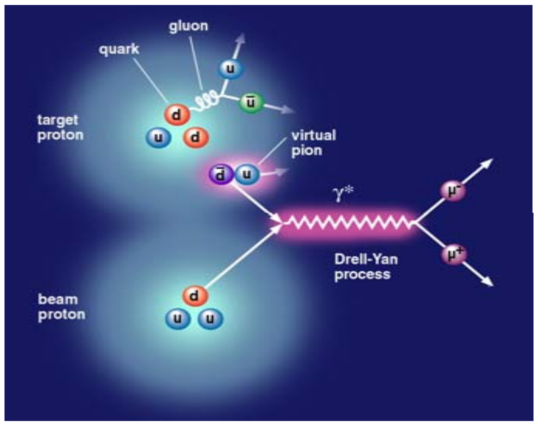
Cos2φ Asymmetry in p+d/p+p Drell-Yan

Lingyan Zhu

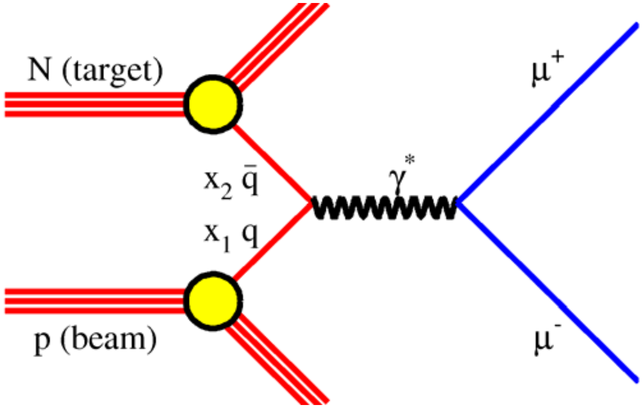
University of Illinois at Urbana-Champaign

FNAL E866/Nusea Collaboration

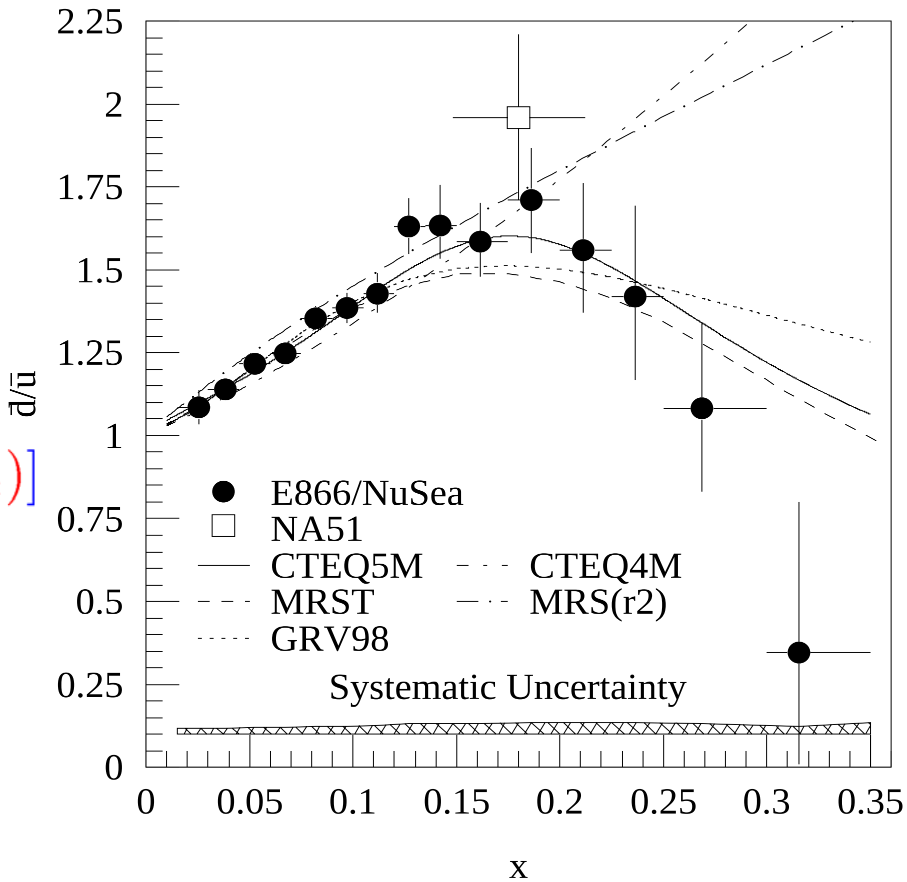


Sea Asymmetry from Drell-Yan

$$pN \rightarrow \mu^+\mu^- X$$



Towell et al., Phys.Rev. D64 (2001) 052002



$$\sigma_{DY} \propto \sum_i e_i^2 \left[q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t)\right]$$

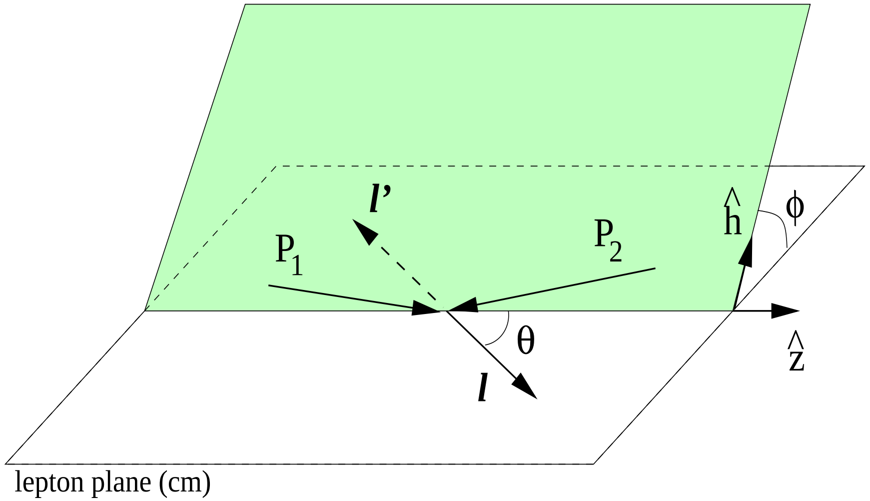
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

Drell-Yan enables us to measured dbar/ubar asymmetry precisely.

Angular Distribution in the Drell-Yan Process

$$pN \rightarrow \mu^+ \mu^- X$$

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



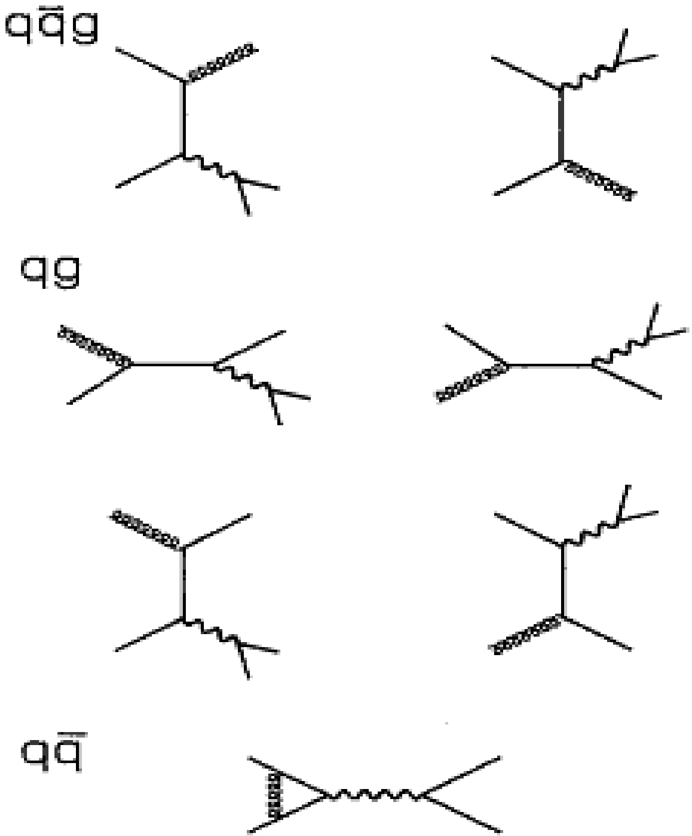
In the simple parton model:

(for massless quarks and θ measured relative to the annihilation axis)

λ=1 and μ=ν=0

$$\frac{d\sigma}{d\Omega} \propto 1+\cos^2\theta$$

First-order QCD Corrections to Drell-Yan



- Increase the overall cross section by a K-factor~2.

- The Lam-Tung relation still hold (in any reference frame for massless quarks), reflecting the spin-1/2 nature of the quarks. Lam & Tung, PRD21,2712(1980)

$$1 - \lambda - 2\nu = 0$$

(Analog to Callan-Gross relation in DIS)

- The NLO correction at $\mathcal{O}(\alpha_s^2)$ to the angular distribution is small. Mirkes & Ohnemus, PRD51,,4891(1995)

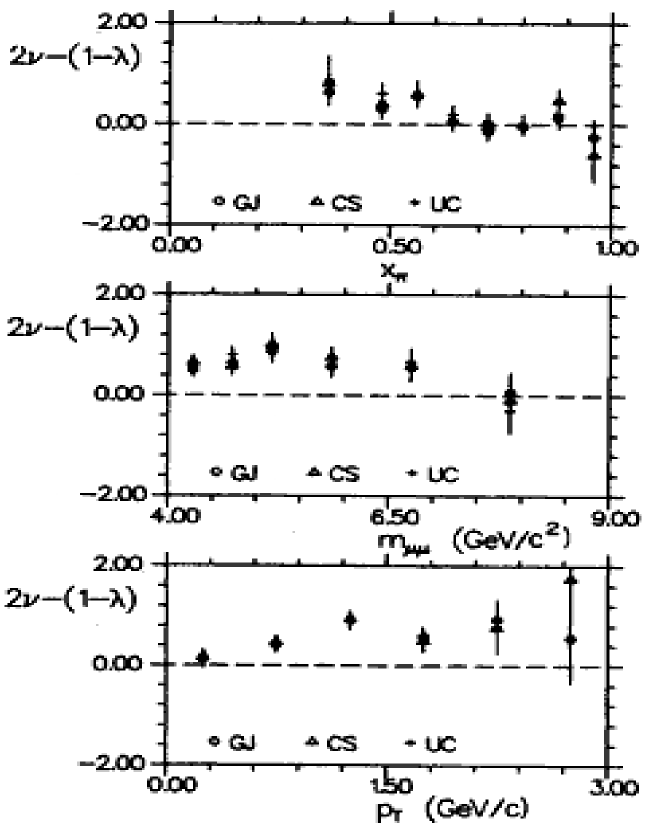
Conway et al., PRD39,92(1989)

The QCD correction to the angular distribution is small.

Violation of the Lam-Tung Relation

E615 at Fermilab: 252 GeV π^- + W

Conway et al., PRD39,92(1989)



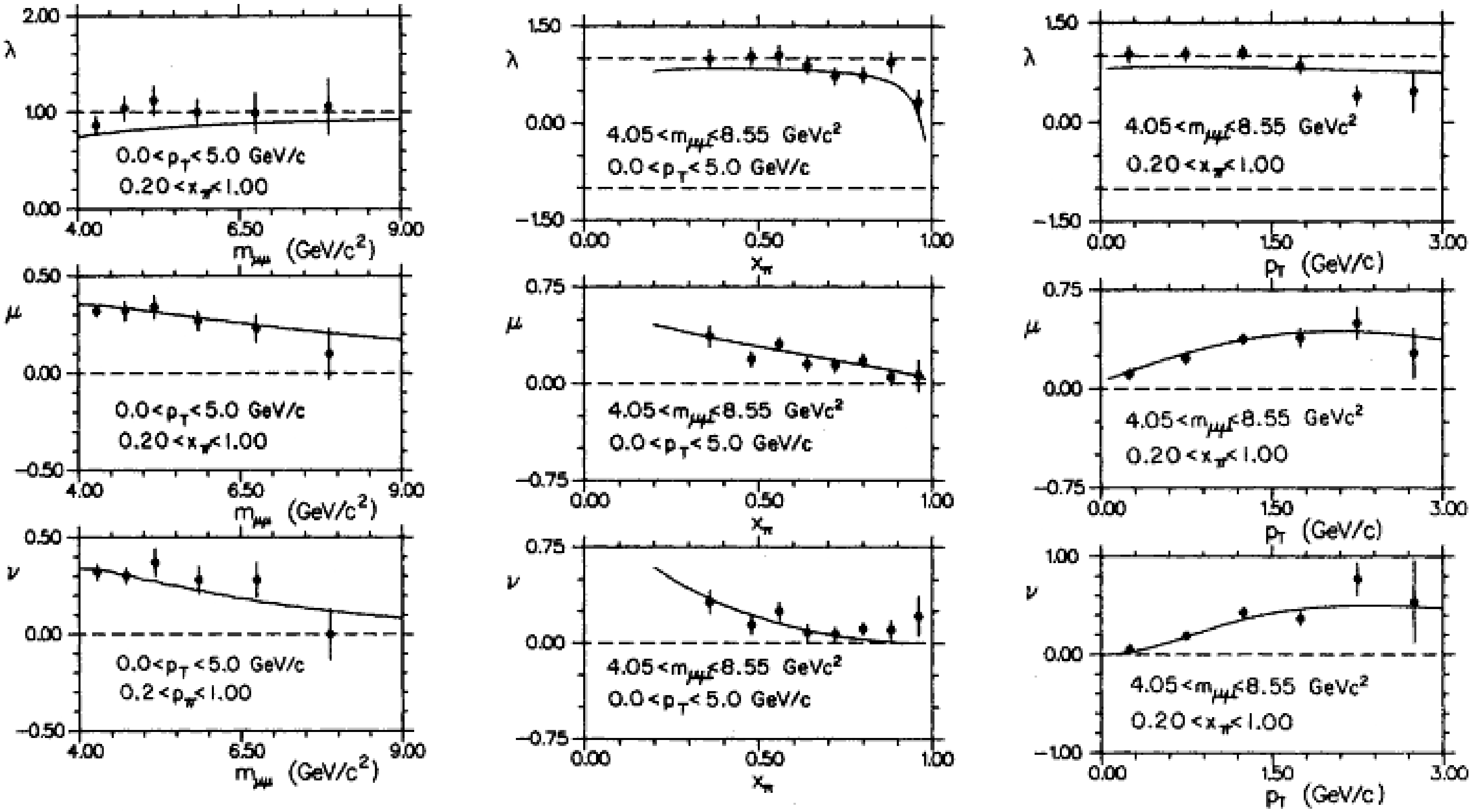
NA10 at CERN:
140/194 GeV π- + W, 286 GeV π- + W/d
Z. Phys. C37, 545 (1988)

- The deviations from $1+\cos^2\theta$ due to the soft-gluon resummation are less than 5%.
  Chiappatta & Bellac,ZPC32,521 (1986)
- The correction due to the intrinsic transverse momenta is estimated to be less than 0.05
  Cleymans & Kuroda, PLB105,68(1981)
- Lam-Tung relation not affected by lowest order QCD correction even at small Q_T.
  Boer & Wogelsang, hep-ph/0604177

Angular Distribution in the πW Drell-Yan Process

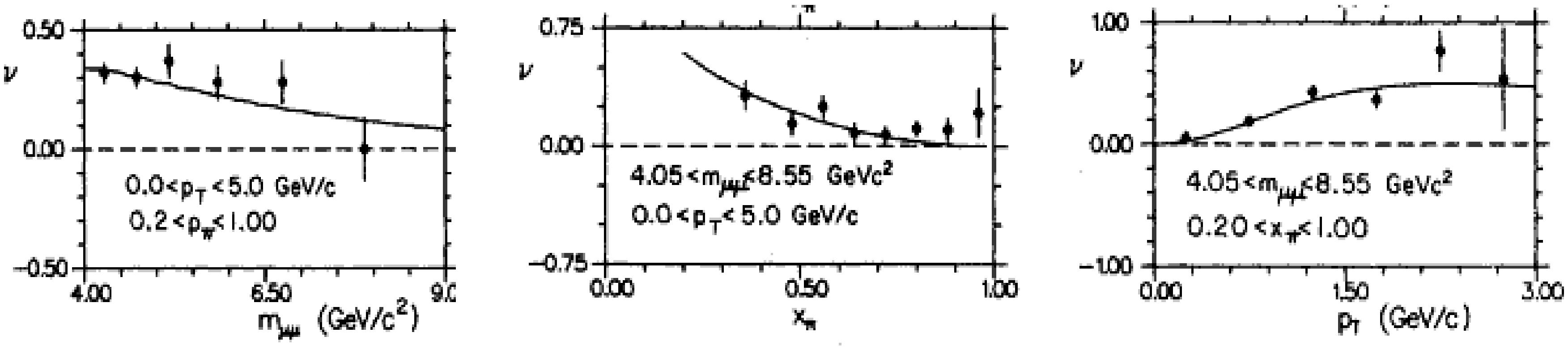
E615 at Fermilab: 252 GeV π^{-} + W

Conway et al., PRD39,92(1989)

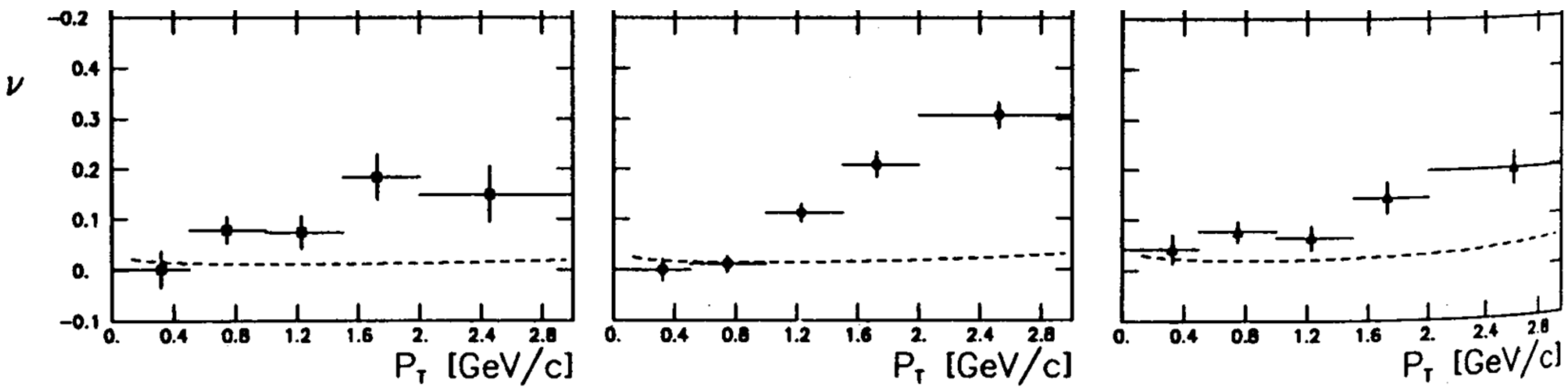


Azimuthal cos2φ Distribution in the πW Drell-Yan

E615 at Fermilab: 252 GeV π^- + W Conway et al., PRD39,92(1989)



NA10 at CERN: 140/194/286 GeV π- + W Z. Phys. C37, 545 (1988)



Possible Explanations for the cos2φ Asymmetry

- The high twist effect.

Brandenburg, Brodsky, Khoze & Muller, PRL73,939(1994).

- The nuclear distortion of hadronic projectile wavefunction, typically a spin-orbit effect occurring on the nuclear surface.

Bianconi & Radici, JPG31,645(2005).

- The spin correlation due to nontrival QCD vacuum.

Brandenburg, Nachtmann & Mirkes, Z. Phy. C60,697(1993); …

- The hadronic effect due to non-zero Boer-Mulders function $h_1^{\perp}$.

Boer, PRD60,014012(1999); …

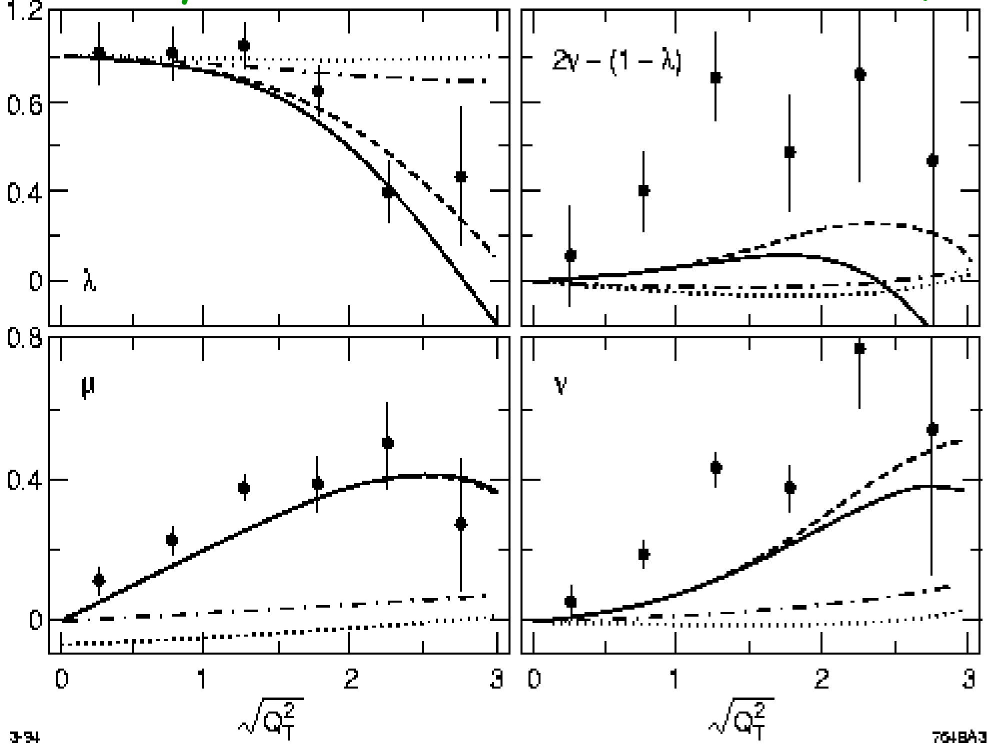
High Twist Effect?

- High twist effect leads to λ=-1 for low mass as $x_\pi \rightarrow 1$.

Berger & Brodsky, PRL42, 940 (1979); Berger, ZPC4,289(1980)

- High twist effect in terms of pion bound state effect:

Brandenburg, Brodsky, Khoze & Muller, PRL73,939(1994)

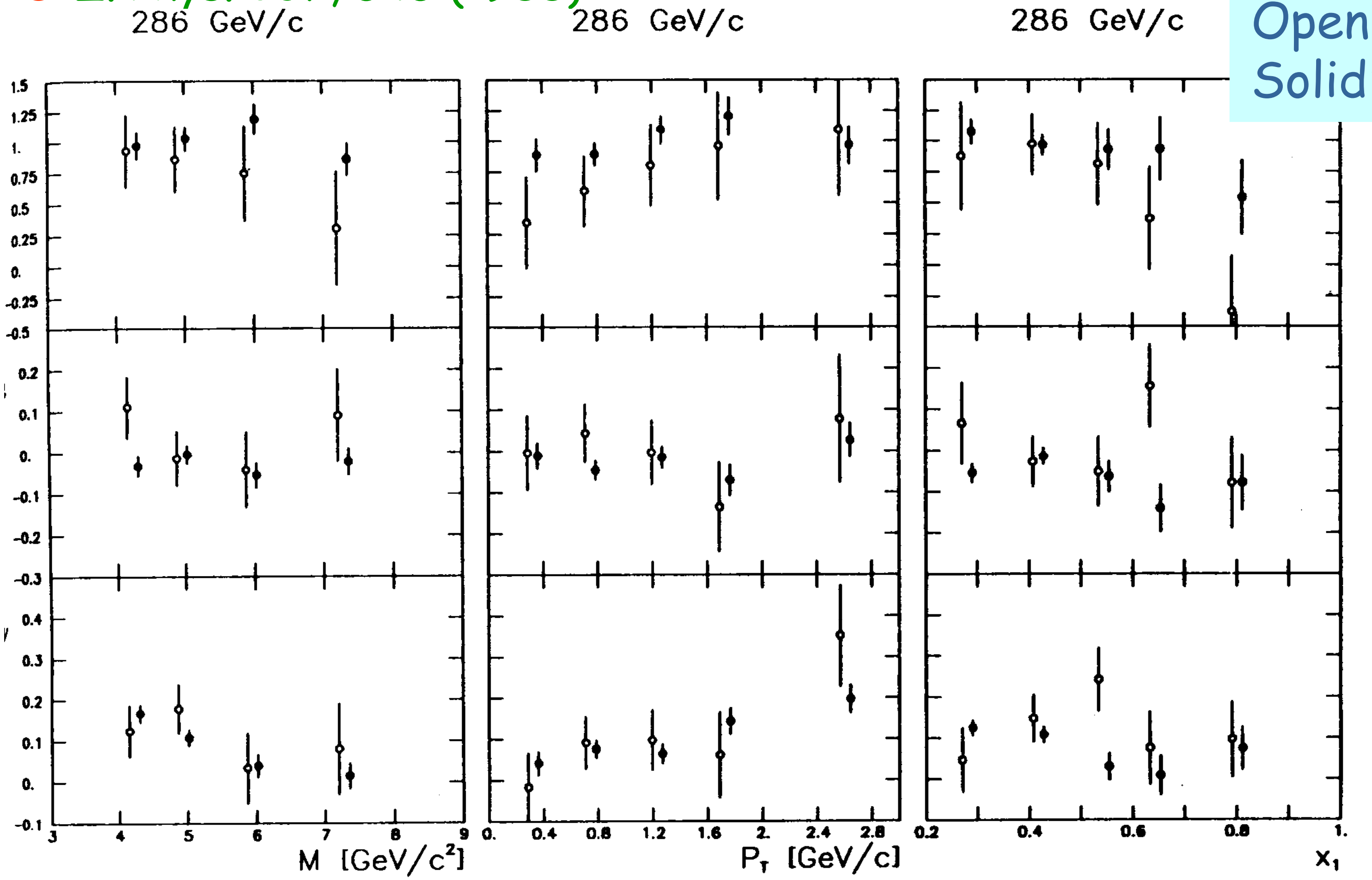


High twist in terms of pion bound state effect is not big enough.

Nuclear Effect?

NA10 Z. Phys. C37, 545 (1988)

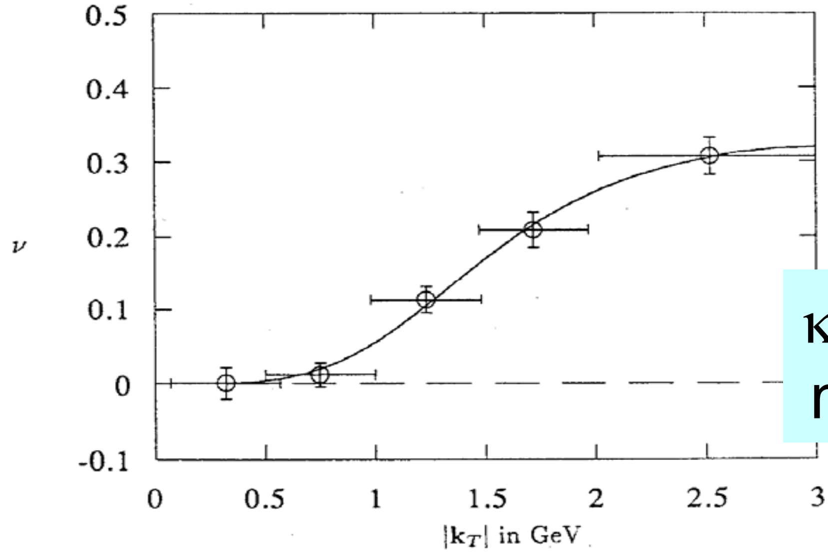
Open: Deuterium
Solid: Tungsten



Nuclear effect should not be the dominant contribution.

QCD Vacuum Effect

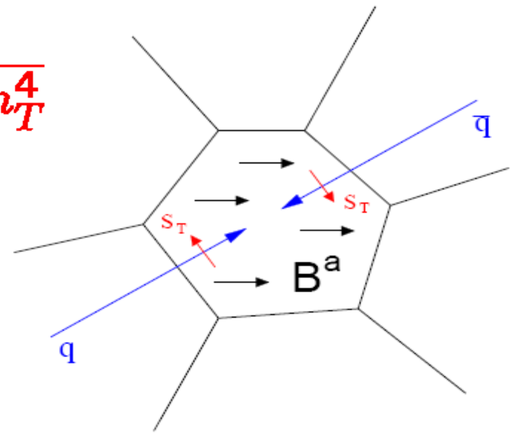
- The factorization-breaking spin correlation due to nontrivial QCD vacuum may fit the NA10 data at 194 GeV
Brandenburg, Nachtmann & Mirkes, Z. Phy. C60,697(1993)



$$\nu \approx 2\kappa = 2\kappa_0 \frac{p_T^4}{p_T^4 + m_T^4}$$

$$\lambda \approx 1; \mu \approx 0$$

κ_0=0.17
m_T=1.5



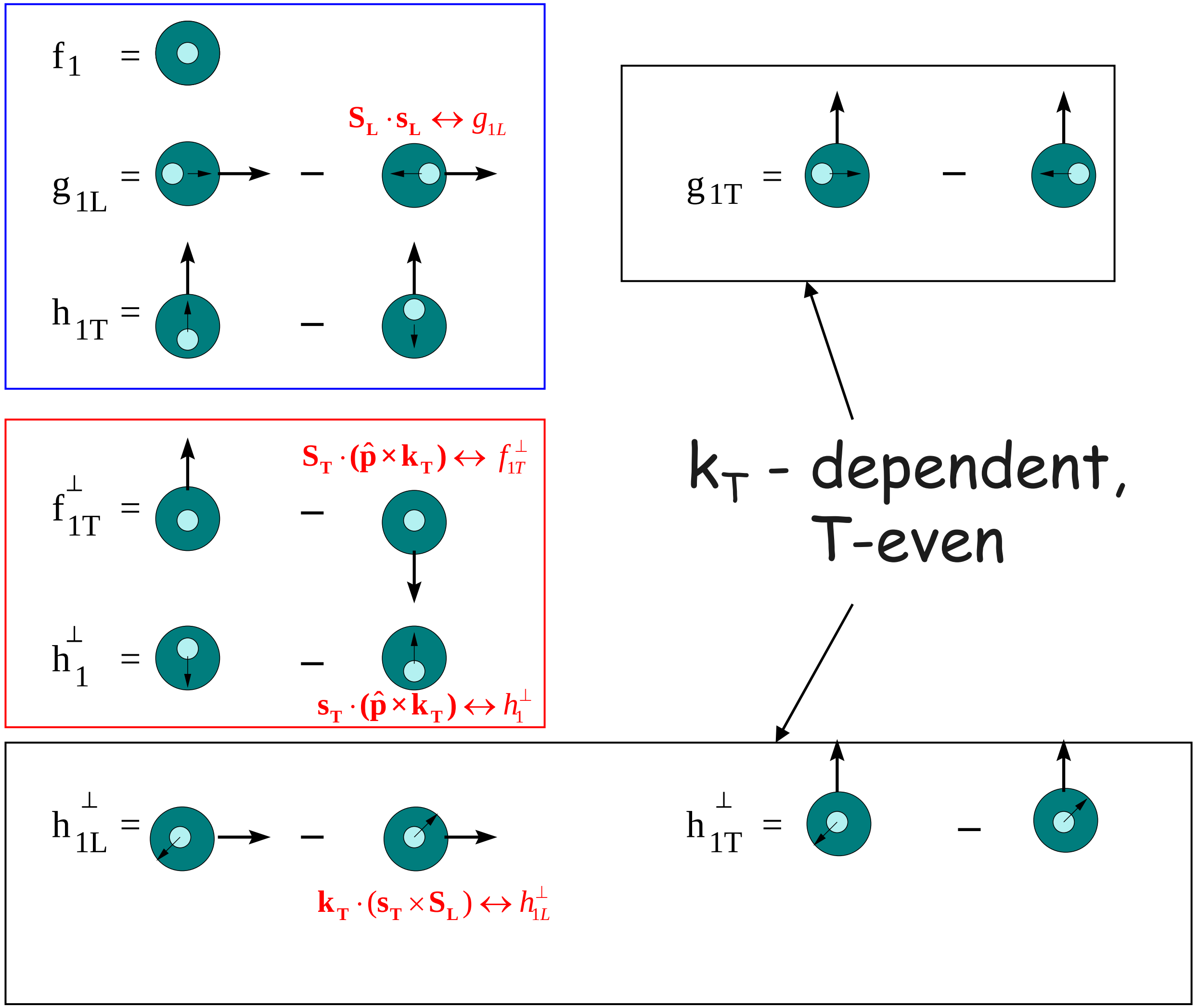
- The helicity flip in the instanton-induced contribution may lead to nontrivial vacuum and violation of the Lam-Tung relation.
Boer,Brandenburg,Nachtmann&Utermann, EPC40,55(2005).
Brandenburg,Ringwald&Uermann, hep-ph/0605234
- This vacuum effect should be flavor blind.

Leading-Twist Parton Distribution Functions

Survive k_T integration

k_T - dependent, T-odd

k_T - dependent, T-even



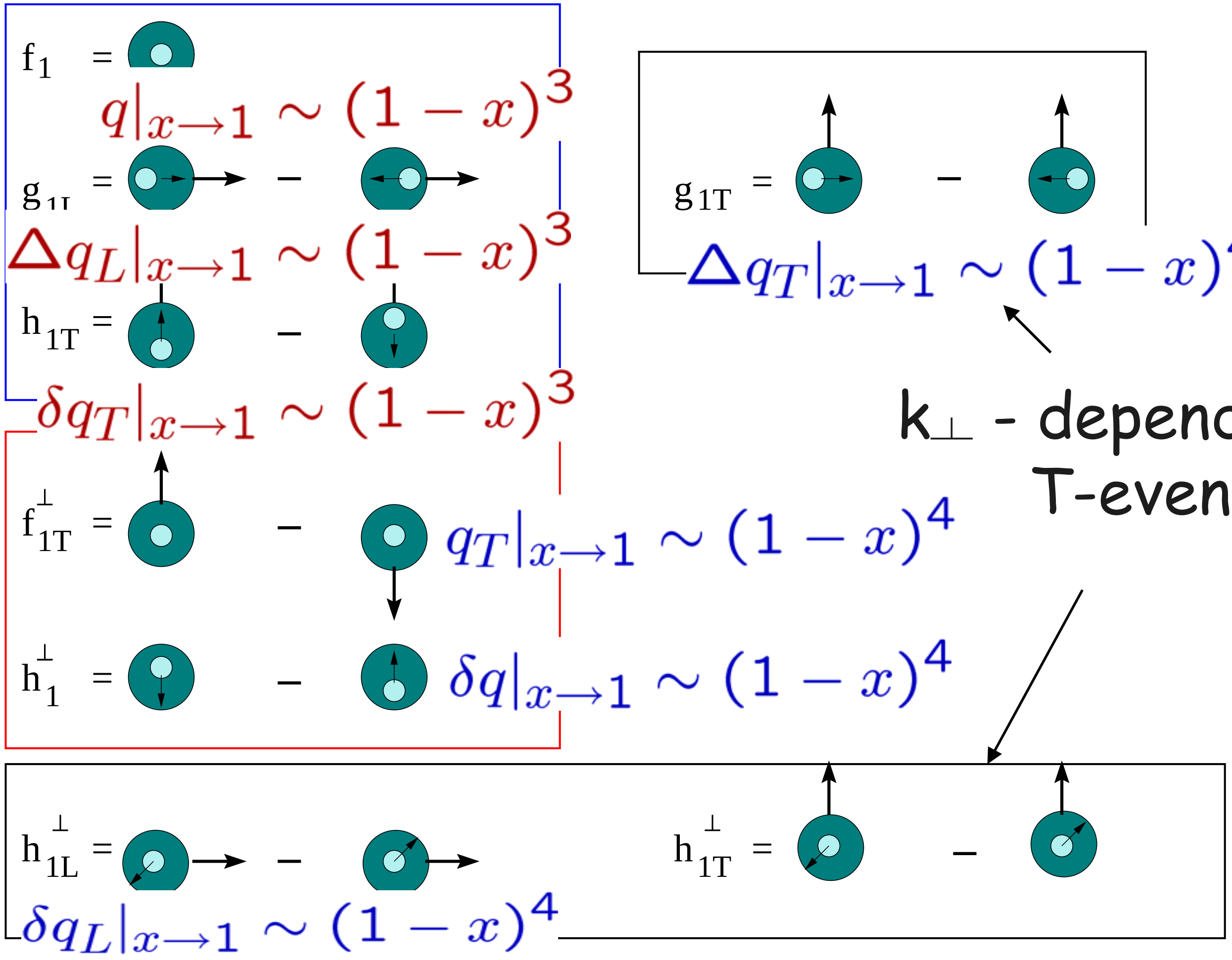
The Large-x Behavior of the PDFs

Brodsky & Yuan, hep-ph/0610236.

Survive $k_\perp$ integration

$k_\perp$-dependent, T-odd

$$\left.\frac{h_1^\perp}{f_1}\right|_{x\to 1} \sim (1-x)$$

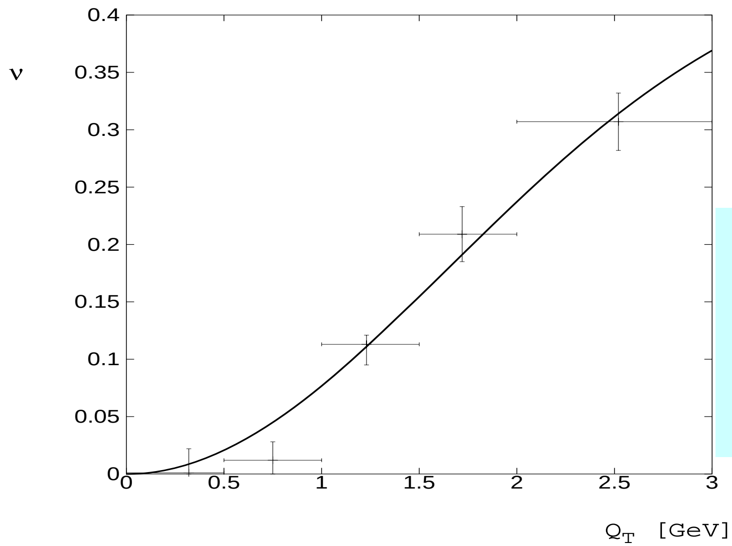


Boer-Mulders Function $h_1^\perp$ –

- An spin-correlation approach in terms of $h_1^\perp$ can fit the NA10 data at 194 GeV. Boer, PRD60,014012(1999)

$$\nu = 2\kappa = 4\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}; \quad \lambda = 1; \mu = 0$$

$$\nu \propto h_1^\perp(x_1)\bar{h}_1^\perp(x_2)$$



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

κ_1=0.5
m_C=2.3
α_T=C_H=1

- On the base of quite general arguments, for $|q_T|$<<Q(=$m_{\mu\mu}$), Salvo,hep-ph/0407208. $\nu \propto |q_T|^2/Q^2$

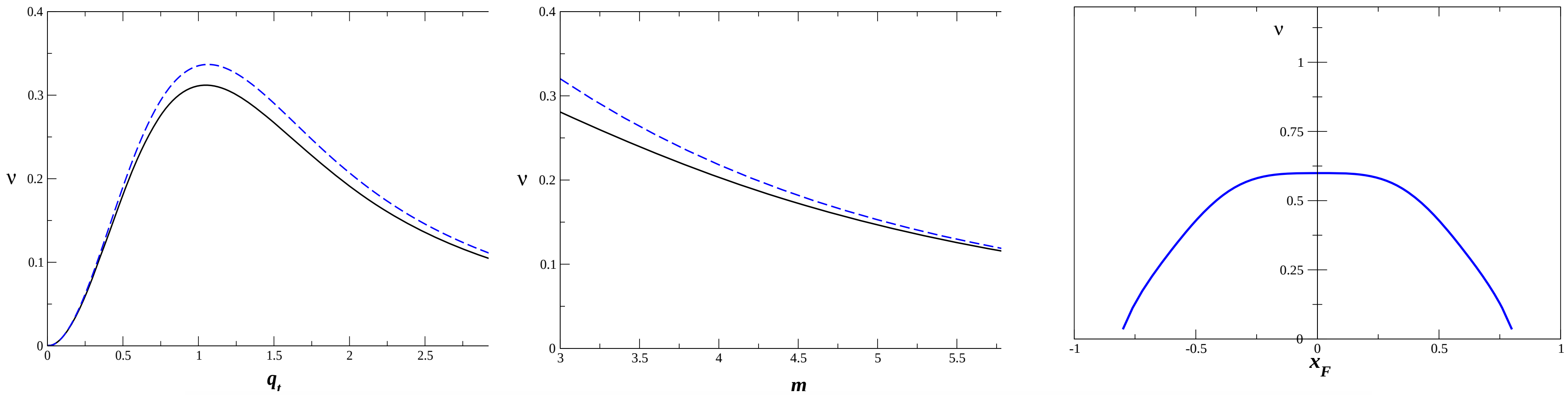
Models for Boer-Mulders Function $h_1^{\perp}$

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

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

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

- Twist 2 (as well as the kinematic twist 4) contribution in a parton-



$$\nu_2 = \frac{\sum_a e_a^2 \mathcal{F}\left[(2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\perp}\cdot\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_{\perp} - \boldsymbol{p}_{\perp}\cdot\boldsymbol{k}_{\perp})h_1^{\perp}(x,\boldsymbol{k}_{\perp})\bar{h}_1^{\perp}(\bar{x},\boldsymbol{p}_{\perp})/(M_1M_2)\right]}{\sum_a e_a^2 \mathcal{F}\left[f_1(x,\boldsymbol{k}_{\perp})\bar{f}_1(\bar{x},\boldsymbol{p}_{\perp})\right]}$$

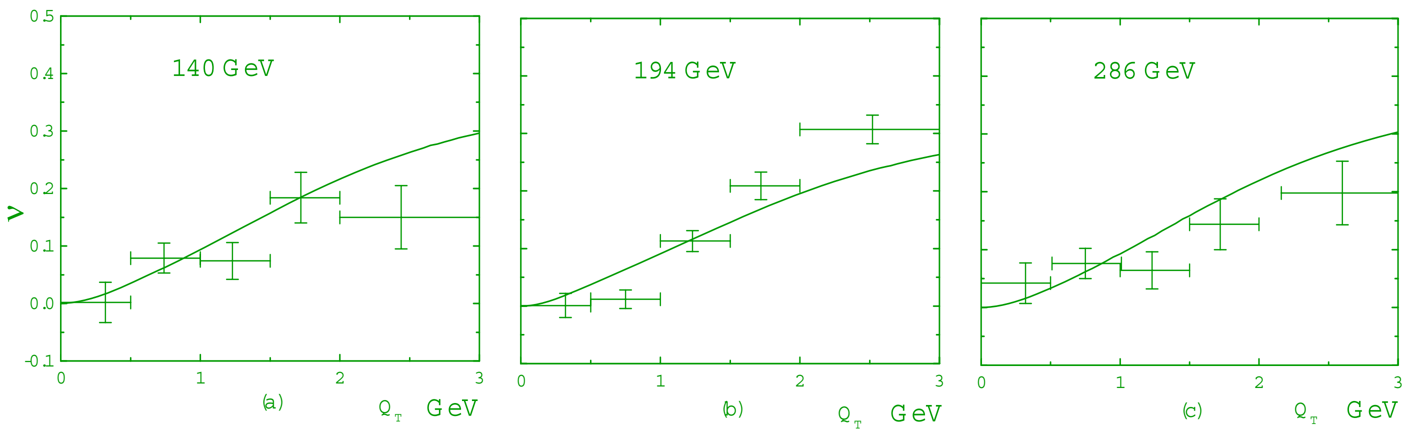
Pion Boer-Mulders Function

- Final-state interaction with one gluon exchange can produce nonzero $h_1^{\perp}$ for the pion in the quark-spectator-antiquark model with constant coupling g_{π}.

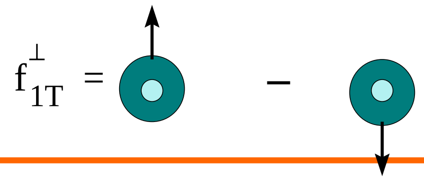
$$h_{1\pi}^{\perp}(x,\mathbf{k}_{\perp}^{2}) = \frac{A_{\pi}(x)}{\mathbf{k}_{\perp}^{2}[\mathbf{k}_{\perp}^{2}+B_{\pi}(x)]} \ln[\frac{\mathbf{k}_{\perp}^{2}+B_{\pi}(x)}{B_{\pi}(x)}]$$

Lu&Ma, PRD70,094044(2004).

- The quark-spectator-antiquark model with effective pion-quark-antiquark coupling as a dipole form factor Lu & Ma, hep-ph/0504184



Sivers Function



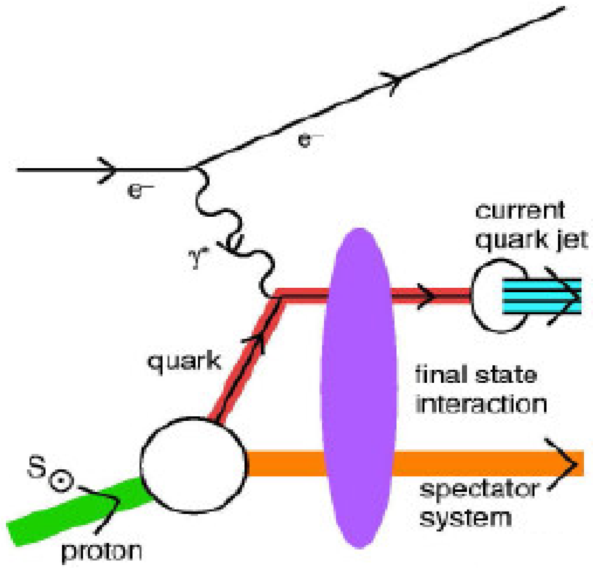
- On the basis of time reversal arguments:

$$f_{1T}^{\perp}(x,p_T^2)=0$$

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)

Models for Sivers Function $f_{1T}^{\perp}$

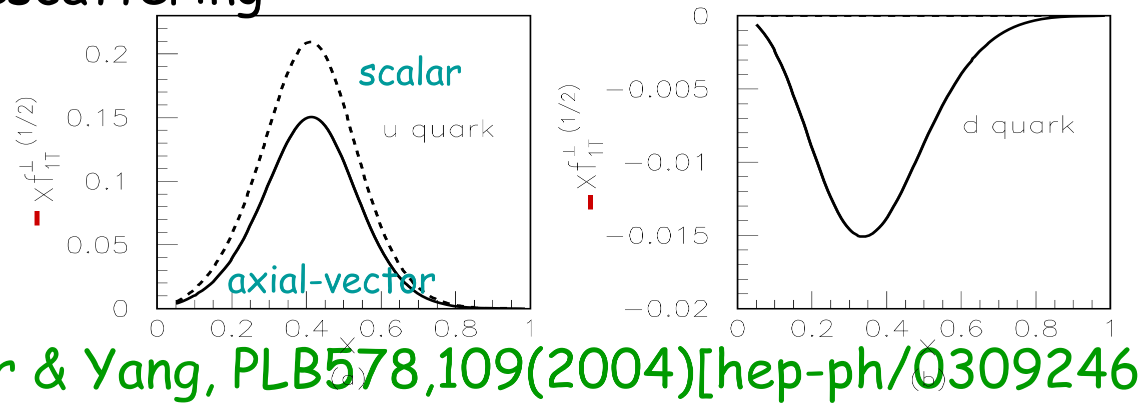
- Calculation fit with MIT bag model in the presence of final state interaction through one gluon exchange

$$f_{1T}^{\perp(1)u} = -0.75x^{1.63}(1-x)^{4.06} = 0.66h_1^{\perp(1)u}$$
$$f_{1T}^{\perp(1)d} = -0.25f_{1T}^{\perp(1)u} = -0.33h_1^{\perp(1)d}$$

Yuan, PLB575, 45(2003)[hep-ph/0308157].

- Calculation in a spectator model with axial-vector diquarks in the presence of gluon rescattering

$$f_{1T}^{\perp(1)u} = h_1^{\perp(1)u}$$
$$f_{1T}^{\perp(1)d} \approx h_1^{\perp(1)d}$$



Bacchetta, Schaefer & Yang, PLB578,109(2004)[hep-ph/0309246]

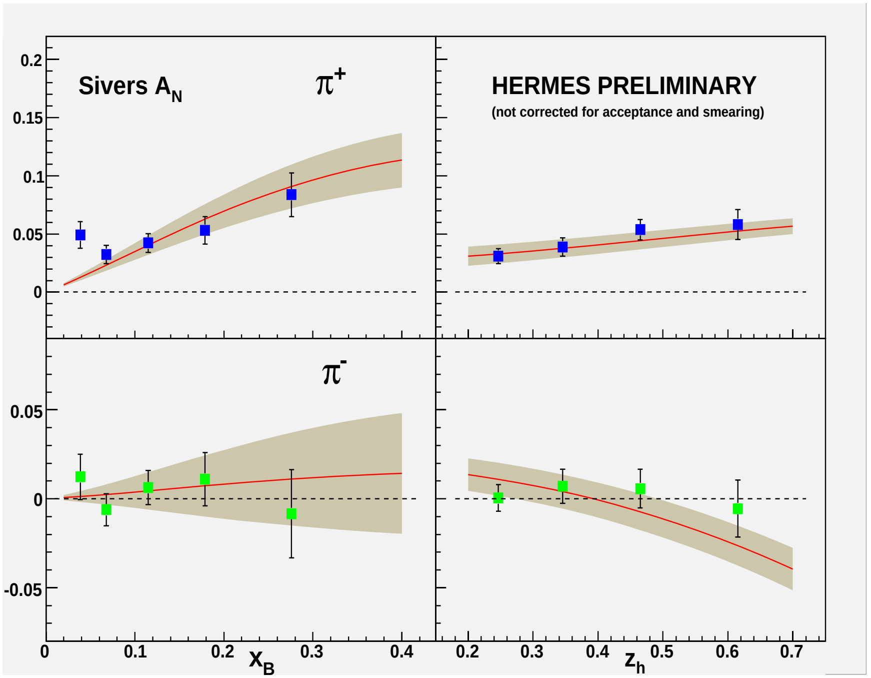
- Calculation in a light-cone SU(6) quark-diquark model

Lu & Ma, NPA741,200 (2004).

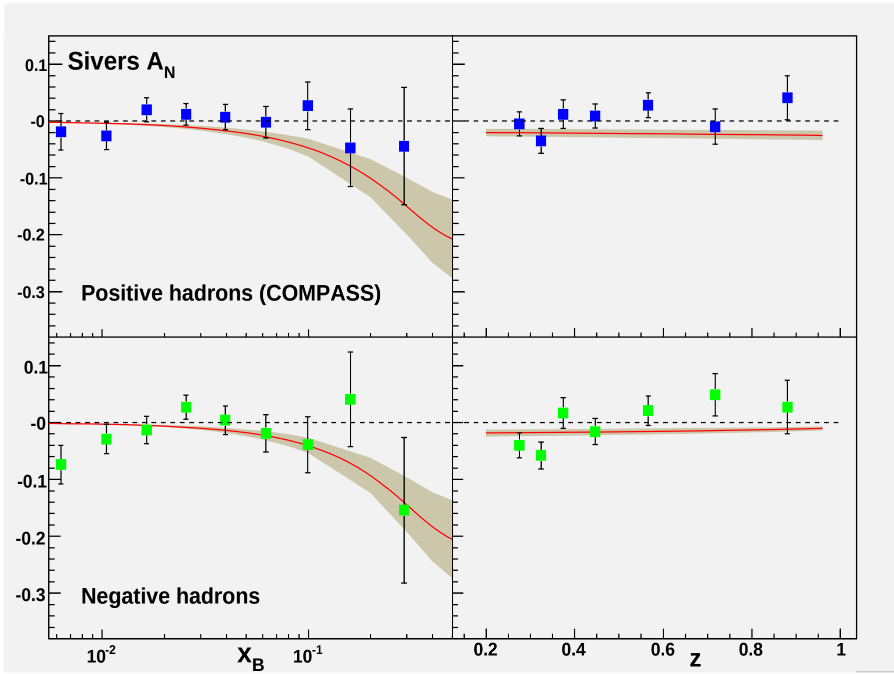
These calculations are before HERMES' transverse data .

Sivers Function Extraction from HERMES Data

Fits to the Hermes data



"Prediction" of the Compass data



Assuming $f_{1T}^{\perp,u}(x) = S_u\, x(1-x)u(x); \quad f_{1T}^{\perp,d}(x) = S_d\, x(1-x)u(x)$

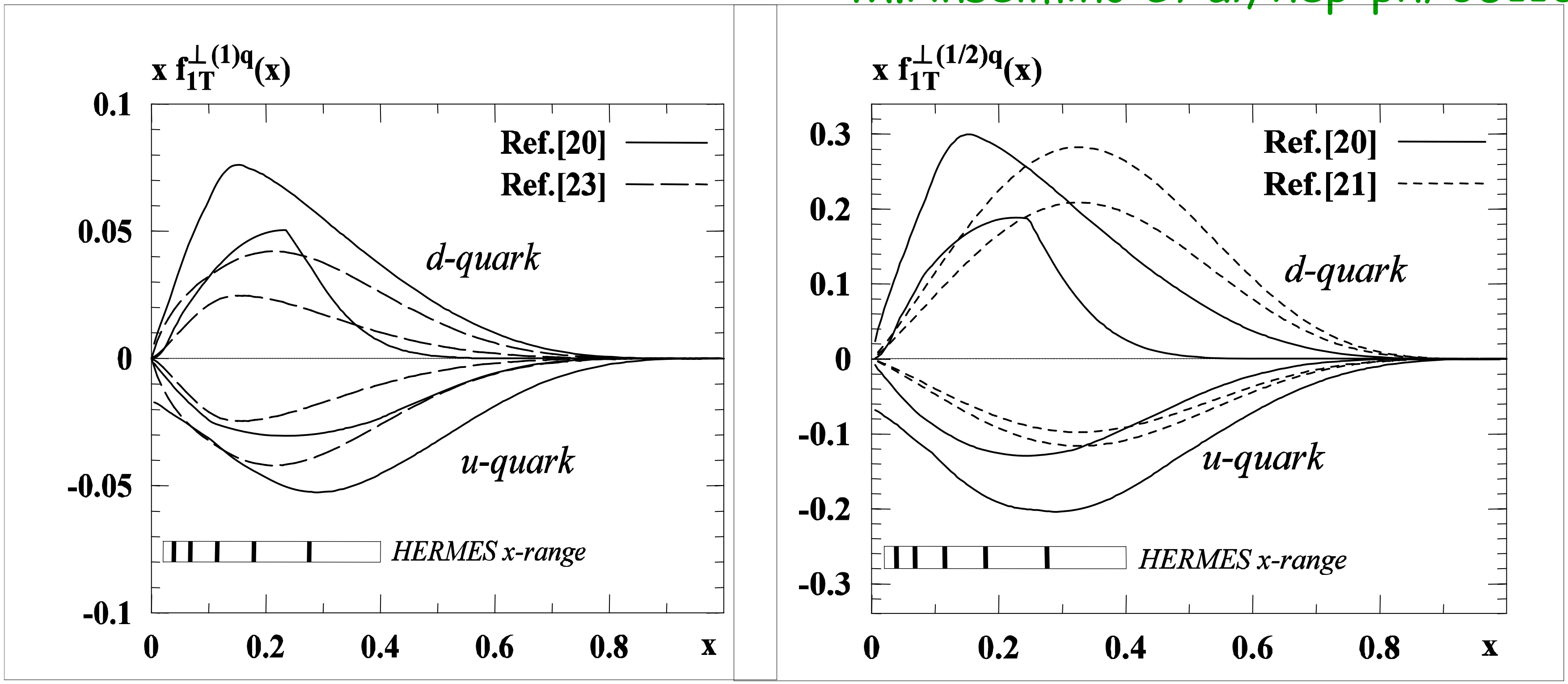
$$S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28$$

Vogelsang and Yuan, Phys.Rev.D72(2005)054028 [hep-ph/0507266]

Striking flavor dependence of the Sivers function

Comparing Sivers Functions from HERMES

M.Anselmino *et al*, hep-ph/0511017



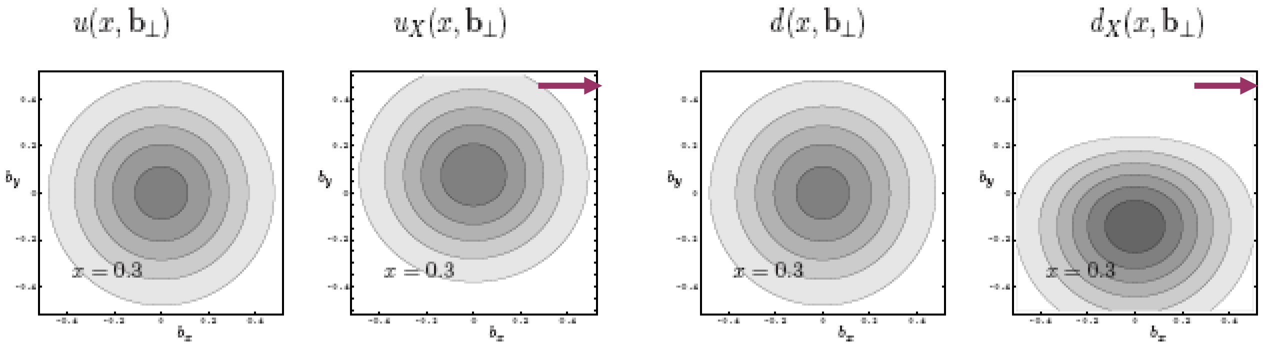
Ref.[20] M.Anselmino *et al*, Phys.Rev.D72(2005)094007[hep-ph/0507181]
Ref.[21] W.Vogelsang & F.Yuan, Phys.Rev.D72(2005)054028[hep-ph/0507266]
Ref.[23] J.C.Collins *et al*, hep-ph/0510342

Satisfactory agreement between different models to fit HERMS data.

An Intuitive Explanation of Sivers Asymmetry

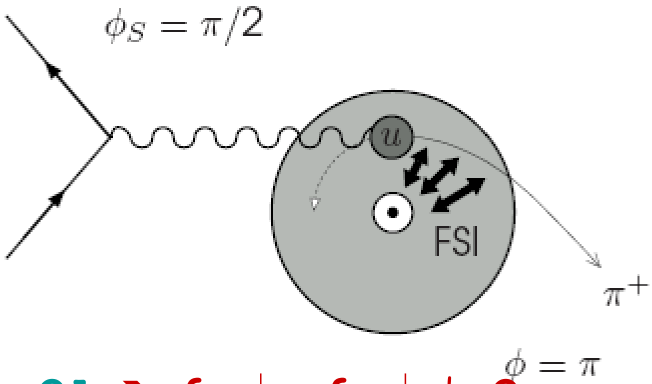
M. Burkardt, Phys. Rev. D66(2002)114005[hep-ph/0209179].

K_u=1.67
K_d=-2.03



The quark distribution in transverse polarized nucleon is deformed because the superposition of translational and orbital motion misleads the photons in the *x*.

Attractive FSI

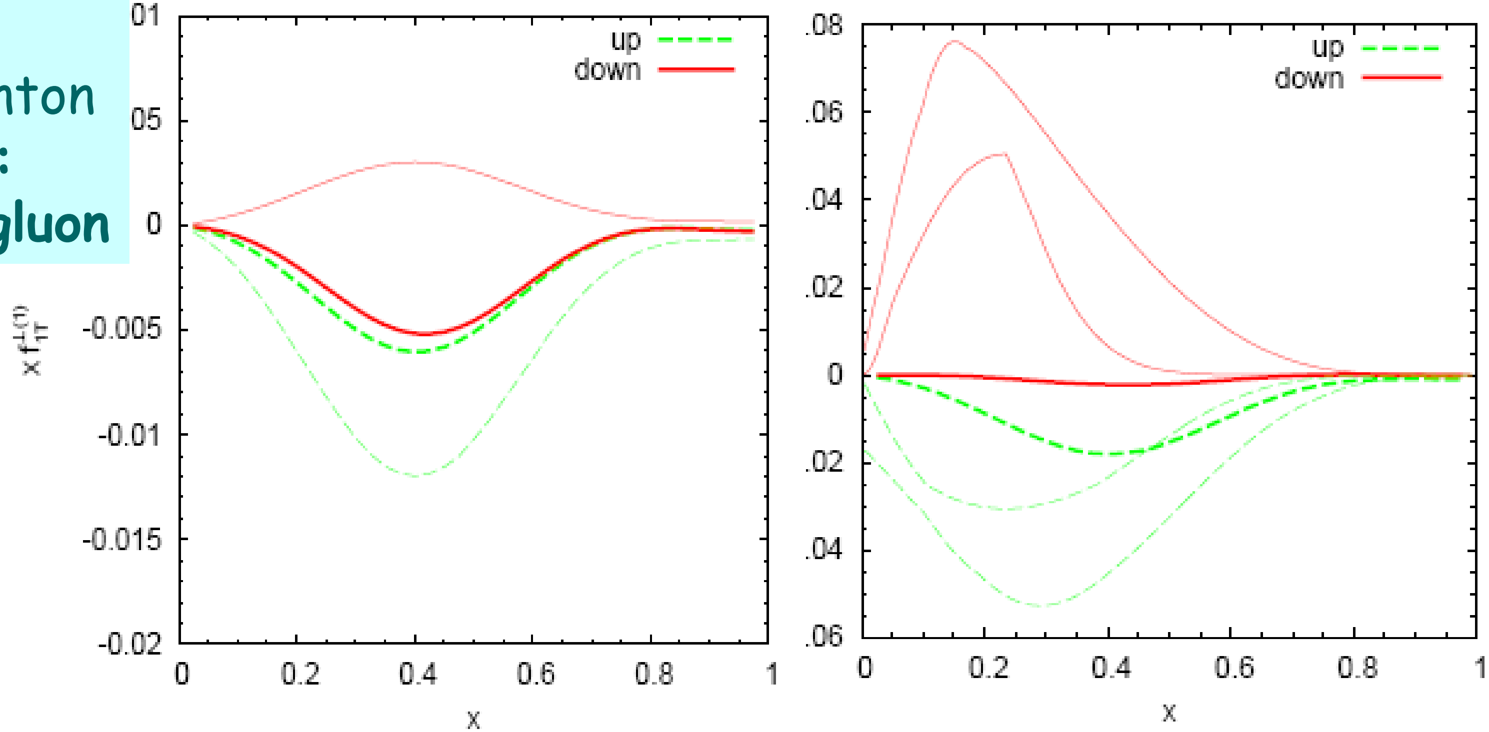


Attractive FSI➔ $f_{1T}^{\perp,q}\ K_q$ <0 [+$K_u\ K_d$<0] ➔ $f_{1T}^{\perp,u}\ f_{1T}^{\perp,d}$ <0

Vacuum Contribution to Sivers Function $f_{1T}^{\perp}$

- Sizable instanton-induced QCD vacuum contribution to the Sivers function, adopting MIT bag model for the quark wave functions.
Cherednikov, D'Alesio, Kochelev & Murgia Phys.Lett.B642:39-47,2006 [hep-ph/0606238].

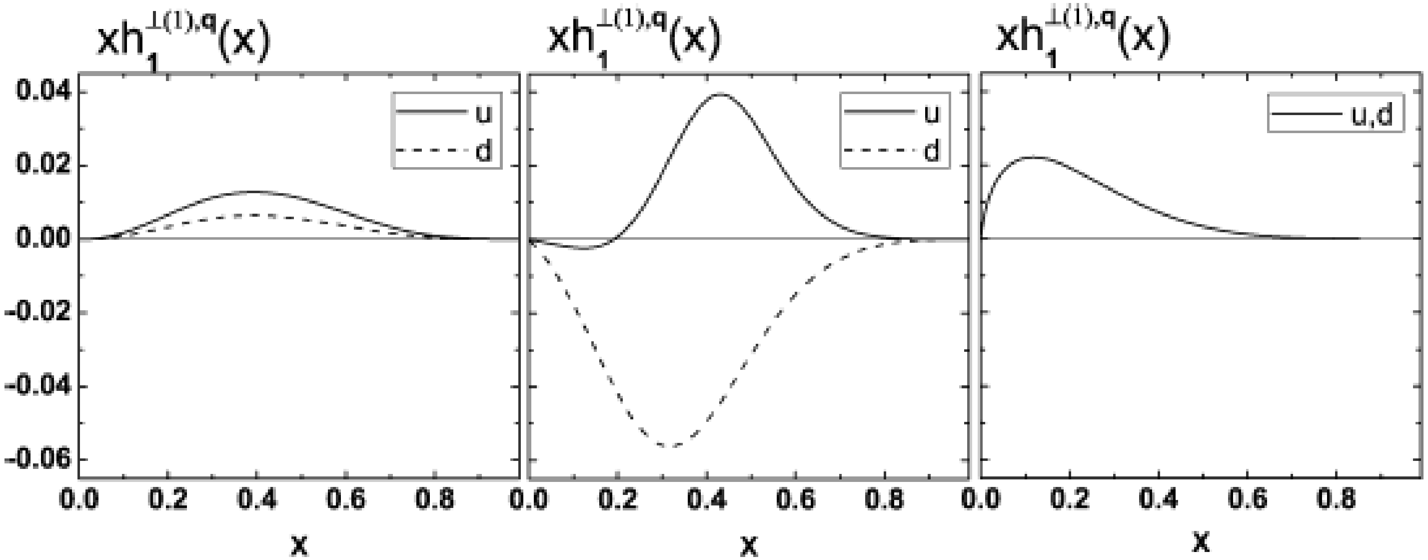
thin: instanton
thick: one-gluon



thin: HERMES
thick: total

Comparing Boer-Mulders Functions from Models

Z. Lu, B.Q. Ma and I. schmidt, Phys. Lett. B639(2006)494.



(a) (b) (c)

(a)MIT bag model: F. Yuan, Phys. Lett. B575,45(2003).

(b)Spectator model with axial-vector diquark: Bacchetta, Schaefer & Yang, Phys. Lett. B578,109(2004).

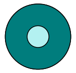
(c)Large-N_c limit, P.V. Pobylitsa, hep-ph/0301236

Knowledge of the Boer-Mulders functions is very poor.

Unpolarized Semi-Inclusive DIS

TWIST-2 With $\mathcal{F}[wqD] \equiv \int d^2\vec{p}_T d^2\vec{k}_T \delta(\vec{p}_T - \vec{q}_T - \vec{k}_T) wqD,$

$$\left[\frac{d\sigma(lH \to l'hX)}{z^2 d\Omega dx dz d^2 q_T}\right]^{twist-2}_{UU} = \frac{\alpha^2 xs}{Q^4} \sum_{q,\bar{q}}$$

f_1 = 

$$\Big\{(1 - y + y^2/2) e_q^2 \mathcal{F}[f_1 D_1]$$

$h_1^\perp$ = 

$$- (1-y) e_q^2 \cos(2\phi) \mathcal{F}\left[\left(2\hat{h}\cdot p_T \hat{h}\cdot k_T - p_T \cdot k_T\right) \frac{h_1^\perp H_1^\perp}{M M_h}\right]\Big\}$$

Cahn Effect

QED Modulation of $f_1 D_1$ term due to intrinsic transverse momentum.

Anselmino et al., PRD71(2005) 074006 [hep-ph/0501196].

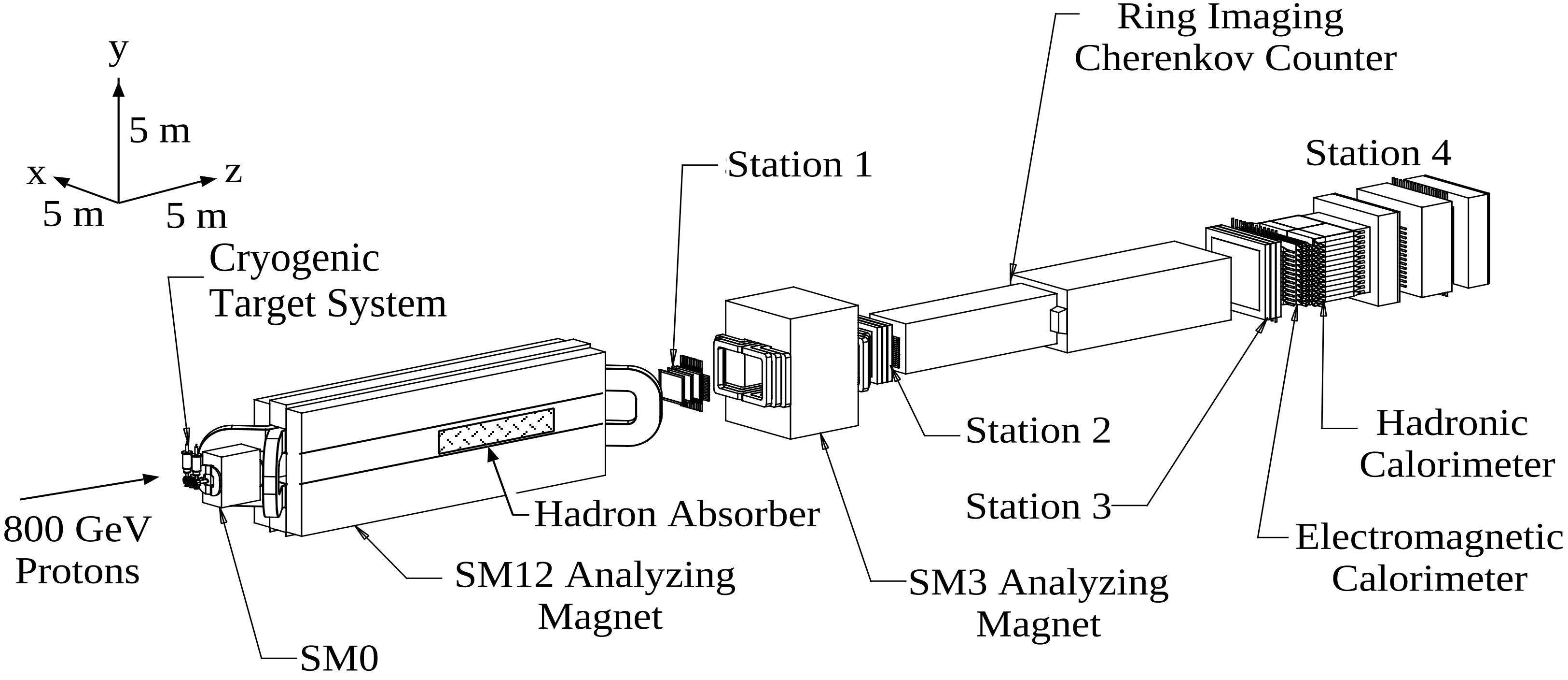
Add to $2(1-y+y^2/2)$: $-4 \frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\, z_h\, P_T}{\langle P_T^2\rangle\, Q} \cos\phi_h$

$$\sigma_{UU}^{ep\to eh} \sim \sum_q C_{Cahn} f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp$$

H. Avakian, Z.-E.Meziani,K.Joo and B.Seitz, JLab proposal PR12-06-112

FNAL E866/NuSea Experiment

FNAL E866 (NUSEA)



Completed Data analysis:

dbar/ubar sea asymmetry

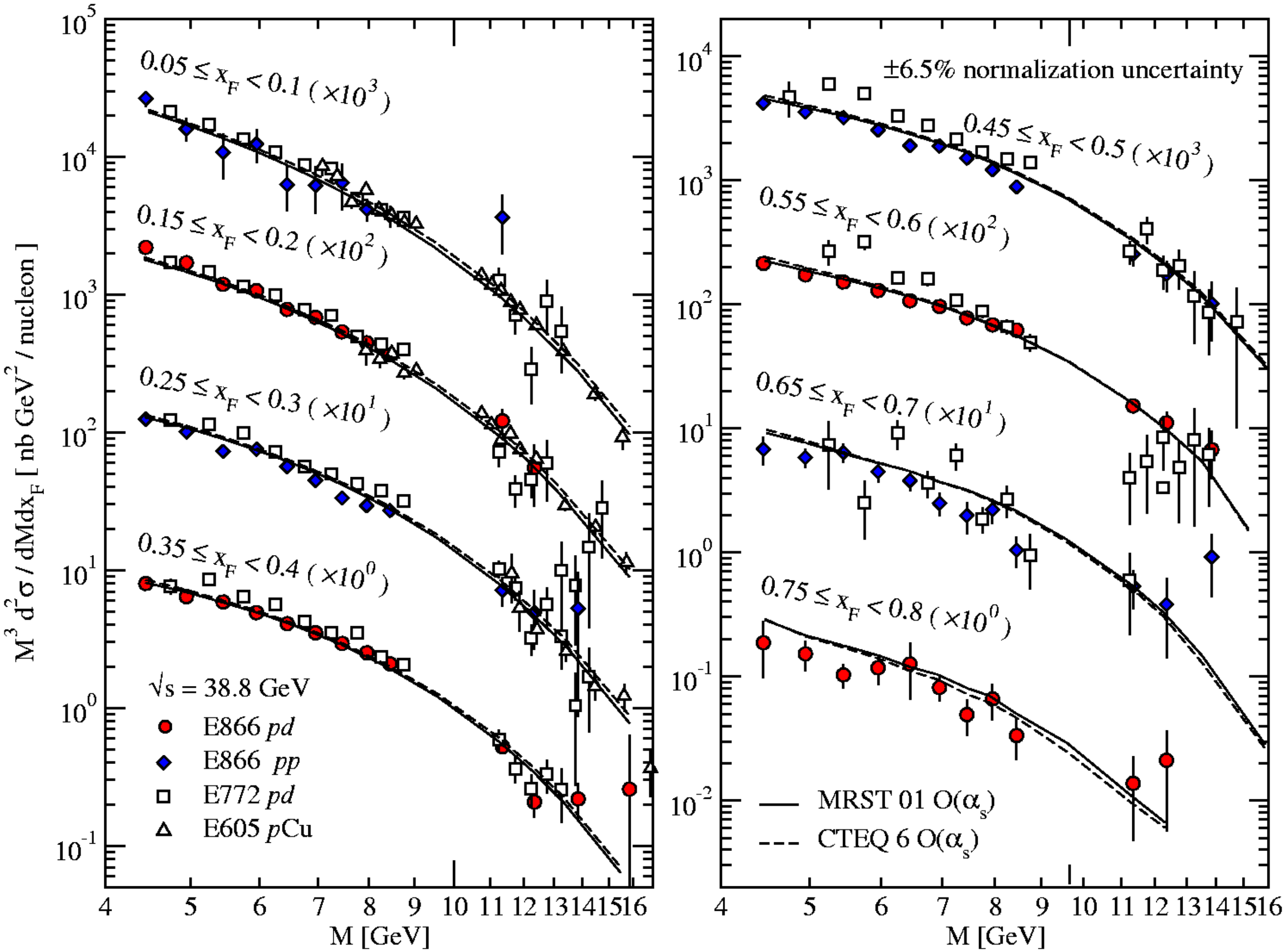
Drell-Yan cross section

lambda for J/Ψ production

lambda for upsilon production

Drell-Yan Cross Section from E866

J.C.Webb et al., hep-ex/0302019.



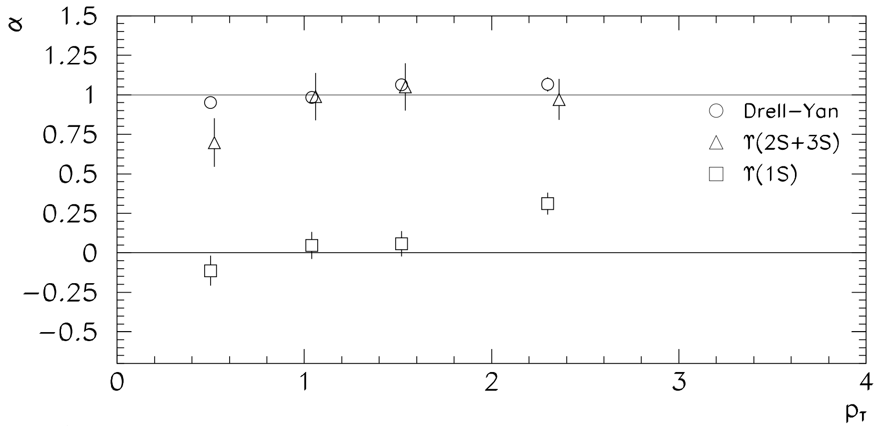
Angular Distribution of E866 p-Cu Data

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta = 1 + \alpha \cos^2\theta$$

- J/ψ: $\lambda = 0.069 \pm 0.004 \pm 0.08$
- Drell-Yan (M=4~7 GeV):

$\lambda = 0.98 \pm 0.04$

T.H. Chang et al., PRL91, 211801 (2003)

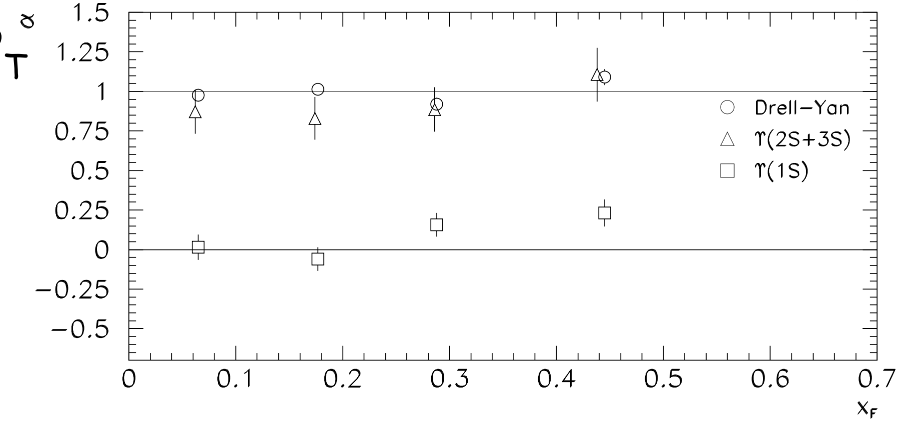


- $\Upsilon(1s)$,$\Upsilon(2s+3s)$: plotted against P_T and x_P.
- Drell-Yan:

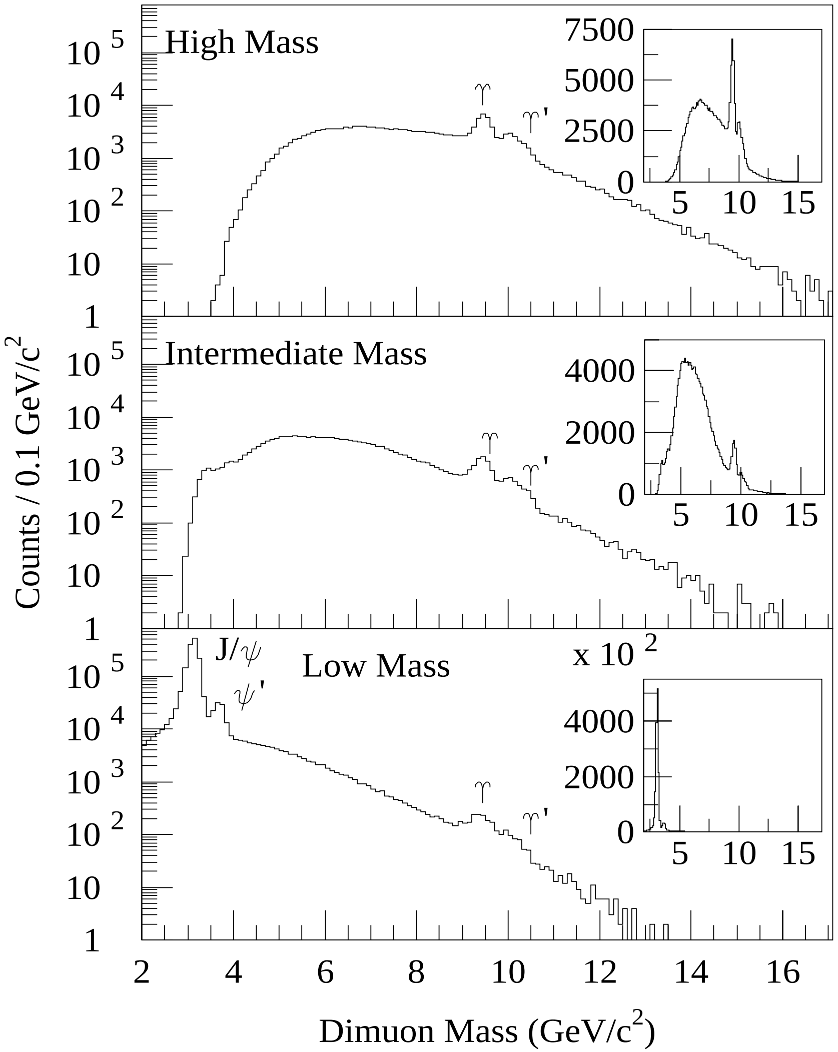
(M=8.1~8.45,11.1~15.0 GeV)

$\alpha = 1.008 \pm 0.016 \pm 0.020$

C.N. Brown et al., PRL86, 2529 (2001)



Dimuon Mass Distribution



$\sqrt{s} = 38.8\text{GeV}$

Target: Proton, Deuterium

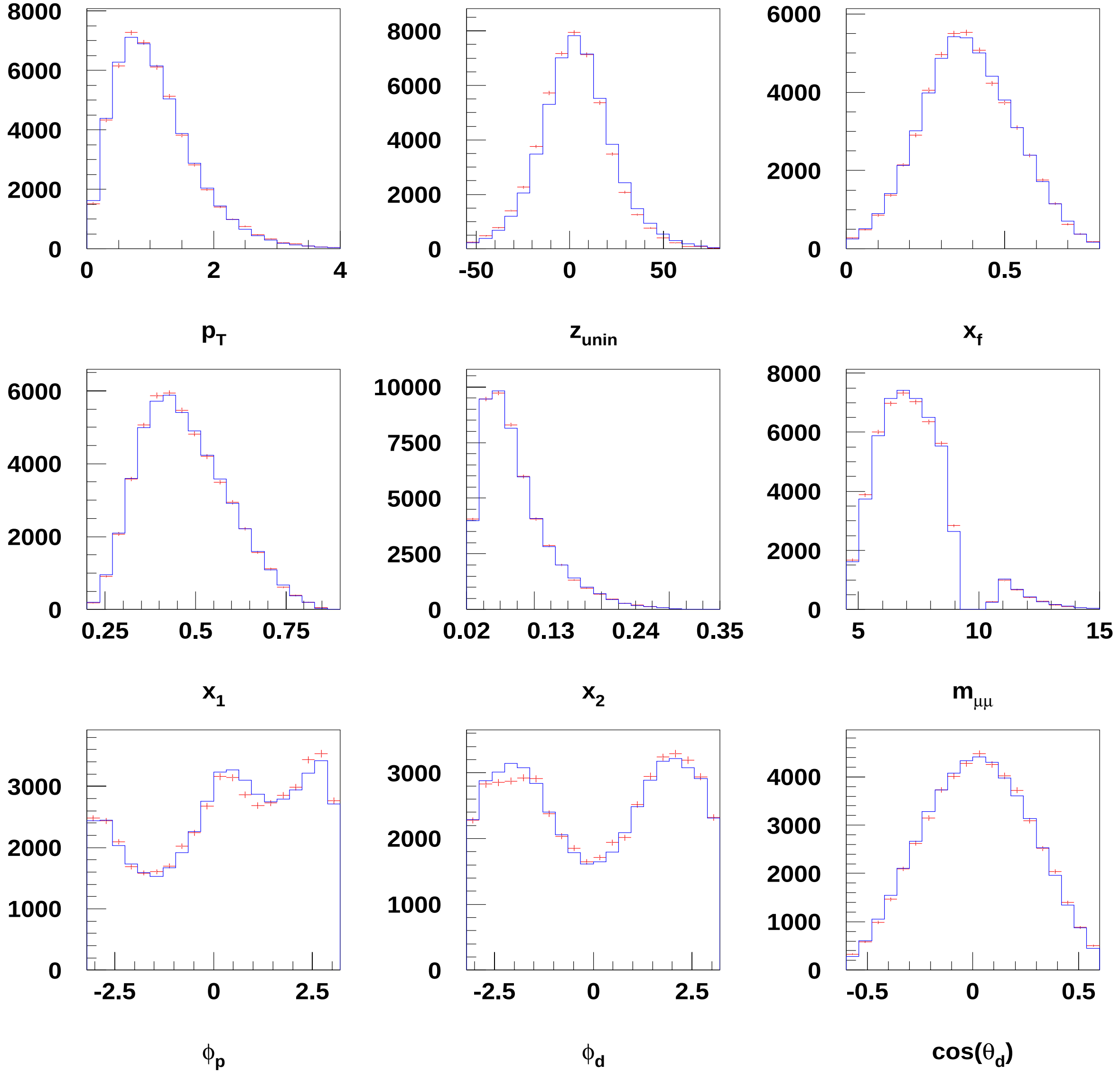
Data used for cos2φ analysis:

High Mass: dset7-39k (+ polarity)
dset8-85k (+ polarity)
dset11-25k (- polarity)

Low Mass: dset5-68k (+ polarity)

Towell et al., Phys.Rev. D64 (2001) 052002

Comparison of data and simulation



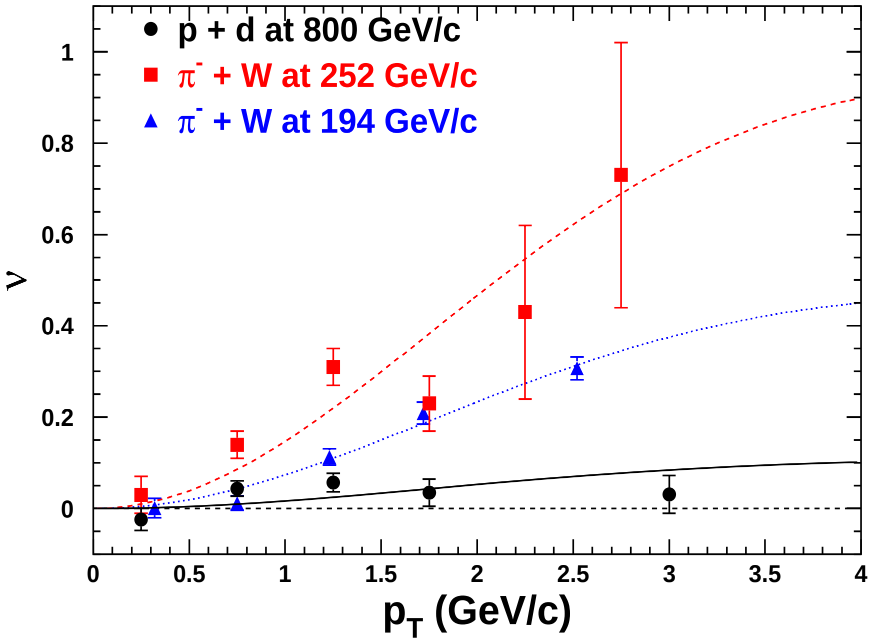
Blue: simulation

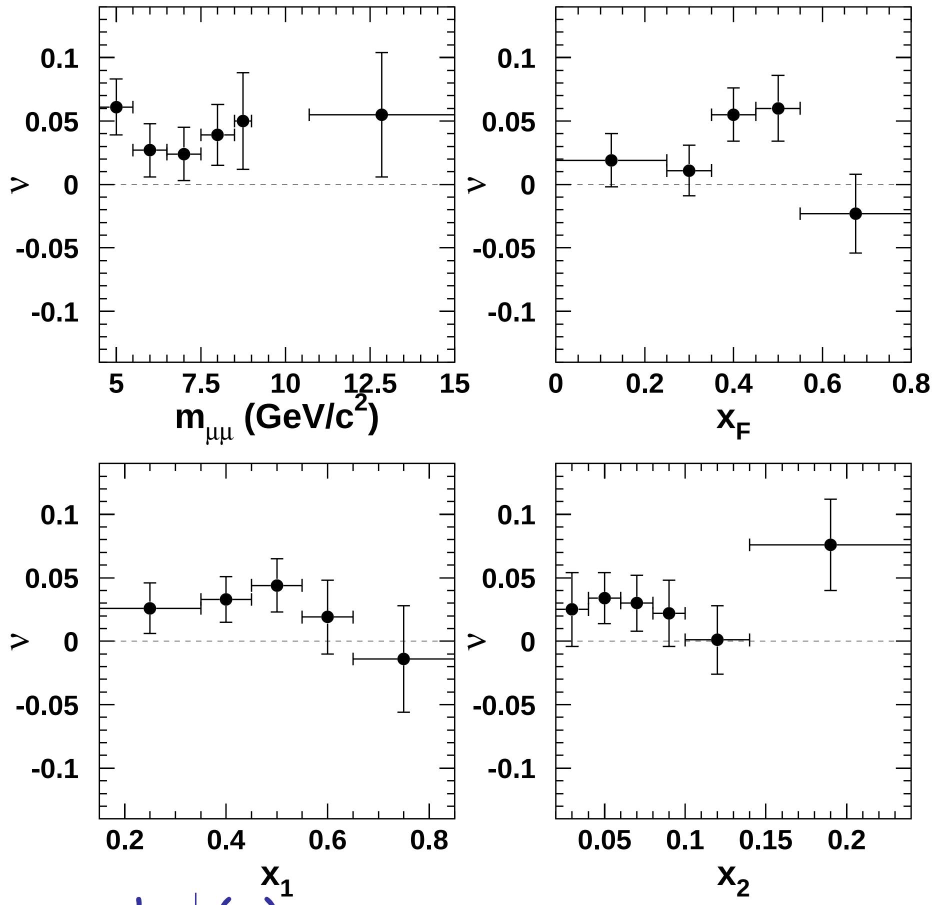
Red: data

(dset8)

Azimuthal cos2Φ Distribution in p+d Drell-Yan

L.Y. Zhu, J.C. Peng, P. Reimer et al., hep-ex/0609005.





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

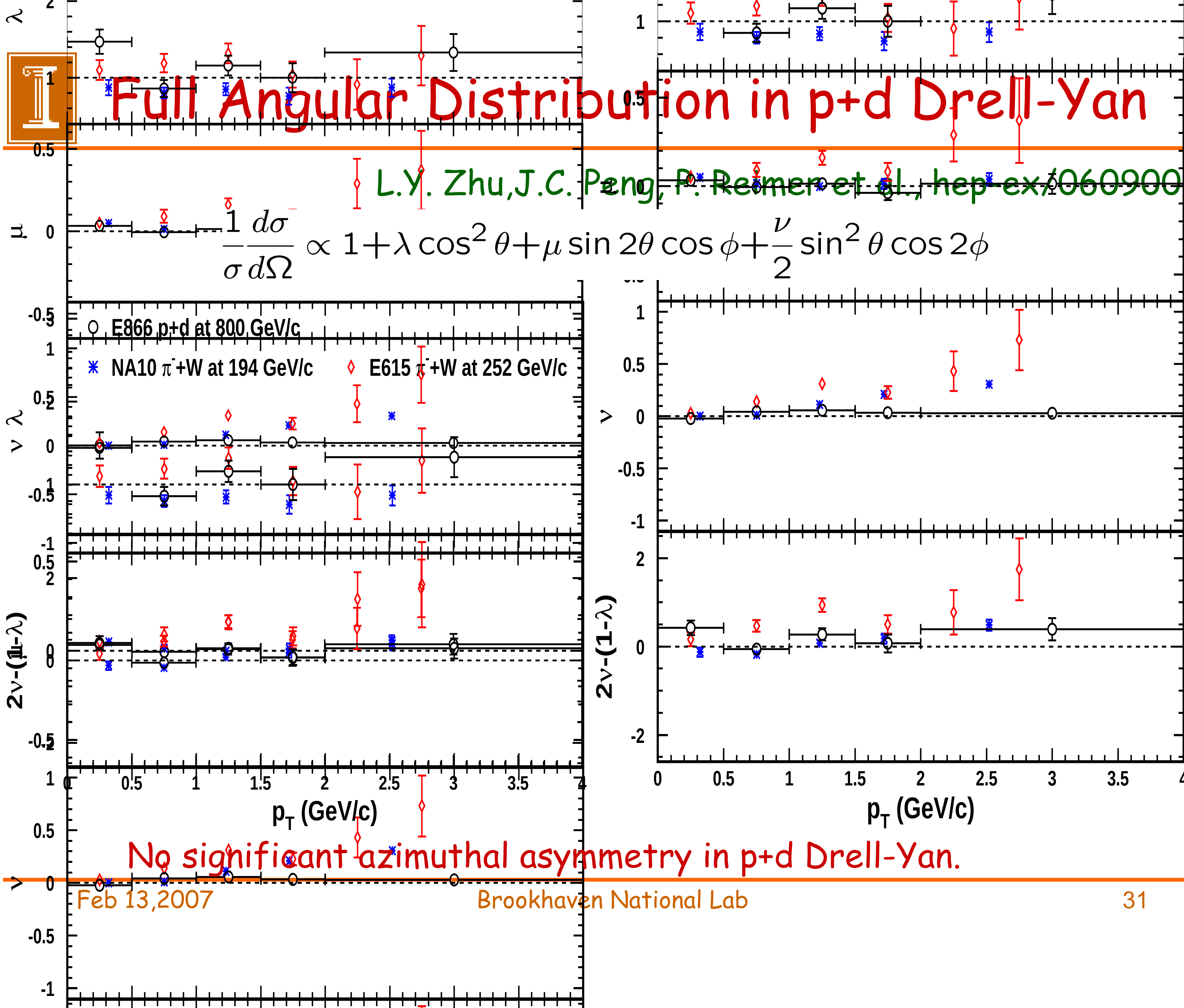
$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^{\perp}(\pi)$ * valence $h_1^{\perp}(p)$

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

Full Angular Distribution in p+d Drell-Yan

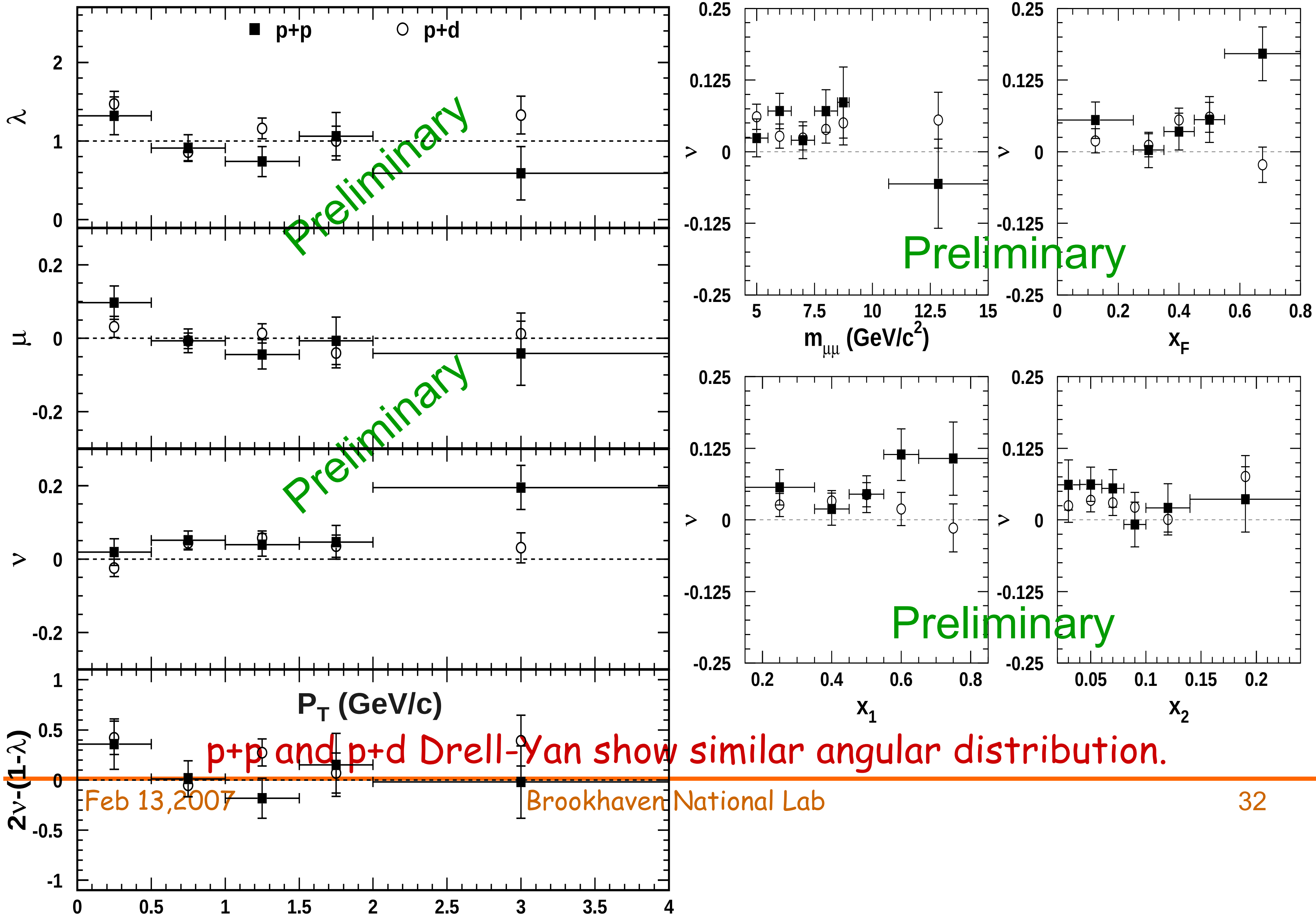
L.Y. Zhu, J.C. Peng, P. Reimer et al., hep-ex/0609005.

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



No significant azimuthal asymmetry in p+d Drell-Yan.

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



p+p and p+d Drell-Yan show similar angular distribution.

Modeling Sea Boer-Mulders Functions

- Z. Lu, B.-Q. Ma and I. Schmidt, hep-ph/0701255

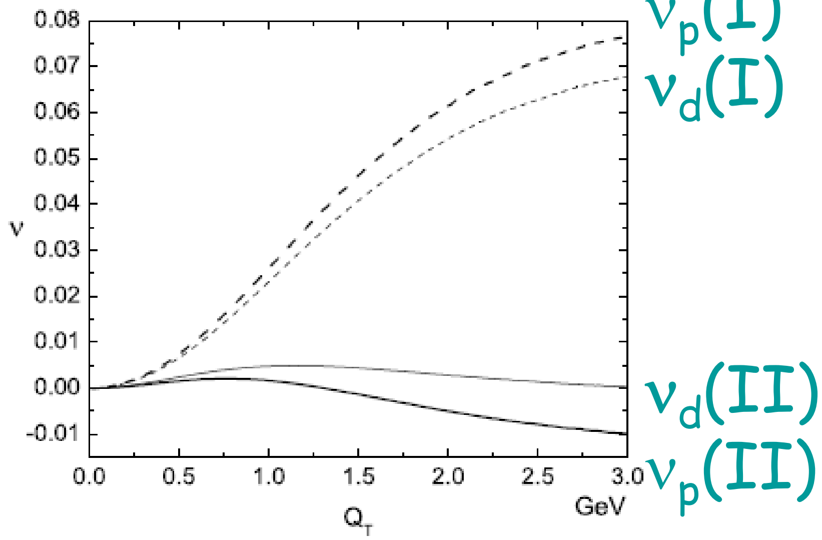
Meson-baryon fluctuation model:

$$p \rightarrow n + \pi^+ \; ; p \rightarrow \Delta^{++} + \pi^-$$

Predictions depend on the choice of valence Boer-Mulders functions:

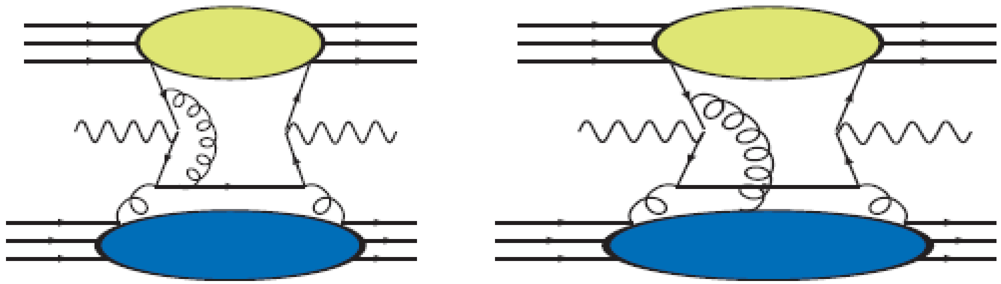
I--scalar diquark;

II—scalar & vector diquark



- Group led by L. Gamburg and G. Goldstein

Two possible contributions to sea from the gauge link.



Probing the sea Boer-Mulders functions may constrain the valence ones.

Summary

- Large cos2ϕ azimuthal asymmetry has been observed in unpolarized π-induced Drell-Yan.
- The are a few possible explanations including the non-trivial vacuum effect and the non-zero Boer-Mulders function . The latter is related to the Sivers function.
- The unpolarized p-induced Drell-Yan data show only percent-level cos2φ azimuthal asymmetry. This may disfavor the flavor blind explanation such as vacuum effect.
- More data on unpolarized Drell-Yan will be availble from the future experiments at FNAL, RHIC with proton beam, COMPASS with pion beam and especially GSI with anti-proton beam, complementary to the SIDIS data at JLab and HERMES.