Transverse Momentum of partons

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Lecture 3

Facts of life

This is a worm gear

These are worm gear distribution functions

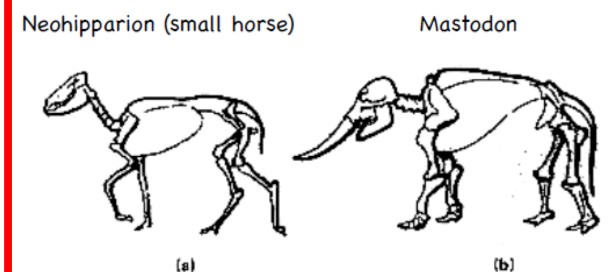
$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$

$g_{1T}^{q}(x,\mathbf{k}_T^2)$

Alessandro Bacchetta

An elephant is not a mouse multiplied by a thousand

Larry Weinstein



This is a pretzel

This is pretzelosity

$h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$

Matthias Burkhardt

We are physicists:
we are arrogant,
we act with prejudice, and
we make assumptions
based on our prejudice.
Whatever we say,
we say it with authority.

Paul Reimer

We will be talking about ...

- Deep Inelastic scattering
- Parton model

Lecture 1

Lecture 2

- Transverse momentum of partons
- 3D kinematics (i.e. kinematics with partonic transverse momentum)
- Integrated distribution and fragmentation functions (transversity and all that ...)
- Transverse Momentum Dependent distribution and fragmentation functions
- Unpolarized SIDIS cross section
- Phenomenology of TMD's: extracting Transverse Momentum Dependent distribution functions from experimental data:

  SIDIS

  e+e- scattering

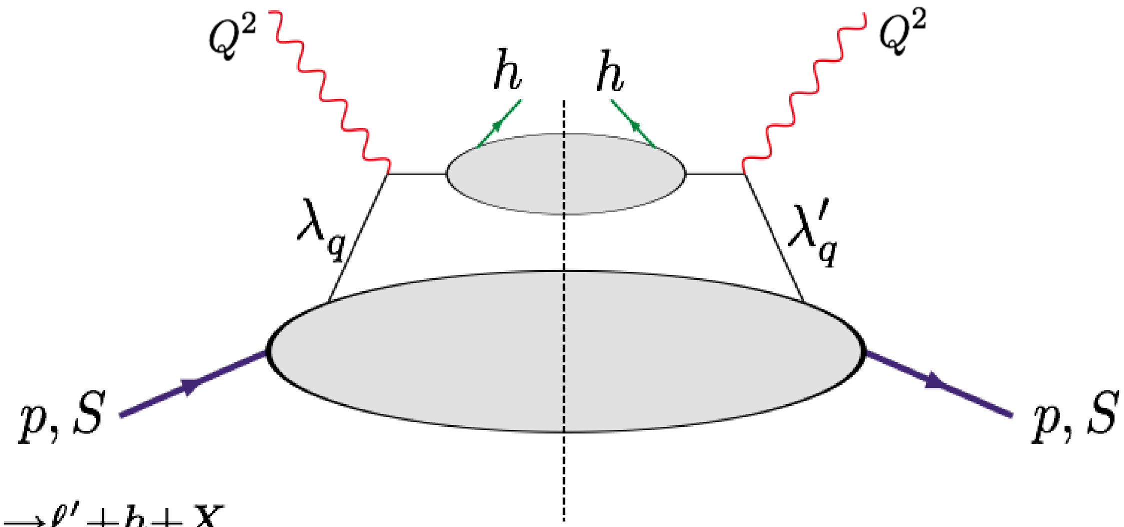
  Drell-Yan

Lecture 3

- Scale dependence and TMD evolution scheme

Unpolarized SIDIS cross section

SIDIS FACTORIZATION



$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell'+h+X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T\, d\phi_S}$$

$$\rho^{\ell,S_\ell}_{\lambda_\ell,\lambda'_\ell} \otimes \rho^{q/p,S}_{\lambda_q,\lambda'_q}\, \hat{f}_{q/p,S}(x,\boldsymbol{k}_\perp) \otimes \hat{M}_{\lambda_\ell,\lambda_q;\lambda_\ell,\lambda_q}\, \hat{M}^*_{\lambda'_\ell,\lambda'_q;\lambda'_\ell,\lambda'_q} \otimes \hat{D}^h_{\lambda_q,\lambda'_q}(z,\boldsymbol{p}_\perp)$$

TMD-PDF

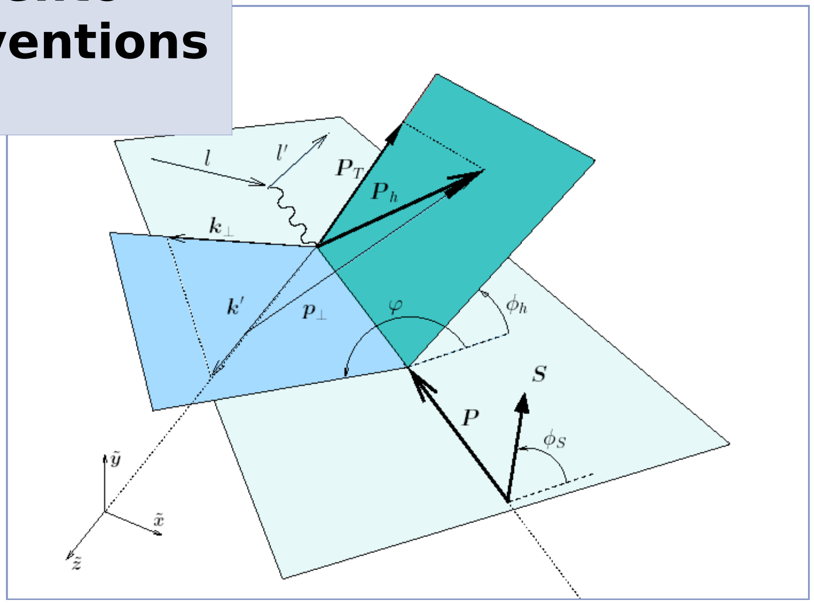
Hard Scattering

TMD-FF

All three fundamental blocks contain phases.
The most general cross-section is obtained when all of them are kept into account.

TMD's in SIDIS

Trento conventions



SIDIS in parton model with intrinsic $k_\perp$

Factorization holds at large Q^2,

and

$$P_T \approx k_\perp \approx \Lambda_{QCD}$$

(Ji, Ma, Yuan)

$$x = x_B \qquad z = z_h \qquad \boldsymbol{P}_T = z\,\boldsymbol{k}_\perp + \boldsymbol{p}_\perp$$

$$\mathcal{O}(k_\perp/Q)$$

Unpolarized Cross Section

$$\mathrm{d}\sigma^{lp\to lhX} = \sum\nolimits_q f_q(x,\boldsymbol{k}_\perp;Q^2) \otimes \boxed{\mathrm{d}\hat{\sigma}^{lq\to lq}(y,\boldsymbol{k}_\perp;Q^2)} \otimes D_q^h(z,\boldsymbol{p}_\perp;Q^2)$$

$$\boxed{d\hat{\sigma}^{\ell q\to\ell q} \propto \hat{s}^2 + \hat{u}^2 = \frac{Q^4}{y^2}\left[1 + (1-y)^2 - 4\,\frac{k_\perp}{Q}\,(2-y)\,\sqrt{1-y}\,\cos\varphi\right]} \qquad \mathcal{O}(k_\perp/Q)$$

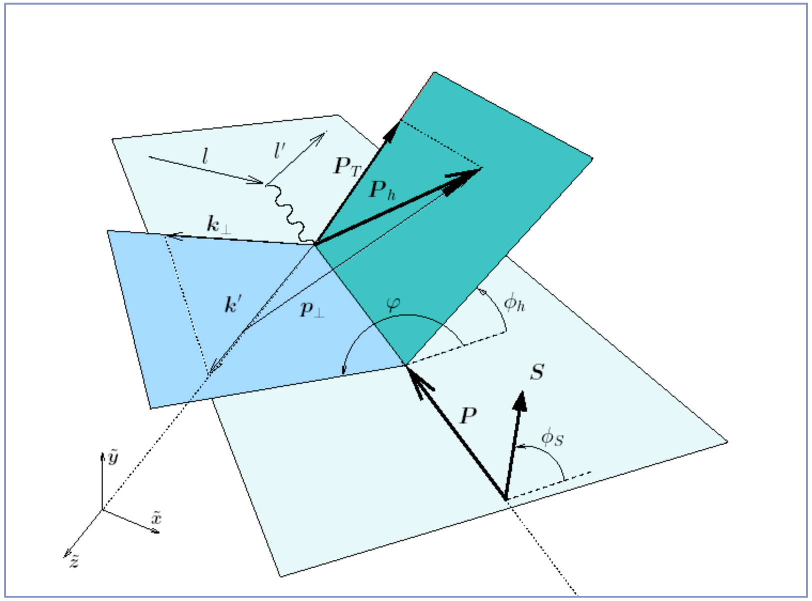
TMD's in SIDIS

$$\begin{aligned}
\ell &= E(1, \sin\theta, 0, \cos\theta) = (E, \boldsymbol{\ell}) \\
\ell' &= \ell - q \\
q &= \frac{1}{2}\left(W - \frac{Q^2}{W}, 0, 0, W + \frac{Q^2}{W}\right) \\
P &= P_0(1, 0, 0, -1)\,,
\end{aligned}$$

$$\boxed{k = \left(xP_0 + \frac{k_\perp^2}{4xP_0}, \boldsymbol{k}_\perp, -xP_0 + \frac{k_\perp^2}{4xP_0}\right)}$$

$$\begin{aligned}
\hat{s} &= xs - 2\boldsymbol{\ell}\cdot\boldsymbol{k}_\perp - k_\perp^2\frac{x_B}{x}\left(1 - \frac{x_B s}{Q^2}\right) \\
\hat{t} &= -Q^2 \\
\hat{u} &= -x\left(s - \frac{Q^2}{x_B}\right) + 2\boldsymbol{\ell}\cdot\boldsymbol{k}_\perp - k_\perp^2\frac{x_B^2 s}{xQ^2}
\end{aligned}$$

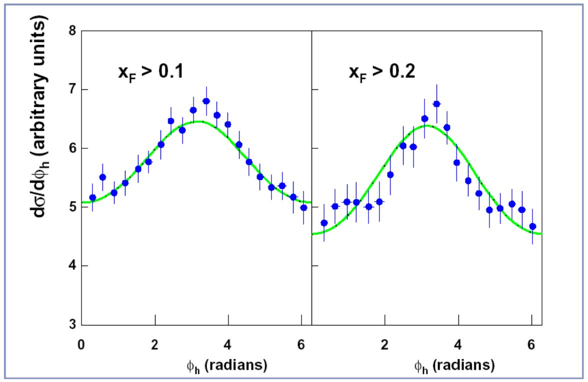
$$x = \frac{1}{2}x_B\left(1 + \sqrt{1 + \frac{4k_\perp^2}{Q^2}}\right)$$



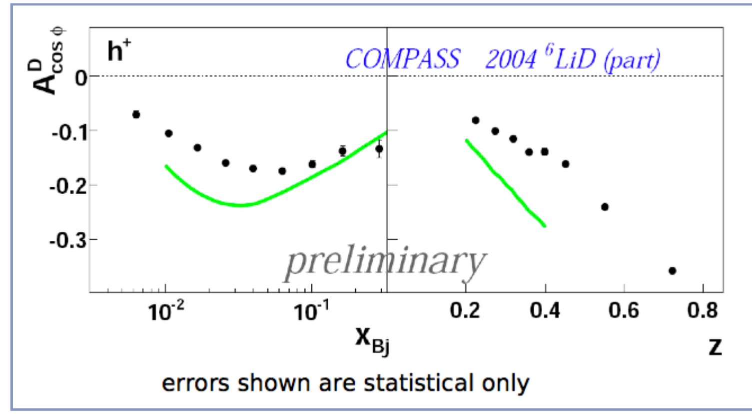
$$\boxed{\begin{aligned}
\hat{s}^2 &= \frac{Q^4}{y^2}\left[1 - 4\frac{k_\perp}{Q}\sqrt{1-y}\,\cos\varphi\right] + \mathcal{O}\left(\frac{k_\perp^2}{Q^2}\right) \\
\hat{u}^2 &= \frac{Q^4}{y^2}(1-y)^2\left[1 - 4\frac{k_\perp}{Q}\frac{\cos\varphi}{\sqrt{1-y}}\right] + \mathcal{O}\left(\frac{k_\perp^2}{Q^2}\right)
\end{aligned}}$$

TMD in unpolarized SIDIS → Cahn Effect

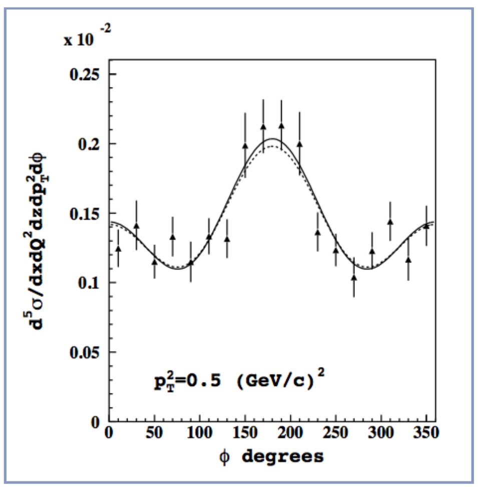
Azimuthal dependence induced by quark intrinsic motion



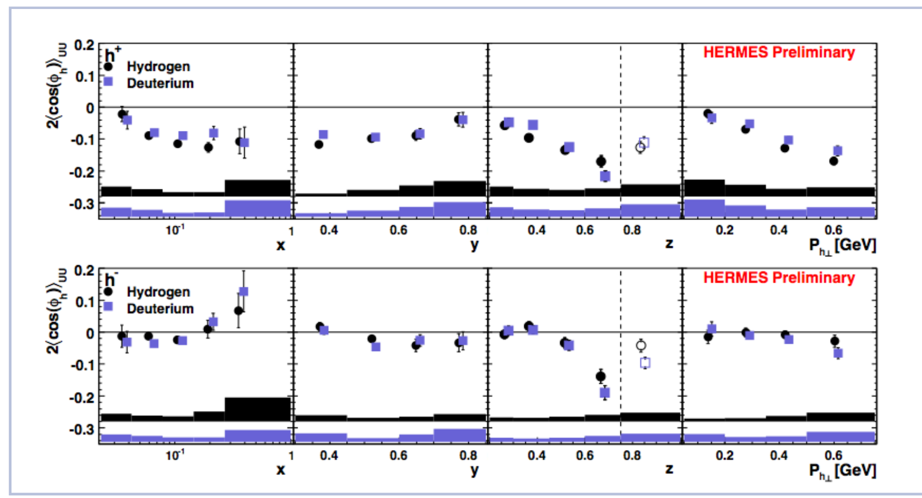
EMC data, μp and μd, E between 100 and 280 GeV



W. Käfer, COMPASS collaboration, talk at Transversity 2008, Ferrara



CLAS data, arXiv:0809.1153 [hep-ex]



F. Giordano and R. Lamb, arXiv:0901.2438 [hep-ex]

Parametrization of the Unpolarized TMD

Assume a simple, factorized form for the TMD distribution and fragmentation functions, with a gaussian dependence on the intrinsic transverse momentum

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

x and z dependence from world data fits

Normalized Gaussian (one free parameter)

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

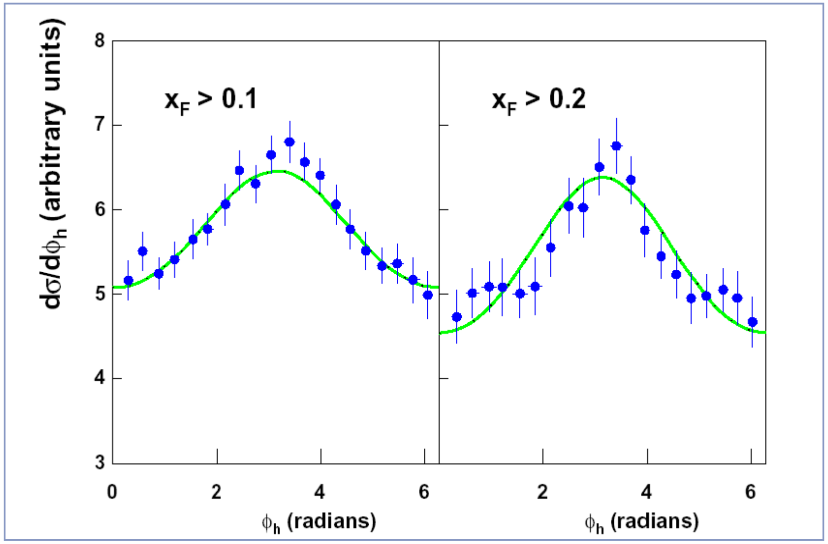
TMD in unpolarized SIDIS → Cahn Effect

Determine the value of the two free parameters by fitting experimental data

$$\langle k_\perp^2 \rangle = 0.28\ (\mathrm{GeV})^2 \qquad \langle p_\perp^2 \rangle = 0.25\ (\mathrm{GeV})^2$$

(Gaussian widths)

M.Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin, Phys. Rev. D71:074006,2005.



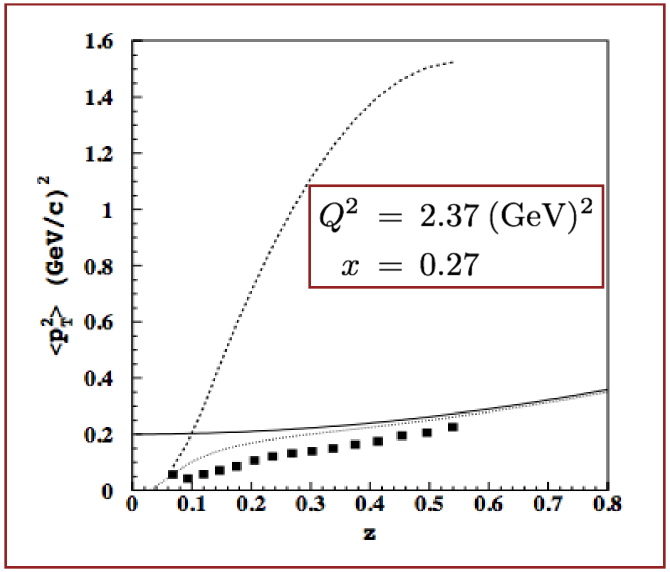
EMC data, μp and μd, *E* between 100 and 280 GeV

A cosφ dependence is also generated by Boer-Mulders⊗Collins term, via a kinematical effect in $d\Delta\hat{\sigma}$, not included in this fit.

At $\mathcal{O}(k_\perp^2/Q^2)$ further dependence on cos(2φ) is generated

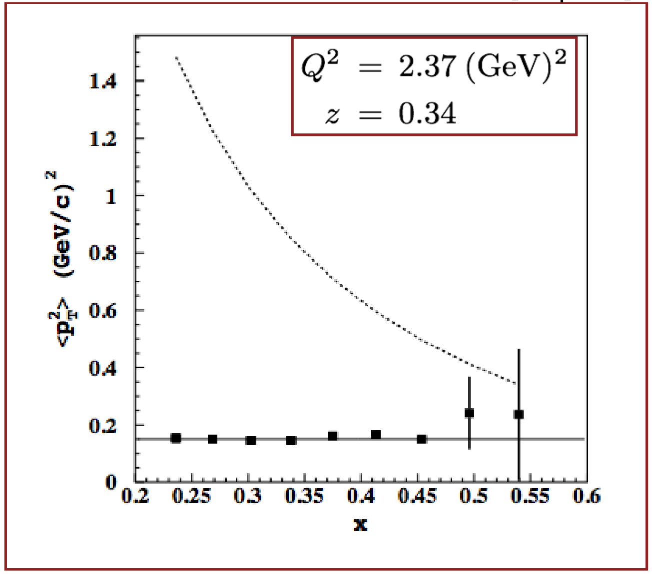
P_T dependence of data in agreement with a Gaussian $k_\perp$ dependence of unpolarized TMDs

CLAS data, arXiv:0809.1153 [hep-ex]



Hint of a z-dependence at small z values

CLAS data, arXiv:0809.1153 [hep-ex]



No hint of x dependence in the explored region

solid line $\rightarrow$ Gaussian TMD's with $\langle k_\perp^2 \rangle = 0.25 \quad \langle p_\perp^2 \rangle = 0.20$

$$\langle P_T^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle \quad \mathcal{O}(k_\perp / Q)$$

Polarized SIDIS cross section

General SIDIS cross section

$$
\begin{aligned}
&\frac{d\sigma^{\ell(S_\ell)p(S)\to\ell' hX}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{p}_\perp\, d\phi_S} = \sum_{q_i}\int d^2\boldsymbol{k}_\perp\, \tilde{J}\,\frac{4e_q^2e^4}{y^2}\Big\{\\
&\frac{1}{2} f_{q_i/p}\left[1+(1-y)^2\right] D^h_{q_f} + \frac{1}{2}\Delta f^{q_i}_{s_y/p}\frac{P_T}{p_\perp}(1-y)\left[\cos(\phi_h+\phi_\perp) - z_h\frac{k_\perp}{P_T}\cos 2\phi_\perp\right]\Delta^N D^h_{q_f}\\
&-2(2-y)\sqrt{1-y}\,\frac{k_\perp}{Q}\left[f_{q_i/p}\cos\phi_\perp D^h_{q_f} + \frac{1}{2}\Delta f^{q_i}_{s_y/p}\frac{P_T}{p_\perp}\left(\cos\phi_h - z_h\frac{k_\perp}{P_T}\cos\phi_\perp\right)\Delta^N D^h_{q_f}\right]\\
&+\frac{1}{2} S_L\Big[-\frac{P_T}{p_\perp}(1-y)\Delta f^{q_i}_{s_x/S_L}\left(\sin(\phi_h+\phi_\perp) - z_h\frac{k_\perp}{P_T}\sin 2\phi_\perp\right)\Delta^N D^h_{q_f}\\
&\qquad +2(2-y)\sqrt{1-y}\,\frac{k_\perp}{Q}\frac{P_T}{p_\perp}\Delta f^{q_i}_{s_x/S_L}\left(\sin\phi_h - z_h\frac{k_\perp}{P_T}\sin\phi_\perp\right)\Delta^N D^h_{q_f}\\
&\qquad +P_z^l\left(\left[1-(1-y)^2\right]\Delta f^{q_i}_{s_z/S_L} D^h_{q_f} - 4y\sqrt{1-y}\,\frac{k_\perp}{Q}\Delta f^{q_i}_{s_z/S_L}\cos\phi_\perp D^h_{q_f}\right)\Big]\\
&+\frac{1}{2} S_T\Big[-\frac{1}{2}\left[1+(1-y)^2\right]\Delta^N f_{q_i/S_T}\sin(\phi_S-\phi_\perp)D^h_{q_f}\\
&\qquad +P_z^l\left[1-(1-y)^2\right]\Delta f^{q_i}_{s_z/S_T}\cos(\phi_S-\phi_\perp)D^h_{q_f} - P_z^l\, 4y\sqrt{1-y}\,\frac{k_\perp}{Q}\Delta f^{q_i}_{s_z/S_T}\cos(\phi_S-\phi_\perp)\cos\phi_\perp D^h_{q_f}\\
&\qquad -\frac{P_T}{p_\perp}(1-y)\Delta^- f^{q_i}_{s_y/S_T}\sin(\phi_S-\phi_\perp)\left(\cos(\phi_h+\phi_\perp) - z_h\frac{k_\perp}{P_T}\cos 2\phi_\perp\right)\Delta^N D^h_{q_f}\\
&\qquad -\frac{P_T}{p_\perp}(1-y)\Delta f^{q_i}_{s_x/S_T}\cos(\phi_S-\phi_\perp)\left(\sin(\phi_h+\phi_\perp) - z_h\frac{k_\perp}{P_T}\sin 2\phi_\perp\right)\Delta^N D^h_{q_f}\\
&\qquad +\frac{P_T}{p_\perp}2(2-y)\sqrt{1-y}\,\frac{k_\perp}{Q}\Delta^- f^{q_i}_{s_y/S_T}\sin(\phi_S-\phi_\perp)\left(\cos\phi_h - z_h\frac{k_\perp}{P_T}\cos\phi_\perp\right)\Delta^N D^h_{q_f}\\
&\qquad +\frac{P_T}{p_\perp}2(2-y)\sqrt{1-y}\,\frac{k_\perp}{Q}\Delta f^{q_i}_{s_x/S_T}\cos(\phi_S-\phi_\perp)\left(\sin\phi_h - z_h\frac{k_\perp}{P_T}\sin\phi_\perp\right)\Delta^N D^h_{q_f}\\
&\qquad +2(2-y)\sqrt{1-y}\,\frac{k_\perp}{Q}\Delta^N f_{q_i/S_T}\sin(\phi_S-\phi_\perp)\cos\phi_\perp D^h_{q_f}\Big]\Big\}\,.
\end{aligned}
$$

General SIDIS cross section

$$
\begin{aligned}
\frac{d\sigma^{\ell(S_\ell)p(S)\to\ell' hX}}{dx_B\,dQ^2\,dz_h\,d^2\boldsymbol{p}_\perp\,d\phi_S} =\ & \\
& \frac{4e^2}{y^2}\Big\{\frac{1+(1-y)^2}{2}F_{UU} + (2-y)\sqrt{1-y}\,\cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h} \\
&+ S_L\Big[(1-y)\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2-y)\sqrt{1-y}\,\sin\phi_h F_{UL}^{\sin\phi_h}\Big] \\
&+ S_L P_z^l\Big[\frac{1-(1-y)^2}{2}F_{LL} + y\sqrt{1-y}\,\cos\phi_h F_{LL}^{\cos\phi_h}\Big] \\
&+ S_T\Big[\frac{1+(1-y)^2}{2}\sin(\phi_h-\phi_S)F_{UT}^{\sin(\phi_h-\phi_S)} \\
&\quad + (1-y)\Big(\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}\Big) \\
&\quad + (2-y)\sqrt{1-y}\Big(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big)\Big] \\
&+ S_T P_z^l\Big[\frac{1-(1-y)^2}{2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\quad + y\sqrt{1-y}\Big(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big)\Big]\Big\}
\end{aligned}
$$

The F structure functions contain all the TMD's

Unpolarized proton and lepton

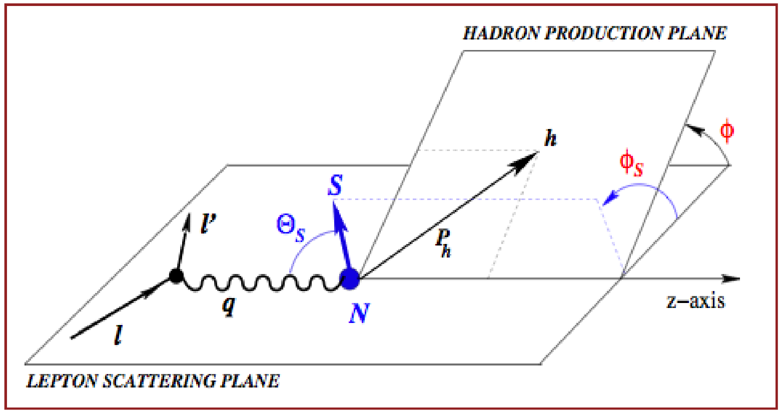
Longitudinally polarized proton, polarized lepton

Transversely polarized proton, unpolarized lepton

Transversely polarized proton, polarized lepton

- **Studying Sivers, Collins and other mechanisms is complicated by the fact that all these effects mix and overlap in the polarized SIDIS cross section and azimuthal asymmetries**
- **Way out : appropriate azimuthal moments of the asymmetries !**

TMDs in polarized SIDIS



$$F_{UU} \sim \sum_a e_a^2 \, f_1^a \otimes D_1^a \qquad F_{LT}^{\cos(\phi-\phi_S)} \sim \sum_a e_a^2 \, g_{1T}^{\perp a} \otimes D_1^a$$

$$F_{LL} \sim \sum_a e_a^2 \, g_{1L}^a \otimes D_1^a \qquad F_{UT}^{\sin(\phi-\phi_S)} \sim \sum_a e_a^2 \, f_{1T}^{\perp a} \otimes D_1^a$$

chiral-even TMDs

$$F_{UU}^{\cos(2\phi)} \sim \sum_a e_a^2 \, h_1^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(\phi+\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^a \otimes H_1^{\perp a}$$

$$F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 \, h_{1L}^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(3\phi-\phi_S)} \sim \sum_a e_a^2 \, h_{1T}^{\perp a} \otimes H_1^{\perp a}$$

chiral-odd TMDs

$$\frac{1}{Q} \cos\phi \, F_{UU}^{\cos\phi} \sim f_1^q \otimes D_1^q \otimes \mathrm{d}\hat{\sigma} + \left(h_1^{q\perp} \otimes H_1^{q\perp} \otimes \mathrm{d}\Delta\hat{\sigma} \right)$$

Cahn kinematical effects

TMD’s in SIDIS one by one …

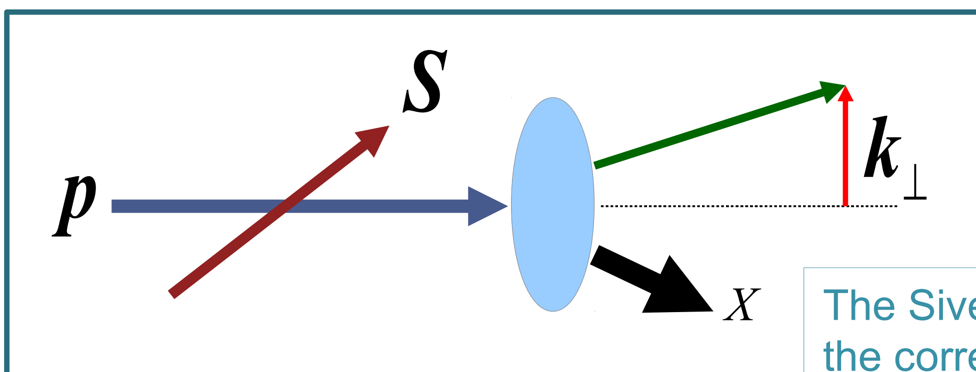
The Sivers Distribution Function

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

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\, \boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

The Sivers function is related to the probability of finding an unpolarized quark inside a transversely polarized proton

The Sivers function is T-odd



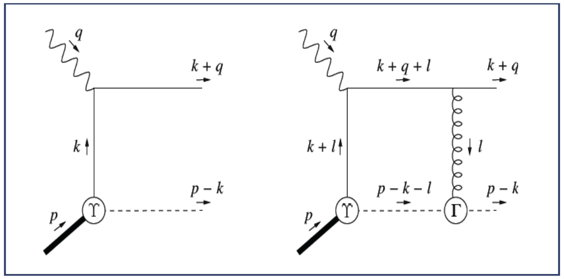
The Sivers function embeds the correlation between the proton spin and the quark transverse momentum

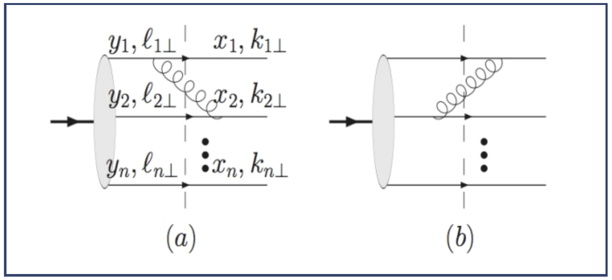
The Sivers Distribution Function

Determining the Sivers function

Models →

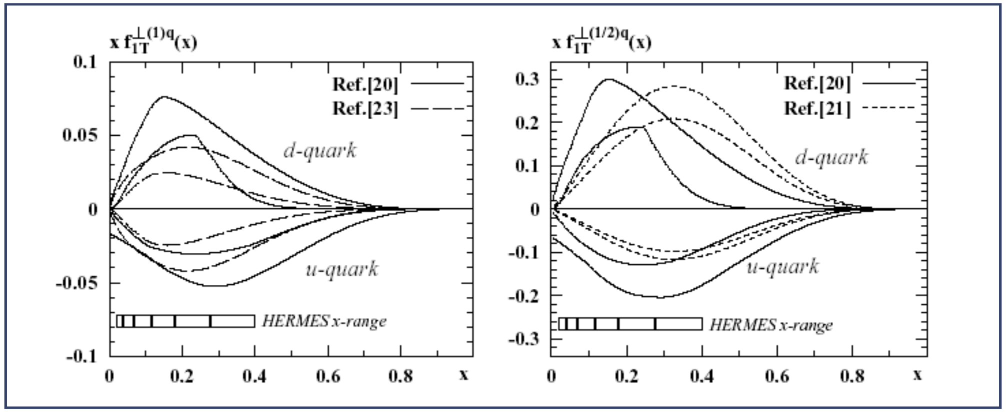
Bacchetta, Gamberg, Goldstain, Mukherjee, Metz, Amrath, Shaefer, Yang, Brodsky, Schmidt, Hwang, Scopetta, Courtoy, Frattini, Vento, Radici, Pasquini, Yuan …





Fits →

M. Anselmino, M. Boglione, J.C. Collins, U. D'Alesio, A.V. Efremov, K. Goeke, A. Kotzinian, S. Menze, A. Metz, F. Murgia, A. Prokudin, P. Schweitzer, W. Vogelsang, F. Yuan



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

The first and 1/2-transverse moments of the Sivers quark distribution functions.
The fits were constrained mainly (or solely) by the preliminary HERMES data in the indicated x-range.
The curves indicate the 1-σ regions of the various parameterizations.

Sivers effect in SIDIS single spin asymmetry

$$A_{UT} = \frac{d\sigma^{\ell p^{\uparrow} \to \ell' h X} - d\sigma^{\ell p^{\downarrow} \to \ell' h X}}{d\sigma^{\ell p^{\uparrow} \to \ell' h X} + d\sigma^{\ell p^{\downarrow} \to \ell' h X}}$$

$$A_{UT}^{\sin(\varphi_h - \varphi_S)} = \frac{\sum_q e_q^2 \int d\varphi_S d\varphi_h \, d^2\vec{k}_\perp \; \Delta^N f_{q/p^{\uparrow}}(x,k_\perp) \, \frac{d\sigma}{dQ^2} D_{h/q}(z,p_\perp) \; \sin(\varphi - \varphi_S) \sin(\varphi_h - \varphi_S)}{\sum_q e_q^2 \int d\varphi_S d\varphi_h d^2\vec{k}_\perp \; f_{q/p}(x,k_\perp) \, \frac{d\sigma}{dQ^2} \, D_{h/q}(z,p_\perp)}$$

Two soft mechanisms at work in SIDIS:

- **Distribution fn. →** probability to find quark q carrying a light-cone fraction x of the parent proton momentum, an intrinsic transverse momentum k⊥, at scale Q2.

- **Fragmentation fn.→** describes the hadronization of the struck quark into the final, detected hadron.

Both mechanisms play an important role in determining total cross section and spin asymmetries

Parametrization of the Sivers distribution function

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

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

$$N_q(x) = N_q\,x^{a_q}\,(1-x)^{b_q}\,\frac{(a_q+b_q)^{(a_q+b_q)}}{a_q^{a_q}\,b_q^{b_q}}$$

with $-1 \le N_q \le 1$

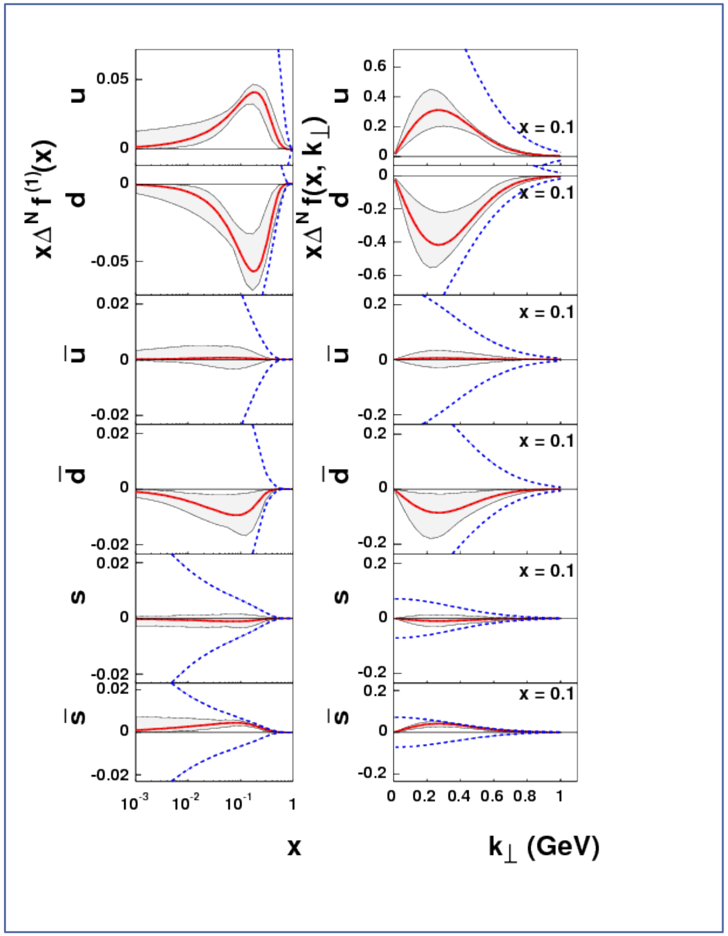
$$f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

$|Nq(x)|$ and $|h(k_\perp)|$ are smaller than 1 for any x and for any $k_\perp$

Positivity Bound $\dfrac{|\Delta^N f_{q/p^\uparrow}(x,k_\perp)|}{2\,f_{q/p}(x,k_\perp)} \le 1$ *automatically satisfied*

Extraction of Sivers Function from SIDIS experimental data

11 parameters fit



$\chi^2/d.o.f. = 1.00$		
$N_u = 0.35^{+0.08}_{-0.08}$ $N_{\bar{u}} = 0.04^{+0.22}_{-0.24}$ $\alpha_u = 0.73^{+0.72}_{-0.58}$ $\beta = 3.46^{+4.87}_{-2.90}$	$N_d = -0.90^{+0.43}_{-0.10}$ $N_{\bar{d}} = -0.40^{+0.33}_{-0.44}$ $\alpha_d = 1.08^{+0.82}_{-0.65}$ $M_1^2 = 0.34^{+0.30}_{-0.16}\ (\mathrm{GeV}/c)^2$	$N_s = -0.24^{+0.62}_{-0.50}$ $N_{\bar{s}} = 1^{+0}_{-0.0001}$ $\alpha_{sea} = 0.79^{+0.56}_{-0.47}$

M.Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Türk, ***Eur.Phys.J.A39:89-100,2009***.

✓ Valence quark

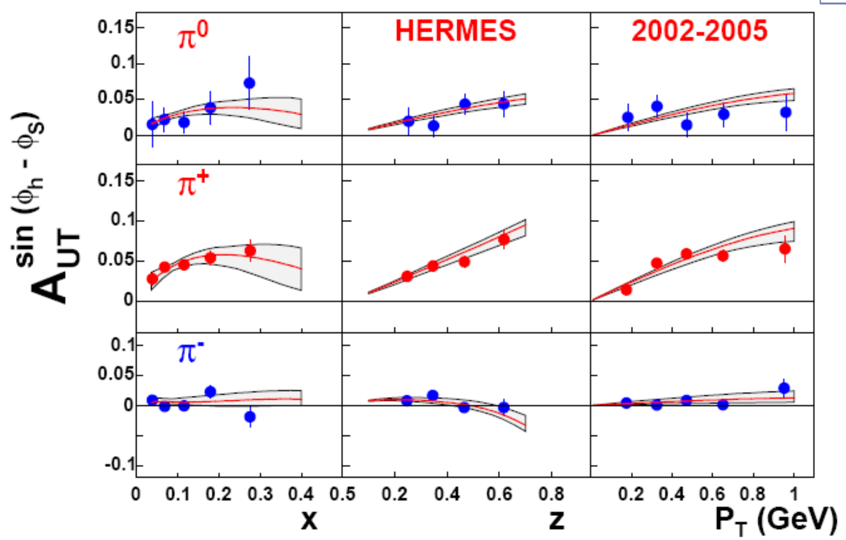
- $\Delta^N f_{u/p^\uparrow} > 0$ $\qquad f_{1T}^{\perp u} < 0$
- $\Delta^N f_{d/p^\uparrow} < 0$ $\qquad f_{1T}^{\perp d} > 0$

✓ Sea quarks

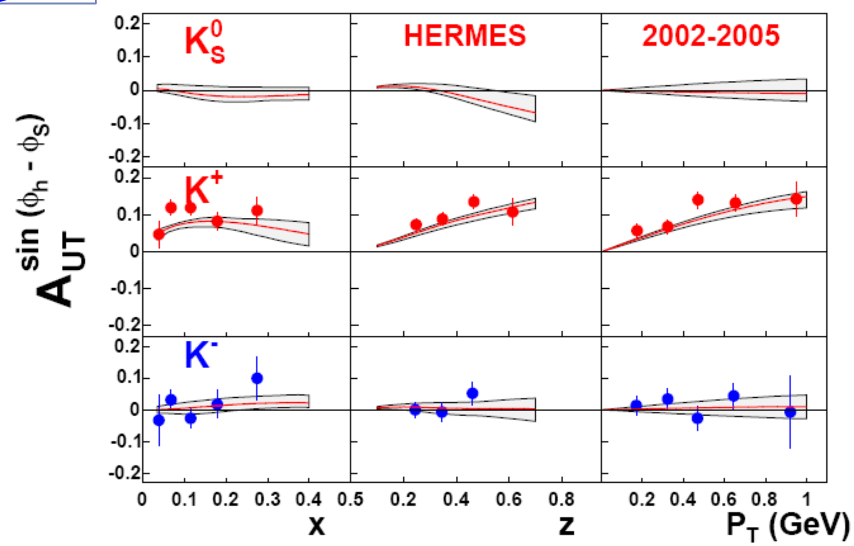
- $\Delta^N f_{\bar{s}/p^\uparrow} > 0$ $\qquad f_{1T}^{\perp \bar{s}} < 0$

Extraction of Sivers Function from SIDIS experimental data

π^+ production at HERMES



K^+ production at HERMES



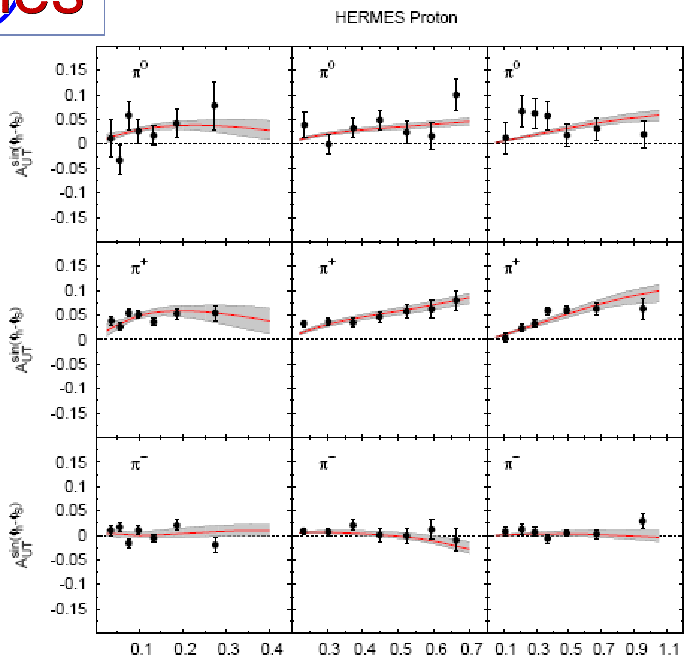
M.Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Türk, ***Eur.Phys.J.A39:89-100,2009***.

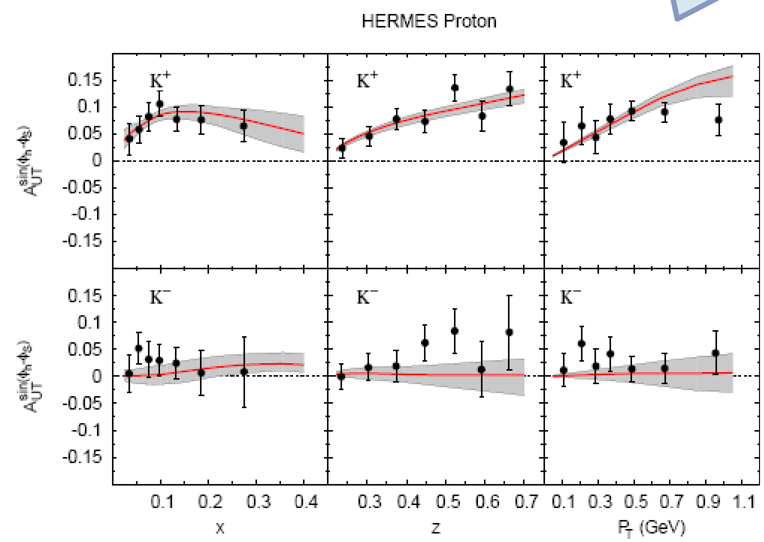
K^0 fragmentation functions

$$D_d^{K_S^0} = D_{\bar{d}}^{K_S^0} = \frac{1}{2}\left[D_u^{K^+} + D_{sea}^{K^+}\right]$$
$$D_{\bar{s}}^{K_S^0} = D_s^{K_S^0} = \frac{1}{2}\left[D_{\bar{s}}^{K^+} + D_{sea}^{K^+}\right]$$
$$D_u^{K_S^0} = D_{\bar{u}}^{K_S^0} = D_{sea}^{K^+} \equiv D_d^{K^+} = D_{\bar{u}}^{K^+} = D_s^{K^+} = D_{\bar{d}}^{K^+}$$

Extraction of Sivers Function from SIDIS experimental data

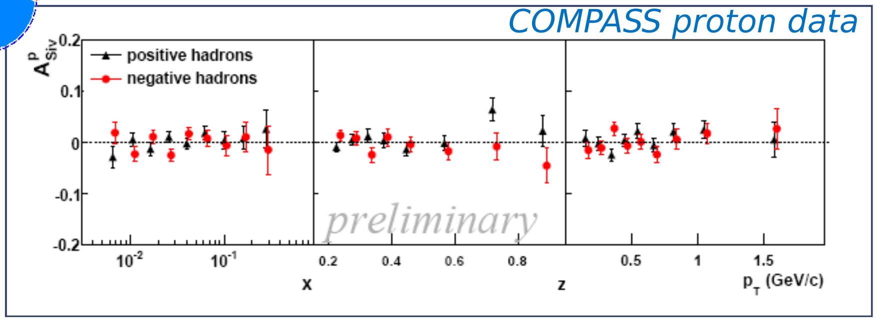
New data (2009) old fit !





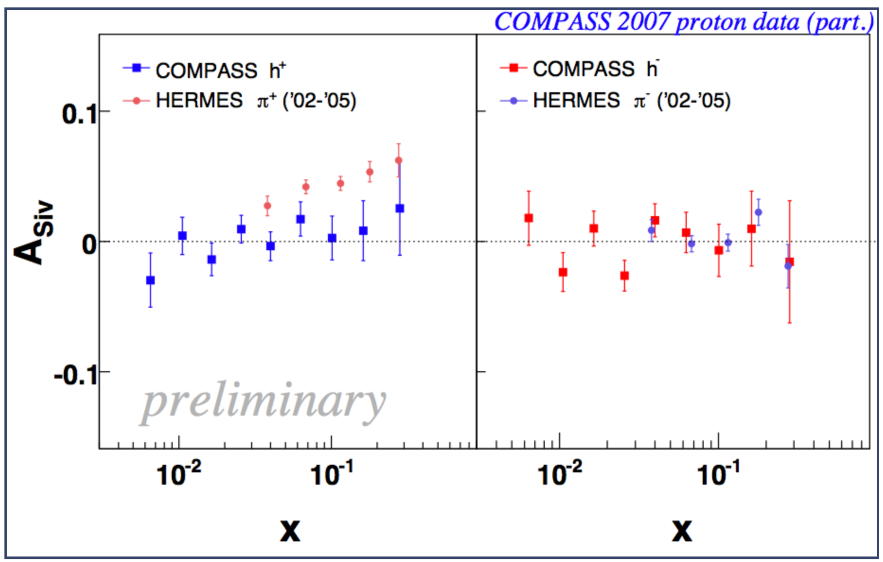
HERMES Collaboration,
Phys.Rev.Lett.103:152002,2009.

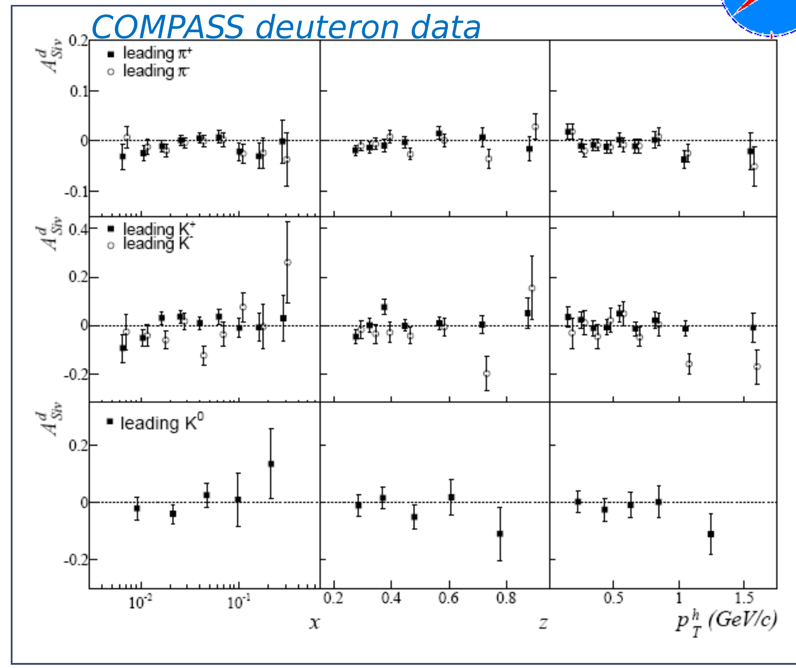
The Sivers Distribution Function



S. Levorato for the COMPASS Collaboration, Transversity 2008

COMPASS vs HERMES, problems?





COMPASS Collaboration, Phys. Lett. B673: 127-135, 2009

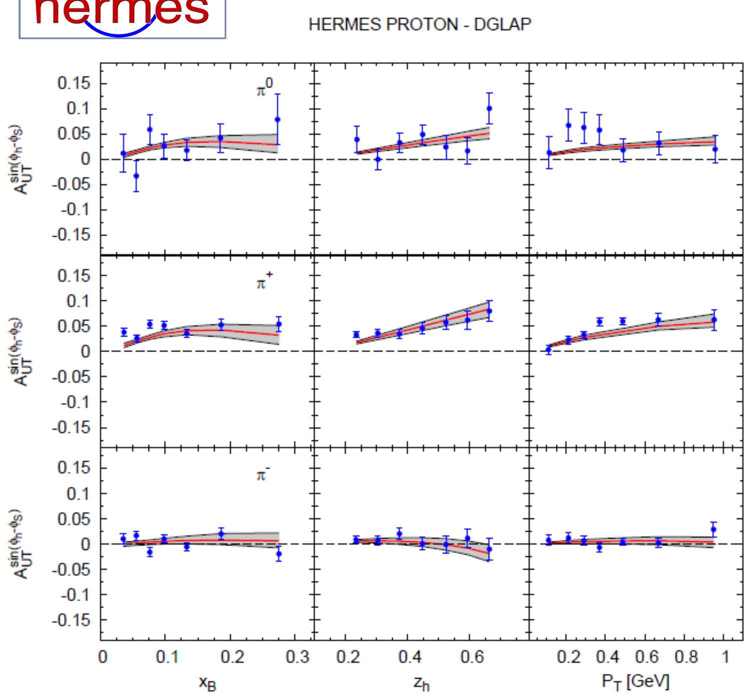
Until recently, Compass found Sivers = 0. Only HERMES data revealed Sivers effect. New Compass Sivers data provide further check!

Courtesy of F. Bradamante

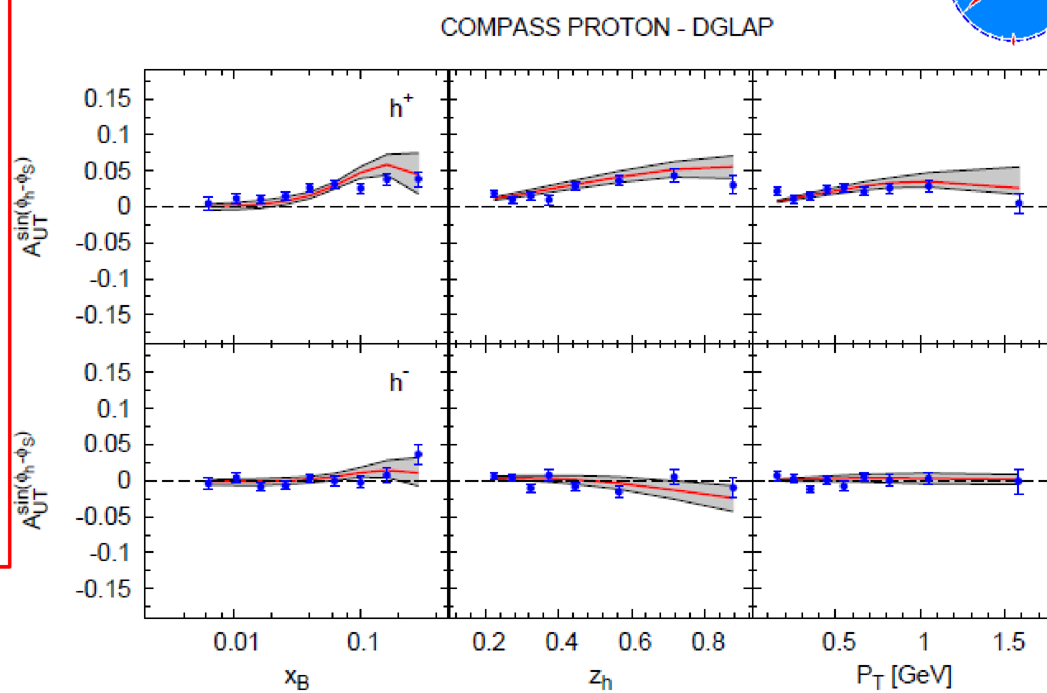
The Sivers Distribution Function

New data, new fit

M. Anselmino, M. Boglione, S. Melis,
ArXiv:1204.1239
Accepted for publication in Phys. Rev. D.



A. Airapetian et al, HERMES Collaboration,
Phys. Rev. Lett. 103,152002 (209)

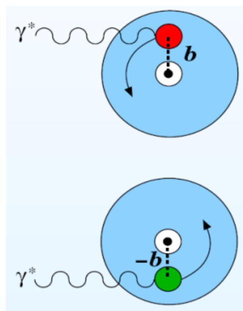


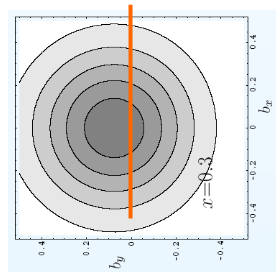
F. Bradamante et al, COMPASS Collaboration, arXiv:1111.0869

The Sivers Distribution Function

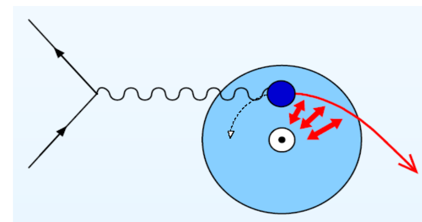
Spin-orbit correlations

A non-zero Sivers function requires non-zero orbital angular momentum !

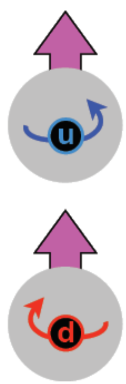


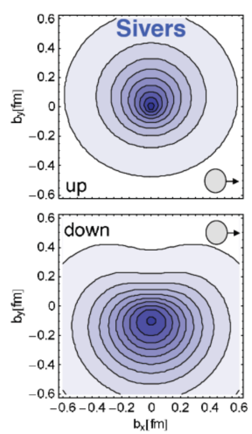


$u_X\,(x,\boldsymbol{b}_\perp)$



[Matthias Burkardt]





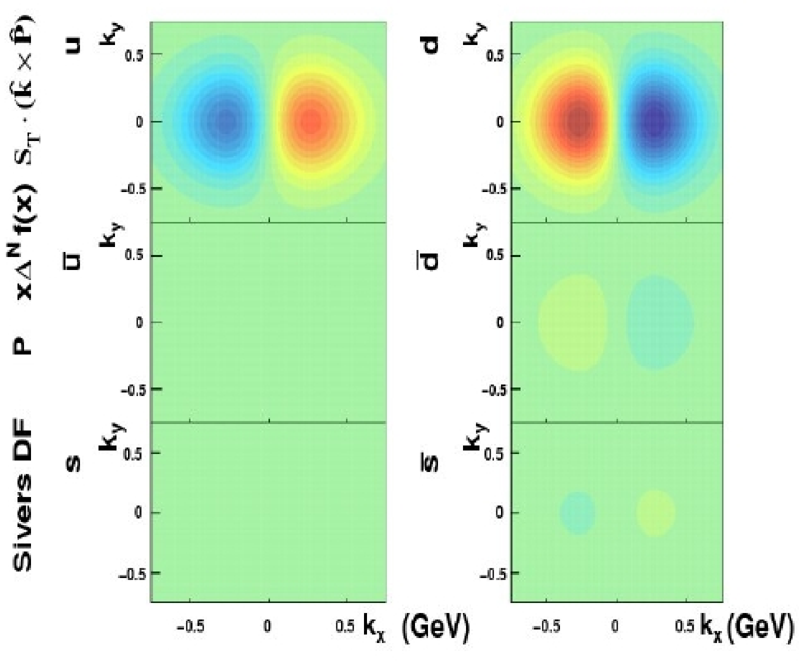
Lu>0

Lattice [P. Haegler et al.]

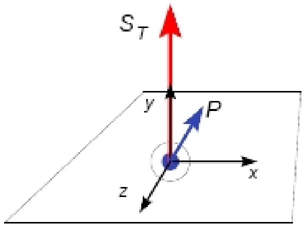
Ld<0

3D view of the proton

The proton moves along $-Z$ direction (into the screen) and S_T is along Y.



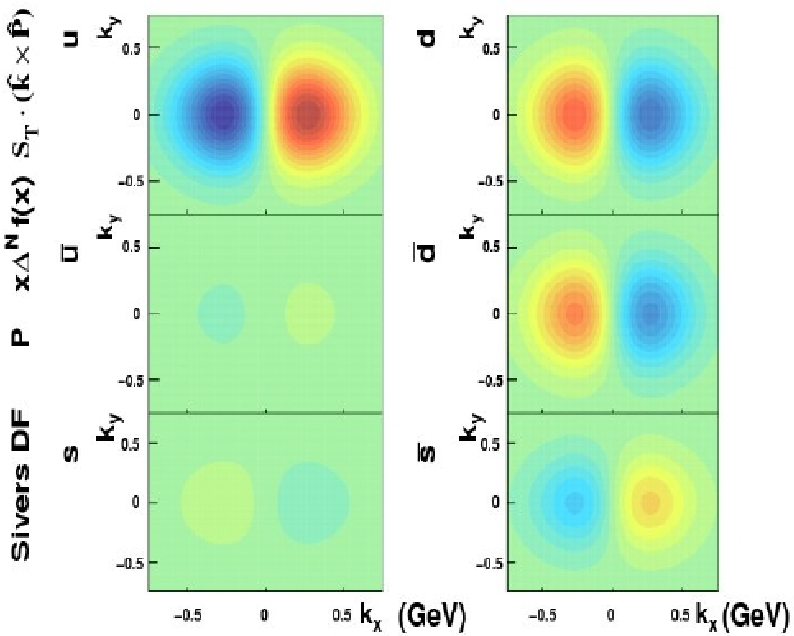
Courtesy of Alexei Prokudin



This is the three dimensional view of the proton as "seen" by the virtual photon.
Red color – more quarks. Blue color – less quarks. Distributions of quarks are not symmetrical and shifted due to final state interactions.
$x = 0.2$

3D view of the proton

The proton moves along $-Z$ direction (into the screen) and S_T is along Y.

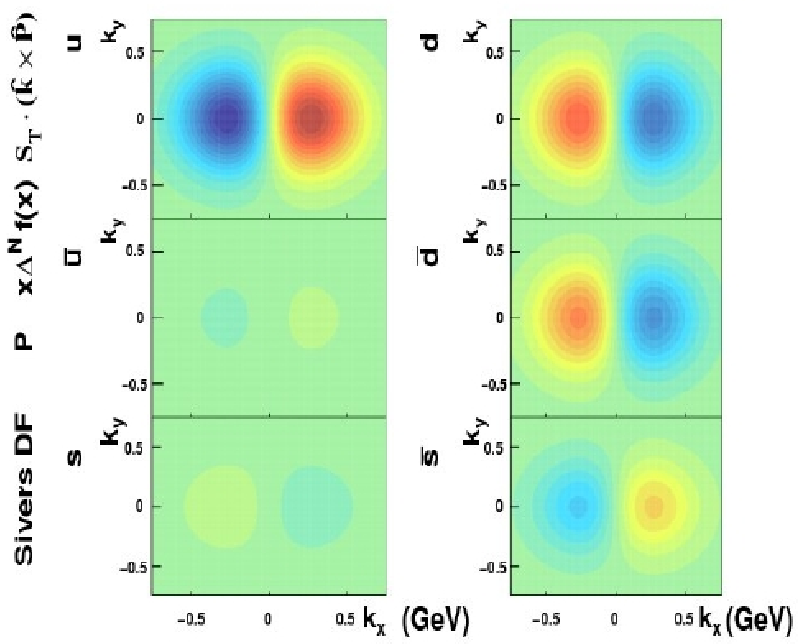


Courtesy of Alexei Prokudin

Sivers functions for u, d and sea quarks are extracted from HERMES and COMPASS data. Red color – more quarks. Blue Color – less quarks. Sivers functions is a left – right asymmetry of quark distribution. $x = 0.01$
More information on sea quarks. Please note that Sivers function is a dipole correlation of the type $S_T \cdot (k \times P)$ one example of those correlations that we almost discarded at the beginning of the seminar using symmetry reasoning.

3D view of the proton

The proton moves along $-Z$ direction (into the screen) and S_T is along Y.



Courtesy of Alexei Prokudin

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More information on sea quarks. Please note that Sivers function is a dipole correlation of the type $S_T \cdot (k \times P)$ one example of those correlations that we almost discarded at the beginning of the seminar using symmetry reasoning.

Summary

- We have seen how TMD distribution functions are parameterized and extracted from experimental data
- The SIDIS unpolarized cross section is laready very interesting as it clearly shows evident signs of the presence of partonic intrinsic transverse momentum.
- The ideal processes to study TMDs are polarized cross sections and spin asymmetries, but they need a careful Fourier analysis to disentangle a large number of terms, each proportional to a different TMD or combination of TMDs.
- In this framework, the valence quark contribution to the Sivers function, which represents the density numer of unpolarized quarks inside a transversely polarized proton, is extracted from data on the SIDIS Sivers azimuthal moment and is, at the moment, known fairly well.