Nucleon Resonances in Exotic Nuclear Matter

Erice International School of Nuclear Physics
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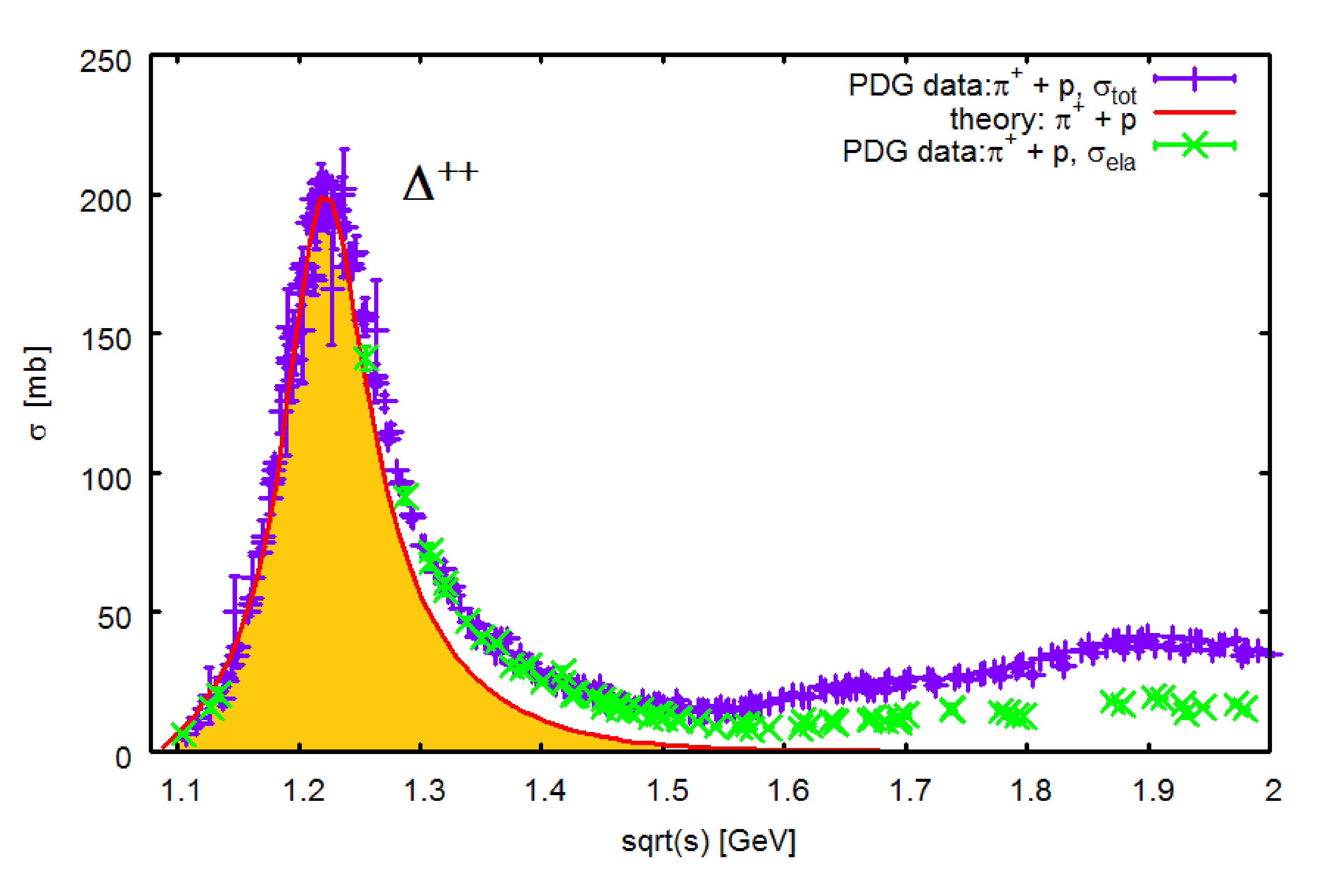
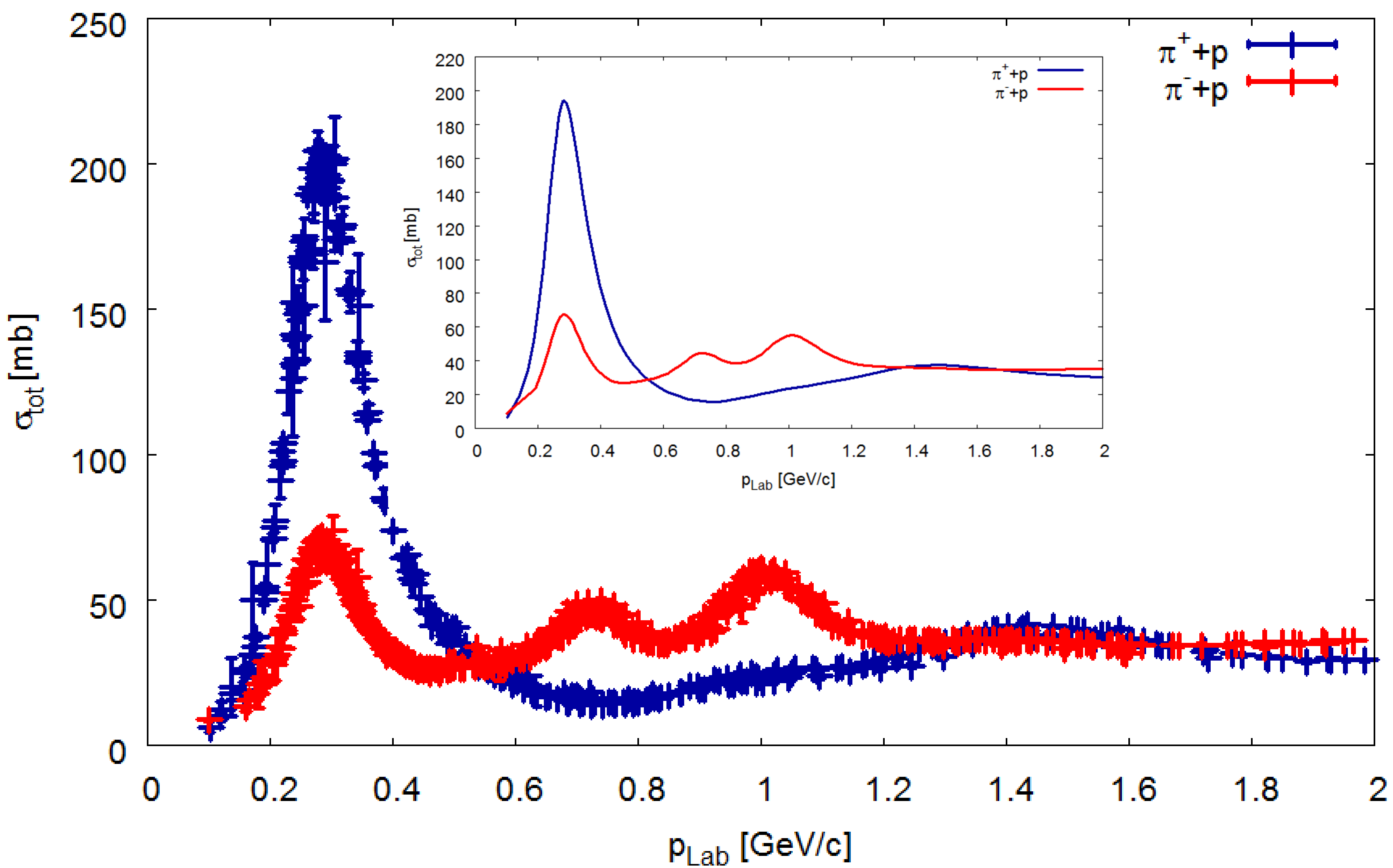
Prelude:
Excitations of the Nucleon

$\Delta_{33}(1232)$ resonance in $\pi + p$ scattering



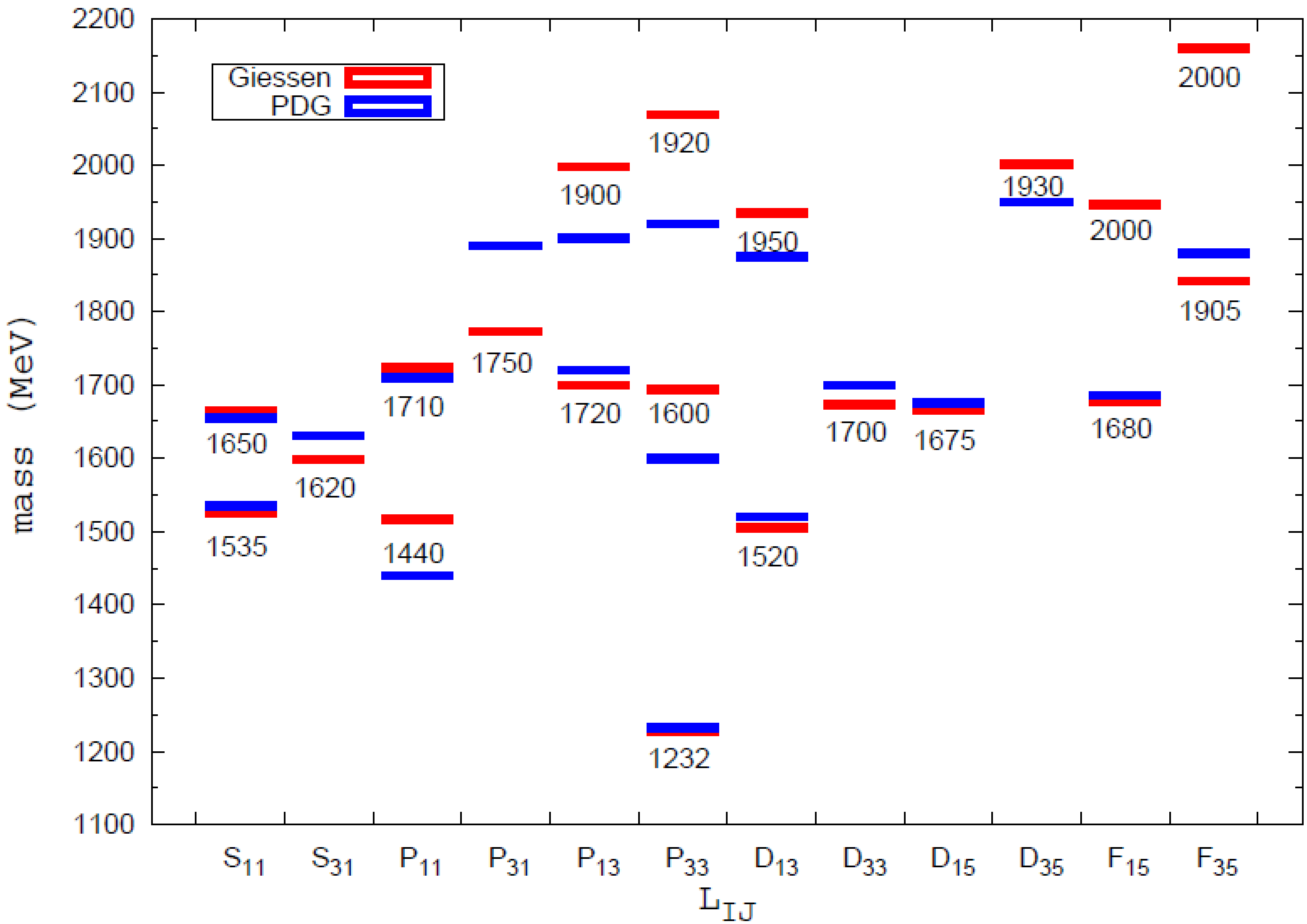
S. Lourenco, H.L., S. Wycech

Resonances in π+N scattering



Level Scheme: GiM coupled channel analysis vs. PDG

(Xu Cao, V.Shklyar, H.L., Phys. Rev. C 88, 055204 (2013))



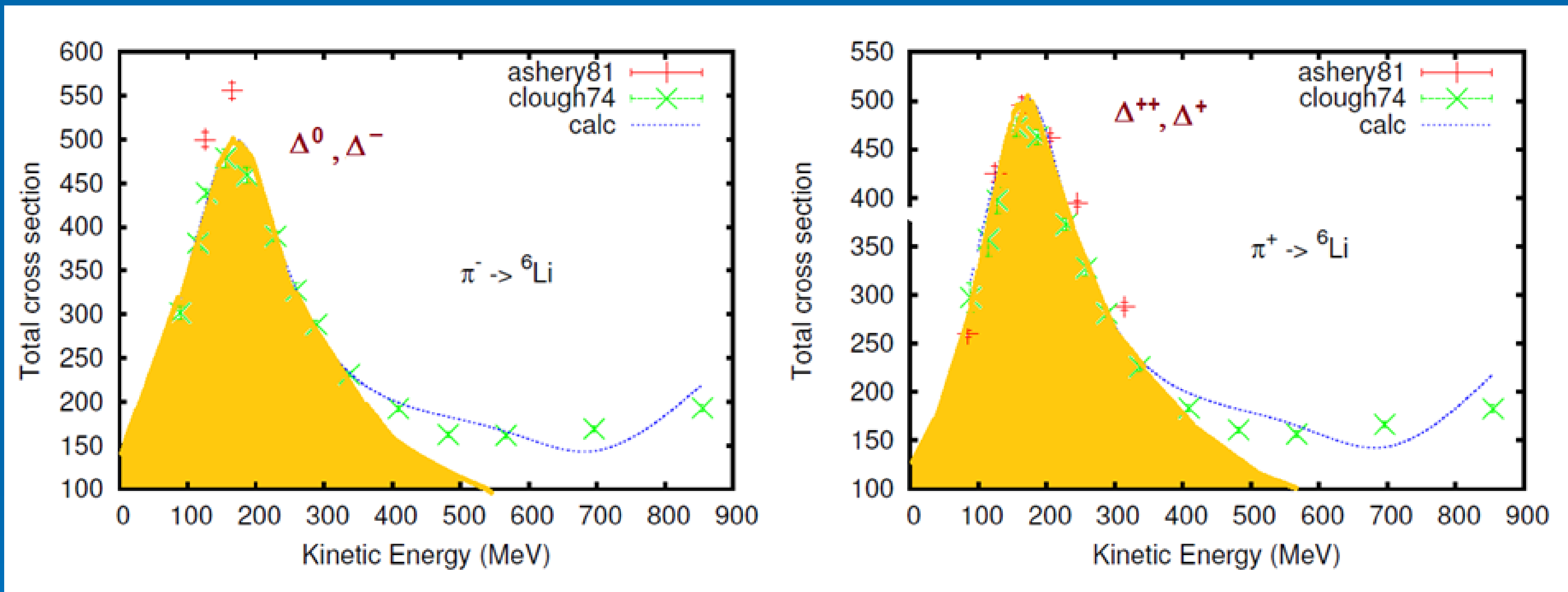
Agenda:

- Resonance excitation in nuclei
- Nuclear structure and the excited nucleon:

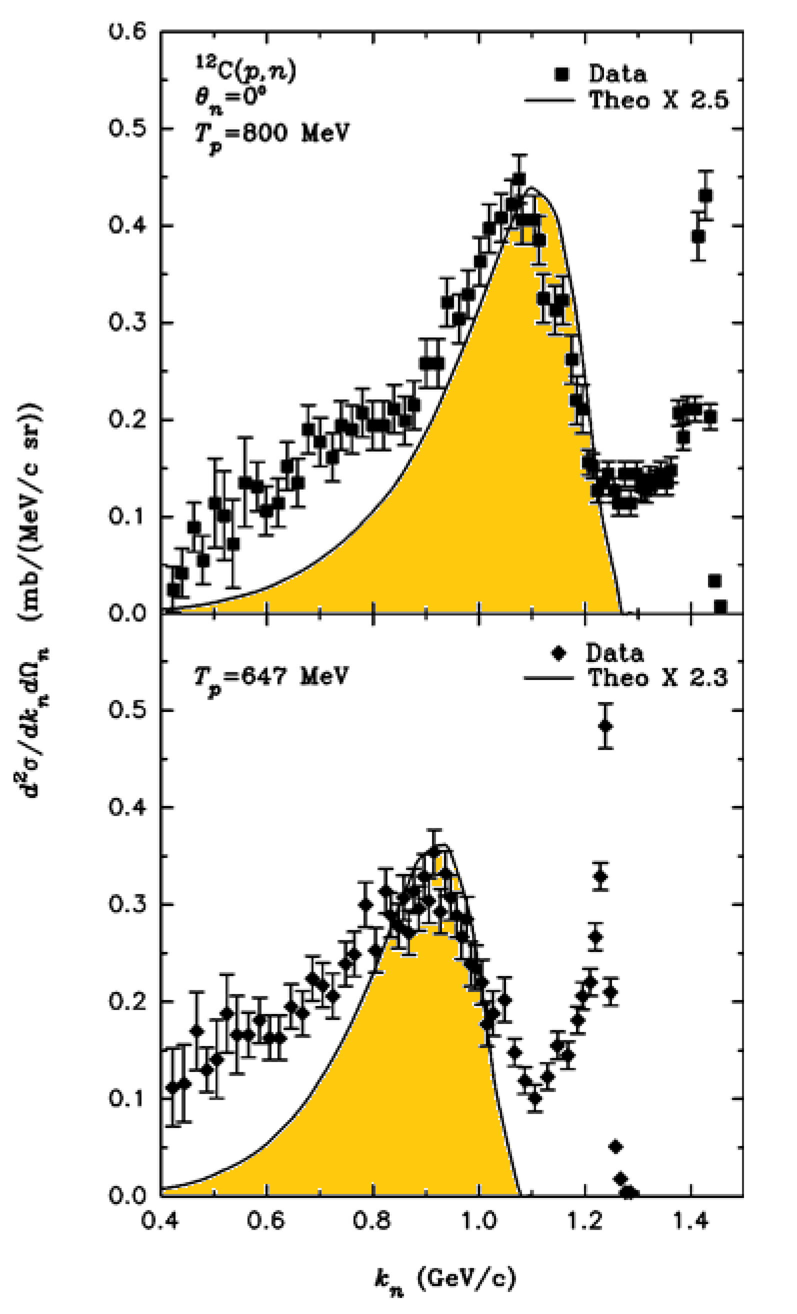
  ΔN^{-1} modes
- Nuclear response functions with resonances
- Astrophysical connections
- Resonance physics at the FRS and Super-FRS

Delta Resonances in Nuclei

Δ_{33}(1232) resonance in $\pi+{}^6$Li scattering



S. Lourenco, H.L. S. Wycech



Incoherent, inclusive (p,n) Reaction

→ Corresponding Experiments at SATURNE in the 1980ties

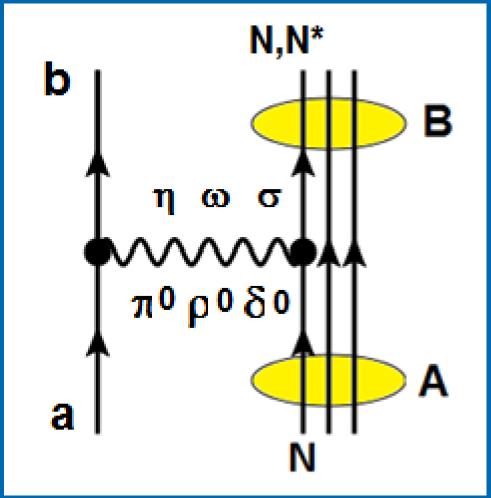
Datta: LAMPF/Los Alamos
C.G. Cassapakis *et al.*, Phys. Lett. B 63:35 1976.

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

Reaction Dynamics

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

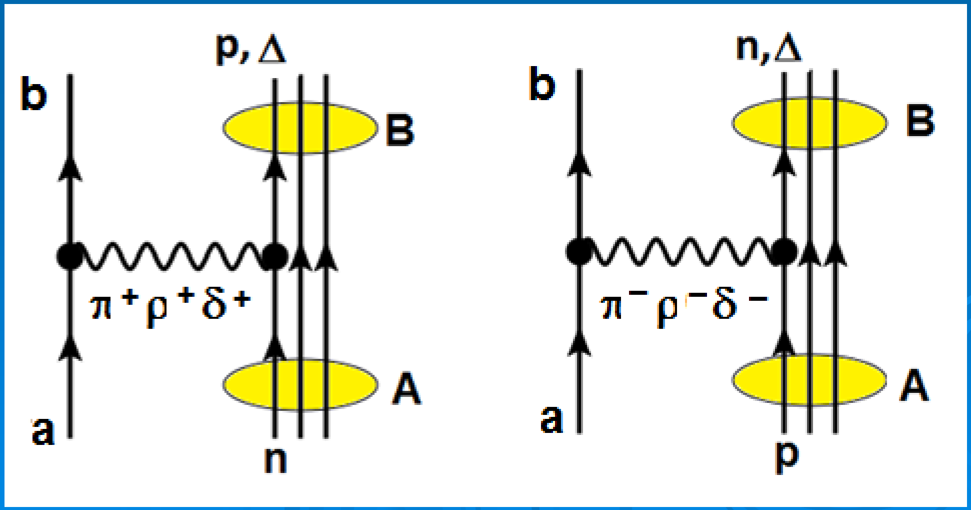
Neutral Current (NC) Reactions



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

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

Charged Current (CC) Reactions



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

Hadronic Tensor in NC/CC Ion-Ion Reactions:

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

Hadronic Tensor:

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

Factorization of the Hadronic Tensor:

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

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

The Cross Section:

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

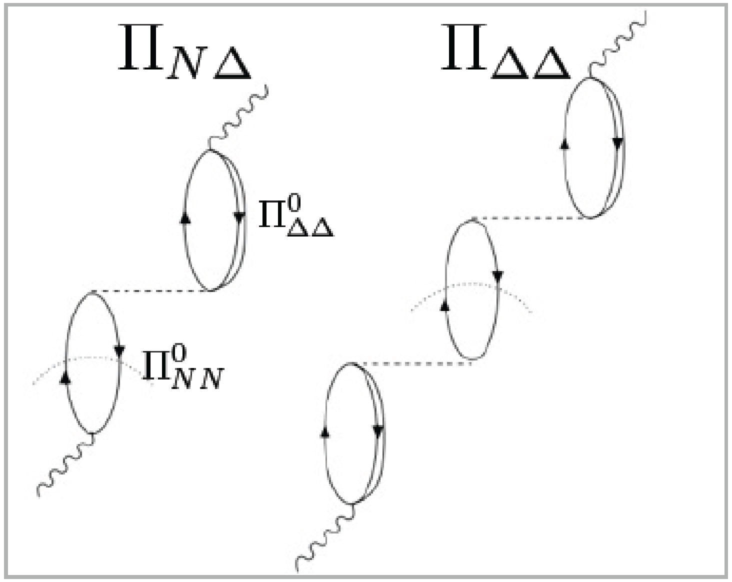
Nuclear Response Functions

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

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

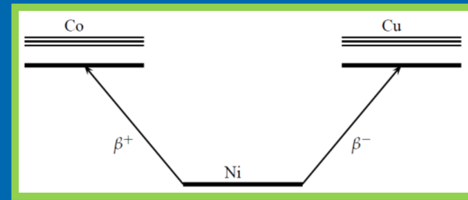
$$\begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix} = \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} + \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} V_{NN} & V_{N\Delta} \\ V_{\Delta N} &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

- 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

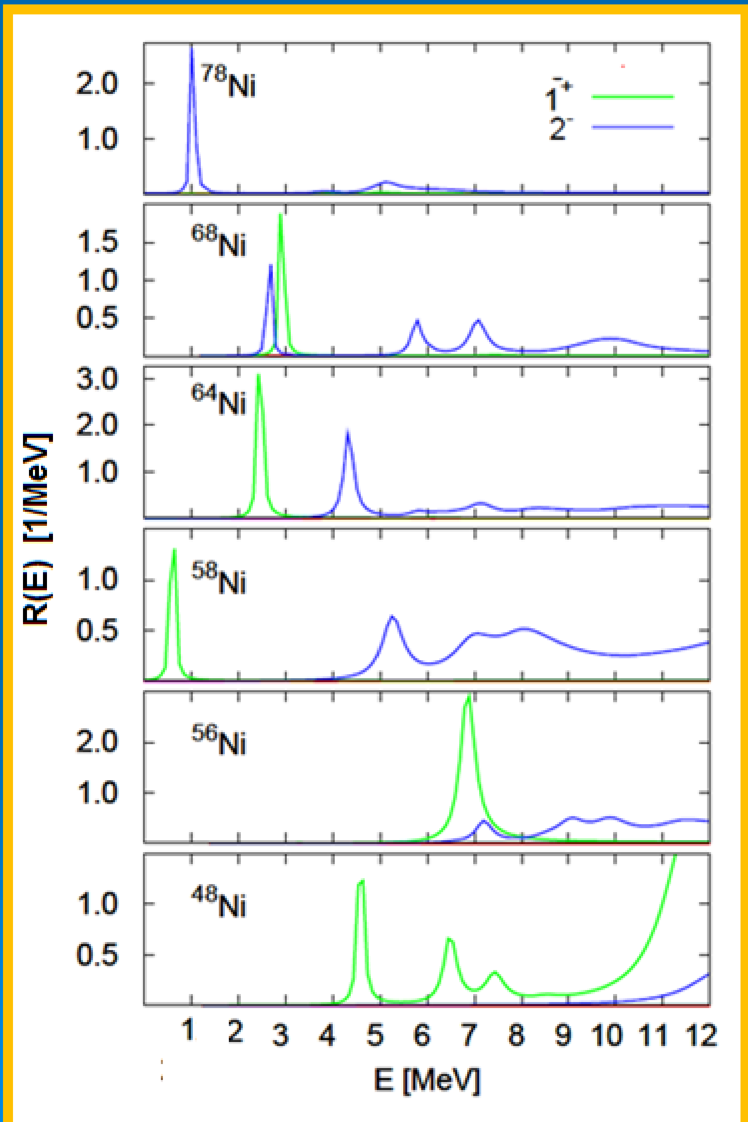


$$\Pi_{NN} = \chi_{\Delta N} \chi_N \Pi^0_{NN}$$

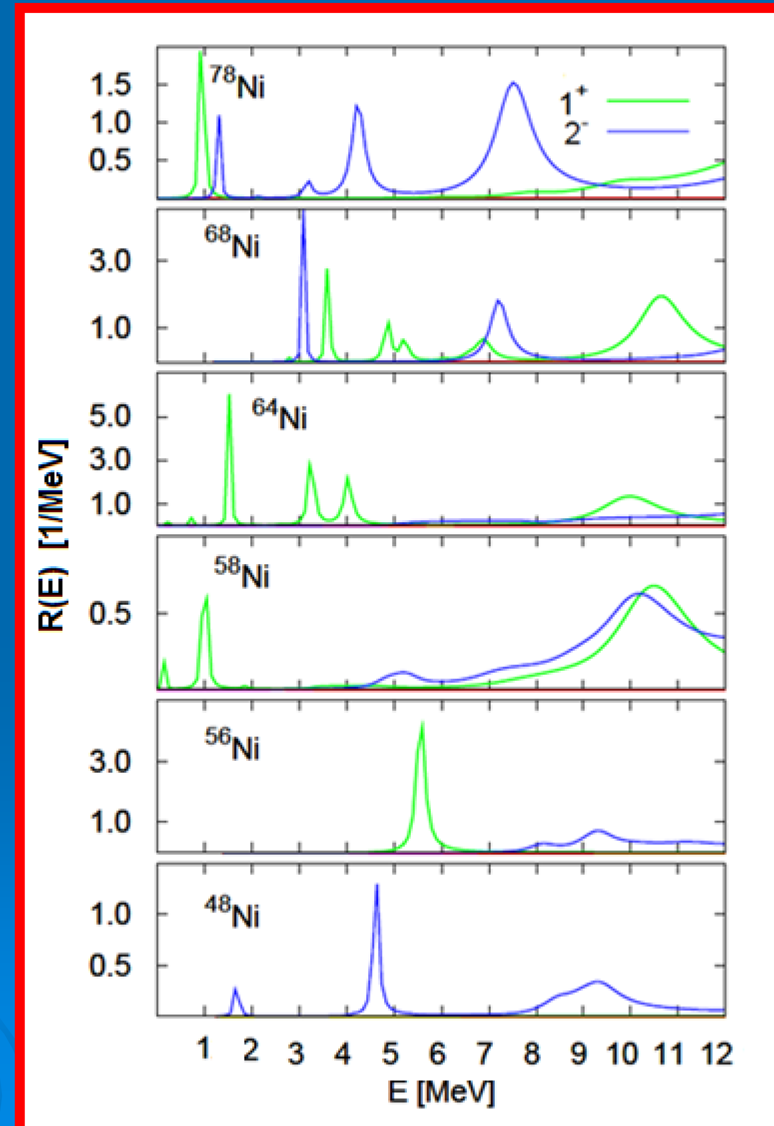
CC QRPA Spin-Multipole Response: L=J-1



$\mathrm{Ni} \rightarrow \mathrm{Co}\ (p \rightarrow n)$

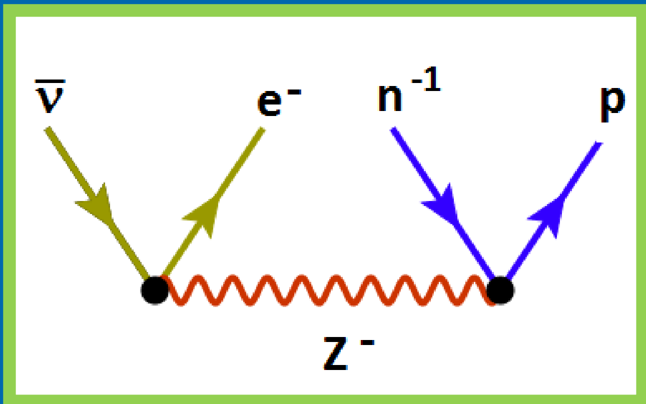


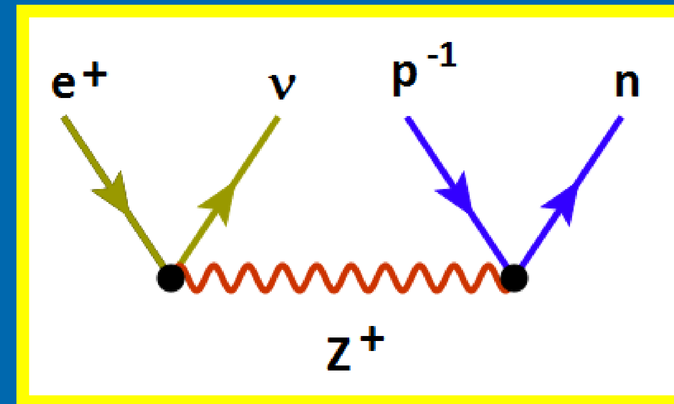
$\mathrm{Ni} \rightarrow \mathrm{Cu}\ (n \rightarrow p)$



Nuclear beta-decay

Weak Charge Changing Currents





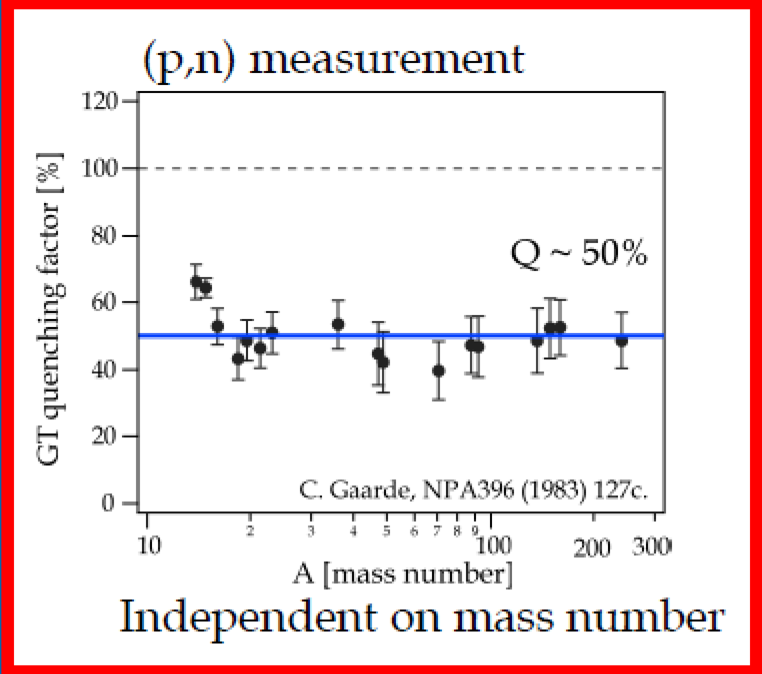
$$M(GT^{\pm}) \propto \left| \left\langle f \left\| \frac{\sigma}{2} \cdot \tau_{\pm} \right\| i \right\rangle \right|^2$$

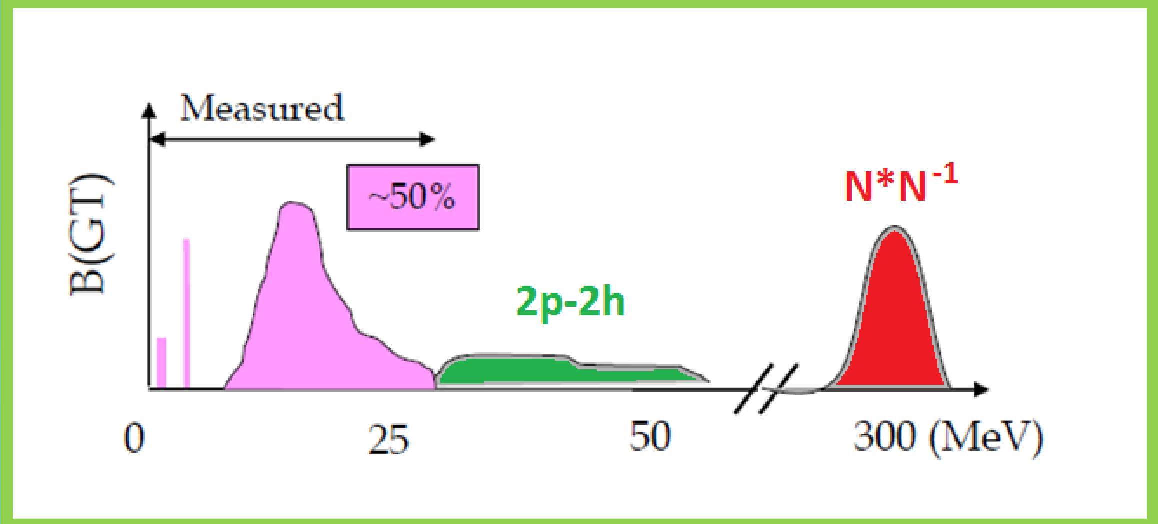
GT sum rule (model independent)

K. Ikeda PL 3, 271 (1963)

$$S_{\beta^-} - S_{\beta^+} = 3(N - Z)$$

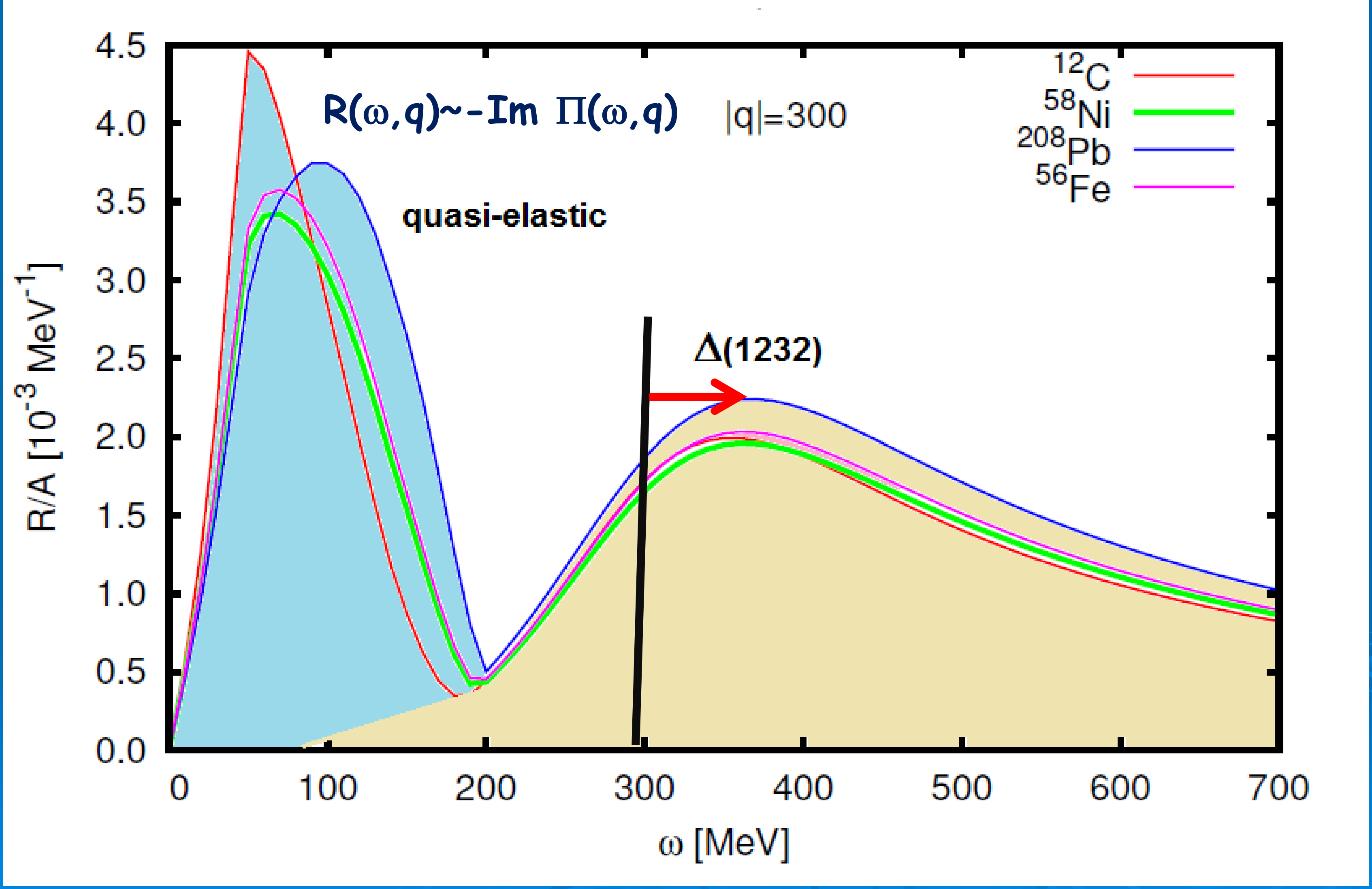
The GT-Quenching Problem:
~50% of the *Ikeda Sum Rule* is missing





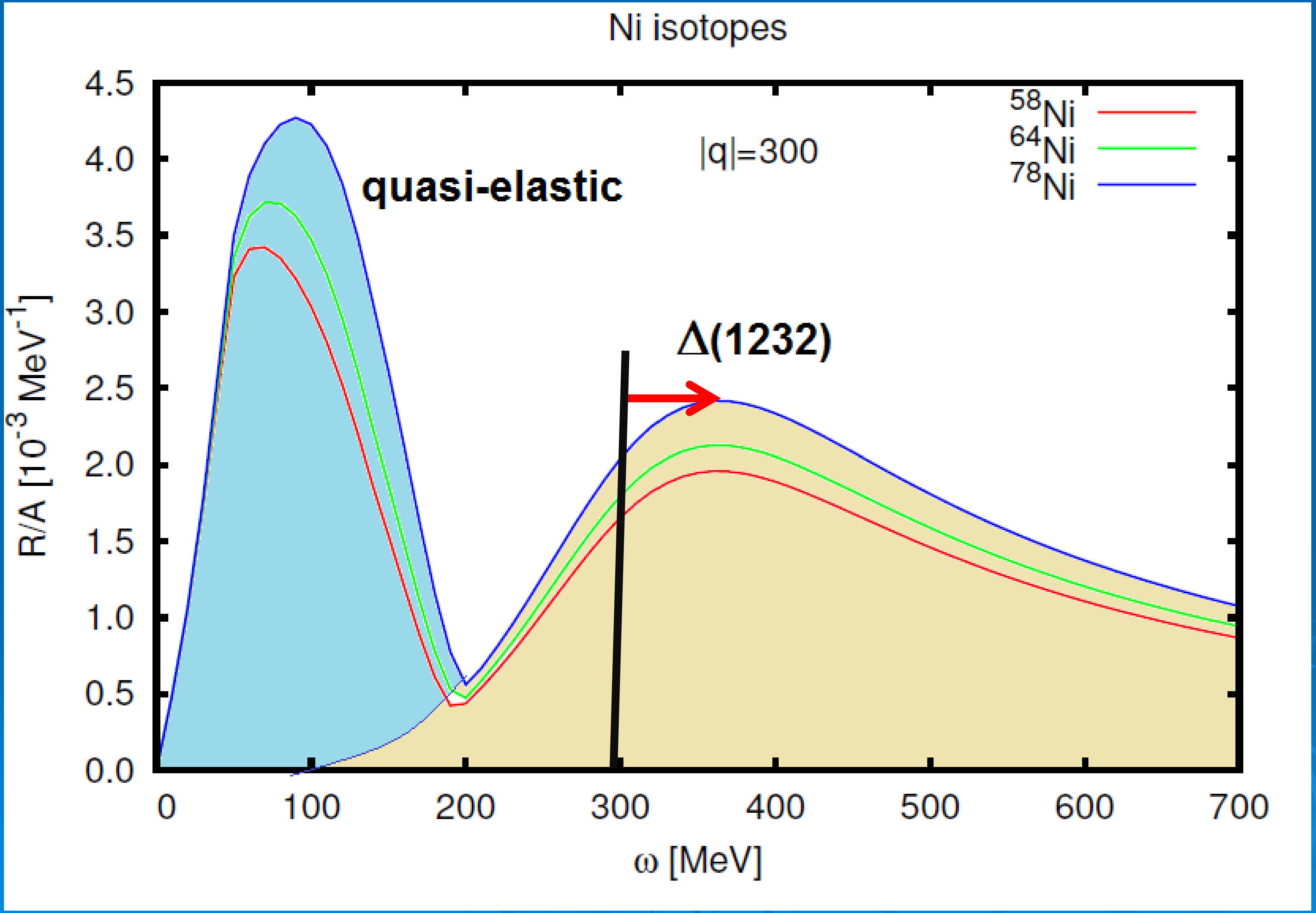
Quasi-Free Nuclear Response

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



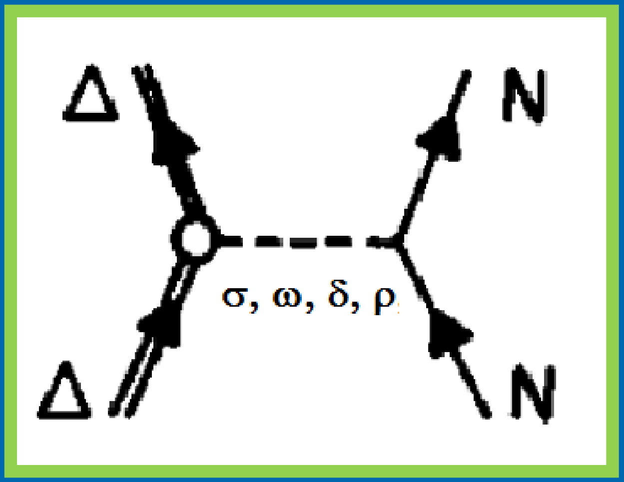
A. Fedoseew, H.L.

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

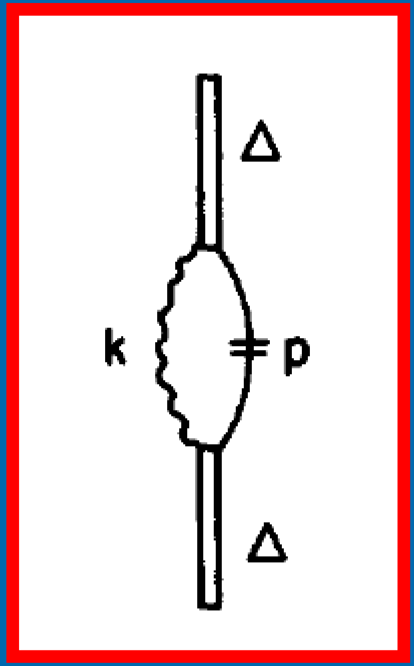


Delta‘s in the Nuclear Medium

Delta Self-Energy in Nuclear Matter



+



Direct Self-energy → Hartree(Fock)-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

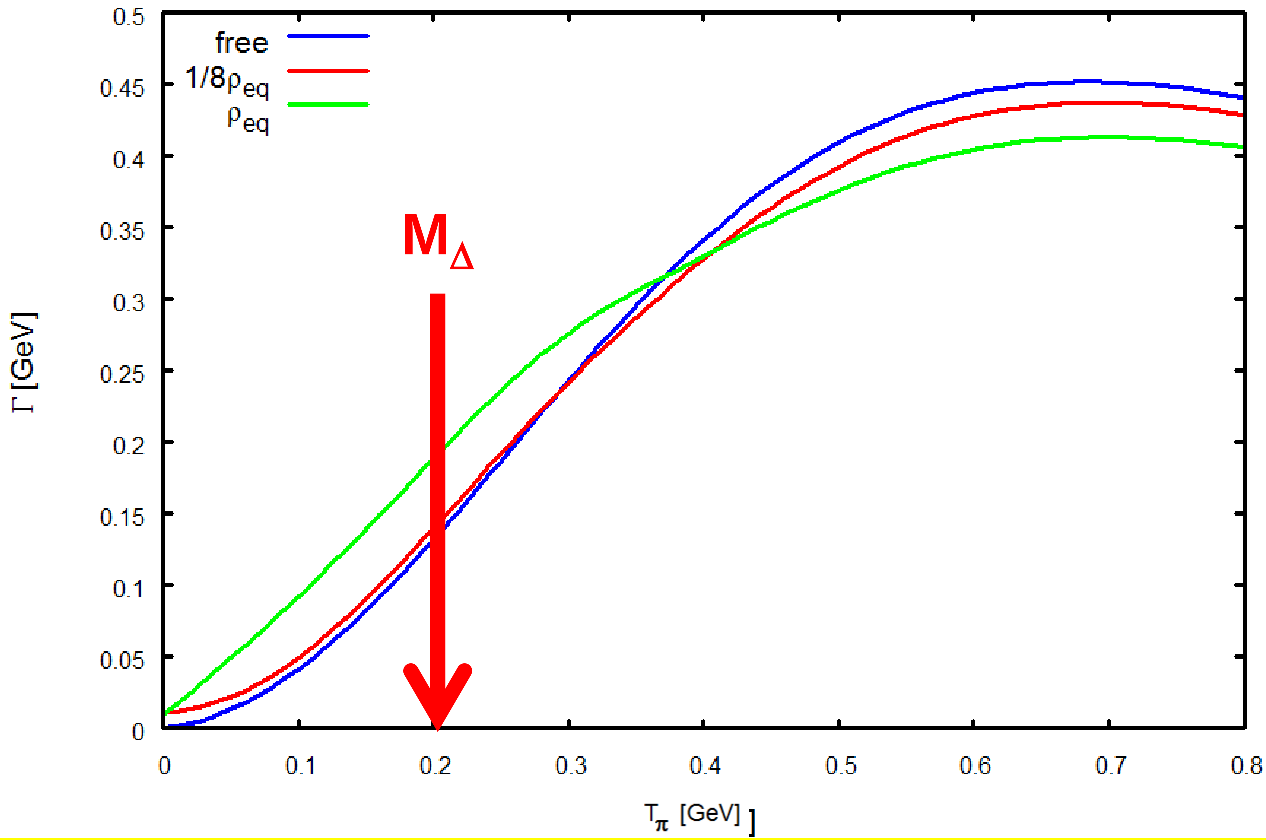
$$\Sigma_{pol}^{(\Delta)} \sim \Sigma_0 - \Sigma_1 t_z^{(\Delta)} \frac{N-Z}{A}$$

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

…see e.g.:

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

In-Medium Δ(1232) Width



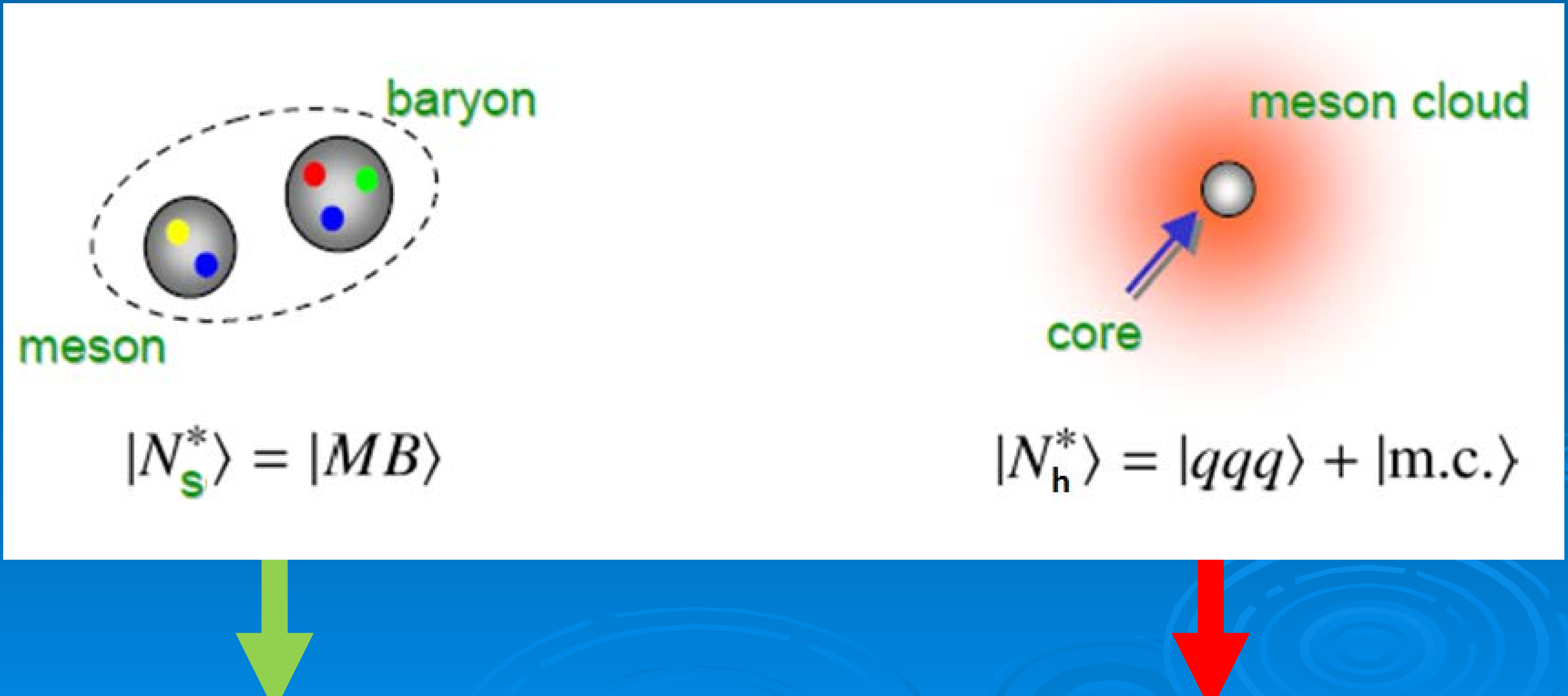
$$\Gamma_{\Delta}(p_{\Delta}^{2},\rho) = -2\,\mathrm{Im}\,\Sigma(p_{\Delta}^{2},\rho) \sim \Gamma_{free}(p_{\Delta}^{2}) + \Gamma_{Pauli}(p_{\Delta}^{2},\rho) + \Gamma_{abs}(p_{\Delta}^{2},\rho)$$

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

QCD Aspects of Resonances:

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

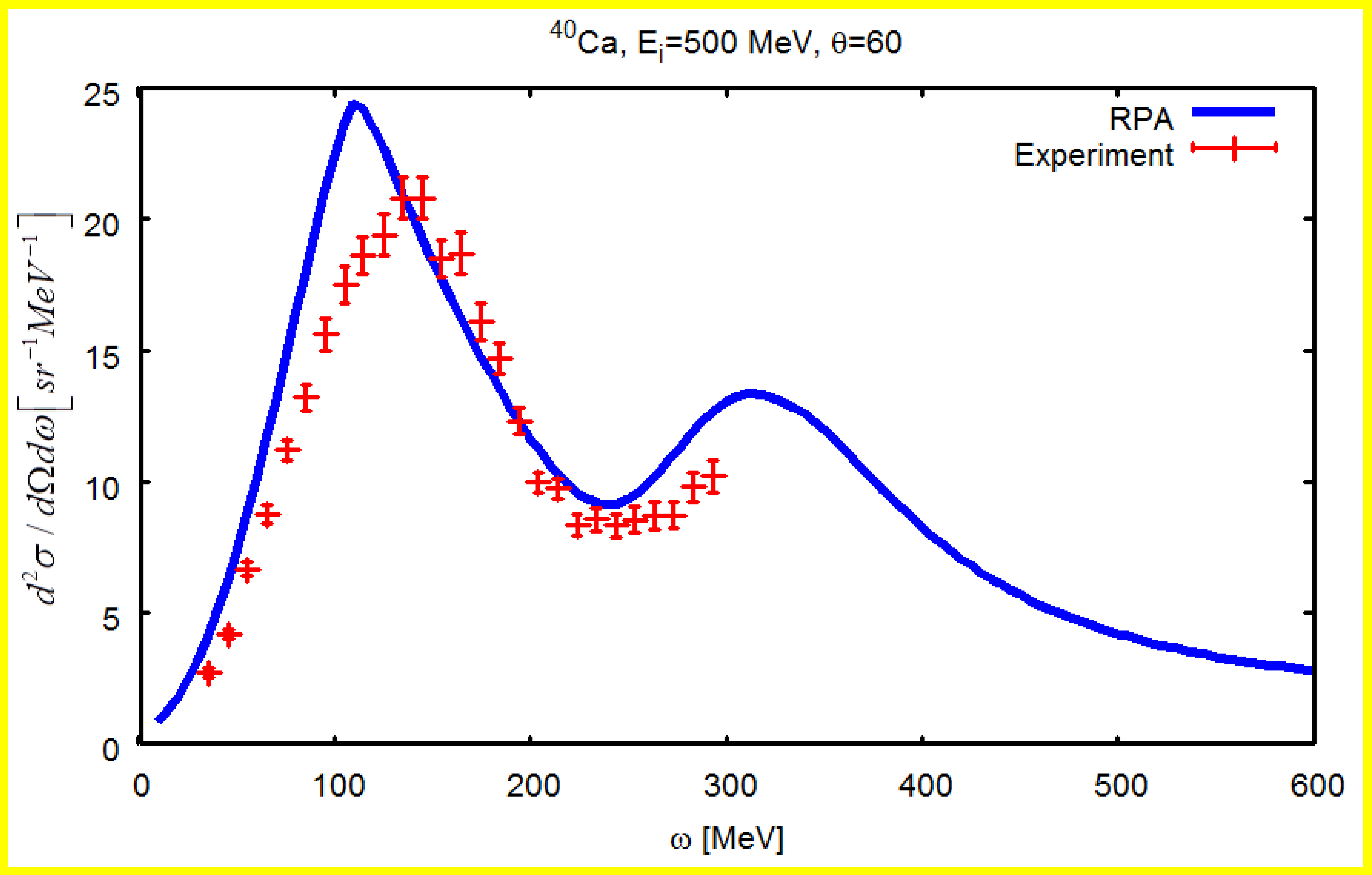
$$\left|N^*\right\rangle = \left|N_s^*\right\rangle + \left|N_h^*\right\rangle = x_1\left|mB\right\rangle + x_2\left|qqq\right\rangle + x_3\left|qqq\right\rangle \otimes \left|q\bar{q}\right\rangle + \ldots$$



Strong Medium Dependence

Weak Medium Dependence

A Test Case:
Quasi-free Inclusive (e,e') Scattering



Connection to Astrophysics: Neutrino-Nucleus Interactions

Neutrino-Nucleus Cross Sections and NΔ-Response Functions: $\nu_\ell + N \rightarrow \Delta \rightarrow N + \pi$ Reactions

$$\frac{\partial^2\sigma}{\partial\Omega\partial k'} = \frac{G_F^2 \cos^2\theta_c (k')^2}{2\pi^2} \cos^2\frac{\theta}{2} \Bigg\{ G_E^2 \left(\frac{q_\mu^2}{q^2}\right)^2 R_\tau^{NN}$$

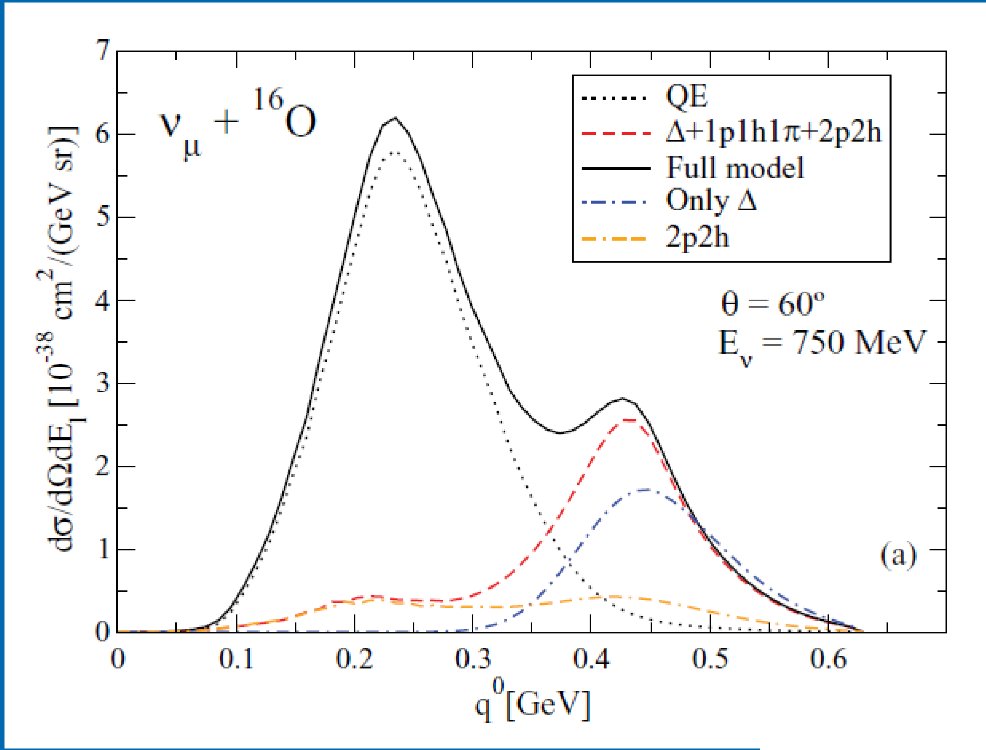
$$+ G_A^2 \frac{(M_\Delta - M_N)^2}{2q^2} R_{\sigma\tau(L)}^{N\Delta} + G_A^2 \frac{(M_\Delta - M_N)^2}{q^2}$$

$$\times R_{\sigma\tau(L)}^{\Delta\Delta} + \left(G_M^2 \frac{\omega^2}{q^2} + G_A^2\right)\left(-\frac{q_\mu^2}{q^2} + 2\tan^2\frac{\theta}{2}\right)$$

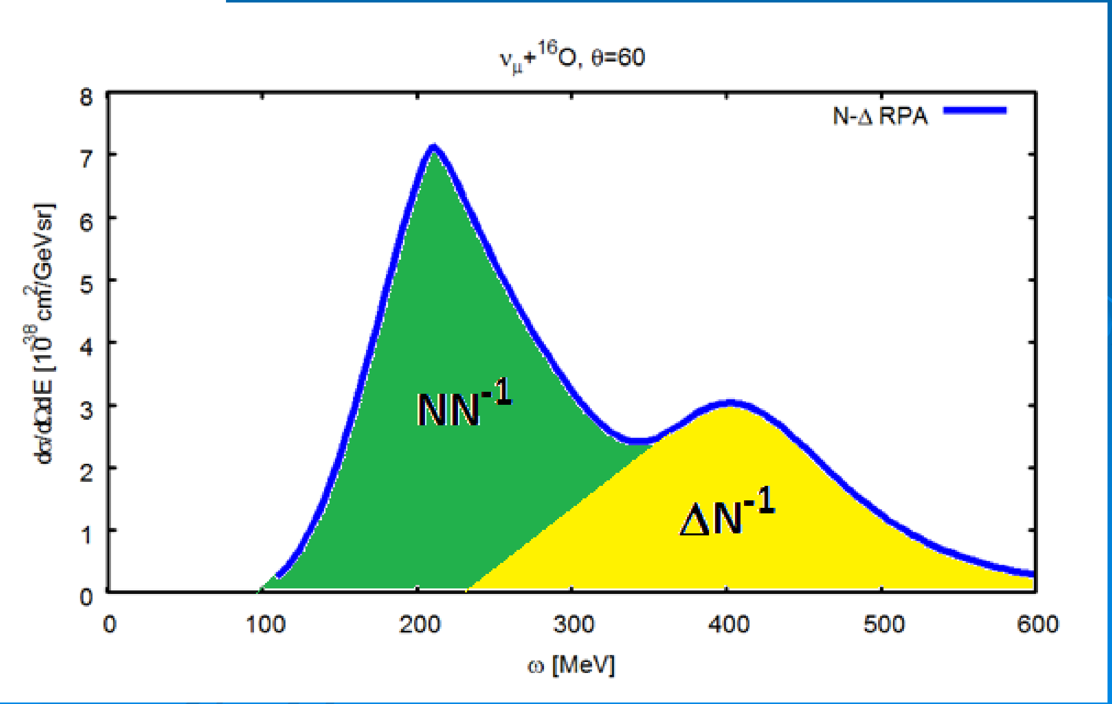
$$\times \left[R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right] \pm 2G_A G_M \frac{k+k'}{M_N}$$

$$\times \tan^2\frac{\theta}{2}\left[R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}\right]\Bigg\}$$

Inclusive CC cross section



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

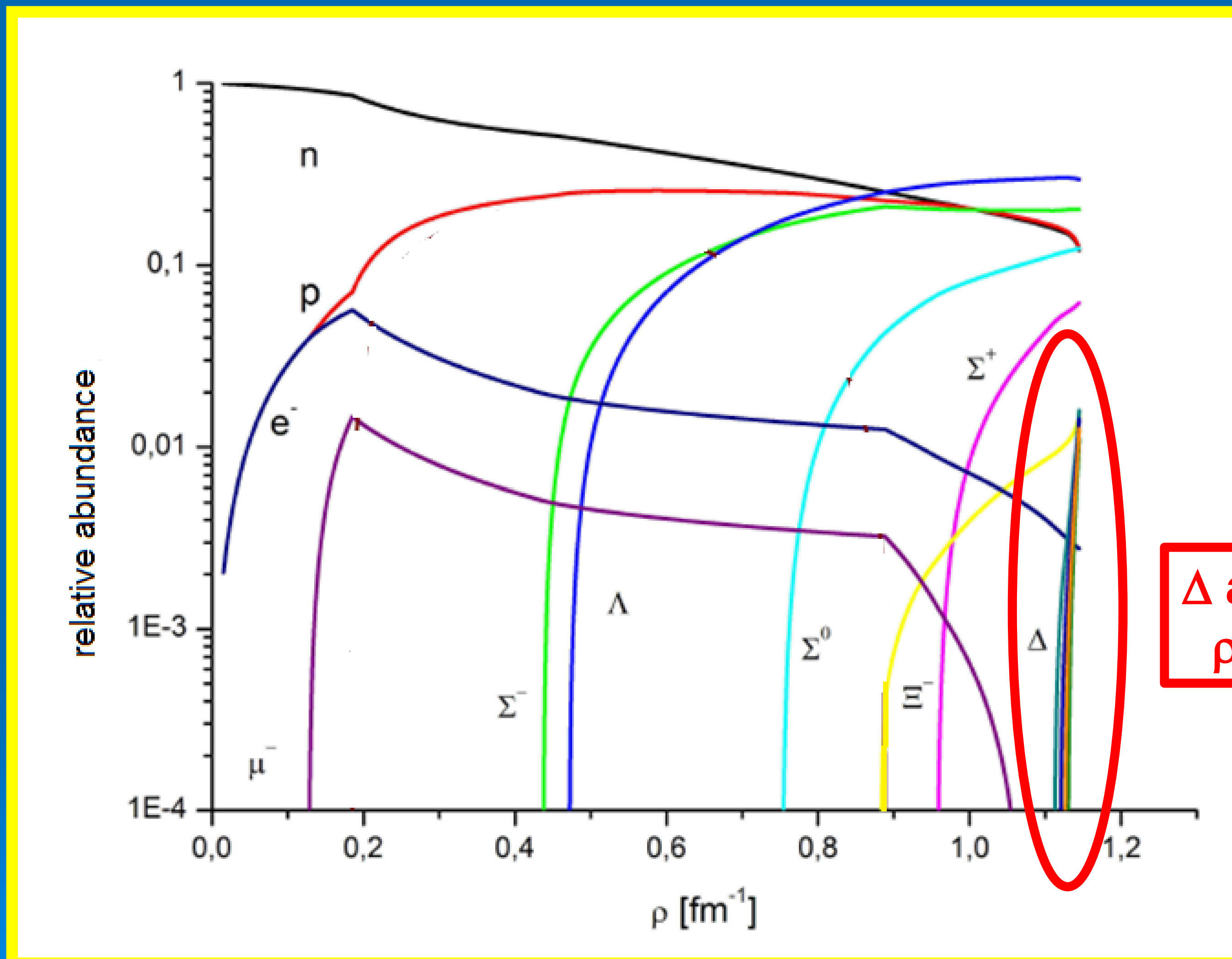


Gießen
„N-Δ RPA“

Connection to Astrophysics: Resonances in Neutron Stars?

Baryon Resonances in Neutron Stars?

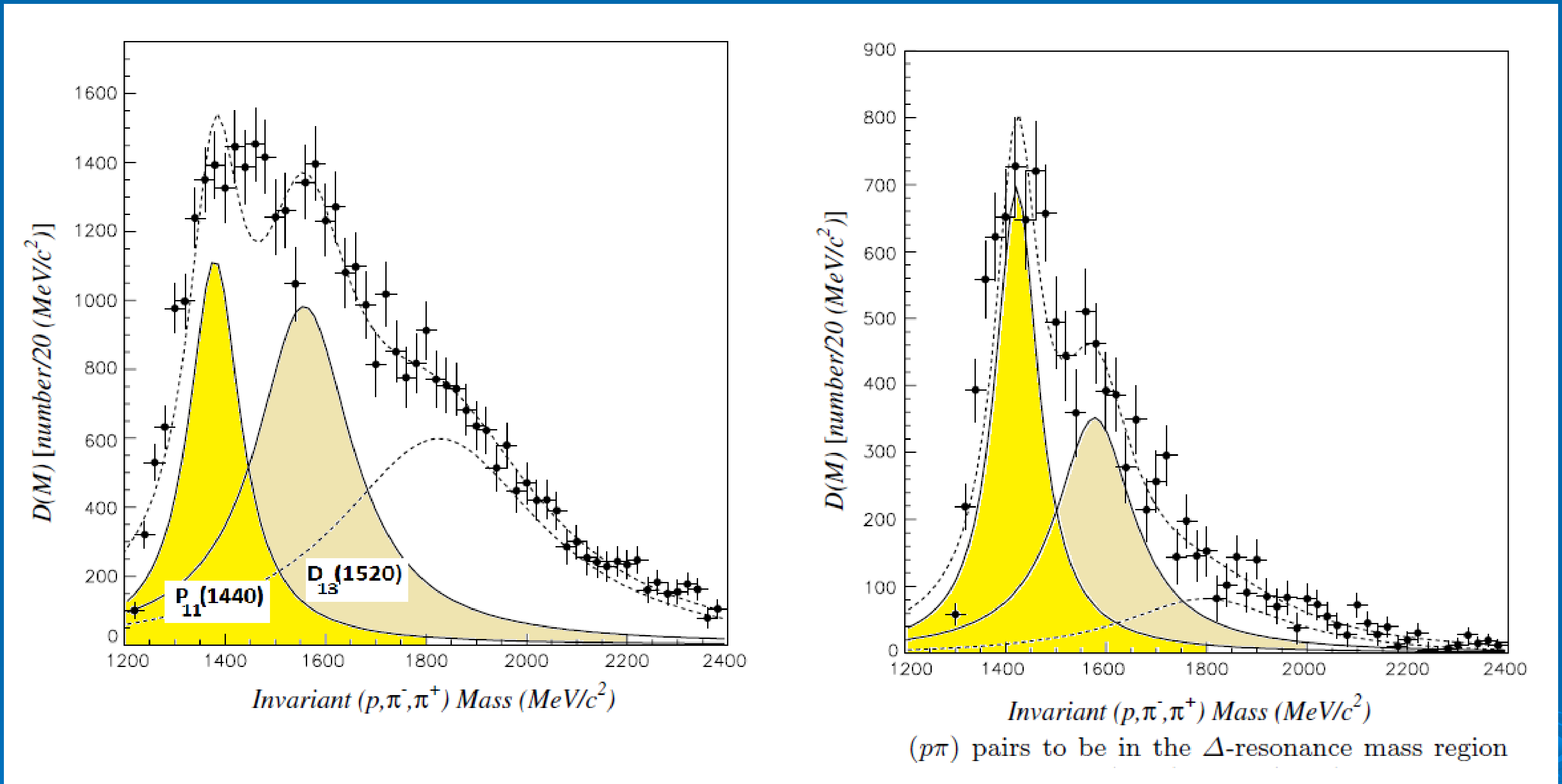
(NN, NY, YY DBHF Interactions)



Δ and N* at $\rho \geq 6 \ldots 7\ \rho_0$

Challenges

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

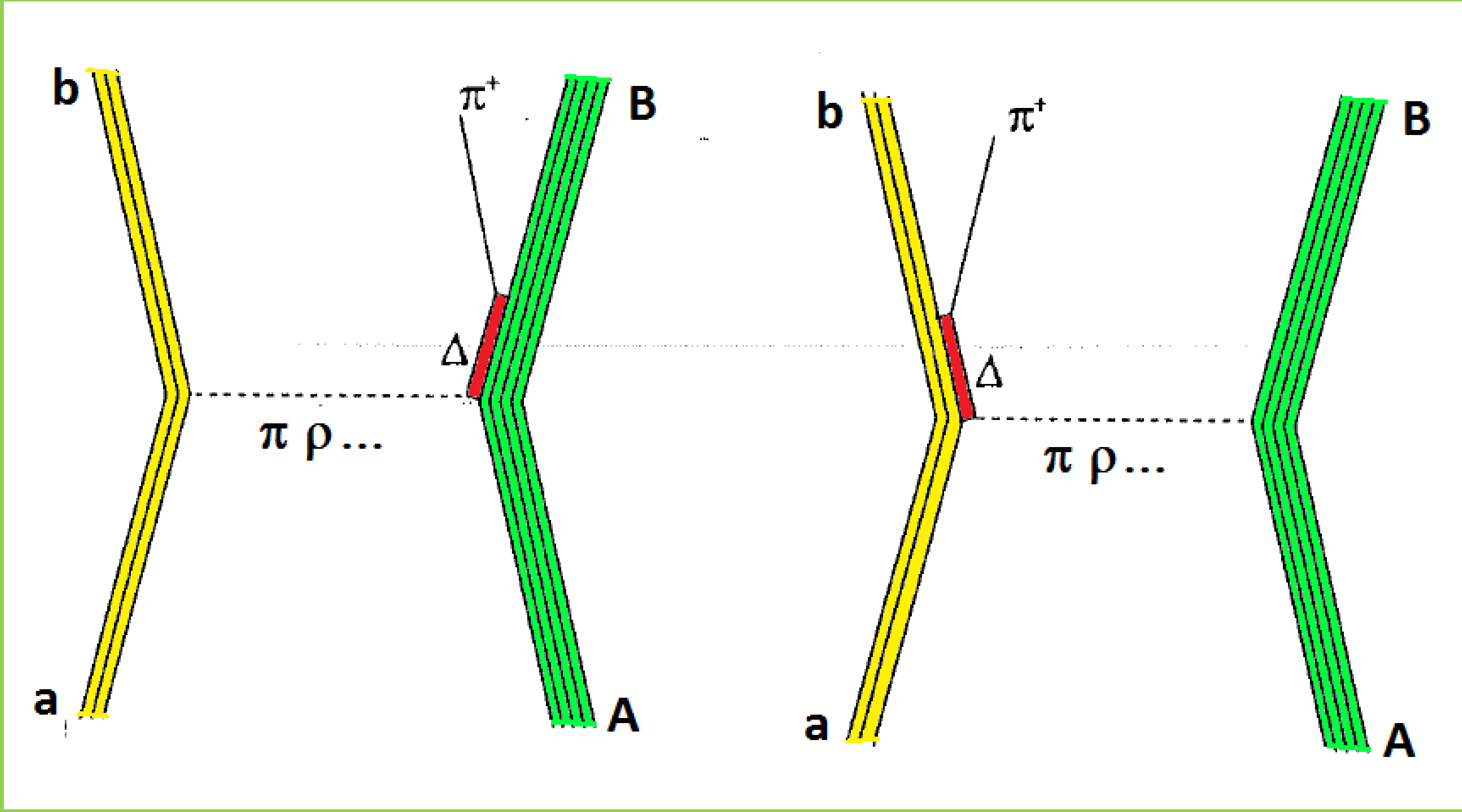


	M (MeV/c^2)	Γ (MeV/c^2)
$N(1440)$	1380 ± 10	130 ± 20
$N(1520)$	1550 ± 20	230 ± 30
The 3rd peak	1810 ± 30	510 ± 40

	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)

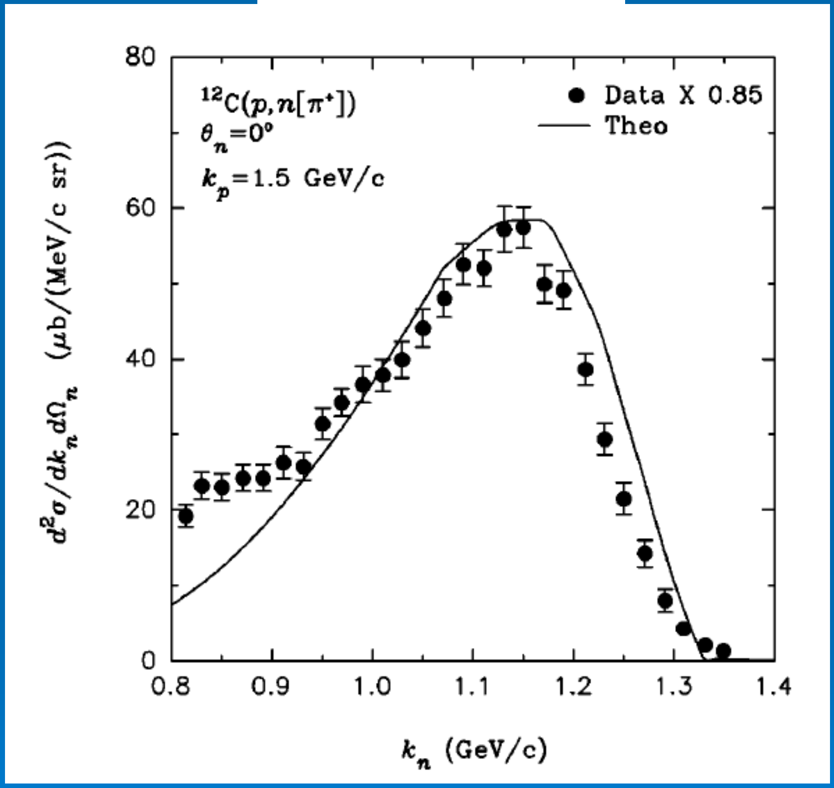
Exclusive Reactions: Resonance Excitation and Meson Production in Ion-Ion Collisions



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

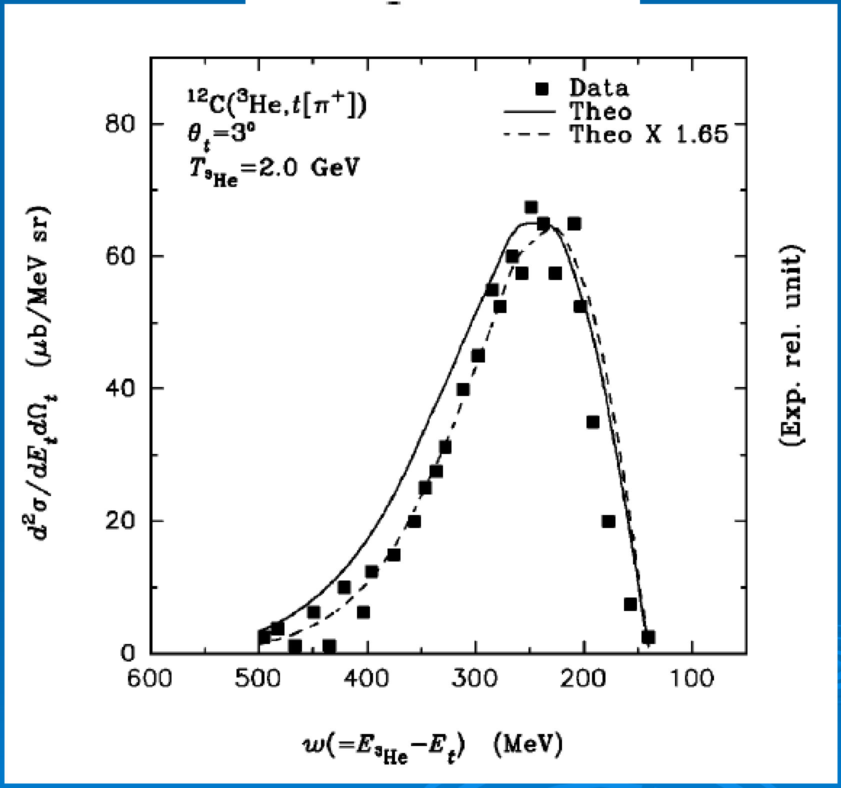
$^{12}C(p,n[\pi^+])$



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

- Resonances in cold, equilibrated nuclear matter
- Resonances as probes for nuclear isospin dynamics
- Resonances and Nuclear Response Functions
- Resonances beyond $\Delta(1232)$: $P_{11}(1440), D_{13}(1520)$…
- Resonances and in-medium self-energies
- Resonance excitation and reaction dynamics
- Resonance tagging by pion production
- Resonances and astrophysics

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