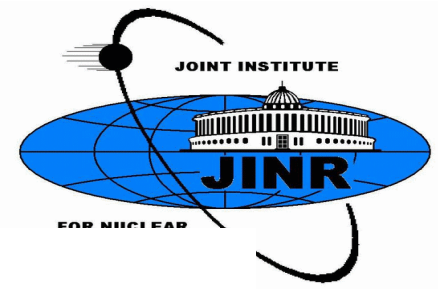
Probing the Deuteron short-range Spin Structure in the (d,p) reactions using polarized deuteron beam at Nuclotron



V.P. Ladygin on behalf of DSS collaboration

59th meeting of the PAC for Particle Physics
22 January 2024

Collaboration

V.A.Baskov[2], E.V.Chernykh[1], V.A.Dronov[2], Yu.N.Filatov[3], Yu.V.Gurchin[1], A.P.Ierusalimov[1], A.Yu.Isupov[1], M.Janek[4], A.M.Kondratenko[5], M.A.Kondratenko[5], V.P.Ladygin[1], N.B.Ladygina[1], K.S.Legostaeva[1], A.N.Livanov[1], A.I.Lvov[2], G.Martinska[6], S.M.Piyadin[1], V.V.Polansky[2], S.G.Reznikov[1], S.S.Sidorin[2], V.V.Syschenko[7], A.A.Terekhin[1], A.V.Tishevsky[1], E.D.Tsyplakov[3], J.Urban[6], I.E.Vnukov[7], I.S.Volkov[1]

Collaboration: **JINR -Russia(4)-Slovakia(2)**

7 Institutes, Universities, Research Centers and Laboratories

12 scientists from JINR

Leader: **Ladygin V.P.**

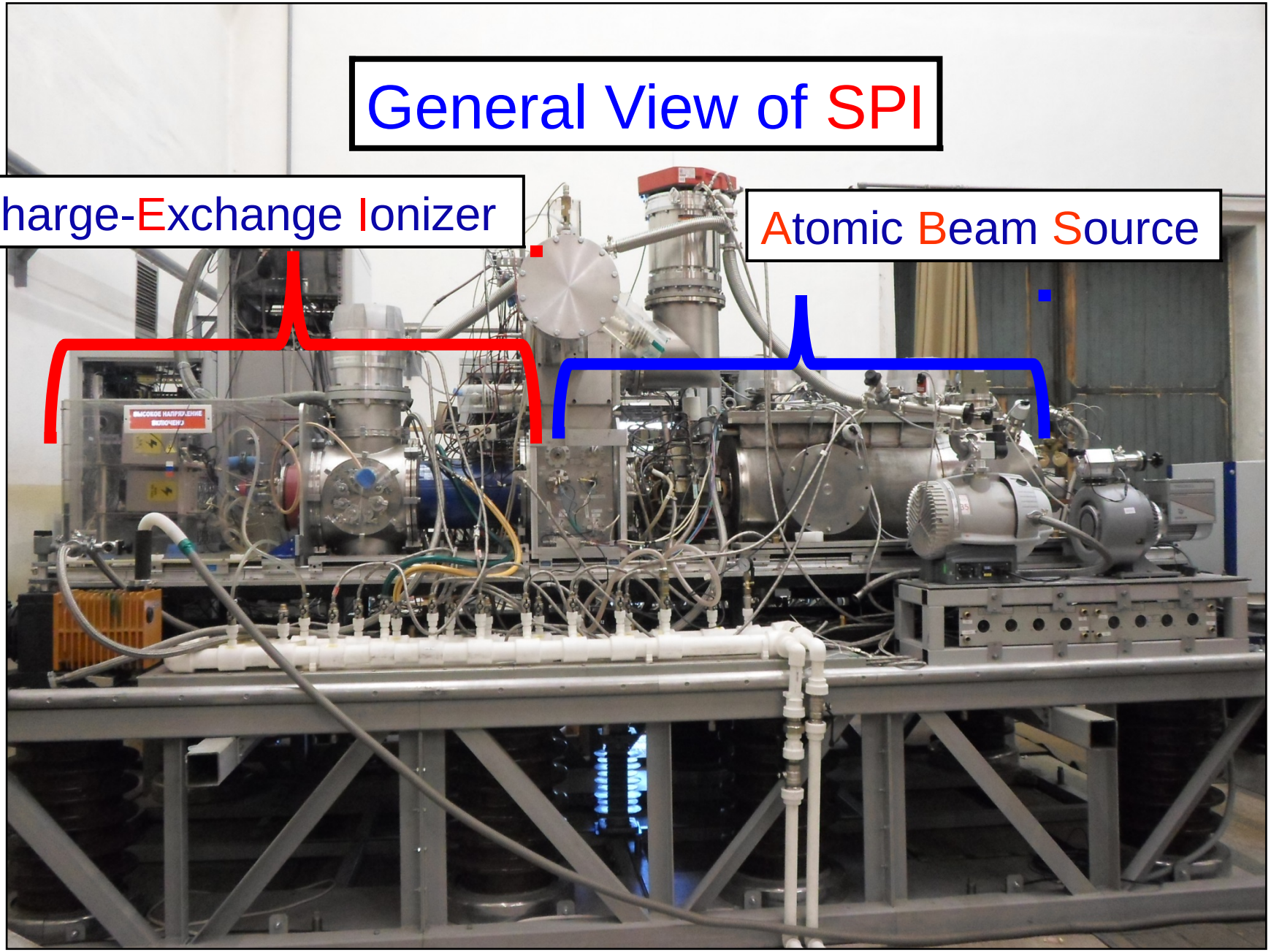
DSS scientific mission

- **Spin structure of the nucleon-nucleon interaction at short distances (Short Range Correlations - SRC)**
- **Beam polarimetry**
- **Experiments on the spin manipulation at Nuclotron**

Most of the results are obtained using new Source of Polarized Ions (SPI) at Nuclotron

(developed partly using the equipment obtained from IUCF polarized ion source).

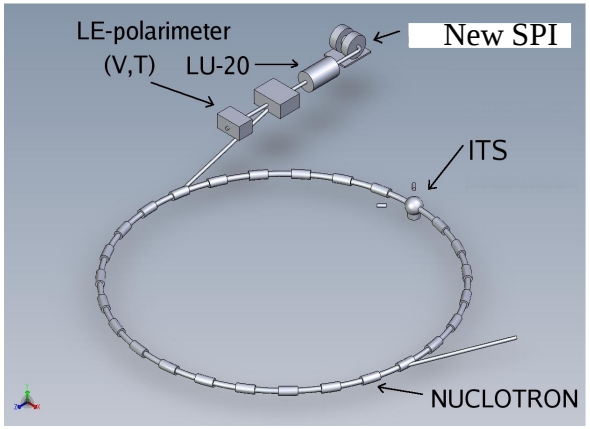
General View of SPI

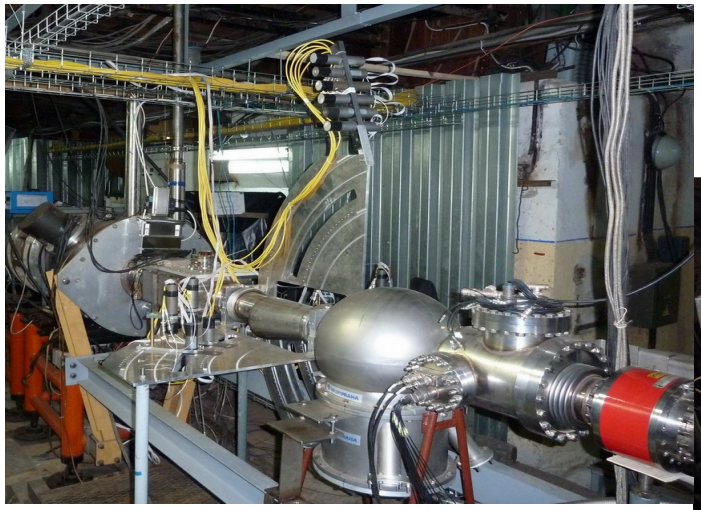


New SPI will increase beam figure of merit by a factor ~10^3

Experiments at Internal Target Station at Nuclotron

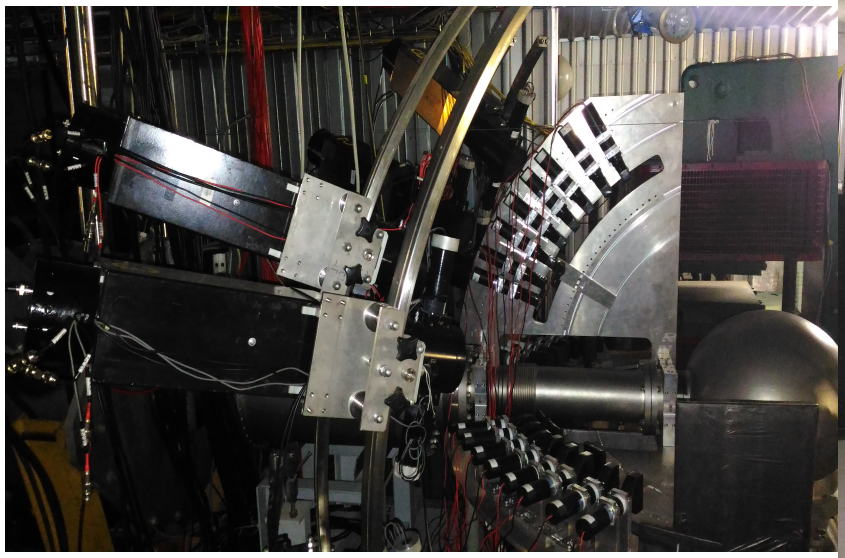
DSS-project

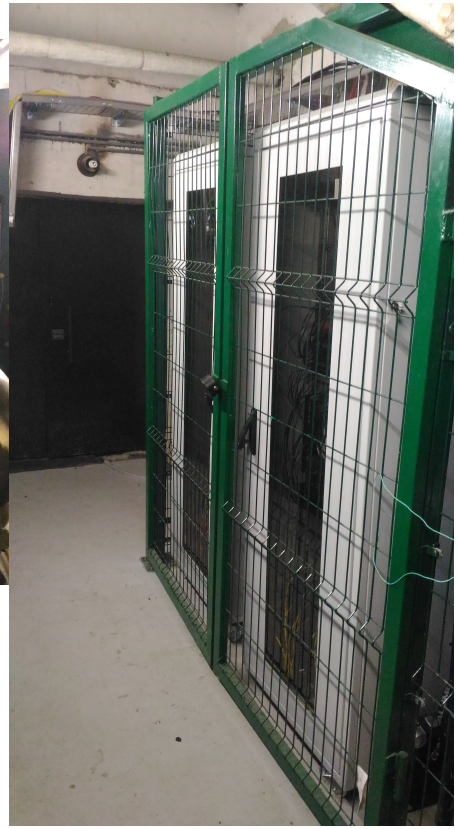




Internal Target Station is very well suited for the measurements of the deuteron- induced reactions observables at large scattering angles.

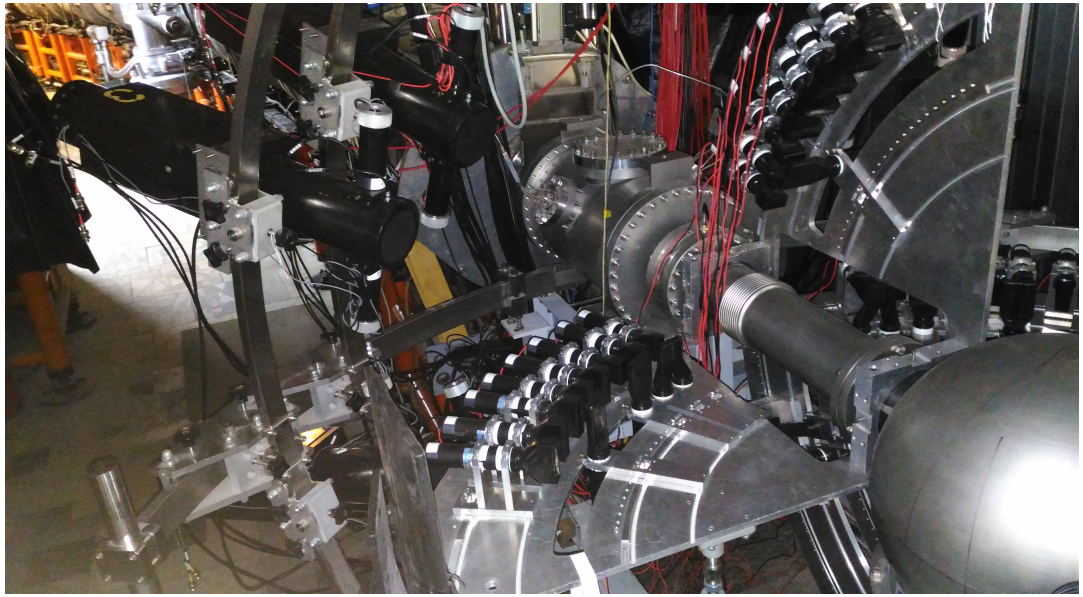
Upgrade of the DSS setup at ITS at Nuclotron





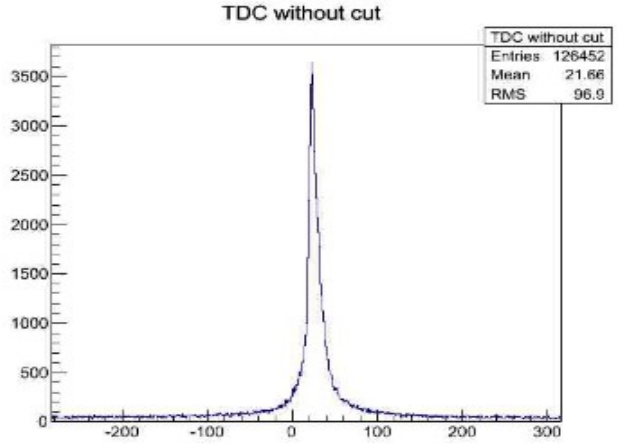
New infrastructure, cabling
HV system (Mpod)
VME DAQ
40 counters for dp-elastic scattering studies
8 dE-E detectors for dp -breakup studies
2 Forward arms for ion-ion collisions studies

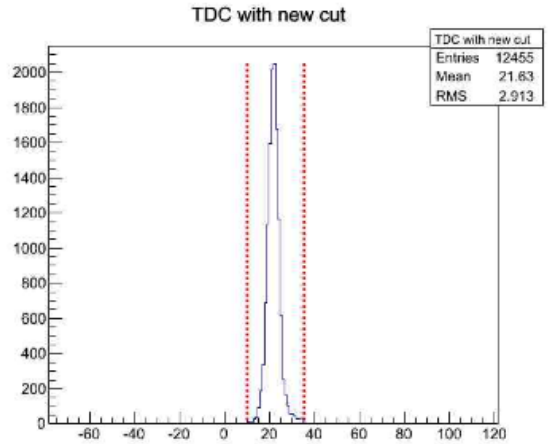
Setup to study dp- elastic scattering at ITS at Nuclotron

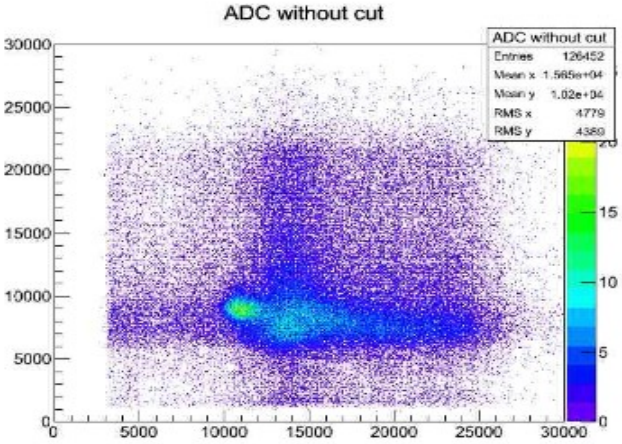


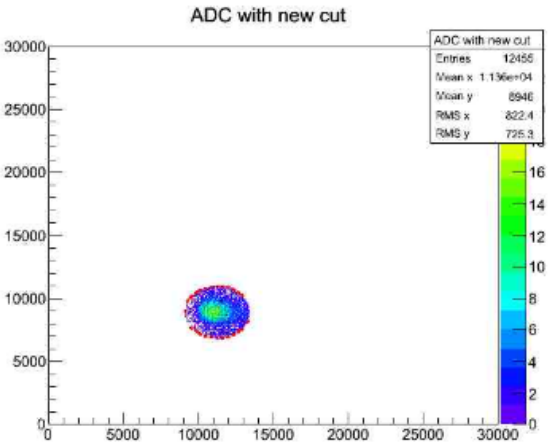
- Deuterons and protons in coincidences using scintillation counters
- Internal beam and thin CH_2 target (C for background estimation)
- Permanent polarization measurement at 270 MeV (between each energy).
- Analyzing powers measurement at 400-1800 MeV
- The data were taken for three spin modes of SPI: unpolarized, “2-6” and “3-5” with $(p_z,p_{zz}) = (0,0)$, $(1/3,1)$ and $(1/3,-1)$.
- Typical values of the polarization were 70-75% from the ideal values.

The dp-elastic scattering events selection





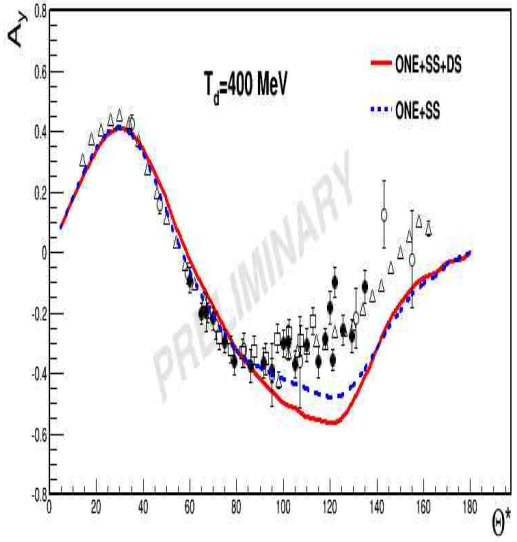


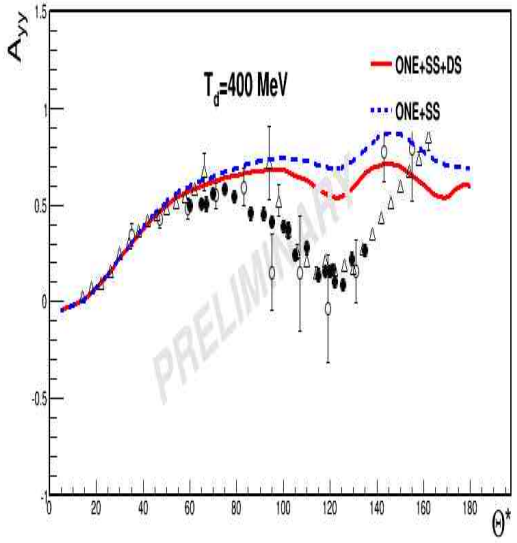


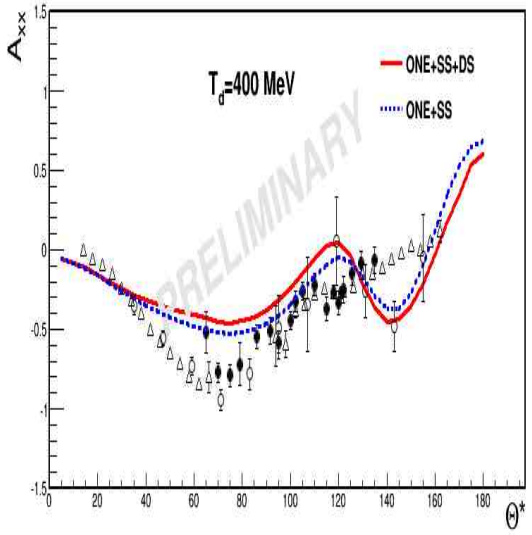
Selection of the dp elastic events by the time difference between the signal appearance from deuteron and proton detectors with the criteria on the amplitude signal correlation.

Angular dependence of the vector and tensor analyzing powers in dp-elastic scattering at 400 MeV

Ay **Ayy** **Axx**



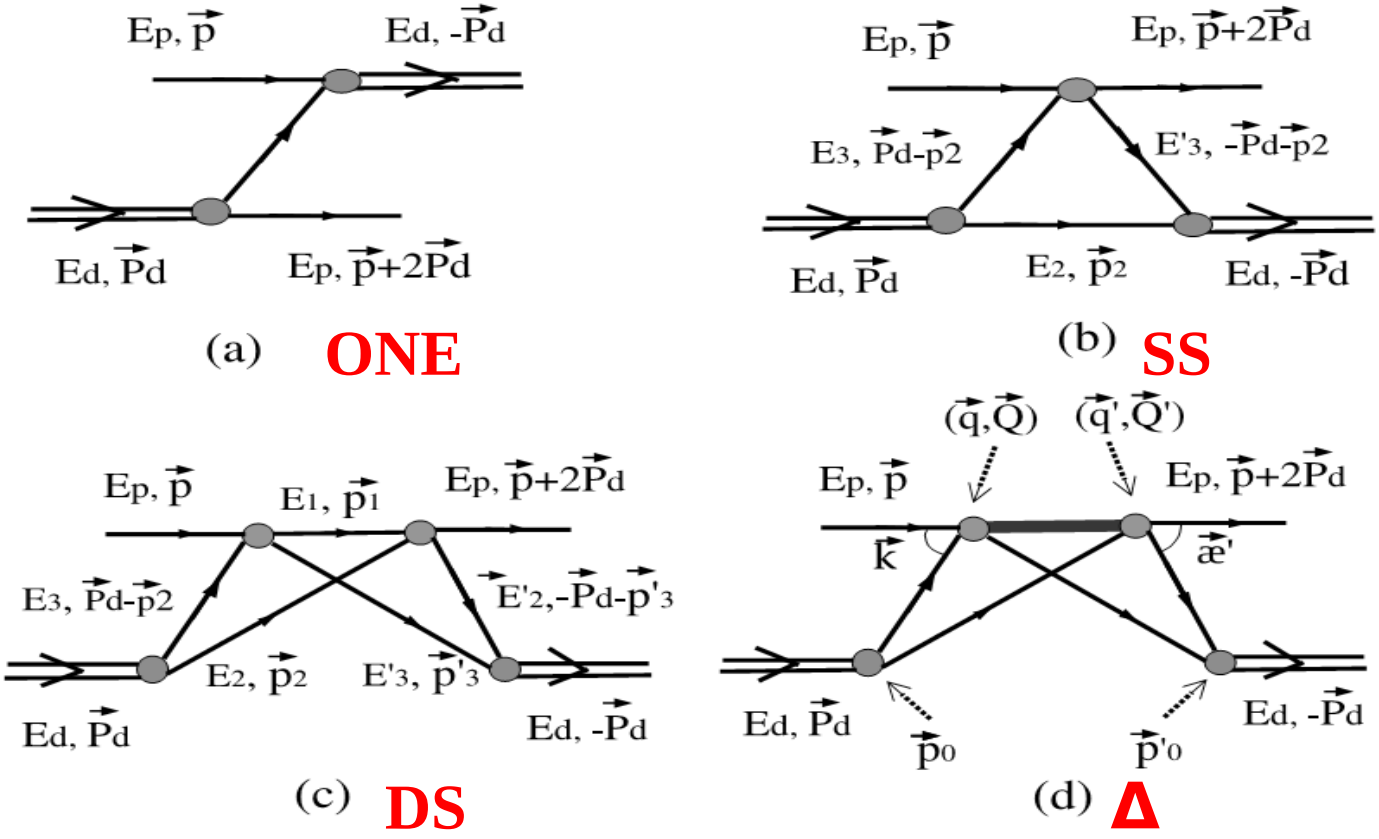




Full symbols are the data from Nuclotron.
Open symbols are the world data (IUCF, Saclay).

Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

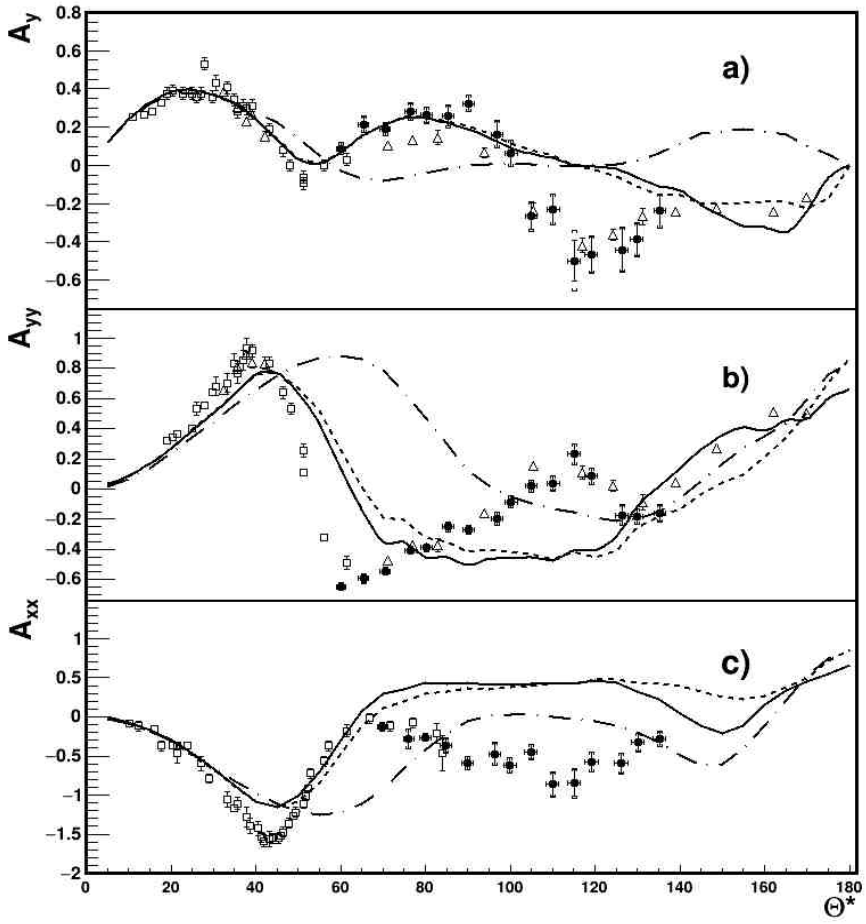
Relativistic multiple scattering model for dp- elastic scattering at moderate energies



ONE+SS+DS - **N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039**
N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

ONE+SS+DS +Δ- **N.B.Ladygina, Eur.Phys.J, A52 (2016) 199**
N.B.Ladygina, Eur.Phys.J, A56 (2020) 133

Angular dependencies of the vector Ay and tensor Ayy and Axx analyzing powers in dp-elastic scattering at 1300 MeV

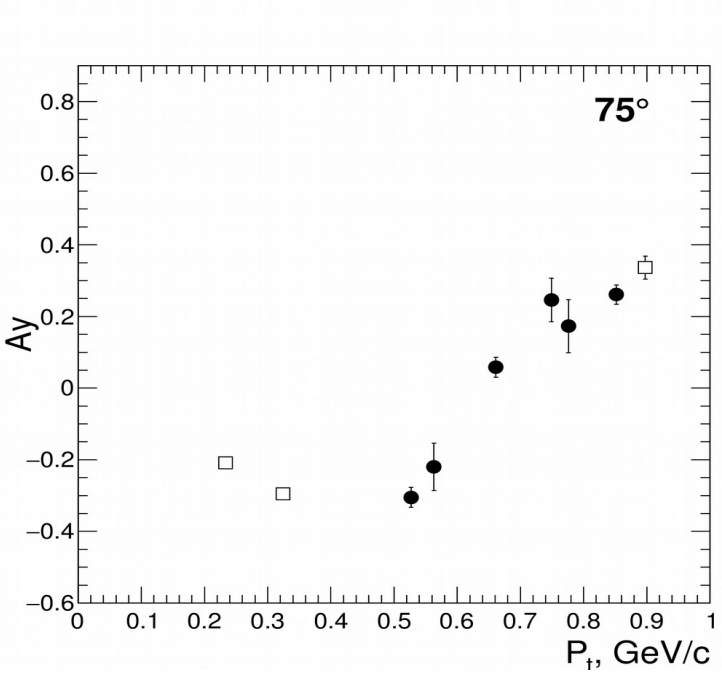


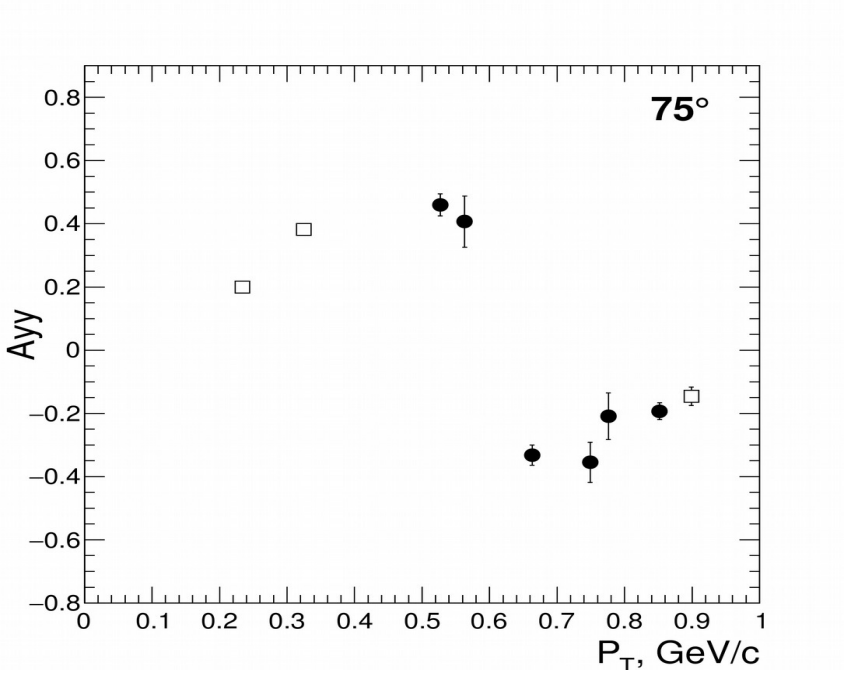
Data shown by the open triangles and squares are obtained at 1200 MeV at Saclay and ANL, respectively.

Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.
+ additional ρ-meson exchange

Structure in Ay-Ayy behaviour observed at Saclay at 1200 MeV and at 100-130 degrees in cms is confirmed, its energy dependence is studied.

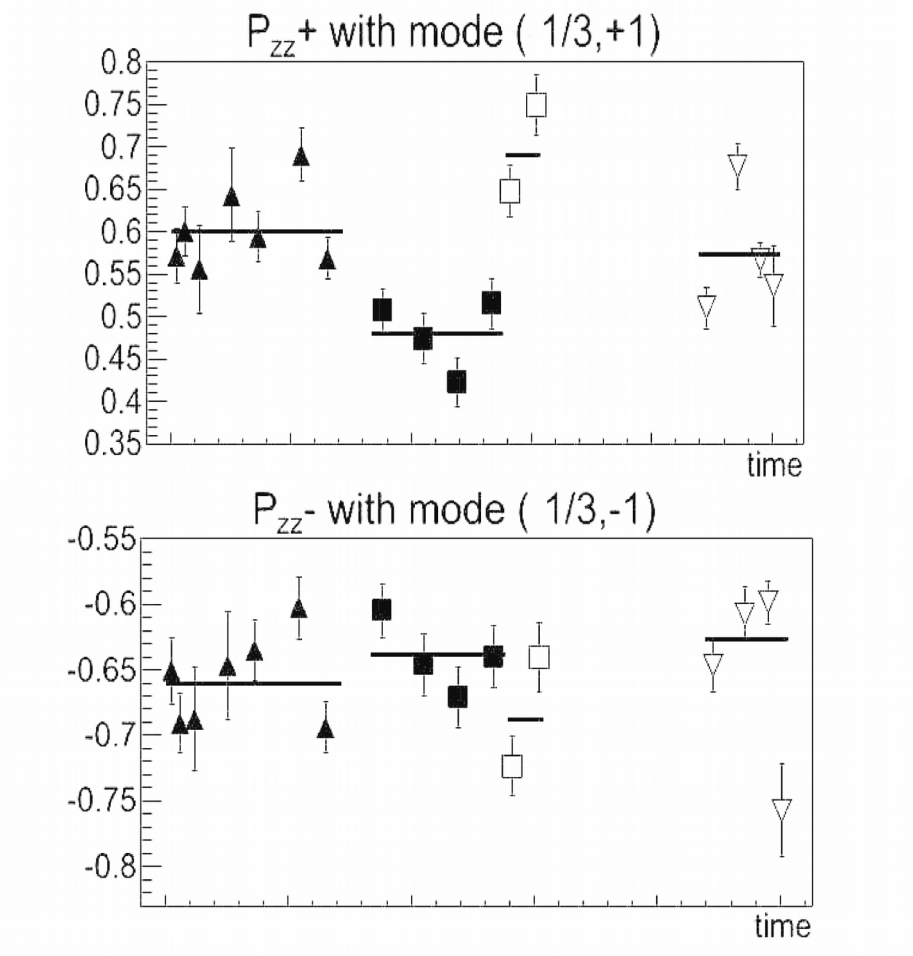
Energy dependence of the vector Ay and tensor Ayy analyzing powers in dp-elastic scattering at 700-1800 MeV

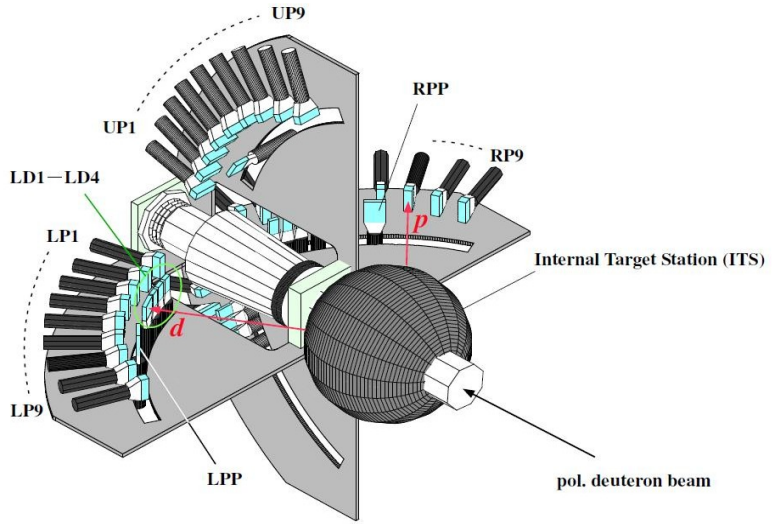




Full circles are new data from Nuclotron.
Open symbols are the world data.
Change the signs of the Ay and Ayy values at 600 MeV/c.
Asymptotic behaviour at large P_T.

Polarization measurements using dp- elastic scattering at 270 MeV at ITS

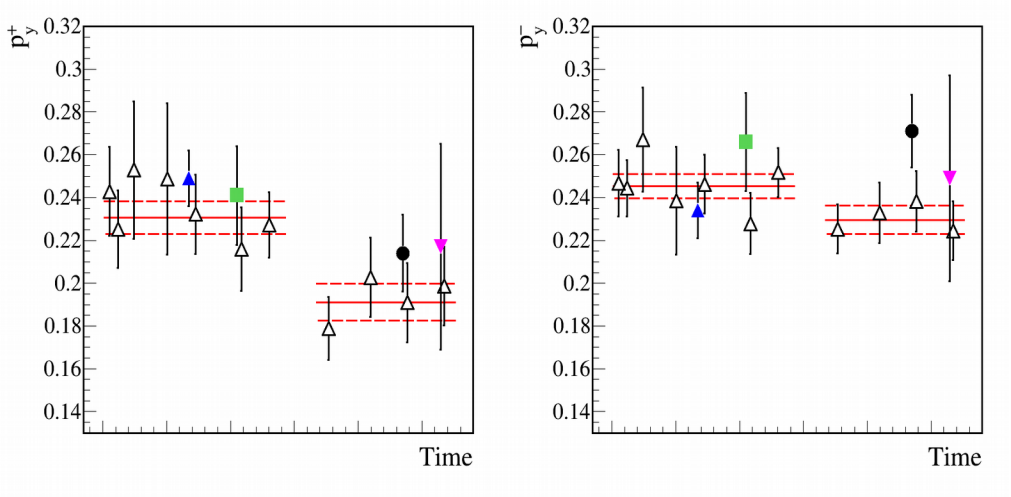


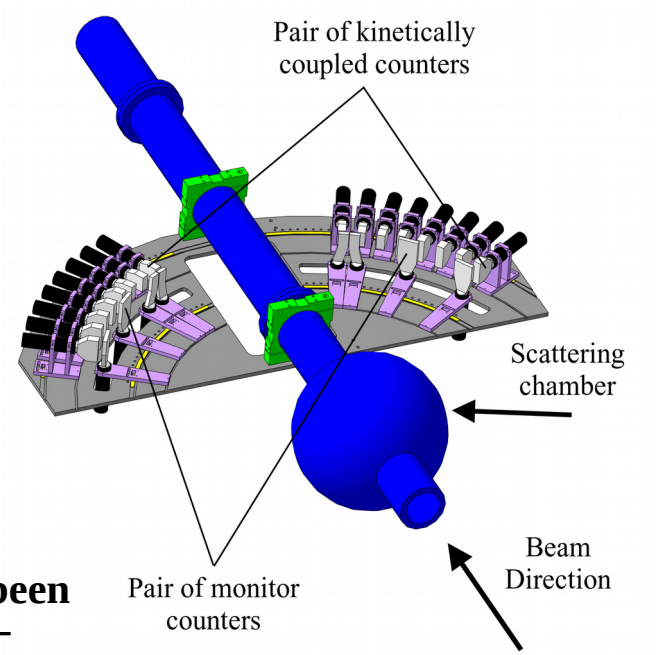


P.K.Kurilkin et al.,
NIM A642 (2011) 45-51.

SPI was tuned for 6 spin modes $(p_z,p_{zz}) = (1/3,1), (1/3,-1), (0,+1), (0,-2), (-2/3,0),(+1,0).$

Vector polarization of the deuteron beam using dp-elastic scattering at 270 MeV and pp- quasielatic scattering at ITS





- **Vector component of the deuteron beam polarization has been measured at 500, 650, 550 and 200 MeV/nucleon using pp-quasielastic scattering.**
- **Detectors placed in the horizontal plane only were used.**
- **Analyzing power values from SAID were used to evaluate the beam polarization values for the pp- quasi- elastic scattering measurements.**

Both methods give the similar results!

First polarized proton beam at Nuclotron

Injection of 5 MeV protons into Nuclotron ring.
Acceleration up to 500 MeV- no serious depolarization resonances.

Unpolarized protons: I∼1.5·10^8 ppp
Polarized protons: I∼2-3·10^7 ppp

IPol=1 P=1 (WFT 1→3)
IPol=2 P=0 (unpolarized)
IPol=3 P=1 (WFT 1→3)

beam 2/3 of time.

Having left-right asymmetries for 6 angles (55^0-85^0 in the cms) we obtained the averaged value of the proton beam polarization

Unpolarized protons: P= 0.038 ±0.023
Polarized protons: P= 0.368 ±0.023

New detection system for proton polarimeter is under preparation.
A.A.Terekhin et al.,Phys.Part.Nucl. 54 (2023) 634.

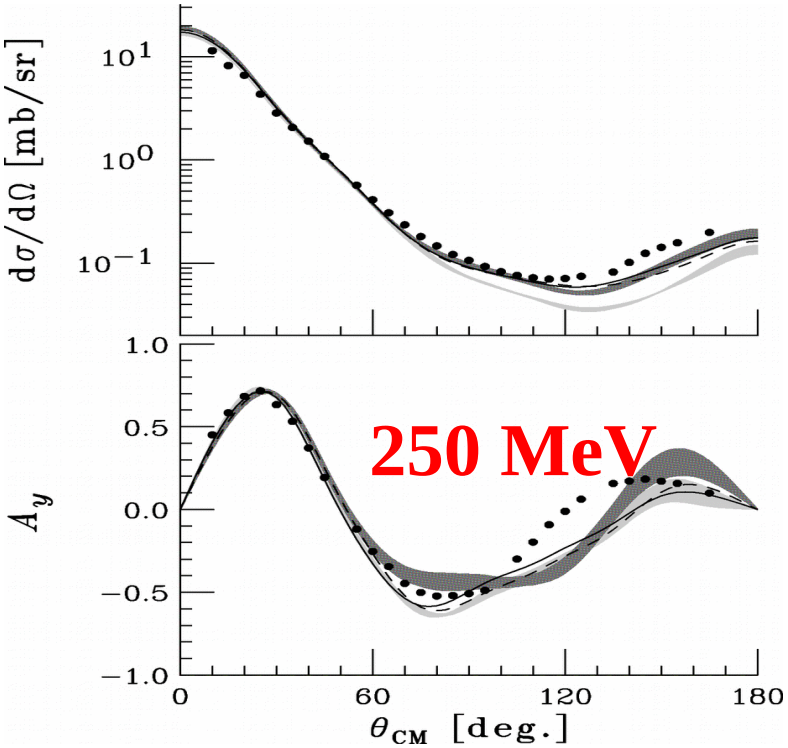
Publications, talks

- **The results are published in 2022-2024 in 16 papers.**

- **The results were reported at Nucleus-2022, DSPIN-2023, IBSHEPP-2023, AYSS2022 , AYSS2023.**

Invited talk at SPIN2023

Energy scan of the proton analyzing power Ay in pd- elastic scattering at large angles



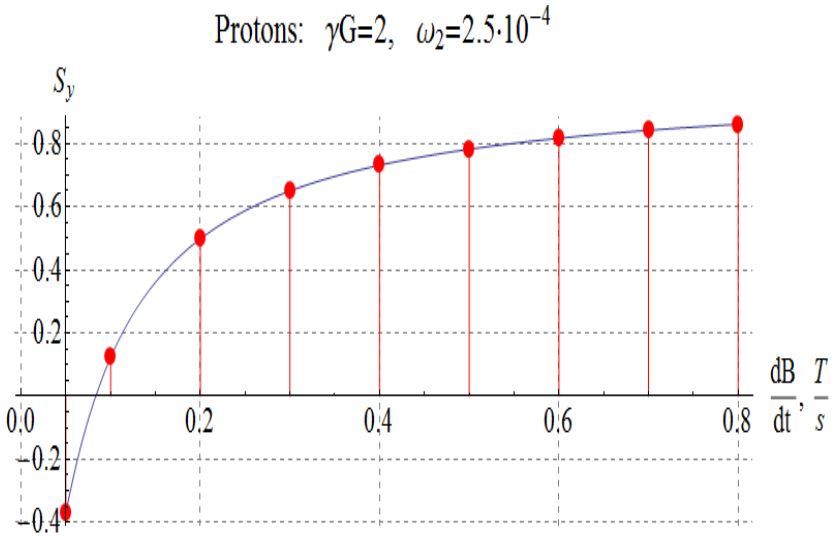
Problems in description at backward angles.

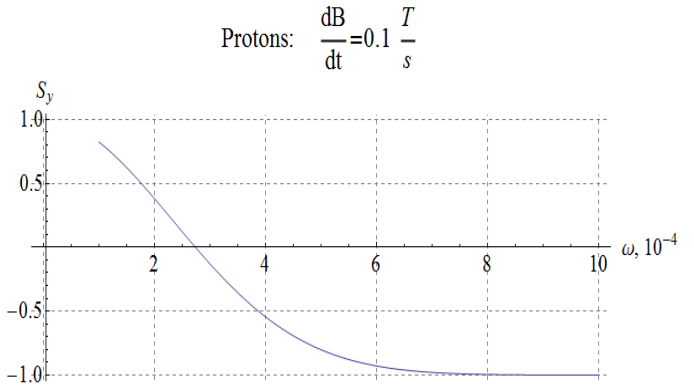
Relativistic effects become large ?

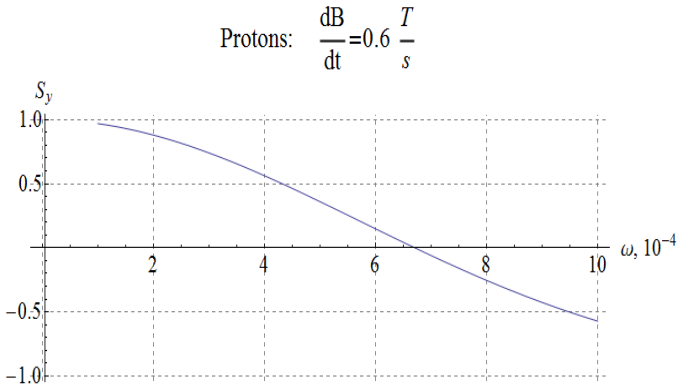
Short range 3NFs manifestation ?

Answers can be obtained from the energy scan at 100-1000 MeV (simultaneously with the polarimetry using pp-quasielastic scattering).

New experiments on the proton spin manipulation







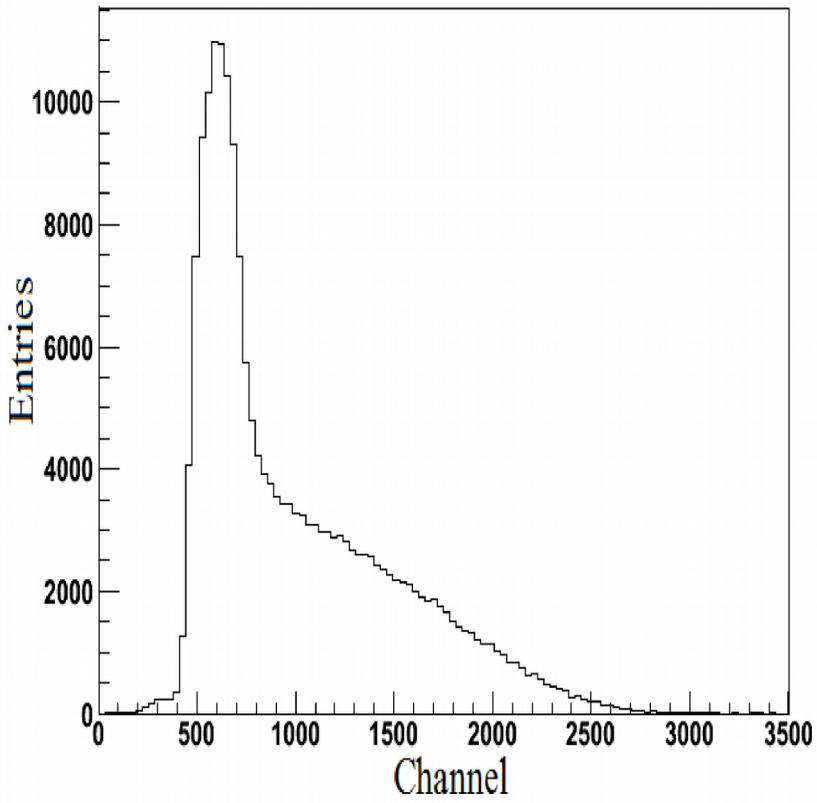
Measurements of the integer resonance γG=k=2 power (Tkin=108 MeV)

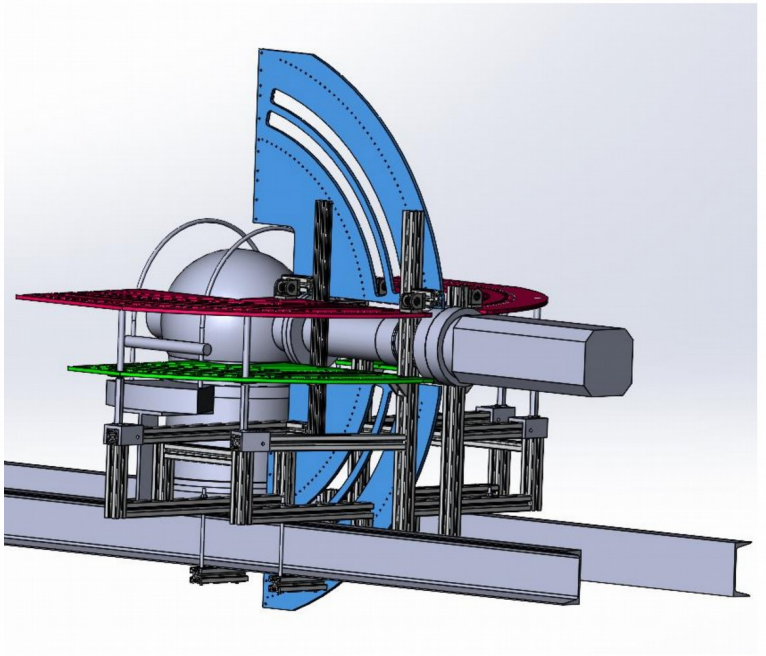
Measurements of the proton beam polarization at 100 and 120 MeV at different dB/dt

Yu.N.Filatov et al.,
JETP Lett. 116 (2022) 413;
JETP Lett. 118 (2023) 387.

The final goal is to prove the possibility of Spin- Transparent mode at integer resonances (for SPD at NICA)

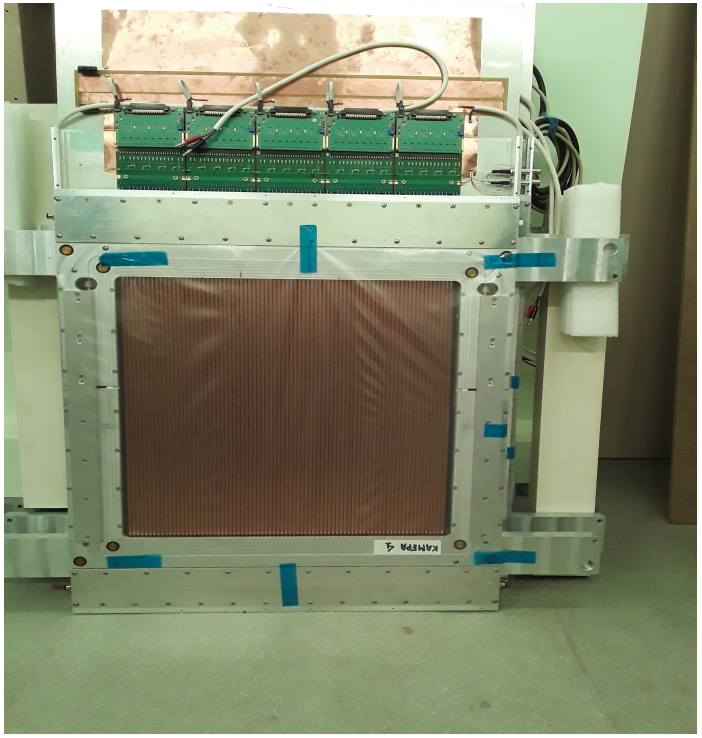
Upgrade DSS polarimeter

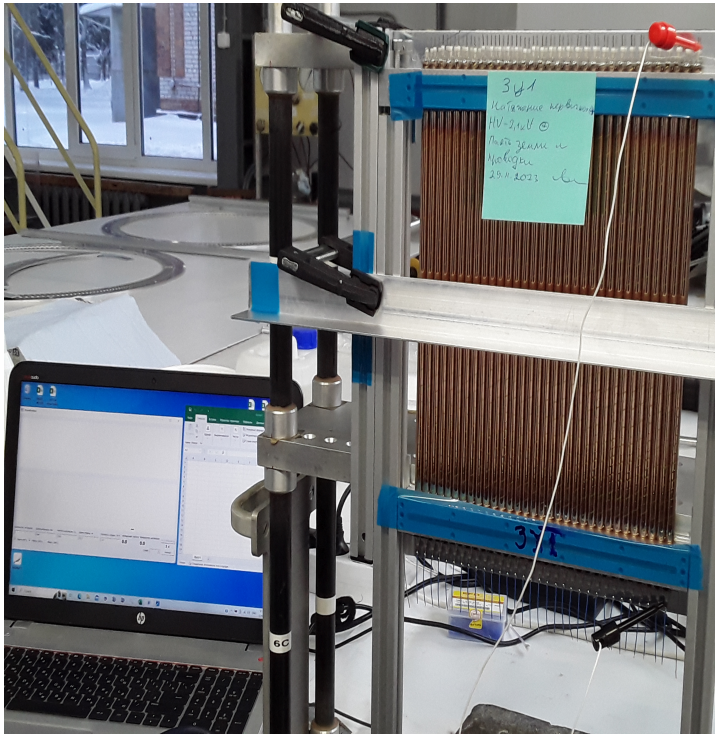




>80 new scintillation counters (BC-408 and H7415 PMT) produced, tested with RA source, 10% are tested with parasitic beam at ITS.
Mechanics -design is performed, partly contracted.

Upgrade of DSS forward arms





4 50x50cm^2 straw chambers with FEE ready and can be used.
20 ETE-9821B PMTs are delivered.
20x20cm^2 straw chambers with FEE will be ready for SPD test zone.
Needs:
Straw chambers, dE-E detectors, mechanics, HV and gas systems.

Beam-time request in 2025-2029

The total beam time request with new PIS in 2025-2029 is 1320 hours for the measurements at ITS. It includes the time within parasitic mode for the tests and commissioning.

1. Ay, Ayy and Axx for intermediate energy dp-elastic scattering (below 700 MeV and in the vicinity of the structure at 100-130 deg.in the cms) with the precision of ±0.02 with averaged beam intensity ~ $5 \cdot 10^9$.
2. Ay, Ayy and Axx for dp-nonmesonic breakup at 400 MeV with averaged beam intensity ~ $5 \cdot 10^9$.
3. Energy scan of the nucleon analyzing power Ay in pp- and pd-elastic scattering at 100-1000 MeV with polarized protons with the precision of ±0.02.
4. Proton beam polarimetry and spin manipulation at Nuclotron.

Risks:
peak intensity was ~ $8 \cdot 10^8$ and ~ $2 \cdot 10^7$ for deuterons and protons, respectively.

Expected results in 2025-2029

1. Study of the energy dependence the deuteron analyzing powers Ay,Ayy and Axx in dp-elastic scattering in the vicinity of the structure observed at 100-130 deg. in the cms.
2. Precise measurements of the analyzing power Ay in pp- quasi-elastic and elastic scattering at the energies 100-1000 MeV significant for partial wave analysis and beam polarimetry at NICA.
3.Measurements of the nucleon analyzing power A_y^p in pd- elastic scattering at the energies 100-1000 MeV.
4. The theoretical analysis of the observables in hadronic reactions with the participation of light nuclei will be continued.
5. Study of dp- non-mesonic breakup in the complanar geometry using straw detectors.
6. Study of the 3 particles correlations in ion-ion collisions using DSS installation with tracking.
7. Measurements of the integer resonances $\gamma G = 2$ and $\gamma G = 3$ powers for polarized proton beam using ITS polarimeter.
8. Study of the polarized beam parameters using deuteron spin flip at 135 MeV/nucleon.
9. Preparation of the ITS polarimetry for the study of the higher integer resonances up to $\gamma G = 7$.
10. R&D for the effective beam polarimetry at Nuclotron and local polarimetry at SPD at collider.

JINR expenses in 2025-2029 yy.

Proposed schedule and resource request for the DSS project

Expenditures, resources, funding sources			Cost (thousands of US dollars)/ Resource requirements	Cost/Resources, distribution by years				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation	50	10	10	10	10	10
		Materials	115	25	25	25	20	20
		Equipment, Third-party company services	180	34	34	34	39	39
		Commissioning						
		R&D contracts with other research organizations	200	40	40	40	40	40
		Software purchasing	5	1	1	1	1	1
		Design/construction	50	10	10	10	10	10
		Service costs (*planned in case of direct project affiliation)*						
Required resources	Standard hours	Resources						
		- the amount of FTE,		10	10	10	10	10
		- accelerator/installation,	1320*	300*	300*	240*	240*	240*
		- reactor,…						
Sources of funding	JINR Budget	JINR budget *(budget items)*	600	120	120	120	120	120
	Extrabudgetary (supplementary estimates)	Contributions by partners Funds under contracts with customers						

* The beam time can be shared in part with other users

New detectors, new mechanics, HV system(CAEN), gas system, electronics

DSS JINR FTE =8.3(6.1+2.2)

V.P.Ladygin	0.7
E.V.Chernykh	0.5
Yu.V.Gurchin	1.0
A.Yu.Isupov	0.8
A.P.Ierusalimov	0.5
N.B.Ladygina	1.0
K.S.Legostaeva	0.5
A.N.Livanov	0.1
S.M.Piyadin	-
S.G.Reznikov	0.8
A.A.Terekhin	0.8
A.V.Tishevsky	0.8
I.S.Volkov	0.8

Overlap with SPD (proton beam and local polarimetry)

SWOT analysis for DSS project

Strengths: The strong points of the DSS- project are the unique physics related with the studies of the short-range correlations spin structure, development of the efficient polarimetry for the deuteron and proton beams, contribution to the first stage physics program at SPD. The project is an inevitable step for spin program at NICA.

Weaknesses: Very high competition for the beam at Nuclotron due to higher priority of the heavy ion program.

Opportunities: Project provides visible role for young scientists, real possibility to defense the thesis (6 PhD thesis and ∼15 Master thesis).

Threats: Sanctions impact on the availability and the cost of the necessary equipment. Also they reflect on the limitation of the scientific contacts and the absence of the exchanges with European and Japanese collaborators.

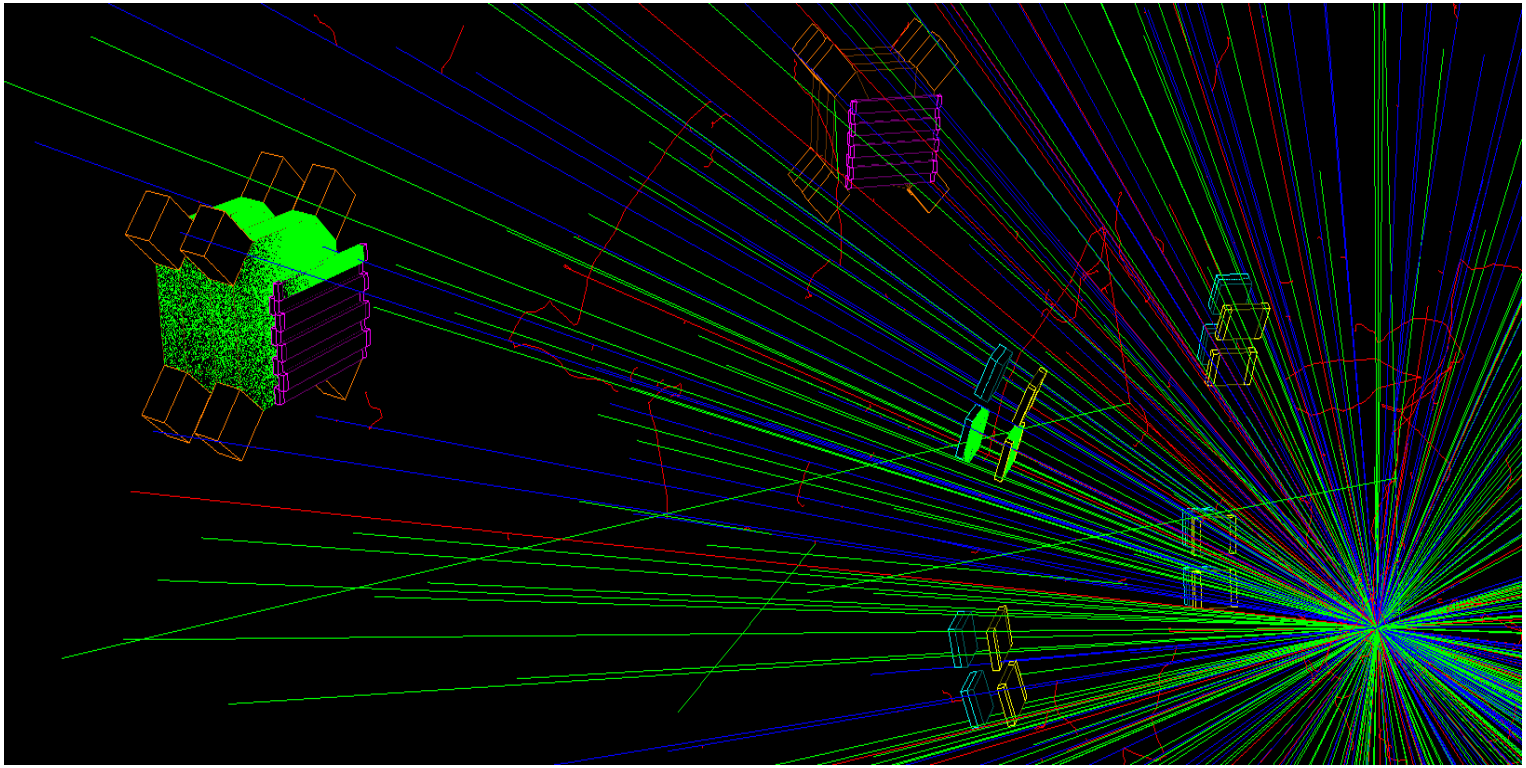
Request

Prolongate the DSS- project for 5 years (2025-2029) with A-priority.

The realization of the project in 2025-2029 will allow
-to obtain the crucial data on the spin structure of 2-nucleon and 3- nucleon short range correlations (2N and 3N SRC);
-to develop the efficient polarimetry and spin manipulation system for Nuclotron/NICA;
-to make a visible contribution to physics program at SPD.

Thank you for the attention!!!

3-particles correlation in Xe+Ag and Xe+W collisions



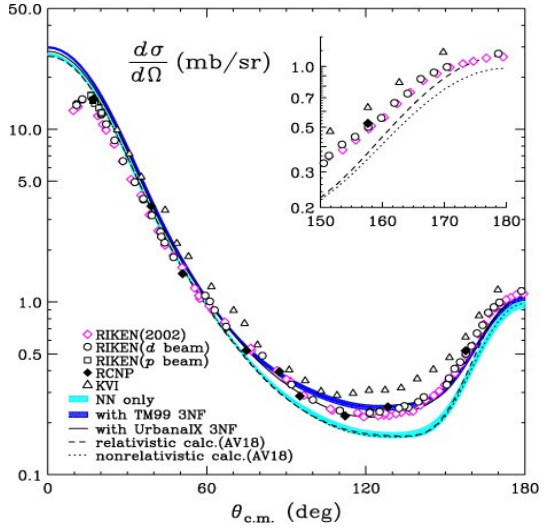
Xe+A collisions were studied at 3.0 and 3.8 GeV/nucleon:
2 charged particles are detected at mid-rapidity,
3-rd in forward direction
PHQMD model is used to simulate the semi-central collisions

Motivation of the dp interaction studies at Nuclotron

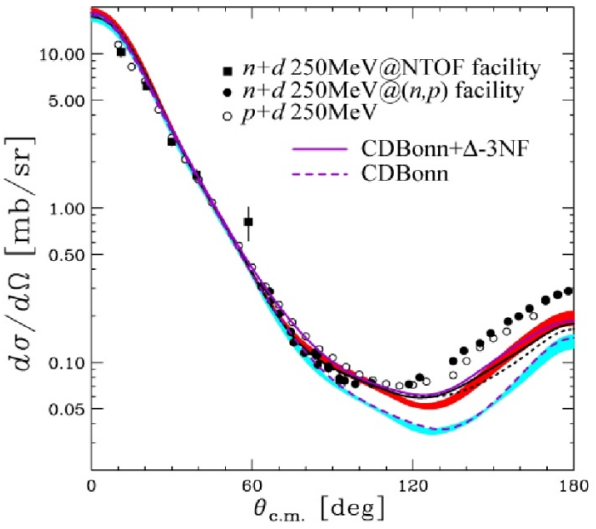
- **Nucleon-nucleon interaction at short distances**

(Short Range Correlations - SRC)

- **Relativistic effects**
- **Transition to the nonnucleonic degrees of freedom**
- **Contribution of three-nucleon forces (3NFs) – Short Range?**

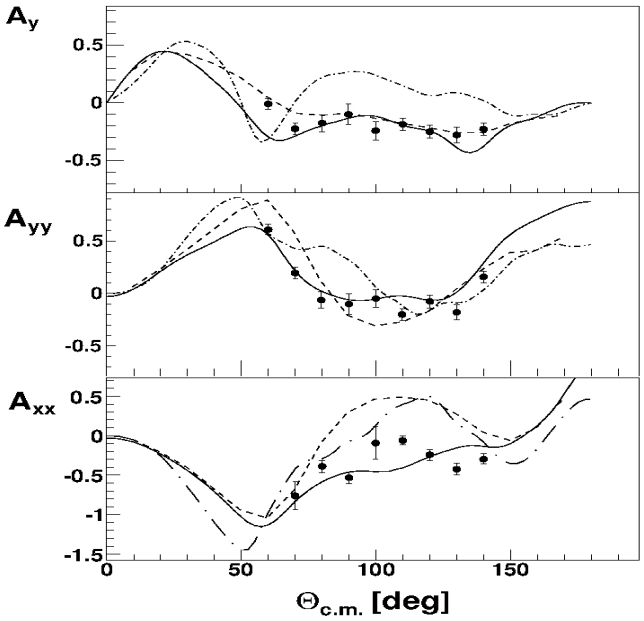


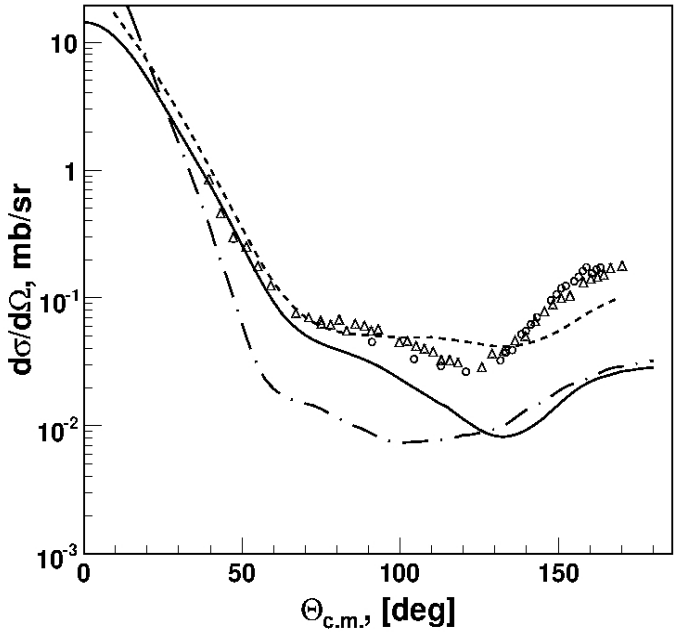
K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)



K. Hatanaka et al., Phys. Rev. C 66, 044002 (2002)

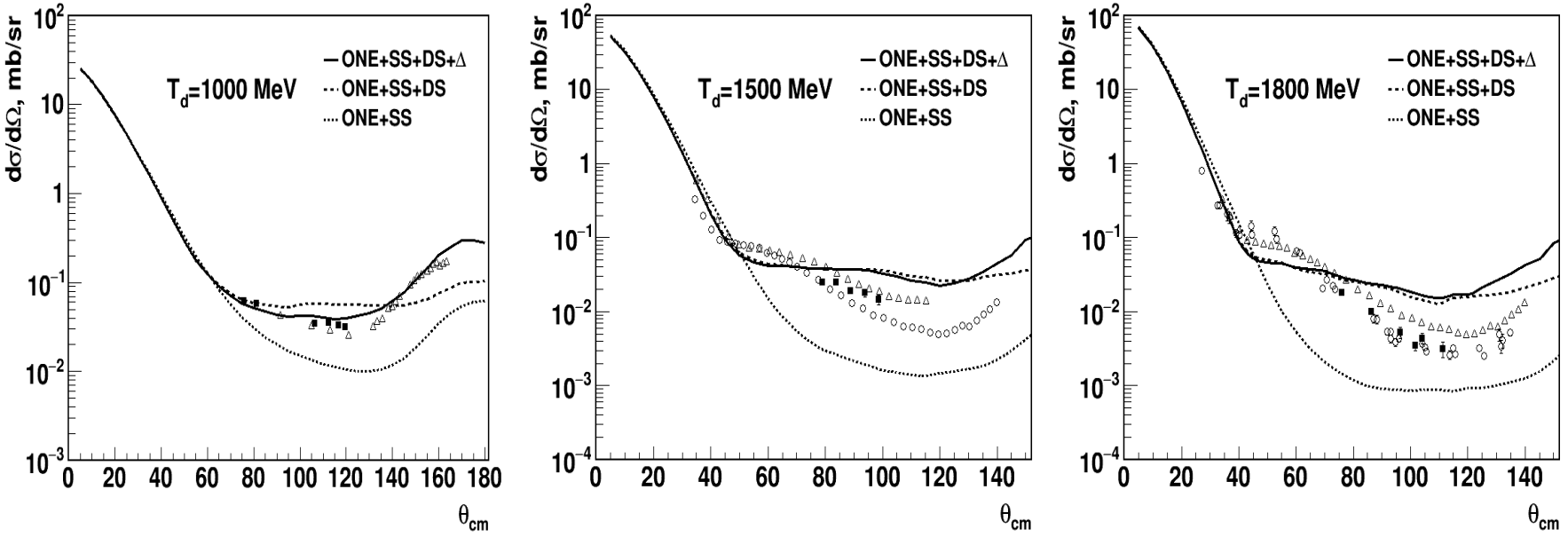
Analyzing powers in dp- elastic scattering at 880 MeV





Dashed lines are the relativistic multiple scattering model calculations using CD -Bonn DWF (N.B.Ladygina, Phys.Atom.Nucl.71 (2008), 2039)
Solid lines are the Faddeev calculations using CD-Bonn potential (H.Witala, private communication)
Dott-dashed lines are the optical-potential calculations using Dibaryon DWF (M.Shikhalev, Phys.Atom.Nucl.72 (2009), 588)
Published in P.K.Kurilkin et al., Phys.Lett.B715 (2012) 61.

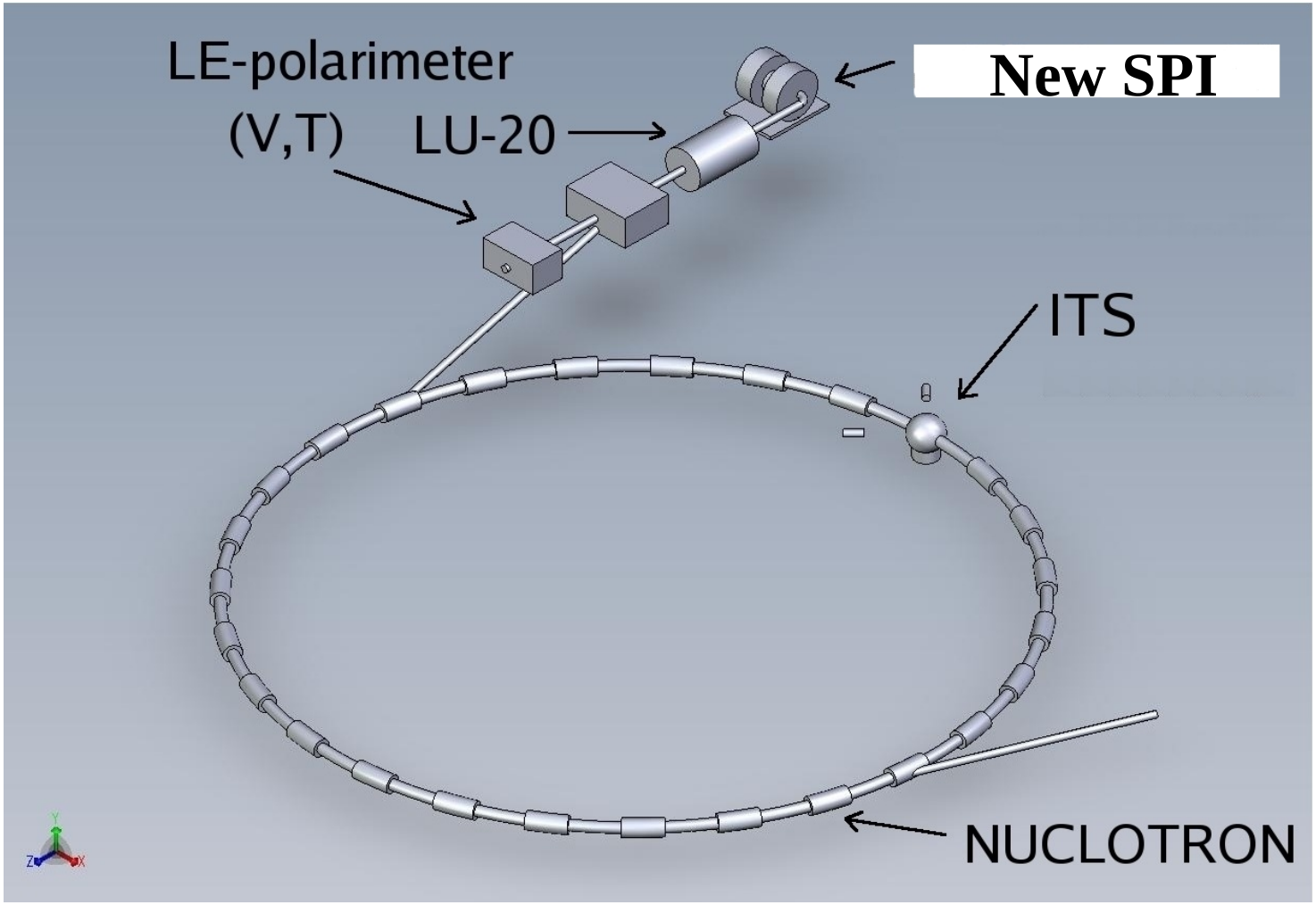
dp- elastic scattering cross section energy scan at 1000-1800 MeV



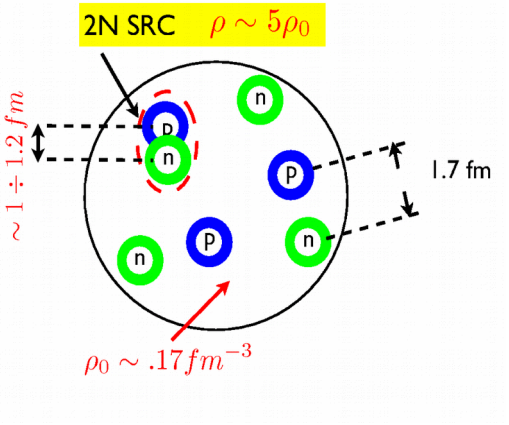
A.A.Terekhin et al., Eur.Phys.J., A55 (2019) 129

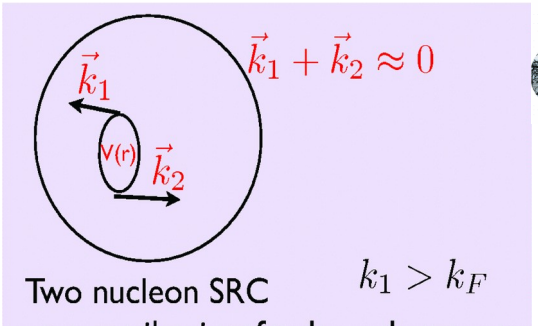
Relativistic multiple scattering model calculation:
N.B.Ladygina, Eur.Phys.J, A56 (2020) 5, 133

Nuclotron-M accelerator complex



Short range correlations (SRCs)





Summary of the theoretical analysis of the experimental findings
practically all of which were predicted well before the data were obtained

More than ~90% all nucleons with momenta k≥300 MeV/c belong to two nucleon SRC correlations — BNL + Jlab +SLAC

Probability for a given proton with momenta 600> k > 300 MeV/c to belong to **pn** correlation is ~ 18 times larger than for **pp** correlation — BNL + Jlab

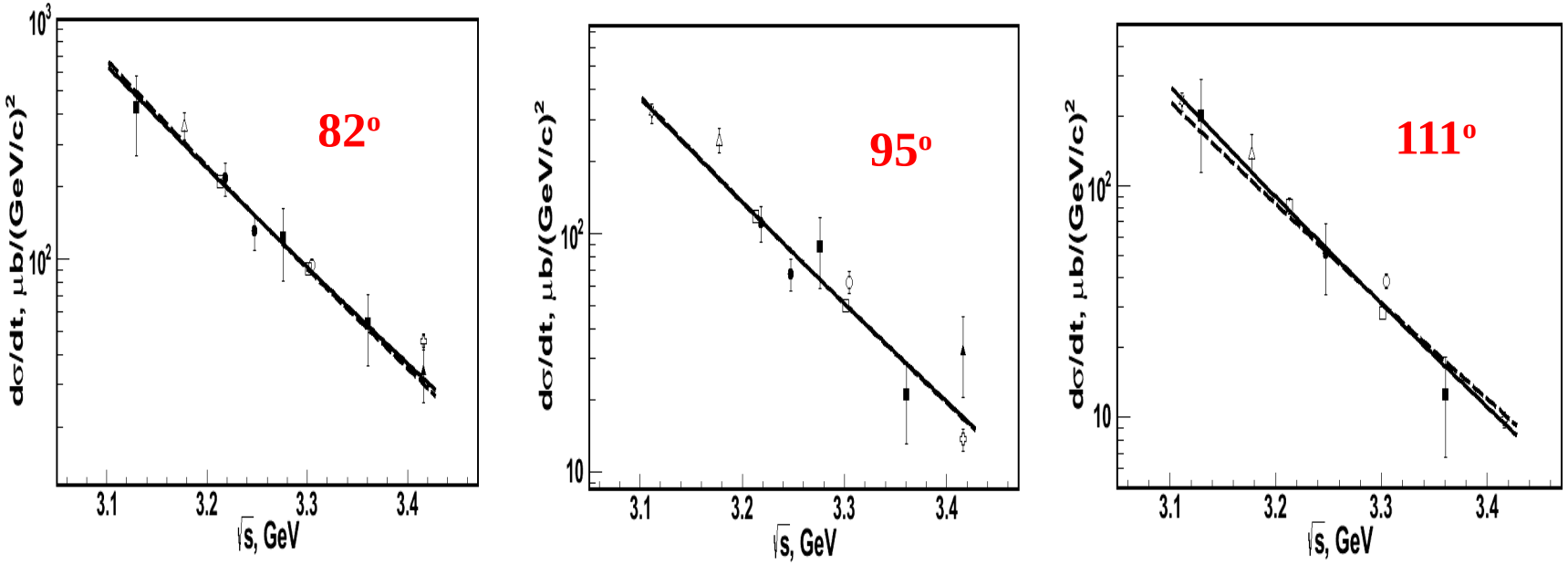
Probability for a nucleon to have momentum > 300 MeV/c in medium nuclei is ~25% — BNL + Jlab 04 +SLAC 93

Probability of non-nucleonic components within SRC is small - < 20% - 2N SRC mostly build of two nucleons not 6q, ΔΔ,... — BNL + Jlab +SLAC

Three nucleon SRC are present in nuclei with a significant probability — Jlab 05

Poor data base on the spin parts of the 2N and 3N short-range correlations. This motivates the necessity to study light nuclei structure at short distances.

dp- elastic scattering cross section scaling properties at the fixed angles in cms



A.A.Terekhin et al., Eur.Phys.J., A55 (2019) 129

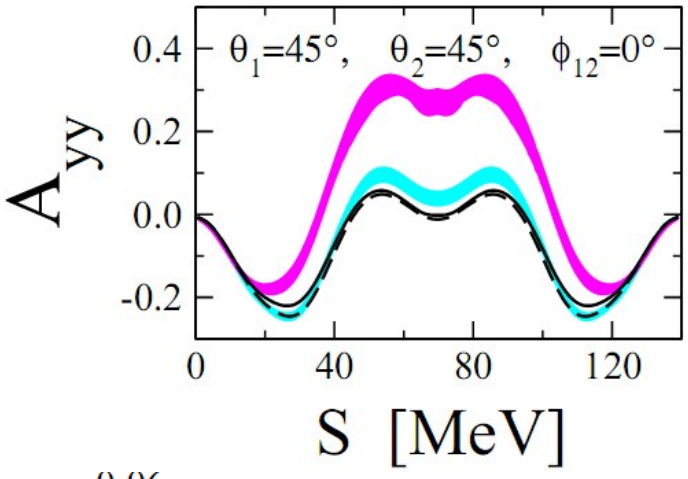
Constituent Counting Rules predictions:

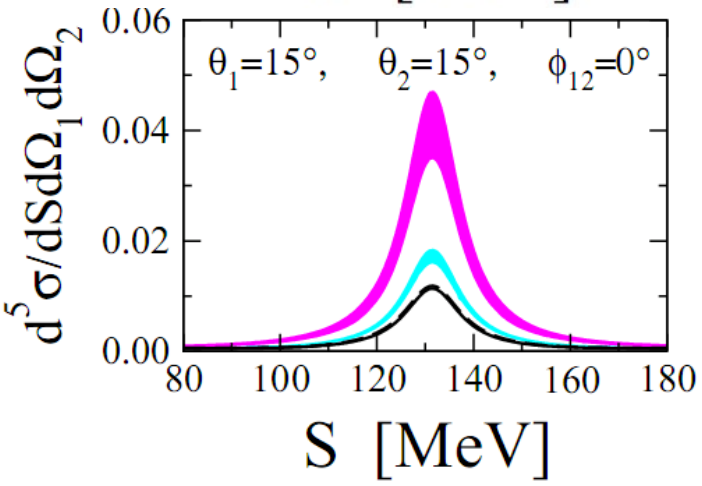
$$\frac{d\sigma}{dt}(ab \to cd) = \frac{f(t/s)}{s^{n-2}} \quad ; \quad n = N_a + N_b + N_c + N_d$$

1. self-similarity,
2. pQCD,
3. AdS/QCD correspondence

S^{-16}

Tensor analyzing power Ayy (top) and differential cross section in selected breakup configurations at 200 MeV (bottom).





•The light shaded band (blue) contains the theoretical predictions based on CD-Bonn, AV18, Nijm I, II and Nijm 93.

•The darker band (magenta) represents predictions when these NN forces are combined with the TM 3NF.

•The solid line is for AV18+Urbana IX and the dashed line for CD Bonn+TM

One can see that the inclusion of 3NF have great impact on the values of analyzing power and cross section.

Θ_1 – polar angle of the 1-st proton.

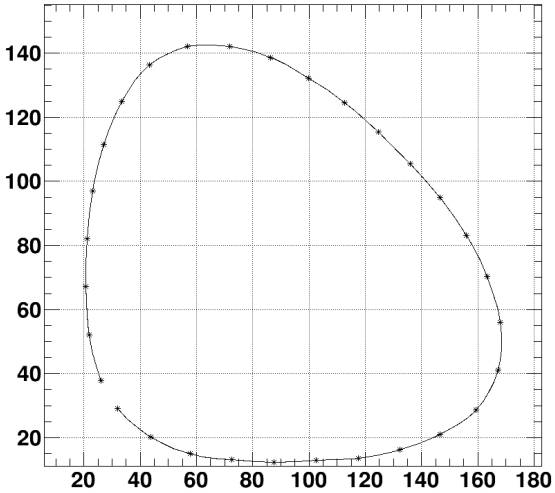
Θ_2 – polar angle of the 2-nd proton.

S – arc length along the kinematical curve.

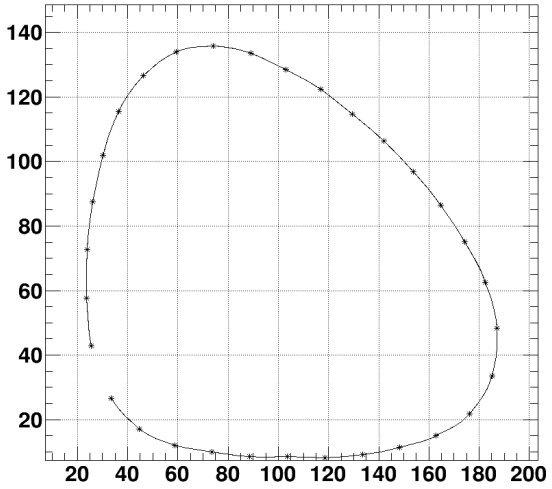
Φ_{12} – azimuthal angle with respect to the horizontal plane.

Dp breakup – S (kinematical) curve

a)



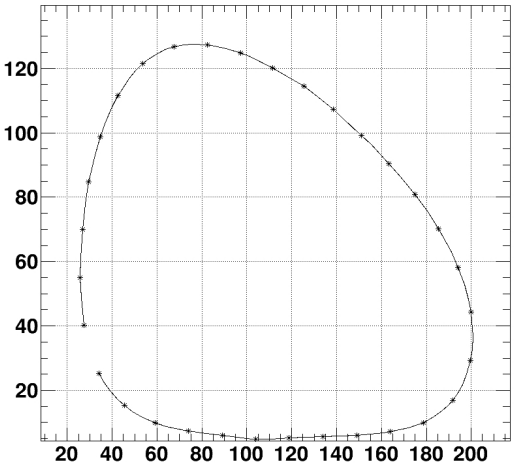
b)



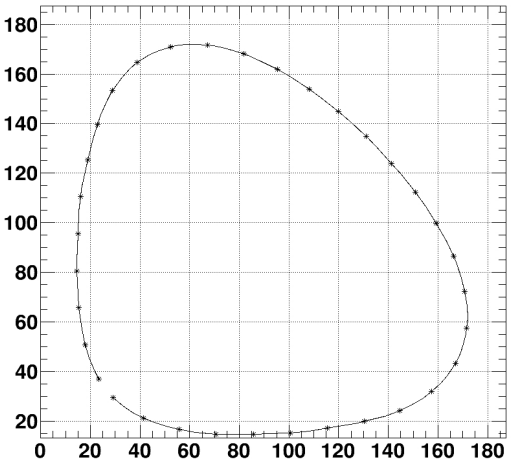
Step = 10 MeV

S- curve:
Anticlockwise
Orientation

c)



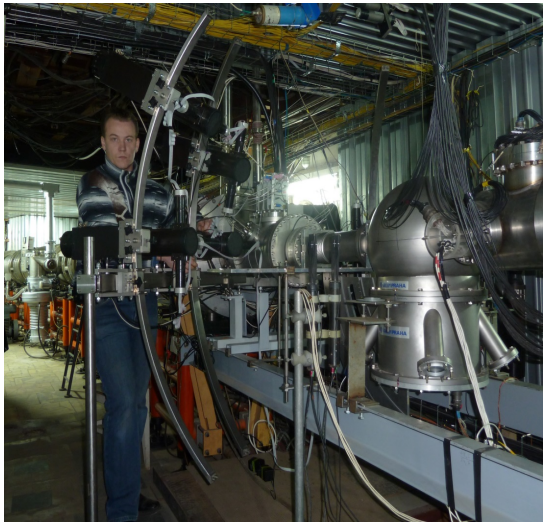
d)



Exp. data are projected into kinematical curve obtained by phase space simulation for the case of 300 MeV of deuteron energy and angles (polar angle1 / polar angle 2 and difference in azimuthal angles):

a) 37.1° / 30.5° / 145°; b) 40.1° / 26.9° / 150.8°; c) 42.1° / 23.3° / 152.1°; d) 34.0° /34.0° / 180°

Dp breakup – cross section



Θ (12°, 45°)
Φ (0°, 360°)
Space angle of
the detector 4.6°.

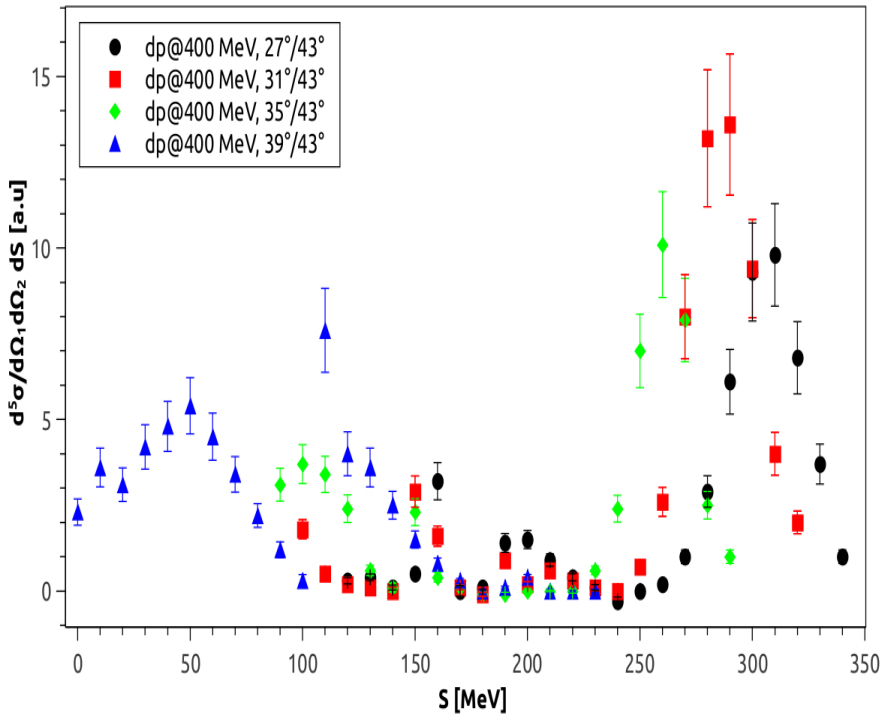
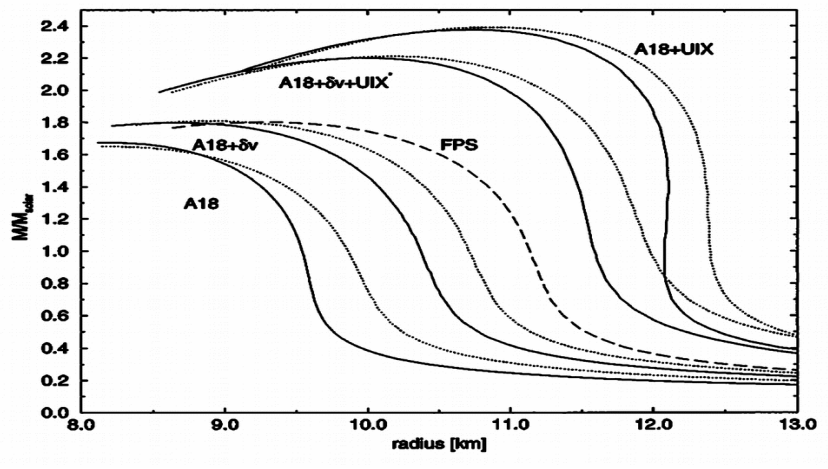
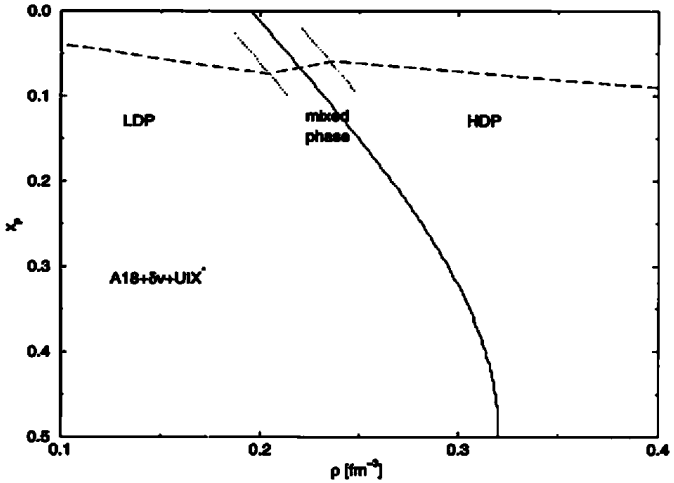


Figure 2: Preliminary results of the five fold differential cross section of *dp* breakup reaction investigated at 400 MeV for the case of detector arms placed at the angles of 27° and 43° (black symbols), 31° and 43° (red symbols), 35° and 43° (green symbols), 39° and 43° (blue symbols), respectively. Only statistical errors are shown.

Few nucleons systems as a tool for dense matter studies

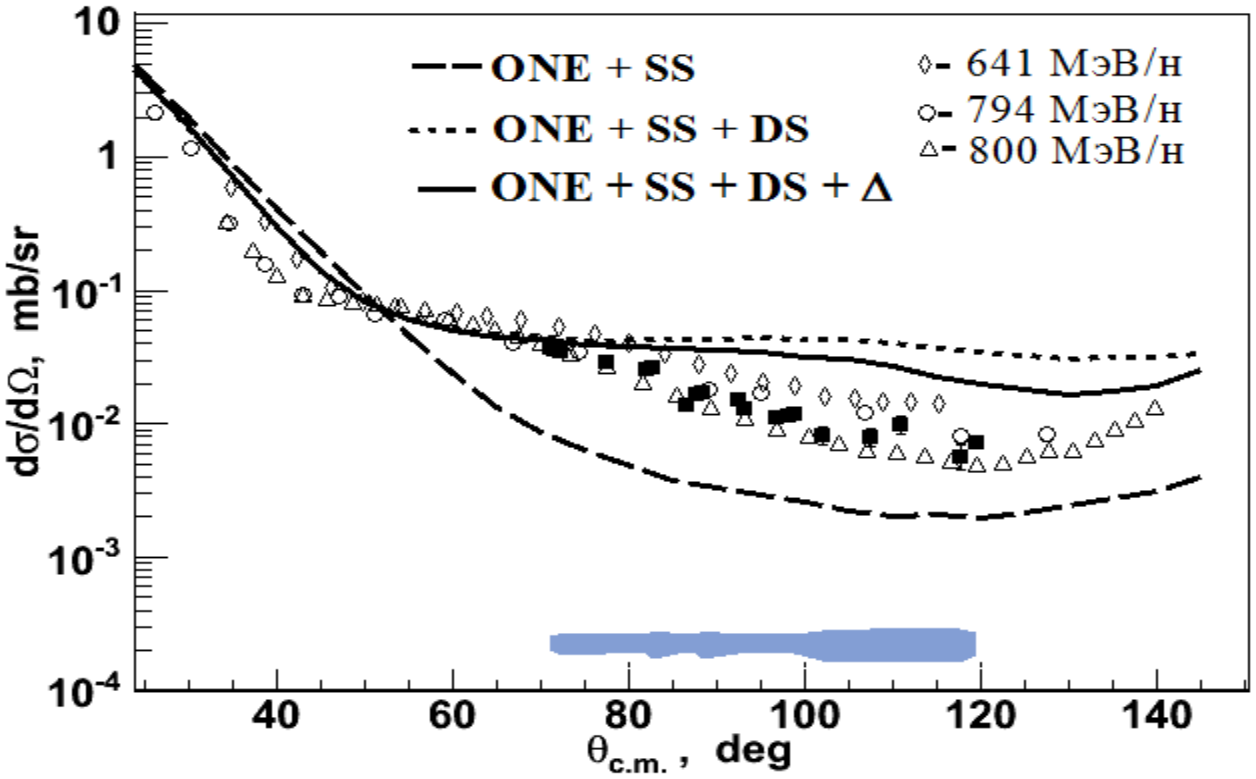
Another way to obtain the information on the EOS at extreme densities (neutron stars) is the studies of the few nucleon systems.





Relativistic effects in 2NF and contribution of 3NF play very important role.

dp- elastic scattering cross section at 1400 MeV

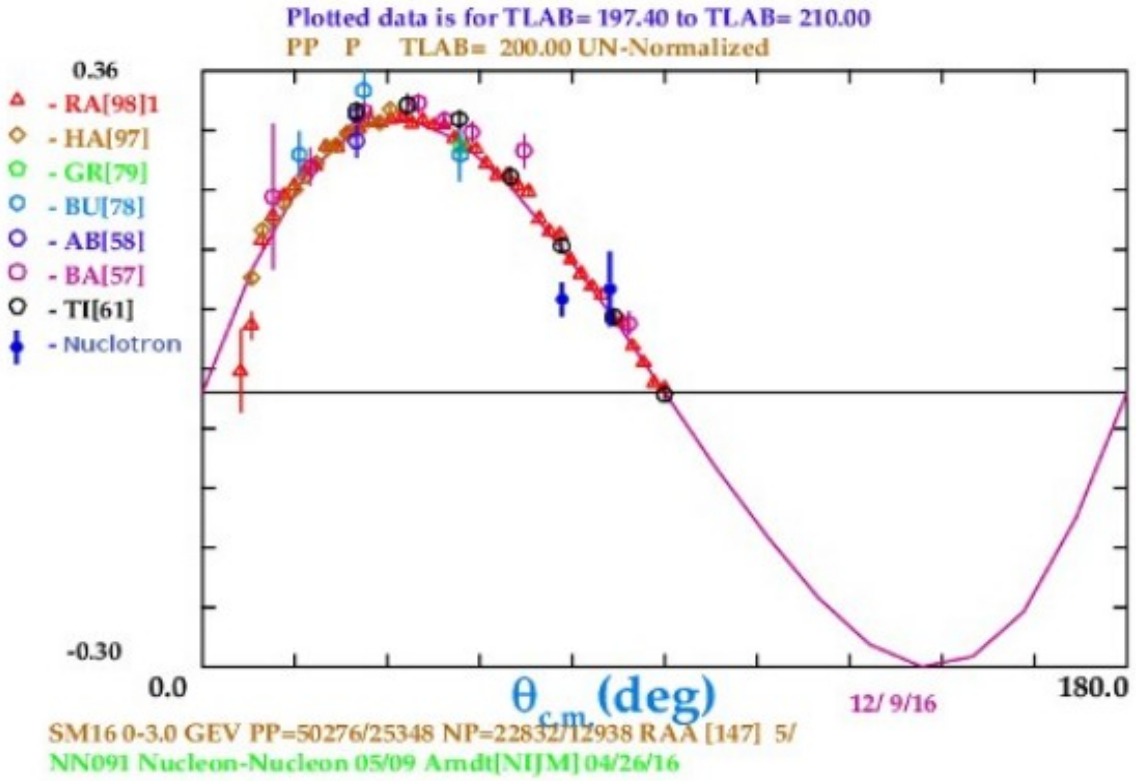


A.A.Terekhin et al., Phys.Atom.Nucl. 80(2017) 1061.

Relativistic multiple scattering model calculation:
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

Final cross section data at 1000, 1300 and 1800 MeV

Ay in dp breakup reaction at 400 MeV, pp-quasielastic data



(pz, pzz)
=
(-1/3, 1)
(-1/3, -1)

Angular dependence of the vector analyzing power **Ay** at energy of **200** MeV/n. Data obtained at Nuclotron JINR are represented by full blue symbols (72.3° and 76.5° in cm). Other symbols - world data.

dp breakup reaction at 400 MeV, analyzing power data

Spherical analyzing powers iT_{11} and T_{20}. Detector configuration is determined by polar θ_1 and θ_2, and azimuthal angles φ. Azimuthal angle is related to the angle of the detector which is closest to beam direction.

pp -quasielastic
72.3° and 76.5°

Conf.	θ_1 [°]	θ_2 [°]	φ [°]	iT_{11}	T_{20}	iT_{11} combined	T_{20} combined
detectors – 5, 4	34.8	52.5	135	0.10 ± 0.02	0	-	-
detectors – 6, 3	36.8	50.4	45	0.11 ± 0.06	0	-	-
detectors – 1, 6	34.8	36.8	135	0.55 ± 0.15	0.13 ± 0.30	0.47 ± 0.10	0.02 ± 0.20
detectors – 5, 2	34.8	36.8	135	0.39 ± 0.13	-0.09 ± 0.27		

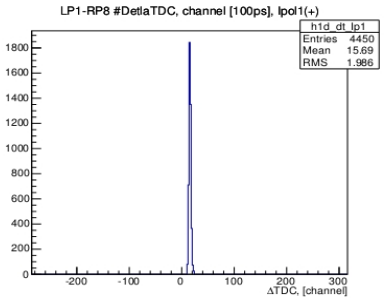
Results combined

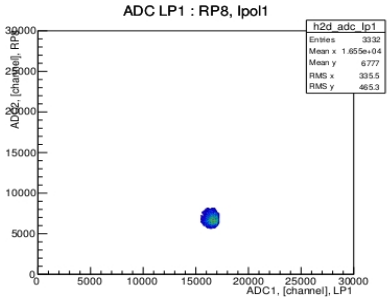
Selection of pp- elastic scattering at 500 MeV.

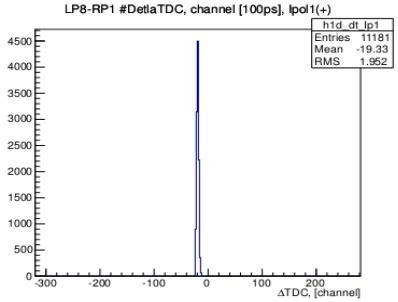
55^0

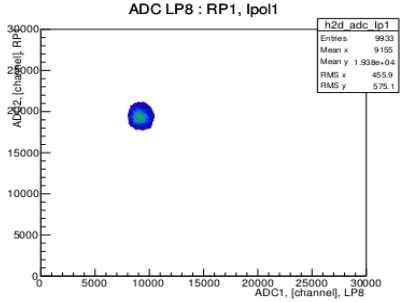
125^0

"_"

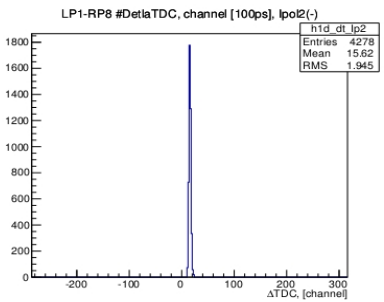


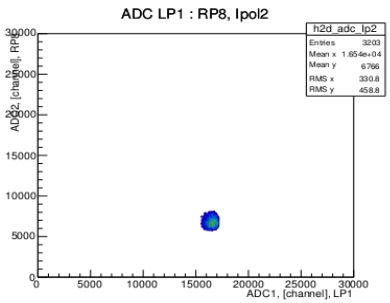


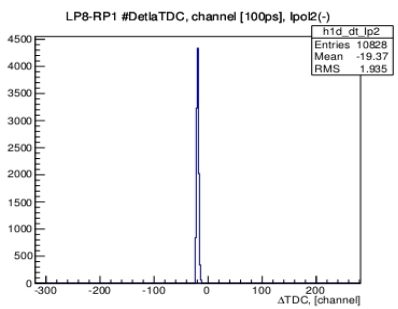


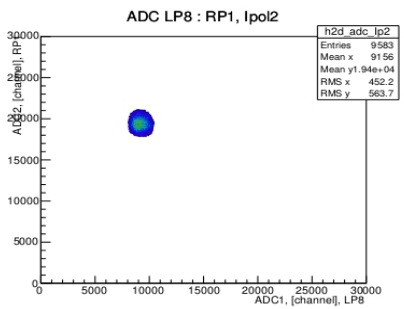


"0"









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