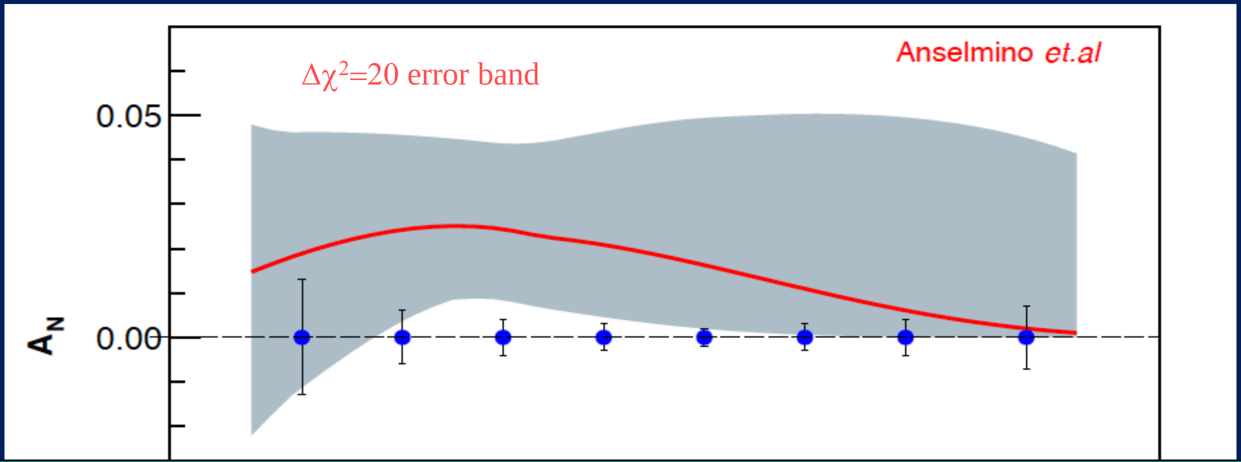


Note:

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

Measure not only sign, but also size and maybe shape of Sivers function!

Additional physics opportunities with transverse polarization

$$\sigma_{UU} \propto f_1 f_1 + \cos 2\phi \, h_1^\perp h_1^\perp ,$$

$$\sigma_{LU} \propto \sin 2\phi \, h_{1L}^\perp h_1^\perp ,$$

Arnold, Metz, Schlegel, PRD79, 034005 (2009)

$$\boxed{\sigma_{TU} \propto f_{1T}^\perp f_1 + \sin 2\phi \, h_1 h_1^\perp + \sin 2\phi \, h_{1T}^\perp h_1^\perp ,}$$

$$\sigma_{LL} \propto g_{1L} g_{1L} + \cos 2\phi \, h_{1L}^\perp h_{1L}^\perp ,$$

$$\sigma_{TL} \propto g_{1T} g_{1L} + \cos 2\phi \, h_1 h_{1L}^\perp + \cos 2\phi \, h_{1T}^\perp h_{1L}^\perp ,$$

$$\boxed{\sigma_{TT} \propto f_{1T} f_{1T} + g_{1T} g_{1T} + \cos 2\phi \, h_1 h_1 + \cos 2\phi \, h_1 h_{1T}^\perp + \cos 2\phi \, h_{1T}^\perp h_{1T}^\perp}$$

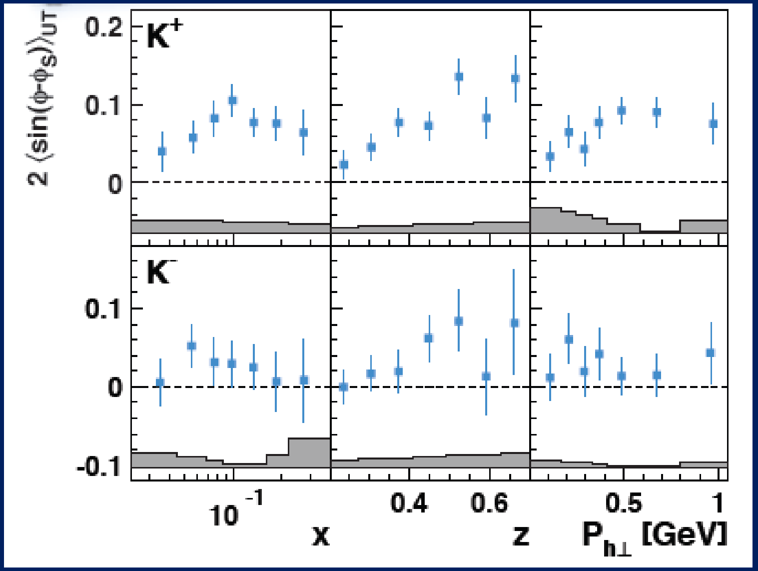
Azimuthal dependence of Drell-Yan cross section in terms of transverse-momentum-dependent distributions

Opportunities with ***longitudinal*** *polarization – See talk by Kwangbok Lee*

Additional physics opportunities with transverse polarization

- Polarized beam → Valence quarks
- Polarized target → Sea quarks
  - Sivers function for sea quarks ~unknown, but hints that it's non-zero
- Single spin: Transversity x Boer-Mulders function
  - Will learn more about Boer-Mulders for sea quarks already from SeaQuest
- Polarized beam *and* target
  - Transversity (valence) x Transversity (sea)
    - Sea quark transversity might be small

HERMES: PRL 103, 152002 (2009)



Status

- Presented to Fermilab PAC June 2012, with follow-up October 2012
- Cost estimate performed in close coordination with Fermilab management earlier this year
  - ~$10.5M, including 50% contingency
- Currently in discussion with funding agencies

P-1027 Collaboration (October 2012)

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 National Laboratory
John Arrington, Don Geesaman Kawtar Hafidi, Roy Holt, Harold Jackson, Paul E. Reimer*, Josh Rubin

University of Colorado
Ed Kinney

Fermilab
Chuck Brown, David Christian

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

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Los Alamos National Laboratory
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University of Maryland
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University of Michigan
Christine Aidala, Wolfgang Lorenzon*, Richard Raymond, Qu Zhongming

National Kaohsiung Normal University
Rurngsheng Guo, Su-Yin Wang

RIKEN
Yuji Goto

Rutgers University
Lamiaa El Fassi, Ron Gilman, Ron Ransome, A. Tadepalli

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

Yamagata University
Yoshiyuki Miyachi

University of Basque Country†
Gunar Schnell

*Co-Spokespersons
†new group (Aug'12)

Collaboration includes most of the SeaQuest groups and one new group (total 16 groups as of October 2012)

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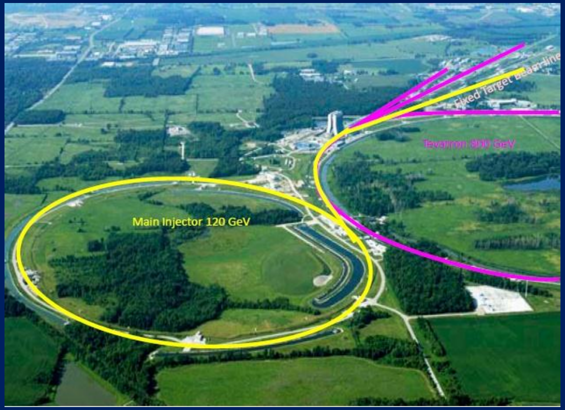
Yamagata University
Yoshiyuki Miyachi

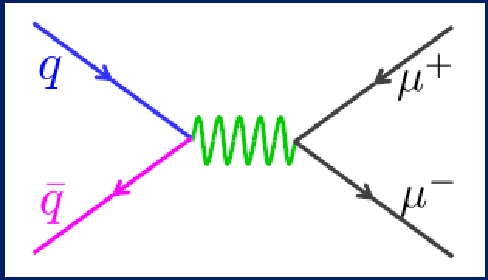
new group (Aug '12)

Working in close collaboration on accelerator issues with Spin@Fermi group, led by Alan Krisch

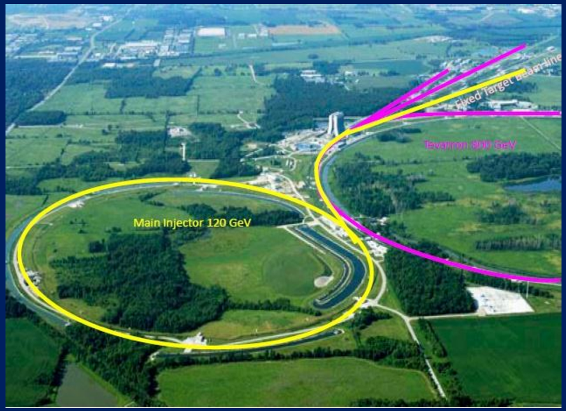
Collaboration includes most of the SeaQuest groups and one new group (total 16 groups as of October 2012)



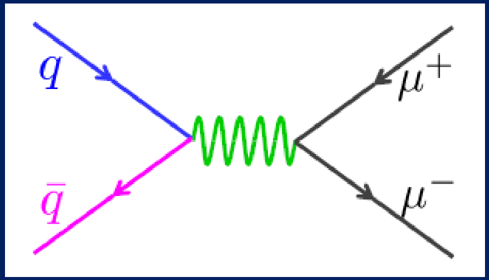
Summary



- Polarizing Main Injector at Fermilab a unique opportunity to perform high-statistics polarized Drell-Yan measurements for $0.35<x<0.85$ as early as ~2015
- Use existing SeaQuest spectrometer and targets
- Would enable mapping out Sivers function at high *x*, providing crucial data to compare *sign*, *magnitude*, *and perhaps shape* to semi-inclusive DIS measurements, testing predicted color interactions in QCD
- Addition of a polarized target would allow access to sea quarks and double-spin measurements → See talk by K. Lee



Summary



- Polarizing Main Injector at Fermilab a unique

Parton *dynamics* within hadrons: a rich area of QCD that we're only just starting to explore!

providing crucial data to compare *sign, magnitude, and*

New collaborators welcome!

- Addition of a polarized target would allow access to sea quarks and double-spin measurements → See talk by K. Lee

Extra material

Planned polarized Drell-Yan experiments

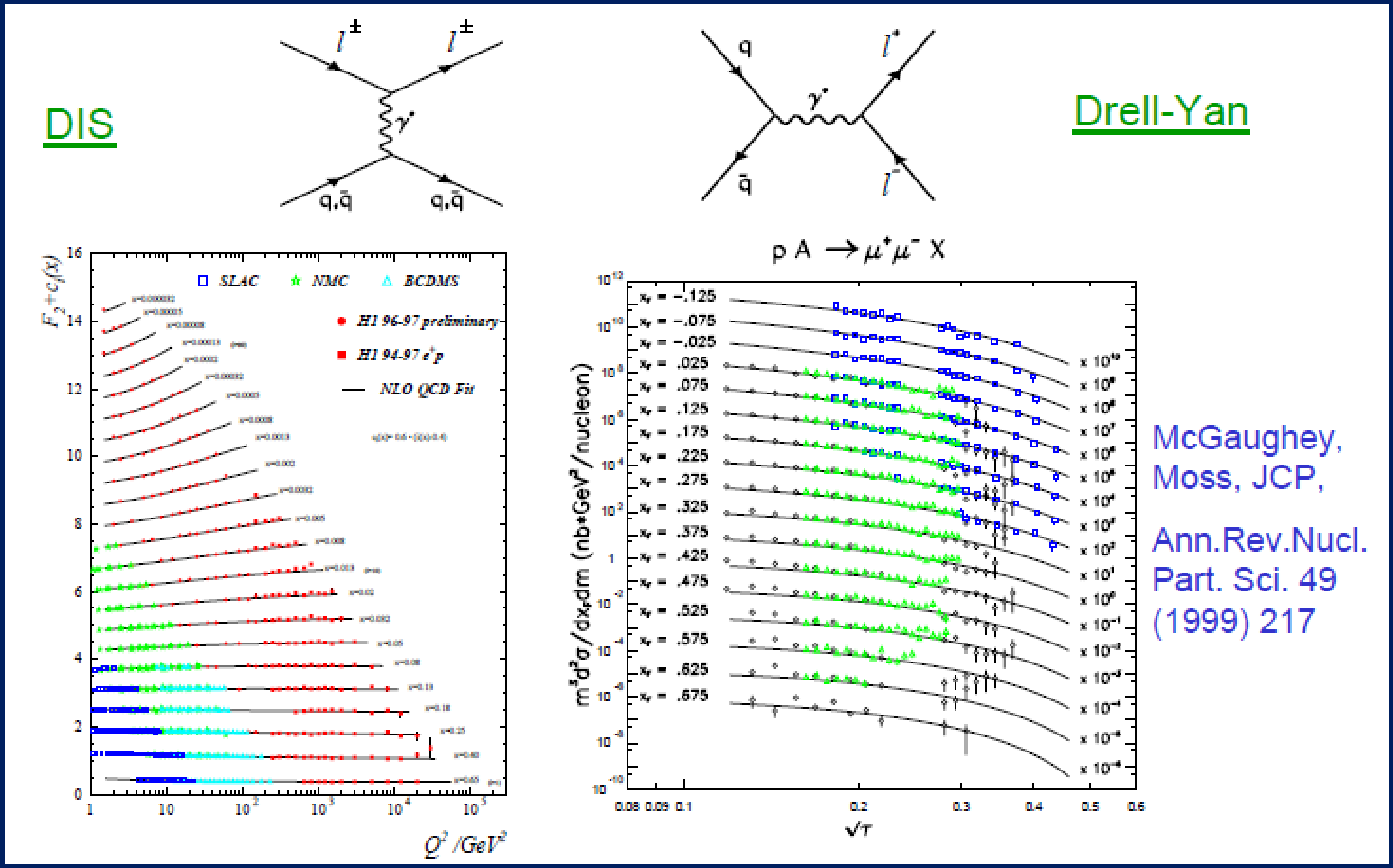
experiment	particles	energy	x_b or x_t	Luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	$x_t = 0.2 - 0.3$	2×10^{33} cm^{-2} s^{-1}	2014
PAX (GSI)	$p^{\uparrow} + p_{bar}$	collider $\sqrt{s}$ = 14 GeV	$x_b = 0.1 - 0.9$	2×10^{30} cm^{-2} s^{-1}	>2017
PANDA (GSI)	$p_{bar} + p^{\uparrow}$	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-2	$p^{\uparrow} + p$	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
pol. SeaQuest[§] (FNAL)	$p^{\uparrow} + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_b = 0.35 - 0.85$	1×10^{36} cm^{-2} s^{-1}	>2015

[§] *L= 1 x 10^{36} cm^{-2} s^{-1} (LH$_2$ tgt limited) / L= 2 x 10^{35} cm^{-2} s^{-1} (10% of MI beam limited)*

Polarized Drell-Yan at Fermilab Main Injector

- Polarized Beam in Main Injector
  - use SeaQuest spectrometer
  - use SeaQuest target
    - liquid H_2 target can take 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-s cycles (1.33-s ramp time, 0.67-s slow extraction) /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)
  - Scenarios:
    - L = 2.0 x 10^{35} /cm^2/s (10% of available beam time: I_{av} = 15 nA)
    - L = 1 x 10^{36} /cm^2/s (50% of available beam time: I_{av} = 75 nA)
  - *x*-range:
    - x_b = 0.35 – 0.85 (valence quarks) x_t = 0.1 – 0.35 (sea quarks)
- Systematic uncertainty in beam polarization measurement $\Delta P_b/P_b$ <5%

Complementarity of Drell-Yan and DIS



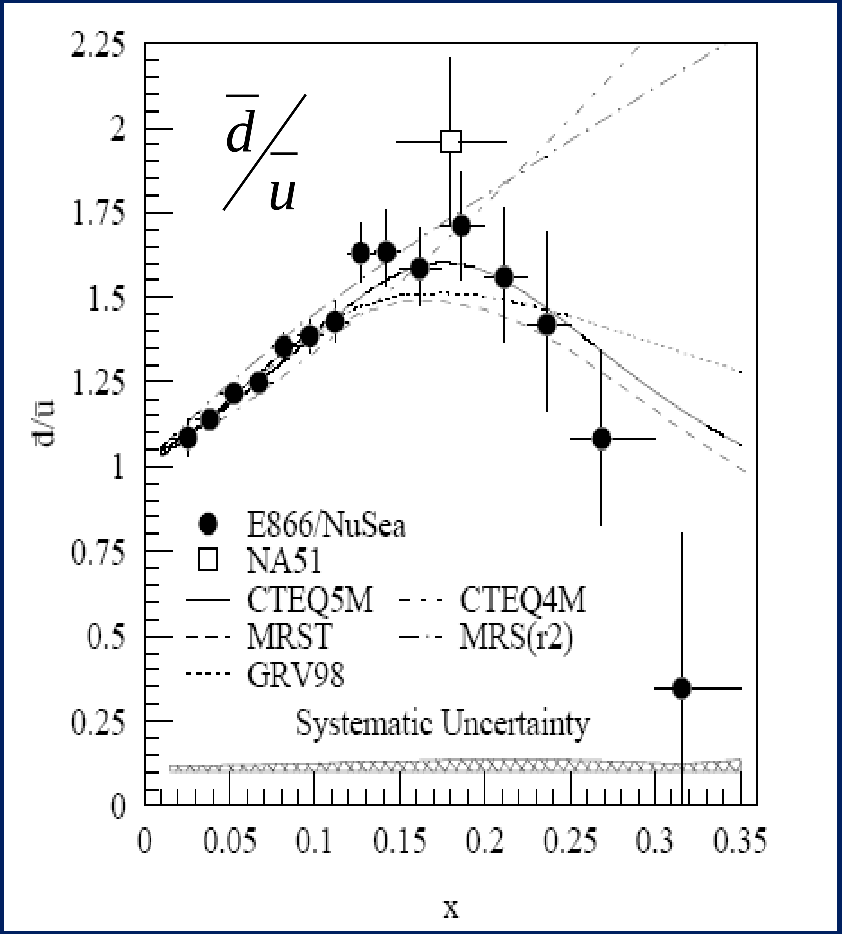
Both Drell-Yan and deep-inelastic scattering are tools to probe the quark and antiquark structure of hadrons!

A (relatively) recent surprise from p+p, p+d collisions

- Fermilab Experiment 866 used proton-hydrogen and proton-deuterium collisions to probe nucleon structure via the Drell-Yan process

$$q + \bar{q} \rightarrow \mu^{+} + \mu^{-}$$

- Anti-up/anti-down difference in the quark sea, with an unexpected *x* behavior!
- Indicates "primordial" sea quarks, in addition to those dynamically generated by gluon splitting!



PRD64, 052002 (2001)

A (relatively) recent surprise from p+p, p+d collisions

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- Anti... in th... unex...
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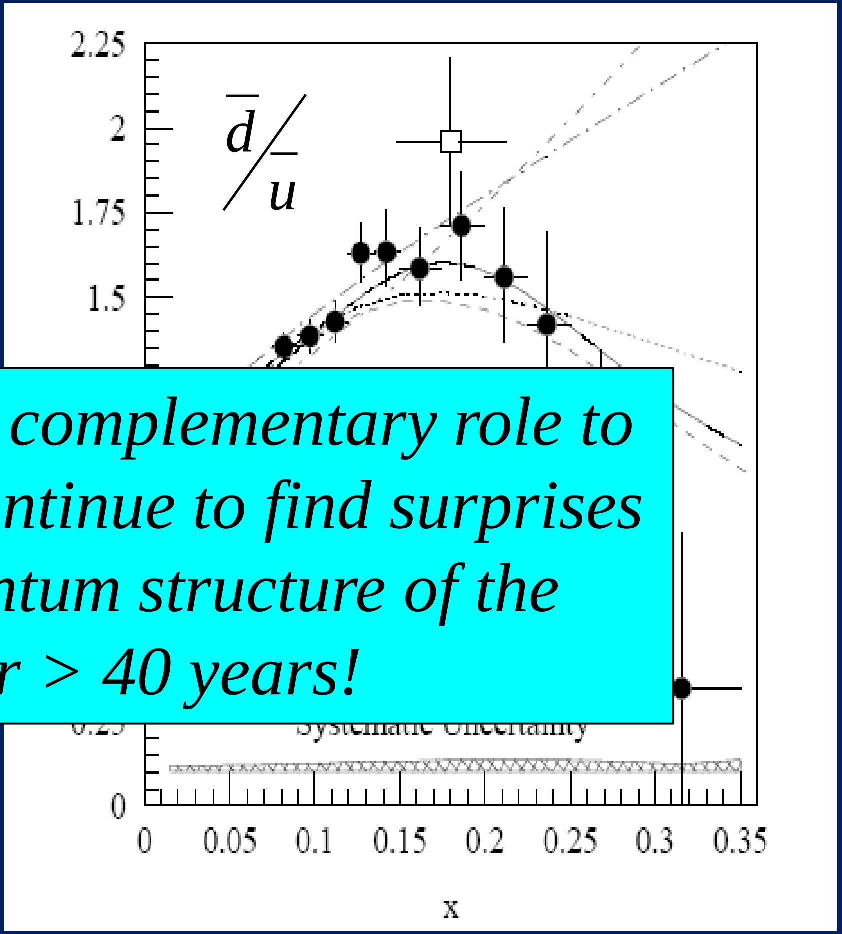


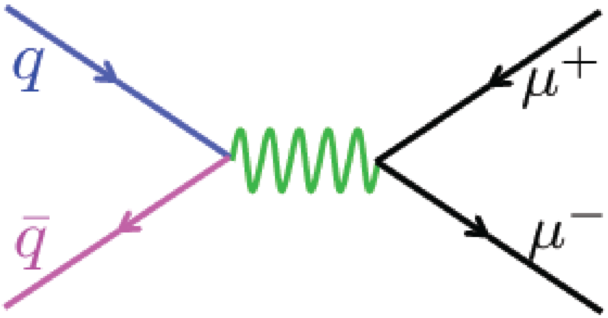
PRD64, 052002 (2001)

Hadronic collisions play a complementary role to e+p DIS and have let us continue to find surprises in the rich linear momentum structure of the proton, even after > 40 years!

Dilepton pair production

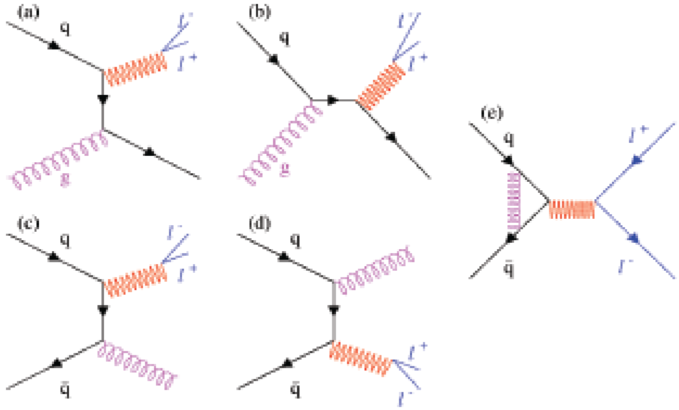
- Measured cross section is a convolution of beam and target parton distributions

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

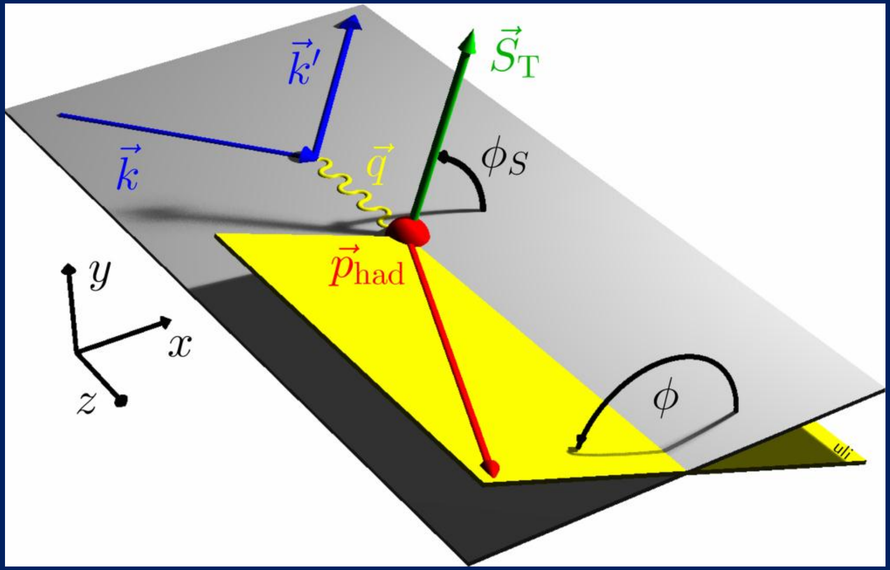


- u-quark dominance
  - $(2/3)^2$ vs. $(1/3)^2$

- Next-to-leading order diagrams complicate the picture and must be considered
- These diagrams are responsible for up to **50% of the measured cross section**
- Intrinsic transverse momentum of quarks (although a small effect, $\lambda > 0.8$)
- **Soft gluon resummation at all orders**



Probing spin-momentum correlations in the nucleon: Measuring transverse-momentum-dependent distributions



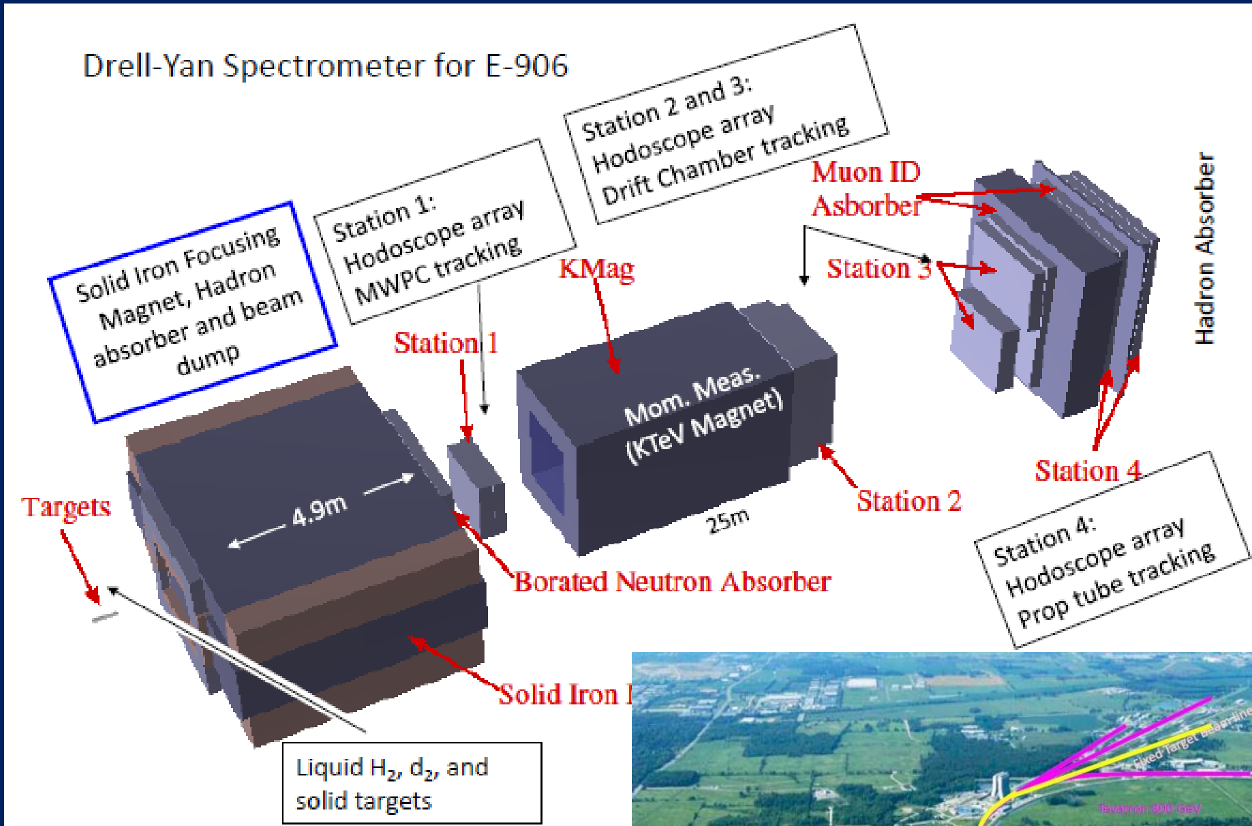
Sivers

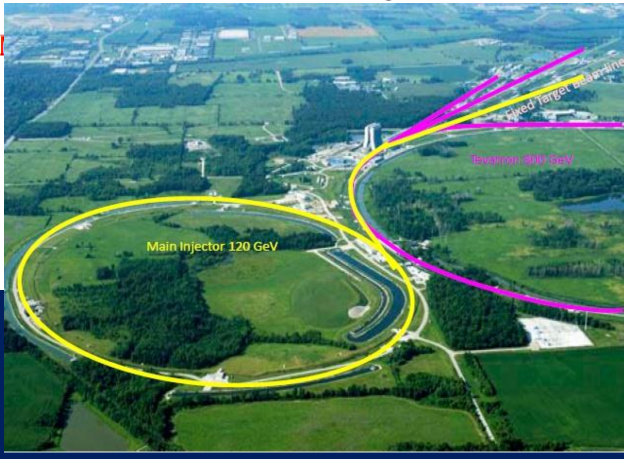
$(\phi - \phi_S)$ **angle of hadron relative to initial quark spin**

Angular dependences in semi-inclusive DIS
→isolation of the various TMD distribution and fragmentation functions

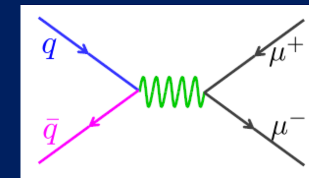
Fermilab E906/SeaQuest:
A dedicated fixed-target Drell-Yan experiment

- Physics programs:
  - Nucleon structure
  - Cold nuclear matter
- 120 GeV/c proton beam from Fermilab Main Injector
- Liquid hydrogen and deuterium, nuclear (C, Ca, W) targets
- Commissioning to start in December, data-taking through ~2015

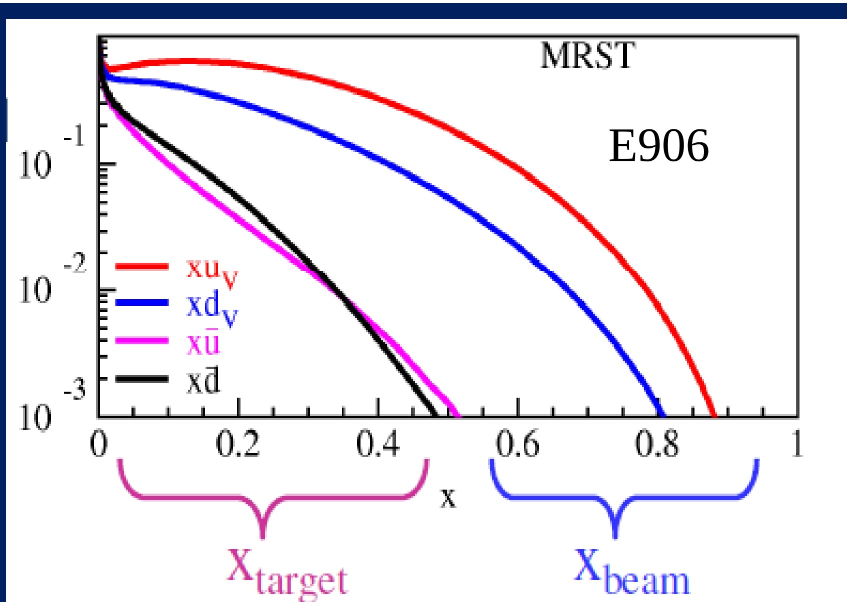




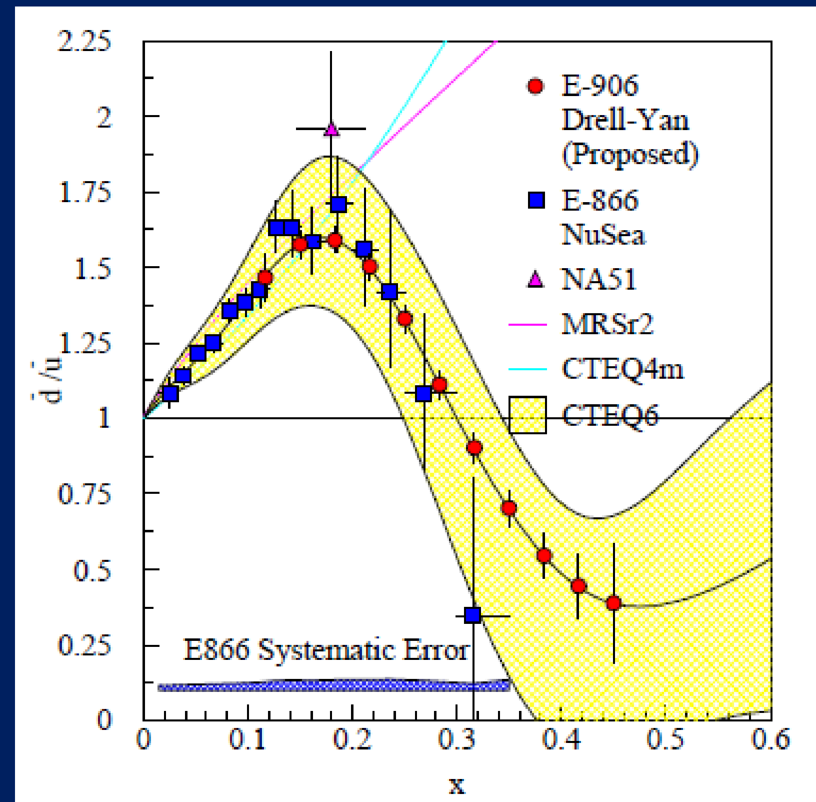
E906/SeaQuest: Probing high-x antiquarks



$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_1(x_1)q_2(x_2) + q_1(x_1)\bar{q}_2(x_2)\right]$$



- Main Injector (E866: 800 GeV)
  - Reach higher *x* values
  - Also improved statistics: D-Y cross section ~1/s



Talk by Chiranjib Dutta, JC7 (Friday)

Transverse Momentum Distributions (Introduction)

survive k_T integration

Sivers Function

k_T - dependent,

Naïve T-odd

Boer-Mulders Function