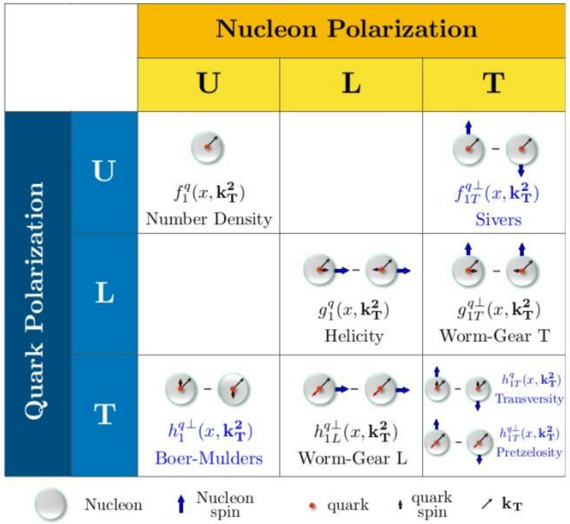
Drell-Yan studies with SPD

A.P.Nagaytsev, JINR, Dubna

International Workshop on Spin Physics at NICA (SPIN-Praha-2018)

Proposed studies.



- Transversity: $A_{UT}^{\sin(\phi_h+\phi_S)}$
- Sivers: $A_{UT}^{\sin(\phi_h-\phi_S)}$
- Pretzelosity: $A_{UT}^{\sin(3\phi_h-\phi_S)}$
- Boer-Mulders: $A_{UU}^{\cos(2\phi_h)}$
- Worm-Gears: $A_{UL}^{\sin(2\phi_h)}$

<u>PDFs proposed to measure are:</u>

- correlation between the transverse polarization of nucleon (transverse spin) and the transverse momentum of non-polarized quarks (Sivers) ;

-correlation between the transverse spin and the longitudinal quark polarization (Worm-gear-T) ;

-distribution of the quark transverse momentum in the non-polarized nucleon (BoerMulders) ;

- correlation between the longitudinal polarization of the nucleon (longitudinal spin) and the transverse momentum of quarks (Worm-gear-L) ;

-distribution of the transverse momentum of quarks in the transversely polarized nucleon (Pretzelosity).

All new PDFs, except $f^{\perp}_{1T}$, are chiral-odd. The Sivers and Boer-Mulders PDFs are T-odd ones. At the sub-leading twist (twist-3).

Drell-Yan studies with SPD.

Two approaches (methods) are proposed to be used for DY studies (see section 2 of SPD LoI).

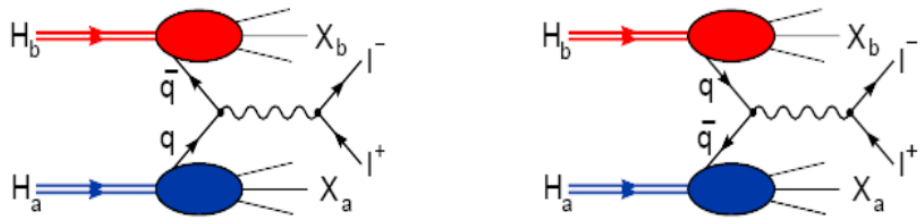
The PDFs studies via Fourier analysis to the measured asymmetries.

S. Arnold, A. Metz and M. Schlegel, Phys. Rev. D79 (2009) 034005
L.P. Gamberg, D.S. Hwang, A. Metz, and M. Schlegel, Phys. Lett. B639(2006) 508
A. Bacchetta, D. Boer, M. Diehl, and P. J. Mulders, JHEP 0808 (2008) 023
M. Anselminoet al., arXiv:1304.7691
Daniel Boer, Leonard Gamberg, Bernhard Musch, Alexei Prokudin, JHEP 1110 (2011) 021
P.J. Mulders and R.D. Tangerman, Nucl. Phys. B461(1996) 197
A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P. Mulders and M. Schlegel, JHEP 0702(2007) 093

Studies of PDFs via integrated/weighted asymmetries.

A. Sissakian, O. Shevchenko, A. Nagaytsev, and O. Ivanov, Pisma Zh.Eksp.Teor.Fiz. 86 (2007) 863-867, JETP Lett. 86 (2007) 751-755,
A. Sissakian, O. Shevchenko, A. Nagaytsev and O. Ivanov, Phys. Rev. D72(2005) 054027
A.Sissakian, et al., Eur. Phys. J. C46 (2006) 147, Eur.Phys.J. C59 (2009) 659-673, Phys.Part.Nucl. 41 (2010) 64-100

Drell-Yan studies via Fourier analysis of measures asymmetries.



(a) (b)

$$\frac{d\sigma}{dx_a dx_b d^2q_T d\Omega} = \frac{\alpha^2}{4Q^2} \times$$

$$\Big\{\Big((1+\cos^2\theta)F_{UU}^{1} + \sin^2\theta\cos 2\phi F_{UU}^{\cos 2\phi}\Big) + S_{aL}\sin^2\theta\sin 2\phi F_{LU}^{\sin 2\phi} + S_{bL}\sin^2\theta\sin 2\phi F_{UL}^{\sin 2\phi}$$

$$+\left|\vec{S}_{aT}\right|\Big[\sin(\phi-\phi_{S_a})(1+\cos^2\theta)F_{TU}^{\sin(\phi-\phi_{S_a})} + \sin^2\theta\Big(\sin(3\phi-\phi_{S_a})F_{TU}^{\sin(3\phi-\phi_{S_a})} + \sin(\phi+\phi_{S_a})F_{TU}^{\sin(\phi+\phi_{S_a})}\Big)\Big]$$

$$+\left|\vec{S}_{bT}\right|\Big[\sin(\phi-\phi_{S_b})(1+\cos^2\theta)F_{UT}^{\sin(\phi-\phi_{S_b})} + \sin^2\theta\Big(\sin(3\phi-\phi_{S_b})F_{UT}^{\sin(3\phi-\phi_{S_b})} + \sin(\phi+\phi_{S_b})F_{UT}^{\sin(\phi+\phi_{S_b})}\Big)\Big]$$

$$+S_{aL}S_{bL}\Big[(1+\cos^2\theta)F_{LL}^{1} + \sin^2\theta\cos 2\phi F_{LL}^{\cos 2\phi}\Big] \qquad (2.1.2)$$

$$+S_{aL}\left|\vec{S}_{bT}\right|\Big[\cos(\phi-\phi_{S_b})(1+\cos^2\theta)F_{LT}^{\cos(\phi-\phi_{S_b})} + \sin^2\theta\Big(\cos(3\phi-\phi_{S_b})F_{LT}^{\cos(3\phi-\phi_{S_b})} + \cos(\phi+\phi_{S_b})F_{LT}^{\cos(\phi+\phi_{S_b})}\Big)\Big]$$

$$+\left|\vec{S}_{aT}\right|S_{bL}\Big[\cos(\phi-\phi_{S_a})(1+\cos^2\theta)F_{TL}^{\cos(\phi-\phi_{S_a})} + \sin^2\theta\Big(\cos(3\phi-\phi_{S_a})F_{TL}^{\cos(3\phi-\phi_{S_a})} + \cos(\phi+\phi_{S_a})F_{TL}^{\cos(\phi+\phi_{S_a})}\Big)\Big]$$

$$+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\Big[(1+\cos^2\theta)\Big(\cos(2\phi-\phi_{S_a}-\phi_{S_b})F_{TT}^{\cos(2\phi-\phi_{S_a}-\phi_{S_b})} + \cos(\phi_{S_b}-\phi_{S_a})F_{TT}^{\cos(\phi_{S_b}-\phi_{S_a})}\Big)\Big]$$

$$+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\Big[\sin^2\theta\Big(\cos(\phi_{S_a}+\phi_{S_b})F_{TT}^{\cos(\phi_{S_a}+\phi_{S_b})} + \cos(4\phi-\phi_{S_a}-\phi_{S_b})F_{TT}^{\cos(4\phi-\phi_{S_a}-\phi_{S_b})}\Big)\Big]$$

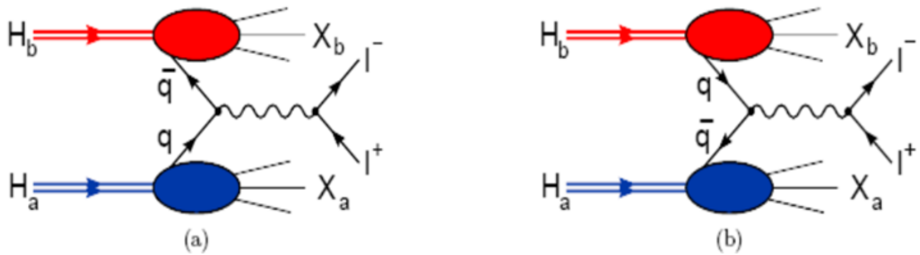
$$+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\Big[\sin^2\theta\Big(\cos(2\phi-\phi_{S_a}+\phi_{S_b})F_{TT}^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})} + \cos(2\phi+\phi_{S_a}-\phi_{S_b})F_{TT}^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})}\Big)\Big]\Big\}$$

where F_{jk}^{i} are the Structure Functions (SFs) connected to the corresponding PDFs. The SFs depend on four variables $P_a \cdot q$, $P_b \cdot q$, $\mathbf{q}_T$ and q^2 or on $\mathbf{q}_T$, q^2 and the Bjorken variables of colliding hadrons, x_a, x_b,

$$x_a = \frac{q^2}{2P_a \cdot q} = \sqrt{\frac{q^2}{s}}e^{y}, \quad x_b = \frac{q^2}{2P_b \cdot q} = \sqrt{\frac{q^2}{s}}e^{-y},$$ y is the CM rapidity and

***The SFs** introduced here **give more detailed information on the nucleon structure than usual structure functions depending on two variables** x_{Bj} and Q^2. The differential cross section includes 24 leading twist SFs.*

Drell-Yan studies via Fourier analysis of measures asymmetries.



Each of them is expressed through a weighted convolution ,C , of corresponding leading twist TMD PDFs :

$$C\left[w(\vec{k}_{aT},\vec{k}_{bT})f_1\bar{f}_2\right] \equiv \frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT} d^2\vec{k}_{bT} \delta^2(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT}) w(\vec{k}_{aT},\vec{k}_{bT}) \times \left[f_{1q}(x_a,\vec{k}_{aT}^2)\bar{f}_{2q}(x_b,\vec{k}_{bT}^2) + \bar{f}_{1q}(x_a,\vec{k}_{aT}^2) f_{2q}(x_b,\vec{k}_{bT}^2)\right]$$

where w is a weight, k_{aT} (k_{bT}) is the transverse momentum of quark (anti-quark) in the hadron Ha (Hb) and f_1 (f_2) is a TMD PDF of the corresponding hadron. The particular SF can include a linear combination of several PDFs. Eventually; one can find expressions for all leading twist SFs of quarks and anti-quarks entering above relation. When both hadrons are non-polarized, they are:

$$F_{UU}^1 = C\left[f_1\bar{f}_1\right], \quad F_{UU}^{\cos 2\phi} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_1^{\perp}\bar{h}_1^{\perp}\right]$$

Drell-Yan studies via Fourier analysis of measures asymmetries.

when only one hadron is polarized (proton or deuteron):

$$F_{LU}^{\sin 2\phi} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_{1L}^{\perp}\bar{h}_1^{\perp}\right] \qquad F_{UL}^{\sin 2\phi} = -C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_1^{\perp}\bar{h}_{1L}^{\perp}\right]$$

$$F_{UT}^{\sin(\phi-\phi_{S_b})} = C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} f_1 \bar{f}_{1T}^{\perp}\right] \qquad F_{TU}^{\sin(\phi-\phi_{S_a})} = -C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} f_{1T}^{\perp}\bar{f}_1\right]$$

$$F_{TU}^{\sin(3\phi-\phi_{S_a})} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{aT}^2(\vec{h}\cdot\vec{k}_{bT})}{2M_a^2 M_b} h_{1T}^{\perp}\bar{h}_1^{\perp}\right]$$

$$F_{UT}^{\sin(3\phi-\phi_{S_b})} = -C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^2(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_1^{\perp}\bar{h}_{1T}^{\perp}\right]$$

$$F_{TU}^{\sin(\phi+\phi_{S_a})} = C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} h_1 \bar{h}_1^{\perp}\right] \qquad F_{UT}^{\sin(\phi+\phi_{S_b})} = -C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_1^{\perp}\bar{h}_1\right]$$

$$F_{LL}^{1} = -C\left[g_{1L}\bar{g}_{1L}\right] \qquad F_{LL}^{\cos 2\phi} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_{1L}^{\perp}\bar{h}_{1L}^{\perp}\right]$$

$$F_{LT}^{\cos(\phi-\phi_{S_b})} = -C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} g_{1L}\bar{g}_{1T}\right] \qquad F_{TL}^{\cos(\phi-\phi_{S_a})} = -C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} g_{1T}\bar{g}_{1L}\right]$$

$$F_{TL}^{\cos(\phi+\phi_{S_a})} = C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} h_1 \bar{h}_{1L}^{\perp}\right] \qquad F_{LT}^{\cos(\phi+\phi_{S_b})} = C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_{1L}^{\perp}\bar{h}_1\right]$$

$$F_{LT}^{\cos(3\phi-\phi_{S_b})} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^2(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_{1L}^{\perp}\bar{h}_{1T}^{\perp}\right]$$

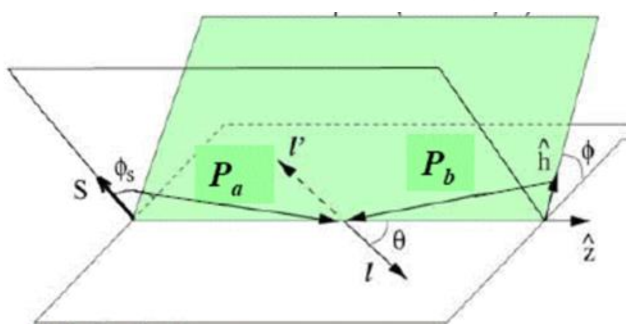
$$F_{TL}^{\cos(3\phi-\phi_{S_a})} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{aT}^2(\vec{h}\cdot\vec{k}_{bT})}{2M_a^2 M_b} h_{1T}^{\perp}\bar{h}_{1L}^{\perp}\right]$$

$$F_{TT}^{\cos(4\phi-\phi_{Sa}-\phi_{Sb})} = C\left[\left(\frac{4(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}]}{4M_a^2 M_b^2} + \frac{\vec{k}_{aT}^2\vec{k}_{bT}^2 - 2\vec{k}_{aT}^2(\vec{h}\cdot\vec{k}_{bT})^2 - 2\vec{k}_{bT}^2(\vec{h}\cdot\vec{k}_{aT})^2}{4M_a^2 M_b^2}\right) h_{1T}^{\perp}\bar{h}_{1T}^{\perp}\right]$$

$$F_{TT}^{\cos(2\phi-\phi_{S_a}-\phi_{S_b})} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{2M_a M_b}(f_{1T}^{\perp}\bar{f}_{1T}^{\perp} - g_{1T}\bar{g}_{1T})\right]$$

$$F_{TT}^{\cos(\phi_{S_b}-\phi_{S_a})} = -C\left[\frac{\vec{k}_{aT}\cdot\vec{k}_{bT}}{2M_a M_b}(f_{1T}^{\perp}\bar{f}_{1T}^{\perp} + g_{1T}\bar{g}_{1T})\right] \qquad F_{TT}^{\cos(\phi_{S_b}+\phi_{S_a})} = C\left[h_1\bar{h}_1\right]$$

$$F_{TT}^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})^2 - \vec{k}_{aT}^2}{2M_a^2} h_{1T}^{\perp}\bar{h}_1\right] \qquad F_{TT}^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})^2 - \vec{k}_{bT}^2}{2M_b^2} h_1\bar{h}_{1T}^{\perp}\right]$$



$$\phi_{Sa} \leftrightarrow -\phi_{Sb},\ \phi \to -\phi,\ \theta \to \pi - \theta$$

Drell-Yan studies via Fourier analysis of measures asymmetries.

The DY cross section cannot be measured directly because there is no single beam containing particles with the U, L and T polarization. To measure SFs entering this equation one can use the following procedure: first, to integrate cross section over the azimuthal angle , second, following the SIDIS practice, to measure azimuthal asymmetries of the DY pair‟s production cross sections.
The integration over the azimuthal angle gives:

$$\sigma_{\text{int}} \equiv \frac{d\sigma}{dx_a dx_b d^2 q_T d\cos\theta} = \frac{\pi\alpha^2}{2q^2} \times \left(1+\cos^2\theta\right)\Big[F_{UU}^1 + S_{aL} S_{bL} F_{LL}^1$$

$$+\left|\vec{S}_{aT}\right|\left|\vec{S}_{bT}\right|\left(\cos(\phi_{S_b} - \phi_{S_a}) F_{TT}^{\cos(\phi_{S_b}-\phi_{S_a})} + D\cos(\phi_{S_a} + \phi_{S_b}) F_{TT}^{\cos(\phi_{S_a}+\phi_{S_b})}\right)\Big]$$

The azimuthal asymmetries can be calculated as ratios of cross sections differences to the sum of the integrated over cross sections. The numerator of the ratio is calculated as a difference of the DY pairs production cross sections in the collision of hadrons H_a and H_b with different polarizations. The azimuthal distribution of DY pairs produced in non-polarized hadron collisions, A_{UU} , and azimuthal asymmetries of the cross sections in polarized hadron collisions, A_{jk}

Drell-Yan studies via Fourier analysis of measures asymmetries.

$$A_{UU} \equiv \frac{\sigma^{00}}{\sigma^{00}_{\rm int}} = \frac{1}{2\pi}(1 + D\cos 2\phi A_{UU}^{\cos 2\phi})$$

$$A_{LU} \equiv \frac{\sigma^{\to 0} - \sigma^{\leftarrow 0}}{\sigma^{\to 0}_{\rm int} + \sigma^{\leftarrow 0}_{\rm int}} = \frac{|S_{aL}|}{2\pi} D \sin 2\phi A_{LU}^{\sin 2\phi}$$

$$A_{UL} \equiv \frac{\sigma^{0\to} - \sigma^{0\leftarrow}}{\sigma^{0\to}_{\rm int} + \sigma^{0\leftarrow}_{\rm int}} = \frac{|S_{bL}|}{2\pi} D \sin 2\phi A_{UL}^{\sin 2\phi}$$

$$A_{TU} \equiv \frac{\sigma^{\uparrow 0} - \sigma^{\downarrow 0}}{\sigma^{\uparrow 0}_{\rm int} + \sigma^{\downarrow 0}_{\rm int}} = \frac{|\vec{S}_{aT}|}{2\pi}\left[A_{TU}^{\sin(\phi-\phi_{S_a})}\sin(\phi-\phi_{S_a}) + D\left(A_{TU}^{\sin(3\phi-\phi_{S_a})}\sin(3\phi-\phi_{S_a}) + A_{TU}^{\sin(\phi+\phi_{S_a})}\sin(\phi+\phi_{S_a})\right)\right]$$

$$A_{UT} \equiv \frac{\sigma^{0\uparrow} - \sigma^{0\downarrow}}{\sigma^{0\uparrow}_{\rm int} + \sigma^{0\downarrow}_{\rm int}} = \frac{|\vec{S}_{bT}|}{2\pi}\left[A_{UT}^{\sin(\phi-\phi_{S_b})}\sin(\phi-\phi_{S_b}) + D\left(A_{UT}^{\sin(3\phi-\phi_{S_b})}\sin(3\phi-\phi_{S_b}) + A_{UT}^{\sin(\phi+\phi_{S_b})}\sin(\phi+\phi_{S_b})\right)\right]$$

$$A_{LL} \equiv \frac{\sigma^{\to\to} + \sigma^{\leftarrow\leftarrow} - \sigma^{\to\leftarrow} - \sigma^{\leftarrow\to}}{\sigma^{\to\to}_{\rm int} + \sigma^{\leftarrow\leftarrow}_{\rm int} + \sigma^{\to\leftarrow}_{\rm int} + \sigma^{\leftarrow\to}_{\rm int}} = \frac{|S_{aL}S_{bL}|}{2\pi}\left(A_{LL}^{1} + DA_{LL}^{\cos 2\phi}\cos 2\phi\right)$$

$$A_{TL} \equiv \frac{\sigma^{\uparrow\to} + \sigma^{\downarrow\leftarrow} - \sigma^{\downarrow\to} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\to}_{\rm int} + \sigma^{\downarrow\leftarrow}_{\rm int} + \sigma^{\downarrow\to}_{\rm int} + \sigma^{\uparrow\leftarrow}_{\rm int}} = \frac{|\vec{S}_{aT}|\,|S_{bL}|}{2\pi}\left[A_{TL}^{\cos(\phi-\phi_{S_a})}\cos(\phi-\phi_{S_a}) + D\begin{pmatrix} A_{TL}^{\cos(3\phi-\phi_{S_a})}\cos(3\phi-\phi_{S_a}) \\ +A_{TL}^{\cos(\phi+\phi_{S_a})}\cos(\phi+\phi_{S_a}) \end{pmatrix}\right]$$

$$A_{LT} \equiv \frac{\sigma^{\to\uparrow} + \sigma^{\leftarrow\downarrow} - \sigma^{\to\downarrow} - \sigma^{\leftarrow\uparrow}}{\sigma^{\to\uparrow}_{\rm int} + \sigma^{\leftarrow\downarrow}_{\rm int} + \sigma^{\to\downarrow}_{\rm int} + \sigma^{\leftarrow\uparrow}_{\rm int}} = \frac{S_{aL}\,|\vec{S}_{bT}|}{2\pi}\left[A_{LT}^{\cos(\phi-\phi_{S_b})}\cos(\phi-\phi_{S_b}) + D\begin{pmatrix} A_{LT}^{\cos(3\phi-\phi_{S_b})}\cos(3\phi-\phi_{S_b}) \\ +A_{LT}^{\cos(\phi+\phi_{S_b})}\cos(\phi+\phi_{S_b}) \end{pmatrix}\right]$$

$$A_{TT} \equiv \frac{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow} - \sigma^{\uparrow\downarrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\uparrow}_{\rm int} + \sigma^{\downarrow\downarrow}_{\rm int} + \sigma^{\uparrow\downarrow}_{\rm int} + \sigma^{\downarrow\uparrow}_{\rm int}} = \frac{|\vec{S}_{aT}\|\vec{S}_{bT}|}{2\pi}\Big[A_{TT}^{\cos(2\phi-\phi_{S_a}-\phi_{S_b})}\cos(2\phi-\phi_{S_a}-\phi_{S_b}) + A_{TT}^{\cos(\phi_{S_b}-\phi_{S_a})}\cos(\phi_{S_b}-\phi_{S_a})$$

$$+D\Big(A_{TT}^{\cos(\phi_{S_b}+\phi_{S_a})}\cos(\phi_{S_a}+\phi_{S_b}) + A_{TT}^{\cos(4\phi-\phi_{S_a}-\phi_{S_b})}\cos(4\phi-\phi_{S_a}-\phi_{S_b})$$

$$+A_{TT}^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})}\cos(2\phi-\phi_{S_a}+\phi_{S_b}) + A_{TT}^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})}\cos(2\phi+\phi_{S_a}-\phi_{S_b})\Big)\Big]$$

In these expressions

$$D = \sin^2\theta/(1+\cos^2\theta)$$

is the depolarization factor and ratio

$$A^{i}_{jk} = F^{i}_{jk}/F^{1}_{UU}$$

of the SFs defined above. The superscripts of the σ^{pq} mean:
$\to$($\leftarrow$) – positive (negative) longitudinal beam polarization in the direction of $P_{a\,cm}$;
$\uparrow$($\downarrow$) – transverse beam polarization with the azimuthal angle φ_{Sa} or φ_{Sb}
(φ_{Sa} +π or φ_{Sb} +π)
0 – non-polarized hadron H_a or H_b
.

Drell-Yan studies via Fourier analysis of measures asymmetries.

Applying the Fourier analysis to the measured asymmetries, one can separate each of all ratios entering previous slide. This will be the ultimate task of the experiments proposed for SPD.

The extraction of different TMD PDFs from those ratios is a task of the global theoretical analysis since each of the SFs is a result of convolutions of different TMD PDFs in the quark transverse momentum space.

For this purpose one needs either to assume a factorization of the transverse momentum dependence for each TMD PDFs, having definite mathematic form (usually Gaussian) with some parameters to be fitted , or to transfer F_{jk}^{I} to impact parameter representation space and to use the Bessel weighted TMD PDFs .

M. Anselmino et al., arXiv:1304.7691 [hep-ph]),
Daniel Boer, Leonard Gamberg, Bernhard Musch, Alexei Prokudin, JHEP 1110 (2011) 021, [arXiv:1107.5294]

- The Structure Functions $F_{jk}^{\,i}$ depend on the variables (x_a, x_b, q_T, q^2). Instead of q_T one may also work with the transverse momentum of one of the hadrons in the CS-frame.

- In the q_T -dependent cross section, all the chiral-odd parton distributions disappear after integrating over the azimuthal angle φ. On the other hand, all the chiral-even effects survive this integration.

- The large number of independent SFs to be determined from the polarized DY processes at NICA (24 for identical hadrons in the initial state) is sufficient to map out all eight leading twist TMD PDFs for quarks and anti-quarks. This fact indicates the high potential of the polarized DY process for studying new PDFs. This process has also a certain advantage over SIDIS which also capable of mapping out the leading twist TMD PDFs but requires knowledge of fragmentation functions.

- The expected sign reversal of T-odd TMDs can also be investigated through the structure in which the Boer-Mulders PDF enters .
- It is very important to measure those new TMD PDFs which are still not measured or measured with large uncertainties. These are Worm-gear-T, L and Pretzelosity PDFs.

Drell-Yan studies via integrated/weighted asymmetries.

An original method for direct extraction of transversity and Boer–Mulders PDFs in the proton from the data on Drell–Yan processes: A.Sissakian, et al., Phys.Part.Nucl. 41 (2010) 64-100

Let us begin the consideration of DY process $H_1 H_2^{\uparrow} \longrightarrow l^+ l^- X,$

Taking into account only dominant electromagnetic contributions and neglecting the contribution of higher harmonics containing the 3φ dependence, we can obtain the following simplified formulas for the cross sections of unpolarized and singly polarized processes:

$$\frac{d\sigma^{(0)}(H_1 H_2 \to l\bar{l} X)}{d\Omega dx_1 dx_2 d^2\mathbf{q}_T} = \frac{\alpha^2}{12Q^2}\sum_q e_q^2 \Big\{ (1+\cos^2\theta) \times \mathcal{F}[\bar{f}_{1q} f_{1q}] + \sin^2\theta\cos(2\phi) \times \mathcal{F}\Big[(2\hat{\mathbf{h}}\cdot\mathbf{k}_{1T}\hat{\mathbf{h}}\cdot\mathbf{k}_{2T} - \mathbf{k}_{1T}\cdot\mathbf{k}_{2T})\frac{\bar{h}_{1q}^{\perp} h_{1q}^{\perp}}{M_1 M_2}\Big]\Big\}$$

$$\frac{d\sigma^{(1)}(H_1 H_2^{\uparrow} \to l\bar{l} X)}{d\Omega d\phi_{S_2} dx_1 dx_2 d^2\mathbf{q}_T} = \frac{\alpha^2}{12Q^2}\sum_q e_q^2 \Big\{ (1+\cos^2\theta) \times \mathcal{F}[\bar{f}_{1q} f_{1q}] + \sin^2\theta\cos(2\phi) \times \mathcal{F}\Big[(2\hat{\mathbf{h}}\cdot\mathbf{k}_{1T}\hat{\mathbf{h}}\cdot\mathbf{k}_{2T} - \mathbf{k}_{1T}\cdot\mathbf{k}_{2T})\frac{\bar{h}_{1q}^{\perp} h_{1q}^{\perp}}{M_1 M_2}\Big] + (1+\cos^2\theta)\sin(\phi-\phi_{S_2})\mathcal{F}\Big[\hat{\mathbf{h}}\cdot\mathbf{k}_{1T}\frac{\bar{f}_1^q f_{1T}^{\perp q}}{M_2}\Big] - \sin^2\theta\sin(\phi+\phi_{S_2})\mathcal{F}\Big[\hat{\mathbf{h}}\cdot\mathbf{k}_{1T}\frac{\bar{h}_{1q}^{\perp} h_{1q}}{M_1}\Big]\Big\}$$

Here, $\hat{\mathbf{h}} \equiv \mathbf{q}_T/|\mathbf{q}_T|$, $h_{1q}(x, \mathbf{k}_T^2)$ is the k_T-dependent transeversity dist $h_{1q}^{\perp}(x,\ \mathbf{k}_T^2)$ while $f_{1T}^{\perp q}(x,\ \mathbf{k}_T^2)$ and are the k_T-dependent T-odd (naive) Boer–Mulders and Sivers functions, respectively. The convolution products of k_T-dependent distributions included are determined as

$$\mathcal{F}[\bar{f}_q f_q] \equiv \int d^2\mathbf{k}_{1T} d^2\mathbf{k}_{2T}\delta^2(\mathbf{k}_{1T}+\mathbf{k}_{2T}-\mathbf{q}_T) \times [f_q(x_1,\mathbf{k}_{1T}^2)\bar{f}_q(x_2,\mathbf{k}_{2T}^2) + (1\leftrightarrow 2)]$$

Drell-Yan studies via integrated/weighted asymmetries.

Unpolarized Drell–Yan Processes.

To extract Boer-Mulders function from the data the procedure of integration/weighting with respect to the transverse momentum of the lepton pair q_T was applied . In order to use the advantages of this procedure, it was proposed to extract from unpolarized Drell–Yan processes the specially weighted and integrated with respect to q_T ratio of cross sections of the form:

$$\hat{R} = \frac{\int d^2\mathbf{q}_T[|\mathbf{q}_T|^2/M_1M_2][d\sigma^{(0)}/d\Omega]}{\int d^2\mathbf{q}_T\sigma^{(0)}}$$

parameterized as

$$\hat{R} = \frac{3}{16\pi}(\gamma(1+\cos^2\theta)+\hat{k}\cos 2\phi\sin^2\theta)$$

which should be compared with the parameterization

$$R = \frac{3}{16\pi}(1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi$$

$$+(\nu/2)\cos 2\phi\sin^2\theta) \quad (\nu \equiv 2\kappa,\ \lambda \simeq 1,\ \mu \simeq 0)$$

Due to the appropriately chosen weighting function $|q_T|^2/M_1M_2$ the integration with respect to q_T results in the following simple formula for k^

$$\hat{k} = 8\frac{\sum_q e_q^2(h_{1q}^{\perp(1)}(x_1)h_{1q}^{\perp(1)}(x_2)+(q\leftrightarrow\bar{q}))}{\sum_q e_q^2(f_{1q}(x_1)f_{1q}(x_2)+(q\leftrightarrow\bar{q}))}$$

$$f_q^{(n)}(x) = \int d^2\mathbf{k}_T\left(\frac{\mathbf{k}_T^2}{2M^2}\right)^n f_q(x,\mathbf{k}_T^2)$$

Thus, it can be seen that the numerator of the expression for k ^ is factorized into the simple product of the first moments of the Boer–Mulders. This factorization allows us to exctract the free-model the first moment of Boer-Mulders PDF from k^ which can be measured in unpolarized Drell–Yan processes.

Drell-Yan studies via integrated/weighted asymmetries.

Single polarized Drell–Yan Processes.

Let us consider single polarized Drell-Yan processes and determine the following single spin asymmetries for them, $H_1 H_2^{\uparrow} \longrightarrow l^+ l^- X,$

$$A_{h(f)} = \int d\Omega d\phi_{S_2} \sin(\phi \pm \phi_{S_2})[d\sigma(\mathbf{S}_{2T}) - d\sigma(-\mathbf{S}_{2T})]$$

$$\times \left(\int d\Omega d\phi_{S_2}[d\sigma(\mathbf{S}_{2T}) + d\sigma(-\mathbf{S}_{2T})] \right)^{-1}$$

It can be easily seen that in the difference of the cross sections *dσ(S $_{2T}$) - dσ(-S $_{2T}$)* only terms containing *sin(φ - φ $_{S2}$)* and *sin(φ + φ $_{S2}$)* survive . Moreover, the properly chosenw eights *sin(φ + φ$_{S2}$)* and *sin(φ - φ$_{S2}$)* allow one to separate the contributions containing the Boer-Mulders and Sivers functions; therefore, finally we obtain

$$A_h = -\frac{1}{4} \frac{\sum_q e_q^2 \mathcal{F}\left[\frac{\hat{\mathbf{h}} \cdot \mathbf{k}_{1T}}{M_1} \bar{h}_{1q}^{\perp} h_{1q}\right]}{\sum_q e_q^2 \mathcal{F}[\bar{f}_{1q} f_{1q}]}$$

$$A_f = \frac{1}{2} \frac{\sum_q e_q^2 \mathcal{F}\left[\frac{\hat{\mathbf{h}} \cdot \mathbf{k}_{2T}}{M_2} \bar{f}_{1q}^{q} f_{1T}^{\perp q}\right]}{\sum_q e_q^2 \mathcal{F}[\bar{f}_{1q} f_{1q}]}$$

$$f_{1T}^{\perp}(x, \mathbf{k}_T^2) \equiv -(M/2|\mathbf{k}_T|)\Delta^N_{q/H^{\uparrow}}(x, \mathbf{k}_T^2)$$

Drell-Yan studies via integrated/weighted asymmetries. Single polarized Drell–Yan Processes.

Let's to apply the procedure of q_T integration/weighting and consider the following asymmetry:

$$\hat{A}_h = \frac{\int d\Omega d\phi_{S_2} \int d^2\mathbf{q}_T(|\mathbf{q}_T|/M_{H_1})\sin(\phi+\phi_{S_2})[d\sigma(\mathbf{S}_{2T}) - d\sigma(-\mathbf{S}_{2T})]}{\int d\Omega d\phi_{S_2} \int d^2\mathbf{q}_T[d\sigma(\mathbf{S}_{2T}) + d\sigma(-\mathbf{S}_{2T})]}$$

Note that the asymmetry $\hat{A}_h$ is similar to the single spin weighted (with the angular weight $sin(\varphi - \varphi_S)$ and the same weight q_T/M) asymmetry

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}} = \frac{\int d\Omega d\phi_{S_2} \int d^2\mathbf{q}_T(|\mathbf{q}_T|/M_{H_2})\sin(\phi-\phi_{S_2})[d\sigma(\mathbf{S}_{2T}) - d\sigma(-\mathbf{S}_{2T})]}{\int d\Omega d\phi_{S_2} \int d^2\mathbf{q}_T[d\sigma(\mathbf{S}_{2T}) + d\sigma(-\mathbf{S}_{2T})]}$$

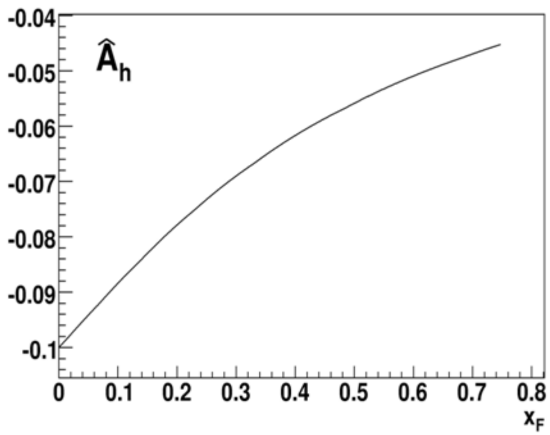
For this asymmetry we again observe the factorization of the contributions:

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}} \equiv 2\hat{A}_n$$

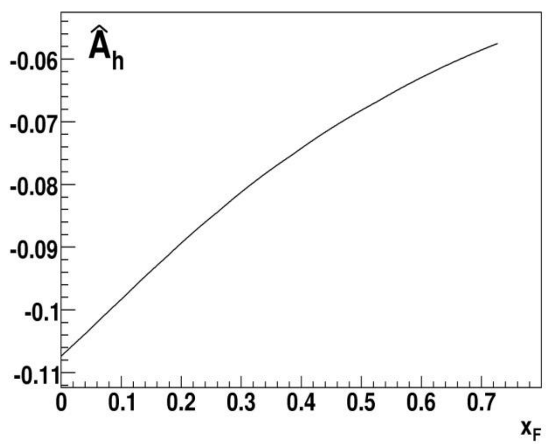
$$= -\frac{\sum_q e_q^2[\bar{h}_{1q}^{\perp(1)}(x_{H_1})h_{1q}(x_{H_2^\uparrow}) + (q \leftrightarrow \bar{q})]}{\sum_q e_q^2[\bar{f}_{1q}(x_{H_1})f_{1q}(x_{H_2^\uparrow}) + (q \leftrightarrow \bar{q})]}$$

Drell-Yan studies via integrated/weighted asymmetries. Single polarized and unpolarized Drell–Yan Processes.

$E_{\pi^-} = 100$ GeV ($\langle Q^2 \rangle = 6.2$ GeV^2)



$E_{\pi^-} = 60$ GeV ($\langle Q^2 \rangle = 5.5$ GeV^2)



SSA was combined with $h_{1u}^{\perp(1)}$ from simulation and h_{1u} was taken from evolution model:

M. Anselmino at al., Phys.Lett. B594:97-104, 2004

V. Barone et al., Phys.Rept.359:1-168,2002

A.V. Efremov et al., hep-ph/0412427

With $h_{1u}^{\perp(1)}$ from analysis of unpolarized DY the h_{1u} can be obtained from the SSA

$$\hat{A}_h \sim \frac{h_{1u}^{\perp(1)}(x_1)\,h_{1u}(x_2)}{f_{1u}(x_1)\,f_{1u}(x_2)}$$

The direct access to transversity

Drell-Yan studies via integrated/weighted asymmetries.

Proton–Proton Collisions.

$$pp \longrightarrow l^+ l^- X$$

$$\hat{k}\Big|_{pp\to l^+l^-X}$$

$$= 8\frac{\sum_q e_q^2[\bar{h}_{1q}^{\perp(1)}(x_1)h_{1q}^{\perp(1)}(x_2) + (q\leftrightarrow\bar{q})]}{\sum_q e_q^2[\bar{f}_{1q}(x_1)f_{1q}(x_2) + (q\leftrightarrow\bar{q})]},$$

$$\hat{R} = \frac{\int d^2\mathbf{q}_T[|\mathbf{q}_T|^2/M_p^2][d\sigma^{(0)}/d\Omega]}{\int d^2\mathbf{q}_T\sigma^{(0)}},$$

$$\hat{R} = \frac{3}{16\pi}(\gamma(1+\cos^2\theta) + \hat{k}\cos 2\phi\sin^2\theta).$$

$$pp^\uparrow \longrightarrow l^+ l^- X,$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}} \equiv 2\hat{A}_h$$

$$= -\frac{\sum_q e_q^2[\bar{h}_{1q}^{\perp(1)}(x_p)h_{1q}(x_{p^\uparrow}) + (q\leftrightarrow\bar{q})]}{\sum_q e_q^2[\bar{f}_{1q}(x_p)f_{1q}(x_{p\uparrow}) + (q\leftrightarrow\bar{q})]},$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}$$

$$= 2\frac{\sum_q e_q^2[\bar{f}_{1q}(x_p)f_{1T}^{\perp(1)q}(x_{p^\uparrow}) + (q\leftrightarrow\bar{q})]}{\sum_q e_q^2[\bar{f}_{1q}(x_p)f_{1q}(x_{p^\uparrow}) + (q\leftrightarrow\bar{q})]},$$

Drell-Yan studies via integrated/weighted asymmetries.

Proton–Proton Collisions.

$$x_p \gg x_{p^\uparrow}$$

neglecting the contributions containing a sea parton's distribution functions for large values of x_p (and correspondingly, valence ones for small values of x_p) and taking into account quark charges and u-dominance at large x we obtain the approximate expressions for asymmetries

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}\Big|_{x_p \gg x_{p^\uparrow}} \simeq 2\frac{\bar{f}_{1T}^{\perp(1)u}(x_{p^\uparrow}) f_{1u}(x_p)}{\bar{f}_{1u}(x_{p^\uparrow}) f_{1u}(x_p)} = 2\frac{\bar{f}_{1T}^{\perp(1)u}(x_{p^\uparrow})}{\bar{f}_{1u}(x_{p^\uparrow})},$$

and

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}\Big|_{x_p \gg x_{p^\uparrow}} \simeq -\frac{h_{1u}^{\perp(1)}(x_p)\bar{h}_{1u}(x_{p^\uparrow})}{f_{1u}(x_p)\bar{f}_{1u}(x_{p^\uparrow})},$$

$$x_p \ll x_{p^\uparrow}$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}\Big|_{x_p \ll x_{p^\uparrow}} \simeq 2\frac{f_{1T}^{\perp(1)u}(x_{p^\uparrow})\bar{f}_{1u}(x_p) + f_{1T}^{\perp(1)d}(x_{p^\uparrow})\bar{f}_{1d}(x_p)}{4f_{1u}(x_p)\bar{f}_{1u}(x_{p^\uparrow}) + f_{1d}(x_{p^\uparrow})\bar{f}_{1d}(x_p)},$$

and

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}\Big|_{x_p \ll x_{p^\uparrow}} \simeq -\frac{4\bar{h}_{1u}^{\perp(1)}(x_p)h_{1u}(x_{p^\uparrow}) + \bar{h}_{1d}^{\perp(1)}(x_p)h_{1d}(x_{p^\uparrow})}{4\bar{f}_{1u}(x_p)f_{1u}(x_{p^\uparrow}) + \bar{f}_{1d}(x_p)f_{1d}(x_{p^\uparrow})},$$

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}\Big|_{x_p \ll x_{p^\uparrow}} \simeq 2\frac{f_{1T}^{\perp(1)u}(x_{p^\uparrow})\bar{f}_{1u}(x_p)}{f_{1u}(x_{p^\uparrow})\bar{f}_{1u}(x_p)} = 2\frac{f_{1T}^{\perp(1)u}(x_{p^\uparrow})}{f_{1u}(x_{p^\uparrow})},$$

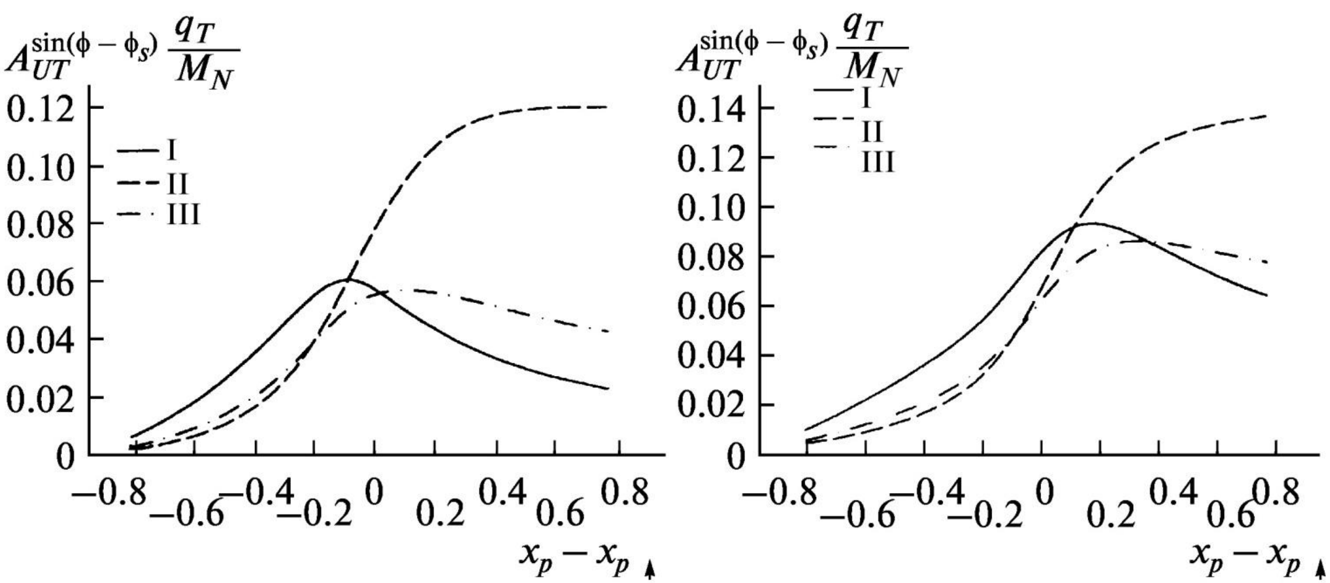
and

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}}\Big|_{x_p \ll x_{p^\uparrow}} \simeq -\frac{\bar{h}_{1u}^{\perp(1)}(x_p)h_{1u}(x_{p^\uparrow})}{\bar{f}_{1u}(x_p)f_{1u}(x_{p^\uparrow})},$$

Drell-Yan studies via integrated/weighted asymmetries.

Numerical Estimates for pp Asymmetries.

NICA kinematics - 10–13 GeV proton beams.
The calculations are performed for Q^2 below and above the production threshold Q^2 = 9.5 GeV^2 of the J/ψ resonance. The three sets of fits for the Sivers function are used in calculations.

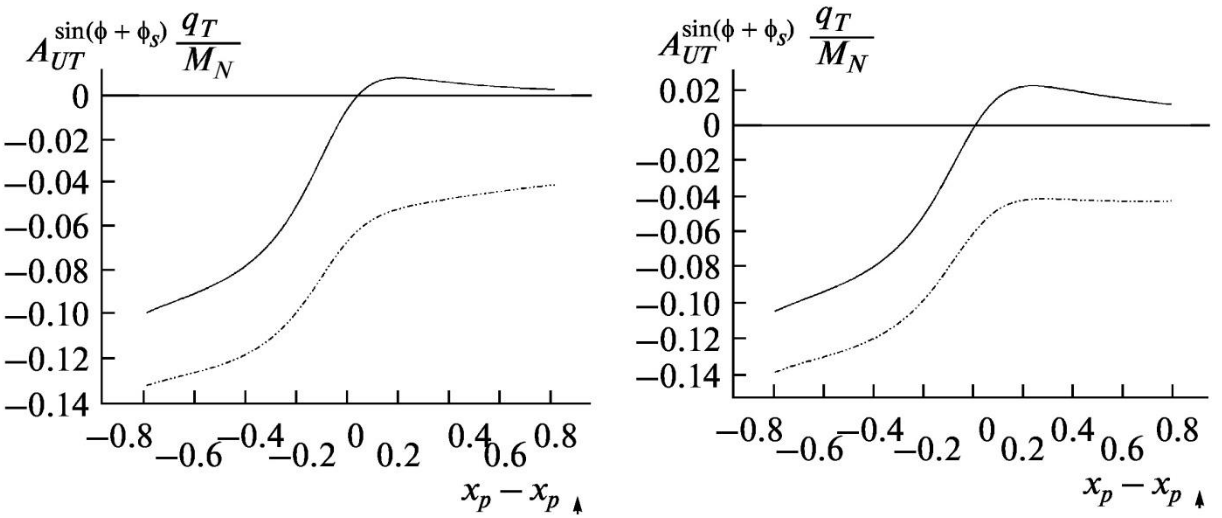


Estimated asymmetries for NICA: s = 400 GeV^2 , Q^2 = (left panel) 4 and (right panel) 15 GeV^2 . Numbers I,II denote fits I, II for the Sivers function.

A. V. Efremov et al., Phys. Lett. B 612, 233 (2005).
J. C. Collins et al., Phys. Rev. D 73, 014021 (2006).

Drell-Yan studies via integrated/weighted asymmetries.

Numerical Estimates for pp Asymmetries.



Estimated asymmetries for NICA, s = 400 GeV^2 for Q^2 = (left panel) 4 and (right panel) 15 GeV^2 . Solid and dashed lines correspond to two versions of evolution model and for transversity. Parameterizations GRV94 and GRSV95 for q(x) and Δq(x), respectively, are used.

Drell-Yan studies via integrated/weighted asymmetries.

Asymmetry in pD and DD Collisions.

The integrated and additionally q_T-weighted asymmetries $A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]}$ and $A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]}$ provide access to the first moments of the Boer-Mulders, $h_{1q}^{\perp}(x,k_T^2)$ and Sivers, $f_{q1T}^{\perp(1)}(x,k_T^2)$

$$A_{UT}^{w[\sin(\phi+\phi_S)]} = \frac{\int d\Omega d\phi_S \sin(\phi+\phi_S)\left[d\sigma^{\uparrow} - d\sigma^{\downarrow}\right]}{\int d\Omega d\phi_S \left[d\sigma^{\uparrow} + d\sigma^{\downarrow}\right]/2} = -\frac{1}{2}\frac{C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_1^{\perp}\bar{h}_1\right]}{C\left[f_1\,\bar{f}_1\right]},$$

$$A_{UT}^{w[\sin(\phi-\phi_S)]} = \frac{\int d\Omega d\phi_S \sin(\phi-\phi_S)\left[d\sigma^{\uparrow} - d\sigma^{\downarrow}\right]}{\int d\Omega d\phi_S \left[d\sigma^{\uparrow} + d\sigma^{\downarrow}\right]/2} = \frac{1}{2}\frac{C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} f_1\,\bar{f}_{1T}^{\perp}\right]}{C\left[f_1\,\bar{f}_1\right]},$$

$$A_{UT}^{w[\sin(3\phi-\phi_S)]} = \frac{\int d\Omega d\phi_S \sin(3\phi-\phi_S)\left[d\sigma^{\uparrow} - d\sigma^{\downarrow}\right]}{\int d\Omega d\phi_S \left[d\sigma^{\uparrow} + d\sigma^{\downarrow}\right]/2} =$$

$$= -\frac{1}{2}\frac{C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^2(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_1^{\perp}\bar{h}_{1T}^{\perp}\right]}{C\left[f_1\,\bar{f}_1\right]}$$

$$A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]}\Bigg|_{x_p \gg x_{p\uparrow}} \approx 2\frac{\bar{f}_{1uT}^{\perp(1)}(x_{p\uparrow})}{\bar{f}_{1u}(x_{p\uparrow})} \quad ; \quad A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]}\Bigg|_{x_p \gg x_{p\uparrow}} \approx -\frac{h_{1u}^{\perp(1)}(x_p)\bar{h}_{1u}(x_{p\uparrow})}{f_{1u}(x_p)\,\bar{f}_{1u}(x_{p\uparrow})}$$

$$A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]} = \frac{\int d\Omega \int d^2\mathbf{q}_T (|\mathbf{q}_T|/M_p)\sin(\phi+\phi_S)\left[d\sigma^{\uparrow} - d\sigma^{\downarrow}\right]}{\int d\Omega \int d^2\mathbf{q}_T \left[d\sigma^{\uparrow} + d\sigma^{\downarrow}\right]/2}$$

$$= -\frac{\sum_q e_q^2\left[\bar{h}_{1q}^{\perp(1)}(x_p)h_{1q}(x_{p\uparrow}) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2\left[\bar{f}_{1q}(x_p)\,f_{1q}(x_{p\uparrow}) + (q \leftrightarrow \bar{q})\right]},$$

$$A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]}\Bigg|_{x_p \ll x_{p\uparrow}} \approx 2\frac{f_{1uT}^{\perp(1)}(x_{p\uparrow})}{f_{1u}^{\perp(1)}(x_{p\uparrow})} \quad ; \quad A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]}\Bigg|_{x_p \ll x_{p\uparrow}} \approx -\frac{\bar{h}_{1u}^{\perp(1)}(x_p)h_{1u}(x_{p\uparrow})}{\bar{f}_{1u}(x_p)\,f_{1u}(x_{p\uparrow})}.$$

$$A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]} = \frac{\int d\Omega \int d^2\mathbf{q}_T (|\mathbf{q}_T|/M_p)\sin(\phi-\phi_S)\left[d\sigma^{\uparrow} - d\sigma^{\downarrow}\right]}{\int d\Omega \int d^2\mathbf{q}_T \left[d\sigma^{\uparrow} + d\sigma^{\downarrow}\right]/2}$$

$$= 2\frac{\sum_q e_q^2\left[f_{1T}^{\perp(1)q}(x_{p\uparrow})\,\bar{f}_{1q}(x_p) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2\left[\bar{f}_{1q}(x_{p\uparrow})\,f_{1q}(x_p) + (q \leftrightarrow \bar{q})\right]},$$

where

$$h_{1q}^{\perp(1)}(x) = \int d^2k_T\left(\frac{k_T^2}{2M_p^2}\right)h_{1q}^{\perp}(x_p,k_T^2) \quad \text{and} \quad f_{qIT}^{\perp(1)}(x) = \int d^2k_T\left(\frac{k_T^2}{2M_p^2}\right)f_{qIT}^{\perp(1)}(x,k_T^2)$$

Drell-Yan studies via integrated/weighted asymmetries.

Asymmetry in pD and DD Collisions.

So far the pp-collisions have been considered. At NICA the pd- and dd-collisions will be investigated as well. As it is known from COMPASS experiment, the SIDIS asymmetries on polarized deuterons are consisted with zero. At NICA one can expect that asymmetries

$$A_{UT}^{w\left[\sin(\phi\pm\phi_S)\frac{q_T}{M_N}\right]}\Bigg|_{pD^\uparrow},\quad A_{UT}^{w\left[\sin(\phi\pm\phi_S)\frac{q_T}{M_N}\right]}\Bigg|_{DD^\uparrow}$$

also will be consistent with zero (subject of tests).

But asymmetries in *Dp*↑ collisions are expected to be non-zero. In the limiting cases $x_D >> x_{p^\uparrow}$ and $x_D << x_{p^\uparrow}$ these asymmetries (**accessible only at NICA**)

$$A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]}(x_D >> x_{p\uparrow})\Bigg|_{Dp\uparrow\to l^+l^-X} \approx \frac{4\,\bar{f}_{1uT}^{\perp(1)}(x_{p\uparrow}) + \bar{f}_{1dT}^{\perp(1)}(x_{p\uparrow})}{4\,\bar{f}_{1u}^{\perp(1)}(x_{p\uparrow}) + \bar{f}_{1d}^{\perp(1)}(x_{p\uparrow})},$$

$$A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]}(x_D << x_{p\uparrow})\Bigg|_{Dp\uparrow\to l^+l^-X} \approx 2\,\frac{4\,f_{1uT}^{\perp(1)}(x_{p\uparrow}) + f_{1dT}^{\perp(1)}(x_{p\uparrow})}{4\,f_{1u}^{\perp(1)}(x_{p\uparrow}) + f_{1d}^{\perp(1)}(x_{p\uparrow})},$$

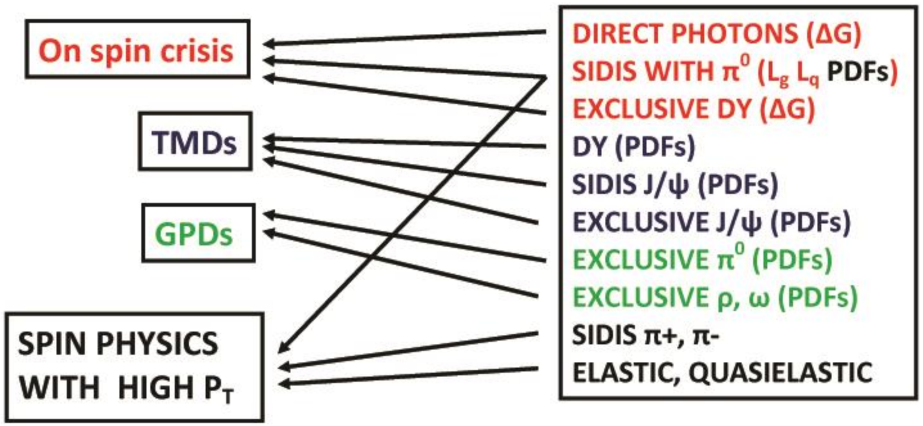
$$A_{TT}^{w[\cos(\phi_{Sb}+\phi_{Sa})\,q_T/M]} \equiv A_{TT}^{int} = \frac{\sum_q e_q^2\left(\bar{h}_{1q}(x_1)h_{1q}(x_2) + (x_1 \leftrightarrow x_2)\right)}{\sum_q e_q^2\left(\bar{f}_{1q}(x_1)\,f_{1q}(x_2) + (x_1 \leftrightarrow x_2)\right)}.$$

$$A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]}(x_D >> x_{p\uparrow})\Bigg|_{Dp\uparrow\to l^+l^-X} \approx -\frac{[h_{1u}^{\perp(1)}(x_D) + h_{1d}^{\perp(1)}(x_D)][4\bar{h}_{1u}(x_{p\uparrow}) + \bar{h}_{1d}(x_{p\uparrow})]}{[\,f_{1u}(x_D) + f_{1d}(x_D)][4\,\bar{f}_{1u}(x_{p\uparrow}) + \bar{f}_{1d}(x_{p\uparrow})]},$$

$$A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]}(x_D << x_{p\uparrow})\Bigg|_{Dp\uparrow\to l^+l^-X} \approx -\frac{[\bar{h}_{1u}^{\perp(1)}(x_D) + \bar{h}_{1d}^{\perp(1)}(x_D)][4h_{1u}(x_{p\uparrow}) + h_{1d}(x_{p\uparrow})]}{[\,\bar{f}_{1u}(x_D) + \bar{f}_{1d}(x_D)][4\,f_{1u}(x_{p\uparrow}) + f_{1d}(x_{p\uparrow})]}.$$

Conclusions

- Measurements of DY processes is one of the main topics of SPD

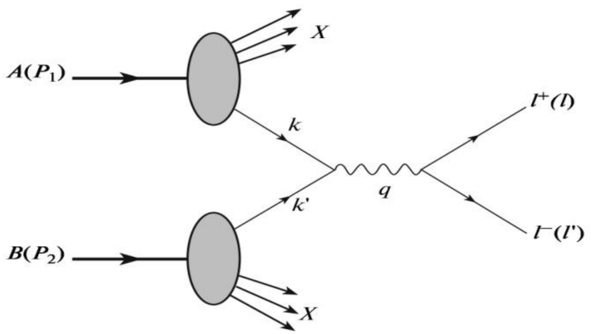


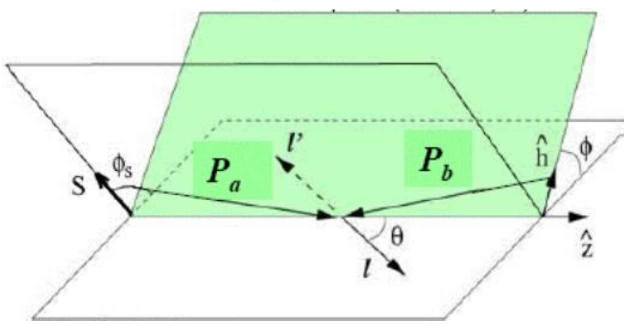
- Two approaches to extraction PDFs are proposed
- Both complement each other and allows to obtain new important data on

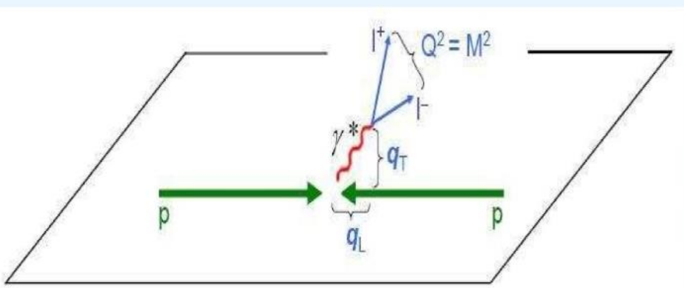
- Transversity: $A_{UT}^{sin(\phi_h+\phi_S)} \propto h_1 \otimes H_1^\perp$
- Sivers: $A_{UT}^{sin(\phi_h-\phi_S)} \propto f_{1T}^\perp \otimes D_1$
- Pretzelosity: $A_{UT}^{sin(3\phi_h-\phi_S)} \propto h_{1T}^\perp \otimes H_1^\perp$
- Boer-Mulders: $A_{UU}^{cos(2\phi_h)} \propto h_1^\perp \otimes H_1^\perp$
- Worm-Gears: $A_{UL}^{sin(2\phi_h)} \propto h_{1L}^\perp \otimes H_1^\perp$; $A_{LT}^{cos(\phi_h-\phi_S)} \propto g_{1T}^\perp \otimes D_1$

BACKUP SLIDES

Drell-Yan studies with SPD.







- $x_1 = \frac{Q^2}{2p_1 q}, \quad x_2 = \frac{Q^2}{2p_2 q}$ – fractions of the longitudinal momentum of the hadrons A and B carried by the quark and antiquark which annihilate into virtual photon
- $s = (p_1 + p_2)^2 \simeq 2p_1 p_2$ – the center of mass energy squared
  $Q^2 = M^2 \simeq x_1 x_2 s \equiv \tau s$
  $y = \frac{1}{2} \ln \frac{x_1}{x_2}$
  $x_F = x_1 - x_2$
  $x_1 = \frac{\sqrt{x_F^2 + 4\tau} + x_F}{2} = \sqrt{\tau} e^y$
  $x_2 = \frac{\sqrt{x_F^2 + 4\tau} - x_F}{2} = \sqrt{\tau} e^{-y}$
- θ – production angle in the dilepton rest frame – polar angle of the lepton pair in the dilepton rest frame
- ϕ – azimuthal angle of lepton pair
- ϕ_S – azimuthal angle of the hadron polarization measured with respect to lepton plane

V.A.Matveev, R.M.Muradian, A.N.Tavkhelidze,
JINR P2-4543, JINR Dubna 1969;SLAC-TRANS-0098 JINR R2-4543,Jun 1969
S.D.Drell, T.M.Yan SLAC-PUB-0755, Jun 1970, Phys.Rev.Lett. 25 (1970)