Transverse Spin and Drell-Yan Process

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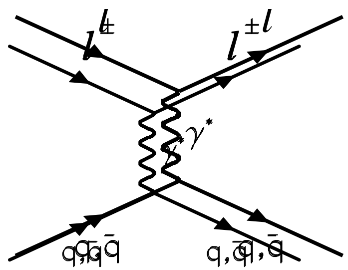
Workshop on "Partonic Transverse Momentum Distributions", Milos, Sept 27 - 29, 2009

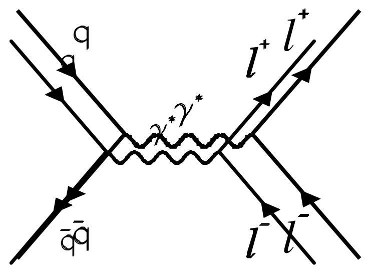
Outline

- Brief overview of TMDs and Drell-Yan
- Recent Drell-Yan results from Fermilab E866 (Boer-Mulders functions)
- Future prospects for Drell-Yan experiments

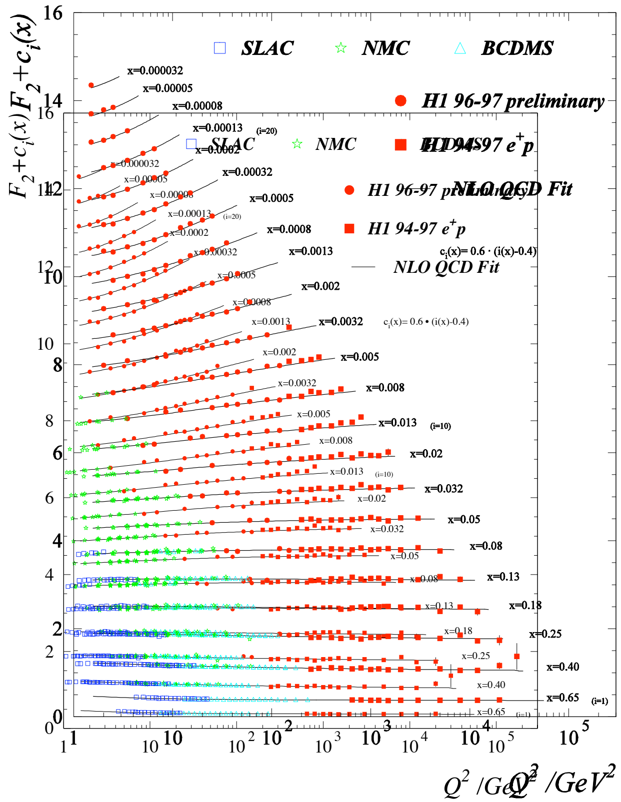
Complimentality between DIS and Drell-Yan

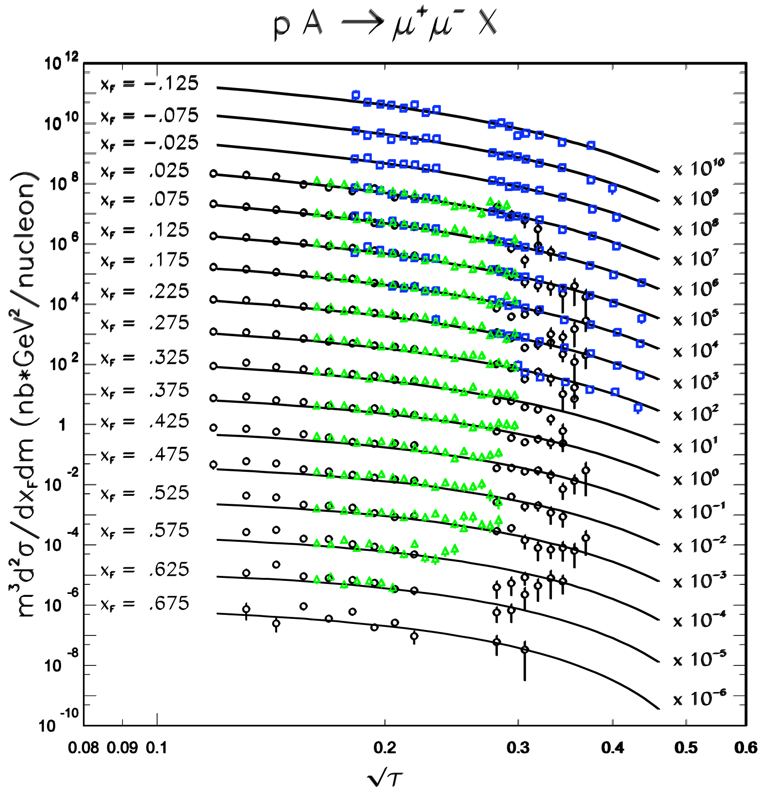
DIS





Drell-Yan





Both DIS and Drell-Yan cross sections are well described by NLO calculations

Three parton distributions describing quark's transverse momentum and/or transverse spin

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}^{N}$

2) Quark transverse spin

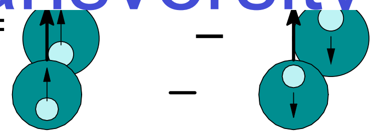
$\vec{s}^{q}$

3) Quark transverse momentum

$\vec{k}^{q}$

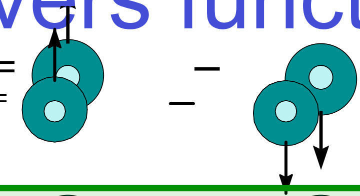
 Three different correlations

1) Transversity

$h_{1T} =$ 

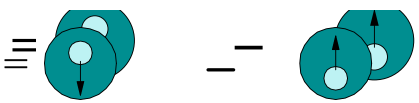
Correlation between $\vec{s}^{q}$ and $\vec{S}^{N}$

2) Sivers function

$f_{1T}^{\perp} =$ 

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

3) Boer-Mulders function

$h_{1}^{\perp} =$ 

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

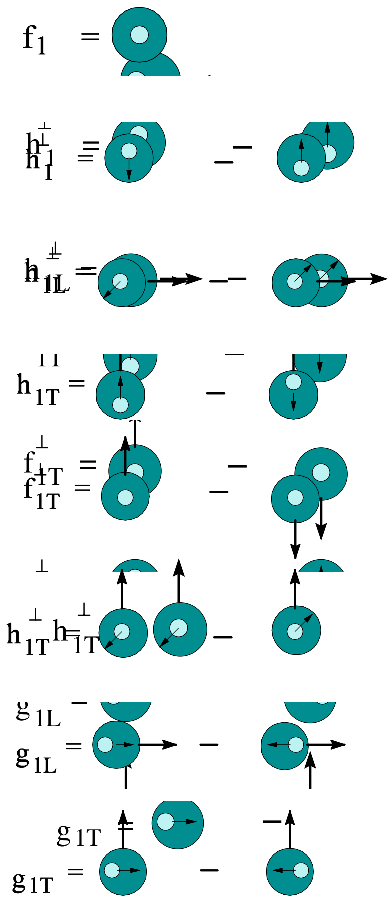
Transversity and TMD PDFs are probed in Semi-Inclusive DIS

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

Boer-Mulders

Transversity

Sivers



Unpolarized

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

$$+ (1-y) \frac{P_{h\perp}^2}{4z^2 M_N M_h} \cos(2\phi_h) \ldots$$

Polarized target

$$2\,|S_L|\,(1-y) \frac{P_{h\perp}^2}{4z^2 M_N M_h} \sin(2\phi_h) \ldots$$

$$+2\,|S_T|\,(1-y) \frac{P_{h\perp}}{zM_h} \sin(\phi_h+\phi_S) \ldots$$

$$+2\,|S_T|\,(1-y+\tfrac{1}{2}y^2) \frac{P_{h\perp}}{zM_N} \sin(\phi_h-\phi_S) \ldots$$

$$+2\,|S_T|\,(1-y) \frac{P_{h\perp}^3}{6z^3 M_N^2 M_h} \sin(3\phi_h-\phi_S) \ldots$$

Polarzied beam and target

$$+\lambda_e\,|S_L|\,y(1-\tfrac{1}{2}y) \ldots$$

$$+\lambda_e\,|S_T|\,y(1-\tfrac{1}{2}y) \frac{P_{h\perp}}{zM_N} \cos(\phi_h-\phi_S) \ldots\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

Transversity and TMD PDFs are also probed in Drell-Yan

Boer-Mulders functions:

- Unpolarized Drell-Yan: dhA_{DY} $_{11}$ cos(2)

Sivers functions:

- Single transverse spin asymmetry in singly polarized Drell-Yan:

$Afxfx^{DY}_{N1qq}$ $_{1}$ ()) – (–

Transversity distributions:

- Double transverse spin asymmetry in doubly polarized Drell-Yan:

$Ahxhx^{DY}_{TTqq}$ $_{11}$()(–)

SIDIS involves combinations of PDF and fragmentation functions

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!

A brief history of some dimuon experiments

1)Fermilab E772

"Nuclear Dependence of Drell-Yan and Quarkonium Production"

Proposed in 1986 and completed in 1988

2)Fermilab E789

"Search for Two-Body Decays of Heavy Quark Mesons"

Proposed in 1989 and completed in 1991

3)Fermilab E866

"Determination of $\bar{d}/\bar{u}$ Ratio of the Proton via Drell-Yan"

Proposed in 1993 and completed in 1996

4)Fermilab E906

"Drell-Yan Measurements of Nucleon and Nuclear Structure with the FNAL Main Injector"

Proposed in 2001, data expected 2010-2012

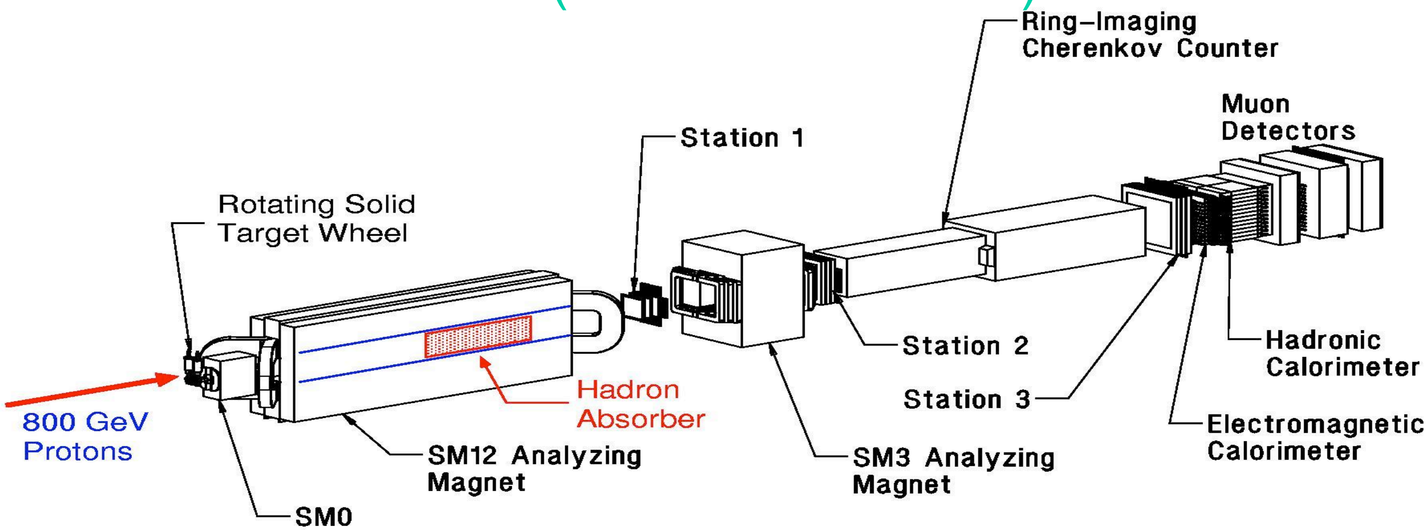
5)J-PARC P-04 (P-24)

"Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron" ("Polarized Proton at J-PARC")

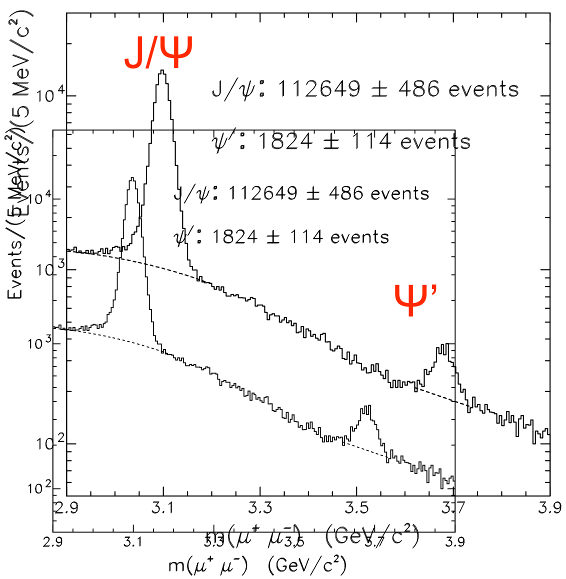
Proposed in 2007/2008

Meson East Spectrometer

(E605/772/789/866)

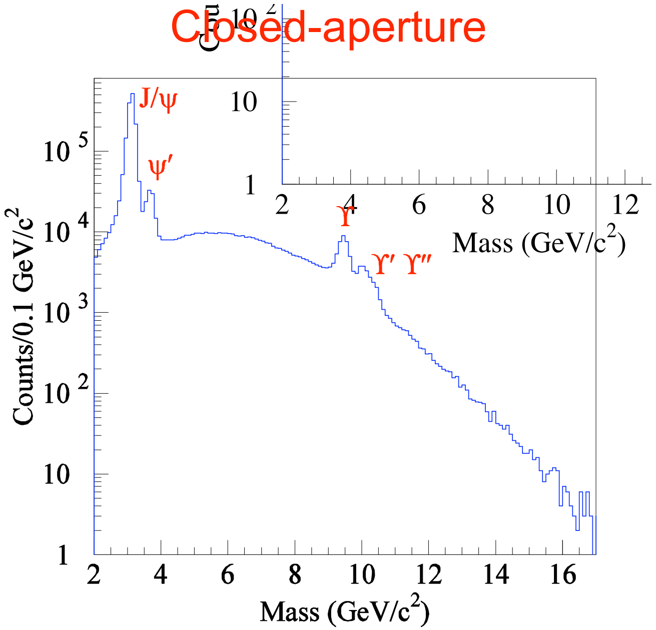


Open-aperture



$\sigma(J/\psi) \sim 15$ MeV

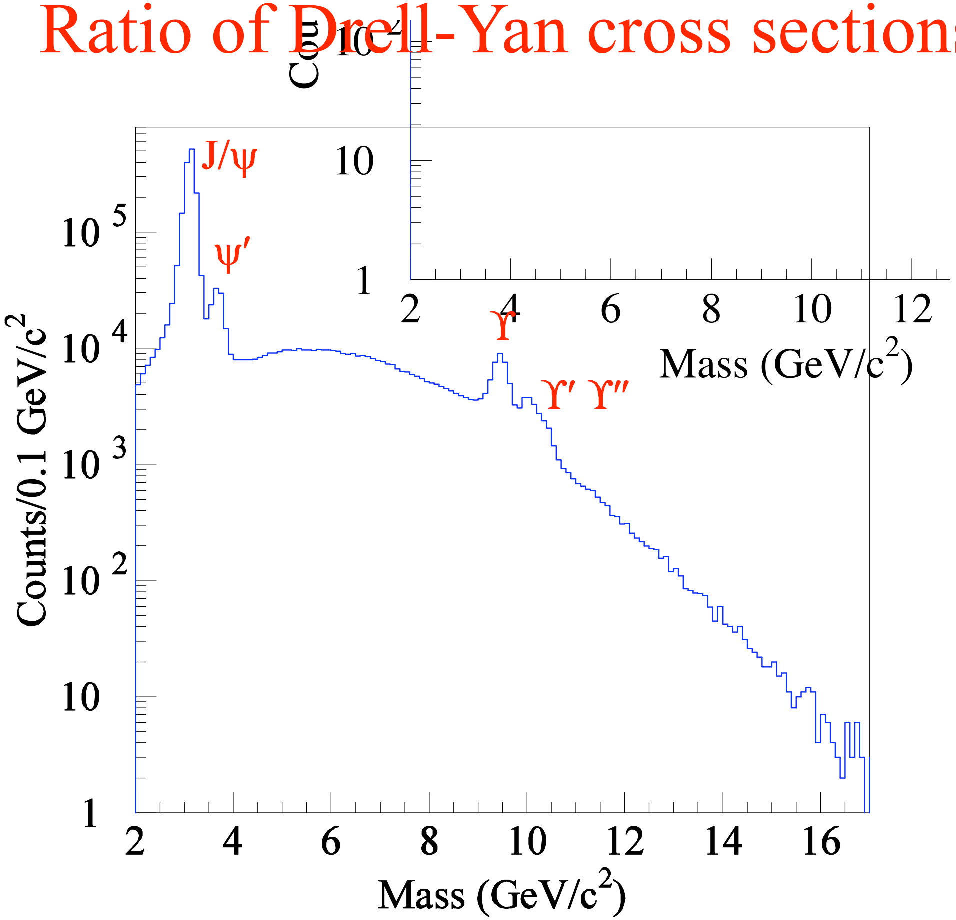
Closed-aperture

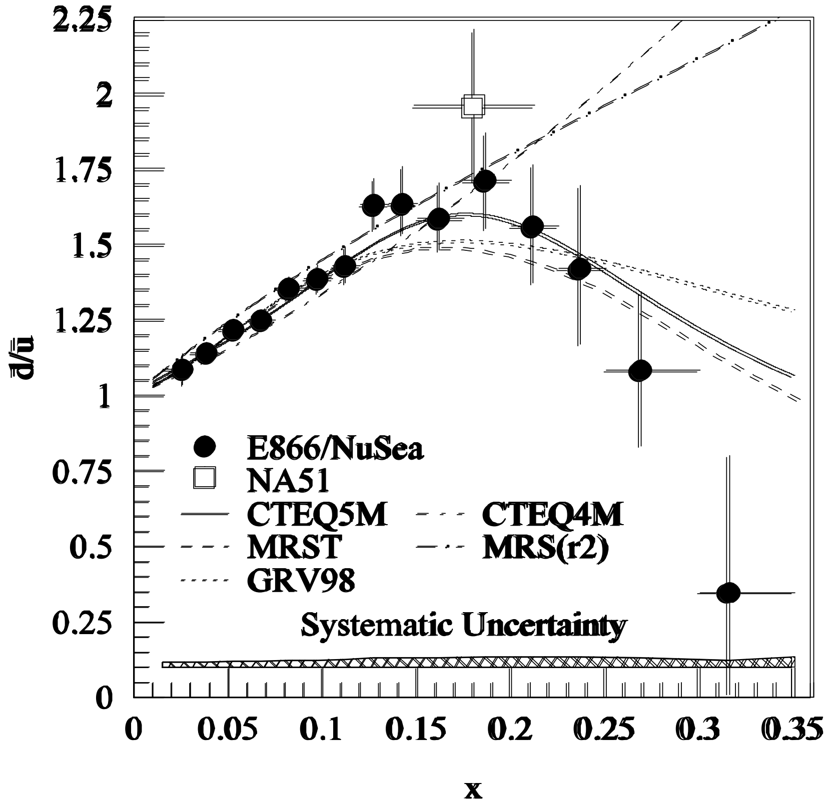


$\sigma(J/\psi) \sim 150$ MeV

$\bar{d}/\bar{u}$ flavor asymmetry from E866 Drell-Yan

Ratio of Drell-Yan cross sections for $p+p$ and $p+d$ at 800 GeV



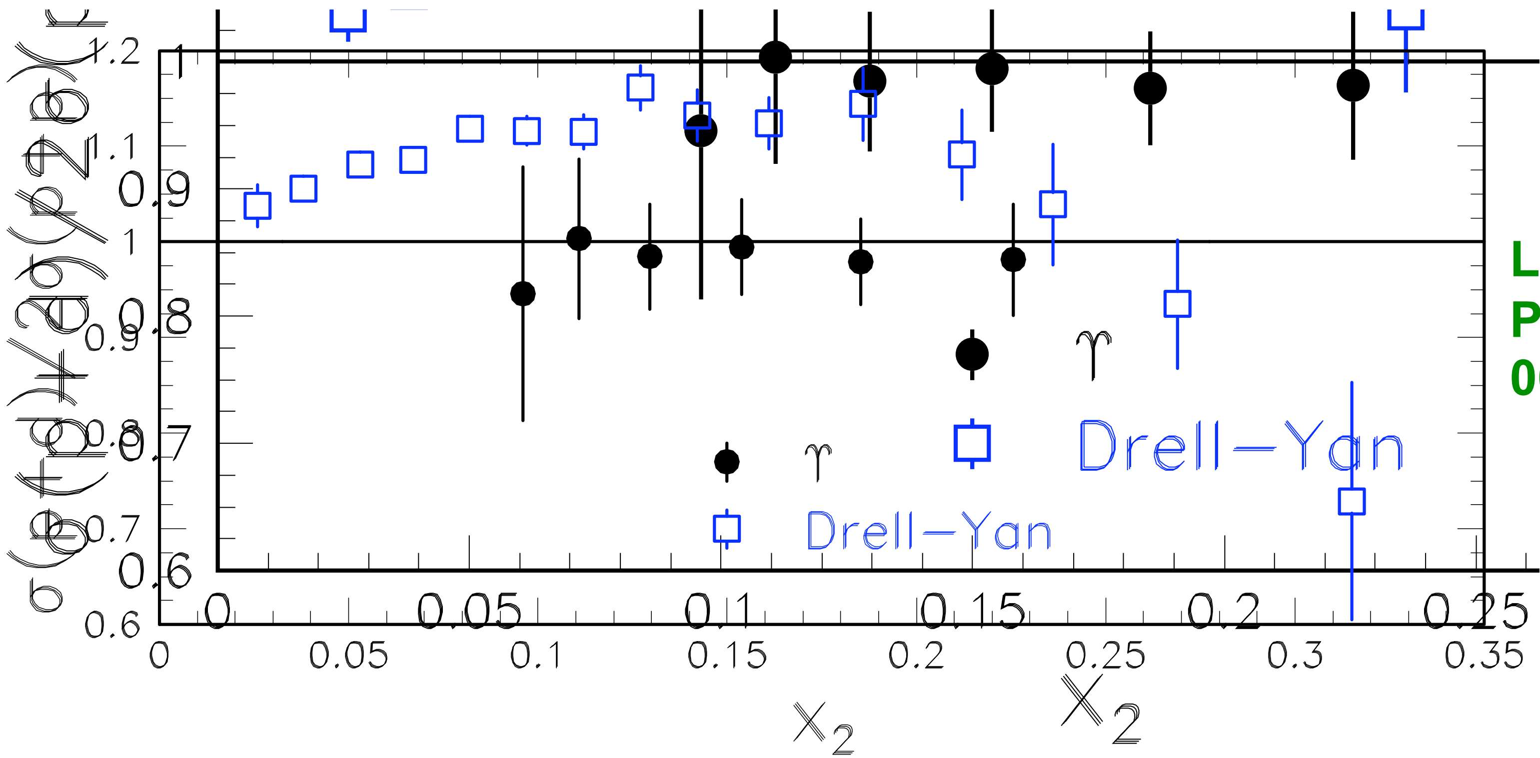


Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx \frac{1}{2}[1+\bar{d}(x)/\bar{u}(x)]$

Observation of large flavor asymmetry for d-bar and u-bar

Gluon distributions in proton versus neutron?

E866data: $\sigma(pd \to \Upsilon X)/2\sigma(pp \to \Upsilon X)$



Lingyan Zhu et al., PRL, 100 (2008) 062301

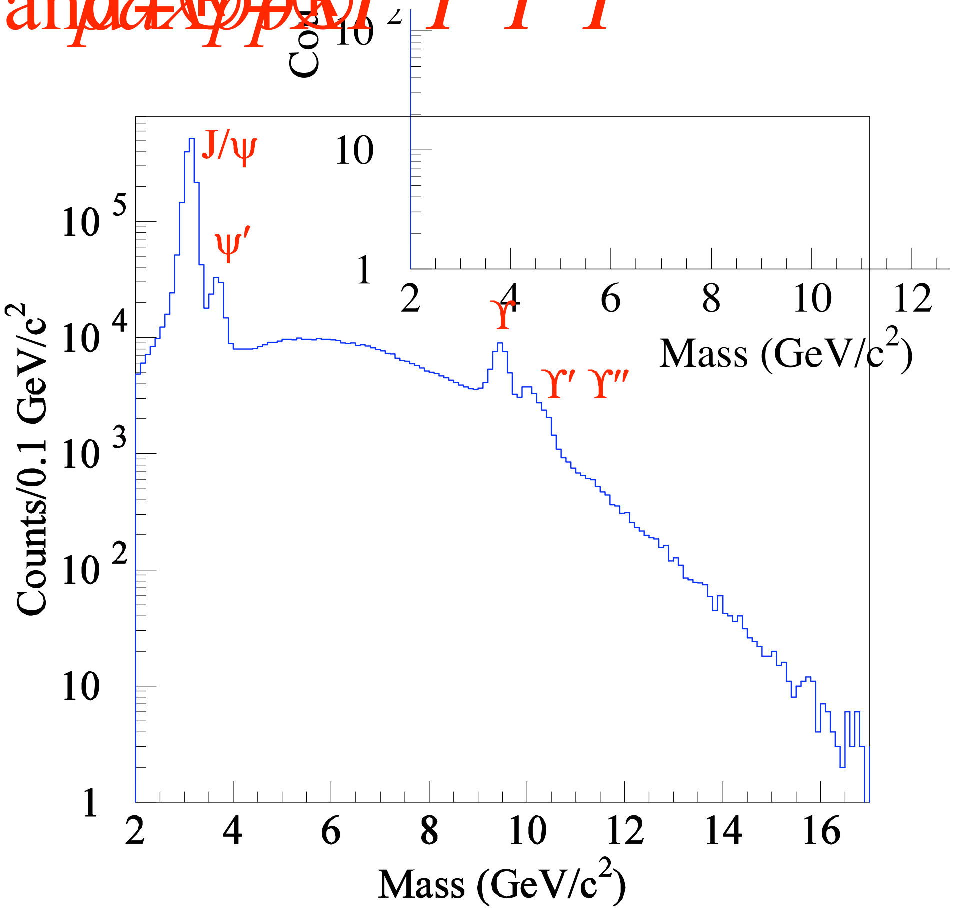
Drell-Yan: $\sigma^{pd}/2\sigma^{pp} \approx [1 + \bar{d}(x)/\bar{u}(x)]/2$

$J/\psi, \Upsilon$: $\sigma^{pd}/2\sigma^{pp} \approx [1 + g_n(x)/g_p(x)]/2$

Gluon distributions in proton and neutron are very similar

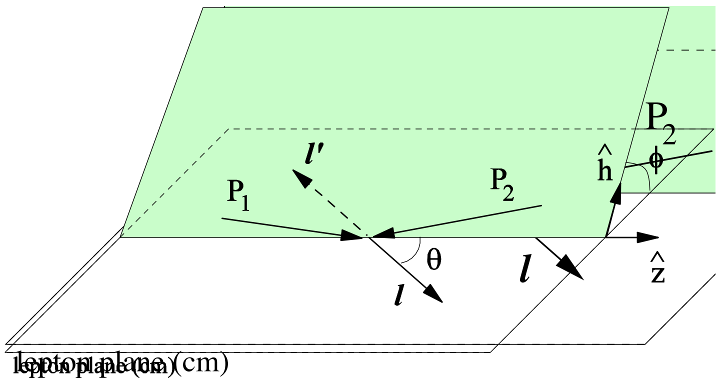
Decay angular distributions from E866 Drell-Yan

800GeVand p+d® p+p® I +2 +2 I I



~ 200,000 high-mass Drell-Yan events

Drell-Yan decay angular distributions



$h_1 h_2 \to \gamma^* X \to l^+ l^- X$ $(q\bar{q} \to \gamma^*)$

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

Collins-Soper frame

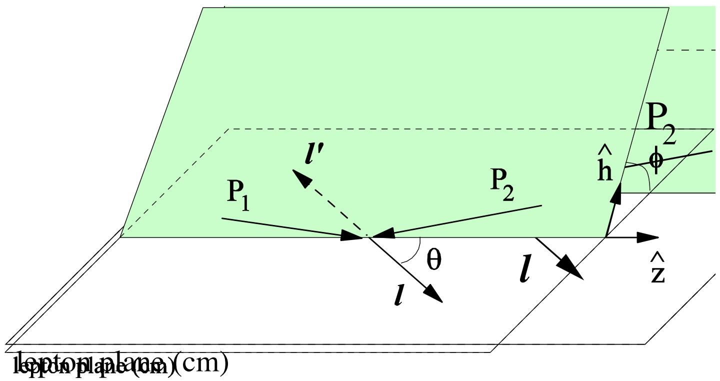
A general expression for Drell-Yan decay angular distributions:

$$\left(\frac{d\sigma}{d\Omega}\right) \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

"Naive" Drell-Yan (transversely polarized γ^*, no transverse momentum) → $\lambda = 1, \mu = \nu = 0$

In general : $\lambda \neq 1, \mu \neq 0, \nu \neq 0$

Drell-Yan decay angular distributions



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

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

Lam-Tung relation: $1 - \lambda = 2\nu$

- Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)
- Insensitive to QCD - corrections

Decay angular distributions in pion-induced Drell-Yan

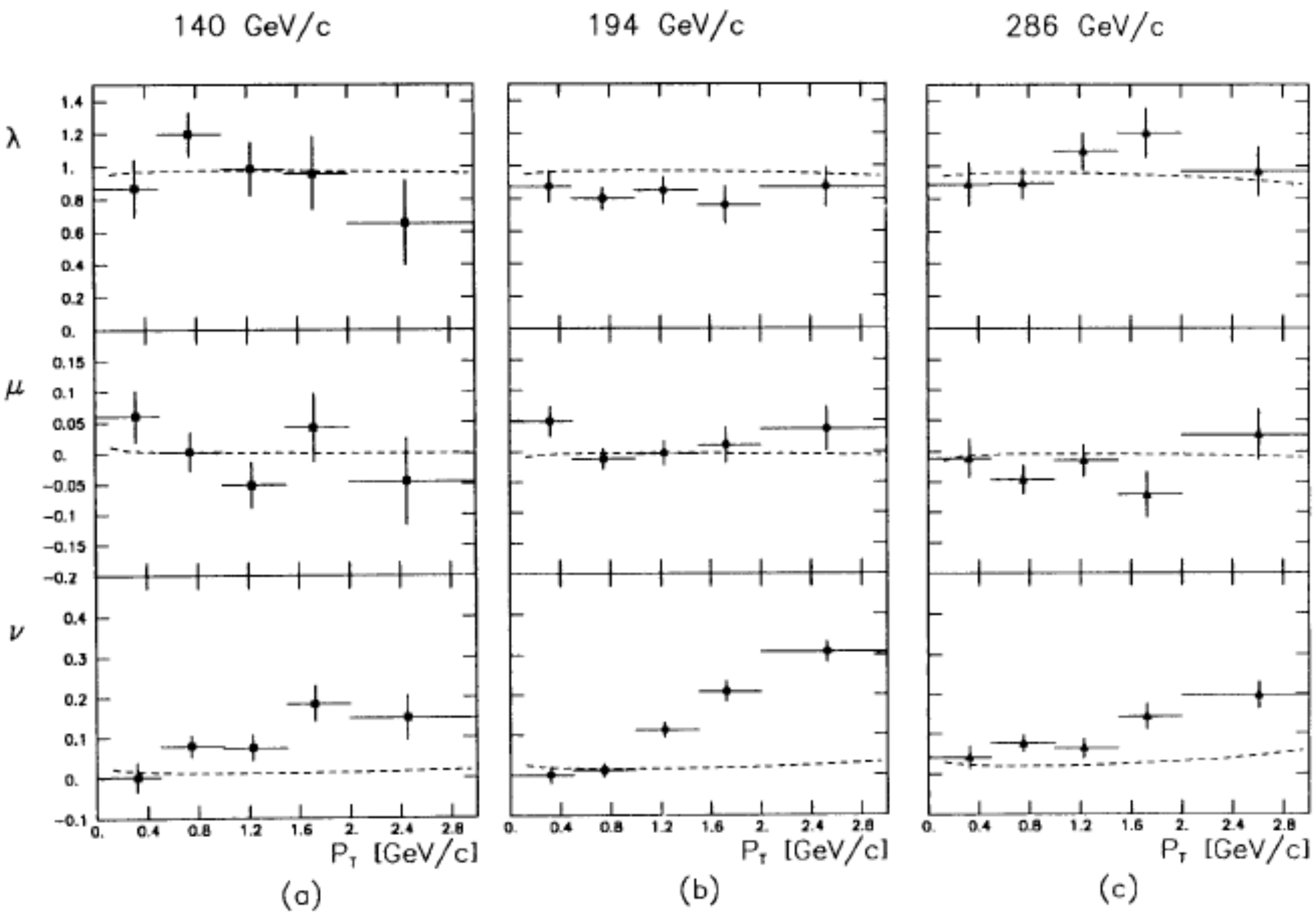


Fig. 3a–c. Parameters λ, μ, and ν as a function of P_T in the CS frame. **a** 140 GeV/c; **b** 194 GeV/c; **c** 286 GeV/c. The error bars correspond to the statistical uncertainties only. The horizontal bars give the size of each interval. The dashed curves are the predictions of perturbative QCD [3]

NA10 $\pi^- + W$

Z. Phys. 37 (1988) 545

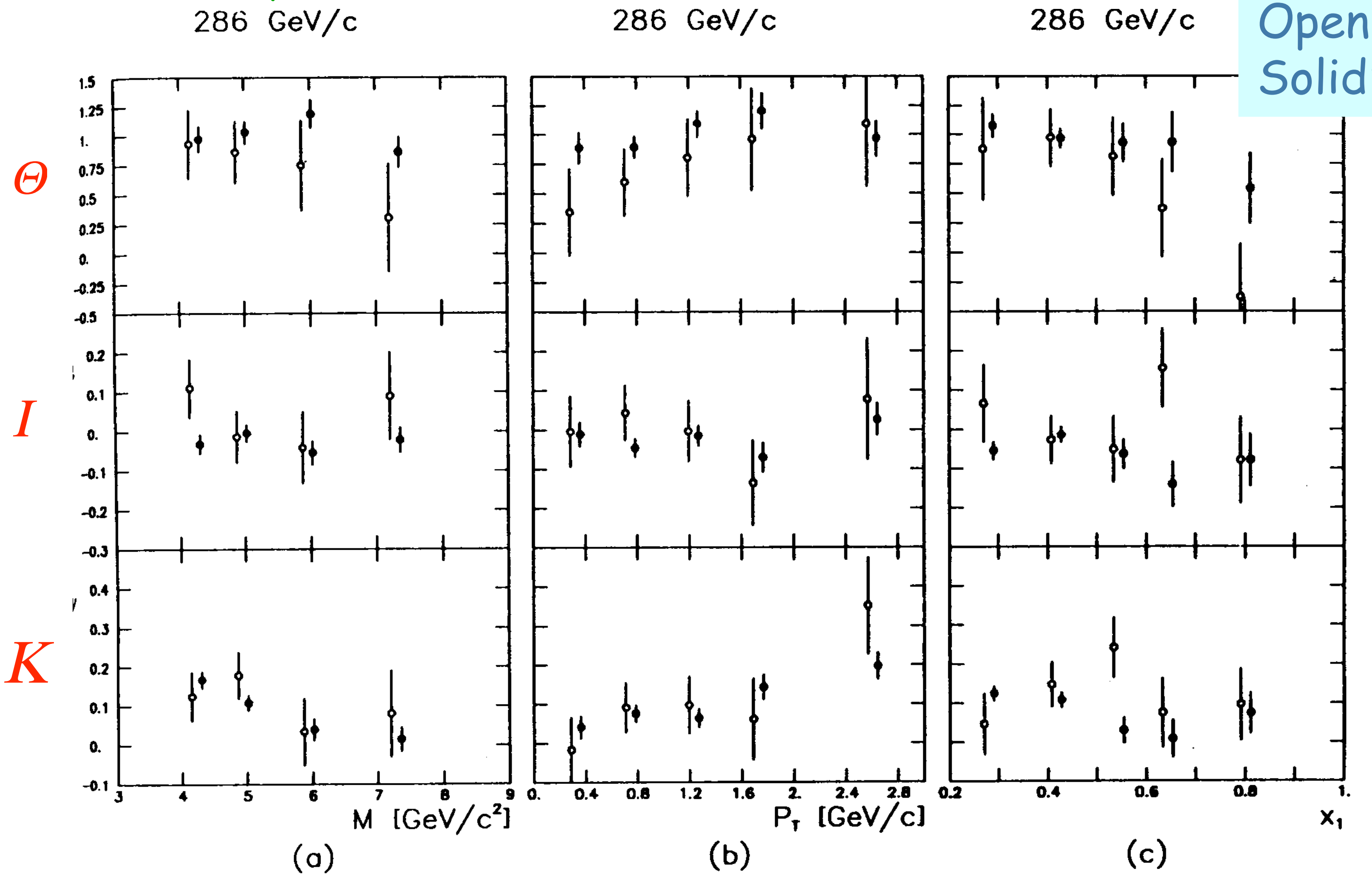
Dashed curves are from pQCD calculations

KK 0 and increases with p_T

Nuclear Effect?

NA10 Z. Phys. C37, 545 (1988)

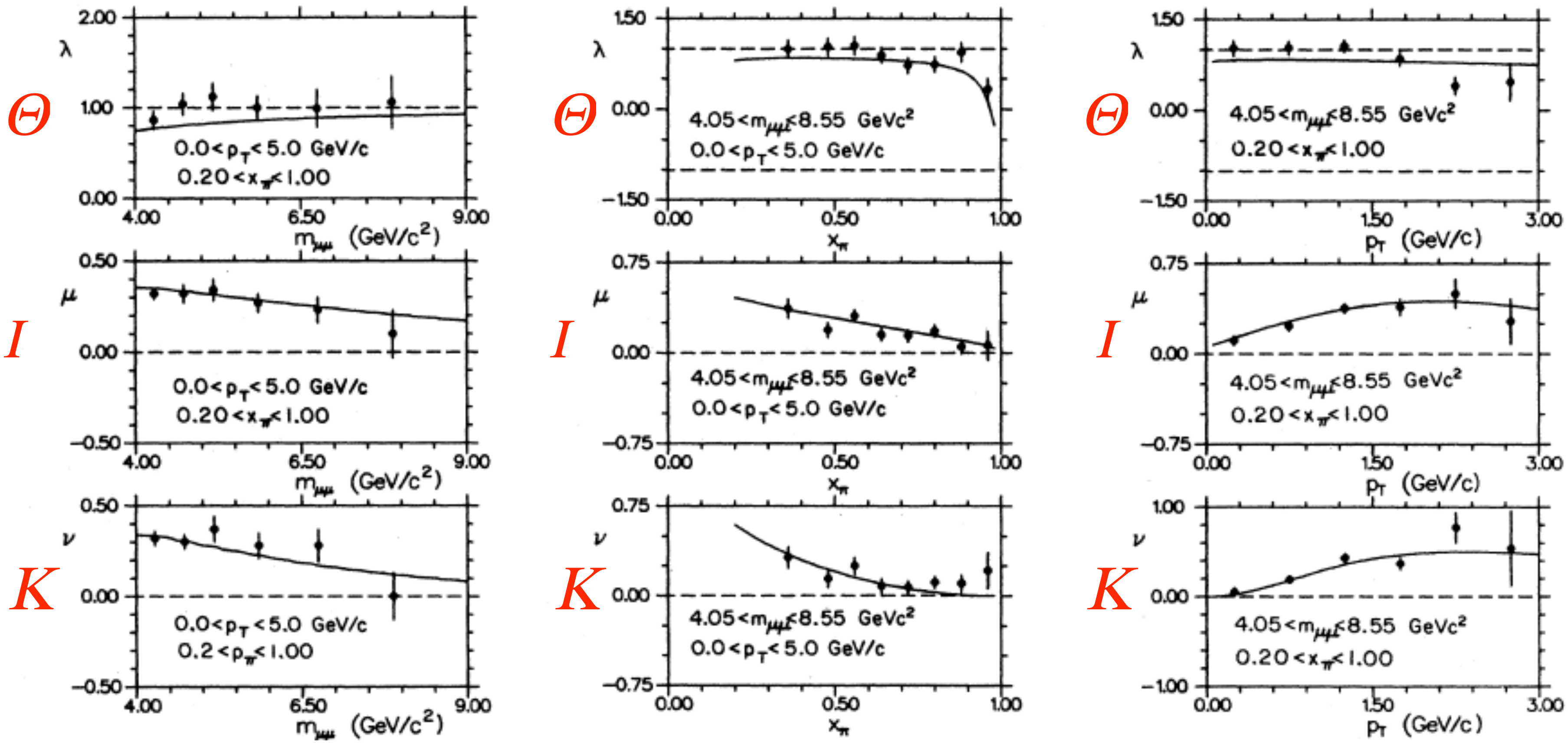
Open: Deuterium
Solid: Tungsten



Nuclear effect seems not to be the dominant contribution.

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV π + W Phys. Rev. D 39 (1989) 92

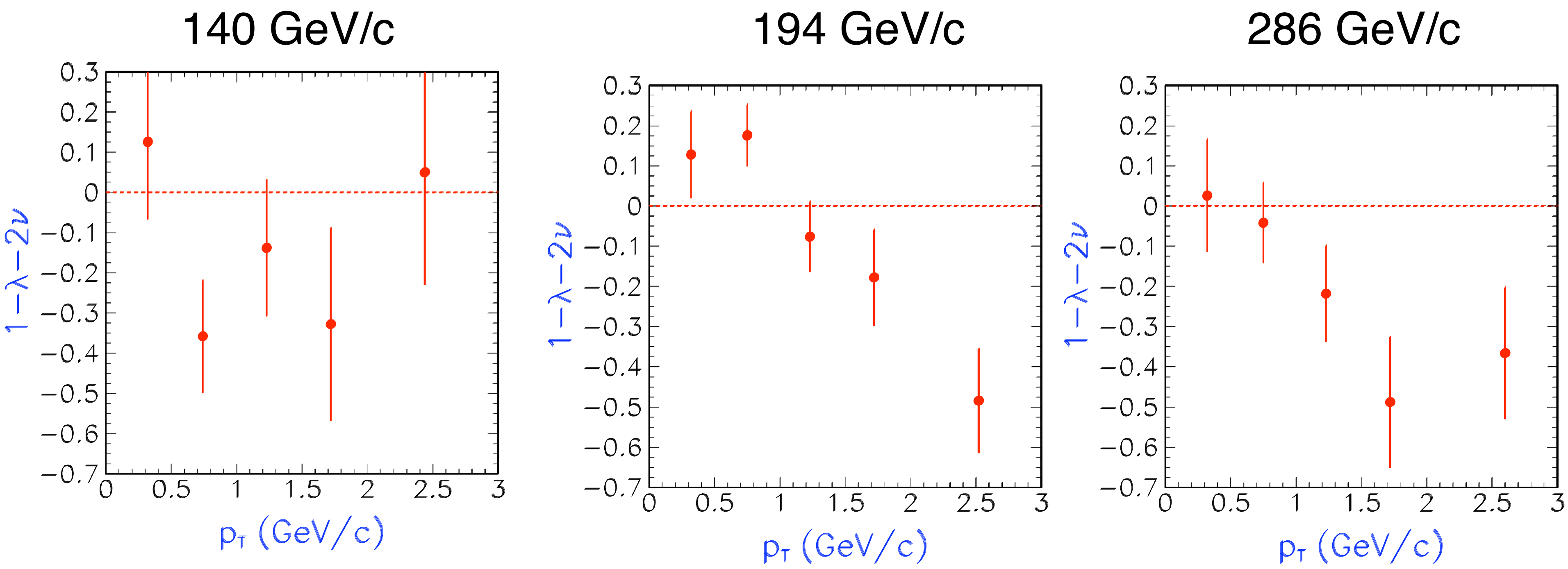


m_{II}(GeV/c²) x_M p_T(GeV/c)

Θ□K.0,0 and they vary with , ,and $m\,p\,x_{I\,T\,M\,T}$

Decay angular distributions in pion-induced Drell-Yan

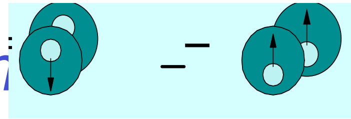
Is the Lam-Tung relation violated?



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.)

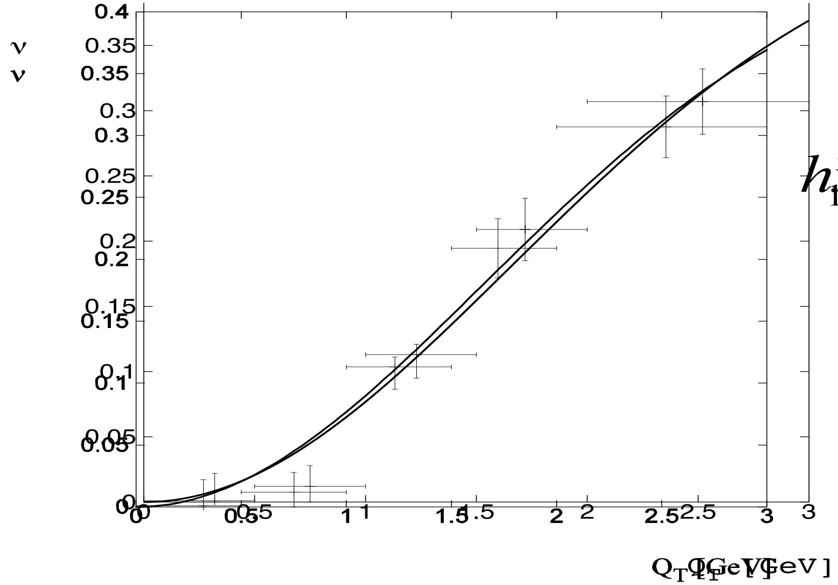
Boer-Mulders function $h_1^\perp$



$h_1^\perp$ represents a correlation between quark's k_T and transverse spin in an unpolarized hadron (analogous to Collins function)

$h_1^\perp$ is a time-reversal odd, chiral-odd TMD parton distribution

$h_1^\perp$ can lead to an azimuthal dependence with κ



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

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

Boer, PRD 60 (1999) 014012

$\kappa_1 = 0.47$, $M_C = 2.3$ GeV

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

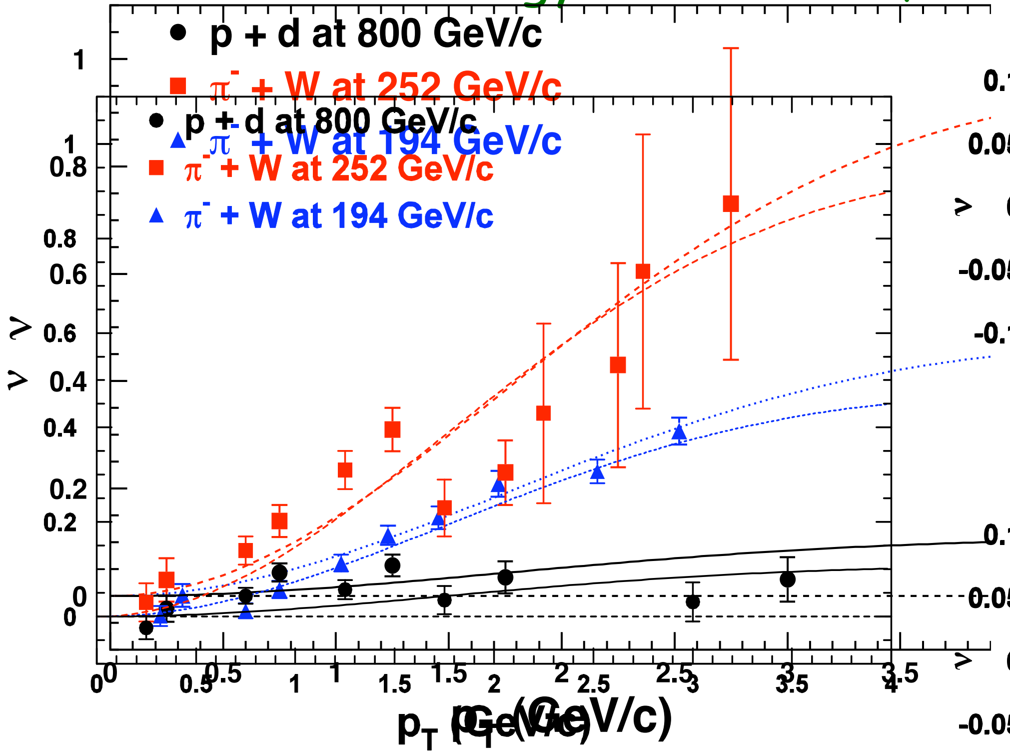
Motivation for measuring decay angular distributions in p+p and p+d Drell-Yan

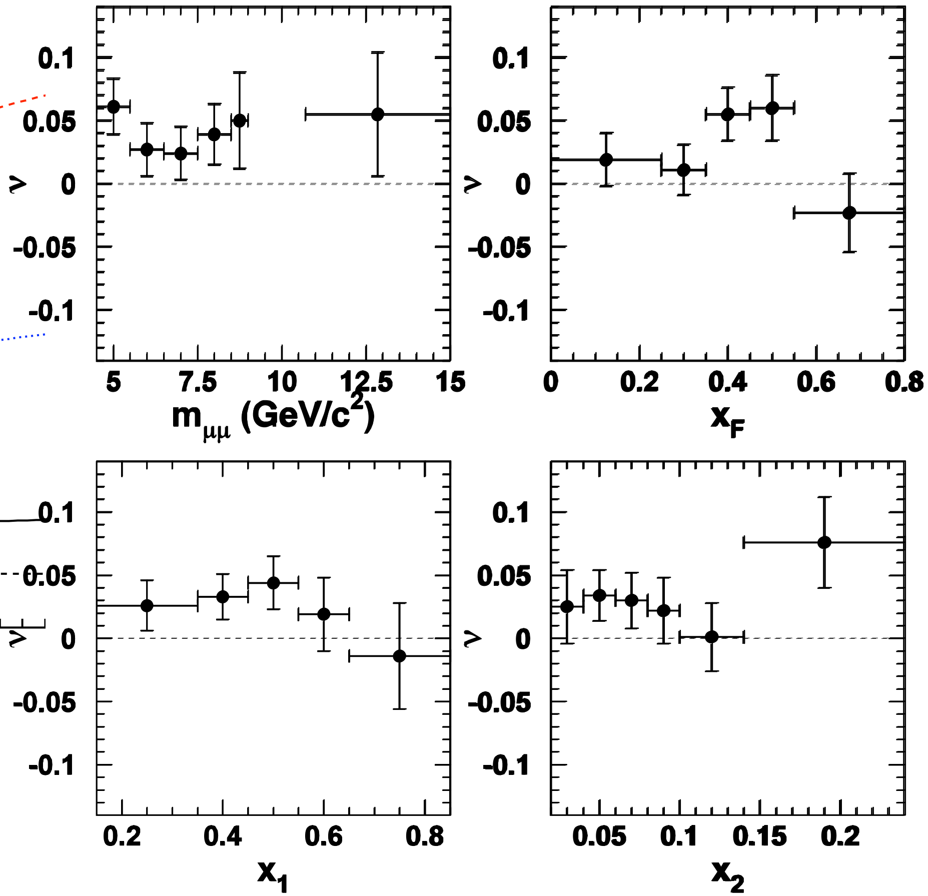
- No proton-induced Drell-Yan azimuthal decay angular distribution data
- Provide constraints on models explaining the pion-induced Drell-Yan data. ($h_1^{\perp}$ is expected to be small for sea quarks. Some other models predict similar effects for p+N and π+N)
- Test of the Lam-Tung relation in proton-induced Drell-Yan
- Compare the decay angular distribution of p+p versus p+d (information on flavor dependence)

First considered at the 2003 transversity workshop in Athens

Azimuthal cos2Φ Distribution in p+d Drell-Yan

Lingyan Zhu et al., PRL 99 (2007) 082301





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 $h_1^{\perp}(p)$]

ν>0 suggests same sign for the valence and sea BM functions

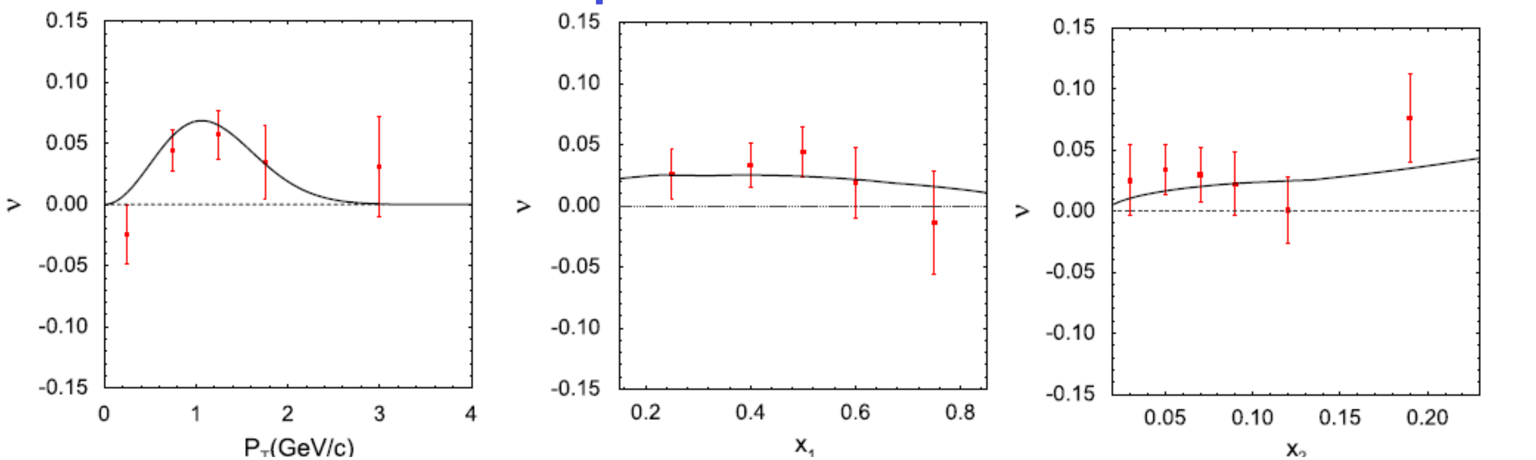
What does the data tell us?

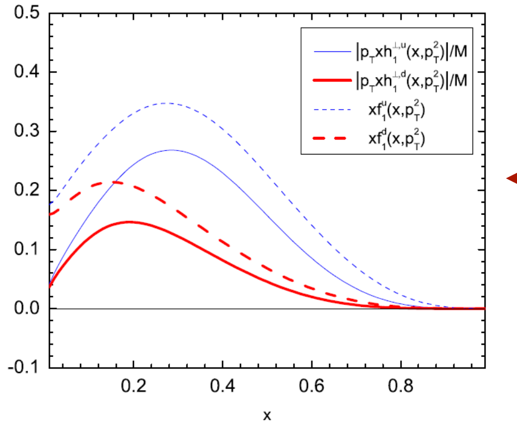
- These results suggest that the Boer-Mulders functions $h_1^{\perp}$ for sea quarks are significantly smaller than for valence quarks and have the same sign as valence quarks.
- A combined analysis of p+p and p+d, together with the π+p and π+d Drell-Yan cos(2Φ) data can lead to extraction of valence and sea Boer-Mulders functions.

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv: 0803.1692)

Fit to the p+d Drell-Yan data





Satisfy the positivity bound

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv: 0803.1692)

Parametrization of the BM functions:

$$h_1^{\perp q}(x,\vec{p}_T^2) = H_q x^c (1-x) f_1^q(x,\vec{p}_T^2) \exp(-\vec{p}_T^2/p_{BM}^2)$$

H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	p_{BM}^2	c	χ^2/dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

H_u and H_d have the same sign and similar magnitude

(in agreement with model calculations (bag-model, quark-diquark, relativistic CQM, Lattice) and the picture given by M. Burkardt)

$H_{\bar{u}}$ and $H_{\bar{d}}$ are smaller by factor of 4 and have opposite sign

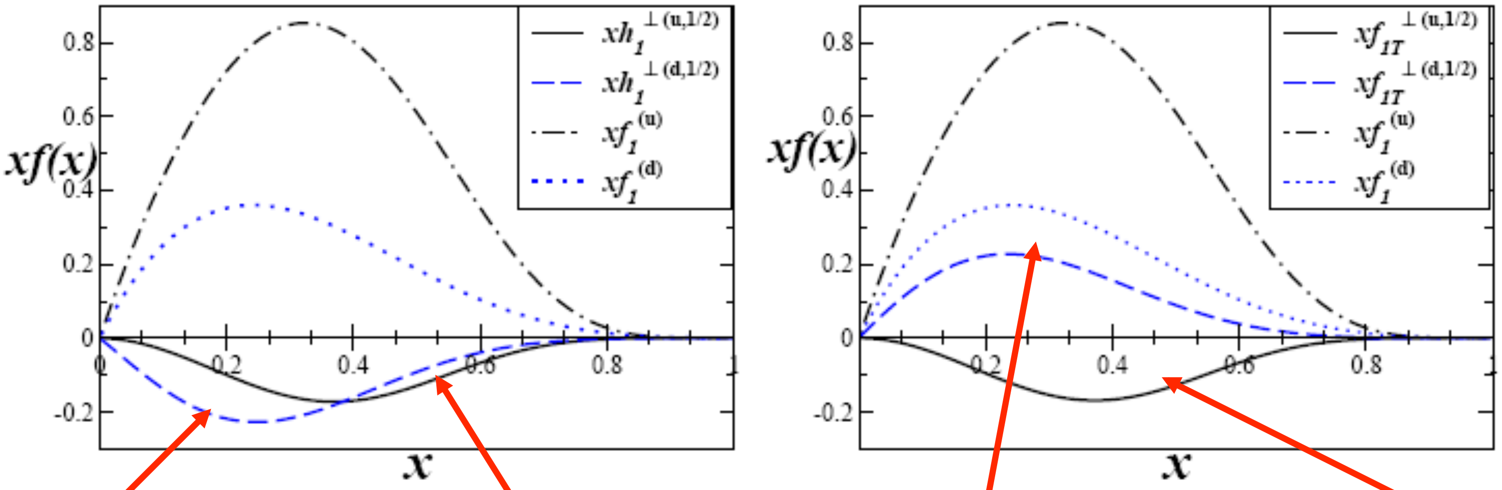
Quark-diquark Models for Boer-Mulders Function $h_1^\perp$

- Initial-state gluon interaction can produce nonzero $h_1^\perp$ for the proton in the quark-scalar diquark model. In this model, $h_1^\perp = f_{1T}^\perp$.

$$h_{1p}^{\perp}(x, \mathbf{k}_\perp^2) = \frac{A_p(x)}{\mathbf{k}_\perp^2[\mathbf{k}_\perp^2 + B_p(x)]} \ln[\frac{\mathbf{k}_\perp^2 + B_p(x)}{B_p(x)}]$$

Boer,Brodsky&Hwang, PRD67,054003(2003).

- Recent quark-diquark model including axial-diquarks Gamberg, Goldstein & Schlegel, arXiv: 0708.0324.

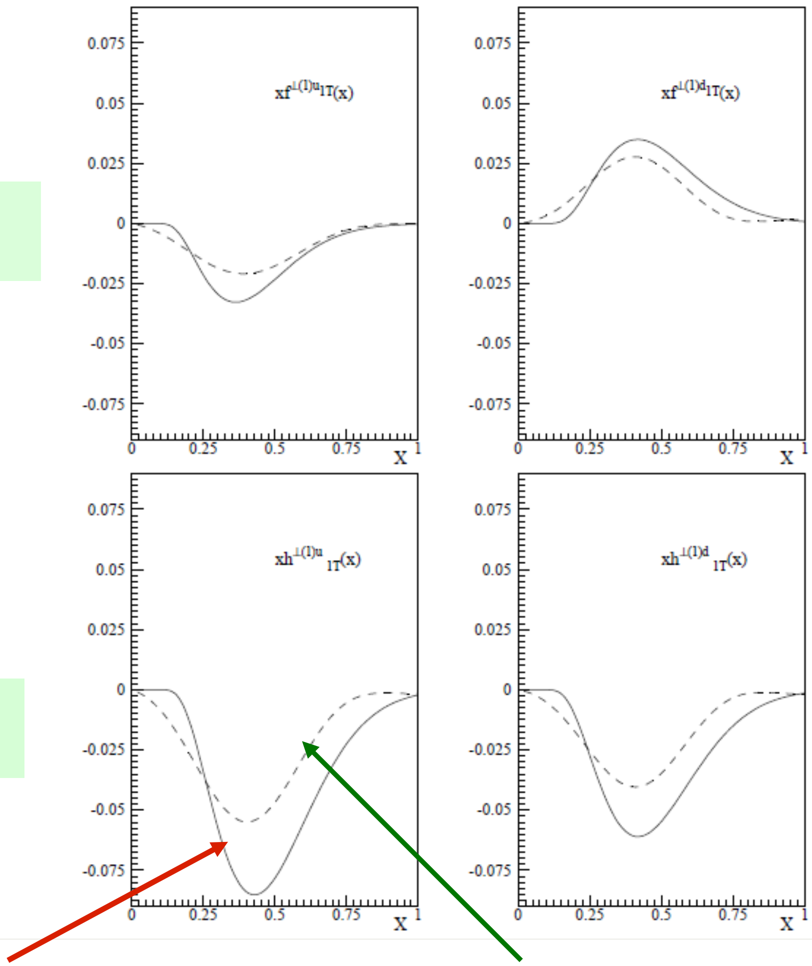


B-M d-quark | B-M u-quark | Sivers d-quark | Sivers u-quark

Bag Model and CQM calculations for Boer-Mulders Function and Sivers function

Sivers u-quark

Sivers d-quark



B-M u-quark

B-M d-quark

Solid curves: CQM, dashed: MIT bag (F. Yuan)

Courtoy, Scopetta, Vento, arXiv: 0909.1404

A simple explanation for the signs of the up- and down-quark Boer-Mulders functions

From fits to SIDIS data, we know that

1) transversity

$h_1(u) > 0$ $h_1(d) < 0$

2) Sivers function

$f_{1T}^{\perp}(u) < 0$ $f_{1T}^{\perp}(d) > 0$

Therefore, one expects for Boer-Mulders function

$h_1^{\perp}(u) < 0$ $h_1^{\perp}(d) < 0$

1) Transversity

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

2) Sivers function

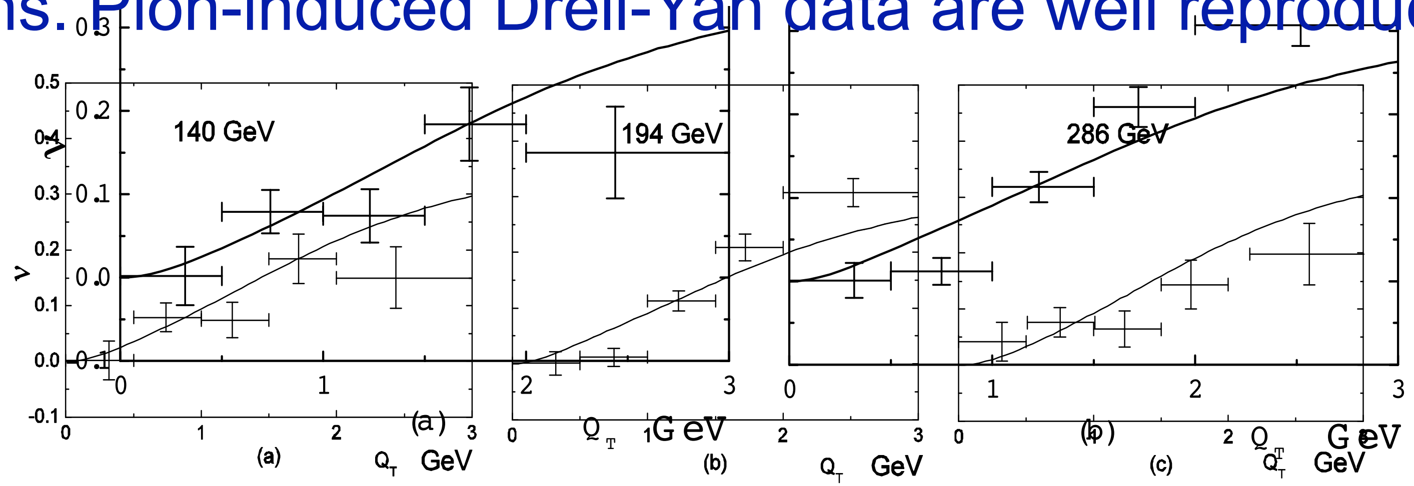
Correlation between $\vec{S}^N$ and $\vec{L}^q$

3) Boer-Mulders function

Correlation between $\vec{s}^q$ and $\vec{L}^q$

Sea-quark Boer-Mulders Functions

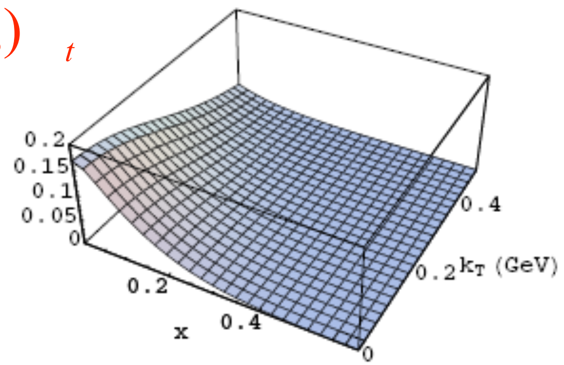
1) Use quark-spectator-antiquark model to calculate pion B-M functions. Pion-induced Drell-Yan data are well reproduced.



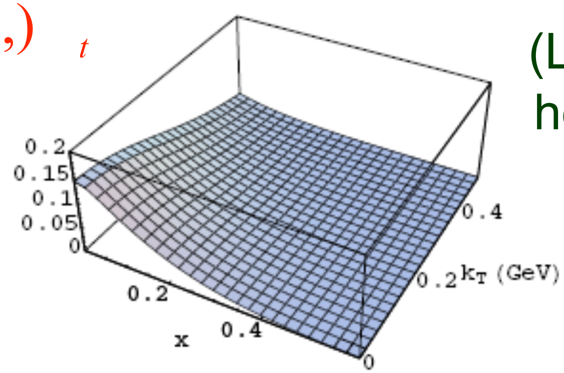
(Lu and Ma, hep-ph/0504184)

2) Use pion-cloud model convoluted with the pion B-M function to calculate sea-quark B-M for proton.

hxk (,) t



hxk (,) t



(Lu, Ma, Schmidt, hep-ph/0701255)

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv: 0803.1692)

Parametrization of the BM functions:

$$h_{1}^{\perp q}(x, \vec{p}_T^{\,2}) = H_q\, x^c (1-x)\, f_1^q(x) \exp(-p_T^2/p_{BM}^2)$$

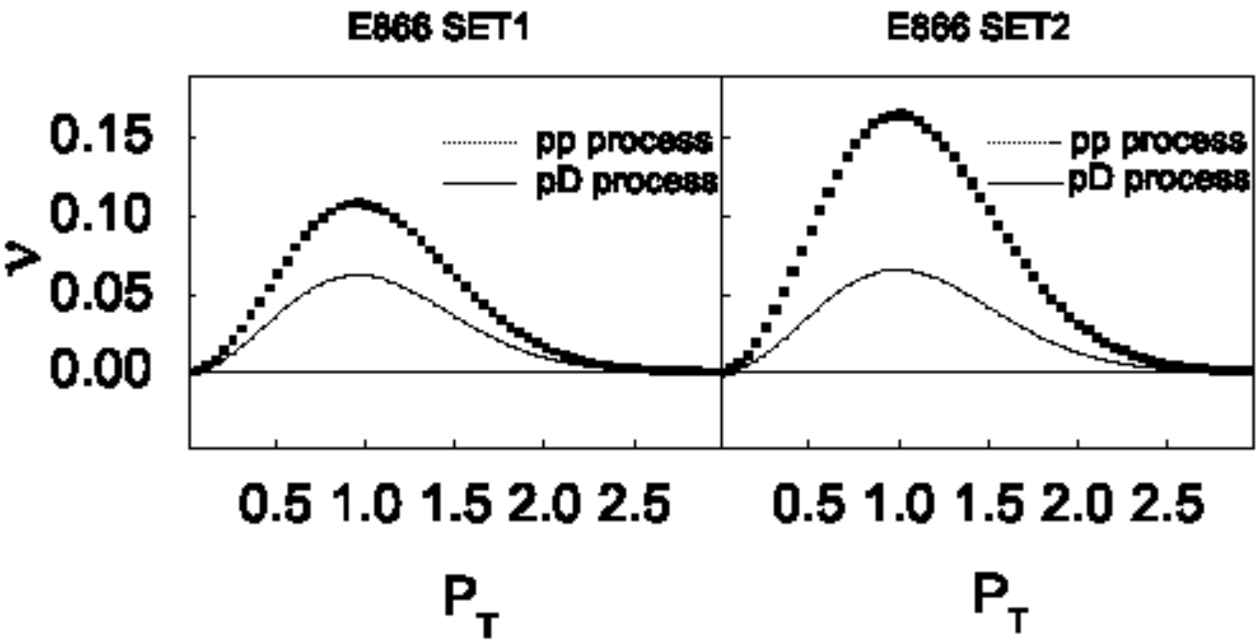
H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	p_{BM}^2	c	χ^2 / dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

It seems unlikely that p+d data alone can determine the flavor structure of BM functions!

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, PR D78 (2008) 034035)

	Set I	Set II
H_u	3.99	4.44
H_d	3.83	-2.97
$H_{\bar u}$	0.91	4.68
$H_{\bar d}$	-0.96	4.98
p^2_{bm}	0.161	0.165
c	0.45	0.82
$\chi^2/d.o.f.$	0.79	0.79



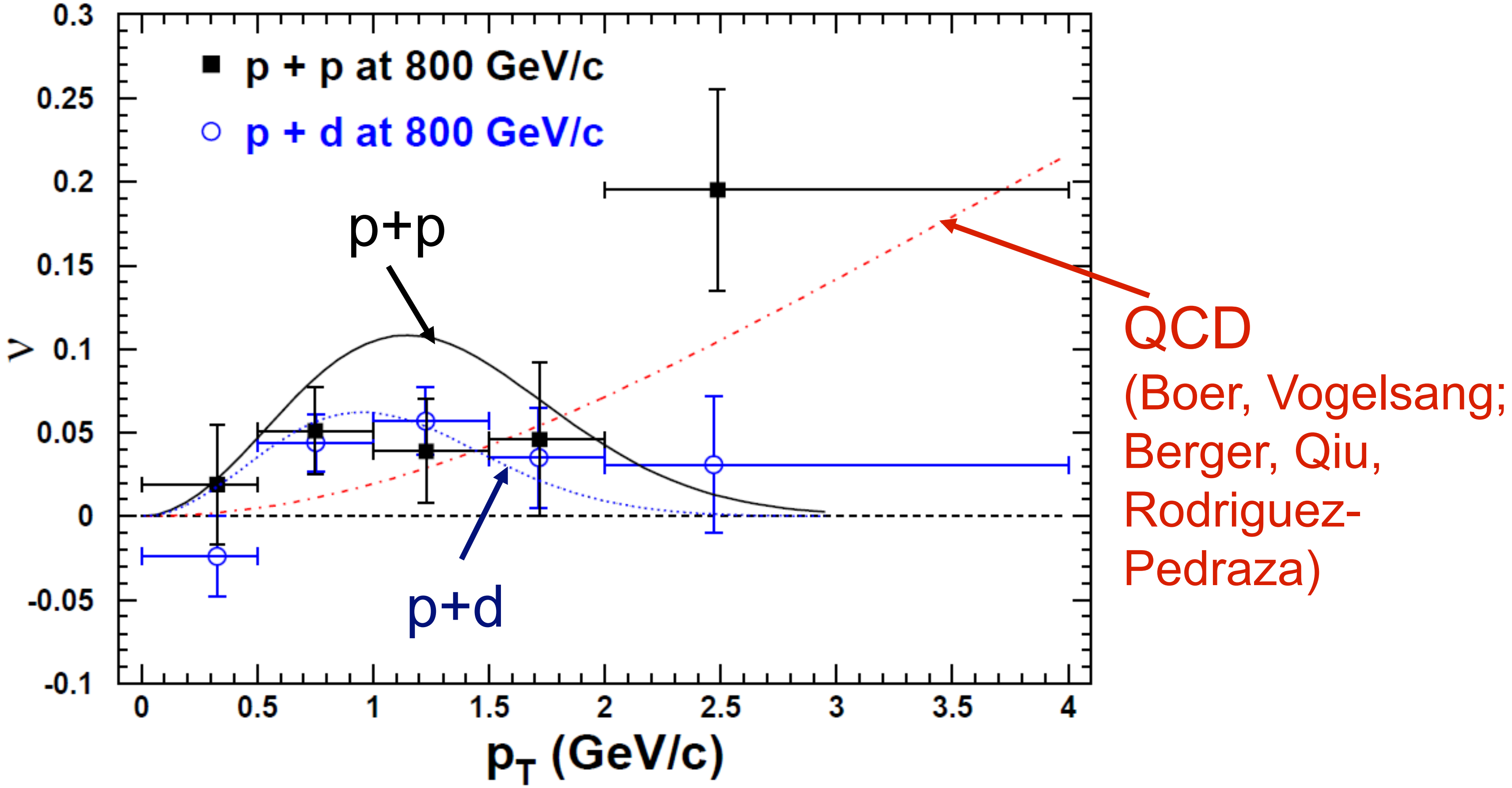
Set I: H_u, H_d have same signs

Set II: H_u, H_d have opposite signs

Predict larger values of ν for p+p than for p+d

New results on cos2Φ Distribution in p+p Drell-Yan

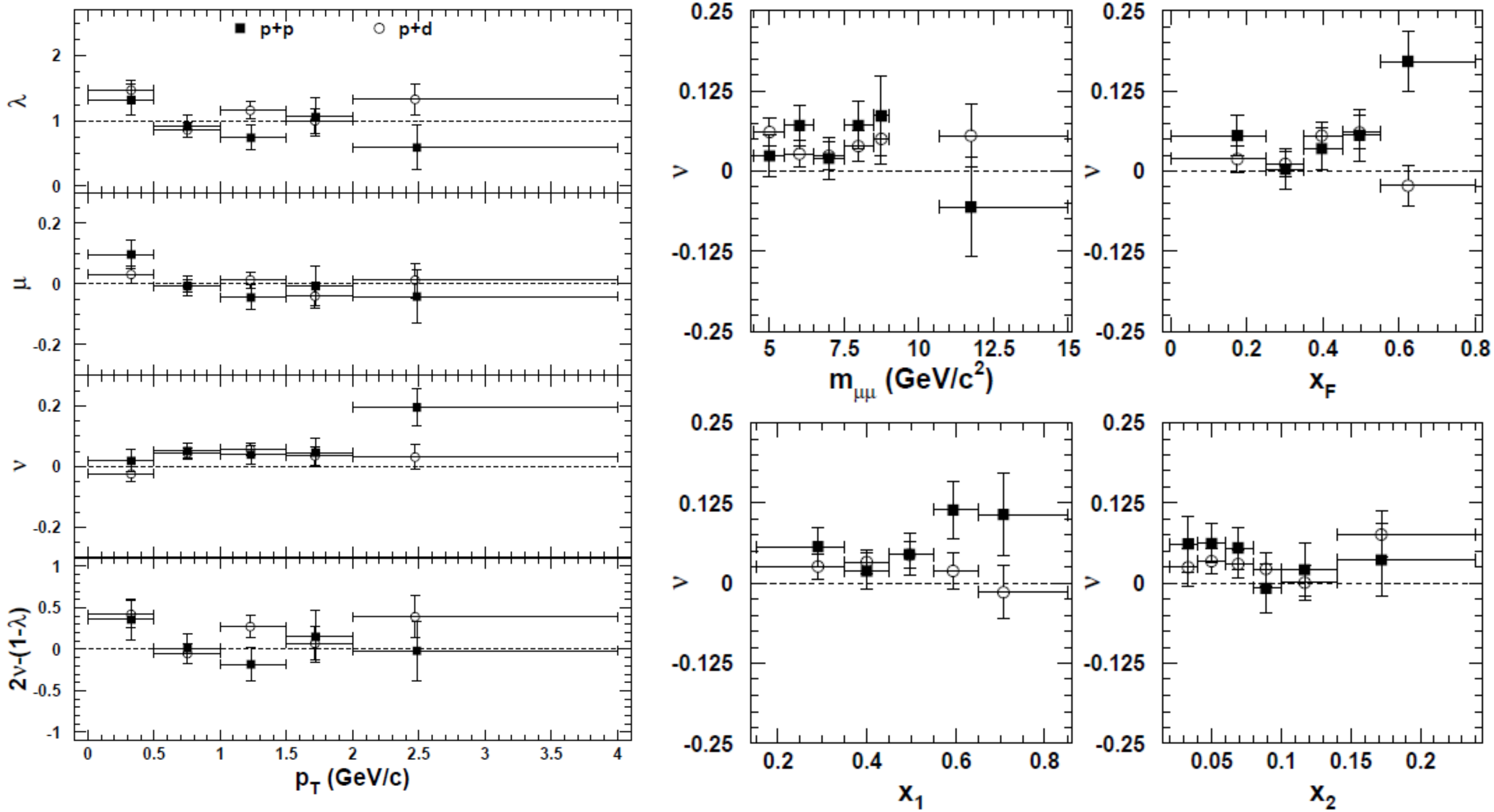
L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



- p+p is similar to p+d; More data at higher p_T is needed
- A global fit to all pion and proton data is needed

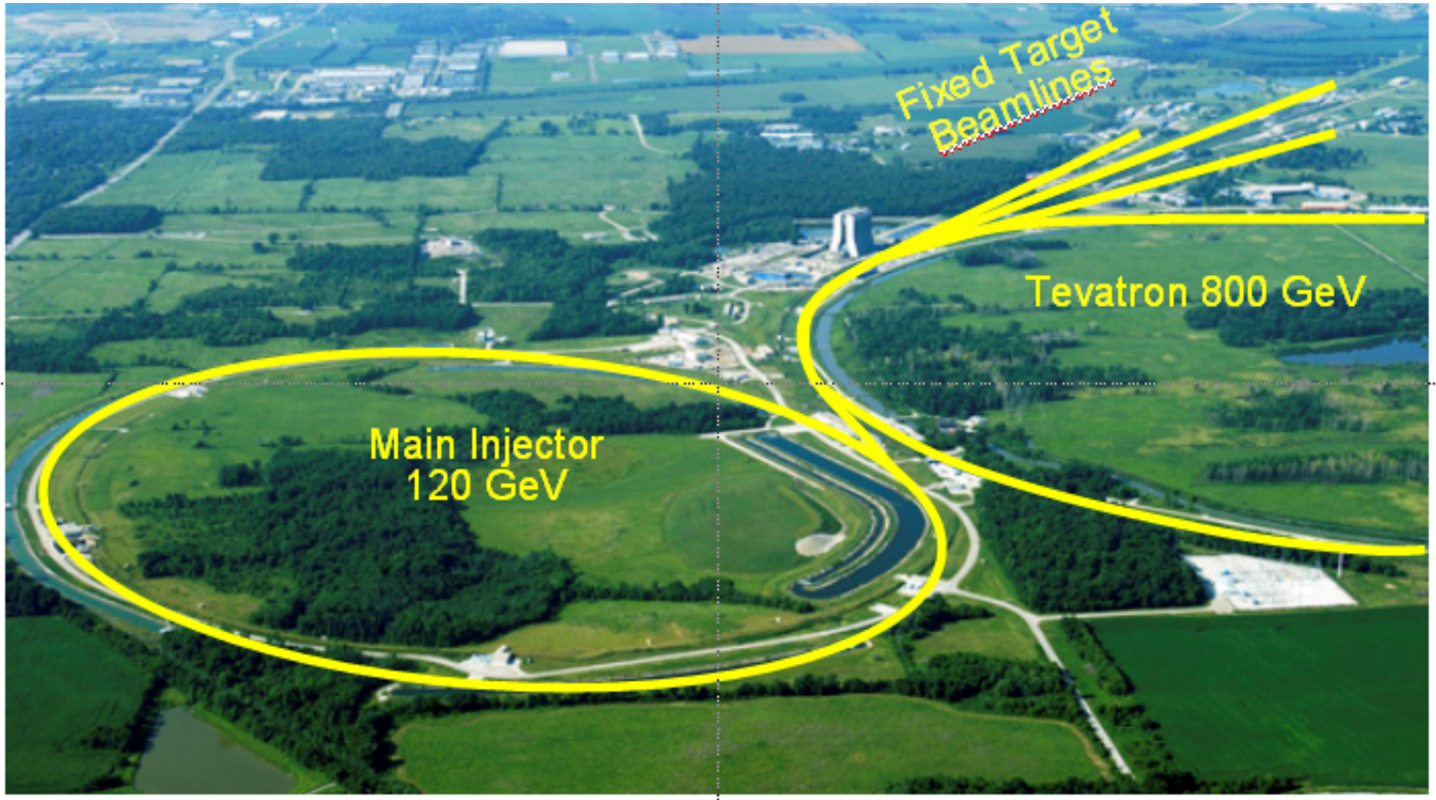
Angular Distribution in E866 p+p/p+d Drell-Yan

L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



p+p and p+d Drell-Yan show similar angular distributions.
Should be analysed togther for better constraints on BM.

Fermilab E906 dimuon experiment (Geesaman, Reimer et al., expected to run ~2010-2012)



- Main goal is to measure the flavor asymmetry for the sea

- Boer-Mulders can also be studied

What more could be done in Fermilab E906?

1) Boer-Mulders functions can be measured at larger *x*

2) Study Nuclear effects of Boer-Mulders functions

3) Measure azimuthal angular dependence of J/Ψ decay

Nuclear modification of spin-dependent PDF?

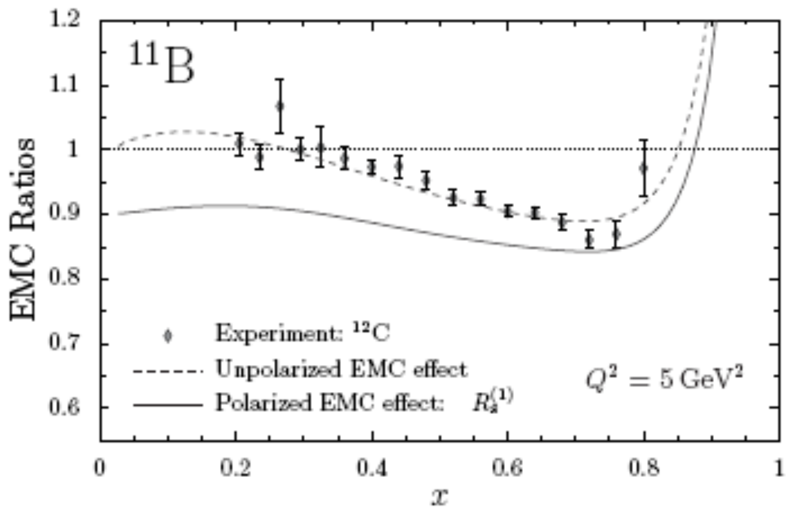


Figure 7: EMC ratios for ^{11}B. The experimental data refer to ^{12}C.

EMC effect for $g_1(x)$

Bentz, Cloet et al., arXiv:0711.0392

Very difficult to measure !

Easier to measure the nuclear modification of Boer-Mulders functions (only unpolarized targets are required)?

(See Bianconi and Radici, J. Phys. G31 (2005) 645)

Future prospect for Drell-Yan experiments

- Fermilab p+p, p+d, p+A
  – Unpolarized beam and target
- RHIC
  – Doubly and singly polarized p+p collision
- COMPASS
  – π-p and π-d with polarized targets
- FAIR
  – Polarized antiproton-proton collision
- J-PARC
  – Possibly polarized proton beam and target

Outstanding questions to be addressed by future Drell-Yan experiments

- 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

Summary

- The Drell-Yan process compliments the SIDIS as a powerful independent tool for measuring transversity and TMD PDFs.
- First results on azimuthal decay angular distributions on unpolarized p-p or p-d Drell-Yan are now available.
- Pronounced cos2Φ azimuthal dependence previously observed in pion-induced Drell-Yan is not observed in p-p or p-d Drell-Yan
- These results suggest that the Boer-Mulders functions $h_1^\perp$ for sea quarks are smaller than for valence quarks.
- Future Drell-Yan experiments at Fermilab, J-PARC and other facilities can provide new information (flavor dependence of valence and sea, opposite sign for SIDIS and D-Y) on Boer-Mulders and other TMDs.