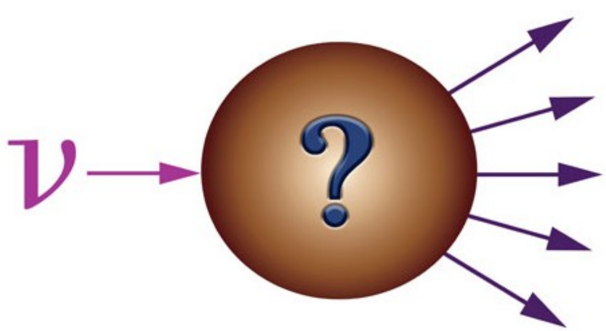
Neutrino scattering measurements: open issues and problems

S.Bolognesi (CEA Saclay)

INT Workshop INT-16-63W

Theoretical Developments in Neutrino-Nucleus Scattering

December 5 - 9, 2016



Outline

HISTORY OF MEASUREMENTS

First generation:

- CC0π with **muon only**

  MiniBooNE on CH

  MINERνA on CH

  T2K on CH and water (new!)

- CC1π with **muon + pion**

  MINERνA on CH

  T2K on CH and water

Second generation:

- CC0π with **muon + proton(s)**

  ArgoNeut on Ar

  T2K on CH: arriving soon...

- **muon + hadronic energy / vertex energy**

  MINERνA on CH

INTERESTING ISSUES

- **Model dependence** of the results: mostly from efficiency corrections

- Complications in the **interpretation of the results** (eg: how much 2p2h do we observe in our data?)

(other interesting analyses on ν_e, $\bar{\nu}_\mu$, iron,... no time to cover everything)

Model-dependence of the experimental results?

Efficiency corrections

In each bin the xsec is estimated from:

$$\sigma = \frac{N_{selected}^{data} \cdot \epsilon}{\Phi \cdot N_{nucleons}}$$

where the **efficiency is computed from Monte Carlo** $\epsilon = \frac{N_{selected}^{MC}}{N_{generated}^{MC}}$

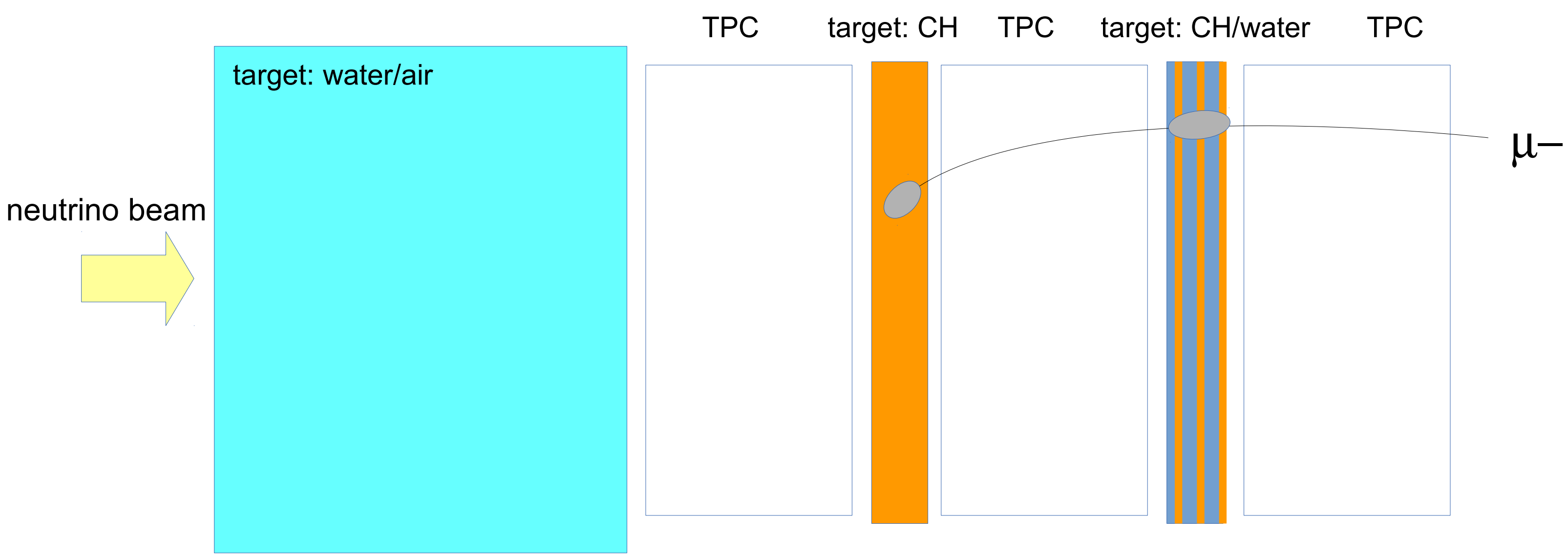
The signal definition matters! Eg: are we measuring CCQE or CCQE+2p2h or CC0π ?

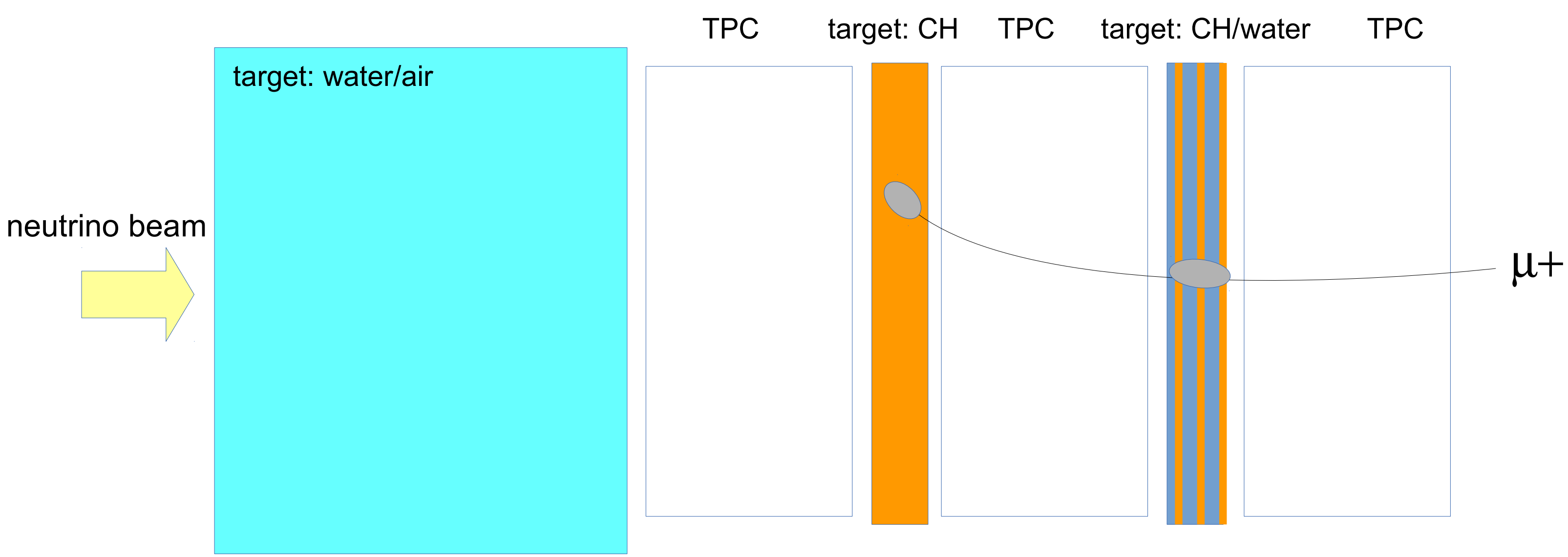
We cannot measure separately CCQE / 2p2h / CC1π with pion absorption (especially if we use only muon kinematics)

But also when we consider full CC0π signal, the efficiency of a given selection may be different for CCQE and 2p2h events → efficiency corrections depends on the assumed relative cross section of 2p2h and CCQE in each bin
(Eg: old analysis without 2p2h simulated in the MC may have biased efficiency corrections)

ND280 measurements

ND280 has been designed to measure forward-going muons (μ- and μ+)

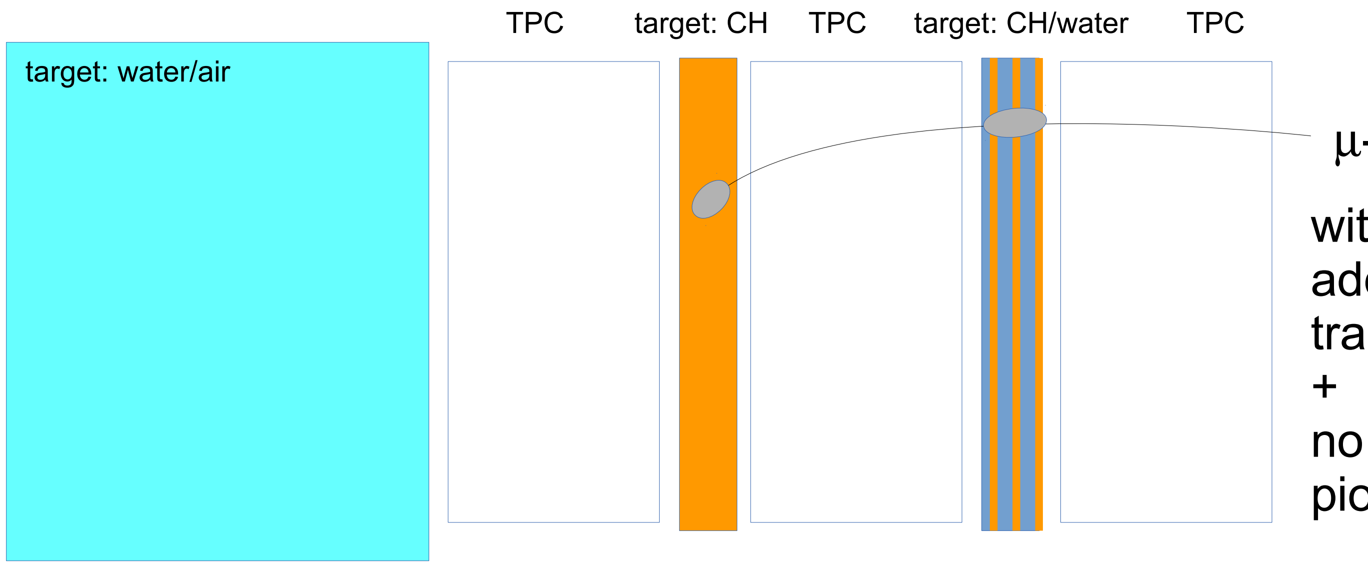




ND280 measurements (2)

ND280 has been designed to measure forward-going muons (m- and m+)

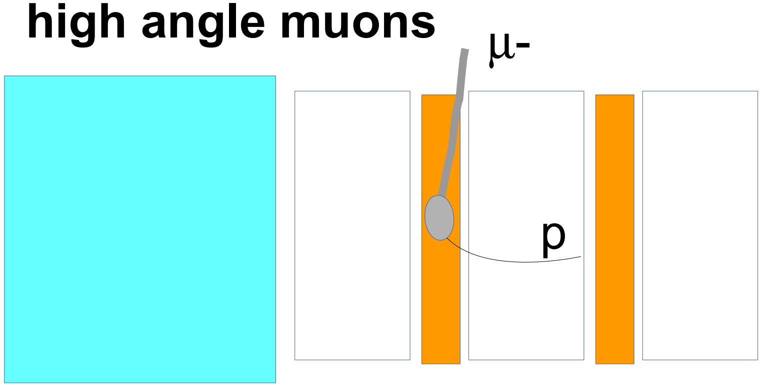
Our cross-section measurements are highly statistically dominated by such events



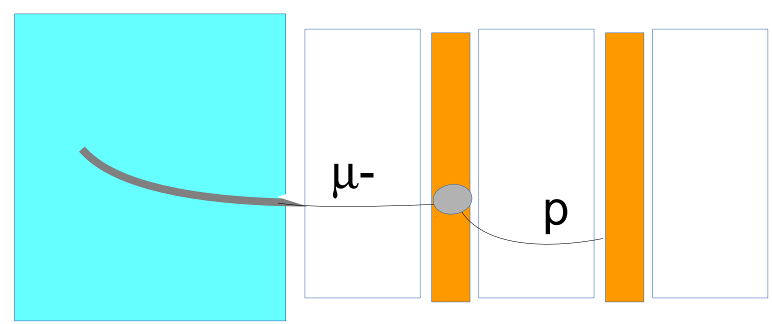
with or without an additional proton track
+
no reconstructed pions

… **but the selection has been modified to recover**

high angle muons

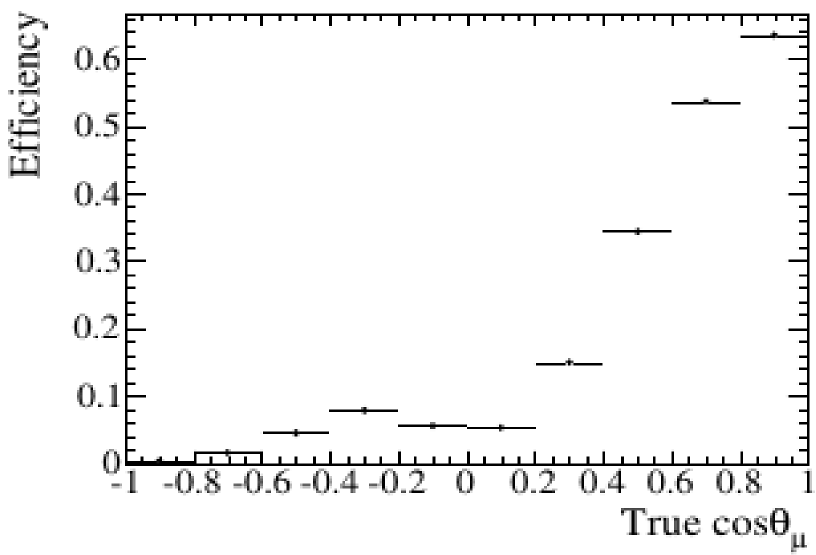


backward muons



in the first CC0π analysis we **requested one proton in the TPC** in order to reject the background in these topologies

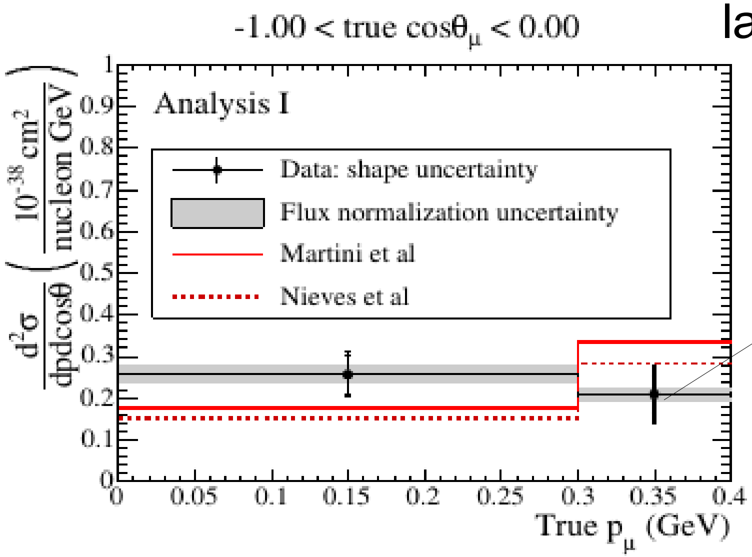
Efficiency uncertainties

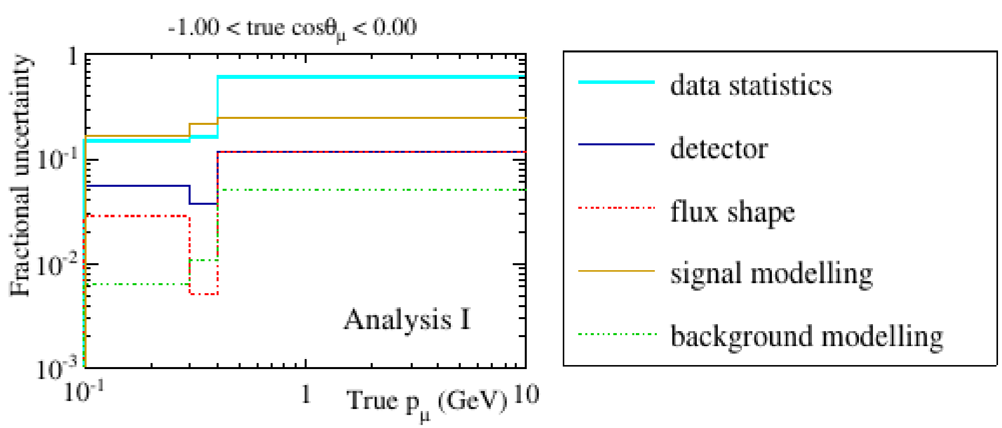


Efficiency for backward muons was pretty low
→ large MC based corrections

Similarly for Minerva: muon has to reach MINOS to get reconstructed

Two options:
- remove the background region from the measurement (fiducial region or limited phase space)
- double differential measurement: clearly separate bins with large MC corrections and include large systematics due to signal modelling





Efficiency bias

- **The efficiency as a function of basic measured variables (eg p_μ, $\cos\theta_\mu$) should be not too much model dependent. But the bias induced by this efficiency correction can be large if:**

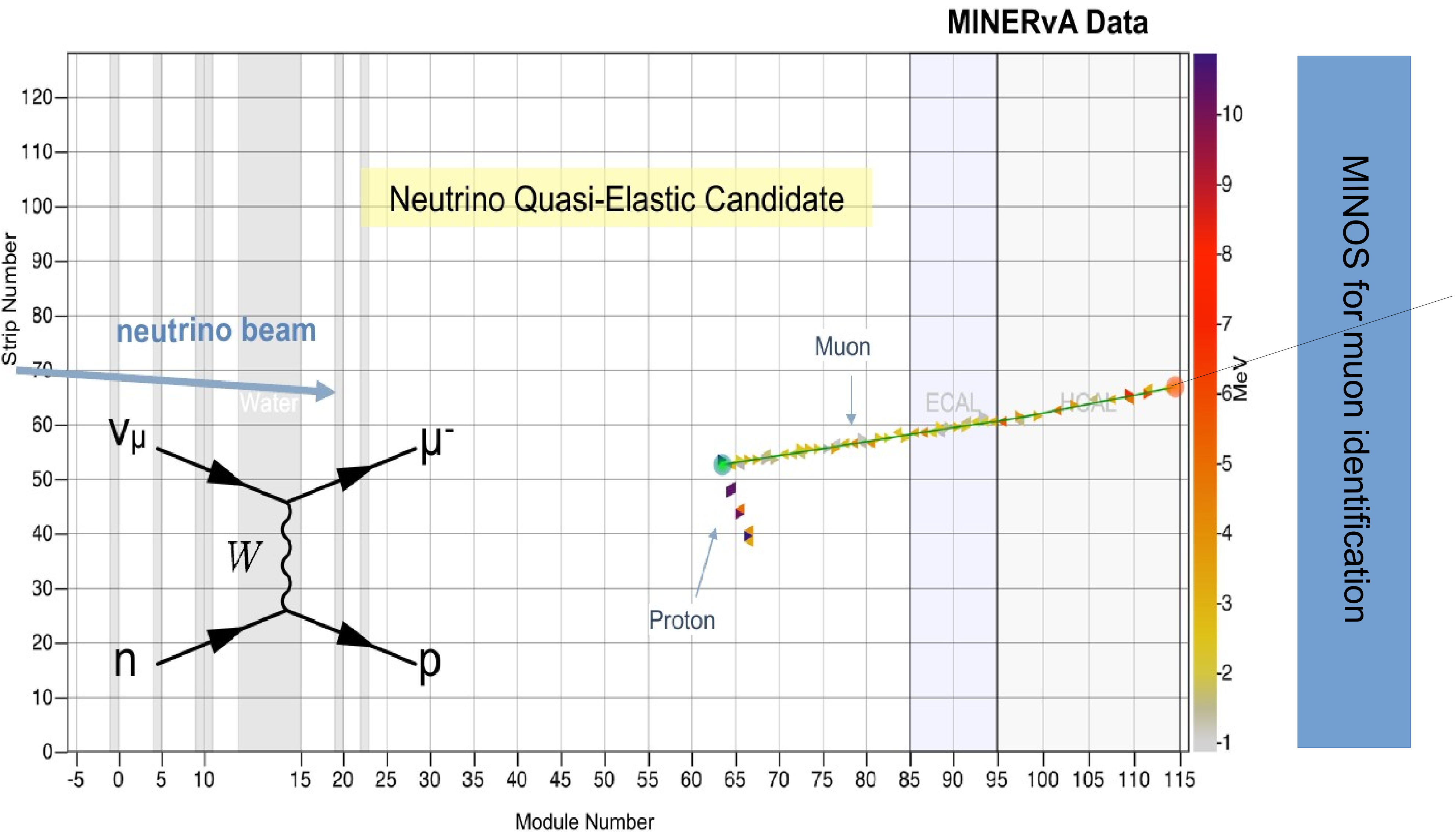
- measurement as a function of variables which we do not measure directly (eg. **Q^2, E_ν**)

  In Q^2 measurements, bwd and low momentum muons get distributed in various different Q^2 bins $\rightarrow$ the efficiency corrections in each Q^2 bin now depends on the assumed muon kinematic distribution in that Q^2 bin

- measurement as a function of one single particle when the multiplicity in the final state is larger

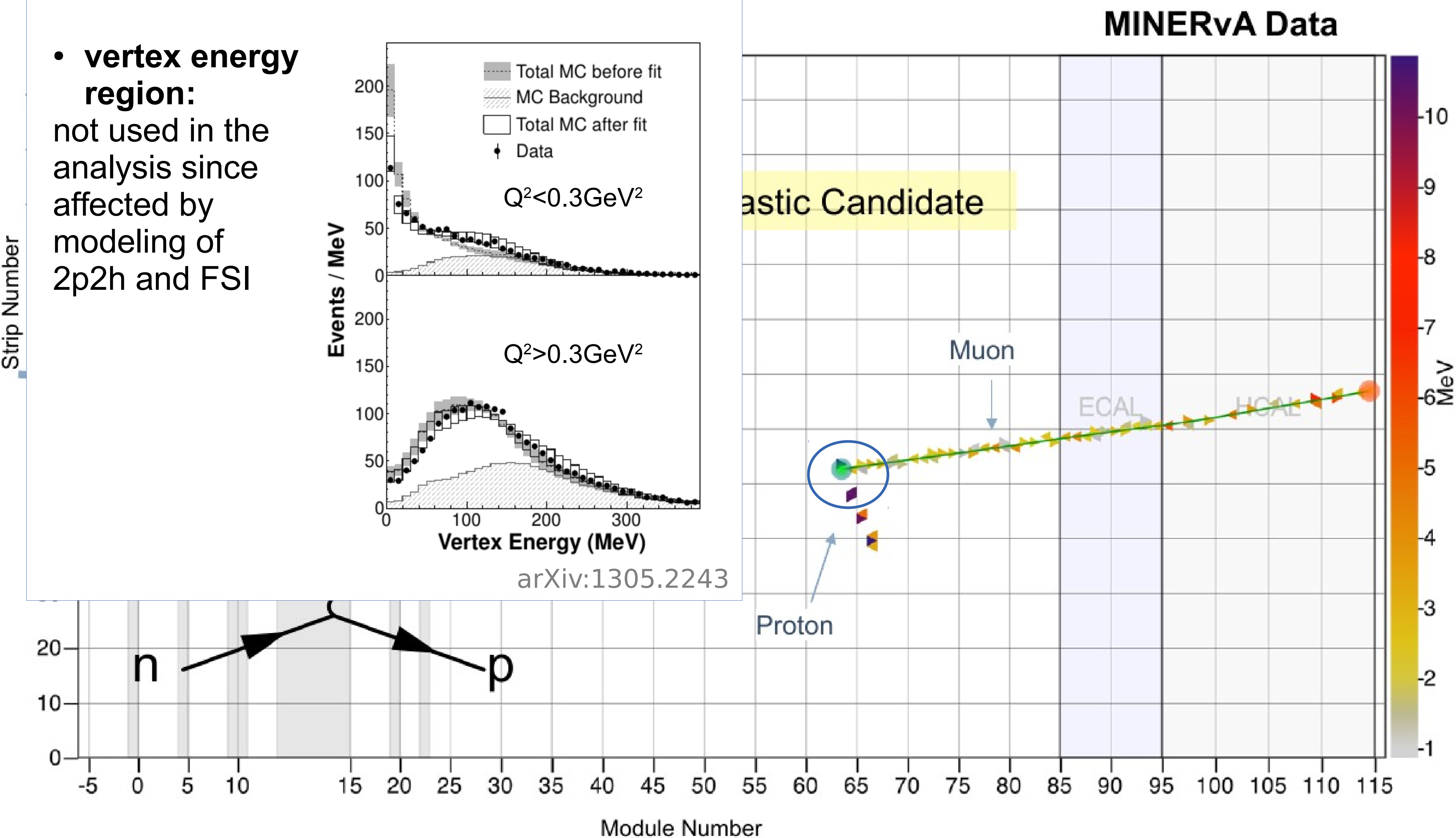
  Eg, muon + pion: in each pion bin the efficiency correction depend on the distribution of muon kinematics in that bin

Another example in Minerva



Another example in Minerva

- **vertex energy region:**
not used in the analysis since affected by modeling of 2p2h and FSI



arXiv:1305.2243

Another example in Minerva

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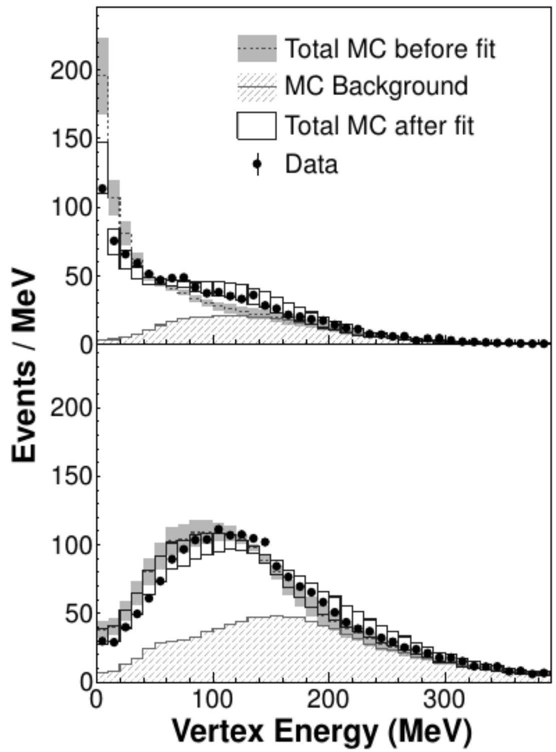
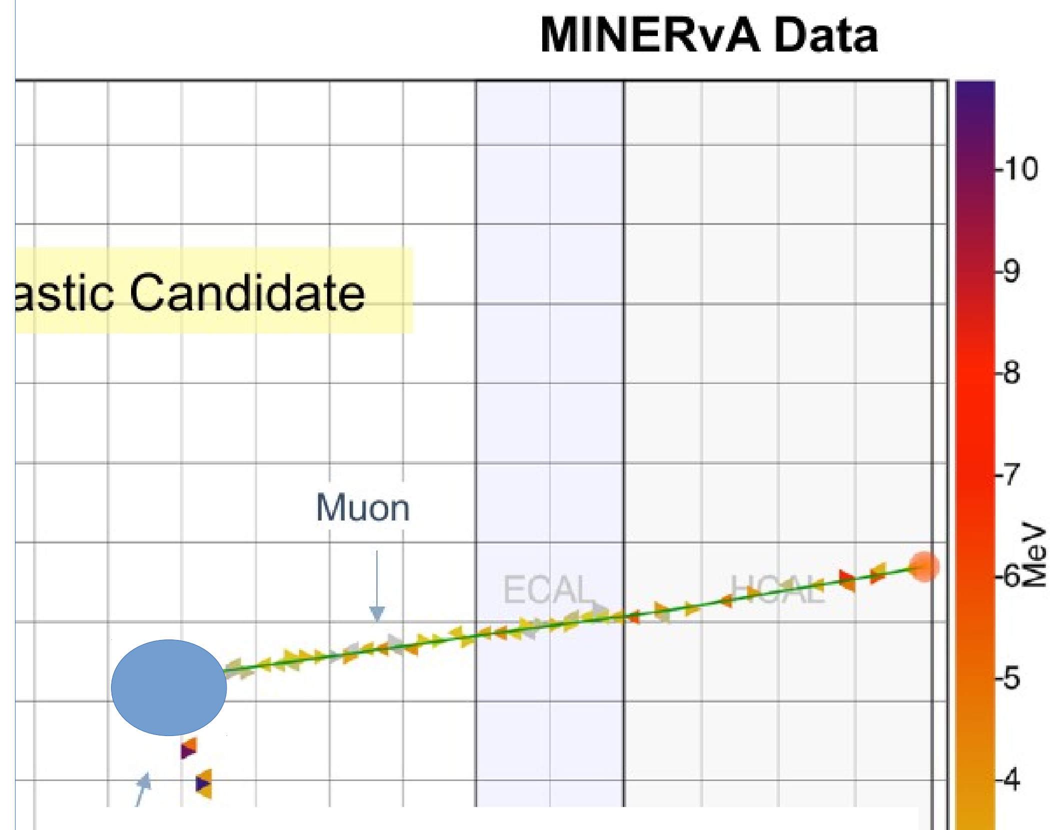
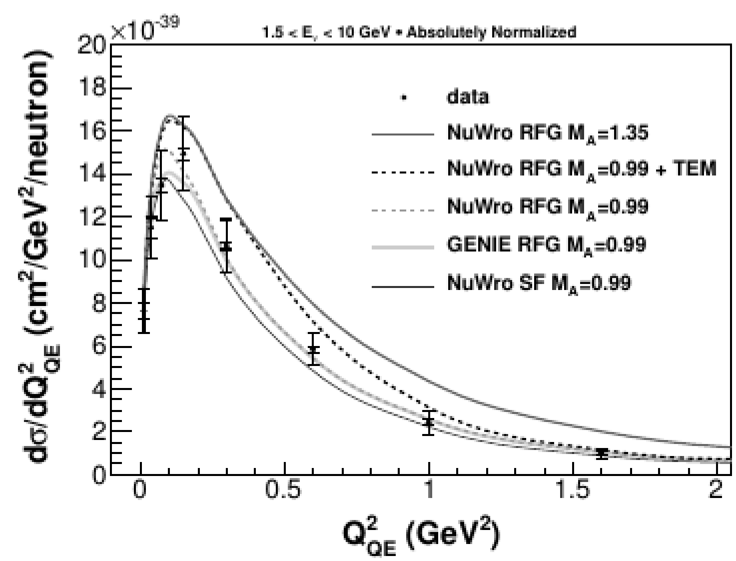


- **all the rest (recoil region)**

  cut: $E_{recoil} < f(Q^2)$ needed to remove pions

Efficiency correction for this cut depends on the assumed proton kinematics (→ possible bias as a function of Q^2)

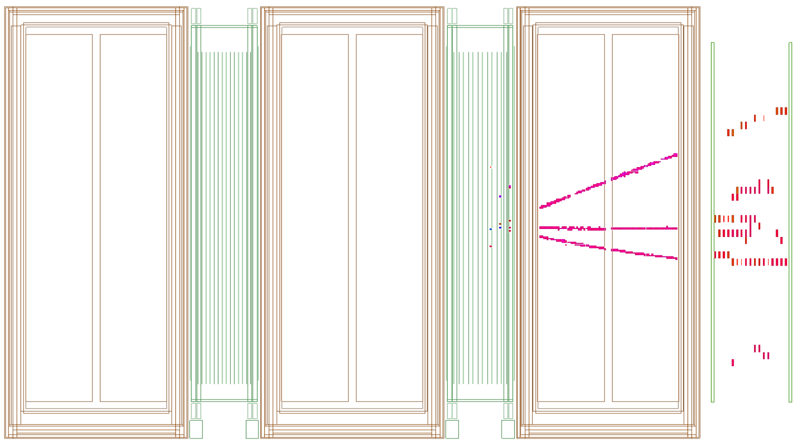




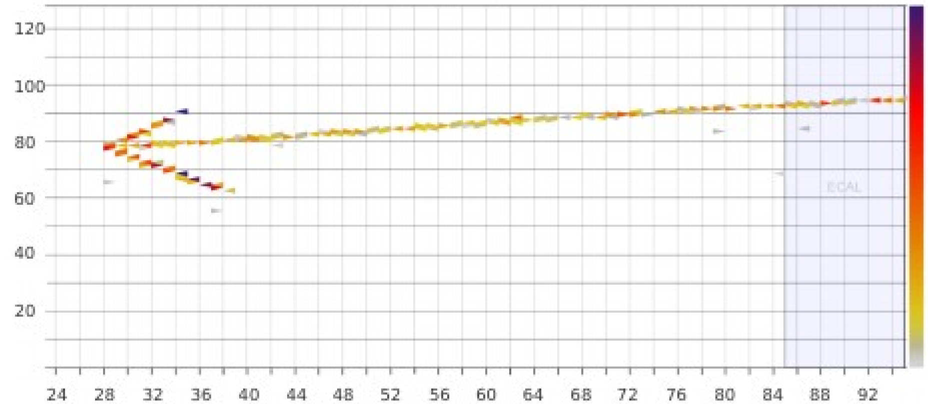
arXiv:1305.2243

Muon + pion

ND280 : μ, p, π candidate



Minerva : μ, p, π candidate



- Model independent efficiency corrections are very difficult (impracticable?) when the particle multiplicity increase

  eg: if muon and pion have very small angle between them is difficult to reconstruct the two tracks separately
  eg: the relative amount of backward muons in each pion kinematic bin may change the efficiency

→ the only (mostly) model-independent efficiency correction should be 4-dimensional (p_μ, $\cos\theta_\mu$, p_π, $\cos\theta_\pi$)

- **Actually the efficiency of pion reconstruction is also very dependent on secondary interactions and final state multiplicity:**

  eg, pion track efficiency in Minerva 42%
  + request for a Michel electron to enrich sample in pi+
  → give final efficiency of 3%: very large efficiency corrections from MC

(ND280 efficiency ~20-26%: TPC charge measurement → no need for Michel electron)

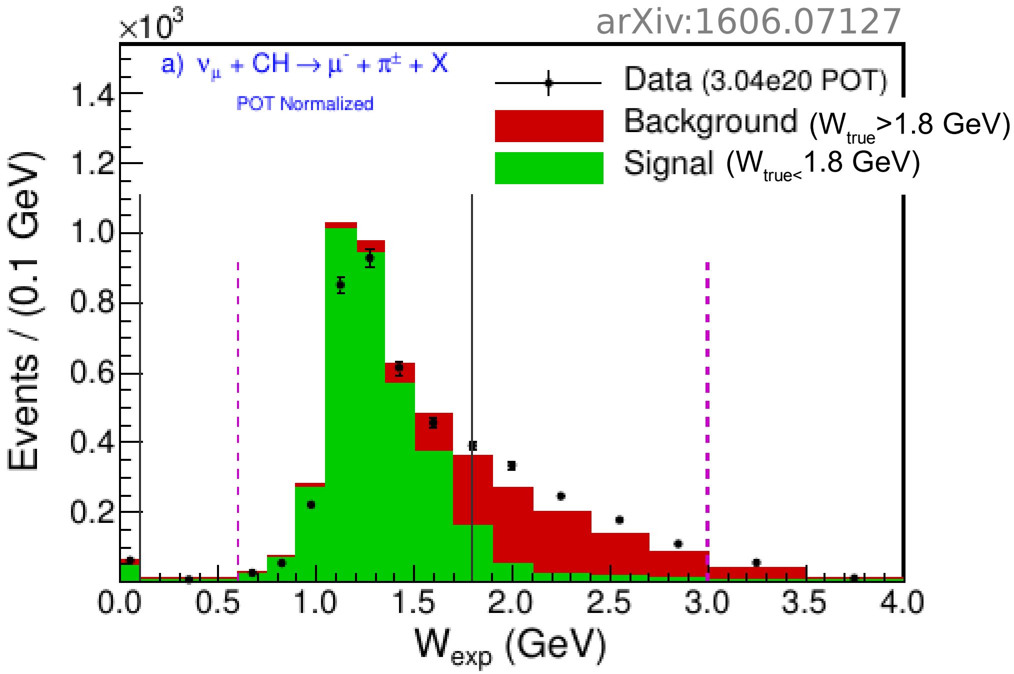
Signal definition

- **Similar to CCQE vs 2p2h, also for CC1π separating different channels (eg Δ vs the rest) is quite a model-dependent analysis**

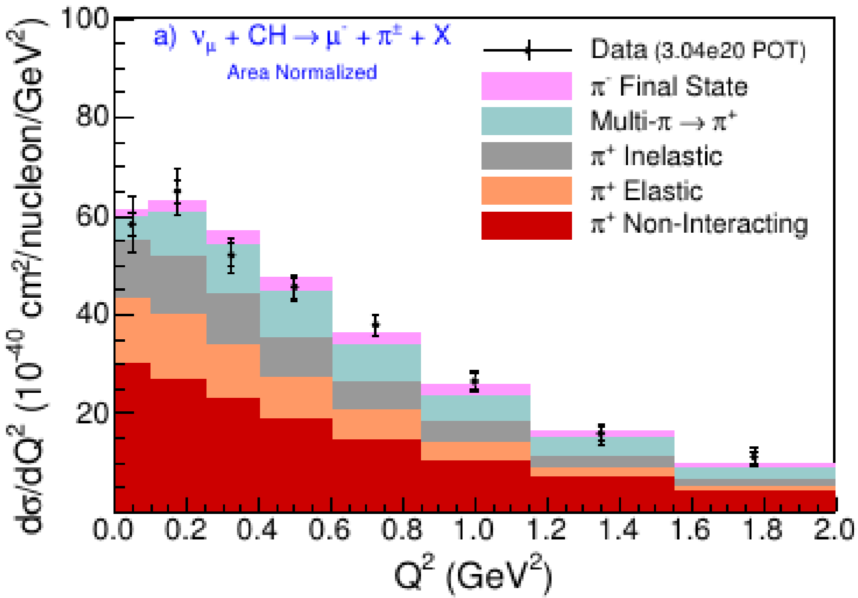
Most recent Minerva analysis: signal defined as pion events with W_{true}<1.8 GeV

- background corrections is tuned from sidebands but is not completely model independent
- events with more than one pion included (~5%)
- request for Michel electron at the end of the pion track → sample enriched in π+ (~1% π-)

All these effects have to be considered when interpreting this measurements...



- **Even more importantly: pion kinematics strongly affected by pion FSI**

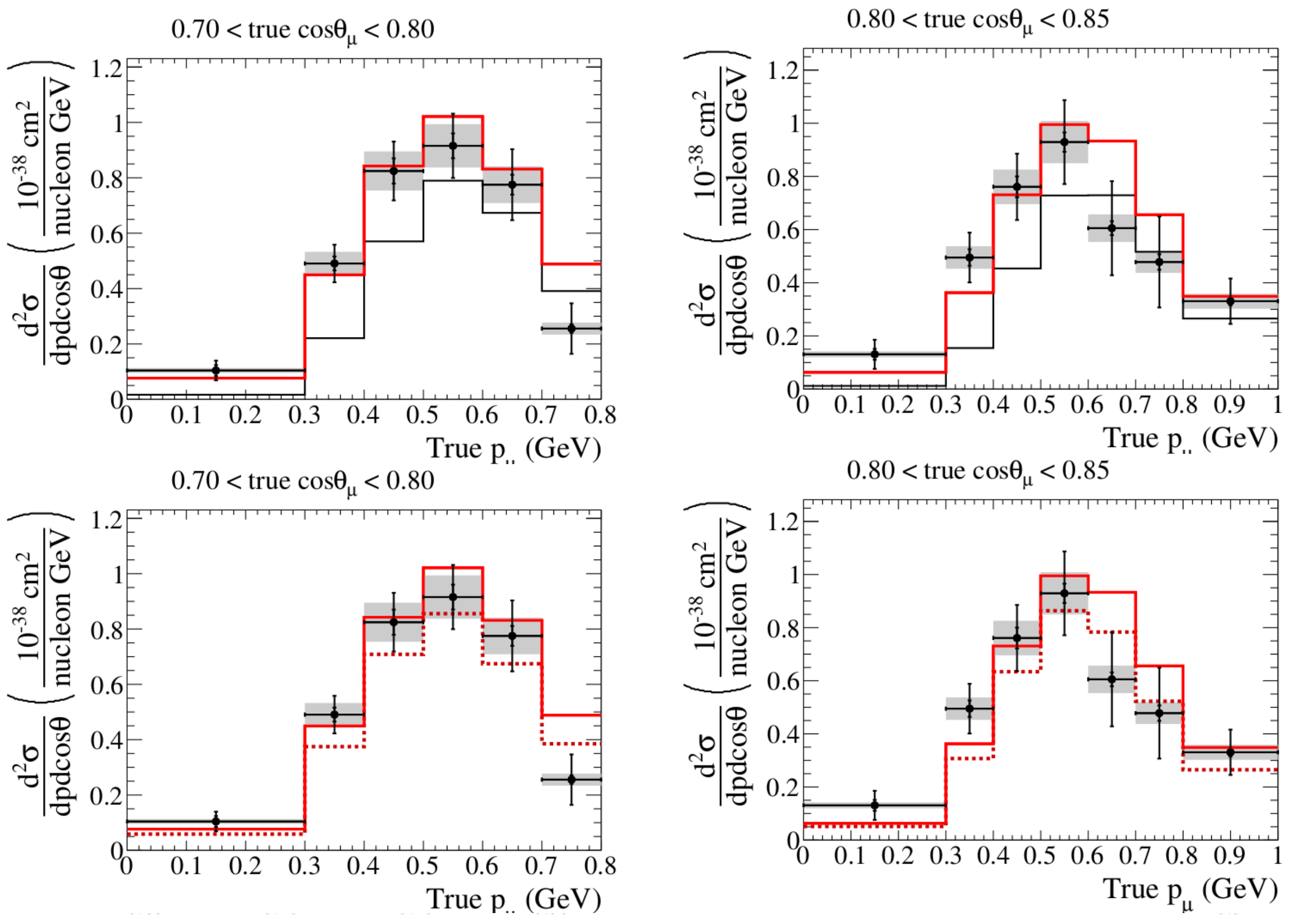


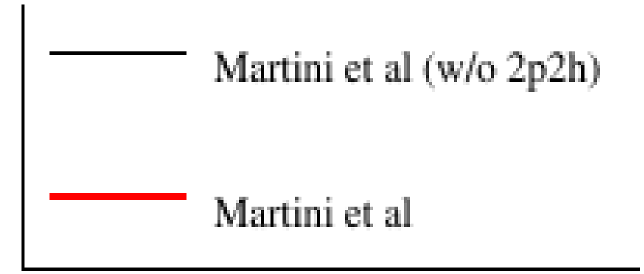
How to interpret the experimental results?

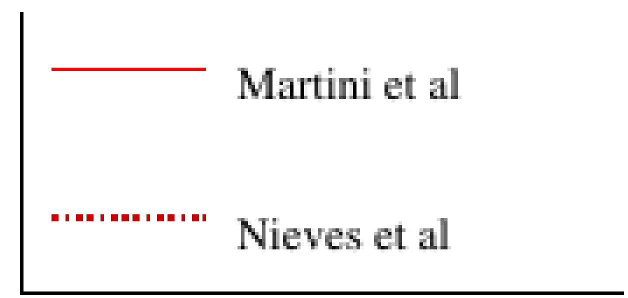
How much 2p2h in our data?

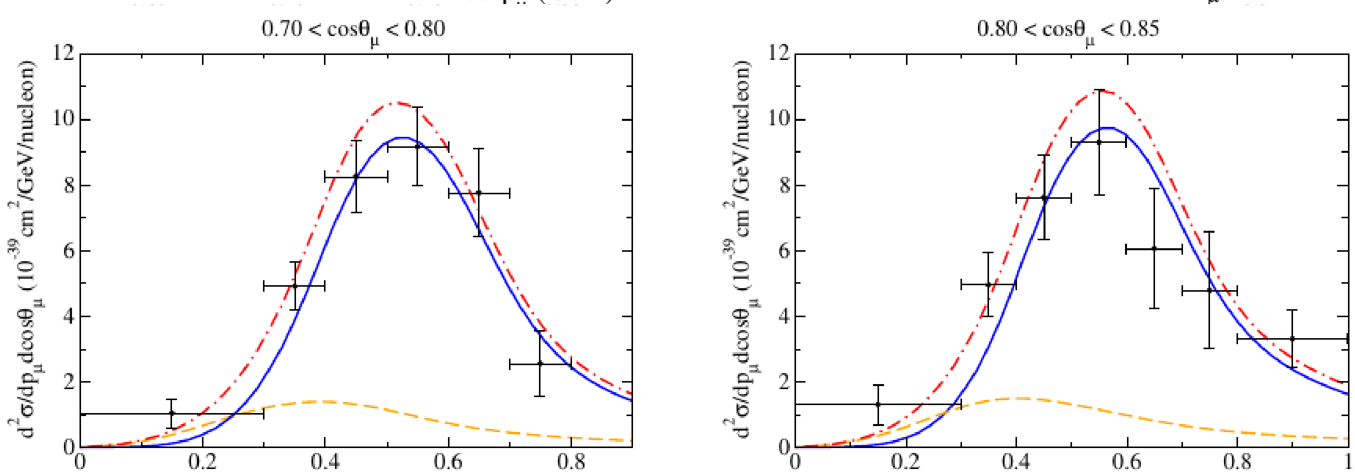
T2K measurement on CH

arXiv:1602.03652









SuSa v2 + MEC

arXiv:1607.08565

'Frankenstein models'

This models do not include the full signal of our experimental measurements (missing CC1pi+abs)

- **Precise knowledge of CC1pi + FSI is a major issue to quantify the amount of 2p2h in our data**
- **But also large uncertainties in what we define 'pure' CCQE:**

  uncertainties on RPA, nucleon form factors, LFG vs SF ...

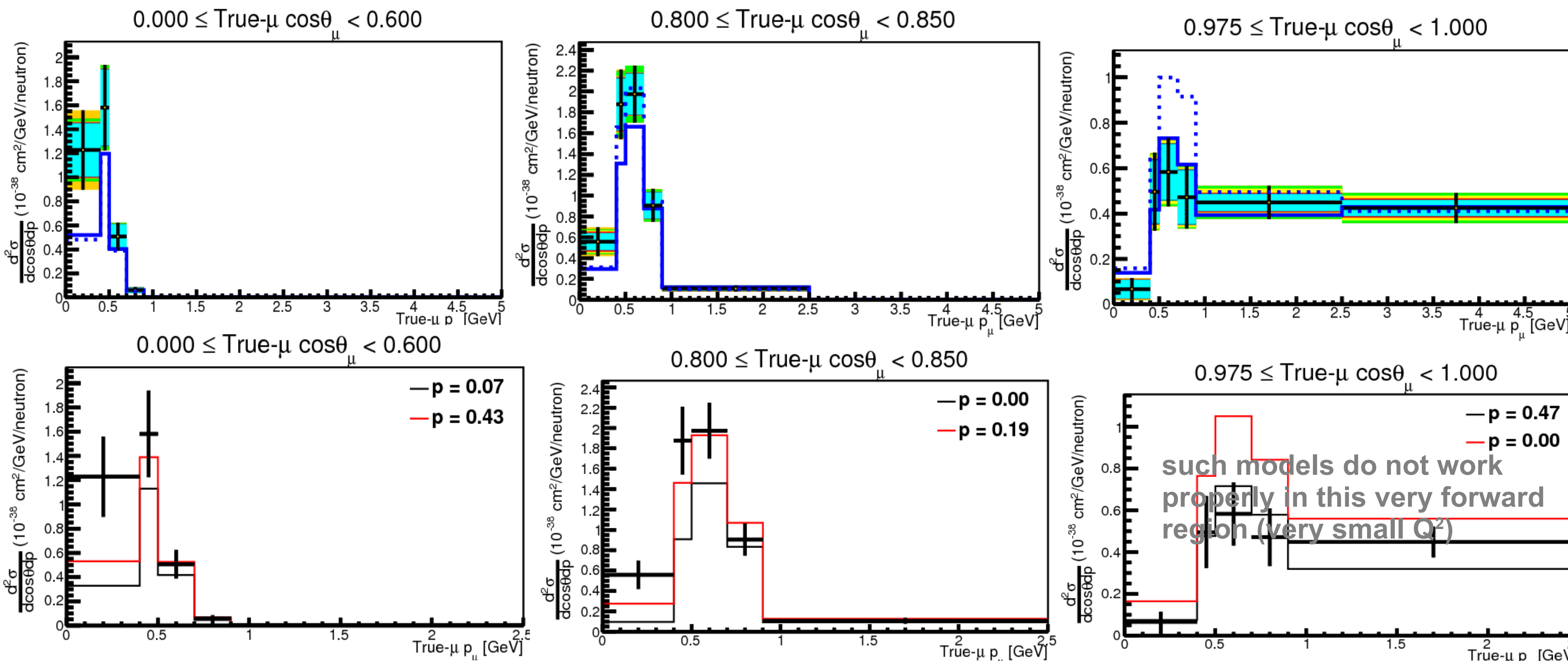
To extractive quantitative statements on CCQE vs 2p2h we need a **parametrization of all these initial and final state nuclear effects** and to quantify them separately → 'Frankenstein' models

Alternative is to avoid to quantify different processes separately and just compare to existing models...

Data-models comparison

NEUT Monte Carlo
GENIE Monte Carlo
CCQE (Martini et al.)
CCQE + 2p2h (Martini et al)

New T2K measurement on water! arXiv:1611.03536



Data-models agreement depends on the phase space region:

→ MC may be outdated/approximated but they are the only one which contain all the processes in our data (CCQE+2p2h+CC1pi+abs)

→ no MC or 'pure' model is today complete and capable to describe all the data precisely

Will the **muon-only data** be enough precise (high statistics) and the theoretical model complete enough to be able to
identify a preferred model,
and/or perform a quantitative and robust estimation of CCQE, 2p2h, CC1pi … ?

One possible way out: increase information on the final state to minimize the degeneracy between different models and between different processes.

Eg: outgoing proton kinematics or 'inclusive' hadronic energy

Summary (first part)

- When comparing your new model to previous data, you should always ask yourself: are the efficiency of the experimental selection similar in my model and in the MC used in the analysis? If not, where the largest difference/bias may be?

  TOOL: **efficiency tables** should be produced by experimentalists and used by theoreticians to mimic the experimental cuts

- When designing your analysis:
  - **multi-differential xsec measurements (p, θ of outgoing particles)** and always test your strategy (eg, eff corrections) on different models

    TOOL: **fake data studies** = perform your analysis on alternative Monte Carlo samples (and report the results of such tests publically)

  - **do not extrapolate to unmeasured regions**: quote also **cross-section limited in the region of high efficiency**

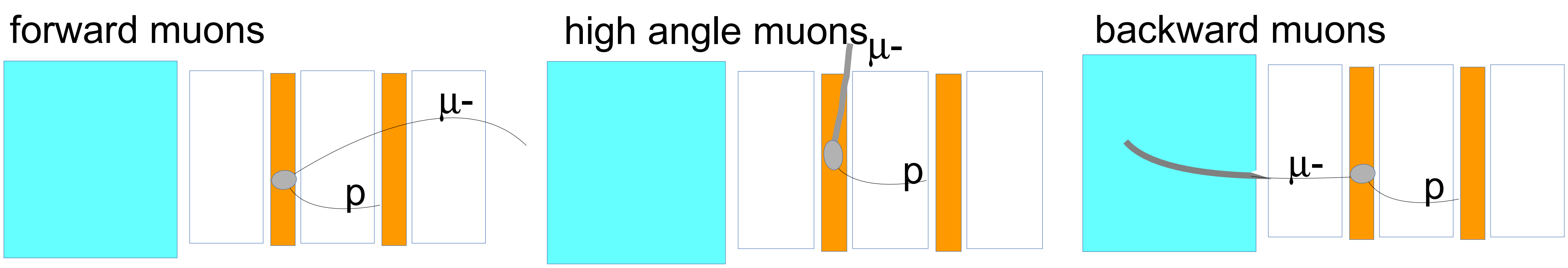
Experimentalists should not ignore the model assumptions in their analyses!
→ *Pittsburgh workshop*

Theoreticians should not ignore how the analysis are performed to make meaningful data-model comparisons! → *2p2h workshop in Saclay, this workshop!*

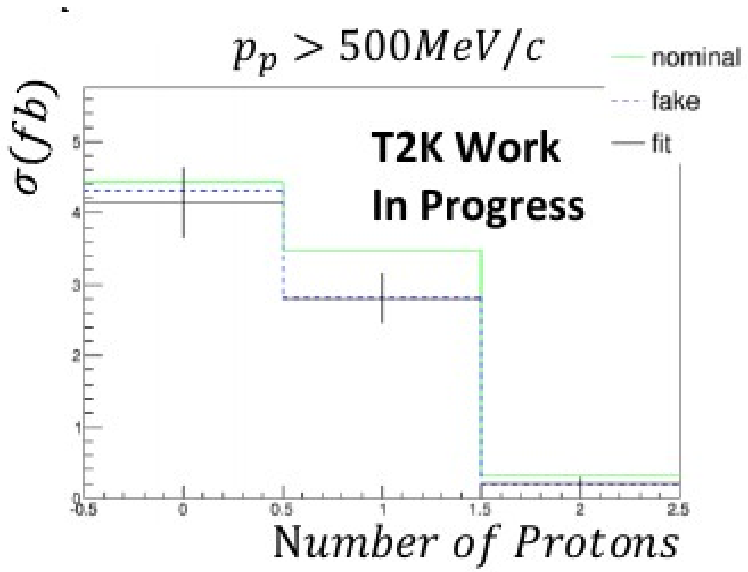
Strict exp.-theor. collaboration is necessary to go forward
(eg: *NuTune workshop last summer* https://indico.fnal.gov/conferenceDisplay.py?confId=11610)

Protons in ND280

Muon + one or more protons:



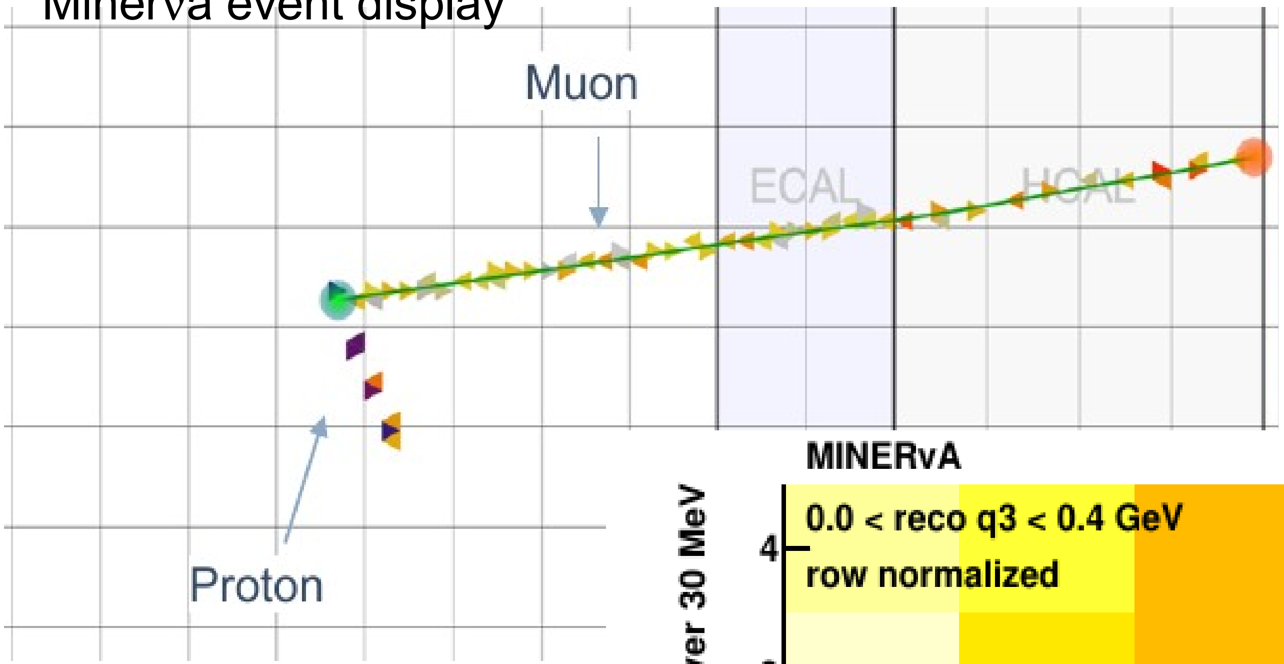
Main limitation: proton threshold for good tracking/ID in TPCs ~500 MeV

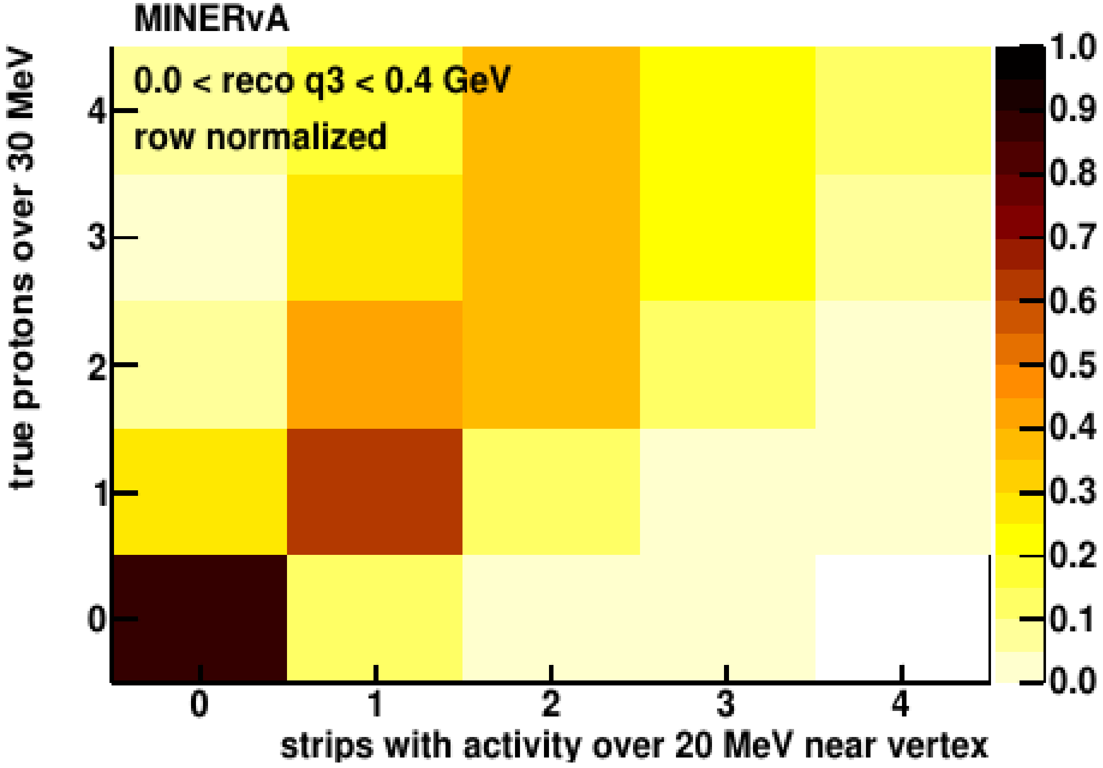


- Fake data: GENIE*
- Nominal MC: NEUT

Protons in Minerva

Minerva event display

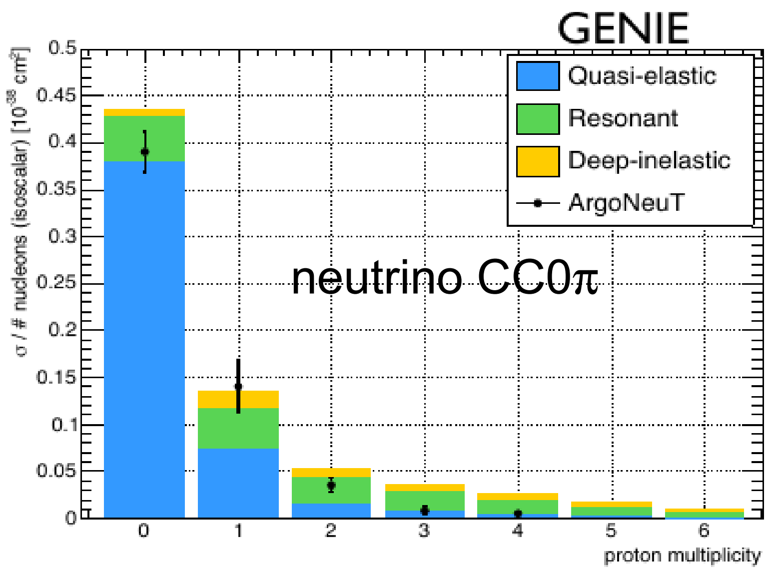


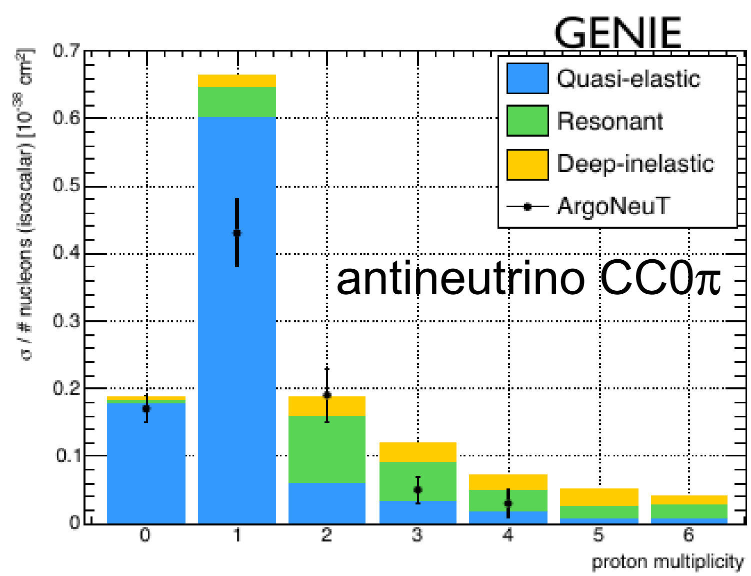


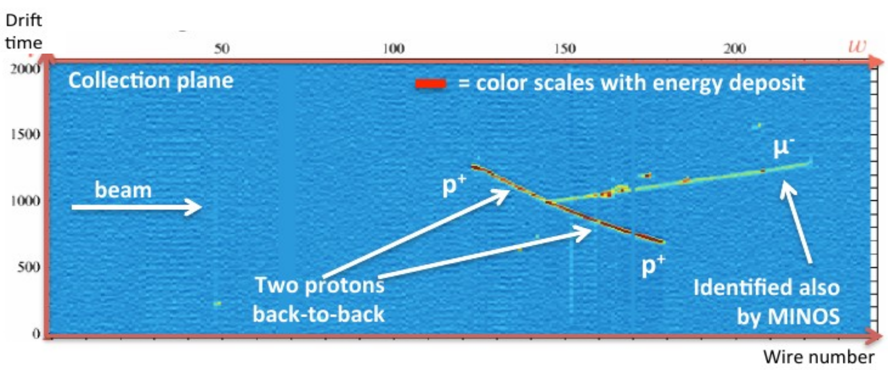
Main limitation:
capability of distinguishing protons between them and with other hadronic deposits

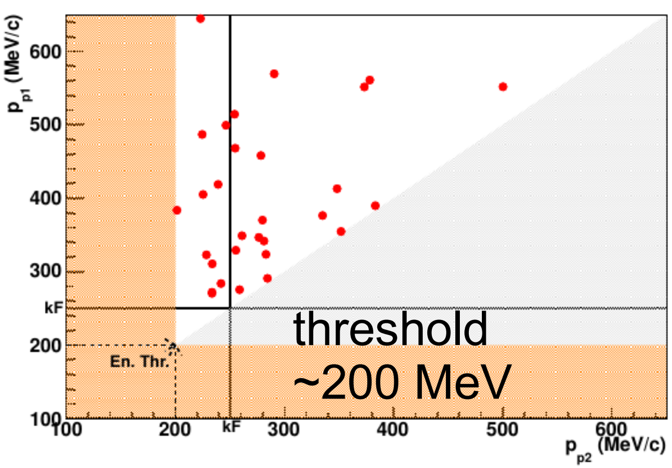
Protons in LAr

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









- **Gas Ar** would give even smaller threshold but limited by statistics → **High Pressure TPC**

Are we able to interpret the results?

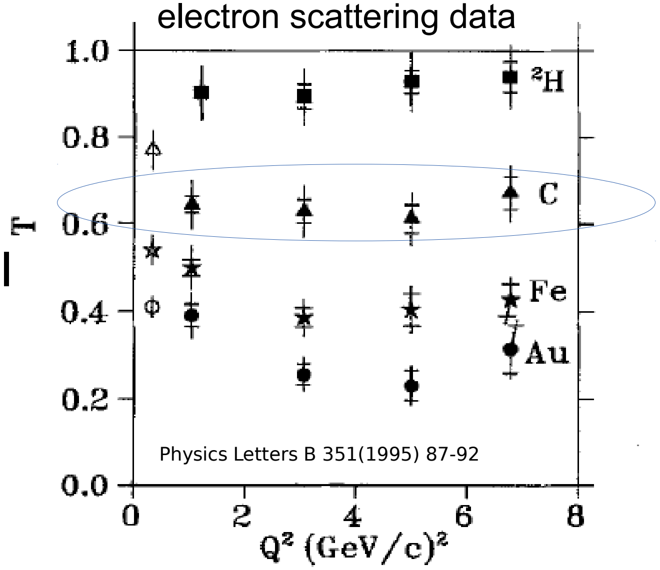
What do we learn from the kinematics of such low energy protons?

- Limited predictivity of the most advanced models (eg proton kinematics in 2p2h ?)
- Main problem: **measured protons depend on the convolution of nuclear effects in the interactions and Final State Interaction**

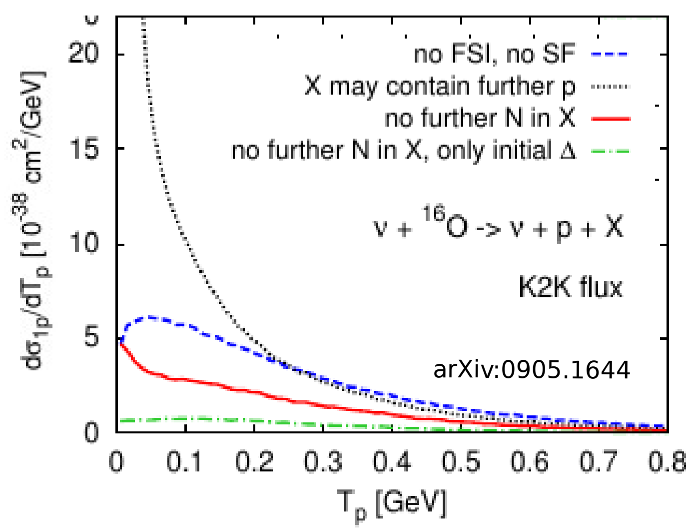
Need to measure proton scattering and improve proton FSI modeling!

>60% of protons undergo FSI

Nuclear transparency in electron scattering data



Cross-section for proton knock-out in GiBUU

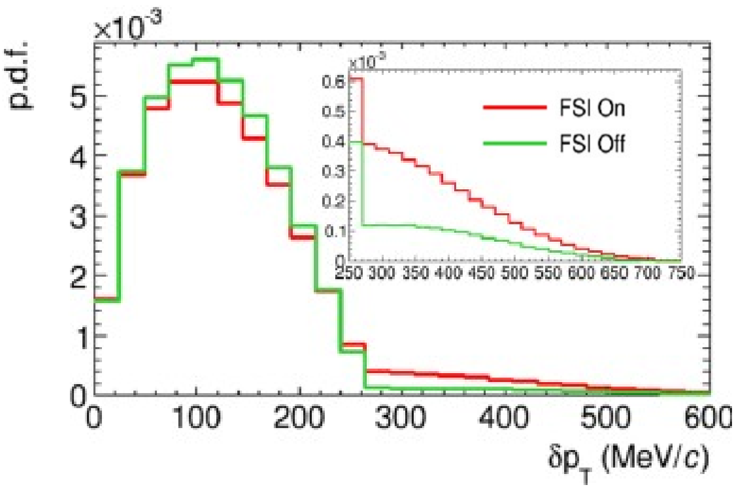


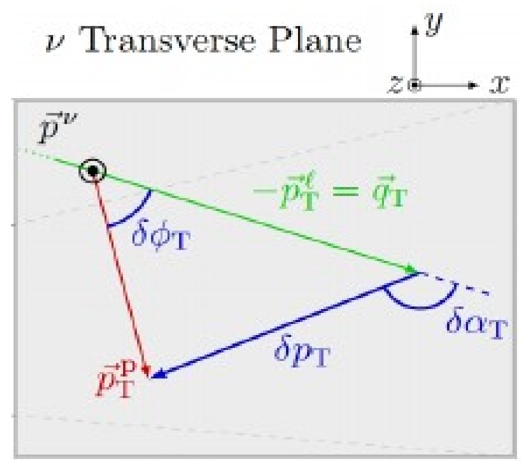
FSI effects change the outgoing proton kinematics

Same issues in pion measurements. I don't have enough time to discuss that but look at this very nice Clarence's talk:
https://indico.fnal.gov/getFile.py/access?contribId=12&sessionId=18&resId=0&materialId=slides&confId=11610

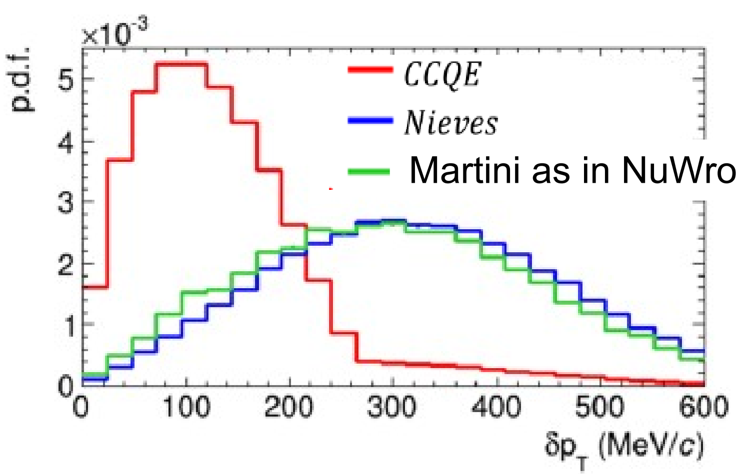
One possible way out: clever variables ?

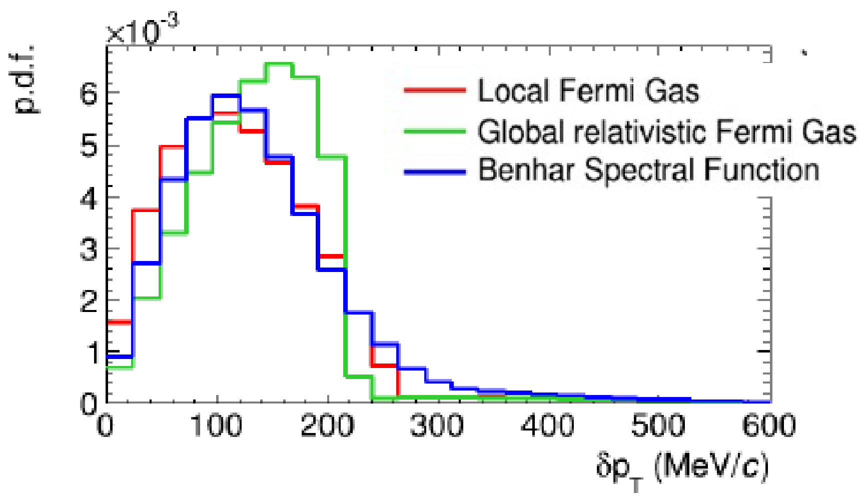
New variables to highlight the various nuclear effects: eg, single transverse variables





arXiv:1512.05748
arXiv:1610.05077





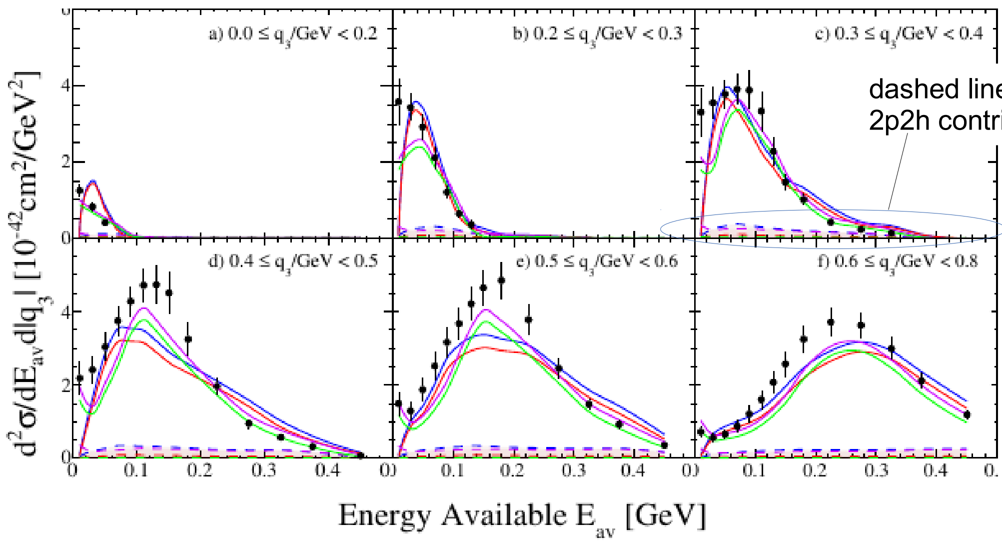
Interesting and complementary way to look at our data but still quite big degeneracies between the various nuclear effects...

Minerva 'calorimetric' measurement

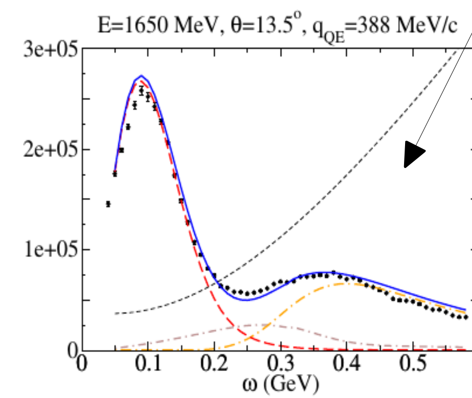
Look at hadronic final state in a more 'inclusive' way: summing all hadronic deposits

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

arXiv:1611.03275

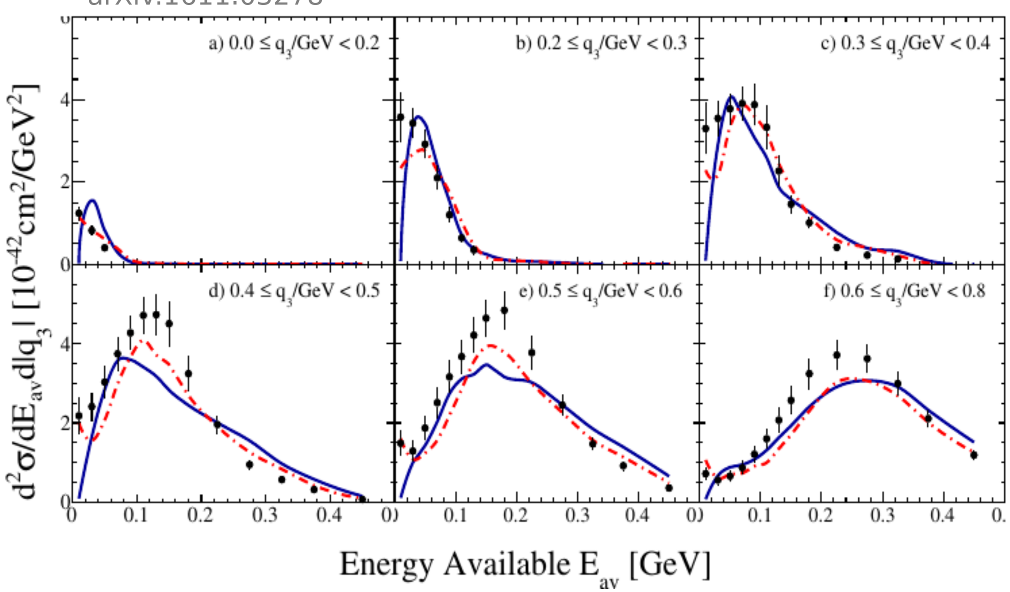


Original aim was to 'isolate' 2p2h in the q0,q3 phase space (~ 'dip' region as in electron scattering)



arXiv:1603.08396 (SuSaV2)

arXiv:1611.03278



Generator	NEUT ——	NuWro ·-·-
Nuclear Model	Relativistic Fermi Gas (RFG) [8]	Local Fermi Gas (LFG)
2p2h Leptonic Model	Nieves [4]	Nieves [4]
Resonant Model	Rein-Seghal (Full) [10]	Rein-Seghal (Delta-only) [10]
FSI Model	Oset [9]	Oset [9]

Again, many nuclear effects convoluted (LFG vs GFG) including CC1π model (eg, nuclear effects on Δ width ?)

Summary (2)

- A new generation of measurements is coming out: **proton kinematics and single (double) transverse variables, calorimetric measurements...**

- The name of the game is always the same: **are we capable of distinguishing/quantify the different nuclear effects separately?**

- Are our models advanced enough to face such new generation of measurements?

BACKUP

Pion reconstruction in MINERνA