

SPIN EFFECTS IN NN -, PD - AND DD - SCATTERING AT SPD NICA

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

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

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

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

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

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

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

T-reversal non-invariance provides two additional amplitudes.

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

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

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

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

...

Number of linearly independent non-zero spin observables:

single-spin (asymmetries A_i , polarizations P_i) – 2

double-spin (A_{ii}, \dots) – 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. Strakovský, 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 poor 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

Helicity amplitudes in Regge formalism

A systematic analysis of pp elastic scattering from COSY-EDDA, SATURNE, GZS ANL

A. Sibirtsev, J. Haidenbauer, H.-W. Hammer et al. EPJA 45 (2010) 357

ω, ρ, f_2, a_2 Regge exchanges and the Pomeron for P_L from 3 GeV/c up to 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):

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

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

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

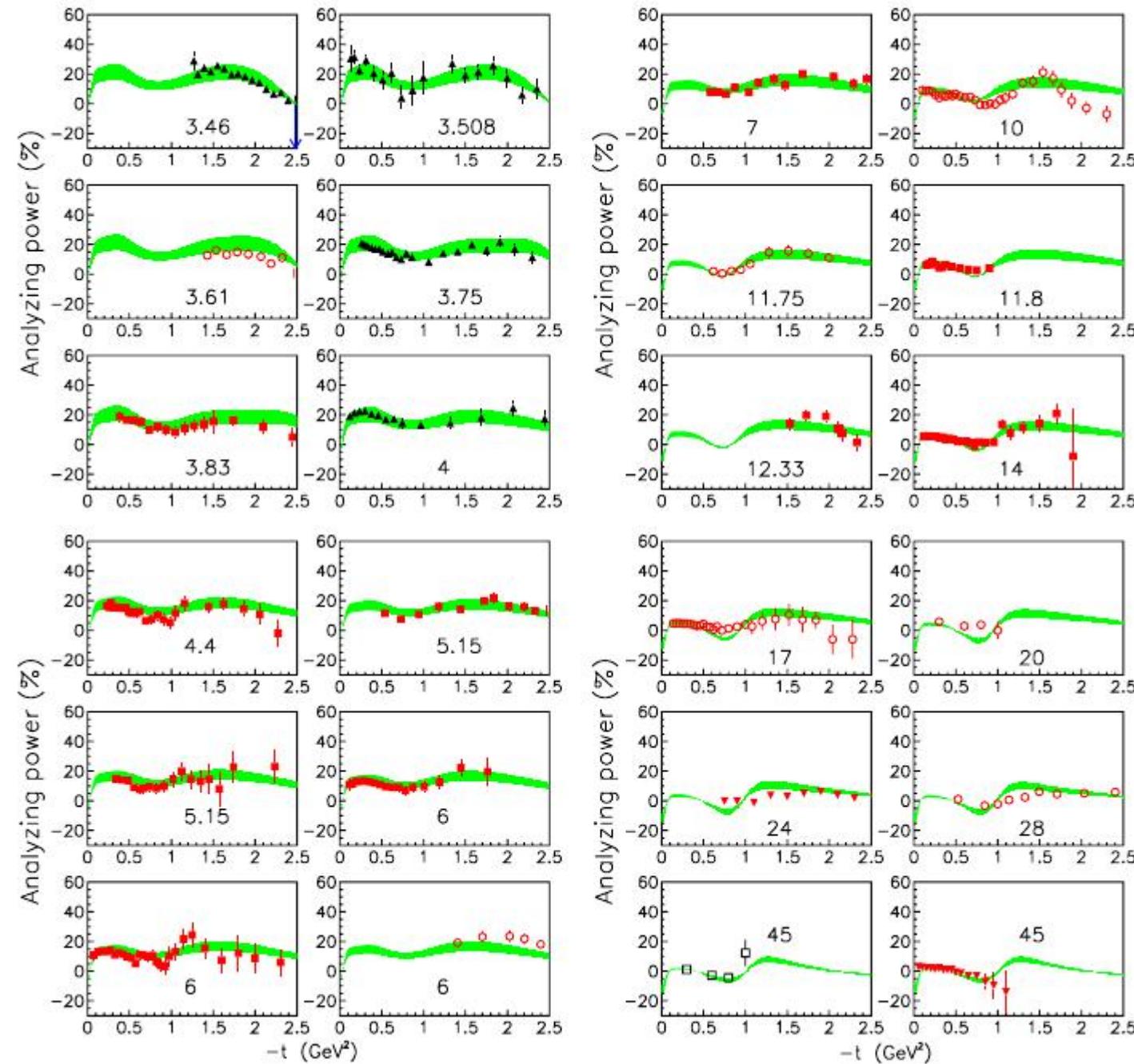
$$\phi(\bar{p}n) = \phi_\omega - \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P$$

However, not all available data

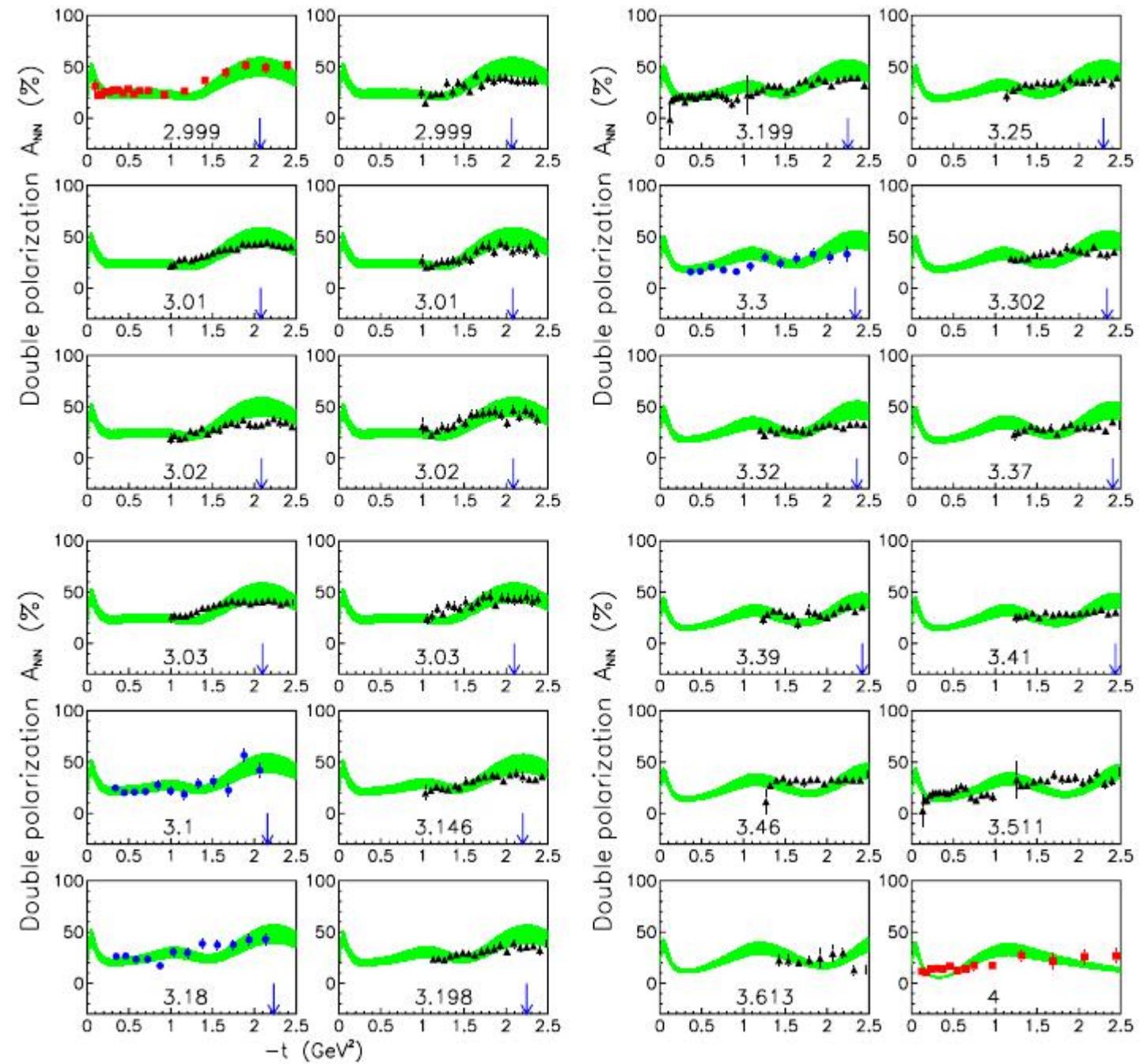
($C_{NN}, C_{LL}, C_{SS}, C_{LS}, D_{NN}, D_{SS}, D_{LS}, K_{NN}, \Delta\sigma_T, H_{SNS}$... measured by ANL at 6 GeV/c, and some at 12 GeV/c) were included into the fit.

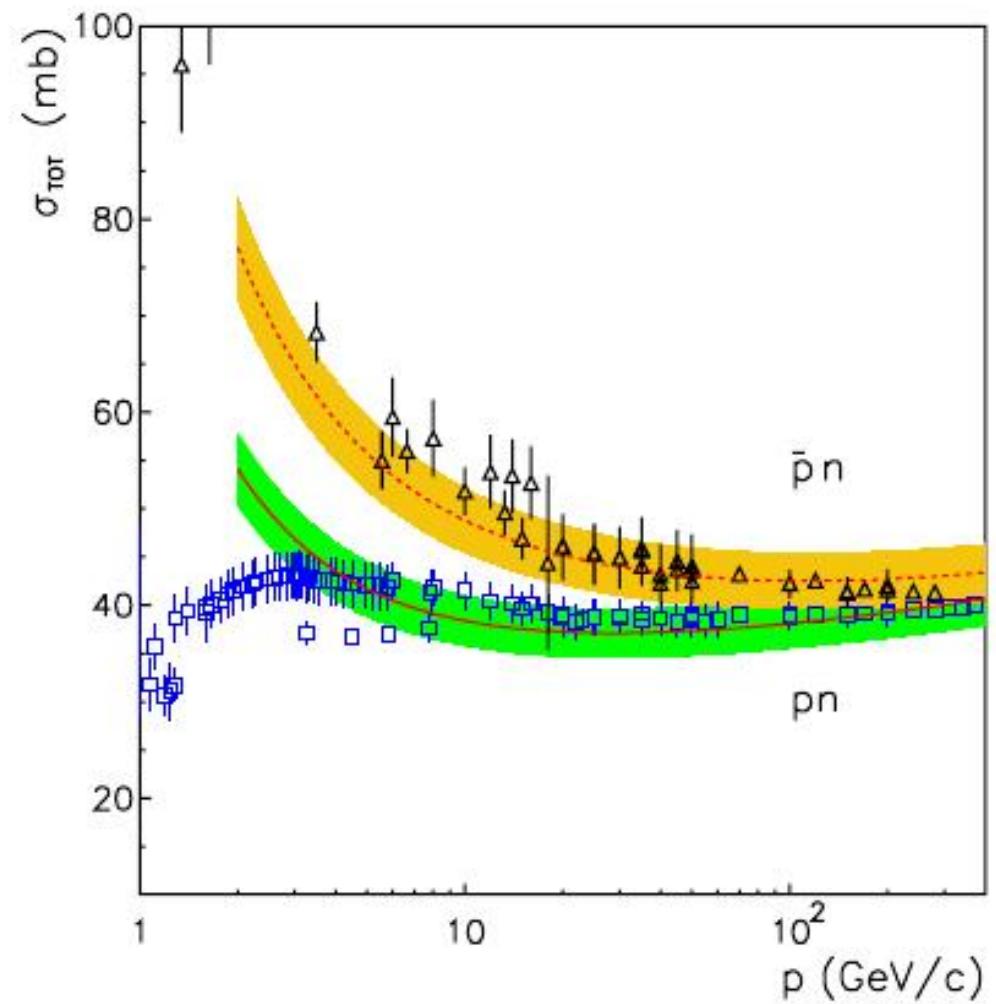
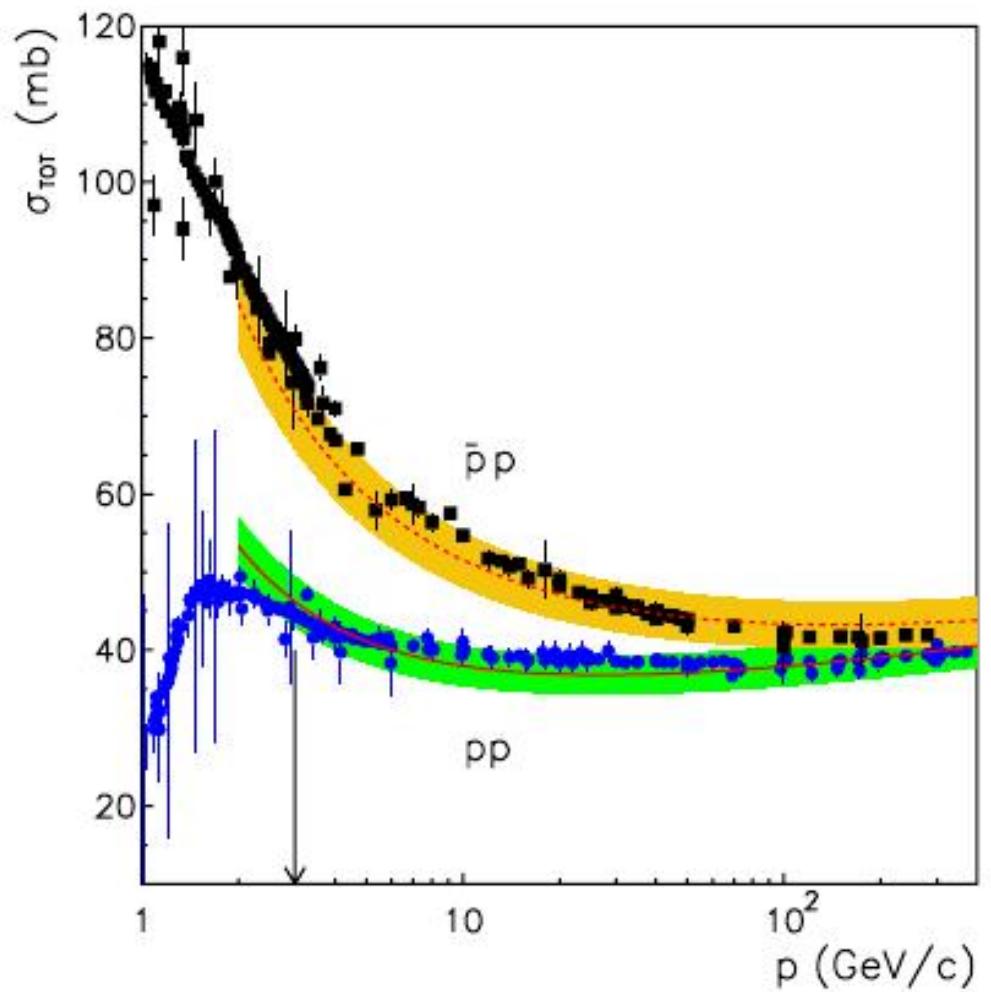
PP elastic scattering

A. Sibirtsev et al, EPJA (2010)



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





R- real-to-imaginary part ratio. A problem with antip-p theory: no zero

A. Sibirtsev et al, EPJA (2010)

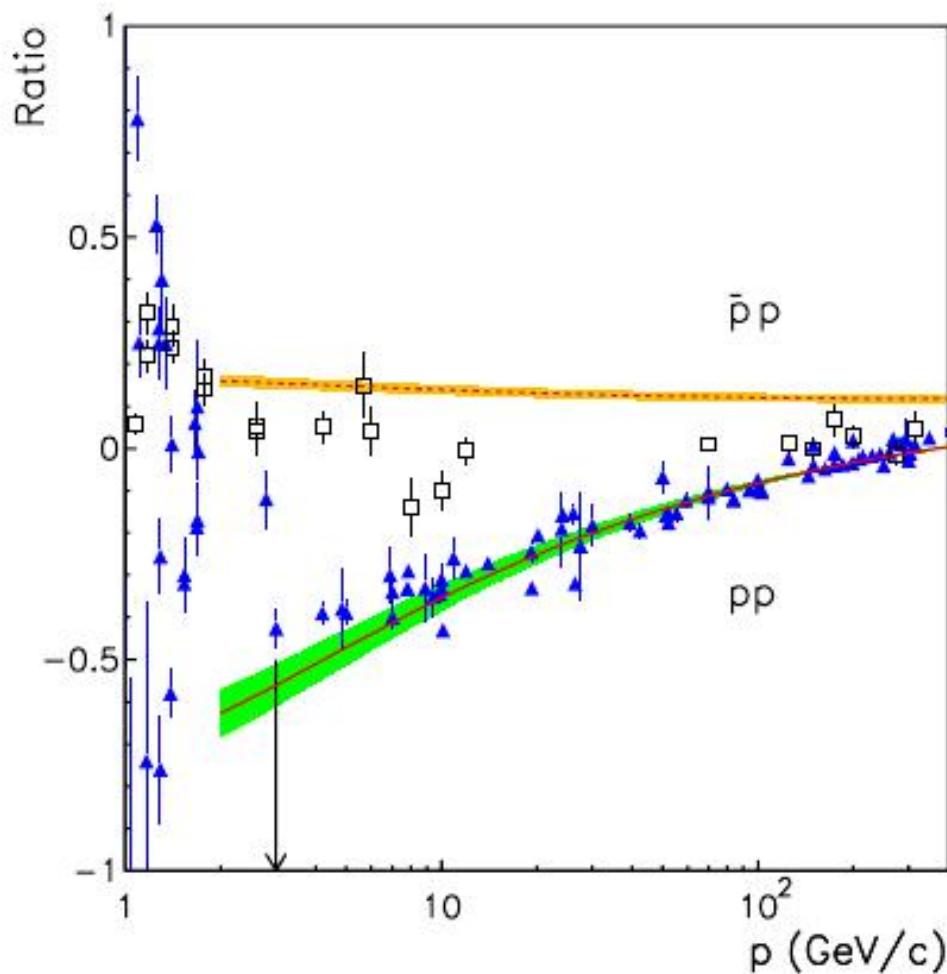
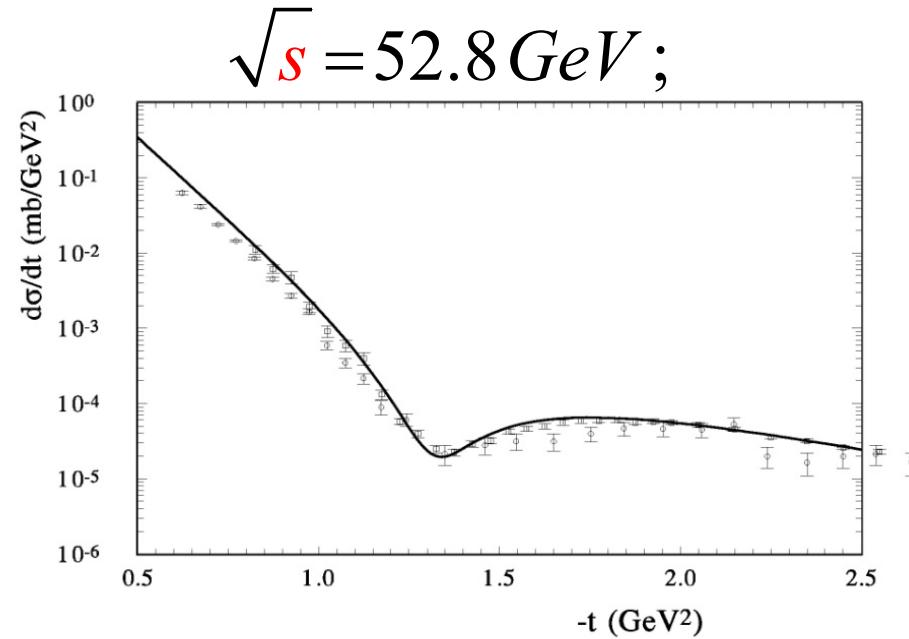
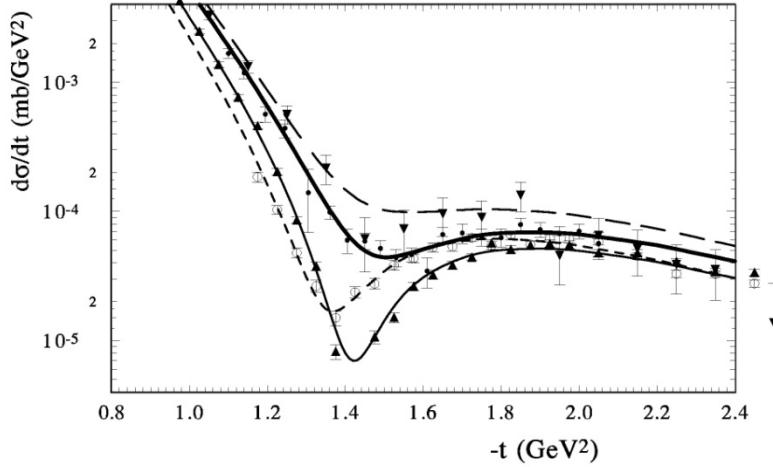
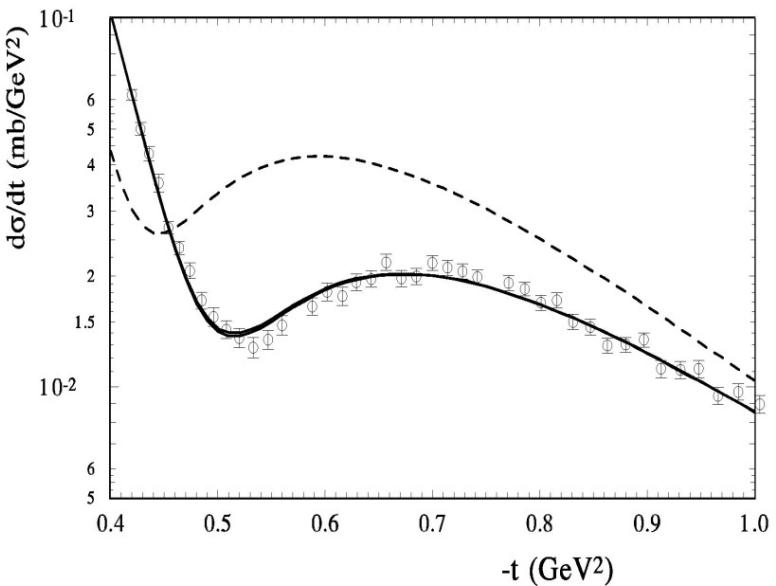


Fig. 16. Ratio of the real-to-imaginary parts of the forward amplitudes for pp (triangles, solid line) and $\bar{p}p$ (squares, dashed line), respectively. The data are taken from the PDG [32].

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



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



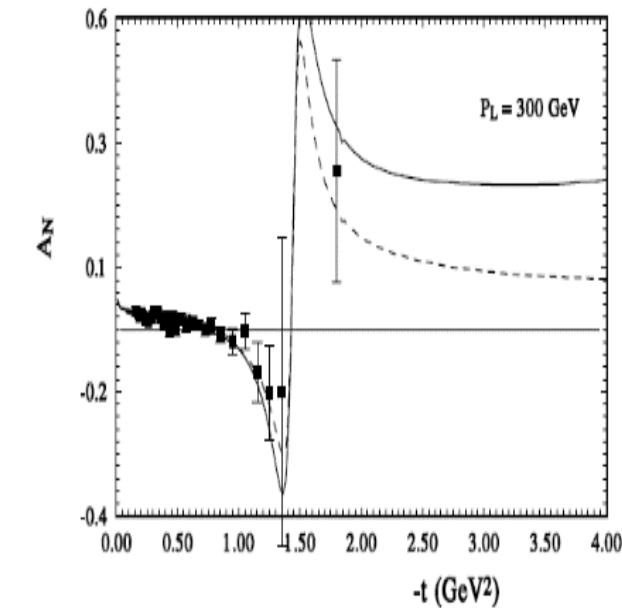
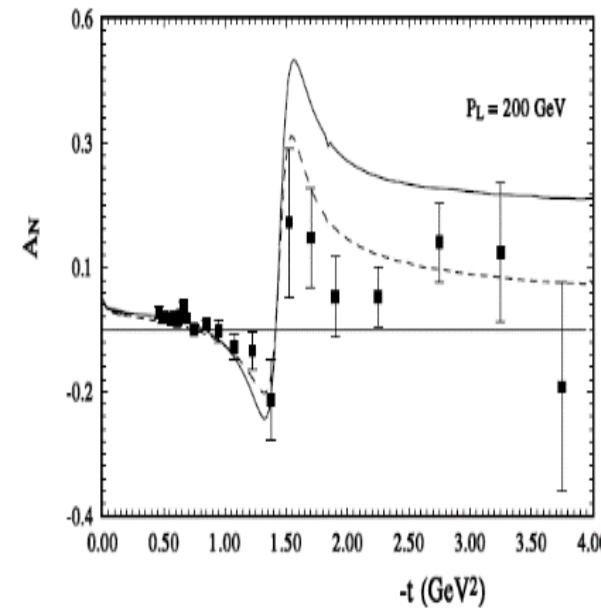
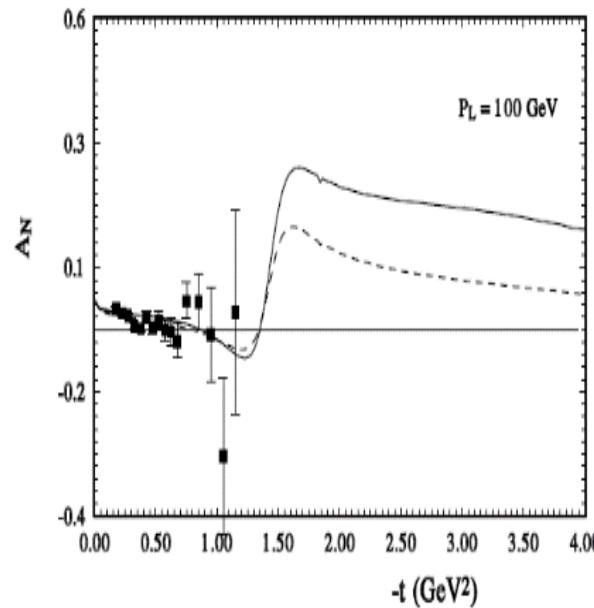
$$\sqrt{s} = 7 \text{ TeV};$$

$$F_h^{sf}(t) \sim \sqrt{-t}/(\frac{4}{9}m_p^2) \sqrt{-t}/(\frac{4}{9}m_p^2) \sqrt{-t}/(\frac{4}{9}m_p^2).$$

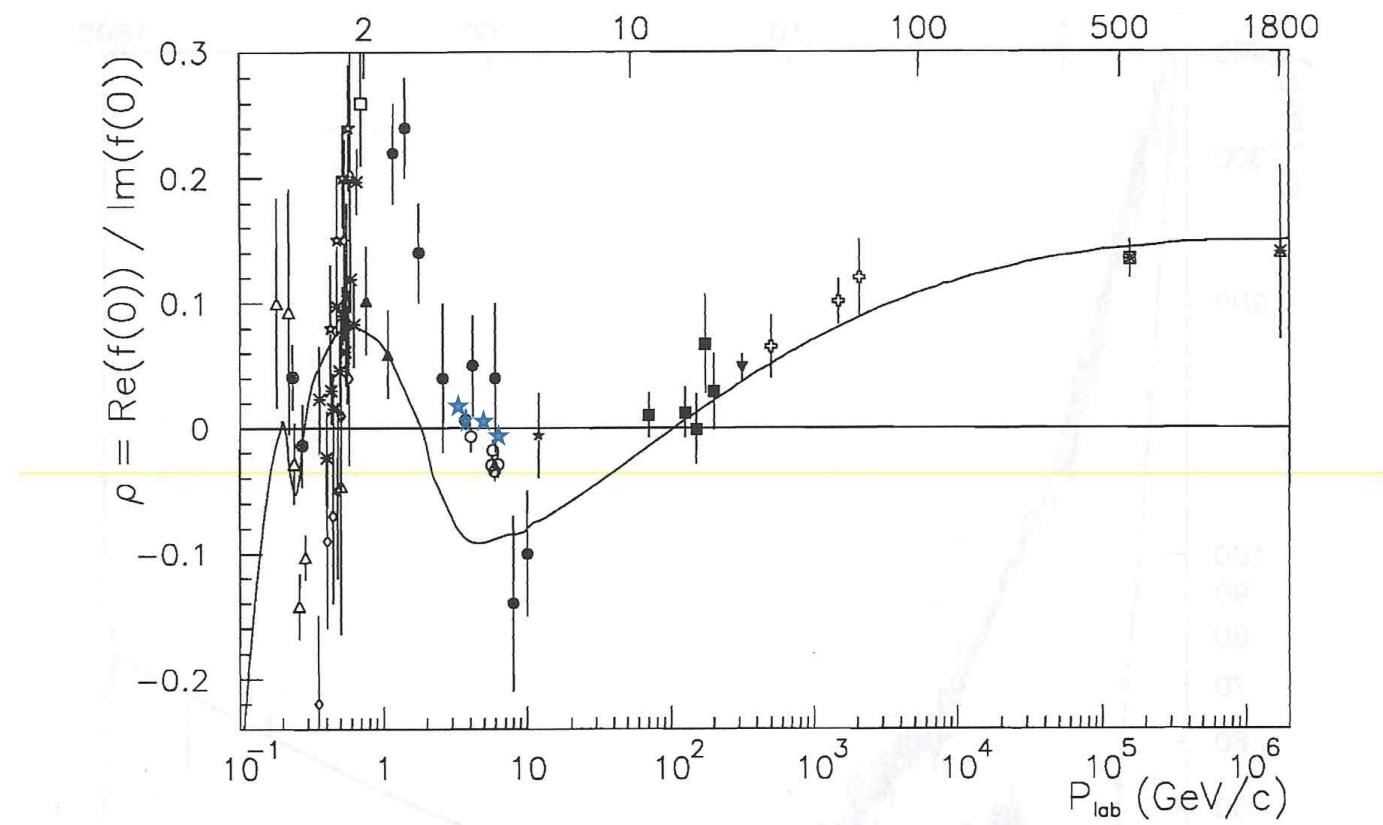
$$F_{sf}(s, t) = h_{sf} q^3 F_1^2(t) e^{-B_{sf} q^2}$$

$$F_{sf}(s, t) = h_{sf} q F_1^2(t) e^{-(r-q)^2}.$$

$$F_{sf}(b, t) = \int_0^\infty q dq J_1(q, b) F_{sf}(s, q).$$

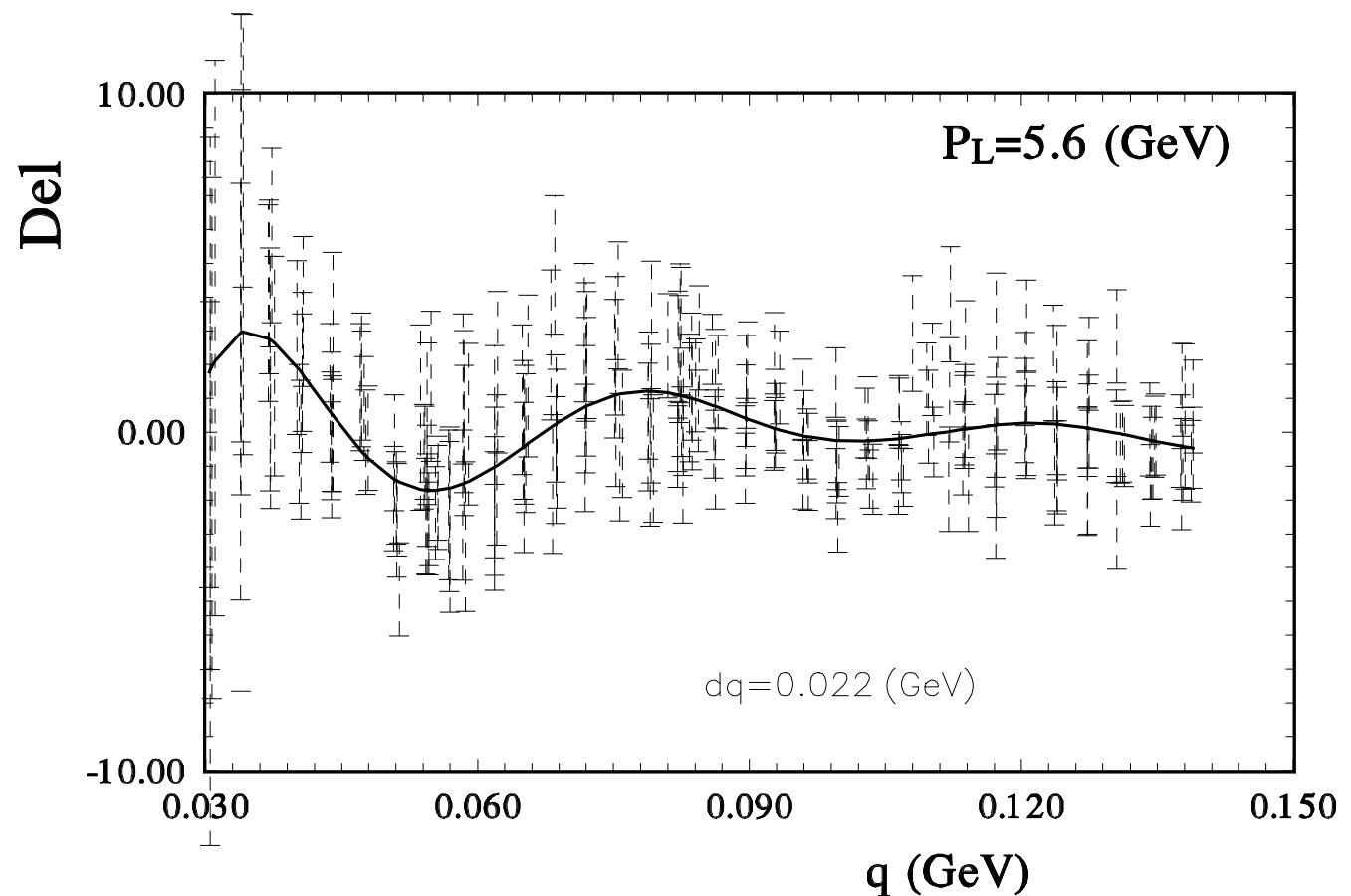


O.V. Selyugin, Mod. Phys. Lett. A 27 (2012) 1250113
A problem with dispersion relations at 5-8 GeV/c .
anti p -p



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

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



To further development of the HEGS model

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

$$9 \leq \sqrt{s} \leq 8000 \text{ GeV}; \quad s_0 = 4m_p^2.$$

$$n=980 \rightarrow 3416; \quad 0.00037 < |t| < 15 \text{ GeV}^2;$$

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

$$\begin{aligned} F^B(\hat{s},t) = & F_2^B(\hat{s},t)(1 + R_1 / \sqrt{\hat{s}})] + F_3^B(\hat{s},t)(1 + R_2 / \sqrt{\hat{s}})] \\ & + F_{odd}^B(s,t); \quad \alpha'(t) = (\alpha_1 + k_0 q e^{k_0 t \ln \hat{s}}) \ln \hat{s}. \end{aligned}$$

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

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

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

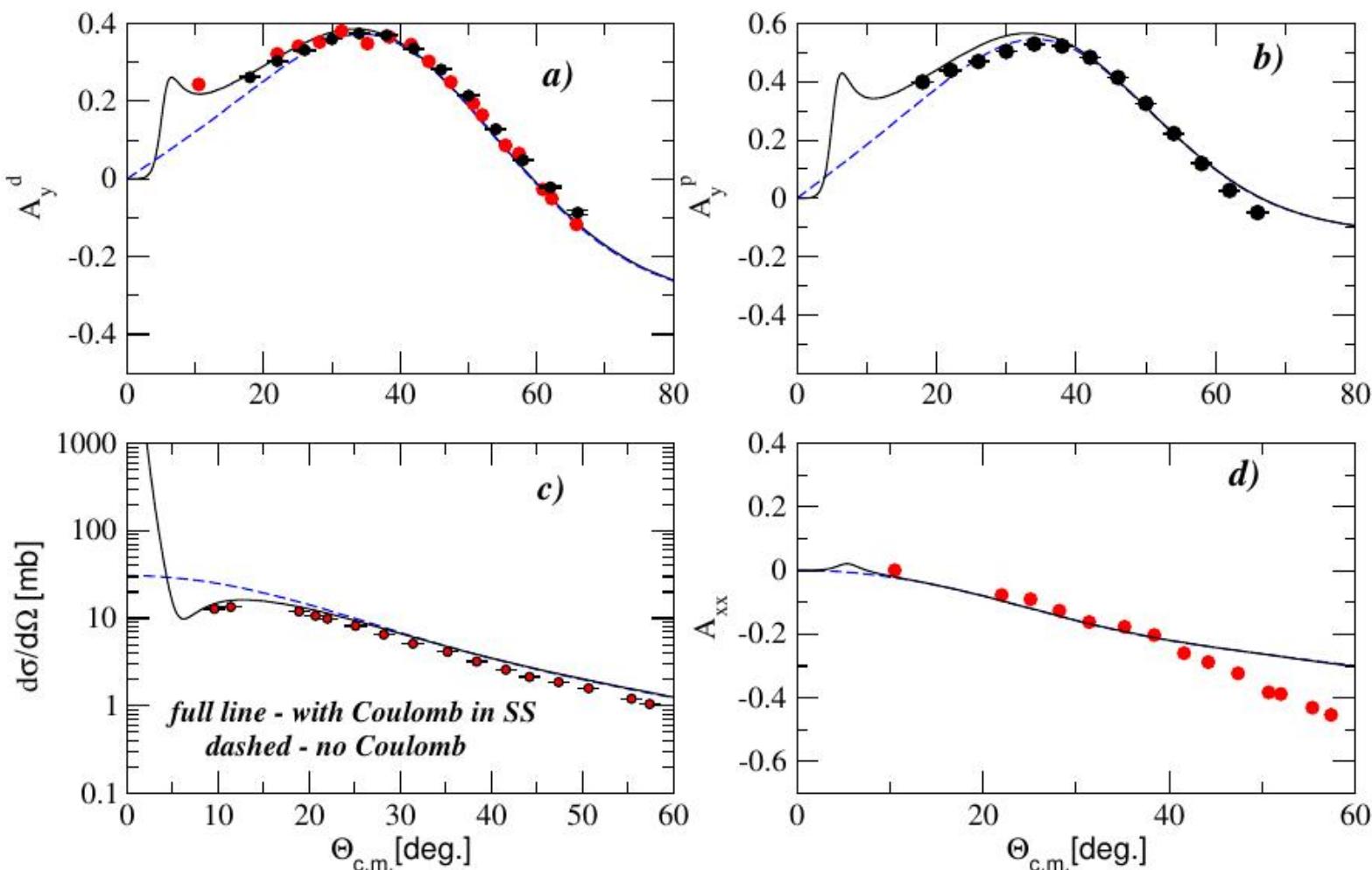
ELASTIC pd and QUASI-ELASTIC $pd \rightarrow (pp)_s n$ SCATTERING

Elastic $pd \rightarrow pd$ transitions

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

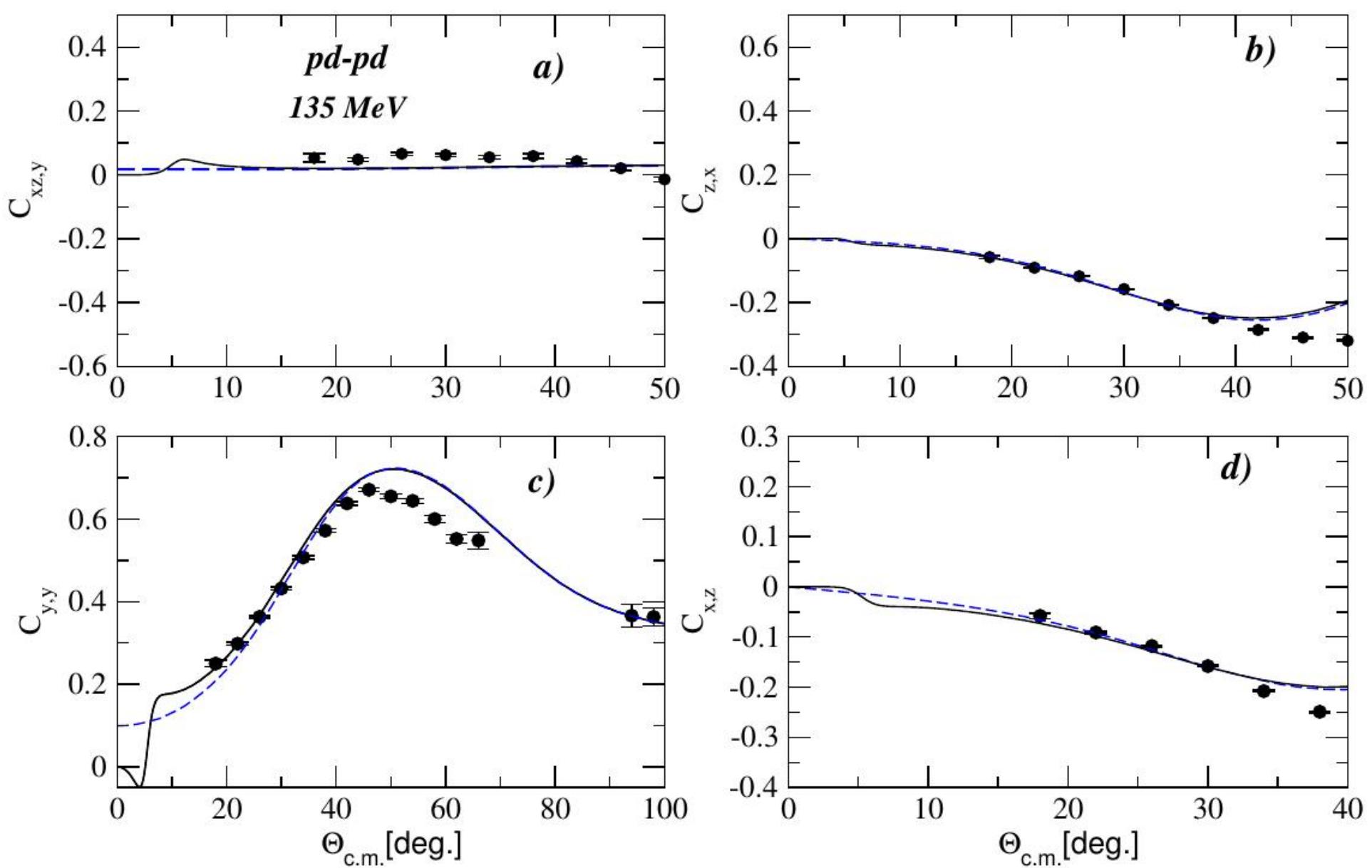
On-shell elastic pN scattering amplitude (**T-even, P-even**)

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



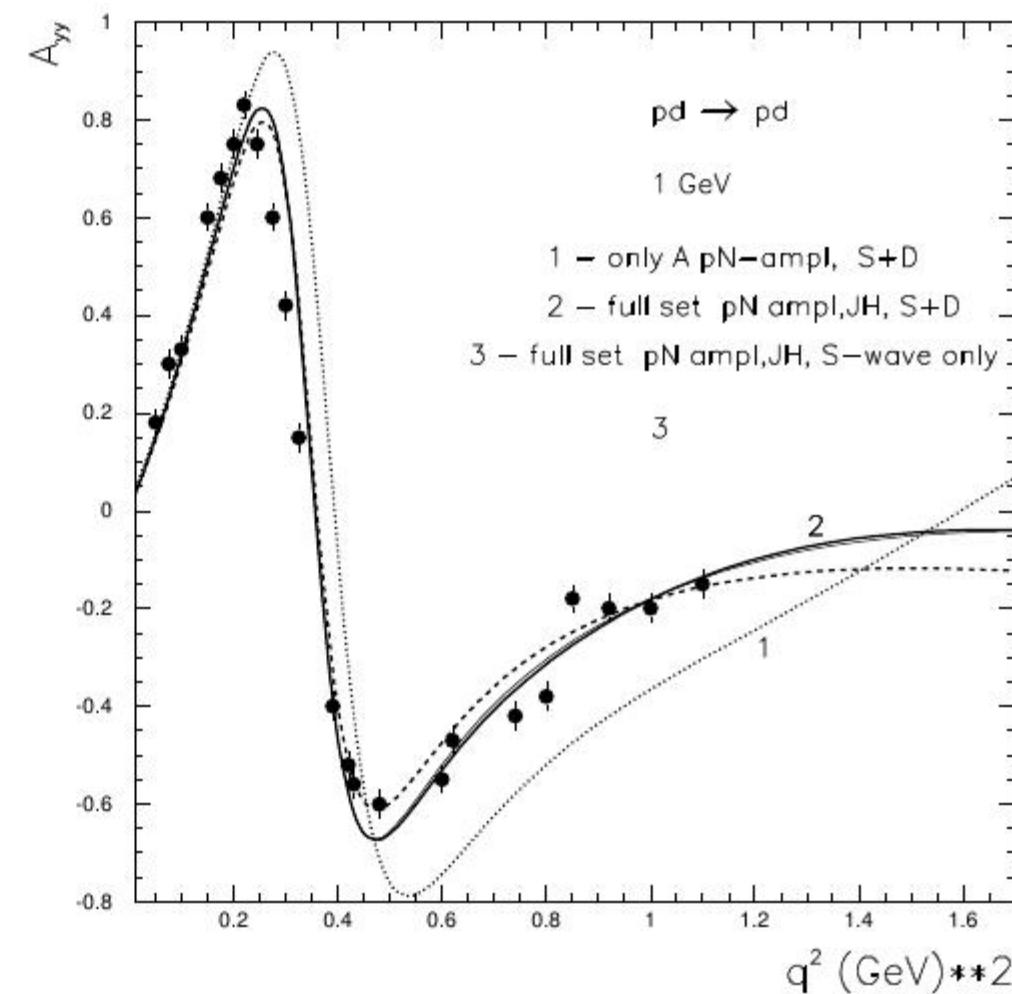
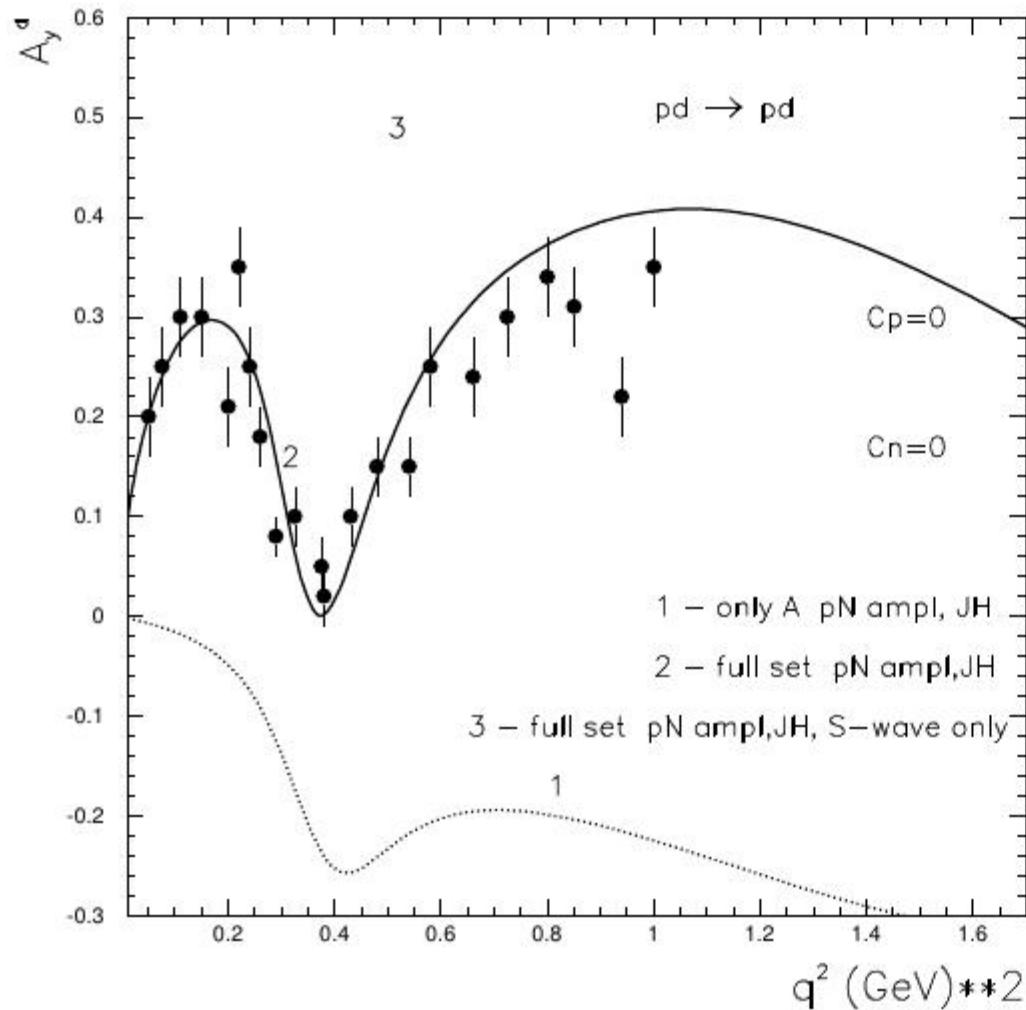
Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)

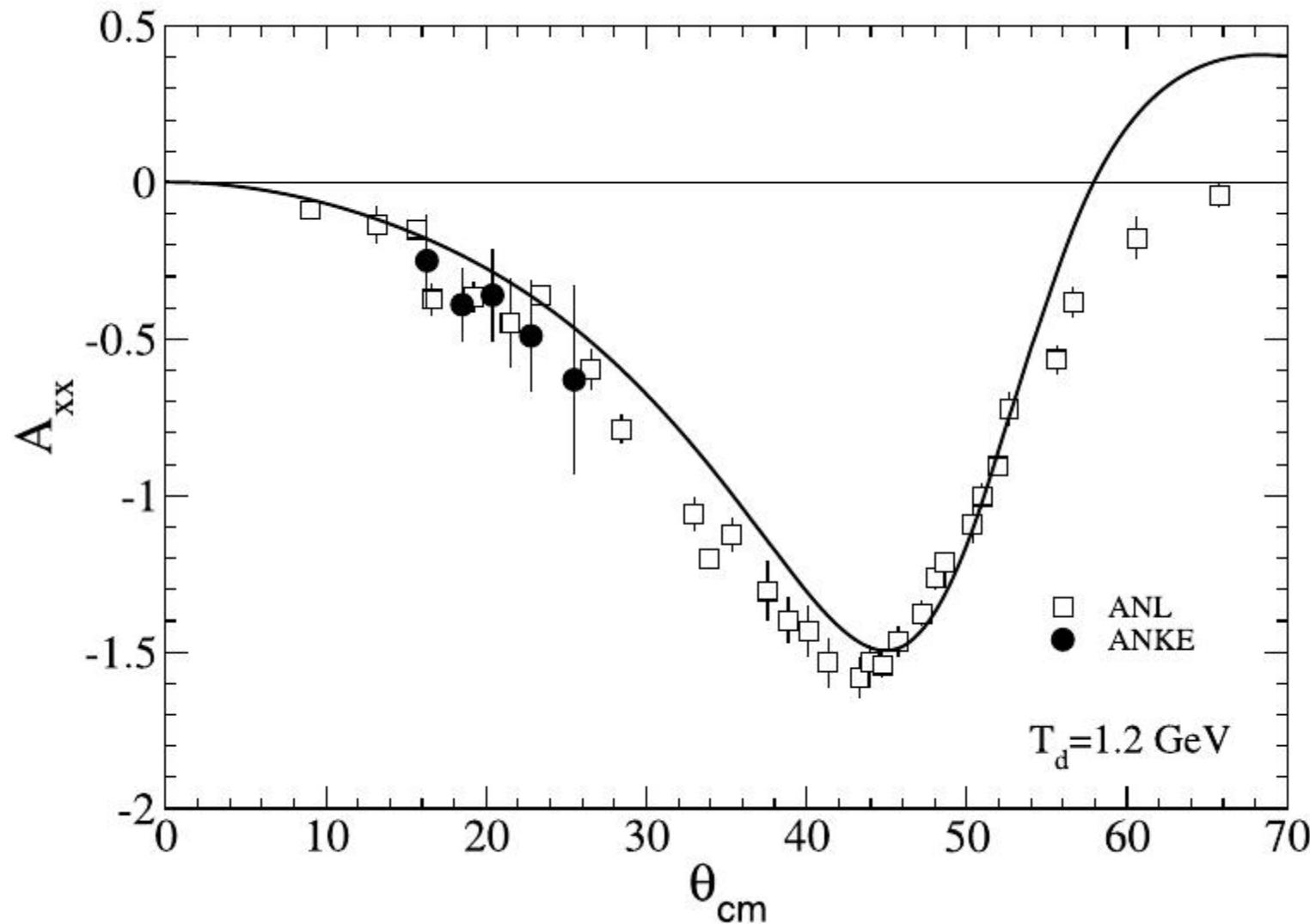
See also Faddeev calculations: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.



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

Test calculations: pd elastic scattering at 1 GeV





$$R = A_y^d / A_y^p$$

Yu.N.U, C. Wilkin, Phys. Lett. B793 (2019) 224,
 $R \neq 2/3$ is sensitive to spin-spin NN terms

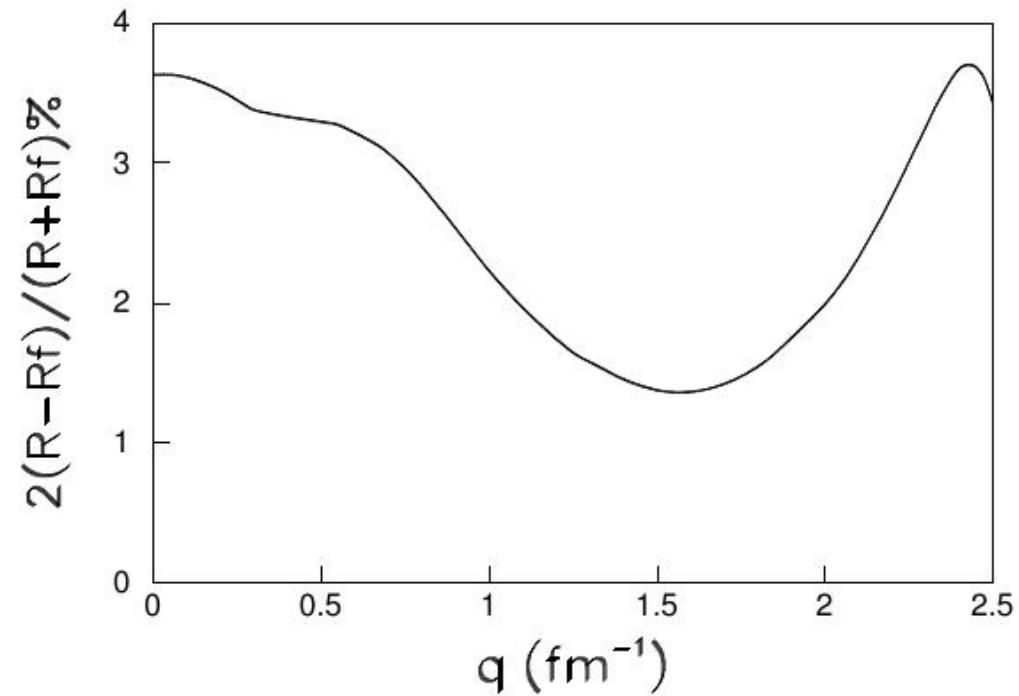
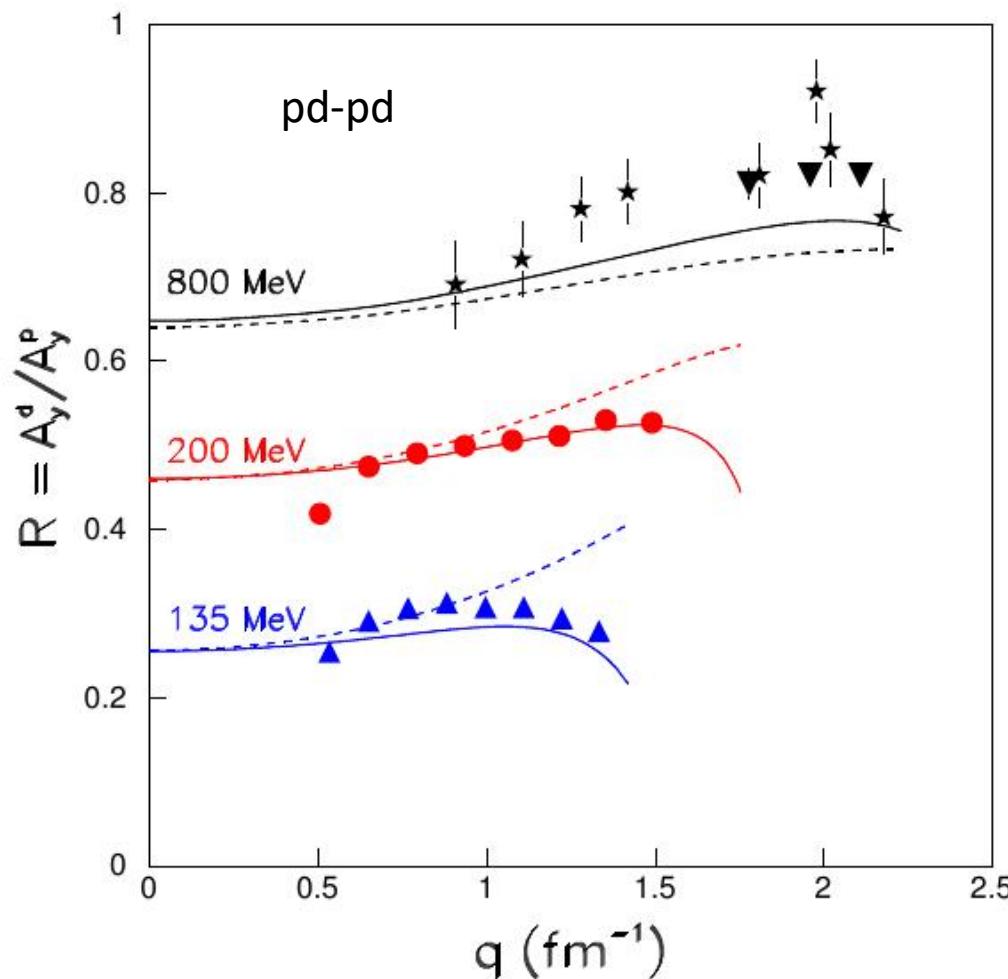


Figure 2: Difference between the predictions of the refined Glauber model [10] without (R) and with (R_f) the NN spin-spin contribution at 800 MeV expressed as a percentage of their average.

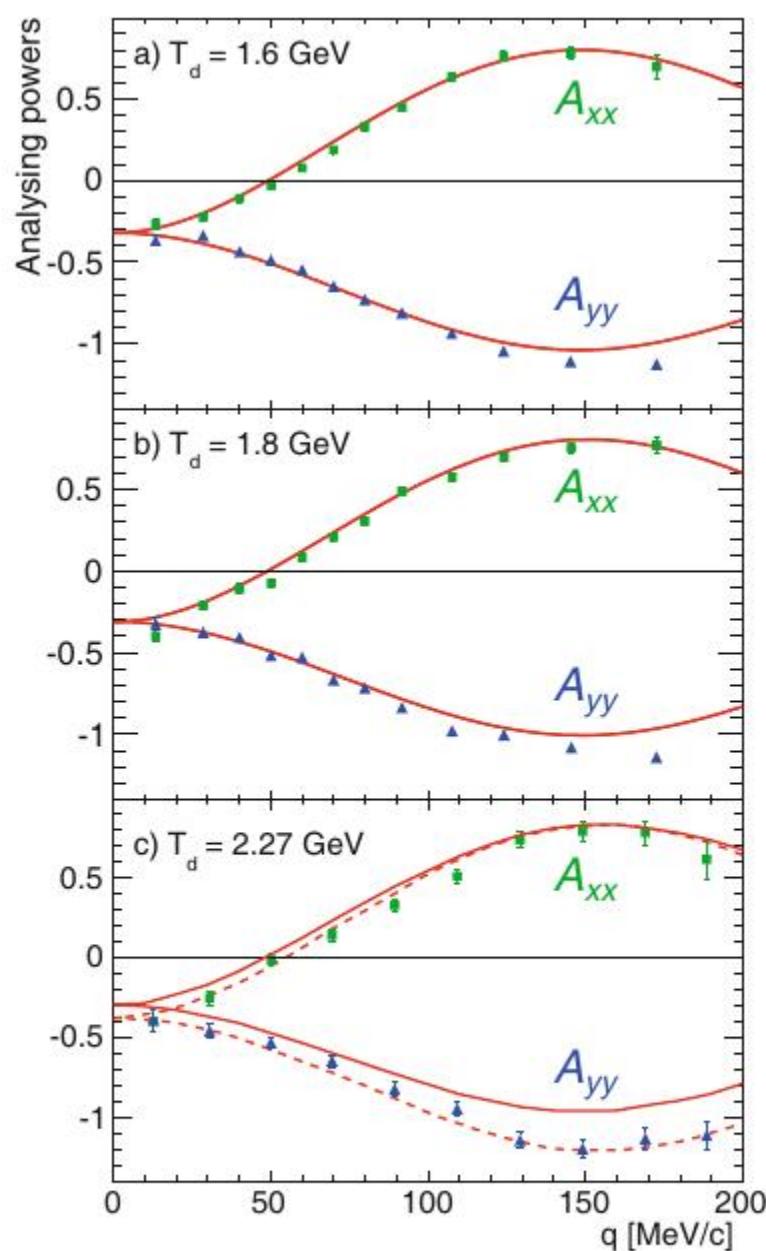
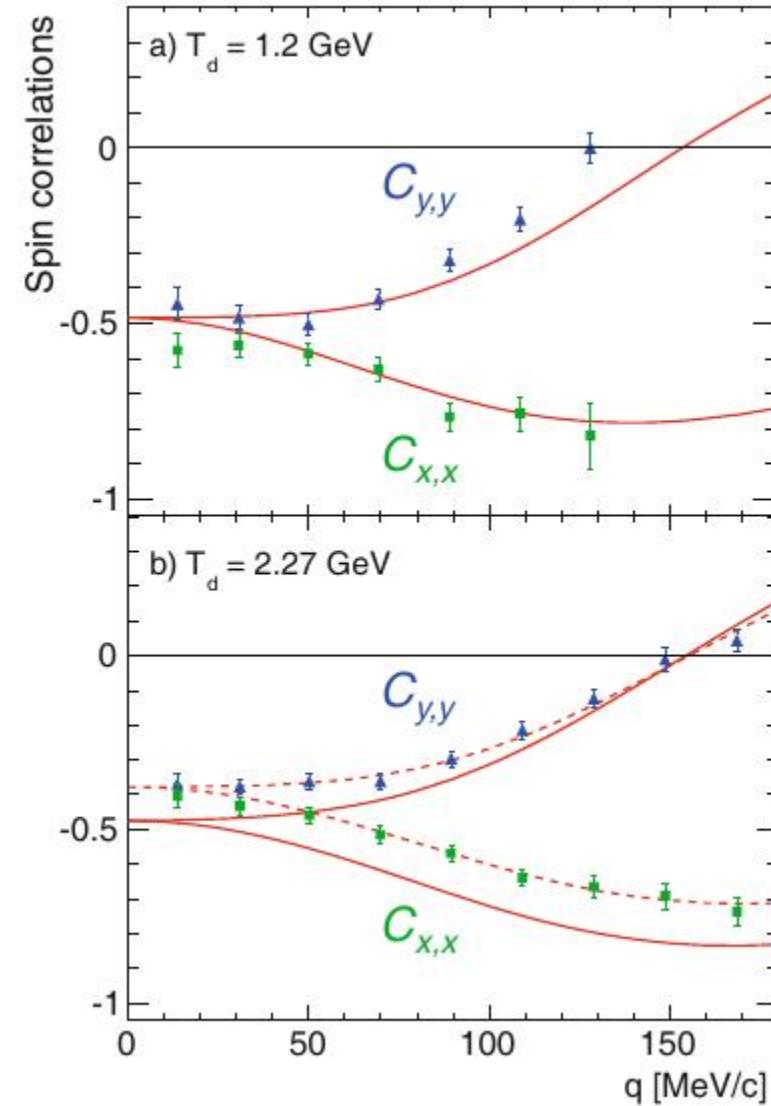
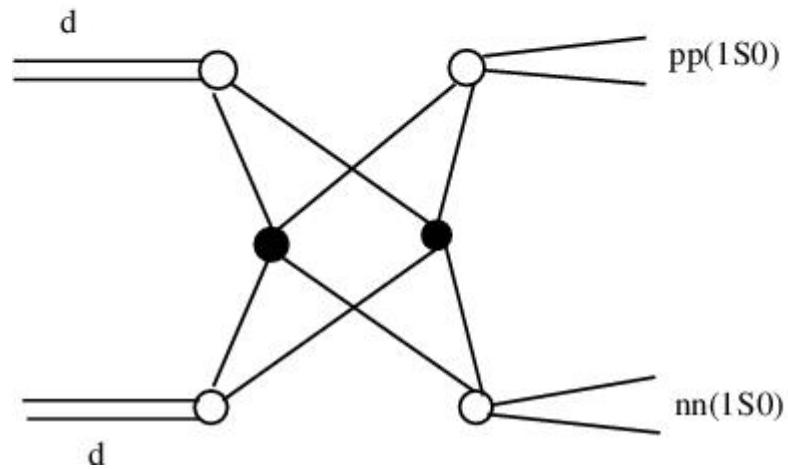
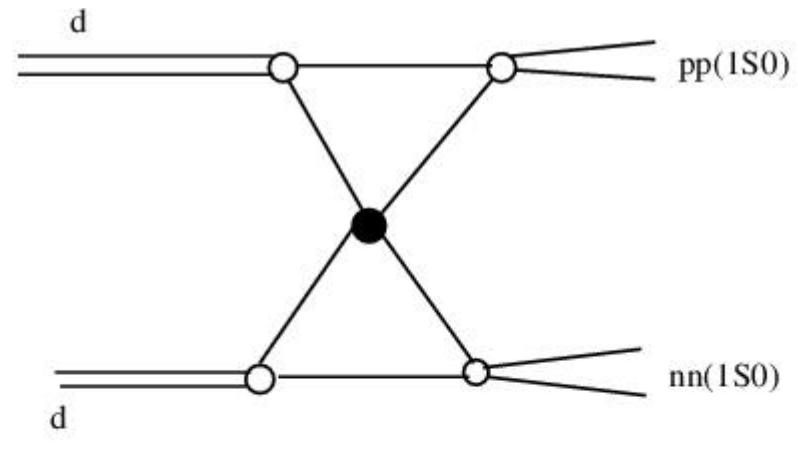


Fig. 8. Tensor analysing powers A_{xx} (squares) and A_{yy} (triangles) of the $\vec{d}p \rightarrow \{pp\}_s n$ reaction at three beam energies for low diproton excitation energy, $E_{pp} < 3 \text{ MeV}$, compared to im-

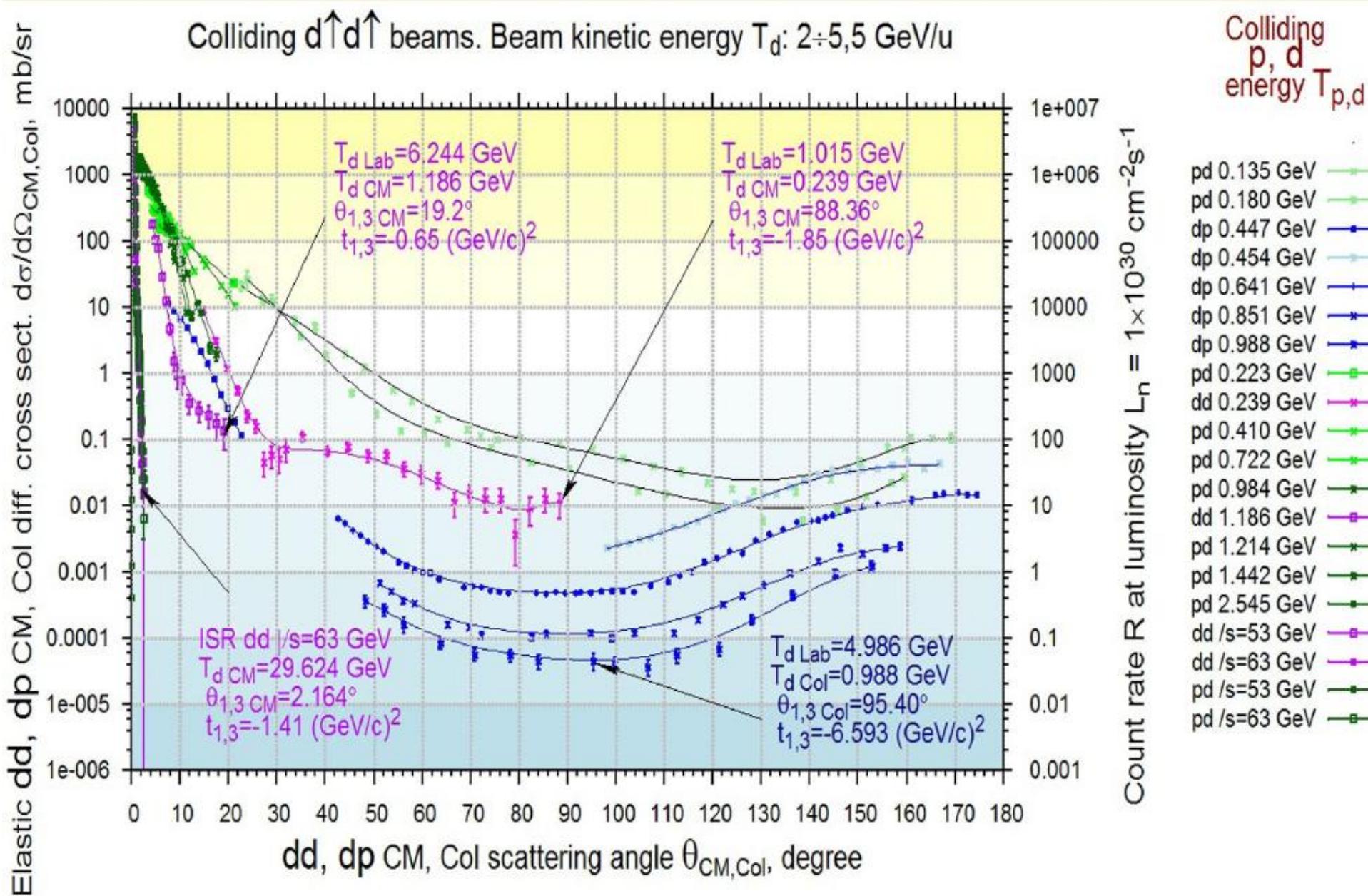


pd->(pp)+n, E_pp<3MeV, 1S0 ANKE
D. Mchedlishvili, et al. EPJA 49 (2013)

dd- elastic and quasi-elastic scattering



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



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 through the QCD θ – term. EDM.
- T-violating P-conserving (TVPC) (flavor-conserving) effects do not arise in SM as Fundamental interactions, although can be generated through weak corrections to TVPV interactions
 - ★ Observed (in K^0, B^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: $g \sim M^4 G_F^2 \sin \delta \sim 10^{-10}$
 - ★ 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.**

T-even P-even

$$M_N(\mathbf{p}, \mathbf{q}; \boldsymbol{\sigma}, \boldsymbol{\sigma}_N)$$

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

T-odd P-even

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

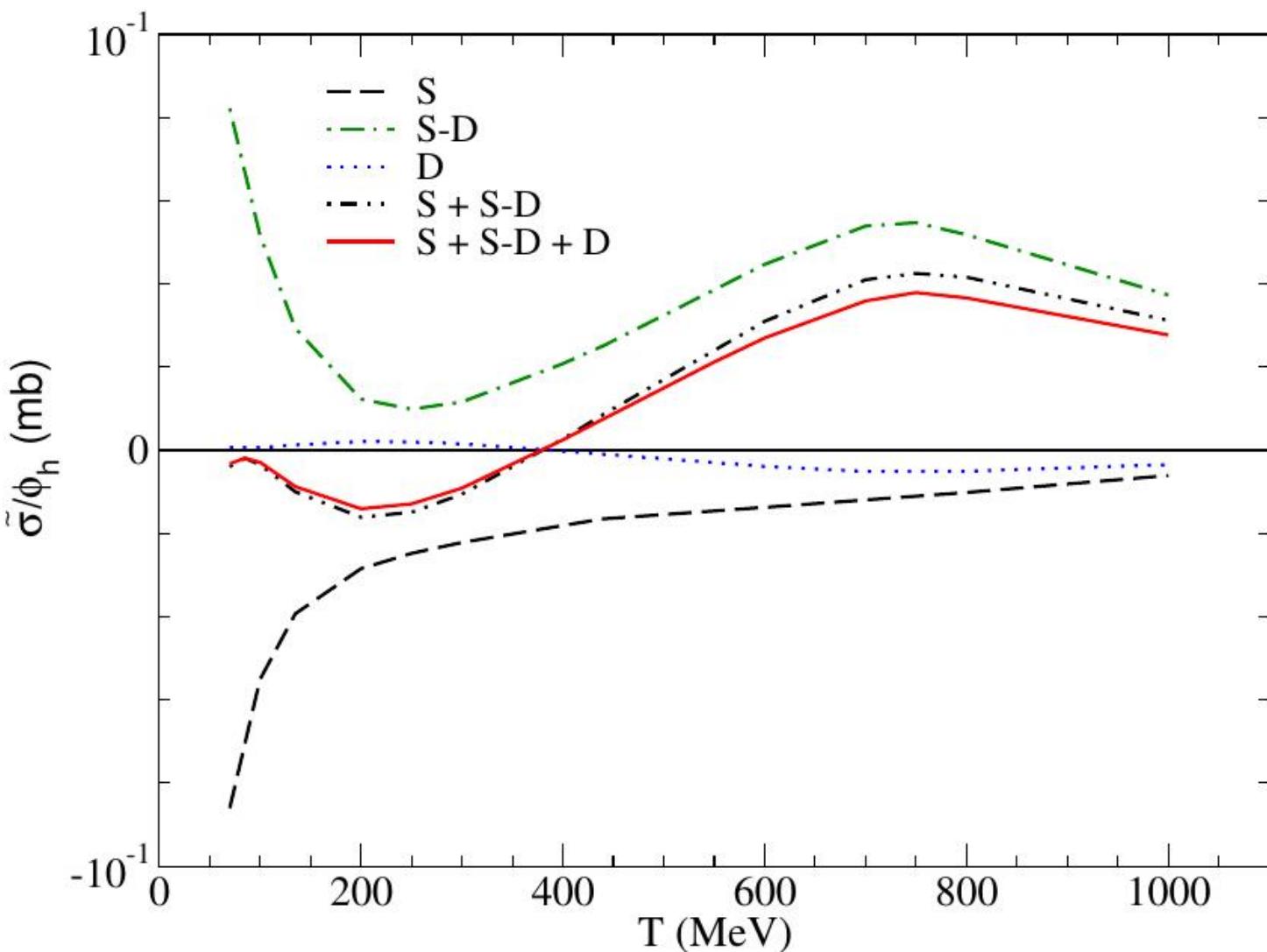
Null-test signal:

$$\begin{aligned} \tilde{g} &= \frac{i}{4\pi m_p} \int_0^\infty dq q^2 \left[S_0^{(0)}(q) - \sqrt{8} S_2^{(1)}(q) - 4 S_0^{(2)}(q) \right. \\ &\quad \left. + \sqrt{2} \frac{4}{3} S_2^{(2)}(q) + 9 S_1^{(2)}(q) \right] [-C'_n(q) h_p + C'_p(q) (g_n - h_n)] \end{aligned}$$

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

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

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



What can be done at SPD NICA?

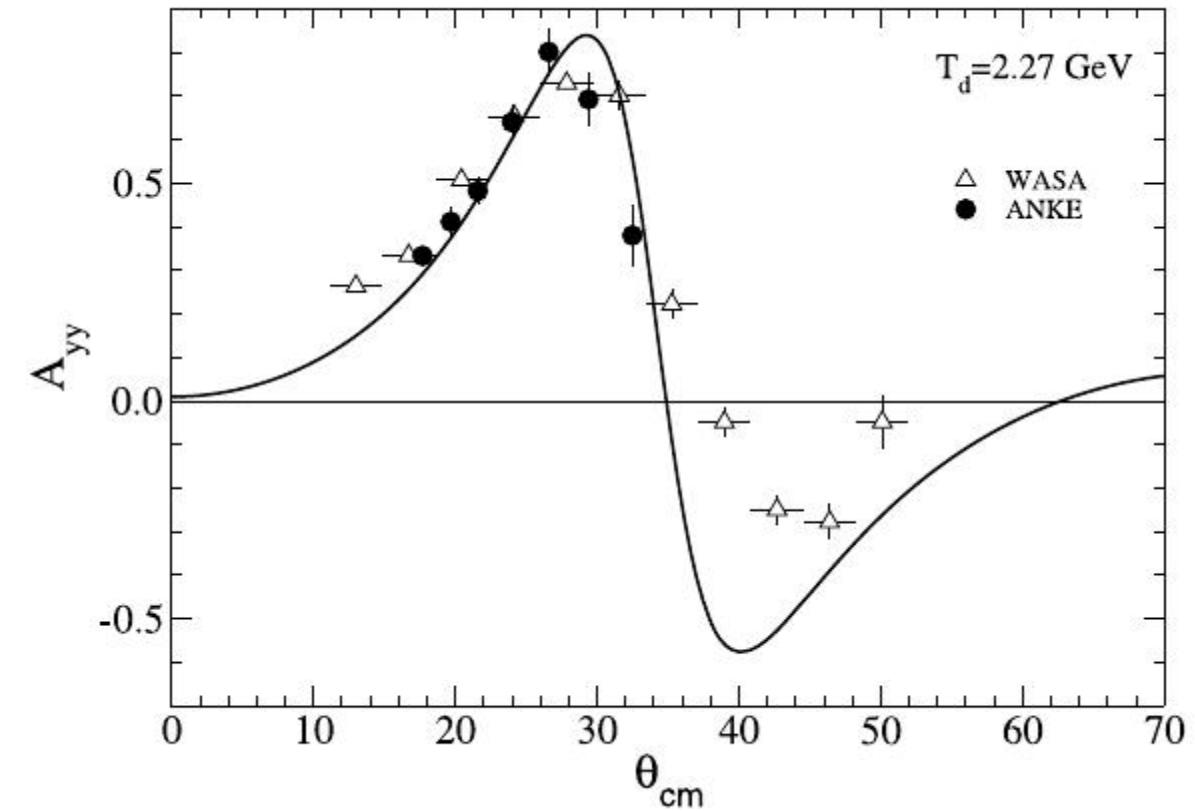
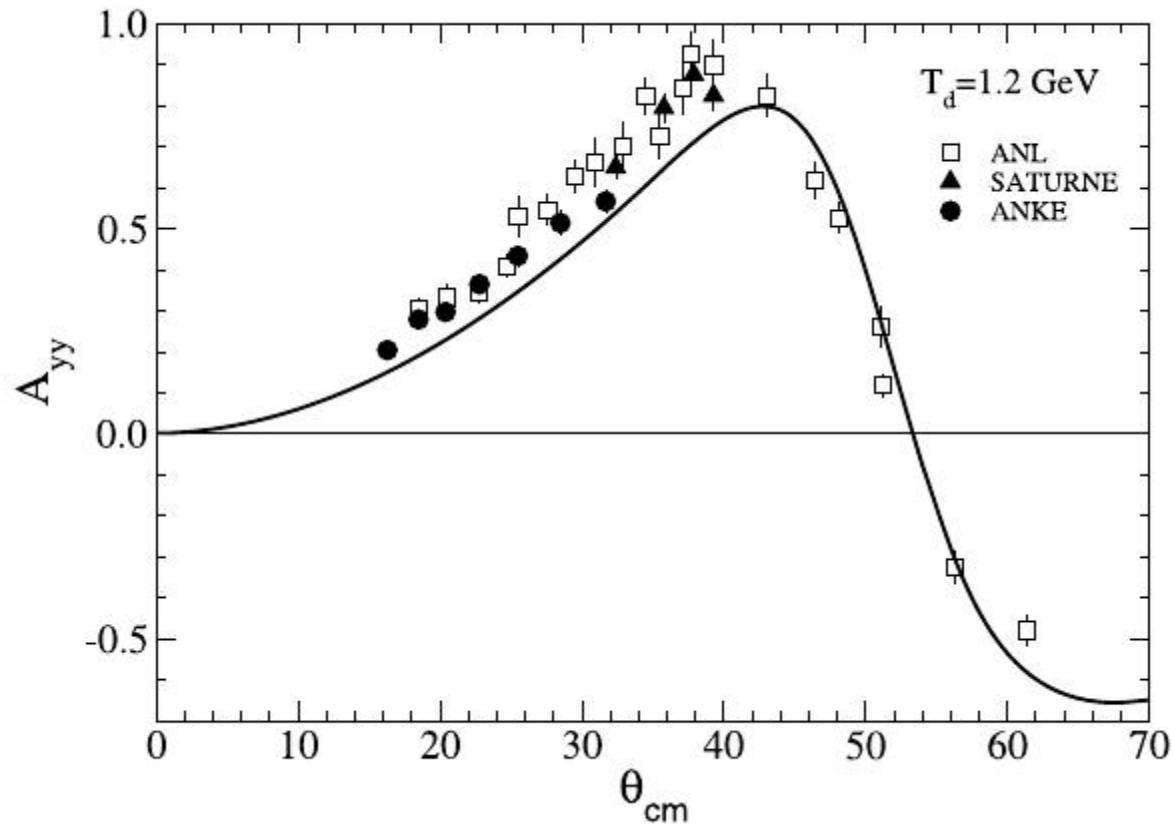
- Measurement of spin observables ($d\sigma/dt$, A_y^p , A_y^d , A_{yy} , A_{xx} , $C_{i,j}$) of pd - elastic, $pd \rightarrow n\{pp\}_s$, $dd \rightarrow dd$, $dd \rightarrow \{pp\}_s + \{nn\}_s$.

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 \Rightarrow 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.

Since NN-forces are fundamental to nuclear physics on the whole it is important to study even their small components, such as spin-spin forces and even at high energies... **via the amplitudes of the NN elastic scattering**

Thank you for attention!



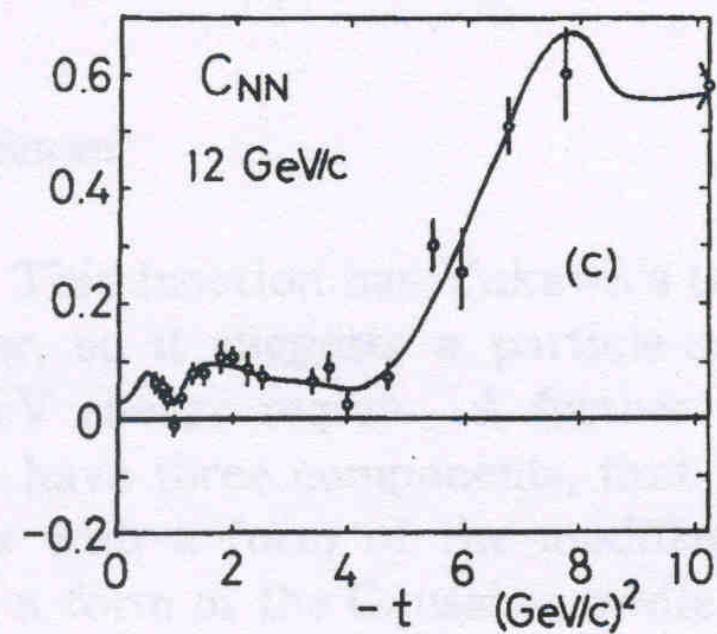
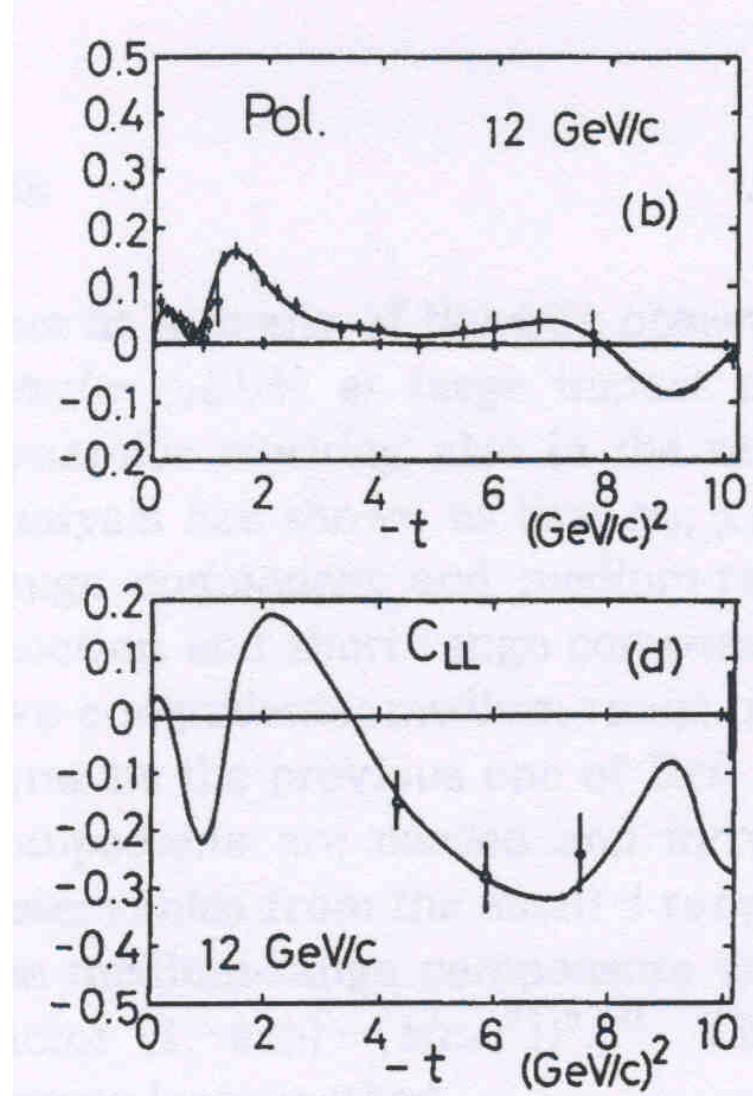


Fig. 2. Calculated results at 12 GeV/c; (a) $d\sigma/dt$, data are from Ref. 20), (b) P , data from Refs. 21) and 22), (c) C_{NN} , data from Ref. 22), (d) C_{LL} , data from Ref. 23).

– *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

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

is much less as compared the SM estimation (B.H.J. McKellar et al. PLB 197 (1987)

$$1.4 \times 10^{-33} e \text{ cm} \leq |d_n| \leq 1.6 \times 10^{-31} e \text{ cm}$$

- 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).

These 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, Elec. Chat. At. Yadr. **37** (2007) 1477

$\vec{n} \rightarrow p e\bar{\nu}$ 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

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

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) \Rightarrow T-violation
- T violation in the K-system:

$$K^0 \rightarrow \bar{K}^0 \text{ and } \bar{K}^0 \rightarrow K^0$$

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

$$\bar{B}^0 \rightarrow B_- \text{ and } B_- \rightarrow \bar{B}^0$$

connected only by T-symmetry transformation

(There are three other independent 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.

HOW TO MEASURE ?

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

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

- 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:

$$\sigma_T = \sigma_{y,xz} + \sigma_{Loss} = \sigma_0 (1 + P_y P_{xz} A_{y,xz}) + \sigma_{Loss} \quad (6)$$

- with:
- σ_0 - 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:

$$\Delta T_{y,xz} = - \tanh(\sigma_0 \Delta d n P_y P_{xz} A_{y,xz}) \quad (8)$$

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

$$\Delta T_{y,xz} = - \sigma_0 \rho d n P_y P_{xz} A_{y,xz} =: - S A_{y,xz} \quad (9)$$