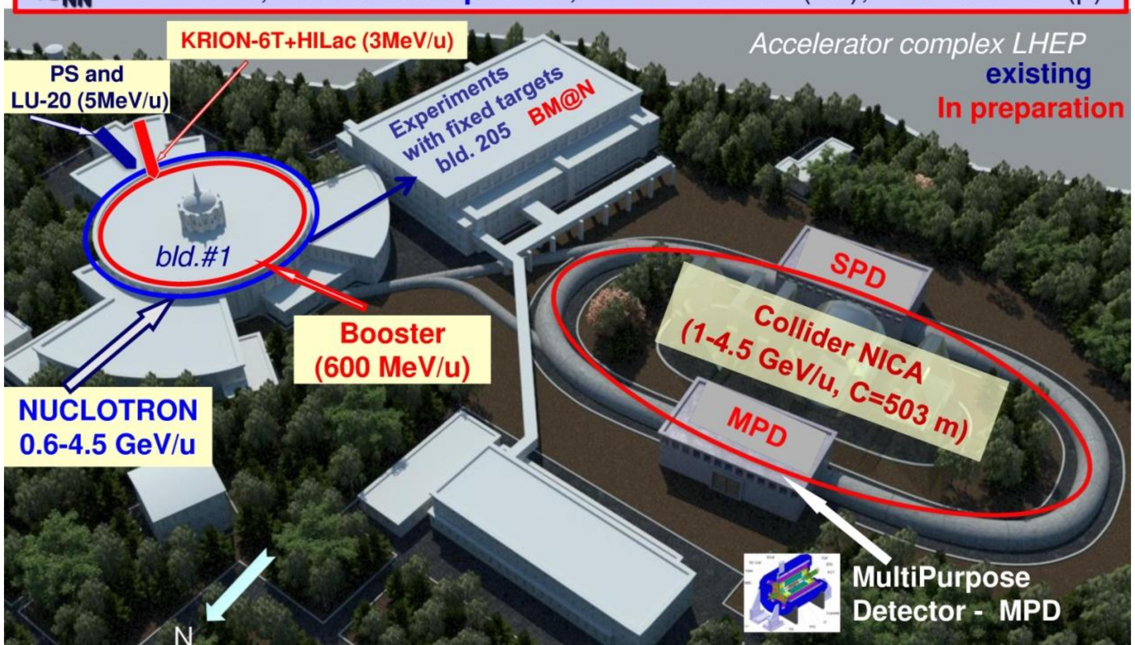
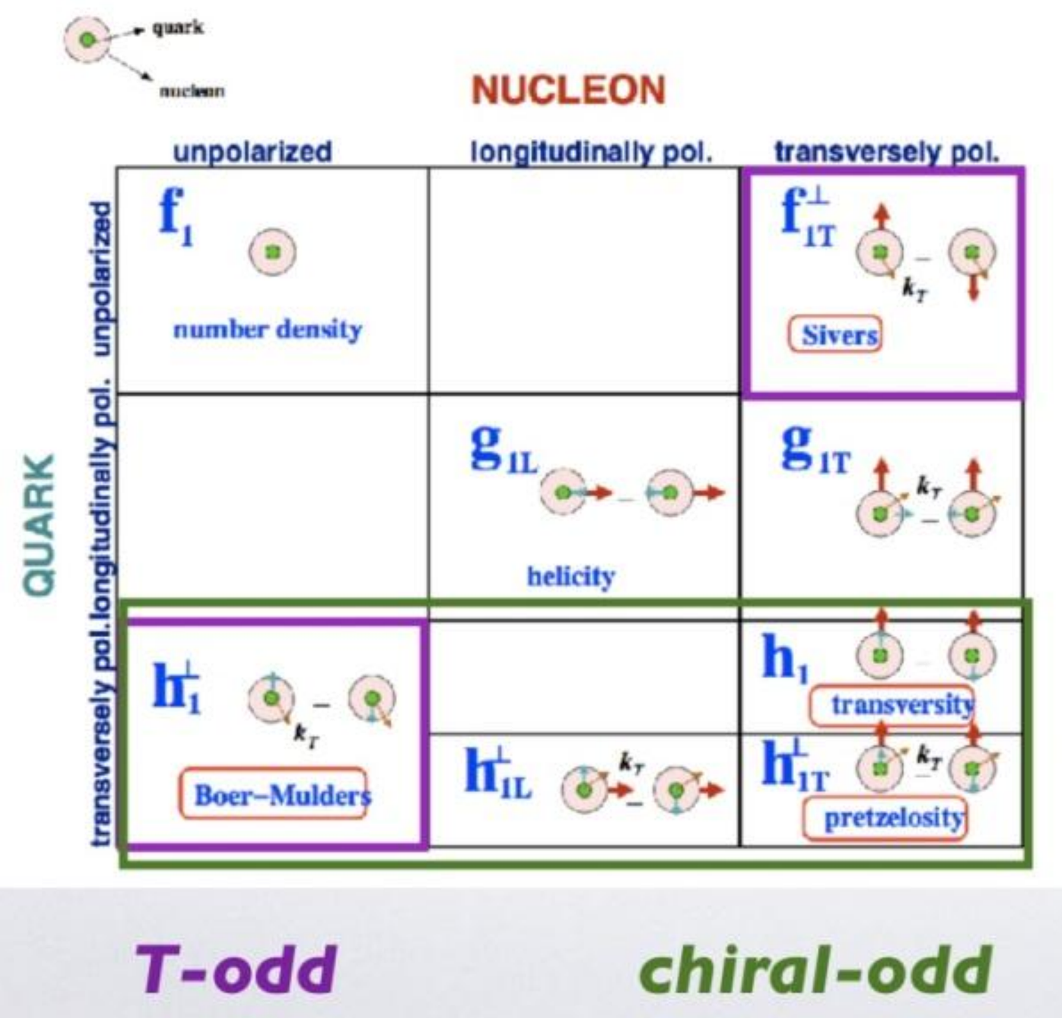
Drell-Yan studies with SPD

Collider basic parameters:
$\sqrt{s_{NN}}$ = **4-11** GeV; ***beams***: *from* **p** to **Au**; **L**~10^{27} $cm^{-2}c^{-1}$ (Au), ~10^{32} $cm^{-2}c^{-1}$ (p)



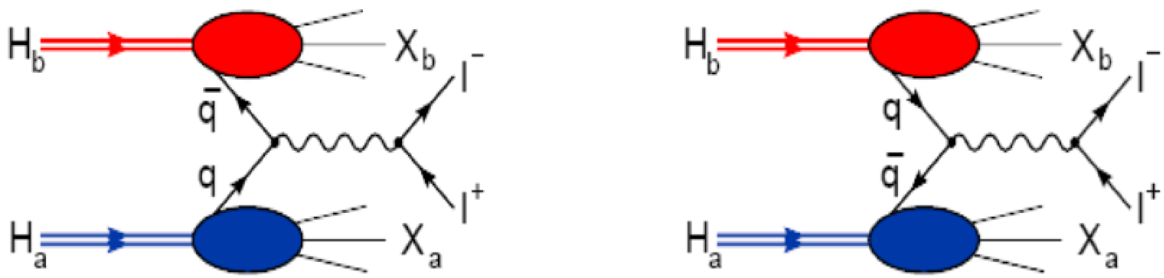
Drell-Yan studies with SPD.



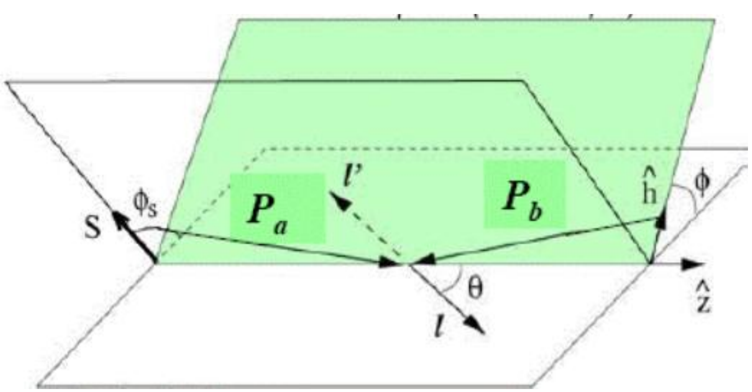
3 PDFs are needed to describe nucleon structure in collinear approximation

8 PDFs are needed if we want to take into account intrinsic transverse momentum k_T of quarks

Drell-Yan studies with SPD.



(a) (b)



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

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

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

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

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

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

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

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

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

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

where F^i_{jk} 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,

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

Drell-Yan studies with SPD.

The 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 *Φs*, second, following the SIDIS practice, to measure azimuthal asymmetries of the DY pair's production cross sections. The integration over the azimuthal angle *Φ* gives:

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

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

Drell-Yan studies with SPD.

The PDFs studies via Fourier analysis to the measured asymmetries.

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

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

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

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

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

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

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

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

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

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

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

The azimuthal asymmetries can be calculated as ratios of cross sections differences to the sum of the integrated over *Φ* cross sections.

The azimuthal distribution of DY pair's produced in non-polarized hadron collisions, A_{UU}, and azimuthal asymmetries of the cross sections in polarized hadron collisions, A_{jk}, are given by relations shown left.

Drell-Yan studies with SPD.

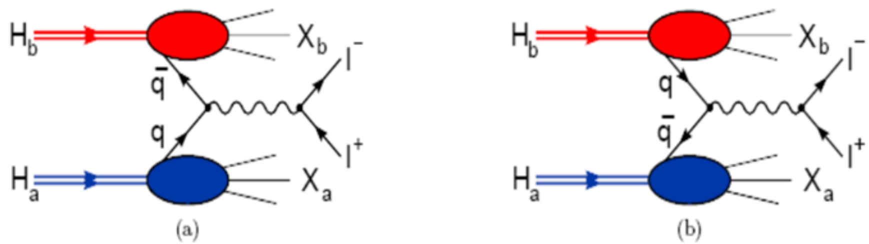
The PDFs studies via Fourier analysis to the measured asymmetries.

Applying the Fourier analysis to the measured asymmetries, one can separate each of all ratios entering previous slide. The extraction of different TMD PDFs from those ratios is a task of the global theoretical analysis (a challenge for the theoretical community) since each of the SFs 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

(M. Anselmino et al., arXiv:1304.7691 [hep-ph]), or to transfer to impact parameter representation space and to use the Bessel weighted TMD PDFs
(Daniel Boer, Leonard Gamberg, Bernhard Musch, Alexei Prokudin, JHEP 1110 (2011) 021, [arXiv:1107.5294])

Drell-Yan studies with SPD.

Studies of PDFs via integrated/weighted asymmetries.



The set of asymmetries mentioned above gives the access to all eight leading twist TMD PDFs. However, sometimes one can work with integrated asymmetries. Integrated asymmetries are useful for the express analysis of data and checks of expected relations between asymmetries mentioned above. They are also useful for model estimations and determination of required statistics . Let us consider several examples starting from the case when only one of colliding hadrons (for instance, hadron "b") is transversely polarized. In this case the DY cross section can be reduced to the expression:

$$
\begin{aligned}
\frac{d\sigma}{dx_a dx_b d^2\mathbf{q}_T d\Omega} = \frac{\alpha^2}{4Q^2}\Bigg\{ & (1+\cos^2\theta)\, C\left[f_1 \bar{f}_1 \right] \\
& + \sin^2\theta \cos 2\phi\, C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_1^{\perp} \bar{h}_1^{\perp} \right] \\
& + |S_{bT}| \Bigg[(1+\cos^2\theta)\sin(\phi-\phi_{S_b})\, C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} f_1 \bar{f}_{1T}^{\perp} \right] - \sin^2\theta \sin(\phi+\phi_{S_b})\, C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_1^{\perp} \bar{h}_1 \right] \\
& - \sin^2\theta \sin(3\phi-\phi_{S_b})\, C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^2(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_1^{\perp} \bar{h}_{1T}^{\perp} \right] \Bigg] \Bigg\}
\end{aligned}
$$

Drell-Yan studies with SPD.

Studies of PDFs via integrated/weighted asymmetries.

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, $f_{q1T}^{\perp(1)}(x,k_T^2)$

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

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

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

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

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

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

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

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

where

$$h_{1q}^{\perp(1)}(x)=\int d^2k_T\left(\frac{k_T^2}{2M_p^2}\right)h_{1q}^{\perp}(x_p,k_T^2)\quad\text{and}\quad f_{q1T}^{\perp(1)}(x)=\int d^2k_T\left(\frac{k_T^2}{2M_p^2}\right)f_{q1T}^{\perp(1)}(x,k_T^2)$$

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

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

Drell-Yan studies with SPD.

Studies of PDFs via integrated/weighted asymmetries.

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

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

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

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

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

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

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

Drell-Yan studies with SPD.

Measurements of integrated/weighted asymmetries.

We propose to perform measurements of asymmetries of the DY pair"s production in collisions of polarized protons and deuterons which provide an access to all collinear and TMD PDFs of quarks and anti-quarks in nucleons.

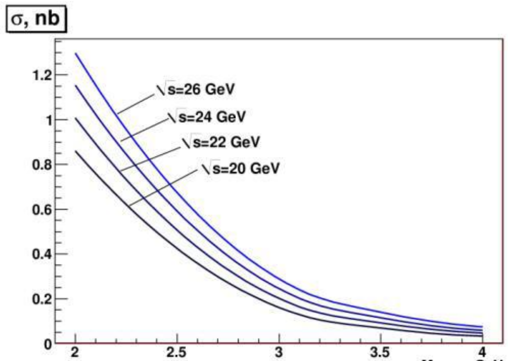
The measurements of asymmetries in production of J/Ψ and direct photons will be performed simultaneously with DY using dedicated triggers.

The set of these measurements will supply complete information for tests of the quark-parton model of nucleons at the twist-two level with minimal systematic errors.

Drell-Yan studies with SPD.

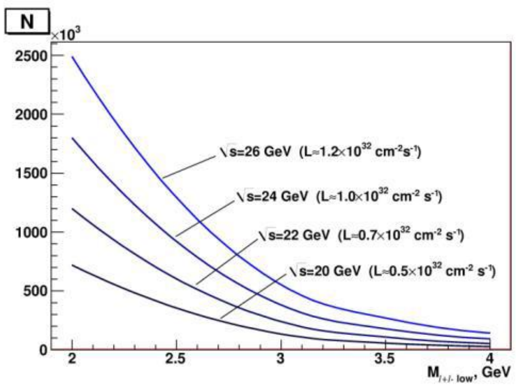
Estimations of DY pairs and J/Ψ production rates.

Estimation of the DY pair's production rate at SPD was performed using the expression for the differential and total cross sections of the pp interactions:



$$\frac{d^2\sigma}{dQ^2dx_1} = \frac{1}{sx_1}\frac{4\pi\alpha^2}{9Q^2}\sum_{f,\bar{f}} e_f^2[f(x_1,Q^2)\bar{f}(x_2,Q^2)]_{x_2=Q^2/sx_1}$$

$$\sigma_{tot} = \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{x_{min}}^{1} dx_1 \frac{d^2\sigma}{dQ^2dx_1},$$



Cross section (left) and number of DY events (right) versus the minimal invariant mass of lepton pair for various proton beam energies

The Table shows values of the cross sections and expected statistics for DY events (K events) per four moths of data taking and 100% acceptance of SPD at two energies.

Lower cut on M_{l+l-} , GeV	2.0	3.0	3.5	4.0
$\sqrt{s}$=24 GeV (L = $1.0\cdot10^{32}$ cm^{-2} s^{-1})				
σ_{DY} total, nb	1.15	0.20	0.12	0.06
events	1800	313	179	92
$\sqrt{s}$=26 GeV (L = $1.2\cdot10^{32}$ cm^{-2} s^{-1})				
σ_{DY} total, nb	1.30	0.24	0.14	0.07
events	2490	460	269	142

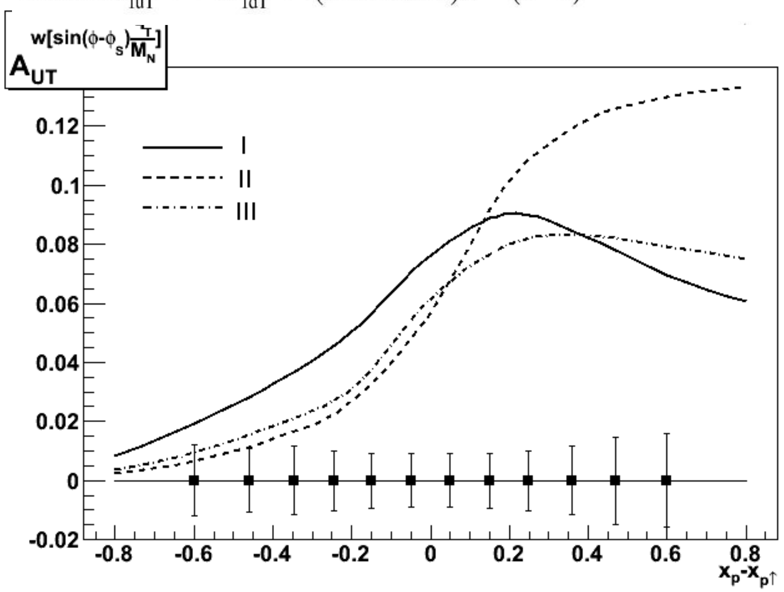
Drell-Yan studies with SPD.

Estimations of DY pairs and J/Ψ production rates.

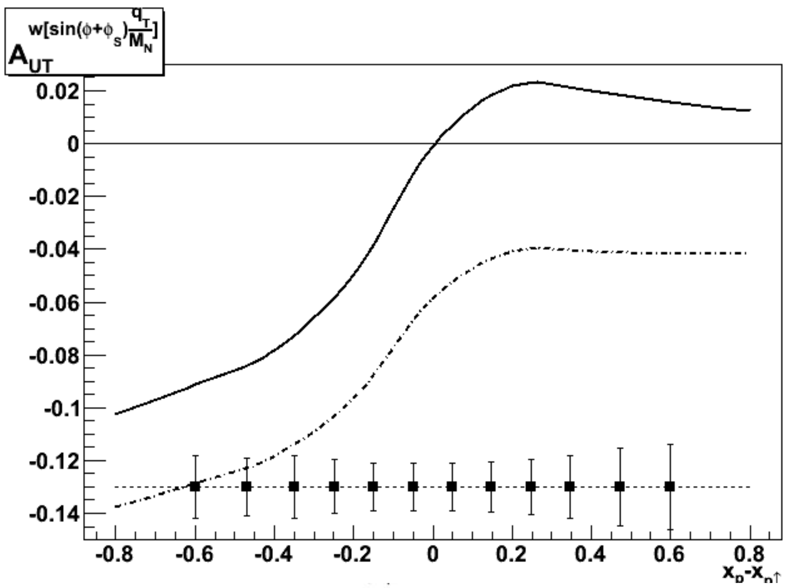
To estimate the precision of measurements, the set of original software packages for MC simulations, including generators for Sivers, Boer-Mulders and Transversity PDFs, were developed in
A.Sissakian, O.Shevchenko, A.Nagaytsev, O.Ivanov, Phys.Part.Nucl.41 (2010) 64-100.
With these packages a sample of 100K DY events was generated in the region of $Q^2 > 11\ \mathrm{GeV}^2$ for comparison with expected asymmetries.

Fit I: $xf_{1uT}^{\perp(1)} = -xf_{1dT}^{\perp(1)} = 0.4x(1-x)^5$; Fit II: $xf_{1uT}^{\perp(1)} = -xf_{1dT}^{\perp(1)} = 0.1x^{0.3}(1-x)^5$

Fit III: $xf_{1uT}^{\perp(1)} = -xf_{1dT}^{\perp(1)} = (0.17...0.18)x^{0.66}(1-x)^5$



Estimated Sivers asymmetry $A_{UT}^{w\left[\sin(\phi-\phi_S)\frac{q_T}{M_N}\right]}$ at $\sqrt{s} = 26$ GeV with $Q^2 = 15\ \mathrm{GeV}^2$.

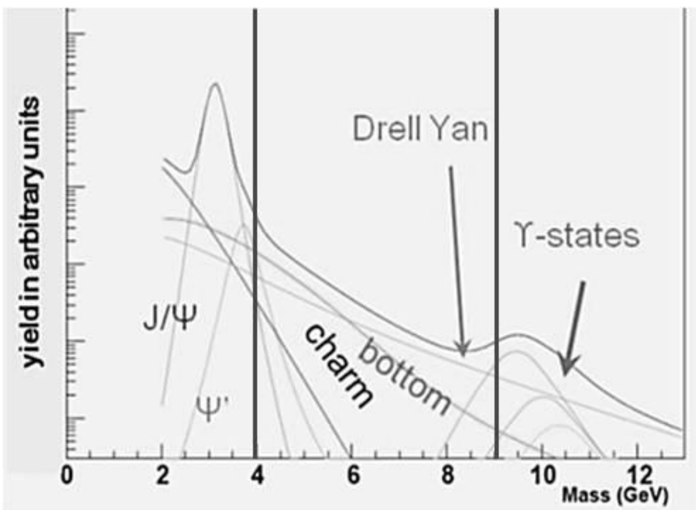


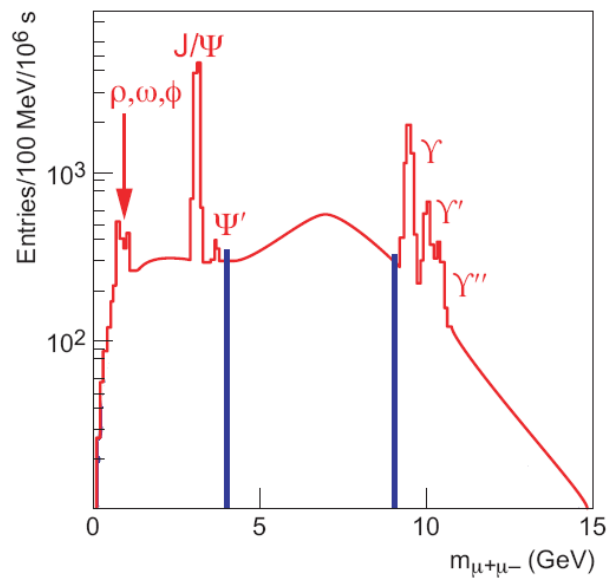
Estimations of Boer-Mulders asymmetry $A_{UT}^{w\left[\sin(\phi+\phi_S)\frac{q_T}{M_N}\right]}$ at $\sqrt{s} = 26$ GeV and $Q^2 = 15\ \mathrm{GeV}^2$. The solid and dotted curves correspond to the first and second versions of the evolution model, respectively. Points with bars show the expected statistical errors obtained with 100K of events

Drell-Yan studies with SPD.

Estimations of DY pairs and J/Ψ production rates.

Statistics of the J/Ψ and DY events (with cut on $M_{l^-l^+}$= 4 GeV) expected to be recorded ("per year") in four months of data taking with 100% efficiency of SPD are given in Table.





$\sqrt{s}$, GeV	24	26	$\sqrt{s}$, GeV	24	26
$\sigma_{J/\psi} \cdot B_{e+e-}$, nb	12	16	σ_{DY} , nb	0.06	0.07
Events "per year"	$18 \cdot 10^6$	$23 \cdot 10^6$	Events "per year"	$92 \cdot 10^3$	$142 \cdot 10^3$

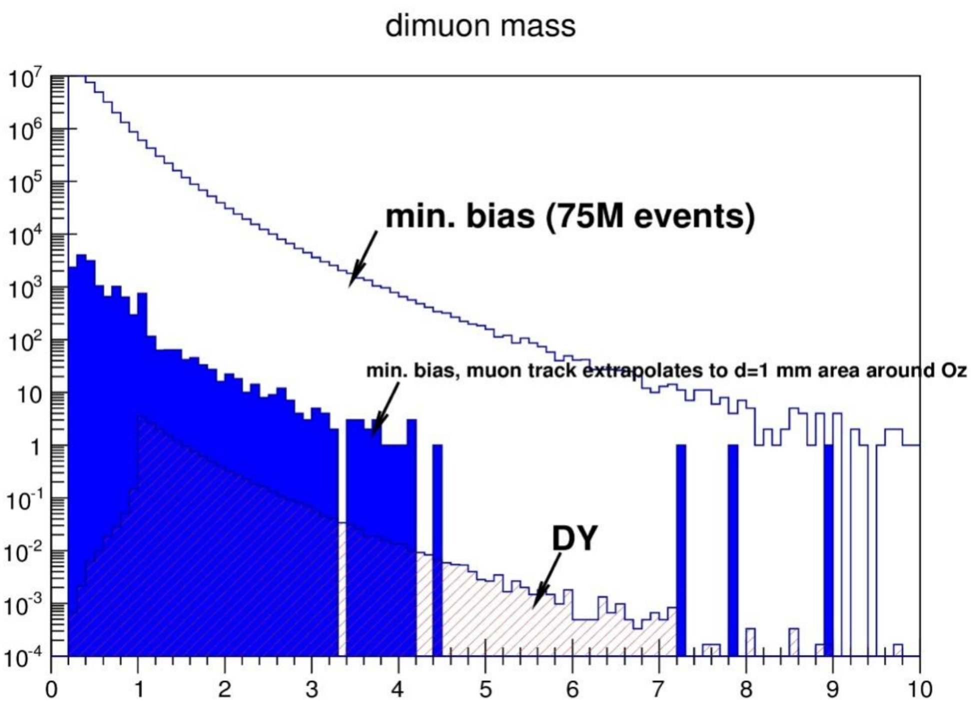
Drell-Yan studies with SPD.

DY background studies

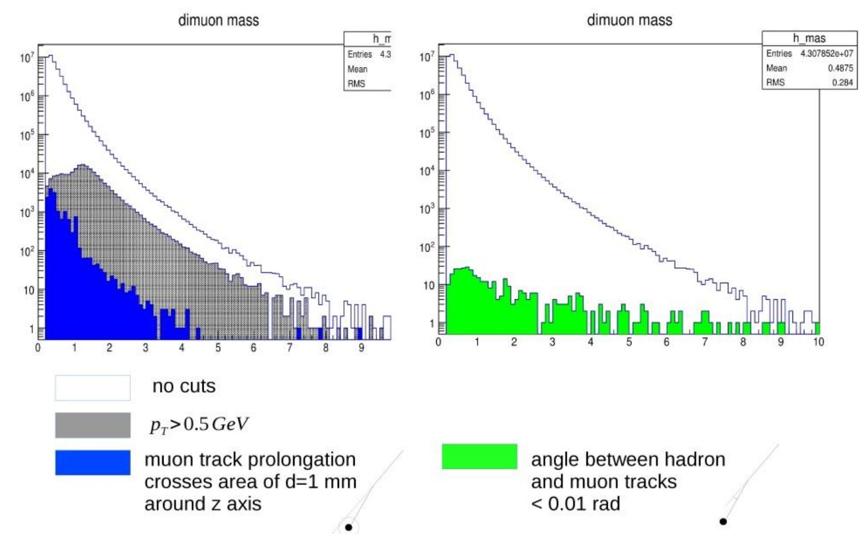
DY and min bias events were generated with PYTHIA 6

- 2 proton beams with E=12 GeV
- Only process $q\bar{q}\rightarrow\gamma^*\rightarrow\mu^+\mu^-$
- $m_{\mu\mu}>1\,GeV$
- Decays of $\pi^\pm, K^\pm, K_L^0$ turned on
- 10^5 events
- $\sigma_{tot}=8.7\,nb$ (ratio $\sigma_{tot}(MB)/\sigma_{tot}(DY)\approx4.5\cdot10^6$)
- Only muons produced in volume with L=8 m and D=7 m were taken into account.

- (For $m_{\mu\mu}>3\,GeV$ $\sigma_{tot}=0.23\,nb$)



- PYTHIA 6
- MSEL=2
- 2 proton beams with E=12 GeV
- Decays of $\pi^\pm, K^\pm, K_L^0$ turned on
- $75\cdot10^6$ events
- $\sigma_{tot}=39.4\,mb$



Tracking system must to be done with very high efficiency to reduce DY background.

Conclusions

We propose to perform measurements of asymmetries of the DY pair's production in collisions of non-polarized, longitudinally and transversally polarized protons and deuterons which provide an access to all leading twist collinear and TMD PDFs of quarks and anti-quarks in nucleons. The measurements of asymmetries in production of J/Ψ and direct photons will be performed as well simultaneously with DY using dedicated triggers. The set of these measurements will supply complete information for tests of the quark-parton model of nucleons at the QCD twist-two level with minimal systematic errors.

Letter of Intent was approved at the meeting of the JINR Program Advisory Committee (PAC) for Particle Physics on 25–26 June 2014.)

New stage og SPD project - From LoI to CRD

Collaborators are welcomed !