'Experimental' perspective (T2K): what we need for the future...

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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

NuTune Workshop – Liverpool – July 2016

What we need from models?

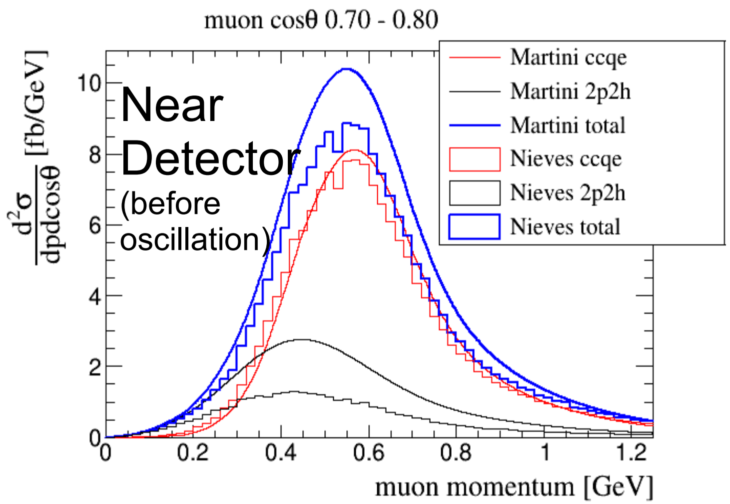
- We use neutrino interaction modelling for:
  - **neutrino oscillation measurements**
    → models needed especially for near to far detector extrapolation
  - **neutrino cross-section measurement**
    - analysis output: data-model (dis-)agreement
    - analysis input: we need good models to correct for detector acceptance and background

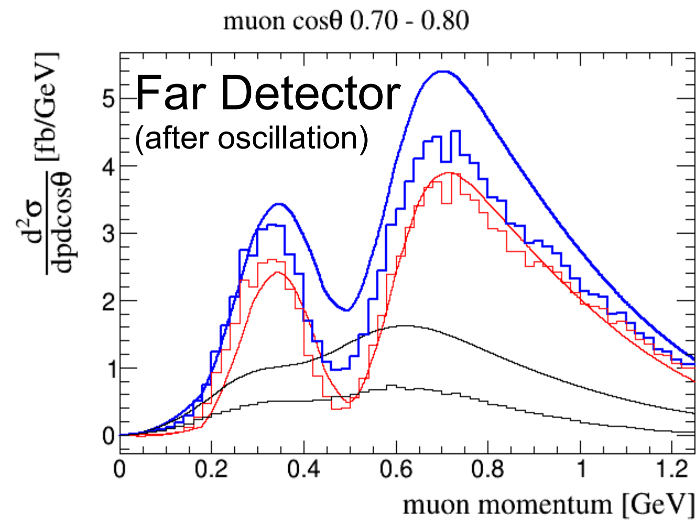
- What we need from models is:
  - a prediction (possibly which could be directly compared to what we measure experimentally)
  - quantitative uncertainty on that prediction (to set systematics uncertainties on our oscillation and xsec measurements)

    → proper dials to 'parametrize' such uncertainties in MC

I will use mostly 2p2h and 1p1h as a case study (most relevant channels at T2K energy)

2p2h at near and far detector

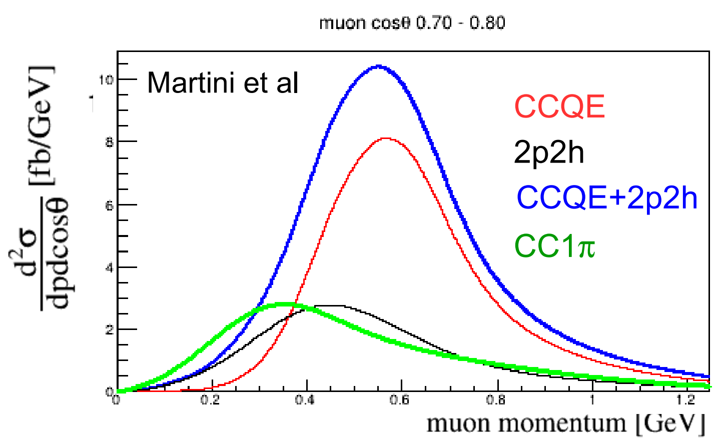




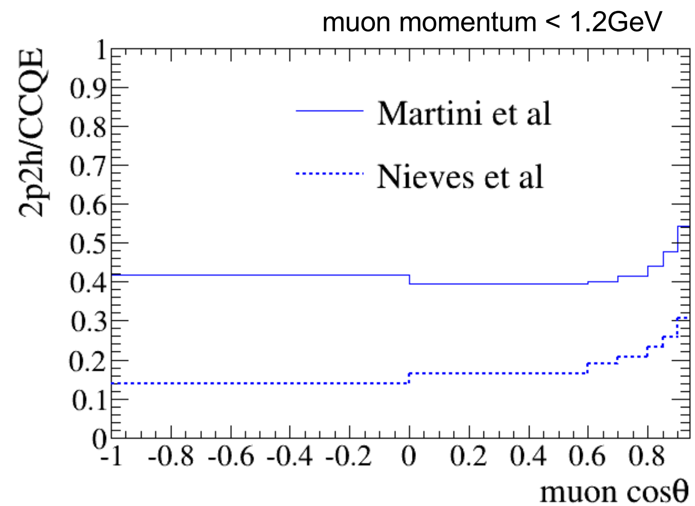
- 2p2h uncertainty is mainly on the overall normalization at ND while at FD 2p2h biases the shape of neutrino energy spectrum (fill the oscillation deep)

At ND 2p2h is slightly lower **muon momentum** than 1p1h

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

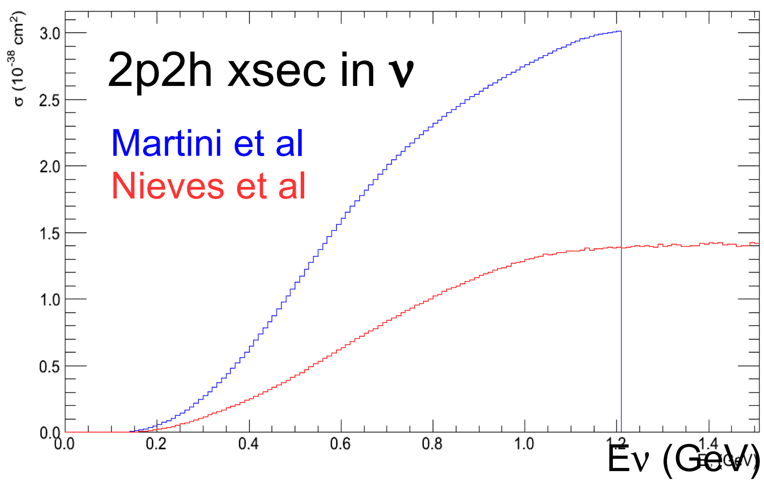


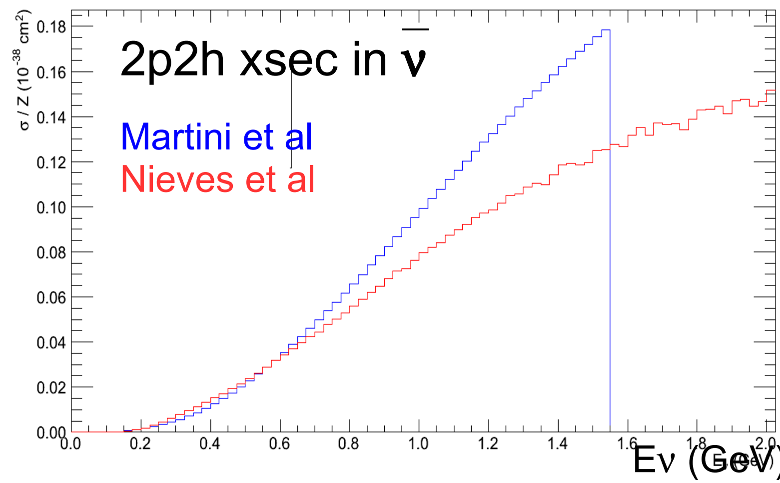
There is no clear enhancement of 2p2h for backward **muon angles**

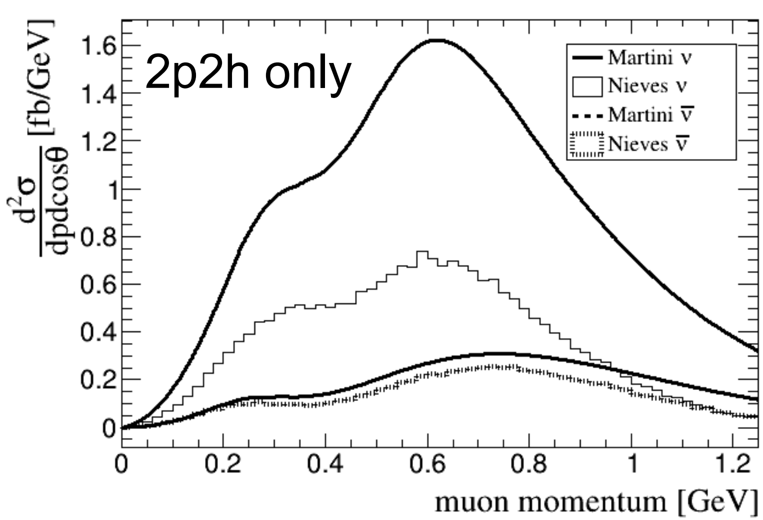


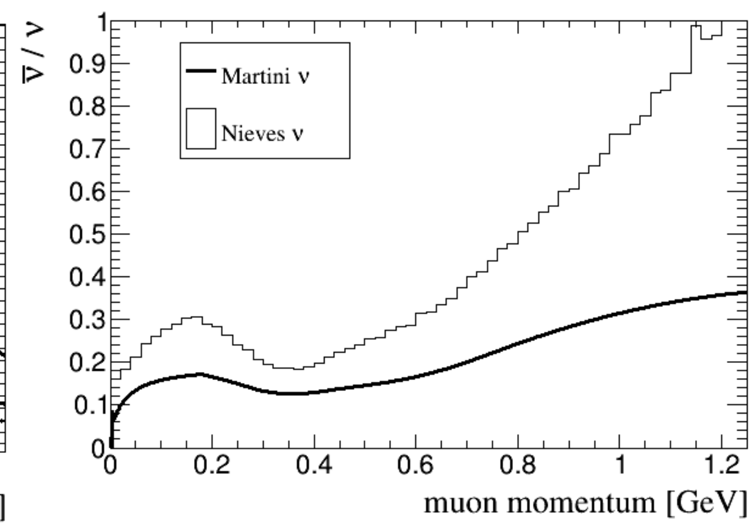
2p2h: ν vs $\bar{\nu}$

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









We need to quantify proper uncertainties on 2p2h as a function of momentum, angle and neutrino 'sign'

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

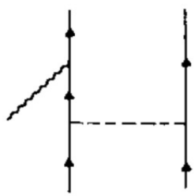
Main references:

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)

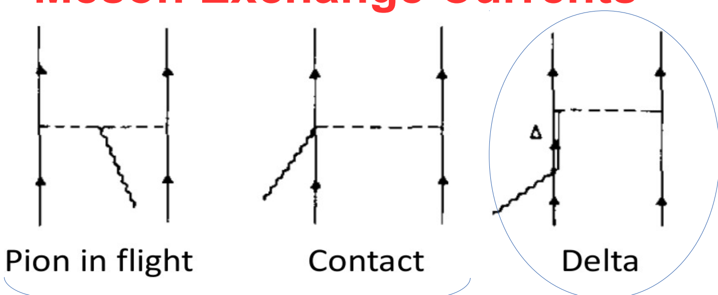
2p2h components (Martini et al.)

NN correlations

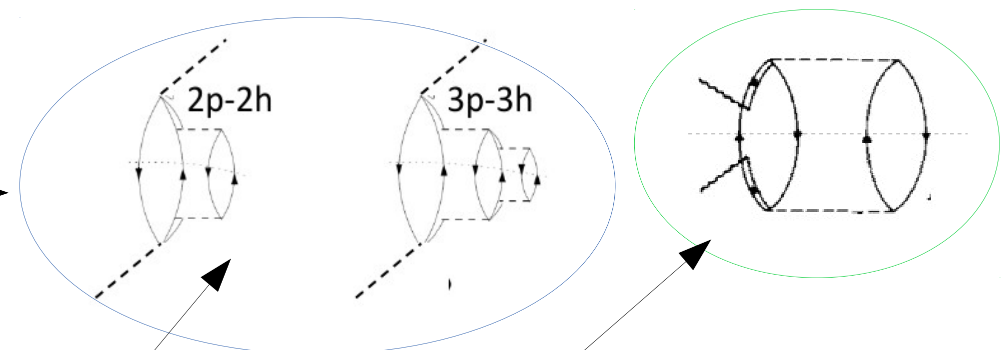


from nuclear response functions for electron scattering (Alberico et al.)
(π propagator + heavier mesons effectively in g')

Meson Exchange Currents



includes

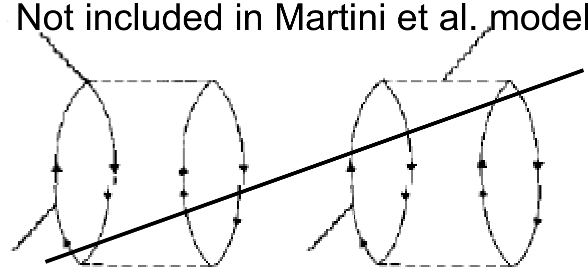


$\Delta^{\pi\text{-less}}$ decay + other Δ MEC (not π-less decay)

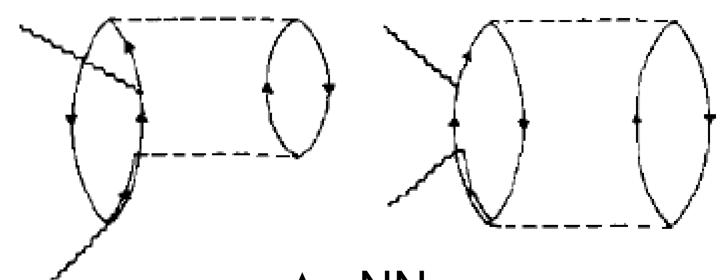
Not included in Martini et al model
(shown to be small)

NN-MEC interference

Not included in Martini et al. model



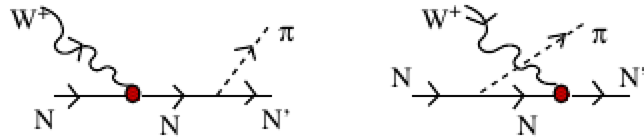
no-Δ-MEC - NN



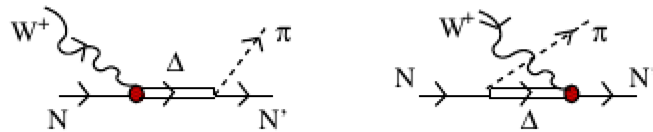
Δ - NN

2p2h components (Nieves et al.)

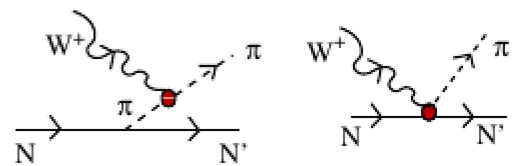
- NN-correlations



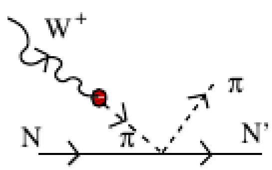
- Δ pi-less decay
  (and other Δ MEC)



- pion in flight and contact term

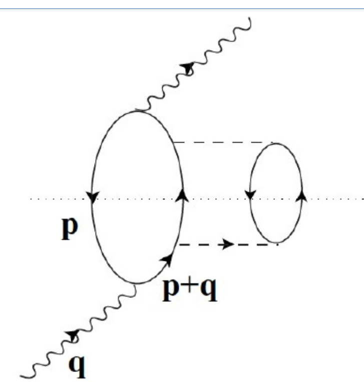


+ one last term
(not included in
Martini et al.)



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

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



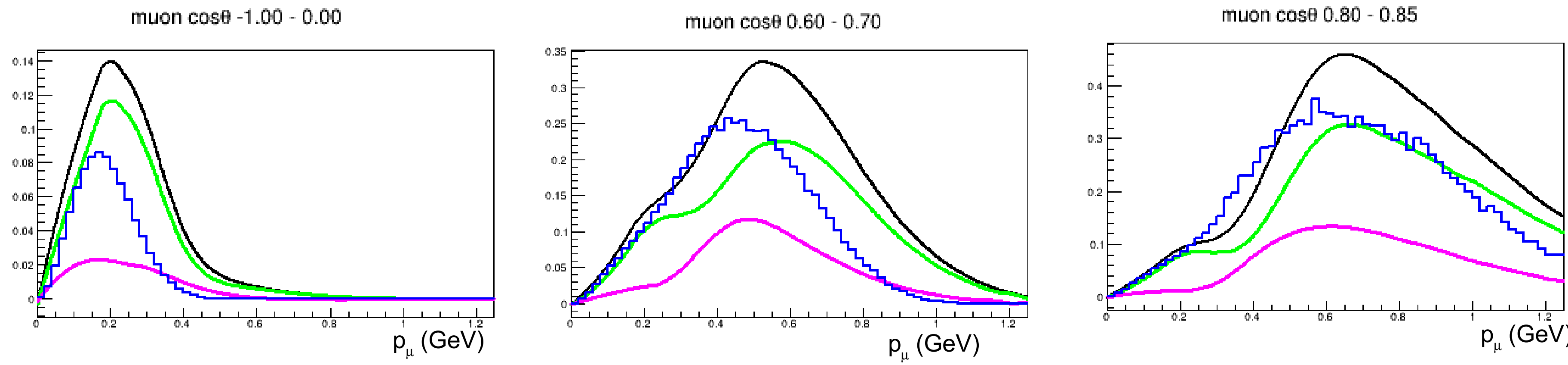
?

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

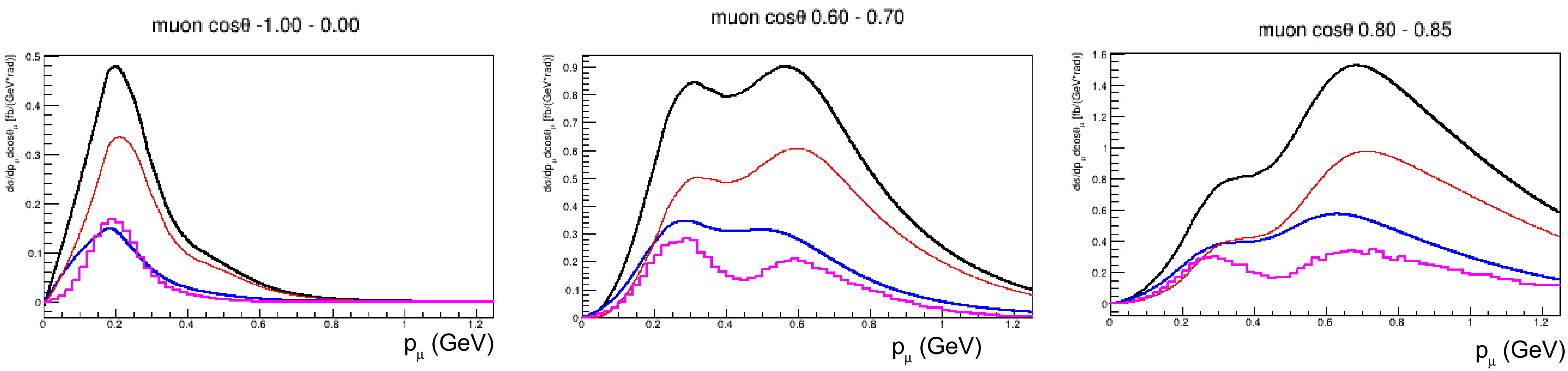
Some difference in shape and normalization (both models based on Oset and Salcedo?)



Nieves not Δ

Martini:
- NN correlations
- NN - Δ-MEC interference
- sum of the two

Huge differences: more than a factor 2...



2p2h: a way out?

- Reliable implementation in MC: hadron tensors formalism

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

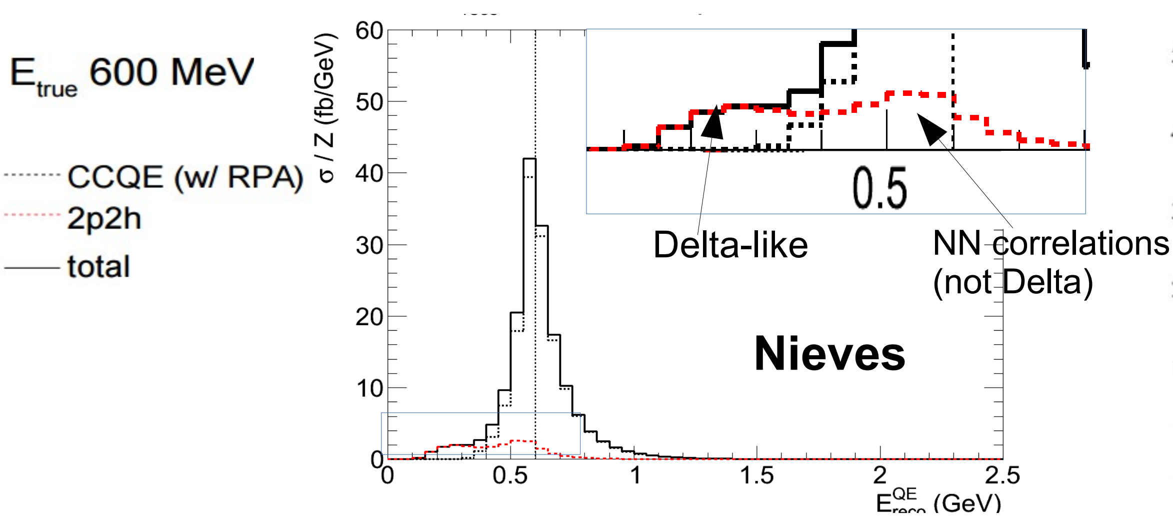
Leptonic tensor: simple EWK vertex (same for all models)

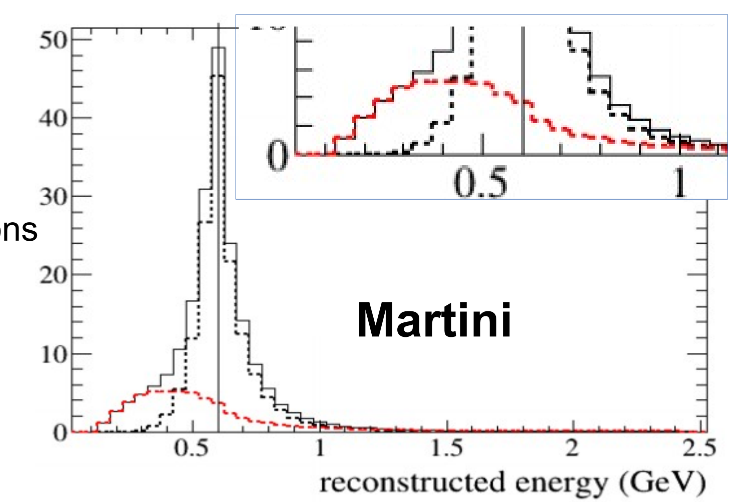
$$L_{\mu\sigma} = L^s_{\mu\sigma} + iL^a_{\mu\sigma} = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma} k\cdot k' + i\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$$

Hadronic tensor: include all the nuclear dynamics (look up tables as a function of q0, q3 with results from different calculations)

Can be used for any model (and for 1p1h as well or any other process)

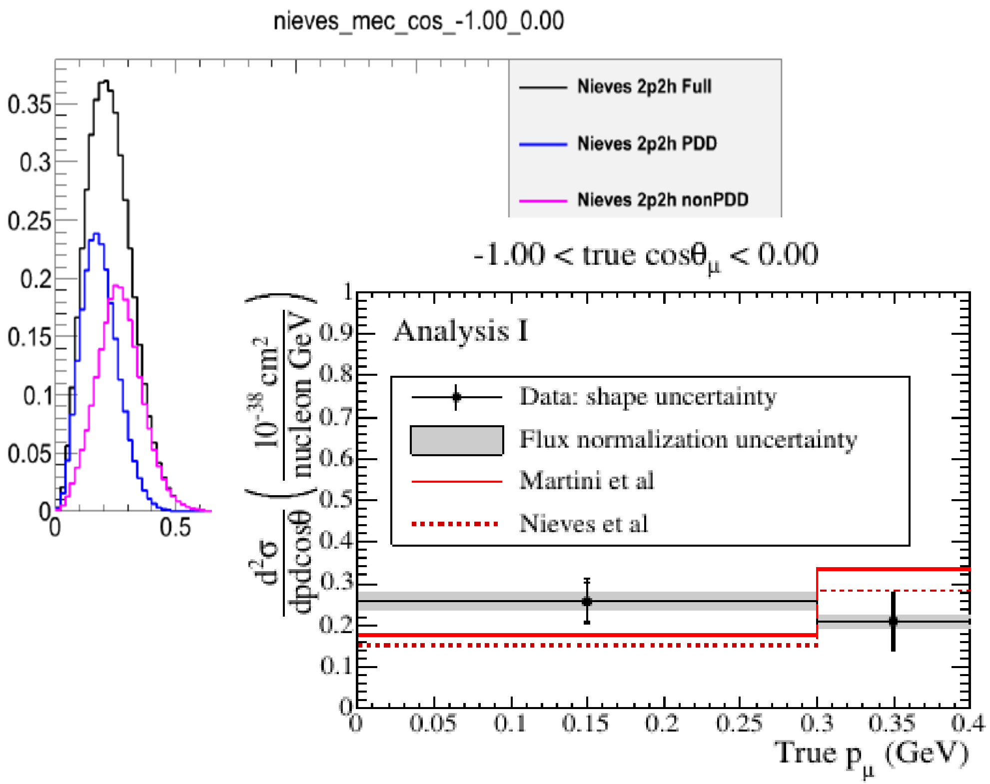
- Need 'modular' implementation for different contributions
  - separate HT for different 2p2h components (Delta, not-Delta, interference)
  - the relative contribution of **each component can be renormalized with separate dial and fitted separately → effective shape uncertainty on 2p2h**

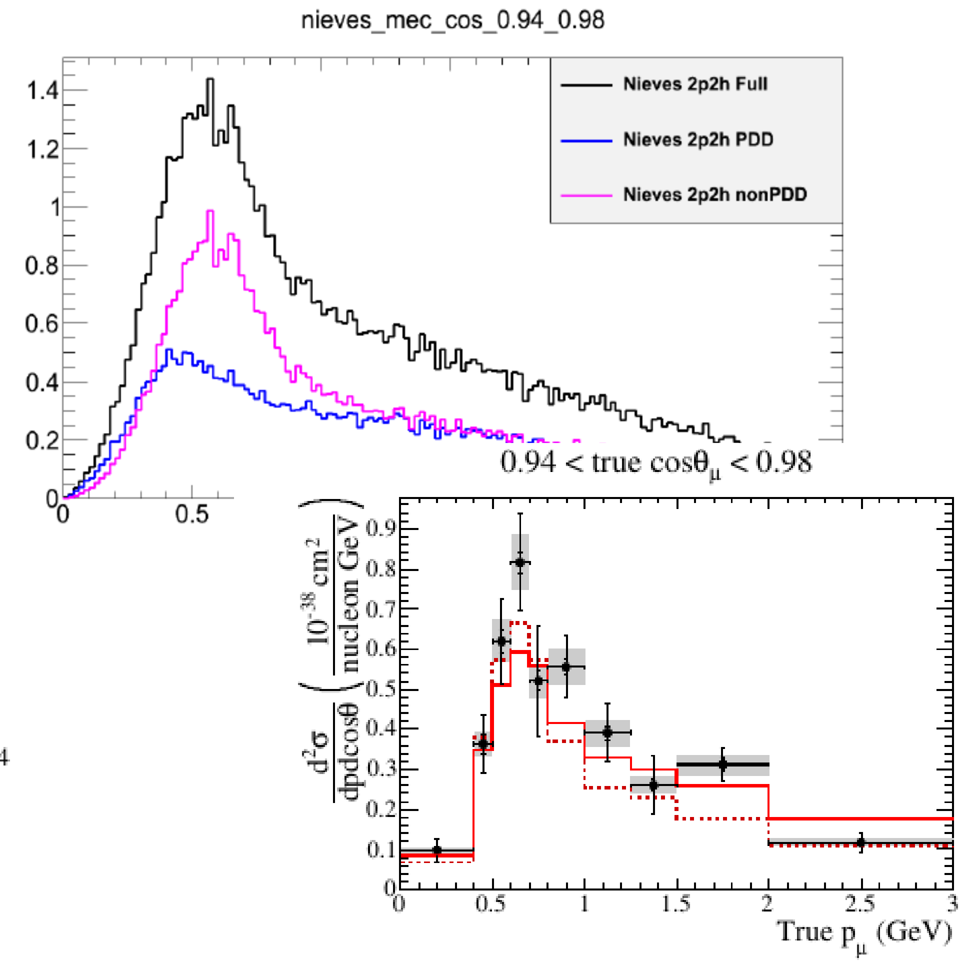




What the data tell us?

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



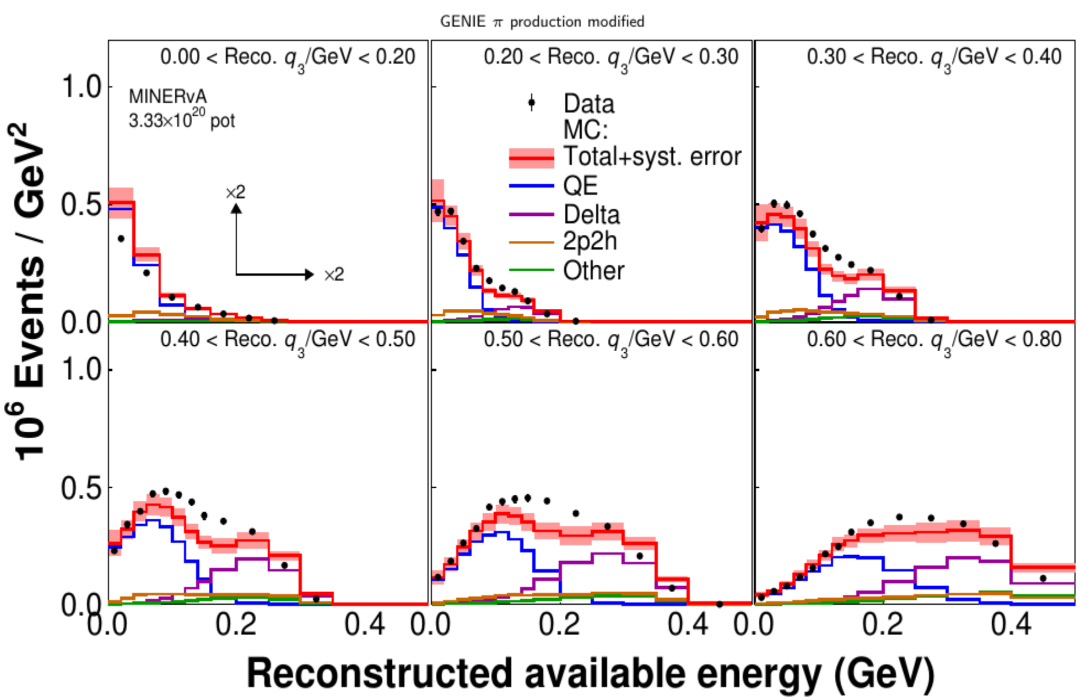


- What about hadronic measurements?

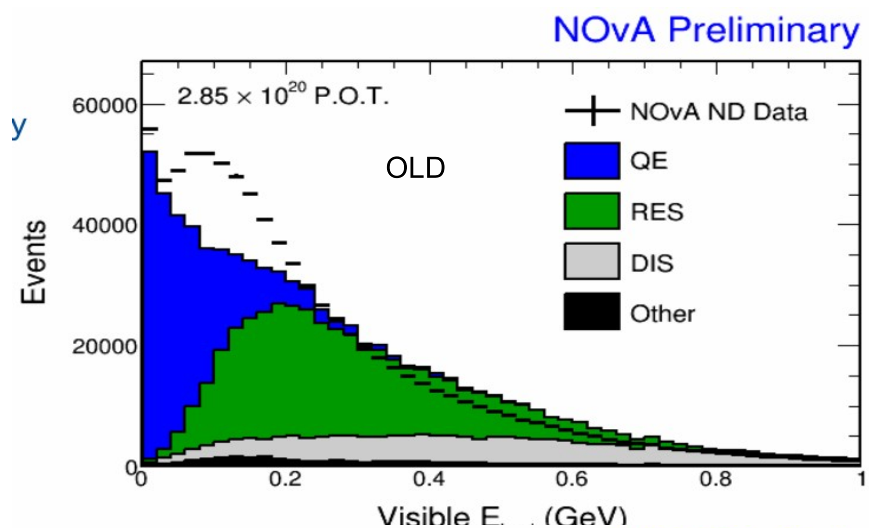
Measurement of hadronic energy

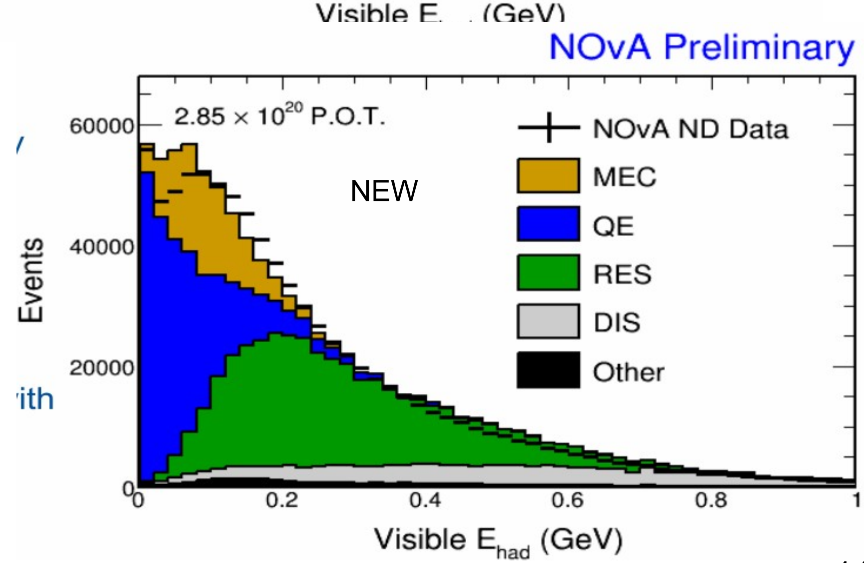
Recent Minerva measurements:
→ possibility to correct as a function of q3, ω

Minerva



→ NOVA: description of 2p2h effects based on parametrization of what is observed in the near detector





Systematics on hadronic energy (1)

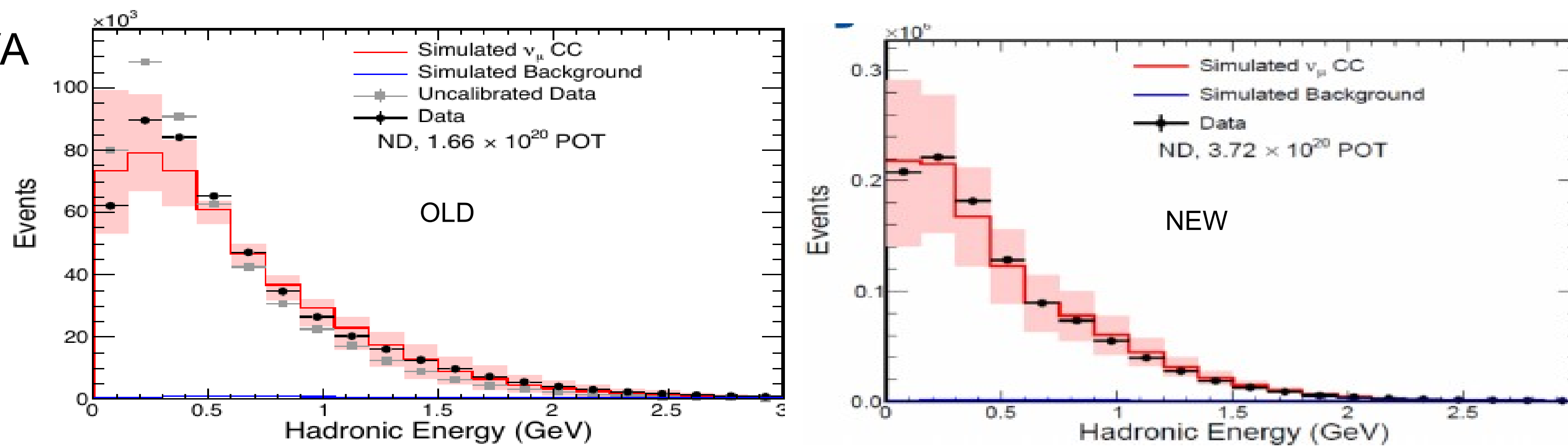
- Minerva measurement (q3, ω) is a very interesting and promising way to look at the data but we are still in the process of understanding the systematics

- NOVA xsec uncertainty ?

- **We have still to fully quantify the model uncertainties related with 'calorimetric' approach to the data**

  Need to disentangle calibration issues and model uncertainties on undetected energy and kinematics of outgoing nucleons

NOVA



We can describe perfectly the near detector data and still be wrong at the far detectors

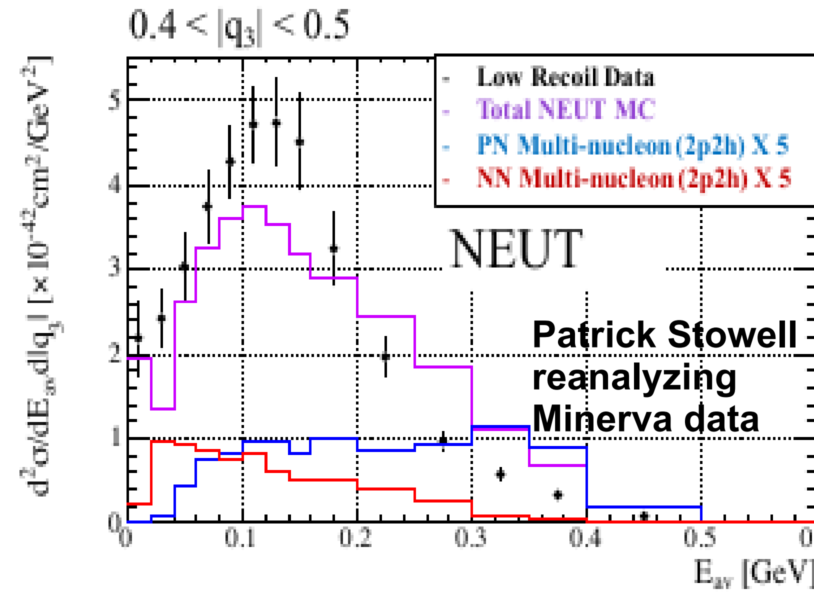
(different Eν spectrum → different relative contribution of processes, different relative contribution of theory/detector systematics ...)

Systematics on hadronic energy (2)

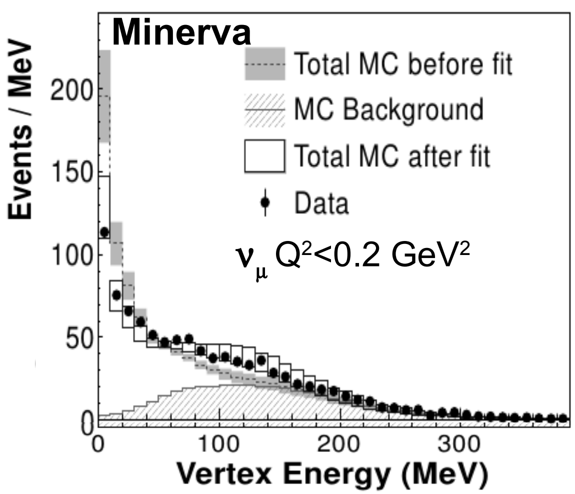
- **Relative amount of nn and np** in the correlated initial state pairs has large impact on 2p2h calorimetric measurement

  Energy released by neutron (nn initial pair) need to be corrected relying on modelling. Fraction nn/np(/pp) not well known

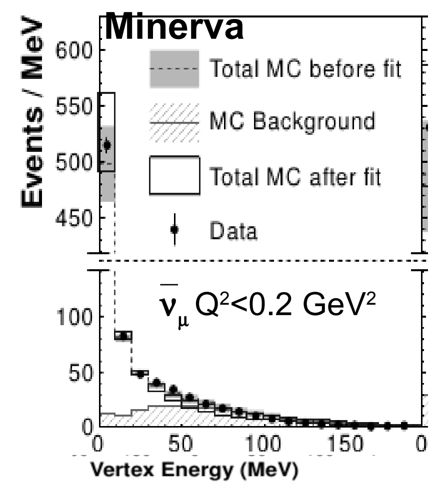
  → this can easily bias the q3,ω parametrization or an empirical extrapolation from near to far detector



- Uncertainty on **'un-detected' energy**: nuclear recoil, binding energy, low energy hadrons...



ν_μ data suggest additional proton with E<225MeV in 25 ± 1(stat) ± 9(syst) % of events



$\bar{\nu}_\mu$ data: no additional proton (low sensitivity of Minerva to low E neutrons)

→ **can we extract something quantitative from these data? Need more established predictions/models for outgoing nucleons**

→ in the meanwhile: **dials (nn/np fraction, Eb,..) with conservative uncertainties**

Predictions for outgoing protons?

- **(Almost) no calculation of cross-section as a function of proton kinematics**
  - First calculation for deuteron at CEA-Saclay workshop Phys. Rev. D 90, 013014 (2014); Phys. Rev. D 92, 053006 (2015)
  - **Nieves/Martini 2p2h models are fully integrated in outgoing nucleons kinematics …** (recent paper from Ghent: first exclusive 2p2h prediction)

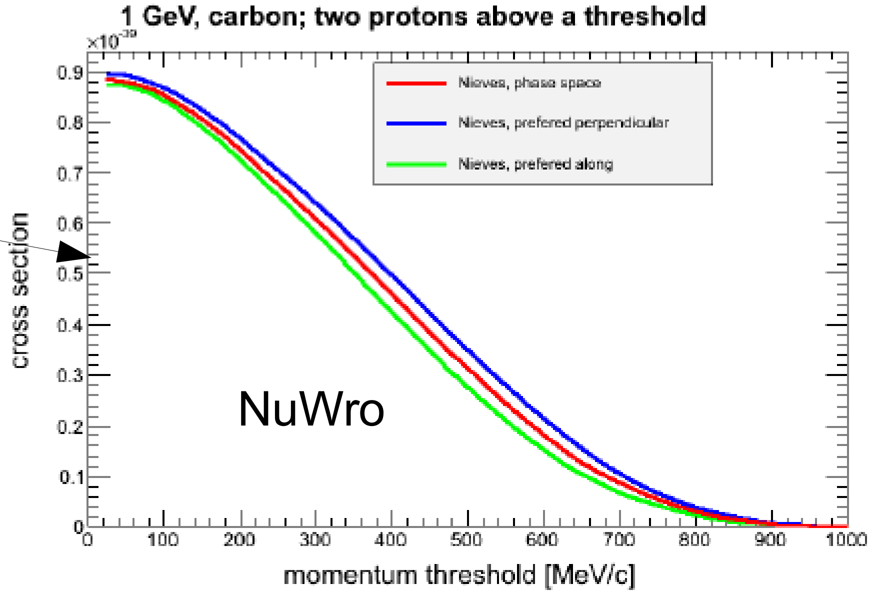
- We need to develop dials to model uncertainties on initial protons and neutrons

  First example from NuWro:

  - initial nucleons-pair momentum from 'Ghent' model

  - dials for outgoing nucleons angle

  (...future HT will be 6D?)



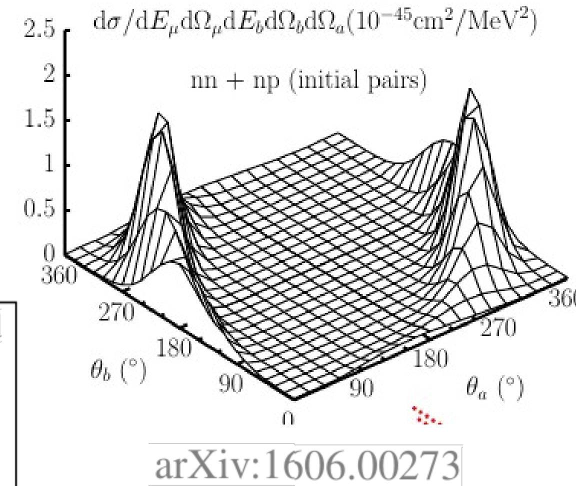
- GENIE proton FSI dials

Dial	Description	Uncertainty (deltaP/P)
GINuke_MFP_N	Nucleon mean free path (total rescat. prob.)	20%
GINuke_FrCEx_N	Nucleon charge exchange probability	50%
GINuke_FrElas_N	Nucleon elastic scattering probability	30%
GINuke_FrInel_N	Nucleon inelastic reaction probability	40%
GINuke_FrAbs_N	Nucleon absorption probability	20%
GINuke_FrPiProd_N	Nucleon pion production probability	20%

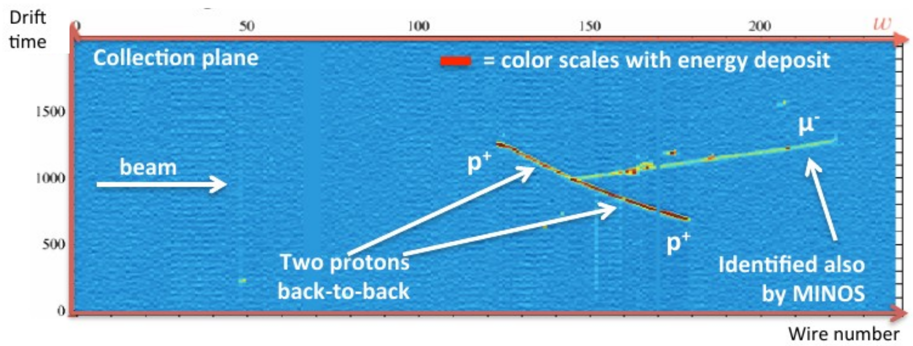
Is this parametrization complete and the uncertainties directly usable?

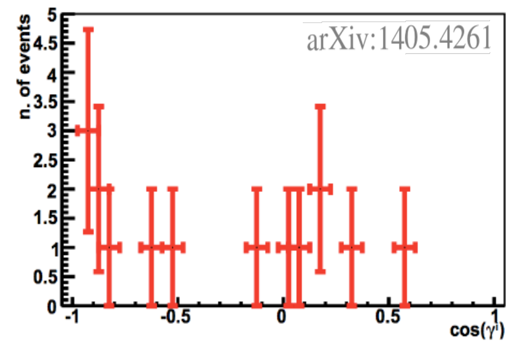
Measurement of outgoing protons

Ghent predictions

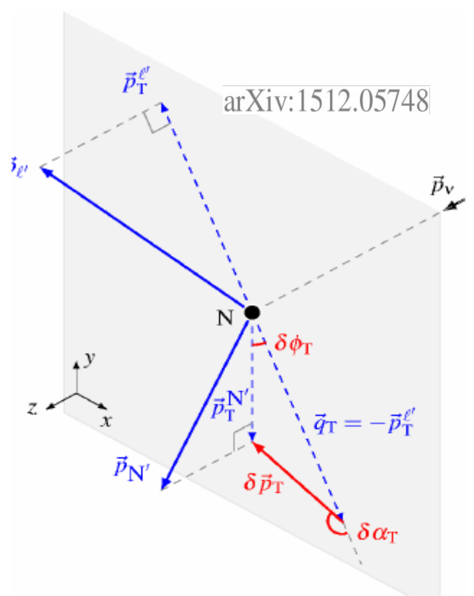


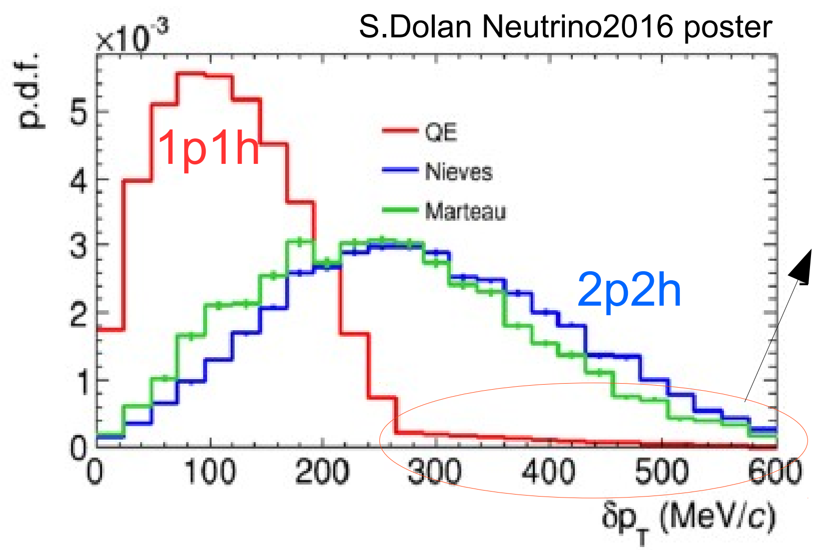
- **ArgoNEUT**: powerful Ar technology but small statistics





- NEW Measurements expected from **ND280**: proton kinematics and transverse variables
  (proton threshold for good tracking/ID ~500 MeV)

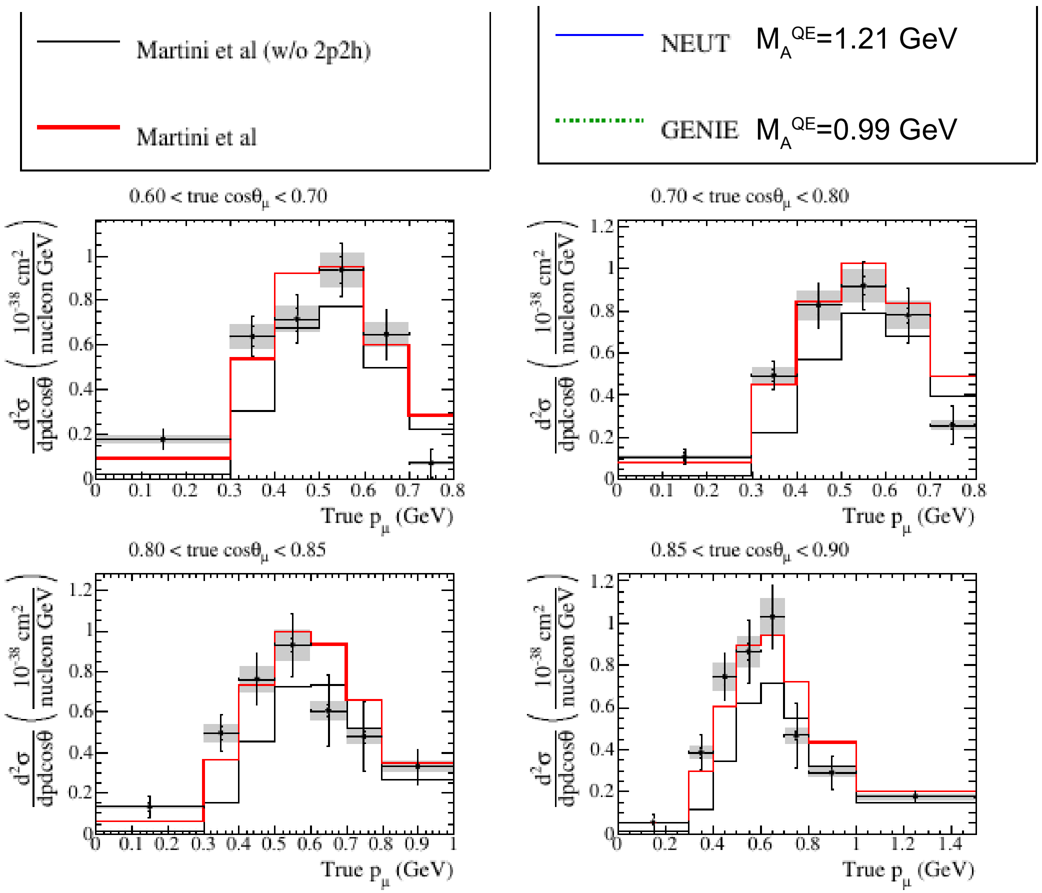


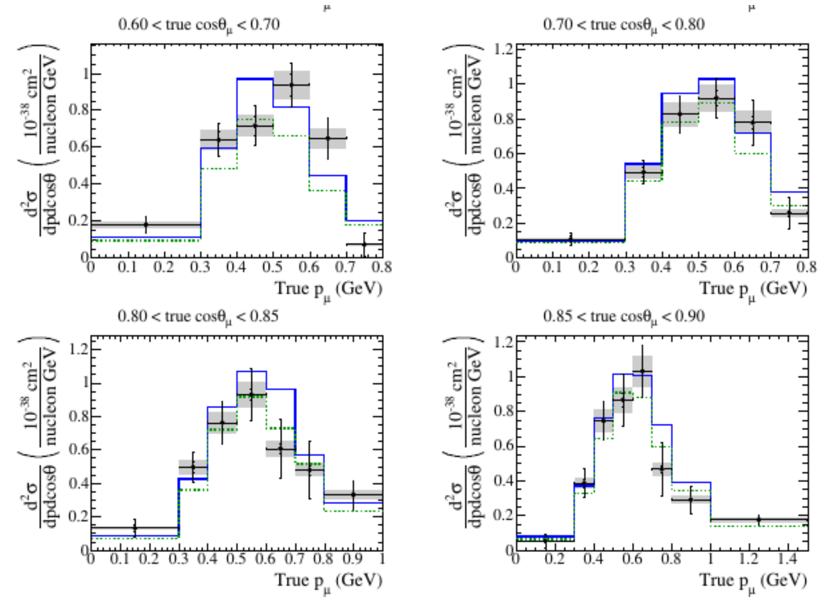


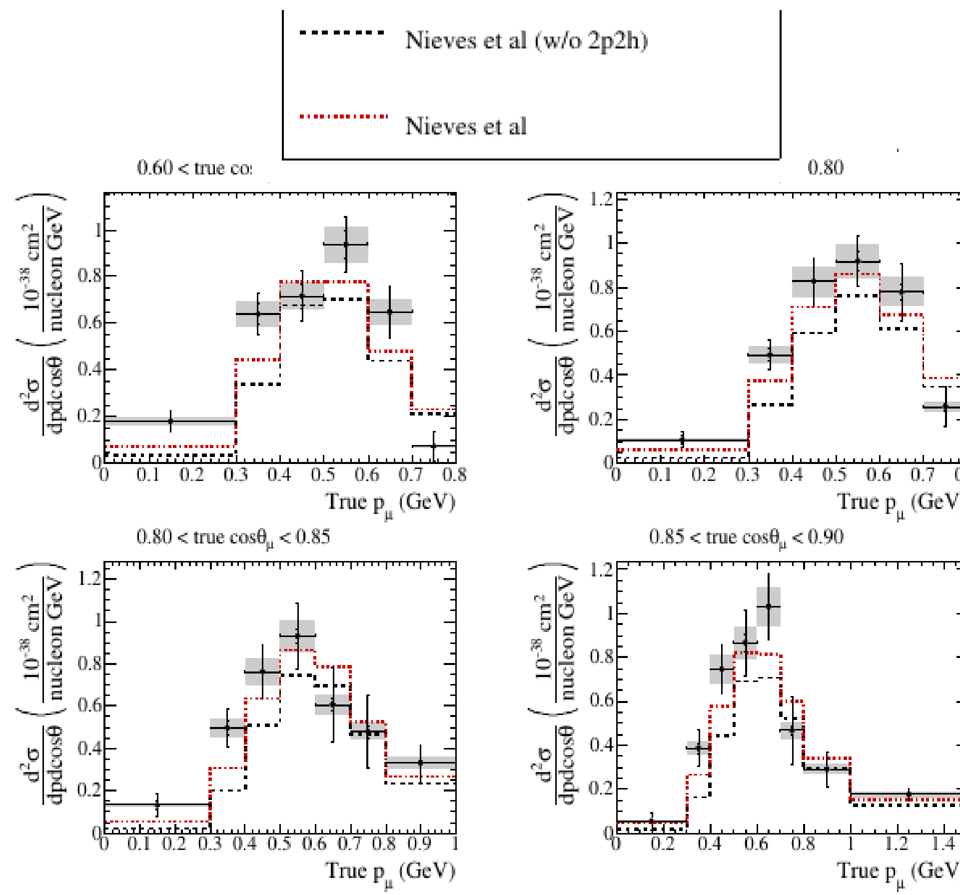
Need proper uncertainties on 1p1h: nucleon distributions in nucleus and final state proton re-interaction ...

Coming back to muon data ...

CC0π T2K measurement







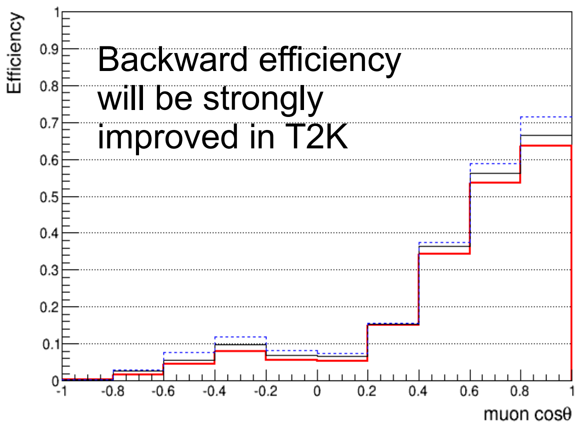
- Cross-section measurements are affected by **systematics on interaction modelling**. Models used as input to the analysis for:
  - unfolding of detector acceptance
  - correction for backgrounds

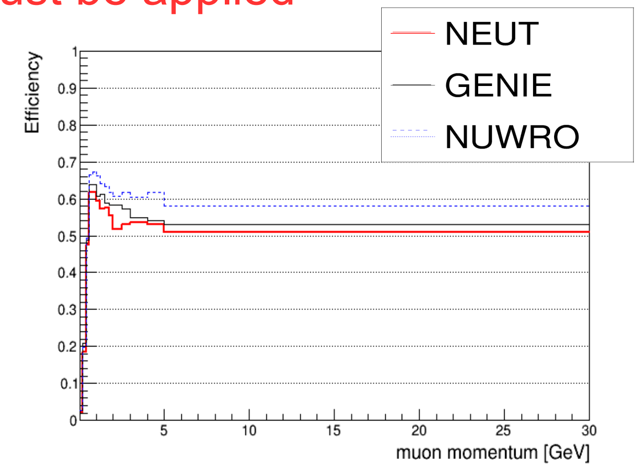
Few examples from this measurement in next slides (analysis built to be very model-independent!!)

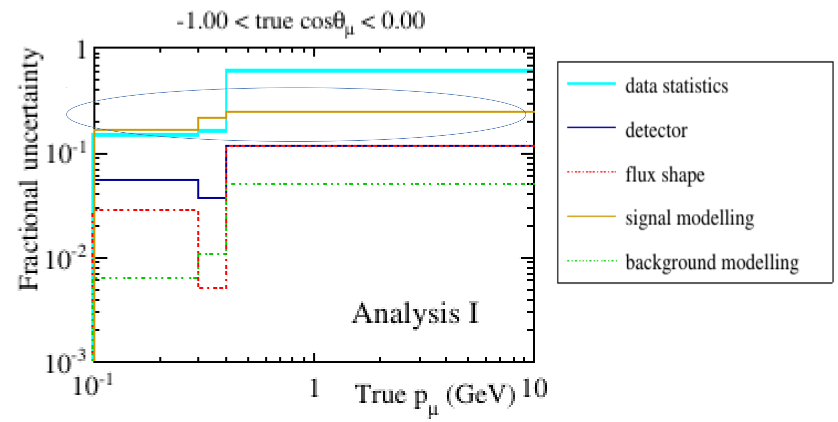
Acceptance corrections

- 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

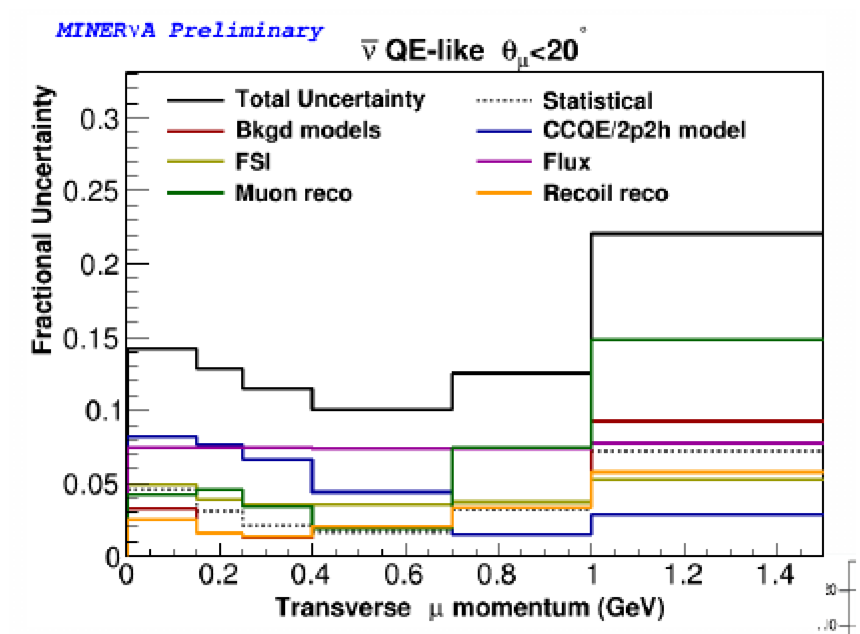






Effect 'covered' by large systematics in bwd region, still the central result may be biased

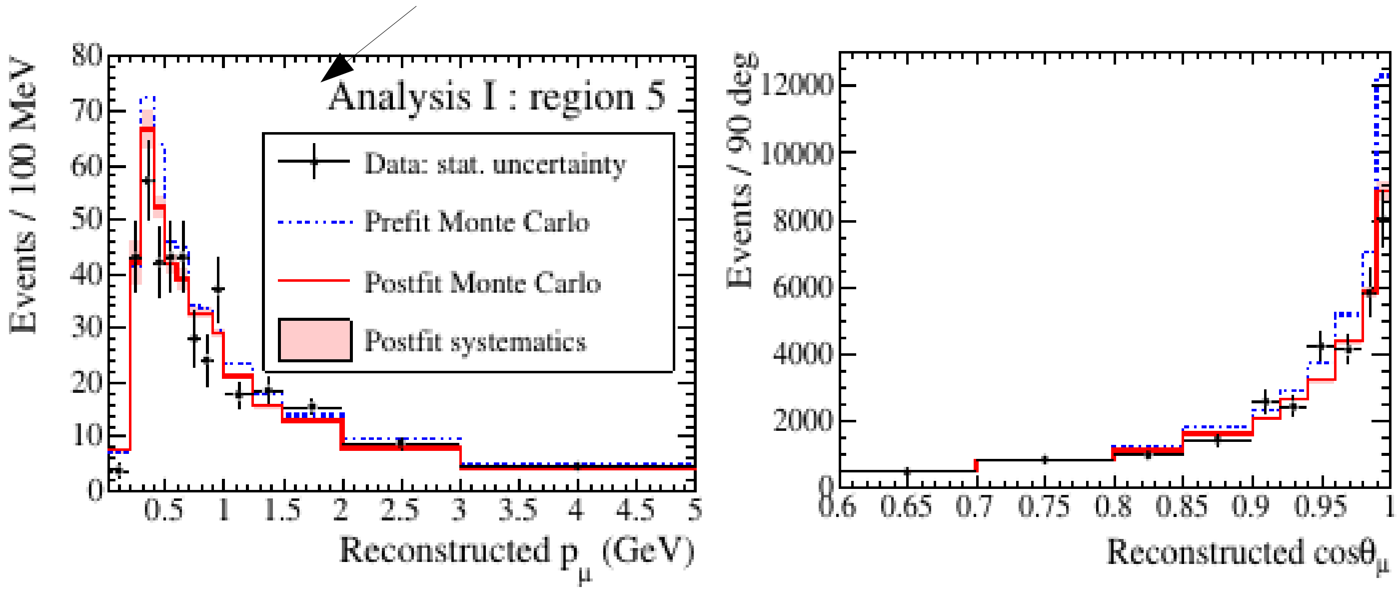
Neutrino2016: similar result from Minerva: large systematics in low momentum because of modelling CCQE/2p2h



Background corrections (1)

- **'Reducible' background:** can be experimentally disentangled from signal
  Eg: pion production through Δ resonant

Fit to data sideband (eg 1pi sample) to constrain this background

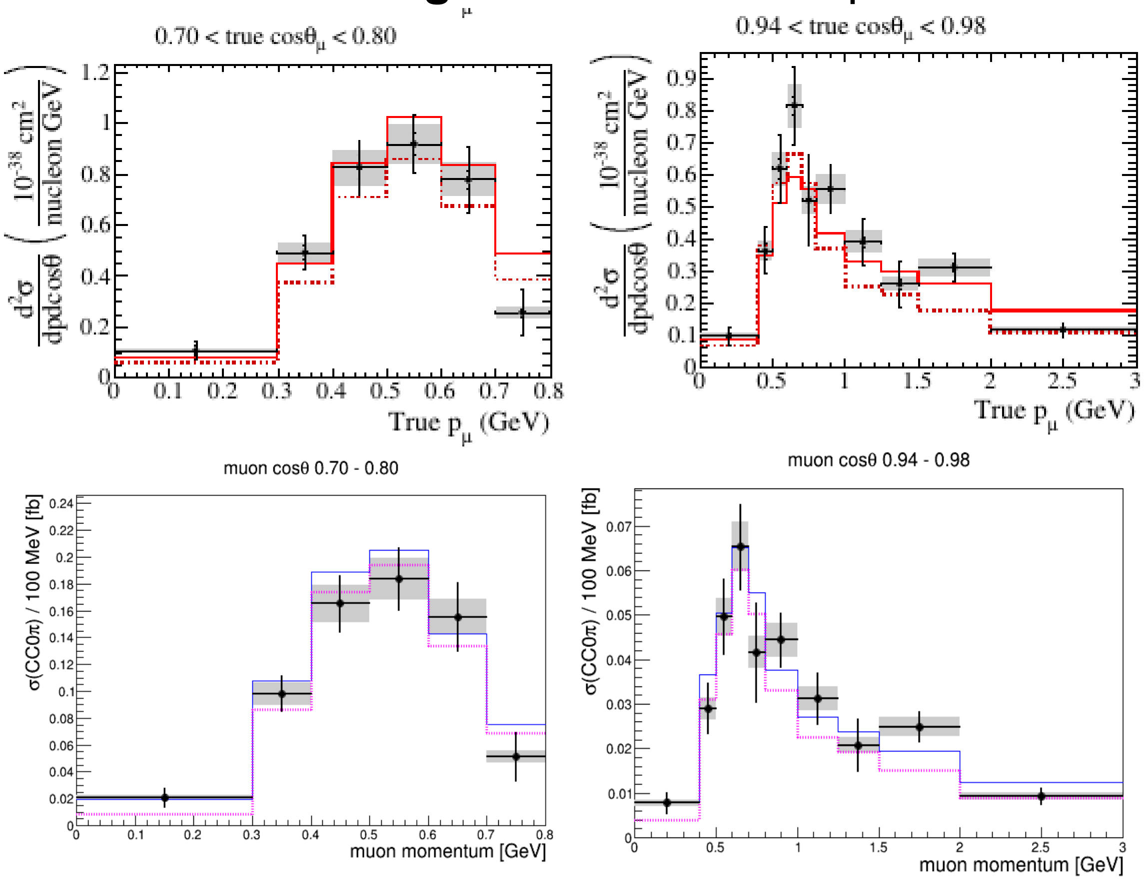


Uncertainties in extrapolating from sidebands to signal region:

- need parametrization in terms of fundamental dials (eg fit MAres, pion FSI xsec, etc... from sidebands)
- the sidebands shound have similar kinematics than your background in signal region

Background corrections (2)

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



Martini et al

Nieves et al

(these models do NOT include CC1π+FSI abs)

NEUT: CC0π (includes CC1π+FSI abs)

NEUT: CCQE

CC1pi + FSI need to precisely quantified to extract 2p2h xsec

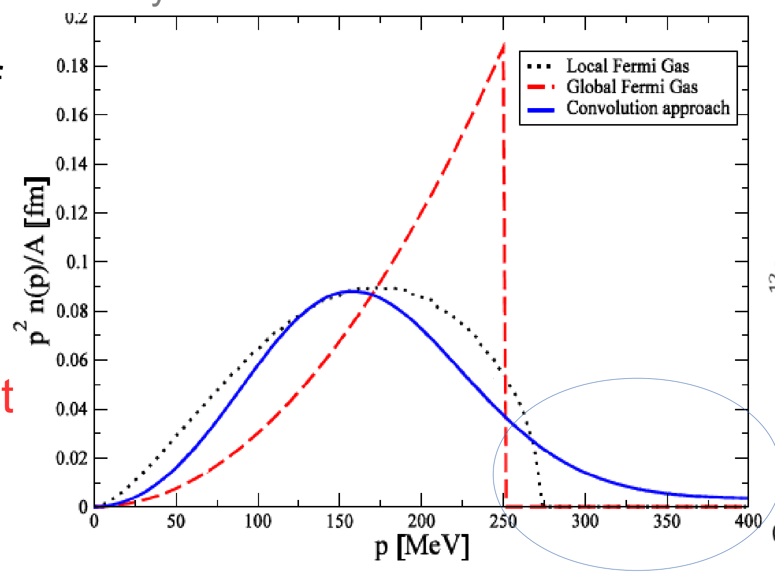
- Even further: what about uncertainties on CCQE (as 'background' to 2p2h)?
  - large uncertainties due to nucleon from factors, RPA corrections, … → see talks from Patrick and Clarence
  - even the separation between CCQE and 2p2h (and between initial and final state interactions) is not necessarily meaningful...

2p2h vs 1p1h

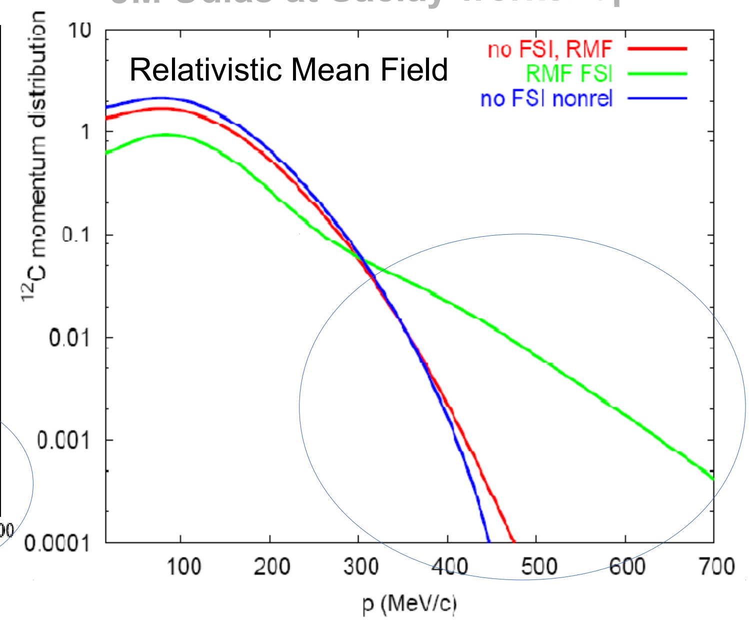
- We should be careful about a too naif approach in the definition of the modelling systematics: **what we call 1p1h and 2p2h really depends on the model.**

- Fermi gas is known to be a poor description of the nuclear matter
- in more sophisticated descriptions (relativistic mean field, SF, …) part of the enhancement that we assign to 2p2h may be actually due to 1p1h

Hayato et al. arXiv:1403.2673v2



JM Udias at Saclay workshop



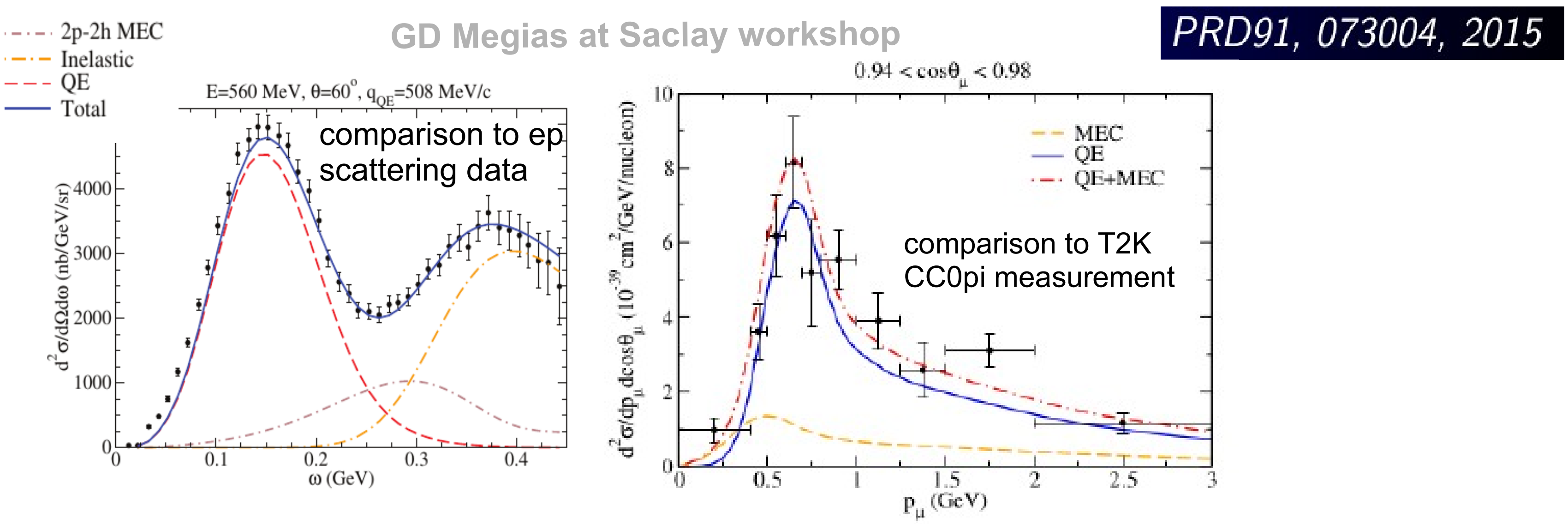
- If we want to 'measure' how much 2p2h in our data we need to address more carefully the 1p1h vs 2p2h uncertainties. Way forward?
  - Local FG + dial to give freedom to move from FG to other descriptions of nuclear matter. Somehow an updated version of pF dial:

  eg: **parametrize the tails (and shape) of nucleon distributions in the nucleus** and let that free to float?

  (possibly use ep scattering data to constrain 1p1h dials ???)

2p2h vs 1p1h: ep scattering data

- New model capable of fitting neutrino-nucleus scattering data (and ep scattering as well!)
  SuperScaling approach with RMF + full MEC calculation



Way forward: **electron scattering implementation in MC with dials allowing the connection to neutrino-scattering?**

Summary

Interaction modelling is important for oscillation analysis: near to far detector extrapolation
But it is also an **input to cross-section measurements** (acceptance corrections and background subtraction)

What do we need:

- **2p2h: effective parametrization** (Delta, not-Delta, interference):
  full understanding of physics beyond model needed for proper near to far detector extrapolation

  Need to evaluate **systematics on hadronic energy:** need exclusive predictions on the outgoing nucleons!

  - nn/np pairs, low momentum protons and energy deposited around the vertex: difficult convolution of model uncertainties and detector threshold/calibration
  - need dials: nn/np, binding energy, proton kinematics,

- **2p2h vs 1p1h:** give enough freedom to the relative contribution
  → dials parametrizing tails of nucleons momentum distribution?

  (on top of 1p1h uncertainties: from factors, RPA … and pion FSI uncertainties)

- *and I didn't even mention pion production: what about nuclear effects?*
  $\Delta \rightarrow \pi N$ different width in medium affects xsec and pion kinematics

What do we need to model?

Uncertainties in ND→FD extrapolation (+ uncertainties in xsec measurements) :

- modeling of A-scaling → cross-sections on different targets
- cross-section in whole phase-space: need to control/model regions of small efficiency in the Near Detector (low momentum, high angle)
- to reconstruct neutrino energy: measure all particles in the final state (need to control energy below detector threshold, eg nucleus recoil and neutrons)
- cross-section asymmetries between different neutrino species → ν vs $\bar{\nu}$, ν_μ vs ν_e

I will use mostly 2p2h and 1p1h as a case study (most relevant channels at T2K energy)

- 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)

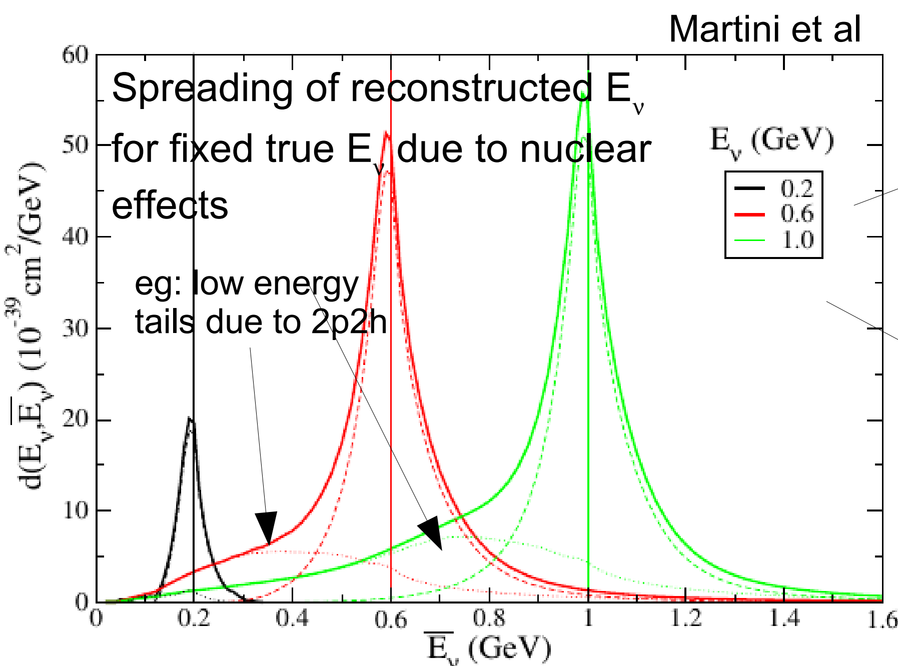
plot? pmu, thetamu for given Q2 bin??

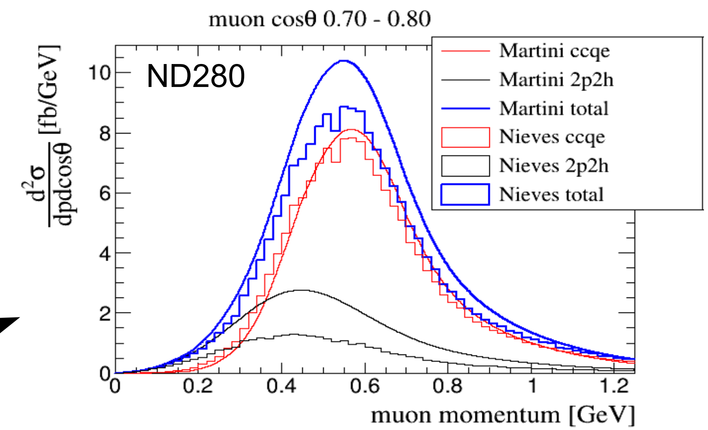
  - In double-differential measurement, you can clearly identify bins with low efficiency
  - In Q^2 measurements, bwd and low momentum muons get distributed in many different Q^2 bins and the efficiency corrections now depends on the assumed muon kinematic distribution in each Q^2 bin

Extracting oscillation parameters: E_ν spectrum

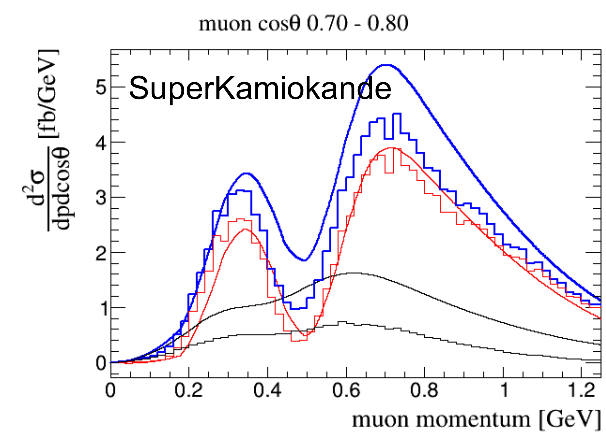
Why we need to know the xsec is such details to perform the ND → FD extrapolation?
ND and FD have different E_ν spectra because of oscillation

- We do not measure E_ν ! Eg, SuperK measures the outgoing muon and infers the neutrino energy on the basis of available models





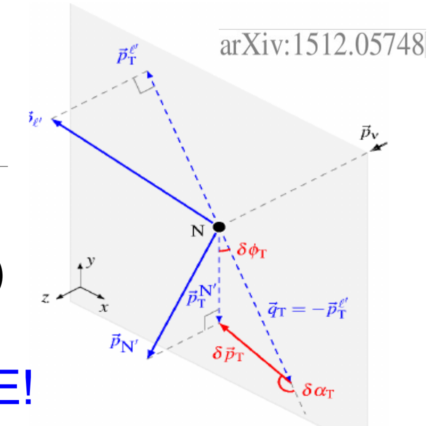
effect on ND flux is just a smearing



One possible way out: measure also outgoing proton (or more in general full hadronic final state)

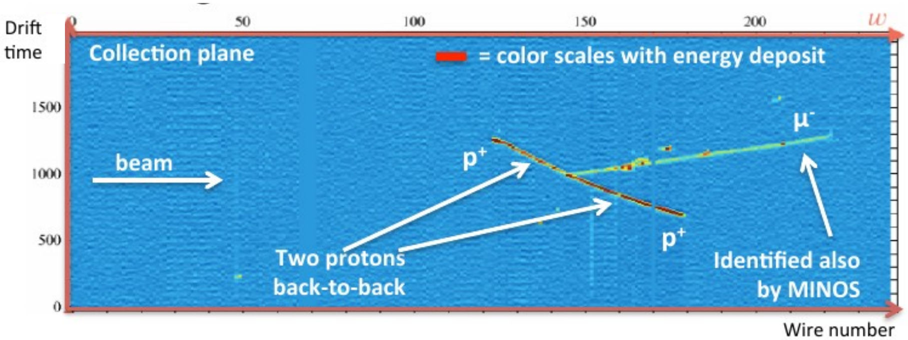
at FD 2p2h events fill the “dip” region sensitive to oscillation → **wrong modelling would cause bias on oscillation parameters**

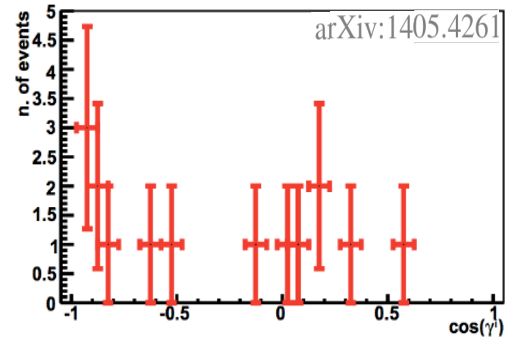
Measurement of outgoing protons

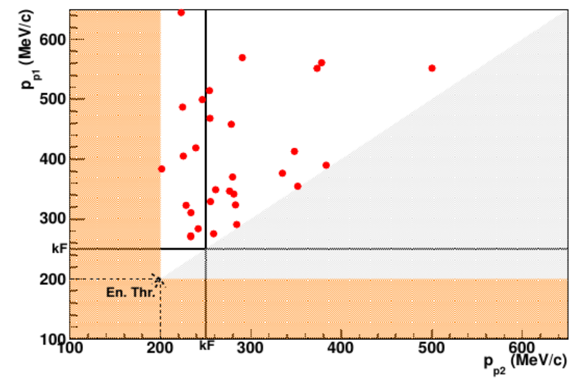


- NEW Measurements expected from **ND280**: proton kinematics and transverse variables (proton threshold for good tracking/ID ~500 MeV)

- **ArgoNEUT**: small statistics but powerful Ar technology → MicroBooNE!



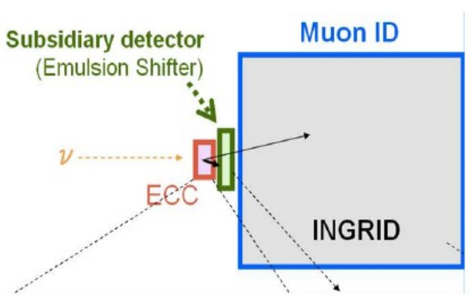


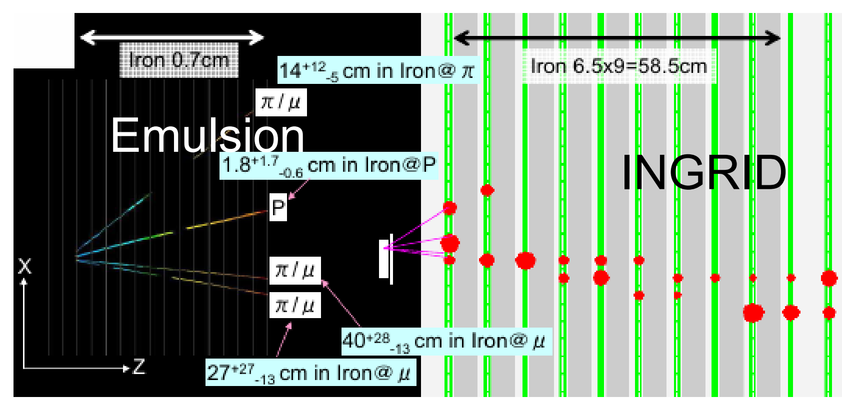


- **Gas Ar** would give even smaller threshold:

NEW results from ND280 TPC will come (small stat) → **HP TPC** under discussion

- **T60:** emulsion detector in front of INGRID at T2K flux (high stat: few thousands ν_μ)





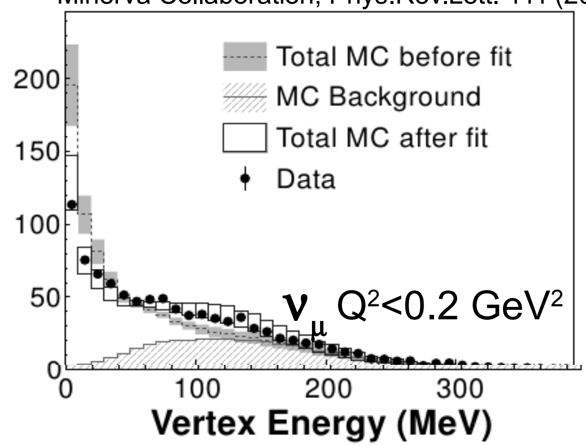
- Main limitation:

  Very limited predictivity of proton kinematics from models!
  And difficult interpretation of the results: disentangling nuclear effects on initial state (Fermi momentum, 2p2h, ...) from Final State re-interactions

'Calorimetric' approach

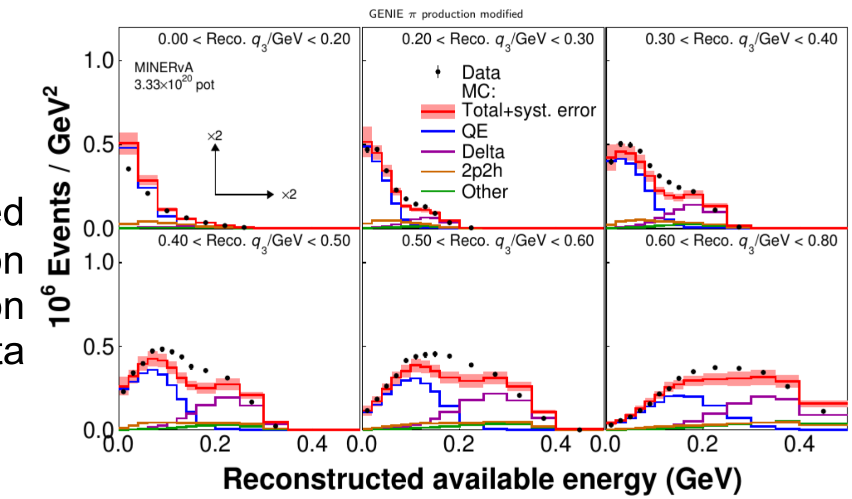
- Minerva: measurement of all the energy around the vertex or all the energy in the event

Minerva Collaboration, Phys.Rev.Lett. 111 (2013) 022502,



- inclusive energy for low momentum particles

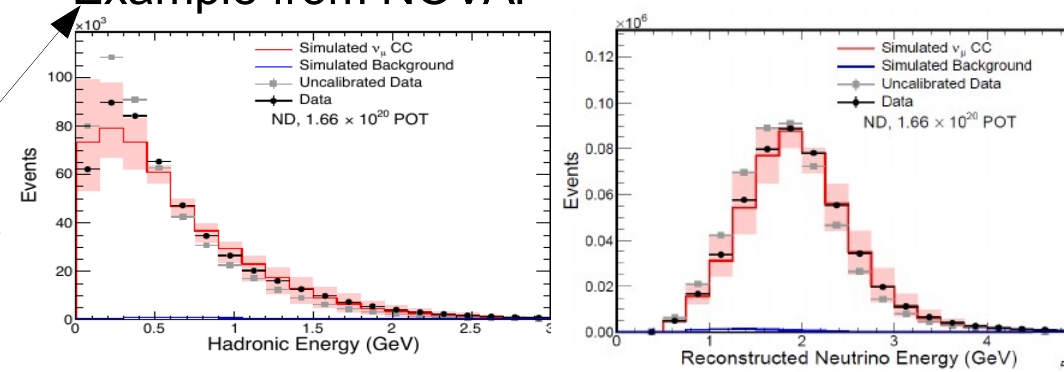
- Eν from total deposited energy (and q3 from muon kinematics) ~ electron scattering data



- **Main limitation:**
  - Calibration issues (no sensitivity to neutrons, energy threshold...)
  - Very limited predictivity from models!

The two problems are tightly convoluted and difficult to disentangle

Example from NOVA:



- **A taste of the future → DUNE:**
  - need to reconstruct precise E_ν shape for good sensitivity (two oscillation maxima)
  - capability of full reconstruction of tracks and showers down to very low threshold

→ **need to reach very good control on detector calibration/uniformity and on neutrino interaction modelling which have convoluted effected in E_ν**

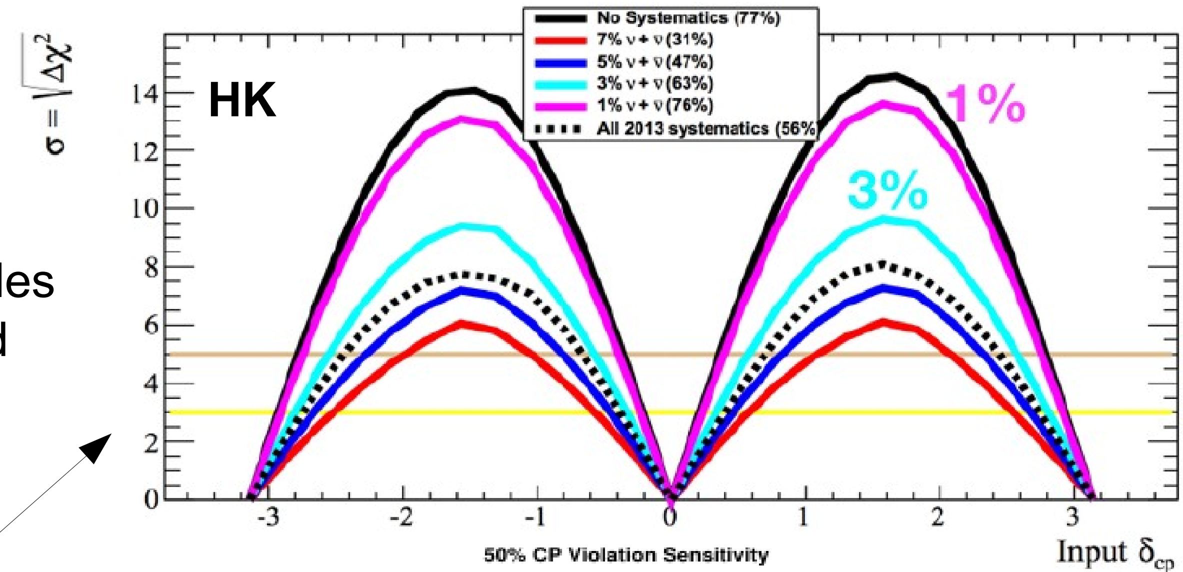
Future experiments: ν_e and $\bar{\nu}$ xsec

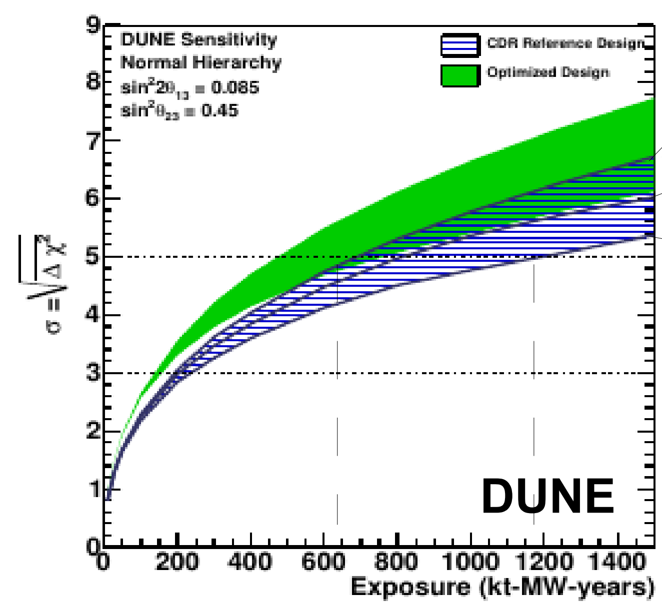
- We are interested to **ν_e appeareance and δ_{CP} from $\nu - \bar{\nu}$ comparison** but in ND we mostly measure ν_μ cross-sections.

- In future (HK, DUNE) large samples of 4 ν species → the uncorrelated uncertainties are relevant
  - **HK** needed uncertainty to have negligible impact on δ_{CP}: **ν_e-$\bar{\nu}_e$ uncorrelated 1-2%**
  - For **DUNE** assumed: **uncorrelated ν_μ - $\bar{\nu}_\mu$ 5%** and **ν_e - $\bar{\nu}_e$ 2%**

T2K: 2015 values

ν_μ sample	ν_e s[…]	[…]le	$\bar{\nu}_e$ sample
7.7%	6.8%	11.6%	11.0%





5% ± 1%

5% ± 2%

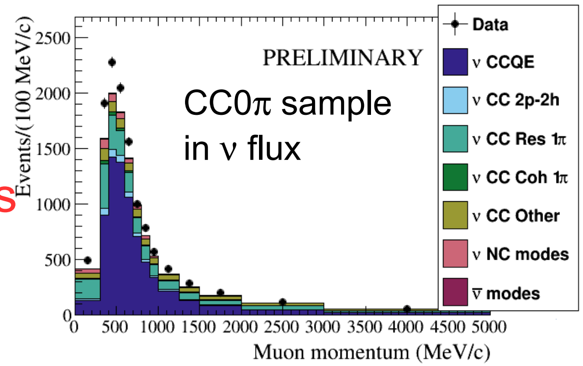
5% ± 3%

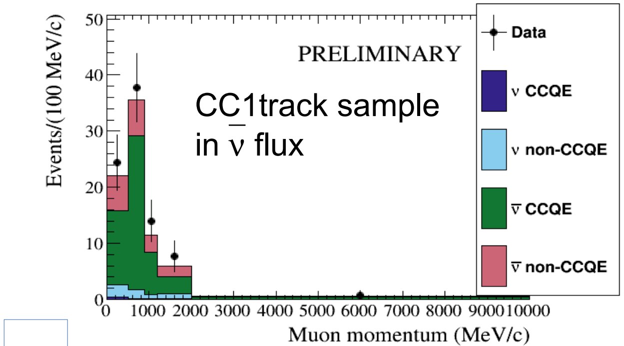
→ equivalent to factor 2 in exposure!

DUNE and HK talks @ NuFact 2015

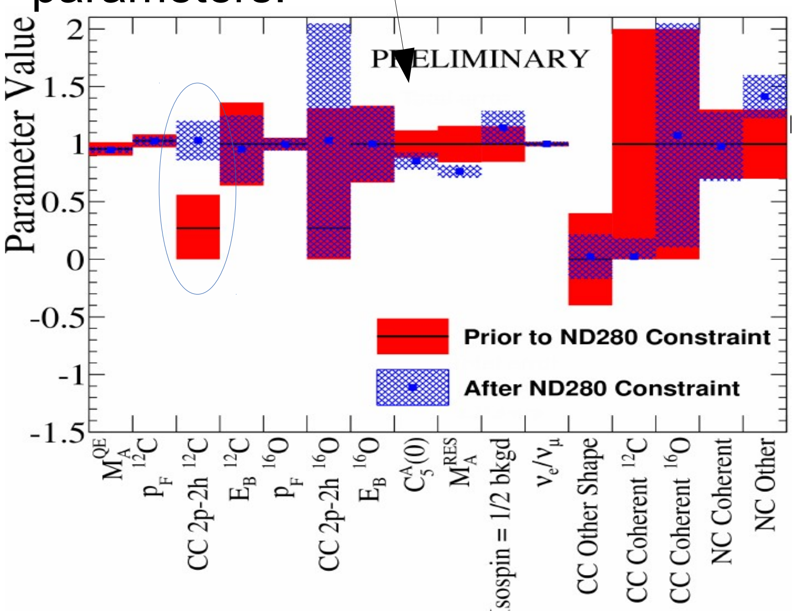
Oscillation analysis (*)

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

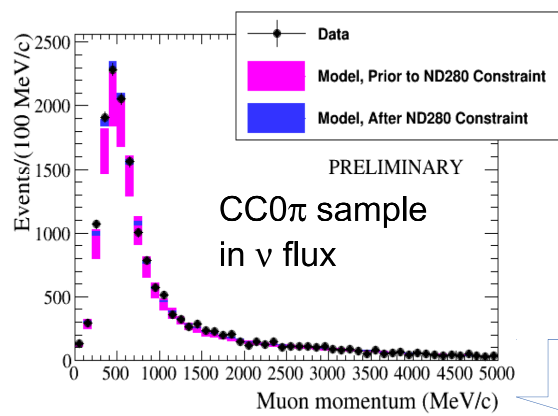


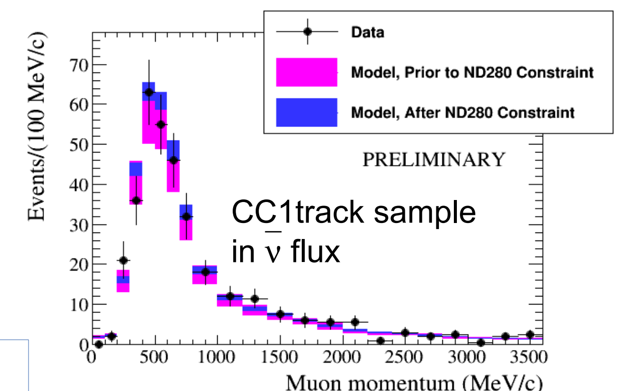


2) Parametrization of uncertainties on (flux and) neutrino interaction modelling in terms of various parameters:



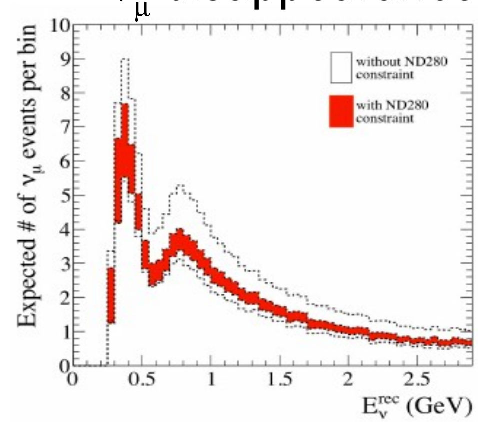
3) **Fit to ND data to constrain such parameters:**



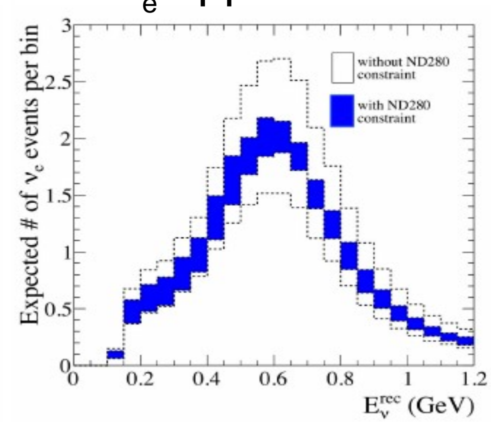


4) **Extrapolation to far detector to predict the oscillated spectrum:**

ν_μ disappearance



ν_e appearance



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

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

Effects of different 2p2h models on muon distributions at SK

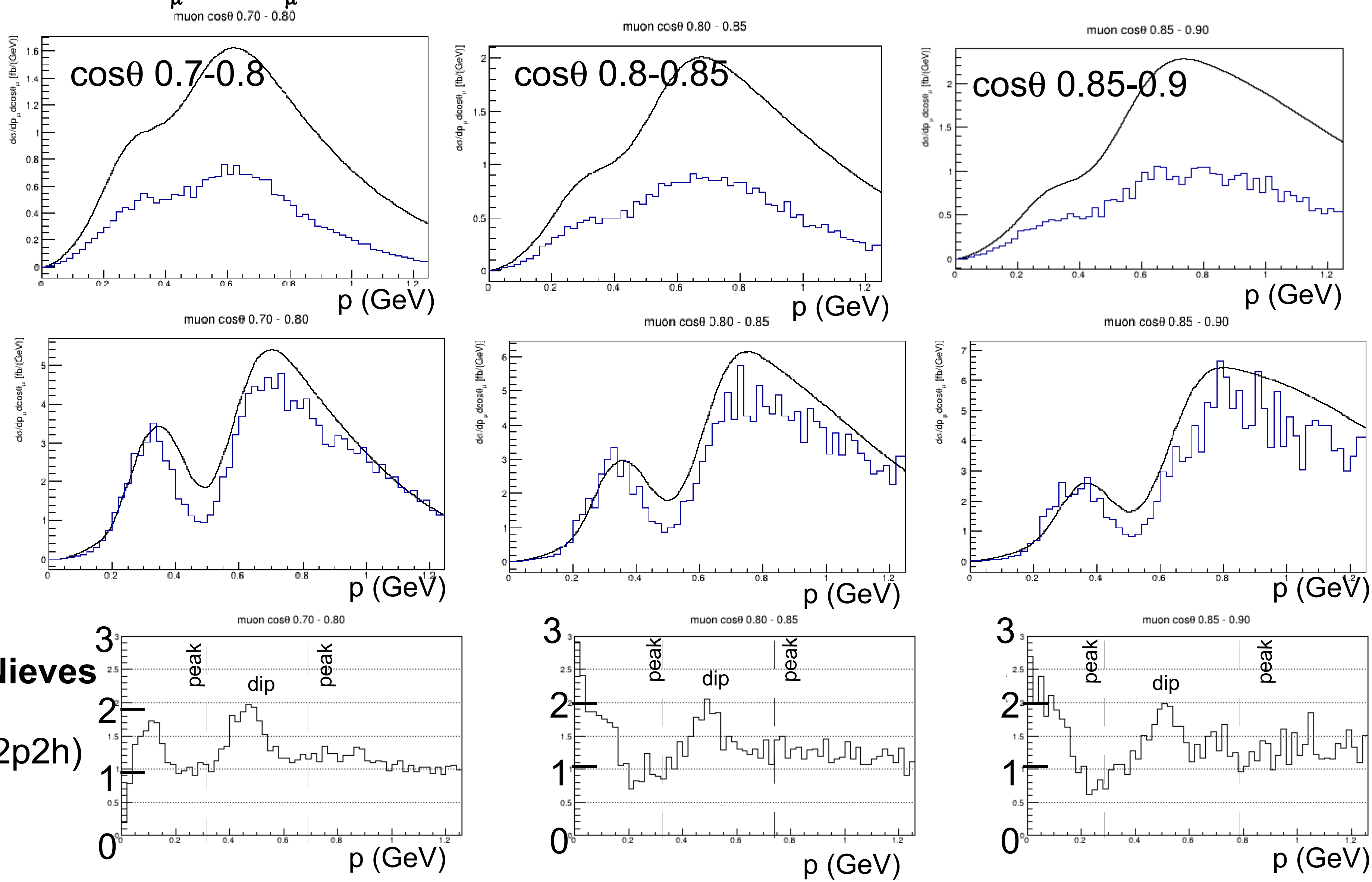
- **SK flux-folded p_μ, $\cos\theta_\mu$ distributions**

Martini (line)
Nieves (histo)

2p2h only

CCQE (RPA) + 2p2h

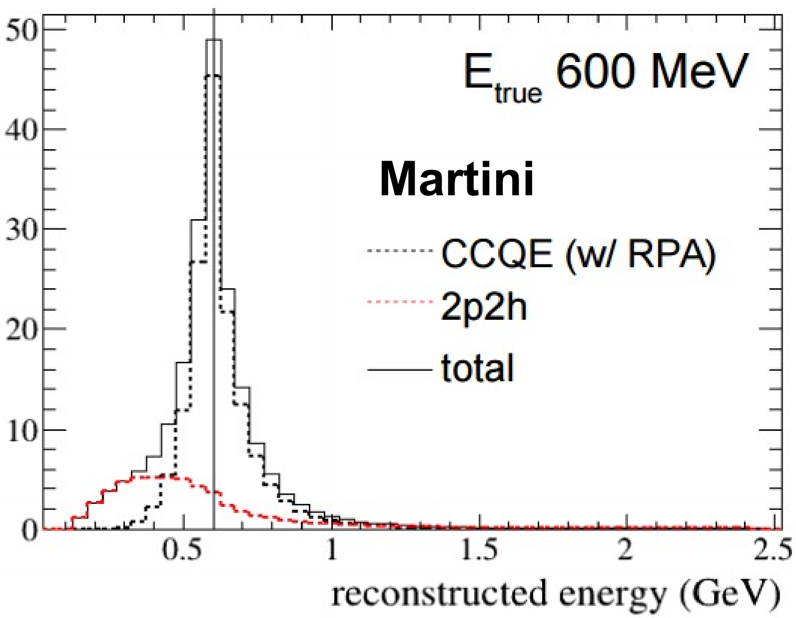
Martini/Nieves ratio (CCQE+2p2h)

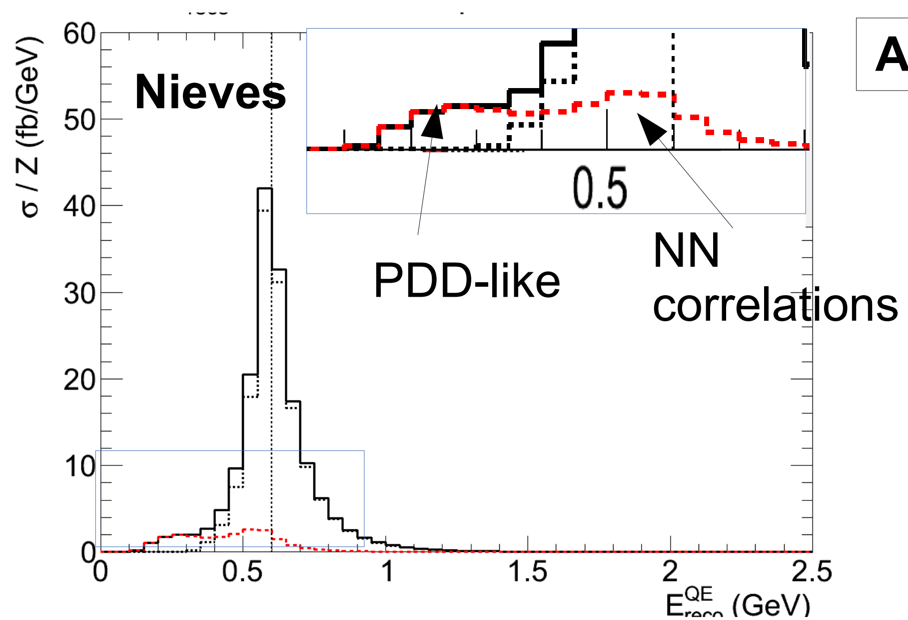


Alternative parametrization

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





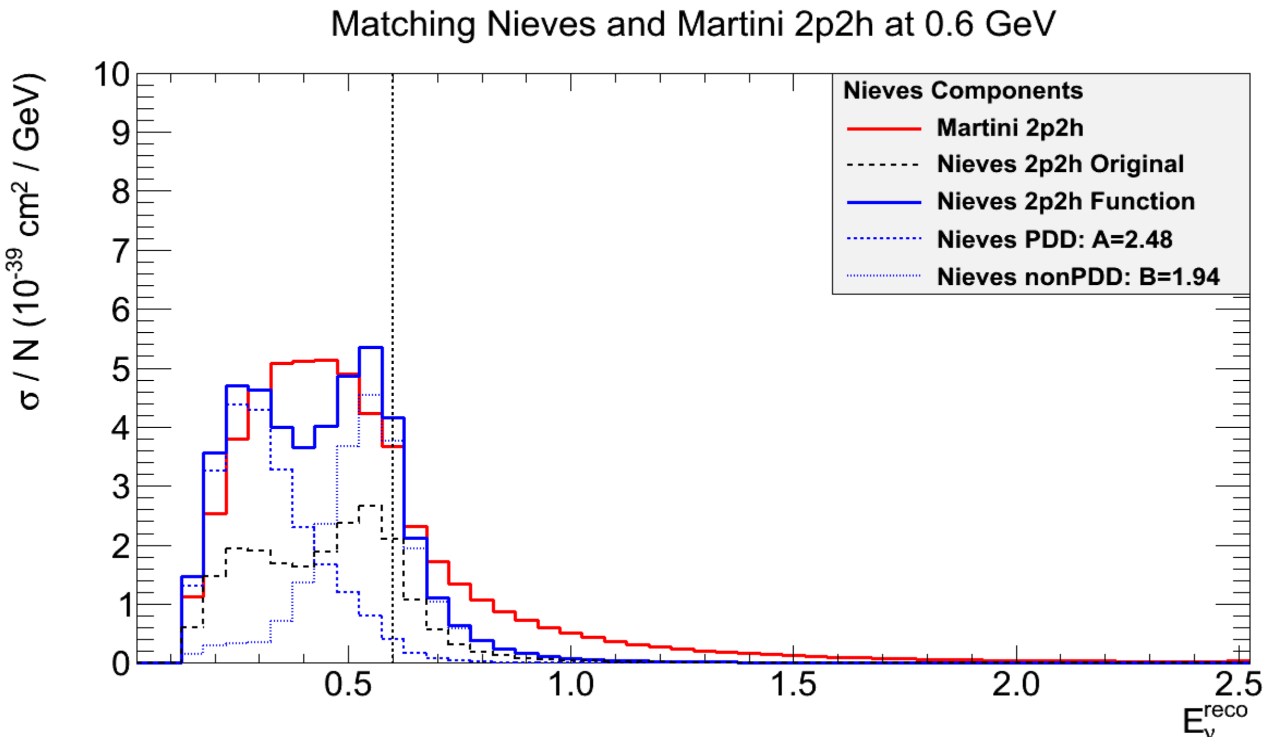
A.Cudd

- **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

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



A.Cudd

- 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

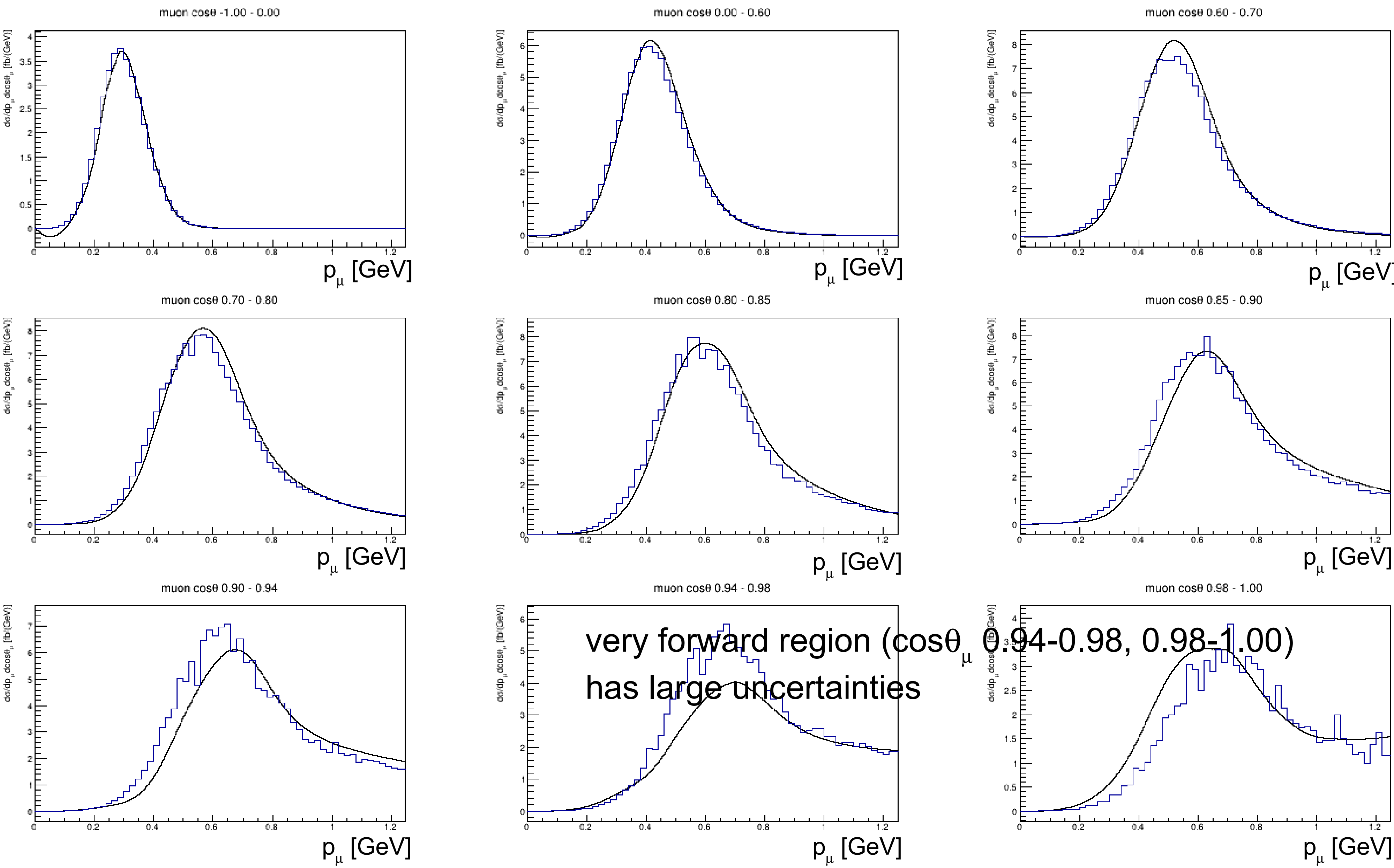
- In the meanwhile, **2 fake datasets:** reweight to make all 2p2h events to look like PDD (left peak) or not-PDD (right peak)

ND280 flux-folded

RPA only (w/o 2p2h)

Martini (line)
Nieves (histo)

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

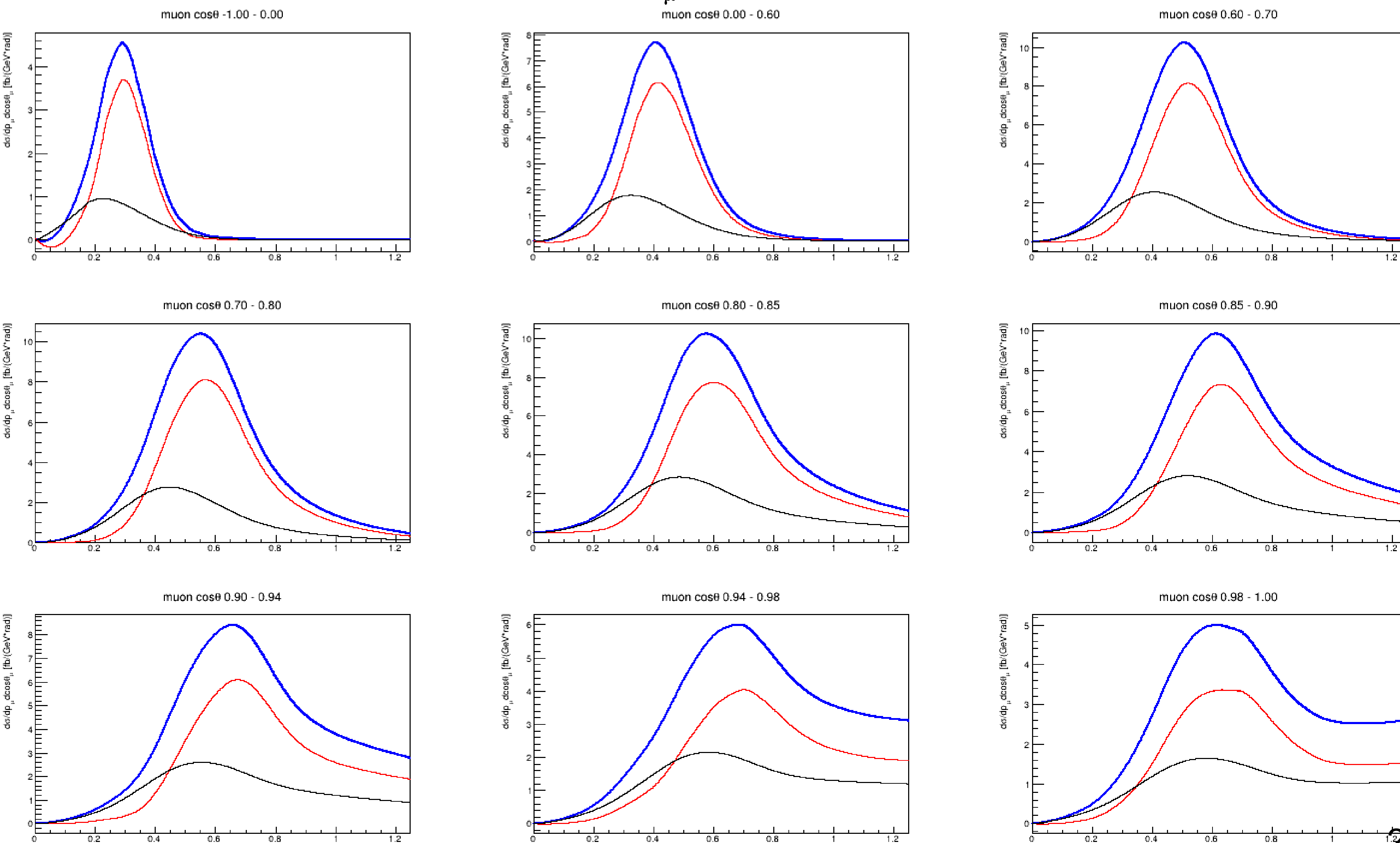


very forward region ($\cos\theta_\mu$ 0.94-0.98, 0.98-1.00) has large uncertainties

Including 2p2h (Martini)

RPA + 2p2h
RPA
2p2h

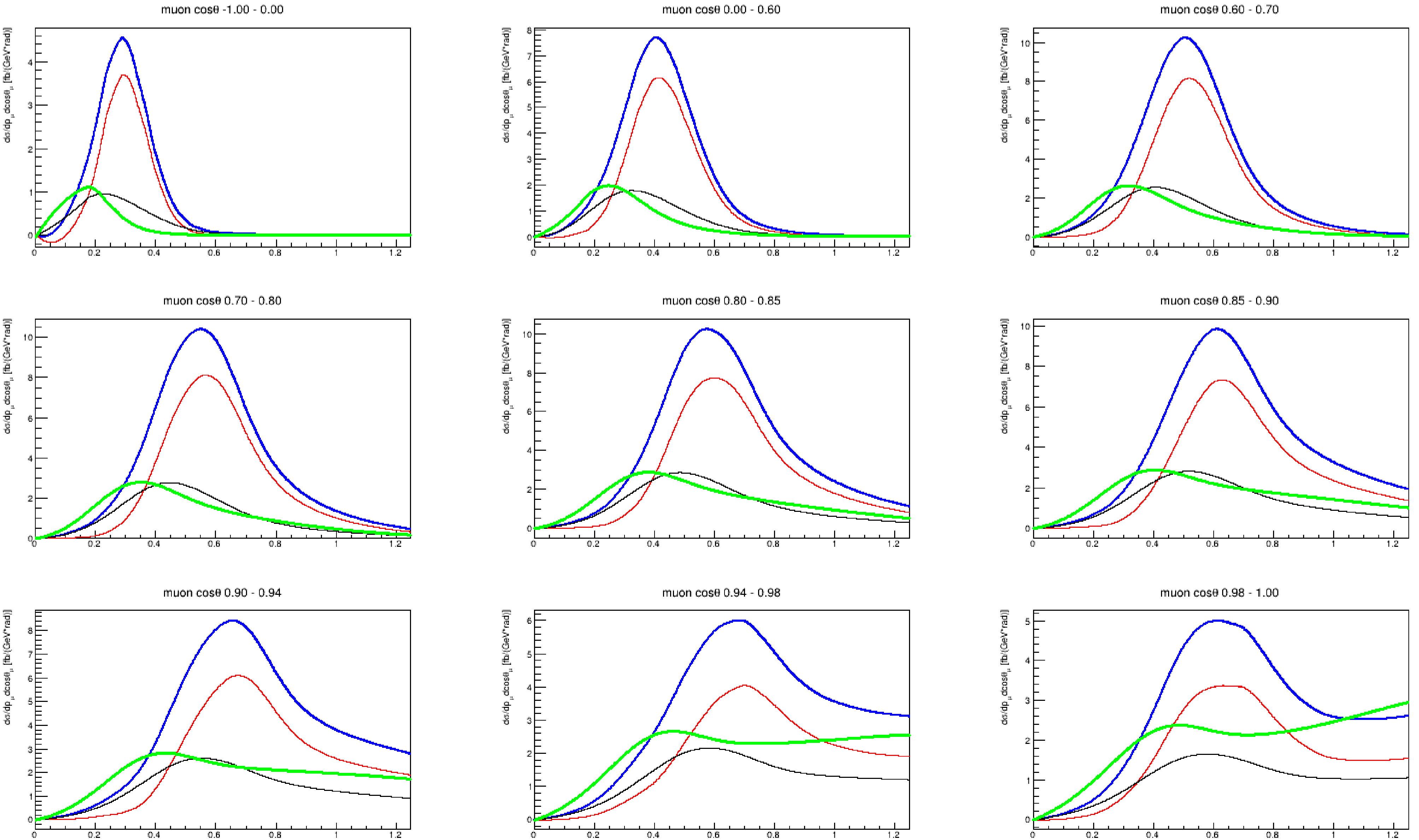
For both models there is a region at **small p_μ where only 2p2h and no 'real' QE is present !**



CC 1π (Martini)

RPA + 2p2h
RPA
2p2h
CC1π

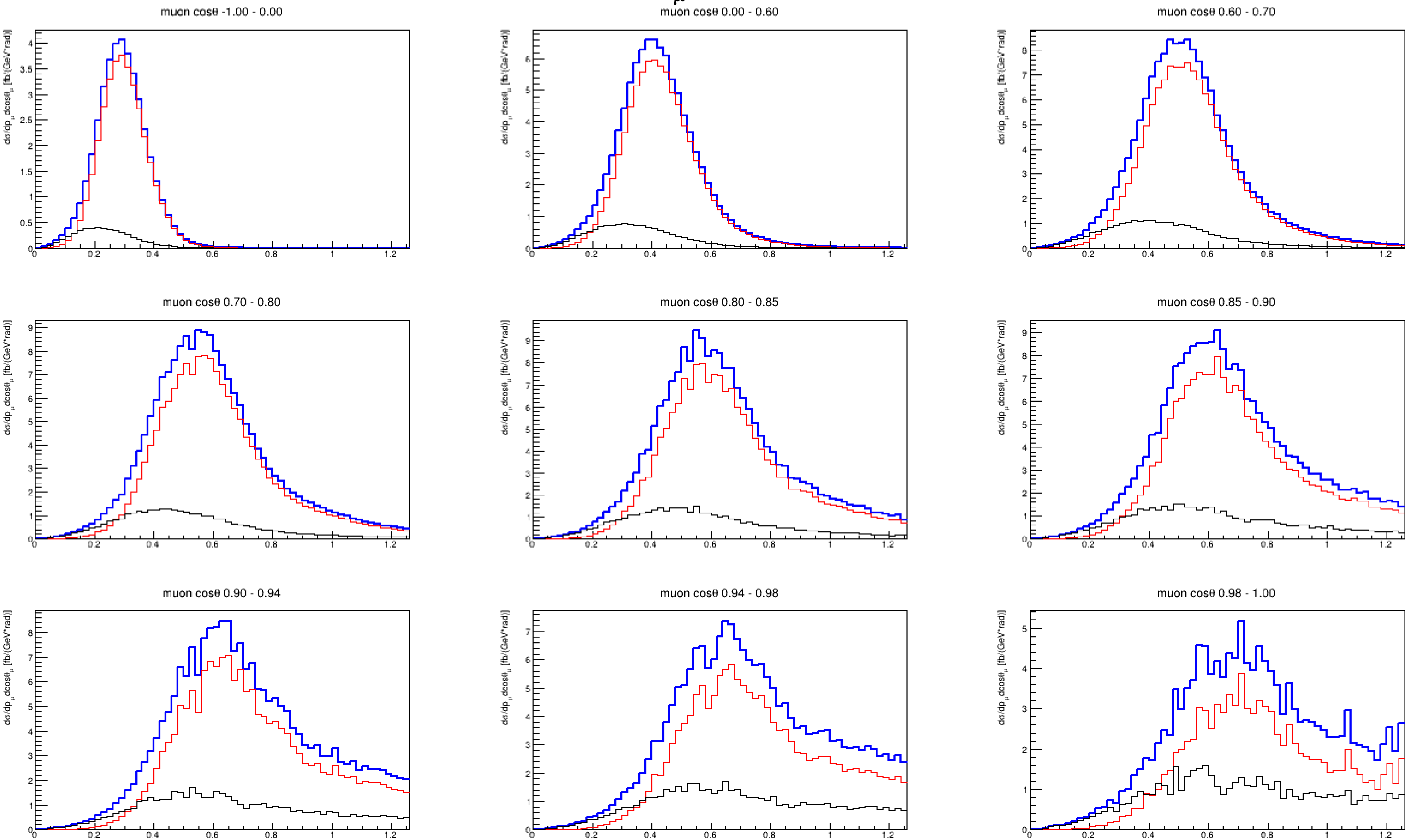
Unfortunately low p_μ is also the region where most of the CC1π background is located



Nieves model

RPA + 2p2h
RPA
2p2h

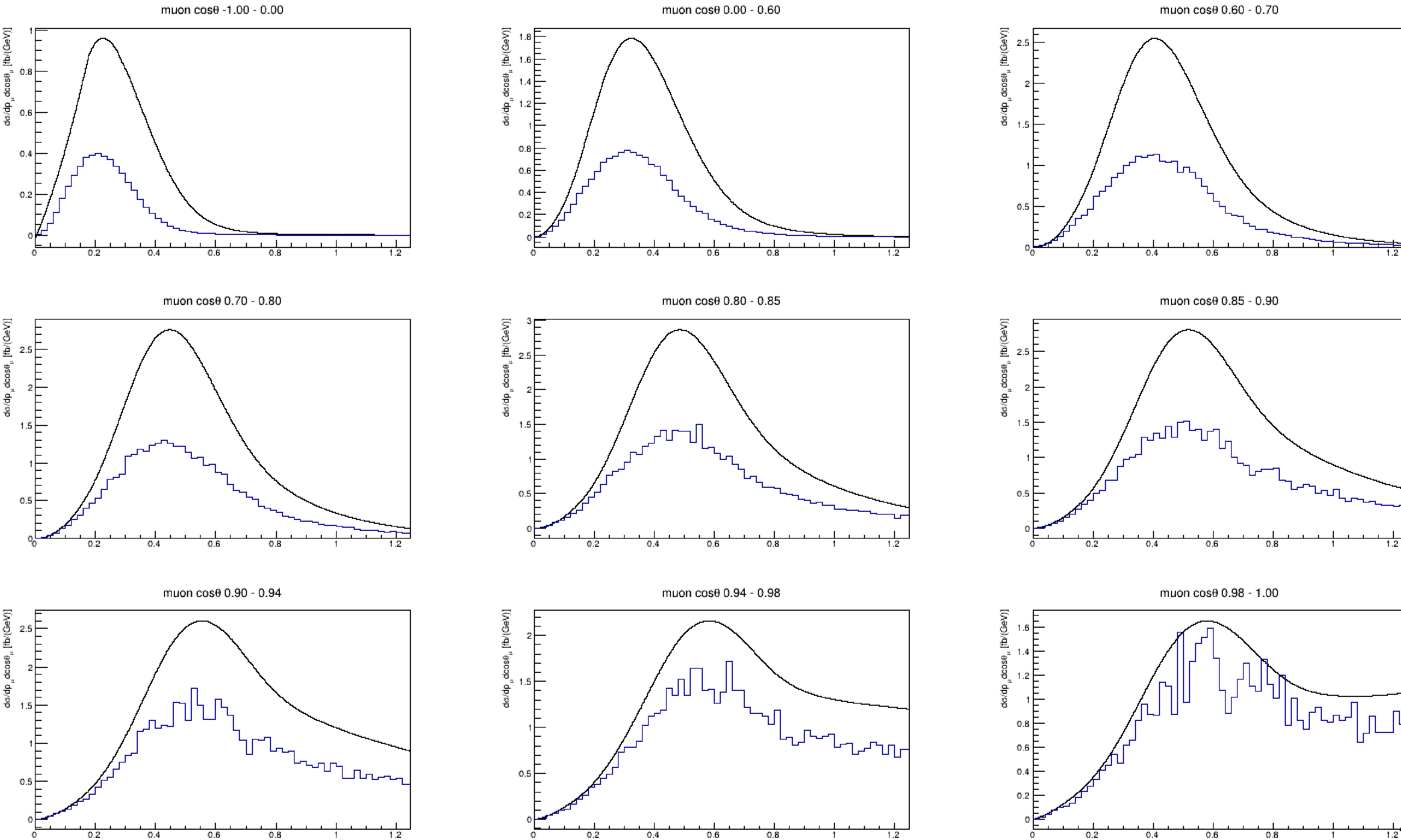
For both models there is a region at **small p_μ where only 2p2h and no 'real' QE is present !**



2p2h only: Nieves vs Martini

Martini (line)
Nieves (histo)

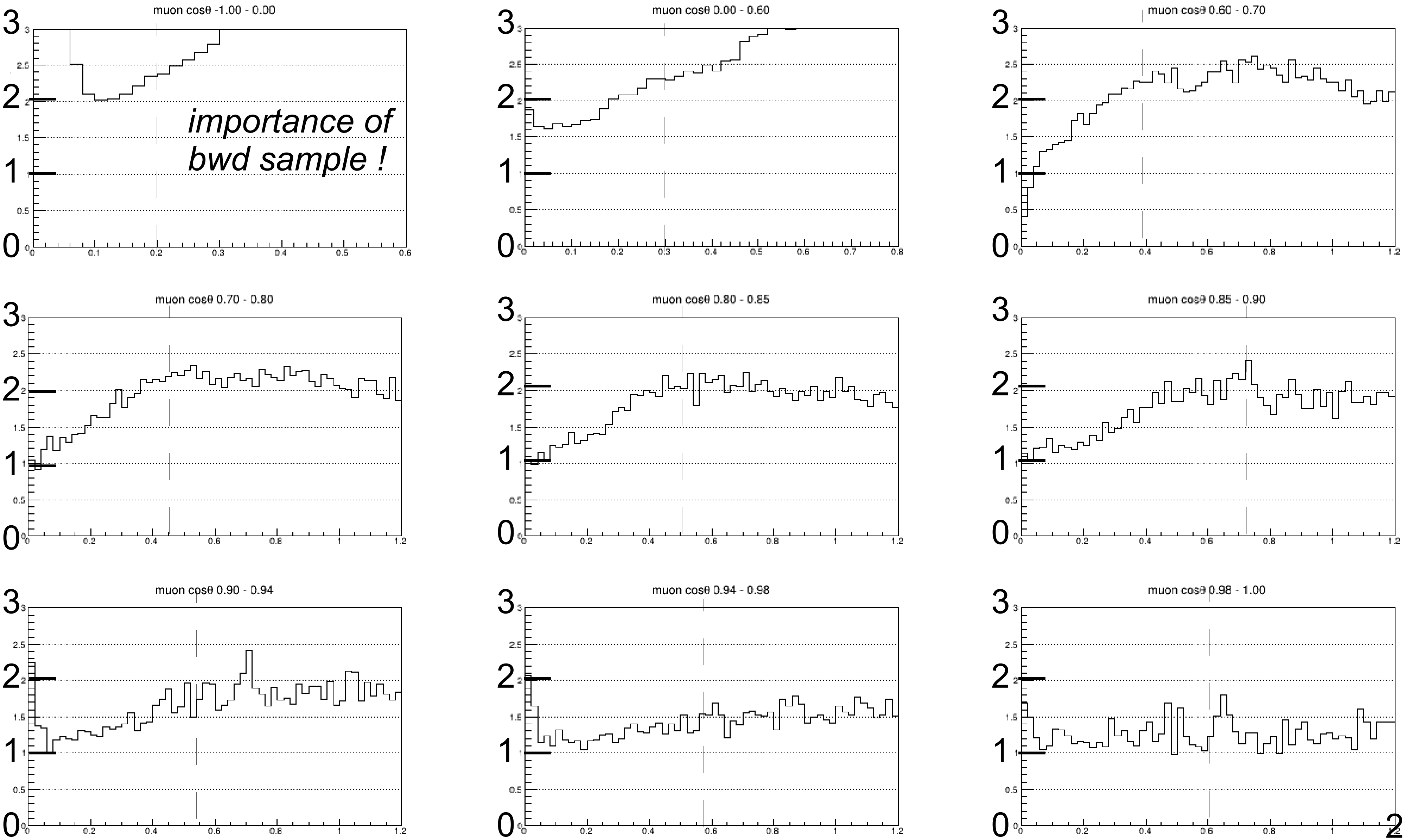
Large (~factor 2) difference between 2p2h effects in Martini and Nieves



2p2h only Martini/Nieves

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

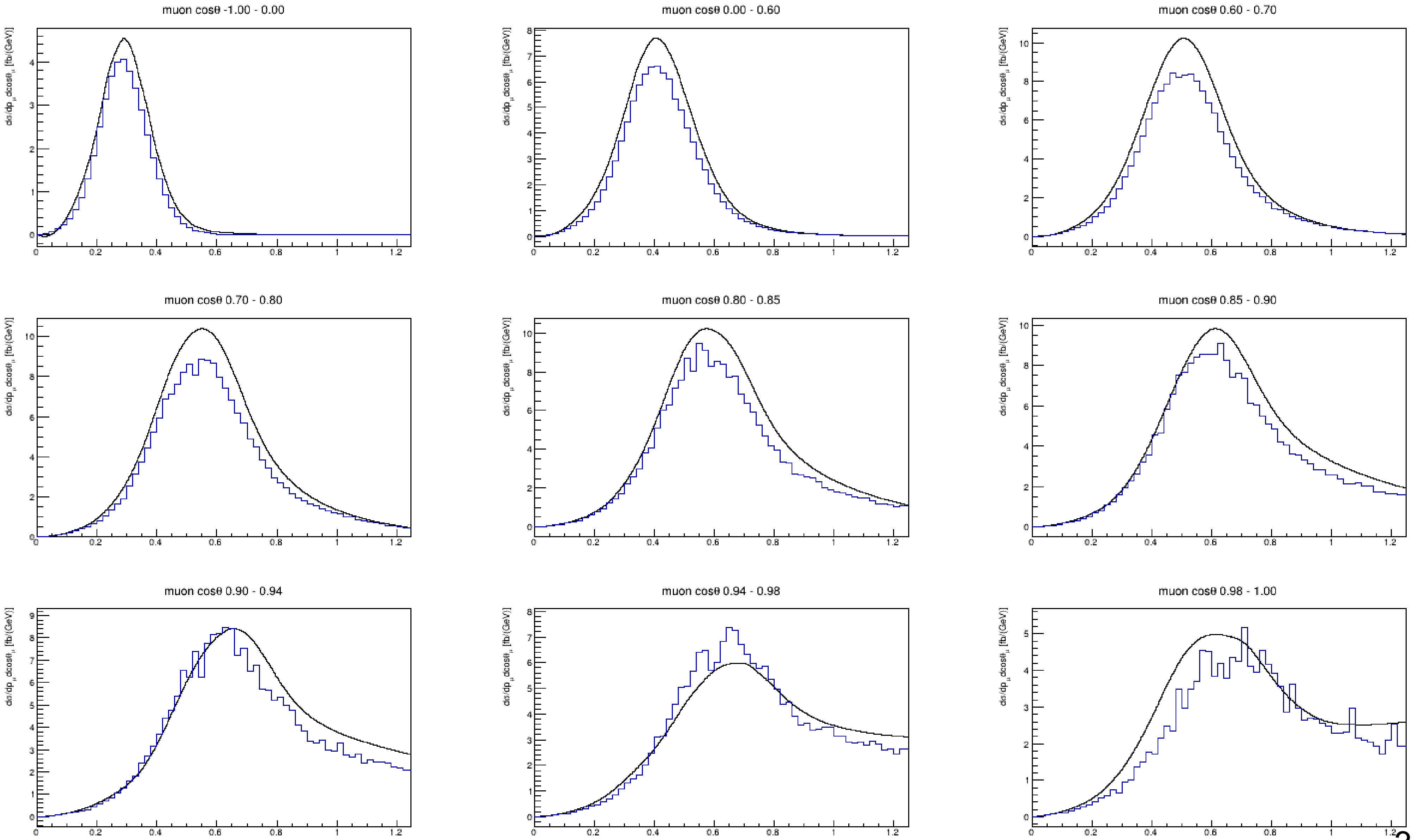
Shape difference: Martini 2p2h tends to shift to larger momentum and larger angles



RPA + 2p2h

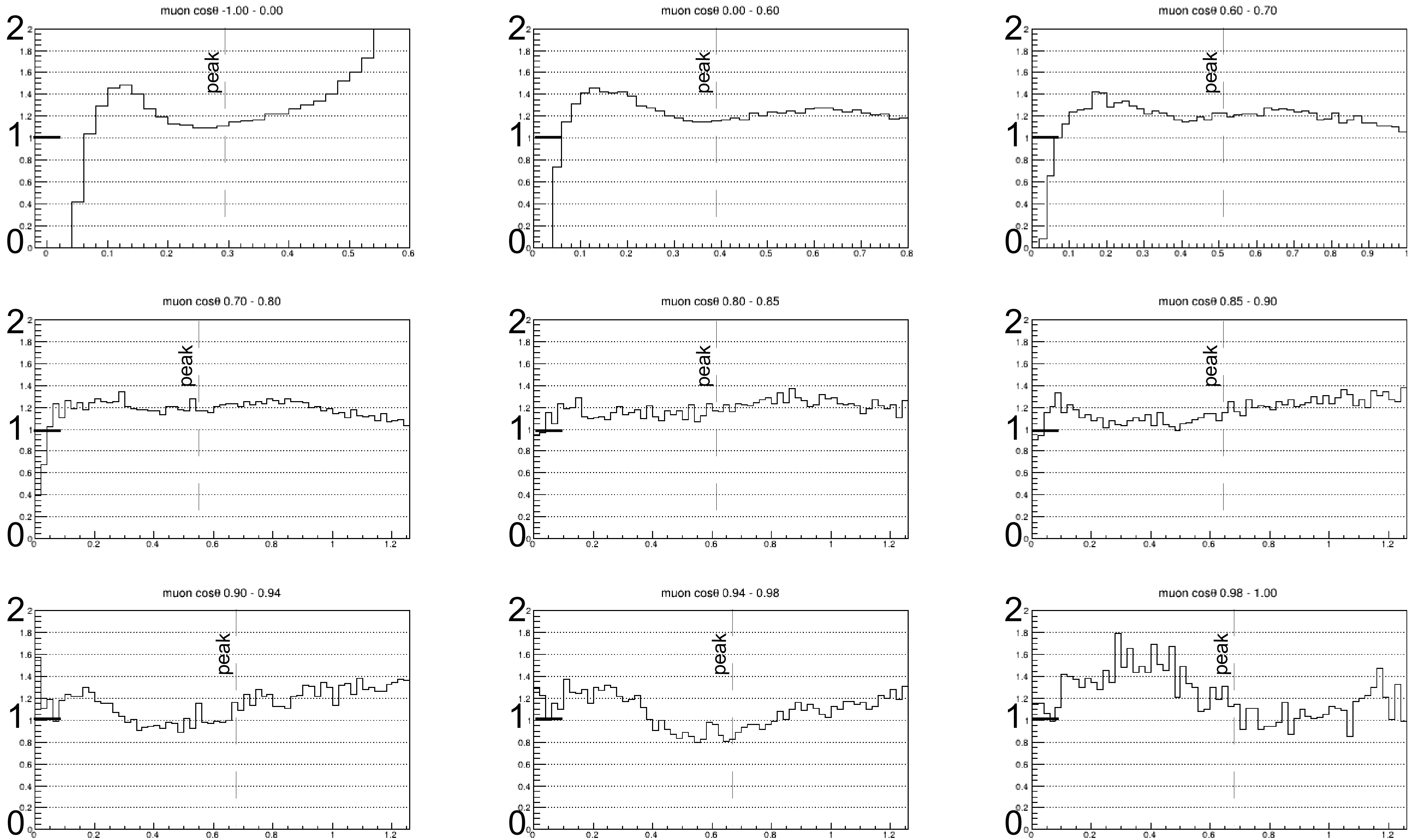
Martini (line)
Nieves (histo)

For the total xsec, differences are 'relatively' small



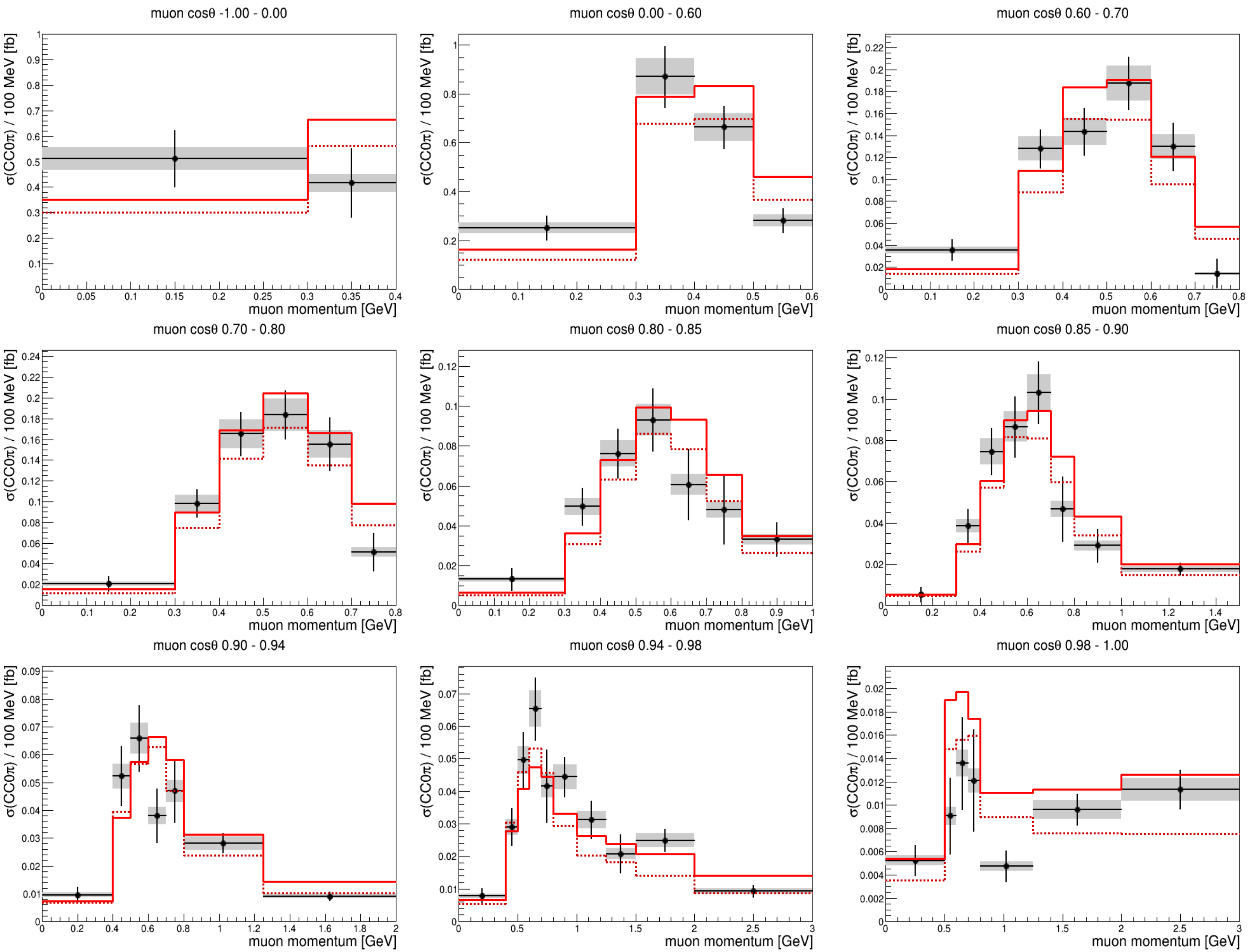
Martini/Nieves ND-flux folded

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:



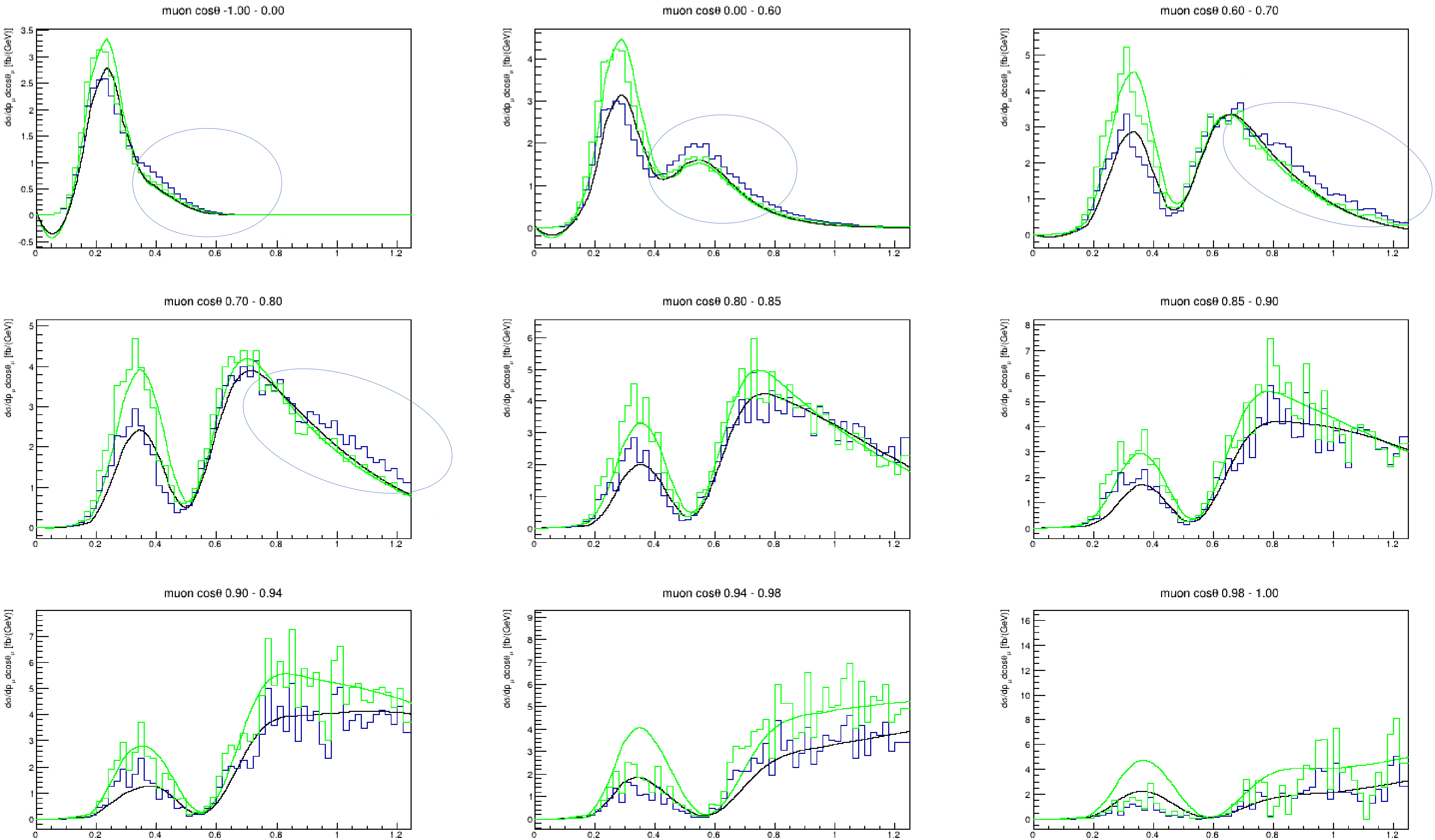
SK flux-folded

Bare and RPA

bare
RPA

Nieves (histogram)
Martini (line)

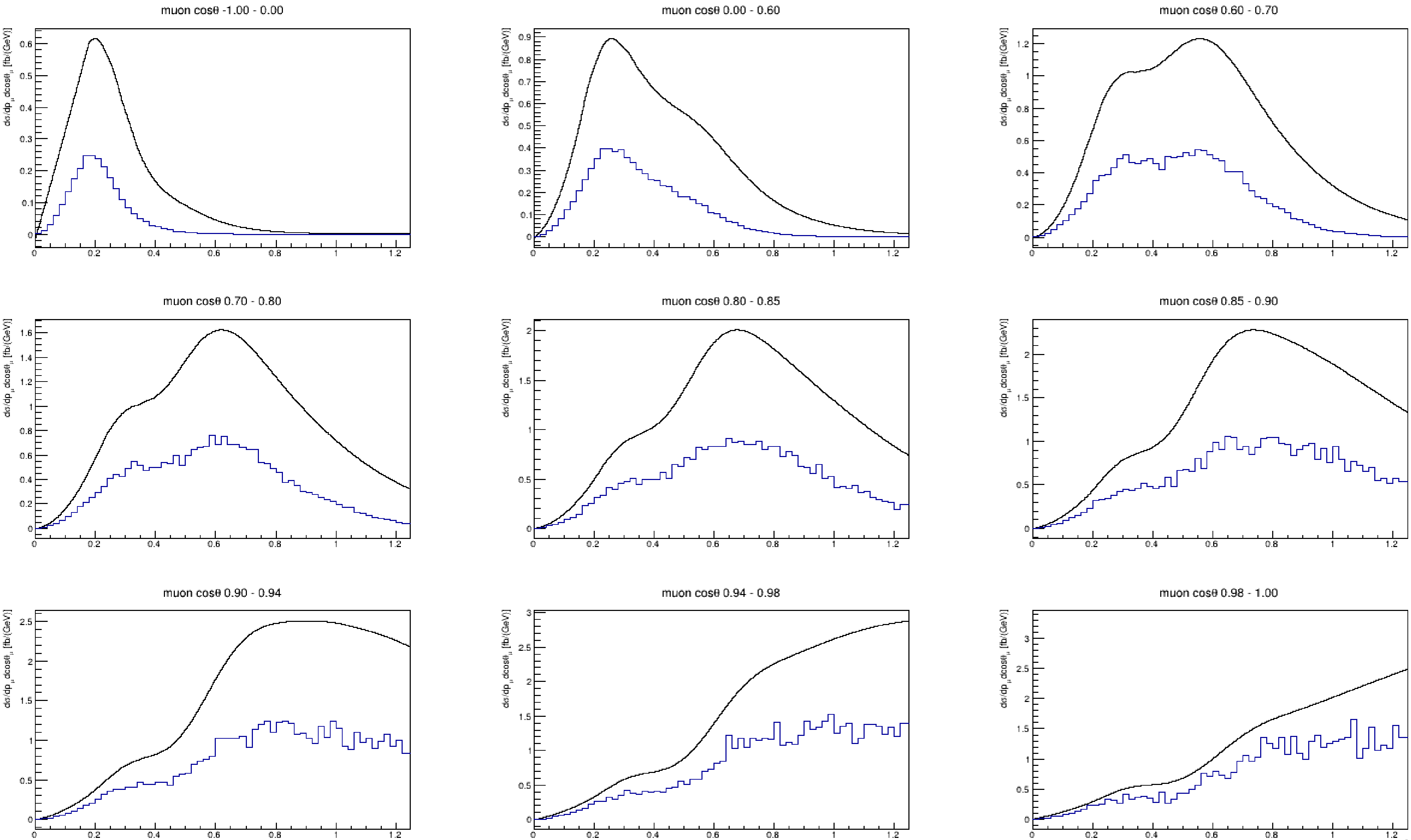
Relatively small differences (positive RPA corrections in Nieves at high pmu)



2p2h only

Martini (line)
Nieves (histo)

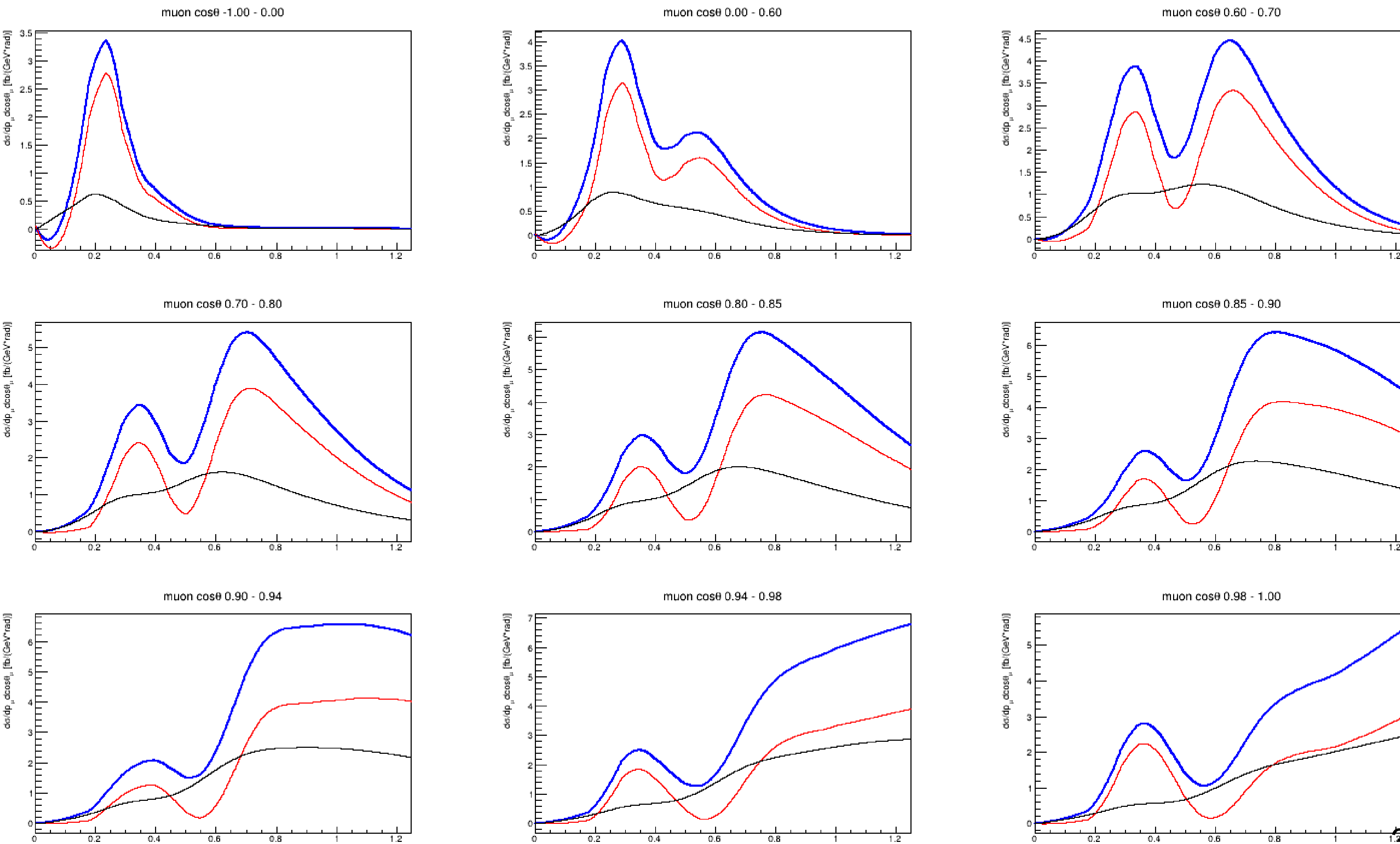
Large differences on 2p2h (~factor 2 as observed with ND flux folding)



Martini

RPA + 2p2h
RPA
2p2h

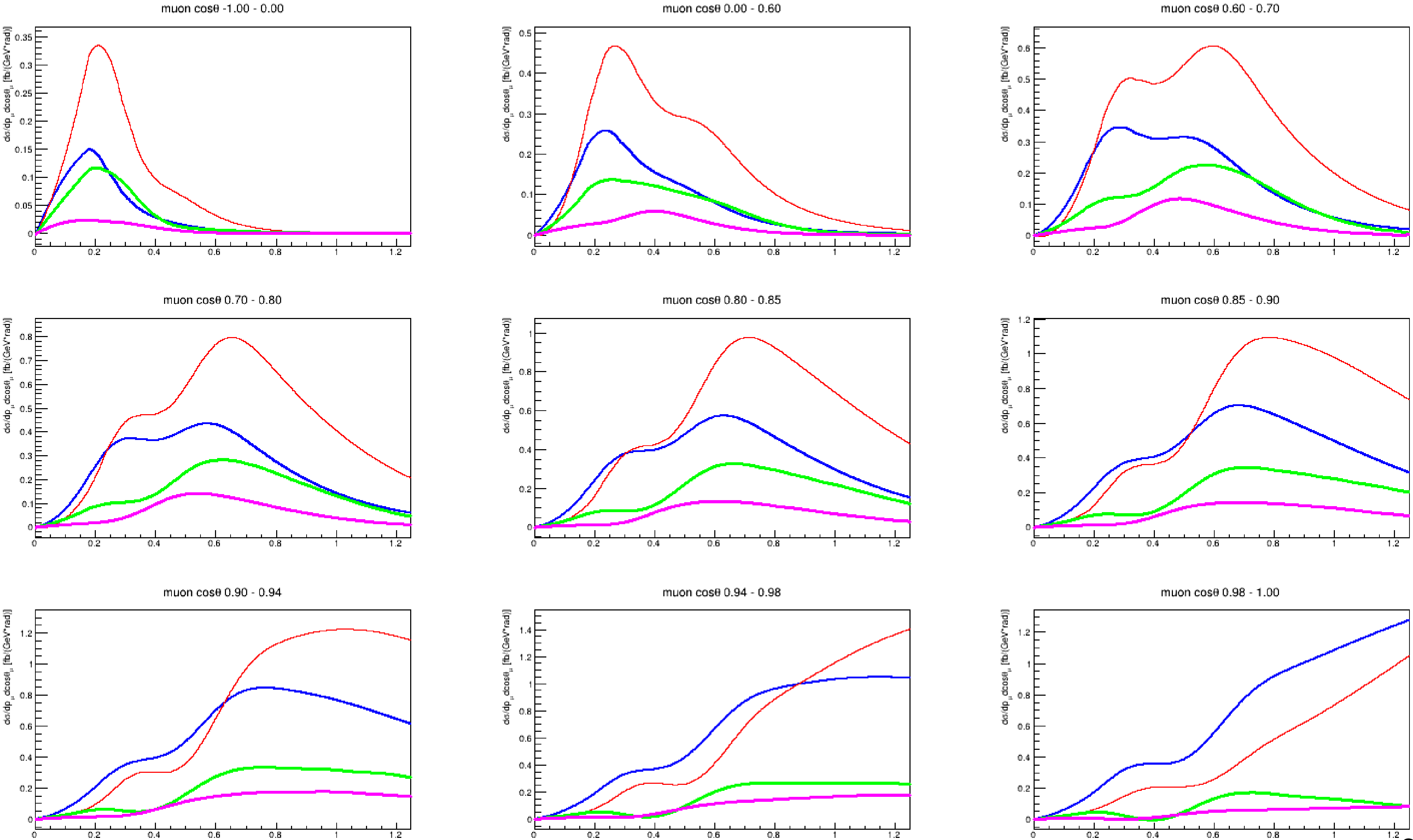
For both models 2p2h tends to fill the oscillation deep (same mechanism as E_ν^{rec} smearing)



Martini 2p2h components

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

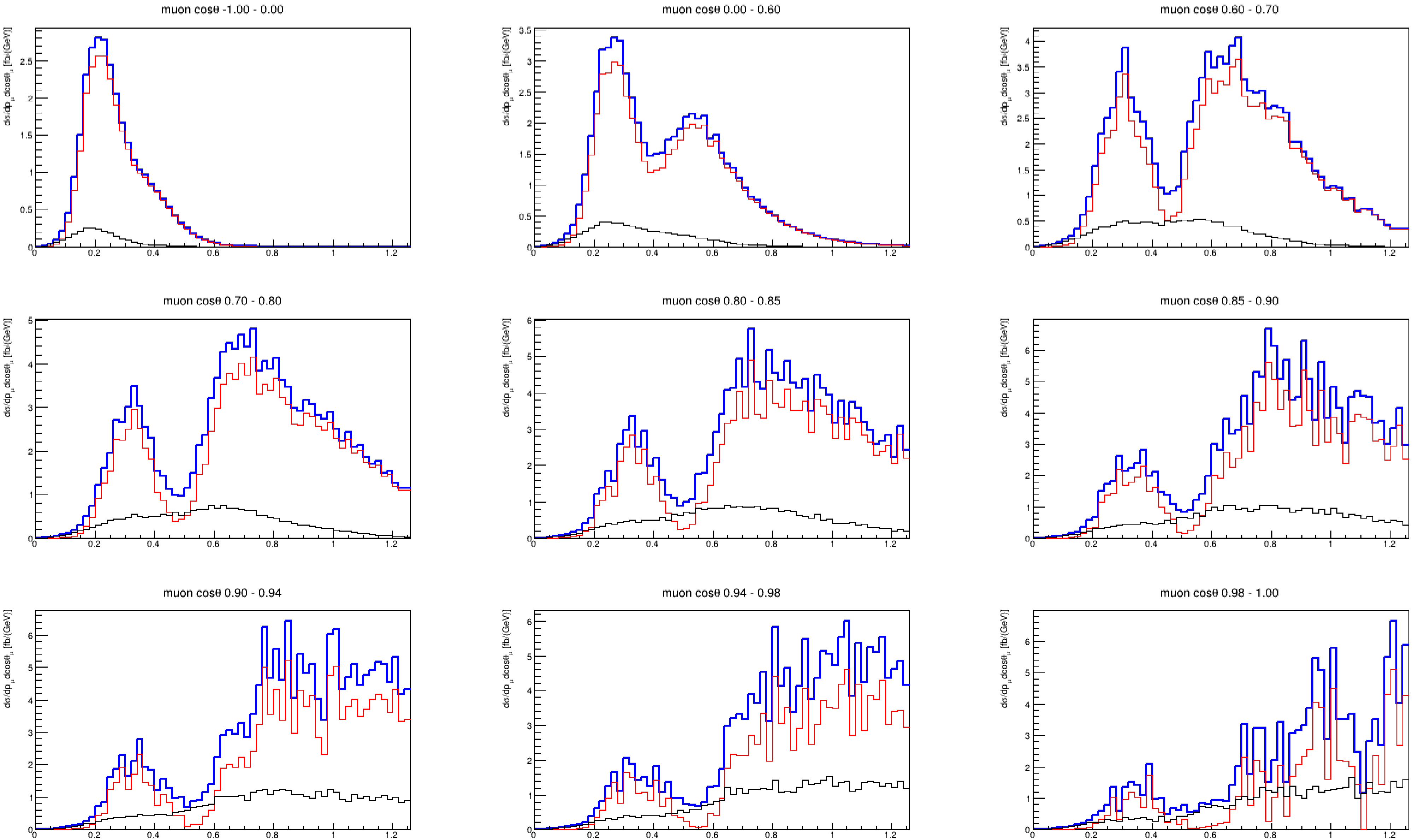
NN correlations   NN-MEC interference   MEC 2p2h $\Delta^{\pi\text{-less}}$ 3p3h



Nieves model

RPA + 2p2h
RPA
2p2h

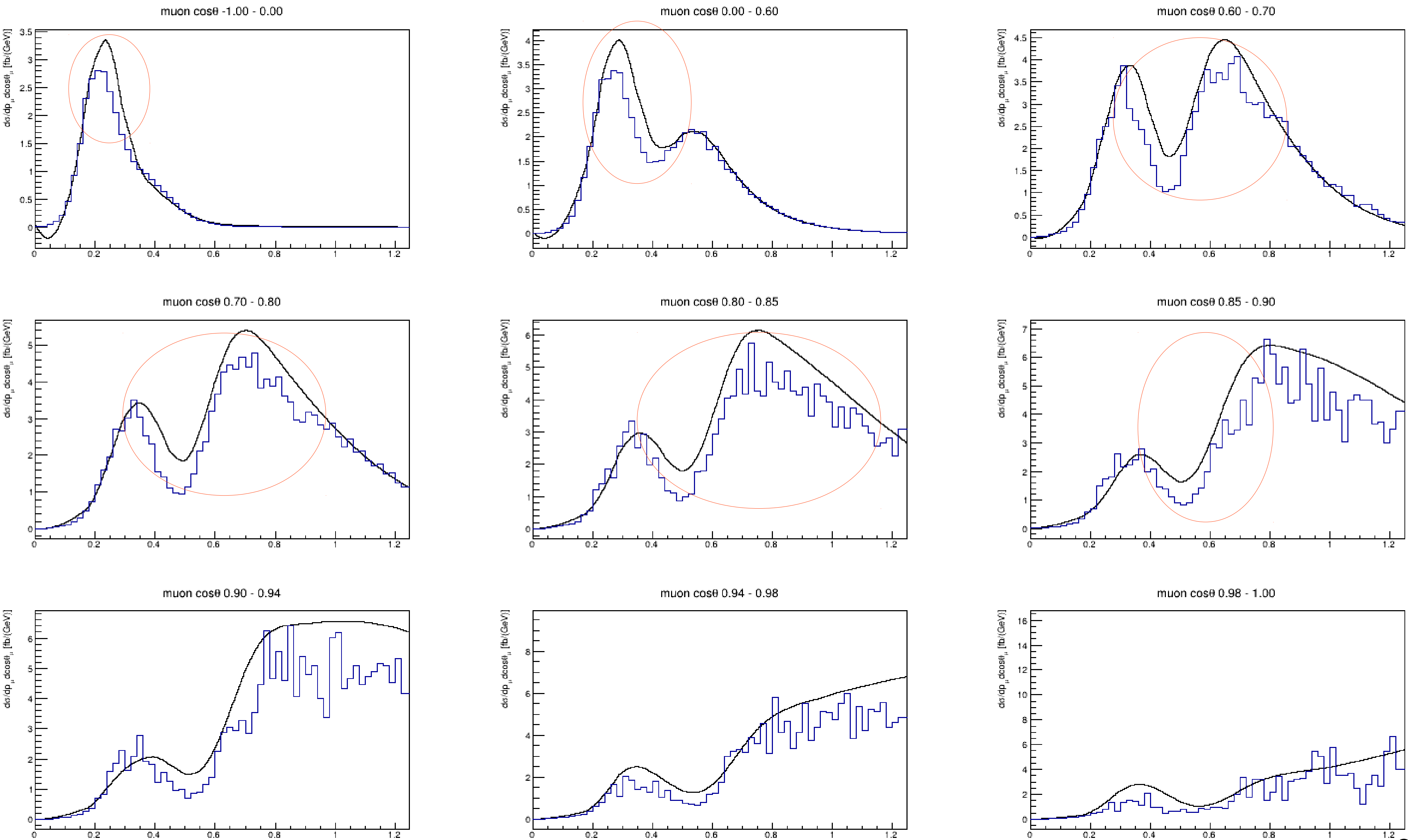
For both models 2p2h tends to fill the oscillation deep (same mechanism as E_ν^{rec} smearing)



RPA + 2p2h

Martini (line)
Nieves (histo)

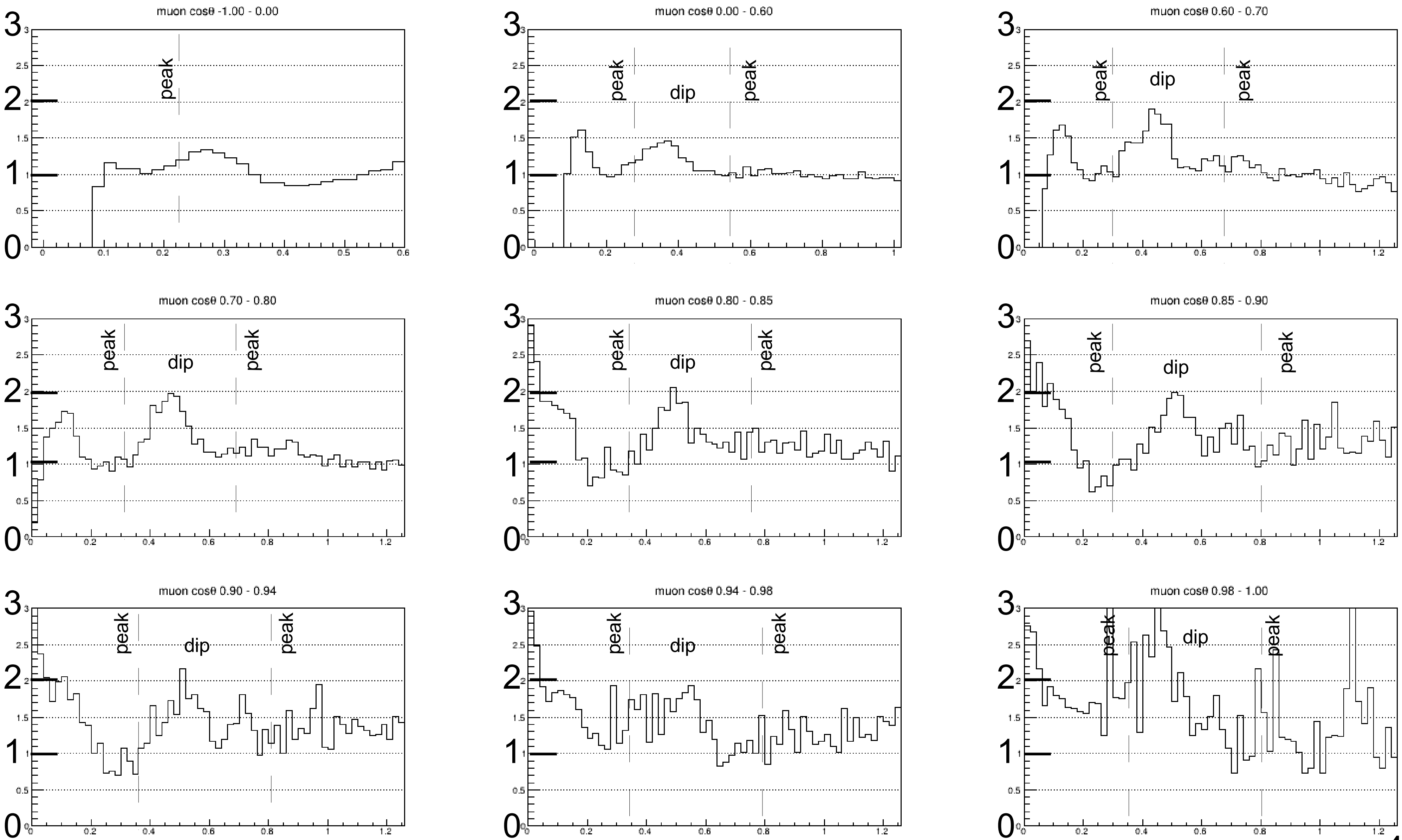
Large differences in spectrum shape predicted at SK, especially at the dip



Martini/Nieves

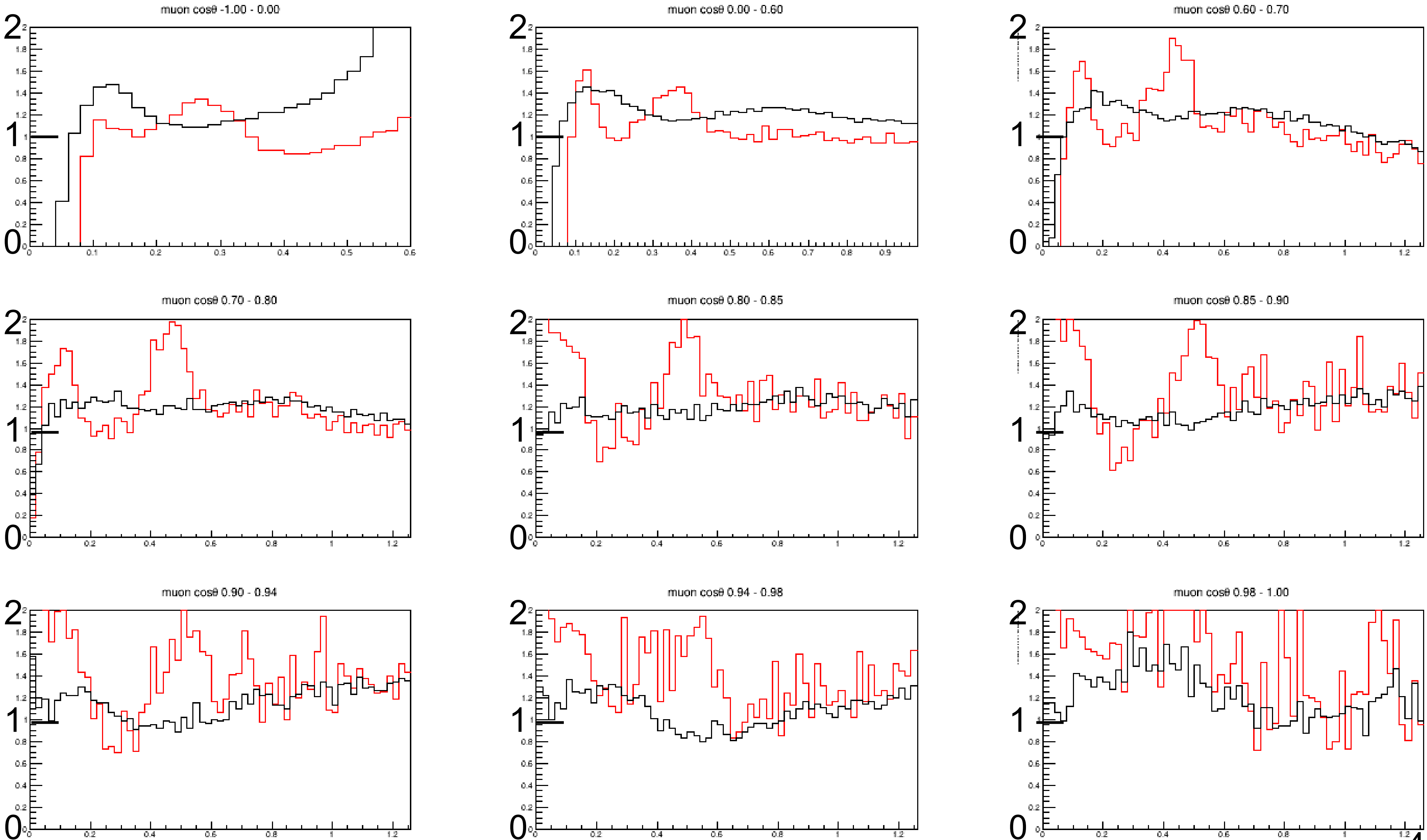
Martini (line)
Nieves (histo)

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:

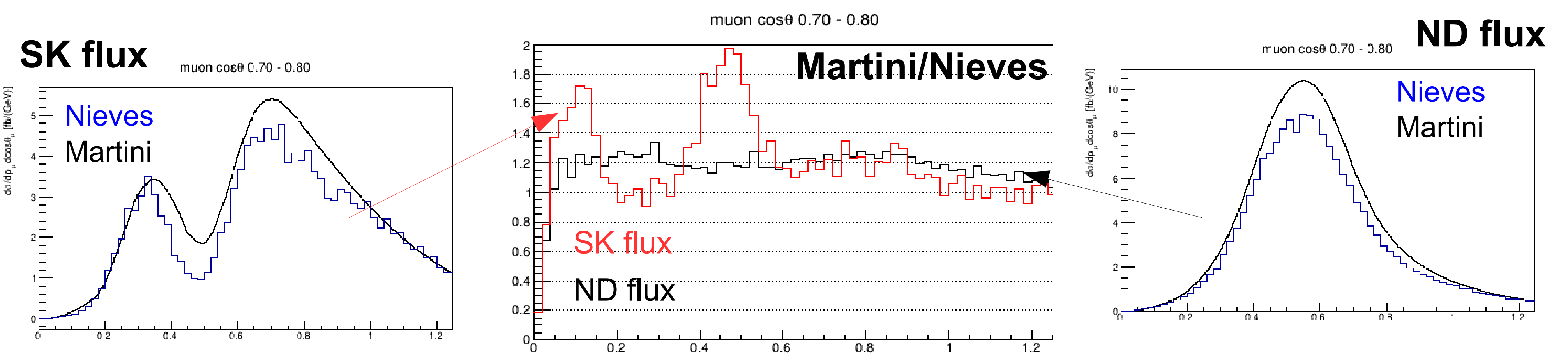
- shift in E_b and local vs global Fermi Gas

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

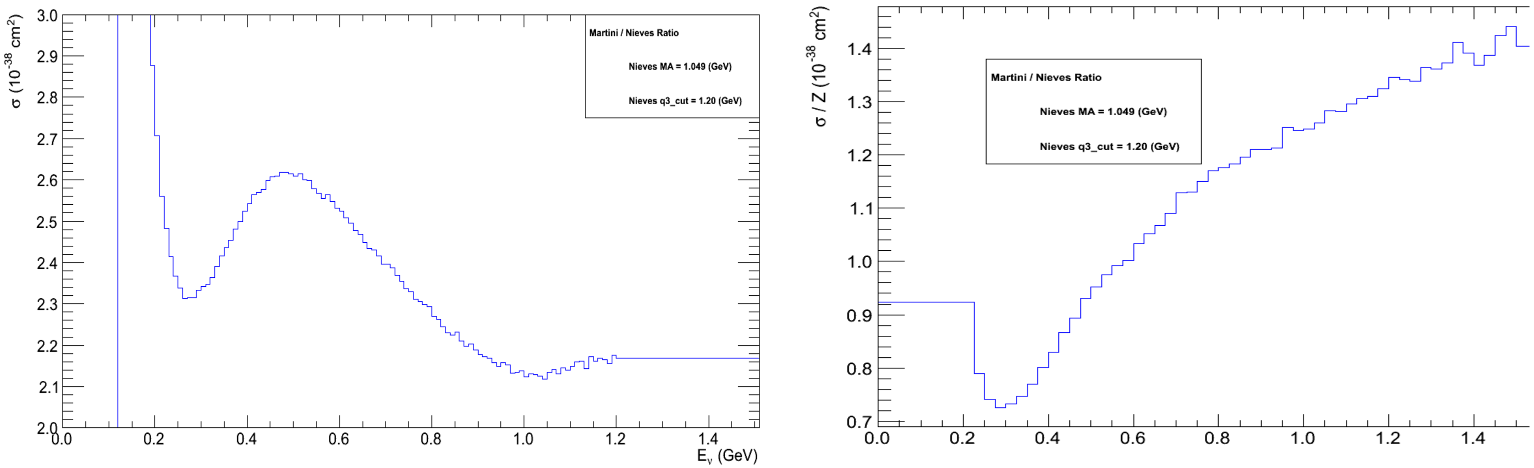


Differences in 2p2h relevant at SK: affect the oscillation deep but difficult to constraint from ND280

Is the shape difference between nu and nubar important?

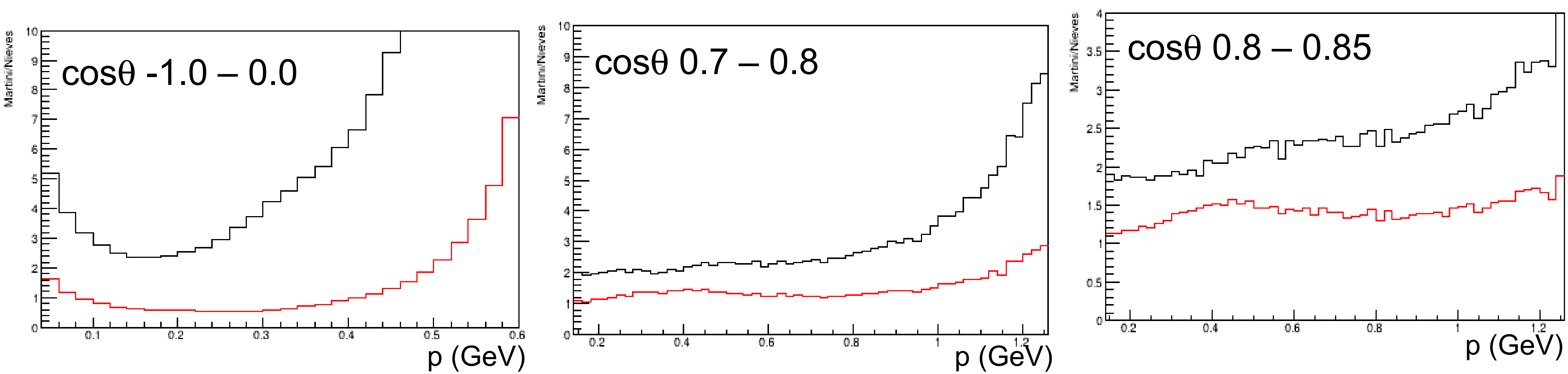
Martini/Nieves ratio (2p2h only)

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

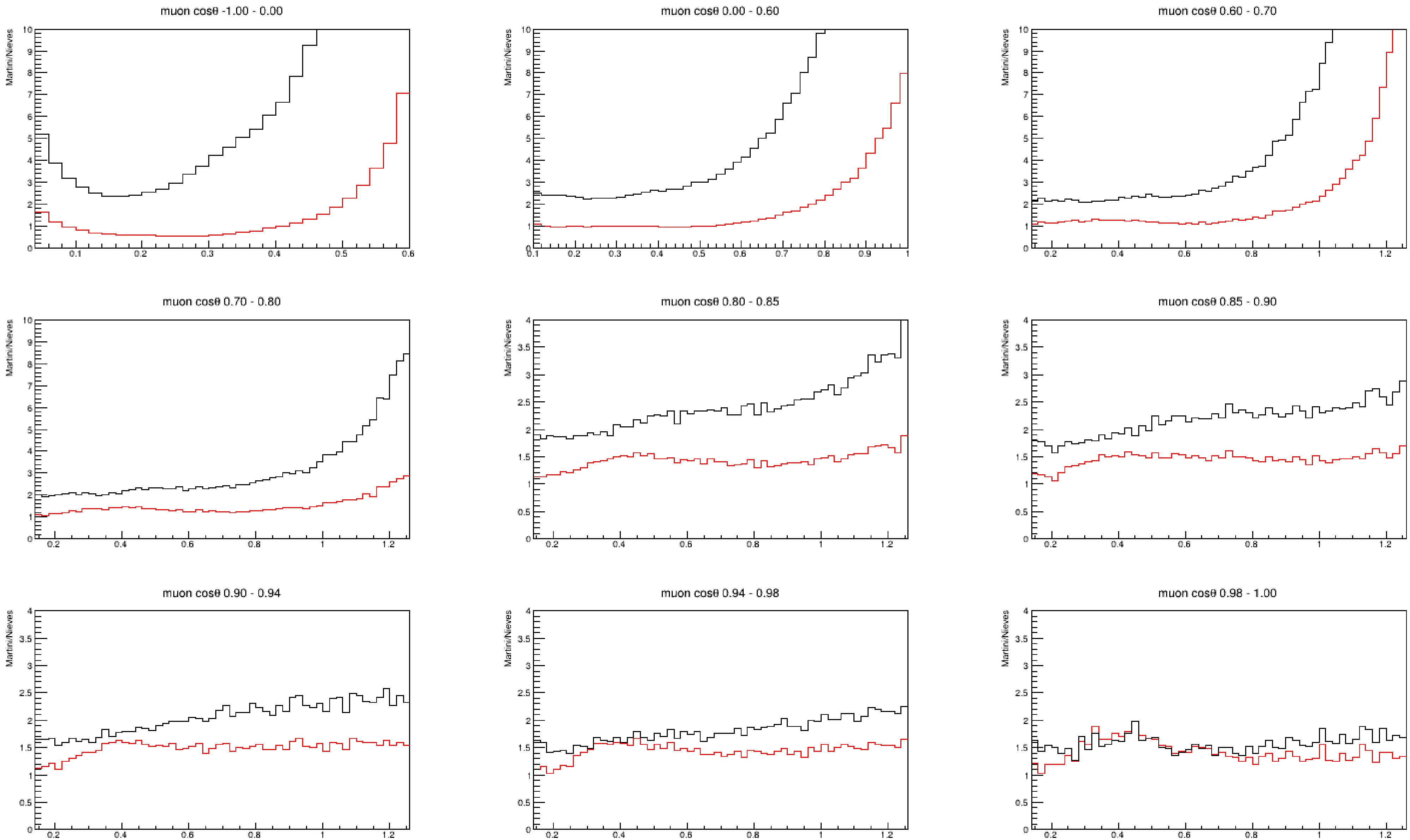


Actually, looking at pmu, cosqmu the difference in shape is similar between nu and nubar

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



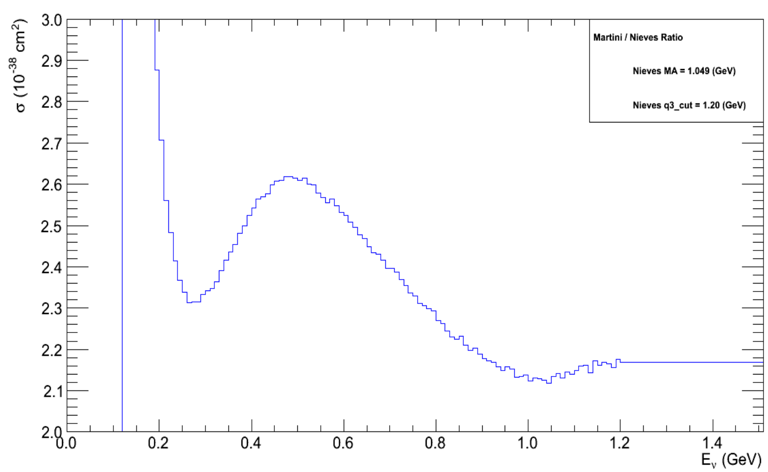
Martini/Nieves 2p2h only

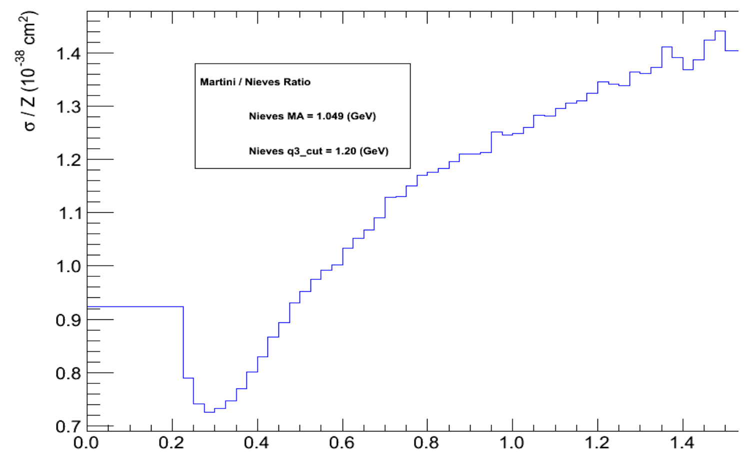


Is the shape difference between nu and nubar important?

Martini/Nieves ratio (2p2h only)

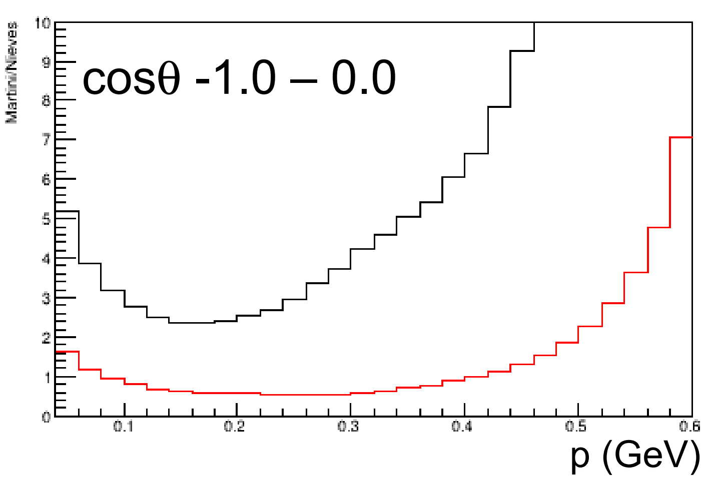
By comparing sEn between nu and nubar would look so...

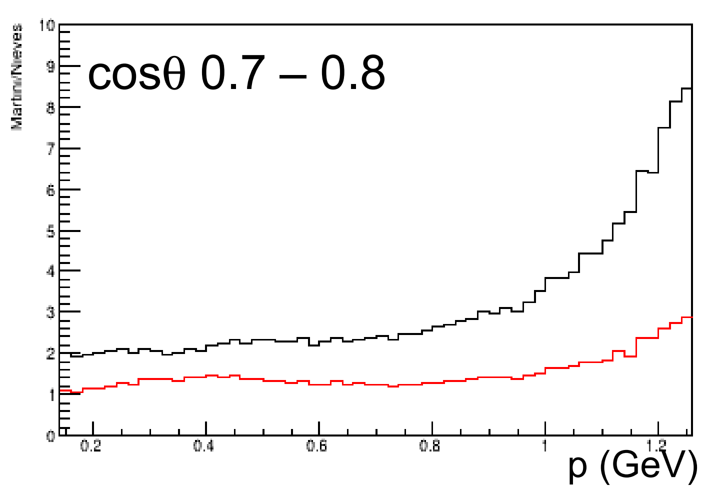


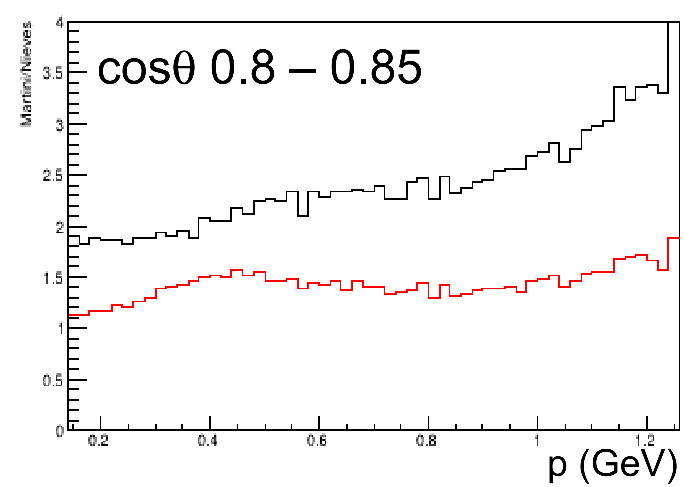


Actually, looking at pmu, cosqmu the difference in shape is similar between nu and nubar

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







Martini/Nieves 2p2h only

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