Baryon Resonances in Nuclear Matter and Neutron Stars

WASA@FRS , November 2017

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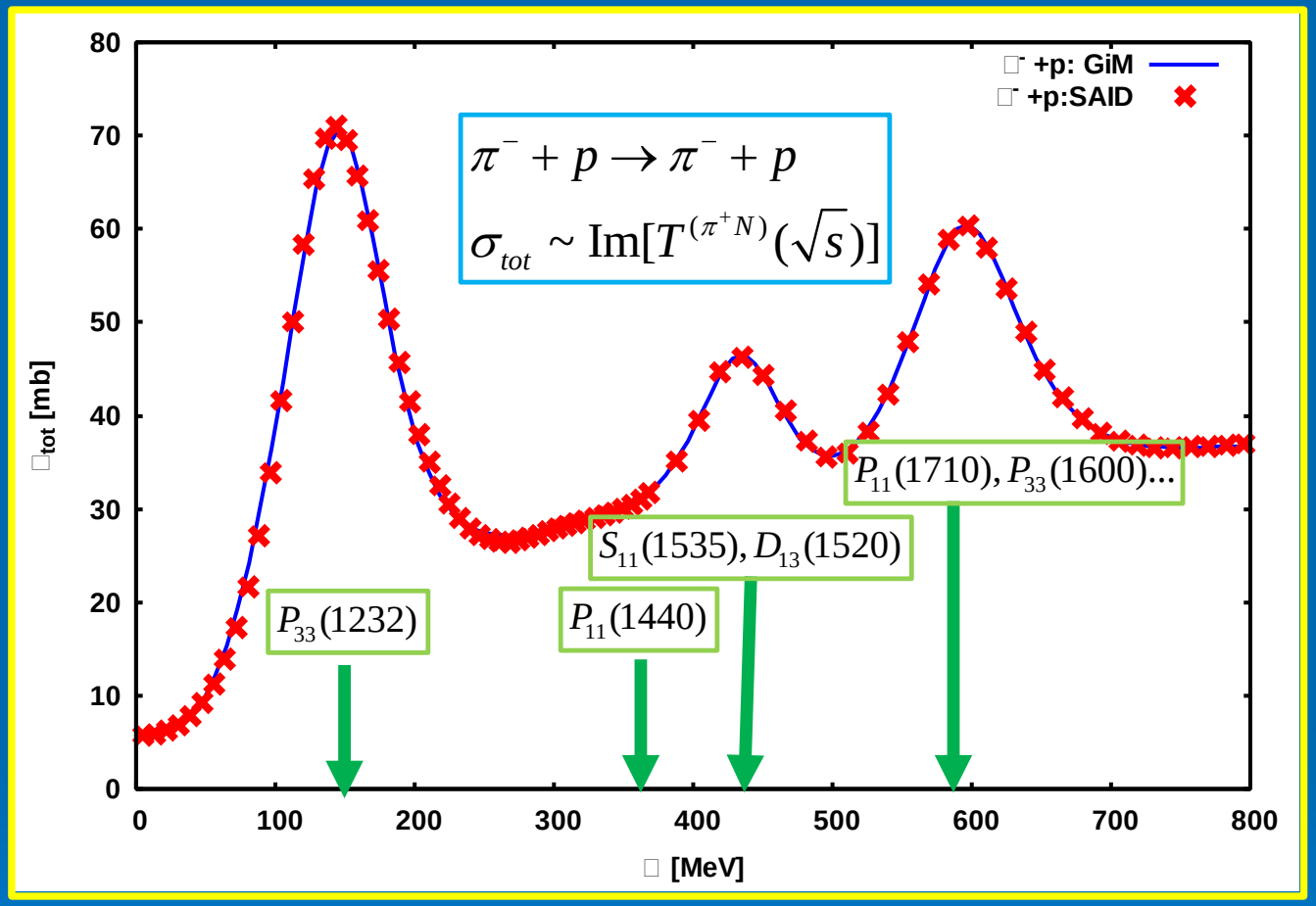
Agenda:

- Resonance excitation in nucleus-nucleus reactions
- The excited nucleon in nuclei: $N^{*}N^{-1}$ modes of excitation
- Nuclear response functions with resonances: N*RPA
- Astrophysics: „resonance puzzle“ in neutron stars

N* Resonance Spectroscopy

Nucleon Resonances in πN Scattering

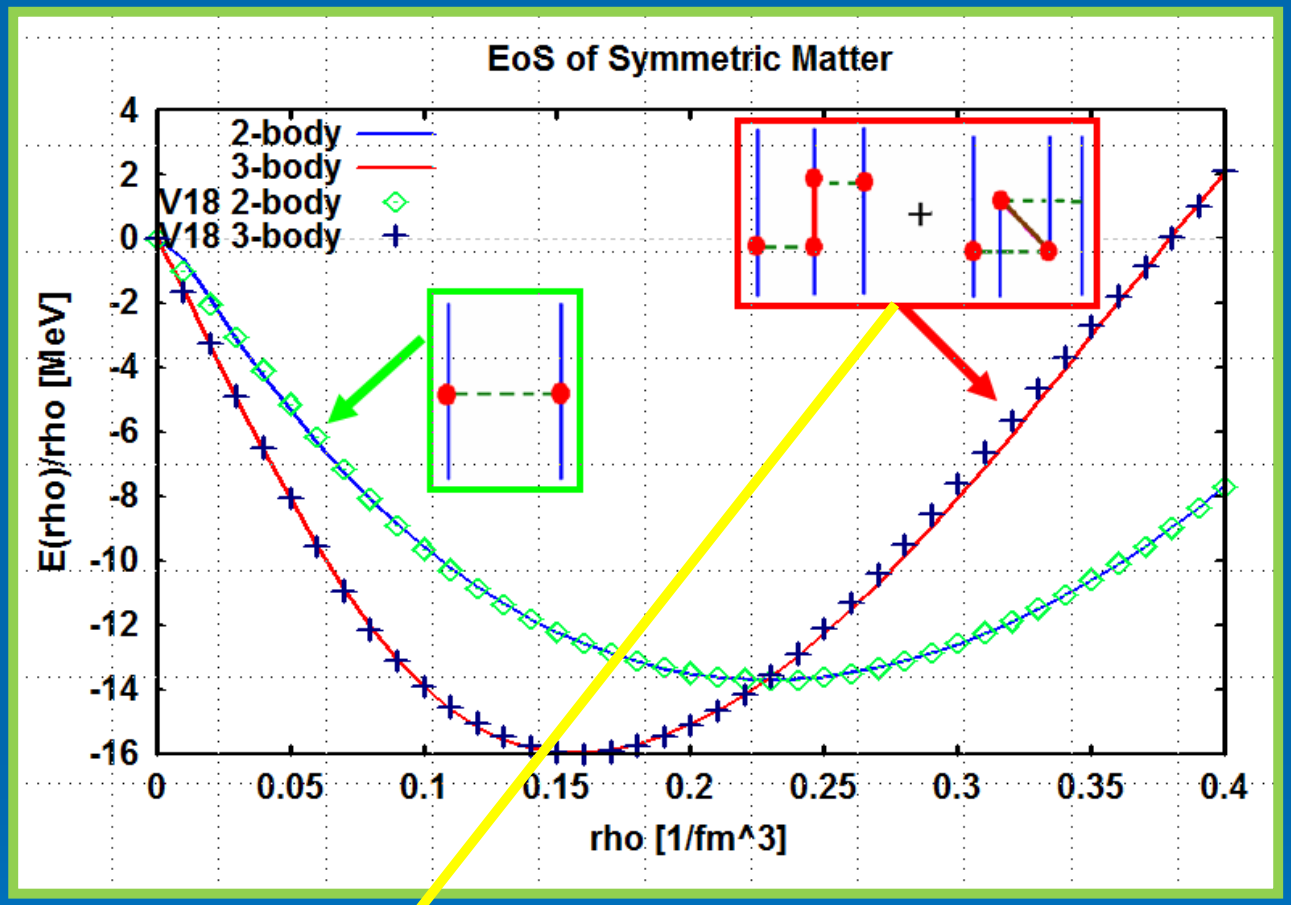


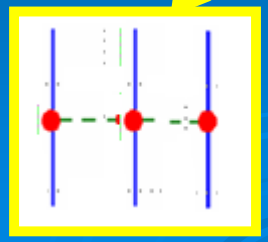
$$\omega = \sqrt{s} - m_p - m_\pi$$

…see e.g. the Giessen Coupled Channels Model (GiM)
(V. Shklyar, Xu Cao, H.L. et al.)

Evidence for Resonances in Nuclei

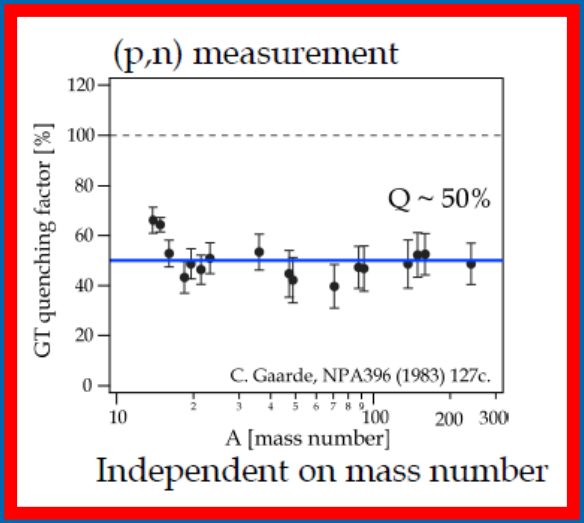
Δ-Resonance and Nuclear Matter Binding Energy



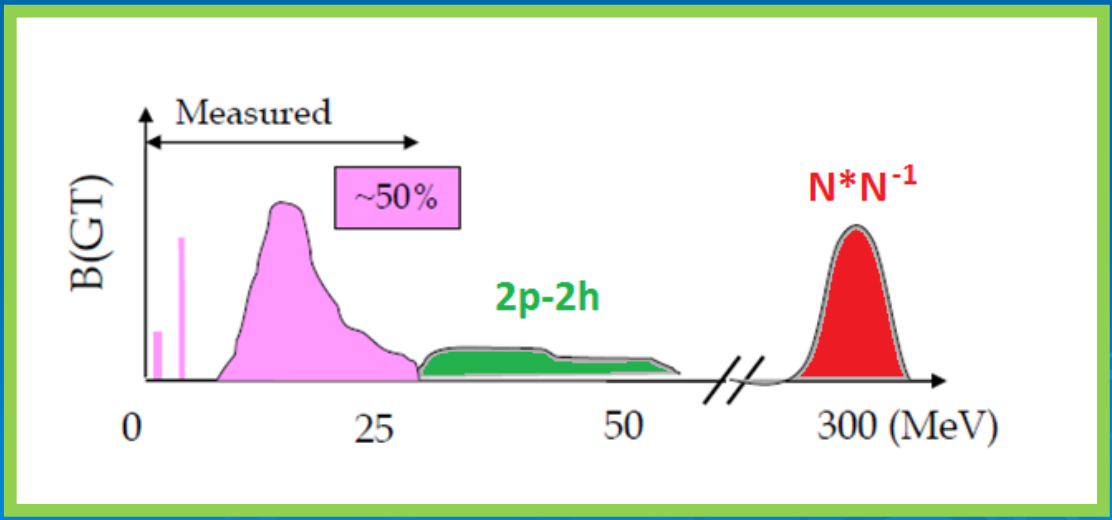


χEFT 3-body Force

Δ-Resonance and the GT-Quenching Problem:



~50% of the *Ikeda Sum Rule* is missing



Resonance Excitation in Nucleus-Nucleus Reactions

…SATURNE@Saclay
and
Synchro-Phasetron@Dubna
(1980ties and 1990ties)

Nucleon Resonances in Nuclei at the FRS@1AGeV

$^{112}Sn \rightarrow {}^{112}In(p^{-1}n)$

$^{112}Sn \rightarrow {}^{112}\mathrm{Sb}(n^{-1}\mathrm{p})$

Projectile:

np^{-1}

$\Delta^{0}p^{-1}$

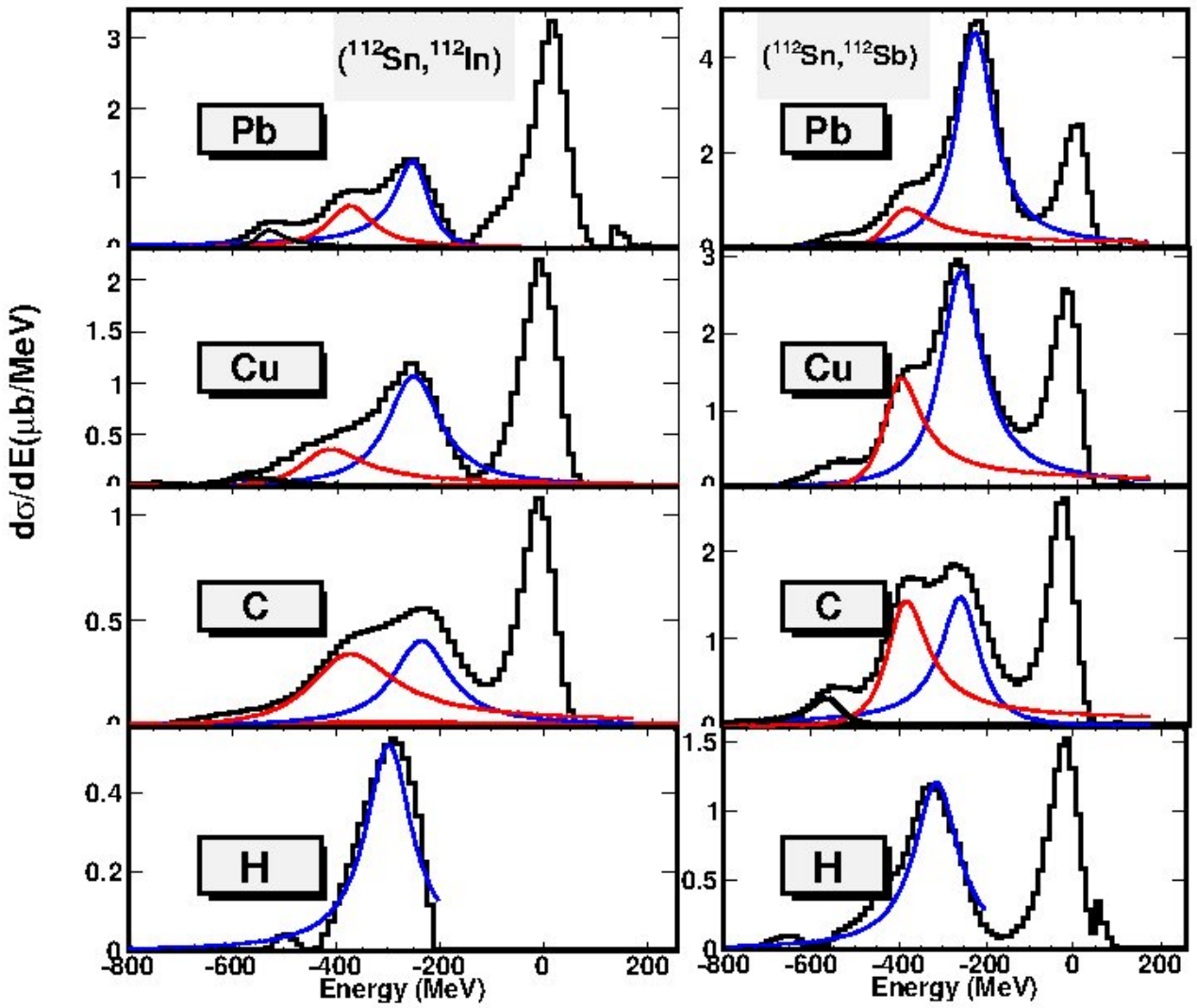
$\Delta^{-}n^{-1}$

Target:

pn^{-1}

$\Delta^{+}n^{-1}$

$\Delta^{++}p^{-1}$



Projectile:

pn^{-1}

$\Delta^{+}n^{-1}$

$\Delta^{++}p^{-1}$

Target:

np^{-1}

$\Delta^{0}p^{-1}$

$\Delta^{-}n^{-1}$

Data: J. Benlliure and the S363 collaboration

Theory of Peripheral Heavy Ion Reactions

$$\frac{d^2\sigma}{d\Omega dE_x} \sim \sum_{bB} \left| M_{aA\to bB}(\omega,\vec{q}) \right|^2 \delta(E_x-\omega) \sim \sum_{bB} \left| \left\langle \chi_\beta^{(-)}, bB \middle| T_{NN} \middle| aA, \chi_\alpha^{(+)} \right\rangle \right|^2 \delta(E_x-\omega) \sim$$

$$\int d^3p \int d\omega \left| N_{\alpha\beta}(\vec{q},\vec{p}) \right|^2 \left[\sum_{S,T=0,1} \left| V_{ST}^{(C)}(p^2) \right|^2 R_{a,ST}(E_x-\omega,\vec{q}-\vec{p}) \bullet R_A^{ST}(\omega,\vec{p}) + \ldots \right]$$

a+A and b+B Elastic Interactions:

$$N_{\alpha\beta}(\vec{q},\vec{p}) = \left\langle \chi_\beta^{(-)} \middle| e^{i\vec{p}\bullet\vec{r}} \middle| \chi_\alpha^{(+)} \right\rangle$$

Projectile−Target Nucleon−Nucleon Interaction:

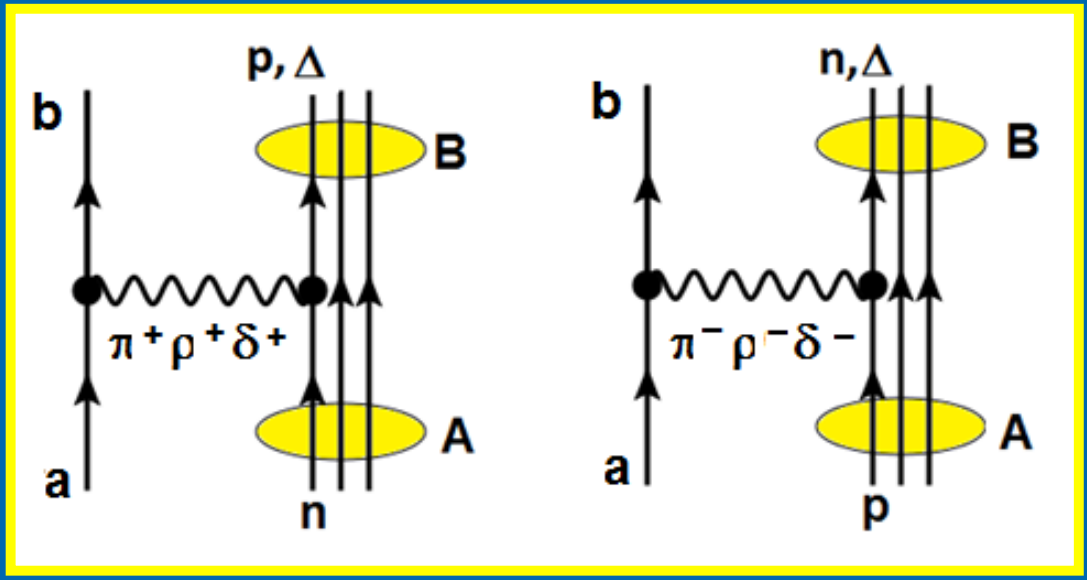
$$T_{NN} = V_{00}^{(C)}(q^2) 1_a 1_A + V_{10}^{(C)}(q^2)\vec{\sigma}_a \bullet \vec{\sigma}_A + V_{01}^{(C)}(q^2)\vec{\tau}_a \bullet \vec{\tau}_A + V_{11}^{(C)}(q^2)\vec{\tau}_a\vec{\sigma}_a \bullet \vec{\tau}_A\vec{\sigma}_A + \ldots$$

Hadronic Tensor:

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

Projectile-Target Nucleon-Nucleon Interactions

Charge Changing $\Delta Q=\pm 1$ Excitation of Quasi-elastic NN^{-1}, and N^*N^{-1} States



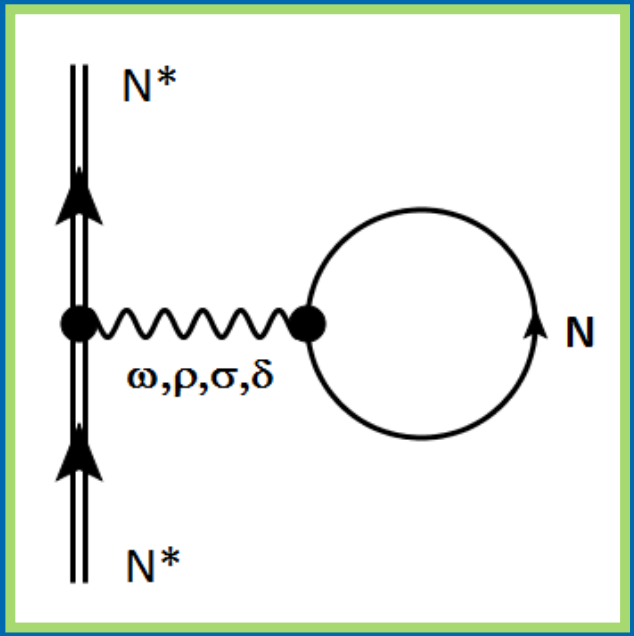
Operator Structure for (NN^{-1}, N^*N^{-1}) excitations:

$$\{1_\sigma, \vec{\sigma}, \vec{\sigma} \bullet \vec{q}, \vec{\sigma} \times \vec{q}\} \otimes \tau^{\pm}$$

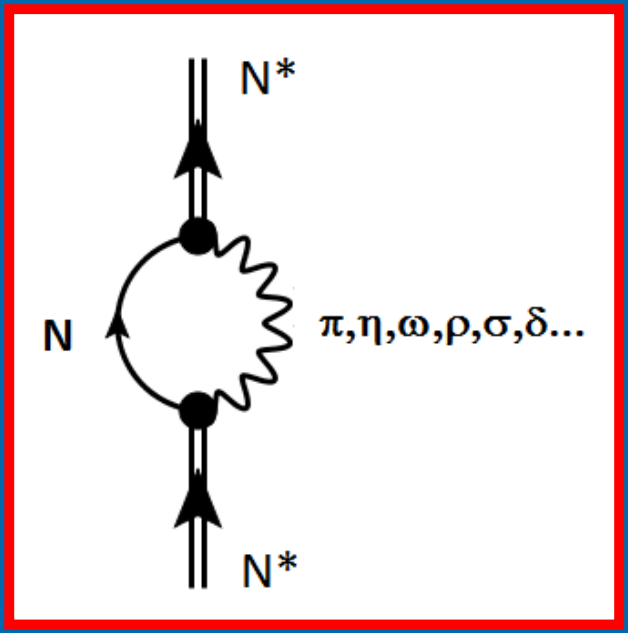
…and quasielastic knockout and multistep reactions!

Resonances in Nuclear Matter

Δ/N* Dynamics in Nuclear Matter



+



Diffractive Self-energy
→ Hartree-Potential

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

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

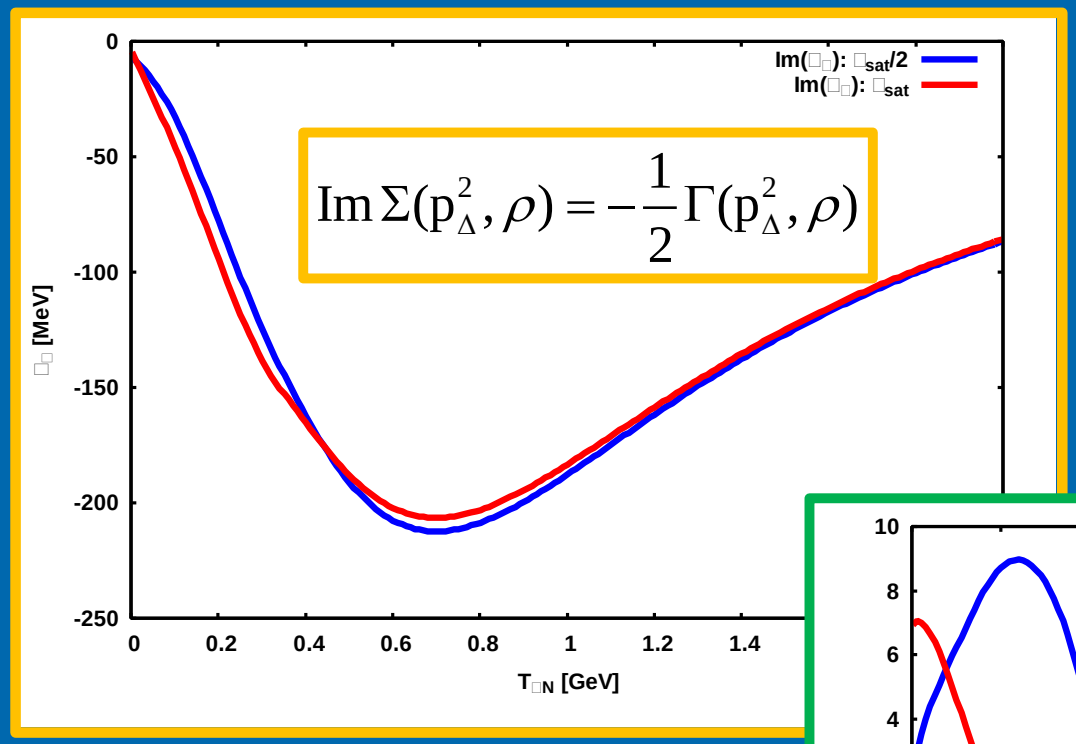
Dynamical Self-Energy
→ dispersive (optical) potential

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

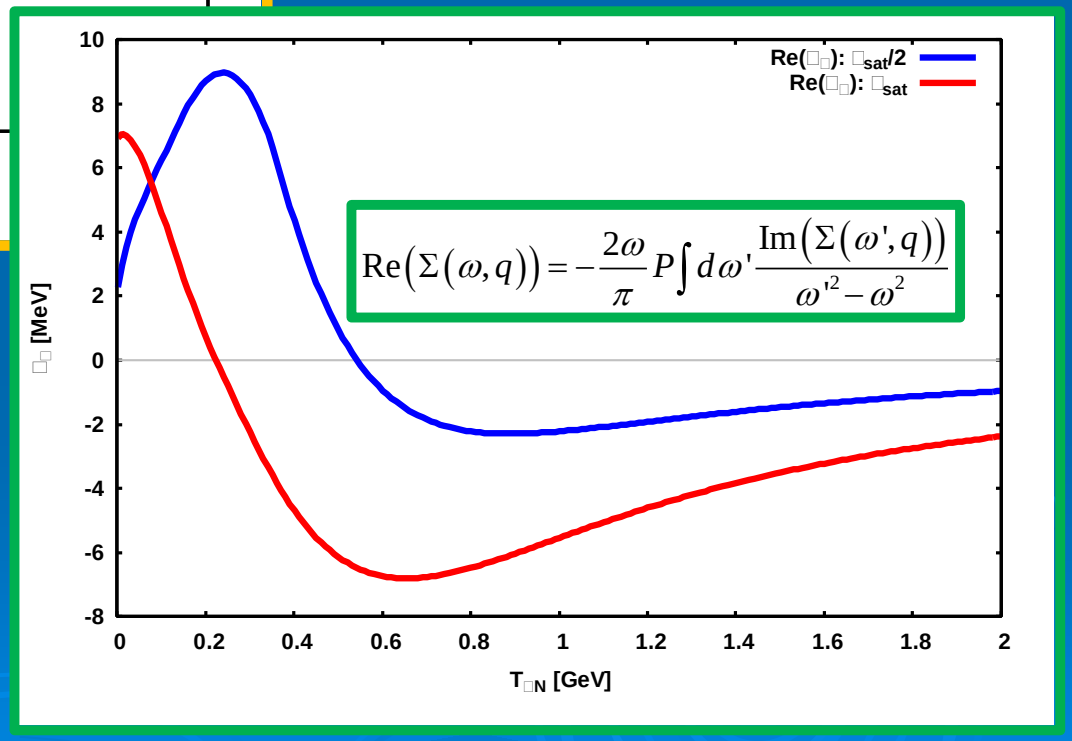
$$\Sigma_\alpha = V_\alpha - iW_\alpha$$

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

Δ In-Medium Self-Energy



$$\mathrm{Im}\,\Sigma(p_\Delta^2,\rho) = -\frac{1}{2}\Gamma(p_\Delta^2,\rho)$$



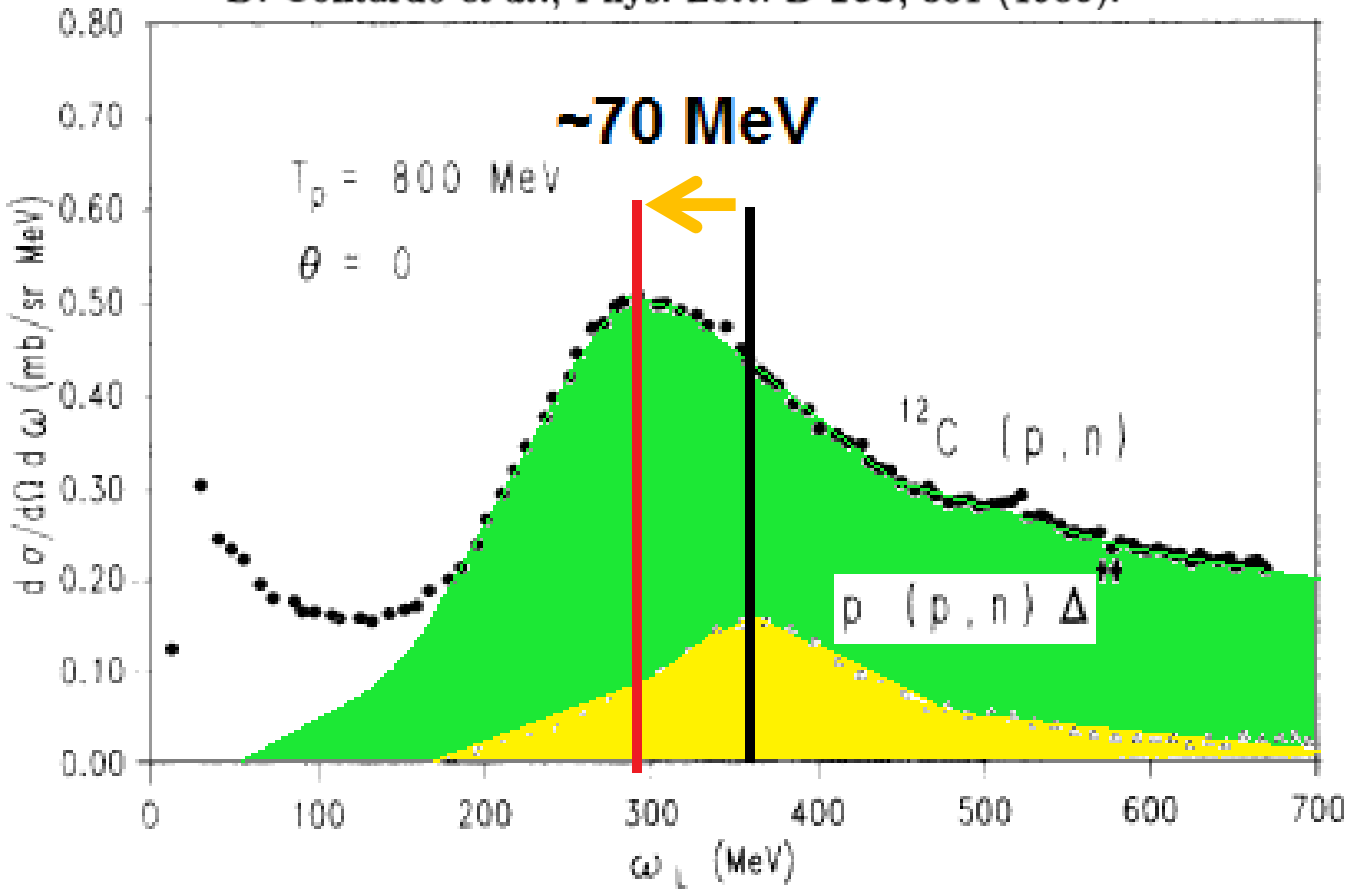
$$\mathrm{Re}\left(\Sigma(\omega,q)\right) = -\frac{2\omega}{\pi} P\int d\omega' \frac{\mathrm{Im}\left(\Sigma(\omega',q)\right)}{\omega'^2-\omega^2}$$

Conclusion:

- **Width: weak dependence on ρ**
- **Shift : strong dependence on ρ**

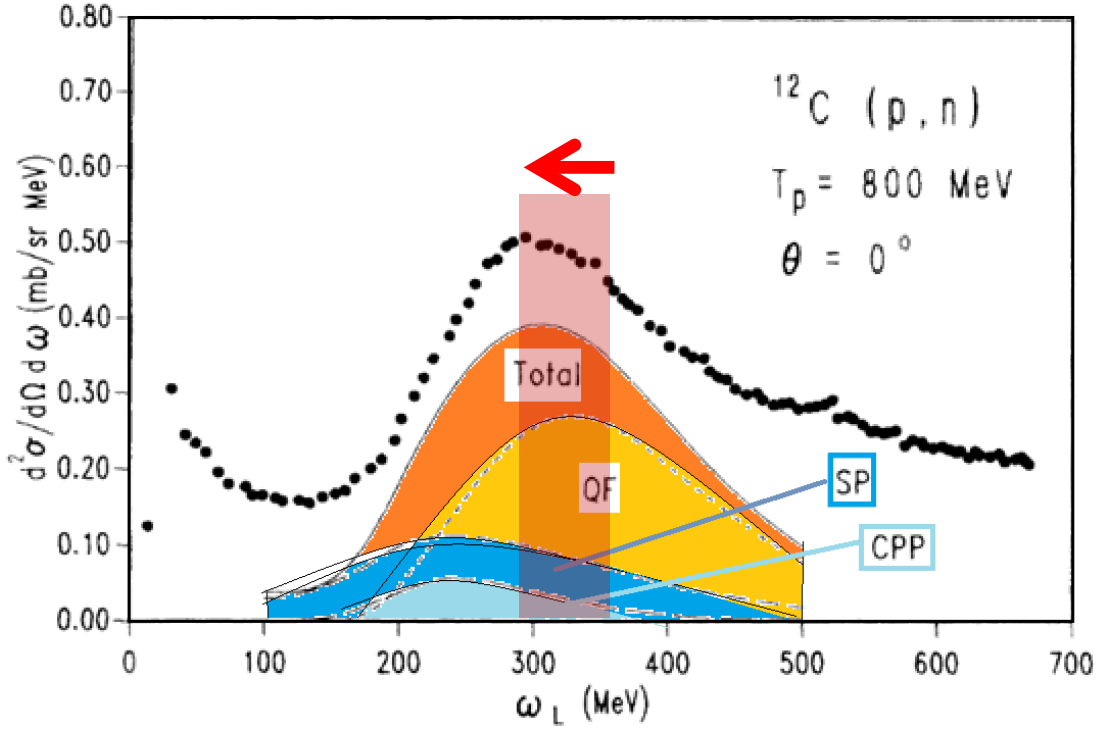
Inclusive $^{12}C(p,n)$-reaction @SATURNE

D. Contardo *et al.*, Phys. Lett. B **168**, 331 (1986).



Experimental zero-degree spectra of the $^{12}C(p,n)$ reaction [5] in comparison with the $p(p,n)\Delta^{++}$ reaction at E =800 MeV.

The origin of the apparent mass shift in stable nuclei…
…a combination of medium and reaction effects



Decomposition of the zero-degree singles cross section into partial cross sections for the ^{12}C (p, n) reaction at E=800 MeV. The different cross section contributions are due to quasifree Δ decay (QF), Δ spreading (SP), and coherent pion production (CPP).

T. Udagawa et al. PRC 49:3162 (1994)

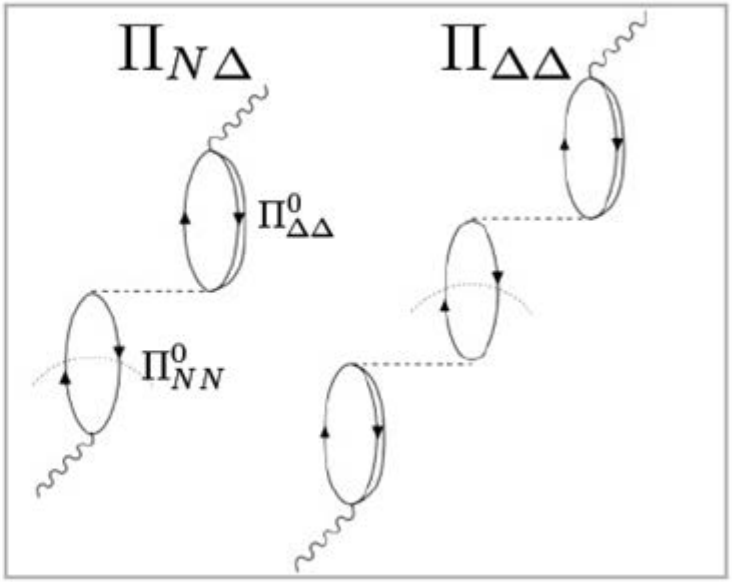
Nuclear Response Functions

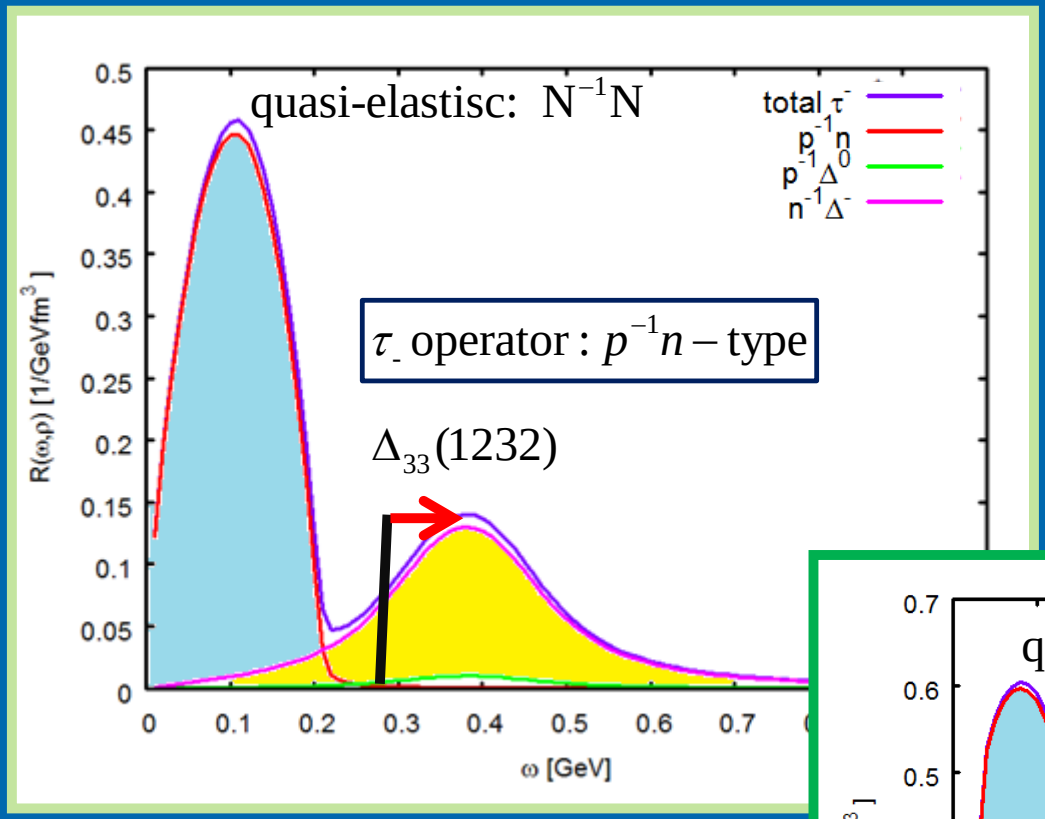
Resonance Excitation in Nuclei: „N*RPA“

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

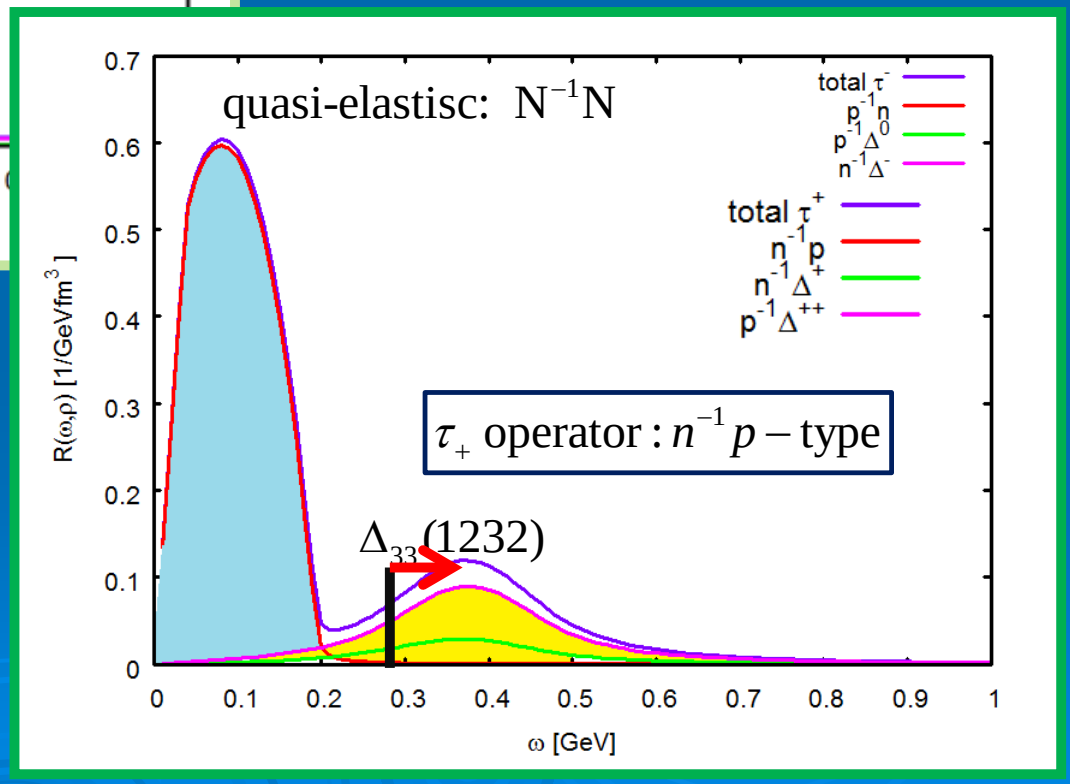
$$\begin{pmatrix} \Pi_{NN} & \Pi_{N\Delta} \\ \Pi_{\Delta N} & \Pi_{\Delta\Delta} \end{pmatrix} = \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} + \begin{pmatrix} \Pi^0_{NN} & 0 \\ 0 & \Pi^0_{\Delta\Delta} \end{pmatrix} \begin{pmatrix} V_{NN} & V_{N\Delta} \\ V_{\Delta N} &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

- 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



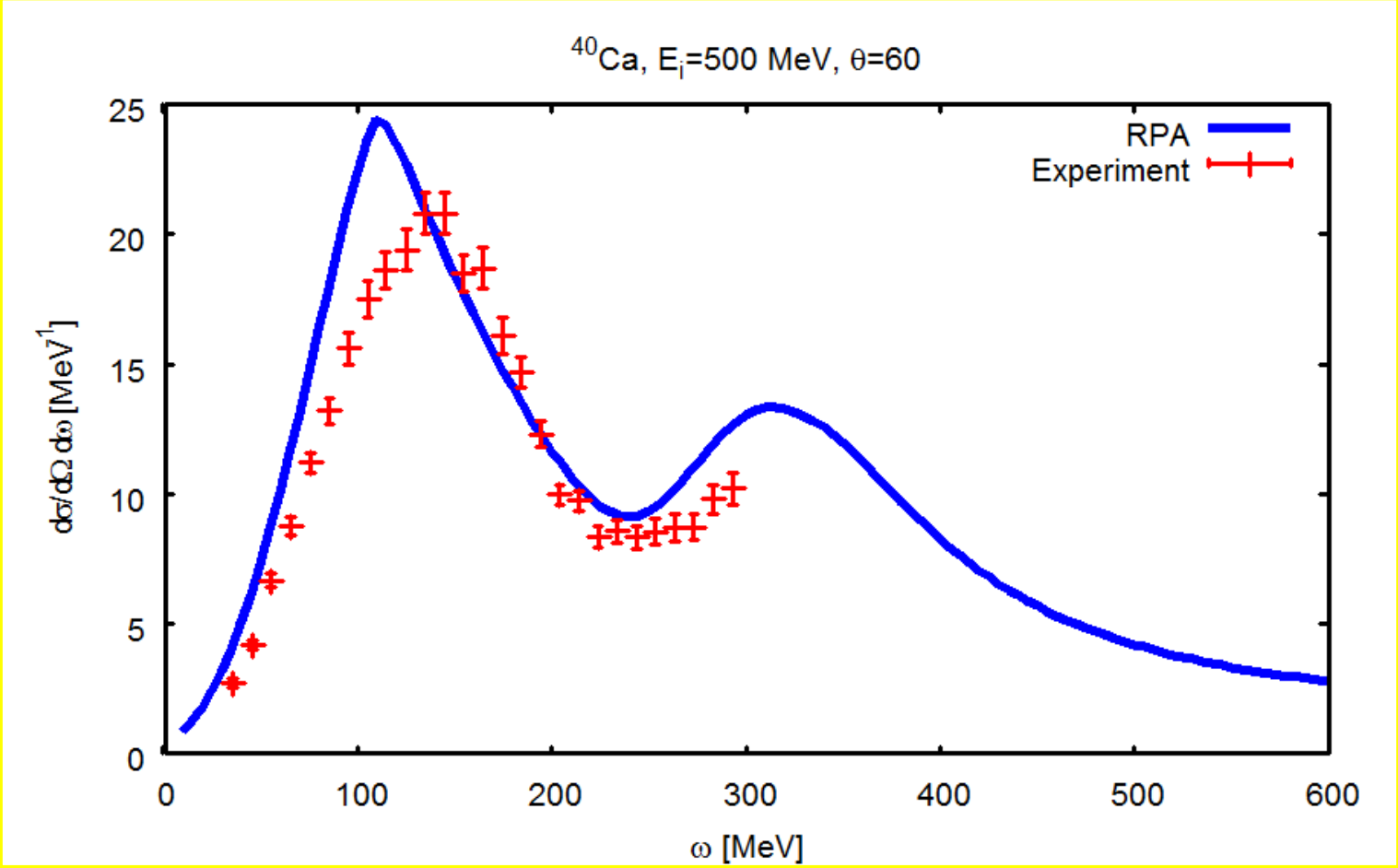


N*RPA:
Z→Z-1
^{124}Sn → ^{124}In
(q=400MeV/c)



N*RPA:
Z→Z+1
^{124}Sn → ^{124}Sb
(q=400MeV/c)

Delta-Resonance Excitation in Inclusive (e,e‘) Scattering

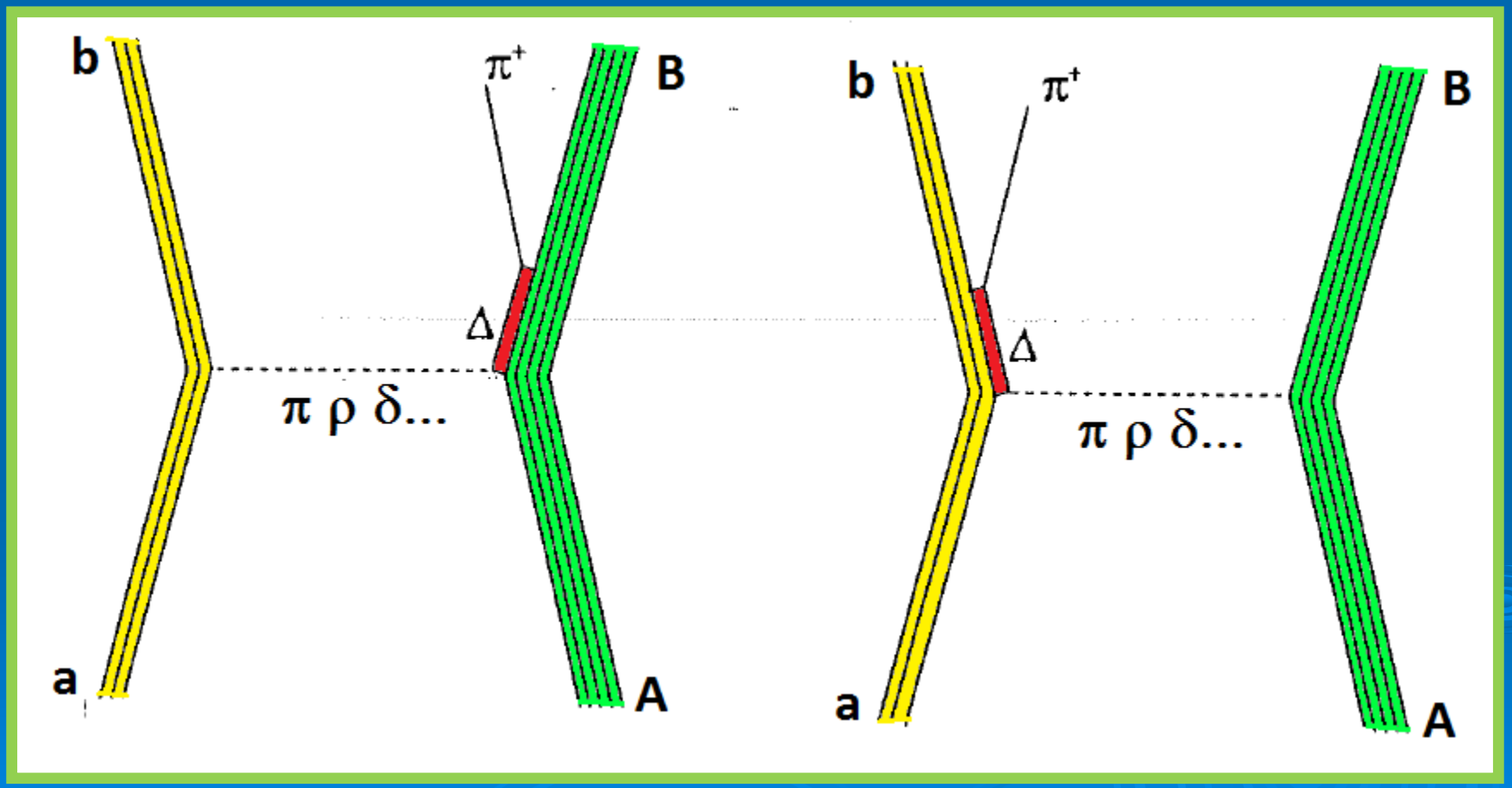


Decay Spectroscopy

$$p + p \rightarrow \begin{cases} n + \Delta^{++} \rightarrow n + p + \pi^{+} \\ p + \Delta^{+} \rightarrow p + n + \pi^{+} \\ \qquad\qquad \rightarrow p + p + \pi^{0} \end{cases}$$

$$p + n \rightarrow \begin{cases} p + \Delta^{0} \rightarrow n + p + \pi^{0} \\ n + \Delta^{+} \rightarrow n + n + \pi^{+} \\ \qquad\qquad \rightarrow p + n + \pi^{0} \end{cases}$$

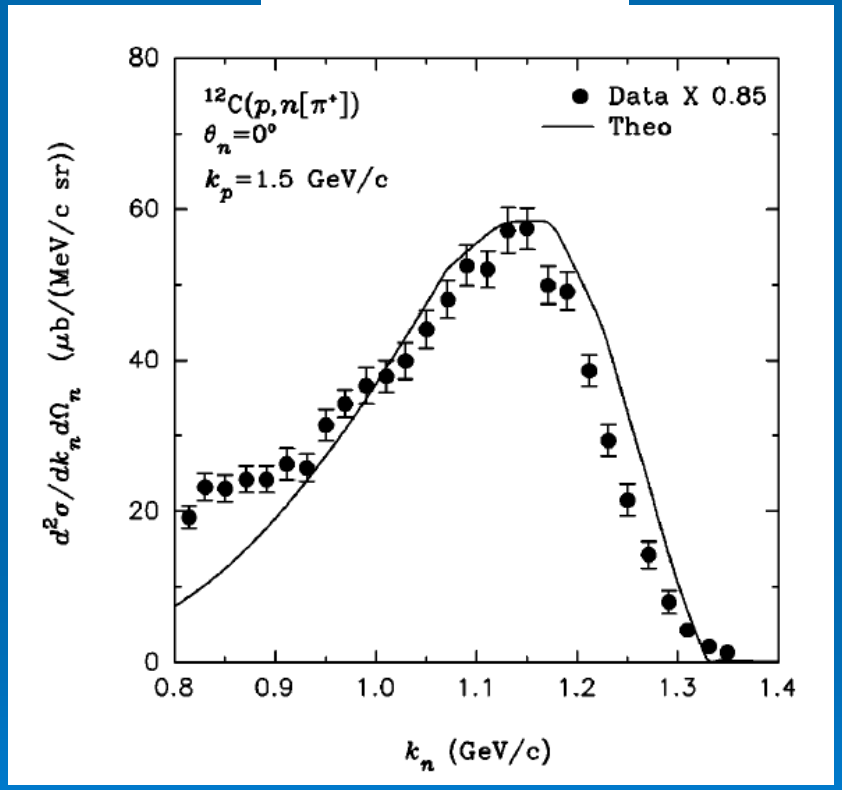
Exclusive Reactions: Resonance Excitation and Meson Production in Ion-Ion Collisions



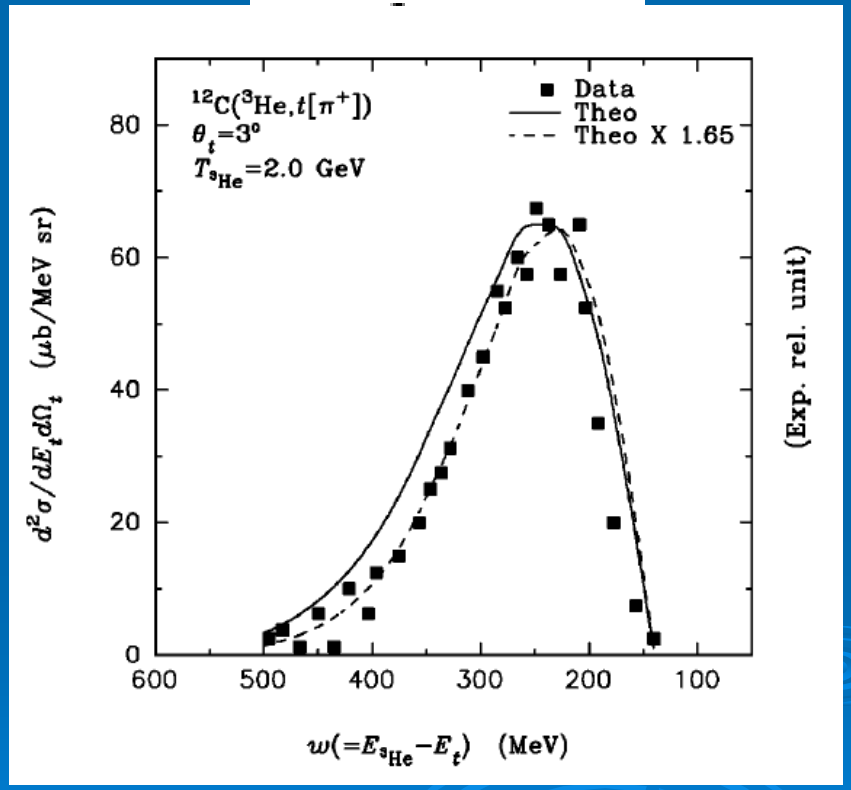
Exclusive reaction: Single-Pion Decay Spectroscopy

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

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



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



FANCY@KEK 88% of 4π

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

DIOGENE@SATURNE ~100% of 4π

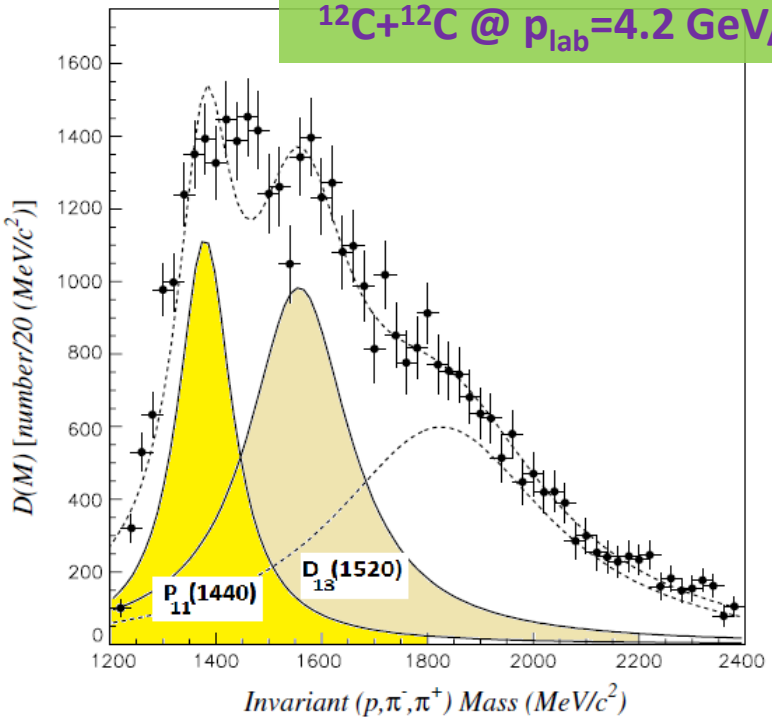
T. Hennino *et al.*, Phys. Lett. B 283, 42 (1992)

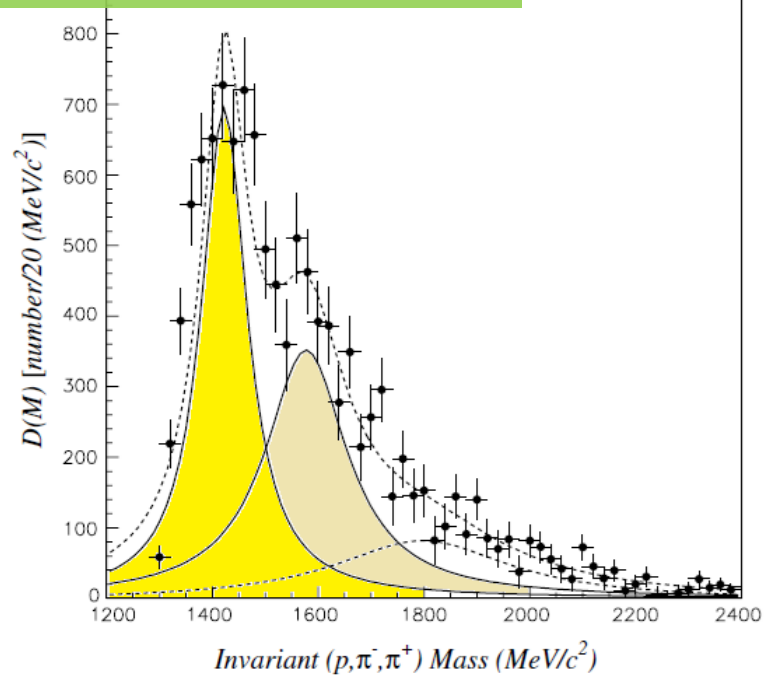
Theory: S. Das, PRC 66:014604 (2002)

Decay Spectroscopy of Higher Resonances in A+A Collisions

(Single and) Double-pion Decay Spectroscopy

$^{12}C+^{12}C$ @ p_{lab}=4.2 GeV/c, Synchro-Phasetron Data





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

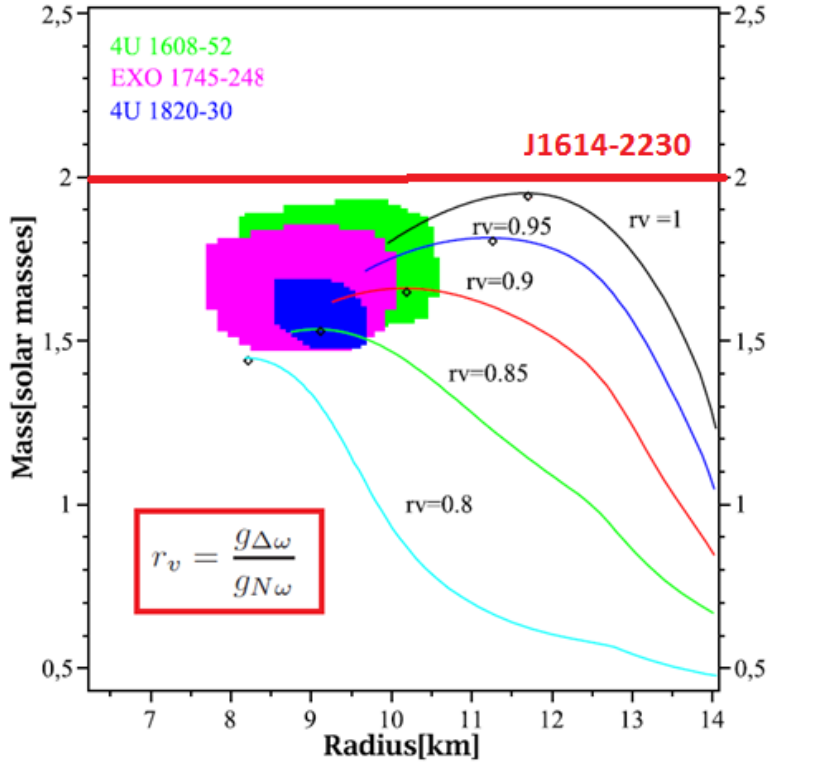
	M (MeV/c^2)	Γ (MeV/c^2)
$N(1440)$	1380 ± 10	130 ± 20
$N(1520)$	1550 ± 20	230 ± 30
The 3rd peak	1810 ± 30	510 ± 40

	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)

N* Resonances in Neutron Stars

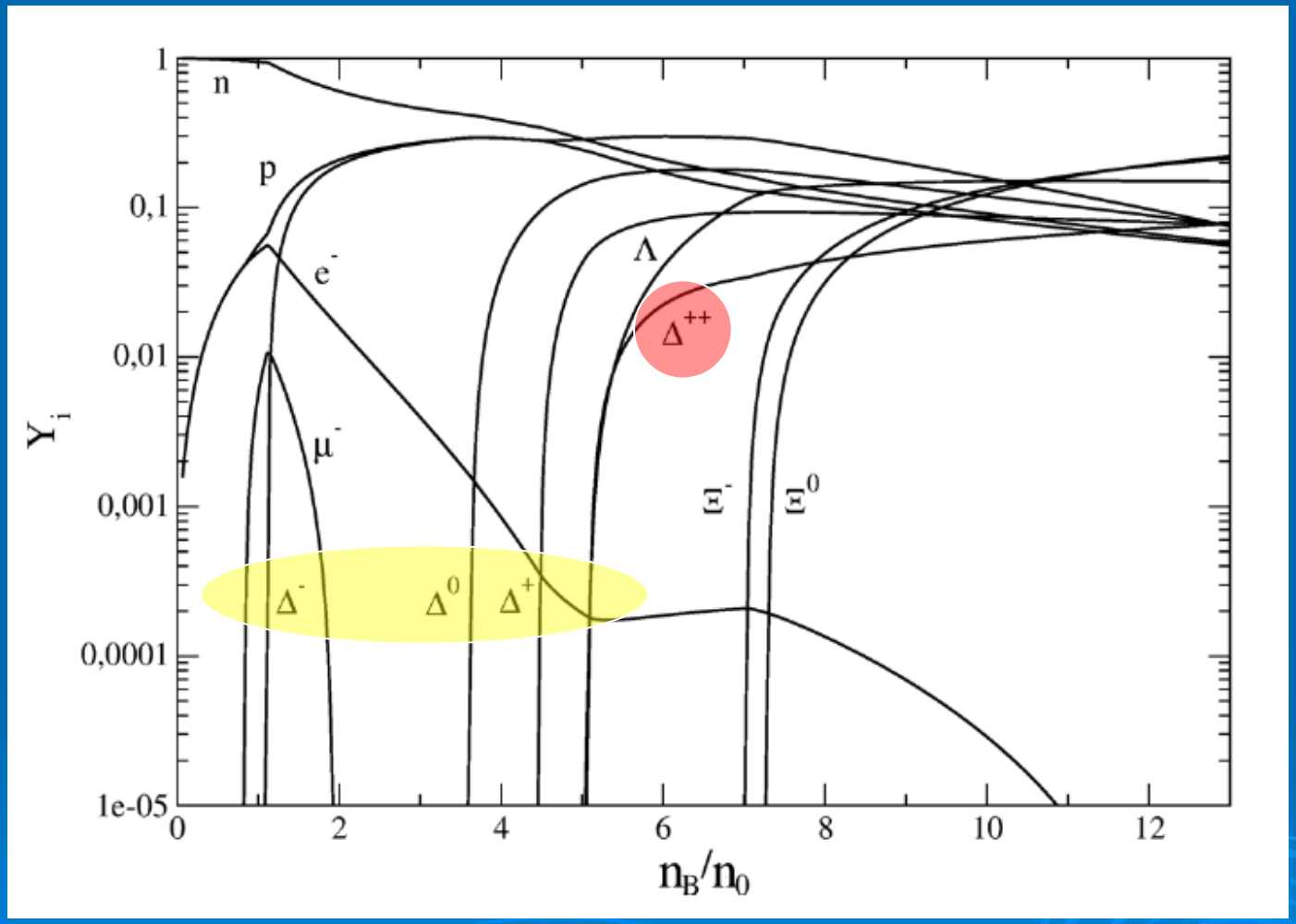
Δ's in Neutron Stars



Mass-Radius-relationship of Neutron stars for various couplings of the Δ resonances, starting from $r_v = 1$ (upper line) to 0.8 (lowest line). Also included are the 1-σ errorbars for measured neutron stars . The black diamond on each curve represents the maximum stable configuration

Schürhoff, Schramm,Dexheimer, 2010

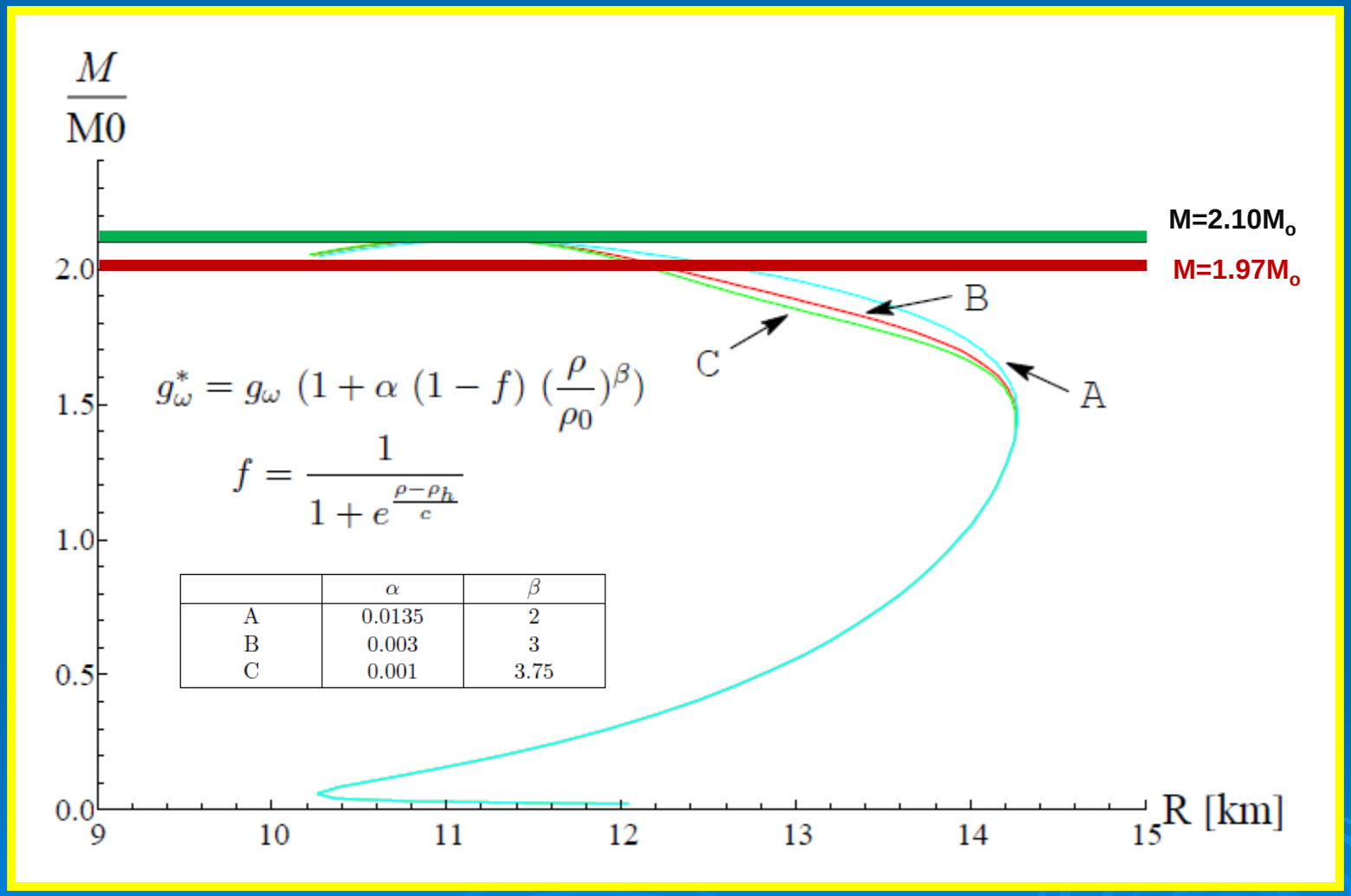
Resonances and Hyperons in Neutron Star Matter



A. Drago et al. Eur. Phys. J. A (2016) **52**

Mass-Radius Relation for a Neutron Star

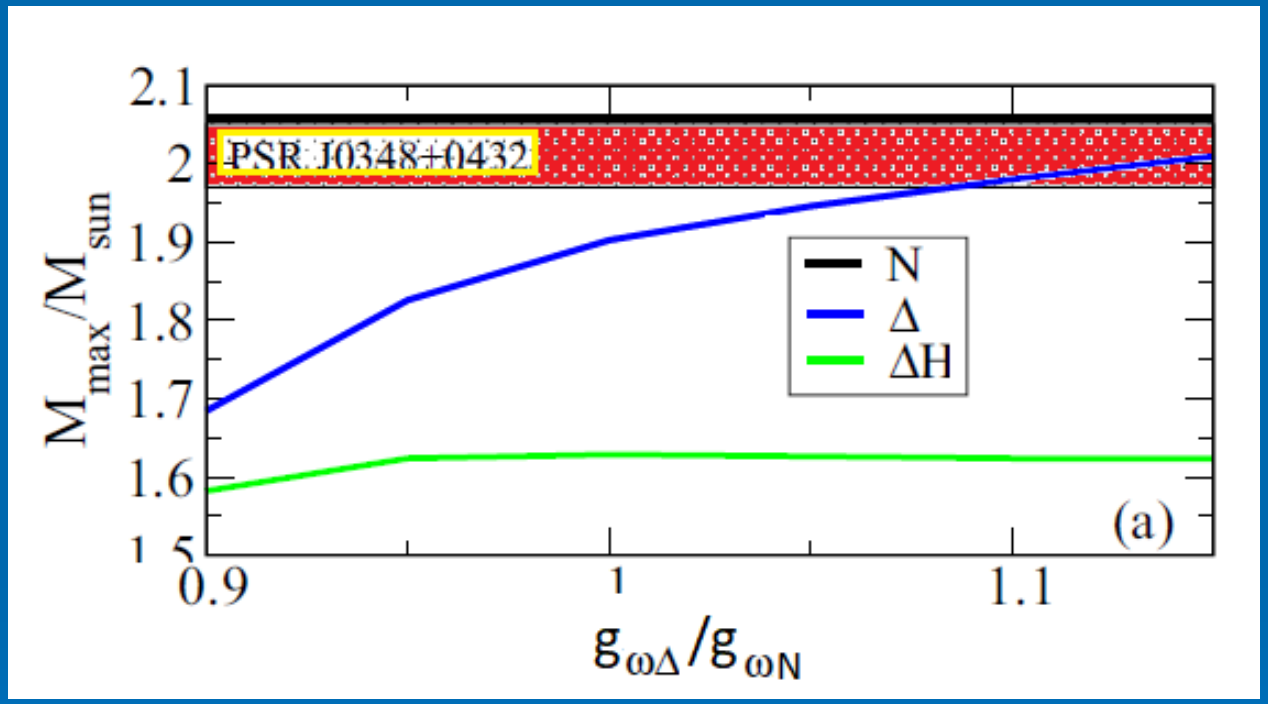
„Driving up the mass by *Vector Repulsion*“



	α	β
A	0.0135	2
B	0.003	3
C	0.001	3.75

J. Wilhelm, H.L, EPJ WoC 107

Resonances and Hyperons in Neutron Star Matter
Maximum Mass of a Neutron Star



…as a function of the ω–Δ vector meson coupling constant

A. Drago et al. Phys. Rev. C 9:065809 (2014)

Summary and Outlook

- Resonances as nuclear structure probes
- Resonances and nuclear isospin dynamics
- Resonances and nuclear response functions
- Resonance tagging by decay spectroscopy
- Resonances beyond $\Delta(1232)$
- Resonance „puzzle“ in neutron stars

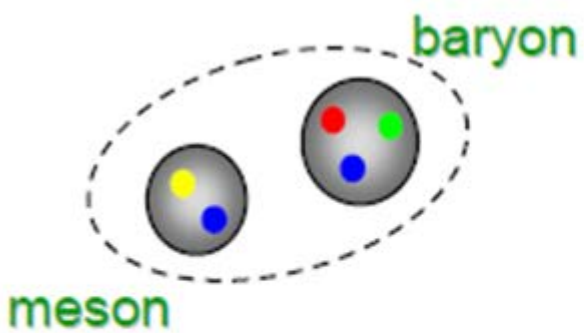
Credits to Andreas Fedoseew and Isaac Vidana
…supported by
DFG, GSI, HIC for FAIR, BMBF

Backup

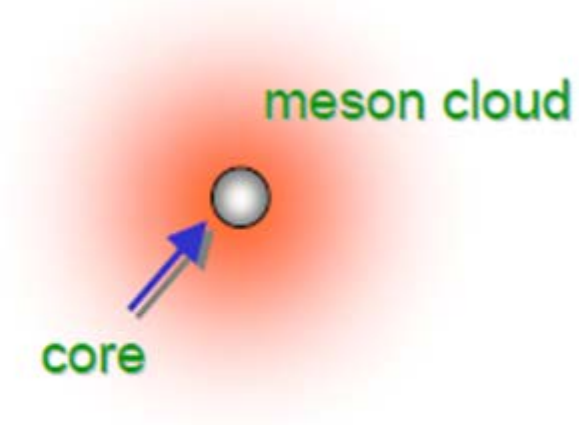
QCD Wave Function of a Resonance

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

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



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



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

Strong Medium Dependence

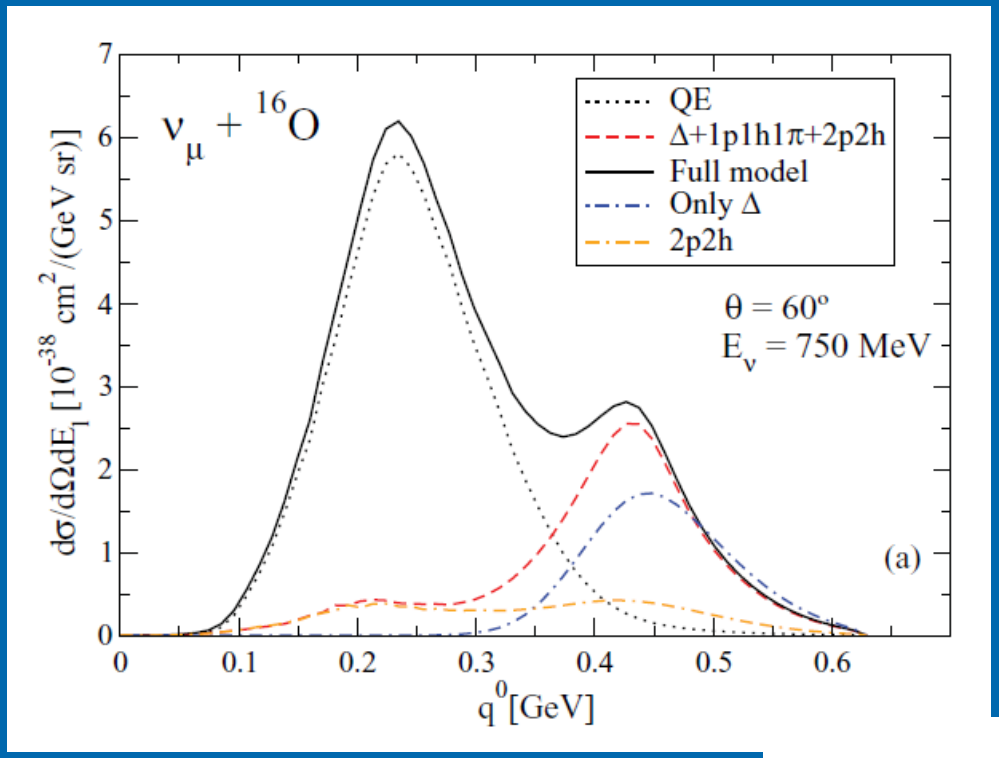
Weak Medium Dependence

N* Resonances and Neutrino-Nucleus Interactions

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

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

Inclusive CC cross section



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

Gießen
„N-Δ RPA“