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Electroweak Reactions on Few-Nucleon Systems

1. Introduction: Why studying Few-Nucleon Physics?
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1. Introduction:

Why studying Few-Nucleon Physics?

- Principal goal of nuclear physics: understanding of hadronic systems, in particular their internal structure
- Fundamental theory: QCD
- Nonperturbative regime: QCD not applicable
  $\longrightarrow$ **effective** theories based on nucleons, mesons, isobars as effective degrees of freedom
- Ideal test object for effective theory: **few-nucleon systems**
  - cleanest theoretical treatment available
  - may serve as effective neutron targets
- Some selected questions:
  - How far in energy and momentum transfer can the effective picture be pushed?
  - Up to which mass number A are **microscopic** calculations feasible?
  - What is the role of relativity?

2. The Two-Nucleon System

Possible reactions in two-nucleon system up to the Δ-region:

NN-scattering:	$NN \to NN$
Compton-Scattering:	$\gamma d \to \gamma d$
Deuteron breakup:	$\gamma d \to NN$, $\quad ed \to e' NN$
Elastic scattering:	$ed \to e' d$
Bremsstrahlung:	$NN \to \gamma NN$
Pionproduction:	$\pi d \to \pi d\,,\, \pi d \rightleftharpoons NN\,,$
	$NN \to \pi NN\,,\, \pi d \to \pi NN$
	$\gamma d \to \pi d\,,\, \gamma d \to \pi NN, \ldots$

Note: different reactions are linked via unitarity ($\to$ Optical Theorem), i.e.

$$\mathrm{Im}\, T(\gamma d \to \gamma d; \theta = 0) \;\sim\; \sigma_{tot}(\gamma d \to NN, \pi d, \pi NN, \ldots)$$

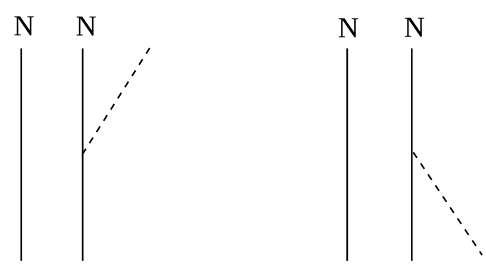
Consequence: Different possible reactions should be treated within **one** framework!

Recently finished (M. S.: habilitation thesis, Universität Mainz):

> Approach which is able to describe consistently **all** possible reactions in the two-nucleon system beyond π-threshold up to the Δ-region.

General structure:

- Introduction of XNN-vertices ($X \in \{\pi, \rho, \omega, \sigma, ...\}$) known from potential theory (i.e. Bonn potential) as basic ingredients of the hadronic interaction V



- Relevant equations:
  - Schrödinger equation for bound state:

$$(H_0 + V)|B\rangle = E|B\rangle$$

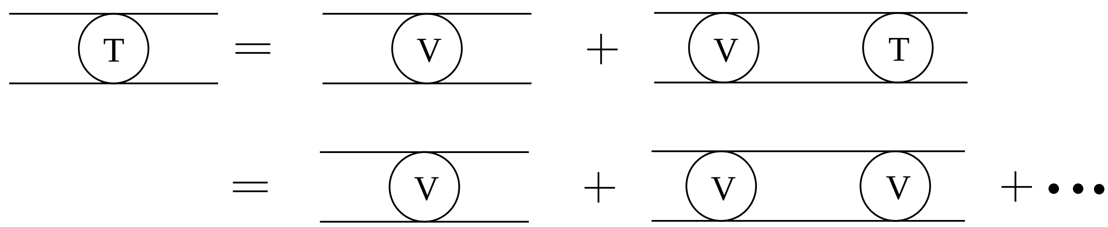
  - Lippmann-Schwinger equation for scattering states:

$$|\Psi\rangle^{\pm} = (1 + G_0(z)T(z))|\phi\rangle^{PW}$$

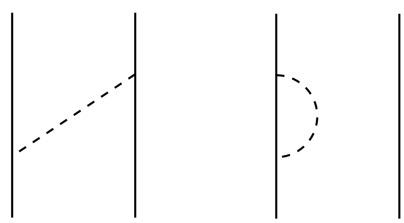
with

$$T(z) = V + VG_0(z)T(z) \ , \quad z = E \pm i\epsilon \ ,$$

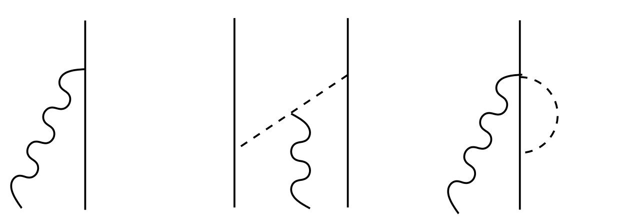
with $G_0(z) = \frac{1}{z - H_0}$:



- Iteration of V via Lippmann-Schwinger equation generates energy-dependent retarded NN-potential as well as self-energy loop diagrams (→ distinction between bare and physical nucleons necessary):

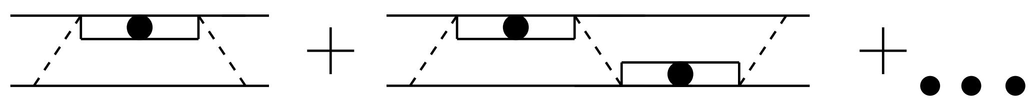


- Electromagnetic currents are implemented via minimal substitution
  → gauge invariance fulfilled

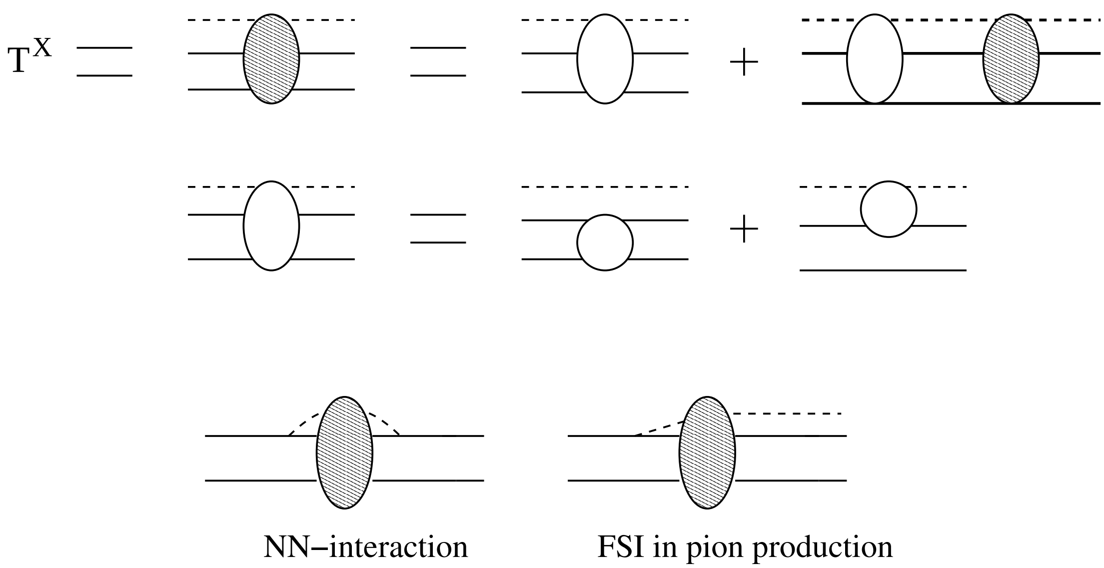


- Note: NN-interaction, internal nucleon structure described by pion cloud, meson exchange currents and e.m. loop diagrams are based on **same** vertices $\longrightarrow$ unitarity fulfilled!

- Δ-degree taken into account **nonperturbatively**, free parameters are extracted from elastic πN-scattering and elementary photopionproduction

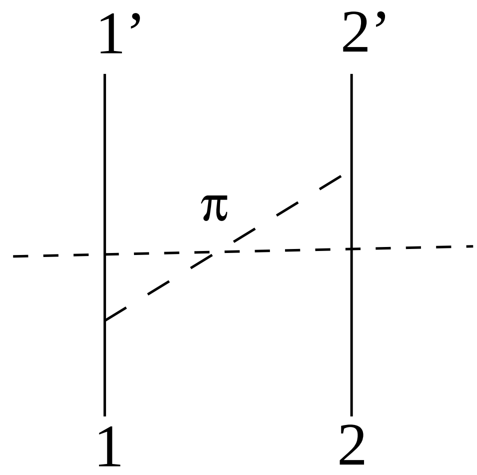


- Mutual interactions within the XNN-system are considered using standard three-body techniques



- Applicable for all hadronic and electromagnetic reactions till about 400-500 MeV excitation energy

- πNN-retardation taken into account



Exact, retarded propagator for πNN-state:

$$G_0(z) = (z - E_N(1') - E_N(2) - E_\pi)^{-1}, \quad z = E + i\epsilon$$

Characteristic features:

- Nonlocal
- Nonhermitean
- Existence of singularities above pion-threshold

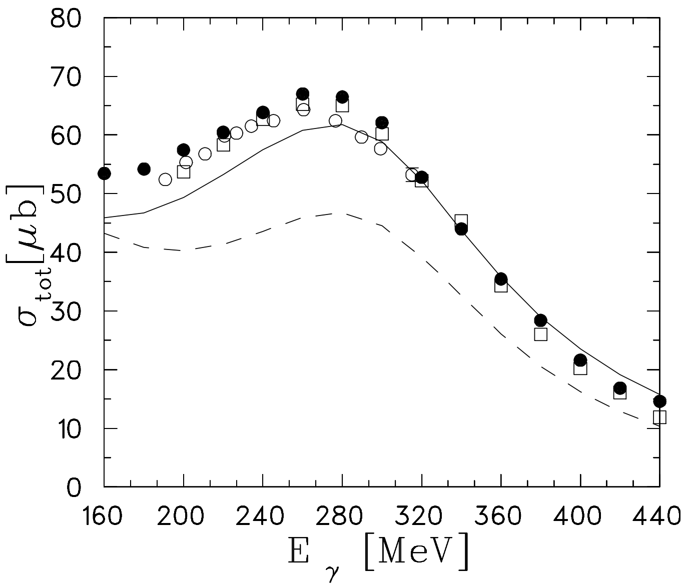
$\rightarrow$ low energy approximation: **static limit**, i. e. nucleons are infinitely heavy during meson exchange:

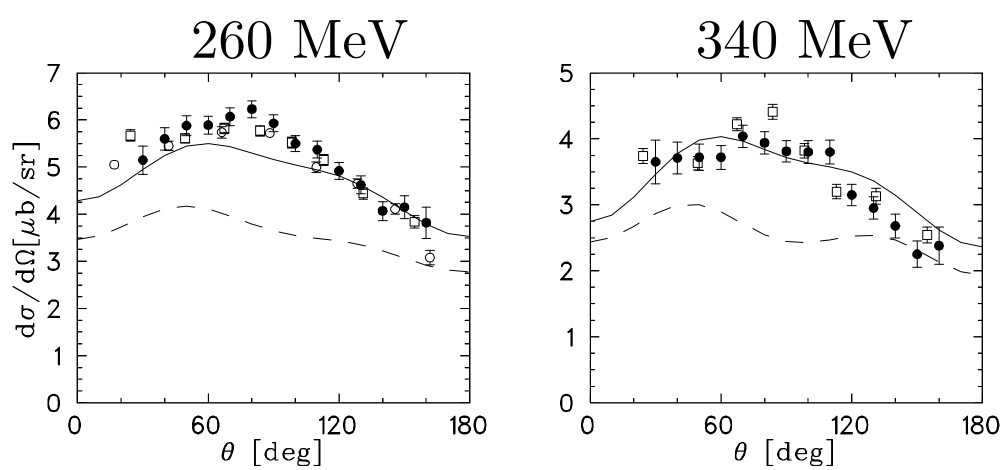
$$G_0(z) \rightarrow G_0^{stat} := -E_\pi^{-1}$$

- Advantage: local, energy independent
- Disadvantages: violation of unitarity, pion is no longer dynamic degree of freedom

Electromagnetic Deuteron Breakup

Significant improvement for Photodisintegration in the Δ-Resonance Region





dashed: calculation of Wilhelm and Arenhövel (1993)

full: retarded calculation (2006)

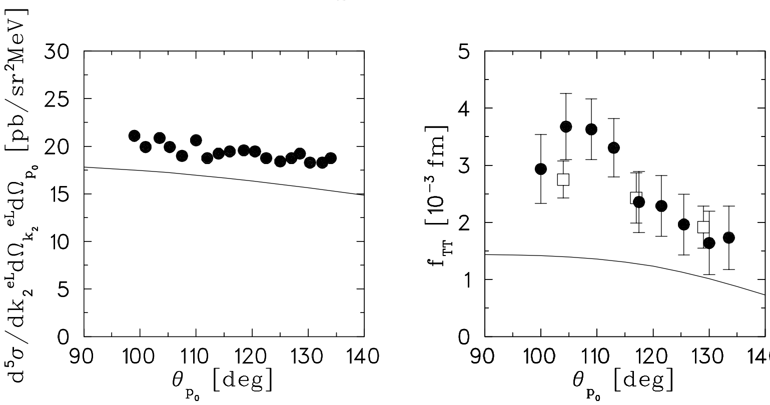
data: □ Bonn (1984), ○ LEGS (1995), • MAMI (1996)

Extension to Electrodisintegration

unpolarized differential cross section in $d(e,e'p)n$:

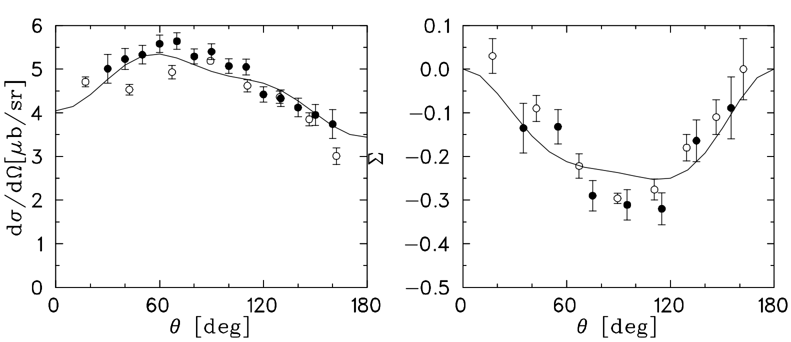
$$\frac{d^3\sigma}{dk_2^{lab}\,d\Omega_e^{Lab}\,d\Omega_{np}} = c\,[\rho_L f_L(\omega,q,\theta) + \rho_T f_T(\omega,q,\theta) + \rho_{LT} f_{LT}(\omega,q,\theta)\cos(\phi) + \rho_{TT} f_{TT}(\omega,q,\theta)\cos(2\phi)]$$

NIKHEF-Experiment: $E_{np} = 280$ MeV, $q^2 = 2.47$ fm^{-2}



Comparison to photodisintegration at $E_\gamma = 300$ MeV

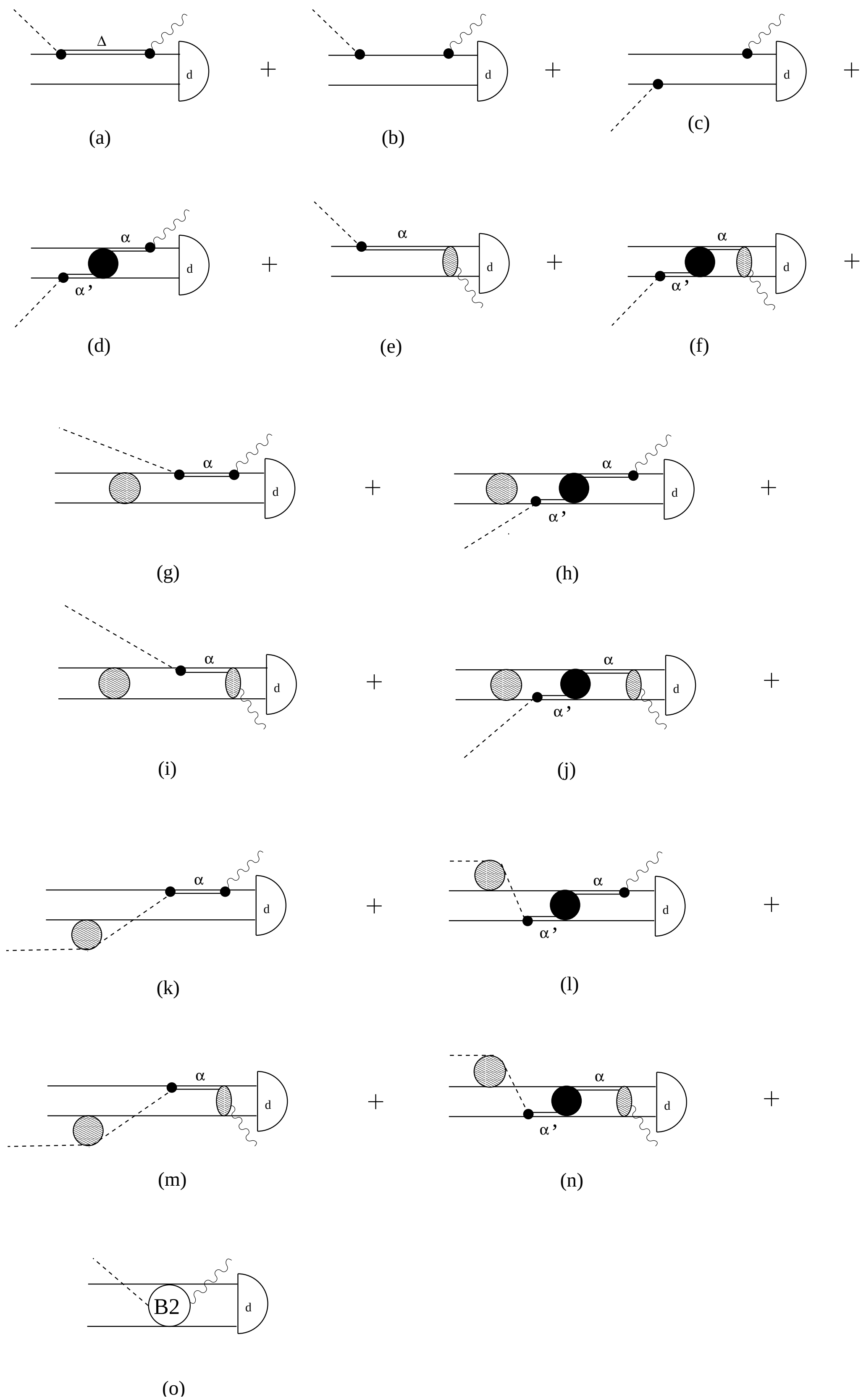
$$Q^2 \to 0: \quad f_{TT} \sim \Sigma_L \frac{d\sigma(\gamma d \to pn)}{d\Omega}$$



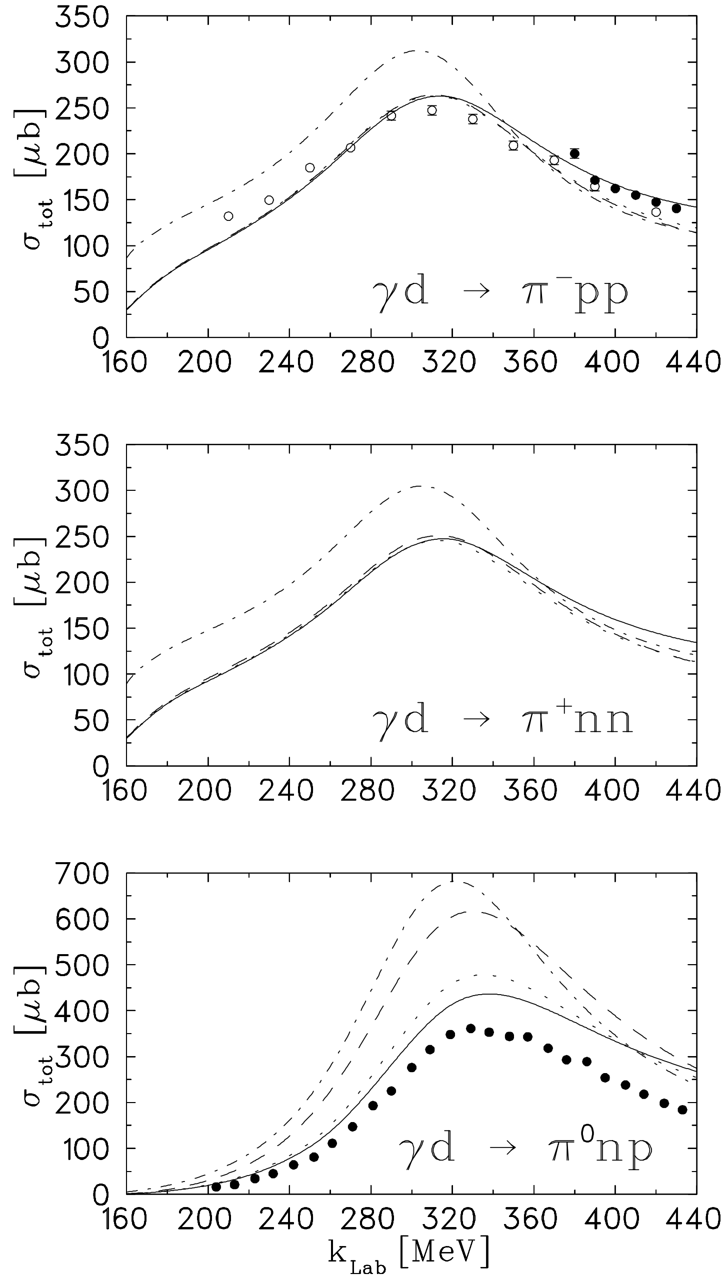
full: retarded approach (2006)

data: • Daphne (1996/1999), ∘ LEGS (1995)

$\gamma d \to \pi N N$



Total cross section for $\gamma d \to \pi NN$



dash-dotted:	elementary reaction $\gamma N \to \pi N$
dashed:	Impulse approximation (IA), i.e. only diagrams (a), (b), (c), (o) included
dotted:	IA + FSI (diagram (g), (k))
full:	full retarded approach

3. More complicated Few-Nucleon Systems

Interesting questions:

- Role of ^{3}He as an effective neutron target
- What is in general the role of three (four,..)-body forces?
- Miscroscopic understanding of **nuclear structure**, i.e.
  - Up to which mass number A are **microscopic** calculations feasible?
  - In the long-term run: Test of typical many-body approximations by building a bridge between classical few-body systems ($A = 2, 3$) and complex nuclei ($A \geq 12$)
- astrophysical applications
- ...

- **Most important observable**:
  inclusive Response function for $\gamma A \to X$

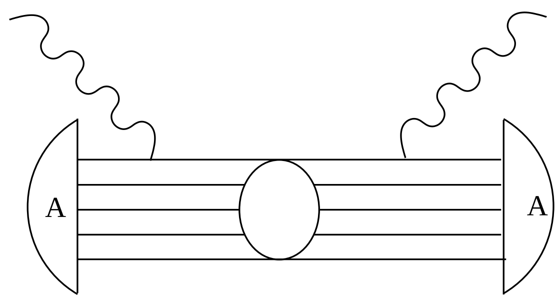
$$R(W) = \int \Psi_f |\langle \Psi_f | \epsilon_\mu J^\mu | \Psi \rangle|^2 \delta(E_f - E_0 - W)$$

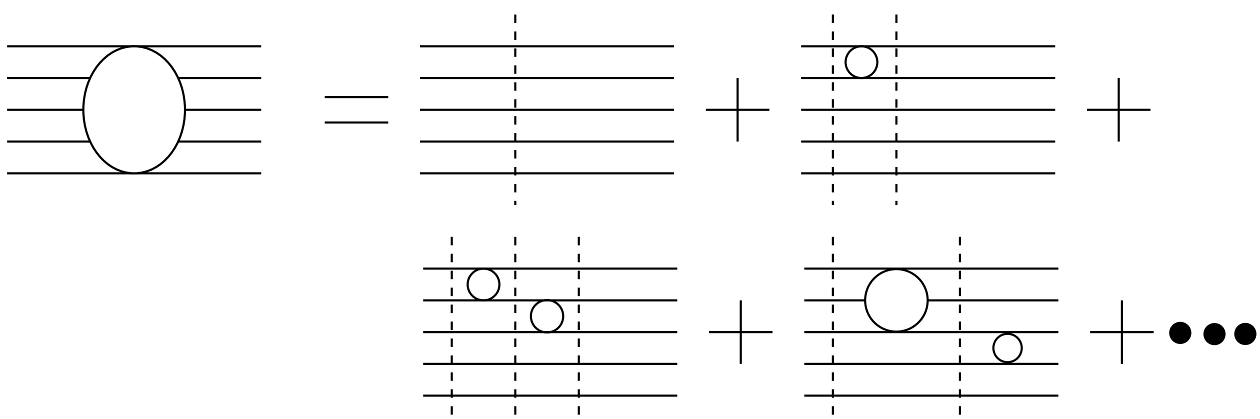
with

$$R(W) \sim \sigma_{tot}(\gamma A \to X, W)$$

- Optical Theorem:

$$\text{Im} \lim_{\epsilon \to 0} T(\gamma A \to \gamma A; W + i\epsilon, \theta = 0) \sim R(W)$$





- Problem: Pole structure of amplitude becomes more and more involved with increasing A!

- Elegant solution: **Lorentz Integral Transformation** (Efros, Leidemann & Orlandini)

$$L(\sigma_r, \sigma_i) = \int_{E_{thres}}^{\infty} dW \frac{R(W)}{(W - \sigma_r)^2 + \sigma_i^2}$$

$$\sim \quad \mathrm{Im}\, T(\gamma A \to \gamma A; \sigma_r + i\sigma_i, \theta = 0)$$

compare: $\sigma_{tot}(W) \sim \mathrm{Im} \lim_{\epsilon \to 0} T(\gamma A \to \gamma A; W + i\epsilon, \theta = 0)$

- **Advantages**:
  - Due to $\sigma_i \neq 0$ fixed (typically 10-20 MeV), no pole structure in $T(\gamma A \to \gamma A)$
    $\longrightarrow$ **bound state problem!**
  - FSI automatically included
  - **microscopic** calculation of electromagnetic reactions on "complex" few-nucleon systems feasible (presently up to $A = 7$), see also contribution by **Sonia Bacca**
  - Applicable also for exclusive cross reactions
- Price to be paid: **inversion** $L \to R$ necessary

Characteristic features of presently available LIT-calculations:

- Realistic hadronic interaction (i.e. AV18, Urbana IX) used, at least for $A = 3, 4$
- In general, calculations are performed in configuration space, taking only **nucleonic** degrees of freedom into account

Planned Extension:

Application of LIT-method in **momentum** space, taking into account Δ and mesonic degrees of freedom

Suitable starting point: ^{3}He

- standard Faddeev-calculations only applicable till π-threshold
- $\rightarrow$ extension planned to higher energy/momentum transfer:
  - Inclusive cross section in the Δ-region
  - Extraction of G_{E_n} at large Q^2
  - GDH sum rule on the neutron using ^{3}He as effective neutron target:

$$I^{GDH} = \int_0^\infty \frac{dk}{k}\Big(\sigma^P(k) - \sigma^A(k)\Big) = 4\pi^2 \kappa^2 \frac{e^2}{m^2} S$$

4. Summary and 0utlook

- Few-nucleon systems important for understanding of strong interaction, nuclear structure and extraction of neutron properties → **very active field**
- Self-consistent approach up to resonance region available for $A = 2$, to be extended for $A = 3$ (**presently under construction**)
- Some recent theoretical progress:
  - Role of retardation clarified
  - Lorentz integral method
  - ...
- Experimental challenge: to provide data in order to test theory; various activities at TJNAF, MAMI, TUNL,...