2p2h Nieves Model: an experimenal view!

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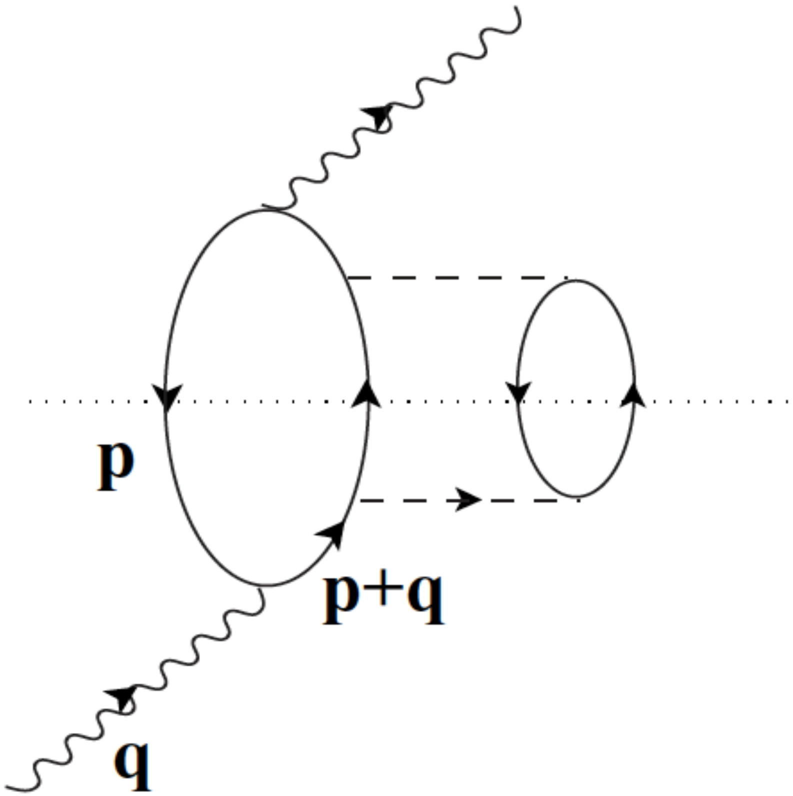
Cross-section

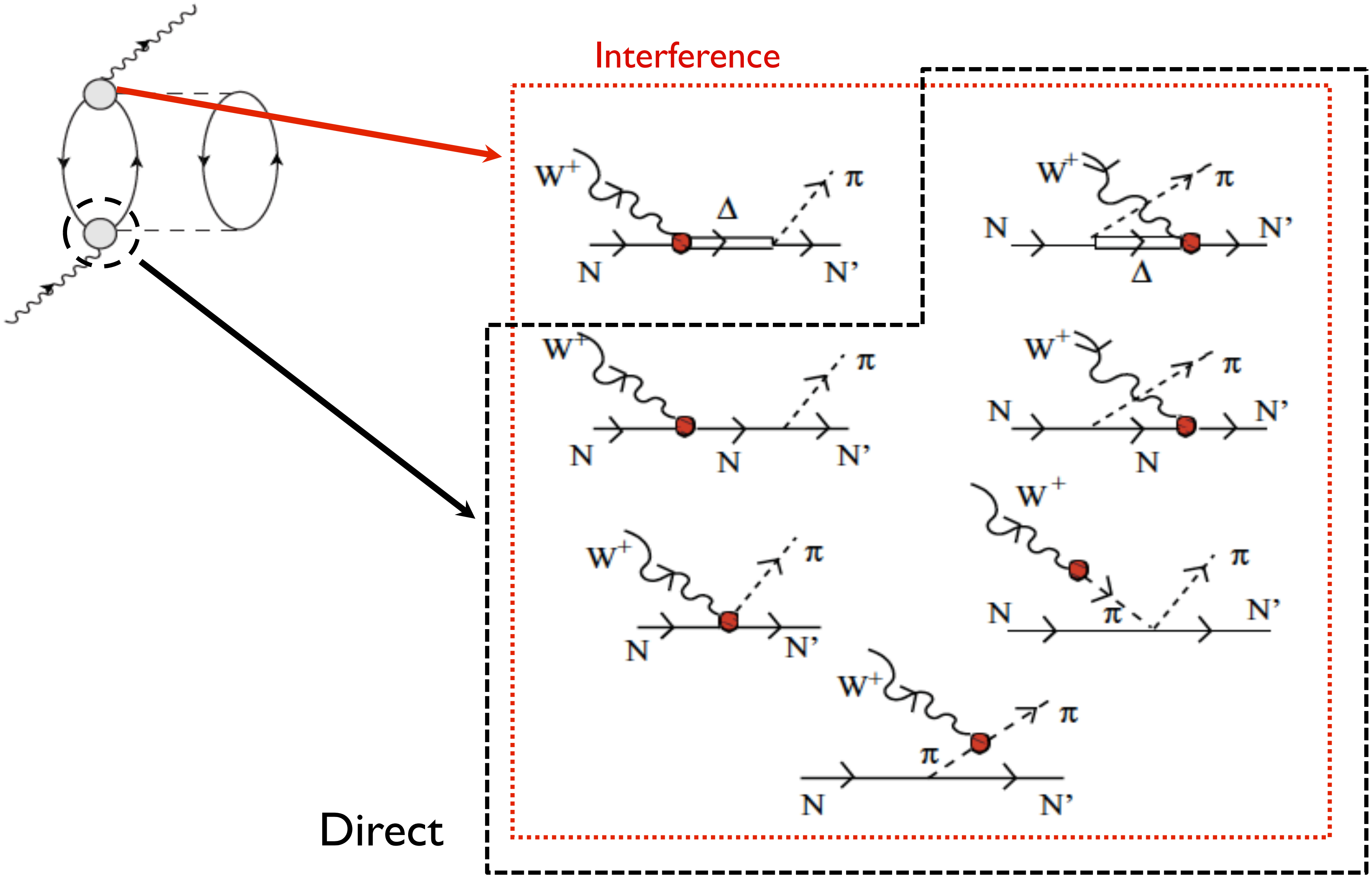
- The cross-section in Nieves model is constructed as the sum of the following components:
    1. Delta
    2. 2 Body
    3. Bubble
    4. Rho contribution.
- The diagrams for the different components are shown below.
- Tensors and cross-sections are available for each of the 4 components and also a duplicated one with the Delta couplings set to 0.

Spectral function contribution

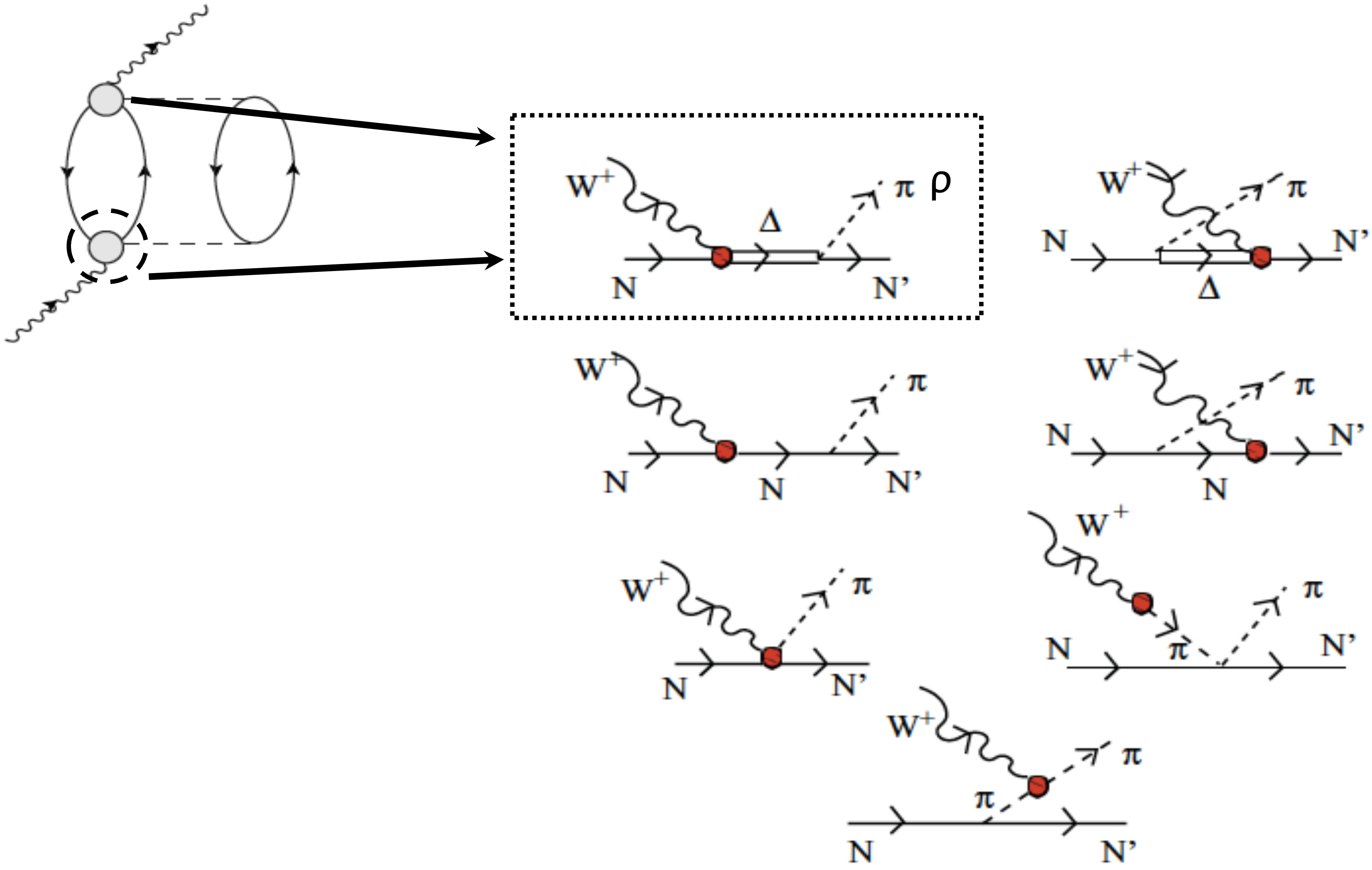


Not included in any of the cases !!!!

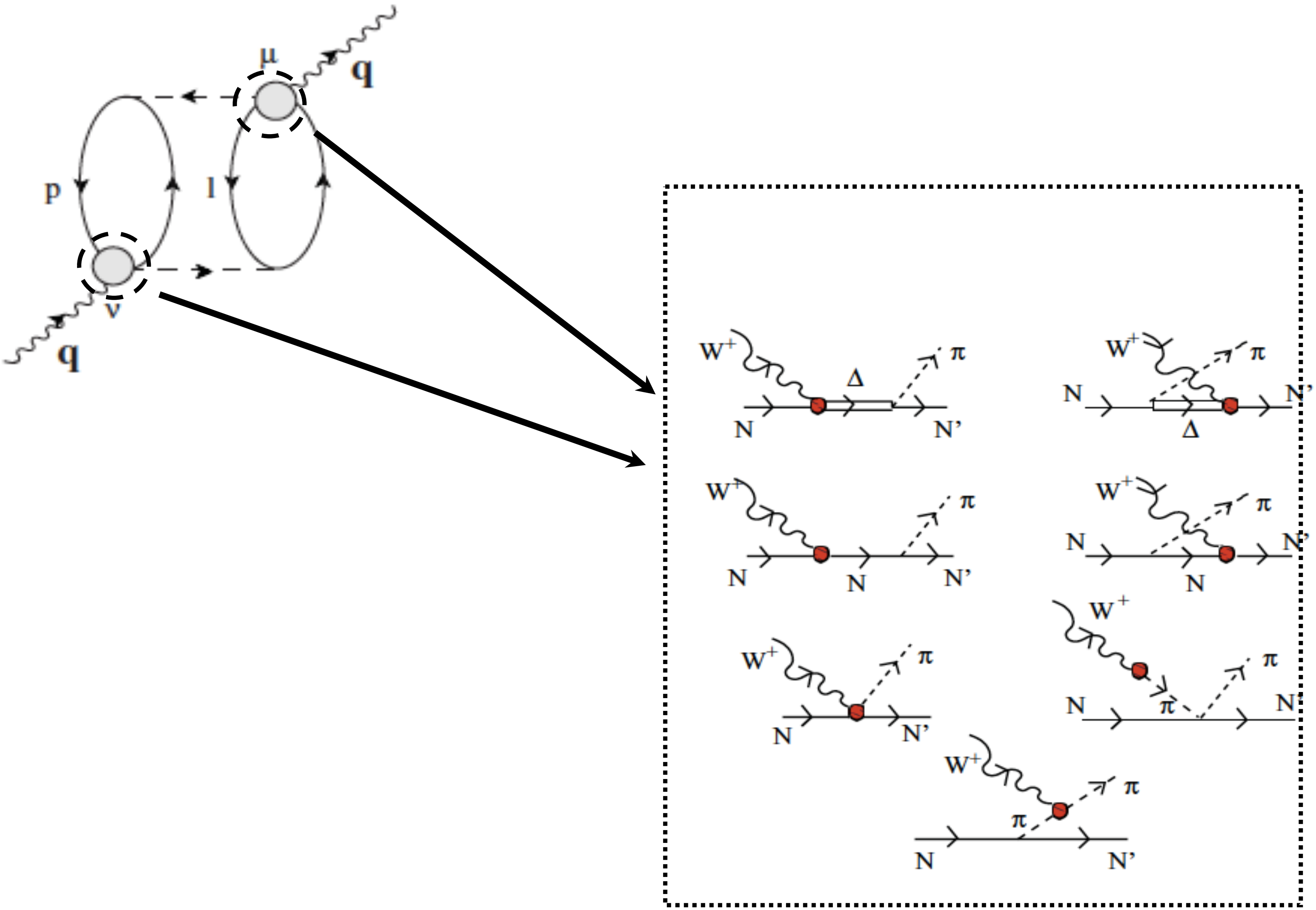
2Body contribution



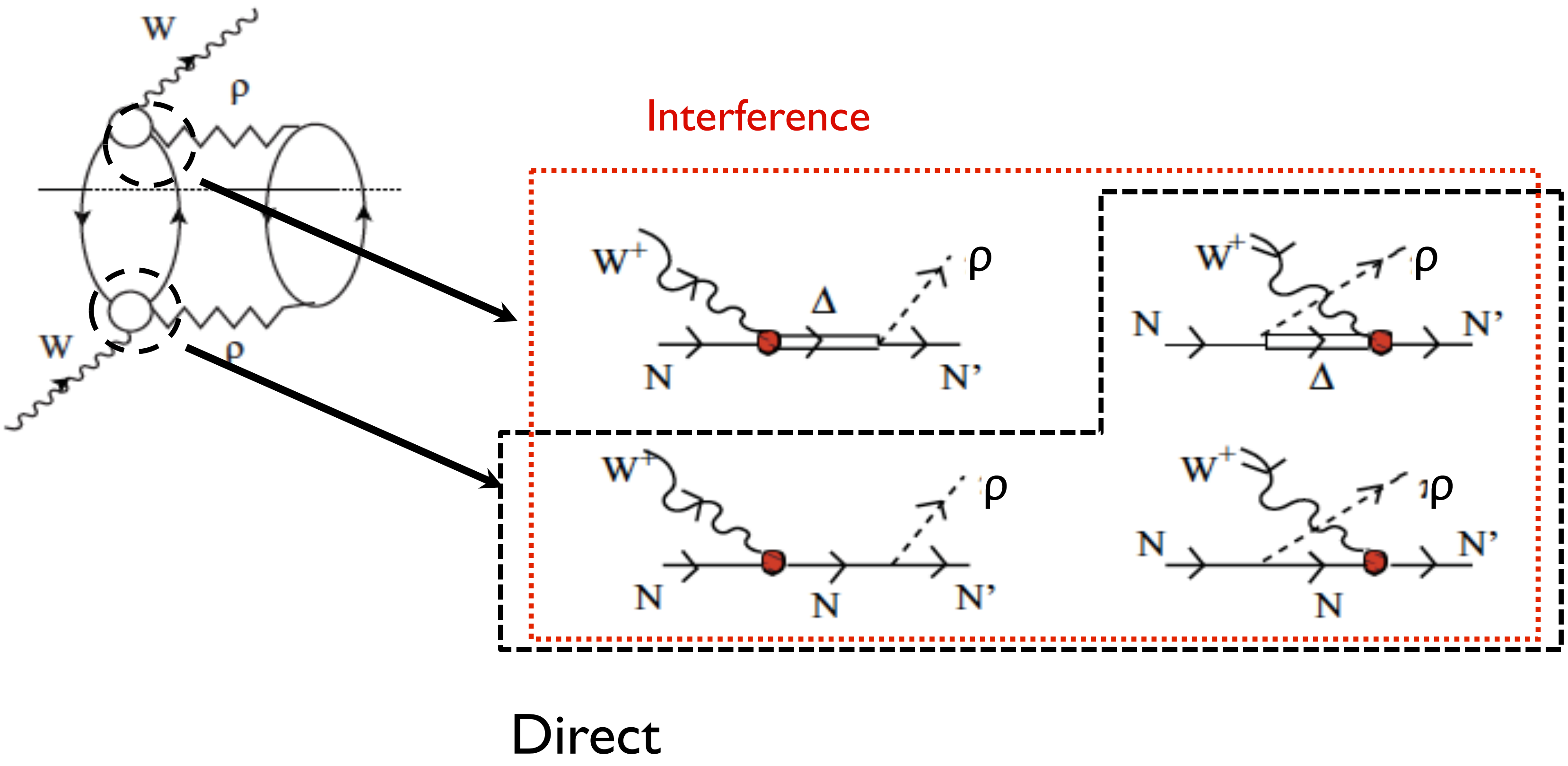
Delta contribution



Bubble contribution



Rho contribution



g'

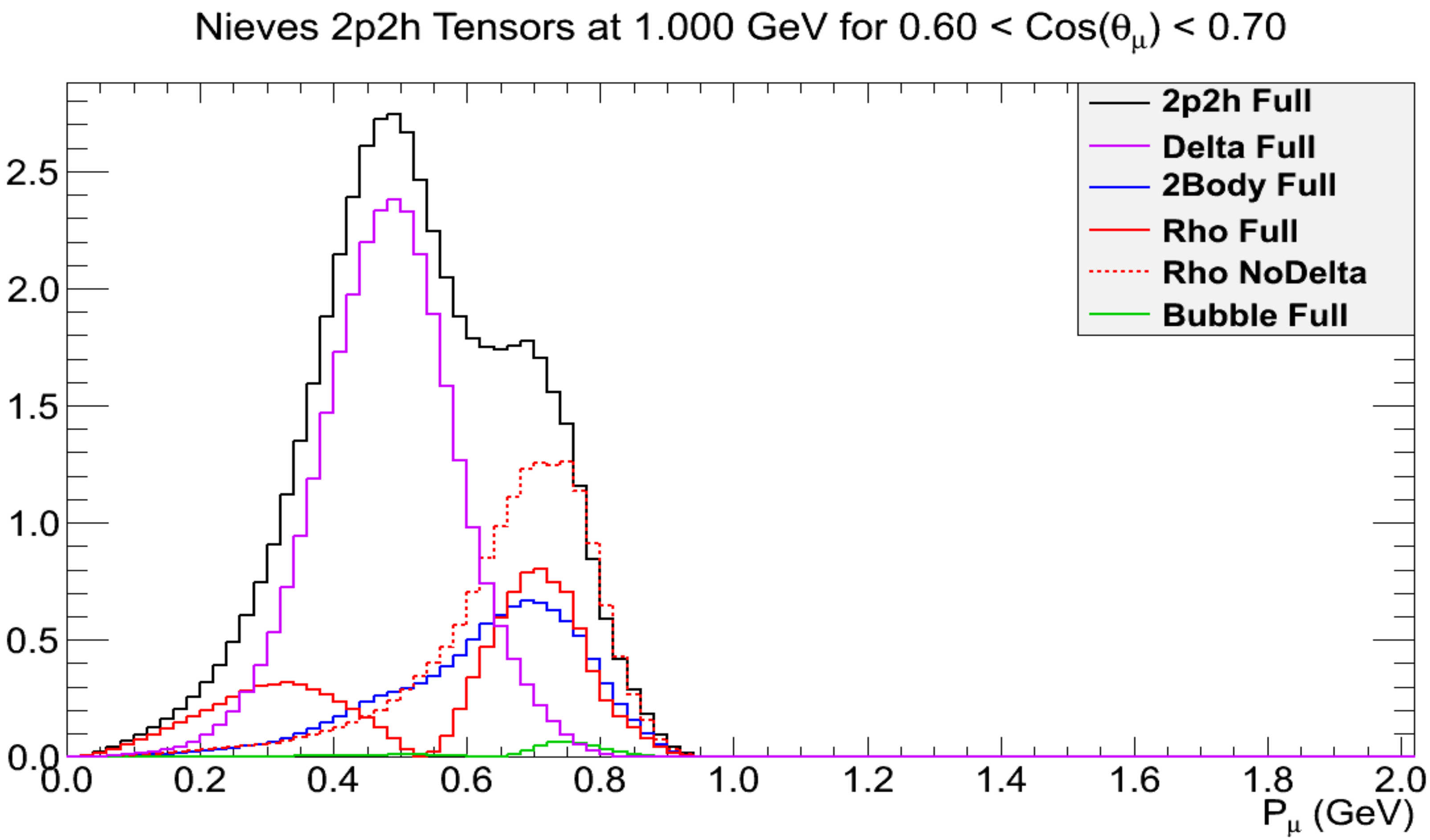
- G' parametrizes the pion and rho contact term.
- The value in Nieves code is 0.63

$$V_t(k) = \frac{f_{\pi NN}^2}{m_\pi^2}\left\{C_\rho F_\rho^2(k)\frac{\vec{k}^2}{k^2 - m_\rho^2} + g_t'(k)\right\},$$

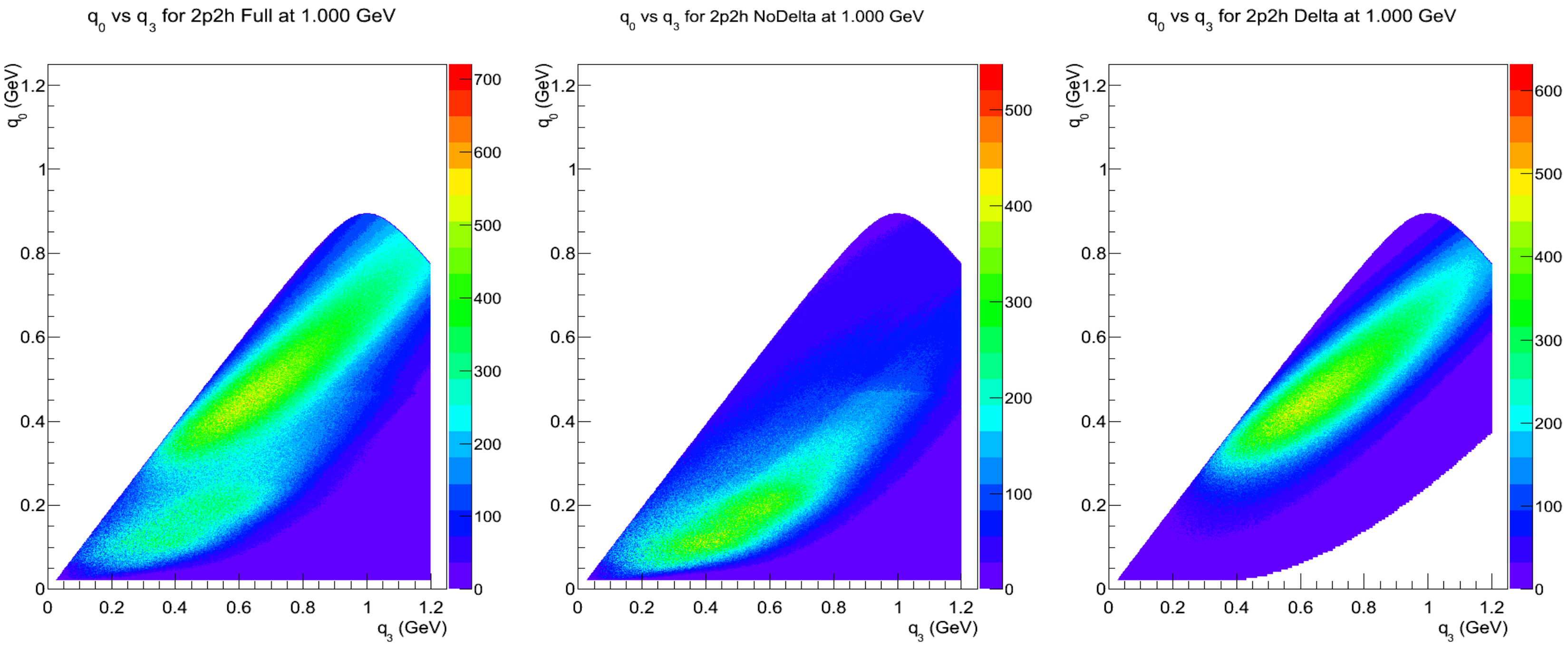
$$C_\rho = 2,\ F_\rho(k) = \frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - k^2},\ \Lambda_\rho = 2.5\ \text{GeV},$$

- G' cancells strongly with the pion propagator but not with the rho (transverse vs longitudinal)

All sub-components

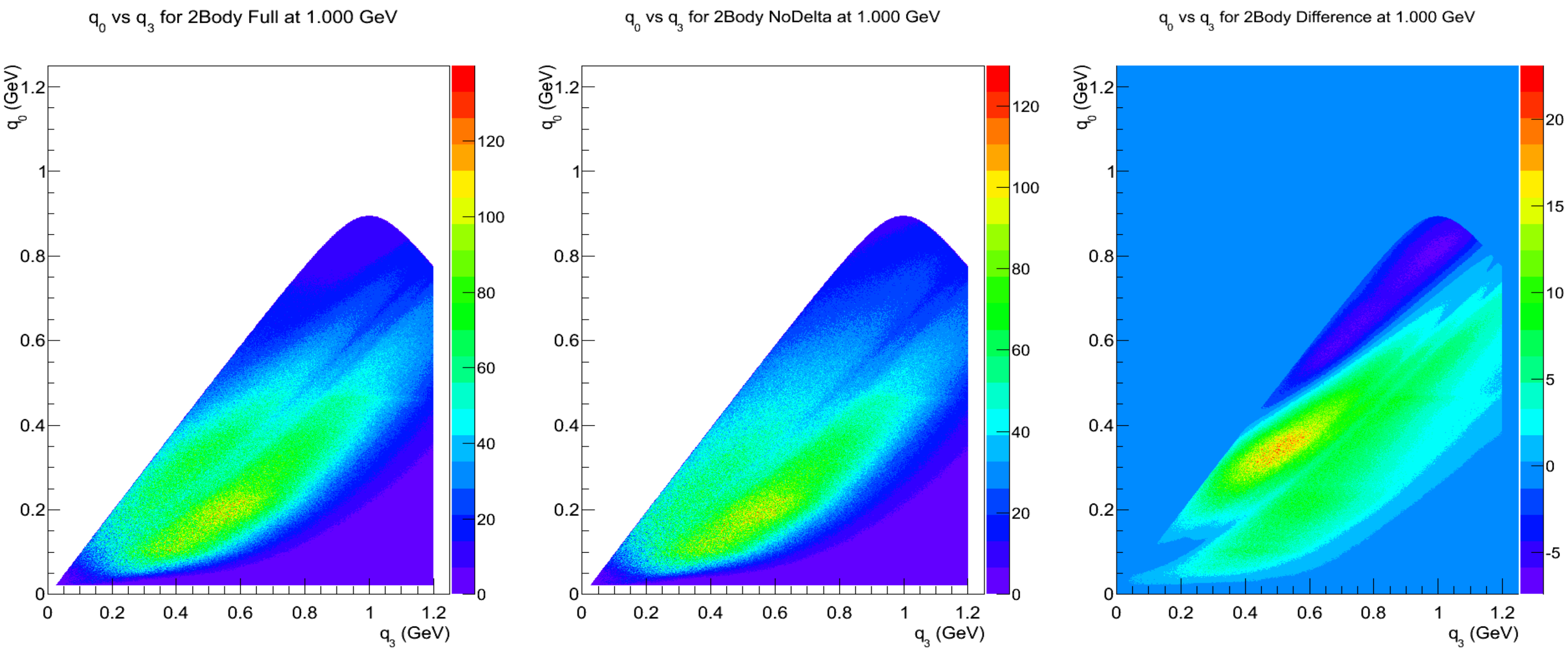


Full tensor

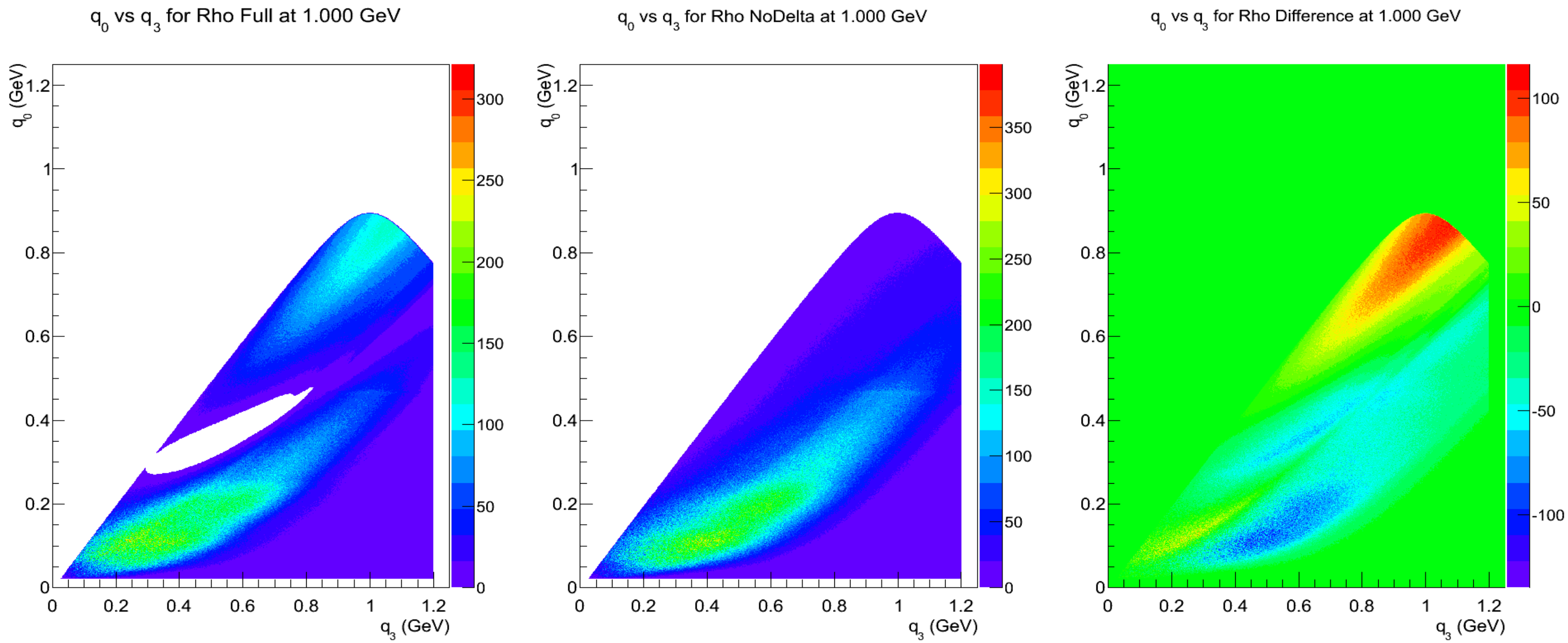


q0 vs q3 for 2p2h Full at 1.000 GeV
q0 vs q3 for 2p2h NoDelta at 1.000 GeV
q0 vs q3 for 2p2h Delta at 1.000 GeV
q0 (GeV)
q3 (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
0
100
200
300
400
500
600
700

Twobody tensor

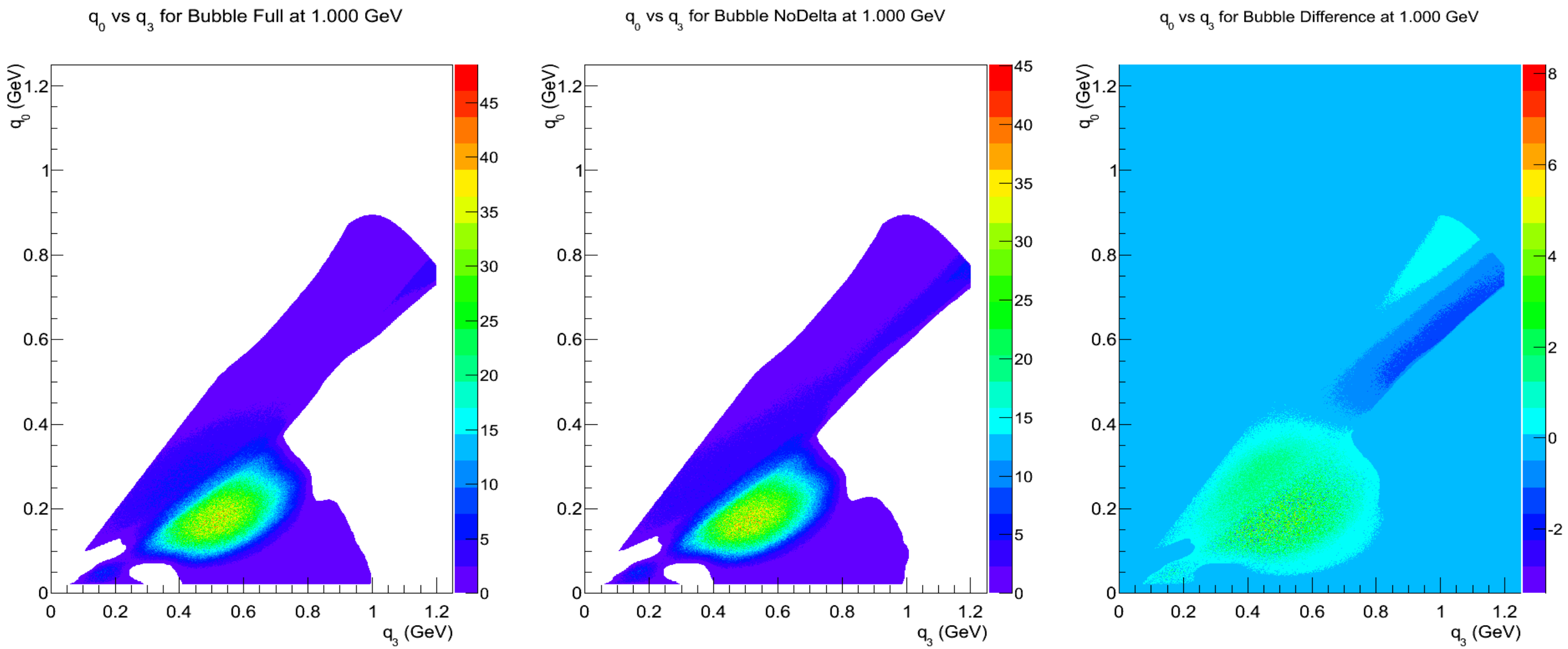


Rho tensor

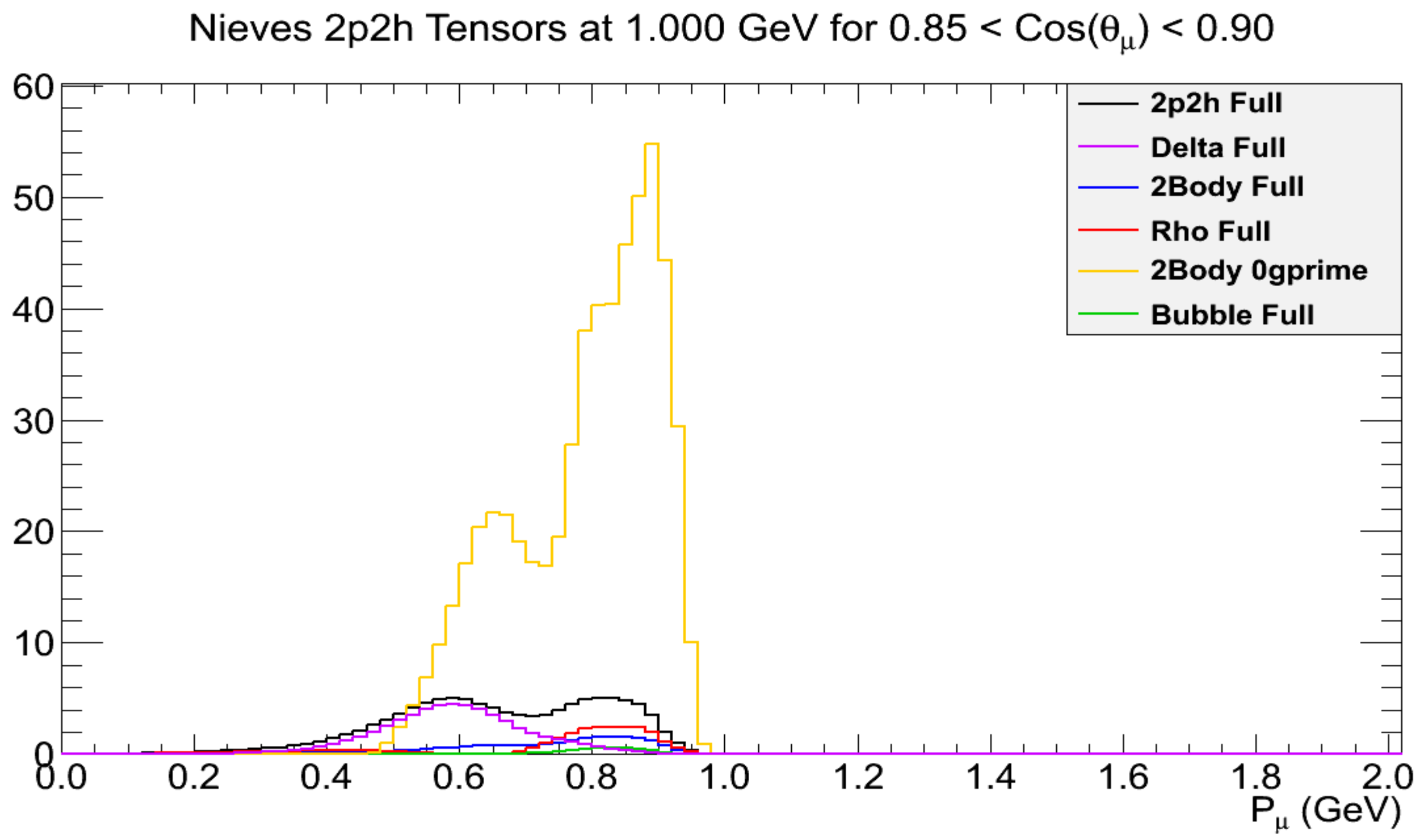


The empty area is a negative cross-section caused by the interference. This is not a real cross-section since we have artificially removed the delta.

Bubble tensor



G' = 0



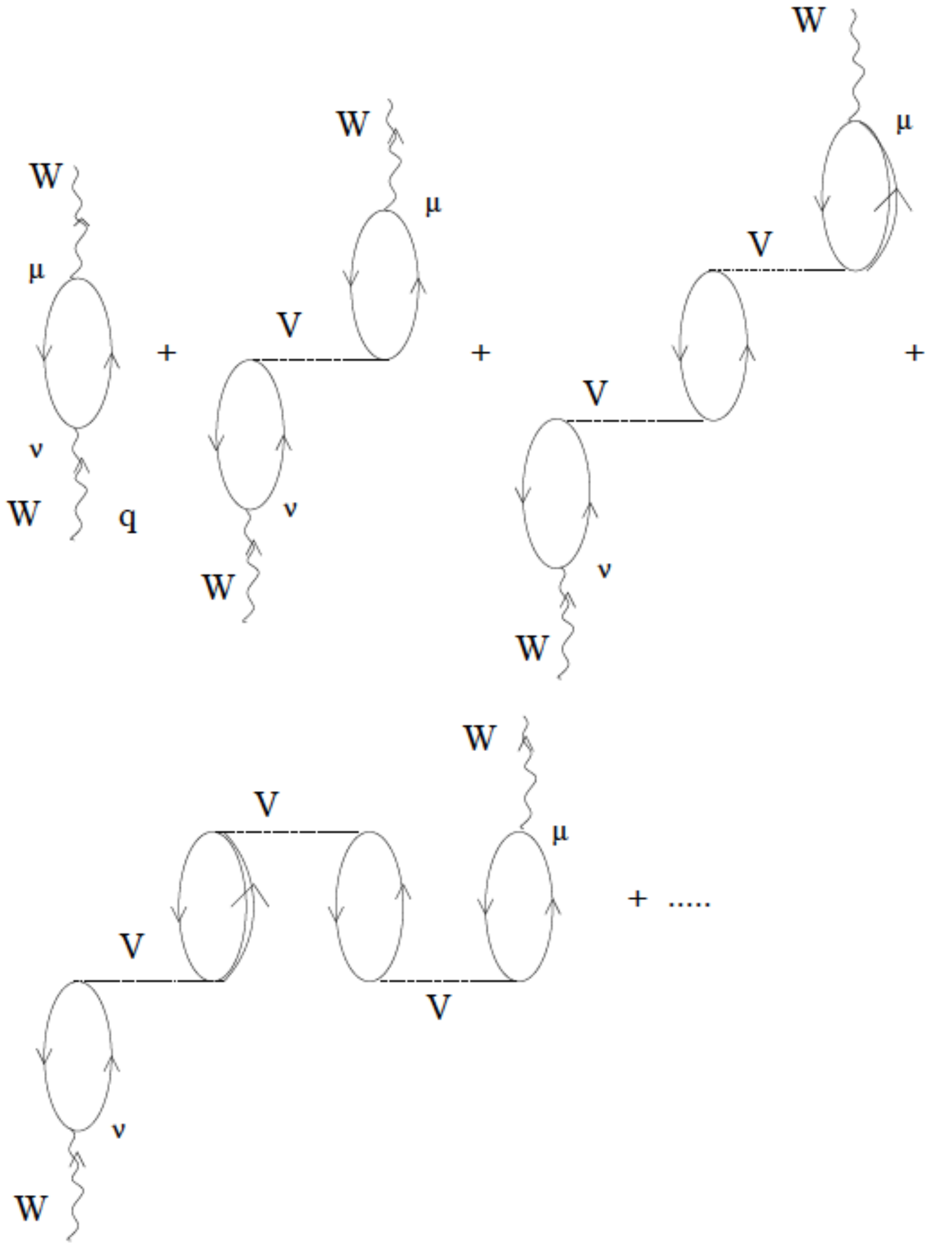
Very strong cancellation !!!

Final states

- Nieves model provides cross-sections for both:
  - nn and np initial states.
- It does not provide the kinematics of these nucleons.

Long range correlations & Random Phase Approximation

RPA



When the electroweak interactions take place in nuclei, the strengths of electroweak couplings may change from their free nucleon values due to the presence of strongly interacting nucleons [12]. Indeed, since the nuclear experiments on β decay in the early seventies [34], the quenching of axial current is a well established phenomenon. We follow here the MBF of Ref. [1], and take into account the medium polarization effects in the 1p1h contribution to the $W-$selfenergy by substituting it by an RPA response as shown diagrammatically in Fig. 3. For that purpose we use an effective ph–ph interaction of the Landau-Migdal type

$$V = c_0 \Big\{ f_0(\rho) + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2 + g_0'(\rho)\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \Big\} \tag{32}$$

where $\vec{\sigma}$ and $\vec{\tau}$ are Pauli matrices acting on the nucleon spin and isospin spaces, respectively. Note that the above interaction is of contact type, and therefore in coordinate space one has $V(\vec{r}_1,\vec{r}_2) \propto \delta(\vec{r}_1 - \vec{r}_2)$. As mentioned before, the coefficients were determined in Ref. [33] from calculations of nuclear electric and magnetic moments, transition probabilities, and giant electric and magnetic multipole resonances. They are parameterized as

$$f_i(\rho(r)) = \frac{\rho(r)}{\rho(0)} f_i^{(in)} + \left[1 - \frac{\rho(r)}{\rho(0)}\right] f_i^{(ex)} \tag{33}$$

where

$$\begin{array}{ll} f_0^{(in)} = 0.07 & f_0'^{(ex)} = 0.45 \\ f_0^{(ex)} = -2.15 & f_0'^{(in)} = 0.33 \\ g_0^{(in)} = g_0^{(ex)} = g_0 = 0.575 & g_0'^{(in)} = g_0'^{(ex)} = g_0' = 0.725 \end{array} \tag{34}$$

and $c_0 = 380$ MeVfm^3. In the $S = 1 = T$ channel ($\vec{\sigma}\vec{\sigma}\vec{\tau}\vec{\tau}$ operator) we use an interaction with explicit π (longitudinal) and ρ (transverse) exchanges, which has been used for the renormalization of the pionic and pion related channels in different nuclear reactions at intermediate energies [1], [4]–[6]. Thus we replace,

$$c_0 g_0'(\rho)\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \to \vec{\tau}_1\vec{\tau}_2 \sum_{i,j=1}^{3} \sigma_1^i \sigma_2^j V_{ij}^{\sigma\tau}, \qquad V_{ij}^{\sigma\tau} = (\hat{q}_i\hat{q}_j V_l(q) + (\delta_{ij} - \hat{q}_i\hat{q}_j)V_t(q)) \tag{35}$$

with $\hat{q} = \vec{q}/|\vec{q}|$ and the strengths of the ph-ph interaction in the longitudinal and transverse channel are given by

$$\begin{aligned} V_l(q^0,\vec{q}) &= \frac{f^2}{m_\pi^2}\left\{\left(\frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2}\right)^2 \frac{\vec{q}^{\,2}}{q^2 - m_\pi^2} + g_l'(q)\right\}, \qquad \frac{f^2}{4\pi} = 0.08, \quad \Lambda_\pi = 1200 \text{ MeV} \\ V_t(q^0,\vec{q}) &= \frac{f^2}{m_\pi^2}\left\{C_\rho\left(\frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - q^2}\right)^2 \frac{\vec{q}^{\,2}}{q^2 - m_\rho^2} + g_t'(q)\right\}, \qquad C_\rho = 2, \quad \Lambda_\rho = 2500 \text{ MeV}, \quad m_\rho = 770 \text{ MeV} \end{aligned} \tag{36}$$

The SRC functions g_l' and g_t' have a smooth $q-$dependence [5, 35], which we will not consider here[7], and thus we will take $g_l'(q) = g_t'(q) = g' = 0.63$ as it was done in the study of inclusive nuclear electron scattering carried out in Ref. [1], and also in some of the works of Ref. [6]. Note that, $c_0 g_0'$ and $g' f^2/m_\pi^2$ differ from each other in less than 10%.

RPA model

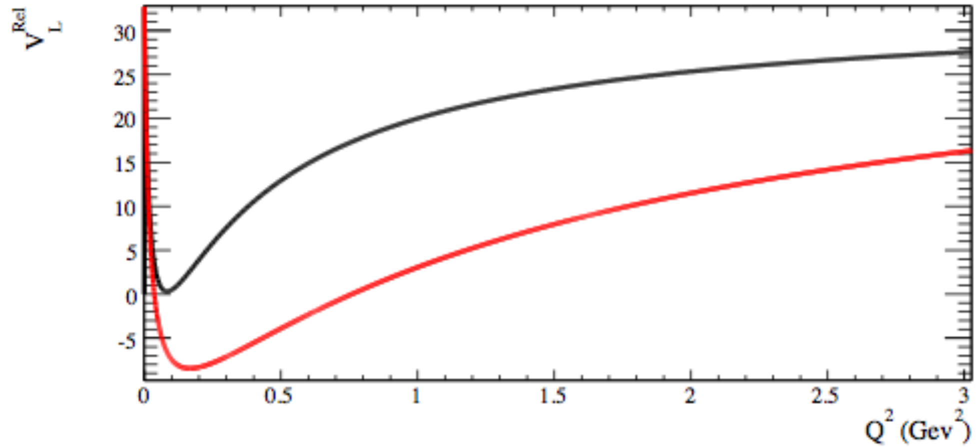
$$V_L^{rel} = 0.08 \frac{4\,\pi}{m_\pi^2} \left(0.63 - \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2} \frac{q^2}{q^2 - m_\pi^2} \right)$$

$$V_L^{nonrel} = 0.08 \frac{4\,\pi}{m_\pi^2} \left(0.63 + \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2} \frac{q_3^2}{q^2 - m_\pi^2} \right)$$

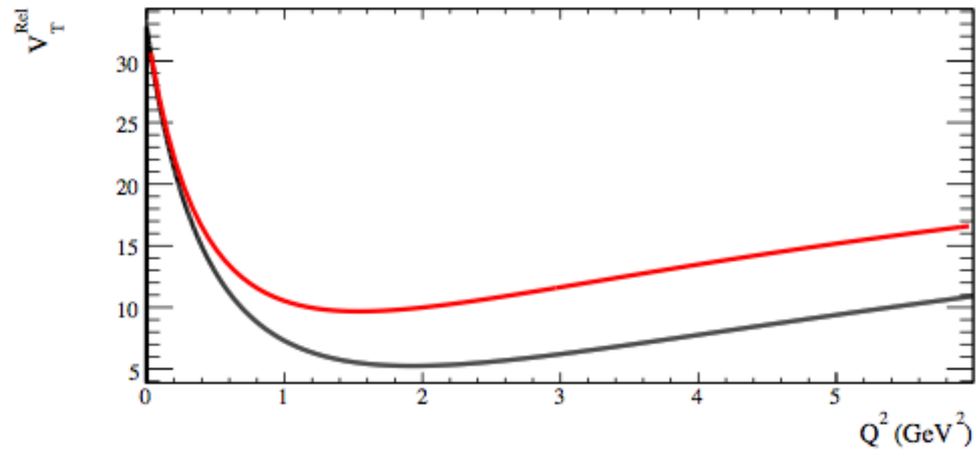
$$V_T^{rel} = 0.08 \frac{4\,\pi}{m_\pi^2} \left(0.63 - 2.\, \frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - q^2} \frac{q^2}{q^2 - m_\rho^2} \right)$$

$$V_T^{nonrel} = 0.08 \frac{4\,\pi}{m_\pi^2} \left(0.63 + 2.\, \frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - q^2} \frac{q_3^2}{q^2 - m_\rho^2} \right)$$

RPA model

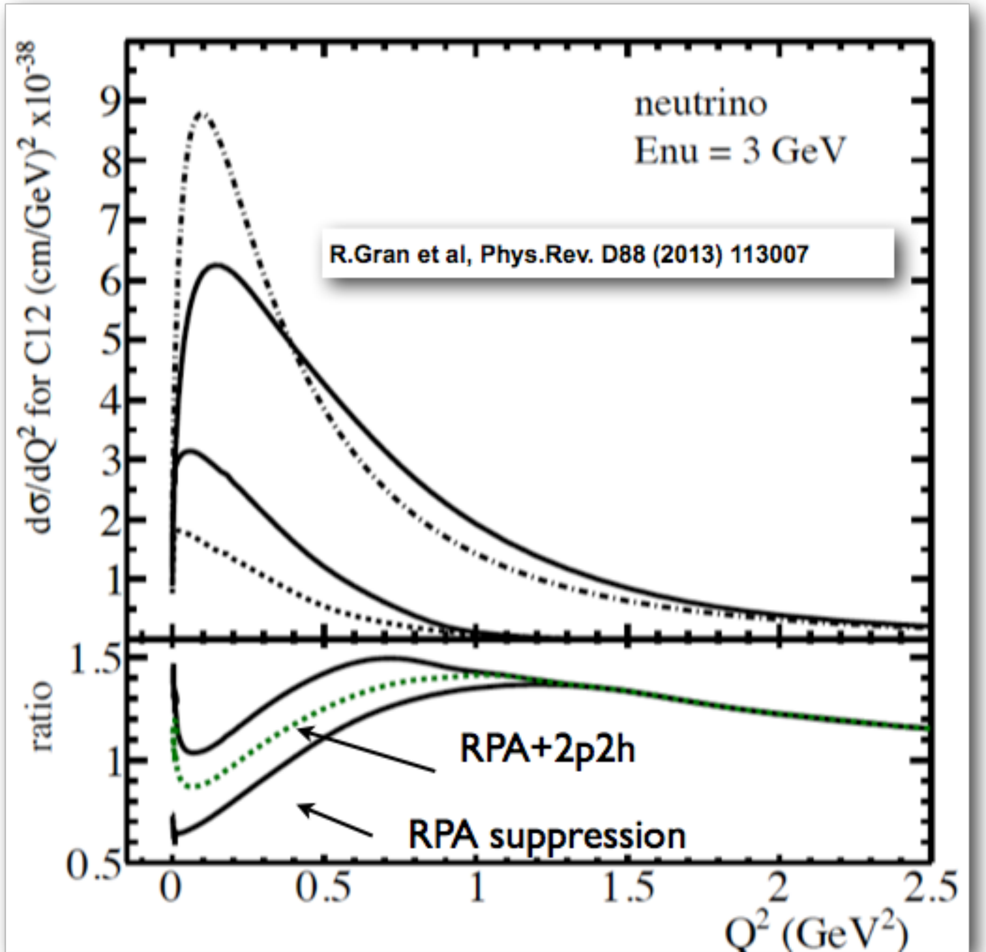


V_L^{Rel}
30
25
20
15
10
5
0
-5
0
0.5
1
1.5
2
2.5
3
Q^2 (Gev^2)



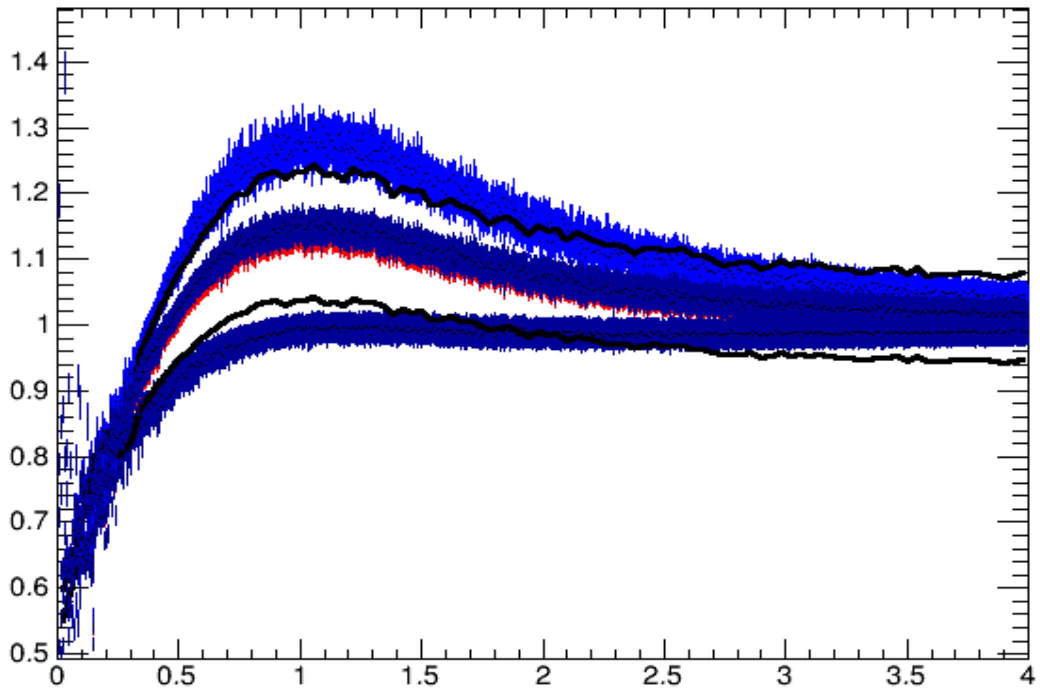
V_T^{Rel}
30
25
20
15
10
5
0
1
2
3
4
5
Q^2 (GeV^2)

RPA and |q3|

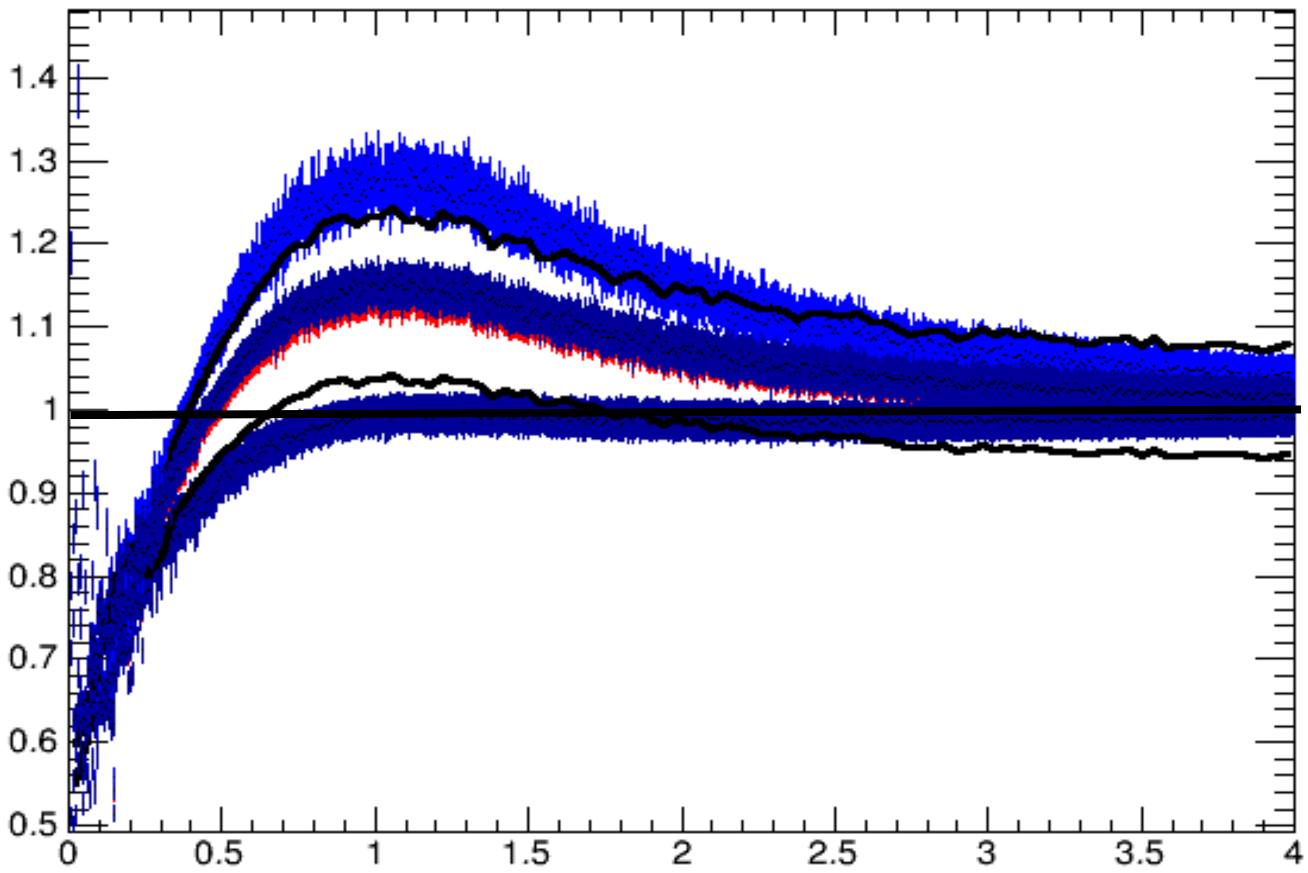

neutrino
Enu = 3 GeV
R.Gran et al, Phys.Rev. D88 (2013) 113007
dσ/dQ² for C12 (cm/GeV)² x10⁻³⁸
ratio
RPA+2p2h
RPA suppression
Q² (GeV²)

RPA model

- The region at $Q^2 \sim 0$ comes from the muon capture measurements.
- We know that RPA$\rightarrow$1 for $Q^2 \rightarrow \infty$.



RPA modelling



On the RPA error

Theoretical uncertainties on quasi-elastic charged-current neutrino-nucleus cross sections

M. Valverde, Jose Enrique Amaro, J. Nieves (Granada U.)

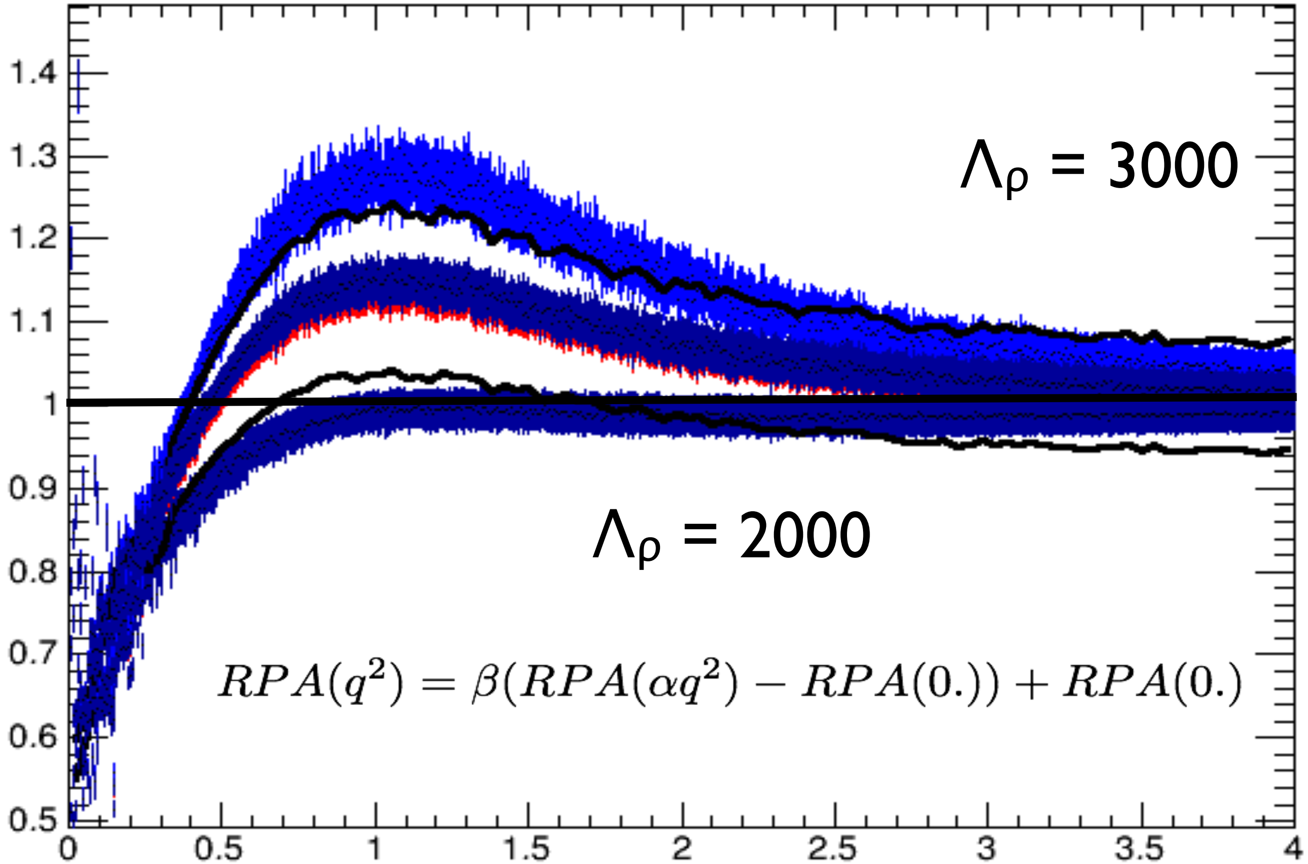
Phys.Lett. B638 (2006) 325-332

Form Factors	Nucleon Interaction
$M_D = 0.843 \pm 0.042$ GeV	$f_0'^{(in)} = 0.33 \pm 0.03$
$\lambda_n = 5.6 \pm 0.6$	$f_0'^{(ex)} = 0.45 \pm 0.05$
$M_A = 1.05 \pm 0.14$ GeV	$f = 1.00 \pm 0.10$
$g_A = 1.26 \pm 0.01$	$f^* = 2.13 \pm 0.21$
	$\Lambda_\pi = 1200 \pm 120$ MeV
	$C_\rho = 2.0 \pm 0.2$
	$\Lambda_\rho = 2500 \pm 250$ MeV
	$g' = 0.63 \pm 0.06$

RPA

10% error

RPA modelling



Λ_π = 1000

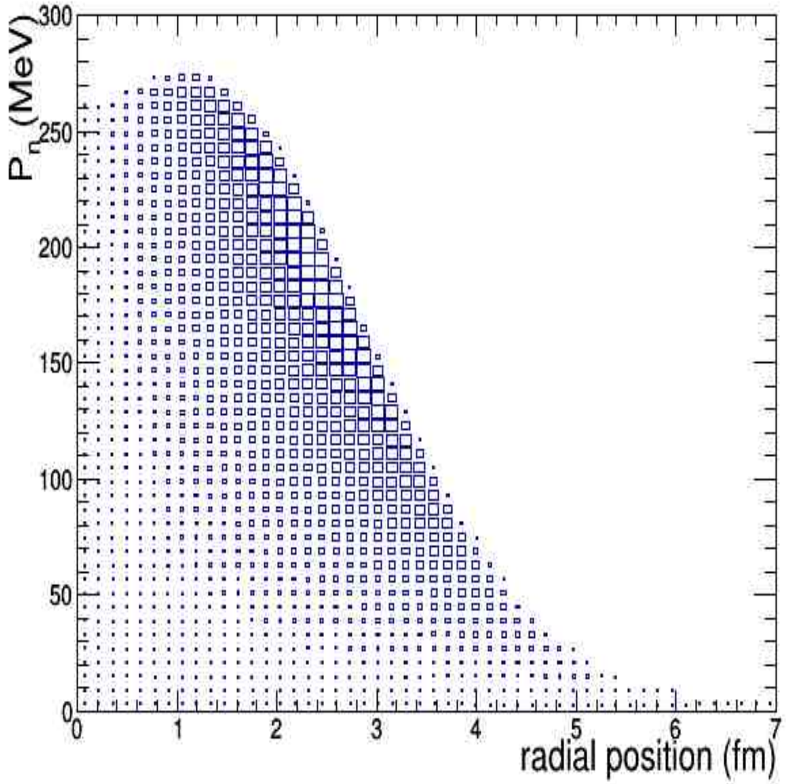
Λ_ρ = 2500
Λ_π = 1200

- Λ_π has little effect on the dependency.

Beyond diagrams: nucleus description and binding energy

Nieves uses LFG

- The potential shape depends on the Nuclei.
- Even the potential shape.



Neut model

- The target nucleon inside the nucleus has an effective mass because the nuclear potential modifies the dispersion relation.

$$E_\nu + E_n = \qquad E_\nu + \sqrt{p_n^2 + (M_n - E_b)^2} = \qquad E_p + E_\mu$$

$$\vec{p}_\nu + \vec{p}_n = \qquad \vec{p}_\mu + \vec{p}_p$$

$$(p_n \ll M_n)\ (E_b \ll M_n)\ (p_n \ll M_n - E_b)$$

$$\sqrt{p_n^2 + (M_n - E_b)^2} \approx M_n(1 - \frac{E_b}{M_n}) \approx M_n - E_b$$

Assumed in CCQE energy reconstruction!

- E_b ~ 25 MeV in Neut for Carbon.

Neut model

nucleon state density

$$dN = 2\frac{4\pi V}{h^3}p^2dp \qquad V = \frac{4}{3}\pi r^3 \ ; \ r = 1.2A^{\frac{1}{3}}fm$$

maximum Fermi momentum

$$p_F = \left(\frac{3h^2N}{8\pi V}\right)^{\frac{1}{3}} \approx 315.\left(\frac{N}{A}\right)^{\frac{1}{3}}$$

~250 MeV/c for isoscalar nuclei

maximum Fermi energy

$$E_F \approx 53.\left(\frac{Z}{A}\right)^{\frac{2}{3}}$$

~33 MeV for isoscalar nuclei

Average Fermi energy or binding energy

$$< E_F >= \frac{3.}{5.}E_F$$

~20 MeV for isoscalar nuclei

- Actually NEUT uses other (close values) for carbon (25 MeV) and Oxygen (27 MeV).

Nieves model

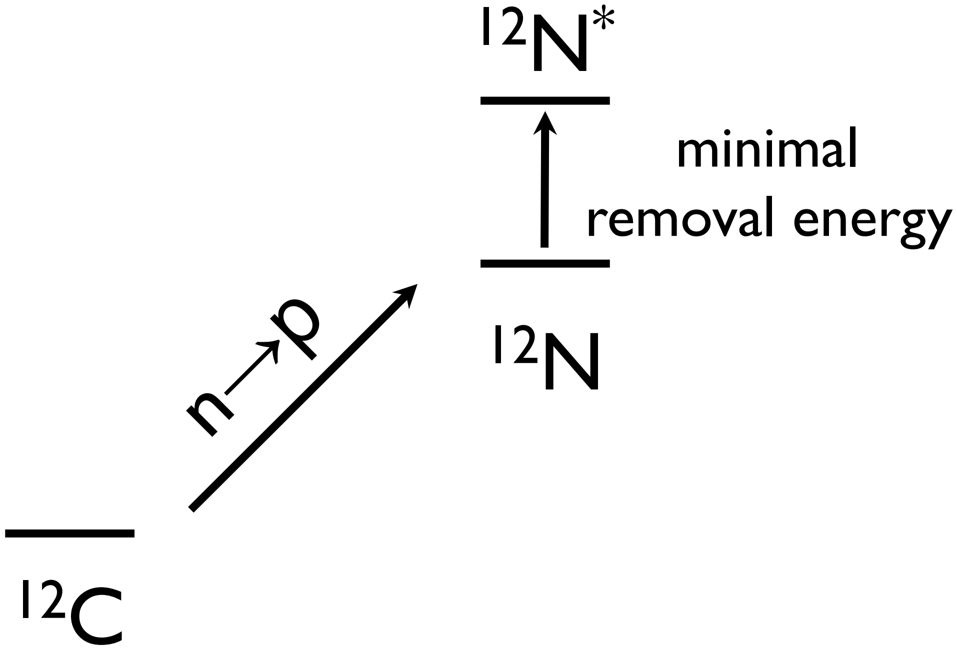
- There is a fraction of the Energy that goes to transform the target nucleus (^{12}C) in the final (excited) nucleus ($^{12}N^*$).

$$
\begin{aligned}
E_\nu + M_{^{12}C} &= E_\mu + E_p + M_{^{12}N^*} \\
\vec{p}_\nu + \vec{p}_n &= \vec{p}_\mu + \vec{p}_p
\end{aligned}
$$

- The masses are tabulated.
- The final nucleus includes also the energy to remove one neutron from the see. This is also tabulated. http://nucleardata.nuclear.lu.se/toi/

$$M_{^{12}N^*} = M_{^{12}N} + \Delta E$$

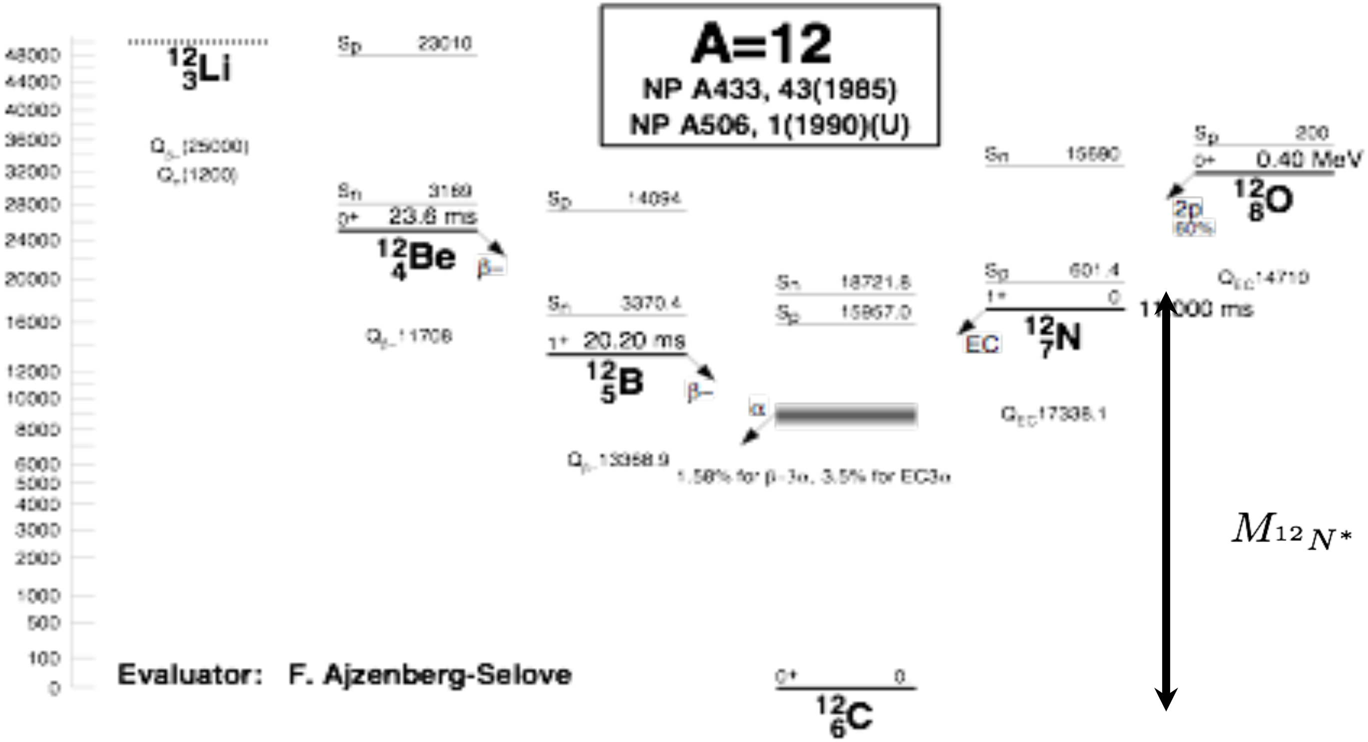
Nieves model



- This can be seen as a two step process:

1. Nucleon is moved out from the sea and changed its nature (n→p , p→n) .
    1. We need to compared the base target with the final nuclei with the proton just outside the Fermi level.
2. The nucleon is accelerated in the interaction.

^{12}C example



$$M_{^{12}N*} - M_{^{12}C}$$

http://nucleardata.nuclear.lu.se/toi/

^{12}C

Comparisons

Target	ν	ν	NEUT
^{12}C	$^{12}C \Rightarrow {}^{12}N$ (Sp) ΔE =16.827+0.601 (MeV)	$^{12}C \Rightarrow {}^{12}B$ (Sp) ΔE=13.880+3.370 (MeV)	25 MeV
^{16}O	$^{16}O \Rightarrow {}^{16}F$ (Sp) ΔE =14.906-0.536 (MeV)	$^{16}O \Rightarrow {}^{16}N$ (Sp) ΔE=10.991+2.489 (MeV)	27 MeV

- Nieves model allows to treat neutrinos and antineutrinos consistent to its nucleus initial and final states and it relies on external data.

Effects on μ kinematics

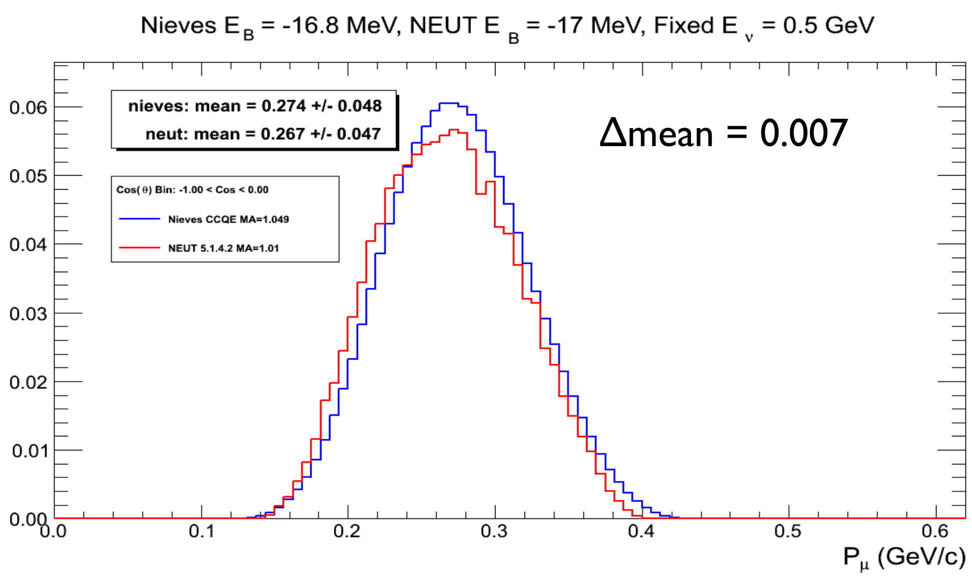
- Compare Neut and Nieves in bins of muon momentum and angle
- Nieves has fixed binding energy and we vary the one of Neut from 25.0 to 17.0
- Caveat: there are other differences in the model so we should not expect perfect agreement.

Effects on μ kinematics

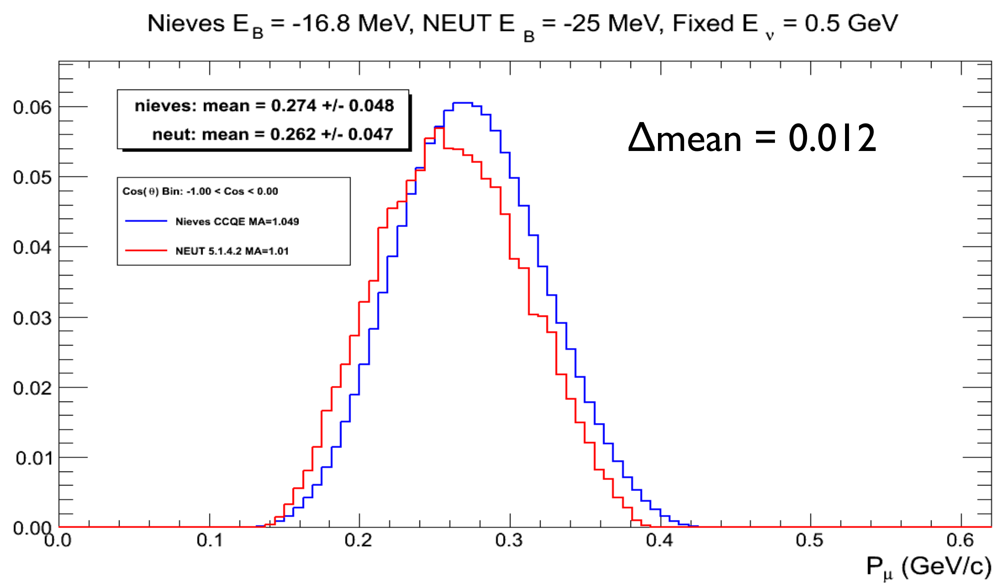
A.Cudd

E_ν = 0.5 GeV

-1. < $\cos \theta_\mu$ < 0.0



Nieves E_b = -16.8 MeV
Neut E_b = -17.0 MeV



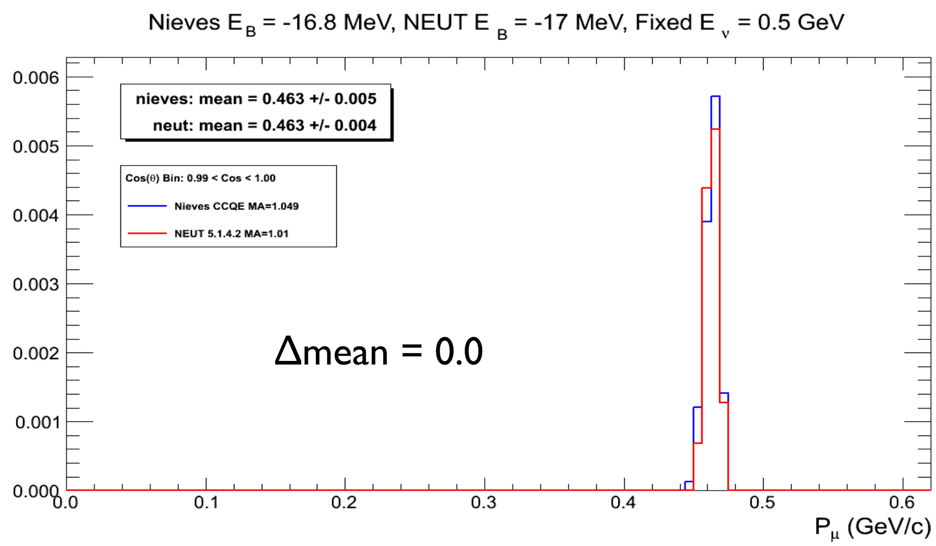
Nieves E_b = -16.8 MeV
Neut E_b = -25.0 MeV

Effects on μ kinematics

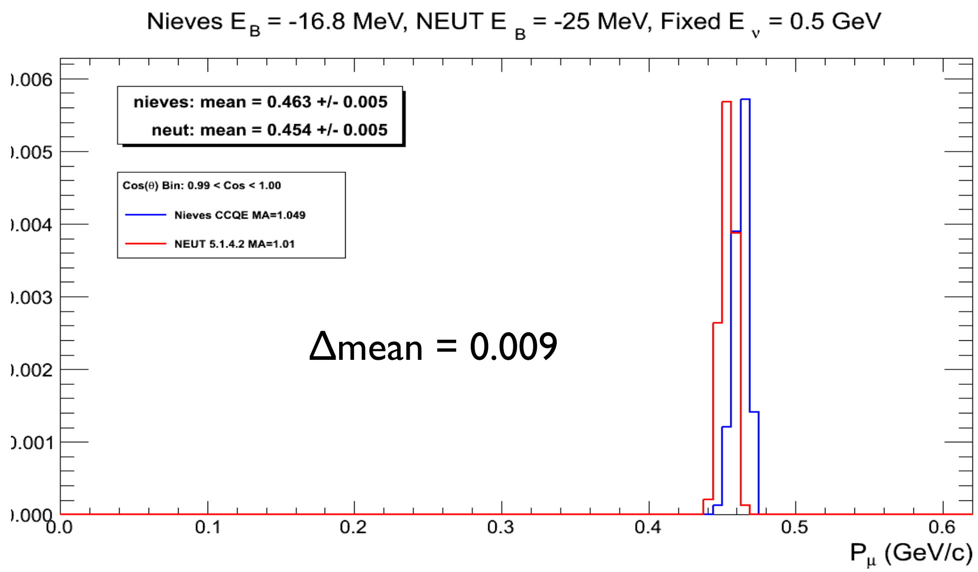
A.Cudd

$E_\nu = 0.5$ GeV

$0.99 < \cos\theta_\mu < 1.0$



Nieves E_b = -16.8 MeV
Neut E_b = -17.0 MeV



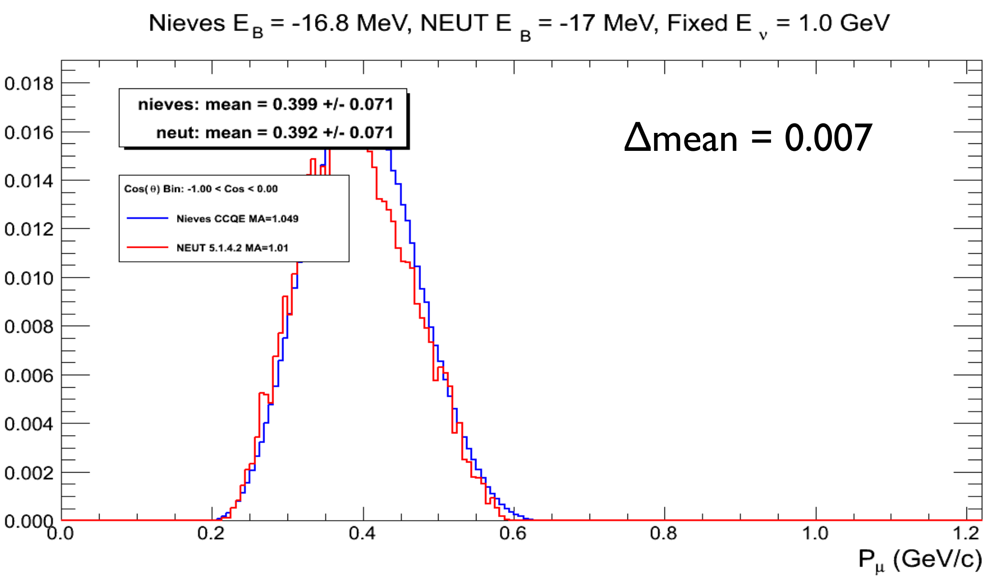
Nieves E_b = -16.8 MeV
Neut E_b = -25.0 MeV

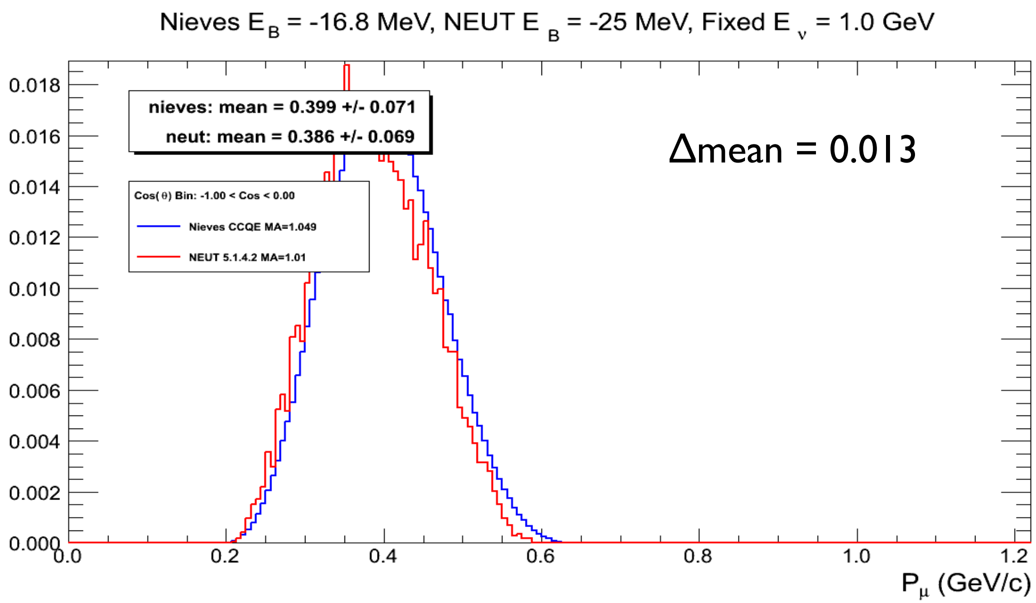
Effects on μ kinematics

A.Cudd

E_ν = 1.0 GeV

$-1.0 < \cos\theta_\mu < 0.0$





Nieves E_b = -16.8 MeV
Neut E_b = -17.0 MeV

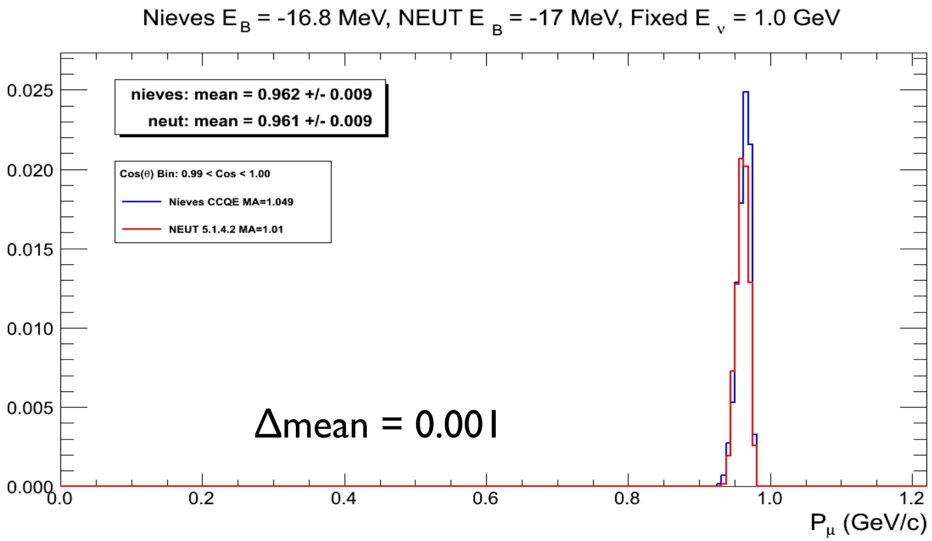
Nieves E_b = -16.8 MeV
Neut E_b = -25.0 MeV

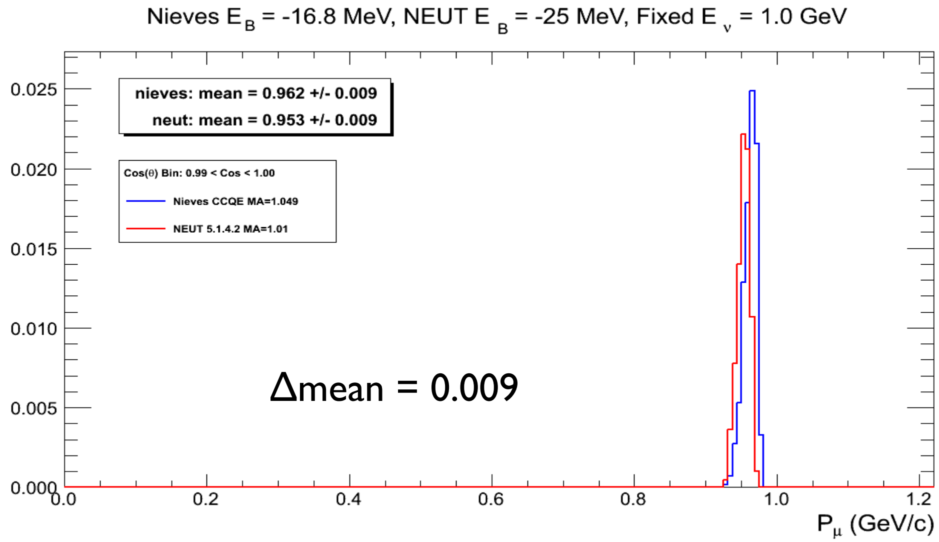
Effects on μ kinematics

A.Cudd

E_ν = 1.0 GeV

0.99 < cos θ_μ < 1.0





Nieves E_b = -16.8 MeV
Neut E_b = -17.0 MeV

Nieves E_b = -16.8 MeV
Neut E_b = -25.0 MeV

Effects on μ kinematics

- Bias in muon momentum for all angles and all relevant neutrino energies.
- Bias is reduced by getting the two binding energies closer.
  - Is model implementation less relevant ?
- Is this a good way to estimate the binding energy from data?
  - More studies about our data sensitivity are needed.

2p2h model & Nucleus

- Nieves model is more “handy” in the case of 2p2h:
  - Cares only about removed energy and the final state is well defined.
- 2p2h is more complex.
  - Potentially 2 initial states (nn & np)
- At the moment, $q_{value} = 0$
  - I need to review the implementation of this model in Nieves 2p2h as I did in 1p1h.