Study of polarization phenomena in pp- and dd-interactions at energy in c.m.s. up to 27 GeV/nucleon with SPD at NICA collider

Roumen Tsenov (LHEP),
SPD project coordinator in JINR

JINR

NICA (Nuclotron based Ion Colider fAcility) is the flagship project in high energy physics of the Joint Institute for Nuclear Research

SPD NICA

Main targets of the NICA project:

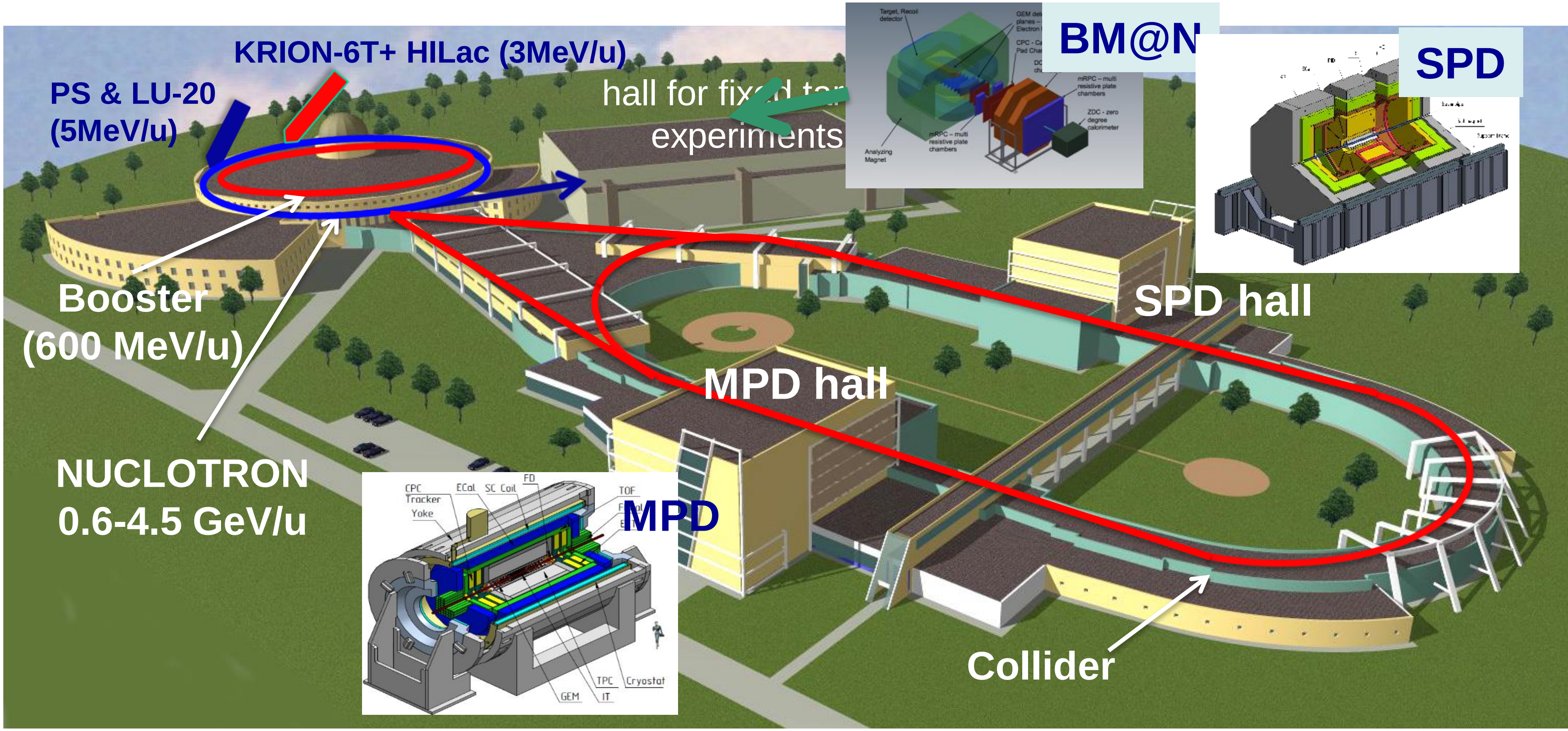
- ***study of hot and dense baryonic matter***
- ***investigation of nucleon spin structure, polarization phenomena***

Ring circumference, m	**503.04**
heavy ions	
energy range for ***Au***$^{79+}$*:* $\sqrt{S_{NN}}$*, GeV*	**4 - 11**
r.m.s. $\Delta p/p$*,* 10^{-3}	**1.6**
Luminosity for ***Au***$^{79+}$*, cm*$^{-2}$ *s*$^{-1}$	**1x10^{27}**
polarized particles	
max. $\sqrt{S}$ *for polarized* ***p****, Gev*	**27**
Luminosity for ***p****, cm*$^{-2}$ *s*$^{-1}$	**1x10^{32}**

The NICA complex

existing facilities

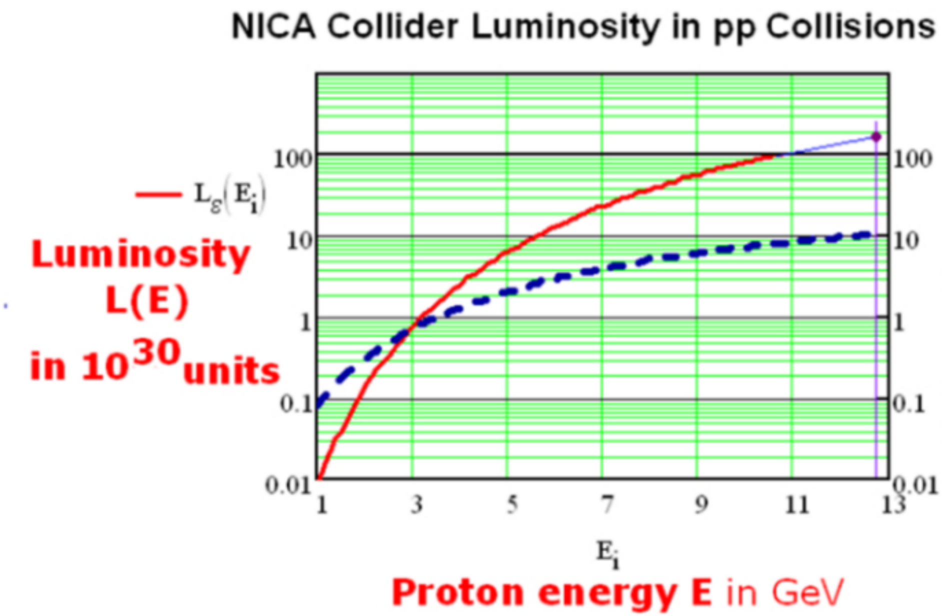
to be constructed



Civil Construction, bld.17

June 2018

Polarized beams



Lpeak ≈ $1.8 \cdot 10^{32}$ cm-2·s-1

particle number per bunch in 10^{11} units

maximum proton number in each ring – $2.2 \bullet 10^{13}$

Bunch crossing each 80 ns;
crossing rate 12.5 MHz .

circumference - 503 m,

number of intersection points (IP) - 2,

beta func

number

number

RMS bu

incoherent tune shift, $\Delta_{Lasslett}$ - 0.027,

beam-beam parameter, ξ - 0.067,

beam emittance ε_{nrm} , π mm mrad - 0.15 (normalized at 12.5 GeV).

Polarized beams

- **p↑p↑** at $\sqrt{s_{pp}}$ **= 12 - 27 GeV, L_{av}** ≈ 10^{32} cm^{-2}s^{-1}
- **d↑d↑** at $\sqrt{s_{NN}}$ **= 4 - 13 GeV**
- *longitudinal and transverse polarization at SPD and MPD*

Start of the SPD project

- **Letter of Intent** presented at the JINR PAC in summer 2014, where:
  - the physics program of the experiment was developed;
  - requirements to NICA polarized beams were formulated;
  - desired detector characteristics and sketch of the facility were given;
- A few presentation at international conferences about the physics potential and program of the SPD were given;
- Several workshops on spin physics at NICA were organized:
  - NICA-SPIN-2013, Дубна, 17-19.03.2013
  - SPIN-Praha-2013, 7-13.07.2013
  - NICA-SPIN-2014, Praha, 11-16.02.2014
  - SPIN-Praha-2015, 26-31.07.2015
  - DSPIN2013, DSPIN2015, DSPIN2017

arXiv: 1408.3959

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

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

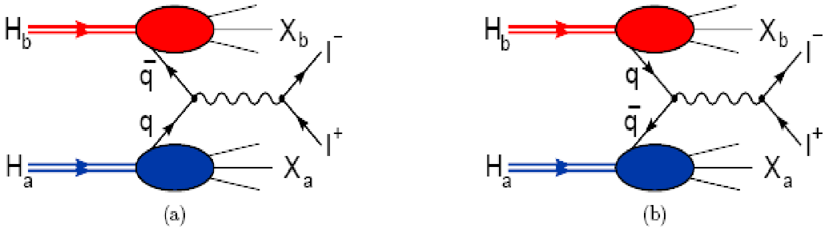
Compiled by the Drafting Committee:
I.A. Savin, A.V. Efremov, D.V. Peshekhonov, A.D. Kovalenko, O.V.Teryaev, O.Yu. Shevchenko, A.P. Nagajcev, A.V. Guskov, V.V. Kukhtin, N.D. Topilin.

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

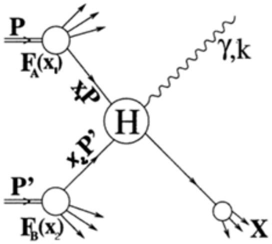
In 2017 a new stage of the project started:
From LoI to CDR (Conceptual Design Report)

Physics tasks

- **Nucleon spin structure studies**
  - **Drell-Yan pair production;**

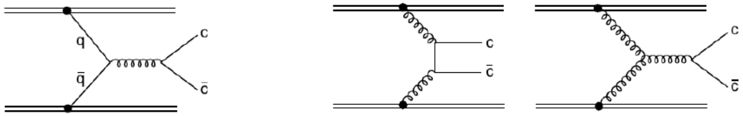


  - **Direct photons;**



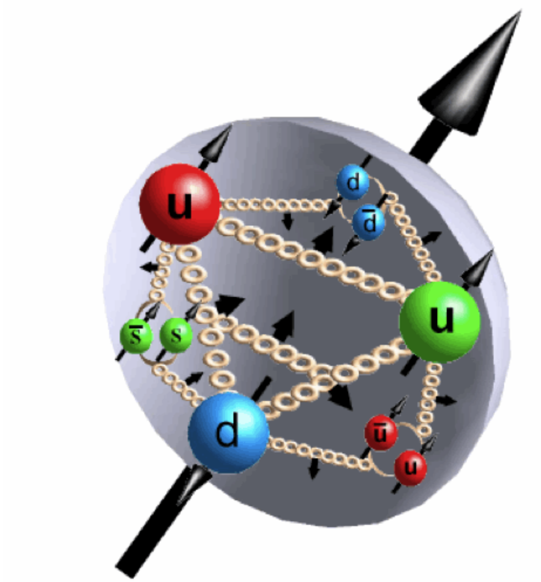
  - **Nucleon PDFs by J/ψ production;**

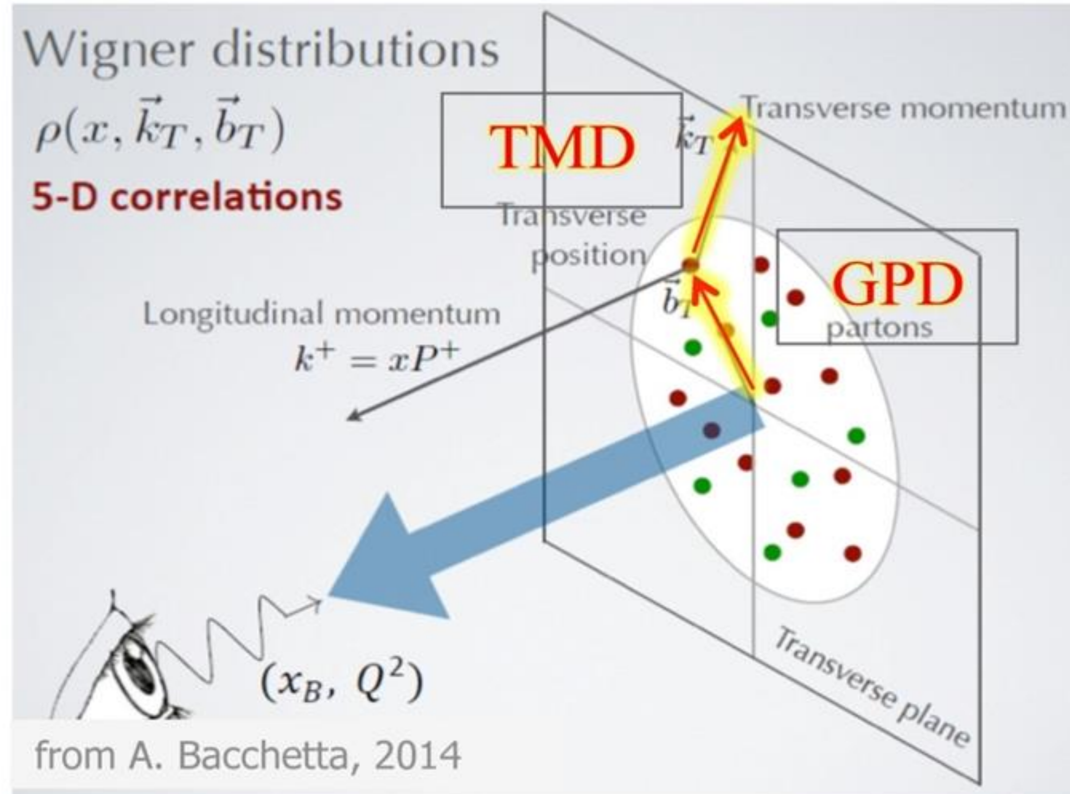
LO $c\bar{c}$ production diagram:



- **Spin-dependent effects in elastic pp, pd and dd scattering;**
- **Spin effects in exclusive hadron production;**
- **Spin effects in production of hadrons with high p_T ;**
- *etc….*

Spin dependent PDFs



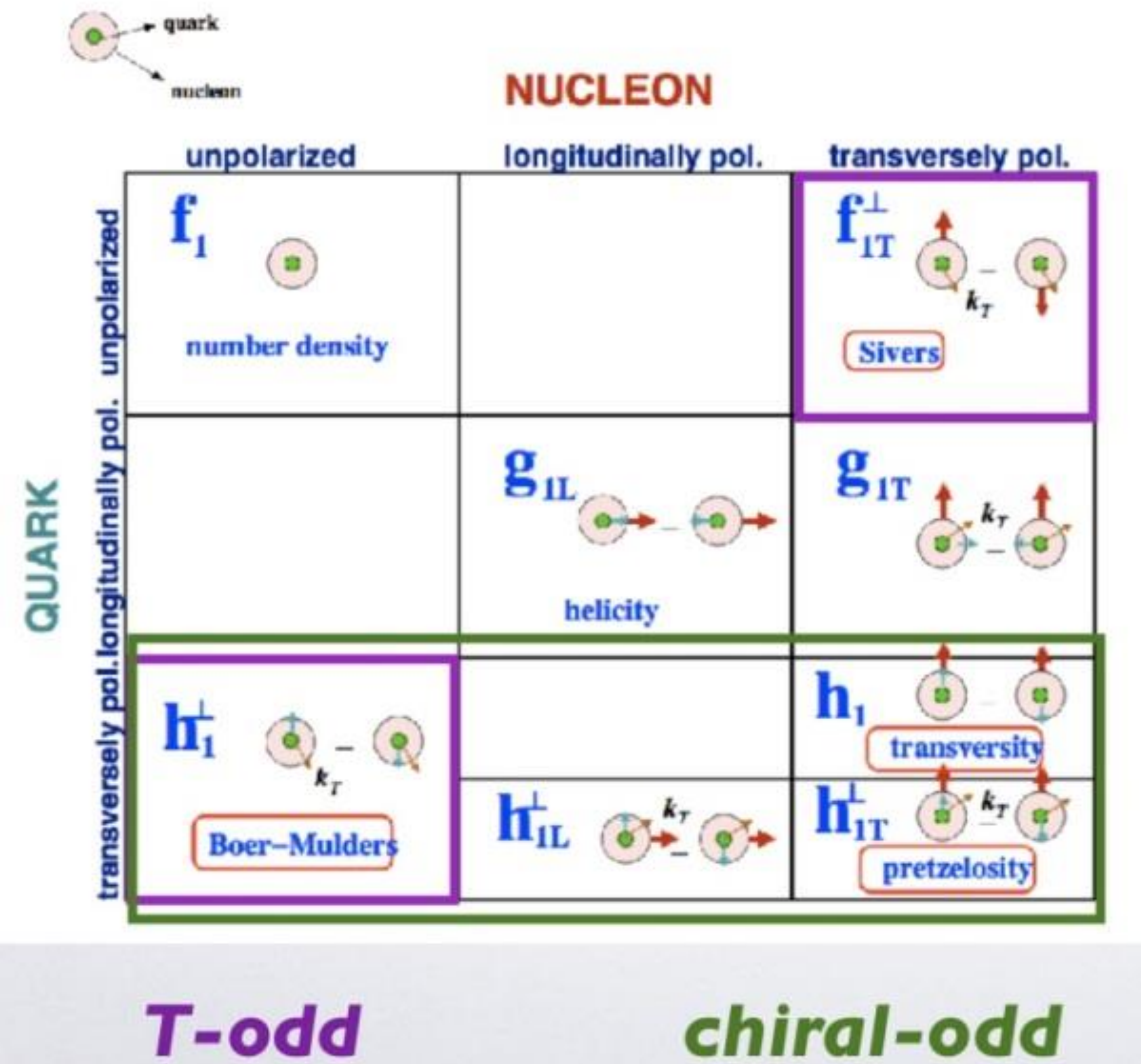


$$\frac{1}{2} = \frac{1}{2}\Sigma_q + \Sigma_g + L_q + L_g .$$

Transversity Momentum Distributions: TMD (x,k_T)
probe the transverse parton momentum dependence

Generalized Parton Distributions : GPD (x,b_T):
probe the transverse parton distance dependence

TMD and GPD



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

Structure functions

1. Transversity: $A_{UT}^{\sin(\phi+\phi_S)}$, represents the number distribution of transversely polarized quarks in a transversely polarized nucleon;

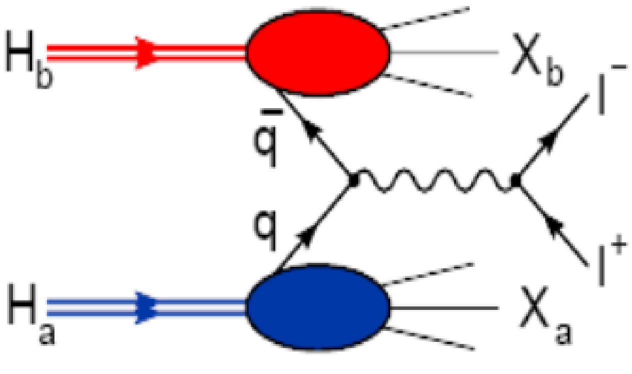
2. Sivers: $A_{UT}^{\sin(\phi-\phi_S)}$, represents the distribution over the transverse momentum of non-polarized quarks in a transversely polarized nucleon;

3. Pretzelosity: $A_{UT}^{\sin(3\phi-\phi_S)}$, represents the distribution over the transverse momentum of transversely polarized quarks in a transversely polarized nucleon;

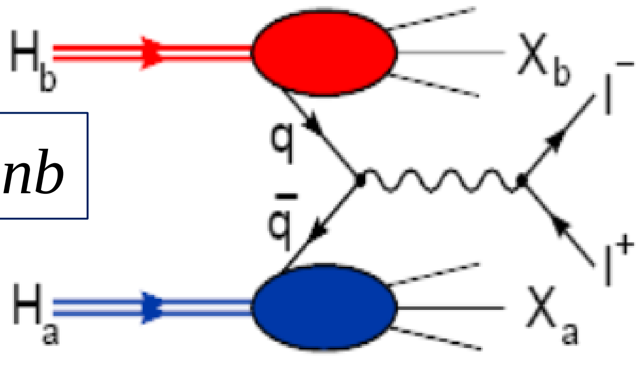
4. Boer-Mulders: $A_{UU}^{\cos(2\phi_h)}$, represents the distribution over the transverse momentum of transversely polarized quarks in a non-polarized nucleon;

5. Worm-Gears: $A_{UL}^{\cos(2\phi_h)}$, represents the distribution over the transverse momentum of longitudinally polarized quarks in a longitudinally polarized nucleon.

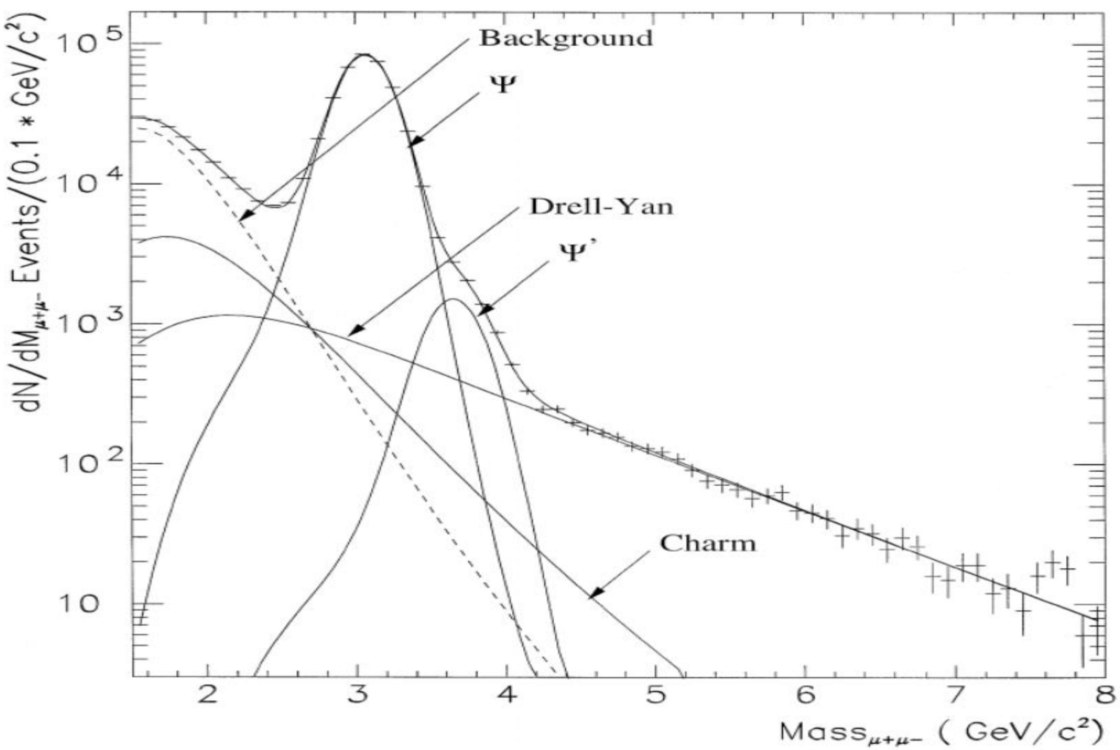
Drell-Yan pairs



$\sigma_{tot} \sim 9\ nb$



Dimuon spectrum from NA51 ($\sqrt{s} = 29.1$ GeV)



COMPASS data, pion beam

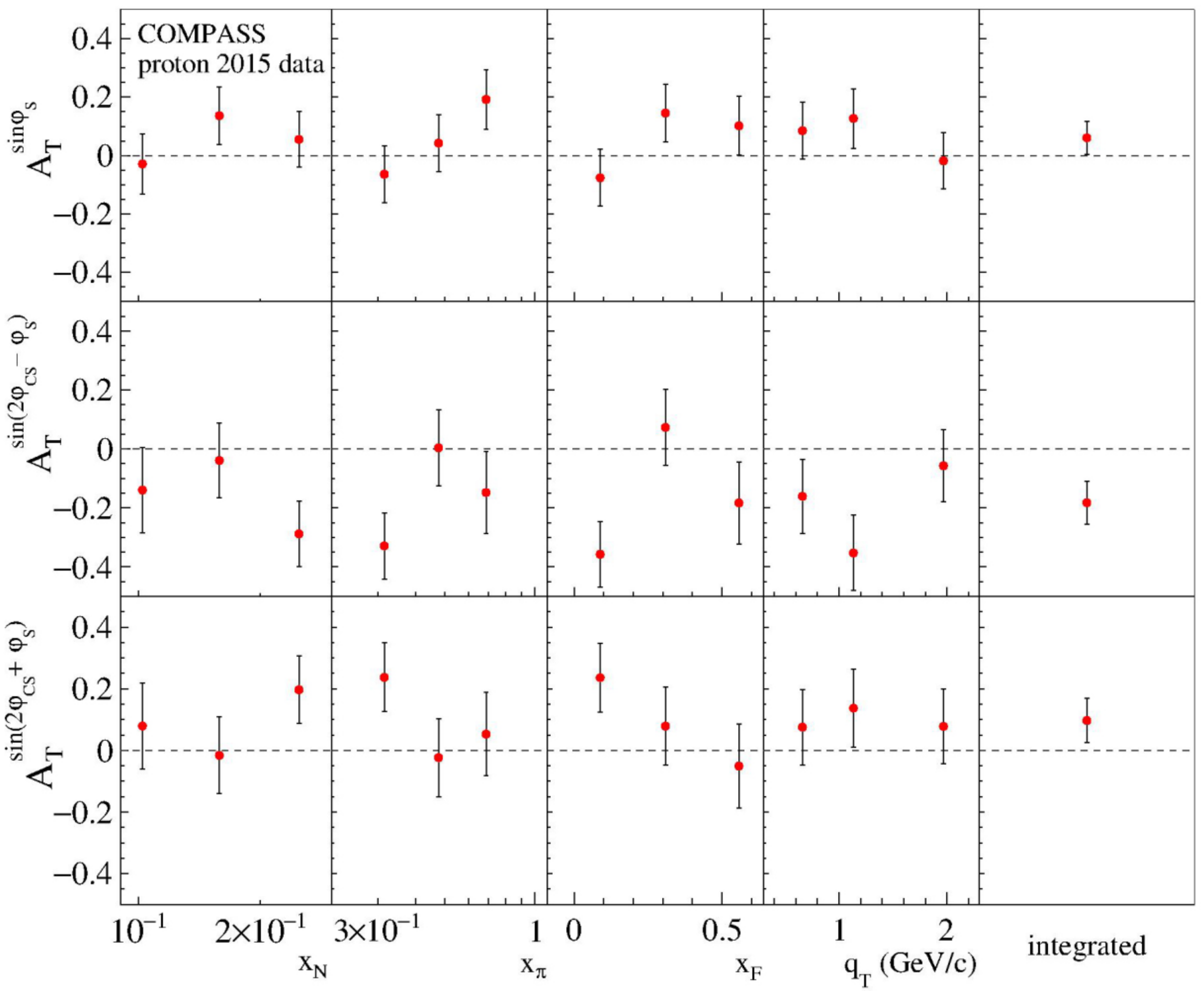


Figure 4: COMPASS data on Drell–Yan pair production spin asymmetries related to Sivers, transversity and pretzelosity TMD PDFs (top to bottom).

Kinematical ranges and statistics

JINR

PRL 119 (2017) 112002

COMPASS-2015 data

- $4.3\ \mathrm{GeV/c^2} < M_{\mu\mu} < 8.5\ \mathrm{GeV/c^2}$
- $q_T > 0.4\ \mathrm{GeV/c}$
- $\langle f \rangle \approx 0.18$
- $\langle P_{Target} \rangle \approx 0.73$

- $\langle x_F \rangle = 0.33$
- $\langle q_T \rangle = 1.2\ \mathrm{GeV/c}$
- $\langle M_{\mu\mu} \rangle = 5.3\ \mathrm{GeV/c^2}$

- $\mathrm{t} \approx 1.08864 \times 10^7\mathrm{s}$ (18 weeks, 126 days)

$\boldsymbol{N_{DY}} = \mathbf{35 \times 10^3}$

SPD

- $4.0\ \mathrm{GeV/c^2} < M_{\mu\mu} < 9.0\ \mathrm{GeV/c^2}$
- $\langle P_{beam\ 1,2} \rangle \approx 0.6$

- $\langle x_F \rangle = 0.0$
- $\langle q_T \rangle = 2.4\ \mathrm{GeV/c}$
- $\langle M_{\mu\mu} \rangle = 4.8\ \mathrm{GeV/c^2}$

- $\mathrm{L} = 10^{32}\ \mathrm{cm^{-2}s^{-1}}$
- $\mathrm{t} = 10^7\mathrm{s}$ (16.5 weeks)
- $\sigma_{DY[4-9]} = 0.074\ \mathrm{nb}$

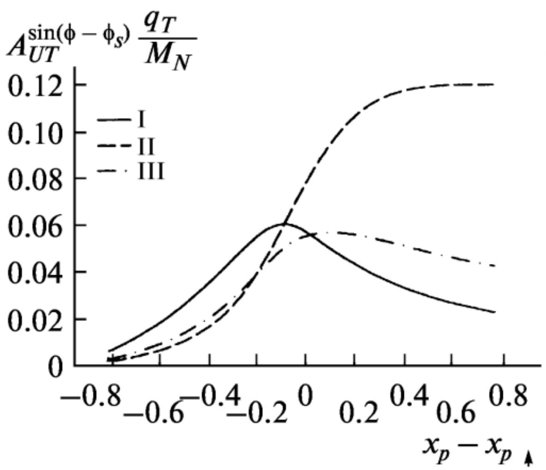
$N_{DY} = \sigma_{DY} \times L \times t$

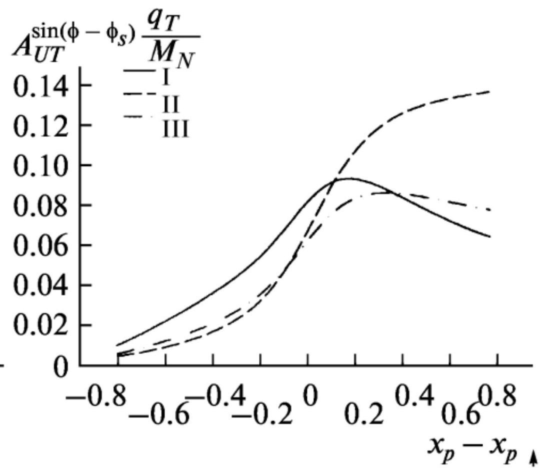
$\boldsymbol{N_{DY}} = \mathbf{88.8 \times 10^3}$

$$dA = \frac{1}{P_{b1}P_{b2}} \times \frac{1}{\sqrt{N}}$$

Asymmetries in DY pair production

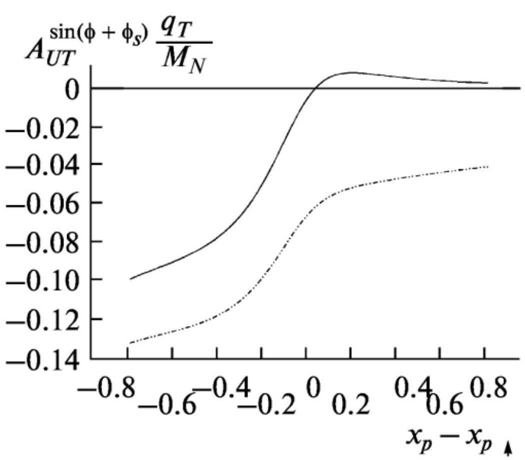
Q^2 = 4 GeV² **Q^2 = 15 GeV²**

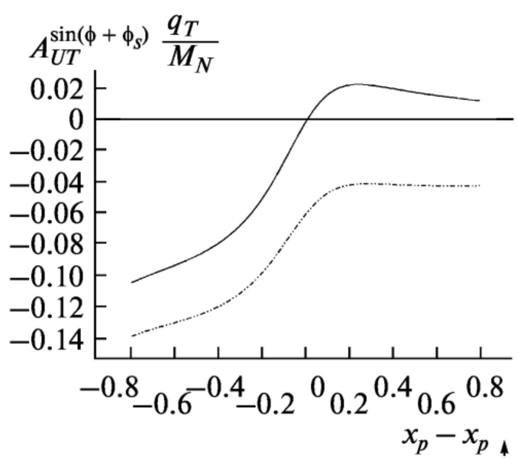




Sivers

J.C.Collins et al., PRD73 (2006)014021



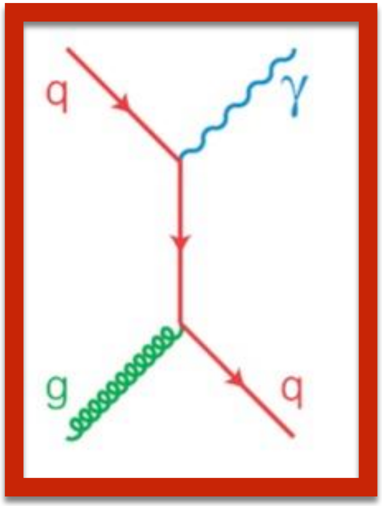


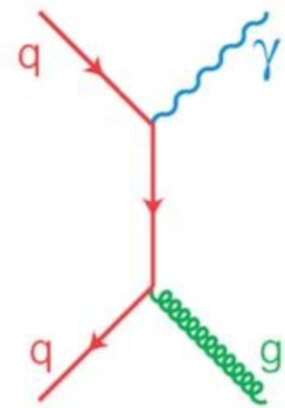
Boer-Mulders

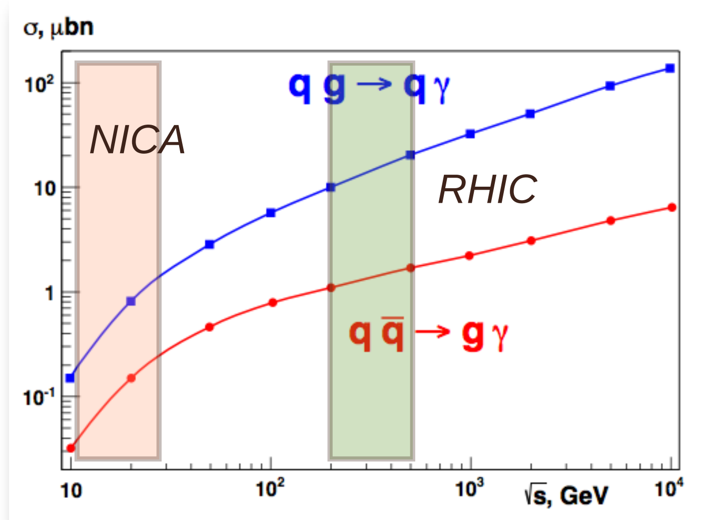
s= 400 GeV²

Prompt photons

The gluon Compton scattering gives access to the gluon content of proton:







Transverse beam polarization: access to the Sivers function for gluons

$$\sigma^{\uparrow} - \sigma^{\downarrow} = \sum_i \int_{x_{min}}^{1} dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})\, e^y} \Big[q_i(x_a, \mathbf{k}_{Ta}) \Delta_N G(x_b, \mathbf{k}_{Tb}) \times \frac{d\hat{\sigma}}{d\hat{t}}(q_i G \to q_i \gamma) + G(x_a, \mathbf{k}_{Ta}) \Delta_N q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(G q_i \to q_i \gamma) \Big]$$

Longitudinal beam polarization: access to gluon polarization Δg/g

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

Prompt photon production cross section

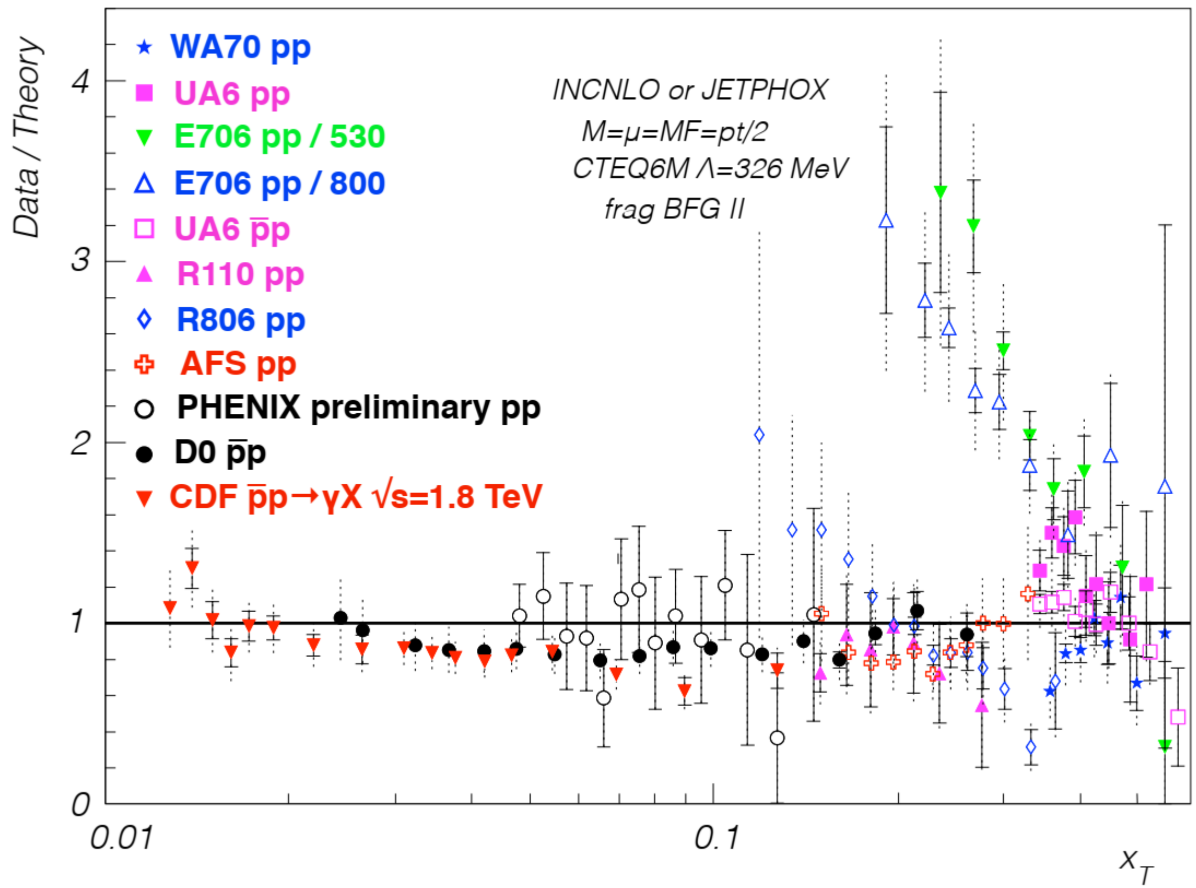
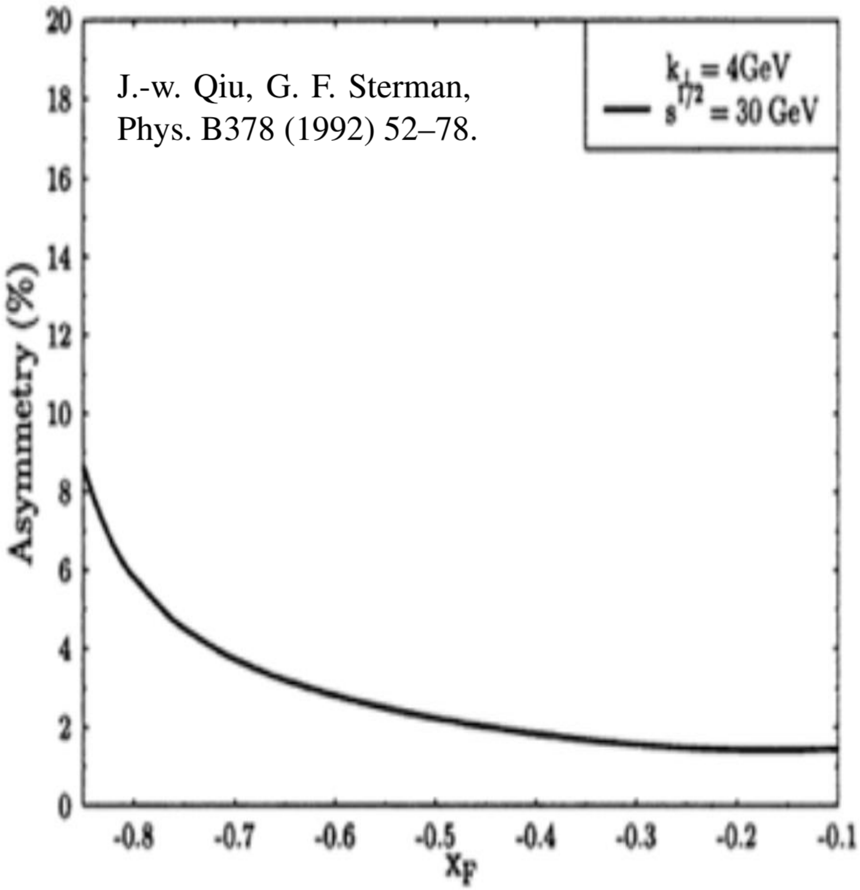
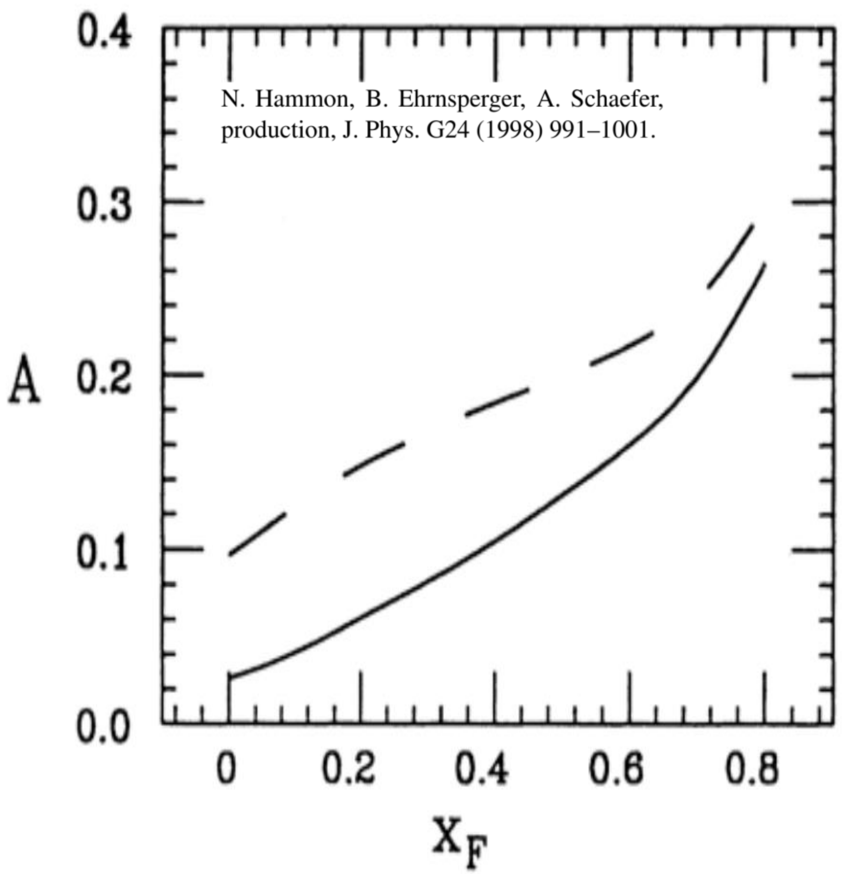


Figure 5: Measured cross section of prompt-photon production divided by the predicted one as a function of the x_T [3].

Expected asymmetries

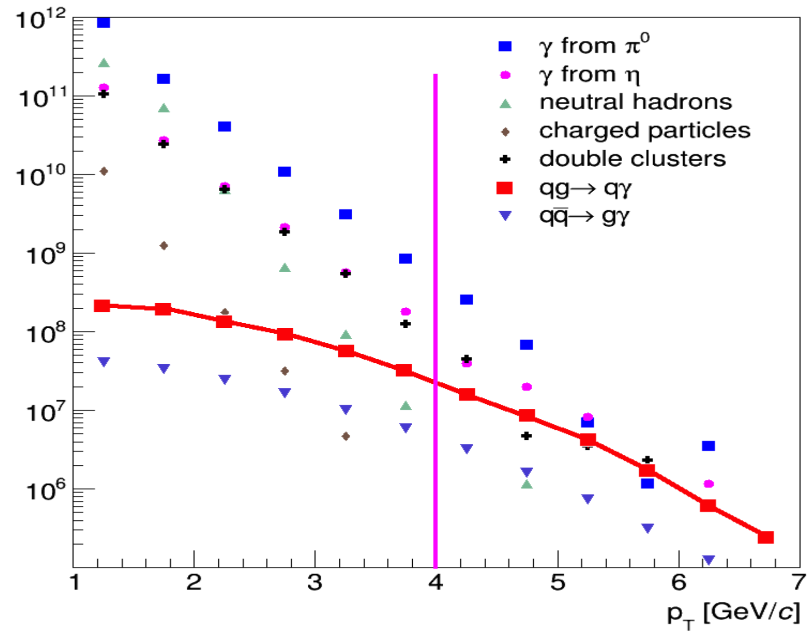




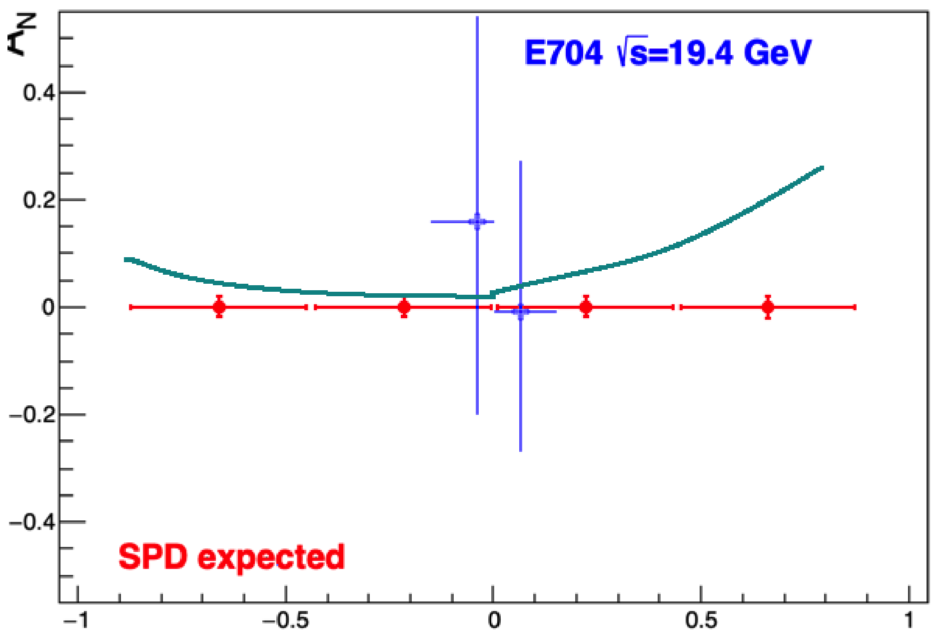
Prompt photon asymmetries: accuracy

Statistics: 3×10^7 prompt photons with p_T>4 GeV/c for one year of data taking (10^7 s). It could keep statistical uncertainty of A_N and A_{LL} asymmetries measurement below 0.001 level.

Main contribution to systematics comes from MC-dependent subtraction of background from decay photons, charged particles etc. The expected total error does not exceed (1-2)×10^{-2}.



Signal and different sources of background for prompt photon production



SPD expectations, previous measurement at similar kinematic range and theory predictions for A_N

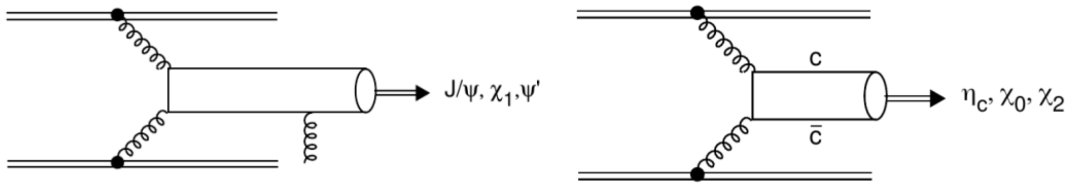
Similar accuracy is expected for A_{LL} while the expected asymmetry is between ±0.05

SPD data for A_N and A_{LL} at √s~20 GeV will be complementary to the expected results from RHIC (√s~200 GeV) and corresponds to the region of typically larger values of ΔG/G

Charmonium production

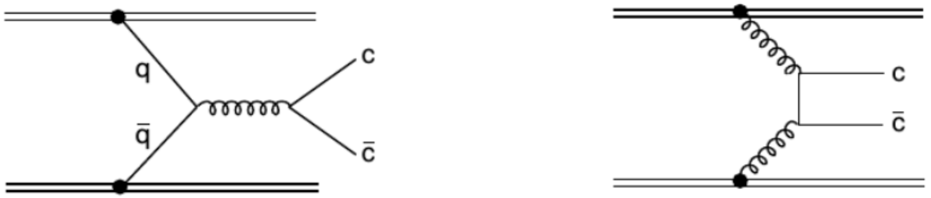
Gluon fusion

Charmonia production is sensitive to gluon distributions of colliding hadrons.

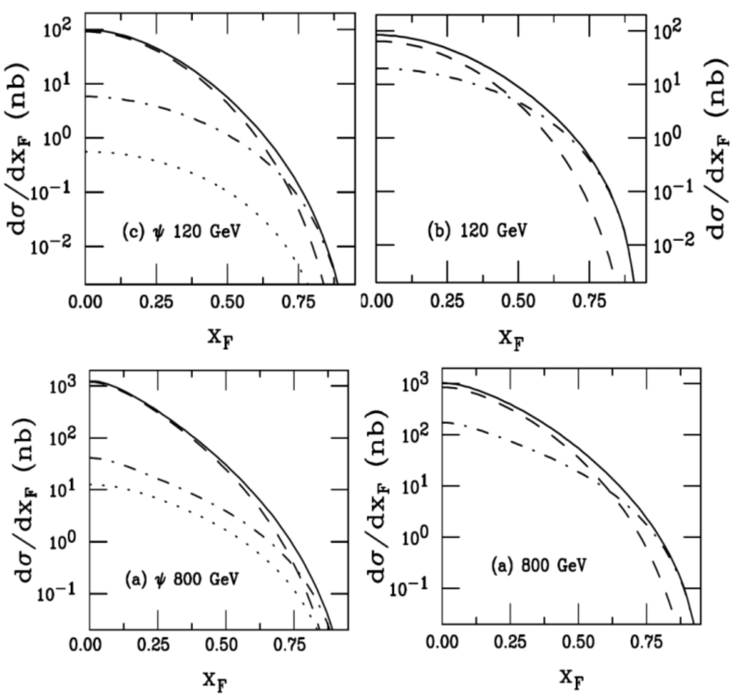


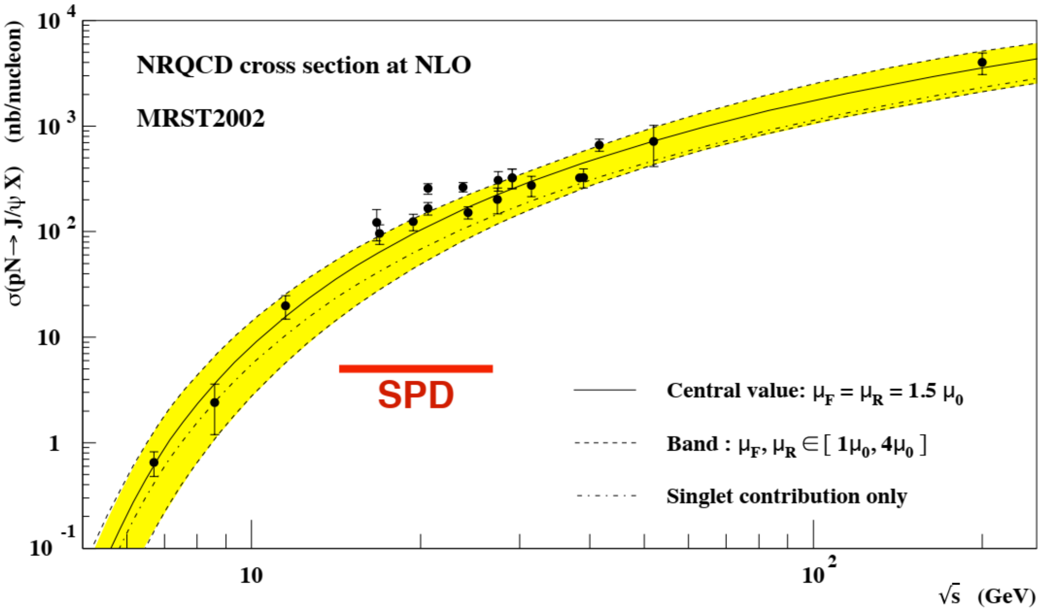
CS diagrams from Int. J Mod Phys A10:3043-3070 1995

Quark annihilation



NRQCD CEM

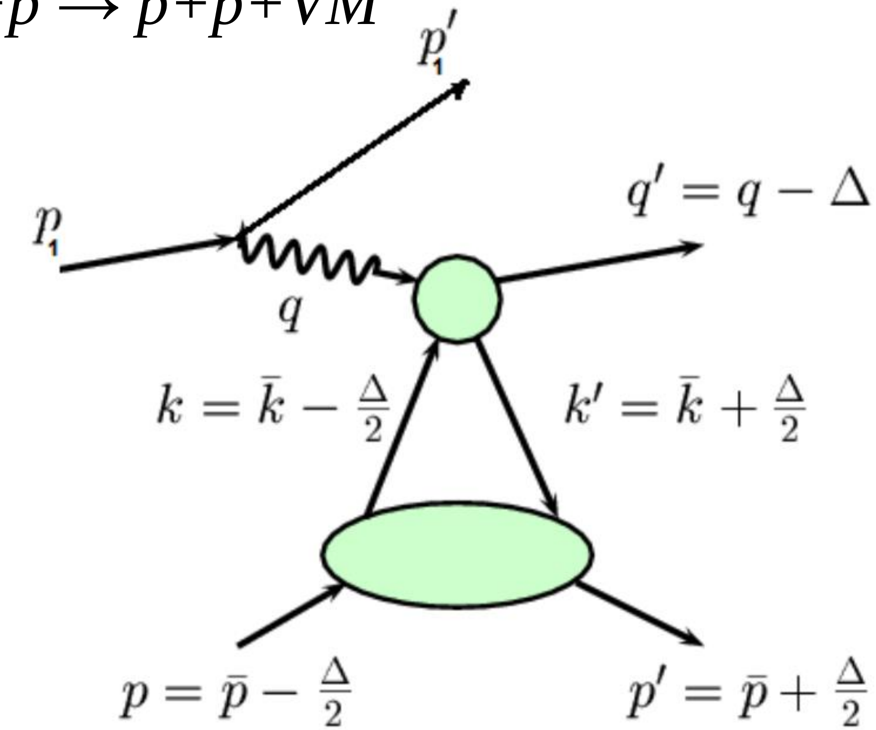


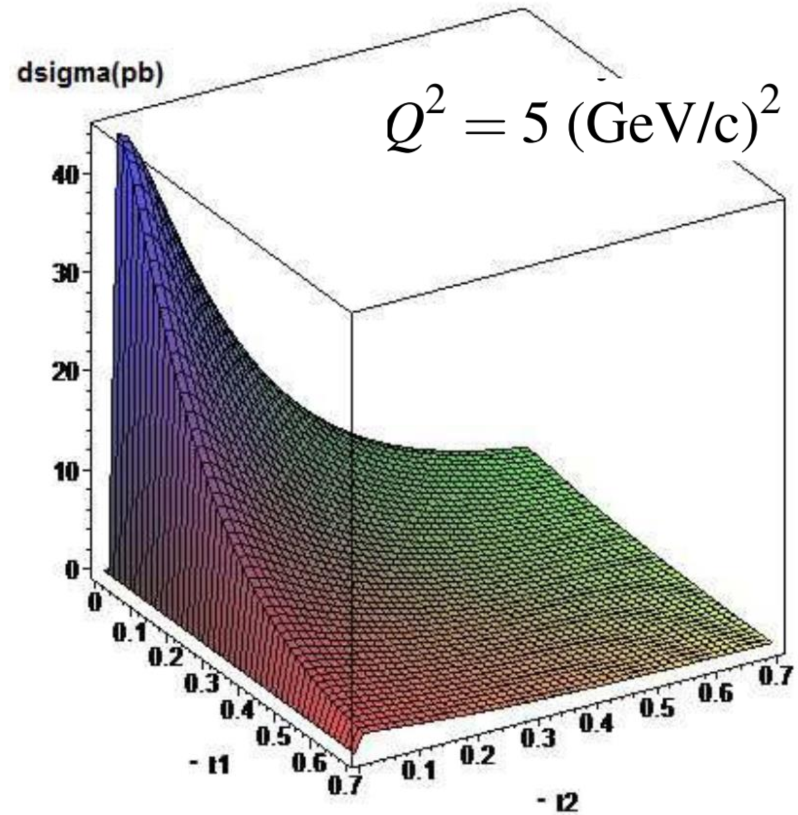


GPD through vector meson exclusive production

Exclusive DY

$p+p \rightarrow p+p+VM$

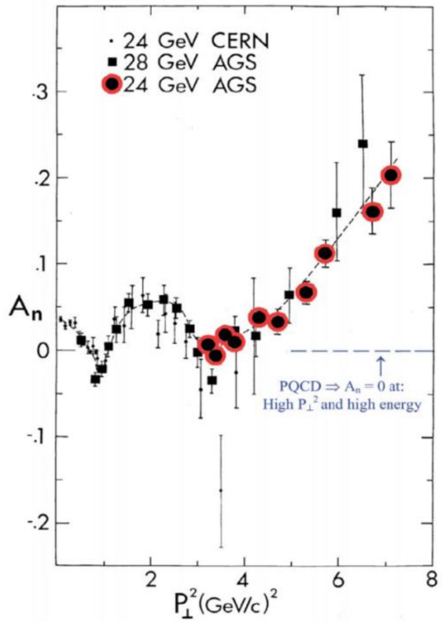


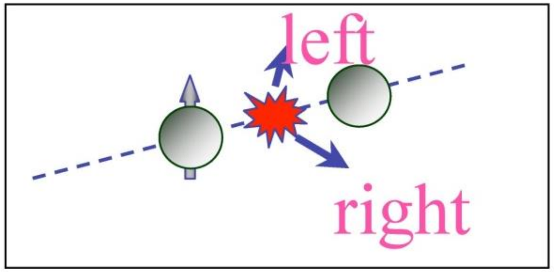


Vector meson production
via photoproduction mechanism or odderon exchange.

Asymmetries in high p_T hadron production

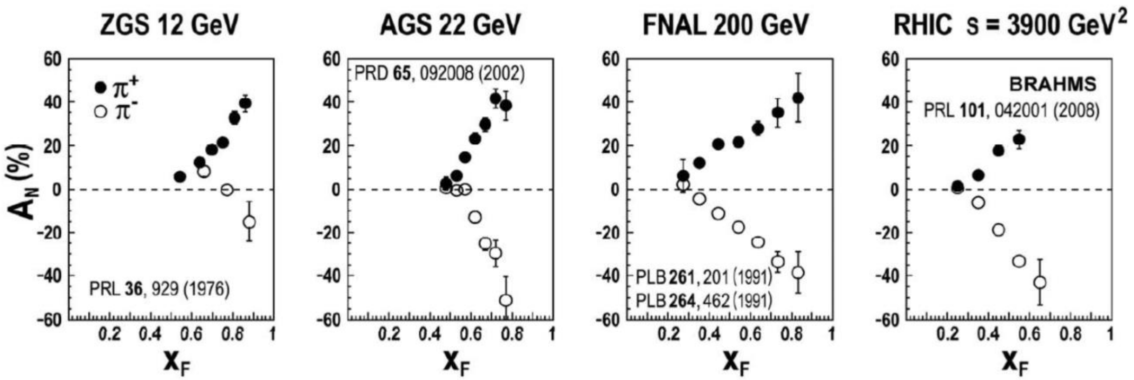
- Diquark properties;
- Confinement laws;
- Nature of the huge spin effects;
- Deuteron spin structure;
- Properties of the bare NΛ- and NK-interactions;
- Nature and properties of the cold super dense baryonic matter (CsDBM) (pA and AA);
- Dilepton production puzzle in np-interaction.

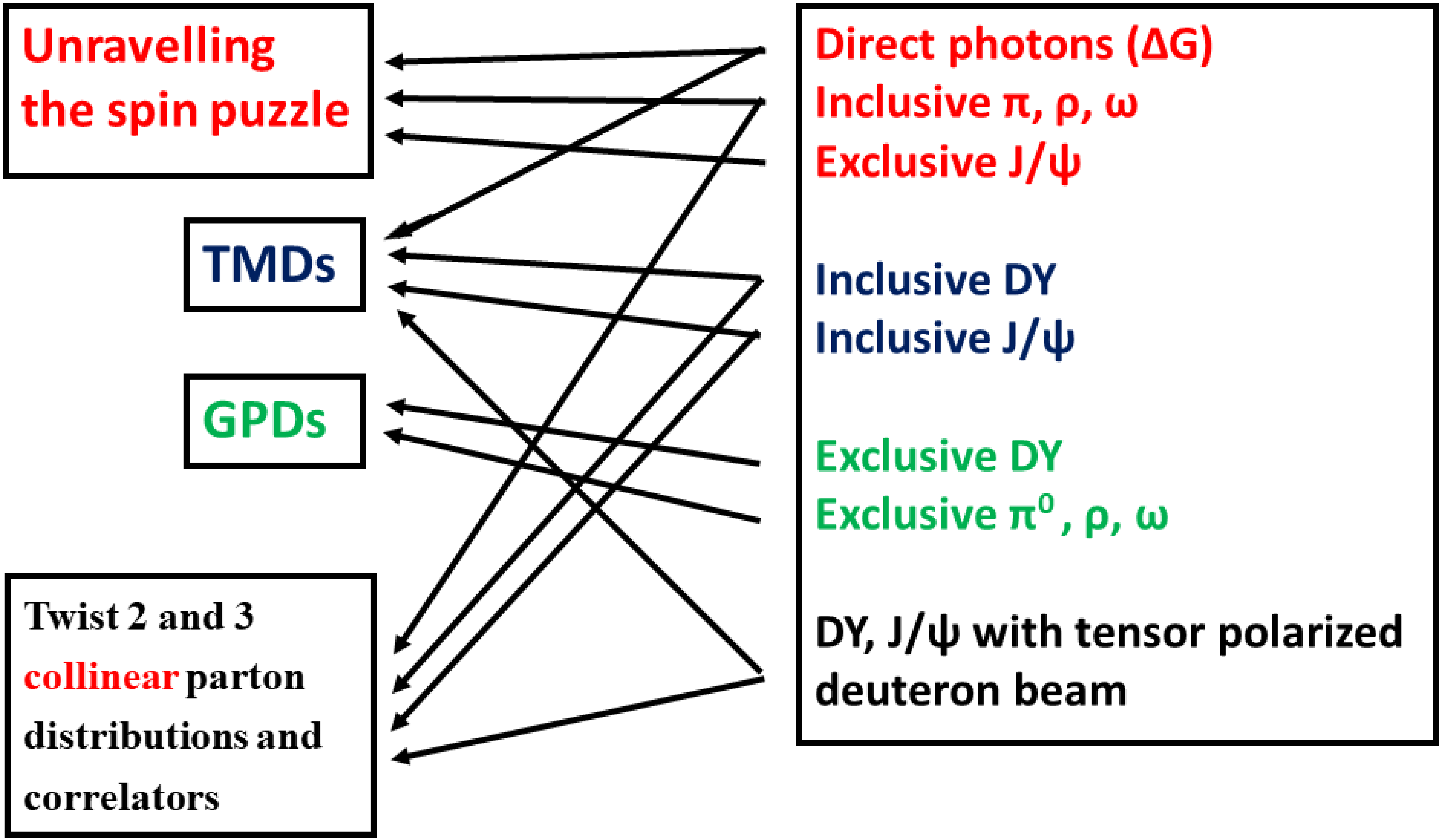




INCLUSIVE PION ASYMMETRY IN PROTON-PROTON COLLISIONS

C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009




Unravelling
the spin puzzle
TMDs
GPDs
Twist 2 and 3
collinear parton
distributions and
correlators
Direct photons (ΔG)
Inclusive π, ρ, ω
Exclusive J/ψ
Inclusive DY
Inclusive J/ψ
Exclusive DY
Exclusive π⁰, ρ, ω
DY, J/ψ with tensor polarized
deuteron beam

SPD advantages:

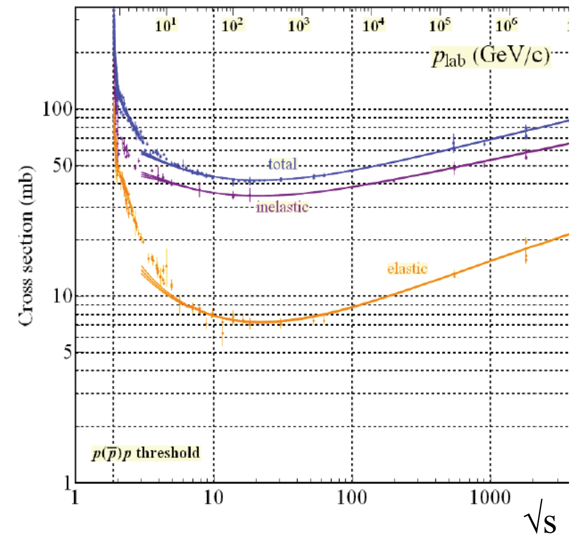
- measurements with pp, pd and dd beams,
- possibility to perform energy scan with small steps,
- measurements via muon and electron-positron pairs,
- operations with non-polarized, transverse and longitudinally polarized beams and their combinations,
- possibility to extract all first order PDFs in one experiment.

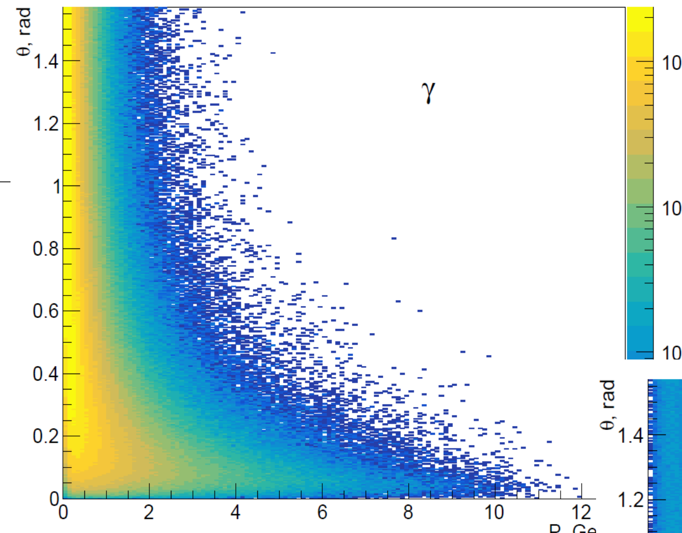
HOME INSTITUTE, EXPERIMENT	RHIC, STAR	RHIC, fsPHENIX	NICA, SPD
Beams	pp, pA, pHe^3	pp pA, pHe^3	pp,pd, dd, pHe^3, dHe^3
Polarization	0.6	0.6	0.6-0.8
Luminosity, cm^{-1} s^{-1}	$5\cdot10^{32}$	$(0.8\text{-}6)\cdot10^{32}$	10^{32}
√s , GeV	160,200, 500	160,200, 500	10-26
X_1, range	0.3-1.0	0.3-1.0	0.1-0.8
Q_T, GeV	1-10	1-10	0.5-6
Lepton pairs	μ+μ-	μ+μ-	μ+μ-, e+e-
Start of data taking	>2020	>2021	2025
Measurements			
Transversity	yes	yes	yes
Boer-Mulders	yes	yes	yes
Sivers	yes	yes	yes
Predzelosity	no	yes	yes
Worm-Gear	yes	no	yes
Flavour separation	yes	yes	yes
Exclusive DY	yes	no	yes
Deuteron quadrupole structure	no	no	yes

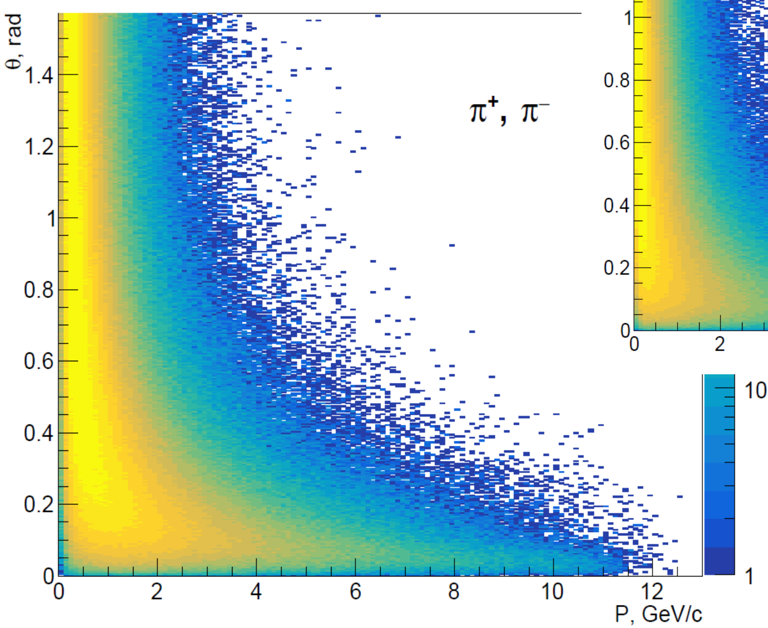
Minimum biased events

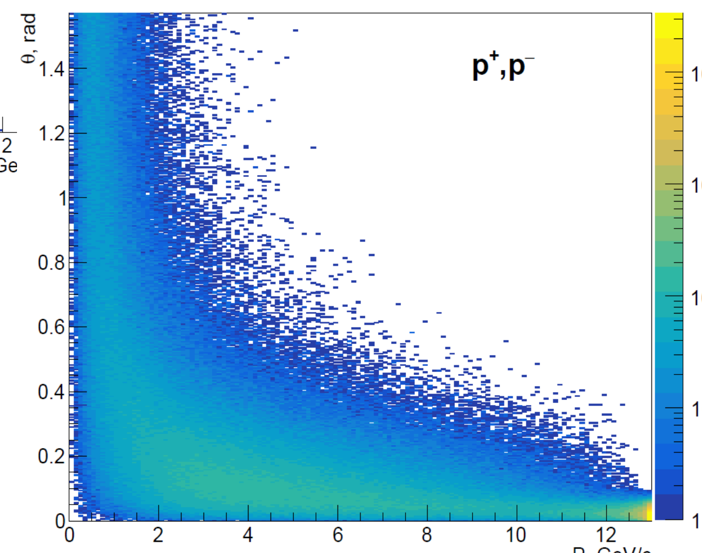
PYTHIA 6, $\sqrt{s_{pp}}$ = 26 GeV; 4 MHz event rate

- Average charged particle multiplicity ≈ 7.8
- Average neutral particle multiplicity ≈ 6.5







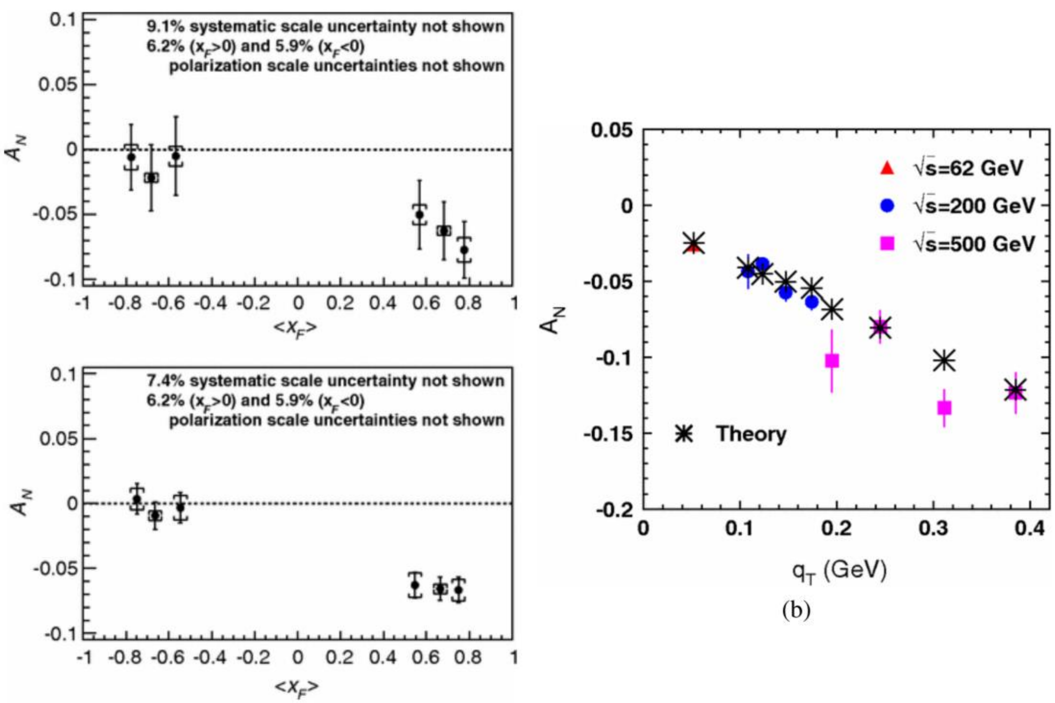


from A. Guskov

Local polarimetry

Asymmetry in inclusive production of charged particles

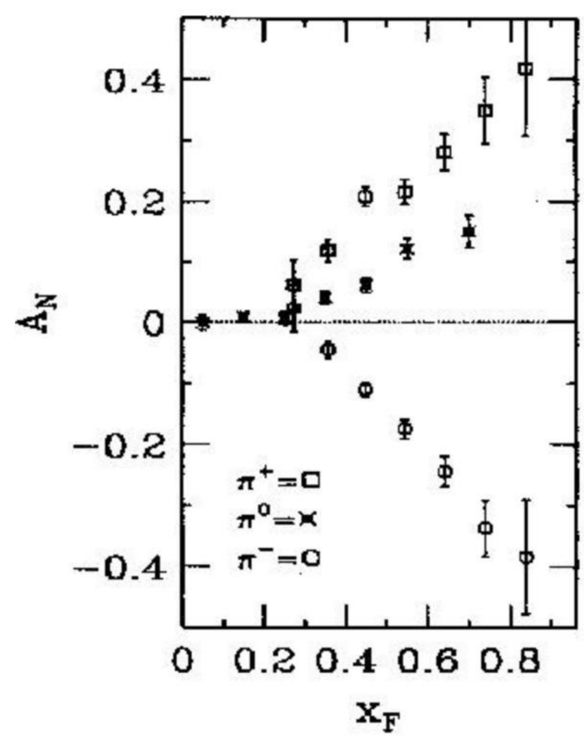
Single transverse spin asymmetry for very forward neutron production



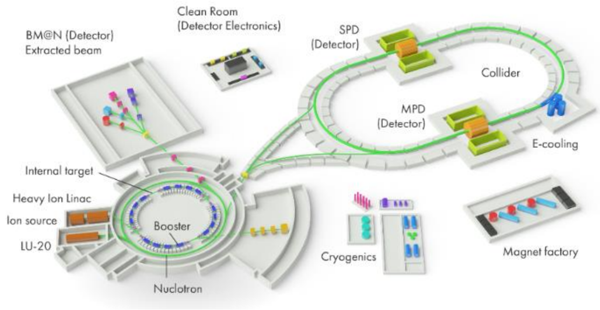
(a)

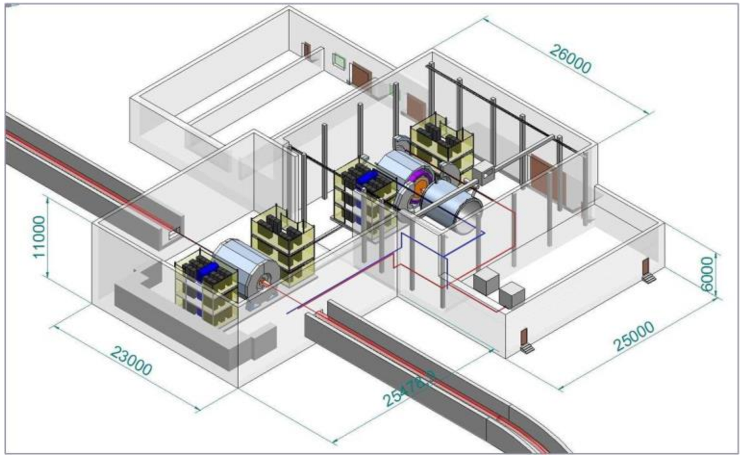
Figure 51: (a) The x_F dependence of A_N for neutron production in the (upper) ZDC trigger sample and for the (lower) ZDC⊗BBC trigger sample. (b) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s}$= 62, 200, 500 GeV measured at PHENIX. The asterisks show the result of the theoretical calculations [90].

Inclusive $pp \to \pi^0 X$ reaction



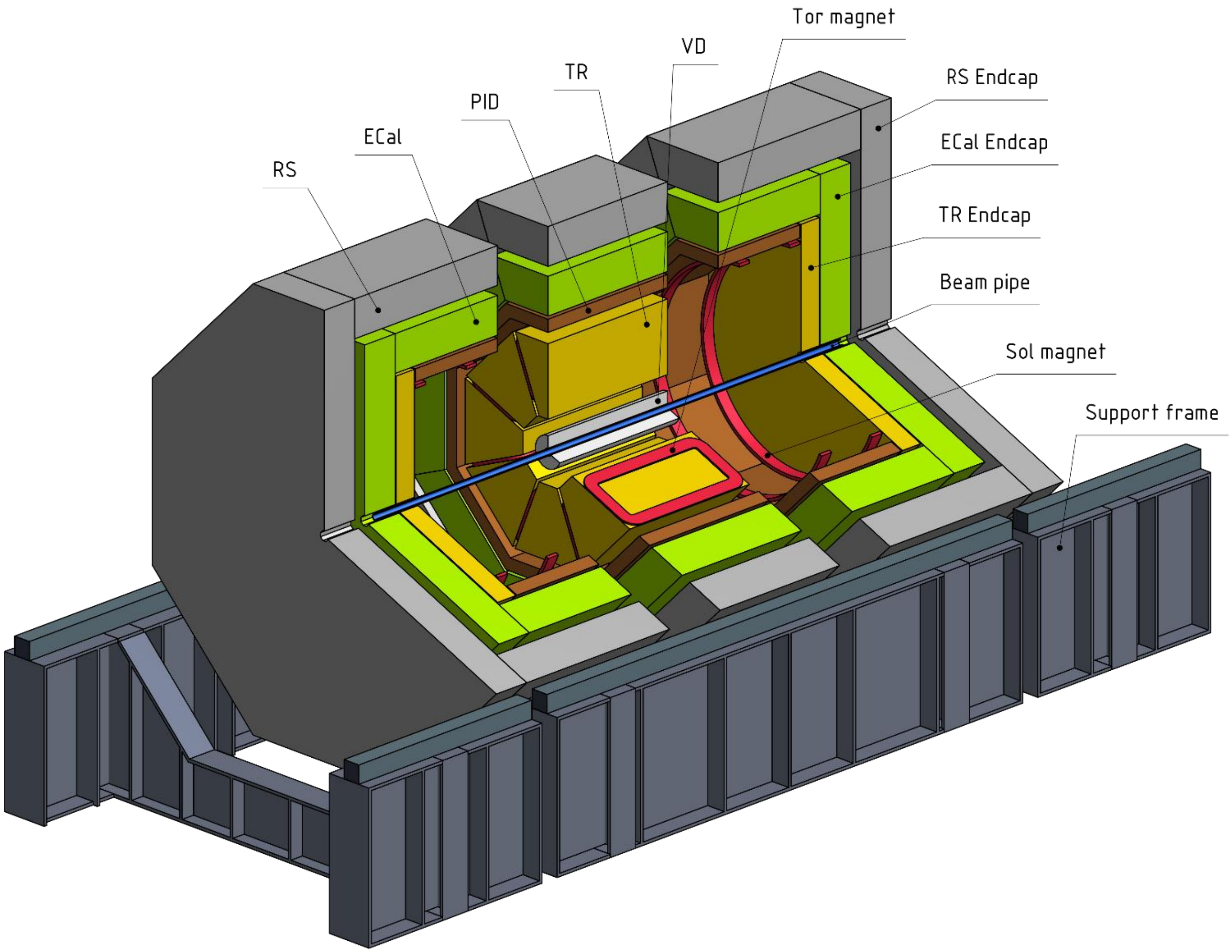
Requirements for the SPD



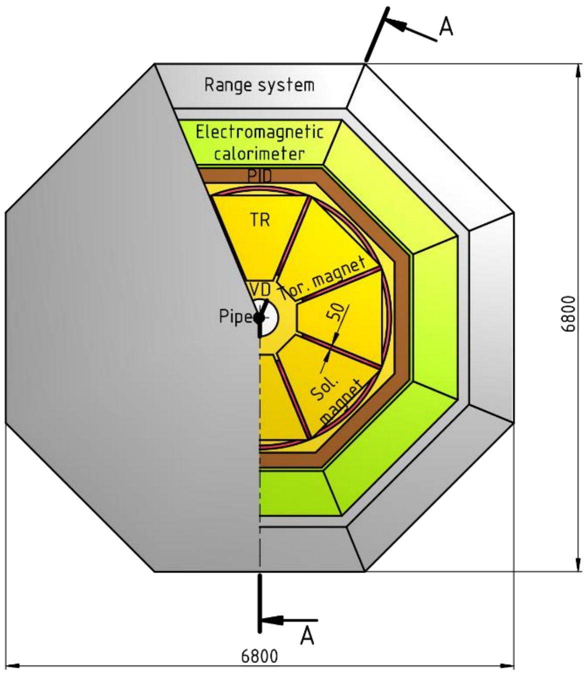


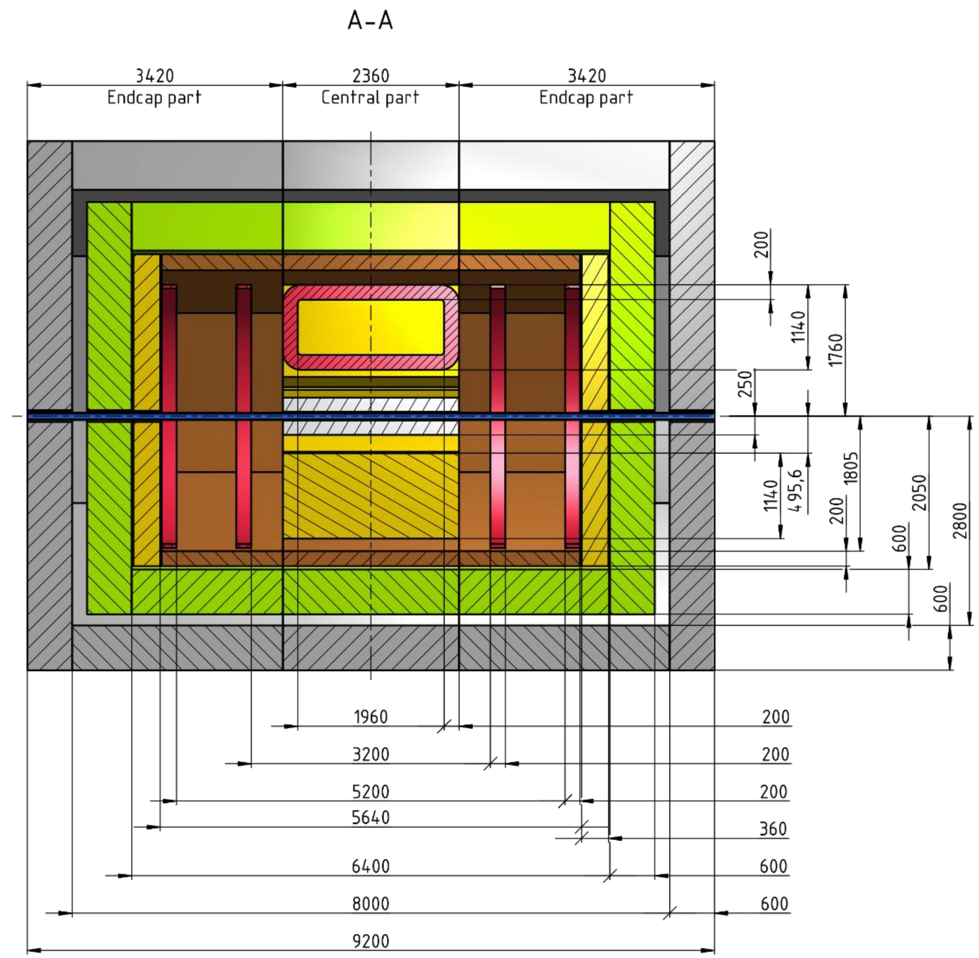
- close to 4π geometrical acceptance;
- high-precision (~50 μm) and fast vertex detector;
- high-precision (~100 μm) and fast tracker,
- good particle ID capabilities;
- efficient muon range system,
- good electromagnetic calorimeter,
- low material budget over the track paths,
- trigger and DAQ system able to cope with event rates at luminosity of 10^{32} $(cm.s)^{-1}$,
- modularity and easy access to the detector elements, that makes possible further reconfiguration and upgrade of the facility.

General view



Dimensions


A
Range system
Electromagnetic calorimeter
PID
TR
VD
Tor. magnet
Pipe
50
Sol. magnet
6800
A
6800


A-A
3420
Endcap part
2360
Central part
3420
Endcap part
200
1140
1760
250
1140
495,6
200
1805
2050
600
2800
600
1960
3200
5200
5640
6400
8000
9200
200
200
200
360
600
600

Hybrid magnetic system

JINR

SPD NICA

½ model symmetry

$$B^{(z)}(x,y,0)=0.$$

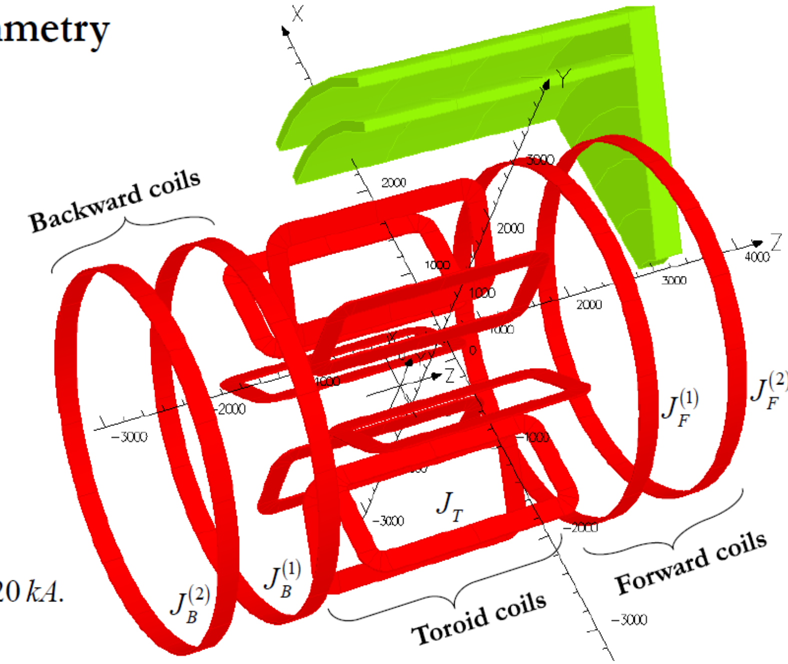
$$J_T = 40\frac{A}{mm^2},$$

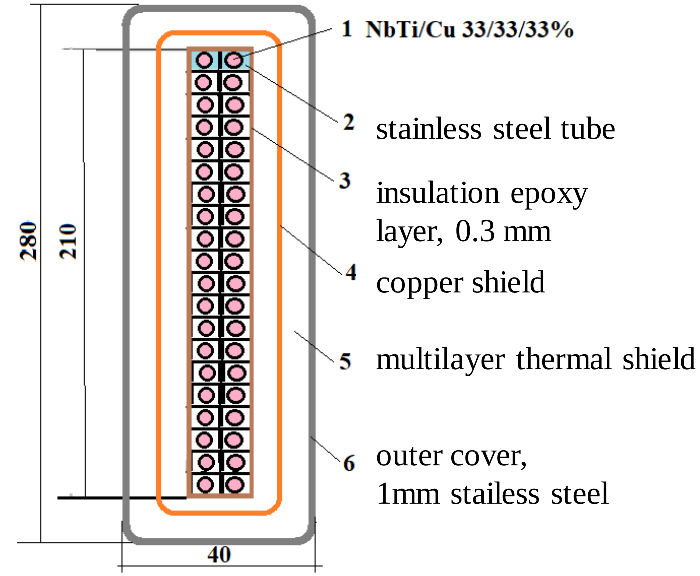
$$J^{(1,2)}_{B\backslash F} = \mp 80\frac{A}{mm^2},$$

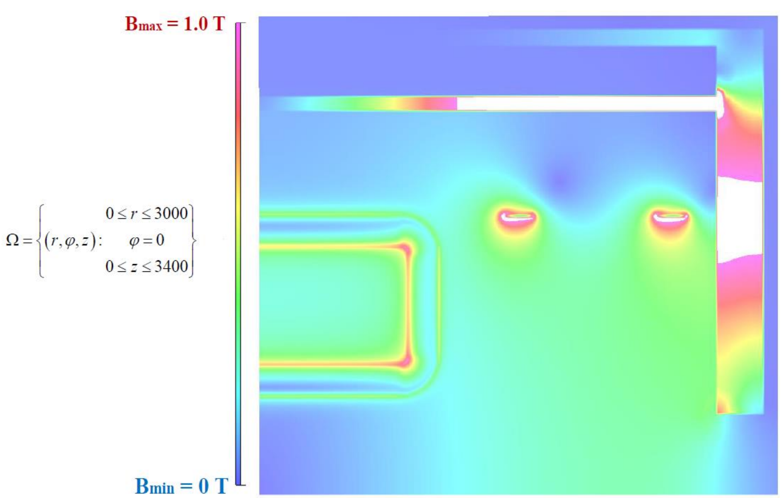
$$S = 200\times 20\,mm^2,$$

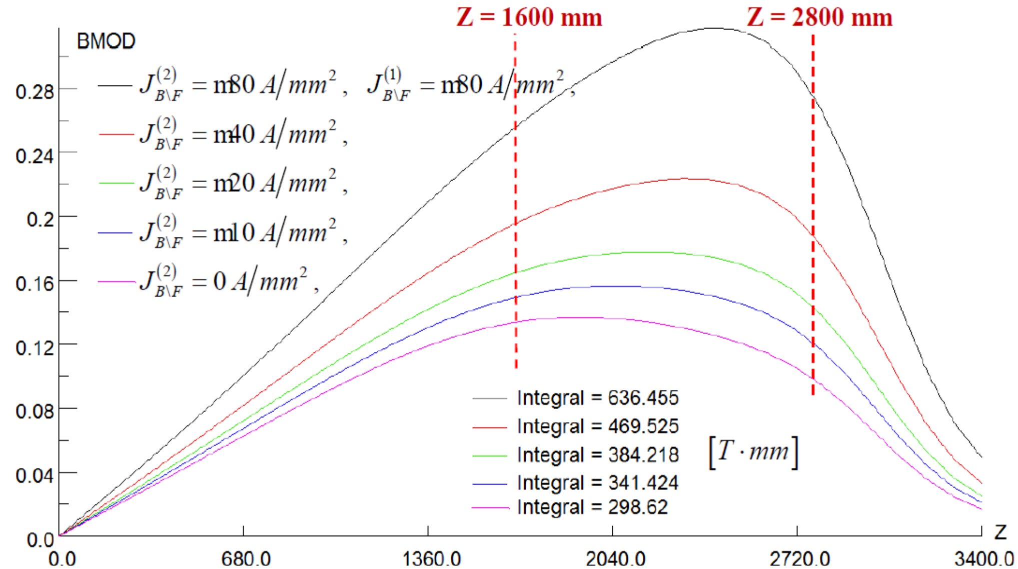
$$I_T = J_T\cdot S = 160\,kA,$$

$$I_{B\backslash F} = J_{B\backslash F}\cdot S = \mp 320\,kA.$$

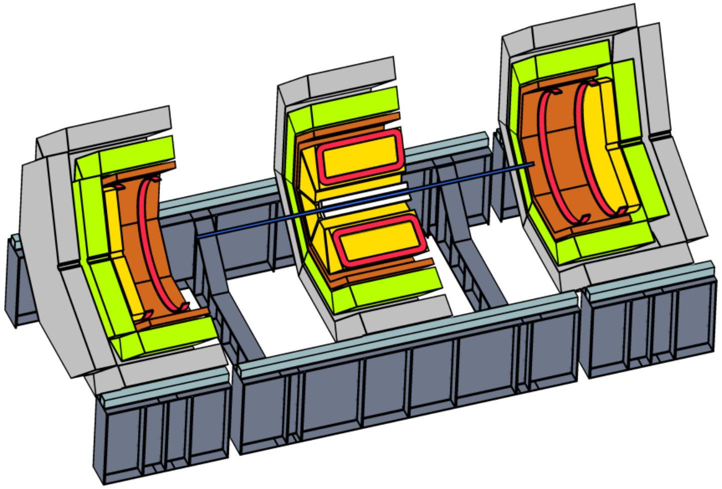


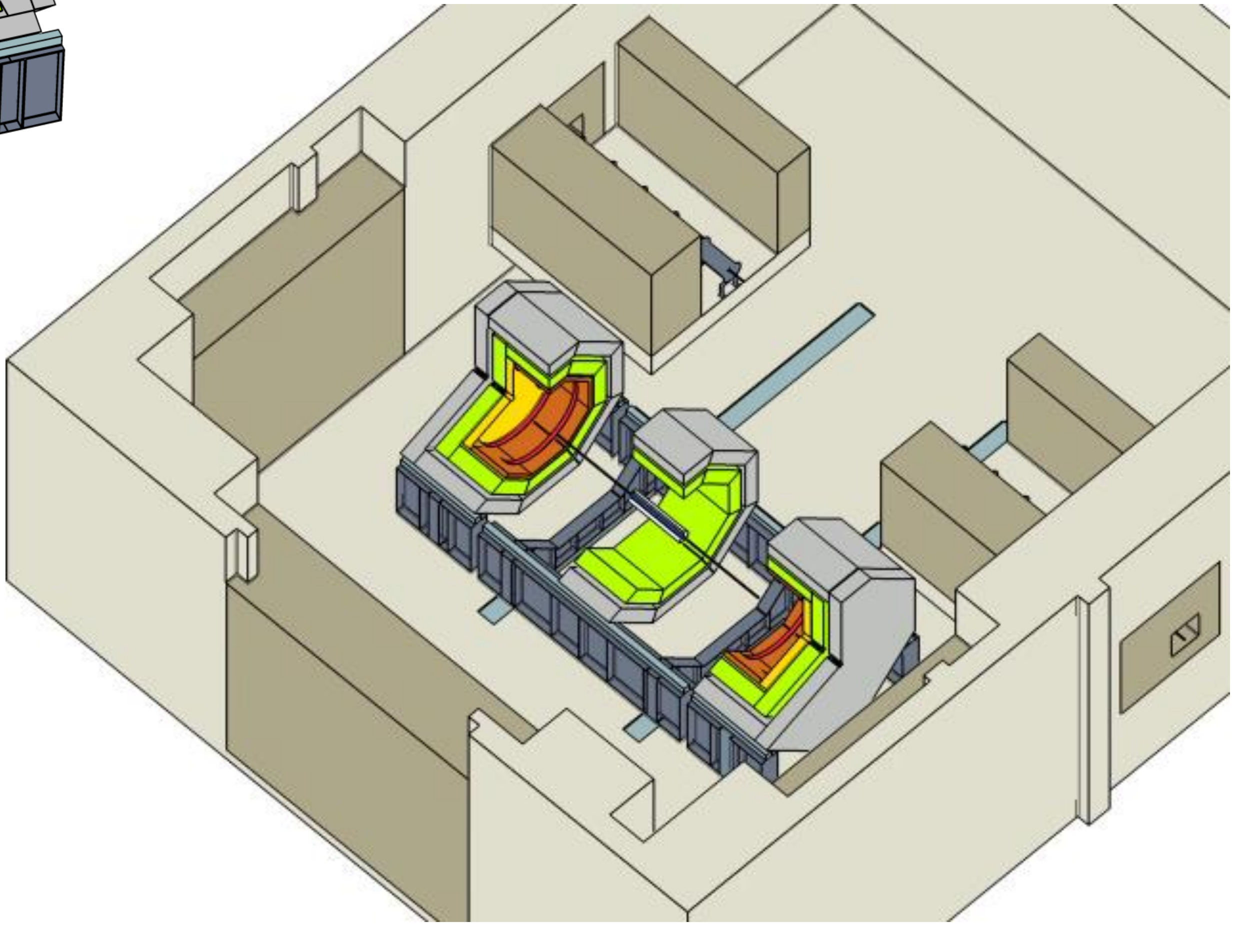




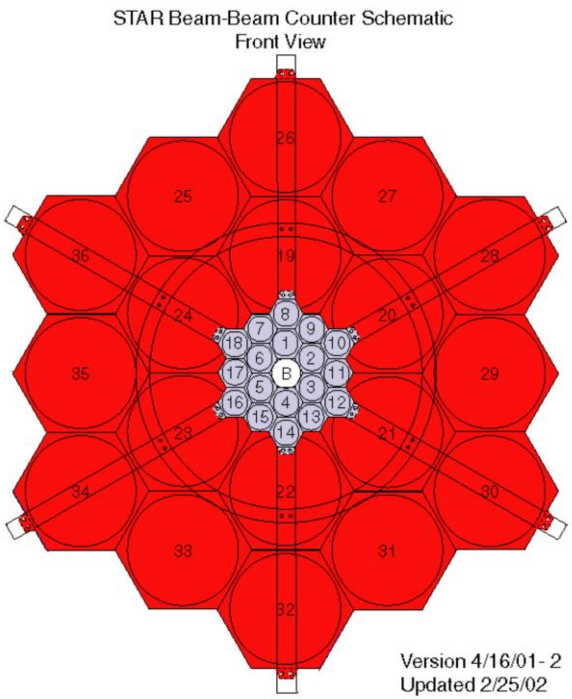


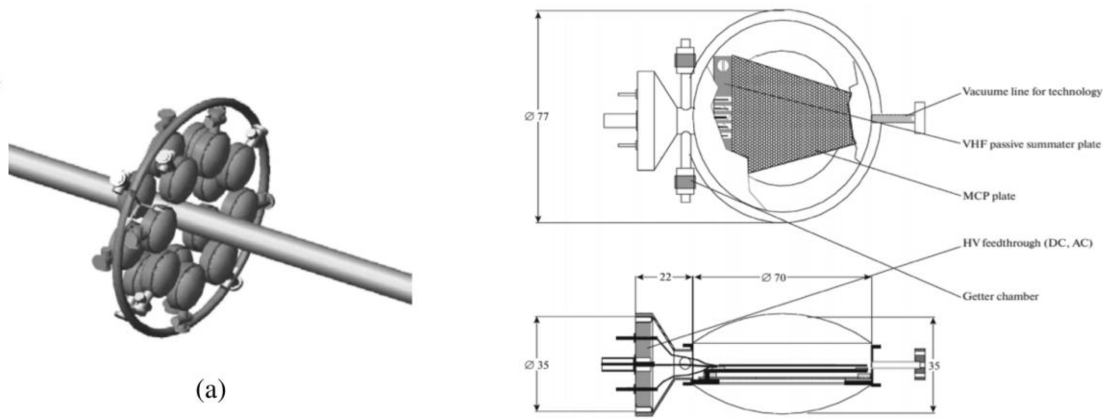
Reconfigurable design





Beam-beam interaction and t0 counters



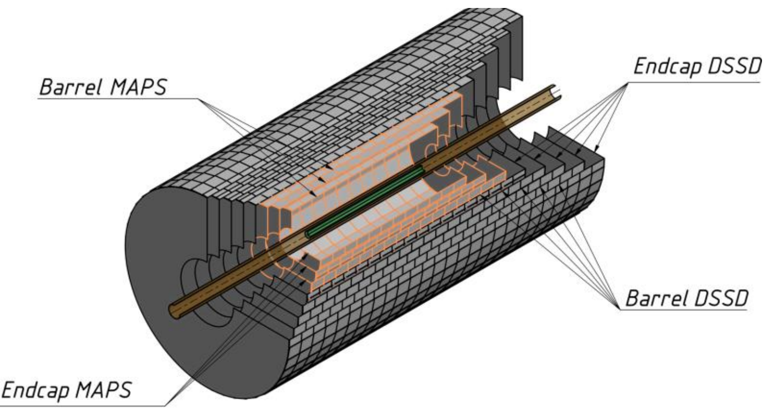


(a)

(b)

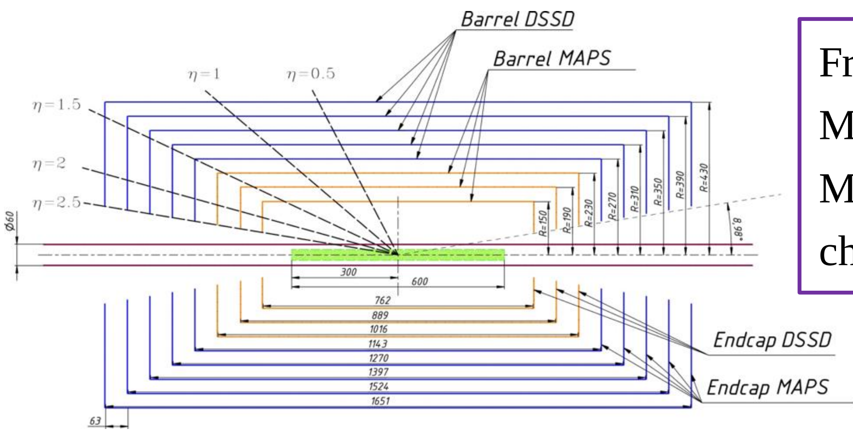
Figure 48: (a) The conceptual general layout of timing and multiplicity detector formed by 16 sectors of MCP placed inside the independent thin wall Ti vacuum chambers around the beam line. (b) General design of the MCP prototype detector embedded into a thin-wall (200 μm) Ti lens-type chamber.

Vertex detector / Inner tracker

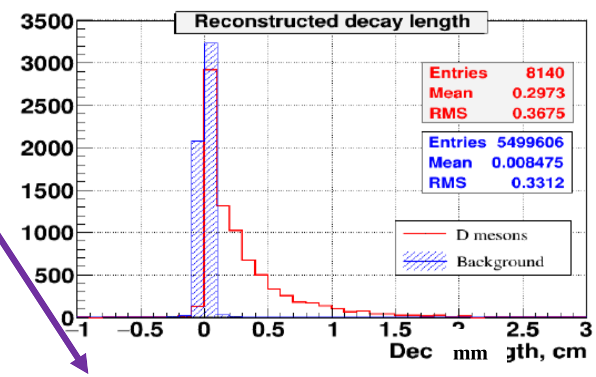


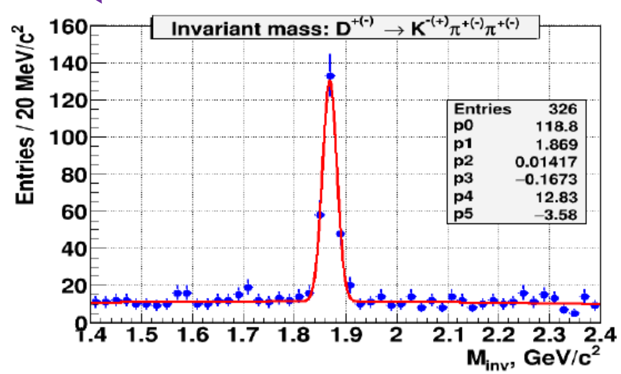
Silicon Vertex Detector

- Silicon vertex detector around the beam pipe;
- Several layers of double sided silicon strips and MAPS;
- Optimized number of layers w.r.t. material budget;
- Goal: few tens of μm resolution for the vertex reconstruction → detection of particles with open charm and rejection of (π) decay muons.



From A. Zinchenko, MPD ITS with MAPS → open charm registration

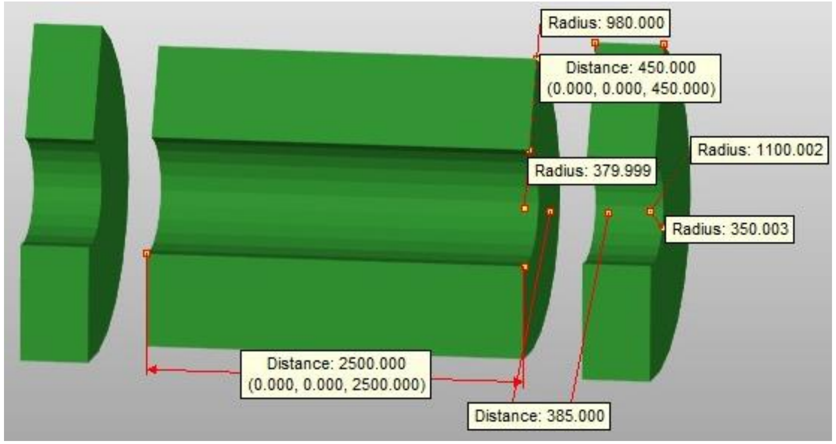




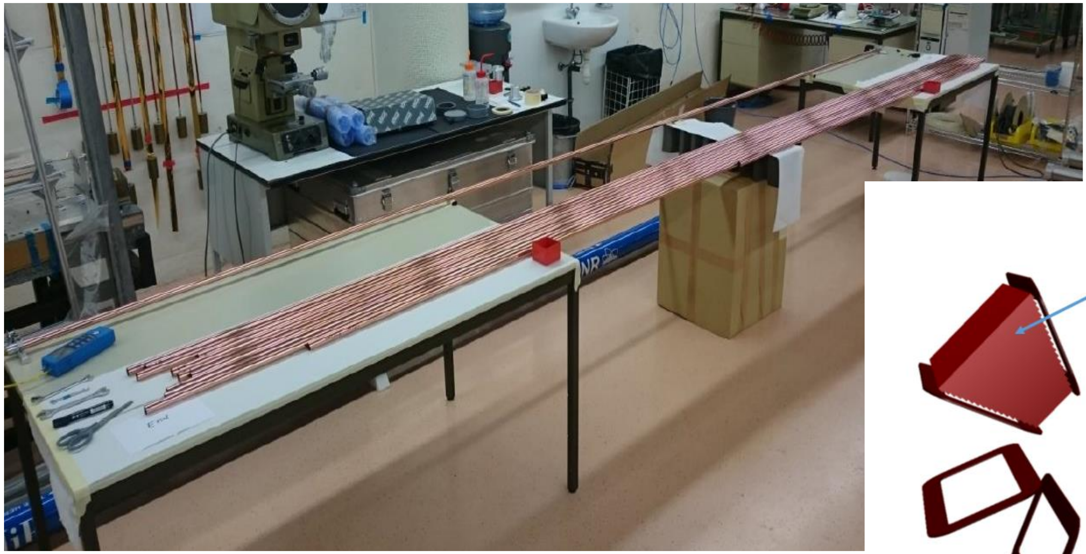
DSSD: 19.5 m^2

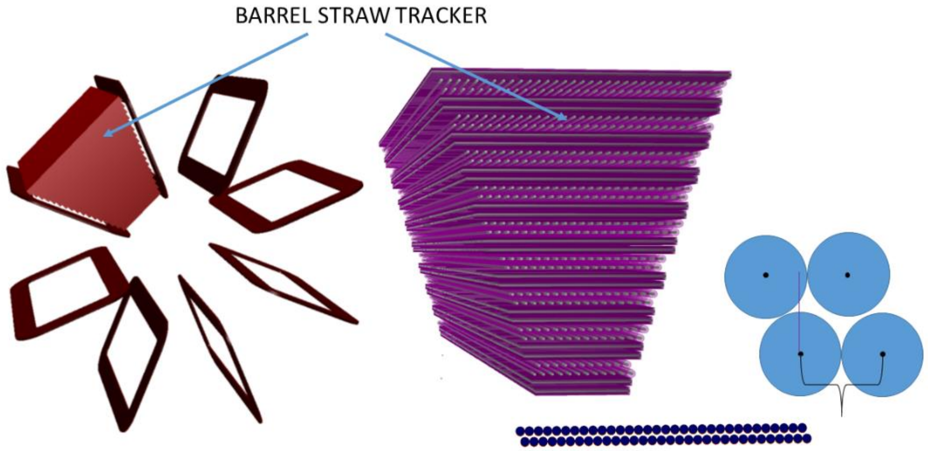
MAPS: 3.5 m^2

Central tracker: straw tubes

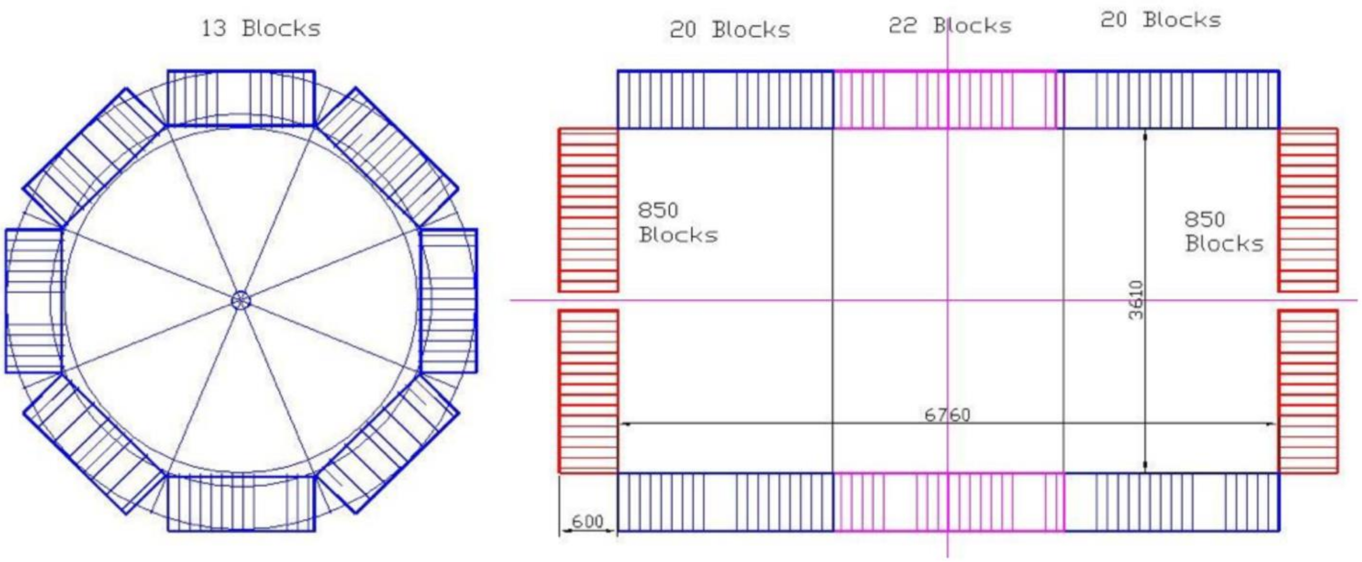


- Minimum material on the particle tracks ($X_0 \sim 0.1$);
- Time (~ 100 ns) and spatial resolution (~100 μm);
- Expected particle rates (DAQ rates) ~ MHz;
- Technology developed also in JINR, production workshops available





Electromagnetic calorimeter



~6500 modules

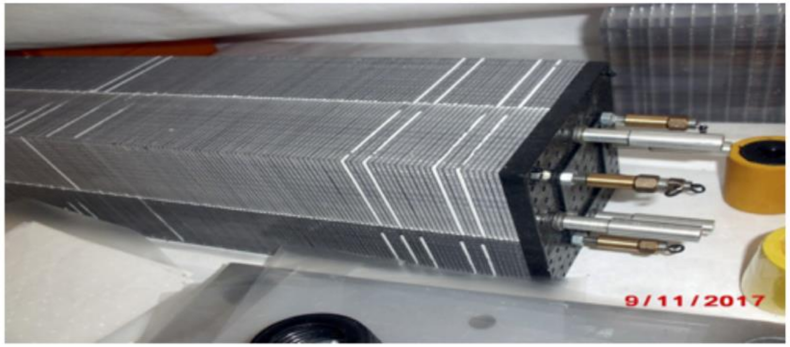
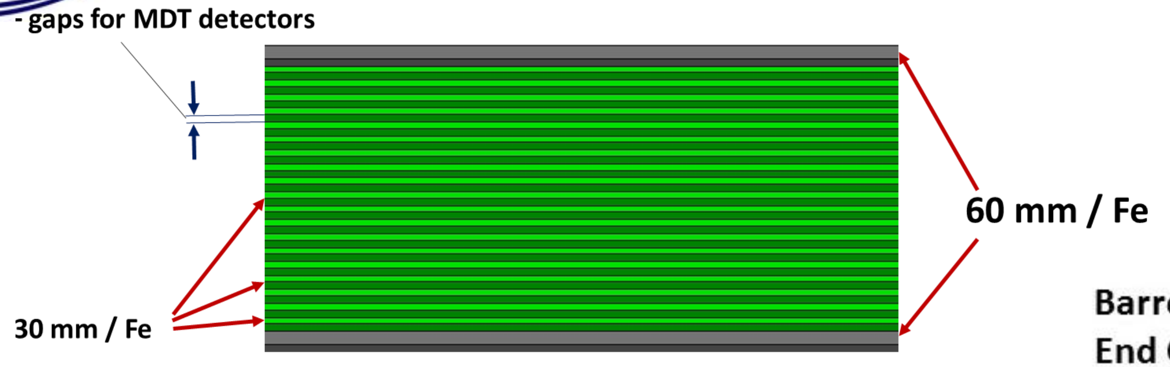


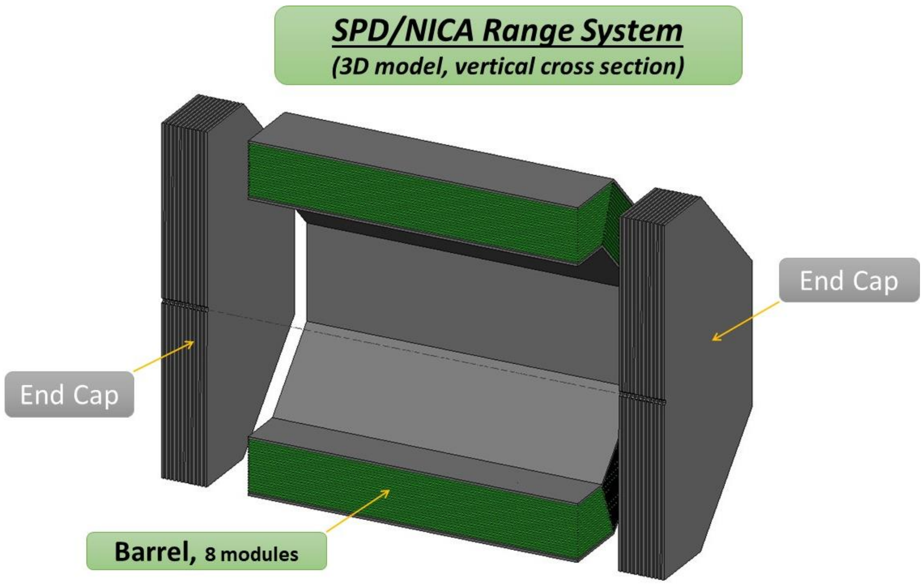
Figure 33: Two by two modules of the KOPIO sampling calorimeter assembled in the single block with 320 layers of lead and scintillator of 0.3 mm and 1.5 mm thick, respectively.

- Photon energy range 0.1 - 10 GeV;
- Due to space limitations the total length of the ECAL module should be less than 50 cm;
- Required energy resolution <10.0%/√E (GeV) and energy threshold below 100 MeV.
- Design ("shashlik") similar of that for KOPIO calorimeter, G. S. Atoian, V. V. Issakov, O. V. Karavichev, T. L. Karavicheva, A. A. Poblaguev, M. E. Zeller, Development of Shashlyk calorimeter for KOPIO, Nucl. Instrum. Meth. A531 (2004) 467–480.
- Crystal variant is being considered, too.

Range system

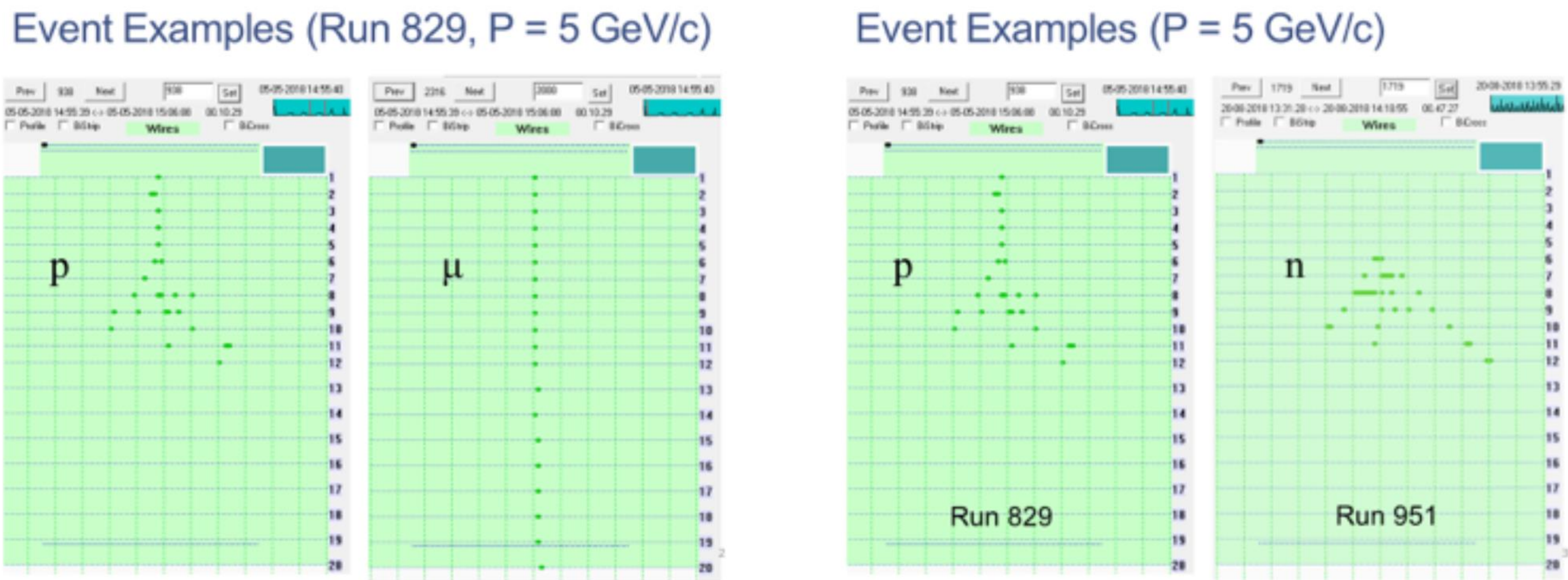


Barrel/Fe: 60+15x30+60 mm (3 λ i);
End Caps/Fe : 9x60 mm (2.8 λ i);
Air gaps = 35 mm; **L /barrel** = 8000 mm;
W = 1224.5 ton
Version : 09.2018



- It should provide good (>95%) muon identification for momenta above 1 GeV.
- Combination of responses from the ECal and RS could give additional lever for regecting of pions and protons in a wide energy range.
- The RS also provides additional coordinate measurement.

Our design will follow closely the design of the PANDA experiment range system (at FAIR, GSI) being developed now at the DLNP of JINR



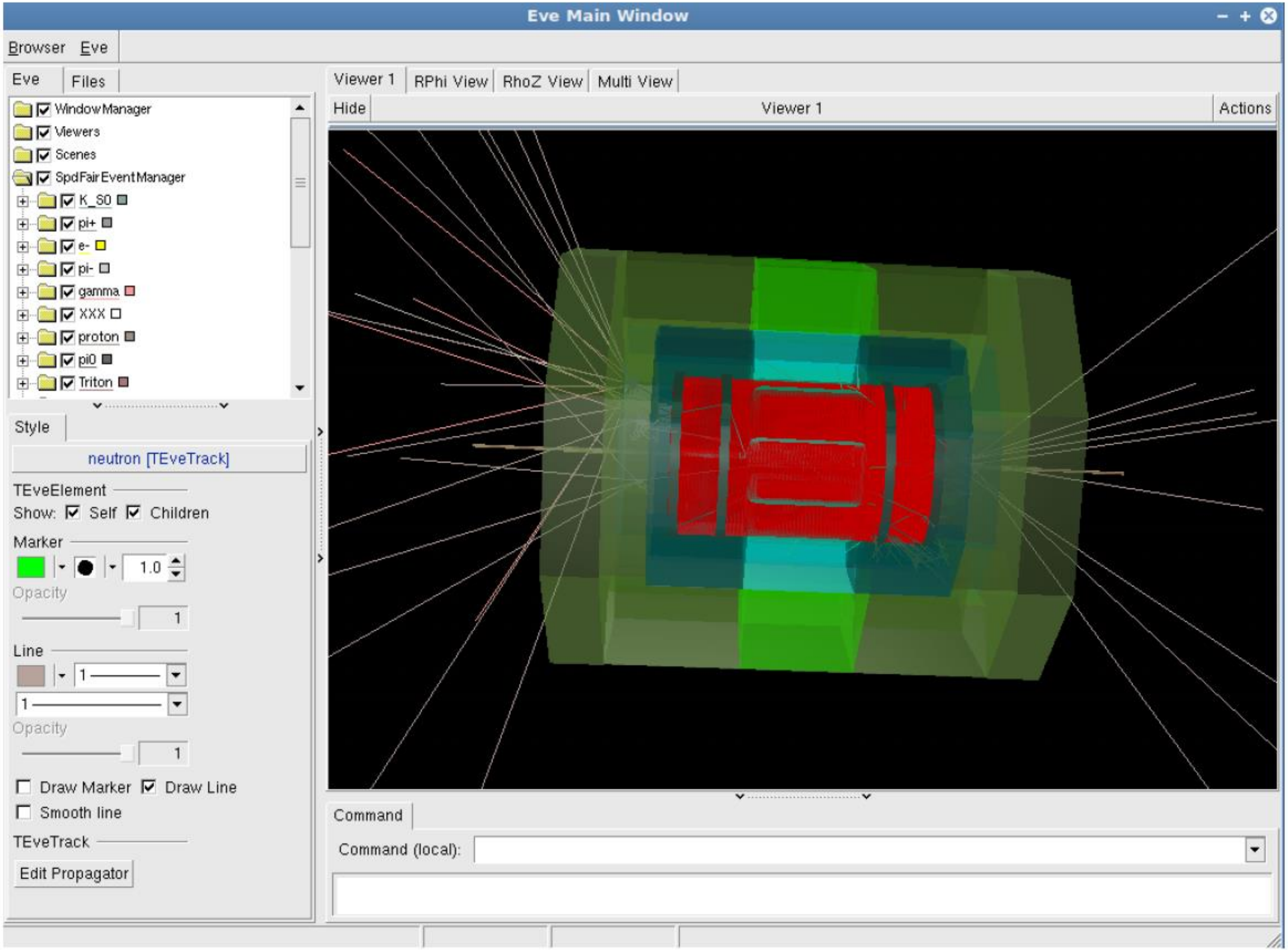
(a) (b)

Figure 43: Demonstration of PID abilities – (a) proton vs. muon, and (b) proton vs. neutron.

DAQ

- The SPD DAQ may be developed *a la* upgraded DAQ of the COMPASS experiment;
- Event rate ~3.0 MHz (at $L=10^{32}$ $cm^{-2}s^{-1}$, $\sqrt{s}=27$ GeV);
- Rough preliminary estimation of the total data flux from the detectors (Si tracker + straw tracker + PID + ECal + range system): 10-20 GBytes/s (no detailed simulation results available yet);
- Triggered or trigger-less DAQ: to be decided.

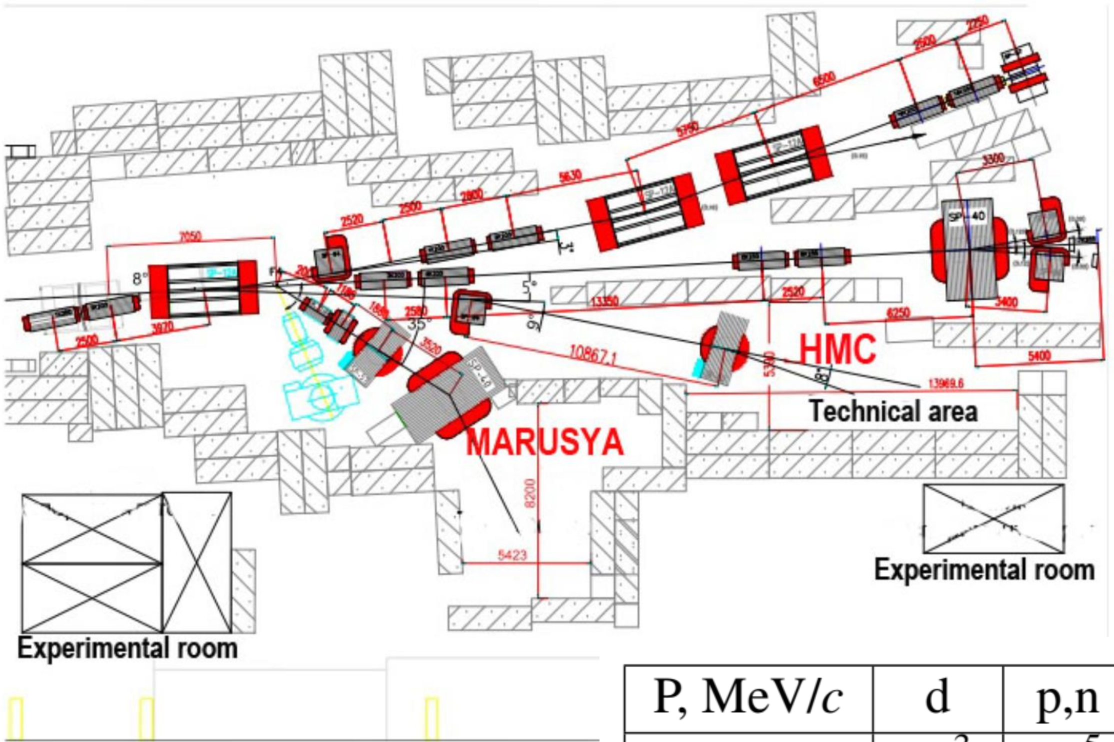
Software and computing



Systems that have not been thought out yet…

- System for particle ID (multigap glass RPCs, Micromegas, Aerogel Cherenkov?);
- "Zero degree" system (fine grained hadron calorimeter?)
- Front-end electronics of the different subsystems;

Beam test facility



P, MeV/c	d	p,n	$\pi^{\pm}$	K^{+}	K^{-}	$\mu^{\pm}$	$e^{\pm}$
400	10^3	10^5	10^5	10^3	10^2	10^3	10^3
800	10^3	10^4	10^4	10^3	10^2	10^3	10^3
1500	10^2	10^4	10^4	10^3	10^2	10^2	10^2
2000	10^4	10^5	10^4	10^3	10^2	10^2	10^2
7000	10^4	10^6	10^3	10^3	10^2	10^2	10^2

Collaborating institutions – 18 so far

- INFN section of Turin and University of Turin;
- ✓ Charles University, Prague;
- ✓ Technical University, Prague
- ✓ Tomsk State University;
- Tomsk Polytechnic University;
- ✓ Institute of Applied Physics of the Belarus Academy of Sciences;
- Gomel State Technical University, Belarus;
- ✓ Institute for High Energy Physics, Protvino;
- ✓ Institute of Nuclear Physics of the Moscow State University;
- Institute for Nuclear Research of the RAS, Troitsk;
- ✓ Lebedev Physics Institute of the RAS, Moscow;
- ✓ Institute for Theoretical and Experimental Physics, Moscow;
- St. Petersburg Nuclear Physics Institute, Gatchina;
- St. Petersburg State University;
- St. Petersburg Polytechnic University;
- Instituto Superior de Tecnologías y Ciencias Aplicadas (INsTEC), Havana University;
- ✓ Warsaw University of Technology;
- ✓ Samara National Research University

Protocols for joint research within the SPD project signed.

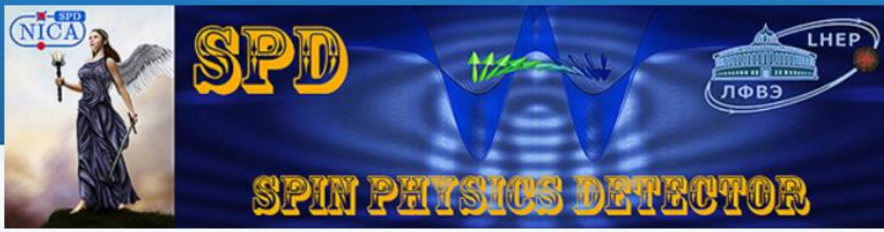
✓ EoI letters received

Bilateral agreements on NICA exist.

Roadmap

- JINR project for the SPD design (Jan. 2019);
- Setting up of the collaboration, MoU (2019);
- Preparation of the Conceptual Design Report (2019);
- Preparation of the Technical Design Report, including prototyping (2020-2022).

Construction of the detector would take at least three years (2022-2025) and first measurements could be expected as early as close to the end of 2025…



International Workshop
"SPD at NICA-2019"

4-8 June 2019
Europe/Moscow timezone

- Overview
- Organizing Committee
- Scientific Program
- Timetable
- Registration
  - Registration Form
- List of participants
- Accomodation
- Transport
- Visa Application
- Contacts

Olga Belova
omatyukhina@jinr.ru

OVERVIEW

The workshop is next in the serie... related to the particles' spin and n... the main goals of the workshop is ... it.

Registration Form

This Internationa...

http://indico.jinr.ru/event/S...

Contacts

/doku.php?id=co...

You are welcome to join the SPD/NICA project!

Web site: *spd.jinr.ru*.

Contact person: Roumen Tsenov (*tsenov@jinr.ru*)

SPD/NICA will provide a unique opportunity
*not available at other facilit*ies
to study all of the PDFs in one experiment
and obtain comprehensive information
on the nucleon spin structure
at high statistical level
with minimal systematic uncertainties

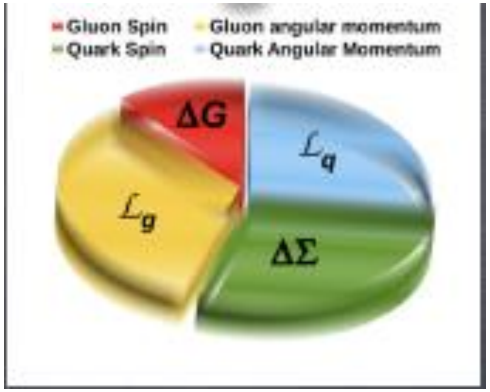
Back-ups

Experiment	CERN, COMP.-II	FAIR, PANDA	FNAL, E-906	SPAS-CHARM	RHIC, STAR	RHIC, PHENIX	NICA, SPD
mode	*FixTar*	*FixTar*	*FixTar*	*FixTar*	*collider*	*collider*	*collider*
Beam/target	π^-, *p*	*anti-p, p*	π^-, *p*	$\pi^\pm$, *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}
$\sqrt{s}$, *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,	$\mu^-\mu^+$	$\mu^-\mu^+$	$\mu^-\mu^+$		$\mu^-\mu^+$	$\mu^-\mu^+$	$\mu^-\mu^+$, 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 separ.	NO	NO	YES		NO	NO	YES
Direct γ	NO	NO	NO		YES	YES	YES

Year 2014

Spin and 3D structure of hadrons

Spin puzzle: small contribution of quarks (may be fractional because of density matrix rather than wave function description) to the proton spin

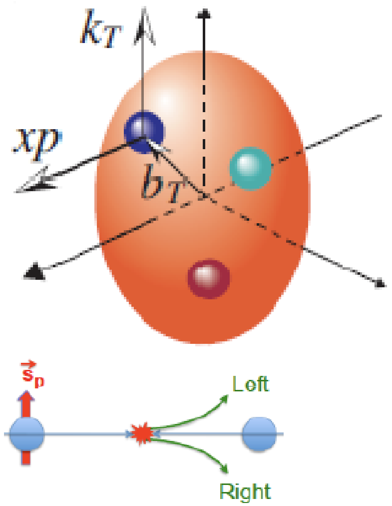


The deficit may be due to:

1.Gluon average spin ΔG, and

2.Orbital motion L related to transverse (completing 3D) structure of proton

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_q + \mathcal{L}_g$$

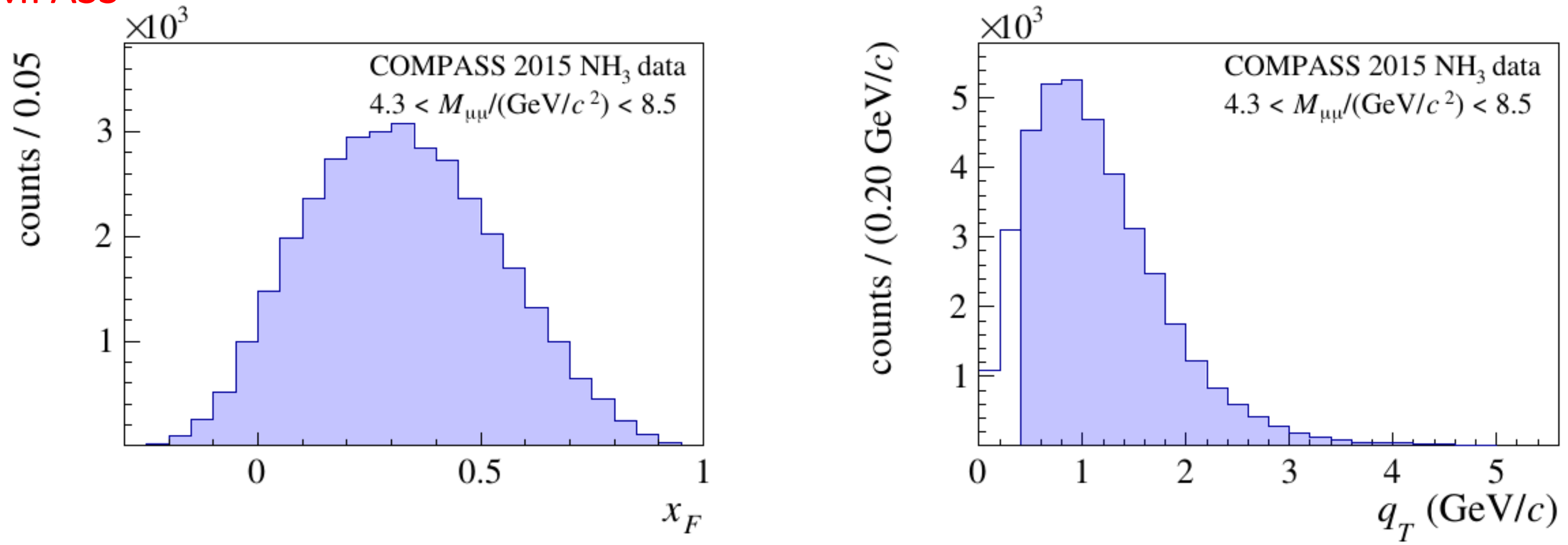


All ingredients can be explored at SPD!

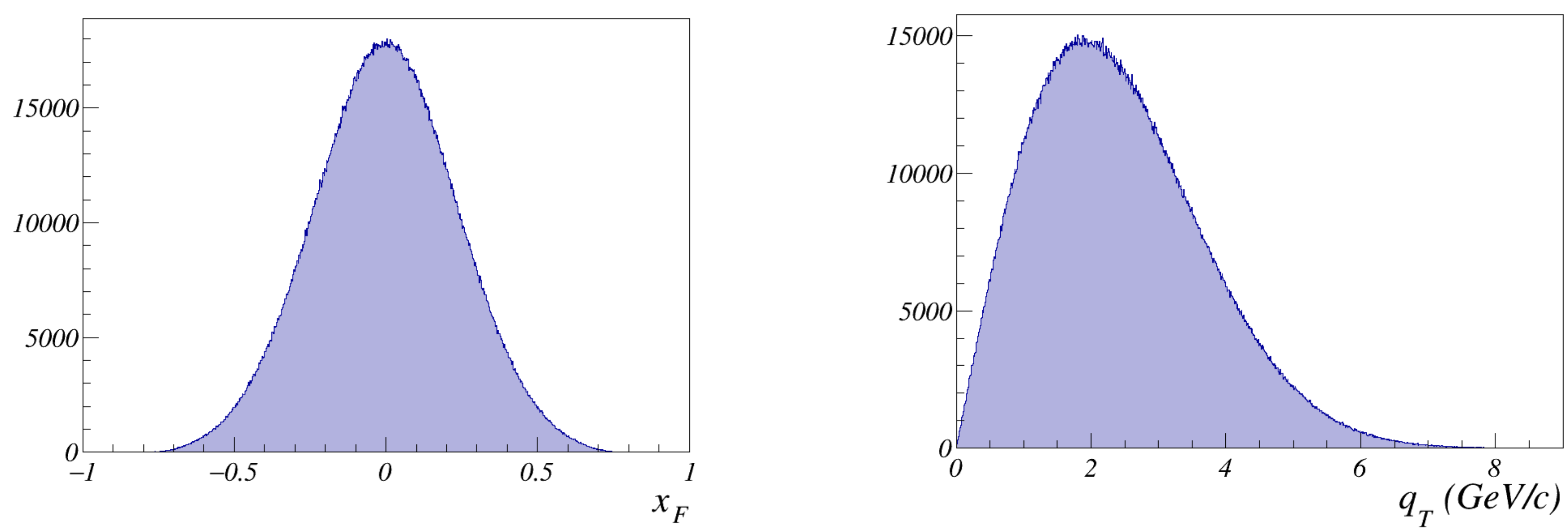
Main instrument: transverse spin asymmetries

The simplest transverse asymmetry : left-right;
more involved: azimuthal modulations

COMPASS


×10^3
counts / 0.05
COMPASS 2015 NH3 data
4.3 < Mμμ/(GeV/c²) < 8.5
xF
×10^3
counts / (0.20 GeV/c)
COMPASS 2015 NH3 data
4.3 < Mμμ/(GeV/c²) < 8.5
qT (GeV/c)

SPD


xF
qT (GeV/c)

Unpolarised Drell-Yan

$$\frac{d\sigma}{d\Omega} \propto (F_U^1 + F_U^2) \times \{1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS} A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}\}$$

$$\lambda = A_U^1, \ \mu = A_U^{\cos\varphi_{CS}}, \ \nu = 2A_U^{\cos 2\varphi_{CS}}$$

Boer-Mulder Boer-Mulder

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,P}^{\perp q}$$

- **"Naïve" Drell-Yan model**

Collinear (k_T= 0) LO pQCD no rad. processes

$\lambda = 1, \ \mu = \nu = 0$

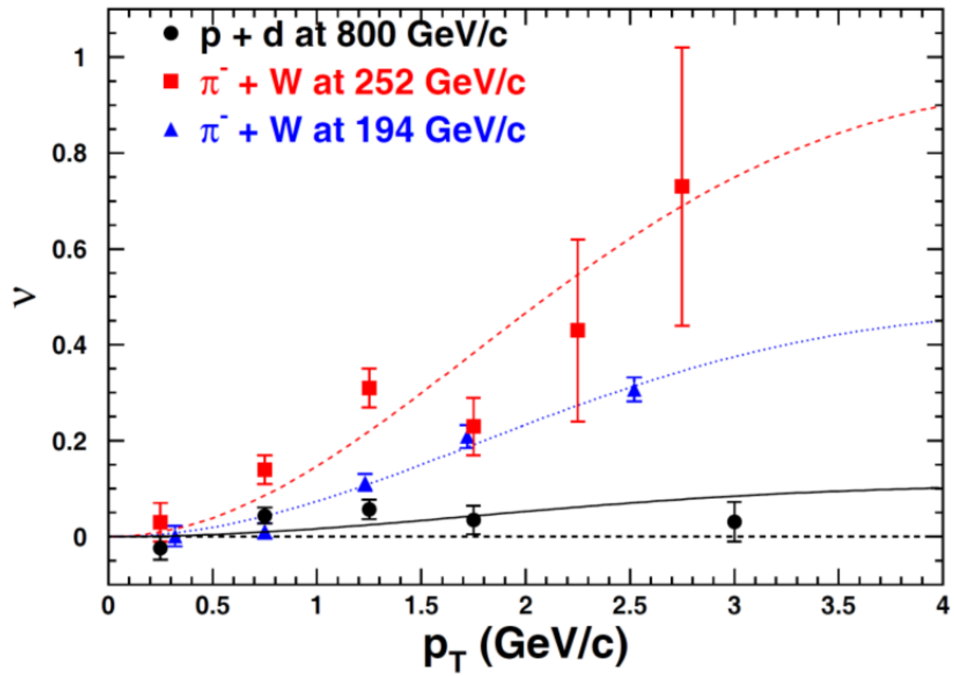
- **Intrinsic transverse motion + QCD effects**

$\lambda \neq 1, \ \mu \neq 0, \ \nu \neq 0$, but $1 - \lambda = 2\nu$ (Lam-Tung)

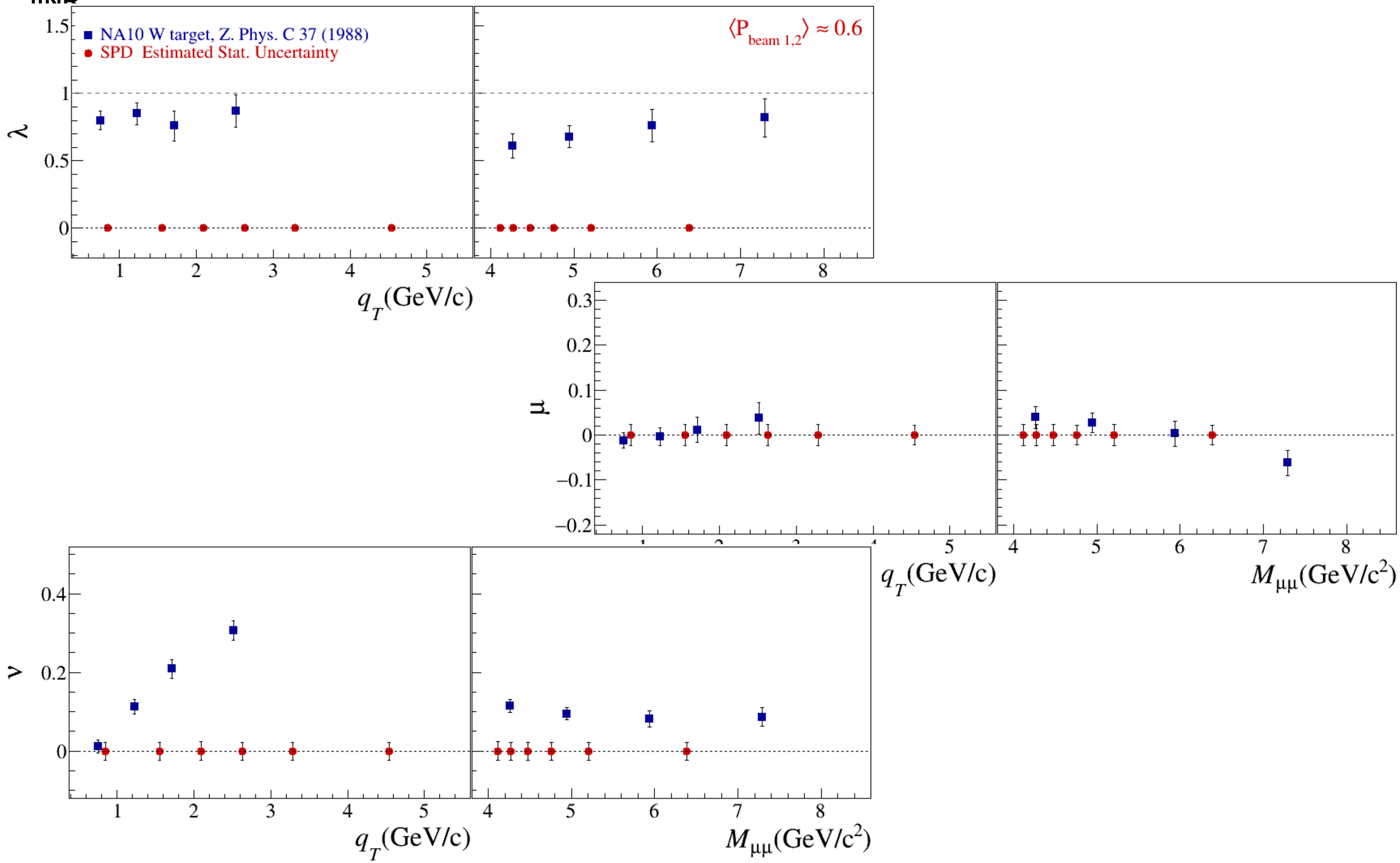
- **Experimentally observed large ν**

and violation of the LT-relation

$\lambda \neq 1, \ \mu \neq 0, \ \nu \neq 0$



DY UA: NA10 vs SPD



In 6 bins
SPD dA ≈ 0.02

with $\langle P_{beam\ 1,2} \rangle = 1.0$ SPD dA ≈ 0.008

Resources

Форма 29

NN пп	Наименование статей затрат	Полная стоимость	2019	2020	2021
1.	Ускоритель, часы	2100	-	700	1400
2.	Конструкт. бюро, нормо-часы,	12250	4000	4000	4250
3.	Опытное пр-во, нормо-часы	12700	4700	4000	4000
4.	Материалы, тыс. долл.	850	445	205	200
5.	Оборудование, тыс. долл.	920	465	235	220
6.	Оплата НИР, тыс. долл.	280	105	105	70
7.	Команд. расходы, тыс. долл., в т. ч.	285	95	95	95
	а) в страны не рублёвой зоны	225	75	75	75
	б) в страны рублевой зоны	60	20	20	20
8.	По протоколам о сотрудничестве	120	30	40	50
	Итого по прямым расходам, тыс. долл.	**2455**	**1140**	**680**	**635**

Ресурсы по подсистемам

	Ускоритель,часы	КБ, часы	ОП, часы	Материалы, k$	Оборуд., k$	НИР, k$	Итого, k$
Калориметр		800	800	25	25	20	70
Мюонная система		1000	1000	135	135	10	280
Идентификация частиц		1000	1000	15	15	40	70
Магнит		2000	2000	15	15	100	130
Трекер		1000	500	135	135	20	290
Вершинный детектор		1500	1500	250	250		500
Система сбора данных					70		70
Компьютинг					30		30
Тестовая зона	1800	3500	4000	250	250		500
Локальная поляриметрия	300	1100	1100	105	105	50	260
Станция мечения		350	800	20	20	40	80
	2100 ч.	**12250ч.**	**12700ч.**	**850 k$**	**920 k$**	**280 k$**	**2050 k$**

ИТОГО из бюджета лаборатории: 2050 k$ + 285 k$ (МНТС) = 2335 k$

JINR participation: 112 authors, 37.7 FTE

- Laboratory of High-Energy Physics
  - authors: 74
  - FTE: 24.4
- Laboratory of Nuclear Problems
  - authors: 30
  - FTE: 11.3
- Laboratory of Theoretical Physics
  - authors: 6
  - FTE: 2
- Directorate (1), Laboratory of Information Technologies (1)