Study of the short-range deuteron spin structure at SPD

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SPD Phase1 Meeting , 25 March 2025

Motivation of the dp and dd interactions studies

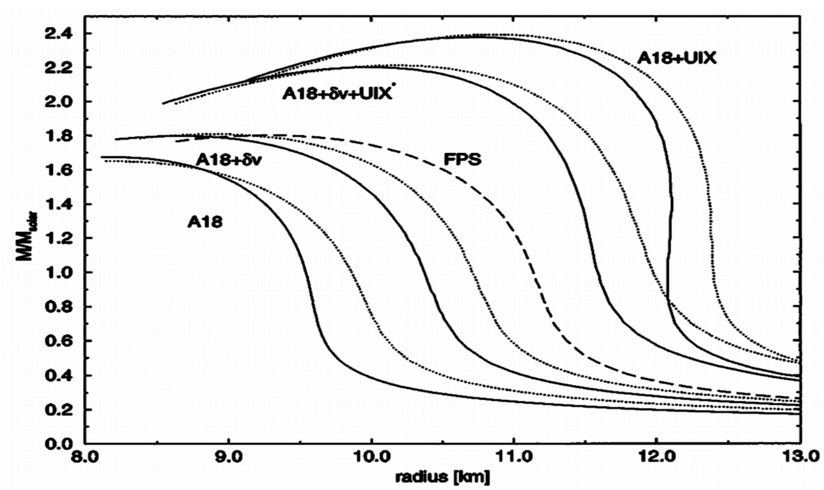
- Nucleon-nucleon interaction at short distances (including its mass off-shell behaviour)
- Relativistic effects
- Transition to the nonnucleonic degrees of freedom
- Contribution of 3-nucleon and 4-nucleon forces

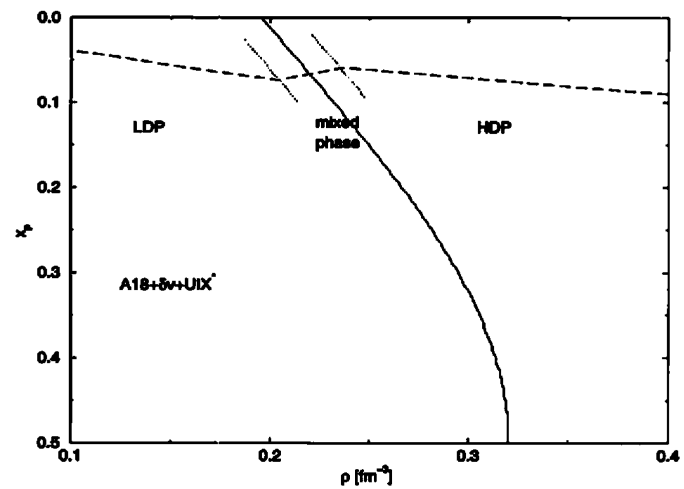
Deuteron : J=1, S=1, I=0

Rich polarization phenomena for dp and dd interaction

Few nucleons systems as a tool for dense matter studies

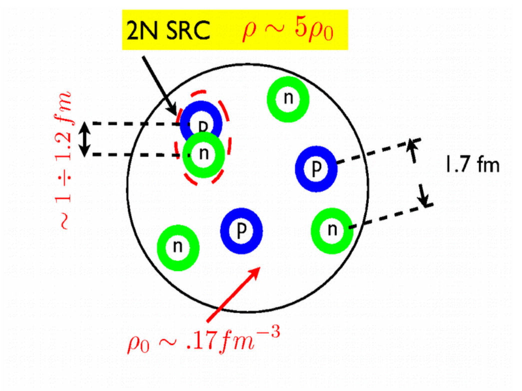
Alternative (to HIC) way to obtain the information on the EOS at extreme densities (neutron stars) is the studies of the few nucleon systems.

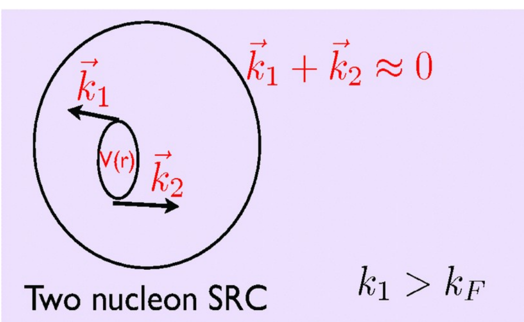




Relativistic effects in 2NF and contribution of 3NF play very important role. (A.Akhmal et al, Phys.Rev. C58 (1998) 1804)

Short range correlations (SRCs)





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 SPD allow to reach p_T >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, $\vec{\mathbf{p}} \to \mathrm{inf}$, 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 $\vec{\mathbf{n}} = \vec{\mathbf{p}}/|\vec{\mathbf{p}}|$

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

Relativization schemes

For the case of the deuteron vertex the internal momentum **k**:

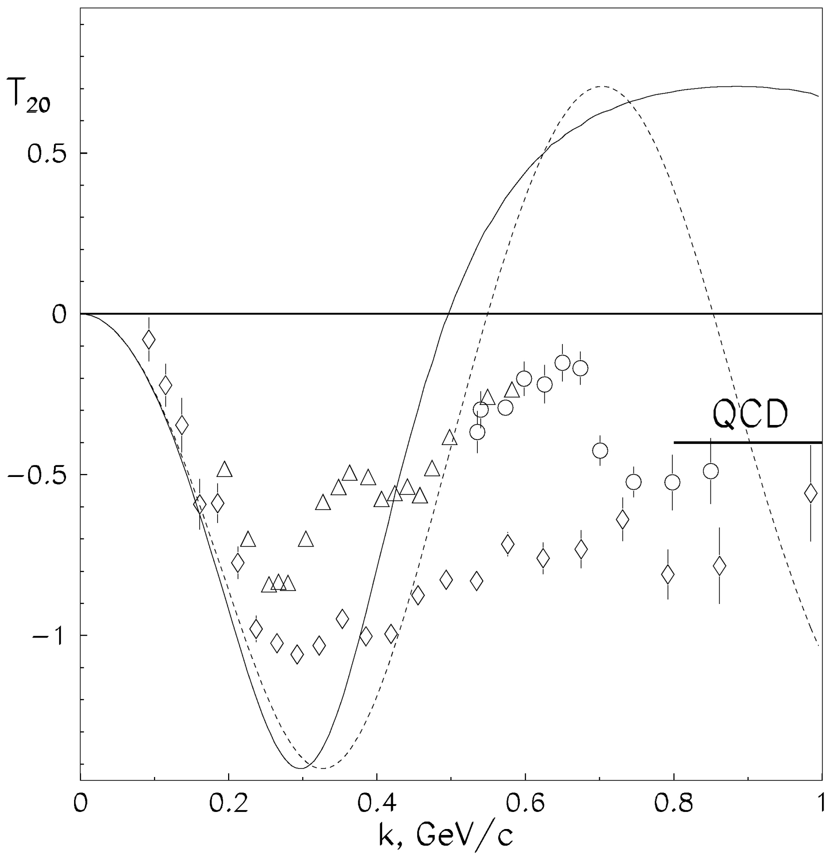
$$k = \sqrt{\frac{m_p^2 + \mathbf{k}_T^2}{4x(1-x)} - m_p^2},$$

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

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.)

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.

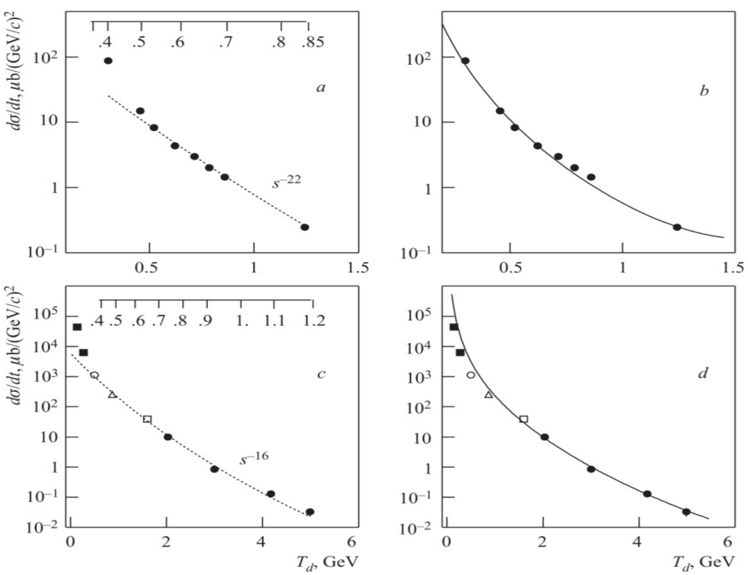
Data:
V.Punjabi et al., Phys.Lett.B350 (1995) 178
L.S.Azhgirey et al., Phys.Lett.B391 (1997) 22
L.S.Azhgirey et al., Phys.Lett.B387 (1996) 37

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, Lepage **pQCD**
Polchinski, Strassler **AdS/QCD correspondence**



Picture is taken from

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

For the reaction **dd → ³Hen**

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

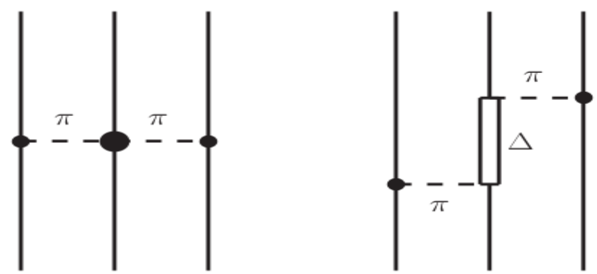
For the reaction **dp → dp**

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

Similar rules for dp-inclusive breakup:
$\sim(1-x)^5$

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.**

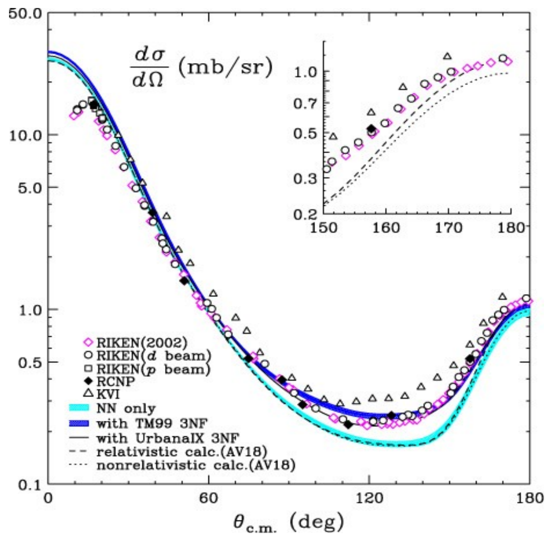


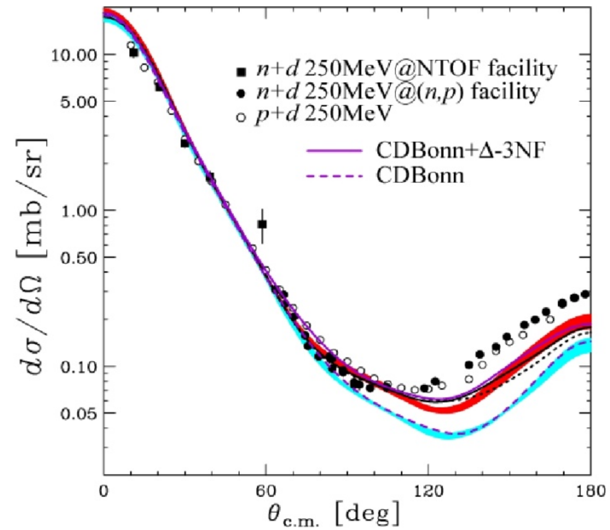
- Tucson-Melbourne
- Brazil
- Urbana-IX
- Fujita-Miyazawa ($N\Delta$)
- Chiral Effective Field Theory

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.

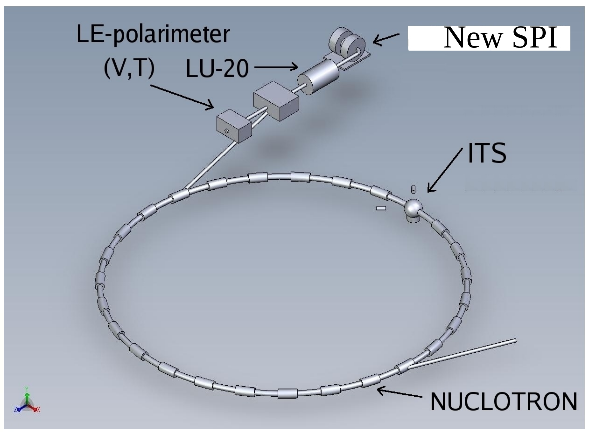
K. Sekiguchi et al., Phys. Rev. Lett. 95, 162301 (2005)

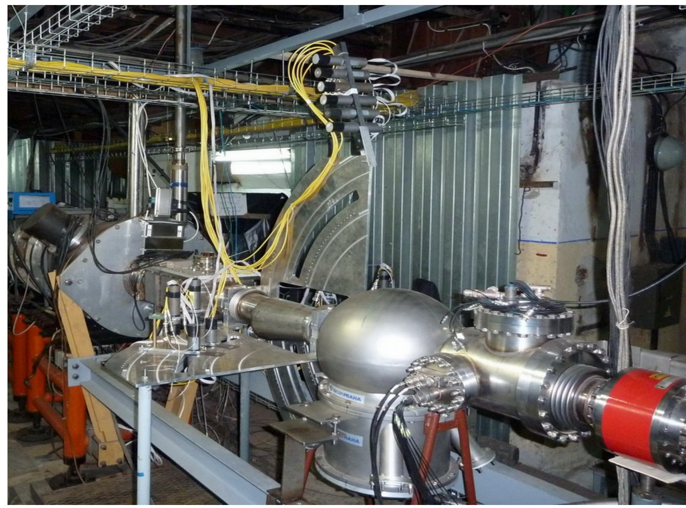
K. Hatanaka et al., Phys. Rev. C 66, 044002 (2002)

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. New types of 3NF (short range, s-channel contributions).

Results at intermediate and high energies from fixed target experiments (Nuclotron & RARF)

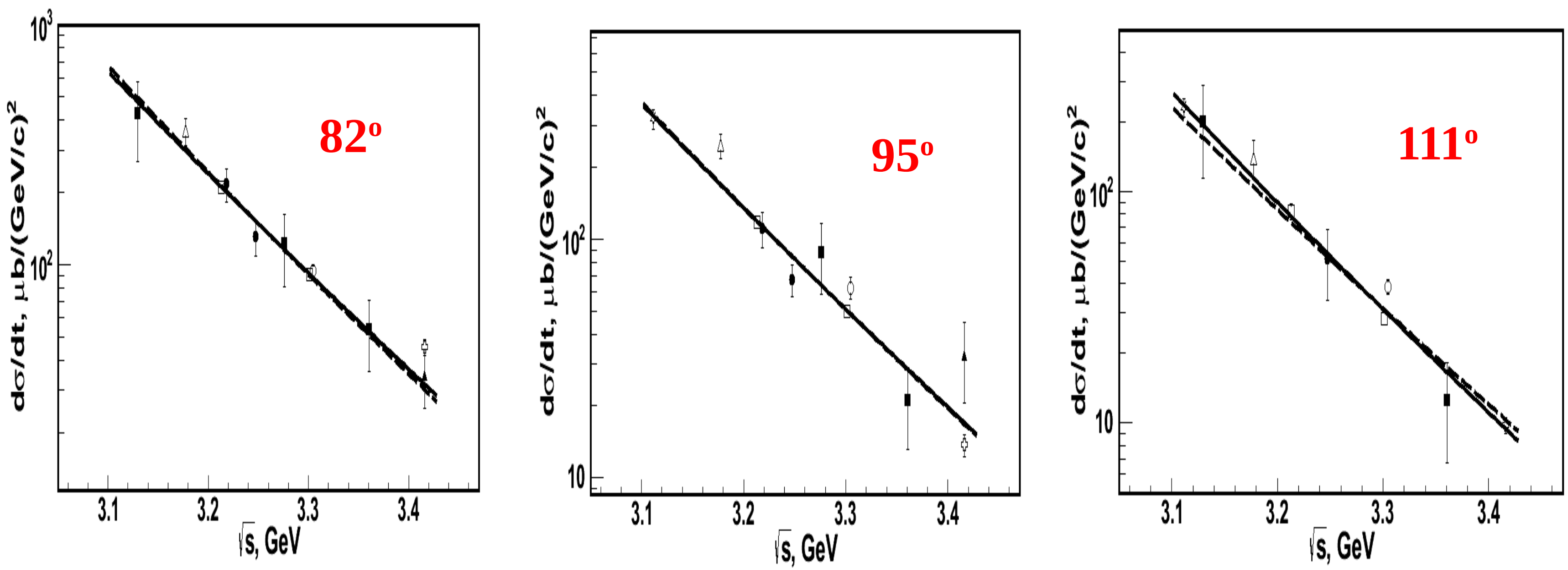
Experiments at Internal Target Station at Nuclotron





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

dp- elastic scattering cross section scaling properties at the fixed angles in cms



A.A.Terekhin et al.,Eur.Phys.J.A55(2019)129

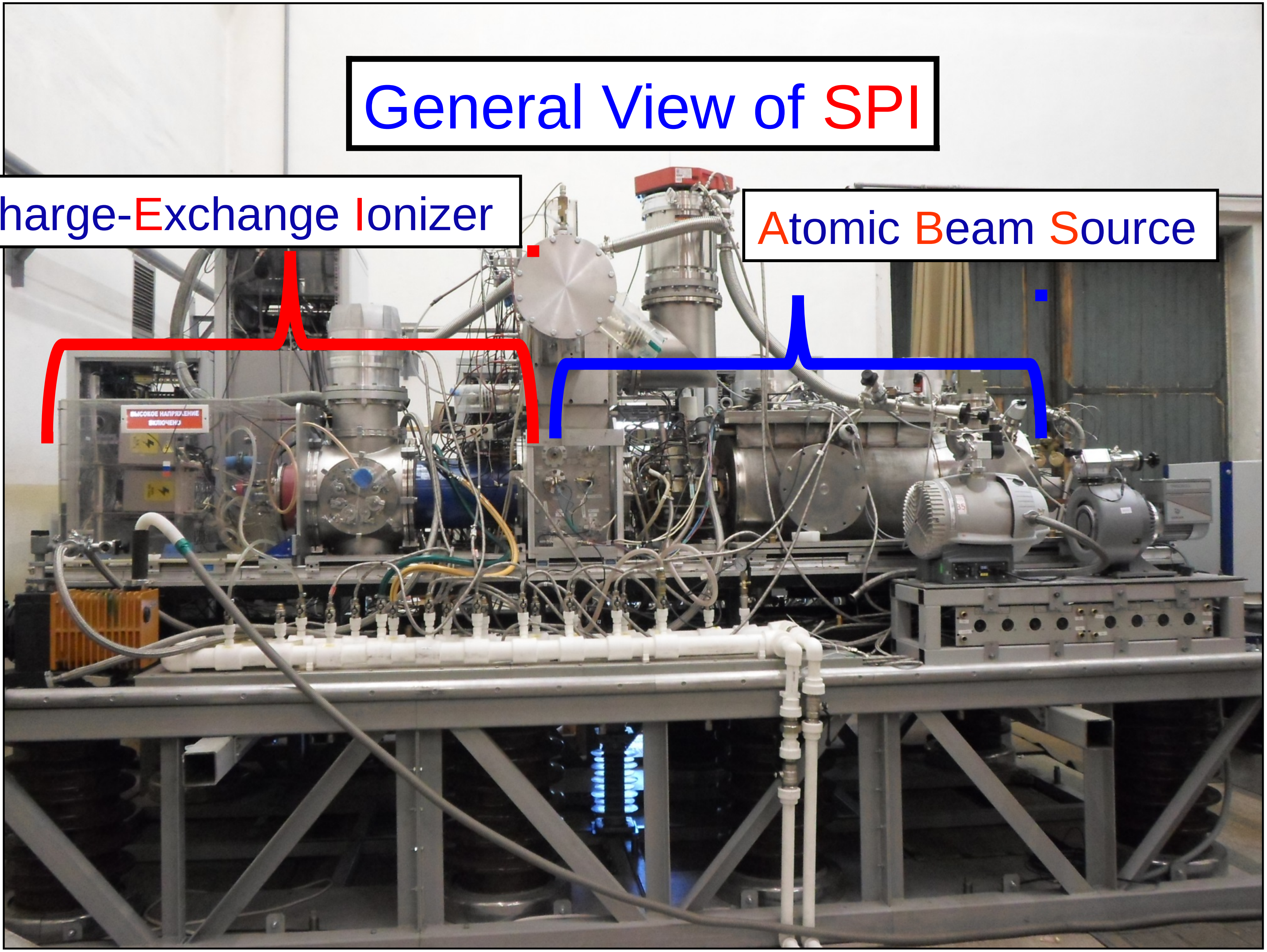
Constituent Counting Rules predictions:

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

1. self-similarity,
2. pQCD,
3. AdS/QCD correspondence

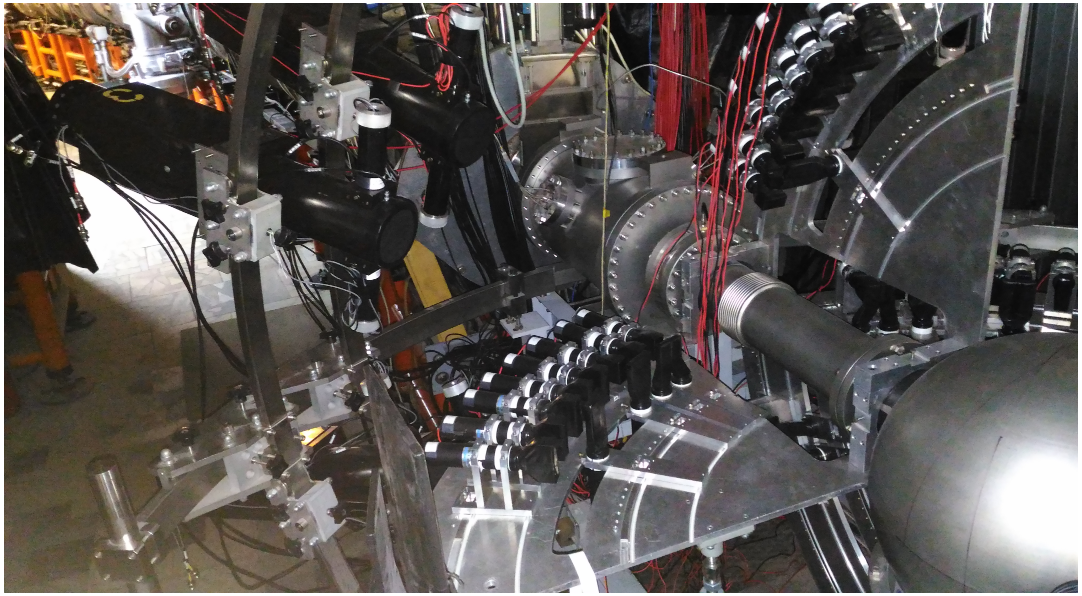
S^{-16}

General View of SPI



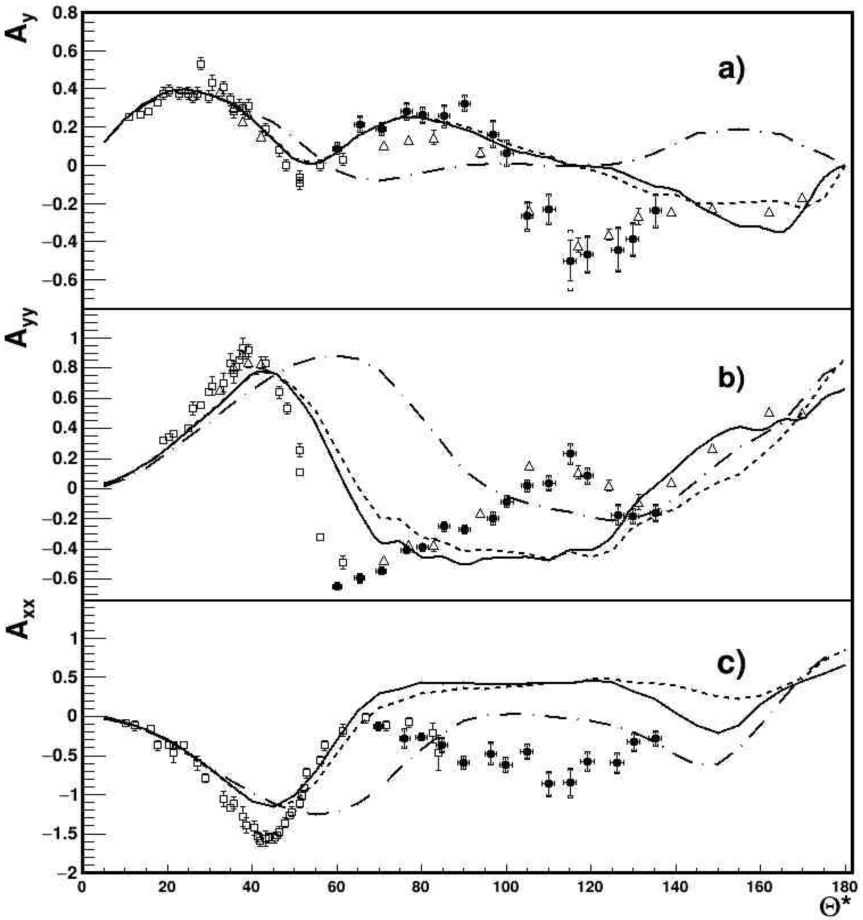
New SPI will increase beam figure of merit by a factor ~10^3

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” 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.

Angular dependencies of the vector Ay and tensor Ayy and Axx analyzing powers in dp-elastic scattering at 1300 MeV

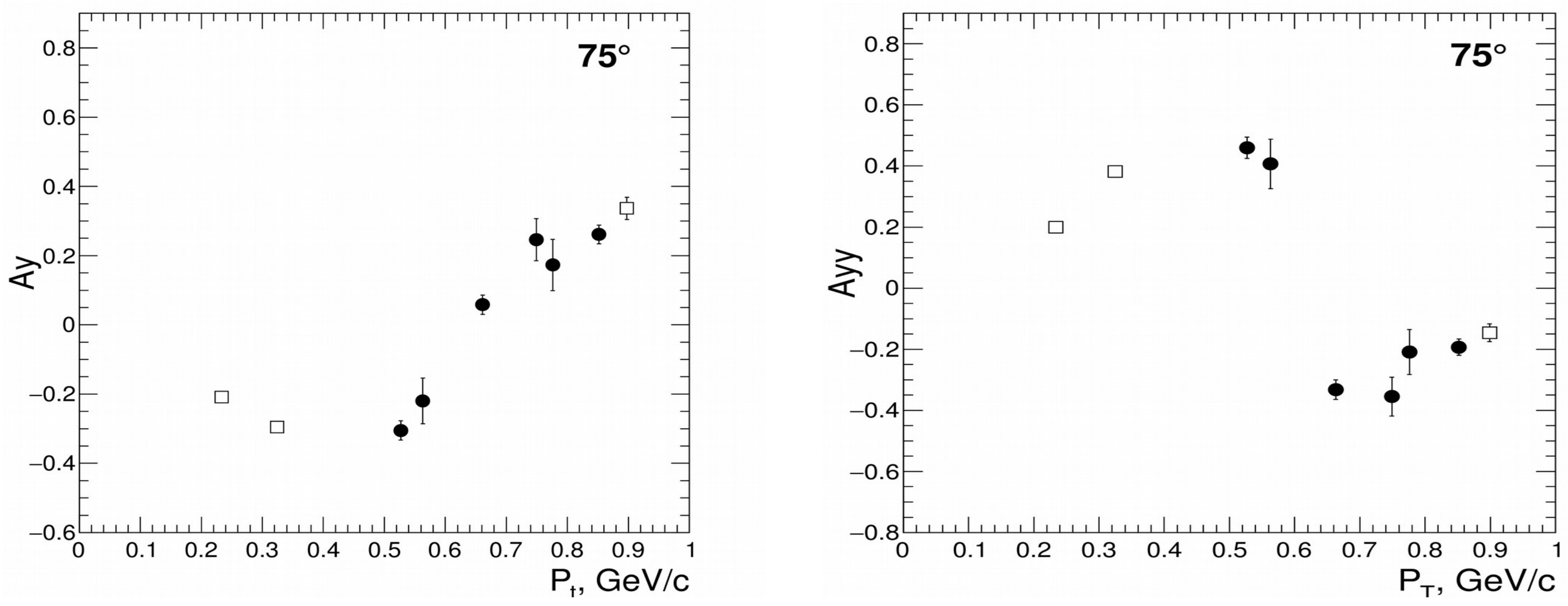


Data shown by the open triangles and squares are obtained at 1200 MeV at Saclay and ANL, respectively.

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

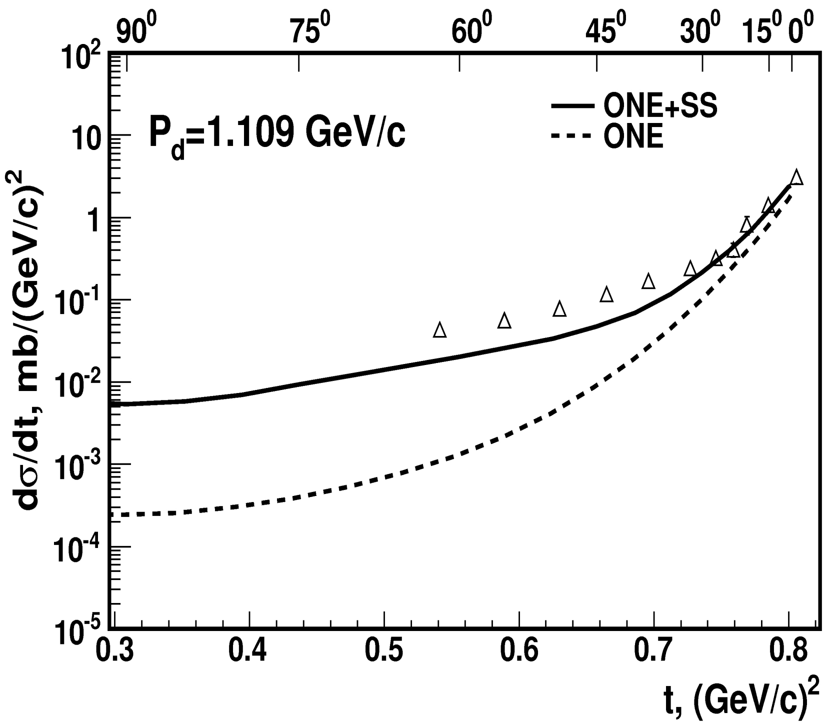
Structure in Ay-Ayy behaviour observed at Saclay at 1200 MeV and at 100-130 degrees in cms is confirmed, its energy dependence is studied.

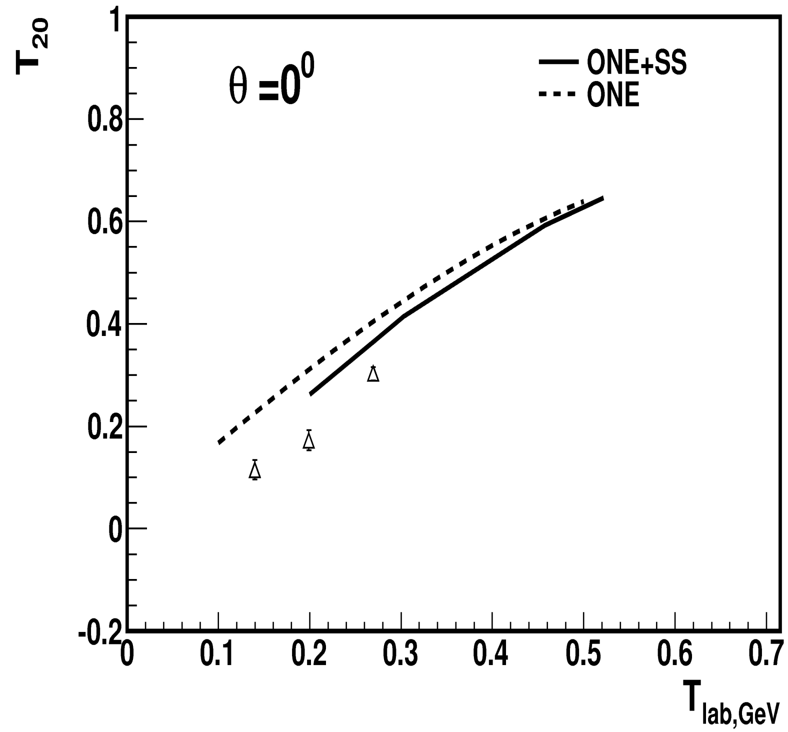
Energy dependence of the vector Ay and tensor Ayy analyzing powers in dp-elastic scattering at 700-1800 MeV



Full circles are new data from Nuclotron.
Open symbols are the world data.
Change the signs of the Ay and Ayy values at 600 MeV/c.
Asymptotic behaviour at large P_T.

dd → ^{3}Hen(^{3}Hp) reactions at Nuclotron energies

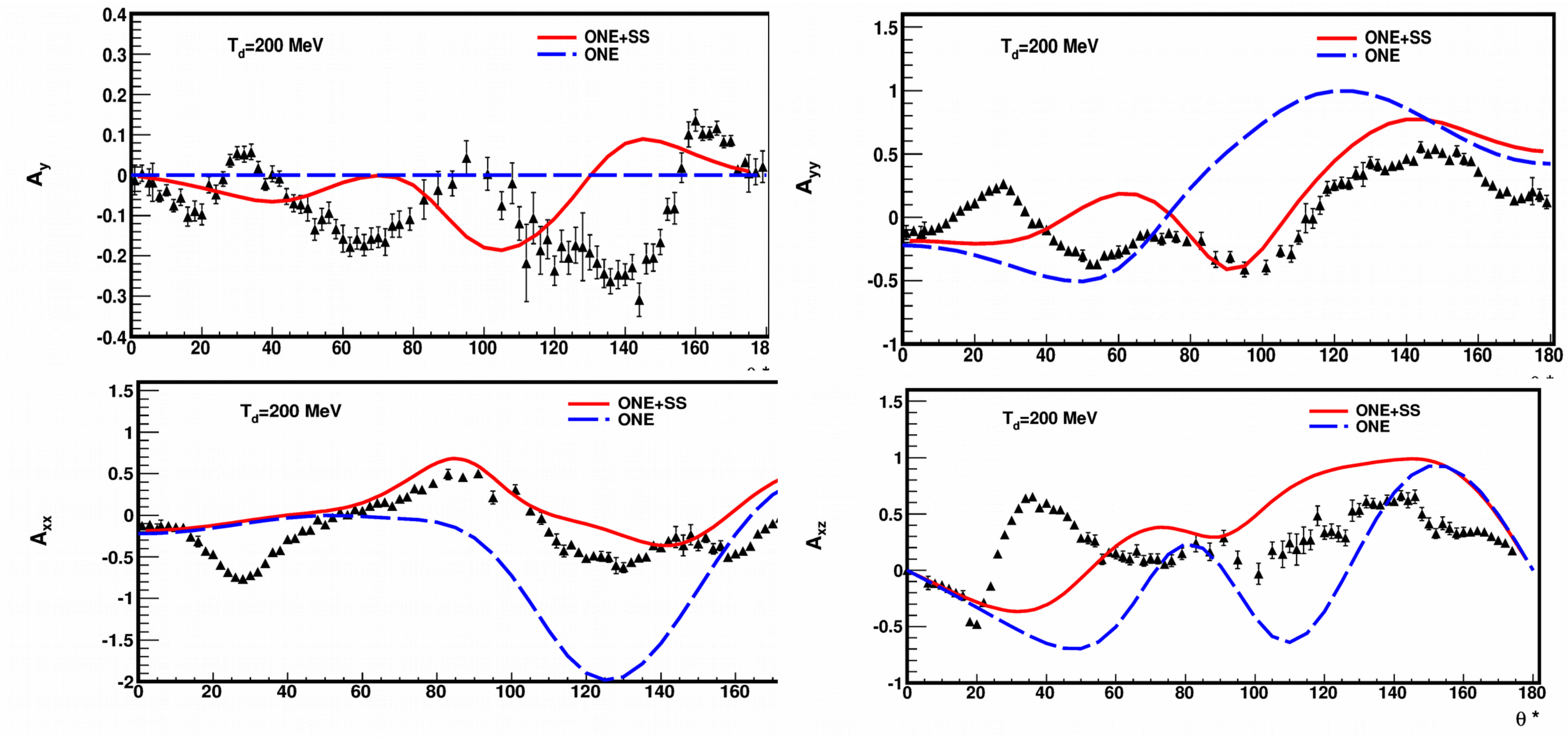




The relativistic multiple scattering model can be successfully used to describe the dd → ^{3}Hen(^{3}Hp) reactions in a GeV region at the Nuclotron.

CS: G.Bizard et al.,Phys.Rev.C22 (1980) 1632.
T_{20}: V.P.Ladygin et al., Phys.Lett.B598 (2004) 47.
Theory: N.B.Ladygina, Few Body Systems 53 (2012) 253.

Deuteron analyzing powers 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.

Data: A.K.Kurilkin et al., Phys.Rev.C87 (2013) 051001.
Theory: N.B.Ladygina, Few Body Systems 53 (2012) 253.

Motivation for SPD

Seems, that the cross section of dp- elastic scattering and $dd \rightarrow {}^3Hen({}^3Hp)$ reaction at SPD energies at large transverse momenta follow to CCR.

Spin effects at Nuclotron energies are large and sensitive to the spin structure of light nuclei.

The asymptotic behaviour of A_y and A_{yy} analyzing powers in dp- elastic scattering is observed at large cms.

Estimations for SPD

1. Based on the fit of the dp- elastic scattering cross section taken from:

A.A.Terekhin et al.,Eur.Phys.J.A55(2019)129

2. $L=10^{29}\ cm^{-2}\ c^{-1}$
3. 75% from the ideal values of the beam polarization
   Spin modes $(p_y, p_{yy})=(0,0); (0,-2); (+1,+1)$ and $(-1,+1)$

$\Delta A_y = 0.03$

ΔA_{yy} and $\Delta A_{xx} = 0.09$ in 30 days of the beam time

for $\sqrt{s}=4.5$ GeV and $\theta=90^o \pm 5^o$

V.V.Abramov et al., Phys.Part.Nucl. 52 (2021) 6, 1044.

dd- collisions

1. There will no **dp-** collisions at the first stage.
One needs to use **dd-** collisions and to study **d"p"-** collisions including **d"p"-** elastic scattering.

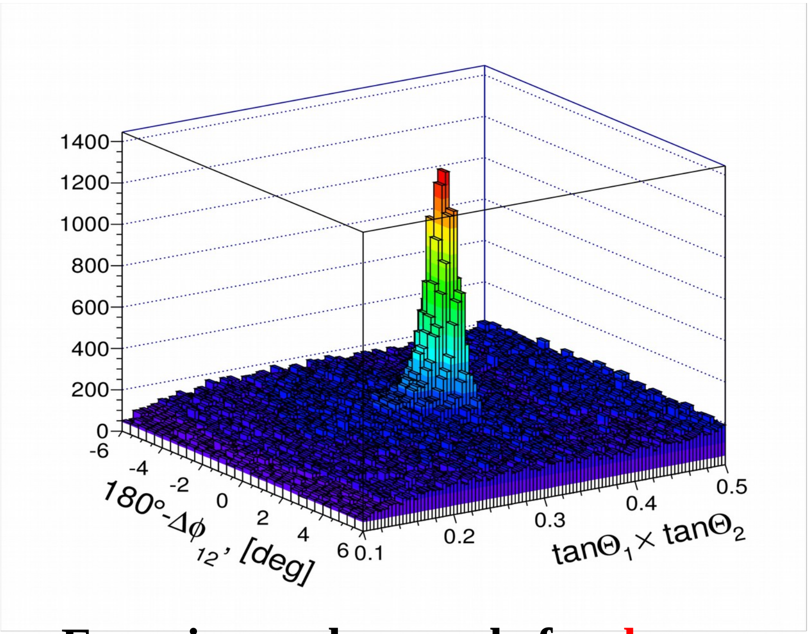
$\sqrt{s}_{dd}$=5.5 GeV corresponds to $\sqrt{s}_{dp} \approx$ 4.0 GeV

2. Absence of TOF PID
   dE/dX in straw seems to be not working also

3. Therefore, only kinematic cuts.
   -matching of 2 tracks in the area of the primary vertex
   -complanarity cut $\Delta\varphi = 180^{o} \pm 5^{o}$
   -cut on polar angles θ
   -cut on 2 momenta correlation
   (But devil is in details... for last 2 cuts)

dd- collisions

In fact, we have 3 different reference frames for
dd- collisions,
NN- collisions,
dp- collisions
For symmetric collisions (dd- and NN-) frames coincide.
Cut θ is different for different frames.



Experimental example for dp-elastic scattering in lab.system

Therefore, cut ($\theta_1+\theta_2$)=180°±N° can be applied only for dd- elastic, "pp"- elastic scattering and dd→^{3}Hp reaction*

For the selection of dp- elastic scattering reaction one needs to go in the dp- cms.

But strong correlation for momenta of the above reactions!

***dd→^{3}Hen reaction can be selected using dE/dX for ^{3}He in straw detector.**

Conclusions and further steps

1. The light nuclei short-range spin structure at SPD can be studied during the Phase1. However, the feasibility studies are required. Some technical problems with tensor observables.

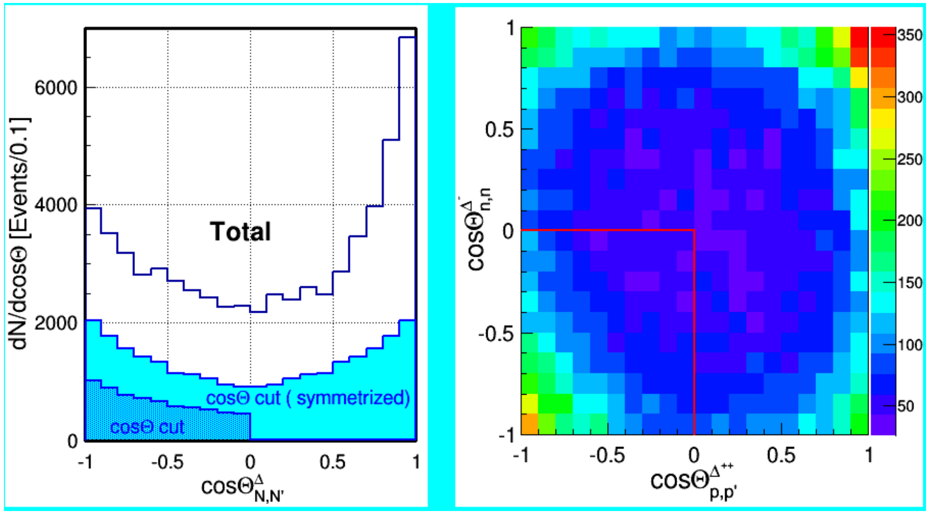
2. Bad news:
Seems, that at Phase0 we'll not able to separate dd- elastic, "pp"- elastic, d"p"- elastic scattering and dd→^{3}Hp reaction with BBC only. One needs other detector with TOF PID.

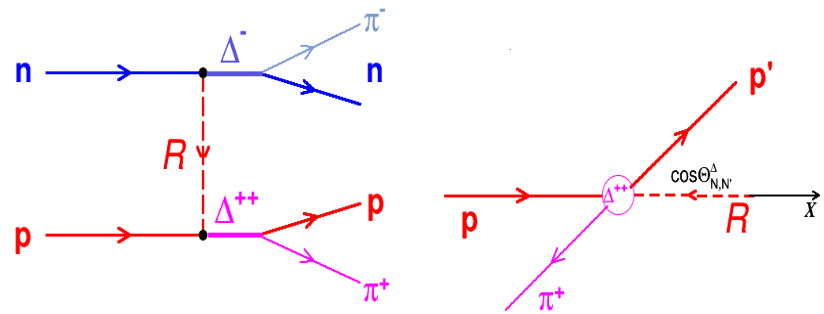
3. Good news (should be carefully checked):
Seems, that for d"p"- elastic scattering studies we can avoid the use of ZDC information, what will significantly increase the number of events-candidates for the analysis.

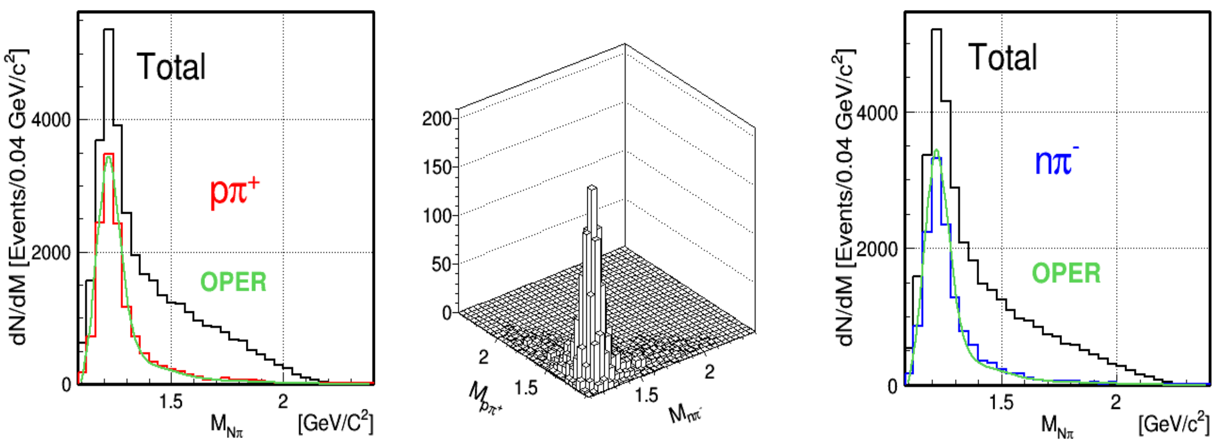
4. Need to have suitable event generator for at least 1 energy for dd- interaction. The binary reactions can be included by "hands" (via Pluto- generator).
Amaresh, Arkady.

5. The channels with more than 1 neutron can be also detected at SPD using RS system. However, development of the advanced kinematical fit is necessary.

Selection of np → $\Delta^{++}\Delta^{-}$







Hidden color from
dd → $\Delta^{++}\Delta^{-}$ +p+n

Needs to measure additional proton and neutron (2 neutrons in the final state).

A.P.Jerusalimov: seminar LHEP 31.01.25

Thank you for the attention!

Relativization schemes

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

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

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

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

Deuteron wave function on the light cone

Relativistic deuteron wave function on light cone is defined by **6** invariant functions $\mathbf{f_1}, ..., \mathbf{f_6}$ (instead of **2** in the non-relativistic case), each of them depends on 2 scalar variables $\mathbf{k}$ and $z = cos(\widehat{\mathbf{kn}})$:

$$\psi(\mathbf{k},\,\mathbf{n}) \;=\; \frac{1}{\sqrt{2}}\sigma f_1 + \frac{1}{2}\left[\frac{3}{k^2}\mathbf{k}(\mathbf{k}\cdot\sigma) - \sigma\right] f_2 + \frac{1}{2}\left[3\mathbf{n}(\mathbf{n}\cdot\sigma) - \sigma\right] f_3 + \frac{1}{2k}[3\mathbf{k}(\mathbf{n}\cdot\sigma) + 3\mathbf{n}(\mathbf{k}\cdot\sigma) - 2\sigma(\mathbf{k}\cdot\mathbf{n})]f_4 + \sqrt{\frac{3}{2}}\frac{i}{k}[\mathbf{k}\times\mathbf{n}]f_5 + \frac{\sqrt{3}}{2k}[[\mathbf{k}\times\mathbf{n}]\times\sigma]f_6,$$

$$(\mathbf{n}\cdot\mathbf{k}) = (\frac{1}{2} - \alpha)\cdot\sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{\alpha(1-\alpha)}}.$$

V.A.Karmanov, J.Carbonell et al.

Dependence of the deuteron structure on 2 internal variables