Spin observables in dd->npd and pd→pd processes at SPD NICA energies

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in collaboration with

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CONTENT

- Motivation:
  Spin–dependent pN-elastic scattering amplitudes are necessary for theoretical interpretation of **nuclear spin observables**, **not yet derived from QCD theory .**

- Phenomenological models for spin-dependent pN elastic scattering at SPD energies.

- Glauber spin-dependent theory of pd-elastic scattering and pN-amplitudes.

- Relations between spin observables for dd→n+p+d and pd->pd within the IA and role of the D-wave of the d.w.f.

- Summary

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pN ELASTIC SCATTERING

NN forces is a basis of nuclear and hadronic physics.
NN-> NN   data on spin dependent pN- amplitudes are noncomplete
 for pp at T>3 GeV   and scare for pn at T>1.2 GeV .
Important TASK: Measurement @ test of spin amplitudes of NN elastic scattering in soft and hard NN- collisions.

$$\phi_1(s,t) = \langle + + |M| + + \rangle,$$
$$\phi_2(s,t) = \langle + + |M| - - \rangle,$$
$$\phi_3(s,t) = \langle + - |M| + - \rangle,$$
$$\phi_4(s,t) = \langle + - |M| - + \rangle,$$
$$\phi_5(s,t) = \langle + + |M| + - \rangle.$$

$$\frac{d\sigma}{dt} = \frac{2\pi}{s^2}\{|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2\}.$$
$$A_N \frac{d\sigma}{dt} = -\frac{4\pi}{s^2}\,\mathrm{Im}\{\phi_5^*(\phi_1 + \phi_2 + \phi_3 - \phi_4)\},$$
$$A_{NN} \frac{d\sigma}{dt} = \frac{4\pi}{s^2}\{2|\phi_5|^2 + \mathrm{Re}(\phi_1^*\phi_2 - \phi_3^*\phi_4)\},$$

Amplitudes: 5 – pp, 6 – pn, TV gives additional terms

>10 Observables are
required for complete
polarization experiment

SPASCHARM, V.V. Abramov et al. PEPAN (2023)

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] $\sqrt{s_{NN}} = 5 - 25 GeV$

Glauber spin-dependent theory of *pd-pd*

and application 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 and 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**

Elastic $pd \to pd$ transitions

$$\hat{M}(\mathbf{q},\mathbf{s}) =$$
$$\exp(\frac{1}{2}i\mathbf{q}\cdot\mathbf{s})M_{pp}(\mathbf{q}) + \exp(-\frac{1}{2}i\mathbf{q}\cdot\mathbf{s})M_{pn}(\mathbf{q}) +$$
$$+\frac{i}{2\pi^{3/2}}\int \exp(i\mathbf{q}'\cdot\mathbf{s})\Big[M_{pp}(\mathbf{q}_1)M_{pn}(\mathbf{q}_2) + p\leftrightarrow n\Big]d^2\mathbf{q}'.$$

Single pN-scattering

Double scattering

On-shell elastic pN scattering amplitude (**T-even, P-even**)

$$\begin{aligned} M_{pN} &= A_N + (C_N\boldsymbol{\sigma}_1 + C'_N\boldsymbol{\sigma}_2)\cdot\hat{\mathbf{n}} + B_N(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{k}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{k}}) + \\ &+ (G_N - H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{n}}) + (G_N + H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathrm{q}})(\boldsymbol{\sigma}_2\cdot\hat{\mathrm{q}}) \end{aligned}$$

M. Platonova, V. Kukulin, PRC **81** (2010) 014004:

GENERAL SPIN STRUCTURE OF THE pd-pd AMPLITUDES AND SPIN OBSERVABLES

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

Yu. N. Uzikov, A. Bazarova, A.A. Temerbayev,

Physics of Particles and Nuclei, 2022, Vol. 53, No. 2, pp. 419—425.

$$\langle p'\mu', d'\lambda'|T|\, p\mu, d\lambda\rangle = \varphi_{\mu'}^{+} e_{\beta}^{(\lambda')*} T_{\beta\alpha}(\mathbf{p}, \mathbf{p}', \boldsymbol{\sigma}) e_{\alpha}^{(\lambda)} \varphi_{\mu}, \quad (1)$$

$$\begin{array}{lll} T_{xx} = M_1 + M_2\sigma_y & T_{xy} = M_7\sigma_z + M_8\sigma_x & T_{xz} = M_9 + M_{10}\sigma_y \\ T_{yx} = M_{13}\sigma_z + M_{14}\sigma_x & T_{yy} = M_3 + M_4\sigma_y & T_{yz} = M_{11}\sigma_x + M_{12}\sigma_z \\ T_{zx} = M_{15} + M_{16}\sigma_y & T_{zy} = M_{17}\sigma_x + M_{18}\sigma_z & T_{zz} = M_5 + M_6\sigma_y, \end{array}$$

12 independent spin amplitudes (i=1,…,12) M_i for P-and T-invariance included.

Any spin observables can be calculated for pd-pd using M_i

Some spin observables for pd-pd

$$\frac{d\sigma}{dt} = \frac{1}{6}\mathrm{Tr}MM^{+}, \quad \mathrm{Tr}MM^{+} = 2\sum_{i=1}^{18}|M_i|^2, \qquad (3)$$

$$A_y^d = \mathrm{Tr}MS_yM^{+}/\mathrm{Tr}MM^{+} = -\frac{2}{\sum_{i=1}^{18}|M_i|^2}\mathrm{Im}(M_1M_9^*$$
$$+ M_2M_{10}^* + M_{13}M_{12}^* + M_{14}M_{11}^* + M_{15}M_5^* + M_{16}M_6^*),$$

$$A_y^p = \mathrm{Tr}M\sigma_yM^{+}/\mathrm{Tr}MM^{+} = \frac{2}{\sum_{i=1}^{18}|M_i|^2}[\mathrm{Re}(M_1M_2^*$$
$$+ M_9M_{10}^* + M_3M_4^* + M_{15}M_{16}^* + M_5M_6^*)$$
$$- \mathrm{Im}(M_8M_7^* + M_{14}M_{13}^* + M_{11}M_{12}^* + M_{17}M_{18}^*)],$$

$$A_{yy} = \mathrm{Tr}MP_{yy}M^{+}/\mathrm{Tr}MM^{+} = 1 - \frac{3}{\sum_{i=1}^{18}|M_i|^2}$$
$$\times (|M_3|^2 + |M_4|^2 + |M_7|^2 + |M_8|^2 + |M_{17}|^2 + |M_{18}|^2),$$

$$A_{xx} = \mathrm{Tr}MP_{xx}M^{+}/\mathrm{Tr}MM^{+} = 1 - \frac{3}{\sum_{i=1}^{18}|M_i|^2}$$
$$\times (|M_1|^2 + |M_2|^2 + |M_{13}|^2 + |M_{14}|^2 + |M_{15}|^2 + |M_{16}|^2),$$

$$C_{y,y} = \mathrm{Tr}MS_y\sigma_yM^{+}/\mathrm{Tr}MM^{+} = -\frac{2}{\sum_{i=1}^{18}|M_i|^2}$$
$$\times [\mathrm{Im}(M_2M_9^* + M_1M_{10}^* + M_{16}M_5^* + M_{15}M_6^*)$$
$$+ \mathrm{Re}(M_{14}M_{12}^* - M_{13}M_{11}^*)],$$

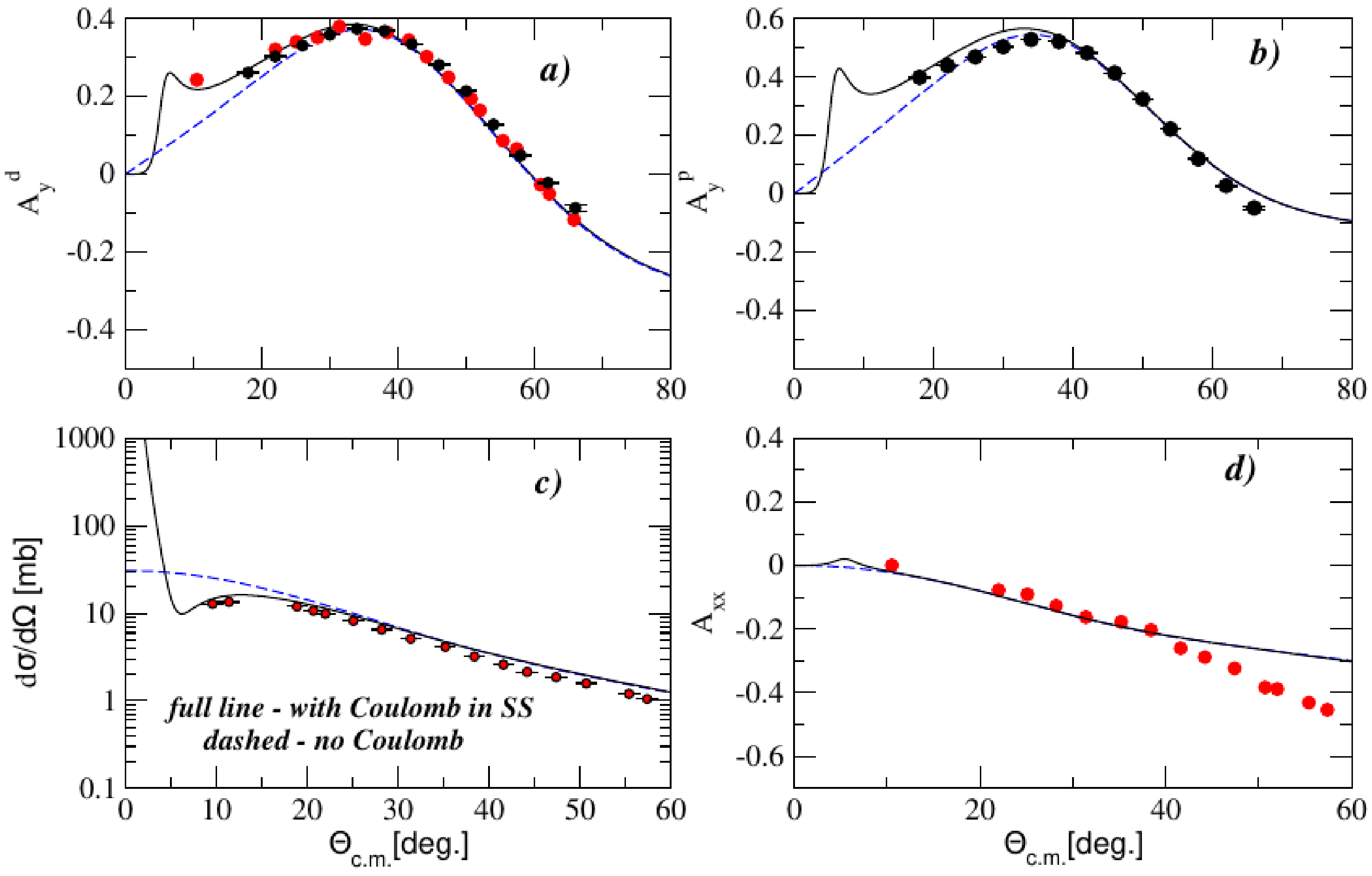
$$C_{x,x} = \mathrm{Tr}MS_x\sigma_xM^{+}/\mathrm{Tr}MM^{+}$$
$$= -\frac{2}{\sum_{i=1}^{18}|M_i|^2}[\mathrm{Im}(M_8M_9^* + M_3M_{11}^* + M_{17}M_5^*)$$
$$+ \mathrm{Re}(M_7M_{10}^* - M_4M_{12}^* + M_{18}M_6^*)],$$

$$C_{xx,y} = \mathrm{Tr}M_{xx}\sigma_yM^{+}/\mathrm{Tr}MM^{+} = A_y^p - \frac{6}{\sum_{i=1}^{18}|M_i|^2}$$
$$\times [\mathrm{Re}(M_2M_1^* + M_{16}M_{15}^*) - \mathrm{Im}(M_{14}M_{13}^*),$$

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

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

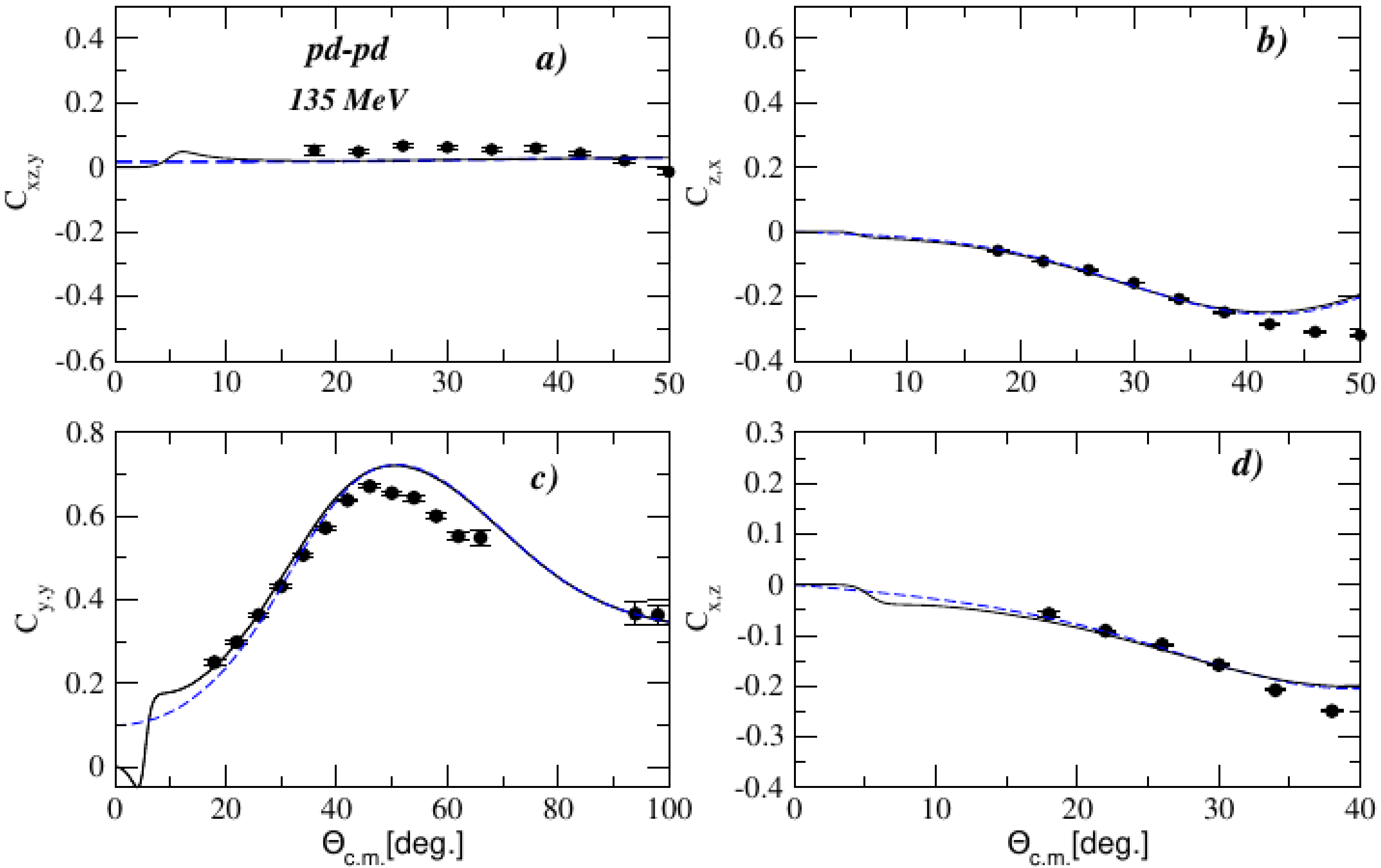
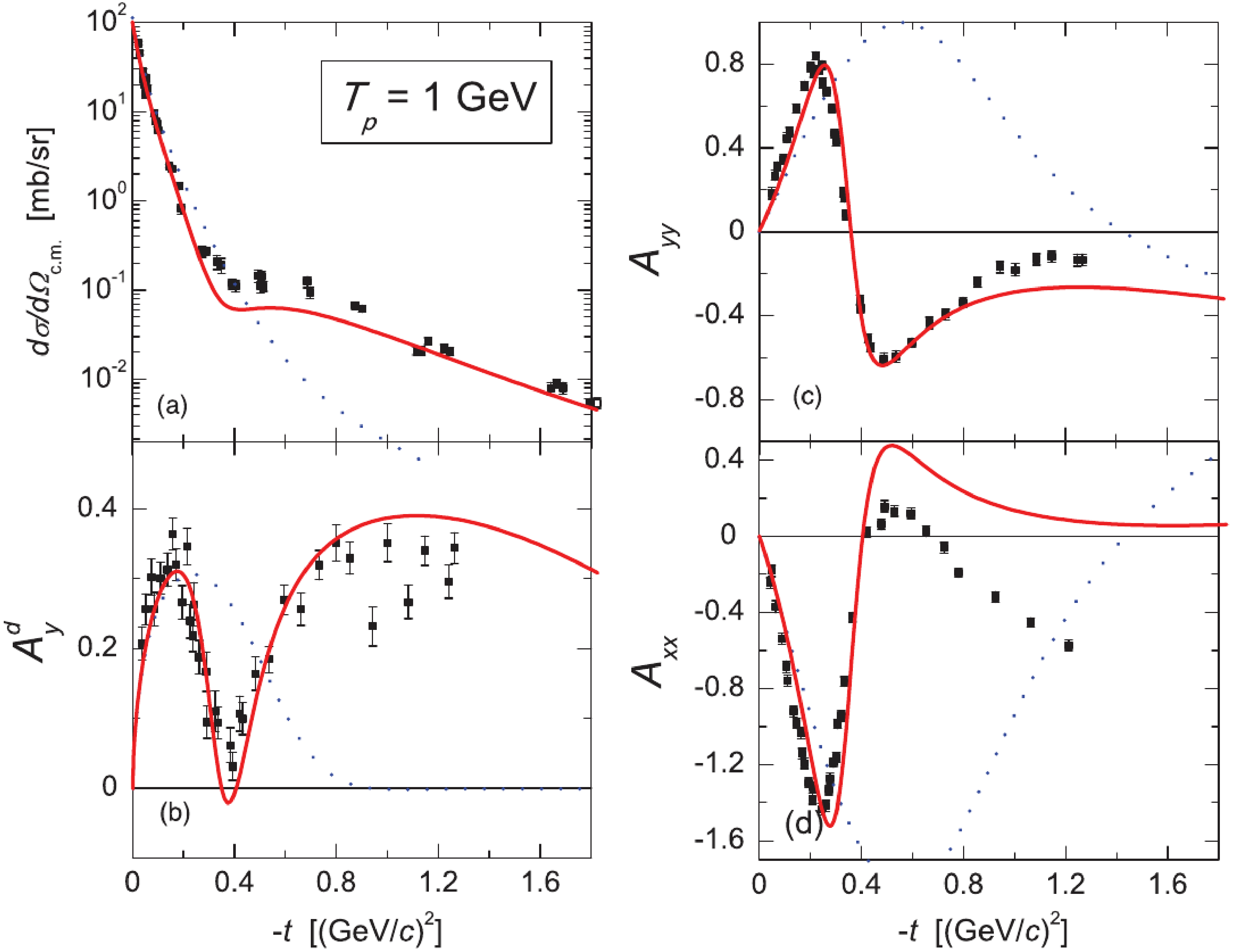


Figure 1: Spin correlation coefficients $C_{xz,y}$ (a), $C_{z,x}$ (b), $C_{y,y}$ (c), $C_{x,z}$ (d) at 135 MeV versus the c.m.s. scattering angle calculated within the modified Glauber model [15] without (dashed lines) and with (full) Coulomb included in comparison with the data from [22].

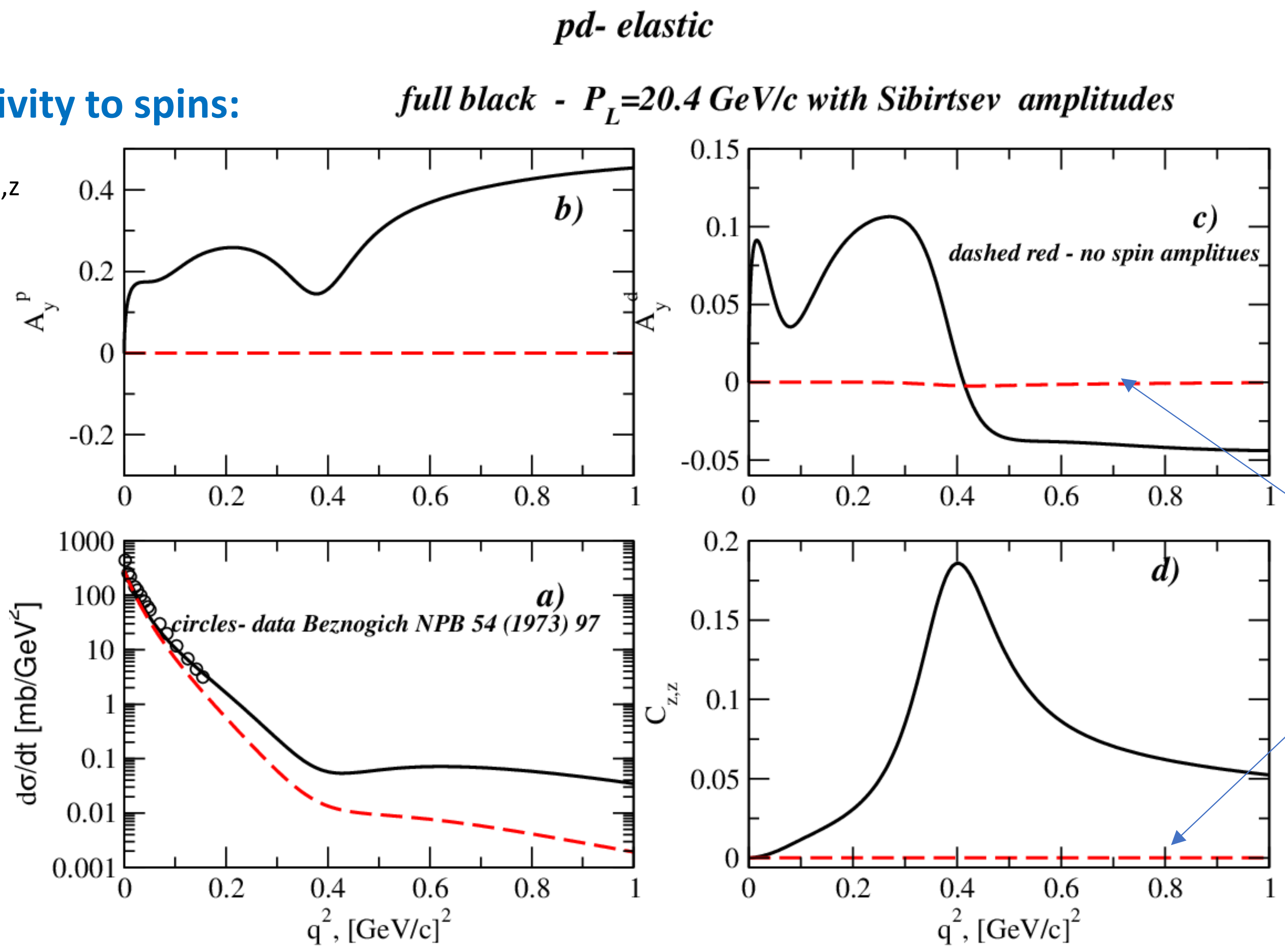
M.N. Platonova, V.I. Kukulin, PRC 81(2010) 014004



pd elastic scattering at SPD energies in Glauber model

High sensitivity to spins:

A_y^p A_y^d $C_{z,z}$



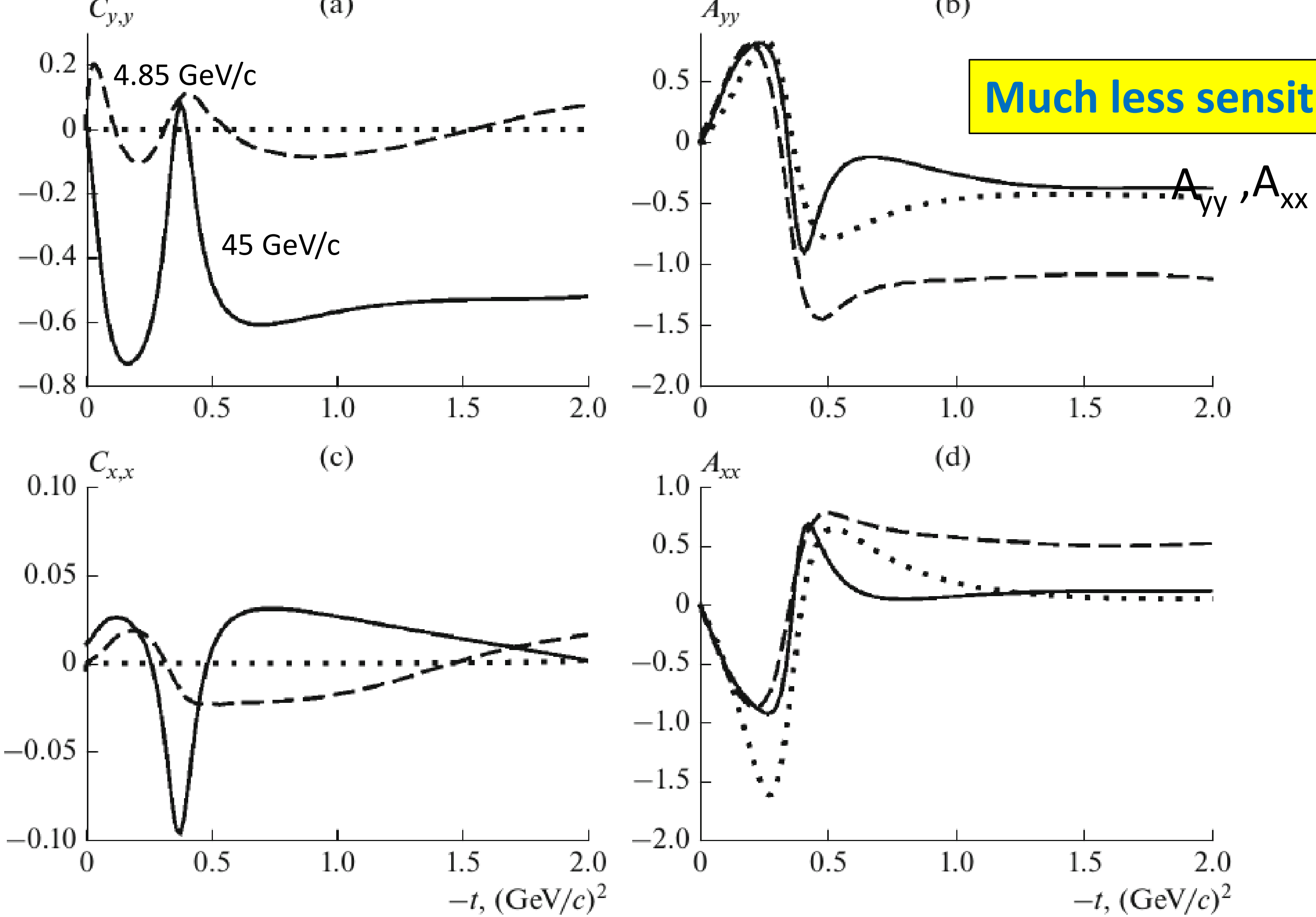
Yu.N.U., A.Bazarova, A. Temerbayev, Phys.Part. Nucl.53 (2022)419;

pN- amplitudes from A. Sibirtsev et al. EPJ A (2010)

Without spin-dependent pN-amplitudes

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

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.

Search for T-invariance violation
in double polarized pd,^{3}Hed, dd- collisions using pN amplitudes

BAU problem: R_{exp}=6.7 10^{-10} , R_{SM}~ 10^{-19}

CP violation beyond the SM (or T-violation under CPT-inv.)

L.B. Okun, Yad.Fiz. 1(1965) 938;

J. Prentki, M.J.G. Veltman (1965);
T.D. Lee, L. Wolfenstein (1965)

TVPC NN forces:
n^{165}Ho, P.R. Huffman et al. PRC 55 (1997)

No data on TVPC effect at SPD NICA energies

T-even P-even pN single spin-flip amplitude phi-5 and also phi_1, phi_3 are necessary to extract the null-test signal of T-violation

Y. Uzikov, M. Platonova, A. Kornev *et al.*, Int. Jour. Mod. Phys. E https://doi.org/10.1142/S0218301324410039 (2024)
Y. N. Uzikov and A. Temerbayev, Phys. Rev. C **92**, 014002 (2015), arXiv: 1506.08303
Y. N. Uzikov and J. Haidenbauer, Phys. Rev. C **94**, 035501 (2016), arXiv: 1607.04409
Y. N. Uzikov and M. N. Platonova, JETP Lett. **118**, 785 (2023), arXiv: 2311.10841

M.N. Platonova, Yu. N. Uzikov, Chin. Phys. C 49, N3 (2025) 034108
B. Gou, V.P. Ladygin, N.N. Nikolaev, F. Rathmann, et al. Nat. Sci.Rev. 3 (2026) 200802 • e-Print: 2608.20945 [nucl-th]
/Talks by N.N. Nikolaev and B.Gou at this conference/

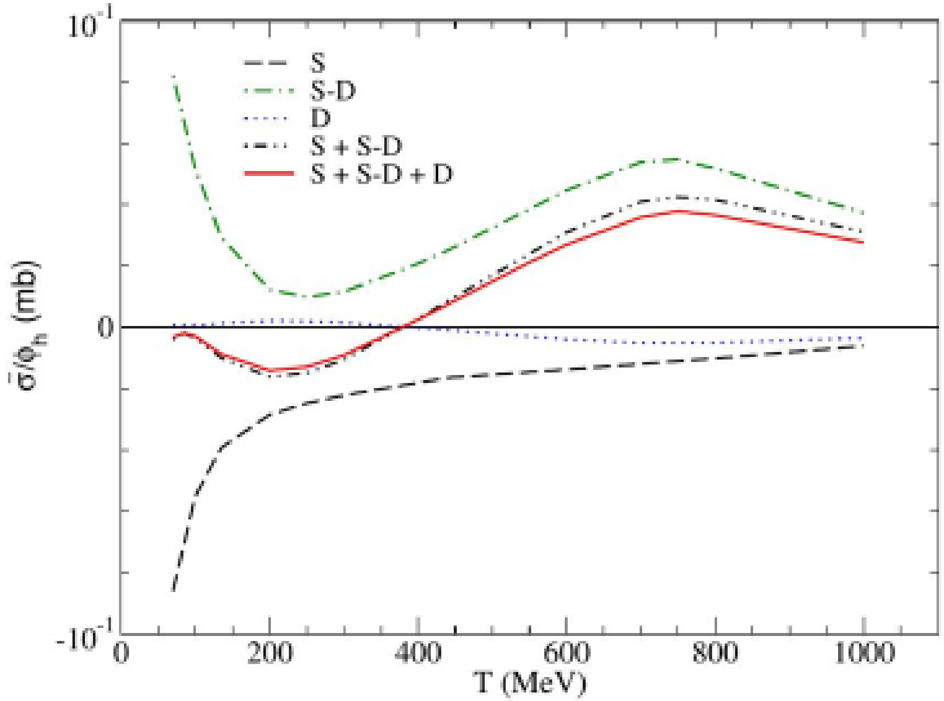
$p^{\uparrow}d^{\uparrow}$

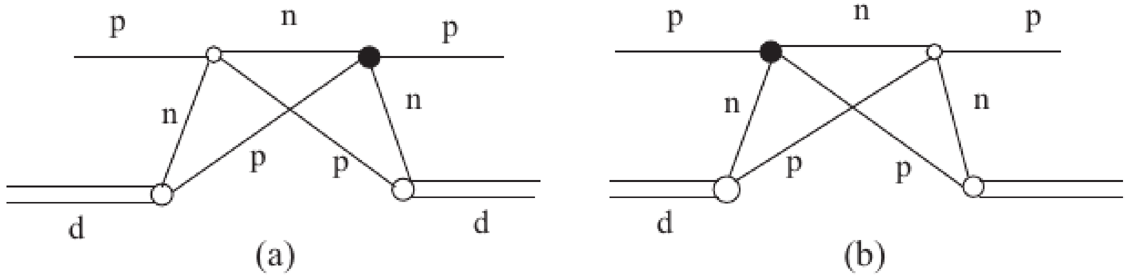
$$\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2(\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz}}_{T-even,P-even} + \underbrace{\widetilde{\sigma}_{tvpc} p_y^p P_{xz}^d}_{T-odd,P-even}$$

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

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

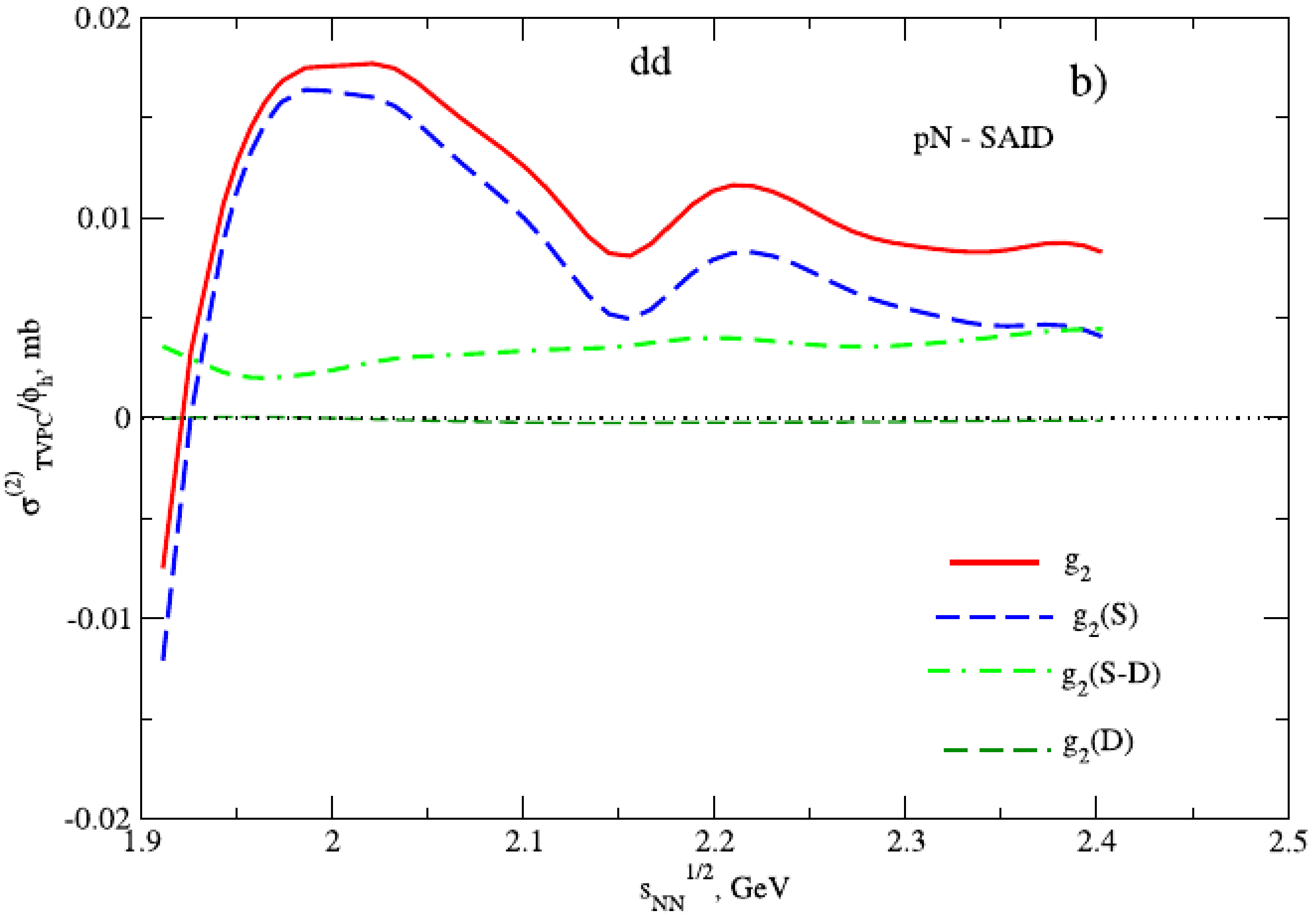




Null-test signal:

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

d↑d↑: ***M.N. Platonova, Yu. N. Uzikov**, Chin. Phys. C 49, N3 (2025) 034108*



Null-test signal in dd:

$$g_2 = \frac{i}{2\pi m}\int_0^\infty dq q^2 \left[Z_0 + Z(q)\right]\zeta(q) h_N(q)\left(C'_n(q) + C'_p(q)\right)$$

T-even P-even

$$M_N = A_N + C_N \boldsymbol{\sigma}_p \cdot \hat{\mathbf{n}} + C'_N \boldsymbol{\sigma}_N \cdot \hat{\mathbf{n}},$$
$$+ B_N(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{k}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{k}}),$$
$$+ (G_N + H_N)(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{q}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{q}}),$$
$$+ (G_N - H_N)(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{n}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{n}});$$

$$A_N = (\phi_1 + \phi_3)/2, \quad B_N = (\phi_3 - \phi_1)/2,$$

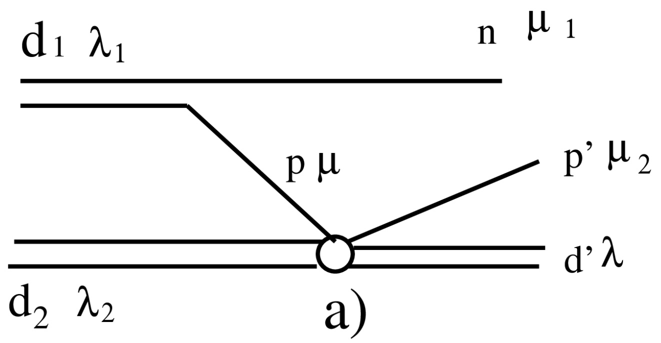
$$C_N = i\phi_5, \quad G_N = \phi_2/2, \quad H_N = \phi_4/2;$$

$$C'_N = C_N + \frac{iq}{2m} A_N.$$

T-odd P-even (TVPC)

$$t_N = h_N[(\boldsymbol{\sigma}_p \cdot \hat{\mathbf{k}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{q}})$$
$$+ (\boldsymbol{\sigma}_p \cdot \hat{\mathbf{q}})(\boldsymbol{\sigma}_N \cdot \hat{\mathbf{k}}) - \frac{2}{3}(\boldsymbol{\sigma}_N \cdot \boldsymbol{\sigma}_p)(\mathbf{q} \cdot \hat{\mathbf{k}})]$$
$$+ g_N[\boldsymbol{\sigma}_p \times \boldsymbol{\sigma}_N] \cdot [\hat{\mathbf{q}} \times \hat{\mathbf{k}}](\boldsymbol{\tau}_p - \boldsymbol{\tau}_N)_z$$
$$+ g'_N(\boldsymbol{\sigma}_p - \boldsymbol{\sigma}_N) \cdot i[\hat{\mathbf{q}} \times \hat{\mathbf{k}}][\boldsymbol{\tau}_p \times \boldsymbol{\tau}_N]_z;$$

FACTORIZATION of the SQUARED MATRIX ELEMENT dd-npd in the IA

IA = 

If final neutron takes one half of the deuteron momentum (S-wave dominance, suppressed p_T momenta), then the pd->pd amplitude can be extracted with minimum distortions.

Transition matrix element for the $dd \to npd$ in IA, S-wave of d.w.f. :

$$M^{\mu_1\mu_2\lambda'}_{\lambda_1\lambda_2} = K\sum_{\mu}(\frac{1}{2}\mu_1\frac{1}{2}\mu|1\lambda_1)u(q)M^{\lambda'\mu_2}_{\lambda_2\mu}(pd \to pd). \qquad (1)$$

$$\overline{|M^{\mu_1\mu_2\lambda'}_{\lambda_1\lambda_2}|^2} = K^2u^2(q)\overline{|M^{\lambda'\mu_2}_{\lambda_2\mu}(pd \to pd)|^2}. \qquad (2)$$

$$d\sigma_{\lambda_2} = \frac{1}{3}\sum_{\lambda_1}\sum_{\mu_1\mu_2\lambda'}|M^{\mu_1\mu_2\lambda'}_{\lambda_1\lambda_2}(dd \to npd)|^2 = K^2u^2(q)\frac{1}{2}\sum_{\mu\lambda'\mu_2}|M^{\lambda'\mu_2}_{\lambda_2\mu}(pd \to pd)|^2.$$

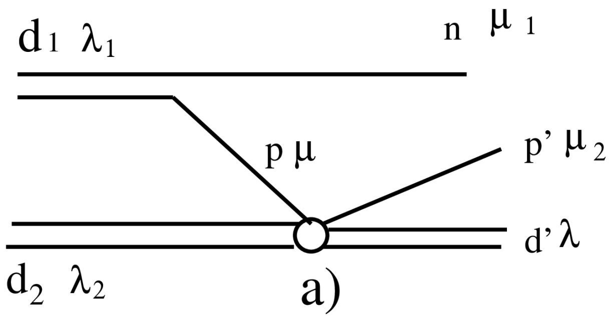
The differential cross section for collision $\vec{1}+\vec{1}$

$$I = I_0\Big[1+\frac{3}{2}P_yA_y+\frac{3}{2}P_y^TA_y^T+\frac{1}{2}P_yP_{yy}^TC_{y,yy}+\frac{1}{2}P_{yy}P_y^TC_{yy,y}+ \frac{9}{4}P_yP_y^TC_{y,y}+\frac{1}{3}P_{yy}A_{yy}+\frac{1}{3}P_{yy}^TA_{yy}^T+\frac{1}{9}P_{yy}P_{yy}^TC_{yy,yy}\Big]. \qquad (3)$$

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

$$I = I_0\Big[1+\frac{3}{2}P_yA_y+P_y^TA_y^T+\frac{1}{3}P_{yy}A_{yy}+\frac{3}{2}P_yP_y^TC_{y,y}+\frac{1}{3}P_{yy}P_y^TC_{yy,y}\Big]. \qquad (4)$$

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 $A_y^{d_1}$:

$$A_y^{d_1}(\vec{d}_1d_2 \to npd) = \frac{d\sigma_{\lambda_1=+1}-d\sigma_{\lambda_1=-1}}{d\sigma_{\lambda_1=+1}+d\sigma_{\lambda_1=0}+d\sigma_{\lambda_1=-1}} = \frac{2}{3}A_y^p(\vec{p}d\to pd)$$

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

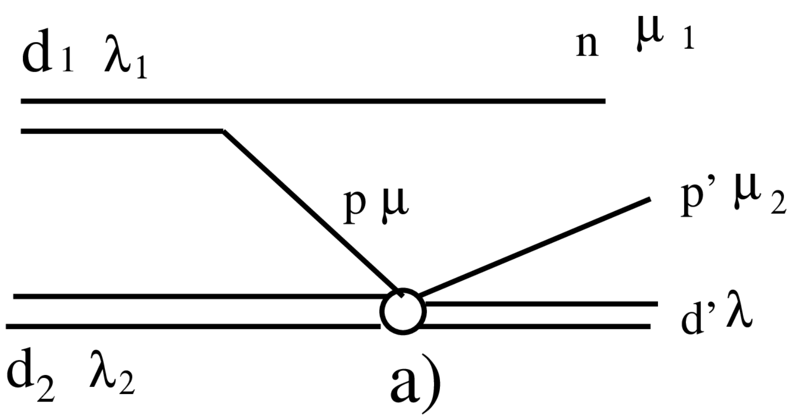
$$C_{y,y} = \frac{(I_{\uparrow\uparrow} - I_{\uparrow\downarrow}) + (I_{\downarrow\downarrow} - I_{\downarrow\uparrow})}{(I_{\uparrow\uparrow} + I_{\uparrow\downarrow}) + (I_{\downarrow\downarrow} + I_{\downarrow\uparrow})}, \tag{5}$$

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

***Yu.N. Uzikov, Phys.Part.Nucl.Lett.* 22 (2025)**
№ 6, 1392-1397; e-Print: 2506.17799 [nucl-th]

***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

Relations between dd→ npd and pd→ pd



D-wave and Rescatterings have to be taken into account

***Yu.N. Uzikov, Phys.Part.Nucl.Lett.* 22 (2025) № 6, 1392-1397;** e-Print: [2506.17799] [nucl-th]

S-wave for IA

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

$d_2^{\uparrow}$: 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:

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

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

D-wave contribution within the IA

$OZ \uparrow\uparrow \vec{p}_d \uparrow\uparrow \vec{p}_n$ For ZDC at SPD $\delta < 0.16^\circ - 0.27^\circ$:

D-wave destrois the above relations

$$< \chi_{\sigma_p}\chi_{\sigma_n}|\Phi_{\lambda_1}(\hat{\mathbf{q}}) >= \sum_{lmM_s} (\frac{1}{2}\sigma_n\frac{1}{2}\sigma_p|1M_s)(1M_s lm|1\lambda_1)u_l(q)Y_{lm}(\hat{\mathbf{q}})$$

$$\rightarrow (\frac{1}{2}\sigma_n\frac{1}{2}\sigma_p|1\lambda_1)D_{\lambda_1}(q)$$

$$Y_{2m}(\theta,\phi) = \delta_{m,0}\sqrt{\frac{5}{16\pi}}(3\cos^2\theta - 1),$$

$$D_{\lambda_1}(q) = Y_{00}[u_0(q) + \frac{1}{\sqrt{10}}a_{\lambda_1}u_2(q)\sqrt{\frac{5}{4}}(3\cos^2\theta - 1)];$$

$$a_\lambda = 1,\ \lambda = \pm 1; \qquad a_\lambda = -2,\ \lambda = 0$$

Tensor analyzing power A_{zz}

$$A_{zz}(d_1^{\uparrow}d_2) = \frac{1-\kappa}{1+\frac{1}{2}\kappa},$$

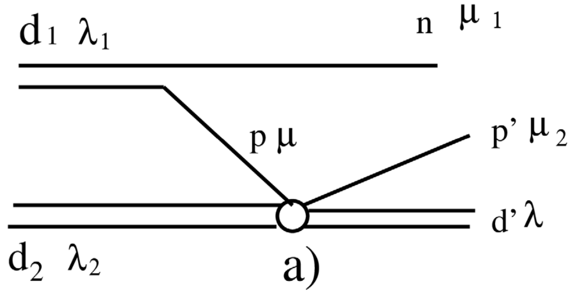
$$\kappa = \frac{|D_{\lambda=0}|^2}{|D_{\lambda=\pm 1}|^2}$$

$$A_{zz}(d_1^{\uparrow}d_2) = \frac{\sqrt{8}wu - w^2}{u^2+w^2}$$

$$D_{\lambda_1=\pm 1} = \left(u_0 + \frac{1}{\sqrt{2}}u_2\right)\frac{1}{\sqrt{4\pi}}$$

$$D_{\lambda_1=0} = \left(u_0 - \sqrt{2}u_2\right)\frac{1}{\sqrt{4\pi}}$$

IA, S-wave: $\kappa = 1 \ \rightarrow \ A_{zz}(d_1^{\uparrow}d_2) = 0$



Spin-spin correlation:

Spin-Spin correlation $C_{z,z}$

$$C_{z,z}(d^{\uparrow}d^{\uparrow} \rightarrow npd) = \frac{1}{1+\frac{1}{2}\kappa}C_{z,z}(p^{\uparrow}d^{\uparrow})$$

For the IA S-wave ($\kappa = 1$):

$$C_{z,z}(d^{\uparrow}d^{\uparrow} \rightarrow npd) = \frac{2}{3}C_{z,z}(p^{\uparrow}d^{\uparrow})$$

(Yu.N.U., Phys. Part. Nucl. Lett. 22, №6 (2025) 1392)

Polarization transfer in (d,p) K_0=1 at k < 0.150 GeV/c :
S-wave dominance in the region in the IA

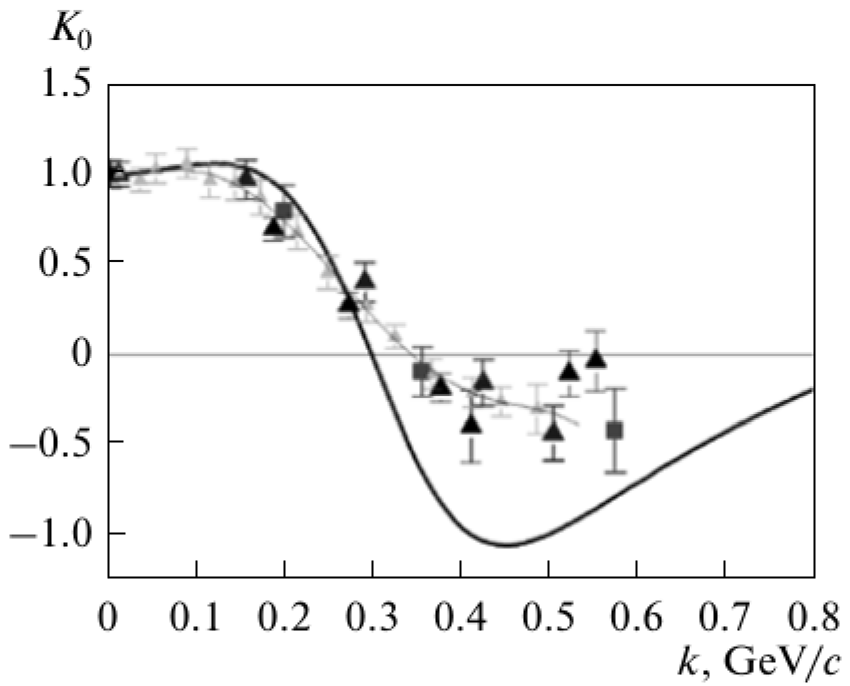


Fig. 3. Polarization transfer coefficient versus k, world data of $p(d, p)X$ and $C(d, p)X$ reaction; a curve calculated in framework of IA, using Paris N–N potential.

$$K_0(d_1^{\uparrow} d_2 \to n^{\uparrow} pd) = \frac{u^2 - \frac{1}{\sqrt{2}} u\, w - w^2}{u^2 + w^2};$$

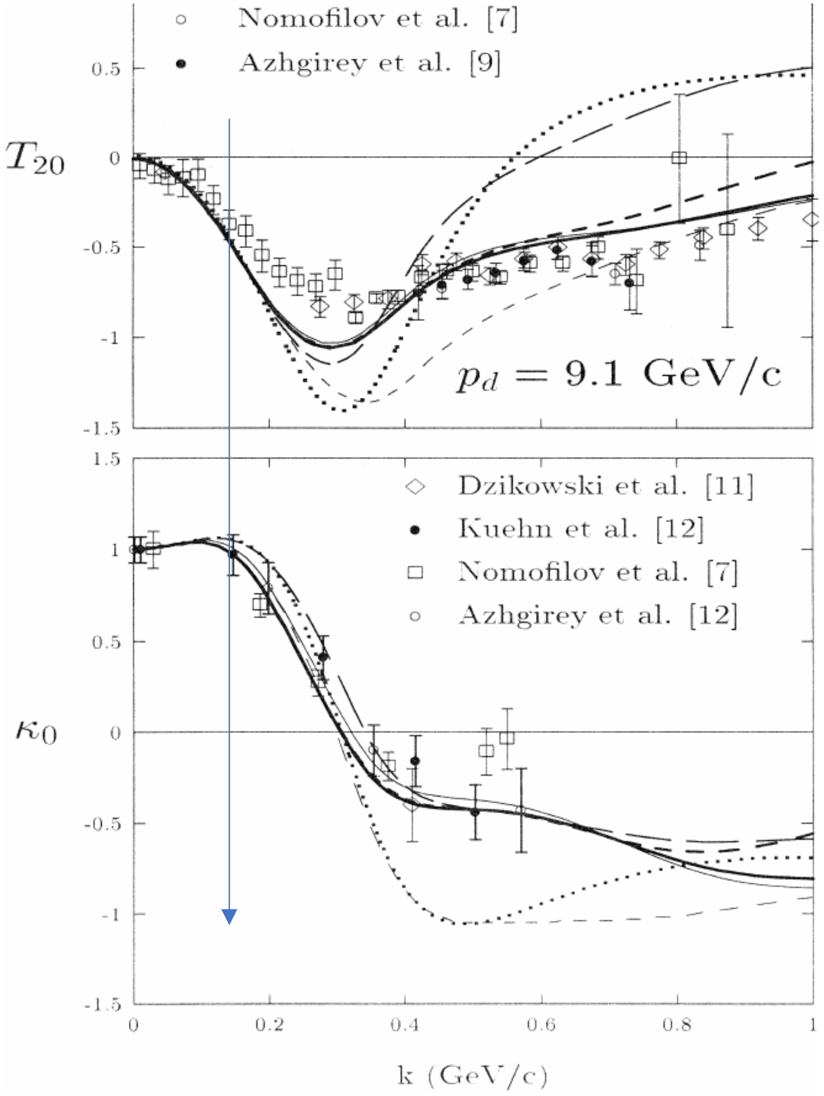
See G.I. Lykasov, Fiz. Elem. Chast. At. Yad. 24(1993) 140.

V.P. Balandin et al. Phys. Part. Nucl. V.45 (2014) 330-332.

However, K_0 is not measured at SPD!

Let us consider T_{20} =A_{zz} /sqrt{2}.

Tensor analyzing power T_{20} in (d,p)



A.P.Kobushkin, PLB 4212 (1998), 53

Polarization transfer in (d,p) is K_0=1 at k < 0.150 GeV/c : S-wave dominance regio=n

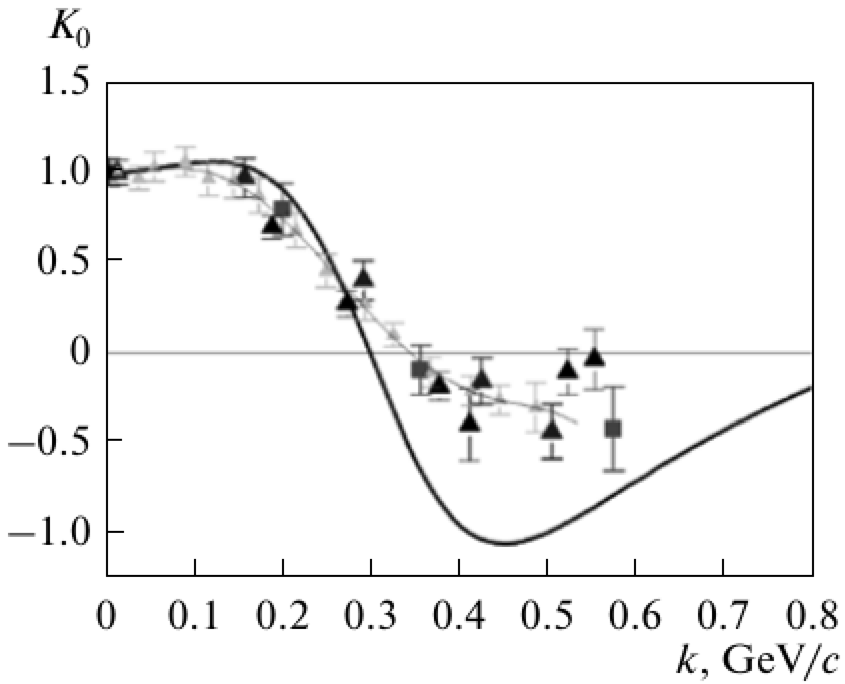


Fig. 3. Polarization transfer coefficient versus k, world data of $p(d, p)X$ and $C(d, p)X$ reaction; a curve calculated in framework of IA, using Paris N–N potential.

V.P. Balandin et al. Phys. Part. Nucl. V.45 (2014) 330-332.

SUMMARY

- NN-NN spin amplitudes are important for hadron physics and for physics BSM
- Can be studied at the first stage of SPD
- Diffraction-> Large cross section
- **Spin observables** A_y, A_{yy}, A_{zz}, $C_{y,y}$, $C_{z,z}$, $C_{y,yy}$ **of the reaction dd→npd are directly related to those for pd->pd in the IA :**
  A^p_y, A^d_y, $C_{y,y}$, $C_{y,yy}$ - highly sensitive to pN spin amplitudes,
  A_{yy}, A_{xx}, A_{zz}- robust observables, suitable for tensor polarimetry.
  K_0 & A_{zz} ⇨ measure of the S/D-ratio at low q =0-2 GeV/c in the IA

- **What has to be done**:
  - Estimation for FSI effects
  - Calculations of A_y, A_{yy}, $C_{y,y}$, $C_{y,yy}$, A_{zz}, $C_{z,z}$ for pd-pd with different pN models
  - Theory of dd-elastic scattering with full spin-dependence

THANK YOU FOR ATTENTION!

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

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

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

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

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

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

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

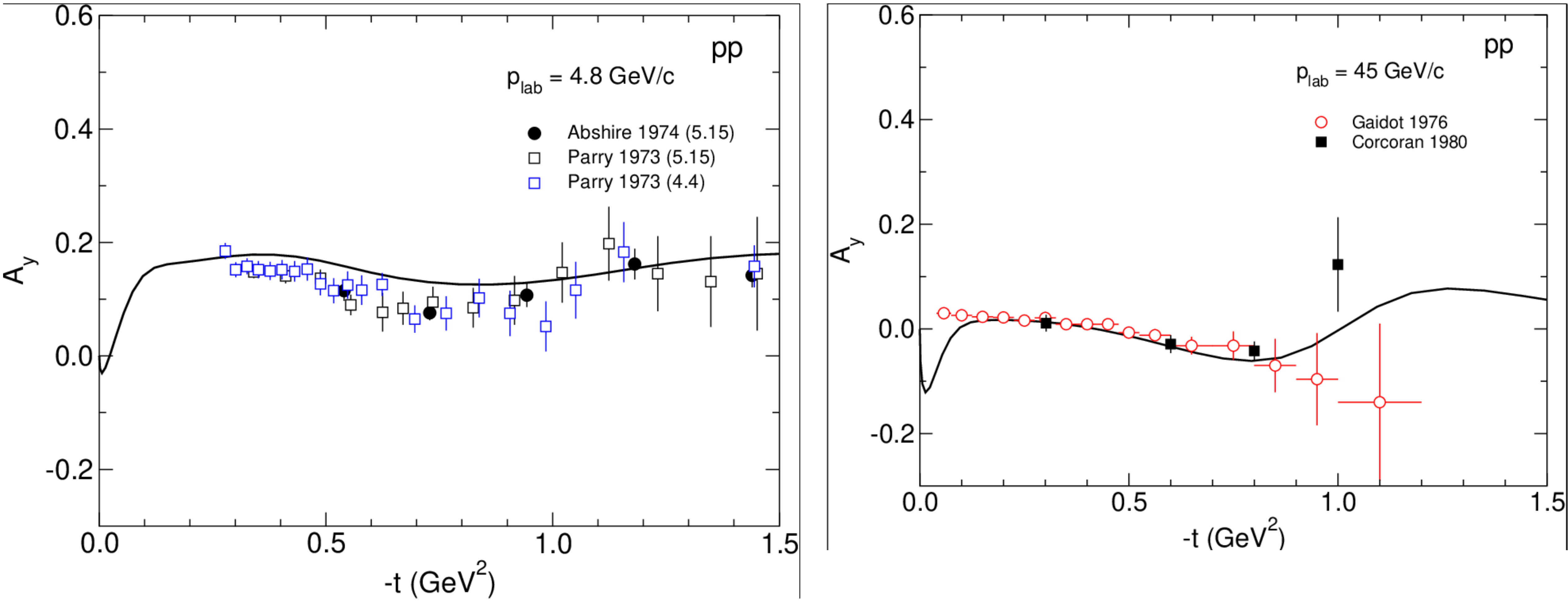
$$\beta_{3i}(t) = c_{3i}\exp(b_{3i}t),$$

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

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

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
pp- data on $d\sigma/dt$ **, A_N, A_{NN}**

A. Sibirtsev et al, EPJA (2010)



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

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

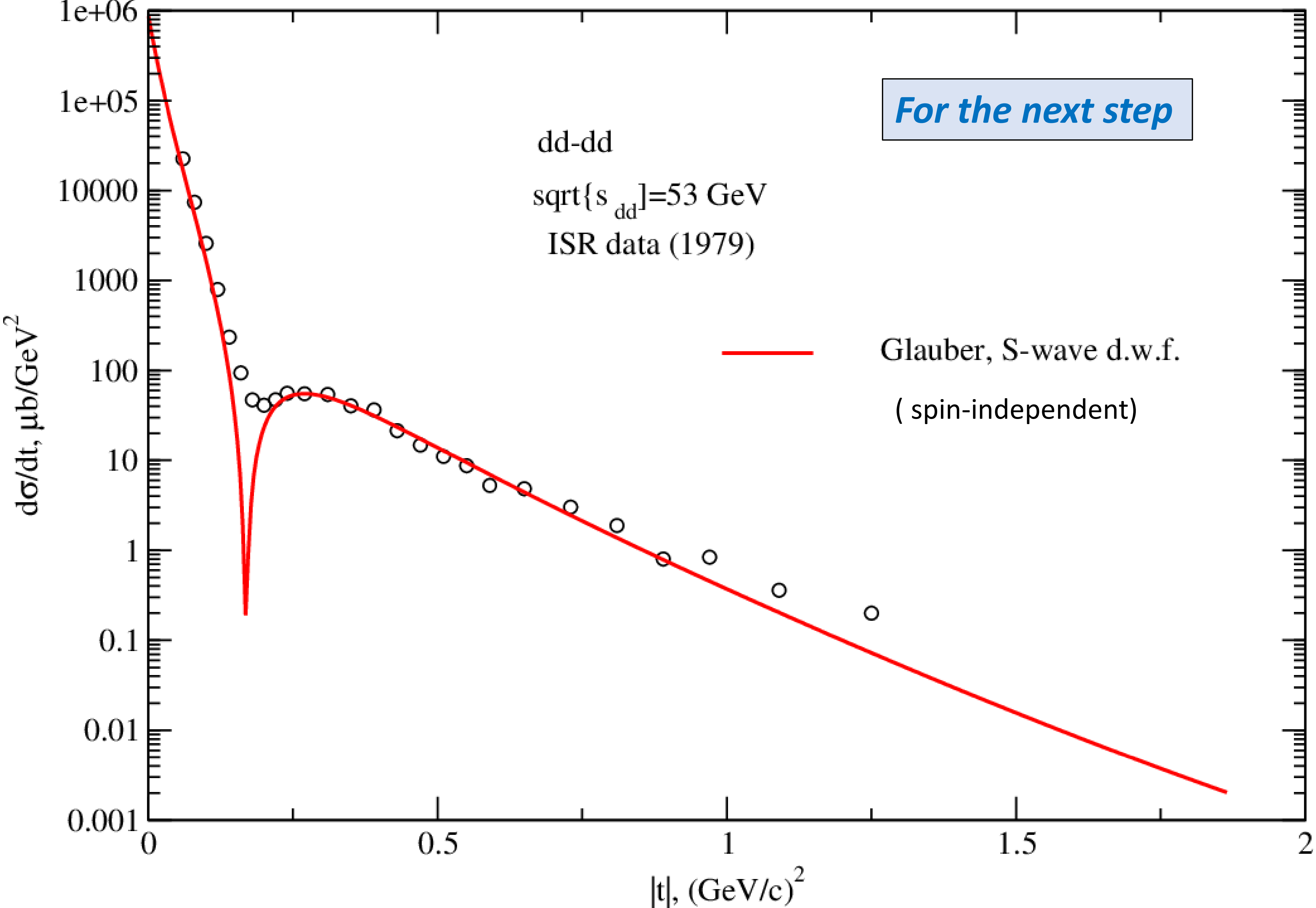
E. Stephan,[1,*] St. Kistryn,[2] R. Sworst,[2] A. Biegun,[1] K. Bodek,[2] I. Ciepał,[2] A. Deltuva,[3] E. Epelbaum,[4] A. C. Fonseca,[5] J. Golak,[2] N. Kalantar-Nayestanaki,[6] H. Kamada,[7] M. Kiš,[6] B. Kłos,[1] A. Kozela,[8] M. Mahjour-Shafiei,[6,†] A. Micherdzińska,[1,‡] A. Nogga,[9] R. Skibiński,[2]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

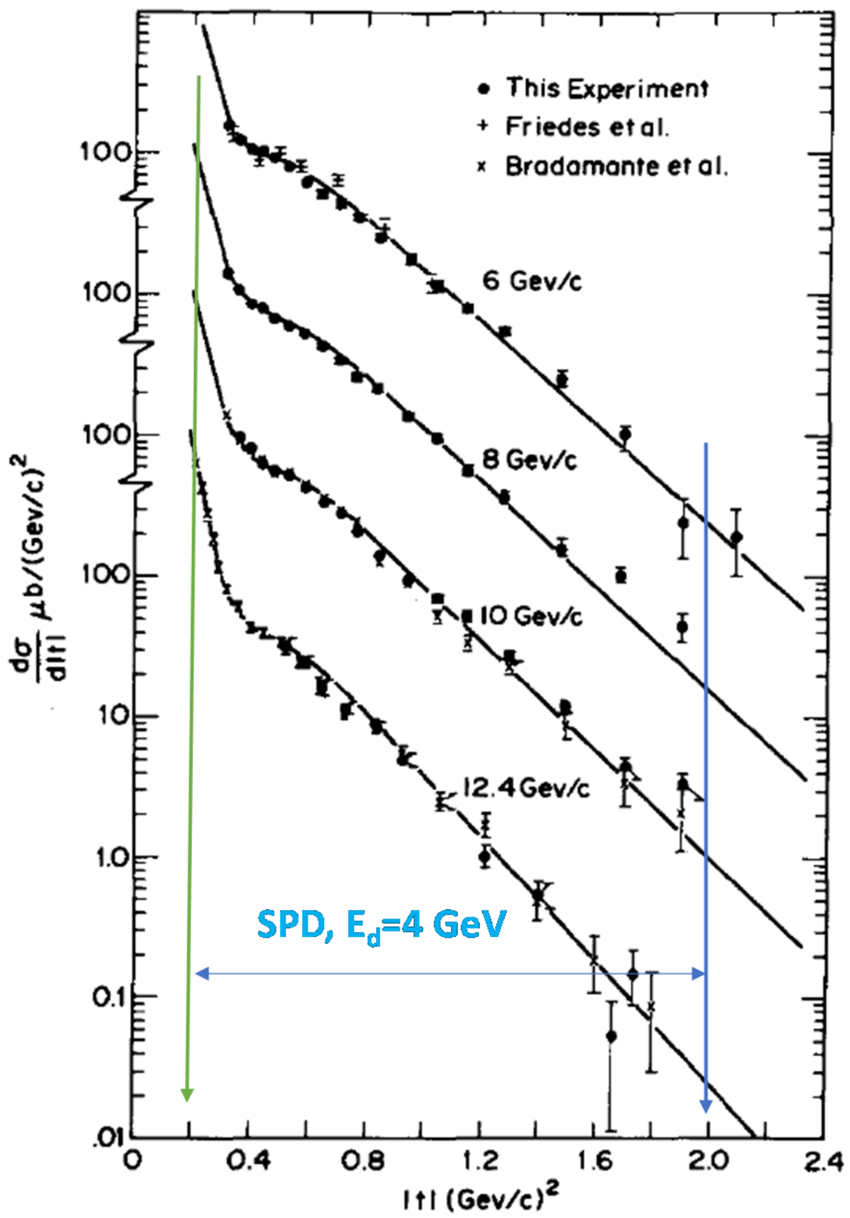
TABLE I. Set of the polarization states used in the $^{1}\mathrm{H}(\vec{d},pp)n$ breakup experiment. The maximum polarizations P_Z, P_{ZZ} (for 100% efficiency of transitions in the ion source) and corresponding combinations of the magnetic fields are shown. The x indicates that the magnetic field is 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


For the next step
dd-dd
sqrt{s dd]=53 GeV
ISR data (1979)
Glauber, S-wave d.w.f.
(spin-independent)
dσ/dt, μb/GeV2
|t|, (GeV/c)2
1e+06
1e+05
10000
1000
100
10
1
0.1
0.01
0.001
0
0.5
1
1.5
2



P. Chanowski et al. PLB 61 (1976)

nd-elastic scattering

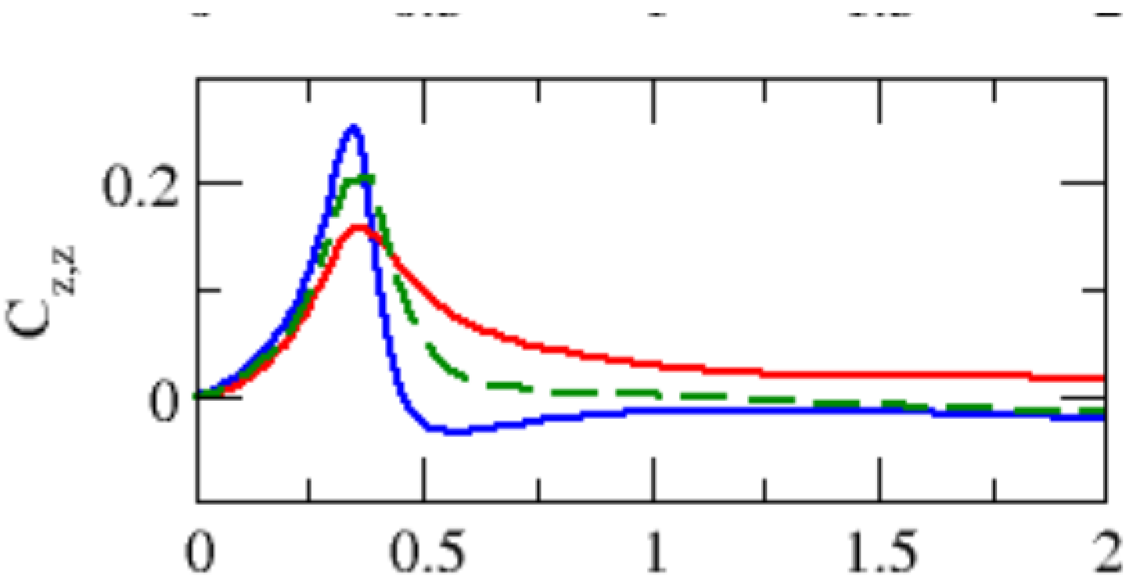
MC simulation for SPD (E_d=4 GeV):

- Kinematic fit with invariant mass constraint (FUMILI fit with 'heavy
- 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

- Boost scattered p,d back to lab frame - require p,d tracks reach MVD (polar angle $\geq 7.13^0$)

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



$C_{z,z}$
0.2
0
0
0.5
1
1.5
2

Numerical results for pd- elastic