2p-2h from an experimental point of view:

future measurements, inputs and needs from theory

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Various people contributed to the studies I will show, in particular:
Andrew Cudd (PhD student at Michigan University), Marco Martini,
Kevin McFarland, Federico Sanchez

2p2h Workshop – CEA Saclay – April 2016

What we need from models?

- We use neutrino interaction modelling for:
  - **neutrino oscillation measurements**
    → models needed especially for near to far detector extrapolation
  - **neutrino cross-section measurement**
    - analysis output: data-model agreement
    - analysis input: we need good models to correct for detector acceptance and background
- What we need from models is:
  - a prediction (possibly which could be directly compared to what we measure experimentally)
  - quantitative uncertainty on that prediction (to set systematics uncertainties on our oscillation and xsec measurements)

This talk will focus on what I know better (?):

- 2p2h with T2K point of view
- Martini et al. and Nieves et al. models which we managed to compare to our data (MC implementation and fruitful collaboration with T2K)

Hopefully after this workshop more models can be added to the list!

Effect of 2p2h on oscillation measurements

- The overall normalization is (in principle) constrained from the near detector.

Largest effects come from near to far extrapolation uncertainties:

→ 2p2h differences between neutrino and antineutrino:

only partially constrained from ND since $\nu/\bar{\nu}$ rate is different between ND and FD because of oscillation

→ 2p2h differences between different targets:

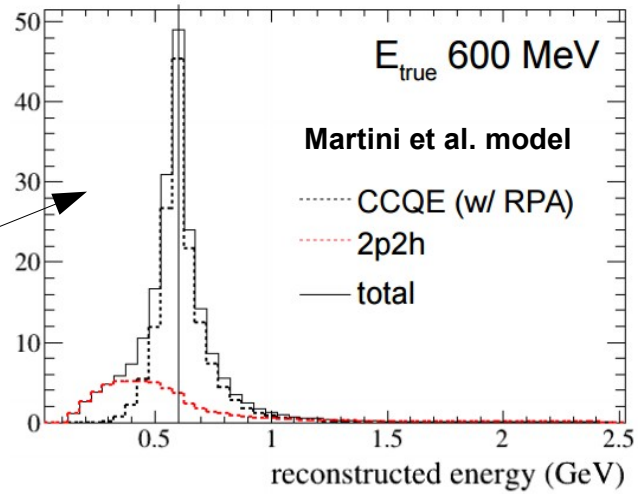
T2K ND has large portion of interactions in C (against O in FD)

→ 2p2h shape as a function of neutrino energy (i.e. muon kinematics)

- large effect in the ND → FD extrapolation due to different flux after oscillation
- biased neutrino energy reconstruction (when using CCQE approximation) in 2p2h events

Here I will show the same issue in terms of more direct experimental variables: muon momentum and angle.

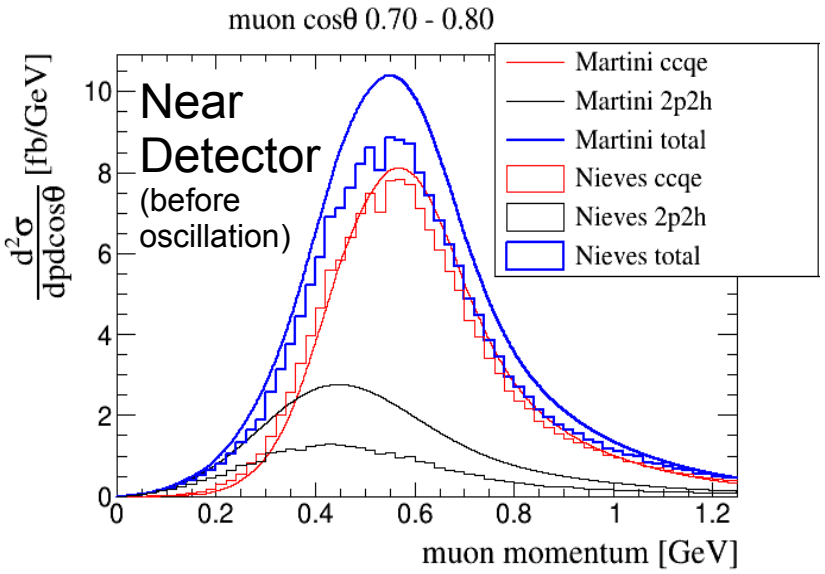
$$\bar{E}_\nu = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos\theta)/M}.$$

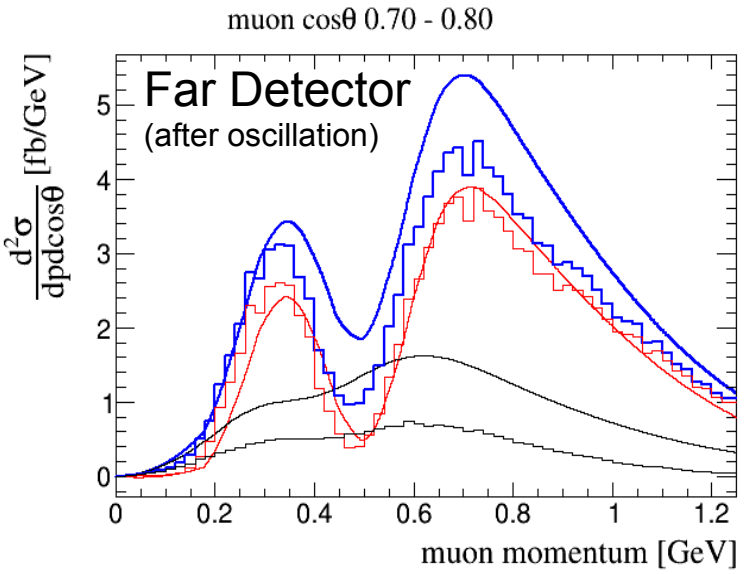


NOTE 1: the actual constraint on the overall 2p2h rate at the ND strongly depends on the assumed shape of 2p2h (and of the CCQE component as well!)

NOTE 2: 2p2h shape vs muon kinematics is also important because of different muon acceptance in ND and FD

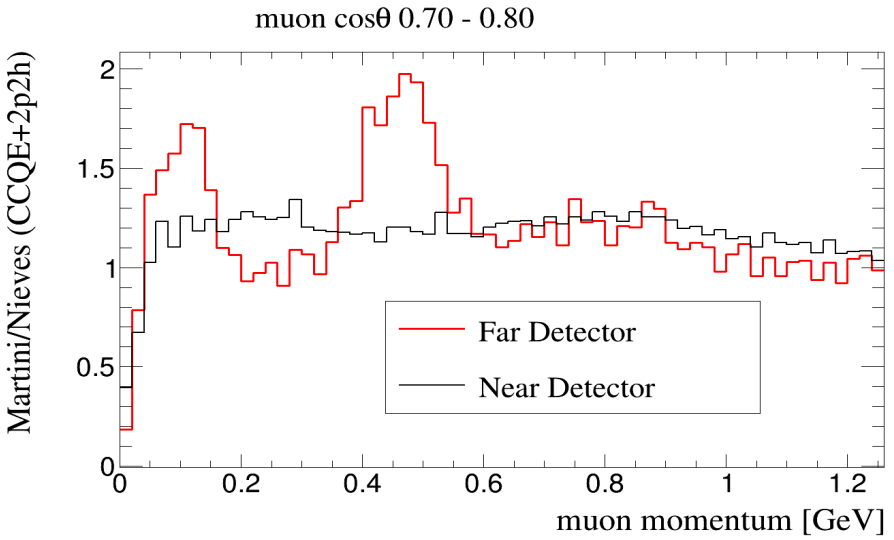
2p2h at near and far detector





- CCQE (including RPA) similar between Martini et al. and Nieves et al.: difference due to 2p2h
- 2p2h events fill the deep of oscillated spectrum
- 2p2h is a factor ~2 larger in Martini et al with respect to Nieves et al

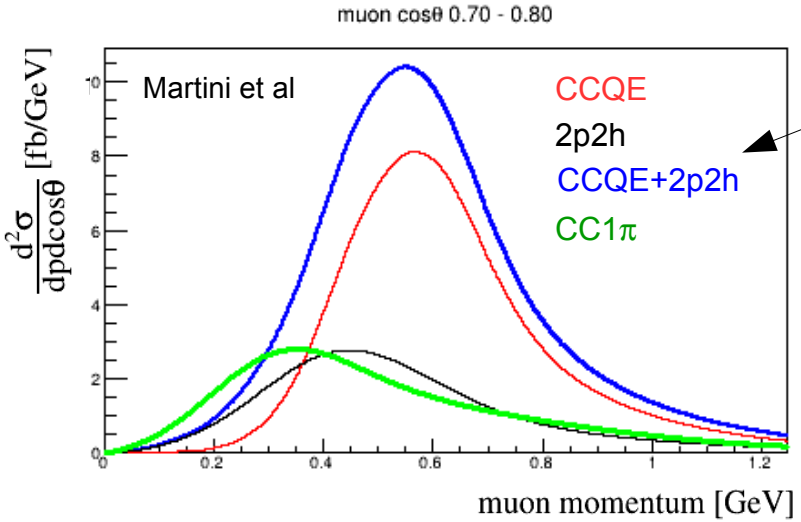
2p2h uncertainty is mainly on the overall normalization at ND
while at FD 2p2h biases the shape of neutrino energy spectrum

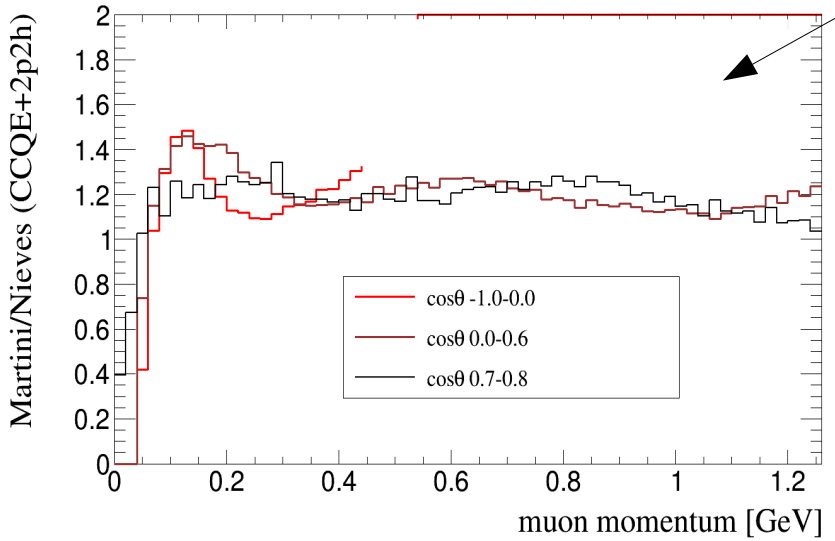


How to improve constrain at ND

The overall rate (ie normalization of xsec) is very degenerate with flux uncertainties: scarce sensitivity of ND to constrain 2p2h?

There are particular kinematics regions where the ND measurements are more sensitive to 2p2h effects, unfortunately they are also the most experimentally complicated regions





- low muon momentum is (obviously) a region with large 2p2h/CCQE ratio

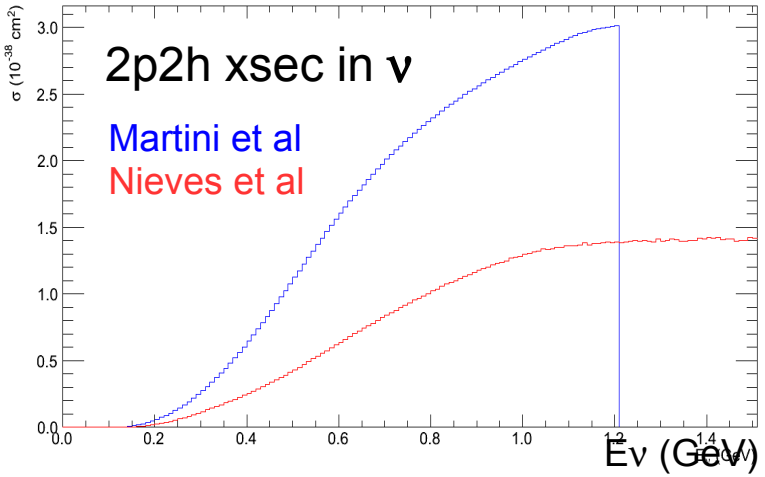
… but is also the region where the CC1π background is larger ...

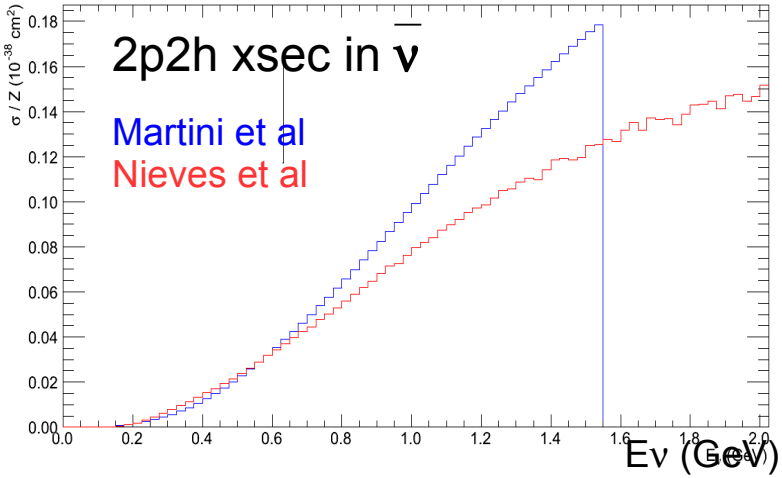
- having large angular acceptance would help

… but both the rate and the efficiency for backward tracks are quite low ...

- Adding more variables: proton kinematics, calorimetric energy, ...

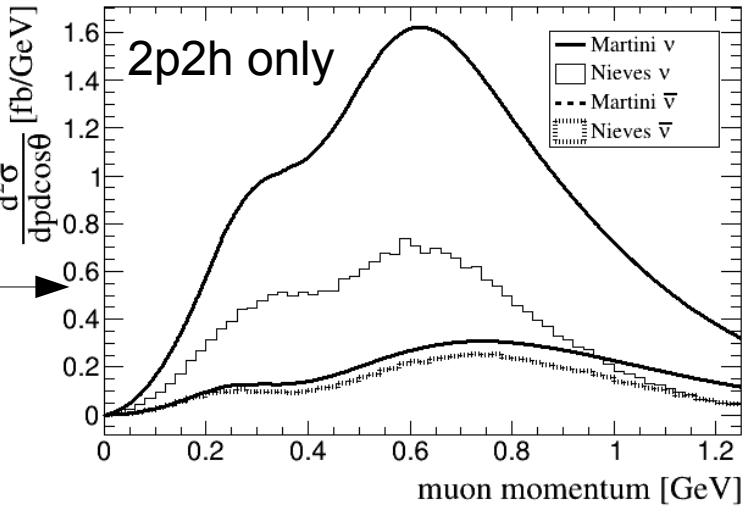
2p2h neutrino vs antineutrino

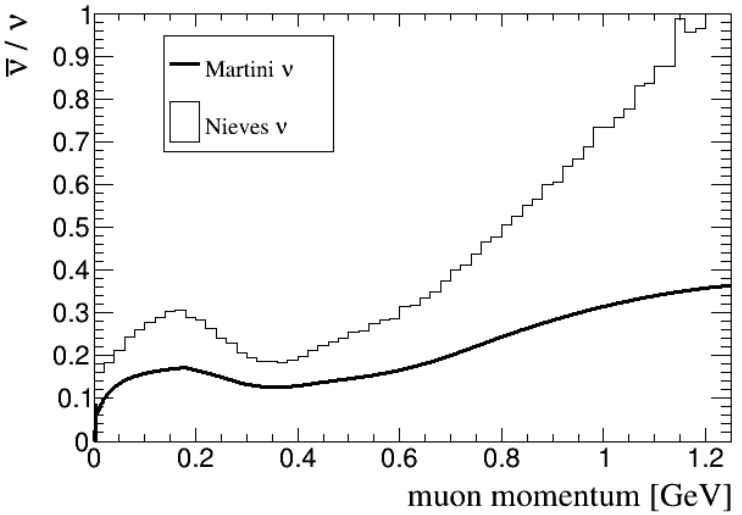




- Important systematics on oscillation analysis (δ_{CP} measurement) :

  effect on FD oscillated spectrum →





- We can use ν/ν̄ xsec measurement at ND to constrain the 2p2h models

Where these differences between the 2p2h models come from and can we use them to guide us to quantification of uncertainties on the 2p2h models ?

→ deeper look at the two models and detailed comparison

(my very poor understanding as an experimentalist...)

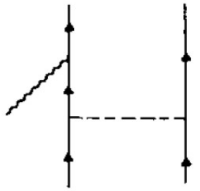
Main references:

M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009)

J. Nieves, I. R. Simo, and M. V. Vacas, Phys. Lett. B **707**, 72 (2012)

2p2h components (Martini et al.)

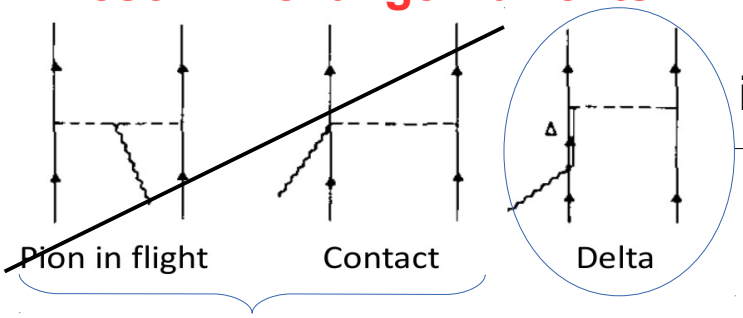
NN correlations



from nuclear response functions for electron scattering (Alberico et al.)

(π propagator + heavier mesons effectively in g')

Meson Exchange Currents



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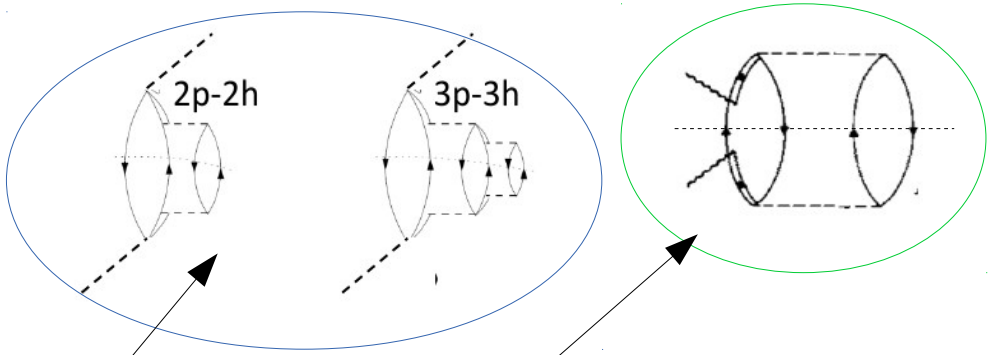
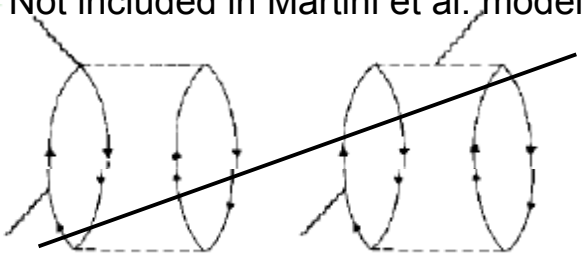


$\Delta^{\pi\text{-less}}$ decay + other Δ MEC (not π-less decay)

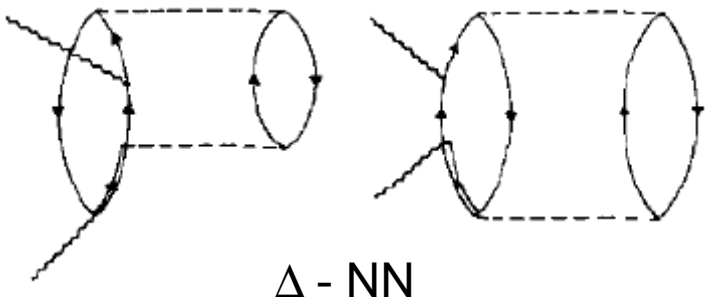
Not included in Martini et al model (shown to be small)

NN-MEC interference

Not included in Martini et al. model



no-Δ-MEC - NN



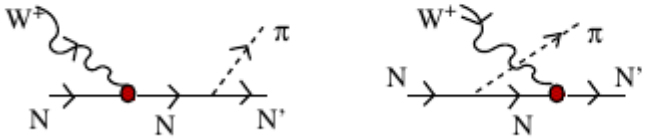
Δ - NN

2p2h components (Nieves et al.)

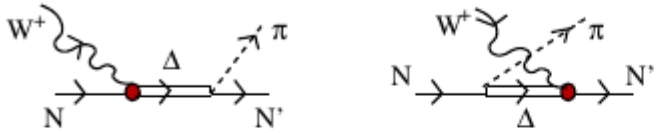
- Much more detailed description in Federico talk.

Here trying to match Martini et al. and Nieves et al. components in the same language...

- NN-correlations

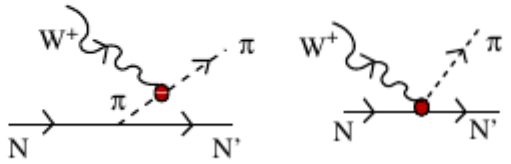


- Δ pi-less decay (and other Δ MEC)

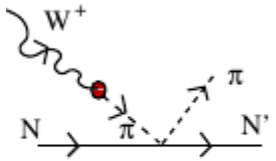


(in most of the diagrams pion and rho propagators + contact term g' considered)

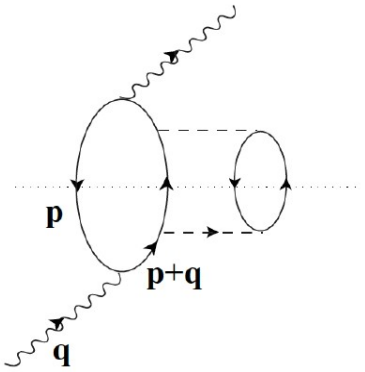
- pion in flight and contact term



+ one last term (not included in Martini et al.)



- NB: this contribution is not included in any if the two models (already in Spectral Function... what about RFG ?)

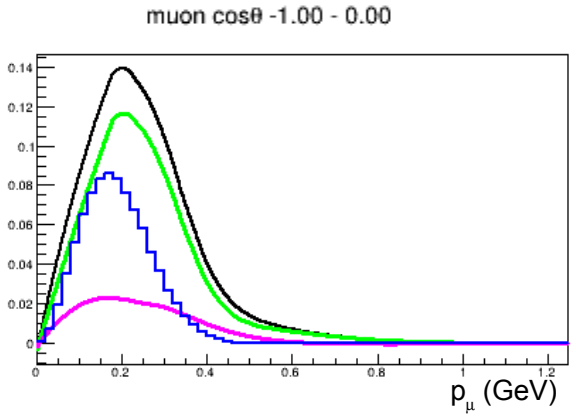


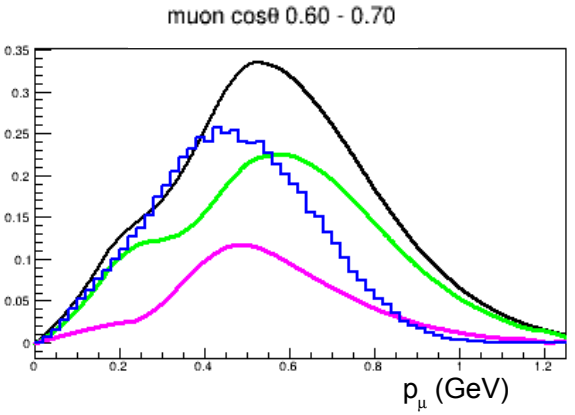
?

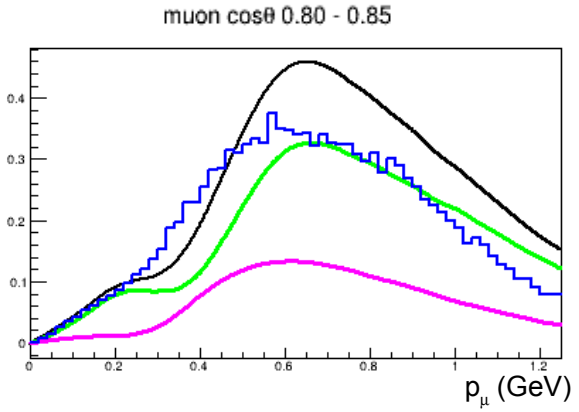
Martini et al.– Nieves et al. comparison by components

Nieves Δ-MEC — Martini: Δ MEC 2p2h; $\Delta^{\pi\text{-less}}$ 3p3h; sum of the two

Some difference in shape and normalization (both models based on Oset and Salcedo?)

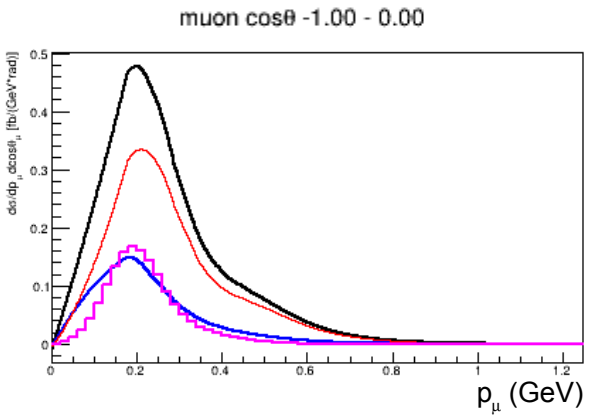


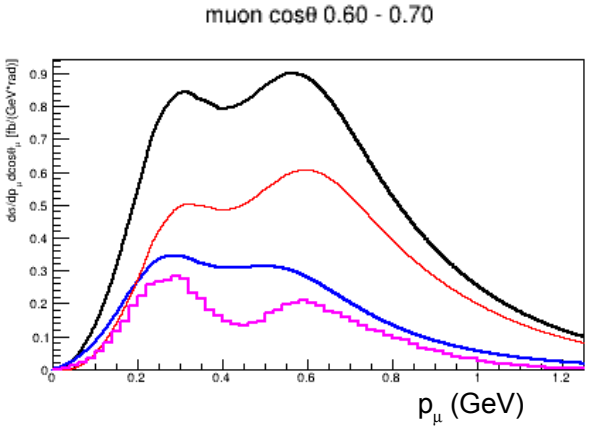


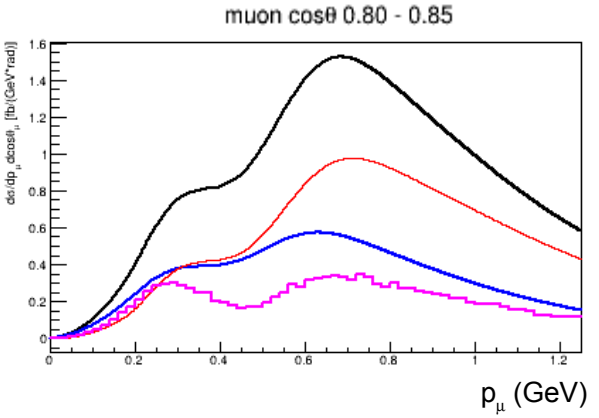


Nieves not Δ — Martini: NN correlations; NN - Δ-MEC interference; sum of the two

Huge differences: more than a factor 2...

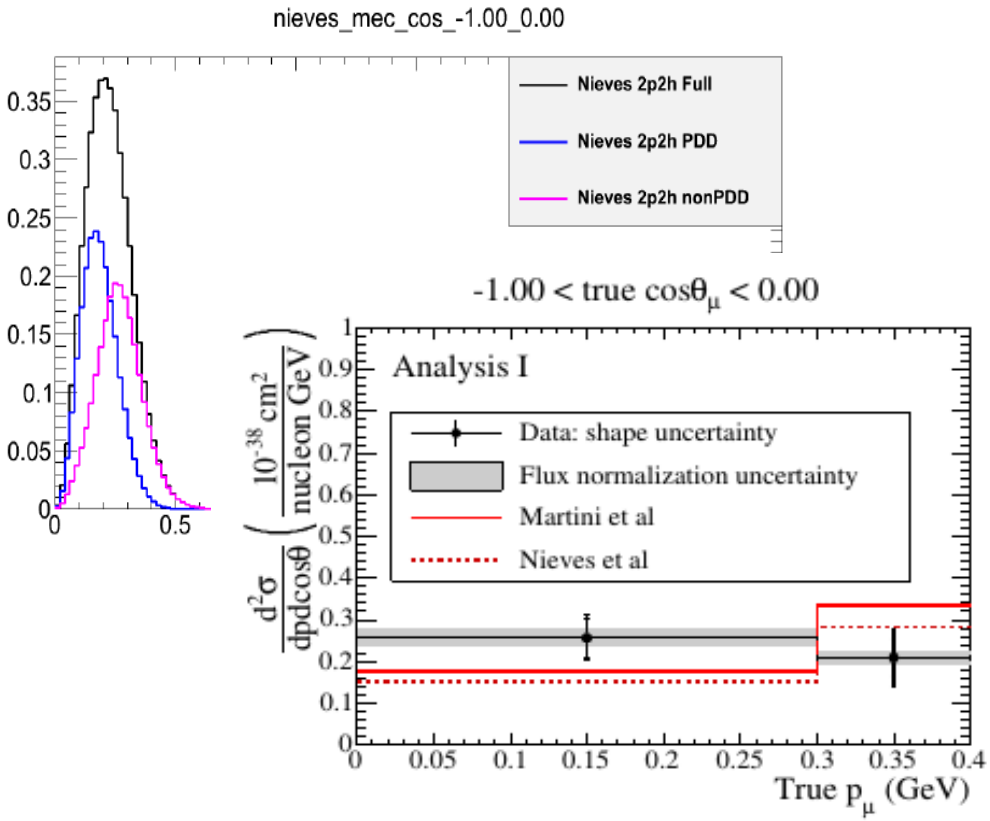


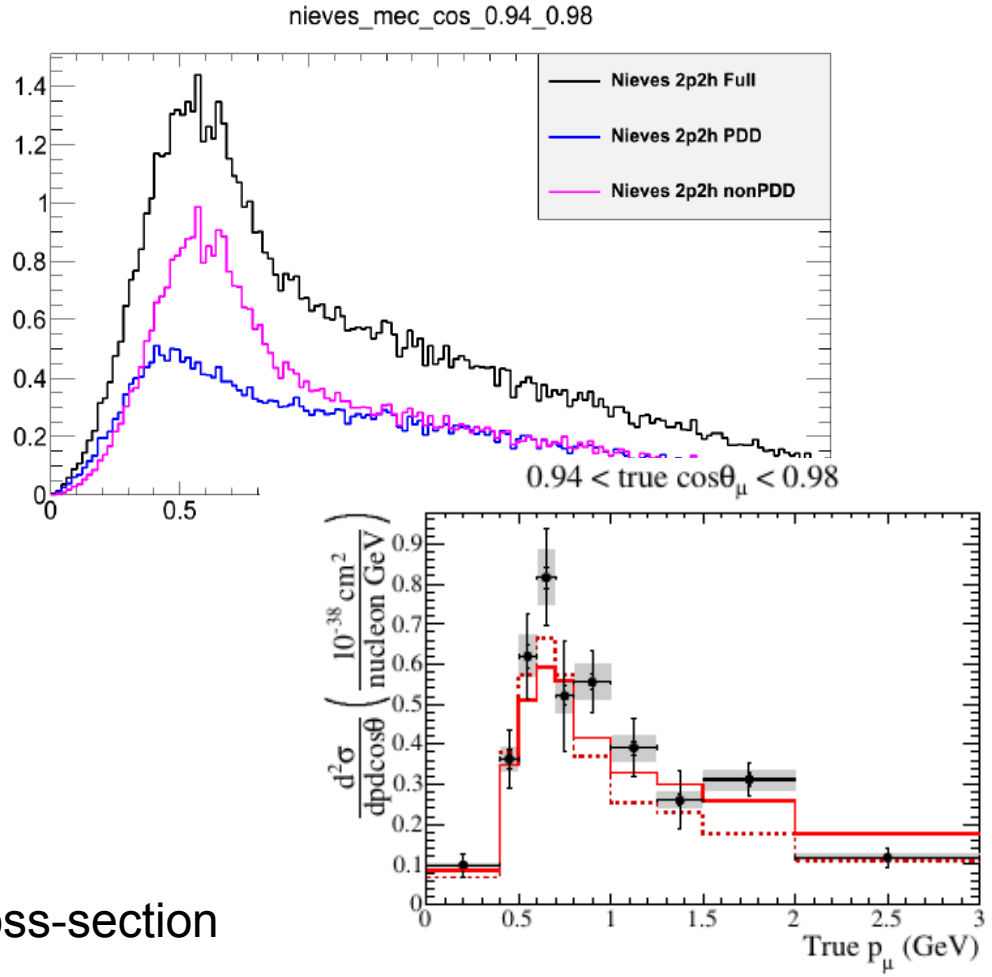




What the data tell us?

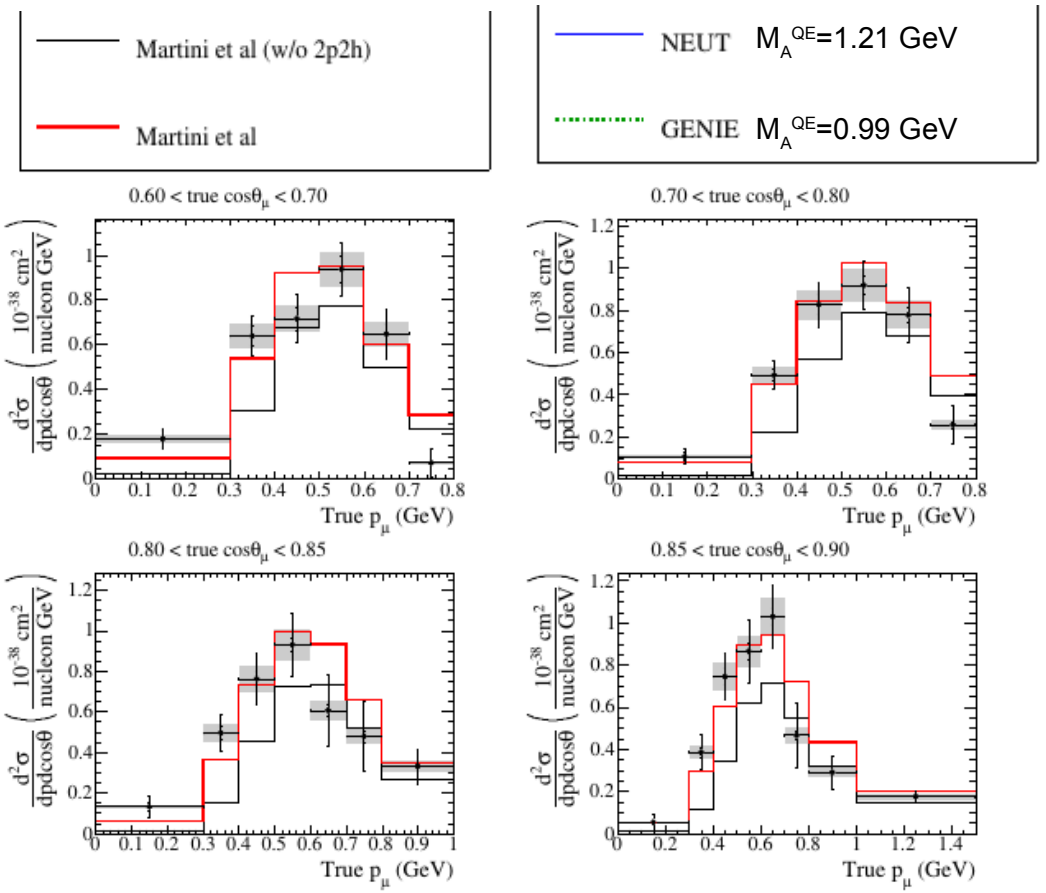
- Can we use near detector data to constrain the different 2p2h components separately?

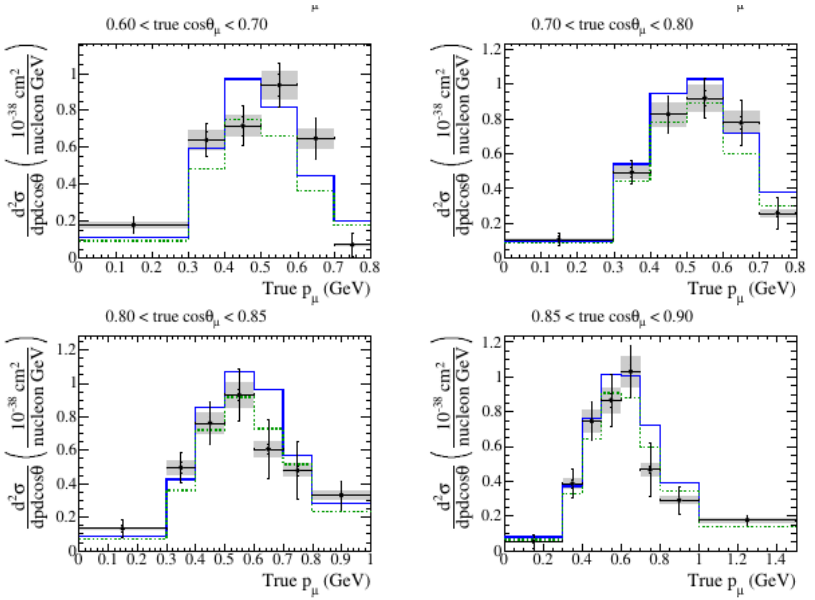


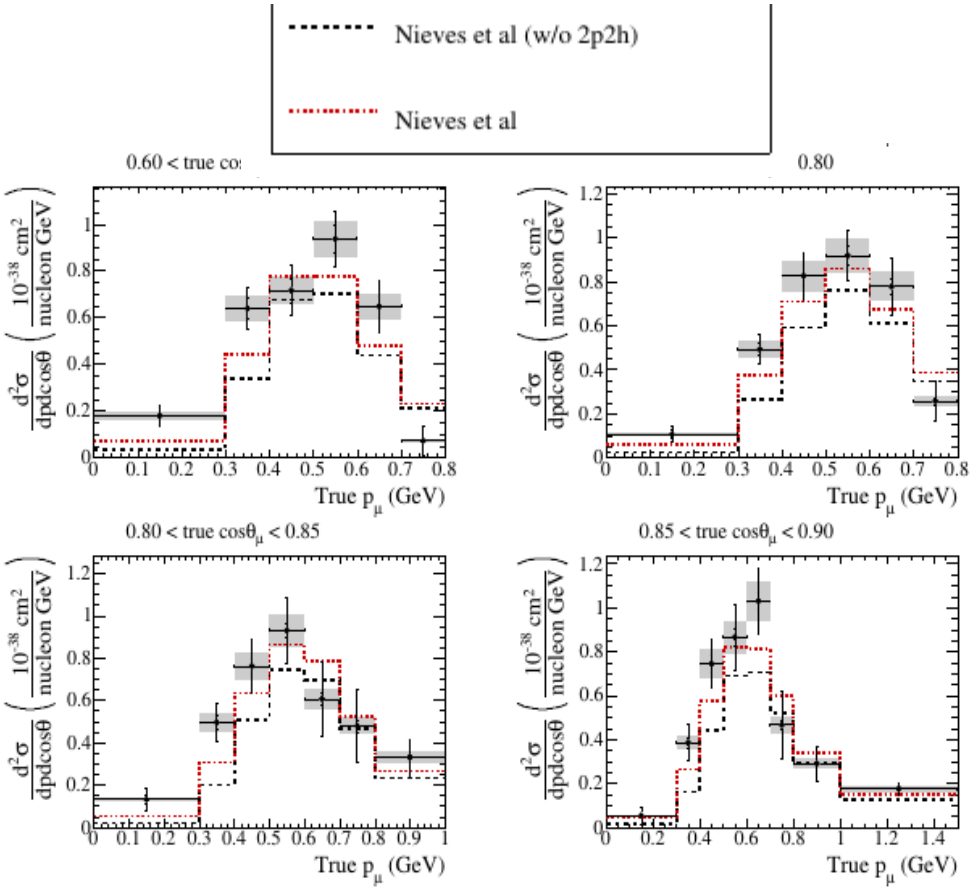


- The power and the limitations of the cross-section measurements ...

CC0π T2K measurement







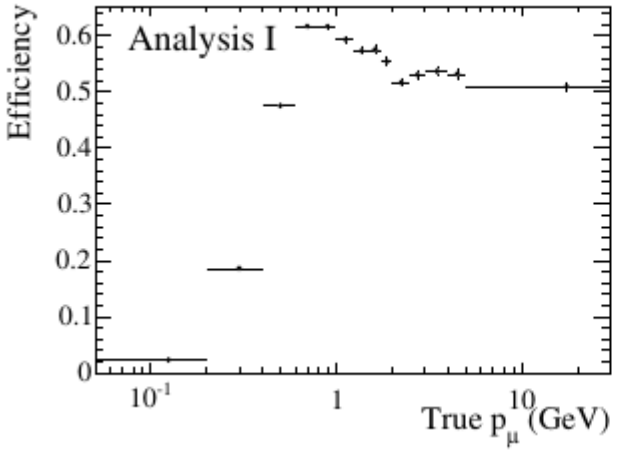
- Cross-section measurements are affected by **systematics on interaction modelling**. Models used as input to the analysis for:
  - unfolding of detector acceptance
  - correction for backgrounds

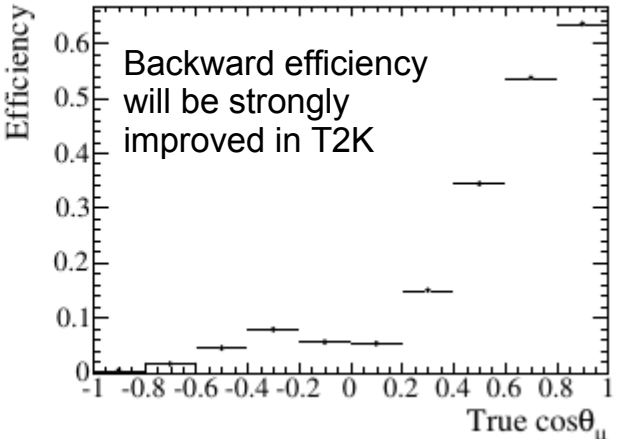
Few examples from this measurement in next slides (analysis built to be very model-independent!!)

Acceptance corrections

- Detector have typically limited acceptance (especially designed for forward muons)

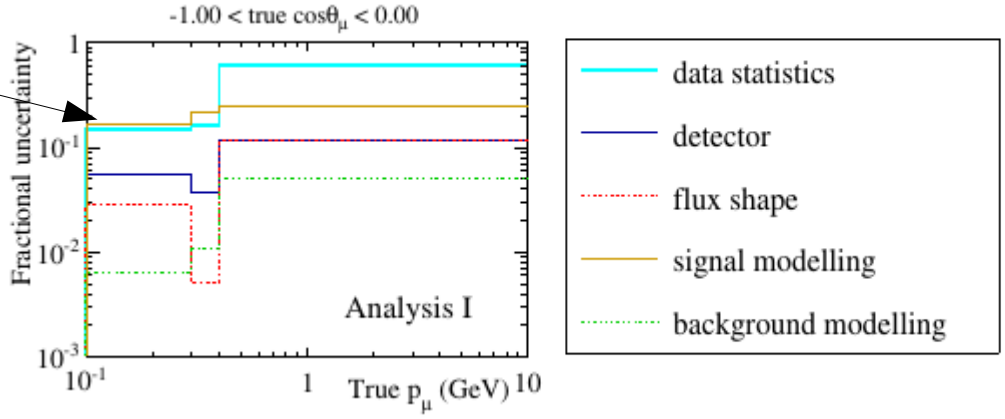
in the regions with small efficiency **(typically high angle and small momentum)** large MC-based corrections must be applied





Eg, these very same efficiency plots are different for NuWro and GENIE → the result of the measurement would be different if those MC are used for the analysis

Effect 'covered' by large systematics in bwd region, still the central result may be biased



- This effect is even worse when the cross-section is measured as a function of variables which we do not measure directly (eg. **Q^2, E_ν**)

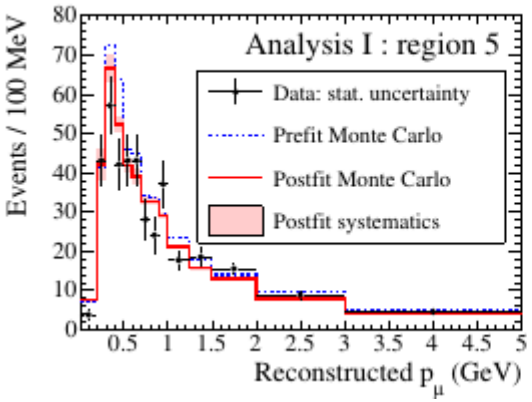
  - In double-differential measurement, you can clearly identify bins with low efficiency
  - In Q^2 measurements, bwd and low momentum muons get distributed in many different Q^2 bins and the efficiency corrections now depends on the assumed muon kinematic distribution in each Q^2 bin

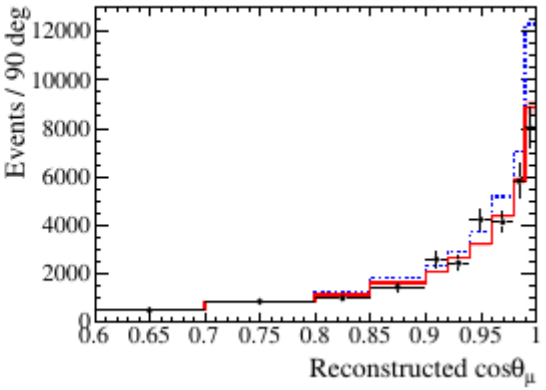
Background corrections

- **'Reducible' background** (ie backgrounds that can be experimentally disentangled from signal).

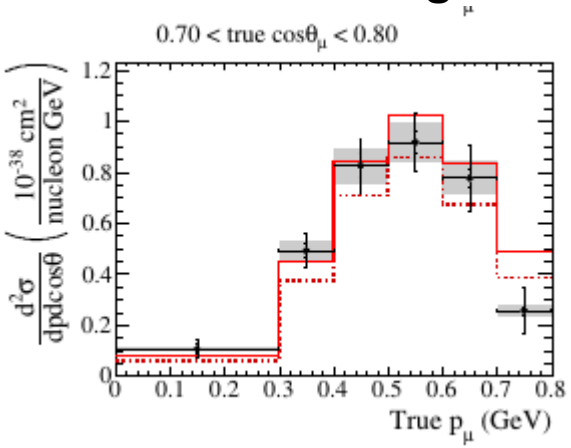
Eg: pion production through Δ resonant

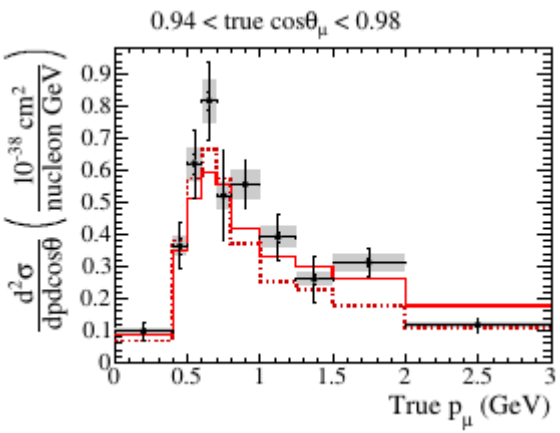
data sideband to constrain it
(uncertainties on extrapolation from sidebands to signal region.
Careful in selecting similar kinematics)

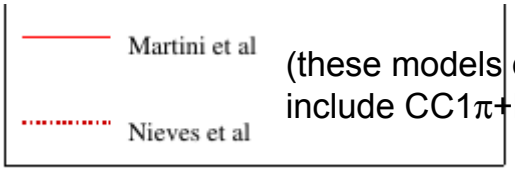




- **'Irreducible' background**: what if the pion is reabsorbed through FSI?







We will include 2p2h models in MC but the large uncertainty due to **CC1pi + FSI will remain an issue to extract/quantify 2p2h**

- Even further: what about uncertainties on CCQE (as 'background' to 2p2h)?
  - even the separation between CCQE and 2p2h (and between initial and final state interactions) is not necessarily meaningful...
  - let's anyway assume the CCQE+2p2h+FSI schema: uncertainties on RPA, nucleon form factors,... need to be properly estimated before stating anything quantitative about 2p2h

Caution

- **Word of caution in the interpretation of the xsec measurements:** they are not just our data, there is a lot of 'massaging' needed which is based on models themselves!

as experimentalists: we need to limit the 'massaging' as much as possible:

- cross-section as a function of variables directly measured in the detector
- limit measurements to regions where we have reasonable acceptance
- always be explicit in reporting this kind of issues in the results

as theoreticians: you should tell us (quantify!) where your models are more/less reliable

Dream of an experimentalist: model published with an error band

(I know is not so simple... but the sad reality is that anyway we need that error band and right now we setup it ourself, do you really trust us massaging your favorite model??)

Be ready for the future

- Xsec fit to multiple sample: **ν + $\bar{\nu}$ + carbon + oxygen (+ ν_e + CC1π + ...)**

  Exploit the different dependence of initial and final state effects for different neutrino species and targets to extract quantitative estimate of different nuclear effects (including 2p2h)

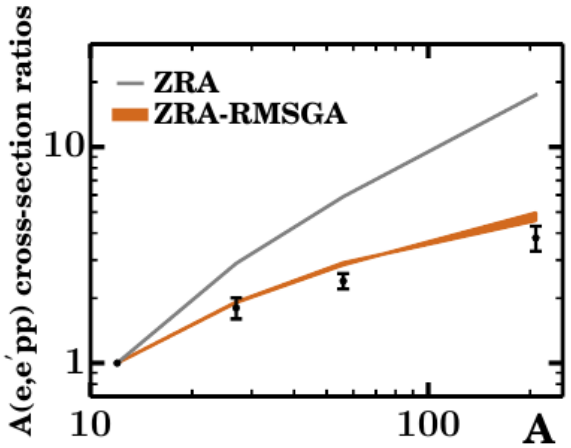
  We need good parametrization of theoretical uncertainties (RPA, 2p2h, FSI, ...) for all the different samples

  Eg, need to study:

  - pion FSI CC1π+abs impact in ν vs $\bar{\nu}$?
  - how 2p2h scale with C → O ?

  Nieves implementation in GENIE suggests $\sigma \sim A - A^2$
  (arXiv:1601.02038)

  Interpretation of electron scattering data, after FSI corrections, suggests much softer dependence (including only SRC?)



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- Reconstruction of multiplicity and kinematics of outgoing protons

  Any prediction power in present 2p2h models ?

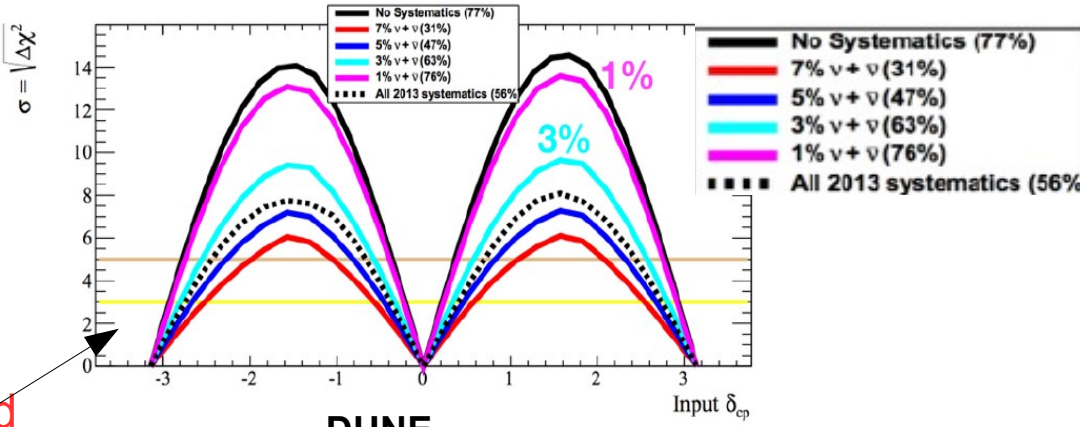
  Do we have any sensible model to compare with? How are we going to use those measurements to learn something? [In few months!]

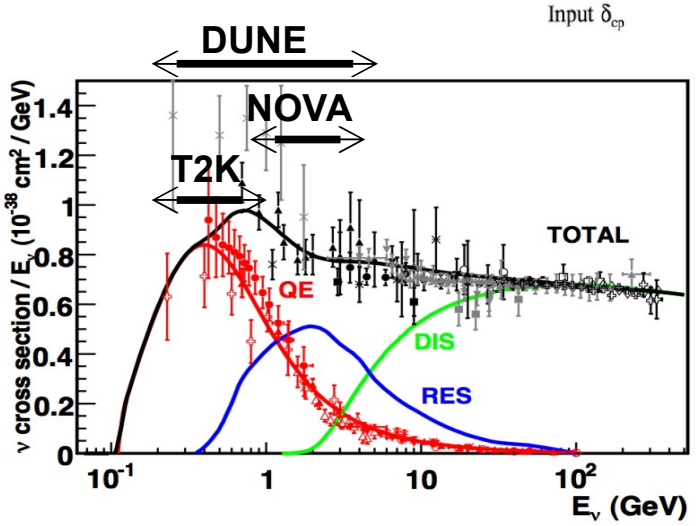
Longer term future

- **HK and DUNE: large samples of ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$** → what matters are the uncorrelated uncertainties between neutrino species

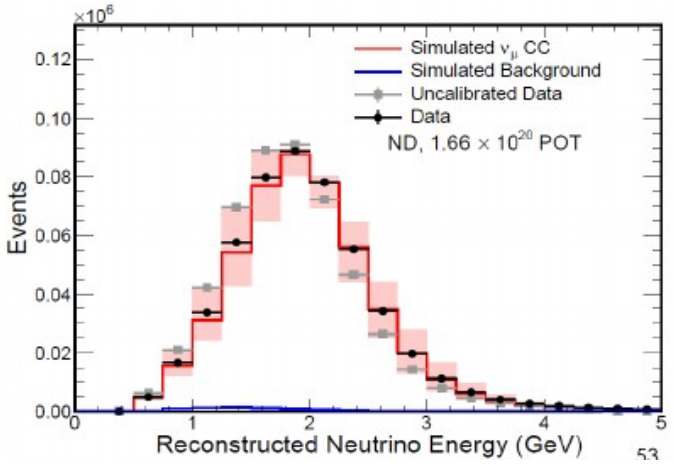
- **Future fluxes (including NOVA), have very large Eν coverage**

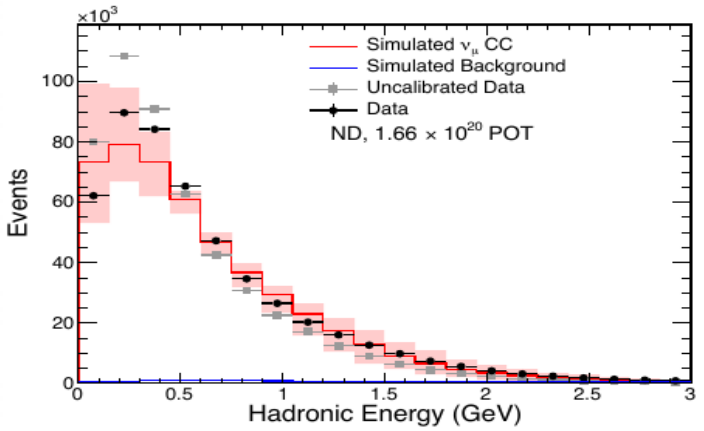
Need to control well all different processes...
(Eg: what about 2p2h in CC1π?)





- NOVA: usage of reconstructed neutrino energy to 'calibrate' the hadronic energy: Actually part (most?) of the data-MC discrepancy may be due to ν interaction models





Taste of the future (DUNE): calorimetry calibration precision tightly convoluted with shape effects in interaction models

The way out?

To disentangle all the different nuclear effects
in view of ~% precision for next generation of long-baselines:

- **long term plan of cross-section measurements**

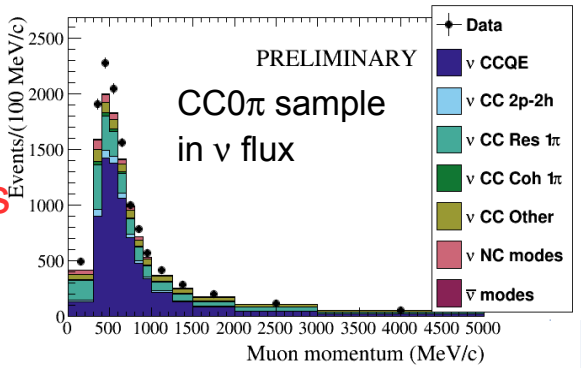
  Exploits at best complementarity between different experiments
  (T2K, Minerva, NOVA, ...)

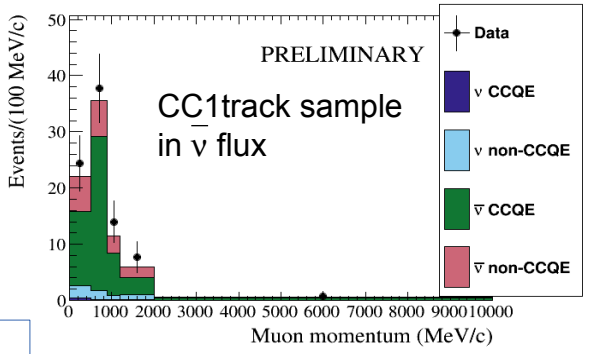
- **strict collaboration between theoreticians and experimentalists for**

→ proper interpretation of the xsec measurements
→ proper quantification of systematics on oscillation analyses

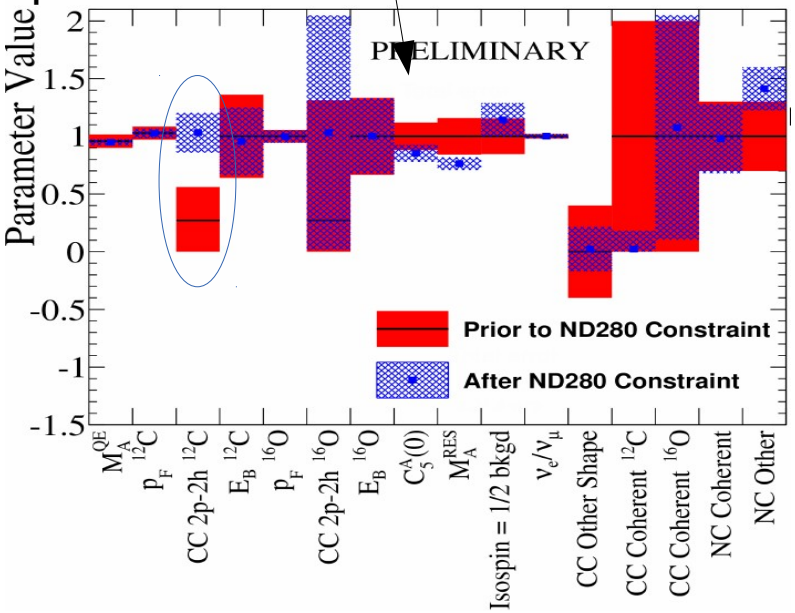
Oscillation analysis (*)

1) Models implemented in MC and compared to ND data: many samples for nu, nubar, CC0pi, CC1pi, multi-tracks etc...

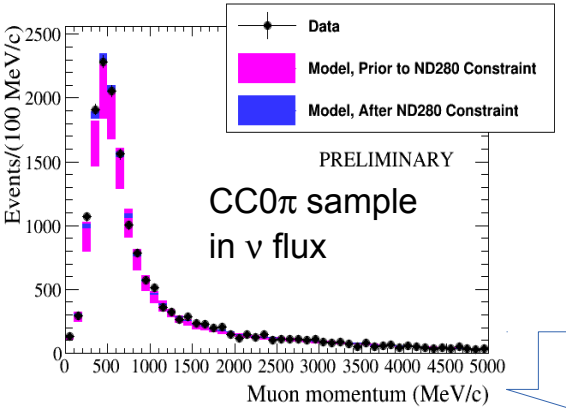


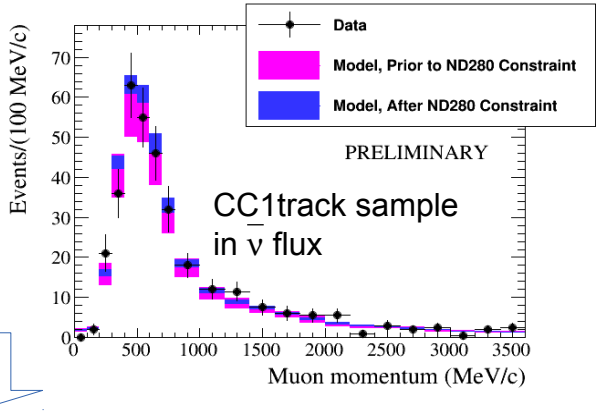


2) Parametrization of uncertainties on (flux and) neutrino interaction modelling in terms of various parameters:



3) **Fit to ND data to constrain such parameters:**

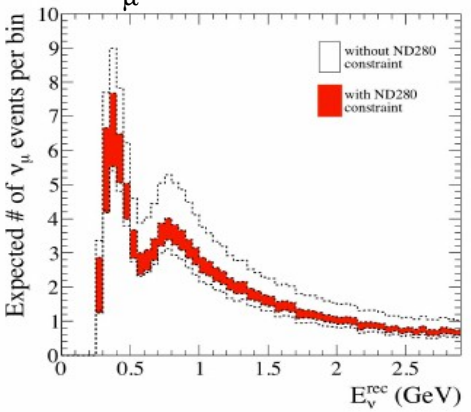




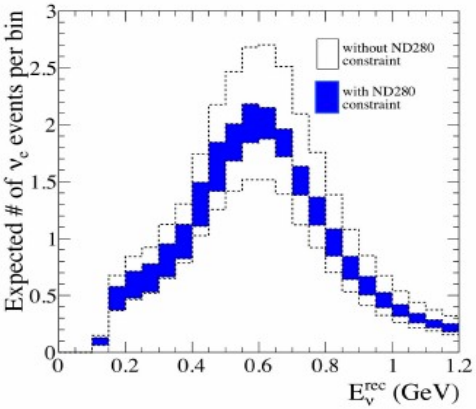
4) **Extrapolation to far detector to predict the oscillated spectrum:**

Best fit to oscillation parameters by comparing predicted and measured spectrum at far detector

ν_μ disappearance



ν_e appearance



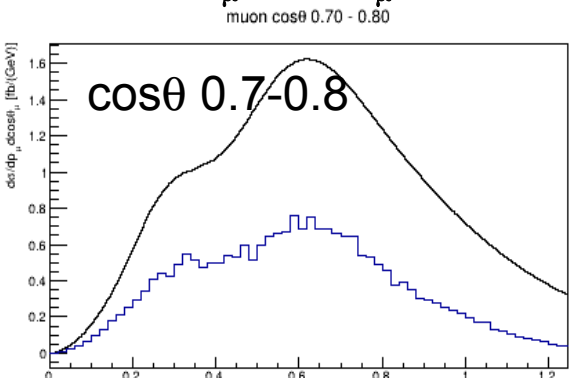
(*) Not all the plots are the most updated ones

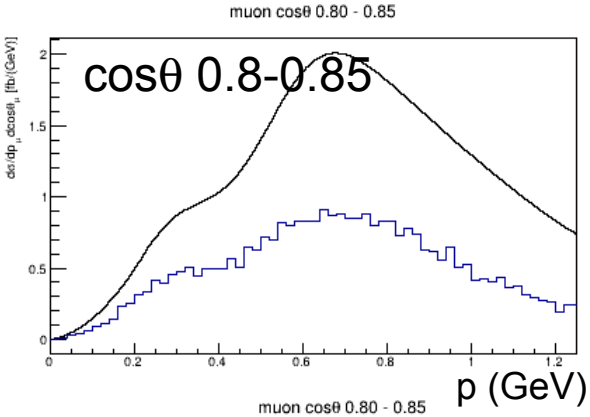
Effects of different 2p2h models on muon distributions at SK

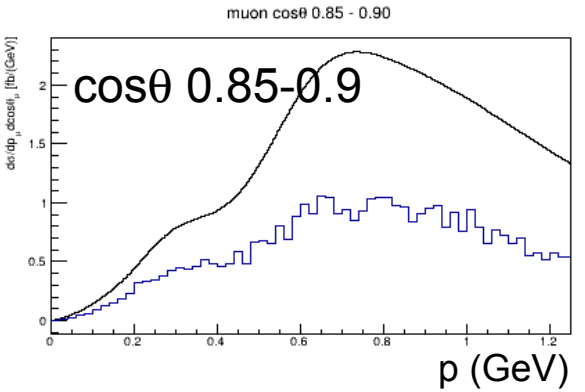
- **SK flux-folded p_μ, $\cos\theta_\mu$ distributions**

Martini (line)
Nieves (histo)

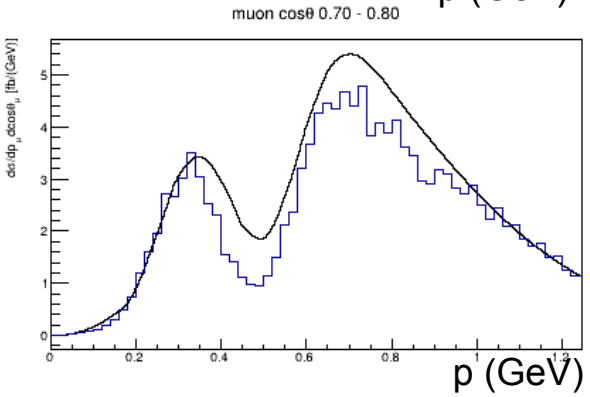
2p2h only

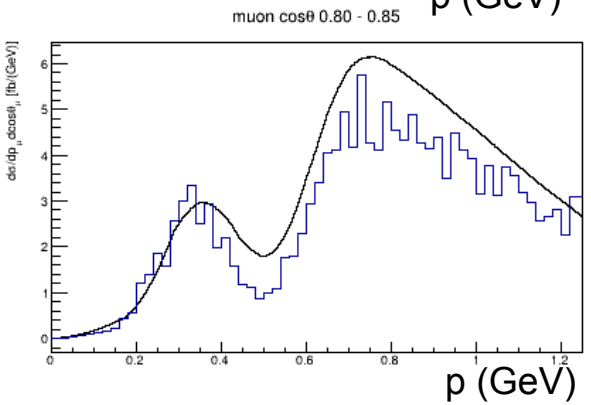


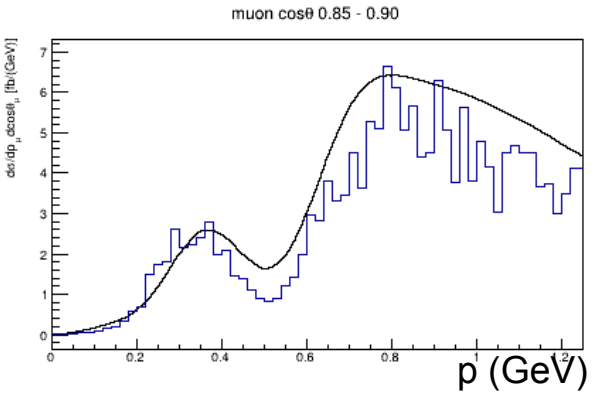




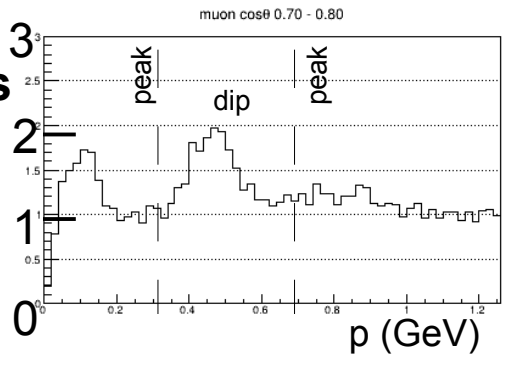
CCQE (RPA) + 2p2h

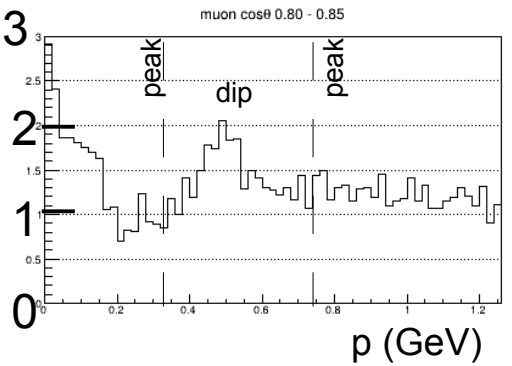


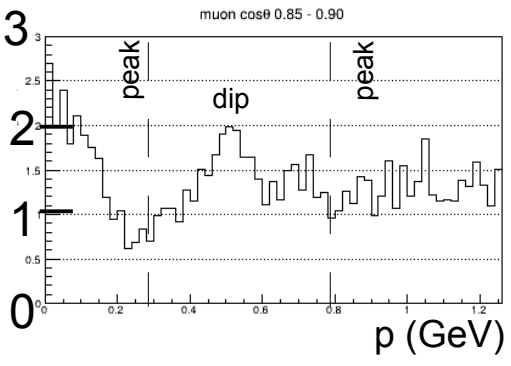




Martini/Nieves ratio (CCQE+2p2h)



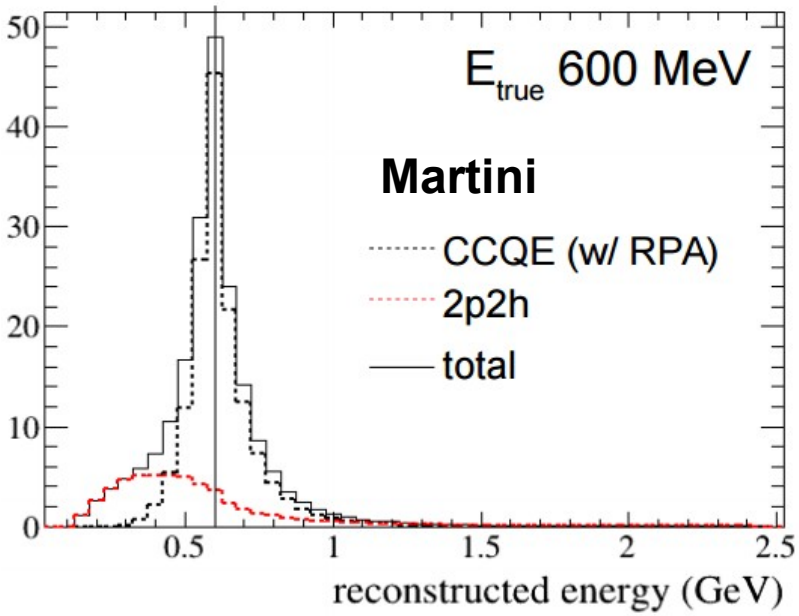


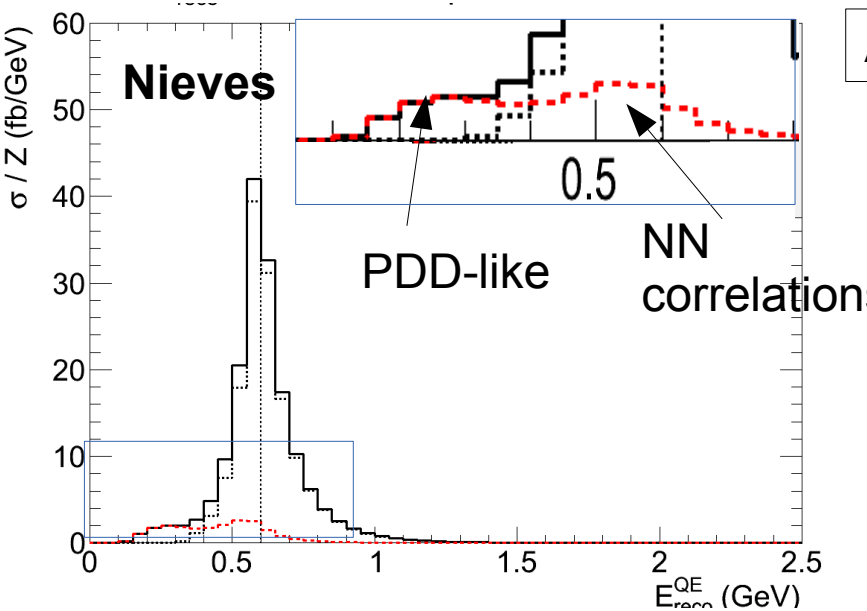


Alternative parametrization

Moreover, another way to parametrize the effects of 2p2h on the observables is looking into the **bias of the reconstructed energy**

Energy computed from muon kinematics with standard CCQE formula



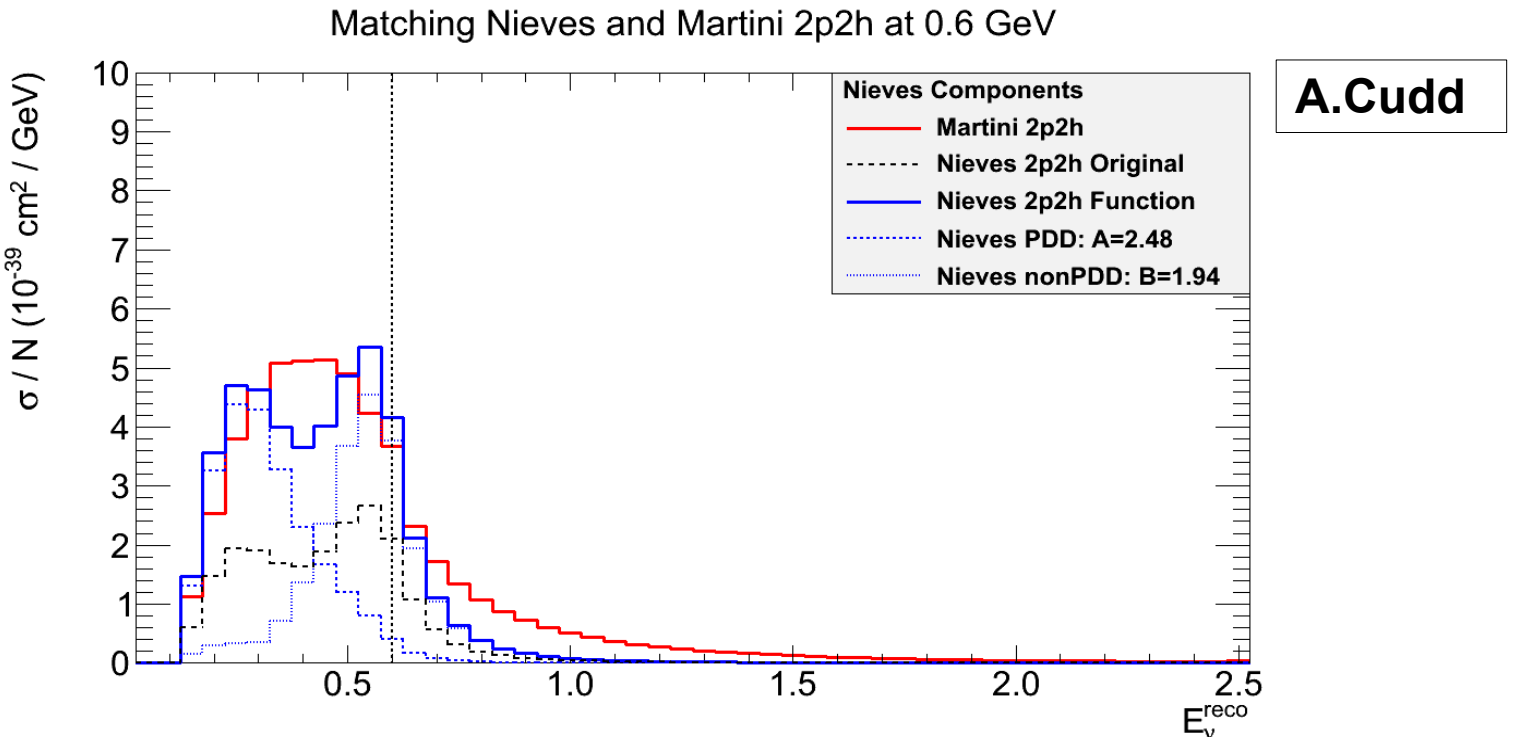


A.Cudd

- **CCQE** centered around the true energy with smearing due (mainly) to Fermi momentum
- **2p2h** component tend to underestimate the energy because:
  - 2 outgoing nucleons, different initial state effects than CCQE
  - CCQE approximations in fromula for reconstructed energy doesn't hold
  - PDD-like (left peak) + NN correlations (right peak) + interference (between the two peaks?)

Attempt of reweighting

$$f^{Martini}(\Delta \mathrm{E}) \sim A \cdot f^{Nieves}_{PDD}(\Delta \mathrm{E}) + B \cdot f^{Nieves}_{Total-PDD}(\Delta \mathrm{E})$$



- Still large difference after reweighting: **Martini has larger interference** which fill the deep between MEC and NN correlations

→ will try again by isolating interference term in Nieves

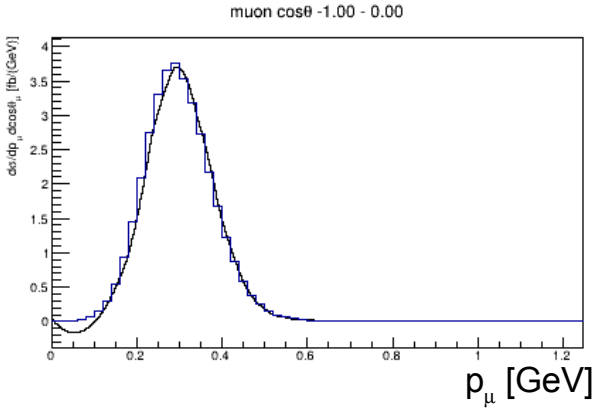
- In the meanwhile, **2 fake datasets:** reweight to make all 2p2h events to look like PDD (left peak) or not-PDD (right peak)

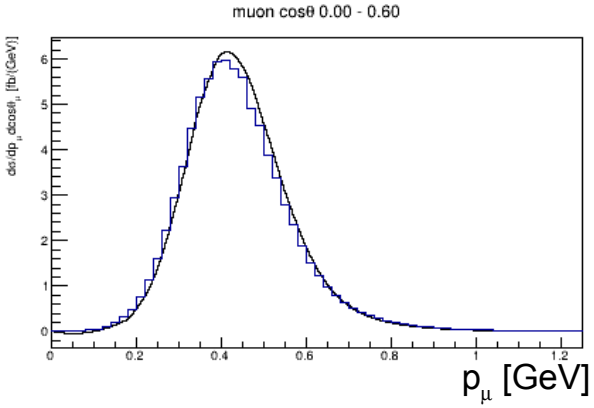
ND280 flux-folded

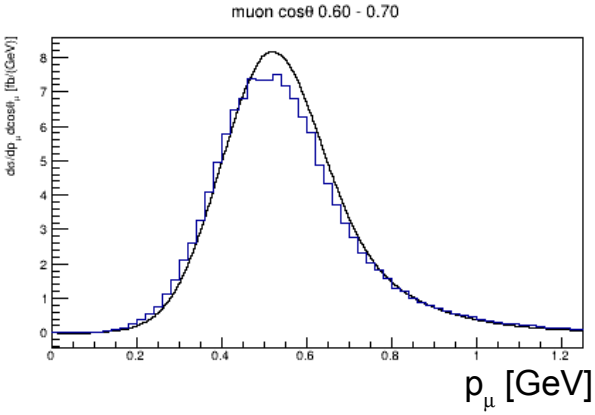
RPA only (w/o 2p2h)

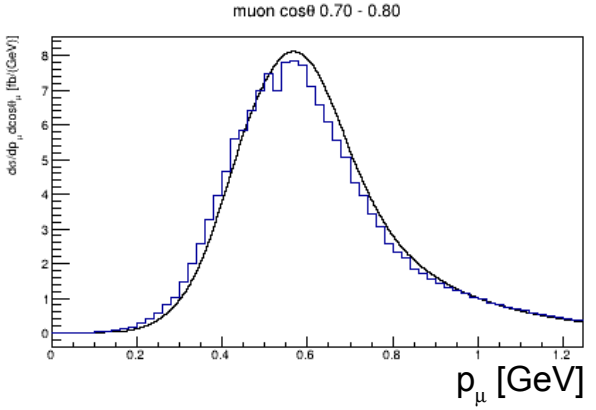
Martini (line)
Nieves (histo)

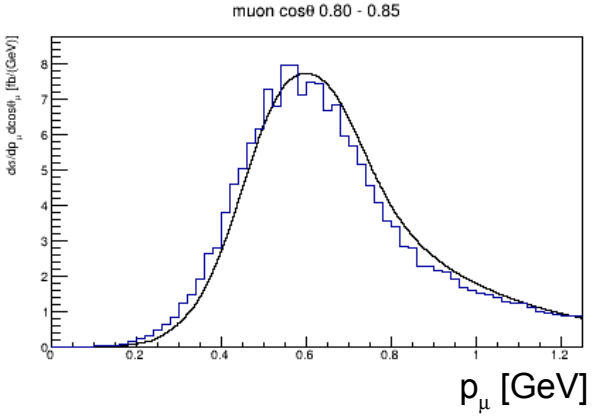
Shift in energy just slightly visible: convolution with ND280 “smears” the effect

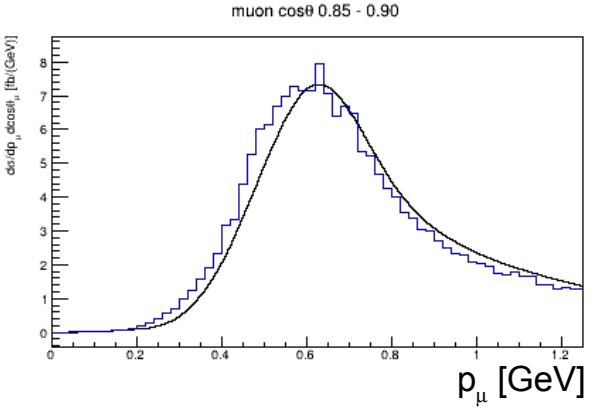


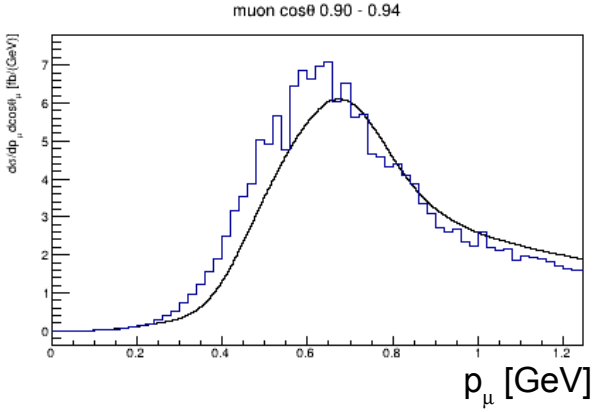


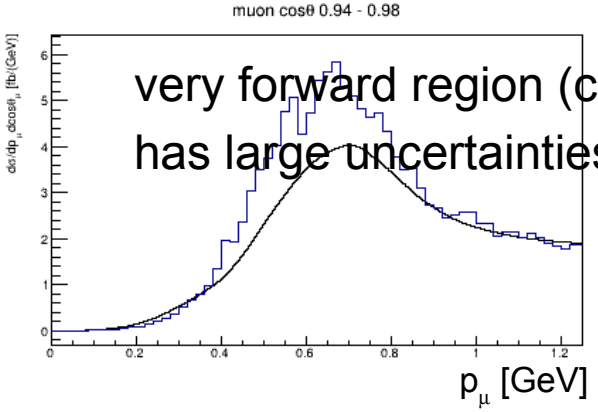


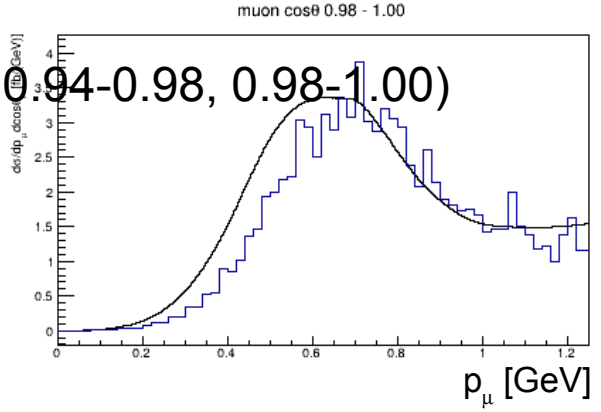










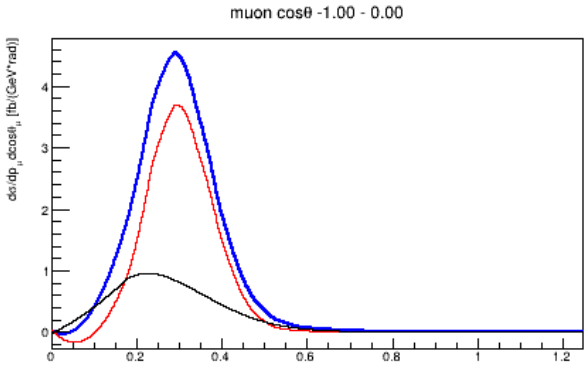


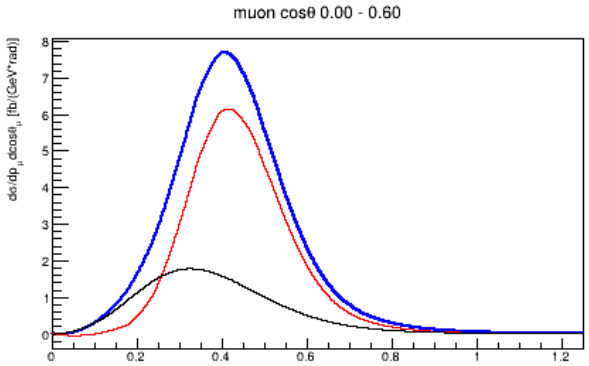
very forward region ($\cos\theta_\mu$ 0.94-0.98, 0.98-1.00) has large uncertainties

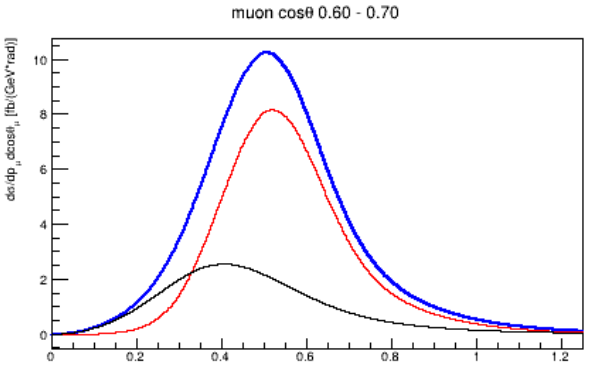
Including 2p2h (Martini)

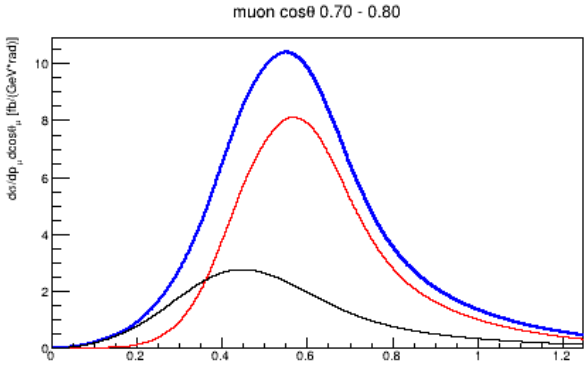
RPA + 2p2h
RPA
2p2h

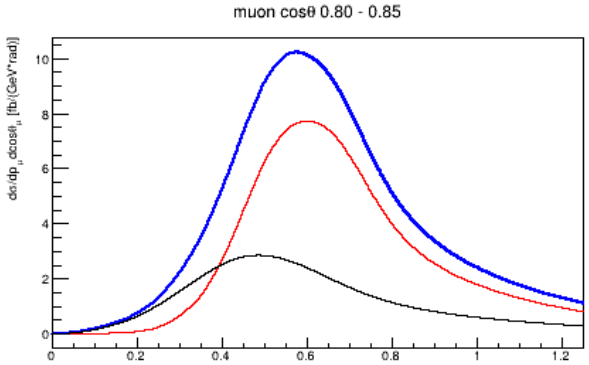
For both models there is a region at **small p_μ where only 2p2h and no 'real' QE is present !**

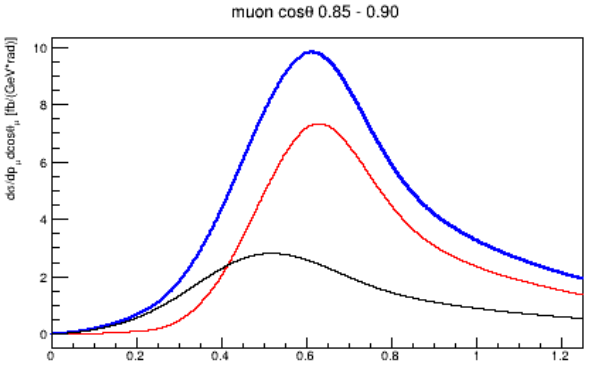


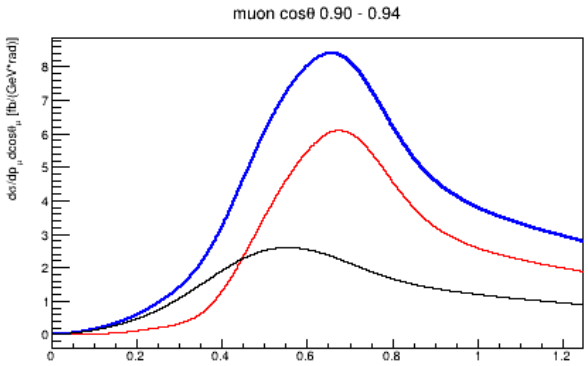


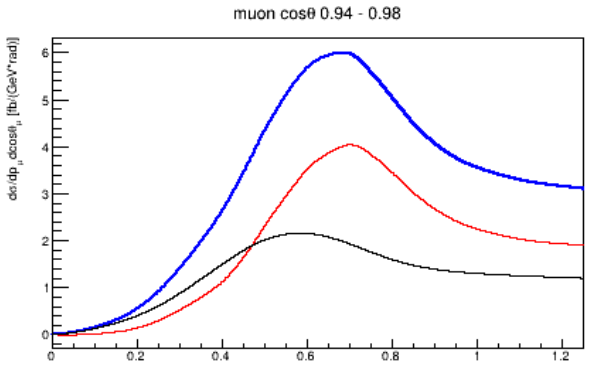


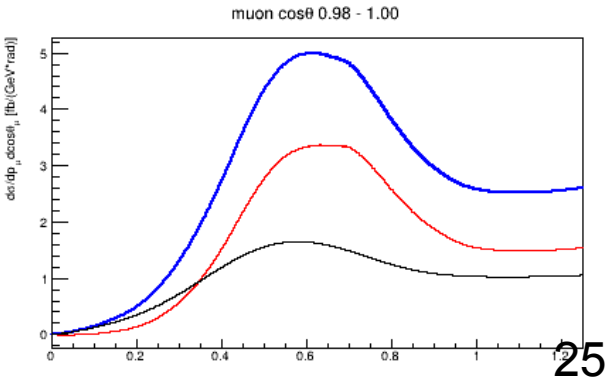








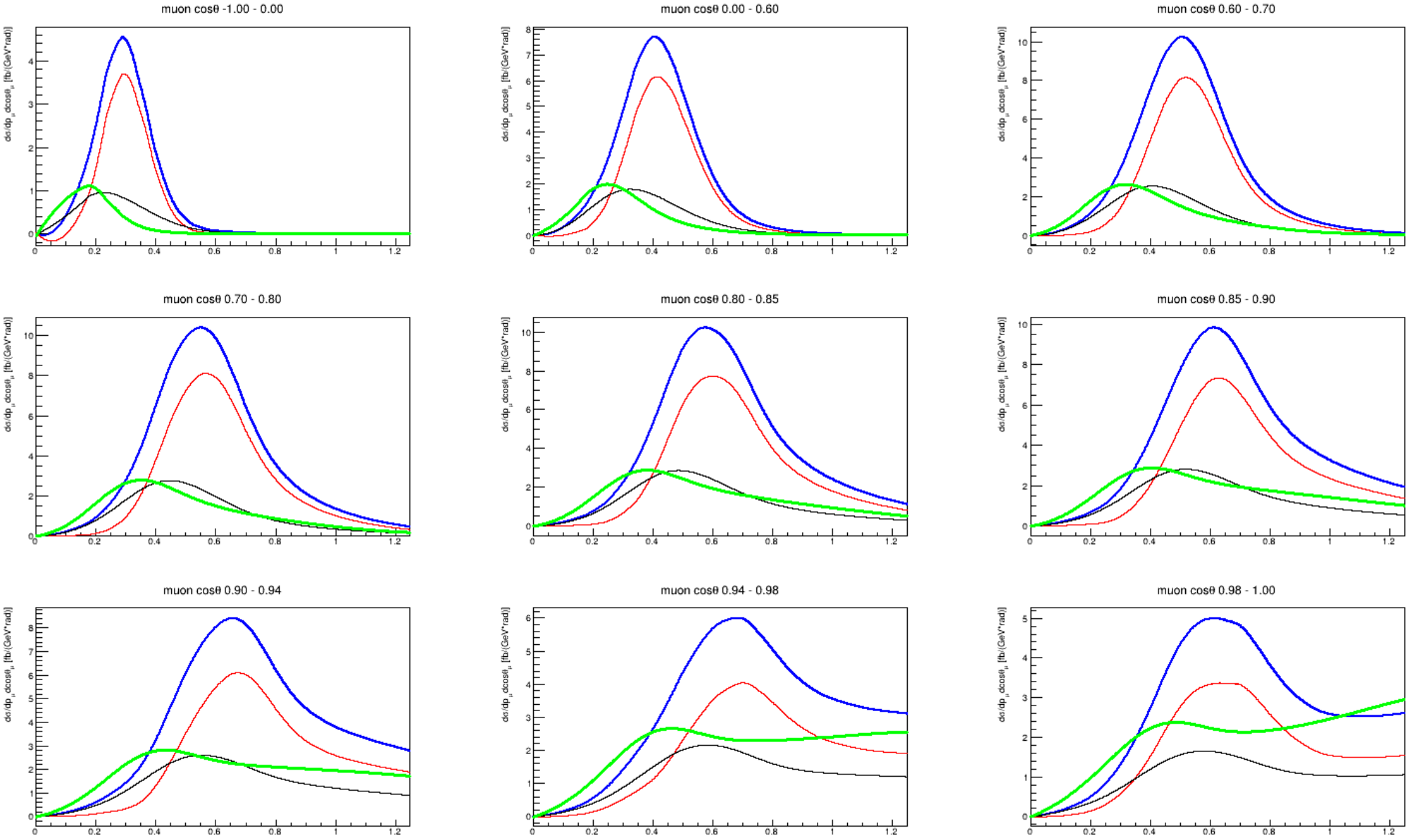




CC 1π (Martini)

RPA + 2p2h
RPA
2p2h
CC1π

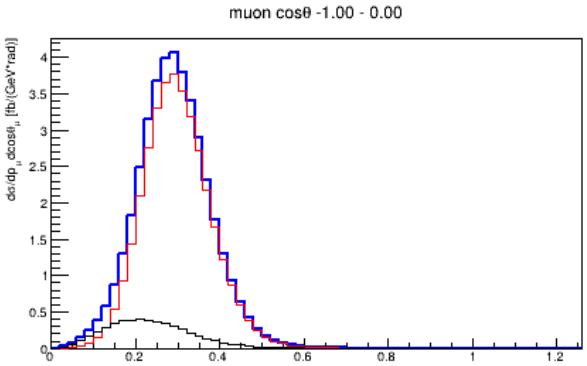
Unfortunately low p_μ is also the region where most of the CC1π background is located

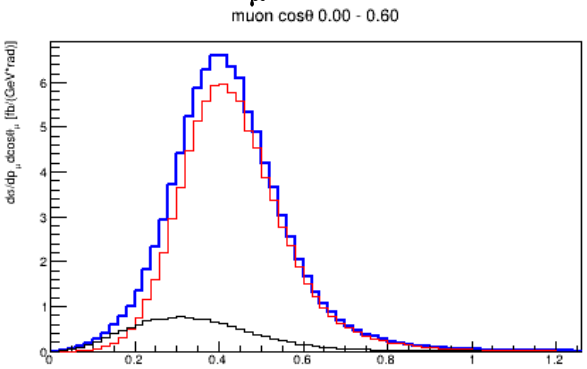


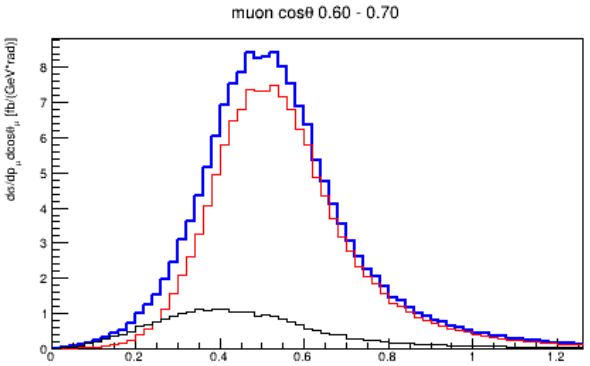
Nieves model

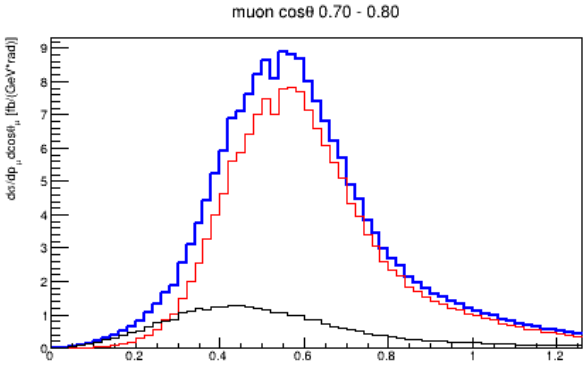
RPA + 2p2h
RPA
2p2h

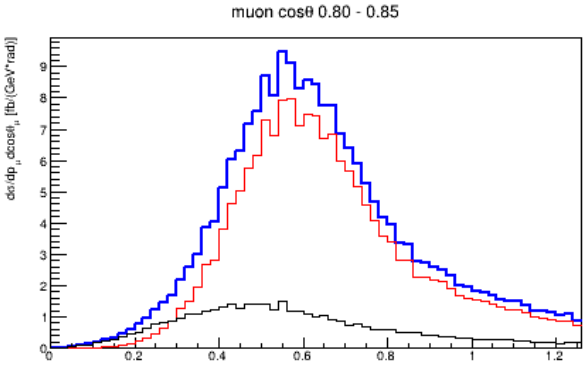
For both models there is a region at **small p_μ where only 2p2h and no 'real' QE is present !**

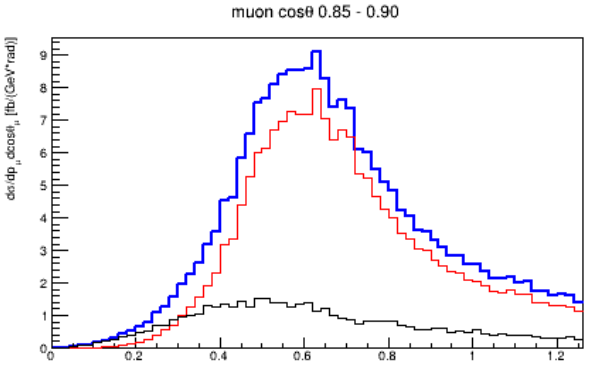


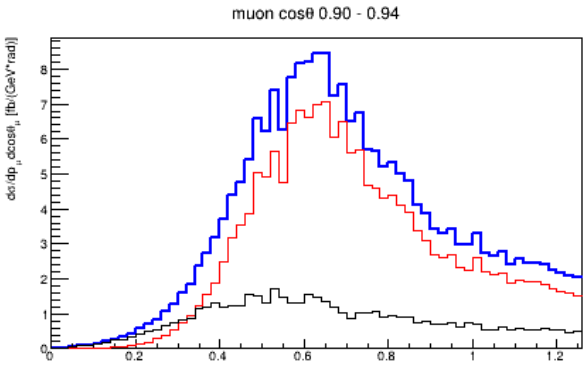


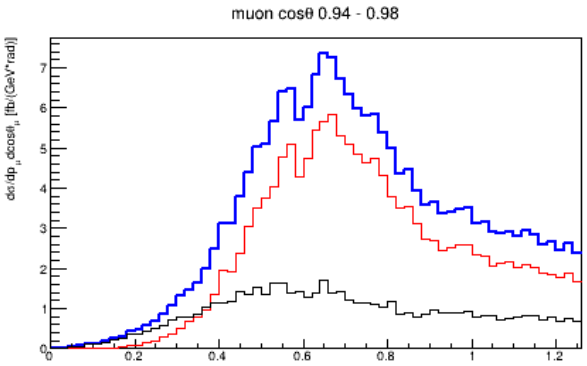


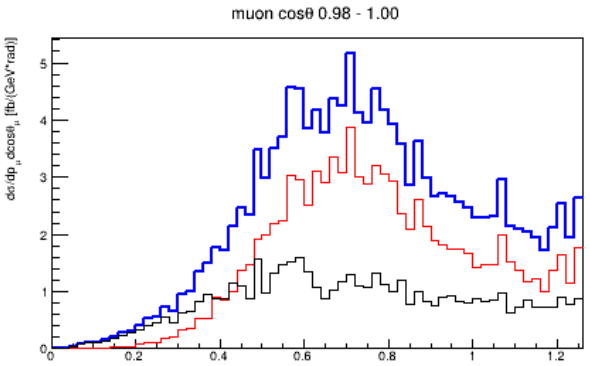








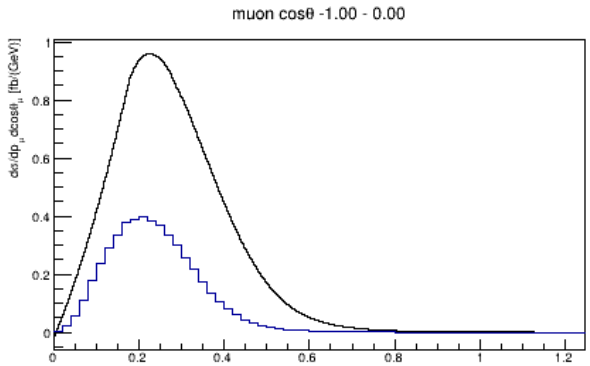


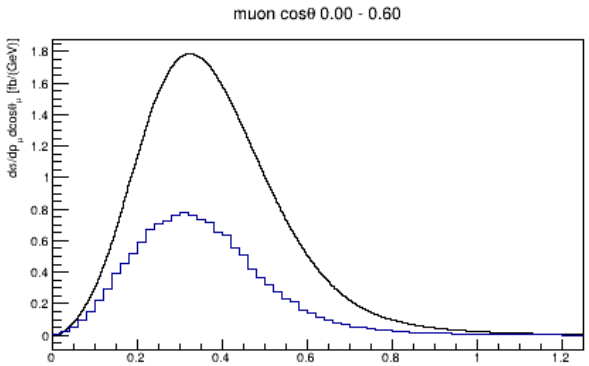


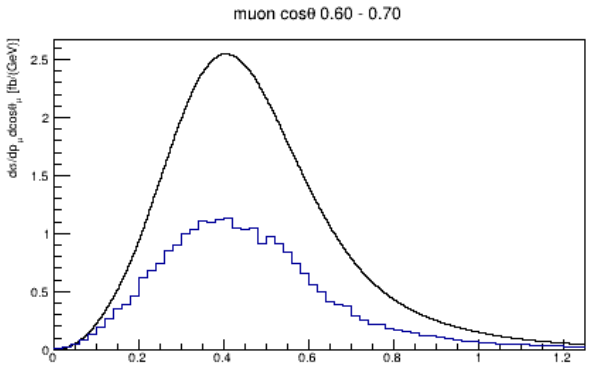
2p2h only: Nieves vs Martini

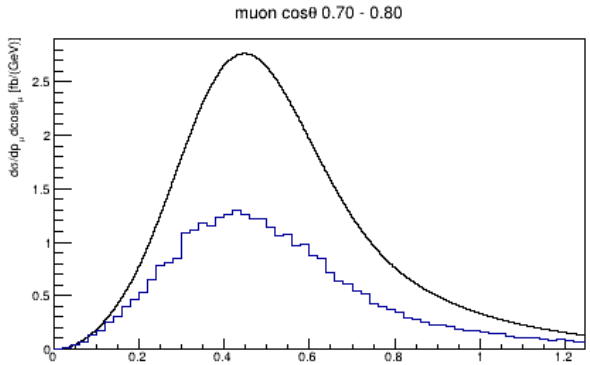
Martini (line)
Nieves (histo)

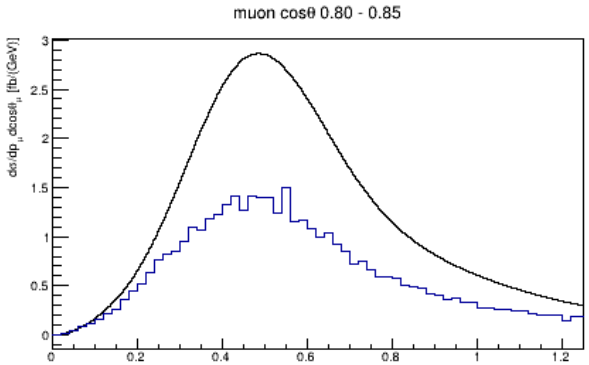
Large (~factor 2) difference between 2p2h effects in Martini and Nieves

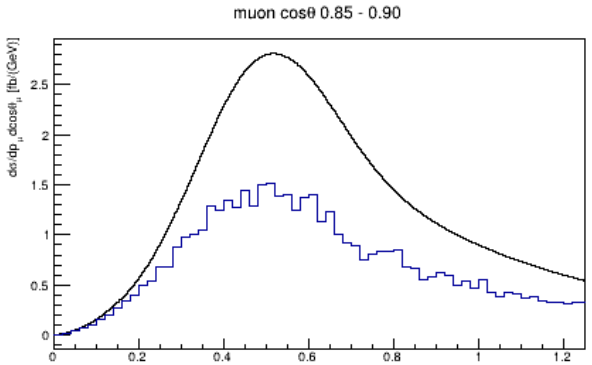


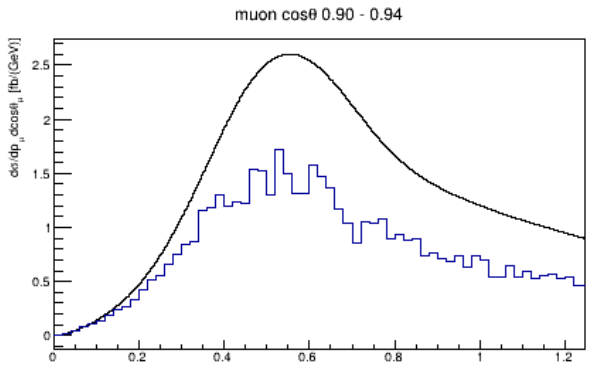


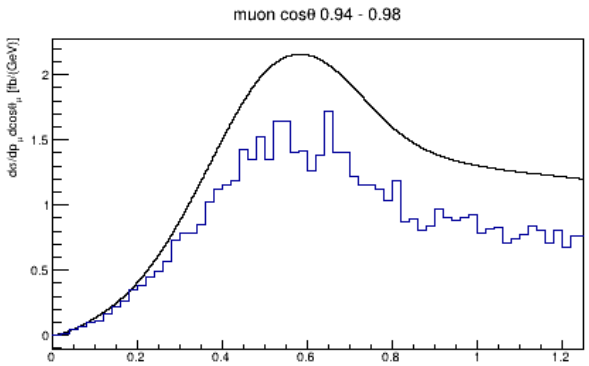


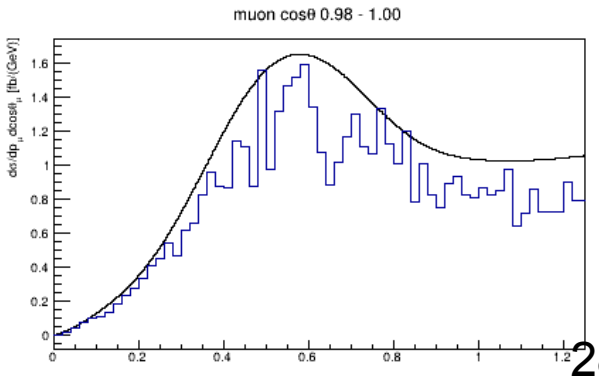








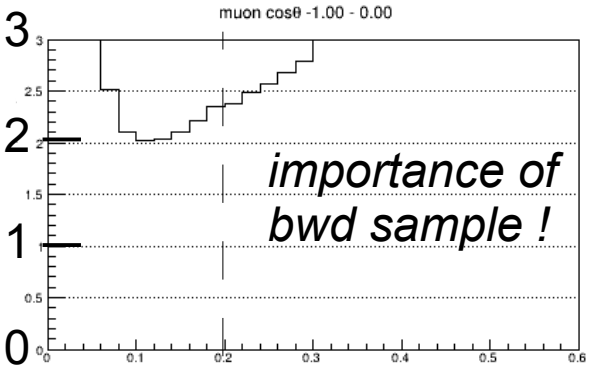


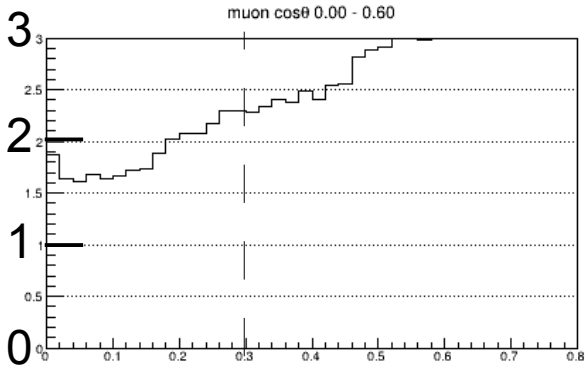


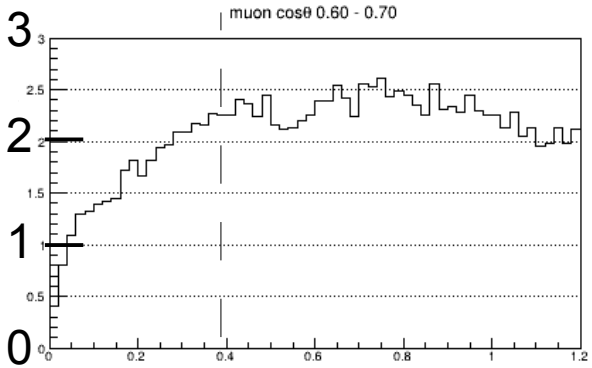
2p2h only Martini/Nieves

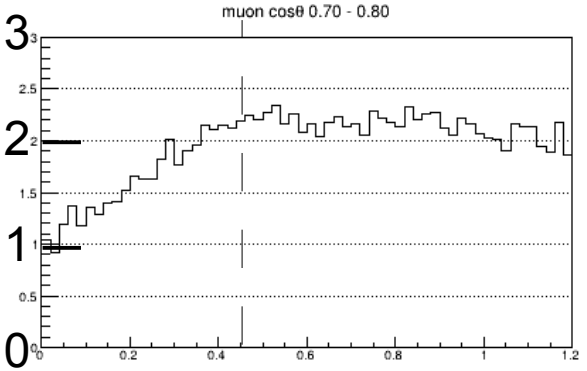
At peak position Martini ~2 times larger (~2.5 for backw muons and ~1.5 for very forw muons)

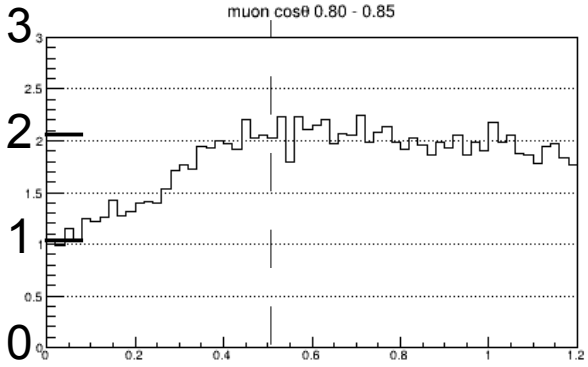
Shape difference: Martini 2p2h tends to shift to larger momentum and larger angles

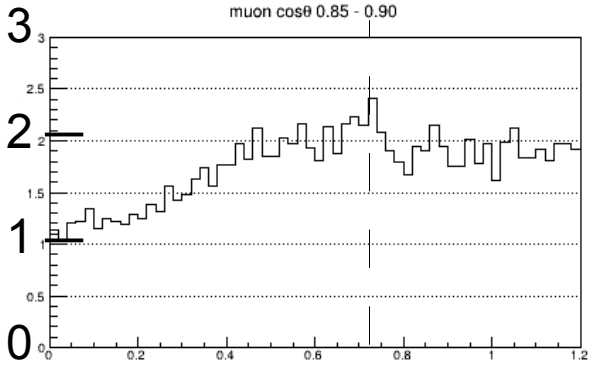


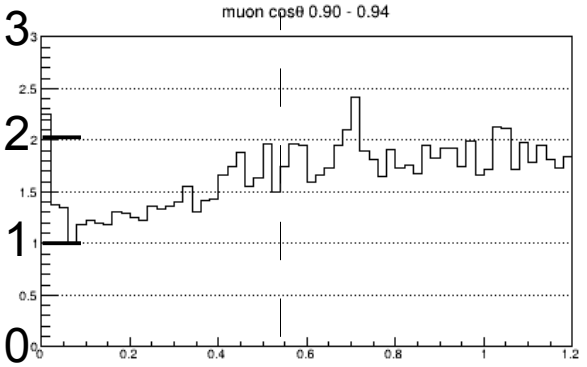


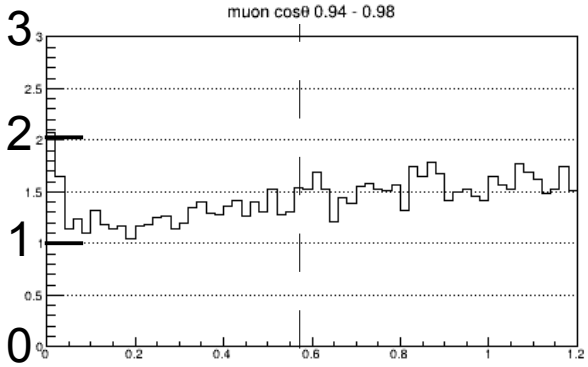


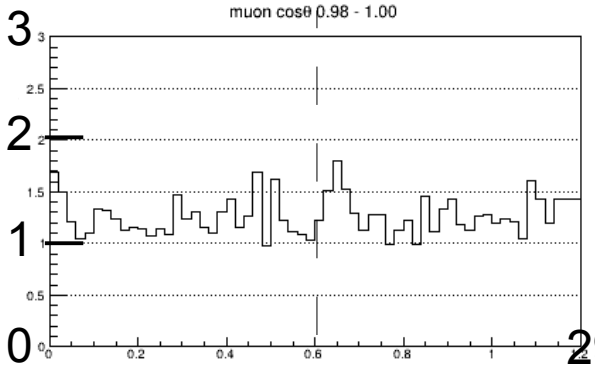








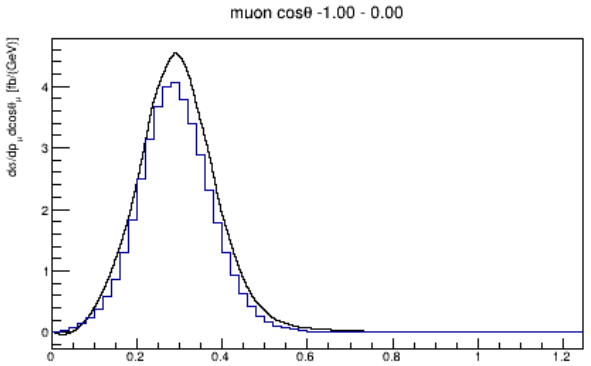


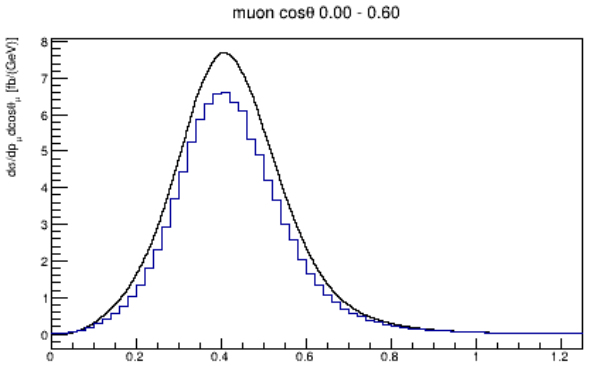


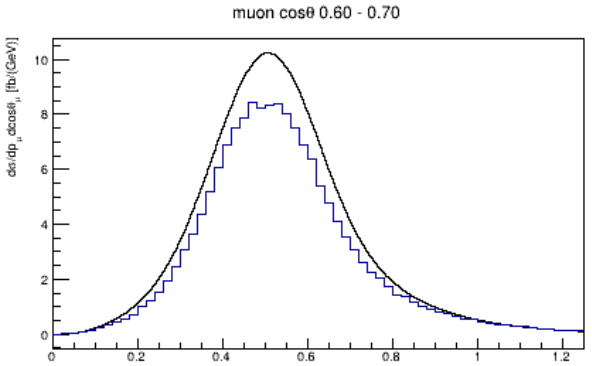
RPA + 2p2h

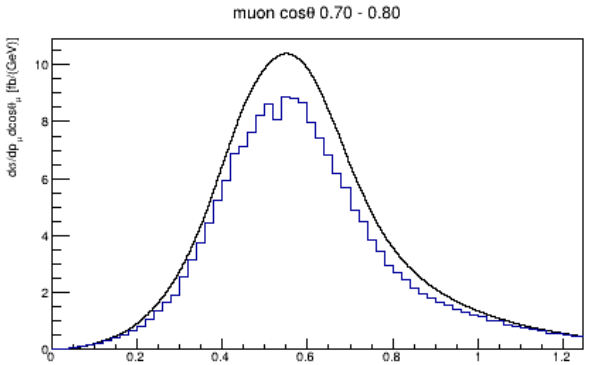
Martini (line)
Nieves (histo)

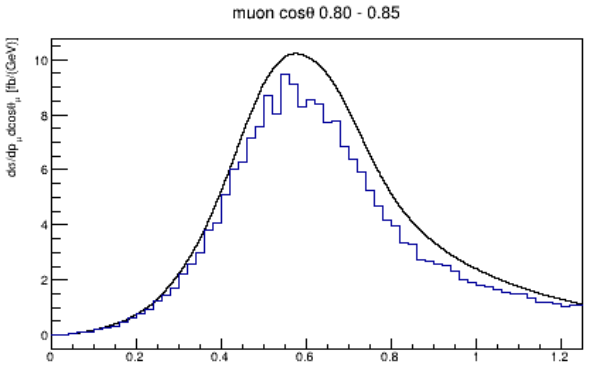
For the total xsec, differences are 'relatively' small

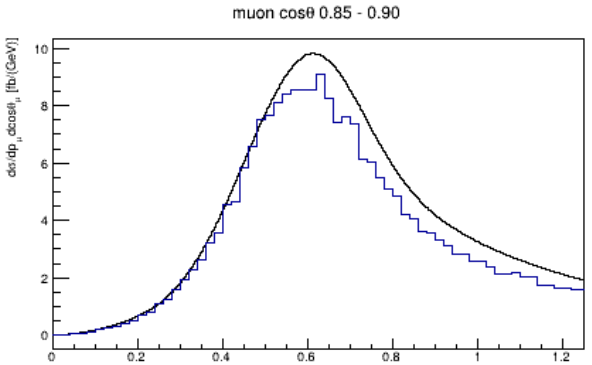


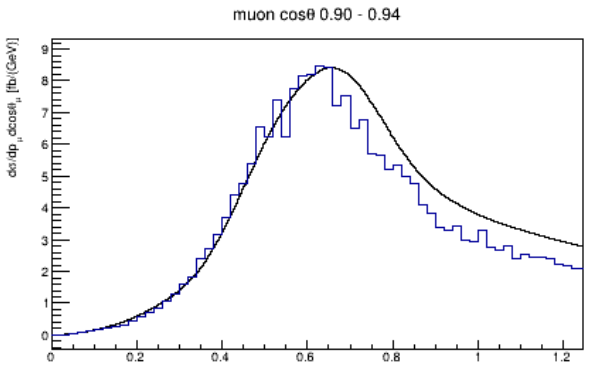


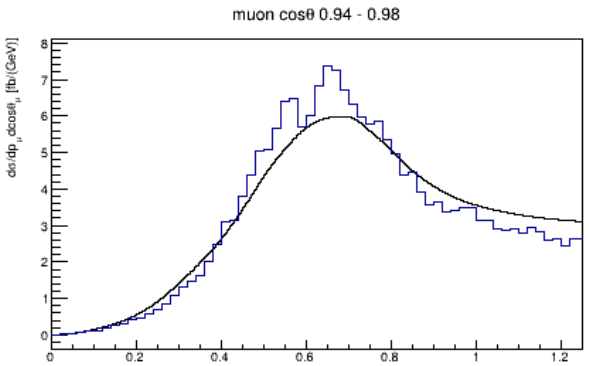


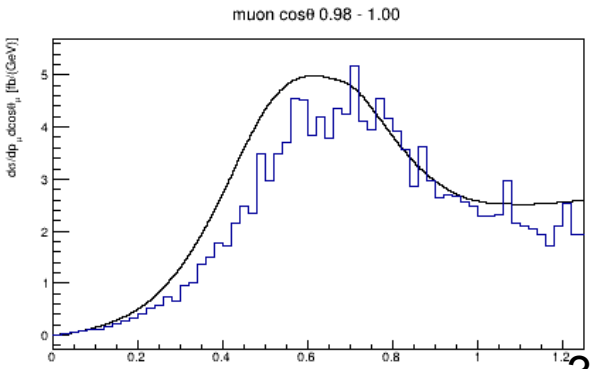








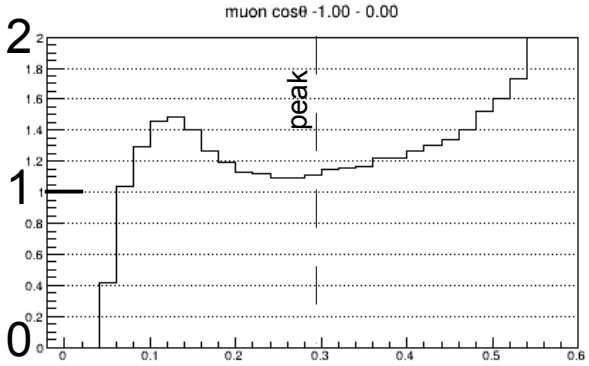


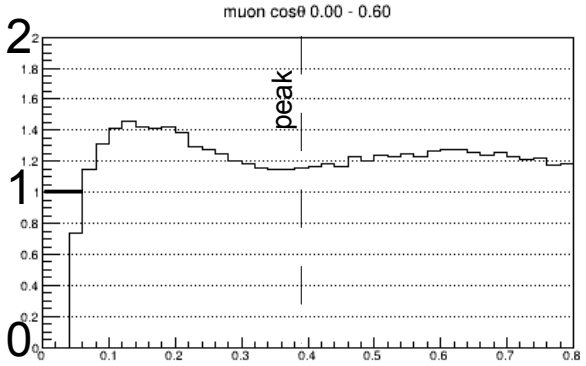


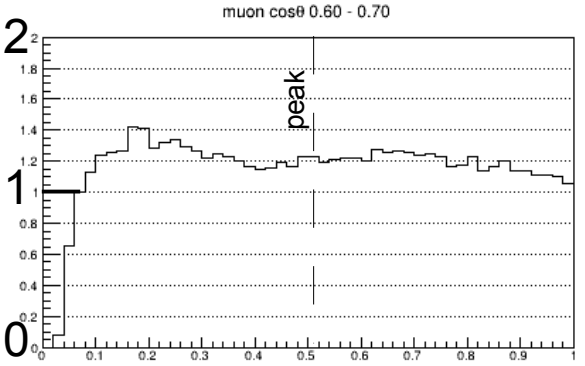
Martini/Nieves ND-flux folded

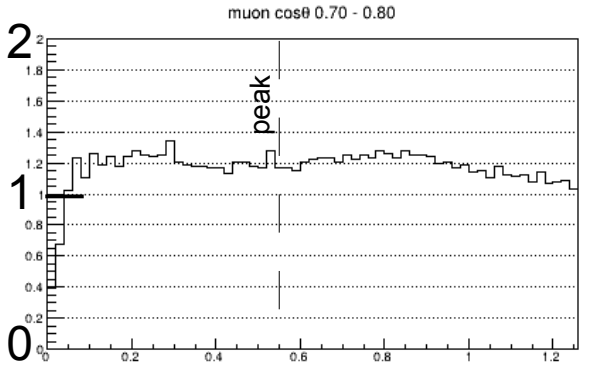
Differences: Martini ~ 20% larger in peak region

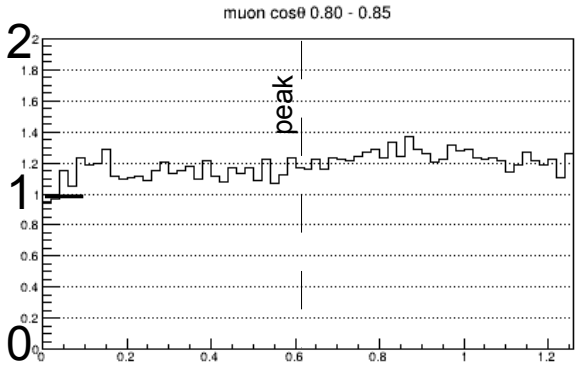
shape difference only for very backward (or very fwd) muons

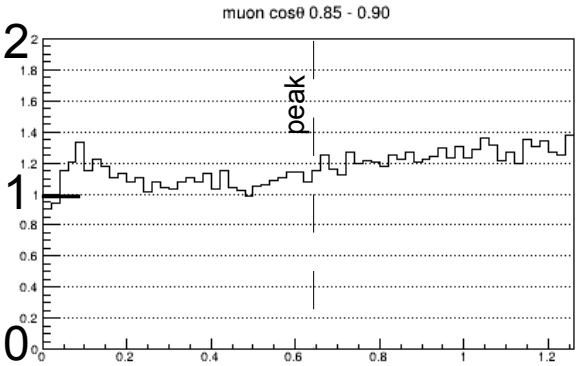


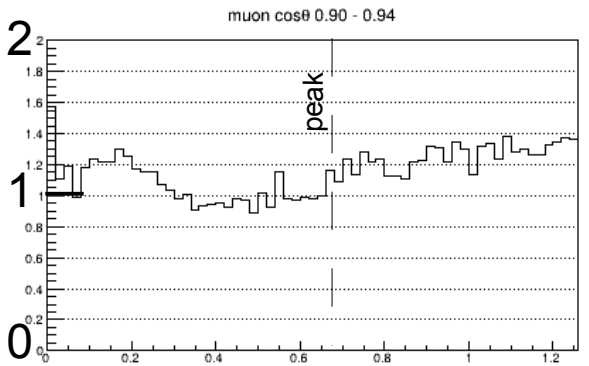


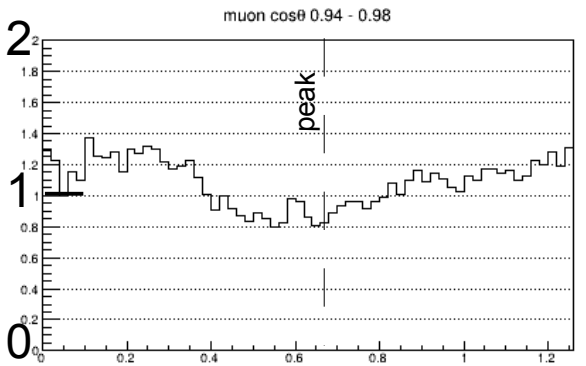


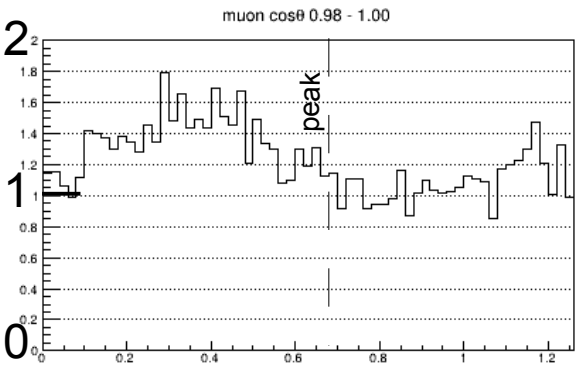






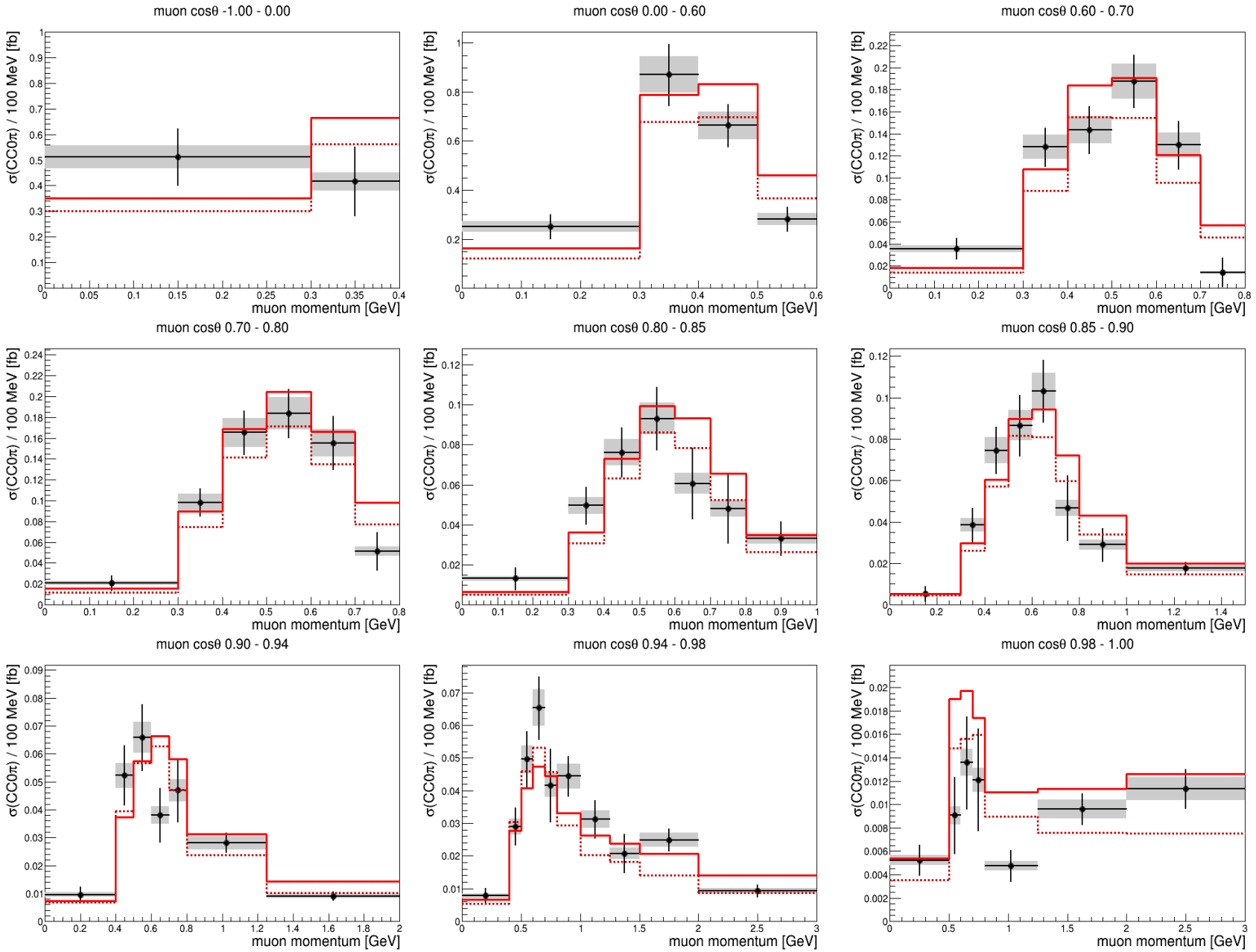






Comparison with CC0π data at ND280

Our data statistics at ND280 do not disentangle (yet!) strongly btw the two models:



normaliz. uncertainties

data with shape uncertainties

Martini RPA+2p2h

Nieves RPA+2p2h

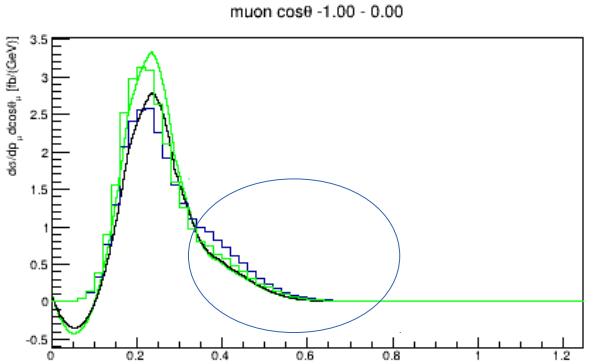
SK flux-folded

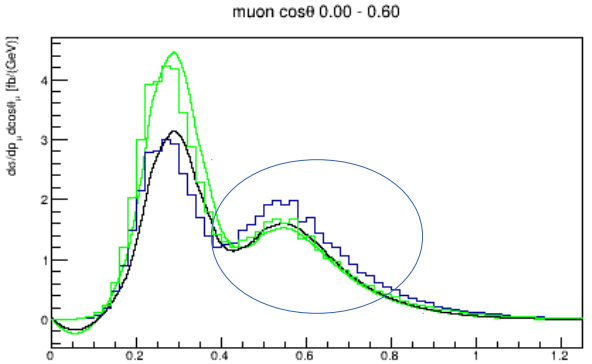
Bare and RPA

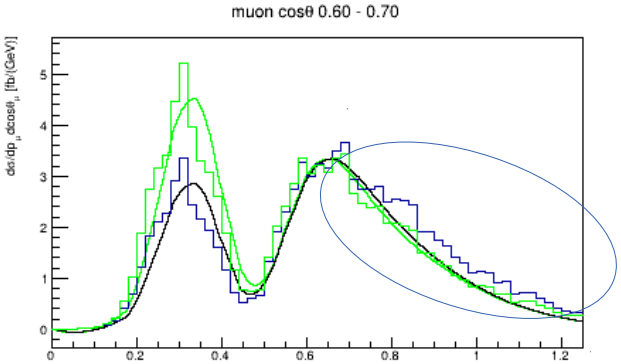
bare
RPA

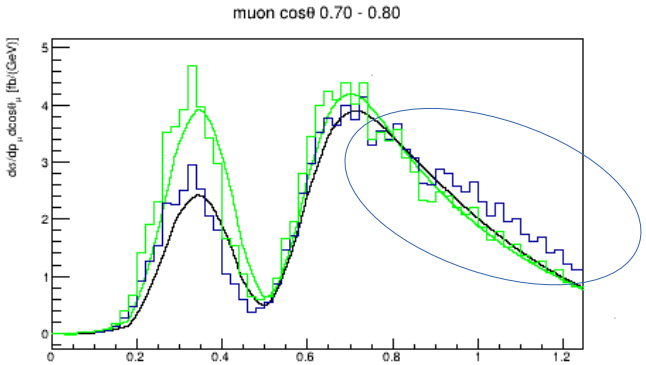
Nieves (histogram)
Martini (line)

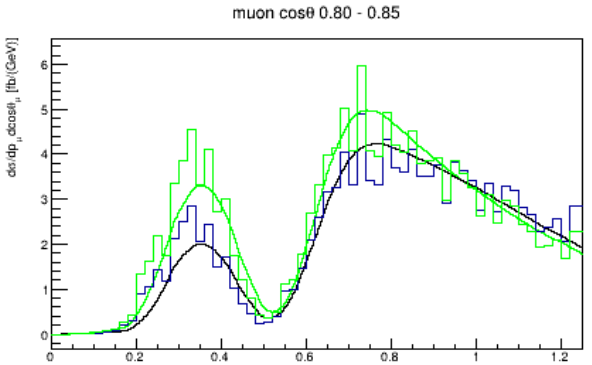
Relatively small differences (positive RPA corrections in Nieves at high pmu)

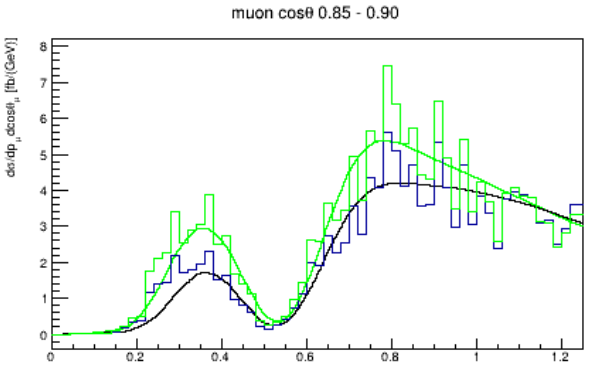


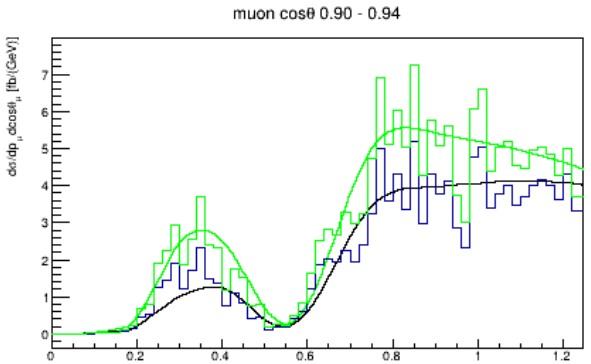


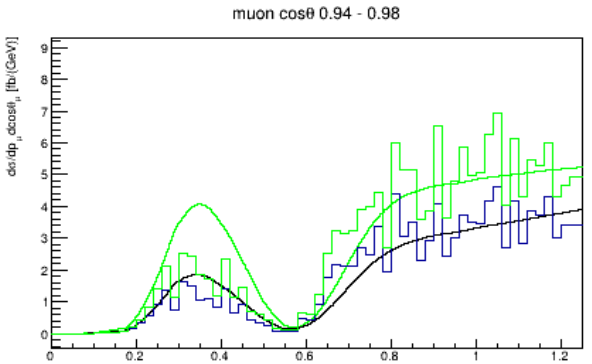


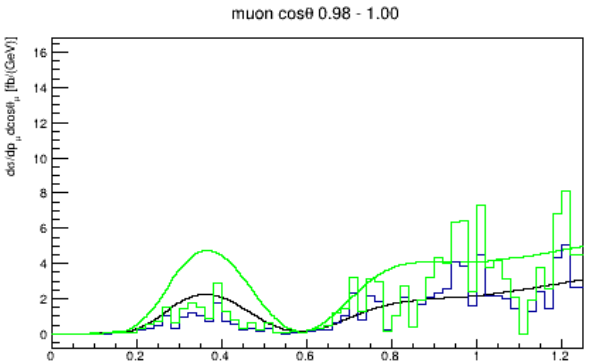








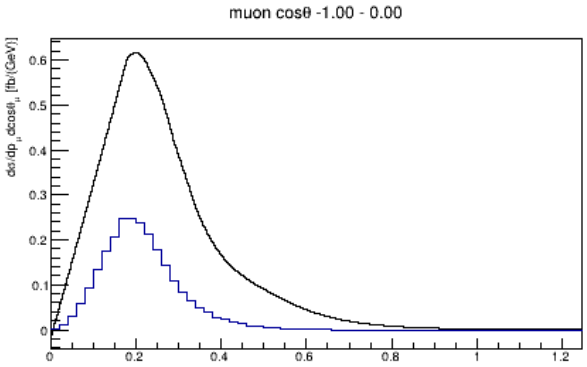


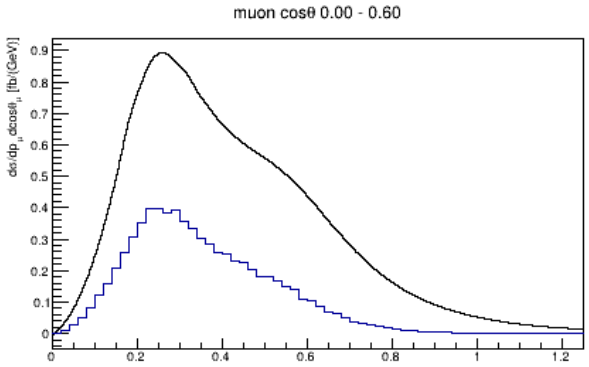


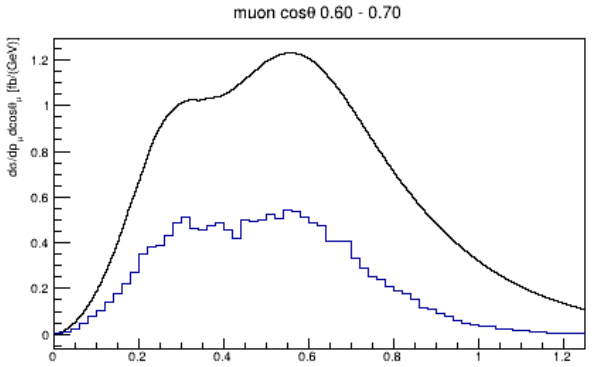
2p2h only

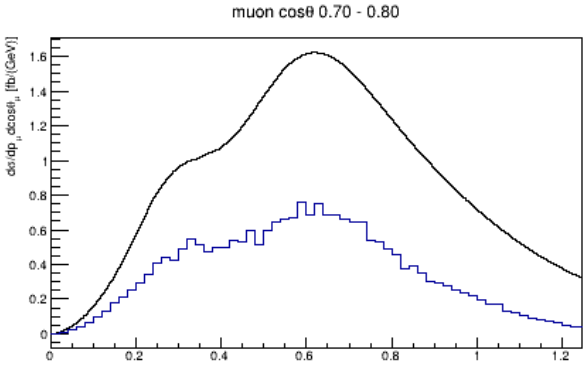
Martini (line)
Nieves (histo)

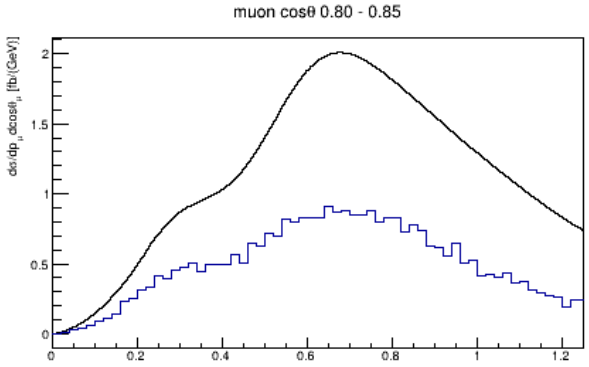
Large differences on 2p2h (~factor 2 as observed with ND flux folding)

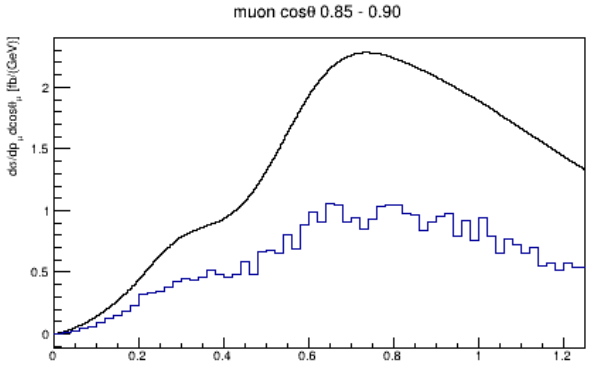


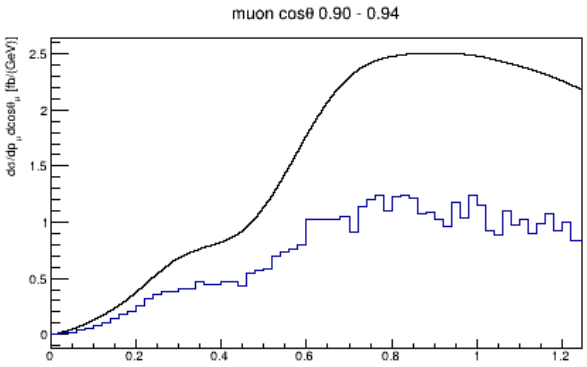


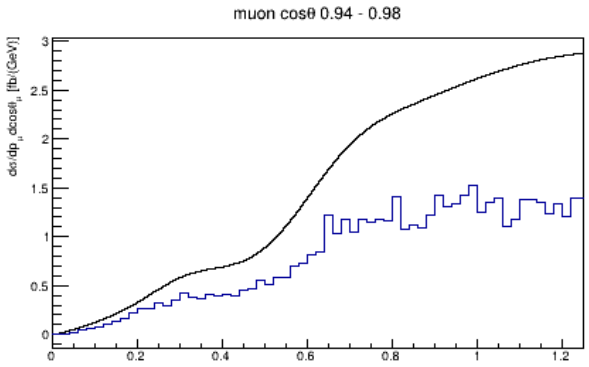


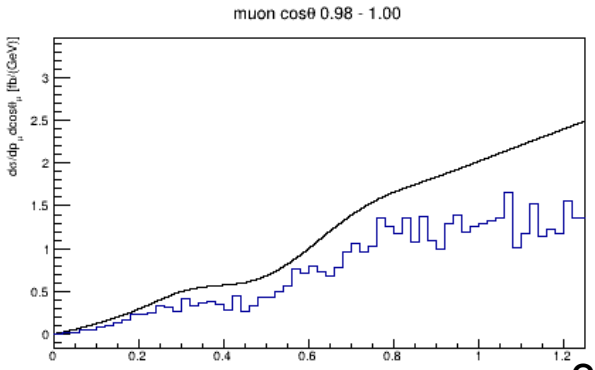








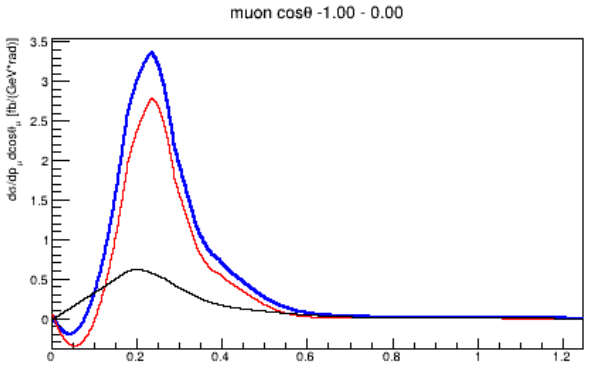


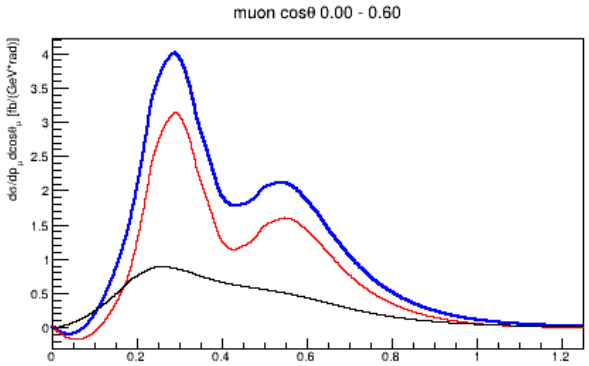


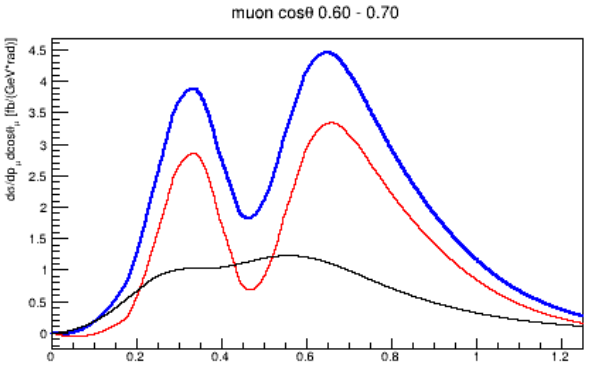
Martini

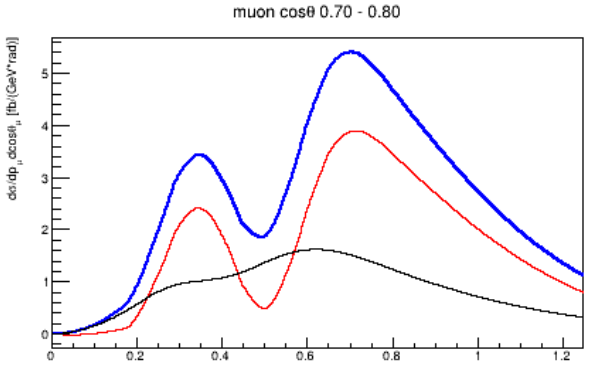
RPA + 2p2h
RPA
2p2h

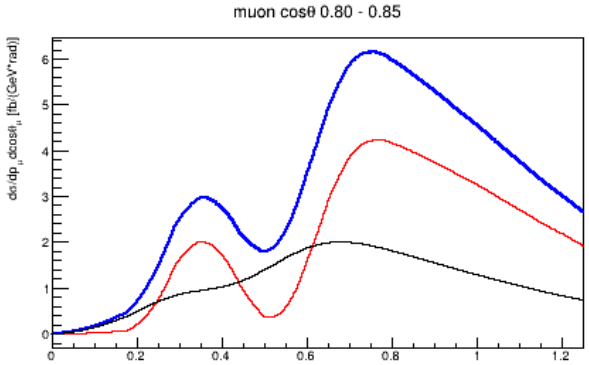
For both models 2p2h tends to fill the oscillation deep (same mechanism as E_ν^{rec} smearing)

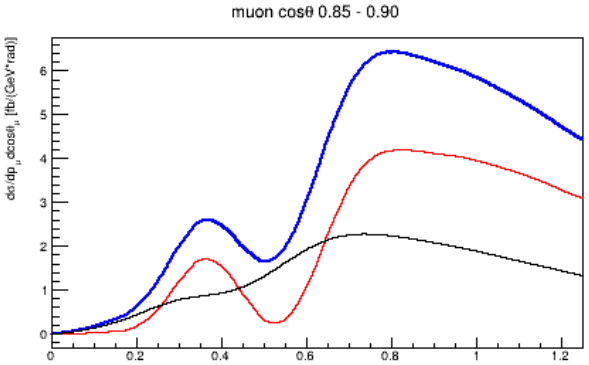


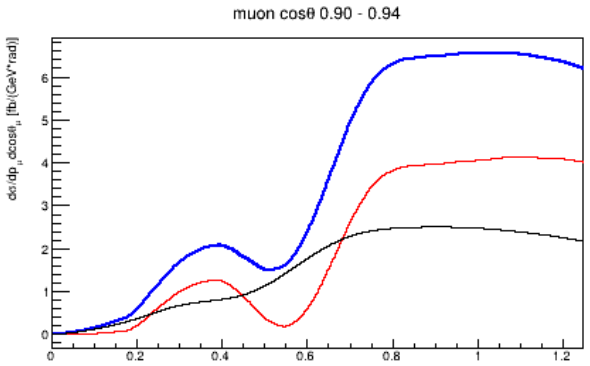


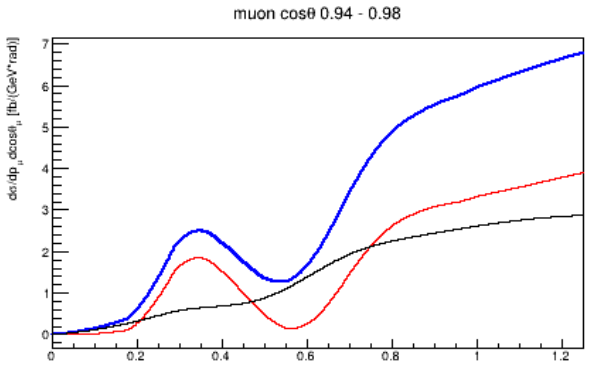


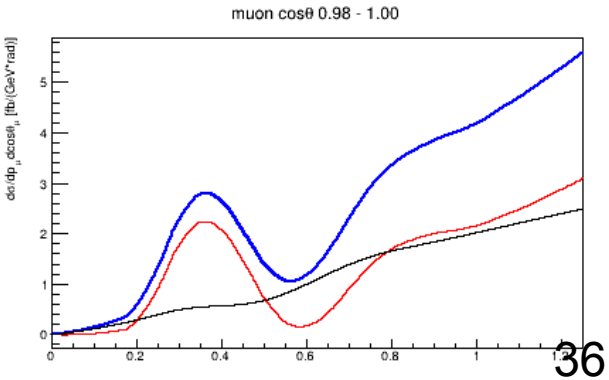








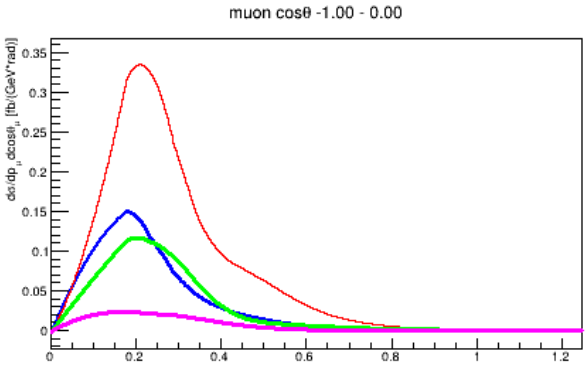


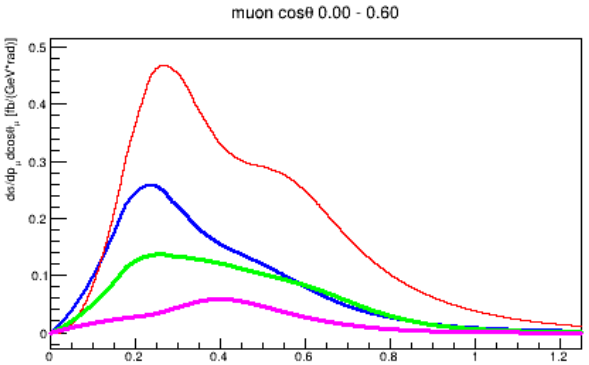


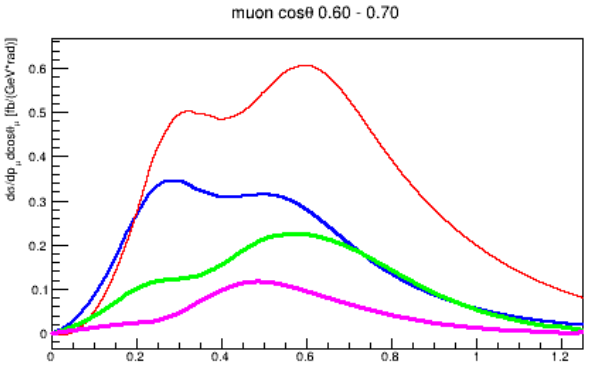
Martini 2p2h components

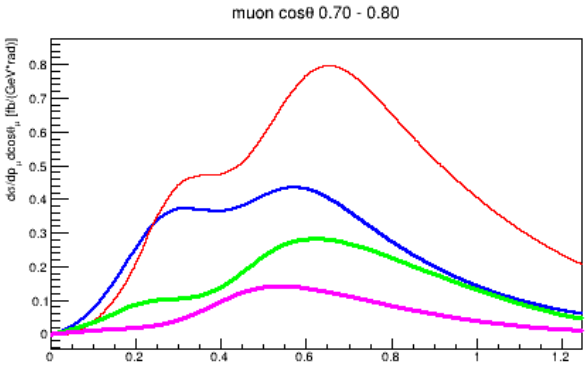
("MEC" includes $\Delta^{\pi\text{-less}}$ and more)

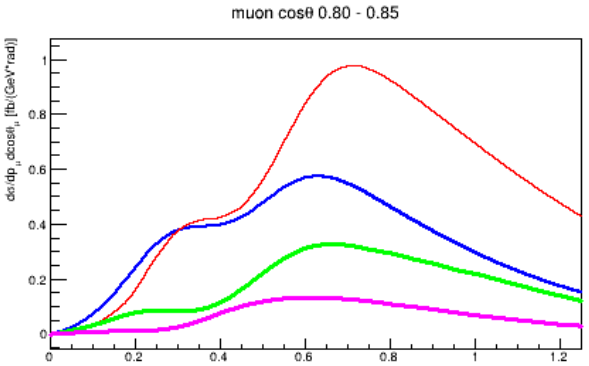
NN correlations NN-MEC interference MEC 2p2h $\Delta^{\pi\text{-less}}$ 3p3h

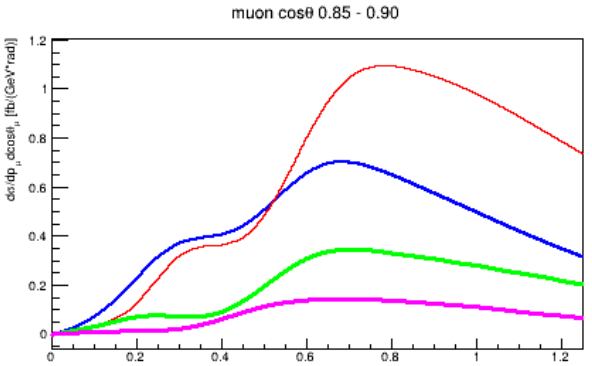


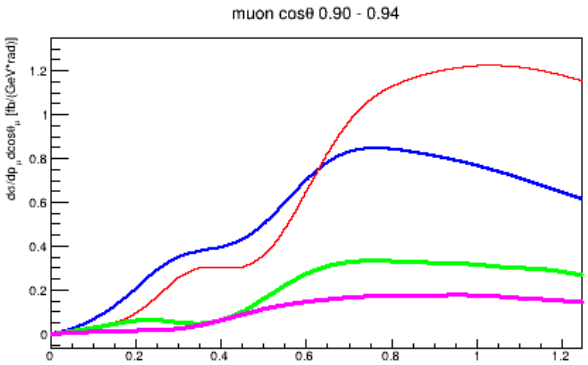


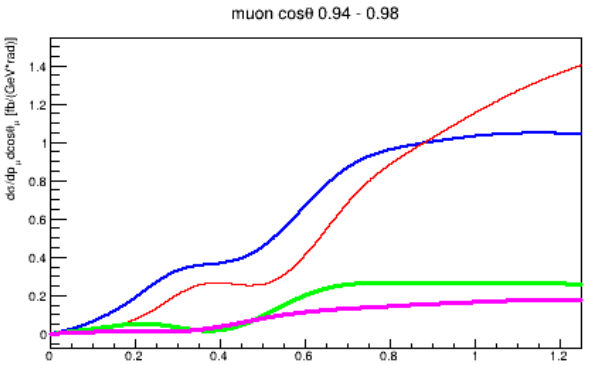


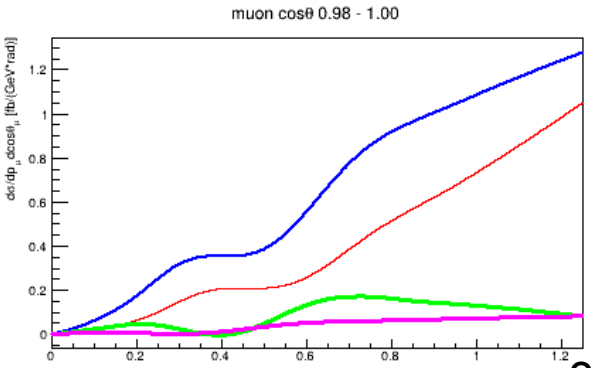








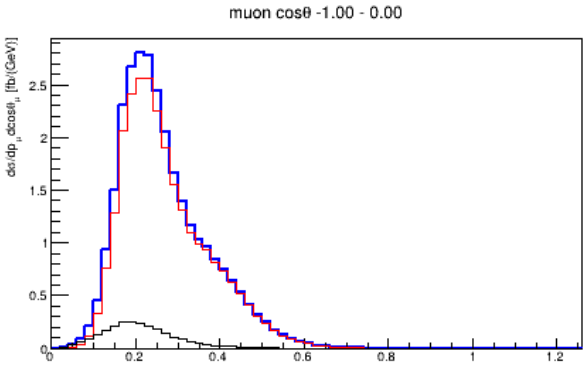


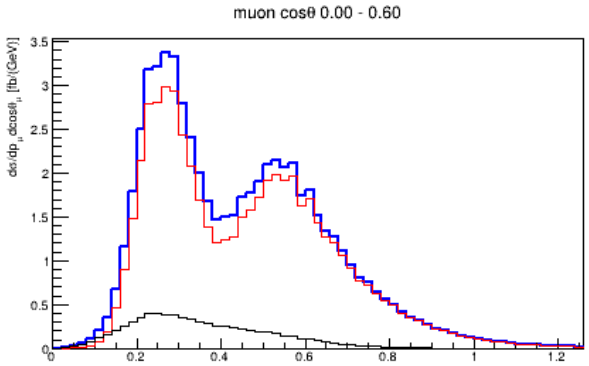


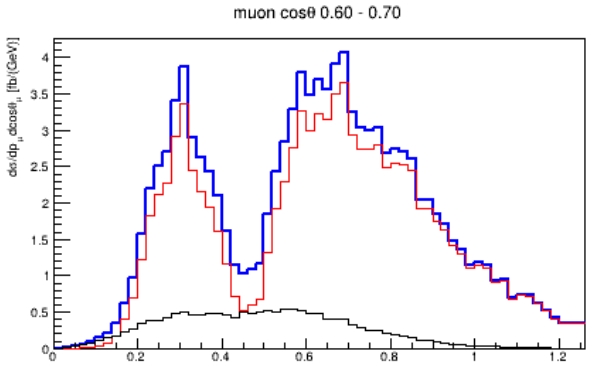
Nieves model

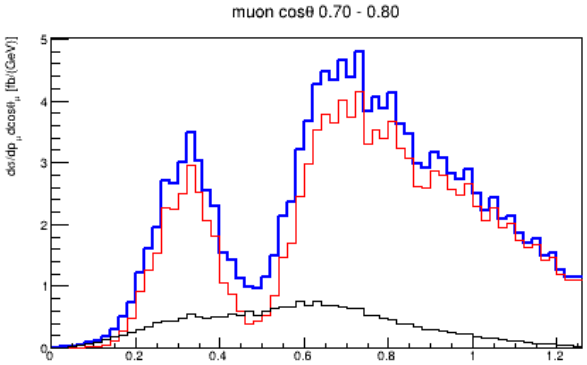
RPA + 2p2h
RPA
2p2h

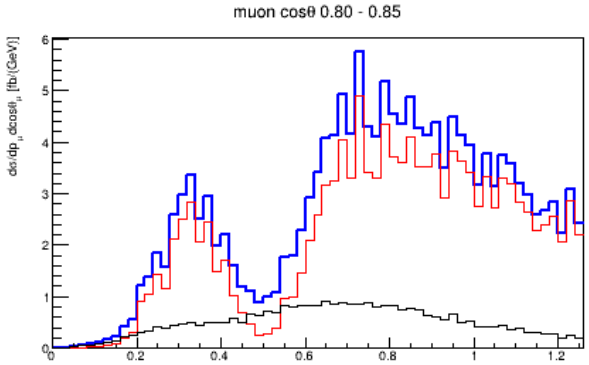
For both models 2p2h tends to fill the oscillation deep (same mechanism as E_ν^{rec} smearing)

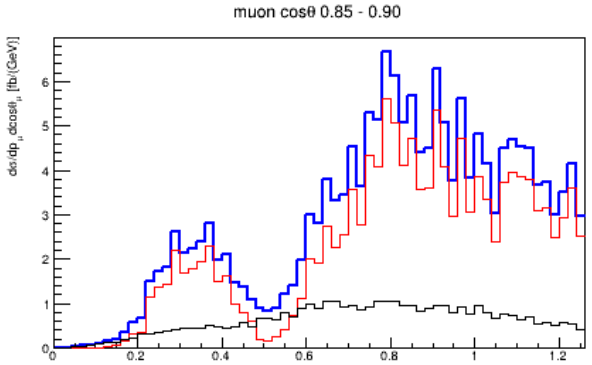


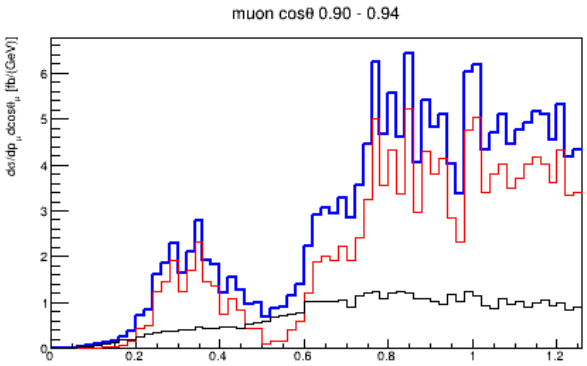


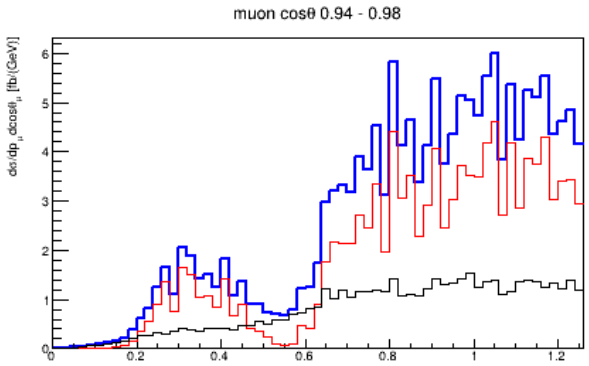


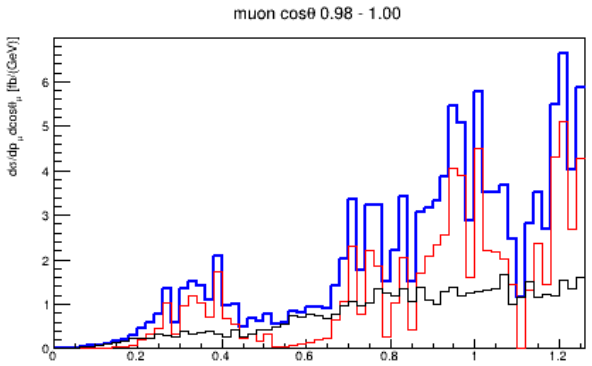








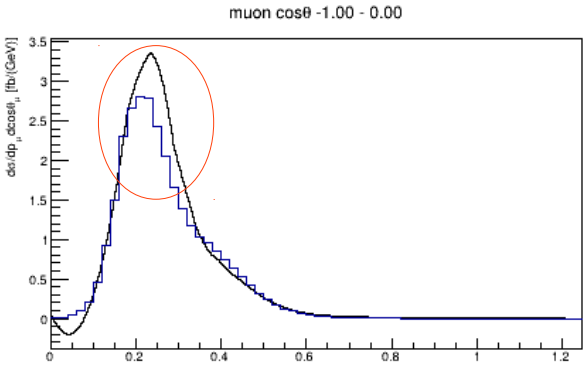


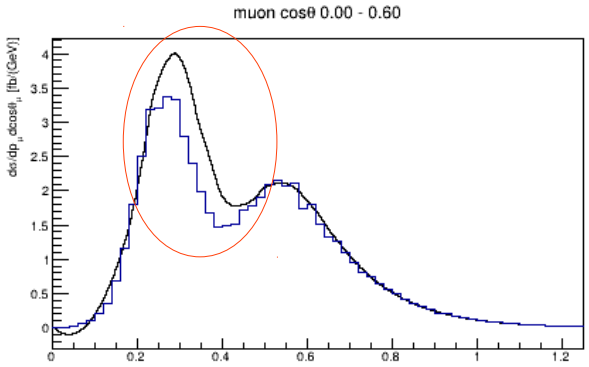


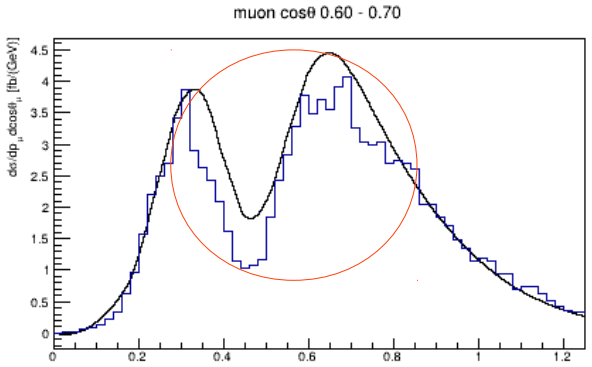
RPA + 2p2h

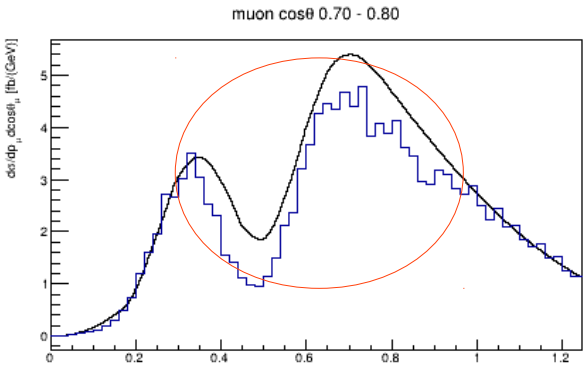
Martini (line)
Nieves (histo)

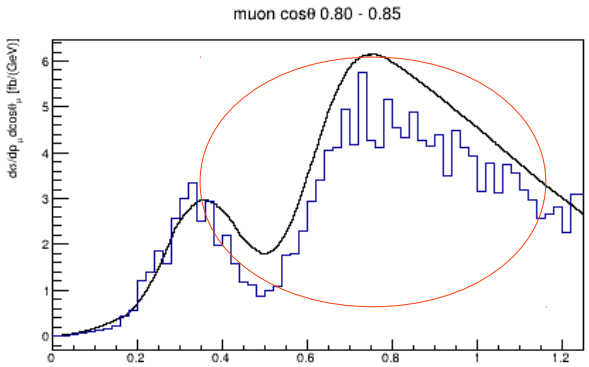
Large differences in spectrum shape predicted at SK, especially at the dip

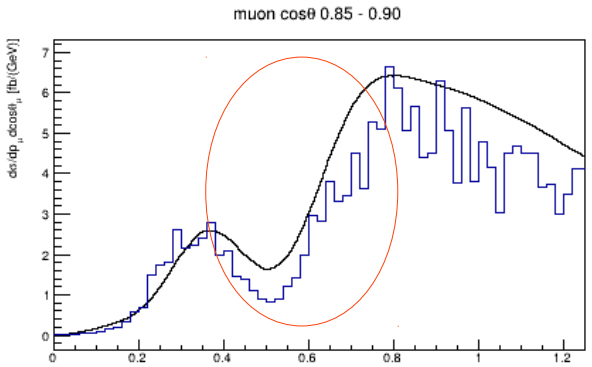


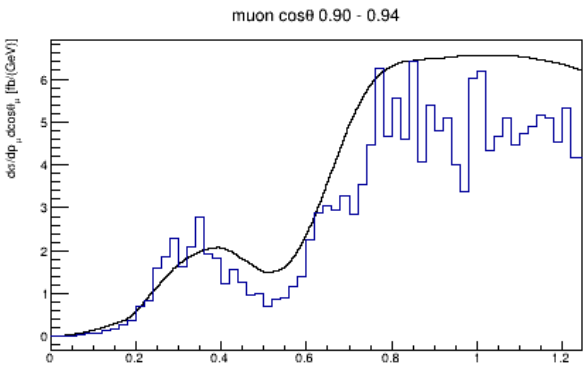


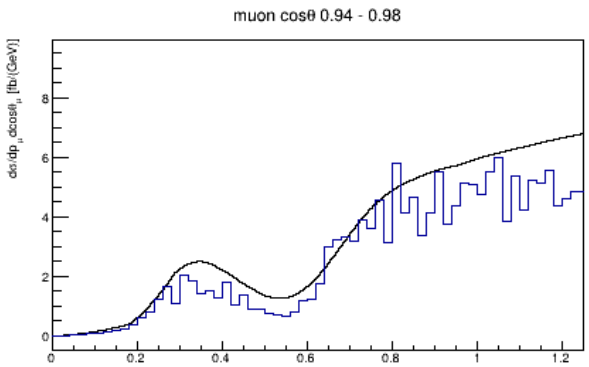


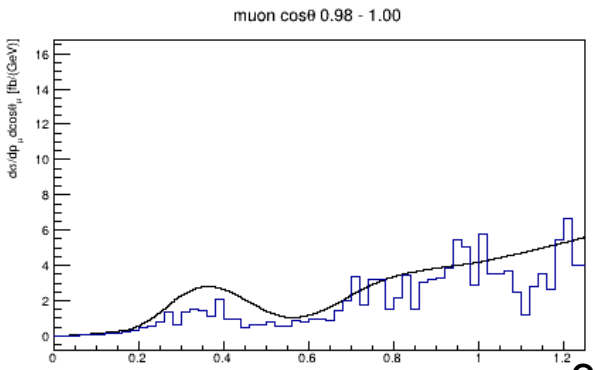








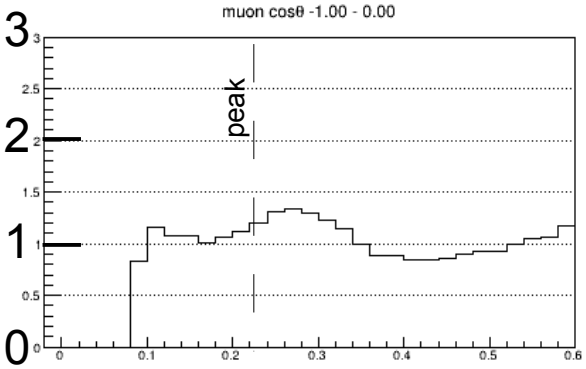


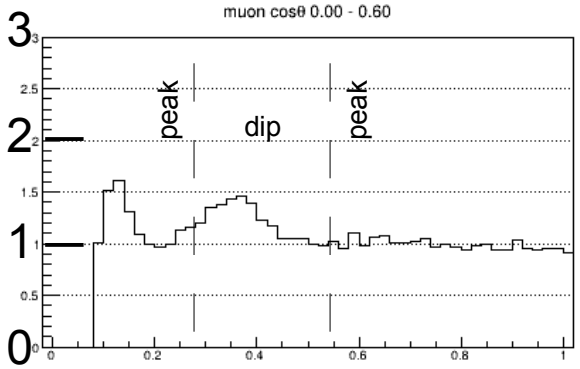


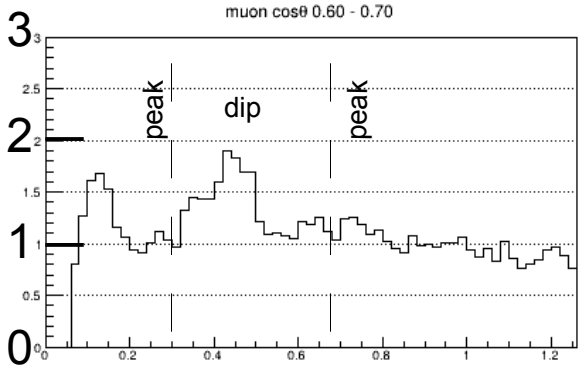
Martini/Nieves

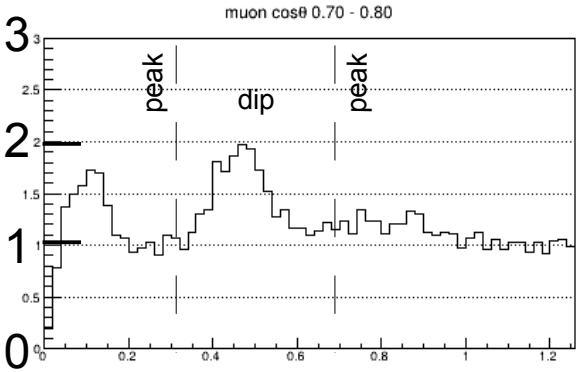
Martini (line)
Nieves (histo)

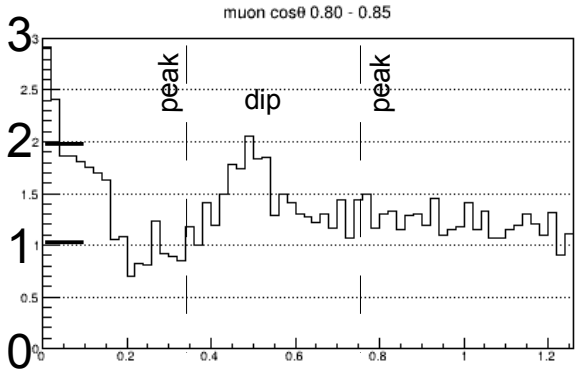
Trying to quantify the effect: **factor 2 difference at the dip and 10-20% at one of the peaks**

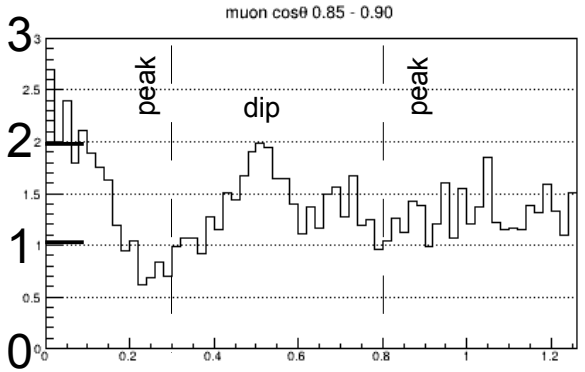


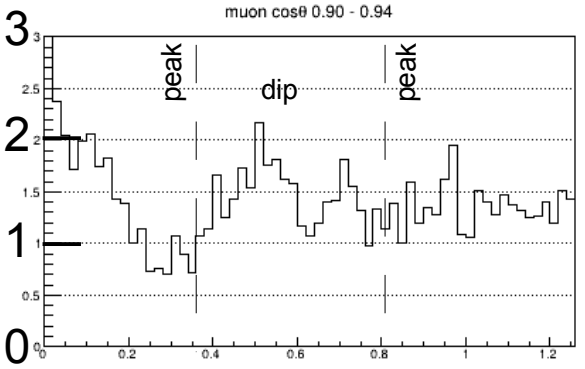


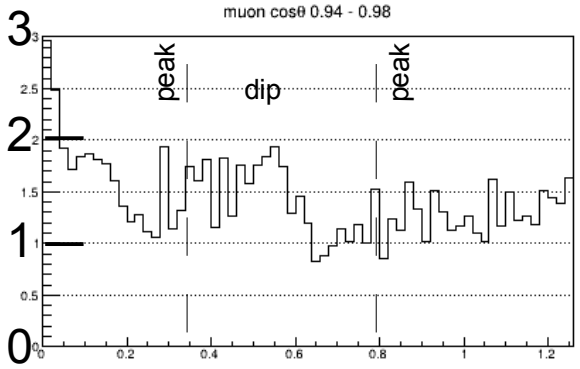


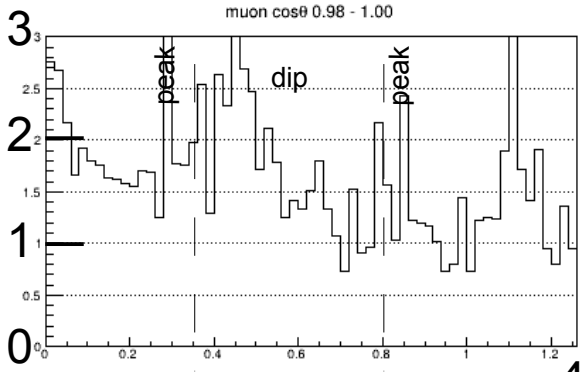






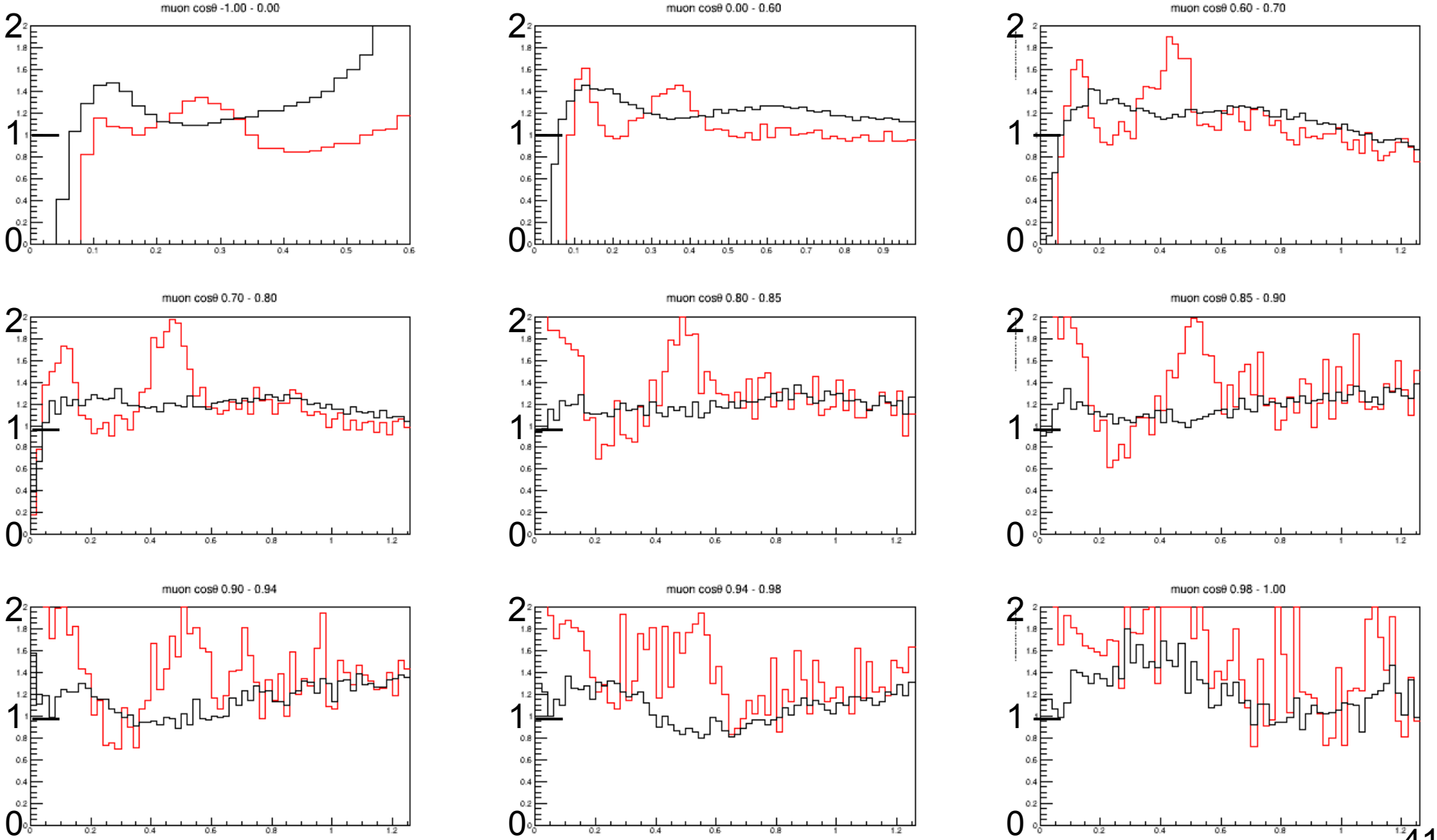






Martini/Nieves SK vs ND folded

SK-flux folded ND-flux folded



Summary

NEUT - Nieves differences:

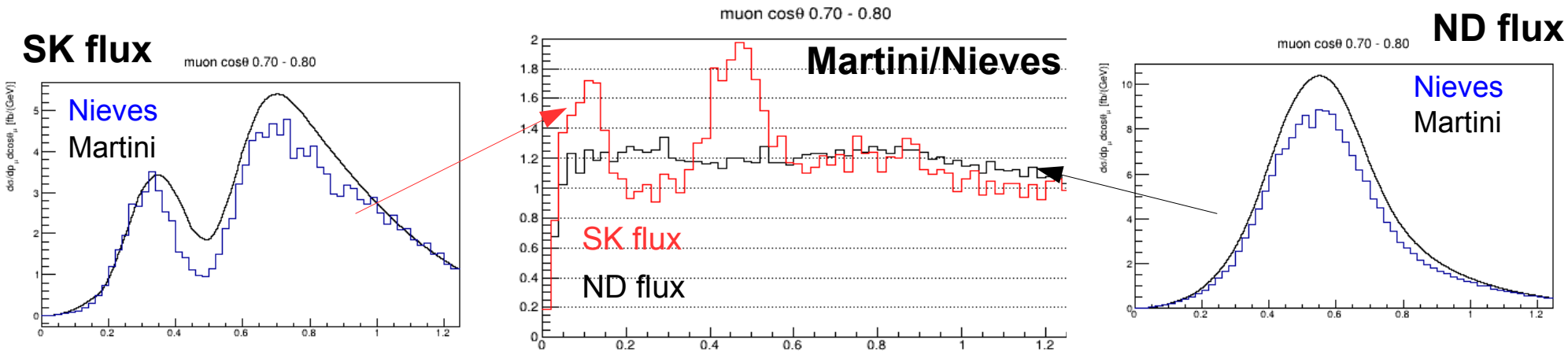
- shift in E_b and local vs global Fermi Gas

Martini - Nieves differences:

- bare has shift in Eν, RPA different at high Q2
- **difference of a ~factor 2 in 2p2h but similar shape**

Folding with ND280 flux tends to wash out differences but folding with SK flux preserve the effect

- 2p2h contribution "fills the deep" to different amount in the 2 models
- also some differences in the peak height

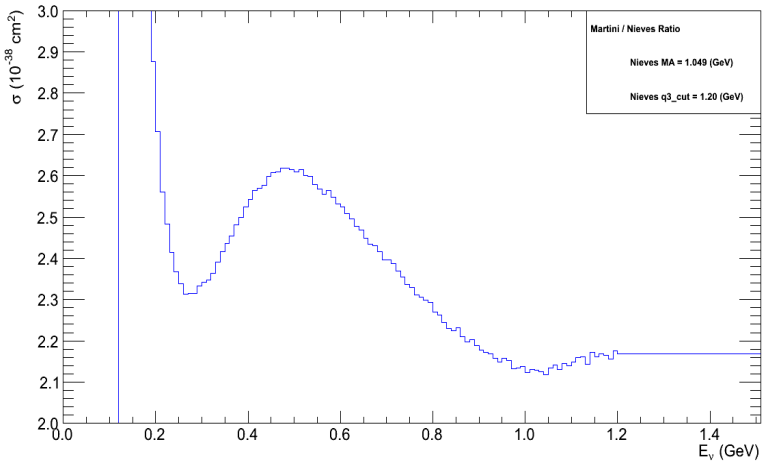


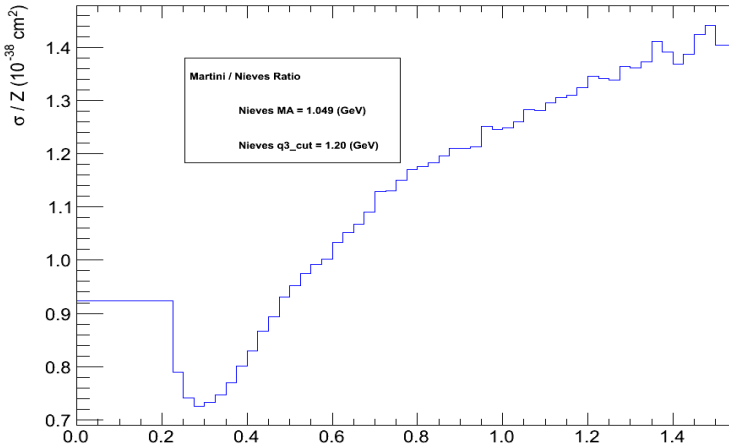
Differences in 2p2h relevant at SK: affect the oscillation deep but difficult to constraint from ND280

Is the shape difference between nu and nubar important?

By comparing sEn between nu and nubar would look so...

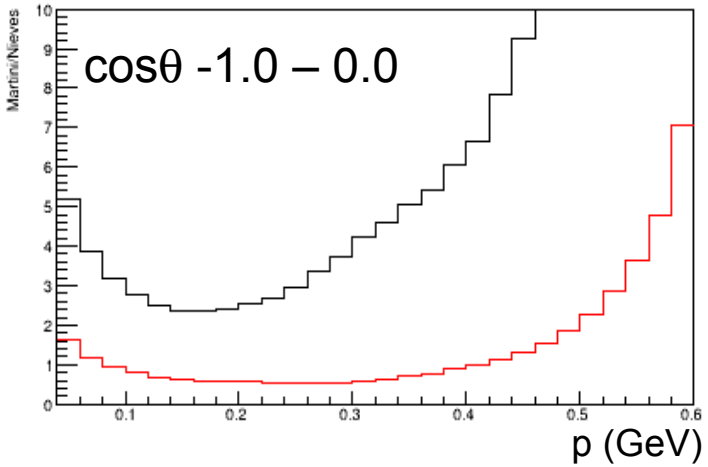
Martini/Nieves ratio (2p2h only)

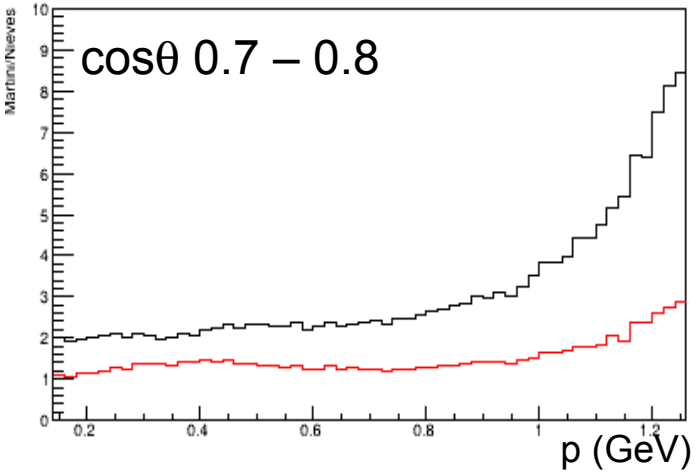


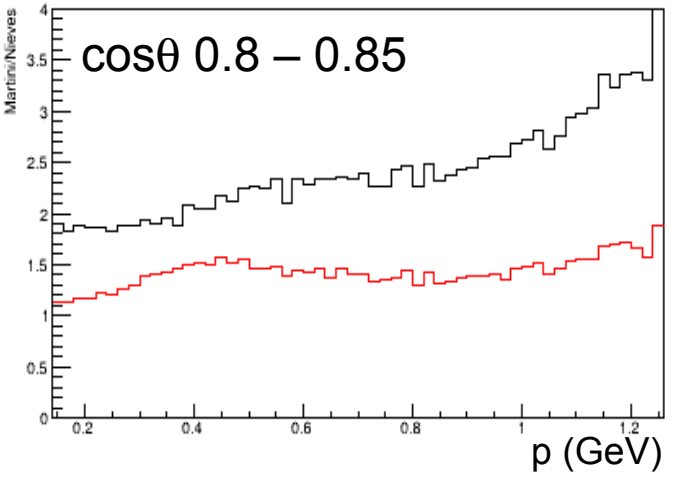


Actually, looking at pmu, cosqmu the difference in shape is similar between nu and nubar

Martini/Nieves ratio (2p2h only, SK flux folded)

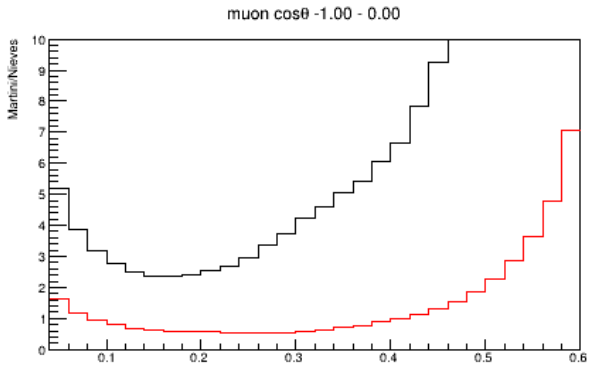


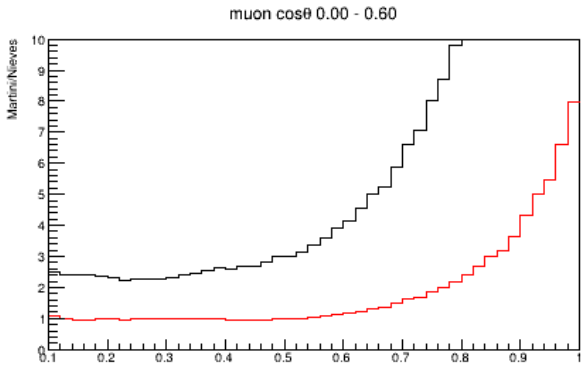


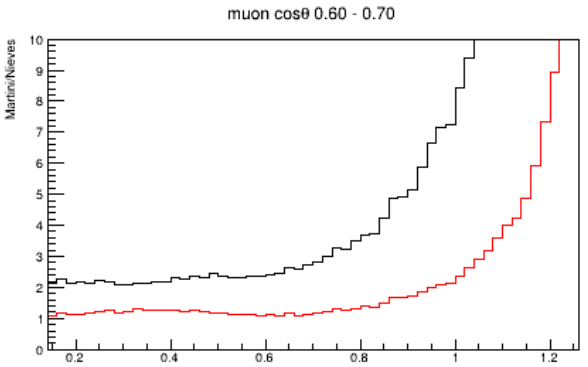


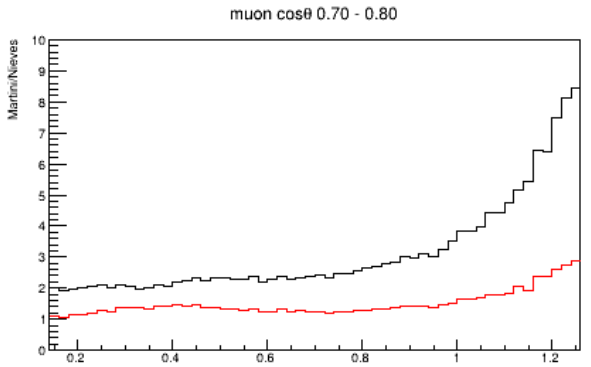
Martini/Nieves 2p2h only

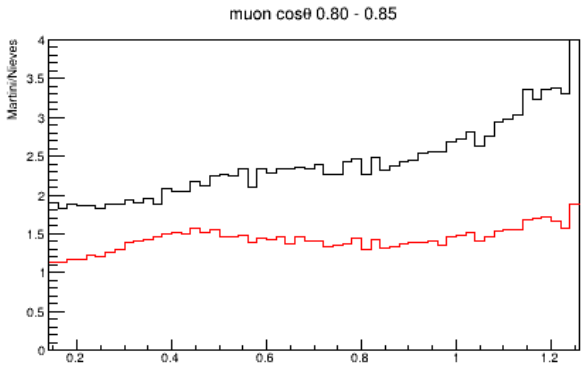
nubar
nu

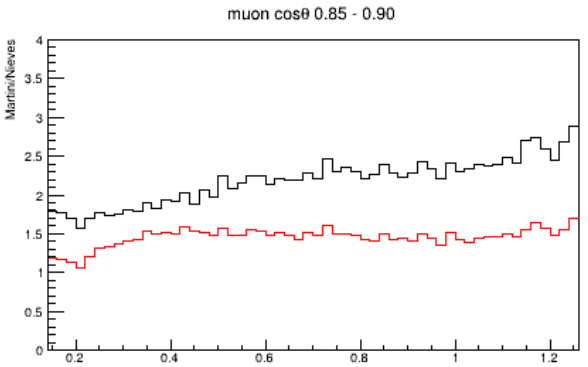


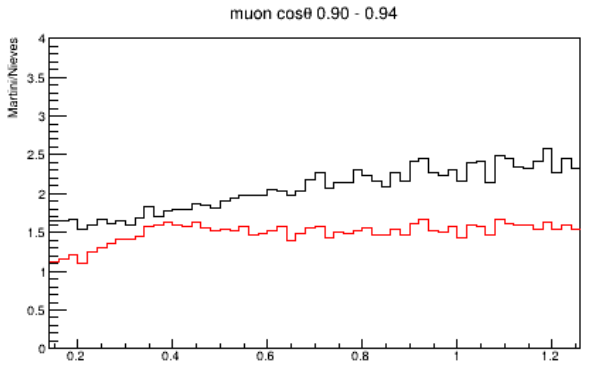


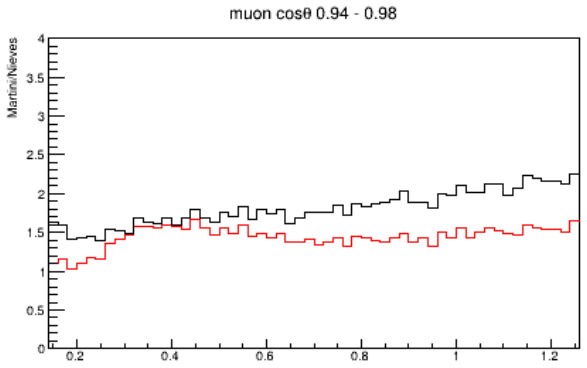


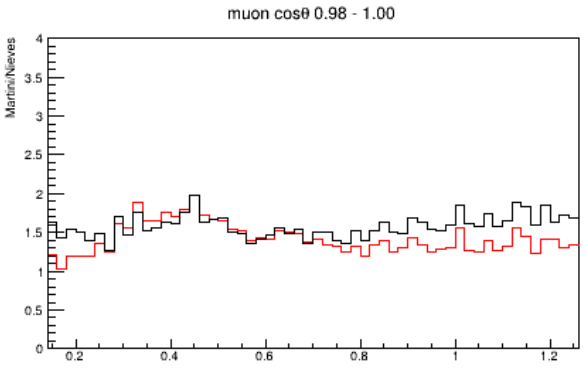












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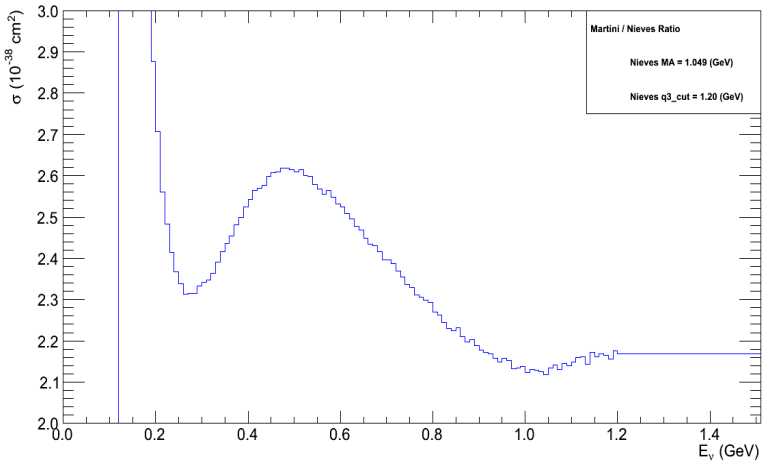
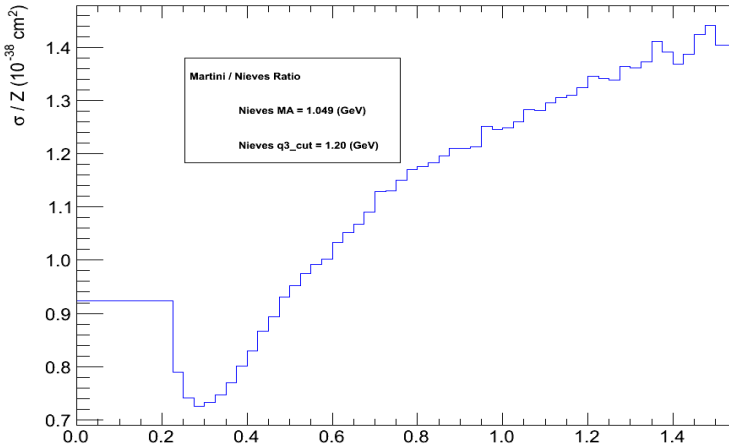
By comparing sEn between nu and nubar would look so...

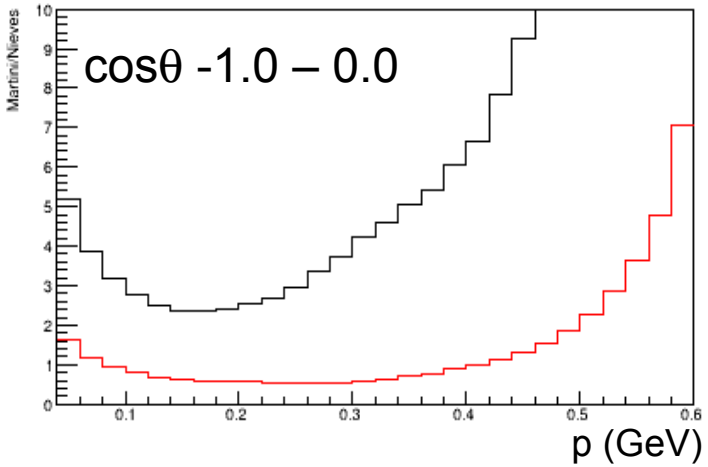
Martini/Nieves ratio (2p2h only)

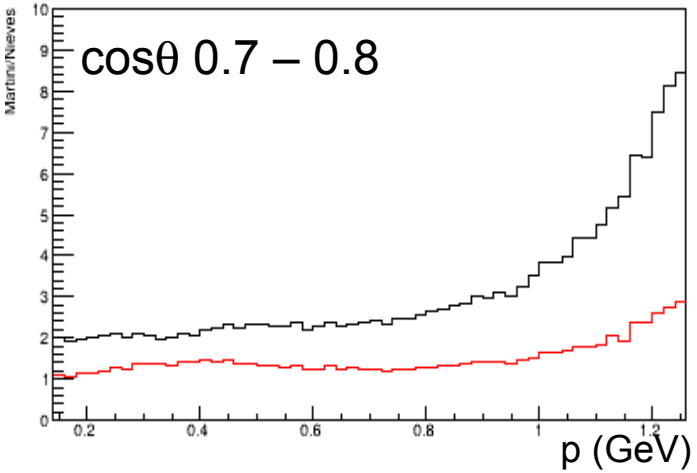


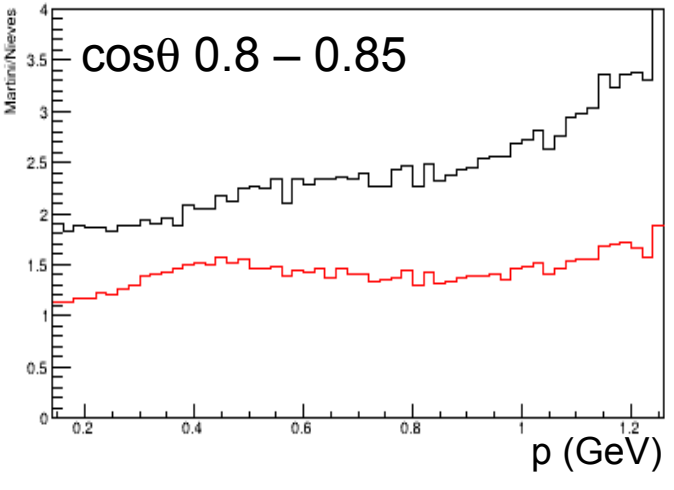


Actually, looking at pmu, cosqmu the difference in shape is similar between nu and nubar

Martini/Nieves ratio (2p2h only, SK flux folded)







Martini/Nieves 2p2h only

nubar
nu