Further direct extractions of the transversity functions

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Trieste, 3 June 2024

Further direct extractions of transversity

point-by-point extractions of h_1

- **first done in 2015 using the Collins and di-hadron asymmetries in SIDIS measuresed on p and d by COMPASS, and in e^+e^- annihilation measured by Belle to extract $h_1^{u_v}(x), h_1^{d_v}(x), xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x).\ xh_1^{\bar{u}}(x)$ and $xh_1^{\bar{d}}(x)$**

  Extracting the transversity distributions from single-hadron and dihadron production

  A. Martin, F. Bradamante, V. Barone, **PRD 91 (2015) 014034**

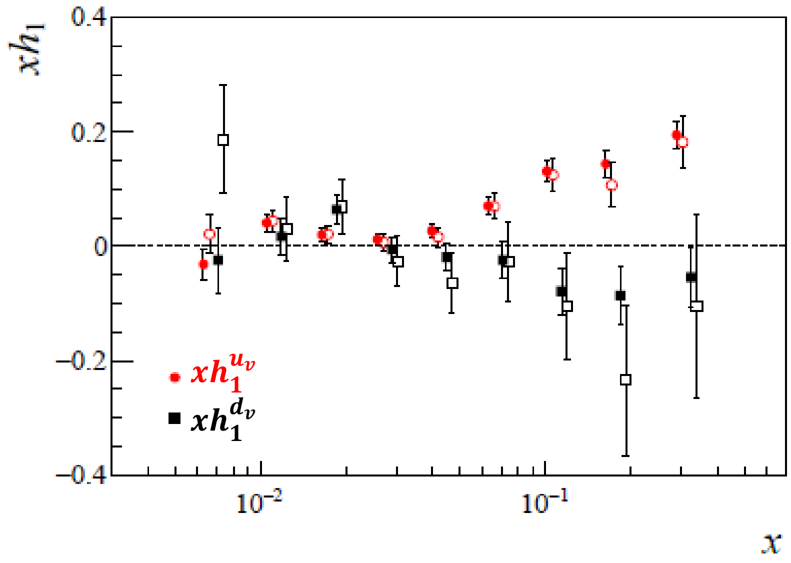
- **redone by COMPASS in 2023 for $h_1^{u_v}(x)$ and $h_1^{d_v}(x)$ using the new d measurements from 2022 data**

  arXiv:**2401.00309** [hep-ex], accepted by PRL, → *Athira talk*

Transversity from COMPASS SIDIS data

COMPASS 2024 arXiv:2401.00309 [hep-ex], accepted by PRL → *Athira talk*

extraction of $h_1^{u_v}(x)$ and $h_1^{d_v}(x)$ using all the COMPASS measurements of the Collins asymmetries p: 2007, 2010, **d:**2002-2004, **2022**



open points:
no 2022 data

u: errors smaller by a factor 1.2 to 1.9
d: errors smaller by a factor 1.7 to 3.1

data	$\delta u = \int_{0.008}^{0.210} dx\, h_1^{u_v}(x)$	$\delta d = \int_{0.008}^{0.210} dx\, h_1^{d_v}(x)$	$g_T = \delta u - \delta d$
no 2022	0.187 ± 0.030	-0.178 ± 0.097	0.365 ± 0.078
with 2022	0.214 ± 0.020	-0.070 ± 0.043	0.284 ± 0.045

$0 < \rho < 0.1$

Further direct extractions of transversity

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- **redone by COMPASS in 2023 for $h_1^{u_v}(x)$ and $h_1^{d_v}(x)$ using the new d measurements from 2022 data**

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- **also, $h_1^{d_v}(x)/h_1^{u_v}(x)$ in 2019, using the p and d Collins difference asymmetries measured by COMPASS**

  Transversity distributions from difference asymmetries in semi-inclusive DIS.

  V. Barone et el., **PRD 99 (2019) 114004**

Further direct extractions of transversity

in this talk, point-by-point extractions of

- $xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)$
- $xh_1^{\bar{u}}(x)$ and $xh_1^{\bar{d}}(x)$ as in PRD 91 (2015) 014034

- $h_1^{d_v}(x)/h_1^{u_v}(x)$ as in PRD 99 (2019) 114004

new: we used all the Collins asymmetries for $h^{\pm}$ measured by COMPASS namely

p from 2007 and 2010 data PLB 717 (2012) 376

d from 2002-2004 and 2022 data NPB 765 (2007) 31, ep-ex/2401.00309 PRL

Transversity from Collins asymmetries - reminder

PRD 91 (2015) 014034

$$A^h_{Coll}(x,z) = \frac{\sum_{q\bar{q}} e_q^2 x h_1^q(x, k_{Th}^2) \otimes H_{1q}^{\perp h}(z, p_{\perp H}^2)}{\sum_{q\bar{q}} e_q^2 x f_1^q(x, k_{Tf}^2) \otimes D_{1q}^{h}(z, p_{\perp D}^2)}$$

assumptions:

- Gaussian Ansatz for the TMD PDFs and FF $\quad h_1^q(x, k_{Th}^2) = h_1^q(x) \frac{e^{-k_{Th}^2/\langle k_{Th}^2\rangle}}{\pi\langle k_{Th}^2\rangle}$,....

$$\Rightarrow \quad A^h_{Coll}(x,z) = C_G \frac{\sum_{q\bar{q}} e_q^2 x h_1^q(x)\, H_{1q}^{h}(z)}{\sum_{q\bar{q}} e_q^2 x f_1^q(x)\, D_{1q}^{h}(z)}$$

$$H_{1q}^h(z) = H_{1q}^{\perp(1/2)}(z)$$

half-moment of $H_{1q}^{\perp h}$

with $\quad C_G = \frac{1}{\sqrt{1+z^2\langle k_{Th}^2\rangle/\langle p_{\perp H}^2\rangle}} \cong 1$ $\quad$ data mostly at low z

- all charged hadrons are pions (75% in COMPASS) and the c quark contribution is negligible at COMPASS energy (beam energy 160 GeV)

- favoured and unfavored FFs

$$D_{1,fav} = D_{1u}^{+} = D_{1d}^{-} = D_{1\bar{u}}^{-} = D_{1\bar{d}}^{+} \qquad D_{1,unf} = D_{1u}^{-} = D_{1d}^{+} = D_{1\bar{u}}^{+} = D_{1\bar{d}}^{-} = D_{1s}^{\pm} = D_{1\bar{s}}^{\pm}$$

$$H_{1,fav} = H_{1u}^{+} = H_{1d}^{-} = H_{1\bar{u}}^{-} = H_{1\bar{d}}^{+} \qquad H_{1,unf} = H_{1u}^{-} = H_{1d}^{+} = H_{1\bar{u}}^{+} = H_{1\bar{d}}^{-}$$

$$H_{1s}^{\pm} = H_{1\bar{s}}^{\pm} = 0$$

Transversity from Collins asymmetries - reminder

PRD 91 (2015) 014034

with these assumptions the Collins asymmetries **measured** with p ans d targets can be written as

$$\boldsymbol{A_p^+(x)} = \tilde{a}_P \frac{4\left(xh_1^u(x) + \tilde{\alpha}xh_1^{\bar{u}}(x)\right) + \left(\tilde{\alpha}xh_1^d(x) + xh_1^{\bar{d}}(x)\right)}{xf_p^+(x)}$$

$$\boldsymbol{A_p^-(x)} = \tilde{a}_P \frac{4\left(\tilde{\alpha}xh_1^u(x) + xh_1^{\bar{u}}(x)\right) + \left(xh_1^d(x) + \tilde{\alpha}xh_1^{\bar{d}}(x)\right)}{xf_p^-(x)}$$

$$\boldsymbol{A_d^+(x)} = \tilde{a}_P \frac{(4+\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (1+4\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^+(x)}$$

$$\boldsymbol{A_d^-(x)} = \tilde{a}_P \frac{(1+4\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (4+\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^-(x)}$$

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$$\boldsymbol{A_p^-(x)} = \tilde{a}_P \frac{4\left(\tilde{\alpha} x h_1^u(x) + xh_1^{\bar{u}}(x)\right) + \left(xh_1^d(x) + \tilde{\alpha} x h_1^{\bar{d}}(x)\right)}{xf_p^-(x)}$$

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Transversity from Collins asymmetries - reminder

PRD 91 (2015) 014034

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$$A_d^+(x) = \tilde{a}_P \frac{(4+\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (1+4\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^+(x)}$$

$$A_d^-(x) = \tilde{a}_P \frac{(1+4\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (4+\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^-(x)}$$

$f_T^{\pm}(x)$ are combinations of unpolarized PDFs and FFs

f.i. $f_p^+ = \left[4\left(f_1^u + \tilde{\beta}f_1^{\bar{u}}\right) + \left(\tilde{\beta}f_1^d + f_1^{\bar{d}}\right) + \tilde{\beta}\left(f_1^s + f_1^{\bar{s}}\right)\right]$

$$\tilde{\beta} = \frac{\int dz\, D_{1unf}(z)}{\int dz\, D_{1fav}(z)}$$

known, evaluated using CTEQ5D (PDFs) and DSS LO (FFs)

Transversity from Collins asymmetries - reminder

PRD 91 (2015) 014034

with these assumptions the Collins asymmetries **measured** with p and d targets can be written as

$$A_p^+(x) = \tilde{a}_P \frac{4\left(xh_1^u(x) + \tilde{\alpha} xh_1^{\bar{u}}(x)\right) + \left(\tilde{\alpha} xh_1^d(x) + xh_1^{\bar{d}}(x)\right)}{xf_p^+(x)}$$

$$A_p^-(x) = \tilde{a}_P \frac{4\left(\tilde{\alpha} xh_1^u(x) + xh_1^{\bar{u}}(x)\right) + \left(xh_1^d(x) + \tilde{\alpha} xh_1^{\bar{d}}(x)\right)}{xf_p^-(x)}$$

$$A_d^+(x) = \tilde{a}_P \frac{(4+\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (1+4\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^+(x)}$$

$$A_d^-(x) = \tilde{a}_P \frac{(1+4\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (4+\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^-(x)}$$

$f_T^{\pm}(x)$ are combinations of unpolarized PDFs and FFs, known

$$\tilde{a}_P = \frac{\int dz\, H_{1fav}(z)}{\int dz\, D_{1fav}(z)}$$ and $$\tilde{\alpha} = \frac{\int dz\, H_{1unf}(z)}{\int dz\, H_{1fav}(z)}$$ are obtained from $e^+e^- \to h_1 h_2 X$

Collins analysing power

$\tilde{a}_P$ and $\tilde{\alpha}$ from Collins asymmetries in e^+e^- - reminder

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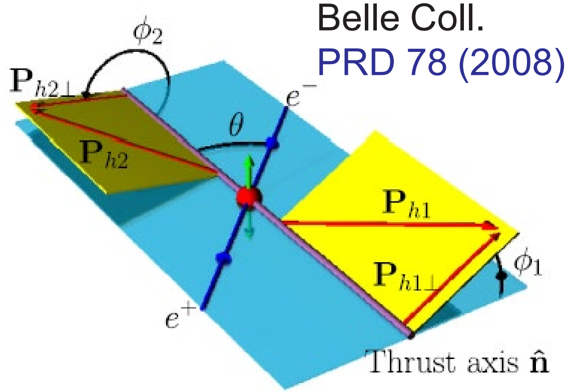
used data:
Belle results on the asymmetry A_{12}
in $e^+e^- \to h_1 h_2 X$ with the two hadrons in different hemispheres, corrected for charm contribution
in the bins in the bins $z_1 = z_2 = z$

Belle Coll.
PRD 78 (2008) 032011



same assumptions on the FFs as for SIDIS
(Belle data are subtracted for charm)

- $$\boldsymbol{\alpha(z)} = \frac{H_{1unf}(z)}{H_{1fav}(z)} = \boldsymbol{-\beta(z)} = -\frac{D_{1unf}(z)}{D_{1fav}(z)}$$

  i.e. $$\frac{H_{1fav}(z)}{D_{1fav}(z)} = -\frac{H_{1unf}(z)}{D_{1unf}(z)}$$

  "scenario 2", suggested by the $^3P_0$ model

⇨ $$\boldsymbol{a_P(z)} = \frac{H_{1fav}(z)}{D_{1fav}(z)} = N'z, \quad N' = 0.501 \pm 0.011$$

$$\boldsymbol{\tilde{a}_P} = \frac{\int dz\, H_{1fav}(z)}{\int dz\, D_{1fav}(z)} = \frac{\int dz\, a_P(z)\, D_{1fav}(z)}{\int dz\, D_{1fav}(z)} = \mathbf{0.173}$$

at Belle

- **same Q^2 evolution of H_1 and D_1**

⇨ at the COMPASS Q^2 values

$$\boldsymbol{\tilde{a}_P = 0.173}$$

$$\boldsymbol{\tilde{\alpha}} = \frac{\int dz\, H_{1unf}(z)}{\int dz\, H_{1fav}(z)} = -\frac{\int dz\, zD_{1unf}(z)}{\int dz\, zD_{1fav}(z)}$$

ranges from -0.43 (highest x)
to -0.34 (lowest x)

$h_1^{q_v}$ from Collins asymmetries - reminder

those values were used to extract

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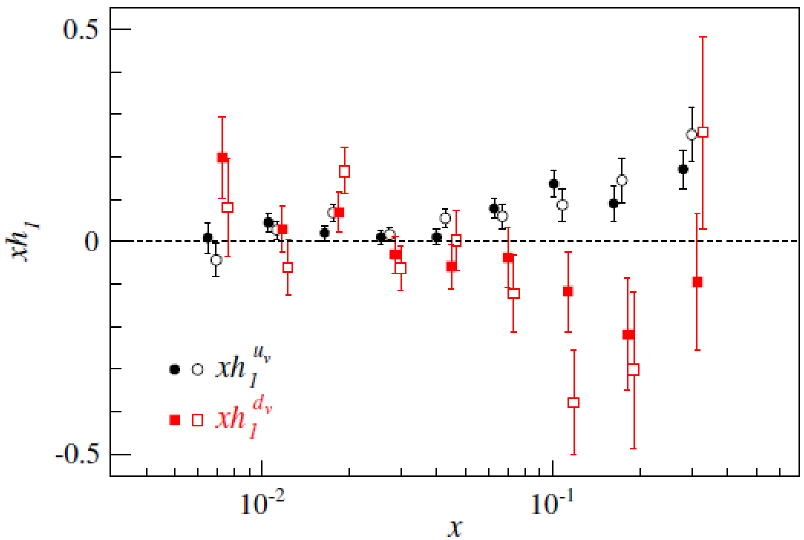
$$xh_1^{u_v} = \frac{1}{5}\frac{1}{\tilde{\alpha}_P(1-\tilde{\alpha})}\left[\left(xf_p^+A_p^+ - xf_p^-A_p^-\right) + \frac{1}{3}\left(xf_d^+A_d^+ - xf_d^-A_d^-\right)\right]$$

$$xh_1^{d_v} = \frac{1}{5}\frac{1}{\tilde{\alpha}_P(1-\tilde{\alpha})}\left[\frac{4}{3}\left(xf_p^+A_p^+ - xf_p^-A_p^-\right) + \left(xf_d^+A_d^+ - xf_d^-A_d^-\right)\right]$$

from the COMPASS Collins asymmetries available at the time

redone by COMPASS arXiv:2401.00309 [hep-ex]

extractions also using the di-hadron asymmetries (open points): good agreement



only statistical errors of the measured asymmetries as quoted by the experimental collaborations

no attempt has been made to try to assign a systematic error to the results.

$h_1^{\bar{q}}$ from Collins asymmetries - reminder

PRD 91 (2015) 014034

going back to the expressions for the four measured Collins asymmetries

$$\boldsymbol{A_p^+(x)} = \tilde{a}_P \frac{4\left(xh_1^u(x) + \tilde{\alpha}xh_1^{\bar{u}}(x)\right) + \left(\tilde{\alpha}xh_1^d(x) + xh_1^{\bar{d}}(x)\right)}{xf_p^+(x)}$$

$$\boldsymbol{A_p^-(x)} = \tilde{a}_P \frac{4\left(\tilde{\alpha}xh_1^u(x) + xh_1^{\bar{u}}(x)\right) + \left(xh_1^d(x) + \tilde{\alpha}xh_1^{\bar{d}}(x)\right)}{xf_p^-(x)}$$

$$\boldsymbol{A_d^+(x)} = \tilde{a}_P \frac{(4+\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (1+4\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^+(x)}$$

$$\boldsymbol{A_d^-(x)} = \tilde{a}_P \frac{(1+4\tilde{\alpha})\left(xh_1^u(x) + xh_1^d(x)\right) + (4+\tilde{\alpha})\left(xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)\right)}{xf_d^-(x)}$$

other combinations which can be used to extract the sea quarks transversity functions:

$$\boldsymbol{xh_1^{\bar{u}}} + \boldsymbol{xh_1^{\bar{d}}} = \frac{1}{15}\frac{1}{\tilde{a}_P(1-\tilde{\alpha}^2)}\left[(4+\tilde{\alpha})xf_d^-A_d^- - (4\tilde{\alpha}+1)xf_d^+A_d^+\right]$$

$$\boldsymbol{xh_1^{\bar{u}}} = \frac{1}{15}\frac{1}{\tilde{a}_P(1-\tilde{\alpha}^2)}\left[(1-4\tilde{\alpha})xf_p^+A_p^+ + (4-\tilde{\alpha})xf_p^-A_p^- - xf_d^+A_d^+ + \tilde{\alpha}xf_d^-A_d^-\right]$$

$$\boldsymbol{xh_1^{\bar{d}}} = \frac{1}{15}\frac{1}{\tilde{a}_P(1-\tilde{\alpha}^2)}\left[(4\tilde{\alpha}-1)xf_p^+A_p^+ - (4-\tilde{\alpha})xf_p^-A_p^- - 4\alpha xf_d^+A_d^+ + \tilde{4}xf_d^-A_d^-\right]$$

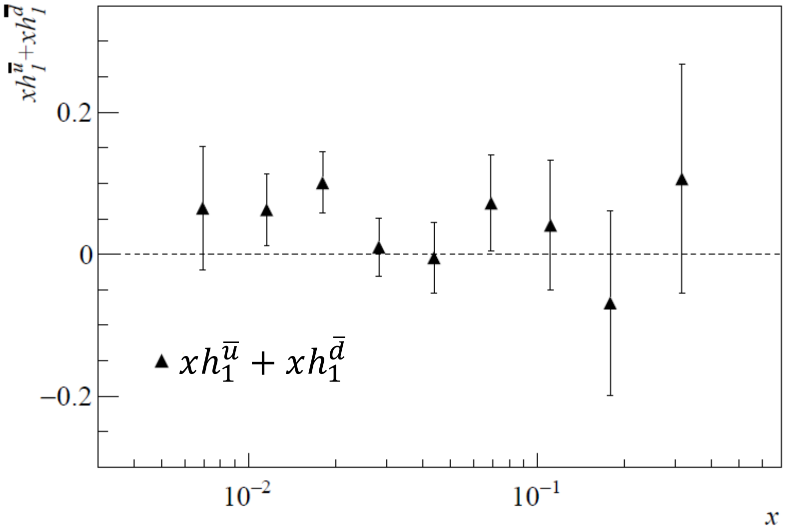
they were evaluated using the same numerical values as for the valence quark transversity

today: results using the new COMPASS data

$xh_1^{\bar{u}}(x) + xh_1^{\bar{d}}(x)$ from Collins asymmetries

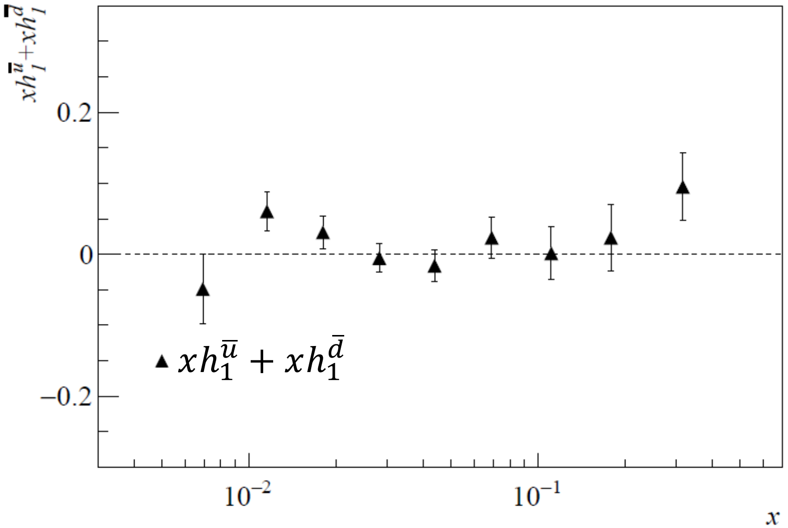
COMPASS data

deuteron 2002-2004



mean value $\mathbf{0.045 \pm 0.020}$
compatible with zero $\chi^2 = 9.7$

deuteron 2002-2004 + **2022**



mean value $\mathbf{0.014 \pm 0.009}$
compatible with zero $\chi^2 = 13.2$

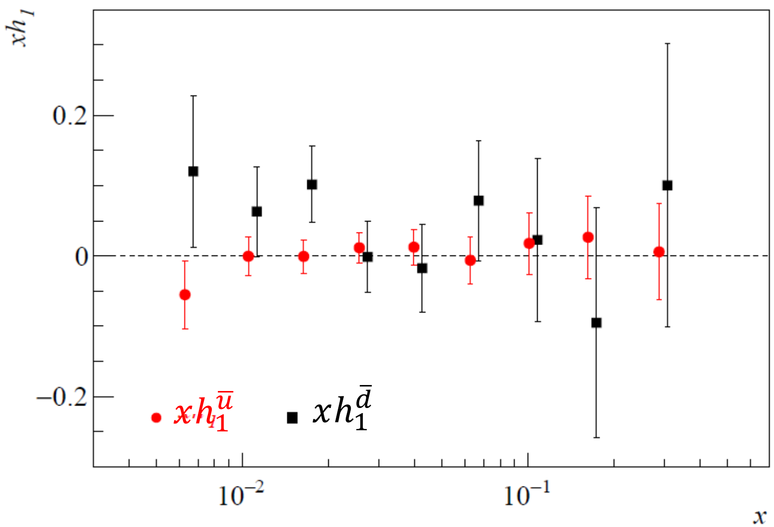
errors reduced by a factor 1.8 to 3.4

expected to vanish in the large N_C limit

$xh_1^{\bar{u}}(x)$ and $xh_1^{\bar{d}}(x)$ from Collins asymmetries

COMPASS data

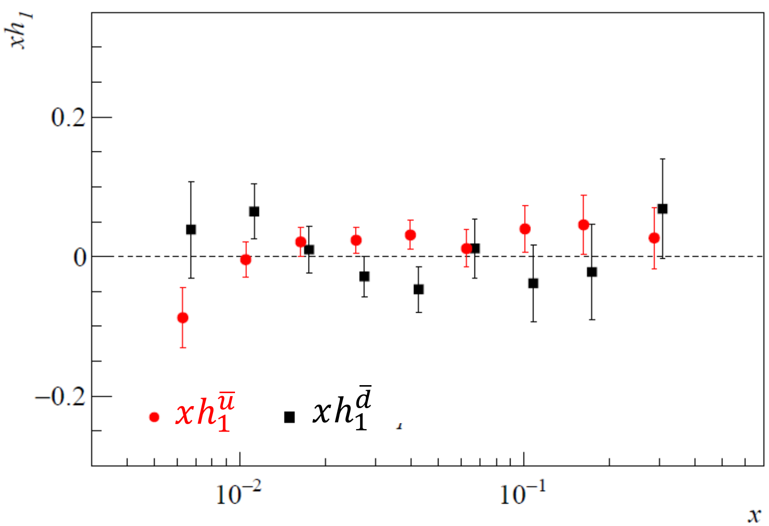
proton 2007+2010
deuteron 2002-2004



$\bar{u}$: mean value $+\mathbf{0.003 \pm 0.011}$
compatible with zero $\chi^2 = 2.3$

$\bar{d}$: mean value $+\mathbf{0.042 \pm 0.025}$
compatible with zero $\chi^2 = 7.2$

proton 2007+2010
deuteron 2002-2004 + **2022**



$\bar{u}$: mean value $+\mathbf{0.017 \pm 0.009}$
compatible with zero $\chi^2 = 11.9$

$\bar{d}$: mean value $-\mathbf{0.003 \pm 0.014}$
compatible with zero $\chi^2 = 7.8$

$\bar{u}$ errors reduced by a factor 1.1 to 1.5
$\bar{d}$: errors reduced by a factor 1.6 to 2.8

$h_1^{d_v}(x)/h_1^{u_v}(x)$ from difference asymmetries

use of difference asymmetries $A^{h^+-h^-}$

main advantage:

$h_1^{d_v}(x)/h_1^{u_v}(x)$
is obtained from the p and d Collins asymmetries in SIDIS only:
the Collins FF is not needed

the method is not new:

used by EMC NPB 321 (1989) 541
quoted in HELP proposal for transversity
and in COMPASS proposal for L and T spin asymmetries
…

E. Christova and E. Leader, NPB 607 (2001) 369, …

V. Barone et el., PRD 99 (2019) 114004

M. Anselmino, R. Kishore and A. Mukherjee, PRD 102 (2020) 9, 096012

$h_1^{d_v}(x)/h_1^{u_v}(x)$ from difference asymmetries - reminder

V. Barone et al PRD 99 (2019) 114004

the difference asymmetries

cross section for h^+, h^- $\quad \sigma_t^{\pm}(\Phi_C) = \sigma_{0t}^{\pm} + f P_t D_{NN} \sigma_{Ct}^{\pm} \sin\Phi_C \,, \qquad t = p, d$

Collin asymmetries $\quad A_{C,t}^{\pm} = \sigma_{Ct}^{\pm}/\sigma_{0t}^{\pm}$

difference asymmetries $\quad A_{D,t} = \dfrac{\sigma_{Ct}^{+} - \sigma_{Ct}^{-}}{\sigma_{0t}^{+} + \sigma_{0t}^{-}}$

$h_1^{d_v}(x)/h_1^{u_v}(x)$ from difference asymmetries - reminder

V. Barone et al PRD 99 (2019) 114004

the difference asymmetries

cross section for h^+, h^- $\sigma_t^{\pm}(\Phi_C) = \sigma_{0t}^{\pm} + f P_t D_{NN} \sigma_{Ct}^{\pm} \sin\Phi_C$, $t = p, d$

Collin asymmetries $A_{C,t}^{\pm} = \sigma_{Ct}^{\pm}/\sigma_{0t}^{\pm}$

difference asymmetries $A_{D,t} = \dfrac{\sigma_{Ct}^{+} - \sigma_{Ct}^{-}}{\sigma_{0t}^{+} + \sigma_{0t}^{-}}$

with the usual assumptions on FFs, difference asymmetries for proton and for deuteron can be written as

$$A_{D,p} = \frac{1}{9}\frac{H_{1fav} - H_{1unf}}{\sigma_{0p}^{+} + \sigma_{0p}^{-}}\left(4h_1^{u_v} - h_1^{d_v}\right)$$

$$A_{D,d} = \frac{1}{3}\frac{H_{1fav} - H_{1unf}}{\sigma_{0d}^{+} + \sigma_{0d}^{-}}\left(h_1^{u_v} + h_1^{d_v}\right)$$

in the ratio, the Collins FFs cancel and it is

$$\frac{A_{D,d}}{A_{D,p}} = 3\left[\frac{(4f_1^u + 4f_1^{\bar{u}} + f_1^d + f_1^{\bar{d}})(D_{1,\text{fav}} + D_{1,\text{unf}}) + 2(f_1^s + f_1^{\bar{s}})D_{1,s}}{5(f_1^u + f_1^d + f_1^{\bar{u}} + f_1^{\bar{d}})(D_{1,\text{fav}} + D_{1,\text{unf}}) + 4(f_1^s + f_1^{\bar{s}})D_{1,s}}\right]\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}}$$

thus, from the ratio of the difference asymmetries on p and d, one obtains $h_1^{d_v}(x)/h_1^{u_v}(x)$

$h_1^{d_v}(x)/h_1^{u_v}(x)$ from difference asymmetries - reminder

V. Barone et al PRD 99 (2019) 114004

how to measure $$A_{D,t} = \frac{\sigma_{Ct}^{+} - \sigma_{Ct}^{-}}{\sigma_{0t}^{+} + \sigma_{0t}^{-}}$$

in principle, one should measure the difference of the cross-section

$$\sigma_t^D(\Phi_C) = +f P_t D_{NN} \sigma_{Ct}^{\pm}(\sigma_{Ct}^{+} - \sigma_{Ct}^{-}) \sin\Phi_C$$

and extract the amplitude of the $\sin\Phi_C$ modulation

experimentally it is easier, if the acceptances for positive and negative hadrons are about the same, as in COMPASS, use the ratios of number of events and obtain the difference asymmetries from

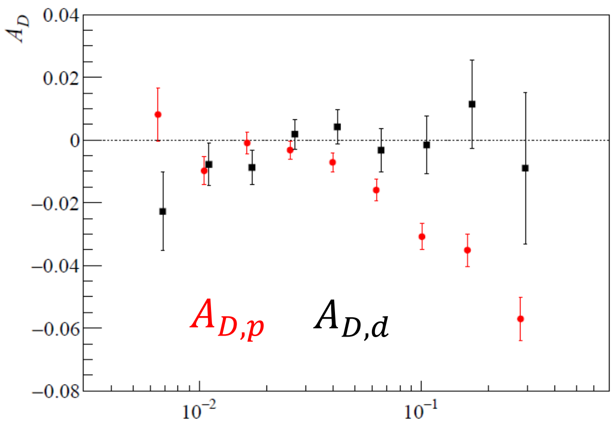
$$A_{D,t} = \frac{\mathrm{var}(A_{Ct}^{-})}{\mathrm{var}(A_{Ct}^{+}) + \mathrm{var}(A_{Ct}^{-})} A_{Ct}^{+} - \frac{\mathrm{var}(A_{Ct}^{+})}{\mathrm{var}(A_{Ct}^{+}) + \mathrm{var}(A_{Ct}^{-})} A_{Ct}^{-}$$

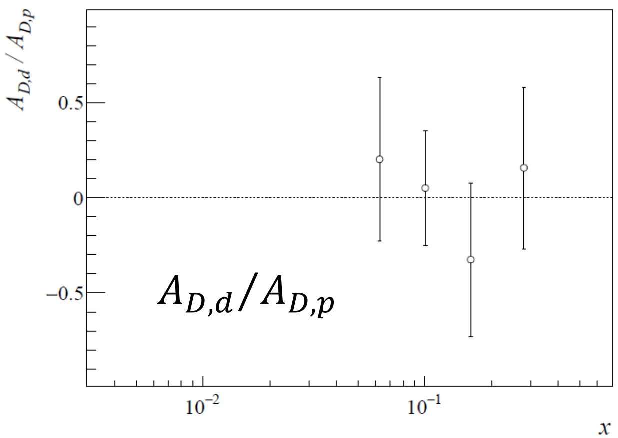
this is the method used in 2019, and it is what we have done now, with the new COMPASS data

$h_1^{d_v}(x)/h_1^{u_v}(x)$ from difference asymmetries

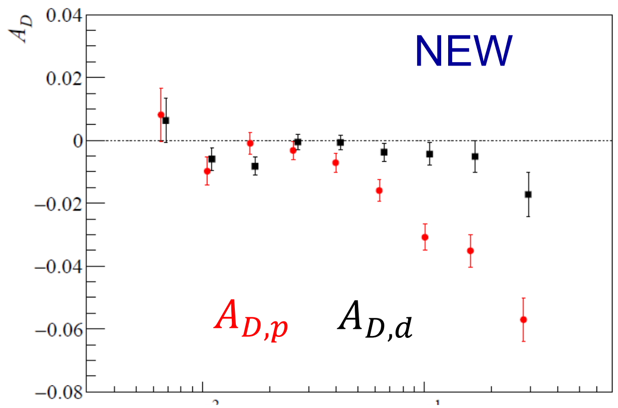
COMPASS data only

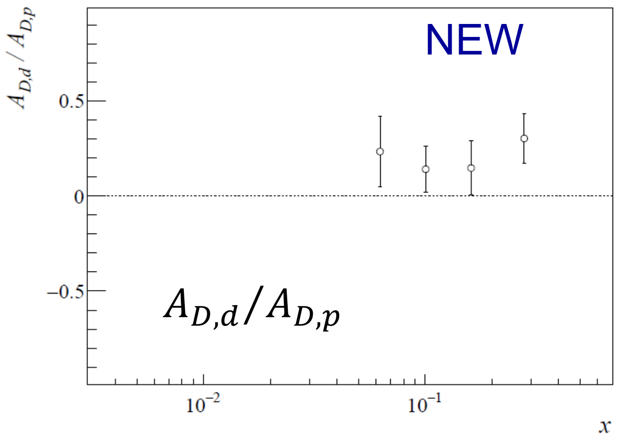
proton 2007+2010
deuteron 2002-2004





proton 2007+2010
deuteron 2002-2004 + **2022**

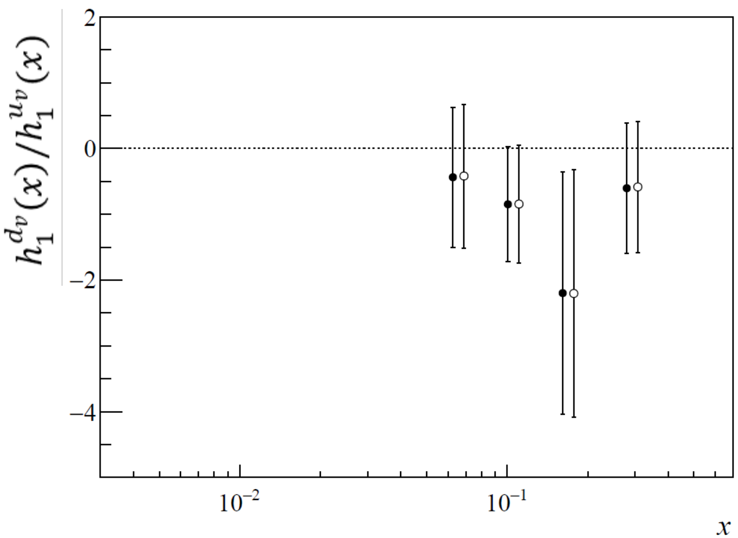




$h_1^{d_v}(x)/h_1^{u_v}(x)$ from difference asymmetries

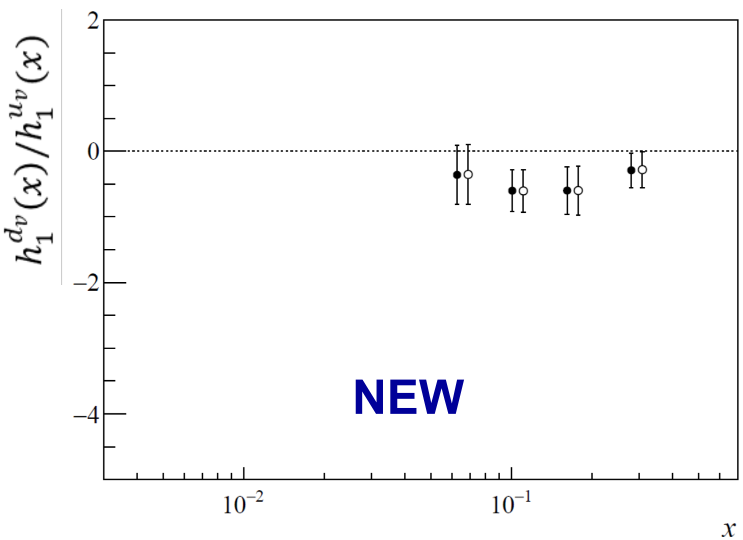
from COMPASS data only

proton 2007+2010
deuteron 2002-2004



mean value -0.79 ± 0.53

proton 2007+2010
deuteron 2002-2004 + **2022**



mean value $\mathbf{-0.45 \pm 0.16}$

errors reduced by a factor 2 to 5

Further direct extractions of transversity

Summary

- in a simple and direct model-independent way we have extracted the u and d quark transversity distributions, both valence and sea, from the COMPASS and the Belle data, and their ratio from the difference asymmetries

- thanks to the new COMPASS results, transversity of the valence d quark
  - turns out to be compatible but smaller than that previously estimated and different from zero
  - no hints for violation of the Soffer bound

- sea-quark transversity functions are better determined and compatible with zero

Thank you