NN SPIN AMPLITUDES AND *PD* SCATTERING

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Content

- Motivation
- Spin amplitudes in NN→NN
- Invariant spin amplitudes in pd→pd
- Spin-dependent Glauber theory of pd elastic scattering
- Inelastic dp-scattering dp→ $\{pp\}(^1S_0)+n$
- dd→ dd and inelastic dd-scattering with formation of $NN(^1S_0)$ pairs
- Search for T-invariance violation in double polarized pd scattering
- Conclusion

Helicity amplitudes of NN-scattering

For identical spin $\frac{1}{2}$ particles under Lorentz and P-,T- invariance:

spin non-flip $\phi_1(s,t) =< ++|M|++ >$

double spin-flip $\phi_2(s,t) =< ++|M|-- >$

spin non-flip $\phi_3(s,t) =< +-|M|+- >$

double spin-flip $\phi_4(s,t) =< +-|M|-+ >$

single spin-flip $\phi_5(s,t) =< ++|M|++- >$.

For non-identical (pn) nucleons one has 6 amplitudes,

T-reversal non-invarinace provides two additional amplitudes.

All spin-observables of NN elastic scattering are described in terms of ϕ_i

$$d\sigma/dt = N[|\phi_1|^2 + |\phi_2|^2 + |\phi_1|^3 + |\phi_4|^2 + 4|\phi_5|^2],$$

$$A_N \sim Im[(\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^*]$$

$$A_{NN} \sim 2|\phi_5|^2 + Re(\phi_1^*\phi_2 - \phi_3^*\phi_4)$$

$$\cdots$$

Number of linearly independent non-zero spin observables:
single-spin (asymmetries A_i, polarizations P_i) – 2
double-spin $(A_{ii}, \ldots)$ – 12
triple-spin – 9
four- spin – 2

Complete polarization experiment
for pp-elastic requires 9 independent observables.
PWA GWU is performed for pp-elastic up to 3.8 GeV/c (SAID webpage:`http://gwdac.phys.gwu.edu`.
R.A. Arndt, I.I. Strakovsky, B.L. Workman PRC 56, 3005 (1997);
PWA for pn- elastic – up 1.2 GeV/c

Concerning SPD NICA, above 3 GeV/c $d\sigma/dt$ and mainly A_N (up to 50 GeV/c) and A_{NN}, C_{LL} (up to 6 GeV/c, 12 GeV/c) are measured. Data on double-spin observables D_{NN}, K_{NN} are rather poore in the region of forward angles.

Parametrizations (fit) of the pp- data:
Regge: W.P. Ford, J.W. Van Orden, Phy.Rev. **C87** (2013) 014004;
A. Sibirtsev et al. Eur.Phys.J. **A 45** (2010) 357;
Eikonal: S. Wakaizumi, M. Sawamoto,Prog. Theor. Phys. v.64 (1980) 1699

A systematic analisys of pp elastic scattering from COSY-EDDA, SATURNE, GZS ANL /A. Sibirtsev et al. EPJA 45 (2010) 357/ ω, ρ, f_2, a_2 Reggeon and Pomeron exchanges for $P = 3 - 50$ GeV/c. Isospin structure and G-parity relations allow to obtain the $\bar{p}p$-, pn- and $\bar{p}n$ elastic amplitudes from the pp amplitudes (J.R. Pelaez, 2006):

$$\phi(pp) = -\phi_\omega - \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P$$
$$\phi(\bar{p}p) = \phi_\omega + \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P$$
$$\phi(pn) = -\phi_\omega + \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P$$
$$\phi(\bar{p}n) = \phi_\omega - \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P$$

However, not all available data ($C_{NN}, C_{LL}, C_{SS}, C_{LS}, D_{NN}, D_{SS}, D_{LS}, K_{NN}, \Delta\sigma_T, H_{SNS}$... measured by ANL at 6 GeV/c, and some at 12 GeV/c) were included into the fit.

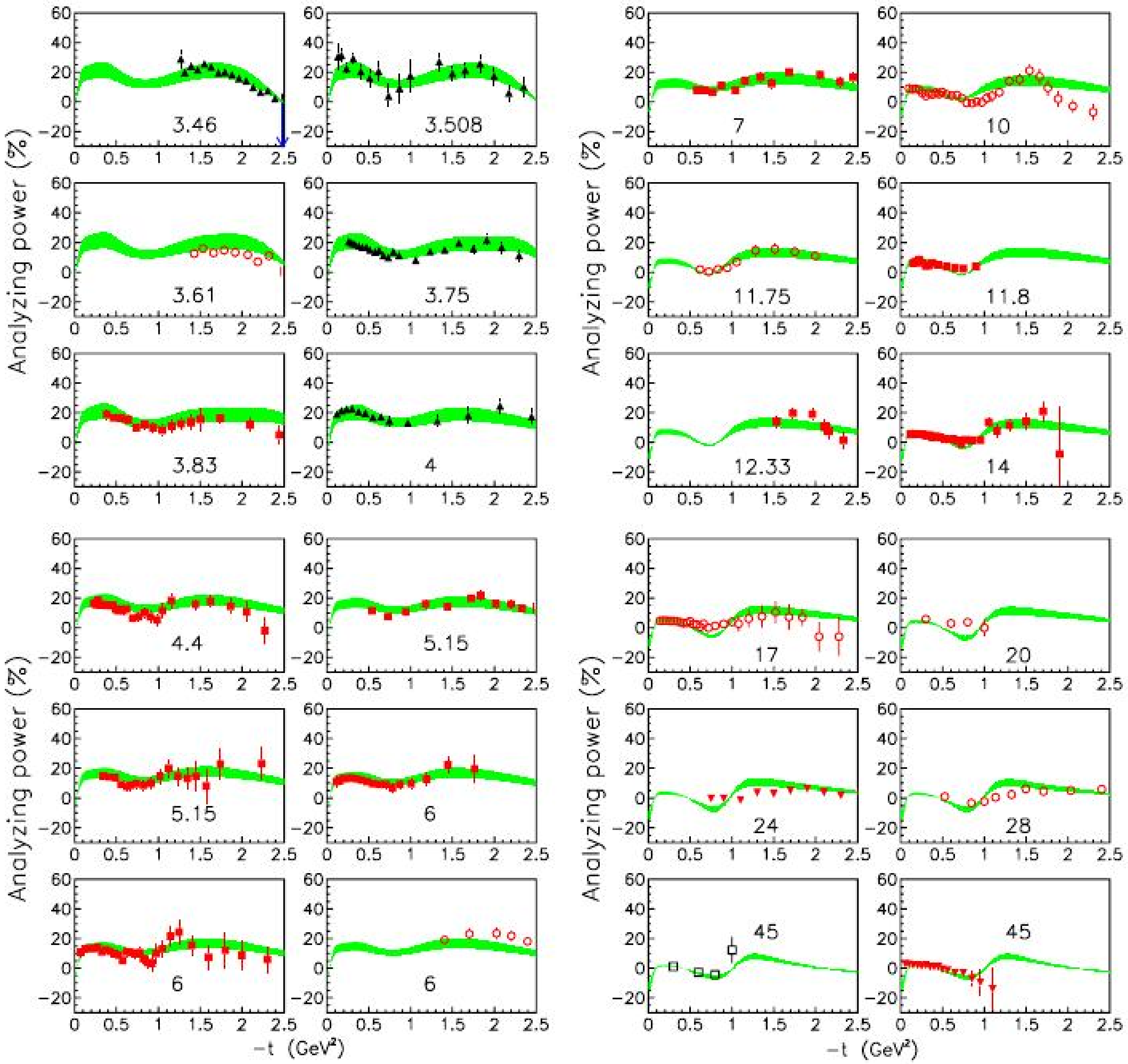
PN elastic scattering

SAID date base:

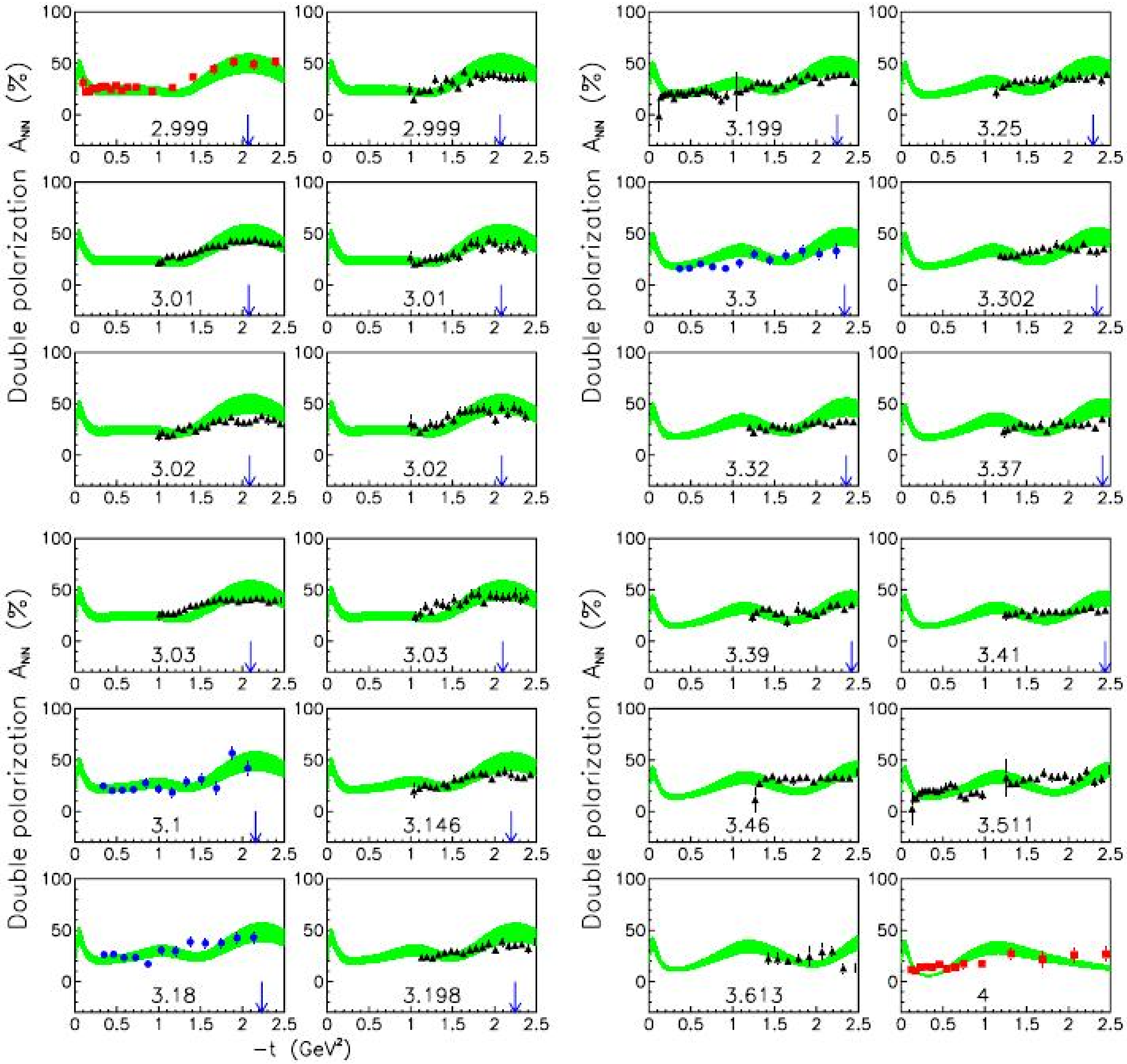
R.A. Arndt et al.m PRC 56 (1997) 3005; http:gwdac.phys.gwu.edu

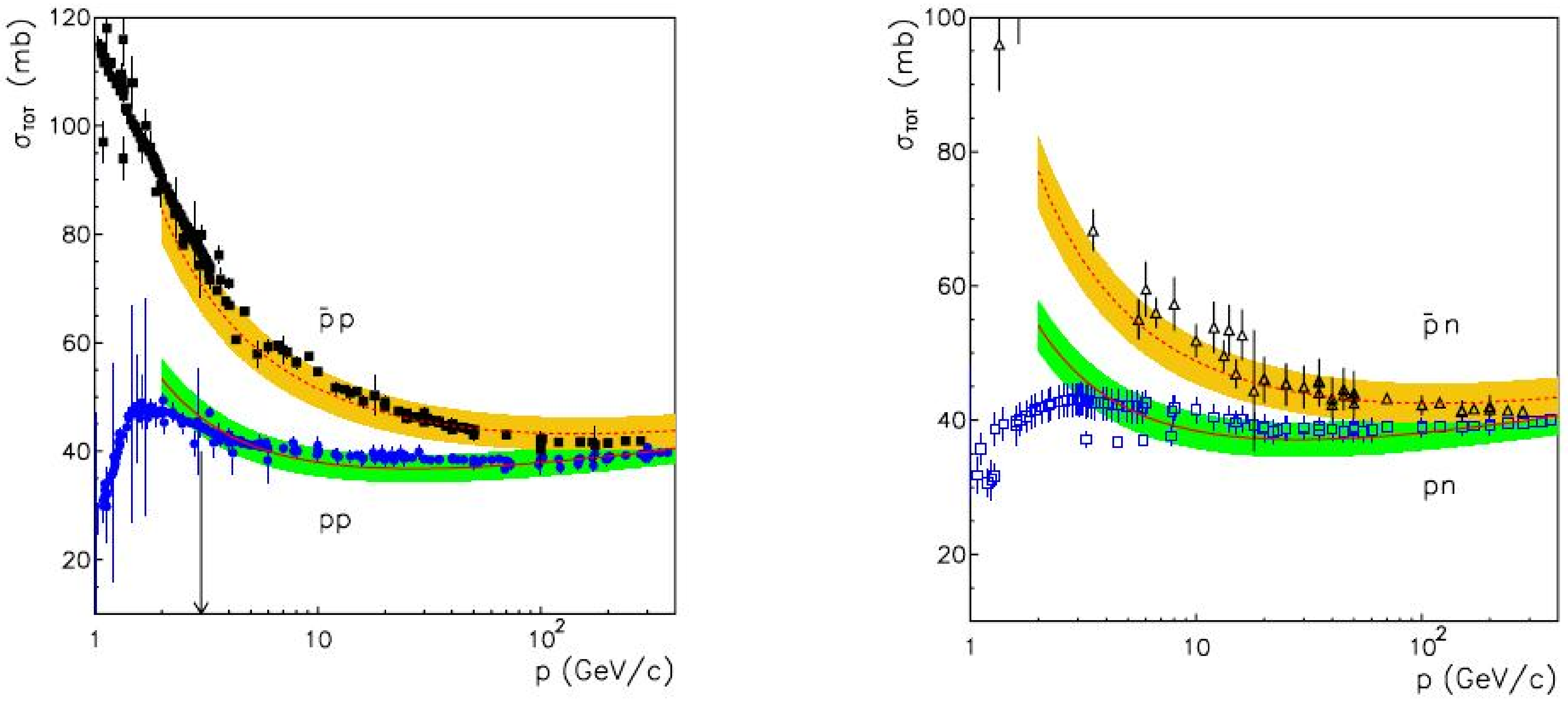
pp up 3.0 GeV/c, pn – up 1.2 GeV

A. Sibirtsev et al, EPJA (2010)



A. Sibirtsev et al, (2010); Only 3-4 GeV/c





A. Sibirtsev et al, EPJA (2010)

$\mathrm{Re}\, f(0^\circ)/\mathrm{Im}(0^\circ)$ ratio.

A problem with antip-p theory: no zero

A. Sibirtsev et al, EPJA (2010)

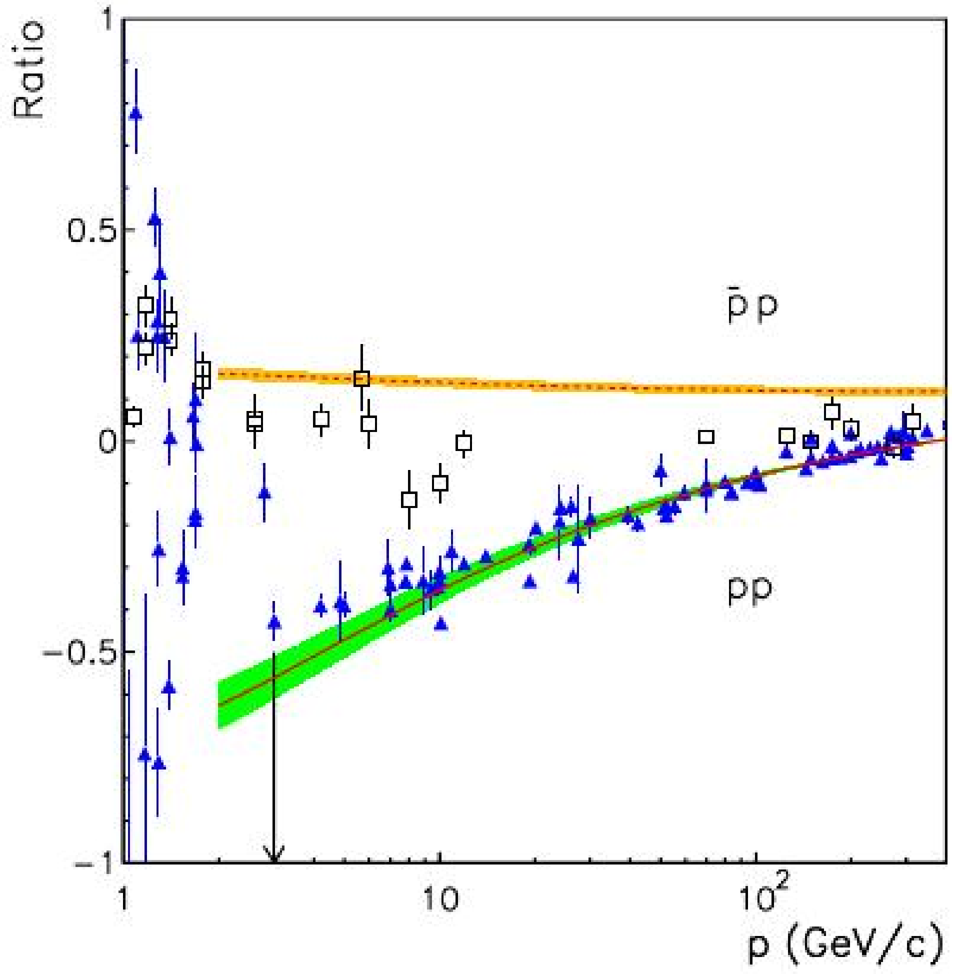
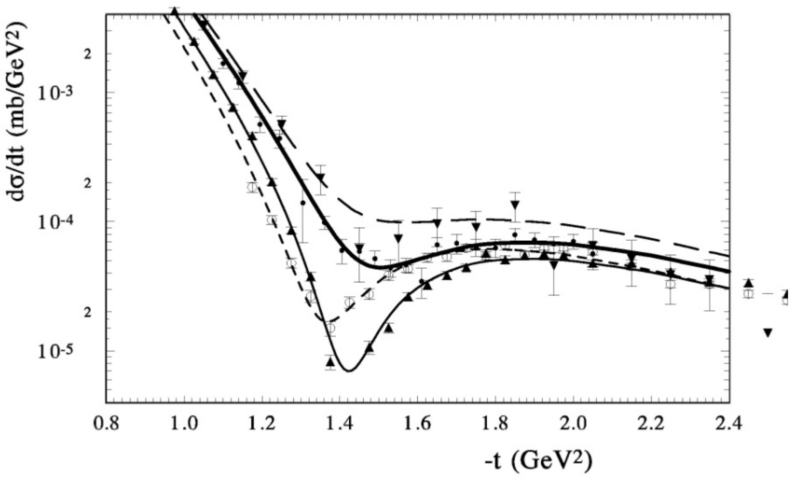
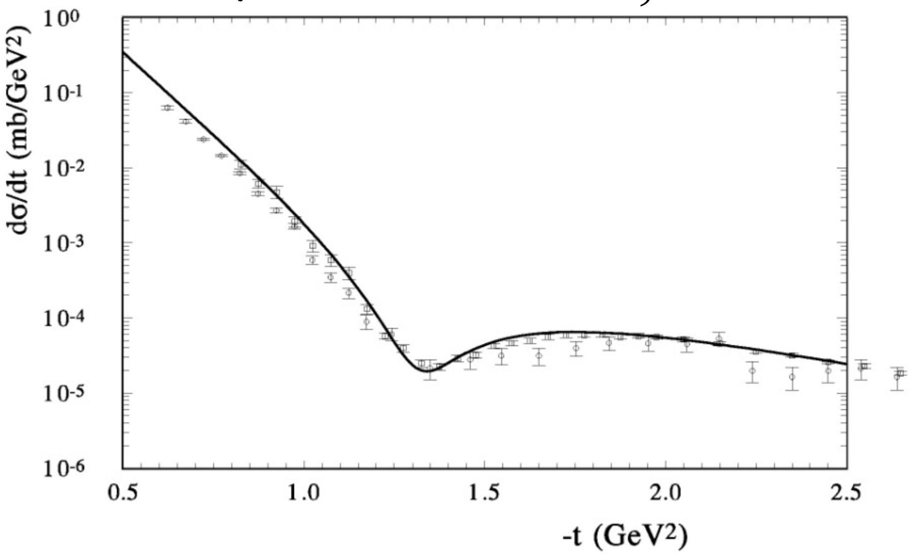


Fig. 16. Ratio of the real-to-imaginary parts of the forward amplitudes for pp (triangles, solid line) and $\bar{p}p$ (squares, dashed line), respectively. The data are taken from the PDG [32].

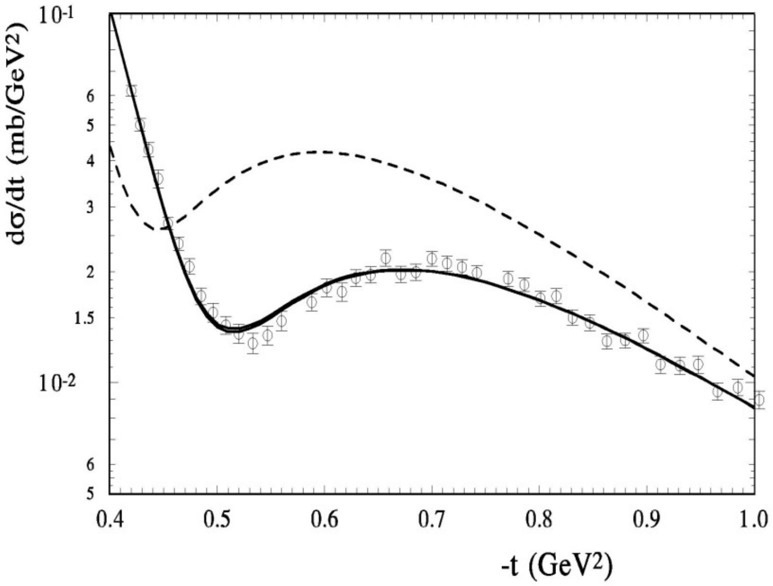
$\sqrt{s} = 13.4;\ 18.4;\ 30.4;\ 44.7\,(GeV);$



$\sqrt{s} = 52.8\,GeV;$

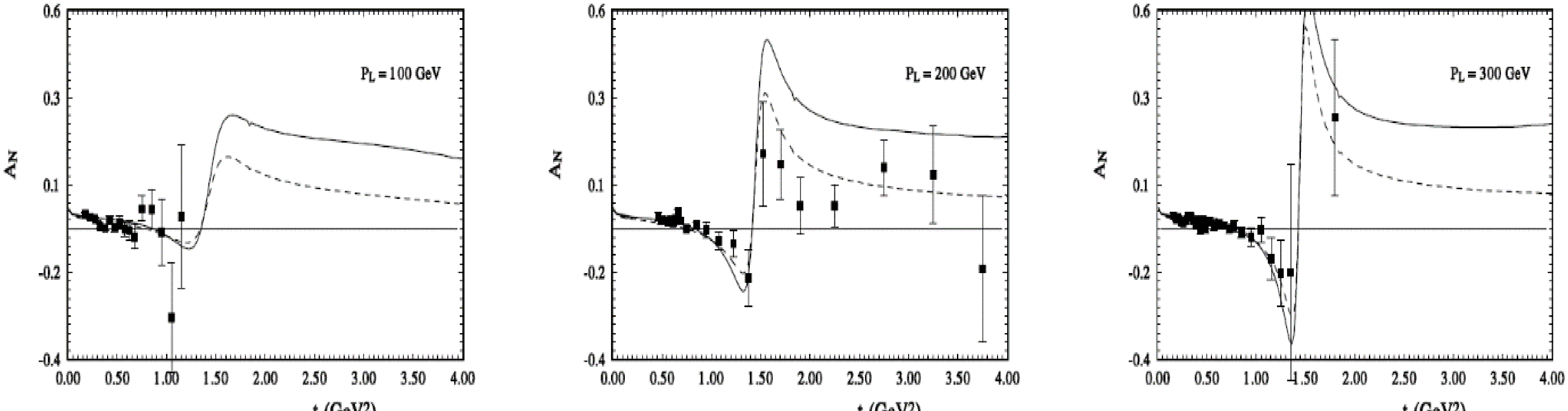


O.V. Selyugin, PRD 91 (2015) high-energy general structure model (HEGS) model



$\sqrt{s} = 7\,TeV;$

O.V.Selyugin, PEPAN letters, 13 (2016) 116



pd ELASTIC SCATTERING

Invariant spin amplitudes of pd- elastic scattering

$$M_{fi} = \varphi^{+}_{\mu'} e^{(\lambda')*}_{\beta} e^{(\lambda)}_{\alpha} T_{\beta\alpha}(\vec{p}, \vec{p}\,', \vec{\sigma}) \varphi_{\mu},$$

$$2 \times 3 \times 2 \times 3 = 36$$

P-invariance (18 amplitudes)

$$T_{\alpha\beta}(-\vec{p}, -\vec{p}\,', \vec{\sigma}) = T_{\alpha\beta}(\vec{p}, \vec{p}\,', \vec{\sigma})$$

T-invariance (lefts 12 amplitudes):

$$T_{\beta\alpha}(\vec{p}, \vec{p}\,', \vec{\sigma}) = T_{\alpha\beta}(-\vec{p}, -\vec{p}, -\vec{\sigma})$$

Phenomenology of the $pd \to pd$ transition

$\hat{\mathbf{q}} = (\mathbf{p} - \mathbf{p}')$, $\hat{\mathbf{k}} = (\mathbf{p} + \mathbf{p}')/$, $\hat{\mathbf{n}} = [\mathbf{k} \times \mathbf{q}]$ – unit vect. ($Z \uparrow\uparrow \hat{\mathbf{k}}$, $X \uparrow\uparrow \hat{\mathbf{q}}$ $Y \uparrow\uparrow \hat{\mathbf{n}}$)

$$M = (A_1 + A_2 \boldsymbol{\sigma}\hat{\mathbf{n}}) + (A_3 + A_4 \boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})^2 + (A_5 + A_6 \boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}})^2 + A_7(\boldsymbol{\sigma}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{k}}) + A_8(\boldsymbol{\sigma}\hat{\mathbf{q}})\left[(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})\right] + (A_9 + A_{10}\boldsymbol{\sigma}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{n}}) + A_{11}(\boldsymbol{\sigma}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{q}}) + A_{12}(\boldsymbol{\sigma}\hat{\mathbf{k}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})\right]$$

– –

$$+(T_{13} + T_{14}\boldsymbol{\sigma}\hat{\mathbf{n}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{q}}) + (\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{k}})\right] + T_{15}(\boldsymbol{\sigma}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{k}}) + T_{16}(\boldsymbol{\sigma}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{q}}) + T_{17}(\boldsymbol{\sigma}\hat{\mathbf{k}})\left[(\mathbf{S}\hat{\mathbf{q}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{q}})\right] + T_{18}(\boldsymbol{\sigma}\hat{\mathbf{q}})\left[(\mathbf{S}\hat{\mathbf{k}})(\mathbf{S}\hat{\mathbf{n}}) + (\mathbf{S}\hat{\mathbf{n}})(\mathbf{S}\hat{\mathbf{k}})\right]$$

$A_1 \div A_{12}$ T-even P-even:
M. Platonova, V.I. Kukulin,PRC **81** (2010) 014004

$\mathbf{T_{13} \div T_{18}}$: TVPC

The polarized elastic differential pd cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{pol} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left[1 + \frac{3}{2} p_j^p p_i^d C_{j,i} + \frac{1}{3} P_{ij}^d A_{ij} + \ldots\right]. \tag{3}$$

Spin observables of the pd-pd

$$A_j^p = \frac{TrM\sigma_j M^+}{TrMM^+},$$

$$A_j^d = \frac{TrM\hat{S}_j M^+}{TrMM^+},$$

$$\hat{P}_{ij} = \frac{3}{2}(\hat{S}_i\hat{S}_j + \hat{S}_j\hat{S}_i) - 2\delta_{ij}$$

$$A_{ij} = \frac{TrM\hat{P}_{ij}M^+}{TrMM^+},$$

$$C_{ij} = \frac{TrM\sigma_i\hat{S}_j M^+}{TrMM^+}, C_{ij,k} = \frac{TrM\sigma_k\hat{P}_{ij}M^+}{TrMM^+},\ldots$$

Elastic $pd \to pd$ transitions

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

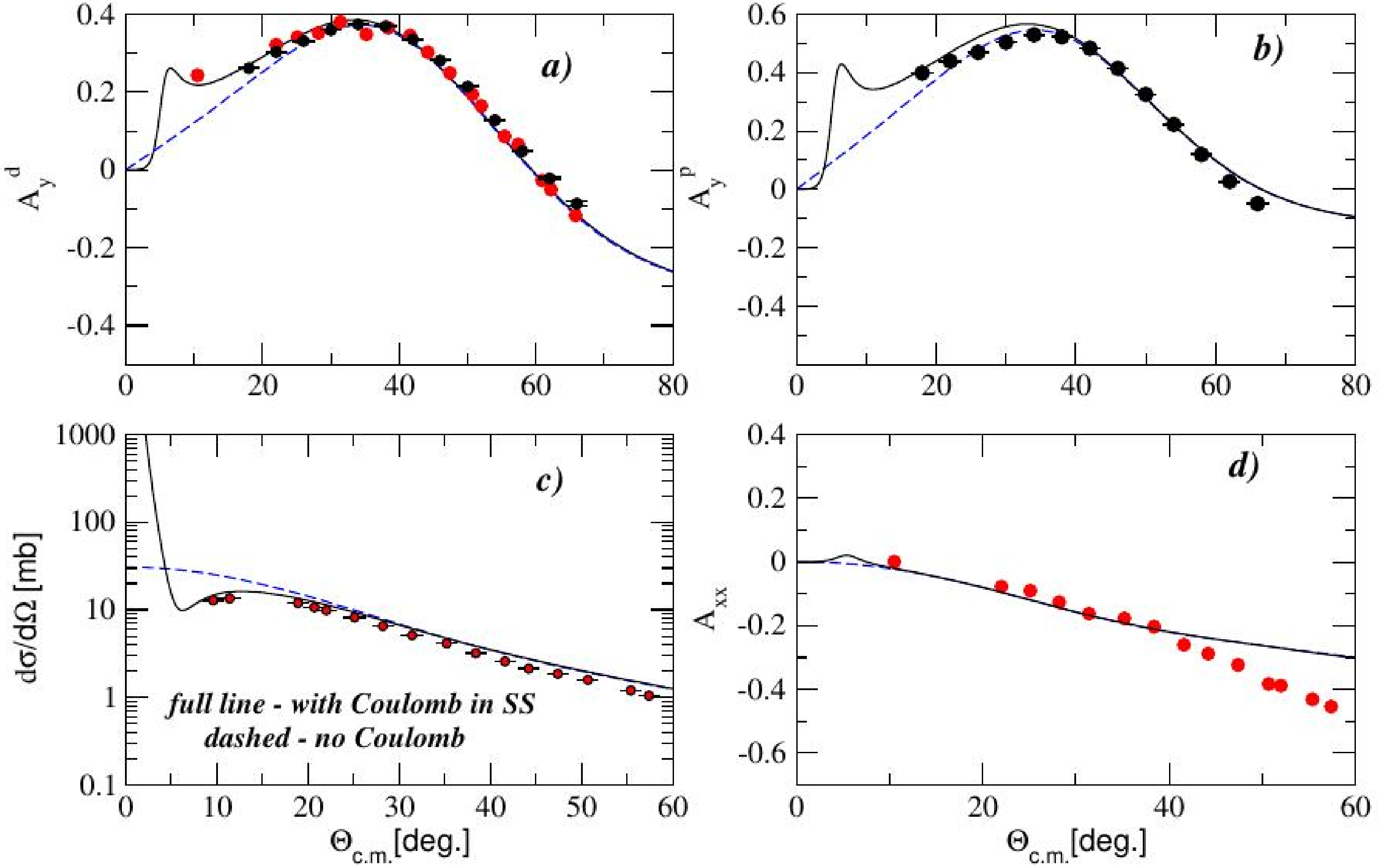
On-shell elastic pN scattering amplitude (**T-even, P-even**)

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

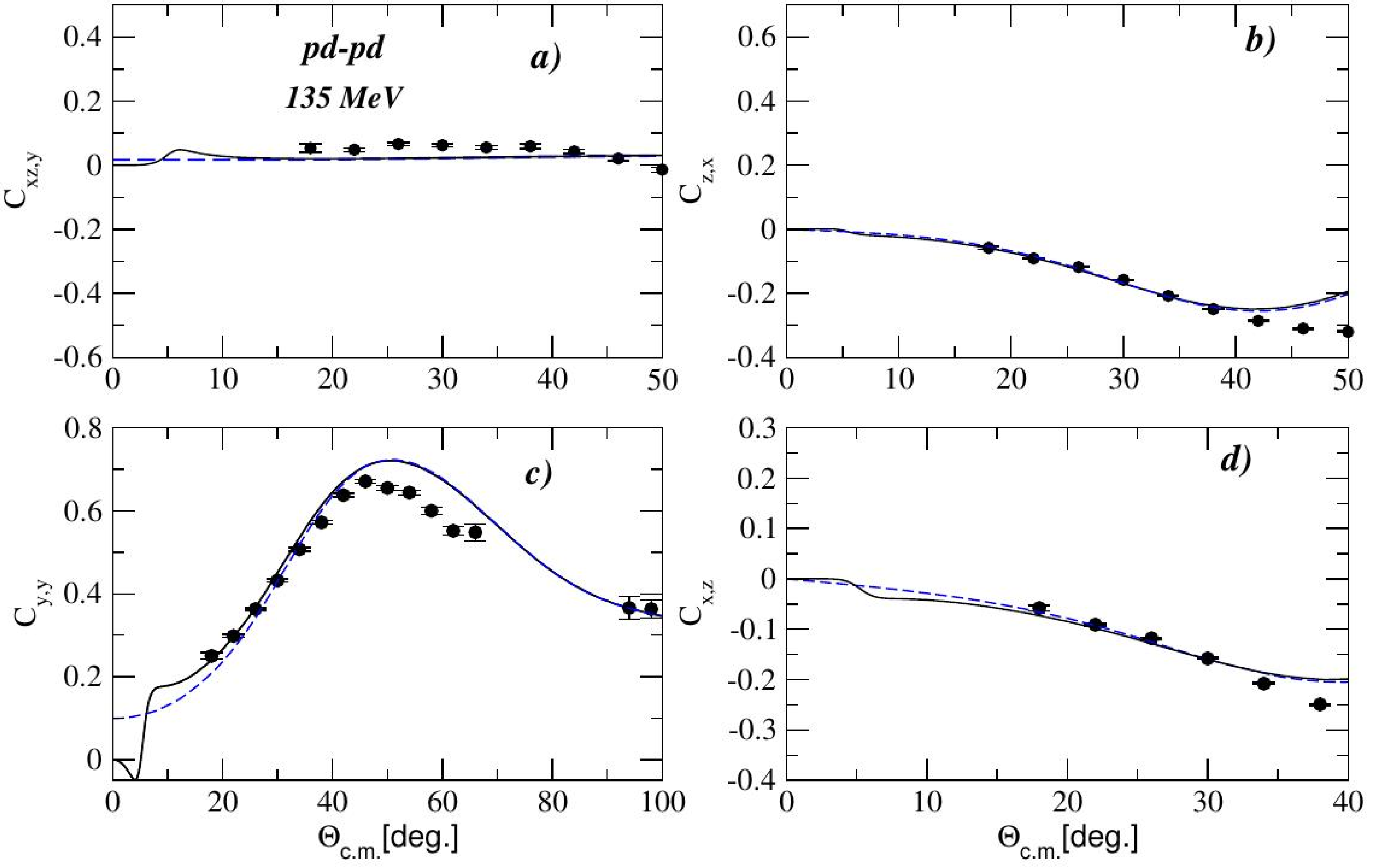
M. Platonova, V. Kukulin, PRC **81** (2010) 014004:

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.



Curves: the modified Glauber model; A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38

Data: von B.Przewoski et al. PRC 74 (2006) 064003

The Glauber model and exact Faddeev calculations

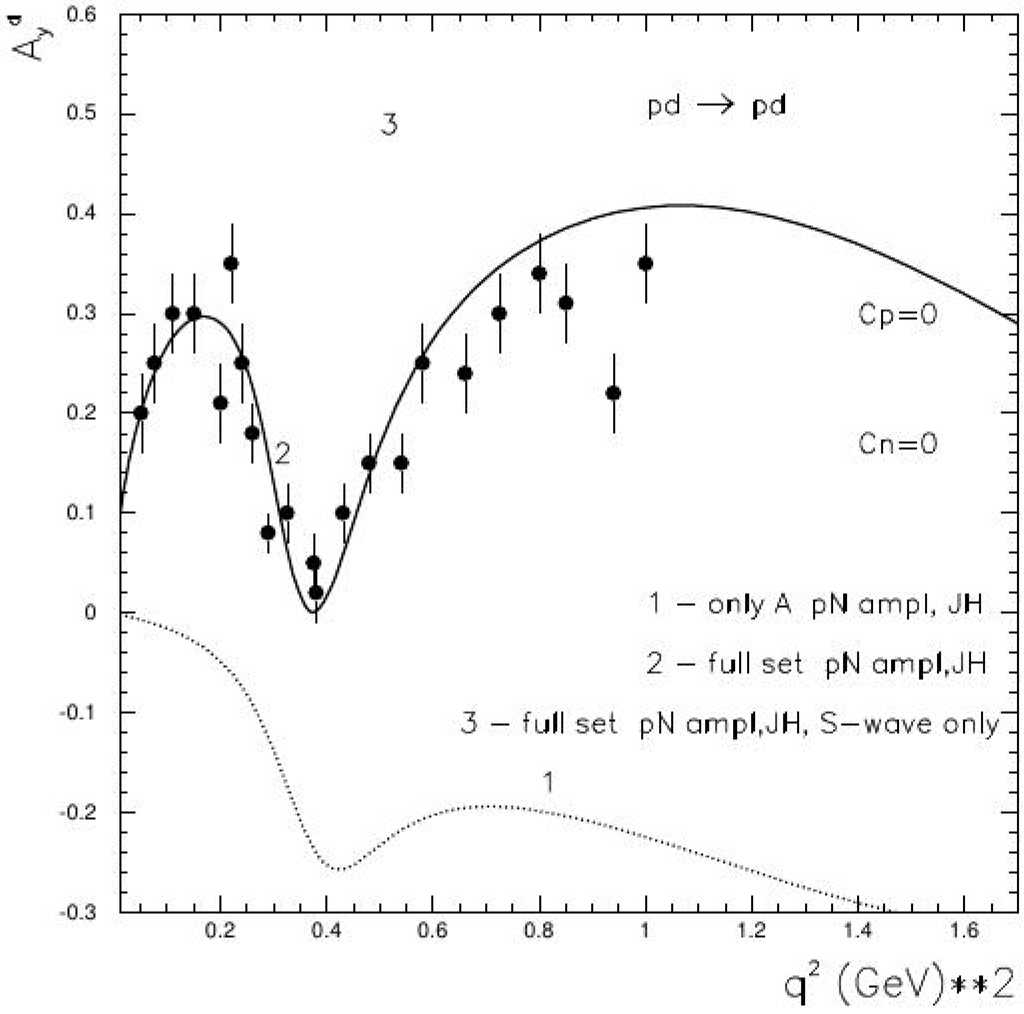
The Glauber theory: eikonal approximation,
on-shell hN-scattering amplitudes (no off-shell effects),
maximal multiplicity is equal to A (no multiple scatterings taken into account in Faddeev calculations)
....

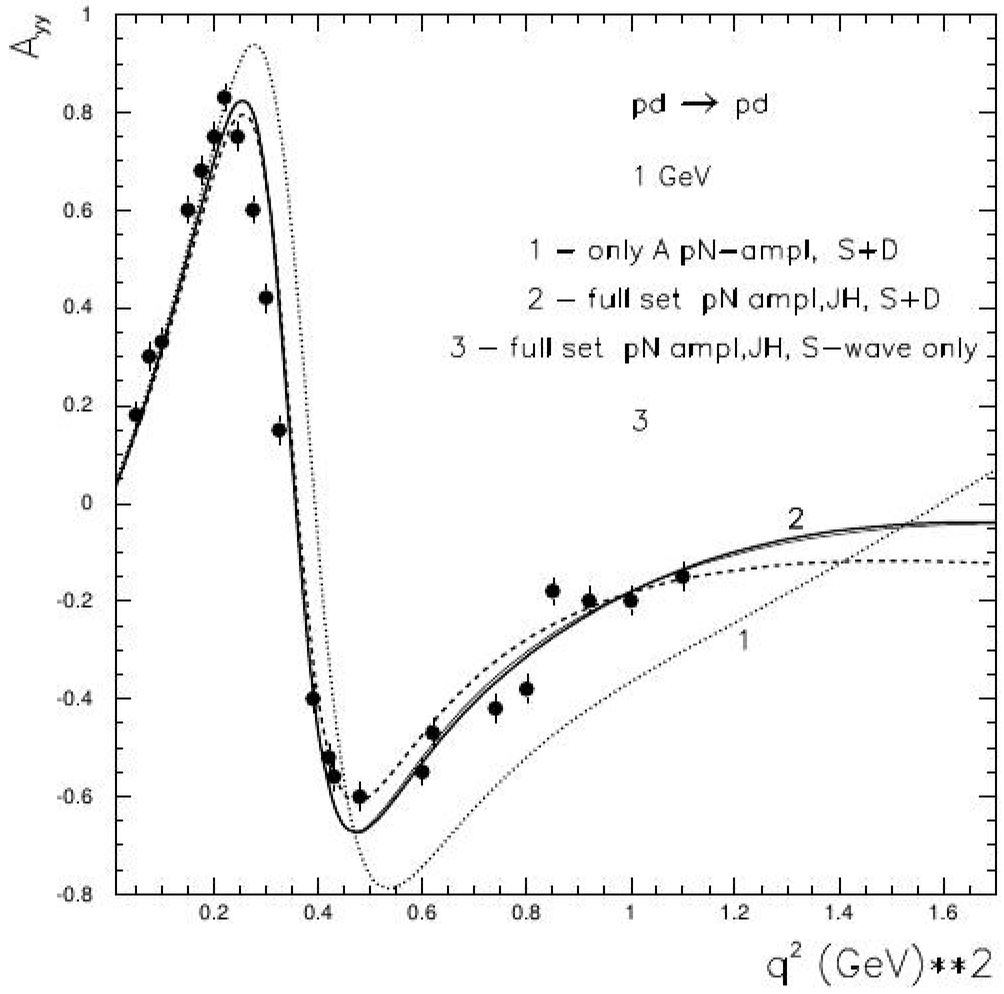
Why the Glauber model is so successful?

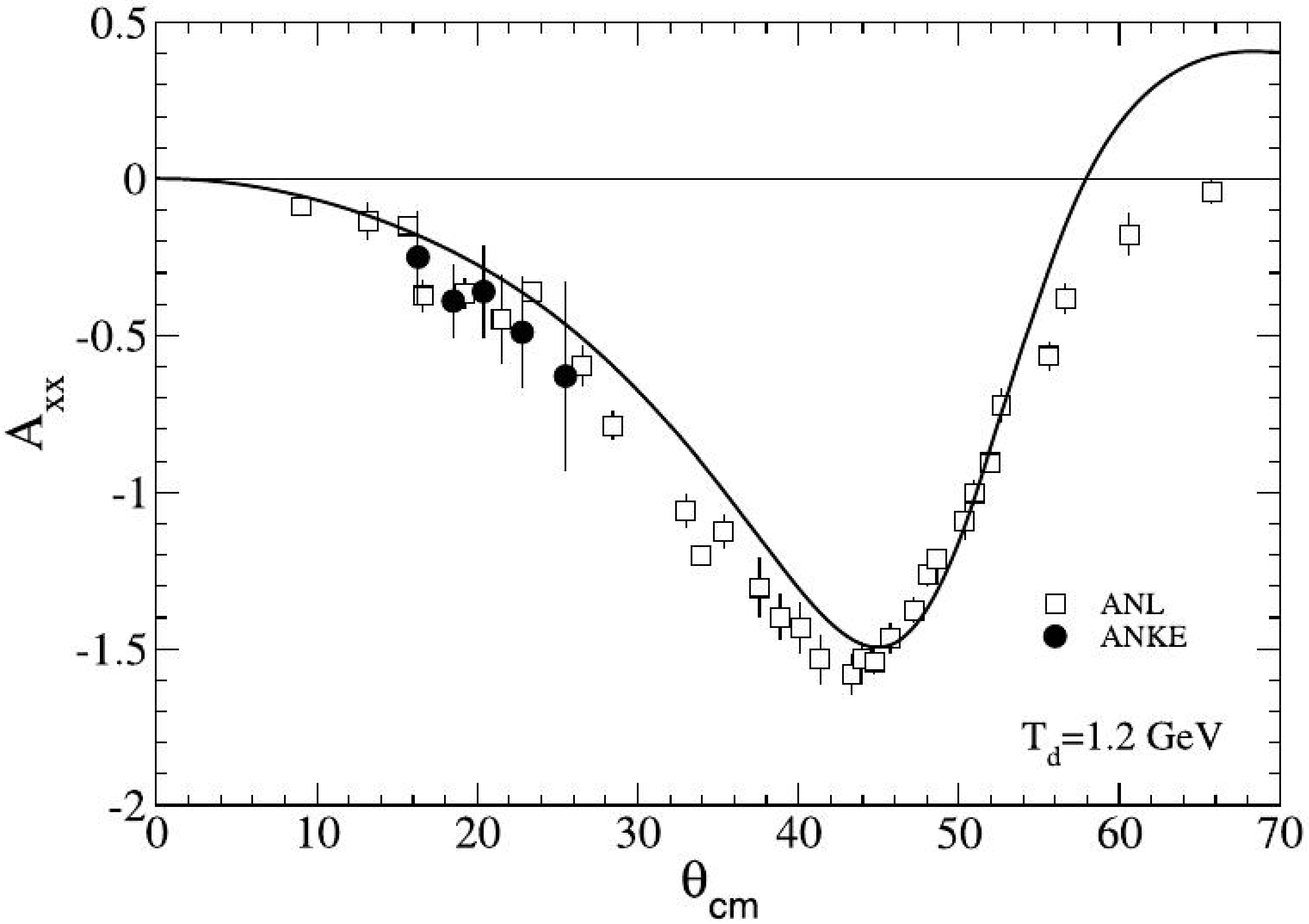
D.R. Harrington, Phys.Rev. 184 (1969) 1745

Compnsations!

Test calculations: pd elastic scattering at 1 GeV







D. Mchedlishvili et al. (ANKE@COSY) Nucl.Phys. A977 (2018)

Vector analyzing powers A_y^p and A_y^d in pd elastic

$$A_y^p = 2\,\mathrm{Re}[2(A_1^* + A_3^* + A_5^*)(A_2 + A_4 + A_6) + A_1^* A_2 - A_3^* A_6 - A_4^* A_5 + 2A_9^* A_{10)}]/(3d\sigma/dt)$$

$$A_y^d = 2\,\mathrm{Re}[2A_1^* + A_3^* + 2A_5^*)A_9 + 2(A_2^* + A_4^* + 2A_6^*)A_{10} + A_7^* A_{12} + 2A_8^* A_{11)}]/(3d\sigma/dt)$$

At q→0, SS- mechanism:

$$R = A_y^d \,/\, A_y^p,\, R(q=0) = \frac{2}{3}$$

$$\mathrm{Re}(A_2^* A_{10})/\mathrm{Re}(A_2^* A_1) = \frac{9}{2}(R - \frac{2}{3})$$

$$A_1 = (S_0 + \sqrt{2}S_2)A_N;\, A_2 = (S_0^{(0)} + \sqrt{2}S_2^{(1)})C_N;\, A_{10} = (S_0^{(0)} + \frac{1}{\sqrt{8}}S_2^{(1)})(G_N - H_N)$$

$$M_N = A_N + (C_N + C_N^{'})\vec{\sigma}\vec{n} + (G_N + H_N)(\vec{\sigma}\vec{q})(\vec{\sigma}_N\vec{q}) + (G_N + G_N)(\vec{\sigma}\vec{n})(\vec{\sigma}_N\vec{n})$$

$$\hat{M} = a + ib\hat{\sigma}_y + ic\hat{S}_y.$$

Here $\hat{\sigma}_y$ and $\ddot{S}_y$ are operators acting, respectively, on the spins of the proton and deuteron. The proton analyzing power results from an interference between the amplitudes a and b whereas that of the deuteron is due to an interference between a and c. Straightforward calculations yield

$$A_y^p = 2Im\{ab^*\}/[|a|^2 + |b|^2 + \tfrac{2}{3}|c|^2],$$
$$A_y^d = \tfrac{4}{3}Im\{ac^*\}/[|a|^2 + |b|^2 + \tfrac{2}{3}|c|^2].$$

$b = c$ at $q \approx 0$ then $R = \dfrac{2}{3}$

It follows from the results given in Table 1 that, within the refined Glauber model, most of the deviations of R from 2/3 at $q = 0$ are due to the spin-spin term in single scattering; the modifications due to the double scattering are small in comparison and may be estimated from theory with sufficient precision. Using the

Table 1

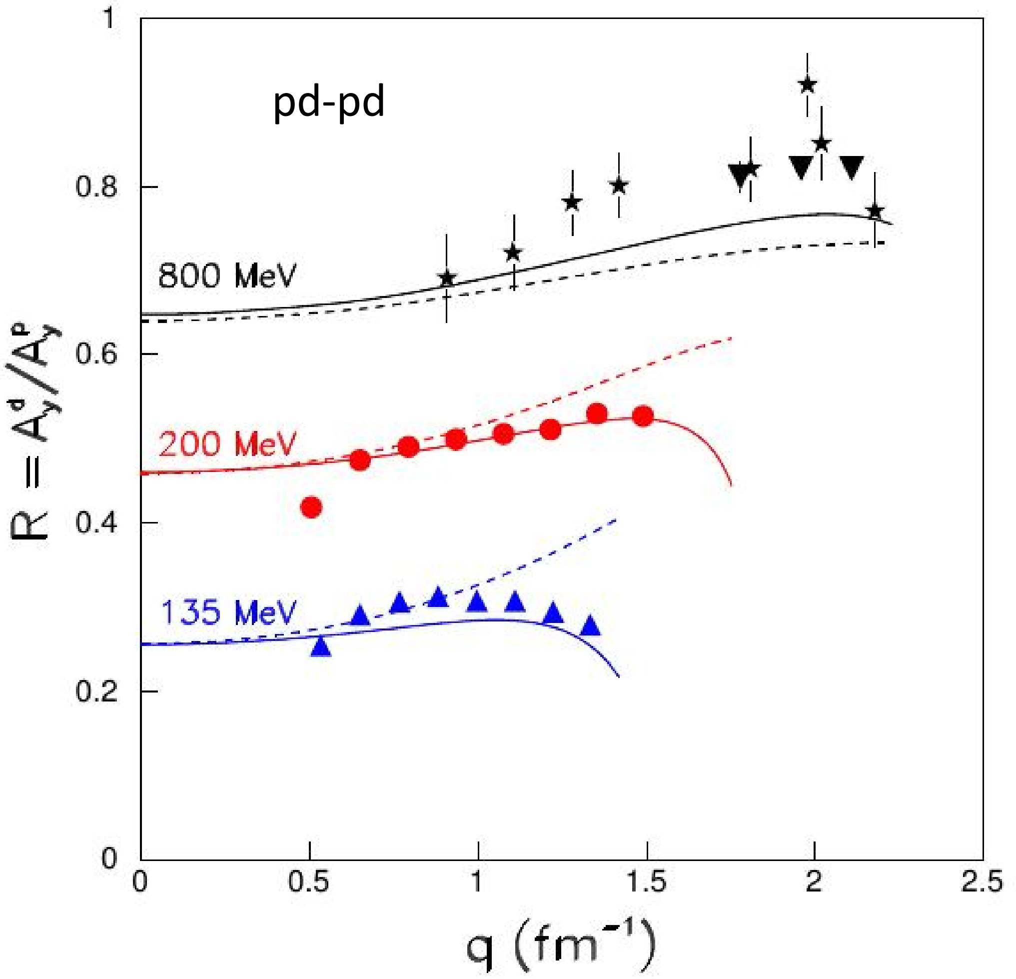
Predicted values of the ratio of deuteron to proton analyzing powers in pd elastic scattering as $q \to 0$. The single (SS) and full ($SS + DS$) models of Ref. [12] were evaluated using as input a partial wave analysis of the nucleon-nucleon amplitudes [16]. The table shows the small deviations of R from 2/3.

T_p MeV	$100(R - 2/3)$	
	SS	SS+DS
135	−1.09	−1.24
200	−0.82	−0.73
250	−1.02	−0.81
450	−2.25	−1.55
600	−4.28	−3.31
800	−2.75	−2.00
1000	−0.36	0.25
1125	1.84	2.35
1135	2.04	2.53

$$R = \frac{A_y^d}{A_y^p}$$

Yu.N.U, C. Wilkin, Phys. Lett. B793 (2019) 224,

δ =R – 2/3 is sensitive to spin-spin NN terms



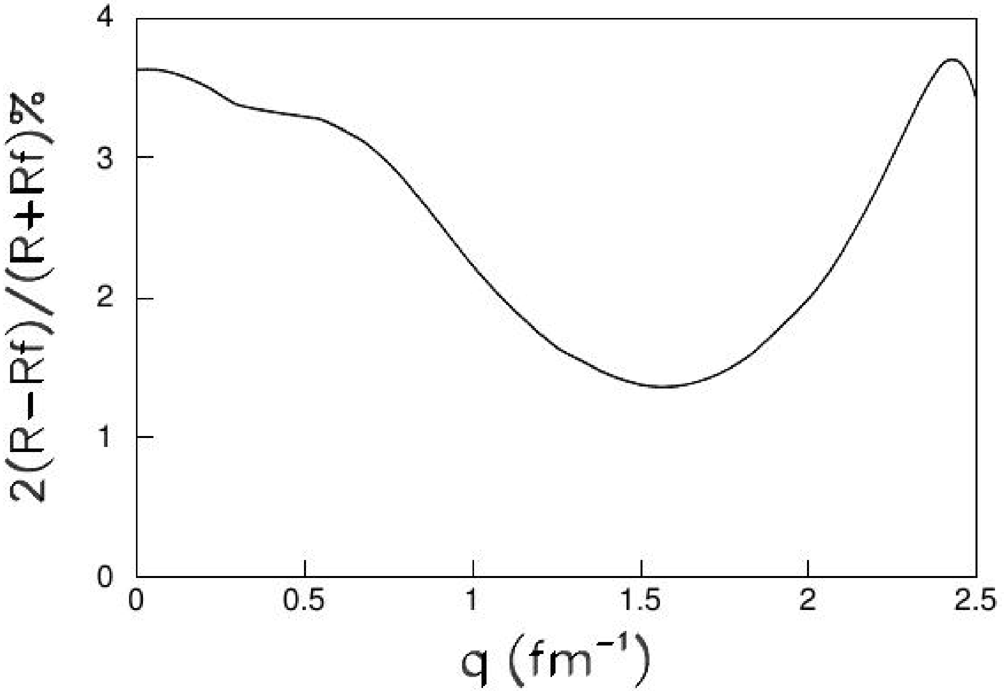
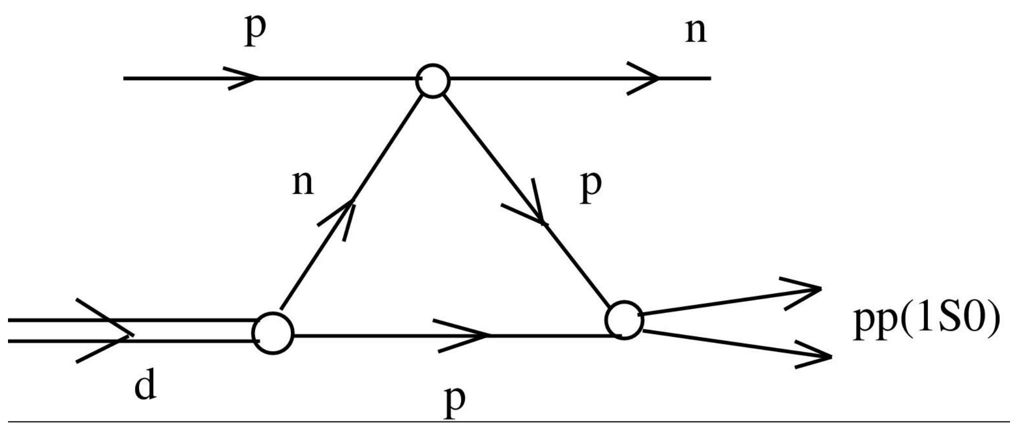


Figure 2: Difference between the predictions of the refined Glauber model [10] without (R) and with (Rf) the NN spin-spin contribution at 800 MeV expressed as a percentage of their average.

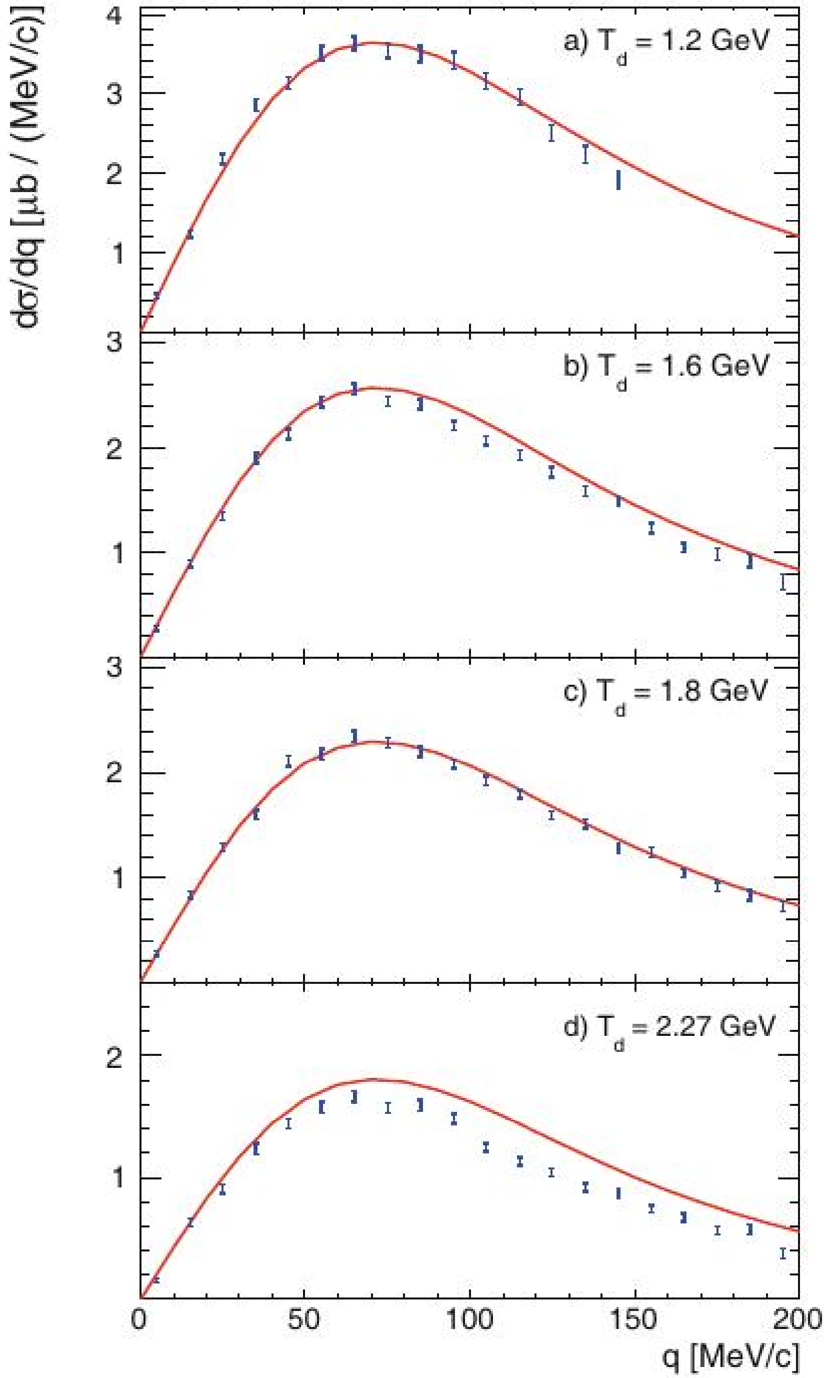
precise measurement of R could provide some information on the NN transverse spin-spin amplitude in the forward direction that is independent of the measurement of the spin dependence of total cross sections and the use of forward dispersion relations [2].

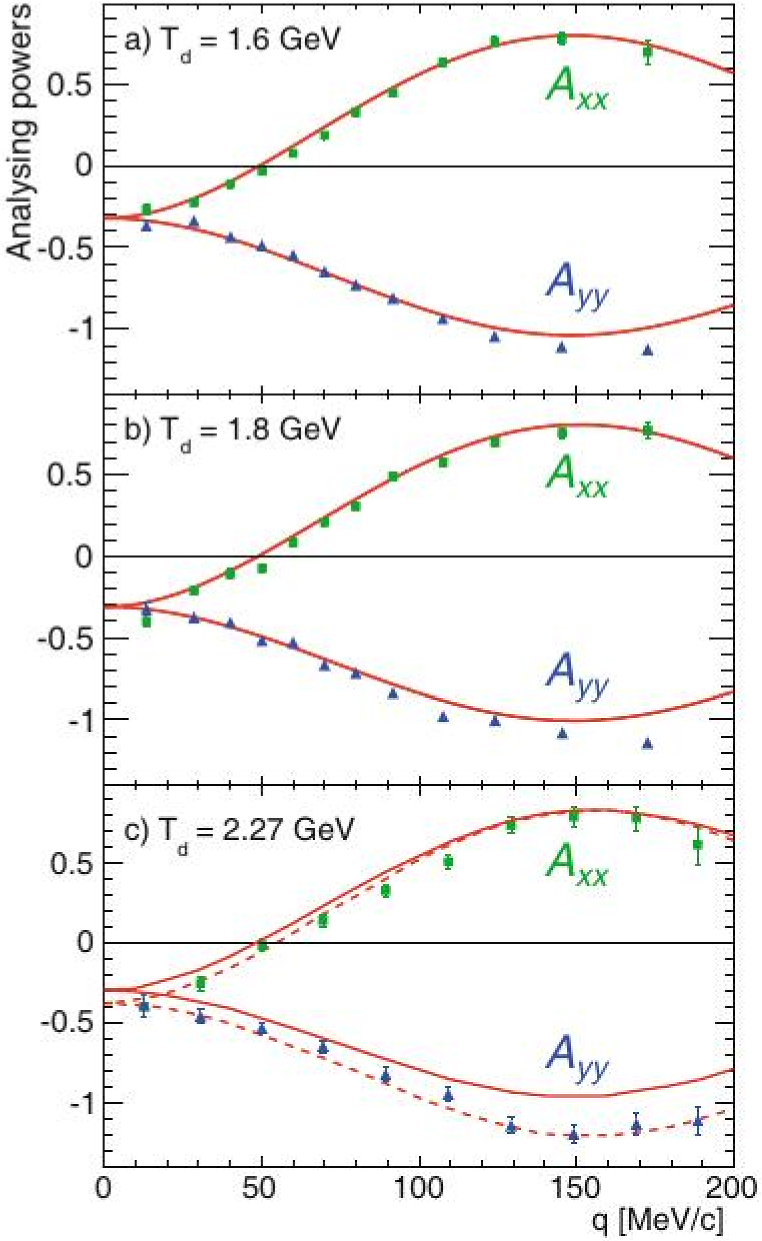
constraint on the spin-spin amplitudes. This may present a severe experimental challenge because, even in the well-controlled IUCF experiment, the overall uncertainty in (A_y^p, A_y^d) was $(0.9\%, 1.5\%)$ and $(2.3\%, 2.0\%)$ at 135 MeV and 200 MeV, respectively [8].

Inelastic dp-scattering dp→ {pp}($^1S_0$)+n

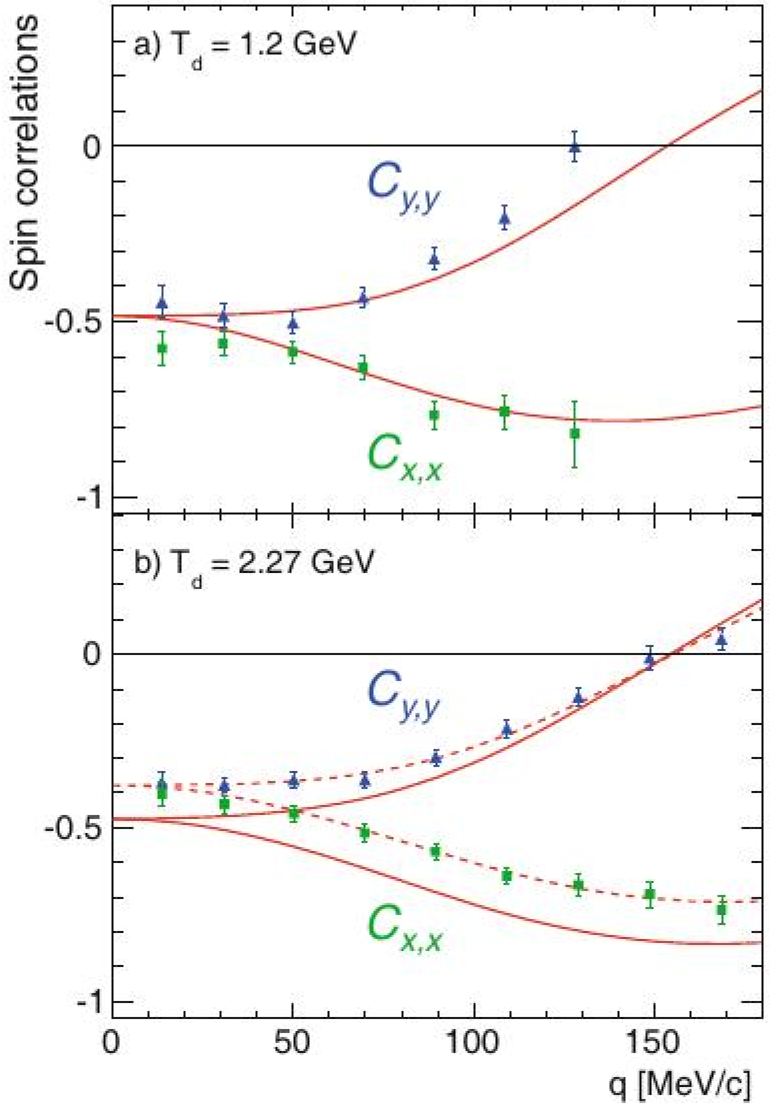


D. Mchedlishvili et al. (ANKE@COSY) Eur.Phys.J A 49 (2013) 49





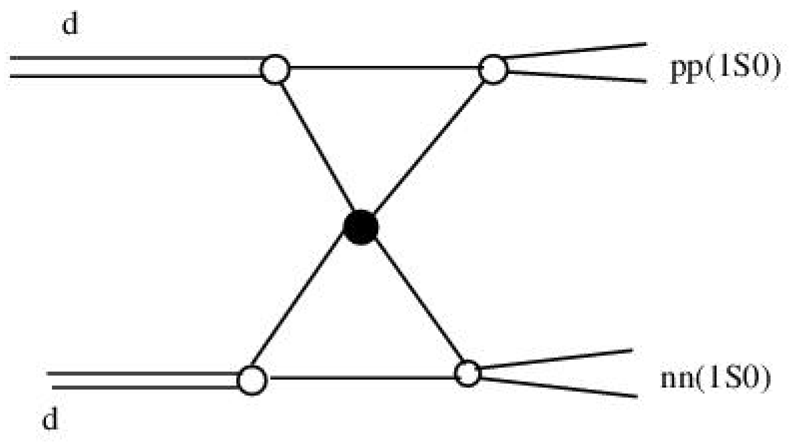
'ig. 8. Tensor analysing powers A_{xx} (squares) and A_{yy} (tri-
ngles) of the $\vec{d}p \to \{pp\}_s n$ reaction at three beam energies for
›w diproton excitation energy, $E_{pp} < 3$ MeV, compared to im-

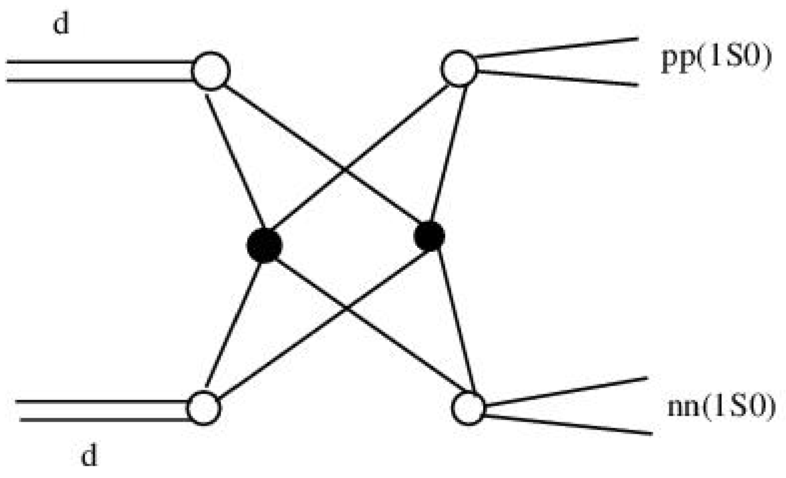


pd-> (pp)+n, E_pp< 3MeV, 1S0 ANKE

D. Mchedlishvili, et al. EPJA 49 (2013)

dd- elastic and quasi-elastic scattering



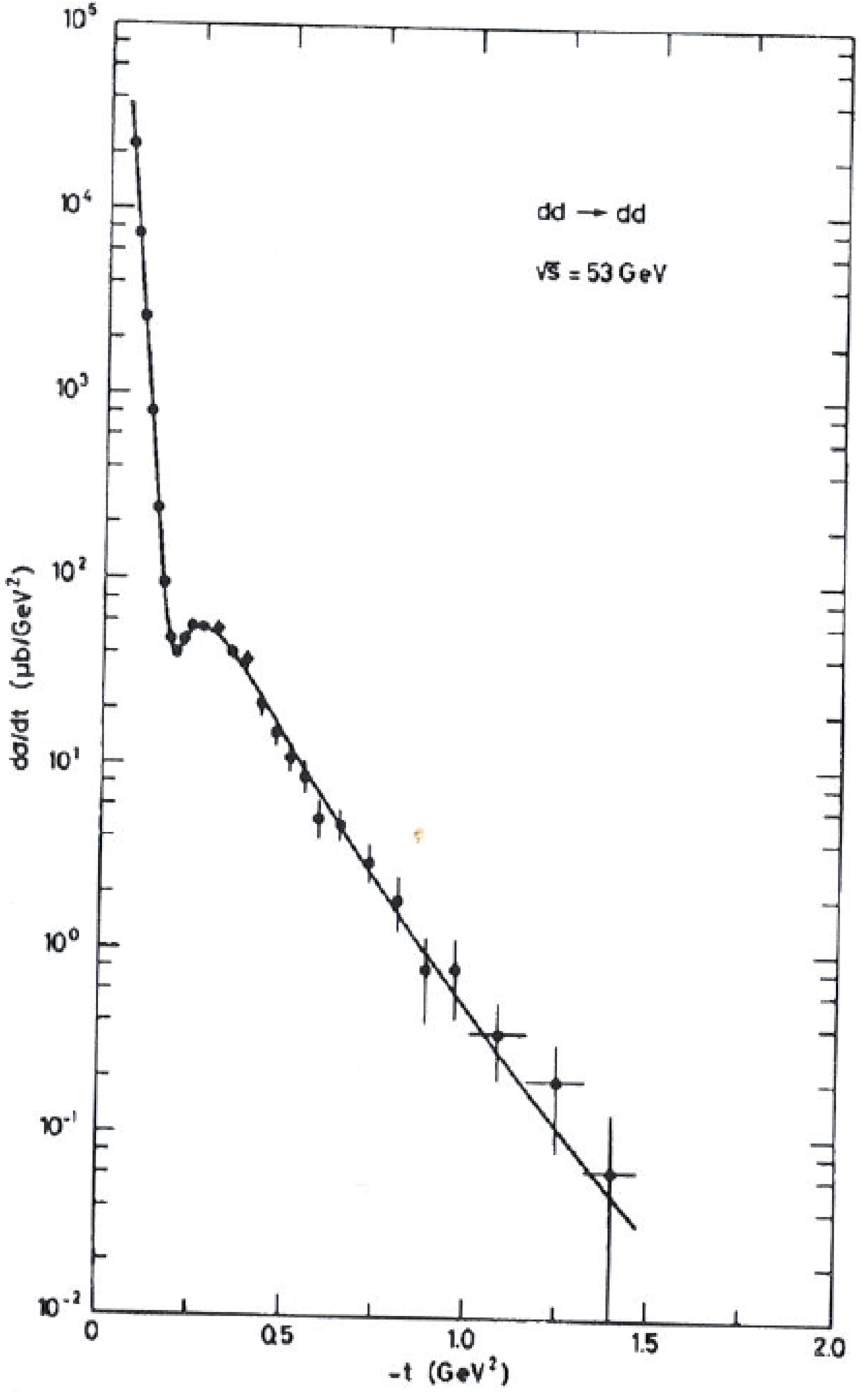


Plan for further calculations

G.Goggi et al. Nucl. Phys. B 149 (1979) 318

"Inelastic intermediate states in proton-deuteron and deuteron-deuteron elastic collisions at the ISR"

The solid curve is the absolute prediction of the full theory Glauber +IS



SEARCH for T-invariance VIOLATION IN DOUBLE POLARIZED PD -SCATTERING

Why search for Time-invariance Violating P-conserving Effects?

- The T- violating, P-violating (TVPV) effects arise in SM through CP violating phase of CKM matrix and the QCD $\theta-$ term.
  EDM.

- T-violating P-conserving (TVPC) (flavor-conserving) effects (first considered by L. Okun, Yad.Fiz. 1 (1965) 938)
  do not arise in SM as Fundamental interactions,

  although can be generated through weak corrections to TVPV interactions

  ⋆ Observed (in K^0, B^0, D^0) CP violation in SM leads to simultaneous violation of T- and P-invariance.
  Therefore, to produce T-odd P-even term one should have one additional P-odd term in the effective interaction: $\mathbf{g \sim M^4 G_F^2} \sin\delta \sim \mathbf{10^{-10}}$

  V.P. Gudkov, Phys. Rep. **212**(1992)77

  ⋆ …much larger g is not excluded by unknown interaction beyond the SM.

  ⋆ **Experimental limits on TVPC effects are much weaker than for EDM.**

Forward elastic pd scattering amplitude (P-even, T-even):

$$e'^{*}_{\beta}\hat{F}_{\alpha\beta}(0)e_{\alpha} = g_1[\mathbf{e}\,\mathbf{e}'^{*} - (\hat{\mathbf{k}}\mathbf{e})(\hat{\mathbf{k}}\mathbf{e}'^{*})] + g_2(\hat{\mathbf{k}}\mathbf{e})(\hat{\mathbf{k}}\mathbf{e}'^{*}) +$$

$$ig_3\{\boldsymbol{\sigma}[\mathbf{e}\times\mathbf{e}'^{*}] - (\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{k}}\cdot[\mathbf{e}\times\mathbf{e}'^{*}])\} + ig_4(\boldsymbol{\sigma}\hat{\mathbf{k}})(\hat{\mathbf{k}}\cdot[\mathbf{e}\times\mathbf{e}'^{*}])+$$

M.P. Rekalo et al., Few-Body Syst. 23, 187 (1998)

. . . and plus **T-odd P-even term**

$$\cdots + g_5\{(\boldsymbol{\sigma}\cdot[\hat{\mathbf{k}}\times\mathbf{e}])(\mathbf{k}\cdot\mathbf{e}'^{*}) + (\boldsymbol{\sigma}\cdot[\hat{\mathbf{k}}\times\mathbf{e}'^{*}])(\mathbf{k}\cdot\mathbf{e})\}$$

Generalized Optical theorem:

$$Im\frac{Tr(\hat{\rho}_i\hat{F}(0))}{Tr\hat{\rho}_i} = \frac{k}{4\pi}\sigma_i$$

T-even P-even

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

T-odd P-even

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

Null-test signal:

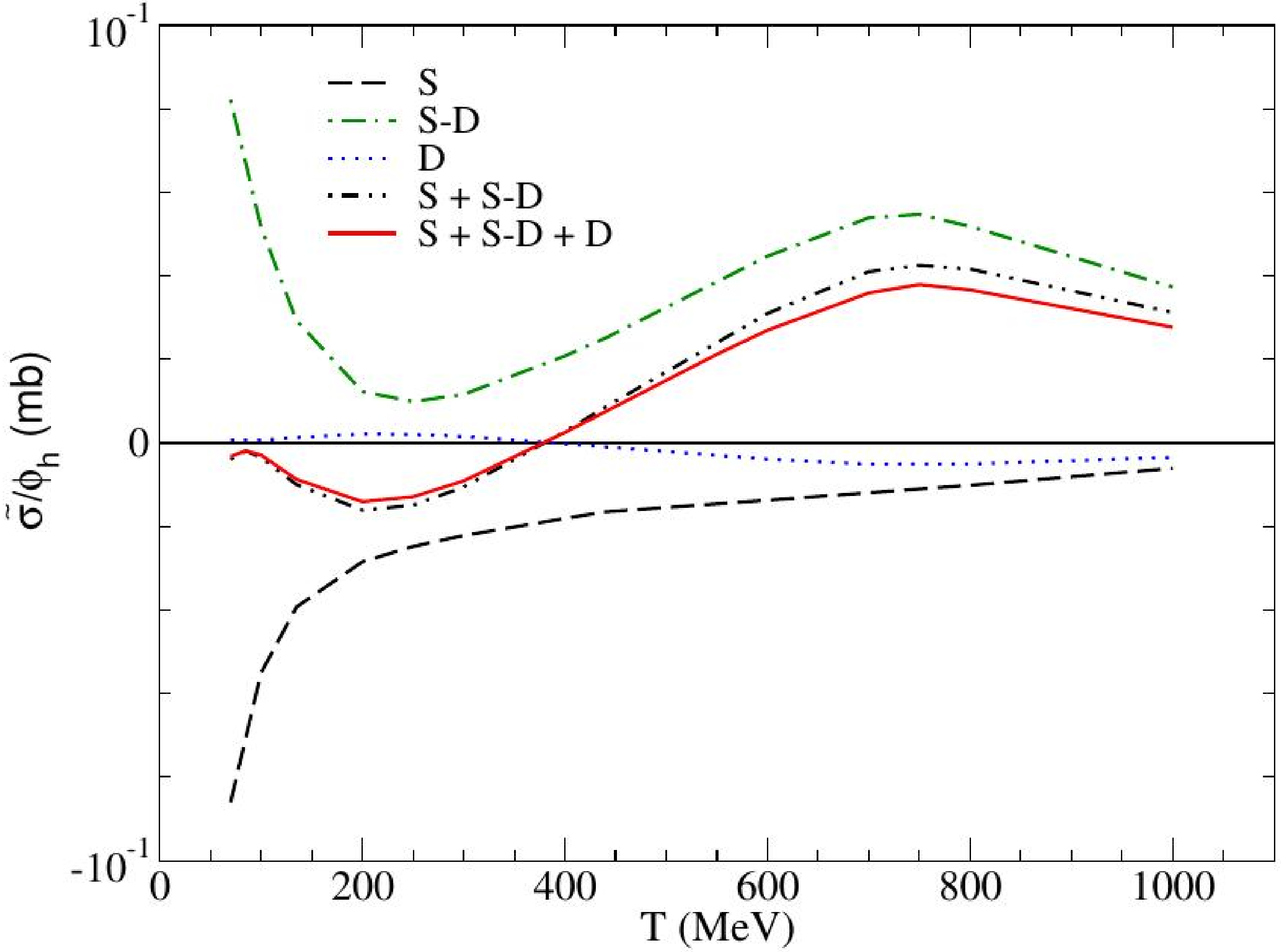
$$\widetilde{g} = \frac{i}{4\pi m_p}\int_0^\infty dq q^2\Big[S_0^{(0)}(q) - \sqrt{8}S_2^{(1)}(q) - 4S_0^{(2)}(q) + \sqrt{2}\frac{4}{3}S_2^{(2)}(q) + 9S_1^{(2)}(q)\Big][-C'_n(q)\,h_p + C'_p(q)(g_n - h_n)]$$

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

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

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

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



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

Conclusion and outlook

- Measurement of spin observables ($d\sigma/dt$, $A_y^p, A_y^d, A_{yy}, A_{xx}, C_{i,j}$) of pd- elastic, $pd \to n\{pp\}_s$, $dd \to dd$, $dd \to \{pp\}_s + \{nn\}_s$ at SPD NICA is important. Available Regge parameterizations for pp amplitudes at $P_L = 3 - 50$ GeV/c (A. Sibirtsev et al. 2010; Van Orden; others) can be used for calculation of these observables within the Glauber theory. Comparison between data and theory **will provide a clean test for the pp- and pn- elastic amplitudes**.

- The ratio $R = A_y^d/A_y^p$ at small q being measured with a high accuracy ($\sim 1\%$) gives an information about **spin-spin transversal NN amplitudes**.

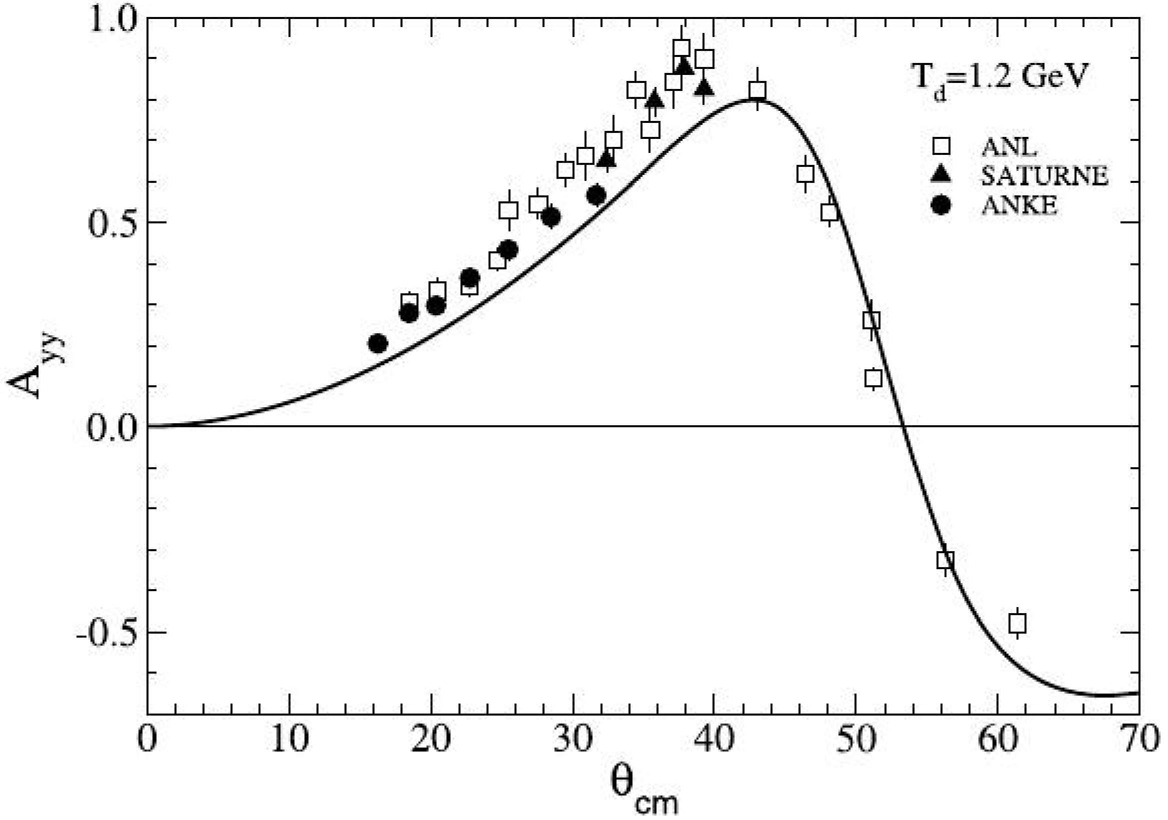
- The Regge pp-formalism provides an **access to $\bar{p}N$ elastic**, but actually was not tested in double spin onservables. The necessary data A_{NN} can be obtained at SPD NICA $\Longrightarrow$ to test the pp-amplitudes, to study **"oscillation effects"** and to test the **dispersion relations** for pN-data.

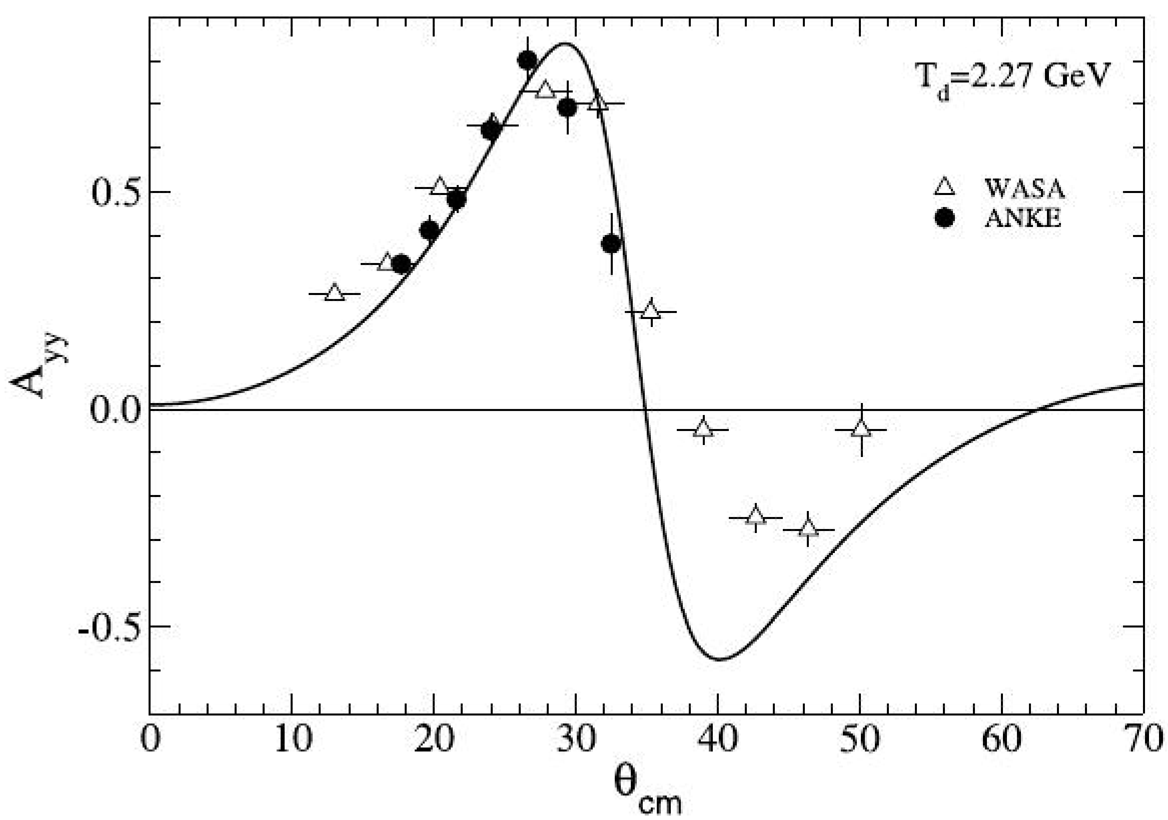
- **Search of T-invariance violation** in double polarized pd and dd scattering at energies corresponding to **the early Universe seems to be very important**. The elastic (T-even) pN- amplitudes at SPD NICA energies are necessary to analyse data of the dedicated experiment.

NN-forces are fundamental to nuclear physics on the whole. It is important to study a full set of their components, including such small components as spin-spin forces both at low and high energies… **via the NN elastic scattering amplitudes**

Thank you for attention!

D. Mchedlishvili et al. Nucl.Phys. A 977 (2018) 14 , pd-elastic





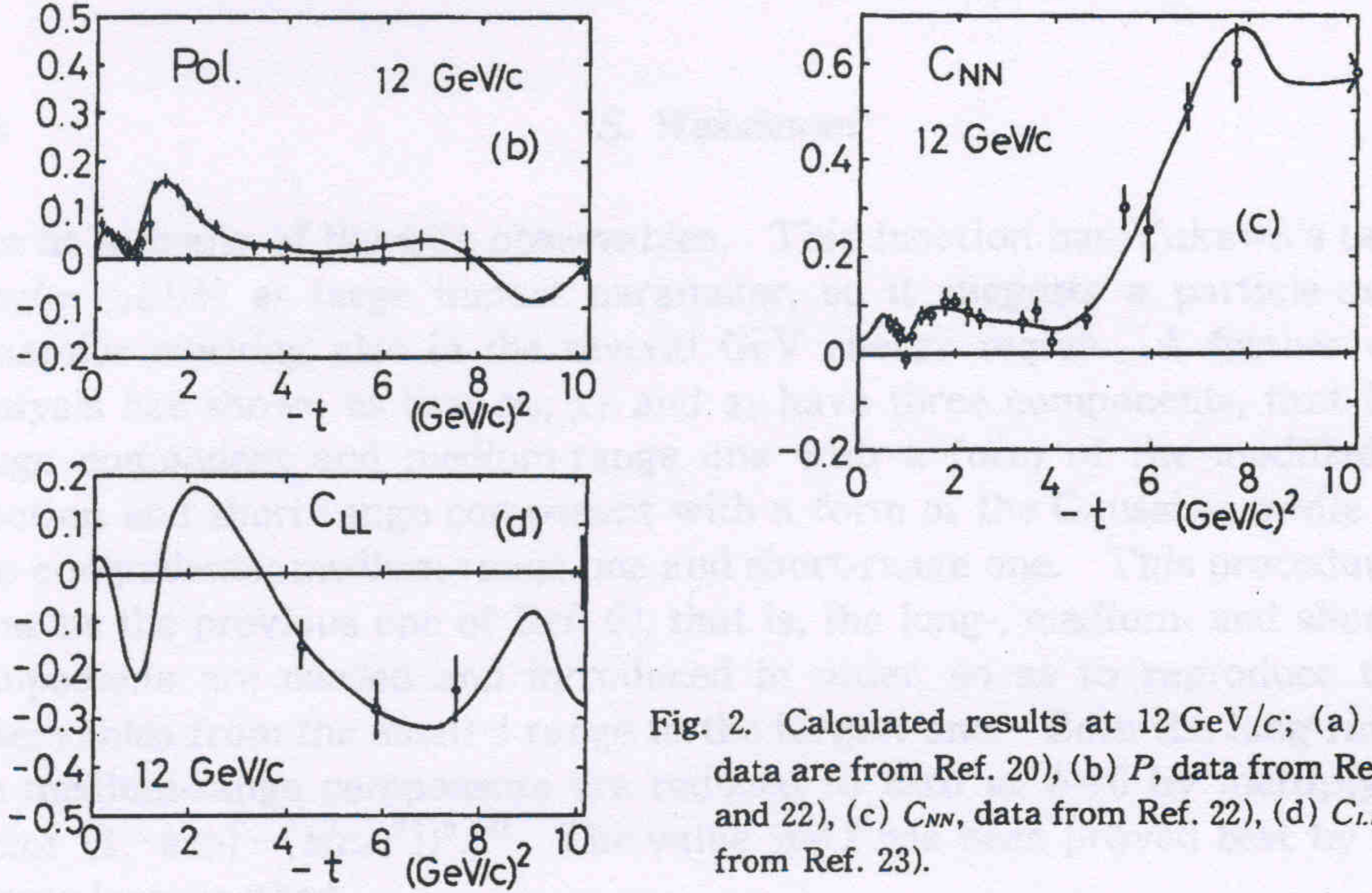


Fig. 2. Calculated results at 12 GeV/c; (a) $d\sigma/dt$, data are from Ref. 20), (b) P, data from Refs. 21) and 22), (c) C_{NN}, data from Ref. 22), (d) C_{LL}, data from Ref. 23).

– *Planned experiments to search for CP violation beyond the SM*

• Detecting a non-zero **EDM** of elementary fermion (neutron, atoms, charged particles). The current experimental limit

$$|d_n| \leq 2.9 \times 10^{-26} e\, cm$$

is much less as compared the SM estimation (B.H.J. McKellar et al. PLB 197 (1987)
$1.4 \times 10^{-33} e\, cm \leq |d_n| \leq 1.6 \times 10^{-31} e\, cm$

• Search for CP violation in the **neutrino sector** ($\theta_{13} \neq 0$, then generation of lepton asymmetry and via $B - L$ conservation to get the BAU).

Thouse are T-violating and Parity violating (TVPV) effects.

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

Search for T-violation in other processes

- Search for T-violation in decays

A.G. Beda, V.P. Skoy, Elem.Chat. At. Yadr. **37** (2007) 1477

$\vec{n} \to p\, e\tilde{\nu}$ or triple nuclear fussion

$$W_{if} \sim X\mathbf{s_n}[\mathbf{k}_n \times \mathbf{k}_\nu] + R\mathbf{s}_n[\mathbf{k}_n \times \mathbf{s}_e]$$

i) FSI with Coulomb

ii) Not all T-odd correlations are related to the true T-invariance violation

- Total cross section of the nA interaction from forward nA scattering amplitude

$$f = \underbrace{A + p_n p_T B(\mathbf{s}\cdot\mathbf{I})}_{strong} + \underbrace{p_n C(\mathbf{s}\cdot\mathbf{k})}_{PV} + \underbrace{p_n p_T D(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])}_{TVPV} + \underbrace{p_T E(\mathbf{k}\cdot\mathbf{I})}_{PV} + \underbrace{p_n p_T F(\mathbf{k}\cdot\mathbf{I})(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])}_{TVPC}$$

T-odd correlations in forward elastic scattering (=in total cross section):

Three-fold $(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])$ – TVPV
five-fold $(\mathbf{k}\cdot\mathbf{I})(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])$ – TVPC

TRANSMISSION experiment!

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 $B_- \to \bar{B}^0$

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.

This process is described by the transmission factor T(n):

$$T(n) = I(n) / I(0) = \exp(-(\sigma_T \rho d\, n)) \qquad (5)$$

with: $I(0)$ - Intensity of the primary beam

$I(n)$ - Intensity of the beam having passed n times the internal target with density ρ and thickness d

σ_T - Total cross-section

ρd - The areal target density

For the case of polarized particles σ_T has to be replaced by:

$$\sigma_T = \sigma_{y,xz} + \sigma_{Loss} = \sigma_o (1 + P_y P_{xz} A_{y,xz}) + \sigma_{Loss} \qquad (6)$$

with: σ_o - Unpolarized total cross-section

σ_{Loss} - Loss cross-section, taking account of beam losses outside of the target

$$\Delta T_{y,xz} = \frac{T^+ - T^-}{T^+ + T^-} = \frac{\exp-(\chi^+) - \exp-(\chi^-)}{\exp-(\chi^+) + \exp-(\chi^-)} \quad (7)$$

with: T^+ -Transmission factor for the proton-deuteron spin-configuration with $P_y \cdot P_{xz} > 0$

T^- -Transmission factor for the time reversed situation, i.e. $P_y \cdot P_{xz} < 0$

$\chi^{+/-}$ -Is the product of the factors $(\sigma T \cdot \rho d \cdot n)$ with respect to the proton-deuteron spin-alignment

this gives:

$$\Delta T_{y,xz} = -\tanh(\sigma_o \Delta d\, n\, P_y\, P_{xz}\, A_{y,xz}) \quad (8)$$

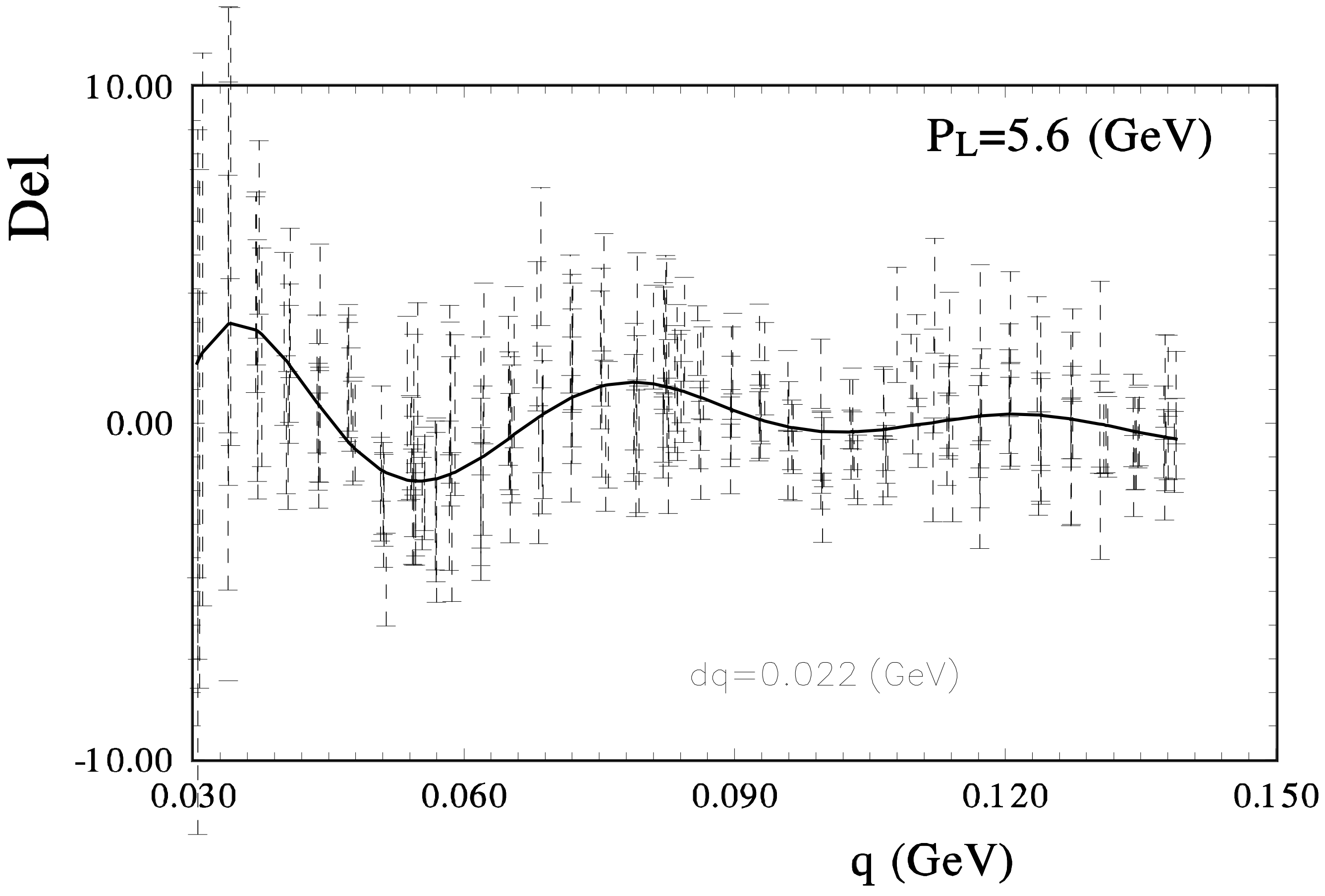
Is the argument of the tanh in equation (8) small, then:

$$\Delta T_{y,xz} = -\sigma_o \rho d\, n\, P_y\, P_{xz}\, A_{y,xz} =: -S\, A_{y,xz} \quad (9)$$

mbox

$$Del = \frac{d\sigma/dt_{data.} - d\sigma/dt_{theor-\exp.}}{d\sigma/dt_{theor-\exp.}}$$

P. Gauron, B. Nicolescu, O.V. Selyugin,PLB 397 (1997)



To further development of the HEGS model

$$\hat{s} = s / s_0 \, e^{i\pi/2};$$

$$s_0 = 4m_p^2.$$

$$9 \leq \sqrt{s} \leq 8000 \, GeV;$$

$$n = 980 \to 3416; \qquad 0.00037 < |t| < 15 \; GeV^2;$$

$$F_1^B(s,t) = h_2 G_{em}(t) \; (\hat{s})^{\Delta_1} e^{\alpha' t \ln(\hat{s})}; \quad F_3^B(s,t) = h_3 G_A(t)^2 \; (\hat{s})^{\Delta_1} e^{\alpha'/4 t \ln(\hat{s})};$$

$$F^B(\hat{s},t) = F_2^B(\hat{s},t)(1 + R_1 / \sqrt{\hat{s}} \;)] \; + F_3^B(\hat{s},t)(1 + R_2 / \sqrt{\hat{s}} \;)]$$

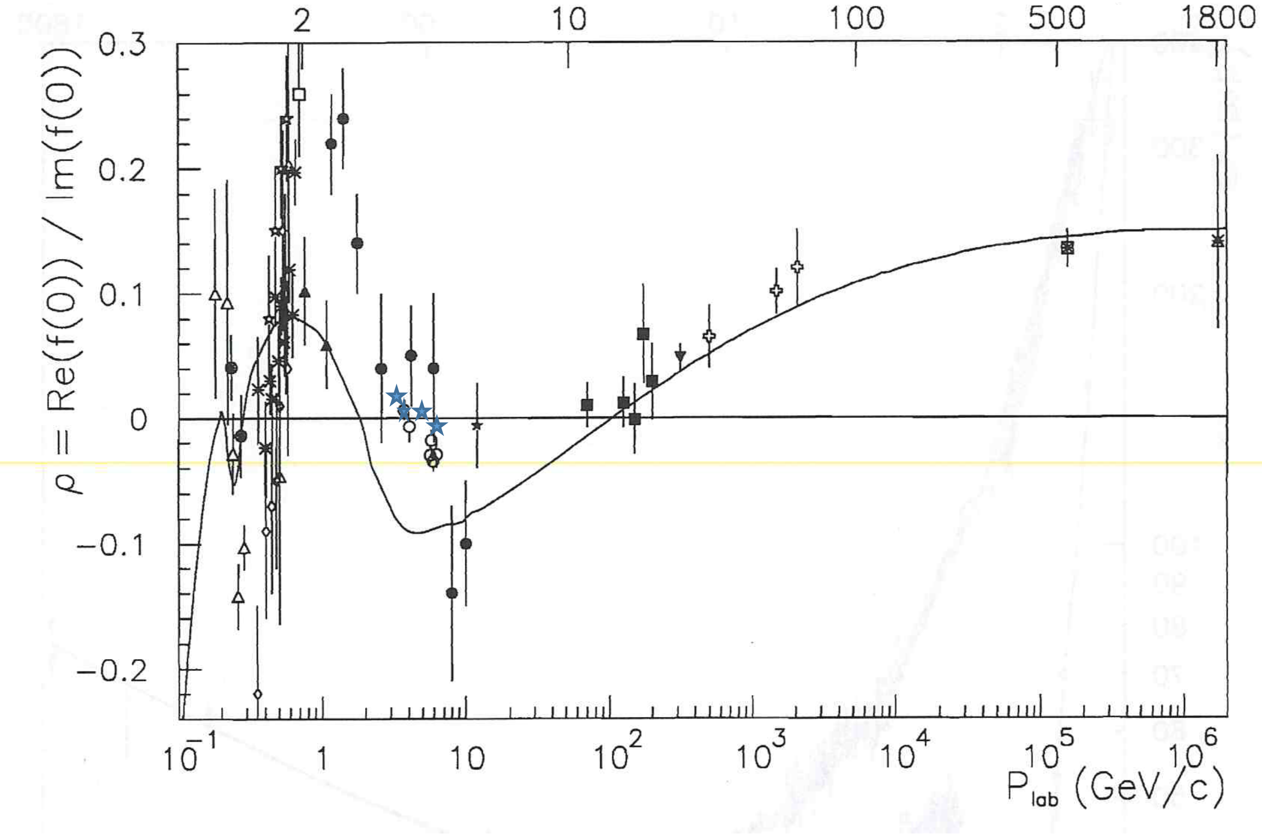
$$+ \; F_{odd}^B(s,t); \qquad \alpha'(t) = (\alpha_1 + k_0 \, q \, e^{k_0 \, t \ln \hat{s}} \;) \ln \hat{s}.$$

$$F_{Odd}^B(s,t) = h_{Odd} \;\; G_A(t)^2 \;\; (\hat{s})^{\Delta_1} \;\; \frac{t}{1 - r_o^2 t} e^{\alpha'/4 t \ln(\hat{s})};$$

$$F^{+-}(s,t) = h_{sf} \; q^3 \;\; G_{em}(t)^2 \; e^{\mu t};$$

M.Galynskii, E.Kuraev, JETP Letters (2012)

O.V. Selyugin, Mod. Phys. Lett. A 27 (2012) 1250113
A problem with dispersion relations at 5-8 GeV/c .
anti p -p



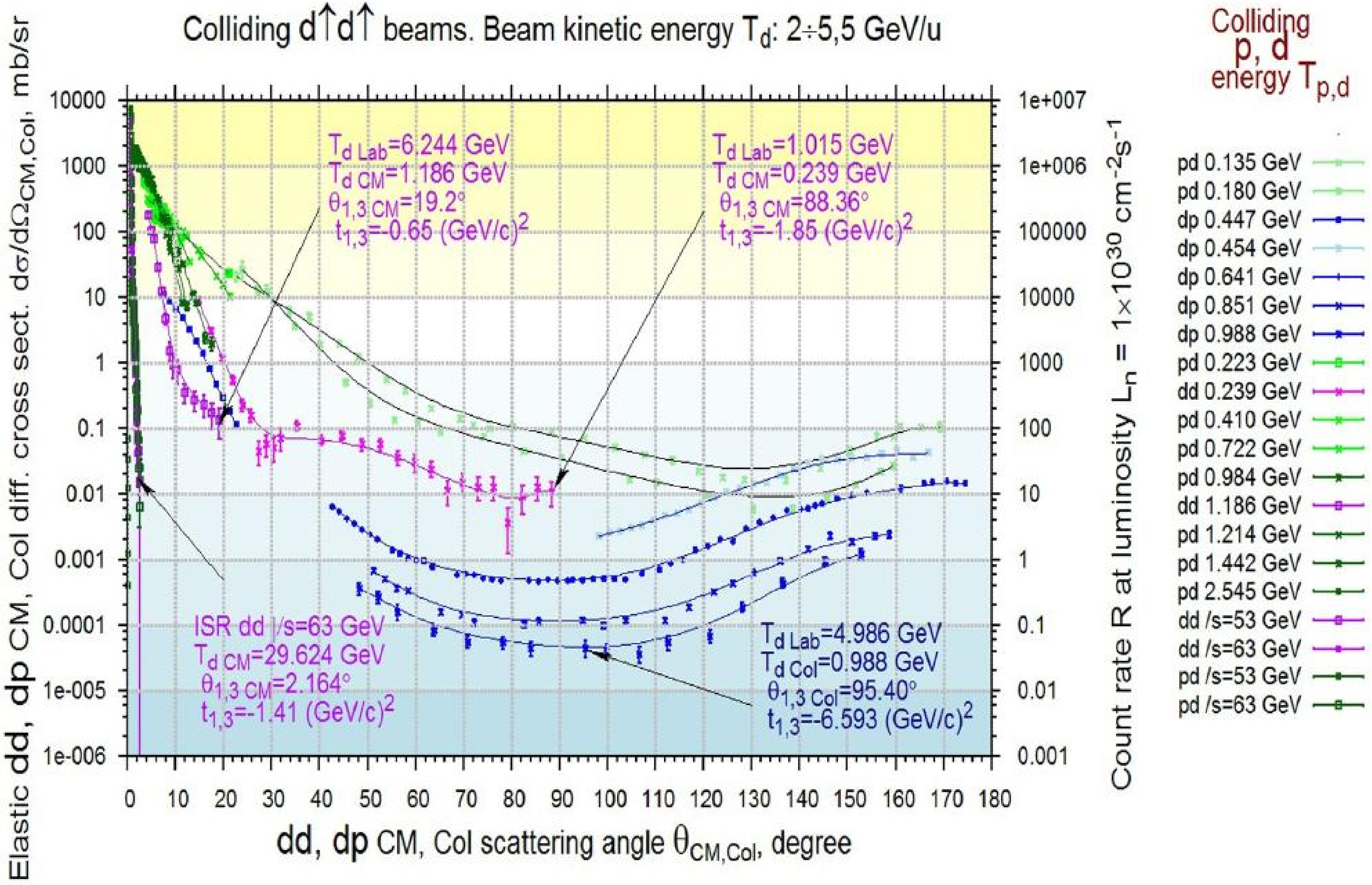
$$M = \tfrac{1}{2}\{(a+b) + (a-b)\,\sigma_{1n}\,\sigma_{2n} + (c+d)\,\sigma_{1m}\,\sigma_{2m} + (c-d)\,\sigma_{1l}\,\sigma_{2l} + e(\sigma_{1n} + \sigma_{2n}) + f(\sigma_{1n} - \sigma_{2n}) + \\ + g(\sigma_{1l}\,\sigma_{2m} + \sigma_{1m}\,\sigma_{2l}) + h(\sigma_{1l}\,\sigma_{2m} - \sigma_{1m}\,\sigma_{2l})\}, \qquad (2.1)$$

where

$$\mathbf{l} = \frac{\mathbf{k}_f + \mathbf{k}_i}{|\mathbf{k}_f + \mathbf{k}_i|}, \qquad \mathbf{m} = \frac{\mathbf{k}_f - \mathbf{k}_i}{|\mathbf{k}_f - \mathbf{k}_i|}, \qquad \mathbf{n} = \frac{\mathbf{k}_i \times \mathbf{k}_f}{|\mathbf{k}_i \times \mathbf{k}_f|} \qquad (2.2)$$

$$f = h = 0\,.$$

Available experimental data set on the differential cross sections for the elastic dp, dd and pd collisions in CM and Collider systems.



What can be done at SPD NICA?

• Measurement of spin observables ($d\sigma/dt$, $A_y^p, A_y^d, A_{yy}, A_{xx}, C_{i,j}$) of pd- elastic, $pd \to n\{pp\}_s$, $dd \to dd$, $dd \to \{pp\}_s + \{nn\}_s$.
Available Regge formalism for pp amplitudes at $P_L = 3 - 50$ GeV/c (A. Sibirtsev et al. 2010; W.Ford, J.W. Van orden, 2013) can be used for calculation of these observables within the Glauber theory. Comparison between data and theory **will be a clean test for the pp- and pn- elastic amplitudes**.

• This Regge pp-formalism provides an **access to $\bar{p}N$ elastic**, but actually was not tested in double spin onservables at i) >4 GeV/c at ii) forward pp-scattering angles. The necessary data on $A_{NN}, A_{LL}, ...$ can be obtained at SPD NICA $\Longrightarrow$ test of the pp-amplitudes, **dispersion relations** for pN, $\bar{p}N$-data, study of **"oscillation effects"**.

• **New theoretical model** for pN-elastic scattering amplitudes at NICA energies with minimum free parameters will be developed (O.V. Selyugin) interpolating between 3 GeV and 10 TeV.

• **Search of T-invariance violation** in double polarized pd-, and dA- scattering at energies corresponding to **the early Universe was not yet performed**. The elastic (T-even) pN- amplitudes at SPD NICA energies are necessary to analyse data of the dedicated experiment.

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

whith

$$\sigma_0 = \frac{4\pi}{k} Im \frac{2g_1 + g_2}{3}, \sigma_1 = -\frac{4\pi}{k} Im g_3,$$
$$\sigma_2 = -\frac{4\pi}{k} Im(g_4 - g_3), \sigma_3 = \frac{4\pi}{k} Im \frac{g_1 - g_2}{6}.$$

/Yu.N. Uzikov, J. Haidenbauer, PRC ***79*** *(2009) 024617; PRC* ***87*** *(2013) 054003/*

$$\widetilde{\sigma}_{tvpc} = -\frac{4\pi}{k} c\, Im g_5$$

$$\frac{1}{2} + 1 \to \frac{1}{2} + 1$$

$(2+1)^2(2\frac{1}{2}+1)^2 = 36$ transition amplitudes

P-parity $\Longrightarrow$ 18 independent amplitudes

T-invariance for $pd \to pd$ $\Longrightarrow$ 12 independent amplitudes

Transition matrix element

$$M_{fi} =< \mu'\lambda'|M|\mu\lambda >$$