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Phenomenological extraction of the Sivers distribution functions & Sivers sign change: an update

Mariaelena Boglione

INFN Torino

UNIVERSITÀ
DEGLI STUDI
DI TORINO
ALMA UNIVERSITAS
TAURINENSIS

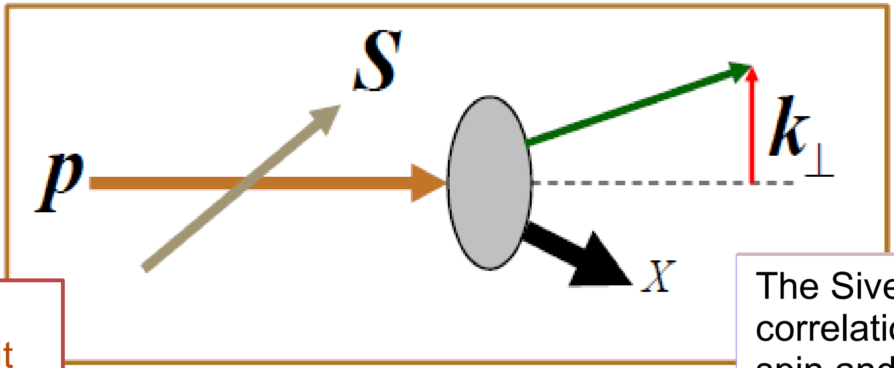
Scuola
di Scienze
della Natura

In collaboration with: M. Anselmino, U. D'Alesio, C. Flores,
J.O. Gonzalez-Hernandez, F. Murgia, A. Prokudin

The Sivers Distribution Function

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

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

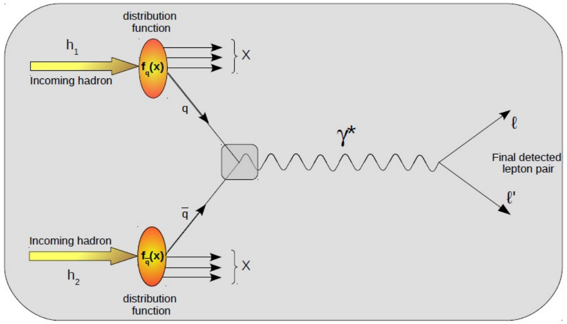


The Sivers function, is particularly interesting, as it provides information on the partonic orbital angular momentum

The Sivers function embeds correlations between proton spin and quark transverse momentum

Where do we learn about the Sivers function ?

Unpolarized and Polarized Drell-Yan scattering



$$\sigma_{Drell-Yan} = f_q(x,k_\perp) \otimes f_{\bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell'}$$

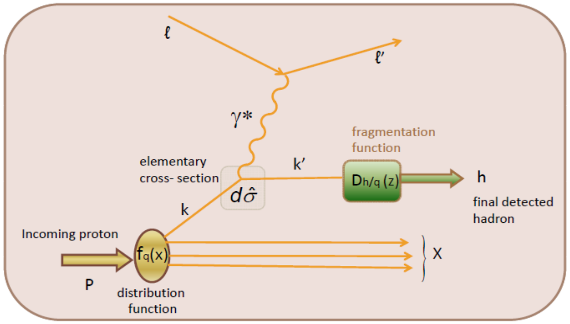
Allows extraction of distribution functions

Fermilab

BROOKHAVEN
NATIONAL LABORATORY

COMPASS

Unpolarized and Polarized SIDIS scattering



$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows extraction of distribution and fragmentation functions

hermes

Jefferson Lab
EXPLORING THE NATURE OF MATTER

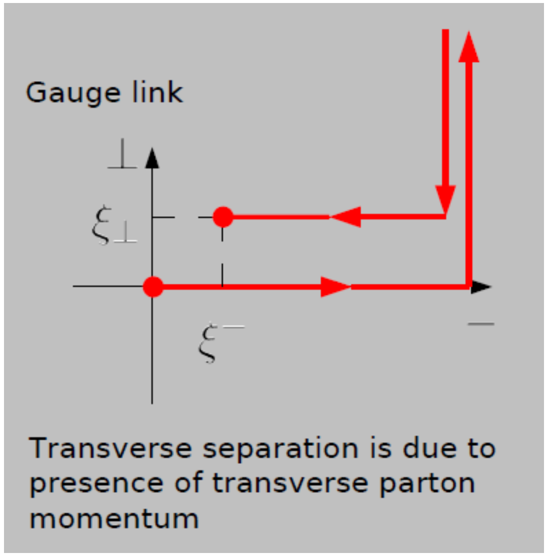
COMPASS

Sivers function sign change

- TMDs have to be defined in a color-gauge invariant way

$$\Phi_{ij}(x,\mathbf{k}_\perp) = \int \frac{\mathbf{d}\xi^-}{(\mathbf{2}\pi)}\frac{\mathbf{d^2}\xi_\perp}{(\mathbf{2}\pi)^\mathbf{2}}\mathbf{e}^{\mathbf{ixP}^+\xi^-}\;\mathbf{e}^{-\mathbf{ik}_\perp\xi_\perp}\langle\mathbf{P},\mathbf{S_P}|\bar\psi_\mathbf{j}(\mathbf{0})\,\mathcal{U}(\mathbf{0},\xi)\,\psi_\mathbf{i}(\xi)|\mathbf{P},\mathbf{S_P}\rangle\Big|_{\xi^+=\mathbf{0}}$$

- The struck quark propagates in the gauge field of the remnant and forms gauge links



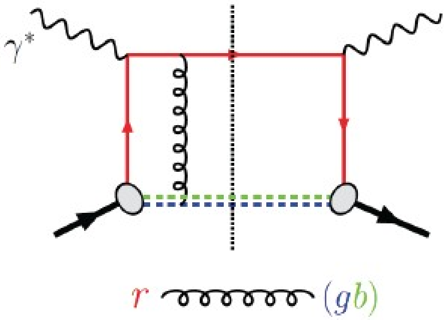
Transverse separation is due to presence of transverse parton momentum

- Gauge links generate initial and final state interactions

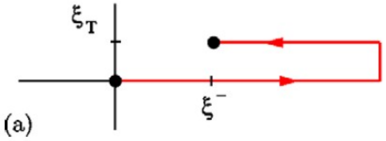
Sivers function sign change

SIDIS

- The gluon couples to the proton remnant after the quark is scattered
- Attractive final state interaction

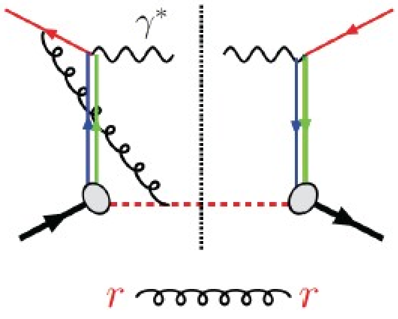


Attractive

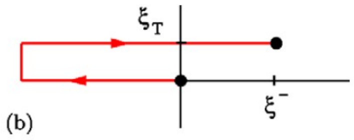


DRELL YAN

- The gluon couples before the quark annihilates
- Repulsive initial state interaction



Repulsive



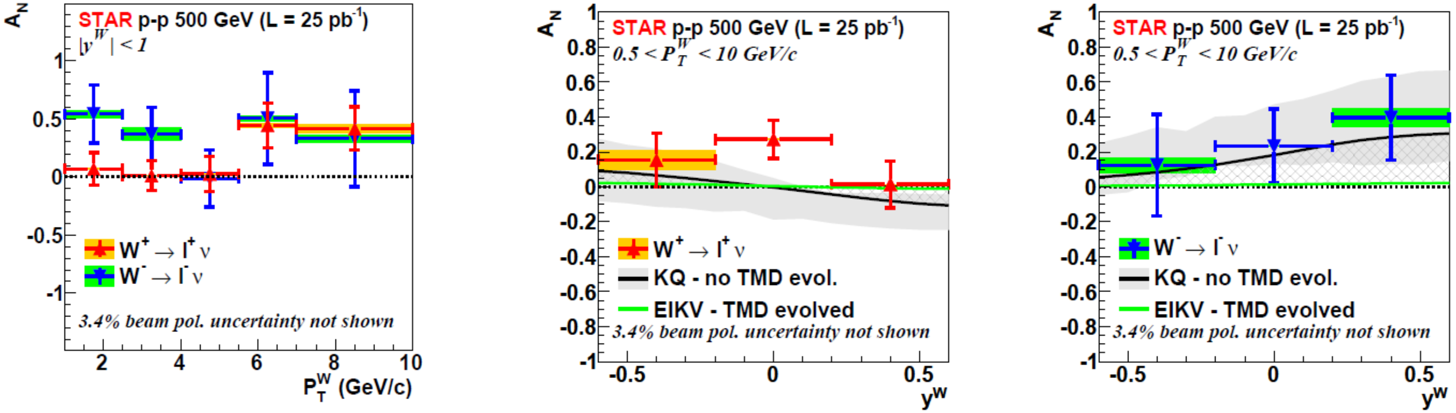
The Sivers function is process dependent: it reverses its sign when measured in SIDIS w.r.t Drell Yan processes

$$\boxed{[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}}$$

Testing the Sivers sign change in Drell-Yan processes

Sivers function in $p^{\uparrow} + p \rightarrow W^{\pm}/Z$ @ RHIC

STAR Collaboration, Phys. Rev. Lett. 116 132301 (2016)



$$A_N^W = \frac{d\sigma^{p\to WX} - d\sigma^{p\to WX}}{d\sigma^{p\to WX} + d\sigma^{p\to WX}} \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$= \frac{\sum_{q_1,q_2} |V_{q_1,q_2}|^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}}_1 \times \hat{\boldsymbol{k}}_{\perp 1})\, \boxed{\Delta^N f_{q_1/p^{\uparrow}}(x_1, k_{\perp 1})}\, f_{q_2/p}(x_2, k_{\perp 2})}{2\sum_{q_1,q_2} |V_{q_1,q_2}|^2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, f_{q_1/p}(x_1, k_{\perp 1})\, f_{q_2/p}(x_2, k_{\perp 2})}$$

Sivers function in $p^\uparrow + p \to W^\pm/Z$ @ RHIC

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, JHEP 1704 (2017) 046

- The quark flavours involved in W production include anti-quarks
- In order to estimate A_N^W, it is important to have a reliable extraction of both quark and anti-quark Sivers functions.

$$\textbf{W+ :}\quad |V_{u,d}|^2 \left(\Delta^N f_{u/} \otimes f_{\bar{d}/p} + \Delta^N f_{\bar{d}/} \otimes f_{u/p}\right) + |V_{u,s}|^2 \cancel{\left(\Delta^N f_{u/} \otimes f_{\bar{s}/p} + \Delta^N f_{\bar{s}/} \otimes f_{u/p}\right)}$$

$$\textbf{W- :}\quad \underbrace{|V_{u,d}|^2 \left(\Delta^N f_{\bar{u}/} \otimes f_{d/p} + \Delta^N f_{d/} \otimes f_{\bar{u}/p}\right)}_{\text{dominant}} + \underbrace{|V_{u,s}|^2 \cancel{\left(\Delta^N f_{\bar{u}/} \otimes f_{s/p} + \Delta^N f_{s/} \otimes f_{\bar{u}/p}\right)}}_{\text{suppressed}}$$

This single spin asymmetry is very sensitive to $\bar{u}$ and $\bar{d}$ as well as u_v and d_v

Extraction of Sivers functions from SIDIS data

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, JHEP 1704 (2017) 046

Unpolarized TMD PDF

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

Unpolarized TMD FF

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

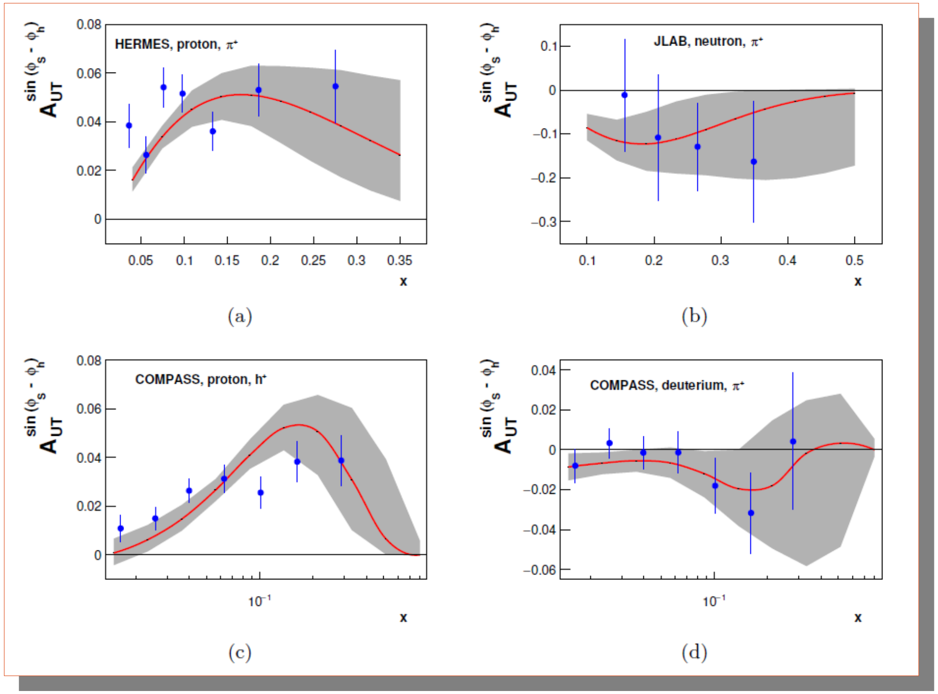
Sivers function parametrized starting from unpolarized PDF

Sivers function

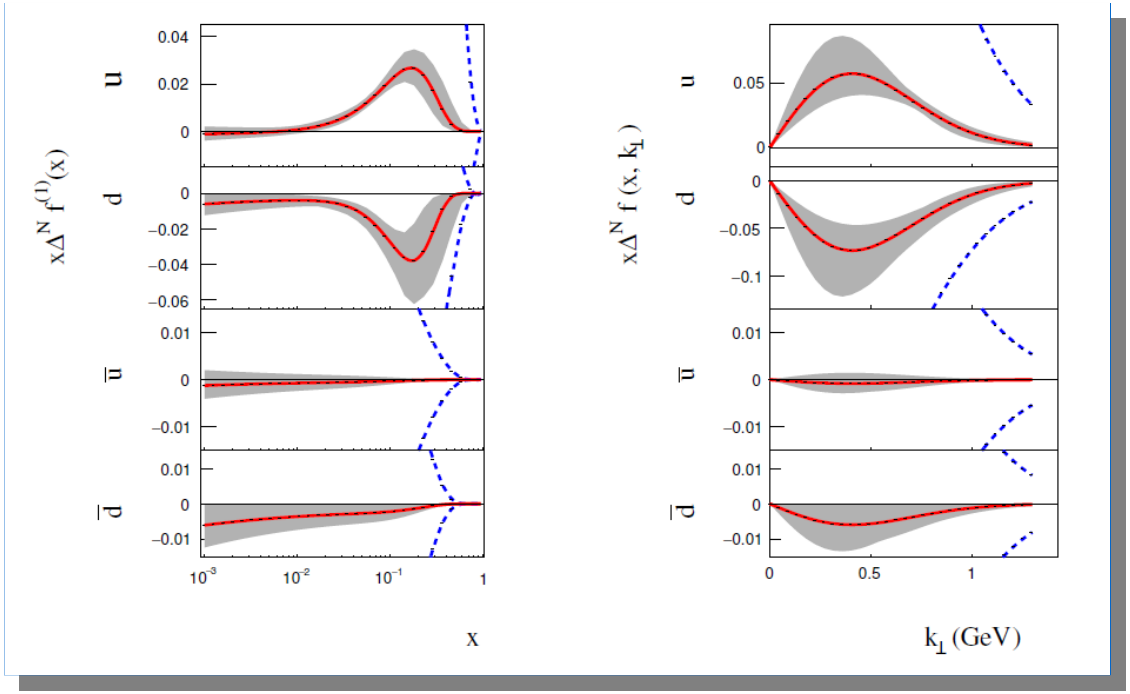
$$\left\{\begin{aligned}
&\Delta^N f_{q/}(x,k_\perp) = 2\,\mathcal{N}_q(x)\,h(k_\perp)\,f_{q/p}(x,k_\perp)\\
&h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M_1}\,e^{-k_\perp^2/M_1^2}\\
&\mathcal{N}_q(x) = N_q\;x^{\alpha_q}(1-x)^{\beta_q}\;\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\,\beta_q^{\beta_q}}\\
&\mathcal{N}_{\bar q}(x) = N_{\bar q}
\end{aligned}\right.$$

Extraction of Sivers functions from SIDIS data

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, JHEP 1704 (2017) 046



$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,P_T) = \frac{[z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle]\langle k_S^2\rangle^2}{[z^2\langle k_S^2\rangle+\langle p_\perp^2\rangle]^2\langle k_\perp^2\rangle} \exp\left[-\frac{P_T^2\, z^2(\langle k_\perp^2\rangle - \langle k_S^2\rangle)}{(z^2\langle k_S^2\rangle+\langle p_\perp^2\rangle)(z^2\langle k_\perp^2\rangle+\langle p_\perp^2\rangle)}\right] \times \frac{\sqrt{2e}\, z\, P_T}{M_1}\, \frac{\sum_q e_q^2\, \mathcal{N}_q(x) f_q(x)\, D_{h/q}(z)}{\sum_q e_q^2\, f_q(x)\, D_{h/q}(z)}\,.$$



$$\left.\begin{aligned}\langle k_\perp^2\rangle &= 0.57\ \mathrm{GeV}^2\\ \langle p_\perp^2\rangle &= 0.12\ \mathrm{GeV}^2\end{aligned}\right\}$$

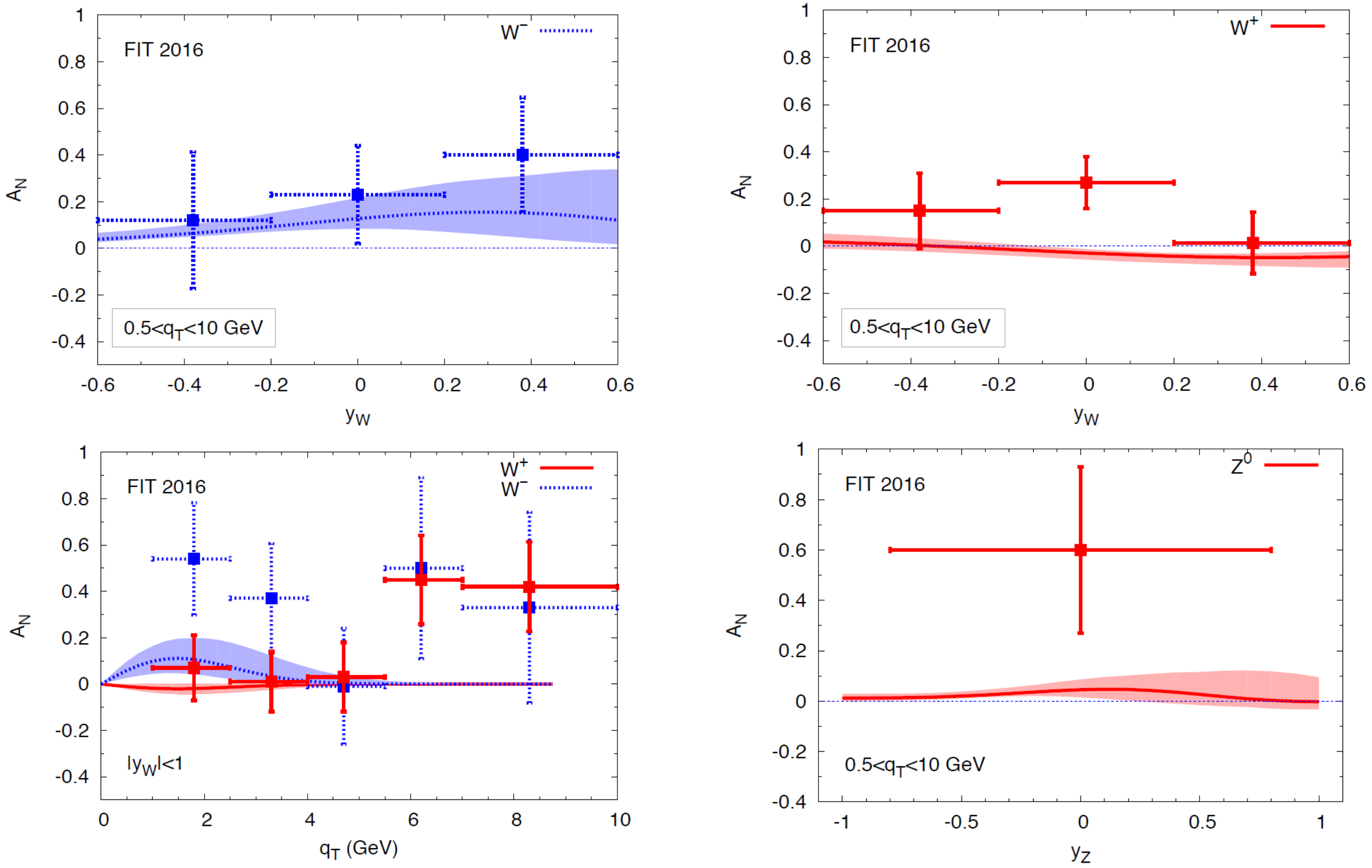
Extracted from
HERMES multiplicities

$$\boxed{\chi^2_{\min}/\mathrm{dof} = 1.29}$$

- u_v well determined
- d_v and $\bar{d}$ poorly determined
- $\bar{u}$: no information (not even sign)

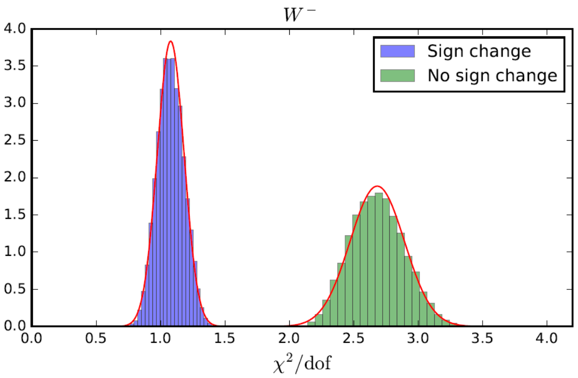
Sivers function in $p^{\uparrow} + p \to W^{\pm}/Z$ @ RHIC

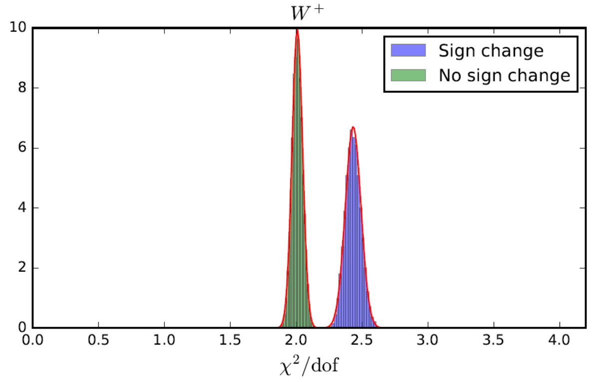
Anselmino, Boglione, D'Alesio, Murgia, Prokudin, JHEP 1704 (2017) 046



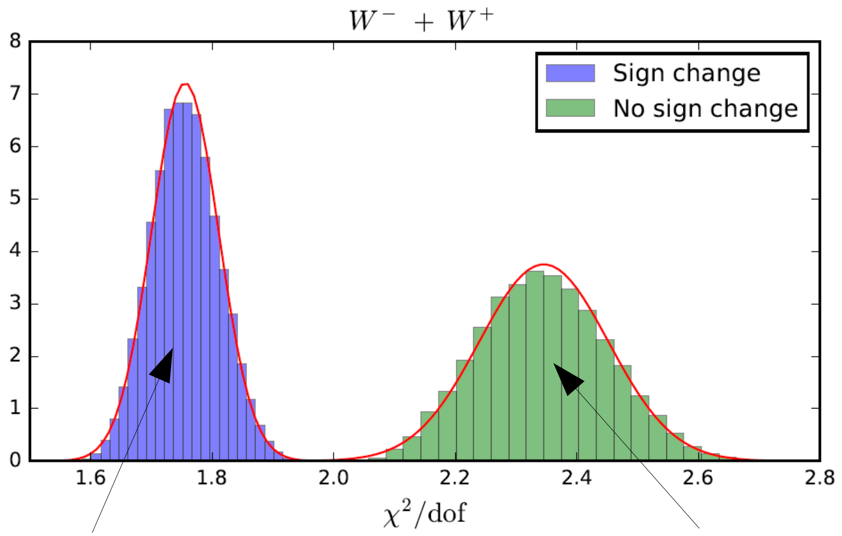
Sivers function in $p^{\uparrow} + p \rightarrow W^{\pm}/Z$ @ RHIC

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, JHEP 1704 (2017) 046





W^- data are compatible with the sign change, while W^+ data may be compatible with either sign of the Sivers function



$\langle\chi^2/\mathrm{dof}\rangle = 1.75$ and $\sigma(\chi^2/\mathrm{dof}) = 0.05$

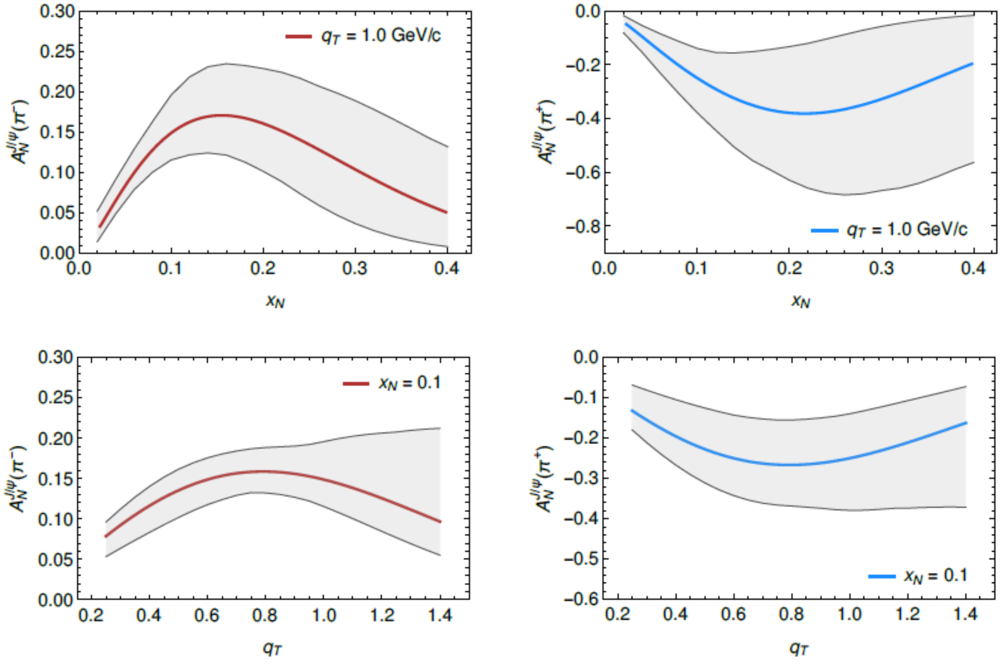
$\langle\chi^2/\mathrm{dof}\rangle = 2.35$ and $\sigma(\chi^2/\mathrm{dof}) = 0.1$

Sivers function in Drell-Yan at the J/Ψ peak

M. Anselmino, V. Barone, M. Boglione, Phys. Lett. B (2017)

$$A_N^{J/\Psi}(\pi^-; x_1, x_2, \boldsymbol{q}_T) \simeq \frac{\int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}}_2 \times \hat{\boldsymbol{k}}_{\perp 2})\, f_{\bar{u}/\pi^-}(x_1, k_{\perp 1})\, \boxed{\Delta^N f_{u/p^\uparrow}(x_2, k_{\perp 2})}}{2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, f_{\bar{u}/\pi^-}(x_1, k_{\perp 1})\, f_{u/p}(x_2, k_{\perp 2})}$$

$$A_N^{J/\Psi}(\pi^+; x_1, x_2, \boldsymbol{q}_T) \simeq \frac{\int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, \boldsymbol{S} \cdot (\hat{\boldsymbol{p}}_2 \times \hat{\boldsymbol{k}}_{\perp 2})\, f_{\bar{d}/\pi^+}(x_1, k_{\perp 1})\, \boxed{\Delta^N f_{d/p^\uparrow}(x_2, k_{\perp 2})}}{2 \int d^2\boldsymbol{k}_{\perp 1}\, d^2\boldsymbol{k}_{\perp 2}\, \delta^2(\boldsymbol{k}_{\perp 1} + \boldsymbol{k}_{\perp 2} - \boldsymbol{q}_T)\, f_{\bar{d}/\pi^+}(x_1, k_{\perp 1})\, f_{d/p}(x_2, k_{\perp 2})}$$



Usual DY elementary cross section

$$e_q^2\,\hat{\sigma}_0 = e_q^2\,\frac{4\pi\alpha^2}{9M^2}$$

With the replacements

$$\left\{ \begin{array}{l} 16\pi^2\alpha^2 e_q^2 \to (g_q^V)^2\,(g_\ell^V)^2 \\[2ex] \dfrac{1}{M^4} \to \dfrac{1}{(M^2 - M_V^2)^2 + M_V^2\,\Gamma_V^2} \end{array} \right.$$

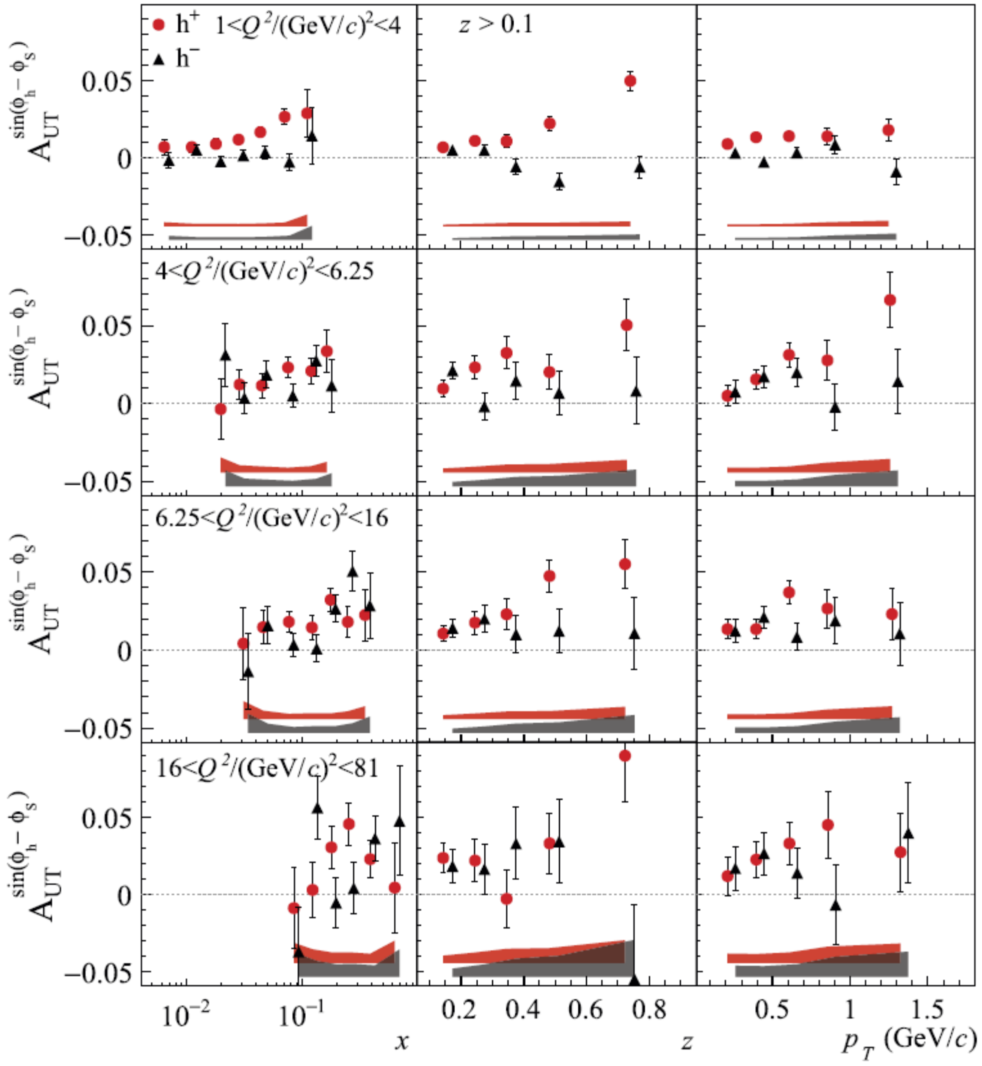
Measurements from COMPASS will soon be available

See talk by B. Parsamyan

2017
new data

Sivers single spin asymmetry in SIDIS at the hard scales of Drell Yan @ COMPASS

COMPASS Collaboration, Phys. Lett. B 770, 138 (2017)

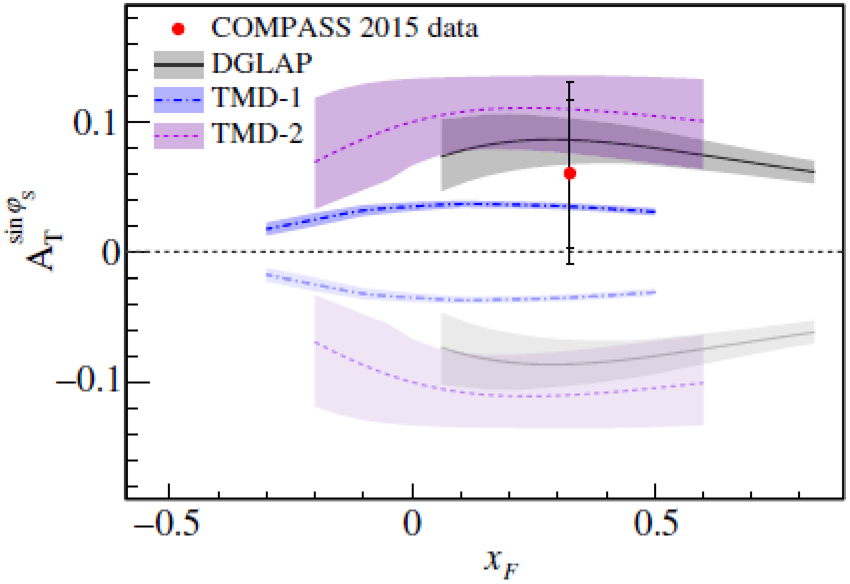


See talk by B. Parsamyan

Sivers single spin asymmetry in pion induced Drell Yan @ COMPASS

COMPASS Collaboration, Phys. Rev. Lett. 119, 112002 (2017)

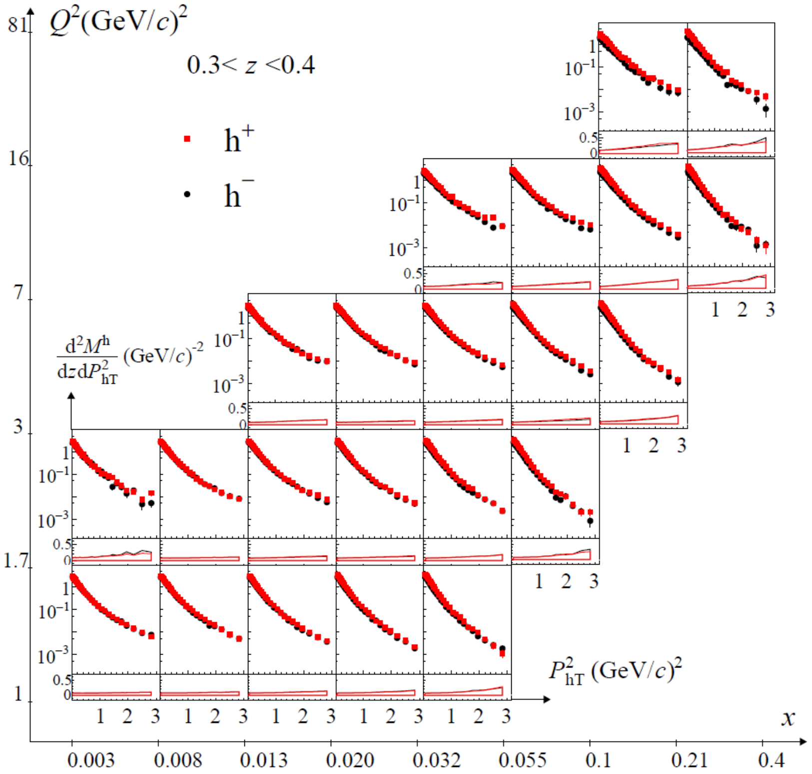
190GeV/c π- beam scattered off a transversely polarized NH3 target (polarized proton)

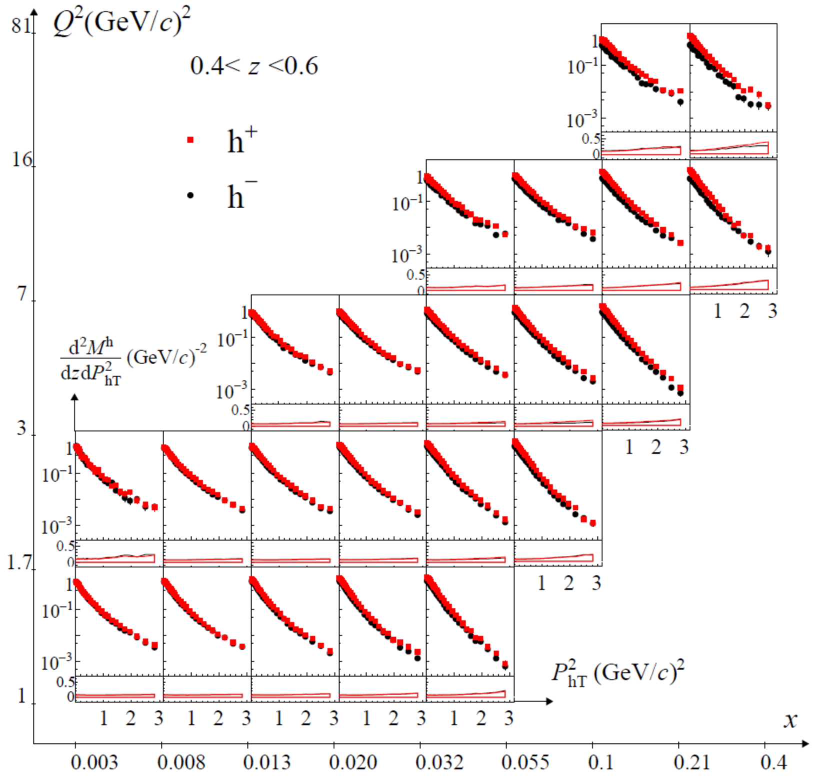


See talk by M. Chiosso

Multidimensional TMD multiplicities @ COMPASS

COMPASS Collaboration, arXiv:1709.07374 [hep-ex]

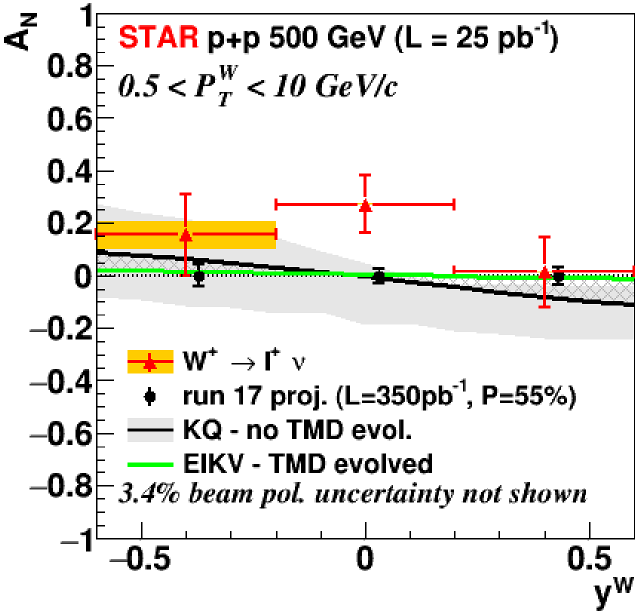


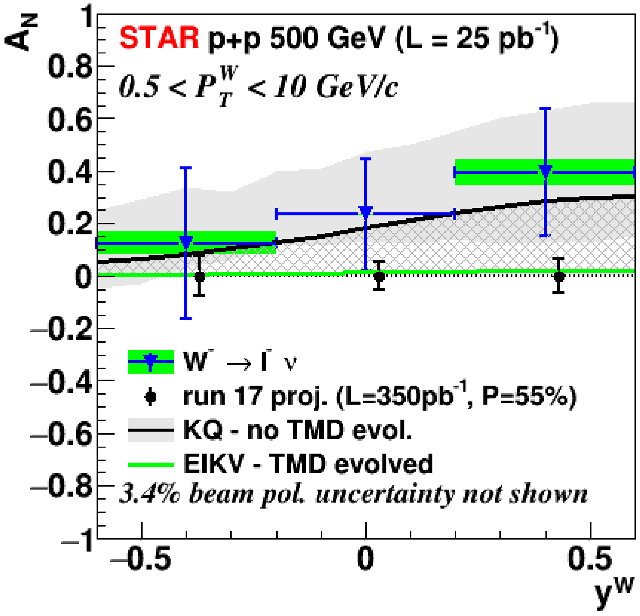


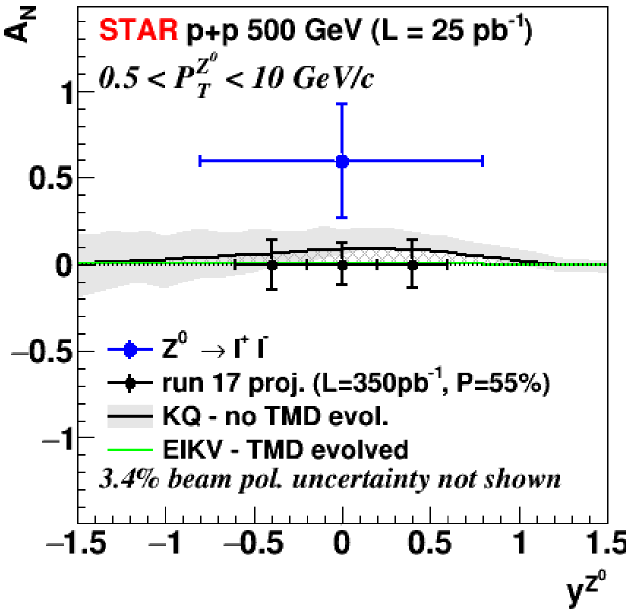
See talk by A. Bressan

Sivers function in $p^{\uparrow} + p \to W^{\pm}/Z$ @ RHIC RUN 2017

STAR Collaboration, Phys. Rev. Lett. 116 132301 (2016)







See talk by E.C. Ashenauer and S. Fazio

Need for a new, comprehensive study of the Sivers effect

Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

New parametrization of the Sivers function

$$\Delta^N f_{q/p^\uparrow} = \underbrace{N_q x^{\alpha_q}(1-x)^{\beta_q}} \frac{M_p}{\langle k_\perp^2\rangle_S} \underbrace{k_\perp \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_S}}{\pi\langle k_\perp^2\rangle_S}}$$

First moment of the Sivers fn.
Flavour dependent (u_v, d_v)

$k_\perp$ dependence of the Sivers fn.
Flavour independent

Sivers functions not proportional to TMD PDFs

No direct control on the positivity bound

Mp is a fixed parameter to give the right dimensions.
It is fixed to 1 GeV

- In perspective: parametrization in terms of momentum better suited for the study of TMD evolution
- It makes the expression of the actual Sivers asymmetry as simple as possible (within this model)

Sivers Asymmetry (numerator)

$$F_{UT}^{\sin(\phi_S-\phi_h)} = \frac{1}{2}\frac{zP_T}{\langle P_T^2\rangle}\frac{e^{-P_T^2/\langle P_T^2\rangle_S}}{\pi\langle P_T^2\rangle_S}\sum_q e_q^2\Big(N_q x^{\alpha_q}(1-x)^{\beta_q}\Big)D_{h/q}(z)$$

Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

Consistent data selection:

- Exclude negative kaons for valence dominance assumption
- u_v seems well constrained
- d_v is <u>not</u> constrained: it can be replaced by sea contributions with equally good fits: hard to distinguish where this contribution comes from
- Sivers sea is totally unconstrained

It is of vital importance to gain information on the d content of the Sivers function

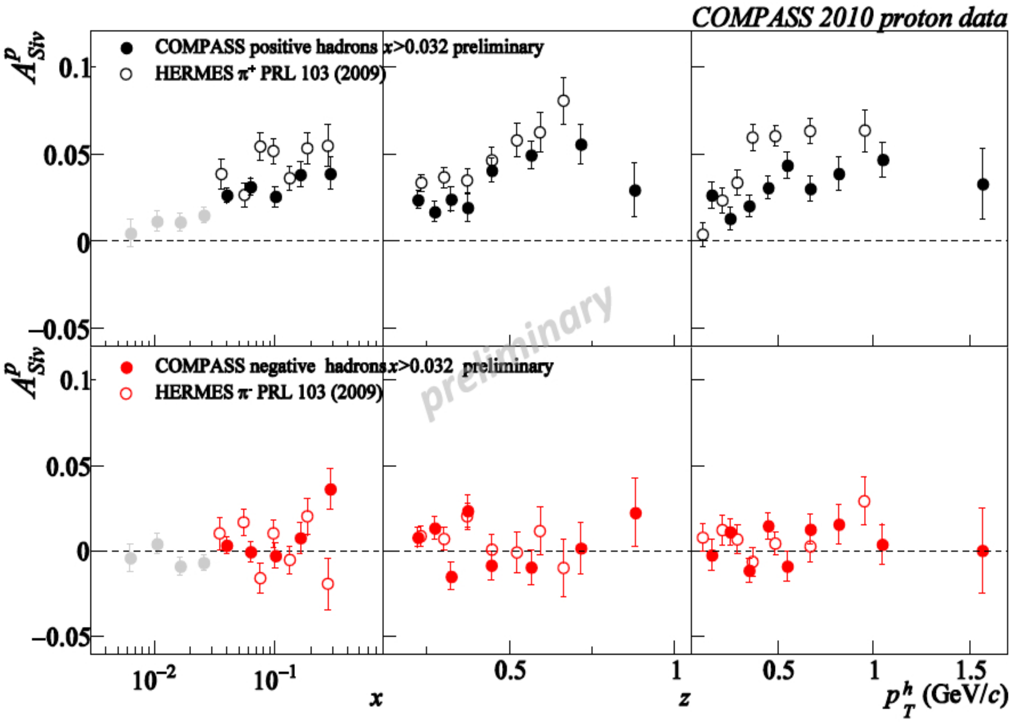
We strongly rely on SIDIS measurements of the Sivers asymmetry on deuterium target @ COMPASS !

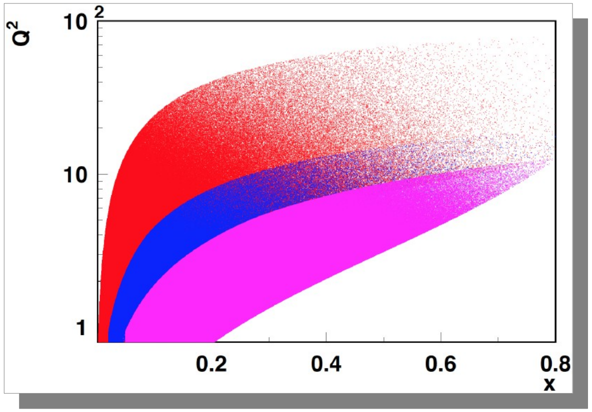
Sivers effect: COMPASS vs. HERMES

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

Apparently … signal of some tension between COMPASS and HERMES data

However, COMPASS and HERMES span different ranges in Q^2 and have different $< Q^2 >$.





Possible signal of TMD evolution?

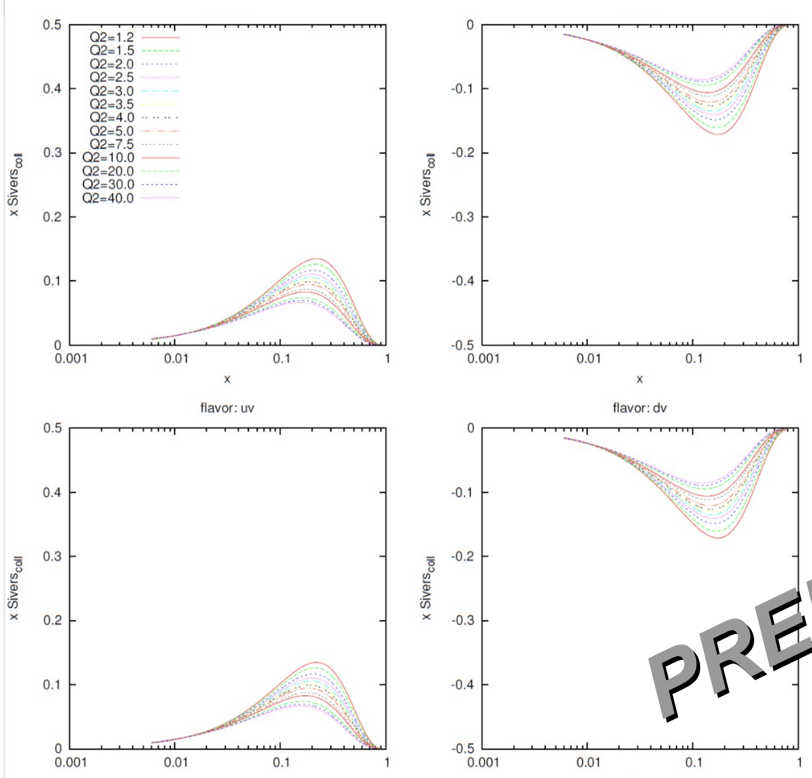
Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

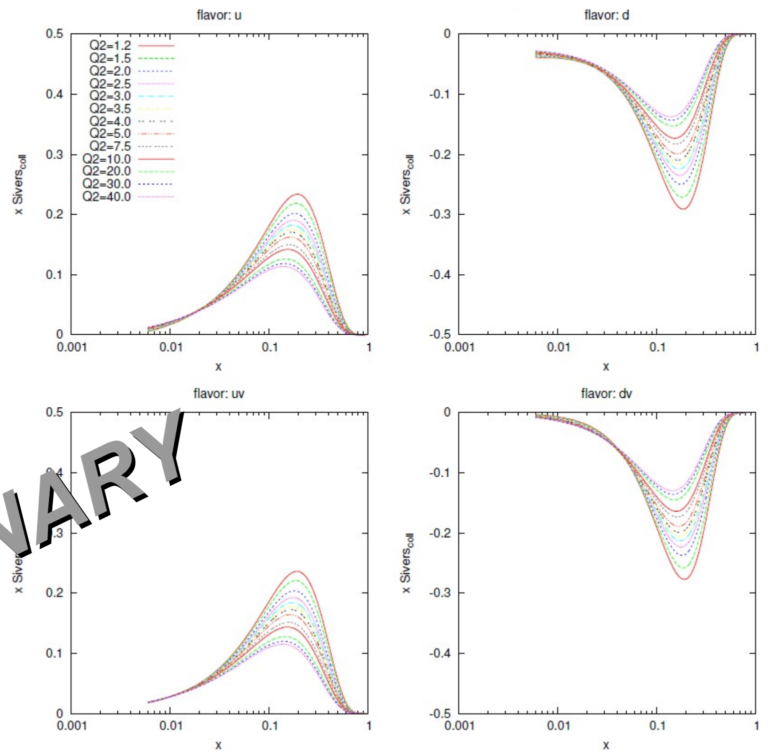
- HERMES 2009
- COMPASS 2009 (deuteron)
- COMPASS 2017 (h+,h-, Q^2 bins)
- JLAB 2011

HOPPET evolution of the whole Sivers function compared to DGLAP evolution of the collinear part only

Siver function with DGLAP evolution of the collinear part



Sivers function with HOPPET evolution of the whole function

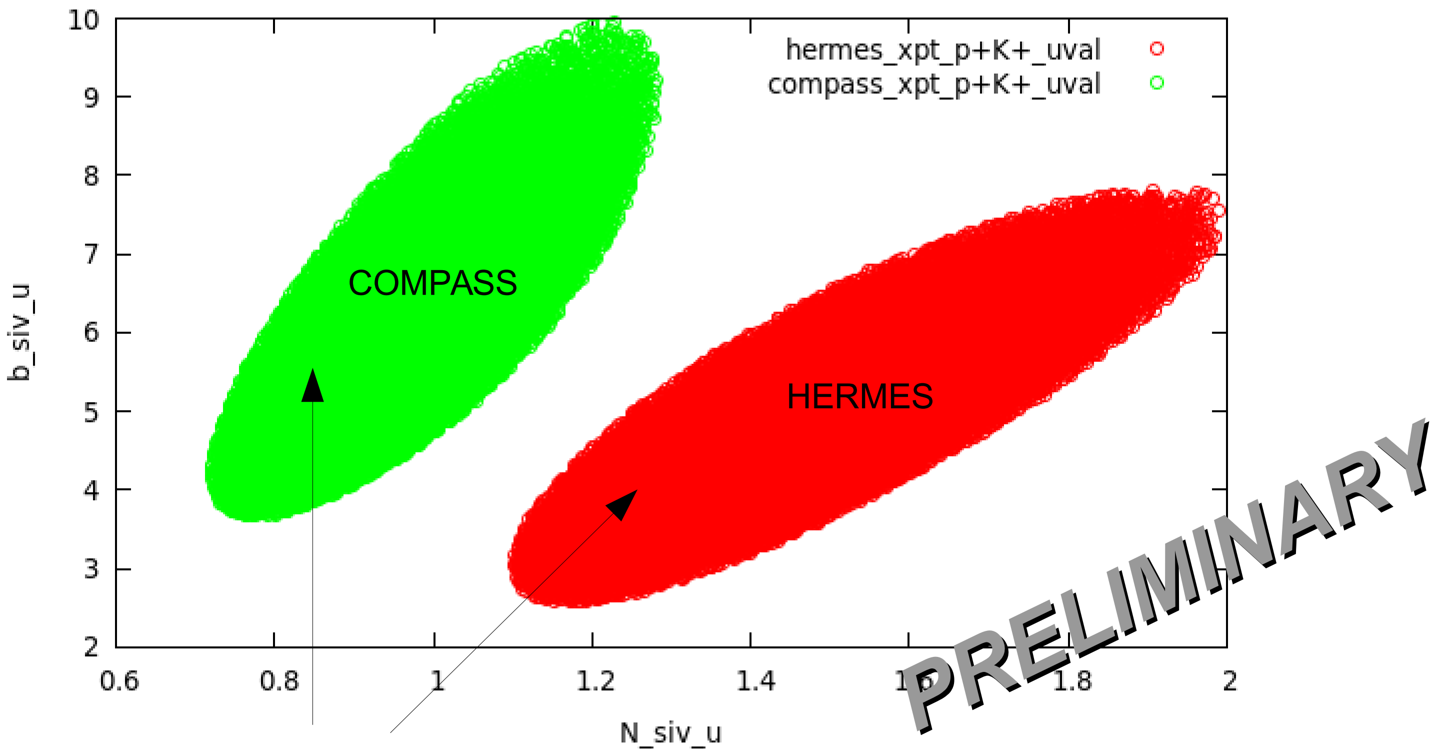


PRELIMINARY

Work in progress …

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

Signal of some tension between independent fit solutions for COMPASS and HERMES data



Independent fits

Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

To calculate any spin asymmetry it is crucial to use the appropriate denominator, i.e. the appropriate unpolarized cross section

$$F_{UU} = \sum_q e_q^2\, f_{q/p}(x_B)\, D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2\rangle}}{\pi\langle P_T^2\rangle}$$

$$\text{with} \qquad \langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$$

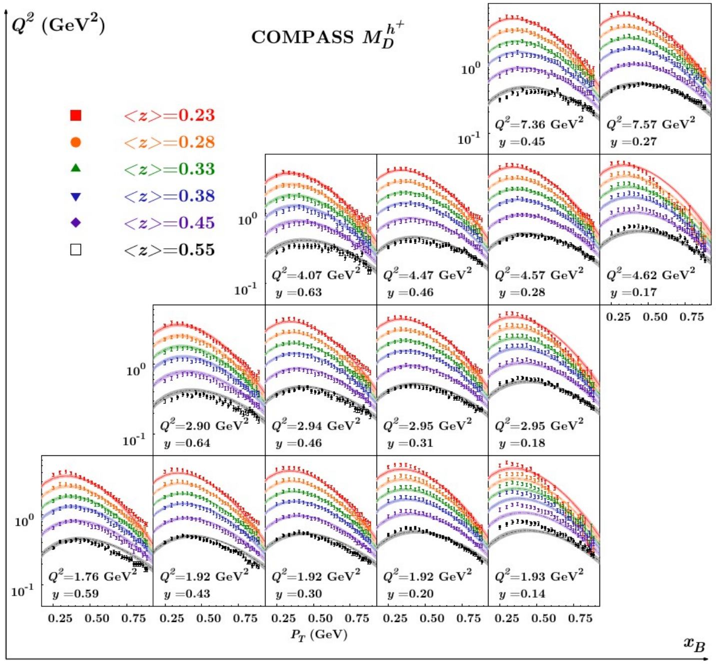
First item on the wish-list:

- Measure p_T distrbutions of unpolarized cross sections in SIDIS, Drell-Yan, e+e- processes, please

Naive TMD approach

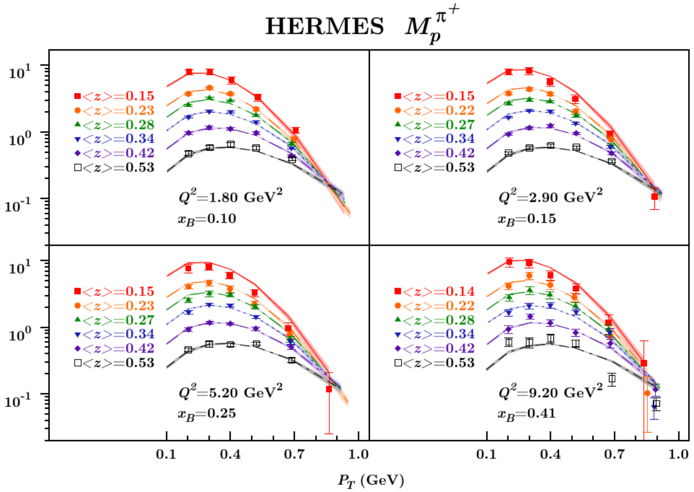
M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005

$$F_{UU} = \sum_q e_q^2 \, f_{q/p}(x_B)\, D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2\rangle}}{\pi \langle P_T^2\rangle} \qquad \text{with} \qquad \langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2 \langle k_\perp^2\rangle$$



COMPASS, Adolph et al., Eur. Phys. J. C 73 (2013) 2531

$$\langle k_\perp^2\rangle = 0.60 \pm 0.14 \text{ GeV}^2$$
$$\langle p_\perp^2\rangle = 0.20 \pm 0.02 \text{ GeV}^2$$
$$\chi^2_{\rm dof} = 3.42$$



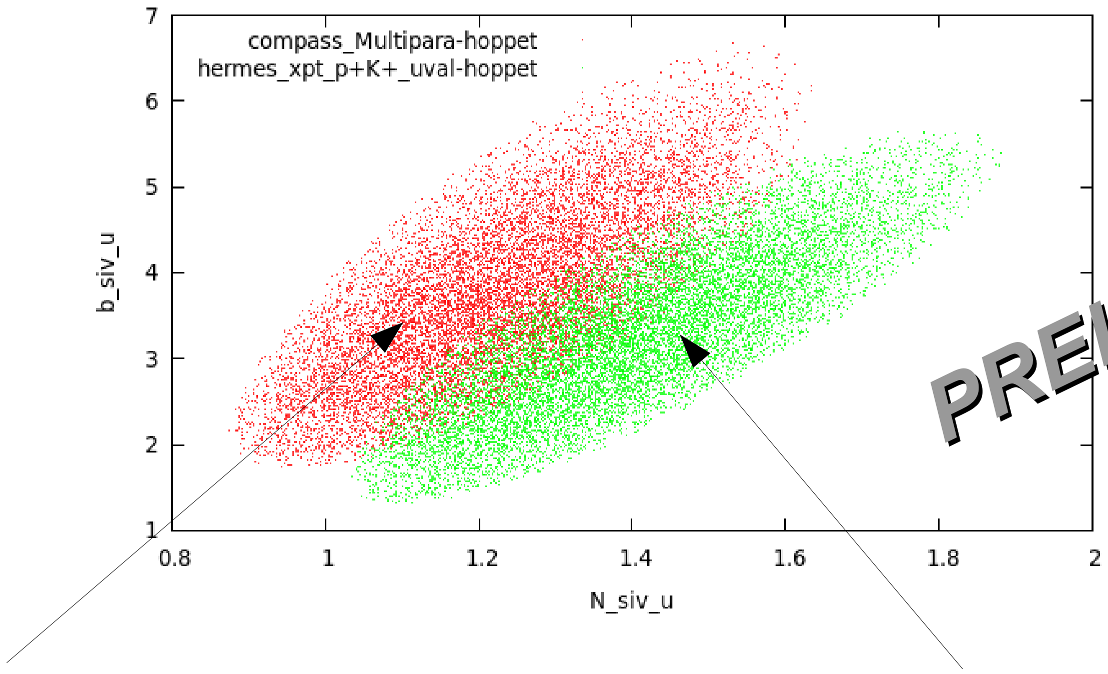
Airapetian et al, Phys. Rev. D 87 (2013) 074029

$$\langle k_\perp^2\rangle = 0.57 \pm 0.08 \text{ GeV}^2$$
$$\langle p_\perp^2\rangle = 0.12 \pm 0.01 \text{ GeV}^2$$
$$\chi^2_{\rm dof} = 1.69$$

Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

Tension relaxes when the asymmetry is computed using the appropriate unpolarized widths for each data set



PRELIMINARY

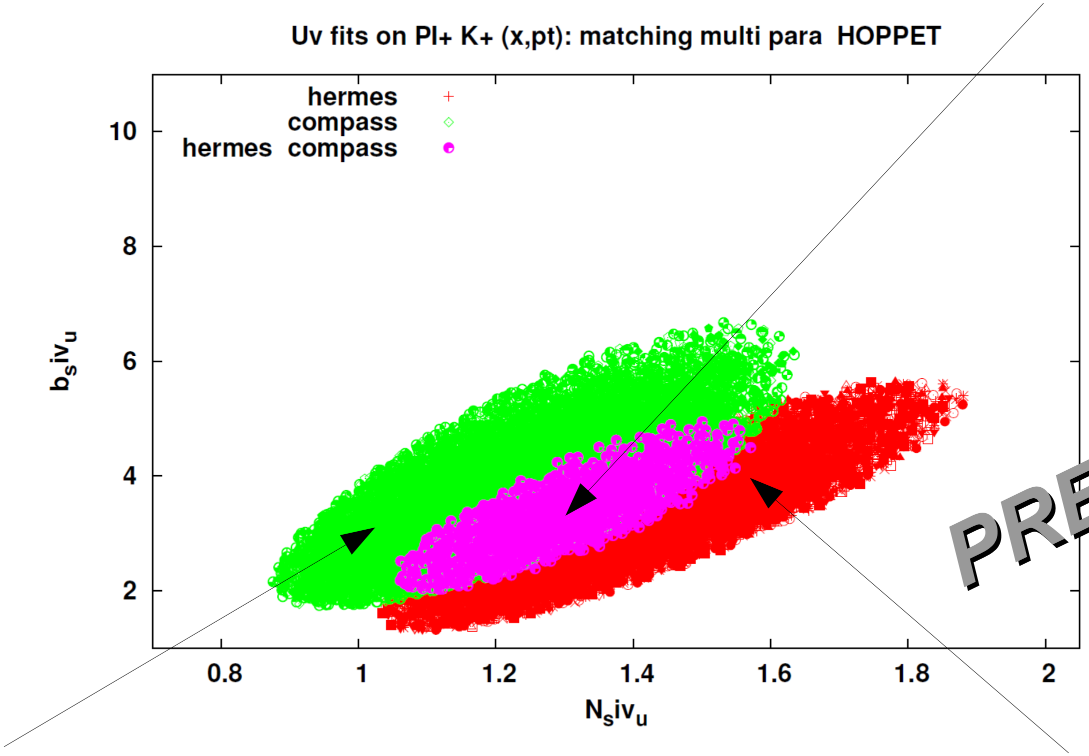
COMPASS-2017
(COMPASS widths + HOPPET evolution)

HERMES-2009
(HERMES widths + HOPPET evolution)

Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

Simultaneous fit of HERMES-2009 (HERMES widths + HOPPET) COMPASS-2017 (COMPASS widths + HOPPET)



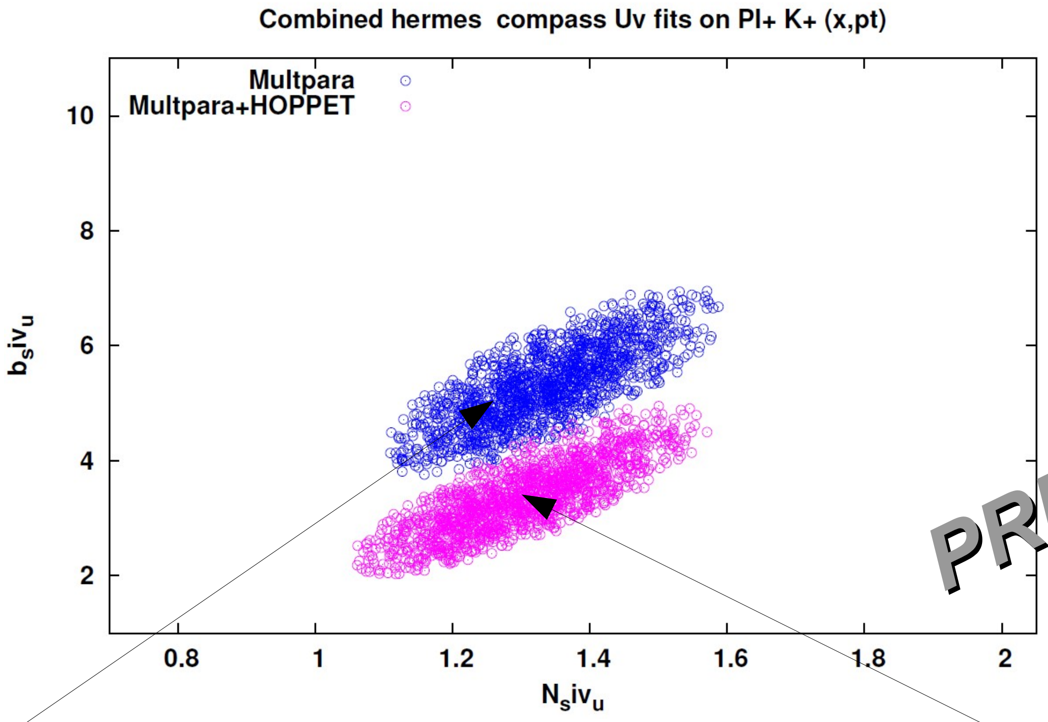
COMPASS-2017
(COMPASS widths + HOPPET evolution)

HERMES-2009
(HERMES widths + HOPPET evolution)

Work in progress ...

Anselmino, Boglione, D'Alesio, Flore, Gonzalez, Murgia, Prokudin

Simultaneous fit of HERMES-2009 (HERMES widths) COMPASS-2017 (COMPASS widths)



PRELIMINARY

No evolution

HOPPET evolution)

Outlooks and perspectives

- Phenomenological studies of TMDs, TMD factorization and TMD extraction have come a long way.
- Some issues remain open and need further investigation
- P_T distributions of SIDIS cross sections need to be measured (over the largest possible P_T range) and further investigated on the phenomenological point of view.
- Simultaneous fits of SIDIS, Drell-Yan and e^+e^- annihilation data are highly recommended, but they should be performed within a consistent and solid framework where they can be implemented.
- Data selection is crucial in global fitting:
  - not too many
    (only data within the ranges where the TMD evolution schemes work should be considered)
  - not too few
    (too strict a selection can bias the fit results and neglect important information from experimental data)