

*25-th International Spin Symposium (SPIN-2023)
24-29 September 2023, Durham, USA*

Spin Physics at Nuclotron: Status and Perspectives

V.P. Ladygin on behalf of DSS collaboration

Outline

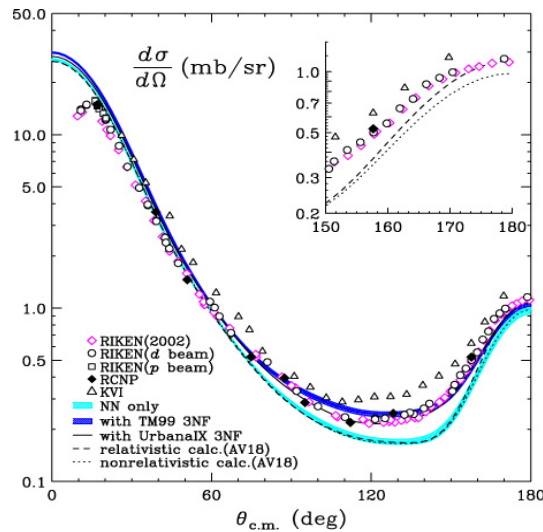
- Nucleon-nucleon interaction at short distances (Short Range Correlations - **SRC**)
- Beam and focal polarimetry
- Experiments on the proton spin manipulation

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

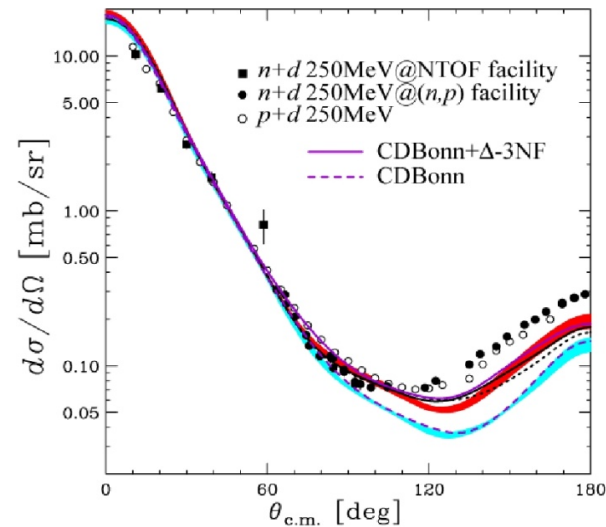
*(developed partly using the equipment obtained from **IUCF** polarized ion source).*

Motivation of the **dp** interaction studies at Nuclotron

- Nucleon-nucleon interaction at short distances
(Short Range Correlations - **SRC**)
- Relativistic effects
- Transition to the nonnucleonic degrees of freedom
- Contribution of three-nucleon forces (3NFs) – Short Range?

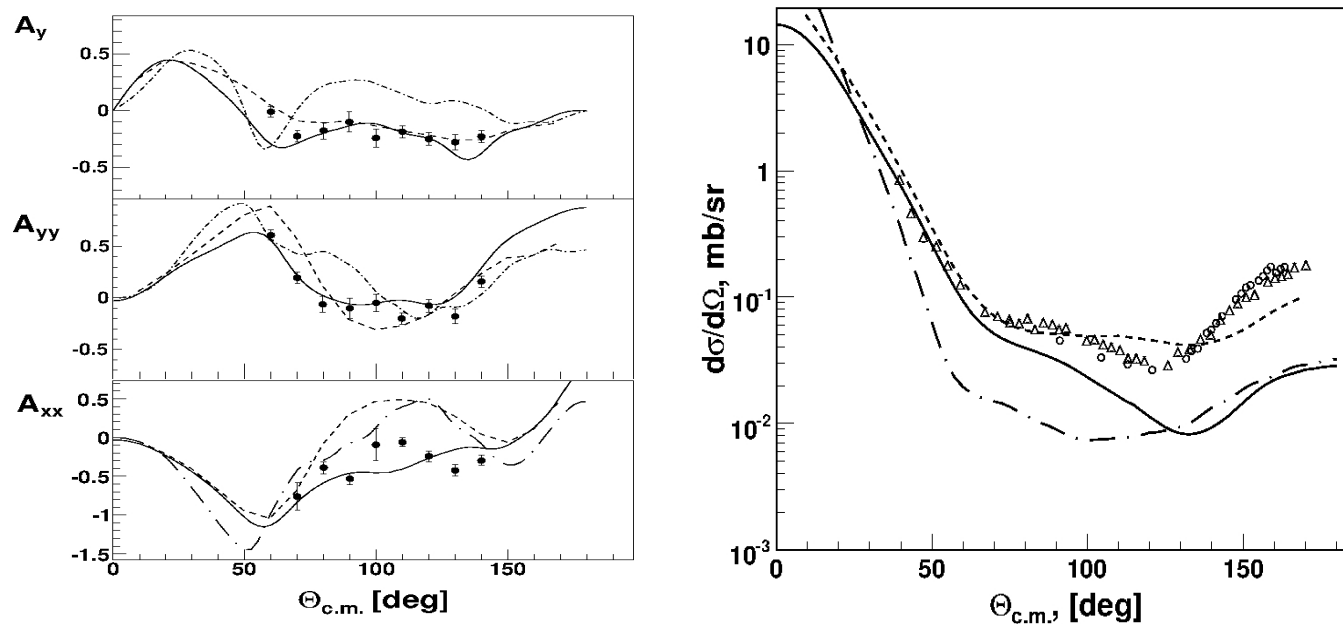


K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)



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

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



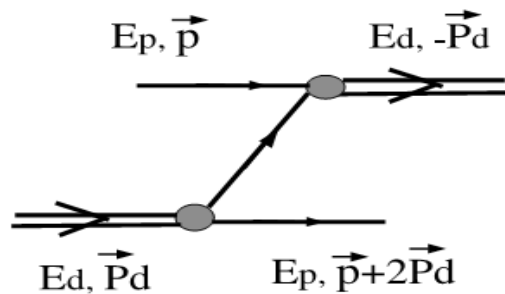
Solid lines are the Faddeev calculations using **CD-Bonn** potential
(**H.Witala, private communication**)

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

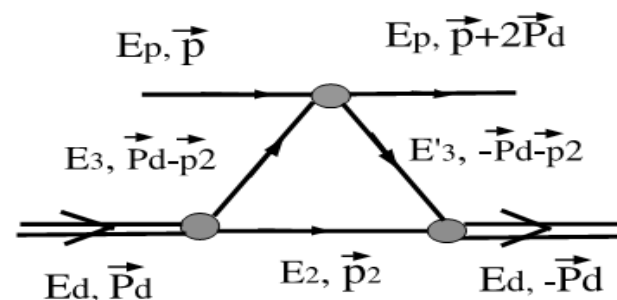
Dott-dashed lines are the optical-potential calculations using **Dibaryon** DWF (**M.Shikhalev, Phys.Atom.Nucl.72 (2009) 588**)

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

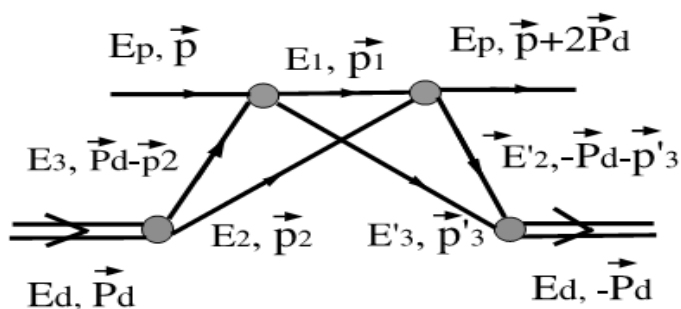
Relativistic multiple scattering model for **dp**- elastic scattering at moderate energies



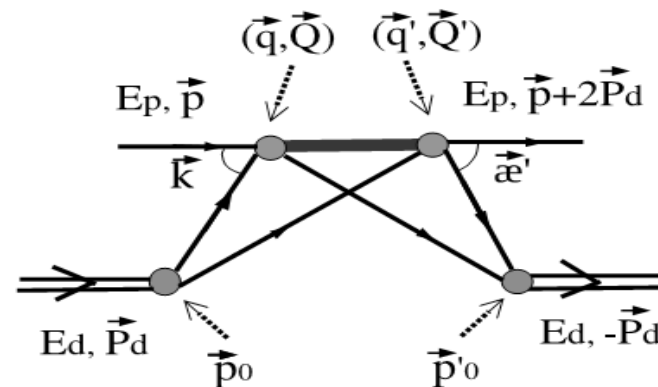
(a) **ONE**



(b) **SS**



(c) **DS**



(d) **Δ**

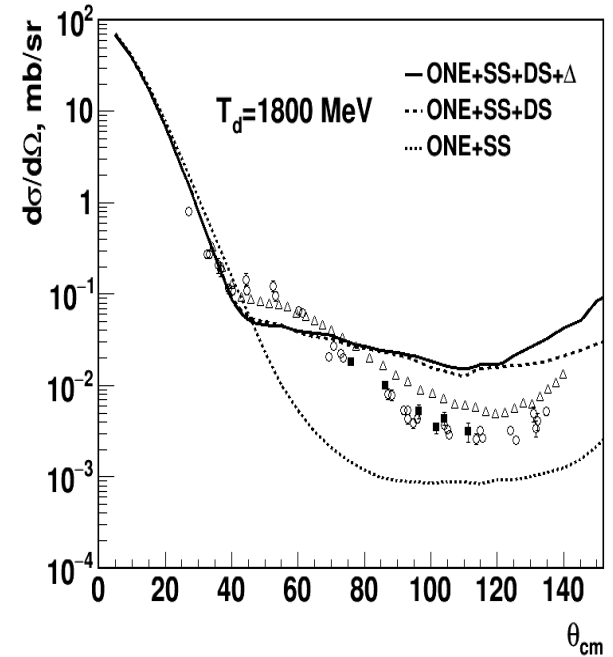
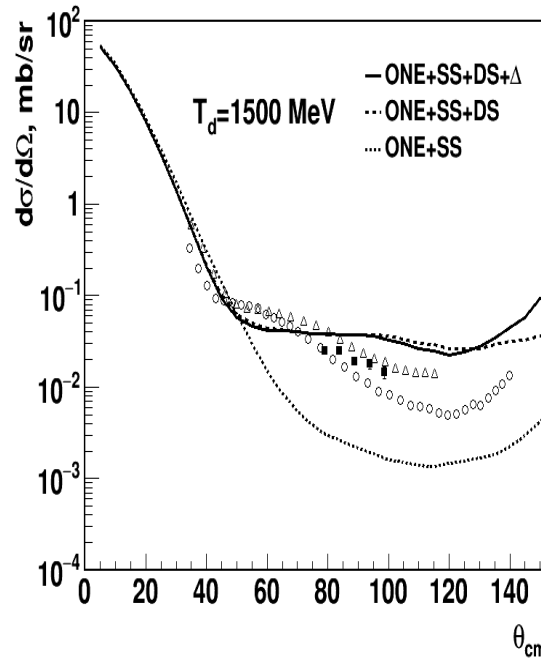
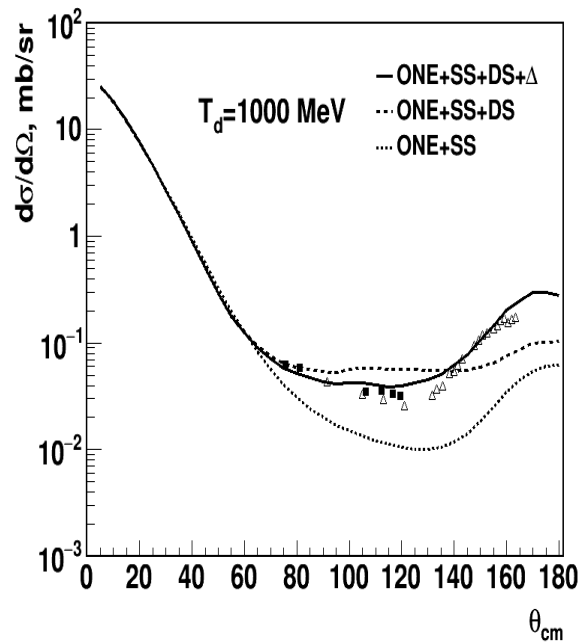
ONE+SS+DS - **N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039**

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

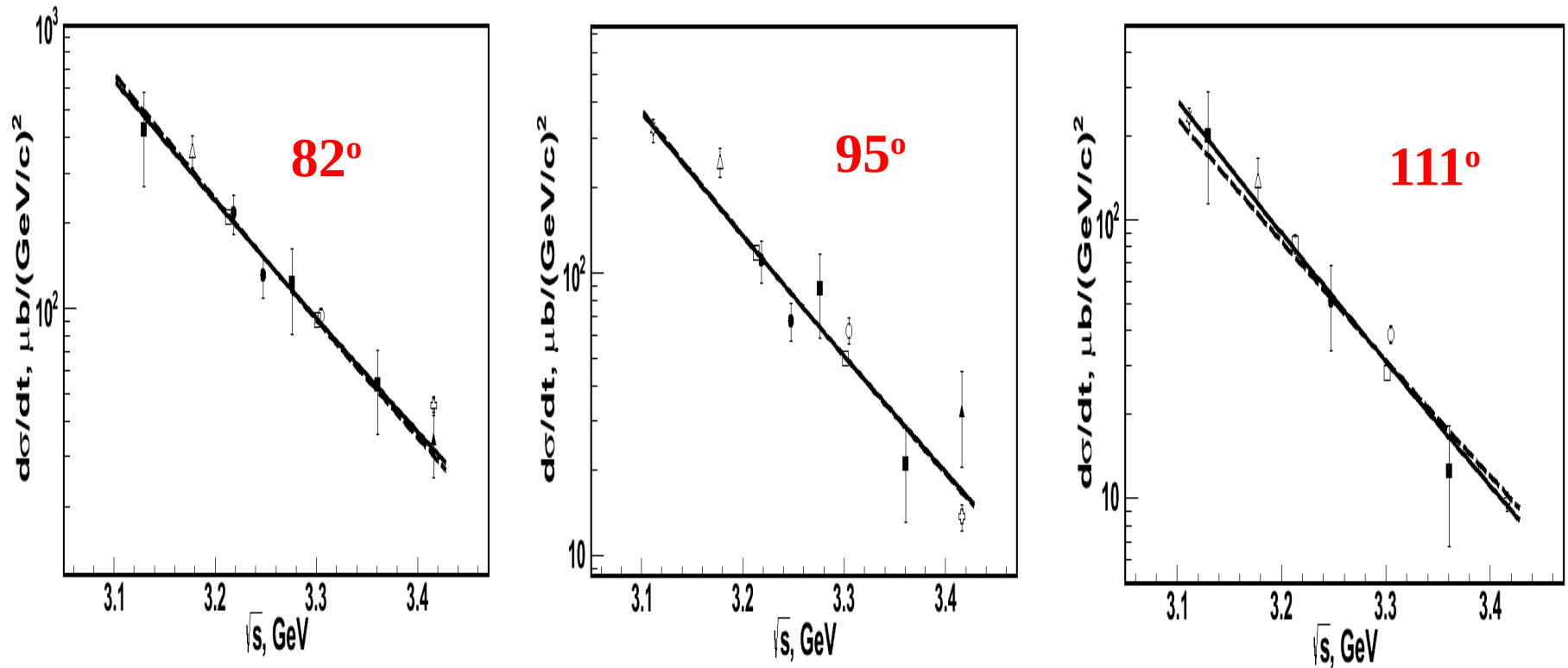
dp- elastic scattering cross section at 1000, 1500 and 1800 MeV



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

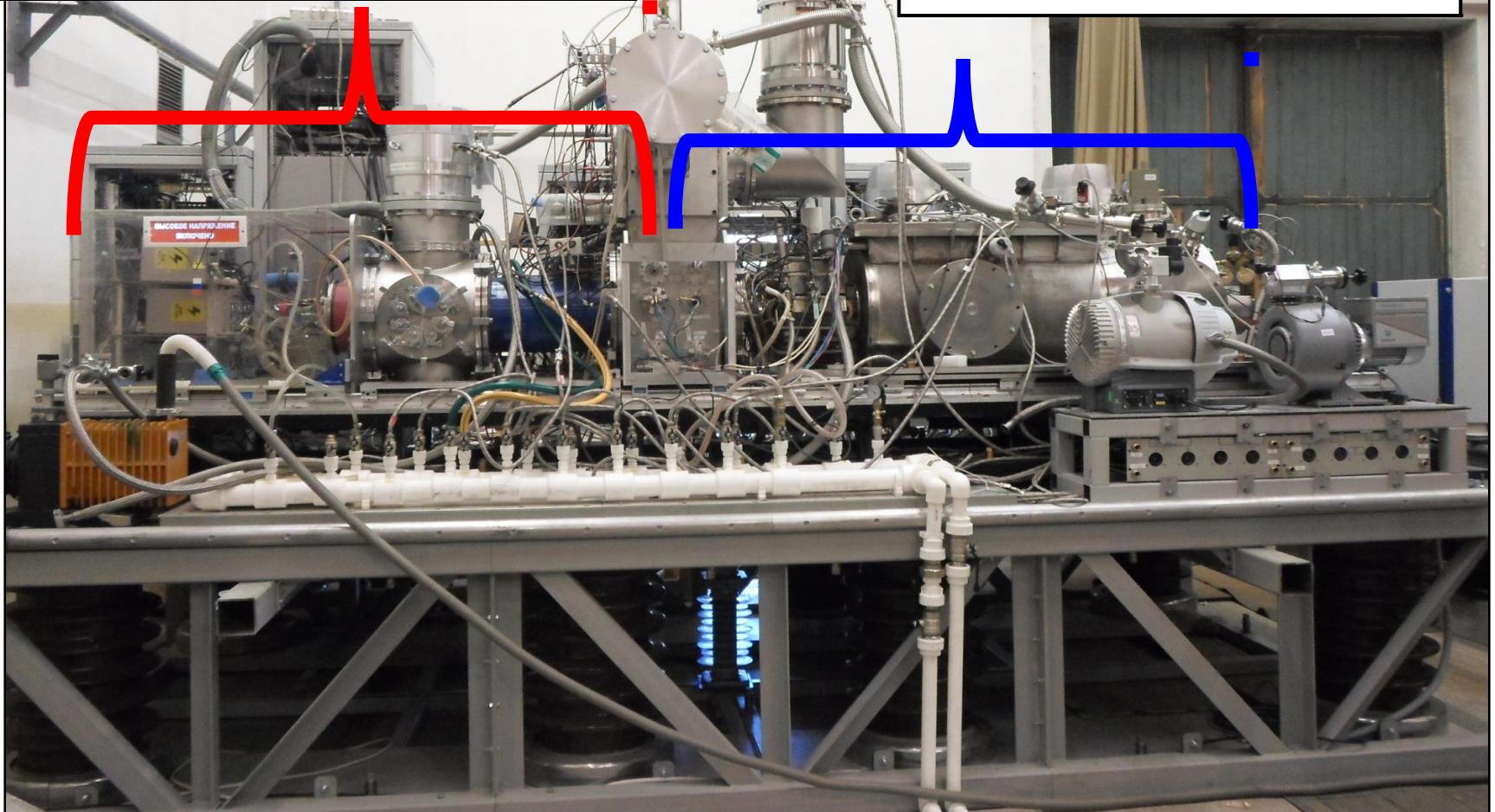
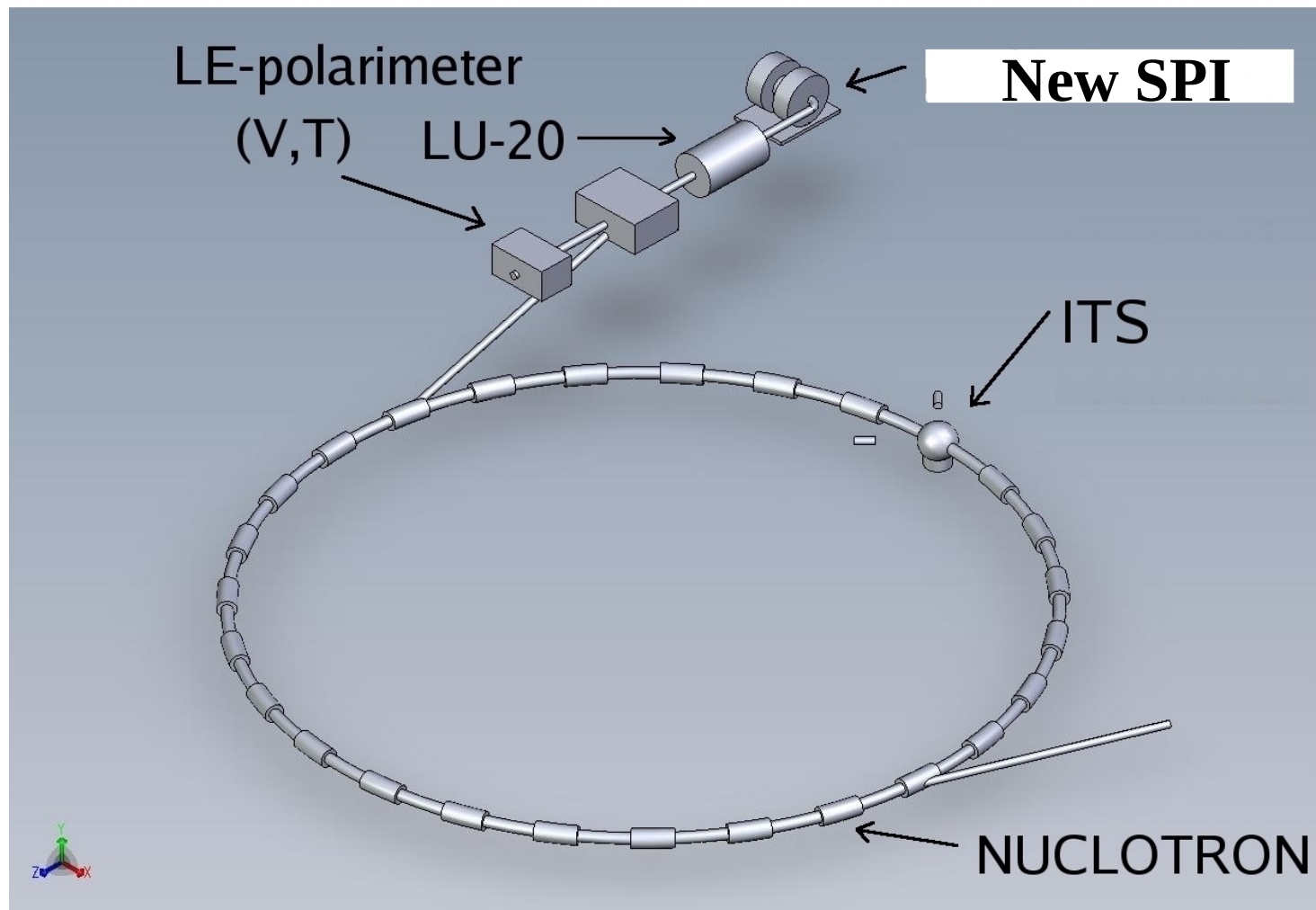


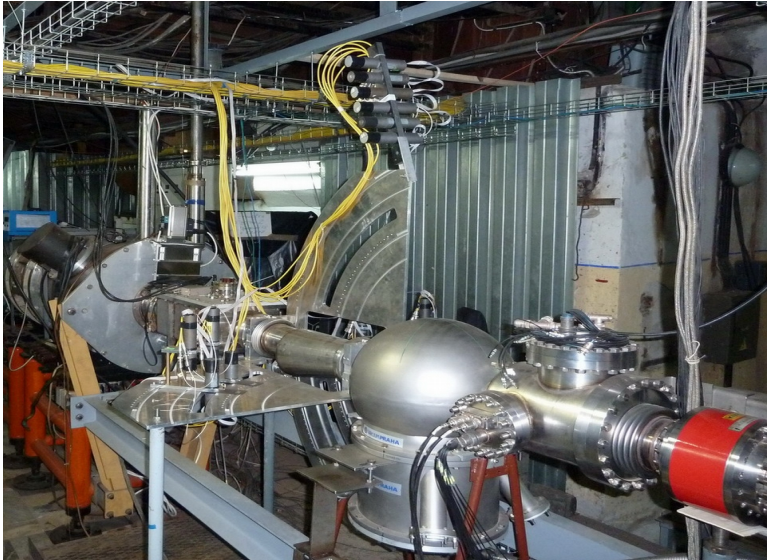
Figure of merit will be increased in future by a factor $\sim 10^3$

Nuclotron-M accelerator complex



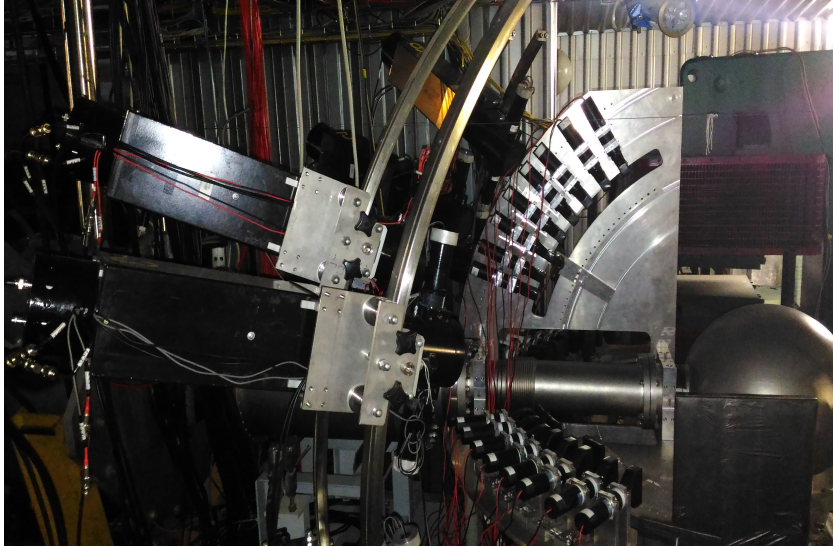
Experiments at Internal Target Station at Nuclotron

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 **DSS** setup at ITS at Nuclotron



New infrastructure, cabling

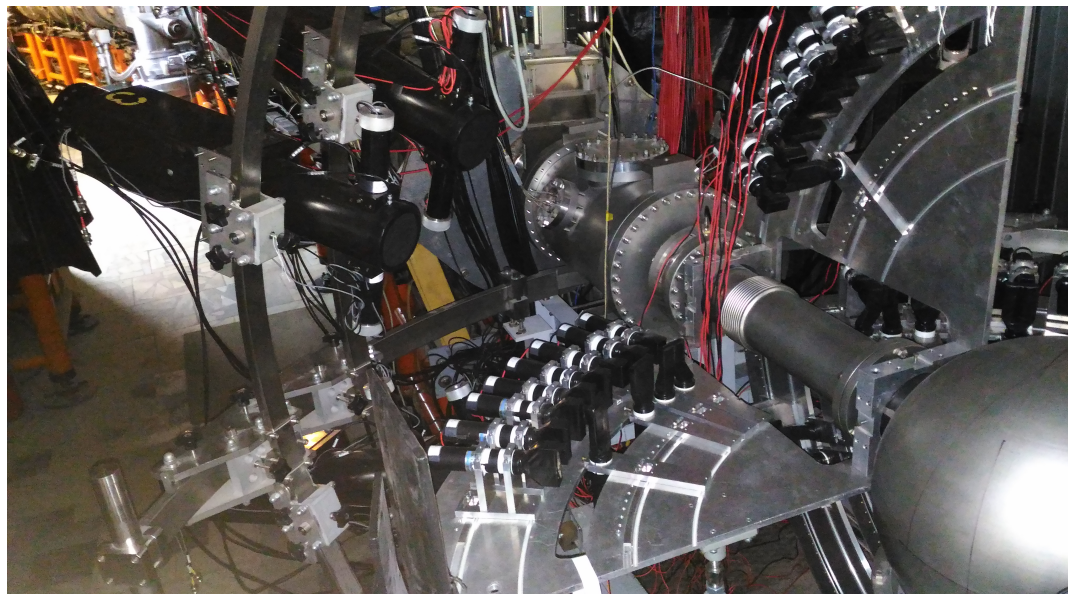
New HV system (Mpod)

New VME DAQ

40 counters for dp-elastic scattering studies

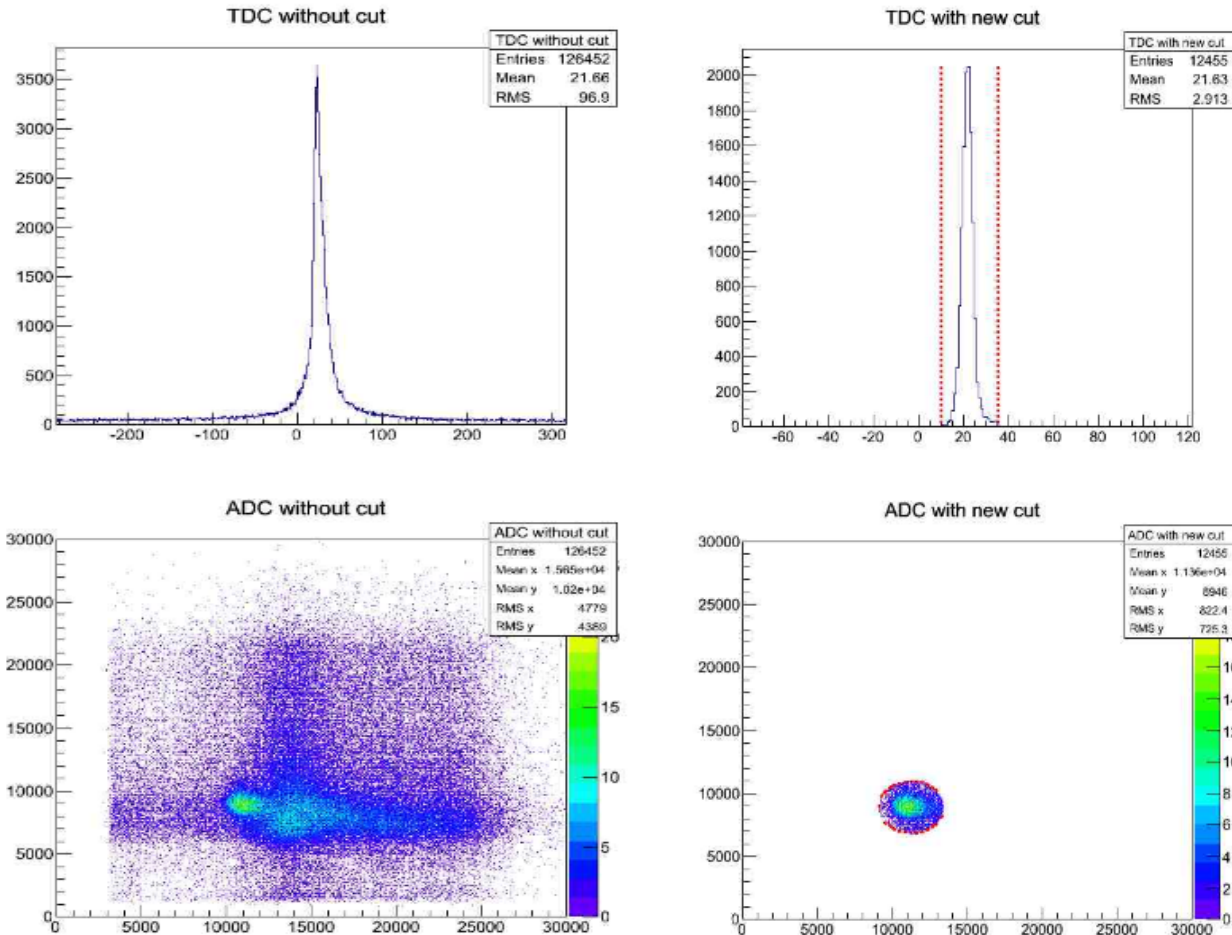
8 dE-E detectors for dp -breakup studies

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” with $(p_z, p_{zz}) = (0,0)$, $(1/3,1)$ and $(1/3,-1)$.
- Typical values of the polarization were 70-75% from the ideal values.

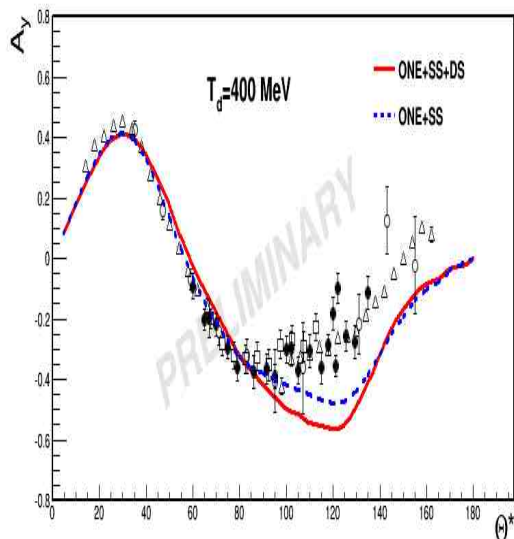
The **dp**-elastic scattering events selection



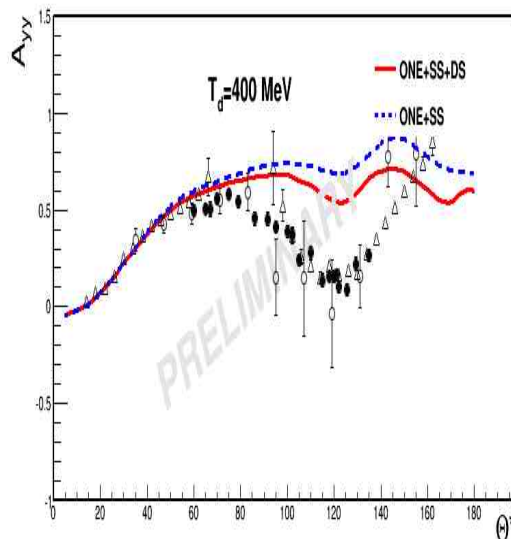
Selection of the dp elastic events by the time difference between the signal appearance from deuteron and proton detectors with the criteria on the amplitude signal correlation.

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

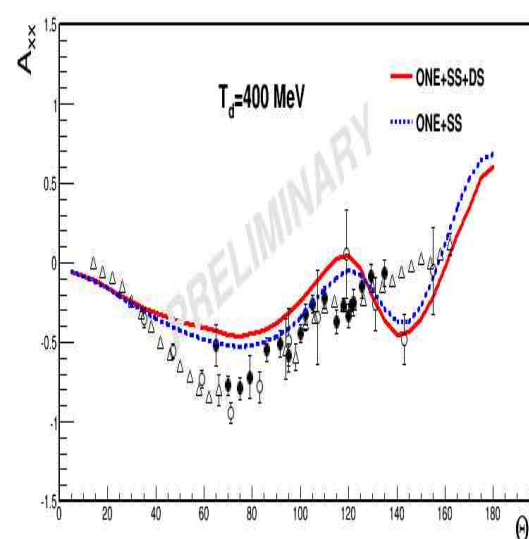
A_y



A_{yy}



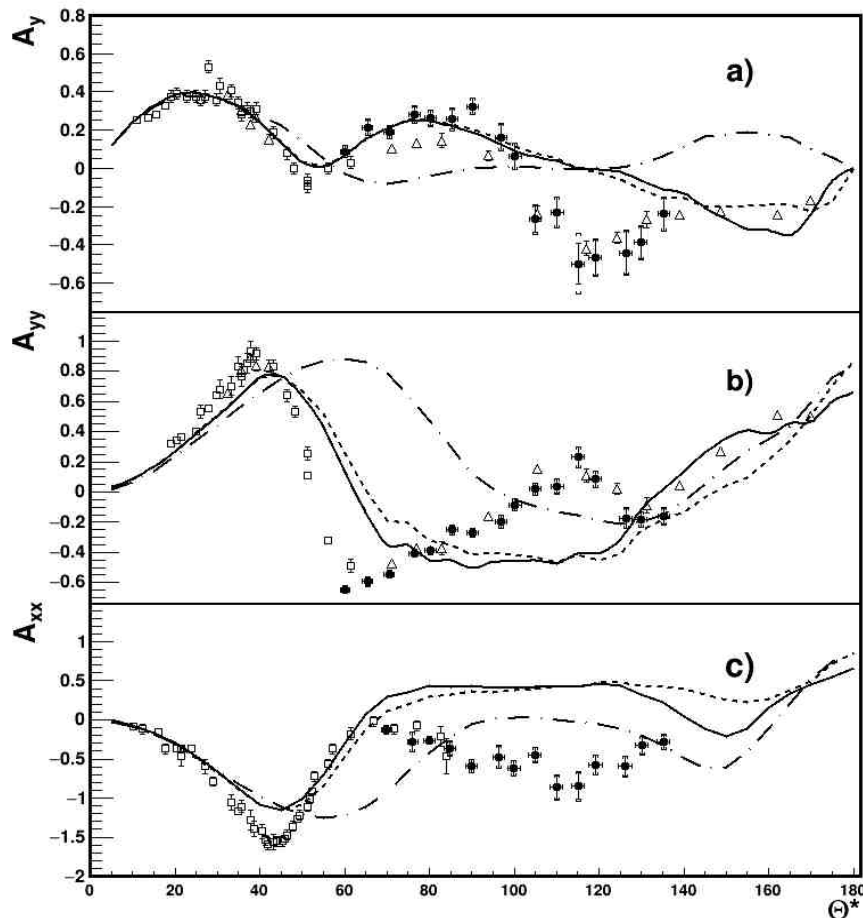
A_{xx}



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

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

Angular dependencies of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in dp -elastic scattering at 1300 MeV



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

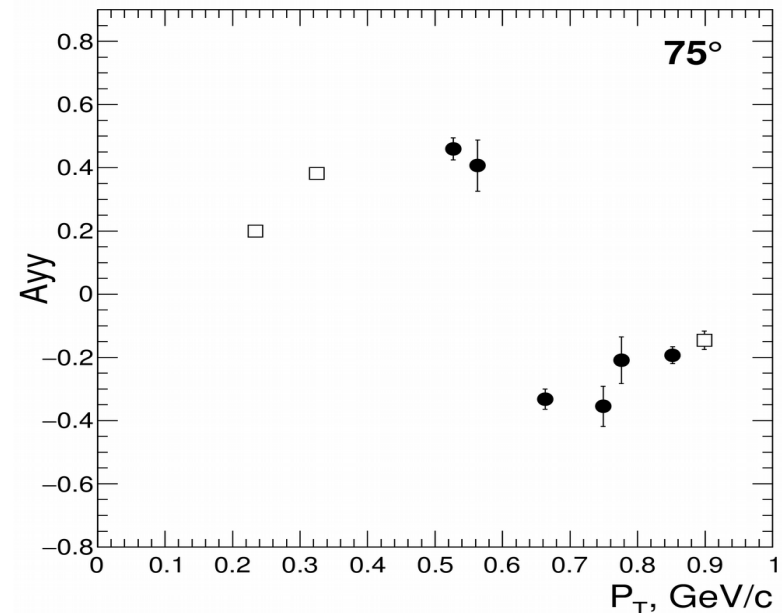
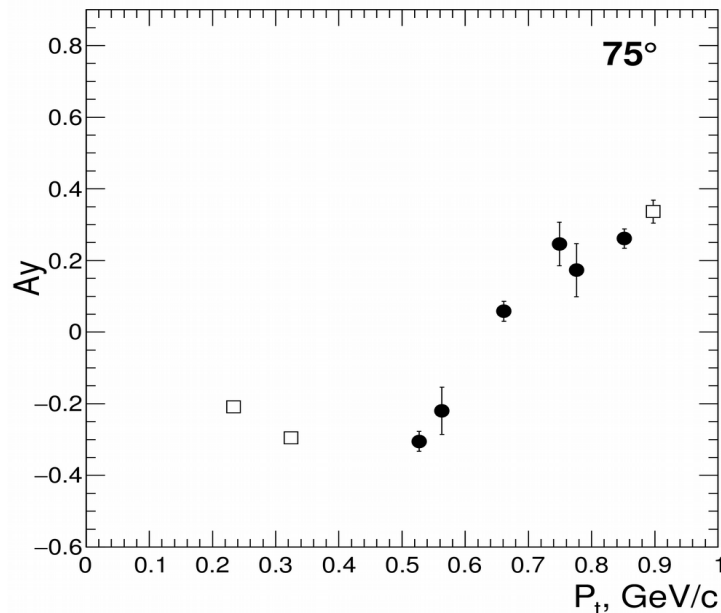
Curves are the relativistic multiple scattering model calculations

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

+ additional ρ -meson exchange

Structure in A_y - A_{yy} behaviour observed at Saclay at 1200 MeV and at 100-130 degrees in cms is confirmed, its energy dependence is studied.

Energy dependence of the vector A_y and tensor A_{yy} analyzing powers in dp-elastic scattering at 700-1800 MeV



Full circles are new data from Nuclotron.

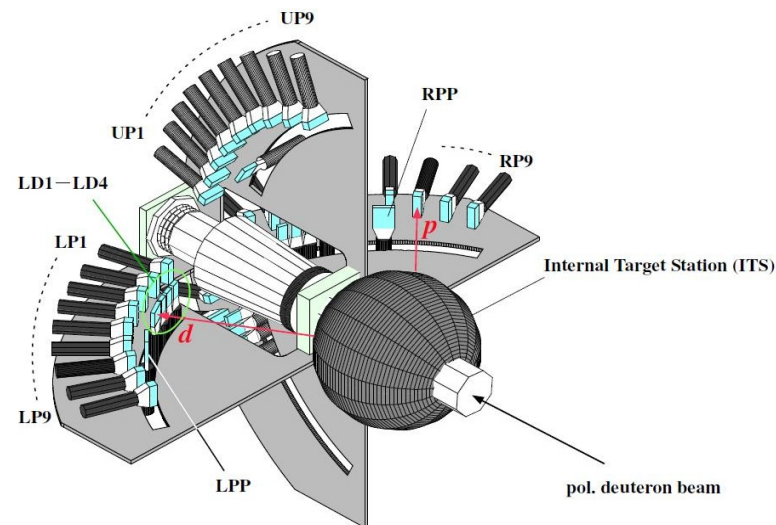
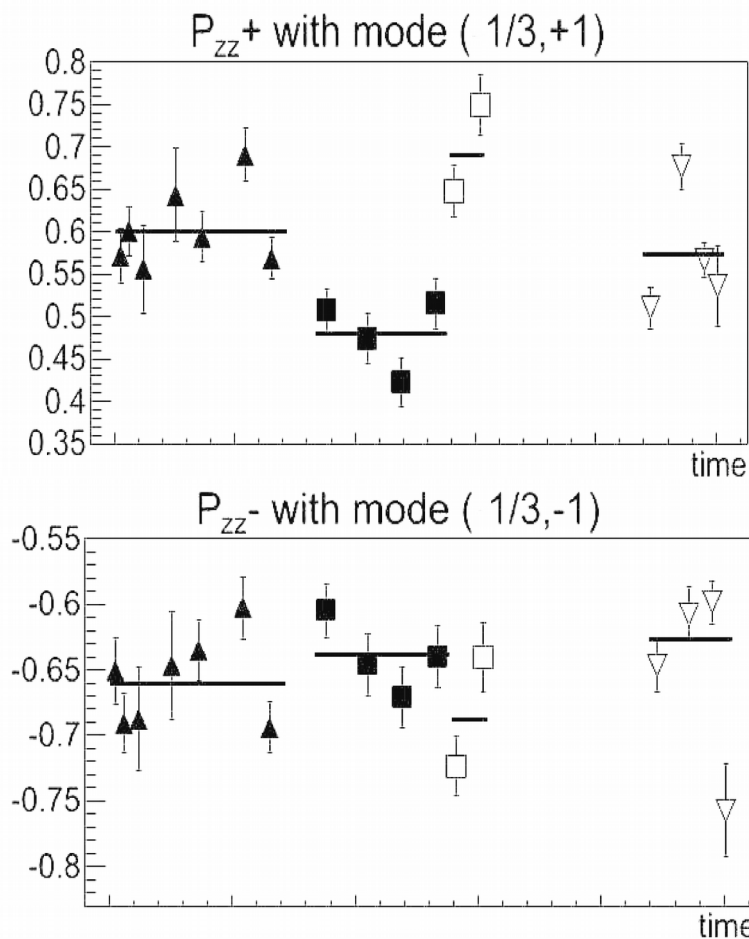
Open symbols are the world data.

Change the signs of the A_y and A_{yy} values at 600 MeV/c.

Asymptotic behaviour at large P_T .

Continuation of the **DSS** physics program with polarized deuteron and proton beams is included in the 7-year JINR Topical Plan for 2024-2030

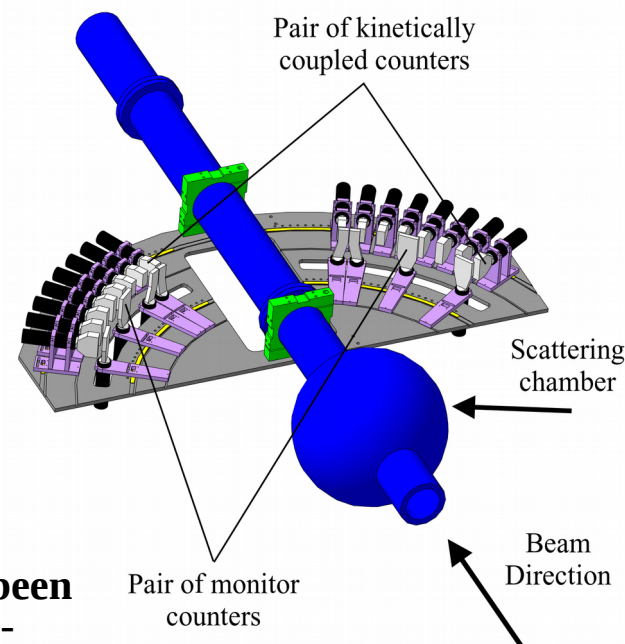
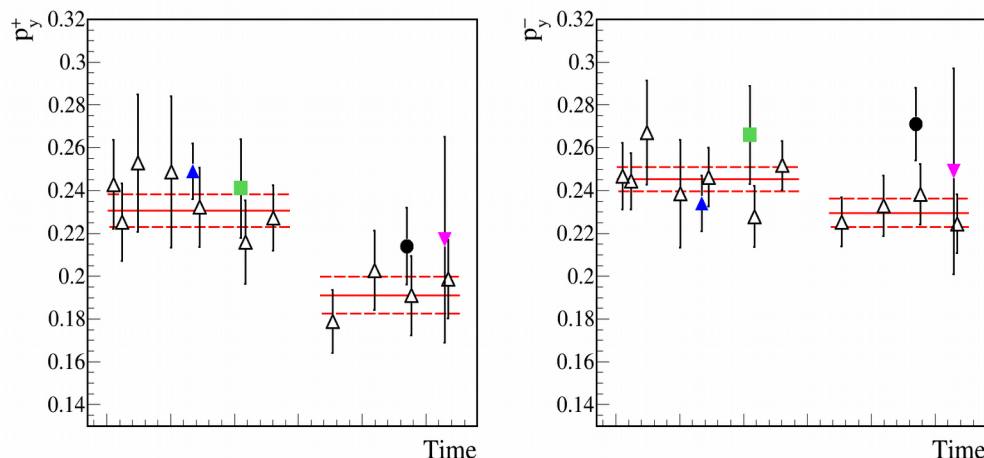
Polarization measurements using **dp**- elastic scattering at **270 MeV** at ITS



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

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

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



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

Both methods gives similar results!

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: $I \sim 2\text{-}3 \cdot 10^7$ 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°-85°** in the cms) we obtained the averaged value of the proton beam polarization

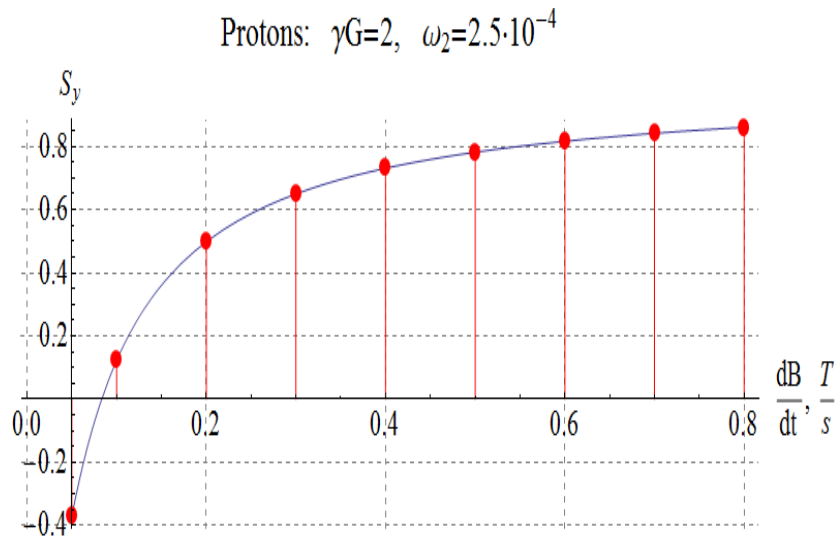
Unpolarized protons: $P = 0.056 \pm 0.021$

Polarized protons: $P = 0.367 \pm 0.015$

New detection system for proton polarimeter is under preparation.

A.A.Terekhin et al., Phys.Part.Nucl. 54 (2023) 634.

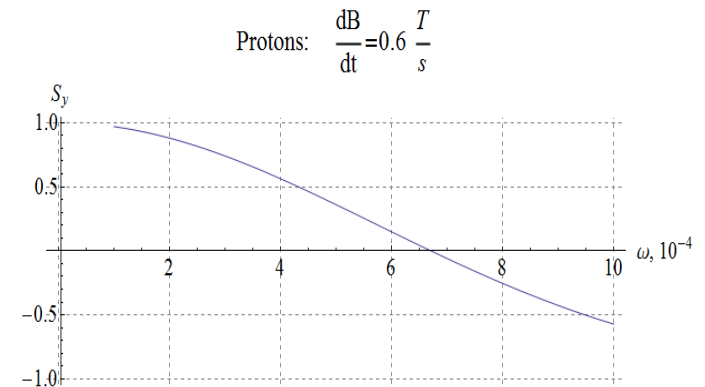
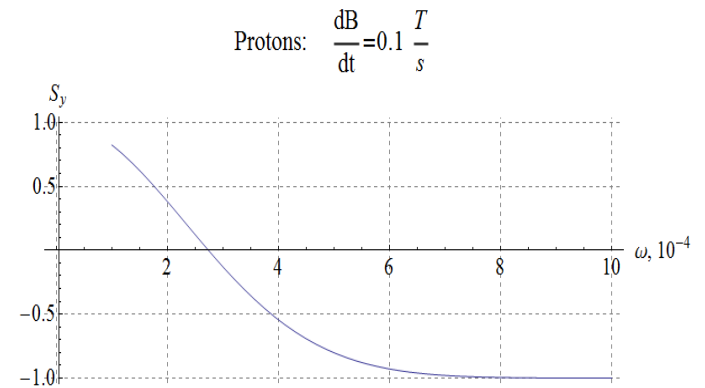
New experiments on the proton spin manipulation



Measurements of the integer resonance
 $\gamma G=k=2$ power (Tkin=108 MeV)

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

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



**Yu.N.Filatov et al.,
 JETP Lett. 116 (2022) 413;
 Pis'ma v JETP 118 (2023) 389.**

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, for the focal and beam polarimetry development.

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 transverse momenta (>600 MeV/c). This can be due to the manifestation of the fundamental degrees of freedom.

The nearest goals are to reach $5 \cdot 10^9$ (CH_2 target limitation) and 10^{10} deuterons/spill for the ITS and extracted beam experiments, respectively; to start the experiments with polarized proton beam.

Thank you for the attention!