Two-Pion Exchange Currents in Photodisintegration of the Deuteron

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Content

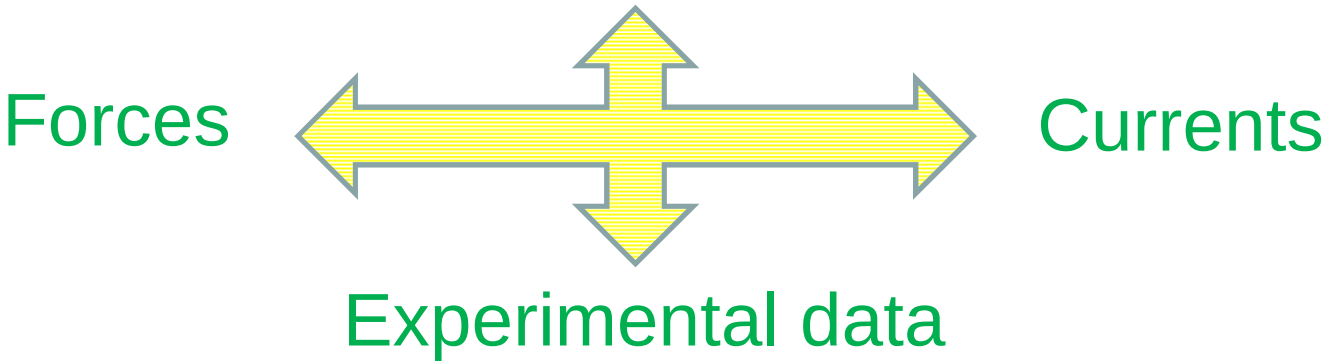
- Chiral Effective Field Theory (ChEFT)
- Electromagnetic current operators within ChEFT
- Calculations of polarization observables in photodisintegration of the deuteron
- Conclusions and outlook

Forces and currents

- Many models
- A lot of experience gained

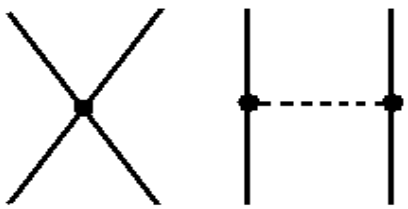
Problem of consistence:
we need a good theory!

Chiral Effective Field Theory

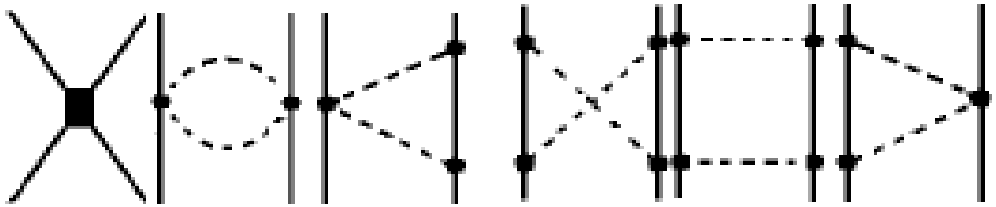


Forces and Currents

The LO nucleon-nucleon potential is given by one pion exchange (OPE) and contact terms.



$$V^{LO} = V_{\rm cont} + V_{1\pi}$$



$$V^{NLO} = V_{\rm cont} + V_{1\pi} + V_{2\pi}$$

The NLO corrections are due to one and two-pion exchanges (TPE) as well as new contact interactions. The N2LO and N3LO include corrections with many-pion exchanges and contact interactions in higher orders.

The current operator must be consistent with the nucleon-nucleon interaction.

The effective operator for two-nucleon (2N) system is a sum of the single nucleon operators and two-nucleon operator:

$$j^{\mu}_{\rm 2N} = j^{\mu}(1) + j^{\mu}(2) + j^{\mu}(1,\,2)\ .$$

Two-nucleon electromagnetic currents

$$j^{\mu}(1,2) = j^{\mu}_{mec}(1,2) + j^{\mu}_{cont}(1,2)$$

$$j^{\mu}_{mec}(1,2) = j^{\mu}_{\pi}(1,2) + j^{\mu}_{2\pi}(1,2) + \cdots$$

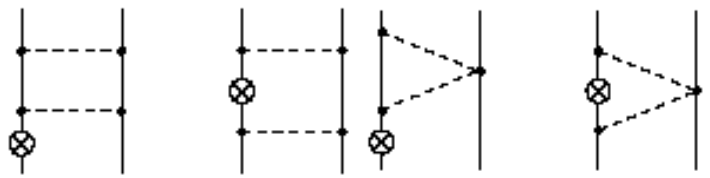
Two-pion exchange (TPE) currents in NLO arise from many complicated processes

S.Pastore et al.-TPE currents based on the time-order perturbation theory ('08)

Results by S. Kölling, E. Epelbaum et al. ('09)

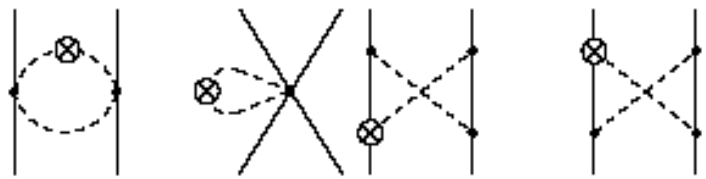
using the method of unitary transformation

Rederived:
single-nucleon current operators
one-pion exchange current operators



+ …

Derived:
(long-ranged) two-pion exchange current operators containing no free parameters



Work in progress:
contact terms

Phys. Rev. C **80**, 045502 (2009)

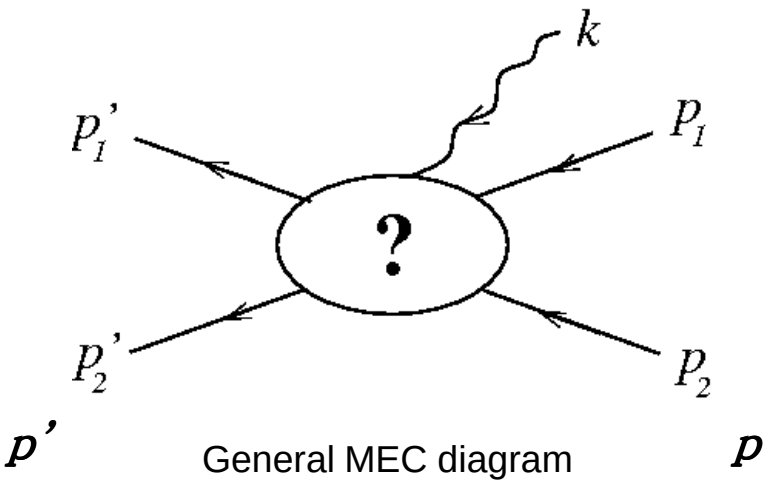
How do we apply the long-ranged two-pion exchange current operators?

We get contributions to:

- 0th component of the current operator (charge density) j^0
- vector components of the current operator $\vec{j}$

The most general expression for the current and the charge density in momentum space is given by:

$$j^0 = \sum_{\alpha=1}^{5} \sum_{\beta=1}^{8} f_\alpha^{\beta S}(\vec{q}_1, \vec{q}_2) T_\alpha O^{\beta S}; \qquad \vec{j} = \sum_{\alpha=1}^{5} \sum_{\beta=1}^{24} f_\alpha^{\beta}(\vec{q}_1, \vec{q}_2) T_\alpha \vec{O}^{\beta}$$



General MEC diagram

$$q_1 = p'_1 - p_1 = p' - p + \tfrac{1}{2} k$$
$$q_2 = p'_2 - p_2 = p - p' + \tfrac{1}{2} k$$
$$k = q_1 + q_2$$

So, for the photodisintegration of the deuteron, we work with the following operators:

$$\left.\begin{aligned}
O^3 &= \vec{q}_1 \times \vec{\sigma}_2 + \vec{q}_2 \times \vec{\sigma}_1 \\
O^4 &= \vec{q}_1 \times \vec{\sigma}_2 - \vec{q}_2 \times \vec{\sigma}_1 \\
O^5 &= \vec{q}_1 \times \vec{\sigma}_1 + \vec{q}_2 \times \vec{\sigma}_2 \\
O^6 &= \vec{q}_1 \times \vec{\sigma}_2 - \vec{q}_2 \times \vec{\sigma}_2 \\
O^7 &= \vec{q}_1(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_2) + \vec{q}_2(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_1) \\
O^8 &= \vec{q}_1(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_2) - \vec{q}_2(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_1) \\
O^9 &= \vec{q}_2(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_2) + \vec{q}_1(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_1) \\
O^{10} &= \vec{q}_2(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_2) - \vec{q}_1(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_1)
\end{aligned}\right\} \mathbf{T_2}$$

$$O^2 = \vec{q}_1 - \vec{q}_2 \quad \Big\} \mathbf{T_3}$$

$$\boxed{T_2 = (\tau_1 - \tau_2)_3 \qquad T_3 = (\tau_1 \times \tau_2)_3}$$

Working with *Mathematica* is quite important!

<u>For example</u>:

$f_2{}^8(q_1, q_2)$

for combination

$$\boxed{T_2 O^8 = (\tau_1 - \tau_2)_3 (\vec{q}_1(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_2) - \vec{q}_2(\vec{q}_1 \cdot \vec{q}_2 \times \vec{\sigma}_1))}$$

$$\begin{aligned}
f_2{}^8 = \frac{e g_A^2 \pi}{2F_\pi^4} \Big[& 8\pi g_A^2 (q_1^2 - 2M_\pi^2) I^{(d+4)}_{(3,1,2)} - g_A^2 M_\pi^2 I^{(d+2)}_{(2,1,2)} + \\
& 192\pi^2 g_A^2 q_1^2 I^{(d+6)}_{(4,1,2)} - 64\pi^2 g_A^2 q_1 q_2 z I^{(d+6)}_{(3,2,2)} + 8\pi g_A^2 I^{(d+4)}_{(2,1,2)} \\
& + (g_A^2 - 1) I^{(d+2)}_{(2,1,0)} + 16\pi (g_A^2 - 1) I^{(d+4)}_{(3,1,0)} \Big] - (1 \leftrightarrow 2),
\end{aligned}$$

where
$z = \hat{q}_1 \, \hat{q}_2$
functions $I(d)(v1,v2,v3)$ correspond to the three-point functions

Results from S. Kölling *et al*. Phys. Rev. C **80**, 045502 (2009)

Two nucleon reactions

The formalism requires knowledge of the consistent potentials and electromagnetic currents.

$$V_{2N}\,,\quad j^{\mu}$$

$$\left|\Psi_{\text{bound}}\right\rangle \qquad \left|\Psi^{\text{pn}}_{\text{scatt}}\right\rangle = \left(1 + G_0 t\right)\left|\text{pn}\right\rangle$$

$$\left(t = V_{2N} + V_{2N} G_0 t\right)$$

G_0 – the free propagator of two nucleon

t – satisfies the Lippmann – Schwinger equation

$$N_{\mu} \equiv \left\langle \Psi^{\text{pn}}_{\text{scatt}} \middle| j^{\mu} \middle| \Psi_{\text{bound}} \right\rangle$$

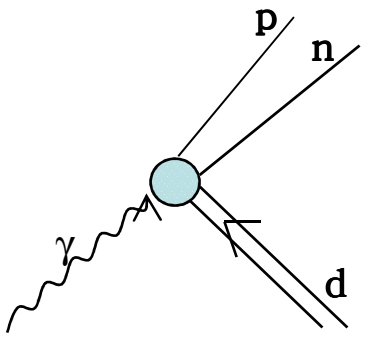
All calculations were made with the chiral potentials and currents.

The AV18 potential and the corresponding currents were used as the reference calculation.

For a given chiral N2LO NN potential we produce:
the deuteron wave function and matrix elements of the t-operator

Photodisintegration of the deuteron

$$\gamma + {}^2H \rightarrow p + n$$



Calculations of polarization observables for two photon energies.

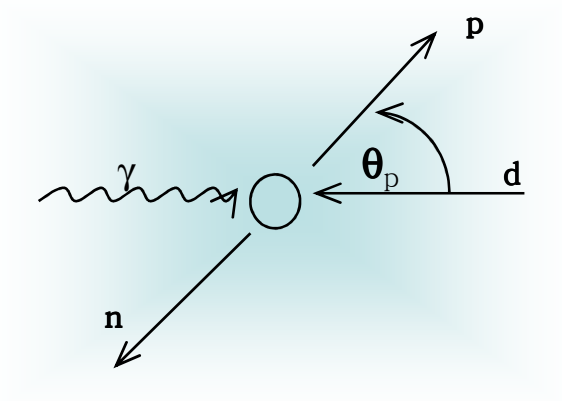
For polarized deuteron target we have

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \sum_{kq} (-1)^q t_{kq} T_{k-q}(\theta)$$

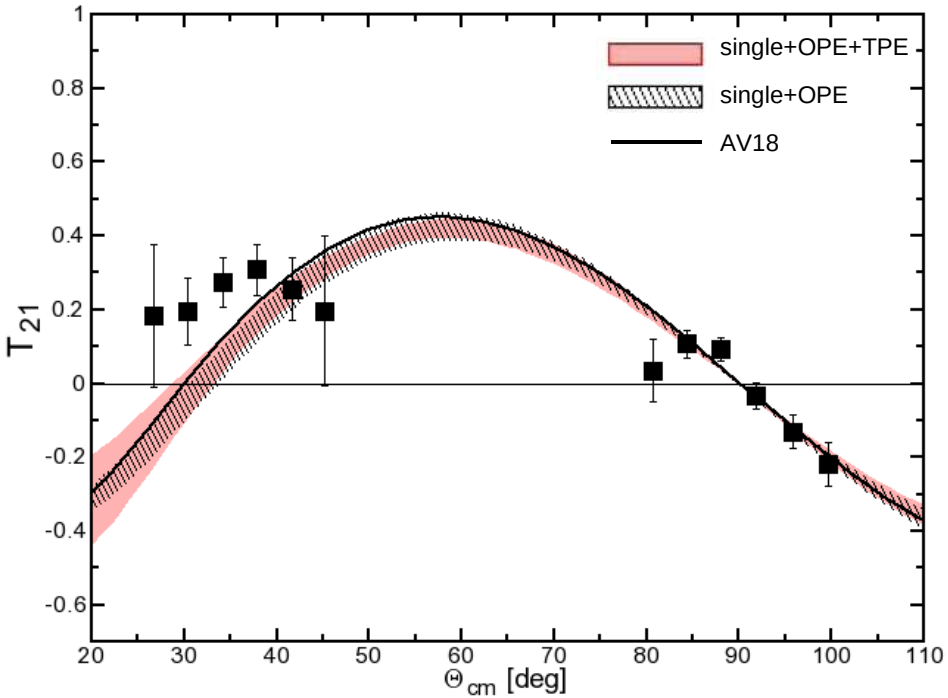
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \left[1 + 2\,\mathrm{Re}(\mathrm{i}\,t_{11})i\,\mathrm{T}_{11} + t_{20}\,\mathrm{T}_{20} + 2\,\mathrm{Re}(t_{21})\,\mathrm{T}_{21} + 2\,\mathrm{Re}(t_{22})\,\mathrm{T}_{22}\right]$$

We calculated the following observables:

- Deuteron analyzing powers: T_{20}, T_{21}, T_{22}
- Photon analyzing power Σ_l
- Differential cross-section

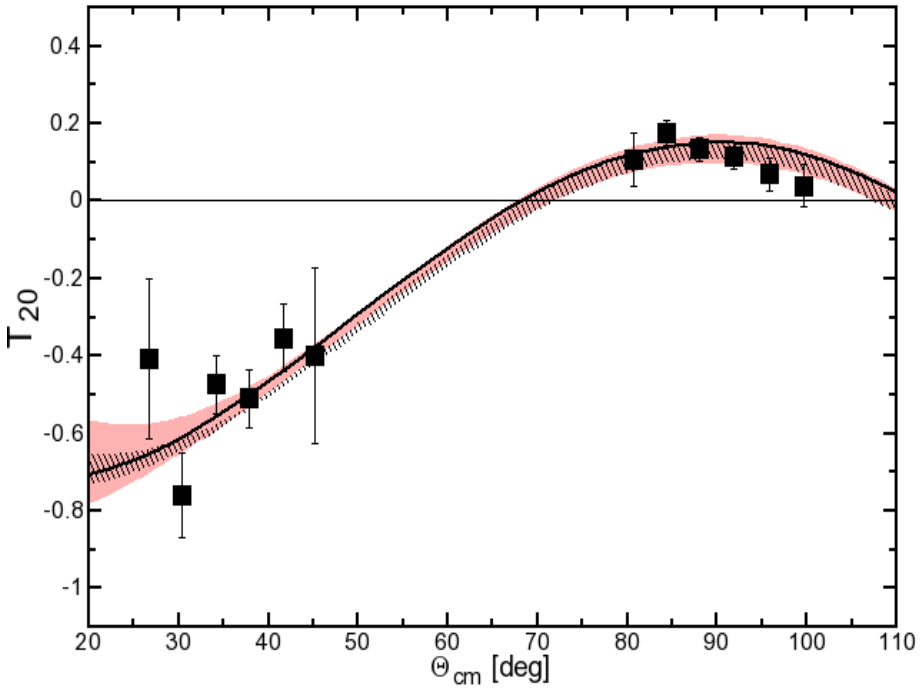


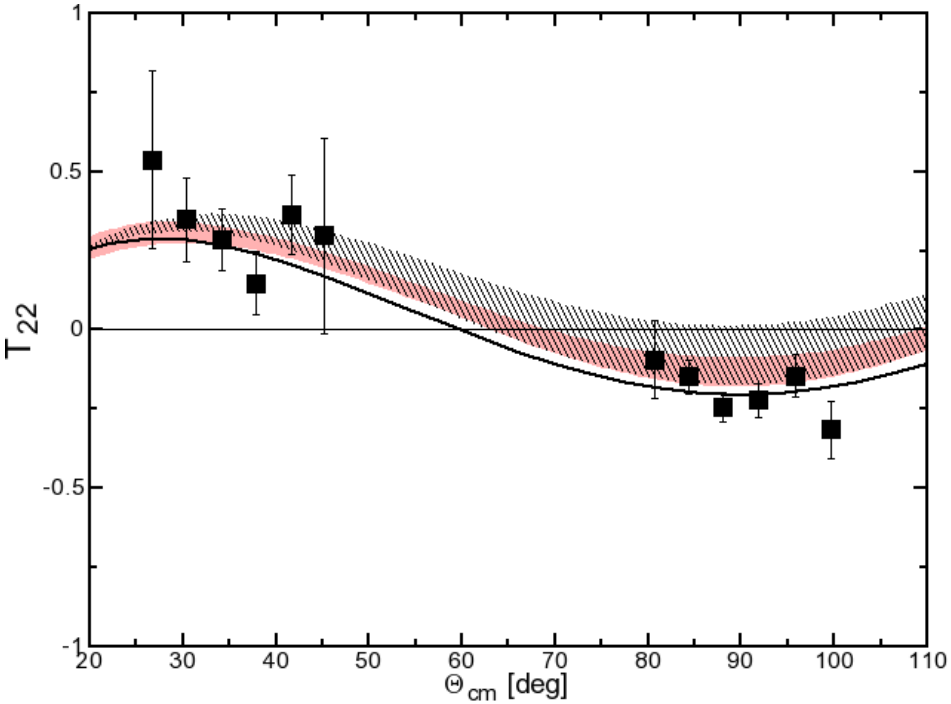
Results for the deuteron tensor analyzing powers for the photon energy bin **25 - 45 MeV**



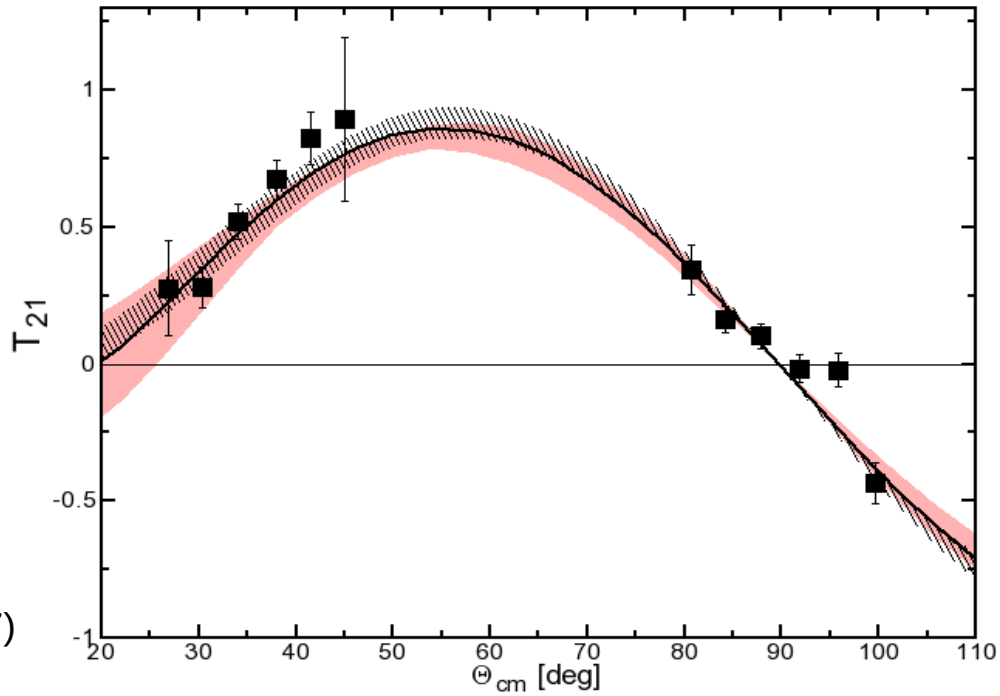
Experimental data from

A. Rachek *et al*., Phys. Rev. Lett. **98**,182303 (2007)





Results for the deuteron tensor analyzing powers for the photon energy bin **45 - 65 MeV**



Experimental data from

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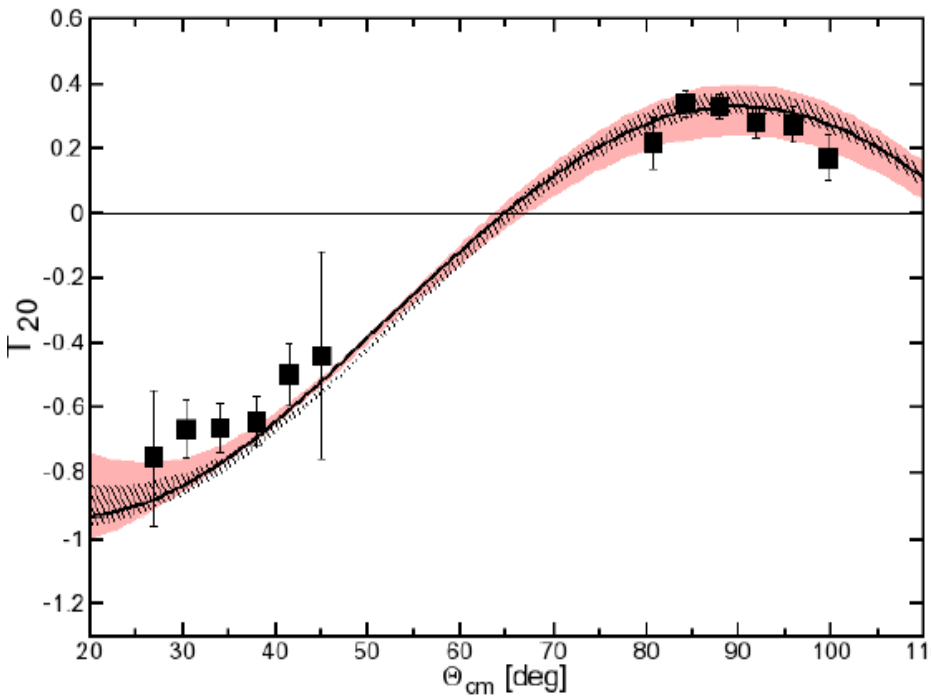
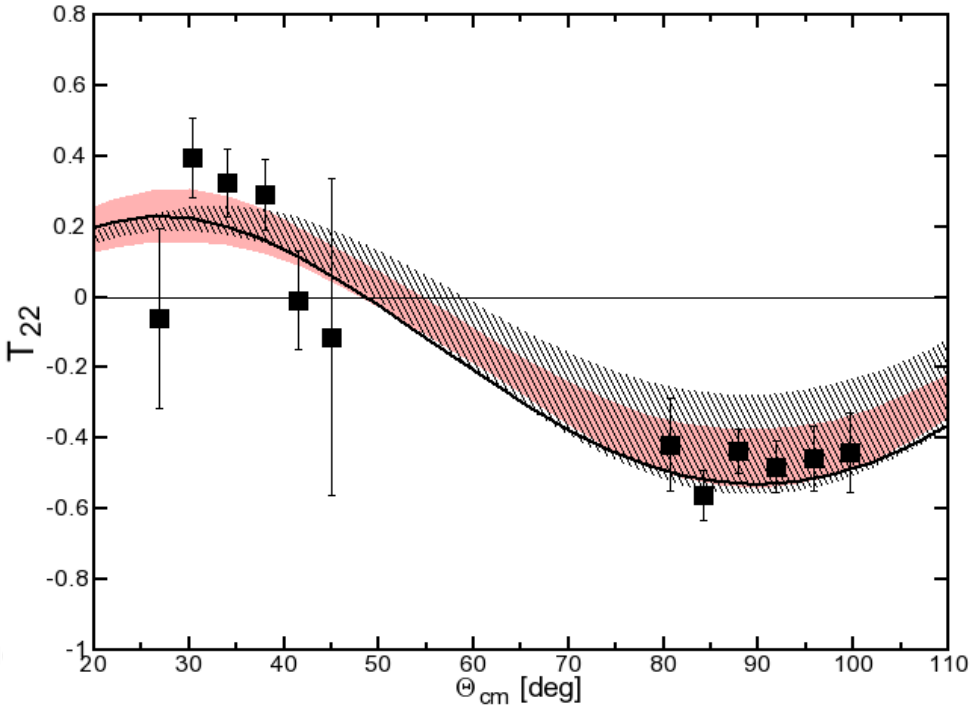
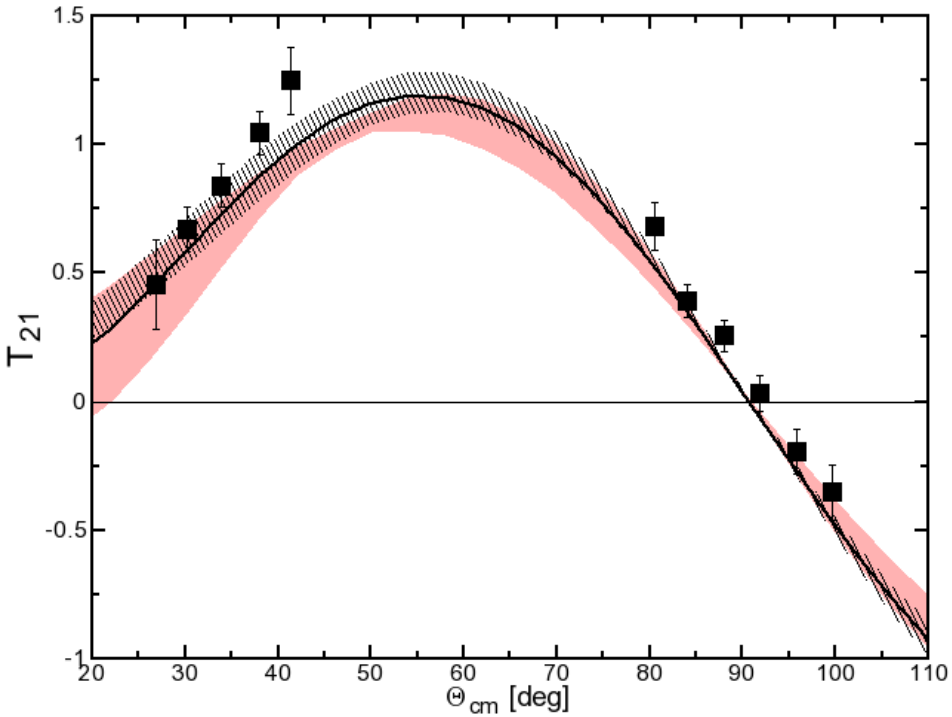


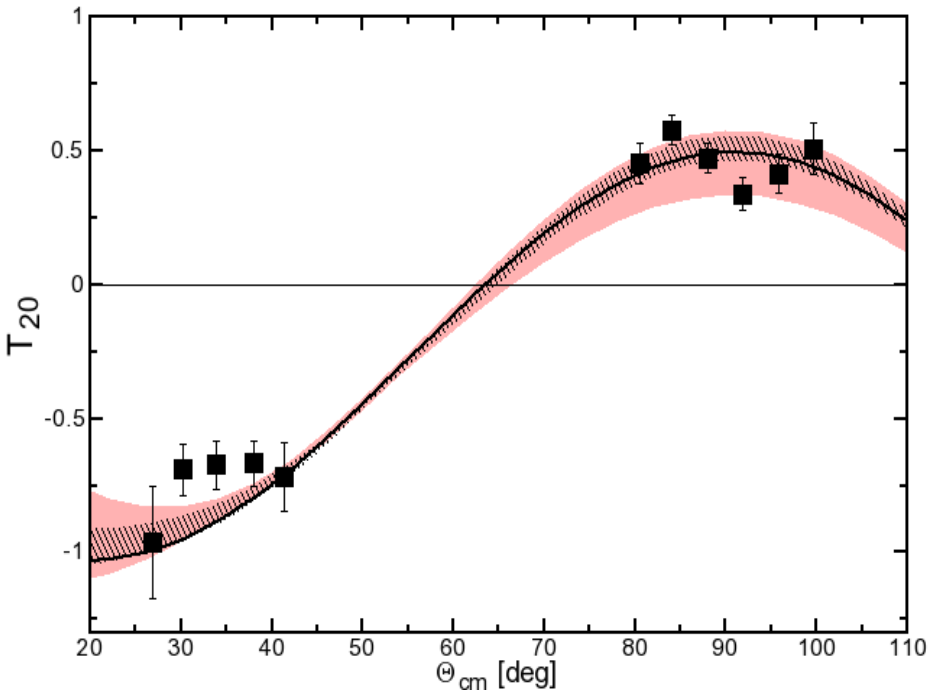


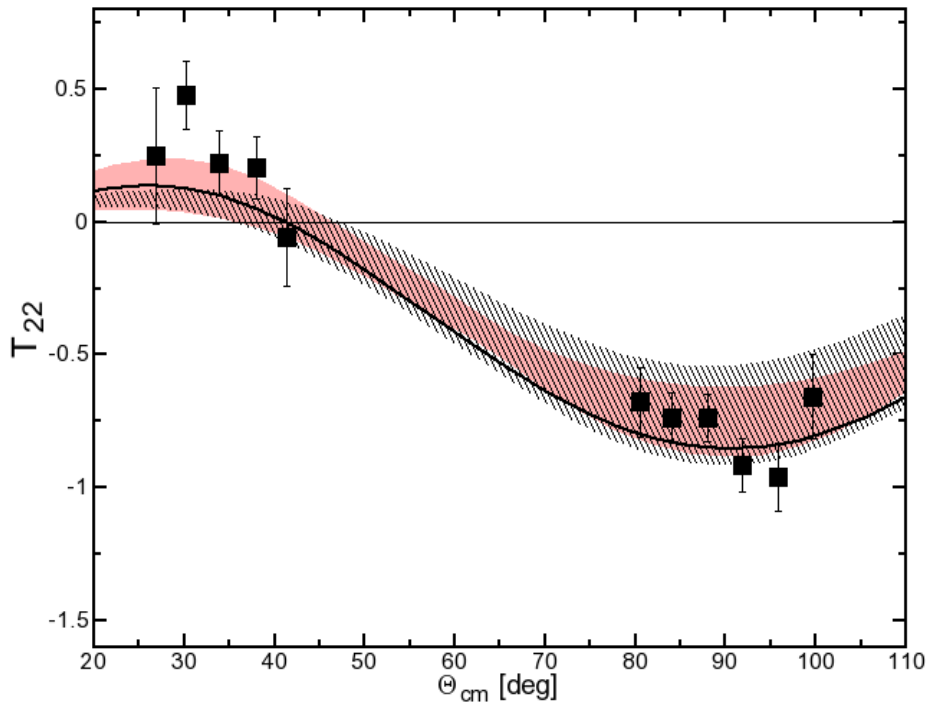
Results for the deuteron tensor analyzing powers for the photon energy bin **65 - 100 MeV**

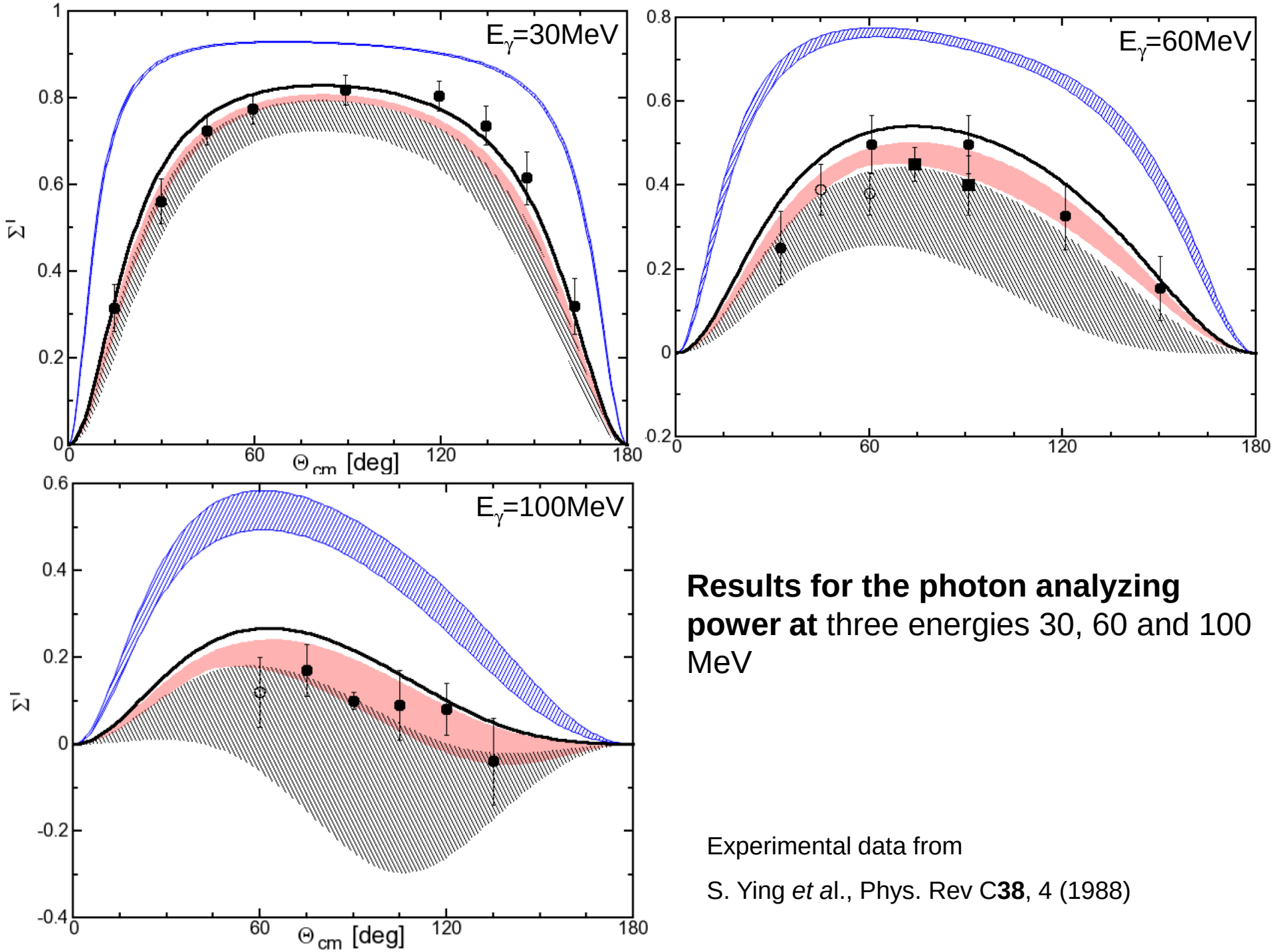


Experimental data from

A. Rachek *et al*., Phys. Rev. Lett. **98**,182303 (2007)



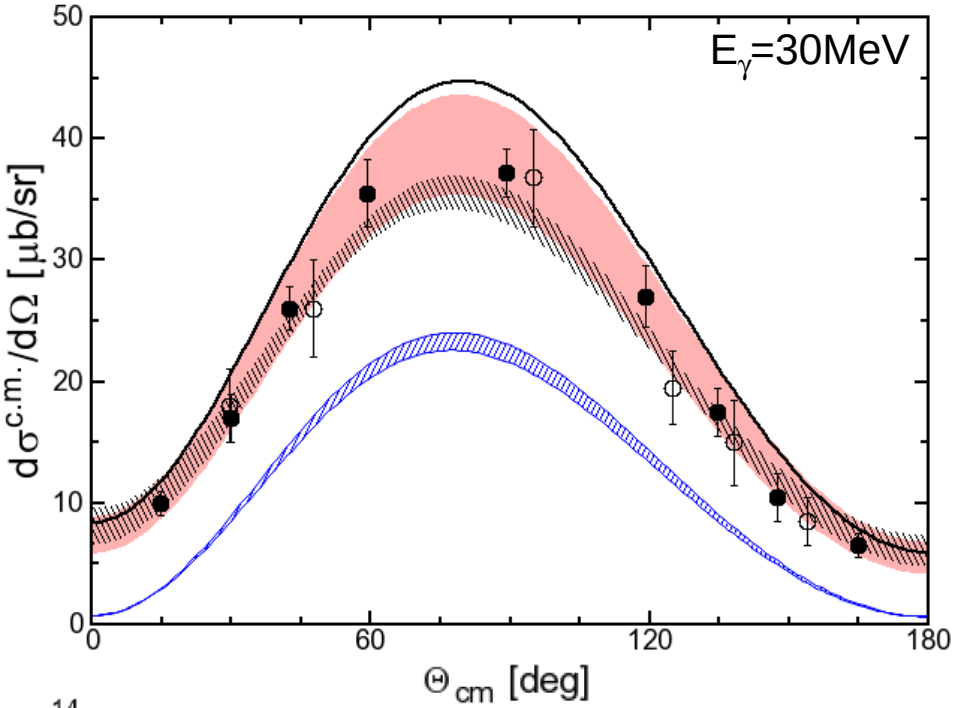


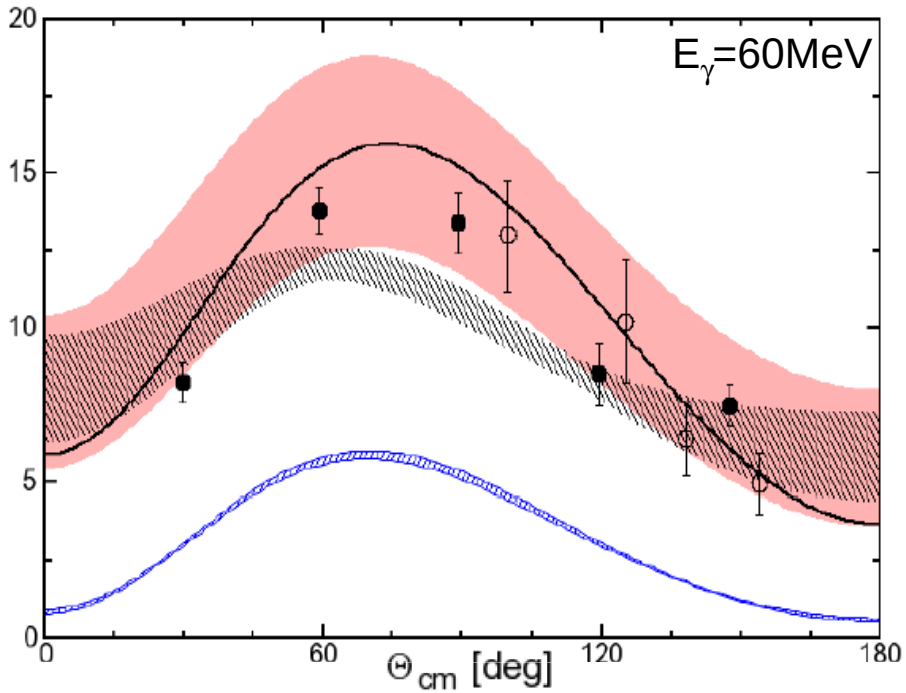


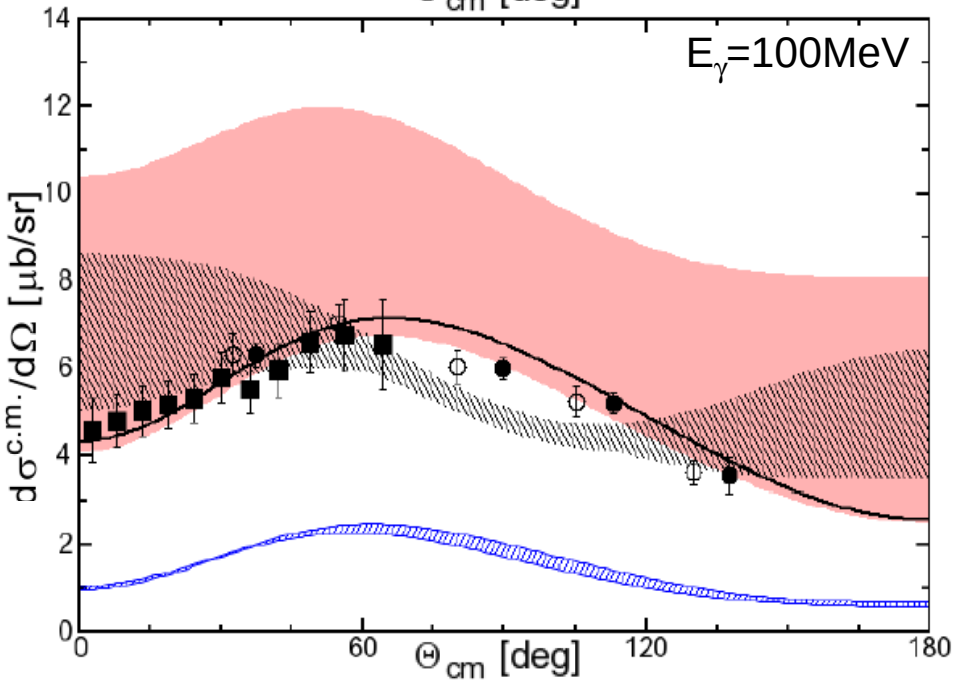
Results for the photon analyzing power at three energies 30, 60 and 100 MeV

Experimental data from

S. Ying *et al*., Phys. Rev C**38**, 4 (1988)







Results for the differential cross section for three photon energies 30, 60 and 100 MeV

Experimental data from

S. Ying *et al.*, Phys. Rev. C**38**,4 (1988)

Conclusions and outlook

- ChEFT has become a standard tool in nuclear physics – it offers a **consistent picture of nuclear forces and nuclear current operators.**
- Chiral 2N and 3N potentials are already used for studying the structure of nuclei and nuclear reactions.
- We used results of ChEFT to compute electromagnetic reactions with few nucleon systems. In particular, we considered **low energy photodisintegration reaction.**
- **We compared predictions based on this approach to the results obtained within** a more traditional framework, where the high precision nucleon-nucleon potential **AV18** and the current operator including meson exchange currents consistent with this force is employed.
- We have shown results for the unpolarized cross sections and various polarization observables.
- The main aim of our work is to create a complete framework for **the description of two- and three-nucleon processes** including many-body **electromagnetic currents and forces in the ChEFT** approach.

Thank you for your attention!

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TOWARZYSTWO DOKTORANTÓW UJ

How we proceed

For deuteron one needs:

$$N^{\mu} \equiv < \vec{p}_0 \,|\left(1 + t(\frac{p_0^2}{m} + i\varepsilon)G_0(\frac{p_0^2}{m} + i\varepsilon)\right) j_{2N}^{\mu}(k)\,|\,\phi_d >$$

How do we do PWD?

$$< p'(l's')\,j'm';t'm_{t'}\,|\,j_{\alpha\beta}(\vec{k}\,\|\,\hat{z})\,|\,p(ls)\,jm;tm_t >=$$

$$\int d\hat{p}'\int d\hat{p}\sum_{m_{l'}} C(l's'\,j';m_{l'},m'-m_{l'},m')Y^*_{l'm_{l'}}(\hat{p}')$$

$$\sum_{m_l} C(lsj;m_l,m-m_l,m)Y_{lm_l}(\hat{p})\,f_{\alpha\beta}(q_1,q_2,\hat{q}_1\cdot\hat{q}_2)$$

$$< t'm_{t'}\,|\,T_{\alpha}\,|\,tm_t >< s'm'-m_{l'}\,|\,O_{\beta}(\vec{q}_1,\vec{q}_2)\,|\,sm-m_l >,$$

$$m' = m'(m,\beta)$$

$$m_{t'} = m_t$$

All integrals, in particular spin and isospin matrix elements:

$$\sum_{m_{l'}} C(l's'j';m_{l'},m'-m_{l'},m')Y^*_{l'm_{l'}}(\hat{p}')$$

$$\sum_{m_l} C(lsj;m_l,m-m_l,m)Y_{lm_l}(\hat{p})\, f_{\alpha\beta}(q_1,q_2,\hat{q}_1\cdot\hat{q}_2)$$

$$<t'm_{t'}|T_\alpha|tm_t><s'm'-m_{l'}|O_\beta(\vec{q}_1,\vec{q}_2)|sm-m_l>$$

are prepared using *Mathematica*

For a given set of quantum numbers: $\{l',s',j',t',l,s,j,m,t,m_t\}$ we identify all non-zero cases and produce a Fortran code (again using *Mathematica*) to get the integrals calculated on a parallel machine.