Search for T-invariance violation in double polarized pd, ^{3}He-d and dd scattering and test of pN spin amplitudes at NICA energies

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The basic question:

"How did it happen that there is enough matter left in the universe to be able to create galaxies, stars, planet and us ?"

B.H.J.McKellar, AIP Conf. Proc. 1657 (2015) 03001

CONTENT

- Motivation: **Baryon Asymmetry of the Universe (BAU)**
- Time-violation Parity-conserving (TVPC) NN interaction
- Null-test signal of TVPC effects in double polarized pd,^{3}Hed, dd scattering at NICA
- Glauber spin-dependent theory of **pd->pd** and test of spin pN-amplitudes.
- NICA SPD: Studying spin observables of **pd->pd** via the **dd-> n+p+d** process.
- Summary and outlook

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

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

CPV observed in K^0,B,D meson physics and baryons decay (2025): $\varepsilon \sim 10^{-3}$

Experiments for search of additional CP- violation:

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

Both are T-violating and P-parity 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 with a scenario "B" for EDM**
A. Kurylov et. al. PRD 63 (2001) 076007 -> in contrast, to R.S. Conti, I.B. Khriplovich, PRL 68 (1992) 3262

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

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 problem, the TVPC can be much stronger at higher energies (NICA), however, no data are available so far at NICA.

Search for TVPC in double polarized scattering (pd, ^{3}Hed,dd)

Null-test signal of Time Violating Parity Conserving (TVPC) effects is a part of total cross section of vector polarized (p_y) p-, ^{3}He-, d-scattering on the tensor polarized (P_{xz}) deuteron.

V. Baryshevsky, Sov. J. Nucl. Phys. 38 (1983) 699; A.L. Barabanov, Yad.Fiz. 44 (1986) 1163.
H.E. Conzett, PRC 48 (1993) 423

Advantages:

- Not necessary to measure two extremely small observables (A_y and P_y) to get their difference (under T-invariance $A_y = P_y$).
- Cannot be imitated by ISI@FSI.

* Not equivalent to spin-correlation in elastic scattering $C_{y,zx}$
* Requires (for static spins) to suppress / exclude the contribution of the P_y^d

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

TVPC ($\equiv$ T-odd P-even) interactions in terms of boson exchanges :

M.Simonius, Phys. Lett. **58B** *(1975) 147; PRL* **78** *(1997) 4161*

- $\star$ $J \geq 1$
- $\star$ π, σ-exchanges do not contribute
- $\star$ The lowest mass meson allowed is the ρ-meson $/I^G(J^{PC}) = 0^+(1^{--})/$
- $\star$ Natural parity exchange $(P = (-1)^J)$ must be charged

* Abnormal parity exchanges $1^+, 2^-$, … no restrictions

TVPC ($\equiv$ T-odd P-even) interactions in terms of boson exchanges :

M.Simonius, Phys. Lett. **58B** *(1975) 147; PRL* **78** *(1997) 4161*

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The TVPC Born NN-amplitude

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

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 $a_1(1170)$-meson exchange $I^G(J^{PC}) = 0^-(1^{+-})$ ...

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

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, $M^{str}_{pn\to np} = M^{str}_{np\to pn}$.

TIVOLI: pd-experiment was planned at COSY, Tp=135 MeV; ***P. Lenisa et al. EPJ- Tech. Instr. (2019) 6***

TVPC signal in pd-transmission experiment

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

T-even (TCPC) amplitude of forward pd-elastic scattering (has to be multiplied by the polarization vector of the deuteron $\varepsilon^*_\beta(\varepsilon_\alpha)$):

$$M_{\beta\alpha}(0) = g_1\delta_{\beta\alpha} + (g_2 - g_1)\hat{k}_\beta\hat{k}_\alpha + ig_3\sigma_i\epsilon_{\beta\alpha i} + i(g_4 - g_3)\sigma_i\hat{k}_i\hat{k}_j\epsilon_{\beta\alpha j}$$

Optical theorem:

$$\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 p_y^p p_y^d + \sigma_3 P_{zz}}_{\text{TCPC}} + \underbrace{\sigma_{TVPC} p_y^p P_{xz}}_{\text{TVPC null-test signal}}$$

$$\sigma_0 = \frac{4}{3}\sqrt{\pi}\mathrm{Im}(2g_1 + g_2), \quad \sigma_1 = -4\sqrt{\pi}\mathrm{Im}g_3, \quad \sigma_3 = 4\sqrt{\pi}\mathrm{Im}(g_1 - g_2).$$

Additional TVPC-term to $M_{\beta\alpha}(0)$: $\tilde{g}_5\sigma_i\hat{k}_\gamma(k_\alpha\epsilon_{\gamma\beta i} + k_\beta\hat{k}_\gamma\epsilon_{\gamma\alpha i})$

$$\sigma_{TVPC} = -4\sqrt{\pi}\frac{2}{3}\mathrm{Im}\tilde{g}_5$$

No interference with T-even P-even terms

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

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 $A_{TVPC} \sim 10^{-6}$

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

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)

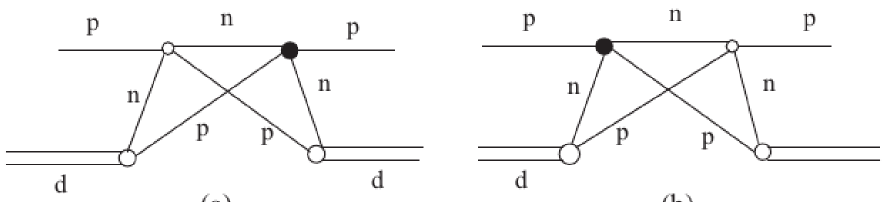
Yu.N. U., A.A. Temerbayev, PRC 92 (2015); **pd**
Yu.N. U., J. Haidenbauer, PRC 94 (2016); **pd**
Yu.N. U., M.N. Platonova, JETP Lett. 118 (2023) 11 ; **^{3}He-d**
Yu.N. U.,M.N. Platonova et al. Int. J. Mod. Phys. E (2024); **dd**
M.N. Platonova, Yu.N. U. Chin. Phys. C 49, N3 (2025) 034108; **dd**

TVPC signal in pd-collision

$$\widetilde{g}_5 = \frac{1}{(2\pi)^{3/2}} \int d^2q' \left\langle \mu' = \frac{1}{2}, \lambda' = 0 \middle| M(\mathbf{q} = 0, \mathbf{q}'; \mathbf{S}, \boldsymbol{\sigma}) \middle| \mu = -\frac{1}{2}, \lambda = 1 \right\rangle$$

$$\widetilde{g}_5 = \frac{i}{4\pi m_p} \int_0^\infty dq q^2 \Big[S_0^{(0)}(q) - \sqrt{8} S_2^{(1)}(q) - 4 S_0^{(2)}(q) + \sqrt{2}\frac{4}{3} S_2^{(2)}(q) + 9 S_1^{(2)}(q) \Big] [-C_n'(q) h_p + C_p'(q)(g_n - h_n)]$$

In the Glauber theory for two-step scattering (single scattering gives zero)



(a) (b)

Deuteron form factors:

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

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

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

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

$$S_1^{(2)}(q) = \int_0^\infty dr\, w^2(r) j_1(qr)/(qr).$$

TCPC pN-amplitude:

$$\begin{aligned} M_N = A_N + C_N \boldsymbol{\sigma}_p \cdot \hat{\mathbf{n}} + C_N' \boldsymbol{\sigma}_N \cdot \hat{\mathbf{n}} \\ + B_N (\boldsymbol{\sigma}_p \cdot \hat{\mathbf{k}})(\boldsymbol{\sigma}_\mathbf{N} \cdot \hat{\mathbf{k}}) \\ + (G_N + H_N)(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{q}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{q}}) \\ + (G_N - H_N)(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{n}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{n}}); \end{aligned}$$

+ TVPC (h_N, g_N, g'_N)

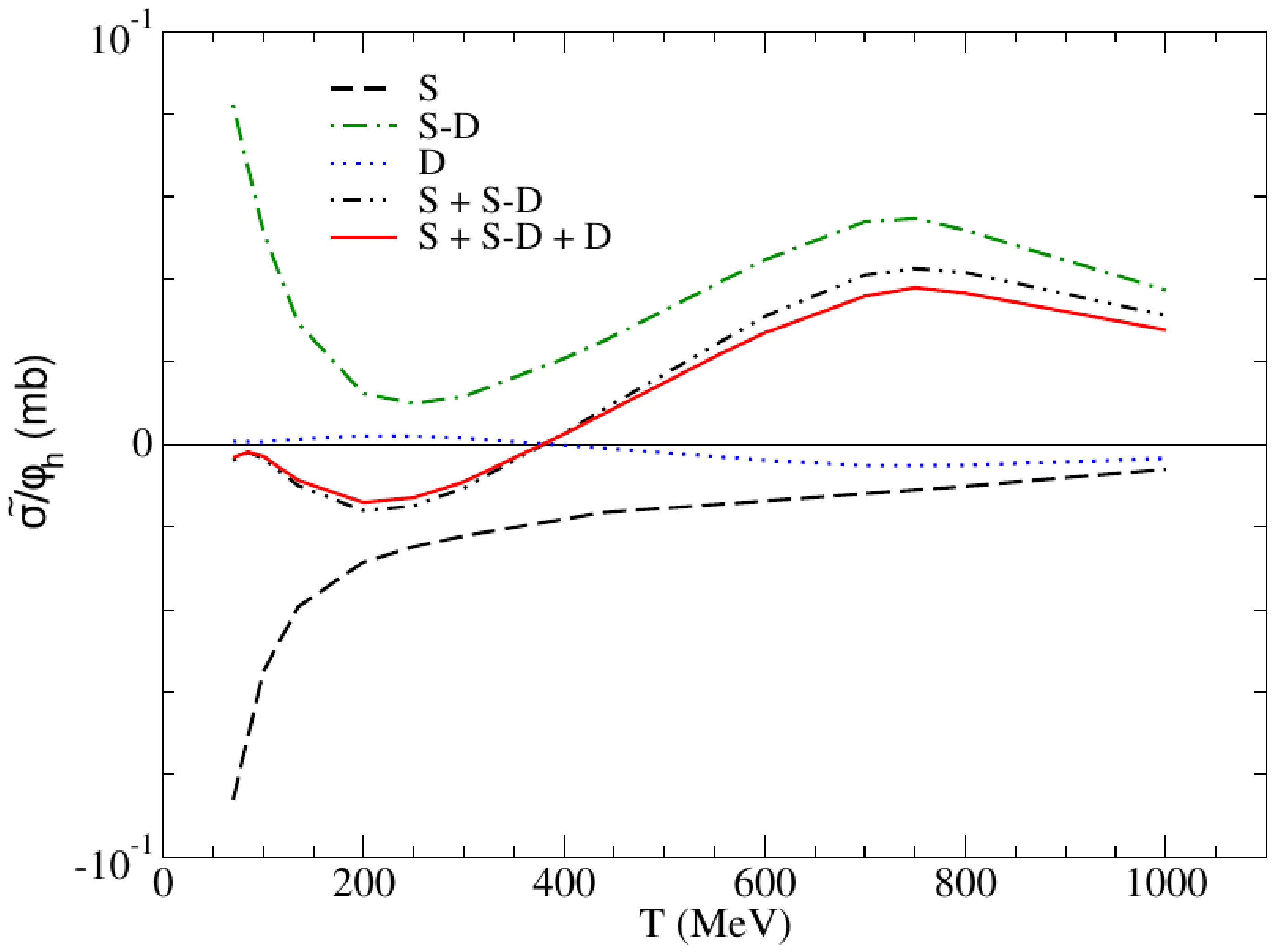
$$C' \approx i\phi_5 + iq/2m(\phi_1 + \phi_3)/2$$

Yu.N.U., A.A. Temerbayev, PRC 92 (2015) 014002;
Yu.N.U., J. Haidenabuer, PRC 94 (2016) 035501.

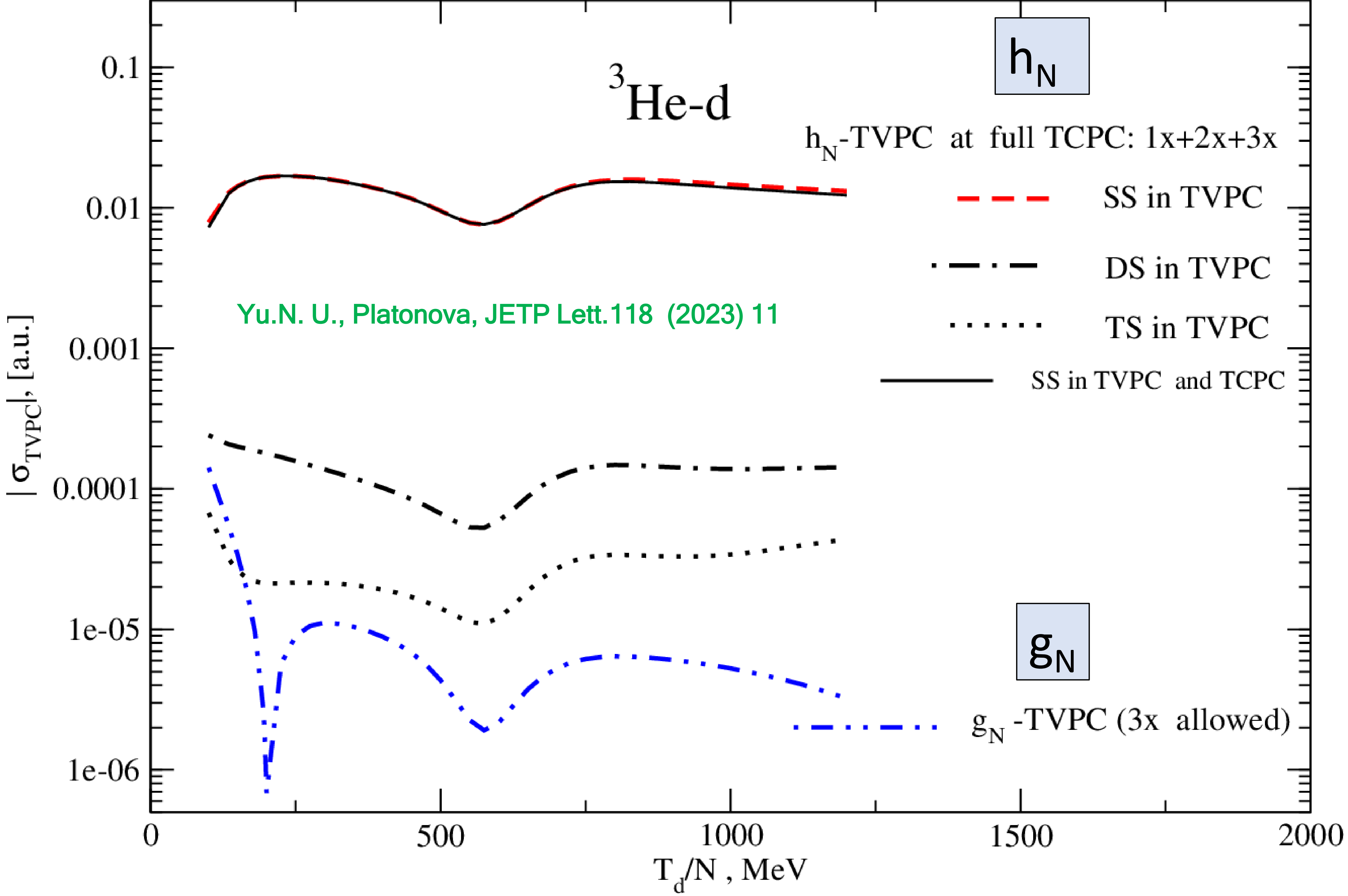
The g'_N-term is zero due to symmetry properties

TVPC signal in *pd*-scattering accounting for *S*- и *D*-waves of the deuteron

(in units of unknown TVPC constant φ_h)

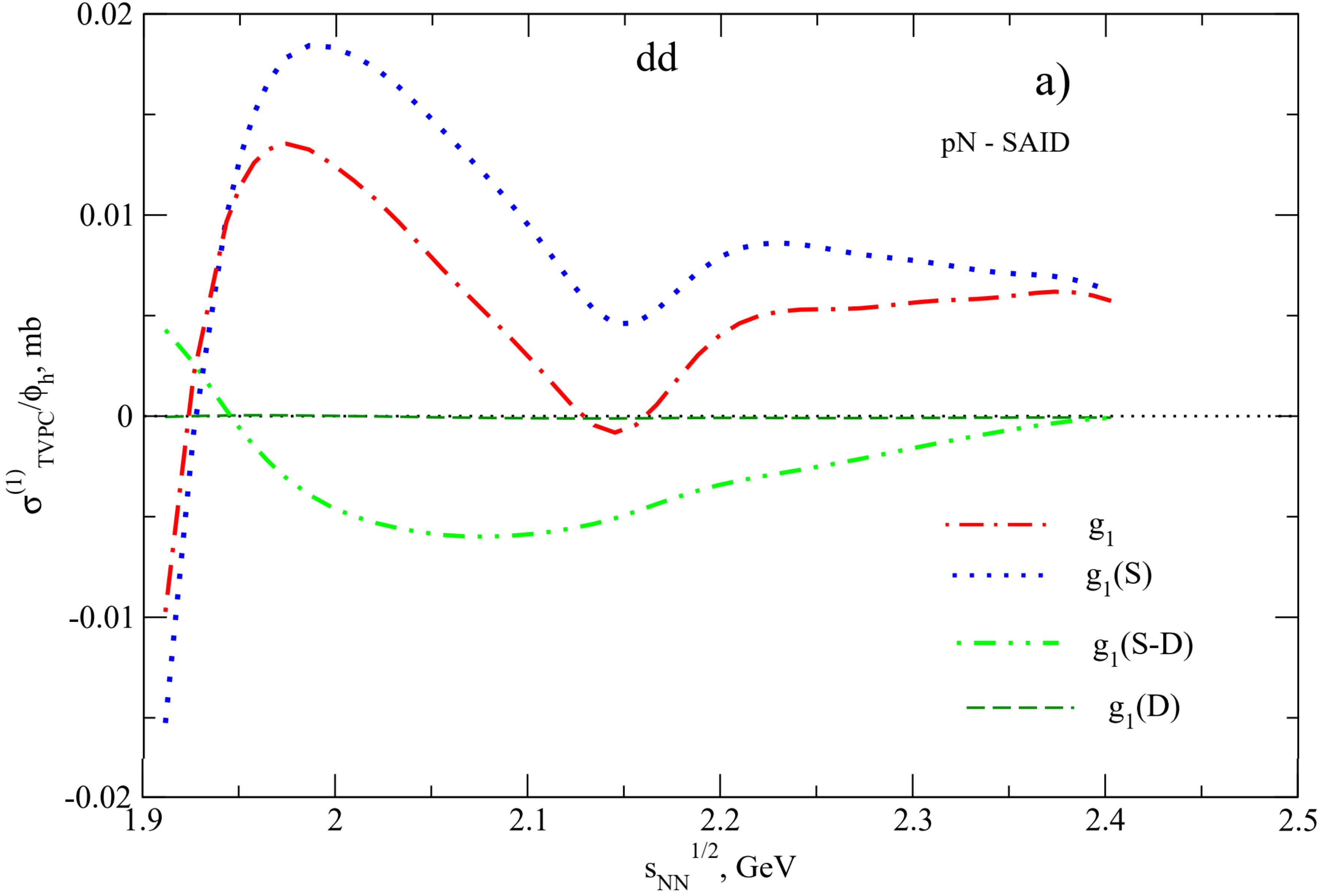


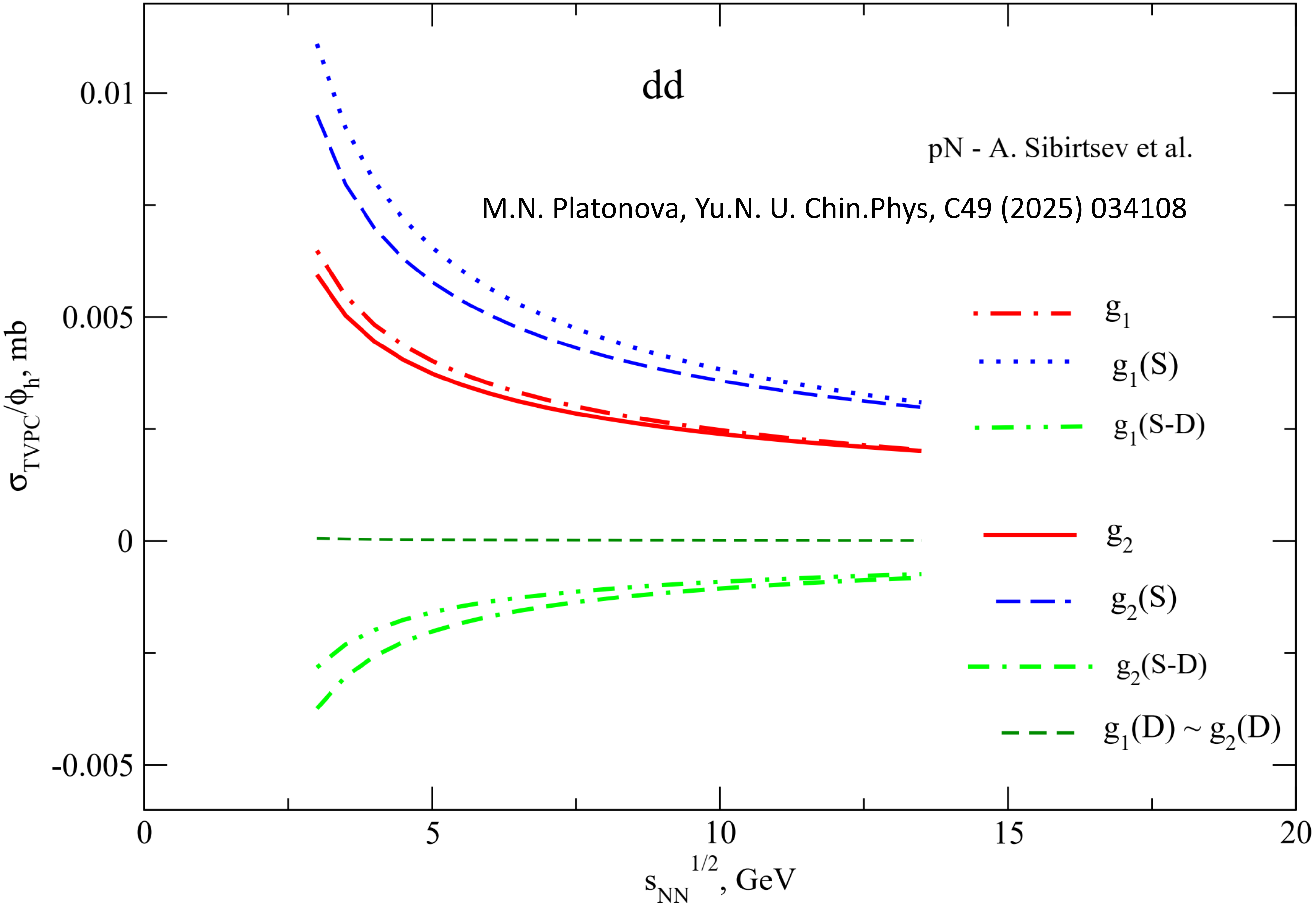
Yu.N. Uzikov, J.Haidenbauer, PRC 94 (2016) 035501

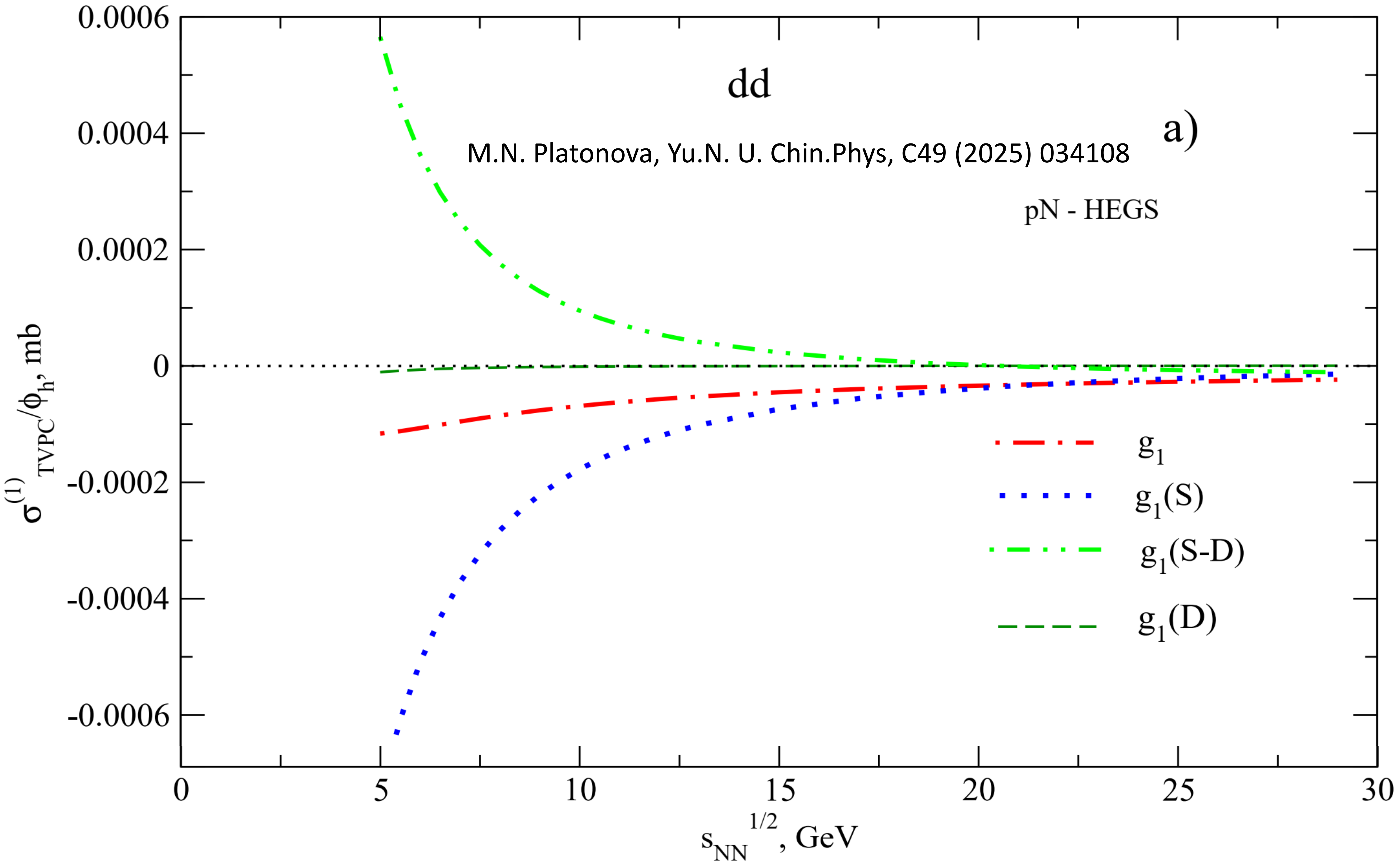


^{3}He-d
h_N
h_N-TVPC at full TCPC: 1x+2x+3x
SS in TVPC
DS in TVPC
TS in TVPC
SS in TVPC and TCPC
Yu.N. U., Platonova, JETP Lett.118 (2023) 11
g_N
g_N -TVPC (3x allowed)
$|\sigma_{TVPC}|$, [a.u.]
T_d/N , MeV
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
500
1000
1500
2000

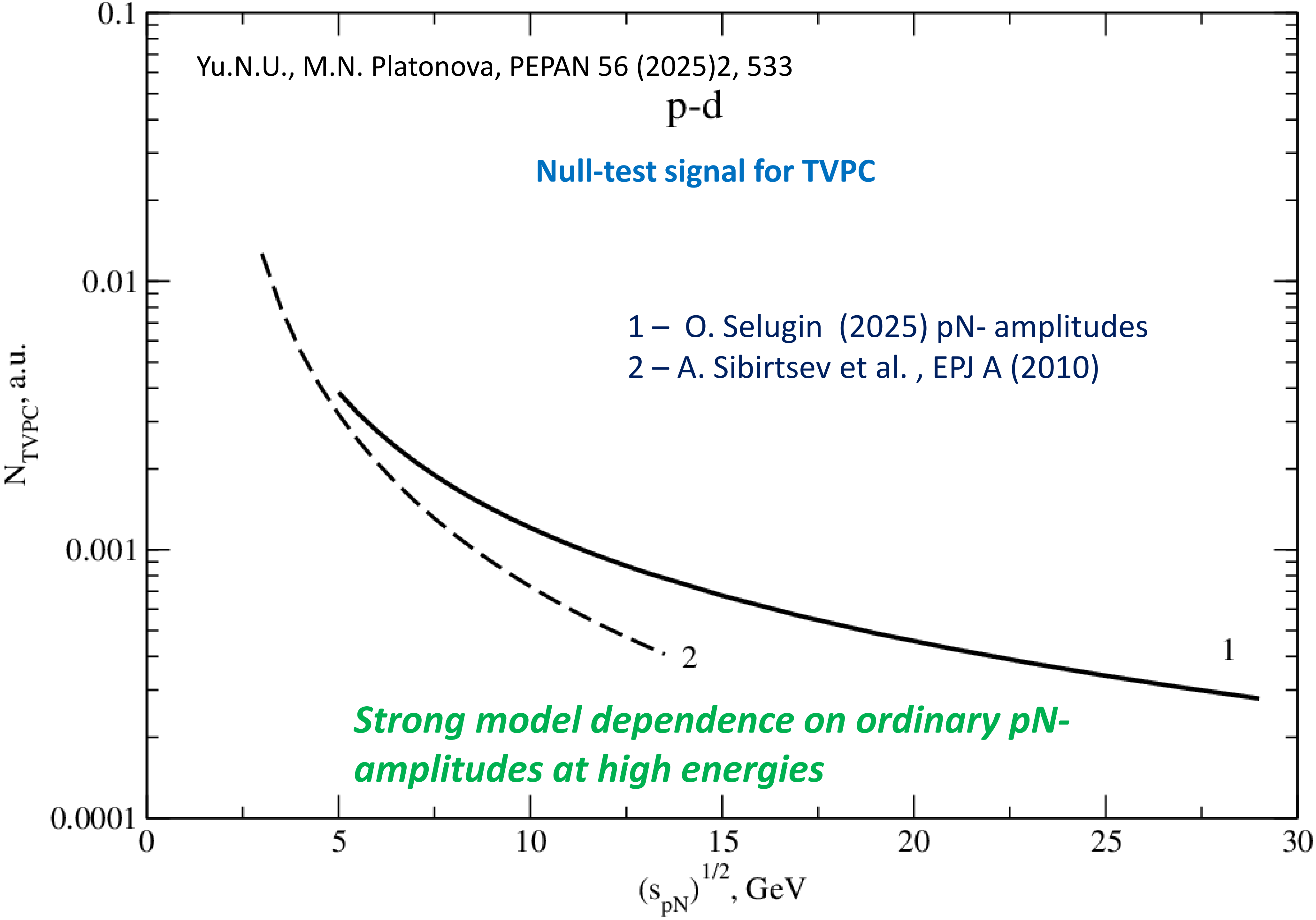
M.N.Platonova , Yu.N. Uzikov, Chin. Phys. C49 (2025) 034108




dd
pN - A. Sibirtsev et al.
M.N. Platonova, Yu.N. U. Chin.Phys, C49 (2025) 034108
g_1
$g_1(S)$
$g_1(S\text{-}D)$
g_2
$g_2(S)$
$g_2(S\text{-}D)$
$g_1(D) \sim g_2(D)$
0.01
0.005
0
-0.005
σ_{TVPC}/ϕ_h, mb
0
5
10
15
20
$s_{NN}^{1/2}$, GeV



dd
a)
M.N. Platonova, Yu.N. U. Chin.Phys, C49 (2025) 034108
pN - HEGS
g_1
$g_1(S)$
$g_1(S\text{-}D)$
$g_1(D)$
$\sigma^{(1)}_{TVPC}/\phi_h$, mb
$s_{NN}^{1/2}$, GeV
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
0
5
10
15
20
25
30


Yu.N.U., M.N. Platonova, PEPAN 56 (2025)2, 533
p-d
Null-test signal for TVPC
1 – O. Selugin (2025) pN- amplitudes
2 – A. Sibirtsev et al. , EPJ A (2010)
Strong model dependence on ordinary pN-amplitudes at high energies
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

Glauber spin-dependent theory of *pd-pd* and test of pN amplitudes

pd-pd: The simplest process with both **pp and** pn-amplitudes involved.

dd-dd elastic is also suitable, but much more complicated,

spin-dependent Glauber formalism is not yet developed.

M.N. Platonova, V.I. Kukulin, Phys.Rev.C 81 (2010) 014004, Phys.Rev.C 94 (2016) 6, 069902; (erratum) e-Print:1612.08694[nucl-th].

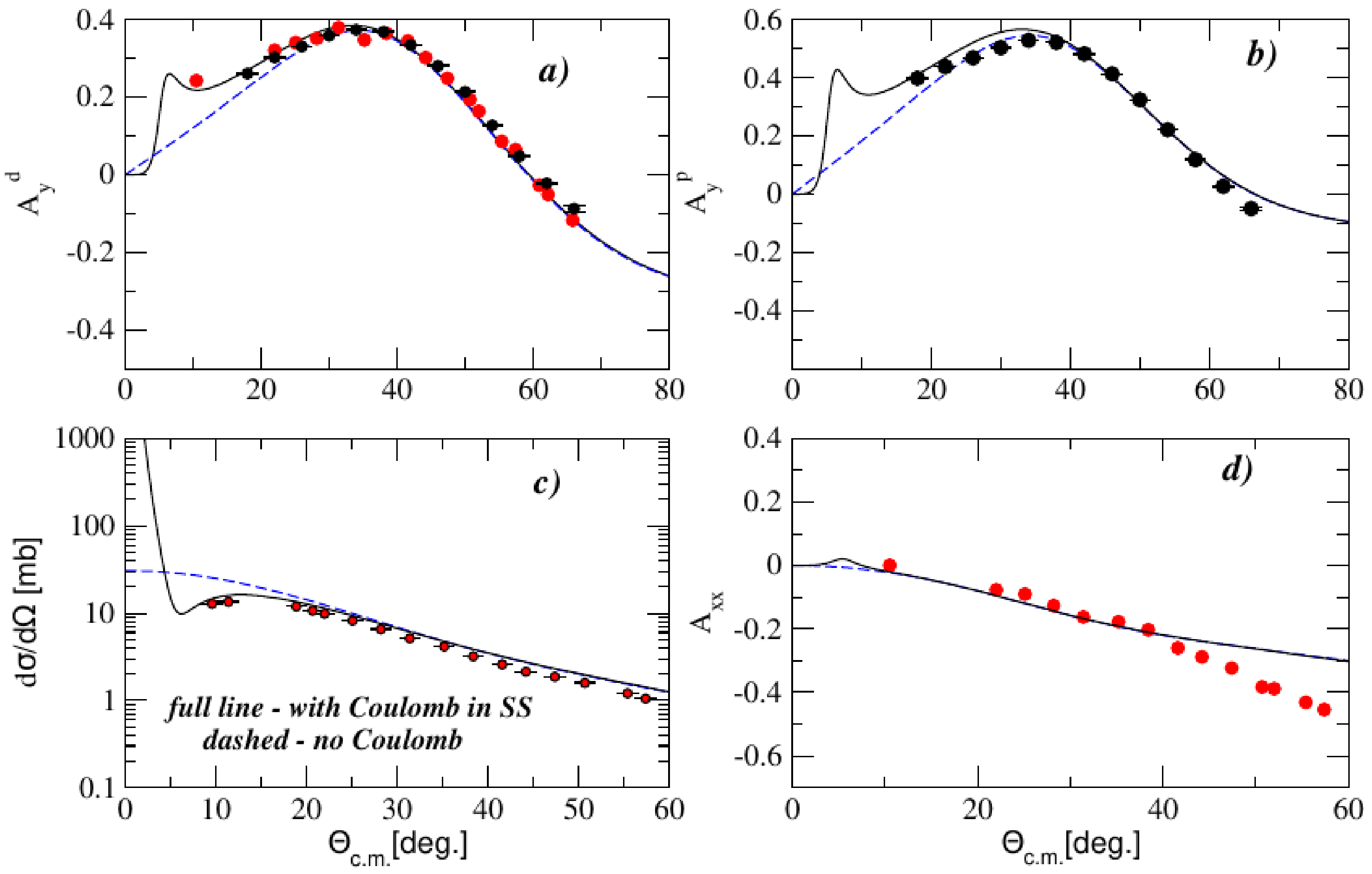
M.N. Platonova, V.I.Kukulin, Eur.Phys.J.A56 (2020) 5, 132; e-Print: 1910.05722[nucl-th]

A.A. Temerbayev, Yu.N. Uzikov, Yad. Fiz. 78(2015)38; Bull. Rus. Ac. Sci. v.80 №3 (2016) 242. **Madison ref. frame**

Test calculations: pd elastic scattering at 135 MeV

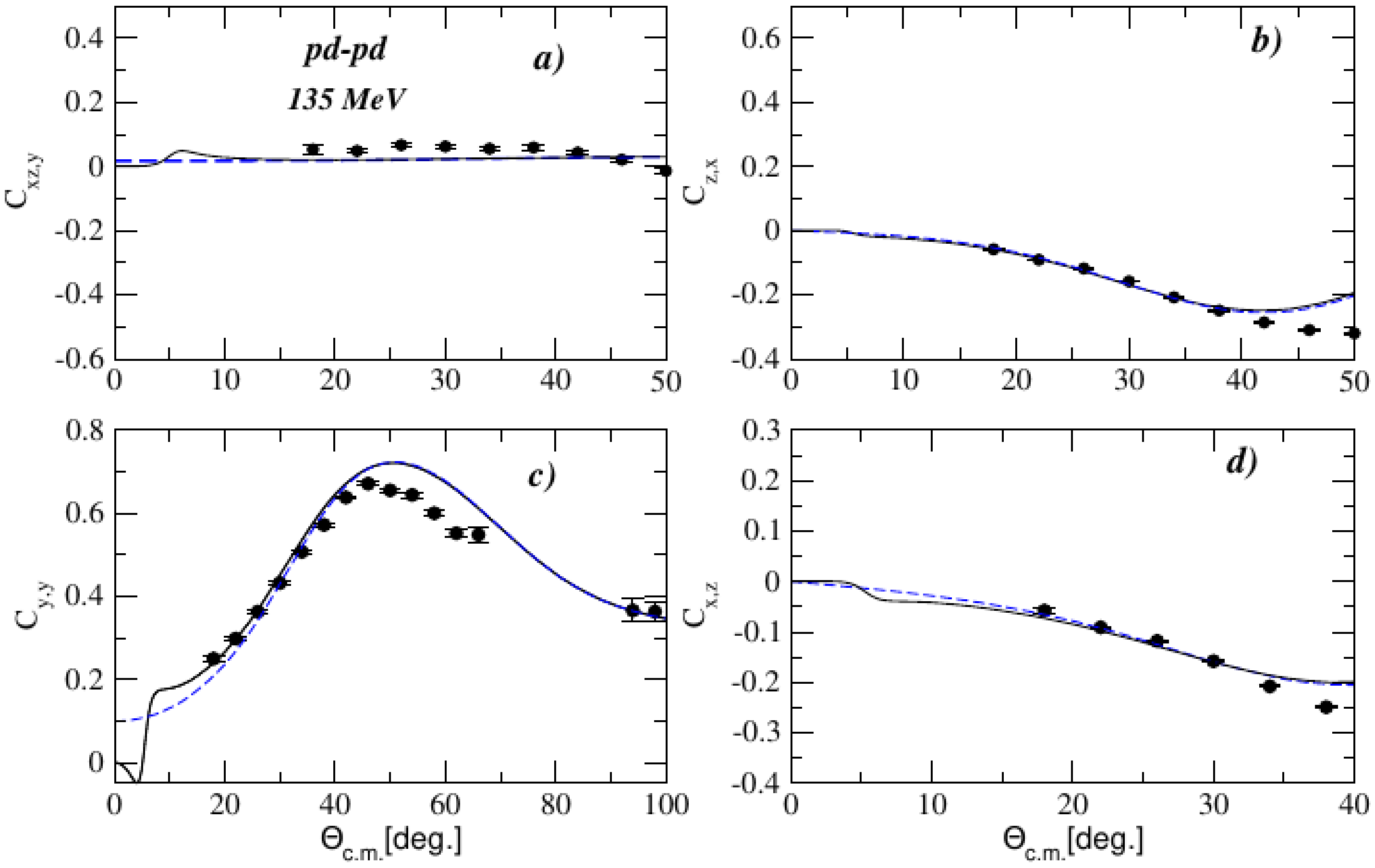
A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38

Glauber is comparable with results of Faddeev calculations



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.

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



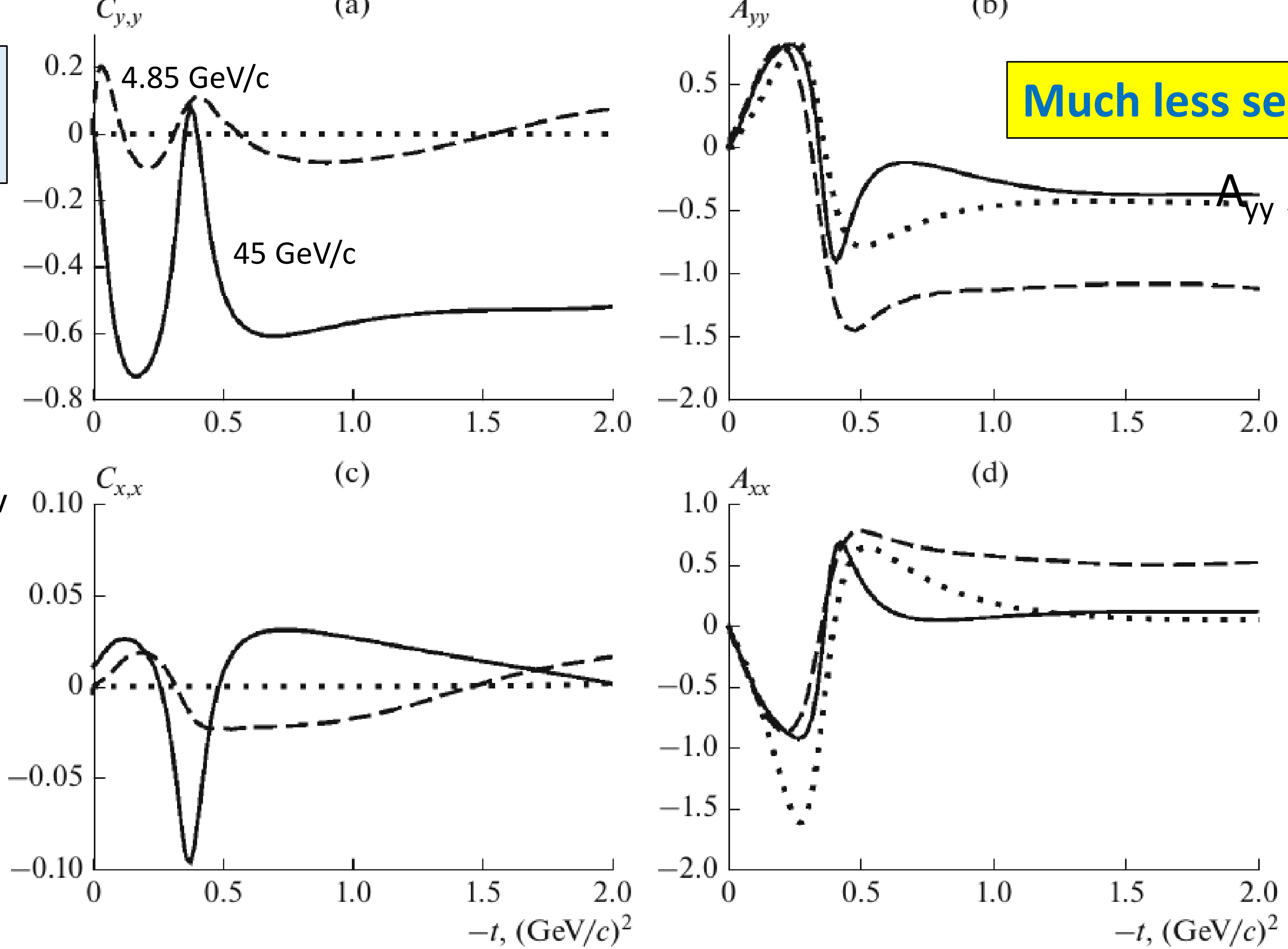
$C_{y,y}$, $C_{x,z}$, $C_{z,x}$, $C_{xz,y}$

Figure 1: Spin correlation coefficients $C_{xz,y}$ (a), $C_{z,x}$ (b), $C_{y,y}$ (c), $C_{x,z}$ (d) at 135 MeV versus the c.m.s. scattering angle calculated within the modified Glauber model [15] without (dashed lines) and with (full) Coulomb included in comparison with the data from [22].

Highly sensitive: $C_{y,y}$, $C_{x,x}$

NICA energies

Yu.N.U., J.Haidenbauer, A.Bazarova, A. Temerbayev PEPAN 53 (2022)2, 419

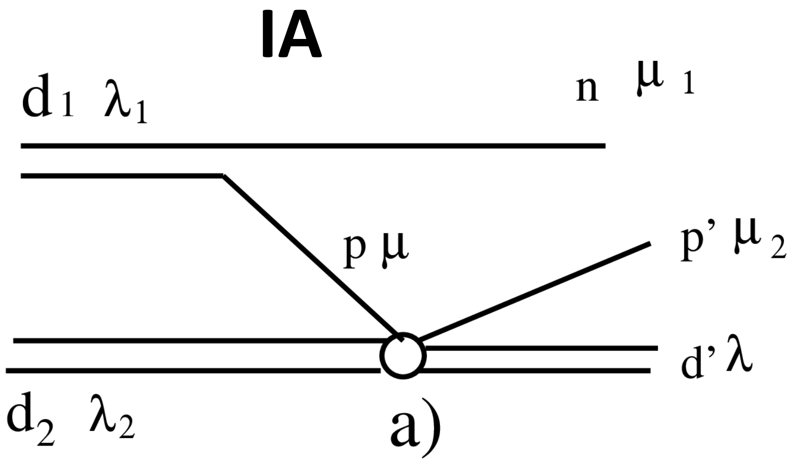


Much less sensitive: A_{yy} , A_{xx}

Dotted : spin-independent pN-amp.

Fig. 4. Results for spin-dependent *pd* observables. Same description of curves as in Fig. 3. The dotted lines are results where the spin-dependent *pN* amplitudes have been omitted in the calculation.

Relations between dd→ npd and pd→ pd in the IA



S-wave dominates at q<0.15 GeV/c and rescatterings are suppressed

Asymmetric pd-mode will be not available at NICA SPD, while symmetric dd mode will be established.

$$|M(dd \to npd)|^2 = K[u^2(q)+w^2(q)]\,|M(pd \to pd)|^2$$

$d_2^{\uparrow}$: Vector or tensor Polarized

$$A_Y^d(dd_2^{\uparrow} \to npd) = A_Y^d(pd^{\uparrow} \to pd),$$

$$A_{YY} = (dd_2^{\uparrow} \to npd) = A_{YY}(pd^{\uparrow} \to pd)$$

$d_1^{\uparrow}$: Vector Polarized

$$A_Y^d(d_1^{\uparrow}d \to npd) = \frac{2}{3}A_Y^p(p^{\uparrow}d \to pd)$$

Both d_1 and d_2 deuterons are vector or tensor polarized:

$$C_{Y,Y}(d^{\uparrow}d^{\uparrow} \to npd) = \frac{2}{3}C_{y,y}(p^{\uparrow}d^{\uparrow} \to pd)$$

$$C_{Y,YY}(d^{\uparrow}d^{\uparrow} \to npd) = \frac{1}{3}C_{y,yy}(p^{\uparrow}d^{\uparrow} \to pd)$$

Yu. N. Uzikov, e-Print: 2506.17799 [nucl-th] (accepted by PEPAN Lett.)

MC simulations: A. Datta, I.I. Denisenko ,Yu.N. U. (in preparation)

SUMMARY AND OUTLOOK

- σ_{TVPC} **is a true null-test observable**, not generated by **ISI&FSI**, analog of EDM.
- **No data on TVPC** effects are available so far **at NICA energies.**
- Energy dependence of the σ_{TVPC} $(pd,{}^3He d,dd)$ is **calculated in the spin-dependent Glauber theory** in broad range of energy
- $d^\uparrow d^\uparrow$ does not contain the *g'*- and g-type of TVPC, i.e. is **optimal to search for the h-type of TVPC**.
- **Strong model dependence on** ordinary TCPC pN amplitudes.
  Test of these amplitudes at NICA energies **is developed** by studying spin observables of **pd-pd** via **dd-npd** at SPD.

For measurement at SPD:

Precessing polarization of the beam & Fourier analysis

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

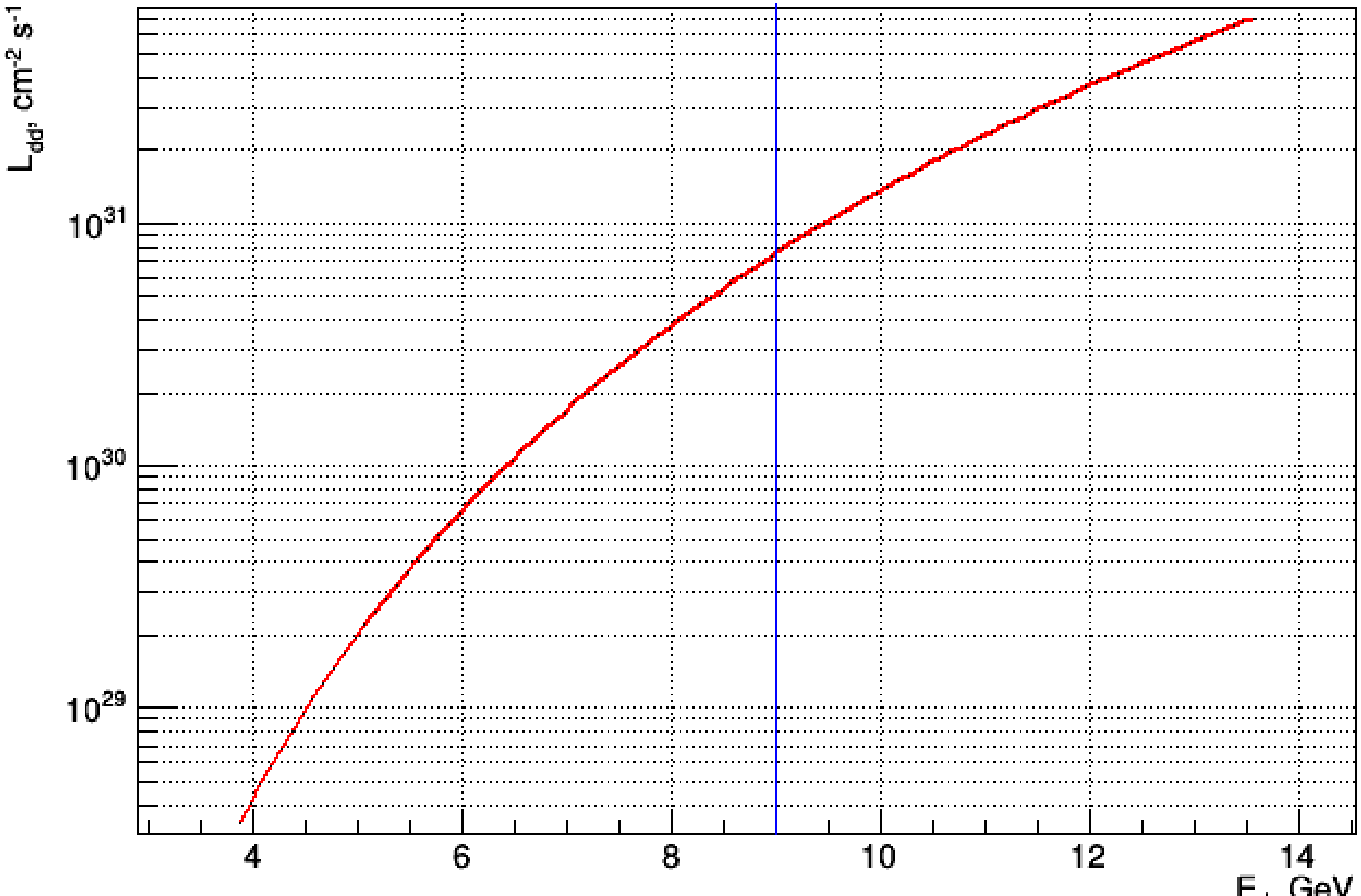
The basic question:

"How did it happen that there is enough matter left in the universe to be able to create galaxies, stars, planet and us ?"

B.H.J.McKellar, AIP Conf. Proc. 1657 (2015) 03001

THANK YOU FOR ATTENTION!

Luminosity at SPD NICA for dd-collisons



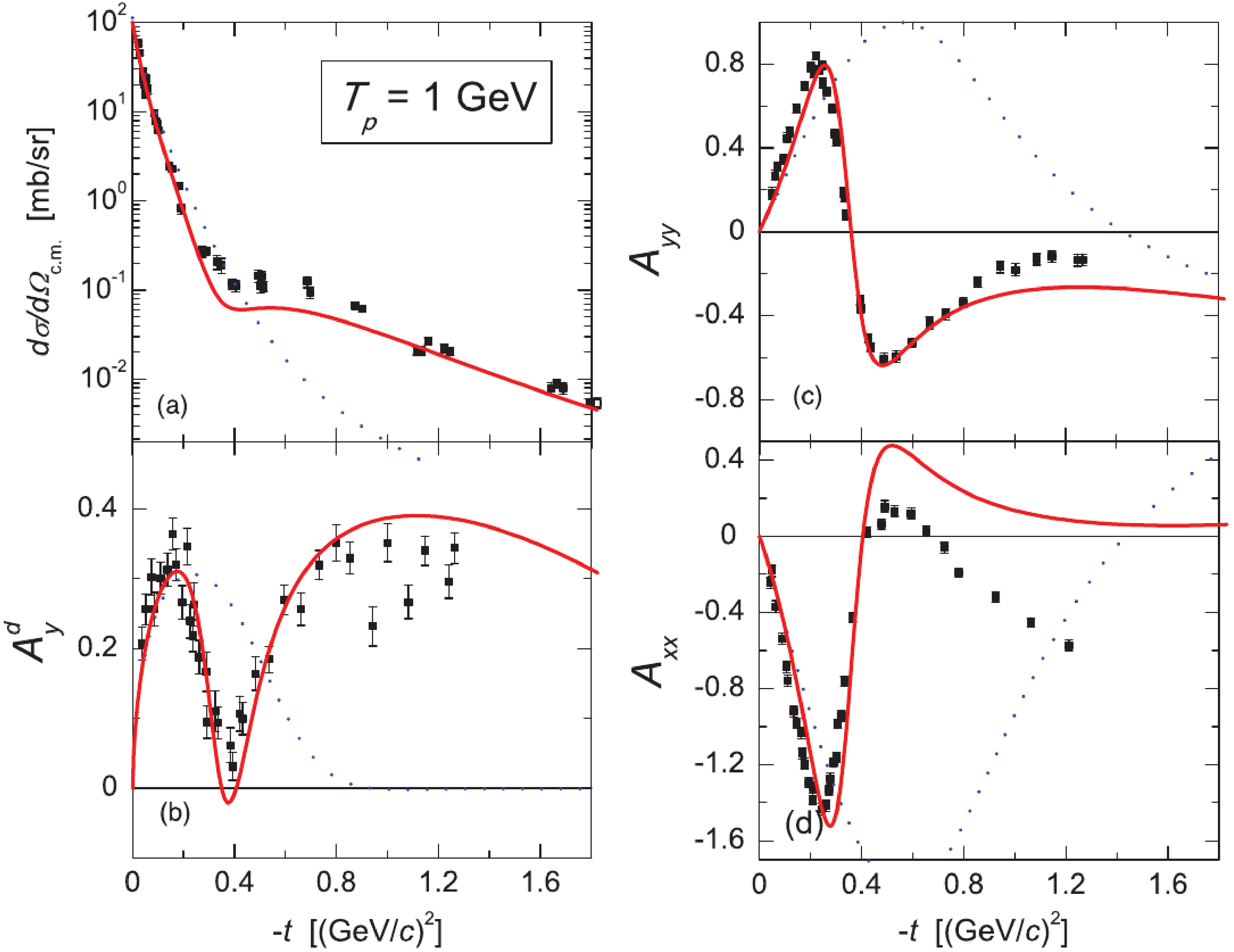
Minimal energy of the deuteron in c.m.s. = 4GeV

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

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

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

M.N. Platonova, V.I. Kukulin, PRC 81(2010) 014004



Time-Reversal Violation in the Kaon and B^0 Meson Systems

- CP-violation in K- and B-meson physics (under CPT) $\Longrightarrow$ T-violation
- T violation in the K-system:

$K^0 \to \bar{K}^0$ and $\bar{K}^0 \to K^0$

Difference between probabilities was observed

A.Angelopoulos et al. (CPLEAR Collaboration) Phys. Lett. **B 444** (1998) 43.

These channels are connected both by T- and CP- transformation!

- Direct observation of T-violation in

$\bar{B}^0 \to B_-$ and $B_- \to \bar{B}^0$ $\qquad B\_ = c\bar{c}K_S^0$

connected only by T-symmetry transformation

(There are three other independet pairs)

J.P. Lees et al. (BABAR Collaboration) PRL **109** (2012) 211801

The results are consistent with current CP-violating measurements obtained invoking CPT-invariance

We will focus on TVPC flavor conserving effects.

Phenomenological models of NN-elastic amplitudes

NN helicity amplitudes:

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

Models:

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

Isospin and G-parity:

$$\phi(pp) = -\phi_\omega - \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P,$$
$$\phi(pn) = -\phi_\omega + \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P.$$

- **W.P. Ford, J. van Orden**, Phys. Rev. C 87 (2013) $\sqrt{s_{pN}} = 2.5 - 3.5 GeV$ (pp, pn; Regge);
- **O.V. Selyugin**, Symmetry., 13 N2 (2021) 164; (Regge –eikonal); *Phys.Rev.D* 110 (2024) 11, 114028 ; e-Print: 2407.01311 [hep-ph] $\sqrt{s_{NN}} = 5 - 25 GeV$

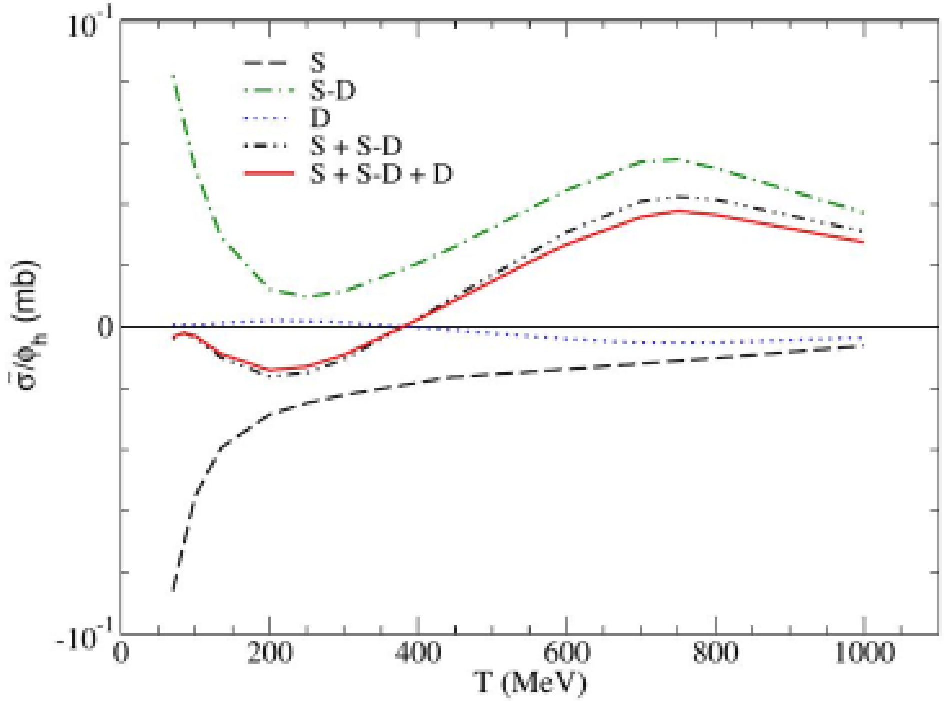
$p^{\uparrow}d^{\uparrow}$

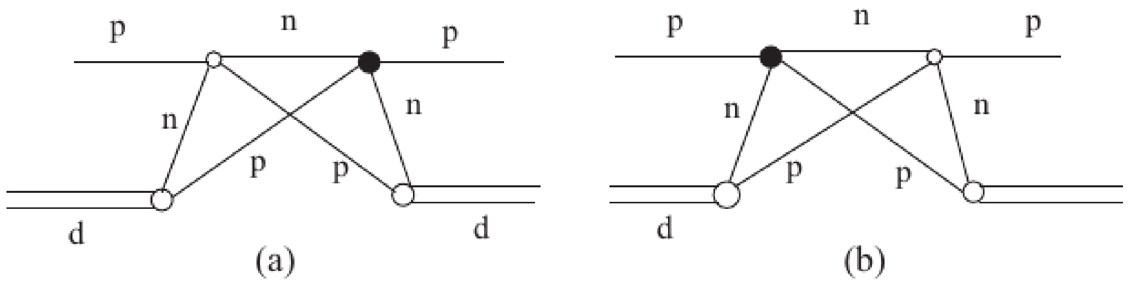
$$\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2(\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz}}_{T-even,P-even} + \underbrace{\widetilde{\sigma}_{tvpc} p_y^p P_{xz}^d}_{T-odd,P-even}$$

$$C' \approx i\phi_5 + iq/2m(\phi_1 + \phi_3)/2$$

Yu.N.U., A.A. Temerbayev, PRC 92 (2015) 014002;
Yu.N.U., J. Haidenabuer, PRC 94 (2016) 035501.

TVPC. The S- and D- wave contributions-I



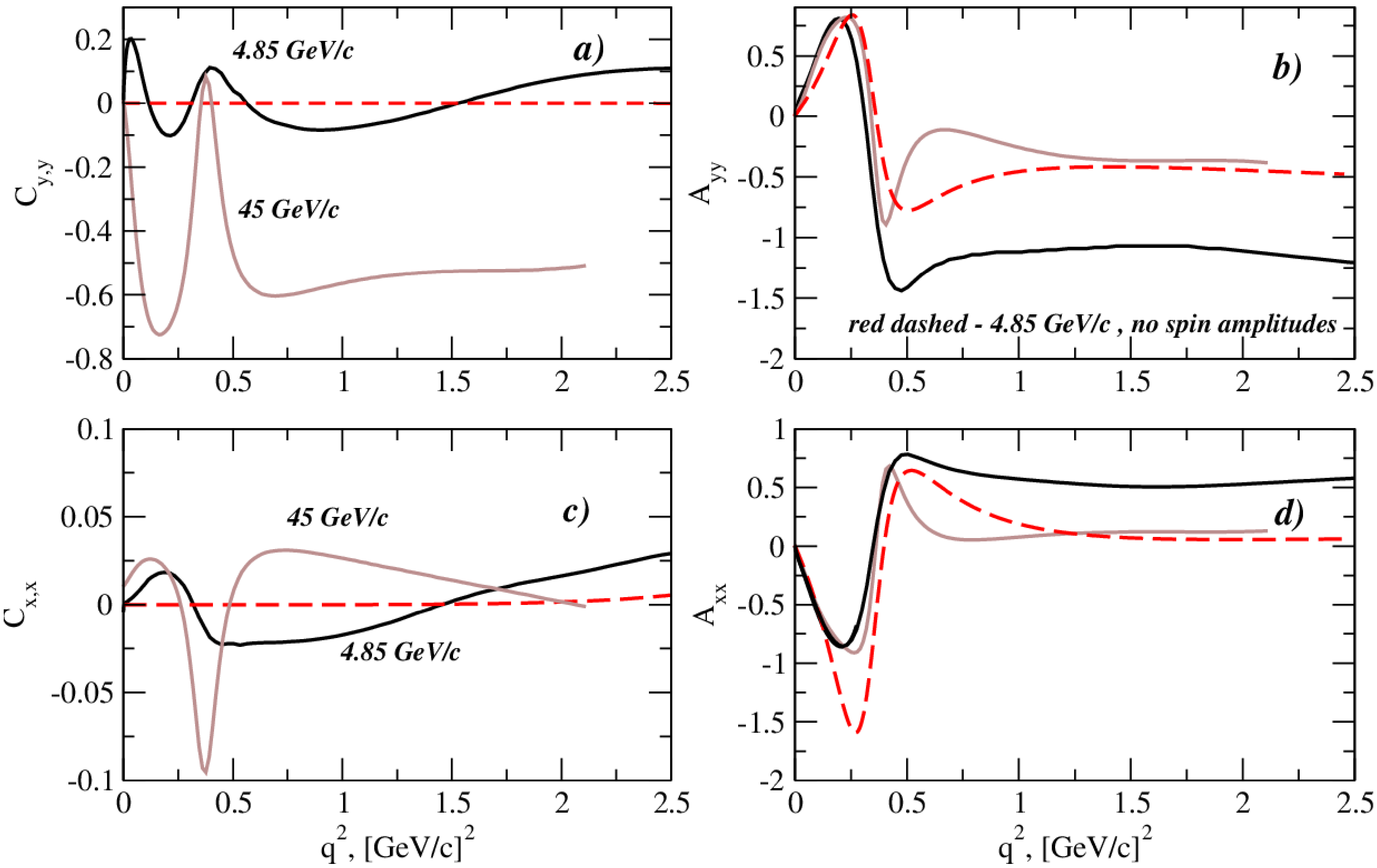


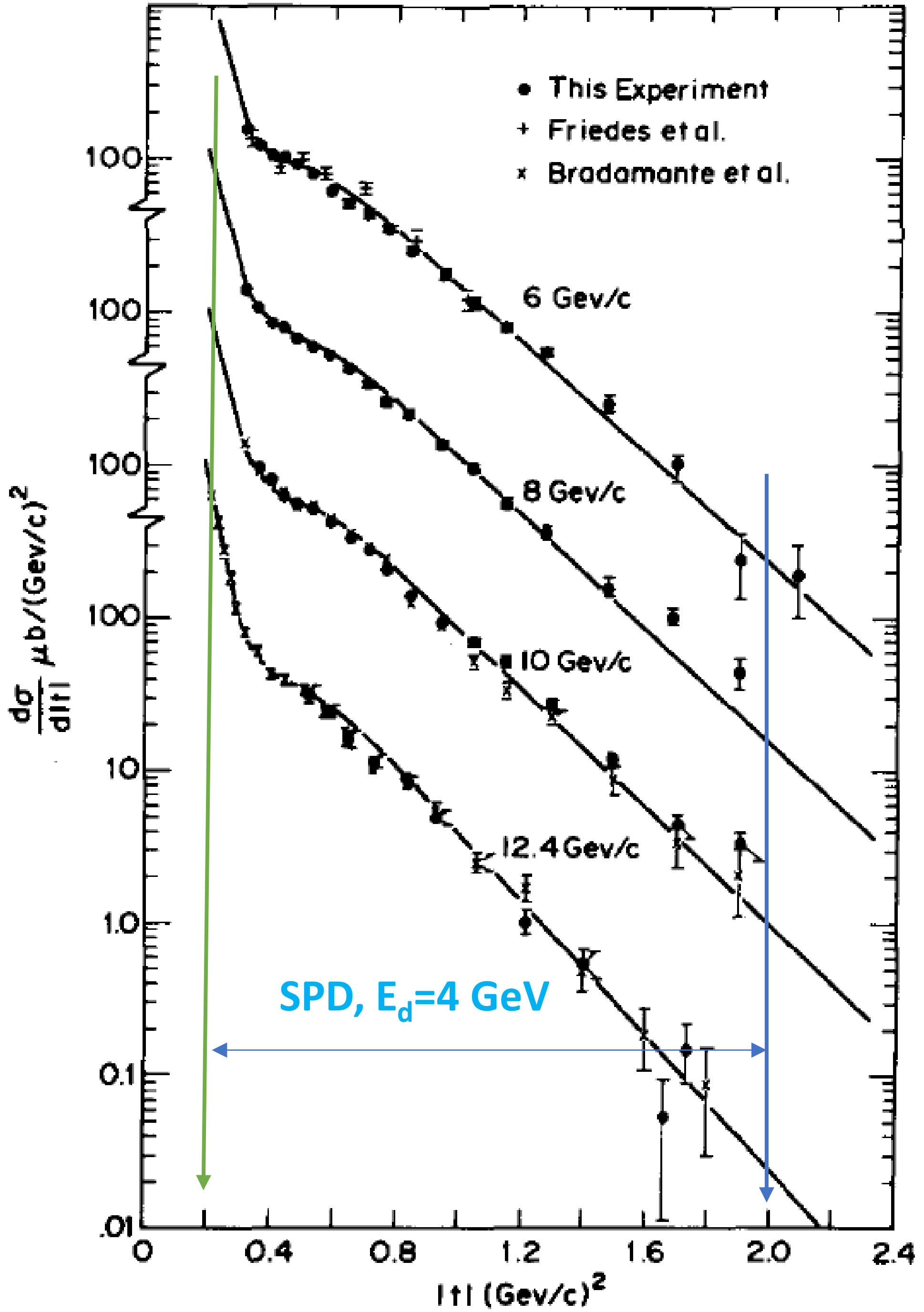
Null-test signal:

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

pd- elastic *with A. Sibirtsev (2010) amplitudes*

dashed red - without spin dependent pN amplitudes 4.85 GeV/c





P. Chanowski et al. PLB 61 (1976)

nd-elastic scattering

MC simulation for SPD (E_d=4 GeV):

- Kinematic fit with invariant mass constraint (FUMILI fit with 'heavy terms' (p,d tracks only))
- Can not distinguish between signal and background - not useful on its own

- Kinematic fit with Lagrange multipliers with 3-momenta constraints(BES-III technique adapted by I. Denisenko)

- Takes into account neutron directions from ZDC

- SPD cannot reliably detect tracks at $\theta < 7^o$, limit on |t|

  At E_d=8 GeV -> |t|=0.9-2.3 GeV^2
  At E_d=6 GeV -> |t|=0.5-2.1 GeV^2

SOME ESTIMATES at E_d=4 GeV

- Pythia8 : $\sigma^{tot} \sim 38$ mb (not very clear, if this is p+p cross-section, nuclear cross-section $\sigma^{tot}_{dd} \sim 160$ mb)
- (Custom) generated signal event : $\sigma^{sig}_{dd} \sim 39.5\ \mu$b
- Assuming $\mathcal{L}_{dd} \sim 4.5 \times 10^{28}$ cm^{-2} s^{-1} for $\sqrt{S_{dd}} = 8$ GeV : PER MONTH ($\frac{10^7}{12}$ s)
  1. 10 billion all d+d events
  2. 1.5 million signal events produced
  3. 74k signal events detected (5% detection efficiency)
- Asymmetries for various spin combinations (vector and tensor) can be measured for the first time in polarized d+d collisions

MC simulations: A. Datta, I.I. Denisenko ,Yu.N. U. (in preparation)

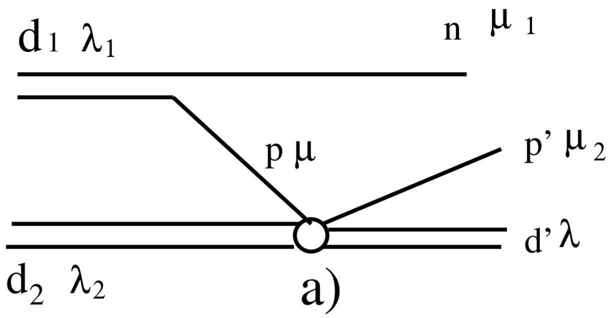
The differential cross section for collision $\vec{1} + \vec{1}$

$$I = I_0\Big[1 + \frac{3}{2}P_y A_y + \frac{3}{2}P_y^T A_y^T + \frac{1}{2}P_y P_{yy}^T C_{y,yy} + \frac{1}{2}P_{yy}P_y^T C_{yy,y} + \frac{9}{4}P_y P_y^T C_{y,y} + \frac{1}{3}P_{yy}A_{yy} + \frac{1}{3}P_{yy}^T A_{yy}^T + \frac{1}{9}P_{yy}P_{yy}^T C_{yy,yy}\Big]. \quad (3)$$

Similarly for collision $\vec{1} + \vec{\frac{1}{2}}$

$$I = I_0\Big[1 + \frac{3}{2}P_y A_y + P_y^T A_y^T + \frac{1}{3}P_{yy}A_{yy} + \frac{3}{2}P_y P_y^T C_{y,y} + \frac{1}{3}P_{yy}P_y^T C_{yy,y}\Big]. \quad (4)$$

Vector analyzing power $A_y^{d_2}$:



$$A_y^{d_2}(d_1\vec{d}_2 = npd) = \frac{d\sigma_{\lambda_2=+1} - d\sigma_{\lambda_2=-1}}{d\sigma_{\lambda_2=+1} + d\sigma_{\lambda_2=0} + d\sigma_{\lambda_2=-1}} = A_y^d(p\vec{d} \to pd)$$

Vector analyzing power $A_y^{d_1}$:

$$A_y^{d_1}(\vec{d}_1 d_2 \to npd) = \frac{d\sigma_{\lambda_1=+1} - d\sigma_{\lambda_1=-1}}{d\sigma_{\lambda_1=+1} + d\sigma_{\lambda_1=0} + d\sigma_{\lambda_1=-1}} = \frac{2}{3}A_y^p(\vec{p}d \to pd)$$

Tenzor analyzing power

$$A_y^d(d_1\vec{d}_2 \to npd) = \frac{d\sigma_{\lambda_2=+1} + d\sigma_{\lambda_2=-1} - 2d\sigma_{\lambda_2=0}}{d\sigma_{\lambda_2=+1} + d\sigma_{\lambda_2=0} + d\sigma_{\lambda_2=-1}} = A_{yy}^d(p\vec{d} \to pd)$$

$C_{y,y}$ needs four options for dd-collision: (i) $P_y = P_y^T = \frac{2}{3}$ (ii) $P_y = \frac{2}{3}$, $P_y^T = -\frac{2}{3}$ and the same for $P_y = -\frac{2}{3}$. One can find the cross section $I_{\uparrow\uparrow}$ for the option (i), a $I_{\uparrow\downarrow}$ for (ii) from Eq. (4). Similarly for $C_{yy,y}$ we use four options with $P_y = 0, P_{yy} = \pm 1$ for d_1 and $P_y = \pm\frac{2}{3}, P_{yy} = 0$ for d_2. One gets

$$C_{y,y} = \frac{(I_{\uparrow\uparrow} - I_{\uparrow\downarrow}) + (I_{\downarrow\downarrow} - I_{\downarrow\uparrow})}{(I_{\uparrow\uparrow} + I_{\uparrow\downarrow}) + (I_{\downarrow\downarrow} + I_{\downarrow\uparrow})}, \qquad (5)$$

$$C_{yy,y} = \frac{(I_{+\uparrow} - I_{+\downarrow}) + (I_{-\downarrow} - I_{-\uparrow})}{(I_{+\uparrow} + I_{+\downarrow}) + (I_{-\downarrow} + I_{-\uparrow})}. \qquad (6)$$

Yu.N. Uzikov, A.A. Temerbayev, Phys. Part. Nucl. **55 (2024) 895;**
e-Print: 2311.12605 [nucl-th]; dd-> npnp and hard pN-elastic scattering