The Structure and Dynamics of Hadrons
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The Transverse Structure of the Nucleon

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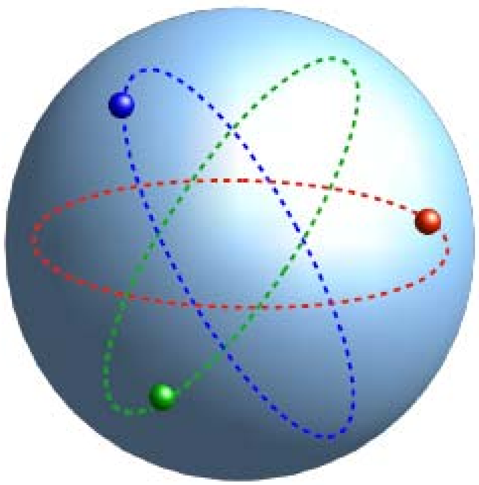
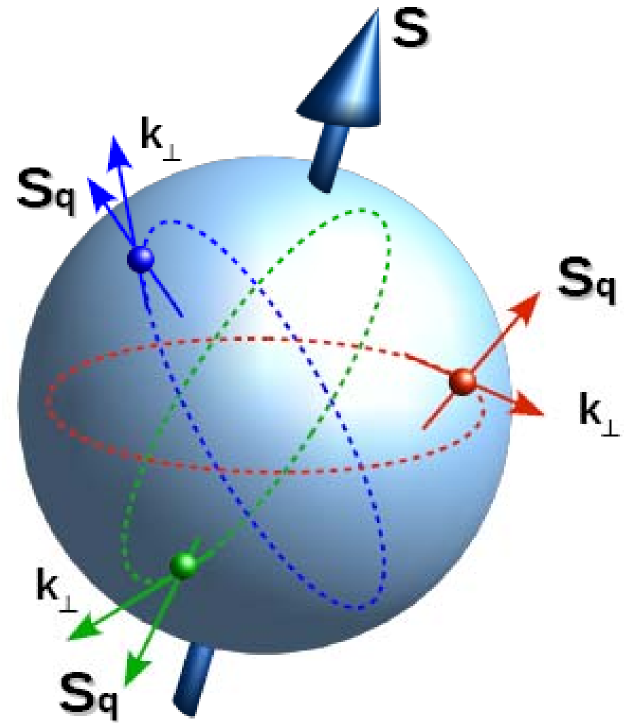
The Transverse 3-D Spin Structure of the Nucleon

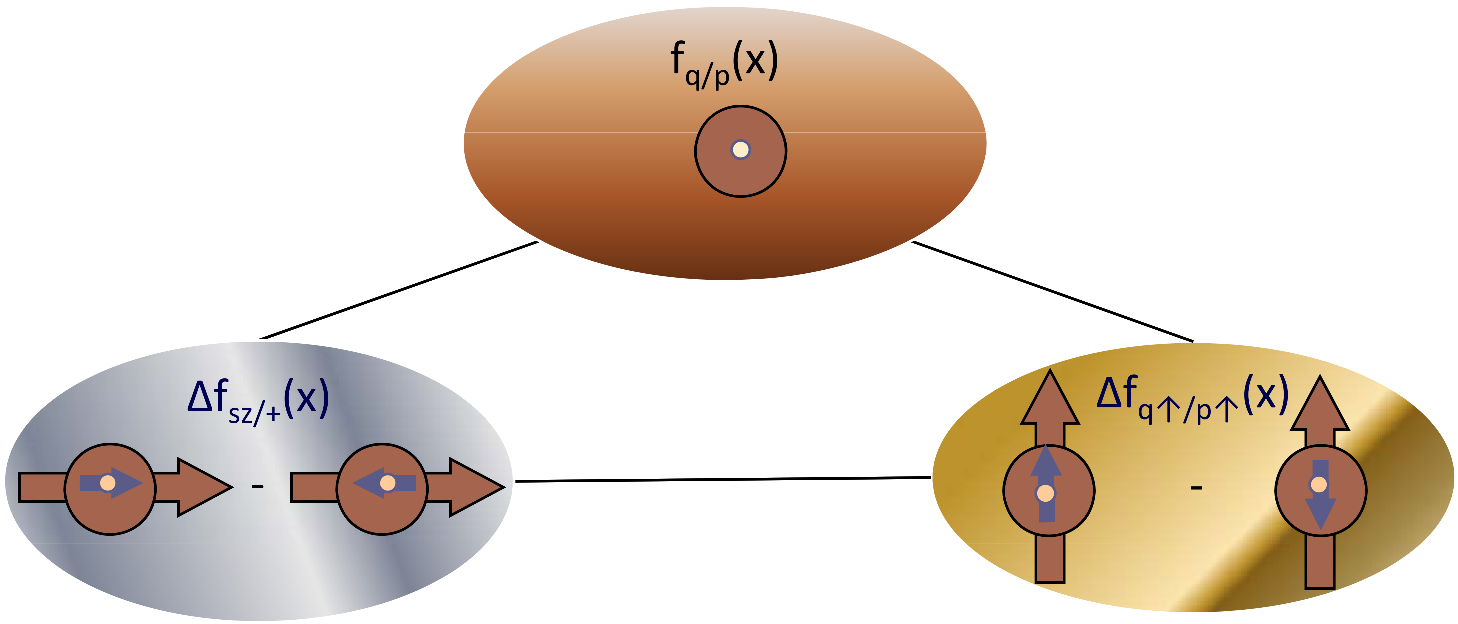




Distribution functions

Unpolarized distribution functions

$q = q_+^+ + q_-^+ \qquad g = g_+^+ + g_-^+$



Helicity distribution functions

$\Delta q = q_+^+ - q_-^+ \qquad \Delta g = g_+^+ - g_-^+$

Transversity distribution functions

$\Delta_T q = q_\uparrow^\uparrow - q_\downarrow^\uparrow$

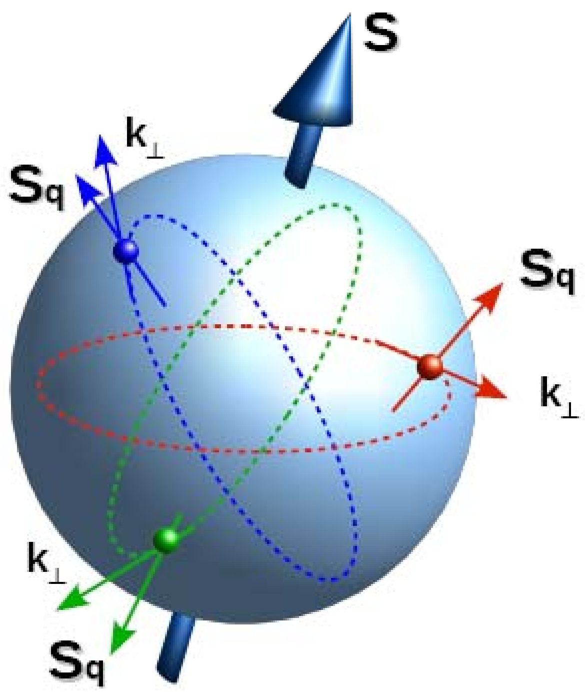
Parton Distribution Functions

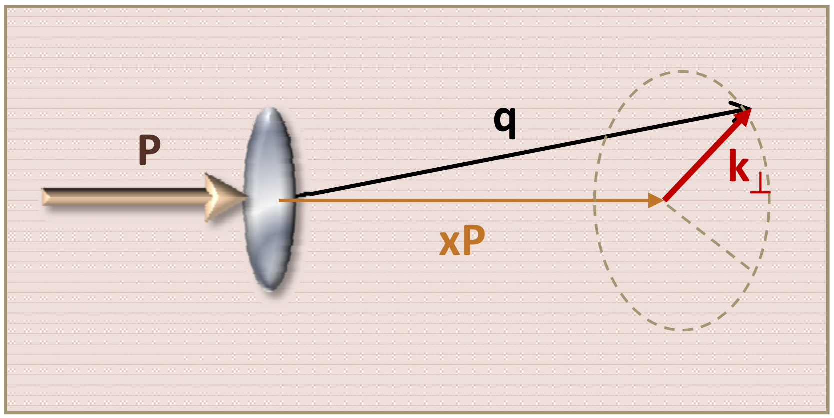
- Very good knowledge of unpolarized distribution functions, $q(x,Q^2)$ *and* $g(x,Q^2)$

- Fairly good knowledge of longitudinally polarized, partonic distributions, $\Delta q(x,Q^2)$; poor knowledge of longitudinally polarized gluons $\Delta g(x,Q^2)$

- NO direct information on transversely polarized partonic distributions, $\Delta_T q(x,Q^2)$, from DIS

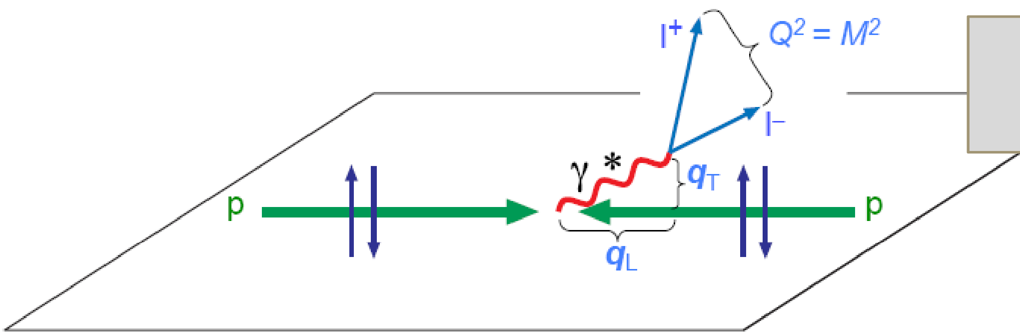
Intrinsic transverse momentum



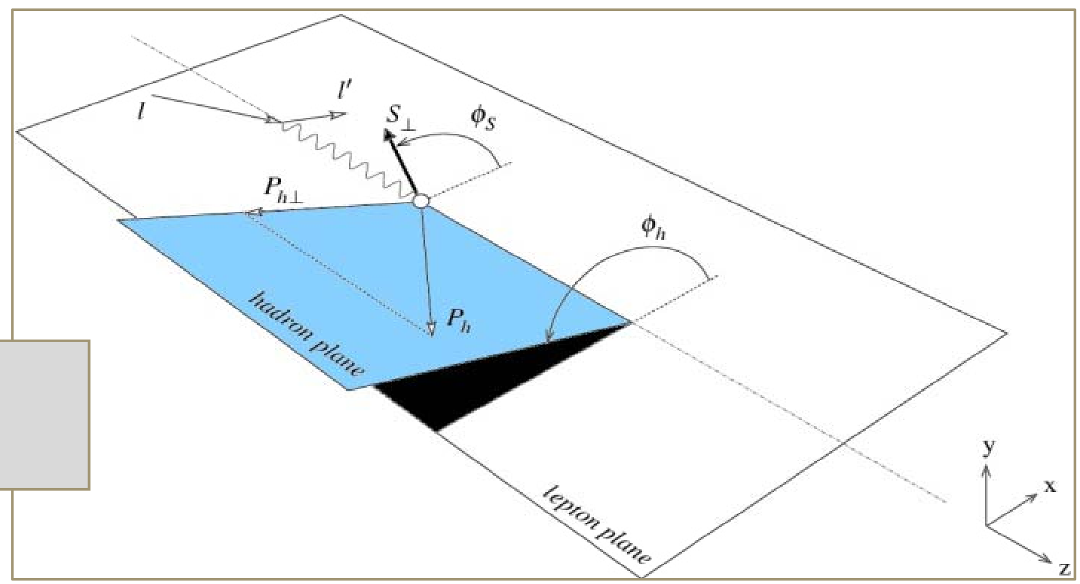


Plenty of theoretical and experimental evidence
for transverse motion of partons within nucleons,
and of hadrons within fragmentation jets

Intrinsic transverse momentum

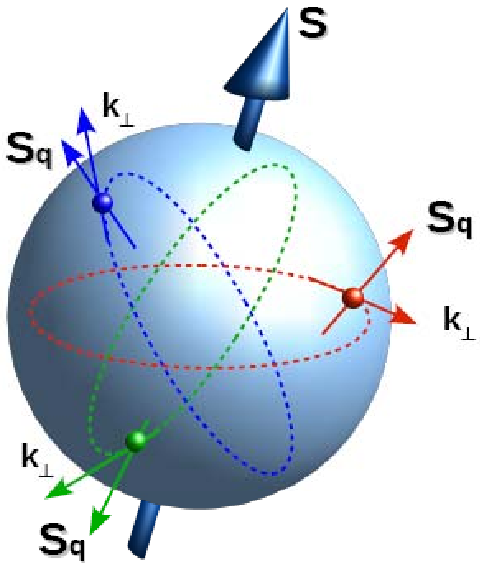


q_T distribution of lepton pairs in D-Y processes



p_T distribution of hadrons in SIDIS

Intrinsic transverse momentum



Distribution and fragmentation functions now depend

❖ on the lightcone momentum fraction
(**x** for the distributions and **z** for the fragmentations)

❖ on $\mathbf{Q^2}$ (→pQCD evolution),

❖ on the intrinsic transverse momentum of the partons,
($\mathbf{k}_\perp$ for the distributions and $\mathbf{p}_\perp$ for the fragmentations)

OPEN QUESTIONS:

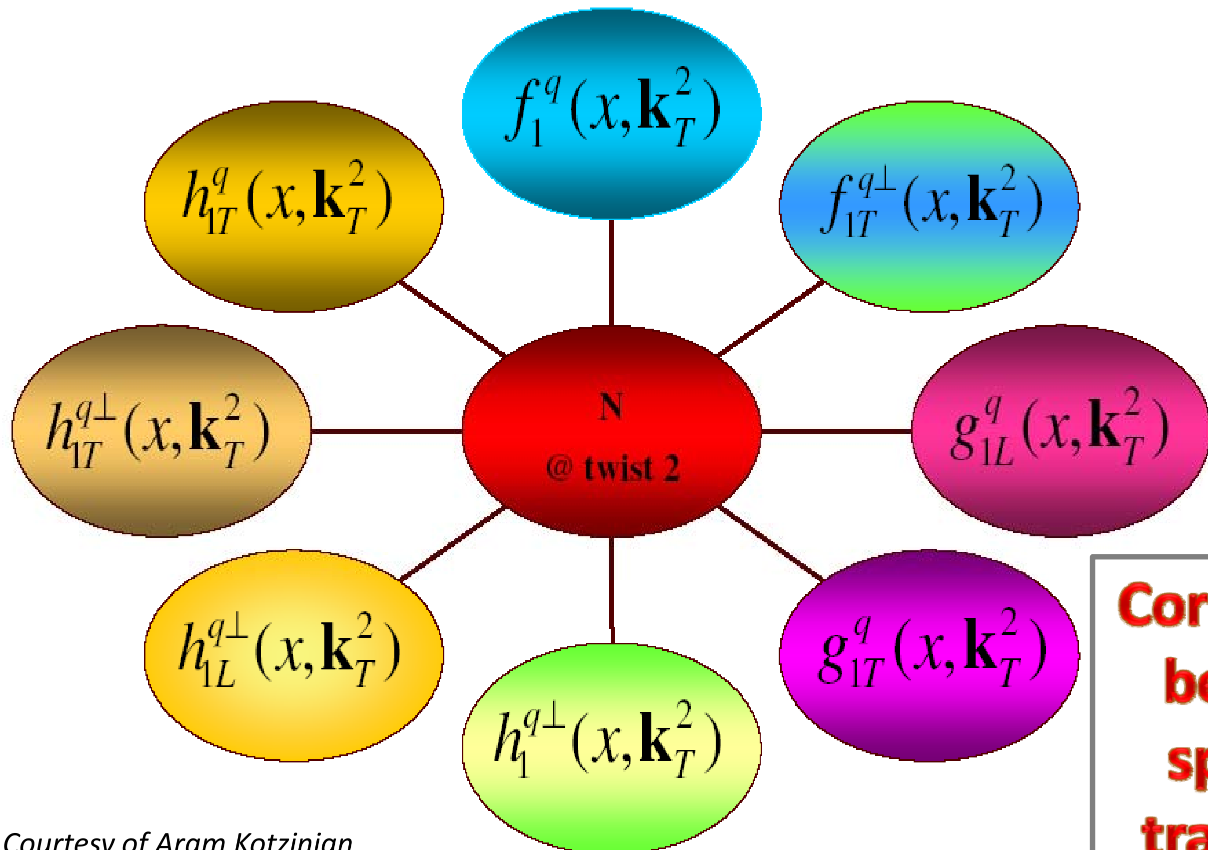
❖How do TMD's depend on the intrinsic transverse momentum ?

✓Gaussian behaviour in the central region …

✓Power law decrease at large transverse momentum…

❖ Does the partonic intrinsic transverse momentum $k_\perp$ ($p_\perp$) depend on x (z) ?

Transverse Momentum Dependent Parton Distribution Functions



Courtesy of Aram Kotzinian

Correlations between spin and transverse momentum

Transverse Momentum Dependent Parton Distribution Functions

QUARK POLARIZATION

NUCLEON POLARIZATION	U	L	T
U	$\mathbf{f_1}(x,k_\perp)$ **Unpolarized**		$\mathbf{h_1^\perp}(x,k_\perp)$ Boer-Mulders
L		$\mathbf{g_1}(x,k_\perp)$ **Helicity**	$h_{1L}(x,\mathbf{k}_\perp)$
T	$f^\perp_{1T}(x,\mathbf{k}_\perp)$ Sivers	$g_{1T}(x,\mathbf{k}_\perp)$	$\mathbf{h_{1T}}(x,\mathbf{k}_\perp)$ $\mathbf{h^\perp_{1T}}(x,\mathbf{k}_\perp)$ **Transversity**

Courtesy of A. Bacchetta

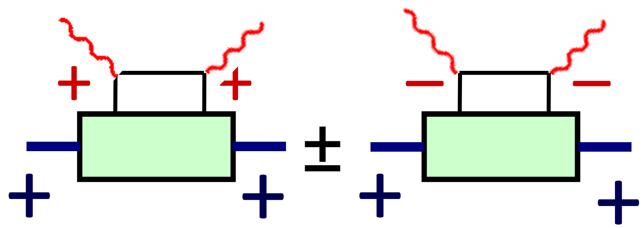
- Functions in bold face survive $k_\perp$ integration
- Functions in shaded cells are naïve T-odd
- Functions in red box are chirally odd

The transversity distribution function

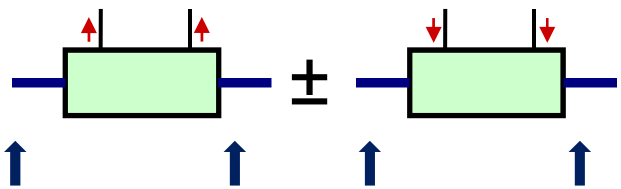
Transversity

- There is no gluon transversity distribution function

- Transversity cannot be studied in deep inelastic scattering because it is chirally odd

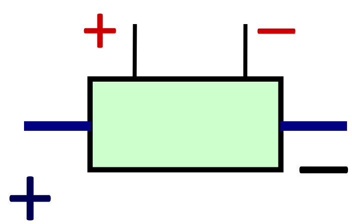


$$ = \begin{matrix} f_{q/p}(x,Q^2) \\ \Delta q(x,Q^2) \end{matrix}$$



$$ = \begin{matrix} f_{q/p}(x,Q^2) \\ h_1(x,Q^2) \end{matrix}$$

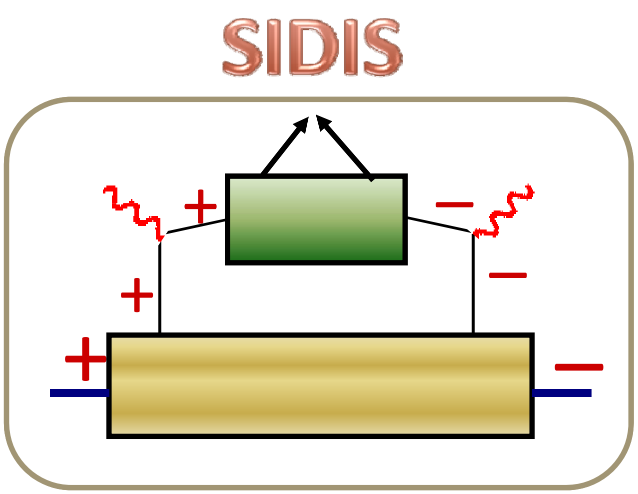
In helicity basis: ↑↓ $= \frac{1}{\sqrt{2}}\left(|+\rangle \pm i\,|-\rangle \right)$

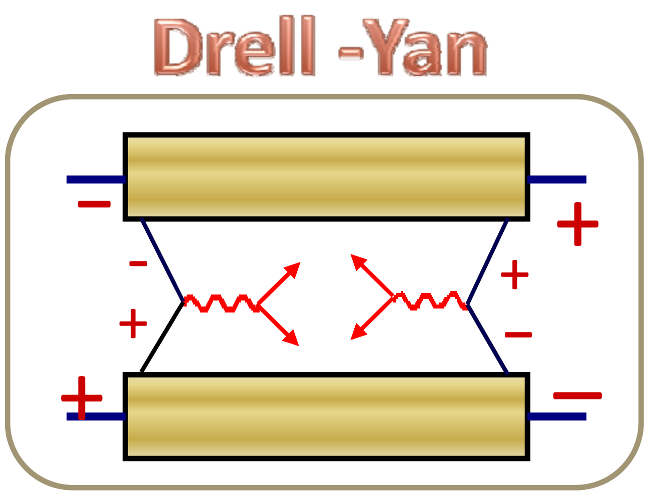
$h_1(x,Q^2) =$ 

decouples from DIS (no quark helicity flip)

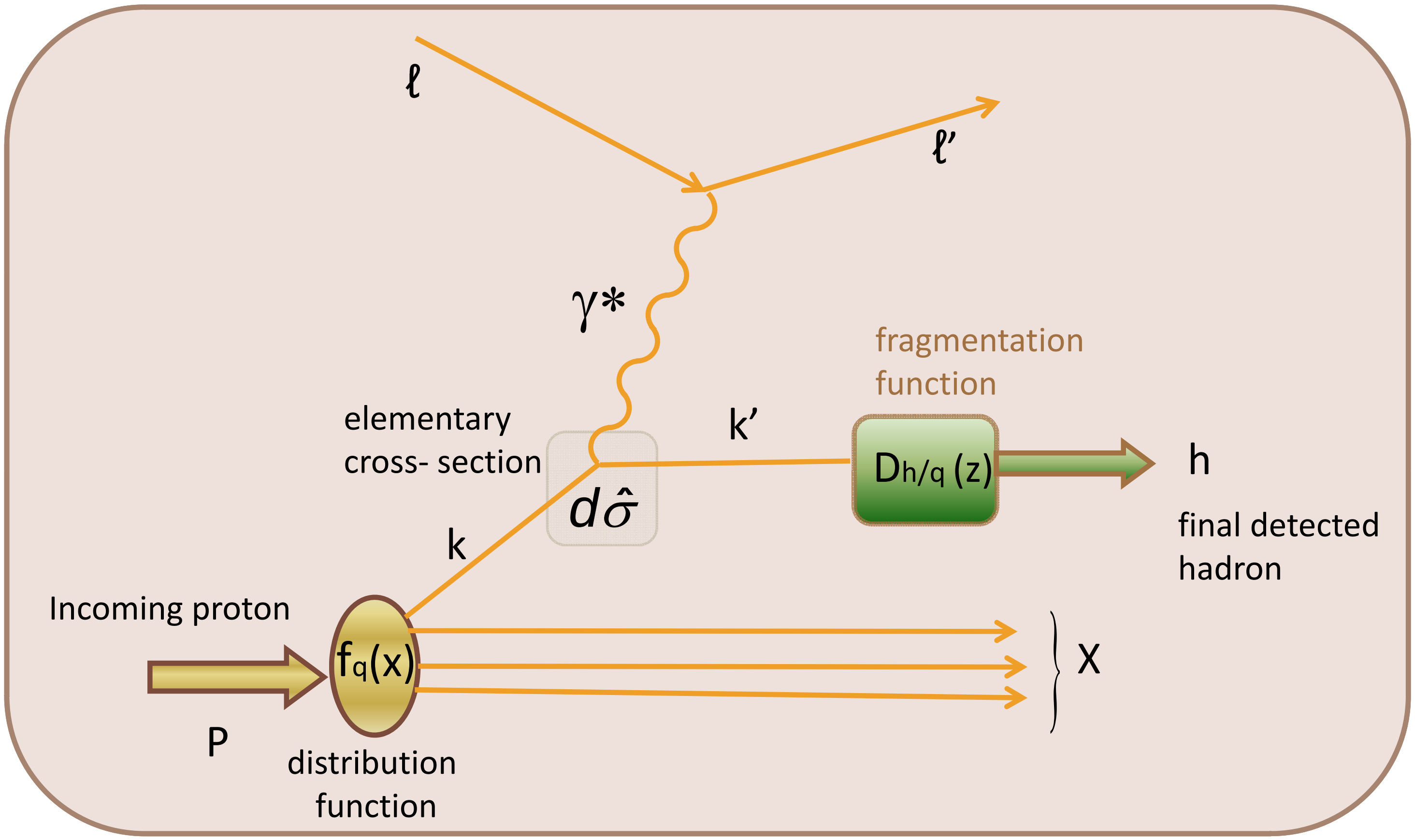
Transversity

- There is no gluon transversity distribution function
- Transversity cannot be studied in deep inelastic scattering because it is chirally odd
- Transversity can only appear in a cross-section convoluted to another chirally odd function



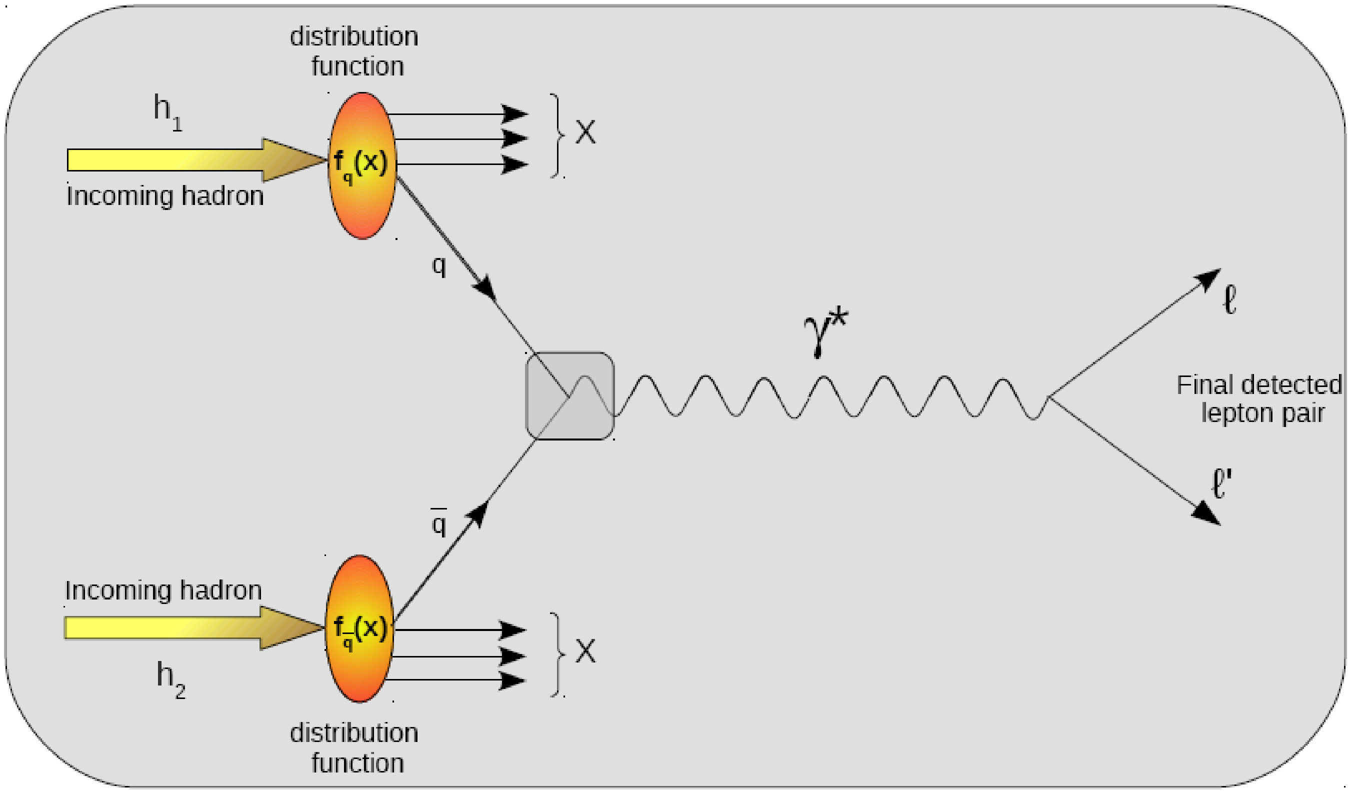


Semi Inclusive Deep Inelastic Scattering



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

Drell – Yan processes



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

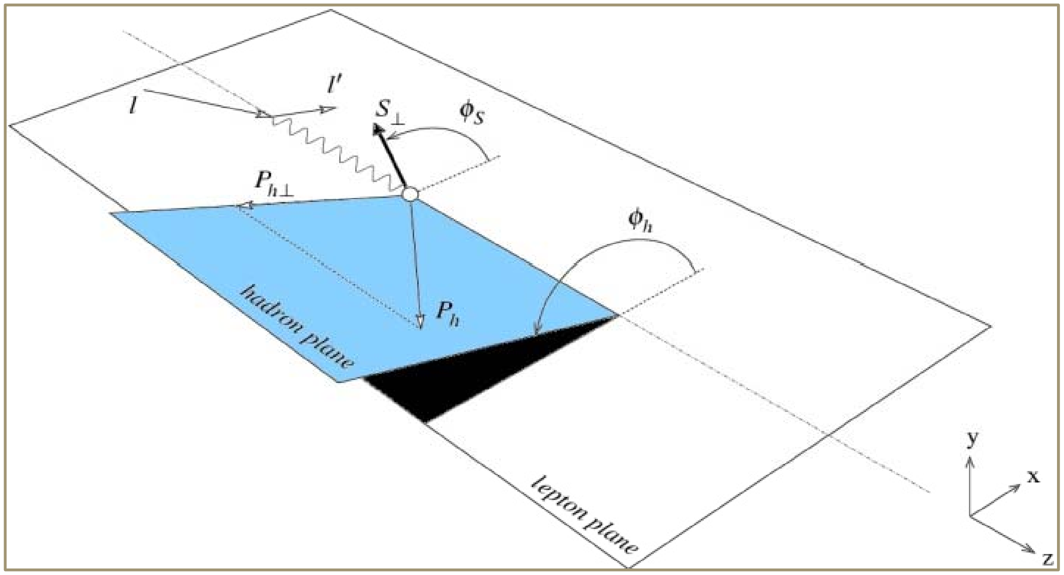
TMD distribution and fragmentation functions in SIDIS processes

TMD's in DIS and SIDIS

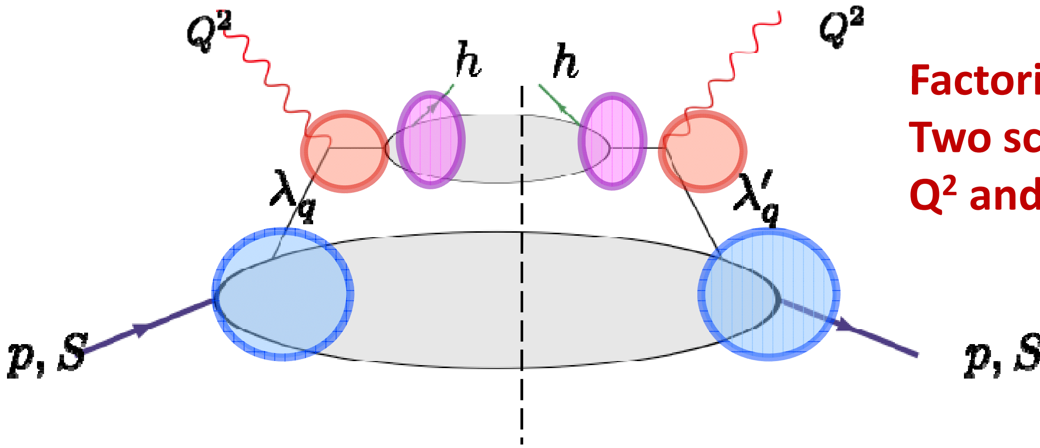
❖The unpolarized and helicity integrated distribution functions are extracted from DIS experimental measurements

❖A first extraction of the **transversity** distribution function has been made by simultaneously fitting SIDIS (HERMES AND COMPASS) data and $e+e^- \rightarrow h_1 h_2 X$ BELLE experimental data

❖The **Sivers** and **Boer-Mulders** functions have been extracted by fitting SIDIS data (HERMES and COMPASS)



SIDIS factorization



Factorization holds
Two scales:
Q^2 and $k_\perp$, with $k_\perp << Q^2$

$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell'+h+X}}{dx_B\,dQ^2\,dz_h\,d^2\boldsymbol{P}_T\,d\phi_S} = \rho^{\ell,S_\ell}_{\lambda_\ell,\lambda'_\ell}\otimes\rho^{q/p,S}_{\lambda_q,\lambda'_q}\,\hat f_{q/p,S}(x,\boldsymbol{k}_\perp)\otimes \hat M_{\lambda_\ell,\lambda_q;\lambda_\ell,\lambda_q}\,\hat M^*_{\lambda'_\ell,\lambda'_q;\lambda'_\ell,\lambda'_q}\otimes\hat D^h_{\lambda_q,\lambda'_q}(z,\boldsymbol{p}_\perp)$$

TMD-PDF hard scattering TMD-FF

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

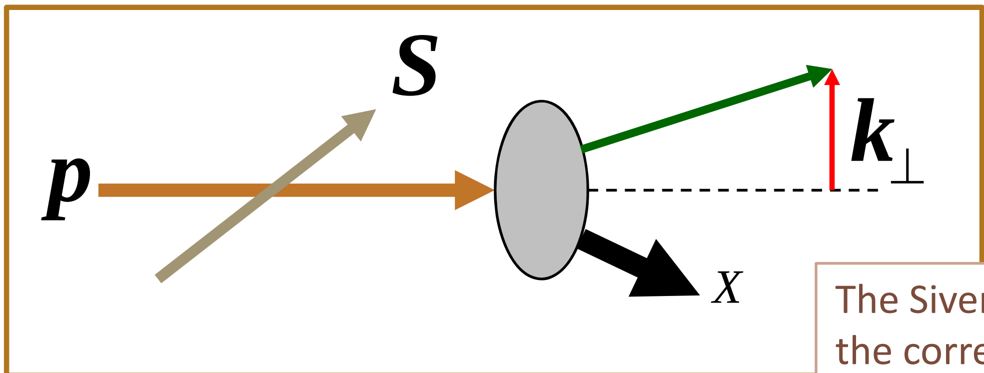
The Sivers distribution function

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

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

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 inbeds the correlation between the proton spin and the quark transverse momentum

The Sivers distribution function in SIDIS

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{d\sigma^{\ell p^\uparrow \to \ell' hX} - d\sigma^{\ell p^\downarrow \to \ell' hX}}{d\sigma^{\ell p^\uparrow \to \ell' hX} + d\sigma^{\ell p^\downarrow \to \ell' hX}}$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q}(x, k_\perp) \otimes \hat{\sigma}^{\ell q \to \ell' q'} \otimes D_{h/q}(z, p_\perp)$$

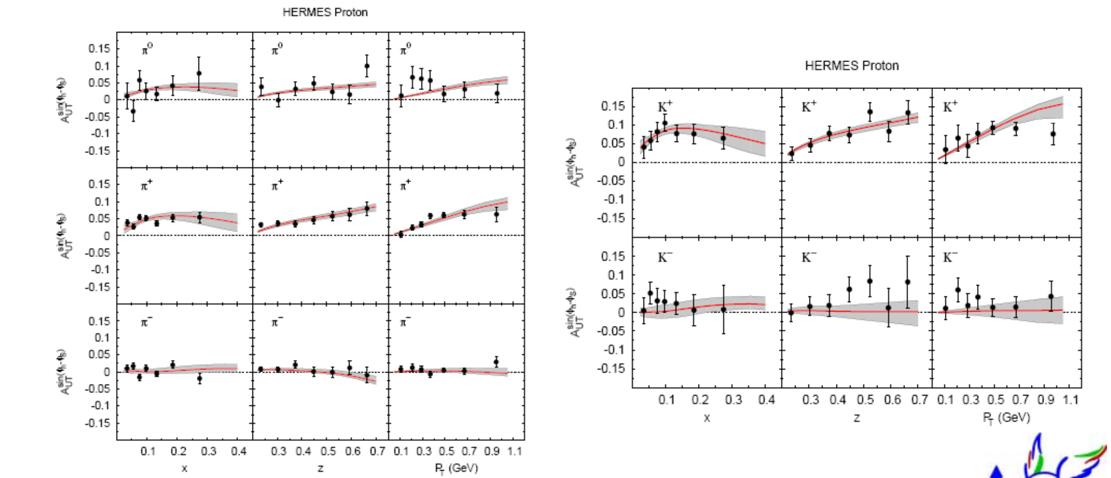
Two soft mechanisms at work in SIDIS:

- **Distribution fn.** → probability to find quark q carrying a light-cone fraction x of the parent proton momentum, an intrinsic transverse momentum $k_\perp$, at scale Q^2.
- **Fragmentation fn.**→ describes the hadronization of the struck quark into the final, detected hadron.

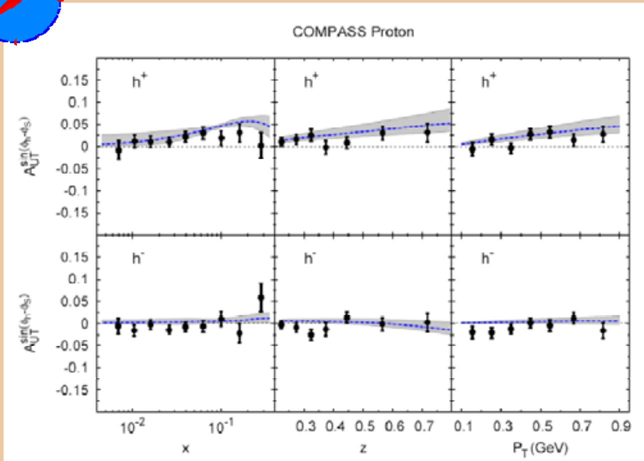
Both mechanisms play an important role in determining total cross section and spin asymmetries

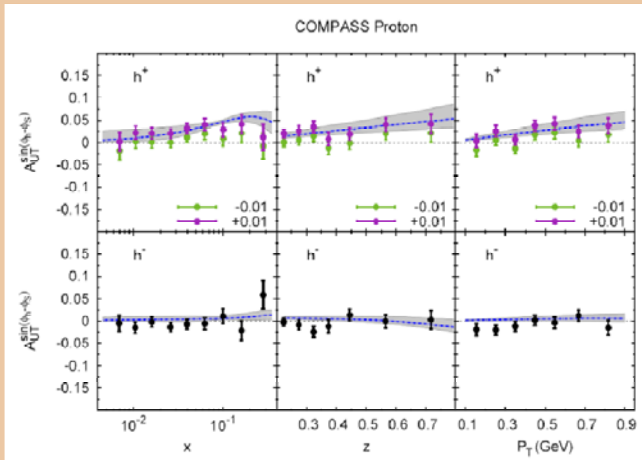
The Sivers distribution function

New preliminary FIT
M.Anselmino, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, arXiv:1012.3565



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



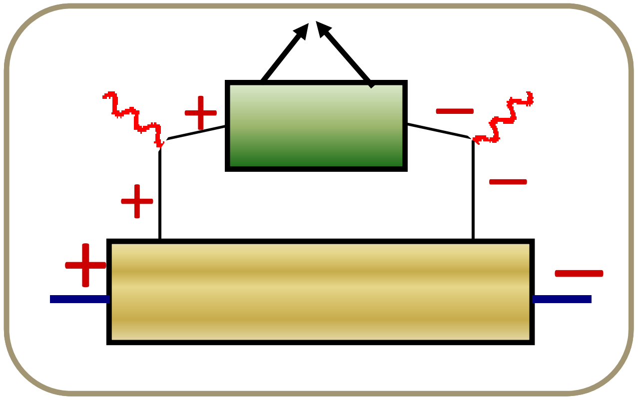


Anna Martin for COMPASS Collaboration - DIS2010
Giulia Pesaro for COMPASS Collaboration – SPIN2010

Transversity

- Transversity cannot be studied in deep inelastic scattering because it is **chirally odd**
- Transversity can only appear in a cross-section convoluted to another **chirally odd** function: in SIDIS cross section it couples to the **Collins fragmentation function**

SIDIS



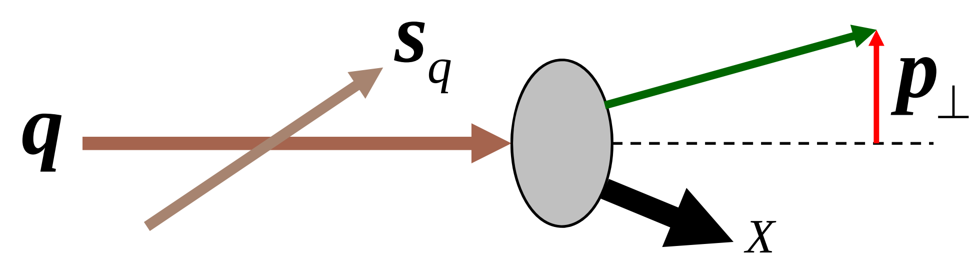
The Collins fragmentation function

$$D_{h/q,s_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\, \boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

$$= D_{h/q}(z,p_\perp) + \frac{p_\perp}{z\,M_h} H_1^{\perp q}(z,p_\perp)\, \boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

The Collins function is related to the probability that a transversely polarized struck quark will fragment into a spinless hadron

The Collins function is chirally odd



The Collins function inbeds the correlation between the fragmenting quark spin and the transverse momentum of the produced hadron

The Collins effect in SIDIS

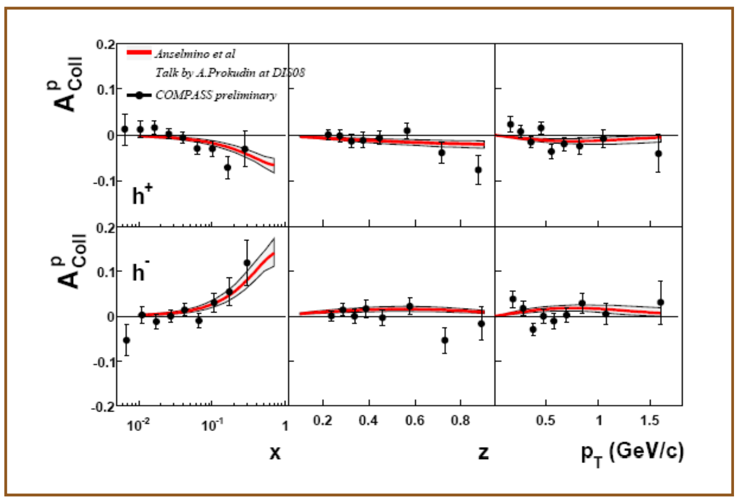
$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q h_{1q}(x, k_\perp) \otimes d\Delta\hat{\sigma}(y, k_\perp) \otimes \Delta^N D_{h/q^\uparrow}(z, p_\perp)$$

The Collins effect in SIDIS couples to transversity

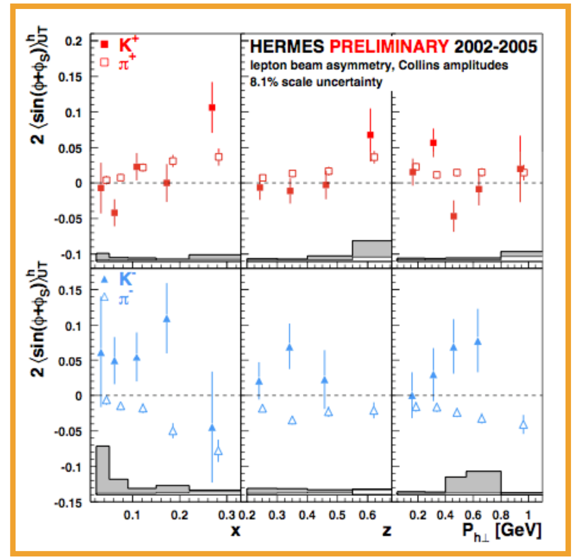
$$A_{UT}^{\sin(\phi+\phi_S)} \equiv 2\,\frac{\int d\phi\, d\phi_S\, [d\sigma^\uparrow - d\sigma^\downarrow]\, \sin(\phi+\phi_S)}{\int d\phi\, d\phi_S\, [d\sigma^\uparrow + d\sigma^\downarrow]}$$

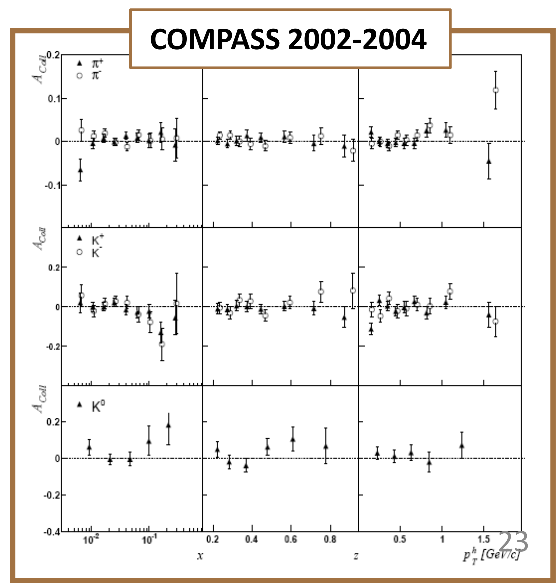
$$d\Delta\hat{\sigma} = d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\uparrow} - d\hat{\sigma}^{\ell q^\uparrow \to \ell q^\downarrow}$$

COMPASS proton data



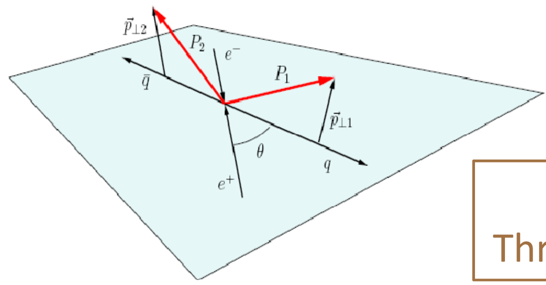
S. Levorato for the COMPASS Collaboration, Transversity 2008





Simultaneous determination of Transversity and Collins functions

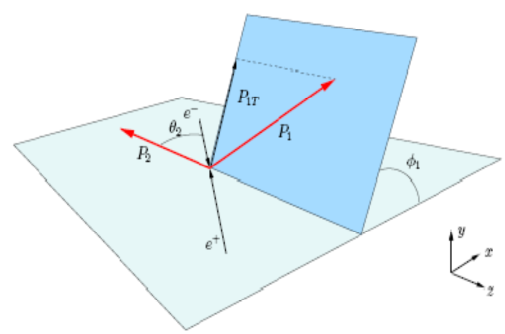
- **We need to determine two convoluted unknown functions**
  - Fix one of the two functions according to some theoretical model and use SIDIS data to determine the other (see for example Efremov, Goeke, Schweitzer)
  - **Perform a simultaneous fit of SIDIS and $e^+e^- \to h_1 h_2 X$ BELLE data.**



BELLE
Thrust axis method

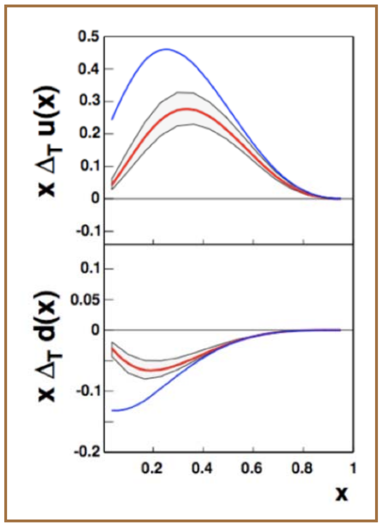
$$A(z_1,z_2,\theta,\varphi_1+\varphi_2) \equiv \frac{1}{\langle d\sigma\rangle}\,\frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\,dz_2\,d\cos\theta\,d(\varphi_1+\varphi_2)} = 1+\frac{1}{8}\,\frac{\sin^2\theta}{1+\cos^2\theta}\,\cos(\varphi_1+\varphi_2)\,\frac{\sum_q e_q^2\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2 D_{h_1/q}(z_1)\,D_{h_2/\bar{q}}(z_2)}\,.$$

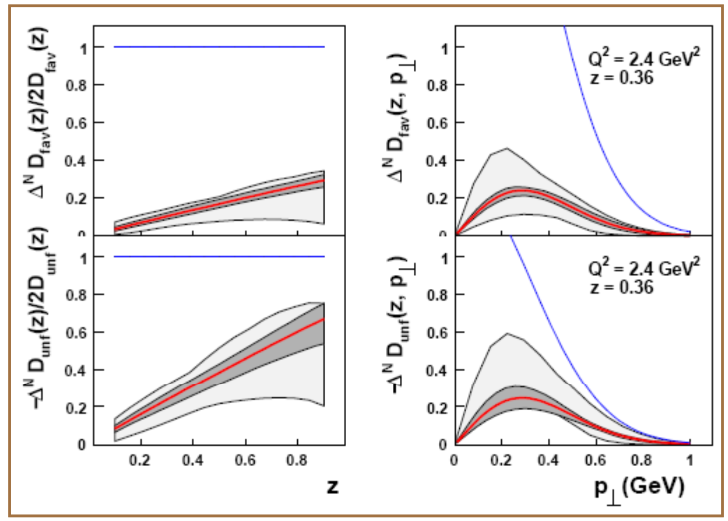
BELLE
Hadronic plane method



$$A(z_1,z_2,\theta_2,\phi_1) = 1+\frac{1}{\pi}\,\frac{z_1\,z_2}{z_1^2+z_2^2}\,\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,\cos(2\,\phi_1)\,\frac{\sum_q e_q^2\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2 D_{h_1/q}(z_1)\,D_{h_2/\bar{q}}(z_2)}$$

Simultaneous determination of Transversity and Collins functions





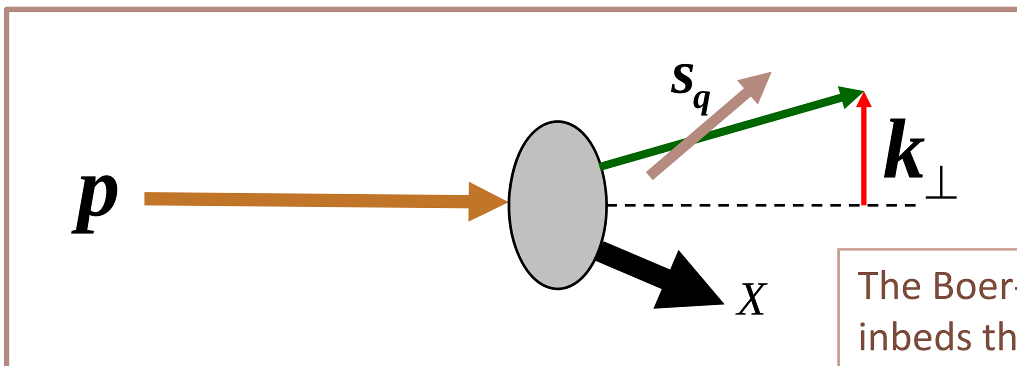
M.Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Türk, Phys.Rev. D75 (2007) 054032, Nucl.Phys.Proc.Suppl. 191 (2009) 98-107.

The Boer-Mulders distribution function

$$f_{q,s_q/p}(x,\boldsymbol{k}_\perp) = \frac{1}{2} f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q^\uparrow/p}(x,k_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$
$$= \frac{1}{2} f_{q/p}(x,k_\perp) - \frac{1}{2}\frac{k_\perp}{M} h_1^{\perp q}(x,k_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

The Boer-Mulders function is related to the probability of finding a polarized quark inside an unpolarized proton

The Boer-Mulders function is chirally odd and T-odd

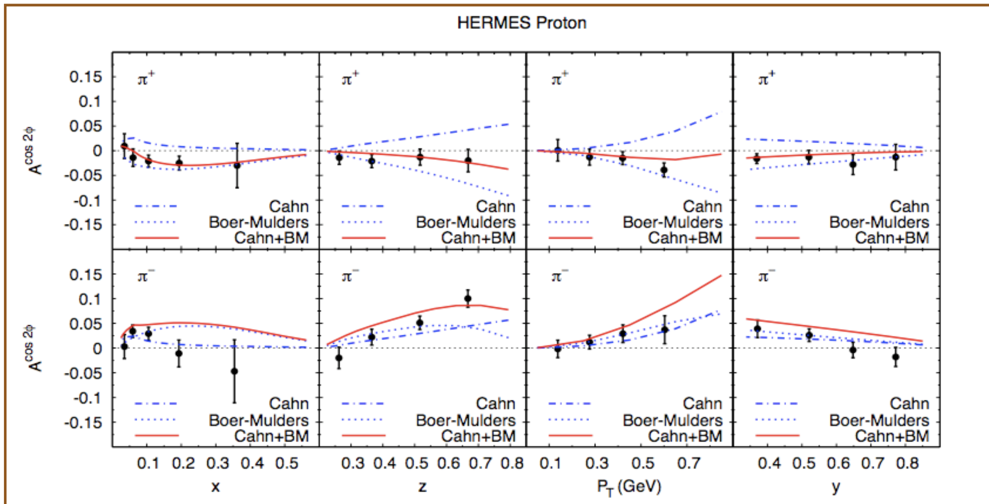


The Boer-Mulders function inbeds the correlation between the quark spin and its transverse momentum

The Boer-Mulders distribution function

Boer-Mulders function $h_1^{\perp}(x, k_{\perp})$ describes distribution of transversely polarised quarks in an unpolarised hadron. $\cos(2\phi_h)$ asymmetry is generated in SIDIS by convolution with Collins FF.

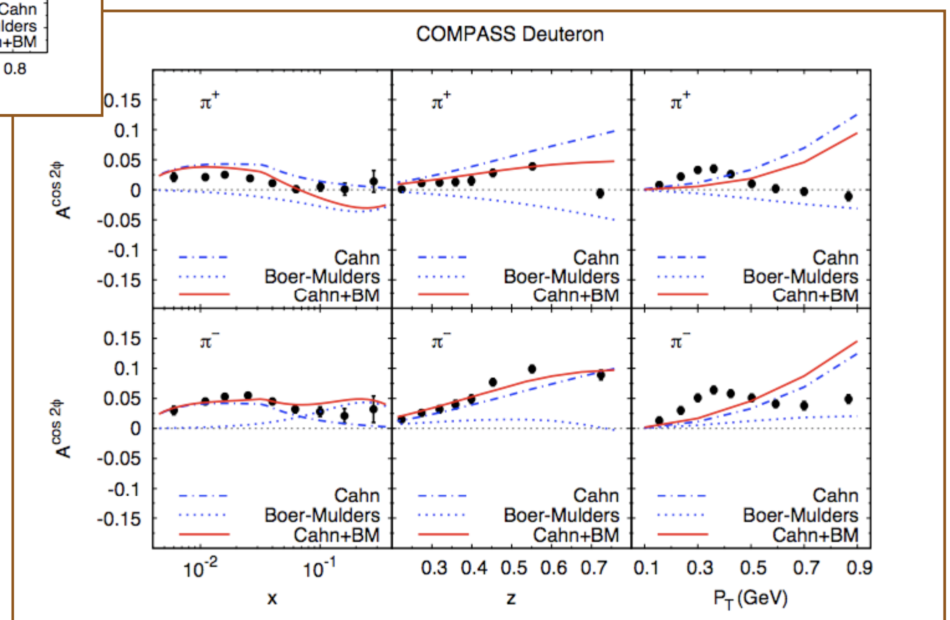
- Large-N_c predictions $h_1^{\perp u} \simeq h_1^{\perp d}$
- Burkardt's approach $h_1^{\perp}$ and $f_{1T}^{\perp}$ are connected to GPD's. $h_1^{\perp u,d} \simeq \frac{\mathcal{K}_T{}^{u,d}}{\mathcal{K}^{u,d}} f_{1T}^{\perp u,d}$, $h_1^{\perp u,d} < 0$
  arXiv:0705.1573 [hep-ph], Phys.Rev.D 72,094020
- Lattice QCD result: $\frac{\mathcal{K}_T{}^u}{\mathcal{K}^u} \simeq \frac{3}{1.67}$, $\frac{\mathcal{K}_T{}^d}{\mathcal{K}^d} \simeq \frac{1.9}{2.03}$
  hep-lat/0612032



V. Barone, S. Melis, A. Prokudin ArXiv: 0912.5194

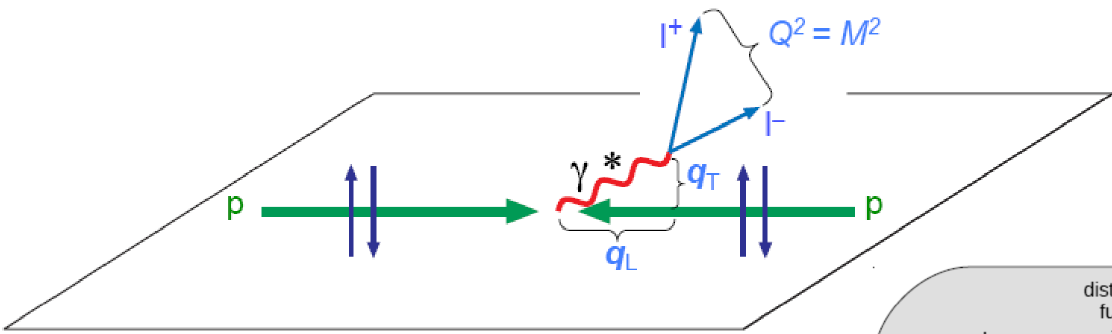
$$h_1^{\perp q}(x, k_{\perp}^2) = \lambda_q \, f_{1T}^{\perp q}(x, k_{\perp}^2)$$

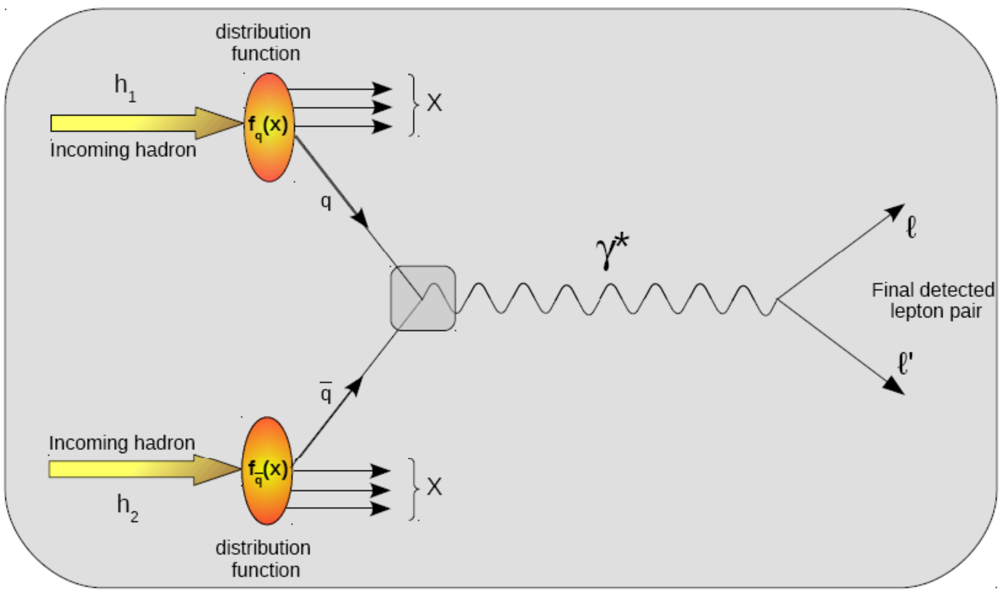
There are two contributions to <cos 2φ>:
•Boer-Mulders + Collins (no suppression in 1/Q)
•Cahn effect at $O(k_{\perp}^2/Q^2)$, which turns out to be large



TMD distribution functions
In Drell-Yan processes

TMD's in Drell-Yan processes





Factorization holds
Two scales: M^2 and q_T, with $q_T << M^2$

Very low q_T are generated by parton intrinsic transverse momenta

The cross section is given by the convolution of two distribution functions (no fragmentation functions)

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

Universality:
SIDIS versus Drell-Yan TMD's

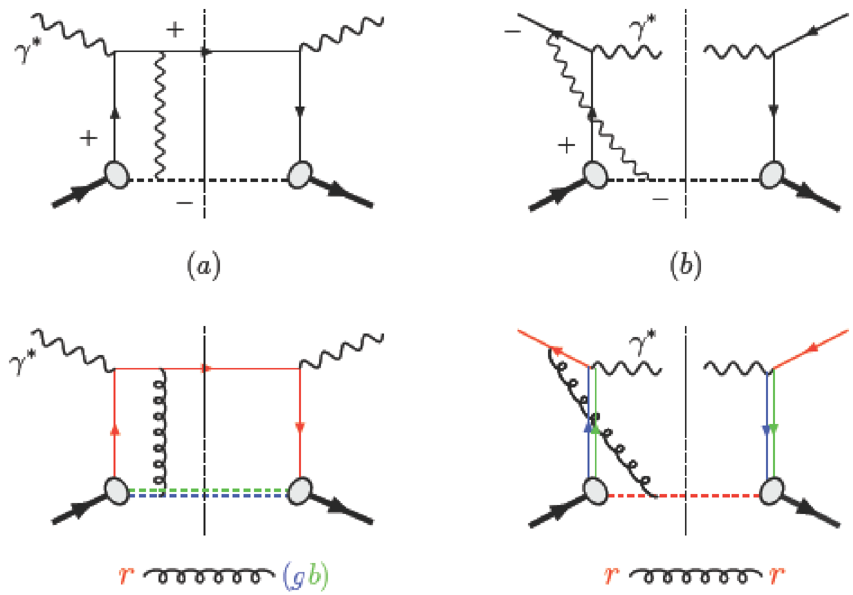
Crucial role of gauge-links in TMDs

Brodsky, Hwang, Schmidt;
Collins; Belitsky, Ji, Yuan;
Boer, Mulders, Pijlman

process-dependence of Sivers functions

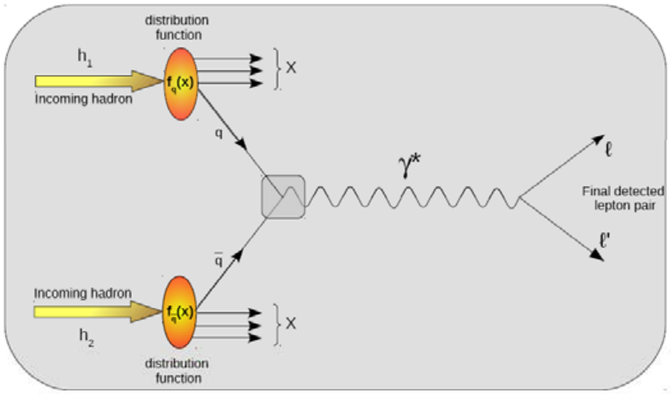
DIS:
"attractive"

D-Y:
"repulsive"



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

TMD’s in Drell-Yan processes



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

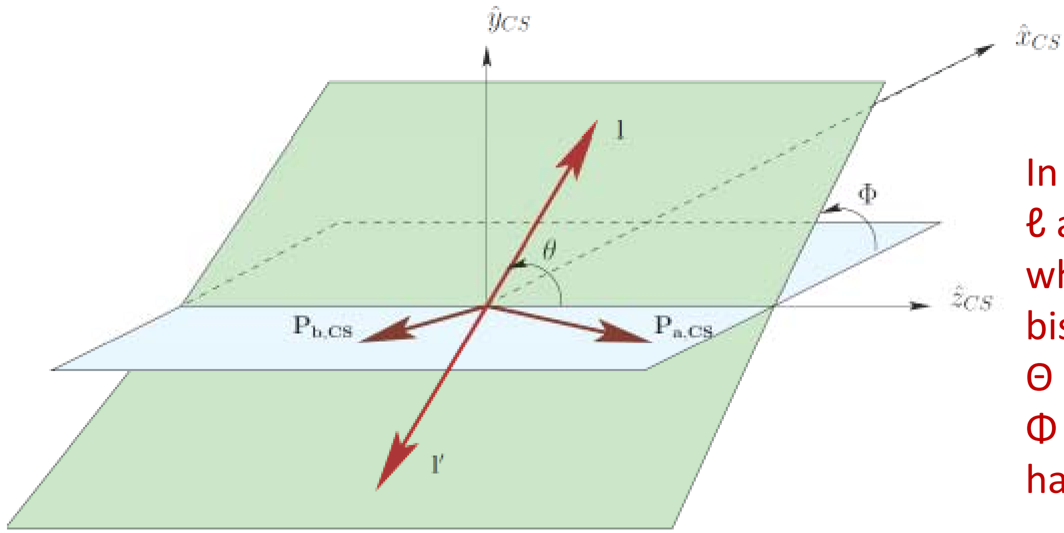
proton-proton (nucleon-nucleon) Drell-Yan: the total cross section, σ, is suppressed by the antiquark parton distribution function (antiquarks from proton sea). — RHIC, FERMILAB

proton-antiproton (nucleon-nucleon) Drell-Yan: the total cross section, σ, is NOT suppressed by parton distribution functions (antiquarks are valence partons in the antiproton). — PANDA, PAX, J-PARC

proton-pion (nucleon-pion) Drell-Yan: the total cross section, σ, is NOT suppressed by parton distribution functions (antiquarks are valence partons in pions). — COMPASS

Unpolarized Drell-Yan processes

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



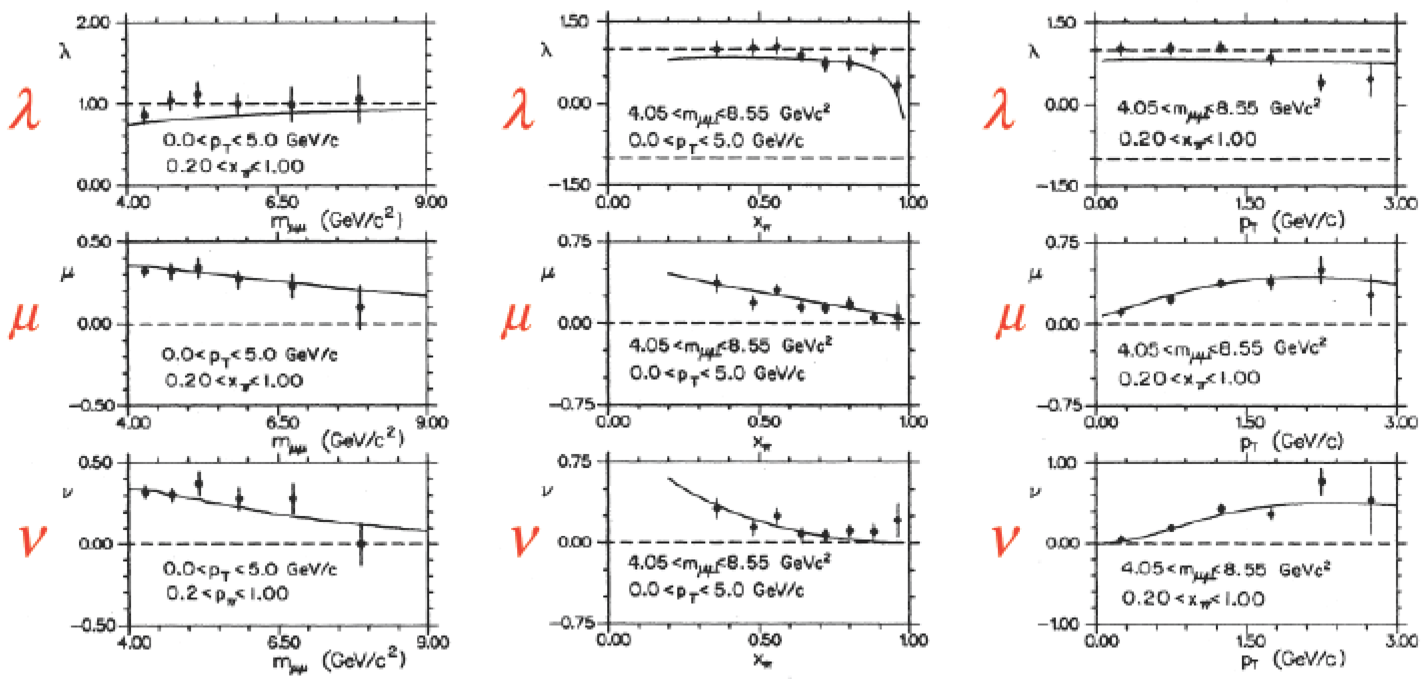
In the Collins-Soper frame ℓ and ℓ' are back to back, while the Z_{CS} axis is the bisector of $\mathbf{P}_a$ and $-\mathbf{P}_b$
Θ is the polar angle of ℓ ,
Φ is the angle between the hadron and the lepton plane.

The unpolarized cross section is already very interesting:
the naïve parton model predicts λ=1, μ=0, ν=0, but …

Unpolarized Drell-Yan processes

Decay angular distributions in pion-induced Drell-Yan

E615 Data 252 GeV $\pi^- + W$ Phys. Rev. D 39 (1989) 92



$m_{\mu\mu}\,(\mathrm{GeV/c^2})$ x_π $p_T\,(\mathrm{GeV/c})$

$$\lambda \neq 1 \quad \mu, \nu \neq 0 \quad 1 - \lambda - 2\nu \neq 0$$

TMD's in unpolarized Drell-Yan processes

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

$$\sigma = f_1^q(x) \otimes f_1^{\bar{q}}(x) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell'}$$

$$\sigma = h_1^{\perp q}(x,k_\perp) \otimes h_1^{\perp \bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell'}$$

In **unpolarized** Drell-Yan processes one can study

- the **unpolarized** parton distribution function
- the **Boer-Mulders** distribution function

RECENT WORK :

Z. Lu, I. Schmidt, Phys. Rev. D81, 043023 (2010)

V. Barone, S. Melis, A. Prokudin, arXiv:1009.3423

Boer-Mulders distribution function from unpolarized Drell-Yan processes

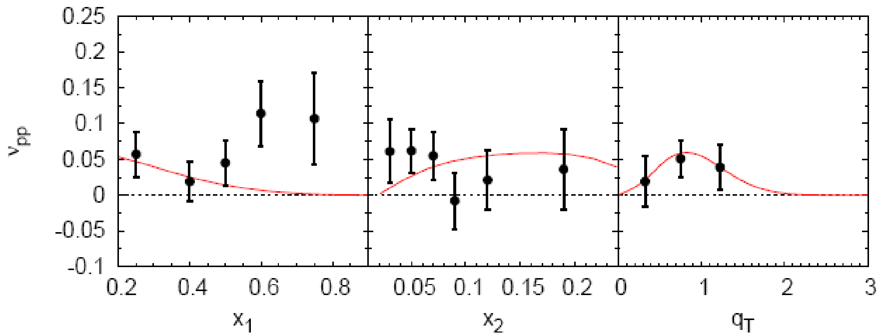
V. Barone, S. Melis, A. Prokudin, arXiv:1009.3423

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

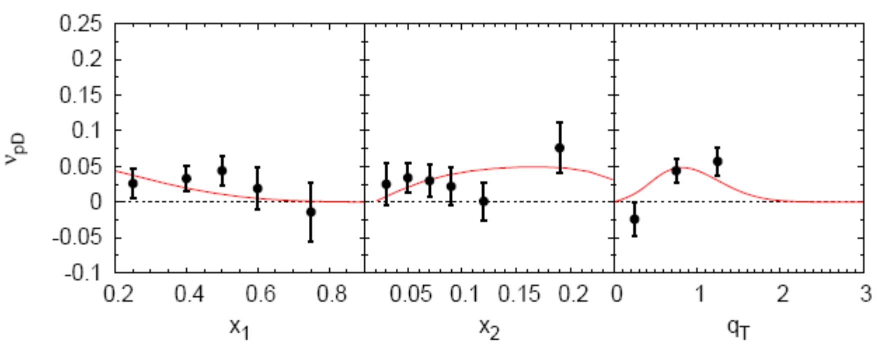
$$\nu \propto \frac{h_1^{\perp a} \otimes h_1^{\perp b}}{f_1^a \otimes f_1^b}$$

Unpolarized Drell Yan processes probe the antiquark Boer-Mulders function, which is not accessible in SIDIS.

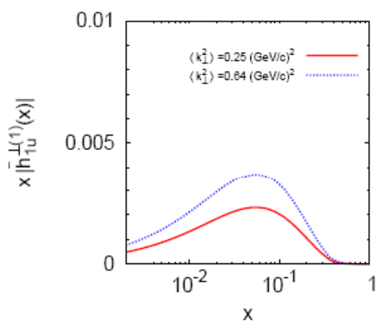
Boer-Mulders distribution function from unpolarized Drell-Yan processes

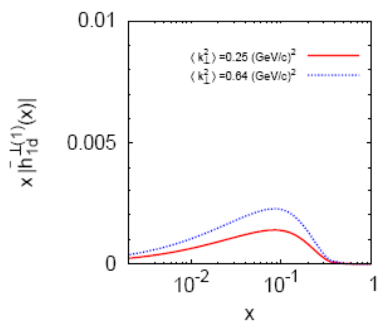


FERMILAB E866/NuSea data on pp and pD Drell-Yan cannot distinguish between fits with very different gaussian widths



BOER-MULDERS FUNCTIONS





V. Barone, S. Melis, A. Prokudin, arXiv:1009.3423

TMD's in single polarized Drell-Yan processes

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

$$\begin{cases} \sigma = f_{1T}^{\perp q}(x,k_\perp) \otimes f_1^{\bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell'} \\ \sigma = h_1^q(x,k_\perp) \otimes h_1^{\perp\bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell'} \end{cases}$$

In single polarized Drell-Yan processes one can study:

❖ **Sivers** parton distribution function

RECENT WORK:
M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, Phys. Rev. D79 (2009) 054010

❖ **Boer-Mulders** distribution function

Predictions could be obtained by using transversity as extracted from SIDIS and e^+e^-. I should work on that !

❖ **Transversity** and **Boer-Mulders** distribution functions

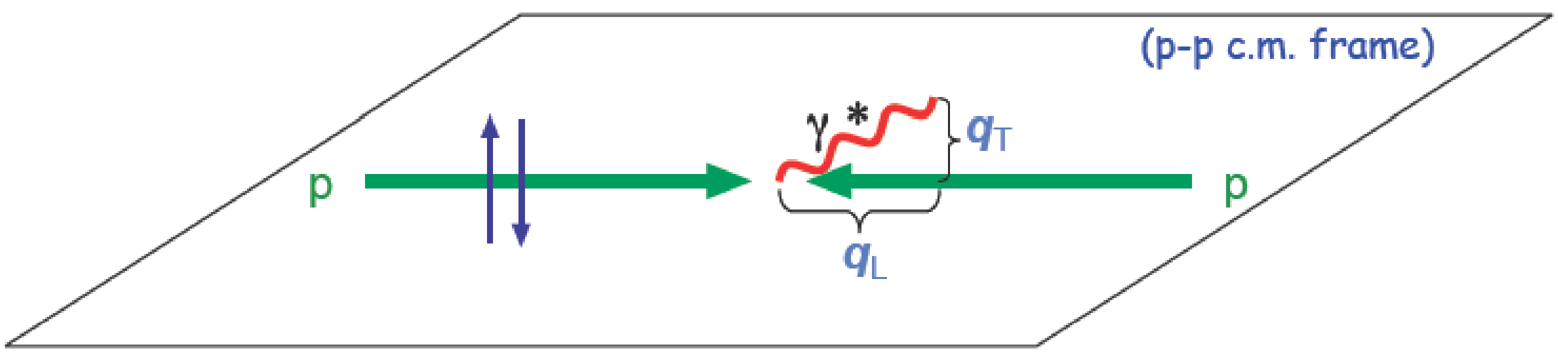
PRESENT and FUTURE EXPERIMENTS:
*RHIC, **COMPASS**, J-PARC, **PANDA**, **PAX***

Sivers distribution function in single polarized Drell-Yan processes

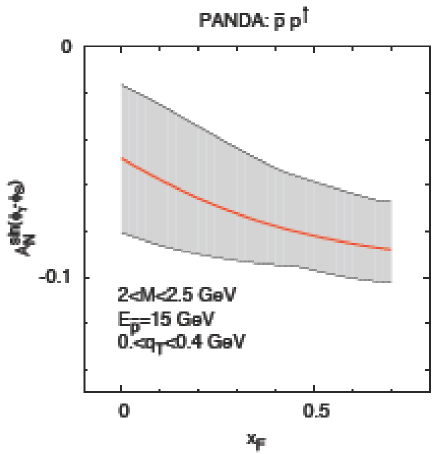
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto \sum_q \Delta^N f_{q/p^{\uparrow}}(x_1, \boldsymbol{k}_{\perp}) \otimes f_{\bar{q}/p}(x_2) \otimes d\hat{\sigma}$$

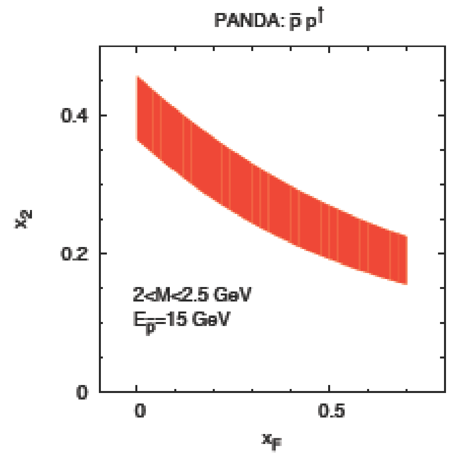
$q = u, \bar{u}, d, \bar{d}, s, \bar{s}$

$$A_N^{\sin(\phi_S - \phi_\gamma)} \equiv \frac{2\int_0^{2\pi} d\phi_\gamma \, [d\sigma^{\uparrow} - d\sigma^{\downarrow}] \, \sin(\phi_S - \phi_\gamma)}{\int_0^{2\pi} d\phi_\gamma \, [d\sigma^{\uparrow} + d\sigma^{\downarrow}]}$$



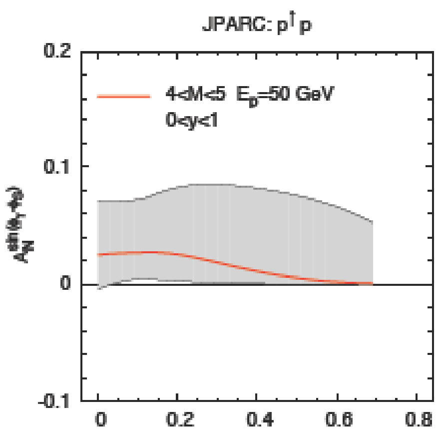
Sivers distribution function in single polarized Drell-Yan processes

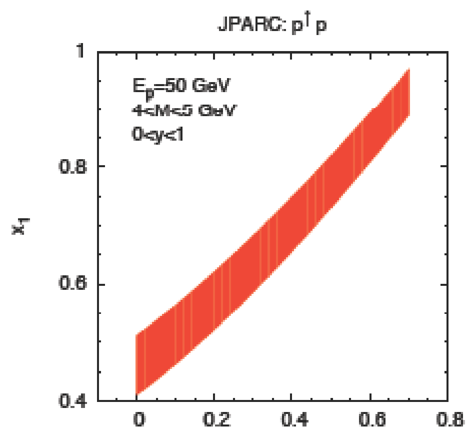




Fixed target mode
$\sqrt{s}$ = 5.47 GeV
$x_F = x_1 - x_2$
X_2 region explored is the same as in SIDIS

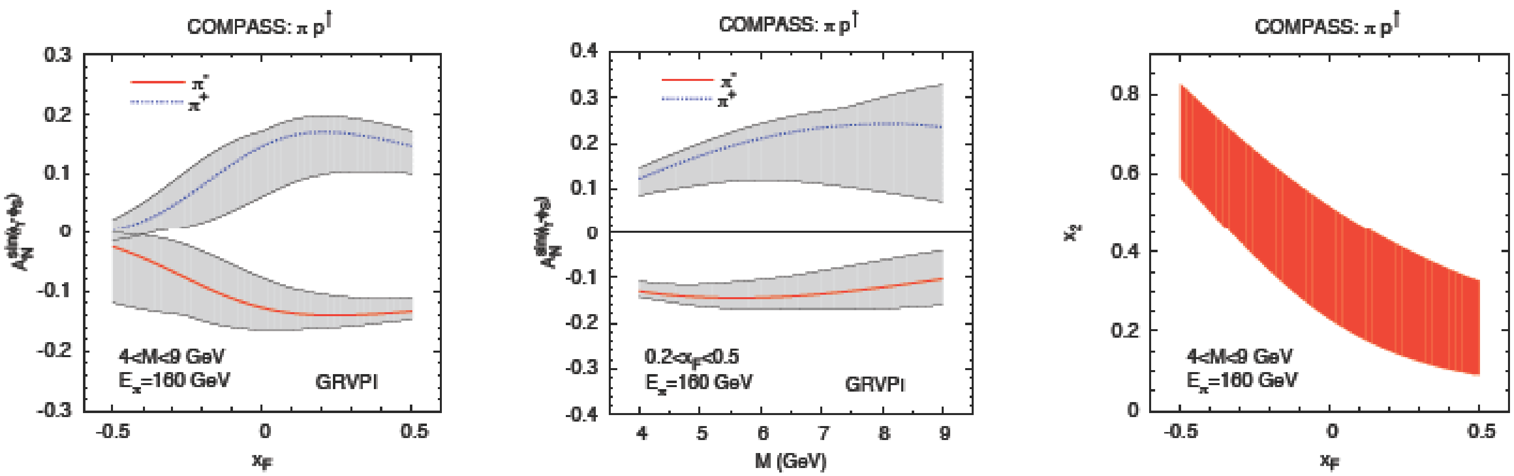
M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, Phys. Rev. D79 (2009) 054010





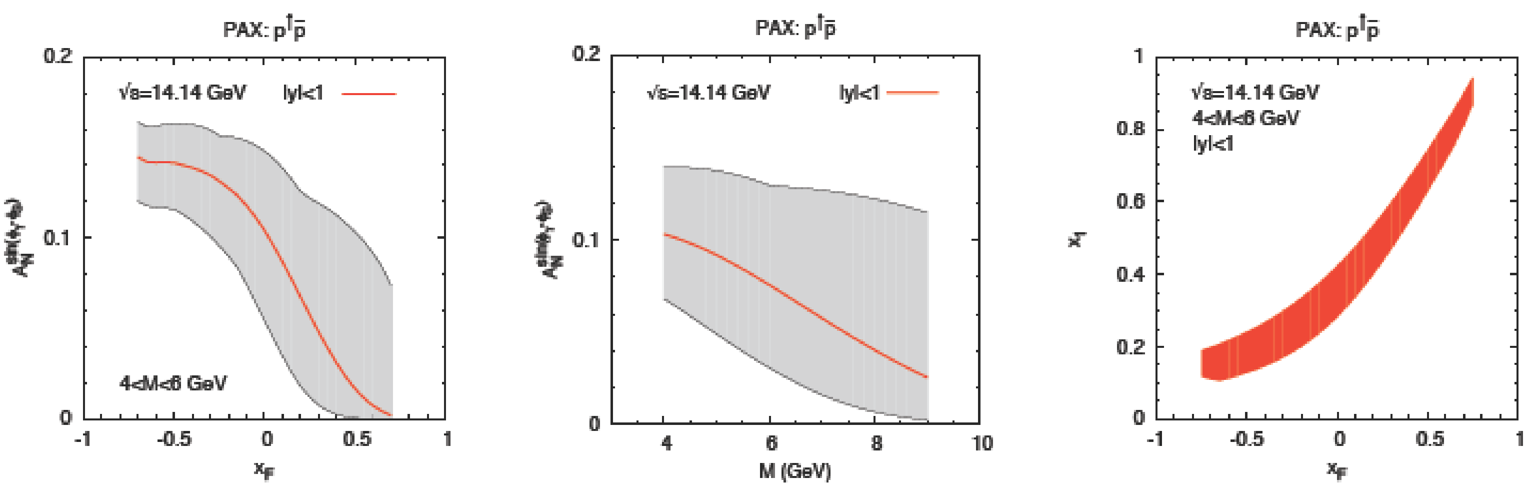
$\sqrt{s}$ = 9.78 GeV
$x_F = x_1 - x_2$
X_1 region explored complementary to that explored in SIDIS

Sivers distribution function in single polarized Drell-Yan processes



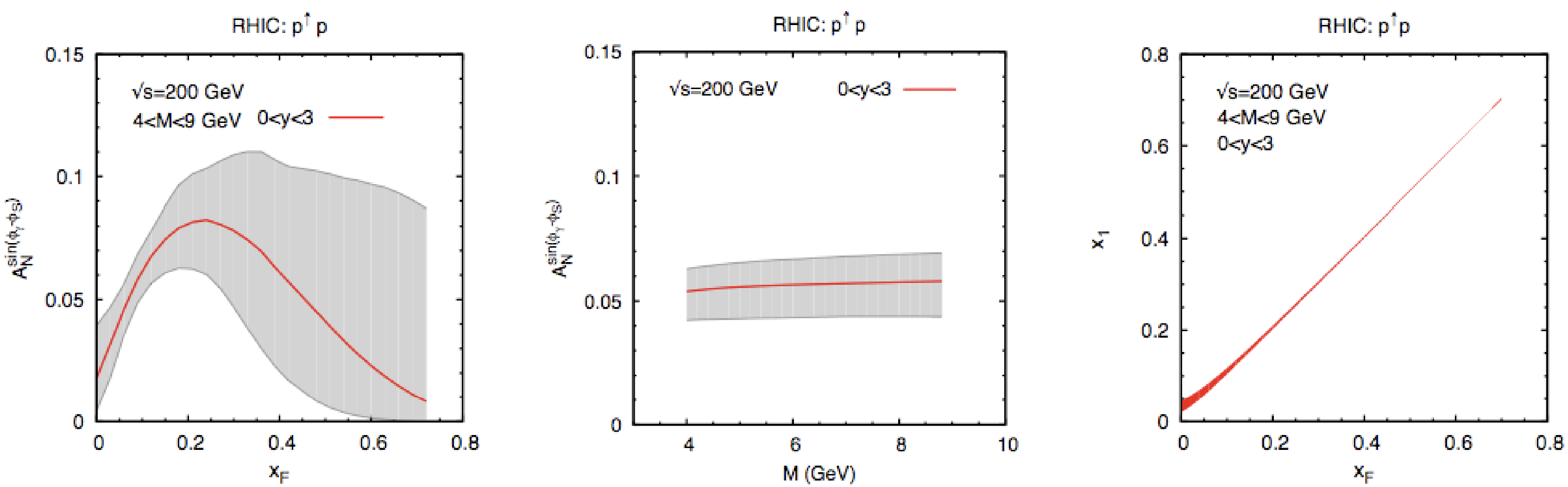
M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin,Phys. Rev. D79 (2009) 054010

Fixed target mode
$\sqrt{s}$ = 17.4 GeV
$x_F=x_1.x_2$
Large-x_2 region explored at negative x_F values



Collider mode
$\sqrt{s}$ = 14.4 GeV
$x_F=x_1.x_2$
Large-x_2 region explored at positive x_F values

Sivers distribution function in single polarized Drell-Yan processes



M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, Phys. Rev. D79 (2009) 054010

BRAHMS STAR PHENIX

$\sqrt{s}$ = 200 GeV

$x_F = x_1 - x_2$

X_1 region explored extends to larger values than that explored in SIDIS

TMD's in doubly polarized Drell-Yan processes

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

$$\begin{cases} \sigma = h_1^q(x, k_\perp) \otimes h_1^{\bar{q}}(x, k_\perp) \otimes \hat{\sigma}^{q\bar{q} \to \ell\ell'} \\ \sigma = f_{1T}^\perp(x, k_\perp) \otimes f_{1T}^\perp(x, k_\perp) \otimes \hat{\sigma}^{q\bar{q} \to \ell\ell'} \end{cases}$$

In doubly polarized Drell-Yan processes one can study

- ❖ **Transversity** parton distribution function

  *At present, RHIC is the only experiment which can measure doubly polarized Drell-Yan, **but** A_{TT} is suppressed by antiquark PDF's !*
  FUTURE EXPERIMENTS: COMPASS, J-PARC, PANDA, PAX

- ❖ **Sivers** distribution function

  RECENT WORK:
  M. Anselmino, M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, Phys. Rev. D79 (2009) 054010

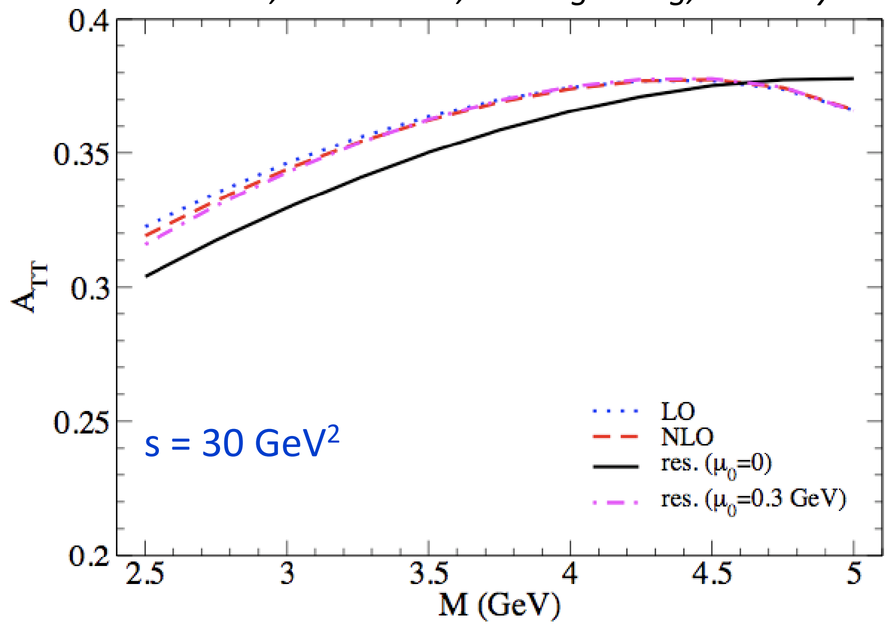
Golden channel to study transversity

The dream experiment: Drell-Yan with polarized antiprotons

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

$$\hat{a}_{TT} = \frac{\sin^2\theta}{1+\cos^2\theta}\cos(2\varphi)$$

H. Shimizu, G. Sterman, W. Vogelsang, H. Yokoya



$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \simeq \hat{a}_{TT}\,\frac{\sum_q e_q^2\, h_{1q}(x_1)\, h_{1q}(x_2)}{\sum_q e_q^2\, q(x_1)\, q(x_2)}$$

Conclusions

❖3-D exploration of the nucleon is starting as we speak:
- Collect as much high-quality data as possible
- Reconstruct the nucleon 3-D structure by "global" analyses

❖Drell-Yan processes are very clean probes and offer the chance to pin down the transversity distribution function

❖Ideal machines:
- X-range including valence-region
- Q^2 and M^2 high enough to control higher-twist corrections
- P_T and q_T ranges large enough to see transition from TMD's to collinear factorization.