

*XX-th Workshop on High Energy Spin Physics (DSPIN-2025)
7-11 September 2026, Dubna, Russia*

Status of the Deuteron Spin Structure studies at at the Nuclotron

V.P. Ladygin on behalf of DSS collaboration

Scientific mission of the experiment on the **D**euteron **S**pin **S**tructure (**DSS**) studies at Nuclotron

Spin structure of the nucleon-nucleon interaction at short distances (Short Range Correlations - **SRC**)

Beam polarimetry

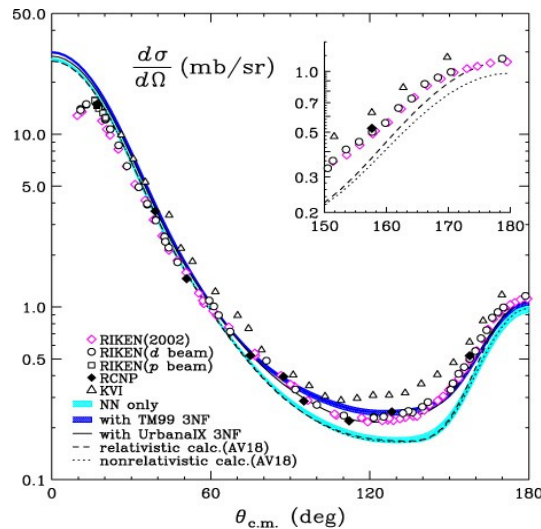
Experiments on the spin manipulation at Nuclotron

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

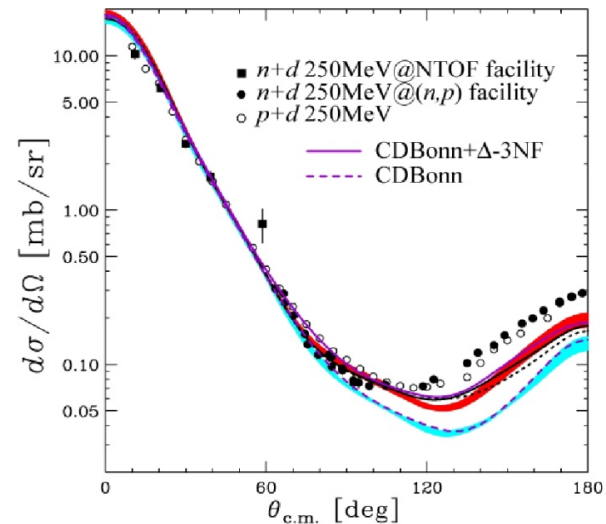
*(developed partly using the equipment obtained from **IUCF** polarized ion source).*

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?

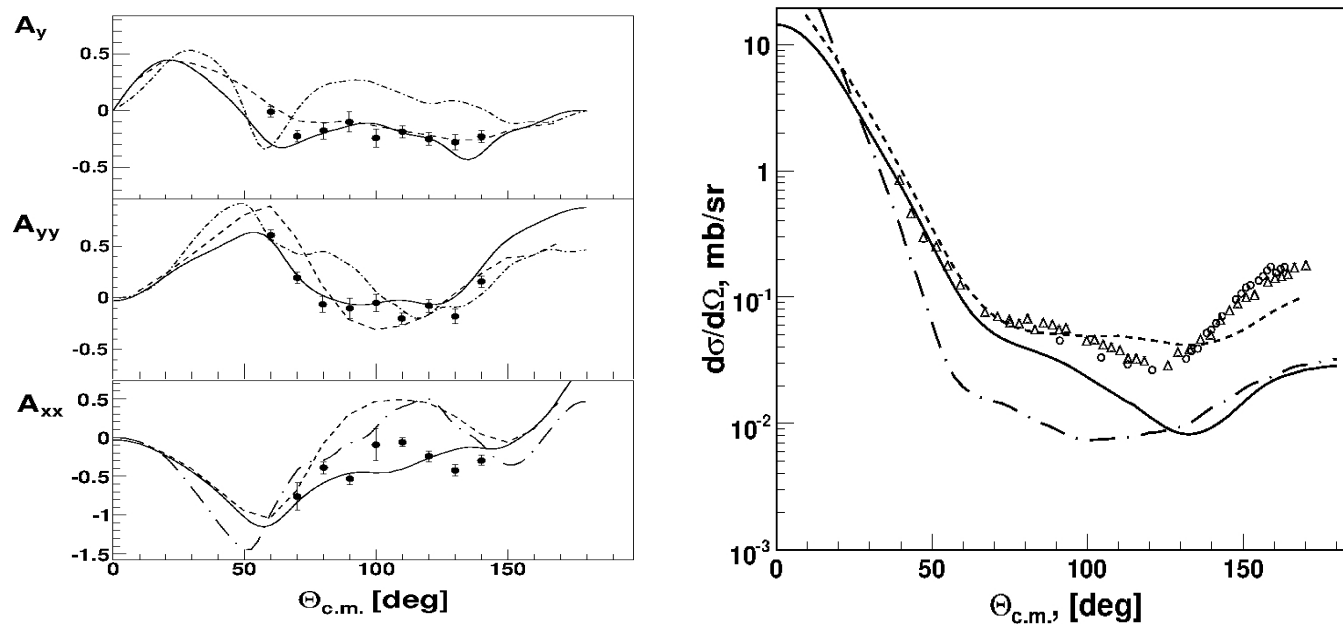


K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)



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

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



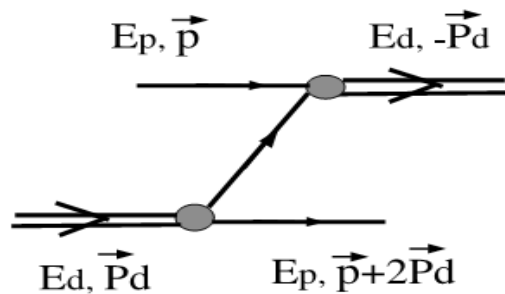
Solid lines are the Faddeev calculations using **CD-Bonn** potential
(**H.Witala, private communication**)

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

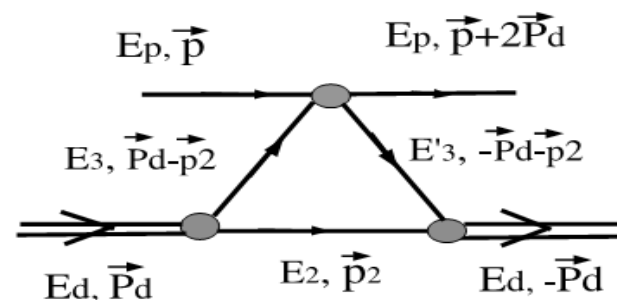
Dott-dashed lines are the optical-potential calculations using **Dibaryon** DWF (**M.Shikhalev, Phys.Atom.Nucl.72 (2009) 588**)

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

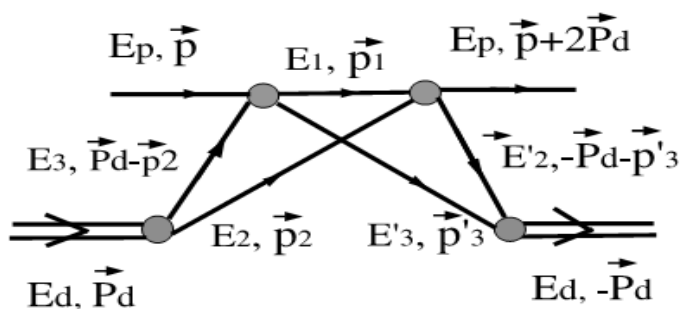
Relativistic multiple scattering model for **dp**- elastic scattering at moderate energies



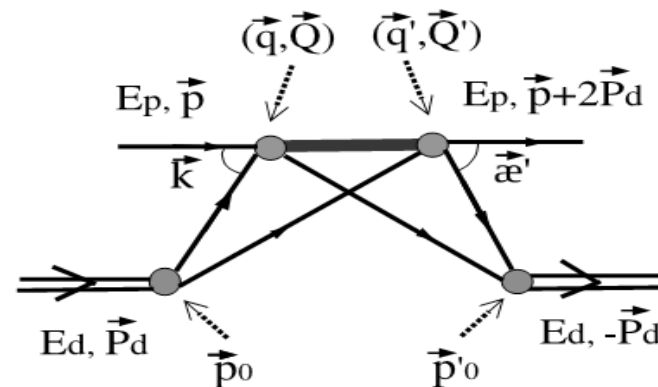
(a) **ONE**



(b) **SS**



(c) **DS**



(d) **Δ**

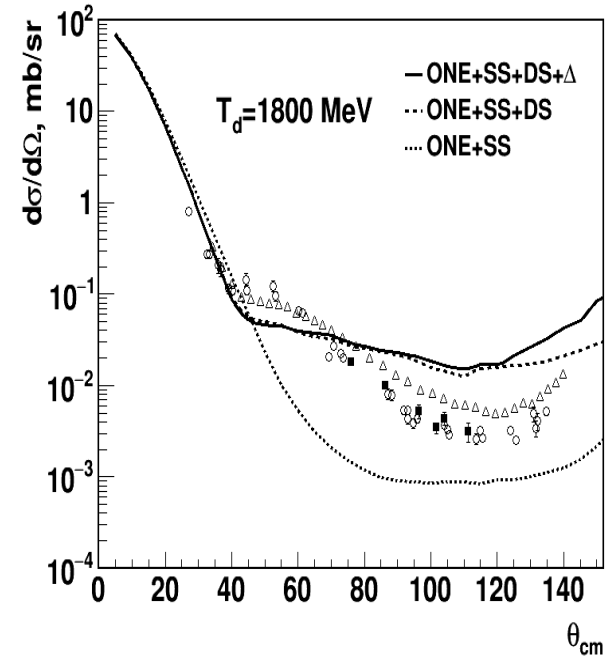
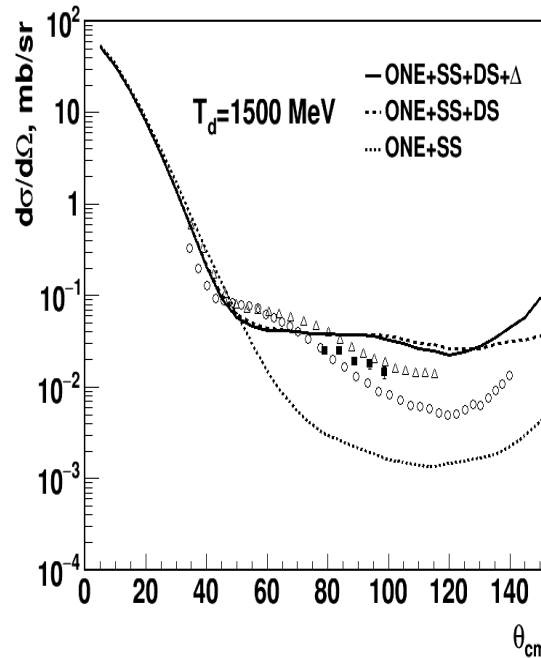
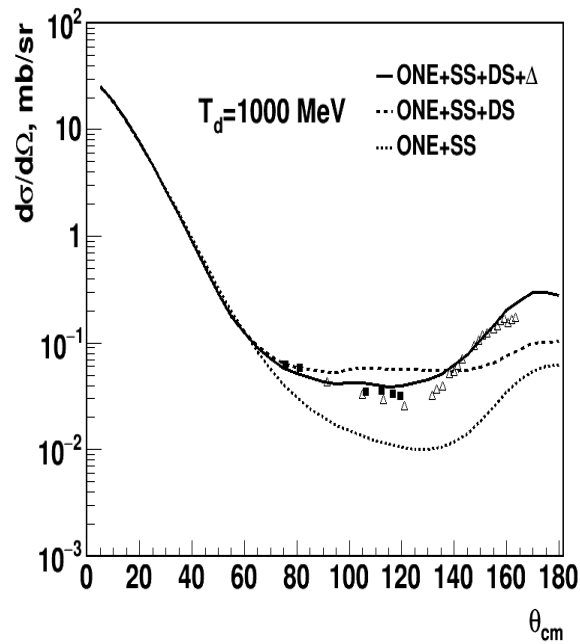
ONE+SS+DS - N.B.Ladygina, Phys.Atom.Nucl.71 (2008) 2039

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

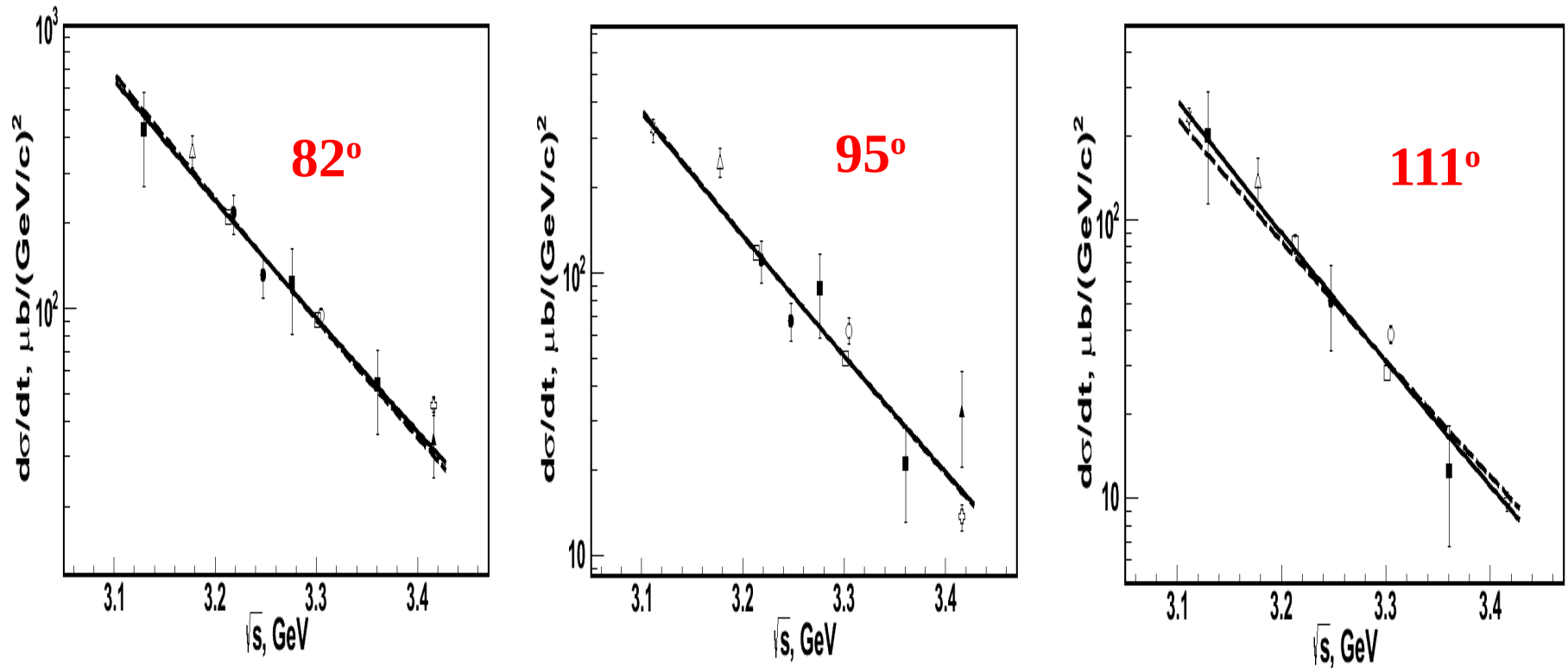
dp- elastic scattering cross section at 1000, 1500 and 1800 MeV



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



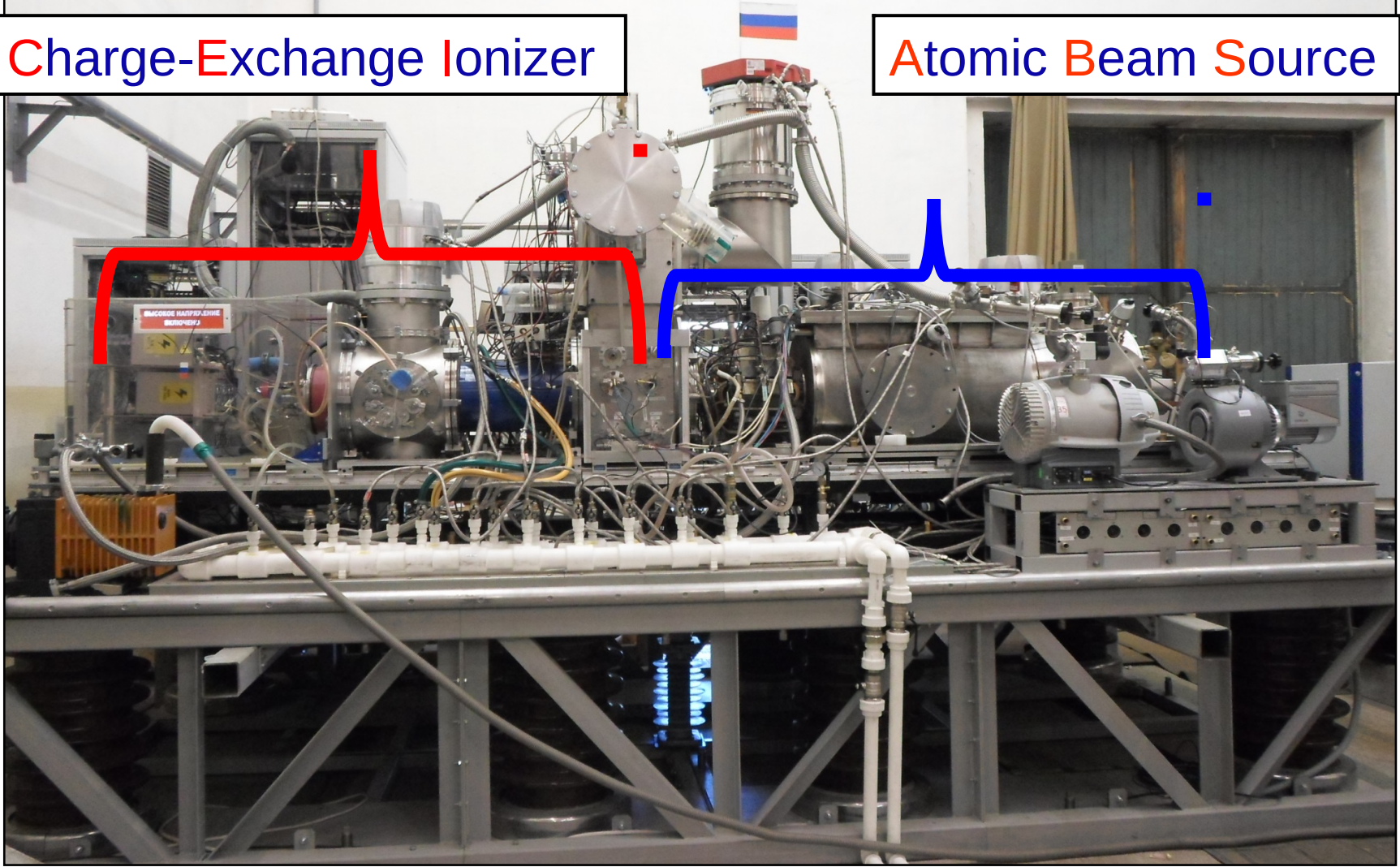
Pictures are taken from **A.A.Terekhin et al., Eur.Phys.J, A55 (2019) 129**

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

General View of SPI

Charge-Exchange Ionizer

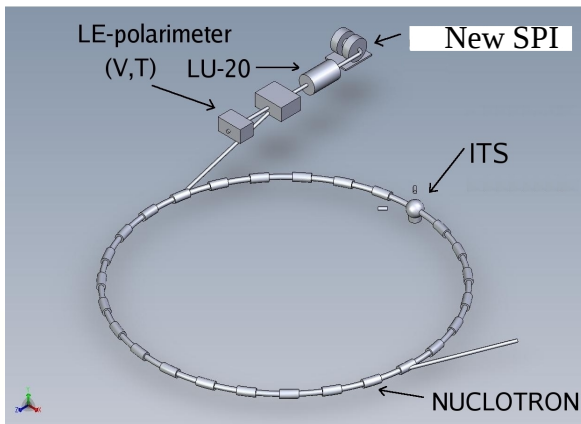
Atomic Beam Source



SPI was put into operation in 2016-2017 with deuterons (tested with protons).
SPI current and polarization (for deuterons) are ~ 3 mA and 70-75%.

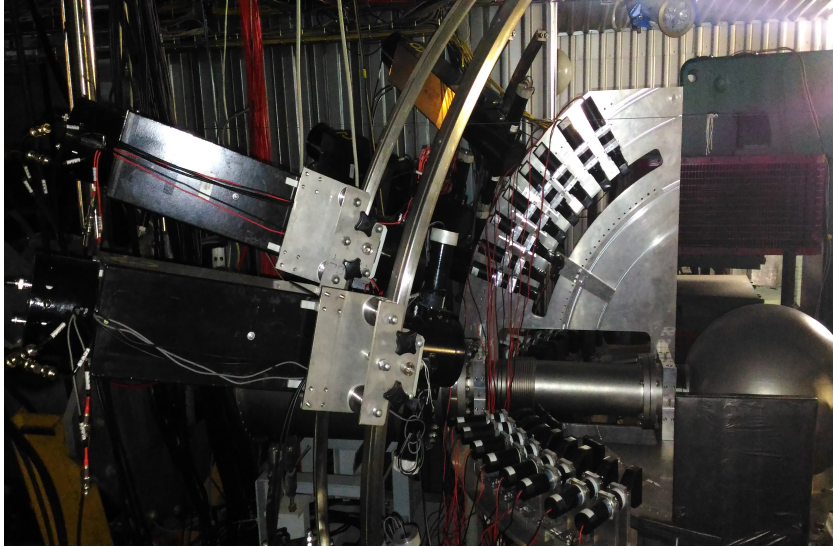
Experiments at Internal Target Station at Nuclotron

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

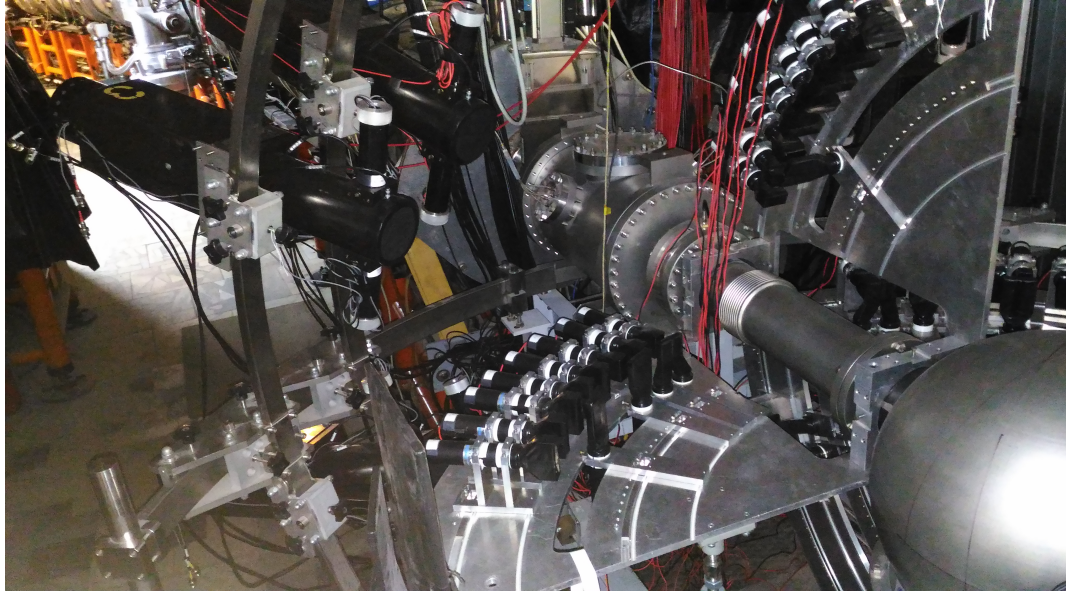
New HV system (Mpod)

New VME DAQ

40 counters for dp-elastic scattering studies

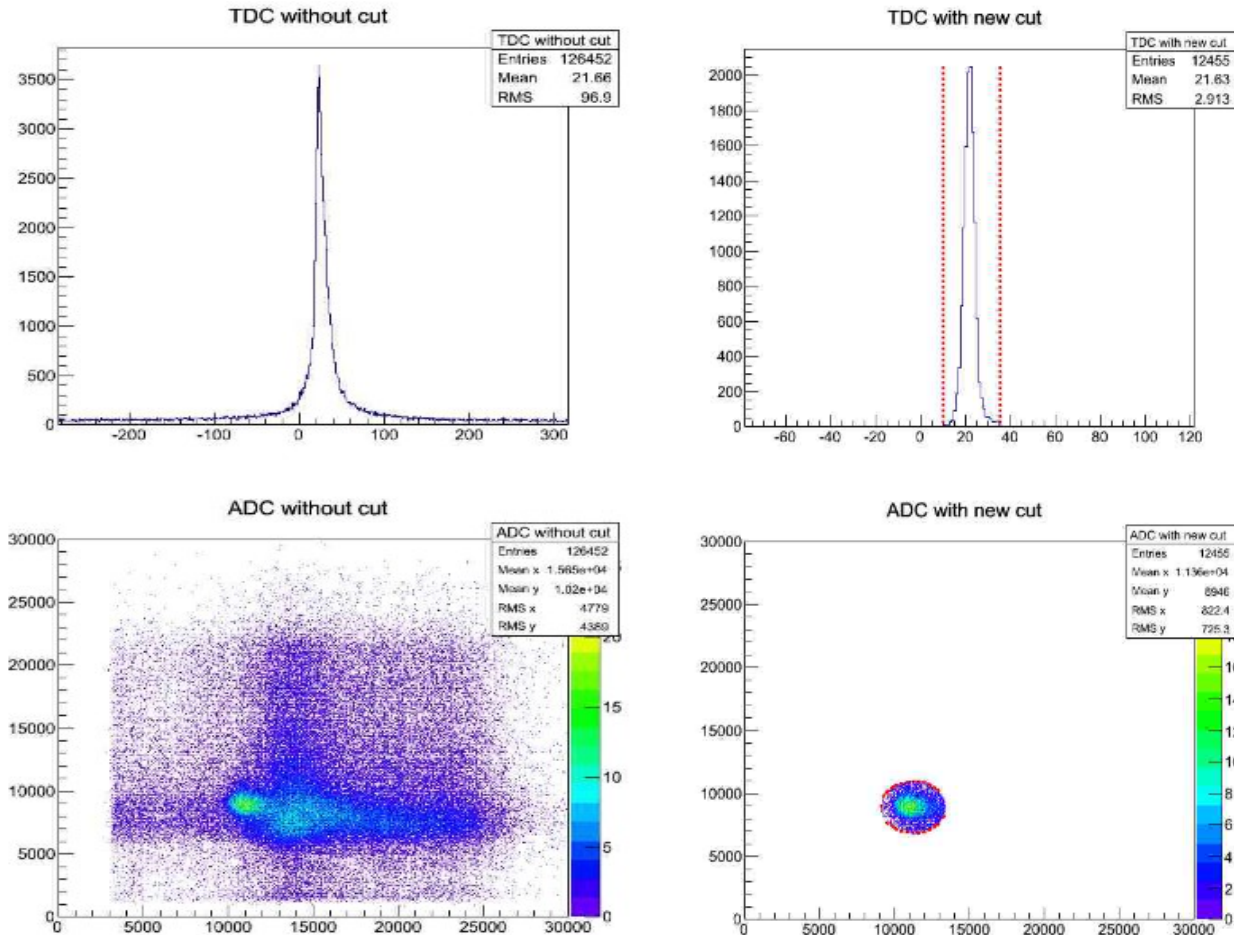
8 dE-E detectors for dp -breakup studies

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.

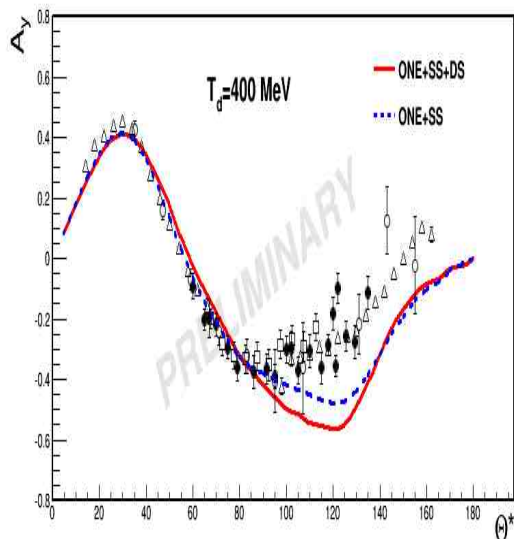
The **dp**-elastic scattering events selection



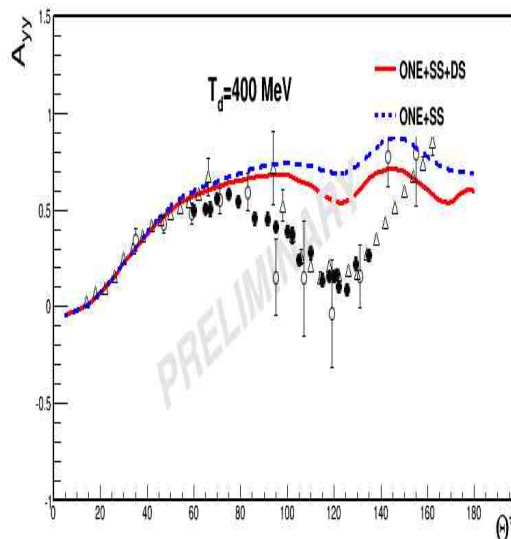
Selection of the dp elastic events by the time difference between the signal appearance from deuteron and proton detectors with the criteria on the amplitude signal correlation.

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

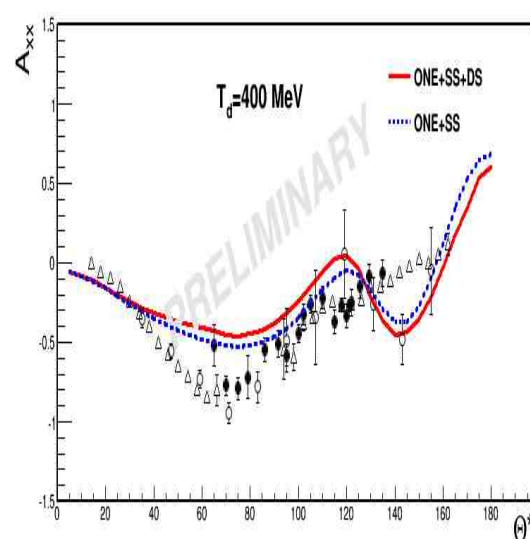
A_y



A_{yy}



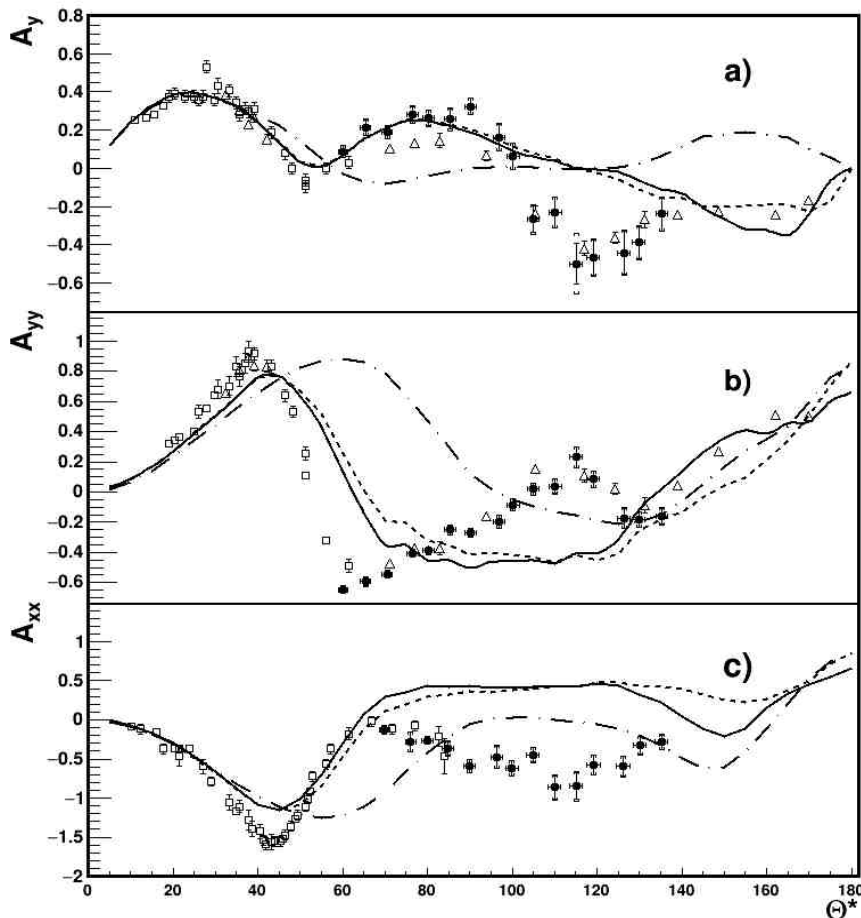
A_{xx}



**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.

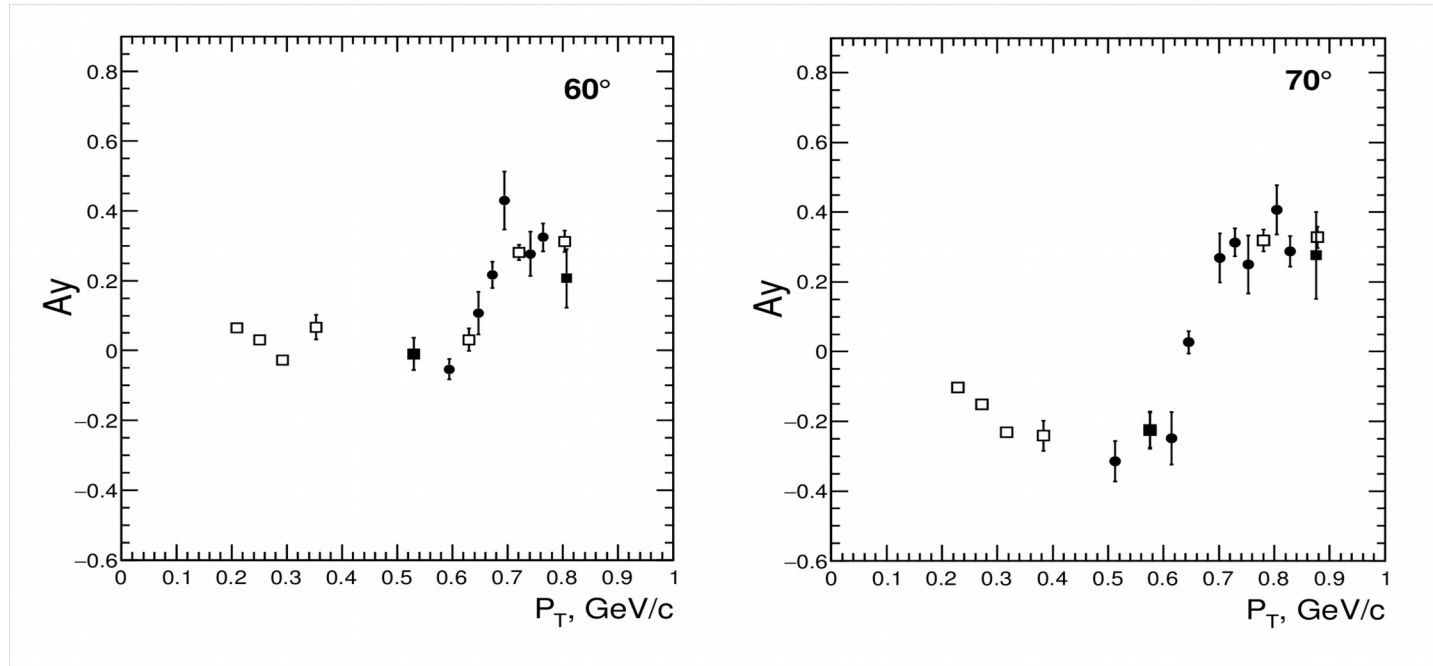
Curves are the relativistic multiple scattering model calculations

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 analyzing power in dp-elastic scattering at 700-1800 MeV



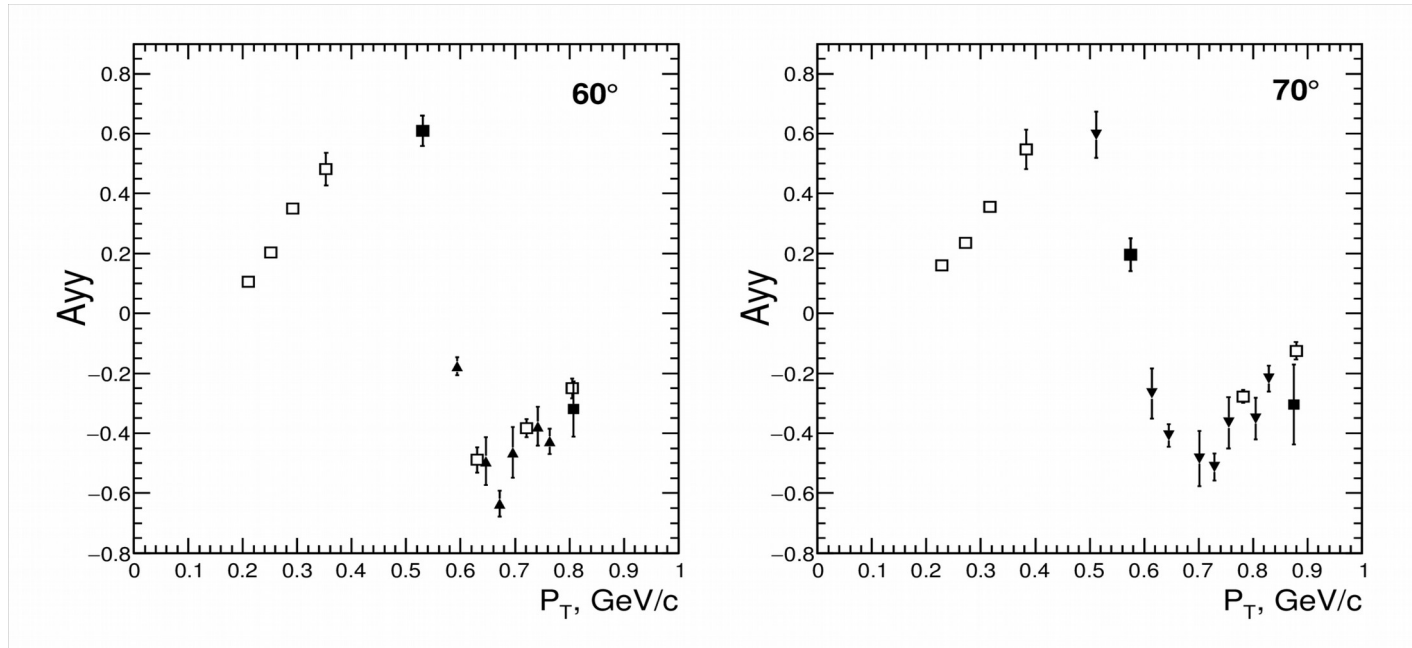
Full circles are new data from Nuclotron.

Open symbols are the world data.

Change the sign of the A_y values at $P_T \sim 600$ MeV/c.

Asymptotic behavior at larger P_T : $\sim +0.3$.

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



Full circles are new data from Nuclotron.

Open symbols are the world data.

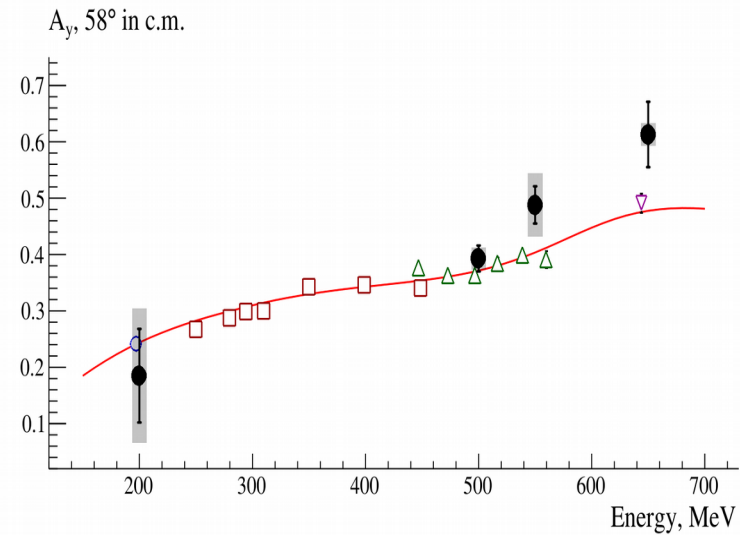
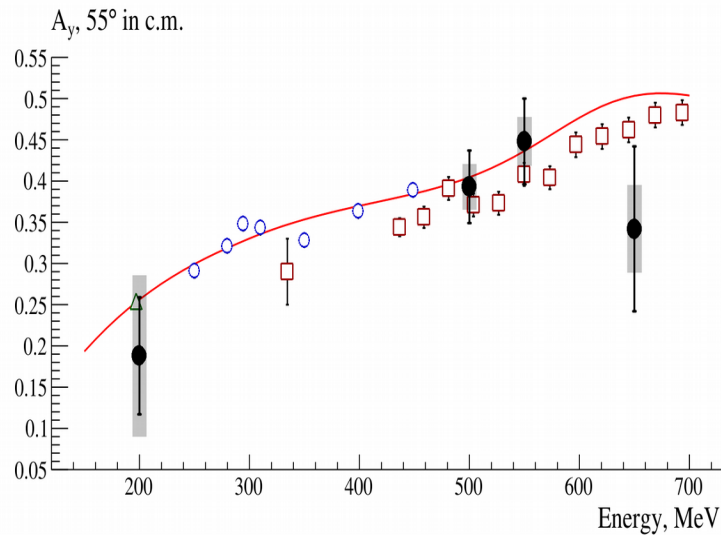
Change the sign of the A_{yy} values at $P_T \sim 600$ MeV/c.

Asymptotic behavior at large P_T : ~ -0.4 .

Similar behavior is observed for A_{yy} in $A(d,p)X$ at large P_T :
change the sign at $P_T \sim 600$ MeV/c and negative asymptotic value.

V.P.Ladygin et al., PLB629 (2005) 60

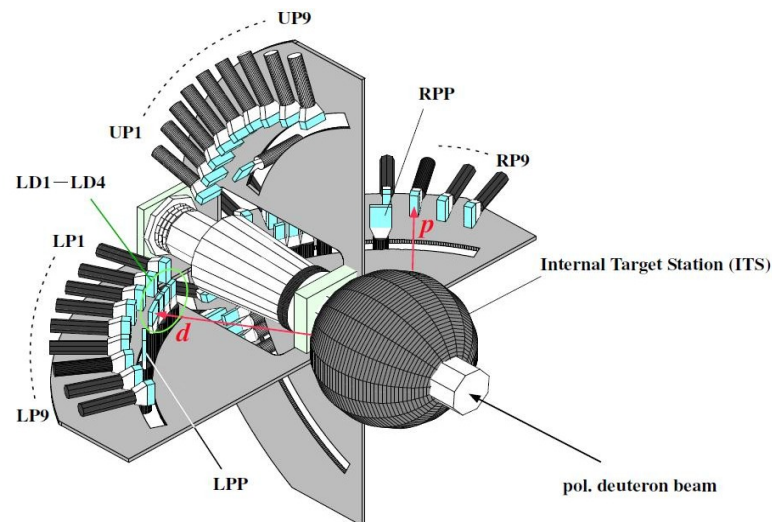
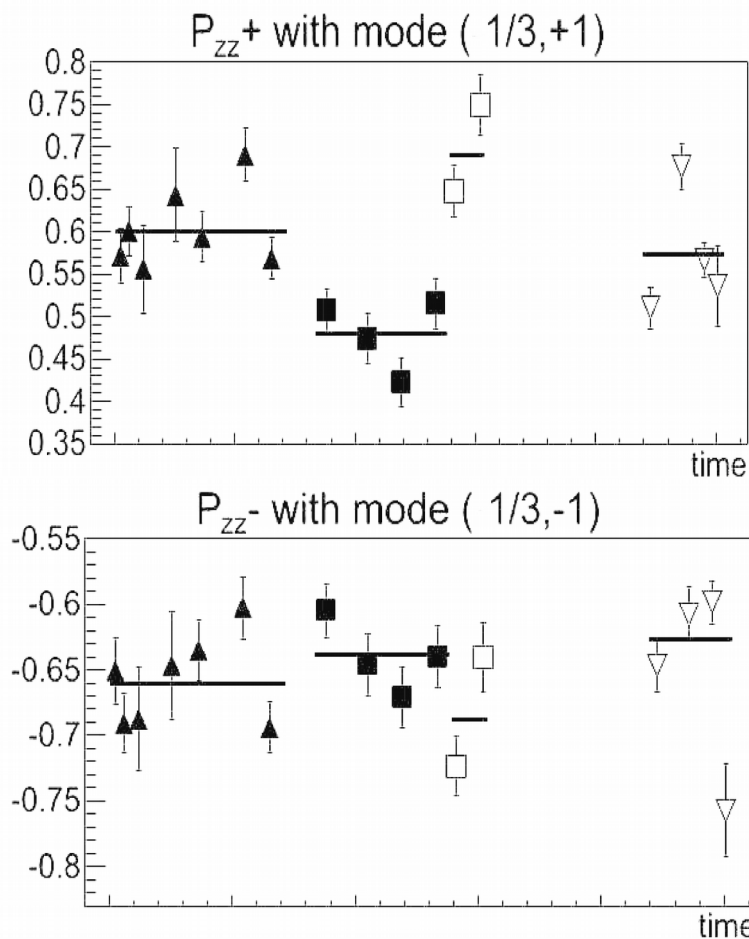
Energy dependence of the A_y analyzing power in **pp**-elastic quasi-scattering at 200-650 MeV/n



Full circles are new data from test run at Nuclotron.
Open symbols are the world data.
Line is the SP07 solution of SAID.

The goal is the precise measurements of the analyzing power A_y in **pp**-quasi-elastic scattering at 550-750 MeV/nucleon in order to check the reason of the anomaly observed in **dp**-elastic scattering.

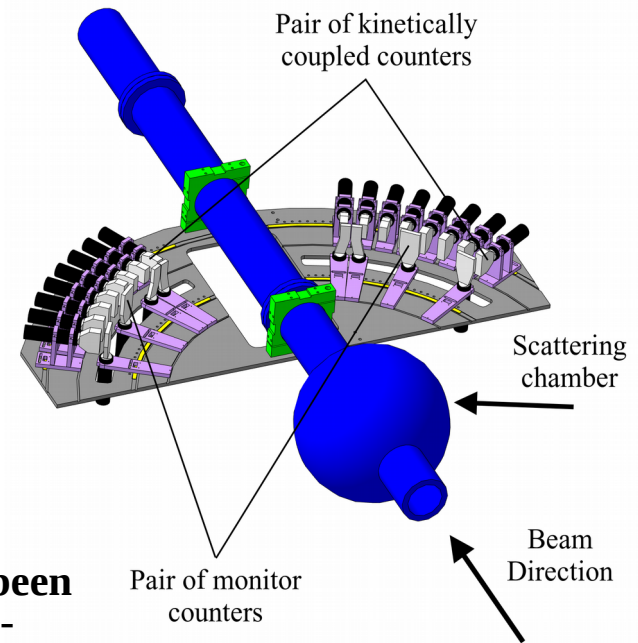
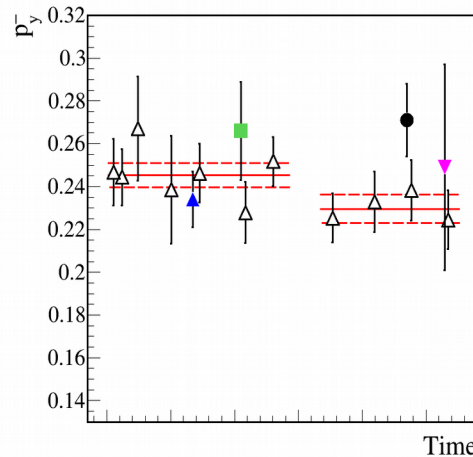
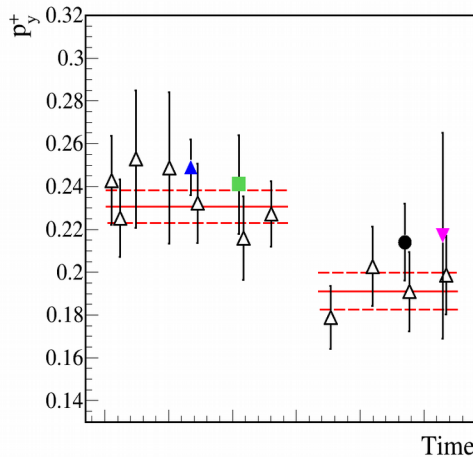
Polarization measurements using **dp**- elastic scattering at **270 MeV** at ITS



**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.

**I.S.Volkov et al.,
submitted to NIM A.**

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: $I \sim 2-3 \cdot 10^7$ 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

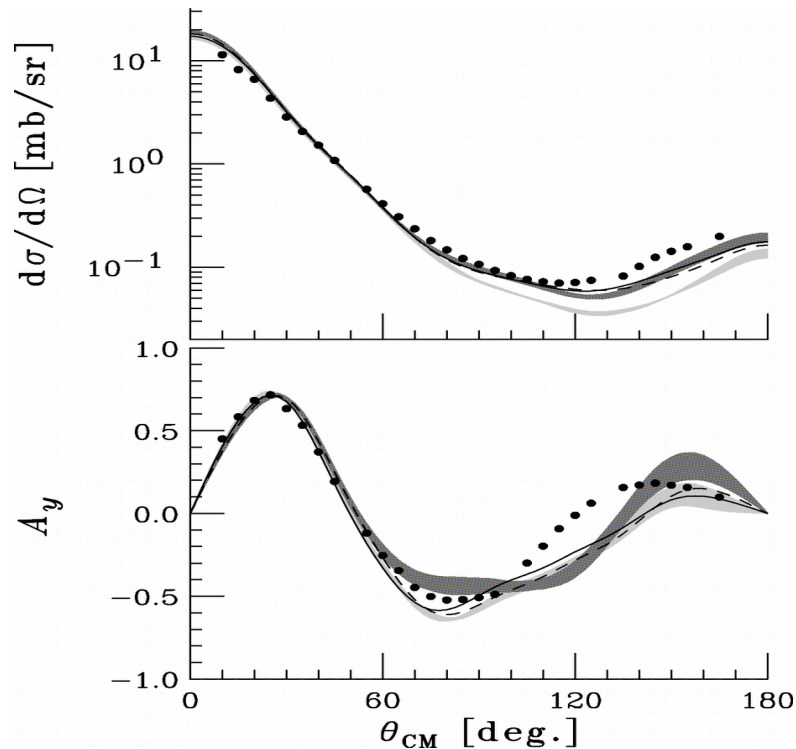
Unpolarized protons: $P = 0.038 \pm 0.023$

Polarized protons: $P = 0.368 \pm 0.023$

New detection system for proton polarimeter is under preparation.

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

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



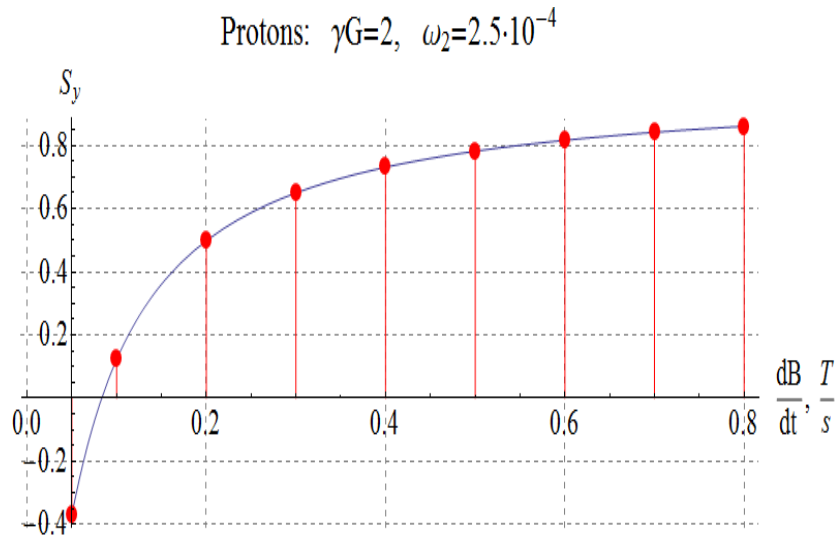
Problems in description at backward angles.

Relativistic effects become large ?

Short range 3NFs manifestation ?

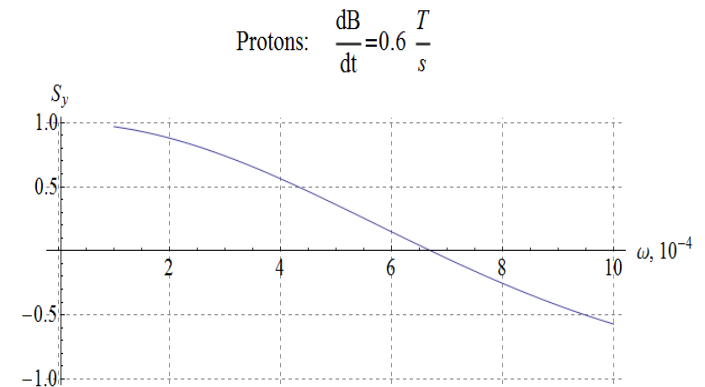
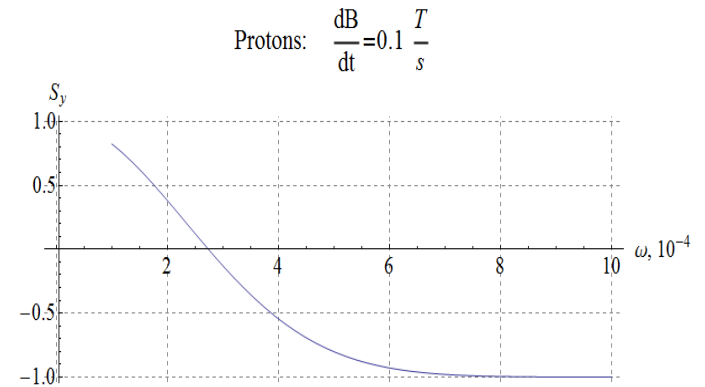
DSS plans are the systematic measurements of A_y in pd - elastic scattering between 100 and 1000 MeV using polarized proton beam. At the first stage deuteron beam will be used.

Experiment on the low integer resonances strength study



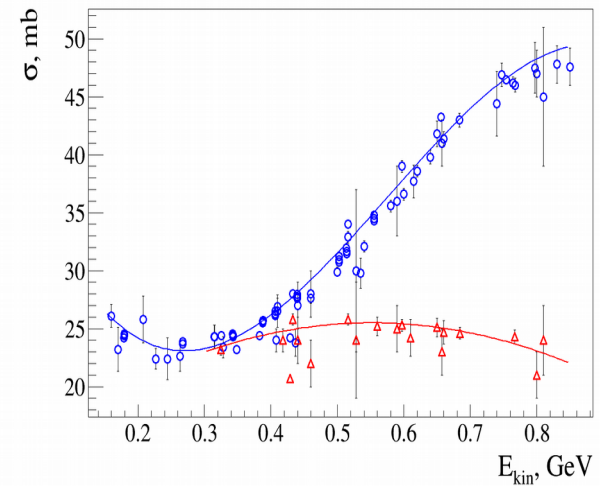
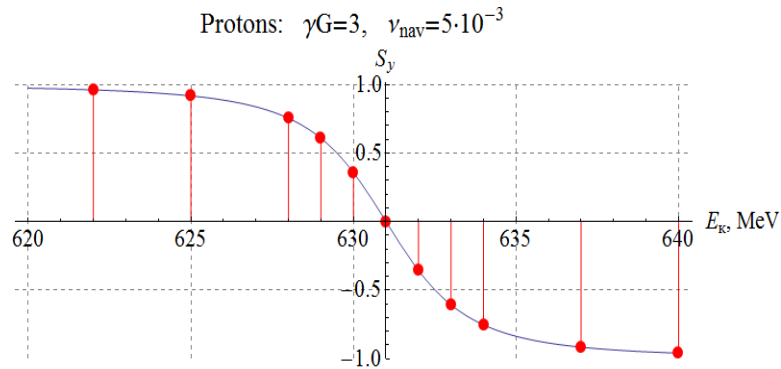
Measurements of the integer resonance $\gamma G=k=2$ strength (Tkin=108 MeV)

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



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

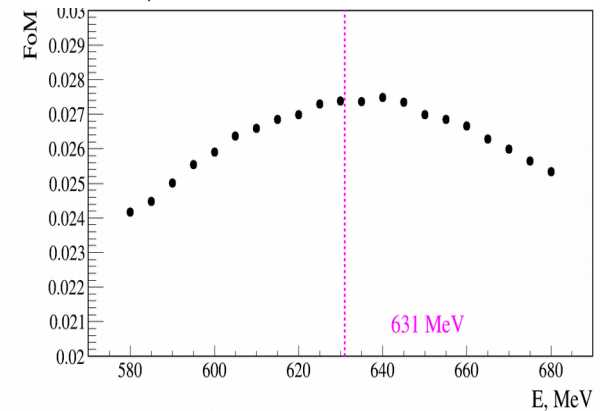
Experiment on the adiabatic passage of the $\gamma G=3$ resonance



Measurements of the beam polarization the integer resonance $\gamma G=k=3$ ($T_{\text{kin}}=631$ MeV)

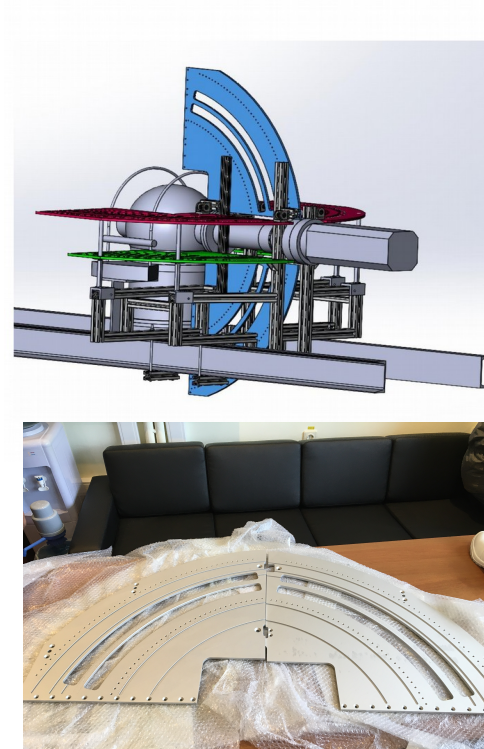
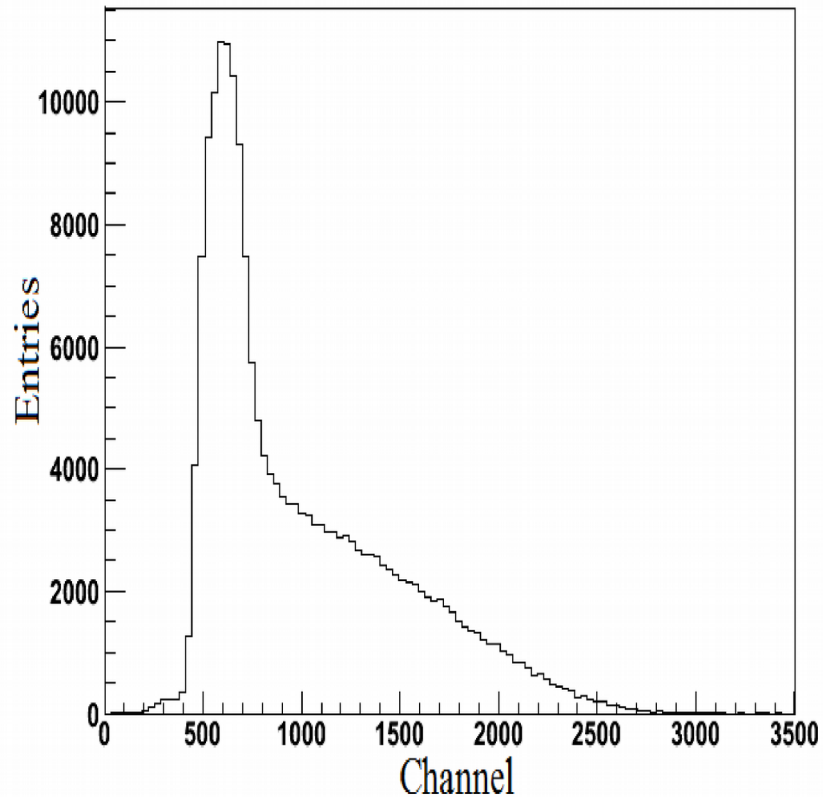
Measurements of the proton beam polarization at 610-650 MeV with small energy steps (1 MeV) using current polarimeter at Nuclotron ITS.

$$F = \sqrt{\frac{1}{N_{\text{tot}} \sigma_{\text{tot}}} \frac{\sigma_{\text{el}}^{pp}}{\sigma_{\text{tot}}} \sum_i [N_i \cdot A_i^2]}$$



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

Upgrade of **DSS** setup (stage 1)



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

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.

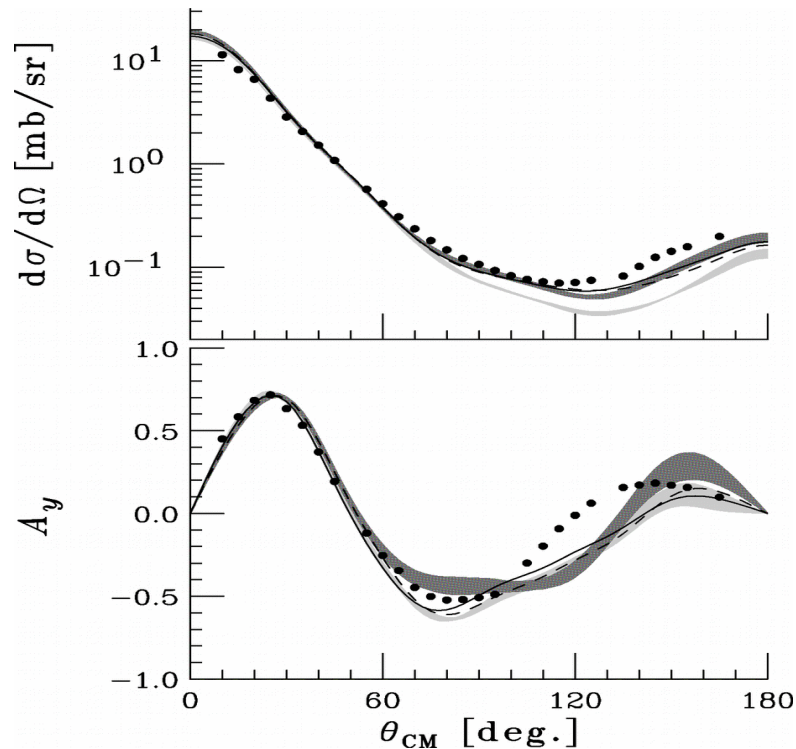
The results obtained at Nuclotron demonstrate the power law scaling behaviour for the cross section as well as the asymptotic values for the **Ay** and **Ayy** analyzing powers in **dp**- elastic scattering at large transverse momenta (>600 MeV/c). This can be due to the manifestation of the fundamental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

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

Thank you for the attention!

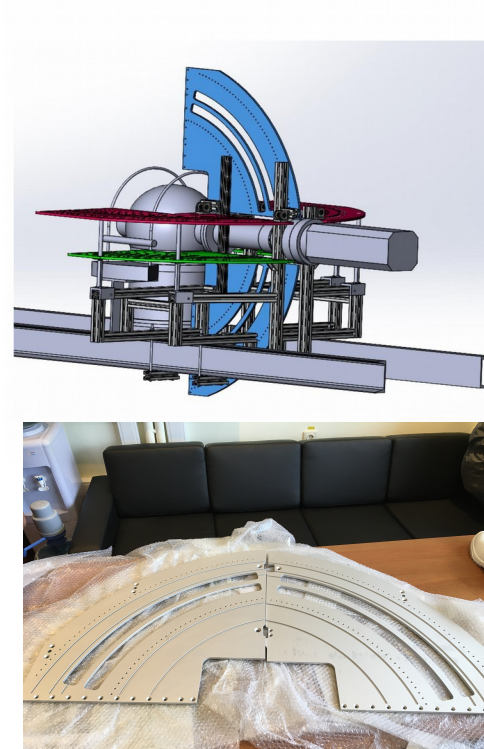
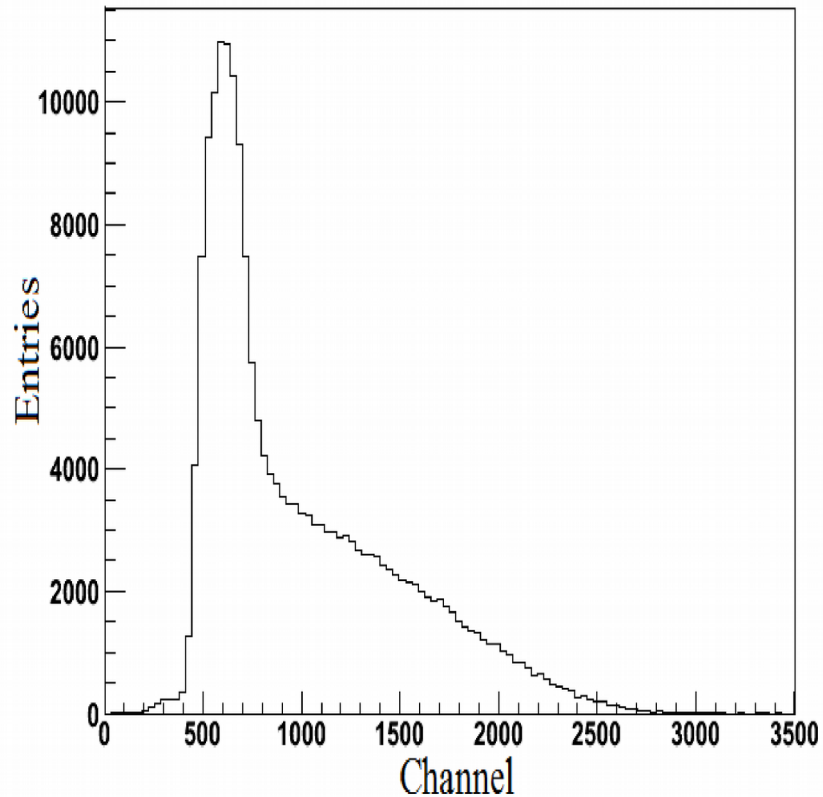
Cross section and proton analyzing power A_y in pd - elastic scattering at 250 MeV



Problems in description at backward angles.
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Short range 3NFs manifestation ?

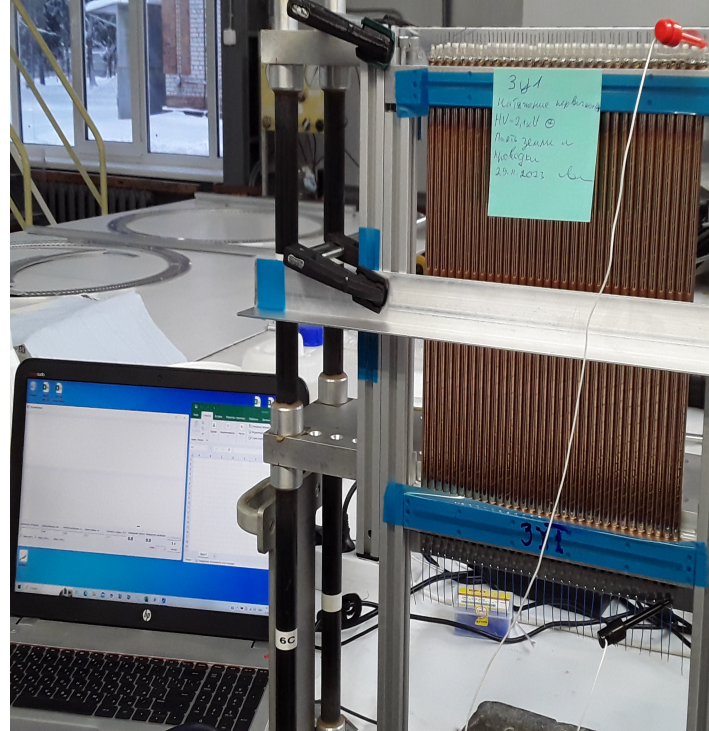
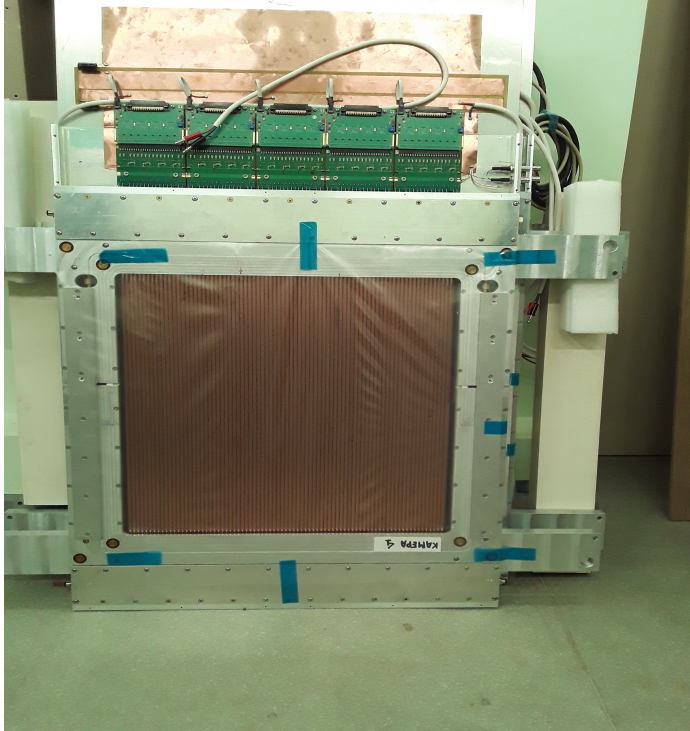
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Upgrade of **DSS** setup (stage 1)



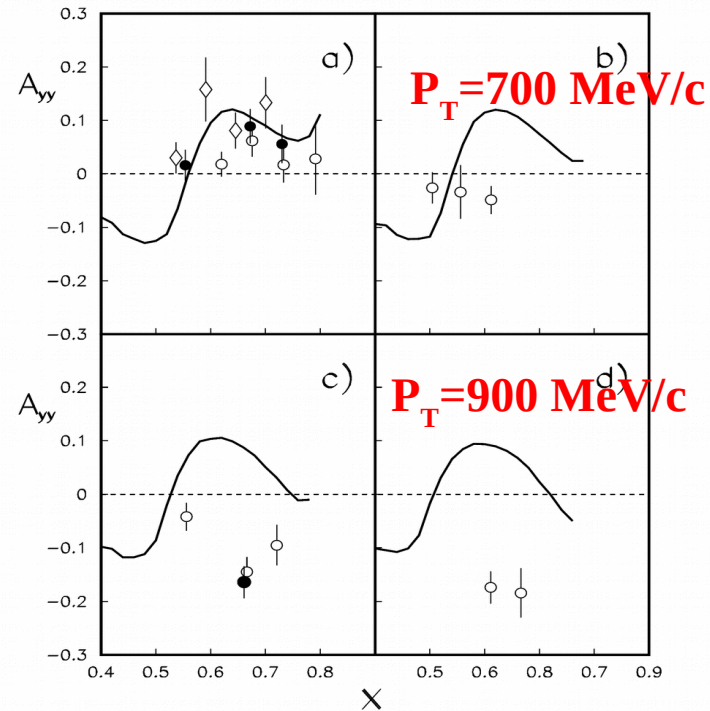
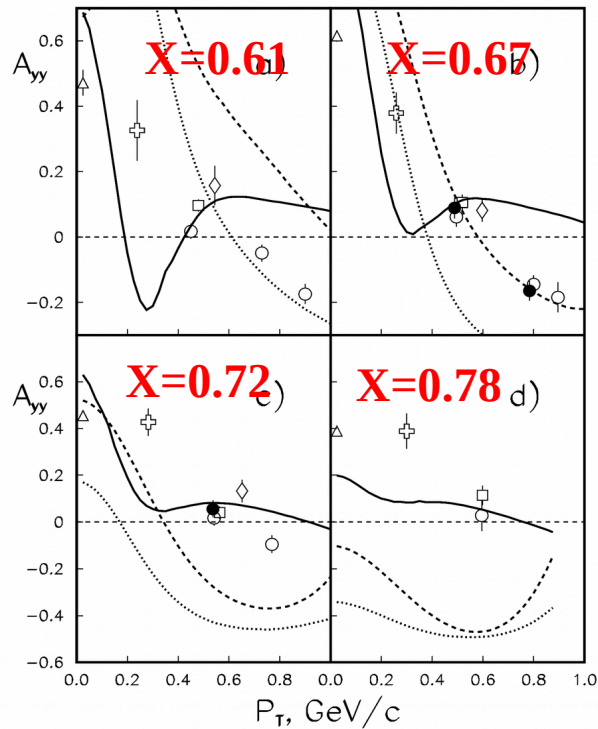
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Upgrade of **DSS** forward arms



4 50x50cm² straw chambers with FEE ready and can be used.
20 ETE-9821B PMTs are delivered.
20x20cm² straw chambers with FEE will be ready for SPD test zone.
Needs:
Straw chambers, dE-E detectors, mechanics, HV and gas systems.

Relativistic effects in deuteron from $A(d,p)X$



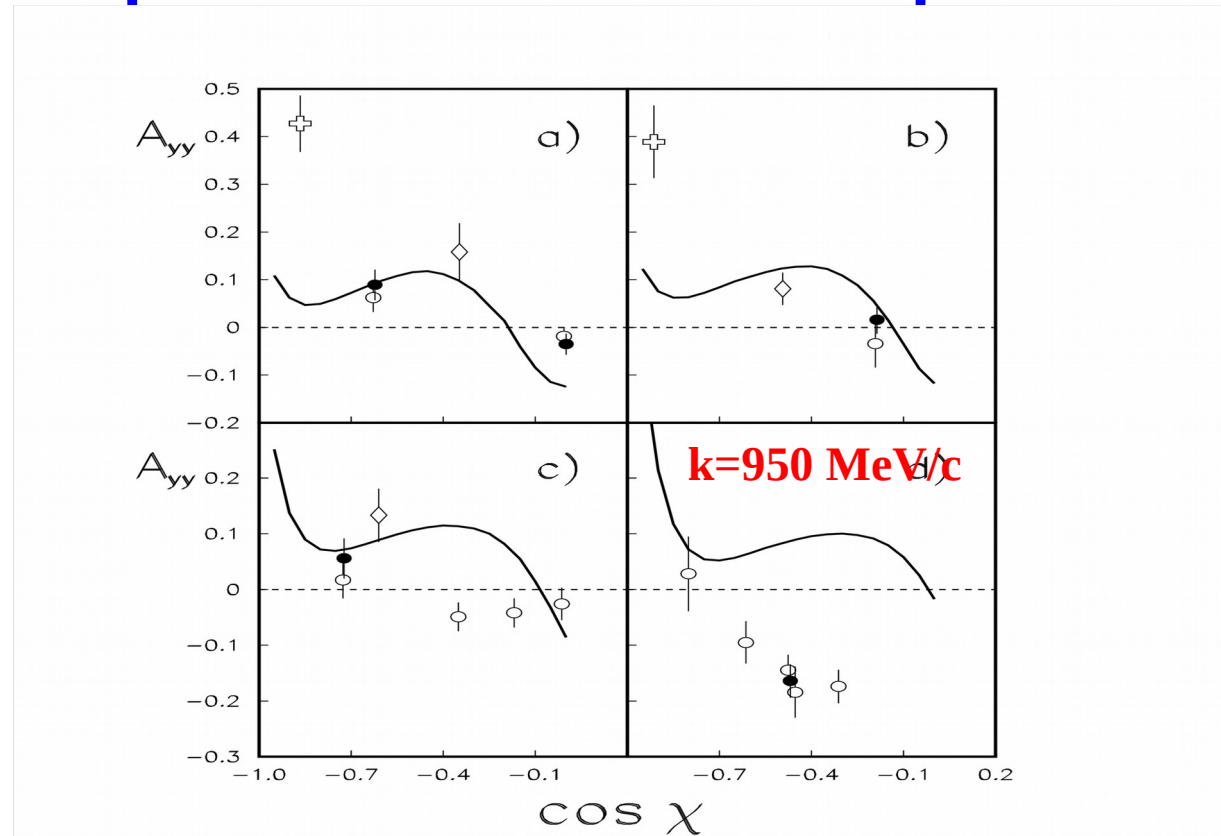
A_{yy} in deuteron inclusive breakup demonstrates the dependence on 2 internal variables: p_T and x_F .

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., PLB629 (2005) 60

Dependence of the deuteron spin structure on $(\mathbf{n}, \mathbf{k})/|\mathbf{k}|$

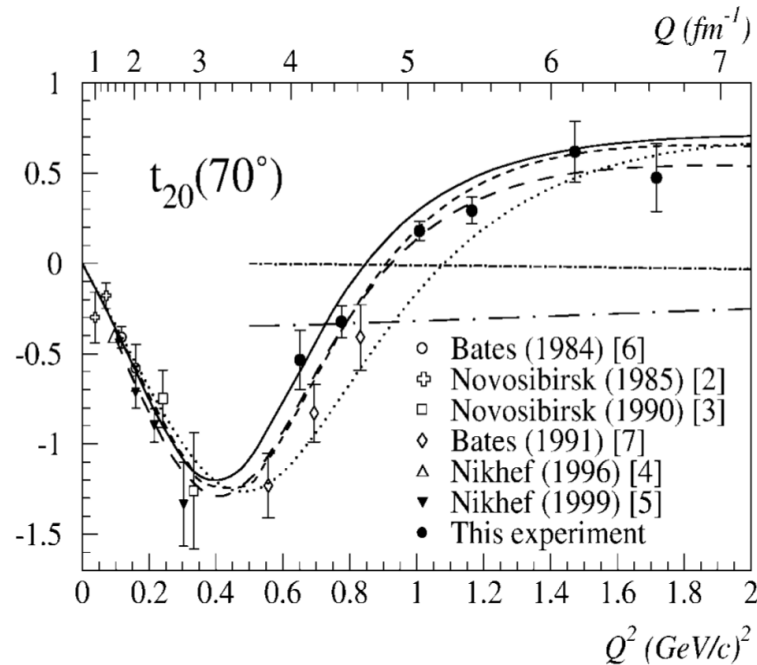


A_{yy} in deuteron inclusive breakup at fixed k demonstrates strong dependence on 2-nd internal variable $(\mathbf{n}, \mathbf{k})/|\mathbf{k}|$.

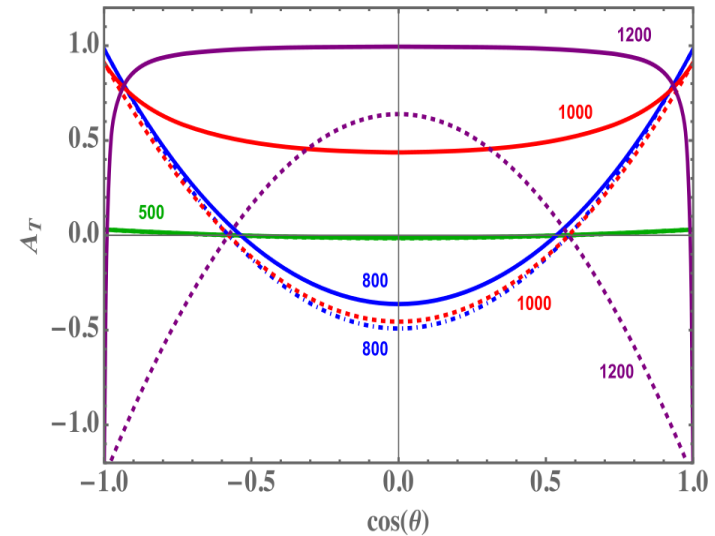
RHS with Karmanov DWF fails to reproduce the data at large k .

V.P.Ladygin et al., PLB629 (2005) 60

Deuteron spin structure from the world data



D.Abbott et al., PRL84(2000)5053



**M.M.Sargsian, F.Vera,
PRL130(2023)112502**

1. Best description of $t_{20}(\text{ed})$ is obtained with Karmanov DWF.
 f_5 term plays very significant role (instead of MEC).
2. Calculations on A_{zz} in $\text{ed} \rightarrow \text{e pn}$ for upcoming experiment at JLAB demonstrate significant dependence on $(n,k)/|k|$ variable at large k .