Transverse Spin effects in SIDIS

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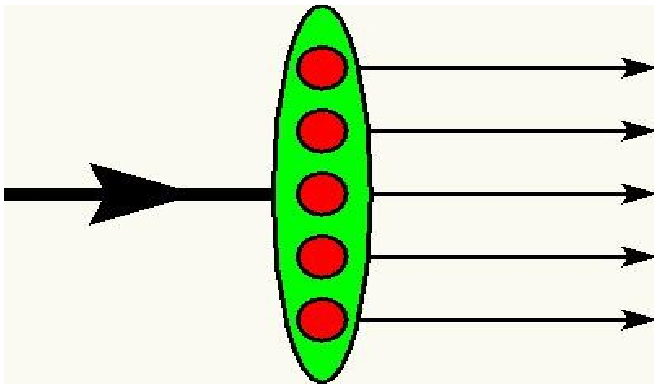
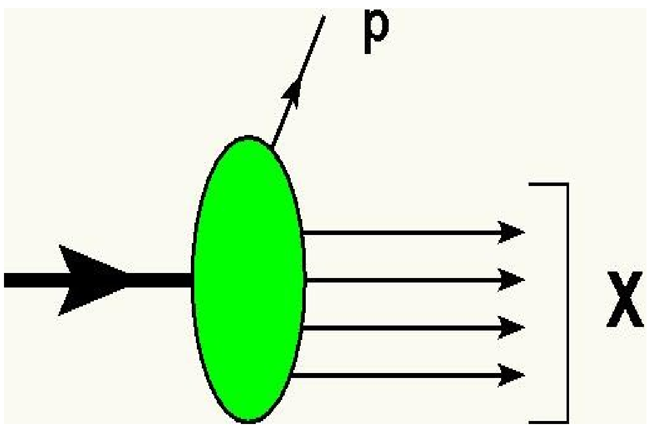
- Transverse Momentum Dependent PDFs
- Transverse spin effects
- Sivers effect $\Longrightarrow$ Kaon SSA

How to build a parton distribution?



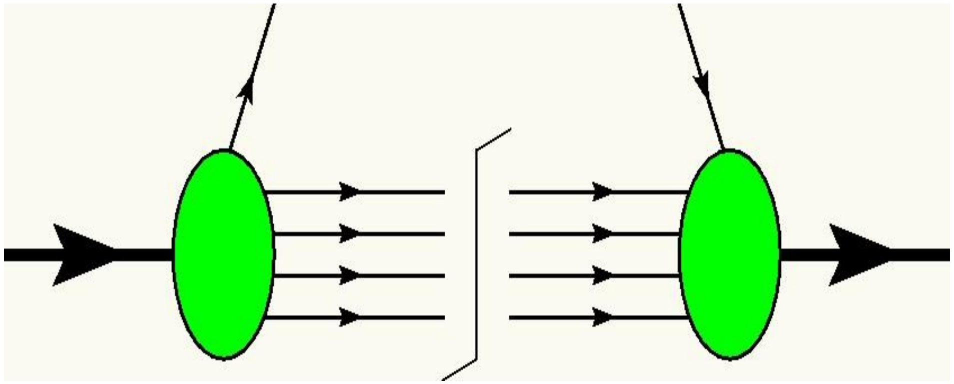
Nucleon as a "pancake":
Partons are "quasi-free"



Amplitude:

$$(2\pi)^4 \delta^{(4)}(p - P + P_X) \langle X \,|\, \psi_i(0) \,|\, P, S \rangle$$

Parton Correlations



"Probability"
= "squared amplitude"

$$\sum_X \left| \langle X \,|\, \psi_i(0) \,|\, P, s \rangle \right|^2 \quad \propto \langle P, S \,|\, \bar{\psi} \sum_X |X\rangle\langle X| \, \psi \,|\, P, S \rangle$$

Fully unintegrated quark correlation

$$\Phi_{ij}(k, P, S) = \int \frac{d^4 z}{(2\pi)^4}\, e^{ik\cdot z} \langle P, S \,|\, \bar{\psi}_j(0)\, \psi_i(z) \,|\, P, S \rangle$$

→ ordinary PDFs, k_T-dependent PDFs,
Parton Correlation Functions

ordinary PDFs

unpolarized distribution:

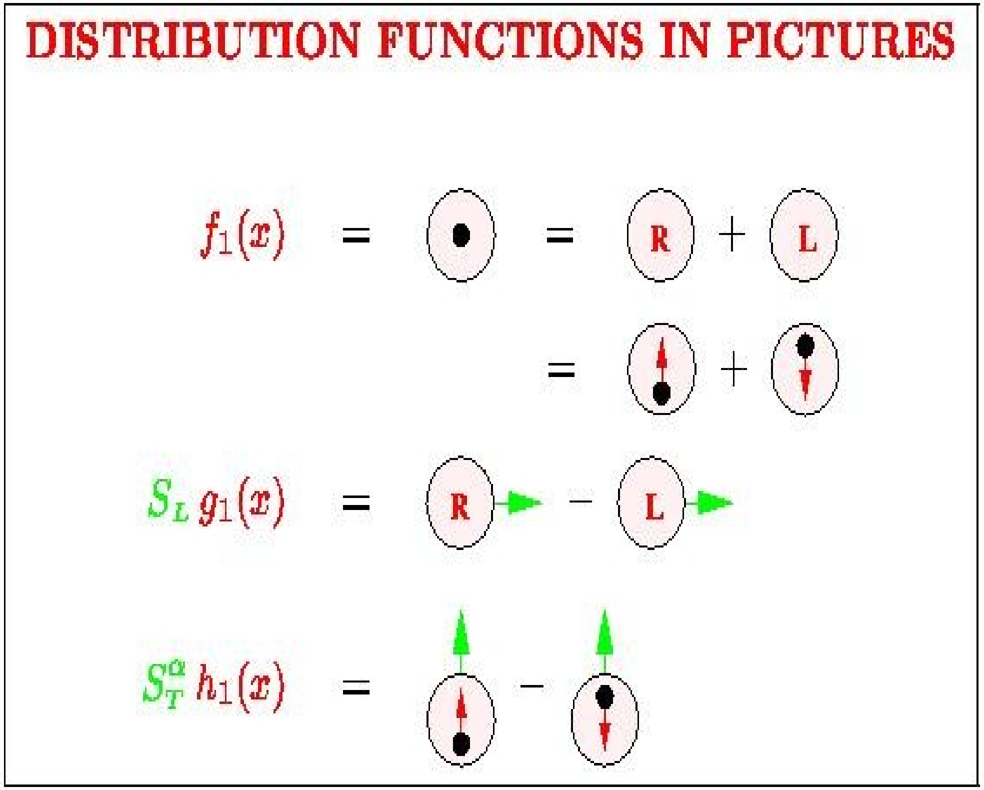
$$\Phi^{[\gamma^+]}(x) = f_1(x)$$

helicity distribution:

$$\Phi^{[\gamma^+\gamma_5]}(x) = S_L\, g_1(x)$$

transversity distribution:

$$\Phi^{[i\sigma^{i+}\gamma_5]}(x) = S_T^i\, h_1(x)$$



Transversity *chirally-odd* → ~~incl. DIS~~

Transverse Momentum Dependent PDFs

unpolarized quarks → Two functions

$$\Phi^{[\gamma^+]}(x,\vec{k}_T) = f_1(x,\vec{k}_T^2) + \frac{\vec{k}_T\times\vec{S}_T}{M} f_{1T}^{\perp}(x,\vec{k}_T^2)$$

longitudinally polarized quarks → Two functions

$$\Phi^{[\gamma^+\gamma_5]}(x,\vec{k}_T) = S_L g_{1L}(x,\vec{k}_T^2) + \frac{\vec{k}_T\cdot\vec{S}_T}{M} g_{1T}(x,\vec{k}_T^2)$$

transversely polarized quarks → Four functions

$$\Phi^{[i\sigma^{i+}\gamma_5]}(x,\vec{k}_T) = S_T^i h_1(x,\vec{k}_T^2) + S_L \frac{k_T^i}{M} h_{1L}^{\perp}(x,\vec{k}_T^2)$$

$$+ \frac{k_T^i(\vec{k}_T\cdot\vec{S}_T) - \frac{1}{2}\vec{k}_T^2\, S_T^i}{M} h_{1T}^{\perp}(x,\vec{k}_T^2) + \frac{\epsilon_T^{ij} k_T^j}{M} h_1^{\perp}(x,\vec{k}_T^2)$$

T-odd TMDs

Time reversal forbids → Sivers function $f_{1T}^{\perp}$

→ Boer-Mulders function $h_1^{\perp}$

unless...

T-odd TMDs

Time reversal forbids

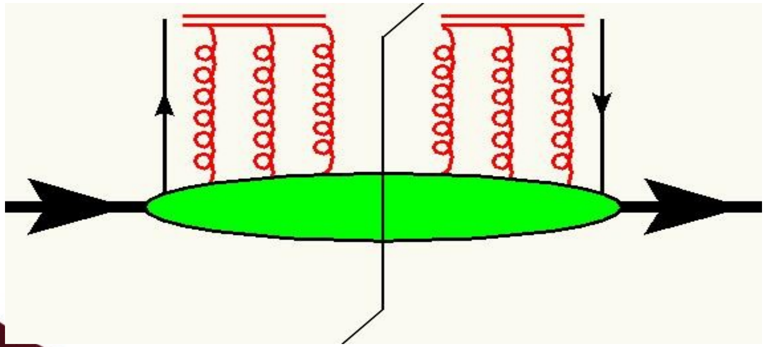
- Sivers function $f_{1T}^{\perp}$
- Boer-Mulders function $h_1^{\perp}$

unless...

Wilson line

$$\langle P, S \,|\, \bar{\psi}_j(0) \quad \mathcal{W}[0, z|\text{path}] \quad \psi_i(z) \,|\, P, S \rangle$$

encodes **Initial / Final state interactions**



Time reversal → switches sign:

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$$

$$h_1^{\perp}\Big|_{DIS} = -h_1^{\perp}\Big|_{DY}$$

DISTRIBUTION FUNCTIONS IN PICTURES

$$f_1(x, p_T^2) =$$

$$\frac{\boldsymbol{p}_T \times \boldsymbol{S}_T}{M}\, f_{1T}^{\perp}(x, p_T^2) =$$

$$S_L\, g_{1L}(x, p_T^2) =$$

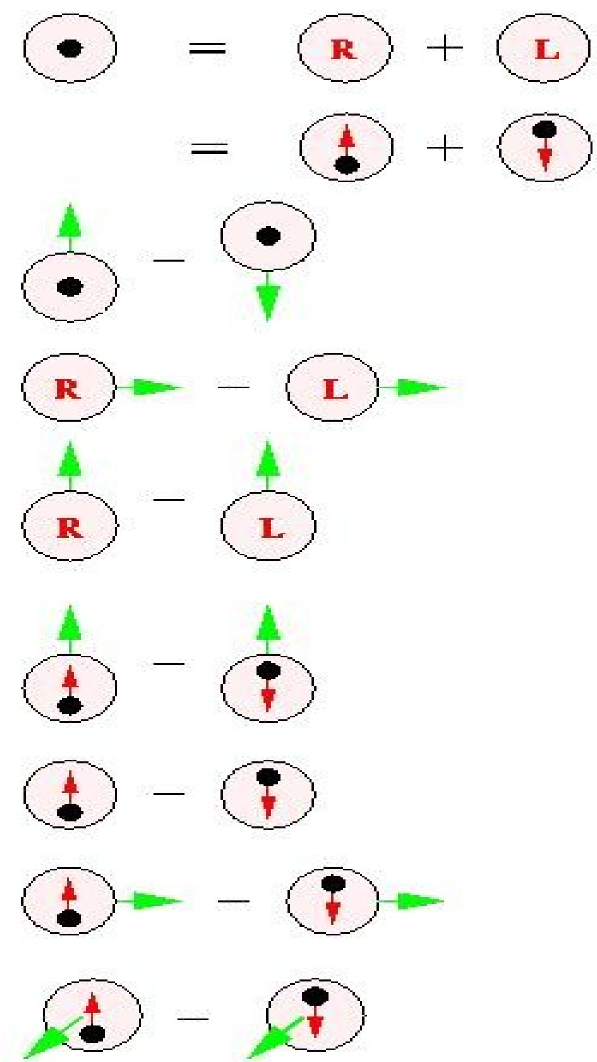
$$\frac{\boldsymbol{p}_T \cdot \boldsymbol{S}_T}{M}\, g_{1T}(x, p_T^2) =$$

$$S_T^{\alpha}\, h_{1T}(x, p_T^2) =$$

$$i\, \frac{p_T^{\alpha}}{M}\, h_1^{\perp}(x, p_T^2) =$$

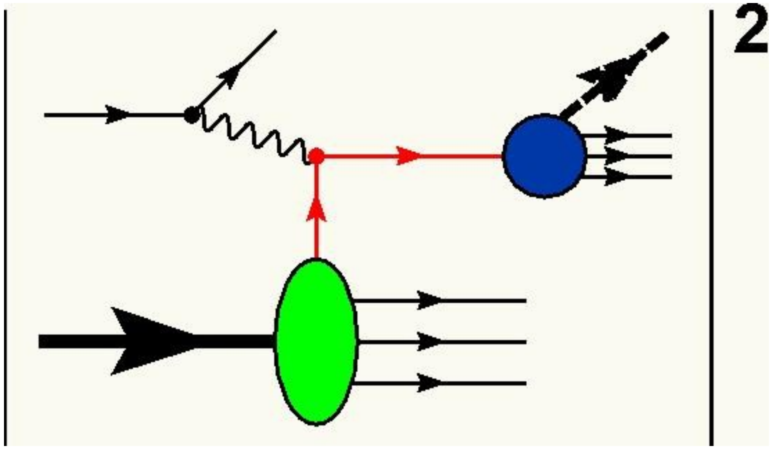
$$S_L\, \frac{p_T^{\alpha}}{M}\, h_{1L}^{\perp}(x, p_T^2) =$$

$$\frac{\boldsymbol{p}_T \cdot \boldsymbol{S}_T}{M}\, \frac{p_T^{\alpha}}{M}\, h_{1T}^{\perp}(x, p_T^2) =$$

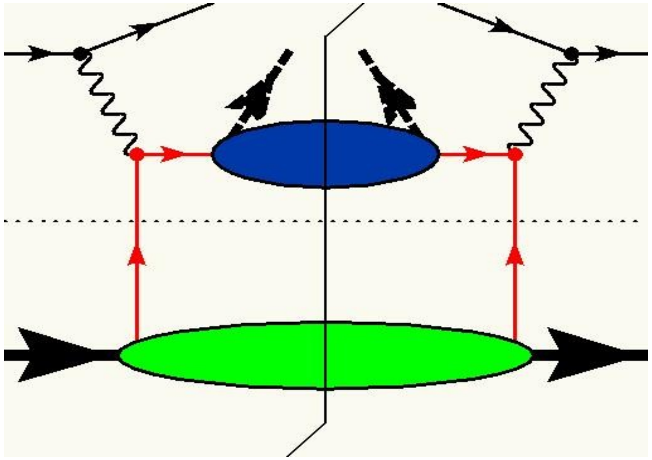


Semi-inclusive DIS

Plugging the TMDs into a physical process: SIDIS



$\propto$



Structure functions = k_T-convolutions of PDFs and FFs

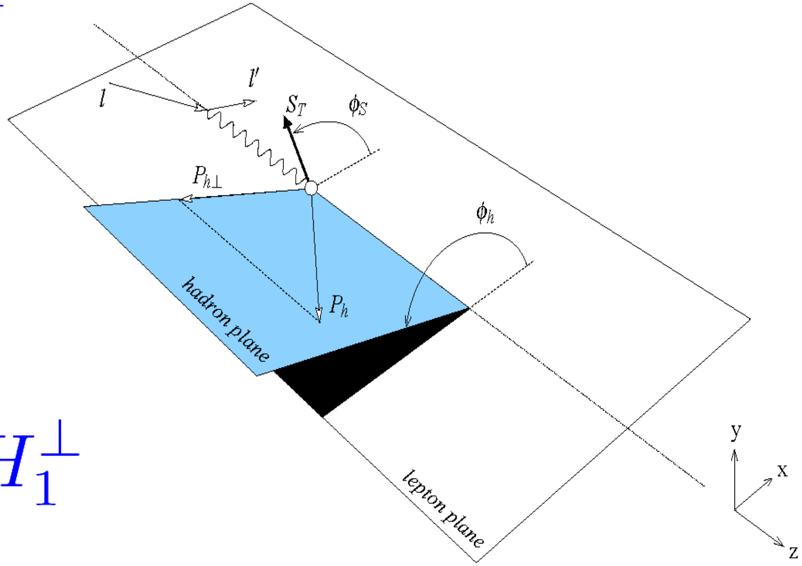
$$\sum_{a=q,\bar{q}} e_a^2 \int d^2k_T d^2p_T\, \delta^{(2)}(\vec{k}_T - \vec{p}_T - \vec{P}_{h\perp}/z_h)\, w(\vec{k}_T, \vec{p}_T) f^a(x_B, \vec{k}_T^2)\, D(z_h, \vec{p}_T^2)$$

$$\equiv f \otimes D$$

Transverse Observables in SIDIS

1.) Sivers asymmetry:

$$\sigma_{UT}^{\text{SIDIS}} \propto \sin(\phi_h - \phi_S) f_{1T}^{\perp} \otimes D_1$$



2.) Collins asymmetry:

$$\sigma_{UT}^{\text{SIDIS}} \propto \sin(\phi_h + \phi_S) h_1 \otimes H_1^{\perp}$$

3.) "pretzelosity":

$$\sigma_{UT}^{\text{SIDIS}} \propto \sin(3\phi_h - \phi_S) h_{1T}^{\perp} \otimes H_1^{\perp}$$

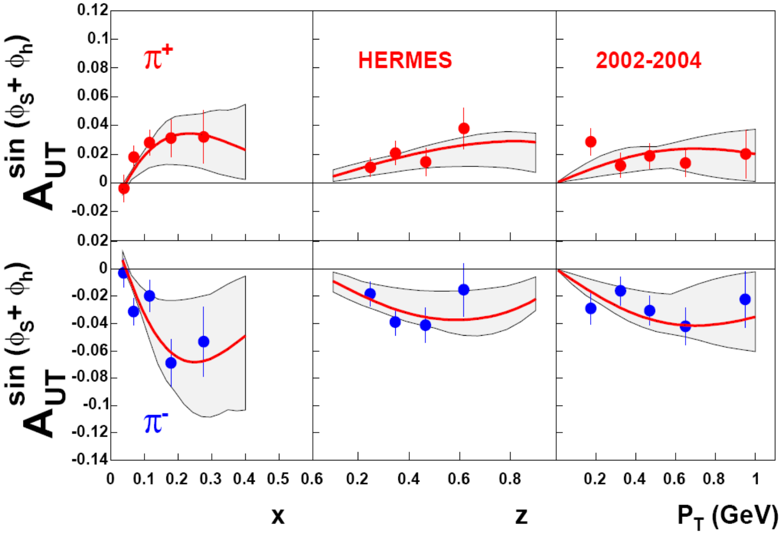
4.) double spin asymmetry:

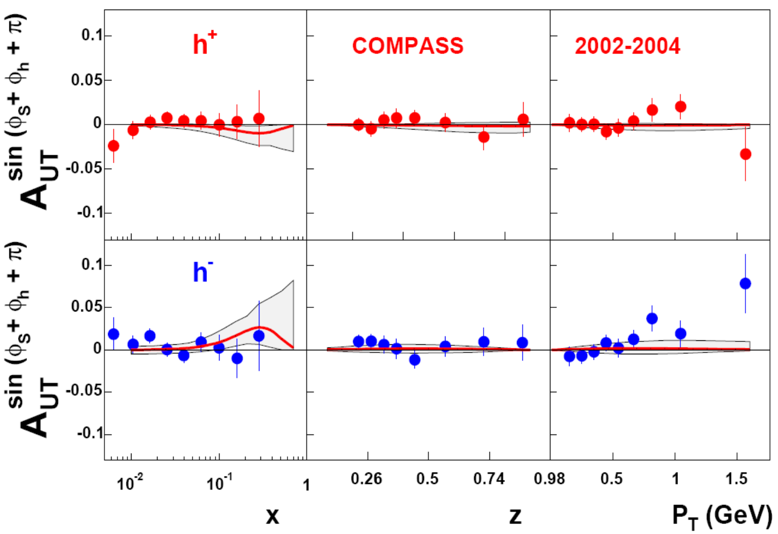
$$\sigma_{LT}^{\text{SIDIS}} \propto \sin(\phi_h - \phi_S) g_{1T} \otimes D_1$$

also: $\cos(2\phi) \propto h_1^{\perp} \otimes H_1^{\perp}$, beam-SSA $\sin(2\phi_h)\, h_{1L}^{\perp} \otimes H_1^{\perp}$

double spin (LL): $\cos(\phi_h)\, g_{1L} \otimes D_1$

Collins Asym. at HERMES/COMPASS



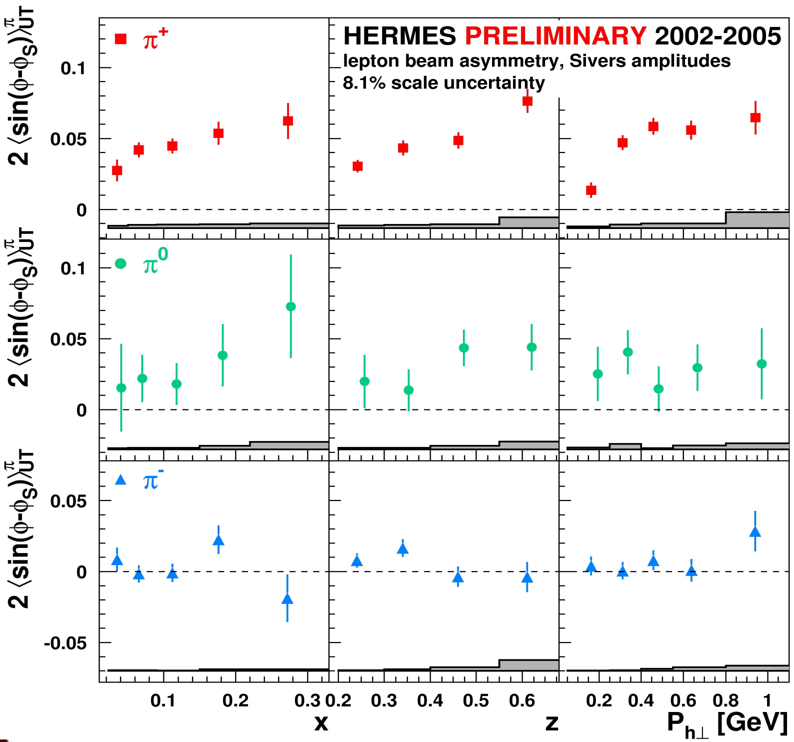


HERMES Coll, hep-ex/0507013

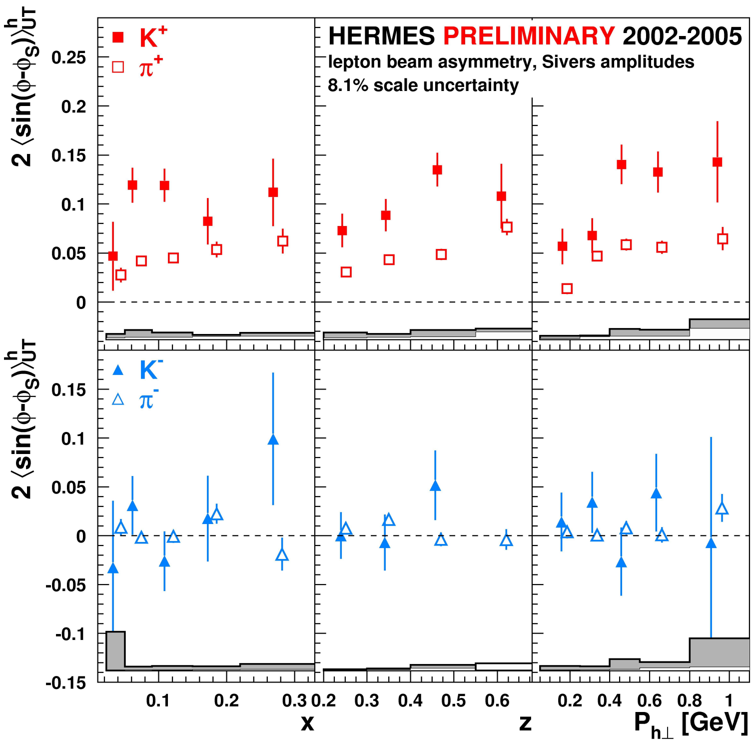
COMPASS Coll, hep-ex/0610068

Sivers Asymmetry at HERMES

Pions



Kaons



0706.2242[hep-ex]

Extraction of Transversity

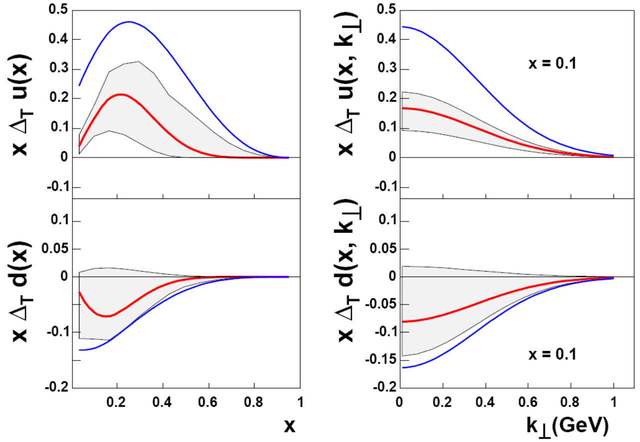
Anselmino et al., PRD75, 054032

Deconvolution of k_T-dependence: $h_1 \otimes H_1^\perp$

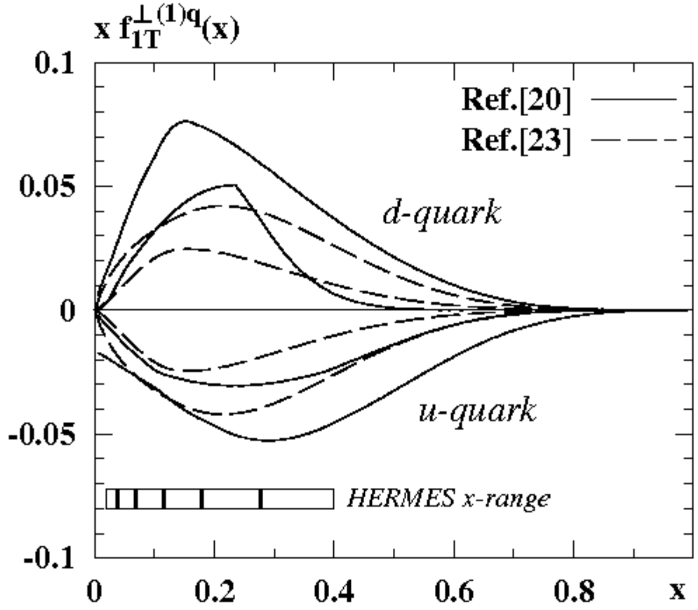
Gaussian ansatz: $h_1(x, \vec{k}_T^2) = h_1(x) \frac{\exp(-\vec{k}_T^2/\langle \vec{k}_T^2 \rangle)}{\pi \langle \vec{k}_T^2 \rangle}$ Collins-FF analog

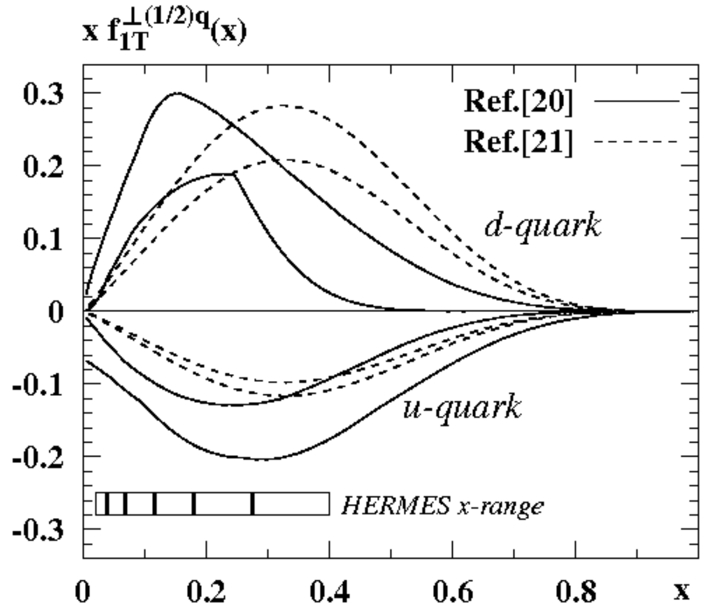
→ Extraction of the pion Collins function from BELLE data in e^+e^--annihilation

→ Extraction of transversity $h_1(x)$ for u- and d-quarks



Extractions of the Sivers function





Anselmino et al., hep-ph/0511017

[20] Anselmino et al., PRD72 (05)

[21] Vogelsang, Yuan, PRD72 (05)

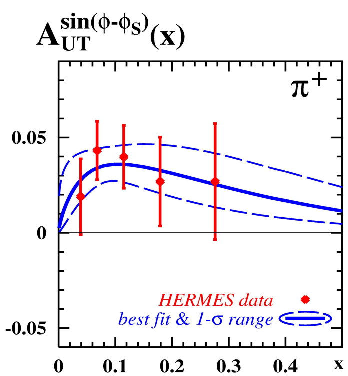
[23] Collins et al., hep-ph/0510342

on behalf of
A. Efremov, K. Goeke, P. Schweitzer
based on Phys.Rev.D73(014021), Phys.Rev.D73(094023), Czech.J.Phys.56(F181), 0801.2238[hep-ph]

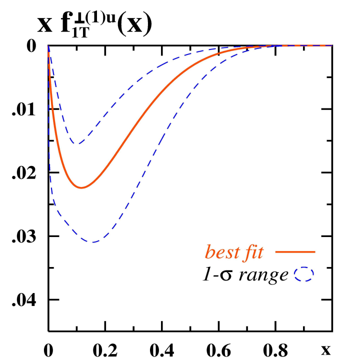
Sivers SSA for Pions:

again Gaussian ansatz: $$f_{1T}^{\perp}(x,\vec{k}_T^2) = f_{1T}^{\perp}(x)\frac{\exp(-\vec{k}_T^2/\langle\vec{k}_T^2\rangle)}{\pi\langle\vec{k}_T^2\rangle}$$

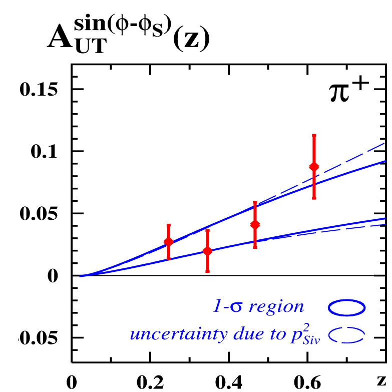
Fit to π^+ HERMES data: $x f_{1T}^{\perp(1)}(x)^u = -x f_{1T}^{\perp(1)}(x)^d = A x^b (1-x)^5 = -0.18 x^{0.66}(1-x)^5$



1. Input (Fit)



2. Sivers function



3. Cross check

including Large-N_c prediction: $$f_{1T}^{\perp u} = -f_{1T}^{\perp d}$$

in agreement with other fit, Anselmino et al., Vogelsang&Yuan

neglect strange and antiquarks. Reasonable?

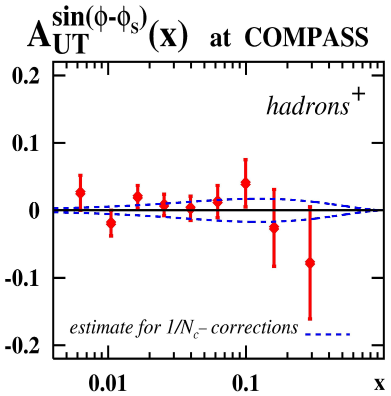
Testing the fit

1.) Sivers SSA on a deuteron at COMPASS:

1/N_c corrections (estimate):

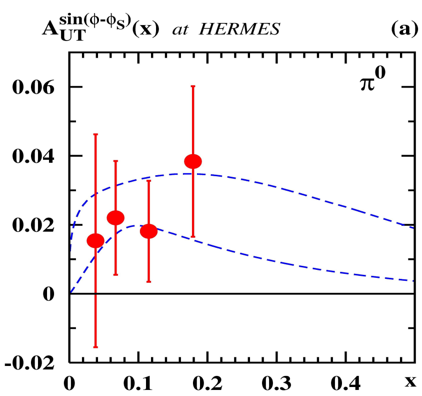
$$\left|\left(f_{1T}^{\perp(1)u} + f_{1T}^{\perp(1)d}\right)(x)\right| = \pm\frac{1}{N_c}\left(f_{1T}^{\perp(1)u} - f_{1T}^{\perp(1)d}\right)(x)$$

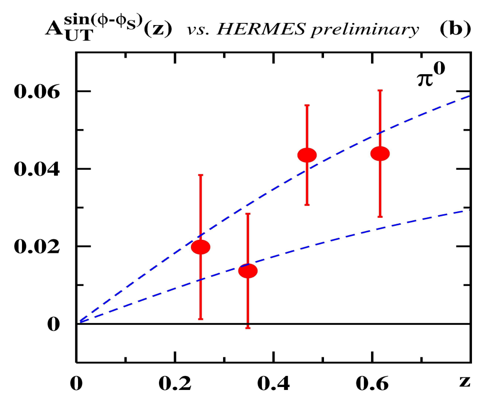
estimate compatible with data



OK

2.) π^0-Sivers SSA at HERMES:





OK

z-dependence of SSA: test for Gaussian ansatz!

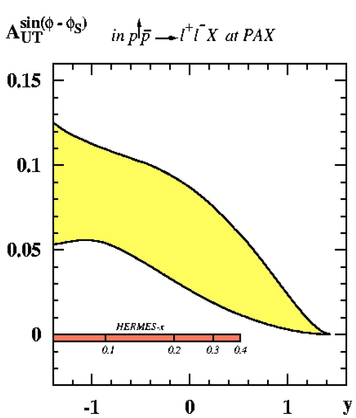
Sivers effect in Drell-Yan

QCD-prediction (Collins2002): $f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$

- sign change can be tested in $h_1^{\uparrow}+h_2 \longrightarrow l^{+}+l^{-}+X$

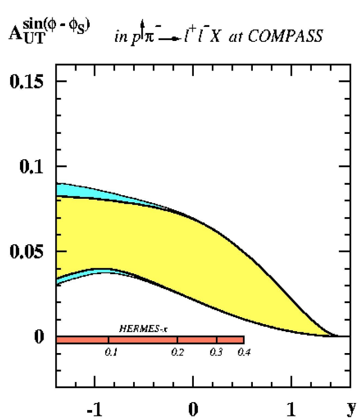
Transverse Asymmetry in DY: $SSA_{UT}^{DY} \propto \sin(\phi-\phi_s)\dfrac{\sum_a e_a^2 f_{1T}^{\perp a}(x_1)\Big|_{DY} f_1^{\bar{a}}(x_2)}{\sum_a f_1^a(x_1) f_1^{\bar{a}}(x_2)}$

<u>Experiments</u>:



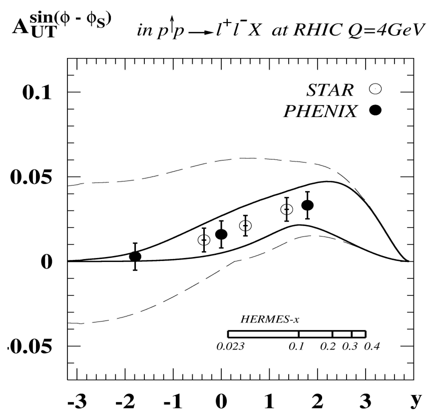
PAX at GSI:

$p^{\uparrow}\bar{p} \longrightarrow l^{+}l^{-}X$



COMPASS:

$p^{\uparrow}\pi^{-} \longrightarrow l^{+}l^{-}X$



RHIC:

$p^{\uparrow}p \longrightarrow l^{+}l^{-}X$

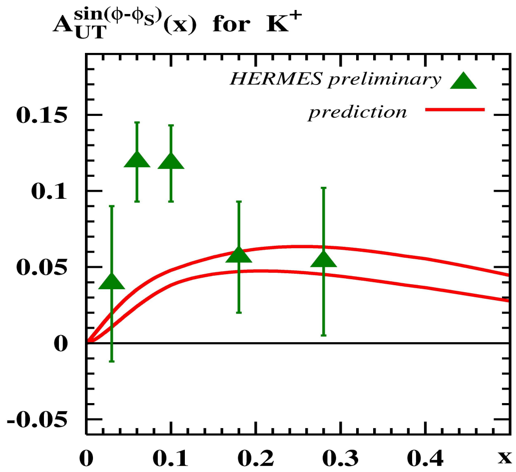
Kaon Sivers effect at HERMES

Difference between π$^+$ and K$^+$: $\bar{d} \leftrightarrow \bar{s}$ "sea-quark effect"

Differences in FF $D_1(z)$ for π$^+$ and K$^+$ and quark masses cancel in ratio!

Expectation: Kaon-SSA $\simeq$ Pion-SSA

But:



red solid line: prediction (Efremov, Goeke, Schweitzer)
data points: prelim. HERMES (Diefenthaler et al.)

x>0.2: "sea-quark" effect small

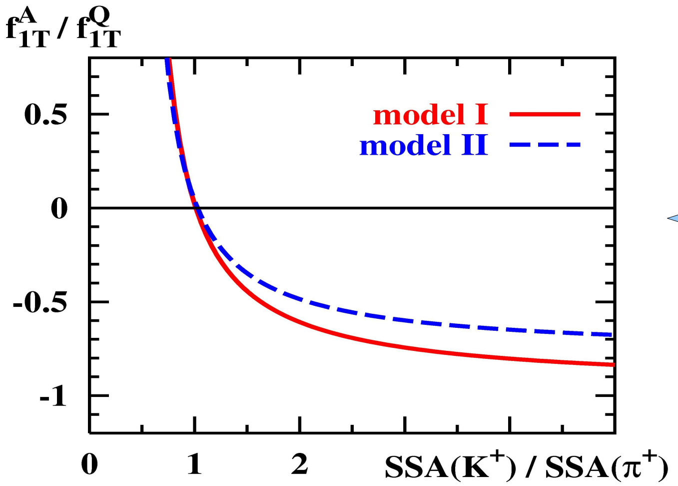
x≈0.15: Kaon-SSA≈2 × Pion-SSA

How large can the effect of anti/strange quarks be?

Estimates of sea-quark Sivers function:

Model I: Valence: $f_{1T}^{\perp Q} \equiv f_{1T}^{\perp u} \sim -f_{1T}^{\perp d}$ Sea: $f_{1T}^{\perp A} \equiv f_{1T}^{\perp \bar{u}} \sim f_{1T}^{\perp \bar{d}} \sim f_{1T}^{\perp s} \sim -f_{1T}^{\perp \bar{s}}$

Model II: Valence: $f_{1T}^{\perp Q} \equiv f_{1T}^{\perp u} \sim -2f_{1T}^{\perp d}$ Sea: $f_{1T}^{\perp A} \equiv f_{1T}^{\perp \bar{u}} \sim f_{1T}^{\perp \bar{d}} \sim f_{1T}^{\perp s} \sim -f_{1T}^{\perp \bar{s}}$



Express ratio SSA(K$^+$)/SSA(π^+) in terms of $f_{1T}^{\perp A} / f_{1T}^{\perp Q}$

Kaon-SSA understandable if:

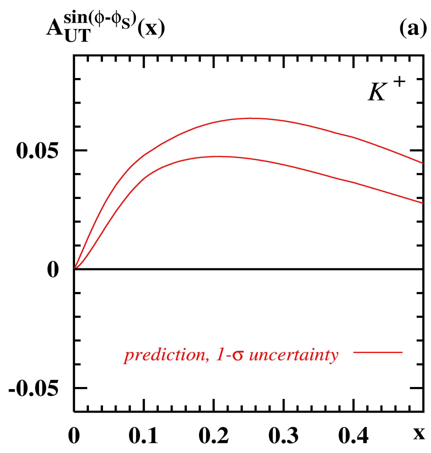
$$|f_{1T}^{\perp sea}| \sim \frac{1}{2} |f_{1T}^{\perp val.}|$$

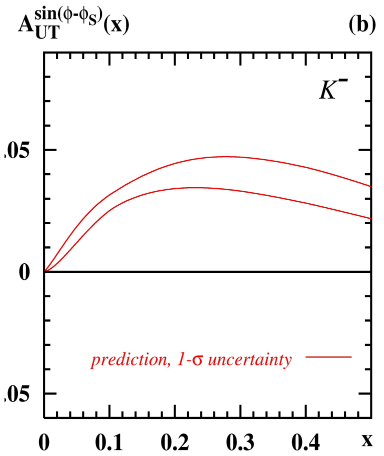
Kaon Sivers SSA at CLAS12

present situation: open questions about the Sivers effect remain.

new and *precise* data for Pions *and* Kaons is needed,
preferably at larger x (complementary to HERMES)

Predictions for CLAS (on the basis of HERMES data) (P. Schweitzer):





π/K measurements at CLAS will provide a more detailed knowledge about the Sivers effect.

Summary

- 8 leading twist observables in SIDIS, 8 leading TMDs

- Transverse spin $\Longrightarrow$ Sivers/Collins effect (but also others...)

- Collins effect: first extraction of transversity distribution.

- Sivers effect: first insight from Pion data (HERMES, COMPASS)
  new insight from Kaon data $\Longrightarrow$ anti/strange-quarks?

- data on Pion and Kaon SSA from CLAS12 will help to clarify the situation and solidify the understanding of the Sivers/Collins effect in SIDIS.

- on the basis of solid SIDIS understanding $\longrightarrow$ DY at RHIC, COMPASS, PAX $\longrightarrow$ test sign change of the Sivers function.

Quark Polarization

Projection of different quark spin polarizations:

$$\Phi^{[\gamma^+]} \propto \langle P, S \,|\, \bar{\psi}\, \gamma^+ \psi \,|\, P, S \rangle \quad \Longrightarrow \quad \bar{u}(k,s)\, \gamma^+ \, u(k,s) \;=\; 2k^+$$

No Polarization

$$\Phi^{[\gamma^+\gamma_5]} \propto \langle P, S \,|\, \bar{\psi}\, \gamma^+\gamma_5\, \psi \,|\, P, S \rangle \quad \Longrightarrow \quad \bar{u}(k,s)\, \gamma^+\gamma_5 \, u(k,s) \;=\; 2ms^+$$

Longitudinal Polarization

$$\Phi^{[i\sigma^{i+}\gamma_5]} \propto \langle P, S \,|\, \bar{\psi}\, i\sigma^{i+}\gamma_5 \,|\, P, S \rangle \quad \Longrightarrow \quad \bar{u}(k,s)\, i\sigma^{i+}\gamma_5 \, u(k,s) \;=\; 2k^+ s_T^i$$

Transverse Polarization

Reductions

Fully Unintegrated Correlator

$$\Phi_{ij}(k,P,S) = \int \frac{d^4z}{(2\pi)^4}\, e^{ik\cdot z} \langle\, P,S\,|\,\bar{\psi}_j(0)\,\psi_i(z)\,|\,P,S\,\rangle$$

Integration over k^-
$k^+ = xP^+$

k_T-dependent Correlator

$$\Phi_{ij}(x,\vec{k}_T,S) \;=\; \int \frac{dz^-\,d^2z_T}{(2\pi)^3}\, e^{ik\cdot z} \langle\, P,S\,|\,\bar{\psi}_{ij}(0)\,\psi_{ij}(z)\,|\,P,S\,\rangle\Big|_{z^+=0}$$

Integration over k_T

collinear Correlator

$$\Phi_{ij}(x,S) \;=\; \int \frac{dz^-}{(2\pi)}\, e^{ixP^+z^-} \langle\, P,S\,|\,\bar{\psi}_{ij}(0)\,\psi_{ij}(z^-)\,|\,P,S\,\rangle$$