Hadron physics with photon beams

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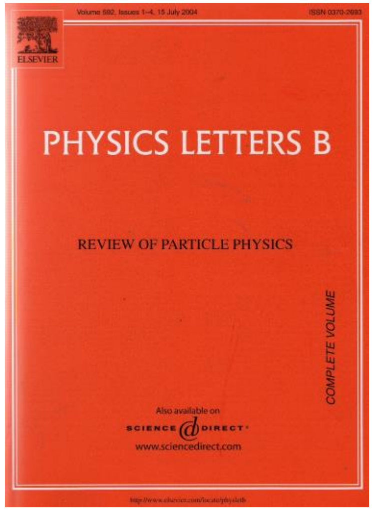
BLTP, JINR, Dubna

The Standard model. The QCD

>300 hadronic states



<u>Degrees of freedom for strong interaction</u>:

fermions: **quarks** bosons: **gluons**

SU(3) gauge symmetry (color)

- QCD: symmetries

Gell-Mann, Ne'eman

flavour SU(3) and chiral symmetry

Georgi, Manohar Large N_c counting (3>>1)

- QCD: dynamics

Fritzsch, Gel-Mann, Leutwyler

hadron currents vs. quark currents

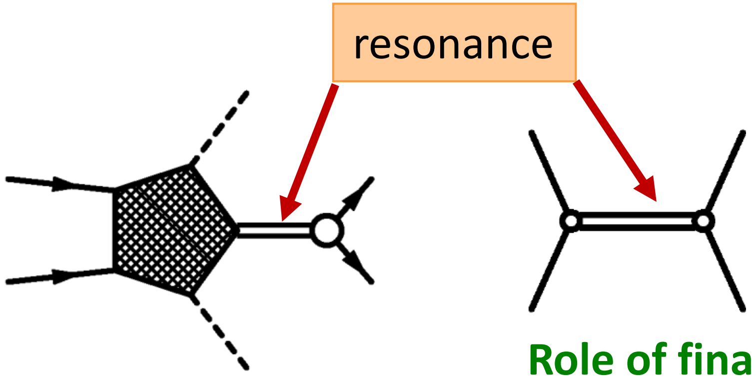
Exp: jets, DIS, pp, p-bar-p, parton distribution functions

<u>hadron spectroscopy</u>

resonances and their decay patterns

new 'exotic states'

Hadrogenesis: what is the resonance nature?

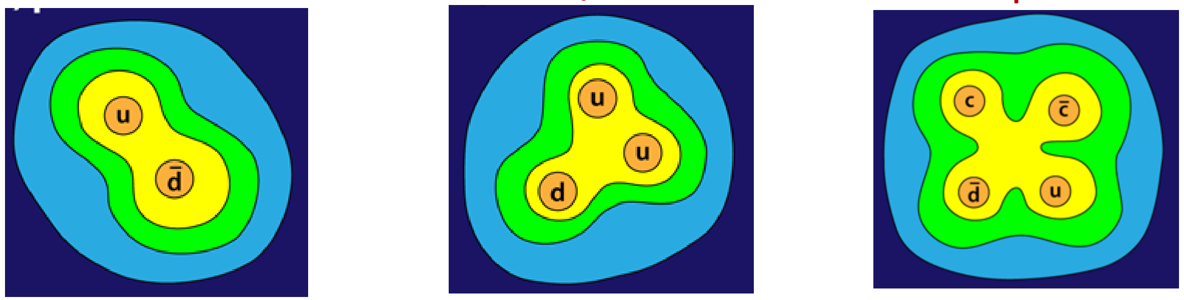


Role of final state interaction (FSI)?

Change of resonance properties in matter → **NICA physics**

- **Quark states**

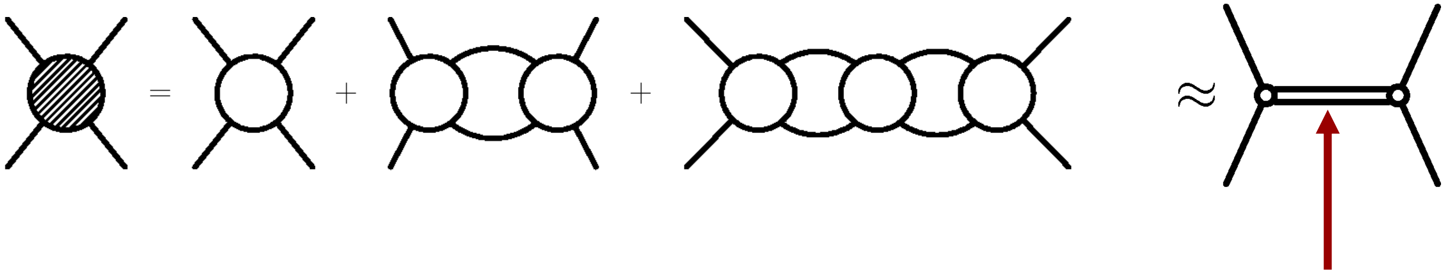
mesons | baryons | tetraquarks | pentaquarks



...

- **Hadron molecules. Dynamically generated resonances**

Scattering equation:



+ background

$$\frac{G_{\rm in}\, G_{\rm out}}{\sqrt{s} - M_{\rm physical} + i\,\Gamma_{\rm tot}}$$

Lippmann-Schwinger, Bethe-Salpeter equation
attractive potential generates a <u>bound</u> state

unitarity, analyticity, crossing symmetry?

Which resonances are generated by coupled channels ?
What are building blocks?

1959

Phil. Mag. 4, 1035 (1959)

Threshold Effects in High Energy Reactions†

By A. I. Baz
Atomic Energy Institute, Moscow, USSR

[Received September 14, 1959]

Abstract

The resonances which occur in high energy phenomena are interpreted in terms of threshold states. Tentative conclusions are drawn regarding the parities of some of the elementary particles.

✔ **Dynamic generation of resonances:** some good candidates

$\Lambda(1405) \leftrightarrow (\bar{K}\,N)$; $N(1535) \leftrightarrow (K\,\Sigma)$; $\Lambda(1520) \leftrightarrow (\bar{K}_\mu\,N)$; $f_0(980) \leftrightarrow (K\,\bar{K})$

✔ **depends on the state and the resolution!**

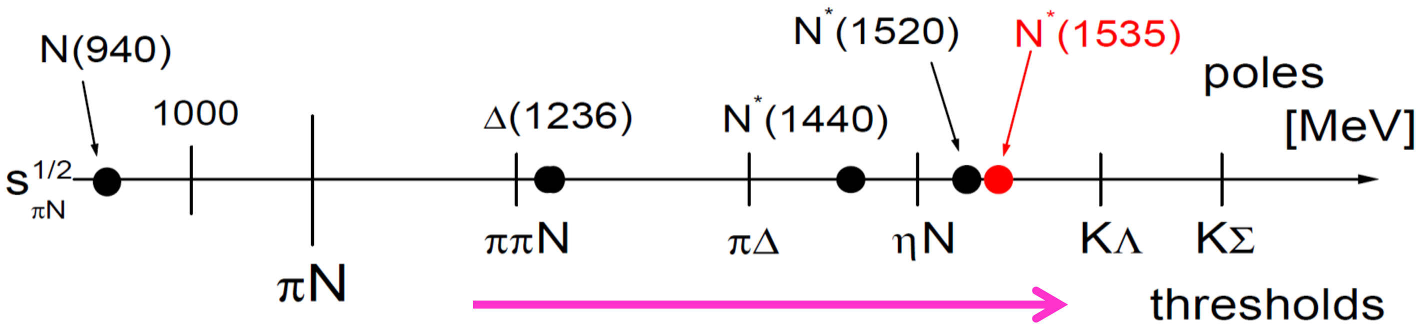
- nuclei: proton and neutron degrees of freedom
- proton and neutron: quark degrees of freedom
- $\Delta(1232)$??
  - Chew and Low 1956: dynamical πN state
  - Gell-Mann & Zweig 1964: bound state of three constituent quarks
  - large-N_c analysis of QCD: at leading order the nucleon and isobar have similar structure

$$J^P = \frac{1}{2}^+$$

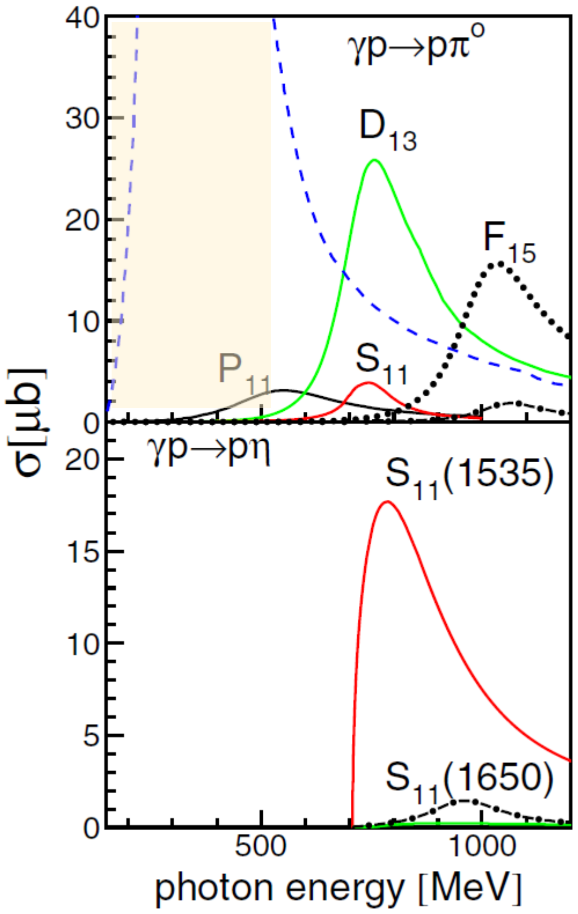
$$J^P = \frac{3}{2}^+$$

Kaiser, Siegel,Weise, *Nucl. Phys.* A 594 (1995) 325
Ramos, Oset, *Nucl. Phys.* A 635 (1998) 99
Meissner, Oller, Nucl. Phys. A 673 (2000) 311
Lutz, EEK *Found.Phys.* 31 (2001) 1671
Lutz, EEK, *Nucl.Phys.* A 700 (2002) 193
……………..

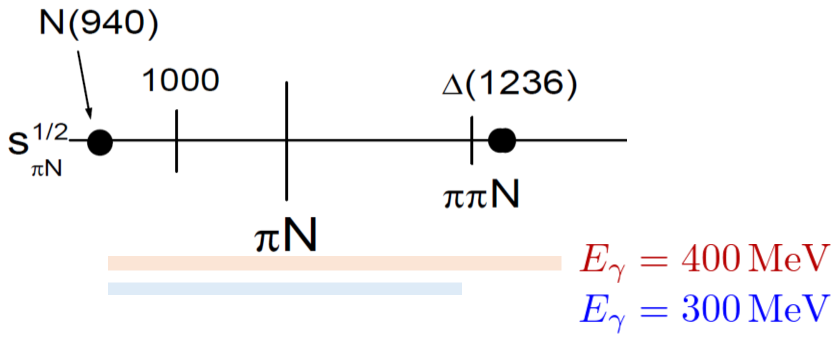
- Pion-nucleon scattering



coupled channel dynamics is important here.



Photon induced reactions

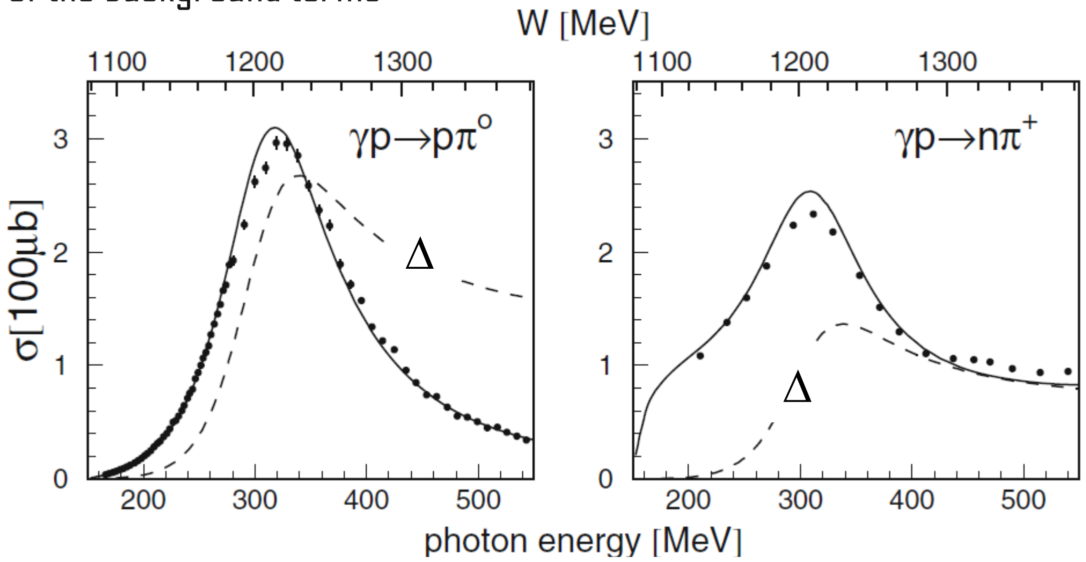


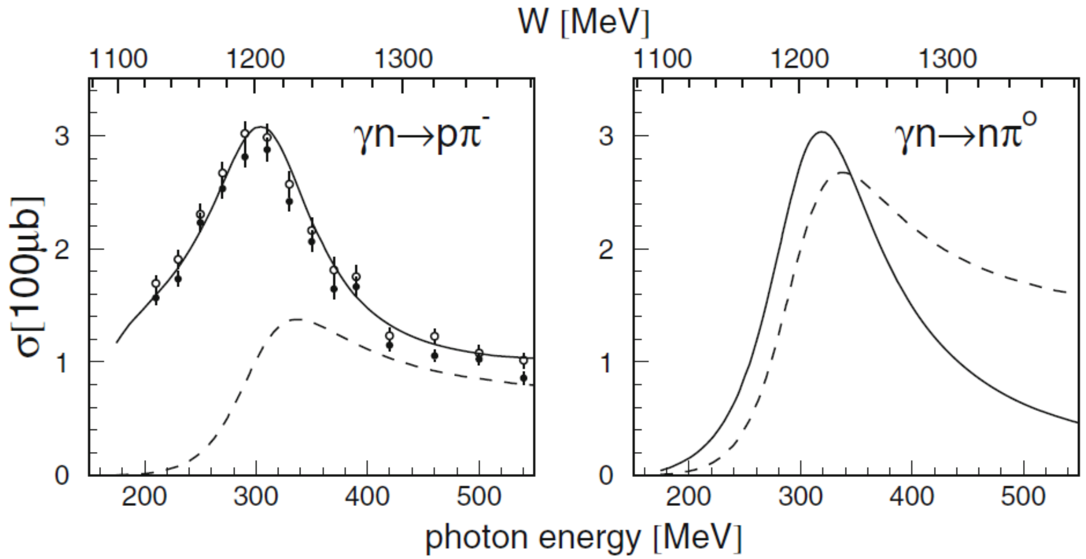
- Pion photoproduction Δ-resonance region

If Δ dominates, isospin relations give

$$\sigma(\gamma p \to p\pi^0) = \sigma(\gamma n \to n\pi^0) = 2\sigma(\gamma p \to n\pi^+) = 2\sigma(\gamma n \to p\pi^-)$$

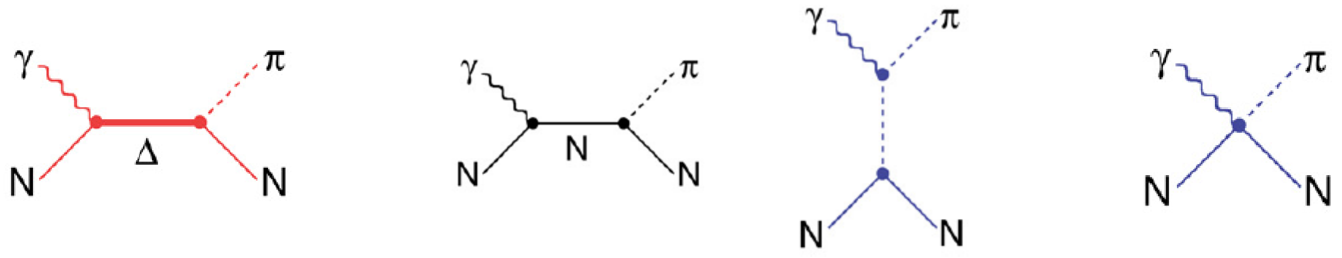
The measured cross sections show a completely different pattern due to the contribution of the background terms



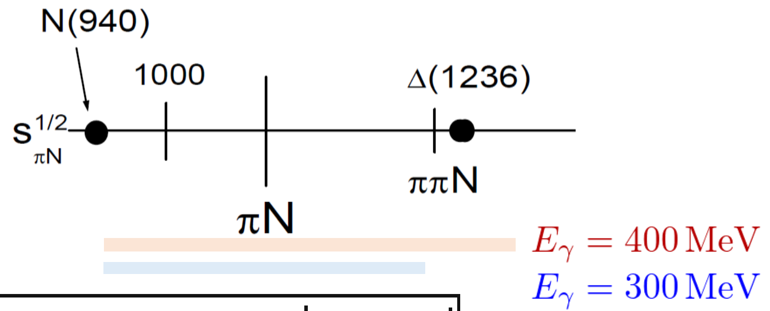


Krusche *Eur. Phys. J. Special Topics* 198 (2011) 199

Lines: MAID model Drechsel, Hanstein, Kamalov, Tiator, *Nucl. Phys.* A 645 (1999) 145

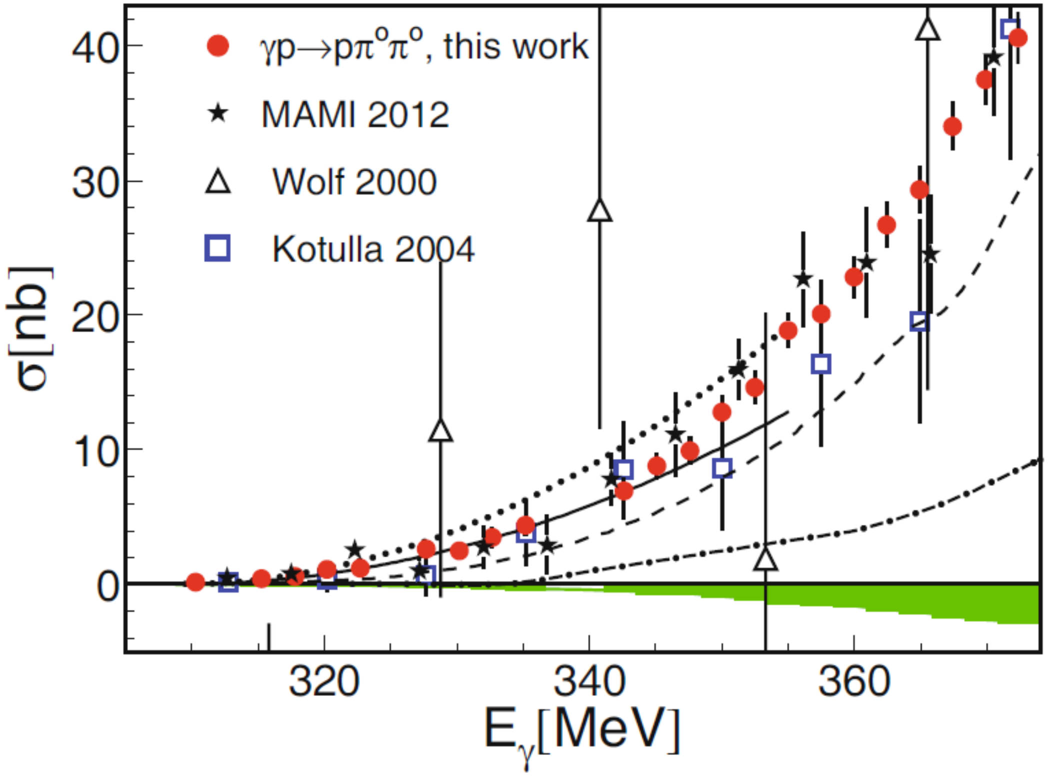


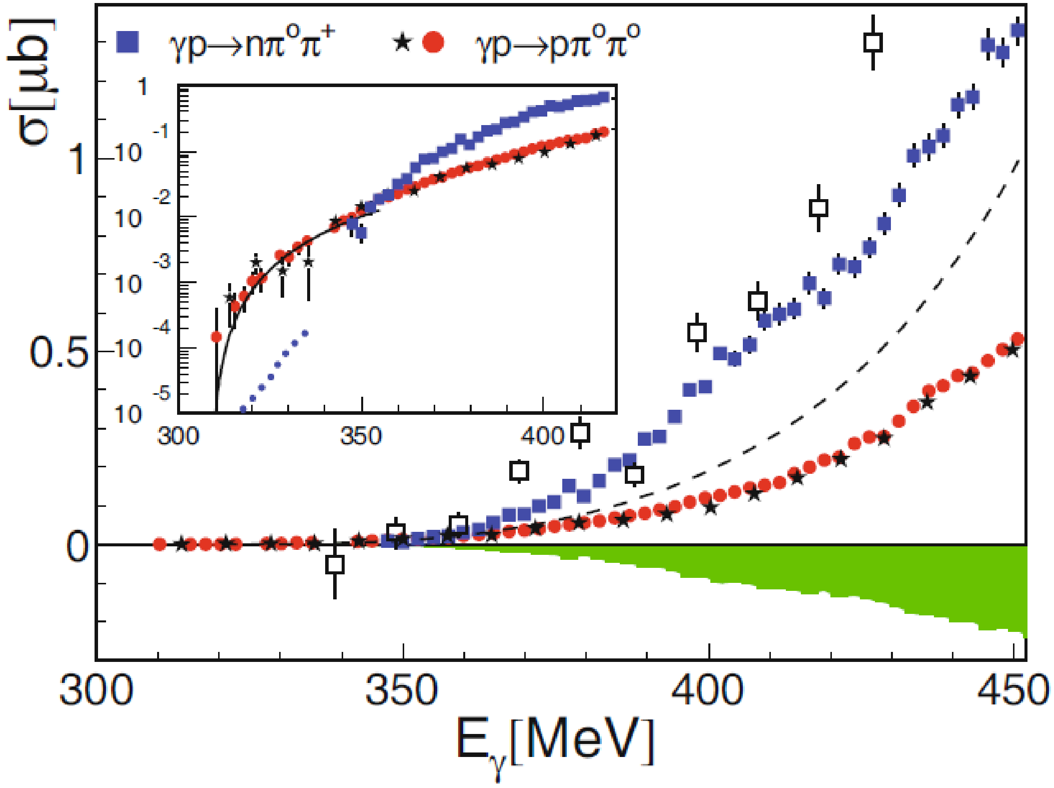
The most interesting but probably the least comprehensible channel in the production of pion pairs is $\pi\pi N$.



- **2-pion photoproduction** Zehr et al, Eur. Phys. J. A 48 (2012) 98

MAMI + Crystal Ball and TAPS detectors



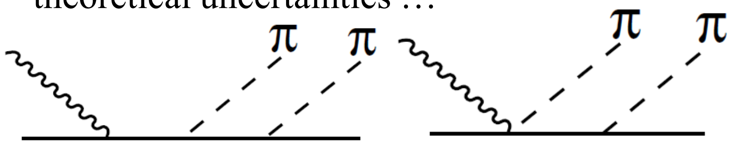


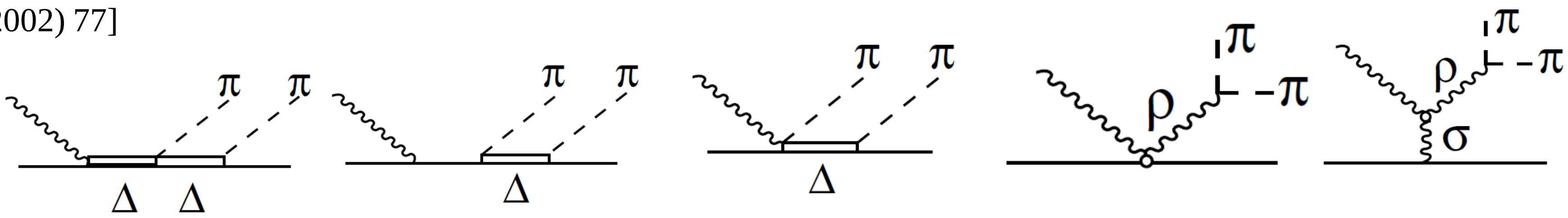
Role of FSI in ππ =(σ,ρ,..) and πN channels

FSI effects almost double the threshold cross-section for the $\pi^0\pi^0$ channel

[Roca, Oset, Vicente Vacas, Phys. Lett. B 541 (2002) 77]

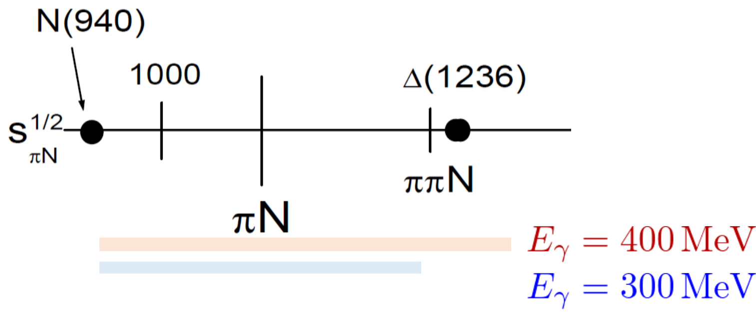
theoretical uncertainties …



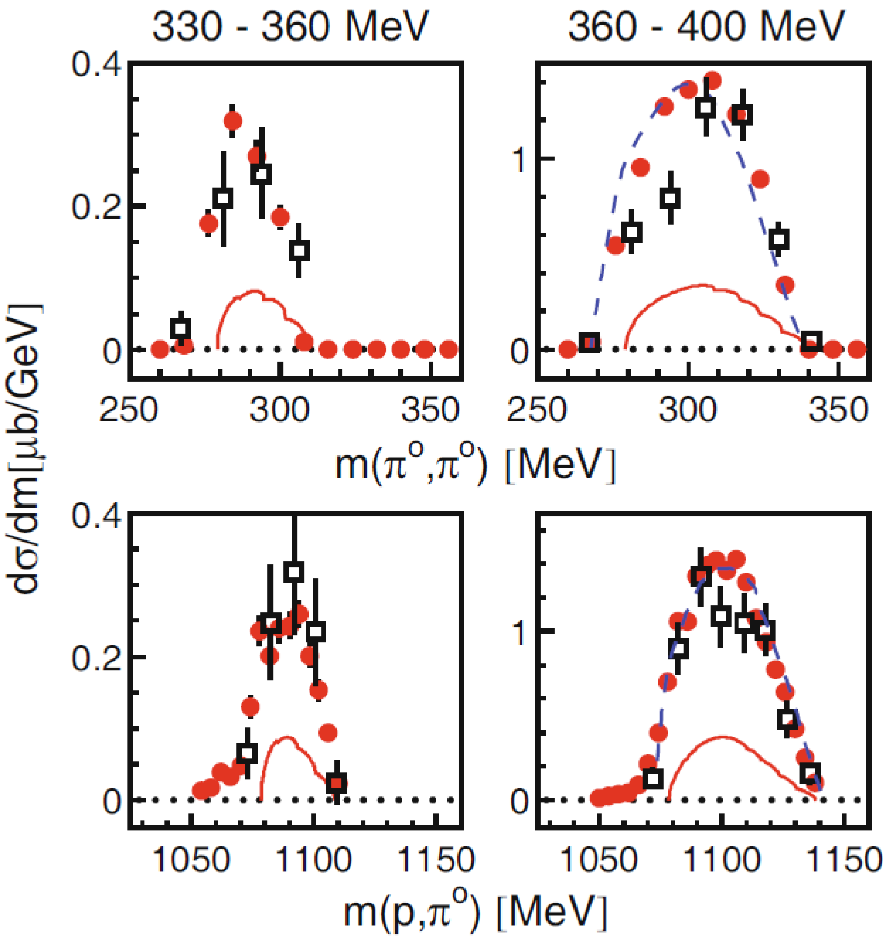


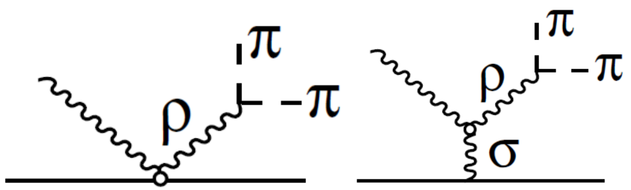
MAMI + Crystal Ball and TAPS detectors

- 2-pion photoproduction



Invariant-mass distributions for $\gamma p \to p\pi^0\pi^0$ in the threshold region.





σ in medium?

Circles: Zehr et al, Eur. Phys. J. A 48 (2012) 98

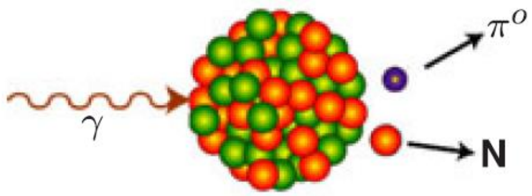
Squares: M. Kotulla et al., Phys. Lett. B 578, 63 (2004).

Pion photoproduction on nuclei

- Reaction mechanisms

Krusche *Eur. Phys. J. Special Topics* 198 (2011) 199

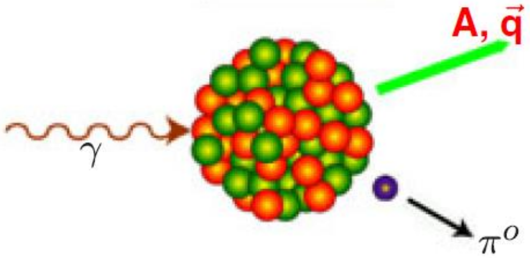
- breakup (quasi-free)



$$\gamma + A \rightarrow \pi^o + A' + N + ...$$

photo-excitation of quasi-free neutrons,
in-medium properties of hadrons,
meson FSI...

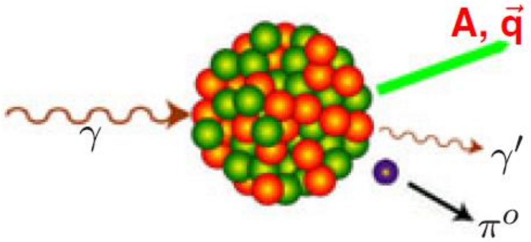
- coherent



$$\gamma + A \rightarrow \pi^o + A$$

spin/iso-spin filters,
meson – nucleus bound states,
in-medium properties,
nuclear form factors

- incoherent



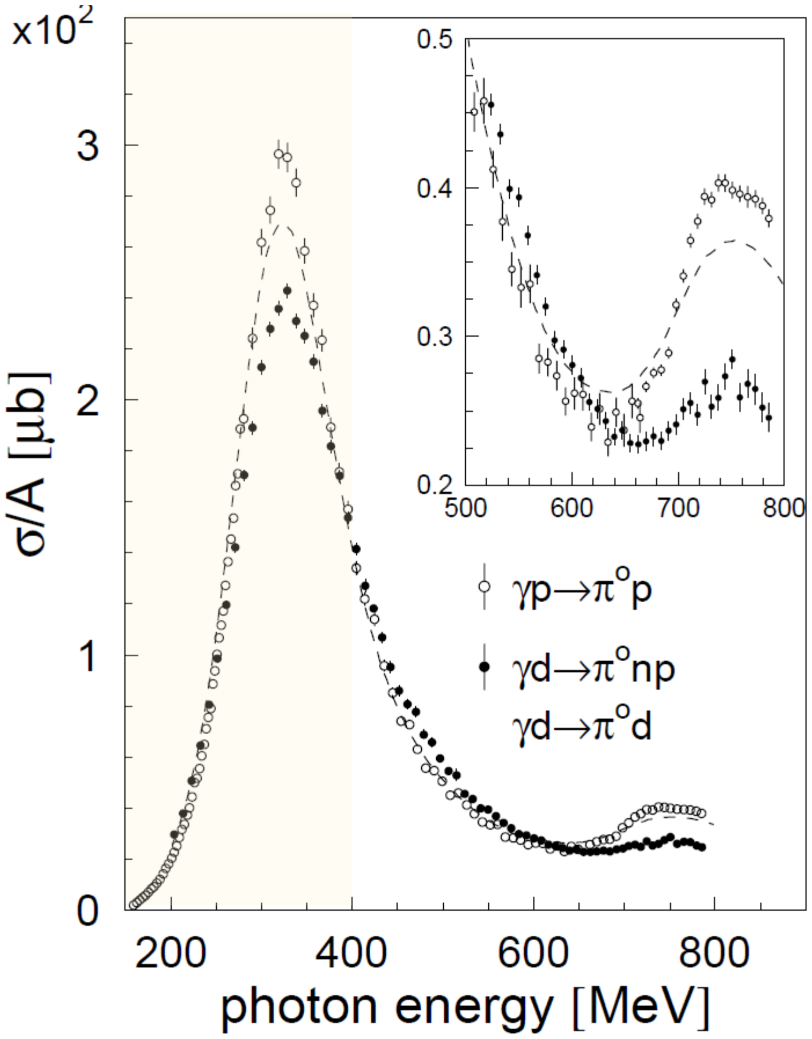
$$\gamma + A \rightarrow \pi^o + A^{\star} \rightarrow \pi^o + A + \gamma$$

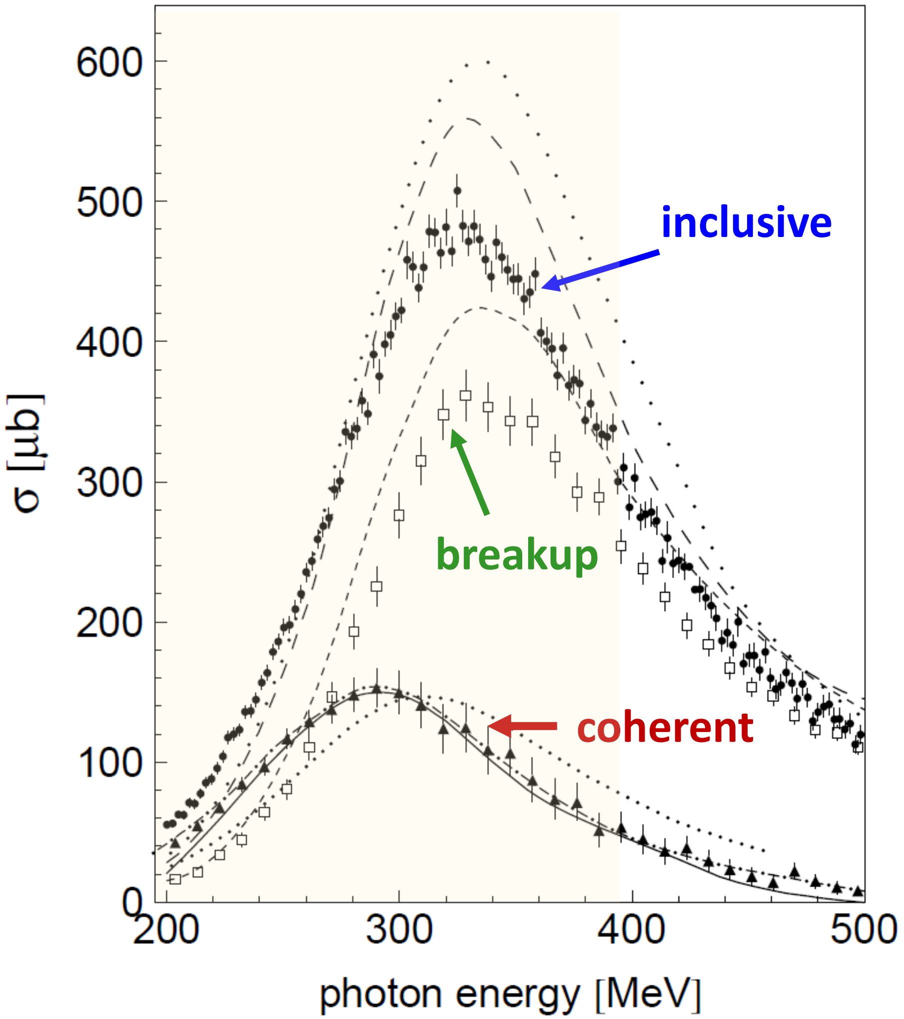
transition form factors,
in-medium properties,
spin/iso-spin selection

These two reaction mechanisms can be separated via their different kinematics.

- Reactions on deuteron

Krusche et al, *Eur. Phys. J.* A 6 (1999) 309

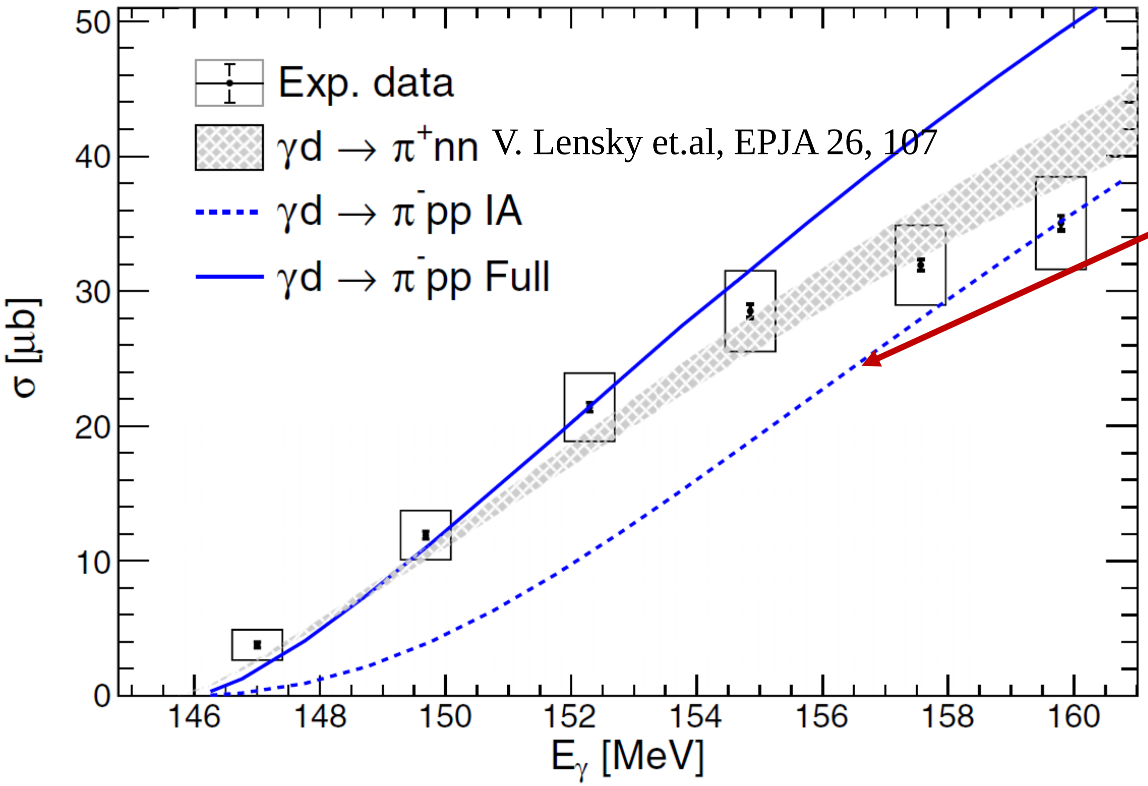


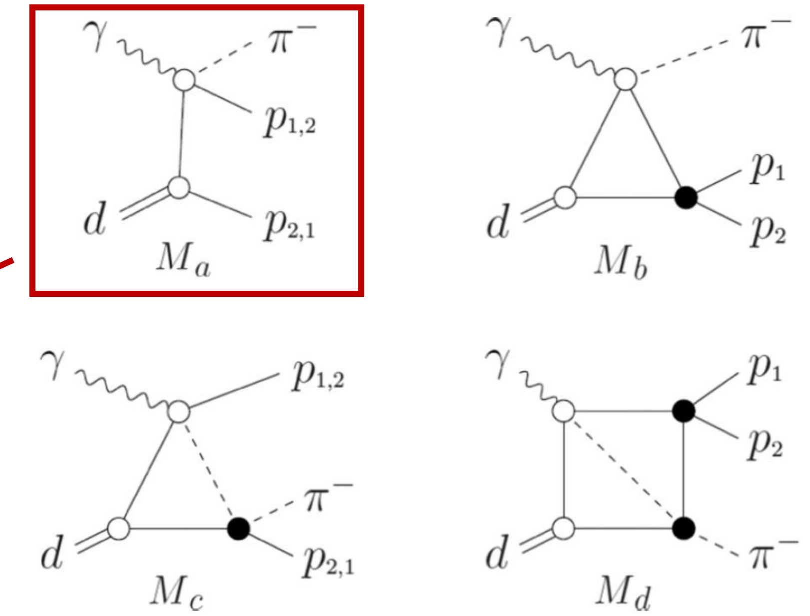


- Reactions on deuteron

Charged pion Strandberg et al (PIONS@MAX-lab Collaboration), *Phys. Rev.* C 101 (2020) 035207

$\gamma d \to \pi^- pp$

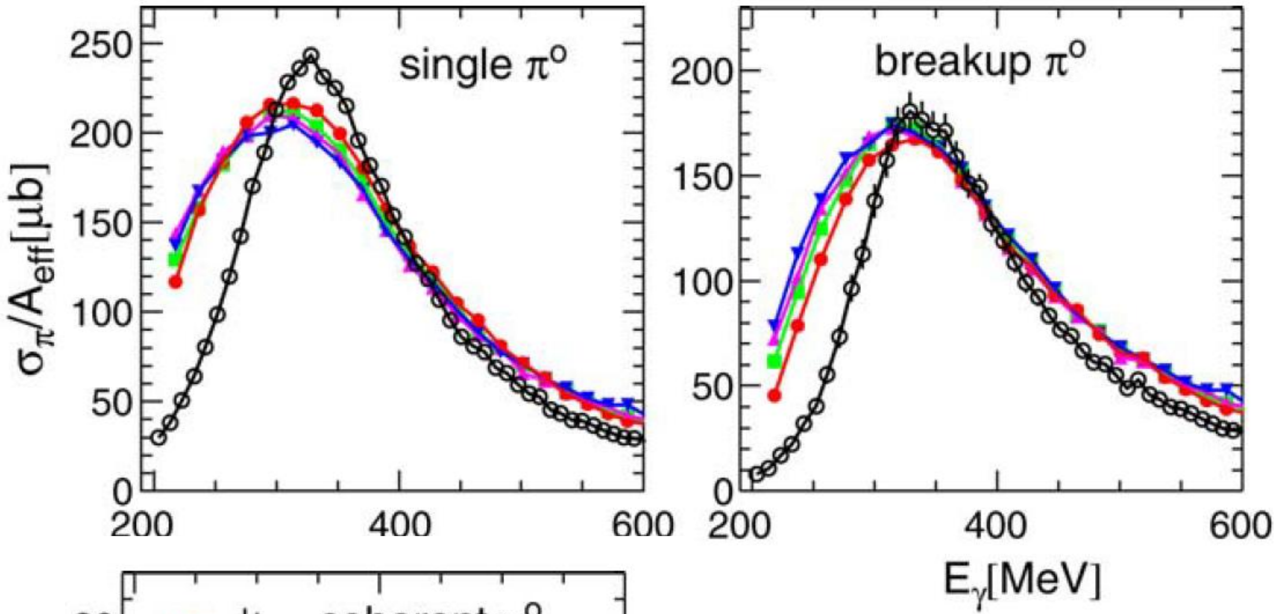


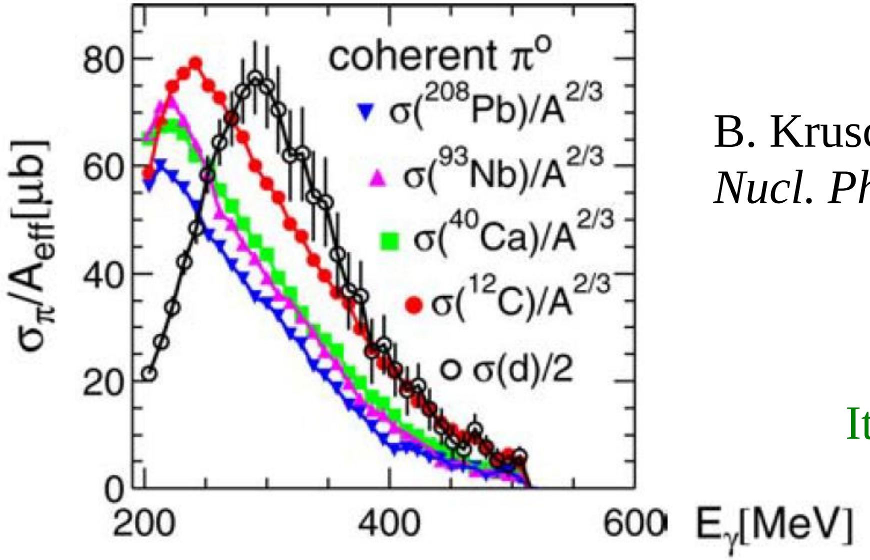


V. E. Tarasov, W. J. Briscoe, H. Gao, A. E. Kudryavtsev, and I. I. Strakovsky, *Phys. Rev.* C 84 (2011) 035203

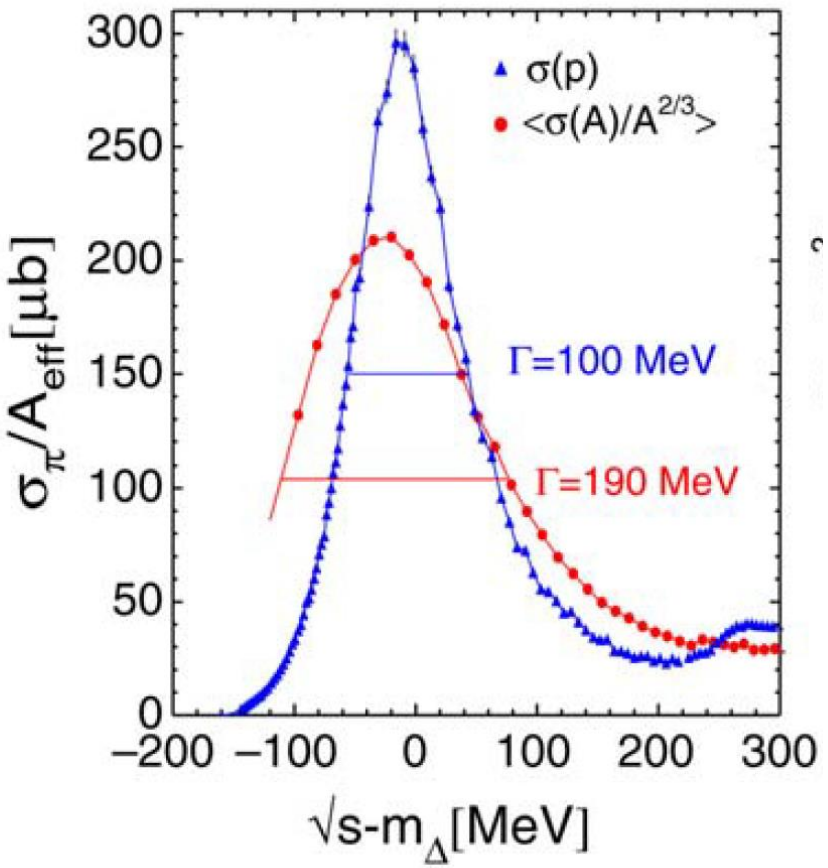
- Reactions on nuclei

A remarkable feature of the photon induced excitation of the Δ(1232) in nuclei is that the maximum of the total photonuclear cross section appears universally at about the same position for all nuclei between lithium and uranium, and that this position almost coincides with the A-resonance maximum in the free γ-proton cross section.



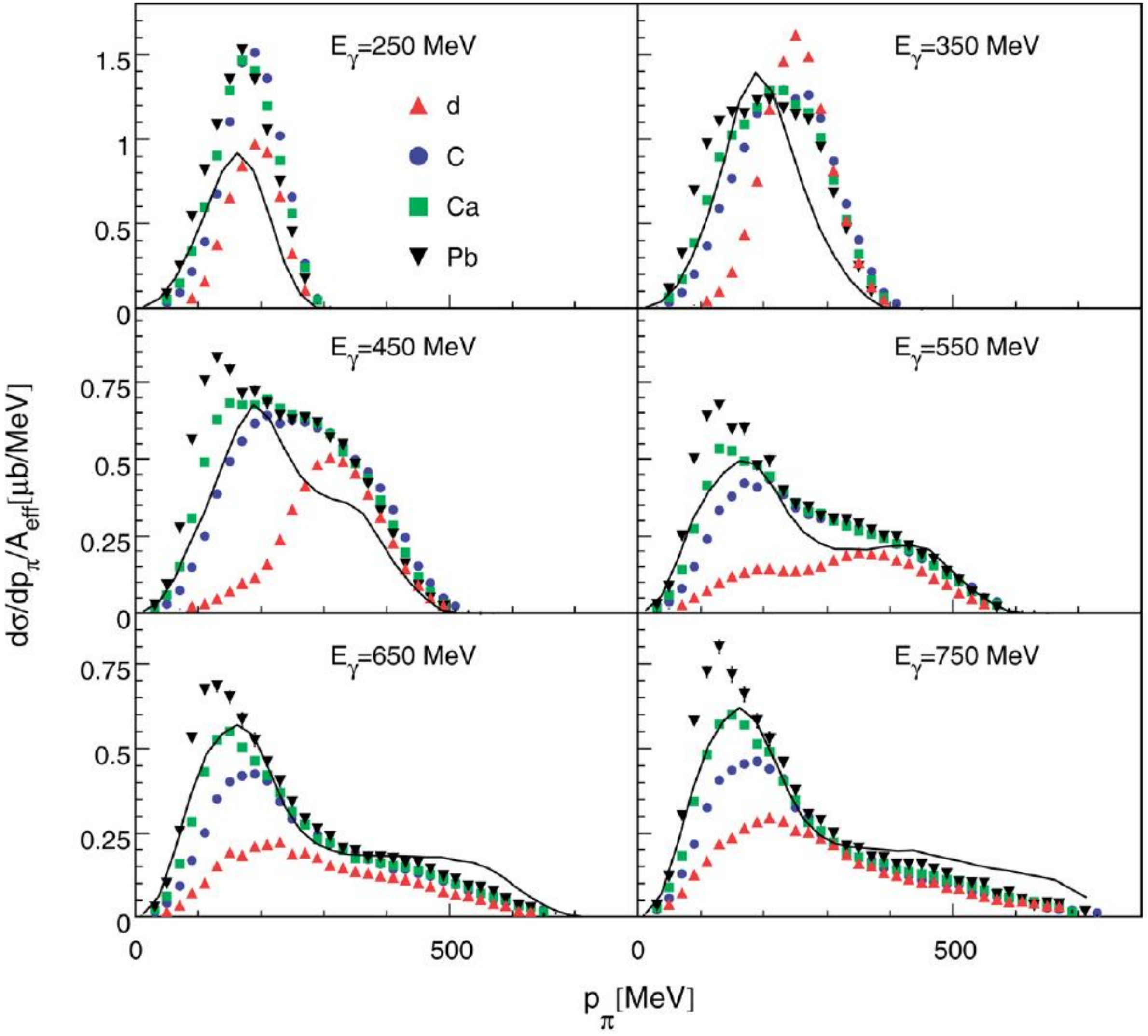


B. Krusche, *Prog. Part. Nucl. Phys*. 55 (2005) 46



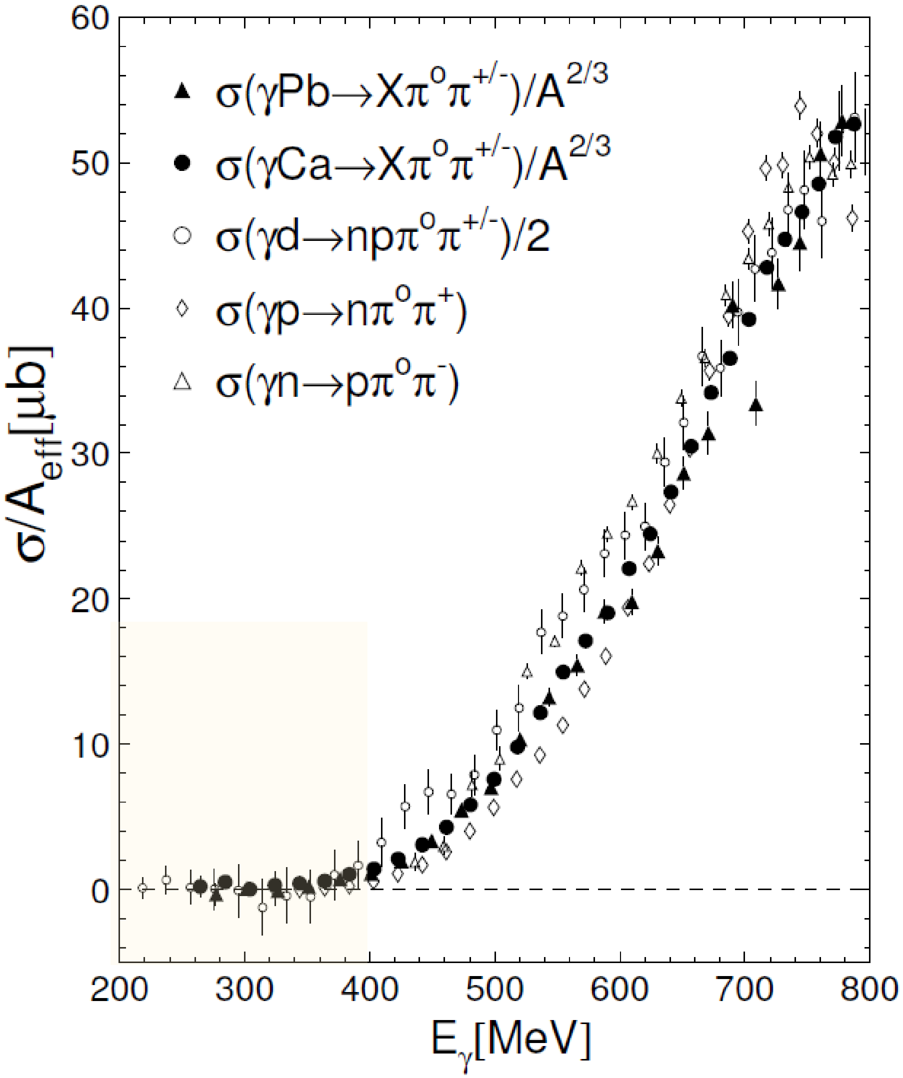
It scales almost perfectly with $A^{2/3}$, which of course indicates strong FSI effects.

Momentum distributions for inclusive π^0 photoproduction from nuclei (scaled by $A_{eff} = A^{2/3}$ for $A > 2$ and by $A_{eff} = 2$ for the deuteron)



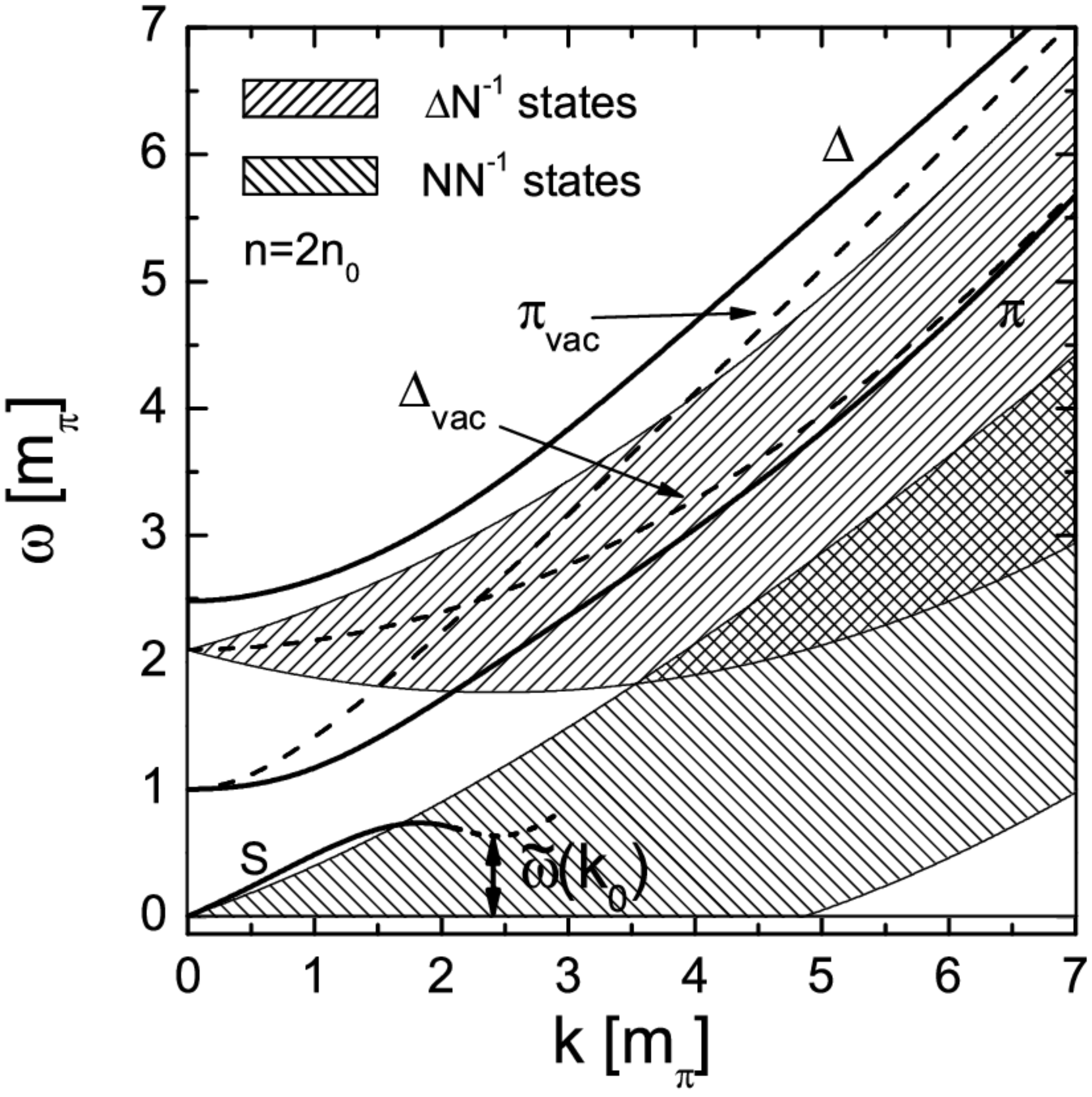
B. Krusche, *Prog. Part. Nucl. Phys*. 55 (2005) 46

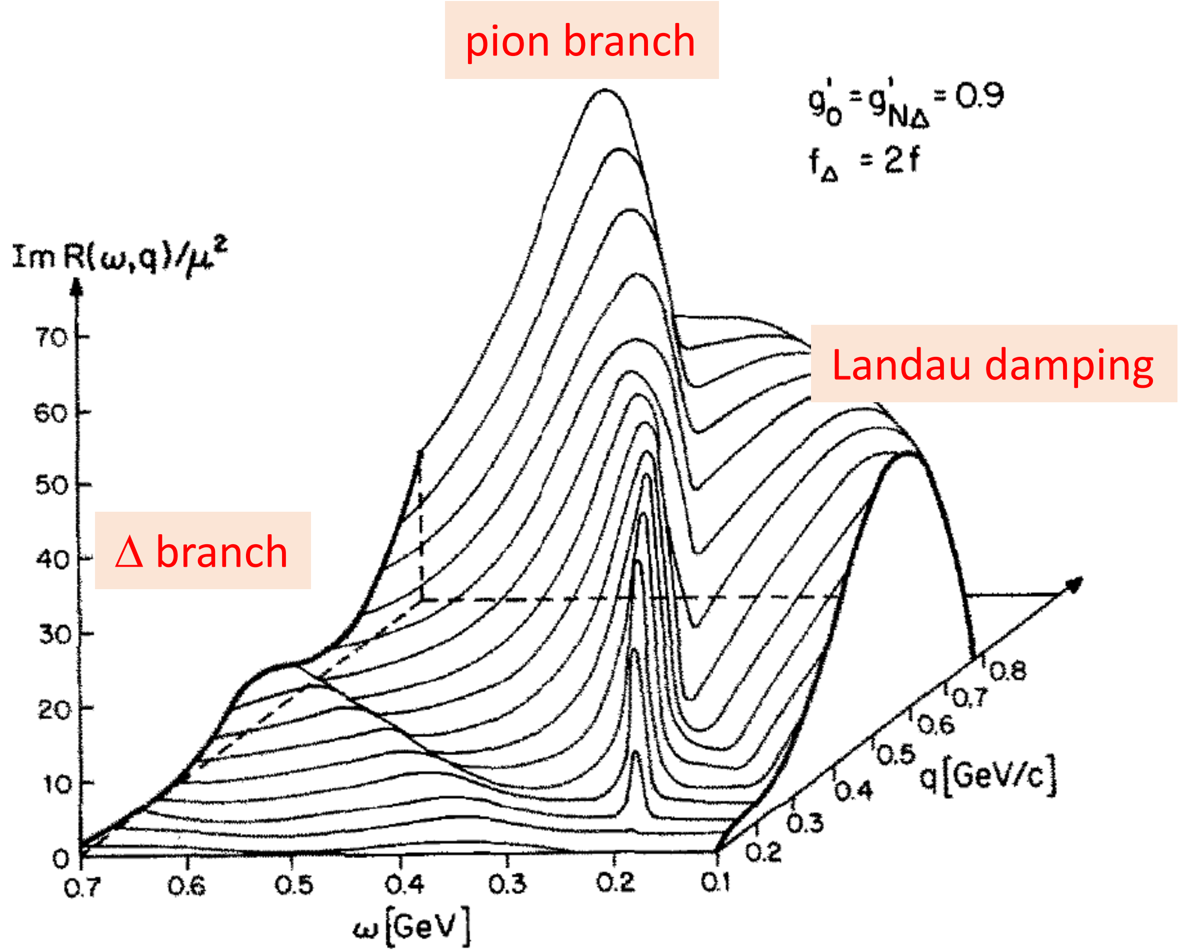
2π production on nuclei



Pion propagation in nucleus?

Pion in medium





A.B. Migdal Rev. Mod. Phys. 50 (1978) 107
A.B. Migdal et al., Phys. Rept. 192 (1990) 179

Complicated intercoupling of π and Δ dynamics in matter

Conclusion

Properties of hadronic resonances are determined by coupled channel dynamics.

To constrained the theoretical models one need good theoretical and experimental control of background process

Photon beams with energies up to 400 MeV can be used to probe one- and two-pion production processes in the region of the Δ(1232) resonance.

two-pion photoproduction are sensitive to various background processes. Challenge for theory.

$\gamma p \to \pi^0\pi^0 p$ $\quad \gamma p \to \pi^0\pi^+ n$ are well measured be TAPS @ MAMI close to threshold

$\gamma p \to \pi^-\pi^+ p$ few data in threshold region

Photoproduction on nuclei: puzzling universality of cross section for various nuclei. No pick shift, but broadening.

$\gamma A \to \pi^0\pi^\pm X$ data available $\sigma < 1\mu$b at threshold (E_γ<400 MeV)

$\gamma A \to \pi^-\pi^+ X$ no data at threshold

Interesting to study angular distributions of pions in $\gamma A \to \pi\pi X$

We need theoretical understanding of pions and Δ in medium and how we can probe it.