The Boer-Mulders – Pretzelosity Asymmetry in π p Drell-Yan at COMPASS

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in collaboration with:

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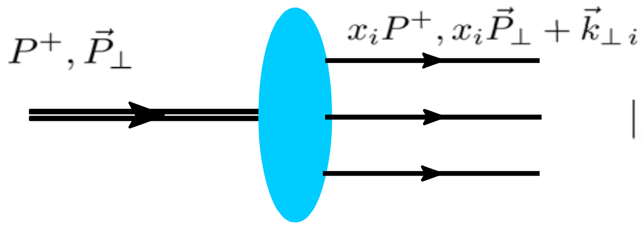
Outline

- Light-Cone Quark Model for proton and pion
- Pretzelosity in SIDIS: model predictions and experimental results
- Pretzelosity in Drell-Yan processes
- Conclusions

Light Cone Wave Function of the Proton



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

❖ 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

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

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

parity
time reversal
isospin symmetry

⟹ 6 independent wave function amplitudes

MODEL

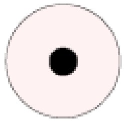
✓ momentum-space component: spherically symmetric

✓ light-front boost to convert the rest-frame spins of quarks in LF spins

✓ two parameters fitted to anomalous magnetic moments of proton and neutron

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

Light Cone Amplitudes Overlap Representation of TMDs

f_1 = 

Δ L$_z$=0

S→ S   P → P

$$f_1^q(x,k_\perp^2) \;=\; {}^{L_z=0}\langle P\uparrow|\sum_\lambda q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=0} + {}^{L_z=1}\langle P\uparrow|\sum_\lambda q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=1}$$

P → P   D → D

$$+\,{}^{L_z=-1}\langle P\uparrow|\sum_\lambda q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=-1} + {}^{L_z=2}\langle P\uparrow|\sum_\lambda q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=2}$$

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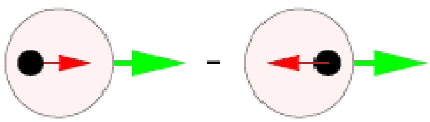
g_{1L} = 

Δ L$_z$=0

S→ S   P → P

$$g_{1L}^q(x,k_\perp^2) \;=\; {}^{L_z=0}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=0} + {}^{L_z=1}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=1}$$

P → P   D → D

$$+\,{}^{L_z=-1}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=-1} + {}^{L_z=2}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\,P\uparrow\rangle^{L_z=2}$$

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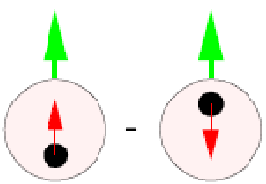
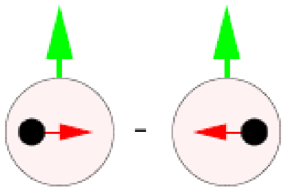
h_1 = 

Δ L$_z$=0

S→ S   P → P

$$h_1^q(x,k_\perp^2) \;=\; \mathrm{Re}[{}^{L_z=0}\langle P\downarrow|q_\downarrow^\dagger q_\uparrow|\,P\uparrow\rangle^{L_z=0}] + 2\mathrm{Re}[{}^{L_z=-1}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\,P\downarrow\rangle^{L_z=-1}]$$

$g_{1T} =$ 

$|\Delta L_z|=1$

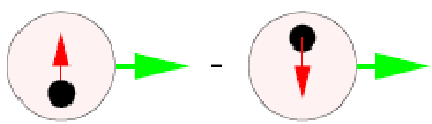
$$g_{1T}^q(x, k_\perp^2) =$$

P→ S   P→ S

$$\frac{2M}{k_\perp^2}\Big(k^x \mathrm{Re}[^{L_z=0}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\ P\downarrow\rangle^{L_z=-1}] + k^y \mathrm{Im}[^{L_z=0}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\ P\downarrow\rangle^{L_z=-1}]$$

P → D   P → D

$$+k^x \mathrm{Re}[^{L_z=-2}\langle P\downarrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\ P\uparrow\rangle^{L_z=-1}] + k^y \mathrm{Im}[^{L_z=-2}\langle P\downarrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|\ P\uparrow\rangle^{L_z=-1}]\Big)$$

$h_{1L}^\perp =$ 

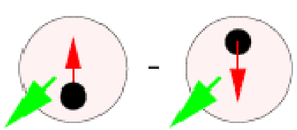
$|\Delta L_z|=1$

S→ P   S→ P

$$h_{1L}^{\perp q}(x, k_\perp^2) = \frac{2M}{k_\perp^2}\Big(\mathrm{Re}[^{L_z=1}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\ P\uparrow\rangle^{L_z=0}] - k^y \mathrm{Im}[^{L_z=1}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\ P\uparrow\rangle^{L_z=0}]$$

P → D   P → D

$$+k^x \mathrm{Re}[^{L_z=2}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\ P\uparrow\rangle^{L_z=1}] - k^y \mathrm{Im}[^{L_z=2}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\ P\uparrow\rangle^{L_z=1}]\Big)$$

$h_{1T}^\perp =$ 

$|\Delta L_z|=2$

P → P   D → S

$$h_{1T}^{\perp q}(x, k_\perp^2) = -\mathrm{Re}[^{L_z=1}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\ P\downarrow\rangle^{L_z=-1}] - 2\mathrm{Re}[^{L_z=0}\langle P\uparrow|q_\downarrow^\dagger q_\uparrow|\ P\downarrow\rangle^{L_z=-2}]$$

Collins SSA

gaussian Ansatz $\Longrightarrow$ $$A_{UT}^{\sin(\phi_h+\phi_S)}(x) = \frac{\sum_a e_a^2\, x\, h_1^a(x)\, \langle B_1\, H_1^{\perp(1/2)a}\rangle}{\sum_a e_a^2\, x\, f_1^a(x)\, \langle D_1^a\rangle}$$

- $h_1(x)$ from Light-Cone CQM evolved at Q^2=2.5 GeV^2, $f_1(x)$ from GRV at Q^2=2.5 GeV^2
- $H_1^{\perp(1/2)}$ from HERMES & BELLE data Efremov, Goeke, Schweitzer, PRD73 (2006); Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)
- $D_1(x)$ at Q^2=2.5 GeV^2 [Kretzer, PRD62, 2000]

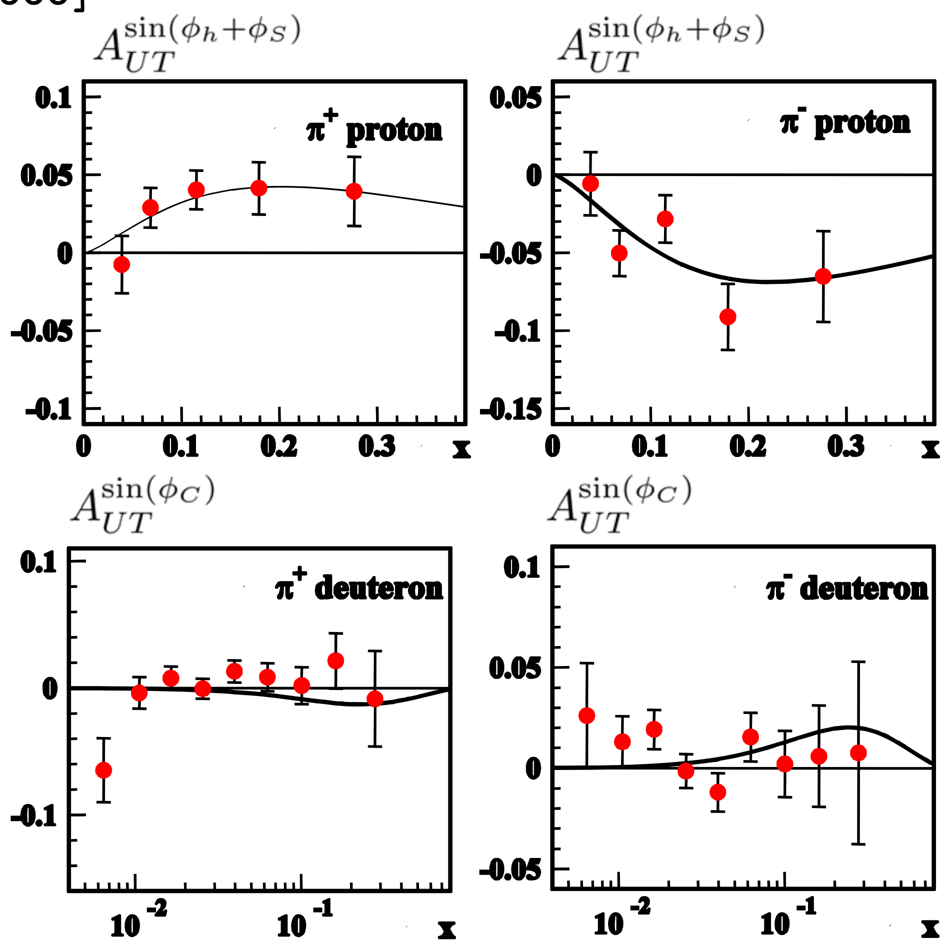
HERMES data:
Diefenthaler, hep-ex/0507013

More recent HERMES and BELLE data not included in the fit of Collins function

COMPASS data:
Alekseev et al,, PLB673, (2009)

$$\phi_C = \phi_h + \phi_S + \pi$$
$$A_{UT}^{\sin(\phi_C)} = -A_{UT}^{\sin(\phi_h+\phi_S)}$$

[Boffi, Efremov, Pasquini, Schweitzer, PRD79, 2009]



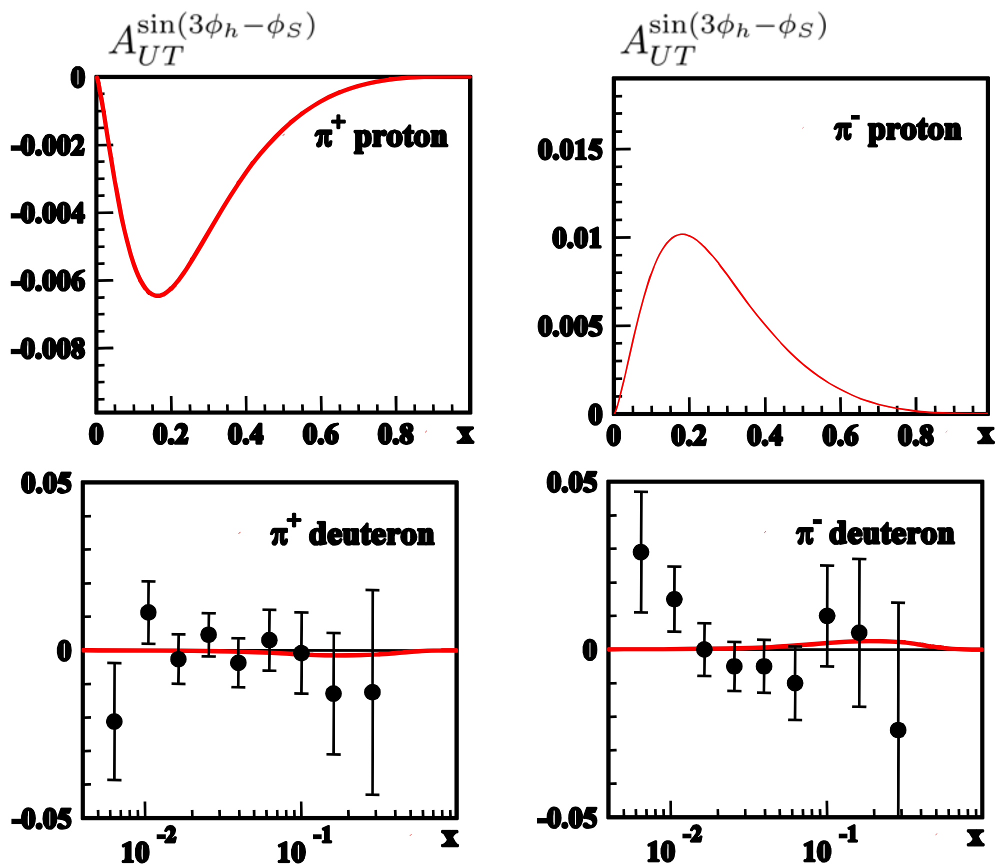
$A_{UT}^{\sin(3\phi_h-\phi_S)}$

gaussian Ansatz $\Longrightarrow$ $A_{UT}^{\sin(3\phi_h-\phi_S)} = -\dfrac{\sum_a e_a^2\, x\, h_{1T}^{\perp(1)\,a}(x)\,\langle B_3 H_1^{\perp(1/2)a}\rangle}{\sum_a e_a^2\, x\, f_1^a(x)\,\langle D_1^a\rangle}$

- $h_{1T}^{\perp(1)}$ from Light-Cone CQM evolved at Q^2=2.5 GeV^2, with the evolution equations of $h_1(x)$
- $f_1(x)$ from GRV at Q^2=2.5 GeV^2
- $H_1^{\perp\,(1/2)}$ from HERMES & BELLE data Efremov, Goeke, Schweitzer, PRD73 (2006); Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)

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

COMPASS Coll.
Kotzinian, arXiv:0705.2402



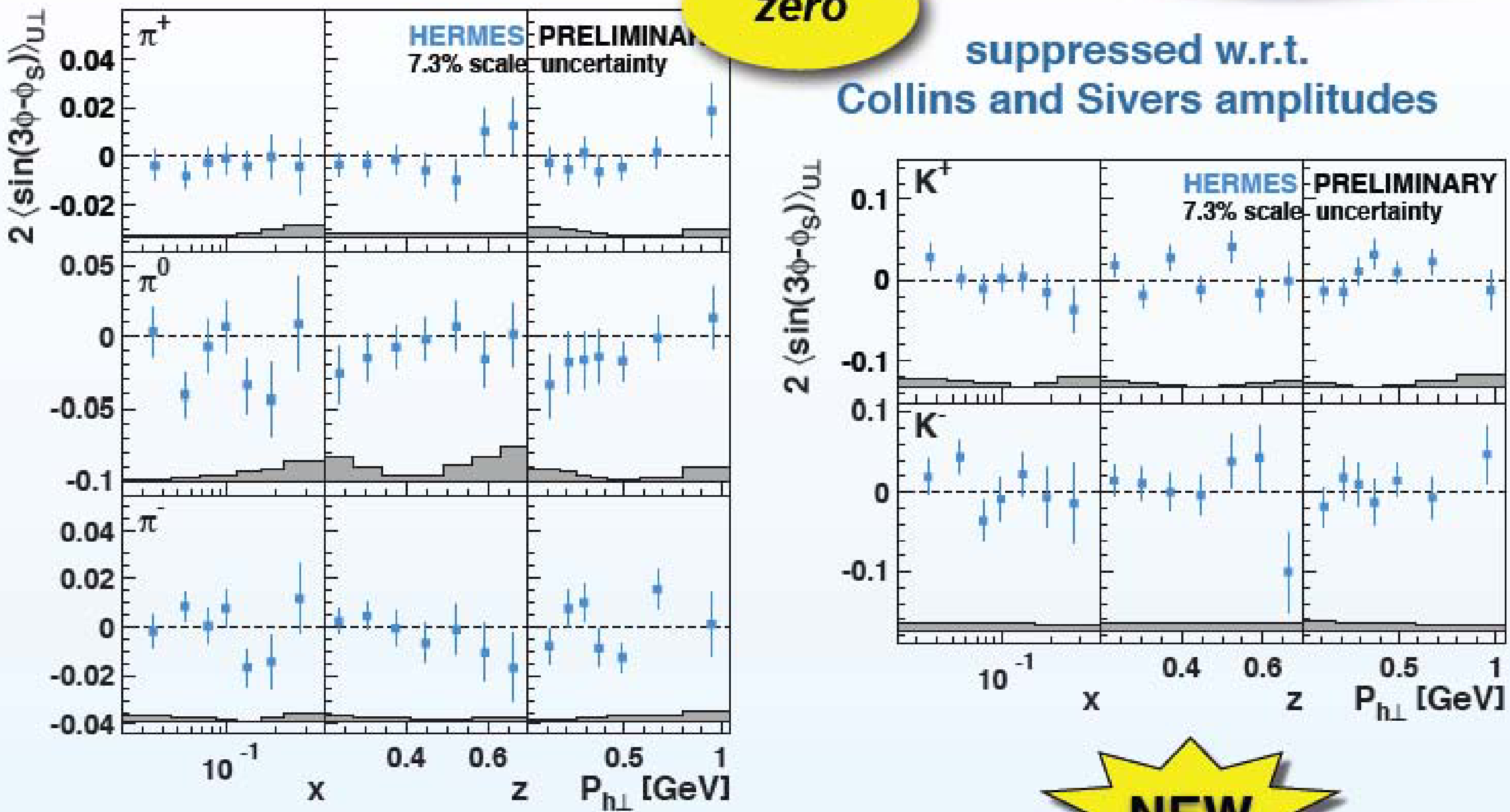
[Boffi, Efremov, Pasquini, Schweitzer, PRD79, 2009]

❹ The $\langle \sin(3\phi - \phi_S) \rangle_{U\perp}$ Fourier component:

sensitive to pretzelosity!

zero

suppressed w.r.t. Collins and Sivers amplitudes



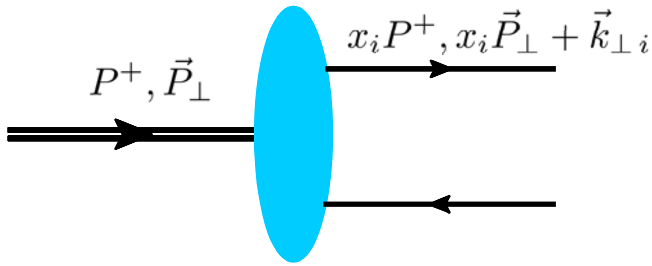
NEW

M. Diefenthaler, EINN 2009

workshop "Partonic transverse momentum distributions" at EINN 2009, September 28th 2009 – p.31/32

Talk of N. Makins, Duke p_T workshop, Durham, March 12-13 2010

Light Cone Wave Function of the Pion



$$| P, \pi \rangle = \sum_\beta \int \mathrm{d}[1]\mathrm{d}[2]\; \Psi^f_{\pi\,\beta}(x_i, \vec{k}_{\perp,i})\, \frac{\delta^{ij}}{\sqrt{3}}\, u^\dagger_{i\lambda_1}(1) \bar{u}^\dagger_{j\lambda_2}(2) | 0 \rangle$$

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

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

parity
time reversal
isospin symmetry

⇒ **2 independent wave function amplitudes**

MODEL

- ✓ momentum-space component: spherically symmetric ⇒ gaussian shape
- ✓ Light-front boost to convert the rest-frame spins of quark and antiquark in LF spins
- ✓ m_q and gaussian width fitted to exp. charge radius and pion decay constant
- ✓ Boer-Mulders function of the pion in one-gluon exchange approximation generated from S-P wave interference

[Efremov, Pasquini, Schweitzer, Yuan, in preparation]

The BM-Pretzelosity Asymmetry in π p Drell Yan

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

ϕ = lepton angle in the CS frame

ϕ_p = proton spin angle in the CM frame

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

$$w(\vec{k}_{Tp},\vec{k}_{T\pi}) = \frac{2(\vec{h}\cdot\vec{k}_{Tp})(2(\vec{h}\cdot\vec{k}_{Tp})(\vec{h}\cdot\vec{k}_{T\pi}) - \vec{k}_{Tp}^2(\vec{h}\cdot\vec{k}_{T\pi})}{2M_p^2 m_\pi} \quad \text{with} \quad \vec{h} = \frac{\vec{q}_T}{q_T}$$

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

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

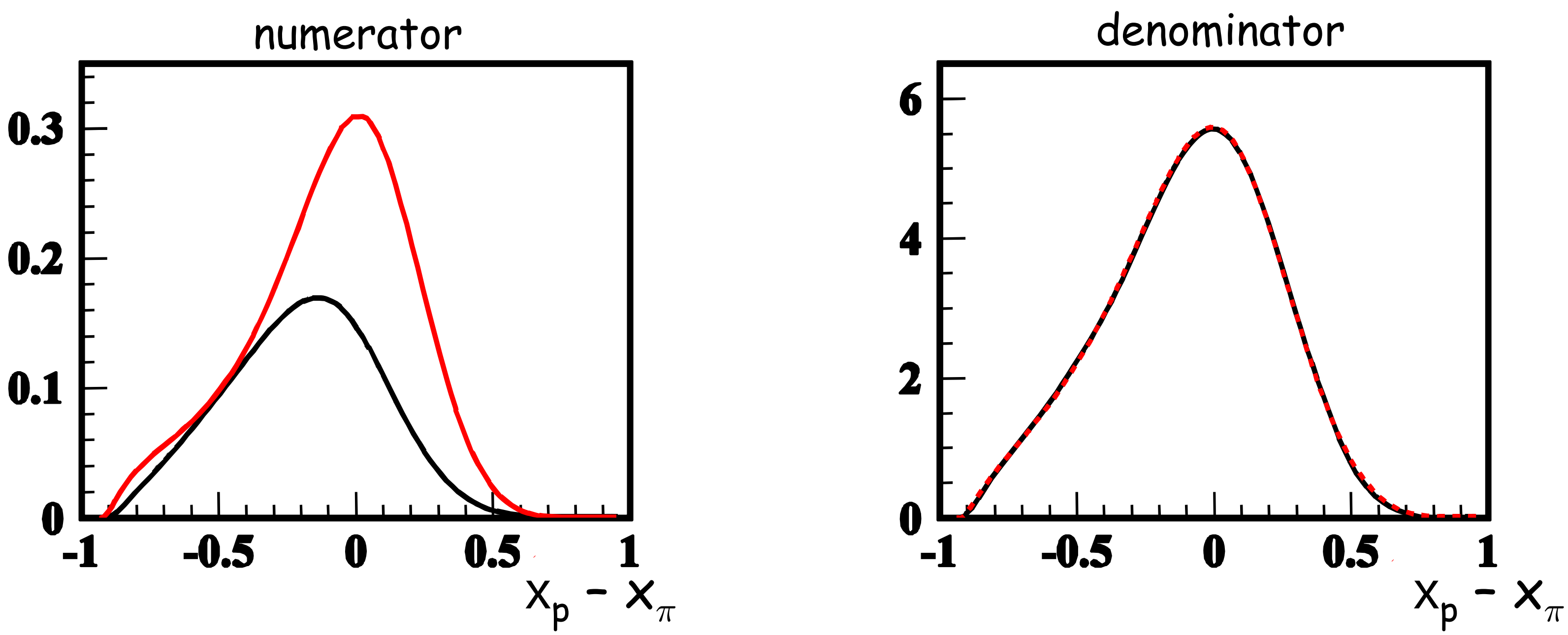
Boer, PRD60 (1999): BM-pretzelosity defined with a different angular distribution

$$A_{TU}^{\sin(3\phi-\phi_S)}$$

ϕ = lepton angle in the CS frame

ϕ_S = proton spin angle in the CS frame

Gaussian Ansatz



COMPASS kinematics: $x_p\, x_\pi = Q^2/s$ with $Q^2 = 20$ GeV^2 and $s = 400$ GeV^2

convolution integral solved exactly, through numerical integration

Gaussian Ansatz

$$F_{TU}^{\sin(2\phi+\phi_p)} = B_{\text{Gauss}} e_u^2\, h_{1T}^{\perp\,(1/2)\,u/p}(x_p)\, h_1^{\perp\,(1)\,\bar{u}/\pi^-}(x_\pi) \qquad F_{UU}^1 = e_u^2\, f_1^{u/p}(x_p) f_1^{\bar{u}/\pi^-}(x_\pi)$$

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

Scale dependence

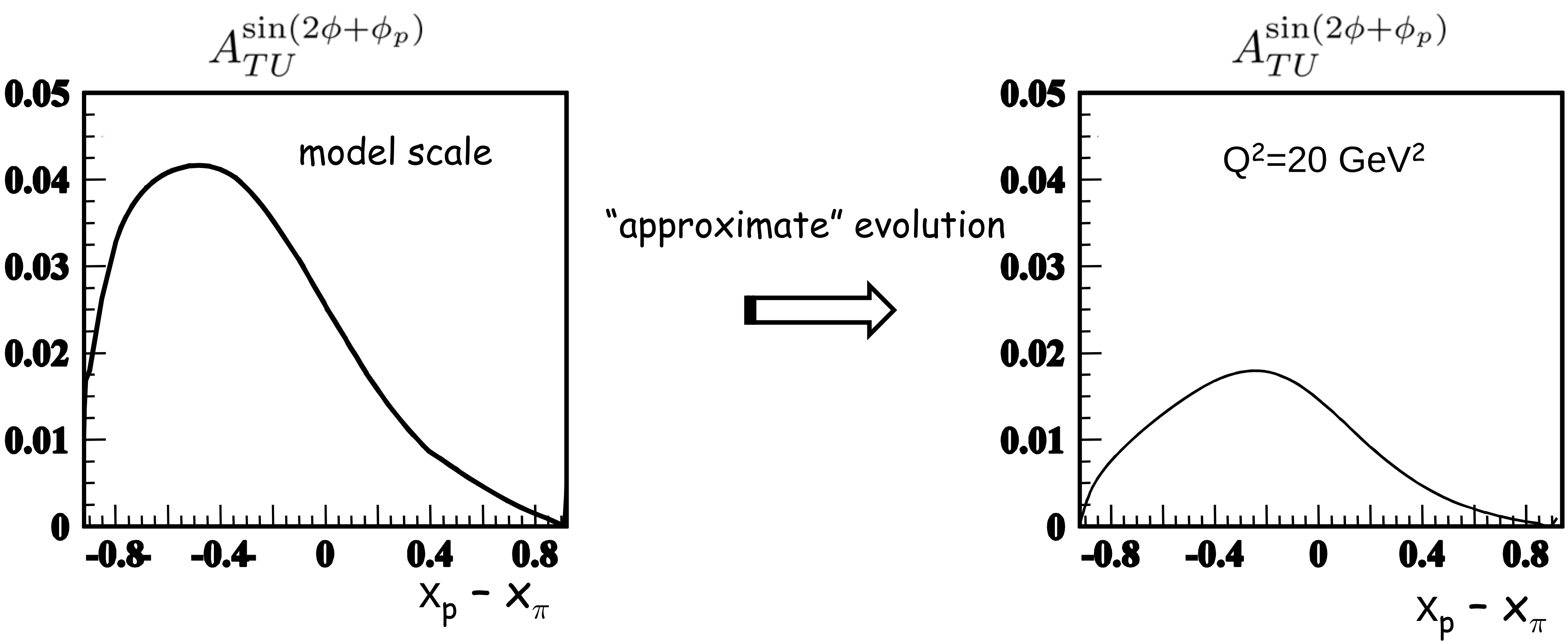
❖ At the hadronic scale μ_0 of the model the valence quarks carry all the momentum of the hadrons $\rightarrow$ $\langle x\,(\mu_0^2)\rangle_V = 1$

❖ To fix the scale μ_0 we evolve back the experimental value of $\langle x(Q^2)\rangle_V$ at large Q^2 until we match the condition $\langle x\,(\mu_0^2)\rangle_V = 1$

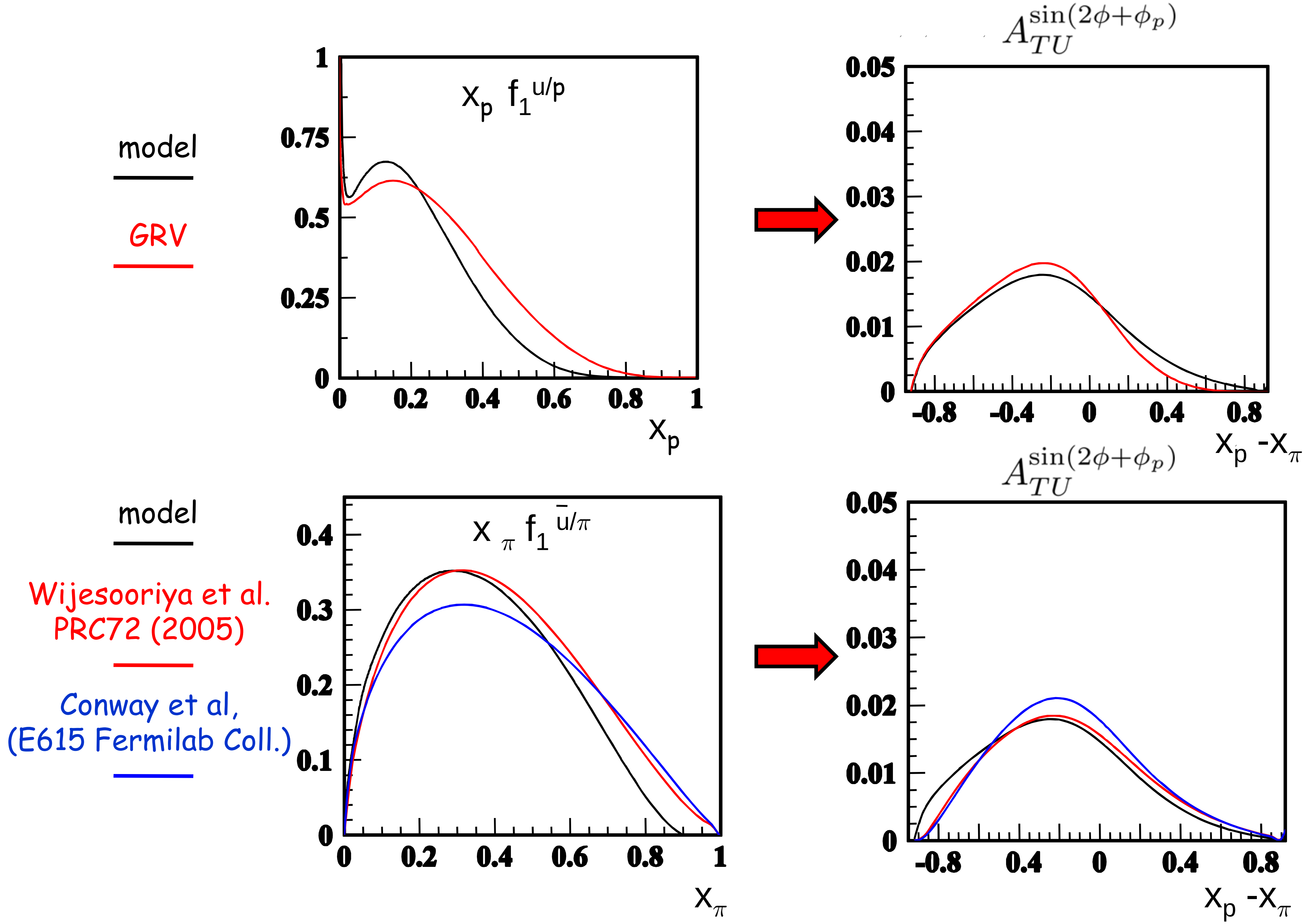
Proton: μ_0 =307 MeV

Pion: μ_0 =335 MeV

❖ Evolutions equations for $h_{1T}^{\perp}$ and $h_1^{\perp}$ are not yet known $\rightarrow$ we include "approximate" evolution effects using the evolution equations of the transversity



Model dependence from f_1^p and f_1^π



Summary

❖ Pretzelosity from SIDIS:

preliminary results from COMPASS and HERMES

data consistent with zero, in agreement with our model predictions

demanding to learn anything about $h^{\perp}_{1T}$ from SIDIS

❖ Pretzelosity from Drell-Yan:

model results are encouraging!

asymmetry of the order of 2% at large negative $x_F = x_p - x_\pi$ where the Gaussian Ansatz works better within the model

small model dependence from f_1^p and f_1^π

to improve the study of the effects of the evolution