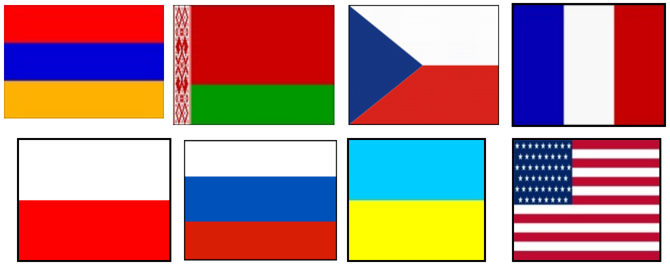

Nec sine te, nec tecum vivere possum. (Ovid)*

Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beam.

Letter of Intent.

Presented by I.A. Savin on behalf of the Drafting Committee:

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A. Nagajcev, A. Guskov, V. Kukhtin, N. Topilin.

LoI signed by 124 authors
representing 23 Institutions
from 8 countries.

http://arxiv.org/abs/1408.3959

Updating list of participants

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Expressed an Interest: Gomel SU, Moscow SU, St. Petersburg (Gatchina), ITEP, Moscow, INFN Torino, Italy

Spin Physics Experiments @ NICA-SPD with polarized proton and deuteron beams.

Letter of Intent is Discussed at :

EU-Russia-JINR @ Dubna Round Table, Dubna, 3-5 March ;
Seminars: LHEP, 7 March; LNP, 23 April; LIT, 24 April; LTP, 22 May;
LHEP NTS(phys), 20 March; NTS JINR, 23 May 2014;
ISHEP QUARKS-2014, Suzdal, Russia, 2-8 June;
4th IWTPPHP, Transversity 2014, Cagliari, Italy, 9-13 June;
PAC JINR, 25-26 June 2014

CONTENT

1. Introduction
2. Physics motivations
3. Requirements to the NUCLOTRON-NICA complex
4. Polarized beams at NICA
5. Requirements to the spin physics detector (SPD)
6. Proposed measurements with SPD
7. Time lines of the project

PAC Recommendations:

….The PAC heard with interest a report on the preparation of the Letter of Intent "Spin physics experiments at NICA-SPD with polarized proton and deuteron beams" presented by I. Savin. The PAC is pleased to see the first steps toward formation of an international collaboration around the SPD experiment. The PAC regards the SPD experiment as an essential part of the NICA research program and encourages the authors of the Letter of Intent to prepare a full proposal and present it at one of the forthcoming meetings of the PAC. …

INTRODUCTION

The proton electromagnetic form factor : $<r_p> = (0.74 \pm 0.24) \cdot 10^{-13}$ cm.

Proton is not an elementary particle but the object with an internal structure (50ties).

Point-like ***constituents*** have been discovered in the proton and called ***partons***, identified later with ***quarks.*** Quarks interact between themselves by ***gluon*** exchange. Gluons are also the nucleon's constituents. They can produce a ***sea*** of virtual quark-antiquark pairs. ***Partons share between themselves fractions, x, of the total nucleon momentum – PDFs. Parton Distribution Functions, depending also on Q^2, are universal characteristics of the internal nucleon structure***.

The quark-parton model (***QPM***) of nucleons, i.e. of the proton and neutron, has been born (70ties): 3 valence quarks & sea of quark-antiquarks.

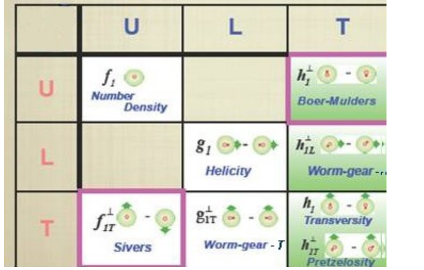
Basic twist-2 PDFs of the nucleons
(vertical – nucleon, horizontal – quark polarization)

N\q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm-gear - L
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear - T	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

T-odd

chiral-odd

Twist-2 PDFs of nucleons :



f_1 - ***density*** of partons in non-polarized nucleon, (x, Q^2);

g_1 - ***helicity*** , longitudinal polarization of quarks in longitudinally polarized nucleon;

h_1 - ***transversity***, transverse polarization of quarks in transversely polarized nucleon ;

$f^{\perp}_{1T}$ - ***Sivers,*** correlation between the transverse polarization of nucleon and the transverse momentum of non-polarized quarks;

$g^{\perp}_{1T}$ - ***worm-gear-T,*** correlation between the transverse spin and the longitudinal quark polarization ;

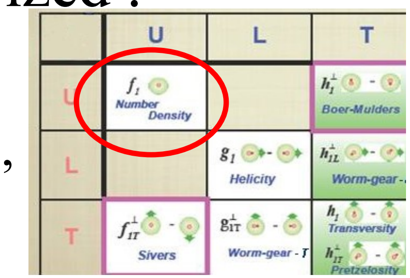
$h^{\perp}_{1}$ - ***Boer-Mulders,*** distribution of the quark transverse momentum in the non-polarized nucleon ;

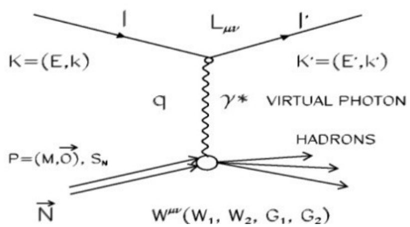
$h^{\perp}_{1L}$ - ***worm-gear-L,*** correlation between the longitudinal polarization of the nucleon (longitudinal spin) and the transverse momentum of quarks ;

$h^{\perp}_{1T}$ - ***pretzelosity,*** distribution of the transverse momentum of quarks in the transversely polarized nucleon ;

PDFs f_1 and g_1 (> 40 years of measurements)

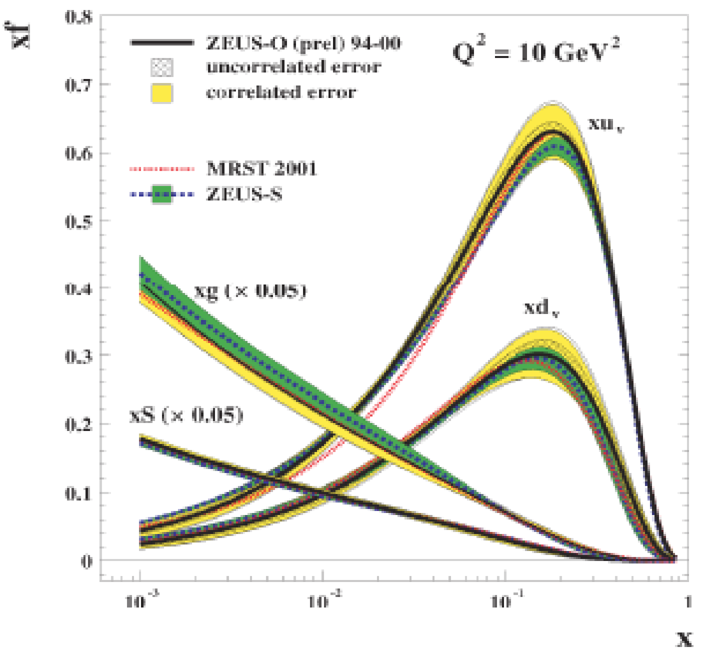
Measured from Inclusive Deep Inelastic lepton (l)-nucleon (N) Scattering (IDIS) : $l + N \rightarrow l' + X$, nucleon can be polarized .





$$\frac{d^2\vec{\sigma}^{S_e S_N}}{d\Omega dE'} = \frac{d^2\sigma^{unp}}{d\Omega dE'} + S_N S_e \frac{d^2\sigma^{pol}}{d\Omega dE'},$$

$$\sigma^{unp} \equiv \frac{d^2\sigma^{unp}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4 x} F_2(x,Q^2)\left[1 - y - \frac{y^2\gamma^2}{4} + \frac{y^2(1+\gamma^2)}{2(1+R(x,Q^2))}\right]$$

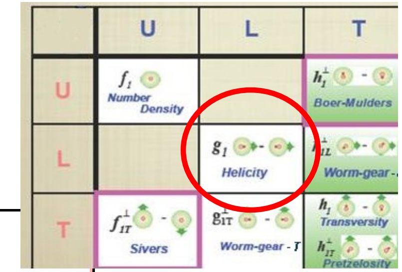


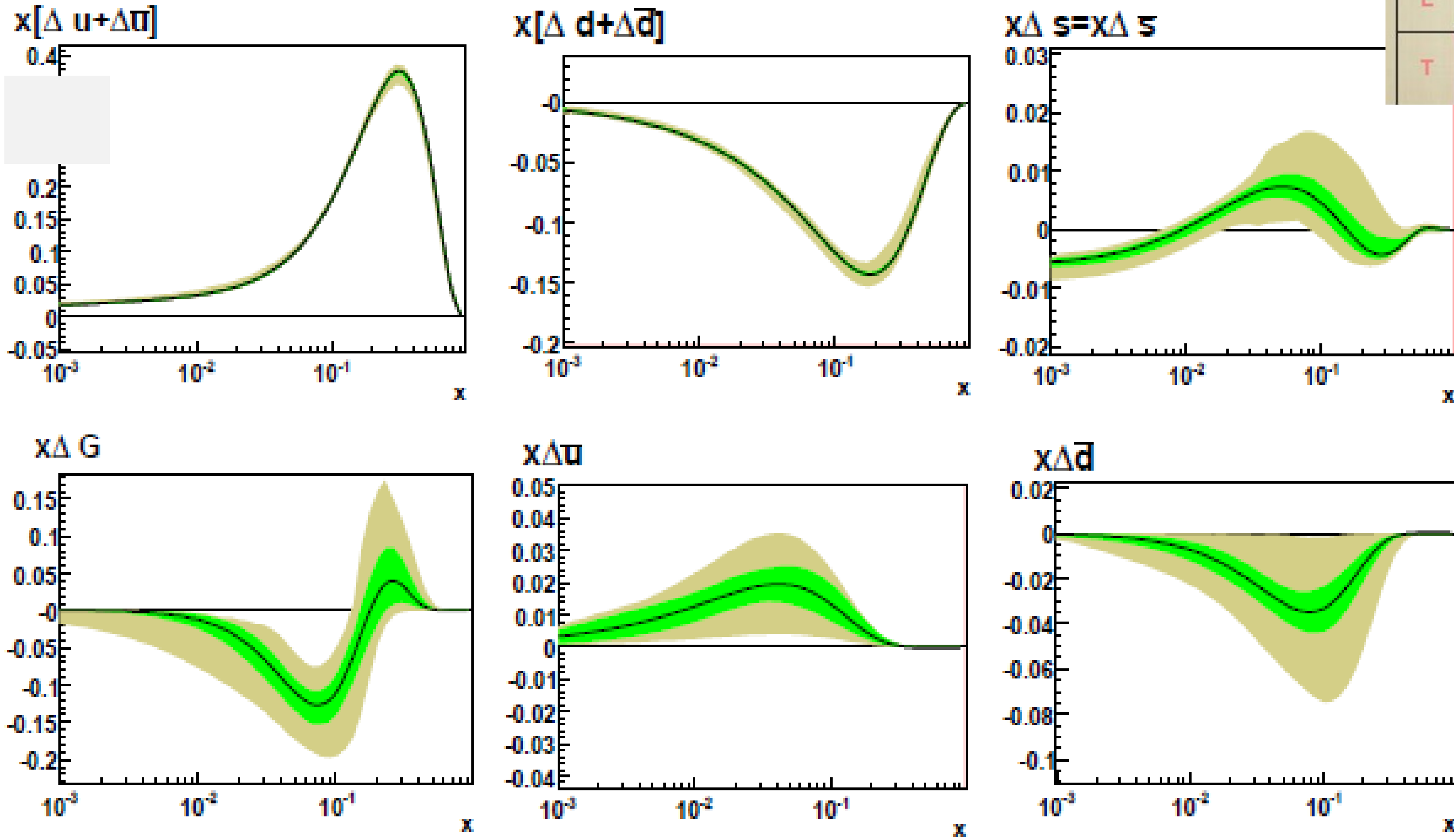
$R(x,Q2)$ and $F_2(x,Q^2)$ have been measured by the collaborations SLAC, EMC, BCDMS, NMC, ZEUS, H_1 and others. (with JINR participation)

In QCD:

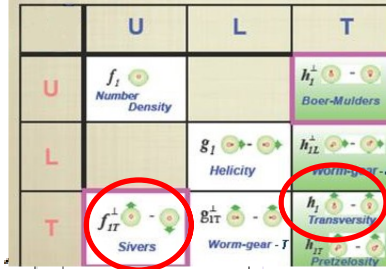
$F_2(x, Q^2) = x\sum_q e^2{}_q\, [\mathbf{q}(x, Q^2) + anti\text{-}\mathbf{q}(x, Q^2)],\ q=u, d, s.$

PDFs $f^a{}_1$ ($a \equiv q$) are determined from the QCD analysis of all IDIS data



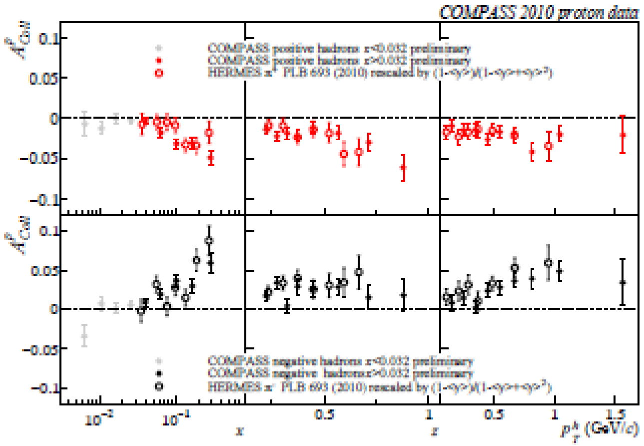


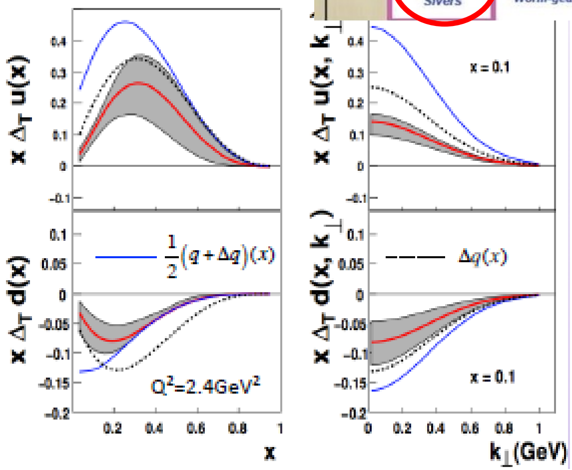
Parton helicity distributions in the longitudinally polarized nucleon at Q^2=3 GeV^2 as a function of x.



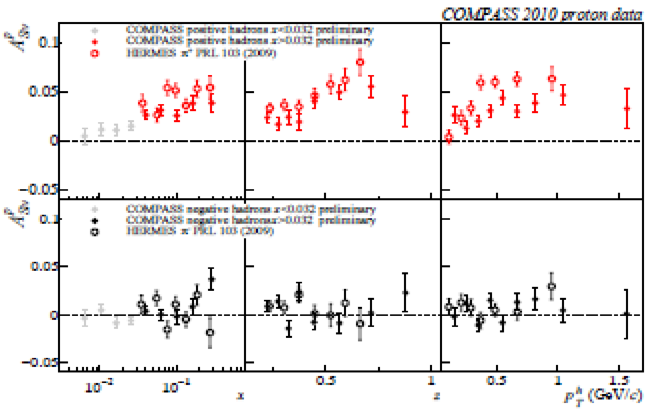
Transverse Momentum Dependent (TMD) PDFs

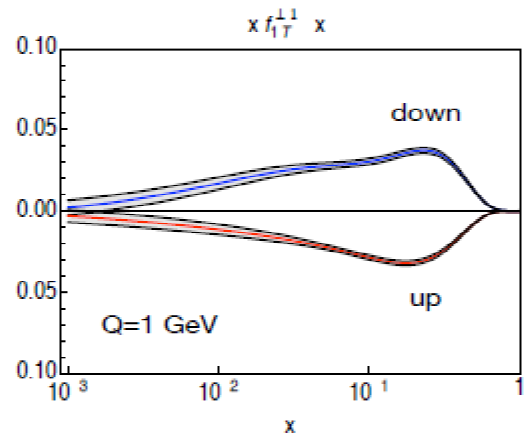
Transversity PDF h_1 ,
Measured recently





Sivers PDF $f^{\perp}_{1T}$.
Measured recently





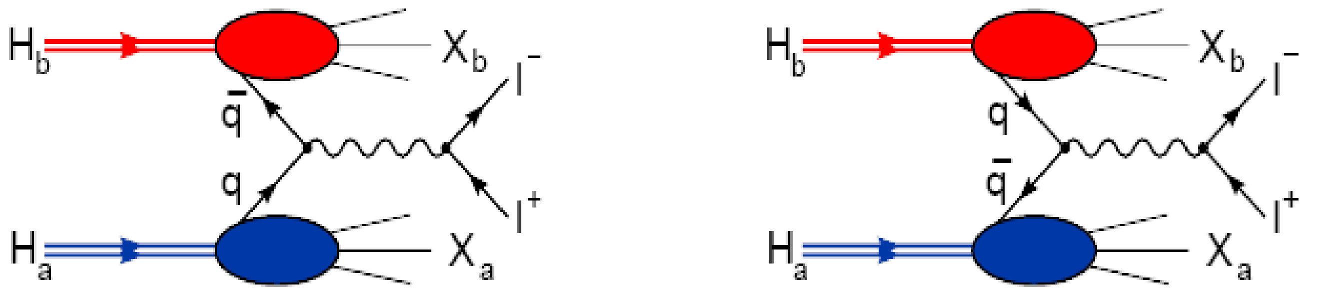
No data : *Pretzelosity PDF* $h^{\perp}_{1T}$ *Worm-gear-L* $h^{\perp}_{1L}$ *Worm-gear-T* $g^{\perp}_{1T}$ *Boer-Mulders* $h^{\perp}_{1}$

Physics motivations for NICA

1. Nucleon spin structure studies using the Drell-Yan mechanism.
2. Direct photons.
3. New nucleon PDFs and J/Ψ production mechanisms.
4. Spin-dependent high-p_T reactions.
5. Spin-dependent effects in elastic *pp* and *dd* scattering.
6. Spin-dependent reactions in heavy ion collisions.

Nucleon structure studies using the Drell-Yan mechanism.

$$H_a(P_a, S_a) + H_b(P_b, S_b) \to l^-(l, \lambda) + l^+(l', \lambda') + X \,,$$



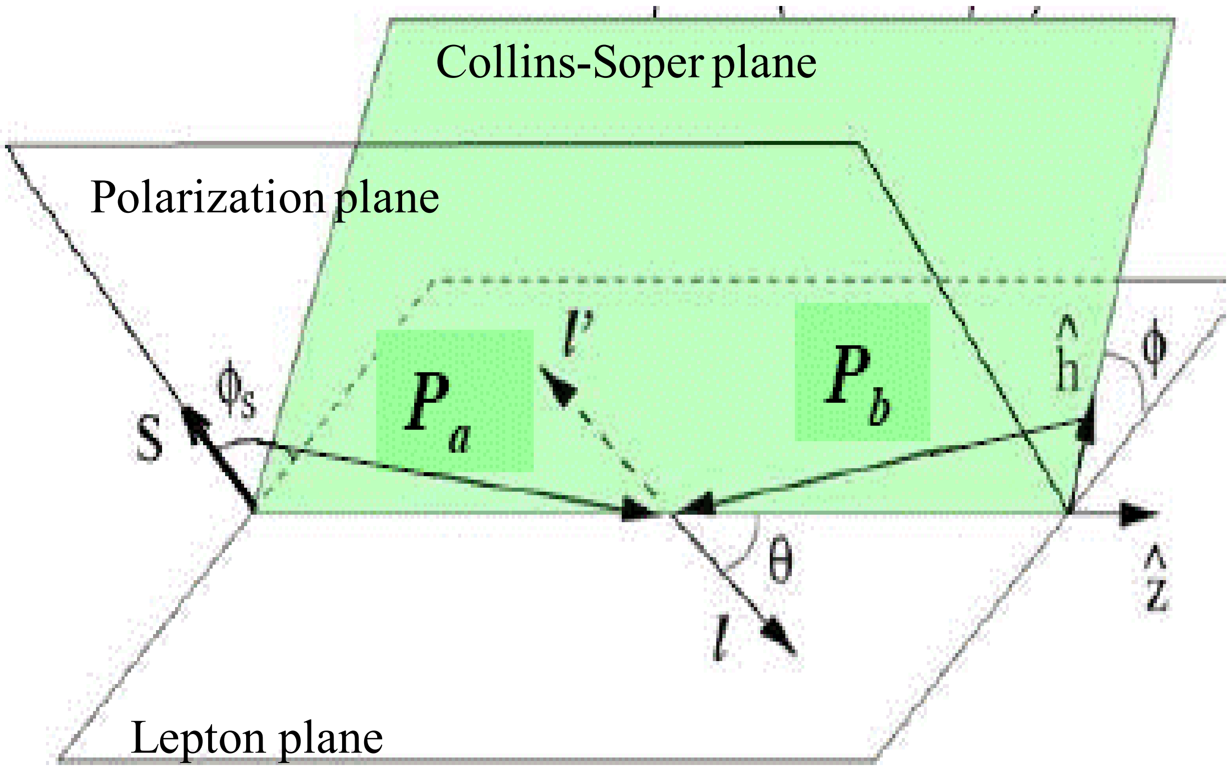
(a) (b)

$$C\left[w(\vec{k}_{aT},\vec{k}_{bT})f_1 f_2\right] \equiv \frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT} d^2\vec{k}_{bT} \delta^2(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT}) w(\vec{k}_{aT},\vec{k}_{bT}) \times$$

$$\left[f_{1q}(x_a,\vec{k}_{aT}^2) f_{2q}(x_b,\vec{k}_{bT}^2) + f_{1q}(x_a,\vec{k}_{aT}^2) f_{2q}(x_b,\vec{k}_{bT}^2)\right],$$

where k_{aT} (k_{bT}) is the transverse momentum of quark in the hadron H_a (H_b) and f_1 (f_2) is a TMD PDF of the corresponding hadron.

The kinematics of the Drell-Yan process is considered usually in the Collins-Soper (CS) reference frame [J.C. Collins, D.E. Soper, and G. Sterman, Nucl. Phys. B250, 199 (1985).]



Results of the most complete theoretical analysis of this process [S. Arnold, A. Metz and M. Schlegel, Phys.Rev. D79 (2009) 034005 [arXiv:hep-ph/0809.2262] are used .

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

$$
\begin{aligned}
&\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})\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_{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})\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\}
\end{aligned}
$$

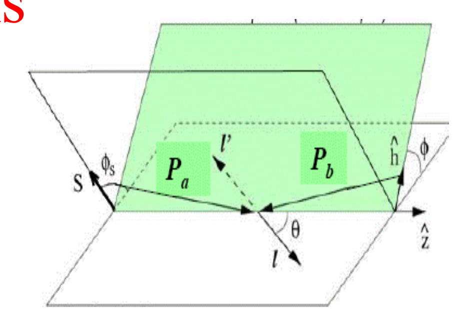
F_j^i are the SFs, depend on four variables $P_a \cdot q$, $P_b \cdot q$, $\boldsymbol{q_T}$ and q^2 or on $\boldsymbol{q_T}$, q^2 and the Bjorken variables of colliding hadrons, x_a, x_b ,

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

, y is the *cm* rapidity.

8 asymmetries to be measured: A_{LU}, A_{UL}, A_{TU} , A_{UT}, A_{LL}, A_{TL}, A_{LT}, A_{TT}

which include 23 modulations with amplitudes $A^{i}_{jk} = F^{i}_{jk} / F^{1}_{UU}$ normalized to unpolarized one.



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

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

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

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

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

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

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

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

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

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

$$+ A^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})}_{TT} \cos(2\phi-\phi_{S_a}+\phi_{S_b}) + A^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})}_{TT} \cos(2\phi+\phi_{S_a}-\phi_{S_b}) \Big)\Big] \qquad (2.1.10)$$

Applying the Fourier analysis to the measured asymmetries, one can separate each of all ratios $A^{i}_{jk} = F^{i}_{jk} / F^{1}_{UU}$.

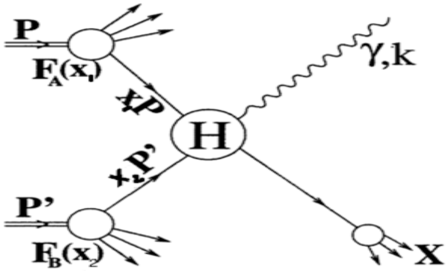
Extraction of different TMD PDFs from these ratios is a task of the global analysis since each of the SFs is a result of convolutions of different TMD PDFs in the quark transverse momentum space. For this purpose one needs either to assume a factorization of the transverse momentum dependence for each TMD PDFs, or to transfer them to impact parameter representation and to use the Bessel weighted TMD PDFs.

Advantages of Drell-Yan process

- The large number of independent structure functions (24 or 16 for identical hadrons)— indicates its high potential for studying TMDs.
- Certain advantage over semi-inclusive DIS being just sufficient to map out, in principle, all the eight leading twist TMDs for *q* and $\bar{q}$.
- There are no indefiniteness with fragmentation functions.
- Data on unpolarized $\pi^- N \rightarrow \mu^- \mu^+ X$ and unpolarised DIS show a rather large $\cos 2\phi$ – evidence for rather large Boer-Mulders function
- Together with rather large transversity h_1 this can give a clue to all other TMDs.
- Boer-Mulders and Sivers TMDs gives the possibility to check revers of sign -- the core of our present understanding of transverse single spin asymmetries.

Direct photons.

Direct photon productions in the non-polarized and polarized *pp (pd)* reactions provide information on the gluon distributions in nucleons

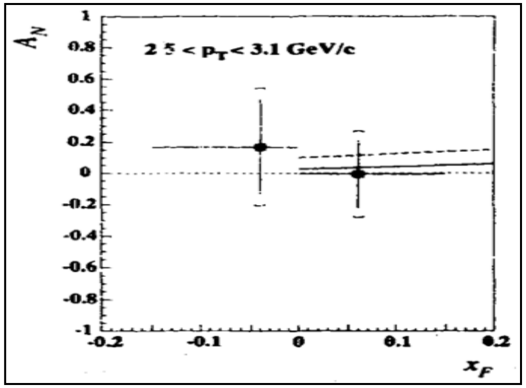


Vertex H corresponds to
$q + qbar \rightarrow \gamma + g$ *or* $g + q \rightarrow \gamma + q$ *hard processes.*

One can show that the polarized gluon distribution (Sivers gluon function) can be extracted from measurement of the transverse single spin asymmetry $A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$. It is of order few %.

Via double spin asymmetry A_{LL} one can measure a gluon polarization in the nucleon:

$$A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \cdot \left[\frac{\sum_q e_q^2 \left[\Delta q(x_2) + \Delta \bar{q}(x_2) \right]}{\sum_q e_q^2 \left[q(x_2) + \bar{q}(x_2) \right]} \right] \cdot \hat{a}_{LL}(gq \rightarrow \gamma q) + (1 \leftrightarrow 2),$$



List of the present and future DY experiments in the world.

Experiment	CERN, COMP.-II	FAIR, PANDA	FNAL, E-906	SPAS-CHARM	RHIC, STAR	RHIC, PHENIX	NICA, SPD
Mode	*Fixed Target*	*Fixed Target*	*Fixed Target*	*Fixed Target*	*Collider*	*Collider*	*C ollider*
Beam/target	*π- / p*	*anti-p / p*	*π- / p*	*π± / pol.p*	*pp*	*pp*	*pp, pd,dd*
Polarization:b/t	*0 / 0.8*	*0 / 0*	*0 / 0*	*0 / 0.5*	*0.5*	*0.5*	*0.9*
Luminosity	$2\cdot10^{33}$	$2\cdot10^{32}$	$3.5\cdot10^{35}$		$5\cdot10^{32}$	$5\cdot10^{32}$	10^{32}
√s, GeV	*19*	*6*	*16*	*8*	*200, 500*	*200, 500*	*10-26*
$x_{1(beam)}$ ***range***	*0.1-0.9*	*0.1-0.6*	*0.1-0.9*	*0.1-0.3*	*0.03-1.0*	*0.03-1.0*	*0.1-0.8*
q_T***, GeV***	*0.5 -4.0*	*0.5 -1.5*	*0.5 -3.0*		*1.0 -10.0*	*1.0 -10.0*	*0.5 -6.0*
Lepton pairs,	*μ-μ+*	*μ-μ+*	*μ-μ+*		*μ-μ+*	*μ-μ+*	*μ-μ+, e+e-*
Data taking	*2014*	*>2018*	*2013*		*>2016*	*>2016*	*>2018*
Transversity	NO	NO	NO		YES	YES	YES
Boer-Mulders	YES	YES	YES		YES	YES	YES
Sivers	YES	YES	YES		YES	YES	YES
Pretzelosity	YES (?)	NO	NO		NO	YES	YES
Worm Gear	YES (?)	NO	NO		NO	NO	YES
J/Ψ	YES	YES	NO		NO	NO	YES
Flavour separation	NO	NO	YES		NO	NO	YES
Direct γ	NO	NO	NO		YES	YES	YES

Requirements to the NUCLOTRON-NICA complex.

Beams. The following beams will be needed, polarized and non-polarized:

$pp, pd, dd, pp\uparrow, pd\uparrow, p\uparrow p\uparrow, p\uparrow d\uparrow, d\uparrow d\uparrow.$

Beam polarizations both at MPD and SPD: longitudinal and transversal. Absolute values of polarizations should be 90-50%. The life time of the beam polarization should be long enough, ≥24h. Measurements of Single Spin and Double Spin asymmetries in *DY* require running in different beam polarization modes: *UU, LU, UL, TU, UT, LL, LT and TL* (spin flipping for every bunch or group of bunches should be considered).

Beam energies: $p\uparrow p\uparrow(\sqrt{s_{pp}}) = 12 \div \geq 27$ GeV (5 ÷ ≥12.6 GeV kinetic energy),

$d\uparrow d\uparrow(\sqrt{s_{NN}}) = 4 \div \geq 13.8$ GeV (2 ÷ ≥5.9 GeV/u ion kinetic energy).

Asymmetric beam energies should be considered also.

Beam luminosities: in the *pp* mode: $L_{average} \geq 1\cdot10^{32}$ cm^{-2}s^{-1} (at $\sqrt{s_{pp}} = 27$ GeV),

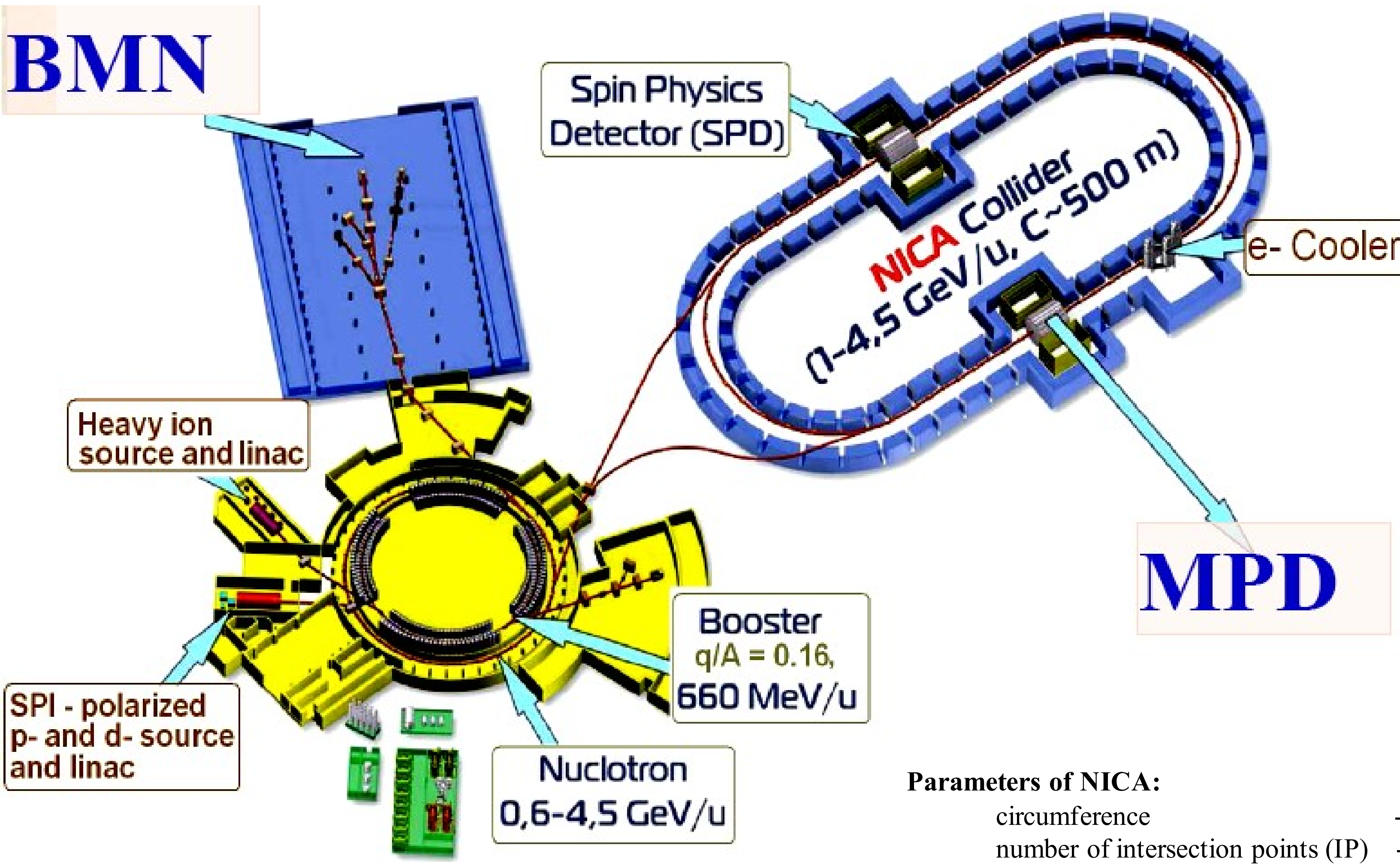
in the *dd* mode: $L_{average} \geq 1\cdot10^{30}$ cm^{-2}s^{-1} (at $\sqrt{s_{NN}} = 14$ GeV).

Polarized beams at NICA.

The NICA complex at JINR has been approved in 2008 assuming two phases of construction.

The first phase, realizing now, includes construction of facilities for heavy ion physics program - MPD.

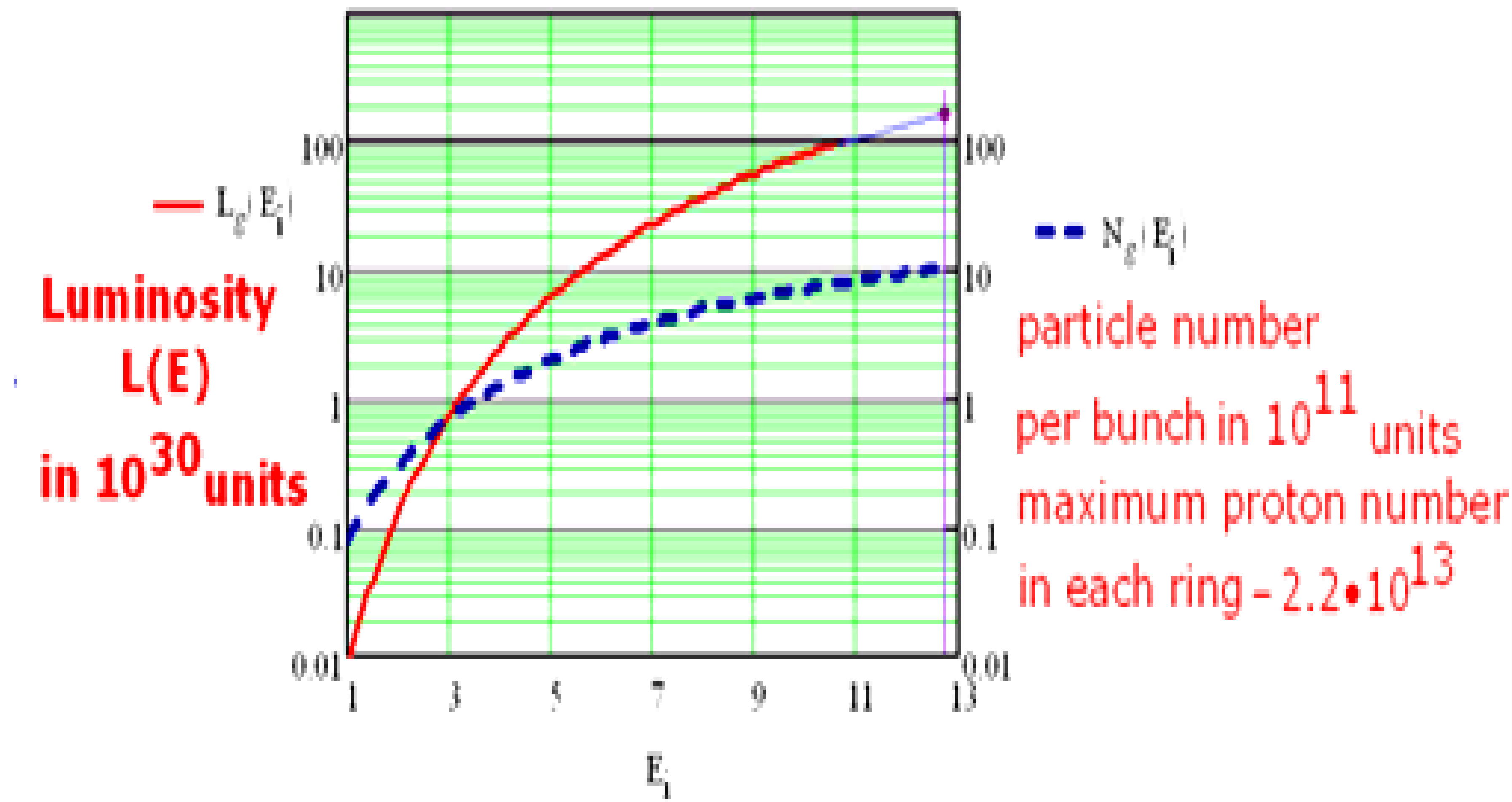
The second phase should include facilities for the program of spin physics studies with polarized protons and deuterons.



Parameters of NICA:

circumference	- 503 m,
number of intersection points (IP)	- 2,
beta function β_{min} in the IP	- 0.35 m,
number of protons per bunch	- $\sim 1\cdot 10^{12}$,
number of bunches	- 22,
RMS bunch length	- 0.5 m,
bunch crossing rate	~ 1/60 ns

.



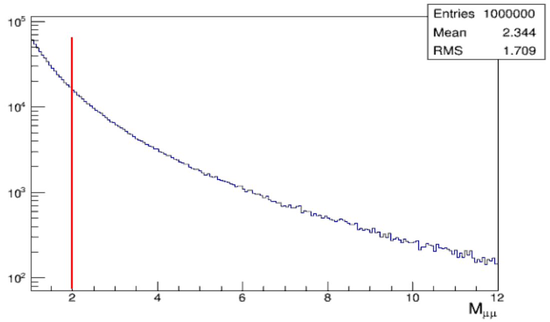
The number of particles reaches a value about $2.2{\cdot}10^{13}$ in each ring and the peak luminosity $L_{peack} = 2{\cdot}10^{32}$ $cm^{-2}s^{-1}$ at 12.7 GeV.

Feasible schemes of manipulations with polarized protons and deuterons at Nuclotron and NICA are suggested. The final scheme will be approved at the later stages of the project.

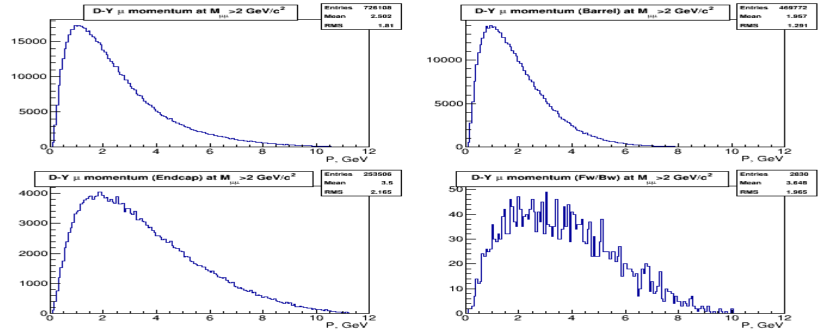
Requirements to the spin physics detector (SPD).

1. Event topologies.
2. Possible layout of SPD.
3. Trigger system.
4. Local polarimeters and luminosity monitors.
5. Engineering infrastructure.
6. DAQ.
7. SPD reconstruction software.
8. Monte Carlo simulations.
9. Slow control.
10. Data accumulation, storing and distribution.

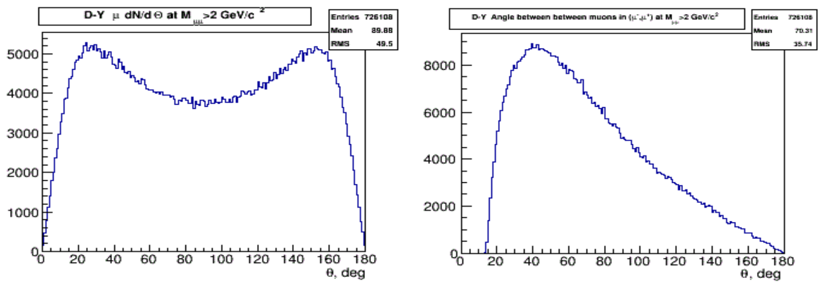
D-Y and direct photons kinematical parameters



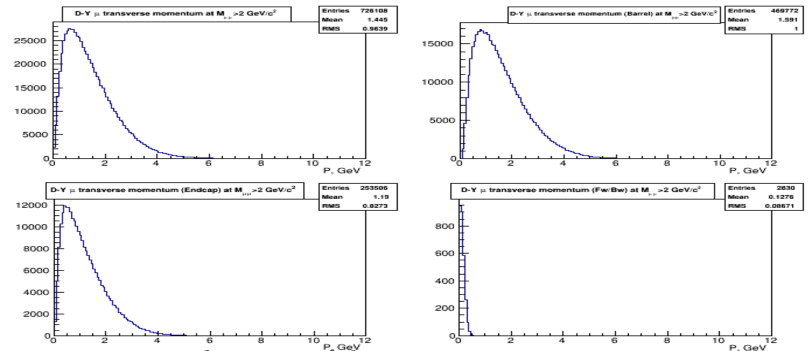
Invariant mass distributions of di-muons.



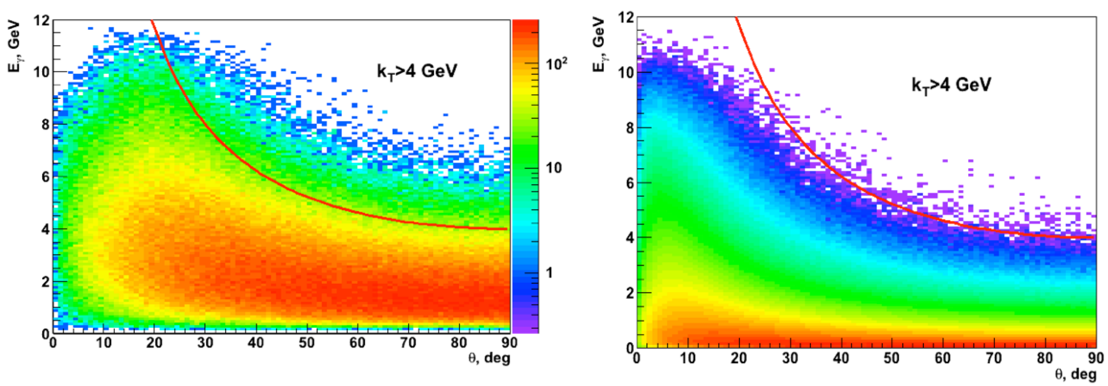
*Distributions of single muon momentum ffor different angular intervals . **Upper:** left- all angles; right - $35^0 \div 145^0$. **Bottom:** left- $3^0 \div 35^0$, right - $0^0 \div 3^0$.*



Left – distribution of events as a function of the single muon polar angle.
Right: the opening angle between two muons.



Distributions of the muon transverse momentum .
Upper: left- all angles; right - $35^0 \div 145^0$.
Bottom: left - $3^0 \div 35^0$; right - $0^0 \div 3^0$.



Distribution of energy E_γ as a function of scatt. angle θ: left - direct photons, right - minimum bias photons. Red lines correspond to the cut $p_T > 4$ GeV.

The conclusions

from brief estimation of the kinematical variables ranges:

The detector should be able to register:

electrons and muons
in the momentum range from 0.1 Gev/c to 10 GeV/c and

photons up to 10 GeV energy

SPD layout.

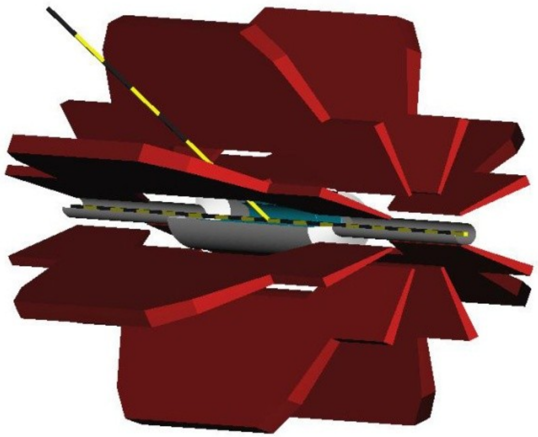
Preliminary considerations of the event topologies have required SPD to be equipped with the sub-detectors covering ~4π angular region around the beams intersection point:
vertex detectors (VD),
tracking detectors (TD),
electromagnetic calorimeters (ECAL),
hadron detectors (HD) ,
muon detectors (MD),

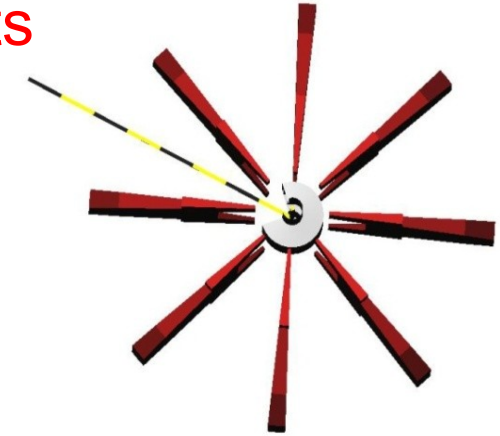
VD, TD and ECAL must be in the magnetic field.

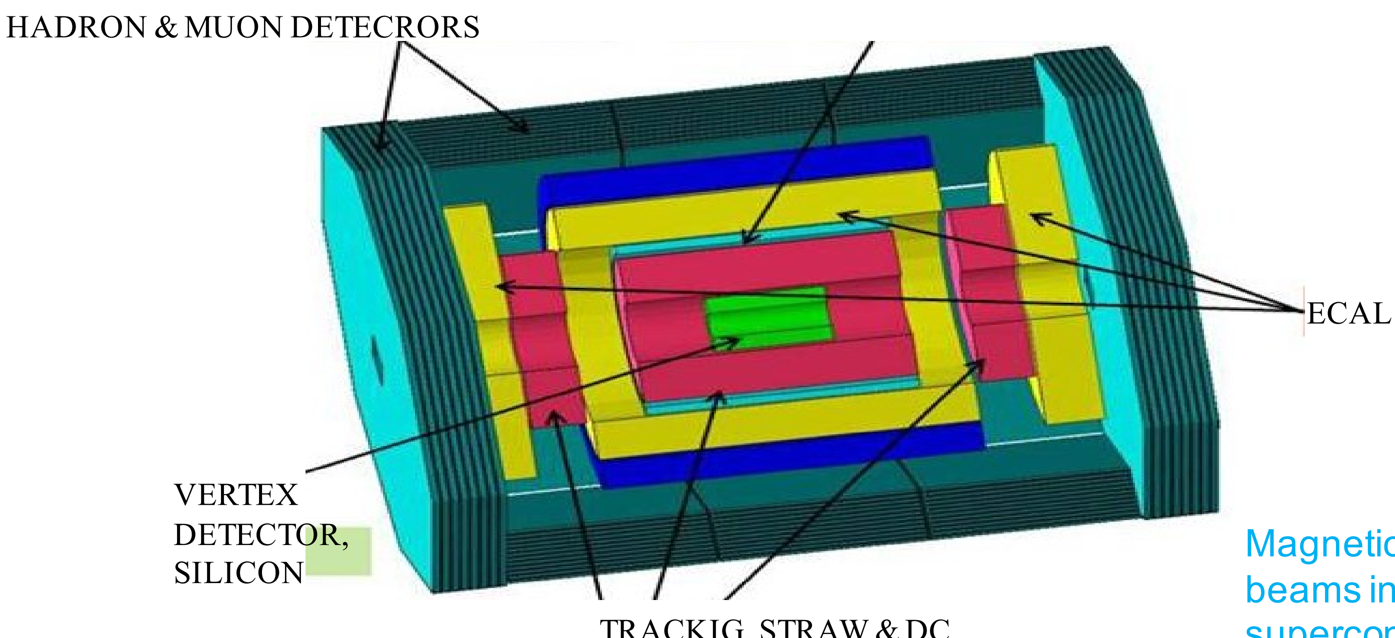
Prototypes of all sub-detectors exist or under development.

There are two options for the magnet: toroid or solenoid.

Magnets







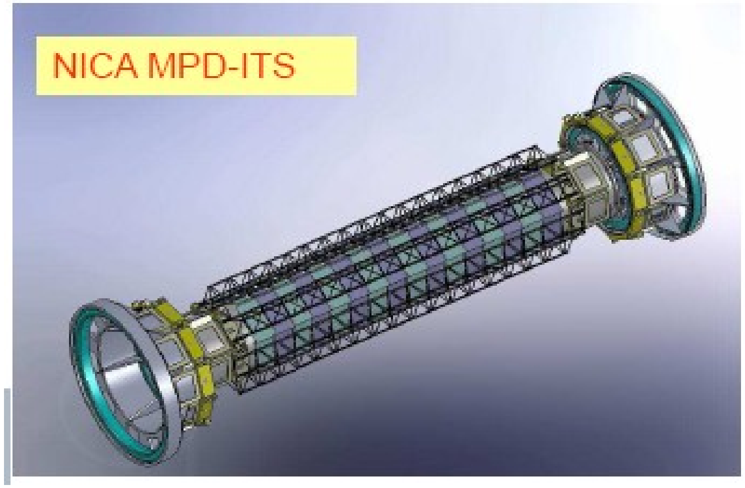
Magnetic vacuum in the beams interaction region – superconducting screen

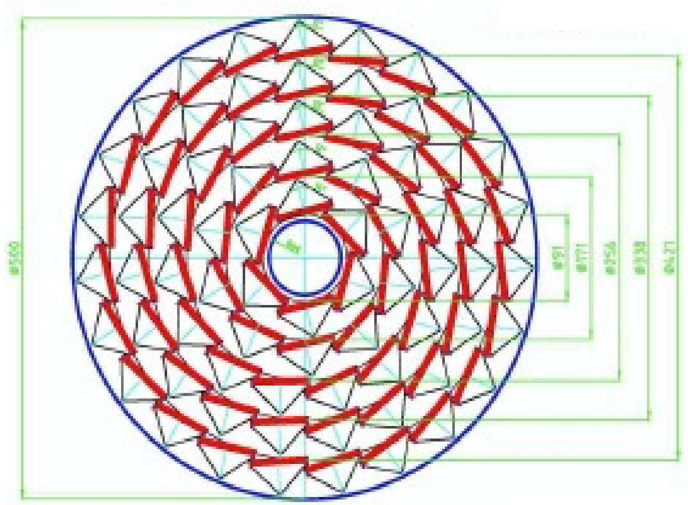
The “almost 4π geometry” requested by DY and direct photons can be realized in the solenoid version of SPD if it has overall length of about 6 m and radius ~ 1.7m.

B = 0.5 T

Vertex detector.

The most obvious version of vertex detector (VD) is a silicon one. Several layers of double -sided silicon strips can provide a precise vertex reconstruction and tracking of the particles before they reach the general SPD tracking system. The design should use a small number of silicon layers to minimize the radiation length of the material. With a pitch of 50-100 μm it is possible to reach a spatial resolution of 20-30 μm. Such a spatial resolution would provide 50-80 μm for precision of the vertex reconstruction. This permits to reject the secondary decay vertexes.





To minimize a background in the DY dimuon sample from π- μ decays, the first detection plane of VD should be as close to the beam as possible.

Tracking.

There are several candidates for a tracking system: conventional drift chambers (DC) and their modification – thin wall drift tubes (straw chambers).
The DCs are the good candidates for tracking detectors in the end cup parts of SPD,
while straw chambers are the best for the barrel part.

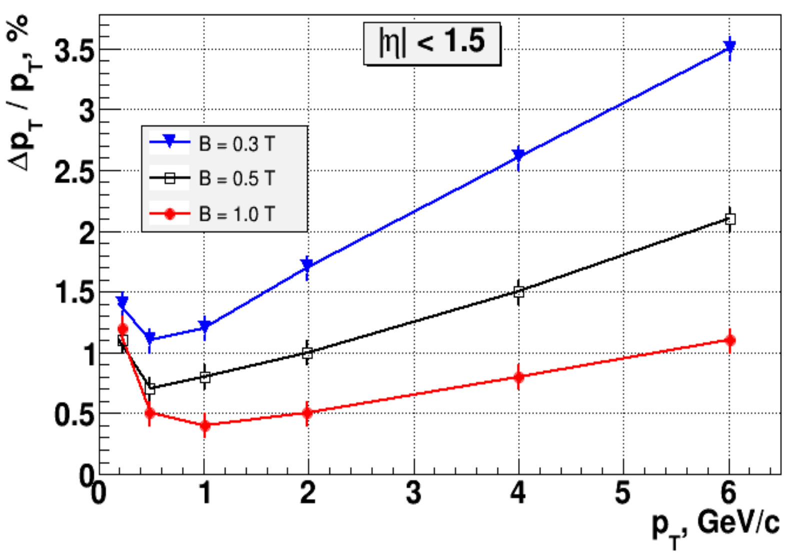
Two groups have developed the technology of straw chamber production at JINR with two-coordinate reed out.

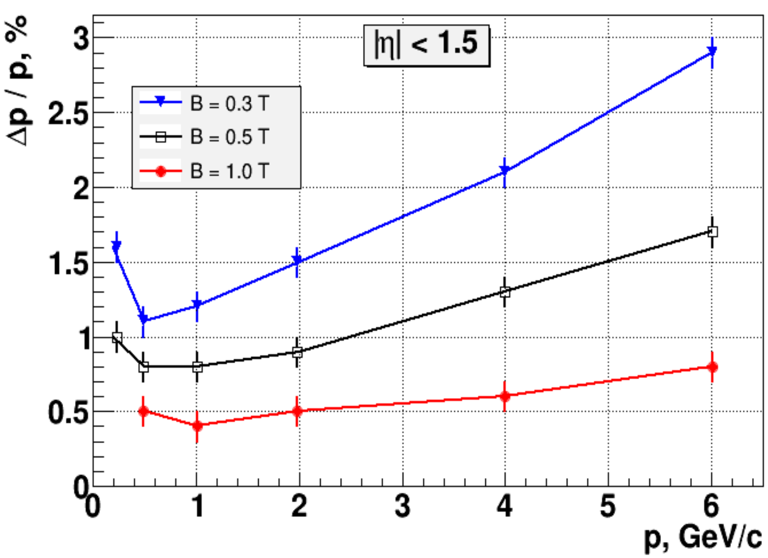
Estimation of Inner Detector momentum resolutions

GEOMETRY: **total coverage η<1,5**

vertex detector: 5 layers of silicon strips
resolutions: σ_φ = 20 μм, σ_Z = 320 μм;

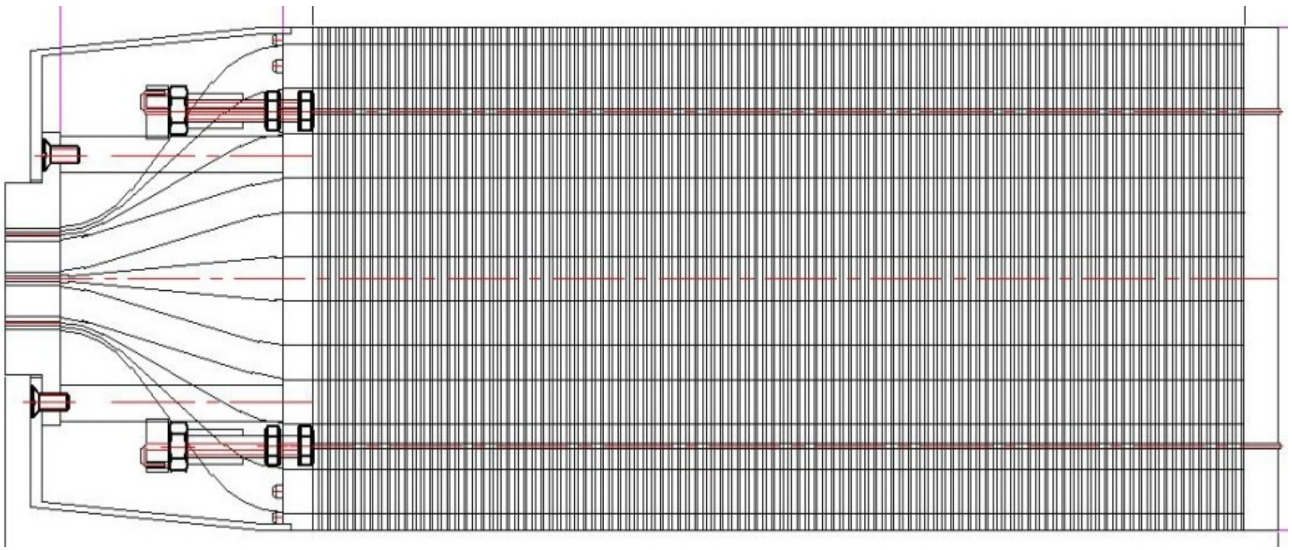
straw tubes : barrel region – 35 layers, 30cm<R<170cm
end-cap region - 10 layers, 175cm<Z<400cm
resolutions: $\sigma_{\phi,R}$ = 170 μм;





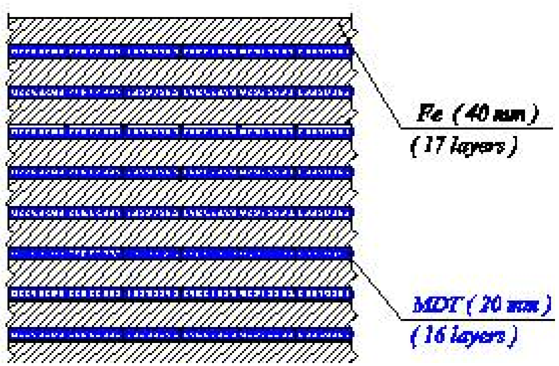
Electromagnetic calorimeters.

The latest version of the electromagnetic calorimeter (ECAL) module, developed at JINR for the COMPASS-II experiment at CERN, can be a good candidate for ECAL in the barrel and in the end cup parts of SPD. The module utilises new photon detector – Avalanche Multichannel Photon Detector (AMPD). AMPD can work in the strong magnetic field.



Hadron (muon) detectors

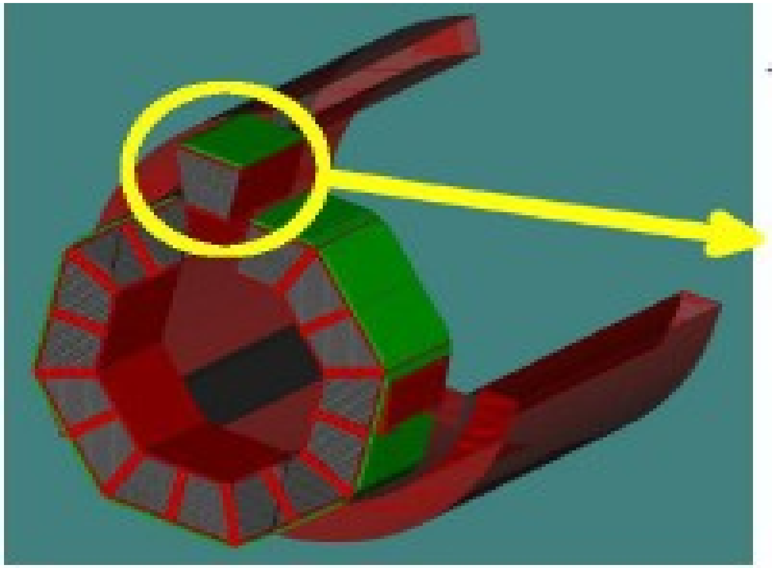
A system of mini-drift chambers interleaved with layers of iron and called the Range System (RS) is developed at JINR for FAIR/PANDA . It can be used in the barrel part of SPD as a hadron and (or) muon detector

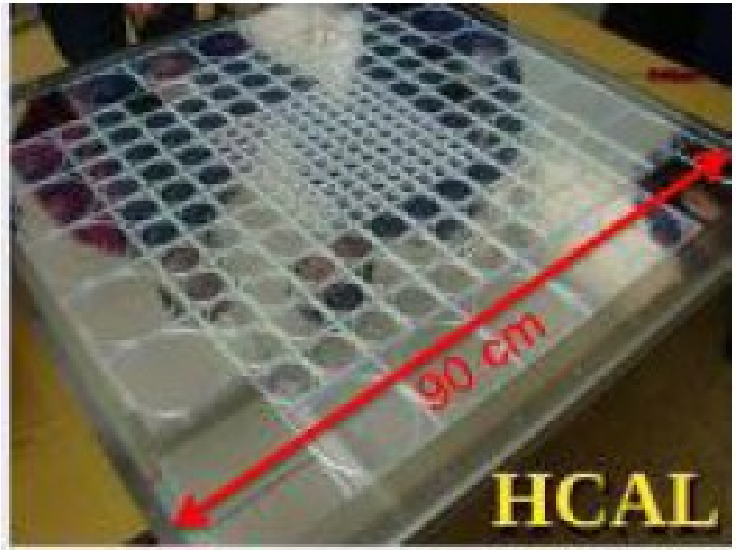


The hadron and muon detectors in the end caps part of SPD are to be identified. As candidates for these detectors, the COMPASS muon wall [9] can be considered. It consists of two layers of mini-drift chambers with a block of absorber between them. A calorimeter version is also suggested.

Hadron (muon) detectors

The more elegant system for hadron and muon detectors of SPD can be constructed using calorimeters. It is suggested recently for the future linear collider. The prototype of the calorimeter module is under the tests. The module includes an electromagnetic and hadron parts. The hadron part consists of the 38 layers of iron (20mm) and scintillator (5mm) plates. The scintillator plate includes 216 tiles of 3x3, 6z6 and 12x12 cm. The light collection is performed with WLS fibers to the silicon PM with 1156 pixels and gain of ~10^5. This type calorimeters can be used both in the barrel and end cup parts of SPD, as well as in trigger system and as internal monitors of the beam polarization.





Physics motivations for NICA

1. Nucleon spin structure studies using the Drell-Yan mechanism.
2. Direct photons.
3. New nucleon PDFs and J/Ψ production mechanisms.
4. Spin-dependent high-p_T reactions.
5. Spin-dependent effects in elastic *pp* and *dd* scattering.
6. Spin-dependent reactions in heavy ion collisions.

The data within the run with the given beams have to be accumulated for all possible physical processes - > requirements for the triggering system

The possible SPD trigger scheme
(based on the ATLAS experience)

Multilevel trigger approach - 3

-Level 1

+ hardware based , programmable menue
+ coarse granularity only calorimeter and muon system used
- > RoI

- High level trigger
  + software based
  + commercial hardware

-Level 2

+ full detector granularity in RoIs

-**Event filter**

+ full detector granularity
+ offline analysis algorithms

Decreasing events rate from ~ 4 MHz up to ~ 200 Hz not loosing events of interest. Depends from event size and store capacity.
The time for analysis at the next level is increasing.
Pipe-lining of information from the given bunch crossing

Scenario of data taking

To measure quantities which are known already to make sure that detector is working properly - U and L (f_1 and g_1)

N\q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm-gear - L
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear - T	h_1 Transversity; $h_{1T}^{\perp}$ Pretzelosity

T-odd

chiral-odd

CONCLUSIONS

1. The comprehensive program of the spin nucleon structure and other spin dependent reactions study is suggested. It can be realized at NICA using the polarized proton, deuteron and heavy ion beams and specialized SPD detector.

2. The program is supported by a number of Laboratories and the world leading experts.

3. The International collaboration can be organized for preparations of the Proposal.

4. Text of the LoI is at http://arxiv.org/abs/1408.3959

Thank you very much
for your attention !!!

Back up slides

More general and exciting relation:

In **all** mentioned models:

$$g_1^q(x) - h_1^q(x) = h_{1T}^{\perp(1)q}(x)$$

'measure' of relativistic effects **= pretzelosity!**

Valid at low scale in large class of relativistic models,
not valid in models with gluons (Meissner, Metz, Goeke 2007),
not valid in QCD (all TMDs independent, not preserved by evolution).

More important is possible access to quark orbital momentum!

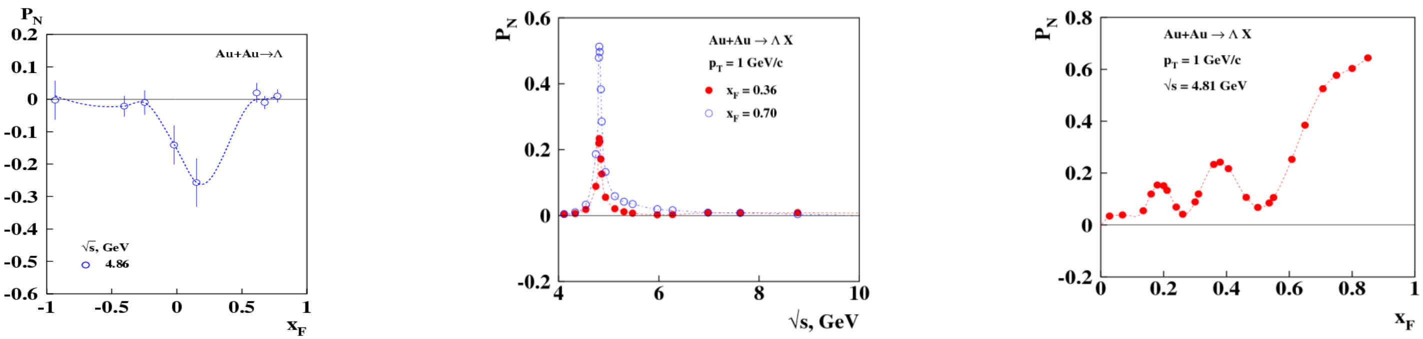
(J.She, J.Zhu,B.Ma, PRD79 (09)054008,
Bag model (Avakian, AE, Schweitzer,Yuan PRD81:074035,2010), Zavada model PoS DIS2010 253

$$L^q(x,\vec{p}_T^{\,2}) = h_1^q(x,\vec{p}_T^{\,2}) - g_1^q(x,\vec{p}_T^{\,2}) = -h_{1T}^{\perp(1)q}(x,\vec{p}_T^{\,2})$$

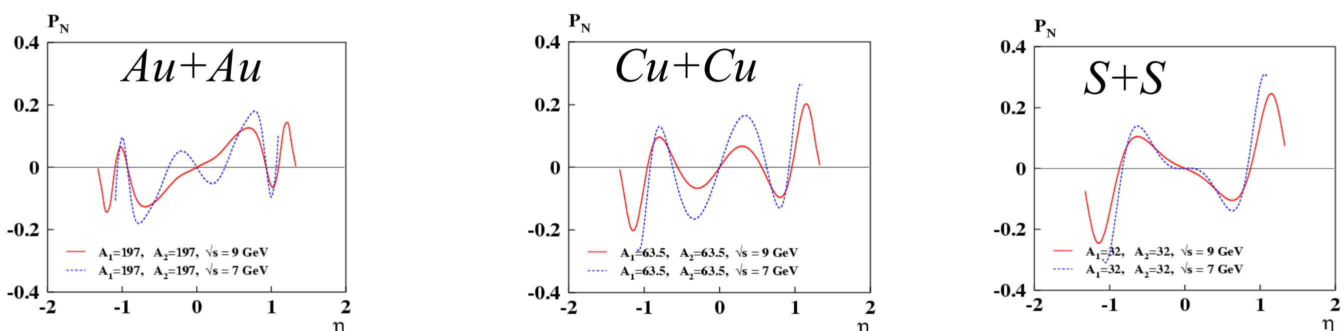
B.Pasquini et al. (LCQCModel) – true only for P_T-integrated

2.6. Spin-dependent reactions in heavy ion collisions

2.6.1. Inclusive particle polarizations in pp, pd and heavy ion collisions



Transverse polarization P_N vs. x_F of Λ from the reaction $Au+Au \rightarrow \Lambda^{\uparrow}+X$ at RHIC

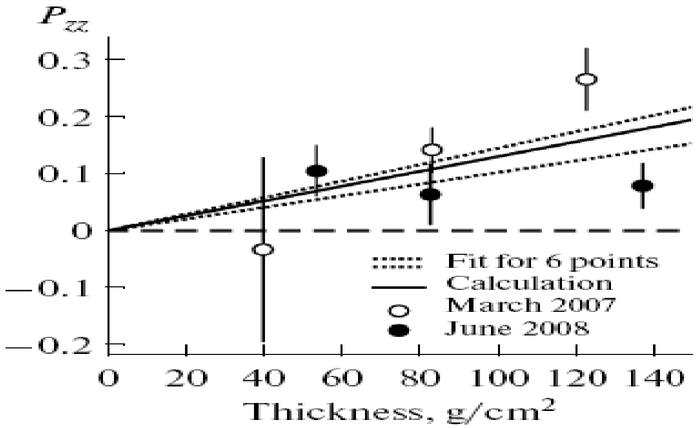


Predictions for P_N vs. pseudo rapidity η for the reaction $A_1+A_2 \rightarrow \Lambda^{\uparrow}+X$ at $\sqrt{s}$=7 and 9 GeV

Systematic studies of inclusive transverse polarizations of hyperons and vector mesons vs. kinematic variables, energy and atomic weight of colliding beam can be performed at SPD and MPD.

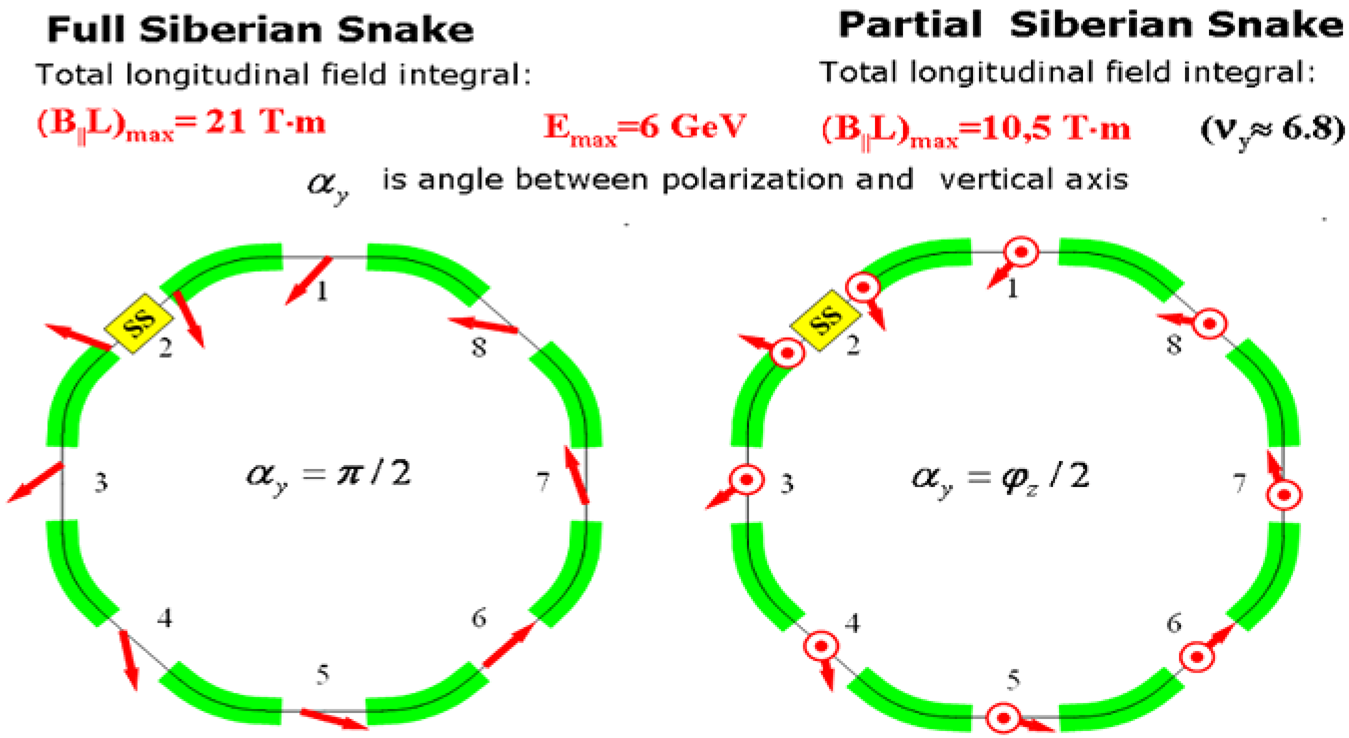
2.6.2. Investigation of the birefringence phenomenon at NICA facility.

Birefringence occurs when spin $S \geq 1$ non-polarized particles pass through isotropic non-polarized matter and is due to the inherent anisotropy of these particles. For example, the tensor polarization, acquired by the non-polarezed deuterons passing through the non-polarized carbon targets, was observed at Nuclotron.



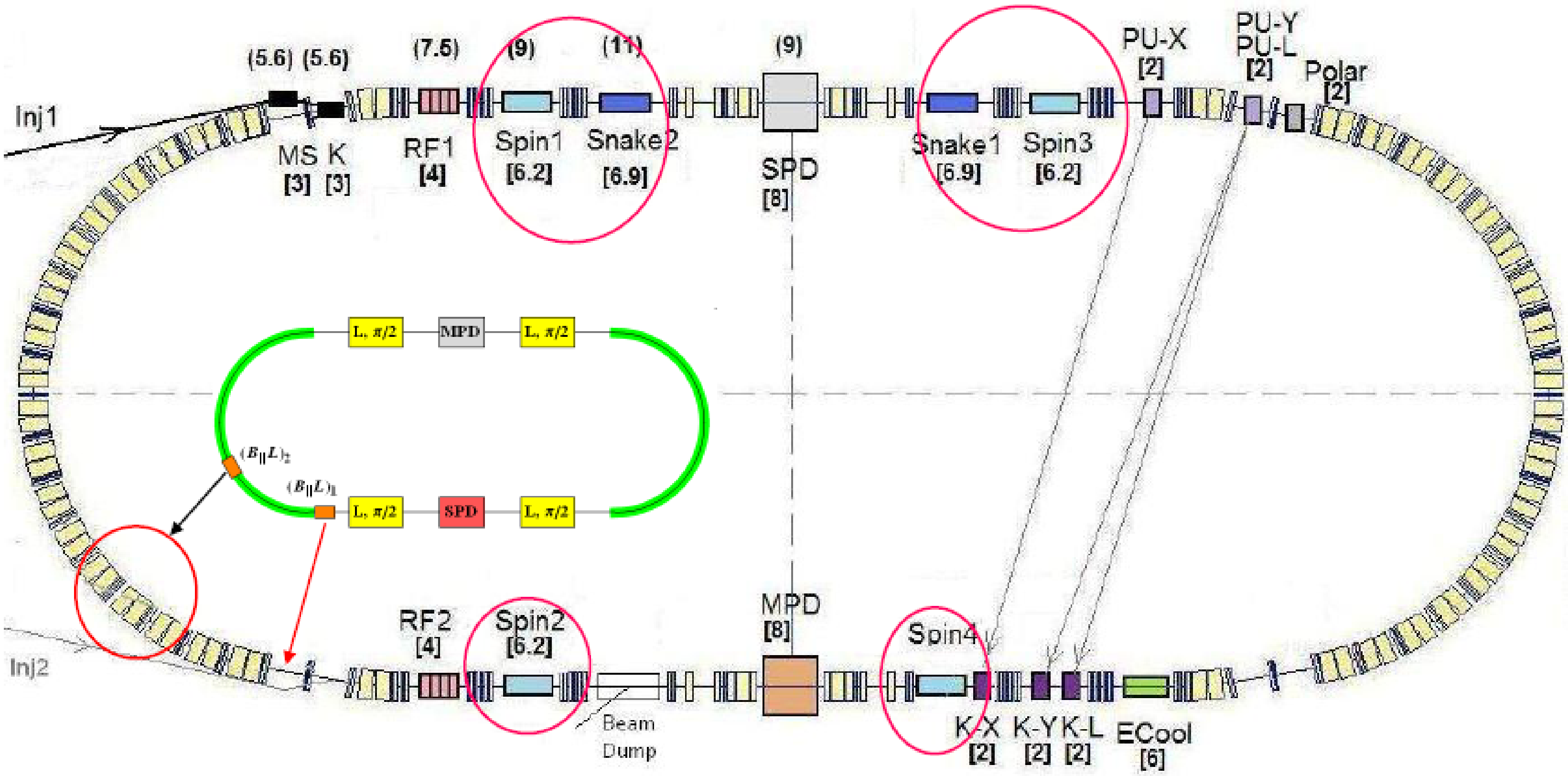
The birefringence phenomena can be further studied at Nuclotron and NICA:
- in few-nucleon systems involving protons and deuterons;
- appearing through the interaction of protons or deuterons with heavy nuclei;
- for heavy nuclei with spin $S \geq 1$.
- with vector particles produced in inelastic collisions.

Proton spin dynamics in the Nuclotron ring in the case of a full or partial snake working synchronously with accelerating cycle



Polarized deuterons acceleration in Nuclotron is possible up to the energy of 5.6 GeV/u

Possible NICA structure for polarized proton and deuteron beams



7. Time lines of the Project

If LoI will be approved by PAC and the JINR Directorate, the corresponding Proposal could be prepared by the end of 2015.

6. Proposed measurements with SPD.

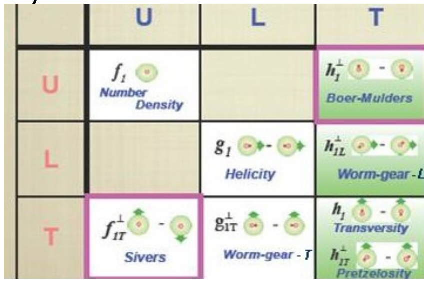
6.1. Estimations of DY and J/Ψ production rates.
6.2. Estimations of direct photon production rates.

We propose to perform measurements of asymmetries of the DY pairs production in collisions of polarized protons and deuterons (Eqs.2.1.0) which provide an access to all collinear and TMD PDFs of quarks and anti-quarks in nucleons.
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.

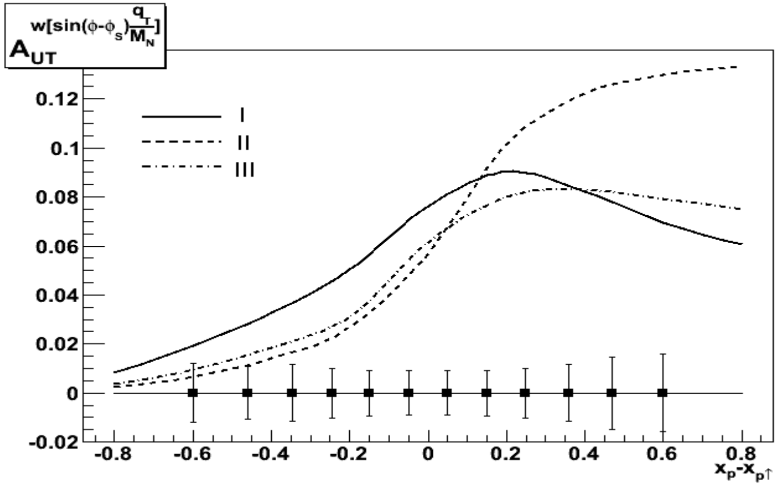
The measurements of asymmetries in production of J/Ψ and direct photons as well as measurements of other reactions mentioned in LoI will be performed simultaneously with DY using dedicated triggers.

6.1. Estimations of DY production rates

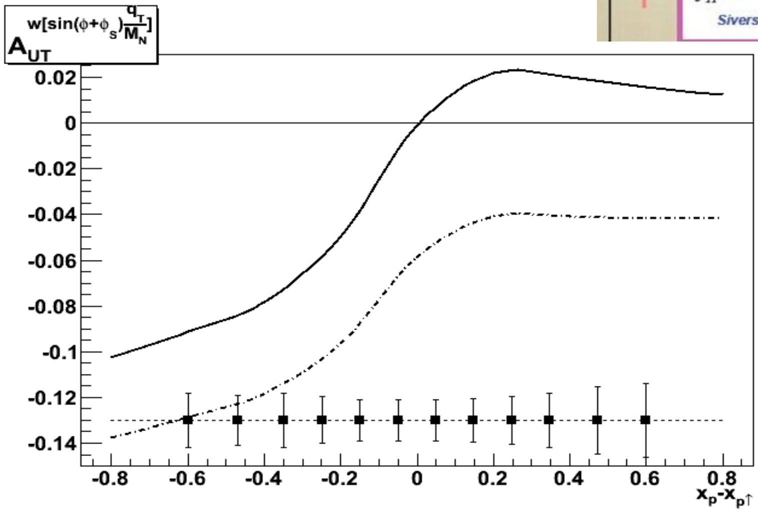
To estimate the precision of measurements, the set of original software packages for MC simulations, including generators for Sivers , Boer-Mulders and Transversity PDFs were developed. With these packages we have generated a sample of 100K DY events (~ 1 year of data taking) for comparison with expected asymmetries.



Sivers



Boer-Mulders



6.2. Estimations of direct photon production rates.

$\sqrt{s}$=24 GeV $L = 1.0 \times 10^{32},\ cm^{-1}s^{-1}$	σ_{tot}, nbarn	$\sigma_{P_T>4\ GeV/c}$, nbarn	Events/year, 10^6	Events/year, 10^6 $(P_T > 4\ GeV/c)$
All processes	1290	42	3260	105
$qg \to q\gamma$	1080	33	2730	84
$q\bar{q} \to g\gamma$	210	9	530	21

$\sqrt{s}$=26 GeV $L = 1.2 \times 10^{32},\ cm^{-1}s^{-1}$	σ_{tot}, nbarn	$\sigma_{P_T>4\ GeV/c}$, nbarn	Events/year, 10^6	Events/year, 10^6 $(P_T > 4\ GeV/c)$
All processes	1440	48	4340	144
$qg \to q\gamma$	1220	38	3680	116
$q\bar{q} \to g\gamma$	240	10	660	28

A_N and A_{LL} could be measured at SPD with statistical accuracy ~0.11% and ~0.18%, respectively, in each of 18 x_F bins (-0.9< x_F < +0.9).

Introduction. 1.2. PDFs f_1 and g_1

Measured from σ^{pol} separated off σ^{tot} in so-called *asymmetries.*

g_1 The cross sections difference, $\Delta\sigma_{//}$, for two opposite longitudinal target polarizations is given by the expression:

$$\Delta\sigma_{//} \equiv \Delta\left(\frac{d^2\sigma_{//}^{pol}}{dxdQ^2}\right) = \frac{16\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{y^2\gamma^2}{4}\right)g_1 - \frac{y\gamma^2}{2}g_2\right],$$

connected with the longitudinal asymmetry, $A_{//}$, defined as

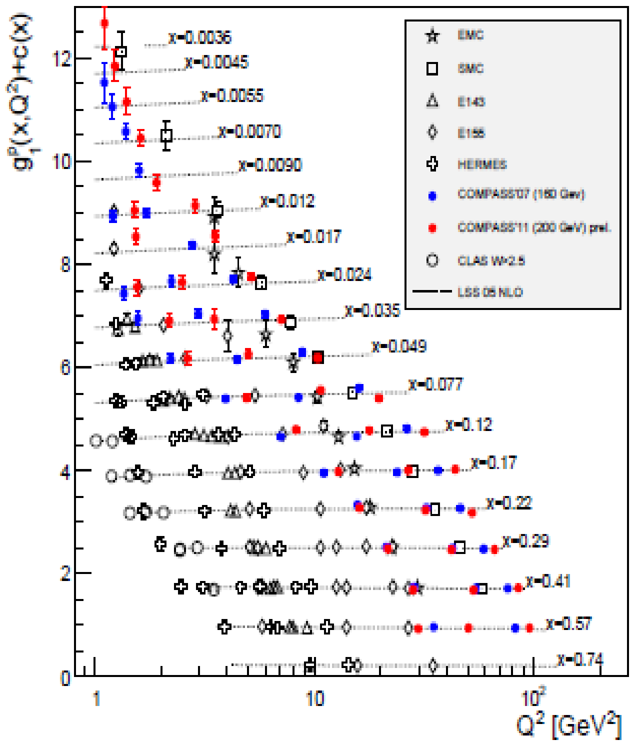
$$A_{//} = \frac{\Delta\sigma_{//}}{2\sigma^{unp}} = \frac{\sigma^{\rightarrow\Rightarrow} - \sigma^{\rightarrow\Leftarrow}}{\sigma^{\rightarrow\Leftarrow} + \sigma^{\rightarrow\Rightarrow}}$$

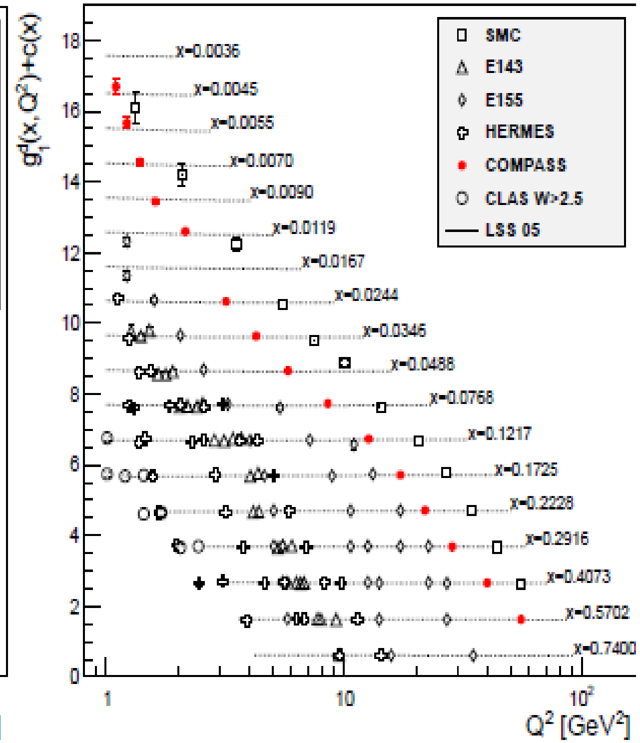
which, in the first approximation, related to g_1:

$$A_{//}/D \approx A_1 \approx (g_1 - \gamma^2 g_2)/F_1 \approx g_1/F_1,$$

The QPM expression for virtual photon asymmetry A_1:

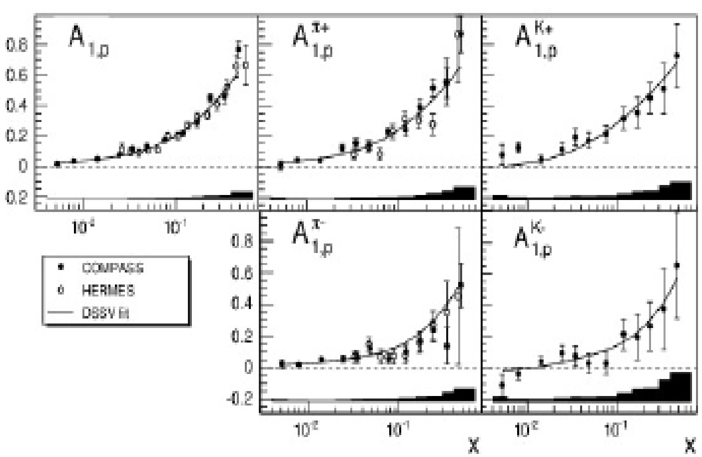
$$A_1^p = \frac{\sigma_{1/2}^p - \sigma_{3/2}^p}{\sigma_{1/2}^p + \sigma_{3/2}^p} = \frac{\sum e_i^2\left[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)\right]}{\sum e_i^2\left[q_i^{\uparrow}(x) + q_i^{\downarrow}(x)\right]} \qquad g_1(x) = \sum_i e_i^2\left[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)\right]$$

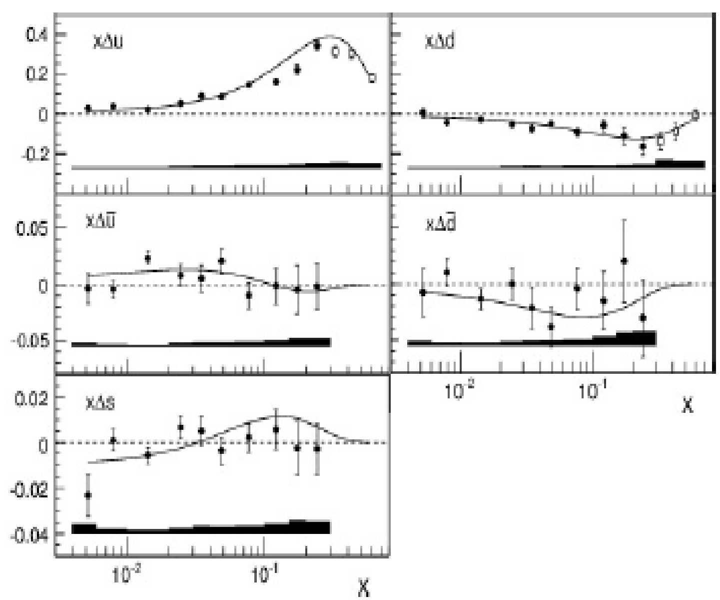




COMPASS, Phys. Lett. B **680** (2009) 217

DSSV, Phys. Rev. D **80** (2009) 034030





Some other actual problems – not well understood in QCD.

2-SPIN PROTON-PROTON ELASTIC CROSS SECTIONS

12 GeV ZGS

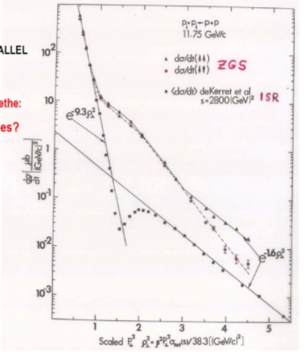
1977-1978

SPINS PARALLEL 4X SPINS ANTIPARALLEL

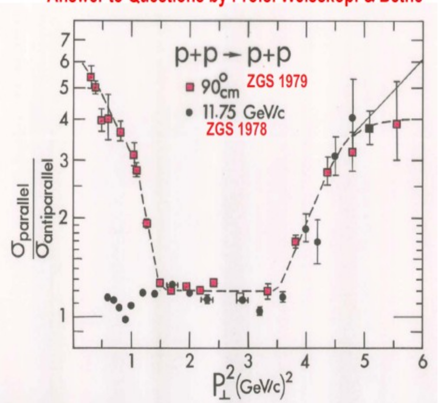
TOTALLY UNEXPECTED

Questions by Profs. Weisskopf & Bethe:

High P_T or 90^o_{cm} Identical Particles?



Answer to Questions by Profs. Weisskopf & Bethe



AGS 1985-1990 A_n

PERTURBATIVE QCD ⇒

A_n = 0 at HIGH $P_\perp^2$ and HIGH ENERGY

$A_n \neq 0$ ⇒

PROBLEM with PQCD?

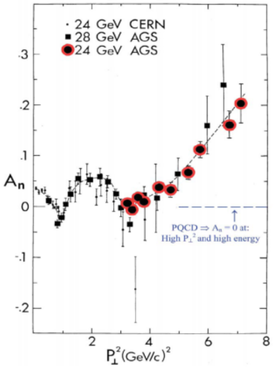
NO MODEL can EXPLAIN ALL

HIGH-$P_\perp^2$ SPIN EFFECTS (A_n & A_{nn})

GOAL

MEASURE A_n (and A_{nn})

up to $P_\perp^2$ = 12 (GeV/c)



INCLUSIVE HYPERON POLARIZATION

Devlin, Pondrum, Bunce, Heller *et al.* 1976-80

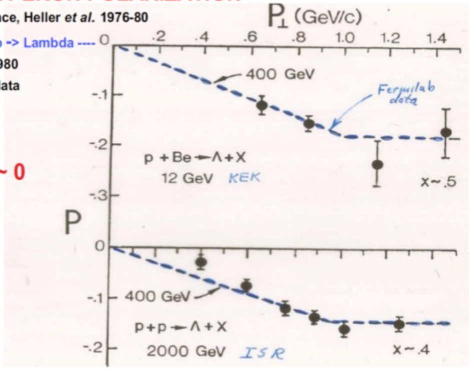
Fermilab 400 GeV p+p -> Lambda ----

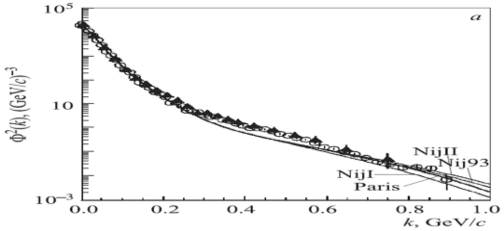
Plot by Heller ~1980

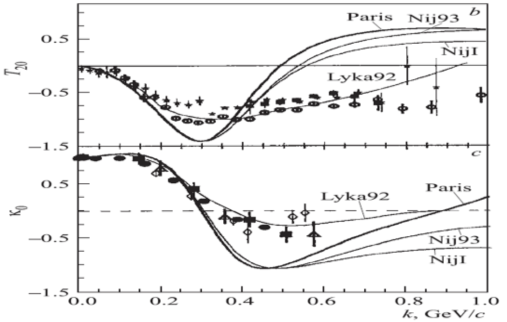
with KEK & ISR data

P ~ 15-20 %

QCD says P ~ 0







The Eqs. above include 24 leading twist SFs. Each of them is expressed through a weighted convolution, C, of corresponding leading twist TMD PDF in the transverse momentum space,

$$C\left[w(\vec{k}_{aT},\vec{k}_{bT})f_1 f_2\right] \equiv \frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT} d^2\vec{k}_{bT} \delta^2(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT}) w(\vec{k}_{aT},\vec{k}_{bT}) \times$$
$$\left[f_{1q}(x_a,\vec{k}_{aT}^2) f_{2\bar{q}}(x_b,\vec{k}_{bT}^2) + f_{1\bar{q}}(x_a,\vec{k}_{aT}^2) f_{2q}(x_b,\vec{k}_{bT}^2)\right],$$

where k_{aT} (k_{bT}) is the transverse momentum of quark in the hadron H_a (H_b) and f_1 (f_2) is a TMD PDF of the corresponding hadron.

Expressions for all leading twist SFs of **quarks** and **antiquarks** are given in the text of LoI. F.e. in the unpolarized case:

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

where $h^{\perp}_1$ is the Boer-Mulders PDF for quarks & anti-quarks.

A number of conclusions can be drawn comparing some asymmetries to be measured.

Let us compare the measured asymmetries A_{LU} and A_{UL} and assume that during these measurements the beam polarizations are equal, i.e. $|S_{aL}|=|S_{bL}|$ and hadrons a,b are identical. Then one can intuitively expect that the integrated over x_a and x_b asymmetries $A_{LU} = A_{UL}$.

Similarly, comparing the asymmetries A_{TU} and A_{UT} or A_{TL} and A_{LT} one can expect that $F_{TU} = F_{UT}$ and $F_{TL} = F_{LT}$.

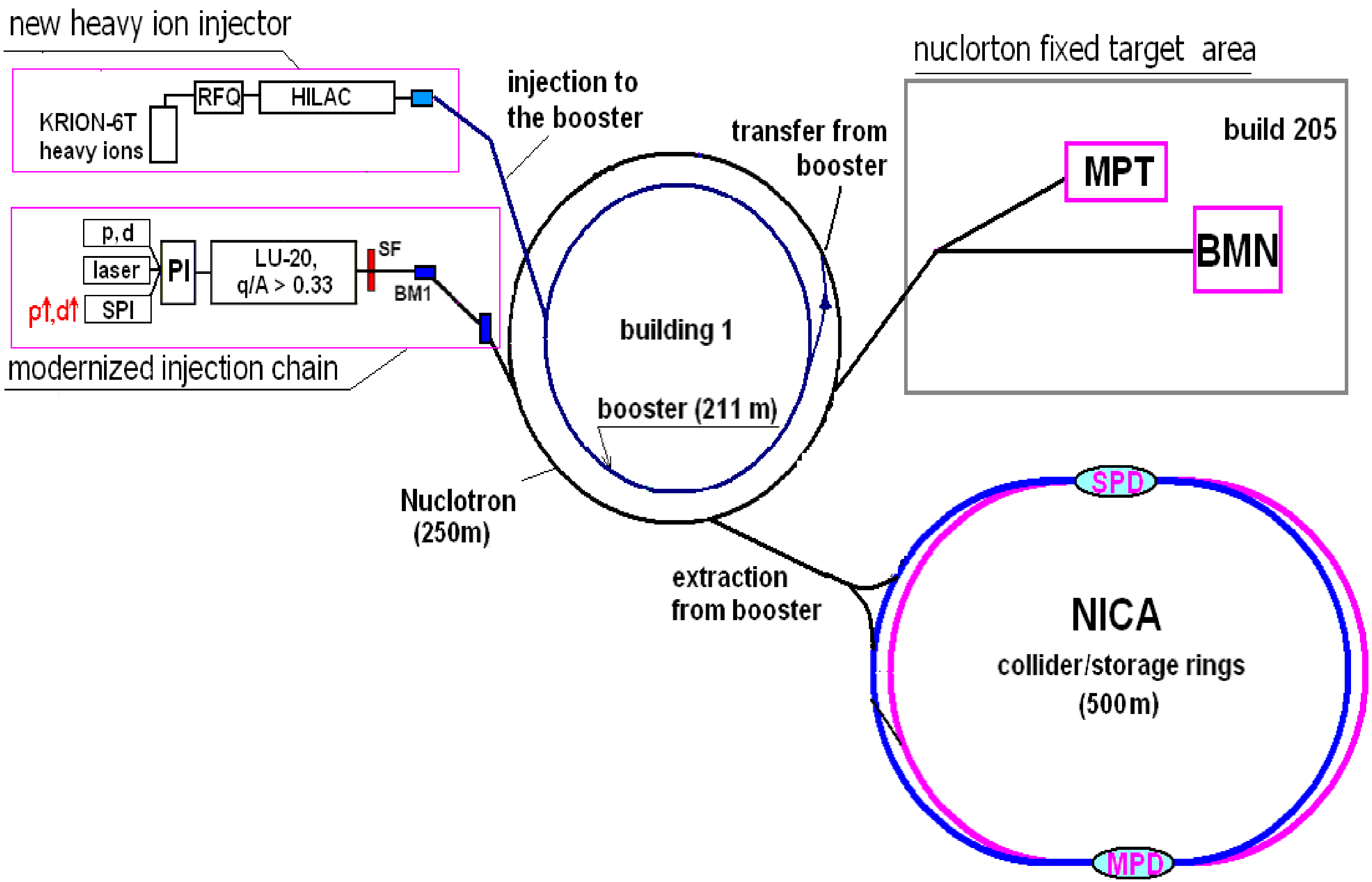
Tests of these expectations would be a good check of the parton model approximations.

Infrastructure**.** The infrastructure of the Nuclotron-NICA complex should include:

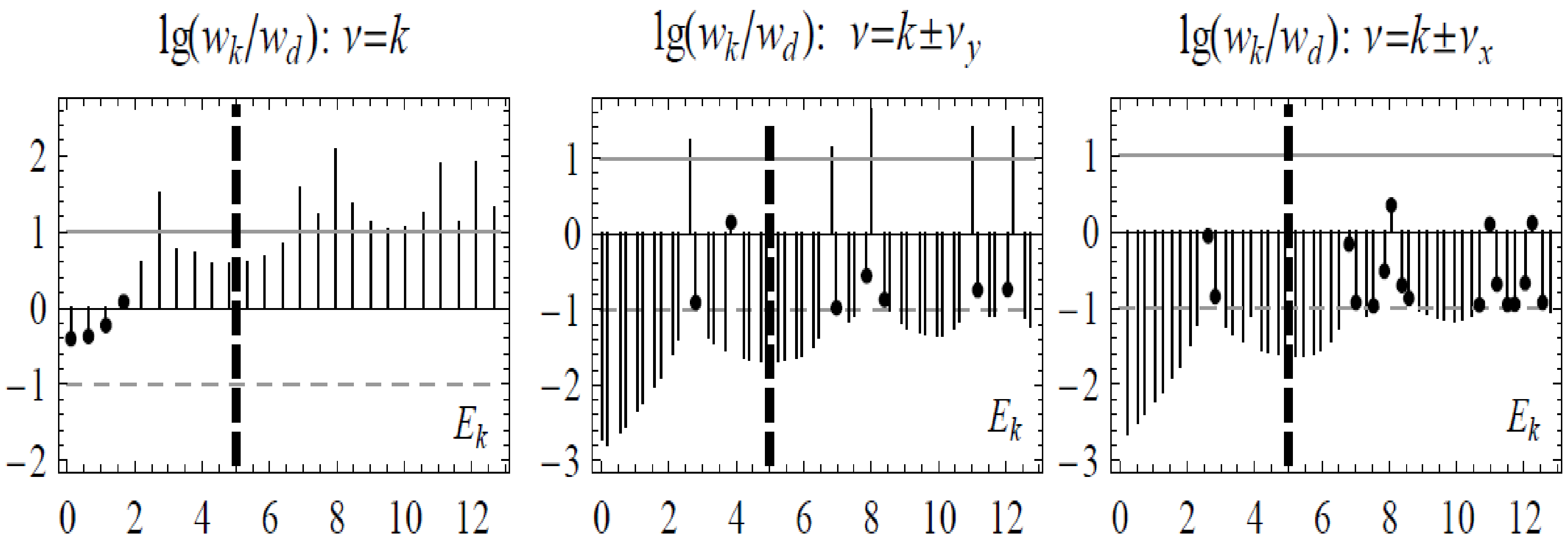
- a source(s) of polarized (non-polarized) protons and deuterons,
- a system of polarization control and absolute measurements (3-5%),
- a system of luminosity control and absolute measurements,
- a system(s) of data distribution on polarization and luminosity to the experiments.

The infrastructure tasks should be subjects of the separate project(s).

Beams intersection area**.** The area of ± 3m along and across of the beams second intersection point, where the detector for the spin physics experiment will be situated, must be free of any collider elements and equipment. The beam pipe diameter in this region should be minimal, 10 cm or less, to guaranty the angular detector acceptance close to 4π. The walls of the beam pipe in the region ± 1m of the beams intersections should have a minimal thickness and made of the low-Z material (Be?).


new heavy ion injector
KRION-6T
heavy ions
RFQ
HILAC
injection to
the booster
transfer from
booster
nuclorton fixed target area
build 205
MPT
BMN
p,d
laser
SPI
pↁ,dↁ
PI
LU-20,
q/A > 0.33
SF
BM1
modernized injection chain
building 1
booster (211 m)
Nuclotron
(250m)
extraction
from booster
SPD
NICA
collider/storage rings
(500m)
MPD

Proton spin resonances in the Nuclotron



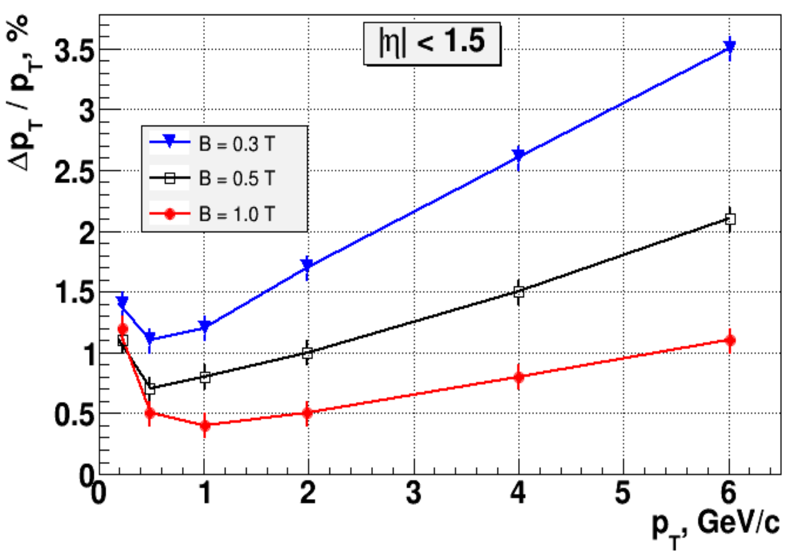
Possible solution is found in the energy range up to 5-6 GeV. Further acceleration can be done at NICA.

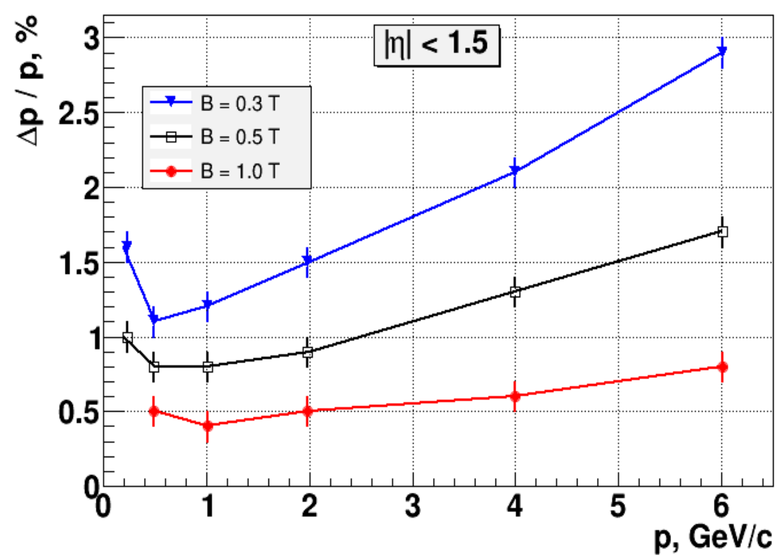
Estimation of Inner Detector momentum resolutions

***GEOMETRY*:** **total coverage η<1,5**

vertex detector: 5 layers of silicon strips
resolutions***: σ_φ = 20 μм, σ_Z = 320 μм;***

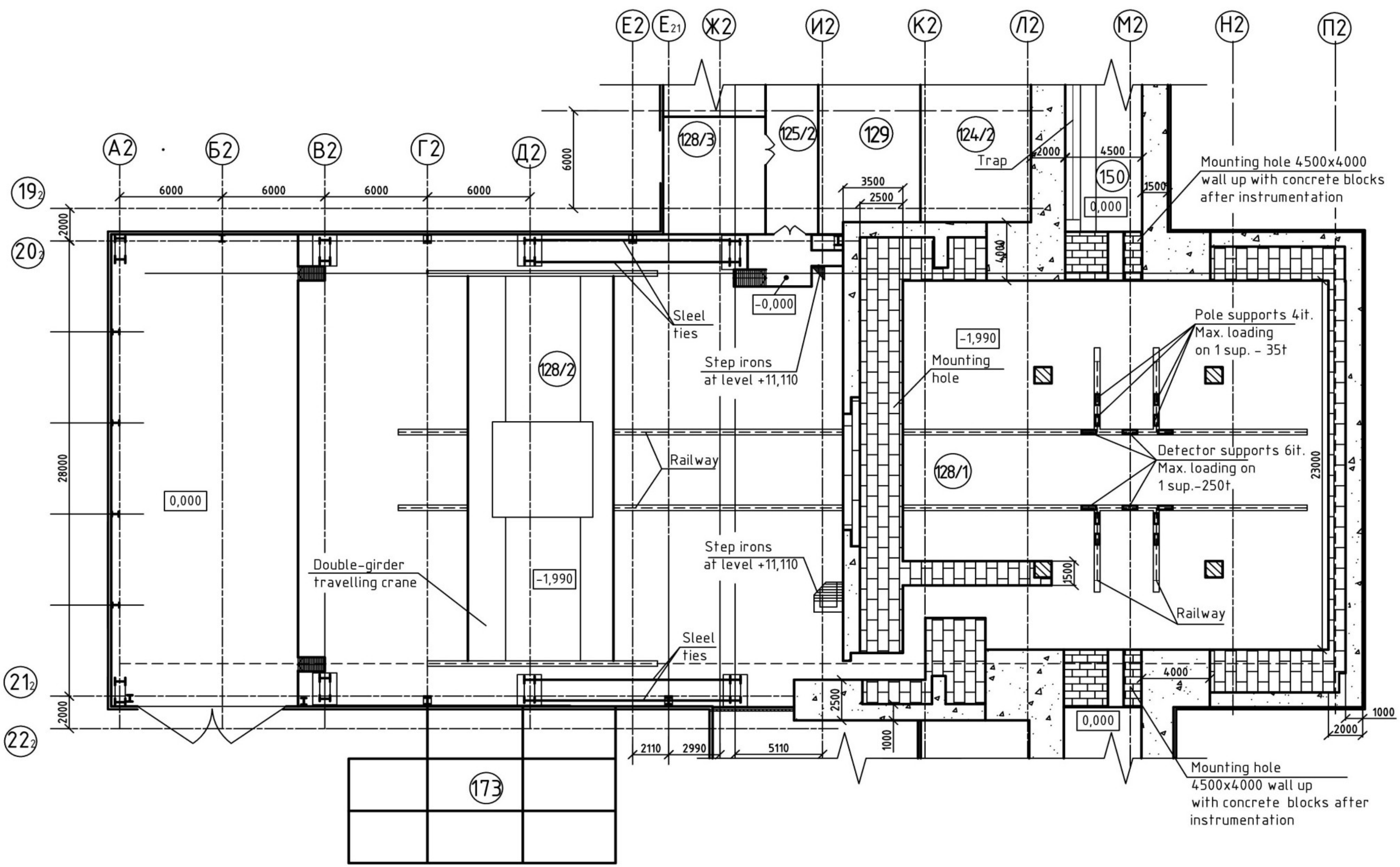
straw tubes : barrel region – 35 layers, 30cm<R<170cm
end-cap region - 10 layers, 175cm<Z<400cm
resolutions: **$\sigma_{\phi,R}$ = 170 μм;**





A.Zinchenko,B.Marinova

SPD experimental area

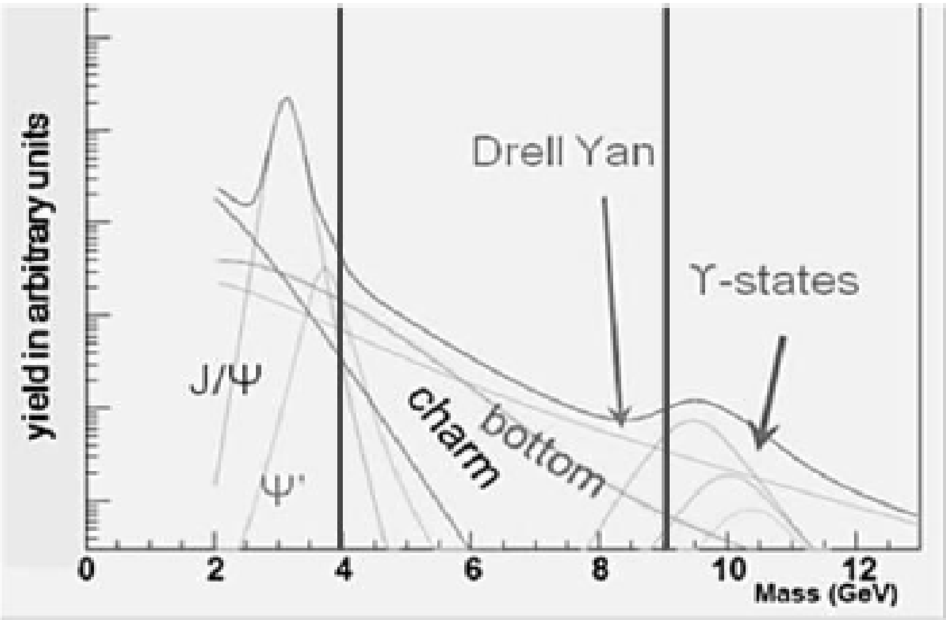


The main background sources:

- reactions with open charm, J/Ψ , Ψ' productions,
- K and π decays,
- due to vertex resolution,
- due to time resolution depens on NICA bunch structure,
- PID misidentification,
- conversion for DY measurements via e+e-.

$$D^0 \rightarrow e^+ anything (6,53\%)$$
$$D^0 \rightarrow \mu^+ anything (6,7\%)$$

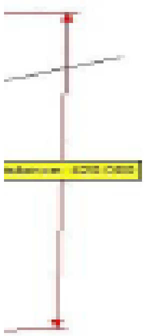
$$J/\psi \rightarrow e^+e^- (5,94\%)$$
$$J/\psi \rightarrow \mu^+\mu^- (5,93\%)$$



MC studies with PYTHIA (mininal bias setting) and GEANT, 100 M generated events.

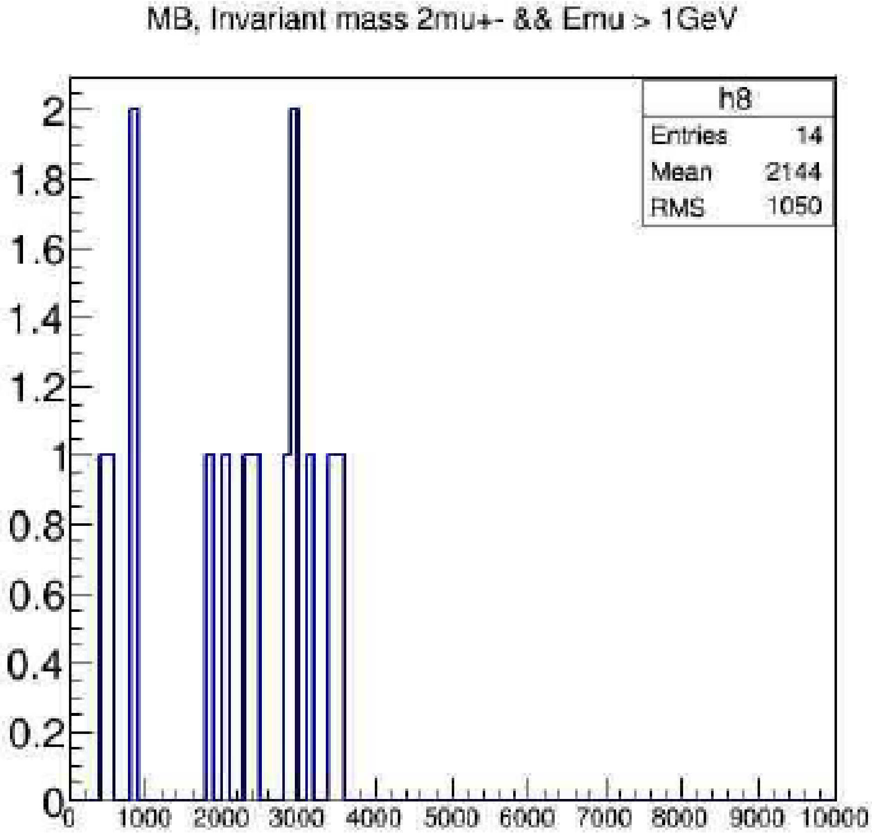
The analysis is performed for volume not covered by detectors (before VD).

The approach to minimize the background contribution for this region can be as follows:



1. To use cut on charge particle energy equal to 1 GeV;
2. To take to reconstruct just events with negative and positive charge particles (trigger selection);
3. To select the events where invariant mass of charge particle (assumed to be muons+/-) is greater then 4 GeV.

4. To select just tracks with XY projection crossing (or close) beam profile.



No background for $M_{\mu\mu}$ > 4 GeV

The MC studies for volumes in Vertex Detector, Central tracker, ECAL and RS are in progress.

Twist-2 PDFs of nucleons :

f_1 - ***density*** of partons in non-polarized (U) nucleon, (x, Q^2);

g_1 - ***helicity*** **,** longitudinal polarization of quarks in longitudinally polarized (L) nucleon;

h_1 - ***transversity,*** transverse polarization of quarks in transversely polarized (T) nucleon ;

$f^{\perp}_{1T}$ - ***Sivers*** **,** correlation between the transverse polarization of nucleon (transverse spin) and the transverse momentum of non-polarized quar

$g^{\perp}_{1T}$ - ***worm-gear-T*** **,**correlation between the transverse spin and the longitudinal quark polarization ;

$h^{\perp}_{1}$ - ***Boer-Mulders*** **,** distribution of the quark transverse momentum in the non-polarized nucleon ;

$h^{\perp}_{1L}$ - ***worm-gear-L*** **,** correlation between the longitudinal polarization of the nucleon (longitudinal spin) and the transverse momentum of quarks ;

$h^{\perp}_{1T}$ - ***pretzelosity*** **,**distribution of the transverse momentum of quarks in the transversely polarized nucleon ;

- **Level 1**
  - + Hardware based
  - + Coarse granularity only calorimeter and muons
- **High Level Trigger (L2 + EF)**
  - + Software based
  - + Commercial hardware
- **Level 2**
  - + Data requested from ROBs over network
  - + Full detector granularity in ROIs
- **Event Filter**
  - + Seeded by L2
  - + Potential full event access
  - + Full detector granularity