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(in collab. with K.Goeke and P. Schweitzer)
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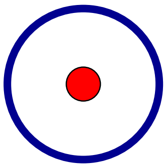
TRANSVERSAL SPIN AZIMUTHAL ASYMMETRIES at COMPASS and HERMES

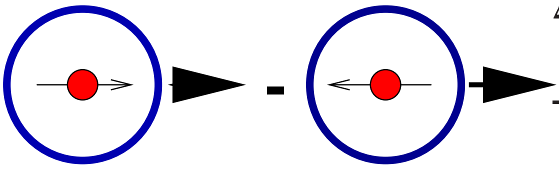
Content

1. Main parton characteristics of hadron.
2. Proton transversity
3. New spin-dependent PDF and PFF's.
4. Azimuthal asymmetries
5. Predictions for COMPASS and HERMES
6. $H_1^\perp$ from $e^+e^- \to 2$-jets.
7. Approximations and model.
8. Results for proton and deuteron target.
9. Conclusions.

There are three main (twist-2) parton characteristics of a hadron.



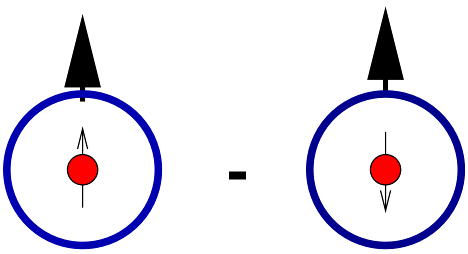
- Non-polarized PDF $f_1^a(x, Q^2)$.
  - — Measured for decades. Rather well known.
  - — Q^2-evolution, $\alpha_s(Q^2)$ extraction
  - — Problem of very small x behavior (bare Pomeron, BFKL-equation)



- Longitudinal spin distribution.

$$\Delta f^a \equiv f_{\rightarrow}^{a\rightarrow} - f_{\rightarrow}^{a\leftarrow} \equiv g_1^a(x, Q^2) \ .$$

  - — Parton content of proton spin. Main problem ΔG. Dedicated experiments (e.g. COMPASS, RHIC).
  - — Sea spin flavour asymmetry. $\Delta \bar{u} \approx -\Delta \bar{d}$ in χQSM



- Transverse spin distribution.

$$\delta f^a \equiv f_{\uparrow}^{a\uparrow} - f_{\uparrow}^{a\downarrow} \equiv h_1^a(x, Q^2)$$

  - — Not measured in DIS (χ-odd).
  - — Density matrix positivity, Soffer inequality $|h_1(x)| \leq \frac{1}{2}[f_1(x) + g_1(x)]$ or $2|h_1(x)| \leq \frac{1}{3} f_1(x) + g_1(x)$ (large N_c).

Polyakov, Pobylitsa, hep/ph/0004094

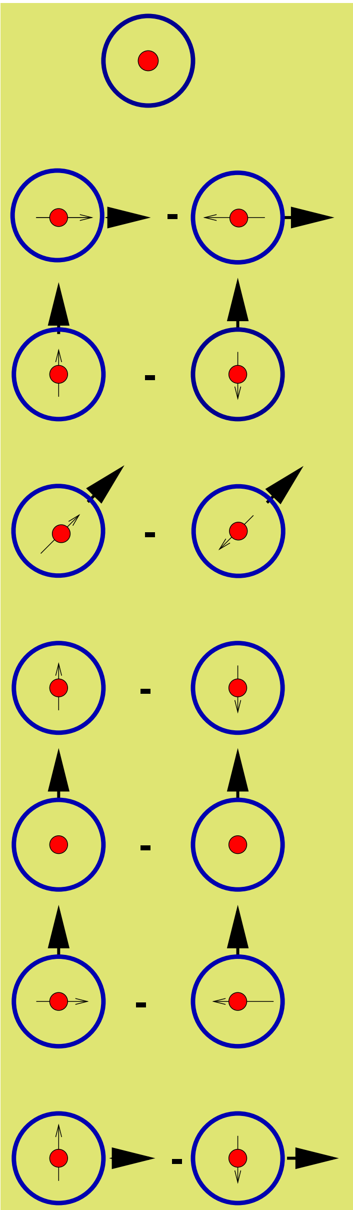
New PFF's and PDF's

Usual PFF $D_{q/H}(z) \equiv D_1(z)$ well known. Spin dependent PFF's $G_1(z)$ and $H_1(z)$ (analog g_1 and h_1) integrated over k_T.

New possibilities with k_T account.

Leading twist, general invariance principles

8 possibilities (helicity basis)



(f_1) D_1

(g_{1L}) G_{1L} $(\boldsymbol{\sigma P})(\boldsymbol{SP})/P^2$

(h_{1T}) H_{1T} $[\boldsymbol{\sigma S} - (\boldsymbol{\sigma P})(\boldsymbol{SP})/P^2]$, χ-odd

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$(h_{1T}^{\perp})$ $H_{1T}^{\perp}$ $\boldsymbol{\sigma}[\boldsymbol{kP}]\boldsymbol{S}[\boldsymbol{kP}]/k_T^2 P^2$, χ-odd

$(h_1^{\perp})$ $H_1^{\perp}$ $\boldsymbol{\sigma}[\boldsymbol{kP}]/k_T P$, χ-odd, T-odd

$(f_{1T}^{\perp})$ $D_{1T}^{\perp}$ $\boldsymbol{S}[\boldsymbol{kP}]/k_T P$, T-odd

$(g_{1T}^{\perp})$ $G_{1T}^{\perp}$ $(\boldsymbol{\sigma P})(\boldsymbol{S k}_T)/P k_T$

$(h_{1L}^{\perp})$ $H_{1L}^{\perp}$ $(\boldsymbol{SP})(\boldsymbol{\sigma k}_T)/P k_T$, χ-odd

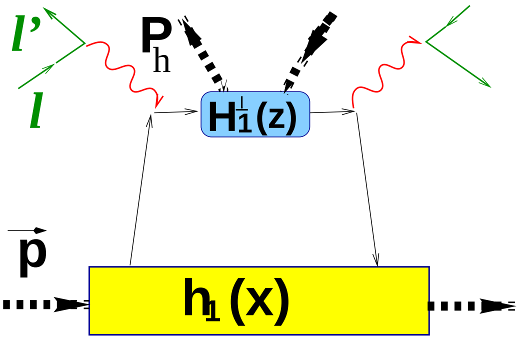
(T-odd $h_1^{\perp}$ and $f_{1T}^{\perp}$ were forbidden by hermiticity but recently seems to be reanimated by Brodsky and Collins.)

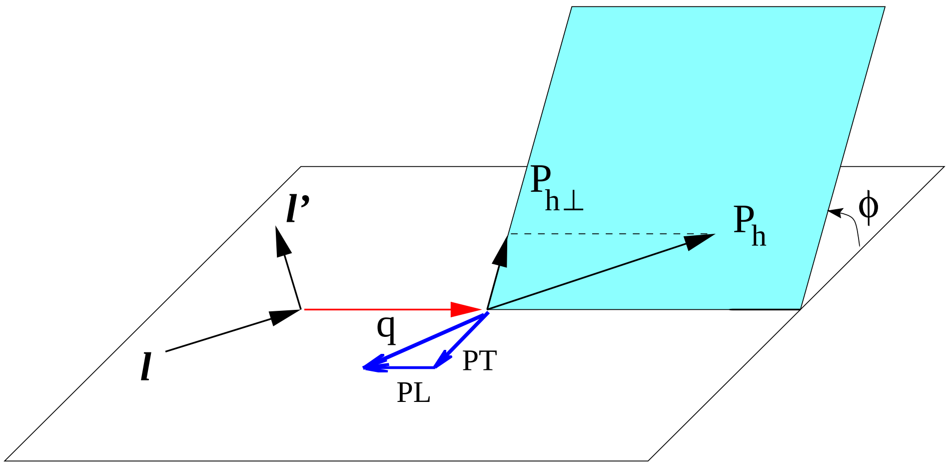
Azimuthal spin asymmetries

$$d\sigma = d\sigma_{00} + P_\mu d\sigma_{L0} + P_L(d\sigma_{0L} + P_\mu d\sigma_{LL}) + P_T(d\sigma_{0T} + P_\mu d\sigma_{LT})$$

with $P_T = P_{\|} \sin\theta_\gamma$, $\sin\theta_\gamma \approx 2\frac{M_N}{Q} x\sqrt{1-y}$

(For longitudinally polarized target $\phi_S = \pi$ or 0.)





00: $x f_1 D_1 + x h_1^\perp H_1^\perp \cos 2\phi - \frac{M}{Q} x^2 f^\perp D_1 \cos\phi$

L0: $\frac{M}{Q} x^2 e(x) H_1^\perp(z) \sin\phi$

0L: $x h_{1L}^\perp(x) H_1^\perp(z) \sin 2\phi \quad + \frac{M}{Q} x^2 h_L(x) H_1^\perp(z) \sin\phi$

LL: $x g_1(x) D_1(z) + \frac{M}{Q} x^2 g_L^\perp(x) D_1(z) \cos\phi$

0T: $x h_1 H_1^\perp \sin(\phi + \phi_S) \quad + x h_{1T}^\perp H_1^\perp \sin(3\phi - \phi_S)$

$+ x f_{1T}^\perp(x) D_1(z) \sin(\phi - \phi_S)$

LT: $x g_{1T}(x) D_1(z) \cos(\phi - \phi_S)$

$\sin 2\phi$ – Most perspective for $P_{\|}$

$\sin(\phi + \phi_S)$ – Most perspective for $P_\perp$

$\sin(\phi - \phi_S)$ and $\cos 2\phi$ – Interesting to observe

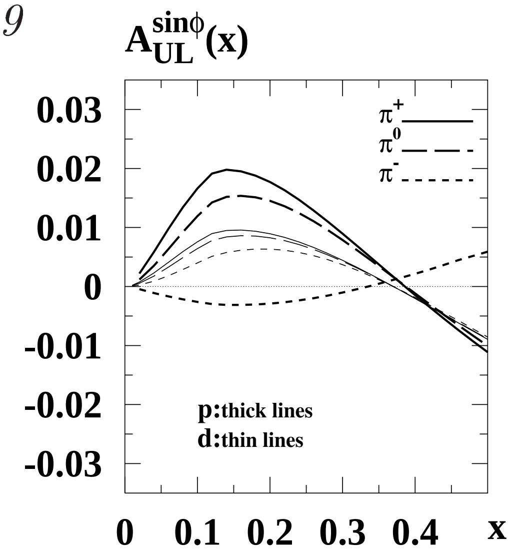
Predictions for COMPASS and HERMES

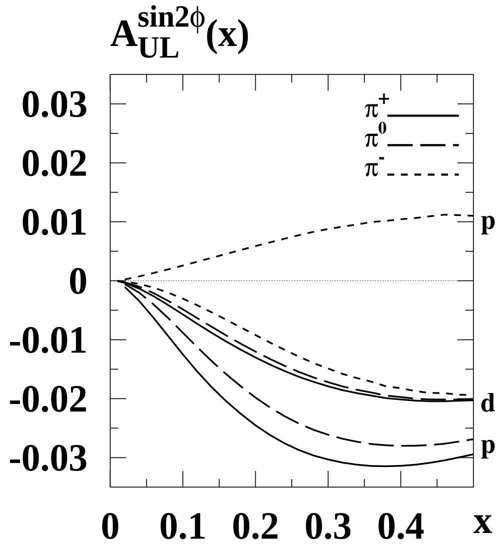
COMPASS: $(E = 160\,GeV,\ W^2 > 15\,GeV^2,\ Q^2 < 50\,GeV^2,\ \langle z\rangle \approx 0.4,\ 0.05 < y < 0.9)$

$$A^W = \frac{\int d\phi dy\, W(\phi)\,(d\sigma^+/P^+dyd\phi - d\sigma^-/P^-dyd\phi)}{\frac{1}{2}\int d\phi dy\,(d\sigma^+/dyd\phi + d\sigma^-/dyd\phi)}$$

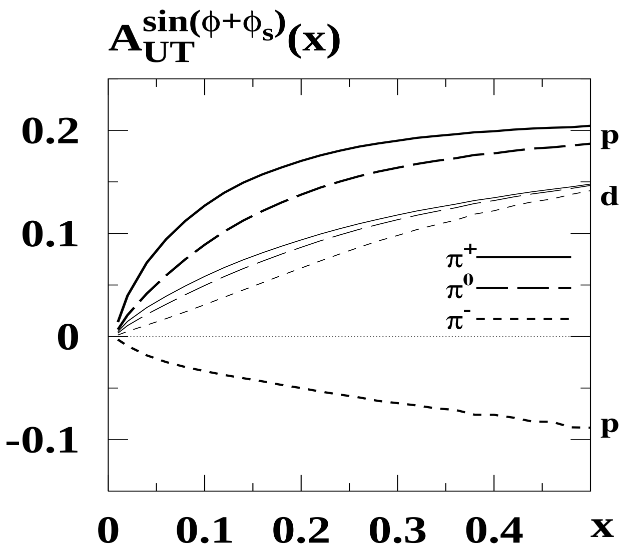
Longitudinal target polarization

A.E., Goeke, Schweitzer
hep/ph/0309209

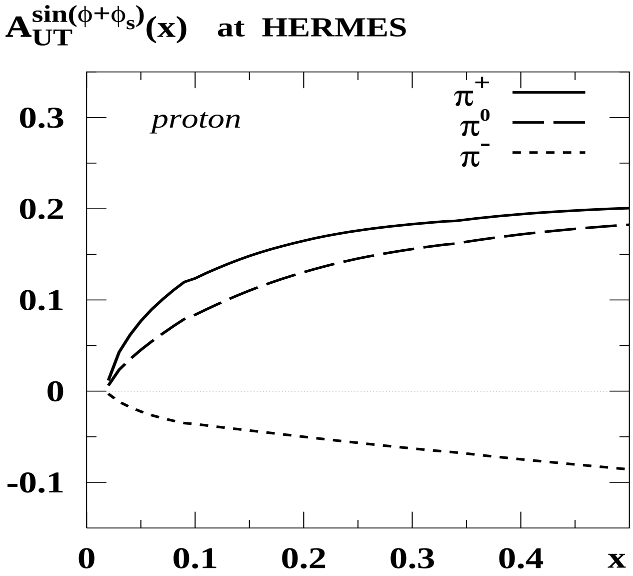


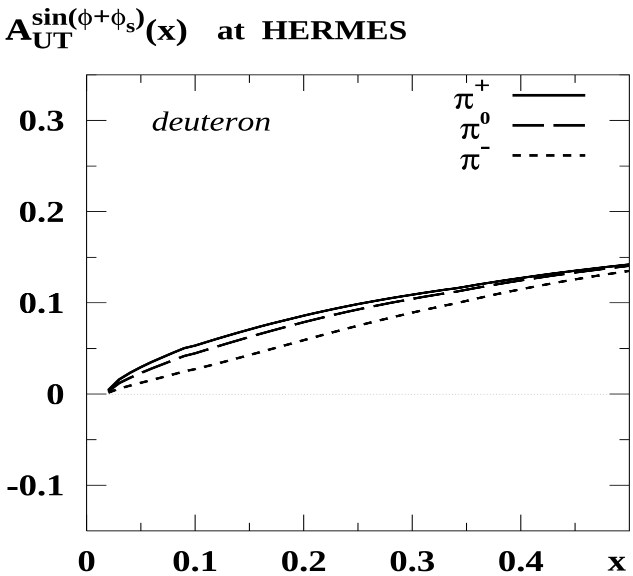


Big asymmetry for transversal target polarization



HERMES: $(E = 26.7\,GeV,\ W > 2\,GeV,$
$1 < Q^2 < 15\,GeV^2,\ \langle z \rangle \approx 0.4,\ 0.2 < y < 0.85,$
$0.023 < x < 0.4,\ P_{h\perp} > 0.4\,GeV)$





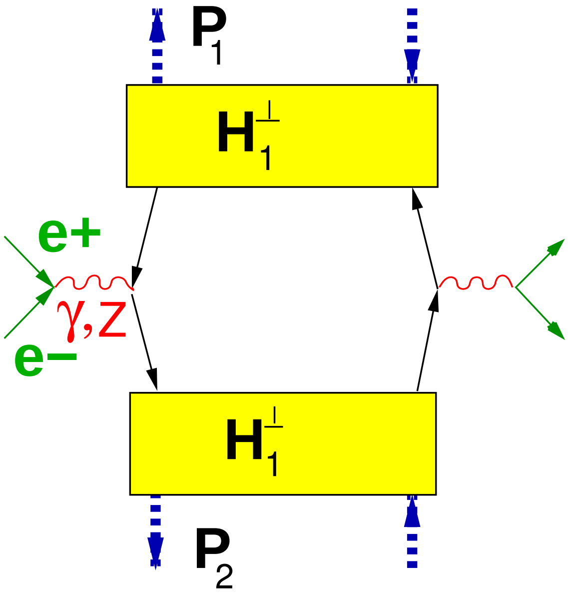
What are ingredients?

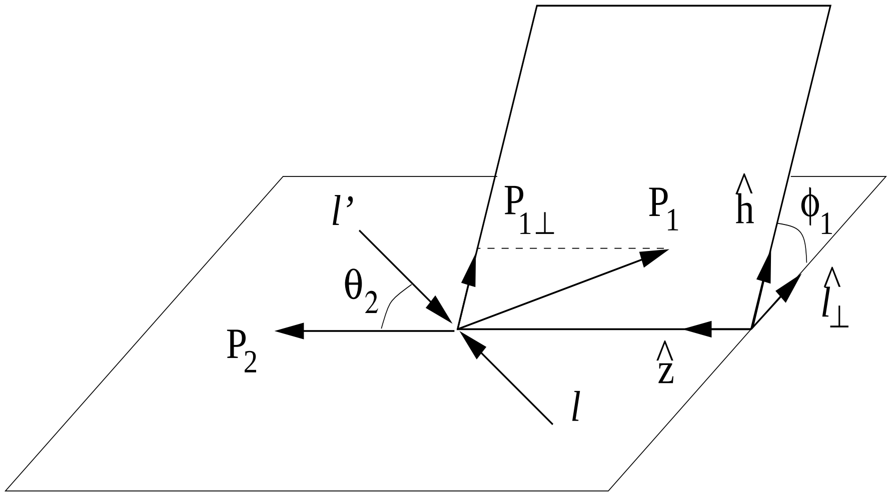
$H_1^\perp$ from $e^+e^- \to$ 2-jets

DELPHI (and other LEP experiments) allows to measure $H_1^\perp(z)$. Non zero transversal spin correlation

$$C_{TT}^{q\bar q} = \frac{v_q^2 - a_q^2}{v_q^2 + a_q^2} \begin{cases} -0.74 & \text{for up quarks} \\ -0.35 & \text{for down quarks} \end{cases}$$

Averaged over flavor $\overline{C_{TT}^{q\bar q}} \approx 0.5$





*Collins NP***B396***(93); Kotzinian NP***B441***(95); Artru, Collins ZP***C69***(96); Mulders, Boer, Jakob, PL***B424***(98).*

Azimuthal correlation of two opposite jet hadrons ("Collins asymmetry")

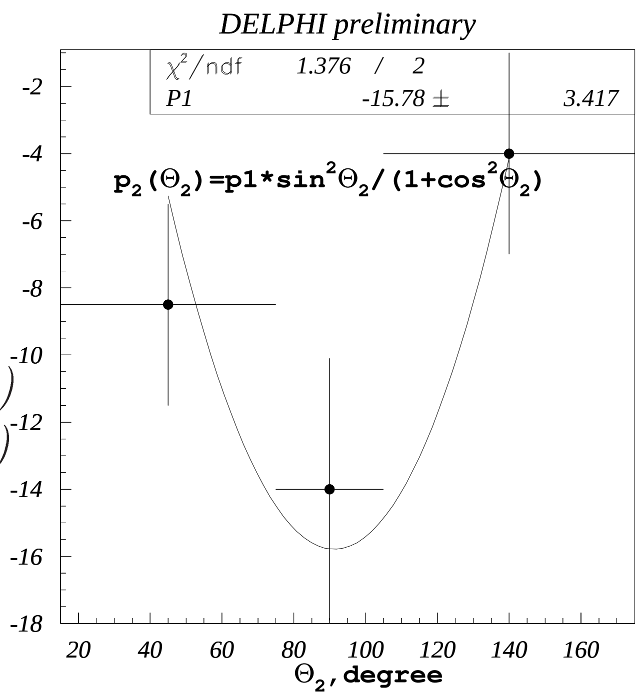
$$\frac{d\sigma}{d\cos\theta_2 d\phi_1} \propto (1+\cos^2\theta_2)\cdot \left(1 + \frac{6}{\pi}\left[\frac{H_1^{\perp q}}{D_1^q}\right]^2 \overline{C_{TT}^{q\bar q}} \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_1)\right)$$

$H_1^\perp$ for 91–95 DELPHI-data

1. Select two-jets hadronic events ($\approx 3.5\,Mev$) (JADE, $y = 0.01$ to 0.08, $T \geq 0.95$)
2. Leading charged particles in each jet,
$$15^\circ < \theta < 165^\circ$$
3. Correction factor $f_{corr} = \frac{\sigma_{\text{JETSET}}}{\sigma_{\text{MC}}}(\theta, \phi)$
4. Fit corrected ϕ-histograms by Expr.
$$P_1(1 + P_2 \cos 2\phi + P_3 \cos\phi)$$

(cos ϕ is due to trivial p_T-dependence of usual fragmentation)

A.E., Smirnova, Tkatchev NP **74,79** *(99) (Proc.Suppl.)*



"Optimistic" value

$$\left\langle \left| \frac{H_1^\perp}{D_1} \right| \right\rangle = 12.5 \pm 1.4\%$$

More reliable value

(in the interval

$45^\circ > \theta > 135^\circ$)

$$\left\langle \left| \frac{H_1^\perp}{D_1} \right| \right\rangle = 6.3 \pm 1.9\%$$

Approximations and model

1. Disregarding interaction dependent twist-3 corrections $\widetilde{H}$ or $\widetilde{h}_L$ (WW-type approximation)

$$\int d^2p_T \left(\frac{p_T^2}{2M^2}\right) h_{1L}^{\perp}(x,p_T) \equiv h_{1L}^{\perp(1)}(x) =$$

$$= -(x/2)h_L(x) = -x^2 \int_x^1 d\xi h_1(\xi)/\xi^2$$

2. Assume favored PFF for D_1 and $H_1^{\perp}$, e.g.

$$D_1^{u/\pi^+}(z) = D_1^{\bar{d}/\pi^+}(z) = D_1^{d/\pi^-}(z) = D_1^{\bar{u}/\pi^-}(z) \equiv D_1(z)$$

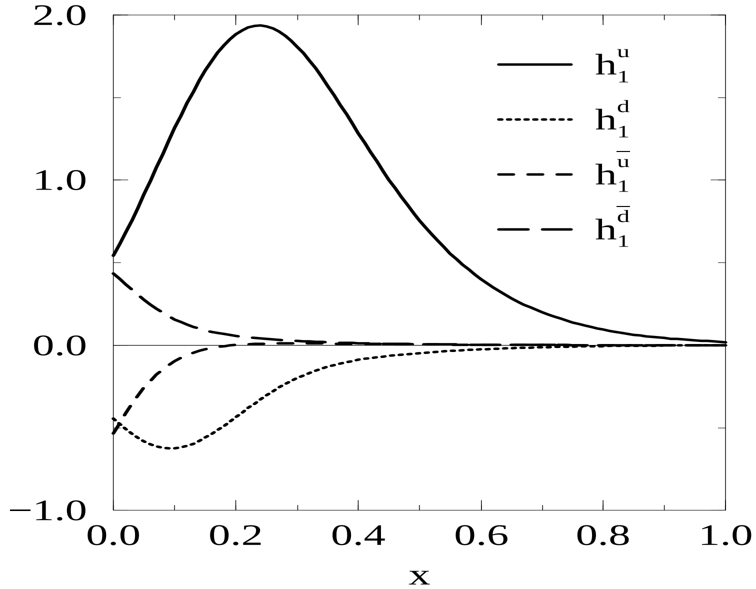
one could extract $[4h_1^u + h_1^{\bar{d}}](x)$ for π^+
or $[4(h_1^u + h_1^{\bar{u}}) + h_1^d + h_1^{\bar{d}}](x)$ for π^0
to compare with a model.

3. Instead, we use chiral soliton model prediction for $h_1^a(x)$ and GRV parameterization for $f_1^a(x)$

(Good ($\approx 20\%$) describes non-polarized and longitudinal spin PDF's.

Satisfies all general QCD requirements.)

*Pobylitsa, Polyakov at al, PL**B389**(96); Schweitzer at al. PR**D64**(01)*



4. Sivers to Collins suppression in SIDIS.

$$\sigma^{\sin\phi}_{U,par} = \sigma^{par}_{UL} + \sigma^{par}_{UT};\ \sigma^{par}_{UT} = \sigma^{\mathrm{Coll}}_{UT} + \sigma^{\mathrm{Siv}}_{UT}$$

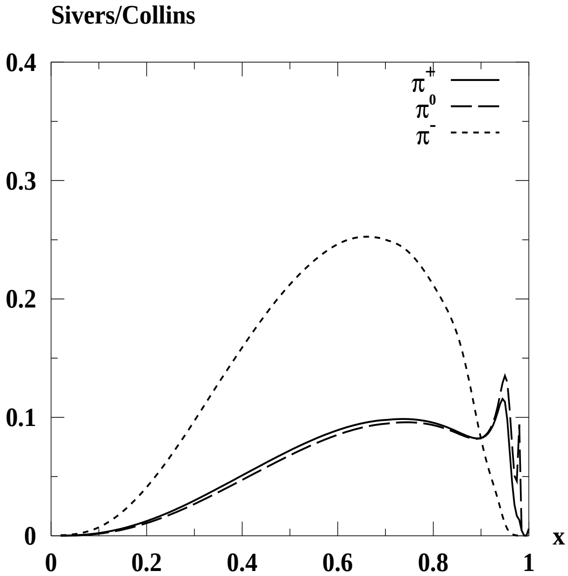
$$R = \frac{A^{\mathrm{Sivers}}_{UT}}{A^{\mathrm{Collins}}_{UT}} = \frac{\pi}{2}\,\frac{M}{\langle k_T\rangle}\,\frac{\langle D_1\rangle}{\langle H_1^\perp\rangle}\,\frac{\langle 1-y+y^2/2\rangle}{\langle 1-y\rangle}\,\frac{f_{1T}^{\perp(1)}(x)}{h_1(x)}$$

*Anselmino, Boglione, Murgia, PL***B362***(95)164*

Assuming pion asymmetries in $p\vec{p}$ (E704) are due to Sivers only gives

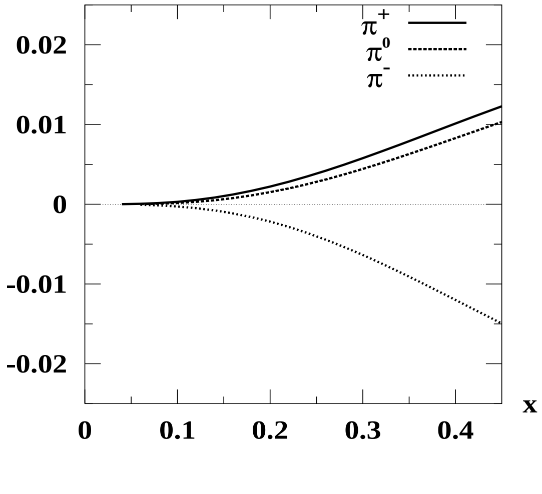
*A.E., Goeke Schweitzer PLB***568***(03)63*

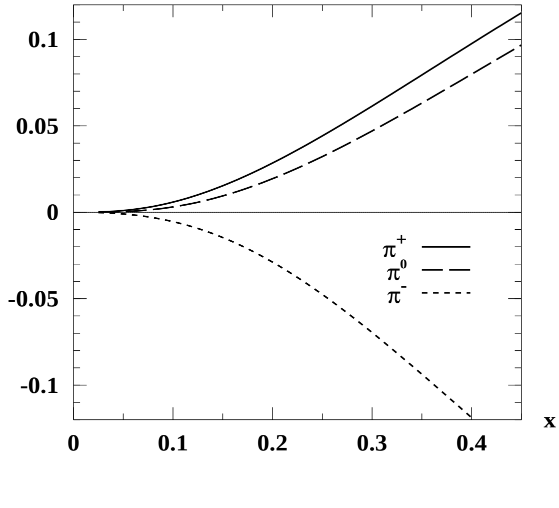
$R^{\pi^+} < 5\%,\ \ R^{\pi^-} < 10\%$
for $x < 0.5$



A_{UT} allows to separate this two effects

$$A^{\sin(\phi+\phi_S)}_{UT} \approx 20\%,\quad A^{\sin(\phi-\phi_S)}_{UT} \approx 10\%$$

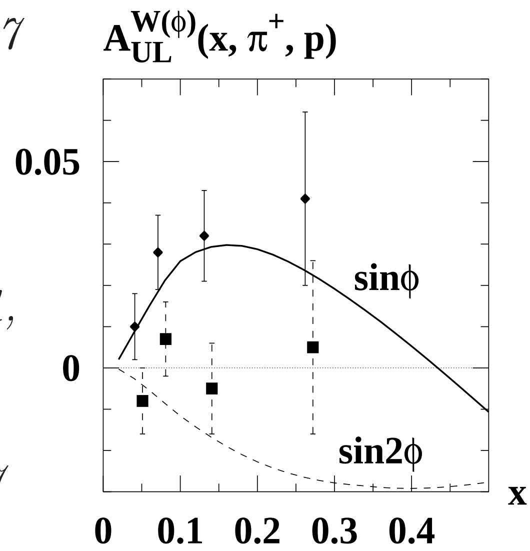


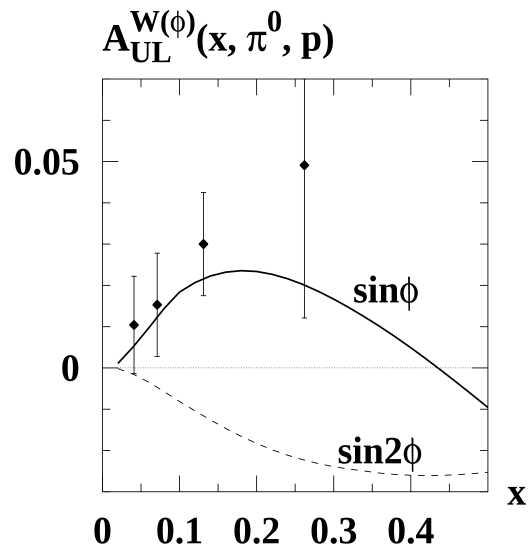


Results for proton target

HERMES
*PRL***84***(00)4047*
*PR***D64**
(01)097101

A.E. at al.
*PL***B478***(00)94,*
A.E., Goeke,
Schweitzer
*PL***B522***(01)37*
Erratum
B544*(02)389*



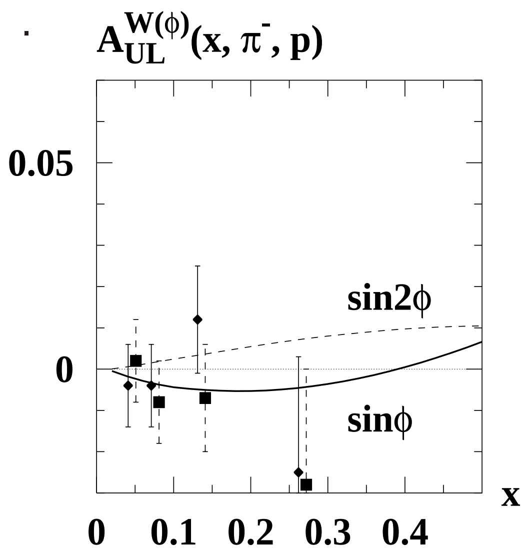


- Agreement with no fit parameters,
- Analyzing power $\frac{\langle H_1^\perp \rangle}{\langle D_1 \rangle}$ is positive,
- "Optimistic" value more preferable,
- The proton tensor charge at $Q^2 = 4\, GeV^2$

$$g_T \equiv \sum_a \int_0^1 dx (h_1^a(x) - h_1^{\bar{a}}(x)) = g_T = 0.6$$

(compare with recent experimental value of axial charge $a_0 = 0.28 \pm 0.05$).

- $A_{UL}^{\sin\phi}$ should cross zero and change sign at $x \approx 0.4 - 0.5$. (Depends on beam energy. COMPASS?)



Interesting to reverse the problem and determine $\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle}$ from π^+ and π^0, using the model h_1^q:

$$A_{UL}^{\sin\phi}(\pi^+) = 0.022\pm0.006 \to \frac{\langle H_1^\perp\rangle}{\langle D_1\rangle} = (11.7\pm3.1)\%$$

$$A_{UL}^{\sin\phi}(\pi^0) = 0.019\pm0.008 \to \frac{\langle H_1^\perp\rangle}{\langle D_1\rangle} = (14.3\pm5.5)\%$$

- Agrees with DELPHI, especially in view of $\approx 20\%$ model error.

A.Bravar NP Proc.Suppl **B79***(99)520*

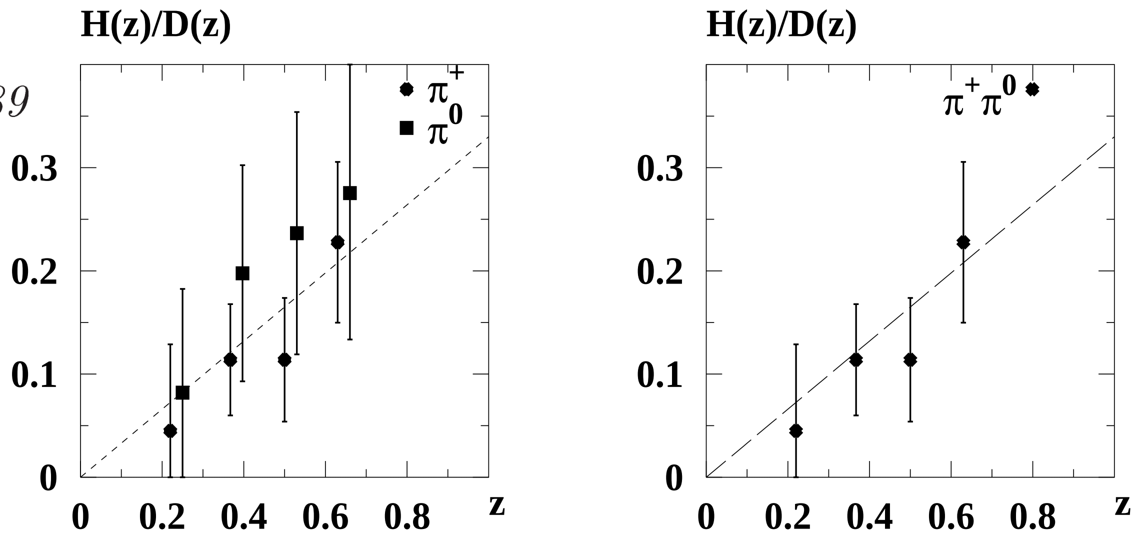
- SMC data gives $\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle} = -(10\pm5)\%$.
- A week scale dependence of the ratio is certified.

More interesting is z-behaviour of $\frac{H_1^\perp(z)}{D_1(z)}$ from z-behaviour of experimental asymmetries

*A.E., Goeke, Schweitzer PL***B544***(02)389*

*Bacchetta at al. PR***D65***(02) 094021*

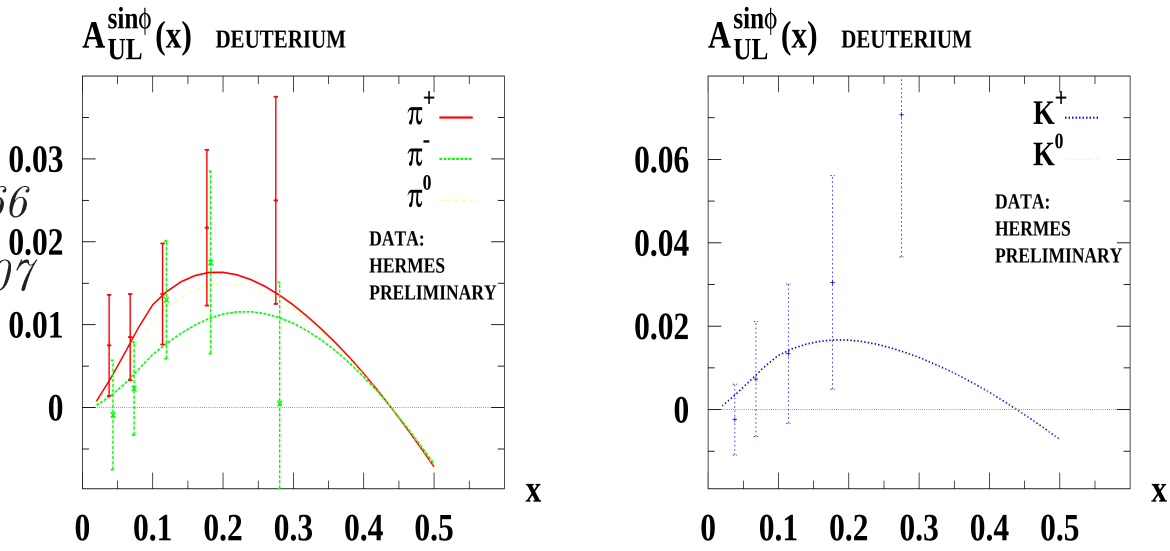
$\frac{H_1^\perp}{D_1} \approx 0.63z^2$



Best fit: $\boxed{H_1^\perp(z) = (0.33\pm0.06)z\,D_1(z)}$

For longitudinally polarized deuterium target

A.E., Goeke Schweitzer, hep/ph/0112166 EPJ C24(02)407



- Almost same for all pion signs and roughly half of the proton's ones.
- Data points are preliminary data of HERMES for π^+, π^- and K^+.

HERMES, hep/ex/0212039

- $\dfrac{\langle H_1^{\perp K}\rangle}{\langle D_1^K\rangle} \simeq \dfrac{\langle H_1^{\perp \pi}\rangle}{\langle D_1^\pi\rangle}$ is assumed;
- Close to zero for K^- and $\bar{K}^0$.
- $A_{UL}^{\sin\phi}$ should cross zero and change sign at $x \approx 0.4 - 0.5$.

<u>Conclusions</u>

1. Definite indications to T-odd PFF and proton transversity are now obtained.
2. The Collins analysing power $\frac{\langle H_1^\perp \rangle}{\langle D_1 \rangle} \approx 10\%$ and grows with z.
3. The proton transversity is order of polarized valence PDF.
4. Asymmetries at transversally polarized target are of special interest (transversity, Collins PFF and Sivers PDF).
5. The proton transversity could be also measured **simultaneously** with $\Delta G(x)$.