Double polarized deuteron-deuteron scattering and test of T-invariance

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CONTENT

- Motivation: **BAU probem**
  Time-reversal Invariance test (TRIC) was planned at COSY in **pd** at 135 MeV.
  Theory: Yu.N.U., A. Temerbayev , PRC 92 (2015); Yu.U., J. Haidenbauer, PRC 94 (2016)
  ^{3}He-d Yu.N.U, M.N. Platonova, JETP Lett. 118 (2023) 11.
  d-d ? M.N. Platonova, Yu.N. U. arXiv: 2410.03262 [nucl-th]

- T-invariance Violating P-parity conserving (**TVPC**) flavor conserving NN interactions
- Null-test signal of TVPC in d-d scattering in Glauber spin-dependent theory
- Numerical results in the GeV region and at NICA SPD energies
- About possible experiment

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N 23-22-00123 https://rscf.ru/project/23-22-00123/

BAU - **Baryon Asymmetry of the Universe (WMAP+COBE)**:
A. Sakharov conditions.
New source of CP-violation (or T-violation under CPT) is required beyond the SM

$$\eta_{\exp} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10} \gg \eta_{SM} \sim 10^{-19}$$

Experiments for search of CP- violation:
*Permanent **EDM** of neutron, neutral atoms, p,d, 3He, leptons.
*Neutrino sector, δ_{CP} phase in PMNS matrix, lepton asymmetry via **B-L** conservation to **BAU**

Both are T-violating and P- violating (TVPV) effects

Much less attention was paid to T-violating P-conserving (TVPC) and flavor conserving effects

first considered by L. Okun and J. Prentki, M.Veltman, L. Wolfenstein (1965) to explain CP violation in kaons; do not arise in SM , being detected at current level of exp. accuracy will be a **direct evidence of physics beyond the SM**.

Experimental limits on TVPC effects are much weaker then for EDM

EFT: **Available experimental restrictions to EDM put no constrains on TVPC (for scenario "B" for EDM)**
A. Kurylov et. al. PRD 63 (2001) 076007 -> in contrast to **(scenario "A"**) / R.S. Conti, I.B. Khriplovich, PRL 68 (1992) 3262; Engel et al. PRD (1996) /

Direct experimental constraints on TVPC

- Test of the detailed balance $^{27}Al(p,\alpha)^{24}Mg$ and $^{24}Mg(\alpha,p)^{27}Al$, $\Delta = (\sigma_{dir} - \sigma_{inv})/(\sigma_{dir} + \sigma_{inv}) \leq 5.1 \times 10^{-3}$ (E.Blanke et al. PRL **51** (1983) 355). Numerous statistical analyses including nuclear energy-level fluctuations are required to relate to the NN T-odd P-even interaction (J.B. French et al. PRL **54** (1985) 2313) $\alpha_T < 2 \times 10^{-3}$ ($\bar{g}_\rho \leq 1.7 \times 10^{-1}$).

- $\vec{n}$ transmission through tensor polarized ^{165}Ho (P.R. Huffman et al. PRC **55** (1997) 2684)

$$\Delta = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-) \leq 1.2 \times 10^{-5}$$

$$\alpha_T \leq 7.1 \times 10^{-4} \quad (\text{or } \bar{g}_\rho \leq 5.9 \times 10^{-2})$$

- Elastic $\vec{p}n$ and $\vec{n}p$ scattering, A^p, P^p, A^n, P^n; CSB ($A = A^n - A^p$) (M. Simonius, PRL **78** (1997) 4161)

$$\alpha_T \leq 8 \times 10^{-5} \ (\text{ or } \bar{g}_\rho < 6.7 \times 10^{-3})$$

Remark: In view of BAU, the TVPC can be much stronger at high (NICA) energies

See S. N. Vergeles, N.N. Nikolaev, Yu.N. Obukhov, A.Yu. Silenko, O. Teryaev, UFN 66 (2023) 109

Search for null-test TVPC signal in double polarized d-d scattering

Null-test signal of Time-invariance Violating Parity Conserving (TVPC) effects is a part of total cross section of pd-, ^{3}Hed-, dd- scattering with one colliding particle being vector polarized (p^b_y) and another one tensor polarized (P_{xz}).

V. Baryshevsky, Sov. J. Nucl. Phys. 38 (1983) 699; A.L. Barabanov, Yad.Fiz. 44 (1986) 1163.

Advantages:

- **Only one observable. Not necessary to measure two observables (A_y and P_y) and determine their very small difference (for T-invariance $A_y = P_y$).**
- **Cannot be imitated by ISI@FSI.**

To compare: EDM (electric dipole moment) of particles and nuclei is a signal of T- and P-violation.

TVPC in pd- transmission experiment

under P-conservation

$$\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2 (\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz}}_{T-even, P-even} + \underbrace{\widetilde{\sigma}_{tvpc} p^p_y P^d_{xz}}_{T-odd, P-even}$$

Null-test signal

TIVOLI – exp. planned at COSY, T_p=135 MeV; P. Lenisa et al. EPJ Tech. Instr. (2019) 6

$$OZ \uparrow\uparrow \vec{k}, OY \uparrow\uparrow \vec{p}^{\,p}; OX \uparrow\uparrow [\vec{p}^{\,p} \times \vec{k}]$$

k – beam momentum

p^p (P^d) - proton (deuteron) polarization

$$A_{TVPC} = (T^+ - T^-)/(T^+ + T^-),$$

T^+ (T^-) – transmission factor for $p^p_y P_{xz} > 0$ ($p^p_y P_{xz} < 0$).
The goal is to improve the direct upper bound on TVPC by one order of magnitude up to $A_{TVPC} \sim 10^{-6}$

General decomposition of the total dd cross section

$$\sigma_{tot} = \sigma_0 + \sigma_{\perp\perp}[\mathbf{P}^{(1)}\cdot\mathbf{P}^{(2)} - (\mathbf{P}^{(1)}\cdot\mathbf{k})(\mathbf{P}^{(2)}\cdot\mathbf{k})]$$
$$+\sigma_{LL}(\mathbf{P}^{(1)}\cdot\mathbf{k})(\mathbf{P}^{(2)}\cdot\mathbf{k}) + \sigma_{T_1}P^{(1)}_{mn}k_m k_n + \sigma_{T_2}P^{(2)}_{mn}k_m k_n +$$

T-even P-even

$$\sigma_{T_1T_2}P^{(1)}_{mn}P^{(2)}_{mn} + \sigma_T P^{(1)}_{mn}k_m k_n P^{(2)}_{ij}k_i k_j + \sigma^{(1)}_{PV}\mathbf{P}^{(1)}\cdot\mathbf{k} + \sigma^{(2)}_{PV}\mathbf{P}^{(2)}\cdot\mathbf{k} +$$
$$\sigma^{(T_1P_2)}_{PV}\mathbf{P}^{(2)}\cdot\mathbf{k}P^{(1)}_{mn}k_m k_n + \sigma^{(T_2P_1)}_{PV}\mathbf{P}^{(1)}\cdot\mathbf{k}P^{(2)}_{mn}k_m k_n +$$

PV

$$\sigma_{TVPV}(\mathbf{k}\cdot[\mathbf{P}^{(1)}\times\mathbf{P}^{(2)}]) +$$

TVPV

$$\sigma^{(1,2)}_{TVPC}k_m P^{(1)}_{mn}\epsilon_{nlr}P^{(2)}_l k_r + \sigma^{(2,1)}_{TVPC}k_m P^{(2)}_{mn}\epsilon_{nlr}P^{(1)}_l k_r.$$

TVPC

$$k_m P^{(1)}_{mn}\varepsilon_{nlr}P^{(2)}_l k_r = P^{(1)}_{xz}P^{(2)}_y - P^{(1)}_{yz}P^{(2)}_x$$

Simplifications: $\sigma_{LL}, \sigma_{\perp\perp}$ *are excluded at* $\vec{P}^{(1)}\vec{k} = 0, P^{(2)}_y = 0$

$\sigma_{0}, \sigma_{T_1}, \sigma_{T_2}, \sigma_{T_1T_2}, \sigma_{T}$ excluded in asymmetry A_{TVPC}

TVPV and PV are negligible ($A \sim 10^{-7}$);

T-invariance: $< f \,|\, S \,|\, i >=< i_T \,|\, S \,|\, f_T >$

On-shell TVPC NN interaction t-operators (M.Beyer, NPA , 1993)

$$t_{pN} = \underbrace{h[(\boldsymbol{\sigma}_1 \cdot \mathbf{p})(\boldsymbol{\sigma}_2 \cdot \mathbf{q}) + (\boldsymbol{\sigma}_2 \cdot \mathbf{p})(\boldsymbol{\sigma}_1 \cdot \mathbf{q}) - (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\mathbf{p} \cdot \mathbf{q})]}_{h1-meson} +$$

$$+ \underbrace{g[\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2] \cdot [\mathbf{q} \times \mathbf{p}](\boldsymbol{\tau}_1 - \boldsymbol{\tau}_2)_z}_{abnormal\, parity\, OBE\, exchanges} + \underbrace{g'(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2) \cdot i\,[\mathbf{q} \times \mathbf{p}][\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2]_z}_{\rho-meson}$$

$\mathbf{p} = \mathbf{p}_f + \mathbf{p}_i,\ \mathbf{q} = \mathbf{p}_f - \mathbf{p}_i$

$$T : \vec{p}_i \to -\vec{p}_f, \vec{p}_f \to -\vec{p}_i \Rightarrow \vec{p} \to -\vec{p}, \vec{q} \to \vec{q}$$

$$\vec{n} = [\vec{q} \times \vec{p}] \to -\vec{n}, \vec{\sigma} \to -\vec{\sigma};$$

g'-term is T-odd due to:

$$< n, p|[\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2]_z|p, n >= -i2,\ < p, n|[\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2]_z|n, p >= i2,$$

in contrast to strong interaction, $M^{str}_{pn \to np} = M^{str}_{np \to pn}$.

Previous theoretical calculations

M. Beyer, Nucl.Phys. A 560 (1993) 895;

d-breakup channel only, 135 MeV;

Y.-Ho Song, R. Lazauskas, V.Gudkov, PRC 84 (2011) 025501; Faddeev eqs., nd-scattering at 100 keV; pd at 2 MeV

We use the Glauber theory:

A.A. Temerbayev, Yu.N. Uzikov, Yad. Fiz. **78** (2015) 38;

M.N. Platonova, V.I. Kukulin, Phys. Rev. C **81**, 014004 (2010)

Yu.N. U., A.A. Temerbayev, PRC 92 (2015); **pd**

Yu.N. U., J. Haidenbauer, PRC 94 (2016); **pd**

Yu.N. U., M.N. Platonova, JETP Lett. 118 (2023) 11 ; **^{3}He-d**

Yu.N. U.,M.N. Platonova et al. Int. J. Mod. Phys. E (2024); **dd**

M.N. Platonova, Yu.N. U. arXiv:2410.03262[nucl-th]; **dd**

dd-dd elastic scattering at θ=0° for TVPC-interaction

$$\hat{M}_{\mathrm{TVPC}}(0) = g_1\hat{O}_1 + g_2\hat{O}_2$$

In pd appears only one Q- operator of this type

$$\hat{O}_1 = \hat{k}_m \hat{Q}^{(1)}_{mn} \varepsilon_{nlr} S^{(2)}_l \hat{k}_r;$$

$$\hat{O}_2 = \hat{k}_m \hat{Q}^{(2)}_{mn} \varepsilon_{nlr} S^{(1)}_l \hat{k}_r;$$

$\hat{k}$ – beam direction

$S_l^{(i)}$ – spin-operator of the i-th deuteron

$$\hat{Q}^{(j)}_{mn} = \frac{1}{2}\left(S^{(j)}_m S^{(j)}_n + S^{(j)}_n S^{(j)}_m - \frac{4}{3}\delta_{mn}\right)$$

- tensor polarization operator

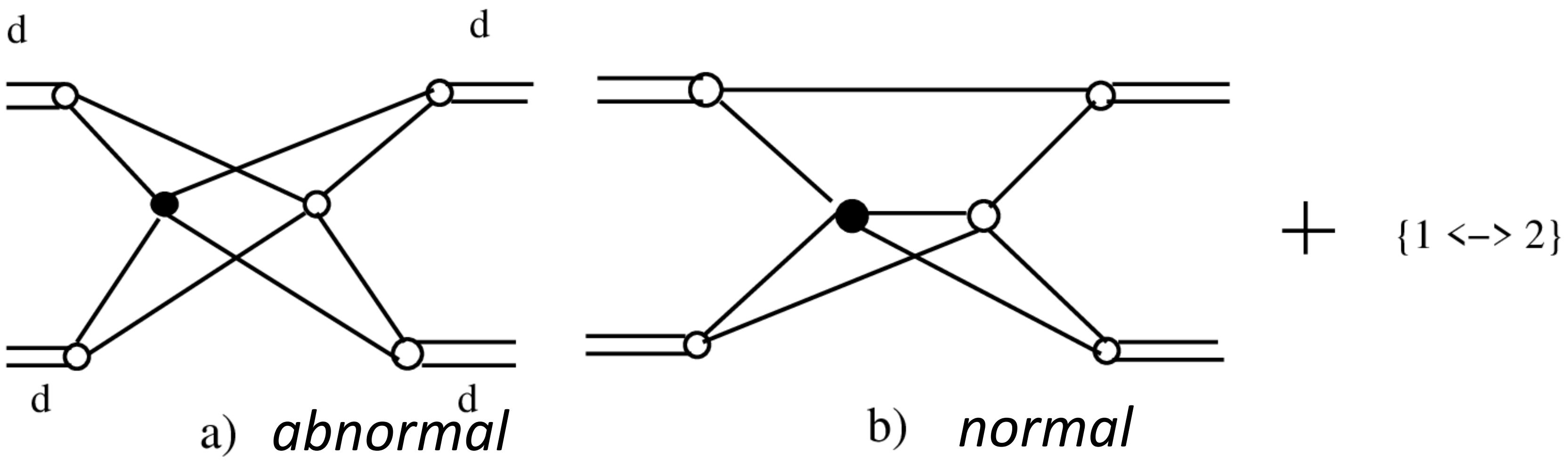
$$M_{-1,1;0,0} = < m_1' = -1, m_2' = 1 | \hat{M}_{\mathrm{TVPC}}(0) | m_1 = 0, m_2 = 0 >,$$

$$M_{1,0;0,1} = < m_1' = 1, m_2' = 0 | \hat{M}_{\mathrm{TVPC}}(0) | m_1 = 0, m_2 = 1 > .$$

$$g_1 = -i(M_{-1,1;0,0} + M_{1,0;0,1}),$$

$$g_2 = -i(M_{-1,1;0,0} - M_{1,0;0,1}),$$

Spin-dependent Glauber theory for the amplitudes g_1 and g_2



Generalized optical theorem:

$$\sigma_{\rm TVPC} = 4\sqrt{\pi}{\rm Im\,Tr}(\hat{\rho}_i \hat{M}_{\rm TVPC}(0))$$
$$= 4\sqrt{\pi}{\rm Im}\left(\frac{g_1}{9}\right)(P^{(1)}_{xz}P^{(2)}_{y} - P^{(1)}_{zy}P^{(2)}_{x})$$
$$+ 4\sqrt{\pi}{\rm Im}\left(\frac{g_2}{9}\right)(P^{(2)}_{xz}P^{(1)}_{y} - P^{(2)}_{zy}P^{(1)}_{x}).$$

TVPC amplitudes for dd

$$g_1 = g_1^{(n)} + g_1^{(a)}$$

$$g_2 = g_2^{(n)} + g_2^{(a)}$$

$$g_1^{(n)} = \frac{i}{\sqrt{2}\pi m_N} Z_0 \int\limits_0^\infty dq q^2 \zeta(q)[h_p(q)C_n(q) + h_n(q)C_p(q)],$$

$$g_2^{(n)} = \frac{i}{\sqrt{2}\pi m_N} Z_0 \int\limits_0^\infty dq q^2 \zeta(q)[h_p(q)C'_n(q) + h_n(q)C'_p(q)],$$

$$g_1^{(a)} = \frac{i}{\sqrt{2}\pi m_N} \int\limits_0^\infty dq q^2 Z(q)\zeta(q)[h_p(q)C_p(q) + h_n(q)C_n(q)],$$

$$g_1^{(a)} = \frac{i}{\sqrt{2}\pi m_N} \int\limits_0^\infty dq q^2 Z(q)\zeta(q)[h_p(q)C_p(q) + h_n(q)C_n(q)],$$

TVPC ordinary hadron pN ampl.

Form factors

$$Z(q) = S_0^{(0)}(q) - \frac{1}{2}S_0^{(2)}(q) - \frac{1}{\sqrt{2}}S_2^{(1)}(q) + \sqrt{2}S_2^{(2)}(q),$$

$$Z_0 = Z(0) = S_0^{(0)}(0) - \frac{1}{2}S_0^{(2)}(0) = 1 - \frac{3}{2}P_D,$$

$$\zeta(q) = S_0^{(0)}(q) + \frac{1}{10}S_0^{(2)}(q) - \frac{1}{\sqrt{2}}S_2^{(1)}(q) + \frac{\sqrt{2}}{7}S_2^{(2)}(q) + \frac{18}{35}S_4^{(2)}(q)$$

M.N. Platonova, Yu.N. Uzikov, arXiv:2410.03262 [nucl-th]

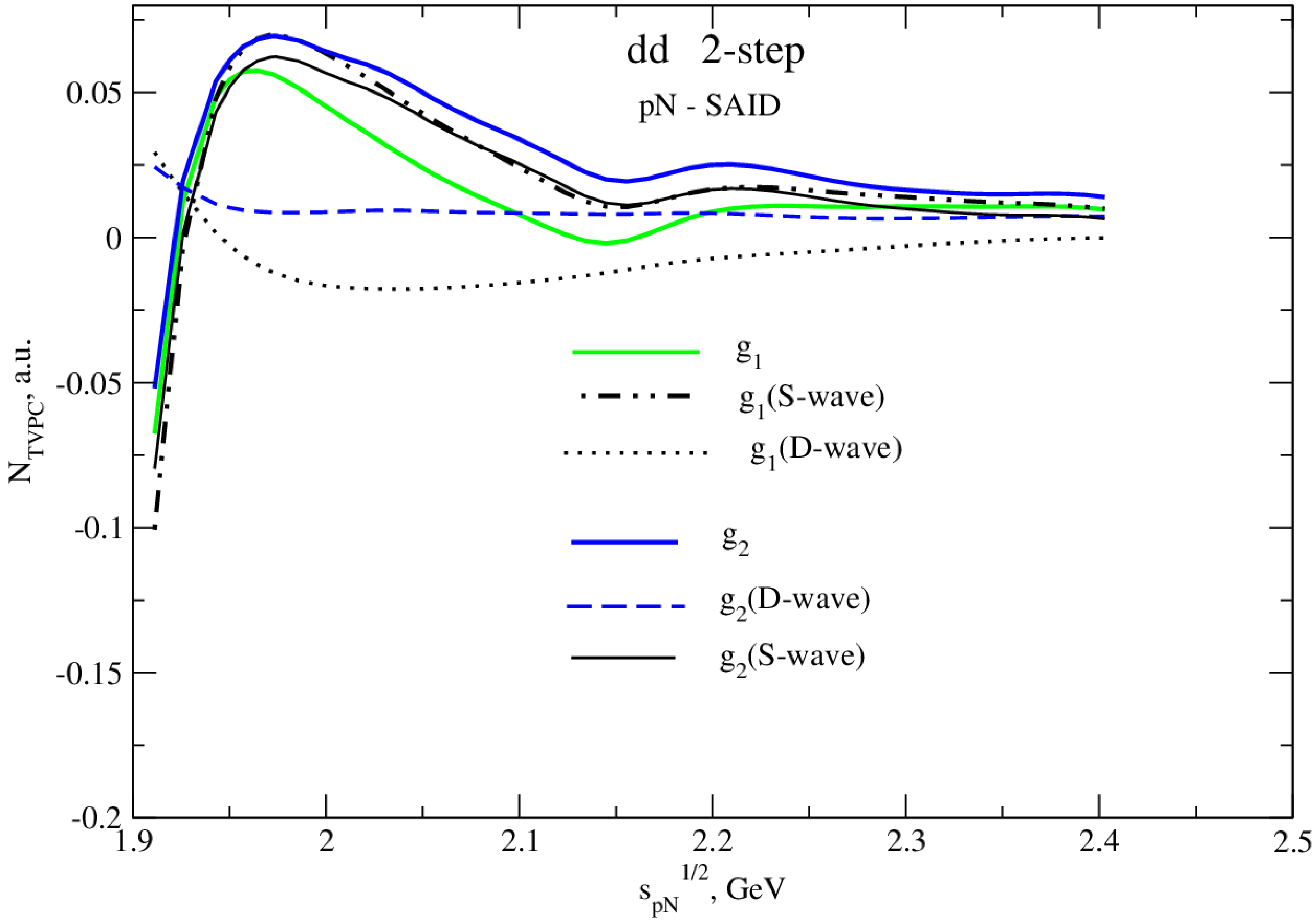
Numerical results

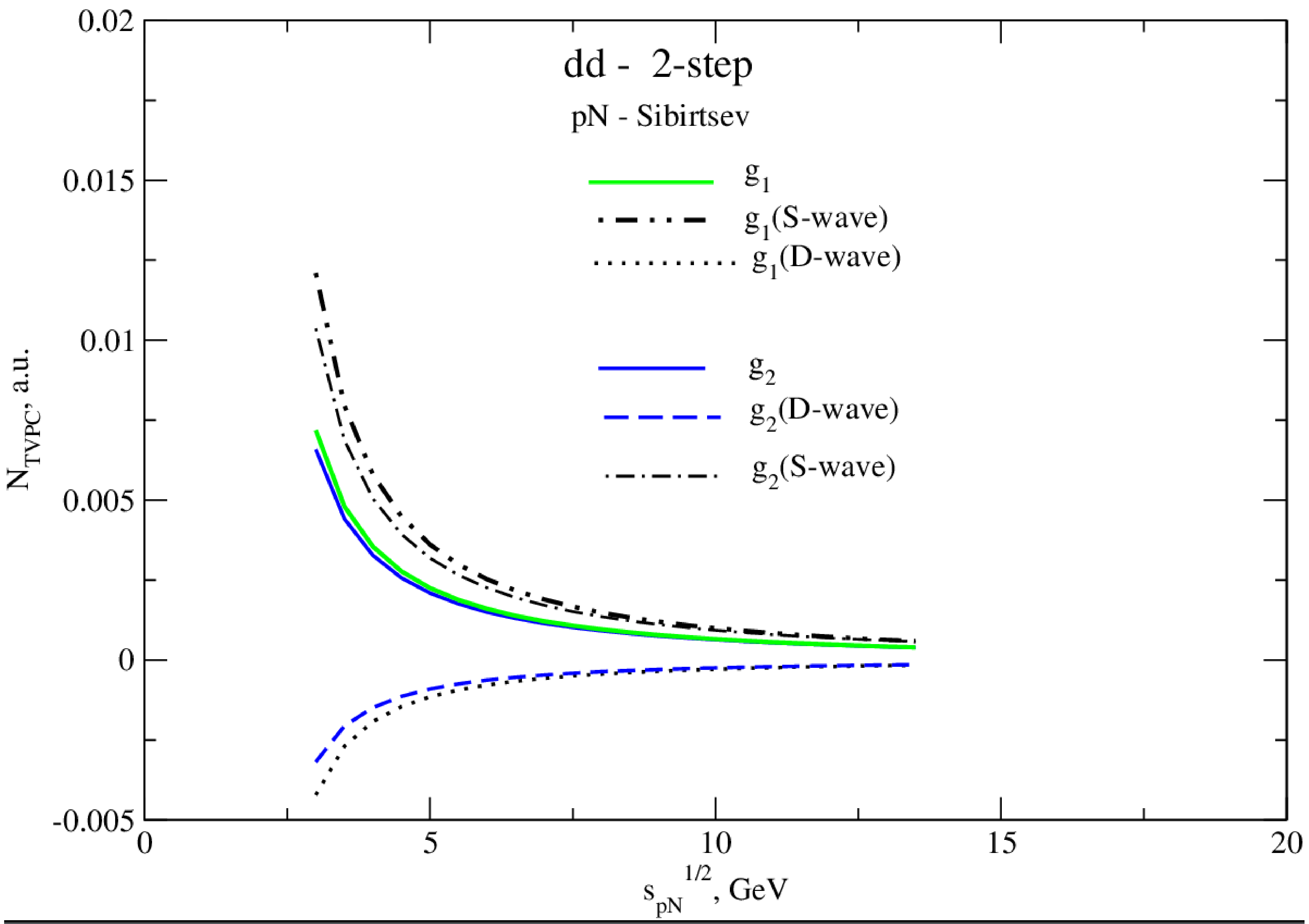
Ordinary NN helicity amplitudes:

SAID: Arndt R.A. et al. PRC 76 (2007) 025209; $\sqrt{s_{NN}} = 1.9 - 2.4 GeV$

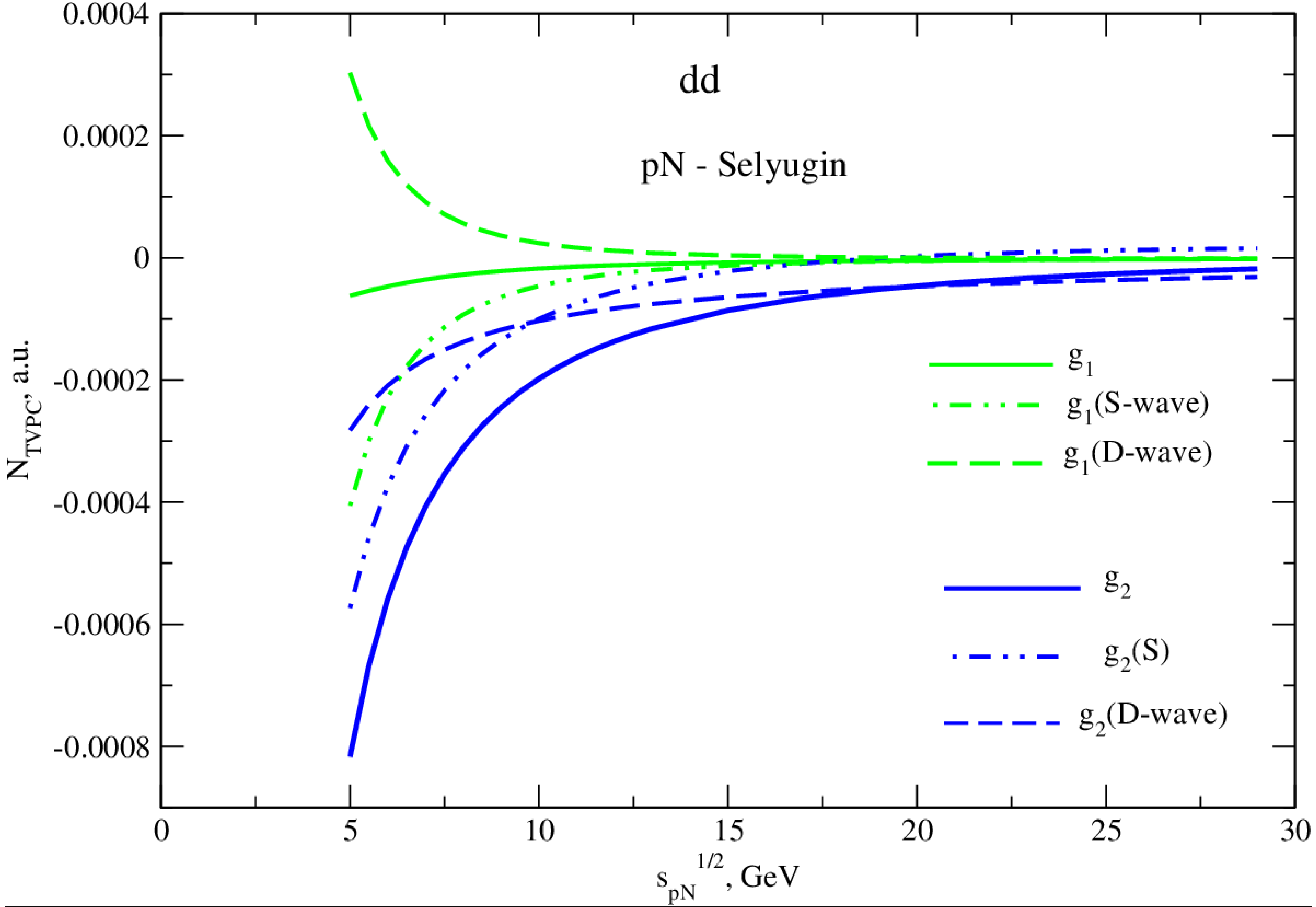
Sibirtsev A. et al., Eur. Phys. J. A 45 (2010) 357; $\sqrt{s_{NN}} = 2.5 - 15 GeV$
arXiv:0911.4637 [hep-ph] (Regge-type parametrization)

Selyugin O.V., Symmetry., 13 N2 (2021) 164; (HEGS –model);
arxi:2407.01311[hep-ph] $\sqrt{s_{NN}} = 5 - 25 GeV$


dd 2-step
pN - SAID
g1
g1(S-wave)
g1(D-wave)
g2
g2(D-wave)
g2(S-wave)
N_TVPC, a.u.
0.05
0
-0.05
-0.1
-0.15
-0.2
1.9
2
2.1
2.2
2.3
2.4
2.5
s_pN^1/2, GeV



dd - 2-step
pN - Sibirtsev
g1
g1(S-wave)
g1(D-wave)
g2
g2(D-wave)
g2(S-wave)
0.02
0.015
0.01
0.005
0
-0.005
N_TVPC, a.u.
0
5
10
15
20
s_pN^1/2, GeV



dd
pN - Selyugin
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
0
5
10
15
20
25
30
N_{TVPC}, a.u.
$s_{pN}^{1/2}$, GeV
g_1
g_1(S-wave)
g_1(D-wave)
g_2
g_2(S)
g_2(D-wave)

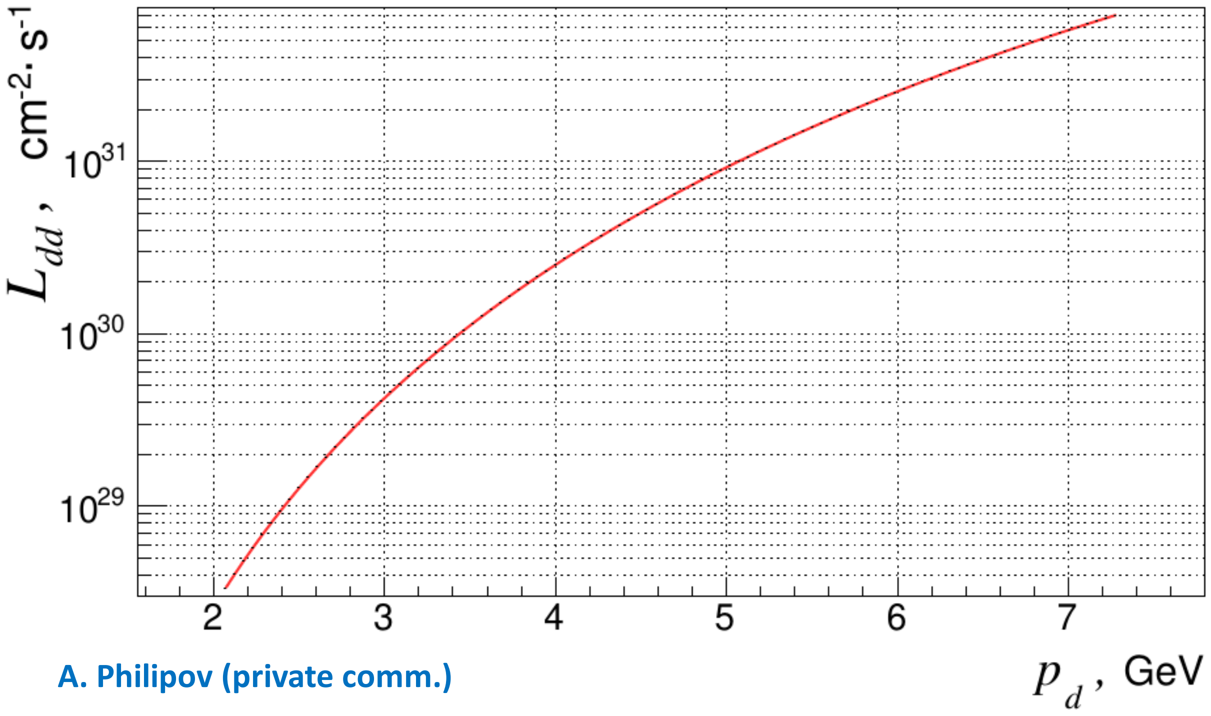
g’ – type of TVPC vanishes in dd-dd, also in pd- and ^{3}He-d for double pN scattering mechanism, in view of <np|g’|pn>= - <np|g’|pn>

g- type vanishes due to <np|g|np>= - <pn|g|pn>
and presence of the $(\tau_i - \tau_j)_z - operator$

h- type of TVPC dominates in dd –dd

That is important for its isolation from the corresponding data.

Luminosity in dd- collision,
p_d is the c.m.s. momentum of the deuteron



A. Philipov (private comm.)

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Effect decreases with energy by one order of magnitude,
but luminosity increases by three orders.

<u>Another point of view</u>: due to the BAU problem,
the TVPC coupling constant at NICA SPD energies can be much stronger than at low energies few MeV.

A high accuracy for the first measurement at high energies is not obligatory.

Two deuteron beams:

Beam d_1:

$$P_y^{(1)} = \pm\frac{2}{3}, P_x^{(1)} = P_z^{(1)} = 0; P_{yy}^{(1)} = 0;$$

$$P_{mn}^{(1)} = 0, (n, m = x, y, z)$$

Axial symmetry along OY axis

Beam d2:

$$P_y^{(2)} = 0, P_x^{(2)} = P_y^{(2)} = 0; P_{xz}^{(2)} = 1, or -2$$

In this case the TVPC cross section $\sigma_{TVPC}^{(2,1)}[k_m P_{mn}^{(2)} \varepsilon_{nlr} P_l^{(1)} k_r]$ can be obtained by measurement of the asymmetry A_{TVPC} in respect of change of the sign $P_y^{(1)}$

$$A_{TVPC} = (T^+ - T^-)/(T^+ + T^-)$$

$T^+(T^-)$ - Transmission factor for $P_y^{(1)} P_{xz}^{(2)} > 0 (P_y^{(1)} P_{xz}^{(2)} < 0)$

PHYSICAL REVIEW C **82**, 014003 (2010)

Vector and tensor analyzing powers in deuteron-proton breakup at 130 MeV

E. Stephan,[1,*] St. Kistryn,[2] R. Sworst,[2] A. Biegun,[1] K. Bodek,[2] I. Ciepał,[2] A. Deltuva,[3] E. Epelbaum,[4] A. C. Fonseca,[5] J. Golak,[2] N. Kalantar-Nayestanaki,[6] H. Kamada,[7] M. Kiš,[6] B. Kłos,[1] A. Kozela,[8] M. Mahjour-Shafiei,[6,†] A. Micherdzińska,[1,‡] A. Nogga,[9] R. Skibiński,[2] H. Witała,[2] A. Wrońska,[2] J. Zejma,[2] and W. Zipper[1]

TABLE I. Set of the polarization states used in the $^1\mathrm{H}(\vec{d},pp)n$ breakup experiment. The maximum polarizations P_Z, P_{ZZ} (for 100% efficiency of transitions in the ion source) and corresponding combinations of the magnetic fields are shown. The x indicates that the magnetic field is switched on, whereas the—indicates that the magnetic field is switched off. I_f denotes the full beam intensity. In the case of transitions with medium field on, the beam intensity is reduced to 2/3 of I_f in the case of 100% efficient transitions.

Polarization states		Magnetic fields				Beam intensity
P_Z	P_{ZZ}	SF1	SF2	MF	WF	
0	0	–	–	–	–	I_f
$+\frac{1}{3}$	$+1$	x	–	–	–	I_f
$+\frac{1}{3}$	-1	–	x	–	–	I_f
0	$+1$	x	–	x	–	$\frac{2}{3}I_f$
0	-2	–	x	x	–	$\frac{2}{3}I_f$
$+\frac{2}{3}$	0	x	x	–	–	I_f
$-\frac{2}{3}$	0	–	–	–	x	I_f

P_{yy}=-2 or P_{yy}=+1 for P_y=0

P_{yy}=0 for P_y=+2/3, -2/3

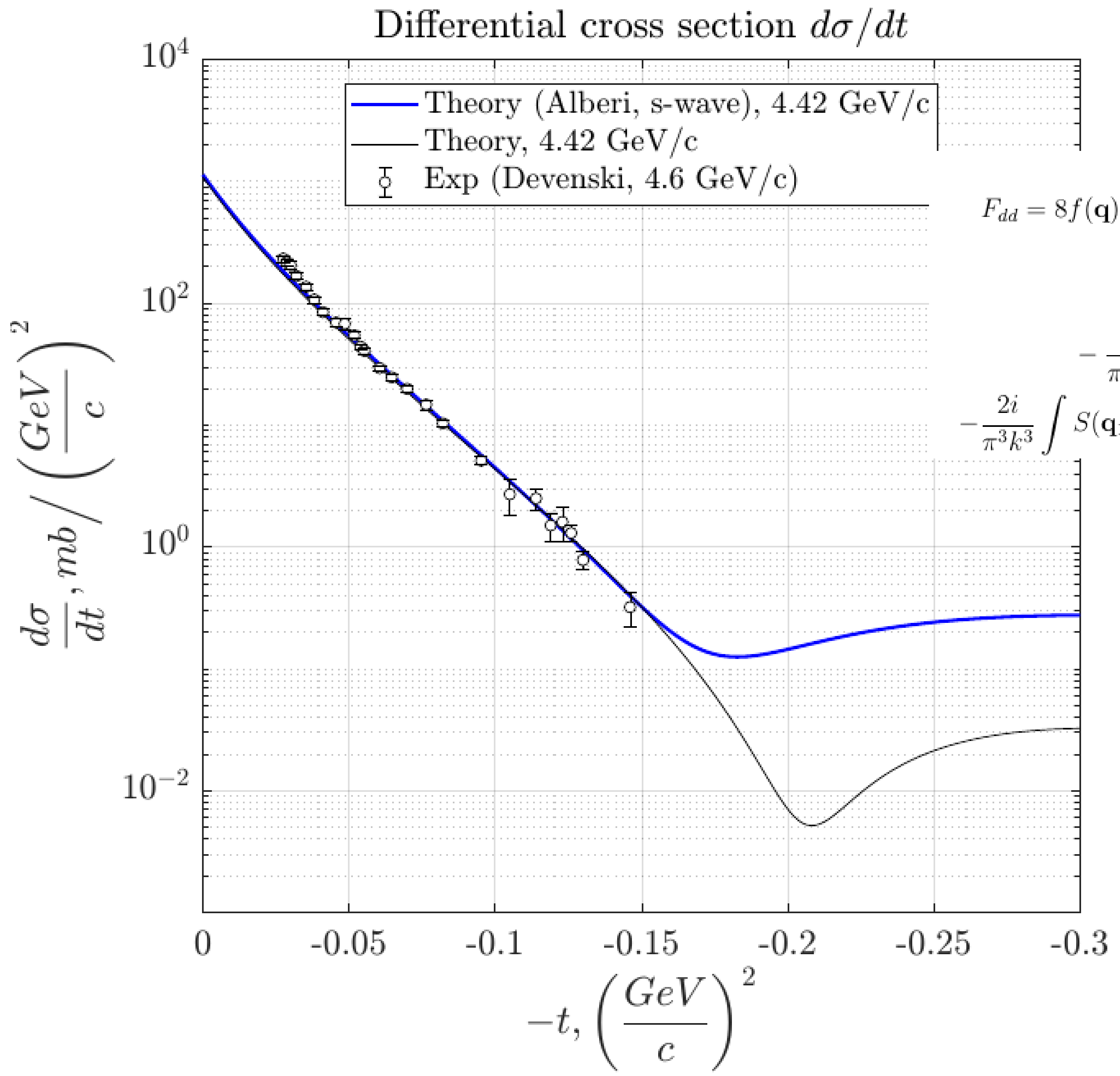
CONCLUSION AND OUTLOOK

- σ_{TVPC} s a true null-test observable, not generated by ISI&FSI, analog of EDM.
- T_p –dependence of the σ_{TVPC}(*d-d*) for the h -type is calculated in Glauber theory with known hadron pN-amplitudes.
- d-d does not contain the *g'*- and g -type, i.e. is **optimal to search for the h-type** ; decreases with energy, but luminosity is increasing.
- Unique possibility to measure σ_{TVPC} at NICA SPD to estimate unknown TVPC constant at early Baryon Universe.
- How to measure at SPD? – Measurement of electric charge current produced by both deuteron beams (similar to TRIC exp. at COSY)
  / or usage of Precessing polarization of the one beam & Fourier analysis
  N. Nikolaev, F. Rathman, A. Silenko, Yu. Uzikov, PLB 811 (2020) 135983)/

THANK YOU FOR ATTENTION!

dd→dd, Glauber model

A. Kornev , START program



$$
\begin{aligned}
F_{dd} = 8f(\mathbf{q})S^2\left(\tfrac{1}{2}\mathbf{q}\right) + \frac{2i}{\pi k}\Bigg[4S\left(\tfrac{1}{2}\mathbf{q}\right)\int S(\mathbf{q}_1) f\left(\mathbf{q}_1 + \tfrac{1}{2}\mathbf{q}\right) f\left(-\mathbf{q}_1 + \tfrac{1}{2}\mathbf{q}\right) \mathrm{d}^2\mathbf{q}_1 + \\
+ 2\int S^2(\mathbf{q}_1) f\left(\mathbf{q}_1 + \tfrac{1}{2}\mathbf{q}\right) f\left(-\mathbf{q}_1 + \tfrac{1}{2}\mathbf{q}\right) \mathrm{d}^2\mathbf{q}_1\Bigg] - \\
- \frac{8}{\pi^2 k^2}\int S(\mathbf{q}_1)S(\mathbf{q}_2) f\left(\tfrac{1}{2}\mathbf{q} - \mathbf{q}_1\right) f\left(\mathbf{q}_1 + \mathbf{q}_2\right) f\left(\tfrac{1}{2}\mathbf{q} - \mathbf{q}_2\right) \mathrm{d}^2\mathbf{q}_1\,\mathrm{d}^2\mathbf{q}_2 - \\
- \frac{2i}{\pi^3 k^3}\int S(\mathbf{q}_1)S(\mathbf{q}_2) f\left(\tfrac{1}{2}\mathbf{q} - \mathbf{q}_1 - \mathbf{q}_3\right) f(\mathbf{q}_3) f(\mathbf{q}_1 + \mathbf{q}_2 + \mathbf{q}_3) f\left(\tfrac{1}{2}\mathbf{q} - \mathbf{q}_2 - \mathbf{q}_3\right) \mathrm{d}^2\mathbf{q}_1\,\mathrm{d}^2\mathbf{q}_2\,\mathrm{d}^2\mathbf{q}_3.
\end{aligned}
$$

G. Alberi et al. NPB 17 (1970) , 621

Without spins in pN

TVPC NN interactions

TVPC ($\equiv$ T-odd P-even) interactions

The most general (off-shell) structure contains 18 terms *P. Herczeg, Nucl.Phys.* ***75*** *(1966) 655*

In terms of boson exchanges :
M.Simonius, Phys. Lett. ***58B*** *(1975) 147; PRL* ***78*** *(1997) 4161*

⋆ $J \geq 1$
⋆ π, σ-exchanges do not contribute
⋆ The lowest mass meson allowed is the ρ-meson $/I^G(J^{PC}) = 1^+(1^{--})/$
Natural parity exchange ($P = (-1)^J$) must be charged

The TVPC Born NN-amplitude

$$\widetilde{V}_{\rho}^{TVPC} = \bar{g}_{\rho} \frac{g_{\rho}\kappa}{2M} [\vec{\tau}_1 \times \vec{\tau}_2]_z \frac{1}{m_{\rho}^2 + |\vec{q}|^2} \times i[(\vec{p}_f + \vec{p}_i) \times \vec{q}] \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \quad (2)$$

C-odd (hence T-odd), only charged ρ's. No contribution to the nn or pp.

$\vec{q} = \vec{p}_f - \vec{p}_i$ dissappeares at $\vec{q} = 0$

⋆ Axial $h_1(1170)$-meson exchange $I^G(J^{PC}) = 0^-(1^{+-})$ ...

EDM and TVPC interactions

J.Engel, P. Frampton, R.P. Springer, PRD **53** (1996) 5112:

$$\mathcal{L}_{NEW} = \mathcal{L}_4 + \frac{1}{\Lambda_{TVPC}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{TVPC}}\mathcal{L}_6 + \frac{1}{\Lambda^3_{TVPC}}\mathcal{L}_7 + \ldots$$

The lowest-dimension flavor conserving TVPC interactions have $d = 7$
/R.S. Conti, I.B. Khriplovich, PRL 68 (1992)/.
These new TVPC can generate a permanent EDM in the presence of a PV SM radiative corrections.
J.Engel et al.: $\bar{g}_\rho \sim 10^{-8}$
M.J. Ramsey-Musolf, PRL 83 (1999): $\alpha_T \leq 10$, $\Lambda_{TVPC} > 150$ TeV

A.Kurylov, G.C. McLaughlin, M.Ramsey-Musolf , PRD 63(2001)076007:

EDM at energies below Λ_{TVPC}

$$d = \beta_5 C_5 \frac{1}{\Lambda_{TVPC}} + \beta_6 C_6 \frac{M}{\Lambda^2_{TVPC}} + \underbrace{\beta_7 C_7 \frac{M^2}{\Lambda^3_{TVPC}}}_{the\,first\,contrb.\,from TVPC}$$

C_d are *a priori* unknown coefficients , β_d calculable quantities from loops, $M < \Lambda_{TVPC}$ - dynamical degrees of freedom

General Decomposition of the pd total X-section (k = collision axis)

$$\sigma_{\mathrm{tot}} = \sigma_0 + \sigma_{\mathrm{TT}} \left[\left(\mathbf{P}^{\mathrm{d}} \cdot \mathbf{P}^{\mathrm{p}} \right) - \left(\mathbf{P}^{\mathrm{d}} \cdot \mathbf{k} \right) \left(\mathbf{P}^{\mathrm{p}} \cdot \mathbf{k} \right) \right]$$ PC TT

$$+ \sigma_{\mathrm{LL}} \left(\mathbf{P}^{\mathrm{d}} \cdot \mathbf{k} \right) \left(\mathbf{P}^{\mathrm{p}} \cdot \mathbf{k} \right) + \sigma_{\mathrm{T}} T_{mn} k_m k_n$$ LL & PC tensor

$$+ \sigma_{\mathrm{PV}}^{\mathrm{p}} \left(\mathbf{P}^{\mathrm{p}} \cdot \mathbf{k} \right) + \sigma_{\mathrm{PV}}^{\mathrm{d}} \left(\mathbf{P}^{\mathrm{d}} \cdot \mathbf{k} \right)$$ PV single spin at NICA

$$+ \sigma_{\mathrm{PV}}^{\mathrm{T}} \left(\mathbf{P}^{\mathrm{p}} \cdot \mathbf{k} \right) T_{mn} k_m k_n$$ PV tensor

$$+ \sigma_{\mathrm{TVPV}} \left(\mathbf{k} \cdot \left[\mathbf{P}^{\mathrm{d}} \times \mathbf{P}^{\mathrm{p}} \right] \right)$$ TVPV

TVPC $$+ \underline{\sigma_{\mathrm{TVPC}} k_m T_{mn} \epsilon_{nlr} P_l^{\mathrm{p}} k_r} \, .$$ (TRIC Proposal in Juelich)

$$k_m T_{mn} \epsilon_{nlr} P_l^{\mathrm{p}} k_r = T_{xz} P_y^{\mathrm{p}} - T_{yz} P_x^{\mathrm{p}}$$

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N. Nikolaev, F. Rathman, A. Silenko, Yu. Uzikov, PLB 811 (2020) 135983

The main idea: precessing polarization of the beam in horizontal plane & Fourier analysis

2-step mechanism

$$\hat{M}^{(2)}(0) = \hat{M}^{(2n)}(0) + \hat{M}^{(2a)}(0),$$
$$\hat{M}^{(2n)}(0) = \frac{i}{2\pi^{3/2}} \int\int\int d^3\rho d^3 r d^2 q \Psi^{+}_{d(12)}(\mathbf{r})\Psi^{+}_{d(34)}(\boldsymbol{\rho}) \left[e^{i\mathbf{q}\boldsymbol{\sigma}}\hat{O}^{(2n)}(\mathbf{q}) + e^{i\mathbf{q}\mathbf{s}}\hat{O}'^{(2n)}(\mathbf{q})\right] \Psi_{d(34)}(\boldsymbol{\rho})\Psi_{d(12)}(\mathbf{r}),$$
$$\hat{M}^{(2a)}(0) = \frac{i}{2\pi^{3/2}} \int\int\int d^3\rho d^3 r d^2 q \Psi^{+}_{d(12)}(\mathbf{r})\Psi^{+}_{d(34)}(\boldsymbol{\rho}) e^{i\mathbf{q}(\mathbf{s}-\boldsymbol{\sigma})}\hat{O}^{(2a)}(\mathbf{q})\Psi_{d(34)}(\boldsymbol{\rho})\Psi_{d(12)}(\mathbf{r}).$$

$$\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2, \ \boldsymbol{\rho} = \mathbf{r}_3 - \mathbf{r}_4$$

1,2 – deuteron target
3,4 - deuteron beam

$$\hat{O}^{(2n)}(\mathbf{q}) = \frac{1}{2}\{M_{p(31)}(\mathbf{q}), M_{n(41)}(-\mathbf{q})\} + \frac{1}{2}\{M_{n(32)}(\mathbf{q}), M_{p(42)}(-\mathbf{q})\},$$
$$\hat{O}'^{(2n)}(\mathbf{q}) = \frac{1}{2}\{M_{p(31)}(\mathbf{q}), M_{n(32)}(-\mathbf{q})\} + \frac{1}{2}\{M_{n(41)}(\mathbf{q}), M_{p(42)}(-\mathbf{q})\},$$
$$\hat{O}^{(2a)}(\mathbf{q}) = M_{p(31)}(\mathbf{q})M_{p(42)}(-\mathbf{q}) + M_{n(32)}(\mathbf{q})M_{n(41)}(-\mathbf{q}).$$

NN-amplitudes

$$M_{N(ij)}(\mathbf{q}) = A_N + C_N(\boldsymbol{\sigma}_i\cdot\hat{n}) + C'_N(\boldsymbol{\sigma}_j\cdot\hat{n})$$
$$+B_N(\boldsymbol{\sigma}_i\cdot\hat{k})(\boldsymbol{\sigma}_j\cdot\hat{k}) + (G_N+H_N)(\boldsymbol{\sigma}_i\cdot\hat{q})(\boldsymbol{\sigma}_j\cdot\hat{q})$$
$$+(G_N-H_N)(\boldsymbol{\sigma}_i\cdot\hat{n})(\boldsymbol{\sigma}_j\cdot\hat{n}),$$

T-even P-even

$$C_N{}' \approx C_N + i\frac{q}{2m}A_N$$

$$\hat{k} = \frac{\mathbf{p}+\mathbf{p}'}{|\mathbf{p}+\mathbf{p}'|}, \quad \hat{q} = \frac{\mathbf{p}-\mathbf{p}'}{|\mathbf{p}-\mathbf{p}'|}, \quad \hat{n} = (\hat{k}\times\hat{q}),$$

C. Sorensen , PRD 19 (1979)

$$t_{N(ij)} = h_N[(\boldsymbol{\sigma}_i\cdot\mathbf{k})(\boldsymbol{\sigma}_j\cdot\mathbf{q}) + (\boldsymbol{\sigma}_i\cdot\mathbf{q})(\boldsymbol{\sigma}_j\cdot\mathbf{k})$$
$$-\frac{2}{3}(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)(\mathbf{q}\cdot\mathbf{k})]/m_p^2$$
$$+g_N[\boldsymbol{\sigma}_i\times\boldsymbol{\sigma}_j]\cdot[\mathbf{q}\times\mathbf{k}](\boldsymbol{\tau}_i-\boldsymbol{\tau}_j)_z/m_p^2$$
$$+g'_N(\boldsymbol{\sigma}_i-\boldsymbol{\sigma}_j)\cdot i[\mathbf{q}\times\mathbf{k}][\boldsymbol{\tau}_i\times\boldsymbol{\tau}_j]_z/m_p^2.$$

TVPC

Deuteron w.f.

$$\Psi^d_{(ij)} = \frac{1}{\sqrt{4\pi}r}\left(u(r) + \frac{1}{2\sqrt{2}}w(r)\hat{S}_{12}(\hat{r};\boldsymbol{\sigma}_i,\boldsymbol{\sigma}_j)\right)$$

$$\hat{S}_{12}(\hat{r};\boldsymbol{\sigma}_i,\boldsymbol{\sigma}_j) = 3(\boldsymbol{\sigma}_i\cdot\hat{r})(\boldsymbol{\sigma}_j\cdot\hat{r}) - \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j$$

AT HIGHER ENERGIES $\sqrt{s_{pN}} = 3-10 GeV^2$

A.Sibirtsev et al., Eur.Phys. J. A 45 (2010) 357

$$\phi_{ai}(s,t) = \pi\beta_{ai}(t)\frac{\xi_i(s,t)}{\Gamma(\alpha(t))}; i = \rho,\omega,a_2,f_2,P; a = 1-5;$$

$$\xi_i(t,s) = \frac{1+S_i\exp[-i\pi\alpha(t)]}{\sin[\pi\alpha_i(t)]}\left[\frac{s}{s_0}\right]^{\alpha_i(t)},$$

$$\alpha_i(t) = \alpha_i^0 + \alpha_i^{'}t,$$

$$\beta_{1i}(t) = c_{1i}\exp(b_{1i}t),$$

$$\beta_{2i}(t) = c_{2i}\exp(b_{2i}t)\frac{-t}{4m_N^2},$$

$$\beta_{3i}(t) = c_{3i}\exp(b_{3i}t),$$

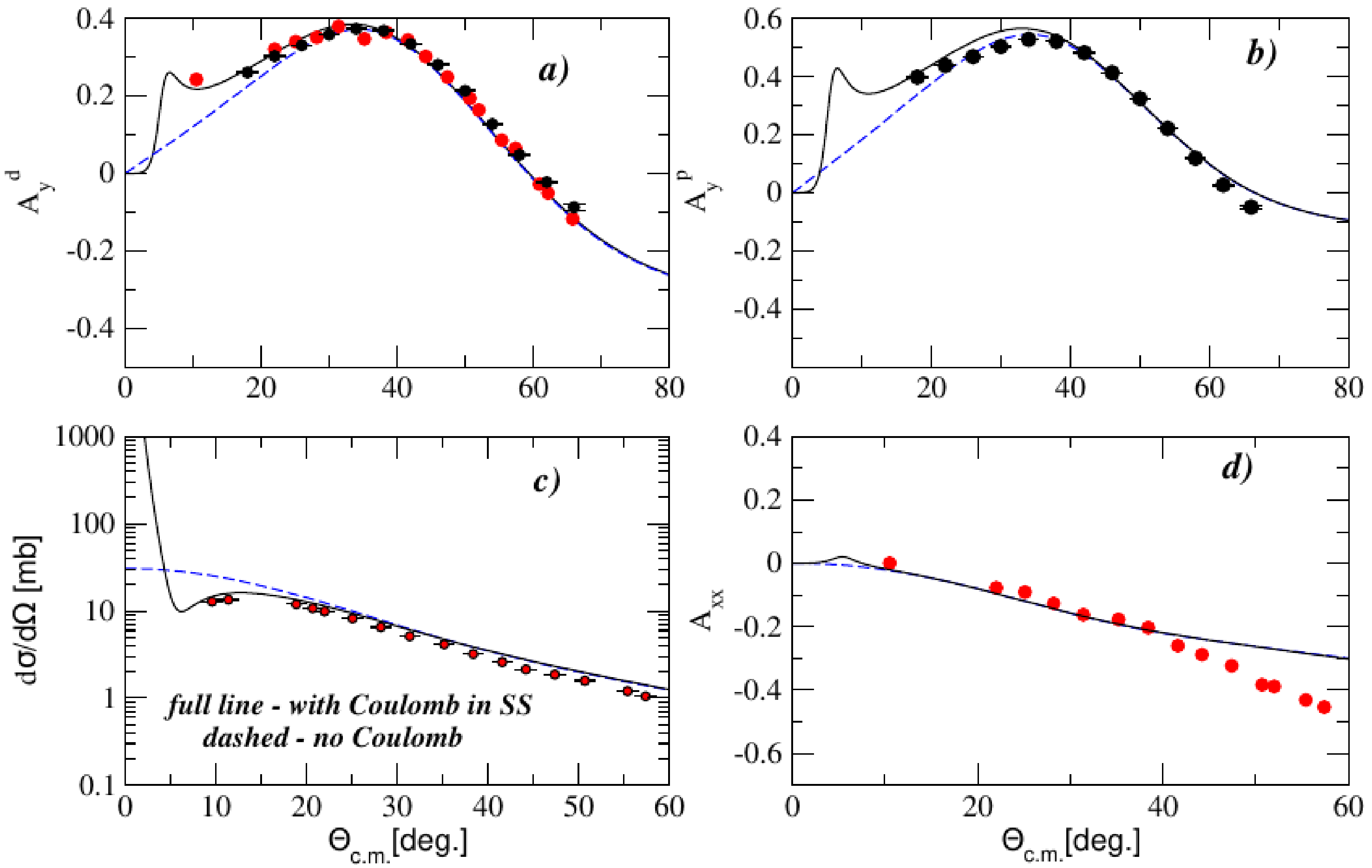
$$\beta_{4i}(t) = c_{4i}\exp(b_{4i}t)\frac{-t}{4m_N^2},$$

$$\beta_{5i}(t) = c_{5i}\exp(b_{5i}t)\left[\frac{-t}{4m_N^2}\right]^{1/2}.$$

The Regge formalism for pp-helicity amplitudes at proton beams momenta p_L= 3-50 GeV/c includes single- Pomeron exchange and trajectories ρ,ω,f_2,a_2
Data on $d\sigma/dt$, A_N, A_{NN}

Test calculations: pd elastic scattering at 135 MeV

A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38

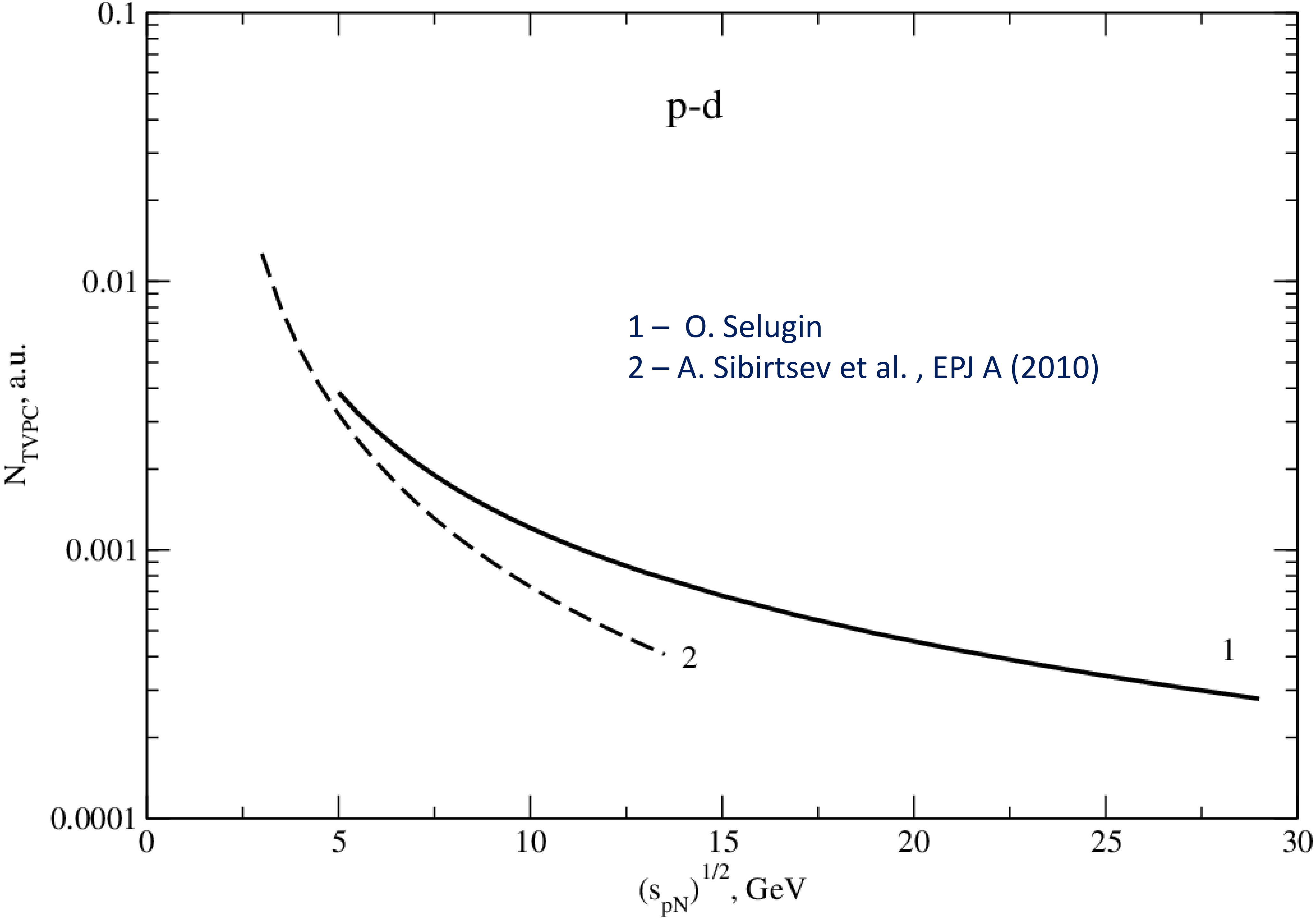


Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)
See also Faddeev calculations: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.

$$\sigma_{tot} = \sigma_0 + \sigma_{TT} p_y^b P_y^t + \sigma_T P_{zz}^t + \sigma_{tvpc} p_y^b P_{xz}^t;$$

$$A = \frac{T^+ - T^-}{T^+ + T^-} \sim \sigma_{tvpc};$$

$$T^+ \Rightarrow p_y^b P_{xz}^t > 0, T^- \Rightarrow p_y^b P_{xz}^t < 0$$



p-d
1 – O. Selugin
2 – A. Sibirtsev et al. , EPJ A (2010)
N_{TVPC}, a.u.
$(s_{pN})^{1/2}$, GeV
0.1
0.01
0.001
0.0001
0
5
10
15
20
25
30
1
2