Azimuthal Spin Asymmetries

in

Light-Cone Quark model

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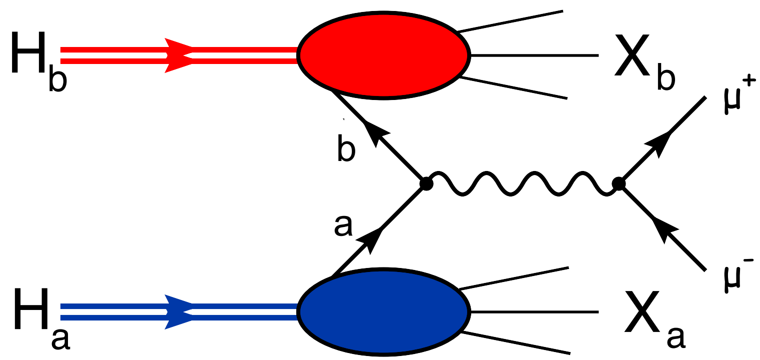
Outline

- ✳Drell-Yan at COMPASS with pion beam and transversely polarized target
  - asymmetry with convolution of proton pretzelosity and pion Boer-Mulders
- ✳TMDs from Light-Cone Quark Model for proton and pion
  - transverse-spin structure of quarks in the pion
  - physical content of proton pretzelosity
- ✳Model results for Drell-Yan asymmetry
- ✳Conclusions

Polarized Drell-Yan at COMPASS

H_b : pion beam

H_a : proton target



✳ DY cross section at leading-twist for transversely polarized target:

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \Big\{ \Big(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi\Big)$$
$$+|\vec{S}_T| \Big[D_{[\sin^2\theta]} \Big(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S)\Big)$$
$$+ A_T^{\sin\phi_S} \sin\phi_S \Big]\Big\}$$

$A_U^{\cos 2\phi}$ Boer-Mulders functions of incoming hadrons

$A_T^{\sin(2\phi+\phi_S)}$ Boer-Mulders functions of pion beam and pretzelosity of nucleon target

$A_T^{\sin(2\phi-\phi_S)}$ Boer-Mulders functions of pion beam and transversity of nucleon target

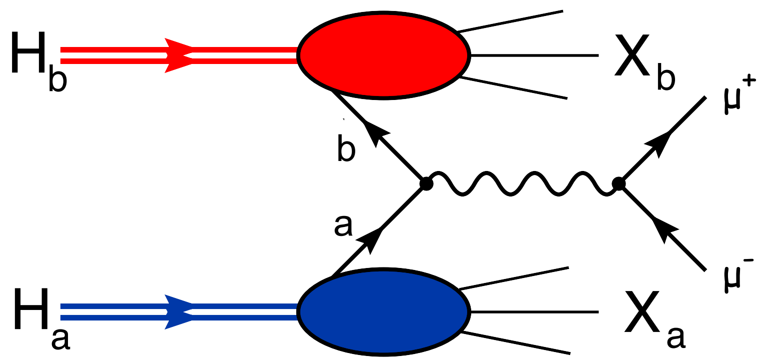
$A_T^{\sin\phi_S}$ unpolarized TMD of pion beam and Sivers function of nucleon target

⇨ talk of C. Quintans

Polarized Drell-Yan at COMPASS

H_b : pion beam

H_a : proton target



✳ DY cross section at leading-twist for transversely polarized target:

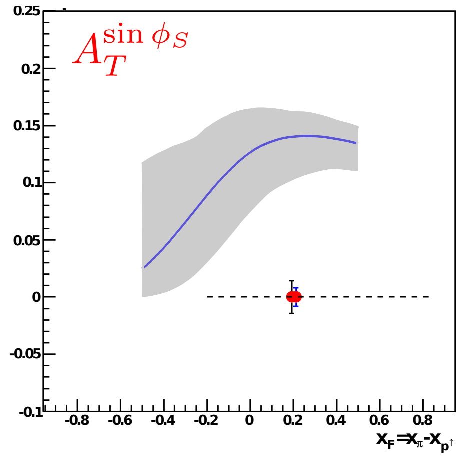
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \left\{ \left(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi\right) + |\vec{S}_T| \left[D_{[\sin^2\theta]} \left(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \right) + A_T^{\sin\phi_S} \sin\phi_S \right] \right\}$$

$A_U^{\cos 2\phi}$	Boer-Mulders functions of incoming hadrons
$A_T^{\sin(2\phi+\phi_S)}$	Boer-Mulders functions of pion beam and pretzelosity of nucleon target
$A_T^{\sin(2\phi-\phi_S)}$	Boer-Mulders functions of pion beam and transversity of nucleon target
$A_T^{\sin\phi_S}$	unpolarized TMD of pion beam and Sivers function of nucleon target

⇨ talk of C. Quintans

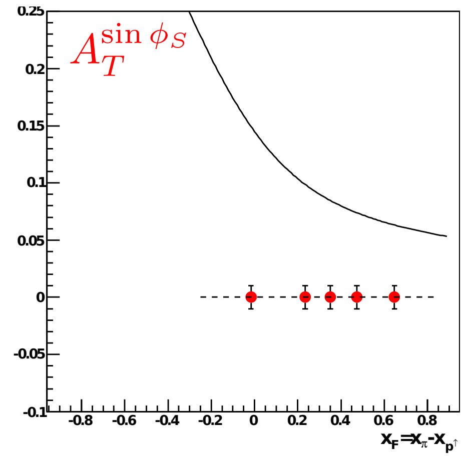
COMPASS-II Proposal

DY: $4 < M_{\mu\mu} < 9$ GeV



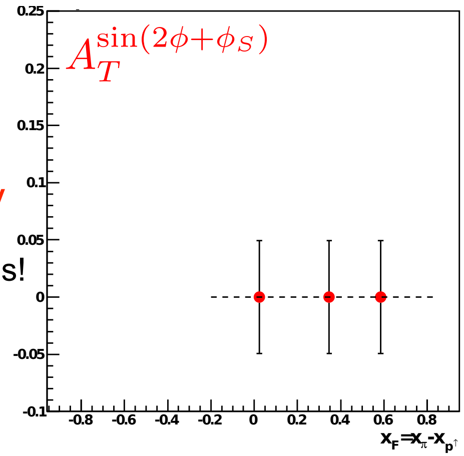
f$_1$⊗Sivers

Anselmino et al., PRD79 (2009)



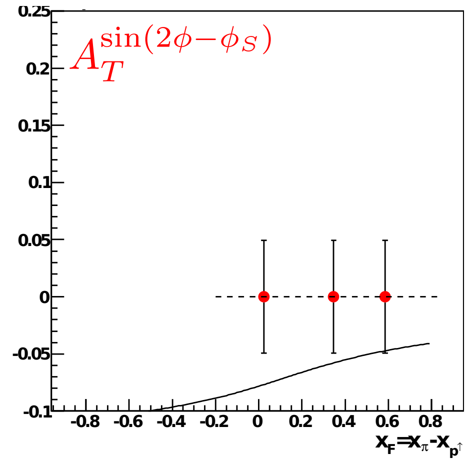
BM⊗BM

Zhang et al., PRD77 (2008)



BM⊗Pretzelosity

no theoretical predictions!



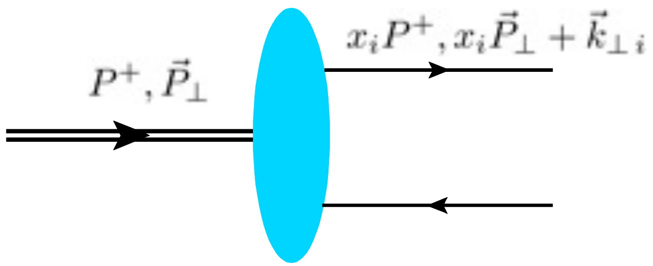
BM⊗Transversity

Sissakian et al., Phys.Part.Nucl.41 (2010)

COMPASS collaboration, COMPASS II proposal, CERN-SPSC-2010-014, SPSC-P-340

Boer-Mulders function of the pion

Light-Cone Wave Function of the Pion



LCWF: $\Psi^{LC}_{\pi\beta}(x_i, \vec{k}_{\perp,i})$

invariant under boost, independent of P^μ

internal variables: $x_i = \frac{p_i^+}{P^+}$, $\sum_{i=1}^{N} x_i = 1$ $\sum_{i=1}^{N} \vec{k}_{\perp\, i} = \vec{0}_\perp$

[Brodsky, Pauli, Pinsky, '98]

$$|P, \pi\rangle = \sum_\beta \int \mathrm{d}[1][2]\, \Psi^{LC}_{\pi\beta}(x_i, \vec{k}_{\perp,i}) \frac{\delta_{ij}}{\sqrt{3}} q^\dagger_{i\lambda_i}(1) \bar{q}^\dagger_{j\lambda_2} |0\rangle$$

LCWF: eigenstate of total orbital angular momentum

$$|\,\pi\rangle = |\,\pi\rangle^{L_z=1}_{-1} + |\,\pi\rangle^{L_z=0}_{0} + |\,\pi\rangle^{L_z=-1}_{1}$$

	$L_z^q = -1$	$L_z^q = 0$	$L_z^q = 1$
$J_z^q = -L_z^q$	$(\uparrow\uparrow)_{LC}$	$(\uparrow\downarrow)_{LC}$	$(\downarrow\downarrow)_{LC}$

parity
time reversal
isospin symmetry

$\Rightarrow$ $\boxed{\text{2 independent wave function amplitudes}}$

Phenomenological Light-Cone Wave Function of the Pion

$$\Psi^{LC}_{\pi\beta}(x_i, \vec{k}_{\perp,i}, \lambda_i) = \Psi^{\text{Mom}}(x_i, \vec{k}^2_{\perp,i}) \otimes \Psi^{\text{Spin}}(x_i, \vec{k}_{\perp,i}\lambda_i)$$

$\ast\Psi^{\text{Mom}}(x_i, \vec{k}^2_{\perp,i})$: momentum-space component → gaussian shape

two parameters: m_q and gaussian width fitted to exp. charge radius and pion decay constant

$\ast\Psi^{\text{Spin}}(x_i, \vec{k}_{\perp,i}, \lambda_i)$: spin-dependent part → eigenstate of the total angular momentum operator in light-front dynamics ($L_z = 0$, $|L_z| = 1$)

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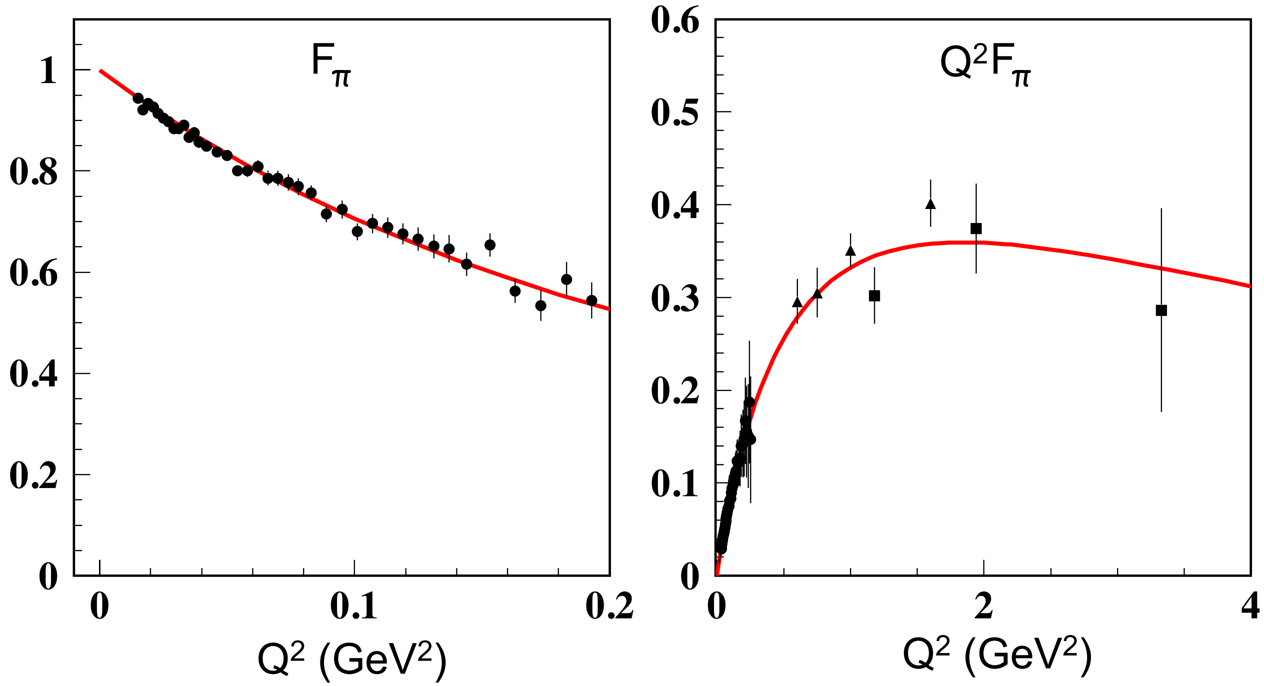
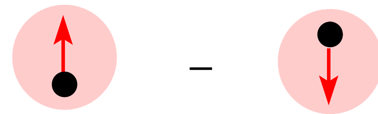
Electromagnetic Form Factor

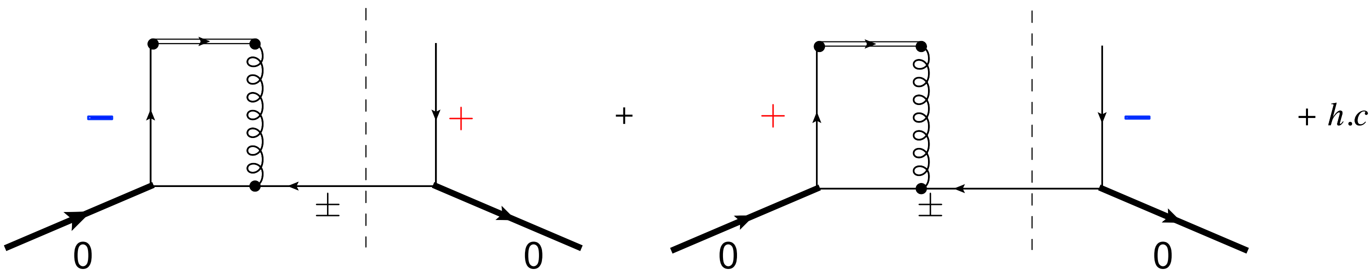


Model calculation of pion Boer-Mulders

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



one-gluon exchange approximation

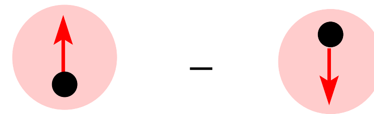


overlap of LCWFs in S and P waves

Mismatch of helicity between initial and final state $\Longrightarrow$ $\Delta L_z = \pm 1$

Model calculation of pion Boer-Mulders

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



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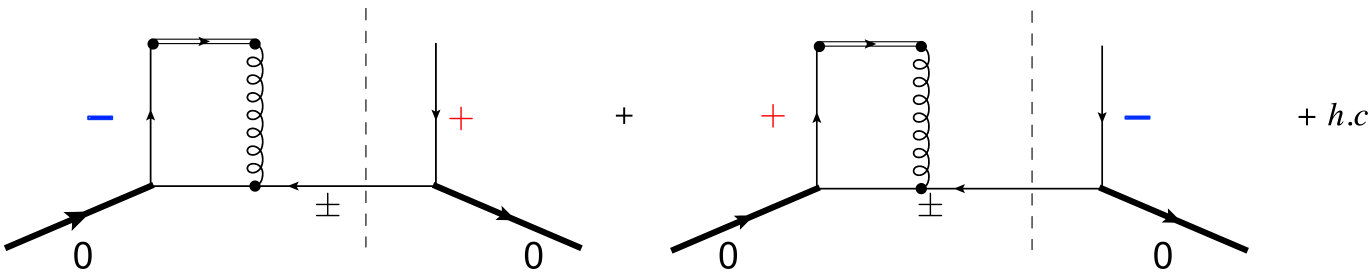


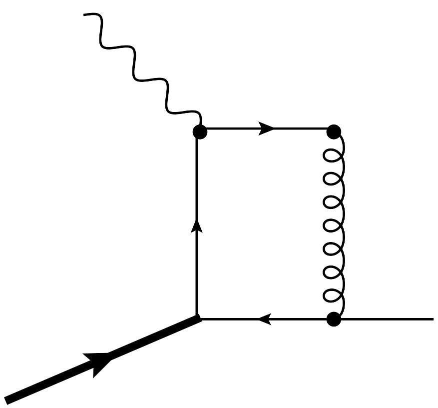
overlap of LCWFs in S and P waves

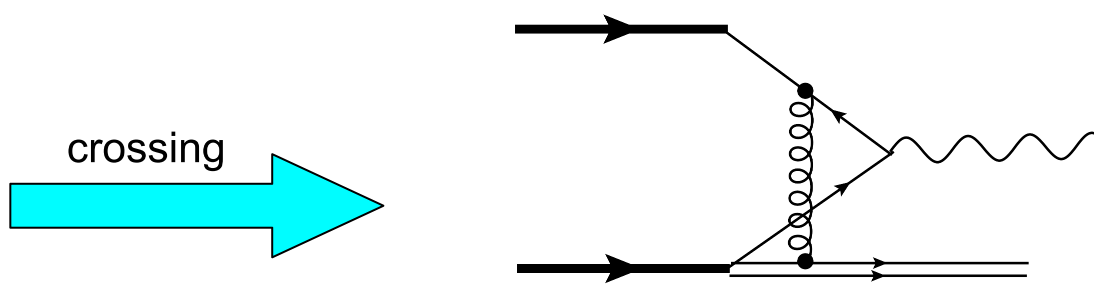
Mismatch of helicity between initial and final state ⟹ $\Delta L_z = \pm 1$

SIDIS
final state interactions

$$h_{1T\,[\mathrm{SIDIS}]}^{\perp} = -h_{1T\,[DY]}^{\perp}$$

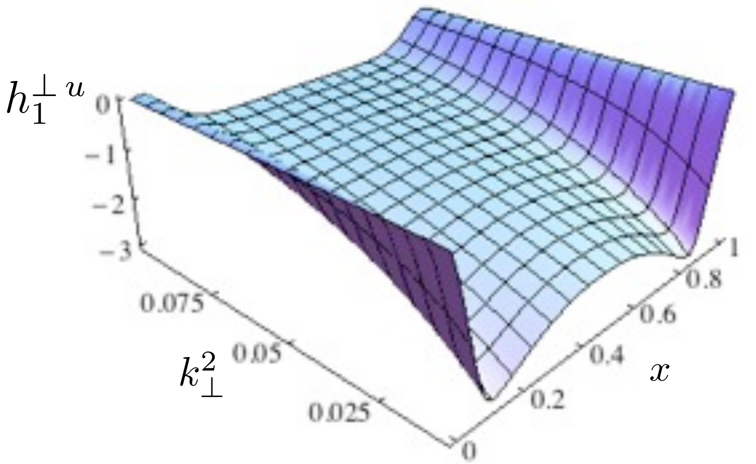
DY
initial state interactions



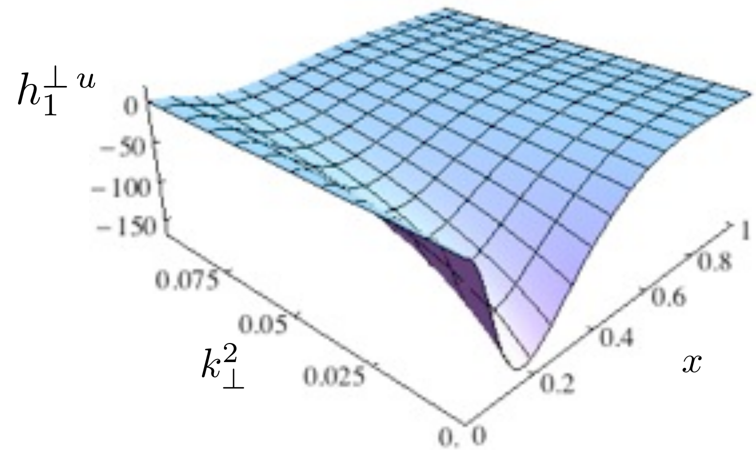


Boer-Mulders functions in LCCQM

Pion



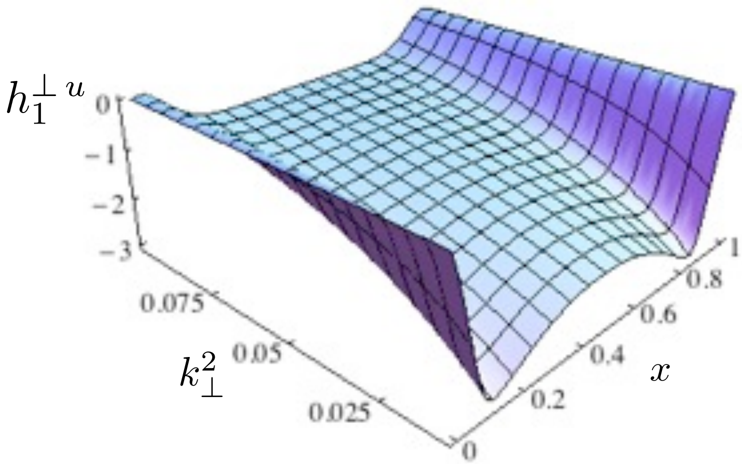
Proton



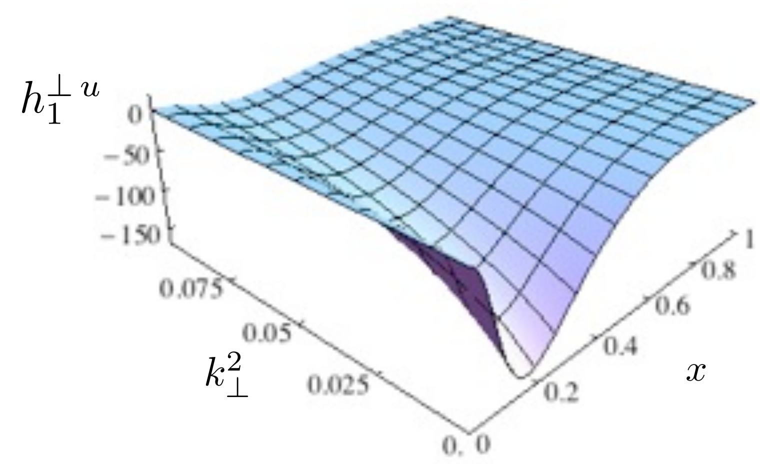
$$h_1^{\perp u}(\pi^+) = h_1^{\perp \bar{d}}(\pi^+) = h_1^{\perp d}(\pi^-) = h_1^{\perp \bar{u}}(\pi^-)$$

Boer-Mulders functions in LCCQM

Pion

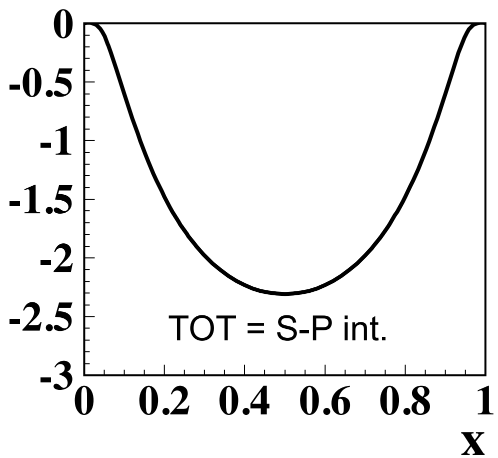


Proton



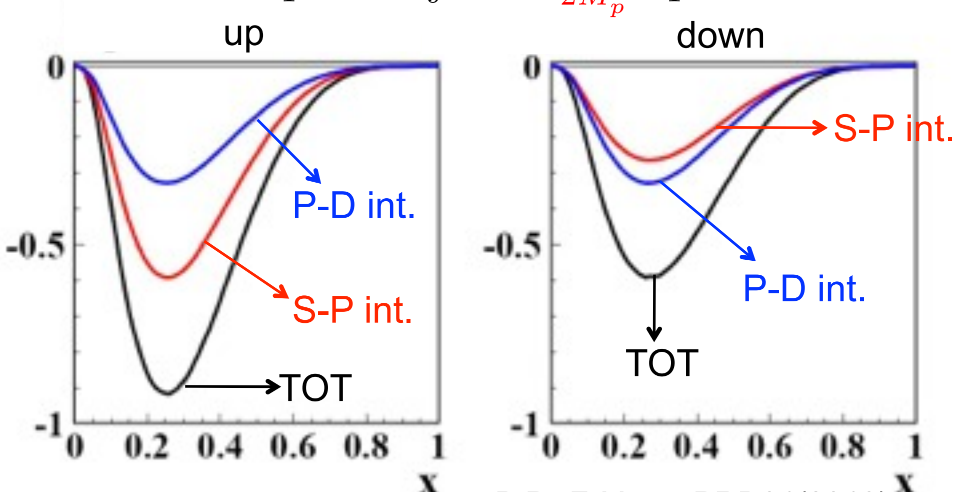
$$h_1^{\perp u}(\pi^+) = h_1^{\perp \bar{d}}(\pi^+) = h_1^{\perp d}(\pi^-) = h_1^{\perp \bar{u}}(\pi^-)$$

$$h_1^{\perp(1)u} = \int \mathrm{d}^2\vec{k}_\perp \frac{k_\perp^2}{2m_\pi^2}\, h_1^{\perp u}$$



B.P., Schweitzer, Efremov, in preparation

$$h_1^{\perp(1)q} = \int \mathrm{d}^2\vec{k}_\perp \frac{k_\perp^2}{2M_p^2}\, h_1^{\perp q}$$

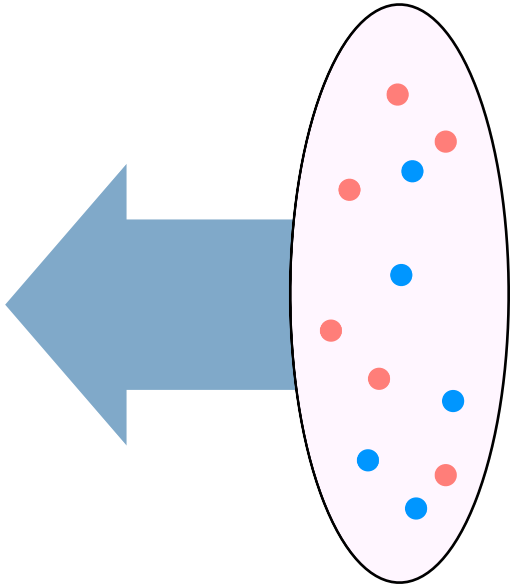


B.P., F. Yuan, PRD81(2010)

Chromodynamic lensing

Burkardt, PRD66 (02)

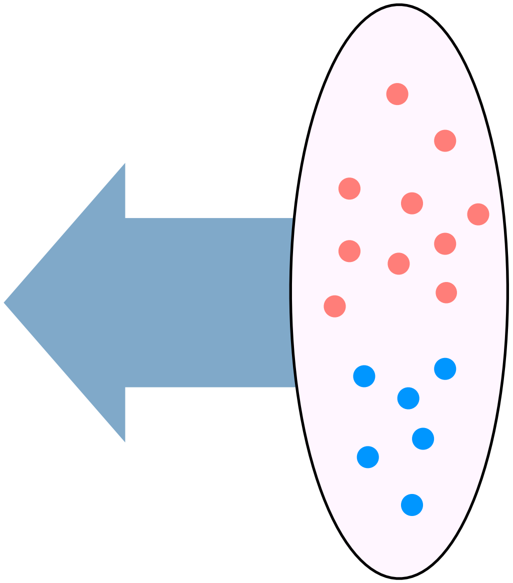
unpolarized quarks



Chromodynamic lensing

Burkardt, PRD66 (02)

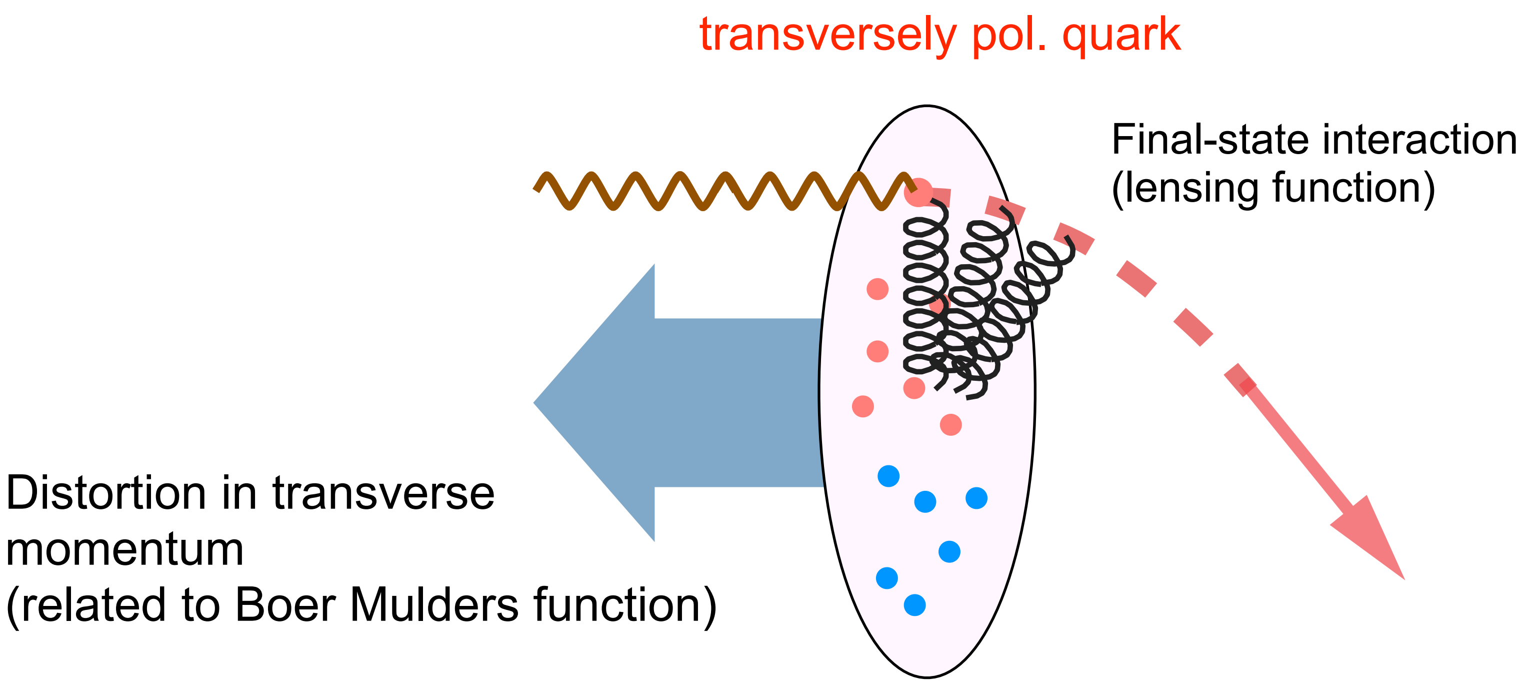
transversely pol. quark



Distortion in impact parameter
(related to GPD E_T)

Chromodynamic lensing

Burkardt, PRD66 (02)



Chromodynamic lensing

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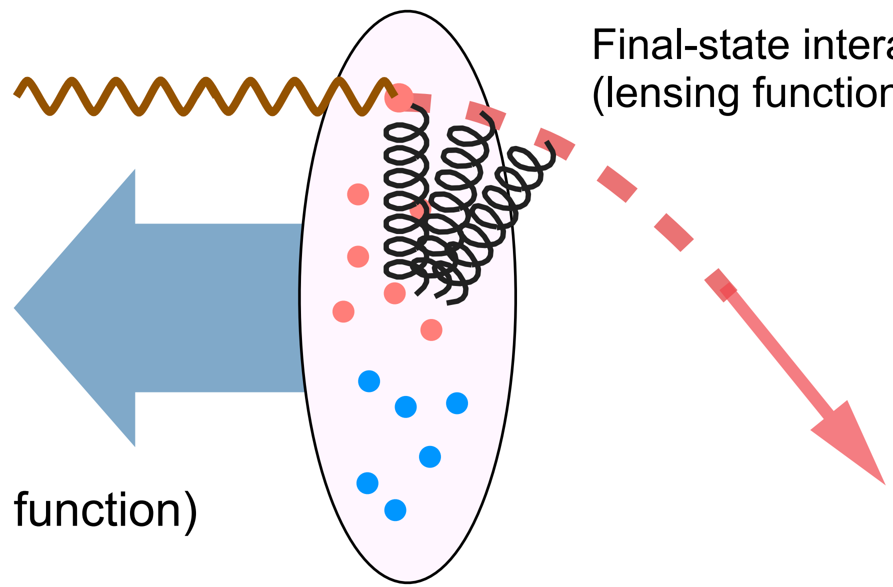


model-dependent relation

$$2m_\pi^2 h_1^{\perp(1)}(x) \approx \int \mathrm{d}^2 b_T \vec{b}_T \cdot \vec{\mathcal{I}}(x, \vec{b}_T) \frac{\partial}{\partial \vec{b}_T^2} \mathcal{E}_T^\pi(x, \vec{b}_T^2)$$

Boer-Mulders function

lensing function

FT of chiral-odd GPD

Pion GPDs in impact parameter space

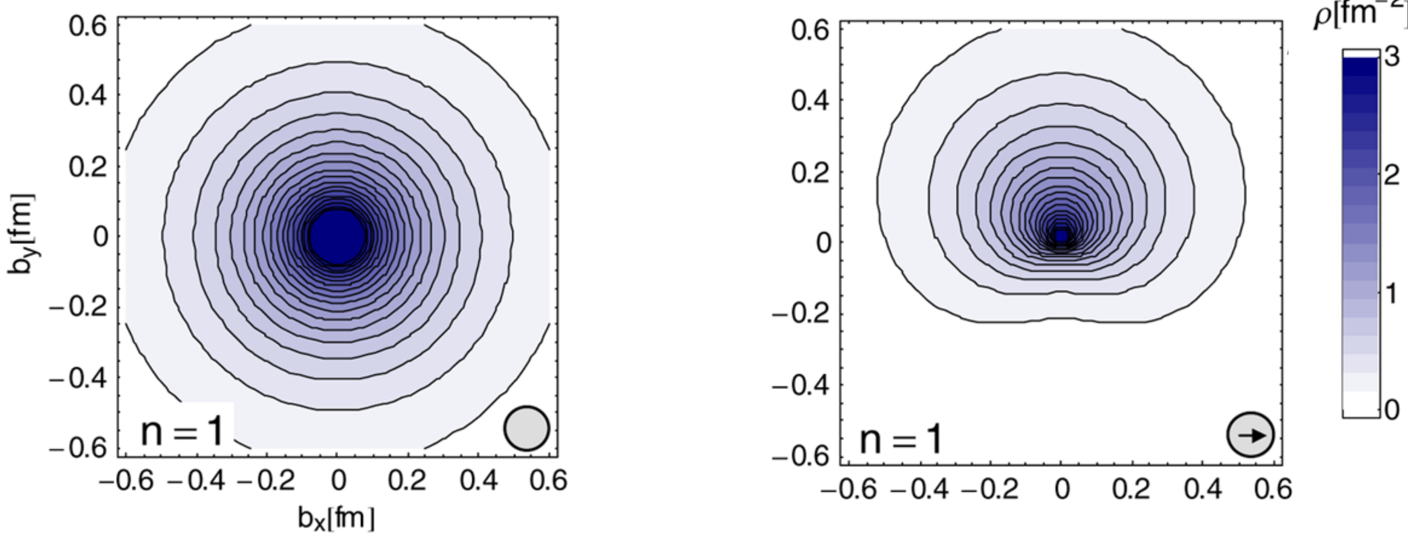
Lattice

$\langle b_y \rangle$=(0.151 ± 0.024) fm

Broemmel et al., PRL101,2008

GPD for unpolarized quark

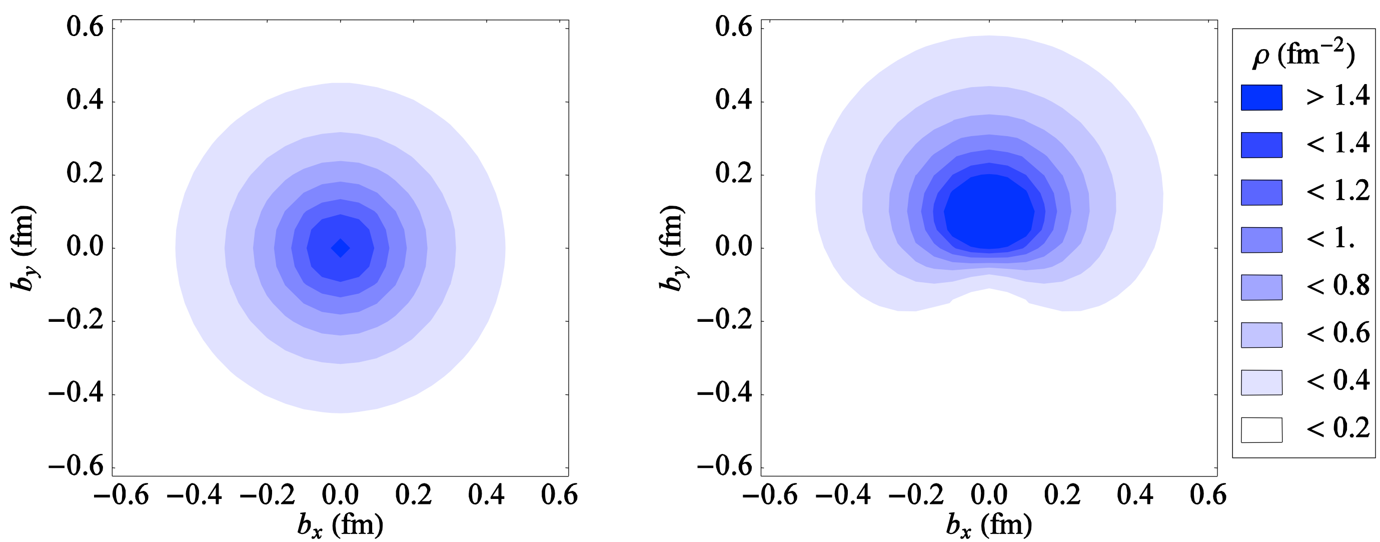
chiral-odd GPD for pol. quark in the x direction



Light-Cone CQM

$\langle b_y \rangle$=0.197 fm

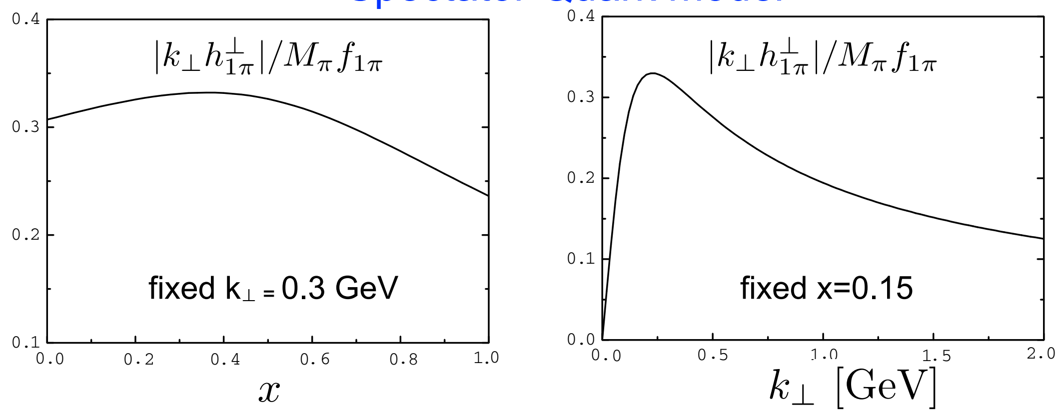
Frederico, Pace, BP, Salme', PRD80 (2009)



Model calculations of pion Boer-Mulders function

Spectator Quark model

Zhun Lu, B.Q. Ma
PRD70 (2011)



pion BM
= $m_\pi \leftrightarrow M_p$
proton BM

Diquark spectator model and LCCQM with one gluon exchange approximation

BM funct. proportional to α_s ⇒ overall normalization constant depending on the model scale

Model calculations of pion Boer-Mulders function

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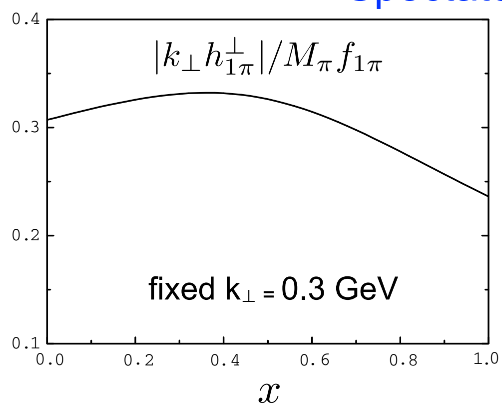
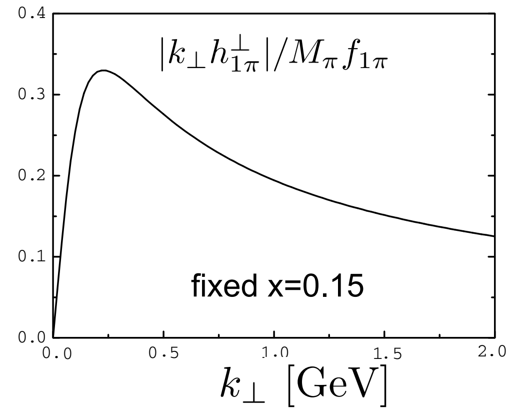




pion BM
= $m_\pi \leftrightarrow M_p$
proton BM

Diquark spectator model and LCCQM with one gluon exchange approximation

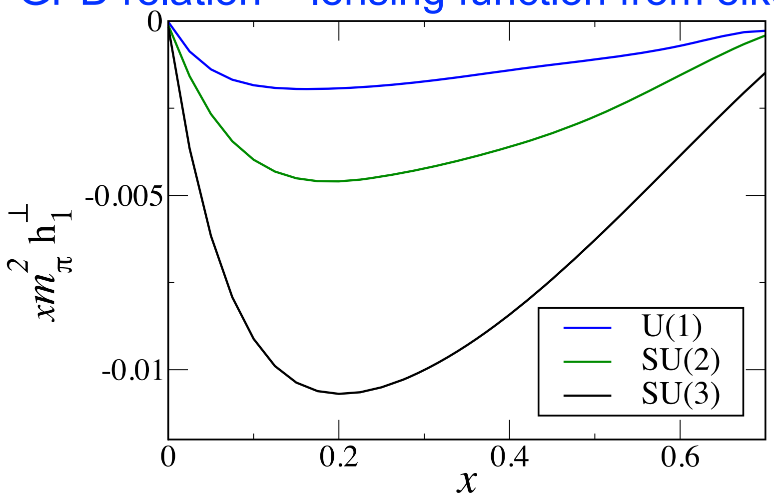
BM funct. proportional to α_s ⇒ overall normalization constant depending on the model scale

Beyond one-gluon exchange approx.

⇓

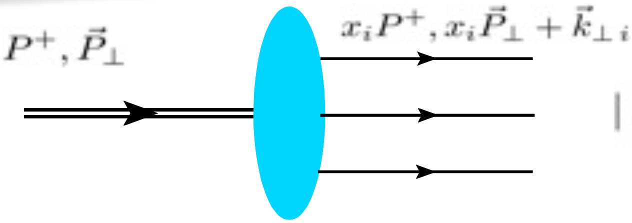
TMD-GPD relation + lensing function from eikonal methods

Gamberg, Schlegel
PLB685 (2010)



Proton Pretzelosity

Light-Cone Wave Function of the Proton



$$| P, \lambda\rangle = \sum_\beta \int \mathrm{d}[1]\mathrm{d}[2]\mathrm{d}[3]\, \Psi^f_{\lambda,\beta}(x_i, \vec{k}_{\perp,i})\, \frac{\varepsilon^{ijk}}{\sqrt{6}}\, u^\dagger_{i\lambda_1}(1) u^\dagger_{j\lambda_2}(2) d^\dagger_{k\lambda_3}(3) | 0\rangle$$

❖ classification of LCWFs in orbital angular momentum components

[Ji, J.P. Ma, Yuan, 03; Burkardt, Ji, Yuan, 02]

$$| P, \uparrow\rangle = | P, \uparrow\rangle^{L_z=2}_{-\frac{3}{2}} + | P, \uparrow\rangle^{L_z=1}_{-\frac{1}{2}} + | P, \uparrow\rangle^{L_z=0}_{\frac{1}{2}} + | P, \uparrow\rangle^{L_z=-1}_{\frac{3}{2}}$$

total quark helicity J^q_z

$$J_z = J_z^q + L_z^q$$

$J_z^q \longrightarrow$	$(\uparrow\uparrow\uparrow)_{LC}$	$(\uparrow\uparrow\downarrow)_{LC}$	$(\uparrow\downarrow\downarrow)_{LC}$	$(\downarrow\downarrow\downarrow)_{LC}$
	$L_z^q = -1$	$L_z^q = 0$	$L_z^q = 1$	$L_z^q = 2$

MODEL

$$\Psi^f_{\lambda\beta}(x_i, \vec{k}_{\perp,i}, \lambda_i) = \Psi^{\mathrm{Mom}}(x_i, \vec{k}^2_{\perp,i}) \otimes \Psi^{\mathrm{Spin}}(x_i, \vec{k}_{\perp,i}\lambda_i)$$

✳ momentum-space component: spherically symmetric

two parameters fitted to anomalous magnetic moments of proton and neutron

✳spin-dependent part ⇨ eigenstate of the total angular momentum operator (S, P, D waves)

[B.P., Cazzaniga, Boffi, PRD78 (2008)]

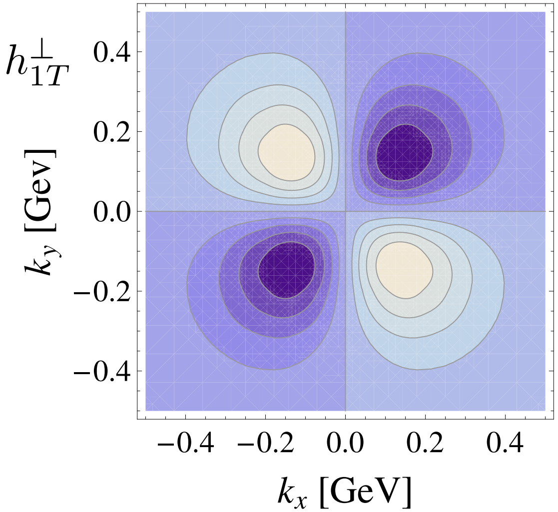
Pretzelosity

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

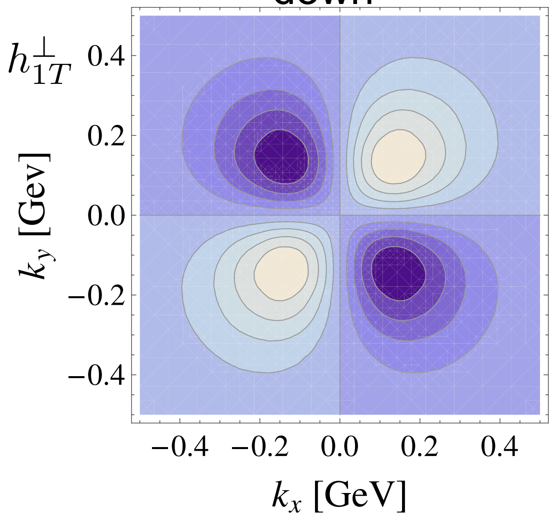
$|\Delta L_z|=2$

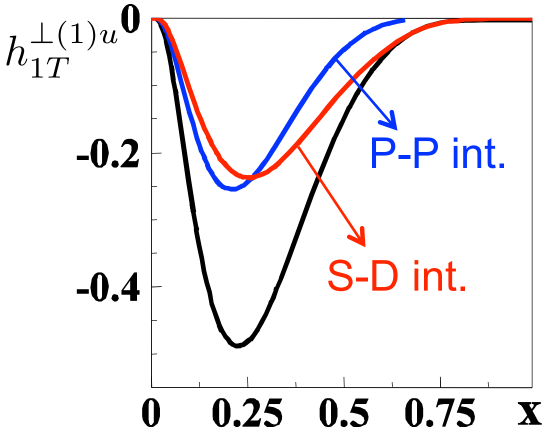
from the initial to the final nucleon state

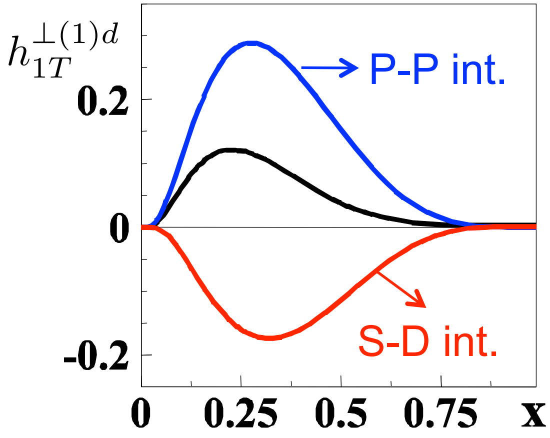
up



down







OAM and Pretzelosity

model-dependent relation

$$\mathcal{L}_z = -\int \mathrm{d}x \mathrm{d}^2\vec{k}_\perp \frac{k_\perp^2}{2M^2} h_{1T}^\perp(x, k_\perp^2)$$

first derived in LC-diquark model and bag model

[She, Zhu, Ma, 2009; Avakian, Efremov, Schweitzer, Yuan, 2010]

$\mathcal{L}_z$

chiral even and charge even

$\Delta L_z = 0$

$h_{1T}^\perp$

chiral odd and charge odd

$|\Delta L_z| = 2$

no operator identity relation at level of matrix elements of operators

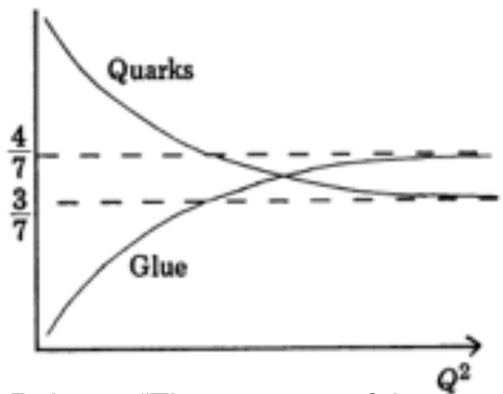
$\Downarrow$

valid in all quark models with spherical symmetry in the rest frame

[Lorce', BP, PLB710 (2012)]

Application to Observables

Fixing the scale of the LCCQM



Roberts, “The structure of the proton”

✳ there exists a scale at which there are no sea and gluons

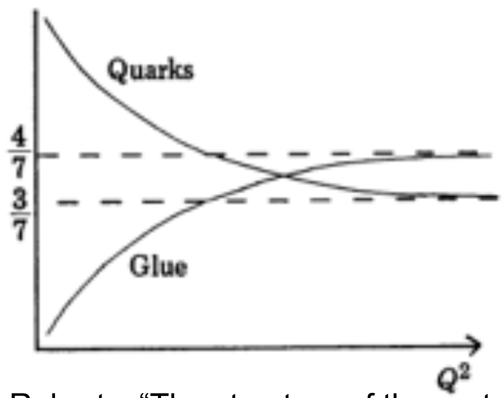
$$\Downarrow$$

✳ the valence quarks carry the whole momentum of the hadron

$$\langle x \rangle_v = 1 \qquad \langle x \rangle_g = \langle x \rangle_{sea} = 0$$

Parisi & Petronzio, Phys. Lett. B 62 (1976)
Traini et al, Nucl. Phys. A 614, 472 (1997)

Fixing the scale of the LCCQM



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Traini et al, Nucl. Phys. A 614, 472 (1997)

	from experiments		hadronic scale of the model
Pion	$Q^2 = 4 \text{ GeV}^2$ $\langle x \rangle_v = 0.47$	NLO evolution $\Rightarrow$	$Q_0^2 \approx 0.31 \text{ GeV}^2$ $\langle x \rangle_v = 1$
Proton	$Q^2 = 10 \text{ GeV}^2$ $\langle x \rangle_v = 0.36$	NLO evolution $\Rightarrow$	$Q_0^2 \approx 0.26 \text{ GeV}^2$ $\langle x \rangle_v = 1$

The BM-Pretzelosity Asymmetry in πp Drell Yan

[Arnold, Metz, Schlegel, PRD79, (2008)]

$$A_{TU}^{\sin(2\phi+\phi_p)} = \frac{F_{TU}^{\sin(2\phi+\phi_p)}}{F_{UU}^{1}}$$

ϕ = lepton angle in the CS frame

ϕ_p = proton spin angle in the CM frame

Numerator ⟶ $F_{TU}^{\sin(2\phi+\phi_p)} = \mathcal{C}\left[w(\vec{k}_{Tp}, \vec{K}_{T\pi})\, h_{1T}^{\perp p}\, h_1^{\perp \pi}\right]$

$$w(\vec{k}_{Tp}, \vec{k}_{T\pi}) = \frac{2(\vec{h}\cdot\vec{k}_{Tp})(2(\vec{h}\cdot\vec{k}_{Tp})(\vec{h}\cdot\vec{k}_{T\pi}) - \vec{k}_{Tp}^2(\vec{h}\cdot\vec{k}_{T\pi})}{2M_p^2 m_\pi}$$

with $\vec{h} = \frac{\vec{q}_T}{q_T}$

Denominator ⟶ $F_{UU}^{1} = \mathcal{C}\left[1\, f_1^p\, f_1^\pi\right]$

The BM-Pretzelosity Asymmetry in πp Drell Yan

[Arnold, Metz, Schlegel, PRD79, (2008)]

$$A_{TU}^{\sin(2\phi+\phi_p)} = \frac{F_{TU}^{\sin(2\phi+\phi_p)}}{F_{UU}^1}$$

ϕ = lepton angle in the CS frame

ϕ_p = proton spin angle in the CM frame

Numerator $\longrightarrow$ $F_{TU}^{\sin(2\phi+\phi_p)} = \mathcal{C}\left[w(\vec{k}_{Tp}, \vec{K}_{T\pi})\, h_{1T}^{\perp p}\, h_1^{\perp \pi}\right]$

$$w(\vec{k}_{Tp}, \vec{k}_{T\pi}) = \frac{2(\vec{h}\cdot\vec{k}_{Tp})(2(\vec{h}\cdot\vec{k}_{Tp})(\vec{h}\cdot\vec{k}_{T\pi}) - \vec{k}_{Tp}^2(\vec{h}\cdot\vec{k}_{T\pi})}{2M_p^2 m_\pi}$$

with $\vec{h} = \frac{\vec{q}_T}{q_T}$

Denominator $\longrightarrow$ $F_{UU}^1 = \mathcal{C}\left[1\, f_1^p\, f_1^\pi\right]$

$\Downarrow$ Gaussian Ansatz

$$F_{TU}^{\sin(2\phi+\phi_p)} = B_{\text{Gauss}} e_u^2 h_{1T}^{\perp(1/2)u/p}(x_p) h_1^{\perp(1)\bar{u}/\pi^-}(x_\pi)$$

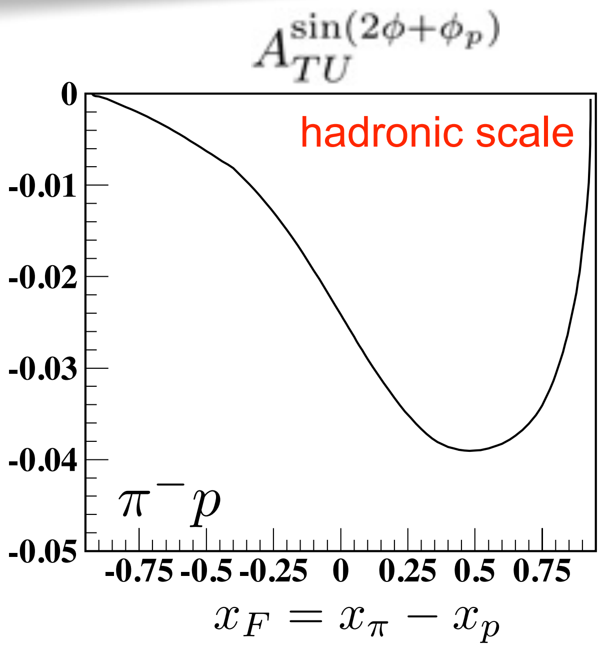
$$F_{UU}^1 = e_u^2 f_1^{u/p}(x_p) f_1^{\bar{u}/\pi^-}(x_\pi)$$

$$h_{1T}^{\perp(1/2)u/p} = \int d\vec{k}_\perp \frac{k_\perp}{2M_p} h_{1T}^{\perp u/p}(x, k_\perp^2)$$

$$B_{\text{Gauss}} = \frac{3}{2}\frac{m_\pi}{M_p}\frac{1}{\left[1+\frac{\langle p_{T\pi}^2\rangle}{\langle p_{Tp}^2\rangle}\right]^{3/2}}$$

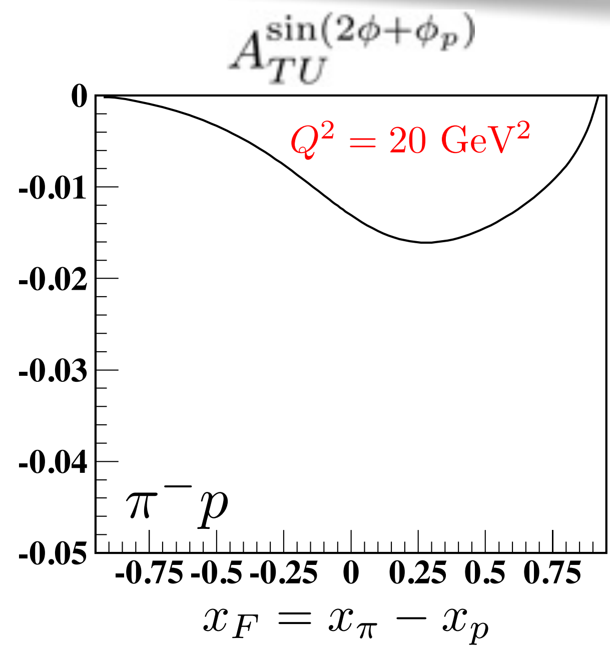
$$h_{1T}^{\perp(1)\bar{u}/\pi^-} = \int d\vec{k}_\perp \frac{k_\perp^2}{2m_\pi^2} h_{1T}^{\perp\bar{u}/\pi}(x, k_\perp^2)$$

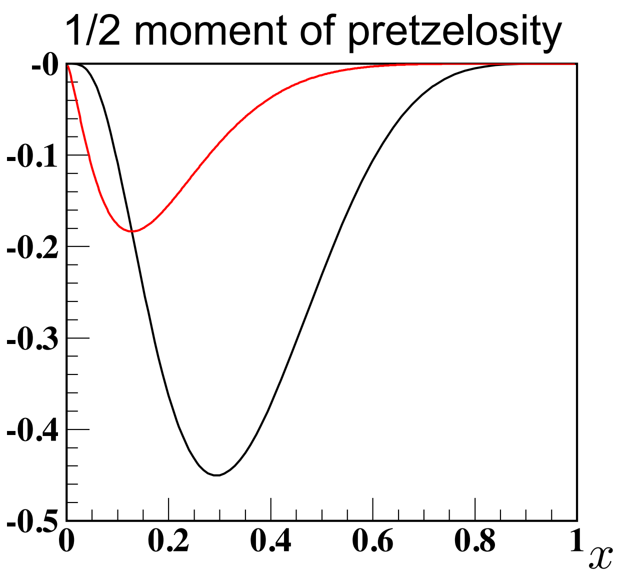
Results from the LCCQM



approximate evolution

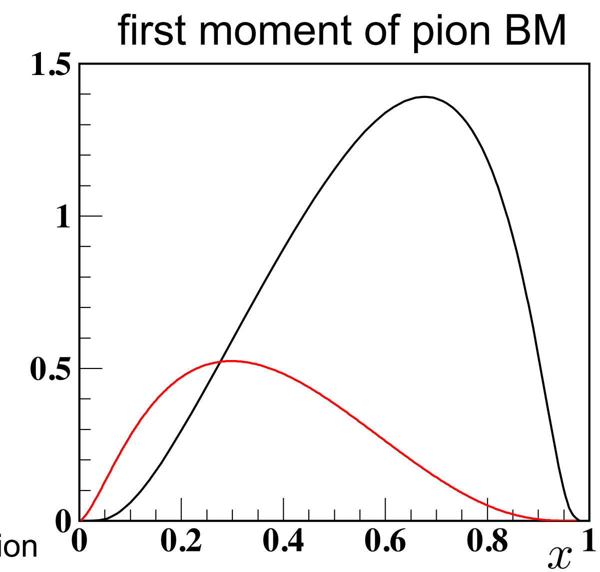
pretzelosity and BM function evolved like transversity





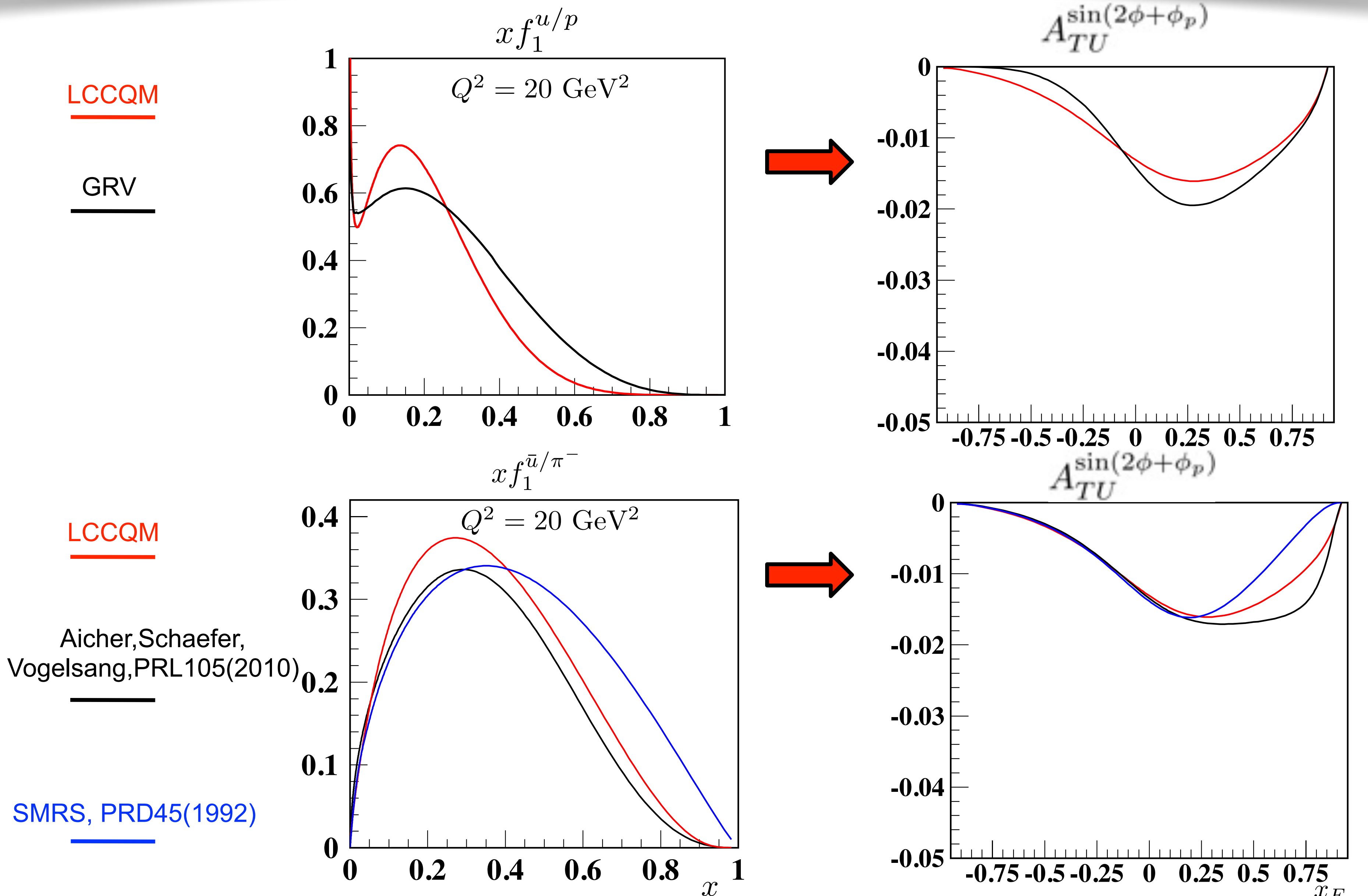
hadronic scale

evolution to Q^2=20 GeV^2



B.P., Schweitzer, Efremov, in preparation

Model dependence from f_1^p and f_1^π



B.P., Schweitzer, Efremov, in preparation

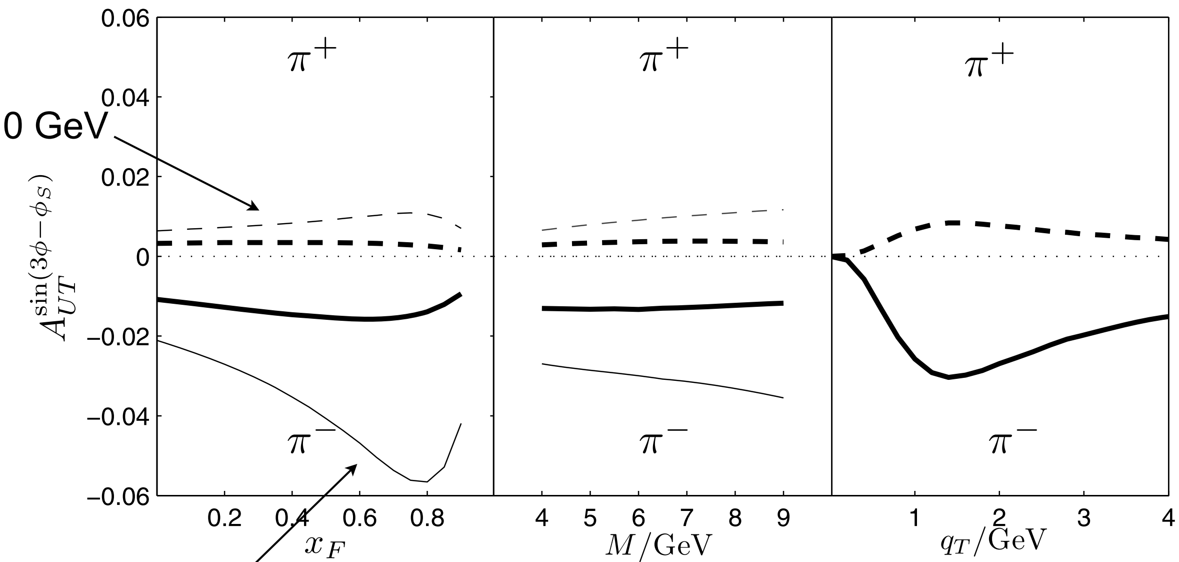
Predictions from other models

⇨ talk of Zhun Lu

Light-cone quark spectator model

Zhun Lu, B.-Q. Ma, PLB696(2011)

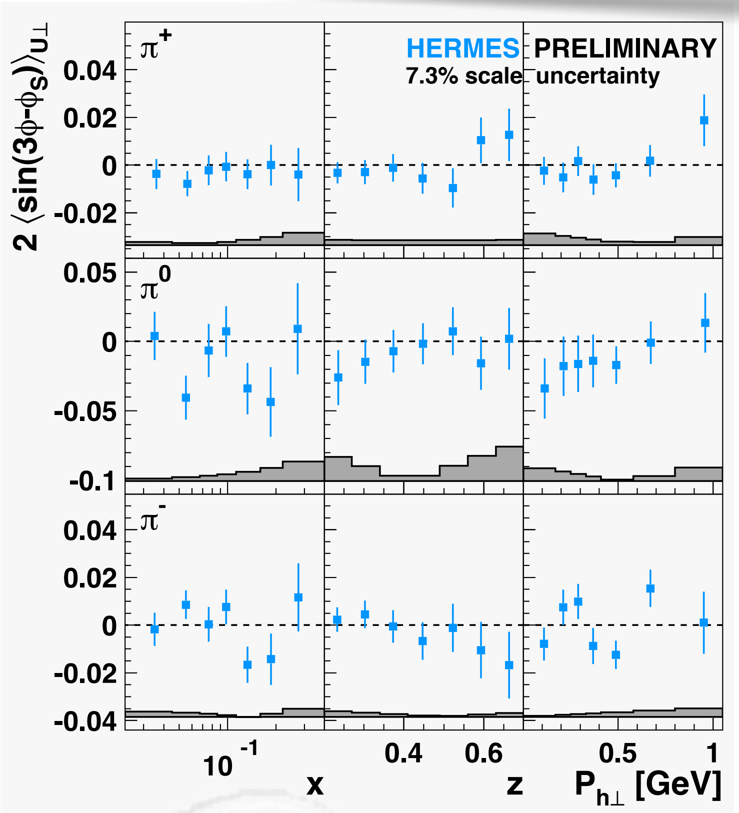
cut in
1.0 GeV < q_T < 2.0 GeV



cut in 1.0 GeV < q_T < 2.0 GeV

Pretzelosity from SIDIS

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto \sum_q e_q^2 h_{1T}^{\perp q} \otimes H_1^{\perp q}$$

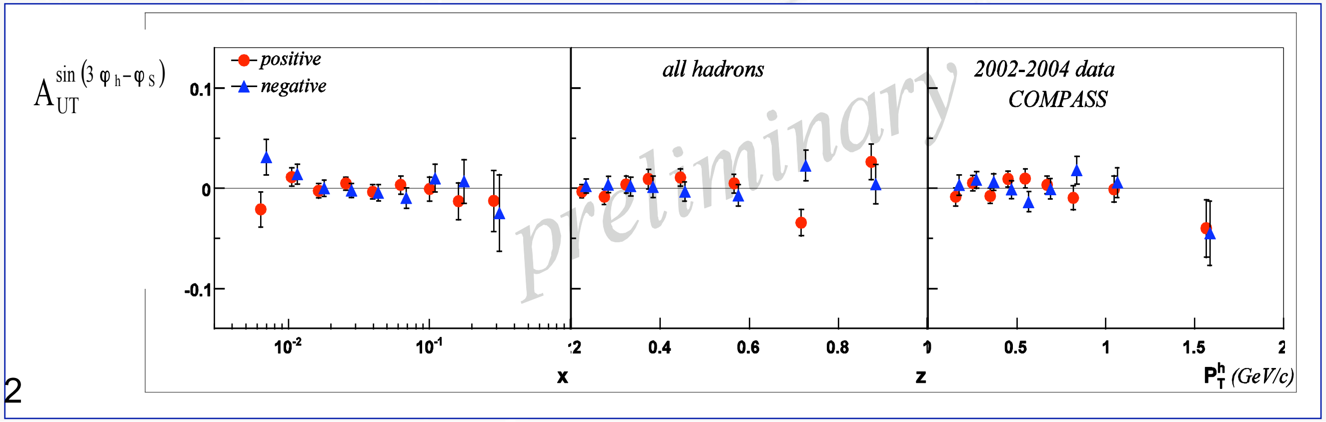


✓ leads to sin (3Φ-Φ$_s$) modulation in A_{UT}

✓ proton (HERMES) and deuteron (COMPASS) data consistent with zero

✓ pretzelosity equal to zero? or just the suppression by third power of $1/P_{h\perp}$?

✓ experiment planned at CLAS12 (H. Avakian at al., LOI 12-06-108)



Gunar Schnell, INT workshop, 2012

Summary

- Polarized Drell-Yan at COMPASS with pion beam: $BM^{\pi} \otimes \text{pretzelosity}^{\text{proton}}$

  complementary to SIDIS to extract information on proton pretzelosity

  new tool to learn about the transverse spin structure of quark in the pion

- Predictions in a Light-Cone Quark model

  small asymmetry of the order of 1-2%, with larger contribution at large x_F

  small model dependence from f_1 of proton
  larger uncertainties from f_1 of pion

  effects of evolution are important and need further studies

- Future plans: extend the analysis within LCCQM to other spin asymmetries of (un)polarized DY