Monte Carlo & Experiments

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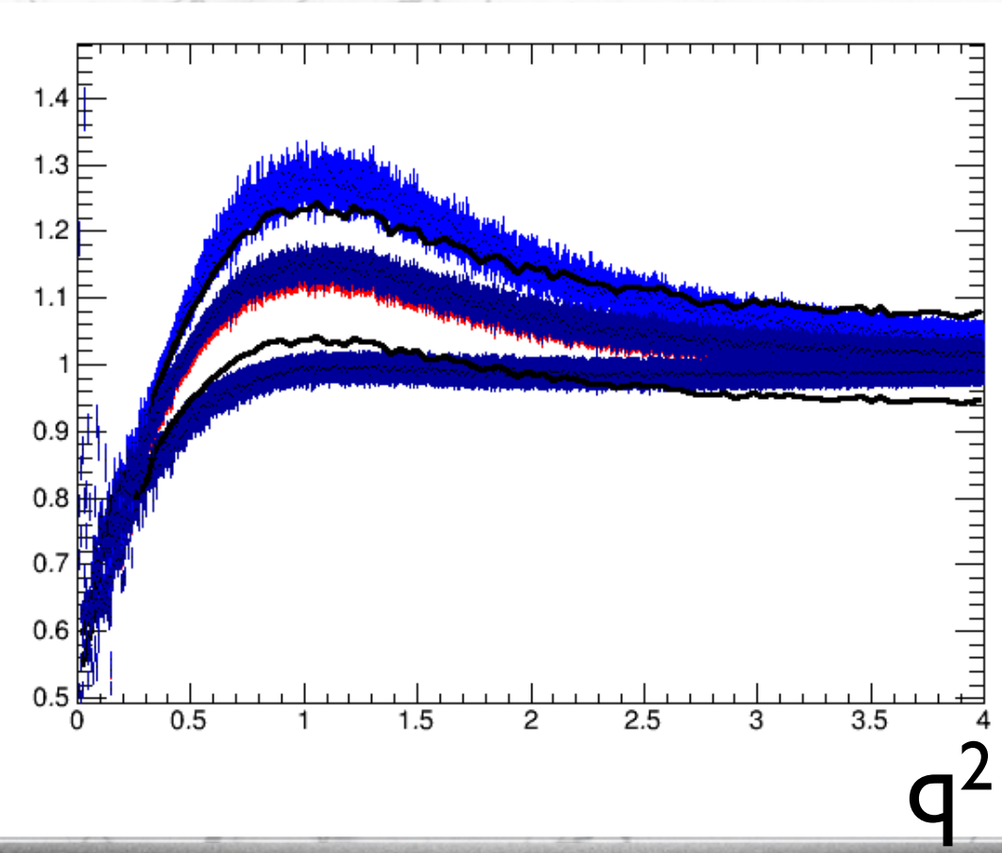
Monte Carlos

- Neut (T2K, SK)
- Genie (Minerva)
- NuWro (T2K & Minerva)
- GiBuu
- Ghent

NEUT - IpIh

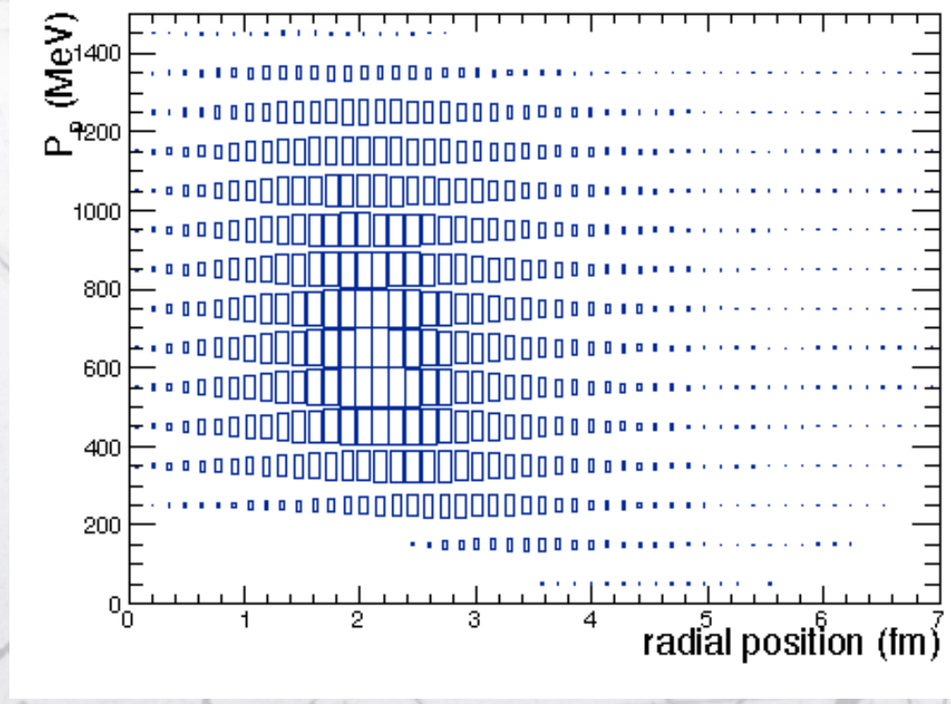
- Implemented a Smith-Monitz with BBA Vector form factors, RFG and RPA weight factor from Nieves.
  - $\sigma_{RPA} = f(q^2) \times \sigma_{Bare}$
- NEUT has also an implementation of Spectral Functions.

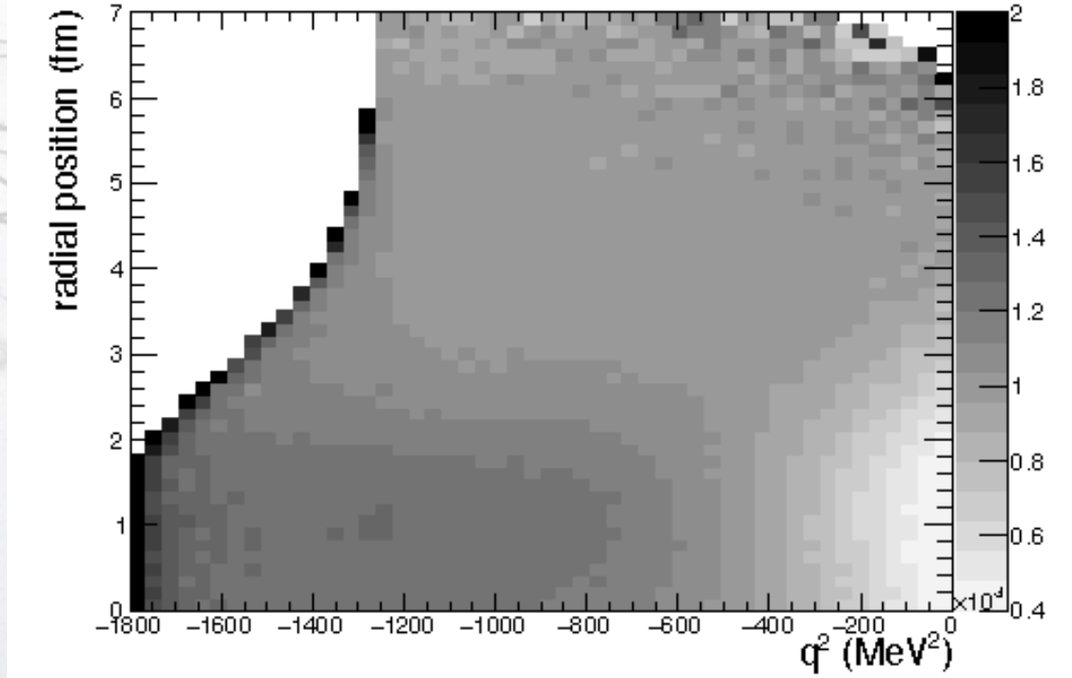
$f(q^2)$



NEUT 1p1h

- Barcelona worked out a 1p1h model based on Nieves (RPA, LFG, etc…) with full kinematics and radial position.
- Plan to include that in NEUT this year to have a "coherent" model.



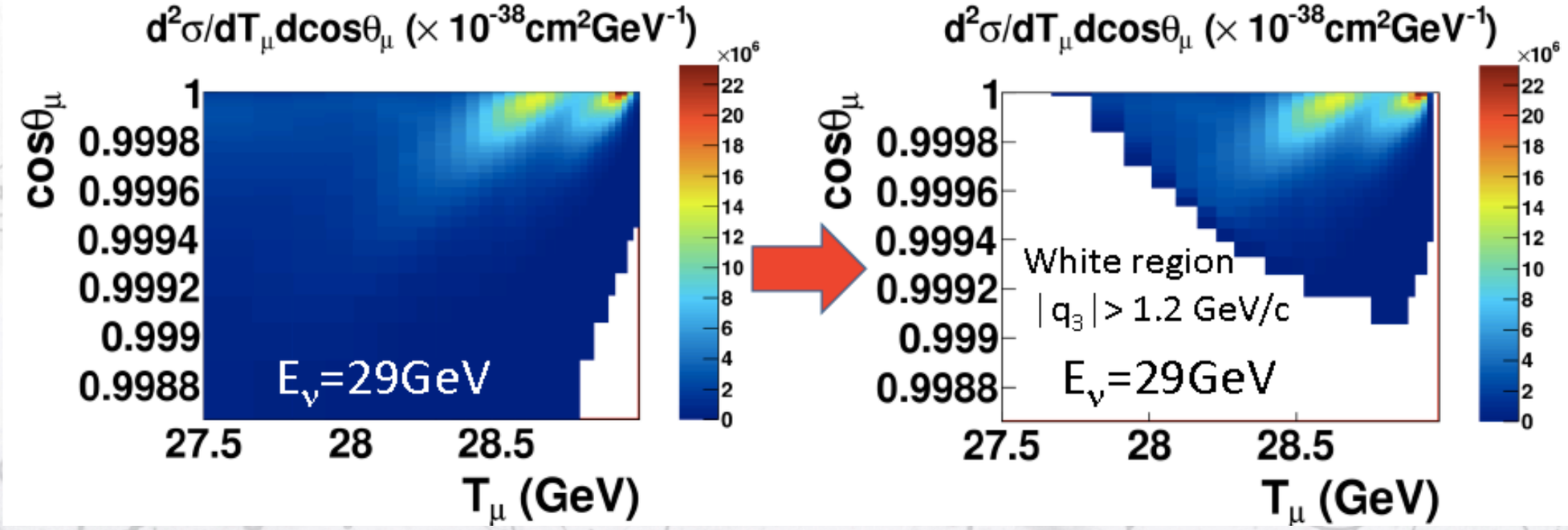


RPA/noRPA

NEUT - 2p2h

- Lepton kinematics (T_μ, $\cos\theta_\mu$)
  Use pre-calculated 2D lookup table.
  (Because of this,
  only ^{12}C, ^{16}O and ^{40}Ca are included.)

Apply $|q_3| < 1.2$ GeV/c constraint



Cross-sections tables as function of (E_ν,p_μ,θ_μ)
Proton kinematics based on Jan's model.
Based on Nieves model ….. because it was available

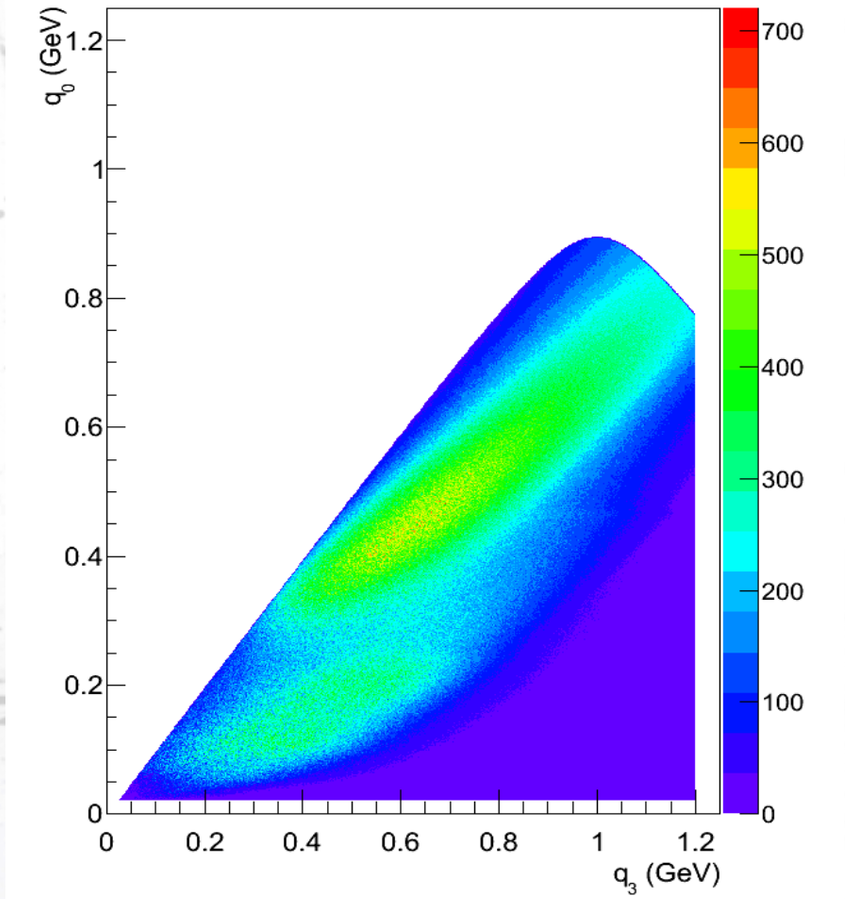
Genie IpIh

- Same approach as T2K:
  - $\sigma_{RPA} = f(q^2) \times \sigma_{Bare} + \sigma_{2p2h}$
  - $f(q^2)$ & σ_{2p2h} are the same although in a different implementation.
  - σ_{Bare} is different.
  - FSI is different !!!!!!

Genie 2p2h

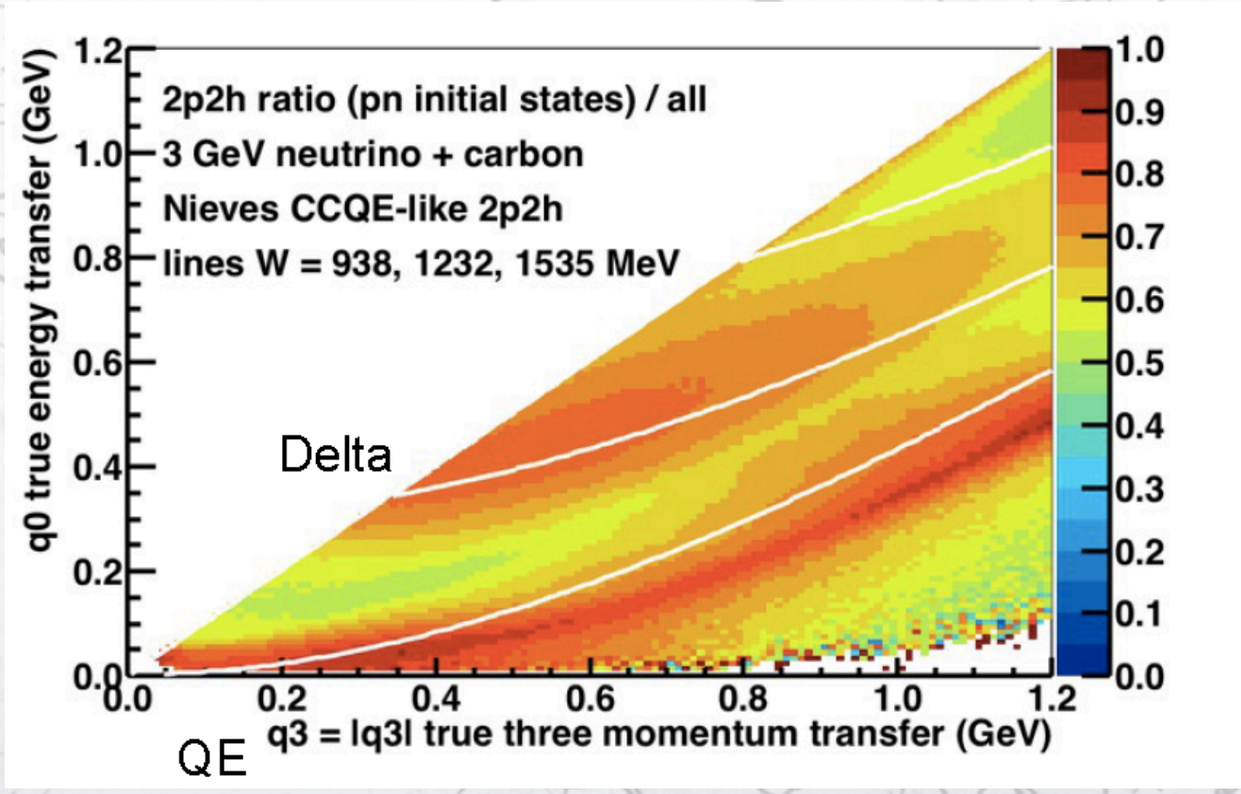
- Based on the Nieves model with Jan's proton kinematics.
- Many improvements with respect to Neut:
  - It uses the Hadron Tensor approach to facilitate the computation.
  - It computes pn / pp ratio according to model.
  -

Genie Hadron Tensor



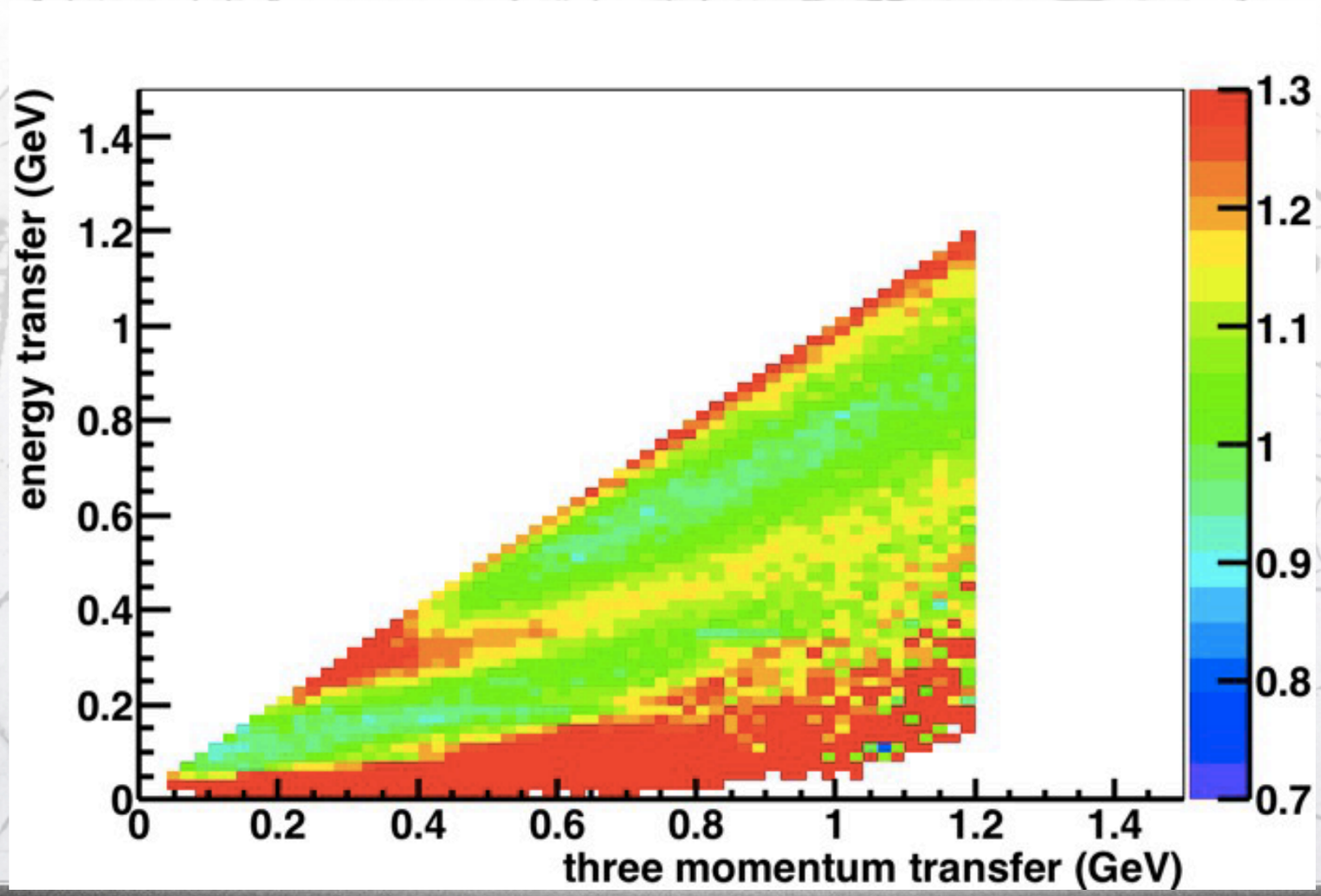
You can plug your favourite model in form of hadron tensors!.

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE'_l} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$



Genie

- Model to go beyond isoscalar:
  - re-weight isoscalar cross.section by the corresponding pp/pn ratio).
  - Change the nuclear Qvalue (1MeV Ar, 14 MeV Ca).



NEUT vs. GENIE

- Since the origin of both models is the Valencia model, they are too similar:
  - this is good on one hand.
  - NEUT needs to adopt the GENIE developments (in progress).
- We need new models to challenge these ones:
  - GIBUU
  - GHENT

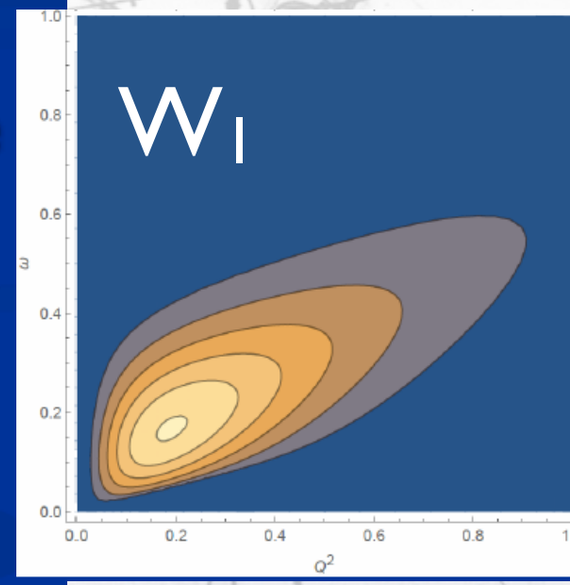
GIBUU

- Very different approach.
- Self-consistent model (beyond CCQE-like)
- Local Fermi Gas.

- Obtain 2p2h structure function W_1 for electrons from experimental fit of MEC contribution by Bosted and Mamyan (arXiv:1203.2262) and Christy (priv. comm.), pure transverse

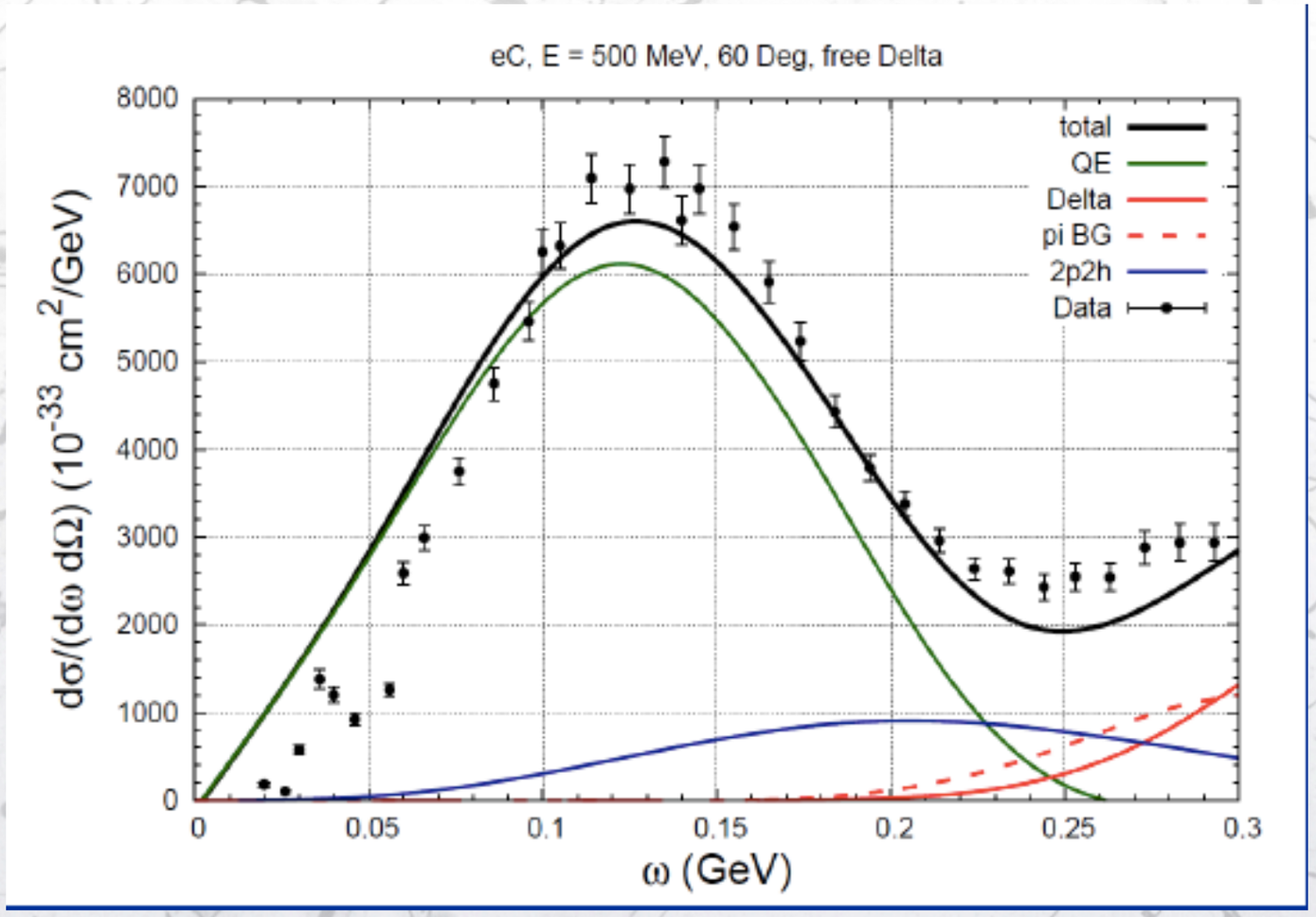
$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2}{Q^4} E'^2 2 \left(\frac{Q^2}{2\vec{q}^2} \cos^2 \frac{\theta}{2} + \sin^2 \frac{\theta}{2} \right) W_1(Q^2, \omega)$$

- 2 incoming target nucleons are chosen at same location, but different momenta < p_F
- 2 outgoing nucleons are chosen according to phase-space, and then propagated out



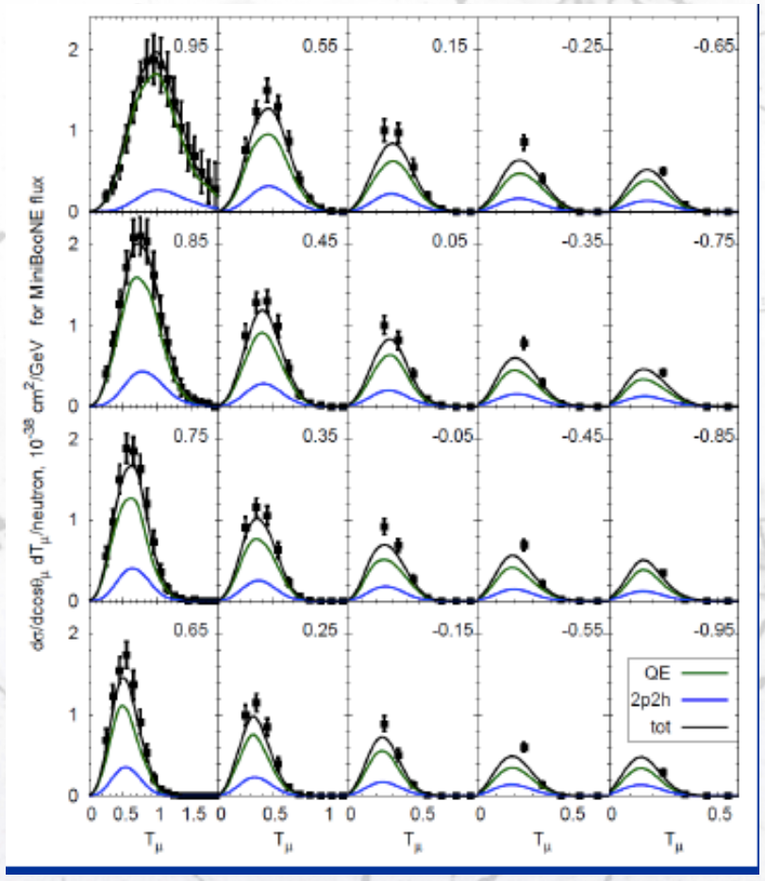
GIBUU

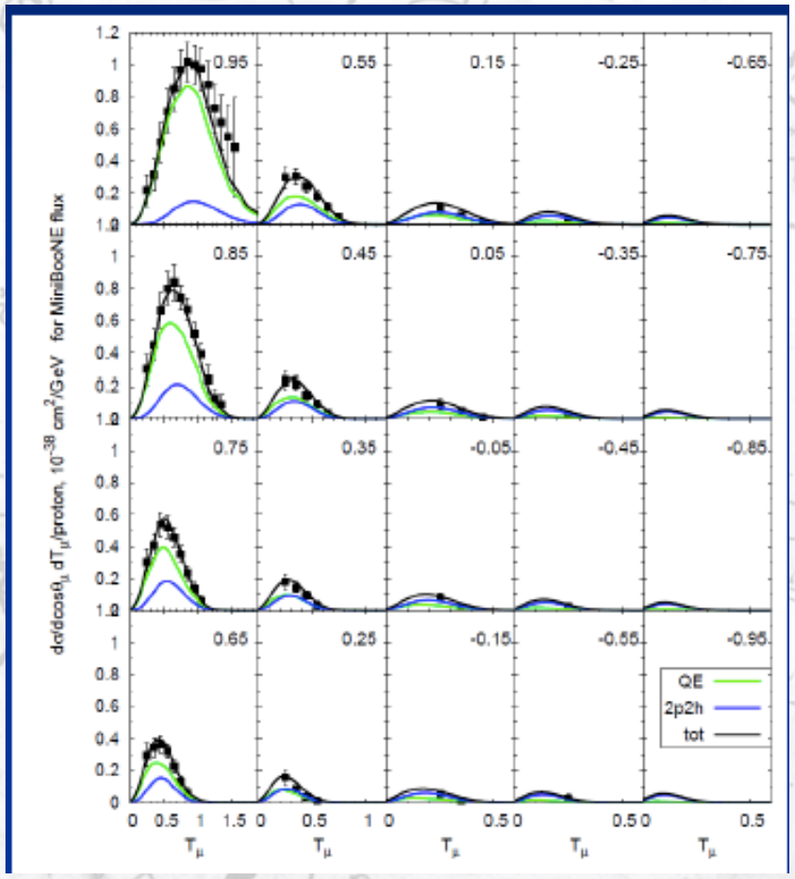
- Tested against electron data !!!!!
- MC should be able to predict both νA and eA.

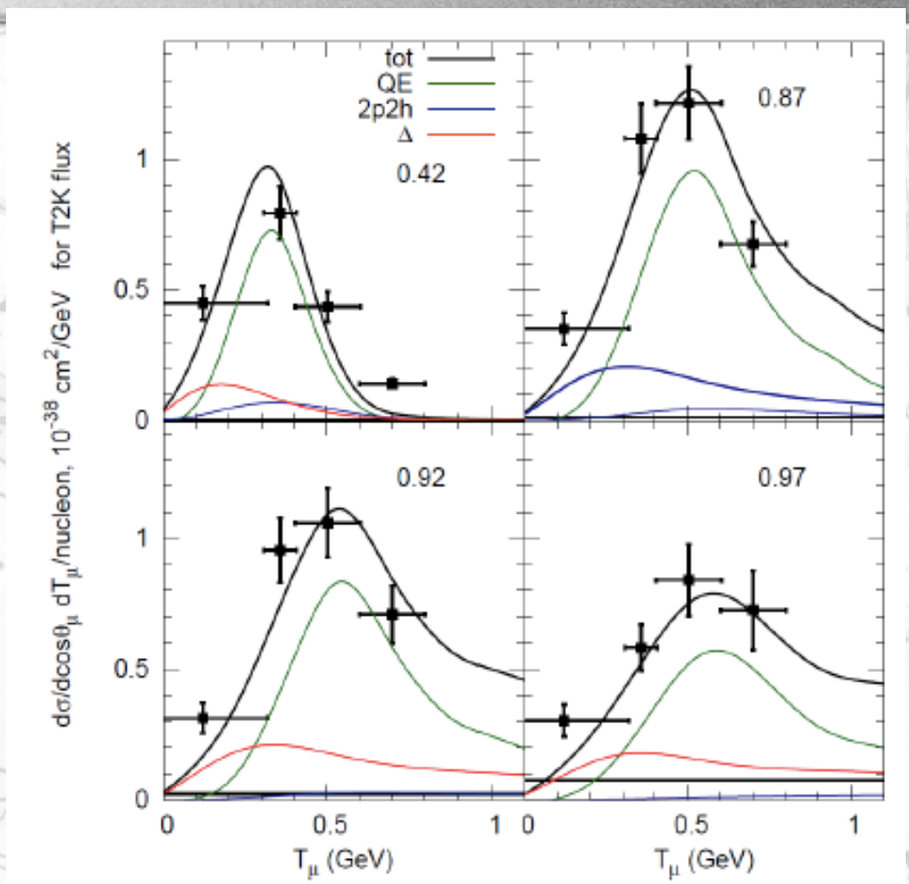


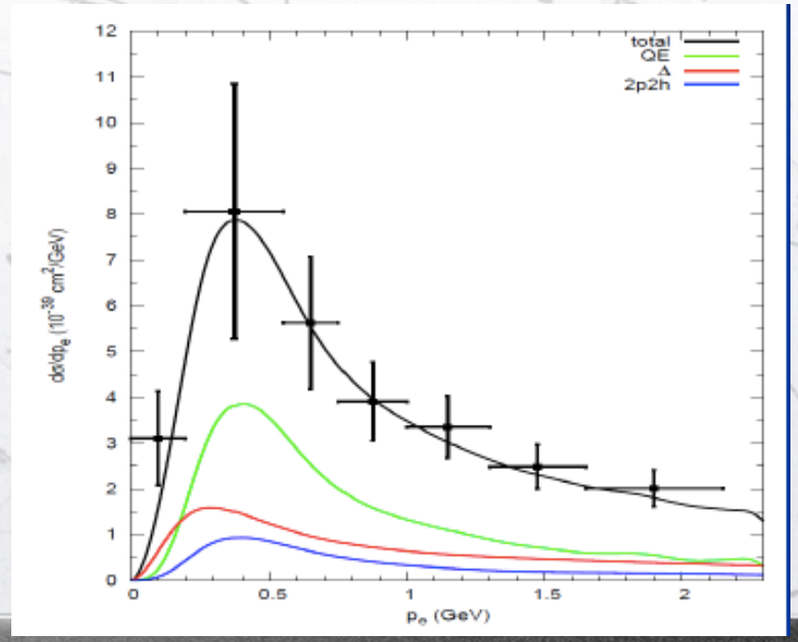
GiBuu

- And (anti)neutrino data



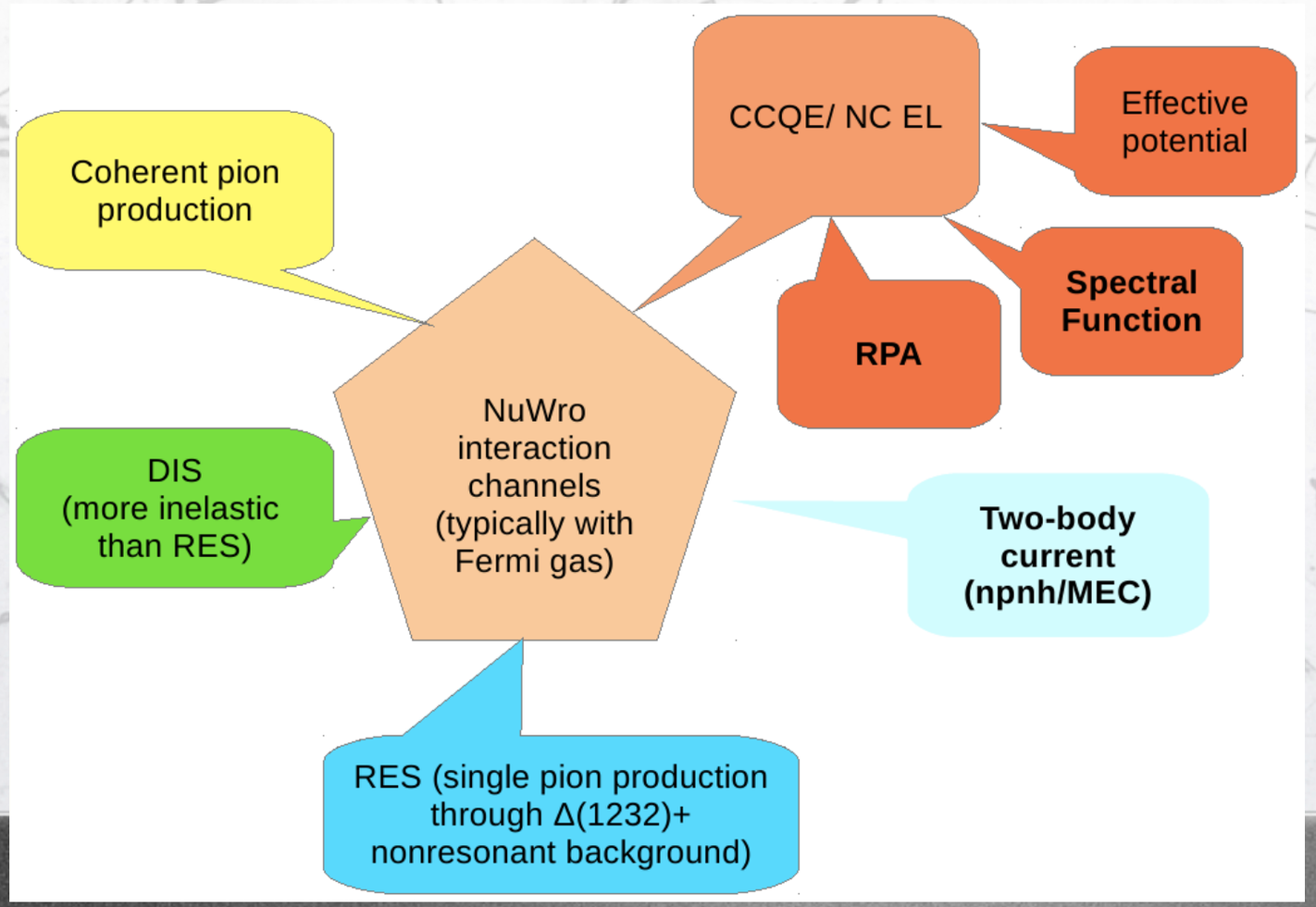






NuWro

- Full MC with many reactions with all ingredients.
- Two models for 2p2h:
  - Nieves
  - transverse enhance model (close to GiBuu model?)



Adopted by T2K and Minerva

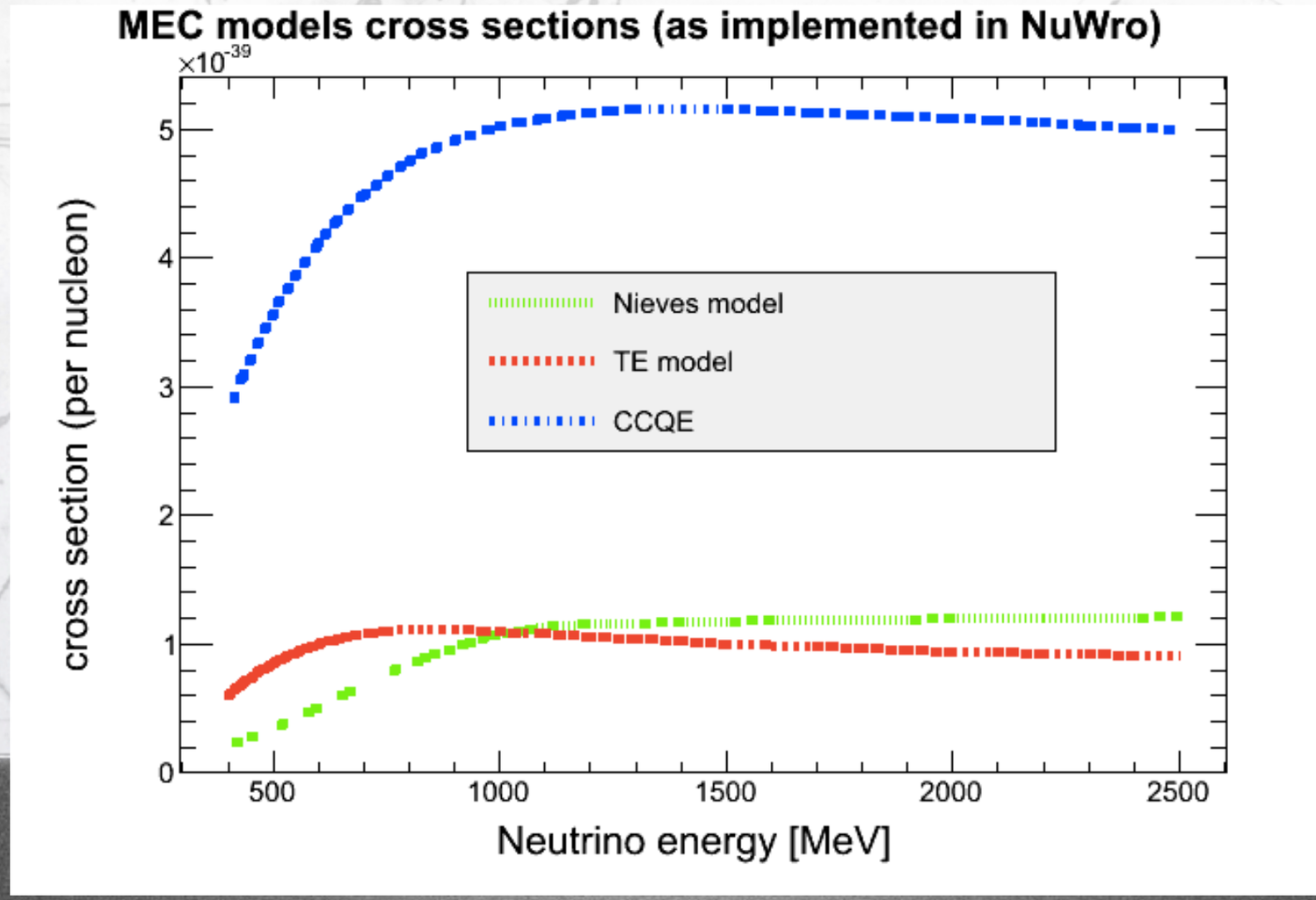
NuWro

- Nieves implemented through hadron tensor.

TE implementation

$$G_M^{p,n}(Q^2) \rightarrow \tilde{G}_M^{p,n}(Q^2) = \sqrt{1 + AQ^2 \exp(-\frac{Q^2}{B})}\, G_M^{p,n}(Q^2)$$

where $G_M^{p,n}(Q^2)$ are electromagnetic form-factors, $A = 6$ GeV^{-2} and $B = 0.34$ GeV^2.



NuWro hadrons

- Implementation of the hadrons (similar as in NEUT and GENIE)

1. q^0 and q are selected; probability distribution is given by double differential cross section (either TE or Nieves model)
2. two initial state nucleons are found based on some assumptions (to be discussed later)
3. hadronic system (both nucleons and 4-momentum transfer) is boosted to its rest frame
4. final state nucleons momenta are selected
5. nucleons are boosted back to the laboratory frame
   - if Pauli blocking condition is imposed the steps (4, 5) are repeated until a configuration is found with both nucleons above the Fermi level
6. both nucleons propagate through nucleus.

- New parameter is added now to choose the preferred direction wrt the momentum transfer to enhance momentum asymmetries.

Ghent

- Ghent group has anounce a MC for 1p1h and 2p2h including final state predictions.
  - we need to work to compare this with previous models and….
  - build a MC for it.

MC review

- Experiments need Monte Carlos that are:
  - Available.
  - Fast (enough)
  - Full kinematics.
  - As many nuclei as possible including non-isoscalar.
  - With access to basic parameters to “tune/adjust”
  - It should come in νA and eA modes!.

Experiments

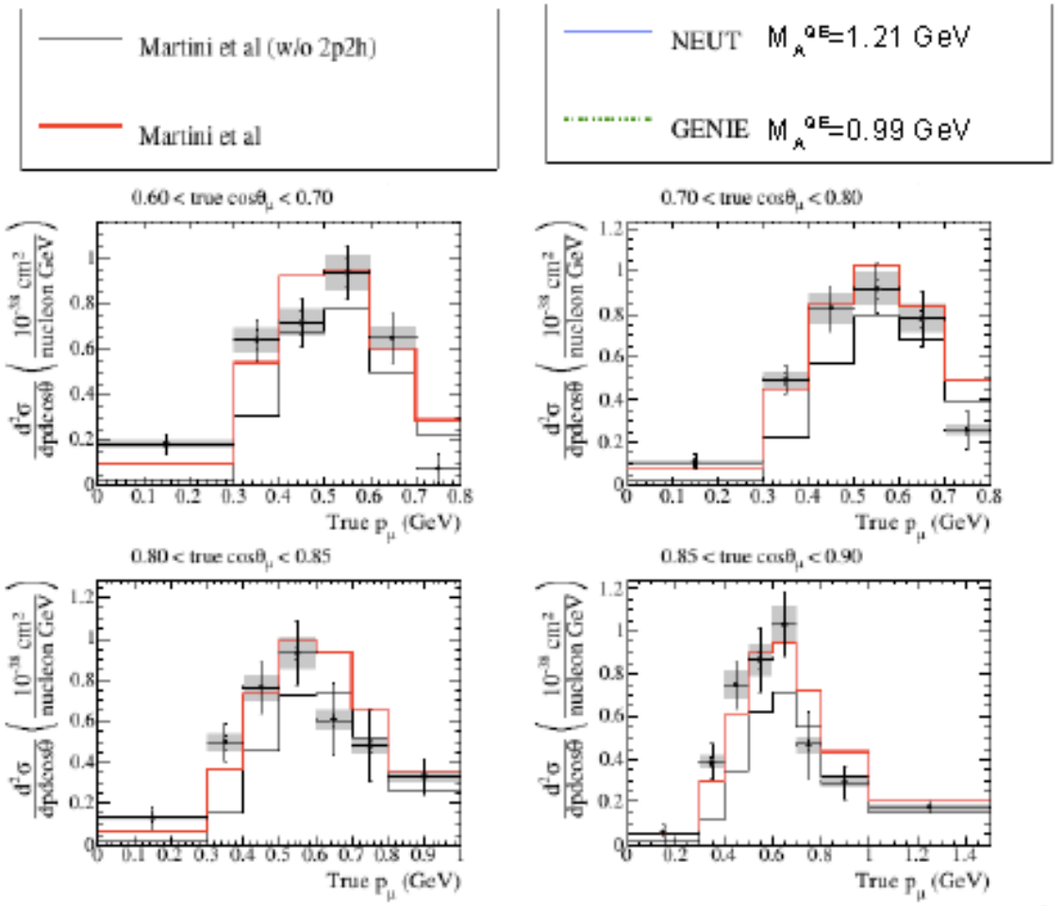
- T2K.
- Minerva.
- Models and experiments.

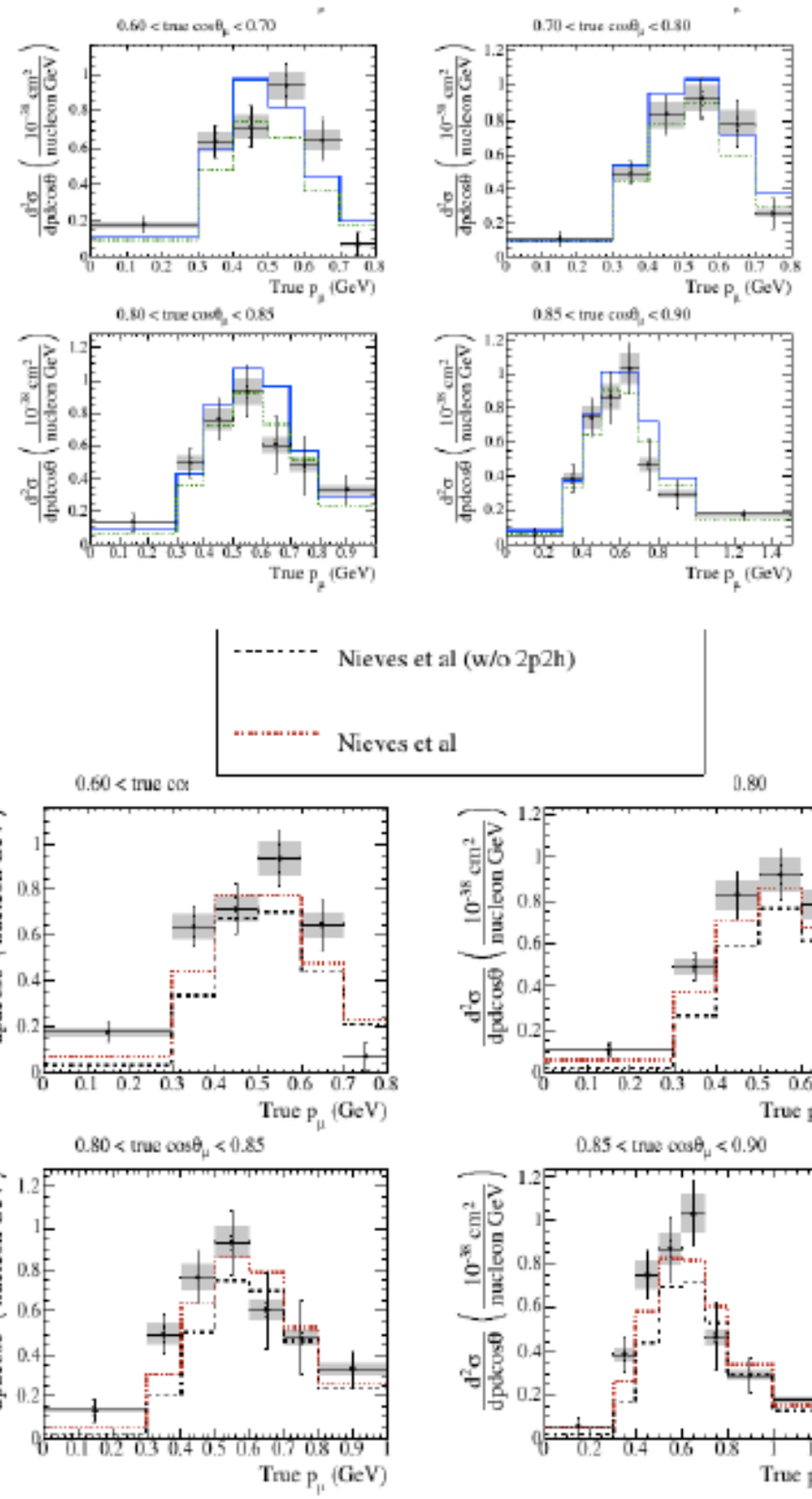
T2K

- T2K uses basically a selection of events with no pion in the final state.
- There is some pion background remaining from bad tagging and FSI.
- No condition on hadronic state beyond that.
- Checks the muon kinematics.
- Comparisons with Nieves and Martini models based on event reweight! Not ideal! .

T2K

CC0π T2K measurement





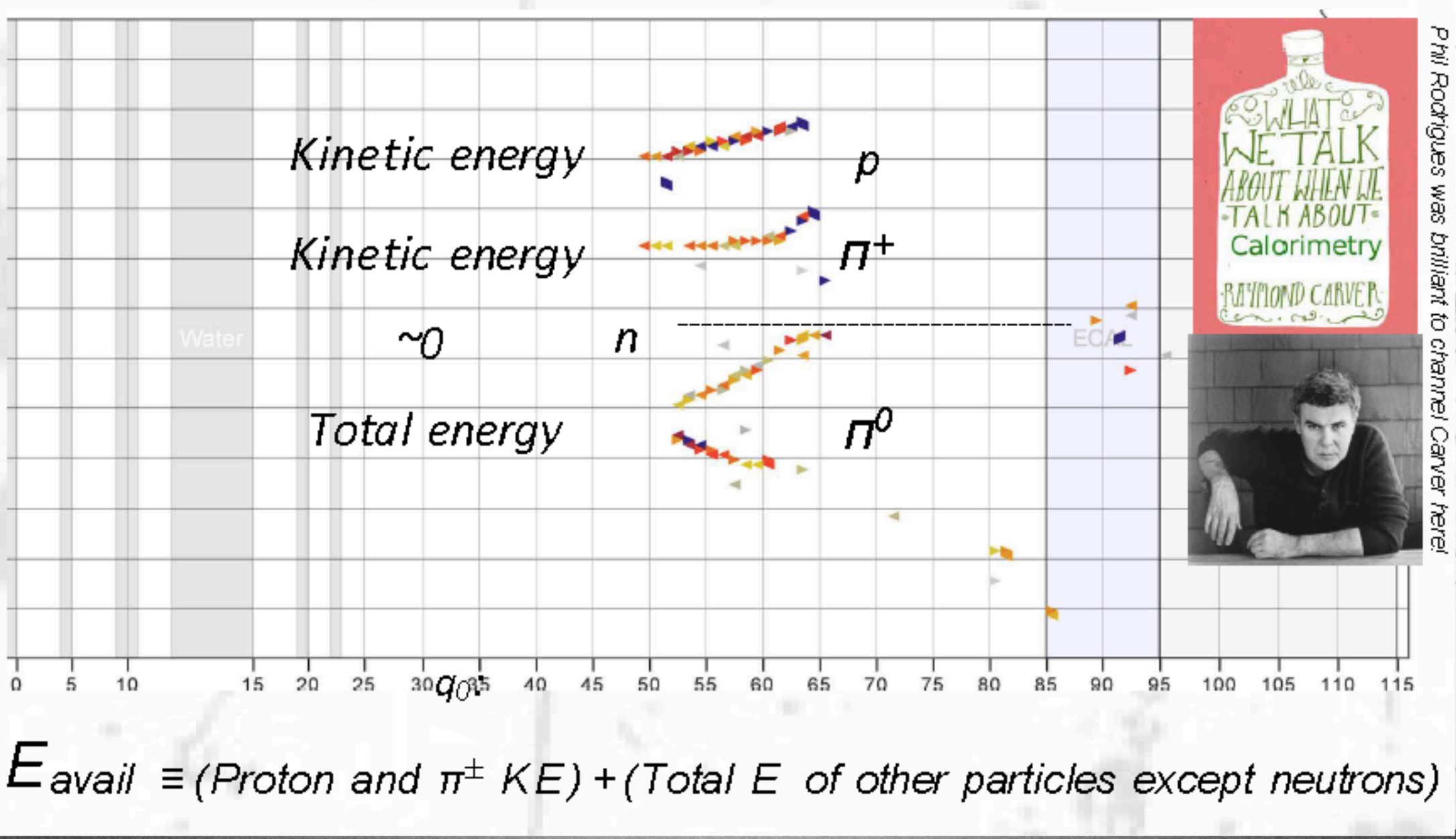
- Cross-section measurements are affected by **systematics on interaction modelling**. Models used as input to the analysis for:
  - unfolding of detector acceptance
  - correction for backgrounds

Few examples from this measurement in next slides (analysis built to be very model-independent!!)

Minerva & available E

Mosel: Minerva is not ideal place to look for 2p2h.

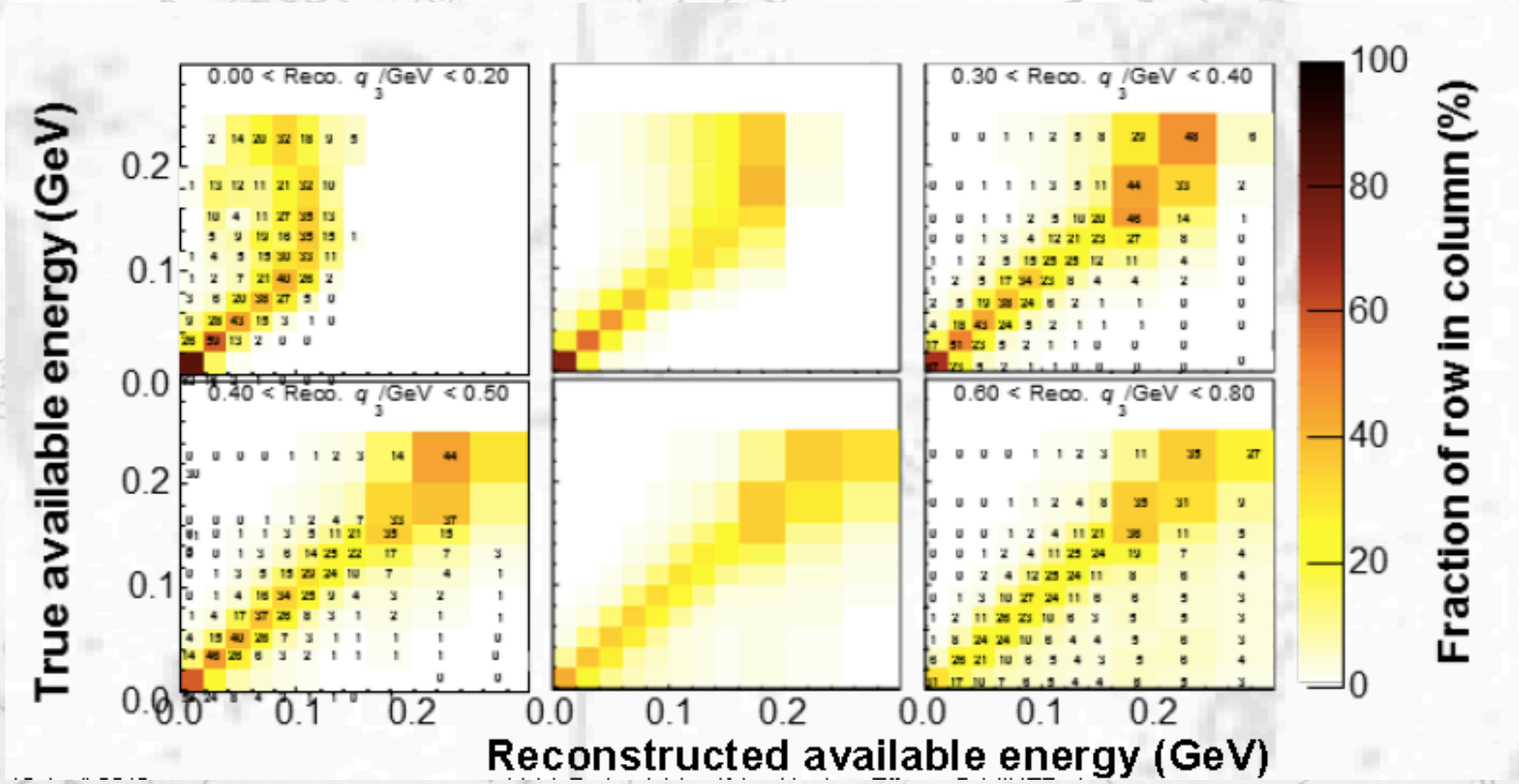
Kevin: … unless you do calorimetry.



$E_{avail} \equiv (\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total E of other particles except neutrons})$

Minerva

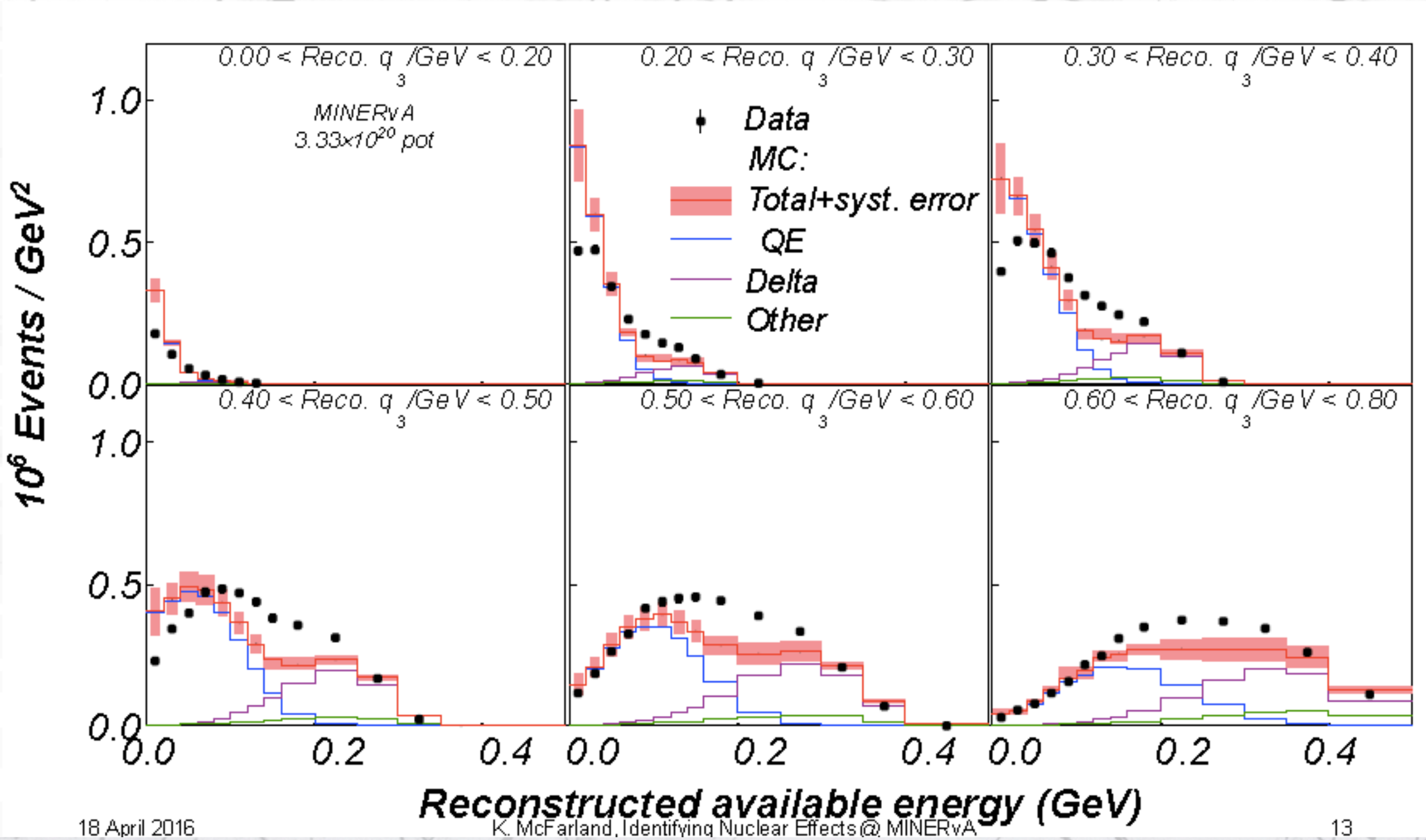
- and it works (in MC),



- With available E q3 can be computed.

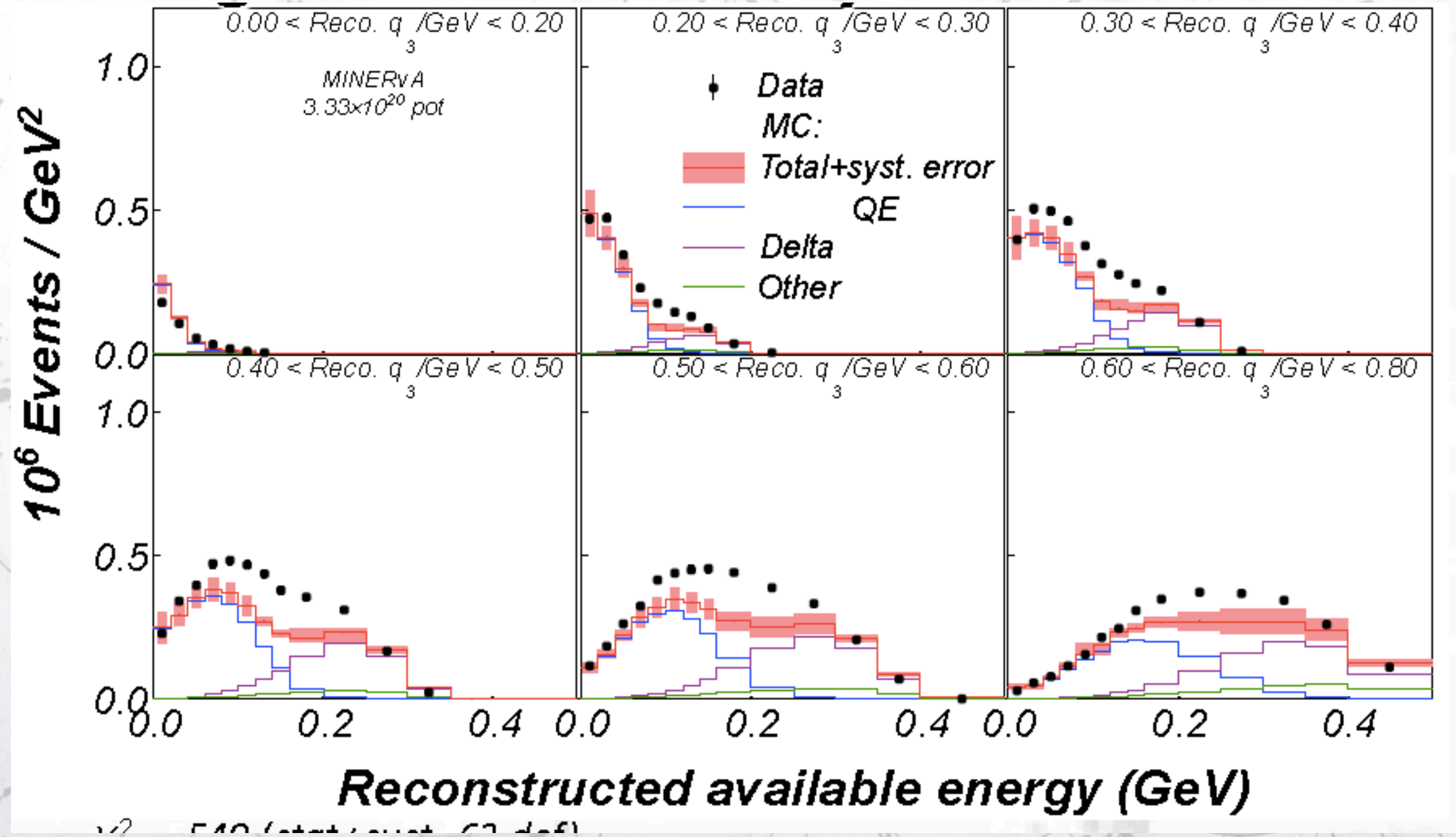
Minerva

- bare Genie



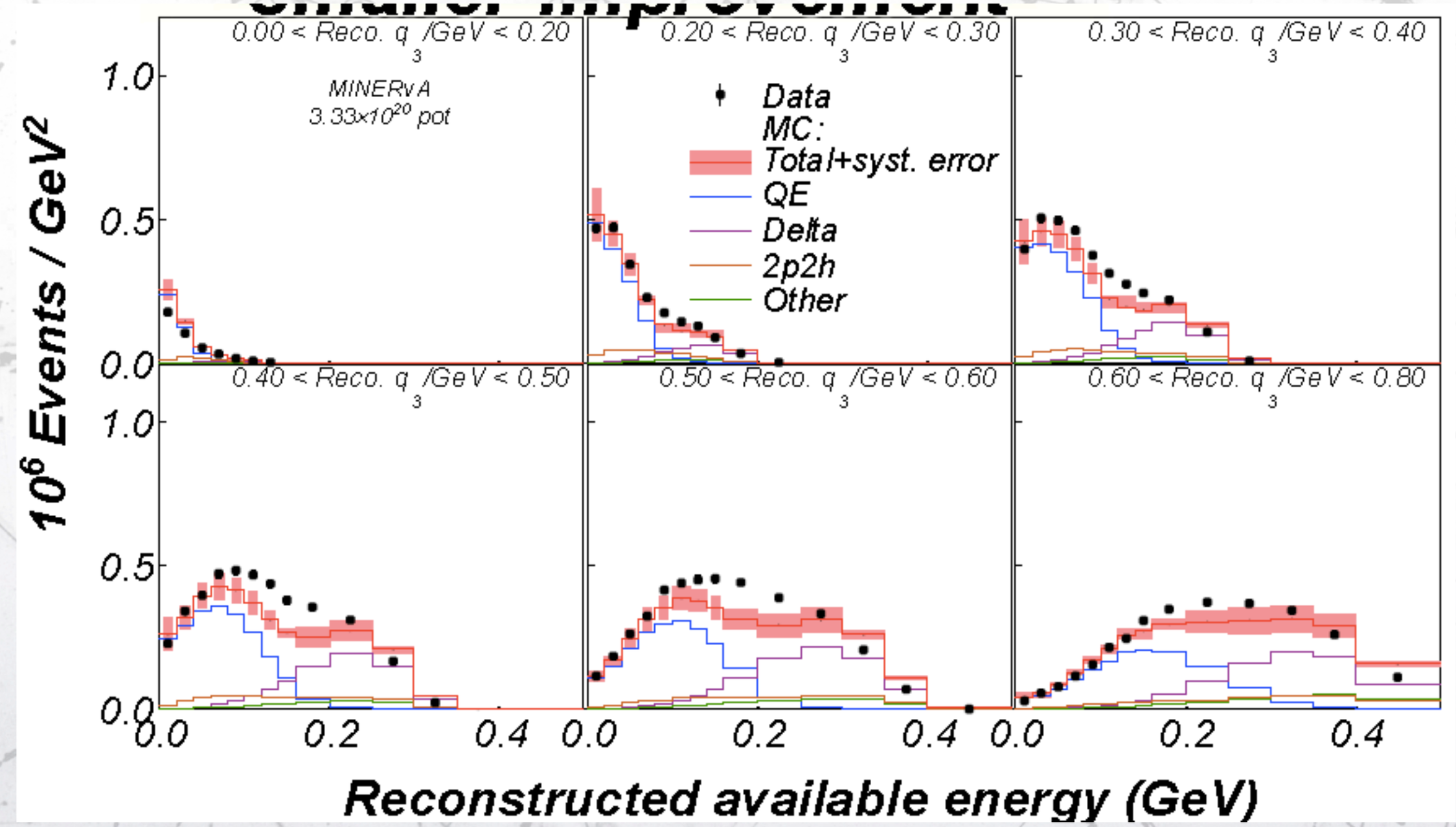
Minerva

- bare Genie + RPA



Minerva

- bare Genie + RPA + Nieves 2p2h

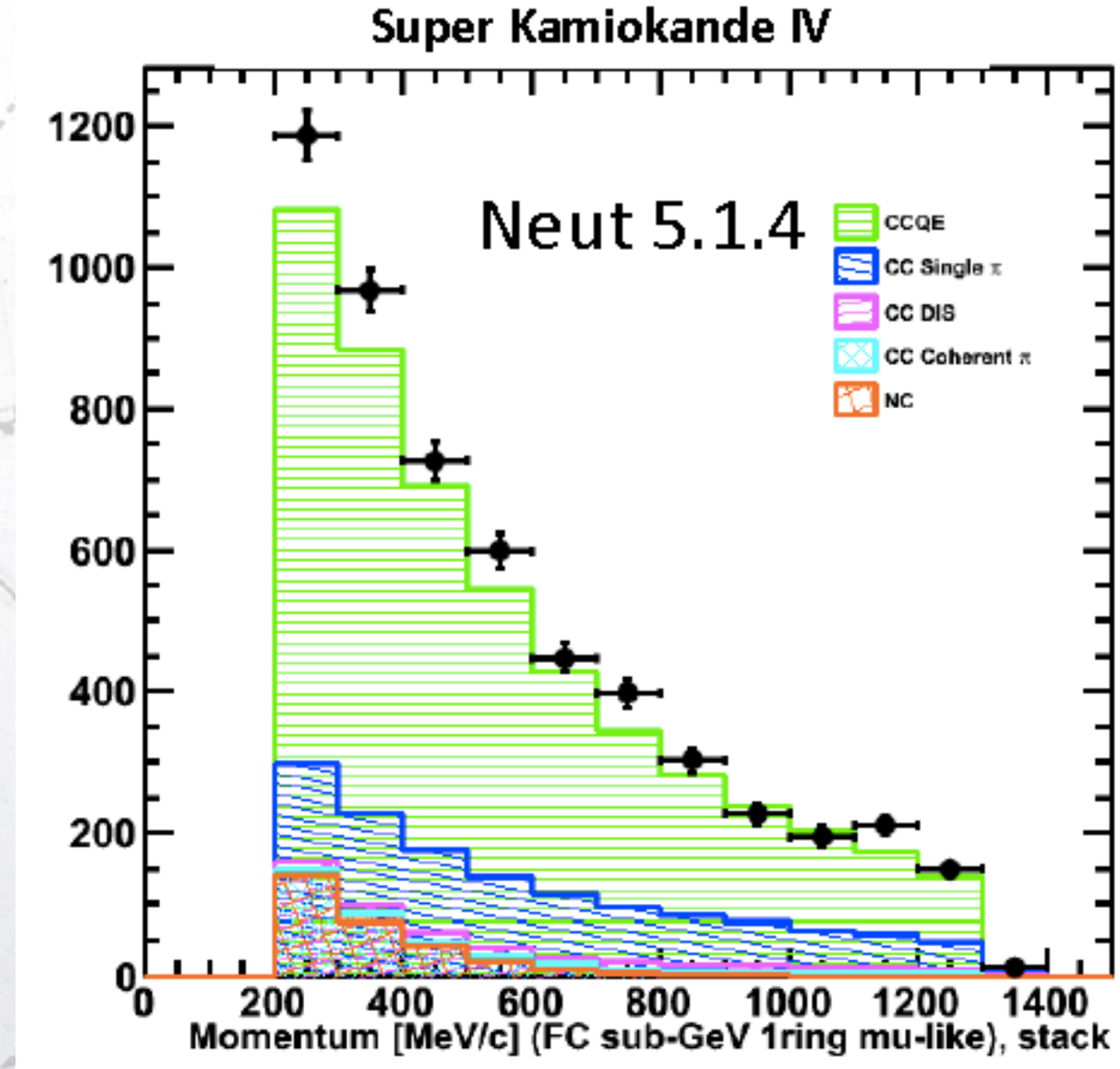


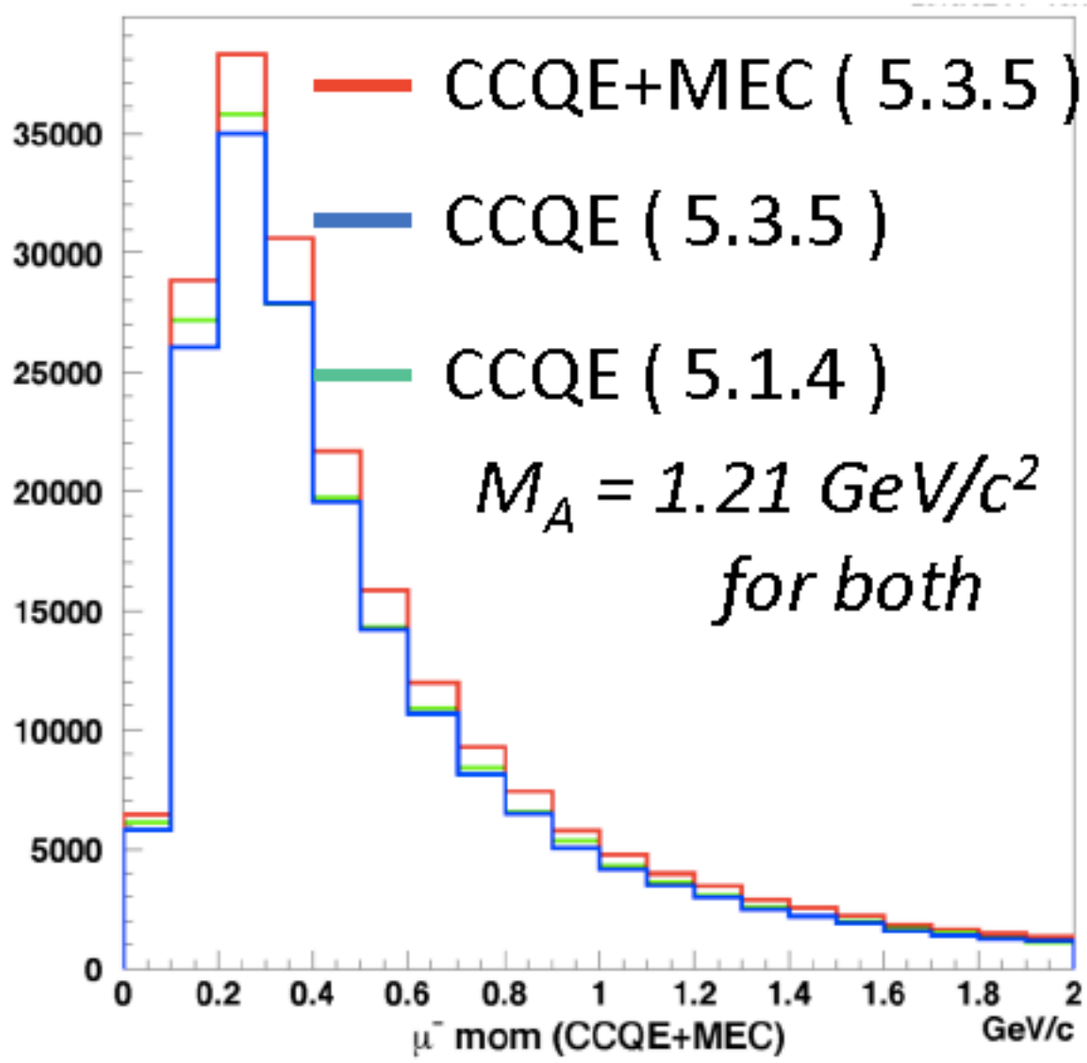
Minerva

- New ways (more direct) to look at the problem to enhance 2p2h contribution.
- This needs to be repeated in T2K (cleaner?).
- Better MC and more models will help:
  - Hadronic energy prediction is a must!.

SK atmospherics

Simple RFG CCQE (M_A = 1.2 GeV/c^2) + 2p2h (MEC)
seems to have better agreements in the low momentum region.
However, this combination may give larger # of events in high momentum region.





Conclusions

- MC:
  - 2p2h & RPA from Nieves incorporated in Neut and Genie.
  - Tensor model can help to incorporate other predictions.
  - GiBUU gives very good results in electron and neutrino scattering.
  - It is critical that the MC actually provide electron and neutrino scattering in the same code.
  - NuWro evolving in the way to incorporate hadron kinematics and new reactions beyond 2p2h.
  - New MC (Ghent) with radically different approach in the horizon !!!

Conclusions

- Experiments:
  - Search of 2p2h from pure leptonic (T2K) and incorporating hadronic energy (Minerva):
    - severe data-MC tensions observed: 2p2h ? 1p1h ? beyond 2p2h !!!!
    - critical that experiments(and theorists) finds alternative observables to tag 2p2h in data.
- exploring the effect of 2p2h in SK atmospheric (work in progress)