Nuclear Effects in Pion Production/Resonance Region

J. Nieves

IFIC (CSIC & UV)

IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT ID VALÈNCIA
EXCELENCIA SEVERO OCHOA

Outline

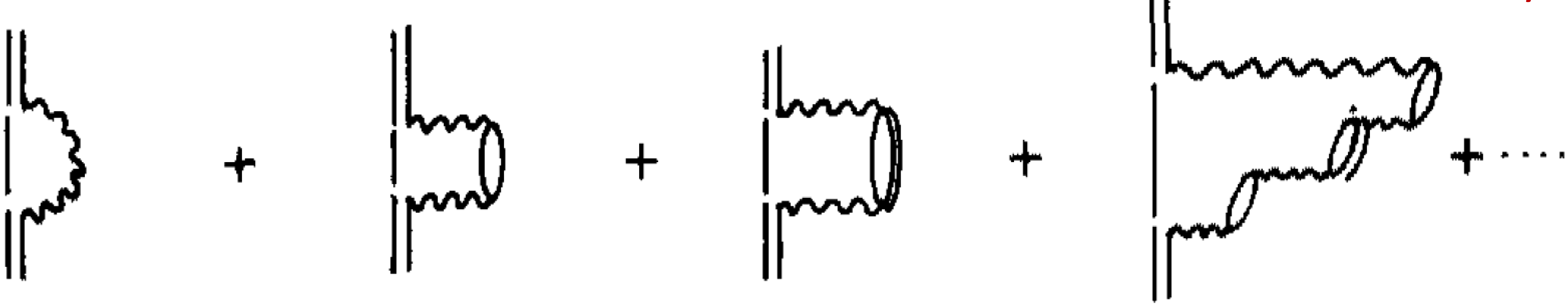
1. Oset-Salcedo model [NPA 468 (1987) 631] to account for the $\Delta(1232)$ spectral function in the medium
2. Impact on FSI effects on pions
3. RPA effects on the real part of the Δ selfenergy
4. 2p2h contributions
5. Conclusions

Many-body approach to the Δ(1232) self-energy in nuclear-matter

- **Change of its dispersive properties in the medium**

$$\frac{1}{\sqrt{s} - M_\Delta + i\,\Gamma_\Delta(s)/2} \Rightarrow \frac{1}{\sqrt{s} - M_\Delta + i\,\Gamma_\Delta(s)/2 - \Sigma_\Delta(s;\rho)}$$

depends on the medium density !



- $\Sigma_\Delta(s;\rho)$ is an optical potential that describes the interaction of the Δ with the nuclear medium.
- $Im\,\Sigma_\Delta(s;\rho)$ accounts for both
  - modifications of the free space decay mode,

$$\Delta \longrightarrow N\pi$$

    1. Pauli blocking + medium corrections for the outgoing nucleon (SF)
    2. Nuclear medium corrections for the outgoing pion: $\Pi(q^0,\vec{q};\ \rho)$ ($\pi-$ selfenergy: pion-nucleus optical potential)

$$q^{02} - \vec{q}^{\,2} = m_\pi^2 + \Pi(q^0,\vec{q};\ \rho)$$

  - new decays modes induced by collisions

$$\Delta N \longrightarrow NN, \Delta N \longrightarrow NN\pi, \Delta NN \longrightarrow NNN$$

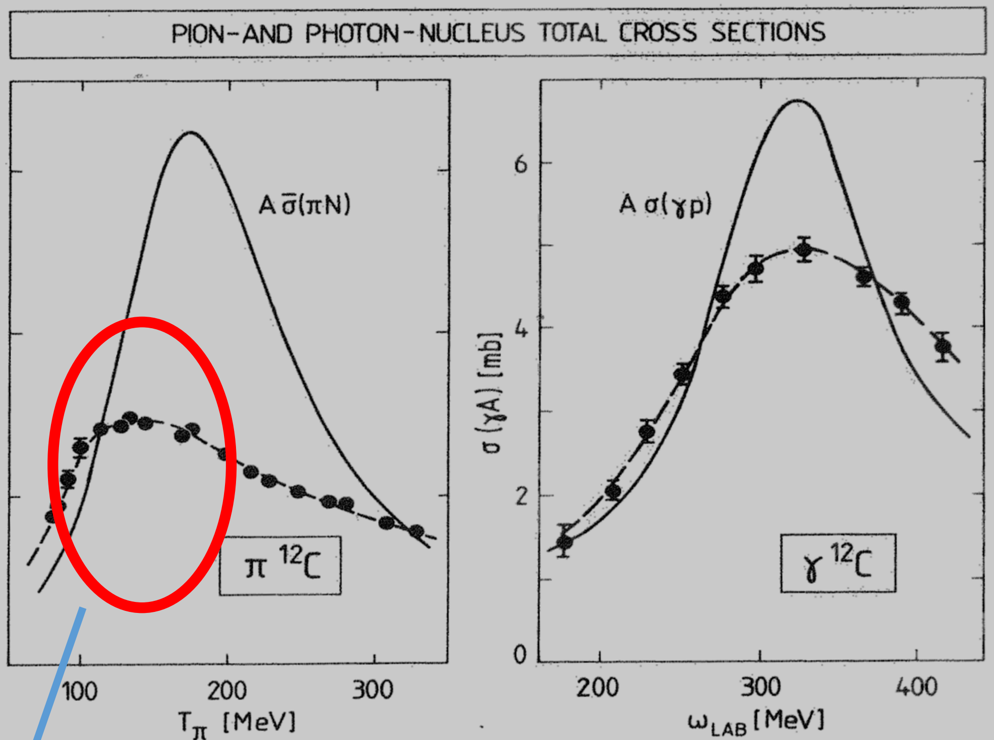
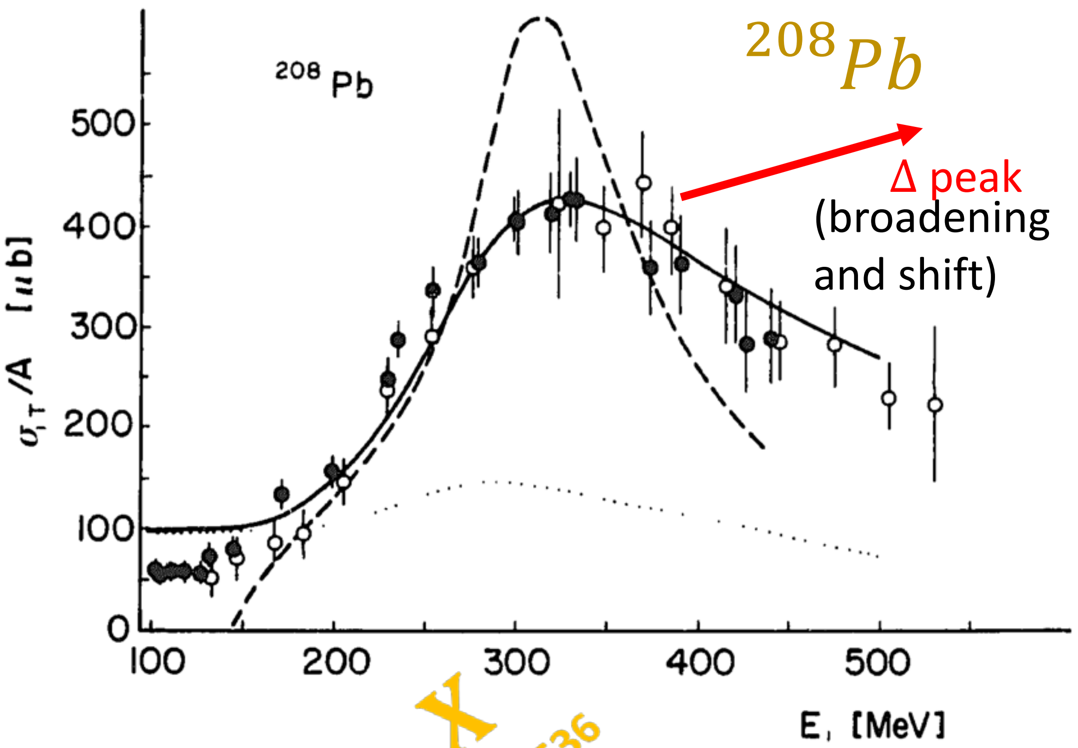


FIG. 8.17. Comparison of $\pi\,^{12}$C and $\gamma\,^{12}$C total cross-sections in the $\Delta(1232)$-resonance region. The sum of the free pion–nucleon cross-sections $A\bar{\sigma}(\pi N) = Z\sigma(\pi p) + N\sigma(\pi n)$ is shown for orientation. The data for $\sigma(\pi\,^{12}C)$ are from Carroll *et al.* (1974); the ones for $\sigma(\gamma\,^{12}C)$ are extrapolated values taken from Rost (1980). The dashed curves are drawn to guide the eye.



^{208}Pb

Δ peak (broadening and shift)

$\gamma A \to X$

Carrasco+Oset, NPA 536 (1992) 445

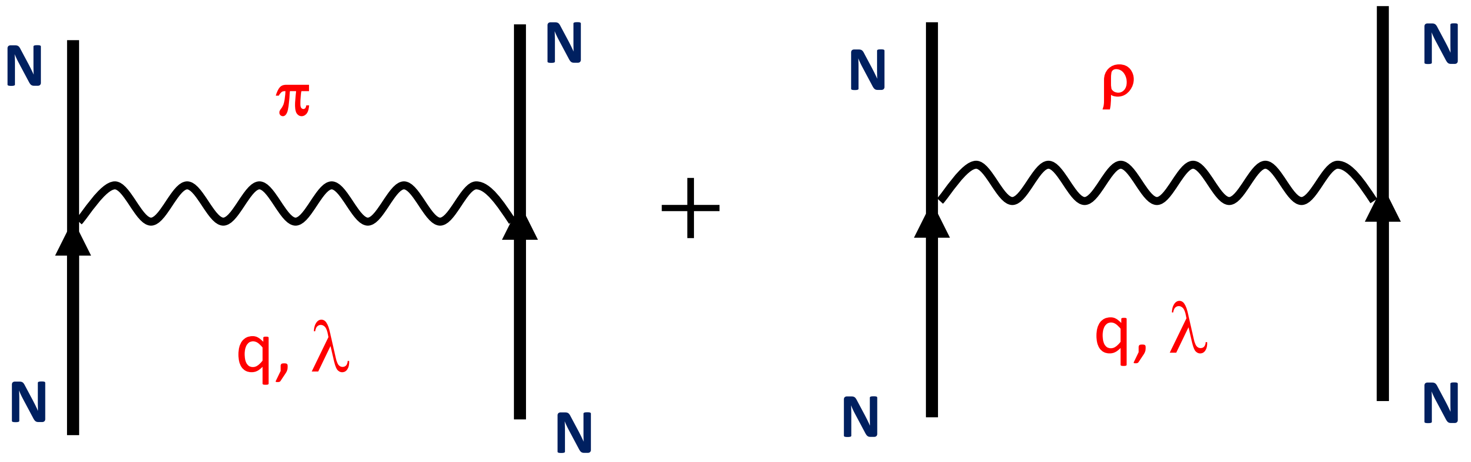
^{12}C (Pions & Nuclei, T.E.O. Ericson and W. Weise)

the γ-nucleus cross section still reflects the position and strength of the free Δ(1232) summed over the individual nucleons, although it is broadened by many-body mechanisms

shift produced by pion-nucleus absorption

$\Sigma_\Delta(s;\rho)$: First ingredient: effective baryon-baryon interaction in the medium

π+ρ exchange



$$\hat{V}_\pi(\mathbf{q}) = \sigma_1^i \sigma_2^j\, \vec{\tau}_1 \vec{\tau}_2 V_{ij}^{\pi}(q), \qquad V_{ij}^{\pi}(q) = \left(\frac{f}{m_\pi}\right)^2 F_\pi^2(q)\, \vec{q}^{\,2}\, D_\pi(q)\, \hat{q}_i\, \hat{q}_j$$

longitudinal !!

$$\hat{V}_\rho(\mathbf{q})\mathbf{q} = \sigma_1^i \sigma_2^j\, \vec{\tau}_1 \vec{\tau}_2 V_{ij}^{\rho}(q), \quad V_{ij}^{\rho}(q) = \left(\frac{f}{m_\pi}\right)^2 F_\rho^2(q)\, \vec{q}^{\,2}\, D_\rho(q) C_\rho\left(\delta_{ij} - \hat{q}_i\, \hat{q}_j\right)$$

transversal !!

$$F_{\pi,\rho}(q) = \frac{\Lambda_{\pi,\rho}^2 - m_{\pi,\rho}^2}{\Lambda_{\pi,\rho}^2 - q^2}, \qquad q^2 = {q^0}^2 - \vec{q}^{\,2}, \quad \Lambda_\pi = 1250\ \text{MeV} = \Lambda_\pi^*, \quad \Lambda_\rho = 2500\ \text{MeV} = \Lambda_\rho^*$$

(off-shell behavior) !!

Because $C_\rho = C_\rho^*, \Lambda_\pi = \Lambda_\pi^*$ and $\Lambda_\rho = \Lambda_\rho^*$, the former potentials also describe the

$$\boldsymbol{\Delta N \rightarrow NN,\ NN \rightarrow \Delta N \text{ and } \Delta\Delta \rightarrow NN}$$

interactions with the following replacements

$$\frac{f}{m_\pi}\,\sigma\tau \rightarrow \frac{f}{m_\pi}\,S\,T \text{ or } \frac{f}{m_\pi} S^\dagger T^\dagger$$

Note $V_{ij}^{\pi}(q) \perp V_{ij}^{\rho}(q)$

Short range correlations: Attributed to the exchange of the ω meson

$\frac{1}{m_\omega}$ defines the range of the correlations

Correlated potential in coordinate space: $\widetilde{V(r)} = V(r)g(r);\ \ g(r) = 1 - j_0(q_c r), q_c \sim m_\omega \sim 783 \text{ MeV}$

Correlated potential in momentum space: $\widetilde{V(q)} = \int \frac{d^3k}{(2\pi)^3}\, g(\vec{k} - \vec{q})V(\vec{k})$

$$g(\vec{k}) = (2\pi)^3\,\delta^3(\vec{k}) - 2\pi^2 \frac{\delta(|\vec{k}| - q_c)}{q_c^2}$$

Juan Nieves, IFIC (CSIC & UV)

NN potential *V(q)*= $c_0\{f_0(\rho)+f_0'(\rho)\vec{\tau}_1\vec{\tau}_2+g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2\}+\vec{\tau}_1\vec{\tau}_2\sum_{i,j=1}^{3}\sigma_1^i\sigma_2^j V_{ij}^{\sigma\tau}$

zero range Landau force
J. Speth et al., Phys. Rep. 33 (1977) 127

$$V_{ij}^{\sigma\tau}=(\hat{q}_i\hat{q}_jV_l(q)+(\delta_{ij}-\hat{q}_i\hat{q}_j)V_t(q))$$

with $\hat{q}_i = {}^{q_i}/_{|\vec{q}|}$

V_π

$$V_l(q^0,\vec{q})=\frac{f^2}{m_\pi^2}\left\{\left(\frac{\Lambda_\pi^2-m_\pi^2}{\Lambda_\pi^2-q^2}\right)^2\frac{\vec{q}^2}{q^2-m_\pi^2}+g_l'(q)\right\},$$

V_ρ

$$\frac{f^2}{4\pi}=0.08,\ \Lambda_\pi=1200\text{ MeV},$$

$$V_t(q^0,\vec{q})=\frac{f^2}{m_\pi^2}\left\{C_\rho\left(\frac{\Lambda_\rho^2-m_\rho^2}{\Lambda_\rho^2-q^2}\right)^2\frac{\vec{q}^2}{q^2-m_\rho^2}+g_t'(q)\right\},$$

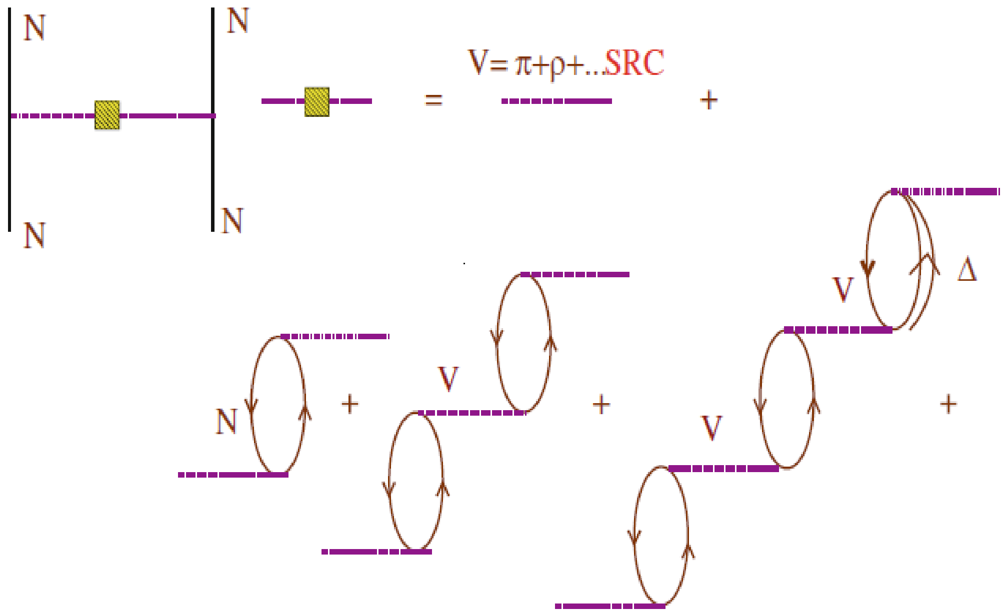
$$C_\rho=2,\ \Lambda_\rho=2500\text{ MeV},\ m_\rho=770\text{ MeV}.$$

SRC

The $N\Delta$ and the $\Delta\Delta$ potentials are obtained from V_l and V_t by replacing

$$\vec{\sigma}\rightarrow\vec{S},\ \vec{\tau}\rightarrow\vec{T}.$$

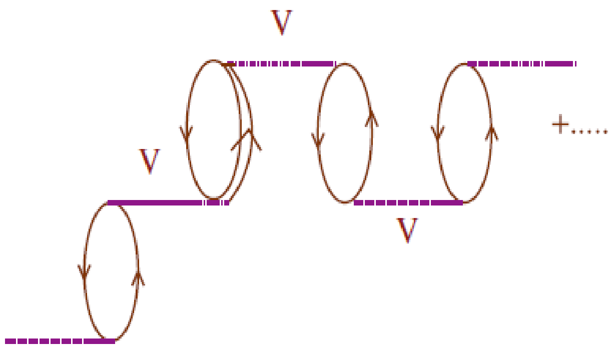
$$f\rightarrow f^*$$



The spin-isospin part of the interaction, taking into account the propagation of the mesons through the medium

$$W_{\sigma\tau}(q) = \sigma_1^i \sigma_2^j\, \vec{\tau}_1 \vec{\tau}_2 V_{ij}^{\sigma\tau}(q) +$$
$$\sigma_1^i \sigma_2^j\, \vec{\tau}_1 \vec{\tau}_2 \{V_{ik}^{\sigma\tau}(q)\ U(q) V_{kj}^{\sigma\tau}(q)\} +$$
$$\sigma_1^i \sigma_2^j\, \vec{\tau}_1 \vec{\tau}_2 \{V_{ik}^{\sigma\tau}(q)\ U(q) V_{km}^{\sigma\tau}(q) U(q) V_{mj}^{\sigma\tau}(q)\} +$$
$$\ldots\ = \sigma_1^i \sigma_2^j\, \vec{\tau}_1 \vec{\tau}_2 W_{ij}^{\sigma\tau}(q)$$

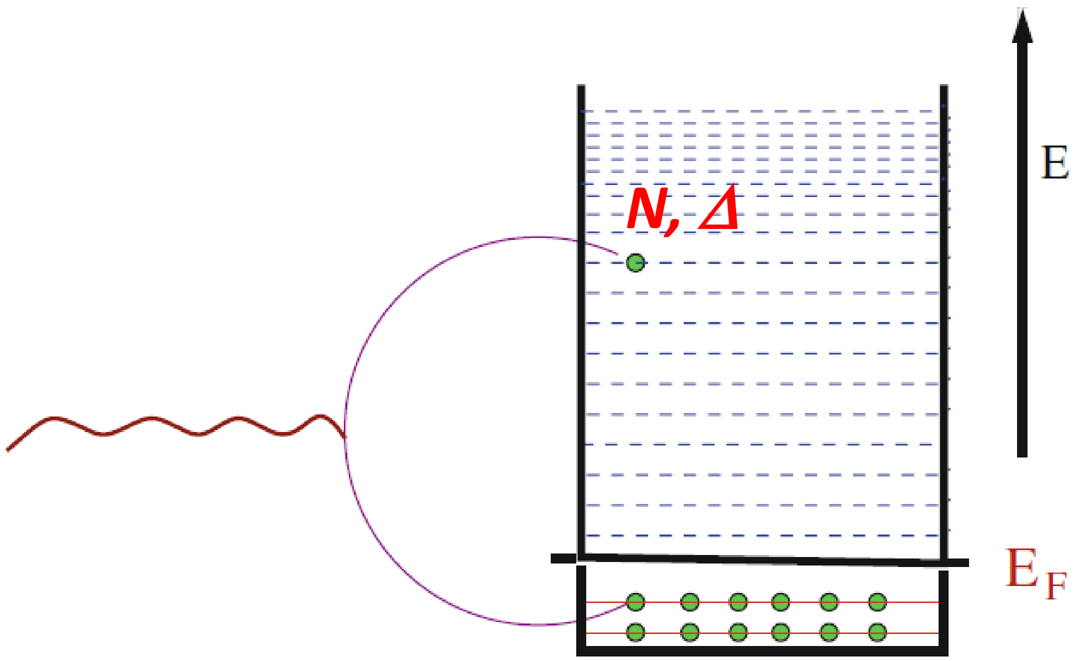
$$U(q) = U_N(q) + U_\Delta(q)$$
(direct + crossed terms)

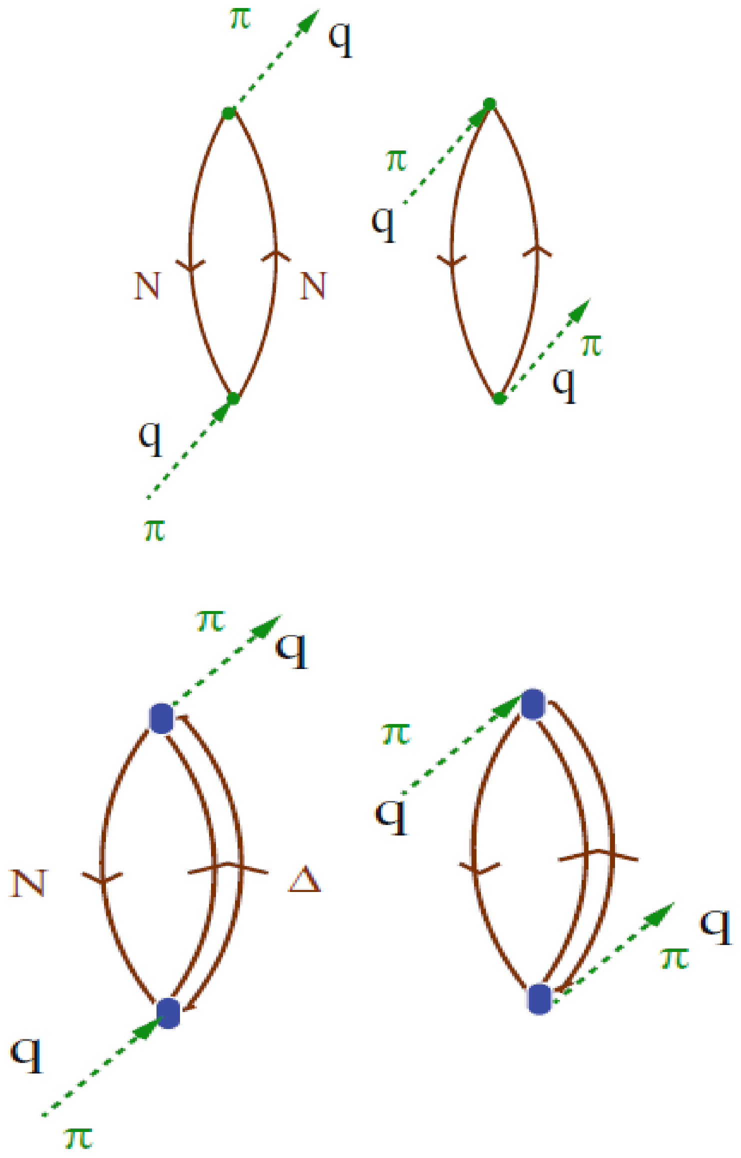


$$W_{ij}^{\sigma\tau}(q) = \frac{V_l(q)}{1-U(q)V_l(q)}\ \hat{q}_i\hat{q}_j\ + \frac{V_t(q)}{1-U(q)V_t(q)}\left(\delta_{ij} - \hat{q}_i\hat{q}_j\right)$$

$\hat{q}_i\hat{q}_j \perp \left(\delta_{ij} - \hat{q}_i\hat{q}_j\right)$

Induced spin-isospin *NN* interaction in a nuclear medium



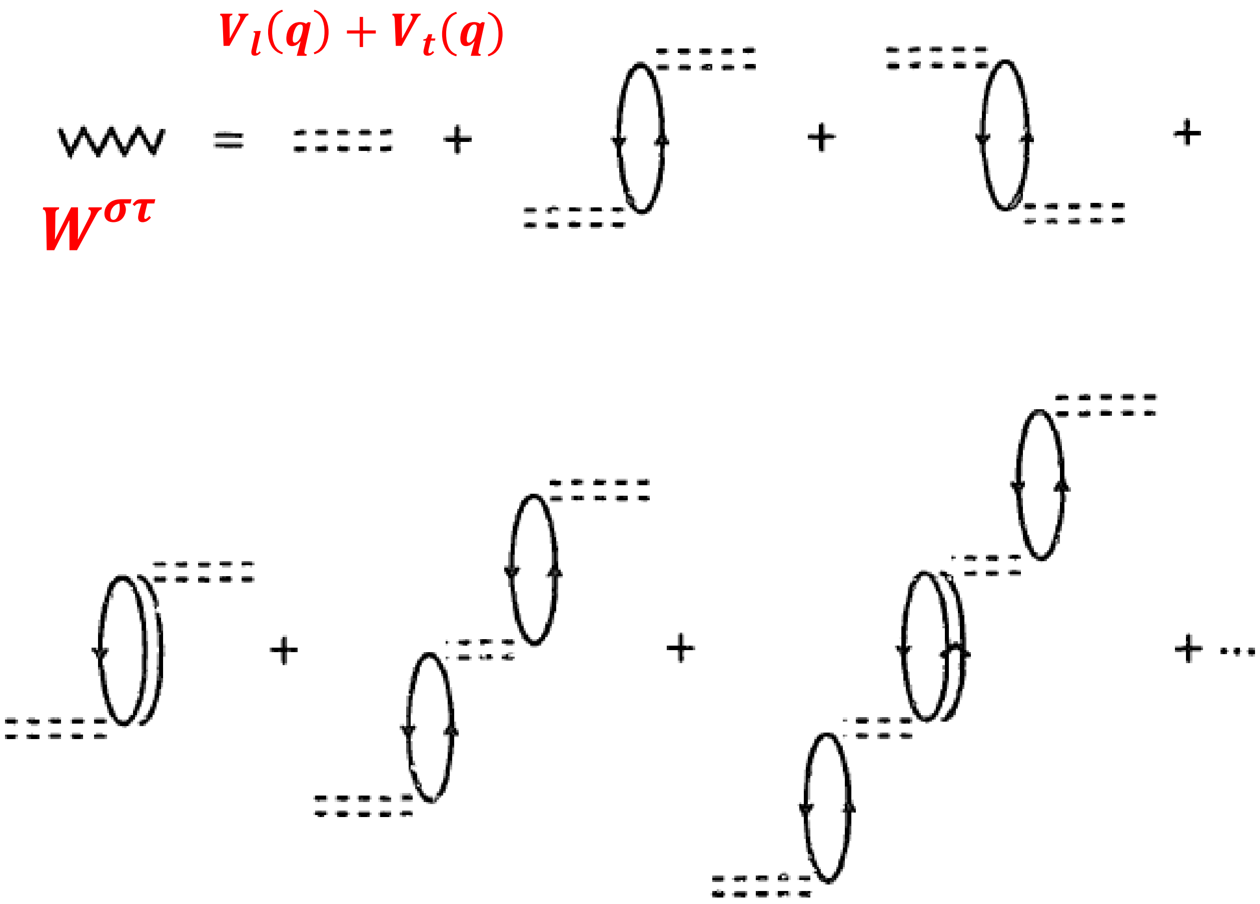


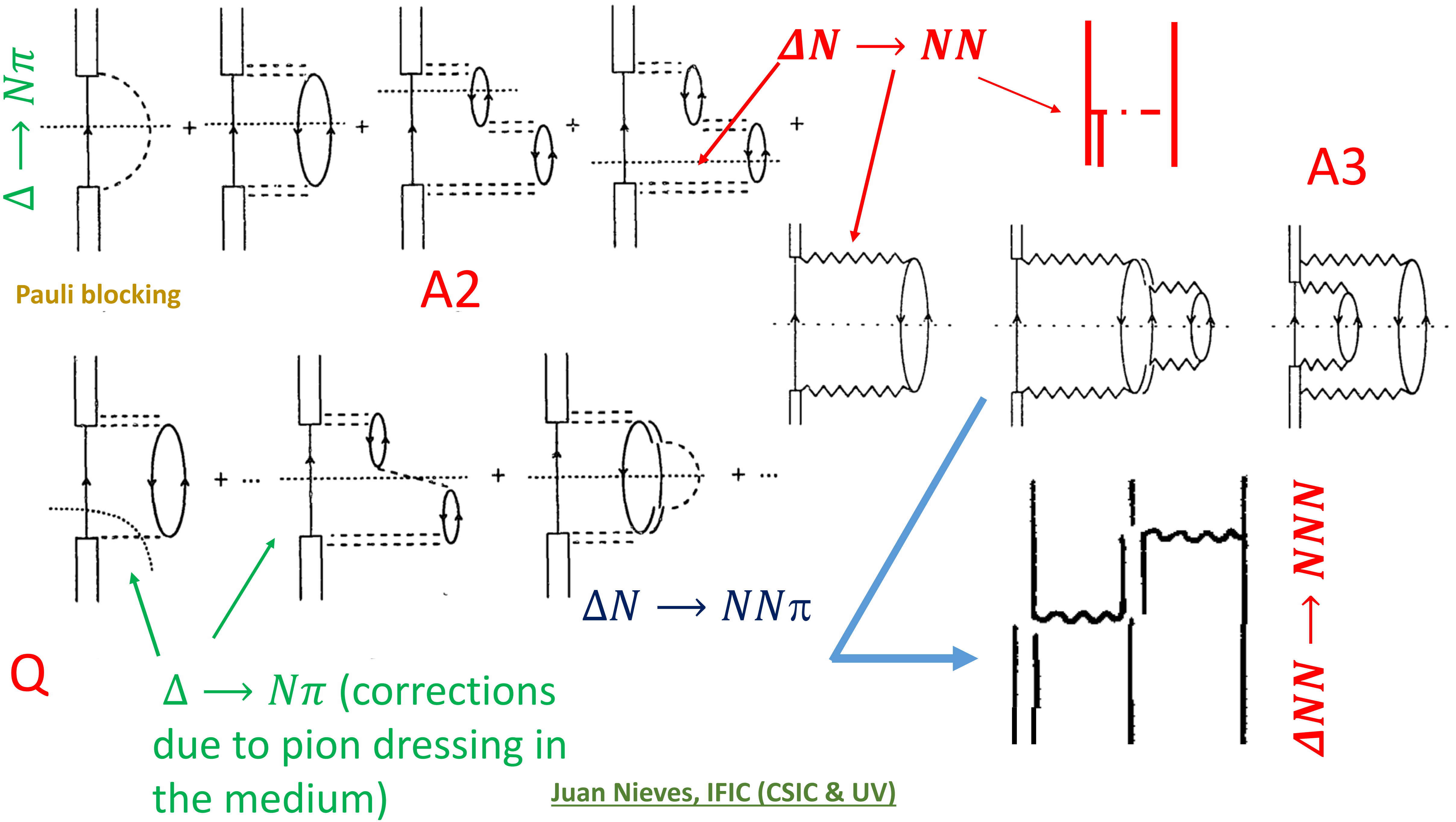
$U(q)=U_N+U_\Delta$ can have both real and imaginary parts. The imaginary part comes from situations in the intermediate states integration, where the are placed on shell [***Cutkowsky's rule*** (Itzykson & Zuber, Quantum Field Theory, McGraw-Hill, New York, 194)].

Diagrammatically,

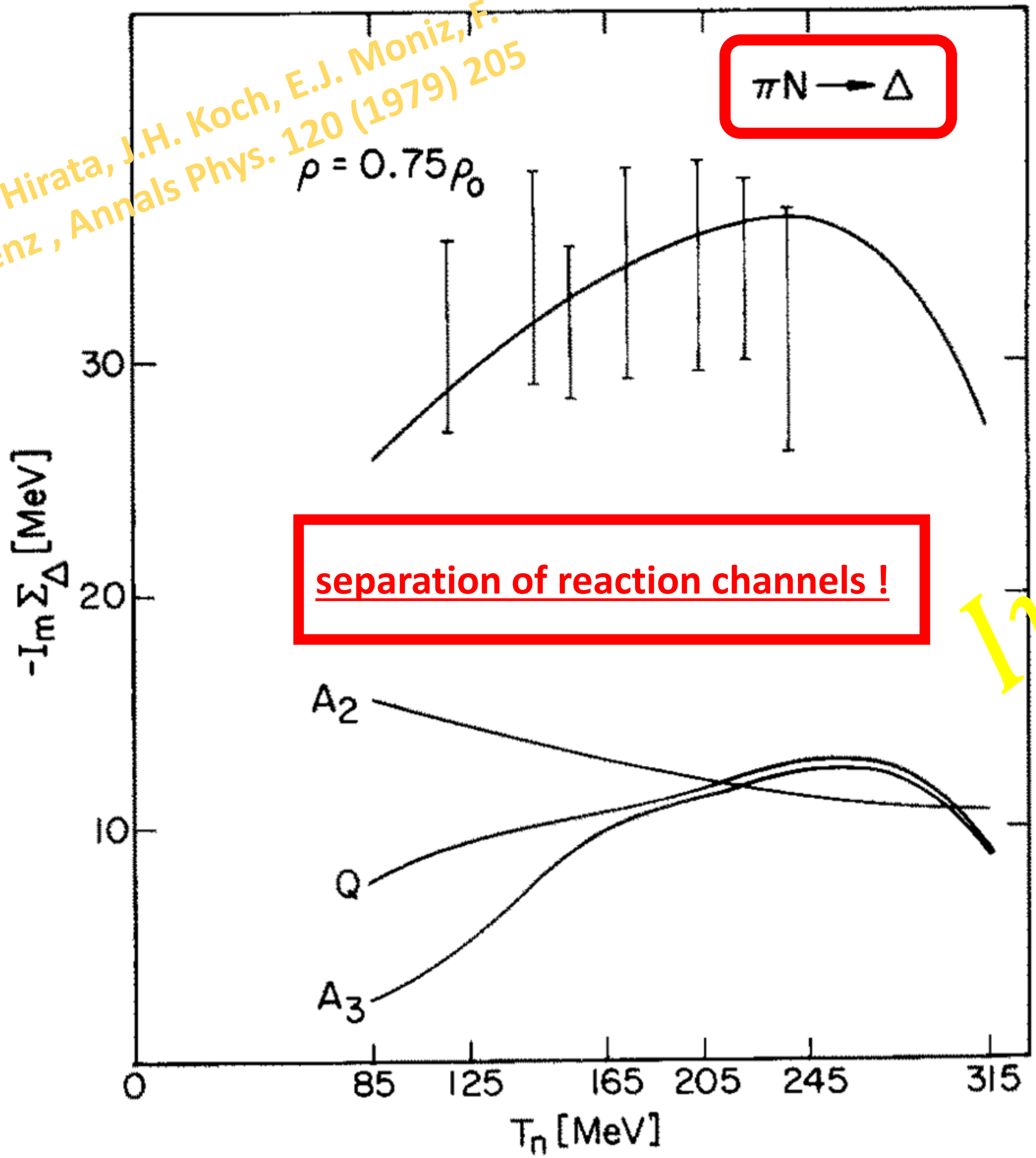
$$W_{ij}^{\sigma\tau}(q) = \frac{V_l(q)}{1-U(q)V_l(q)}\ \hat{q}_i\hat{q}_j\ + \frac{V_t(q)}{1-U(q)V_t(q)}\left(\delta_{ij} - \hat{q}_i\hat{q}_j\right)$$

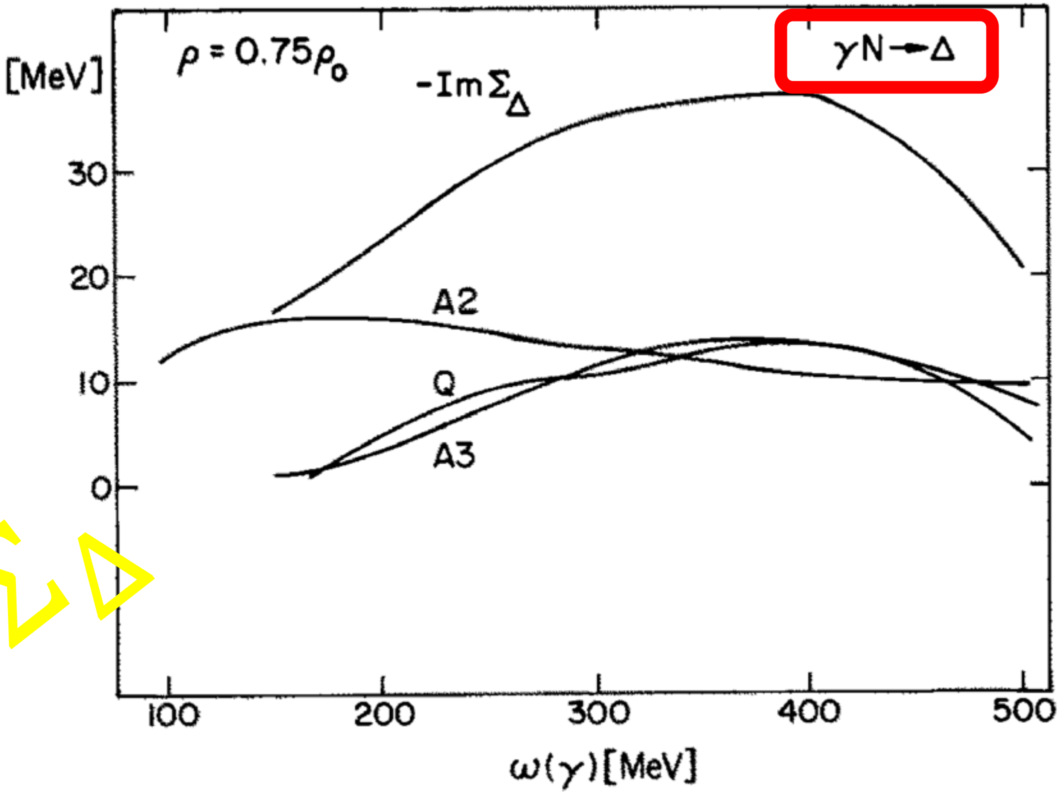
From the spin-isospin interaction, we construct the induced interaction by exciting *ph* and *Δh* components in a RPA sense





Δ → Nπ
Pauli blocking
A2
ΔN → NN
A3
Q
Δ → Nπ (corrections due to pion dressing in the medium)
ΔN → NNπ
ΔNN → NNN





ImΣΔ

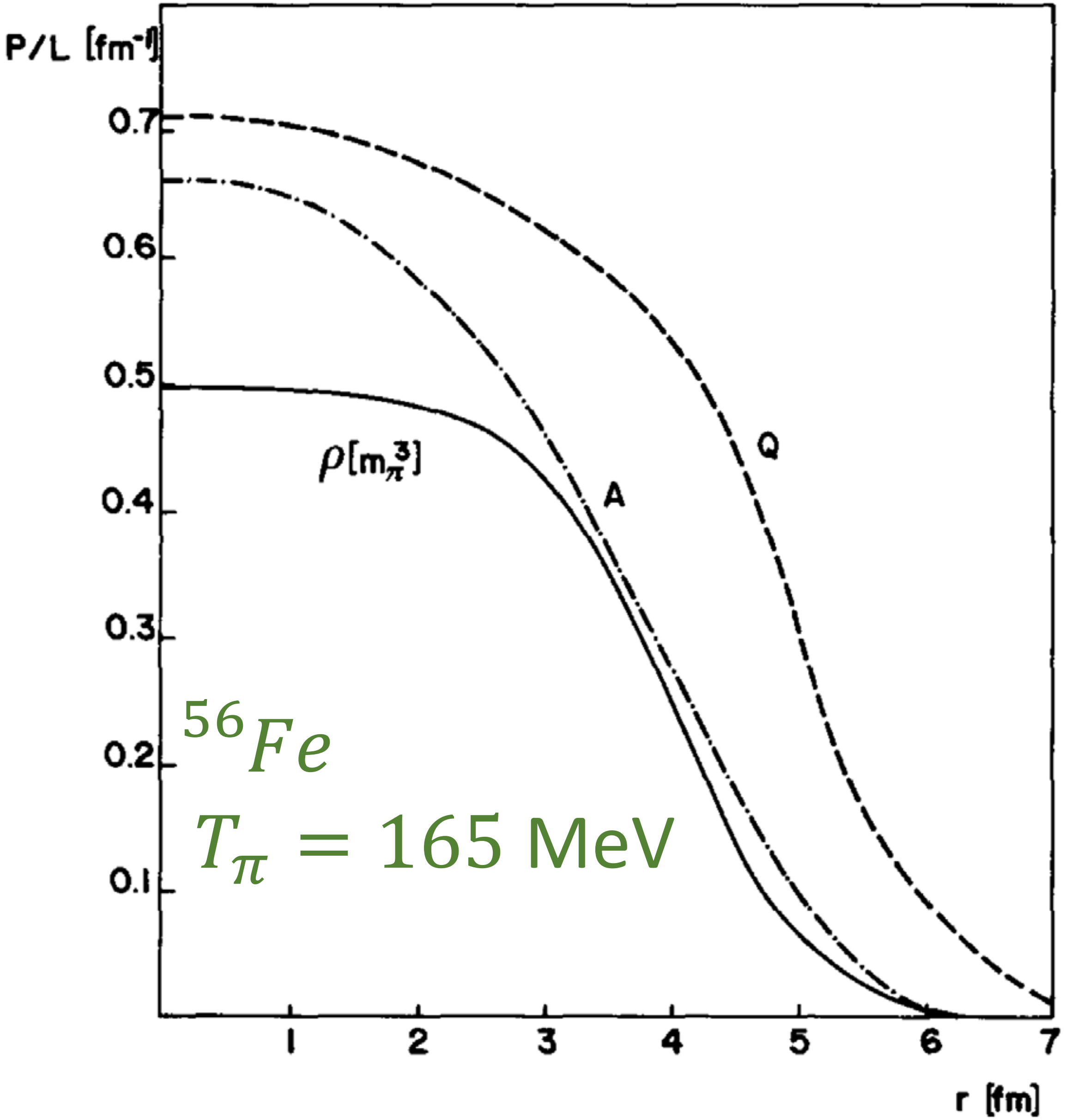
Tensor contribution negligible

$$\Sigma(k) = \Sigma_0(k) + \Sigma_2(k)(3S^\dagger \cdot \hat{k} S \cdot \hat{k} - 1)$$

Oset-Salcedo model [NPA 468 (1987) 631]

$Im\Sigma_\Delta$ determines FSI effects on pions…

$$\Pi(q^0,\vec{q};\ \rho) \propto \frac{1}{\sqrt{s} - M_\Delta + i\,\Gamma_\Delta(s)/2 - \Sigma_\Delta(s;\rho)}$$



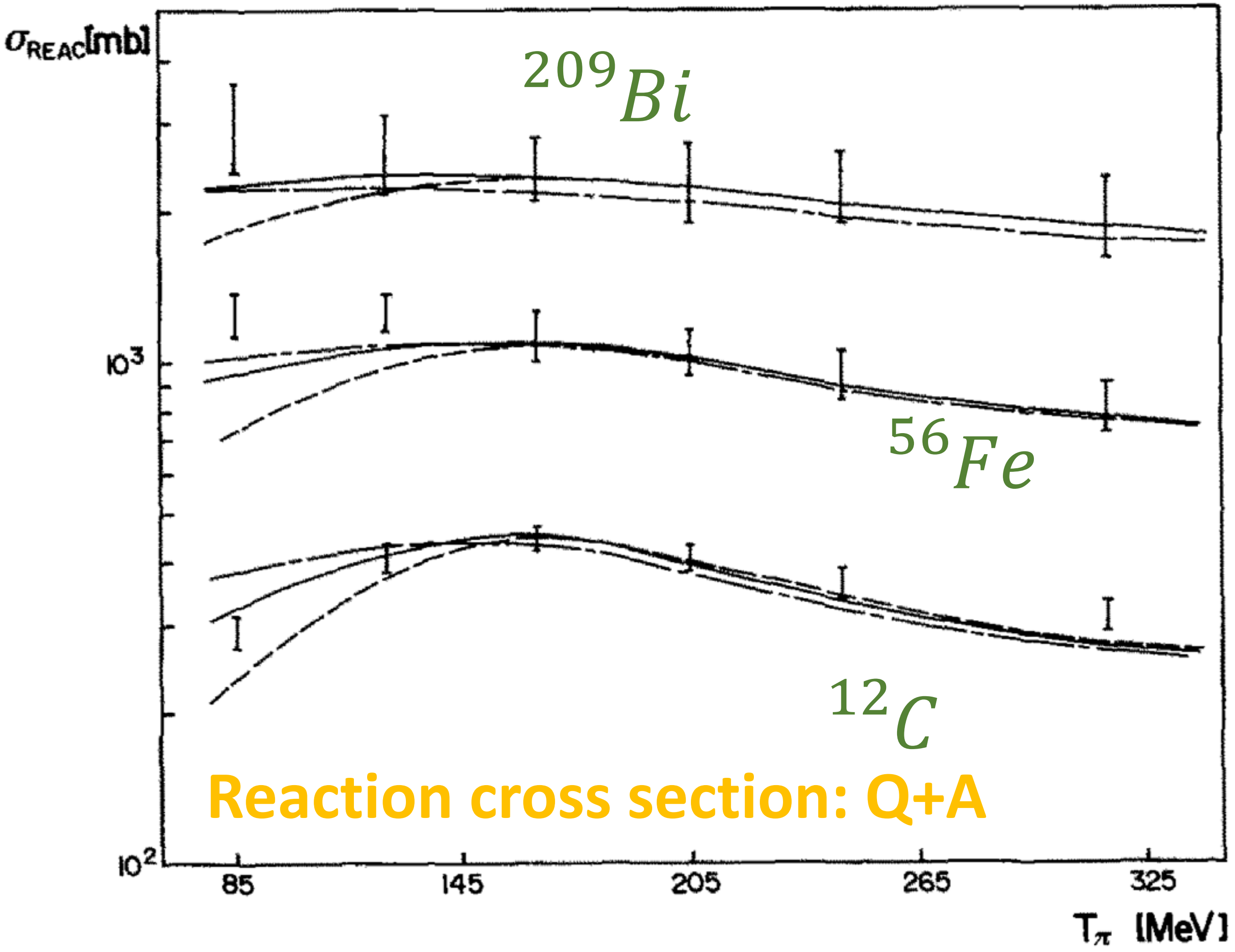
^{56}Fe

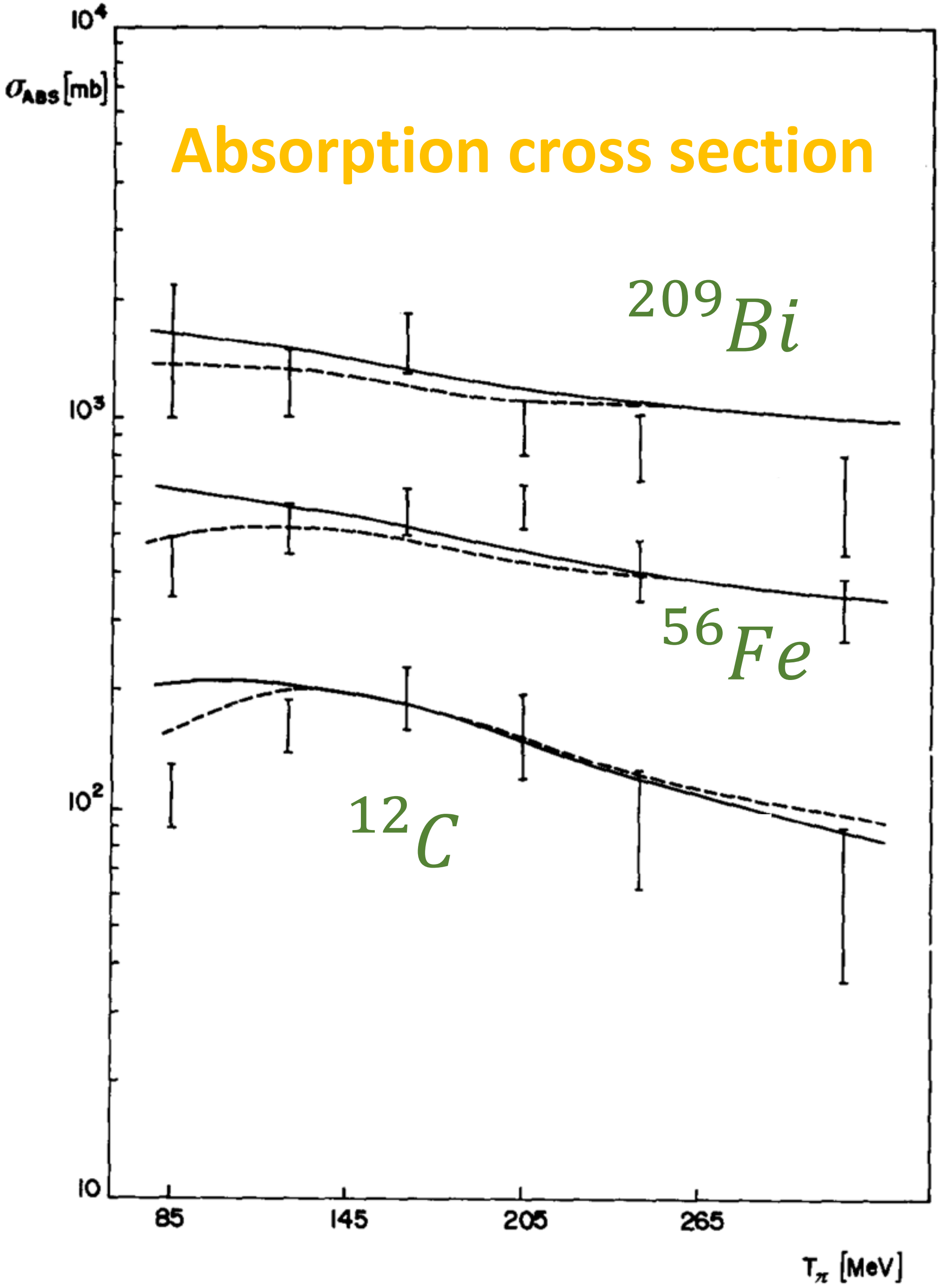
$T_\pi = 165$ MeV

Probability per fm for π QE scattering and absorption as a function of the nuclear radius [NPA484 (1988) 557]

$\pi^\pm$ – nucleus reactions

- $\pi^\pm$ – nucleus reactions
  - ✓ $\pi^\pm A_Z \rightarrow \pi^\pm A_Z$ [elastic]
  - ✓ $\pi^\pm A_Z \rightarrow \pi' X$ [quasielastic]
  - ✓ $\pi^\pm A_Z \rightarrow X$ (no pions) [absorption]

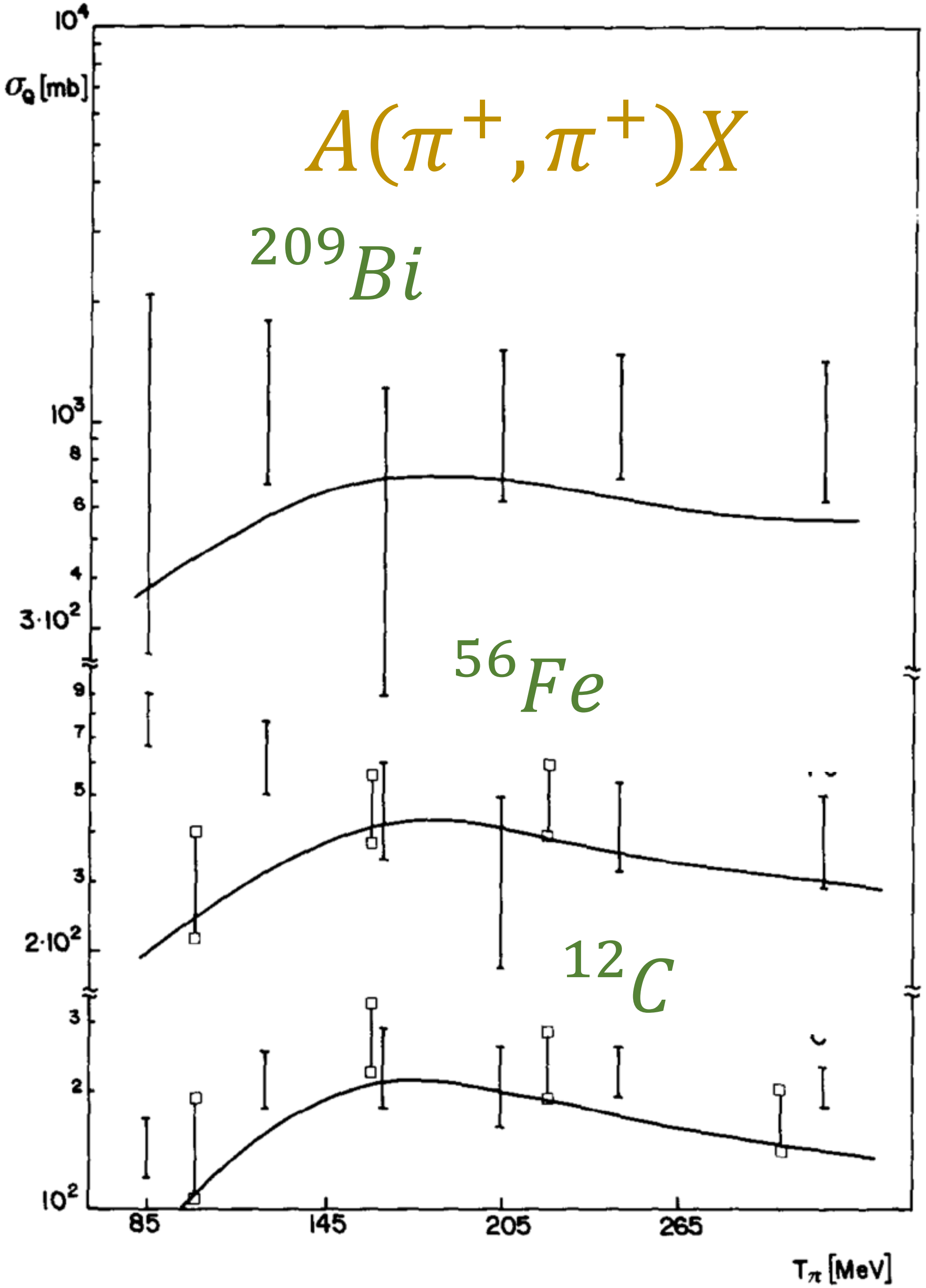


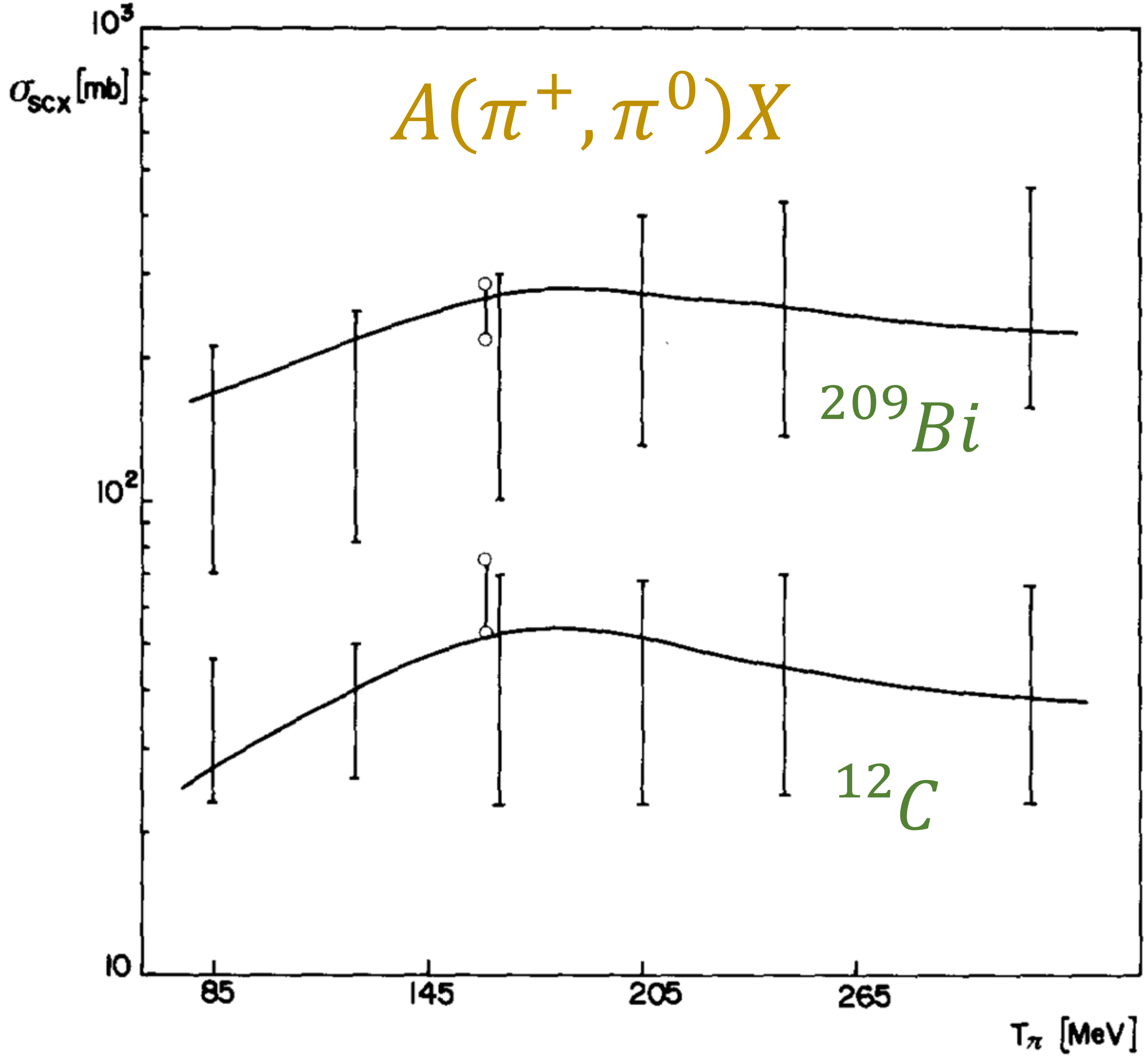


Absorption + Quasielastic= Reaction

Q= pions which have changed either charge, energy or momentum

Juan Nieves, IFIC (CSIC & UV)

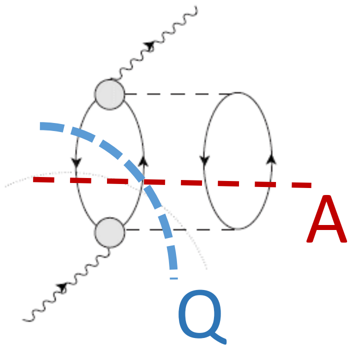

$A(\pi^+,\pi^+)X$
^{209}Bi
^{56}Fe
^{12}C
σ_e [mb]
10^4
10^3
$3 \cdot 10^2$
$2 \cdot 10^2$
10^2
85
145
205
265
T_π [MeV]

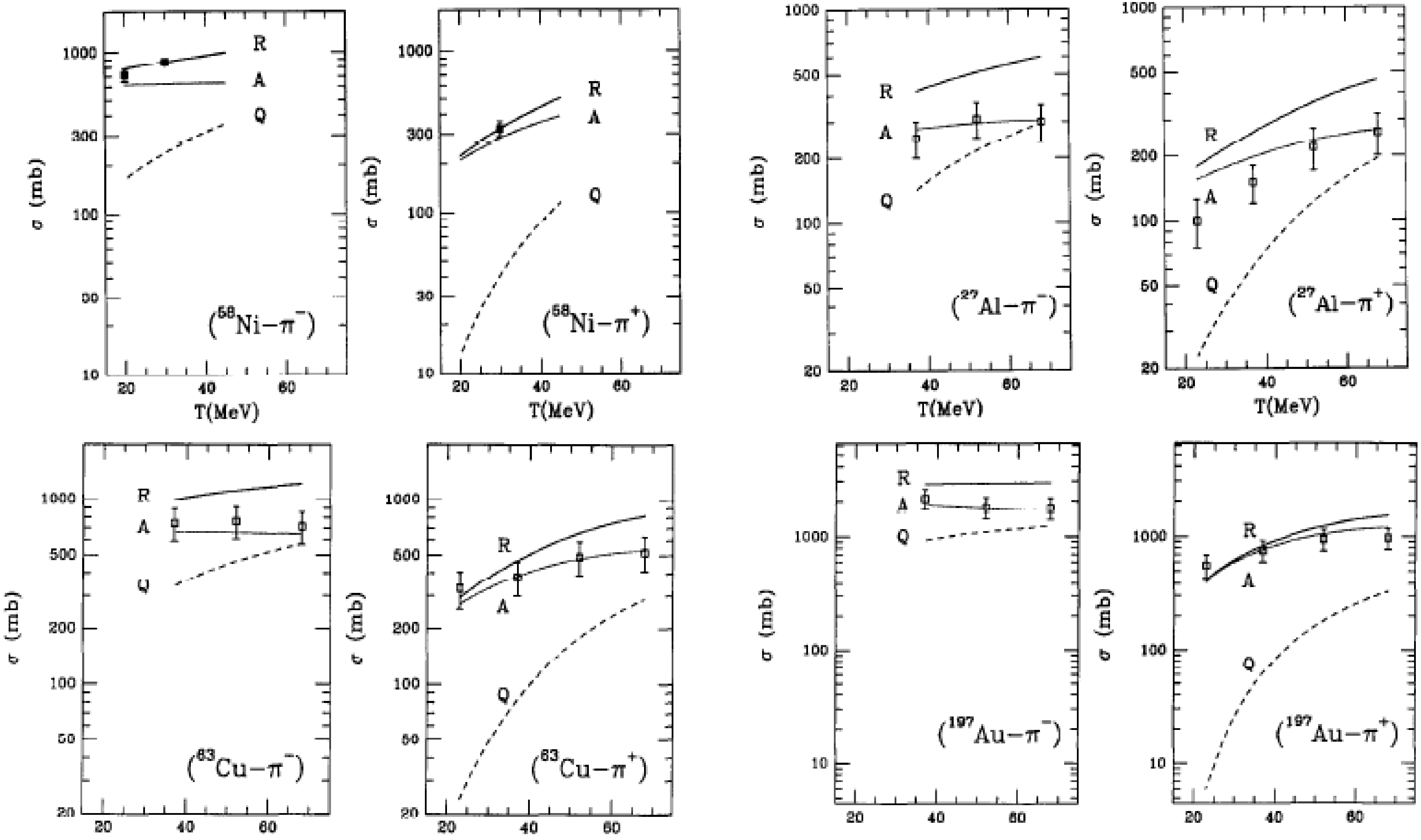

$A(\pi^+,\pi^0)X$
^{209}Bi
^{12}C
σ_{scx} [mb]
10^3
10^2
10
85
145
205
265
T_π [MeV]

[J. Nieves et al., NPA 554 (1993) 554]   Q+R = A

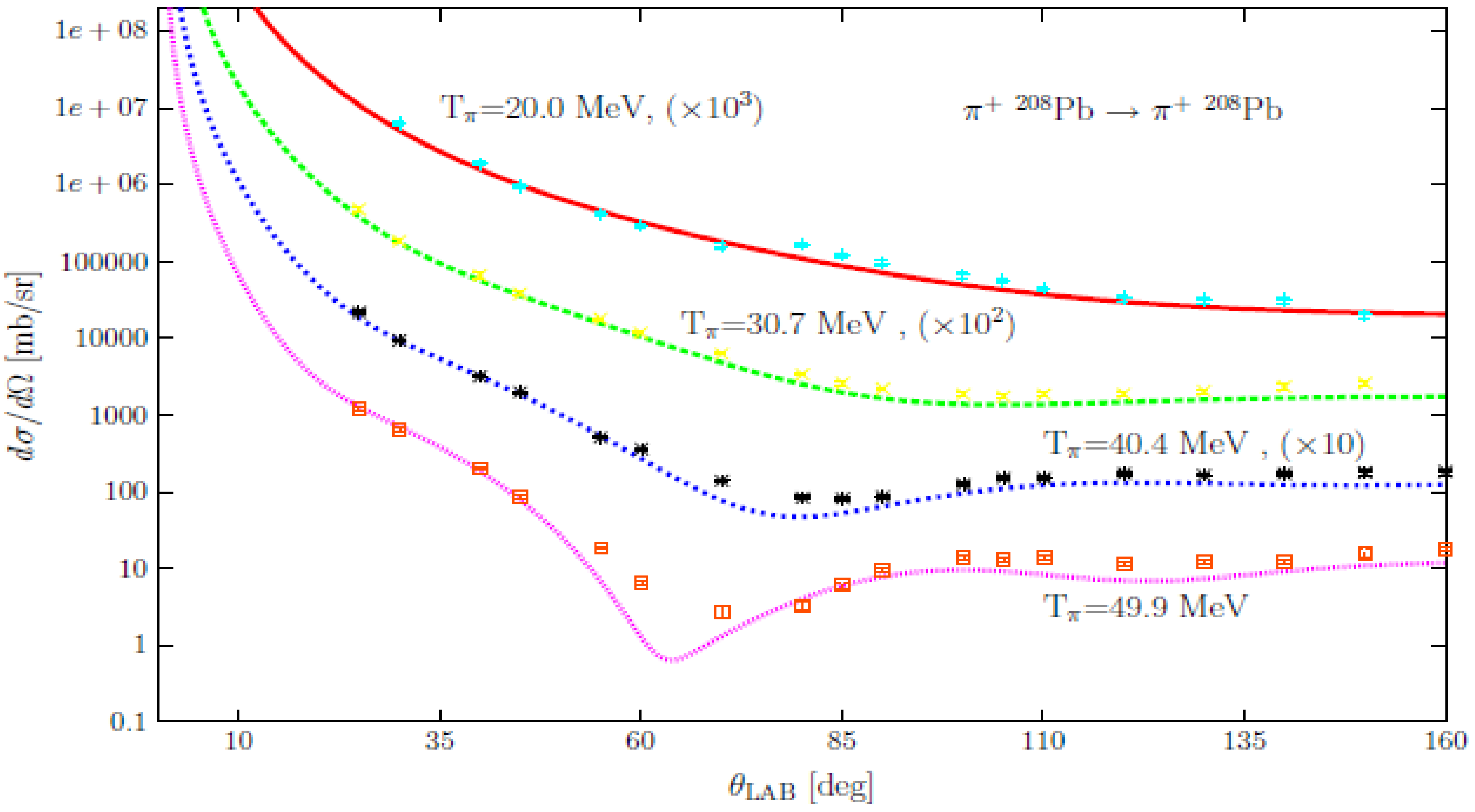
Absorption + Quasielastic= Reaction

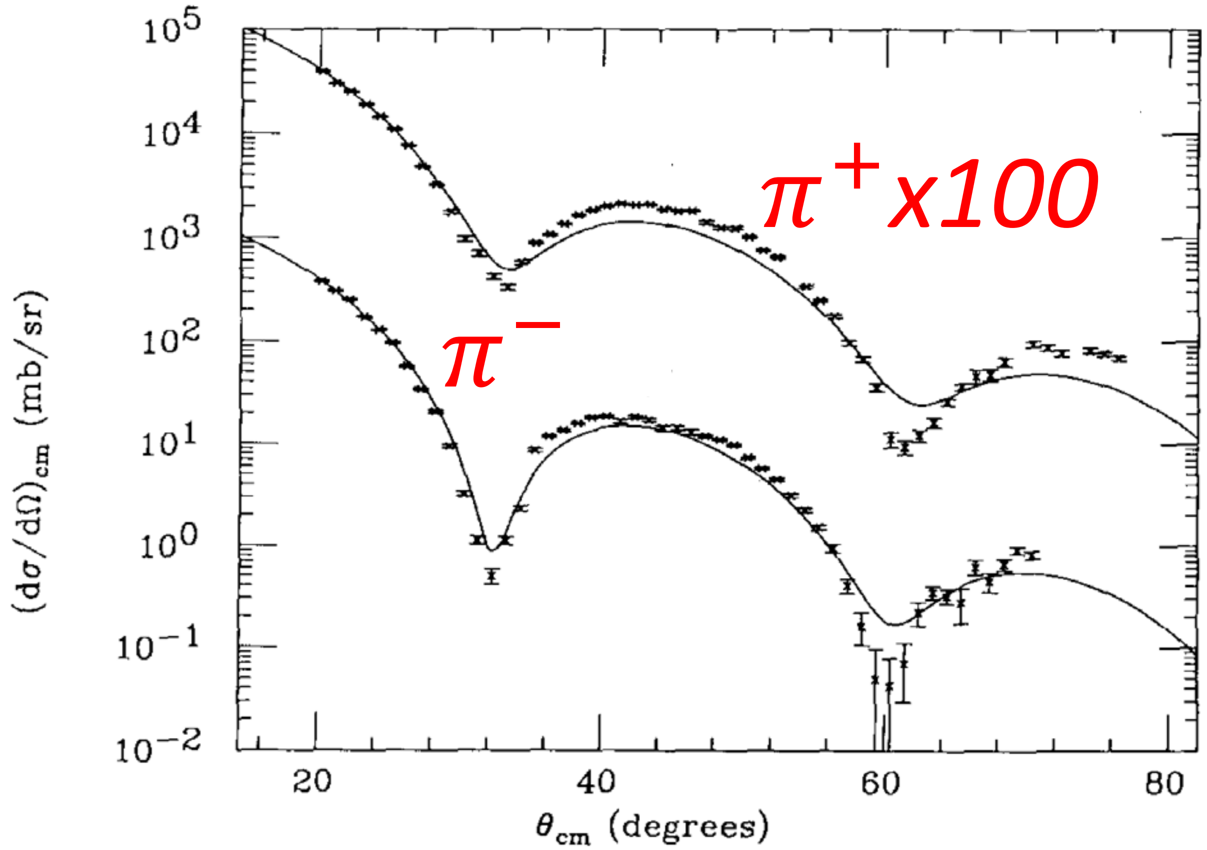
Q= pions which have changed either charge, energy or momentum

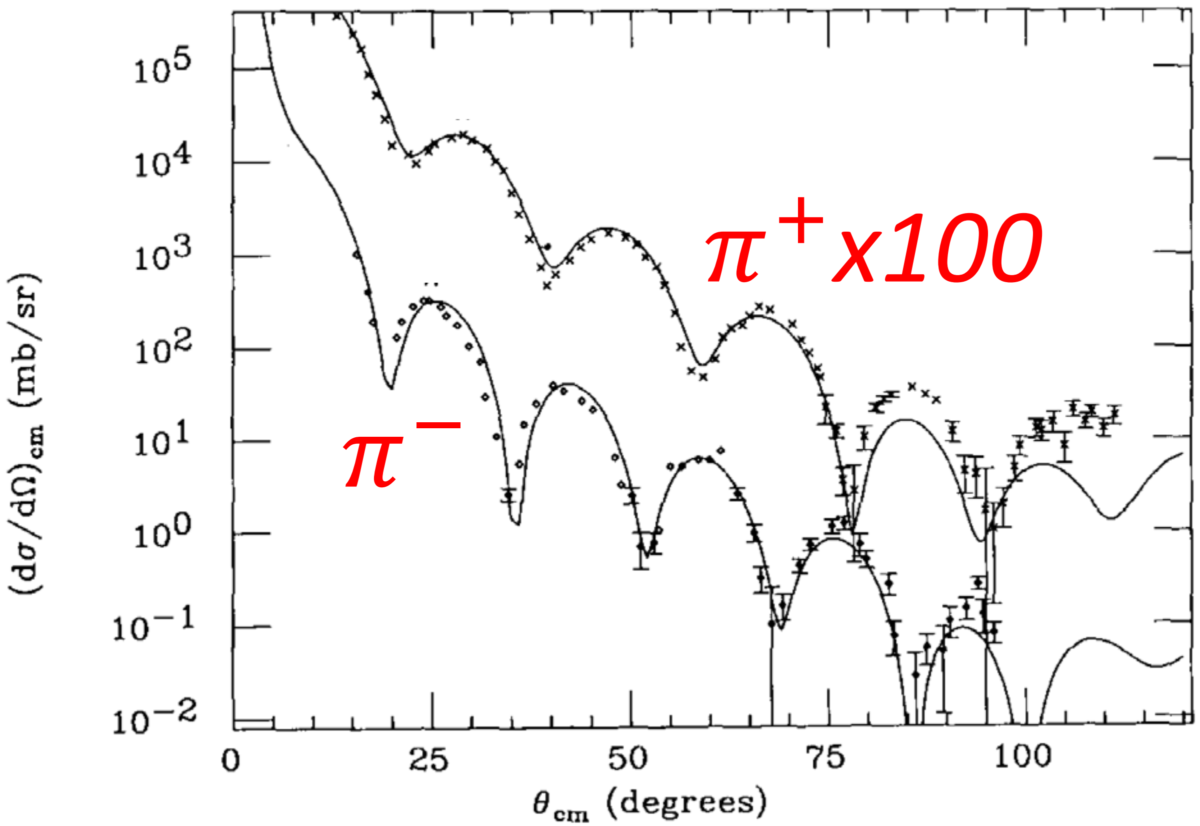




[J. Nieves et al., NPA 554 (1993) 554]





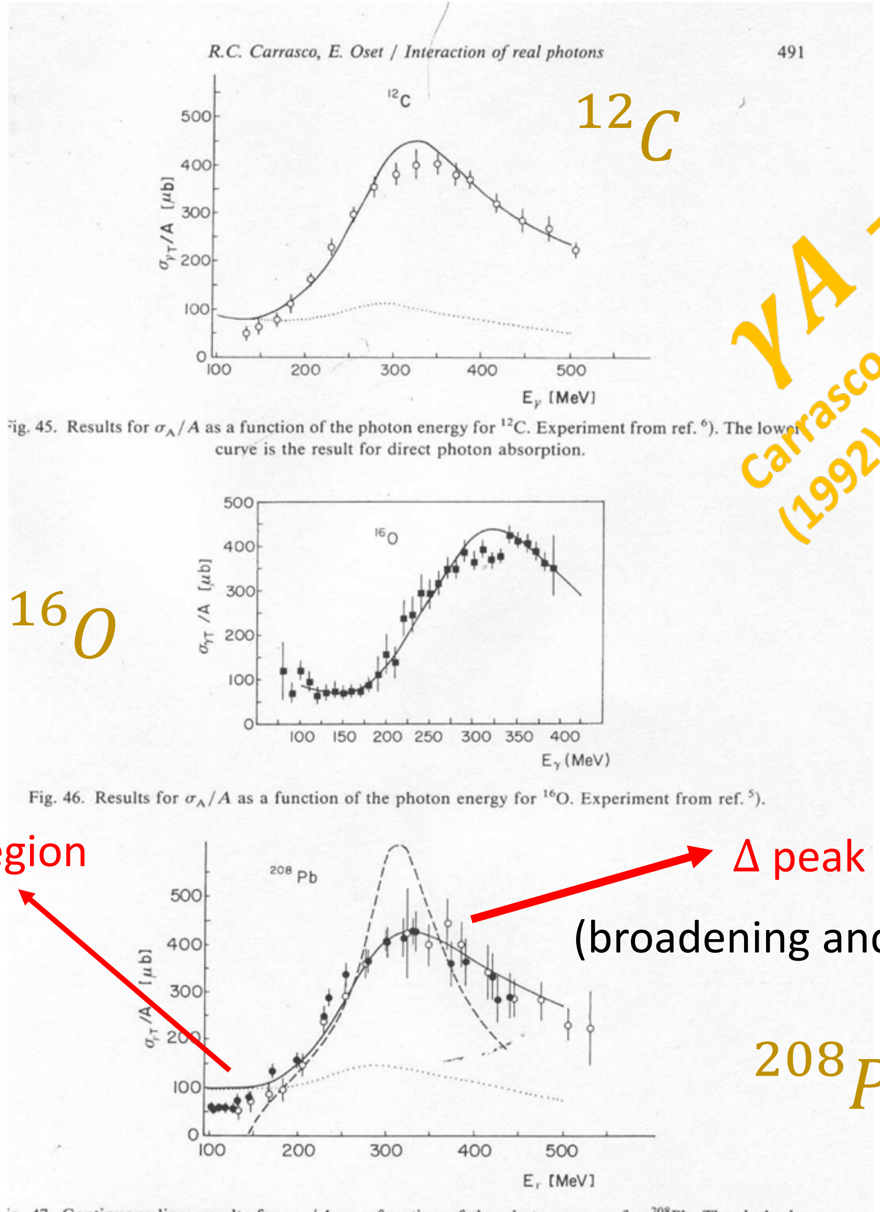


$^{40}Ca, T_\pi = 180$ MeV

$^{208}Pb, T_\pi = 162$ MeV

✓$\pi^\pm A_Z \to \pi^\pm A_Z$ [elastic]

[C. García-Recio et al., NPA 526 (1991) 685]



ig. 45. Results for σ_A/A as a function of the photon energy for ^{12}C. Experiment from ref. [6]). The lower curve is the result for direct photon absorption.

Fig. 46. Results for σ_A/A as a function of the photon energy for ^{16}O. Experiment from ref. [5]).

ig. 47. Continuous line: results for σ_A/A as a function of the photon energy for ^{208}Pb. The dashed ne shows the impulse approximation result $(Z\sigma_{\gamma p}+N\sigma_{\gamma n})/A$ for comparison. The dotted line is the esult for direct photon absorption. Experimental data: dark dots from ref. [3]), while dots from ref. [6]).

$\gamma A \to X$

Carrasco+Oset, NPA 536 (1992) 445

$$\frac{d^2\sigma}{d\Omega dp}$$

Carrasco+Oset+Salcedo, NPA 541 (1992) 583

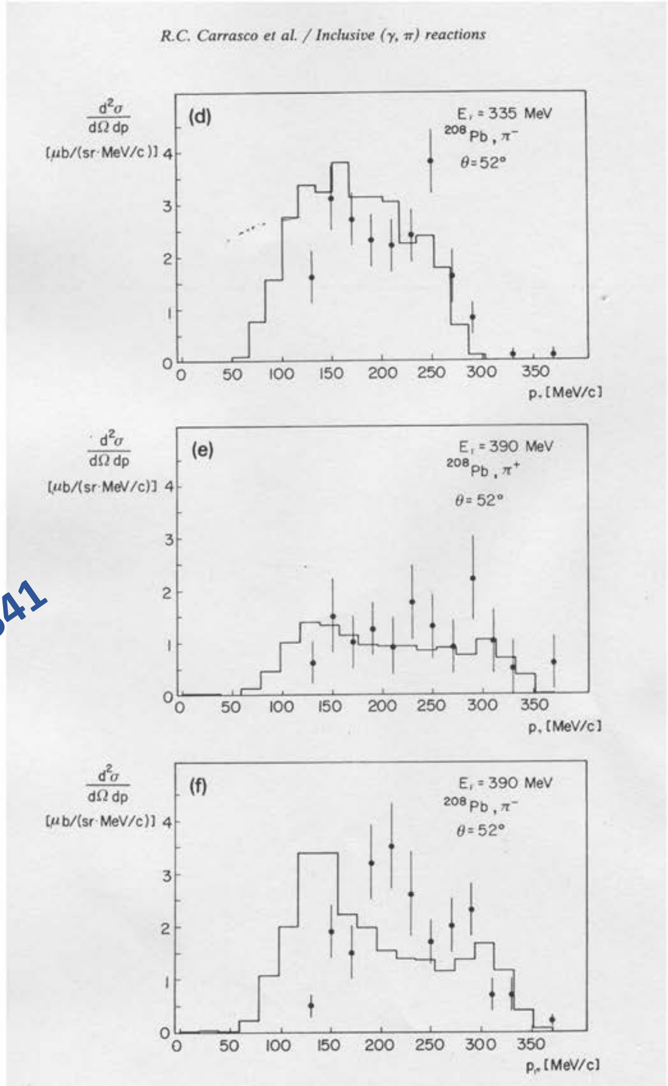
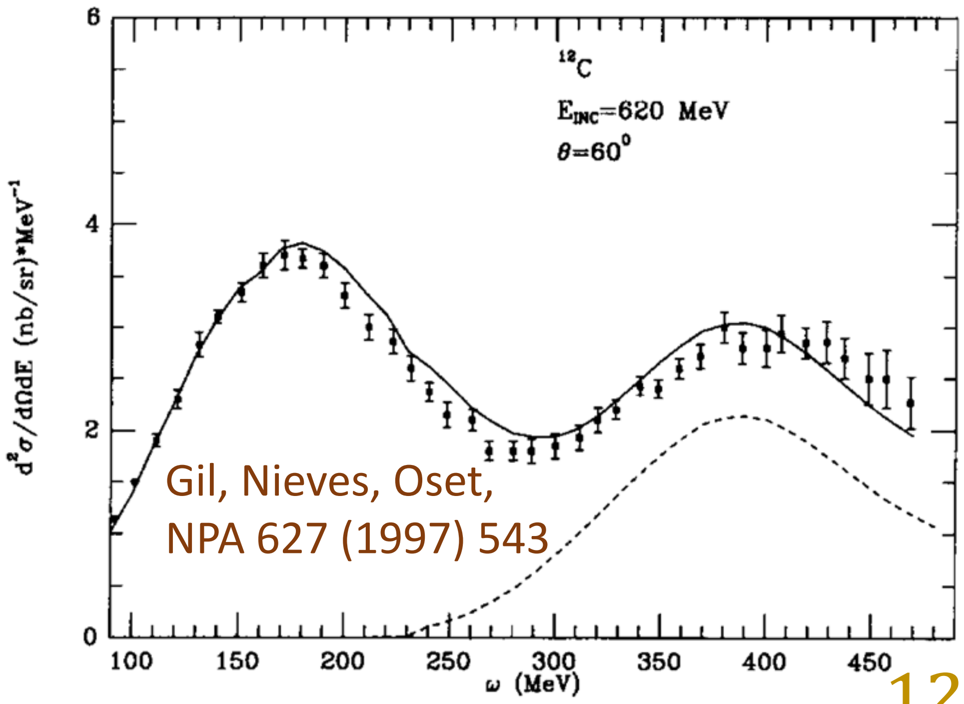


Fig. 17—continued.

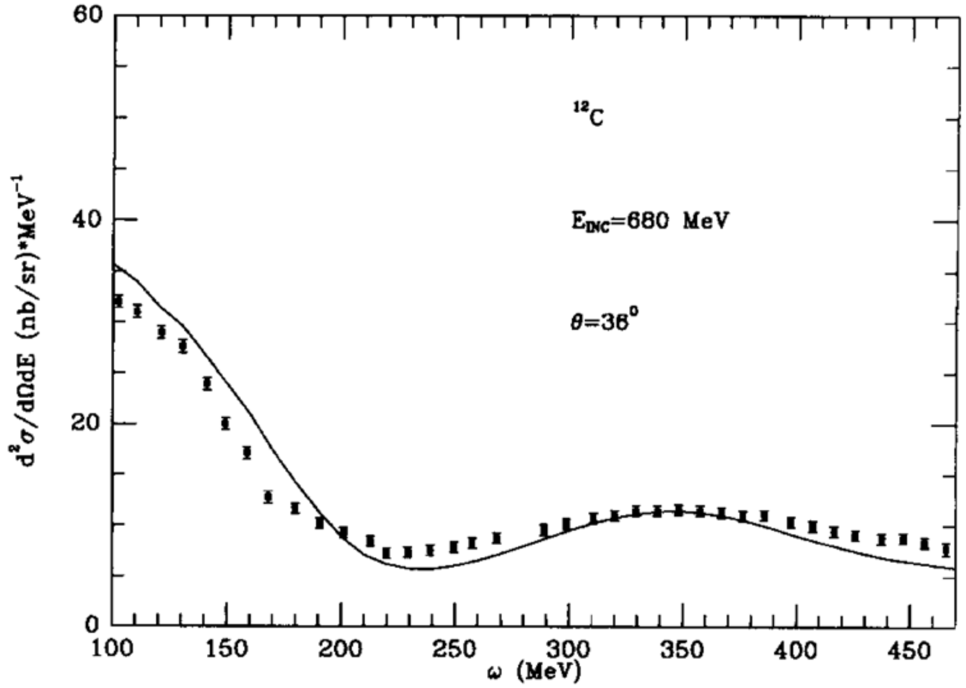
$$\gamma + {}^{208}\text{Pb} \to X + \pi^{\pm}$$

Juan Nieves, IFIC (CSIC & UV)

Juan Nieves, IFIC (CSIC & UV)



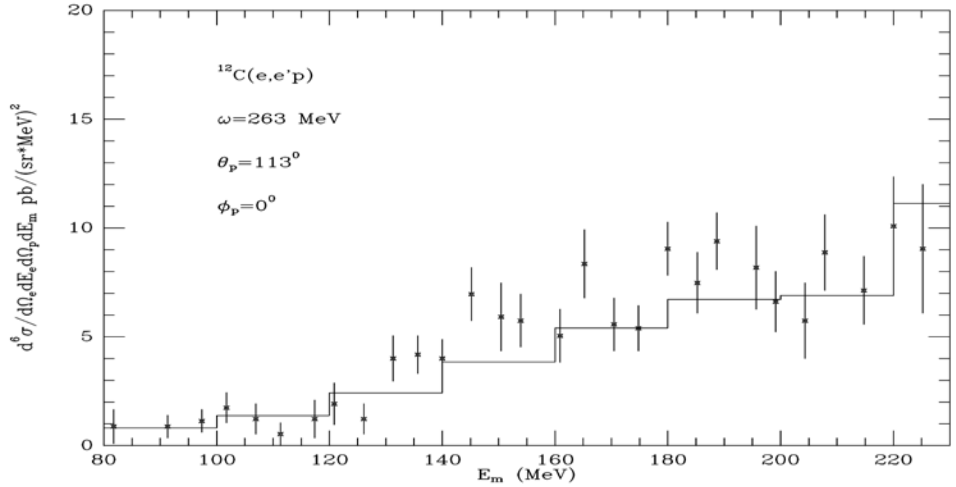
Gil, Nieves, Oset,
NPA 627 (1997) 543



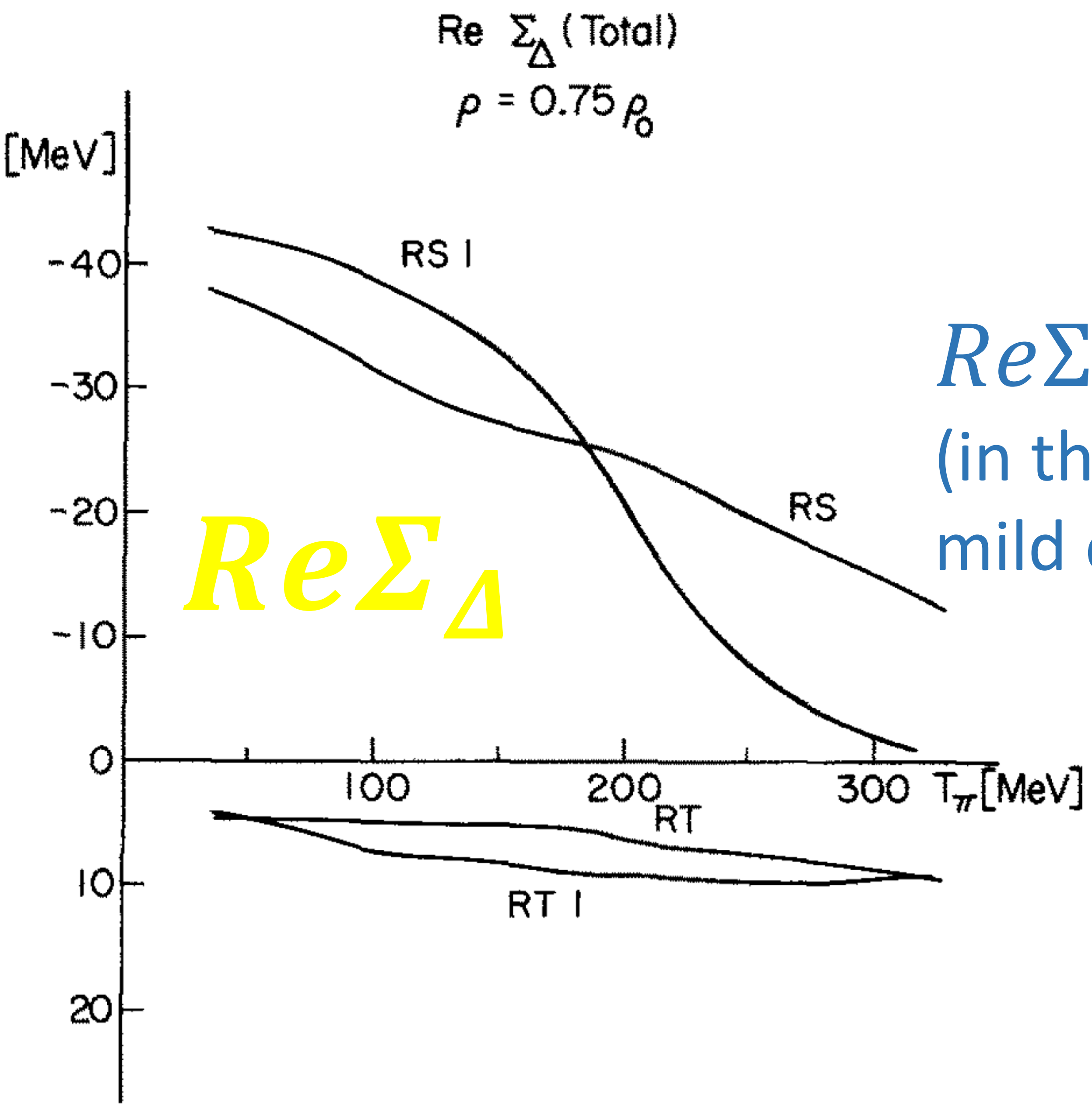
$^{12}C\,(e,e'X)$

and by means of a Monte Carlo simulation we obtain cross sections for the processes $(e,e'N)$, $(e,e'NN)$, $(e,e'\pi)$, ...

Gil, Nieves, Oset,
NPA 627 (1997) 599



$^{12}C\,(e,e'p)$



$$\Sigma(k) = \Sigma_0(k) + \Sigma_2(k)(3S^\dagger \cdot \hat{k} S \cdot \hat{k} - 1)$$

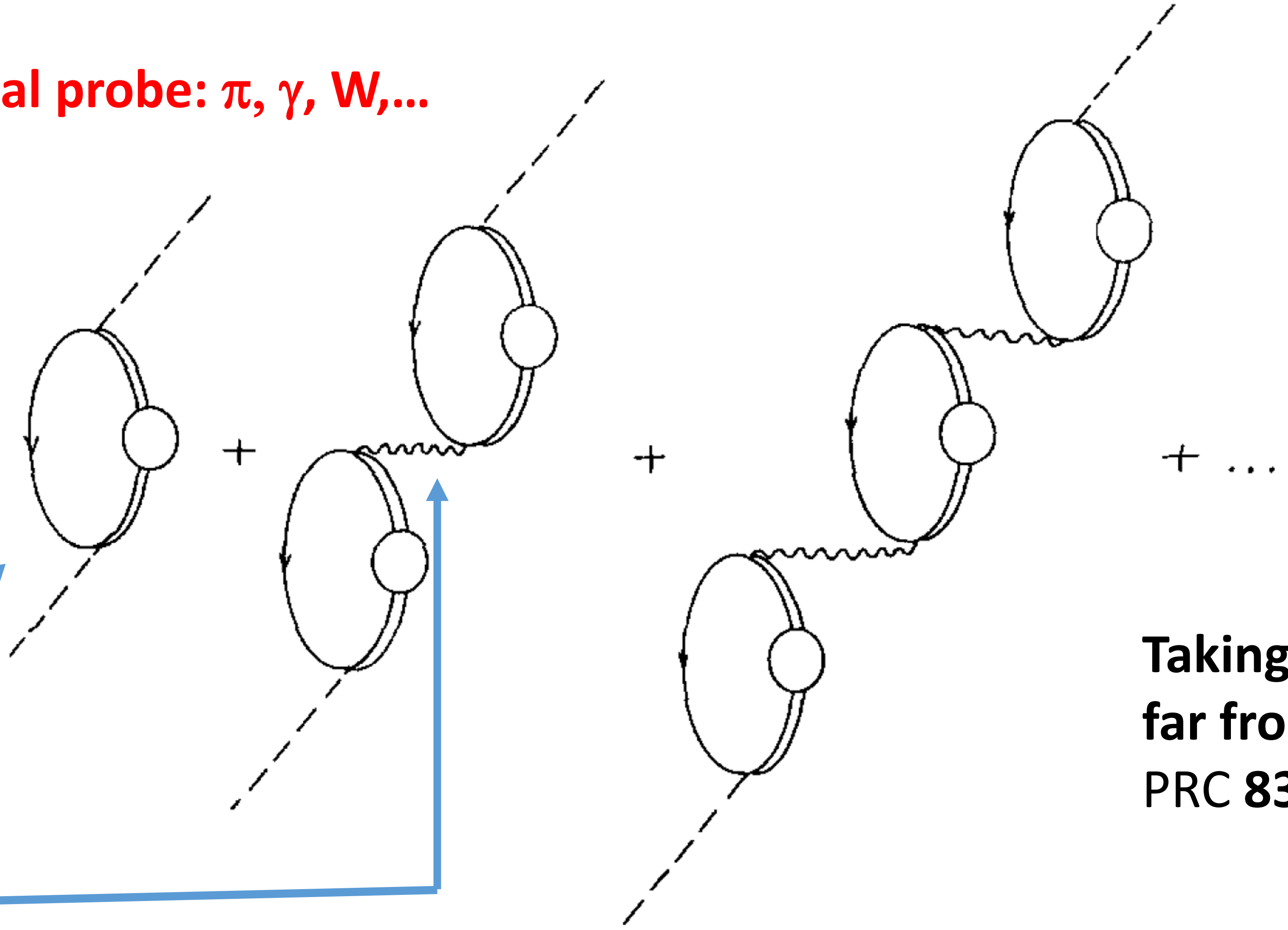
tensor contribution small

$Re\Sigma_\Delta \approx -33\ \rho/\rho_0$ MeV

(in the resonance region, though it has a mild energy dependence)

… but more important: RPA re-summation changes also the position of the Δ peak!

external probe: π, γ, W,…

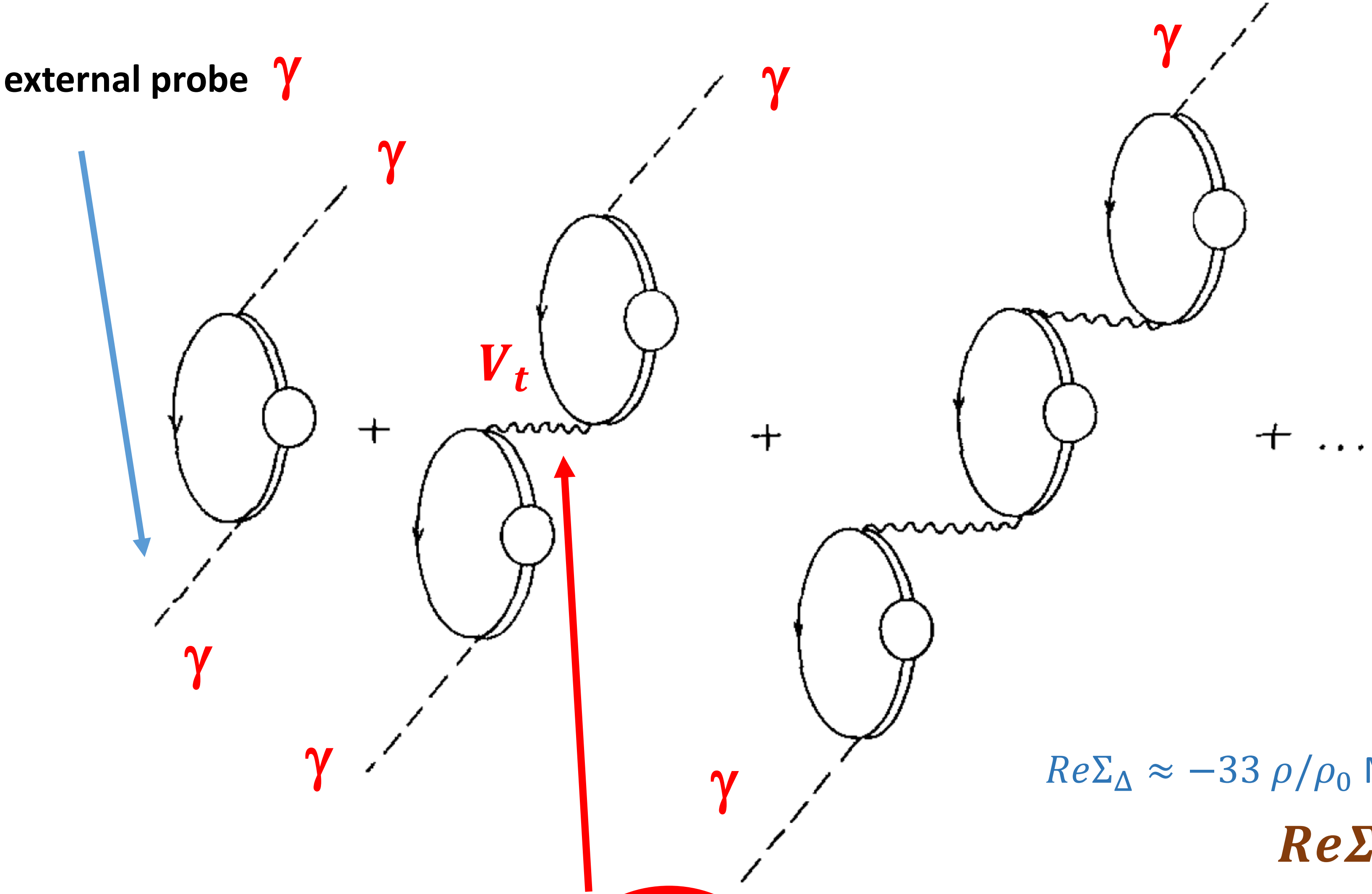


Taking into account these effects is far from being trivial for neutrinos!

PRC **83**, 045501 (2011)

$$W_{ij}^{\sigma\tau}(q) = \frac{V_l(q)}{1-U(q)V_l(q)}\,\hat{q}_i\hat{q}_j + \frac{V_t(q)}{1-U(q)V_t(q)}\left(\delta_{ij} - \hat{q}_i\hat{q}_j\right)$$

Effective baryon-baryon interaction in the medium



If the external probe is transversal, for instance a real photon γ

the transverse part V_t of the interaction is selected

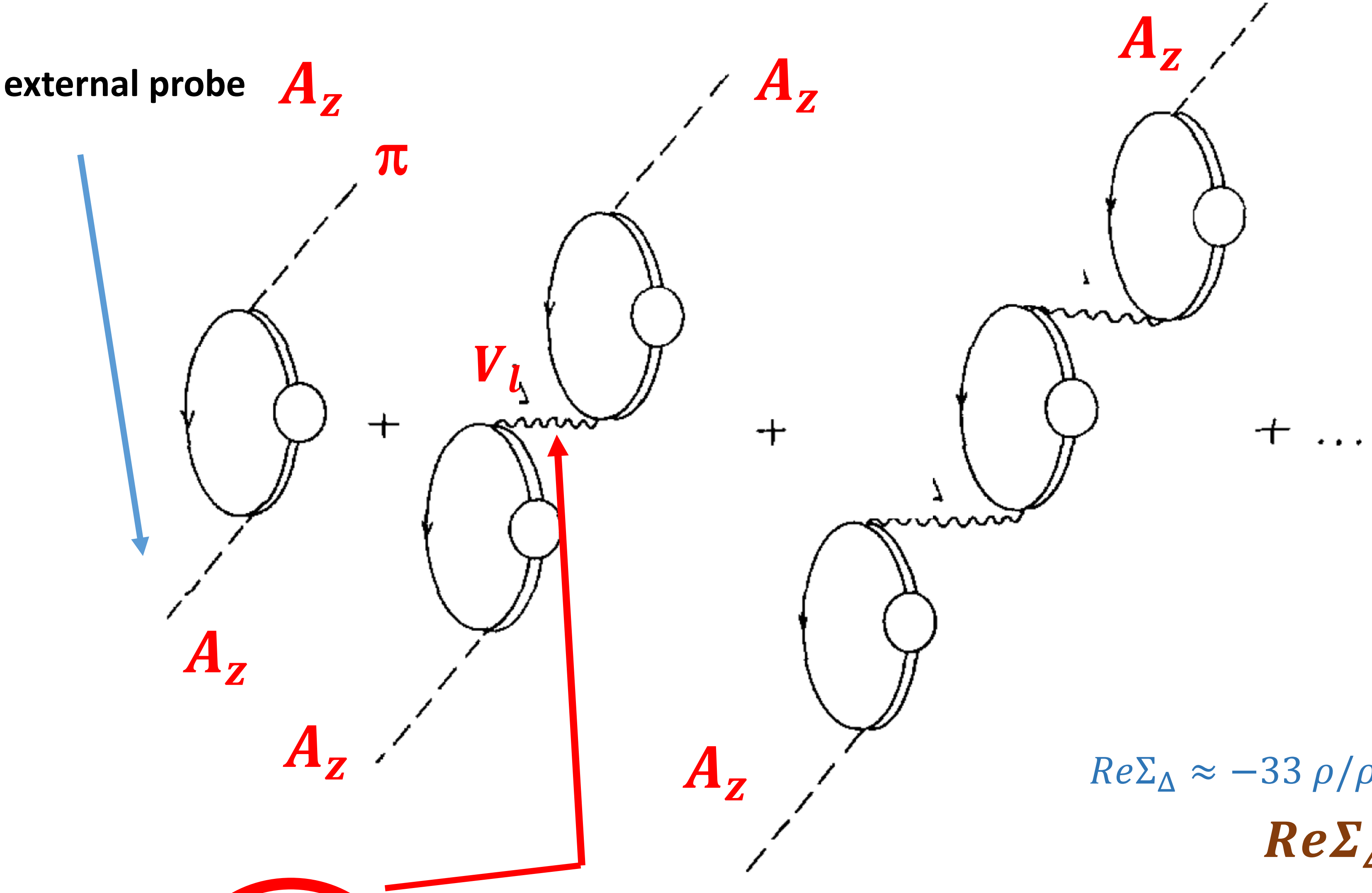
$Re\Sigma_\Delta \approx -33\ \rho/\rho_0$ MeV

$$\boldsymbol{Re\Sigma_\Delta \rightarrow Re\Sigma_\Delta + \frac{4}{9}\left(\frac{f^*}{m_\pi}\right)^2 V_t \rho}$$

$$\approx 40\ \rho/\rho_0 \text{ MeV}$$

$$W_{ij}^{\sigma\tau}(q) = \frac{V_l(q)}{1-U(q)V_l(q)}\ \hat{q}_i\hat{q}_j + \frac{V_t(q)}{1-U(q)V_t(q)}\left(\delta_{ij} - \hat{q}_i\hat{q}_j\right)$$

Effective baryon-baryon interaction in the medium



If the external probe is longitudinal, for instance the longitudinal part of the axial current, A_z or a π

⇓

the transverse part V_l of the interaction is selected

$Re\Sigma_\Delta \approx -33\, \rho/\rho_0$ MeV

$$Re\Sigma_\Delta \rightarrow Re\Sigma_\Delta + \frac{4}{9}\left(\frac{f^*}{m_\pi}\right)^2 V_l\, \rho$$

$$\approx \pm 25\, \rho/\rho_0 \text{ MeV}$$

strong q^2 dependence, the overall sign is even not fixed!

$$W_{ij}^{\sigma\tau}(q) = \frac{V_l(q)}{1-U(q)V_l(q)}\, \hat{q}_i\hat{q}_j + \frac{V_t(q)}{1-U(q)V_t(q)}\, (\delta_{ij} - \hat{q}_i\hat{q}_j)$$

Effective baryon-baryon interaction in the medium

NN potential $V(q) = c_0\{f_0(\rho) + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2\} + \vec{\tau}_1\vec{\tau}_2 \sum_{i,j=1}^{3} \sigma_1^i \sigma_2^j V_{ij}^{\sigma\tau}$

zero range Landau force
J. Speth et al., Phys. Rep. 33 (1977) 127

$$V_{ij}^{\sigma\tau} = (\hat{q}_i\hat{q}_j V_l(q) + (\delta_{ij} - \hat{q}_i\hat{q}_j)V_t(q))$$

with $\hat{q}_i = {}^{q_i}/_{|\vec{q}|}$

V_π

$$V_l(q^0,\vec{q}) = \frac{f^2}{m_\pi^2}\left\{\left(\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2}\right)^2 \frac{\vec{q}^2}{q^2 - m_\pi^2} + g_l'(q)\right\},$$

$$\frac{f^2}{4\pi} = 0.08,\ \Lambda_\pi = 1200\ \text{MeV},$$

V_ρ

$$V_t(q^0,\vec{q}) = \frac{f^2}{m_\pi^2}\left\{C_\rho\left(\frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - q^2}\right)^2 \frac{\vec{q}^2}{q^2 - m_\rho^2} + g_t'(q)\right\},$$

$$C_\rho = 2,\ \Lambda_\rho = 2500\ \text{MeV},\ m_\rho = 770\ \text{MeV}.$$

SRC

The $N\Delta$ and the $\Delta\Delta$ potentials are obtained from V_l and V_t by replacing

$$\vec{\sigma} \to \vec{S},\ \vec{\tau} \to \vec{T}.$$

$$f \to f^*$$

For neutrinos, external probe $W^{\pm}, Z$, the RPA sum CAN NOT be accounted for by an overall change of the real part of the Δ propagator. One needs to split the hadron tensor into components and depending of its nature (longitudinal or transverse) use the appropriate replacement:

$$Re\Sigma_\Delta \rightarrow Re\Sigma_\Delta + \frac{4}{9}\left(\frac{f^*}{m_\pi}\right)^2 V_t\,\rho$$

$$Re\Sigma_\Delta \rightarrow Re\Sigma_\Delta + \frac{4}{9}\left(\frac{f^*}{m_\pi}\right)^2 V_t\,\rho$$

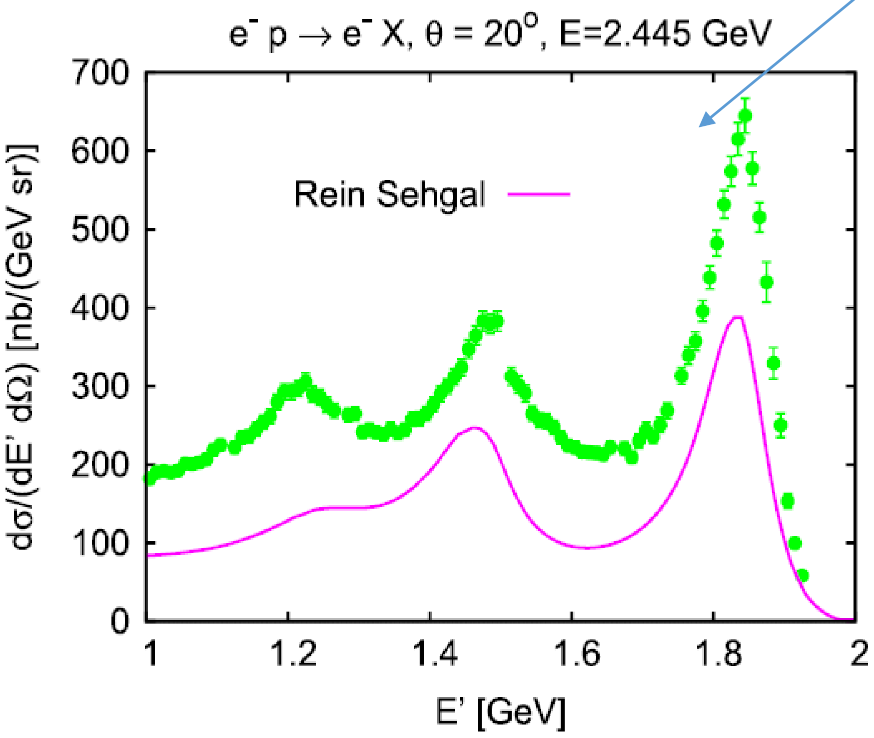
PRC **83**, 045501 (2011)

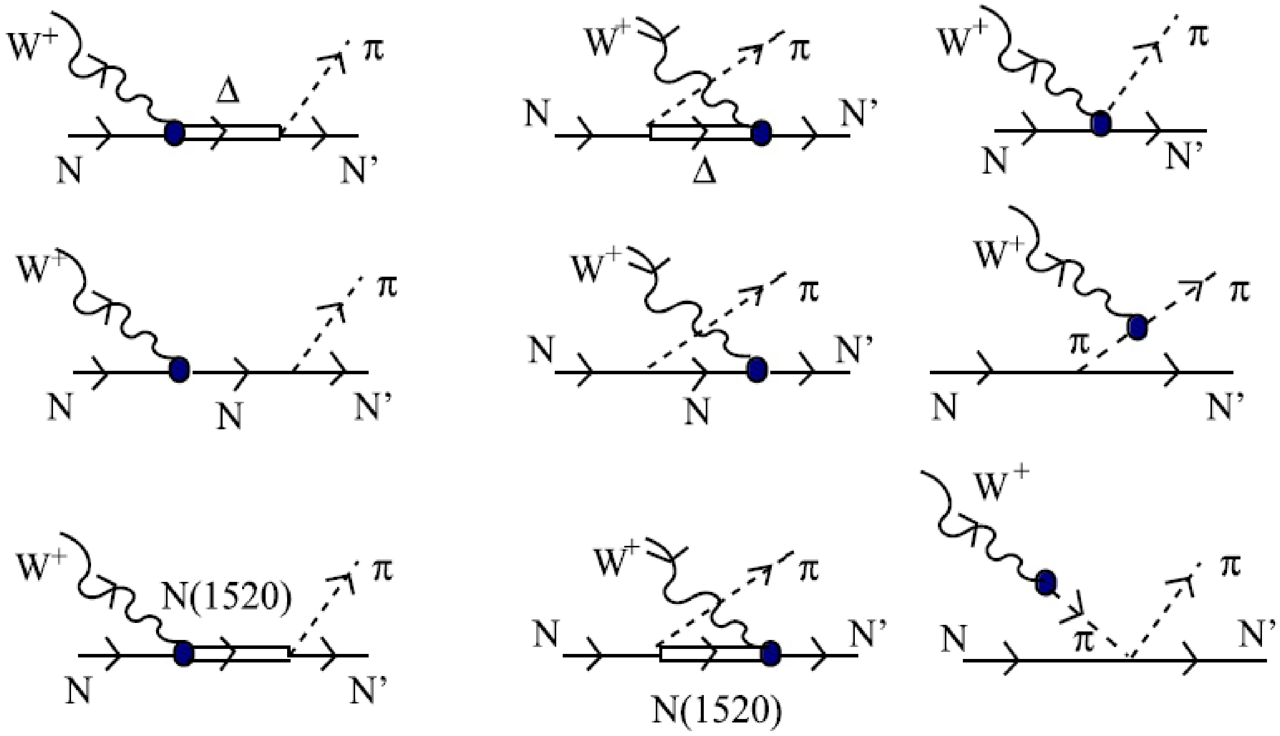
$$\Pi_{W,Z}(q^0, \vec{q};\ \rho) \propto \frac{1}{\sqrt{s} - M_\Delta + i\Gamma_\Delta(s)/2 - Re\Sigma_\Delta(s;\rho) - iIm\Sigma_\Delta(s;\rho)} + \text{RPA}$$

0 0

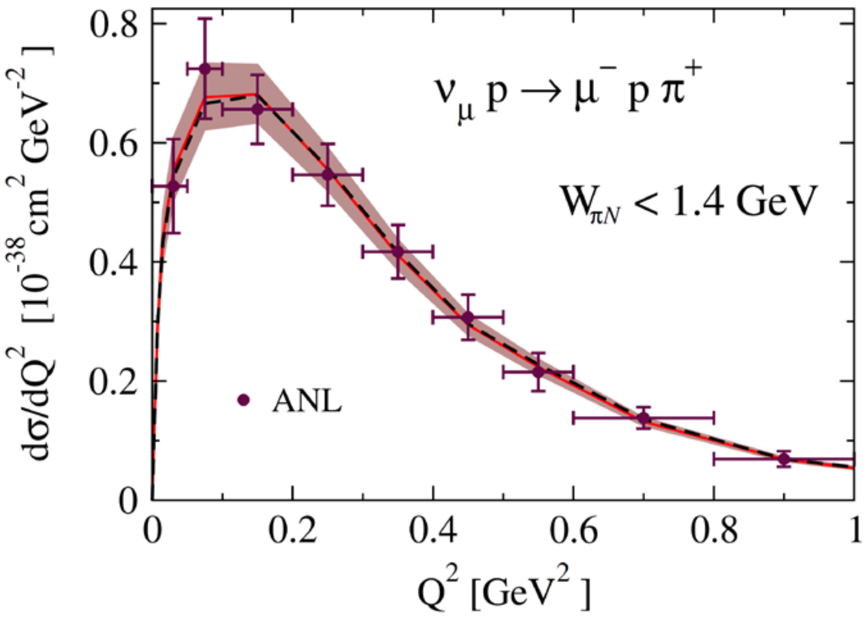
Neutrino Resonance Production

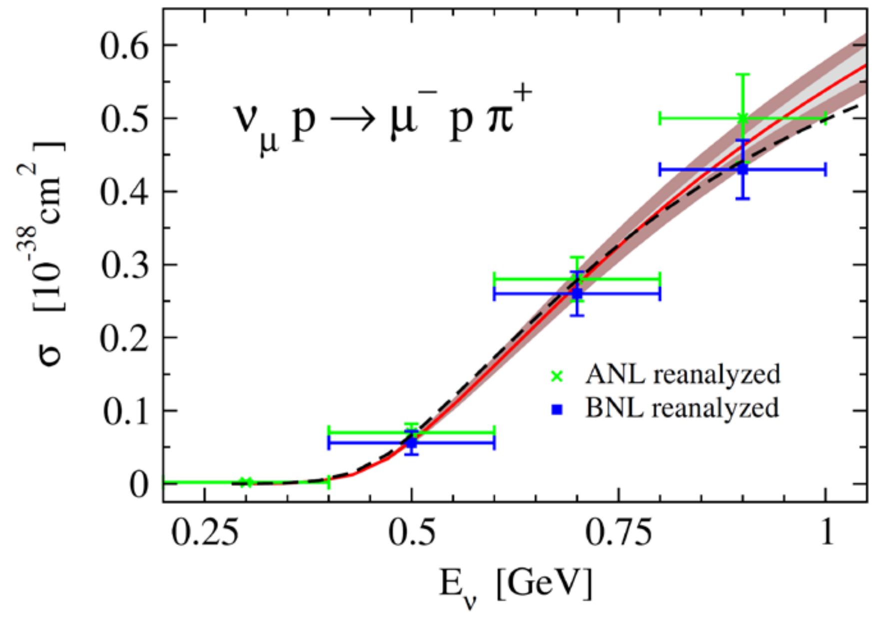
Deficiencies of the Rein Sehgal model! $\Rightarrow$ **Improved models**



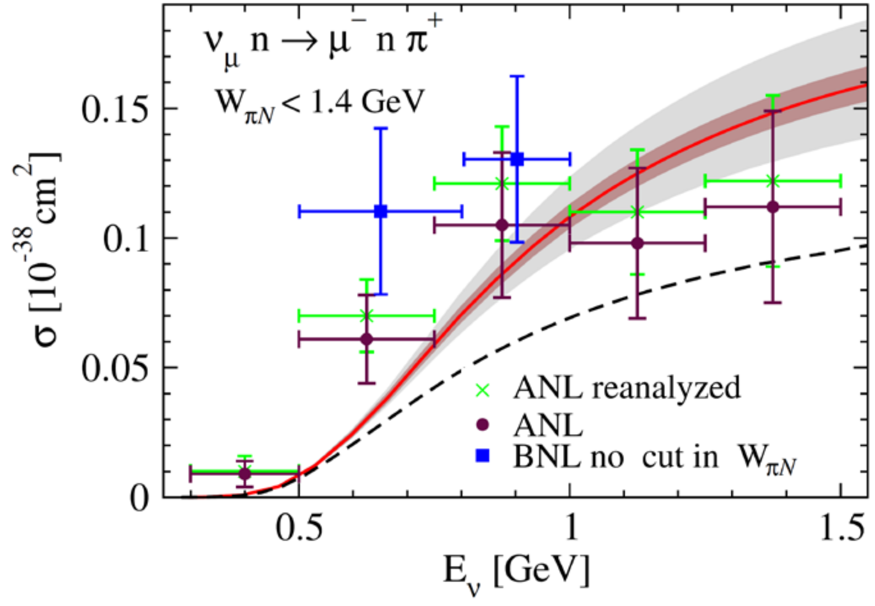


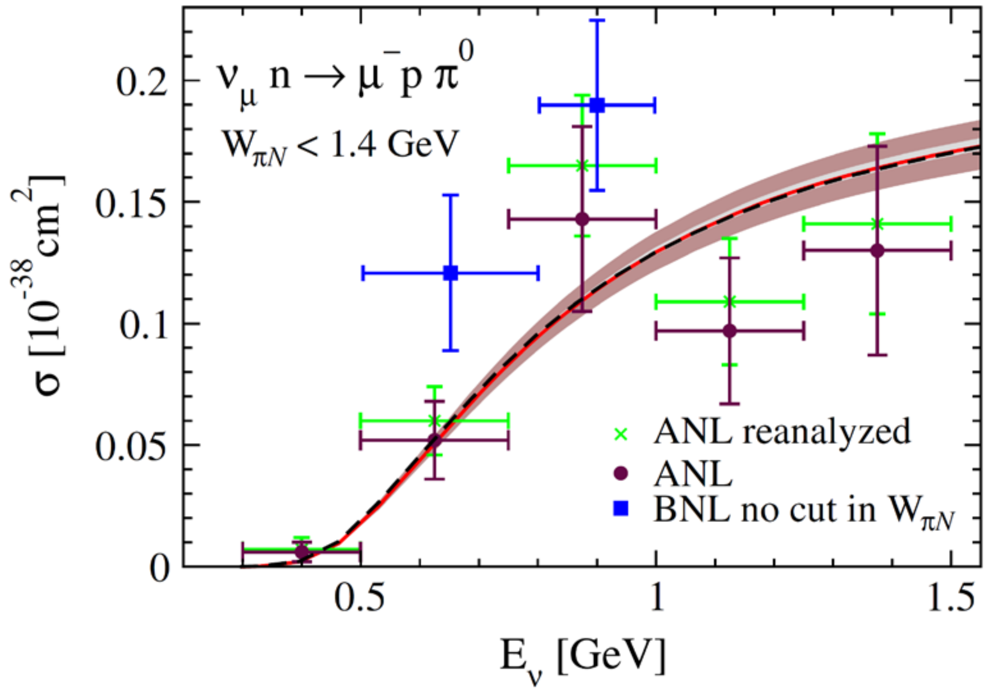
Electron data $\Rightarrow$ Resonance vector form factors !
PCAC $\Rightarrow$ Resonance axial form factors !
Background: chiral symmetry (when possible !)

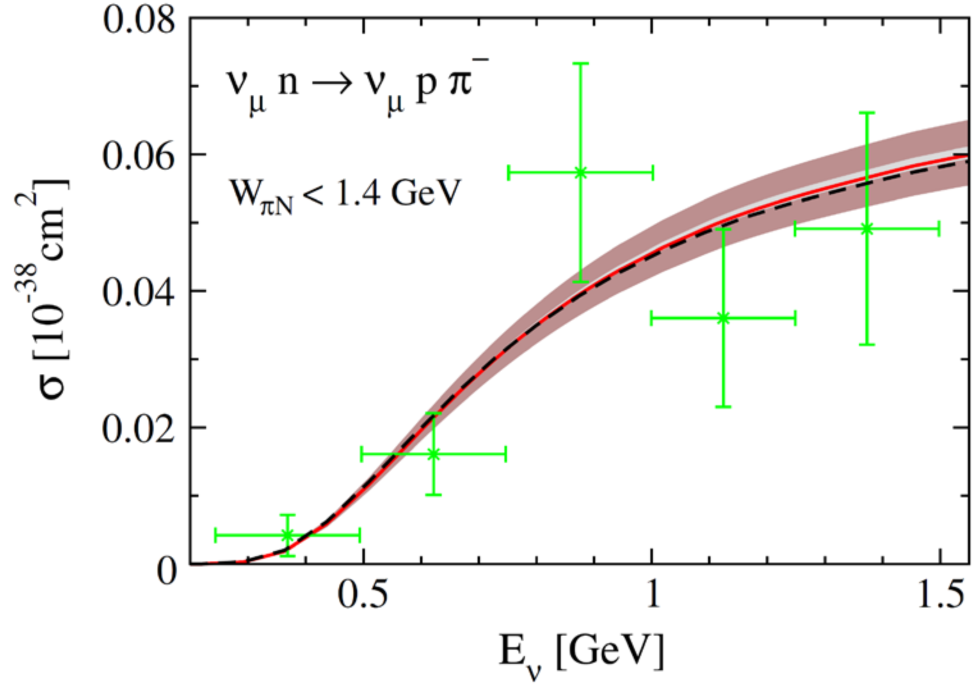




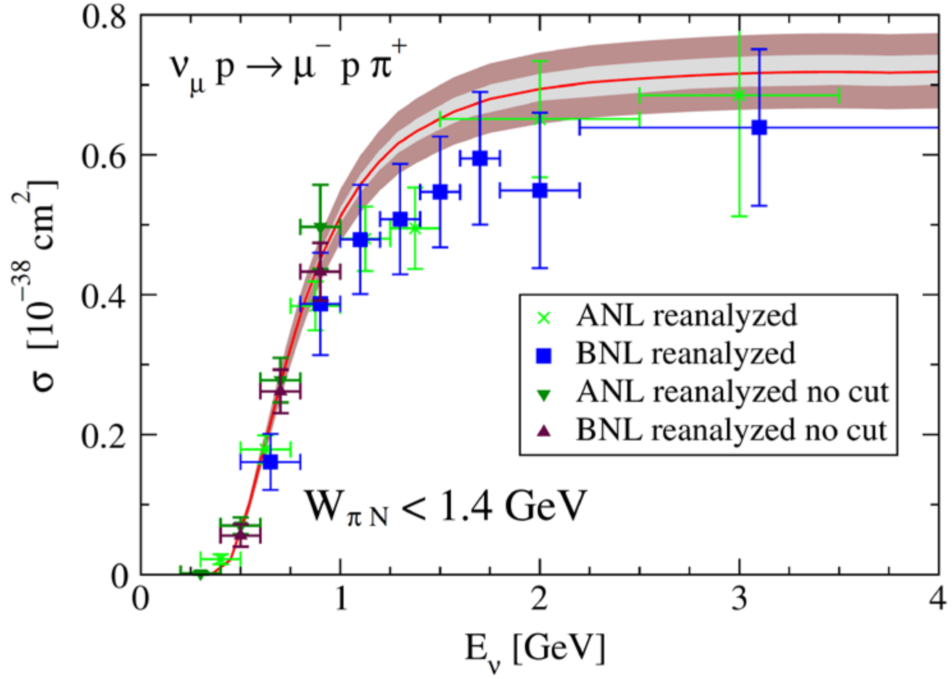
Watson's theorem
deuterium effects
local terms in Δ
propagator
(see Hernandez's
talk)



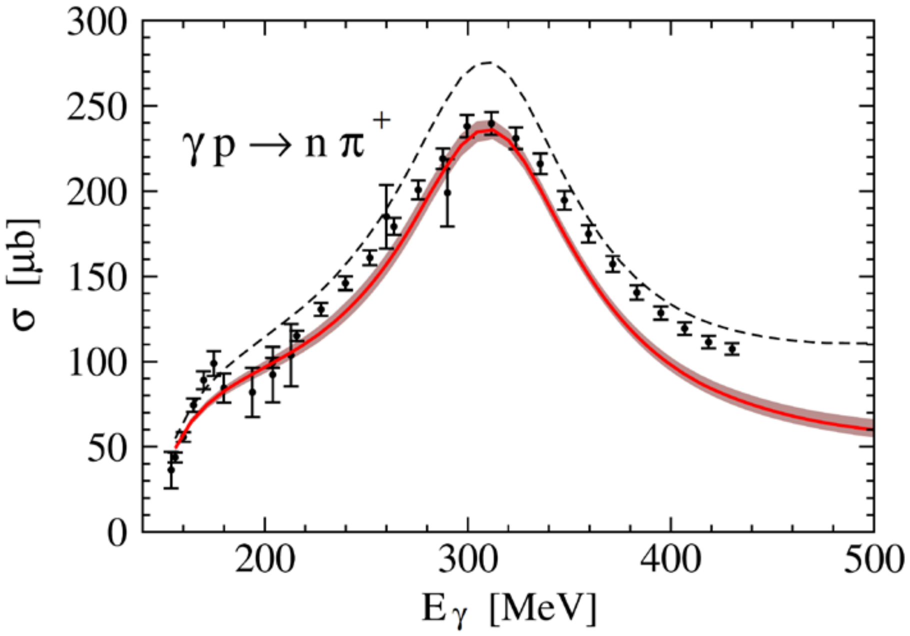


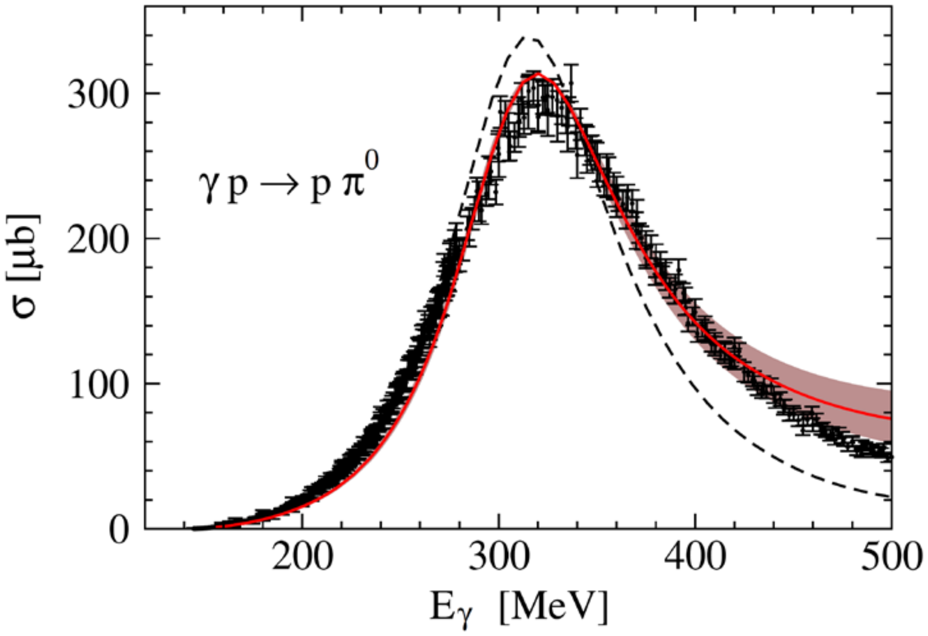


Watson's theorem
deuterium effects
local terms in Δ propagator
(see Hernandez's talk)

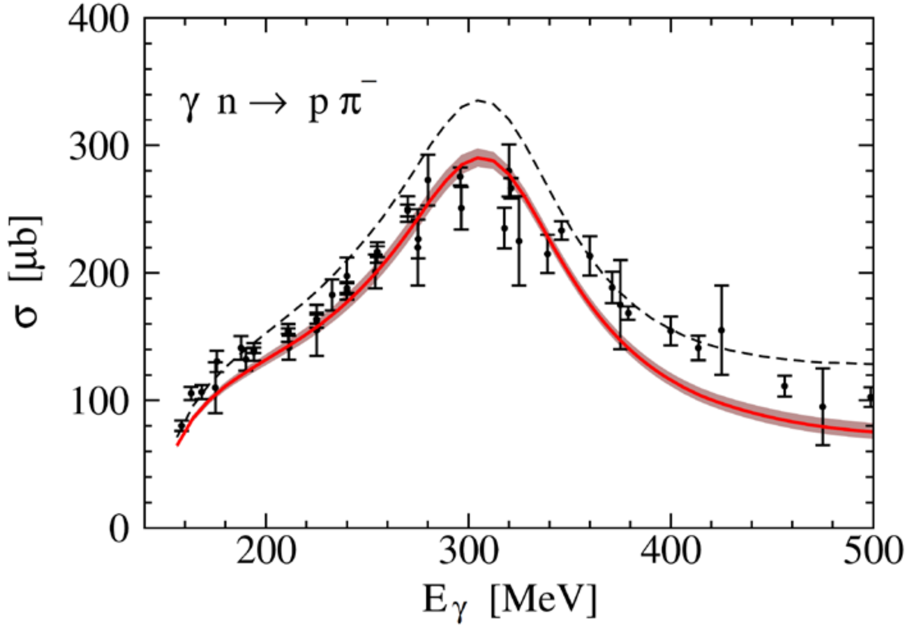


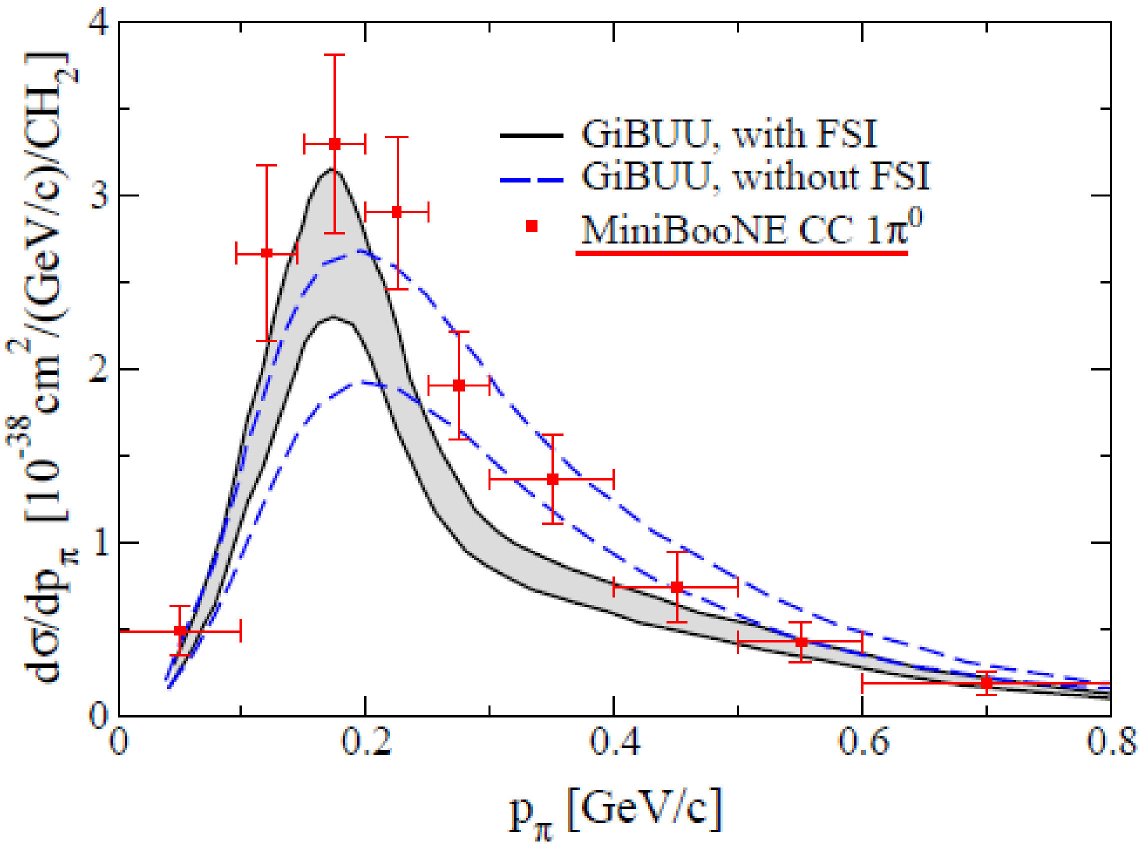
Juan Nieves, IFIC (CSIC & UV)



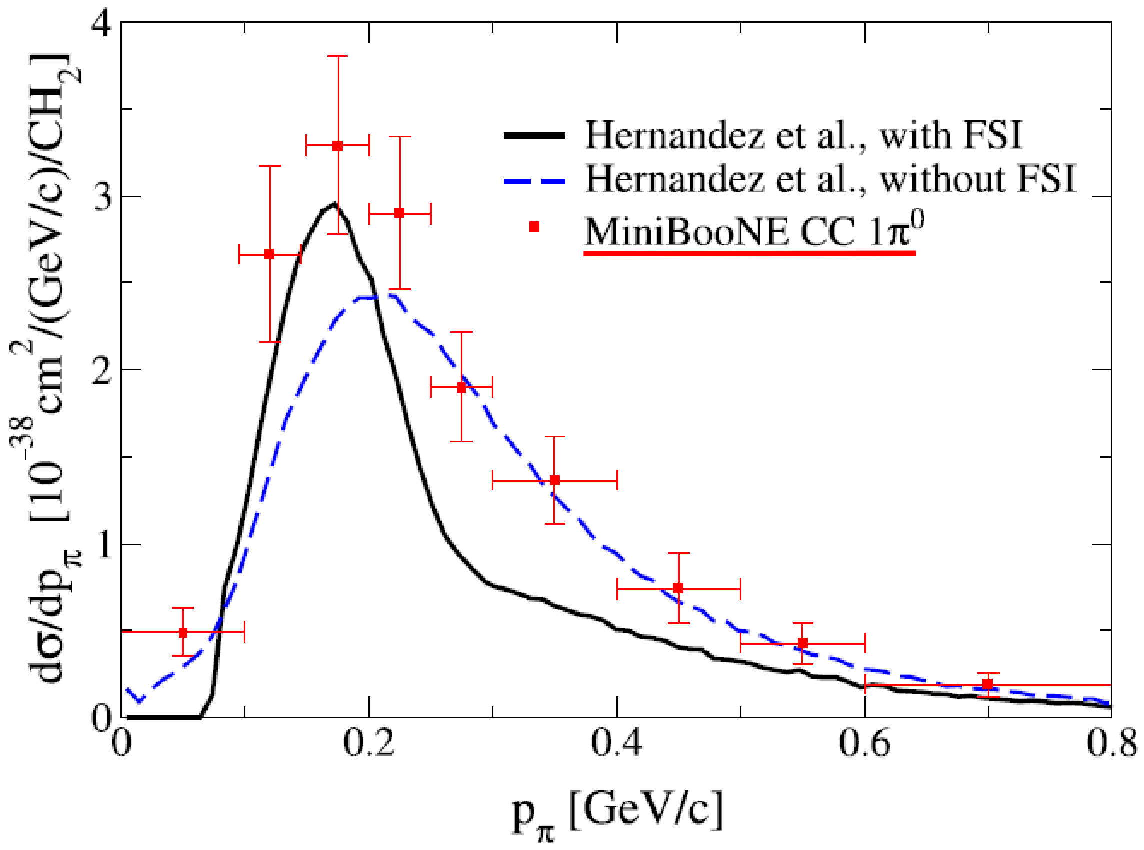


Watson's theorem
deuterium effects
local terms in Δ propagator
(see Hernandez's talk)



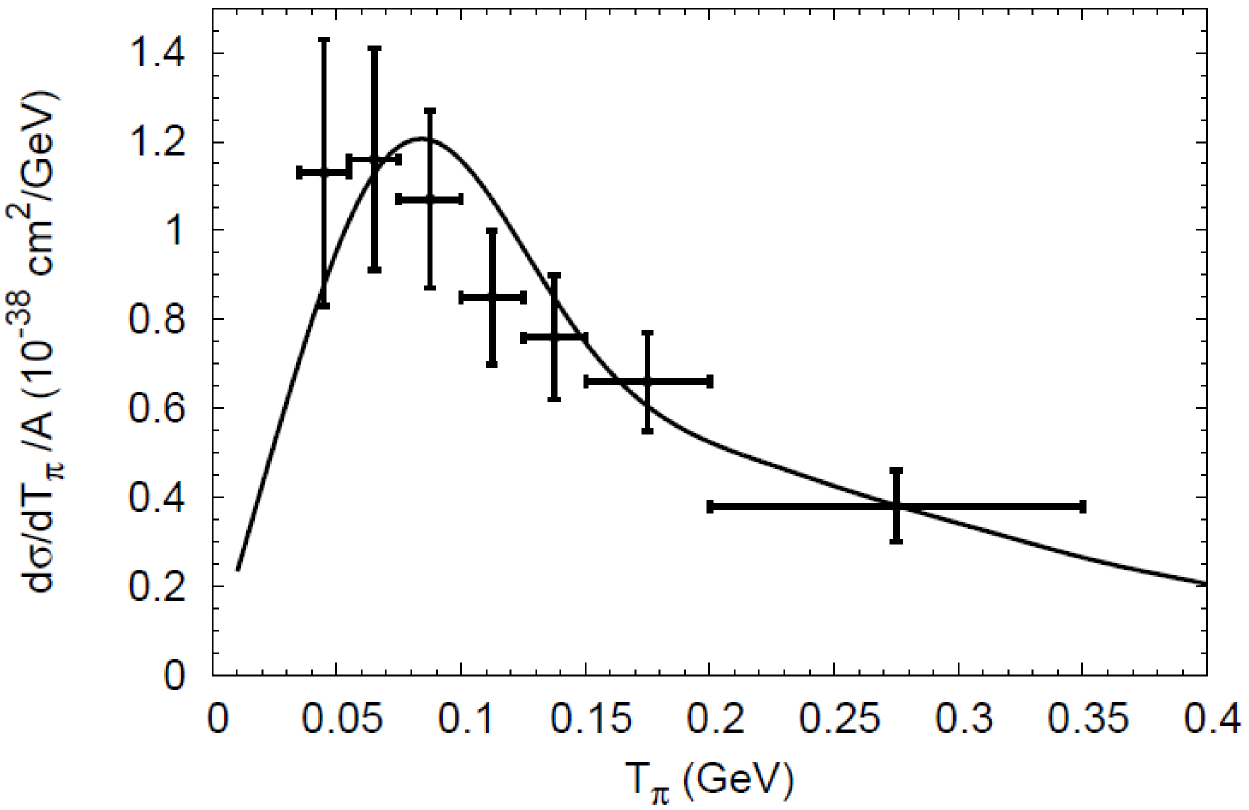


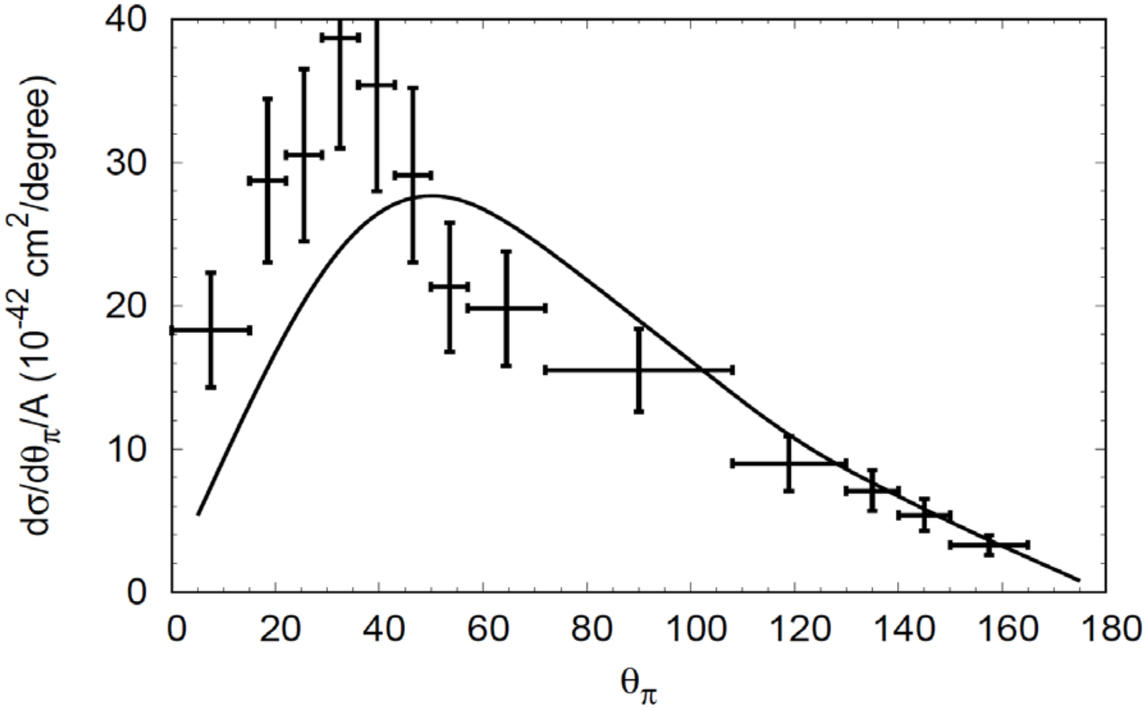
O. Lalakulich, U. Mosel, PRC 87 (2013)



E. Hernandez, J. Nieves M.J. Vicente-Vacas, PRD 87 (2013)

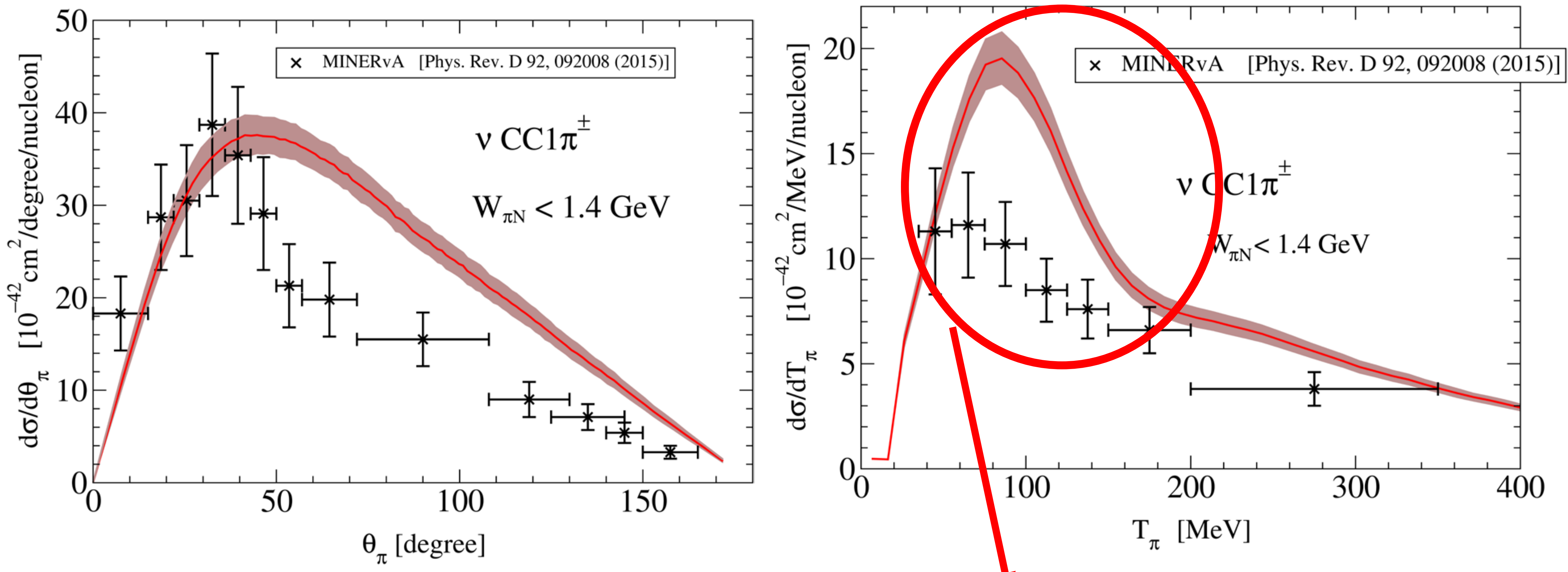
MiniBooNE: problems to describe pion production in nuclei (FSI, coherent production …) → MINERνA and T2K will shed light ….





U. Mosel and K. Gallmeister (GiBUU), 1702.04932: Comparison to MINERνA data with $W_{\pi N} < 1.4$ GeV

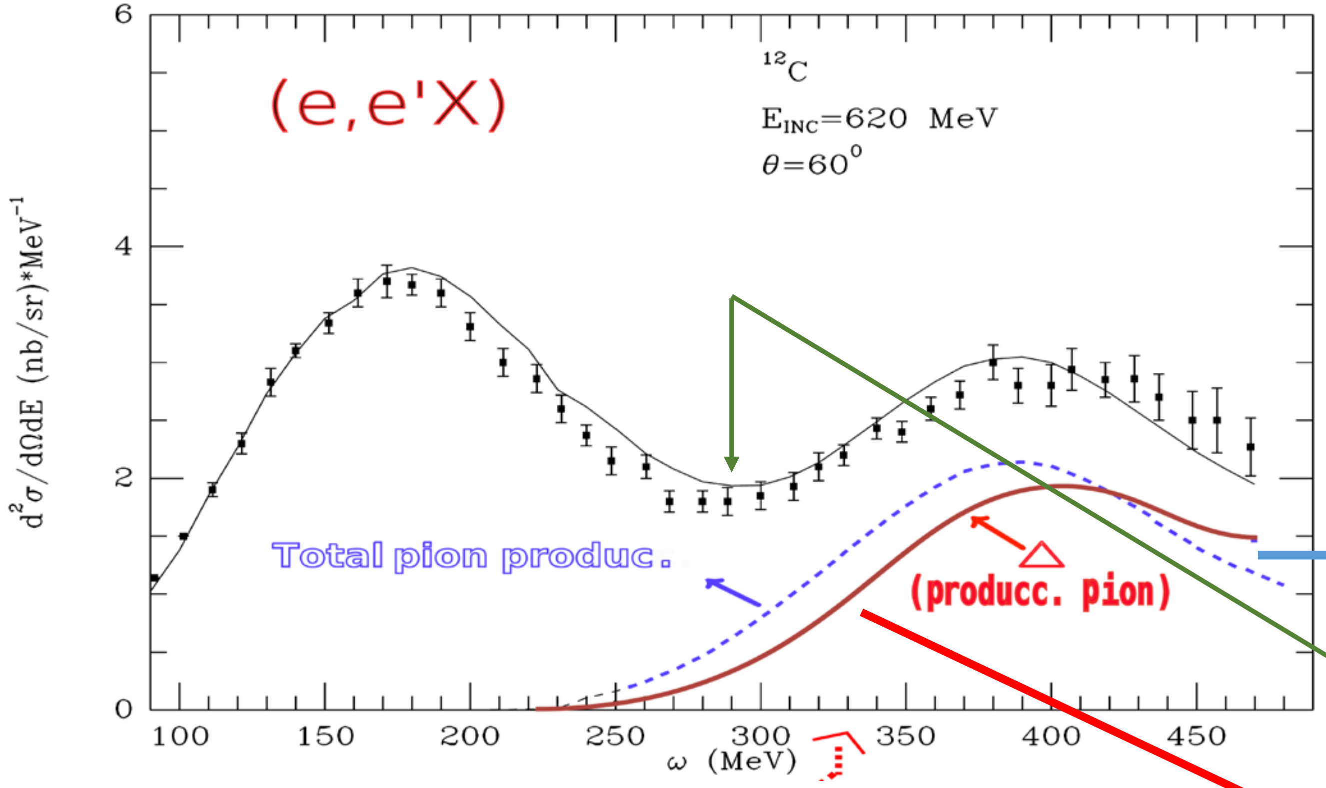
MINERνA and MiniBooNE data compatible?



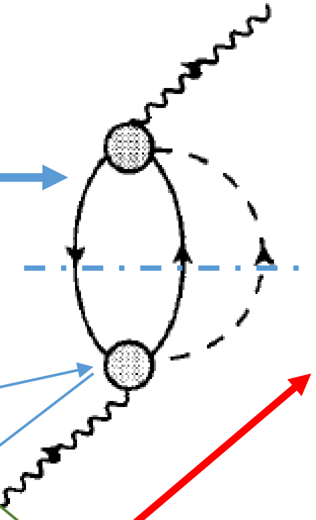
open problem
⟶discrepancy with:

- ✓ data
- ✓ GiBUU (origin of the difference ?)

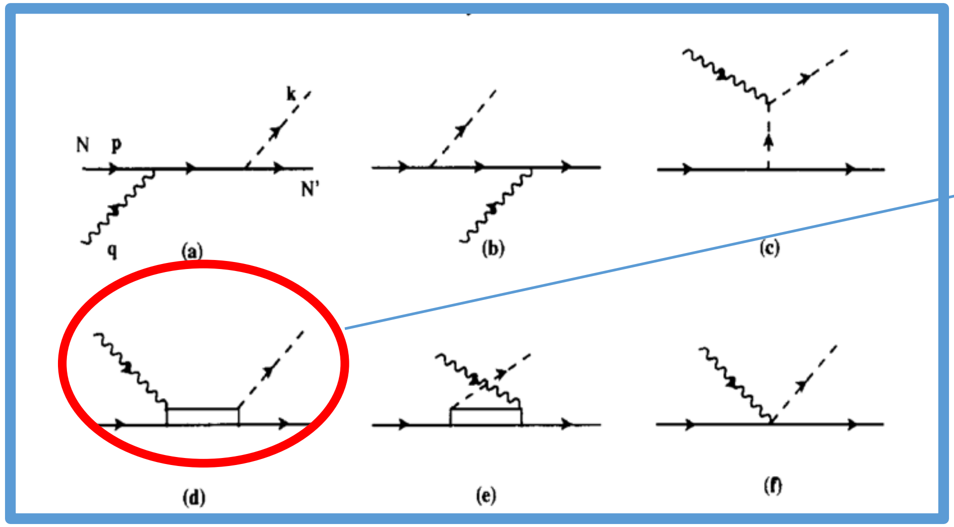
RPA effects on the real part of Δ–selfenergy ??



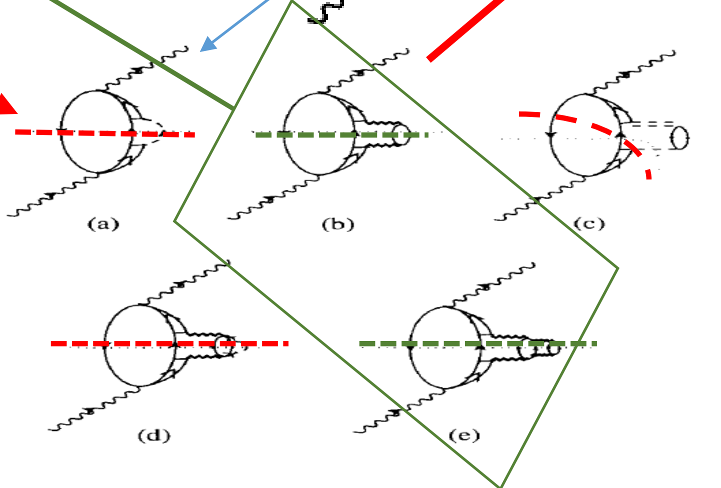
- Δ dominant component of the pion production contribution
- Missing strength both at the dip region and the Δ peak



2p2h

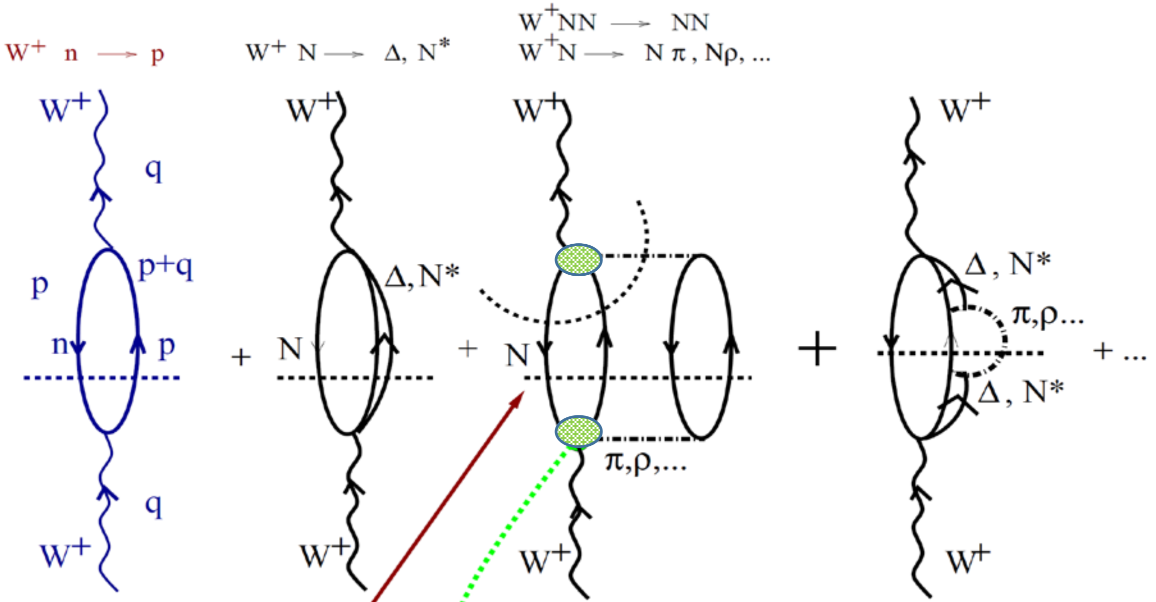


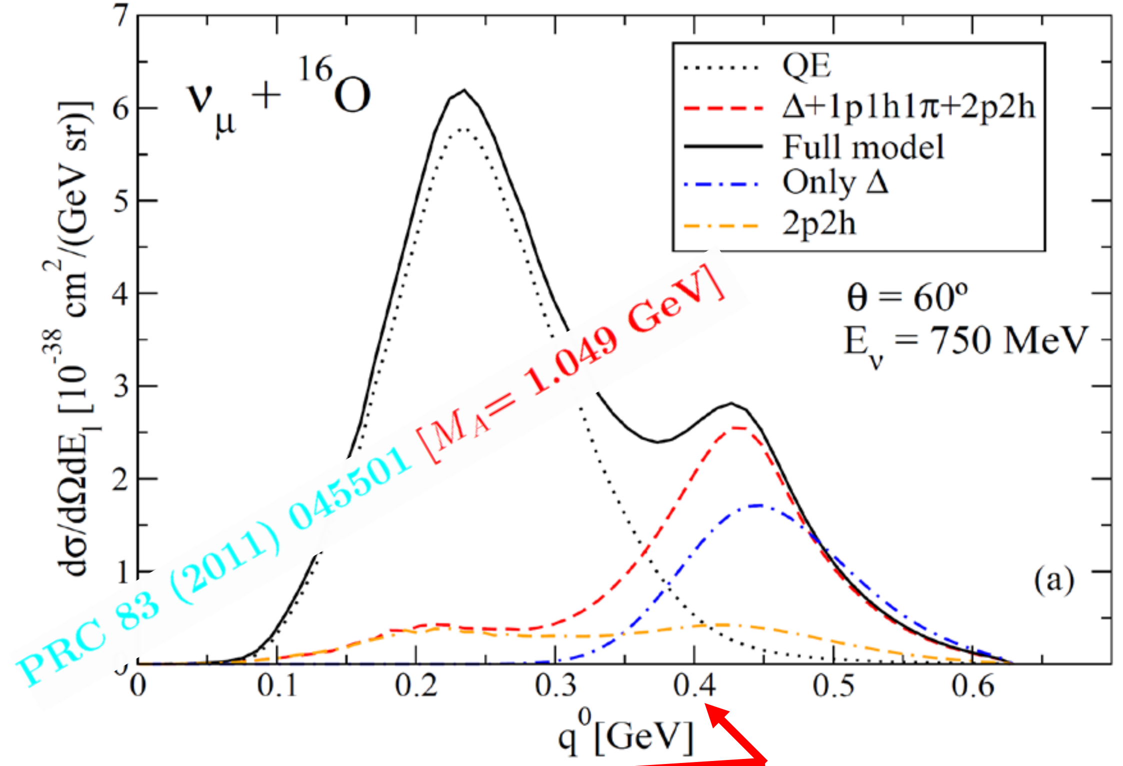
one of the terms generates the Δ contribution



Juan Nieves, IFIC (CSIC & UV)

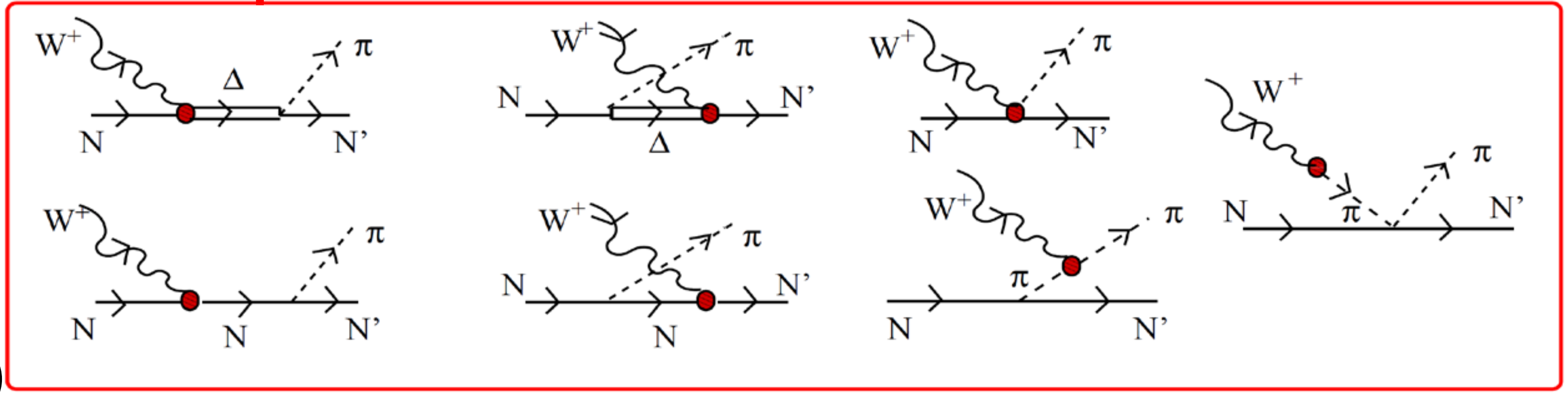
$\nu + A \rightarrow l + X$





MEC ⟶ QE like !

2p2h



PRD D76 (2007) 033005
PRD D81 (2010) 085046

+ PRD 93 (2016) 014016 (Watson's theorem)
+ PRD 95 (2017) 053007 (local terms in Δ propagator)

Juan Nieves, IFIC (CSIC & UV)

CONCLUSIONS

- Σ_Δ accounts for the important modifications of Δ properties inside of a nuclear medium

- It requires a realistic effective baryon-baryon interaction in the medium at intermediate energies
- There are problems to describe pion production in nuclei. RPA effects??