Baryon Resonances in Nuclei Theoretical Perspectives

NUSTAR Collaboration Meeting
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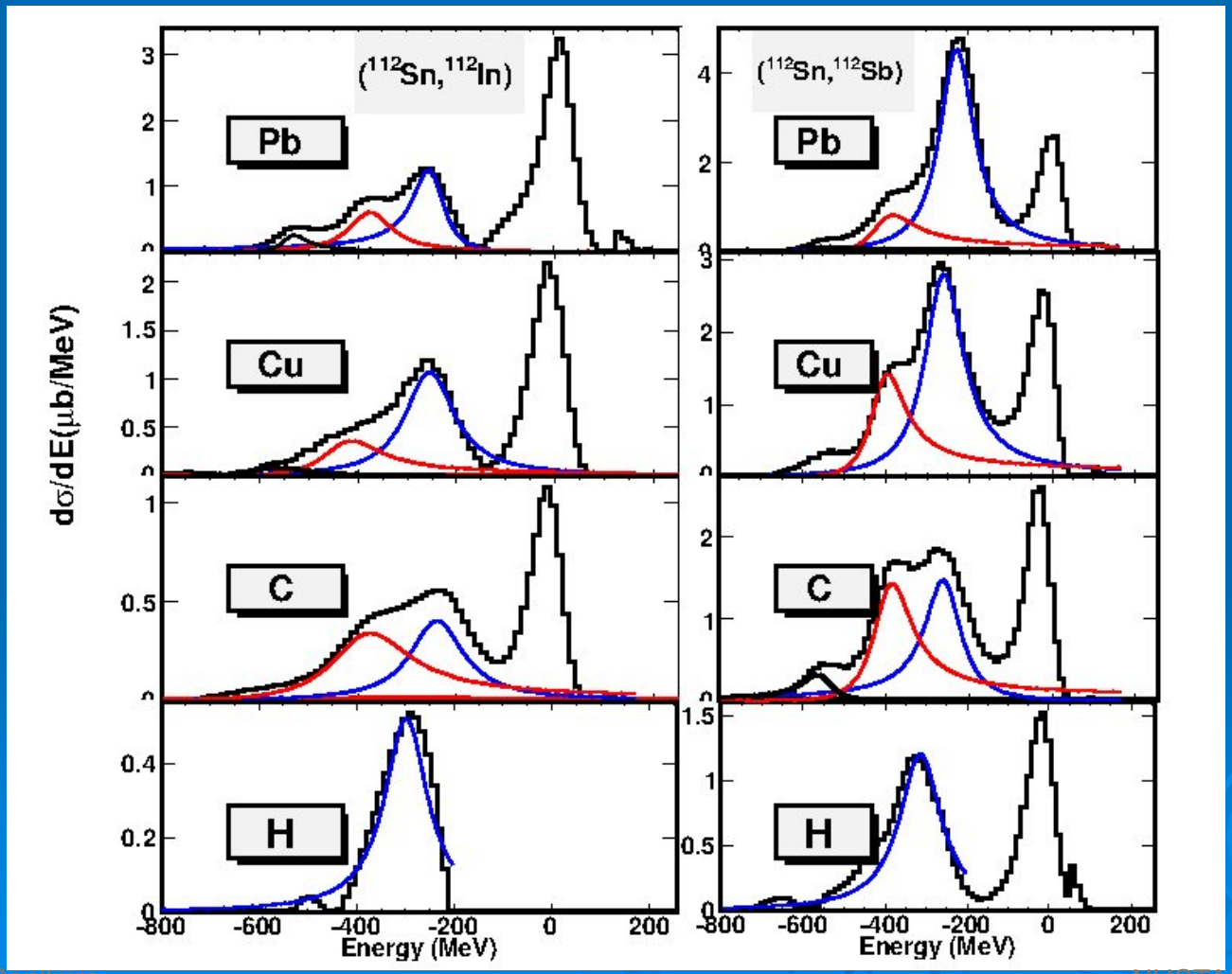
Agenda:

- Resonances in nucleus-nucleus reactions
- Nuclear structure and the excited nucleon: ΔN^{-1} modes
- Nuclear response functions with resonances
- Astrophysical connection: neutrino-nucleus interactions

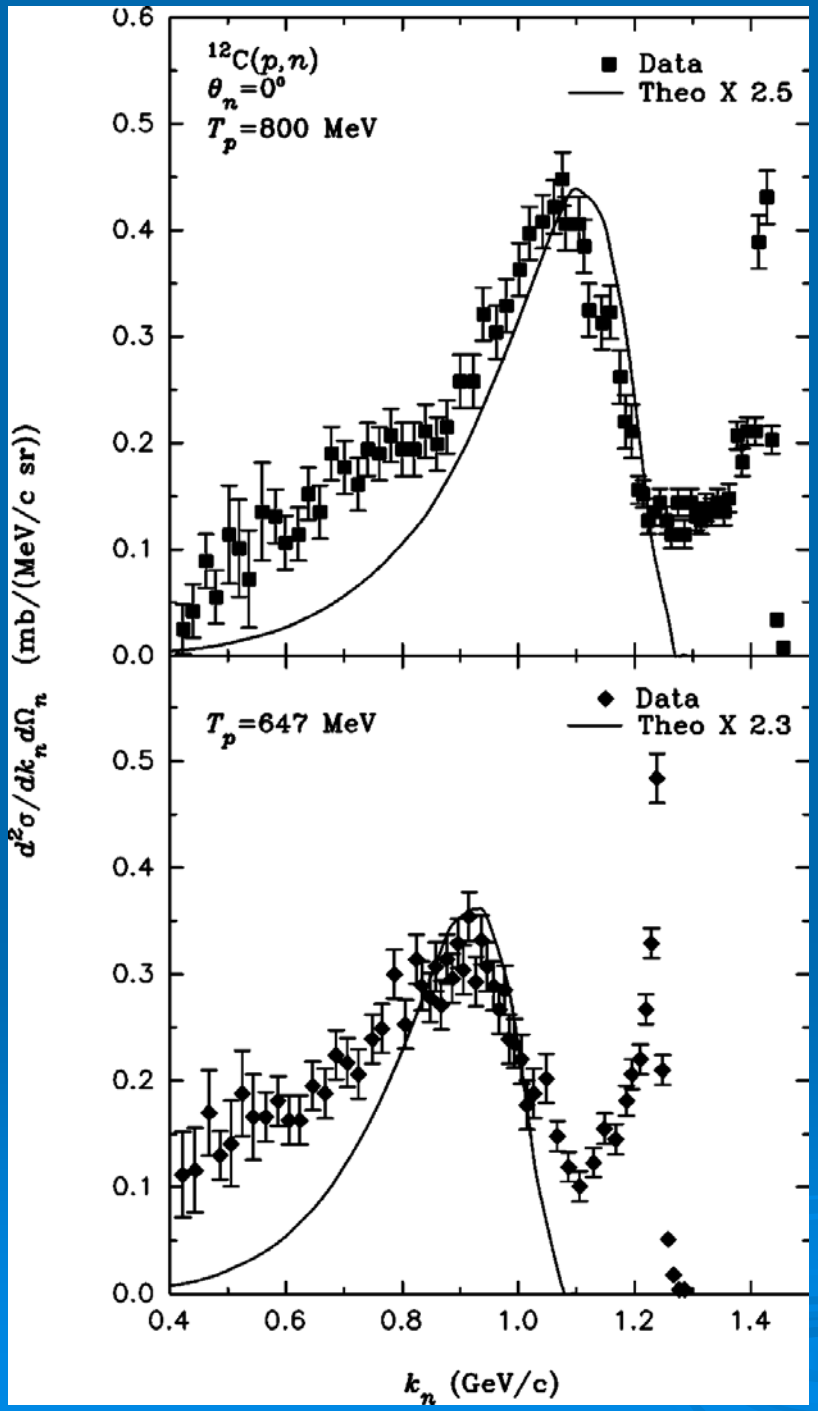
Delta Excitation in Nucleus-Nucleus Reactions

Recent measurements with the FRS

Unfolding the missing-energy with the experimental response function



c/o
J. Benlliure
&
D. Cortina



Incoherent (p,n)-type Reactions: Inclusive reaction studies

→ Observation of the outgoing nucleon/nucleus only

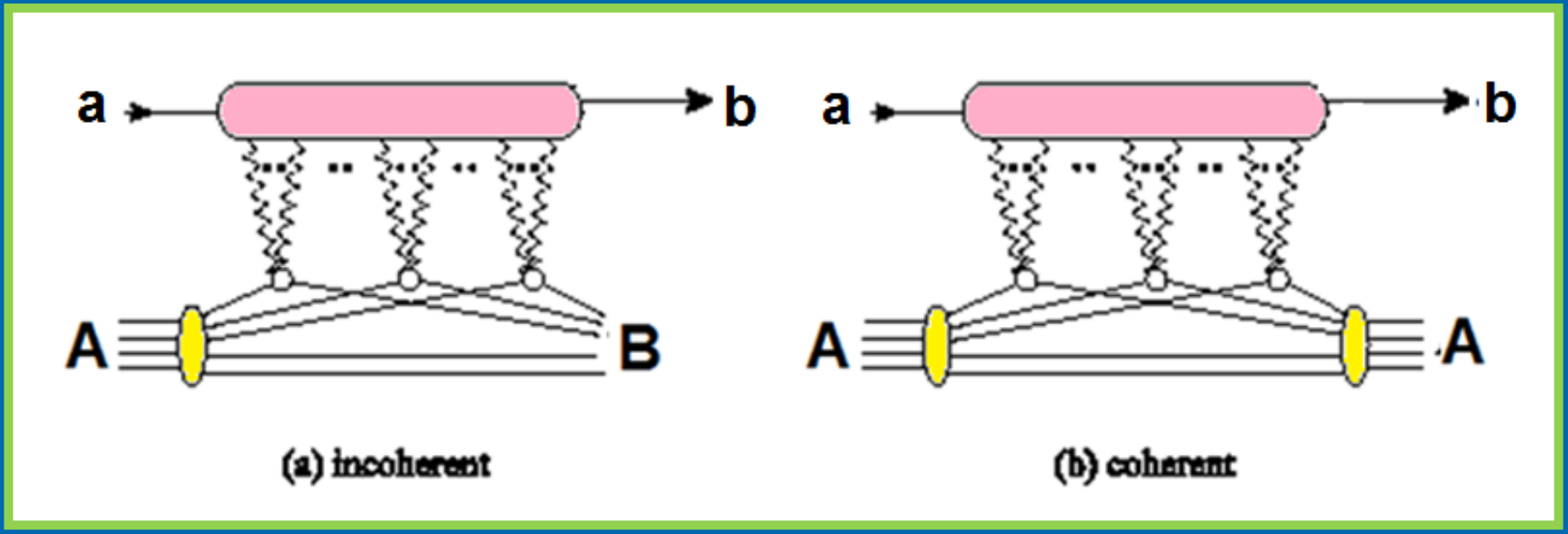
→ integration over all other channels

→ Similiar Experiments at SATURNE in the 1980ties

Theory:
S. Das, PRC 66:014604 (2002)

Datta: LAMPF/Los Alamos
C.G. Cassapakis *et al.*, Phys. Lett. B 63:35 1976.

Coherent and incoherent Reactions

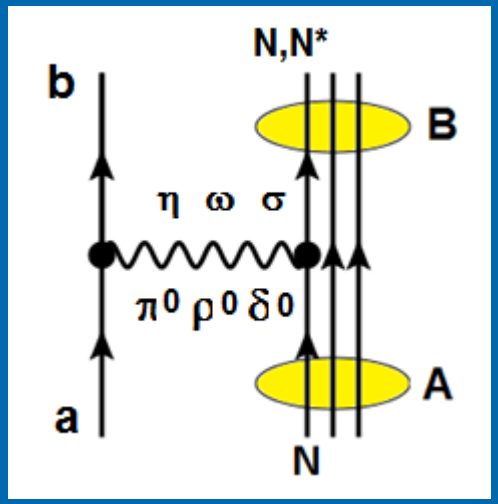


inclusive: decay of B or b not observed
exclusive: decay of B or b observed

The FRS/Super-FRS case:

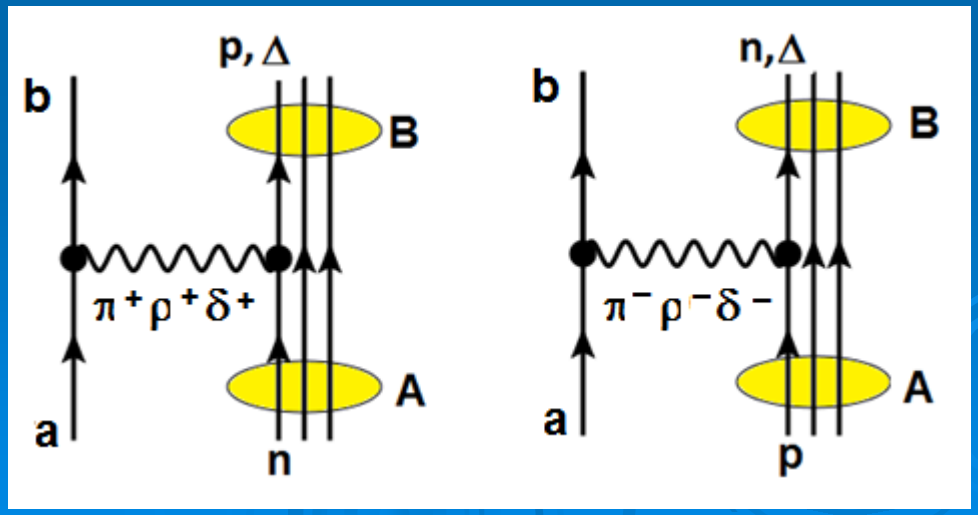
- Coherent w.r.t to the exotic beam-like nucleus b
- Inclusive w.r.t to the target-like nucleus B
- Future option: observation of pion emisssion as tagger on N*-excitation in either a→b or A→B

Inelastic Hadronic Reactions:
Charge Conserving ΔQ=0 Excitation of Quasi-elastic and Resonance States



$$\{1_\sigma, \vec{\sigma}\} \otimes \{1_\tau, \tau^0\}$$

Charge Exchange Hadronic Reactions:
Charge Changing ΔQ=±1 Excitation of Quasi-elastic and Resonance States



$$\{1, \vec{\sigma}\} \otimes \tau^{\pm}$$

Hadronic Tensor in NC/CC Reactions:

$$d^2\sigma \sim \sum_{bB} \left| M_{aA\to bB}\left(\omega,\vec{q}\right)\right|^2 = \sum_{\mu\nu} \left| V_\mu(q^2) V_\nu(q^2)\right|^2 W_{a,\mu\nu}\left(\omega,\vec{q}\right) W_A^{\mu\nu}\left(\omega,\vec{q}\right)$$

Hadronic Tensor:

$$W_X^{\mu\nu}\left(\omega,\vec{q}\right) = T_X^{\mu}\left(\omega,\vec{q}\right) T_X^{\nu}\left(\omega,\vec{q}\right) = -\frac{1}{\pi}\,\mathrm{Im}\left(\left\langle X \left| T^{\dagger\mu} G_X\left(\omega,\vec{q}\right) T^{\nu} \right| X \right\rangle\right)$$

Factorization of the Hadronic Tensor:

$$W_X^{\mu\nu}\left(\omega,\vec{q}\right) \sim \mathrm{N}(\sqrt{s}) \left| F_X(\vec{q})\right|^2 R^{\mu\nu}\left(\omega,q\right)$$

$$R^{\mu\nu}\left(\omega,q\right) = -\frac{1}{\pi}\,\mathrm{Im}\left(\Pi^{\mu\nu}\left(\omega,q\right)\right)$$

The Cross Section:

$$d^2\sigma \sim \sum_{\mu\nu} \left| F_{a\mu}(q^2)\right|^2 \left| F_{A\nu}(q^2)\right|^2 R_{a,\mu\nu}\left(\omega,\vec{q}\right) R_A^{\mu\nu}\left(\omega,\vec{q}\right)$$

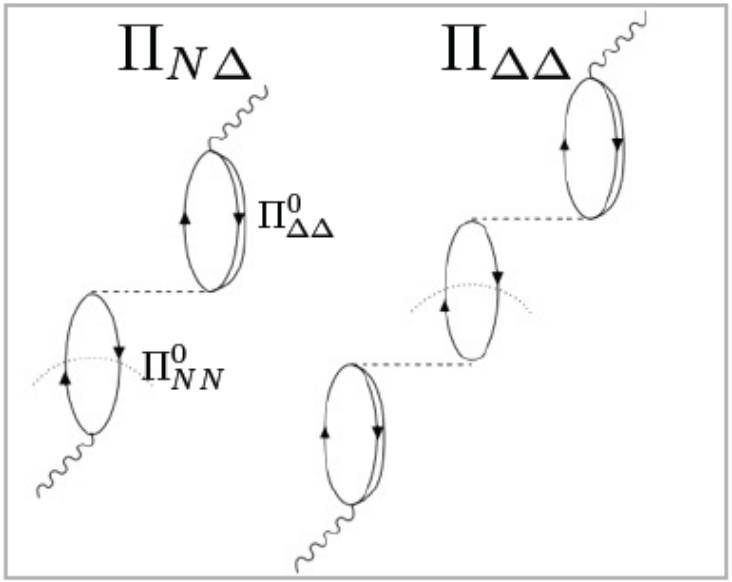
Nuclear Response Functions

Resonance Excitation in Nuclei: „ΔN^{-1} RPA“

$$\Pi = \Pi^0 + \Pi^0 \hat{V} \Pi$$

$$\begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix} = \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} + \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} V_{NN} & V_{N\Delta} \\ V_{\Delta N} & V_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix}$$

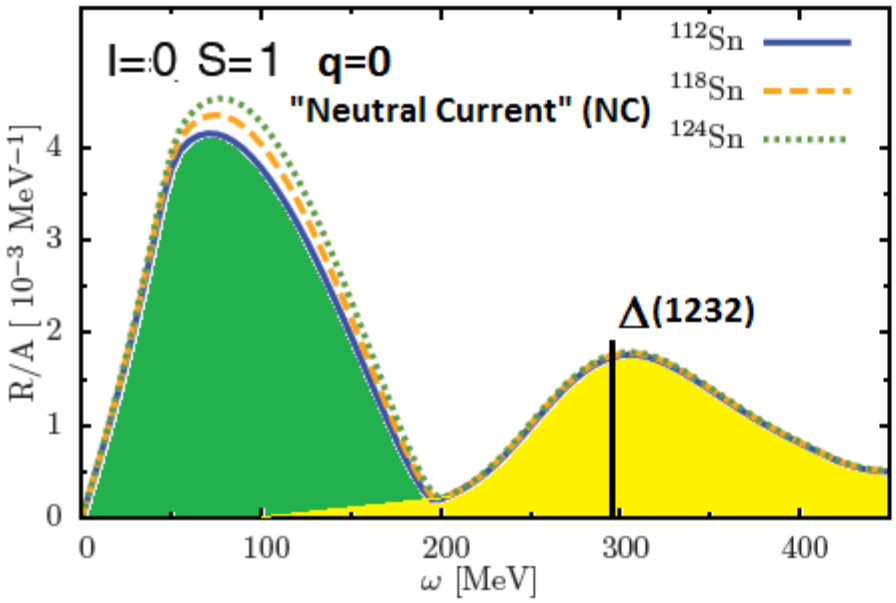
- Full RPA includes Δ-N mixing
- Non-perturbative problem
- QE-peak is influenced by intermediate Δ-hole pairs
- Structure of the spin-isospin response can give a deeper understanding of the Δ-N interaction

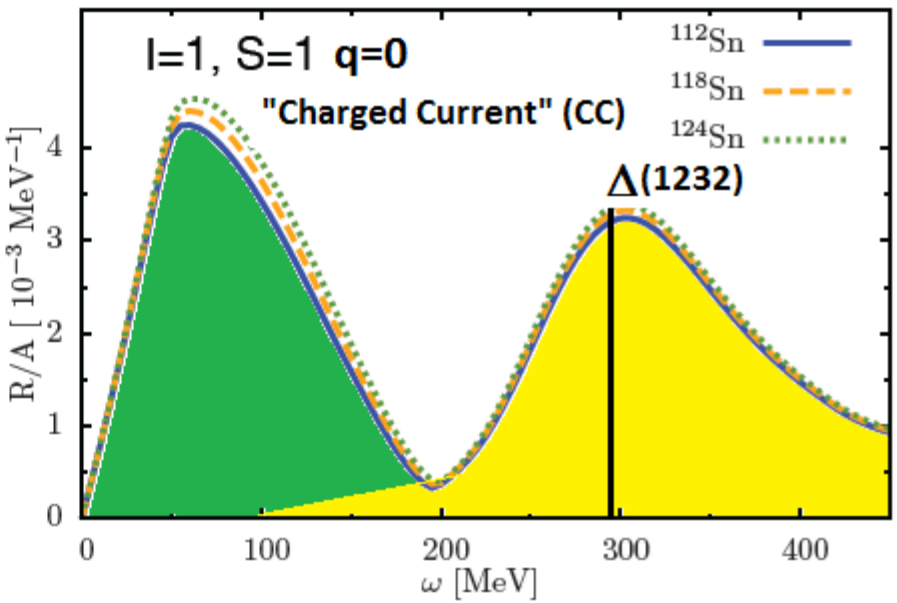


$$\Pi_{NN} = \chi_{\Delta N} \chi_N \Pi^0_{NN}$$

Spin Response Functions $R(\omega,q)=-\mathrm{Im}\,\Pi(\omega,q)$@Sn-chain: RPA results for

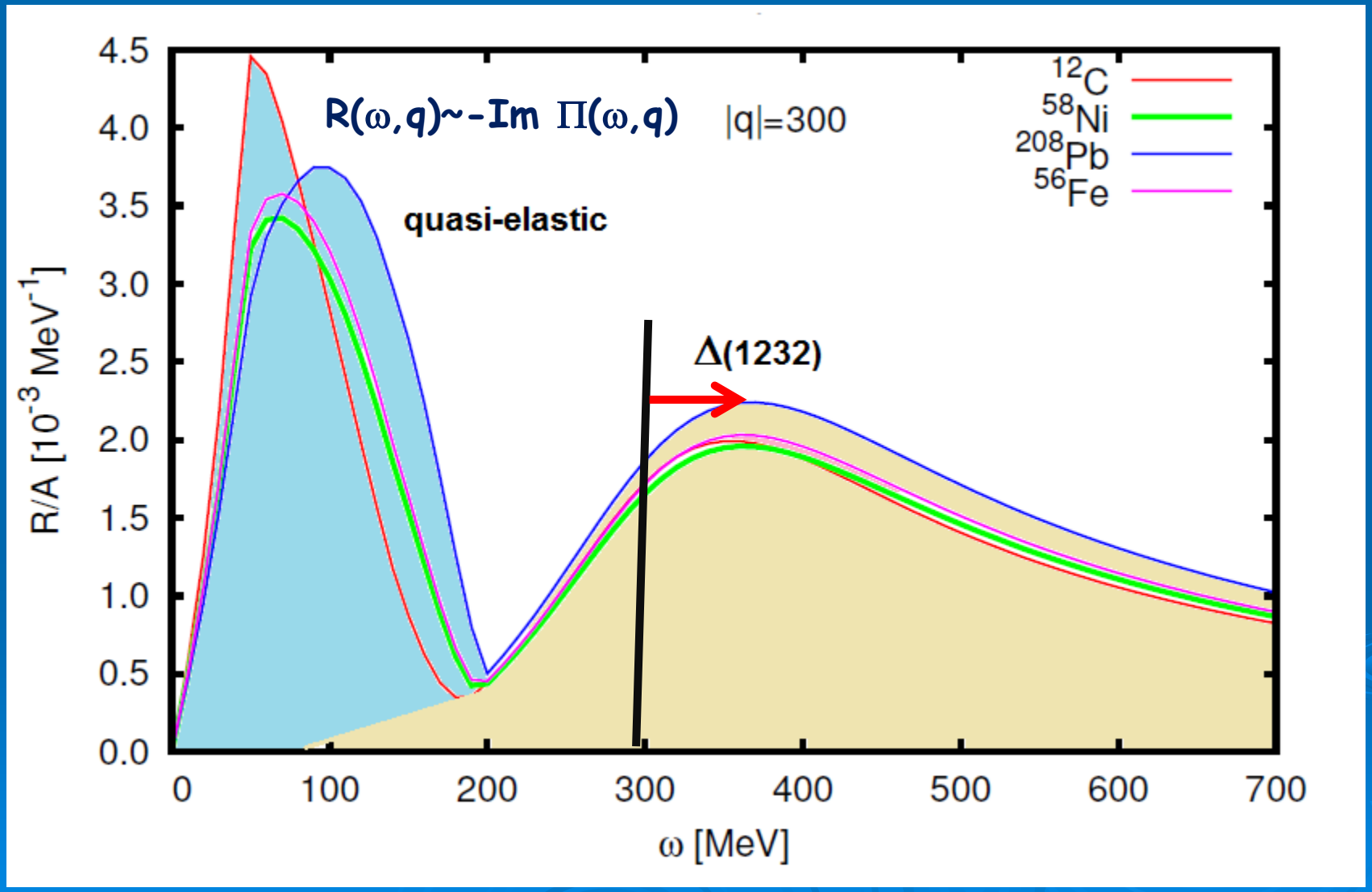
- $T_a=\tau_0$ (I=0: NN^{-1})
- $T_a=\tau_-$ (I=1: pn^{-1} & Δn^{-1} transitions)





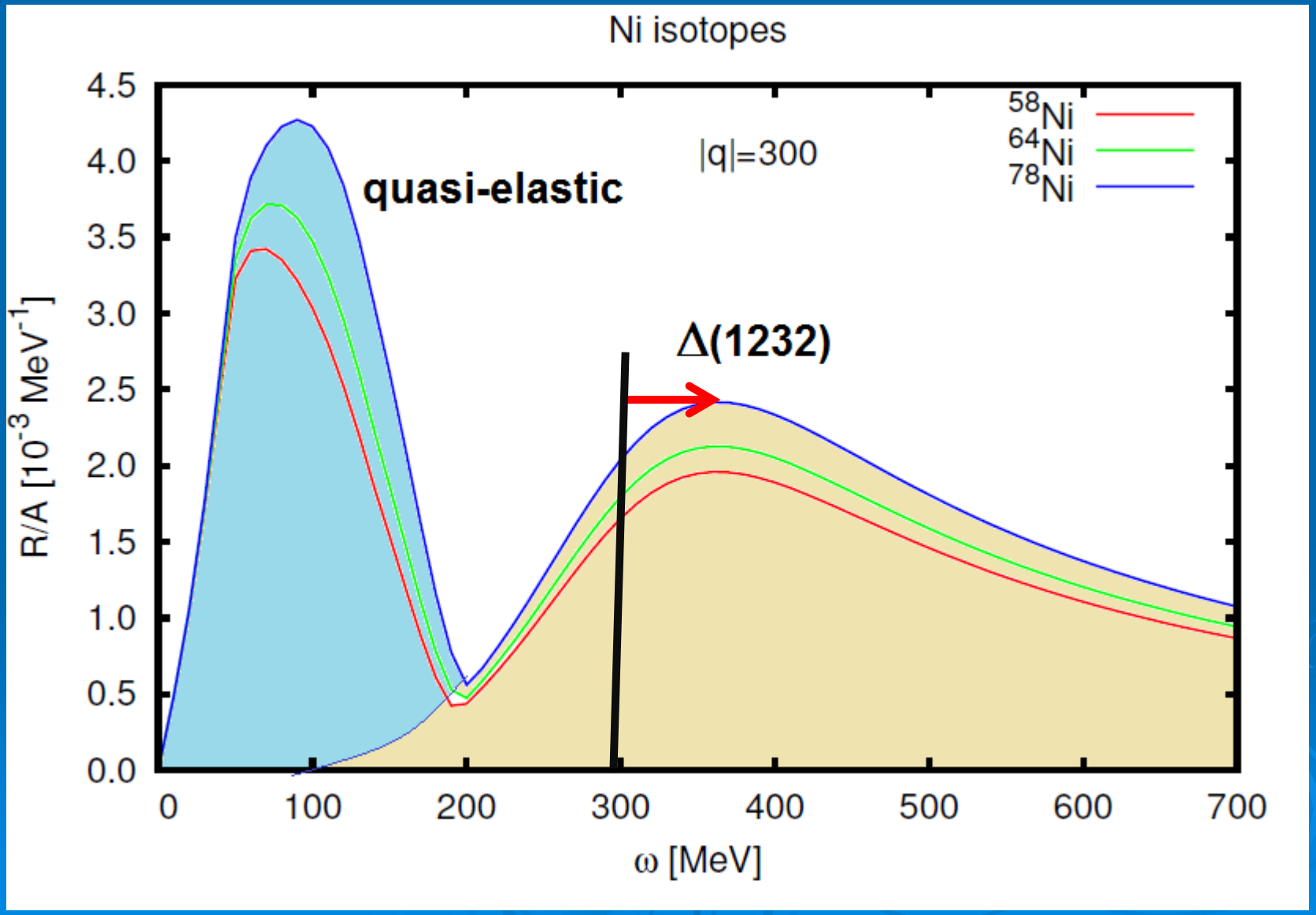
- Vanishing momentum transfer q=0
- Δ self-energy neglected
- Tensor interaction from π,ρ exchange neglected

Response Functions (per nucleon) in β-table Nuclei: RPA results for $T_a=\tau_-$ (pn^{-1} & Δn^{-1} transitions)

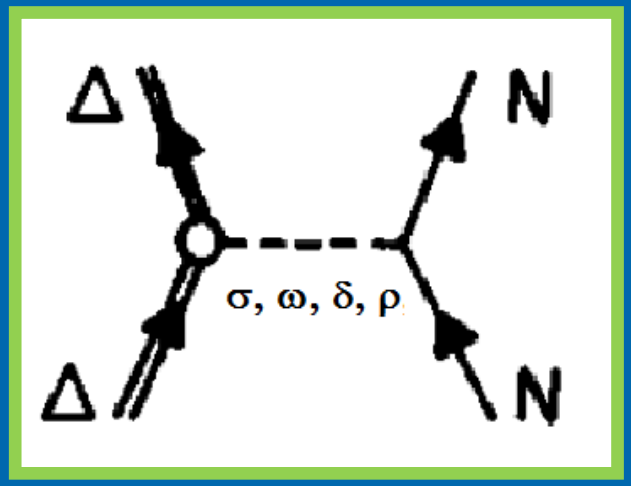


A. Fedoseew, H.L.

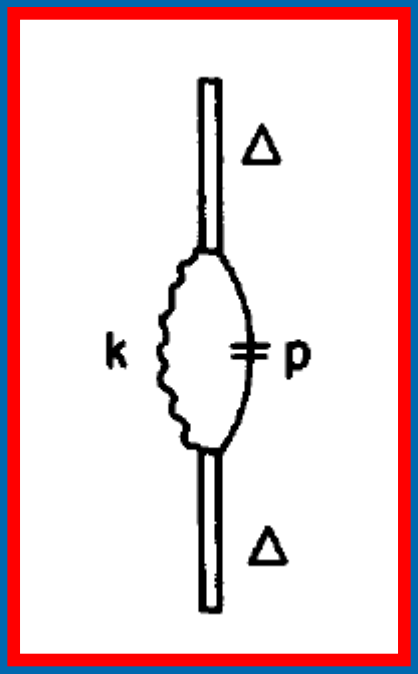
Response Functions (per nucleon!) along the Ni-chain: RPA results for $T_a=\tau_-$ (pn^{-1} & Δn^{-1} transitions)



Delta Self-Energy in Nuclear Matter



+



Direct Self-energy → Hartree-Potential

$$U_\Delta^{(H)} = U_0 + U_1 \tau_\Delta \cdot \tau_N$$

$$U_\Delta^{(H)} \sim U_0 + U_1 t_z^{(\Delta)} \cdot \frac{N-Z}{A}$$

Polarization Self-Energy → dispersive (optical) potential

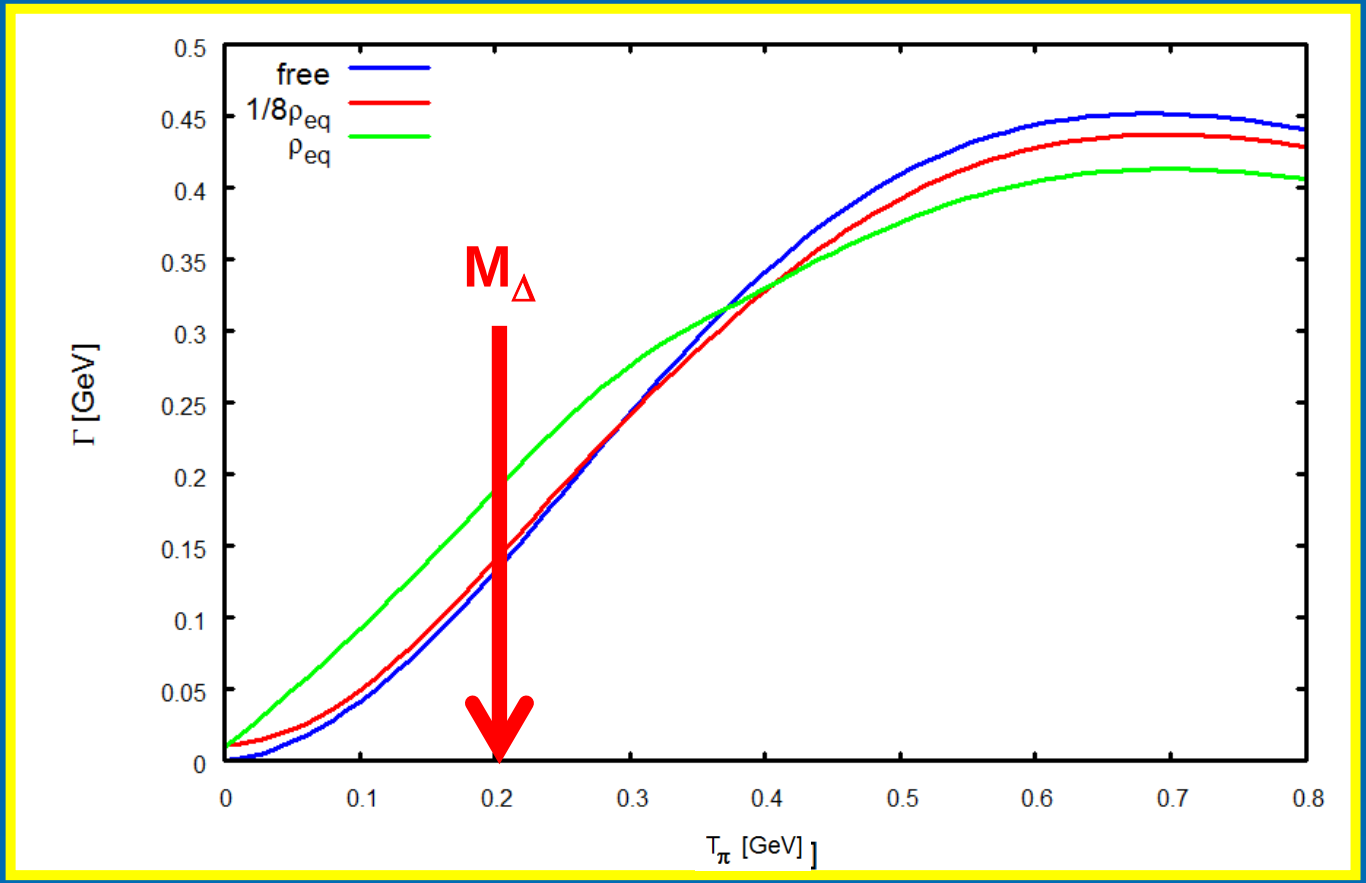
$$\Sigma_{pol}^{(\Delta)} \sim \Sigma_0 + \Sigma_1 t_z^{(\Delta)} \frac{N-Z}{A}$$

$$\Sigma_\alpha = V_\alpha - iW_\alpha$$

…see e.g.:

E. Oset, L.L. Salcedo, NPA 468 (1987) 631; G.E. Brown, W. Weise, Phys. Rept. 22 (1975) 279

In-Medium Delta(1232) Width



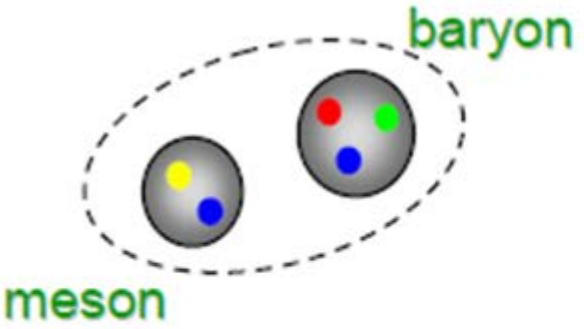
$$\Gamma_\Delta(p_\Delta^2,\rho) = -2\,\mathrm{Im}\,\Sigma(p_\Delta^2,\rho) \sim \Gamma_{free}(p_\Delta^2) + \Gamma_{Pauli}(p_\Delta^2,\rho) + \Gamma_{abs}(p_\Delta^2,\rho)$$

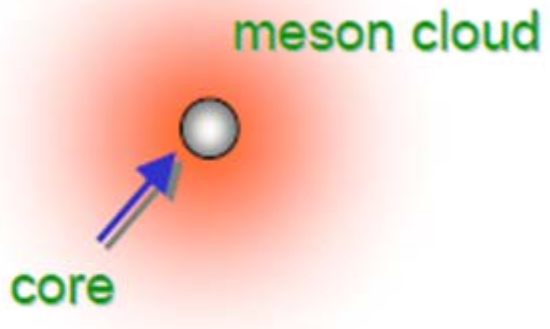
$$\mathrm{Re}\left(\Sigma(\omega,q)\right) = -\frac{2\omega}{\pi} P\int d\omega' \frac{\mathrm{Im}\left(\Sigma(\omega',q)\right)}{\omega'^2-\omega^2}$$

QCD Aspects of Resonances:

- hadronic (*soft scale*) *molecular-type* components $|N_s\rangle$
- QCD (*hard scale*) confined components $|N_h\rangle$

$$\left|N^*\right\rangle = \left|N_s^*\right\rangle + \left|N_h^*\right\rangle = x_1\left|mB\right\rangle + x_2\left|qqq\right\rangle + x_3\left|qqq\right\rangle \otimes \left|q\bar{q}\right\rangle + \ldots$$





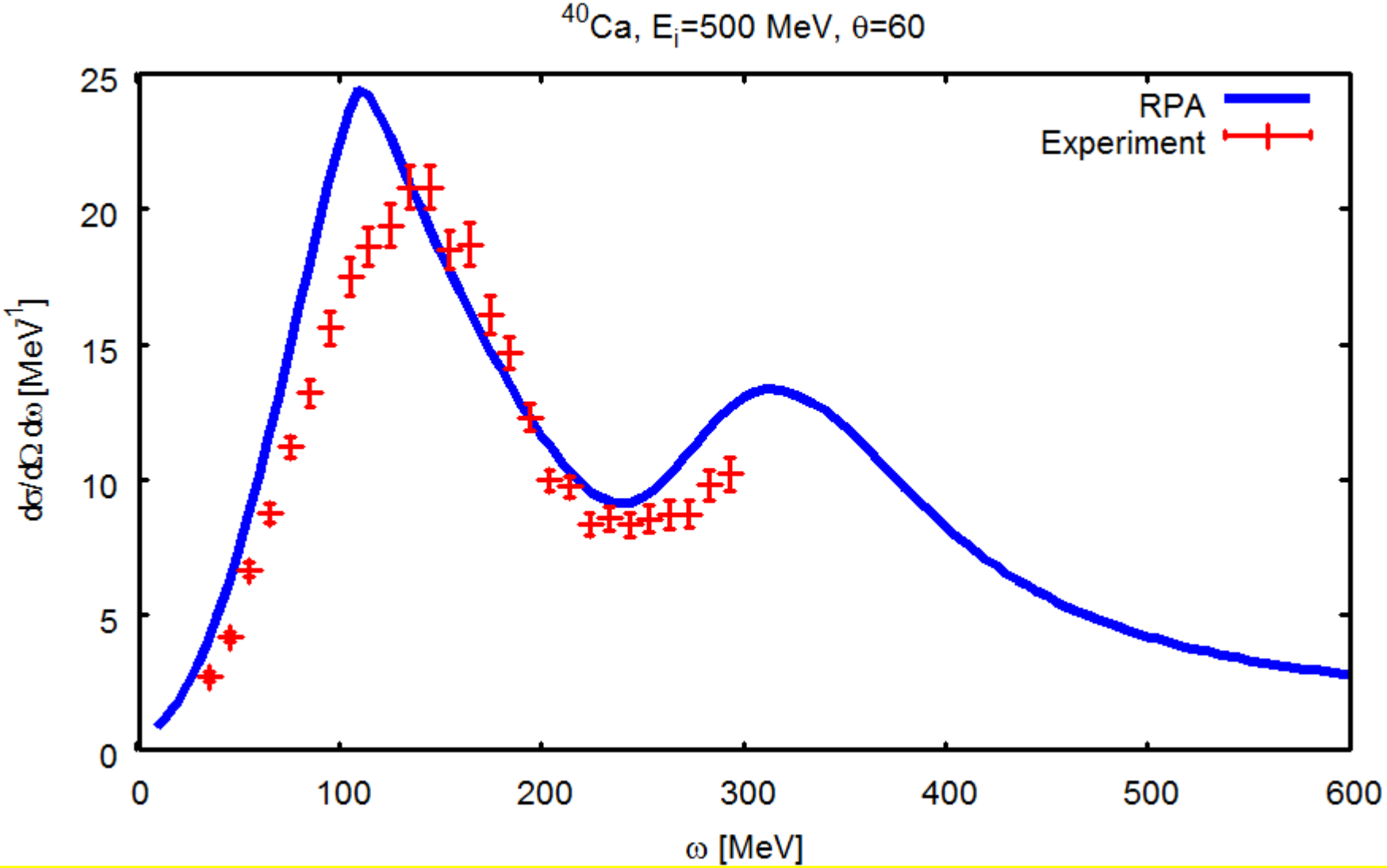
$$|N_s^*\rangle = |MB\rangle$$

$$|N_h^*\rangle = |qqq\rangle + |\text{m.c.}\rangle$$

Strong Medium Dependence

Weak Medium Dependence

A Test Case:
Quasielastic Inclusive (e,e') Scattering

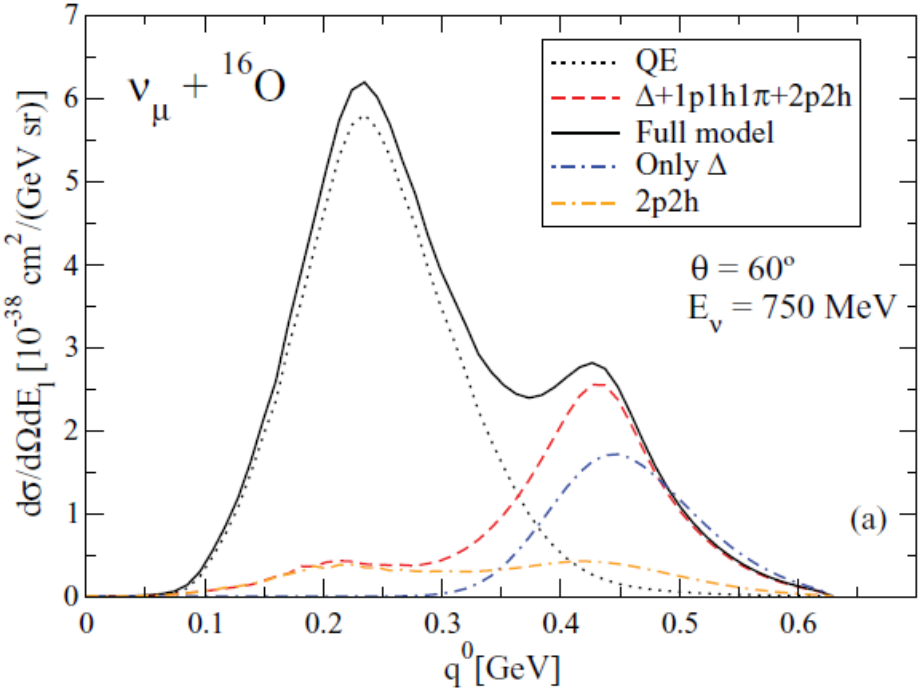


Connection to Astrophysics: Neutrino-Nucleus Interactions

Neutrino-Nucleus Cross Sections and NΔ-Response Functions: ν_e+N→Δ→N+π Reactions

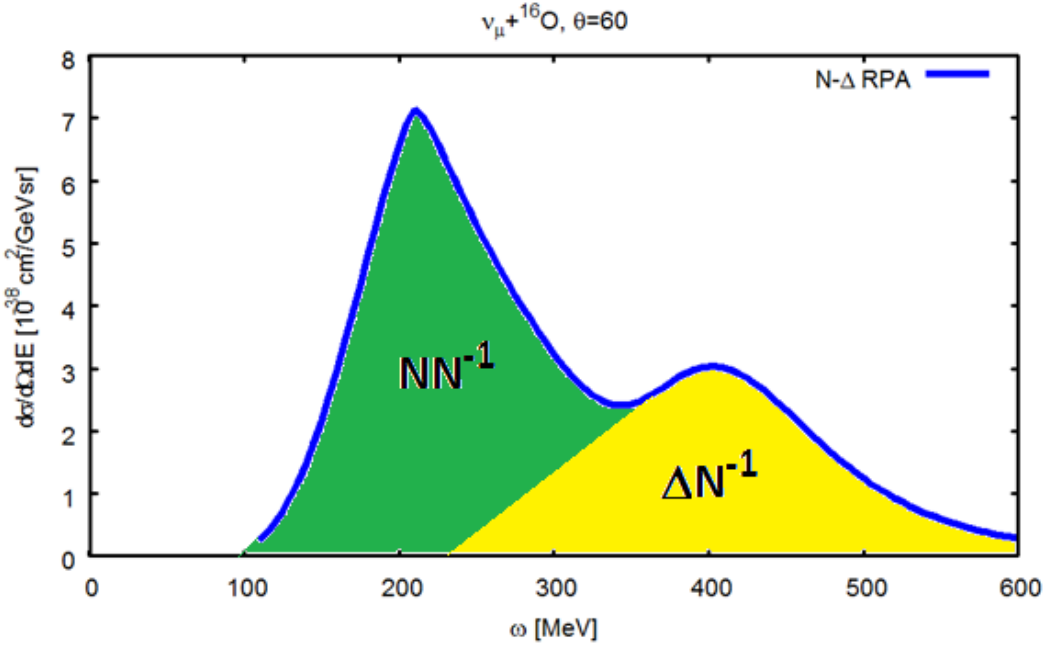
$$\frac{\partial^2\sigma}{\partial\Omega\partial k'} = \frac{G_F^2\cos^2\theta_c(k')^2}{2\pi^2}\cos^2\frac{\theta}{2}\left\{G_E^2\left(\frac{q_\mu^2}{q^2}\right)^2 R_\tau^{NN}\right.$$
$$+ G_A^2\frac{(M_\Delta - M_N)^2}{2q^2}R_{\sigma\tau(L)}^{N\Delta} + G_A^2\frac{(M_\Delta - M_N)^2}{q^2}$$
$$\times R_{\sigma\tau(L)}^{\Delta\Delta} + \left(G_M^2\frac{\omega^2}{q^2} + G_A^2\right)\left(-\frac{q_\mu^2}{q^2} + 2\tan^2\frac{\theta}{2}\right)$$
$$\times\left[R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right] \pm 2G_A G_M\frac{k+k'}{M_N}$$
$$\left.\times\tan^2\frac{\theta}{2}\left[R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right]\right\}$$

Inclusive CC cross section



J. Nieves, I. Ruiz Simo, M. J. Vicente Vacas
PRC **83**, 045501 (2011)

Gießen
„N-Δ RPA“

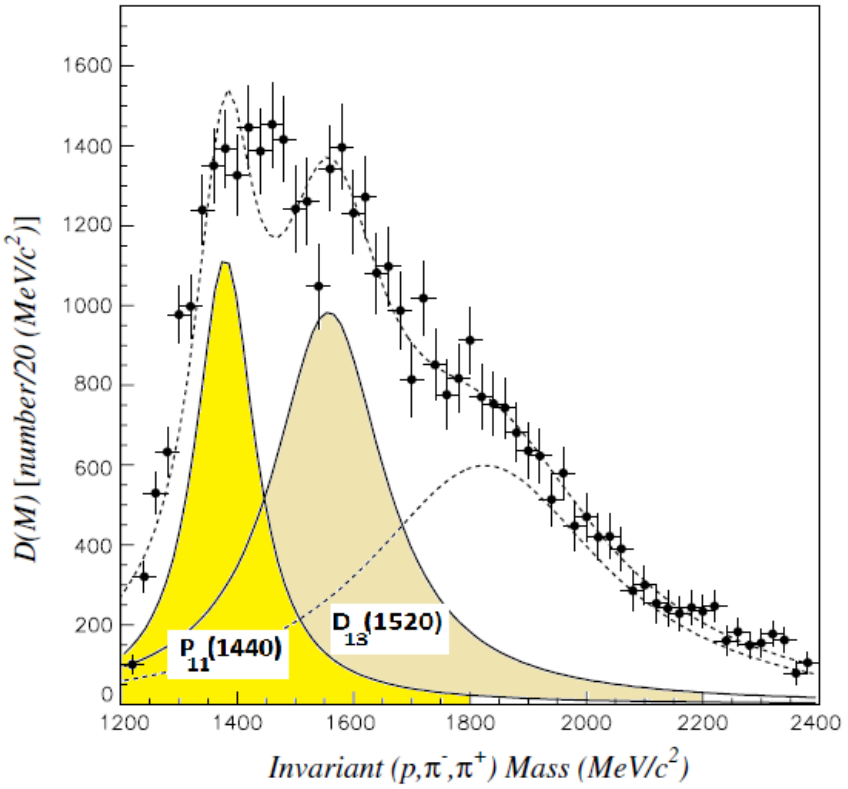


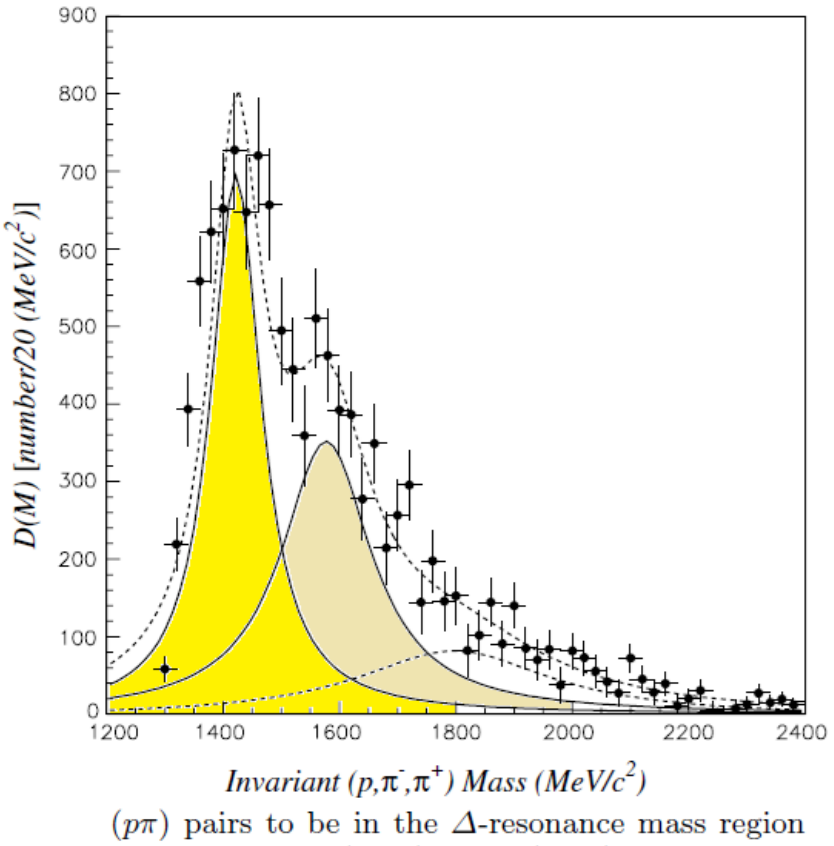
Challenges

Topics@Super-FRS

- Unique: resonance spectroscopy in asymmetric nuclear matter
- Nuclear Response on sub-nuclear excitations
- Nuclear Response at large energy&momentum transfer
- Meson production with secondary beams
- Theory: dynamics of N* excitation
- Theory: dynamical self-energies in asymmetric matter
- Complementary to R^3B: quasi-free knockout through resonance excitation
- Connection to CBM: resonance physics in cold nuclear matter at equilibrium
- Connection to astrophysícs: NC/CC weak interactions
- Super-FRS: going beyond the Delta resonance
  → $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$…

Excitation of Higher Resonances in A+A Collisions
12C+12C @ 4.2 AGeV





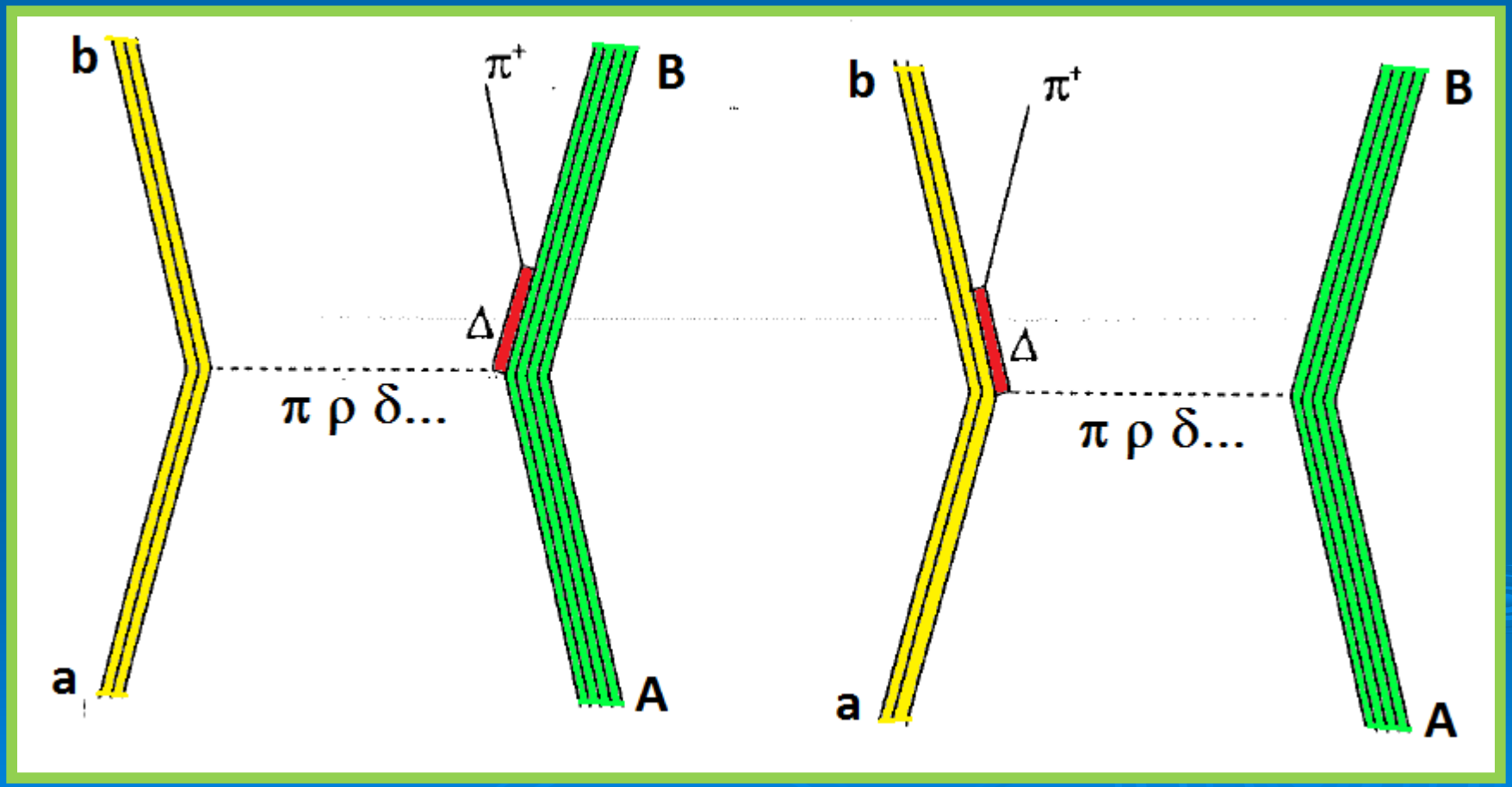
($p\pi$) pairs to be in the Δ-resonance mass region

	M (MeV/c^2)	Γ (MeV/c^2)
$N(1440)$	1380 ± 10	130 ± 20
$N(1520)$	1550 ± 20	230 ± 30
The 3rd peak	1810 ± 30	510 ± 40

	M (MeV/c^2)	Γ (MeV/c^2)
$N(1440)$	1420 ± 10	105 ± 15
$N(1520)$	1570 ± 20	190 ± 60
The 3rd peak	1790 ± 120	410 ± 90

Eur. Phys. J. A **20**, 351–354 (2004)

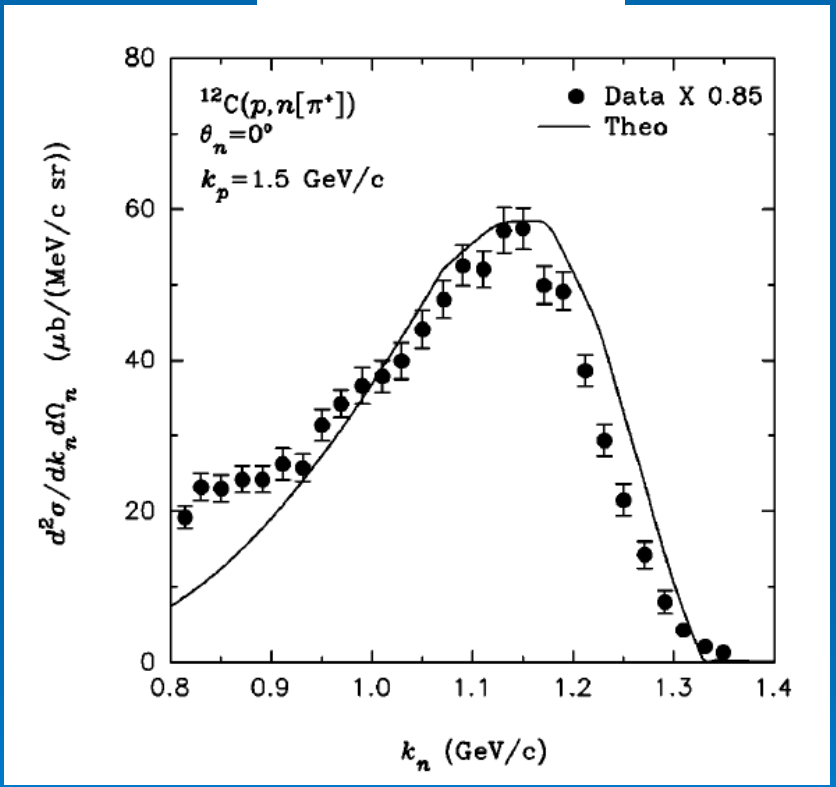
Exclusive Reactions: Resonance Excitation and Meson Production in Ion-Ion Collisions



Exclusive reaction studies:

- (p,n) reaction at KEK@T_{lab}=830Mev on ^{12}C
- (^{3}He,t) reaction at Saturne@T_{lab}=2GeV on ^{12}C

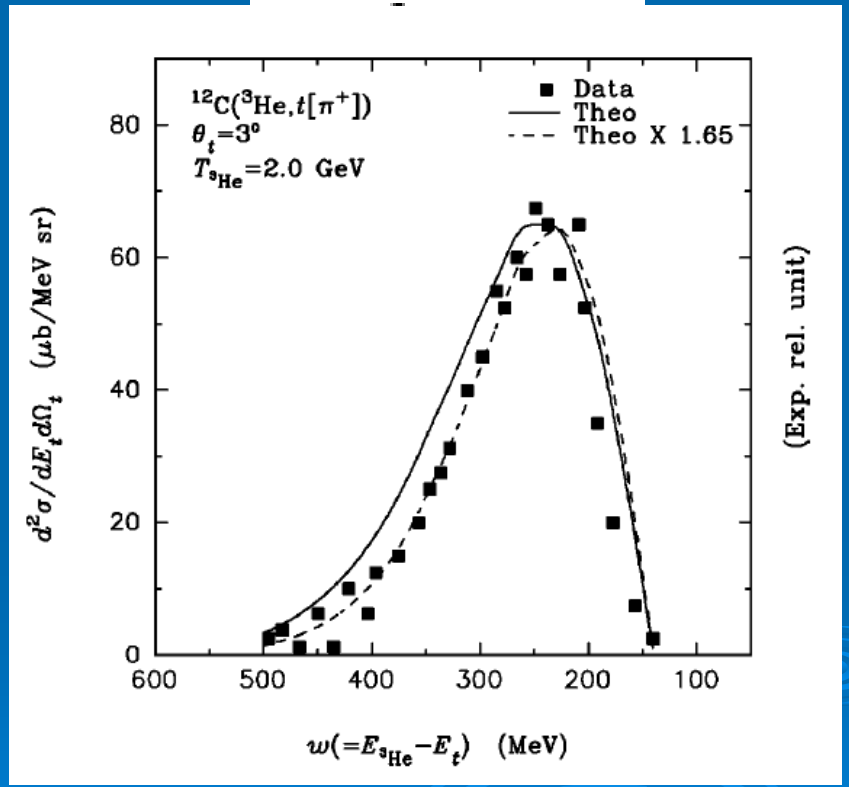
$^{12}C(p,n[\pi^+])$



FANCY@KEK 88% of 4π

J. Chiba *et al.*, Phys. Rev. Lett. 67, 1982 (1991)

$^{12}C(^3He,t[\pi^+])$



DIOGENE@SATURNE ~100% of 4π

T. Hennino *et al.*, Phys. Lett. B 283, 42 (1992)

Theory: S. Das, PRC 66:014604 (2002)

Summary and Outlook

- Baryon Resonances and „Charged Current" physics
- Resonances as nuclear structure probes
- Resonances and nuclear isospin dynamics
- DFT with nucleons and resonances
- Pion production and resonance tagging?
- Resonances beyond $\Delta(1232)$?
- Resonances and ph-interaction?
- Reaction dynamics of resonance excitation?

Credits to
Andreas Fedoseew, Julian Georg and Stefanie Lourenco