

ECT* -Workshop, July 25-29, 2005:
Probing microscopic structure of the lightest nuclei
in electron scattering at JLab energies and beyond

ELECTROMAGNETIC PRODUCTION OF MESONS ON THE DEUTERON: ACHIEVEMENTS AND PROBLEMS

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1. Introduction and motivation
2. Theoretical framework
3. Specific reactions on the deuteron:
 - (a) Single pion photoproduction
 - (b) Eta photoproduction
 - (c) Double pion photoproduction
4. The GDH sum rule for the deuteron
5. Conclusion and outlook

1. INTRODUCTION AND MOTIVATION

PRESENT THEORETICAL DILEMMA:

- We believe that the dynamics of strong interaction is governed by QCD with basic quark-gluon degrees of freedom.
- However, in the non-perturbative regime it is difficult to solve QCD at present in terms of these d.o.f.
- Therefore heuristic introduction of EFFECTIVE degrees of freedom in terms of meson and nucleon d.o.f., i.e. implicit elimination of QCD d.o.f.
- Lacking proper methods for explicit elimination, hadron PROPERTIES and COUPLINGS are taken from PHENOMENOLOGY.
- For nuclear structure further reduction by eliminating meson d.o.f \rightarrow purely BARYONIC D.O.F., either nucleons only or nucleons and isobars, with construction of BARYONIC EFFECTIVE OPERATORS as two- and many-body operators, e.g. NN-interaction, three-body forces, exchange currents.

SPECIFIC PROBLEMS:

- (1) The role of MANY-BODY FORCES, in particular, how well do we understand THREE-BODY FORCES?
- (2) How reliable are our models for other TWO- and MANY-BODY OPERATORS induced by the strong interaction like, e.g., meson exchange currents?
- (3) How reliable is the implicit OFF-SHELL EXTRAPOLATION of the effective NN-interaction and other operators, e.g., e.m. one-body current, which are fixed by parametrizing the on-shell situation alone? In principle, vertices and form factors, reflecting the internal structure of the participating hadrons, will have specific off-shell extensions determined by their internal d.o.f.
- (4) A related problem is: To what extent will SINGLE PARTICLE PROPERTIES of BOUND NUCLEONS be changed? This problem is of particular interest with respect to neutron properties.
CAVEAT: “medium modification” is a purely theoretical concept, because it cannot be separated from other competing interaction effects!
- (5) What is the role of RELATIVITY?

WHY STUDY E.M. MESON PRODUCTION ON FEW-NUCLEON SYSTEMS?

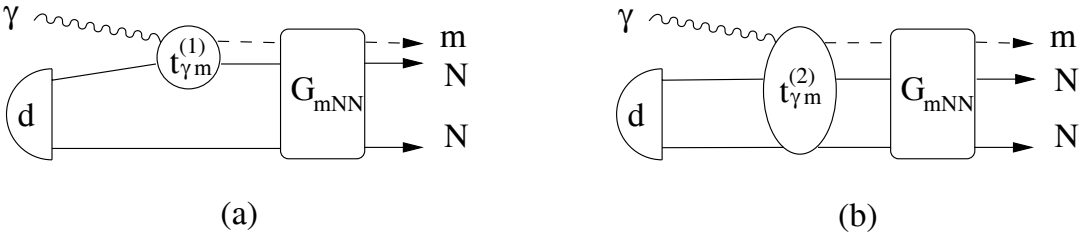
- Study of the specific role of meson d.o.f in nuclear dynamics.
- Few-body nuclei are laboratories for testing present models of the strong interaction.
- One can make “exact” predictions for reactions on light nuclei without introducing uncontrollable numerical approximations.
- Few-body nuclei serve as effective neutron targets.
- Study of possible medium influences on elementary process.

The virtues of the electromagnetic probe as a diagnostic tool follow from the fact, that

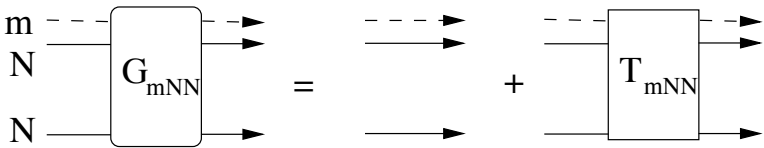
- its interaction with matter is well known already from macroscopic phenomena, and
- its interaction is weak enough so that in most cases lowest order perturbation is sufficient, allowing quite a simple interpretation of observables in terms of current matrix elements.

2. THEORETICAL FRAMEWORK

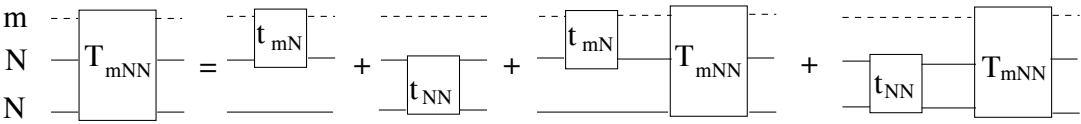
Basic process for meson photoproduction on the deuteron with e.m. one- and two-body production operators:



with final state three-body mNN -propagator:

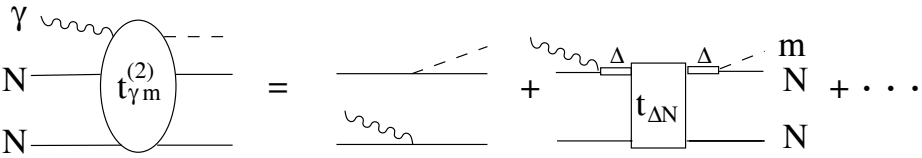


T_{mNN} denotes t-matrix of final state interaction:



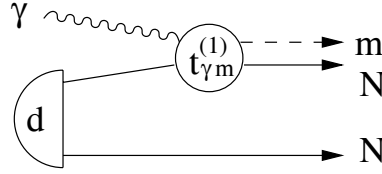
with two-body mN - and NN -t-matrices.

Examples for two-body operators:



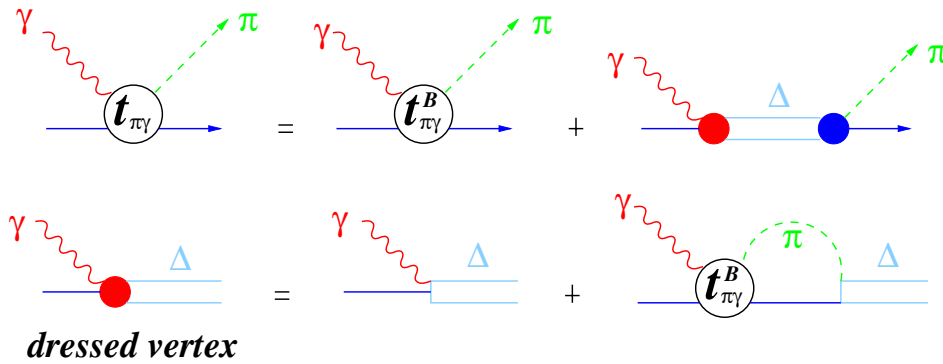
VARIOUS APPROXIMATIONS:

- Impulse approximation (IA) neglecting $t_{\gamma m}^{(2)}$ and T_{mNN} :



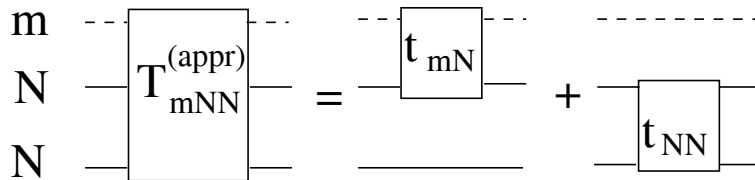
One-body current from

- (i) unitarized tree diagrams of effective Lagrangean,
- (ii) dynamical model



- (iii) phenomenological model (e.g. MAID).

- Approximate treatment of final state interaction by including rescattering in two-body subsystems only:



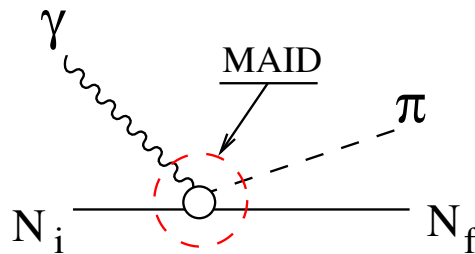
3. SPECIFIC REACTIONS ON THE DEUTERON

(a) Incoherent pion production $\gamma d \rightarrow \pi NN$

(nucl-th/0506015, nucl-th/0506018)

INGREDIENTS:

- Impulse approximation plus approximate FSI ($T_{\pi NN}^{(appr)}$).
- Elementary amplitude $\gamma N \rightarrow \pi N$ from MAID 2003:

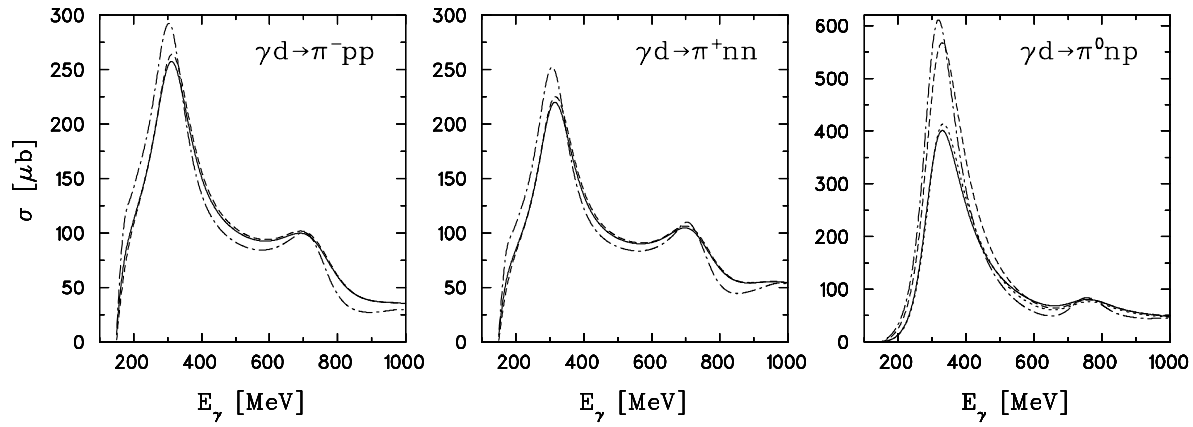


- NN -interaction: Separable parametrization of Paris potential, partial waves up to $^{2s+1}L_j = {}^3D_3$.
- πN -interaction: Separable model of S. Nozawa *et al.*, partial waves up to $L_{2T2J} = D_{35}$.

PROBLEM:

- Uncertainties due to off-shell extrapolation of the elementary amplitude.

RESULTS FOR TOTAL CROSS SECTION:



Dashed: IA; Solid: IA+FSI; Dash-dot: elementary reaction.
 Right panel: Dotted: IA with orthogonalization.

▷ For π^\pm NN -FSI effects are small and πN -FSI negligible, broadening of resonance structure.

- Average cross section is the same for N and d

$$\bar{\sigma}(E) = \frac{1}{E - E_{th}} \int_{E_{th}}^E \sigma(E_\gamma) dE_\gamma$$

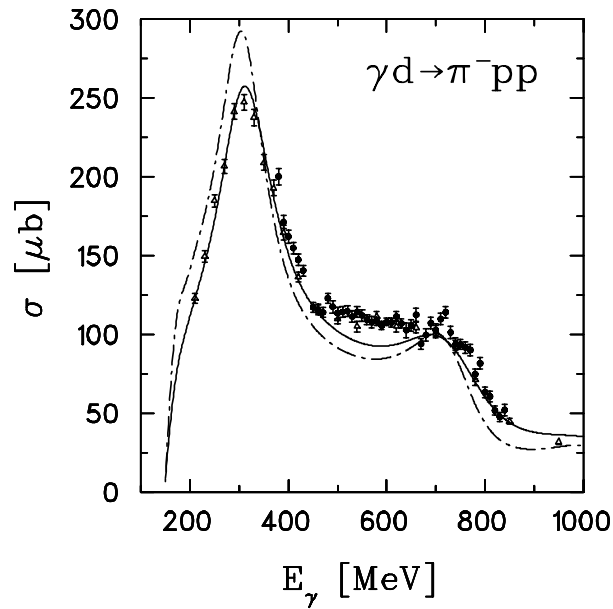
- π^- : $\bar{\sigma}_{\gamma d}(1 \text{ GeV}) = 106.95 \mu\text{b} \approx \bar{\sigma}_{\gamma n}(1 \text{ GeV}) = 106.36 \mu\text{b}$
- π^+ : $\bar{\sigma}_{\gamma d}(1 \text{ GeV}) = 100.82 \mu\text{b} \approx \bar{\sigma}_{\gamma p}(1 \text{ GeV}) = 101.73 \mu\text{b}$

▷ For π^0 NN -FSI effects are sizeable. Reduction of σ^{IA} in the $\Delta(1232)$ region.

- FSI-effects mainly due to non-orthogonality of NN -final plane wave to deuteron: $\langle np(IA) | d \rangle \neq 0$.
- Orthogonalization of NN -plane wave eliminates most of FSI effect (see IA-d curve).

COMPARISON WITH DATA FOR $\gamma d \rightarrow \pi^- pp$:

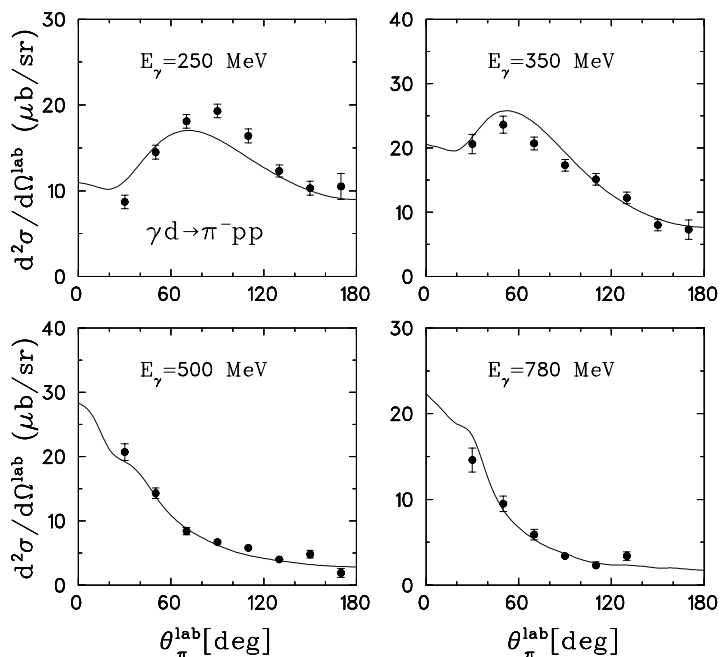
- Total cross section:



Dash-dot: elementary reaction;

Exp. data: P. Benz *et al.* (1973) and M. Asai *et al.* (1990).

- Angular distributions:

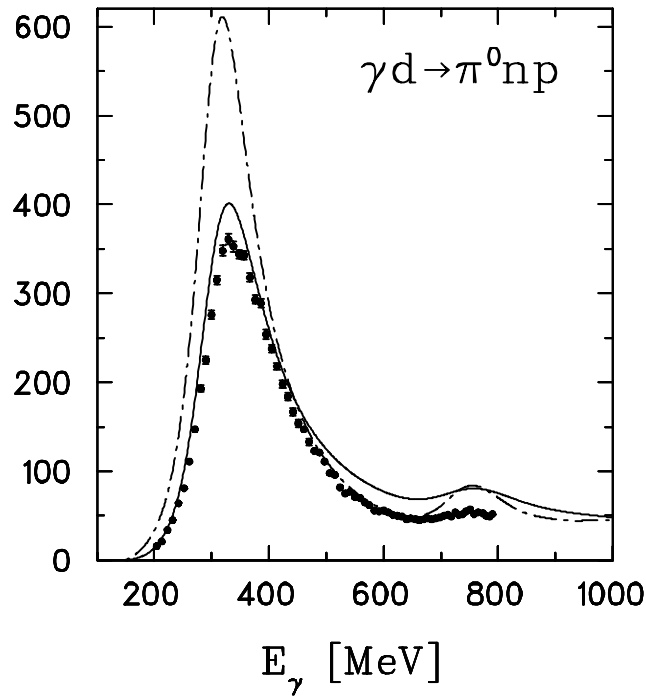


Exp. data: P. Benz *et al.* (1973).

▷ Satisfactory agreement over a wide energy region.

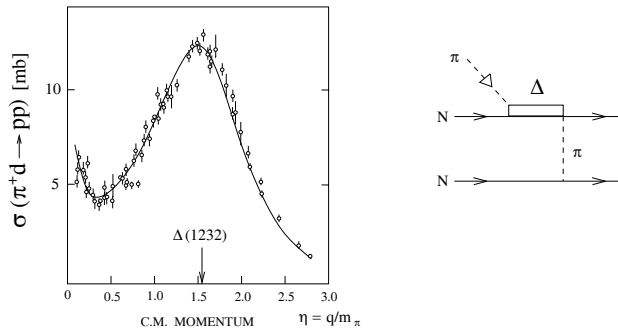
COMPARISON WITH DATA FOR $\gamma d \rightarrow \pi^0 np$:

- Total cross section:



Exp. data: B. Krusche *et al.* (1999).

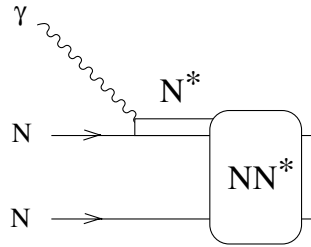
- ▷ Slight overestimation in $\Delta(1232)$ region.
Perhaps, two-nucleon absorption is missing.



- ▷ Strong disagreement in the second resonance region,
 $\sigma^{th} \approx 1.5 \sigma^{exp}$.

POSSIBLE EXPLANATIONS?

▷ Additional absorption mechanism?



- But: Why is same effect not seen in $\gamma d \rightarrow \pi^- pp$?

▷ Is neutron amplitude smaller than predicted by MAID in this energy region, i.e.

$$\sigma(\gamma n \rightarrow \pi^0 n) < \sigma^{MAID}(\gamma n \rightarrow \pi^0 n)?$$

- According to calculations for second resonance region

$$\sigma(\gamma d \rightarrow \pi^0 np) \approx \sigma(\gamma p \rightarrow \pi^0 p) + \sigma(\gamma n \rightarrow \pi^0 n)$$

- Thus Krusche *et al.* conclude from experiment

$$R = \sigma(d(\gamma, \pi^0 p)) / \sigma(d(\gamma, \pi^0 n)) \approx 3.$$

- However, Bacci *et al.*, PLB **39** (1972): $R \approx 1$.

- New direct measurement of this ratio is needed!

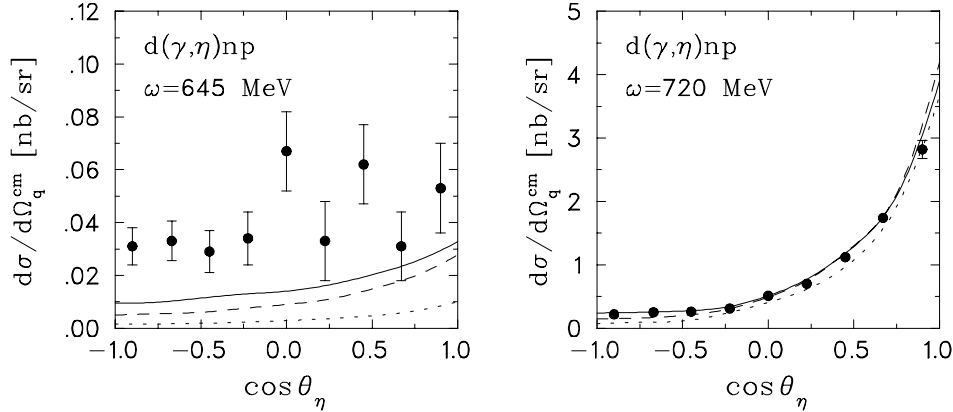
▷ Large error due to off-shell extrapolation of MAID?

- Comparison of experimental results for

$$\sigma(\gamma d \rightarrow \pi^+ nn) \text{ and } \sigma(\gamma p \rightarrow \pi^+ n) \text{ could clarify the role of "deuteron effects".}$$

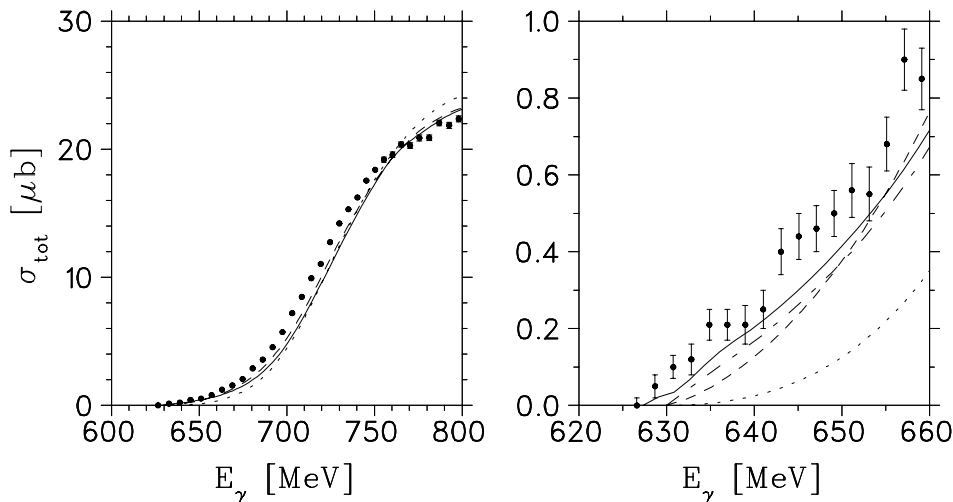
(b) Incoherent eta production $\gamma d \rightarrow \eta NN$

- FSI is very important near threshold (Z.Phys. A **359** (1997)):



Dotted: IA; Dashed: IA + NN -rescattering; Solid: IA + $T_{\eta NN}^{(appr)}$.
Exp.: B. Krusche *et al.*, PRL (1995)

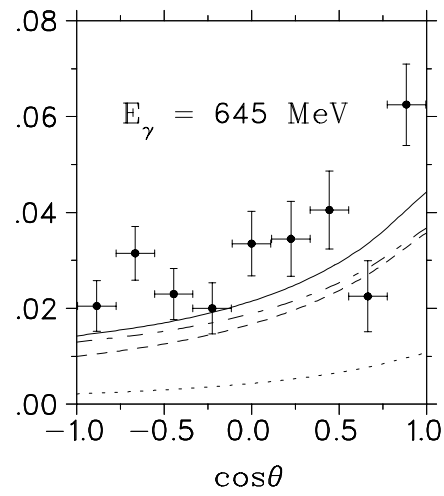
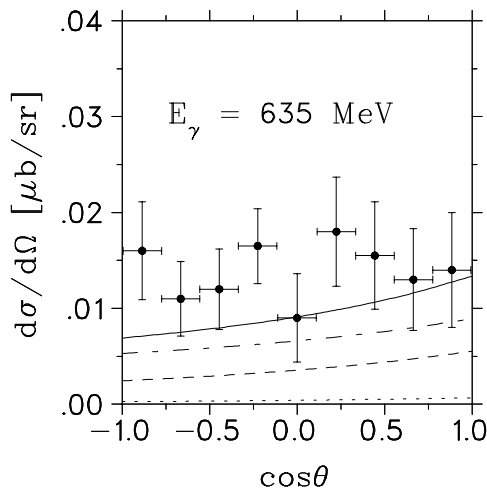
- Three-body treatment of ηNN interaction is needed (Nucl.Phys. A **359** (2001)).



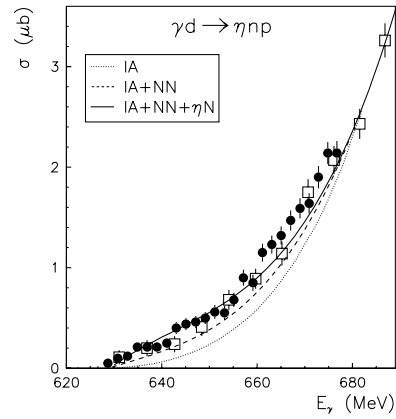
Exp.: V. Hejny *et al.*, EPJA **13** (2002).

Dotted: IA; Dashed: IA + $T_{\eta NN}^{(appr)}$

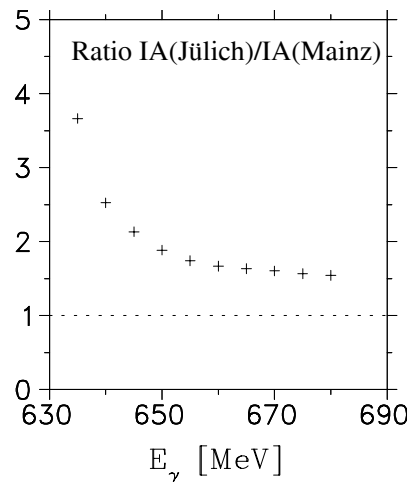
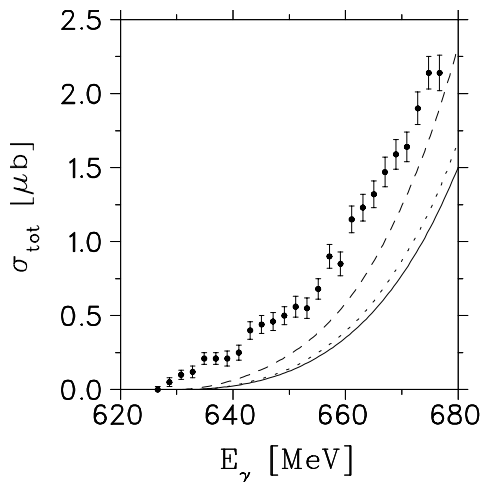
Dash-dot: IA + $T_{\eta NN}$ (3-body); Solid: + coherent contribution.



- Results at variance with Jülich-model (A.Sibirtsev *et al.*, PRC **64** (2001); PRC **65** (2002); PRC **65** (2002)).
- Already simple rescattering model can reproduce the experimental cross section.
- not confirmed by Sauermann *et al.* (PLB 409 (1997)) and our calculation.



IA shows large differences between Jülich and Mainz, which cannot be explained by differences between the model ingredients.



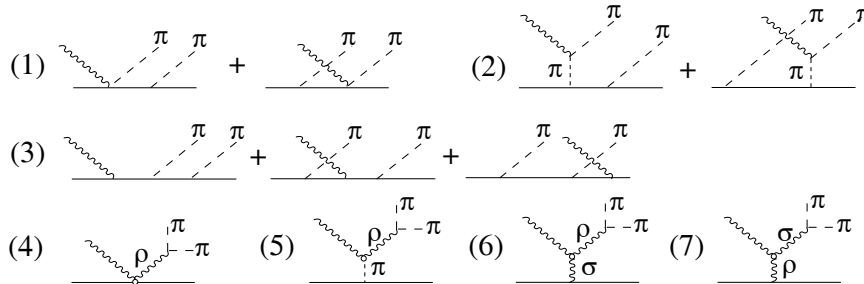
Dashed: A.Sibirtsev *et al.*; Dotted: C.Sauermann *et al.*;
Solid: our result.

(c) Incoherent two-pion production

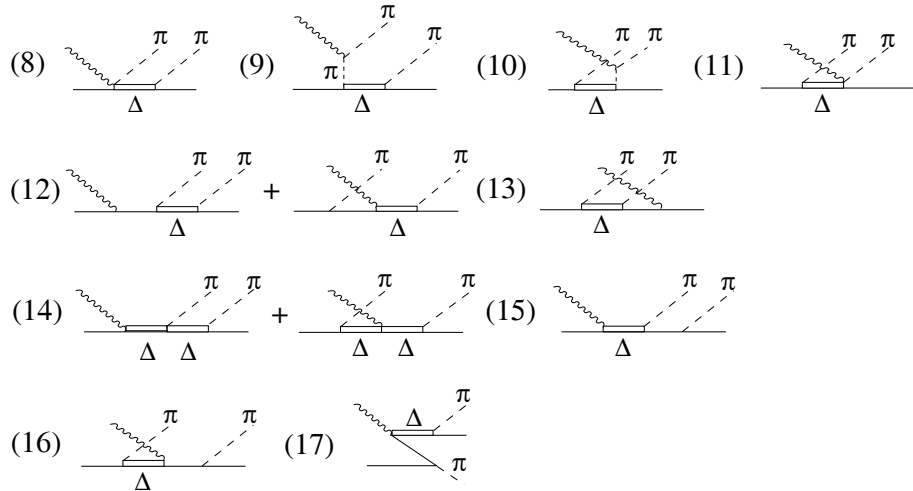
THE MODEL FOR THE ELEMENTARY REACTION:

- Tree diagrams with Born and resonance contributions.
- Resonances: $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $S_{31}(1620)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{33}(1700)$, $P_{13}(1720)$
- Diagrams:

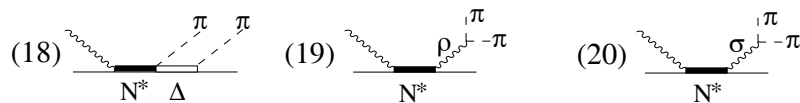
N-BORN TERMS



Δ -BORN TERMS

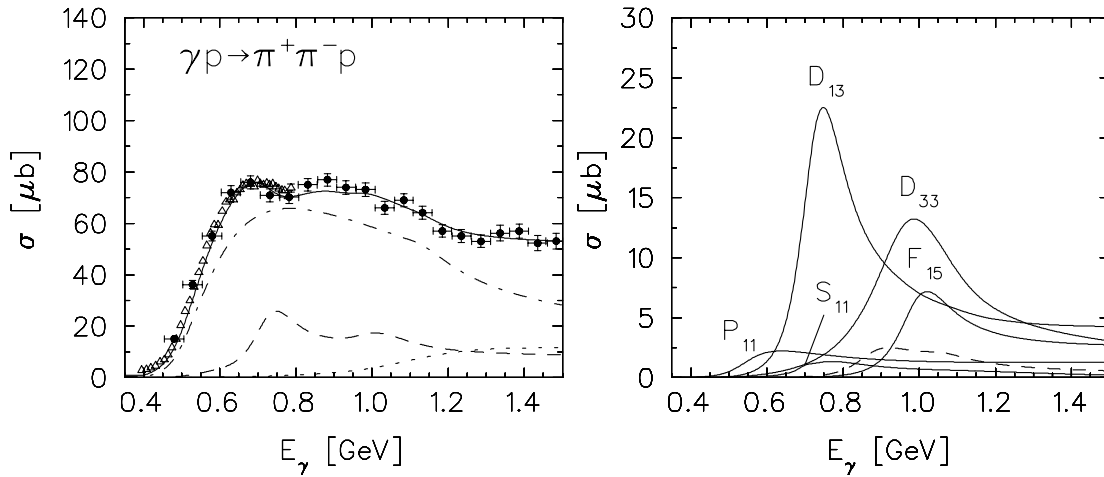


RESONANCE TERMS



- Resonance parameters and coupling strengths from experiment. One fit parameter.
- Model is valid up to $E_\gamma = 1.5$ GeV

TOTAL CROSS SECTION FOR $\gamma p \rightarrow \pi^+ \pi^- p$:



Data: ABBHBM (1968) and A. Braghieri *et al.* (1995).

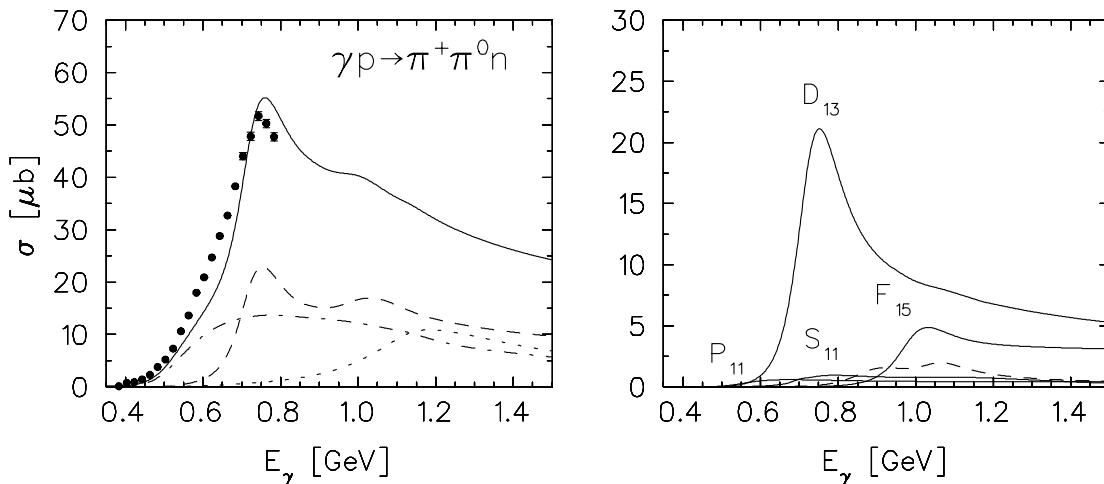
Dash-dot: Born contributions; Dashed: resonance contributions

Dotted: ρ -meson contributions; Solid: complete calculation.

Right panel:

Dashed: sum of $S_{31} + P_{13} + D_{15}$.

TOTAL CROSS SECTION FOR $\gamma p \rightarrow \pi^+ \pi^0 n$:



Left panel:

Data: W. Langgärtner *et al.* (2001)

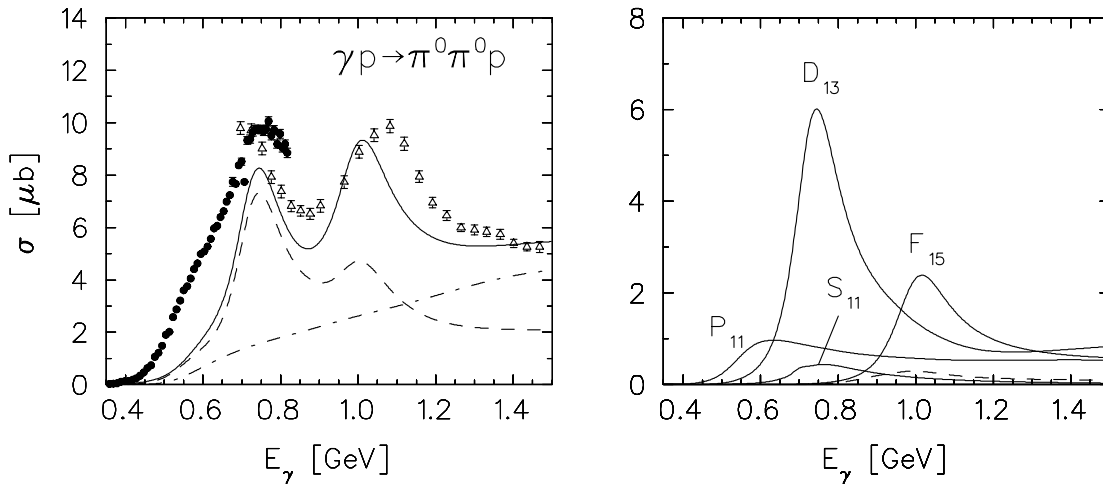
Dash-dot: Born contributions; Dashed: resonance contributions

Dotted: ρ -meson contributions; Solid: complete calculation.

Right panel:

Dashed: sum of $S_{31} + P_{13} + D_{15}$.

TOTAL CROSS SECTION FOR $\gamma p \rightarrow \pi^0 \pi^0 p$:



Left panel:

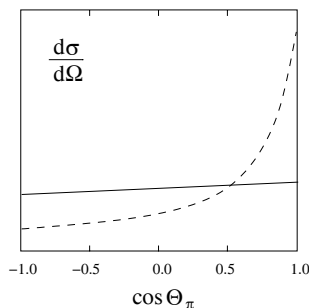
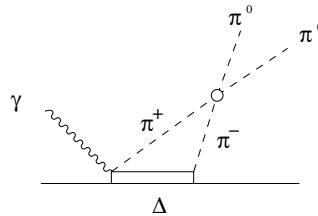
Data: M. Wolf *et al.* (2000) and GRAAL (2003).

Dash-dot: Born contributions; Dashed: resonance contributions
Solid: complete calculation.

Right panel:

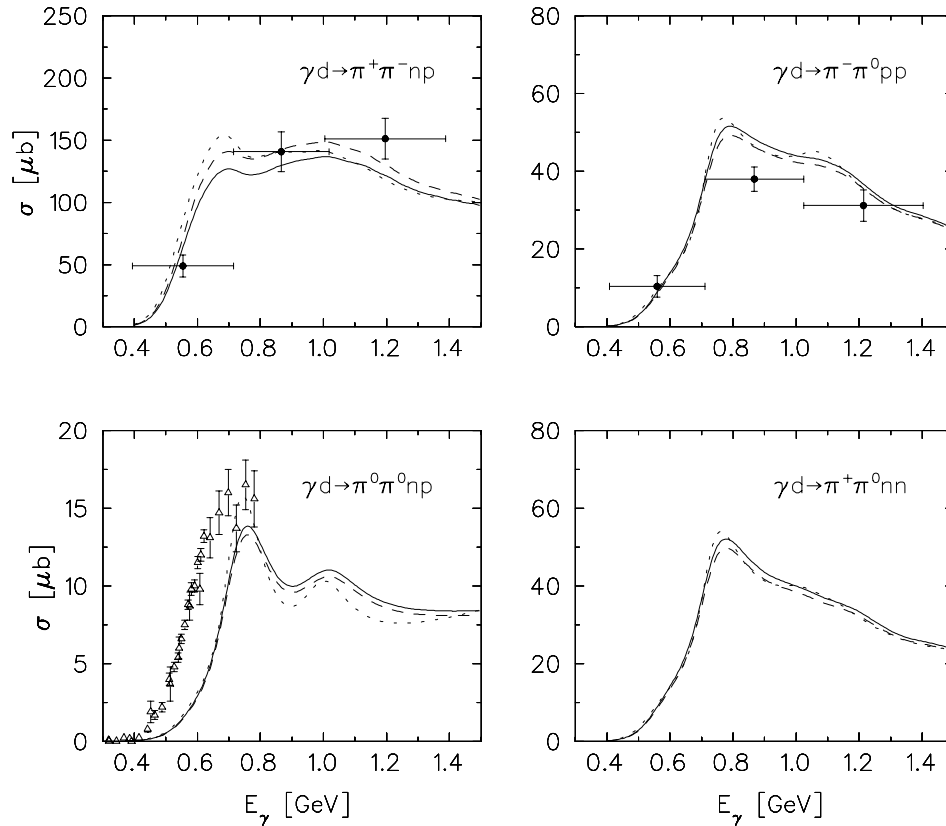
Dashed: sum of $S_{31} + P_{13} + D_{15}$.

- Severe underestimation above threshold.
- Linear energy dependence for $450 \leq E_\gamma \leq 700$ MeV points to large s -wave contribution.
- Kroll-Rudermann term does not contribute to $\pi^0 \pi^0$.
- Rescattering $\pi^+ \pi^- \rightarrow \pi^0 \pi^0$?
- Data for $\frac{d\sigma}{d\Omega_\pi}$ can help to estimate the role of s -waves



- s -wave dominates
- - - s -wave is suppressed

TOTAL CROSS SECTIONS FOR TWO-PION PRODUCTION ON DEUTERON



Data: R. Schiffer *et al.* (1972) and B. Krusche *et al.* (1999).
 Dashed: impulse approximation; Solid: IA + NN -rescattering;
 Dotted: elementary reaction.

▷ For $\pi^0\pi^0$ - and $\pi^+\pi^-$ -channels, sizeable differences to elementary reaction. FSI leads essentially to broadening.

▷ Comparison with other models:

- K.Ochi, M.Hirata, and T.Takaki: $\sigma(\pi^0\pi^0)$ is close to our result.
- J.A.Gomez Tejedor and E.Oset describe $\pi^0\pi^0$ data for the total cross section but have problems with linear beam asymmetry
- L.Y.Murphy and J.M.Laget: anomalously large contribution from $P_{11}(1440) \rightarrow \sigma N \rightarrow \pi^0\pi^0 N$, not confirmed by other authors.

4. THE GDH SUM RULE FOR THE DEUTERON

(H. A., A. F., M. Schwamb, PRL **93**, 202301 (2004))

GERASIMOV-DRELL-HEARN sum rule (1965/66)

$$I^{GDH} = \int_0^\infty \frac{d\omega}{\omega} \left(\underbrace{\sigma^P(\omega) - \sigma^A(\omega)} \right) = 4\pi^2 \kappa^2 \frac{e^2}{M^2} S,$$

spin asymmetry of total absorption x-section

Deuteron is isoscalar with small $\kappa_d = -0.143$ [n.m.].

$$\rightarrow I_d^{GDH} = 0.65 \mu\text{b}$$

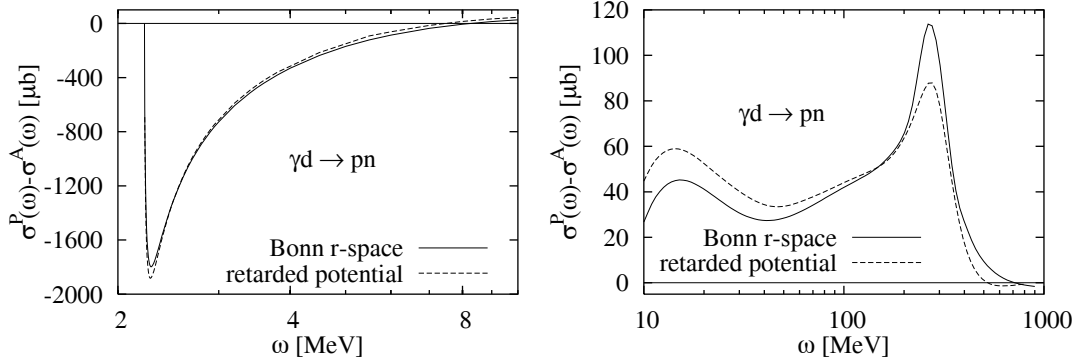
Absorptive processes:

- (i) photodisintegration $\gamma + d \rightarrow n + p$,
- (ii) single pion production
 - coherent: $\gamma d \rightarrow d\pi^0$,
 - incoherent: $\gamma d \rightarrow NN\pi$,
- (iii) two pion production etc.

Neglecting interference effects \rightarrow estimate of positive GDH contribution from meson production:

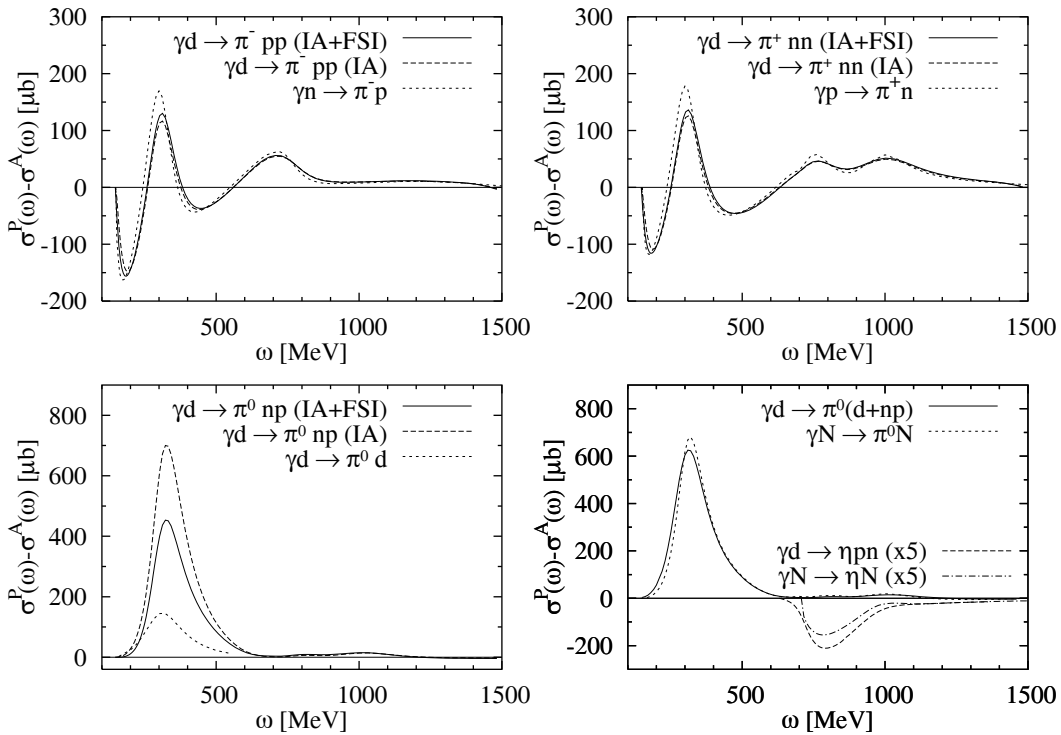
$$I_p^{GDH} + I_n^{GDH} = 438 \mu\text{b}$$

SPIN ASYMMETRY OF PHOTODISINTEGRATION $d(\gamma, p)n$:



Near threshold spin asymmetry is dominated by isovector M1 transition to 1S_0 -state \rightarrow large negative spin asymmetry and GDH contribution:

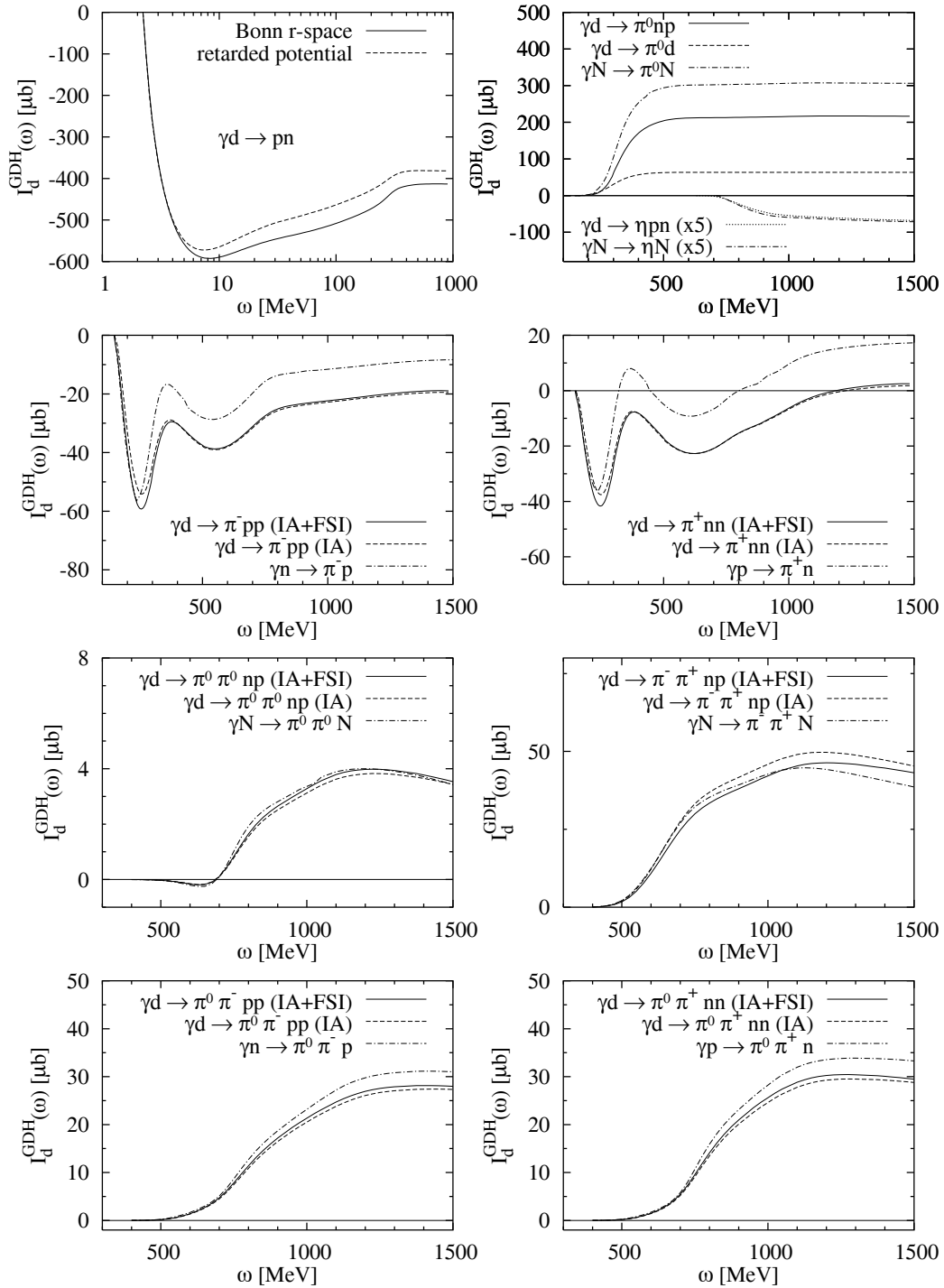
SPIN ASYMMETRY OF SINGLE PION AND ETA PRODUCTION:



Significant differences between spin asymmetries of pion photoproduction on nucleon and deuteron.

Contribution of various channels to finite GDH integral:

$$I^{GDH}(\omega) = \int_0^\omega \frac{d\omega'}{\omega'} \left(\sigma^P(\omega') - \sigma^A(\omega') \right).$$



Sizeable differences between charged pion production on nucleon and deuteron because of (i) FERMI motion and (ii) FSI.

Contributions of single π production on nucleon and deuteron to finite GDH integral up to 1.5 GeV in μb .

nucleon	$\pi^0 p$	$\pi^0 n$	$\pi^- p$	$\pi^+ n$
	159.10	147.34	-8.39	17.28
deuteron	$\pi^0 d$	$\pi^0 np$	$\pi^- pp$	$\pi^+ nn$
	63.26	216.61	-18.94	2.51

Contributions of double π production on nucleon and deuteron to finite GDH integral up to 1.5 GeV in μb .

	$\pi^+ \pi^-$	$\pi^0 \pi^0$	$\pi^+ \pi^0$	$\pi^- \pi^0$
neutron	22.23	1.82		31.01
proton	16.36	1.60	33.28	
deuteron	43.16	3.53	29.46	27.98

Contributions of various channels to finite GDH integral up to 0.9 GeV for $\gamma d \rightarrow np$ and 1.5 GeV for $\gamma d \rightarrow \pi(d + NN)$, $\gamma N \rightarrow \pi N$ and $\gamma N \rightarrow \pi\pi N$ in μb .

	np	π	$\pi\pi$	η	Σ	GDH
n		138.95	55.06	-5.77	188.24	233.16
p		176.38	51.24	-8.77	218.85	204.78
d	-381.52	263.44	104.13	-13.95	-27.90	0.65

Largest uncertainty in the two-pion contribution of about 20 %.

4. CONCLUSIONS AND OUTLOOK

- Electromagnetic reactions provide a powerful diagnostic tool for analyzing the role of meson degrees of freedom in few-nucleon systems.
- Such reactions serve as critical tests for theoretical frameworks.
- Present theoretical approaches provide a reasonable description of various meson photoproduction reactions on a level of accuracy of 10–20 %.
- Severe problems occur in π^0 -production on the deuteron in the second resonance region (overestimation by factor 1.5), and in $\pi^0\pi^0$ -production (missing *s*-wave contribution).
- Polarization observables are expected to be more sensitive to finer but important dynamical details.

FUTURE NEEDS IN THEORY:

- The time is ripe to aim at a comparison between theory and experiment with an accuracy of a few percent or even less.
- To this end we need theoretical approaches which guarantee consistency on that level of accuracy, i.e. which avoid present patchwork treatments using for each reaction a different ansatz.

IN PARTICULAR WE NEED

A UNIFIED HADRONIC MODEL DESCRIBING

- elastic NN-scattering below and above pion threshold,
- inelastic reactions $NN \rightarrow NN\pi$, $NN\pi\pi$, $NN\eta$, etc.,
- elastic and inelastic pion nucleon scattering,
- electromagnetic reactions like COMPTON scattering, disintegration, π and η production (M. Schwamb).

Such a model should incorporate also the requirements of special relativity. In the long run, the question of OFF-SHELL PROPERTIES has to be tackled, too.

FUTURE NEEDS IN EXPERIMENT:

- We need systematic experimental data of high precision over a large range of energy and momentum transfers for a variety of hadronic and electromagnetic reactions.
- High precision inclusive data are already quite valuable, but exclusive data provide much more details about the underlying dynamics.
- Especially experimental data on various polarization observables are urgently needed, since they allow in general much more stringent tests of theoretical models.

Finally, such a program can only be pursued by a close collaboration between experimental and theoretical groups.