TMDs Phenomenology in SIDIS and DY

Studying the hadron structure in Drell-Yan reactions
CERN, 25-27th April 2010

Stefano Melis
Universita' del Piemonte Orientale
INFN, Sezione di Torino & G.C. Alessandria

Summary

- Sivers function in SIDIS from fits
- Conclusions I
- Boer-Mulders function from fit (SIDIS&DY)
- Conclusions II

Sivers function in SIDIS from fits

Sivers function in SIDIS from fits

- Most recent fits

[1] Anselmino et al. , Eur. Phys. J. A39, 89-100 (2009)

[2]Arnold, Efremov, Goeke, Schlegel, Schweitzer, arXiv:0805.2137 (2008)

✔Fits of HERMES (2002-5) and COMPASS (Deuteron 2003-4) data on π and K production

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

Polarized SIDIS $lp^{\uparrow} \rightarrow l'h+X$

Extraction of the Sivers Function

- The cross section can be written as:

$$d\sigma^{lp^{\uparrow} \to l'hX} = \sum_q f_{q/p^{\uparrow}}(x, \boldsymbol{k}_{\perp}, Q^2) \otimes d\sigma^{lq \to l'q} \otimes D_q^h(z, \boldsymbol{p}_{\perp}, Q^2)$$

Polarized PDF

Fragmentation Function

Elementary Cross section

Polarized SIDIS:

Extraction of the Sivers Function

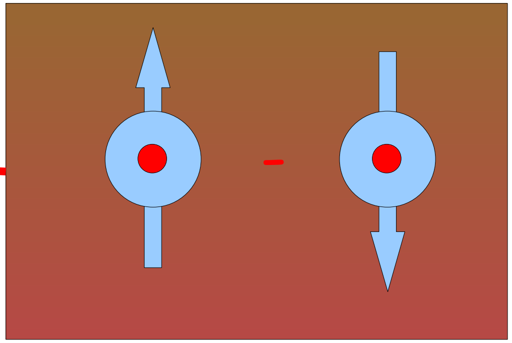
- If we consider the transverse motion and its correlation with the spin of the proton then:

$$f_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}_T\cdot(\hat{\boldsymbol{P}}\times\hat{\boldsymbol{k}}_\perp)$$

$$= \underbrace{f_{q/p}(x,k_\perp)}_{\text{Unp. PDF}} - \underbrace{\frac{k_\perp}{m_p} f_{1T}^\perp(x,k_\perp)}_{\text{Sivers function}}\,\boldsymbol{S}_T\cdot(\hat{\boldsymbol{P}}\times\hat{\boldsymbol{k}}_\perp)$$

✔Torino vs Amsterdam notation

$$\frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp) = -\frac{k_\perp}{m_p} f_{1T}^{\perp q}(x,k_\perp)$$



Polarized SIDIS:

Extraction of the Sivers Function

➢ If we consider the transverse motion and its correlation with the spin of the proton then:

$$\begin{aligned} f_{q/p^\uparrow}(x,\boldsymbol{k}_\perp) &= f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\, \boldsymbol{S}_T \cdot (\hat{\boldsymbol{P}} \times \hat{\boldsymbol{k}}_\perp) \\ &= f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\, \underbrace{\sin(\varphi - \phi_S)} \end{aligned}$$

✔ Azimuthal phase: angle between $k_\perp$ and the spin

✔ Bound:

$$\frac{|\Delta^N f_{q/p^\uparrow}(x,k_\perp)|}{2 f_{q/p}(x,k_\perp)} \leq 1$$

Polarized SIDIS:

Extraction of the Sivers Function

- We can build an azimuthal weighted asymmetry

$$A_{UT}^{\sin(\phi_h-\phi_S)} = 2\,\frac{\int d\phi_S\, d\phi_h\,[d\sigma^{\uparrow}-d\sigma^{\downarrow}]\,\sin(\phi_h-\phi_S)}{\int d\phi_S\, d\phi_h\,[d\sigma^{\uparrow}+d\sigma^{\downarrow}]}$$

- In details:

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\sum_q \int d\phi_S\, d\phi_h\, d^2\boldsymbol{k}_\perp\, \Delta^N f_{q/p^\uparrow}(x,k_\perp)\sin(\varphi-\phi_S)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}\; D_q^h(z,p_\perp)\sin(\phi_h-\phi_S)}{\sum_q \int d\phi_S\, d\phi_h\, d^2\boldsymbol{k}_\perp\, f_{q/p}(x,k_\perp)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}\; D_q^h(z,p_\perp)}$$

[1] Anselmino et al. , Eur. Phys. J. A39, 89-100 (2009)

Polarized SIDIS:

Extraction of the Sivers Function

- Gaussian smearing for both unpolarized PDF and FF

✎ $$f_{q/p}(x, k_\perp) = f_q(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}$$

GRV98 set

$$\langle k_\perp^2 \rangle = 0.25 \; (\mathrm{GeV}/c)^2$$

✎ $$D_q^h(z, p_\perp) = D_q^h(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2/\langle p_\perp^2 \rangle}$$

DSS set

$$\langle p_\perp^2 \rangle = 0.20 \; (\mathrm{GeV}/c)^2$$

[*]Cahn cosϕ analysis, Anselmino et. Phys. Rev D71, 074006 (2005)

Polarized SIDIS:

Extraction of the Sivers Function

- Simple parametrization of the Sivers function

$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x,k_\perp)$$

Unpolarized PDF

$$\mathcal{N}_q(x) = N_q\, x^{\alpha_q}(1-x)^{\beta_q}\,\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\,\beta_q^{\beta_q}} \leq 1$$

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M_1}\,e^{-k_\perp^2/M_1^2} \leq 1$$

N_q, α_q, β_q & M_1 free parameters

Polarized SIDIS:

Extraction of the Sivers Function

- **HERMES** (2002-5)
  (x,z,P_T) π&K
- **COMPASS** (2004)
  (x,z,P_T) π&K
- 11 free parameters:

  N_u N_d $N_{\bar{u}}$ $N_{\bar{d}}$ N_s $N_{\bar{s}}$

  α_u α_d α_{sea}

  β M_1

✔GRV98 PDF

✔DSS FF

✔Gaussians: $\langle k_\perp^2\rangle = 0.25$ $(\mathrm{GeV}/c)^2$
$\langle p_\perp^2\rangle = 0.20$ $(\mathrm{GeV}/c)^2$
(from Cahn effect)

✔Simulated evolution (unp.-like)

✔ $$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x,k_\perp)$$

✔ $$\mathcal{N}_q(x) = N_q\,x^{\alpha_q}(1-x)^{\beta_q}\,\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\,\beta_q^{\beta_q}}$$

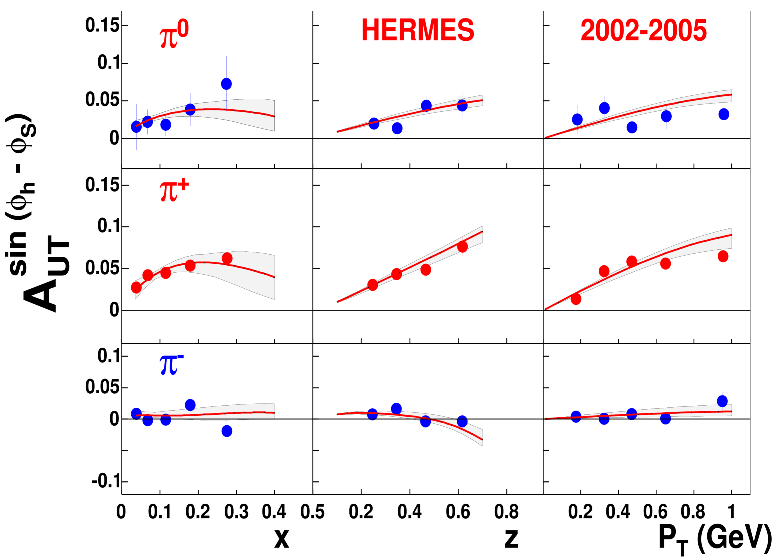
✔ $$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M_1}\,e^{-k_\perp^2/M_1^2}$$

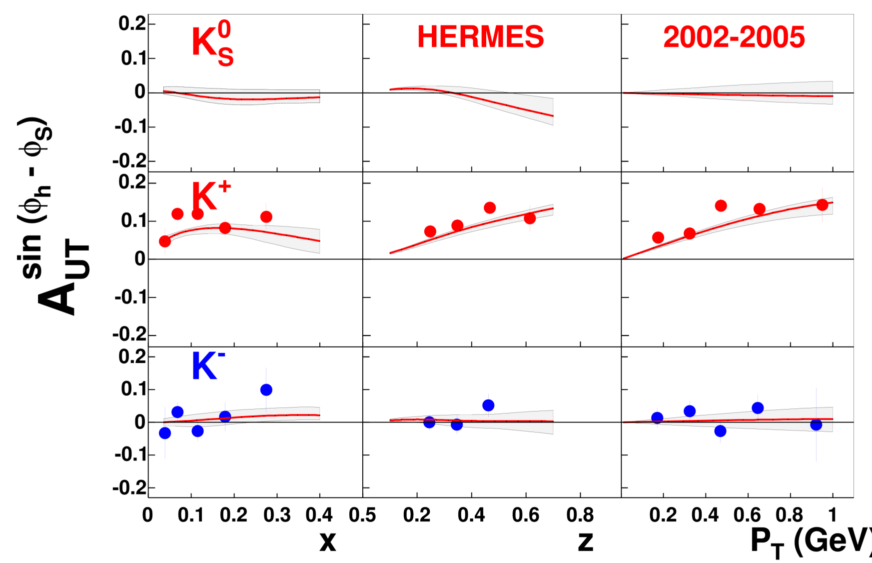
•Anselmino et al. Eur. Phys. J. A39,89

Polarized SIDIS:

Extraction of the Sivers Function

HERMES Proton Target

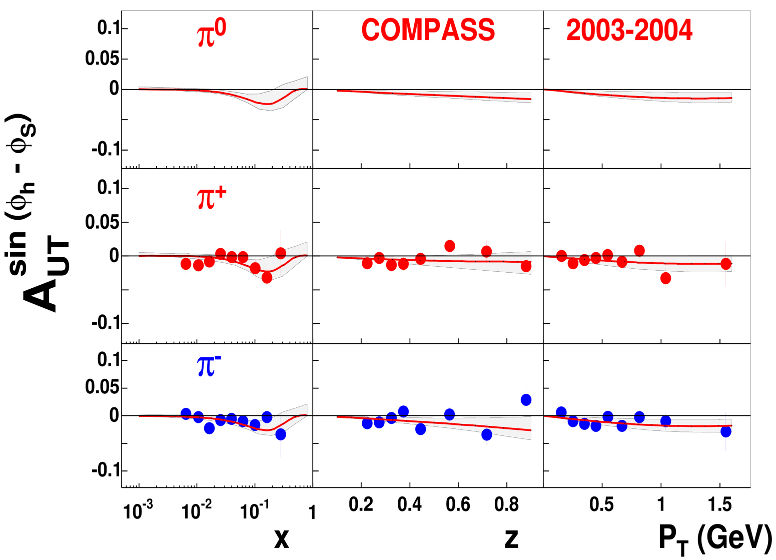


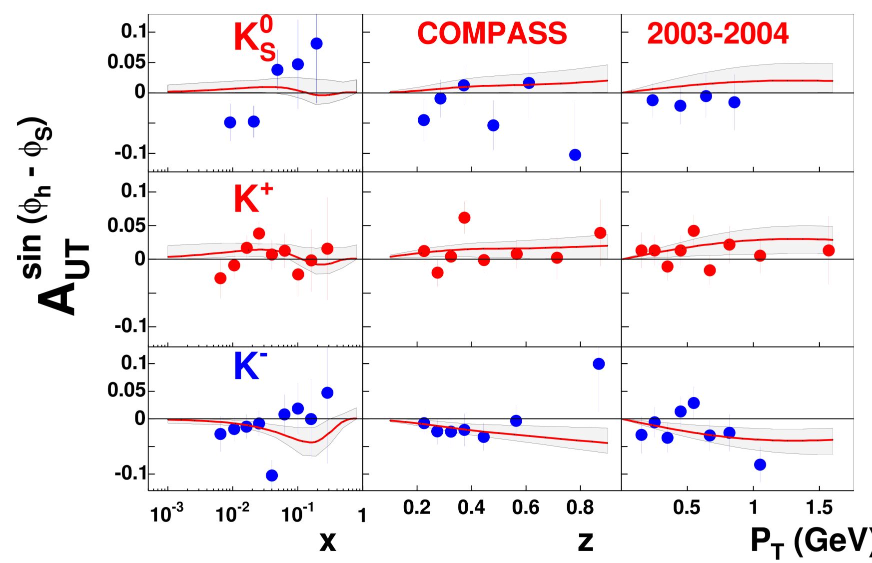


Polarized SIDIS:

Extraction of the Sivers Function

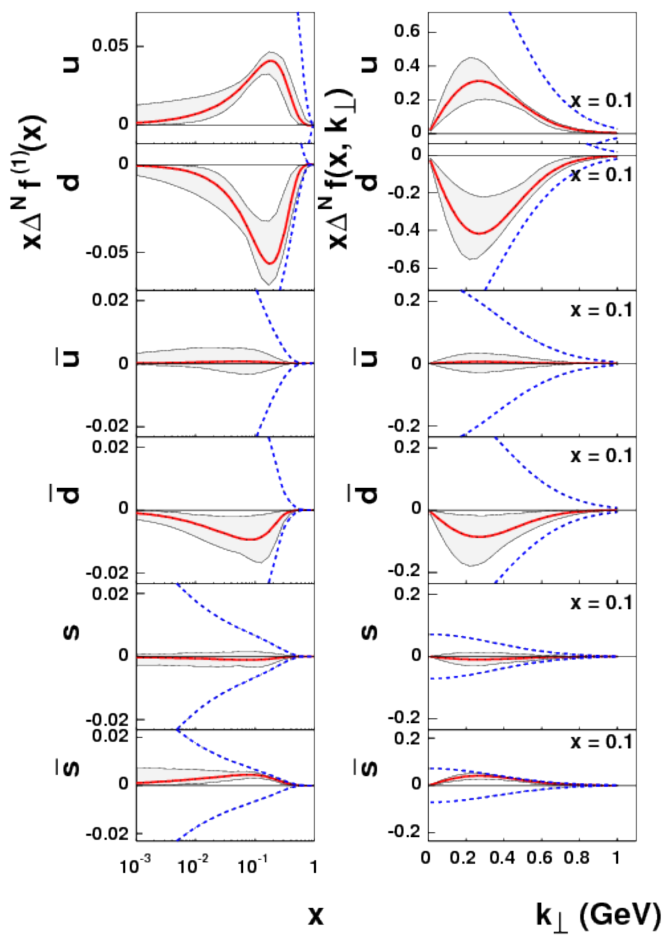
COMPASS Deuteron Target





Polarized SIDIS:

Extraction of the Sivers Function



✔ Valence quark

- $\Delta^N f_{u/p^\uparrow} > 0 \quad \Rightarrow f_{1T}^{\perp u} < 0$
- $\Delta^N f_{d/p^\uparrow} < 0 \quad \Rightarrow f_{1T}^{\perp d} > 0$

✔ Sea quarks

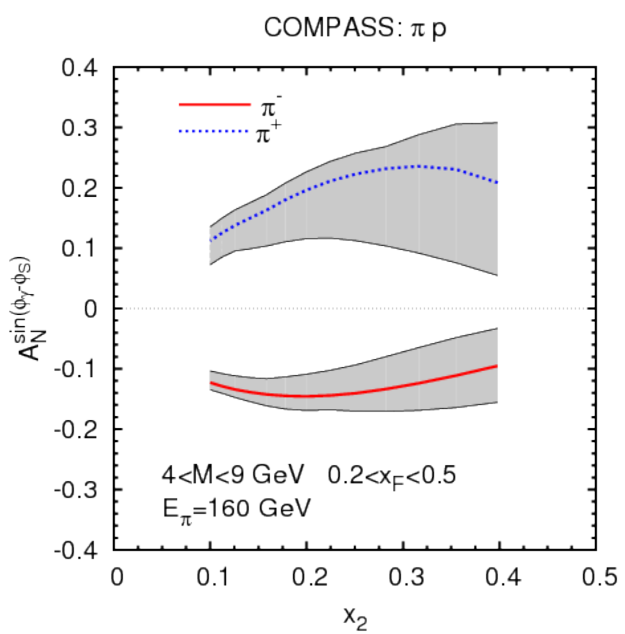
- $\Delta^N f_{\bar{s}/p^\uparrow} > 0 \quad \Rightarrow f_{1T}^{\perp \bar{s}} < 0$

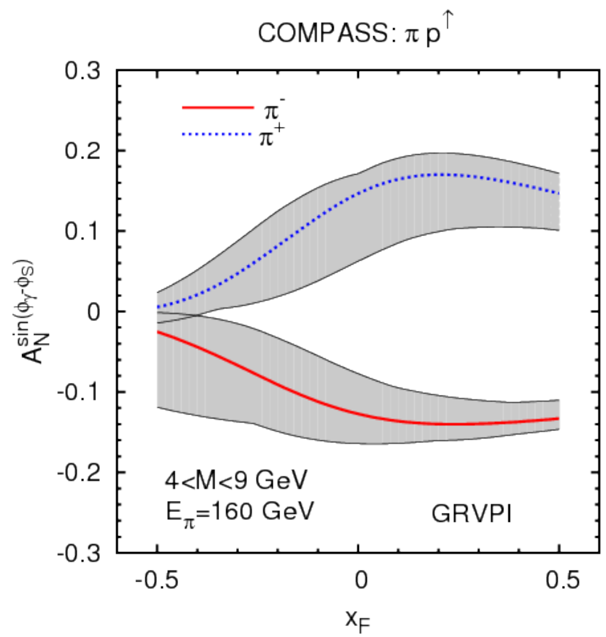
$\chi^2/d.o.f = 1$		
$N_u = 0.35^{+0.078}_{-0.079}$	$N_d = -0.9^{+0.43}_{-0.098}$	$N_s = -0.24^{+0.62}_{-0.5}$
$N_{\bar{u}} = 0.037^{+0.22}_{-0.24}$	$N_{\bar{d}} = -0.4^{+0.33}_{-0.44}$	$N_{\bar{s}} = 1^{+0}_{-0.0001}$
$\alpha_u = 0.73^{+0.72}_{-0.58}$	$\alpha_d = 1.1^{+0.82}_{-0.65}$	$\alpha_{sea} = 0.79^{+0.56}_{-0.47}$
$\beta = 3.5^{+4.9}_{-2.9}$	$M_1^2 = 0.34^{+0.3}_{-0.16}$ GeV^2	

→ $\Delta^N f_q^{(1)}(x) \equiv \int d^2 \boldsymbol{k}_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x)$

Predictions for COMPASS DY

- Polarized NH_3
- Pion beam
- Valence region for the Sivers function





Large measurable asymmetry!!!

- Anselmino et al. Phys. Rev. D79,054010

[2]Arnold, Efremov, Goeke, Schlegel, Schweitzer,
arXiv:0805.2137 (2008)

Polarized SIDIS:

Extraction of the Sivers Function

- Gaussian smearing for unpolarized PDF, FF and Sivers function

  - ✎ $\langle k_\perp^2 \rangle = 0.33\ (\mathrm{GeV}/c)^2$ for the unpolarized PDF [*]
  - ✎ $\langle p_\perp^2 \rangle = 0.16\ (\mathrm{GeV}/c)^2$ for the unpolarized FF [*]
  - ✎ $\langle k_\perp^2 \rangle_{\mathrm{Siv}} = 0.2\ (\mathrm{GeV}/c)^2$ for the Sivers function [*]

[*] Collins et al. Phys. Rev. D73, 014021 (2006)
Values obtained analyzing the kinematic of HERMES

Polarized SIDIS:

Extraction of the Sivers Function

- Parametrization of the first moment of the Sivers function

$$f_{1T}^{\perp q(1)}(x) = A_q \frac{\langle k_\perp \rangle}{2m_p} f_{q/p}(x)$$

where:

$$f_{1T}^{\perp q}(x) = \int d\boldsymbol{k}_\perp^2 \frac{\boldsymbol{k}_\perp^2}{2m_p} f_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2)$$

$|A_q| < 1$ q = all light flavours

$$\langle k_\perp \rangle = \frac{\sqrt{\pi}}{2} \sqrt{\langle k_\perp^2 \rangle} = 0.5 \ (\mathrm{GeV}/c)$$

Polarized SIDIS:

Extraction of the Sivers Function

- **HERMES** (2002-5)
  (x) π&K

- **COMPASS** (2004)
  (x) π&K

- 4 free parameters:
  A_u A_d $A_{\bar{u}}$ $A_{\bar{d}}$ $A_s=1$ $A_{\bar{s}}=-1$

✔GRV98 PDF

✔Kretzer FF

✔Gaussians: $\langle k_\perp^2 \rangle = 0.33\ (GeV/c)^2$
$\langle p_\perp^2 \rangle = 0.16\ (GeV/c)^2$
$\langle k_\perp^2 \rangle_{Siv} = 0.20\ (GeV/c)^2$

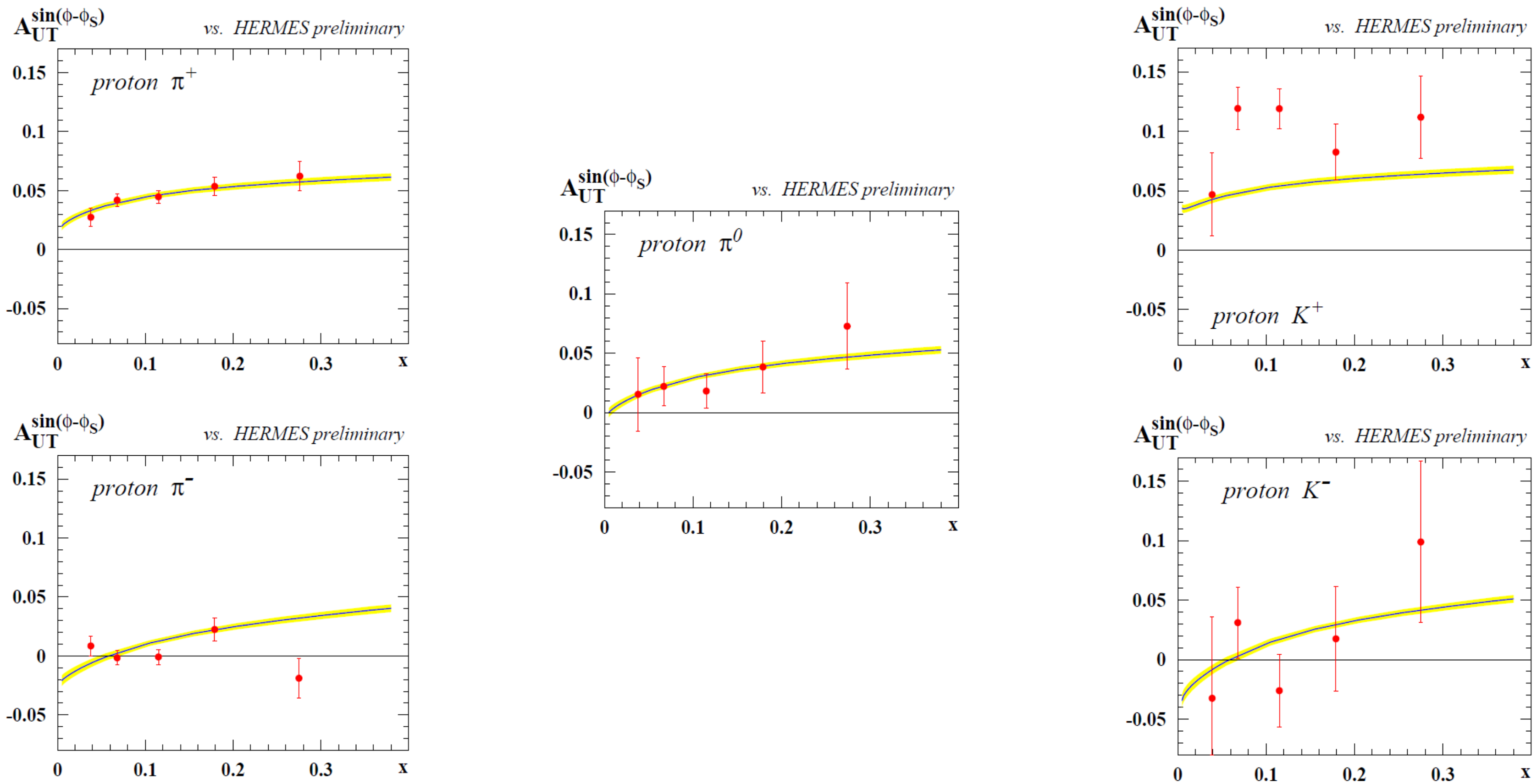
✔$Q^2 = 2.5\ (Gev/c)^2$

✔$$f_{1T}^{\perp q(1)}(x) = A_q \frac{\langle k_\perp \rangle}{2m_p} f_{q/p}(x)$$

Polarized SIDIS:

Extraction of the Sivers Function

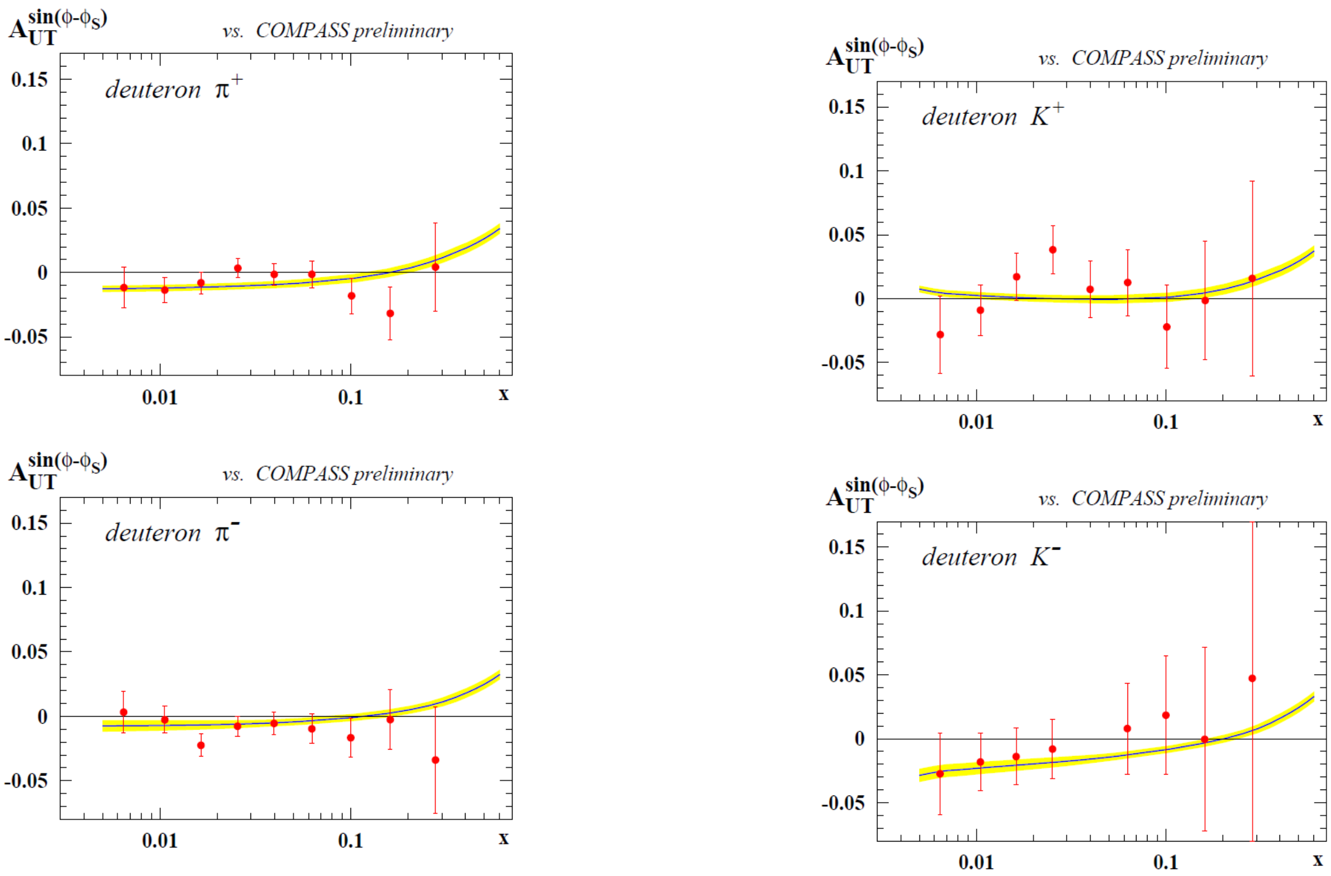
HERMES Proton Target



Polarized SIDIS:

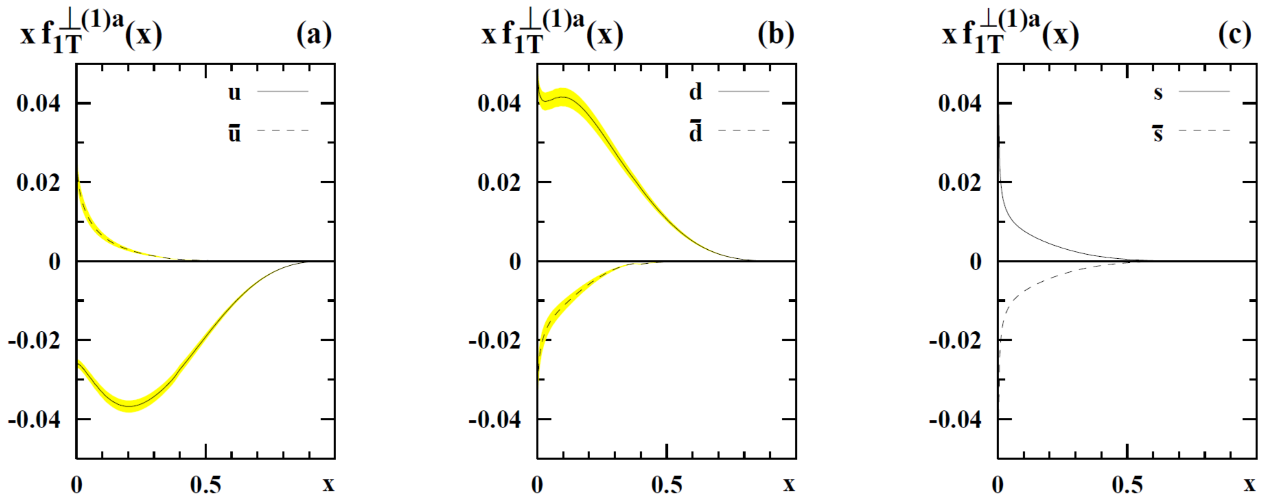
Extraction of the Sivers Function

COMPASS Deuteron Target



Polarized SIDIS:

Extraction of the Sivers Function



✔Valence quark

- $f_{1T}^{\perp u} < 0 \Rightarrow \Delta^N f_{u/p^\uparrow} > 0$
- $f_{1T}^{\perp d} > 0 \Rightarrow \Delta^N f_{d/p^\uparrow} < 0$

✔Sea quarks

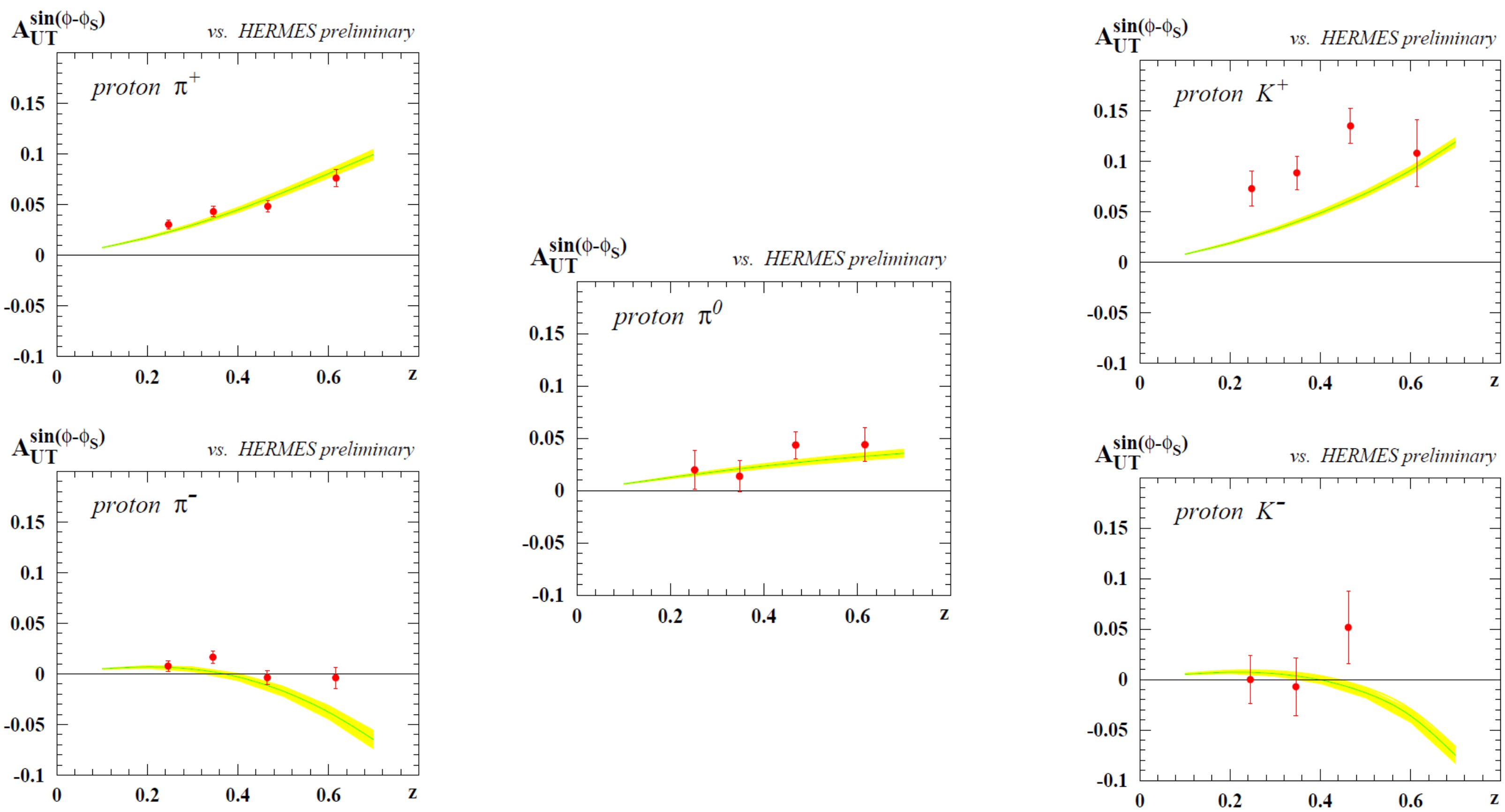
- $f_{1T}^{\perp \bar{s}} < 0 \Rightarrow \Delta^N f_{\bar{s}/p^\uparrow} > 0$

$$\chi^2_{\mathrm{d.o.f.}} = 1.3 \quad \begin{array}{lll} A_u = -0.21 \pm 0.01 & A_{\bar{u}} = \ \ 0.23 \pm 0.02 & A_s \overset{\text{fixed}}{=} +1 \\ A_d = \ \ 0.38 \pm 0.03 & A_{\bar{d}} = -0.28 \pm 0.04 & A_{\bar{s}} \overset{\text{fixed}}{=} -1 \end{array}$$

Polarized SIDIS:

Extraction of the Sivers Function

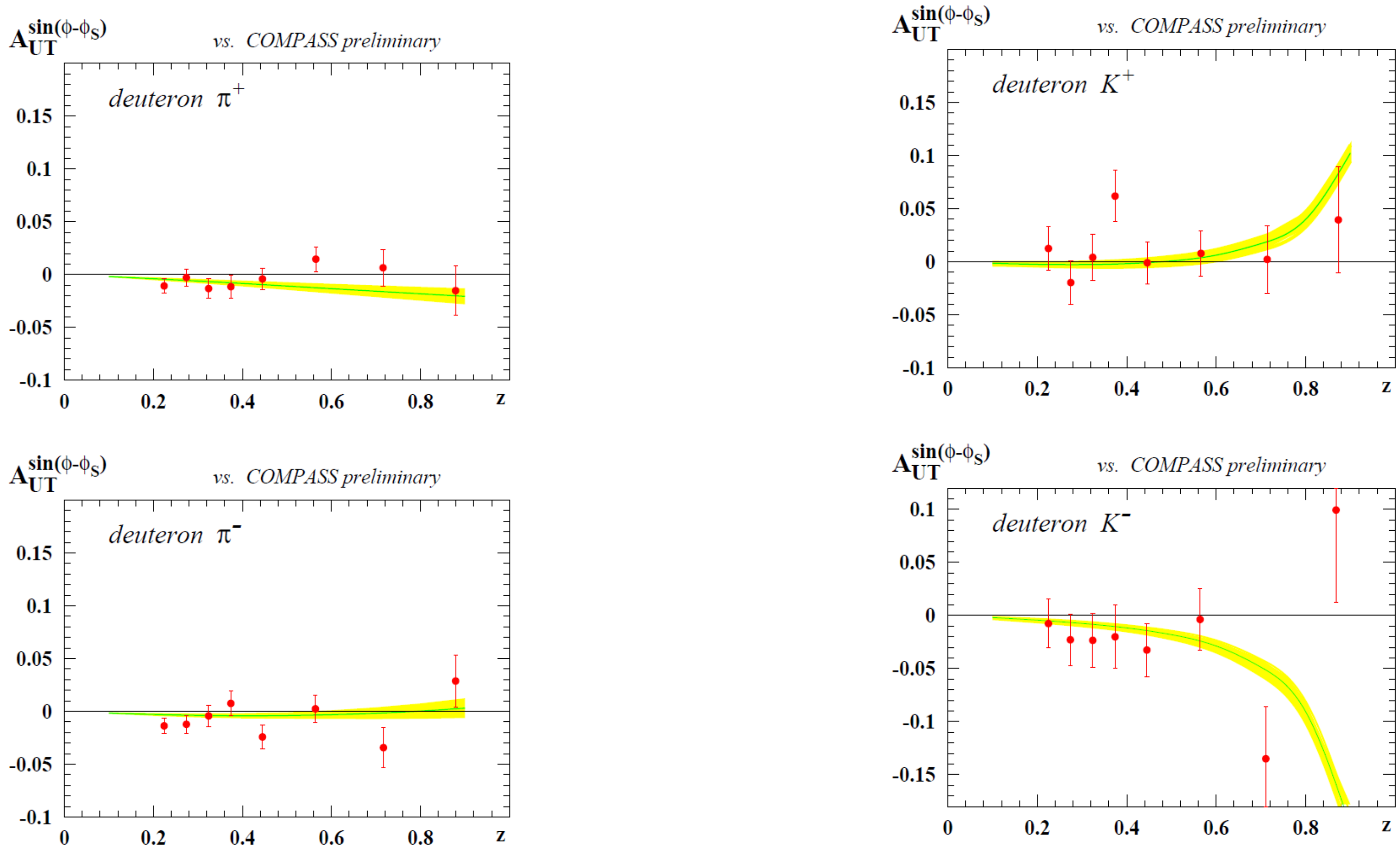
HERMES Proton Target (Predictions)



Polarized SIDIS:

Extraction of the Sivers Function

COMPASS Deuteron Target(Predictions)



Conclusions I

- The main results of the two fits are the same:
  - u and d quark Sivers functions are opposite in sign and similar in magnitude
  - The two fits agree in the sign of the Sivers functions for u,d, $\bar{s}$ quarks

- Open questions: Average transverse momentum
  Evolution equation....

- Analysis of new data! (COMPASS proton)

- Waiting for polarized DY!

Boer-Mulders function from fits

Boer-Mulders function from $A^{\cos 2\phi}$ in SIDIS

- Most Recent fit

[3] V. Barone, S. Melis and A. Prokudin
ArXiv:0912.5194 (to be published in Phys. Rev. D)

✔Fits of HERMES (proton and deuteron) and COMPASS (deuteron) data on charged hadrons production

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution

Unpolarized PDF

Unpolarized FF

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp})$ subleading Cahn+Boer-Mulders effect

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp})$ subleading Cahn+Boer-Mulders effect

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp)$ subleading Cahn+Boer-Mulders effect

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp)$ subleading Cahn+Boer-Mulders effect

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp})$ subleading Cahn+Boer-Mulders effect

Boer-Mulders function ($h_1^{\perp}$)

Collins function ($H_1^{\perp}$)

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A =\propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp})$ subleading Cahn+Boer-Mulders effect
- $C \propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp)$ subleading Cahn+Boer-Mulders effect
- $C \propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

Leading Twist BM

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp)$ subleading Cahn+Boer-Mulders effect
- $C \propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

Twist-4 Cahn

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A =\propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $B \propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp})$ subleading Cahn+Boer-Mulders effect
- $C \propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$ +...other unknown twist-4 terms?

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $C \propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

$$A^{\cos 2\phi} = 2\frac{\int d\sigma \cos 2\phi}{\int d\sigma} = \frac{C}{A}$$

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A =\propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $C \propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

Unpolarized PDF&FF gaussian as in Anselmino et al. [1]

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $C \propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

Collins function as in Anselmino et. al arXiv: 0812.4366v1

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The angular distribution in the unpolarized SIDIS can be written as

$$d\sigma = A + B\cos\phi + C\cos 2\phi$$

- $A = \propto f_1 \otimes D_1$ is the usual ϕ-independent contribution
- $C \propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$ BM effect+Twist-4 Cahn effect

BM that we want to extract from the fit of $A^{\cos 2\phi}$ data

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- Simple parametrization of the Boer-Mulders functions:

  - $h_1^{\perp q}(x, k_\perp) = \lambda_q \, f_{1T}^{\perp q}(x, k_\perp)$ for valence quarks
  - $h_1^{\perp q}(x, k_\perp) = -|f_{1T}^{\perp q}(x, k_\perp)|$ for sea quarks

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- HERMES proton and deuteron target (x, z, P_T) charged hadrons
- COMPASS deuteron target (x, z, P_T) charged hadrons
- 2 free parameters:

  $\lambda_u \quad \lambda_d$

- Sivers function as in [*]

FIT I

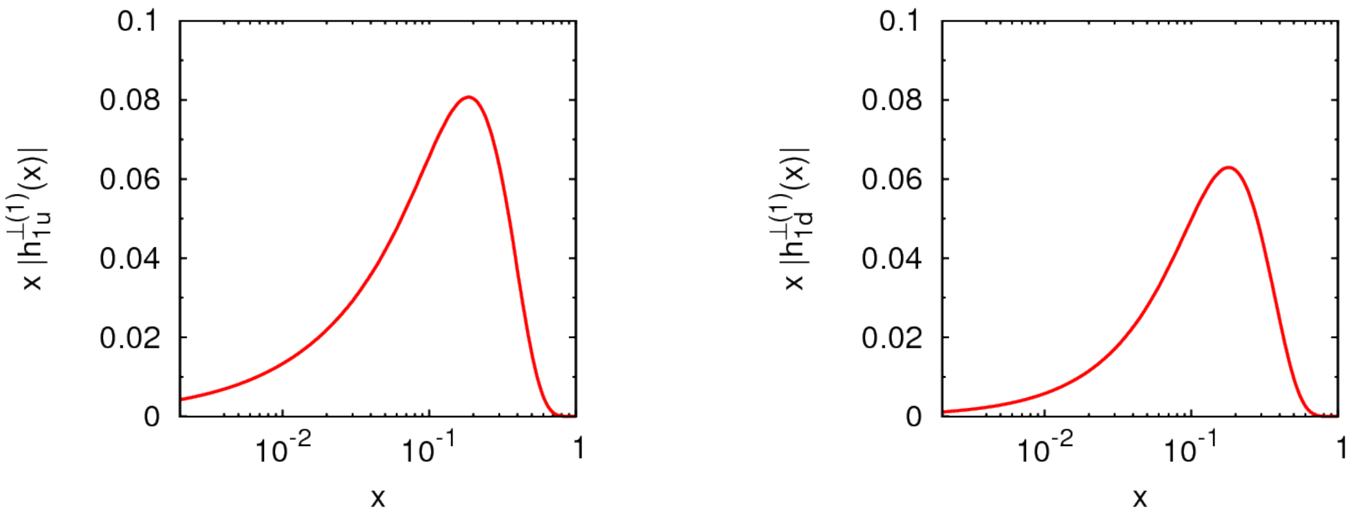
- ✔GRV98 PDF
- ✔DSS FF
- ✔Gaussians: $\langle k_\perp^2 \rangle = 0.25\ (GeV/c)^2$
  $\langle p_\perp^2 \rangle = 0.20\ (GeV/c)^2$
  (from Cahn-cosϕ effect)
- ✔Simulated evolution (unp.)

- ✔ $h_1^{\perp q}(x, k_\perp) = \lambda_q\, f_{1T}^{\perp q}(x, k_\perp)$
- ✔ $h_1^{\perp q}(x, k_\perp) = -|f_{1T}^{\perp q}(x, k_\perp)|$

• [*]Anselmino et al. Eur. Phys. J. A39,89

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function



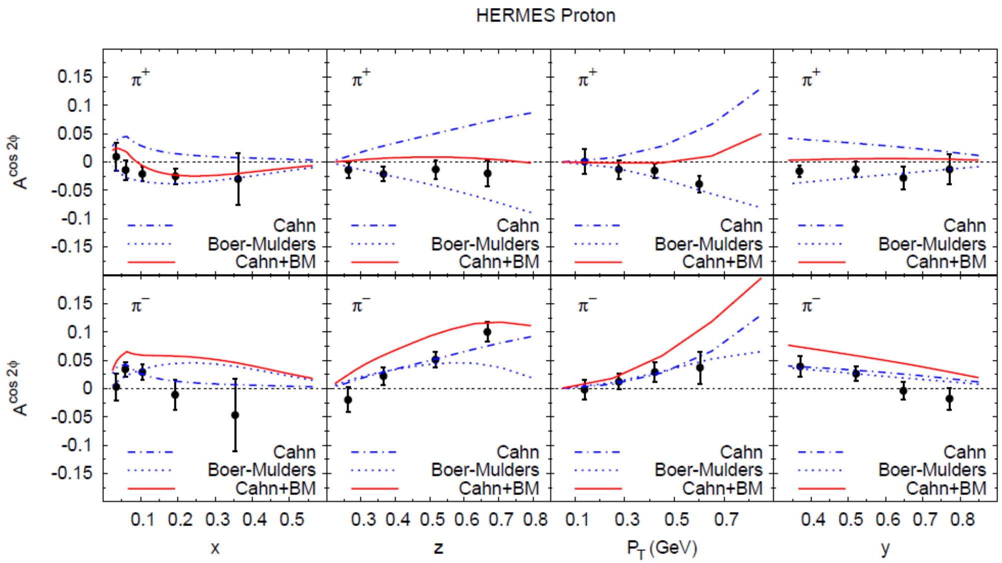
FIT I

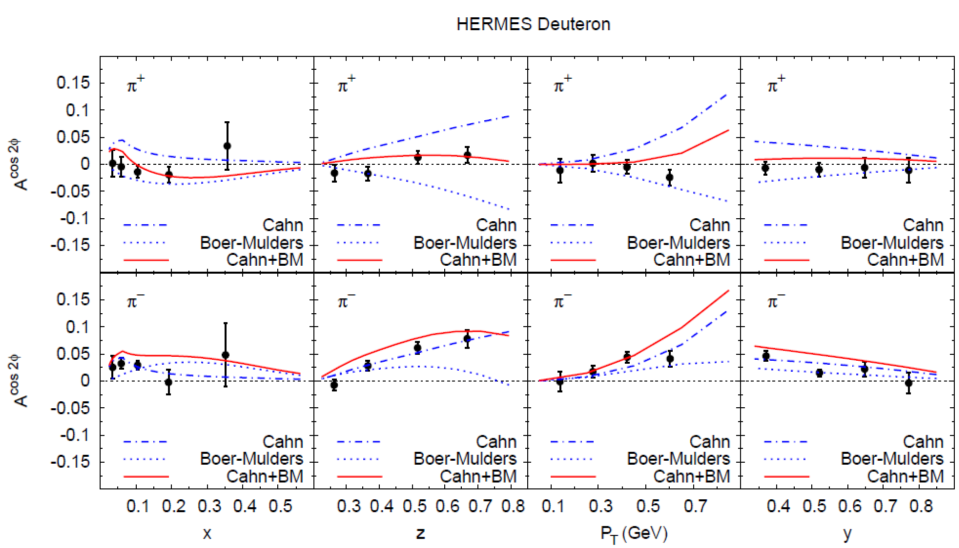
- $\diamond\chi^2/d.o.f. = 3.73$
- $\bullet\lambda_u = 2.0 \pm 0.1$
- $\bullet\lambda_d = -1.11^{+0.00}_{-0.02}$

$\Rightarrow h_1^{\perp d}$ and $h_1^{\perp u}$ both negative

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function



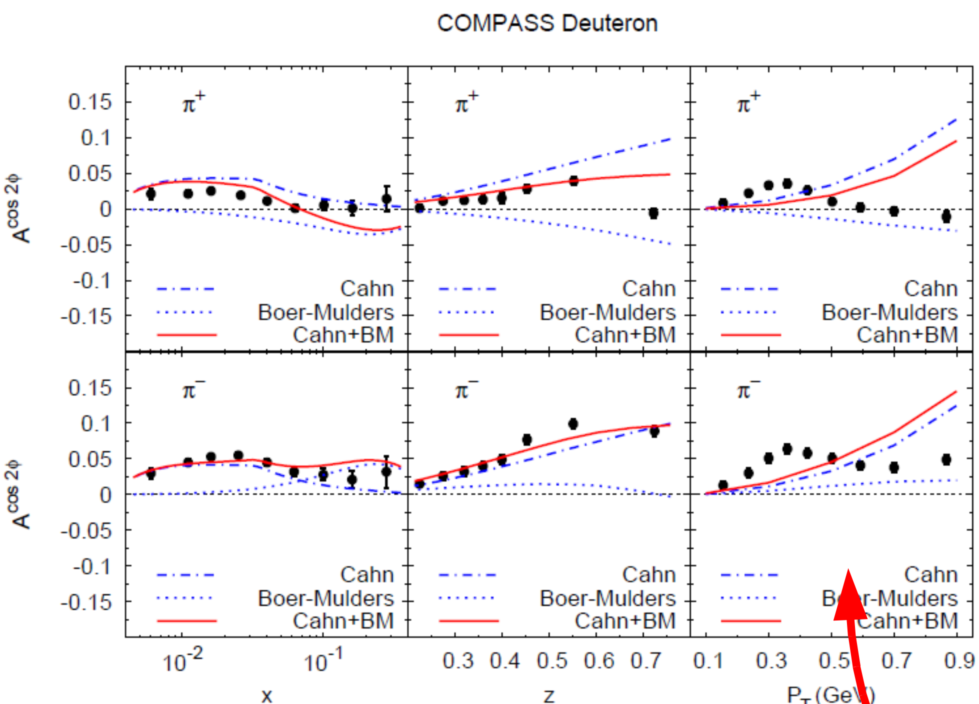


hermes

- ✔Cahn effect (Twist-4)comparable to BM effect
- ✔Same sign of Cahn contribution for positive and negative pions
- ✔BM contribution opposite in sign for positive and negative pions

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function



✔Cahn effect (Twist-4) comparable to BM effect

✔Same sign of Cahn contribution for positive and negative pions

✔BM contribution opposite in sign for positive and negative pions

Data in p_T not included in the fit

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- The Cahn effect is a crucial ingredient

✔Gaussians: $\langle k_\perp^2 \rangle = 0.20\ (GeV/c)^2$
$\langle p_\perp^2 \rangle = 0.25\ (GeV/c)^2$

From Ref.[*]: analysis of Cahn $\cos\phi$ effect from EMC data

[*] Anselmino et al. Phys. Rev. D71 074006 (2005)

Unpolarized SIDIS:
Extraction of the Boer-Mulders Function

- The Cahn effect is a crucial ingredient

✔Gaussians: $\langle k_\perp^2 \rangle = 0.25\ (GeV/c)^2$
$\langle p_\perp^2 \rangle = 0.20\ (GeV/c)^2$

} From Ref.[*]: analysis of Cahn $\cos\phi$ effect form EMC data

COMPASS	HERMES
$\langle k_\perp^2 \rangle = 0.25\ (GeV/c)^2$	$\langle k_\perp^2 \rangle = 0.18\ (GeV/c)^2$
$\langle p_\perp^2 \rangle = 0.20\ (GeV/c)^2$	$\langle p_\perp^2 \rangle = 0.20\ (GeV/c)^2$
~EMC	~HERMES MC

[*] Anselmino et al. Phys. Rev. D71 074006 (2005)

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- FIT II

COMPASS	HERMES
$\langle k_\perp^2 \rangle = 0.25\ (GeV/c)^2$	$\langle k_\perp^2 \rangle = 0.18\ (GeV/c)^2$
$\langle p_\perp^2 \rangle = 0.20\ (GeV/c)^2$	$\langle p_\perp^2 \rangle = 0.20\ (GeV/c)^2$
~EMC	~HERMES MC

FIT II

$\diamond\ \chi^2/d.o.f. = 2.41$

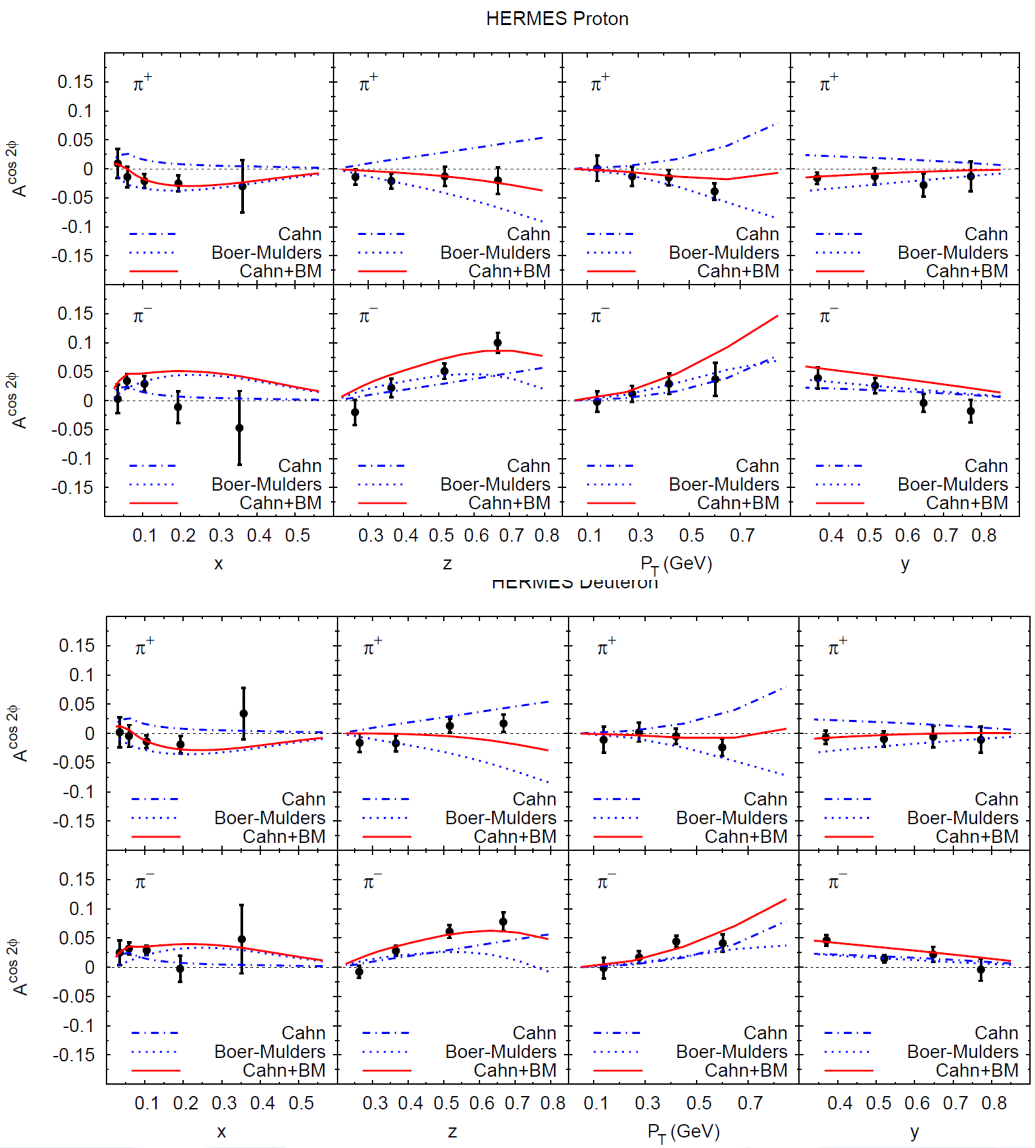
$\bullet\ \lambda_u = 2.1 \pm 0.1$

$\bullet\ \lambda_d = -1.11^{+0.00}_{-0.02}$

Better description of HERMES but the BM is unchanged

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function



Boer-Mulders function in DY from fits

- Most Recent fit

[4] Lu and Schimdt, Phys. Rev. D81, 043023 (2010)

✔Fit of FERMILAB data, unpolarized DY, pp and pD scattering

Boer-Mulders function in DY from fits

- General expression for the dilepton angular distributions in the dilepton rest frame:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi(\lambda+3)}\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+(\nu/2)\,\sin^2\theta\cos 2\phi\right]$$

$$\nu \propto \frac{h_1^{\perp a}\otimes h_1^{\perp b}}{f_1^a \otimes f_1^b}$$

Boer-Mulders functions

Unpolarized PDFs

Boer-Mulders function in DY from fits

- Parametrization of the Boer-Mulders function and of the unpolarized PDF

  - Unpolarized PDFs as in Anselmino et al.

  - $$h_1^{\perp q}(x, \boldsymbol{p}_T^2) = h_1^{\perp q}(x) \frac{\exp(-\boldsymbol{p}_T^2 / p_{bm}^2)}{\pi p_{bm}^2}$$

$$h_1^{\perp q}(x) = H_q x^{c^q} (1-x)^b f_1^q(x)$$

H_q, c_q, b and p_{BM} free parameters

Unpolarized DY:

Extraction of the Boer-Mulders Function

- 9 free parameters:

$H_1 = H_u\ H_{\bar{u}}$ c_u b

$H_2 = H_d\ H_{\bar{d}}$ c_d

$c_{\bar{u}}$ p_{BM}

$H_3 = H_u\ H_{\bar{d}}$ $c_{\bar{d}}$

✔MSTW 2008 LO PDF

✔Gaussians: $\langle k_\perp^2 \rangle = 0.25\ (GeV/c)^2$ (as in SIDIS!)

- FERMILAB E866 pp and pD data (x_1, x_2, x_f, M, P_T)

✔ $$h_1^{\perp q}(x, \boldsymbol{p}_T^2) = h_1^{\perp q}(x) \frac{\exp(-\boldsymbol{p}_T^2 / p_{bm}^2)}{\pi p_{bm}^2}$$

✔ $$h_1^{\perp q}(x) = H_q x^{c^q} (1-x)^b f_1^q(x)$$

Unpolarized DY:

Extraction of the Boer-Mulders Function

$$H_1 = 0.62^{+0.52}_{-0.29}, \quad H_2 = 1.45^{+1.30}_{-1.12}, \quad H_3 = 0.61^{+0.50}_{-0.55},$$

$$c_u = 0.63^{+0.53}_{-0.21}, \quad c_d = 0.47^{+0.36}_{-0.39}, \quad c_{\bar{u}} = 0.07^{+0.06}_{-0.05},$$

$$c_{\bar{d}} = 0.75^{+0.72}_{-0.52}, \quad b_0 = 0.17^{+0.15}_{-0.14}, \quad p^2_{bm} = 0.173^{+0.027}_{-0.033}$$

$$\chi^2/\mathrm{d.o.f} = 0.84$$

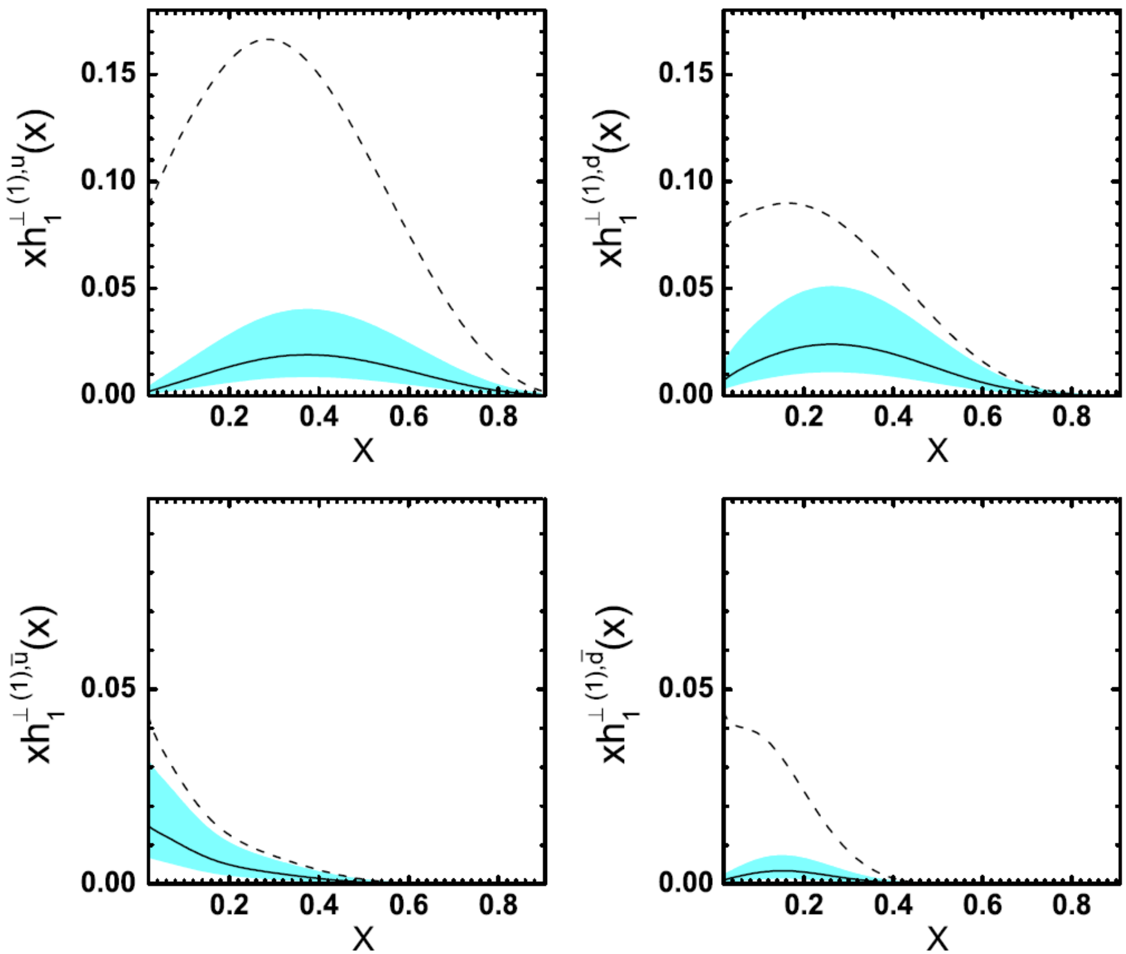
$$\frac{|p_T h_1^{\perp q}(x, \boldsymbol{p}_T^2)|}{M} \leq f_1^q(x, \boldsymbol{p}_T^2) \quad \Rightarrow \quad H_u = 0.59^{+0.64}_{-0.31}, \quad H_d = 1.37^{+1.53}_{-0.72},$$

$$H_{\bar{u}} = 1.10^{+1.21}_{-0.57}, \quad H_{\bar{d}} = 1.08^{+1.18}_{-0.56}.$$

It is not the statistical error on the extraction!
Central values are only geometrical mean values.

Unpolarized DY:

Extraction of the Boer-Mulders Function

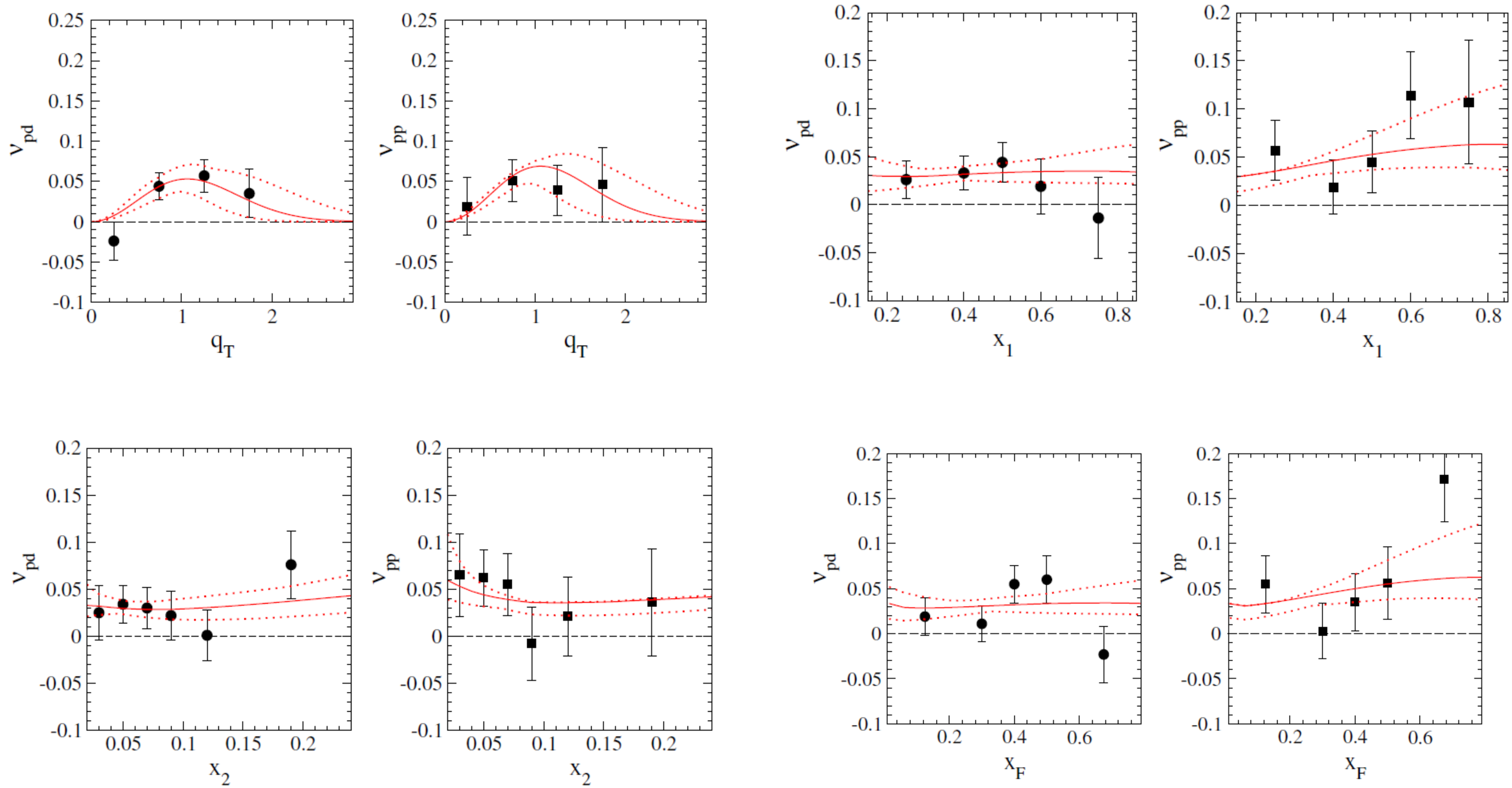


The dotted line is the bound

The bands do not represent the statistical error on the extraction! Central values are only geometrical mean values.

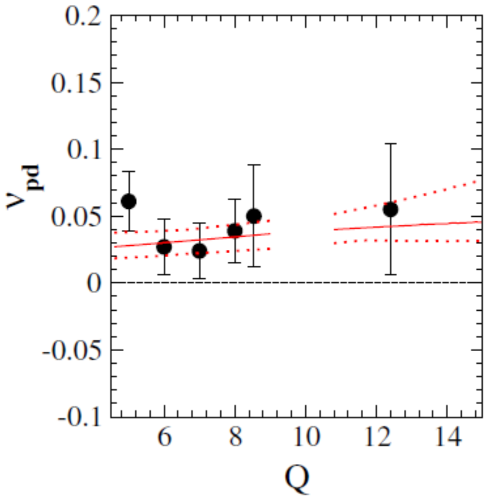
Unpolarized DY:

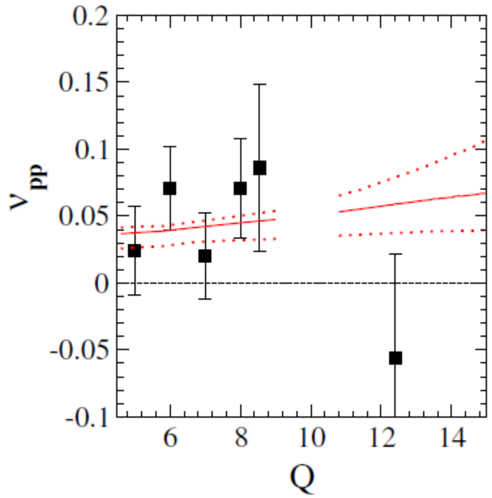
Extraction of the Boer-Mulders Function



Unpolarized DY:

Extraction of the Boer-Mulders Function





Conclusions II

- The two fits agree in the relative sign of the u and d BM functions

- The two fits disagree in the magnitude of the BM functions

- Notice that DY pp/pD data are not sufficient
  to separate quark and antiquark
  Similarly in SIDIS we cannot extract efficiently antiquark

- Open questions: How these two different kinematics can be related?
  Average transverse momentum...
  Evolution equation....

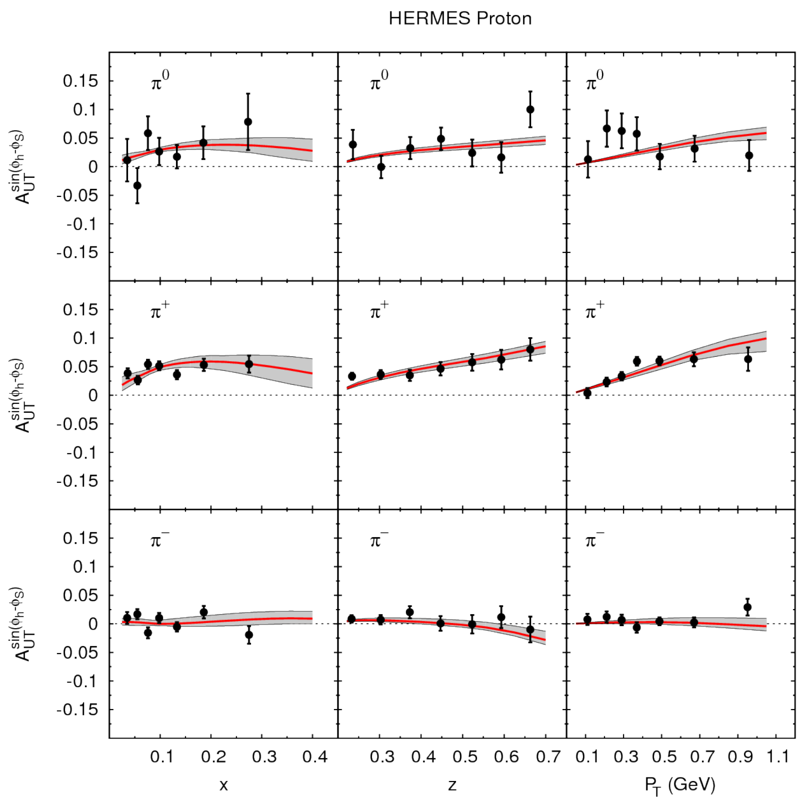
The analysis of BMP has shown the importance
of the knowledge of average transverse momentum
See also: Schweitzer, Teckentrup and Metz, ArXiv: 1003.2190

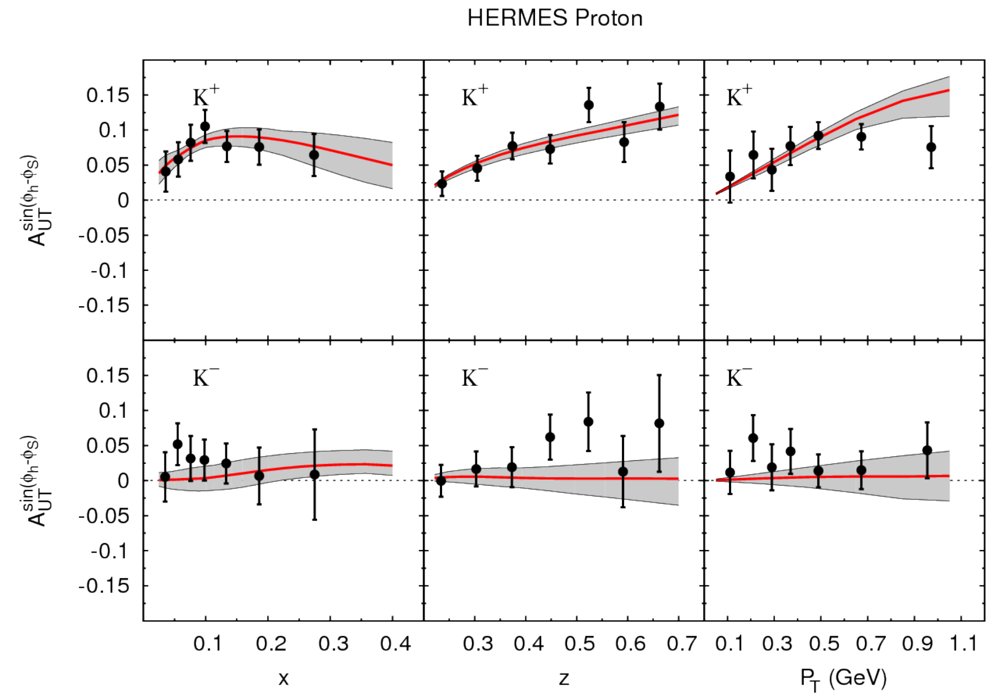
Back up

Polarized SIDIS:

Extraction of the Sivers Function

HERMES Proton Target-2009



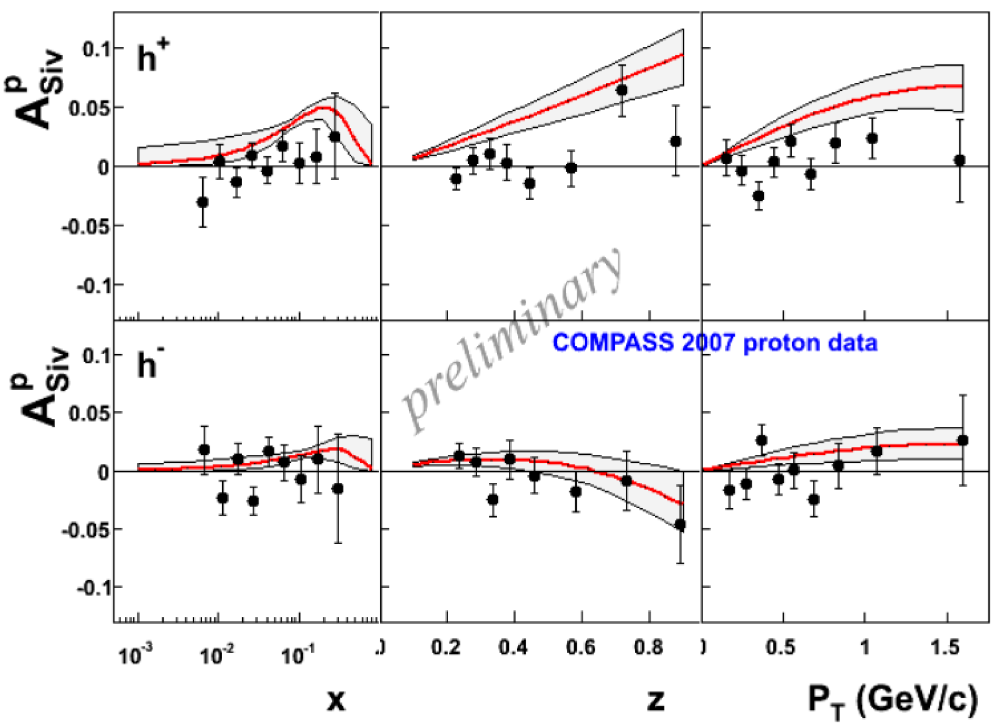


- A. Airapetian et al., Phys. Rev. Lett. 103 (2009) 152002

Polarized SIDIS:

Extraction of the Sivers Function

COMPASS Proton Target (Prediction!)



Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- Simple parametrization of the Boer-Mulders functions:

  - $h_1^{\perp q}(x, k_\perp) = \lambda_q \, f_{1T}^{\perp q}(x, k_\perp)$ for valence quarks
  - $h_1^{\perp q}(x, k_\perp) = -|f_{1T}^{\perp q}(x, k_\perp)|$ for sea quarks

- Models inspired:

$$h_1^{\perp q}(x, k_\perp) = \frac{\kappa_T^q}{\kappa^q} f_{1T}^{\perp q}(x, k_\perp)$$

Tensor magnetic moment

Anomalous magnetic moment

Burkardt, Phys. Rev. D72, 094020 (2005)
Gockeler, Phys.Rev.Lett.98:222001,2007.

Unpolarized SIDIS:

Extraction of the Boer-Mulders Function

- Simple parametrization of the Boer-Mulders functions:

  - $h_1^{\perp q}(x, k_\perp) = \lambda_q \, f_{1T}^{\perp q}(x, k_\perp)$ for valence quarks
  - $h_1^{\perp q}(x, k_\perp) = -|f_{1T}^{\perp q}(x, k_\perp)|$ for sea quarks

- Models inspired:

$$h_1^{\perp q}(x, k_\perp) = \frac{\mathcal{K}_T^q}{\mathcal{K}^q} f_{1T}^{\perp q}(x, k_\perp)$$

- $h_1^{\perp u}(x, k_\perp) \simeq 1.80 f_{1T}^{\perp u}(x, k_\perp) < 0$
- $h_1^{\perp d}(x, k_\perp) \simeq -0.94 f_{1T}^{\perp d}(x, k_\perp) < 0$