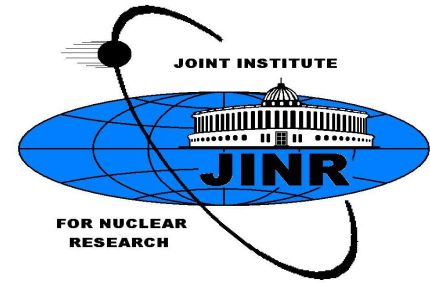XXIV International Baldin Seminar
on High Energy Physics Problems
Relativistic Nuclear Physics & Quantum Chromodynamics

September 17 - 22, 2018, Dubna, Russia

JOINT INSTITUTE
JINR
FOR NUCLEAR RESEARCH

Energy dependence of the vector Ay and tensor Ayy and Axx analyzing powers in deuteron- proton elastic scattering at large scattering angles

V.P. Ladygin on behalf of DSS collaboration

Outline

- **Motivation**
- **Review of dp-elastic scattering studies at intermediate energies**
- **Recent results on dp-elastic scattering obtained at Nuclotron JINR**
- **Conclusion**

DSS collaboration: 12 Institutes and Universities from
Bulgaria-JINR-Japan-Romania-Russia-Slovakia

Three body problem according to H.Sakai

'How about the problem of the three bodies?' whispered Kriltsov, smiling with great effort.
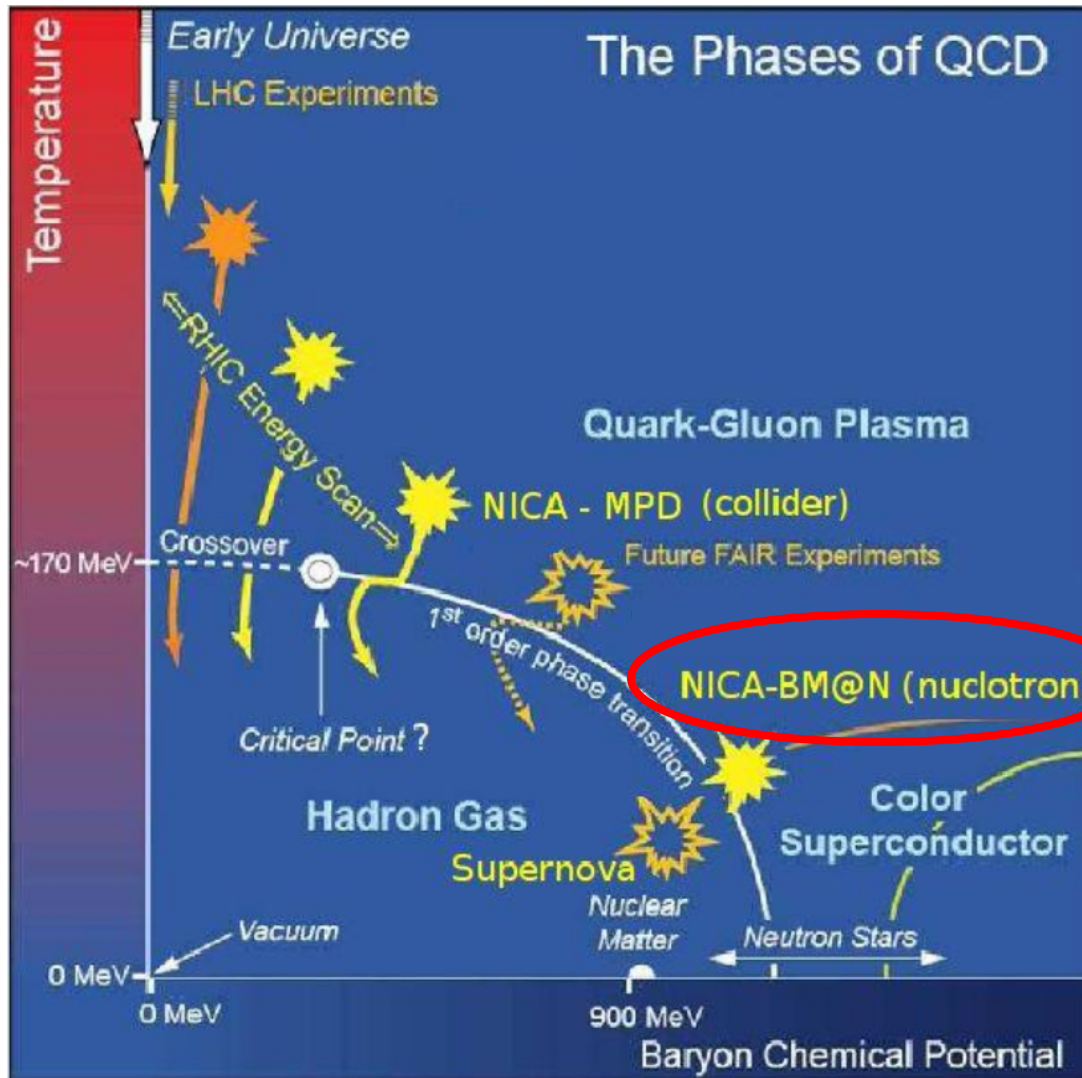
'The solution is difficult? '

Resurrection, 1899, Chapter XX
by Leo Tolstoy

Motivation of the dp interaction studies

- **Nucleon-nucleon interaction at short distances (including its mass off-shell behaviour)**
- **Relativistic effects**
- **Transition to the nonnucleonic degrees of freedom**
- **Contribution of three-nucleon forces (3NFs)**

stalled from E.L.Bratkovskaya

Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

Many theoretical approaches: transport, thermodynamics etc. transferred to the event generators UrQMD, HSD, LAQGSM ...
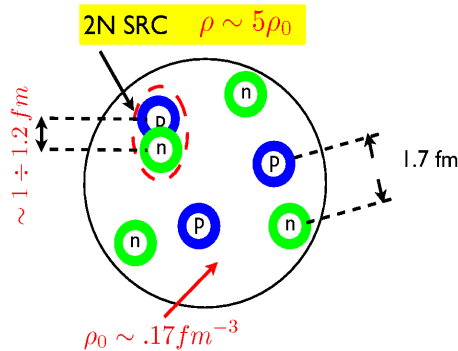
Lattice QCD calculations

Few nucleons systems as a tool for dense matter studies

Alternative way to obtain the information on the EOS at extreme densities (neutron stars) is the studies of the few nucleon systems.
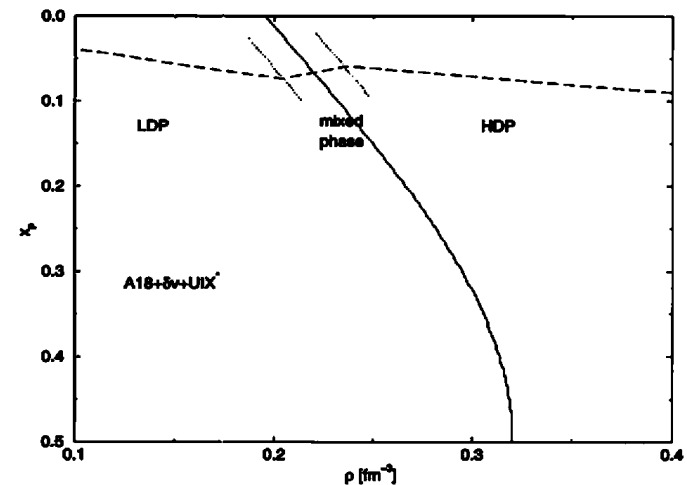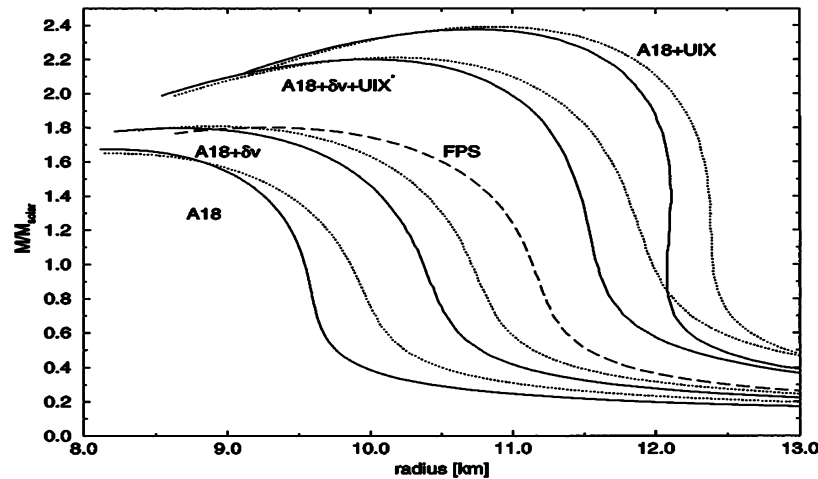
Relativistic effects in 2NF and contribution of 3NF play very important role. (**A.Akhmal et al, Phys.Rev. C58 (1998) 1804**)

Short range correlations (SRCs)

2N SRC $\quad \rho \sim 5\rho_0$

$\sim 1 \div 1.2\,fm$

1.7 fm

$\rho_0 \sim .17\,fm^{-3}$

$\vec{k}_1$

$\vec{k}_1 + \vec{k}_2 \approx 0$

V(r) $\vec{k}_2$

Two nucleon SRC

$k_1 > k_F$

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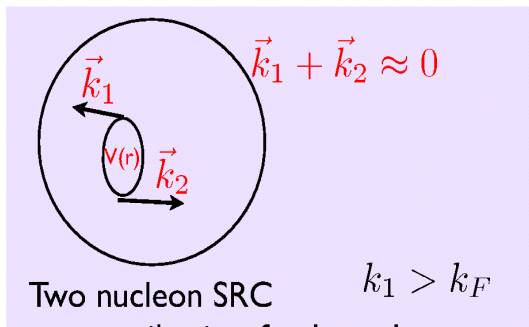
Poor data base on the spin parts of the 2N and 3N short-range correlations. This motivates the necessity to study light nuclei structure at short distances.

Experiments at Nuclotron allow to reach $p_T \sim$ 1 GeV/c

Relativistic effects

- The principal feature of the relativistic quantum mechanics is the impossibility to separate the relative motion of the constituents and motion of the composite system as a whole. This leads to the dependence of the **relativistic** wave function not only on the relative momenta of the nucleons $\vec{q}$ inside the composite system, but also on the total momentum $\vec{p}$ of this system

$$\Psi = \Psi(\vec{q}, \vec{p})$$

- Therefore, **relativistic** wave function is the function of the relative momentum $\vec{q}$ in each new reference system.

- However, it is enough to know wave function in the infinite momentum frame, $\vec{p} \to \inf$, where the structure of the wave function simplifies. Namely, the dependence on $|\vec{p}|$ disappears, only the dependence on the direction of the vector $\vec{n} = \vec{p}/|\vec{p}|$

$$\Psi = \Psi(\vec{q}, \vec{n})$$
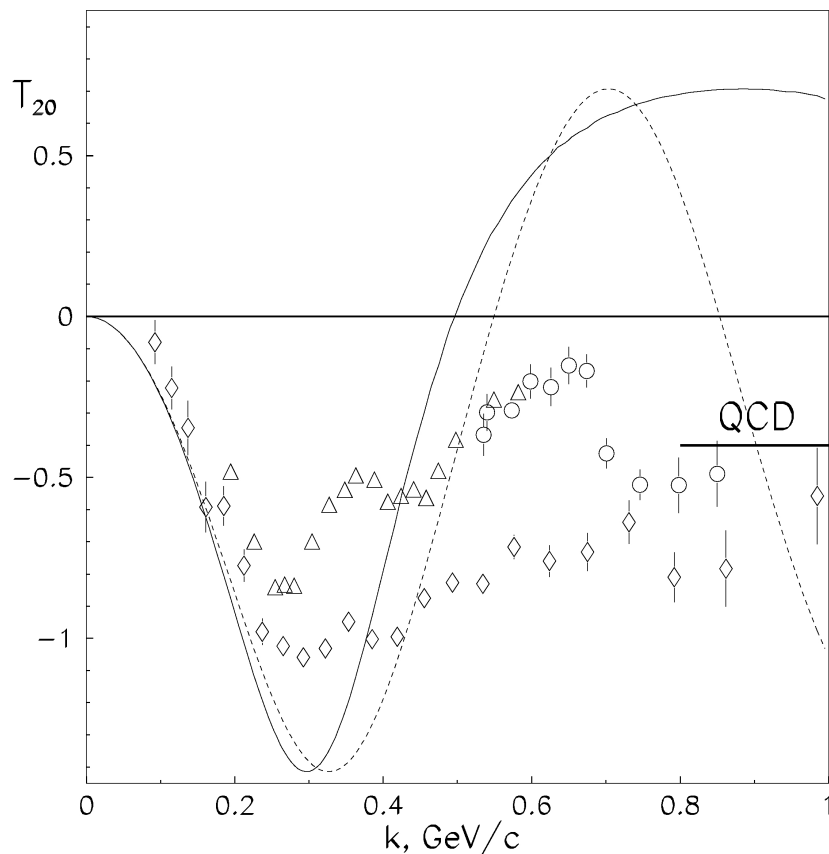
Relativistic effects in 2N SRCs (deuteron)
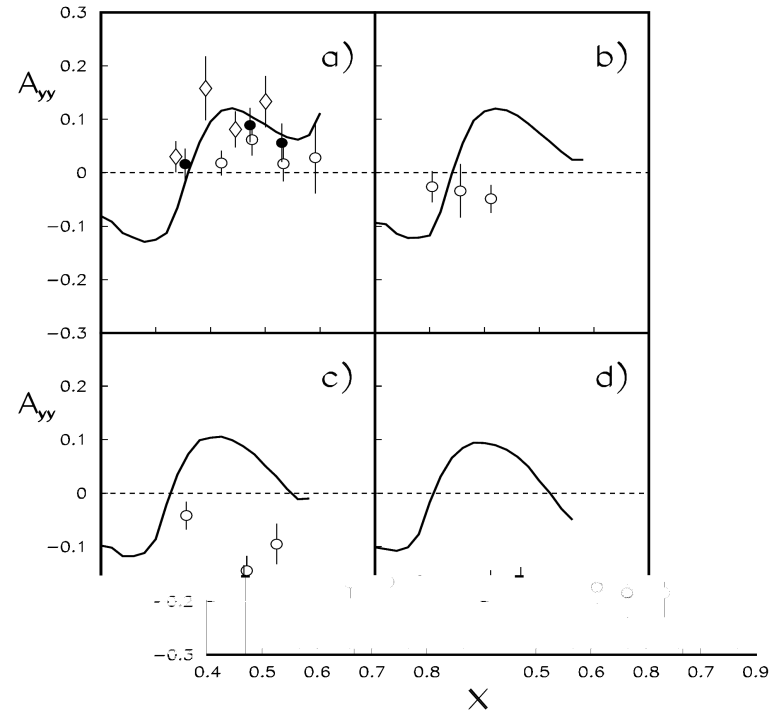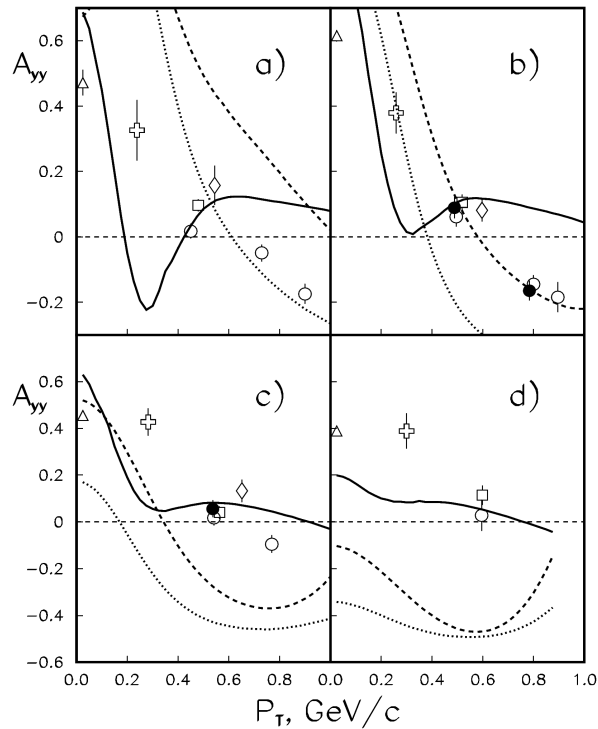
A_{yy} in deuteron inclusive breakup demonstrates the dependence on 2 internal variables: p_T and x_F.

A_{yy} changes the sign at p_T of about 600 MeV/c independently on x_F.
A_{yy} demonstrates negative asymptotic at large p_T .

V.P.Ladygin et al., Phys.Lett. B629 (2005) 60

Non-nucleonic degrees of freedom

When the distances between the nucleons are comparable with the size of the nucleon, the nucleon-nucleon interaction is a **non-local**.

The fundamental degrees of freedom, quark and gluons in the frame of QCD, begin also to play a role at the internucleonic distances comparable with the size of the nucleon.

They can manifest as **ΔΔ**, NN*, N*N*, 6q etc.components.

Data:
V.Punjabi et al., Phys.Lett.B350 (1995) 178
L.S.Azhgirey et al., Phys.Lett.B391 (1997) 22
L.S.Azhgirey et al., Phys.Lett.B387 (1996) 37

Fundamental (quark) degrees of freedom

At high energy **s** and large transverse momenta p_t the constituent counting roles (CCR) predict the following behavior of the differential cross section for the binary reactions:

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

(Matveev, Muradyan, Tavkhelidze, Brodsky, Farrar et al.)
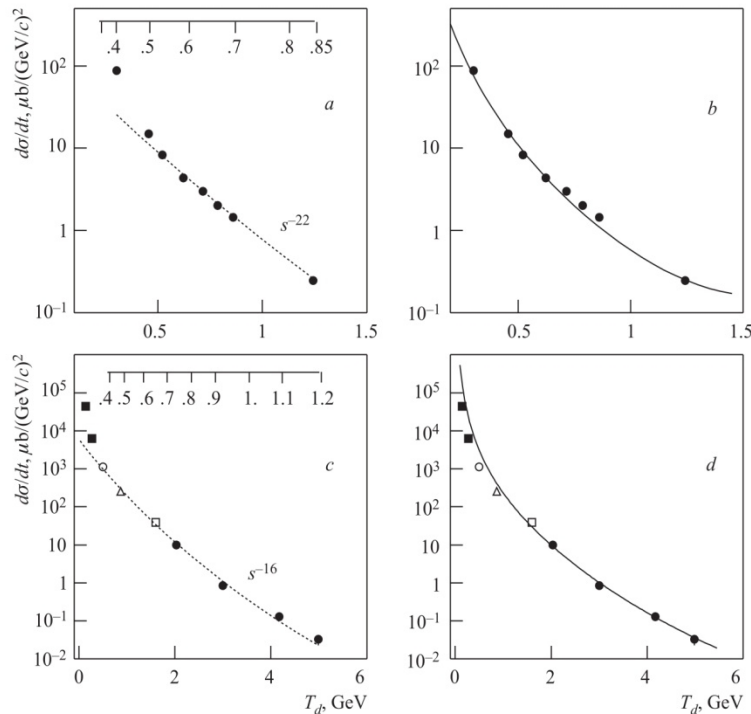
Yu. N. Uzikov

JETP Lett, 81 (2005) 303-306

For the reaction **dd → ^{3}Hen**

$$N_A + N_B + N_C + N_D - 2 = 22$$

For the reaction **dp → dp**

$$N_A + N_B + N_C + N_D - 2 = 16$$

The regime corresponding to CCR can occur already at $T_d \sim 500$ MeV

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Three Nucleon Forces

- **Modern NN potentials (CD-Bonn, AV-18, Njimegen etc.) accurately reproduce the NN data set up to about 350 MeV. However they fail in the description of the triton binding energy and data on unpolarized dp-elastic scattering and breakup.**

- **Incorporation of three nucleon forces (3NF), when interaction depends on the quantum numbers of the all three nucleon, allows to reproduce the binding energy of the three-nucleon bound systems and the data on unpolarized dp- interaction.**
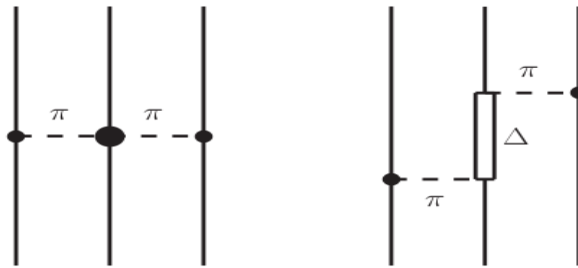
- Tucson-Melbourne
- Brazil
- Urbana-IX
- Fujita-Miyazawa ($N\Delta$)
- Chiral Effective Field Theory

Needs to be very careful: according to the theorem of W.N.Polyzou and W.Gloeckle, Few Body Syst. 9 (1990) 97, off-shell behaviour of 2NF can imitate 3NF effect.

Triton binding energy without 3NF:
Y.Fujiwara et al., Phys.Rev.C66 (2002) 021001(R)

12

Cross section in dp- elastic scattering at intermediate energies
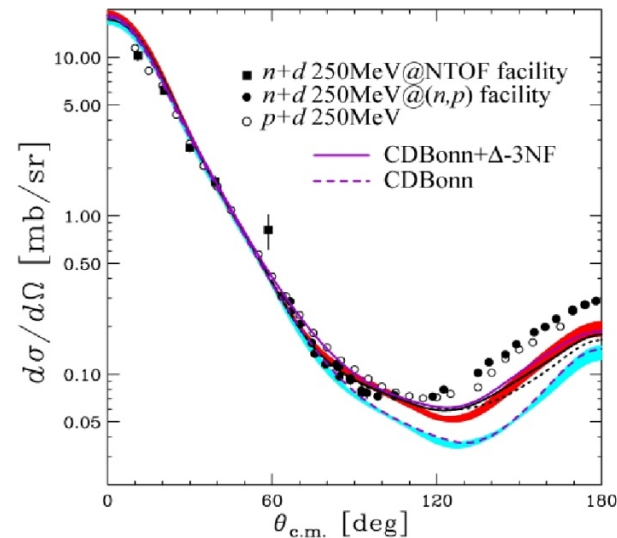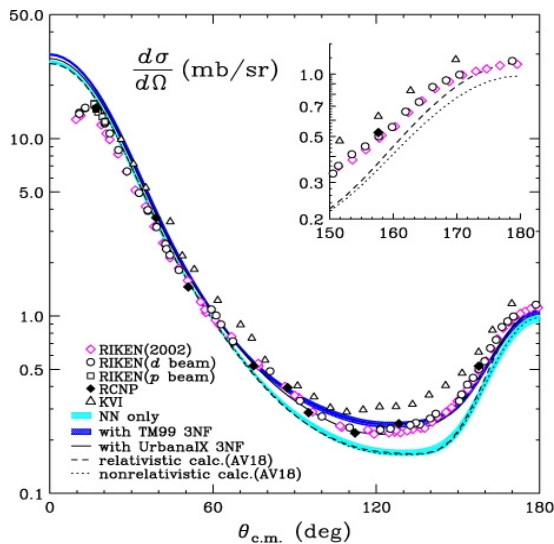
The differential cross section in elastic Nd scattering at the energy of 135 (left figure) and 250 (right figure) MeV/u.

K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)   K. Hatanaka et al., Phys. Rev. C 66, 044002 (2002)

The cross section data for dp- elastic scattering are reproduced well up to 150 MeV taking into account 3NF. Manifestation of three-nucleon forces effect in the cross-section of dp-elastic scattering at this energy: up to 30% in the vicinity of Sagara discrepancy.

But the problems in the description are at higher energies.

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Deuteron analyzing powers in dp- elastic scattering at intermediate energies (140, 200, 270 MeV)
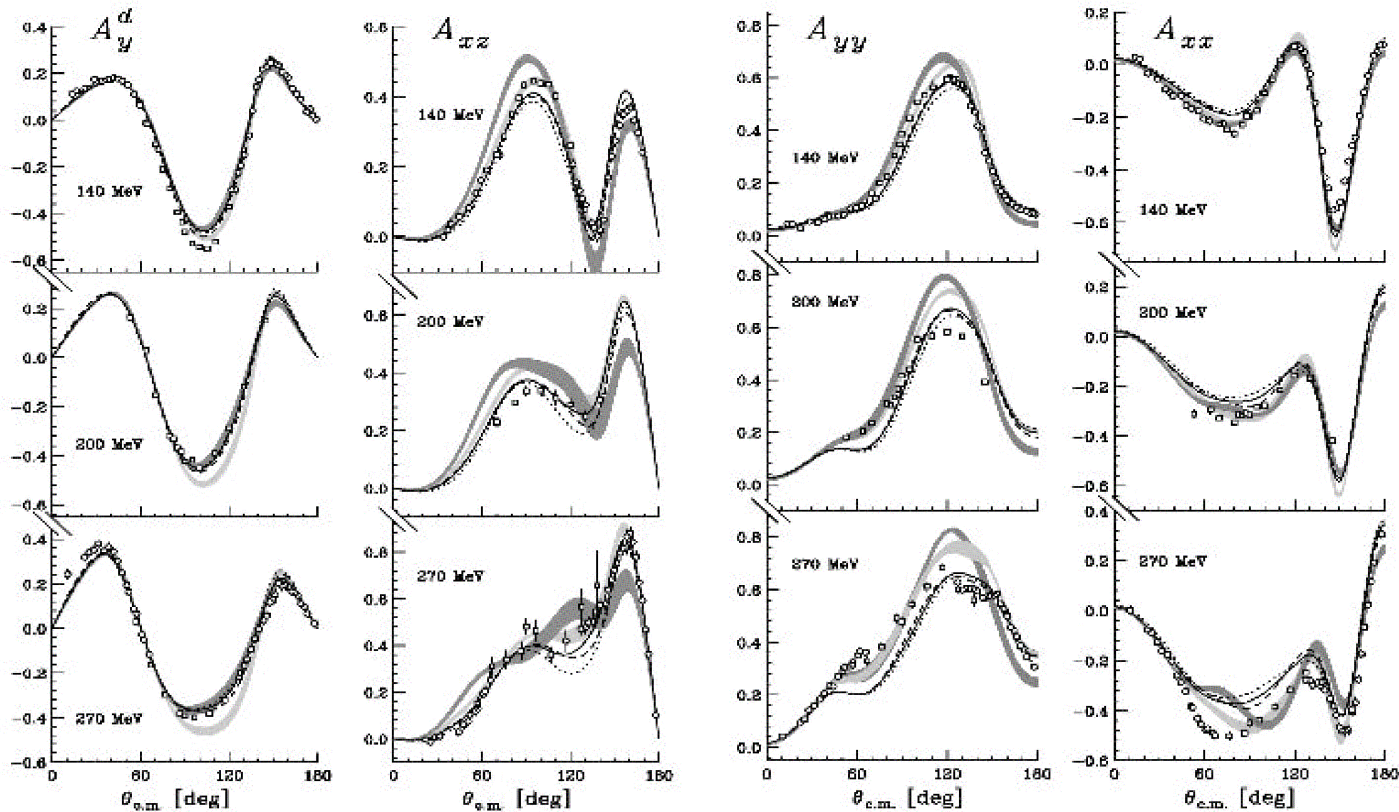
Polarization data for dp- elastic scattering are not described even with the 3NFs inclusion (except for Ay).

The spin part of 3NFs is missed!

Importance of the spin part of 3NF for the light nuclei binding energies
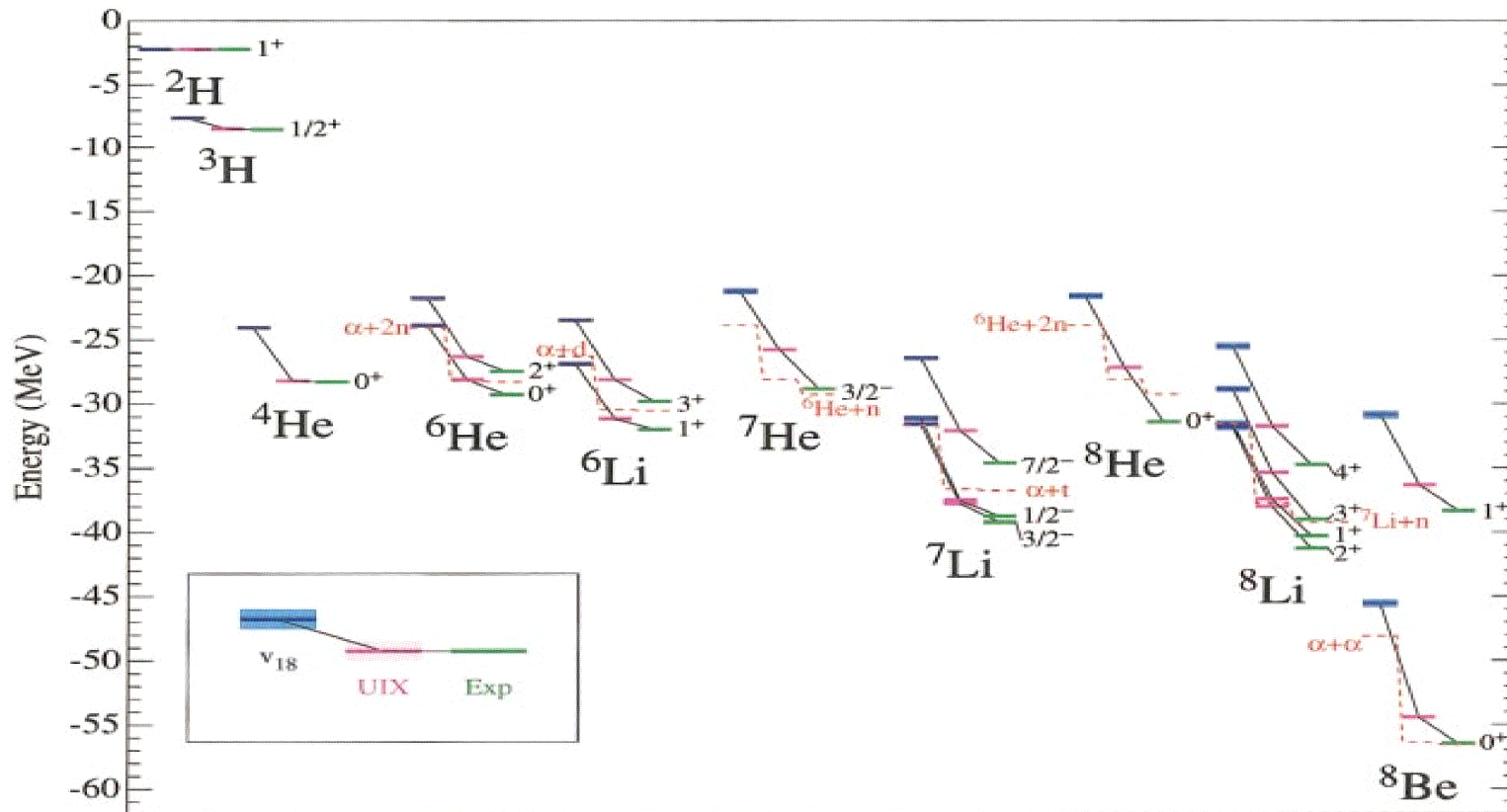
Spin parts of the 2N and 3N correlations are important to describe the light nuclei structure.
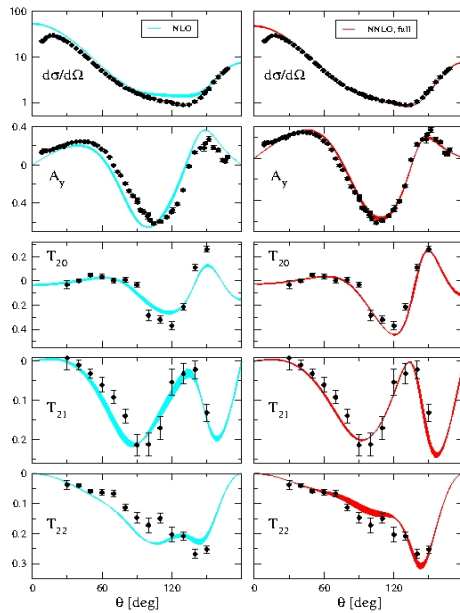
(S.C.Pieper et al., Phys.Rev.C64 (2001) 014001)

Cross section and proton analyzing power Ay in pd- elastic scattering at 250 MeV
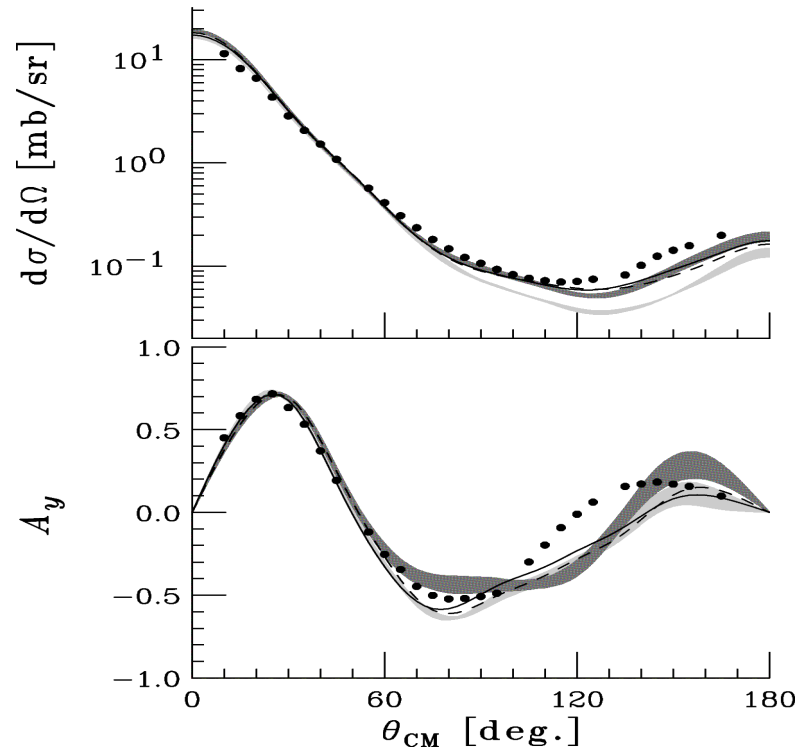
Problems in description at backward angles.
Relativistic effects become large ?
Short range 3NFs manifestation ?

Chiral Effective Field Theory
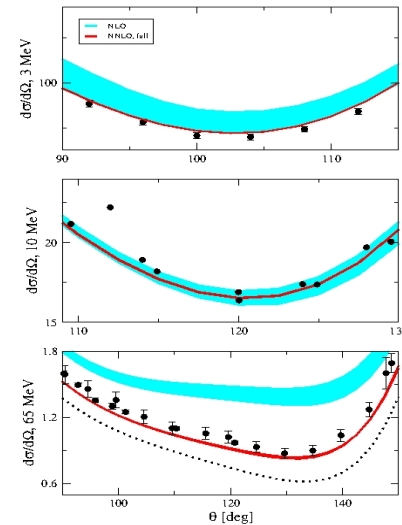
NNLO allows to describe the data up to 65 MeV/n

CFET is out of game above the pion threshold production!
However, new calculations exist at 200 MeV/nucleon.

Status of dp- elastic scattering

Inclusion of modern 3NFs allows to describe cross section and deuteron vector analyzing power of dp- elastic scattering up to 135 MeV/nucleon, while the tensor observables are not described.

The data at higher energies (up to 300 MeV/nucleon) are not described even taking into account relativistic effects.

The reason of the discrepancy is nowadays called the importance of the short range 3NFs which are still not included.

1. The systematic study of hadronic reactions induced by deuterons at Nuclotron will allow to study the structure of 2N and 3N forces, including their short-range parts.

2. Development of the relativistic models for the description of these reactions is required.

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The purpose of the **DSS** experimental program is to obtain the information about 2NF   and 3NF (*including their spin – dependent parts*) from two processes:

1.dp-elastic scattering at the energies between 300 - 2000 MeV;

2.dp-breakup with registration of two protons at deuteron energies of 300 - 500 MeV. (**talk of M.Janek**)

Analyzing powers in dp- elastic scattering at 880 MeV
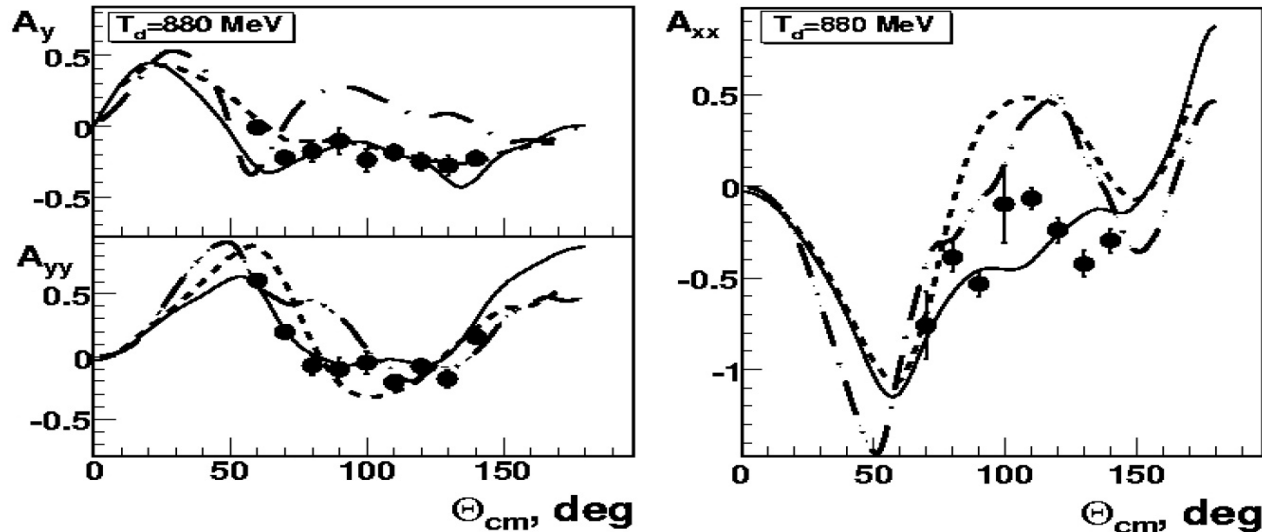
Dashed lines are the multiple scattering model calculations using CD
-Bonn DWF (N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039)

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) 61-65

Cross section in dp- elastic scattering at 880 MeV

- **The results of the multiple scattering model are in agreement with the cross section data in the range 30 - 130º.**

- **Double scattering dominates over single scattering at the angles larger than 70º.**

- **Deviation of the data on the calculations at backward angles are related with the s-type of the FM 3NF.**

- **How to find the manifestation of 3N short range forces?**

Relativistic multiple scattering model calculation:
 N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

World data:

N.E.Booth et al., Phys.Rev.D4 (1971) 1261

J.C.Alder et al., Phys.Rev.C6 (1972) 2010

 Picture is taken from
 P.K.Kurilkin et al., Phys.Lett.B715 (2012) 61-65

Relativistic multiple scattering model for **dp**- elastic scattering at moderate energies
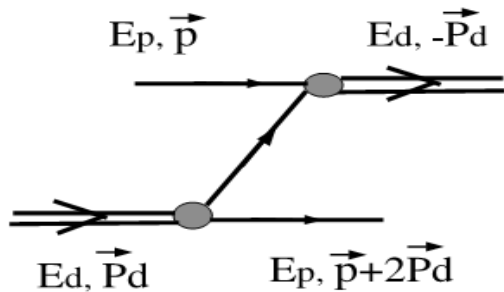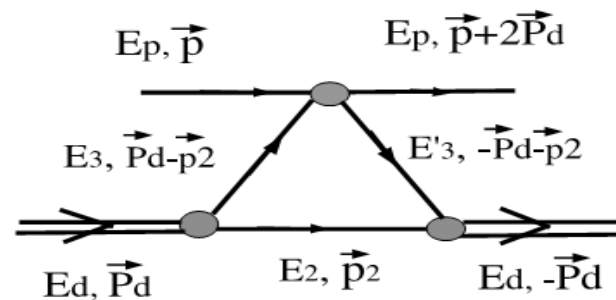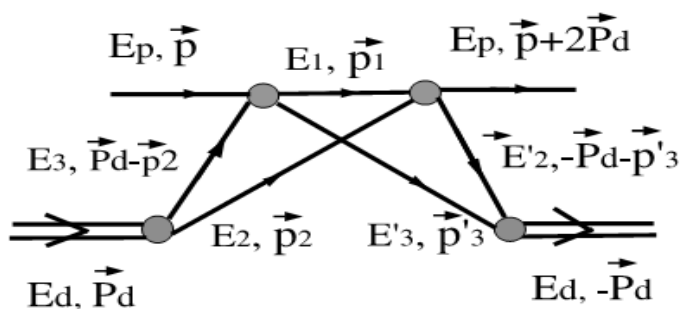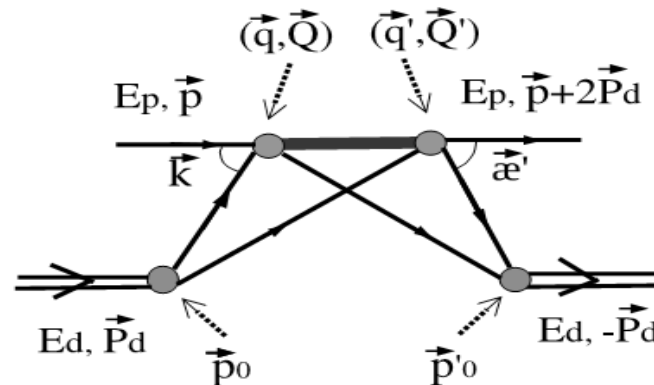
ONE+SS+DS -   **N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039**
                          N.B.Ladygina, Eur.Phys.J, A42 (2009) 91
ONE+SS+DS +▲- **N.B.Ladygina, Eur.Phys.J, A52 (2016) 199**

dp- elastic scattering cross section at 880 MeV
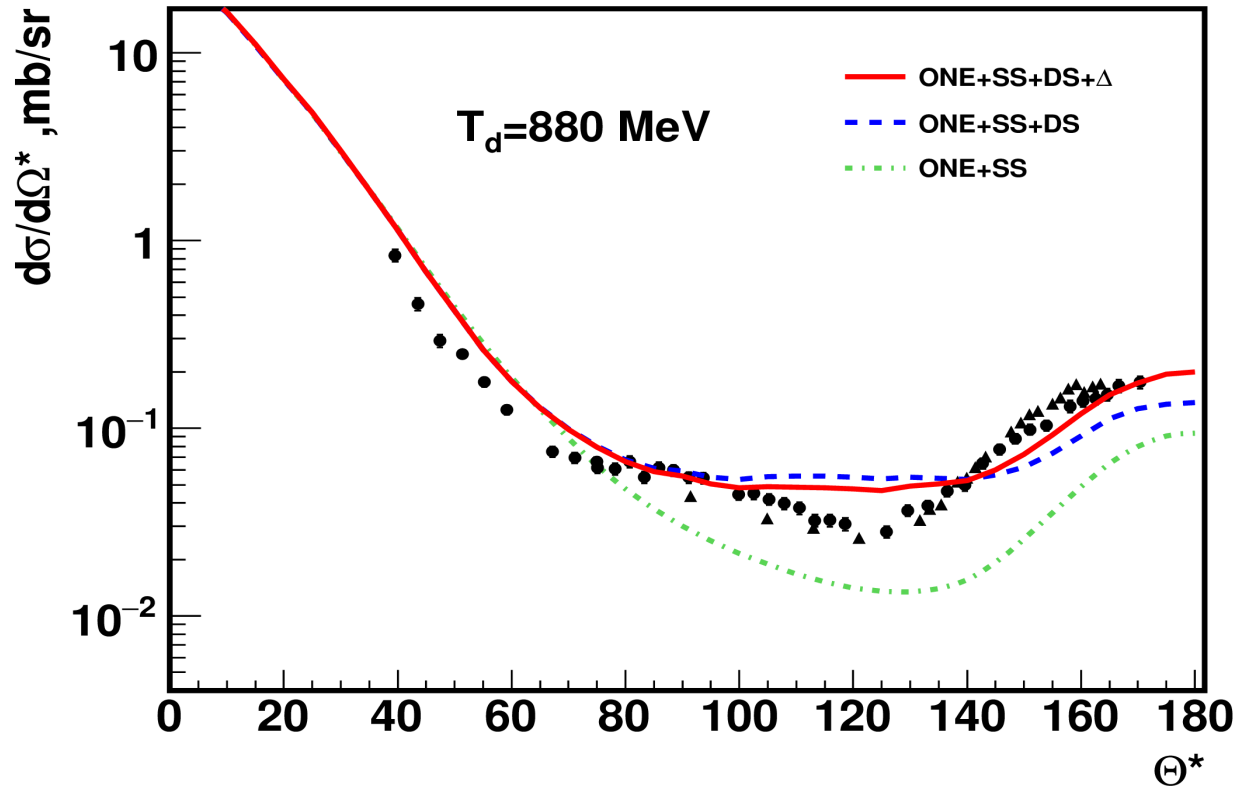
Relativistic multiple scattering model calculation:
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

dp- elastic scattering cross section at 1400 MeV
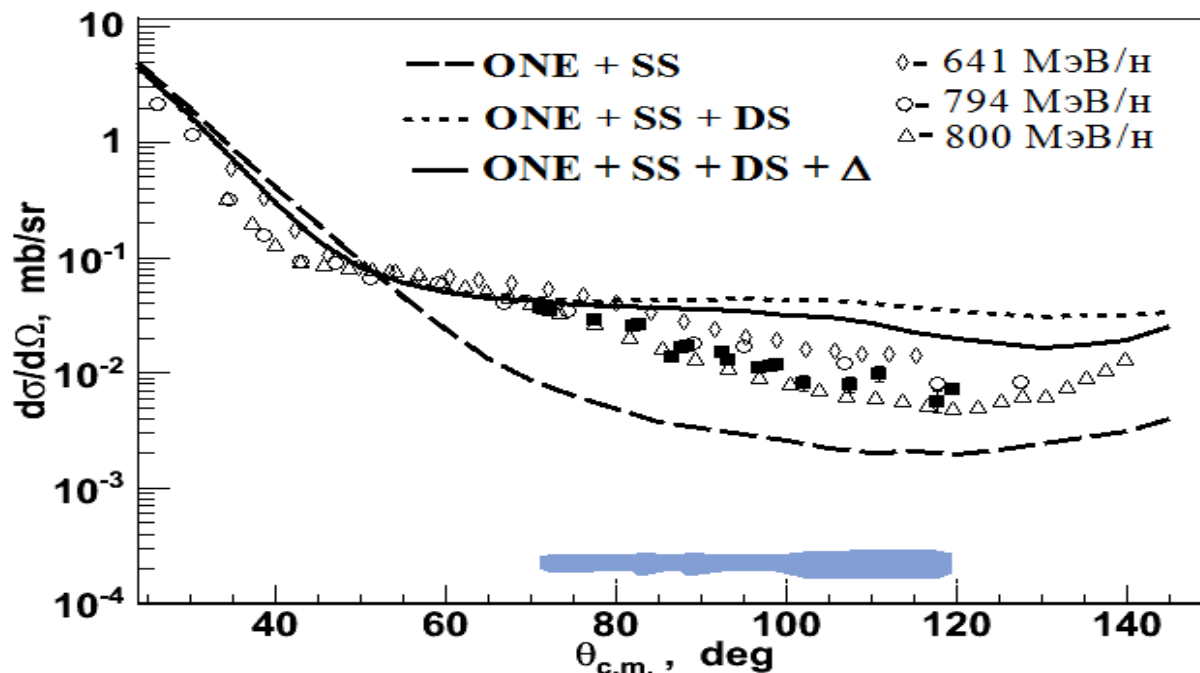
A.A.Terekhin et al.,   Phys.Atom.Nucl. 80(2017) 1061.

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

Final cross section data at 1000, 1300 and 1800 MeV

(talk of A.Terekhin)

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A_y and A_{yy} in dp- elastic scattering at 2000 MeV
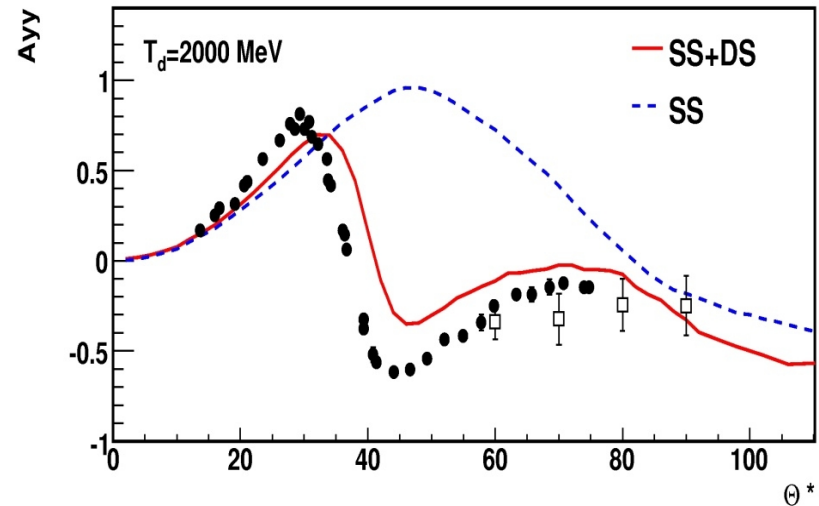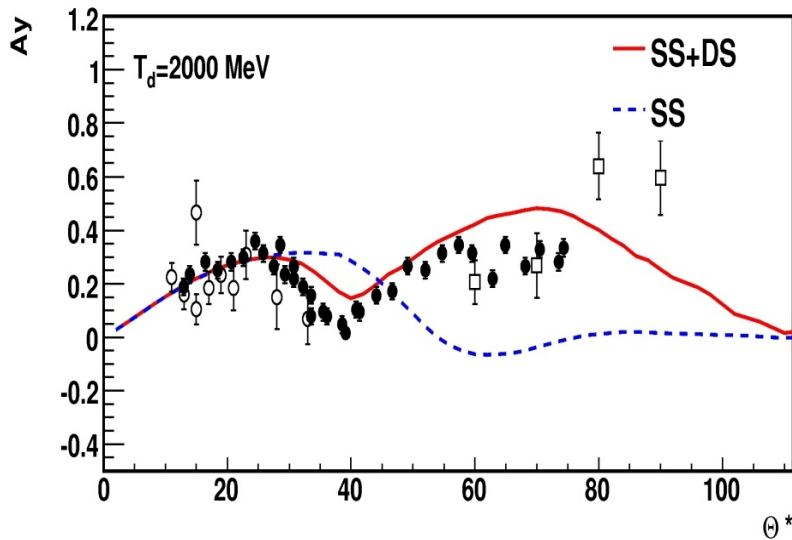
Open squares are the data obtained at Nuclotron JINR.
Open circles are the Synchrophasotron data (V.V.Glagolev, Eur. Phys. J. A48 (2012) 182)

Solid symbols are the data obtained by ANL group (Haji-Saied et al., Phys.Rev.C.36 (1987) 2010).

Dashed and solid lines are the relativistic multiple scattering model calculations using CD- Bonn DWF taking into account single scattering and single+double scattering, respectively.

Energy dependence of the dp-elastic scattering analyzing powers at fixed scattering angles in the c.m.s.
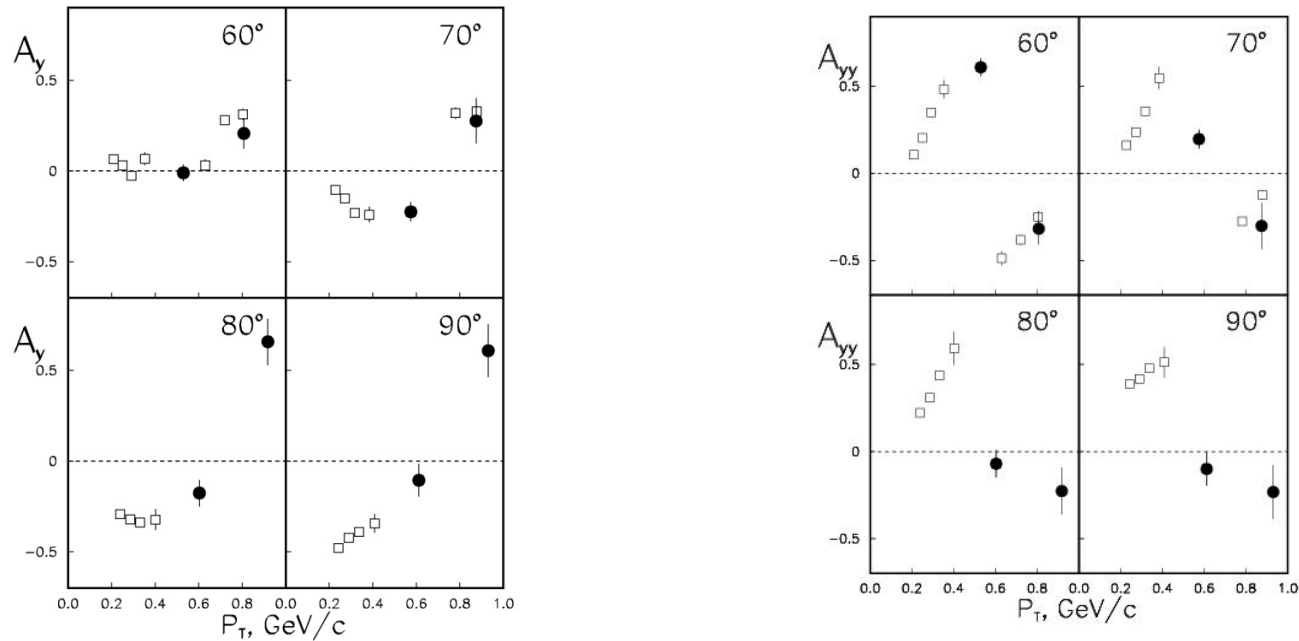
- **Full symbols are the data obtained at JINR**
- **Open symbols are the data obtained at RIKEN, Saclay and ANL**
- **The study of the energy dependence of the analyzing powers in dp- elastic scattering at large p_T is one of the tools to study spin effects in cold dense matter**

General View of SPI

Charge-Exchange Ionizer

Atomic Beam Source
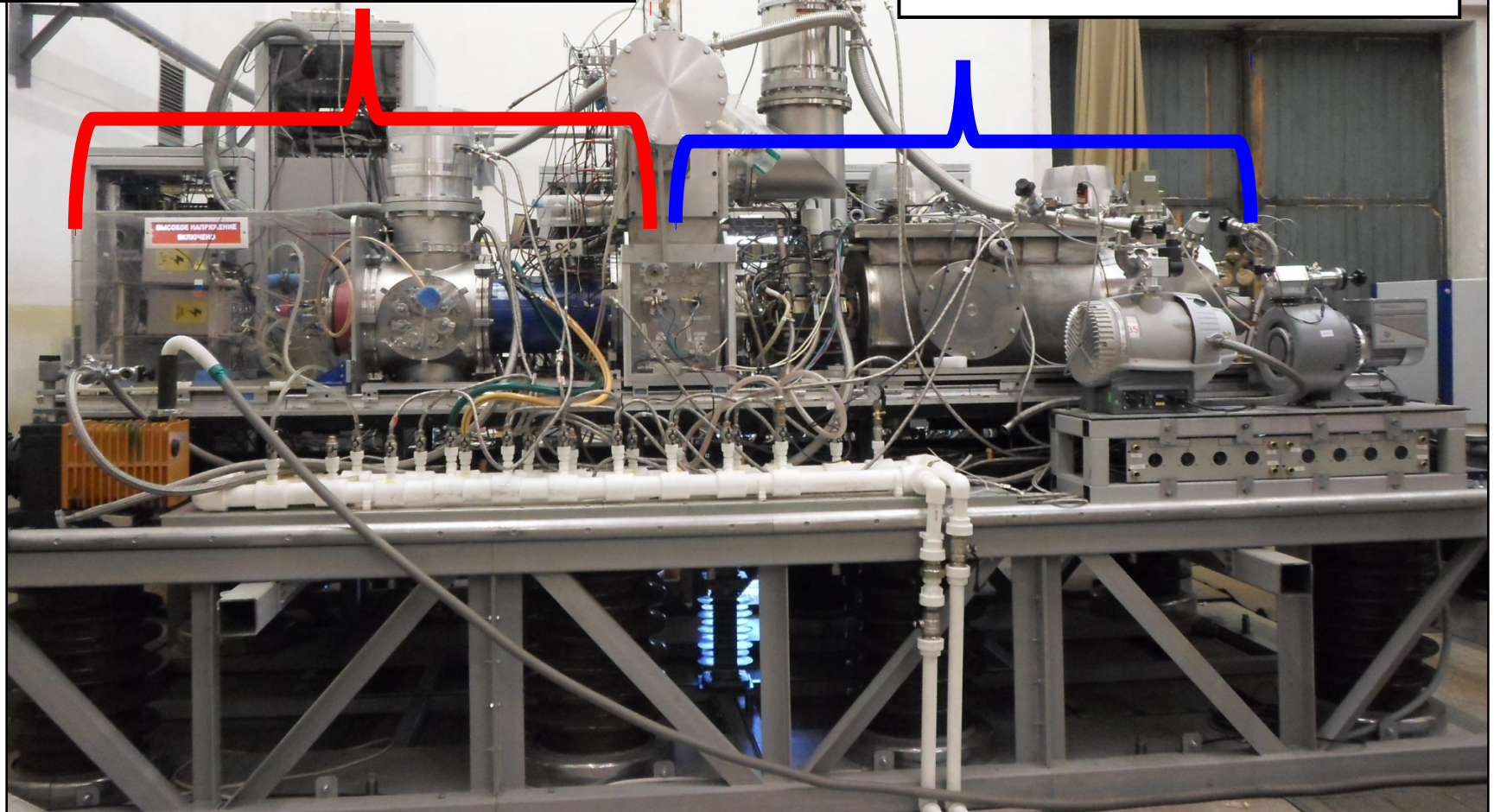
Figure of merit will be increased in future by a factor ~10³

Nuclotron-M accelerator complex
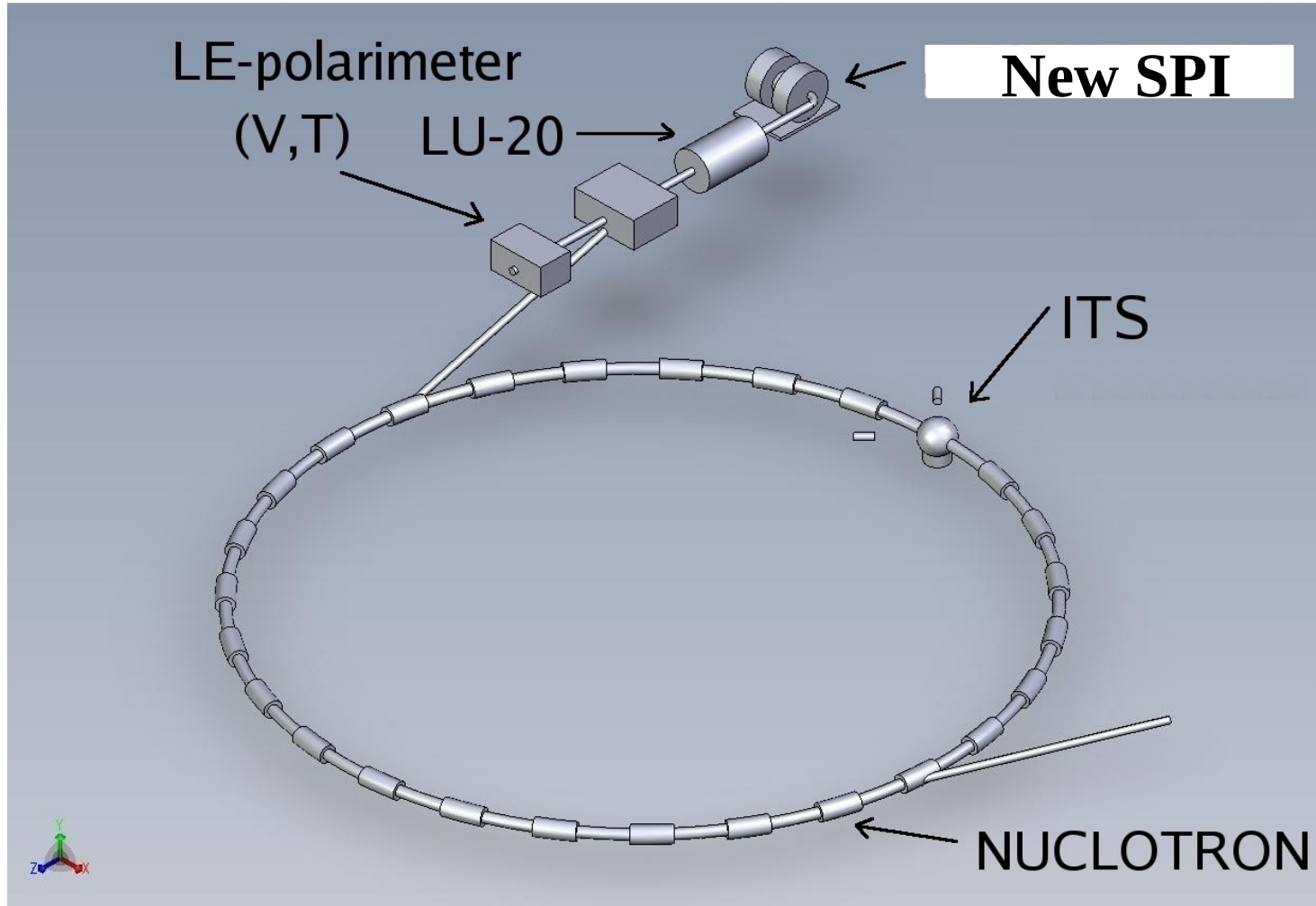
Experiments at Internal Target Station at Nuclotron
DSS-project
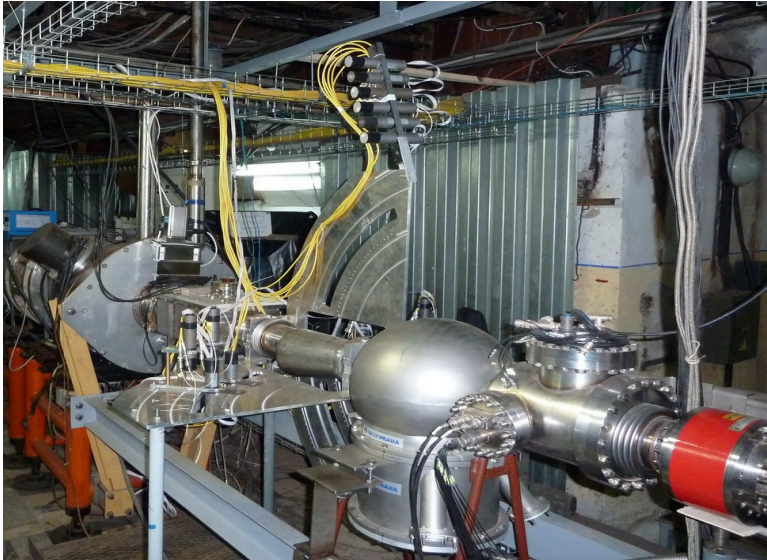
Internal Target Station is very well suited for the measurements of the deuteron- induced reactions observables at large scattering angles.

Upgrade of the Delta-LNS (DSS) setup at ITS at Nuclotron
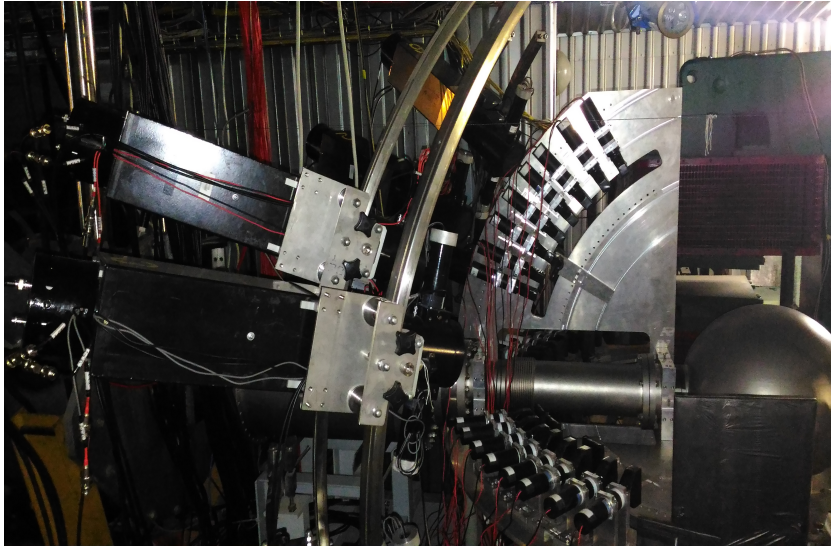
New infrastructure, cabling
New HV system (Mpod)
New VME DAQ
40 counters for dp-elastic scattering studies
8 dE-E detectors for dp -breakup studies

Results from the commissioning run at Nuclotron at 270 MeV (June 2016)
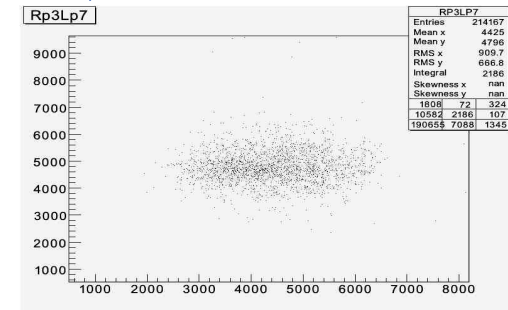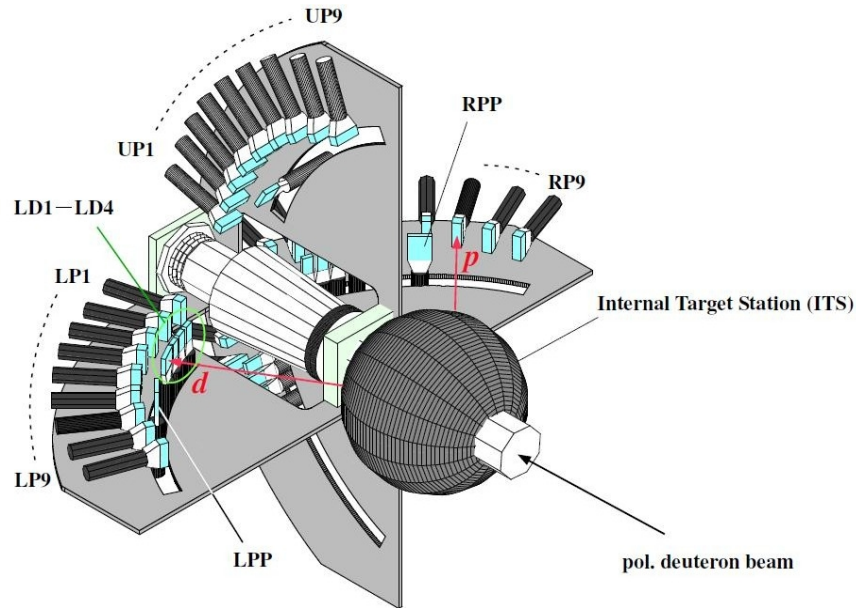
DP
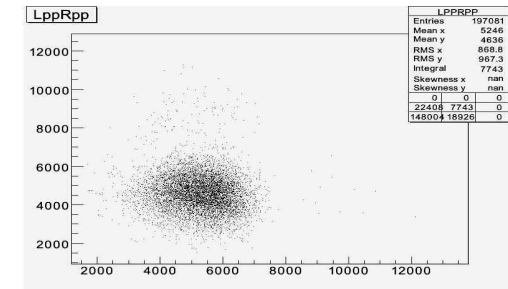
PP

- **Deuterons and protons in coincidences using scintillation counters**
- **Internal beam and thin CH$_2$ target (C for background estimation)**
- **Measurements at 270 MeV**

- **The setup was ready to take the polarized data.**

Setup to study dp- elastic scattering at ITS at Nuclotron in 2016-2017.
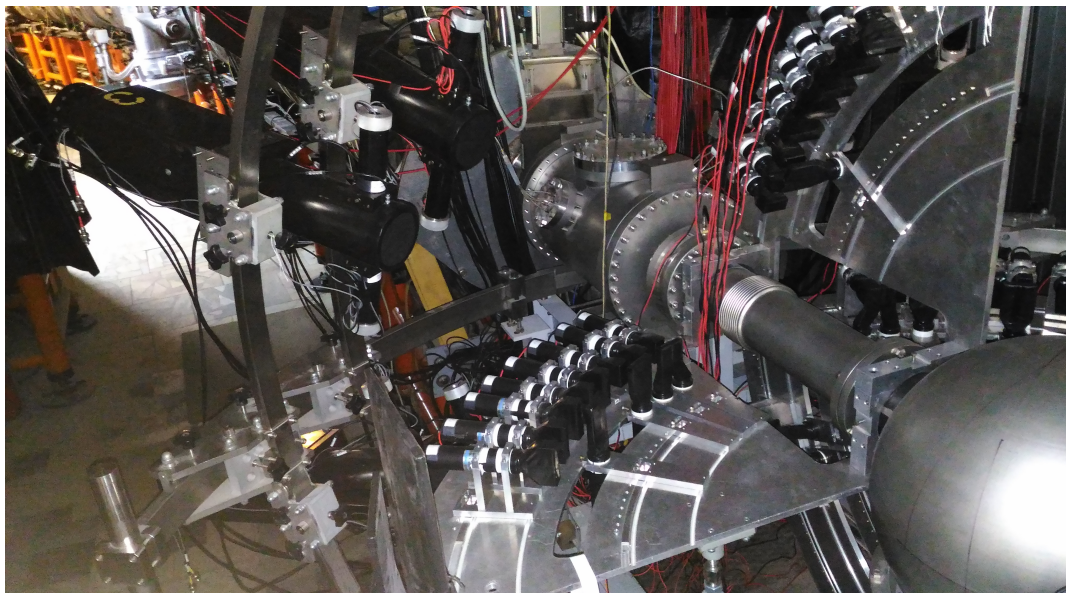
- Deuterons and protons in coincidences using scintillation counters
- Internal beam and thin CH_2 target (C for background estimation)
- Permanent polarization measurement at 270 MeV (between each energy).
- Analyzing powers measurement at 400-1800 MeV
- The data were taken for three spin modes of SPI: unpolarized, "2-6" and "3-5" (p_z, p_{zz}) = (0,0), (-1/3,1) and (-1/3,-1).
- Typical values of the polarization was 70-75% from the ideal values.

(talks of A.Yu.Isupov and Ya.Skhomenko).

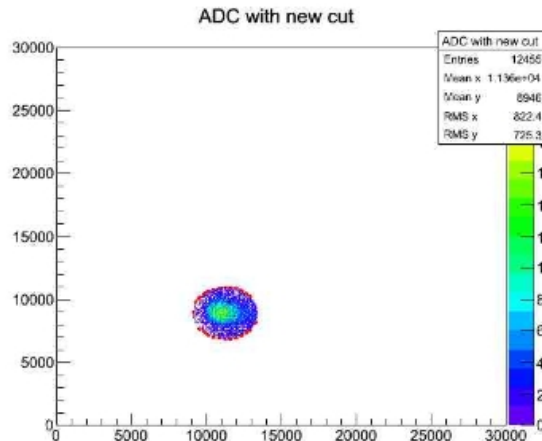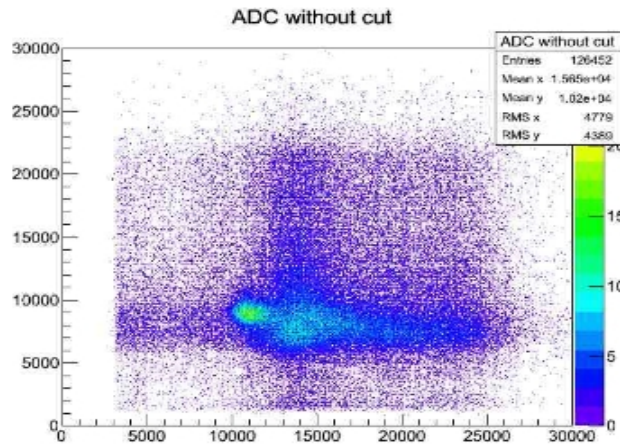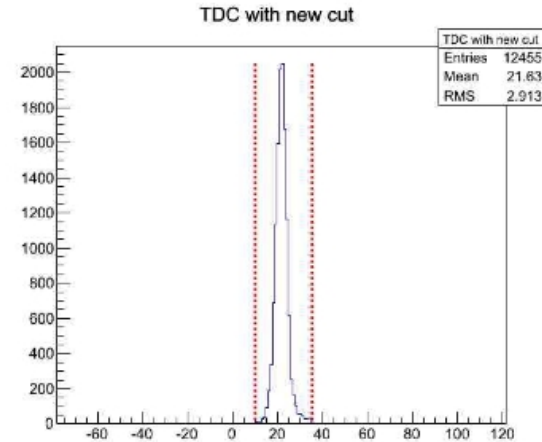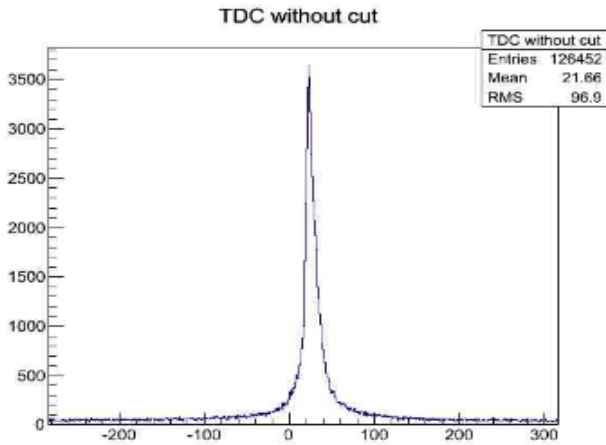# Polarization measurements using dp- elastic scattering at 270 MeV
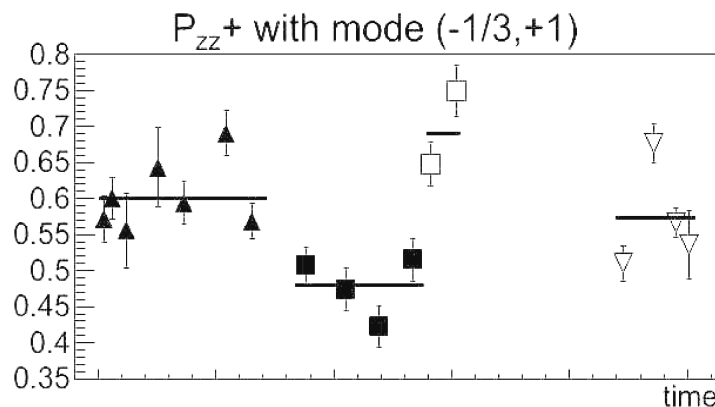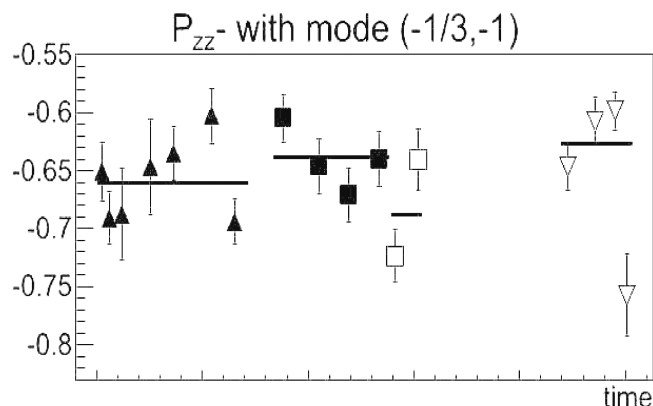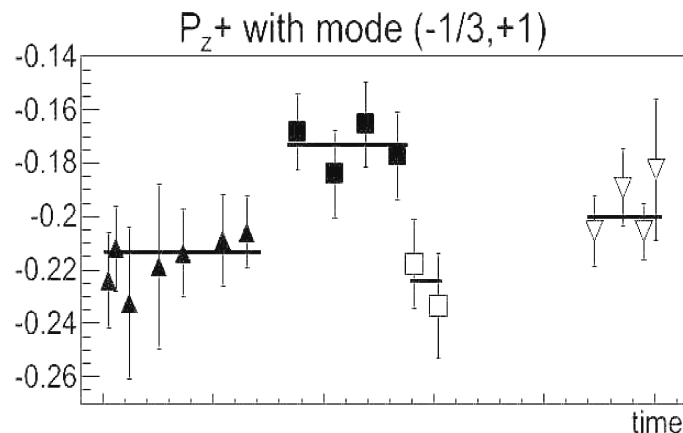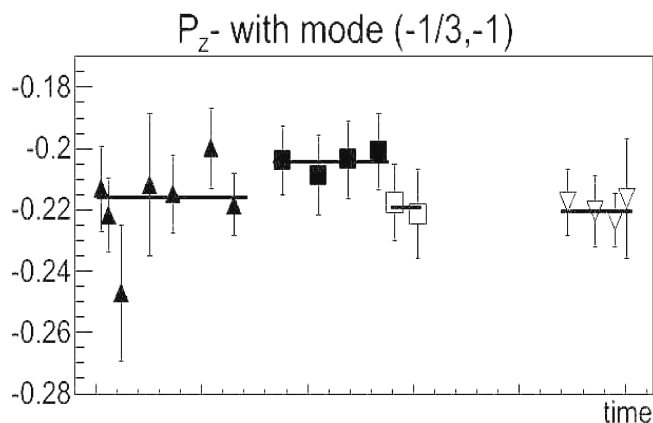
SPI was tuned for 6 spin modes $(p_z, p_{zz}) = (-1/3, 1), (-1/3, -1), (0, +1), (0, -2), (-2/3, 0), (+1, 0).$
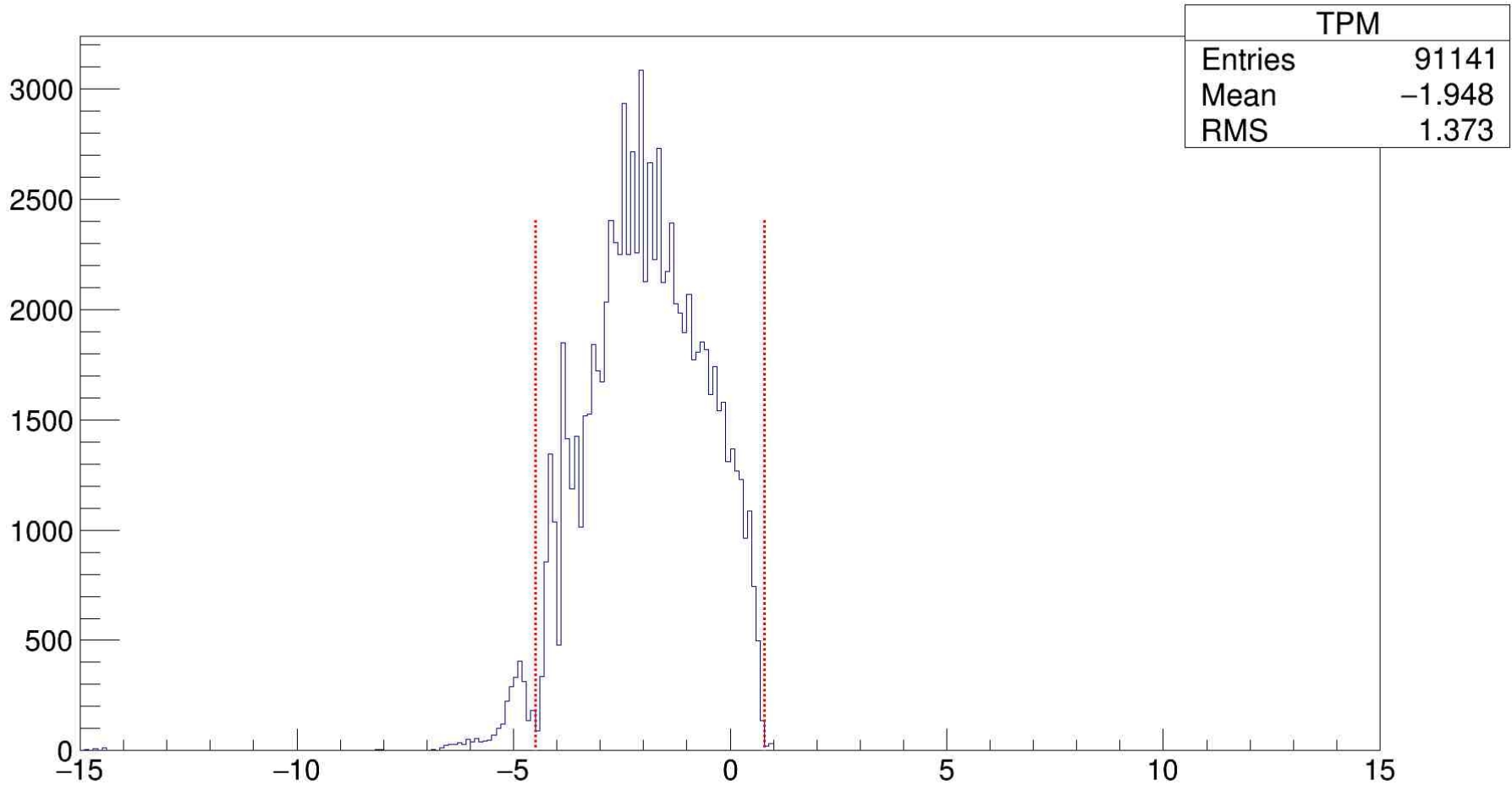
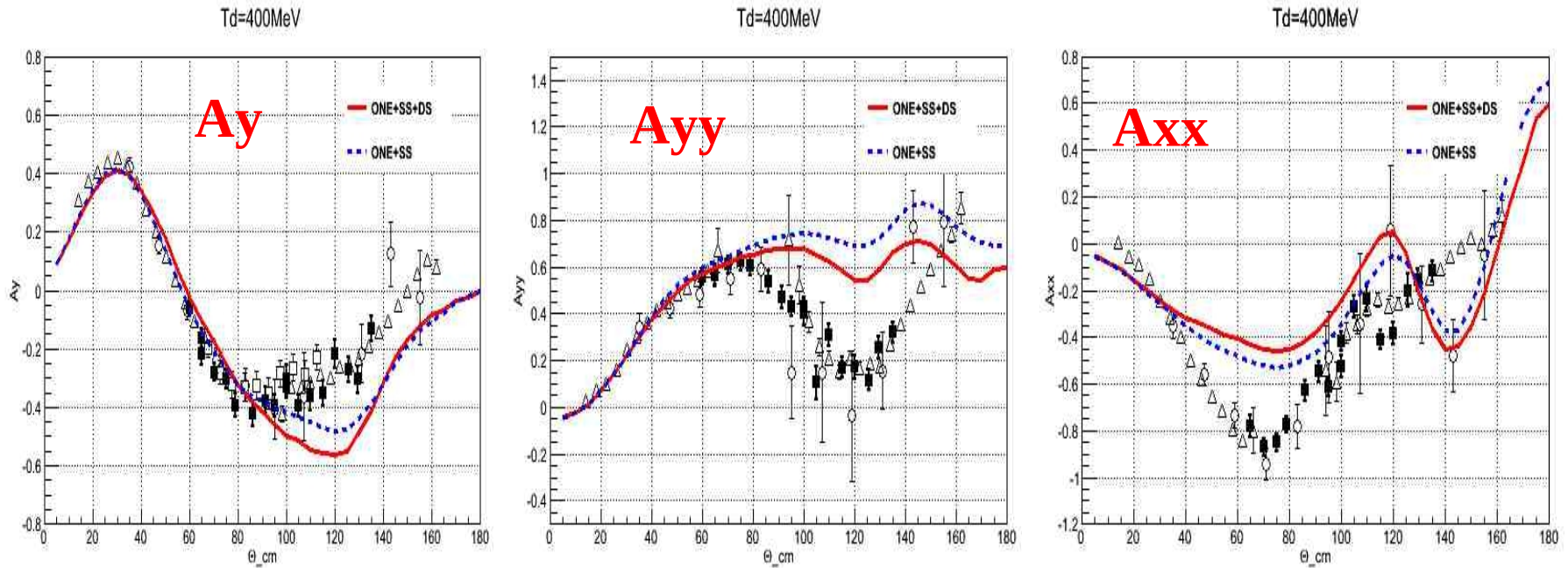# The dp-elastic scattering events selection

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.

Target Position Monitor cut

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

Full squares are the data from Nuclotron (December 2016)

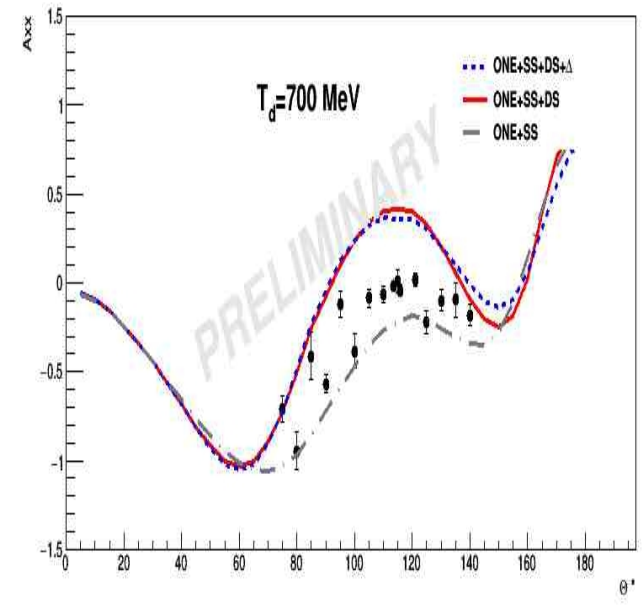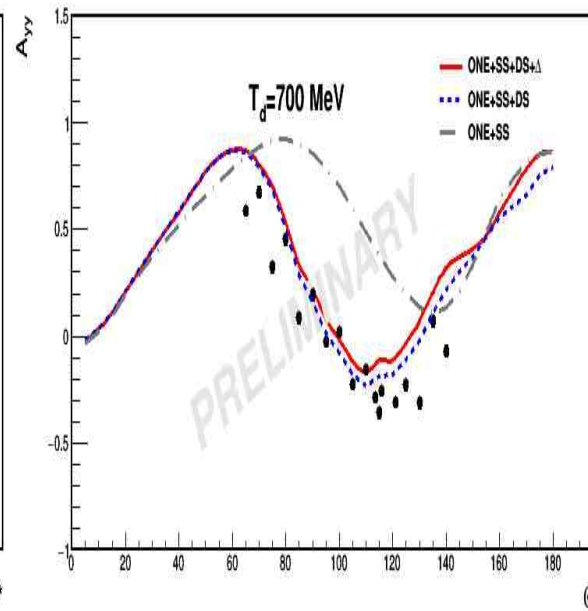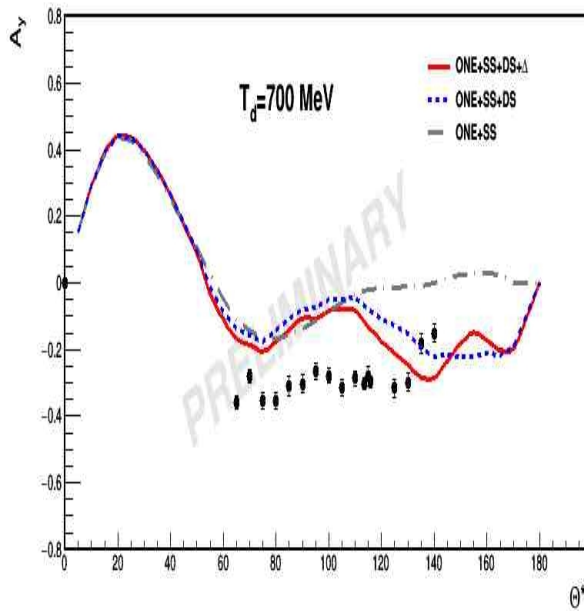**Curves are the relativistic multiple scattering model calculations**
N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

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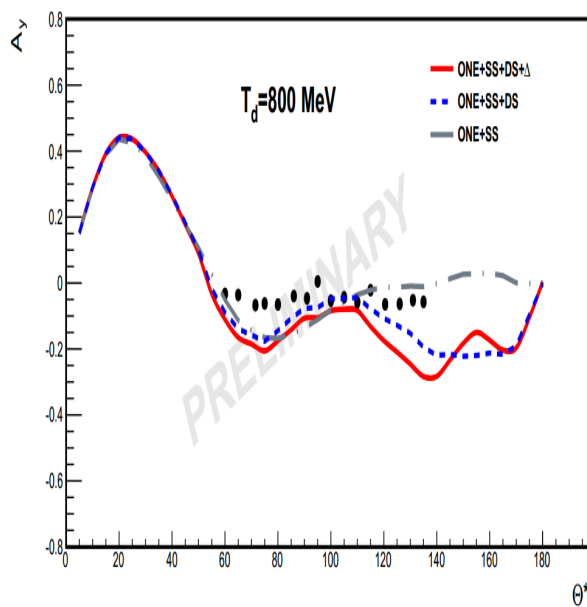
Ay

Ayy

Axx

Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

Angular dependence of the vector and tensor analyzing powers in **dp**-elastic scattering at **800 MeV**

Ay   Ayy   Axx

Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

(**talk of O.Mezhenska**)

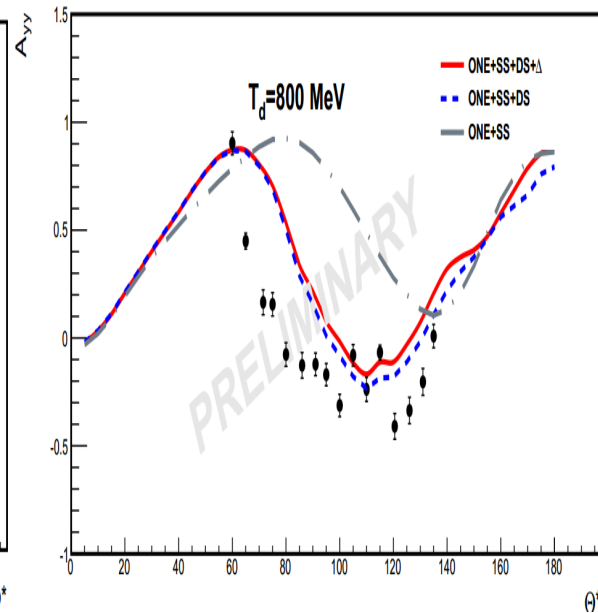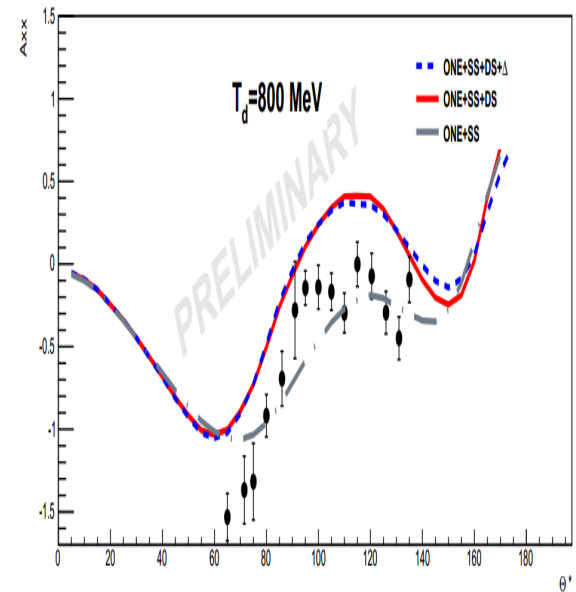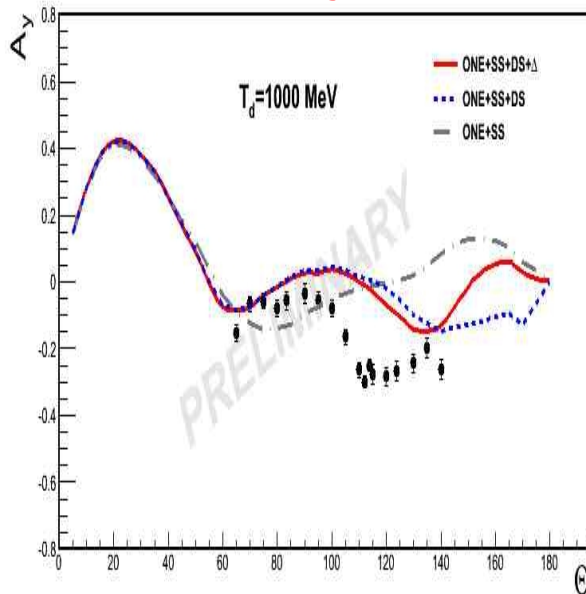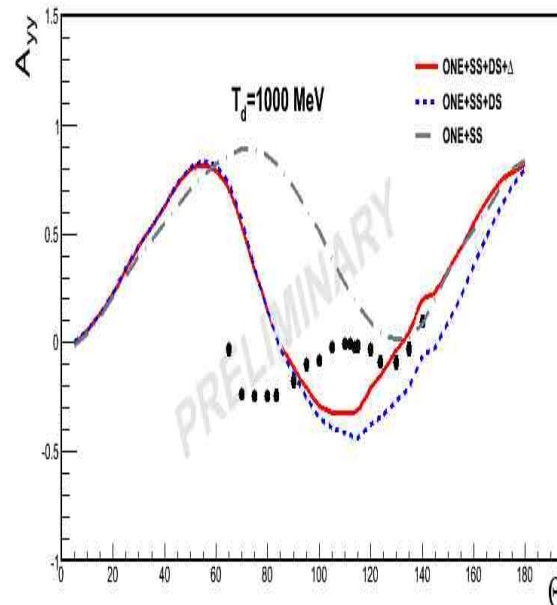# Angular dependence of the vector and tensor analyzing powers in dp-elastic scattering at 1000 MeV
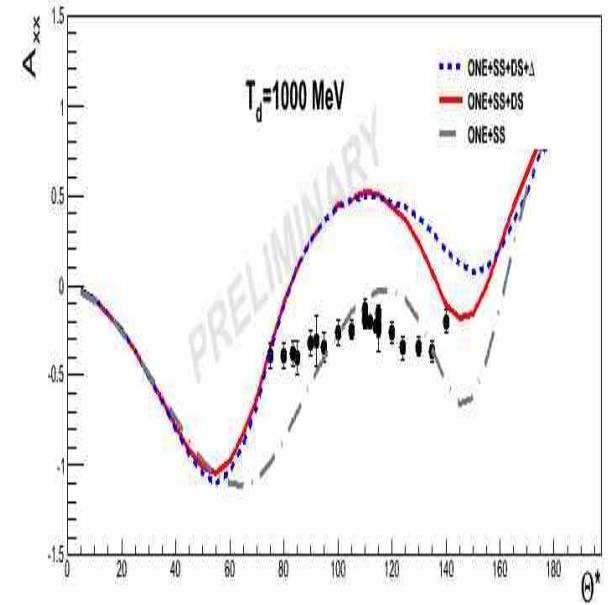
Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

Energy dependence of the vector analyzing power Ay in dp-elastic scattering at 700-1800 MeV
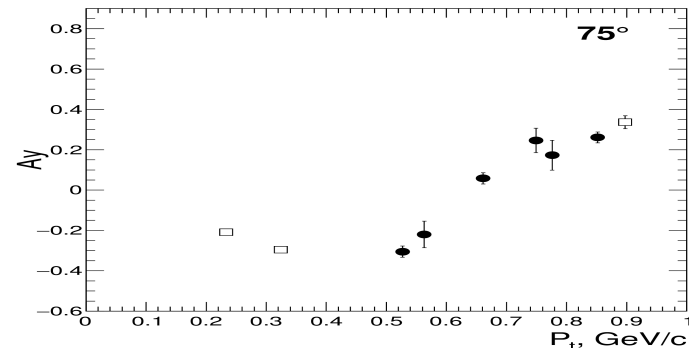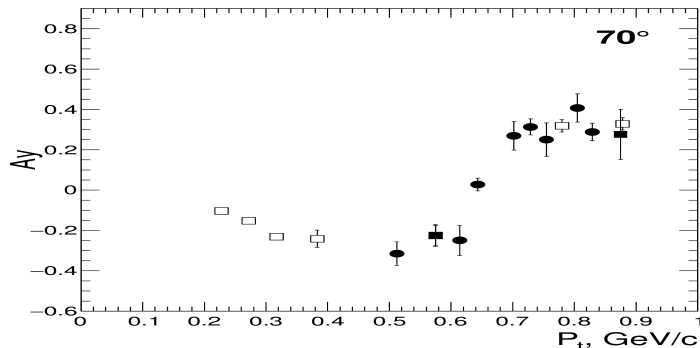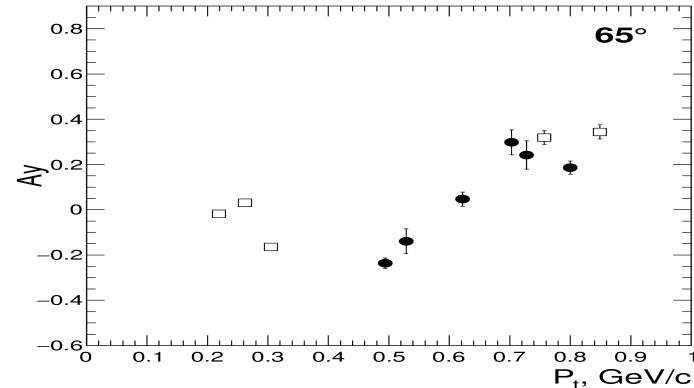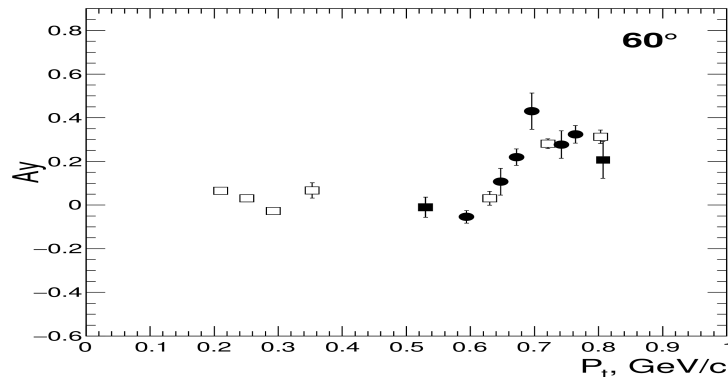
Full circles are the new preliminary data from Nuclotron (2016-2017).
Full squares are the data from Nuclotron (2005).
Open symbols are the world data.

Energy dependence of the tensor analyzing power Ayy in dp-elastic scattering at 700-1800 MeV
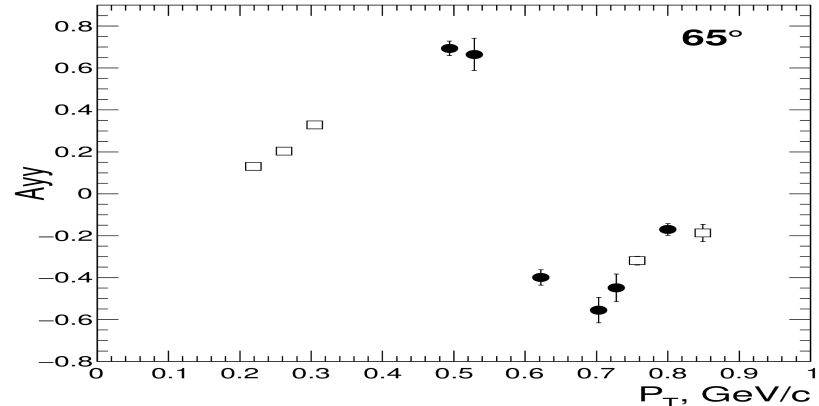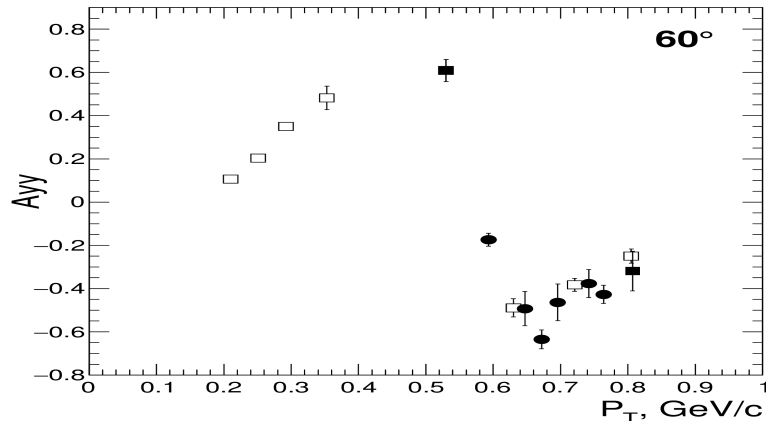
Full circles are the new preliminary data from Nuclotron (2016-2017).
Full squares are the data from Nuclotron (2005).
Open symbols are the world data.

Conclusion

Upgraded Nuclotron with new SPI provides quite unique opportunity for the studies of the spin effects and polarization phenomena in few body systems.

The realization of the DSS program at ITS will allow to obtain the crucial data on the spin structure of 2-nucleon and 3- nucleon short range correlations.

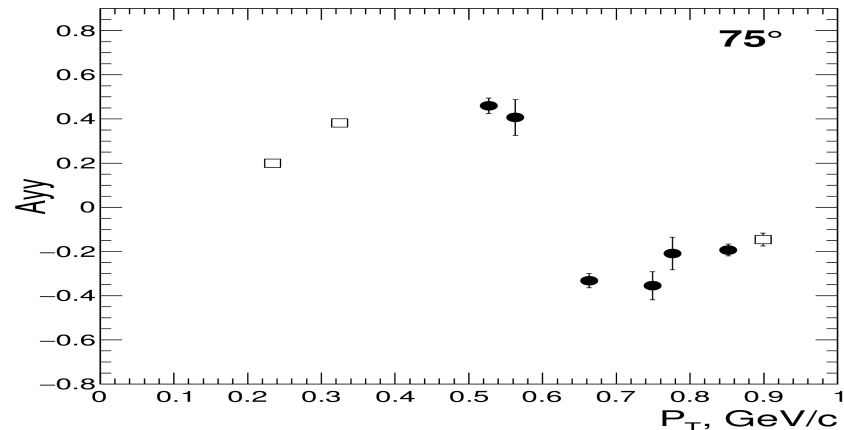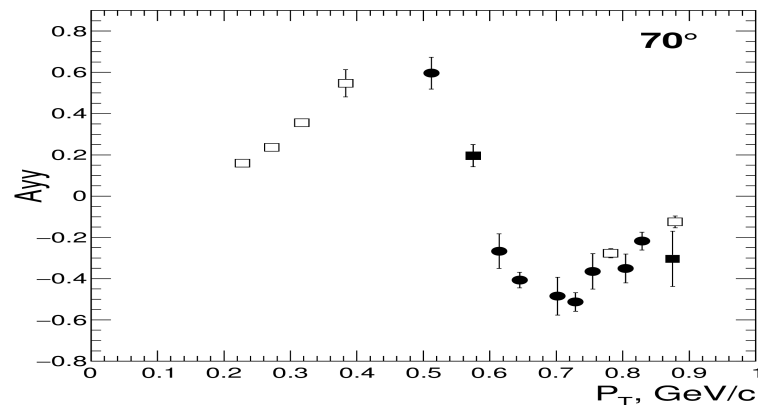**The first natural step in these studies, namely, the energy scan of the deuteron analyzing powers in dp- elastic scattering has been performed in 2016-2017.**

Next experiments using polarized deuterons and protons at ITS are in preparation.

The extention of the studies to the high energies is possible with the extracted polarized deuteron and proton beams.

Polarized protons at ITS.

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 the asymmetries for 8 angles (55^0-125^0 in the cms) we obtained the averaged value of the proton beam polarization

Unpolarized protons: P= 0.017 ±0.021
Polarized protons: P=-0.354 ±0.022

Need to produce new detection system for protons.
V.P.Ladygin et al.,J.Phys.Conf.Ser. 938 (2017) 012008

Further DSS plans

Final analysis of the systematic data on the cross section and analyzing powers A_y, A_{yy} and A_{xx} in dp- elastic scattering between 270 MeV and 2000 MeV at ITS.

Preparation of the experiments on the systematic studies of the analyzing powers A_y, A_{yy} and A_{xx} in dp- elastic scattering between 270 MeV and 500 MeV using new SPI at Nuclotron to study the manifesttion of the short-range 3NFs.

Preparation for the taking of new polarized data for the dp (pd)- nonmesonic breakup at the energies between 300 and 500 MeV for different kinematic configurations at ITS with polarized beams.

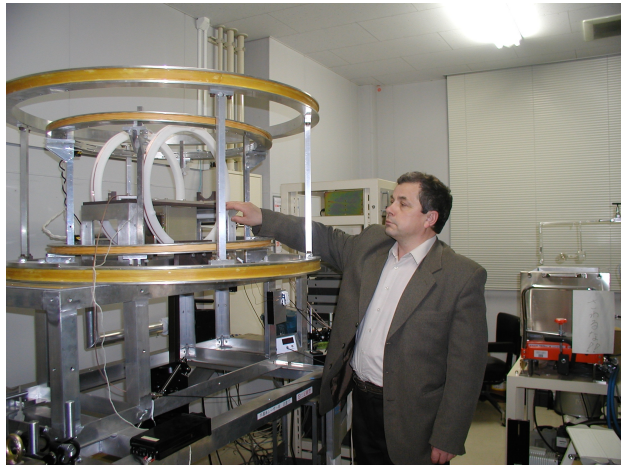**Preparation of the experiment on the energy scan of the nucleon analyzing power A_y^p in pd- elastic scattering between 135 MeV and 1000 MeV at ITS.**
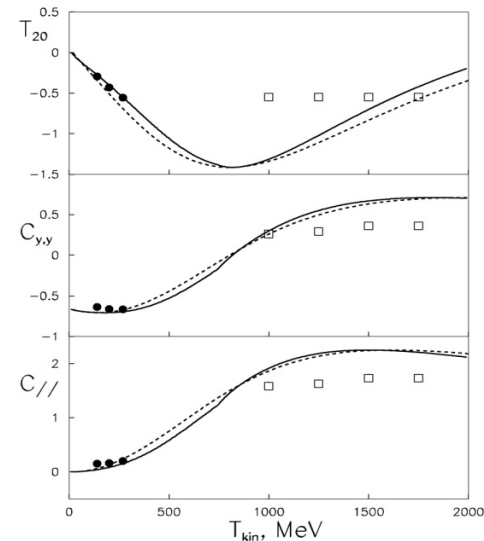
Program is approved by JINR PAC for 2019-2021 yy.

Thank you for the attention!

Polarization observables for polarized deuteron induced reactions

Target position is in F5

^{3}He(d,p)^{4}He

- The measurements of the tensor analyzing power T_{20} and spin correlation $C_{y,y}$ in the ^{3}He(d,p)^{4}He reaction in the kinetic energy range between 1.0 and 1.75 GeV can be performed at the BM@N area.
- The polarization observables for the p(d,p)d, d(d,p)t and d(A,p(0º))X at intermediate and high energies also can be studied.
- Non-nucleonic degrees of freedom and baryonic resonances properties can be studied in the d(A,d(0º))X and d(A,π⁻(0º))X reactions at different energies.
- The tensor analyzing power T_{20} can be studied for the meson production in the d(A,3He(0º))X reactions.

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Polarization effects in the $dd \rightarrow {}^3\text{Hen}({}^3\text{Hp})$ reactions at Nuclotron energies
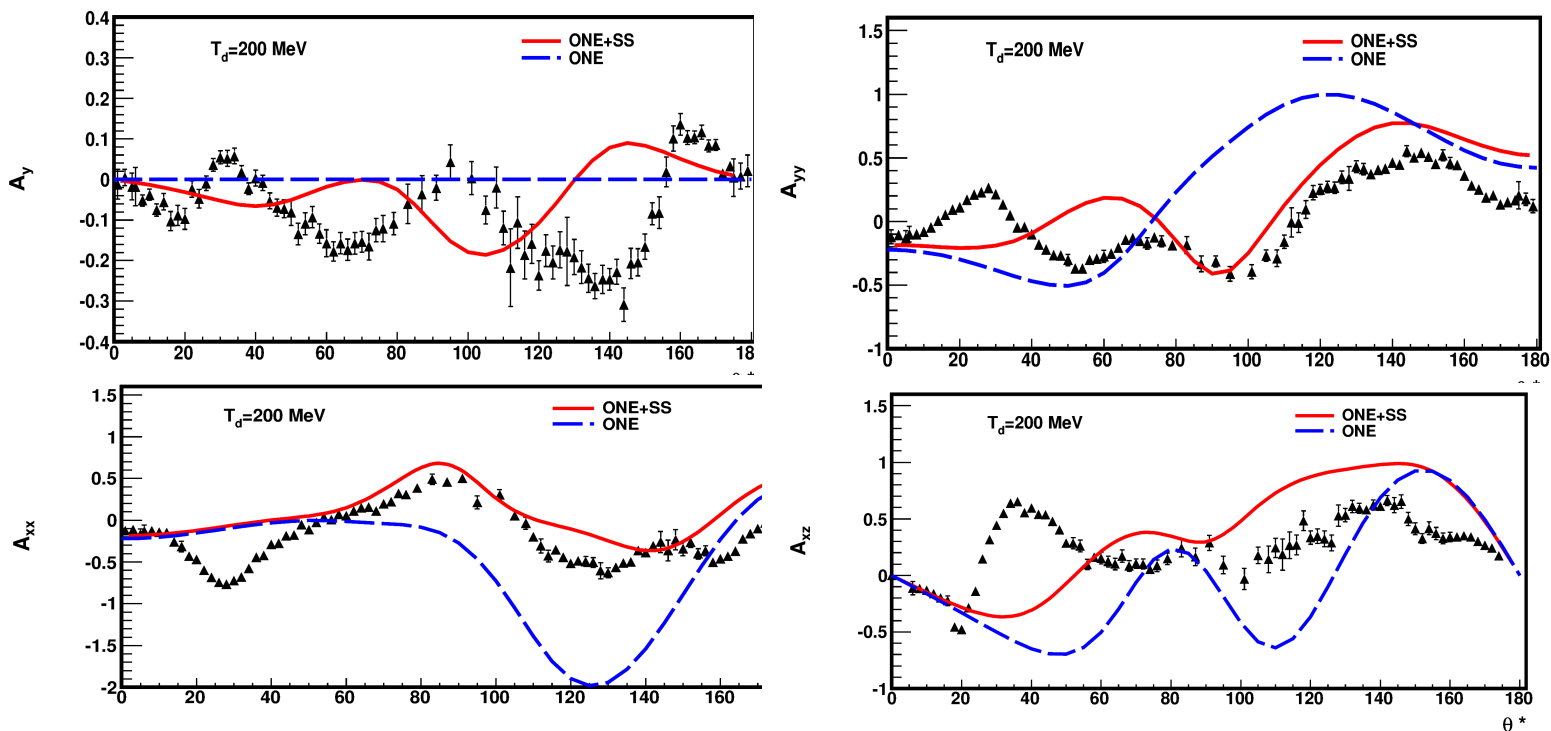
The relativistic multiple scattering model was successfully used to describe the
$dd \rightarrow {}^3\text{Hen}({}^3\text{Hp})$ reactions in a GeV region at the Nuclotron.
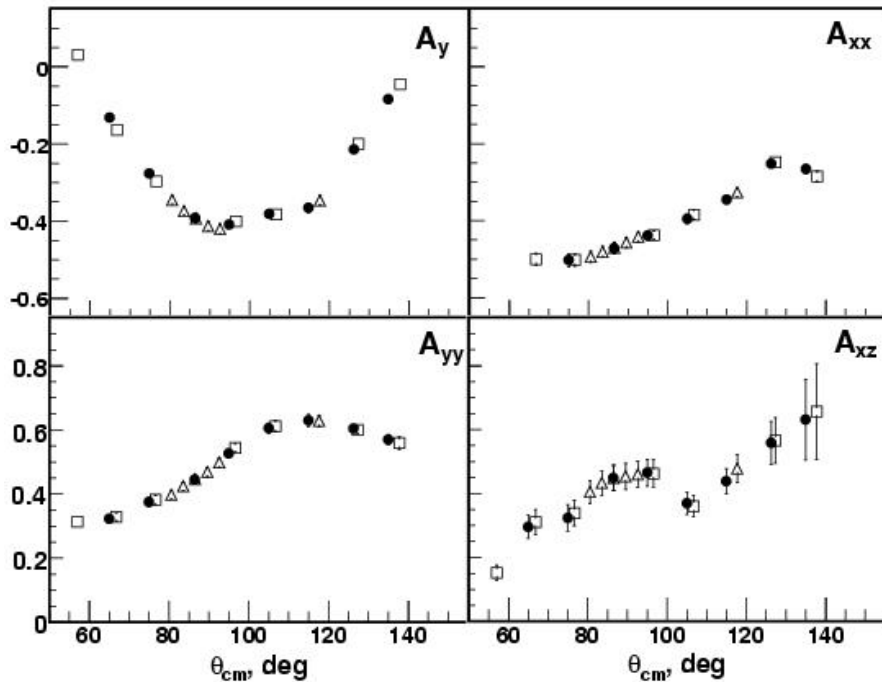The calculations require a large amount of CPUs.
The results were published in FBS, PRC, PPN.

N.Ladygina - theory
A.Kurilkin – experiment

Measurement of the deuteron beam polarization at ITS using DSS detection system at 270 MeV

Cubic spline interpolation:

(x_i, y_i) на $[A, B]$

$$f(x) = ax^3 + bx^2 + cx + d$$

$$f''(A) = f''(B) = 0$$

K.Sekiguchi et al., Phys. Rev. C65 (2002) 034003

K.Sekiguchi et al., Phys. Rev.C70 (2004) 014001

K.Suda, et al., Nucl. Instr. Meth. in Phys. Res. A572 (2007) 745

Vector Ay and tensor analyzing powers A_{yy}, A_{xx} and A_{xz} of dp- elastic scattering as a function of deuteron scattering angle in c.m.s. at deuteron beam energy of 270 MeV. □, Δ- the world data. Extrapolated values of the analyzing powers are marked by ●.

Measurement of the deuteron beam polarization at ITS using DSS detection system at 270 MeV
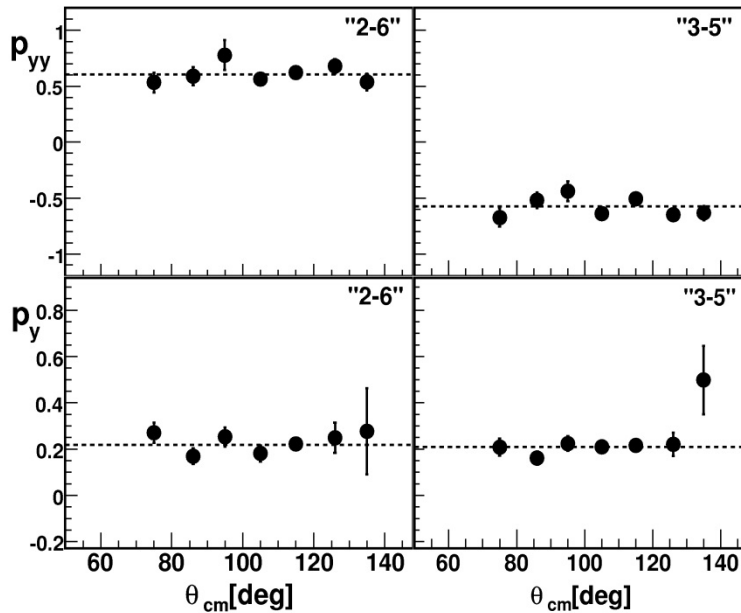
Tensor p_{yy} and vector p_y polarization of the beam for "2-6" and "3-5" spin modes of PIS POLARIS as a function of the deuteron scattering angle in the cms.

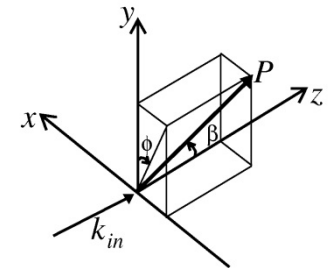$$ß = -90.3° \pm 1.2°$$

$$F_i^2 = \int \varepsilon A_i^2 \, d\Omega$$

$F_y \sim 1.0* 10^{-4}, \ F_{yy} \sim 1.8*10^{-4}, \ F_{xx} \sim 0.8*10^{-4}$

Pzz = 0.605 ± 0.025
Pz = 0.216 ± 0.015   "2-6"
Pz = 0.208±0.012   "3-5"
Pzz=0.69±0.3   "3-5"

- **Reference deuteron beam polarimeter at Nuclotron.**

  P.K.Kurilkin et al., Nucl. Instr. and Meth. A 642 (2011) 45

Relativization schemes

For the case of the deuteron vertex the internal momentum $\mathbf{k}$:

$$k = \sqrt{\frac{m_p^2 + \mathbf{k}_T^2}{4x(1-x)} - m_p^2},$$

$$x = \frac{E_p + p_{pl}}{E_d + p_d},$$

where $\mathbf{E_d}$ and $\mathbf{p_d}$ are the energy and momentum of the initial deuteron, respectively, $\mathbf{p_{pl}}$ is the longitudinal momentum of the proton, $\mathbf{m_p}$ and $\mathbf{E_p}$ are the mass and energy of the proton, respectively.

- Minimal relativization scheme (Dirac, Weinberg, Frankfurt& Strikman)

- Bete-Salpeter equation solving (Tjon&Keisler, Bondarenko et al.)

- Quasi-potential wave functions (Gross, Braun&Tokarev, Kaptari et al.)

- Covariant theory on the light cone (Karmanov et al.)