Dubna, Russia, October 5-6, 2020

Analyzing powers in dp- elastic scattering at large transverse momenta*

V.P. Ladygin on behalf of DSS collaboration

*** supported in part by RFBR under grant 19-02-00079a**

Outline

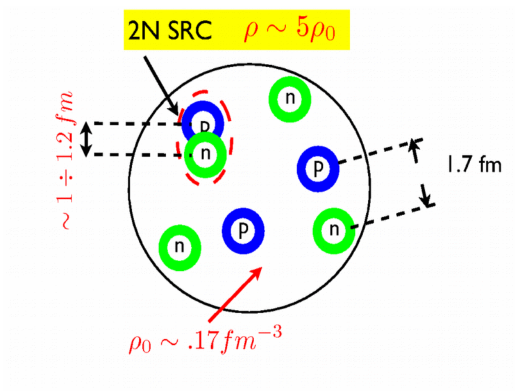
- **Motivation**
- **Review of dp-elastic scattering studies at intermediate energies**
- **Results on dp-elastic scattering obtained at Nuclotron JINR**
- **Studies at SPD**
- **Conclusion**

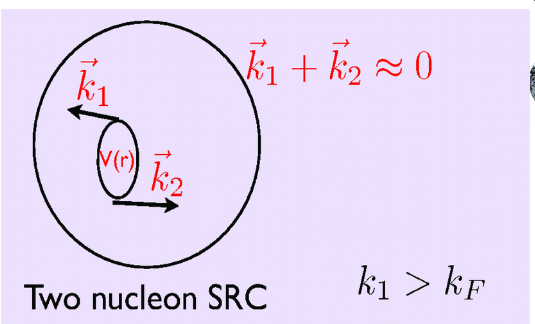
DSS collaboration: 12 Institutes and Universities from
Bulgaria-JINR-Japan-Romania-Russia-Slovakia

Motivation of the dp interaction studies

- 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 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.

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 $\vec{\mathbf{q}}$ inside the composite system, but also on the total momentum $\vec{\mathbf{p}}$ of this system

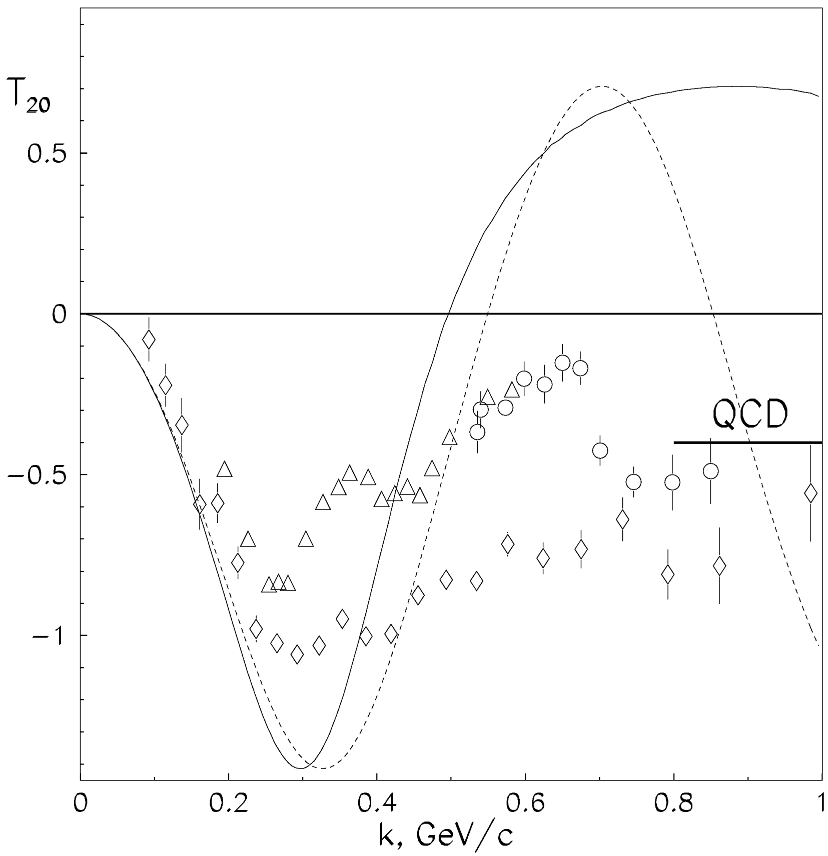
$$\Psi = \Psi(\vec{\mathbf{q}}, \vec{\mathbf{p}})$$

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

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

$$\Psi = \Psi(\vec{\mathbf{q}}, \vec{\mathbf{n}})$$

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.

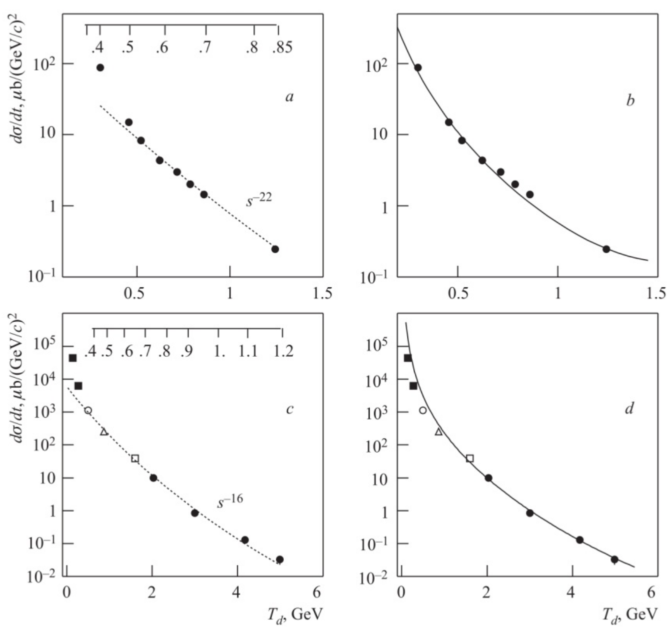
Data:
V.Punjabi et al., Phys.Lett.B350 (1995) 178
L.S.Azhgirey et al., Phys.Lett.B391 (1997) 22
L.S.Azhgirey et al., Phys.Lett.B387 (1996) 37

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:

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

Matveev, Muradyan, Tavkhelidze -self similarity
Brodsky, Farrar et al. -perturbative QCD
J. Polchinski, M.J. Strassler -AdS/QCD correspondance



Yu. N. Uzikov , JETP Lett, 81 (2005) 303-306

For the reaction **dd → ³Hen**

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

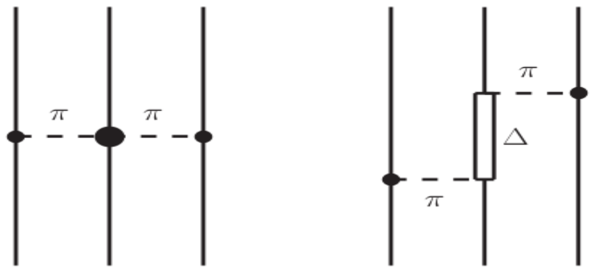
For the reaction **dp → dp**

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

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

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.**

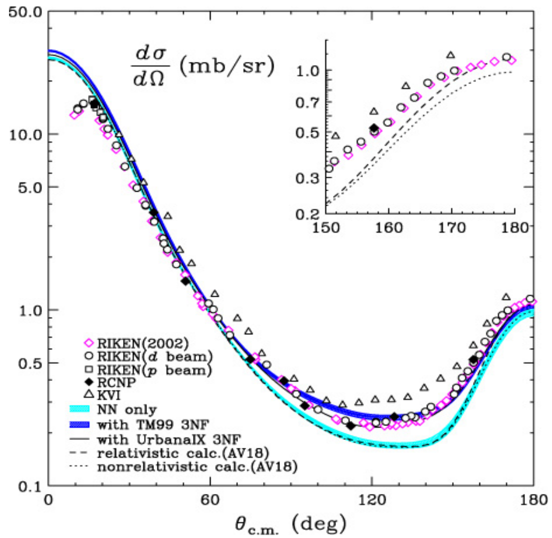


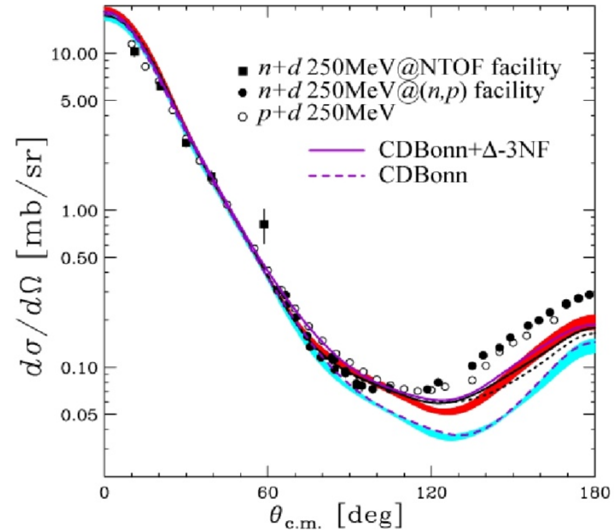
- Tucson-Melbourne
- Brazil
- Urbana-IX
- Fujita-Miyazawa ($N\Delta$)
- Chiral Effective Field Theory

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)

Cross section in dp- elastic scattering at intermediate energies





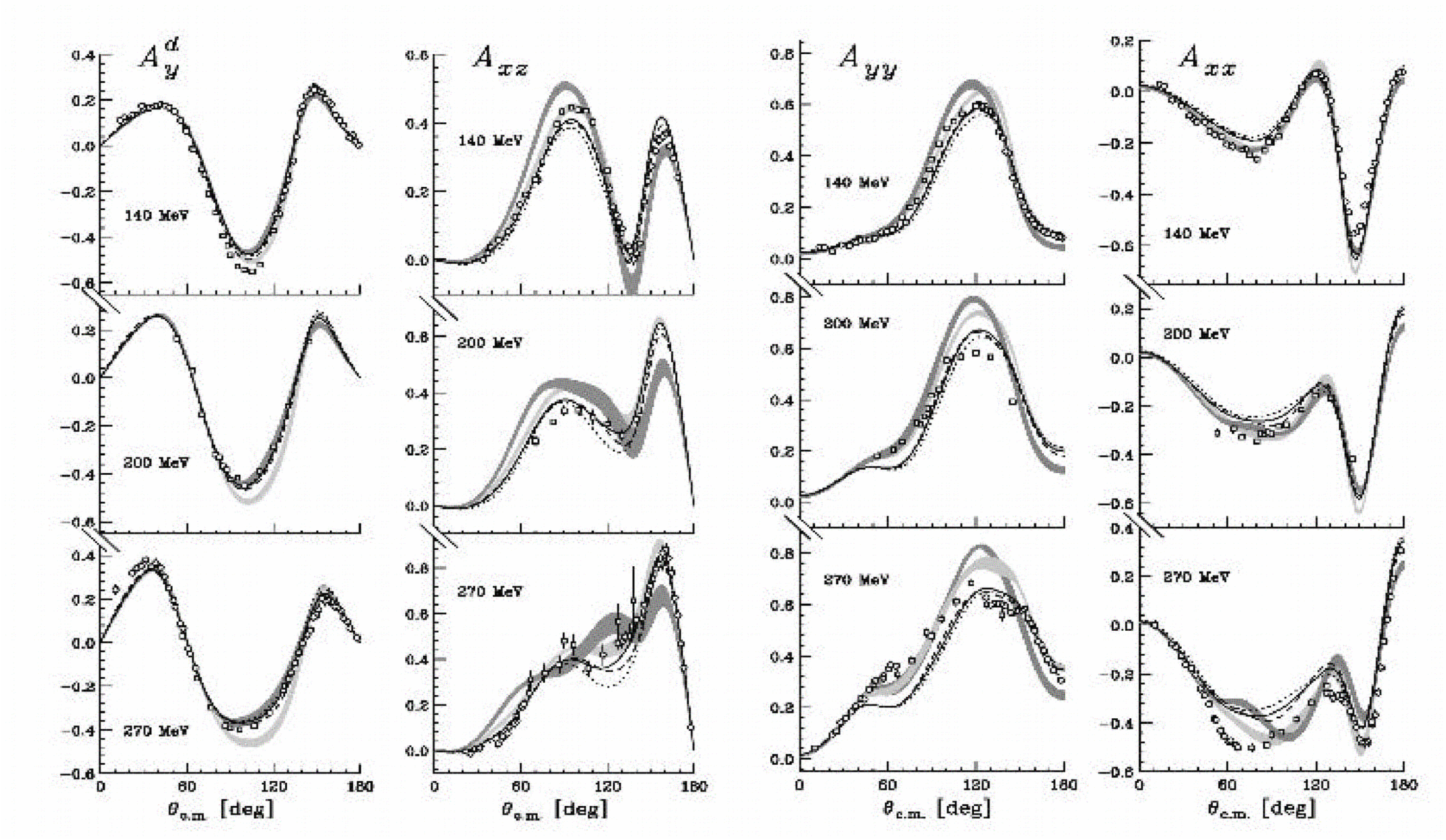
The differential cross section in elastic Nd scattering at the energy of 135 (left figure) and 250 (right figure) MeV/u.

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.

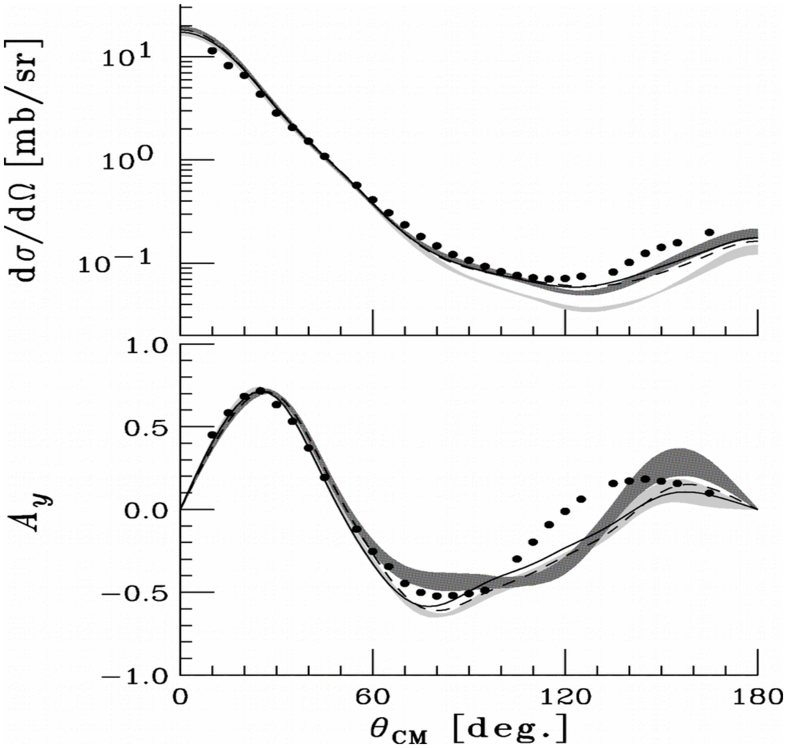
Deuteron analyzing powers in dp- elastic scattering at intermediate energies (140, 200, 270 MeV)



Polarization data for dp- elastic scattering are not described even with the 3NFs inclusion (except for Ay).

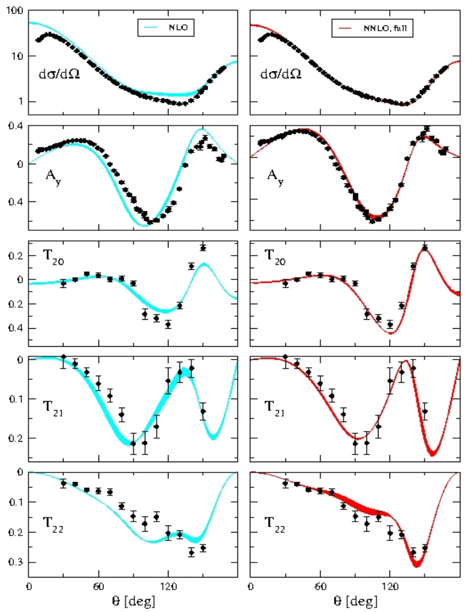
The spin part of 3NFs is missed!

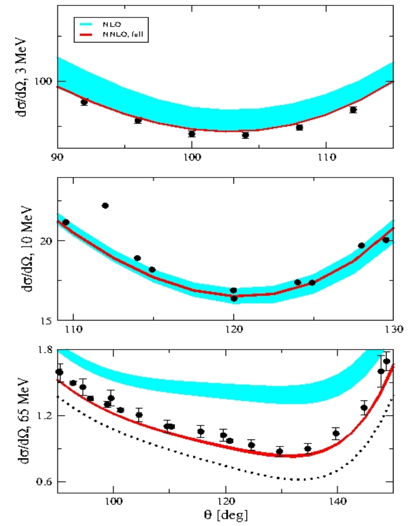
Cross section and proton analyzing power Ay in pd- elastic scattering at 250 MeV



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.

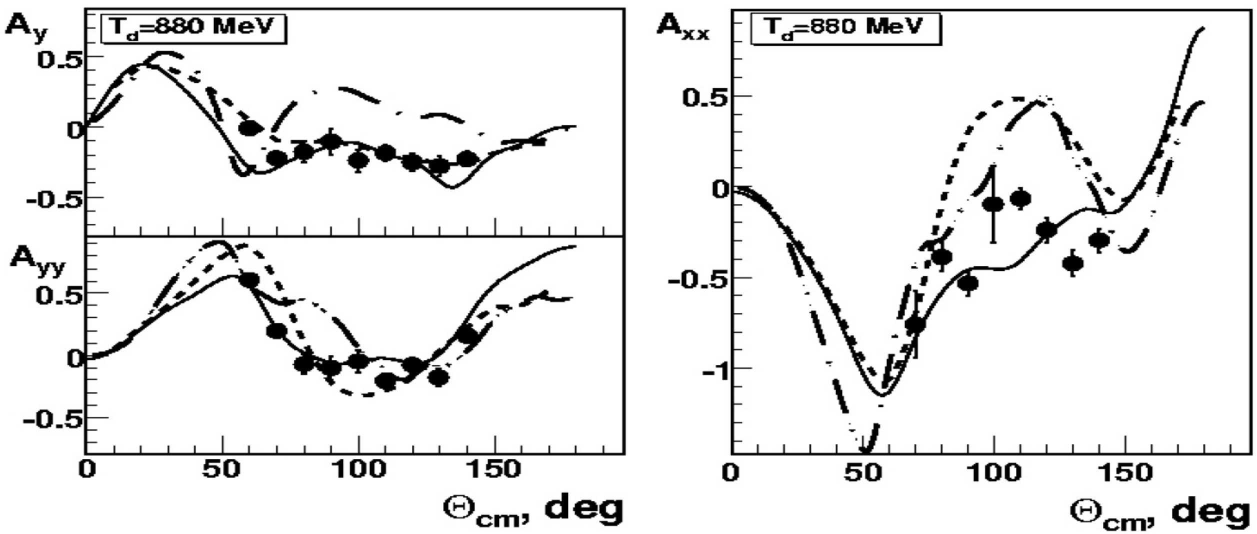
1. The systematic study of hadronic reactions induced by deuterons at Nuclotron will allow to study the structure of 2N and 3N forces, including their short-range parts.

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

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.

Analyzing powers in dp- elastic scattering at 880 MeV



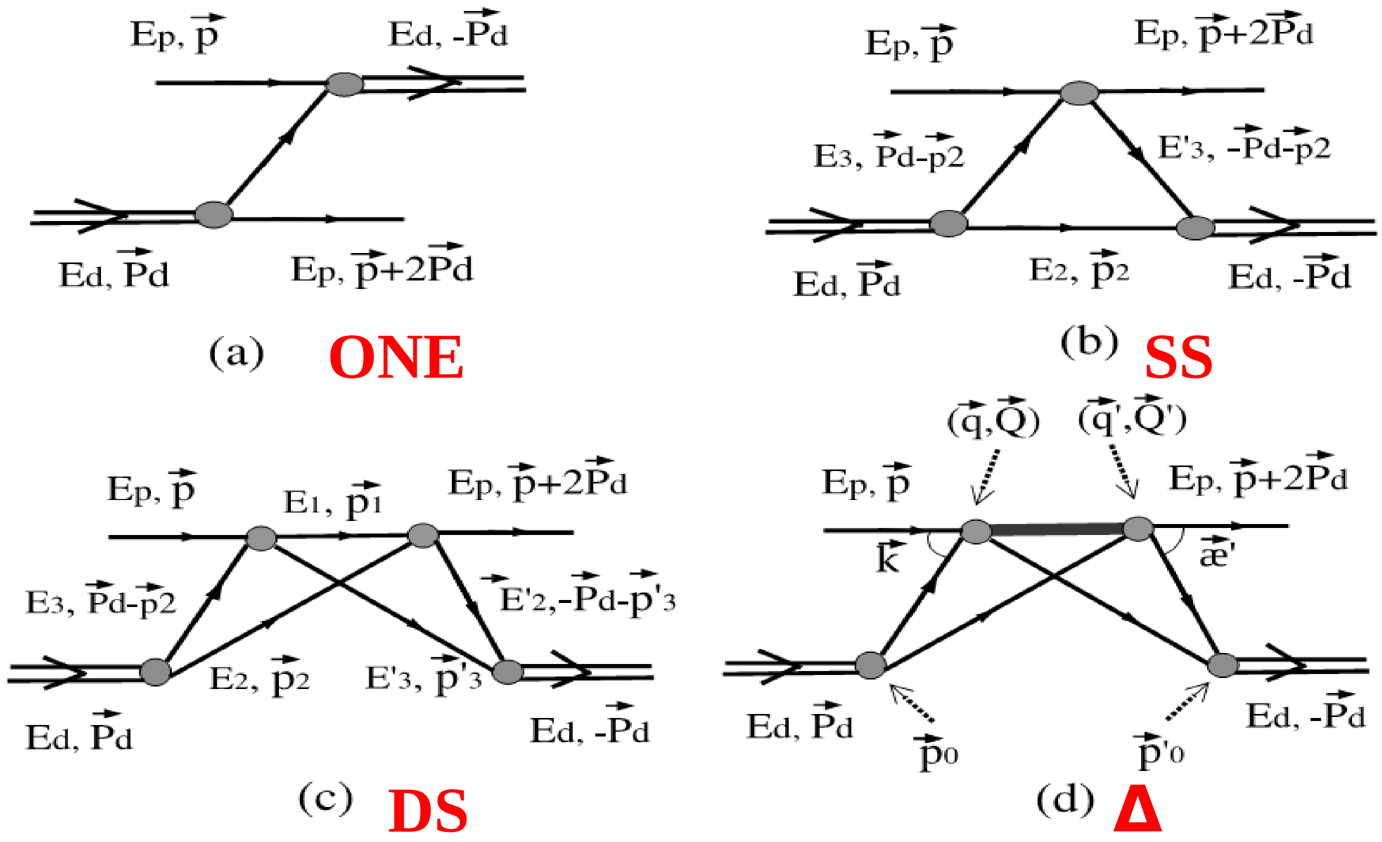
Dashed lines are the multiple scattering model calculations using CD -Bonn DWF (N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039)

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

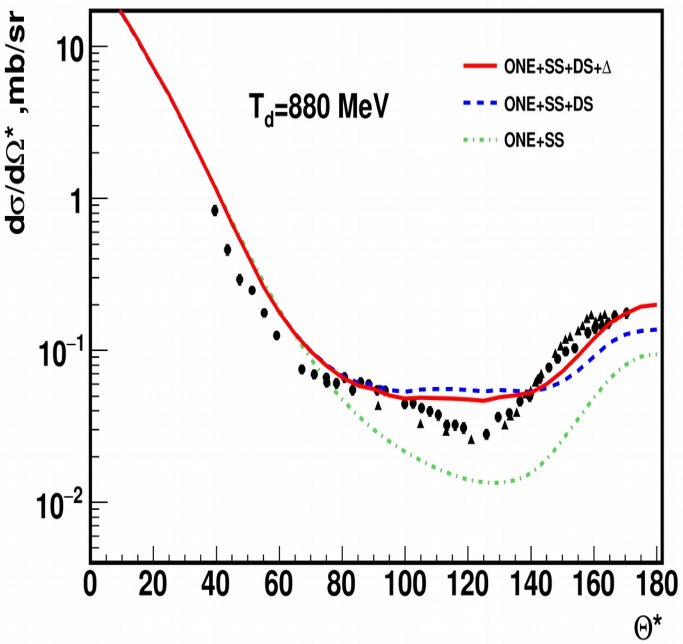
Relativistic multiple scattering model for dp- elastic scattering at moderate energies



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

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?

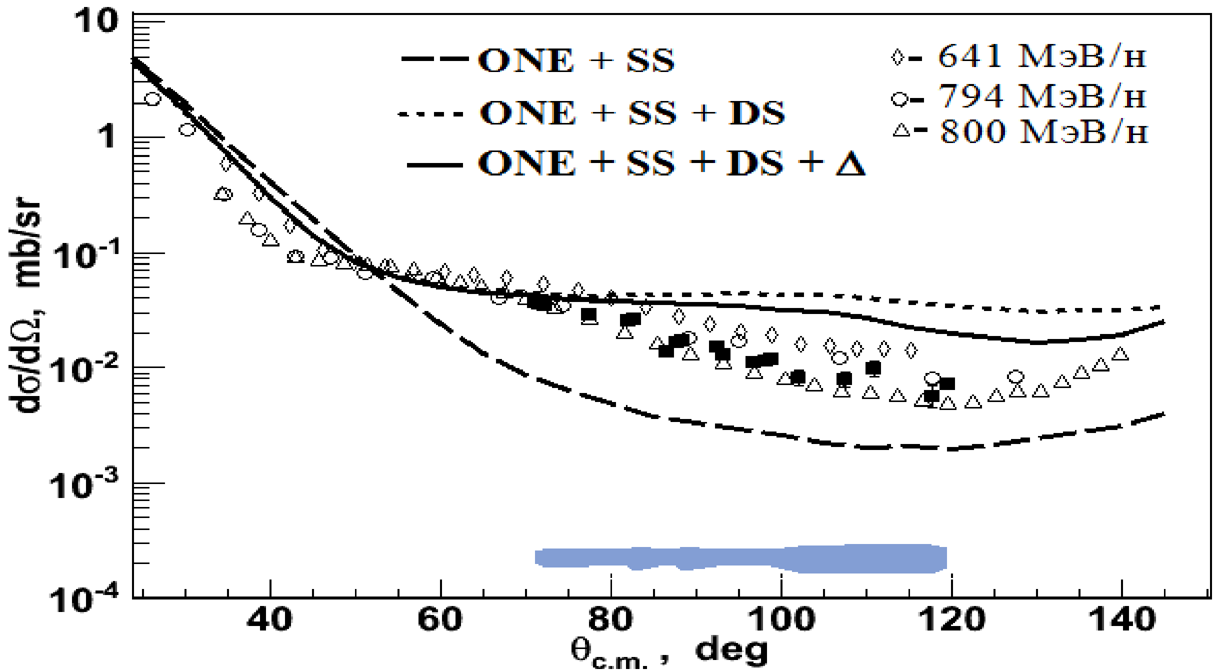
Relativistic multiple scattering model calculation:
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199

World data:

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

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

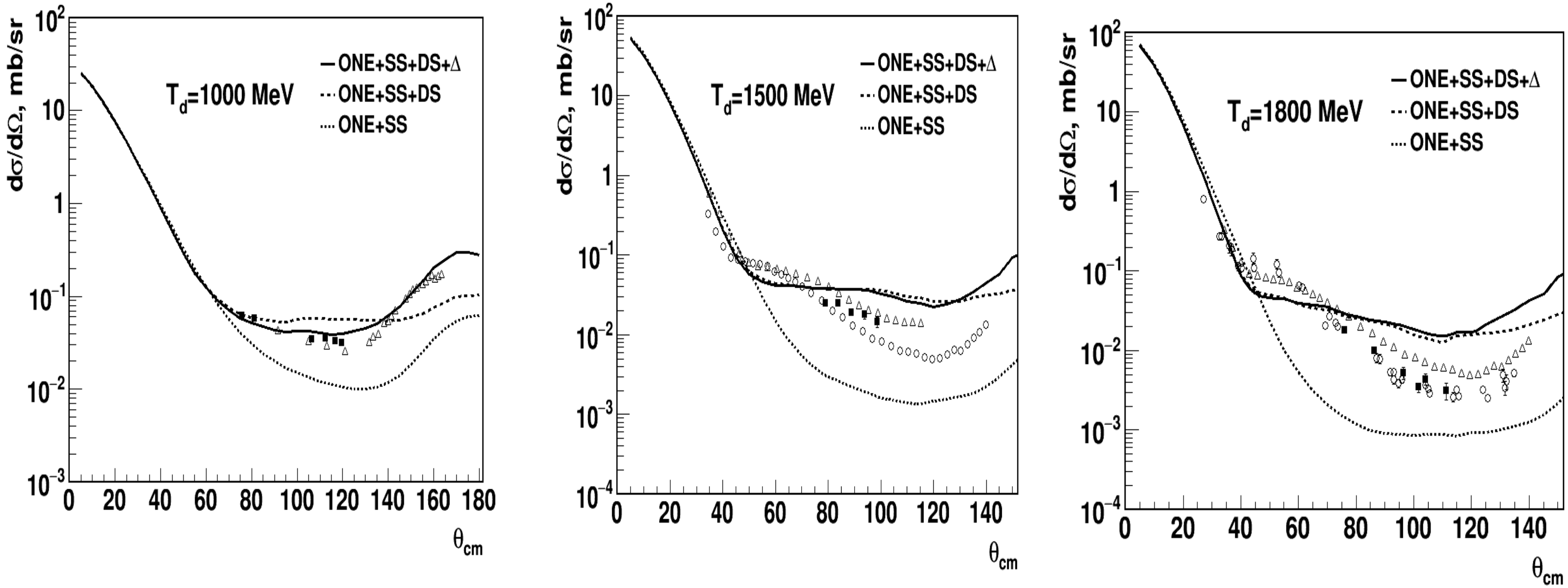
dp- elastic scattering cross section at 1400 MeV



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

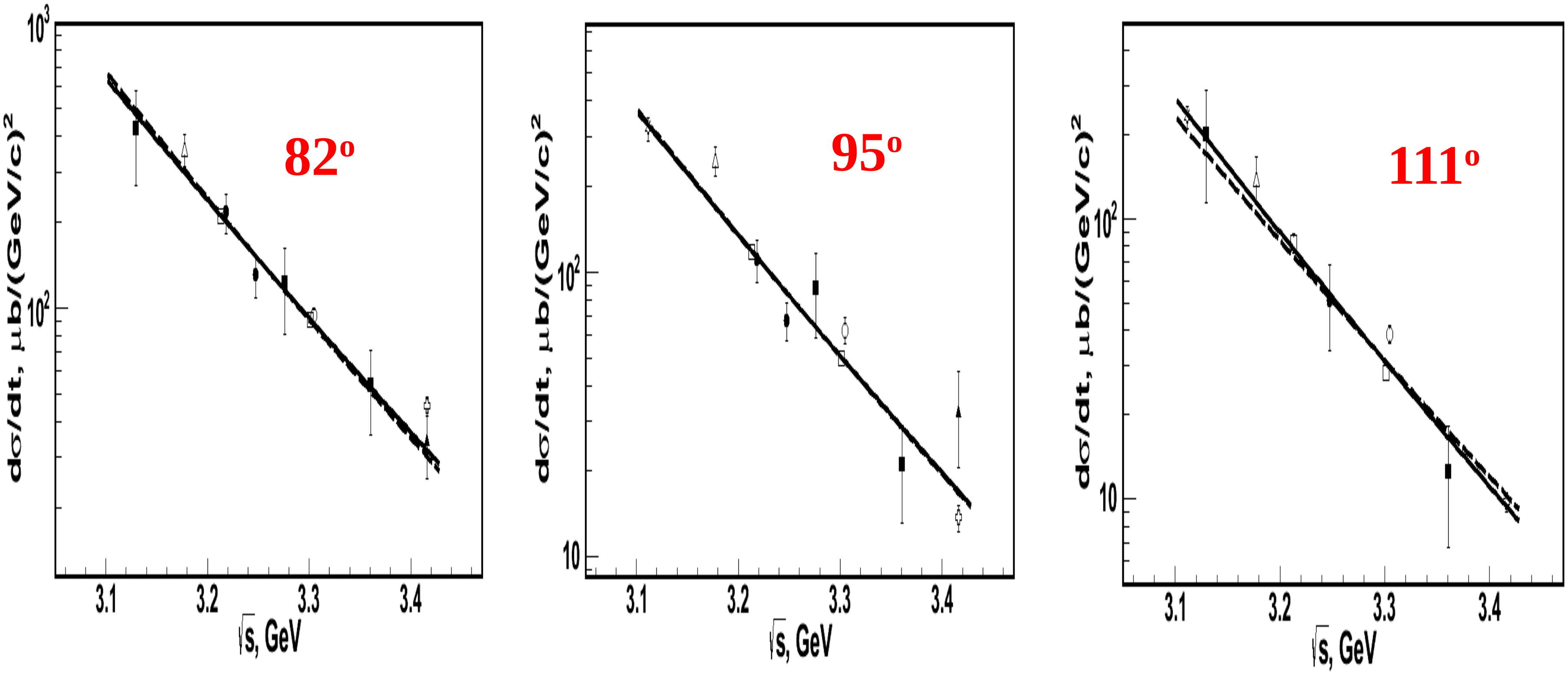
dp- elastic scattering cross section at 1000, 1500 and 1800 MeV



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

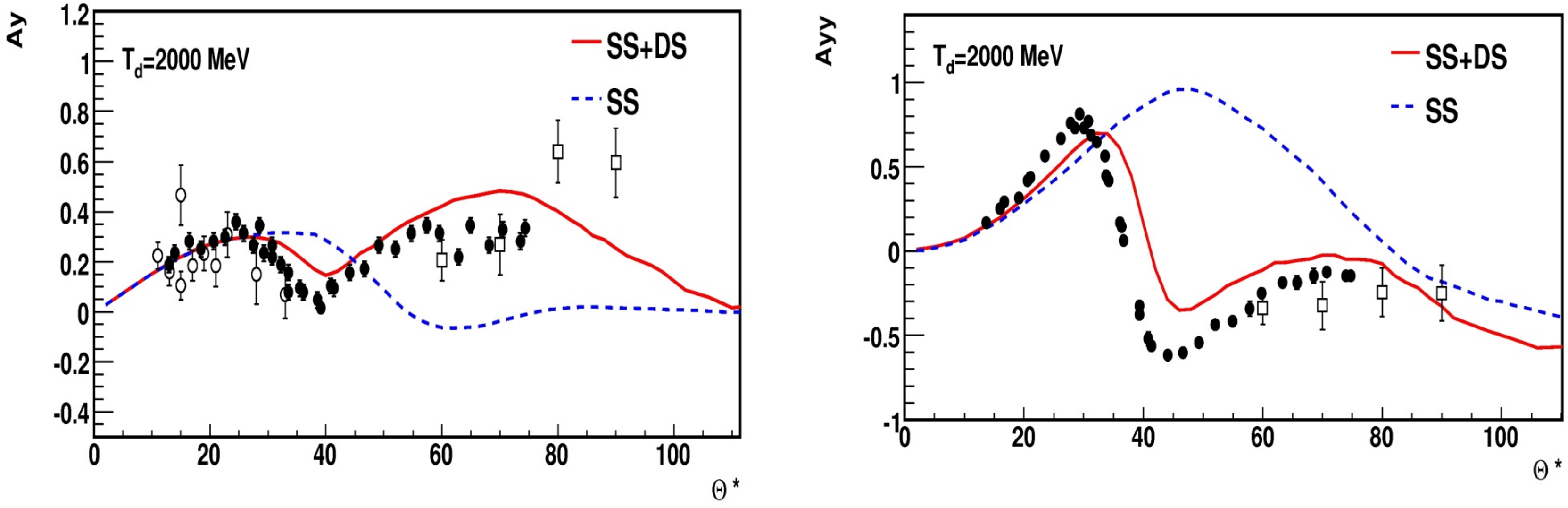
CCR for dp- elastic scattering cross section



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.

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.

General View of SPI

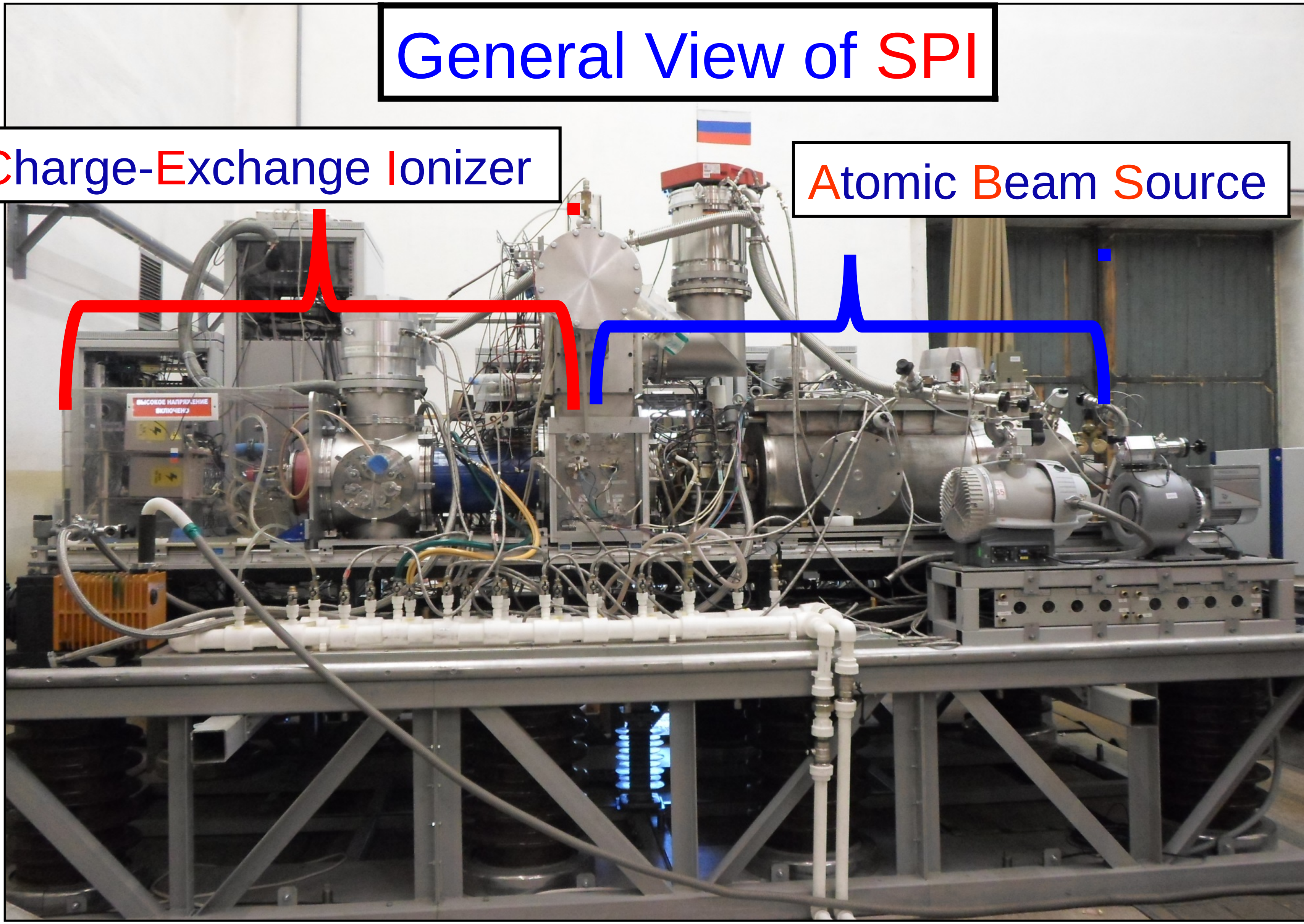
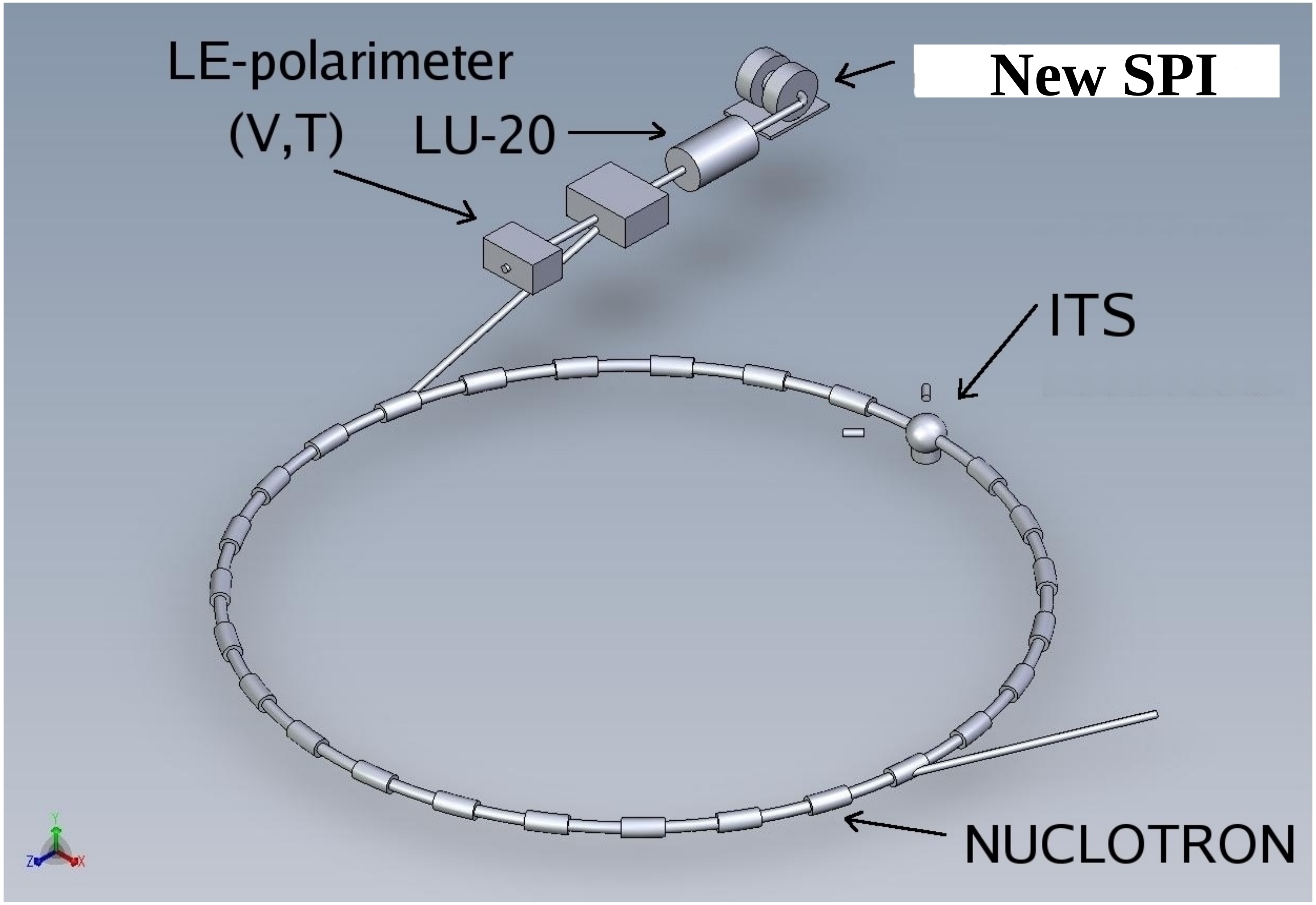
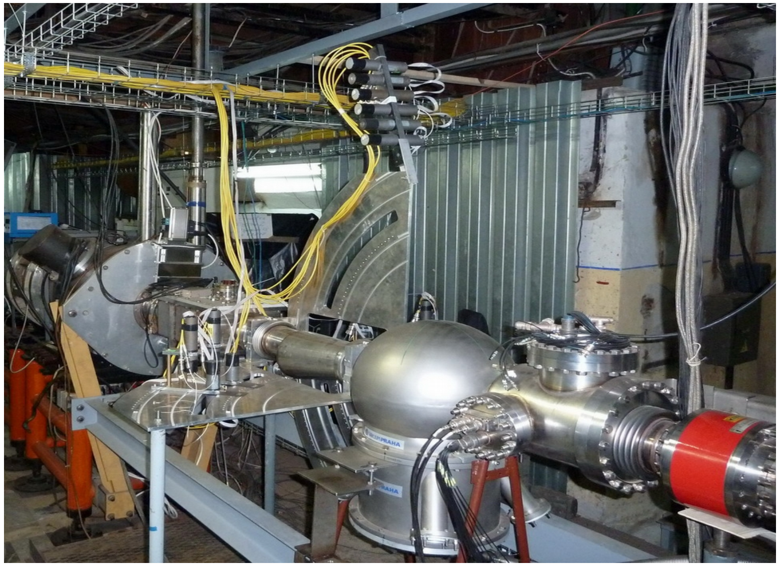


Figure of merit will be increased in future by a factor ~10^3

Nuclotron-M accelerator complex

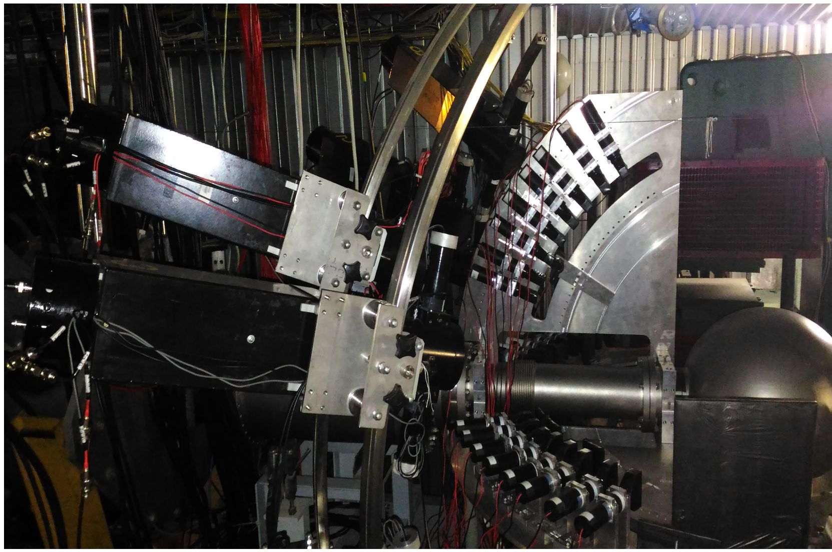


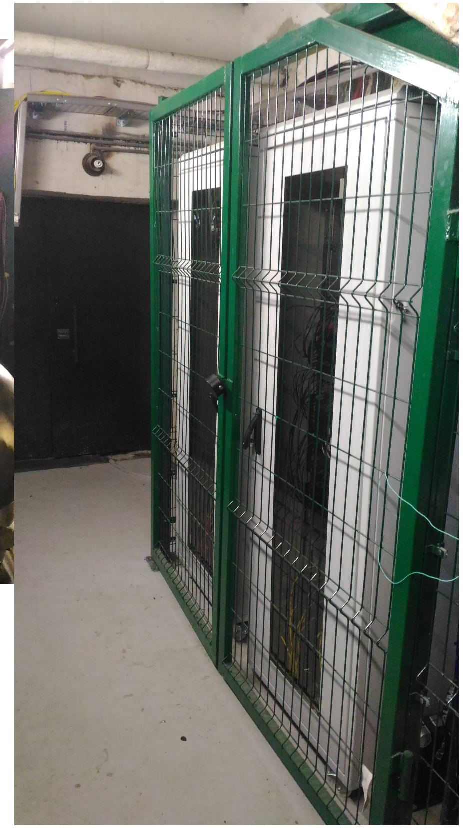
Experiments at Internal Target Station at Nuclotron
DSS-project



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

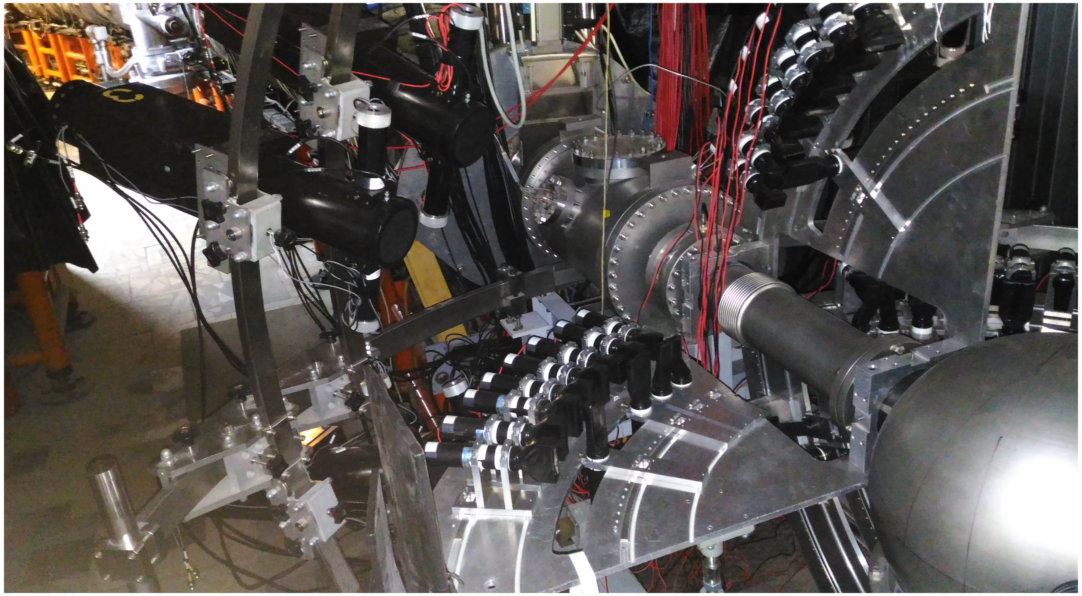
Upgrade of the Delta-LNS (DSS) setup at ITS at Nuclotron





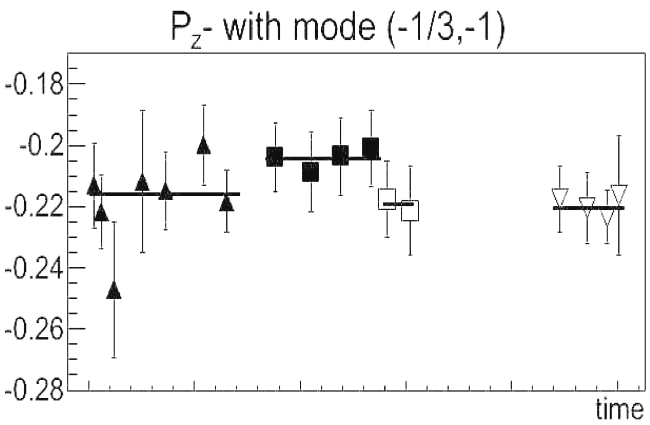
New infrastructure, cabling
New HV system (Mpod)
New VME DAQ
40 counters for dp-elastic scattering studies
8 dE-E detectors for dp -breakup studies

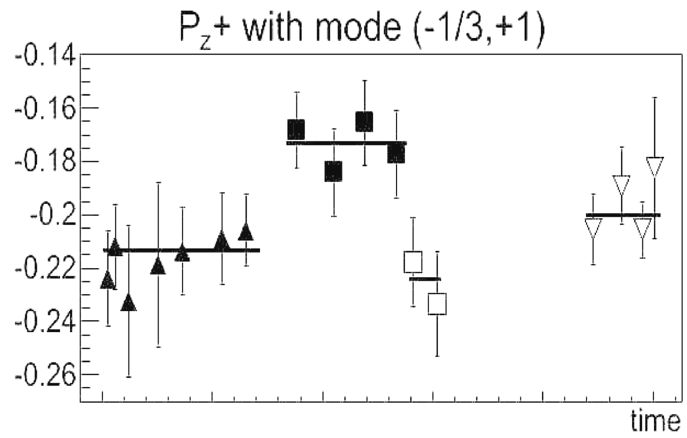
Setup to study dp- elastic scattering at ITS at Nuclotron

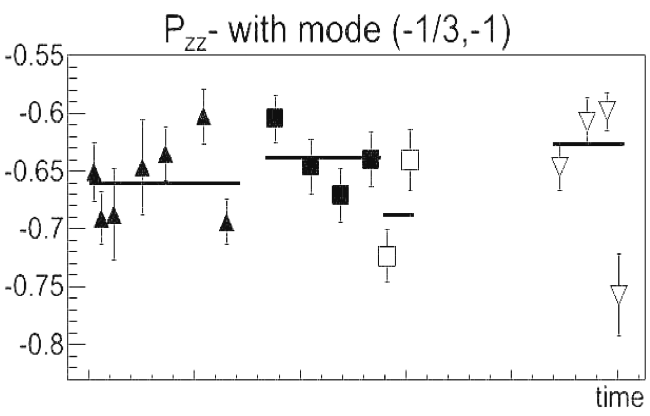


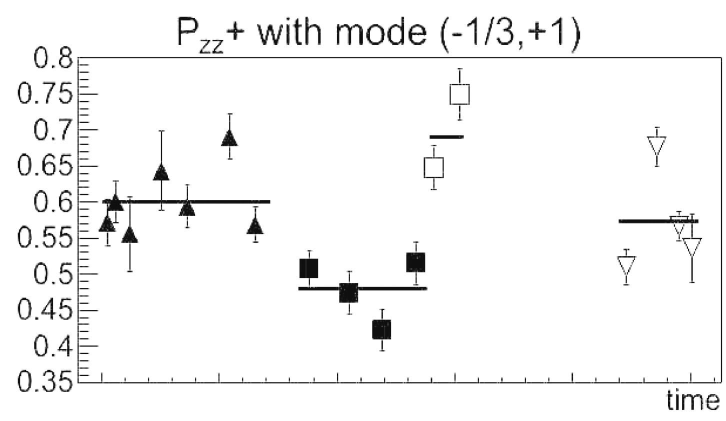
- **Deuterons and protons in coincidences using scintillation counters**
- **Internal beam and thin CH_2 target (C for background estimation)**
- **Permanent polarization measurement at 270 MeV (between each energy).**
- **Analyzing powers measurement at 400-1800 MeV**
- **The data were taken for three 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.**

Polarization measurements using dp- elastic scattering at 270 MeV



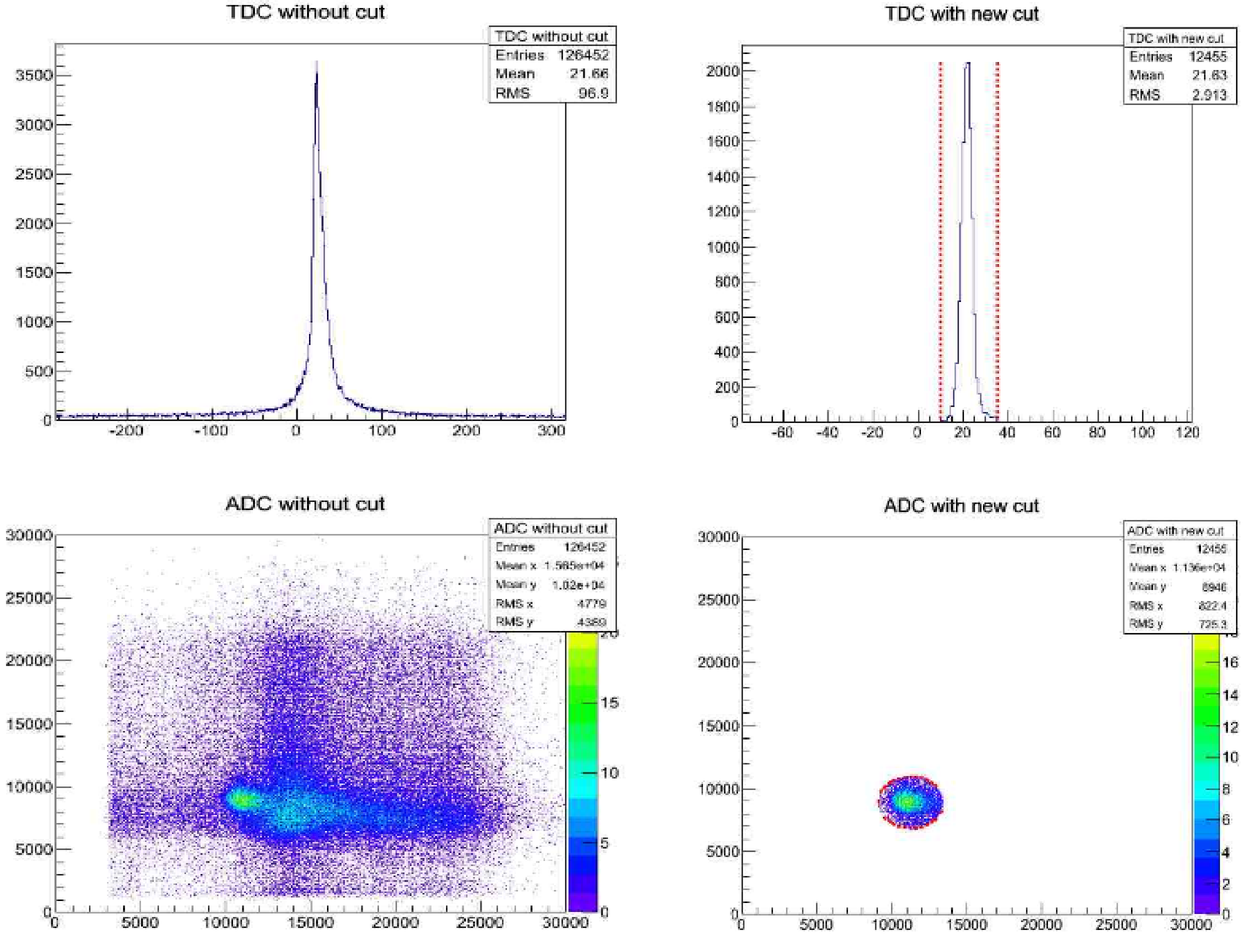






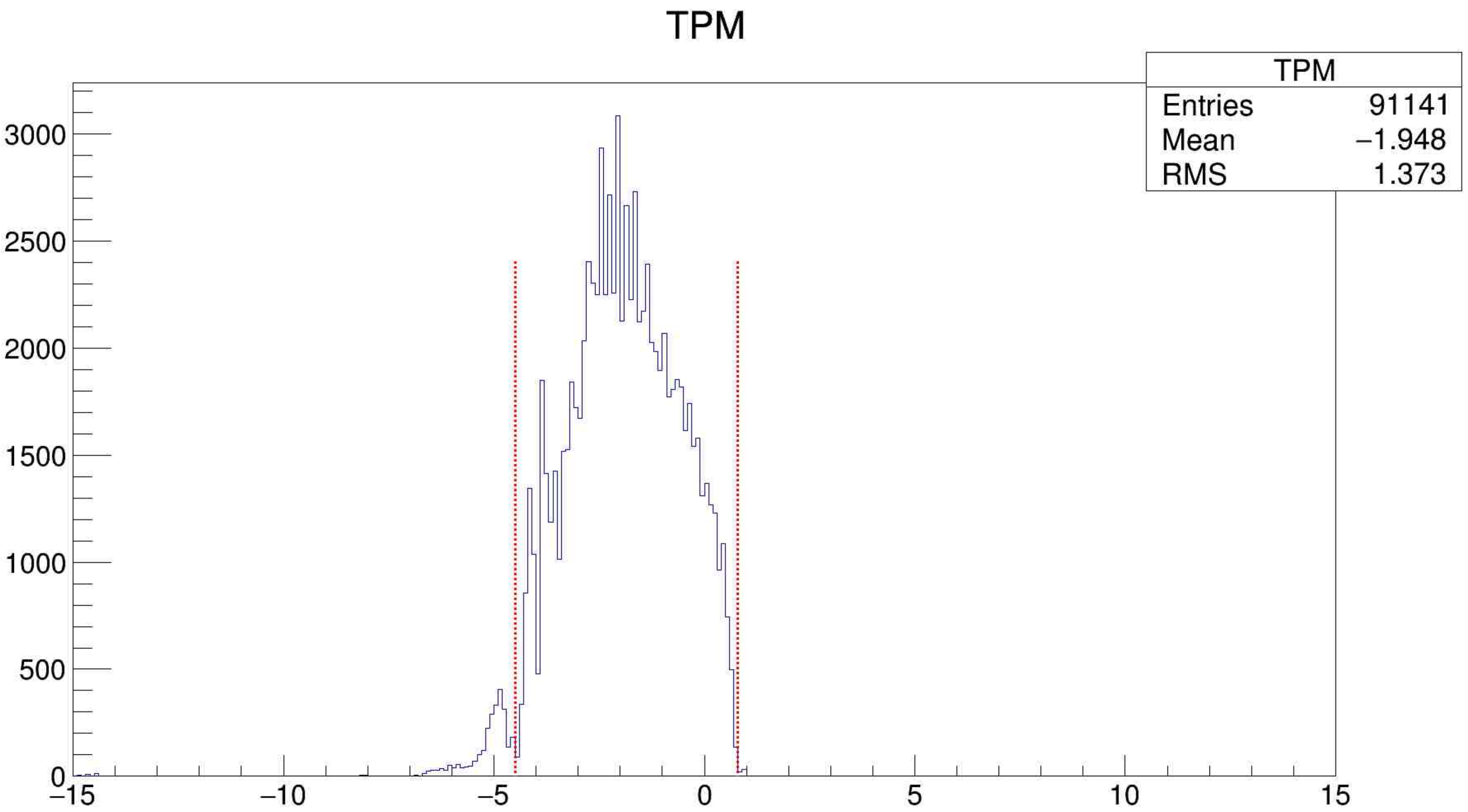
SPI was tuned for 6 spin modes (p_z,p_{zz}) = (1/3,1), (1/3,-1), (0,+1), (0,-2), (-2/3,0),(+1,0).

The dp-elastic scattering events selection



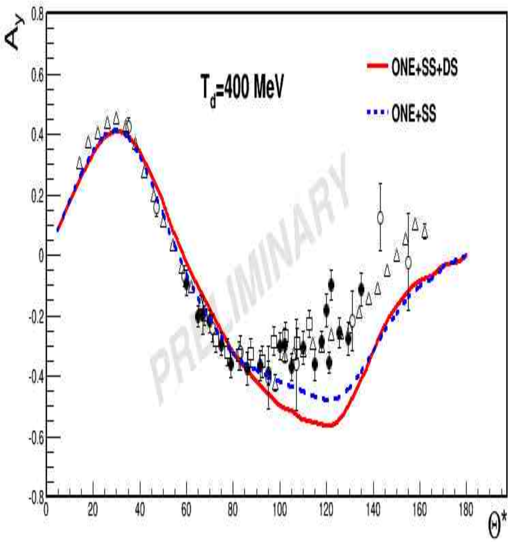
Selection of the dp elastic events by the time difference between the signal appearance from deuteron and proton detectors with the criteria on the amplitude signal correlation.

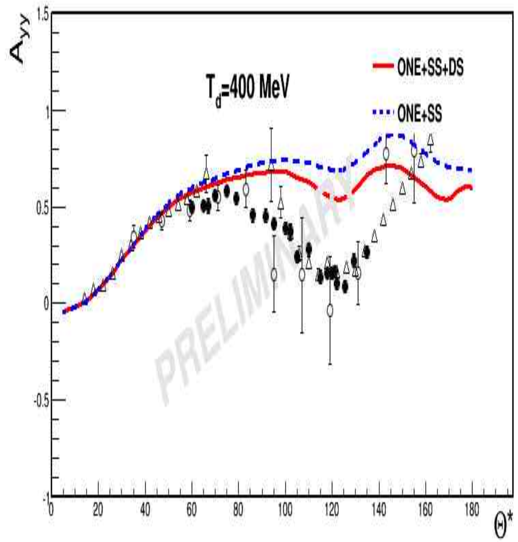
Target Position Monitor cut

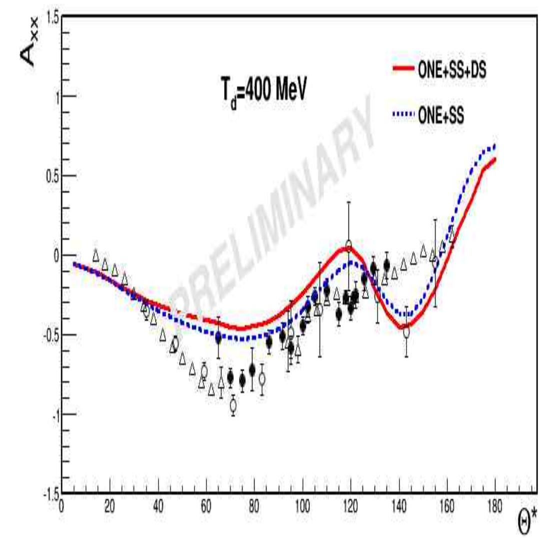


Angular dependence of the vector and tensor analyzing powers in dp-elastic scattering at 400 MeV

Ay **Ayy** **Axx**





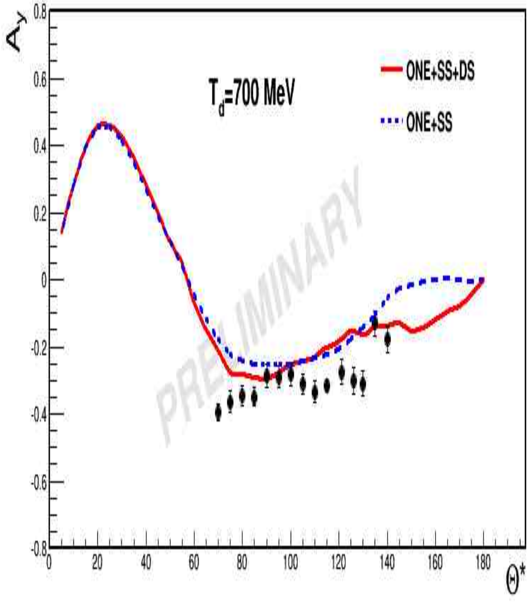


Full squares are the data from Nuclotron.
Open symbols are the world data (IUCF, Saclay).

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

Ay



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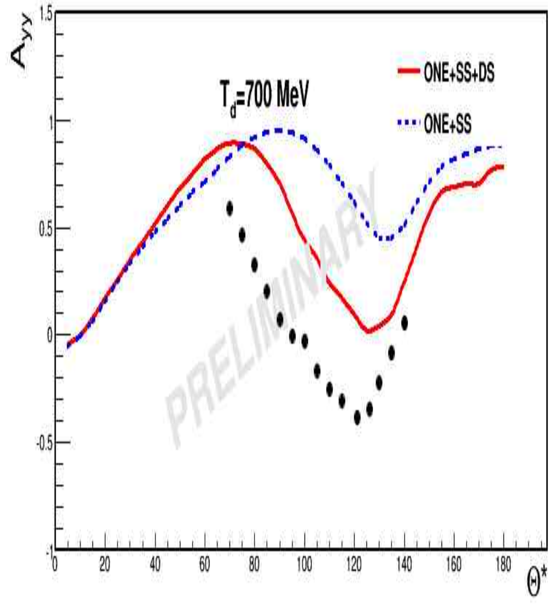

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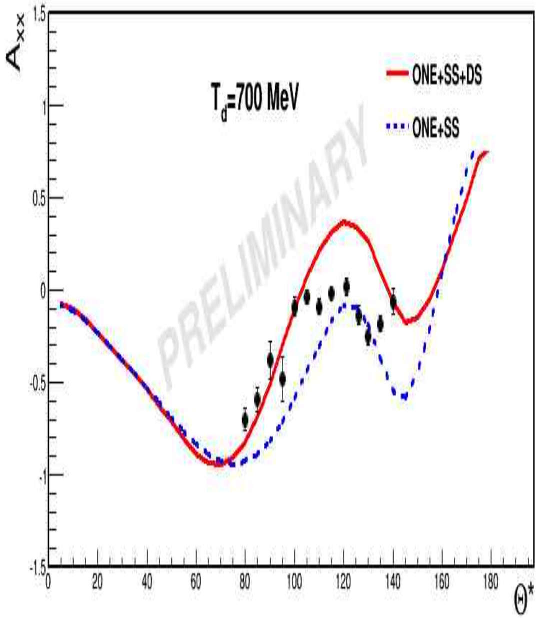
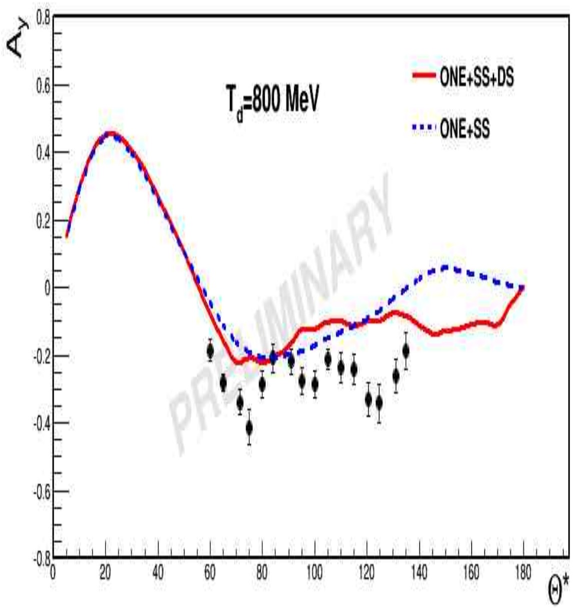


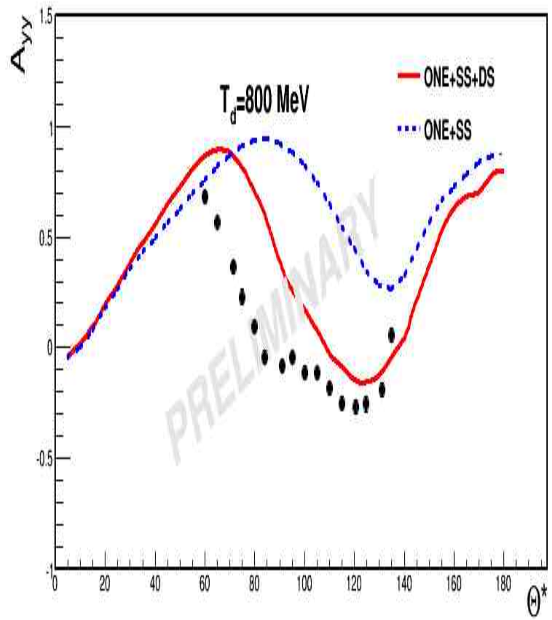
Curves are the relativistic multiple scattering model calculations

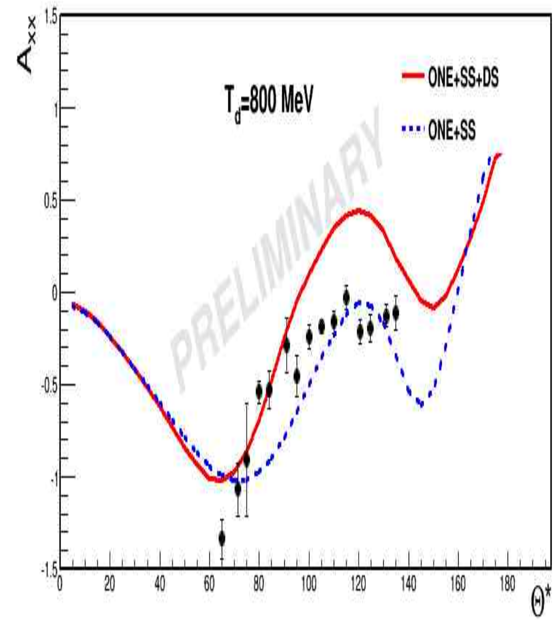
N.B.Ladygina, Eur.Phys.J, A42 (2009) 91
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199 – contribution of Δ is negligible

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

Ay **Ayy** **Axx**



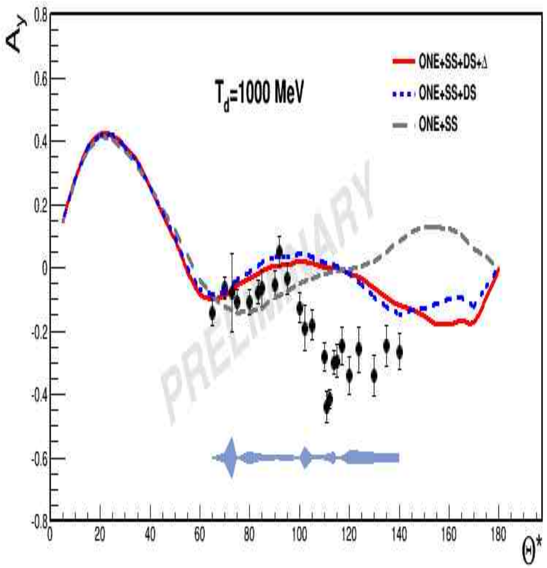




Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A42 (2009) 129
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199– contribution of Δ is small

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

Ay



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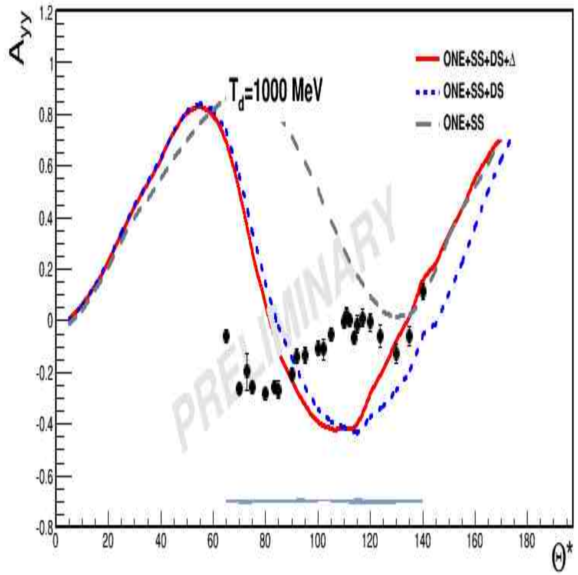

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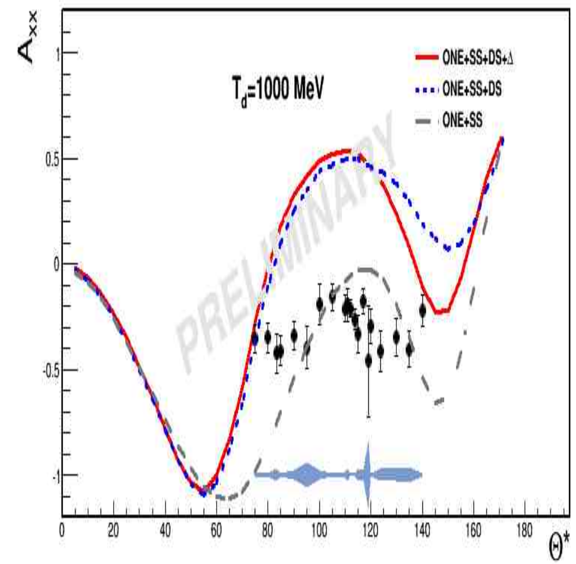
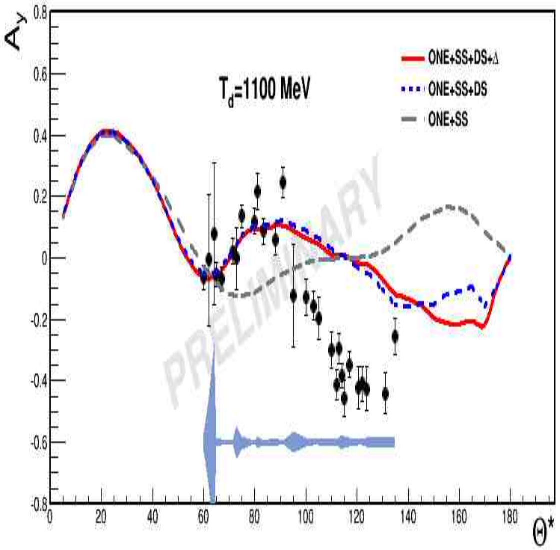


Curves are the relativistic multiple scattering model calculations

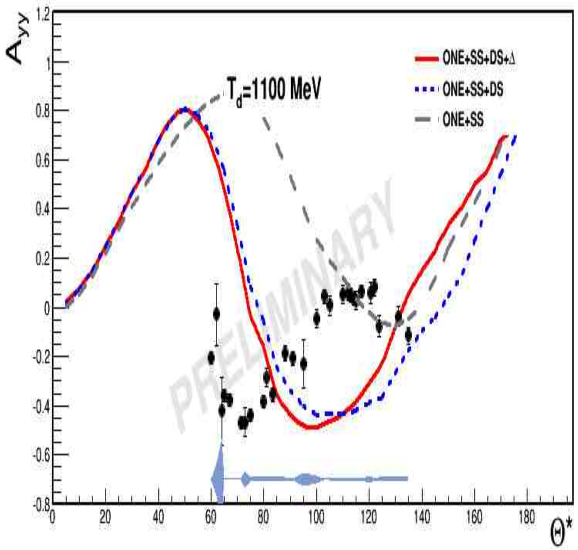
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

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

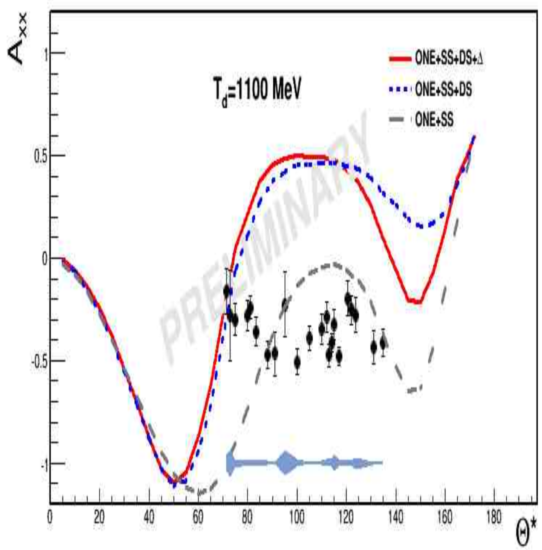
Ay



Ayy



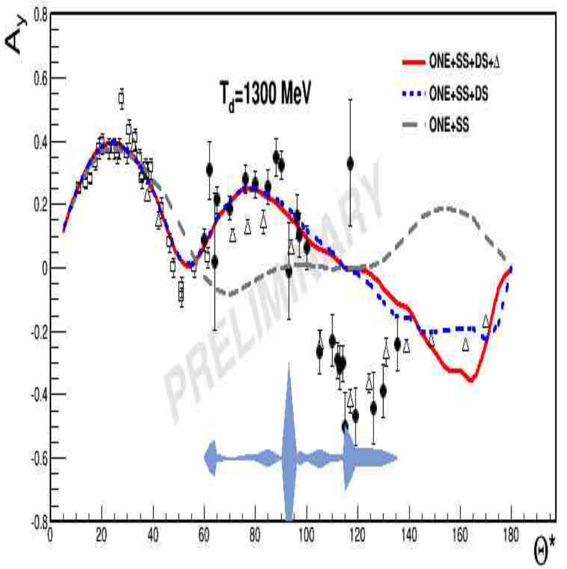
Axx



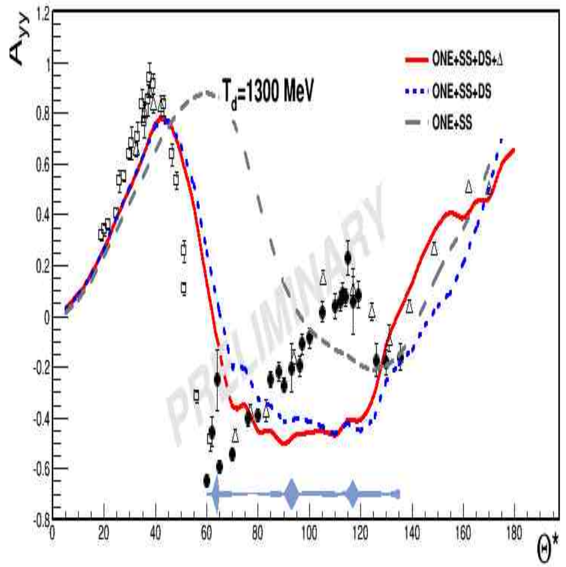
Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

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

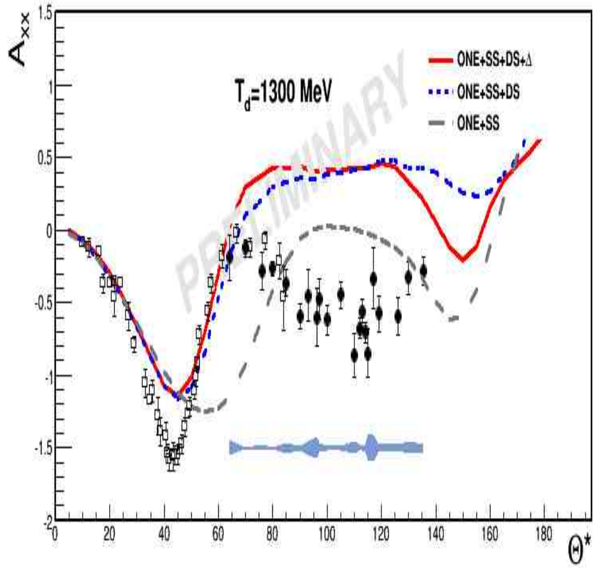
Ay



Ayy



Axx

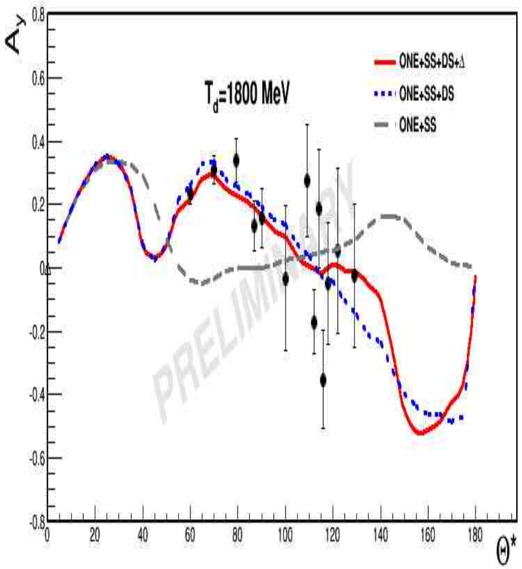


Data shown by the open symbols are obtained at 1200 MeV at Saclay

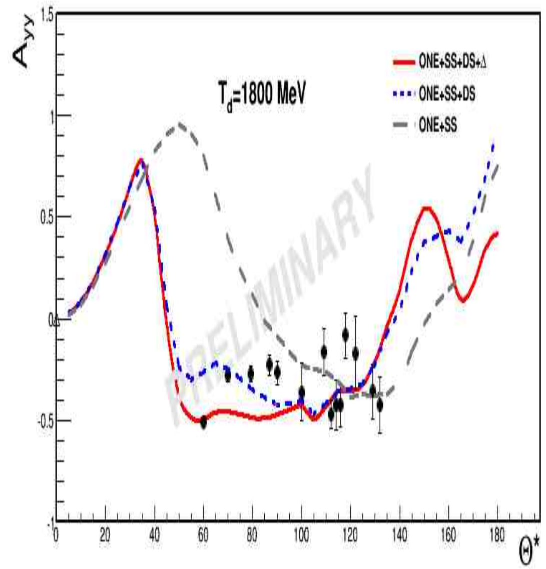
Curves are the relativistic multiple scattering model calculations
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.
+ additional ρ-meson exchange

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

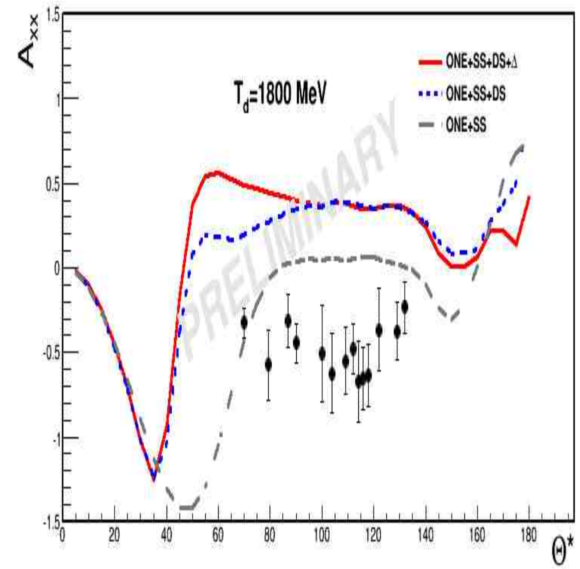
Ay



Ayy



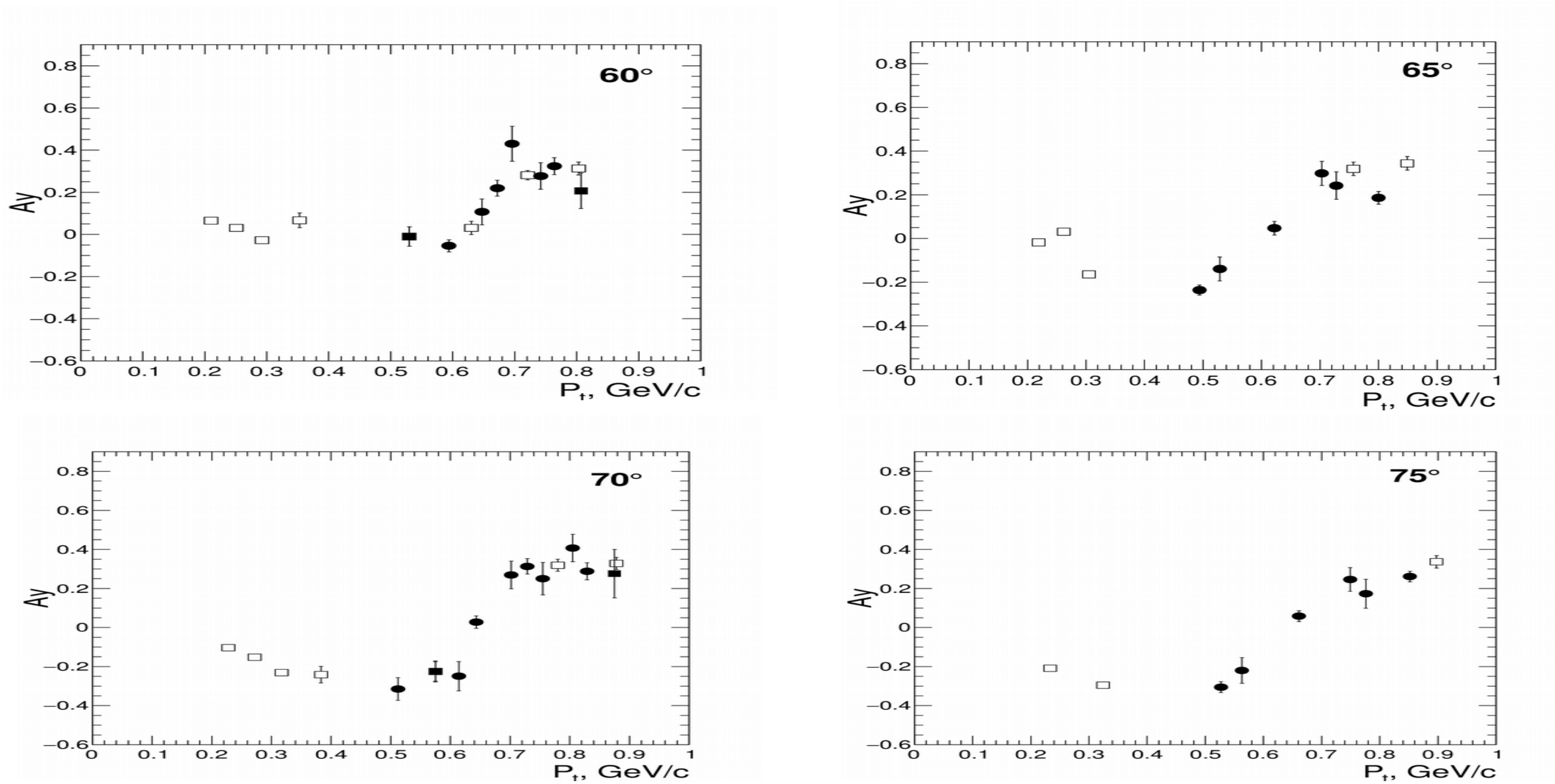
Axx



Curves are the relativistic multiple scattering model calculations

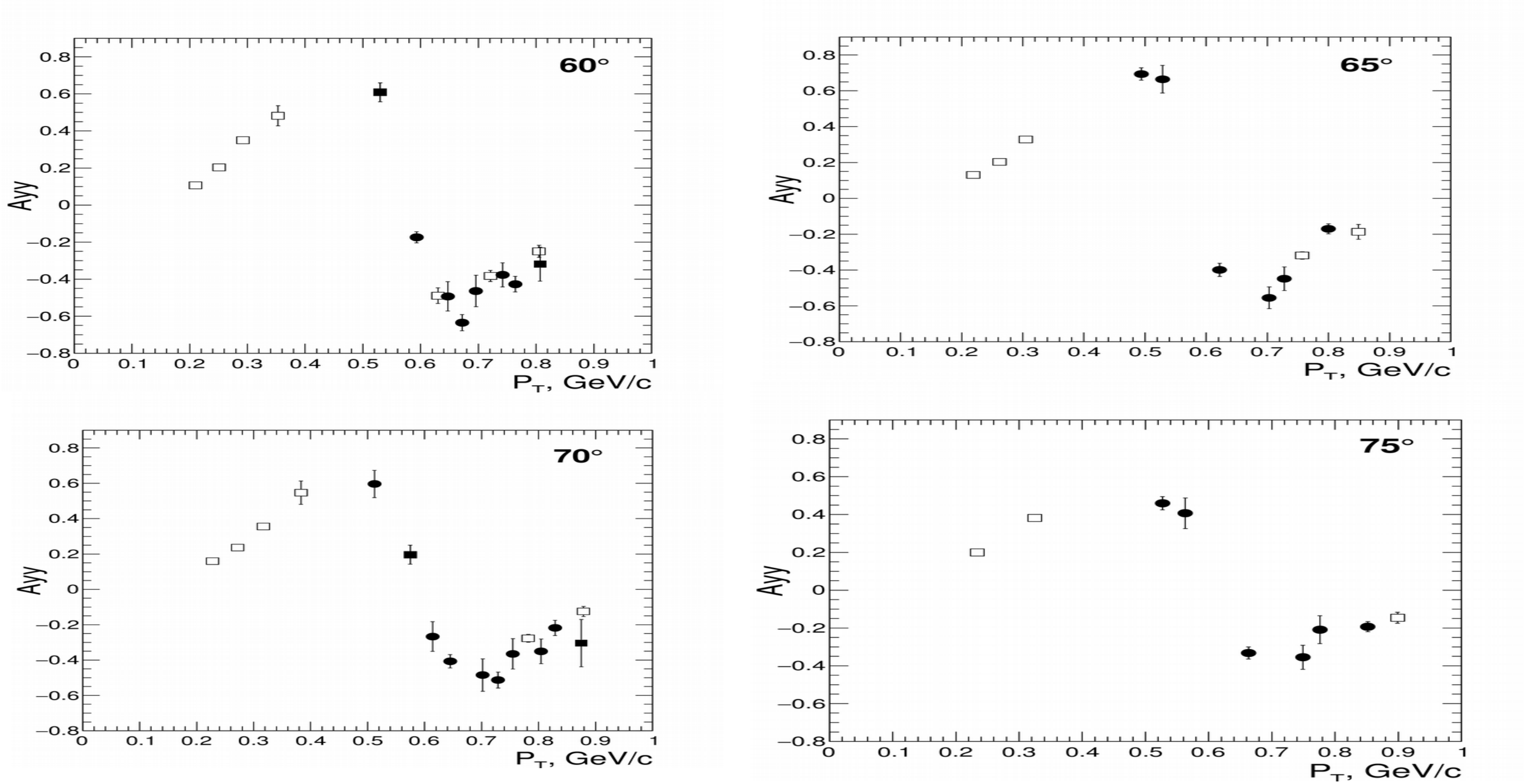
N.B.Ladygina, Eur.Phys.J, A52 (2016) 199, ibid A56 (2020) 133.

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



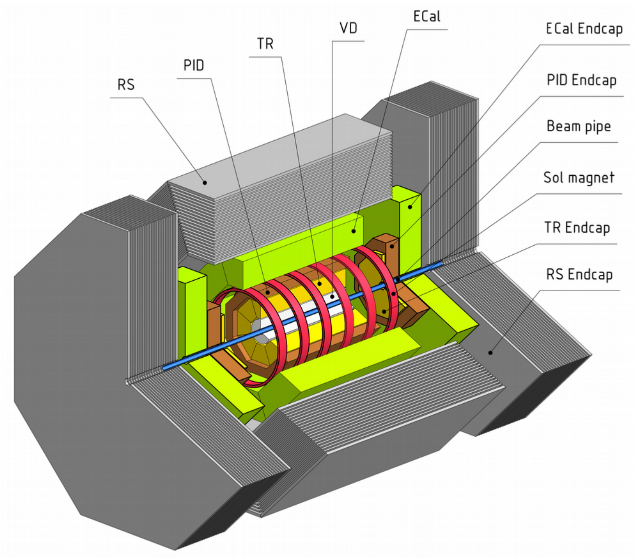
Full circles are the new preliminary data from Nuclotron.
Full squares are the data from Nuclotron (2005).
Open symbols are the world data.

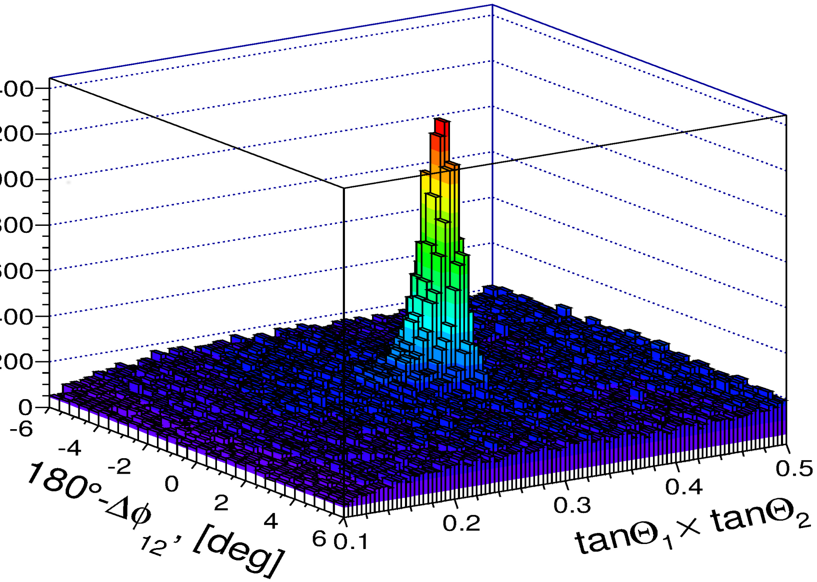
Energy dependence of the tensor analyzing power Ayy in dp-elastic scattering at 700-1800 MeV



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

Selection of dp-elastic scattering events at SPD





Lab. frame case

1. **Selection using polar and azimuthal angles correlations.**
2. **Further background suppression using momentum and vertex reconstruction information.**

Good tool for alignment procedure

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 Ay and Ayy analyzing powers in dp- elastic scattering at large tranverse momenta (>600 MeV/c). This can be due to the manifestation of the fundamental degrees of freedom.

These studies in dp- (dd-) collisions can be performed at higher energies and higher transverse momenta at SPD.

Thank you for the attention!

Polarized protons at Nuclotron.

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

Unpolarized protons: I~$1.5 \cdot 10^{8}$ ppp
Polarized protons: I~$2\text{-}3 \cdot 10^{7}$ ppp

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

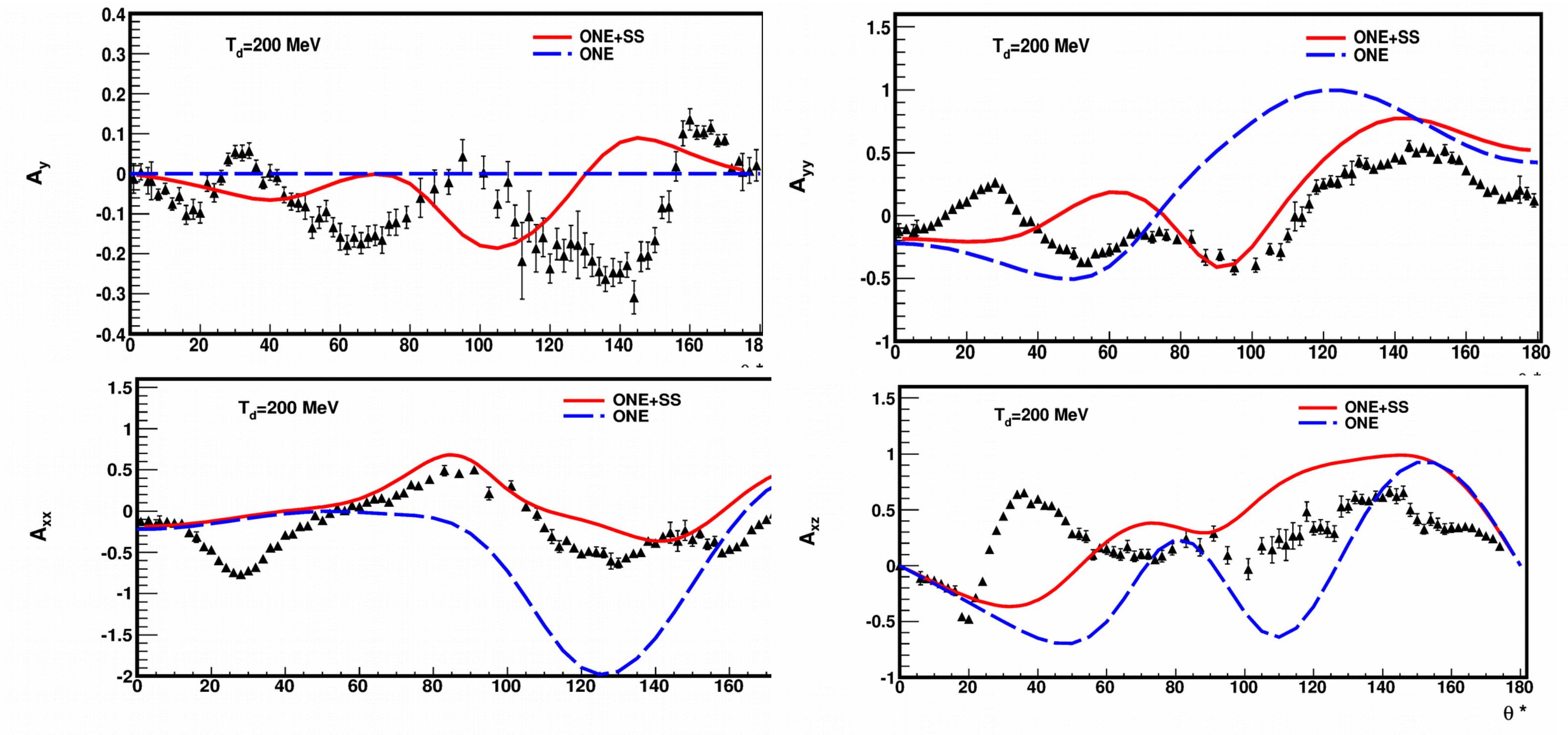
beam 2/3 of time.

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

Unpolarized protons: P= -0.056±0.021
Polarized protons: P=-0.367 ±0.015

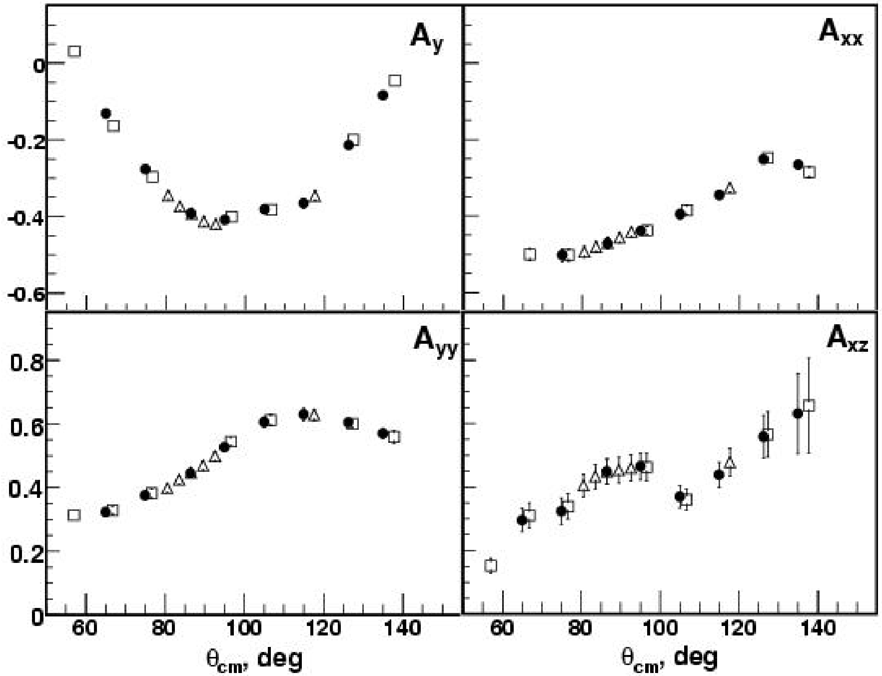
Need to produce new detection system for protons.
(talk of A.Terekhin)

Polarization effects in the dd → ^{3}Hen(^{3}Hp) reactions at Nuclotron energies



The relativistic multiple scattering model was successfully used to describe the dd → ^{3}Hen(^{3}Hp) reactions in a GeV region at the Nuclotron.

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



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 ●.

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

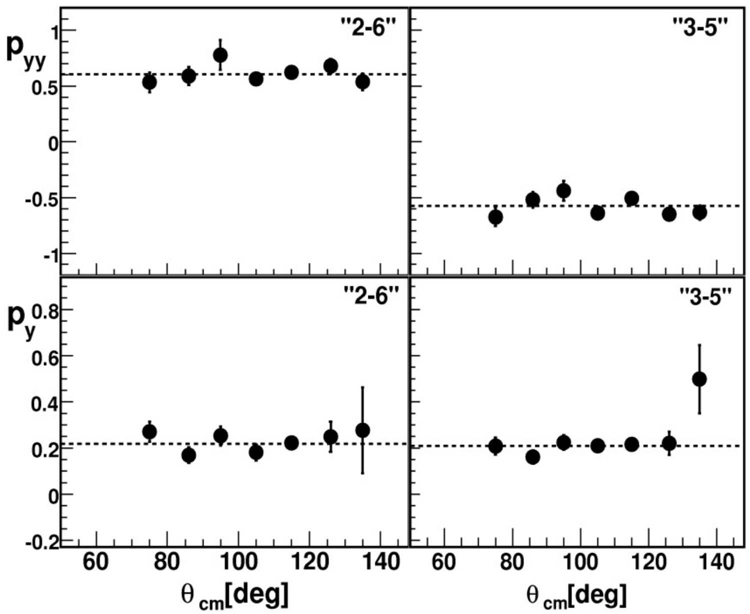
K.Sekiguchi et al.,

Phys. Rev.C70 (2004) 014001

K.Suda, et al.,

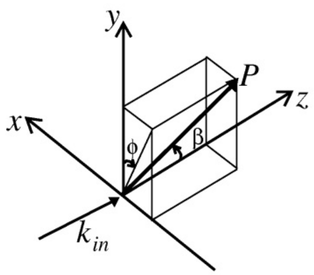
Nucl. Instr. Meth. in Phys. Res. A572 (2007) 745

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.

ß = -90.3º ± 1.2º



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

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

- **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 **k**:

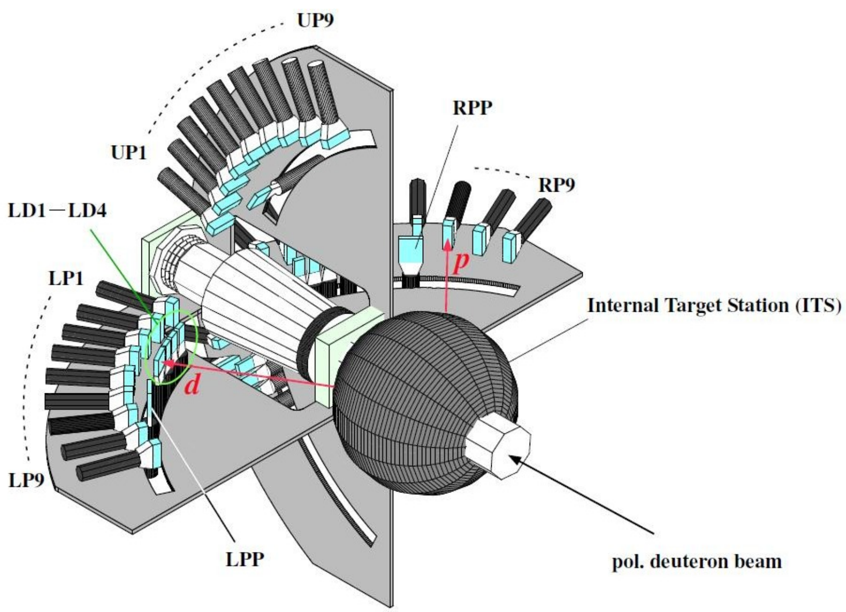
$$k = \sqrt{\frac{m_p^2 + \mathbf{k}_T^2}{4x(1-x)} - m_p^2},$$

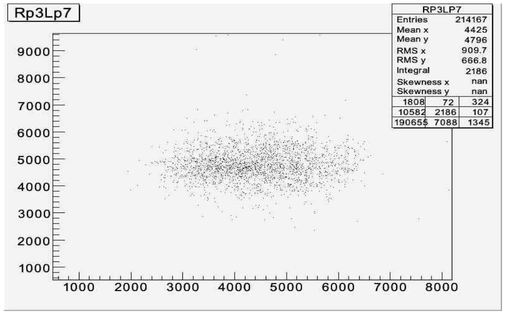
$$x = \frac{E_p + p_{pl}}{E_d + p_d},$$

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.

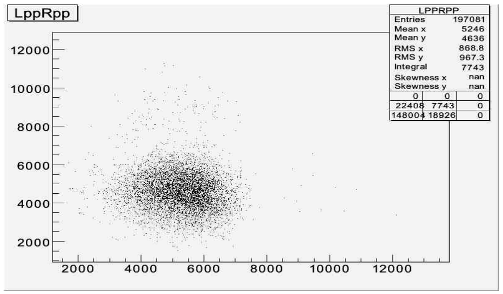
- Minimal relativization scheme (Dirac, Weinberg, Frankfurt& Strikman)
- Bete-Salpeter equation solving (Tjon&Keisler, Bondarenko et al.)
- Quasi-potential wave functions (Gross, Braun&Tokarev, Kaptari et al.)
- Covariant theory on the light cone (Karmanov et al.)

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





DP



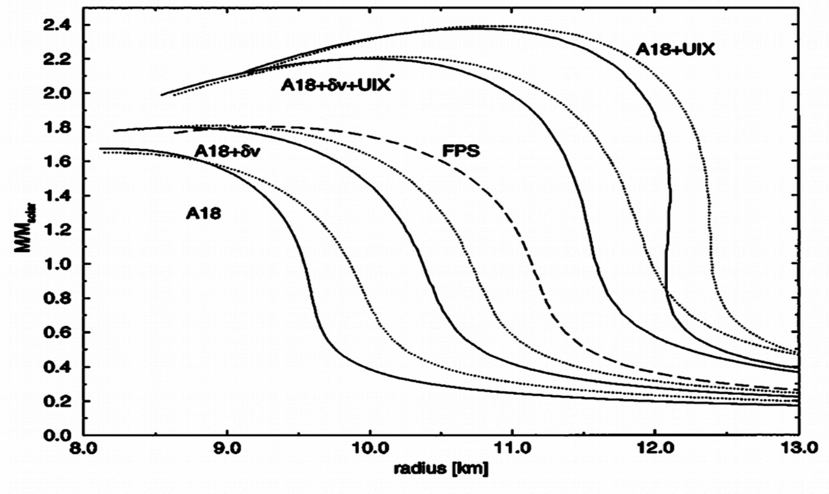
PP

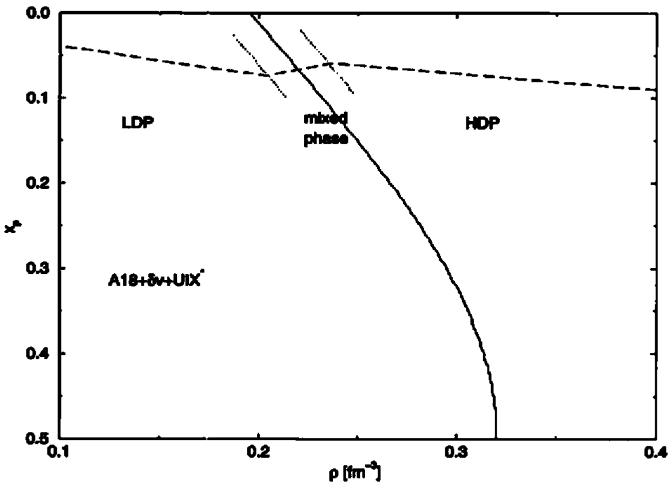
- **Deuterons and protons in coincidences using scintillation counters**
- **Internal beam and thin CH_2 target (C for background estimation)**
- **Measurements at 270 MeV**

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

Few nucleons systems as a tool for dense matter studies

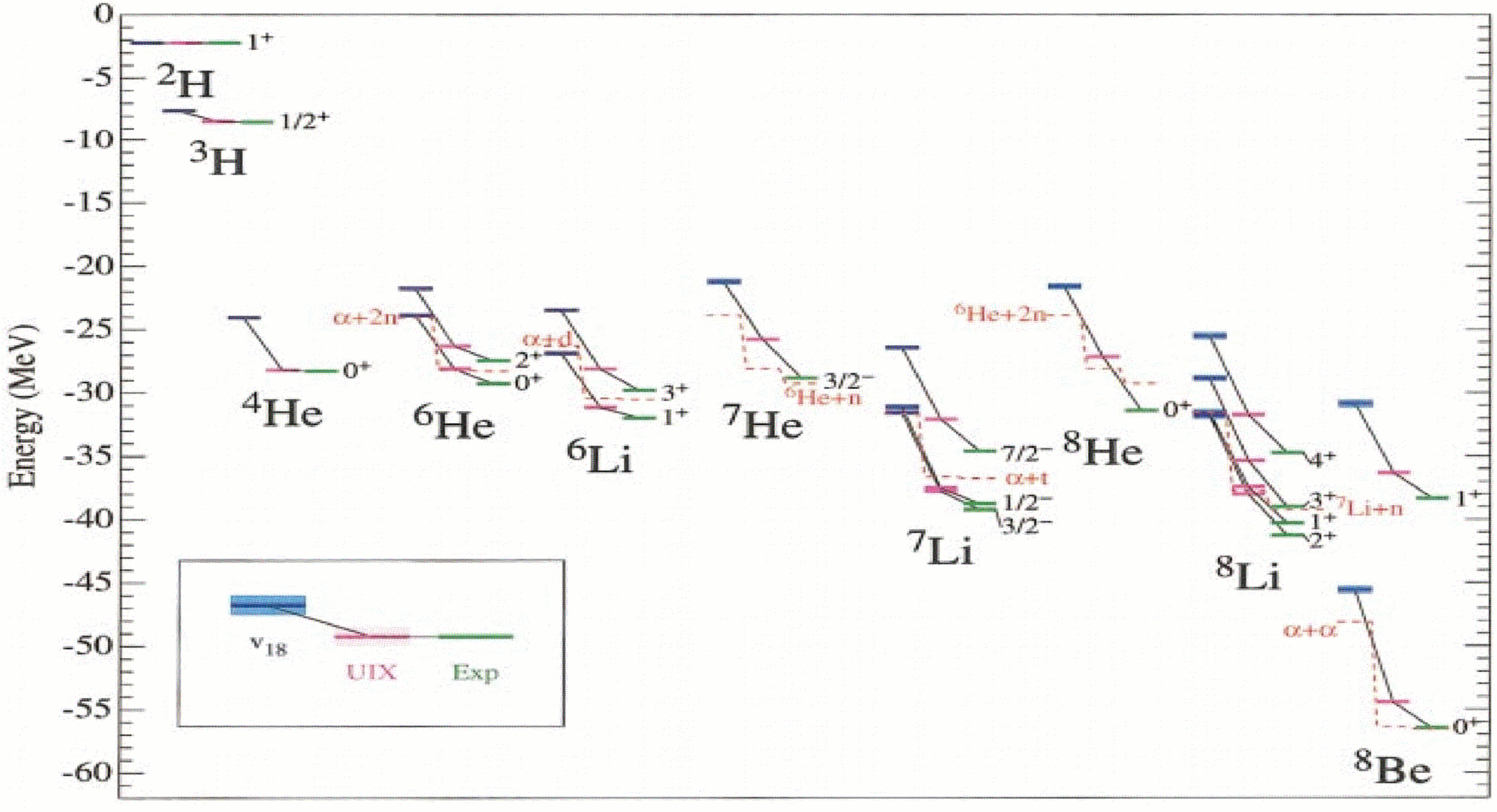
Alternative way to obtain the information on the EOS at extreme densities (neutron stars) is the studies of the few nucleon systems.





Relativistic effects in 2NF and contribution of 3NF play very important role. (A.Akhmal et al, Phys.Rev. C58 (1998) 1804)

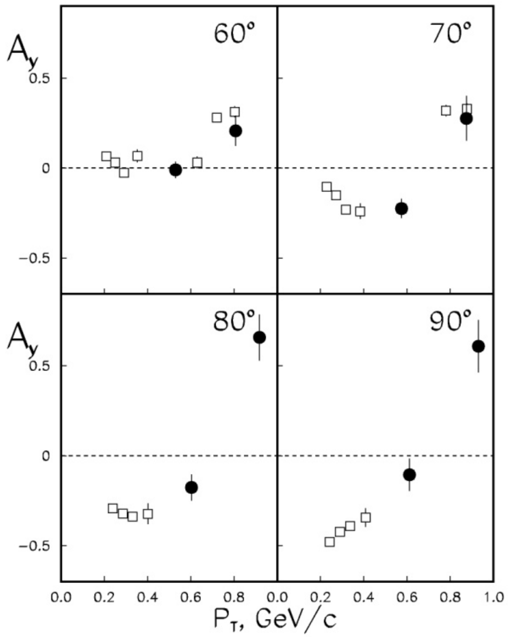
Importance of the spin part of 3NF for the light nuclei binding energies

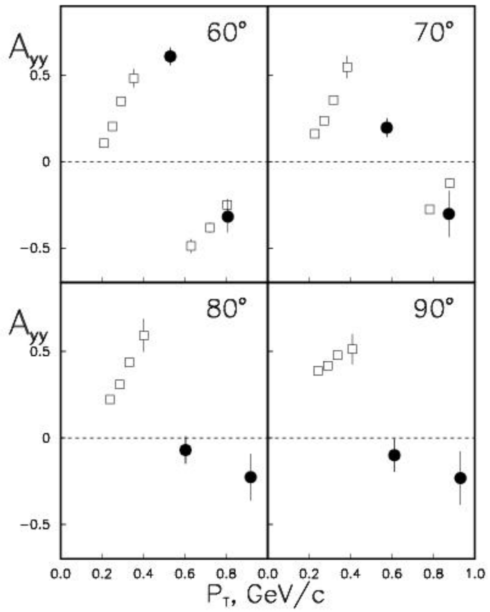


Spin parts of the 2N and 3N correlations are important to describe the light nuclei structure.

(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**