Transverse Spin Effects in Future Drell-Yan Experiments

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

Transversity 2014, Chia, June 9-13, 2014

Transverse structures of the nucleons

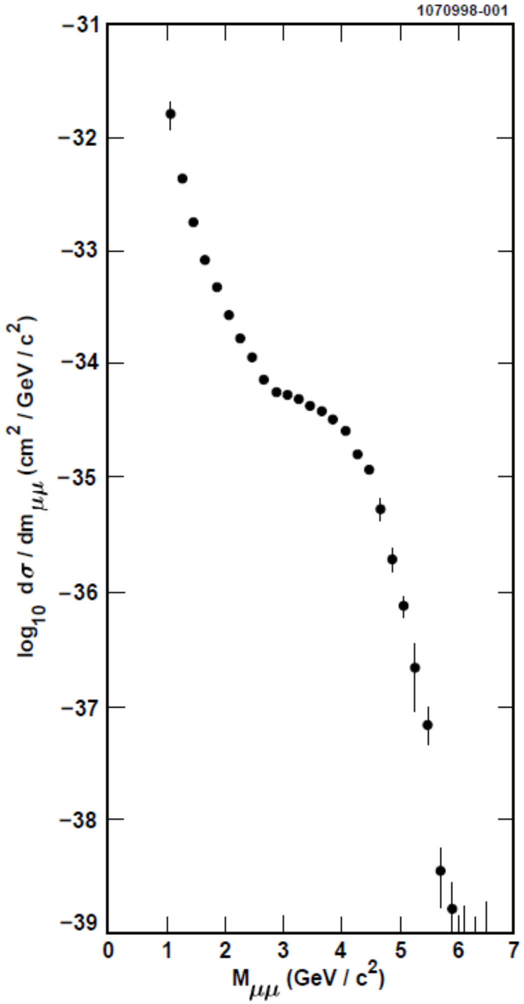
Why is it interesting?

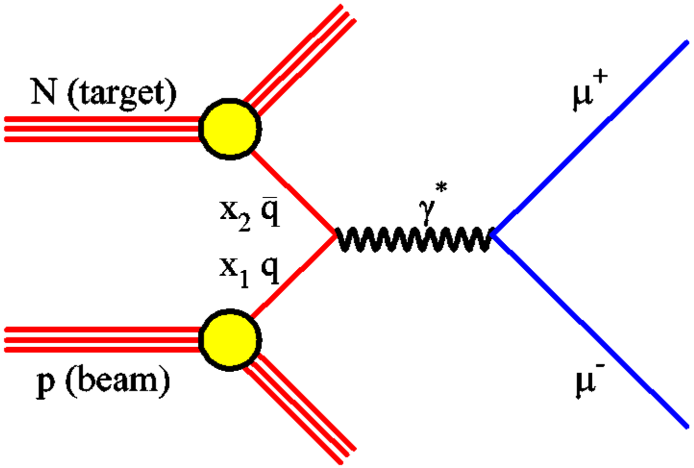
- Transverse degrees of freedom offer new insights on the nucleon structure
- TMDs provide stringent tests for various nucleon models
- The progress of lattice QCD calculations allow direct comparison with the experiments
- Novel parton distributions are accessible by experiments using lepton as well as hadron beams

The Drell-Yan Process

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)





$$\left(\frac{d^2\sigma}{dx_1 dx_2}\right)_{D.Y.} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_a e_a^2 \left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1) q_a(x_2) \right]$$

Naive Drell-Yan and Its Successor*

T-M. Yan
Floyd R. Newman Laboratory of Nuclear Studies
Cornell University
Ithaca, NY 14853

September 23, 2013

Abstract

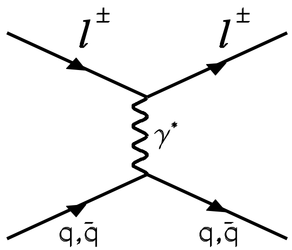
We review the development in the field of lepton pair production since proposing parton-antiparton annihilation as the mechanism of massive lepton pair production. The basic physical picture of the Drell-Yan model has survived the test of QCD, and the predictions from the QCD improved version have been confirmed by the numerous experiments performed in the last three decades. The model has provided an active theoretical arena for studying infrared and collinear divergences in QCD. It is now so well understood theoretically that it has become a powerful tool for new phyiscs information such as precision measurements of the W mass and lepton and quark sizes.

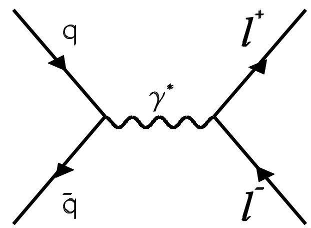
- "… our original crude fit did not even remotely resemble the data. Sid and I went ahead to publish our paper because of the model's simplicity…"
- "… the successor of the naïve model, the QCD improved version, has been confirmed by the experiments…"
- "The process has been so well understood theoretically that it has become a powerful tool for precision measurements and new physics."

*Talk given at the Drell Fest, July 31, 1998, SLAC on the occasion of Prof. Sid Drell's retirement.

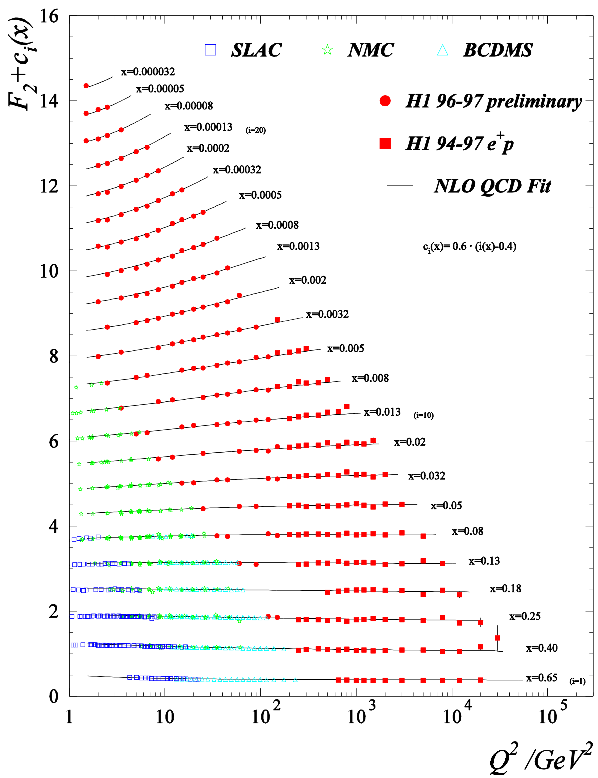
Complimentality between DIS and Drell-Yan

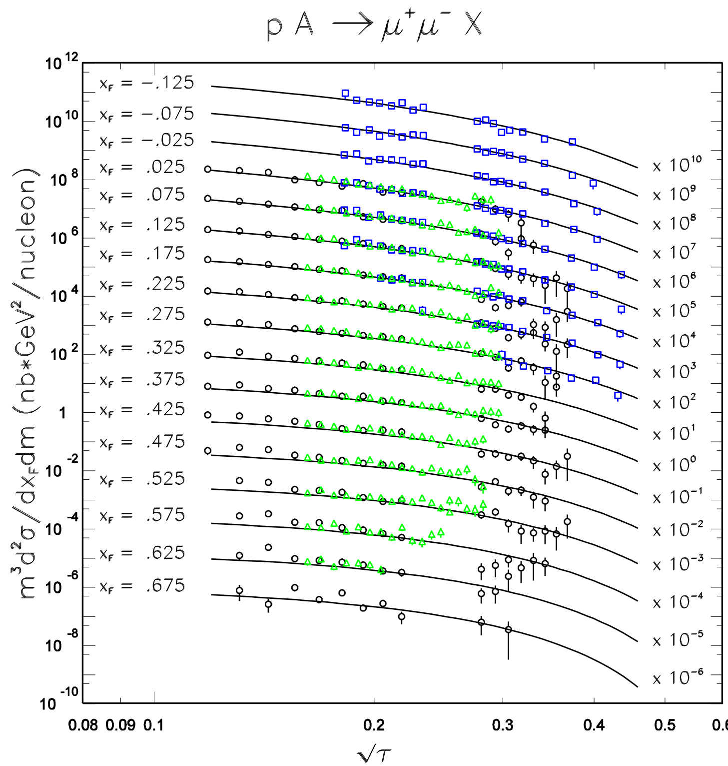
DIS





Drell-Yan





Ann.Rev.Nucl. Part. Sci. 49 (1999) 217

Both DIS and Drell-Yan process are tools to probe the quark and antiquark structure in hadrons (factorization, universality)

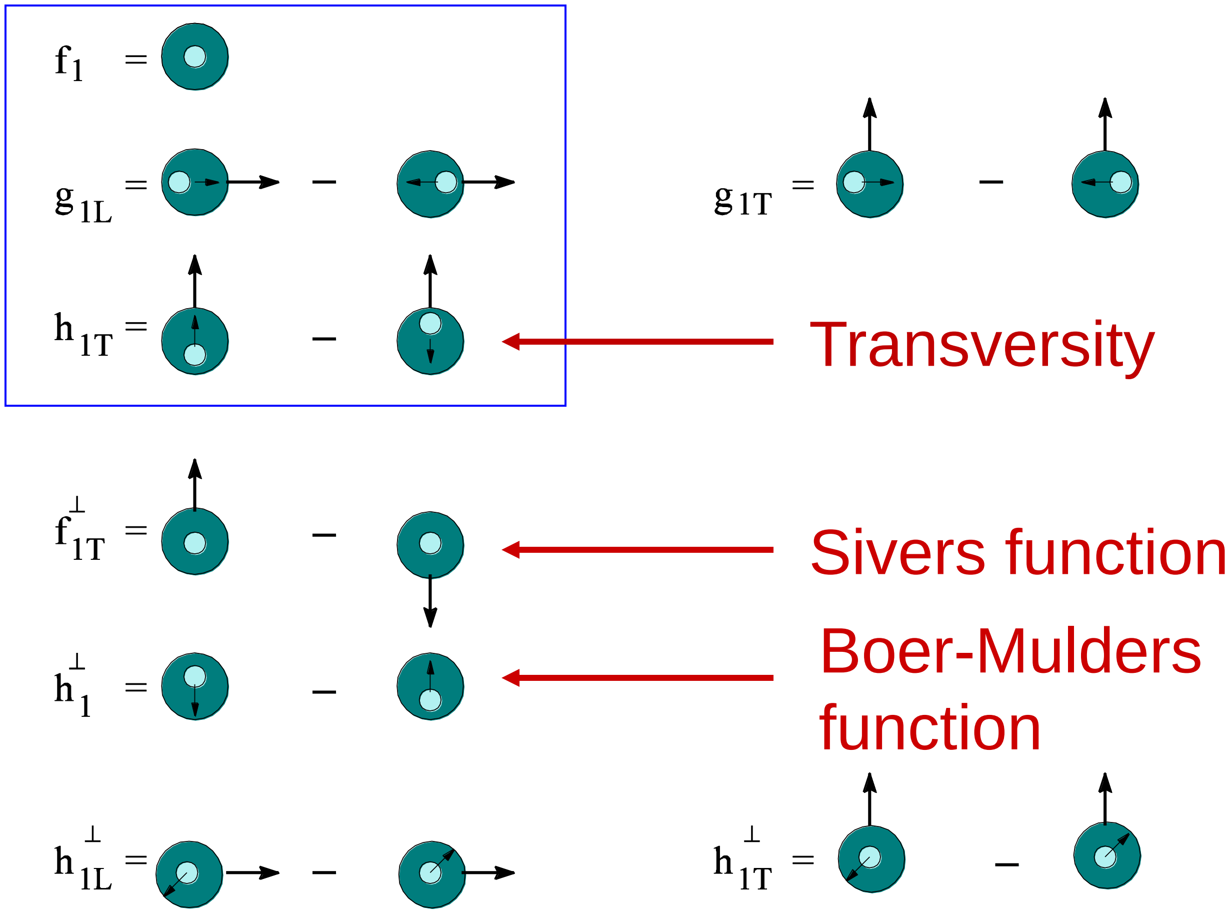
Transverse Momentum Dependent (TMD) Quark Distributions

Leading-Twist Quark Distributions

(A total of eight distributions)

Three survive after K⊥ integration

The other five are transverse momentum (K⊥) dependent (TMD)



Three parton distributions describing transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

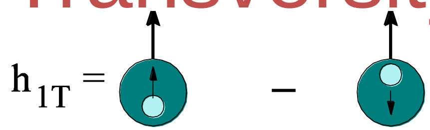
$\vec{s}_\perp^q$

3) Quark transverse momentum

$\vec{k}_\perp^q$

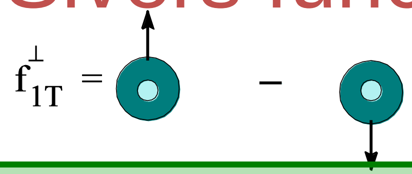
$\Rightarrow$ Three different correlations

1) Transversity



Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function



Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function

Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

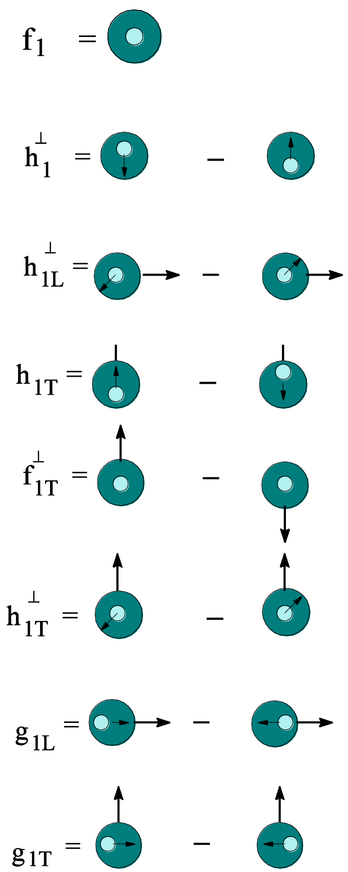
Transversity and TMD PDFs are probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

Boer-Mulders

Transversity

Sivers



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarzied beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

Transversity and Transverse Momentum Dependent PDFs are also probed in Drell-Yan

a) Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}(x_q)h_1^{\perp}(x_{\bar{q}})\cos(2\phi)$

b) Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$$A_N^{DY} \propto f_{1T}^{\perp}(x_q)\, f_{\bar{q}}(x_{\bar{q}})$$

c) Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$$A_{TT}^{DY} \propto h_1(x_q)h_1(x_{\bar{q}})$$

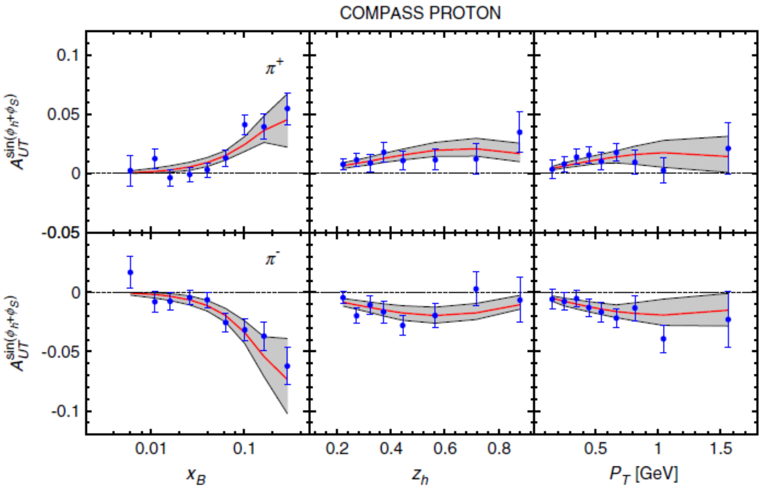
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

•9

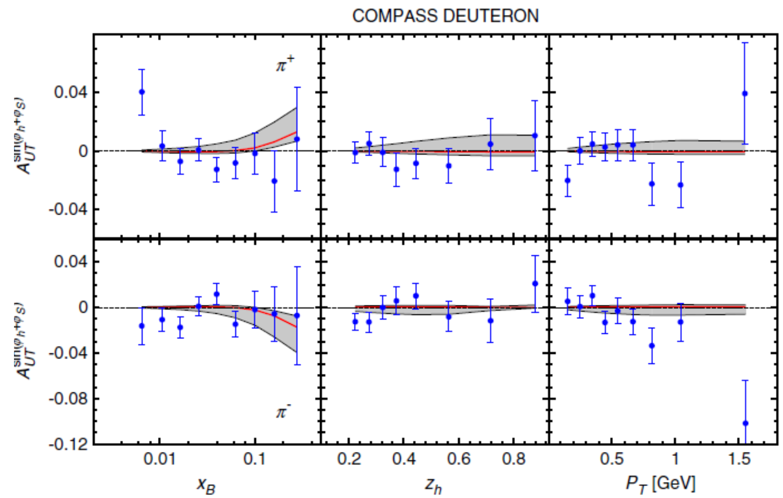
Extraction of Transversity and Collins fragmentation function from SIDIS and Belle data

Torino group, Anselmino et al., PRD 87, 094019 (2013)



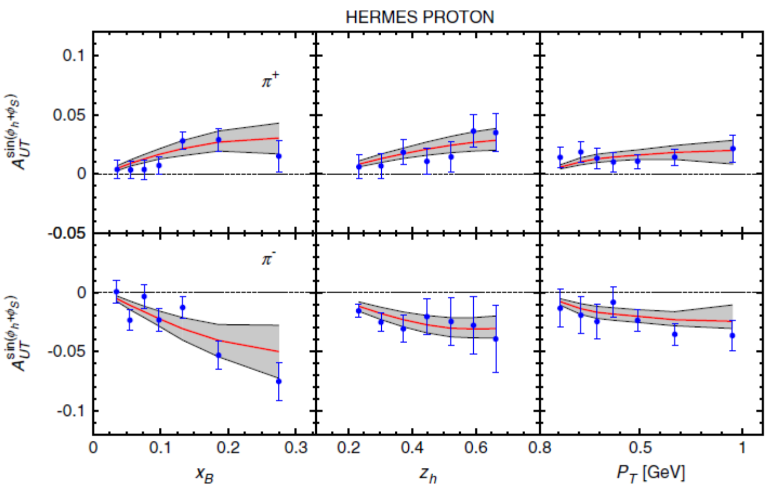
SIDIS

on *p*



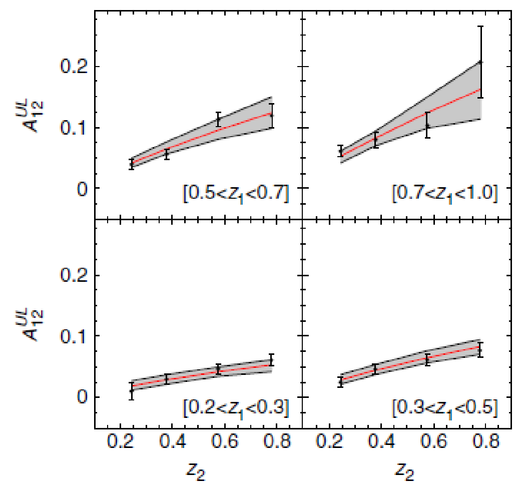
SIDIS

on *d*



SIDIS

on *p*



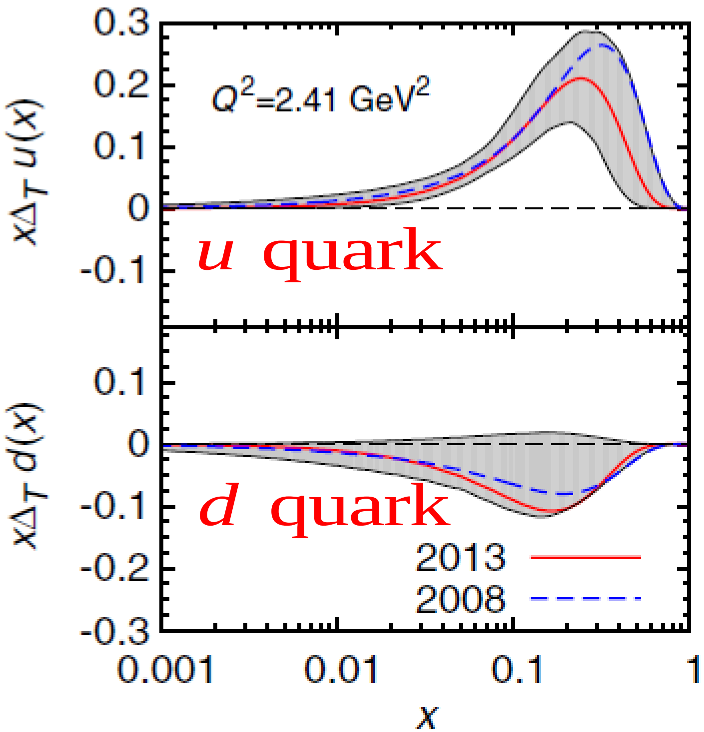
Belle

$e^{+}e^{-}$

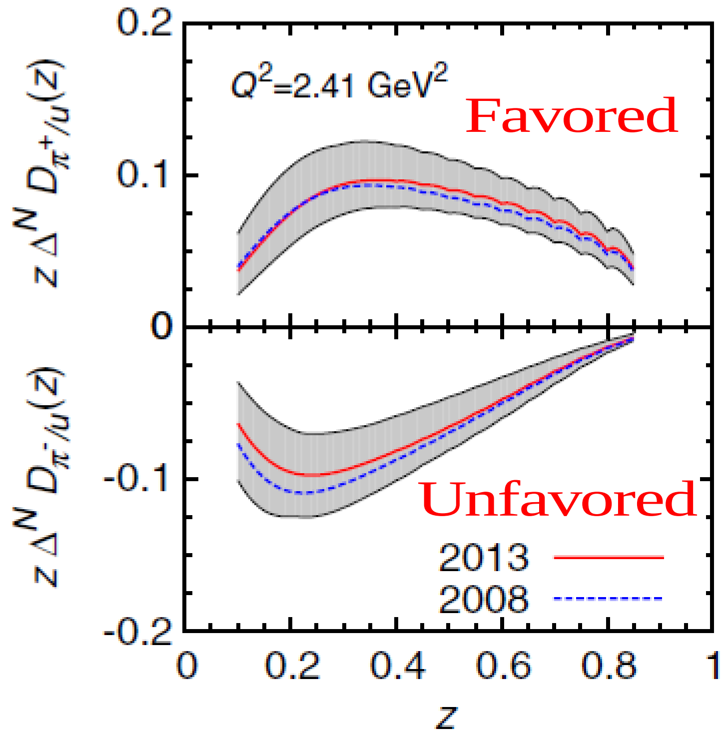
Extraction of Transversity and Collins fragmentation function from SIDIS and Belle data

Torino group, Anselmino et al., PRD 87, 094019 (2013)

Transversity

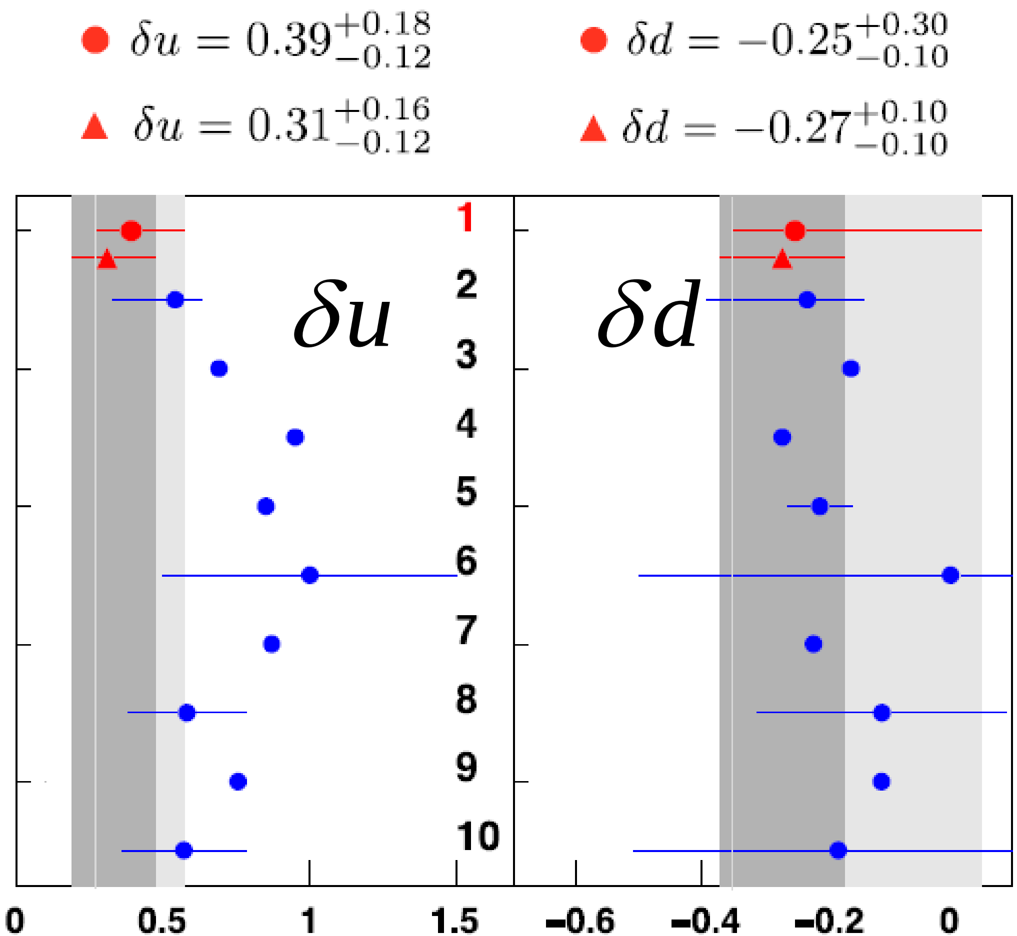


Collins pion FF



Extraction of nucleon tensor charge

Torino group, Anselmino et al., PRD 87, 094019 (2013)



$\Delta u = 0.787$ $\Delta d = -0.319$

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

1 : Extractions from global fits (using two different Collins FF parameterizations)

2-10: Predictions from various models (including LQCD)

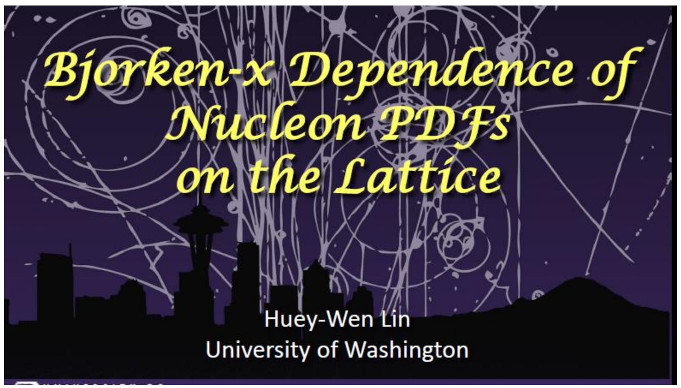
- Tensor charges are smaller than axial charge
- Difference between data and theory could be partly caused by neglecting sea transversity in the extraction?

Recent progress in LQCD suggests the possibility to calculate the *x*-dependence of parton distributions

PRL **110**, 262002 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Parton Physics on a Euclidean Lattice

Xiangdong Ji[1,2]



Transversity Distribution

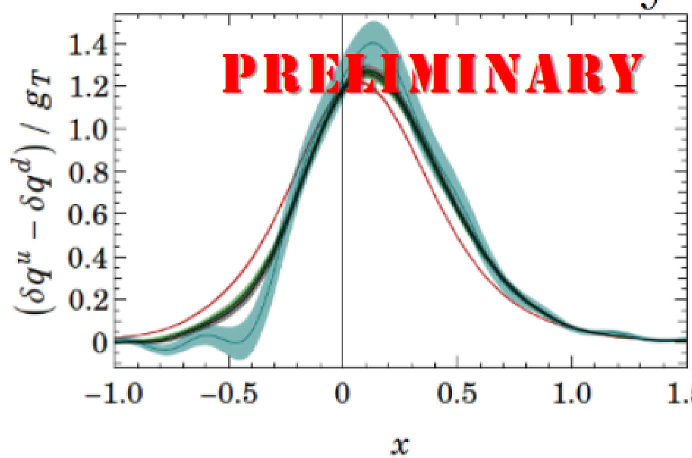
§ Exploratory study

- We found $\delta\bar{u} < \delta\bar{d}$ with large sea asymmetry
- Chiral quark-soliton model

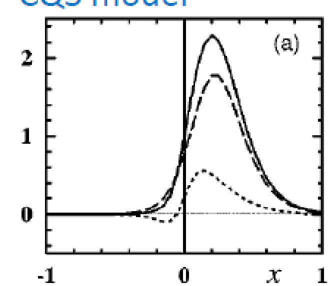
$$\int dx\, \frac{\delta\bar{u}(x) - \delta\bar{d}(x)}{g_T} \approx -0.320\,(18)$$

$$\int dx\, \left(\delta\bar{u}(x) - \delta\bar{d}(x)\right) \approx -0.082$$

B. Dressler et al., hep-ph/9809487



CQS model



P. Schweitzer et al. PRD 64, 034013 (2001)

The *x*-dependence of the quark and antiquark transversity distributions can be calculated (not just their moments)

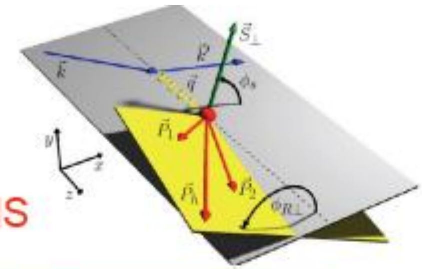
Predicts large sea-quark transversity!

Some remaining questions on transversity to be addressed by future experiments

- Magnitude and sign of the sea-quark transversity?
- Large sea-quark flavor asymmetry for transversity from recent lattice QCD (similar to the unpolarized sea and the helicity sea)?
- Other methods to extract the transversity (without using the Collins fragmentation functions)?
- Verify the expected slower Q^2-evolution with data at much higher Q^2 (EIC)?

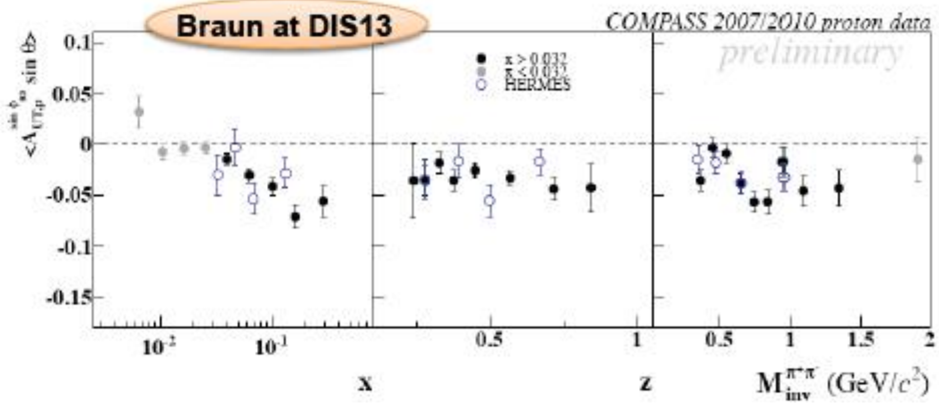
Extraction of Transversity and dihadron interference fragmentation function from SIDIS and Belle data

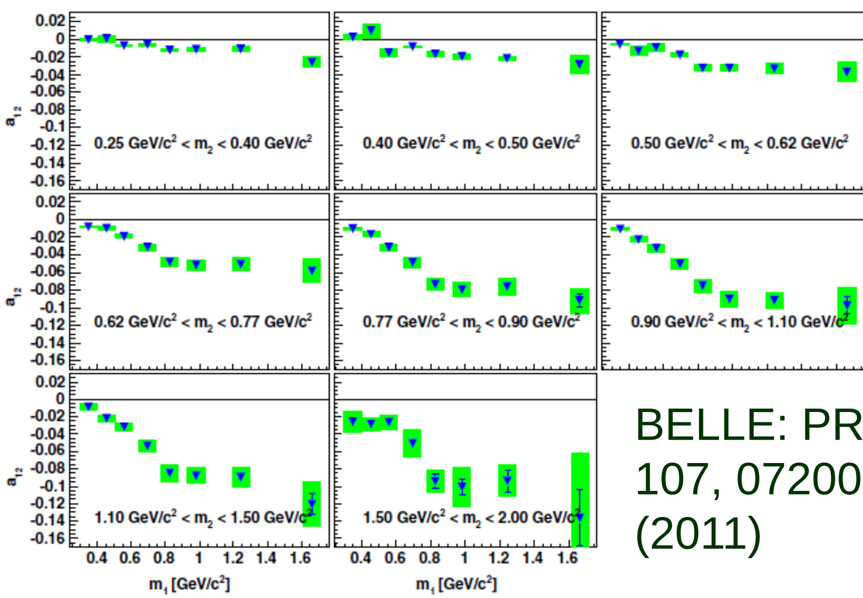
SIDIS



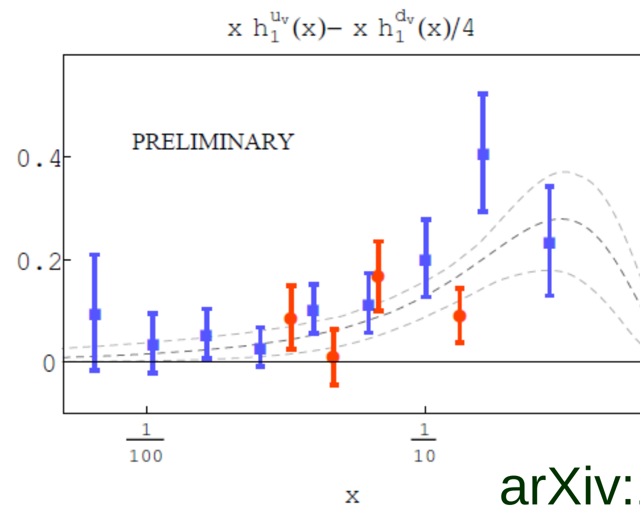
COMPASS, arXiv: 1202.6150

HERMES, arXiv: 0803.2367





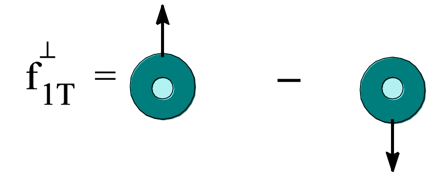
BELLE: PRL 107, 072004 (2011)



arXiv:1206.1836

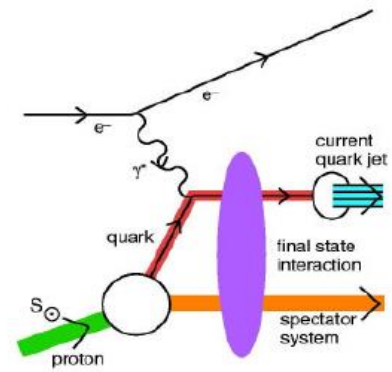
Extracted transversity consistent with single-hadron SIDIS method

Sivers Function (proposed in 1990)

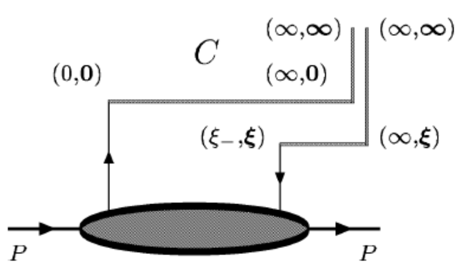


• On the basis of time reversal arguments:
$f_{1T}^{\perp}(x,p_T^2)=0$
Collins, NPB396, 161(1993)

• Final-state interaction from gluon exchange between the quark and the spectator lead to nonzero Sivers function.
Brodsky, Hwang & Schmidt, PLB530, 99(2002).



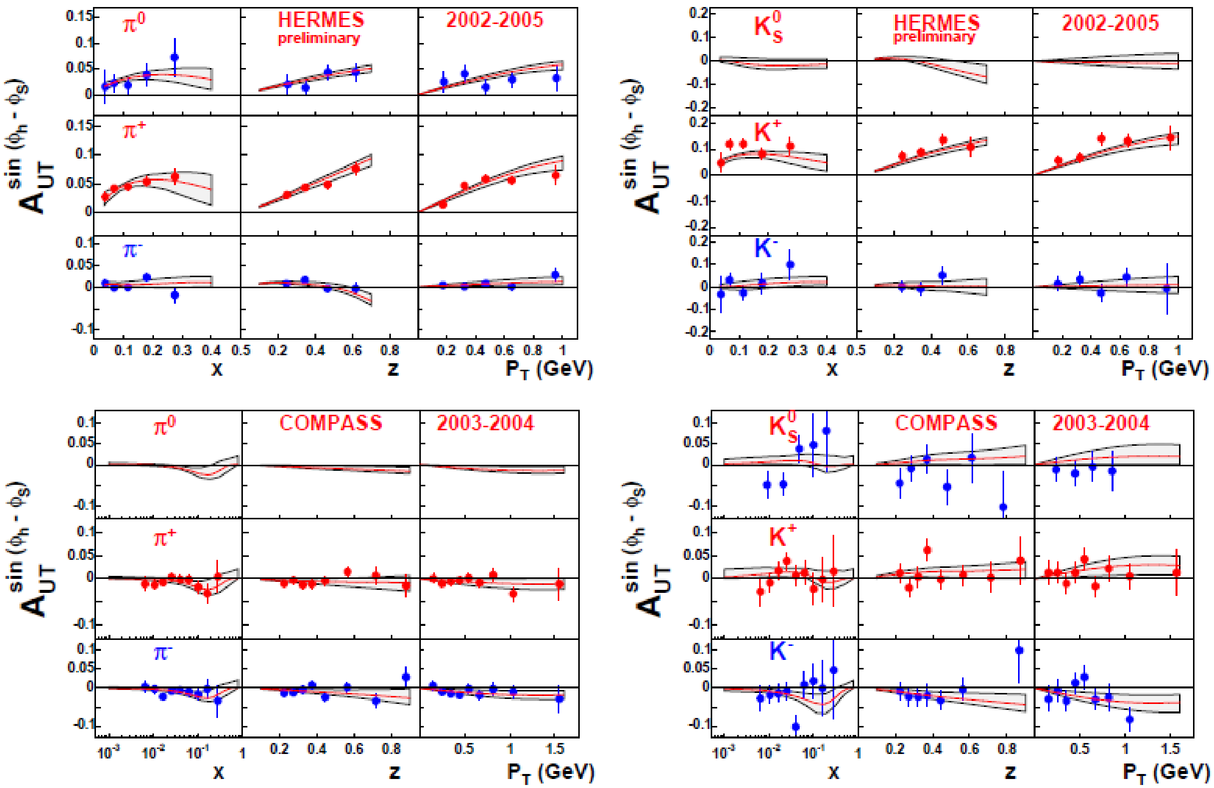
• Final-state interaction can be reproduced by a prescription of the light-cone singularities or an extra gauge link at the spatial infinity for the parton distributions.
Ji & Yuan, PLB543,66(2002).

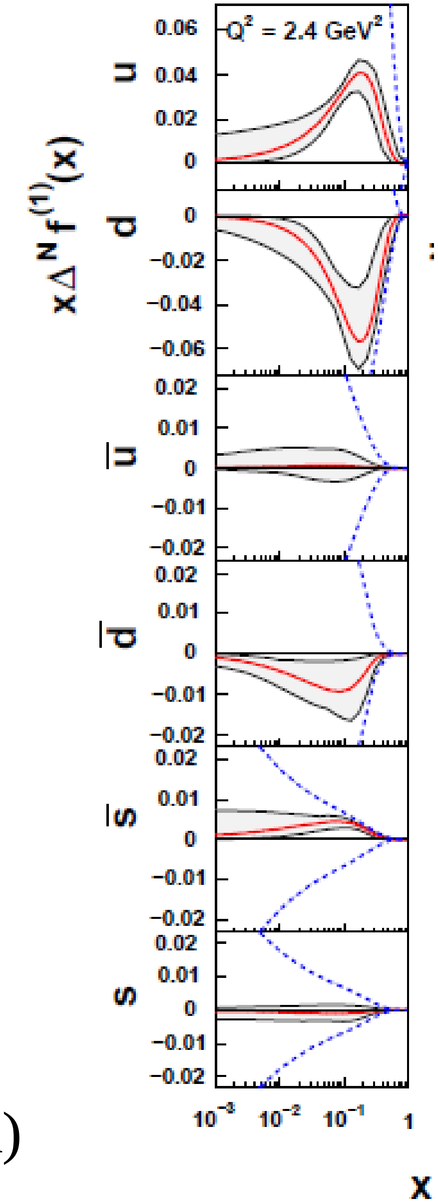


• Add final state interaction to the time reversal arguments:
$f_{1T}^{\perp}(x,p_T^2)_{SIDIS}=-f_{1T}^{\perp}(x,p_T^2)_{DY}$
Collins, PLB536, 43(2002)

Extraction of Sivers function from SIDIS data

Torino group, Anselmino et al.,
Eur. Phys. J. A39 (2009) 89





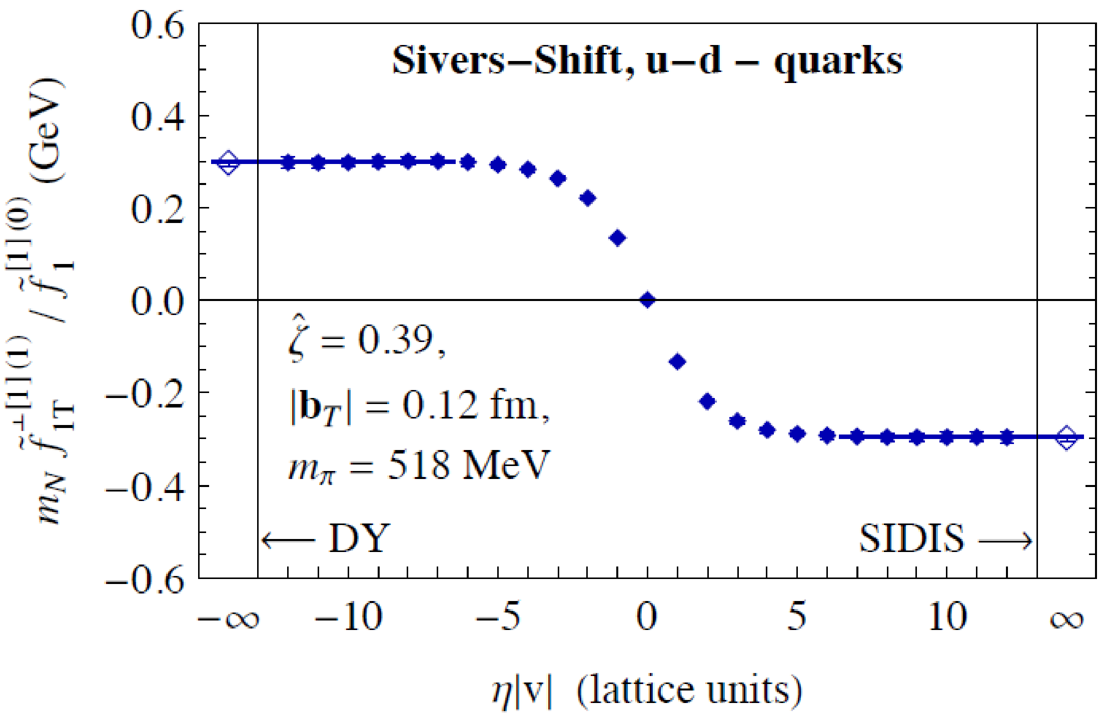
- u – and d - quark Sivers functions have opposite signs
- Sea-quark Sivers functions are non-zero (from K^+ data)

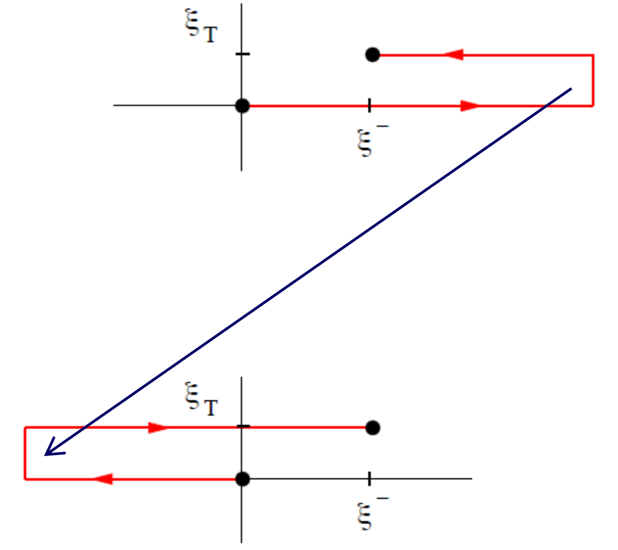
Outstanding questions on Sivers function

- Does Sivers function change sign between DIS and Drell-Yan?
- Sign and magnitude of the sea-quark Sivers functions?
- Q^2-evolution of the Sivers function?

Sivers function on the lattice

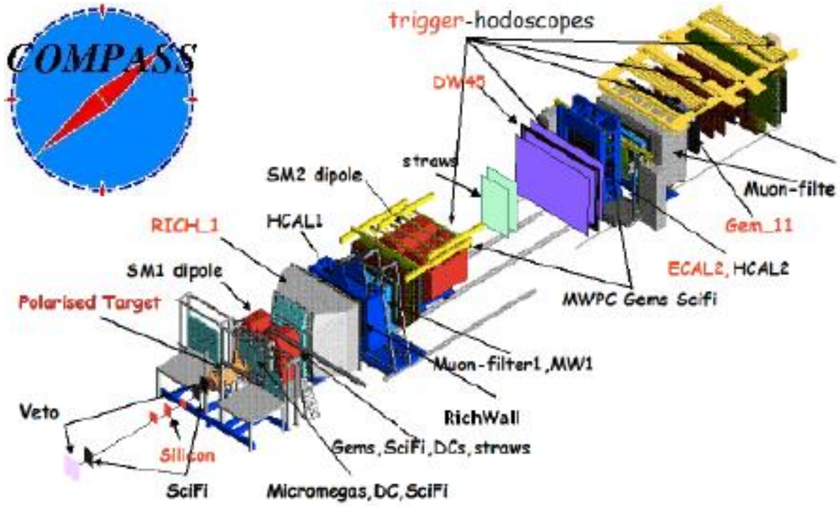
Musch, Haegler, Engelhardt, Negle & Schaeffer, PRD 85 (2012) 094510



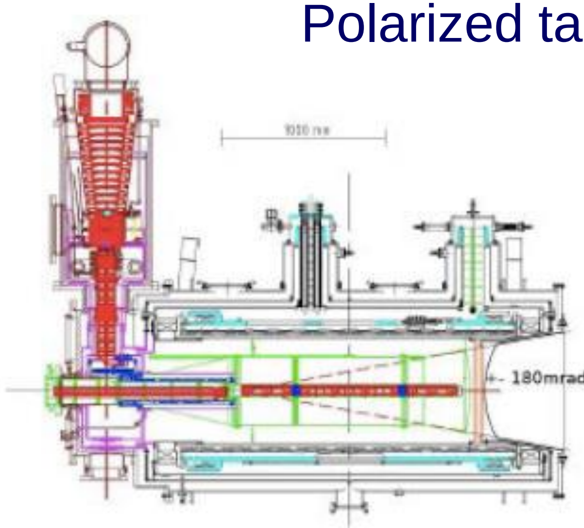


As the vertical gauge link goes from ∞ (SIDIS) to -∞ (Drell-Yan), the sign of Sivers function changes

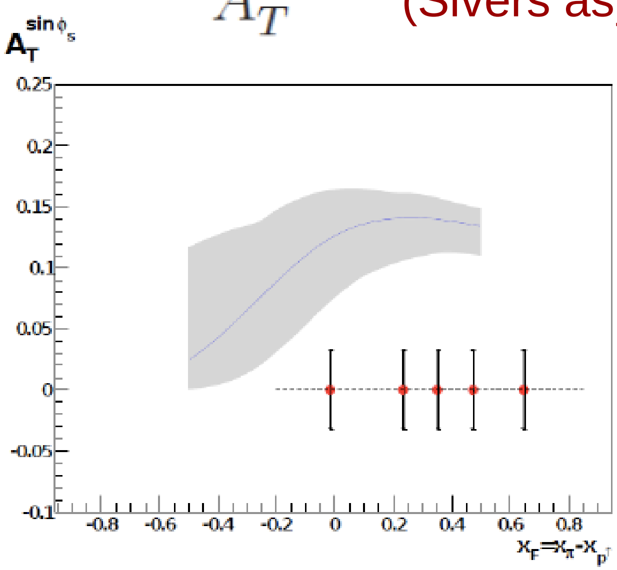
Polarized Drell-Yan with 190 GeV/c pion beam



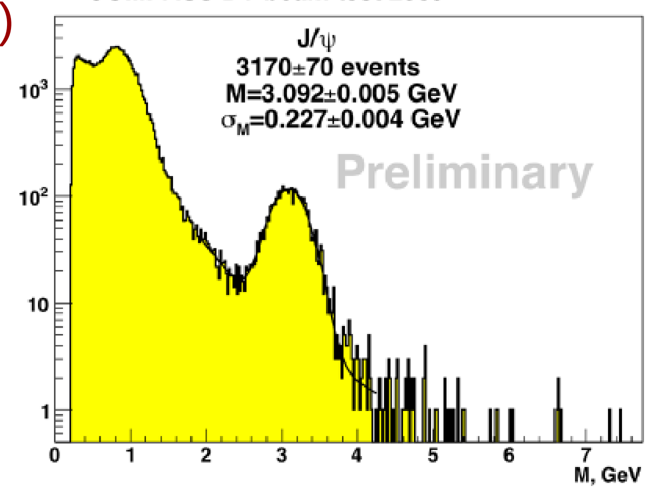
Polarized target



$A_T^{\sin\phi_S}$ (Sivers asymmetry)



COMPASS DY beam test 2009



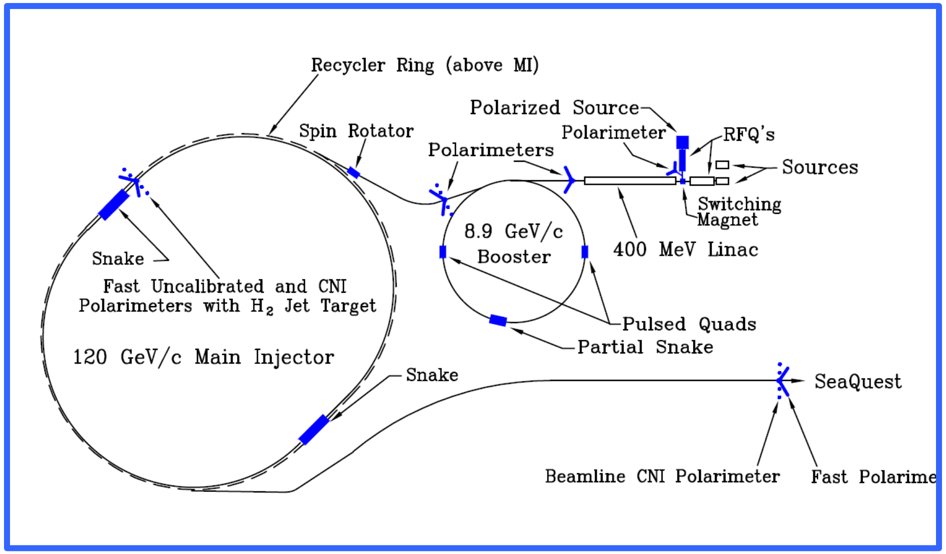
Expect data-taking in 2014-2015

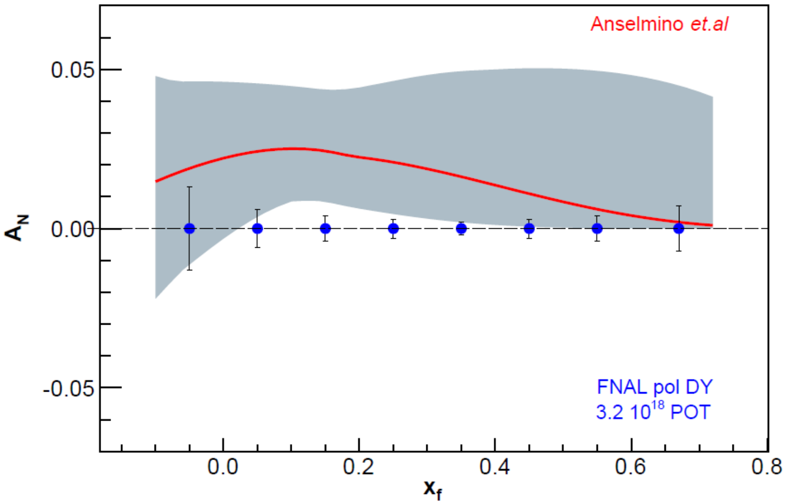
See talk by Michela Chiosso

Proposal to measure Sivers in polarized Drell-Yan at Fermilab

Proposal (P-1027) (Polarized Drell-Yan with polarized proton beam)

(W. Lorenzon, P. Reimer, et al.)





Main goals: 1) Accelerate polarized proton beam at the Main Injector

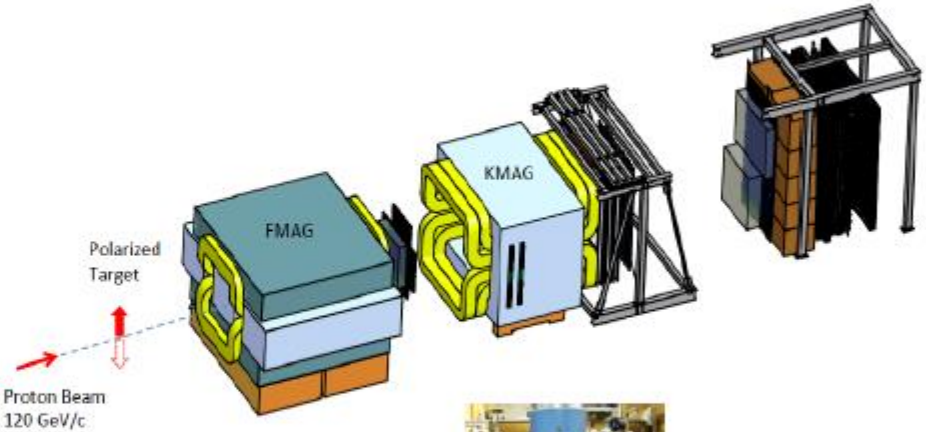
2) Test "sign-change" of T-odd Sivers function in Drell-Yan

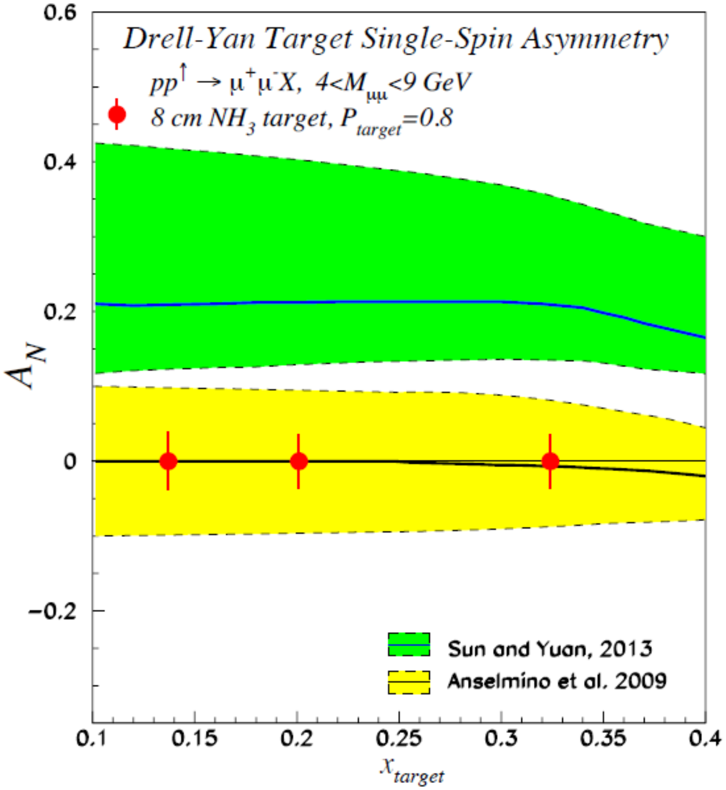
- Propose using the existing dimuon spectrometer
- Possibility of polarized target is also being considered

Another proposal to measure sea-quark Sivers in polarized Drell-Yan at Fermilab

P-1039 Collaboration:

Co-Spokespersons: A. Klein, X. Jiang
Los Alamos National Laboratory





Statistics shown for one calendar year of running :
$\mathcal{L}$ = 1.4 *10^{43} /cm^2 ⟷ POT = 2.1*10^{18}
Request for two calendar years of beam time

Comparison between three polarized DY experiments (for probing the Sivers functions)

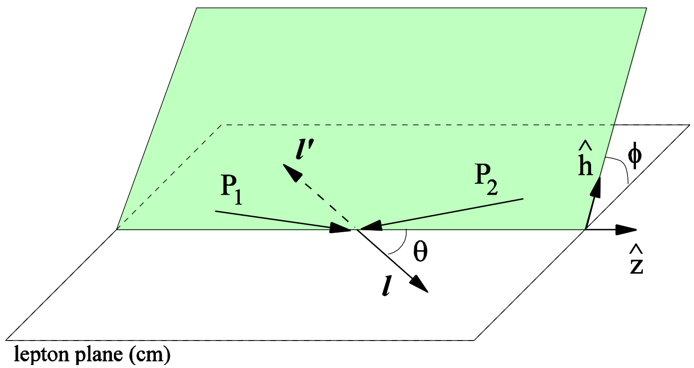
COMPASS, P-1027 and P-1039

	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
P-1027 $p^\uparrow p \to \mu^+\mu^- X$	✔	✗	Valence quark	Sign change and size of Sivers distribution for valence quark
P-1039 $pp^\uparrow \to \mu^+\mu^- X$	✗	✔	Sea quark	Size and sign of Sivers distribution for Sea quarks, if DY $A_N \neq 0$.

From A. Klein and X. Jiang

The Boer-Mulders function

A long-standing puzzle in Drell-Yan angular distributions



Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

Naive Drell-Yan gives $\lambda=1, \mu=0, \nu=0.$

λ can differ from 1, but should satisfy $1-\lambda=2\nu$ (Lam-Tung)

– Reflect the spin-1/2 nature of quarks

(analog of the Callan-Gross relation in DIS)

Decay angular distributions in pion-induced Drell-Yan

$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

NA10 π^- +W

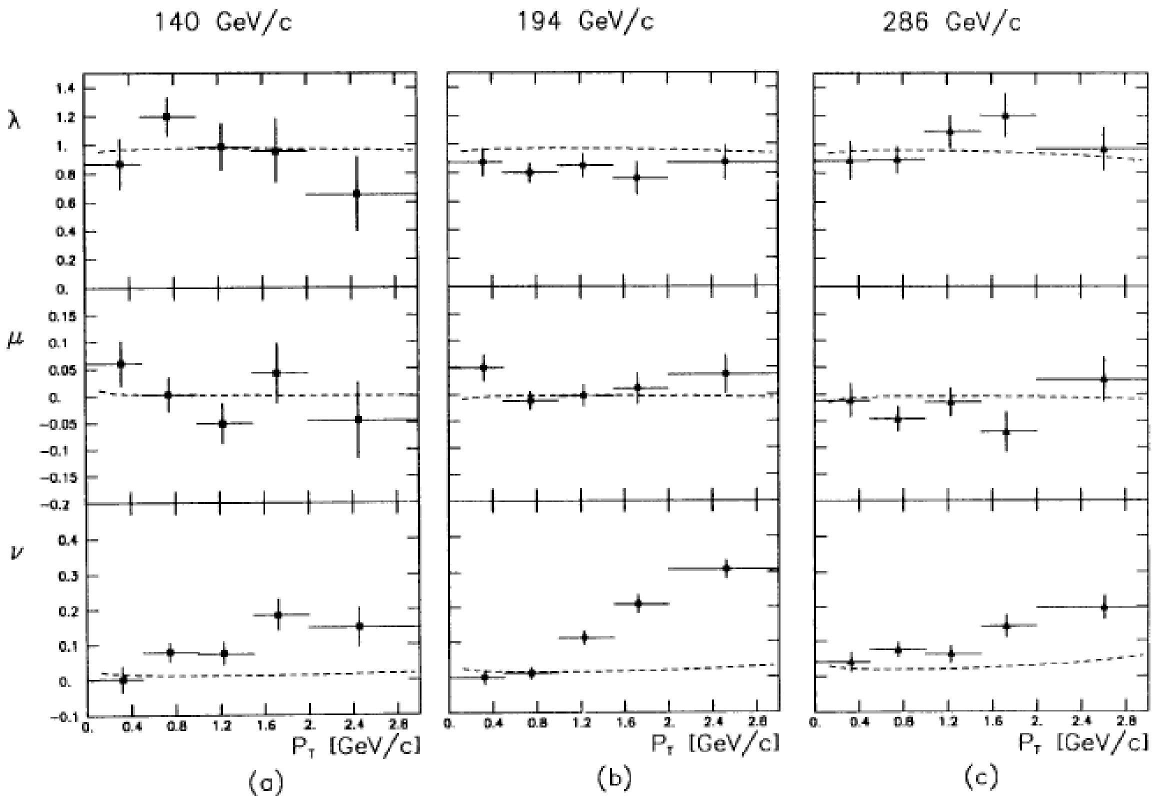


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

Z. Phys.

37 (1988) 545

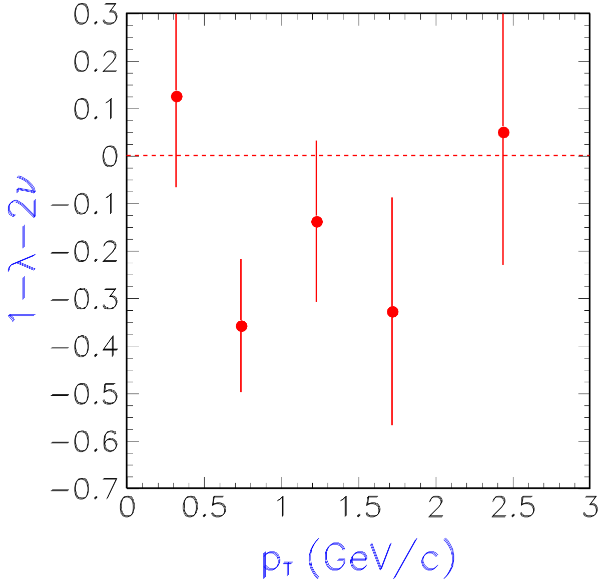
Dashed curves are from pQCD calculations

$\nu \neq 0$ and ν increases with p_T

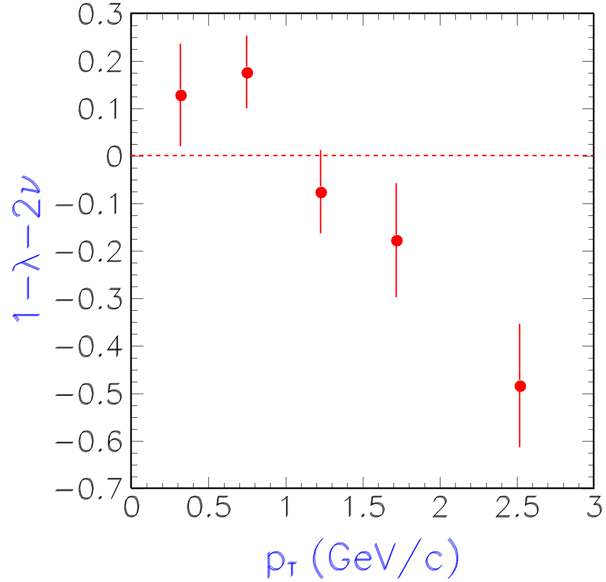
Decay angular distributions in pion-induced Drell-Yan

Is the Lam-Tung relation violated?

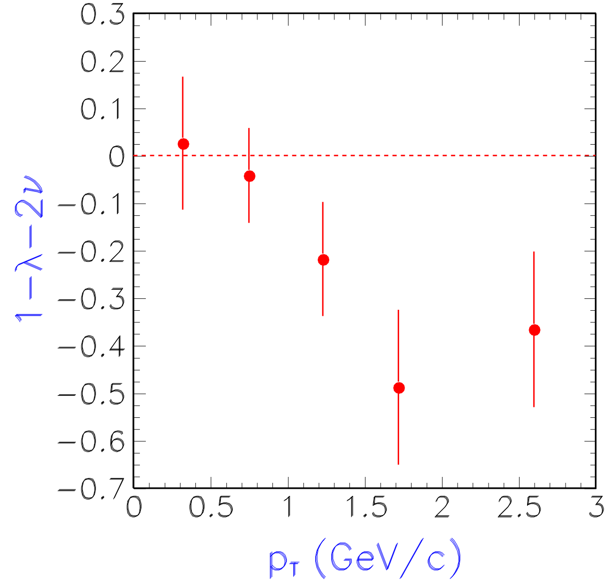
140 GeV/c



194 GeV/c



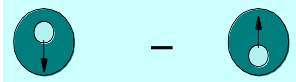
286 GeV/c



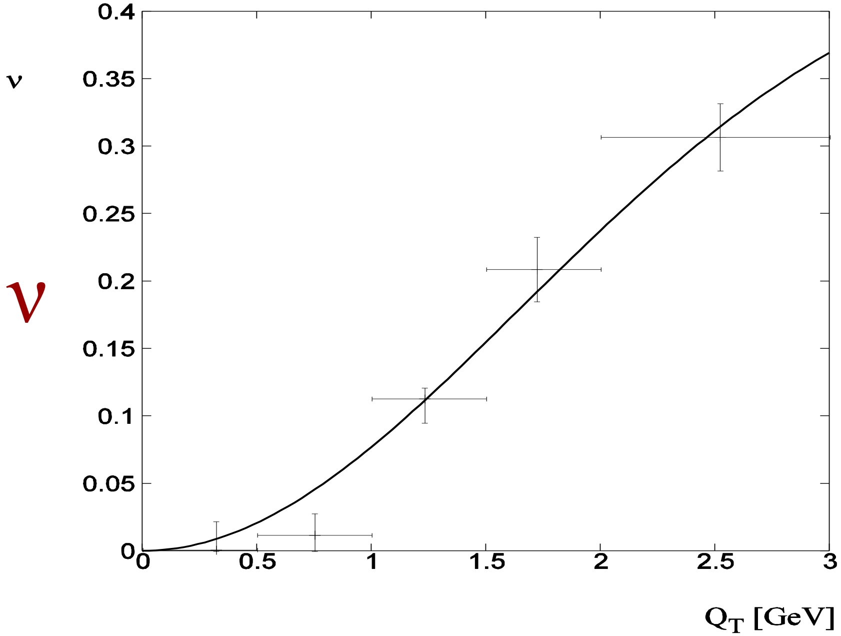
Data from NA10 (Z. Phys. 37 (1988) 545)

Violation of the Lam-Tung relation suggests interesting new origins (Brandenburg, Nachtmann, Mirkes, Brodsky, Khoze, Müller, Eskolar, Hoyer,Väntinnen, Vogt, etc.)

Boer-Mulders function $h_1^{\perp}$



- Boer pointed out that the cos2ϕ dependence can be caused by the presence of the Boer-Mulders function.
- $h_1^{\perp}$ can lead to an azimuthal dependence with $\nu \propto \left(\frac{h_1^{\perp}}{f_1}\right)\left(\frac{\overline{h}_1^{\perp}}{\overline{f}_1}\right)$



$$h_1^{\perp}(x,k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

$$\nu = 16\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}$$

Boer, PRD 60 (1999) 014012

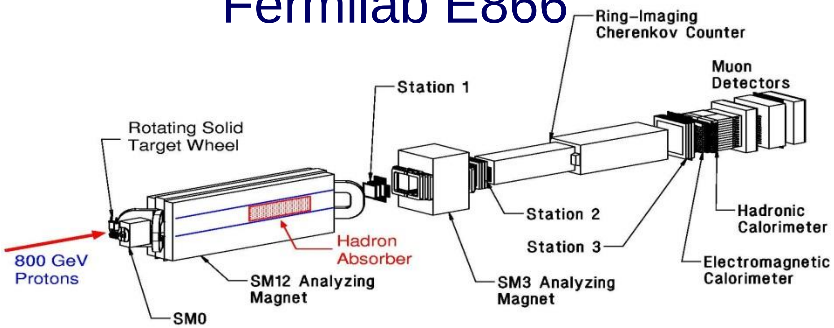
κ_1=0.47, M_C=2.3 GeV

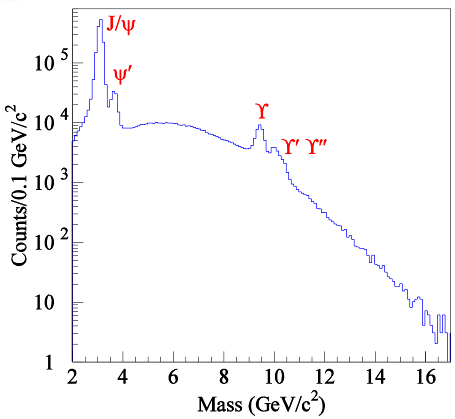
ν>0 implies valence BM functions for pion and nucleon have same signs

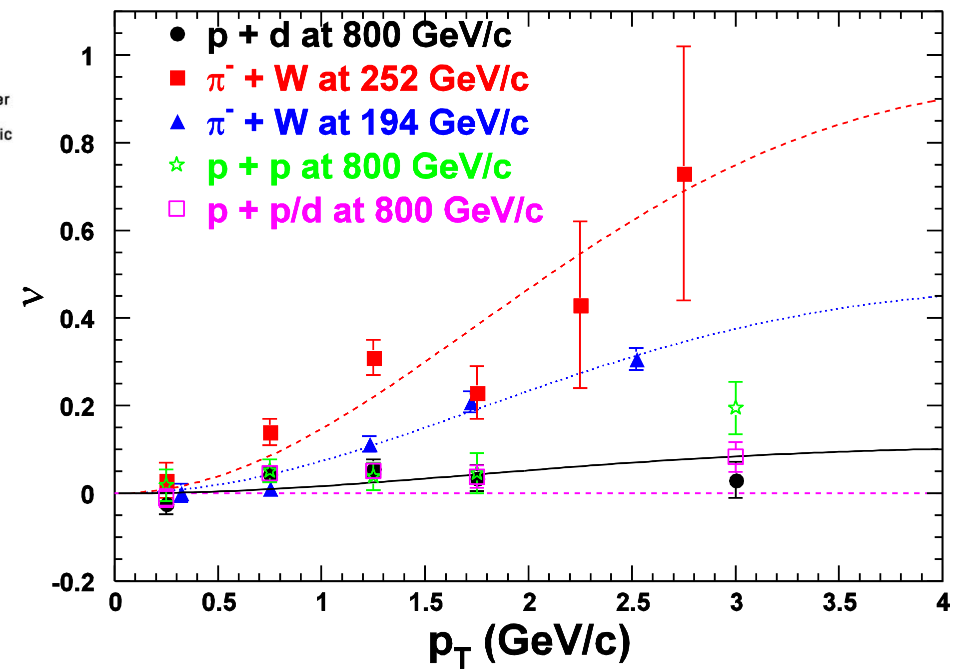
Azimuthal cos2Φ Distribution in p+d Drell-Yan

Lingyan Zhu et al., PRL 99 (2007) 082301;
PRL 102 (2009) 182001

Fermilab E866







With Boer-Mulders function $h_1^\perp$:

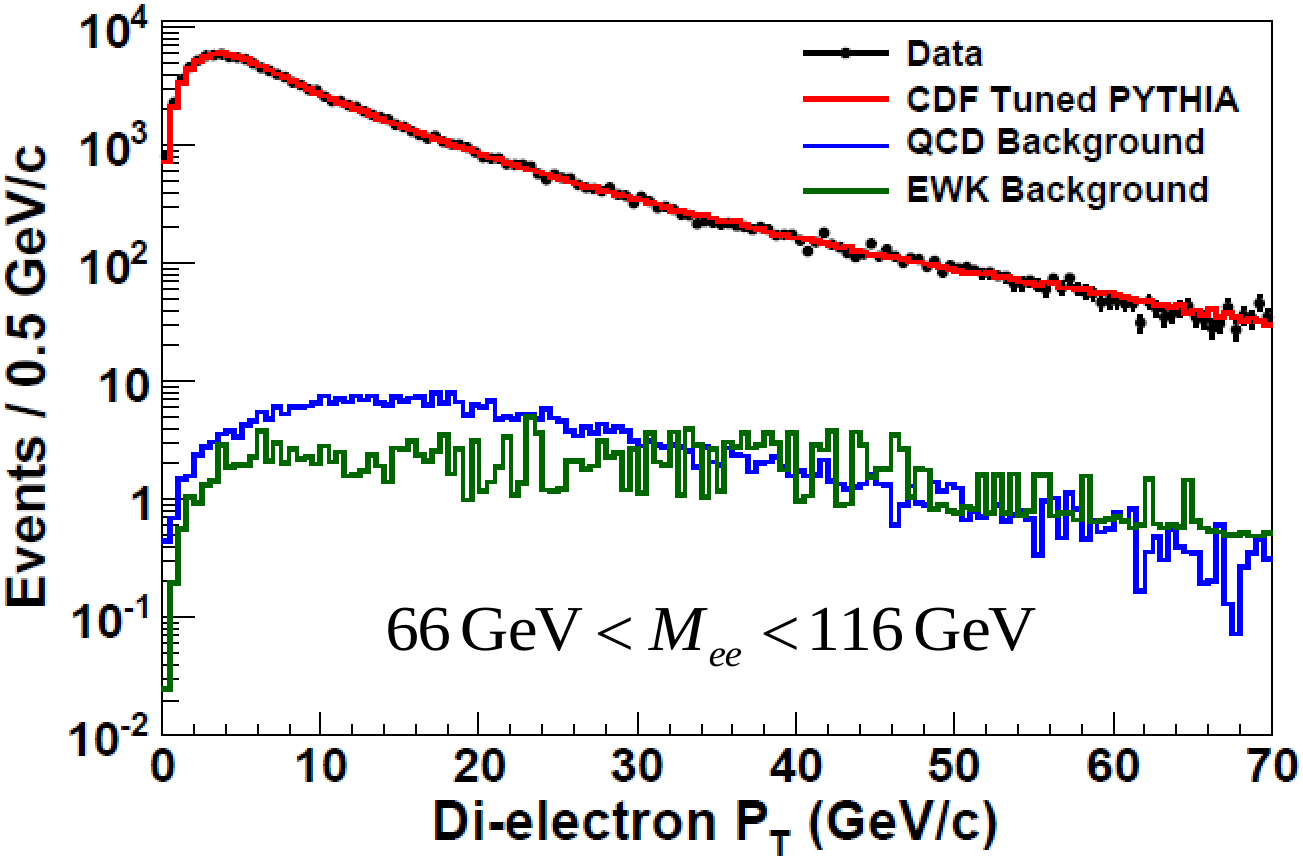
$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^\perp(\pi)$] * [valence $h_1^\perp(p)$]

$\nu(pd \rightarrow \mu+\mu- X) \sim$ [valence $h_1^\perp(p)$] * [sea $h_1^\perp(p)$]

Sea-quark BM function is much smaller than valence BM function

Result from CDF on Lam-Tung relation

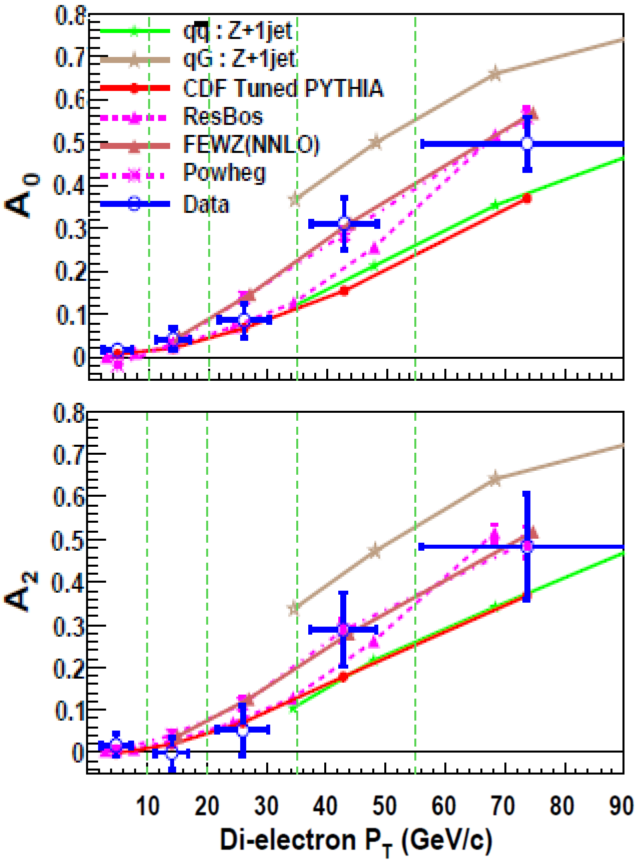
$$p + \bar{p} \rightarrow e^+ + e^- + X \quad \text{at} \sqrt{s} = 1.96\,\text{TeV}$$



arXiv:1103.5699

Result from CDF on Lam-Tung relation

$$p+\bar{p}\rightarrow e^{+}+e^{-}+X \quad \text{at } \sqrt{s}=1.96\,\text{TeV}$$



$$\frac{d\sigma}{d\cos\theta}\propto(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_4\cos\theta$$

$$\frac{d\sigma}{d\phi}\propto 1+\beta_3\cos\phi+\beta_2\cos 2\phi+\beta_7\sin\phi+\beta_5\sin 2\phi$$

$$\beta_3=3\pi A_3/16,\ \beta_2=A_2/4,\ \beta_7=3\pi A_7/16$$

$$\text{Lam-Tung relation} \Rightarrow A_0=A_2$$

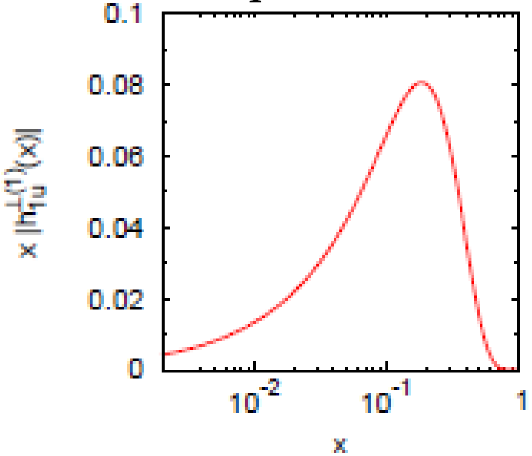
P_T bin	A_0 ($\times10^{-1}$)	A_2 ($\times10^{-1}$)
0–10	$0.17\pm0.14\pm0.07$	$0.16\pm0.26\pm0.06$
10–20	$0.42\pm0.25\pm0.07$	$-0.01\pm0.35\pm0.16$
20–35	$0.86\pm0.39\pm0.08$	$0.52\pm0.51\pm0.29$
35–55	$3.11\pm0.59\pm0.10$	$2.88\pm0.84\pm0.19$
>55	$4.97\pm0.61\pm0.10$	$4.83\pm1.24\pm0.02$

arXiv:1103.5699

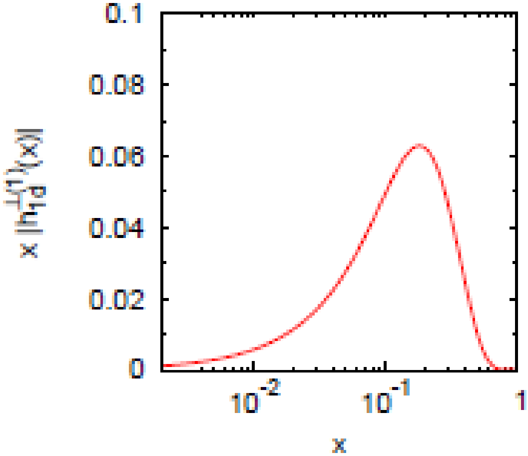
$\langle A_0 - A_2\rangle = 0.02 \pm 0.02$

Extraction of Boer-Mulders function from SIDIS and Drell-Yan data

u - quark B-M



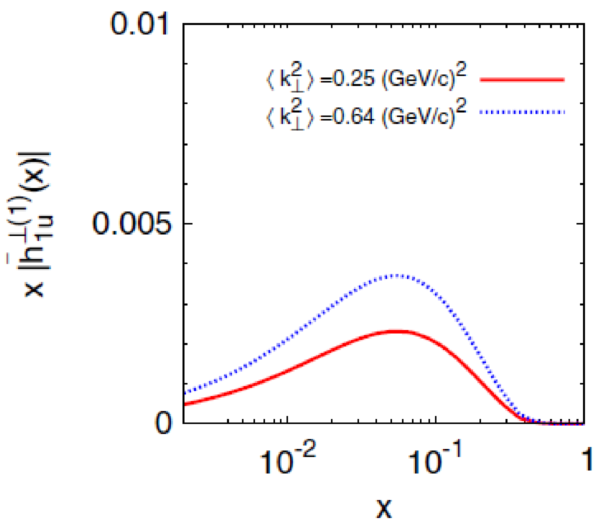
d - quark B-M



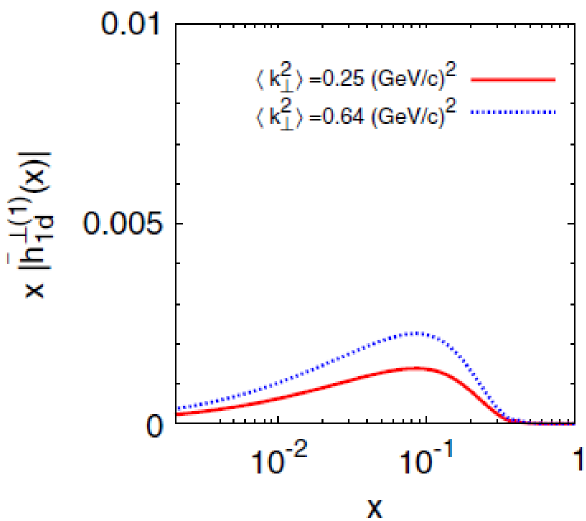
From SIDIS

PR D81, 114026 (2010)

$\bar{u}$ B-M



$\bar{d}$ B-M

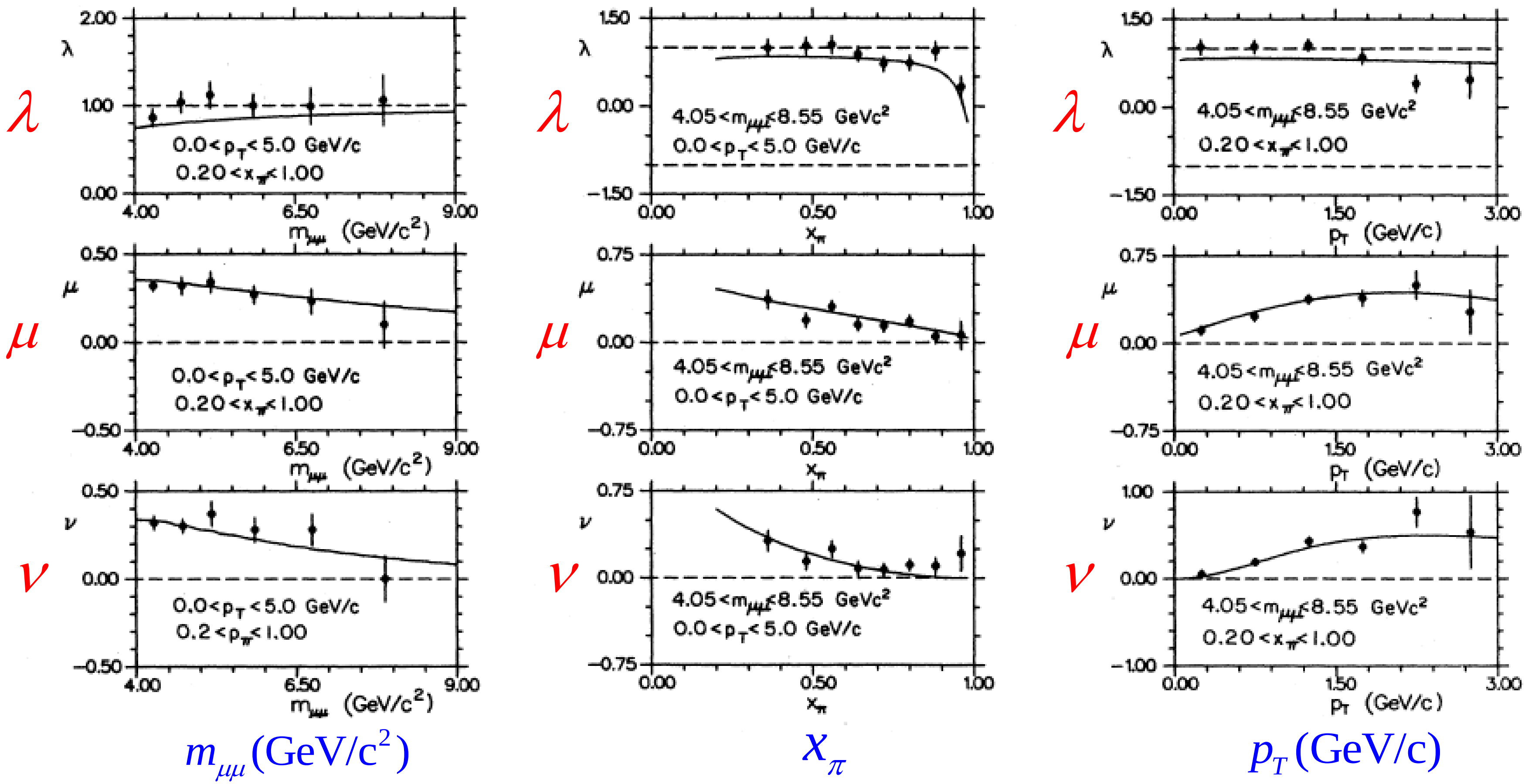


From Drell-Yan

PRD82,114025 (2010)

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV $\pi^- + W$ Phys. Rev. D 39 (1989) 92

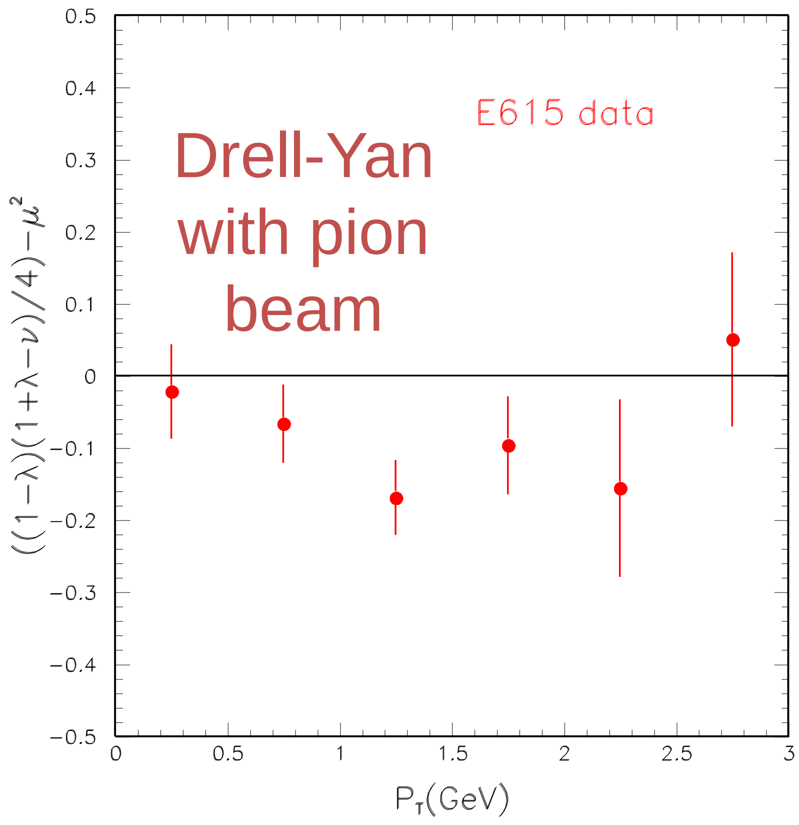


$$\lambda \neq 1,\ \mu \neq 0,\ \nu \neq 0$$ and they vary with $m_{\mu\mu}$, p_T, and x_π

$\mu^2 \leq (1-\lambda)(1+\lambda-\nu)/4$ predicted by O. Teryaev based on positivity

Is the $\mu^2 \le (1-\lambda)(1+\lambda-\nu)/4$ inequality valid?

$$(1-\lambda)(1+\lambda-\nu)/4-\mu^2 \ge 0?$$



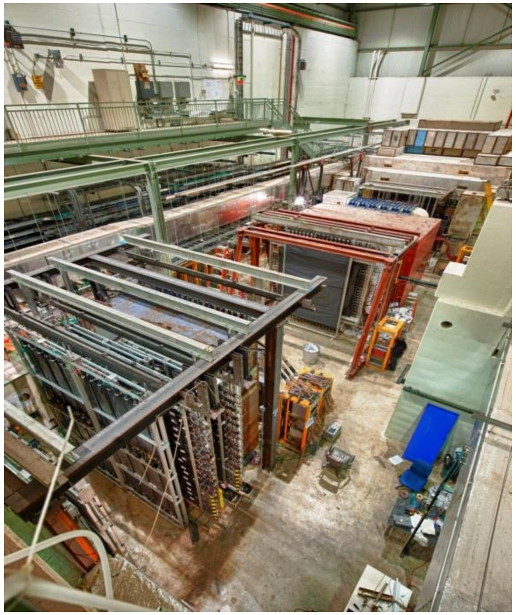
The inequality appears to be violated!

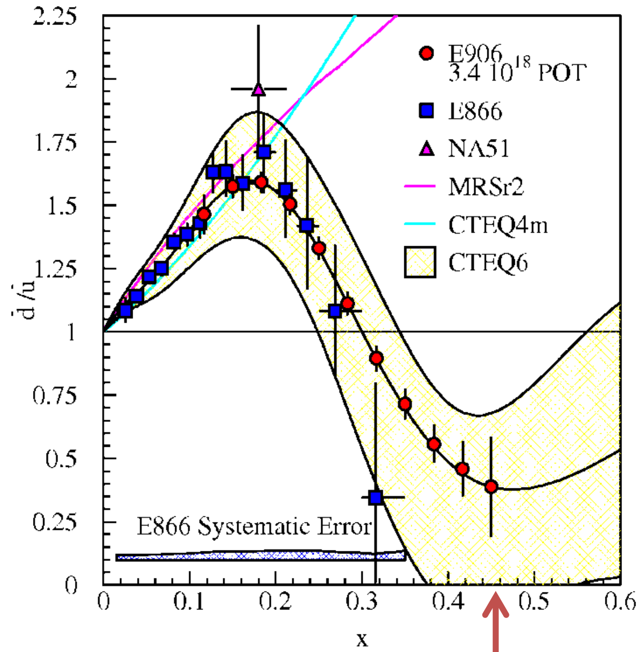
(Teryaev and JCP)

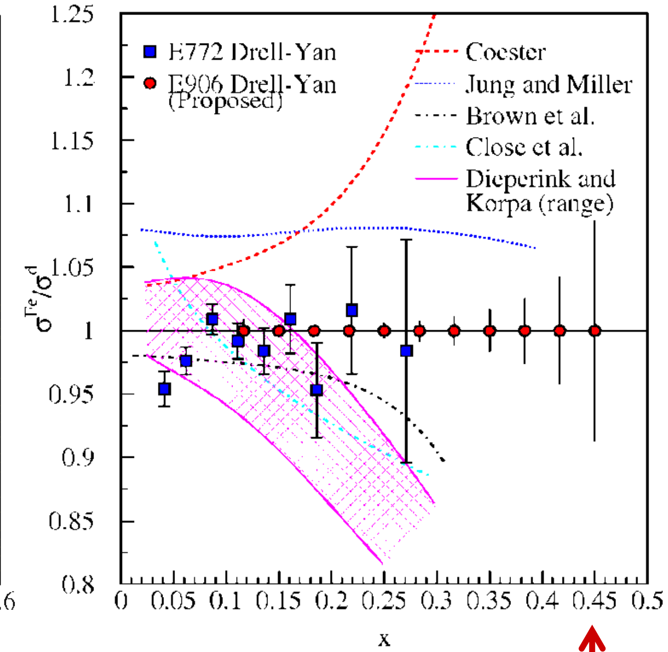
Our knowledge of D-Y azimuthal angular dependence is still incomplete (Data from COMPASS and E906 are anticipated)

E906/Seaquest Drell-Yan Experiment at Fermilab

SeaQuest Experiment (Unpolarized Drell-Yan using 120 GeV proton beam)







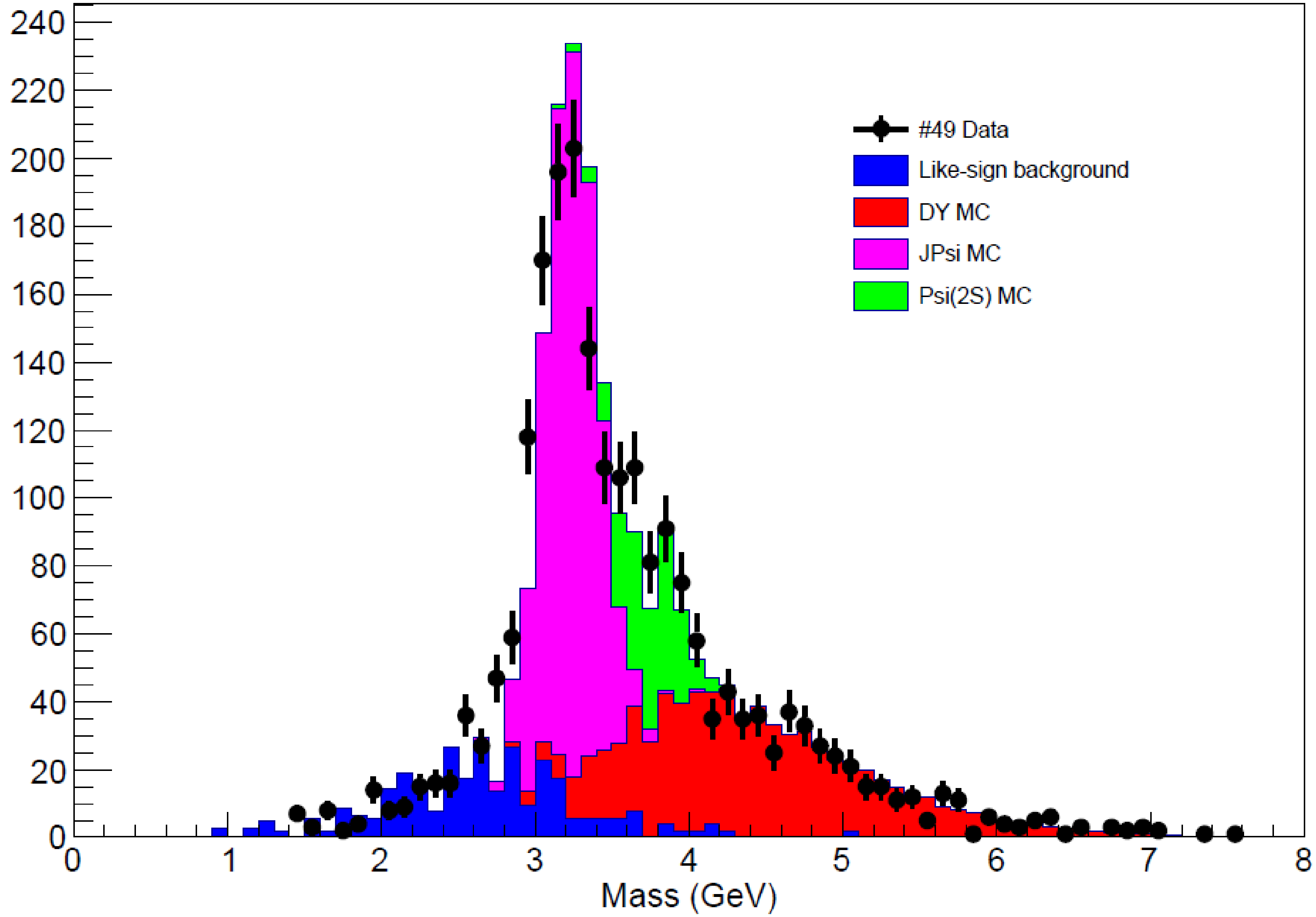
Main goals: 1) Measure $\bar{d} / \bar{u}$ flavor asymmetry up to $x \sim 0.45$

2) Measure EMC effect of antiquarks up to $x \sim 0.45$

- 2-year production run in 2014-2015
- Additional physics topics include Boer-Mulders measurements

Dimuon mass spectra from SeaQuest/E906

(Preliminary analysis of a small fraction of data)



Physics run started Feb. 2014

Can the existing Drell-Yan data already test the predicted sign-change of B-M function?

1) From SIDIS data, one deduces that the proton B-M functions are negative for both u and d quarks:

$$h_{1,u}^{\perp,DIS}(p) < 0\ ;\ \ h_{1,d}^{\perp,DIS}(p) < 0$$

2) From NA10 pion Drell-Yan data, one deduces that the product of the pion valence quark B-M function and the proton valence quark B-M function is positive. Using u-quark dominance, we have:

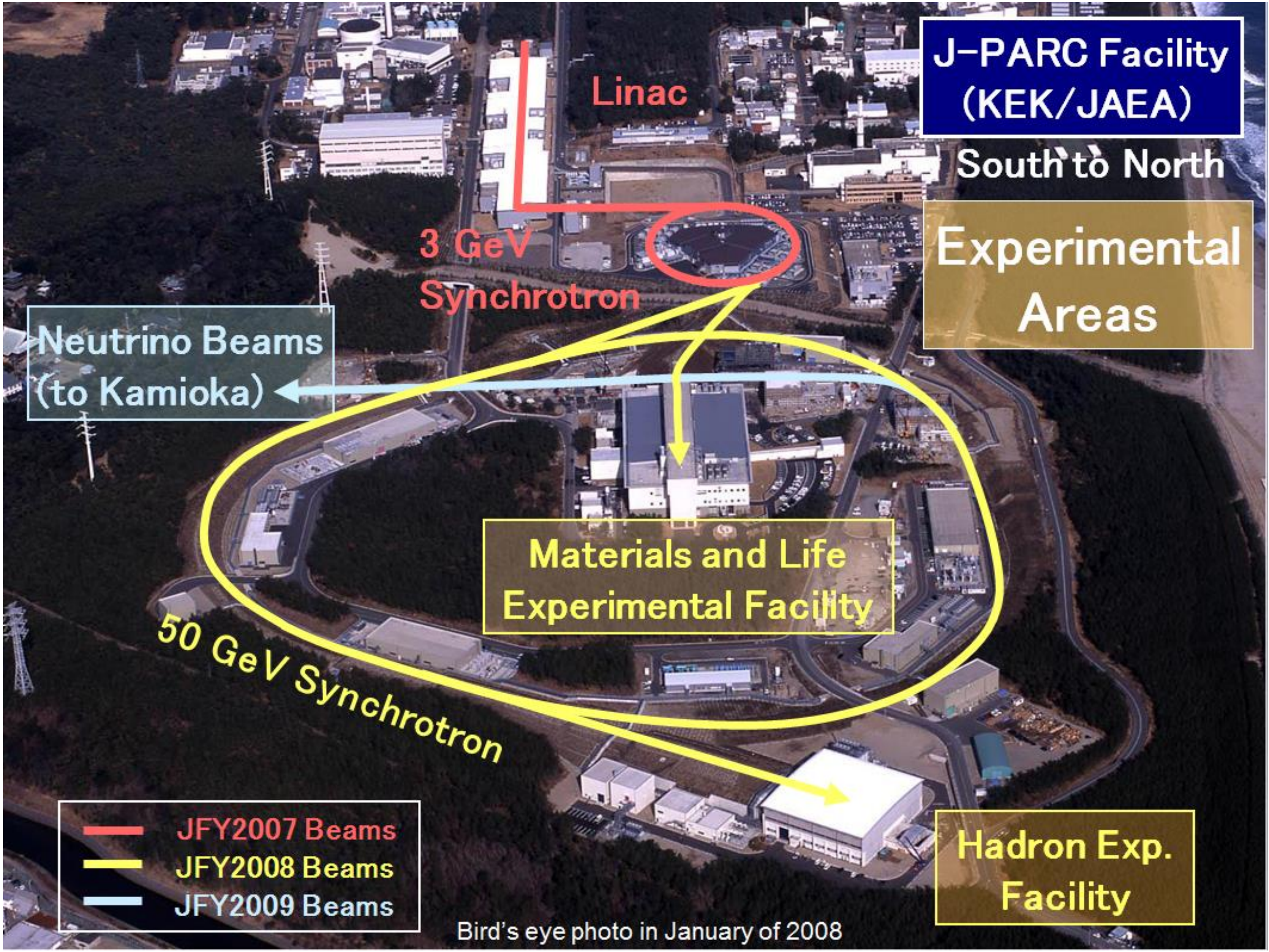
$$h_{1,u}^{\perp,DY}(p) * h_{1,u}^{\perp,DY}(\pi) > 0$$

Therefore, either a) $h_{1,u}^{\perp,DY}(p) > 0;\ h_{1,u}^{\perp,DY}(\pi) > 0 \quad (sign-change)$

or b) $h_{1,u}^{\perp,DY}(p) < 0;\ h_{1,u}^{\perp,DY}(\pi) < 0 \quad (no\, sign-change)$

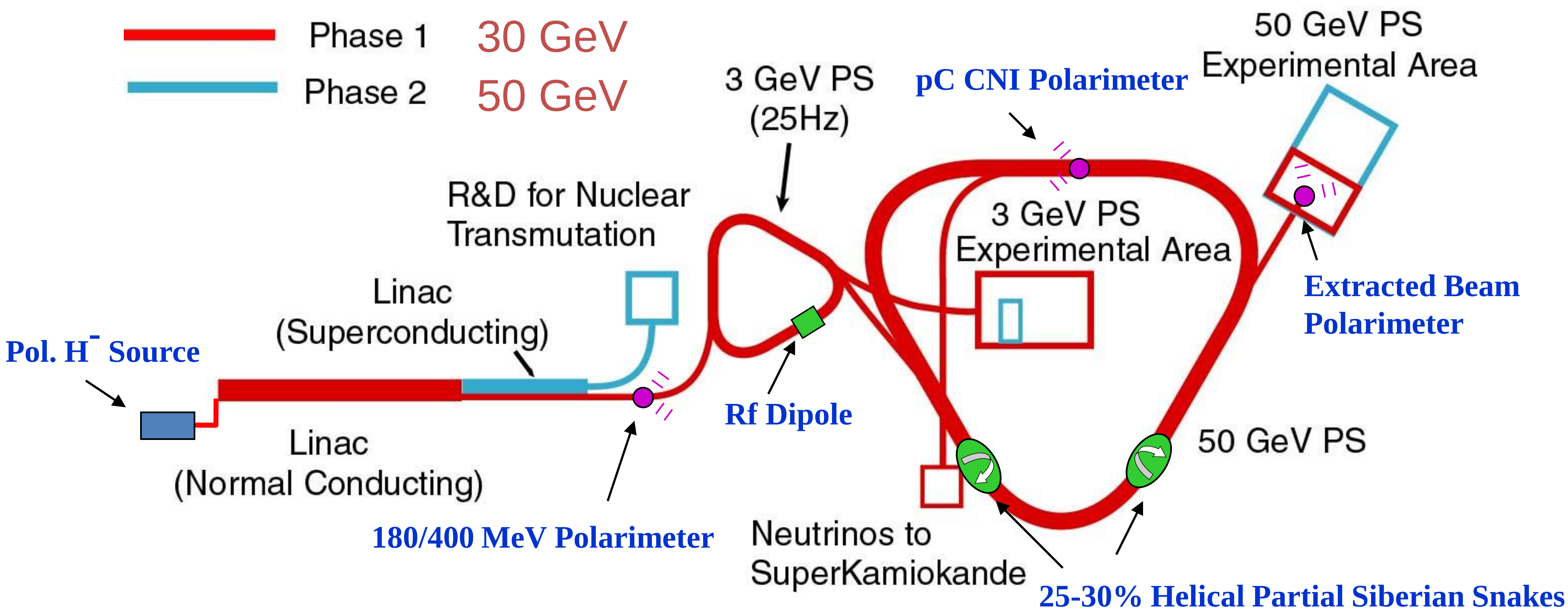
3) The crucial measurement is to determine the sign of the pion B-M function in polarized $\pi - p$ D-Y, since the $\sin(\phi+\phi_S)$ modulation is sensitive to the sign of $h_{1,u}^{\perp,DY}(\pi)$.

To be measured at COMPASS


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Experimental
Areas
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental Facility
50 GeV Synchrotron
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Hadron Exp.
Facility
Bird's eye photo in January of 2008

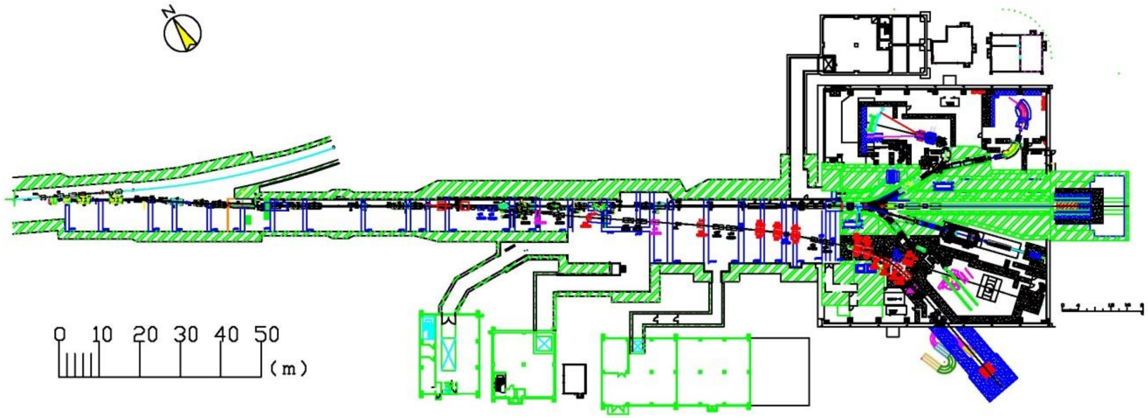
Polarized proton beam at J-PARC ?

- **Polarized proton beam at J-PARC with**
  - **Polarized H$^-$ source**
  - **RF dipole at 3 GeV RCS**
  - **Two 30% partial snakes at 50 GeV Main Ring**



- P04: Measurement of high-mass dimuon at 50 GeV
- P24: Polarized proton acceleration at J-PARC

Physics with High-Momentum Beams at J-PARC

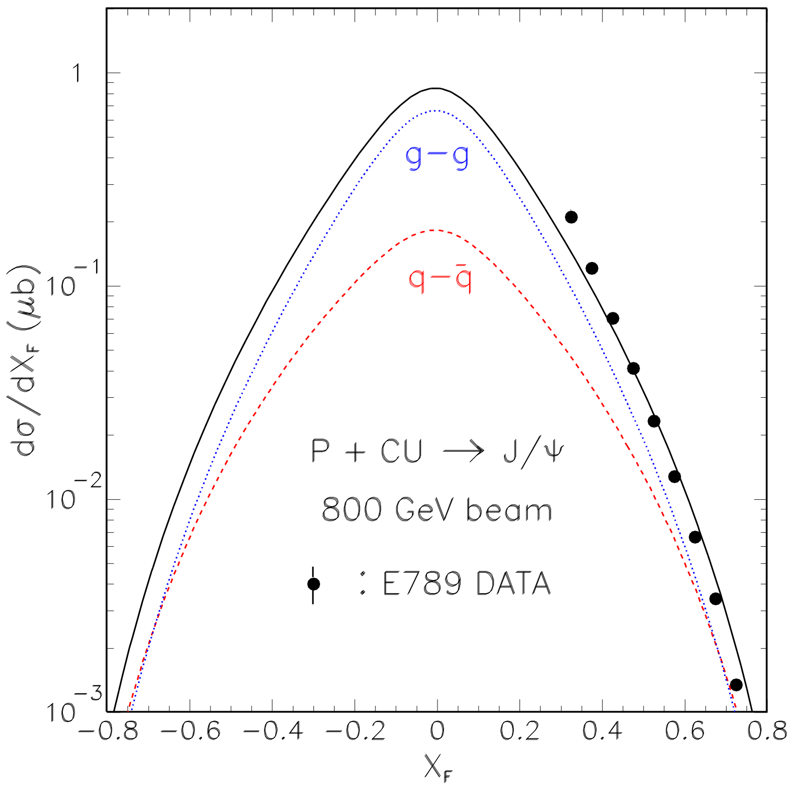


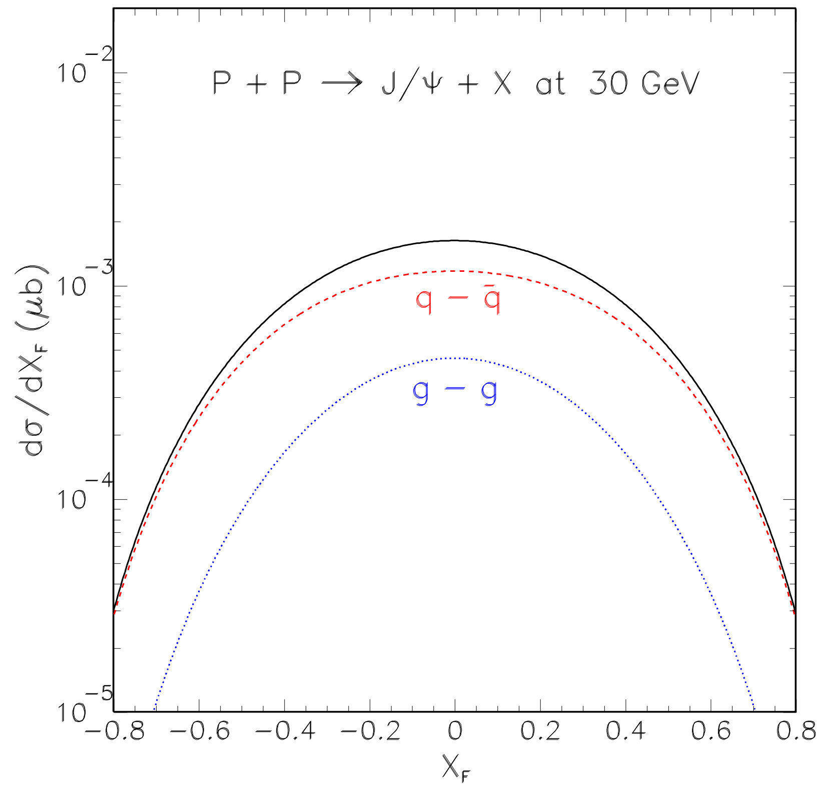
- “High-momentum beam line” (+ COMET beam line) has been funded!
- High-momentum primary proton beam (30GeV)
  - Meson mass modification inside nuclei
  - Dilepton measurement for nucleon and baryon structure
- High-momentum meson (pion) beam (~<15 GeV/c)
  - Pion-induced Drell-Yan?
  - Baryon spectroscopy with pion beams.

J/Ψ Production at 30 GeV

At 800 GeV, J/Ψ production is dominated by gluon-gluon fusion

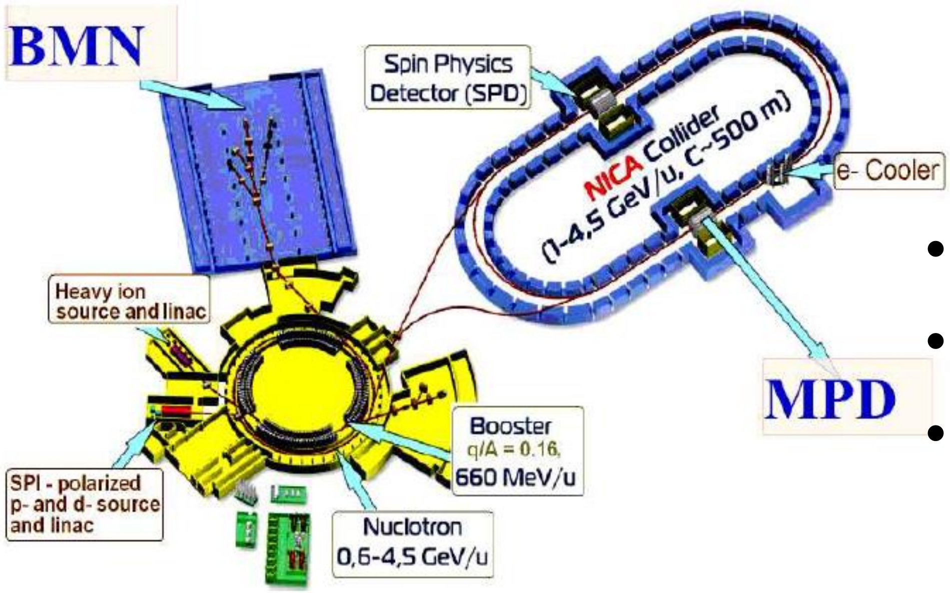
At 30 GeV J/Ψ production is dominated by quark-antiquark annihilation





J/Ψ production at 30 GeV is sensitive to quark and antiquark distributions

Prospects of polarized Drell-Yan at NICA



(See talk by Teryaev)

- Polarized proton and deuteron
- Maximum c.m. energy of 27 GeV
- Polarized Drell-Yan is a major physics topics

Single-spin asymmetry in transversely polarized D-Y

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}} = -\frac{\sum_q e_q^2 \,[\bar{h}_{1q}^{\perp(1)} h_{1q} + (q \leftrightarrow \bar{q})]}{\sum_q e_q^2 \,[\bar{f}_{1q} f_{1q} + (q \leftrightarrow \bar{q})]}$$

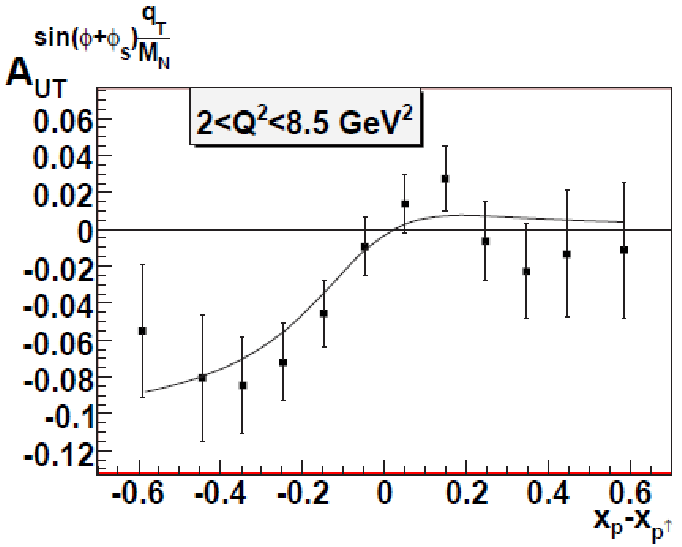
B-M function

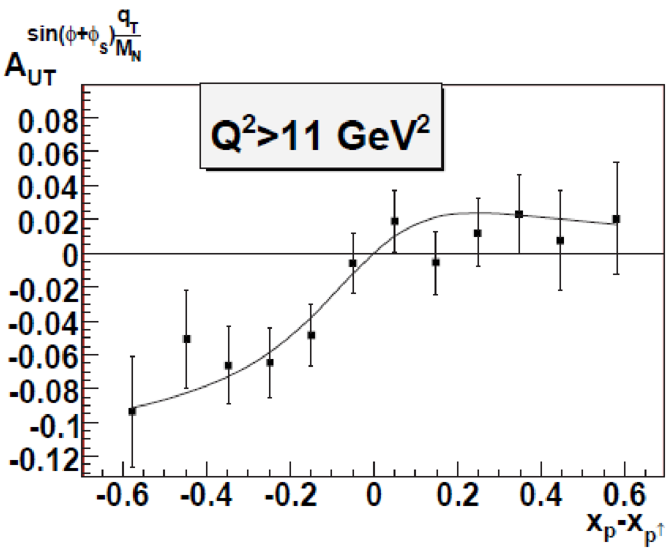
$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M_N}} = 2\frac{\sum_q e_q^2 [\bar{f}_1^q f_{1T}^{\perp q(1)} + (q \leftrightarrow \bar{q})]}{\sum_q e_q^2 \,[\bar{f}_{1q} f_{1q} + (q \leftrightarrow \bar{q})]}$$

Sivers function

Predicted SSA of polarized Drell-Yan at NICA

$$A_{UT}^{\sin(\phi+\phi_S)\frac{q_T}{M_N}} = -\frac{\sum_q e_q^2 \, [\bar{h}_{1q}^{\perp(1)} h_{1q} + (q \leftrightarrow \bar{q})]}{\sum_q e_q^2 \, [\bar{f}_{1q} f_{1q} + (q \leftrightarrow \bar{q})]}$$



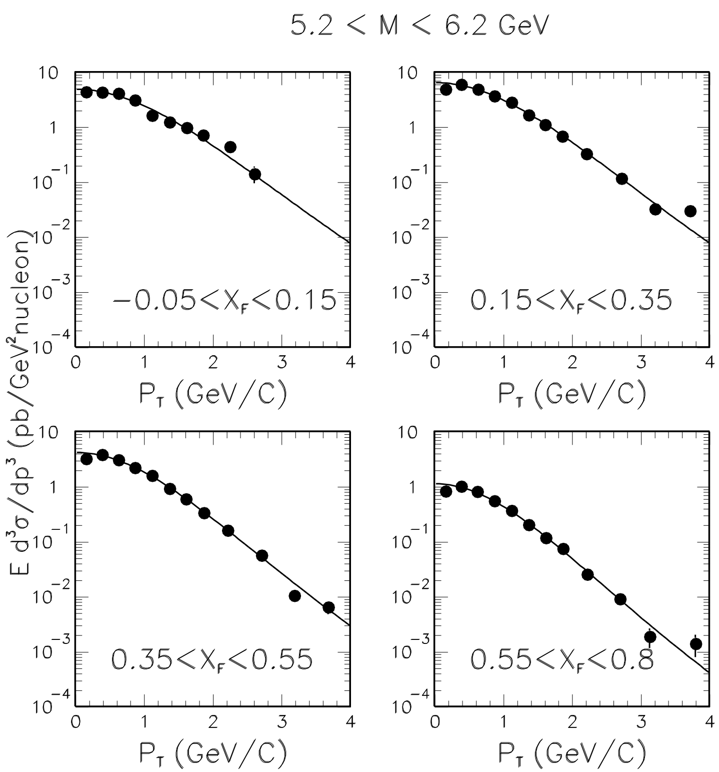


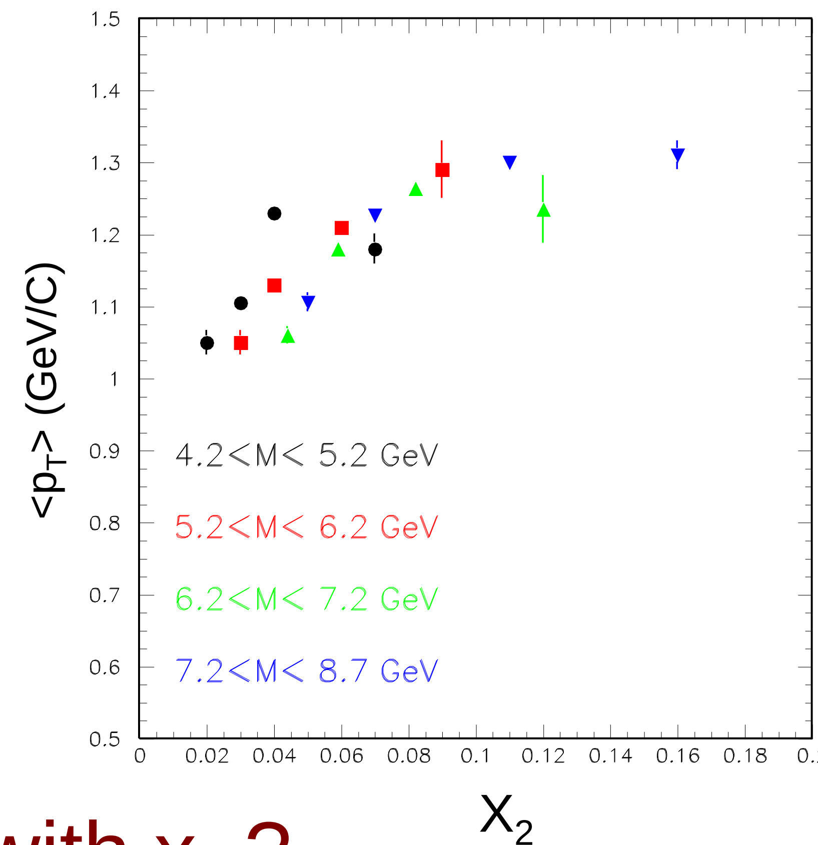
B-M function

- Sensitive to the sign of the Boer-Mulders function in Drell-Yan
- Could provide a test for the predicted sign-change of the Boer-Mulders function?

Possible *x*-dependent $\langle p_T \rangle$?

E866 p+d D-Y data (800 GeV beam)





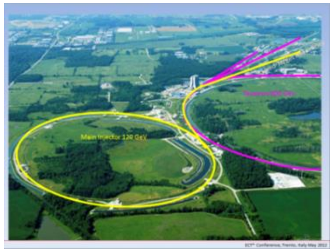
$\langle p_T \rangle$ scale with x_2 ?

Analysis is near completion. D-Y data at lower beam energies (SeaQuest, COMPASS, NICA) are anticipated.

Global interest in polarized Drell-Yan measurements

- Fermilab (proton beam, unpolarized, polarized beam/target possible)
- COMPASS (pion beam, polarized target)
- FAIR (polarized antiproton beam)
- RHIC (polarized proton beam)
- J-PARC (proton beam, polarzied beam possible)
- JINR NICA (proton beam)

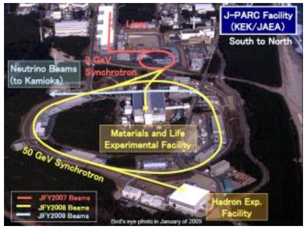
Fermilab



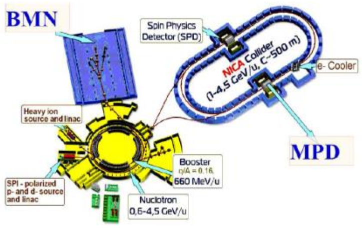
COMPASS

RHIC

J-PARC



NICA



Outstanding questions to be addressed by future Drell-Yan experiments

- Favor asymmetry of the sea-quark at large-x
- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan