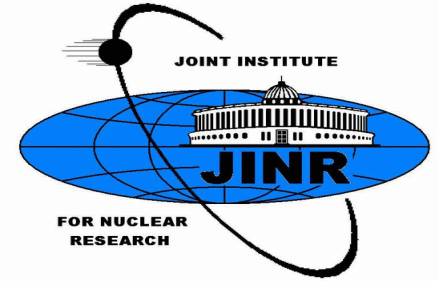




24th International Spin Symposium
October 18 -22, 2021



Deuteron analyzing powers A_y , A_{yy} and A_{xx} in dp-elastic scattering at large transverse momenta

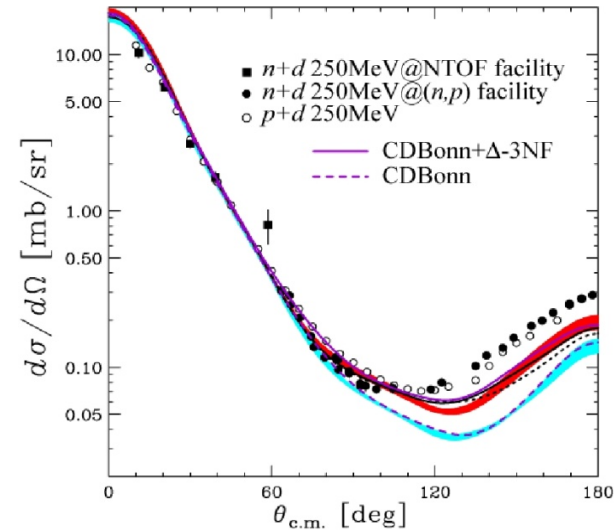
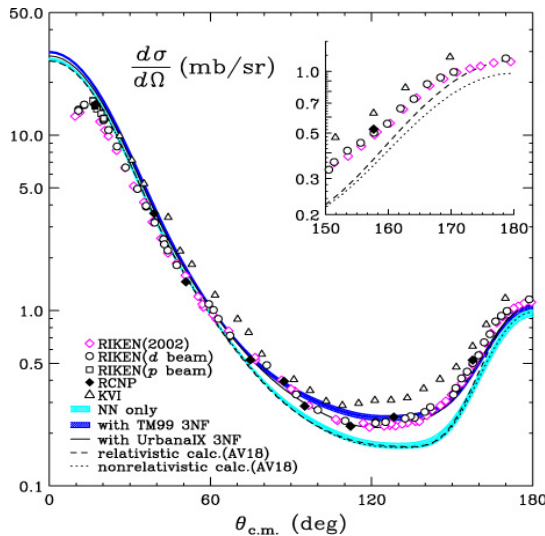
V.P. Ladygin on behalf of DSS collaboration

11 Institutes and Universities from
Bulgaria-JINR-Japan-Romania-Russia-Slovakia

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)

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.

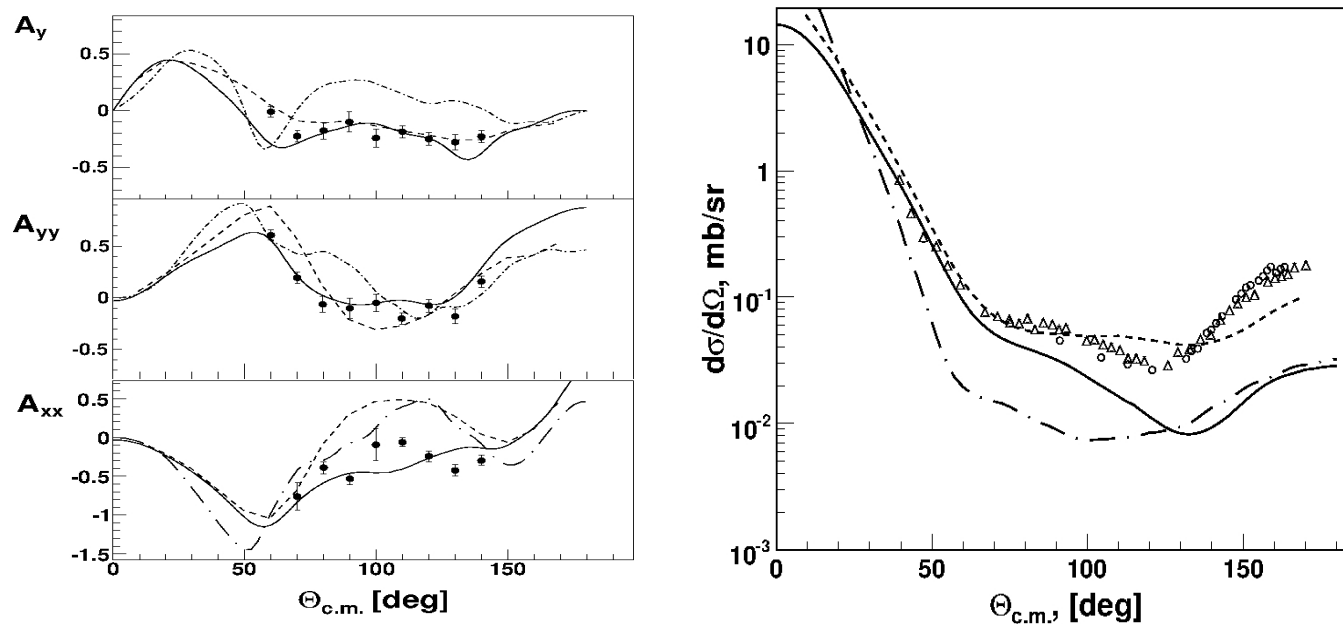
K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)

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 and polarization observables (in particular, for the tensor analyzing powers).

Analyzing powers in **dp**- elastic scattering at 880 MeV



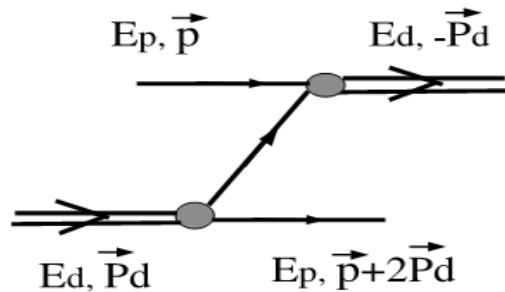
Dashed lines are the multiple scattering model calculations using **CD-Bonn DWF** (**N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039**)

Solid lines are the Faddeev calculations using **CD-Bonn** potential (**H.Witala, private communication**)

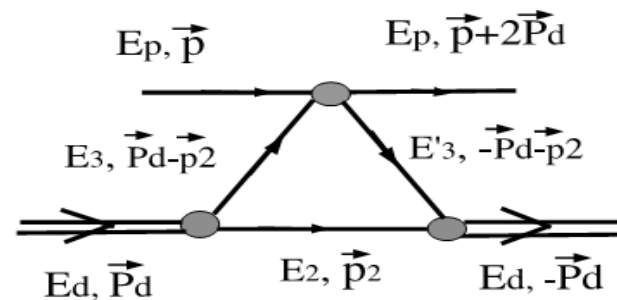
Dott-dashed lines are the optical-potential calculations using **Dibaryon DWF** (**M.Shikhalev, Phys.Atom.Nucl.72 (2009) 588**)

Published in **P.K.Kurilkin et al., Phys.Lett.B715 (2012) 61-65**

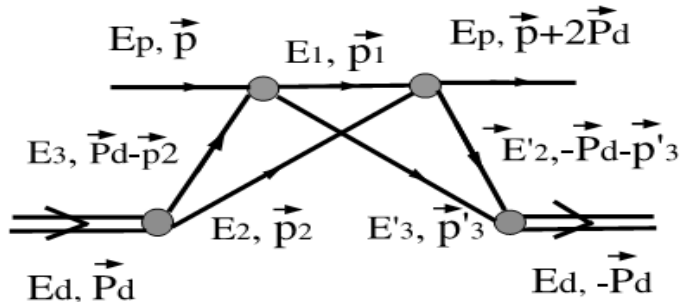
Relativistic multiple scattering model for **dp**- elastic scattering at moderate energies



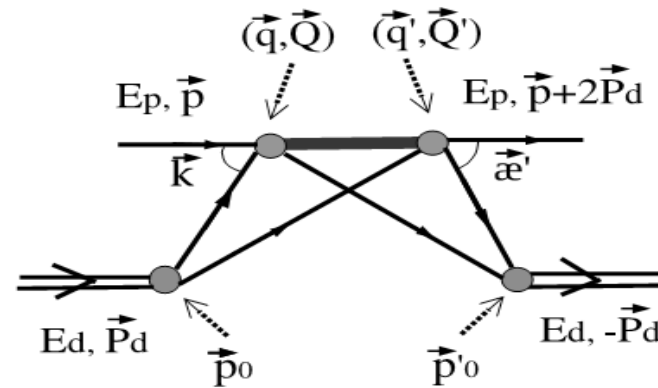
(a) **ONE**



(b) **SS**



(c) **DS**



(d) **Δ**

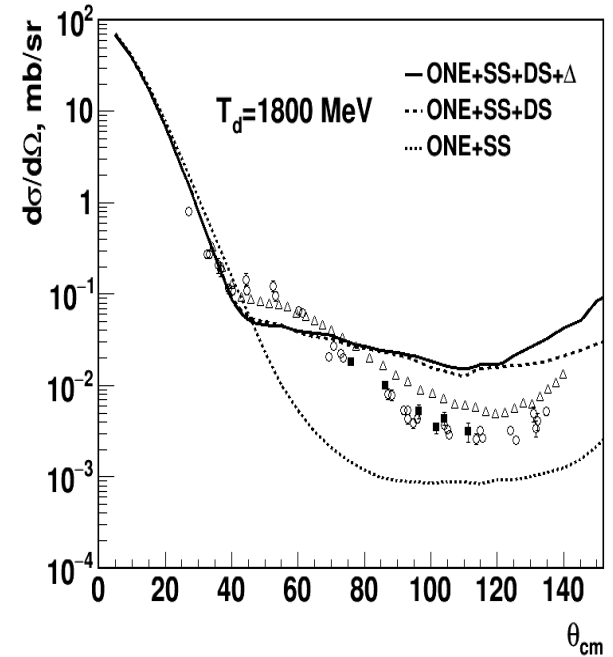
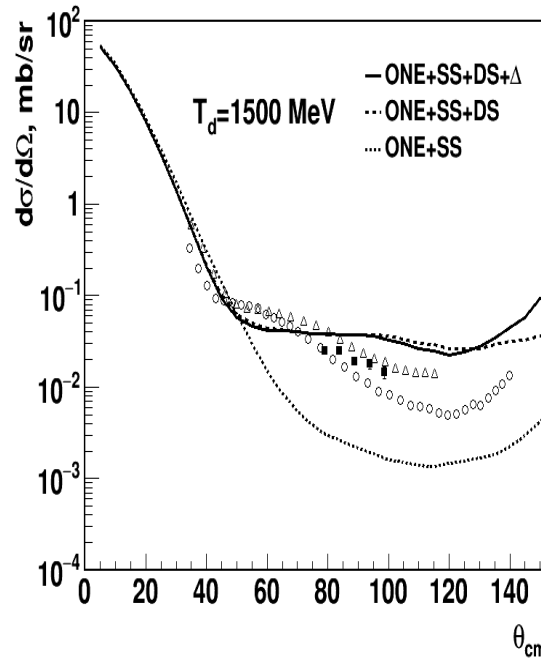
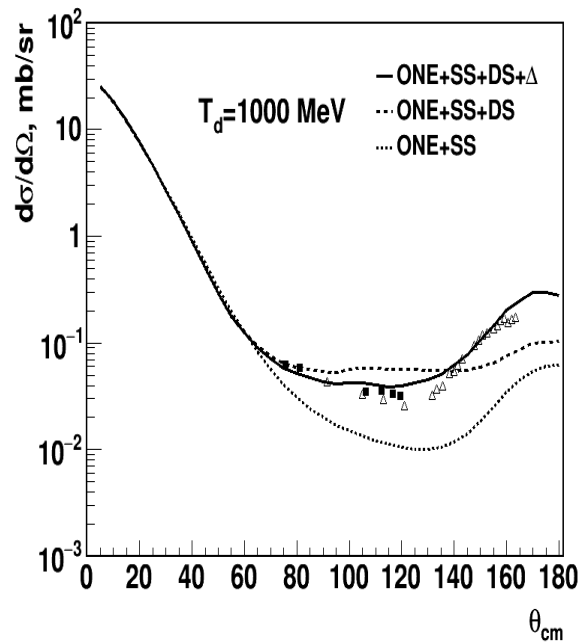
ONE+SS+DS - N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039

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

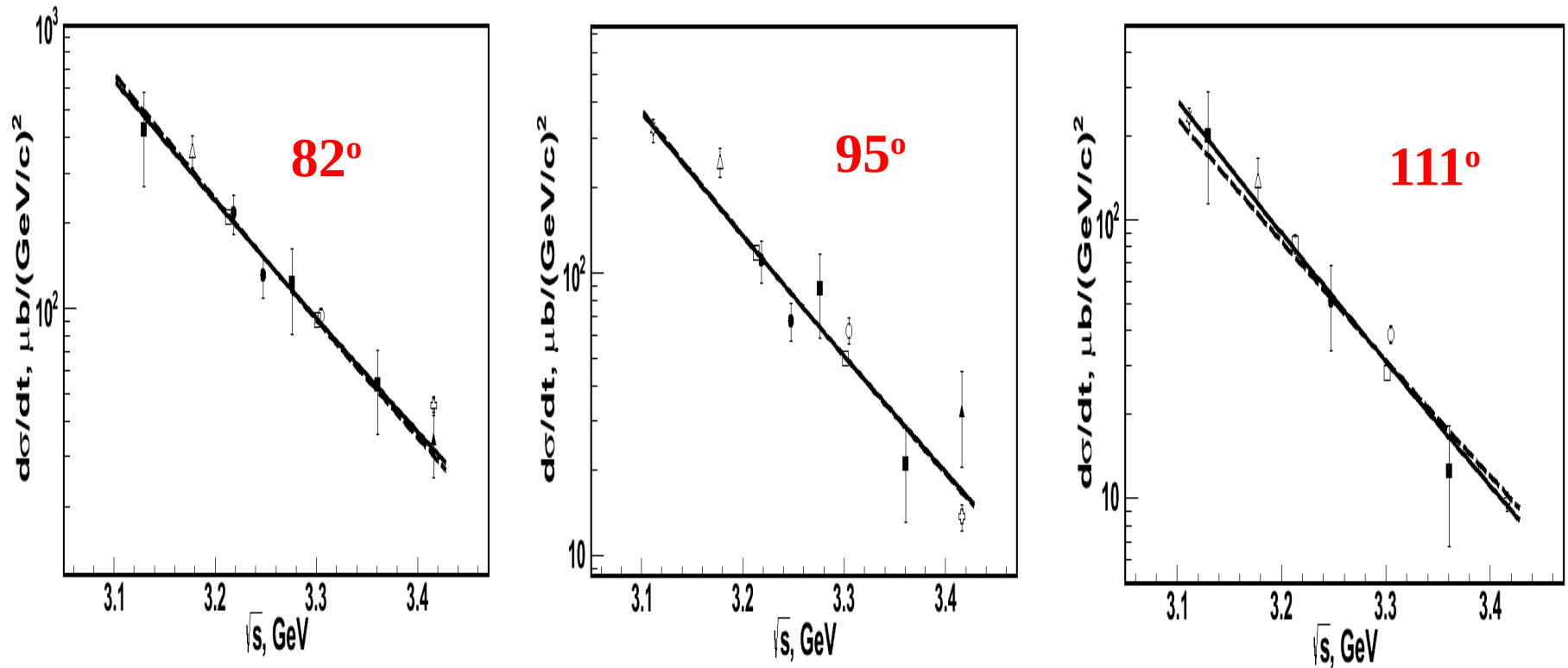
dp- elastic scattering cross section at 1000, 1500 and 1800 MeV



Pictures are taken from **A.A.Terekhin et al., Eur.Phys.J, A55 (2019) 129**

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

CCR for **dp**- elastic scattering cross section



Pictures are taken from **A.A.Terekhin et al., Eur.Phys.J, A55 (2019) 129**

Lines are the results of the fit by the S^{-16} (dashed) and S^{-n} (solid) dependencies.

General View of SPI

Charge-Exchange Ionizer

Atomic Beam Source

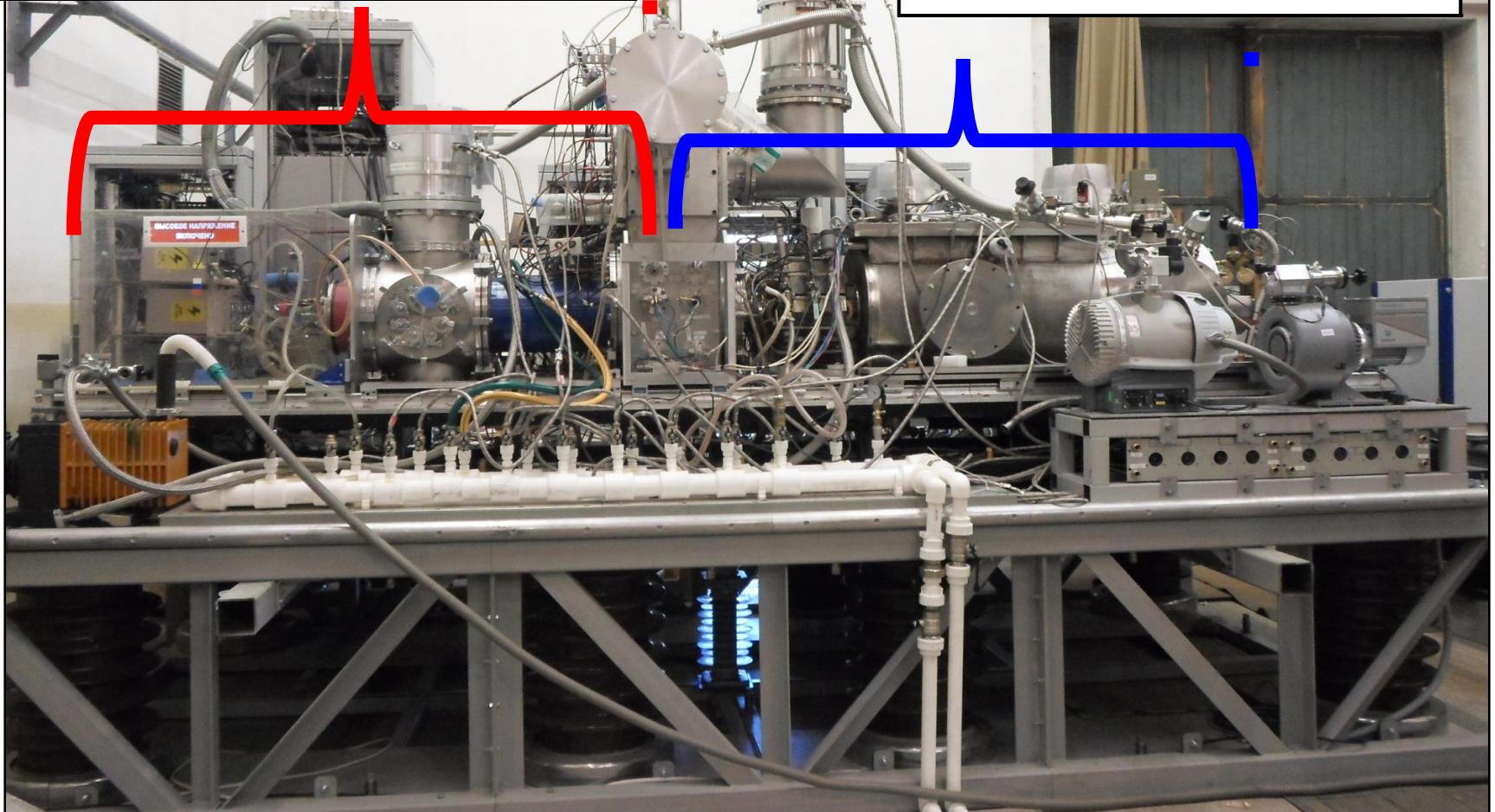
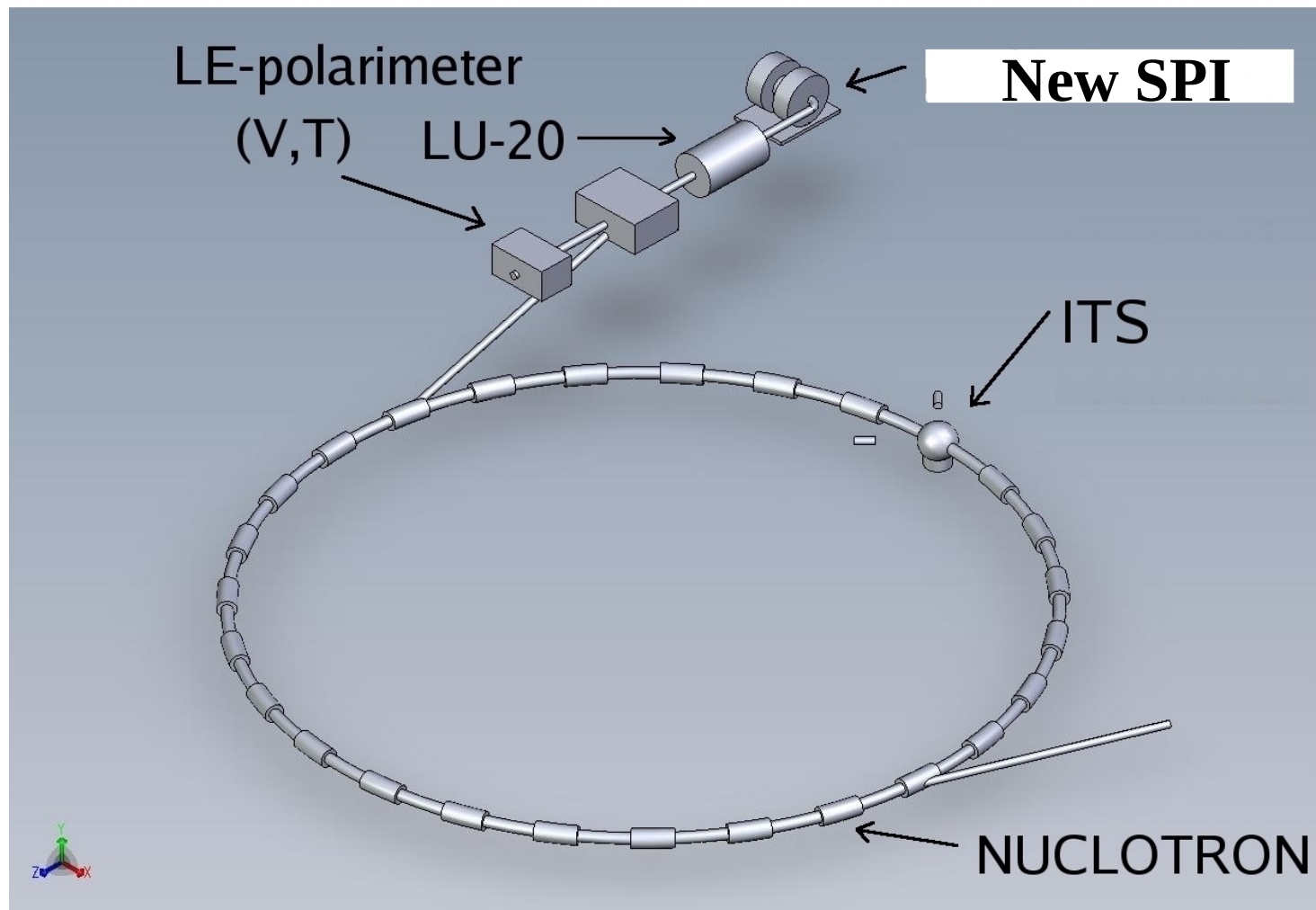


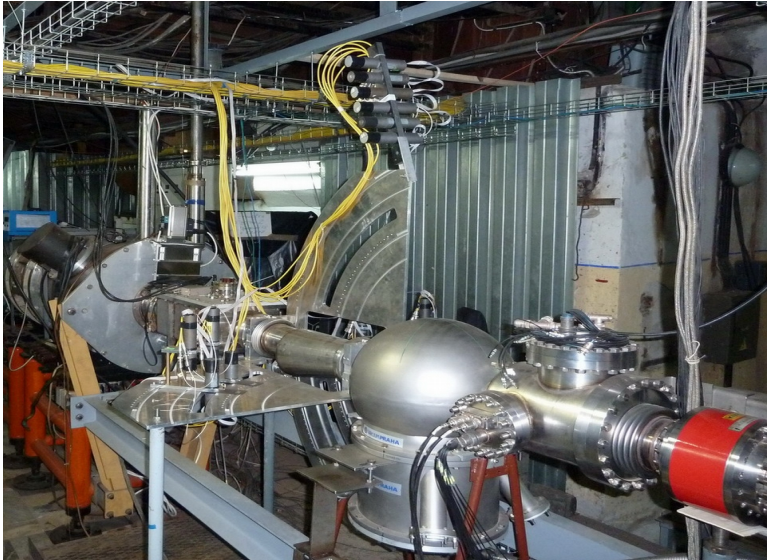
Figure of merit will be increased in future by a factor $\sim 10^3$

Nuclotron-M accelerator complex



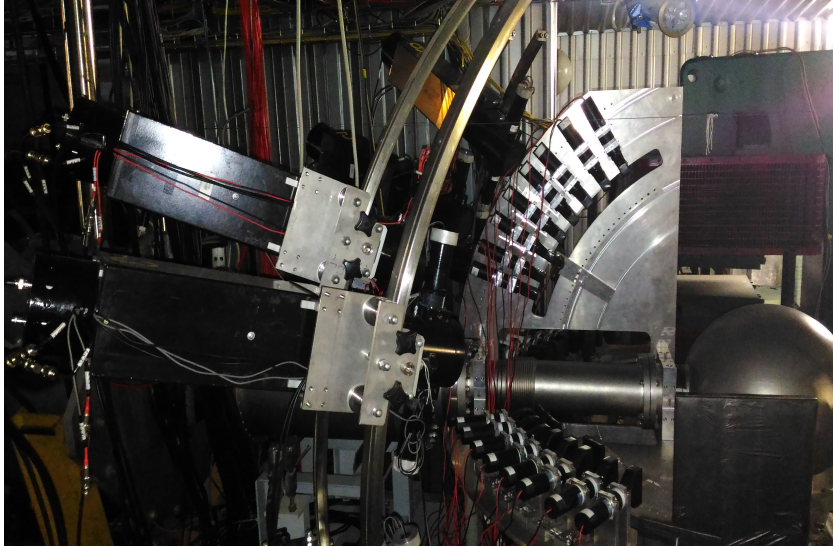
Experiments at Internal Target Station at Nuclotron

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

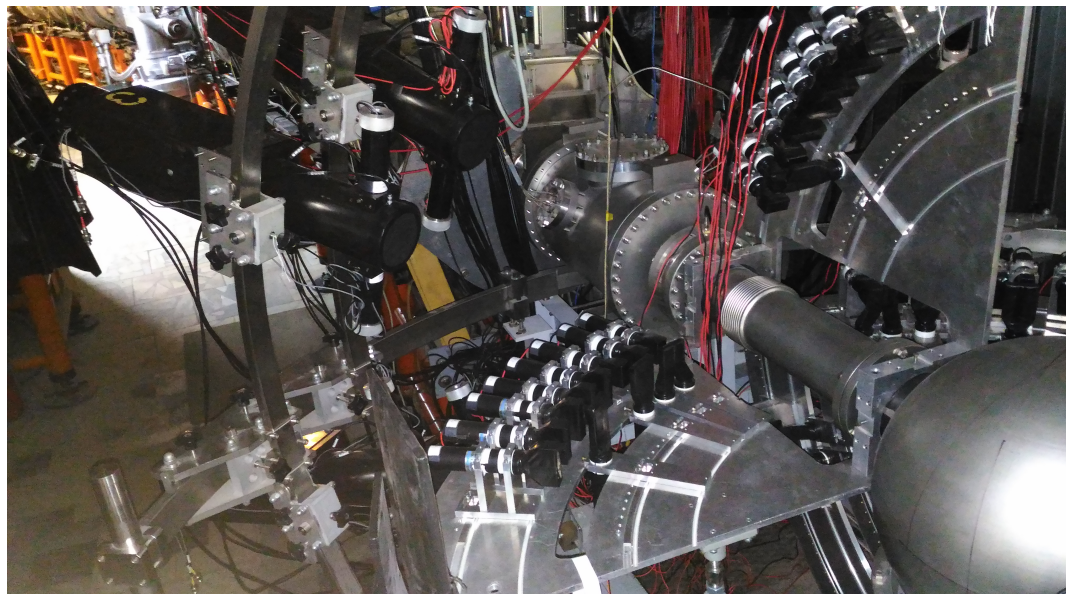
New HV system (Mpod)

New VME DAQ

40 counters for dp-elastic scattering studies

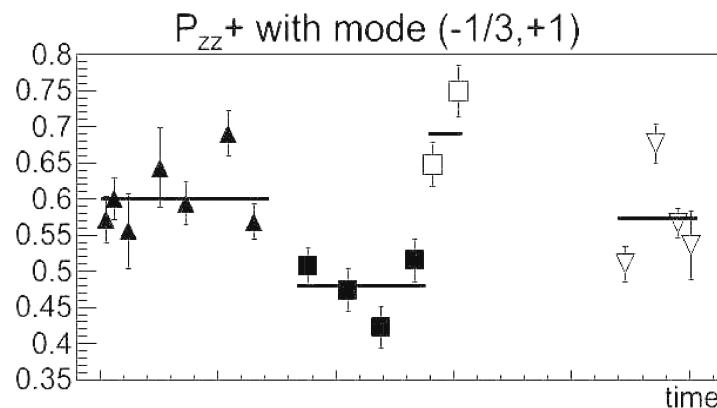
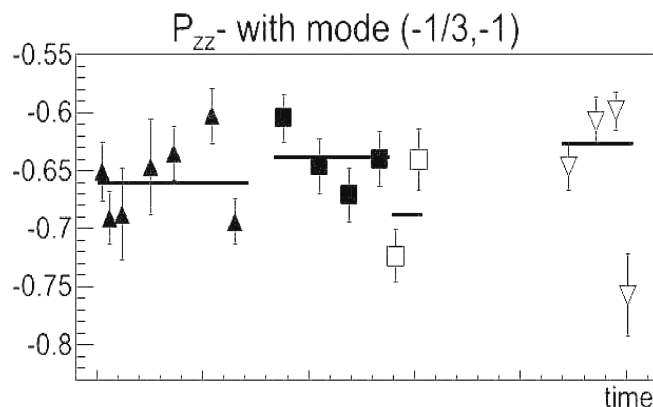
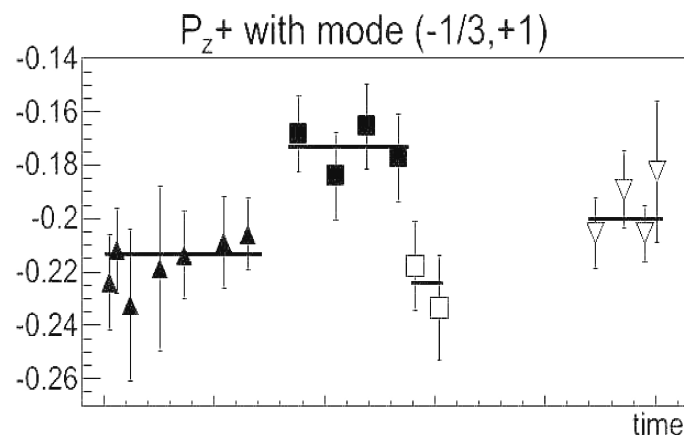
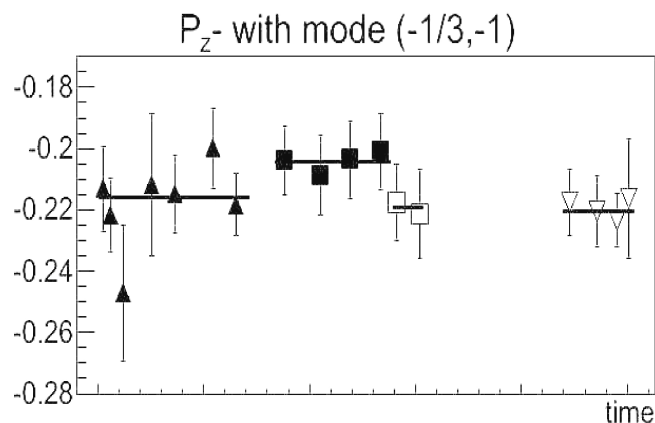
8 dE-E detectors for dp -breakup studies

Setup to study **dp**- elastic scattering at ITS at Nuclotron



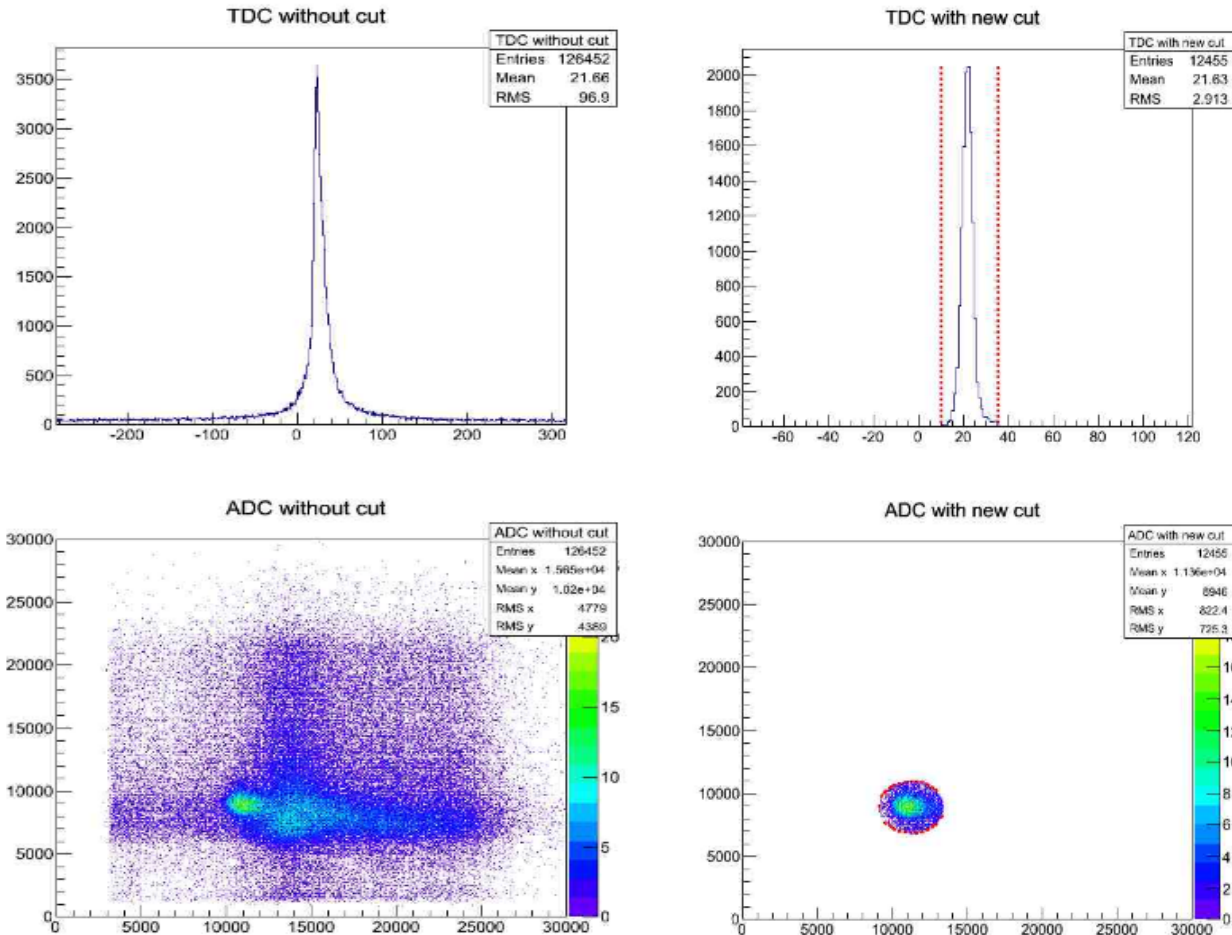
- Deuterons and protons in coincidences using scintillation counters
- Internal beam and thin **CH₂** target (**C** for background estimation)
- Permanent polarization measurement at **270** MeV (between each energy).
- Analyzing powers measurement at **400-1800** MeV
- The data were taken for three 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.

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



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

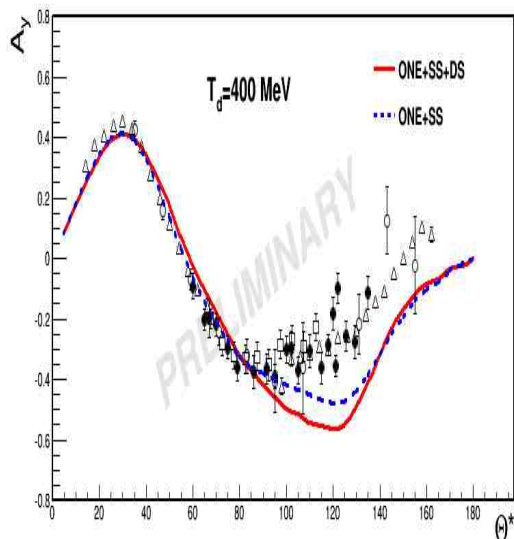
The **dp**-elastic scattering events selection



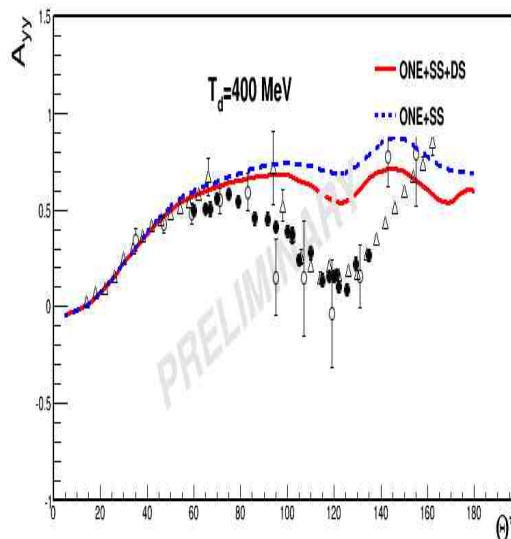
Selection of the dp elastic events by the time difference between the signal appearance from deuteron and proton detectors with the criteria on the amplitude signal correlation.

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

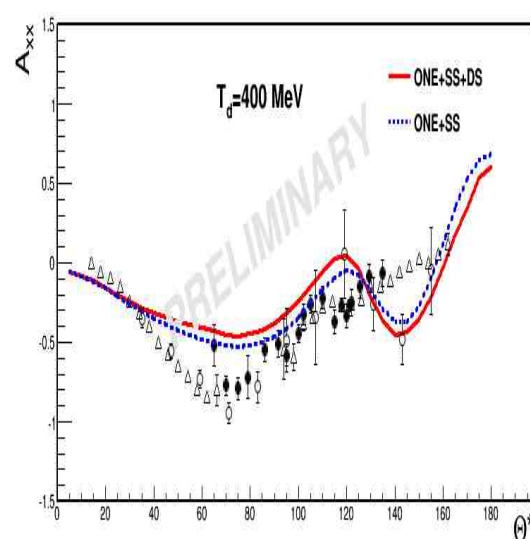
A_y



A_{yy}



A_{xx}

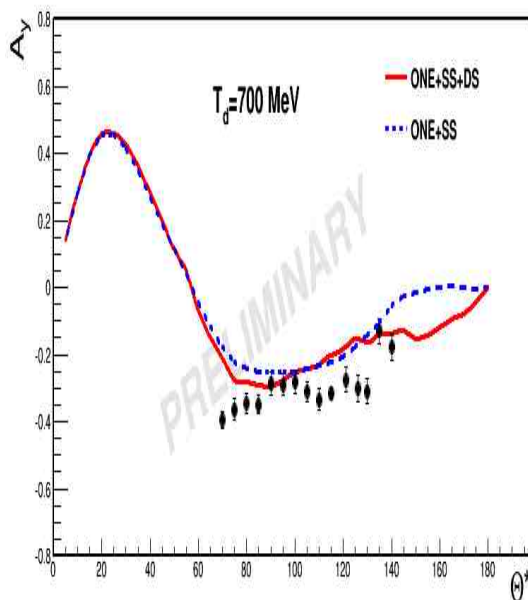


**Full squares are the data from Nuclotron.
Open symbols are the world data (IUCF, Saclay).**

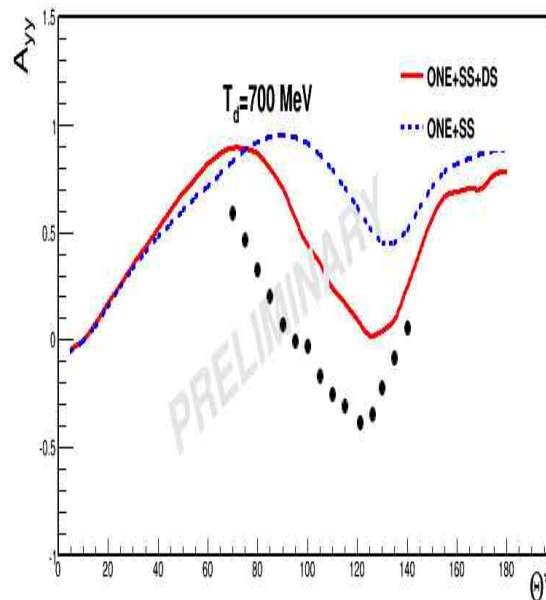
**Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A42 (2009) 91**

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

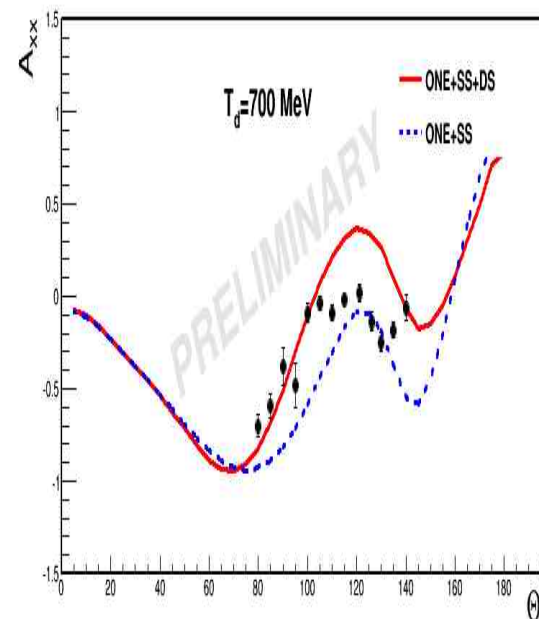
A_y



A_{yy}



A_{xx}



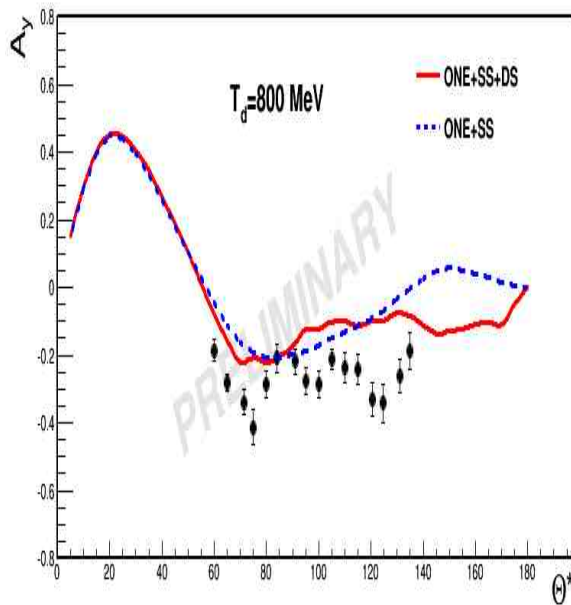
Curves are the relativistic multiple scattering model calculations

N.B.Ladygina, Eur.Phys.J, A42 (2009) 91

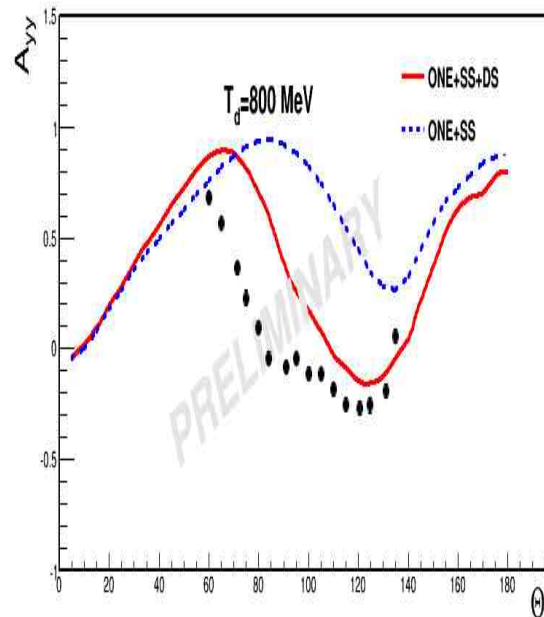
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199 – contribution of Δ is negligible

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

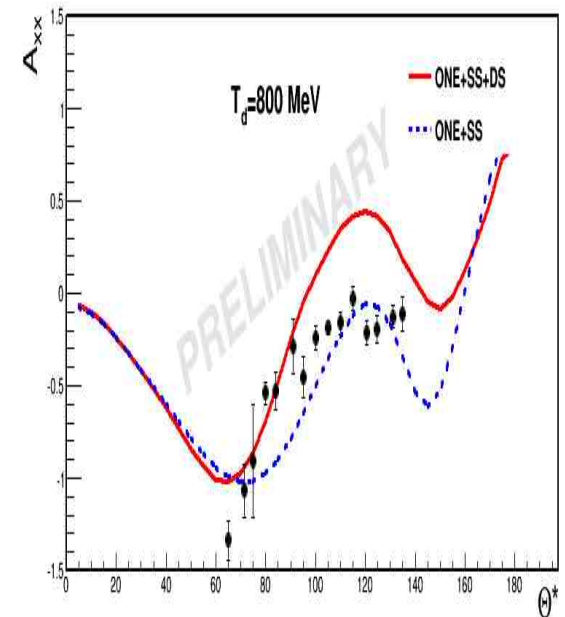
A_y



A_{yy}



A_{xx}



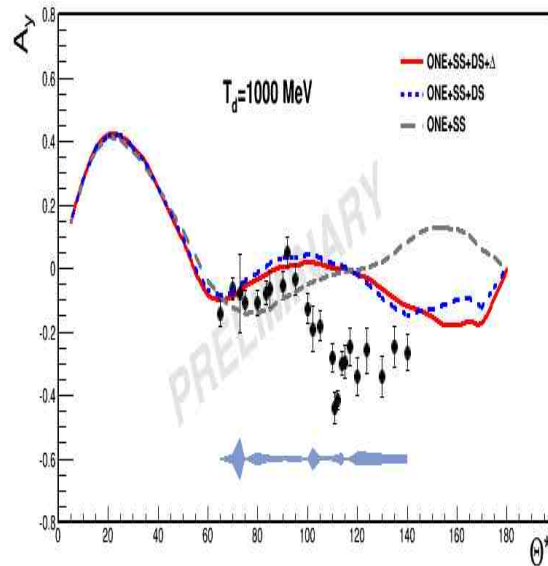
Curves are the relativistic multiple scattering model calculations

N.B.Ladygina, Eur.Phys.J, A42 (2009) 129

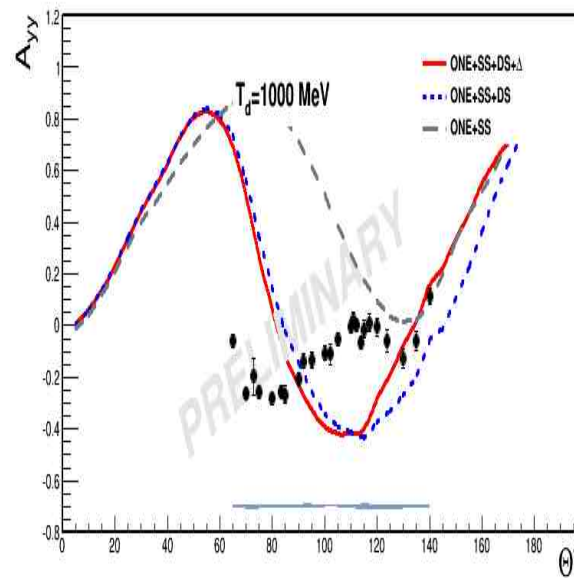
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199 – contribution of Δ is small

Angular dependence of the vector and tensor analyzing powers in **dp**-elastic scattering at **1000 MeV**

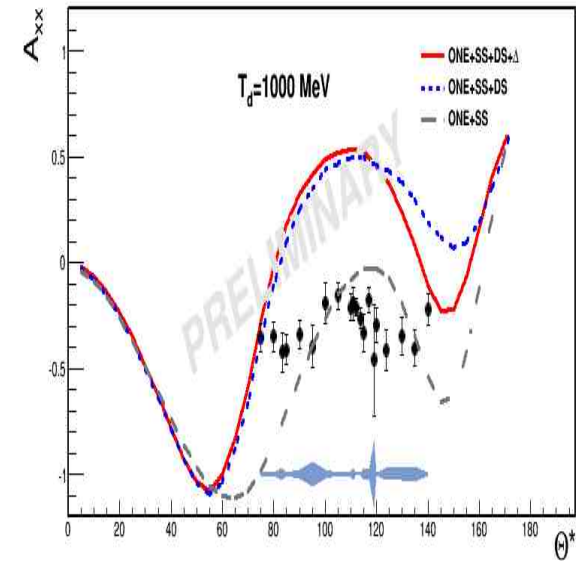
A_y



A_{yy}



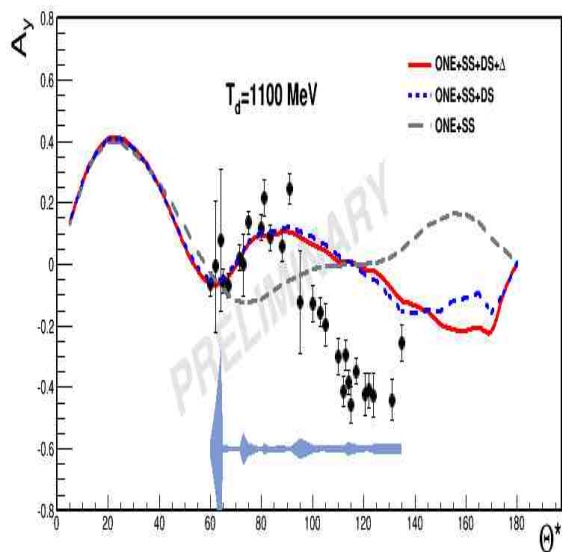
A_{xx}



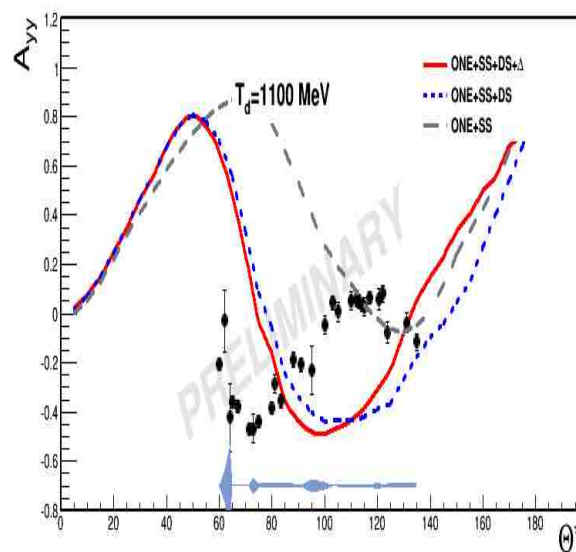
Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

Angular dependence of the vector and tensor analyzing powers in **dp**-elastic scattering at **1100 MeV**

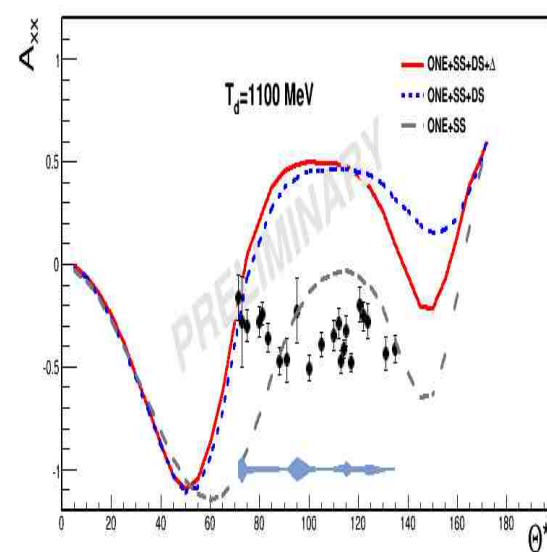
A_y



A_{yy}



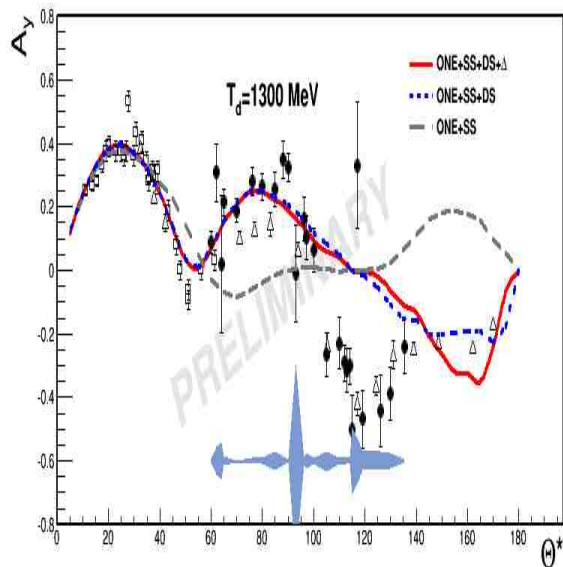
A_{xx}



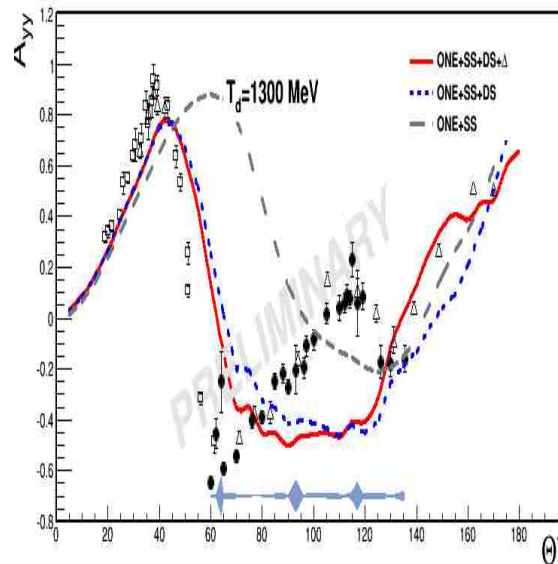
Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

Angular dependence of the vector and tensor analyzing powers in **dp**-elastic scattering at **1300 MeV**

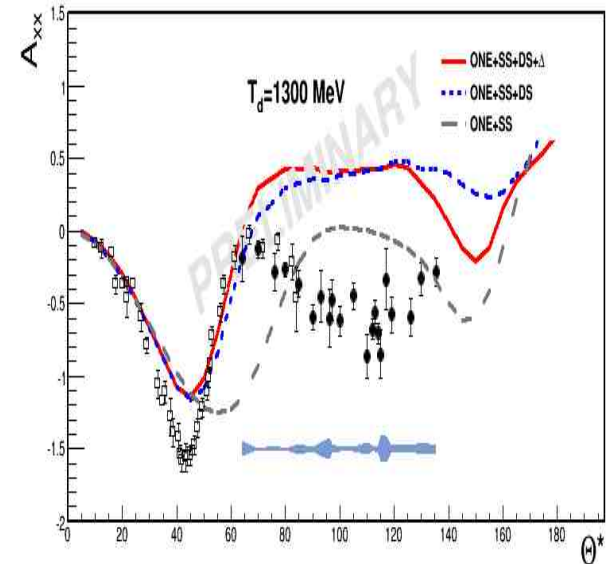
A_y



A_{yy}



A_{xx}



Data shown by the open symbols are obtained at 1200 MeV at Saclay

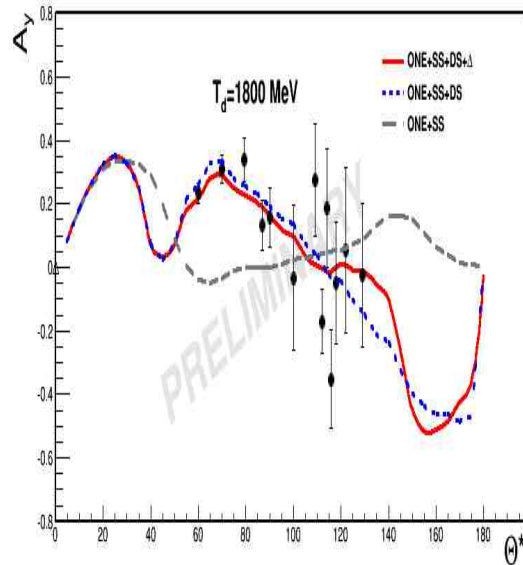
Curves are the relativistic multiple scattering model calculations

N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

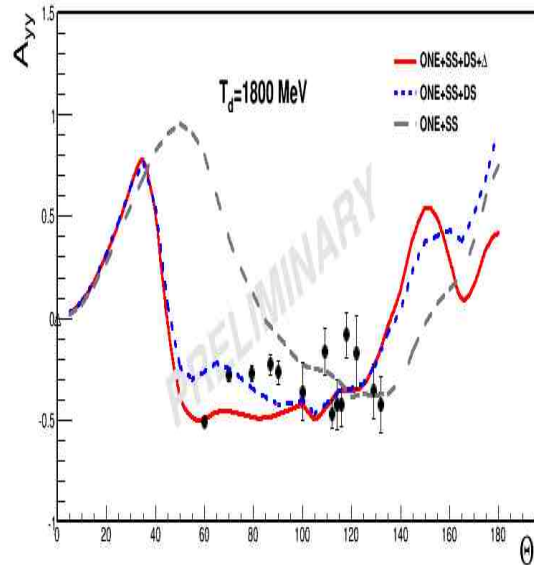
+ additional **ρ** -meson exchange

Angular dependence of the vector and tensor analyzing powers in **dp**-elastic scattering at **1800 MeV**

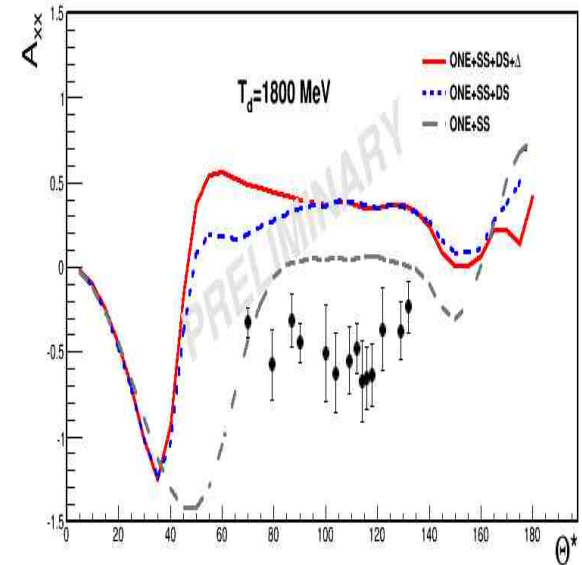
A_y



A_{yy}

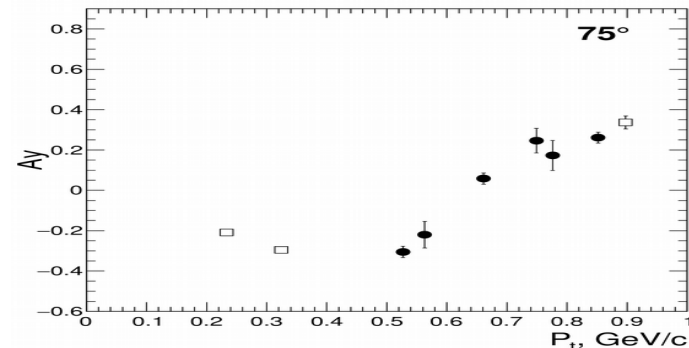
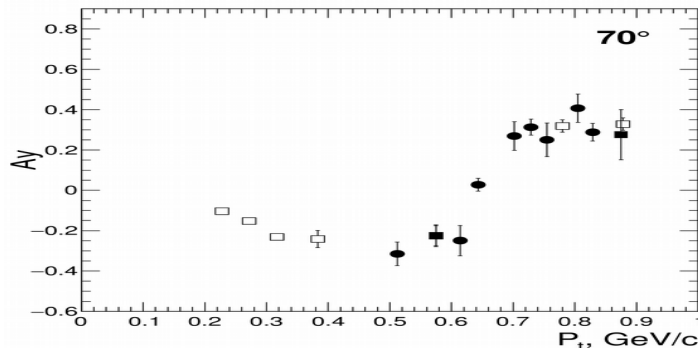
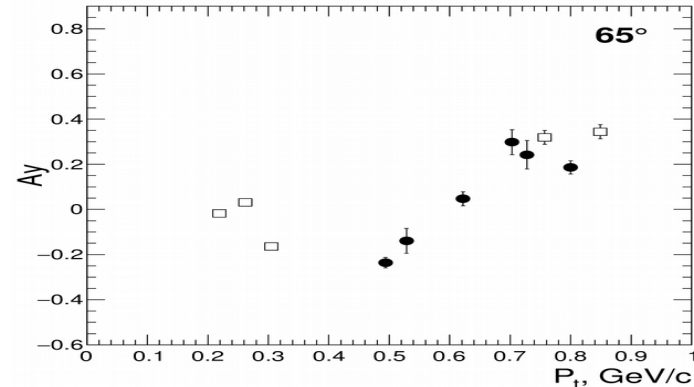
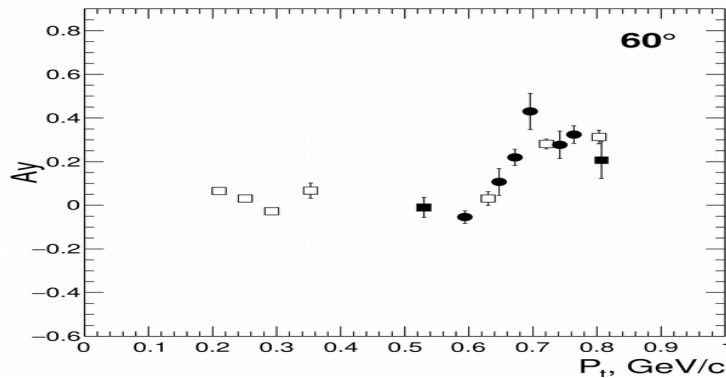


A_{xx}



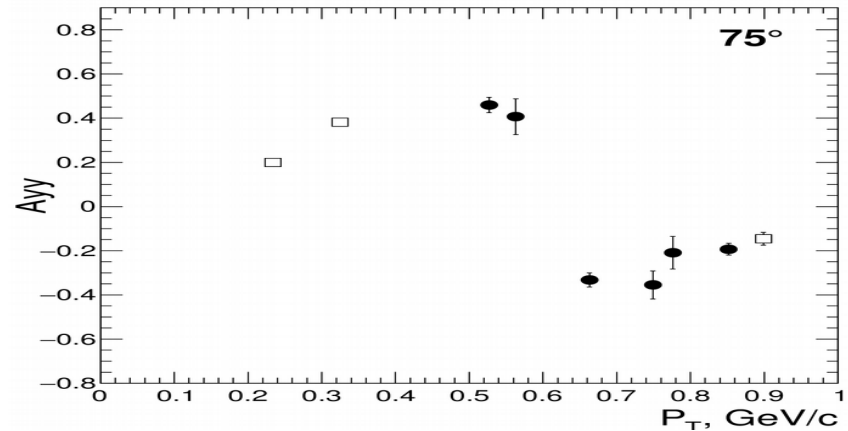
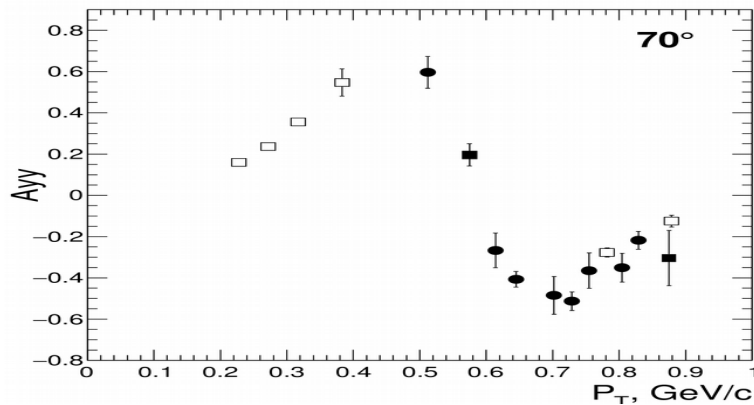
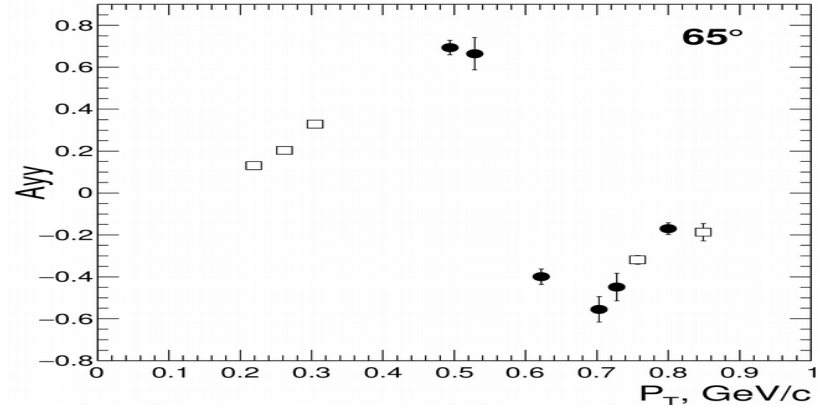
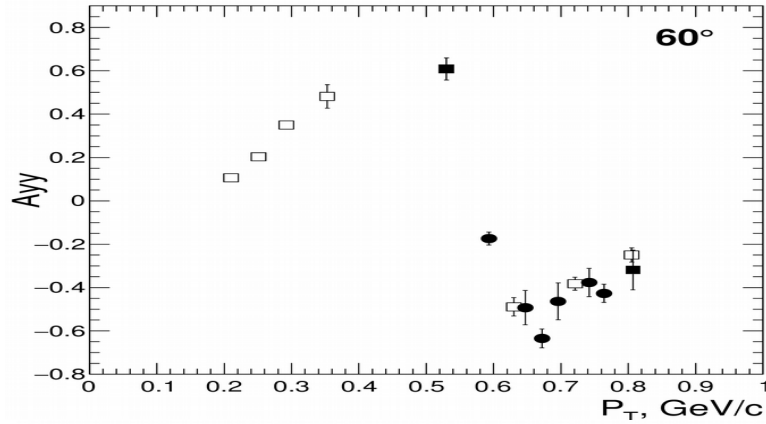
Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

Energy dependence of the vector analyzing power A_y in dp-elastic scattering at 700-1800 MeV



Full circles are the new preliminary data from Nuclotron.
Full squares are the data from Nuclotron (2005).
Open symbols are the world data.

Energy dependence of the tensor analyzing power A_{yy} in dp-elastic scattering at 700-1800 MeV



Full circles are the new preliminary data from Nuclotron.
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 using polarized deuteron and proton beams.

The results obtained at Nuclotron demonstrate the power law scaling behaviour for the cross section as well as the asymptotic values for the **A_y** and **A_{yy}** analyzing powers in **dp**- elastic scattering at large transverse momenta (>600 MeV/c). This can be due to the manifestation of the fundamental degrees of freedom.

These studies can be continued by the energy scan of the deuteron analyzing powers in **dp**- and proton analyzing power in **pd**- elastic scattering using high intensity polarized deuteron and proton beam, respectively.

Thank you for the attention!

Status of **dp**- elastic scattering

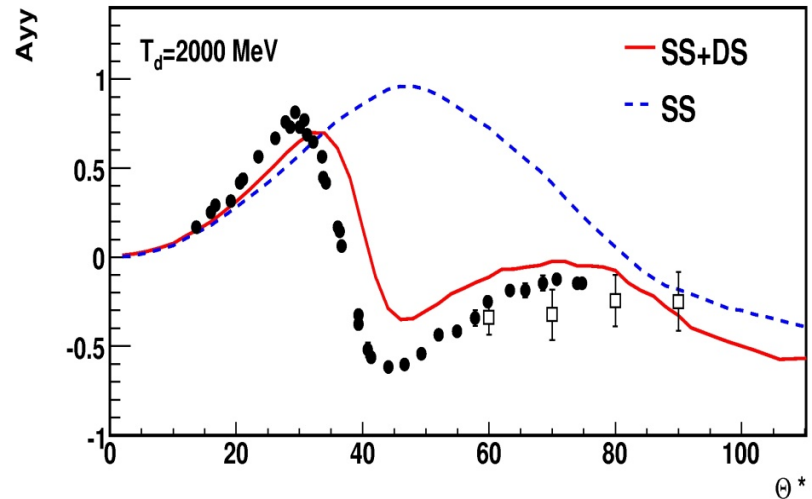
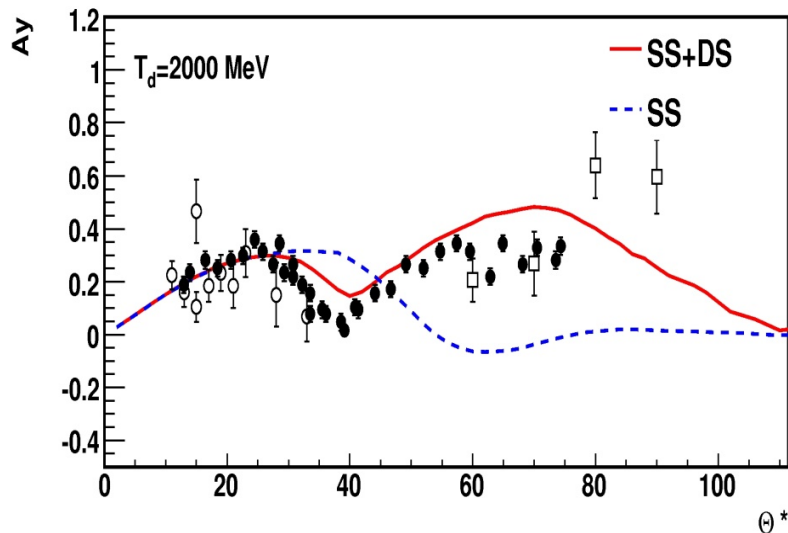
Inclusion of modern 3NFs allows to describe cross section and deuteron vector analyzing power of **dp**- elastic scattering up to 135 MeV/nucleon, while the tensor observables are not described.

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.

A_y and A_{yy} in **dp**- elastic scattering at 2000 MeV



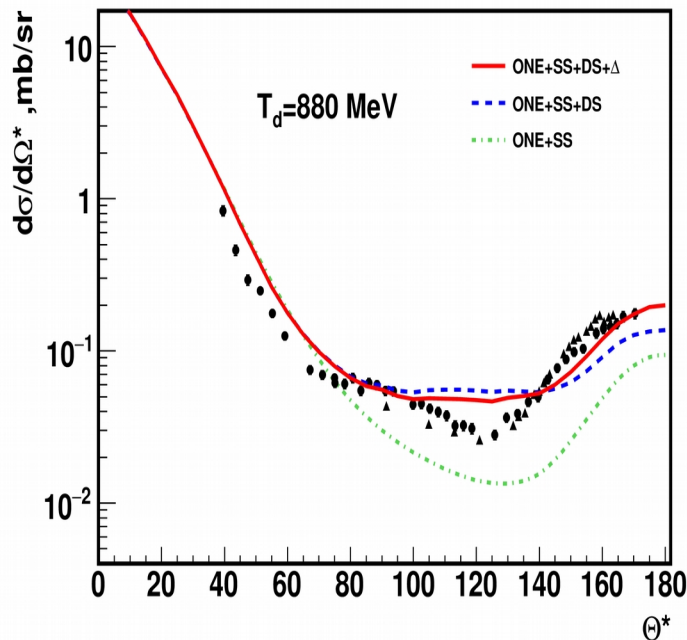
Open squares are the data obtained at Nuclotron **JINR**.

Open circles are the Synchrotron 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.

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 - 100°**.
- Double scattering dominates over single scattering at the angles larger than **70°**.
- 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?

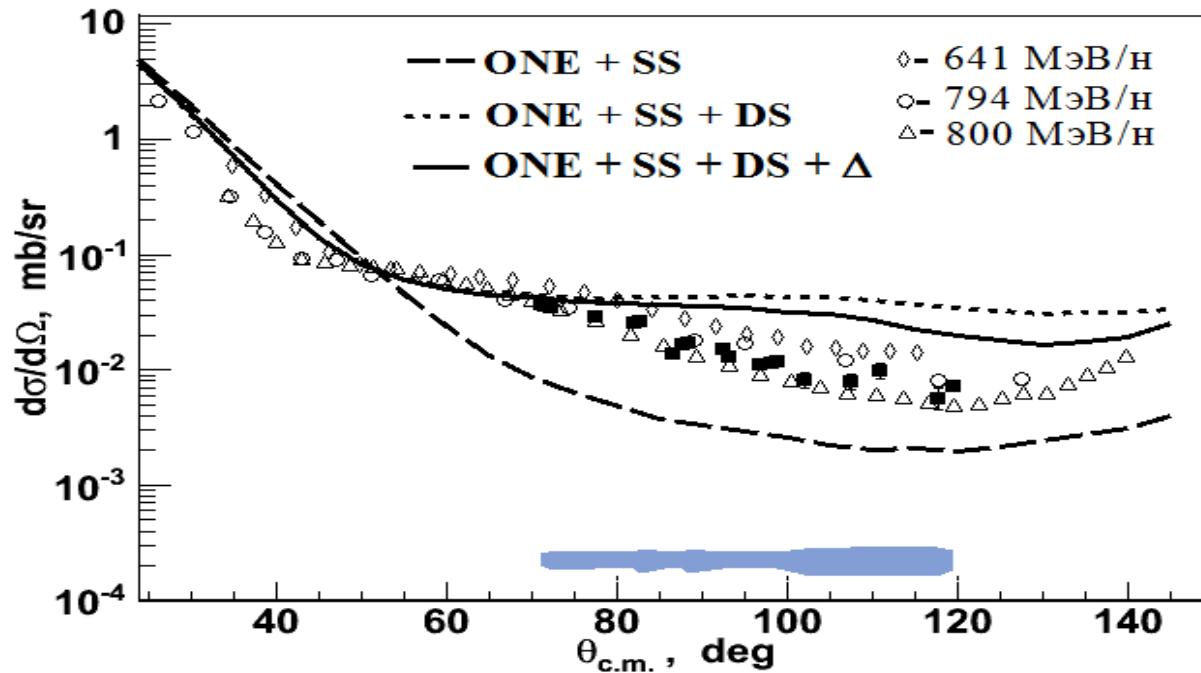
World data:

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

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

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

Polarized protons at Nuclotron.

Injection of **5 MeV** protons into Nuclotron ring.

Acceleration up to **500 MeV**- no serious depolarization resonances.

Unpolarized protons: $I \sim 1.5 \cdot 10^8$ ppp

Polarized protons: $I \sim 2-3 \cdot 10^7$ 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 **6** angles (**55°-85°** in the cms) we obtained the averaged value of the proton beam polarization

Unpolarized protons: $P = -0.056 \pm 0.021$

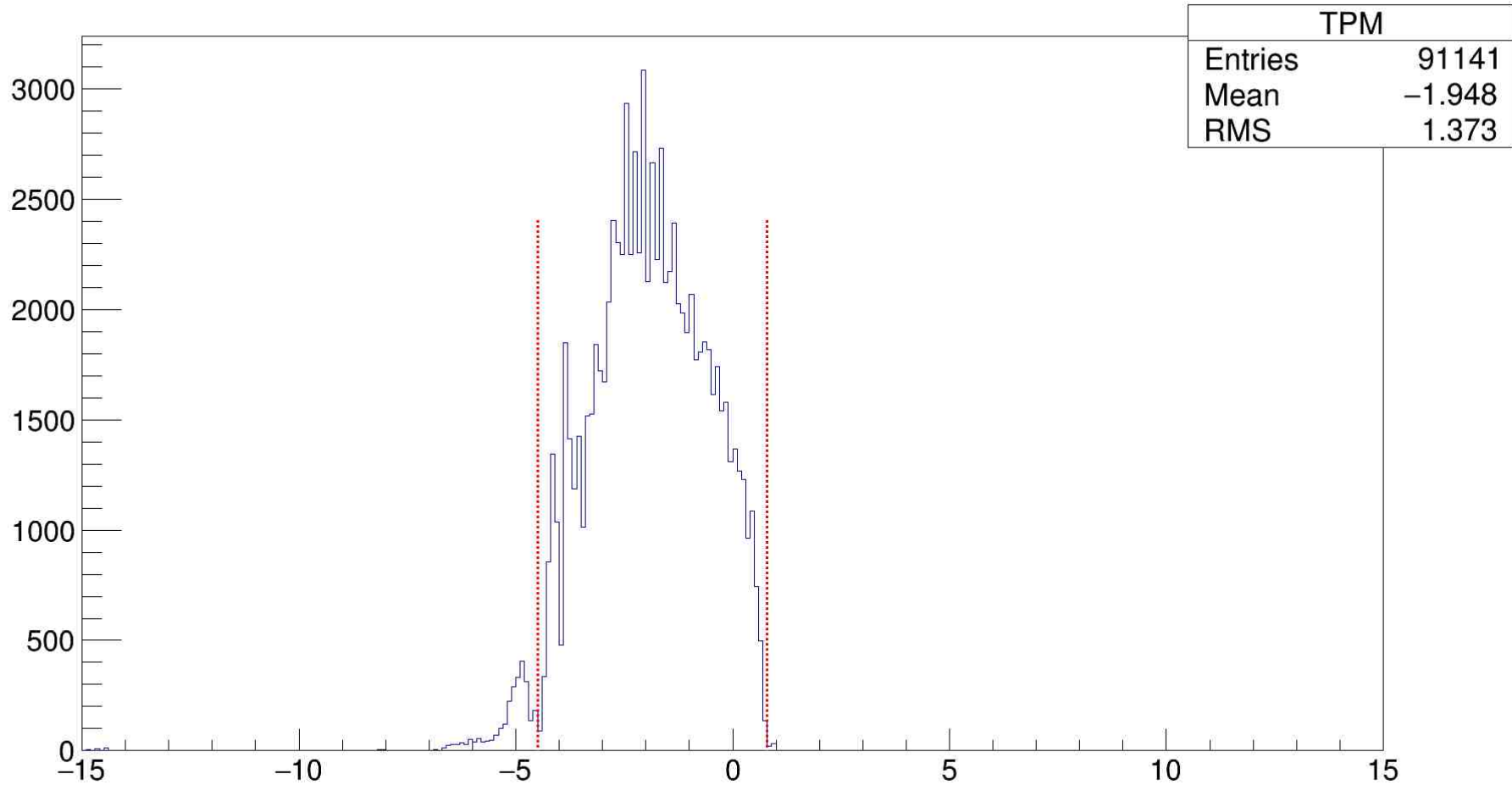
Polarized protons: $P = -0.367 \pm 0.015$

Need to produce new detection system for protons.

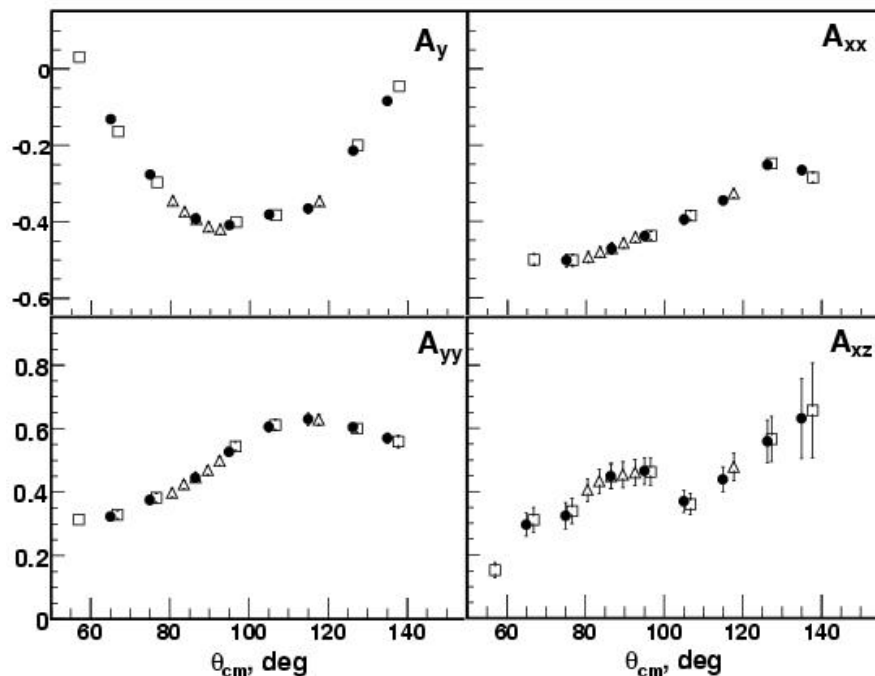
(talk of **A.Terekhin**)

Target Position Monitor cut

TPM



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



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

Cubic spline interpolation:

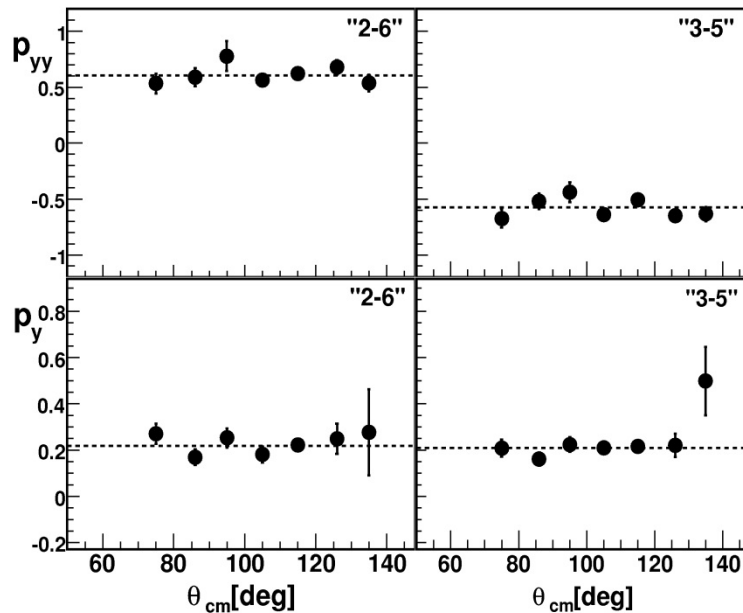
(x_i, y_i) на $[A, B]$

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

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

**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**

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

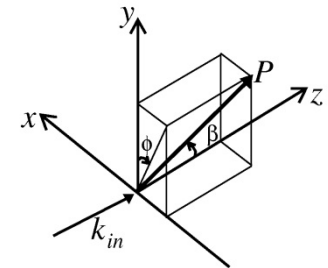


Tensor p_{yy} and vector p_y polarization of the beam for “2-6” and “3-5” spin modes of PIS POLARIS as a function of the deuteron scattering angle in the cms.

$$\beta = -90.3^\circ \pm 1.2^\circ$$

$$F_i^2 = \int \epsilon A_i^2 d\Omega$$

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



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

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

Relativization schemes

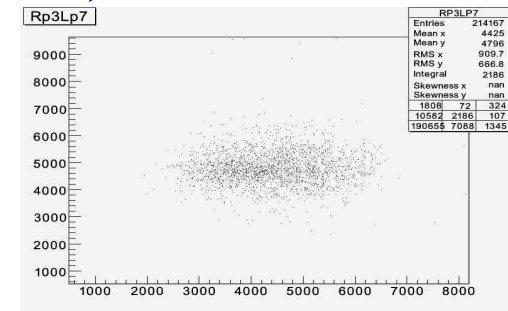
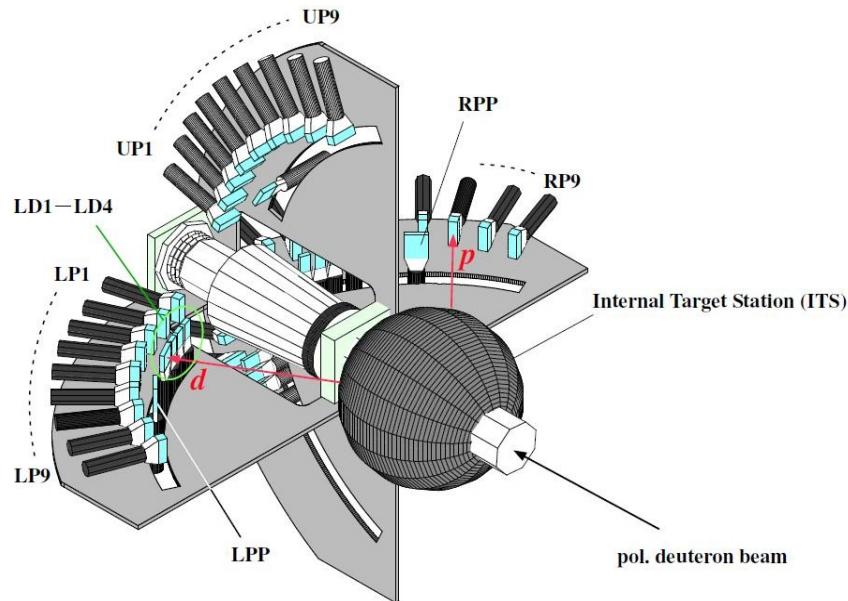
For the case of the deuteron vertex the internal momentum \mathbf{k} :

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

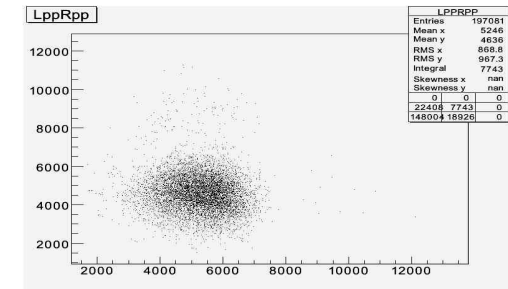
where \mathbf{E}_d and \mathbf{p}_d are the energy and momentum of the initial deuteron, respectively, \mathbf{p}_{pl} is the longitudinal momentum of the proton, \mathbf{m}_p and \mathbf{E}_p are the mass and energy of the proton, respectively.

- 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.)

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



DP

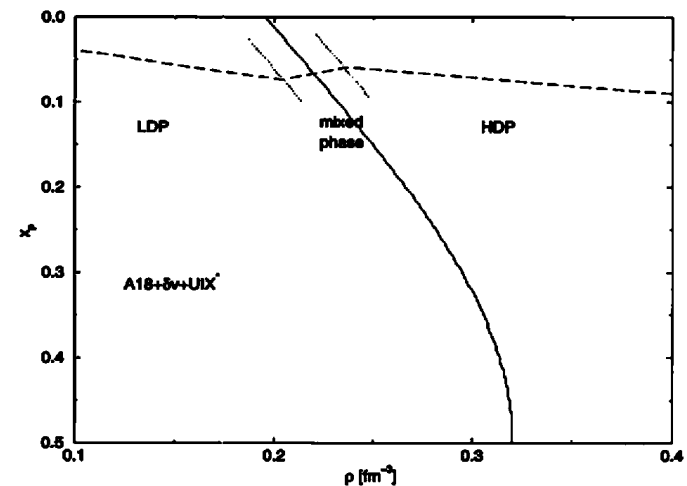
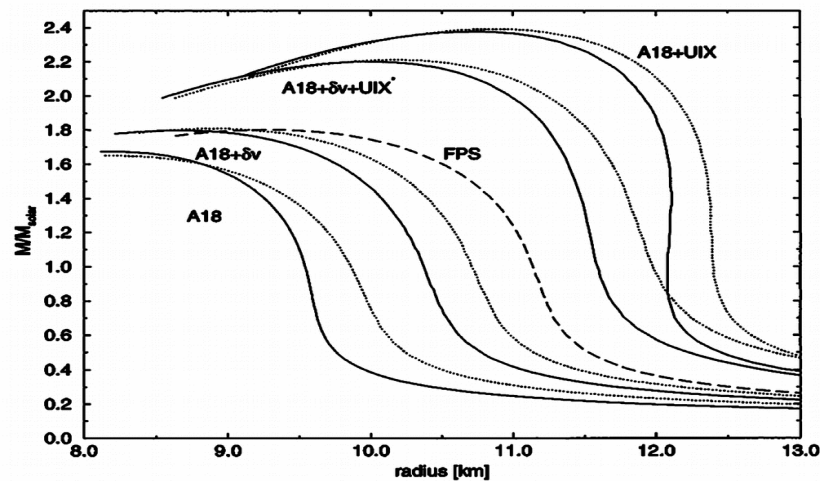


PP

- 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.

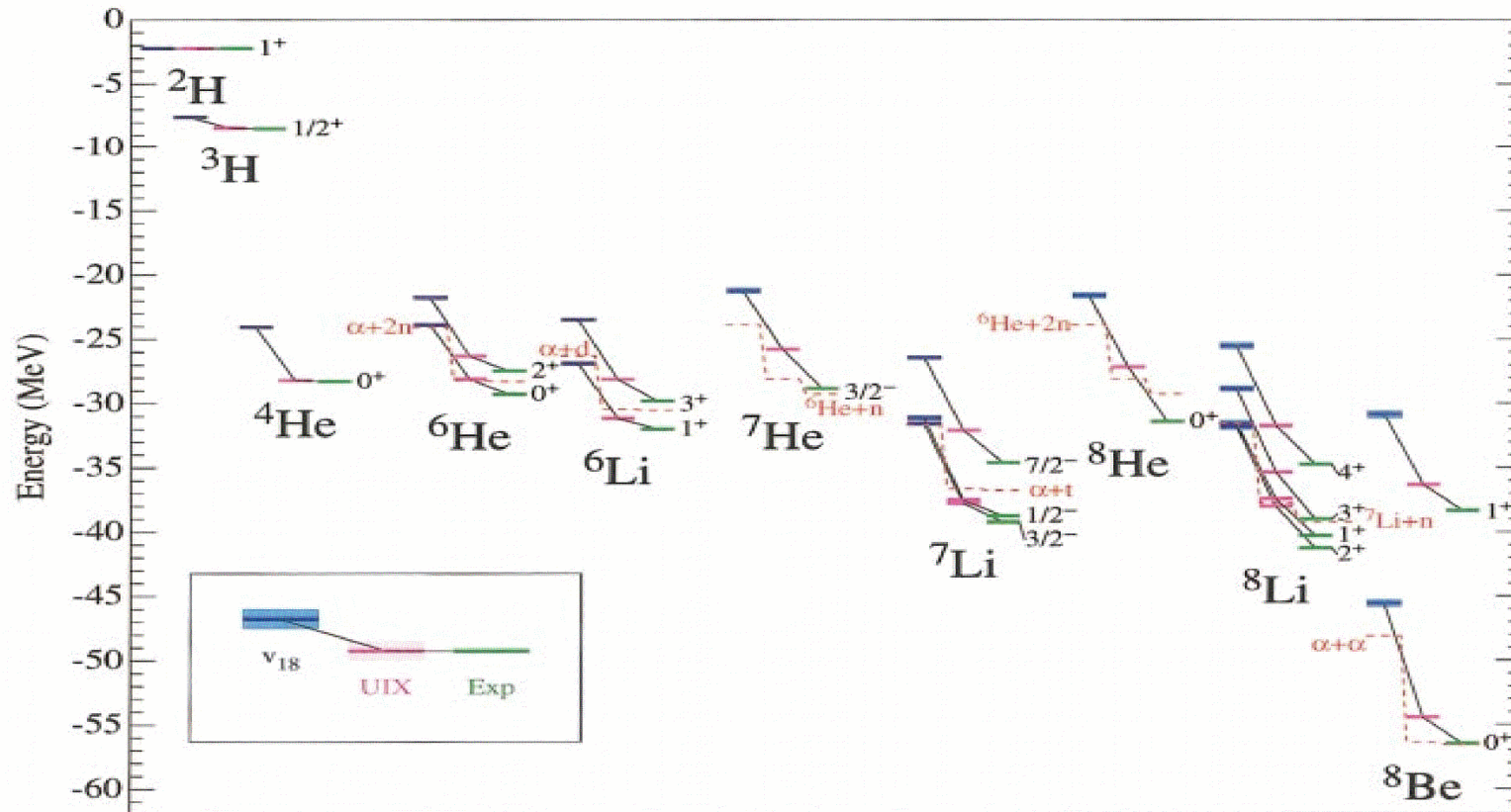
Few nucleons systems as a tool for dense matter studies

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)

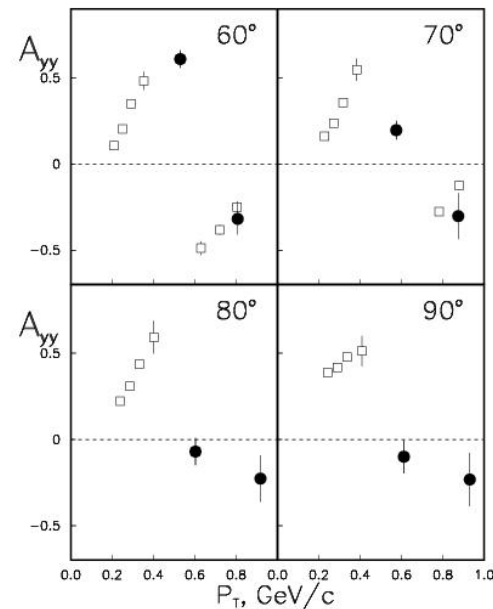
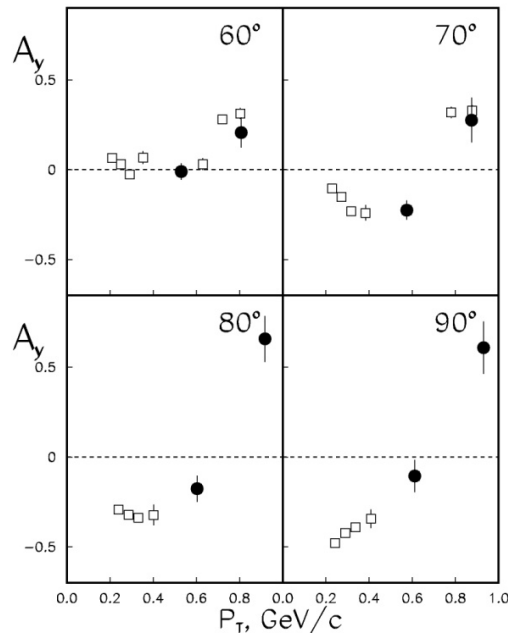
Importance of the spin part of 3NF for the light nuclei binding energies



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)

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**