Electromagnetic interactions of the deuteron at low and intermediate energies

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Deuteron research as a way to study neutron

Due to the absence of a free dense neutron target, reactions on a nucleus, primarily on a deuteron, is a source of information about the neutron and about the "elementary" amplitudes of interaction on it.

Interest in the studied reactions
is due to the following reasons

Electromagnetic reactions on the nucleon provide possibility to study the structure of the nucleon at medium and large distances.

Compton scattering is the source of nucleon polarizabilities.
Photoproduction of a pion on a nucleon:

- source of multipole expansion coefficients, etc.;
- pion – Goldstone QCD boson, a consequence of chiral symmetry breaking;
- the possibility of additional study of nucleon-nucleon and pion-nucleon interactions.

Compton scattering on the deuteron and neutron polarizabilities

Nucleon polarizabilities

Nucleons are particles with an internal structure, the existence of which is manifested, among other things, in electromagnetic interactions.

Under the action of an external electromagnetic field, nucleons exhibit the property of polarizability. In the presence of an external field, the nucleon is deformed, acquiring additional energy

$$V_{pol}(r) = -\frac{1}{2} 4\pi [\alpha \mathbf{E}^2(r) + \beta \mathbf{H}^2(r)]$$

Contribution to the scattering amplitude

$$T_{pol} = 4\pi \left[\omega^2 \, \alpha \, \mathbf{e} \cdot \mathbf{e}'^* + \beta \, (\mathbf{e} \times \mathbf{k}) \cdot (\mathbf{e}'^* \times \mathbf{k}') \right],$$

where $\mathbf{e}(\mathbf{e}')$ and $\mathbf{k}(\mathbf{k}')$ are the polarization and momentum vectors of the initial (final) photon, ω is the photon energy.

Compton scattering on the proton

The expansion of the differential cross section in the laboratory system, taking into account the polarizabilities, has the form

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Po}}-\frac{e^2}{4\pi m}\omega^2\left[\frac{\alpha+\beta}{2}\left(1+\cos\Theta\right)^2+\frac{\alpha-\beta}{2}\left(1-\cos\Theta\right)^2\right]+O(\omega^4),$$

$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Po}}$ – Powell cross section of photon scattering by a point charged particle of spin ½ with an anomalous magnetic moment

Compton scattering on the neutron

The expansion of the differential cross section in the laboratory system, taking into account the polarizabilities, has the form

$$\frac{d\sigma}{d\Omega} = \cancel{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Po}}} - \cancel{\frac{e^2}{4\pi m}\omega^2\left[\frac{\alpha+\beta}{2}(1+\cos\Theta)^2 + \frac{\alpha-\beta}{2}(1-\cos\Theta)^2\right]} + O(\omega^4),$$

In Compton scattering on a neutron, polarizabilities appear at ω^4

Baldin sum rule

One can calculate the sum of the polarizabilities by (Baldin, 1960)

$$\alpha_N + \beta_N = \frac{1}{2\pi^2} \int_{\omega_0}^{\infty} \frac{\sigma_N(\omega)}{\omega^2} d\omega,$$

with ω_0 is the photoabsorption threshold on the nucleon (Levchuk & L'vov, 2000)

$$\alpha_p + \beta_p = 14.0 \pm 0.5; \qquad \alpha_n + \beta_n = 15.2 \pm 0.5$$

in units 10^{-4} Fm^3

Experimental data for the proton

An analysis of experimental data on the differential cross section of Compton scattering on a proton at energies $\omega < 150$ MeV gave the values

$$\alpha_p = 11.7 \pm 0.8(exp) \pm 0.7(theory)$$

and

$$\beta_p = 2.3 \pm 0.9(exp) \pm 0.7(theory)$$

Experimental data for the neutron

There are related difficulties:

the absence of a dense, stable neutron target;

smallness of the differential cross section for Compton scattering on a neutron.

Neutron scattering in the Coulomb field of heavy nuclei (Enik, 1997):

$$\alpha_n \sim 7 \div 19$$

Experimental data for the neutron

$$\gamma d \to \gamma' np$$

Theory (Levchuk, L'vov, Petrun'kin, 1994)

Experiment (Kossert et al., 2002)

- Scattering angle – 136^0
- Photon energy – $200 \div 400$ MeV

$$\alpha_n = 12.5 \pm 1.8(stat)^{+1.1}_{-0.6}(syst) \pm 1.1(model)$$

$$\beta_n = 2.7 \mp 1.8(stat)^{+0.6}_{-1.1}(syst) \mp 1.1(model)$$

Experimental data for the neutron

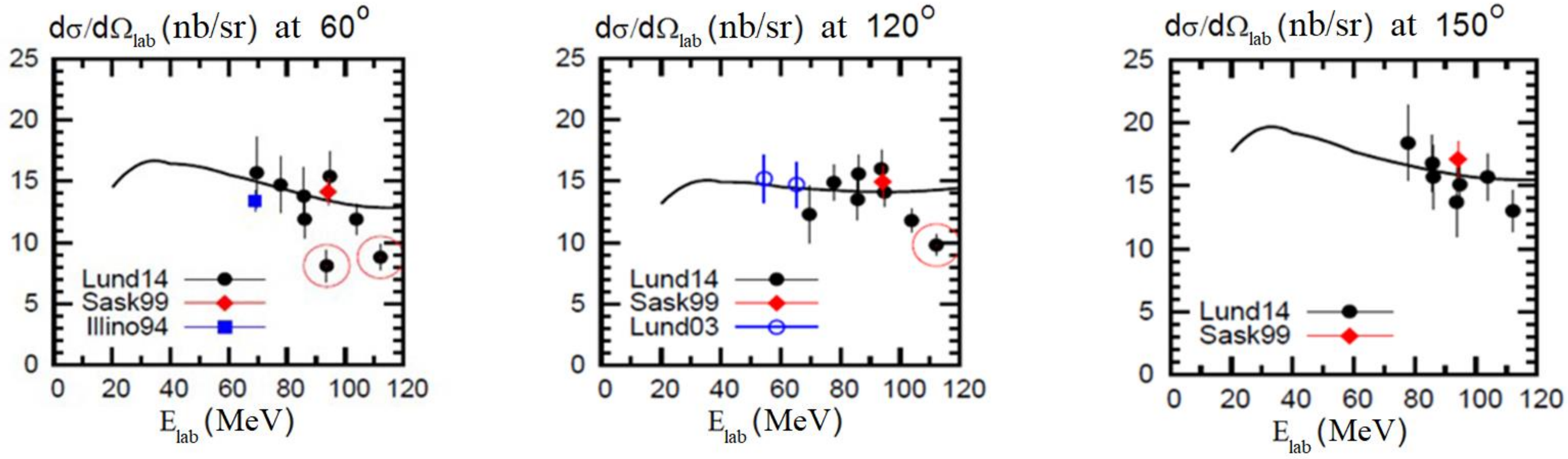
$$\gamma d \to \gamma' d'$$

One can measure $\alpha_s = \frac{\alpha_p+\alpha_n}{2}$, $\beta_s = \frac{\beta_p+\beta_n}{2}$ and use known proton data

$$\alpha_p = 11.7 \pm 1.1, \quad \beta_p = 2.3 \pm 1.1$$

Experimental data for the neutron

Thus, the result of data processing within the framework of the model (Levchuk & Lvov, 2000) gives us the following values



$$\alpha_s = 12.7 \pm 0.7, \qquad \beta_s = 2.1 \pm 0.6 \qquad \chi^2 / N_{dof} = 49/48$$

$$\alpha_s = 13.0 \pm 0.7, \qquad \beta_s = 2.2 \pm 0.6 \qquad \chi^2 / N_{dof} = 88/51$$

Experimental data for the neutron

$$\gamma d \to \gamma' d'$$

$$\alpha_s = 12.7 \pm 0.7, \qquad \beta_s = 2.1 \pm 0.6$$

$$\Downarrow$$

$$\alpha_n = 13.7 \pm 1.8, \qquad \beta_n = 1.9 \pm 1.6$$

Results

$$\gamma d \to \gamma' np$$

$$\alpha_n = 12.5 \pm 1.8(stat)^{+1.1}_{-0.6}(syst) \pm 1.1(model)$$

$$\beta_n = 2.7 \mp 1.8(stat)^{+0.6}_{-1.1}(syst) \mp 1.1(model)$$

$$\gamma d \to \gamma' d'$$

$$\alpha_n = 13.7 \pm 1.8, \qquad \beta_n = 1.9 \pm 1.6$$

Incoherent pion photoproduciton on the deuteron in threshold energy region

$$\gamma d \to \pi N N$$

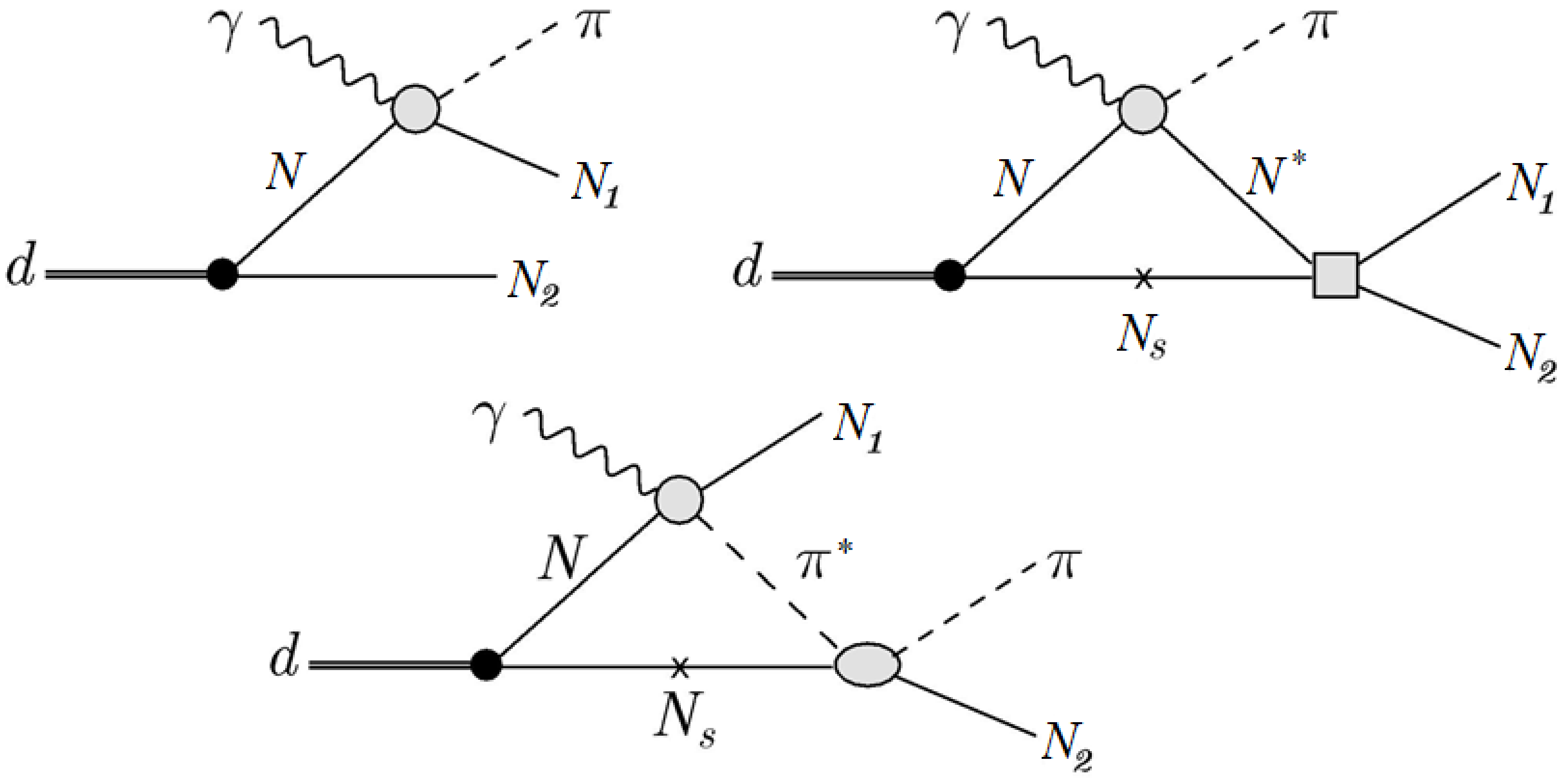
Research motivation

Previously available experimental data described energies above 200 MeV (with a threshold about 150 MeV).

2018: The first measurements of the cross sections of the reaction $\gamma d \rightarrow \pi^- pp$ in the threshold energy region $E_\gamma < 160$ MeV

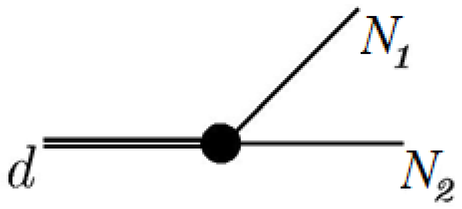
(MAX IV laboratory, Lund university).

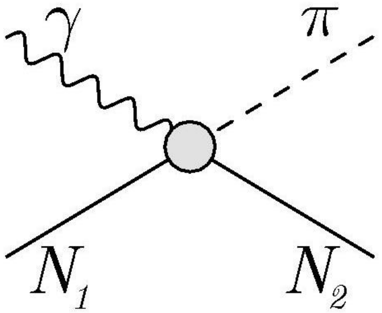
Diagrammatic model



Diagrammatic model

- For the deuteron vertex, the deuteron wave function from CD-Bonn NN-potential is used.
- For the pion photoproduction on the nucleon, MAID07 model is used
- The pp-scattering amplitude is obtained by solving the Lippmann-Schwinger integral equation for CD-Bonn potential.
- The πN-scattering amplitude is the solution of the Lippmann-Schwinger equation for the separable potential constructed in the work





Machleidt, R. High-precision, charge-dependent Bonn nucleon-nucleon potential / R. Machleidt // Phys. Rev. C – 2001. – Vol. 63, № 2 – 024001(32).

A unitary isobar model for pion photo- and electroproduction on the proton up to 1 GeV / D. Drechsel [et al.] // Nucl. Phys. A – 1999. – Vol. 645, Iss. 1. – P. 145–174.

Nozawa S., Blankleider B., Lee T. S. H. *Nuclear Physics A*, 1990, vol. 513, iss. 3–4, pp. 459–510.

Energy dependence of the total cross section of the reaction $\gamma d \rightarrow \pi^- pp$

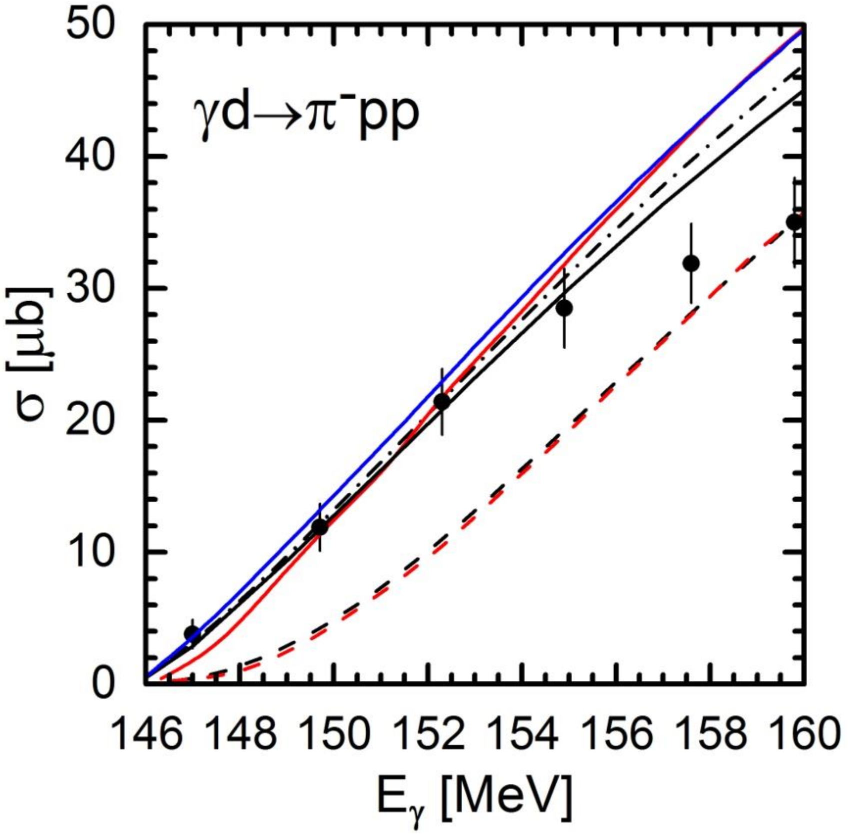
Experimental data:
MAX IV Laboratory,
Lund University (2018).

Solid red line:

Near-threshold π^- photoproduction on the deuteron / Strandberg, B. [et al.] // Phys. Rev. C. – 2020. – Vol. 101, Iss. 3 – 035201(7).

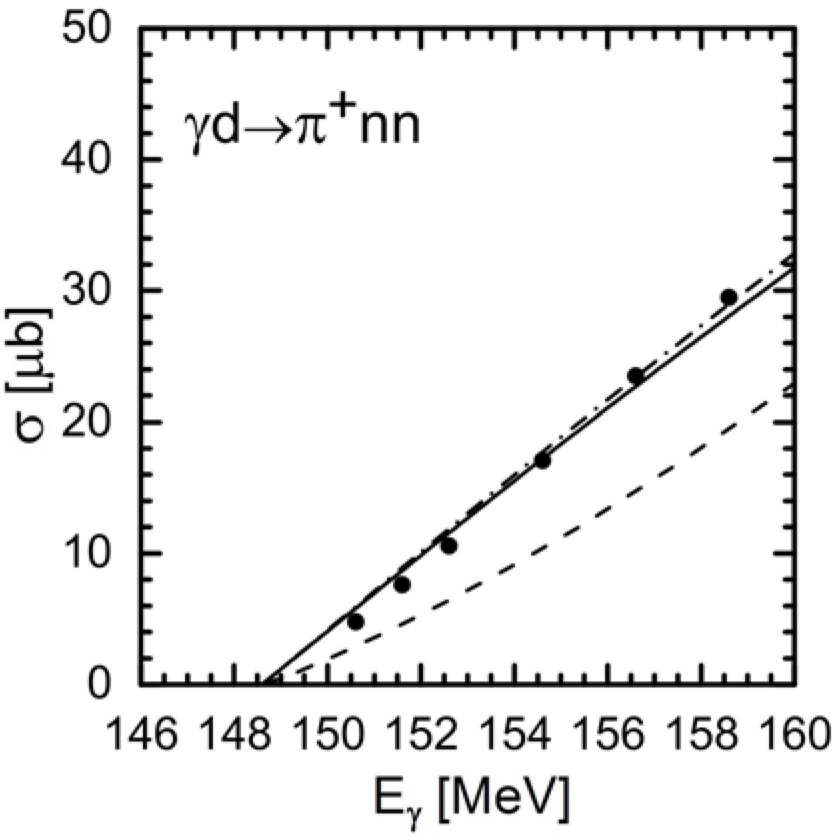
Solid blue line:

Near-threshold incoherent pion photoproduction on the deuteron with final-state interaction effects / E. M. Darwish [et al.] // Annals of Physics. – 2019. – Vol. 411 – 167990(26).



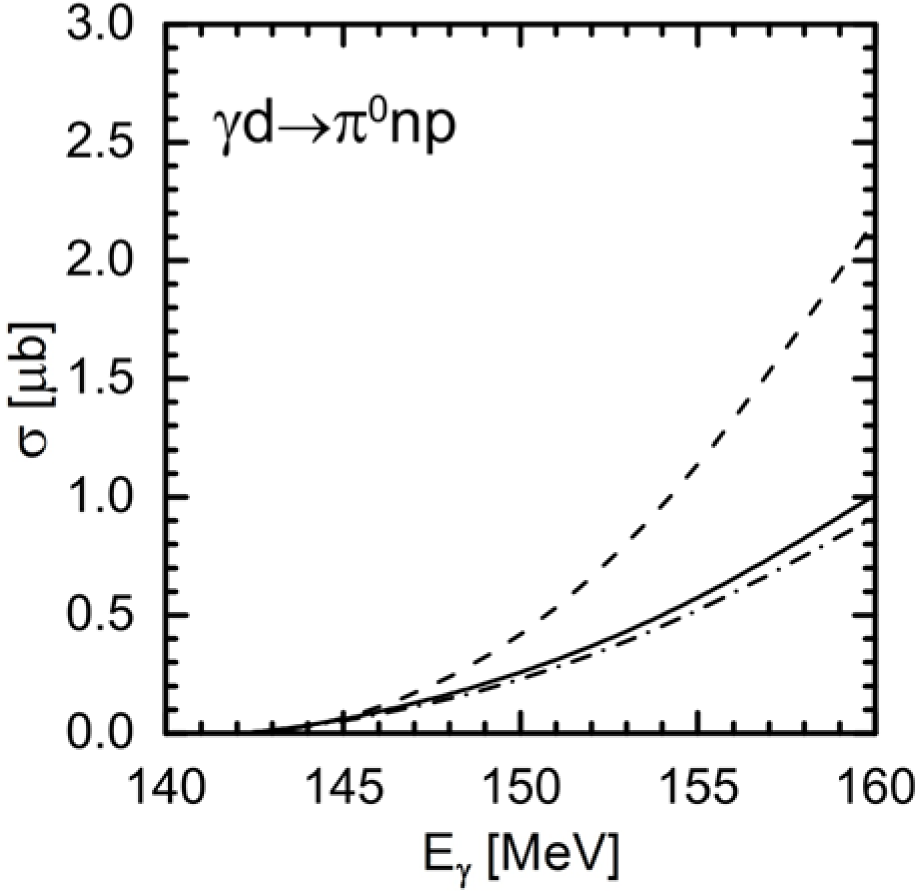
Energy dependence of the total cross section of the reaction $\gamma d \to \pi^+ nn$

It is noteworthy that the behavior of the data on reaction $\gamma d \to \pi^+ nn$ is similar to the given theoretical predictions for the reaction $\gamma d \to \pi^- pp$



^{2}H(γ,π^+)*nn* total cross section from threshold to ΔE=22 MeV / E. C. Booth [et al.] // Phys. Rev. C – 1979. – Vol. 20, № 4 – P. 1217–1220.

Energy dependence of the total cross section of the reaction



Single spin asymmetries

- $\Sigma = \frac{(d\sigma/d\Omega_\pi)^{\parallel} - (d\sigma/d\Omega_\pi)^{\perp}}{(d\sigma/d\Omega_\pi)^{\parallel} + (d\sigma/d\Omega_\pi)^{\perp}} = -\frac{1}{S} 2 \int_{q_{\min}}^{q_{\max}} f q^2 dq \int d\Omega_{\mathbf{P}}\ \mathrm{Re} \sum_{m_2 m_1 m_d} \langle m_2 m_1 | T | +1 m_d \rangle \langle m_2 m_1 | T | -1 m_d \rangle^*$

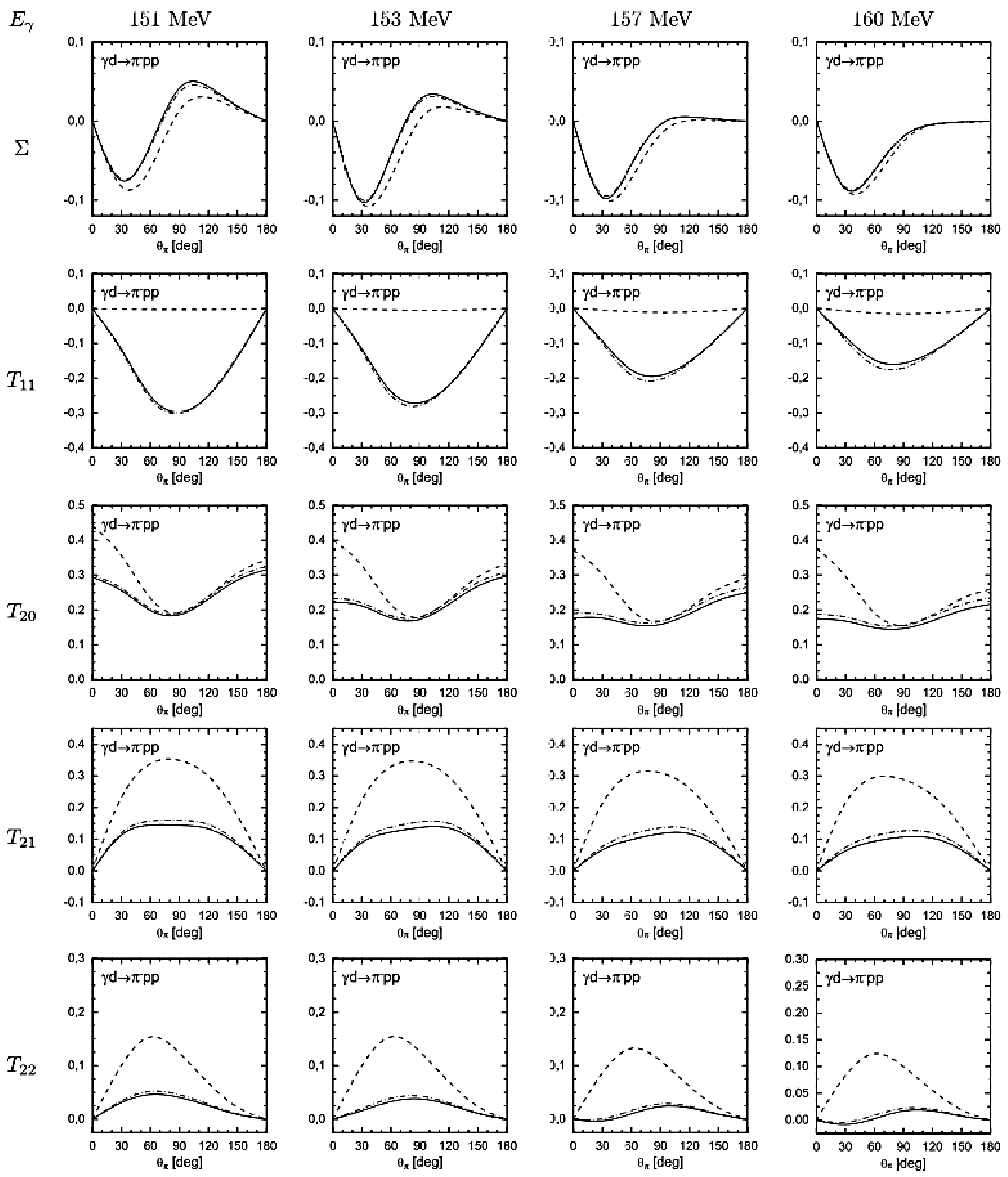
- $T_{11} = \frac{1}{S} \sqrt{6} \int_{q_{\min}}^{q_{\max}} f q^2 dq \int d\Omega_{\mathbf{P}}\ \mathrm{Im} \sum_{m_2 m_1 \lambda} (\langle m_2 m_1 | T | \lambda + 1 \rangle - \langle m_2 m_1 | T | \lambda - 1 \rangle) \langle m_2 m_1 | T | \lambda 0 \rangle^*$

- $T_{20} = \frac{1}{S} \frac{1}{\sqrt{2}} \int_{q_{\min}}^{q_{\max}} f q^2 dq \int d\Omega_{\mathbf{P}}\ \mathrm{Re} \sum_{m_2 m_1 \lambda} (|\langle m_2 m_1 | T | \lambda - 1 \rangle|^2 + |\langle m_2 m_1 | T | \lambda + 1 \rangle|^2 - 2 |\langle m_2 m_1 | T | \lambda 0 \rangle|^2)$

- $T_{21} = \frac{1}{S} \sqrt{6} \int_{q_{\min}}^{q_{\max}} f q^2 dq \int d\Omega_{\mathbf{P}}\ \mathrm{Re} \sum_{m_2 m_1 \lambda} (\langle m_2 m_1 | T | \lambda - 1 \rangle - \langle m_2 m_1 | T | \lambda + 1 \rangle) \langle m_2 m_1 | T | \lambda 0 \rangle^*$

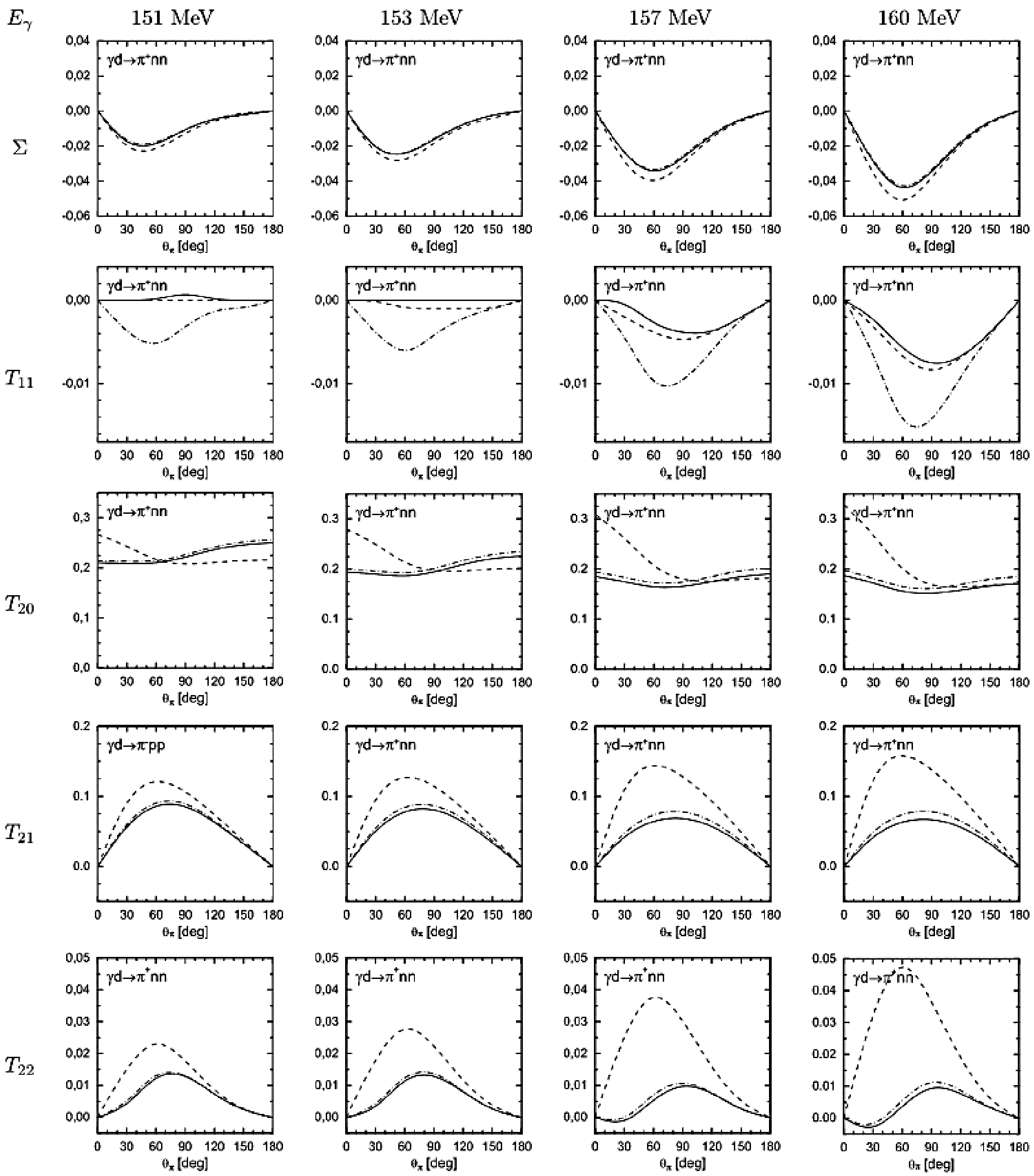
- $T_{22} = \frac{1}{S} 2\sqrt{3} \int_{q_{\min}}^{q_{\max}} f q^2 dq \int d\Omega_{\mathbf{P}}\ \mathrm{Re} \sum_{m_2 m_1 \lambda} \langle m_2 m_1 | T | \lambda - 1 \rangle \langle m_2 m_1 | T | \lambda + 1 \rangle^*$

Angular distributions of single spin asymmetries for the reaction $\gamma d \to \pi^- pp$ at various photon lab-energies



E_γ
151 MeV
153 MeV
157 MeV
160 MeV
Σ
T_{11}
T_{20}
T_{21}
T_{22}
γd→π⁻pp
θπ [deg]

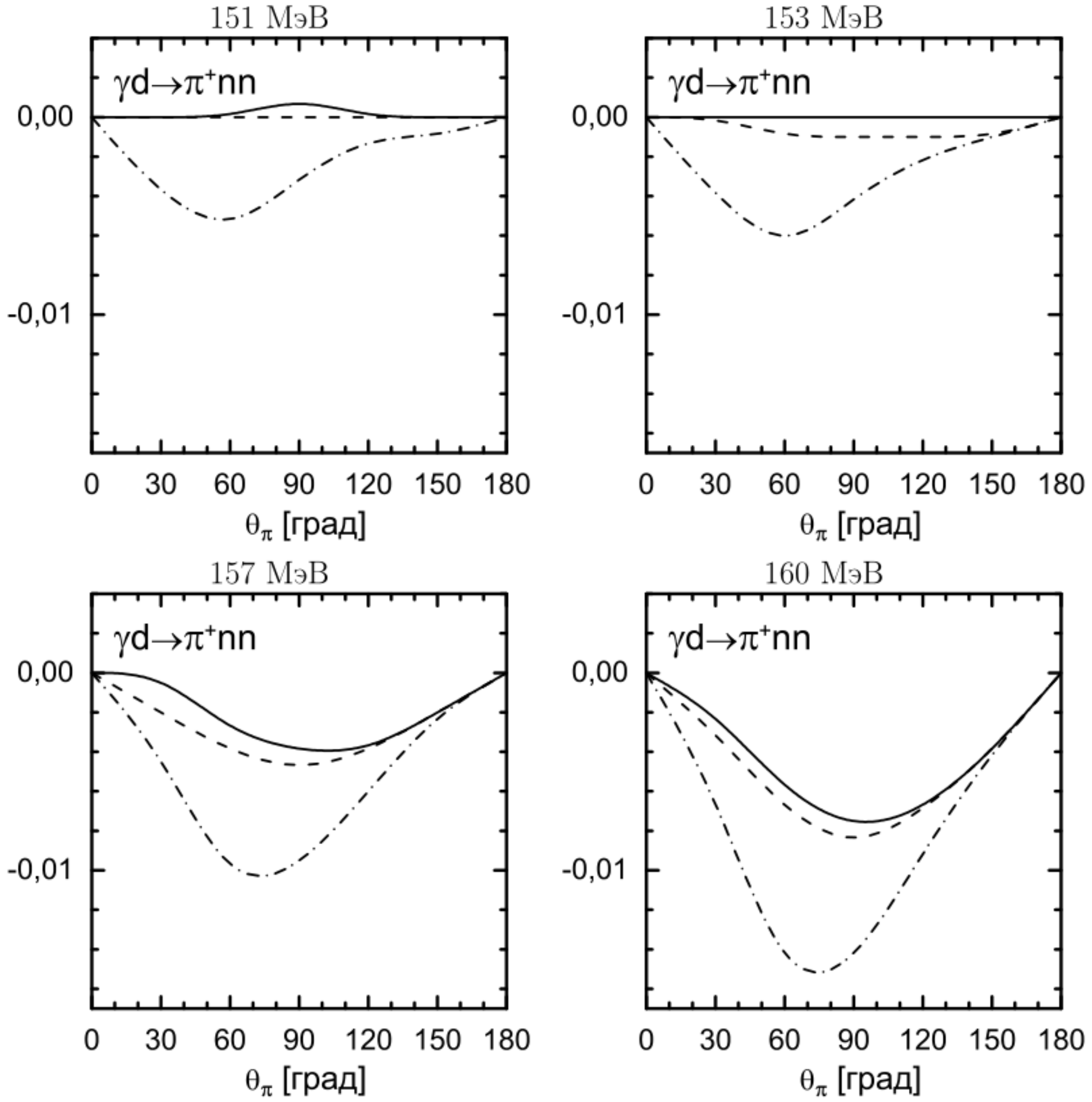
Angular distributions of single spin asymmetries for the reaction $\gamma d \to \pi^+ nn$ at various photon lab-energies



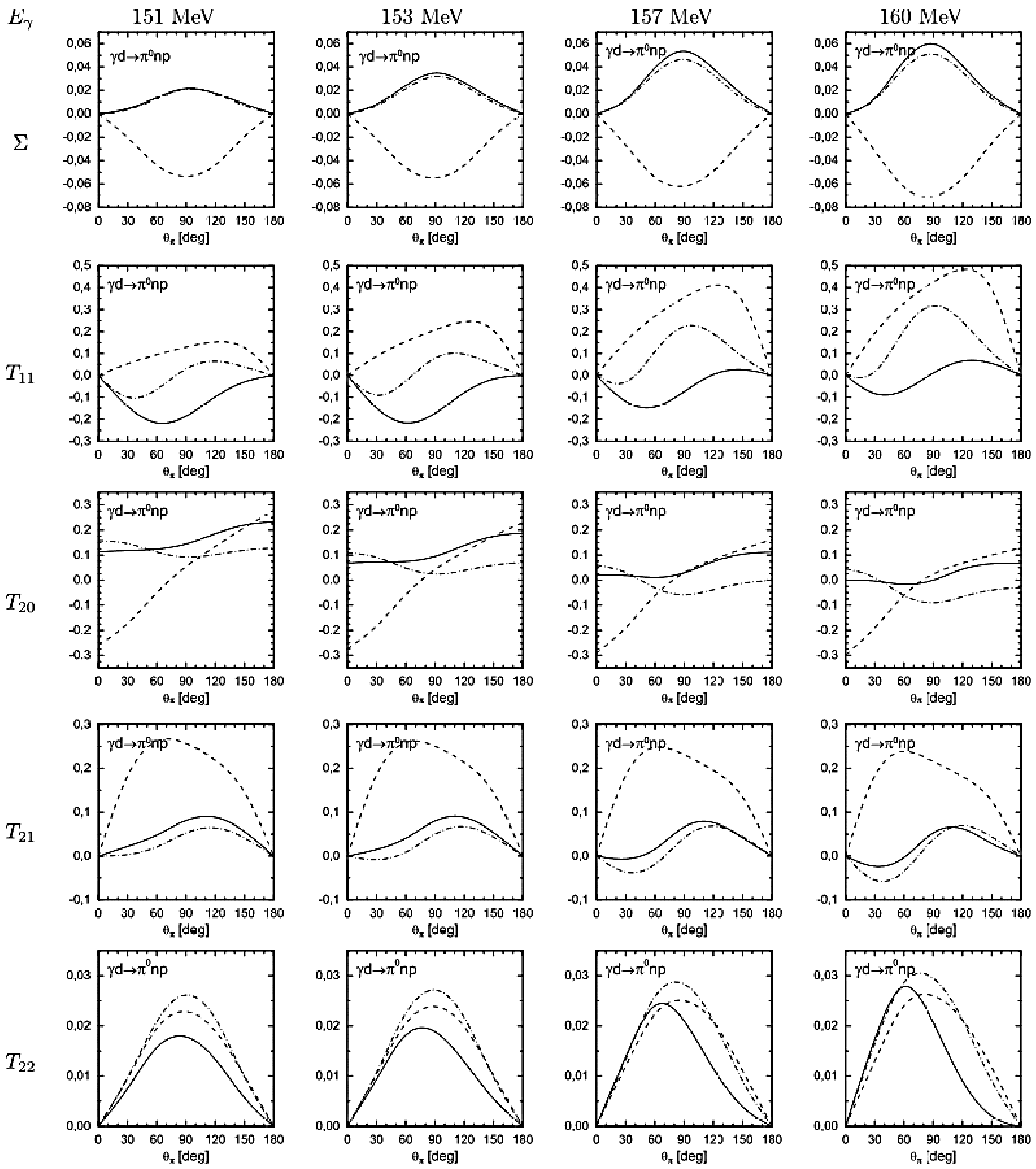
Eγ
151 MeV
153 MeV
157 MeV
160 MeV
Σ
T11
T20
T21
T22
γd→π⁺nn
γd→π⁻pp
θπ [deg]

$\gamma d \to \pi^+ nn$

T_{11}



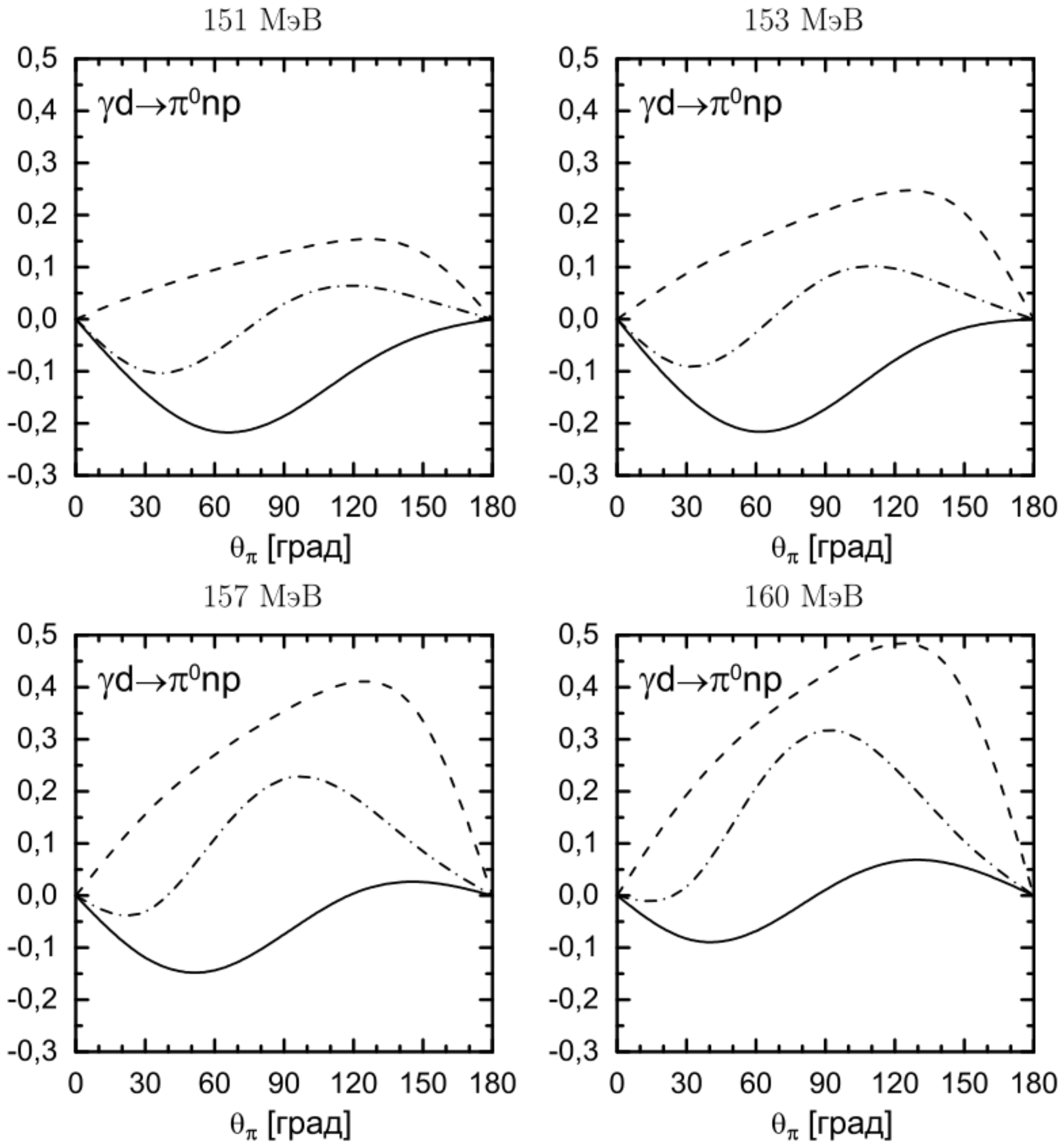
Angular distributions of single spin asymmetries for the reaction $\gamma d \to \pi^0 np$ at various photon lab-energies



E_γ
151 MeV
153 MeV
157 MeV
160 MeV
Σ
T_{11}
T_{20}
T_{21}
T_{22}
$\gamma d \rightarrow \pi^0 np$
θ_π [deg]

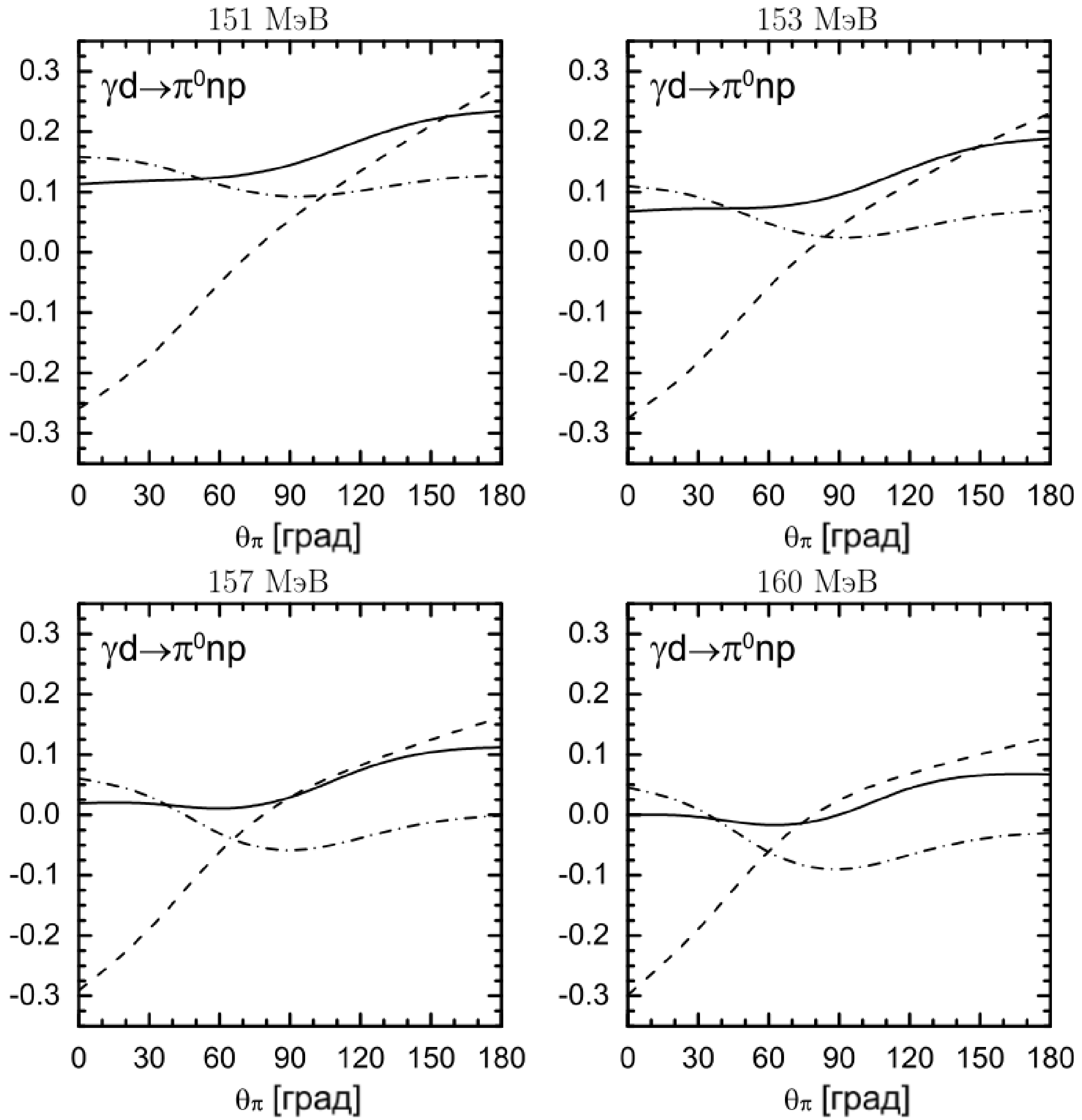
$\gamma d \to \pi^0 np$

T_{11}



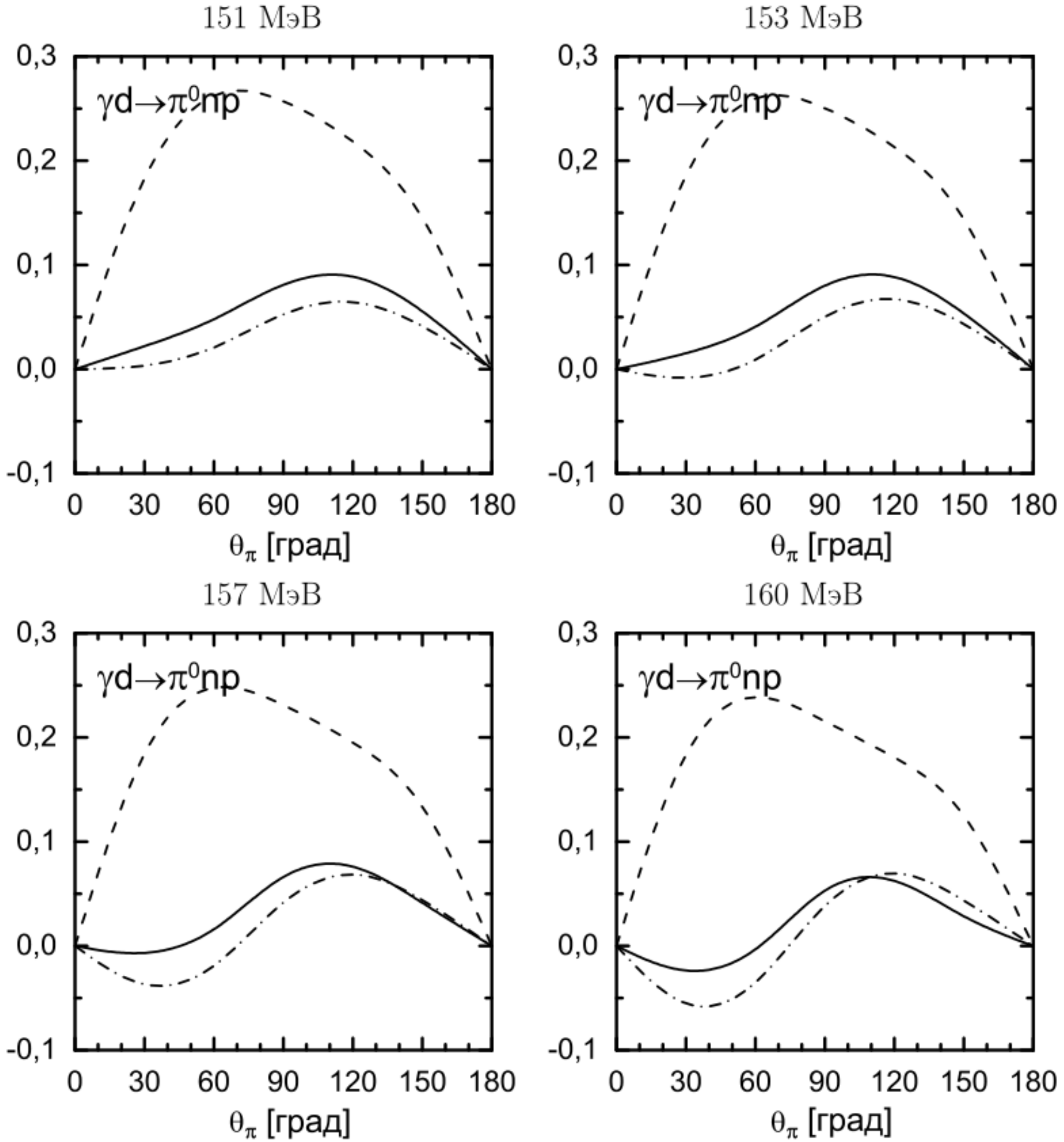
$\gamma d \to \pi^0 np$

T_{20}



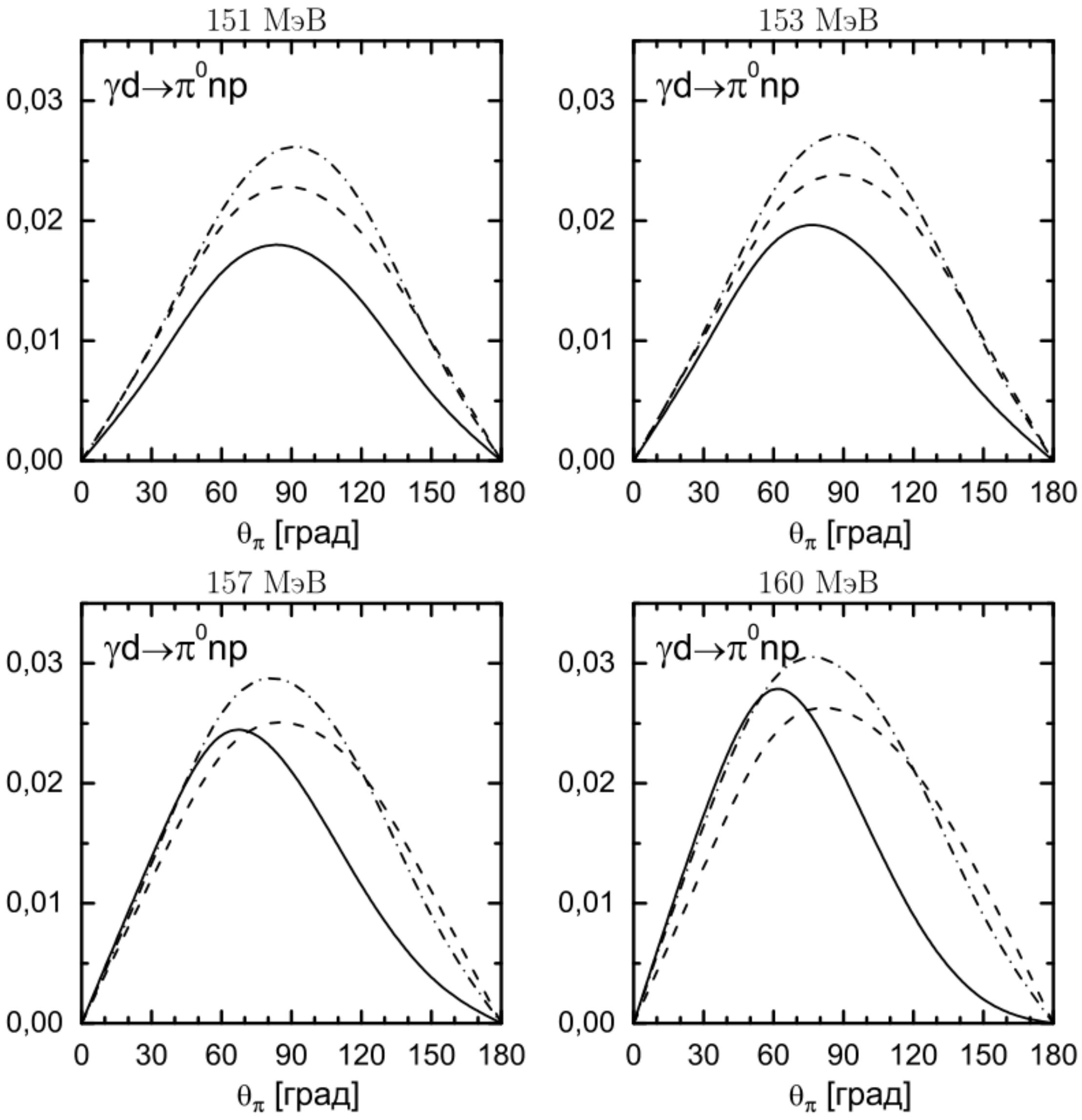
$$\gamma d \to \pi^0 np$$

$$T_{21}$$



$\gamma d \rightarrow \pi^0 np$

T_{22}



Conclusion

- Total cross sections for $\gamma d \to \pi NN$ in threshold energy region:

$\gamma d \to \pi^+ nn$ – good agreement.

$\gamma d \to \pi^- pp$ – good agreement up to $\mathrm{E}_\gamma = 155$ MeV, but for 158 and 160 MeV data are overestimated.

- Single spin asymmetries for $\gamma d \to \pi NN$ in threshold energy region:

There is a relatively large contribution of the diagram with πN rescattering for some asymmetries. That may provide a tool for studying the pion and
πN interactions.

The tensor analyzing power component T_{20} in the reaction $\gamma d \to \pi^0 d'$ in Δ resonance region

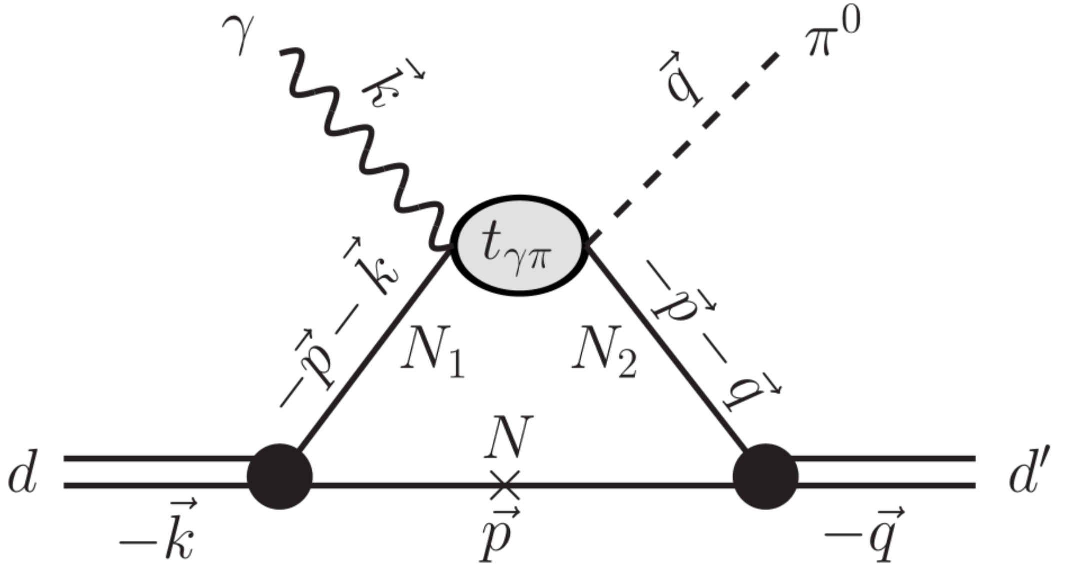
Research Motivation

In 2020, the data for unique measurements of the tensor analyzing power T_{20} for the reaction $\gamma d \to \pi^0 d$ were published. The measurements were performed at VEPP-3 electron storage ring at the Budker Institute of Nuclear Physics in Novosibirsk, Russia.

Measurement of the tensor analyzing power T_{20} for the reaction $\gamma d \to \pi^0 d$ / V.V. Gauzshtein [et al.] // Eur. Phys. J. – 2020. – Vol. 56, No. 6. – 169 (7).

Model of the reaction

We work in the framework of the plane wave impulse approximation (PWIA).



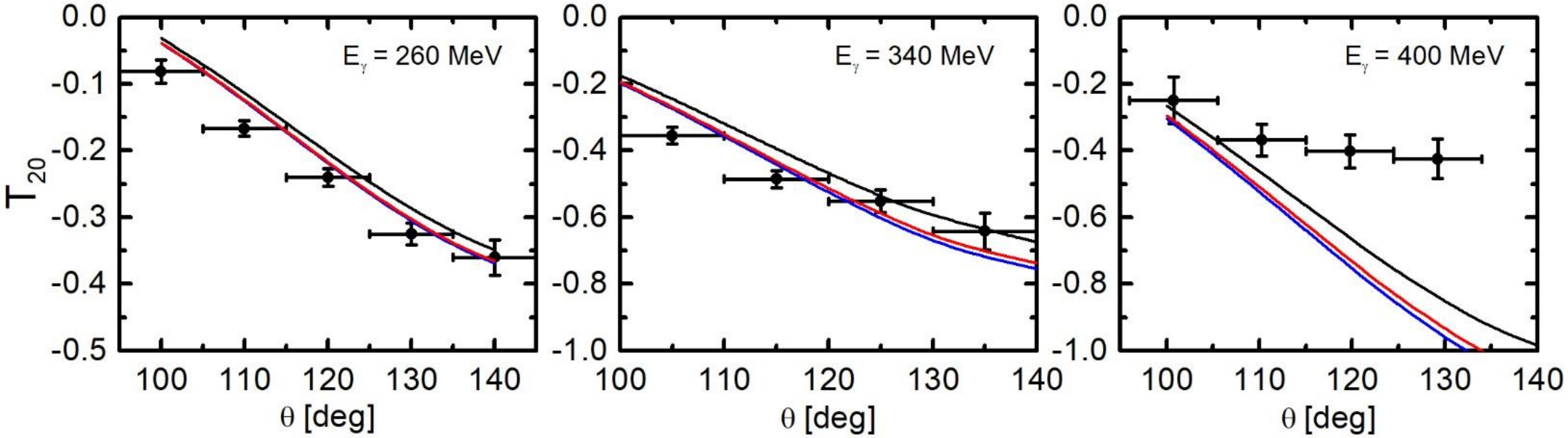
Model of the reaction

- For the deuteron vertex, we use the deuteron wave function obtained from CD-Bonn NN potential.
- For $\gamma N \to \pi N$ elementary amplitude we use unitary isobar model MAID07 in CGLN parameterization.

A unitary isobar model for pion photo- and electroproduction on the proton up to 1 GeV / D. Drechsel [et al.] //Nucl. Phys. A – 1999. – Vol. 645, Iss. 1 – P. 145–174.

Relativistic Dispersion Relation Approach to Photomeson Production / G.F. Chew [et al.] / Phys. Rev. – 1957. – Vol. 106, No. 6. – P. 1345–1355.

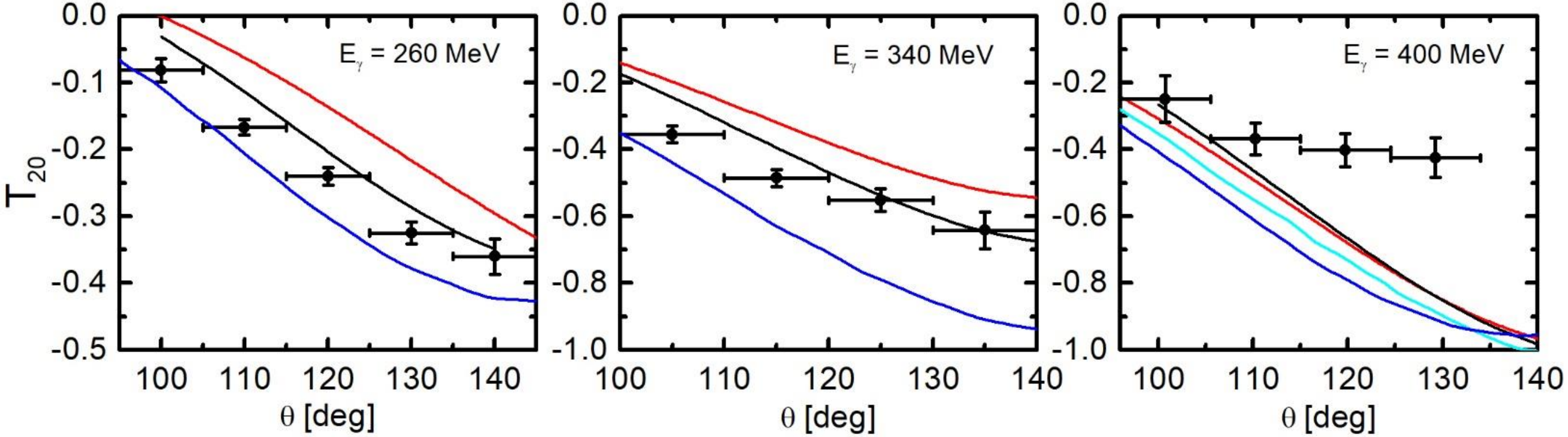
Potential dependence of the results for T_{20}



- Black line: CD-Bonn;
- Blue line: V18;
- Red line: Nijm93.

The results for NijmII coincide with the results for V18.

Model dependence of the results for T_{20}



Experimental data: V.V. Gauzshtein [et al.] // Eur. Phys. J. – 2020. – Vol. 56, No. 6. – 169 (7).

Black lines: MAID07 + CD Bonn deuteron wave function (our results).

Blue lines: Coherent π^0 and η photoproduction on the deuteron / S.S. Kamalov, L. Tiator, C. Bennhold // Phys. Rev. C – 1997. – Vol. 55, No. 1 – P. 98–110.

Red lines: MAID07 + CD Bonn wave function (E.M. Darwish // Private communication).

Cyan line: Coherent pion photoproduction on the deuteron in the Δ resonance region / P. Wilhelm, H. Arenhövel // Nucl. Phys. A. – 1995. – Vol. 593. – No. 4. – P. 435–462.

THANKS FOR YOUR ATTENTION!