The ratio R_{dp} of the quasi-elastic nd→p(nn) to the elastic np→pn charge-exchange process yields at 0^o over 0.55 - 2.0 GeV neutron beam energy region

Measurements were carried out at the Nuclotron of the Veksler and Baldin Laboratory of High Energies of the Joint Institute for Nuclear Research (JINR) at the neutron beam kinetic energies 0.55, 0.8, 1.0, 1.2, 1.4, 1.8 and 2.0 GeV.

The obtained $R_{dp} = d\sigma/d\Omega(nd) / d\sigma/d\Omega(np)$ values remain nearly constant with energy.

The new data are compared with existing ones, measured only at energies below 1 GeV.

The investigations are being carried out under the program of the first priority JINR project "Delta-Sigma" Experiment.

Participants of this study

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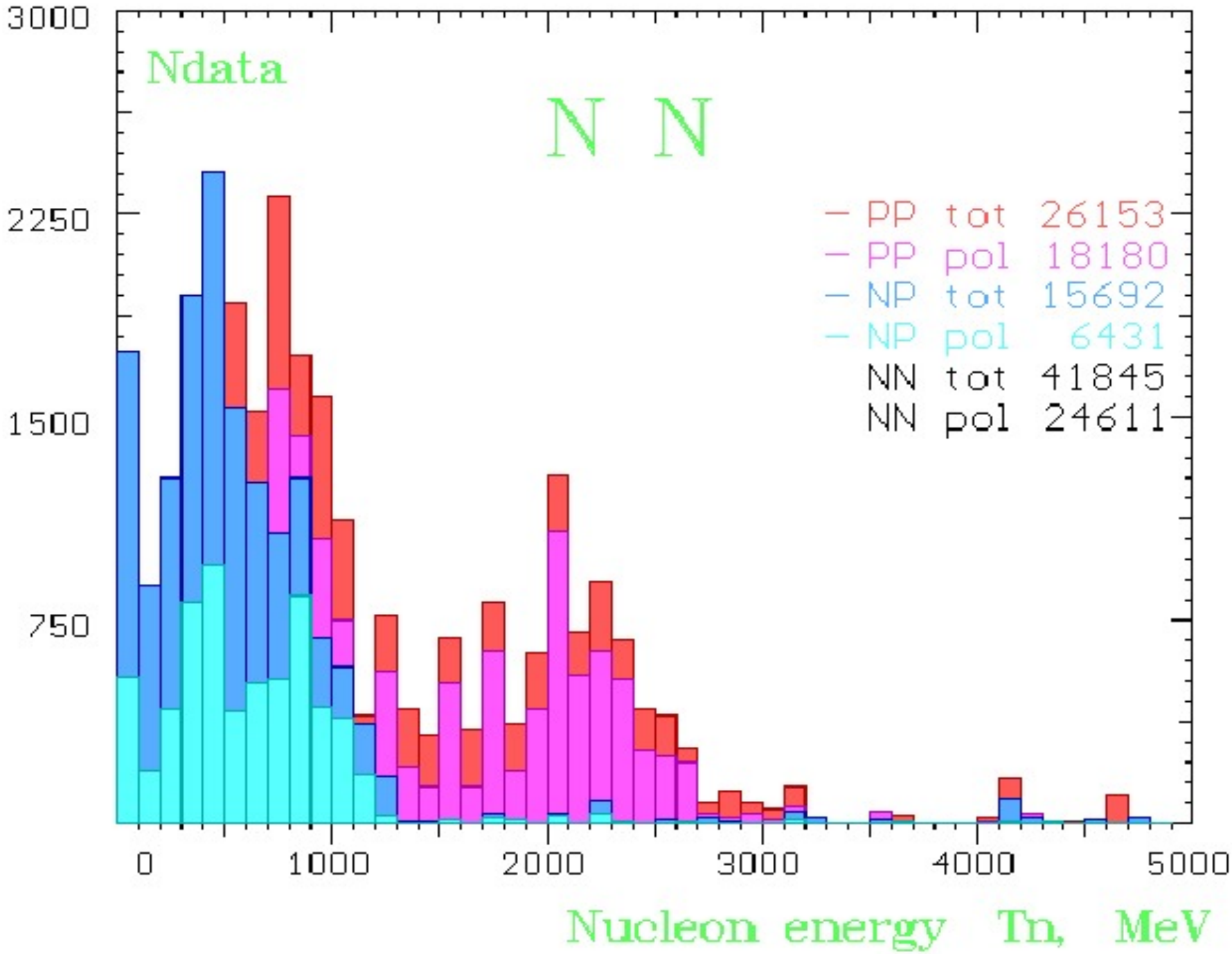
Outline

- **Introduction.**

  Aims of the "Delta-Sigma" experiment. Program, tools.
- **Determination of $A_{00kk}(np)$, $A_{00nn}(np)$ and R_{dp} observables.**
- **Experimental set-up and the neutron beam parameters.**
- **Magnetic spectrometer for investigation of the elastic $np \rightarrow pn$ charge exchange process.**
- **A number of characteristics of the magnetic spectrometer and studied process.**
- **Procedure of the data treatment and the R_{dp} results.**
- **Conclusion.**

The theory of the nucleon-nucleon (NN) interaction in the range of about 1-10 GeV is one of the most pressing open questions of modern nuclear/particle physics.
Below that energy range, chiral effective field theory applies as well as meson theory.
At very high energies (~ 100 GeV) perturbative QCD can be used.
But it is the "intermediate" region of a few GeV where theory has big problems.
For our understanding of the fundamental NN interaction on a broad scale, it is vital to have data for np spin observables in the GeV region.

The aim of the project "Delta-Sigma" Experiment
http://www.jinr.ru/PAC_2006_apr/PAC_pp/13.7.%20DELTA-SIGMA/
(see also Ref.[29] in arXiv:0706.2195 [nucl-th])
is to extend the investigations of NN interaction over a new high 1.2 – 3.7 GeV energy region of free polarized neutron beams, provided at present only by the JINR VBLHE accelerator.


Ndata
N N
PP tot 26153
PP pol 18180
NP tot 15692
NP pol 6431
NN tot 41845
NN pol 24611
3000
2250
1500
750
0
1000
2000
3000
4000
5000
Nucleon energy Tn, MeV

The main task of the "Delta-Sigma" Experiment is determination for the first time the imaginary and real parts of spin-dependent forward scattering NN amplitudes over this energy region.

To reach this aim, a sufficient data set on energy dependencies of np spin-dependent observables have to be obtained for direct and simple reconstruction of these amplitudes.

The Delta-Sigma experiment research program

1. Using longitudinally *(L)* and transverse *(T)* polarized neutron beams and polarized proton target to measure the energy dependencies of

   a) the total cross section differences $\Delta\sigma_L(np)$ and $\Delta\sigma_T(np)$ for parallel and antiparallel directions of beam and target polarizations, with energy steps of *100–200 MeV* and expected statistical errors of *1 mb*.

The observables $\Delta\sigma_L(np)$ and $\Delta\sigma_T(np)$ are linearly related to the imaginary parts of the two spin-dependent forward scattering invariant amplitudes *c* and *d* via optical theorems and allow to extract these imaginary parts.

   b) the spin-correlation parameters $A_{00kk}(np)$ and $A_{00nn}(np)$ with expected statistical errors of *0.02 – 0.05* (simultaneously with and independently of the $\Delta\sigma_{L,T}(np)$ measurements) .

The $A_{00kk}(np)$ and $A_{00nn}(np)$ values will be obtained from a registration of yields of elastic charge exchange process $np \rightarrow pn$ at *0* angle. They are related to the real part of the amplitudes mentioned above and data to be obtained will be used to extract ones.

The Delta-Sigma experiment research program

2. Using high intensity unpolarised neutron beam and liquid hydrogen and deuterium targets, to measure

c) the ratio $R_{dp} = [d\sigma/d\Omega(nd)] / [d\sigma/d\Omega(np)]$ for elastic charge exchange process $np \rightarrow pn$ at 0 angle on deuterium and hydrogen targets with 5% statistical errors at the same energies as for i. 1.

Experimental observable R_{dp} is the ratio of a quasi-elastic nd scattering differential cross section to the free np elastic scattering one.

The values of R_{dp} can give one additional relation between spin-dependent NN-amplitudes and a set of such data allows to avoid one uncertainty of extraction of amplitudes real parts.

The data set on energy behaviors of spin-dependent observables $\Delta\sigma_{L,T}(np)$, $A_{00kk}(np)$, $A_{00nn}(np)$ and R_{dp} will be obtained for the first time over the energy range of neutron beam of 1.2–3.7 GeV.

Besides the direct amplitude reconstruction, this data set will be used to extend the NN phase shift analysis to more high energies and to verify the dynamical model predictions.

Accelerators and tools

- The Nuclotron VBLHE, JINR.

  Relativistic *1 – 5 GeV*
  polarized neutron beams with average polarization value of 0.53,
  orientation of polarization *L* or *T* and
  reversion of polarization direction cycle by cycle;
  unpolarized neutron beam with high intensity
  ($4x10^6$ n/cycle at *T_n = 2 GeV)*.

- Large *(140 cm^3)* polarized proton target with polarization value of *0.7–0.8*.

- Cryogenic hydrogen *H_2* and deuterium *D_2* targets *(L = 34 cm)* .

- " Delta-Sigma" set-up with:

- monitor and transmission neutron detectors;
- magnetic spectrometer with proportional chambers;
- detectors for target surrounding;
- time-of-flight system;
- adequate data acquisition system.

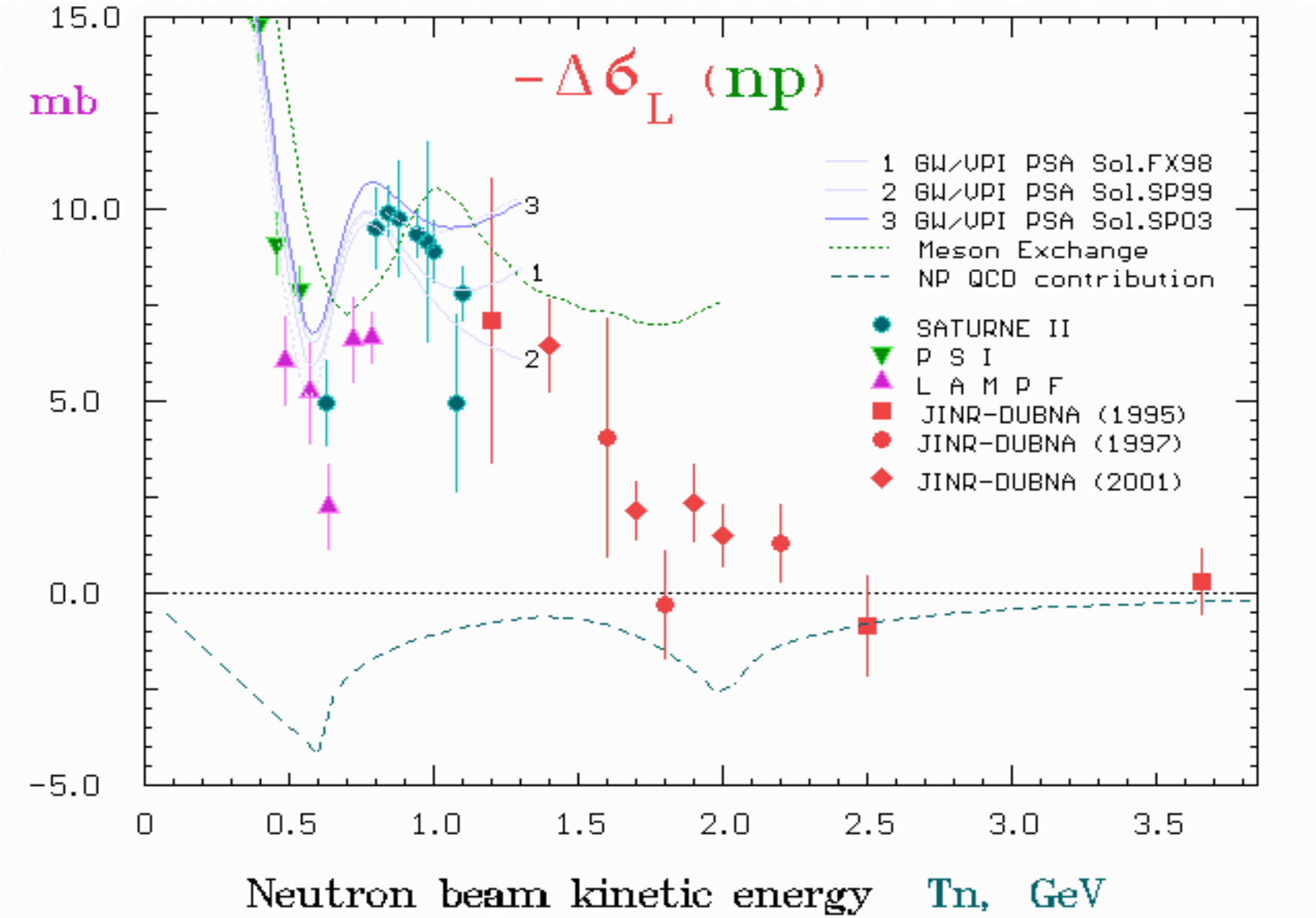
Measurements of the $-\Delta\sigma_L$ (np) energy dependence were in the main completed using L-polarized neutron beam from the Synchrophasotron and the Dubna L-polarized proton target .

Results were published in:

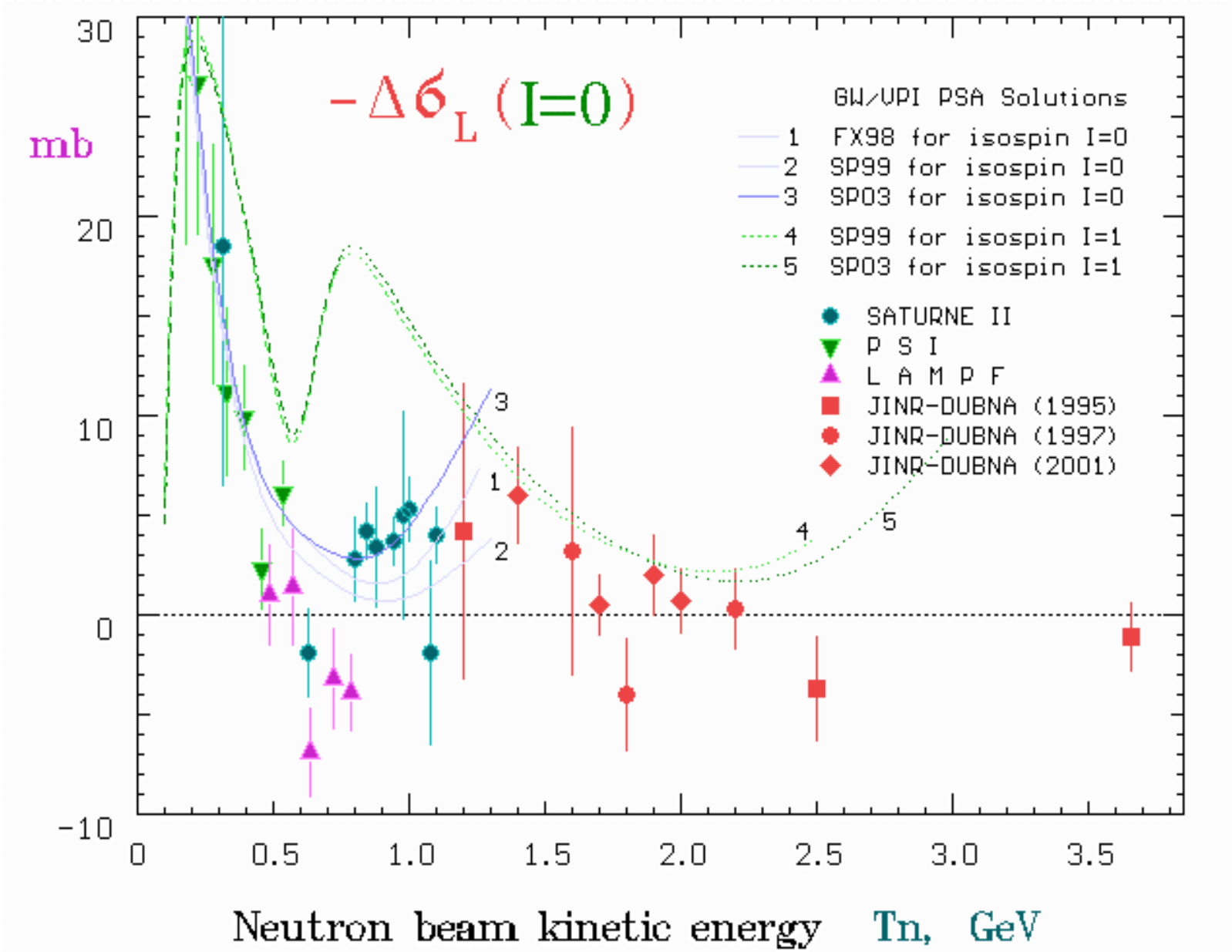
References on $-\Delta\sigma_L$ (np) results

1. B.P.Adiasevich, V.G.Antonenko, S.A.Averichev, L.S.Azhgirey et al. **Zeitschrift fur Physik C71 (1996) 65.**
2. V.I.Sharov, S.A.Zaporozhets, B.P.Adiasevich, V.G.Antonenko et al. **JINR Rapid Communications 3[77]-96 (1996) 13.**
3. V.I.Sharov, S.A.Zaporozhets, B.P.Adiasevich, N.G.Anischenko et al. **JINR Rapid Communications 4[96]-99 (1999) 5.**
4. V.I.Sharov, S.A.Zaporozhets, B.P.Adiasevich, N.G.Anischenko et al. **European Physical Journal C13 (2000) 255.**
5. V.I.Sharov, N.G.Anischenko, V.G.Antonenko, S.A.Averichev et al. **European Physical Journal C37 (2004) 79-90.**
6. V.I.Sharov, N.G.Anischenko, V.G.Antonenko, S.A.Averichev et al. **Yadernaya Fizika v.68, №11 (2005) 1858-1873.**
   Physics of Atomic Nuclei v.68, №11 (2005) 1796-1811.

Energy Dependence of the $-\Delta\sigma_L$ (np) Observable Obtained with Free Neutron Polarized Beams



Energy Dependence of the $-\Delta\sigma_L$ (I=0)



The continuation of measurements of the $\Delta\sigma_{L,T}$ (np) and A_{00kk}(np) and A_{00nn}(np) energy dependences using L and T orientations of beam and target polarizations will be possible in the near future when the new high intensity source of polarized deuterons (CIPIOS) will be put in operation at the Nuclotron and when the T mode of target polarization will be ready.

During the last period, in frame of the project experimental program, the studies of elastic np->pn charge exchange process are carried out using high intensity unpolarized neutron beams and cryogenic H_2 and D_2 targets (l=34 cm).

The results of these measurements will be presented below.

Measurements of the $A_{00kk}(np)$ and $A_{00nn}(np)$ from $np \rightarrow pn$ process at 0^o in Lab

- **If the scattered particles are detected at 0^o angle then only two non-vanishing spin-dependent quantities $A_{00nn}(E,0^o)$ and $A_{00kk}(E,0^o)$ can be measured from the $np \rightarrow pn$ scattering.**

  C.Lechanoine-Leluc and F.Lehar. Rev. Mod. Phys. 65, 47 (1993).

  J. Ball, R.Binz, J.Bystricky et al. Eur.Phys.J. C 5, 57 (1998).

- **These *NN*-observables are connected with invariant amplitudes by (the centre of mass system):**

$$d\sigma/d\Omega\,(\pi) = \tfrac{1}{2}[|a|2 + |b|2 + |c|2 + |d|2], \quad (17)$$

$$d\sigma/d\Omega\, A_{00nn}(\pi) = \tfrac{1}{2}[|a|2 - |b|2 - |c|2 + |d|2], \quad (18)$$

$$d\sigma/d\Omega\, A_{00kk}(\pi) = Re\, a^* d + Re\, b^* c. \quad (19)$$

- **These equations can be transformed to:**

$$d\sigma/d\Omega\,(1 + A_{00kk}) = |b + c|2 = A + (Re\, b + Re\, c)2, \quad (20)$$

$$d\sigma/d\Omega\,(1 - A_{00kk} - 2A_{00nn}) = |b - c|2 = B + (Re\, b - Re\, c)2, \quad (21)$$

$$d\sigma/d\Omega\,(1 - A_{00kk} + 2A_{00nn}) = |b + c - 2d|2 = C + (Re\, b + Re\, c - 2Re\, d)2, \quad (22)$$

where terms *A, B, C* contain the amplitudes imaginary parts only.

- **The amplitudes real parts *b, c*, and *d* can be determined from equations *(20), (21), (22)* using known imaginary ones.**

- **Experimental observable**

$$R_{dp} = d\sigma/d\Omega(nd) / d\sigma/d\Omega(np) \qquad (23)$$

is the ratio of a quasi-elastic *nd* scattering differential cross section to the free *np* elastic scattering one. At $\theta_{CM} = \pi$ (F.Lehar. Private communication)

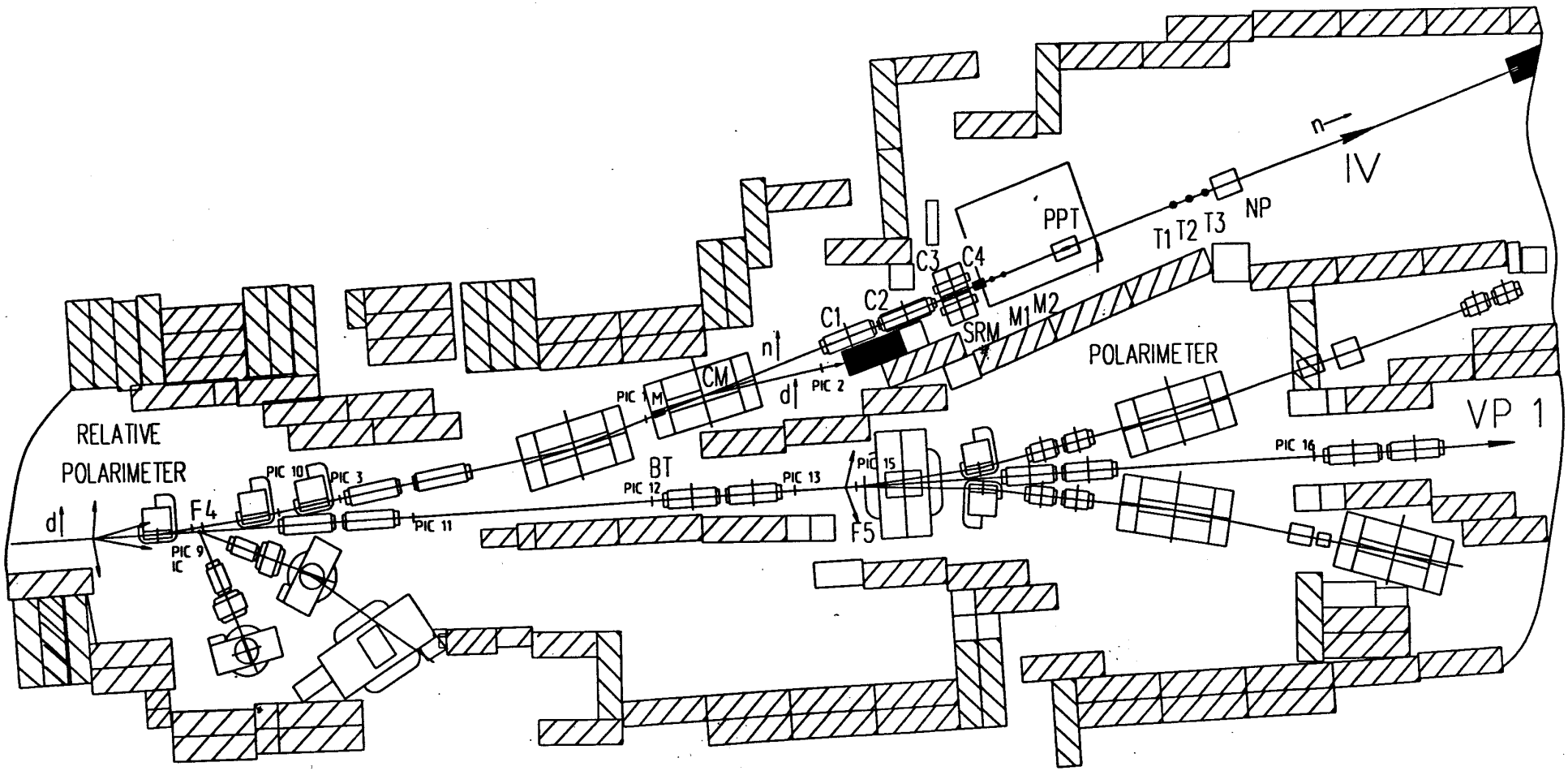
$$R_{dp}(\pi) = (2/3) \cdot d\sigma/d\Omega^{SD}(np) / d\sigma/d\Omega(np), \qquad (24)$$

$$R_{dp}(\pi) = (2/3) \cdot [0.25 \cdot |a - b|^2 + 0.5 \cdot (|c|^2 - |d|^2)] / 0.5 \cdot (|a|^2 + |b|^2 + |c|^2 + |d|^2), \qquad (25)$$

where $d\sigma/d\Omega^{SD}(np)$ is the "spin-dependent" part of the *np→pn* differential cross section.

- **Energy dependence of the ratio R_{dp} for elastic charge exchange process *np→pn* at *0°* in Lab (or elastic *np→np* backward scattering in C.M.S.) is being measured using high intensity unpolarised neutron beam from the Nuclotron and the magnetic spectrometer of the Delta-Sigma set-up with liquid hydrogen and deuterium targets.**

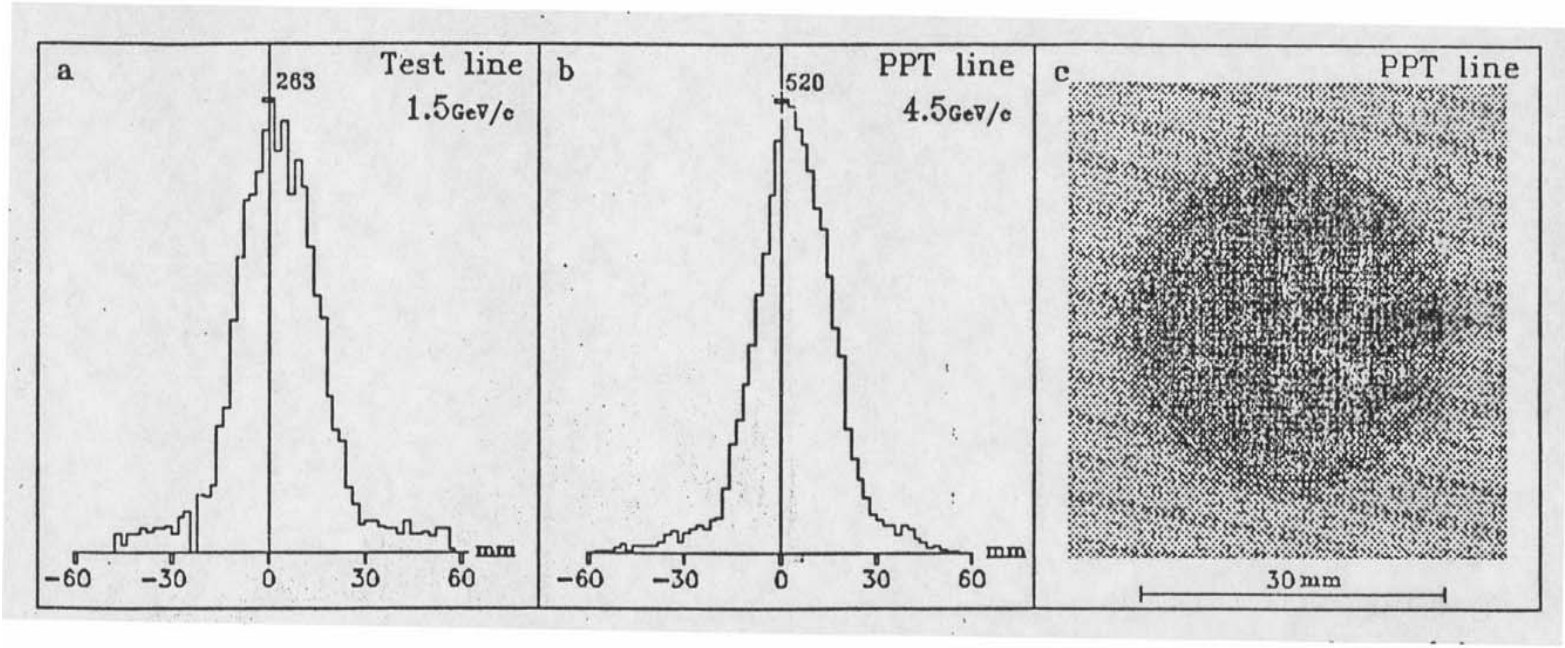
- **The values of R_{dp} can give one additional relation between spin-dependent *NN*-amplitudes and a set of such data allows to avoid one uncertainty of extraction of amplitudes real parts.**



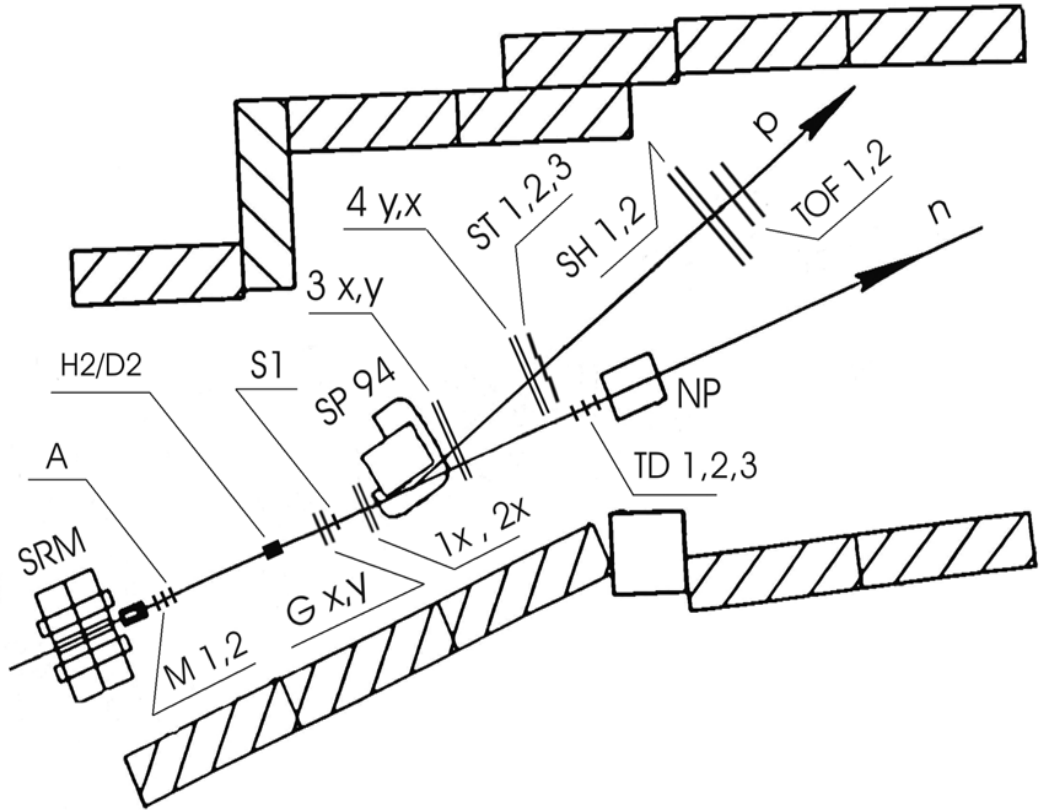
DELTA-SIGMA Setup at the Polarized Neutron Beams of the JINR VBLHE

VP 1 **– beam line of polarized deuterons;** ***1V*** **– beam line of polarized neutrons;**
BT **– beryllium neutron production target;** ***IC*** **– ionization chamber;**
PIC 1-3, 9-16 **– multiwire proportional/ionization chambers;** ***CM*** **– sweeping magnet;**
C1-C4 **– set of neutron beam collimators;** ***SRM*** **– neutron spin rotating magnet;**
PPT **– polarized proton target;** ***NP*** **– neutron profilometer**

Neutron Beam Parameters



- The beam of free quasi-monochromatic neutrons is obtained by break-up at 0^o of deuterons in the Beryllium target BT (20 cm×8×8 cm^2).
- Neutron beam is formed by a set of collimators C1–C4.
- The deuteron beam momentum P_d is known with accuracy of ~1 %.
- The neutron beam has the momentum $P_n = P_d /2$ with a gaussian momentum spread of FWHM ~ 5 %.
- Intensity of prepared neutron beam at $T_n = 2.0$ GeV was ~$4 \cdot 10^6$ n/cycle.



Spectrometer of the “Delta-Sigma” set-up

- The magnetic spectrometer consist of the analyzing dipole SP94, two sets of the multiwire proportional chambers PCs: Gx, Gy, 1x, 2x before and PCs: 3x, 3y, 4x, 4y after SP94 for momentum analyzis of detected secondaries;
- Time-of flight system S1, TOF1,2 for particle identification;
- Liquid H_2 / D_2 or solid CH2 / CD2 targets inserted in the neutron beam line instead of the PPT and surrounded by a device DTS for detecting of charged recoils and gammas;
- Trigger counters A, S1, ST1,2,3.

Multiwire proportional chambers

Wires spacing is 2 mm for all PCs.

PCs name

Before analysing magnet:

Gx, Gy	64 wires	(128 mm).
1x, 2x	96 wires	(192 mm).

After analysing magnet:

3x, 4x	192 wires	(384 mm).
3y, 4y	144 wires	(288 mm).
Total:	**848 wires**	

PCs efficiencies at 1.4 GeV. H2 target.

			Zero	All	One	Two	Cl2	Mn2
On - line								
1	1x	3	0.026	0.974	0.880	0.069	0.049	0.020
2	2x	4	0.032	0.968	0.859	0.082	0.069	0.013
3	3x	5	0.049	0.951	0.512	0.393	0.388	0.005
4	3y	6	0.031	0.969	0.868	0.070	0.060	0.009
5	gy	2	0.015	0.985	0.885	0.072	0.058	0.014
6	gx	1	0.010	0.990	0.868	0.092	0.077	0.015
7	4x	7	0.058	0.942	0.561	0.339	0.330	0.008
		Total:		**0.798**				

				Off – line	EffPC	dEffPC	(One + Cl2)
1	1x	3			0.948	0.003	
2	2x	4			0.951	0.003	During the data treatment, the
3	3x	5			0.948	0.003	information from PC 1x “or” PC 2x
4	3y	6			0.972	0.004	and PC 3x “or”/”and” PC 4x
5	gy	2			0.957	0.003	was used.
6	gx	1			0.959	0.003	
7	4x	7			0.917	0.003	
			Total:		**0.887**		

Some characteristics of the spectrometer.

Accuracies:

θ_x :

bin 1.97 mrad, instrum. error 0.83 mrad for PCs Gx-1x,

bin 1.79 mrad, instrum. error 0.76 mrad for PCs Gx-2x.

θ_y :

bin 0.61 mrad, instrum. error 0.26 mrad for PCs Gy-3y.

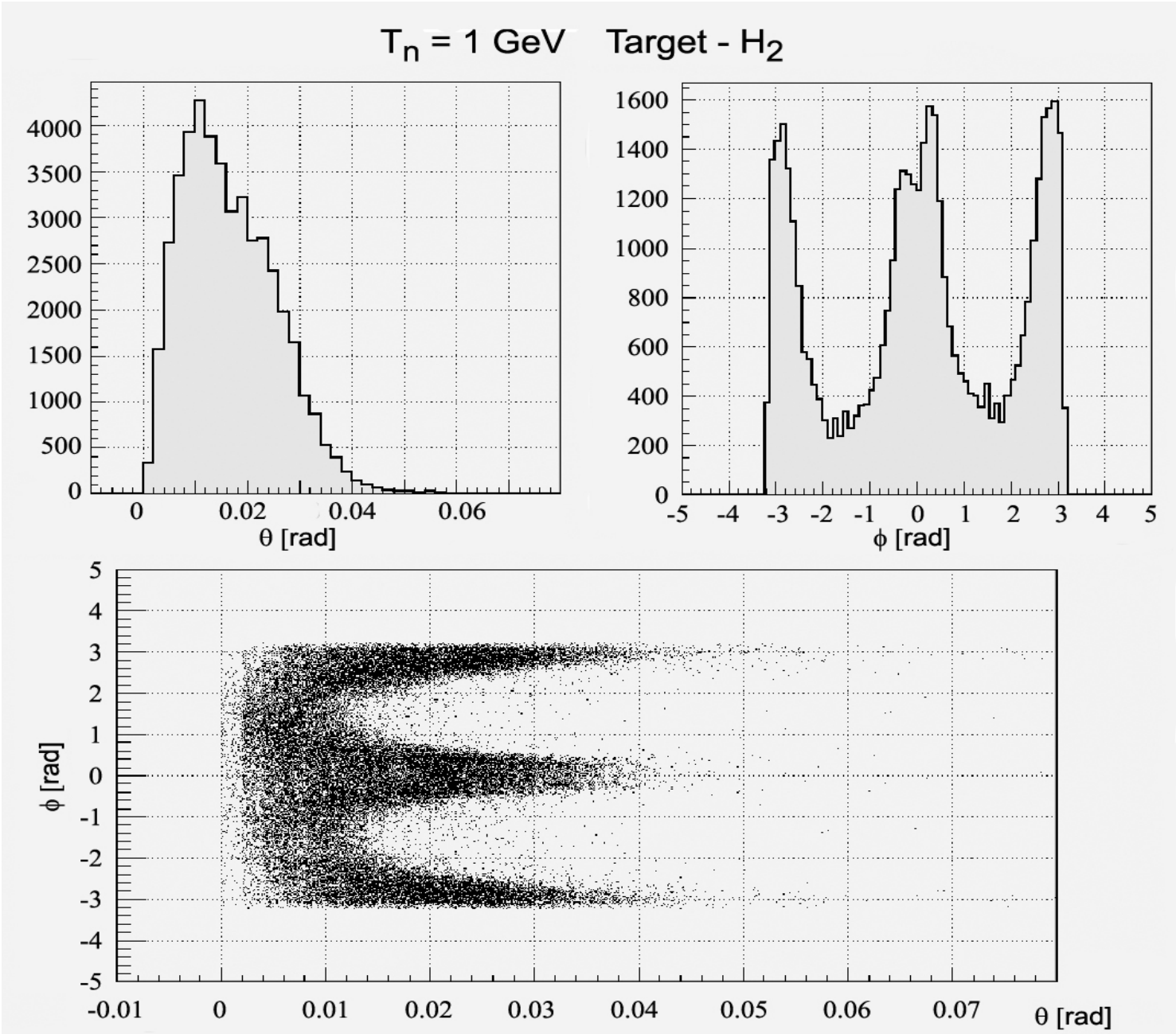
$\sigma P/P$:

measured at the extracted deuteron beam

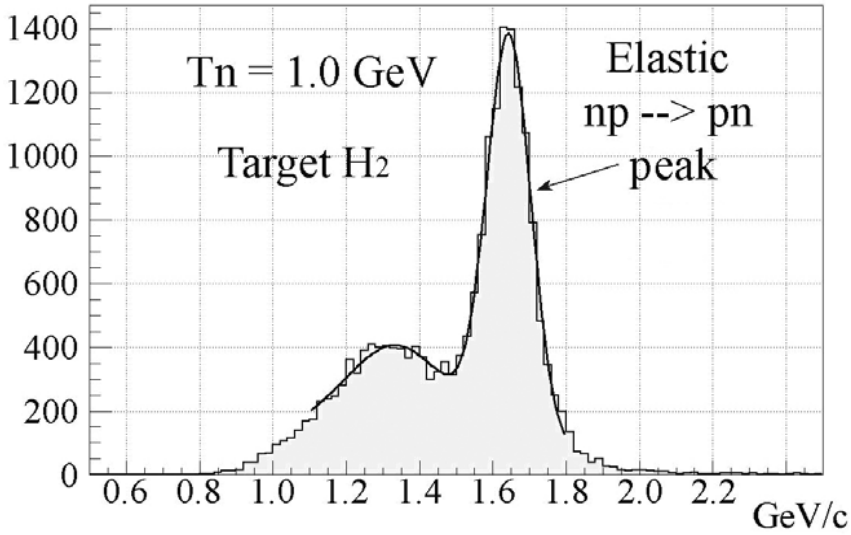
1.40 % using PCs Gx, 1x “or” 2x,(3x “and” 4x) or (3x “or” 4x),

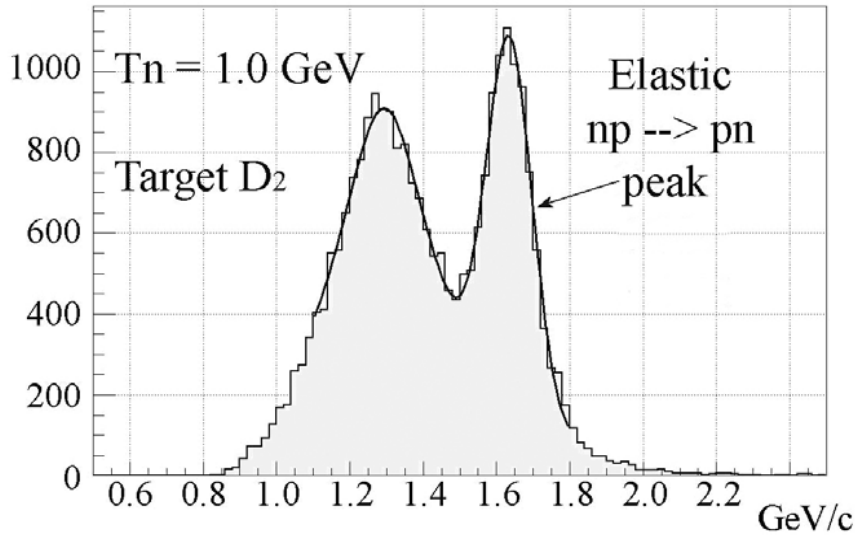
1.37 % using PCs Gx, 2x, 3x and 4x only.

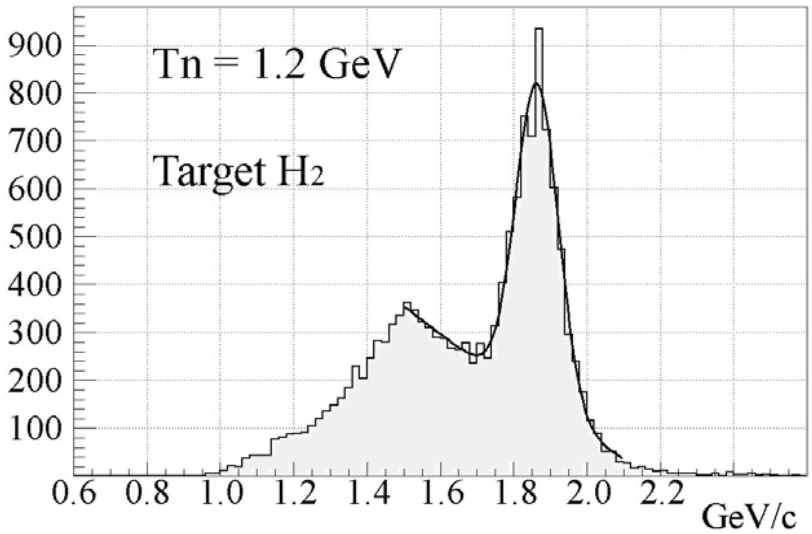
Detected events distribution in the θ vs φ plane

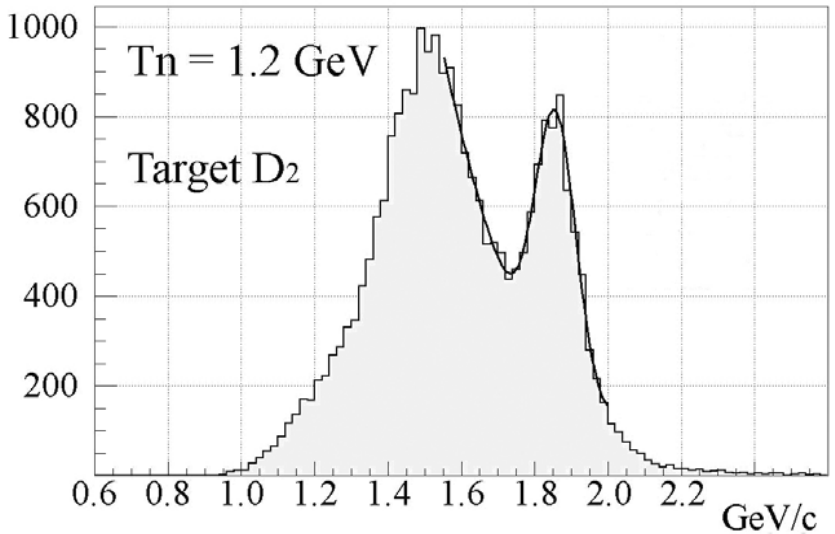


The momentum spectra of charged secondaries for H_2 and D_2 liquid targets at the neutron beam energies of 1.0 and 1.2 GeV.

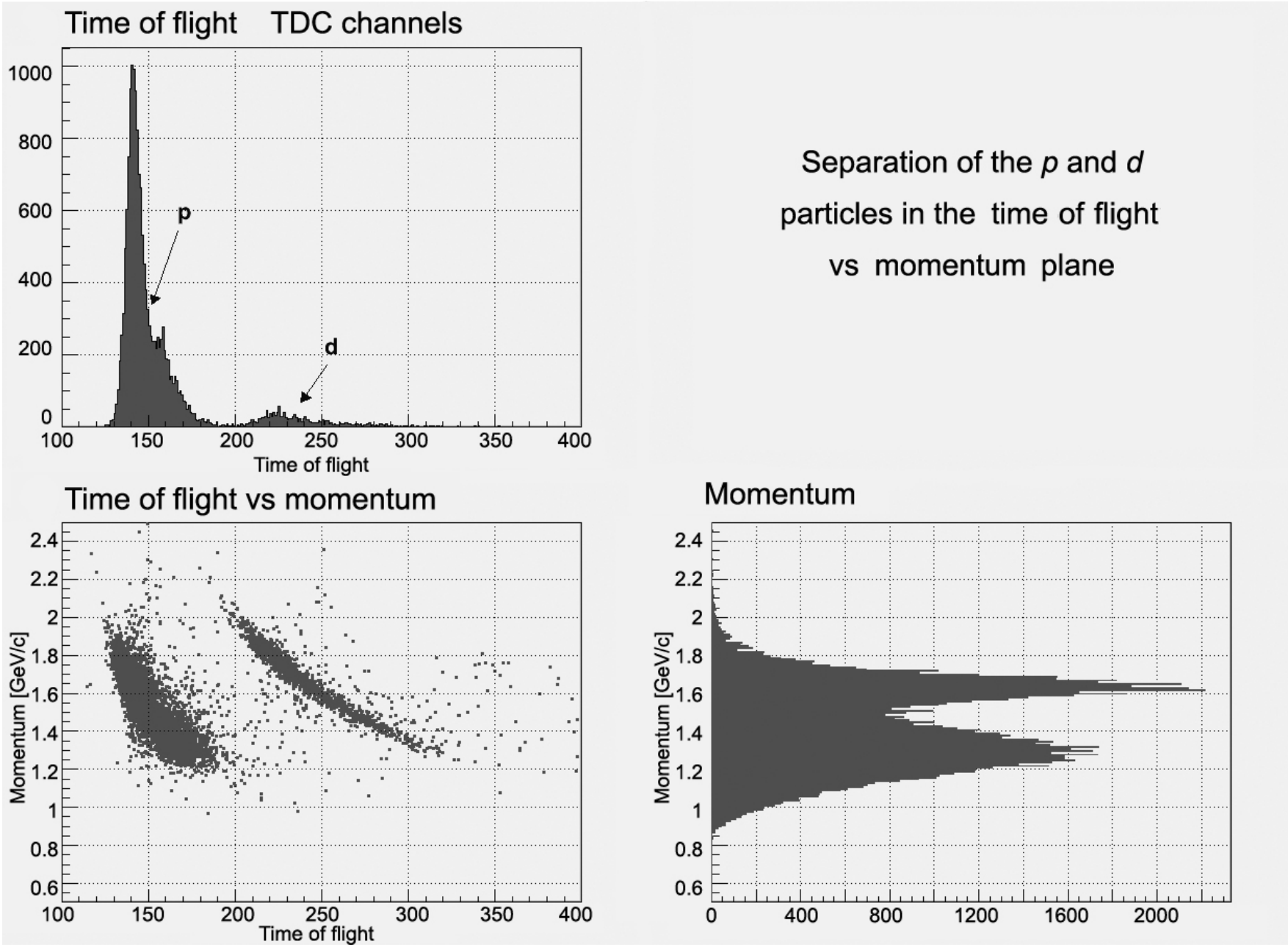




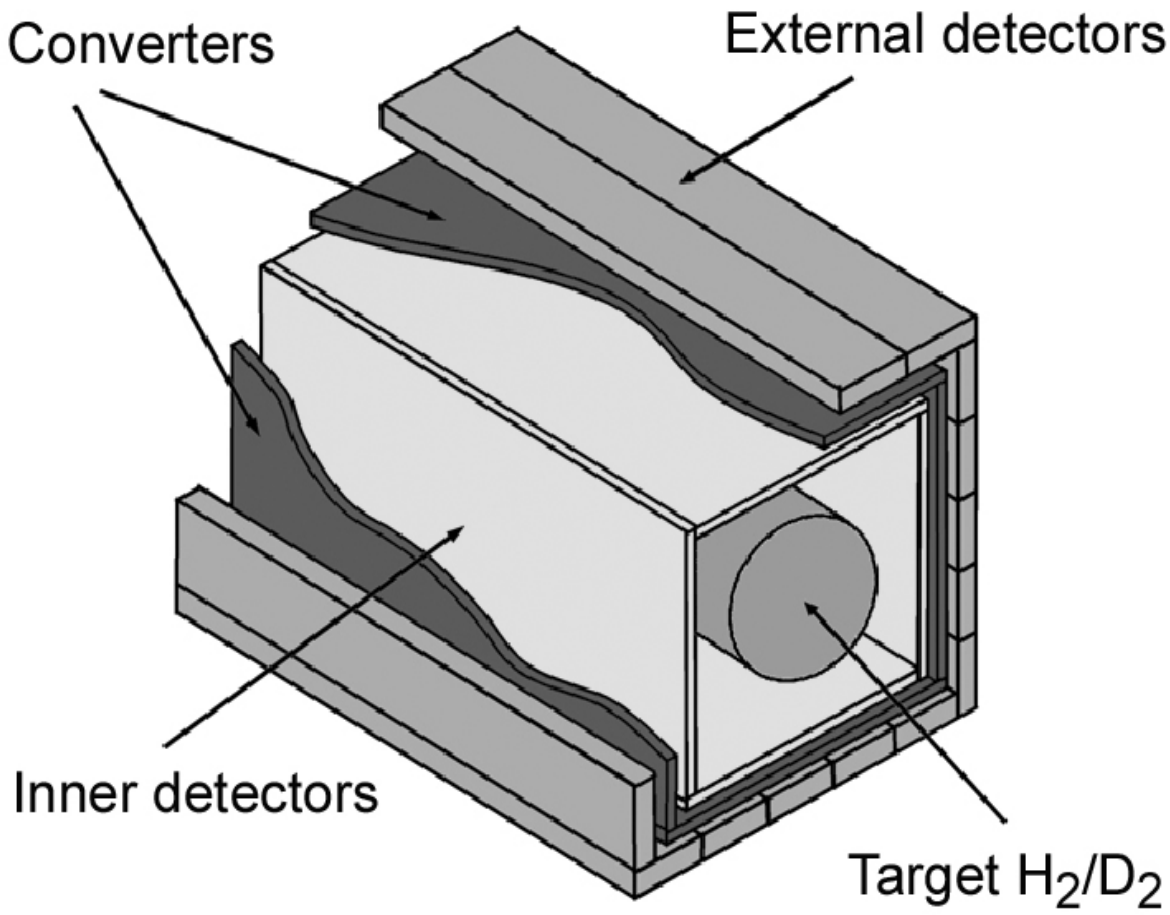


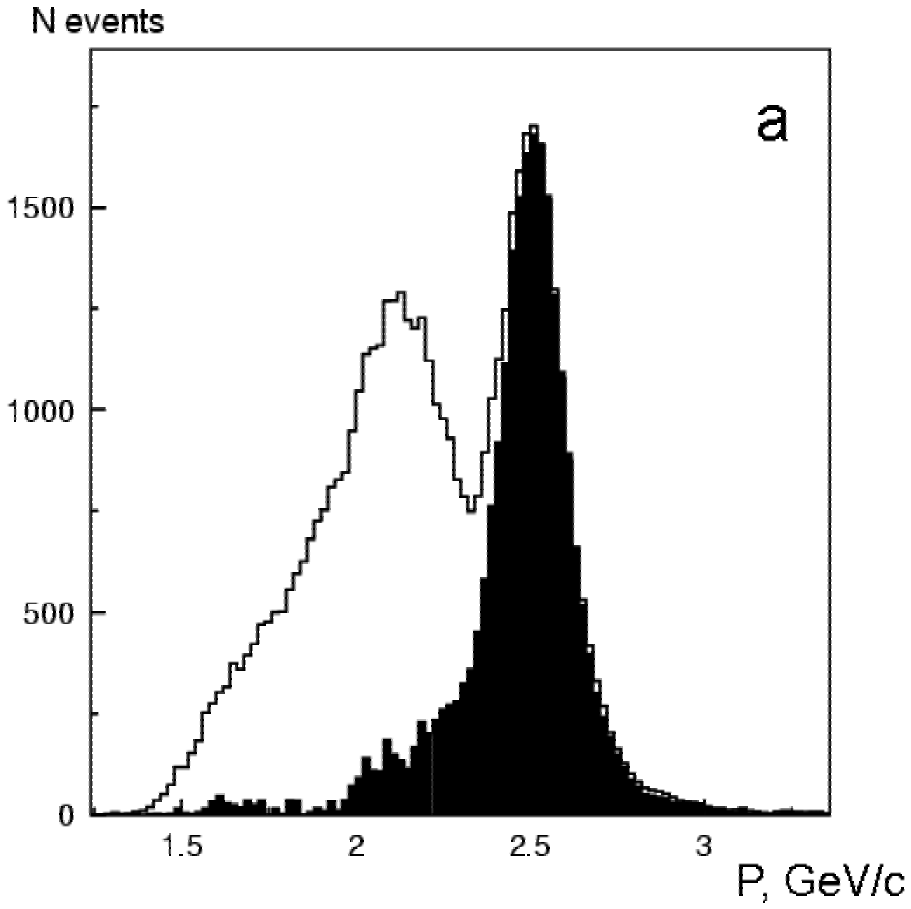


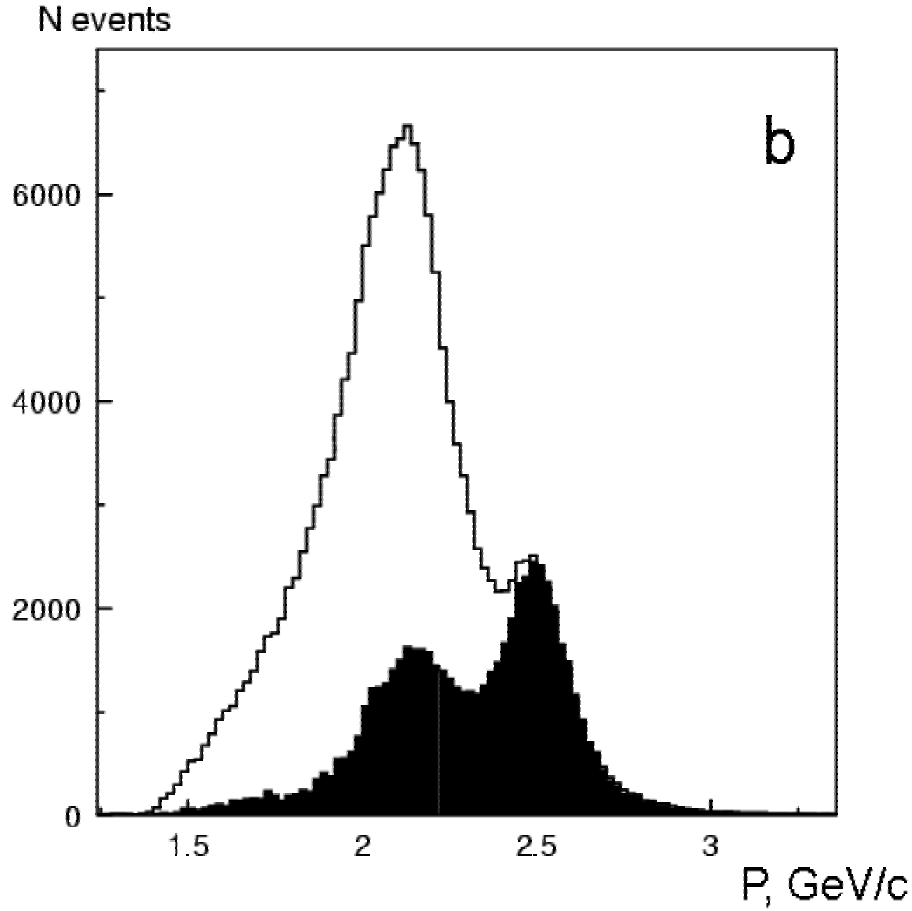
Separation of the *p* and *d* particles by the TOF vs momentum



Detectors for the target surrounding (DTS)







Information from the detectors for target surrounding DTS allows to suppress the contributions from other (inelastic) np-reaction channels.

The momentum spectra of charged secondaries at the neutron beam energy of 1.8 GeV.

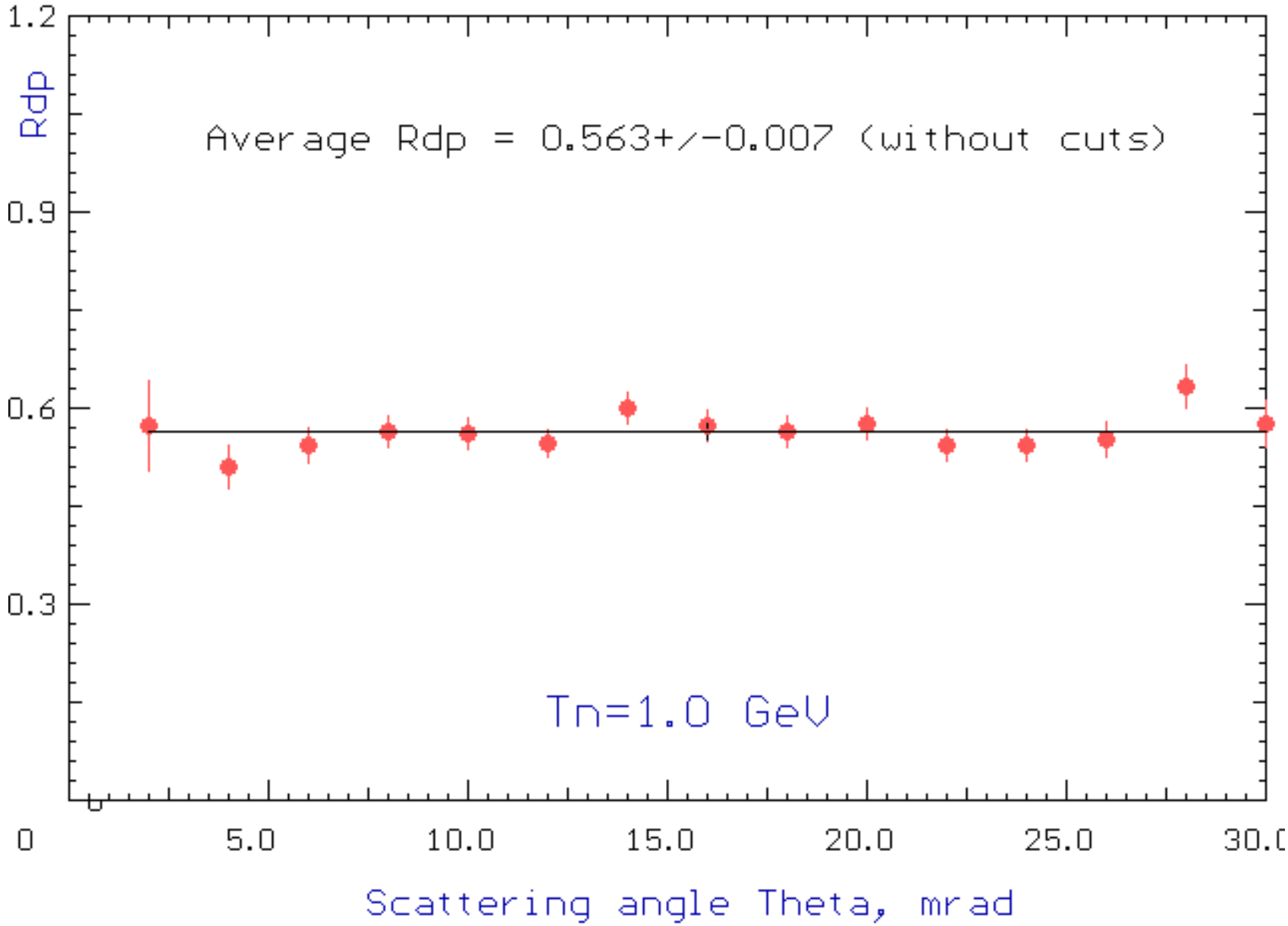
a- with liquid hydrogen target **b- with liquid deuterium target**

Systematical errors.

Estimations for data at Tn = 1.4 GeV.

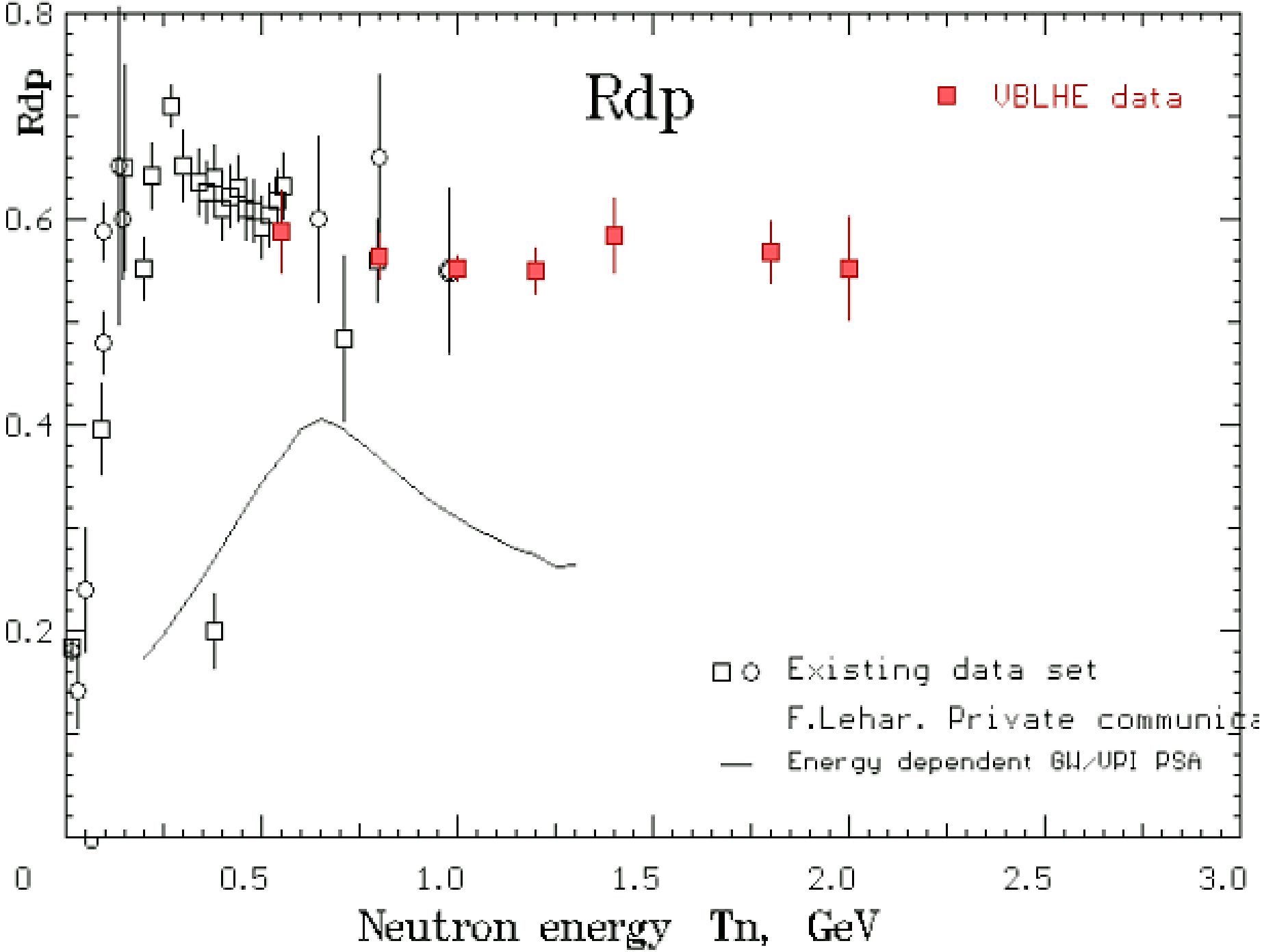
Sources of systematic error	Absolute values of the Rdp error
1. Total PC efficiency	**0.0041**
2. Trigger PC efficiency	**0.0039**
3. Efficiency of the DTS	**0.0238**
4. Efficiency of TOF	**0.0046**
5. d-admixtures determination	**0.0053**
6. Error in shift determination of the H2 and D2 elastic peak center positions	**0.0245**
7. Number of H/D nuclei in the targets	**0.0014**
Total:	**0.0354**

The ratio R_{dp} angular distribution at Tn = 1.0 GeV



Values of $R_{dp} = d\sigma/d\Omega\ (nd) / d\sigma/d\Omega\ (np)$. Total errors are the quadratic sums of statistical and systematic uncertainties.

NN	Tn, GeV	Pn, GeV/c	R_{dp}	Errors		
				Stat.	Syst.	**Total**
1	0.550	1.1559	**0.5886**	0.0242	0.0317	**0.0399**
2	0.800	1.4640	**0.5646**	0.0165	0.0132	**0.0211**
3	1.000	1.6968	**0.5522**	0.0085	0.0095	**0.0128**
4	1.200	1.9222	**0.5506**	0.0109	0.0189	**0.0218**
5	1.400	2.1426	**0.5847**	0.0254	0.0247	**0.0355**
6	1.800	2.5734	**0.5673**	0.0158	0.0245	**0.0292**
7	2.000	2.7854	**0.5523**	0.0137	0.0223	**0.0500**


Rdp
Rdp
VBLHE data
Existing data set
F.Lehar. Private communica
Energy dependent GW/VPI PSA
0.8
0.6
0.4
0.2
0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron energy Tn, GeV

Conclusion

The possibilities for $A_{00kk}(np)$, $A_{00nn}(np)$ and Rdp measurements, using prepared magnetic spectrometer, were demonstrated.

New results at $\theta_{CM} = \pi$ for $R_{dp} = d\sigma/d\Omega(nd) / d\sigma/d\Omega(np)$ – the ratio of a quasi-elastic nd scattering differential cross section to the free np elastic scattering one at $0.5, 0.8, 1.0, 1.2, 1.4, 1.8$ and 2.0 GeV are presented.

We are grateful to the JINR, JINR VBLHE and DLNP Directorates for these investigations support. The investigations were supported in part by the Russian Foundation for Basic Research (Grant № 07–02–01025).