What do we need to improve simulation programs ?

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Disclaimer

- This is not intended to be a comparison of existing MC models.
- Some of the proposals I make are already implemented in certain models.
  - Be proud and do not defend your model!
- Please, look at the overall spirit of the talk and do not fight for model validity.

Nucleus description

- The nucleus description is probably the main source of differences.
- Implementation of :
  - Fermi Momentum.
  - Pauli blocking.
  - Bind energy.
  - Long/short range correlations.
- But also, "ab initio" calculations vs. impulse approximation.

Fermi momentum

- Actually 4 different implementations:
  - Relativistic Fermi gas.
  - Local Fermi gas. (Radial dependency)
  - Spectral functions (for light nuclei)
  - “Ab initio” calculations (non impulse approximation).
- Except for the “Ab initio” all the others can be applied to the usual “impulse" approximation.

MC should be able to run the code for all of them

Not obvious for the “ab initio” calculations.

Pauli Blocking

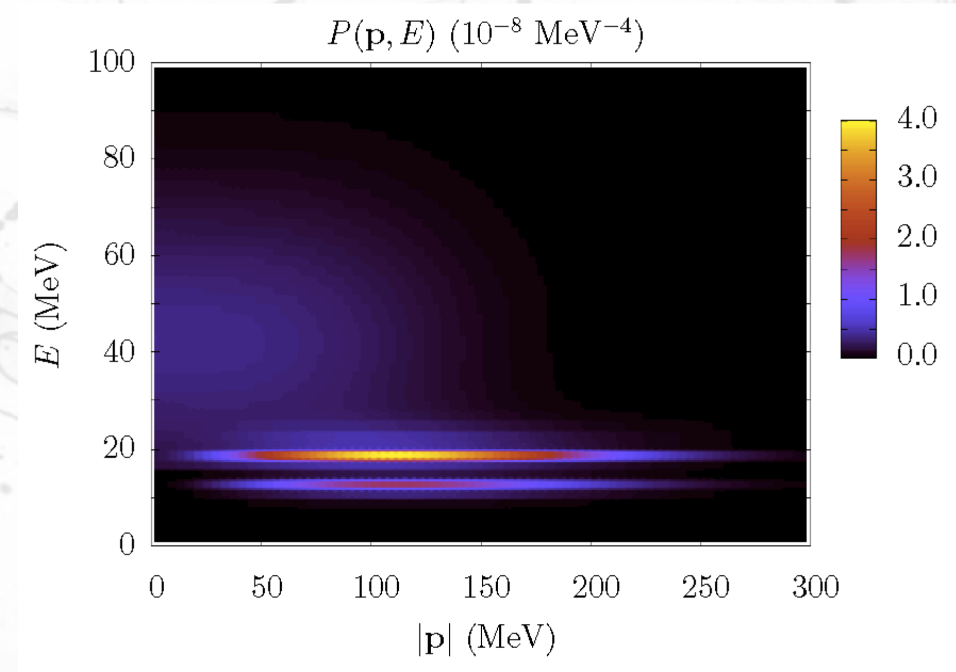
- Same 4 different implementations:
  - Relativistic Fermi gas.
  - Local Fermi gas.
  - Spectral functions
  - "Ab initio" calculations (non impulse approximation).

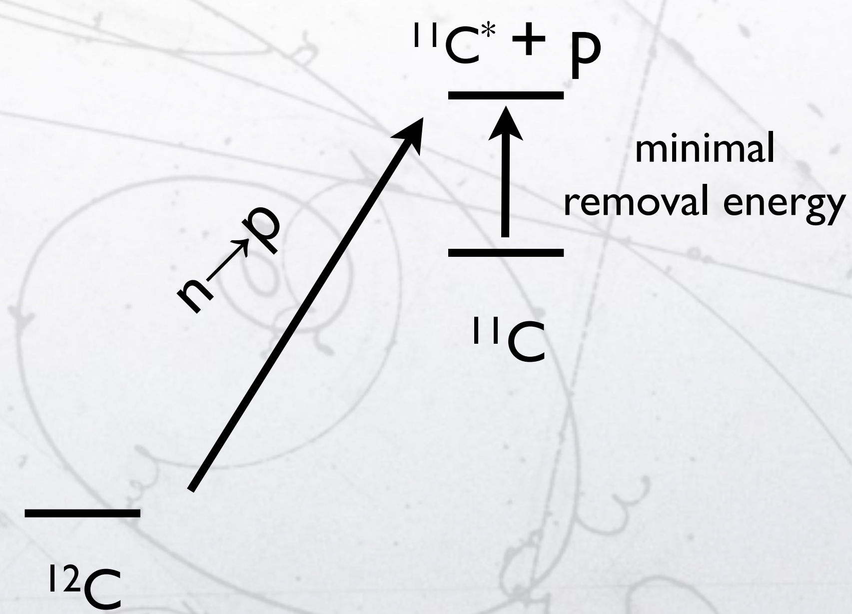
Pauli blocking should be also implemented consistently for the Final State Interactions.

Pauli blocking is delicate to re-weight in case of single Fermi level (RFG).

Bind Energy

- (As far as I know) for impulse approximation there are 3 ways to implement it:
  - Effective target mass ($m \rightarrow m\text{-}E_b$)
  - Dispersion relation (Spectral function).
  - Nuclear removal energy.

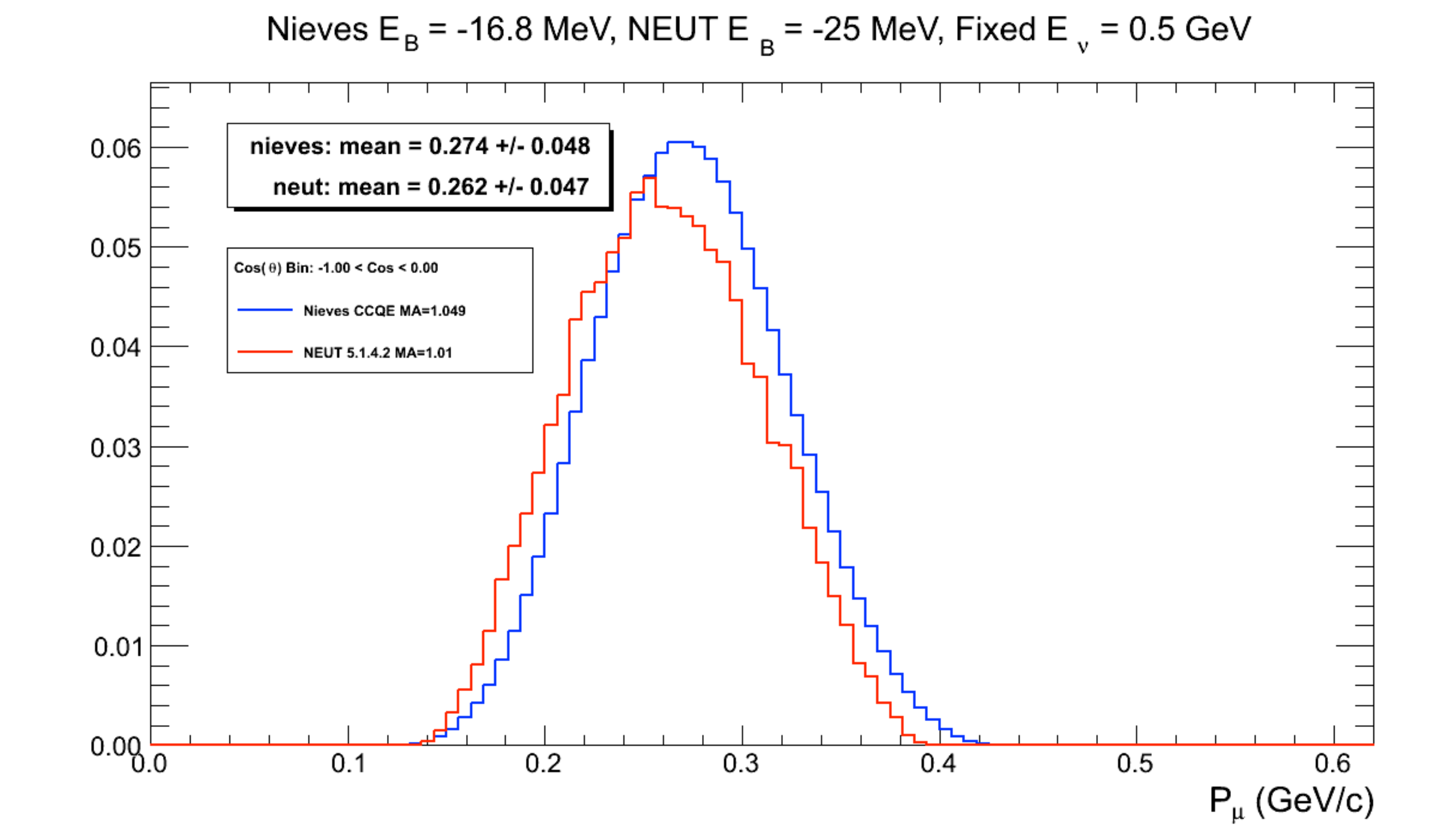




Bind energy is variable because final nuclear states might be excited.

~6 MeV γ in SK

- Effect is visible at T2K energies.
- Since the Bind Energy is not a fixed value (0- 10 MeV) this could smear distributions.



Nieves E_b = -16.8 MeV

Neut E_b = -25.0 MeV

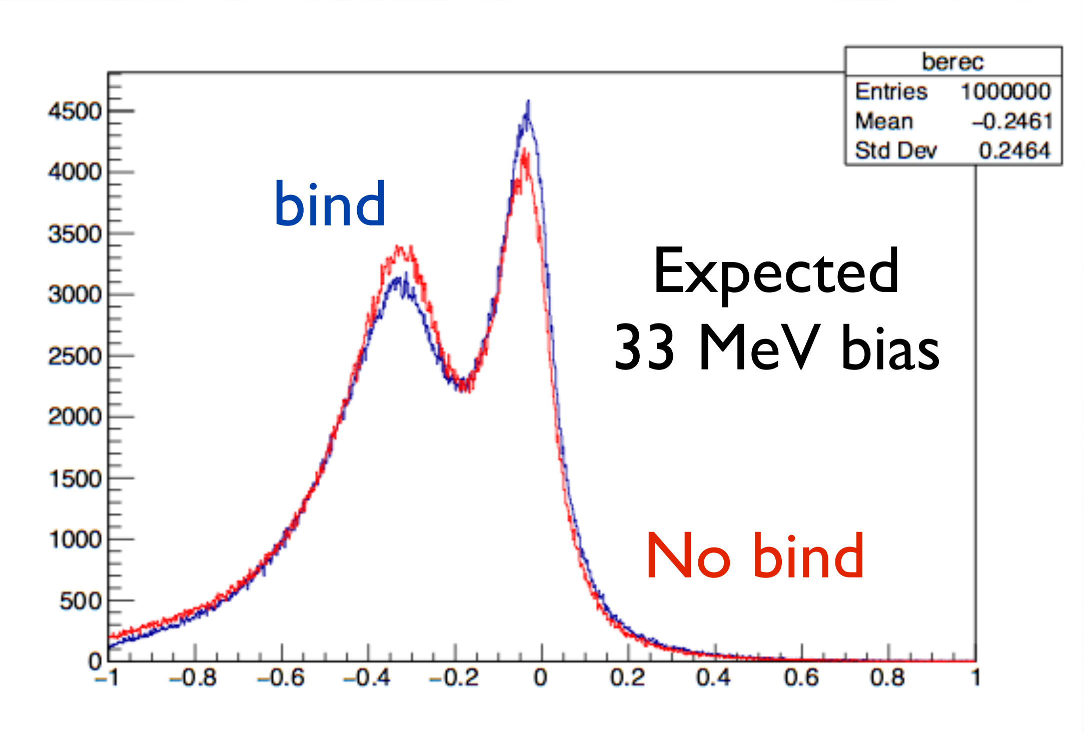
Bind energy is a delicate parameter for event re-weight making calculations complicated.

Bind Energy

- For two body currents, the calculations are going to be different:

$$\nu_\mu + {}^{12}_{6}C \rightarrow {}^{10}_{6}C + n + p + \mu^-$$

- $M_{10C} + m_p + m_n - M_{12C}$ = 24.16 MeV.
- While the $(m-E_b)$ will be of the order of 2 E_b.



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Bind Energy

- And consistent for neutrinos and antineutrinos:

Target	ν	$\bar{\nu}$	NEUT
^{12}C	$^{12}C \Rightarrow {}^{12}C + p$ ΔE =17.43 MeV	$^{12}C \Rightarrow {}^{12}B + n$ ΔE=17.25 MeV	25 MeV
^{16}O	$^{16}O \Rightarrow {}^{16}O + p$ ΔE =14.37 MeV	$^{16}O \Rightarrow {}^{16}N + n$ ΔE=13.48 MeV	27 MeV

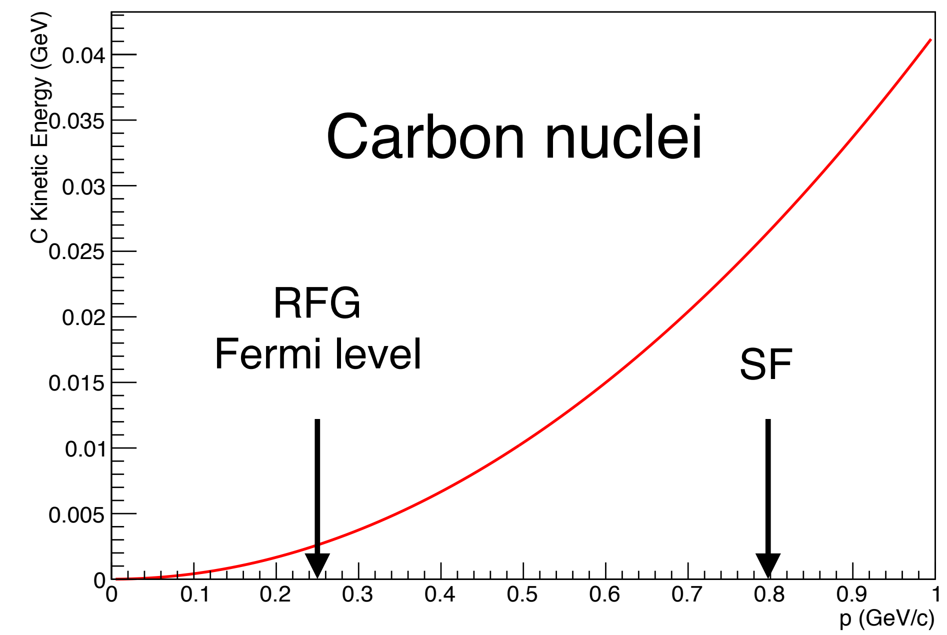
Final state interactions

- Strong interactions are complicated. Many channels, unknown cross-section, resonances, etc…
- Several models:
  - Semi-classical Cascade model with(out) medium corrections based on the old Oset et al.
  - Quantum kinetic transport theory.
- Normally tuned to external data.
  - Assumption: Interactions with nucleons in medium = free nucleons.

Not sure what to do here. We need eA data and probably a direct comparison for the two main models from initial hadrons inside the nucleus.

Vertex activity

- New detector technology (Gas and Liquid TPC's) will require a more precise determination of the activity at the interaction vertex:
  - Low energy nuclear evaporation.
  - Nuclear gamma/alpha de-excitations.
  - Nuclear kinetic energy (also affecting E-p balance)
  - …

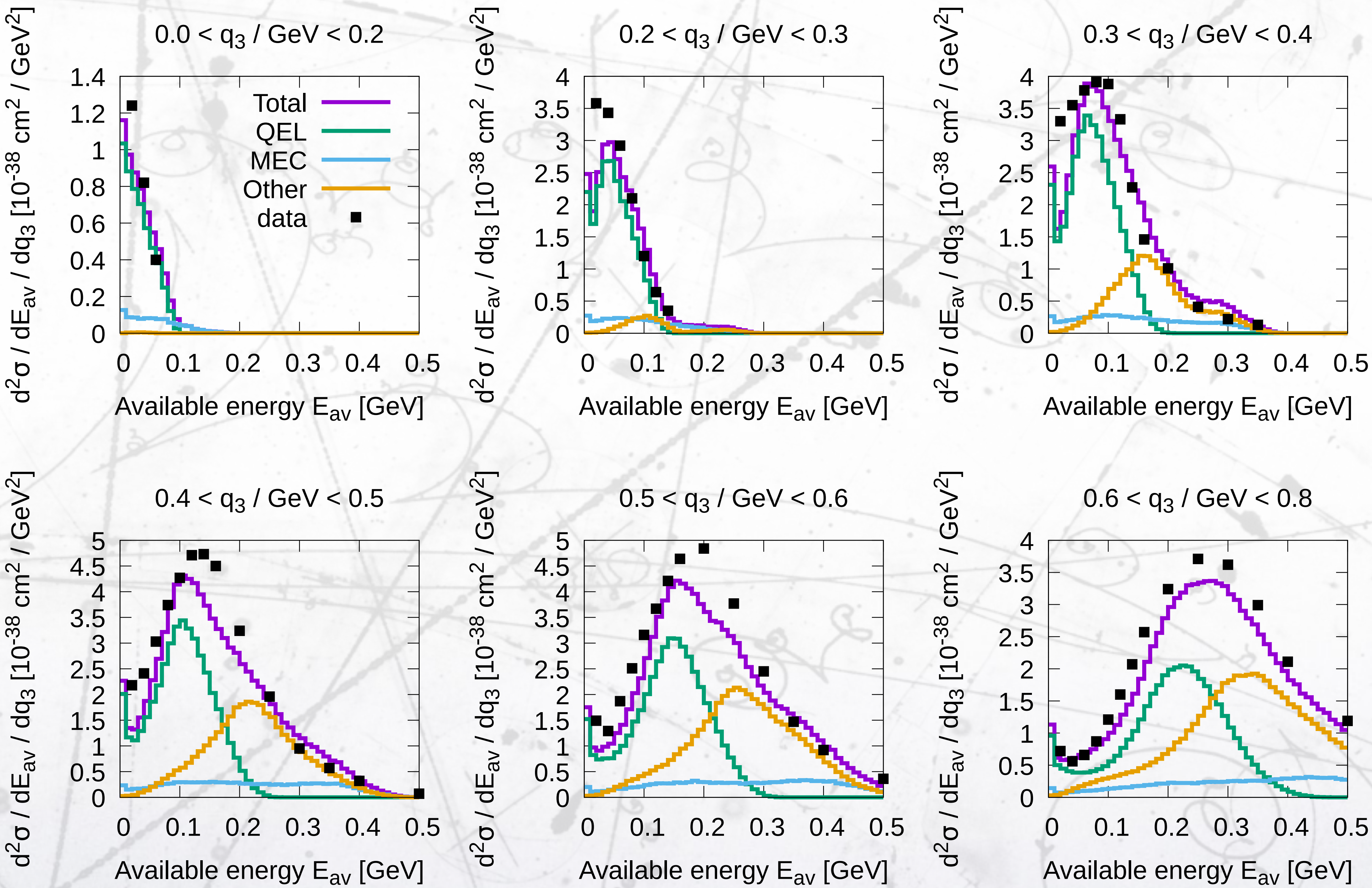


How far are we of this type of implementations?

Sometimes there should be a correlated pair emitted. How?

Are they really needed ?

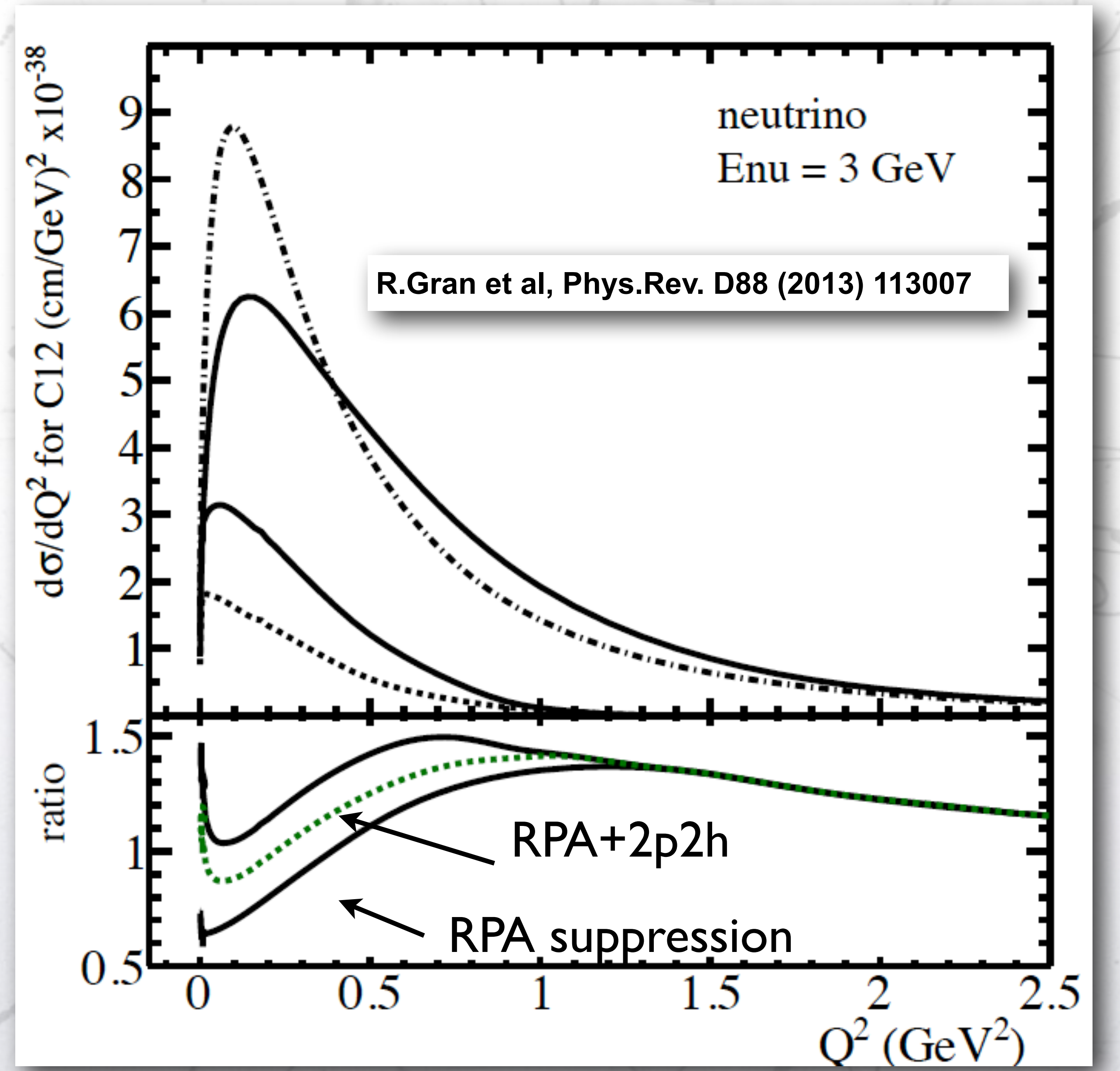
Vertex Activity

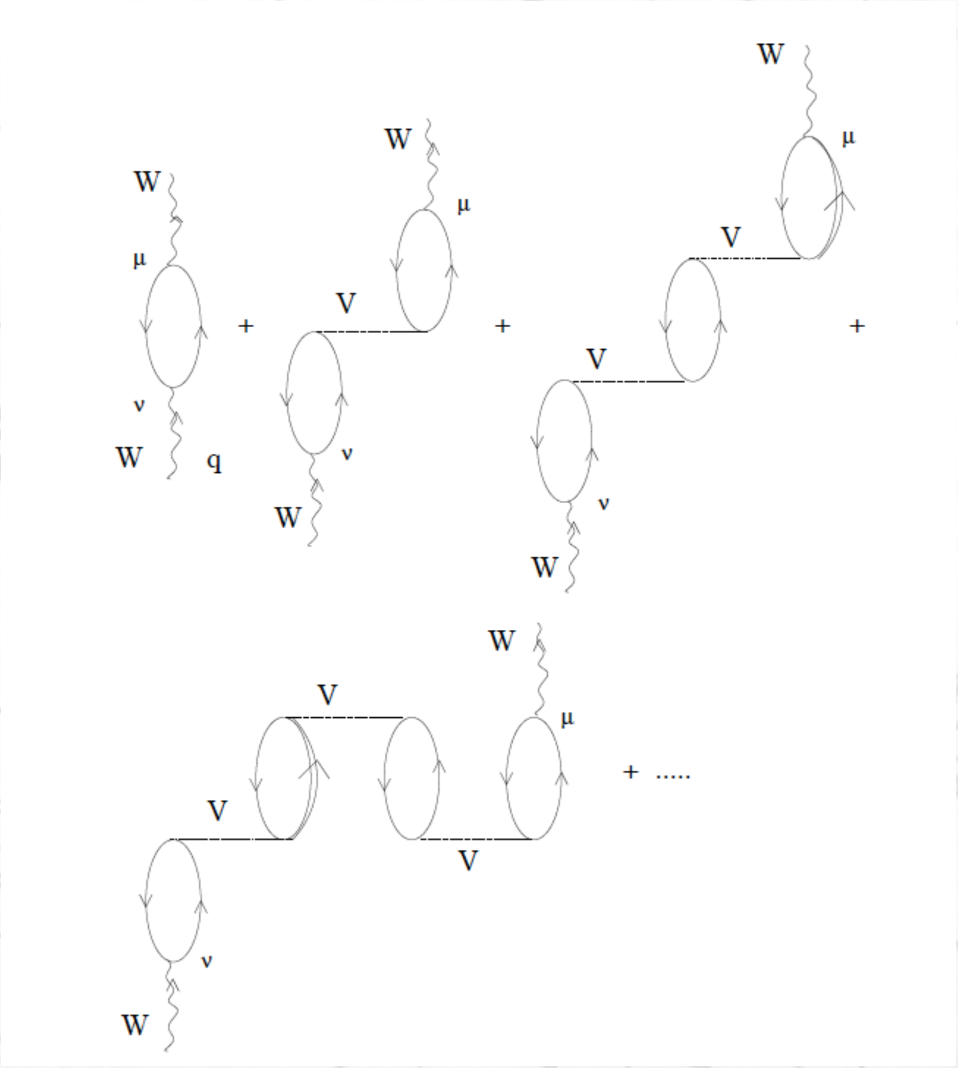


Available energy in Minerva is the sum of proton and charged pion kinetic energy and neutral pion, electron, and photon total energy

Long range correlations

- Based on RPA calculations.

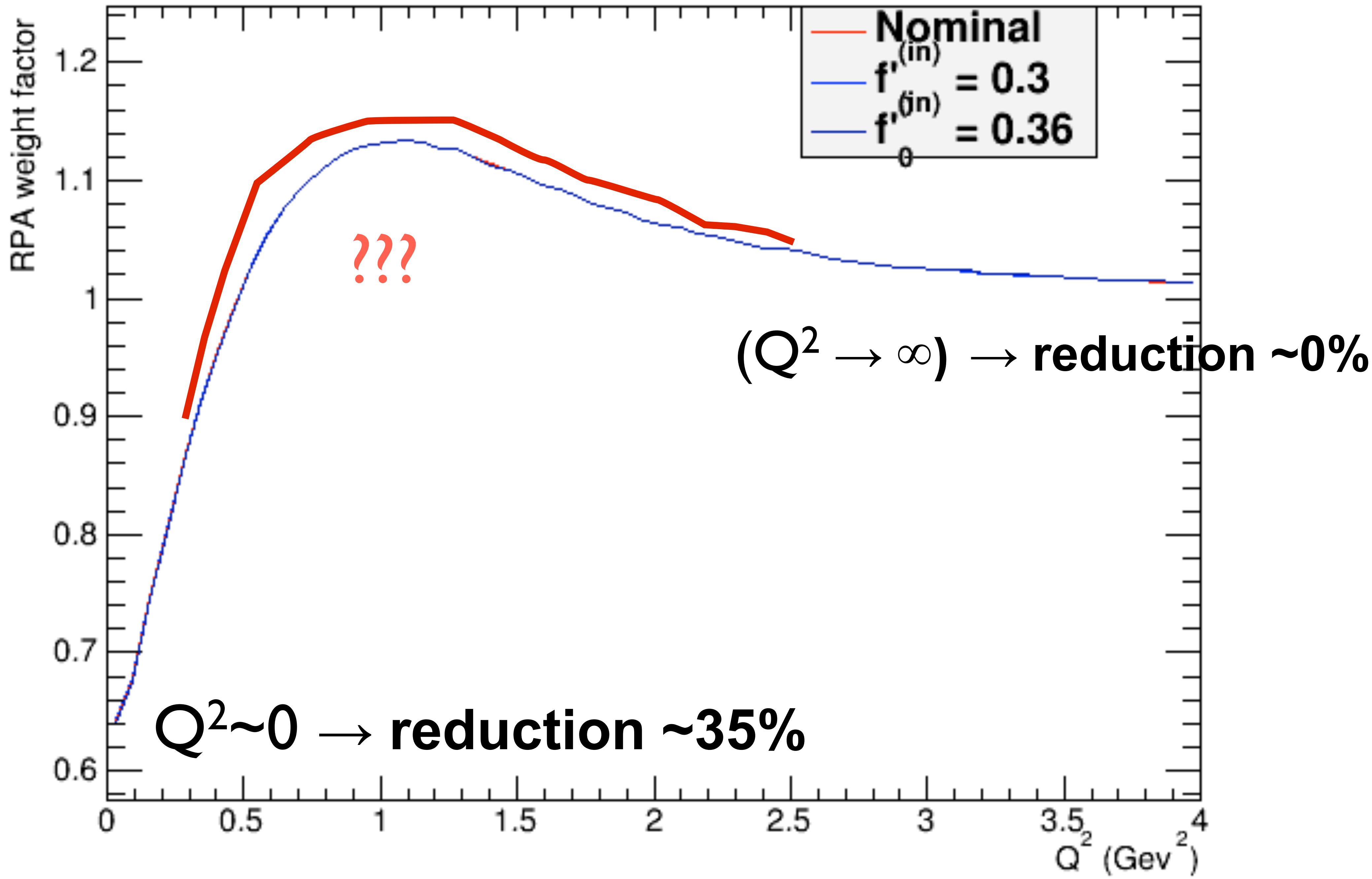




$$V_L^{rel} = 0.08 \frac{4\pi}{m_\pi^2}\left(0.63 - \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2}\frac{q^2}{q^2 - m_\pi^2}\right)$$

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

LRC phenomenology



Long Range Correlations

- Very uncertain in many regions of q^2:
  - MC needs to be implemented with uncertainties.
  - Need data to constrain the parameters.
- Phenomenological calculations points to a multiplicative factors:

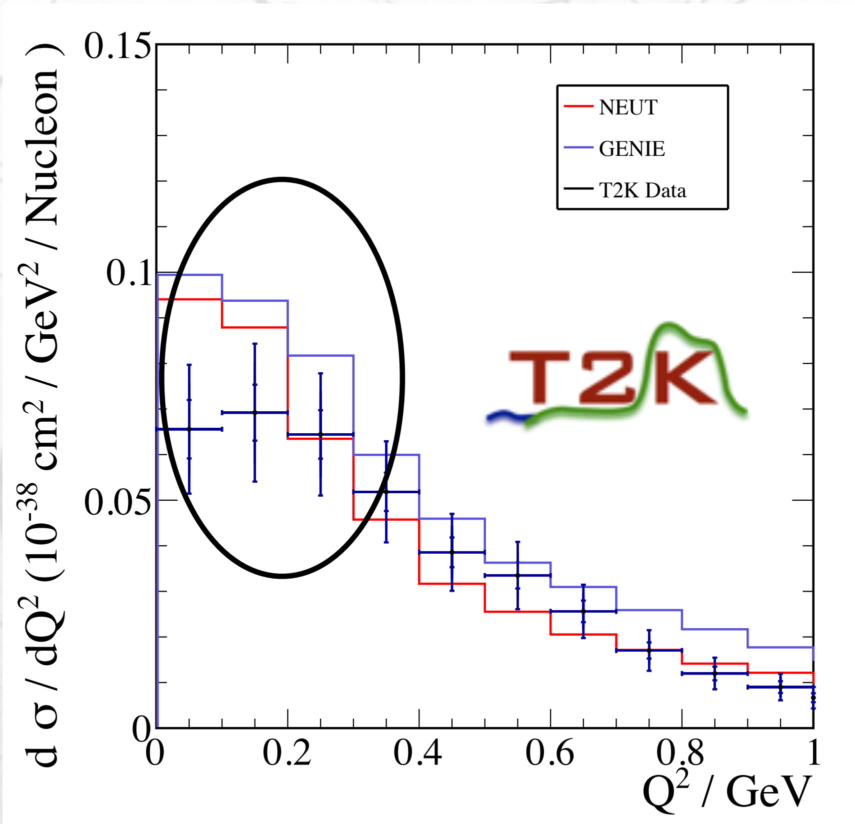
$$\frac{d\sigma}{dq^2} = f_{RPA}(q^2)\frac{d\sigma_{Nucleon}}{dq^2}$$

- But!, this is only computed for CCQE.

Same should be present for CCΔ !!!!

Is $RPA_{CCQE} \sim RPA_{CC\Delta}$?

Calculations needed !



Other stuff

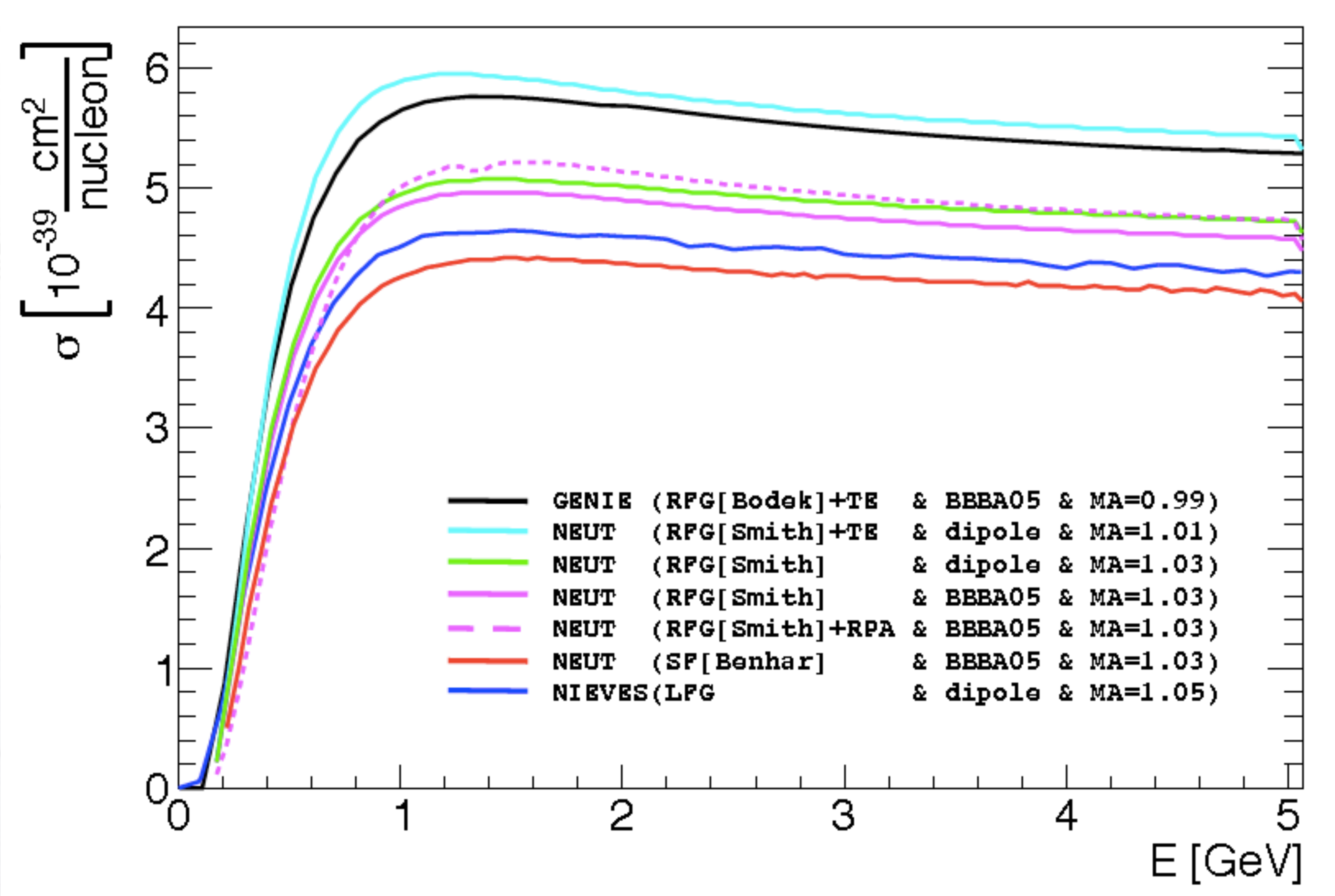
- Coulomb potential corrections:
  - Nieves model implementation predicts ~5MeV shifts in lepton Energy.
- Electron production bremsstrahlung emission.
- Missing channels to which we start to be sensitive:
  - Single gamma emission.
  - …

Impact on experiments to be determined

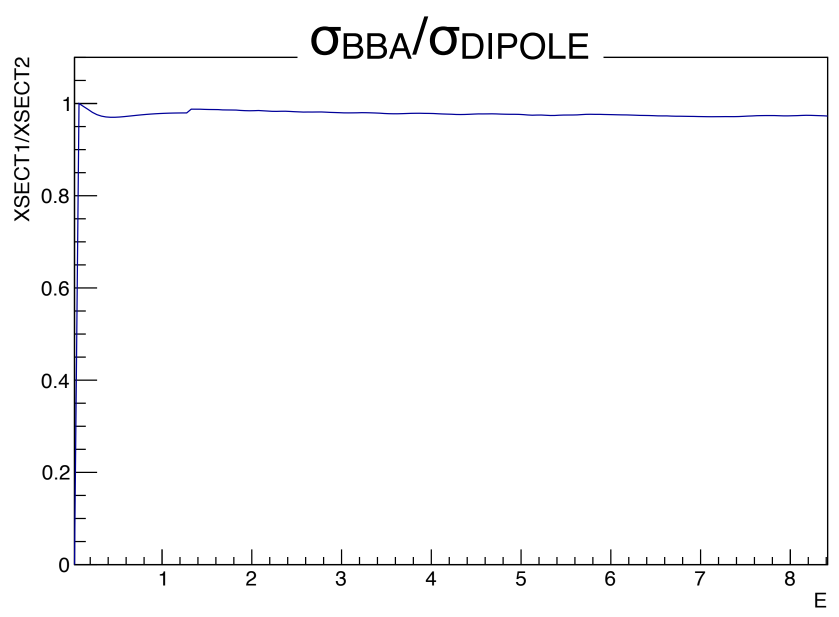
$\sigma(\nu_\mu)/\sigma(\nu_e)$

Background for oscillations

- Do MC models agree at nucleon level ?
- A one to one nucleon level comparison might be enlightening?. Do they already exist ?



Are these differences only Nuclear effects ?



2 body currents

- **CCQE-like two body currents** are implemented in a variety of models:
  - Enhance transverse.
  - microscopic models, …
- Not even similar models provide similar results.
  - Why?
  - Model comparisons are critical here.

Not a solid model in our MC's yet.

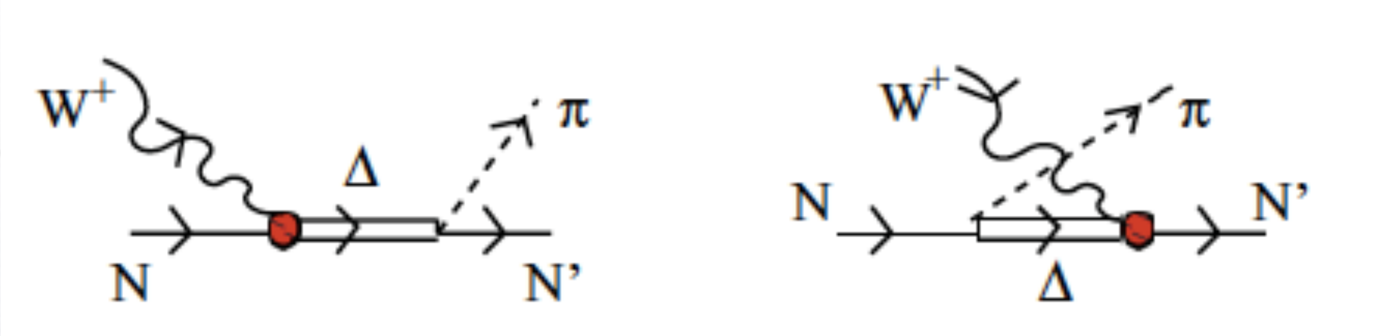
limits in the model? Interpretation of experimental results? …

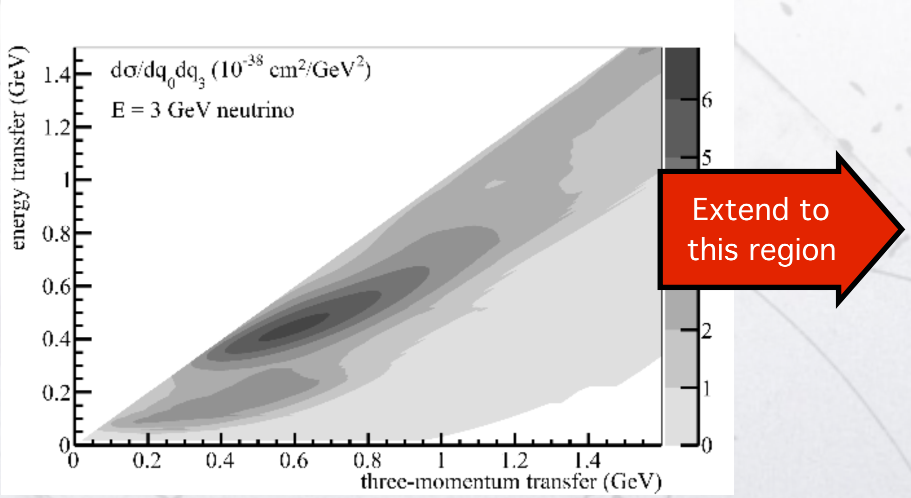
2 body currents

- Similar to CCQE-like there should be some **CCπ-like two body currents.**
  - Two body current with pion emission.
  - Is this relevant ? Can we estimate it ?

We could start with a process similar to the pion-less Δ decay for 2π emission.

- There should be also **CCQE-like with some higher mass resonance** contribution (following the microscopic model):





We need models and implementations in MC.

Δ production

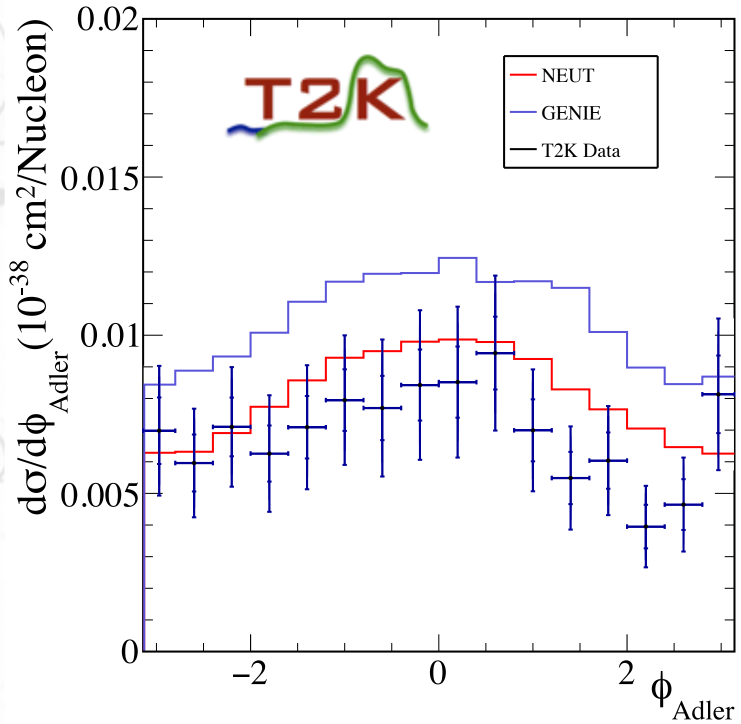
- New data is more and more precise exploring new observables.

  Phys. Rev. D 93 (2016) no.9, 093015

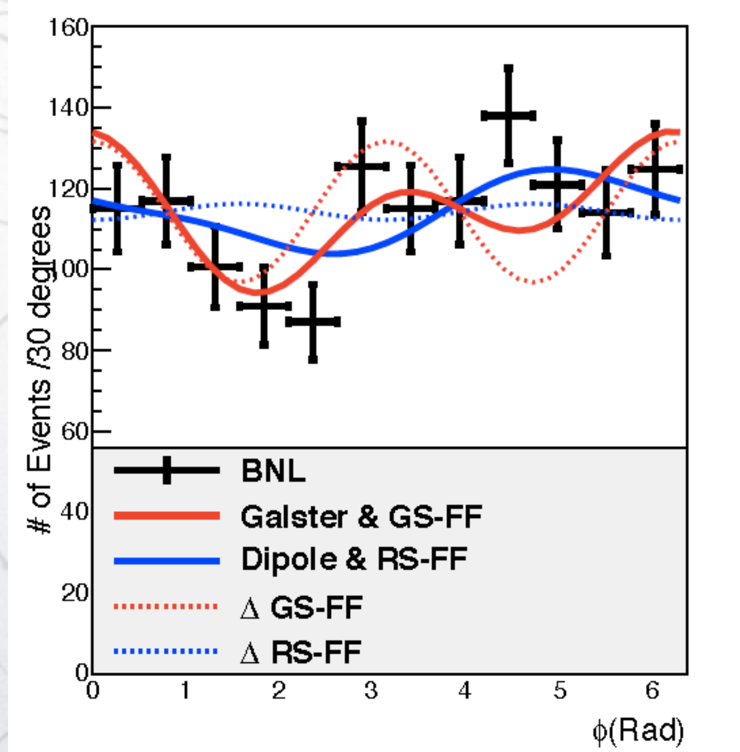
- The "standard" Rein and Sehgal is not able to account for these details.
- New developments by M.Kabirnezhad.
  - Resonant and non-resonant contributions using helicity amplitudes.

https://indico.cern.ch/event/432527/contributions/1071837/

- This development is done already in a way to be included in MC (Neut).



$\nu\, p \to \mu^-\, p\, \pi^+$ (W<1.4 GeV)



And beyond….

- The region above the Δ has been ignored systematically by theory and experiments (except Minerva).
- New generation of experiments will rely on this region to do oscillation physics…

Inclusive models

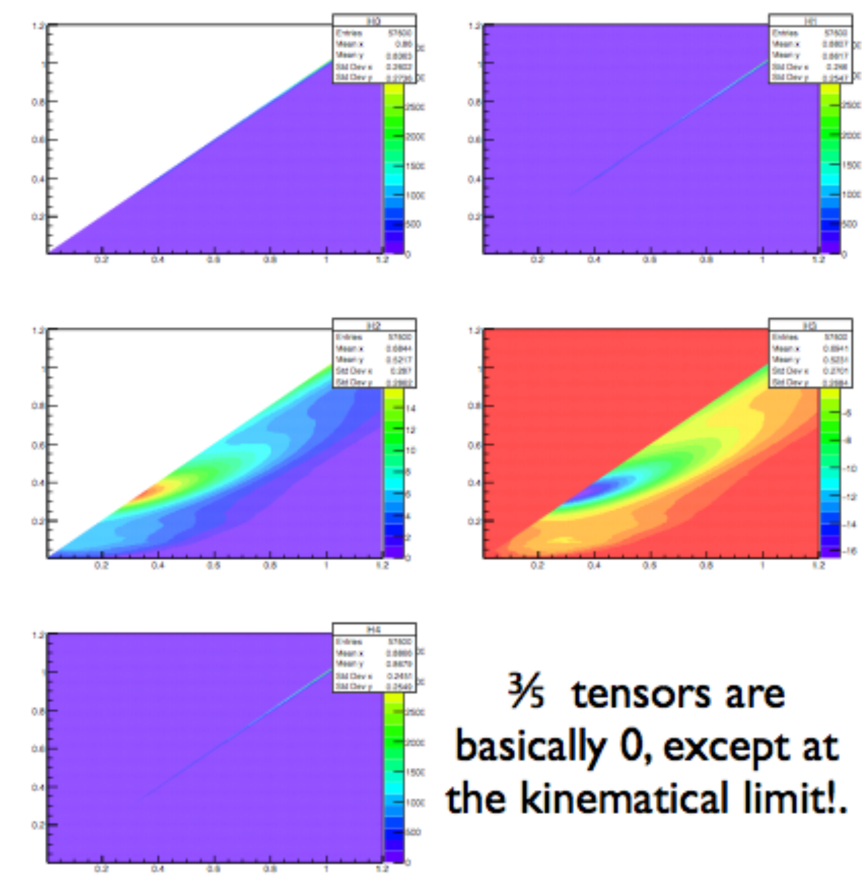
- New inclusive (only lepton kinematics) models available:
  - "Ab initio" calculations.
  - SuSa predictions (with excellent eA & νA agreement).
- Do we include them in our MC?
  - How do we handle them?

Hadron tensor

- The cross-section is a contraction of the Lepton ($L_{\mu\nu}$) and the Hadron tensors ($H^{\mu\nu}$)

$$\frac{d^2\sigma}{d\cos\theta\, dT_\mu} = G\, k'\, k_0' \left| L_{\mu\nu}^{Nieves} H^{\mu\nu} \right|$$

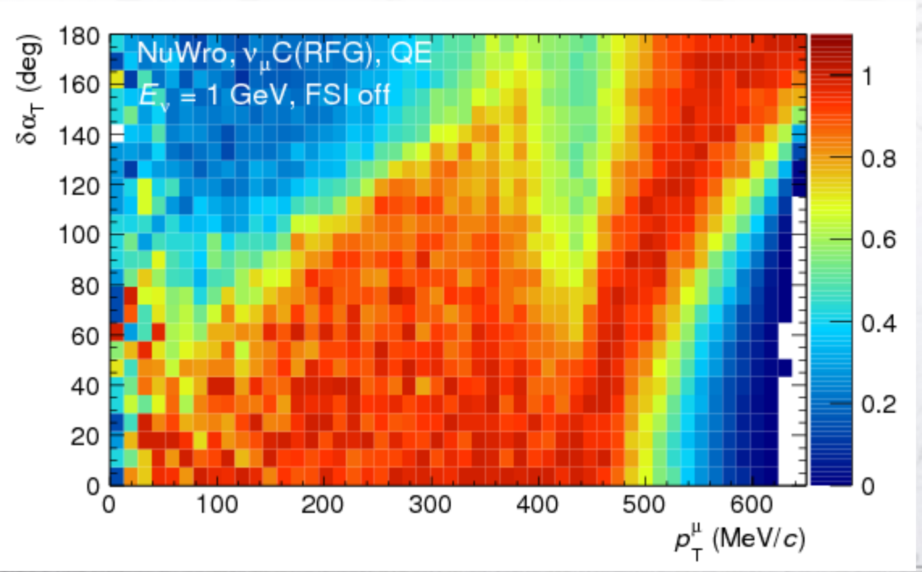
- The Hadron tensor is precomputed in an "slow" MC.
- The Hadron tensor can be computed under several conditions:
  - pp or pn final states.
  - with some model ingredients: Δ, non-Δ, interference, ρ propagator, …
- This can be used to understand contributions or to implement re-weights.



Hadron tensor

- The hadron kinematic prediction is done factorising the problem:
  - Hadron tensor to compute lepton kinematics.
  - Ad-hoc calculations for the hadrons assuming energy and momentum conservation.
- We need to be sure that the calculations are done under the same assumptions: LFG, nucleon pair correlations, etc…

Hadron-lepton correlation is lost. We have to be careful interpreting the results!



Transverse observables using hadron direction and momentum might be wrongly predicted.

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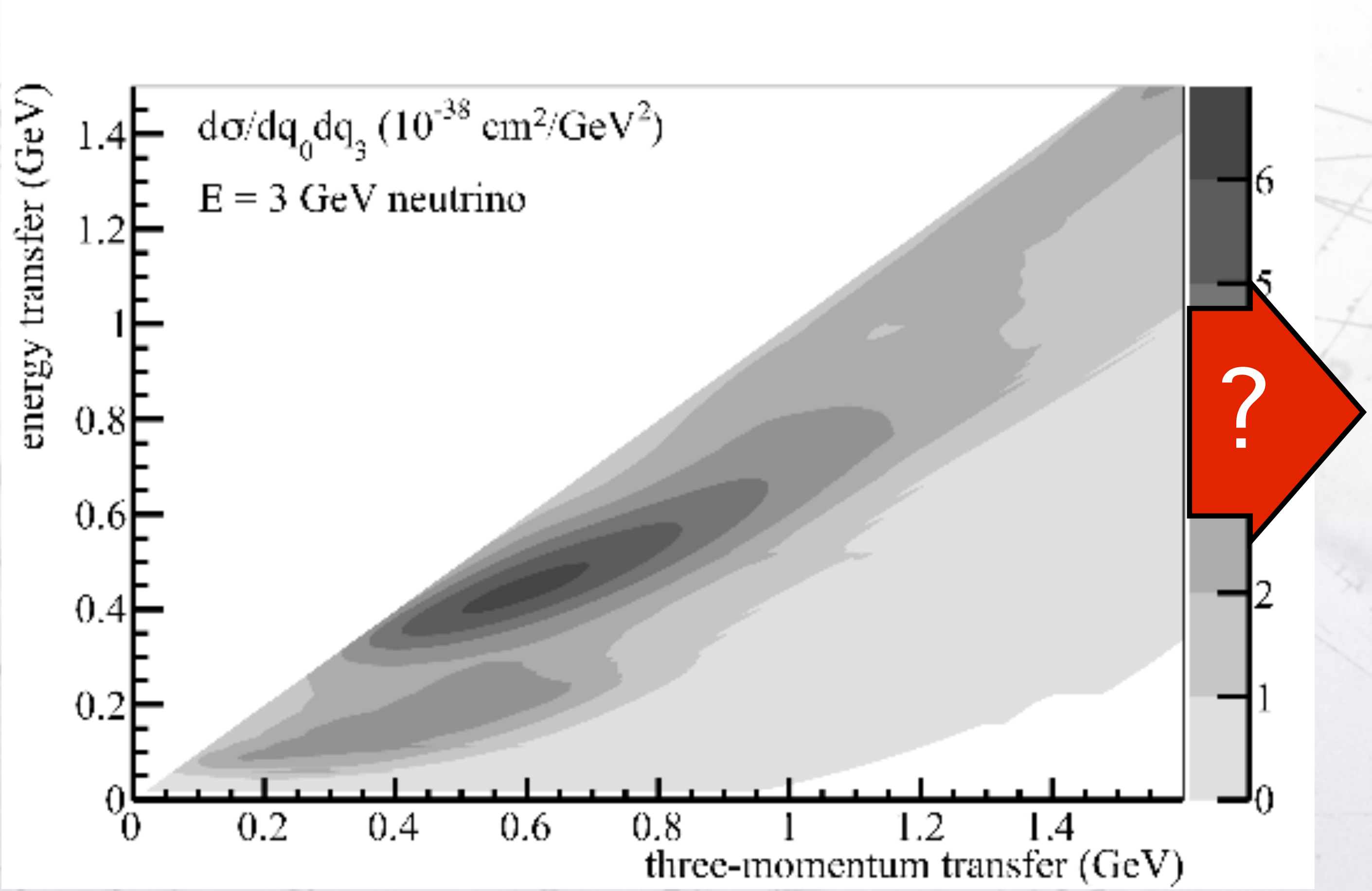
Hadron tensor

- The idea of the Hadron Tensor can be expanded to cases where only the lepton kinematics is predicted:
  - “Ab initio” calculations.
  - SuSa model.
  - …
- This might be a simple universal way to include those models in our MC’s.

I believe that in cases of one body currents and proper hadron initial conditions, the kinematics of the hadrons is accurate on average, except for cases with LFG and radial position.

Limits of models

- The validity of the models is normally restricted to some kinematical phase space.
- This is a critical point for broad band beam neutrino MC's.
- One of the most relevant cases now is the 2p2h.



Not only a limit of the model but also the channels included in the model !

Limits of models

- Is it possible to merge models with some "smart" transition function ?
- As far as I know there is only one case implemented in our MC's with limited impact on the predictions:
  - multipion to DIS transition.

Can we use inclusive and semi-inclusive models to complement this regions?

Double Counting

- This is not a "pure" MC issue but a relevant item.
  - How do we ensure that the there is no double counting in our implementation ?
  - Some examples:
    - Multipion vs. DIS
    - Initial state nucleon-nucleon correlation vs. 2 body currents.

Re-weight

- Partly, the solution to the variation of cross-section parameters is given by the reweighing technique.
  - This is a must for "all" MC in the future.
- Problems with re-weight technique in cases of multiple model applications like the FSI re-interactions.
- Problems in on-off parameters like bind energy or Pauli blocking.
- Not always trivial to implement:
  - in T2K we have parametrised RPA in a simple manner, but this parametrisation is not well maintained when varying the model parameters.

Electron Scattering

- Any future neutrino cross-section experiment should be able to provide also electron-nucleus scattering predictions.
  - eA should be part of the validation of the MC.
- Electron-scattering is and will be a reference data sample to check the validity of models.
  - both at the lepton and the hadron levels.

It is interesting to define a set of electron scattering data as a reference for neutrino MC in the future as part of NUISANCE.

Speed

- New experiments are getting to the level of pileup at the near detector sites.
- New and more complex MC will require more and more CPU time.
    - Hadron tensor approach helps but at a cost.
- We have in neutrino experiments 2 type of events:
    - backgrounds in surrounding material.
    - Interactions in active fiducial volume.

We might need a simplified MC for the backgrounds.

This requieres a full set of developments to ensure the consistency of both.

Closing remarks

- Our MC's show poor agreement with data.
  - A long way to go to have a "satisfactory" MC.
- Many of the actions to be taken are related to model development.
  - Some others can be implemented already now as alternatives. (Bind Energy,…)
- One of the main issues is to have a model valid in full kinematic space.
  - We should explore alternatives to have composed models covering different regions.
- New low threshold experiments will stress our MC models to levels not seen before. This will allow us to improve the model but we also need to improve our MC.
- eA is a must for the future MC code. We will be using more and more eA data to tune our MC and to improve the validity of our predictions.