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

M.N. Platonova[1,2] **and** **Yu. N. Uzikov**[2]

[1]*D.V. Skobeltsyn INP, M.V. Lomonosov Moscow State University*

[2]*JINR, V.P. Dzhelepov Laboratory of Nuclear Problems,*

74th International Conference on Nuclear Physics, Nucleus-2024
" Fundamental Problems and Applications", Dubna, 1-5 July 2024

CONTENT

- Motivation (**BAU**)

  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 ?
- T-invariance Violating P-parity conserving (**TVPC**) NN interactions
- Null-test TVPC signal in d-d scattering within Glauber spin-dependent theory
- Numerical results in the GeV region and NICA SPD energies
- Conclusion

This work is supported by the RSCF grant № 23-22-00123 :
Search for T-invariance violation in scattering of polarized protons, ^{3}He nuclei and deuterons on polarized deuterons.
https://www.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

$$\eta_{\exp} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6\times10^{-10} \gg \eta_{SM} \sim 10^{-19}$$

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) 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 as a fundamental interaction.

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 /

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)

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

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

Search for TVPC in double polarized p-d, ^{3}He-d and 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:

- **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.

Disadvantage:

- **Requires to suppress / exclude (for stationary spin method) the contribution of the P_y^t**

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

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

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

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

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

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

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

$$k_m T_{mn}\epsilon_{nlr}P^{\rm p}_l k_r = T_{xz}P^{\rm p}_y - T_{yz}P^{\rm p}_x$$

13

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

TVPC in pd- transmission experiment

under P-conservation

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

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

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

k – beam momentum

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

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

T^+ (T^-) – transmission factor for $p_y^p P_{xz} > 0$ ($p_y^p P_{xz} < 0$).

The goal is to improve the direct upper bound on TVPC by one order of magnitude up to $A_{TVPC} \sim 10^{-6}$

TVPC NN interactions

TVPC (≡ 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

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

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 $I^G(J^{PC}) = 0^-(1^{+-})$ ...

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

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 theory

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., 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

dd-dd elastic scattering at $\theta=0^o$ for TVPC-interaction

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

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

$S^{(i)}_l$ – 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

$$M_{-1,1;0,0} = < m'_1 = -1, m'_2 = 1|\hat{M}_{\rm TVPC}(0)|m_1 = 0, m_2 = 0 >,$$

$$M_{1,0;0,1} = < m'_1 = 1, m'_2 = 0|\hat{M}_{\rm TVPC}(0)|m_1 = 0, m_2 = 1 > .$$

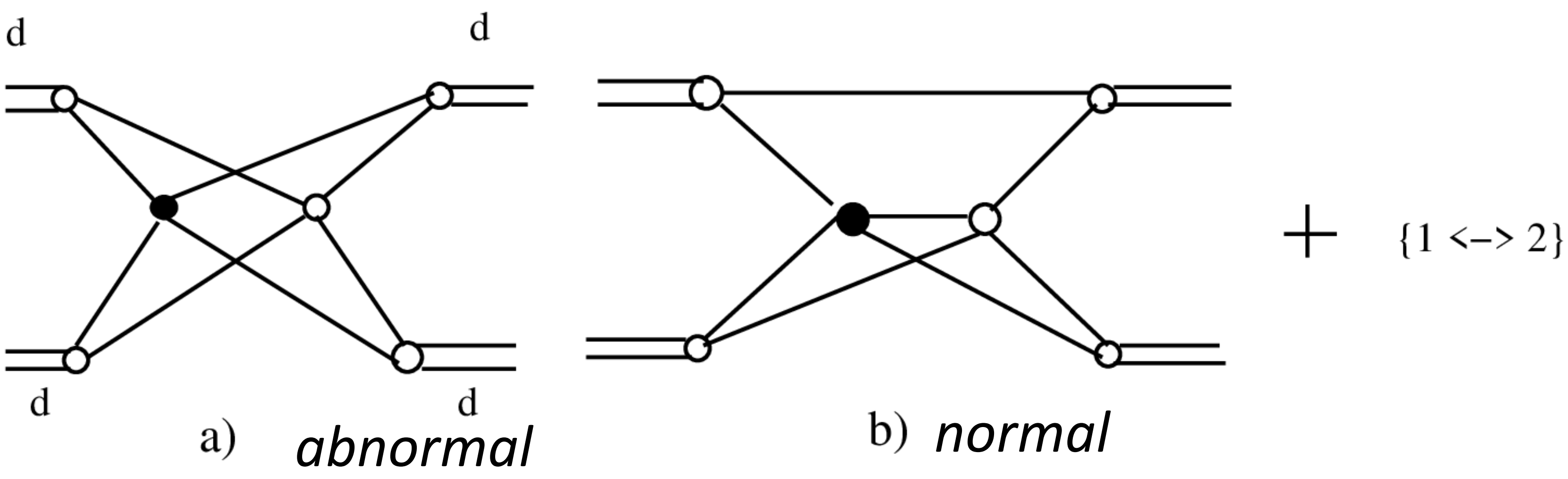
$$g_1 = -i(M_{-1,1;0,0} + M_{1,0;0,1}),$$

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

Generalized optical theorem:

$$
\begin{aligned}
\sigma_{\rm TVPC} &= 4\sqrt{\pi}{\rm Im}\,{\rm Tr}(\hat{\rho}_i \hat{M}_{\rm TVPC}(0)) \\
&= 4\sqrt{\pi}{\rm Im}\left(\frac{g_1}{9}\right)(P_{xz}^{(1)}P_y^{(2)} - P_{zy}^{(1)}P_x^{(2)}) \\
&+ 4\sqrt{\pi}{\rm Im}\left(\frac{g_2}{9}\right)(P_{xz}^{(2)}P_y^{(1)} - P_{zy}^{(2)}P_x^{(1)}).
\end{aligned}
$$

Spin-dependent Glauber theory for the amplitudes g_1 and g_2



2-step mechanism

$$\hat{M}^{(2)}(0) = \hat{M}^{(2n)}(0) + \hat{M}^{(2a)}(0),$$

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

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

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

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

T-even P-even

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

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

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

C. Sorensen , PRD 19 (1979)

TVPC

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

Deuteron w.f.

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

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

TVPC amplitudes for dd

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

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

$$g_1^{(n)} = \frac{i}{\sqrt{2}\pi m_N} Z_0 \int_0^\infty dq q^2 \zeta(q)[h_p(q)C_n(q) + h_n(q)C_p(q)],$$

$$g_2^{(n)} = \frac{i}{\sqrt{2}\pi m_N} Z_0 \int_0^\infty dq q^2 \zeta(q)[h_p(q)C'_n(q) + h_n(q)C'_p(q)],$$

$$g_1^{(a)} = \frac{i}{\sqrt{2}\pi m_N} \int_0^\infty dq q^2 Z(q)\zeta(q)[h_p(q)C_p(q) + h_n(q)C_n(q)],$$

$$g_1^{(a)} = \frac{i}{\sqrt{2}\pi m_N} \int_0^\infty dq q^2 Z(q)\zeta(q)[h_p(q)C_p(q) + h_n(q)C_n(q)],$$

Form factors

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

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

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

Deuteron form factors

$$S_0^{(0)}(q) = \int_0^\infty dr u^2(r) j_0(qr),$$

$$S_0^{(2)}(q) = \int_0^\infty dr w^2(r) j_0(qr),$$

$$S_2^{(1)}(q) = 2\int_0^\infty dr u(r) w(r) j_2(qr),$$

$$S_2^{(2)}(q) = -\frac{1}{\sqrt{2}}\int_0^\infty dr w^2(r) j_2(qr),$$

$$S_4^{(2)}(q) = \frac{1}{2}\int_0^\infty dr w^2(r) j_4(qr).$$

TVPC in pd:

$$\tilde{g} = \frac{i}{4\pi m_p}\int_0^\infty dq q^2 [S_0^{(0)}(q) - \sqrt{8} S_2^{(1)} - 4 S_0^{(2)}(q) + 9 S_1^{(2)}(q) + \sqrt{2}\frac{4}{3} S_2^{(2)}(q)][-C_n'(q) h_p + C_p'(q)(g_n - h_n)],$$

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

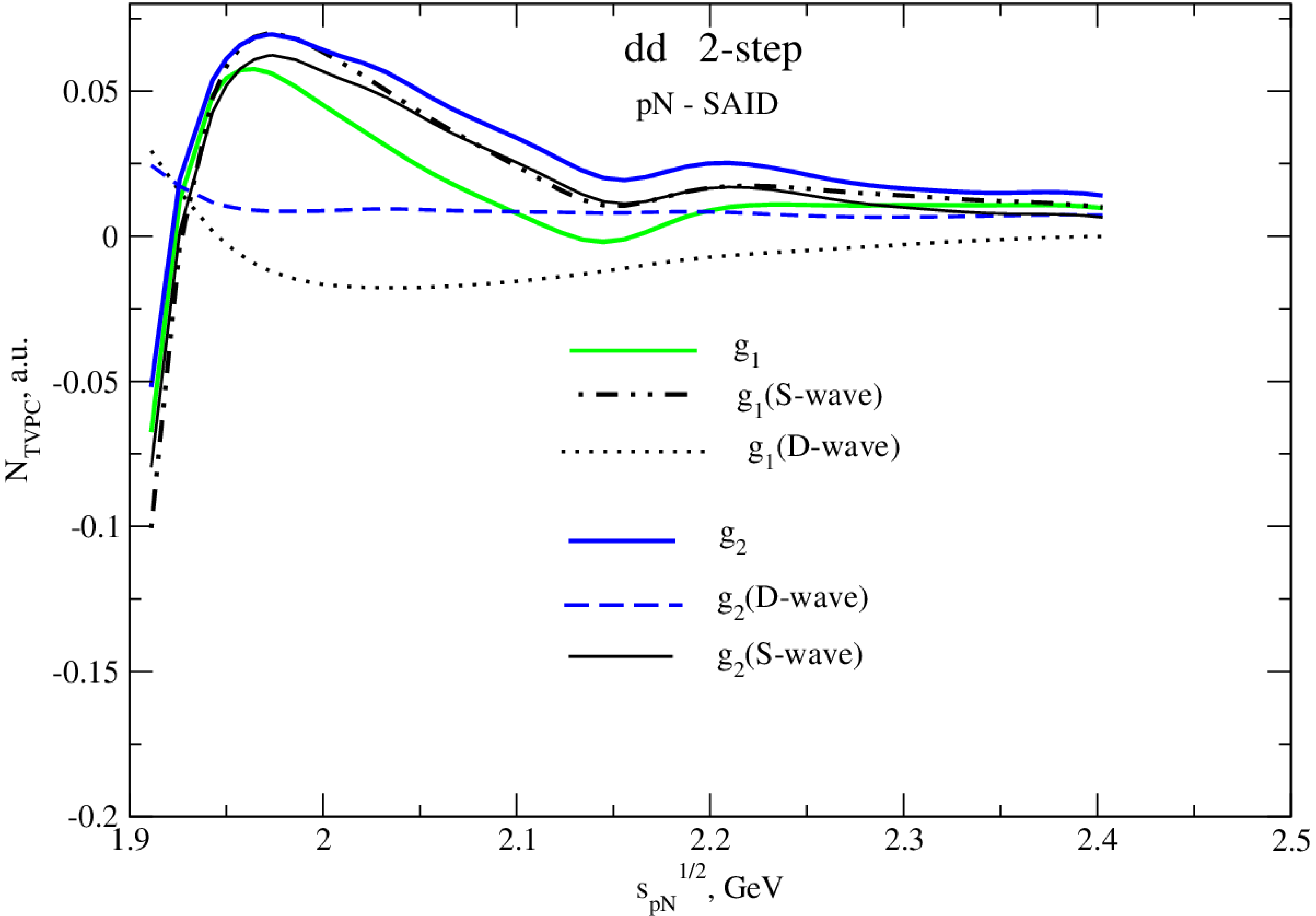
Numerical results

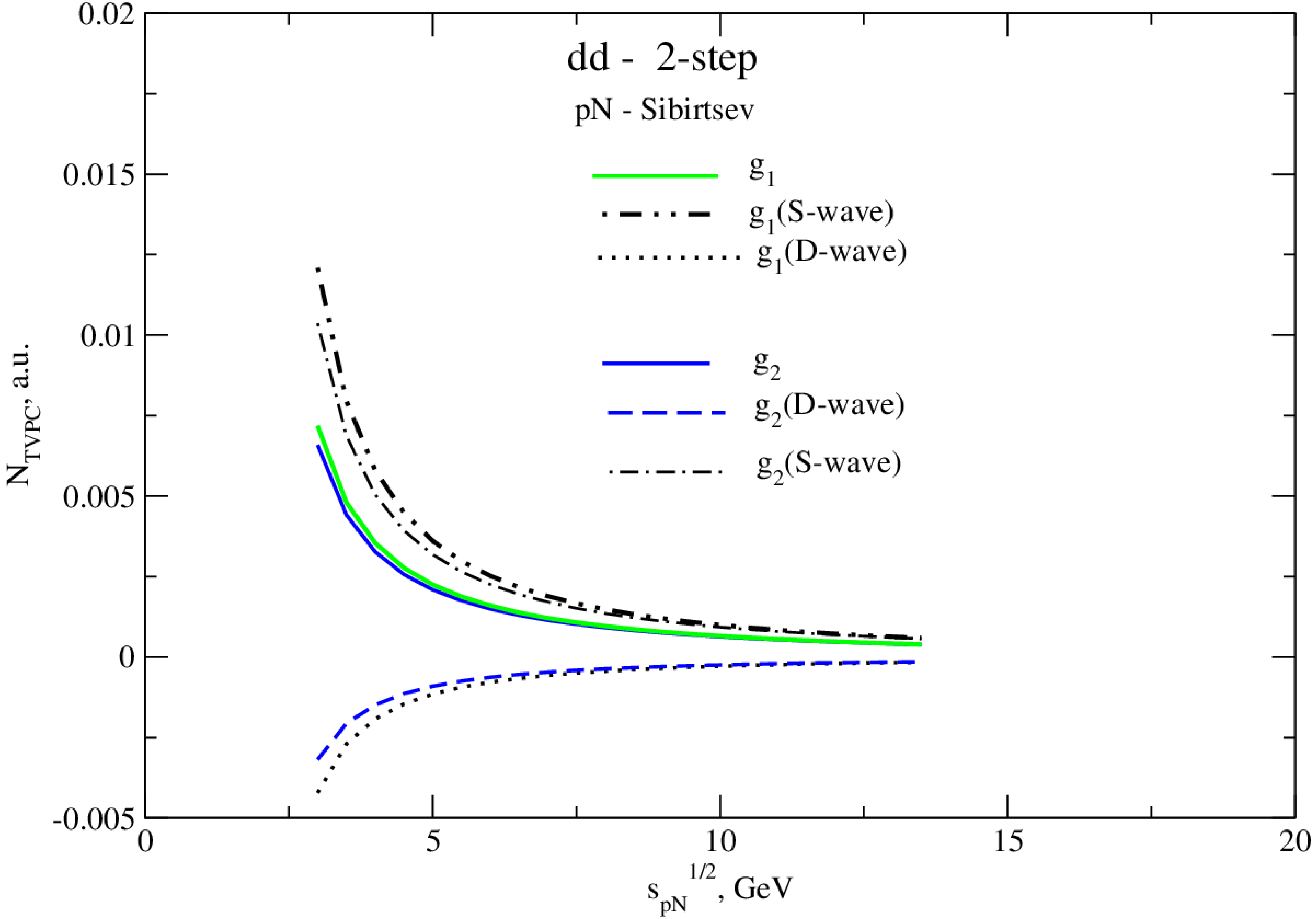
pN amplitudes:

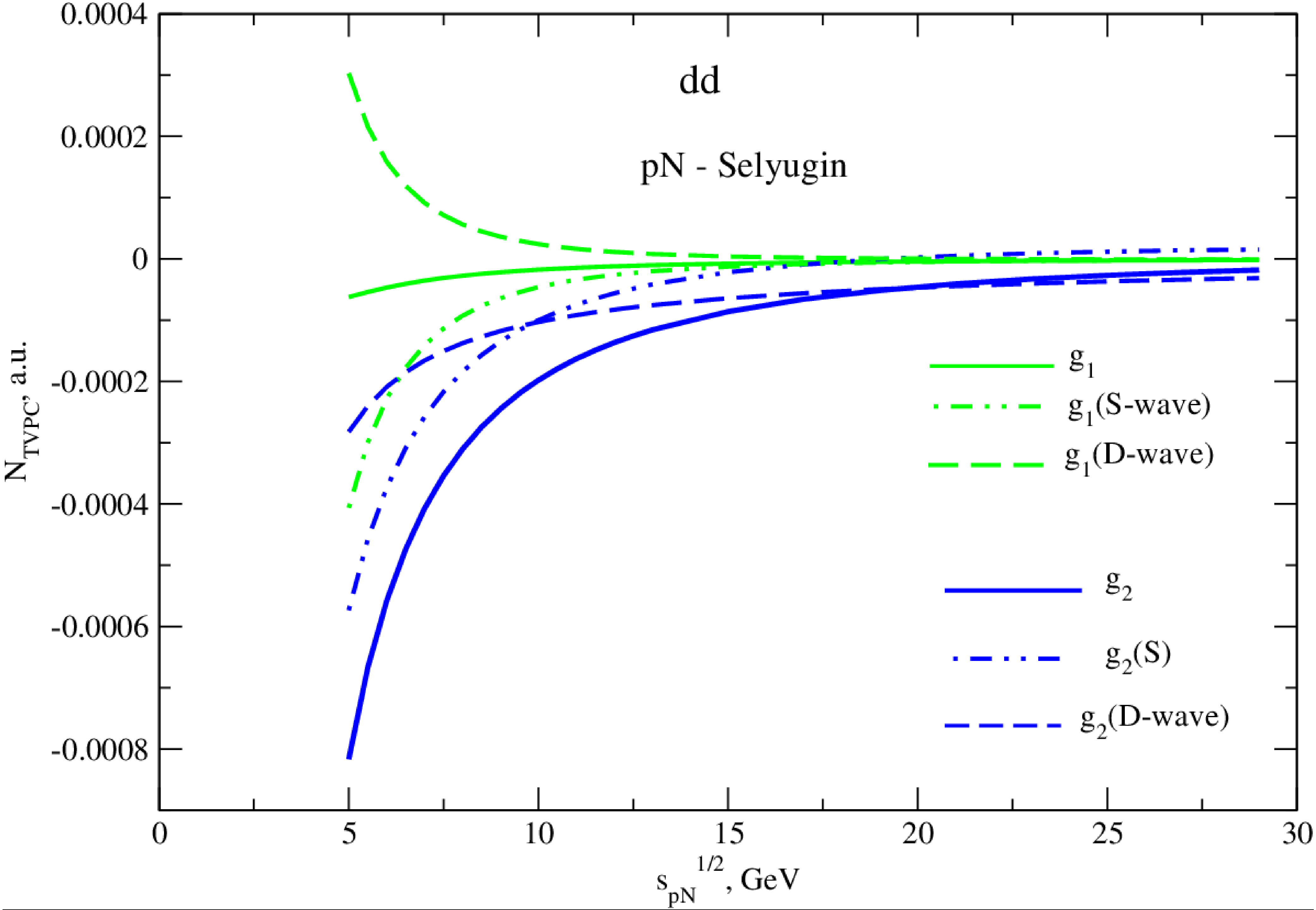
SAID: Arndt R.A. et al. PRC 76 (2007) 025209;

Sibirtsev A. et al., Eur. Phys. J. A 45 (2010) 357;
arXiv:0911.4637 [hep-ph] (Regge-type parametrization)

Selyugin O.V., Symmetry., 13 N2 (2021) 164; (HEGS –model)


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


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


dd
pN - Selyugin
g1
g1(S-wave)
g1(D-wave)
g2
g2(S)
g2(D-wave)
N_TVPC, a.u.
s_pN^1/2, GeV
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
0
5
10
15
20
25
30

g' – type of TVPC vanishes in dd-dd, like 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

CONCLUSION AND OUTLOOK

- σ_{TVPC} is a true null-test observable, not generated by ISI&FSI, analog of EDM.
- T_p –dependence of the $\sigma_{TVPC}(d\text{-}d)$ for the h -type is calculated in Glauber theory with hadron pN-amplitudes.
- d-d does not contain the *g′*- and g -type of TVPC, i.e. is **optimal to search for h-type** , but decreases with increasing energy.
- Dependence on the T-even P-even pN model is sizeable.

- How to measure at SPD?

  Precessing polarization of the beam & Fourier analysis

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

THANK YOU FOR ATTENTION!

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): $\alpha_T \le 10$, $\Lambda_{TVPC} > 150$ TeV

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

EDM at energies below Λ_{TVPC}

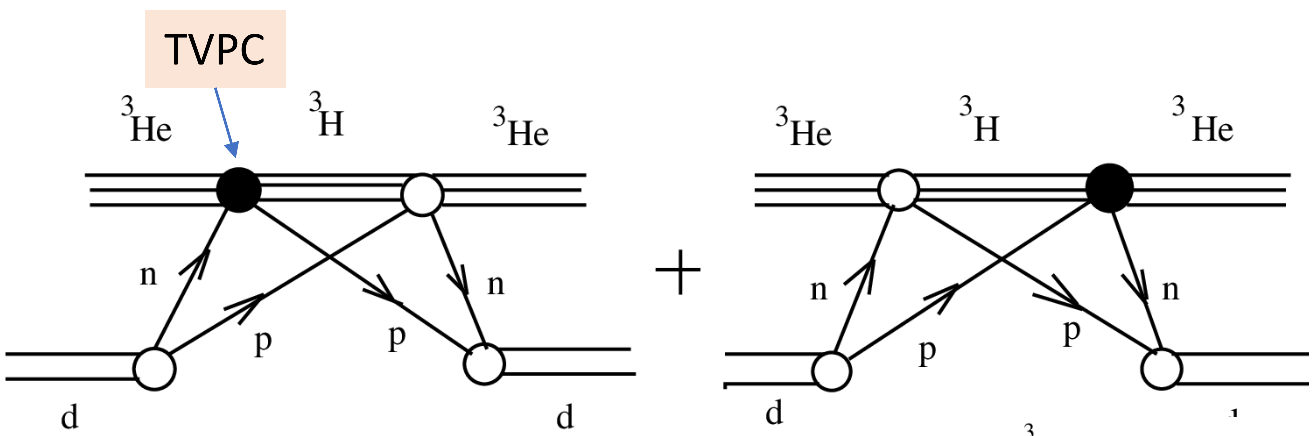
$$d = \beta_5 C_5 \frac{1}{\Lambda_{TVPC}} + \beta_6 C_6 \frac{M}{\Lambda^2_{TVPC}} + \underbrace{\beta_7 C_7 \frac{M^2}{\Lambda^3_{TVPC}}}_{the\,first\,contrb.\,from\,TVPC}$$

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

g' –term of TVPC in ^{3}He-d.

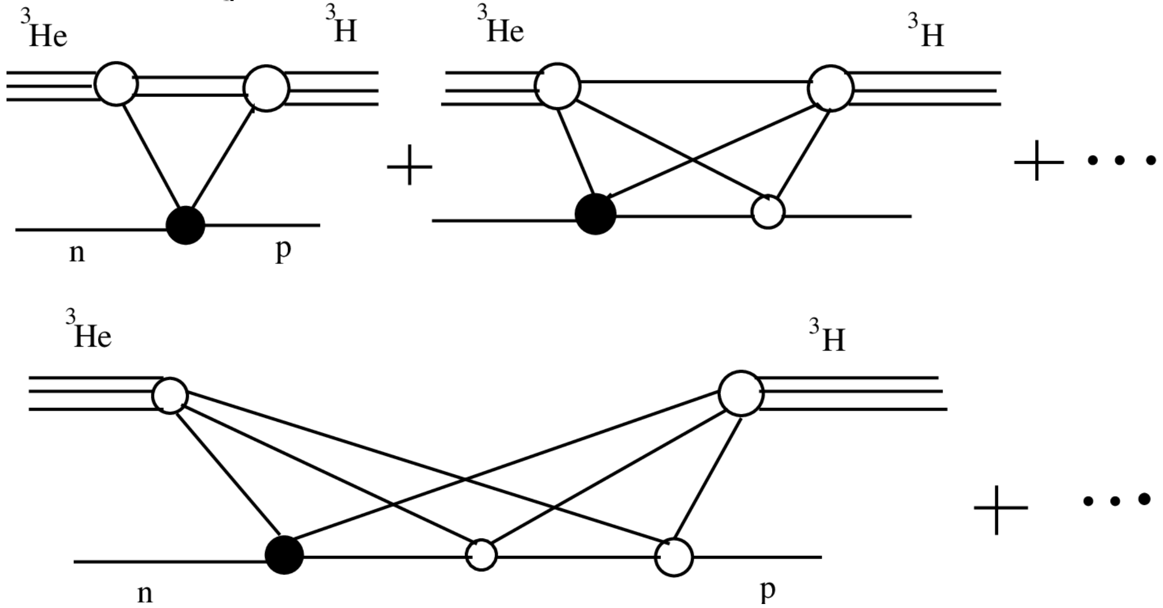
Charge-exchange pn<->np:

$$\langle n,p|[\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z|p,n\rangle = -i2, \quad \langle p,n|[\boldsymbol{\tau} \times \boldsymbol{\tau}_N]_z|n,p\rangle = i2.$$



= 0

$$< 3Hen\,|\,\hat{g}'\,|\,3Hp >= -< 3Hp\,|\,\hat{g}'\,|\,3Hen >$$



$F_{TCPC}(n^3He \rightarrow p^3H) = F_{TCPC}(p^3H \text{->} n^3He)$

g'-term in ^{3}He-d vanishes like in pd

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

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

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

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

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

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

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

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

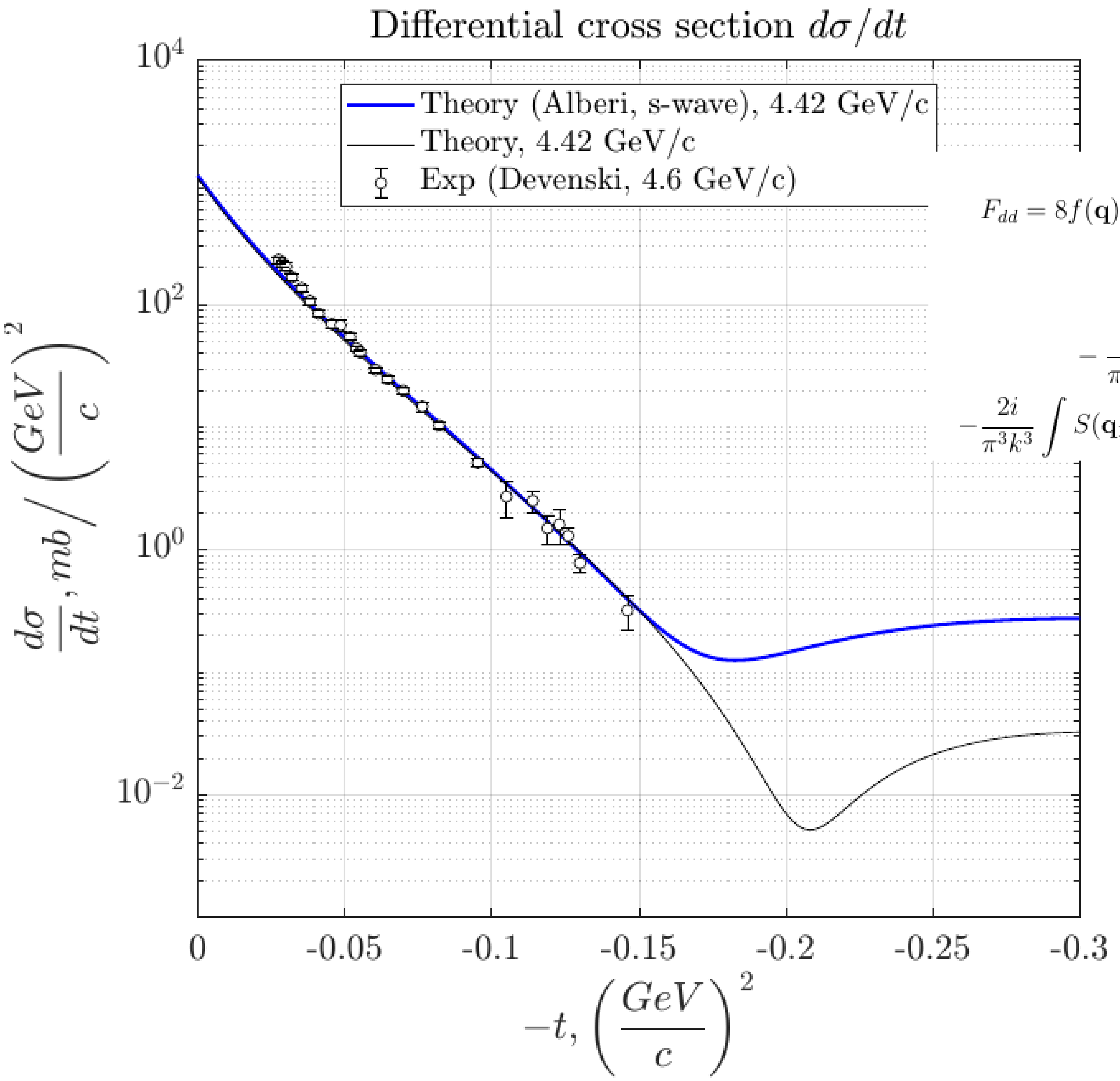
$$\beta_{4i}(t) = c_{4i}\exp(b_{4i}t)\frac{-t}{4m_N^2},$$

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

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}

dd→dd, Glauber model

A. Kornev , START program



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

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

Without spins in pN

The T-invariance:

$$T\mathcal{H}T^{-1} = \mathcal{H},$$

then the S-matrix

$$S = \lim_{t_1\to\infty} \lim_{t_2\to\infty} = \exp^{-i\mathcal{H}(t_2-t_1)},$$

transforms as

$$T\mathcal{S}T^{-1} = \mathcal{S}^{+},$$

or $T^{-1}\mathcal{S}^{+}T = \mathcal{S}$. Therefore (T is antilinear)

$$< f, S\, i >=< f, T^{-1}S^{+}T\, i >=< T f, S^{+}T\, i >^{*}=< f_T, S^{+}i_T >^{*}$$

in other words, the T-invariance:

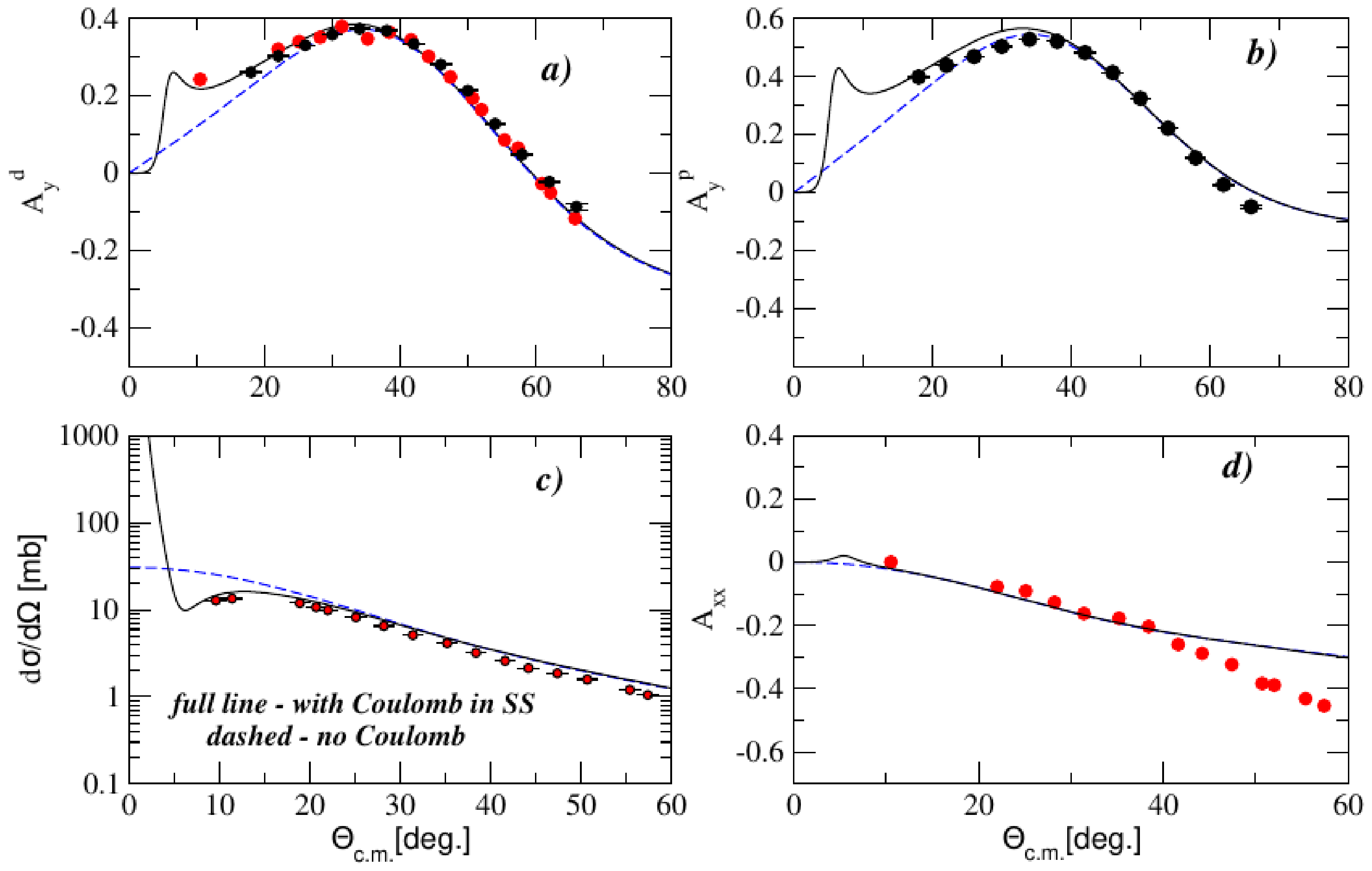
$$< f|\mathcal{S}|i >=< i_T|S|f_T >$$

(See, S.M. Bilen'kii, L.I. Lapidus, R.M. Ryndin, Usp. Phys. Nauk. 95 (1968) 489
J.R.Taylor, Sattering Theory. Quantum theory of Nonrelativistic collisions, N-Y, 1972)

$$S^{J}_{a,b} = S^{J}_{b,a}$$

Test calculations: pd elastic scattering at 135 MeV

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

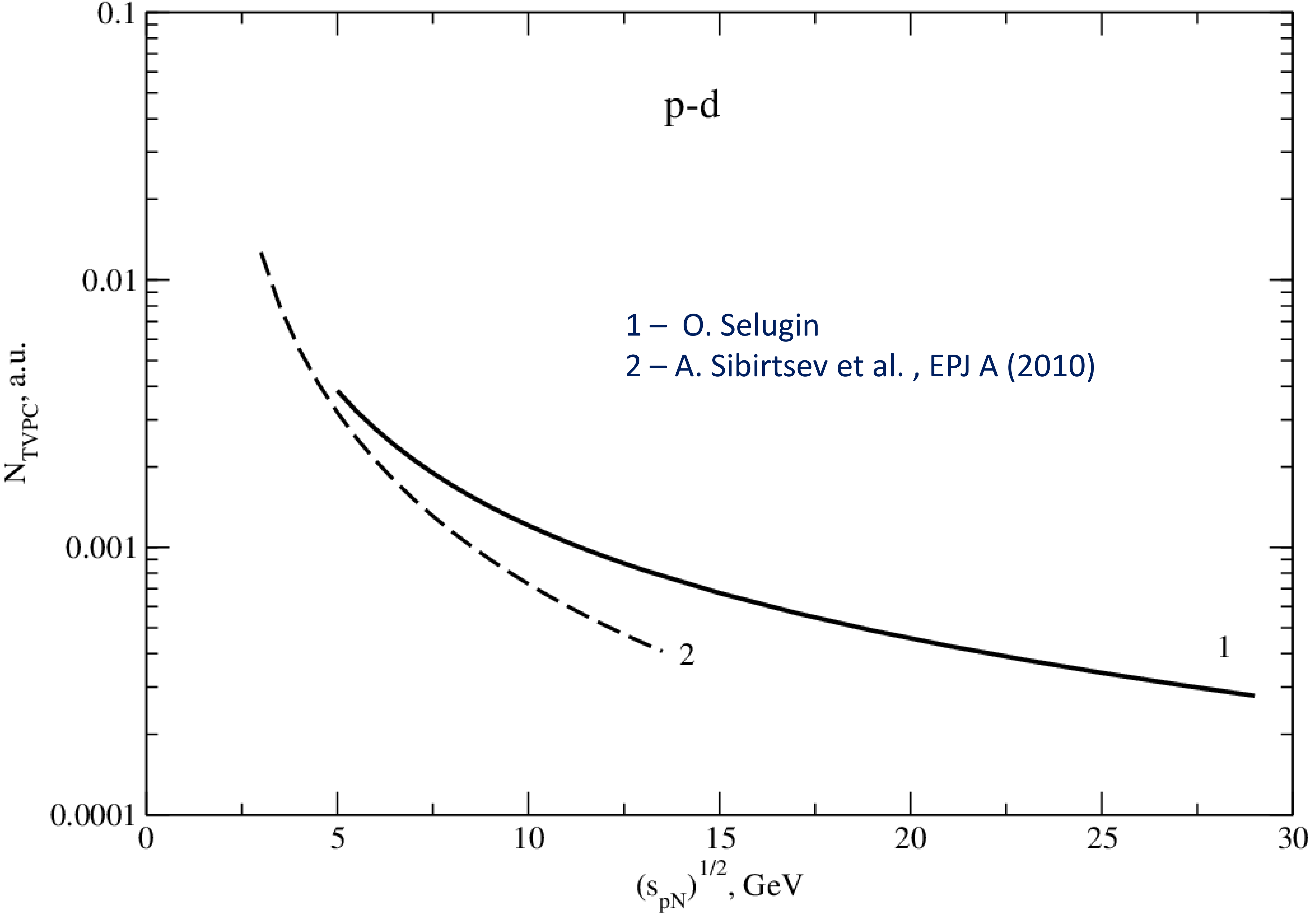


Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)
See also Faddeev calculations: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.

$$\sigma_{tot} = \sigma_0 + \sigma_{TT} p_y^p P_y^d + \sigma_t P_{zz} + \sigma_{tvpc} p_y^p P_{xz};$$

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

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



0.1
0.01
0.001
0.0001
0
5
10
15
20
25
30
p-d
1 – O. Selugin
2 – A. Sibirtsev et al. , EPJ A (2010)
N_TVPC, a.u.
2
1
(s_pN)^1/2, GeV