Recent neutrino cross-section measurements at T2K

S.Bolognesi
(IRFU, CEA Saclay)

JENNIFER Plenary meeting – September 2016 - London

A hot topic...

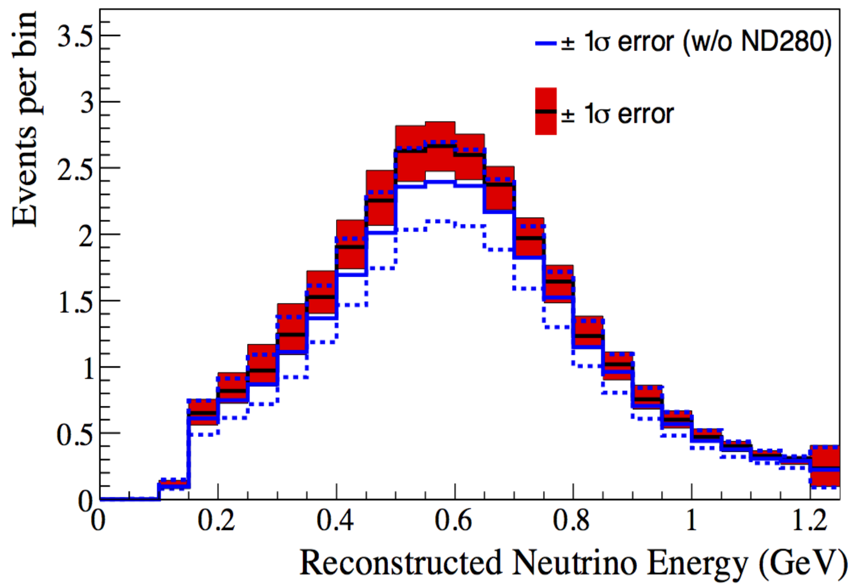
- **Oscillation measurements in Far Detector constrained from Near Detector (xsec x flux)**

  ND→FD extrapolation :
  - different acceptance and target
  - different E_ν spectrum
  - $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu$

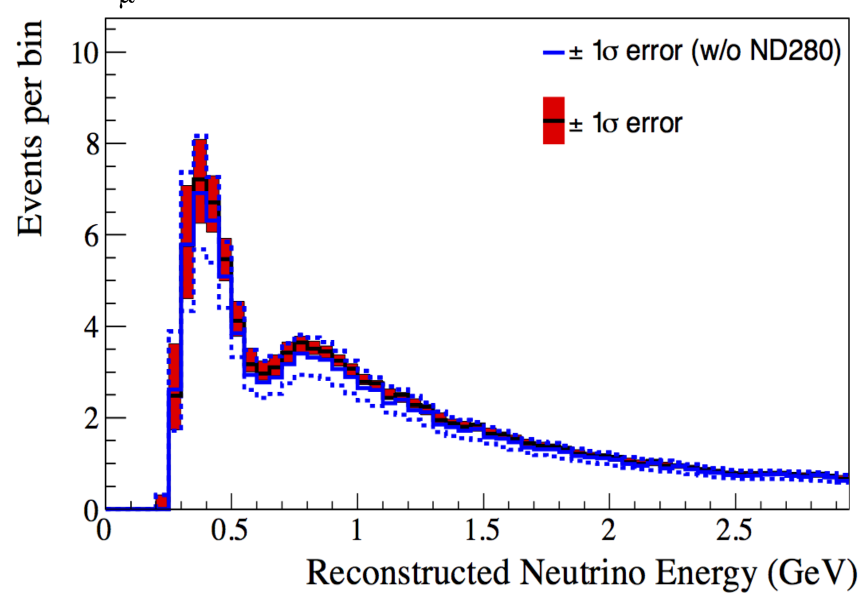
  → **rely on models to extrapolate**

- Measurement of ν xsec at ND is **experimentally complicated:**
  - E_ν not known: xsec measurement always convoluted with flux → importance of minimization of uncertainties in flux modeling (and/or ratio measurements)
  - E_ν inferred from final state leptons/hadrons which have limited angular acceptance, threshold on low energy particles, very small info on recoiling nucleus...

ν_e at SuperKamiokande



ν_μ at SuperKamiokande



What do we need to measure?

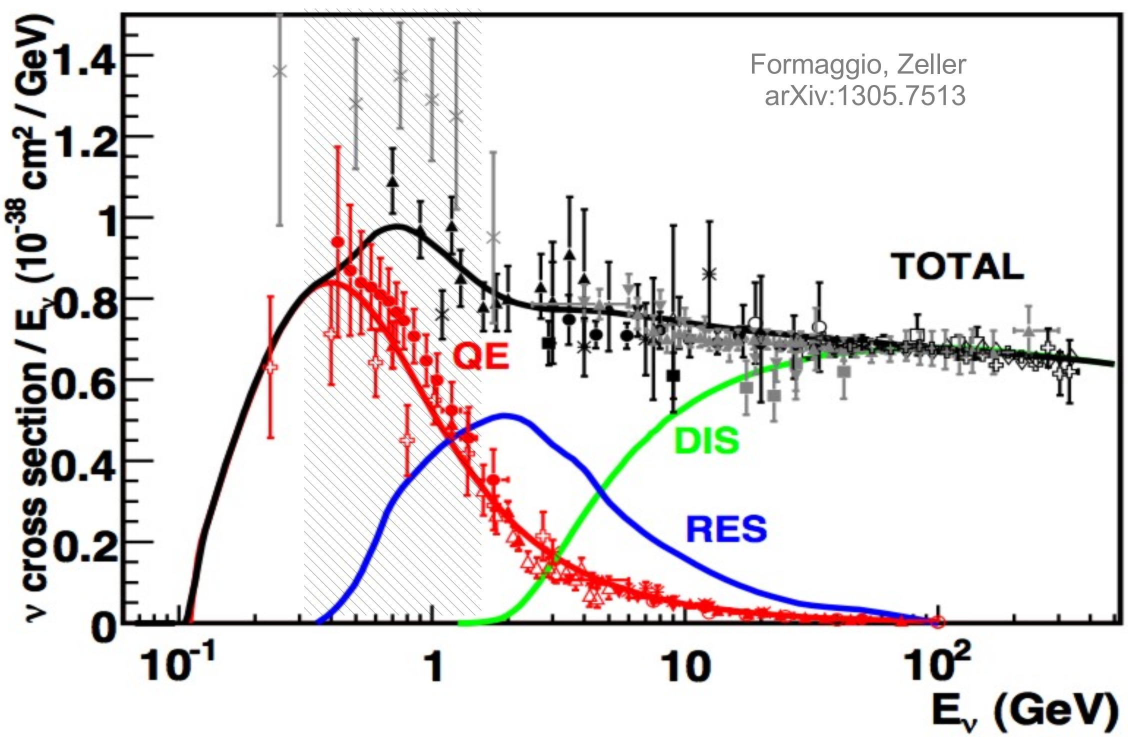
Uncertainties in ND→FD extrapolation :

- different E_ν distribution (because of oscillation) ⇒ need to reconstruct the neutrino energy from the final state particles
- different target ⇒ A-scaling: measure cross-sections on different targets (and/or on the same target of FD)
- different acceptance ⇒ measurement of cross-section in the larger possible phase-space: increase angular acceptance of ND
- different neutrino flavor (because of oscillation) ν ($\bar{\nu}$) flux has typically a wrong sign component ⇒ measure cross-section asymmetries between different neutrino species (eg ν vs $\bar{\nu}$ important for for δ_{CP})

Outline

- **Neutrino xsec as a <u>nuclear physics</u> problem**

T2K flux



- **CC0π dominant at T2K**

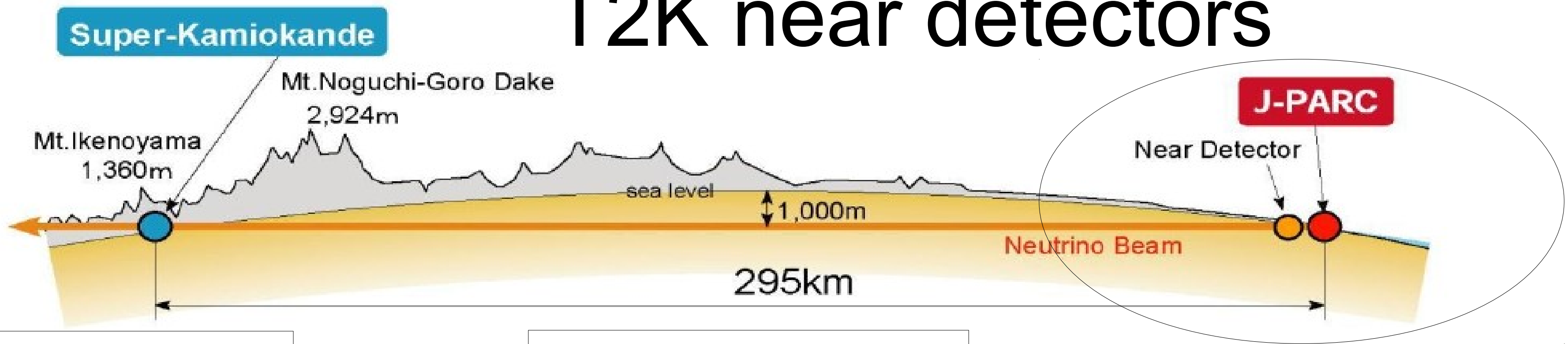
  → from the detector measurement (muon+proton) to the incoming neutrino energy

- **CC1π (+ DIS)**

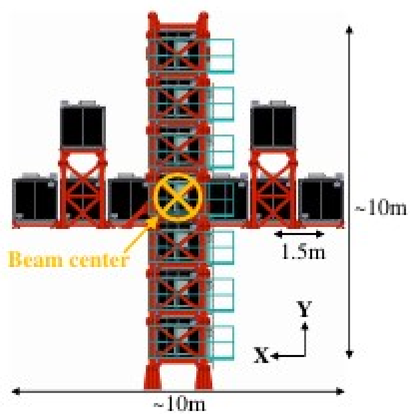
  → how to disentangle Final State Interaction effects

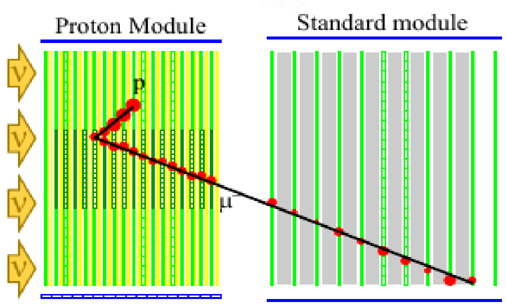
- **Impact on present and future oscillation measurements (δ_{CP}) : $\bar{\nu}_\mu$**

T2K near detectors



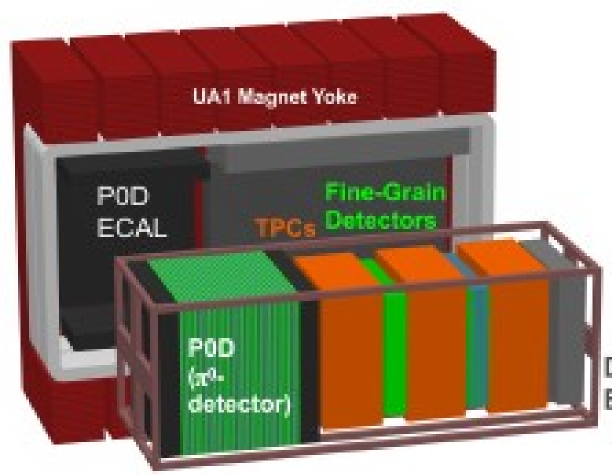
INGRID : on-axis

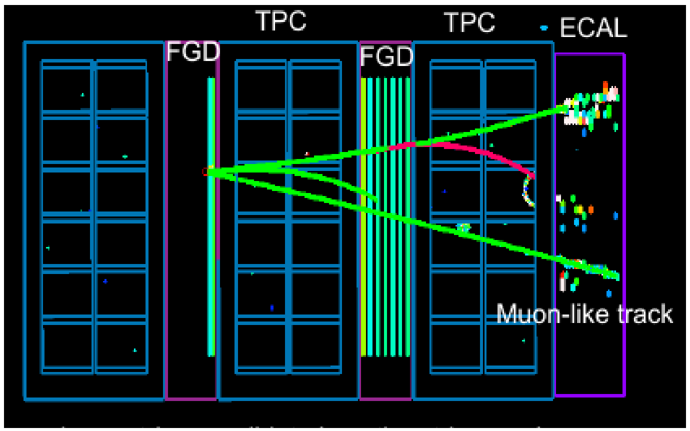




- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass**

ND280 : off-axis (2.5°)

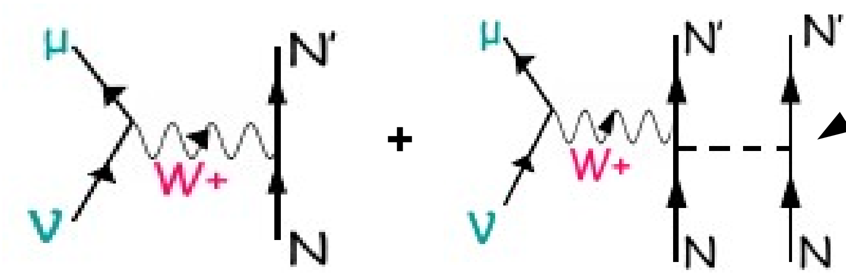




- fully magnetized (0.2 T)
- FGD: CH scintillators alternated with H_2O
- TPC → **good tracking efficiency, resolution** (6% p_T<1GeV) **and particle ID**
- P0D scintillator with water target

CC0π: recent results

- **Neutrino interactions model tuned from bubble chambers νH data**
  modern experiments scattering on heavy target (C,O) → nuclear effects



2p2h

ν_μ **n p → μ^- p p**

$\bar{\nu}_\mu$ **n p → μ^+ n n**

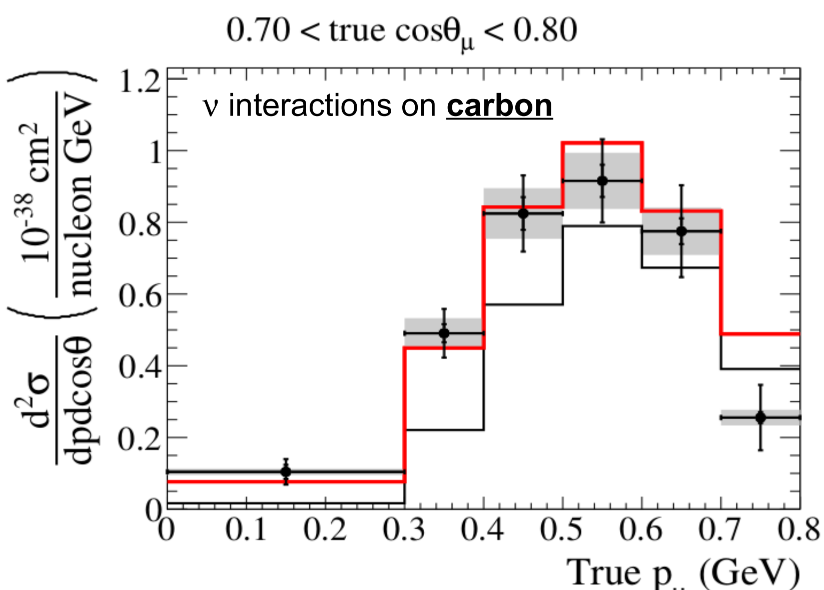
Charged Current Quasi-Elastic

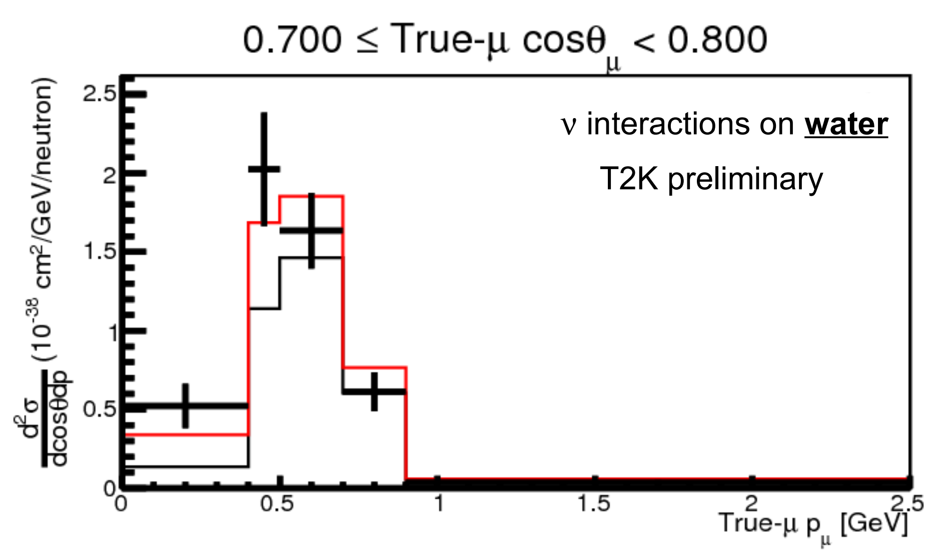
higher order corrections in nuclear target

Model delevoped by Martini et al.

—— CCQE

—— CCQE + 2p2h (multi-nucleon interactions)

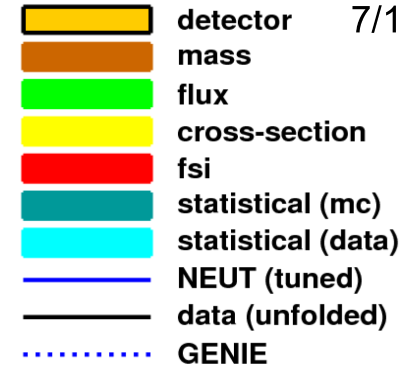


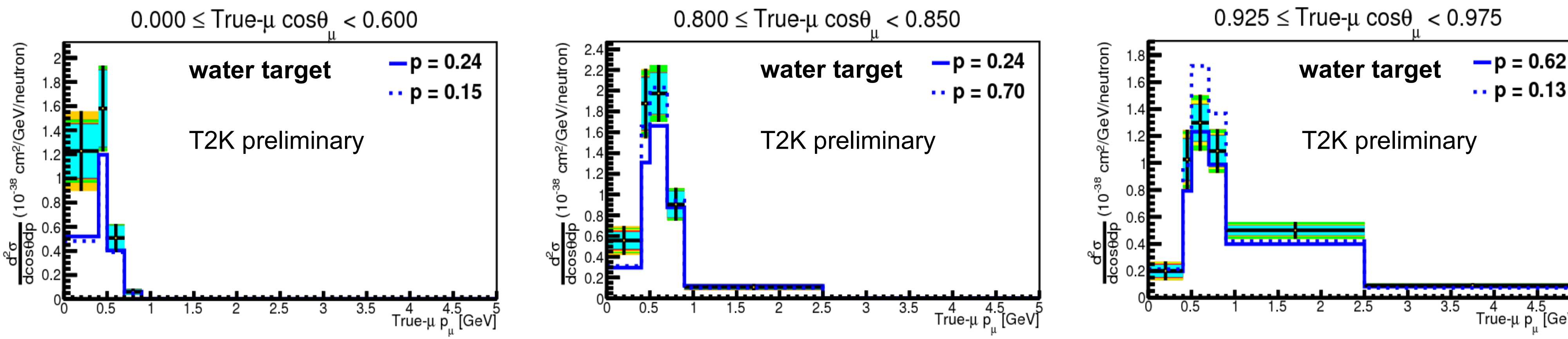


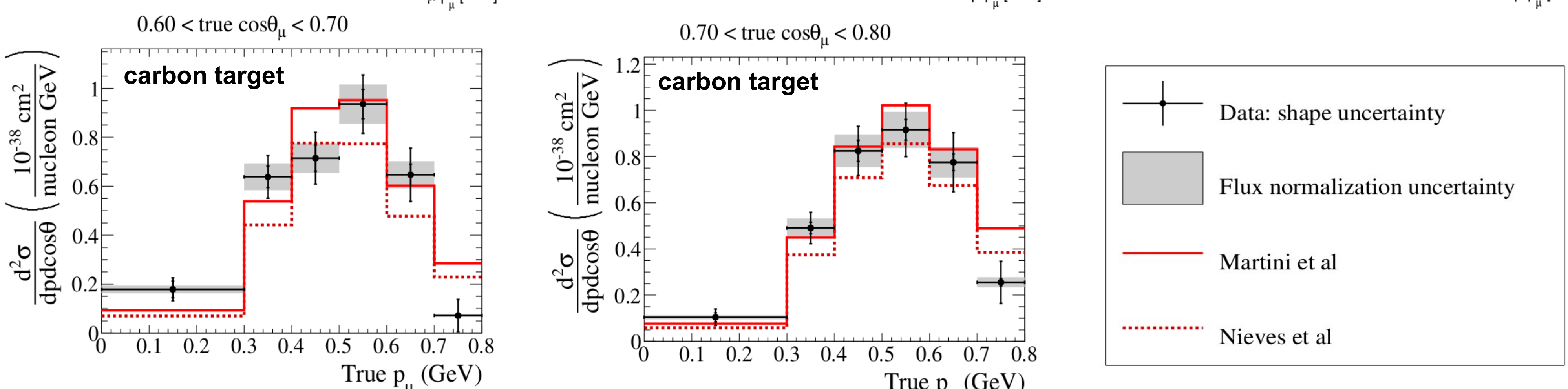
CC0π: models and MC

Measurements still dominated by statistical uncertainty

No universally preferred model or MC







The only way out: **increase/improve the experimental data**

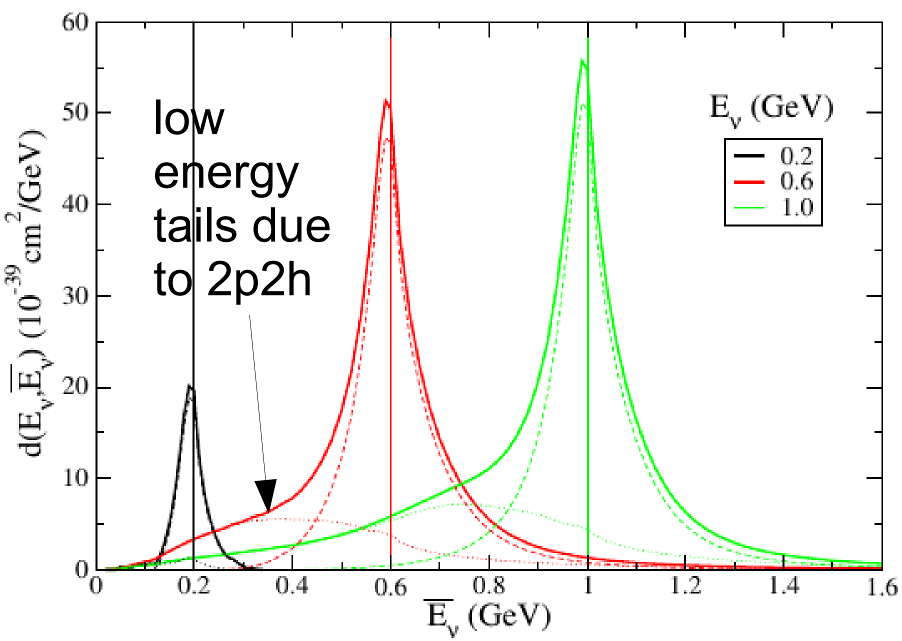
improve neutrino interaction modelling

Why we need good models?

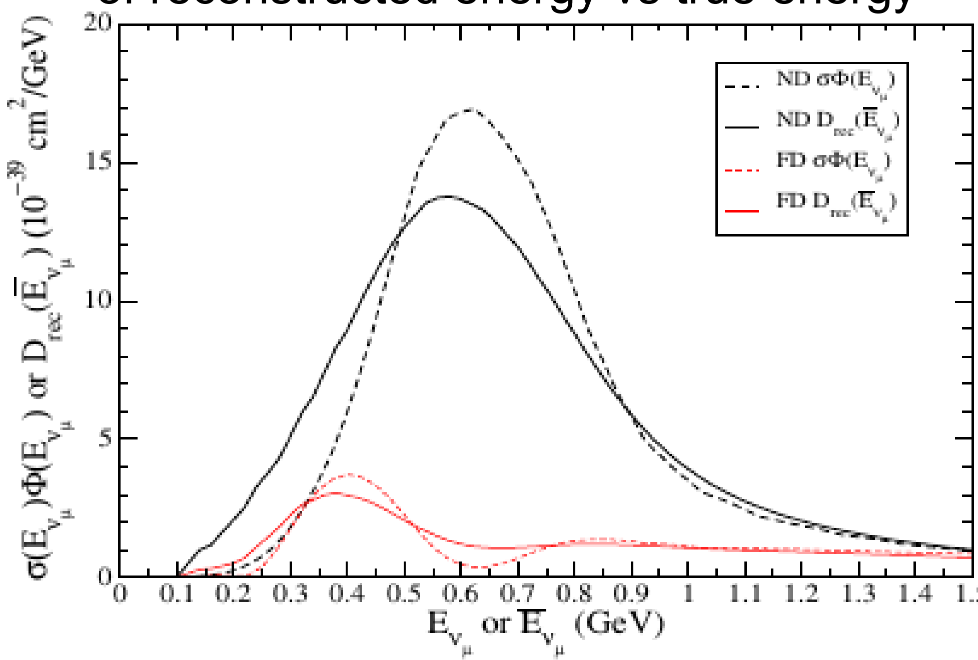
Phys.Rev. D87 (2013) no.1, 013009

Neutrino oscillation goes like ~L/E_ν but we do not measure E_ν ! We measure the outgoing muon at SuperKamiokande and we infer the neutrino energy on the base of available models

Distribution of true energy for a given reconstructed energy



Near Detector and Far Detector spectra of reconstructed energy vs true energy

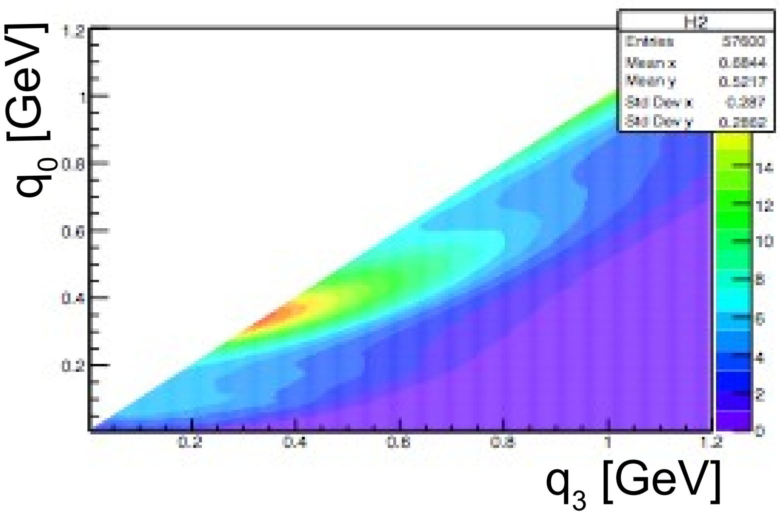


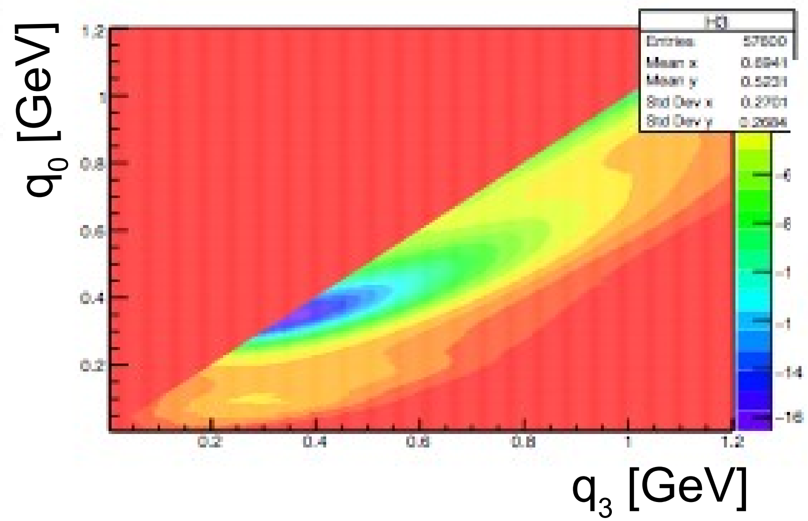
2p2h events fill the "dip" region sensitive to neutrino oscillation → **wrong modelling would cause bias on oscillation parameters**

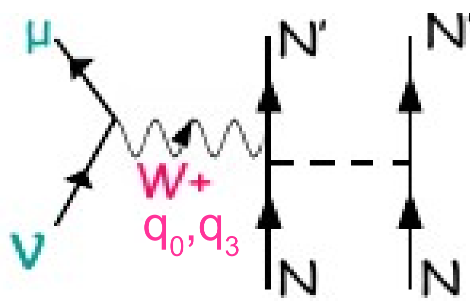
From models to Monte Carlo

- **Various 2p2h models available → completely generic mechanism to include any model in MC simulation: Hadron Tensors**

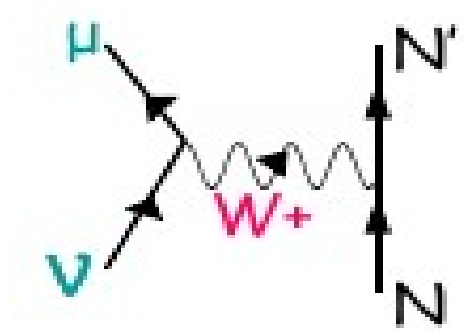
  Lookup tables encoding the nuclear physics as a function of transferred quadrimomentum to the nucleus

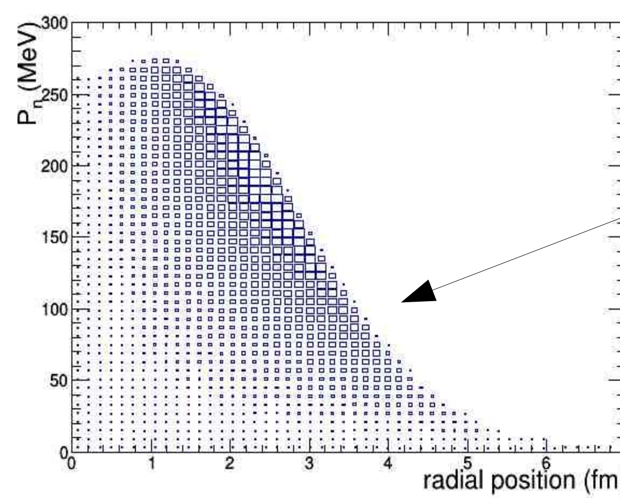






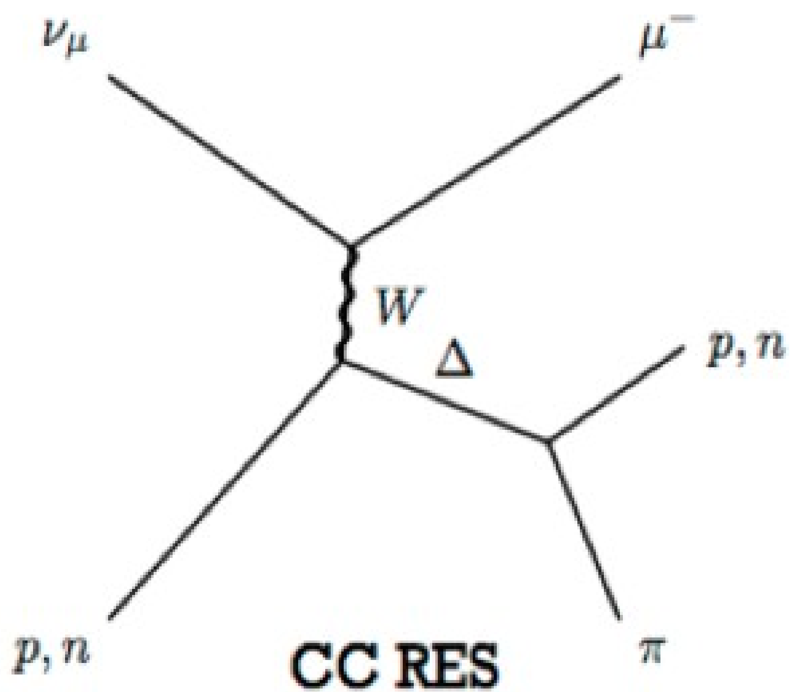
- **Nuclear effects important also on single nucleon scattering** (screening, binding energy, ...)

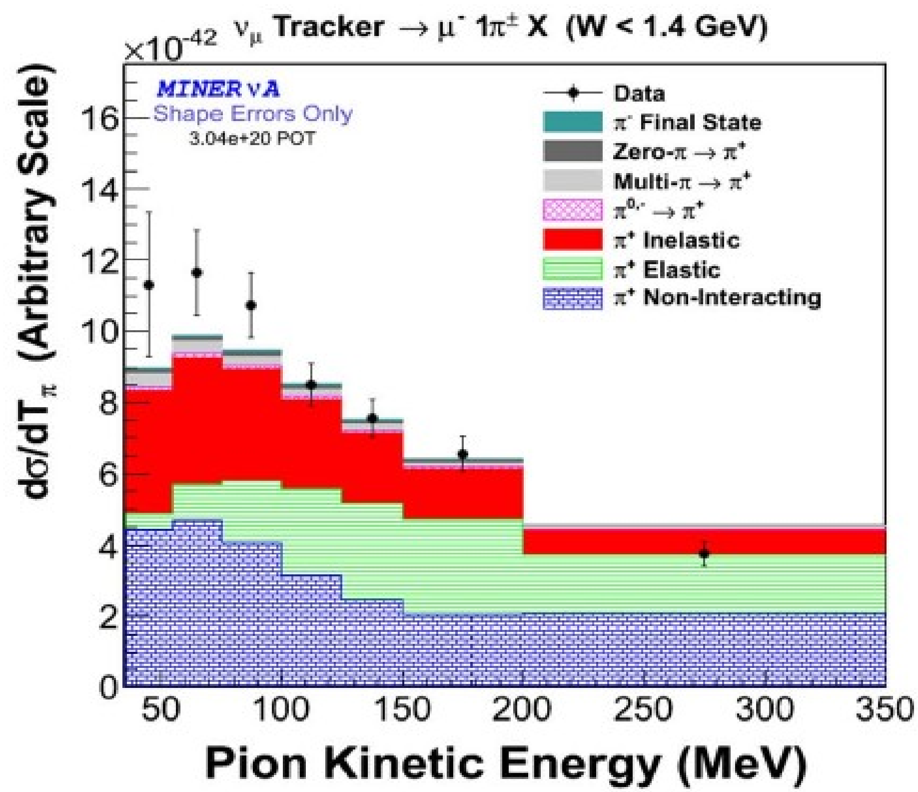




Nucleus modeled as a Fermi gas of nucleons: **nucleon momentum as a function of its radial position in the nucleus**

CC1π



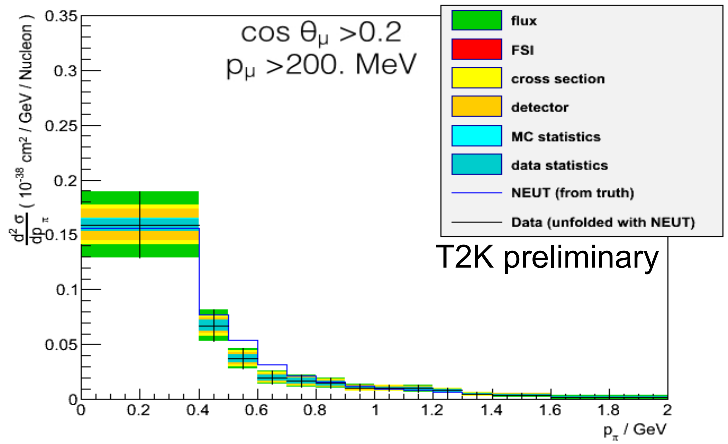


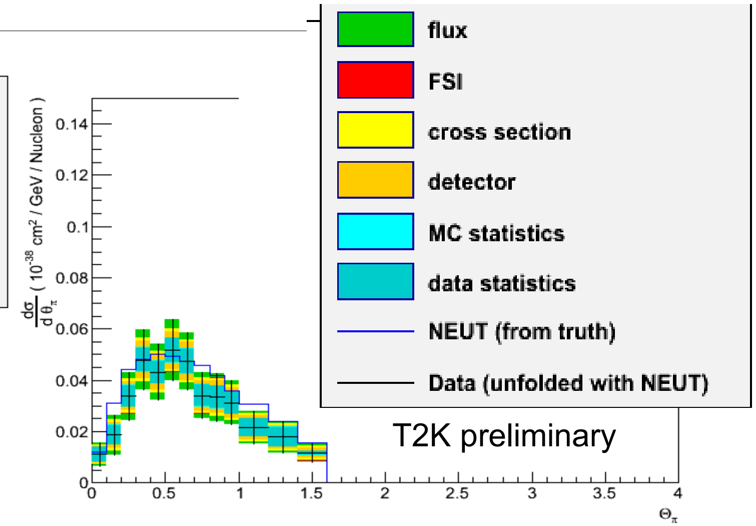
Large effects from Final State Interaction: re-scattering of the π inside the nucleus (nuclear physics again!)

Cross-section and FSI have different A-dependence → important effect when extrapolation from ND and FD with different material

CC1π recent results

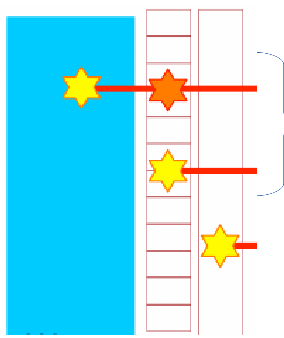
- **T2K FGD1 CC1π**: carbon





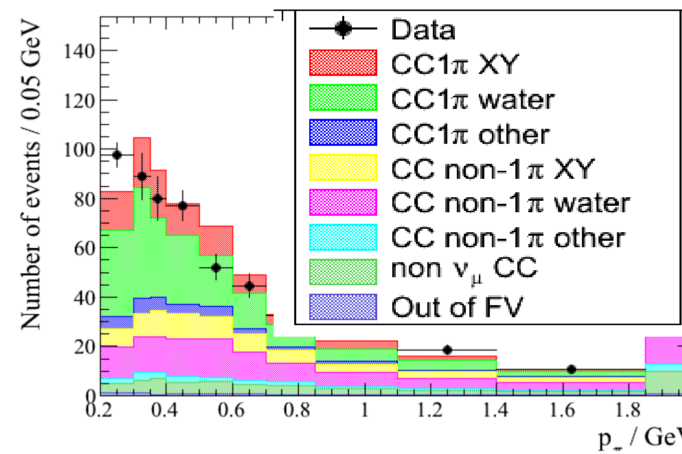
- **T2K FGD2 CC1π**: water and carbon

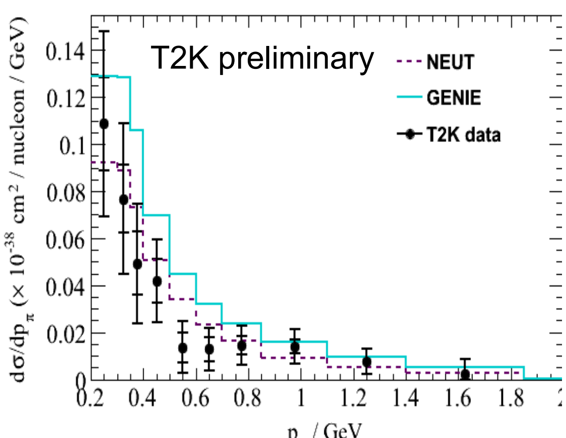
passive water interleaved with CH scintillator modules

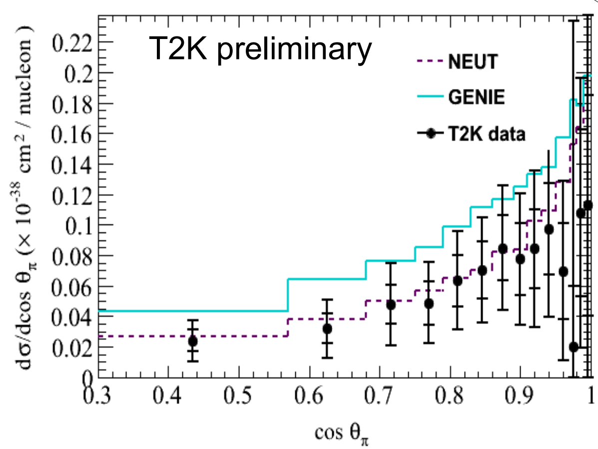


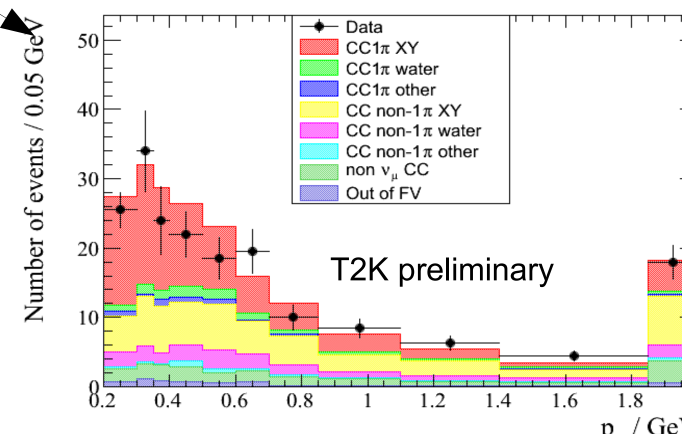
upstream modules CH+H_2O

downstream modules CH only









What do we need to measure?

Uncertainties in ND→FD extrapolation :

✔ • different E_ν distribution (because of oscillation) ⇨ need to reconstruct the neutrino energy from the final state particles

✔ • different target ⇨ A-scaling: measure cross-sections on different targets (and/or on the same target of FD)

➔ • different acceptance ⇨ measurement of cross-section in the larger possible phase-space: increase angular acceptance of ND

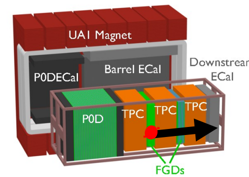
➔ • different neutrino flavor (because of oscillation) ν ($\bar{\nu}$) flux has typically a wrong sign component ⇨ measure cross-section asymmetries between different neutrino species (eg ν vs $\bar{\nu}$ important for for δ_{CP})

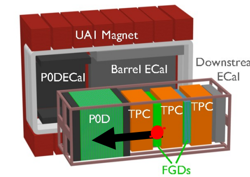
Extended acceptance

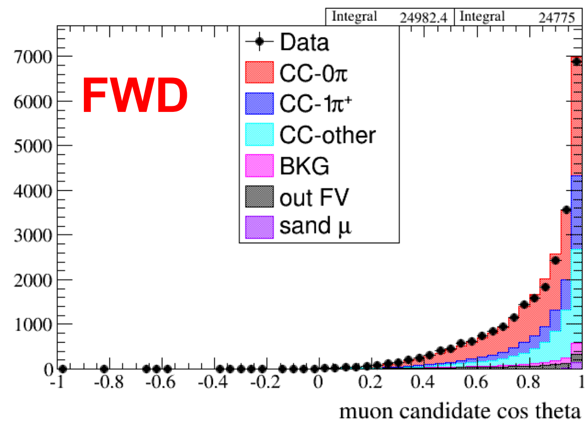
T2K work in progress

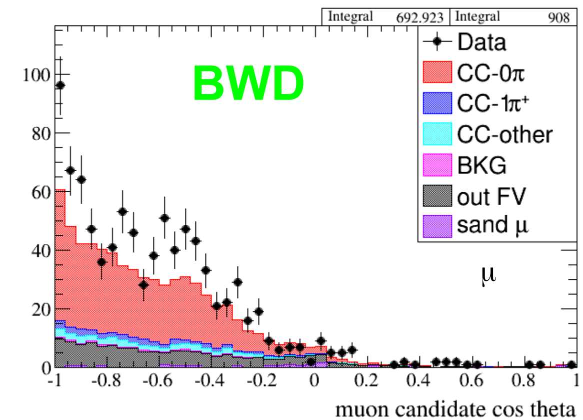
SuperKamiokande events have muons over all angles (4π acceptance): backward muons happen for high transferred momentum to the nucleus

Need to constrain such kinematics region with Near Detector
→ **new improved selection**

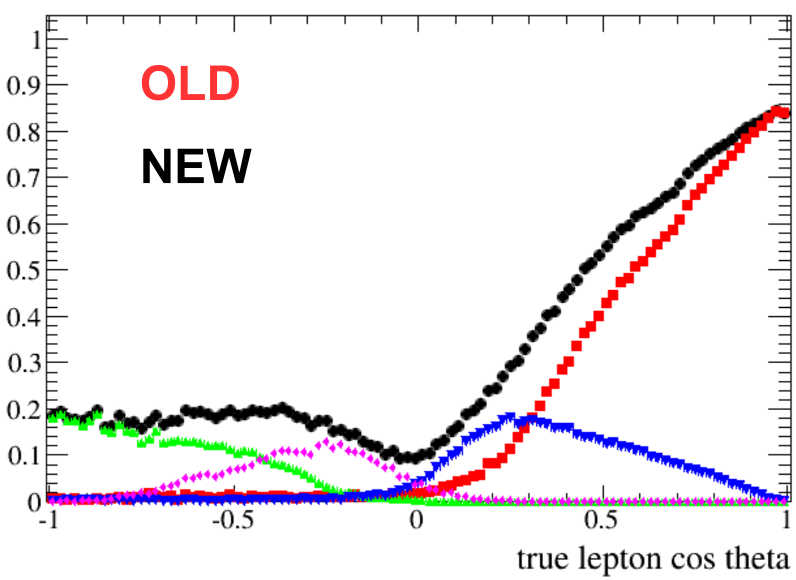


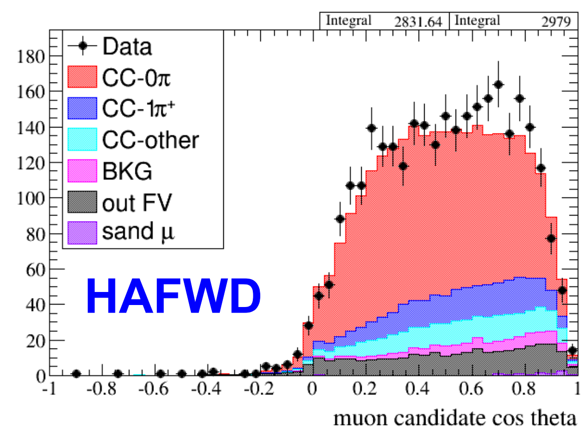


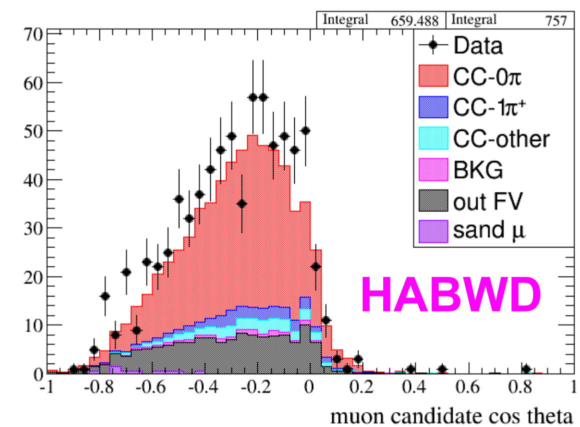


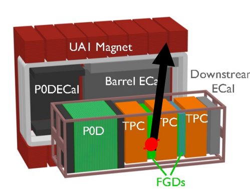


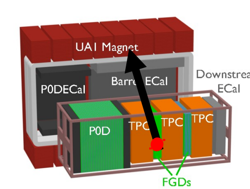
Reconstruction efficiency







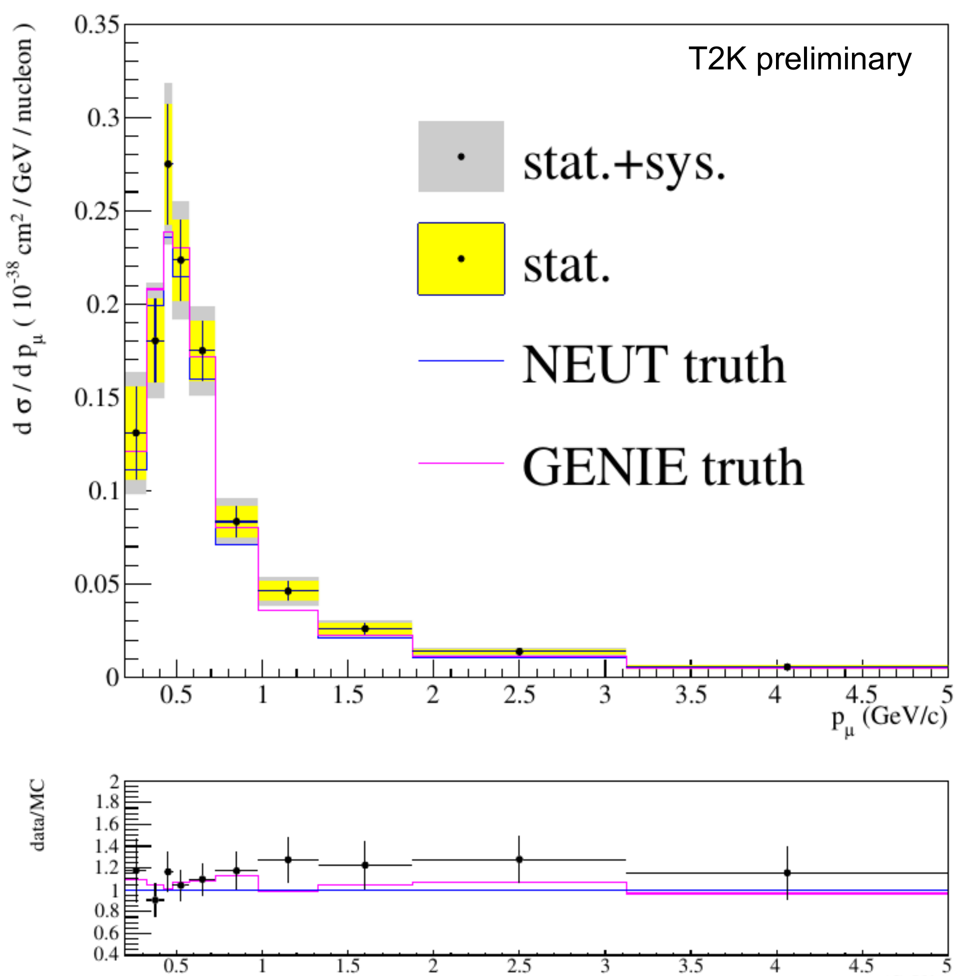


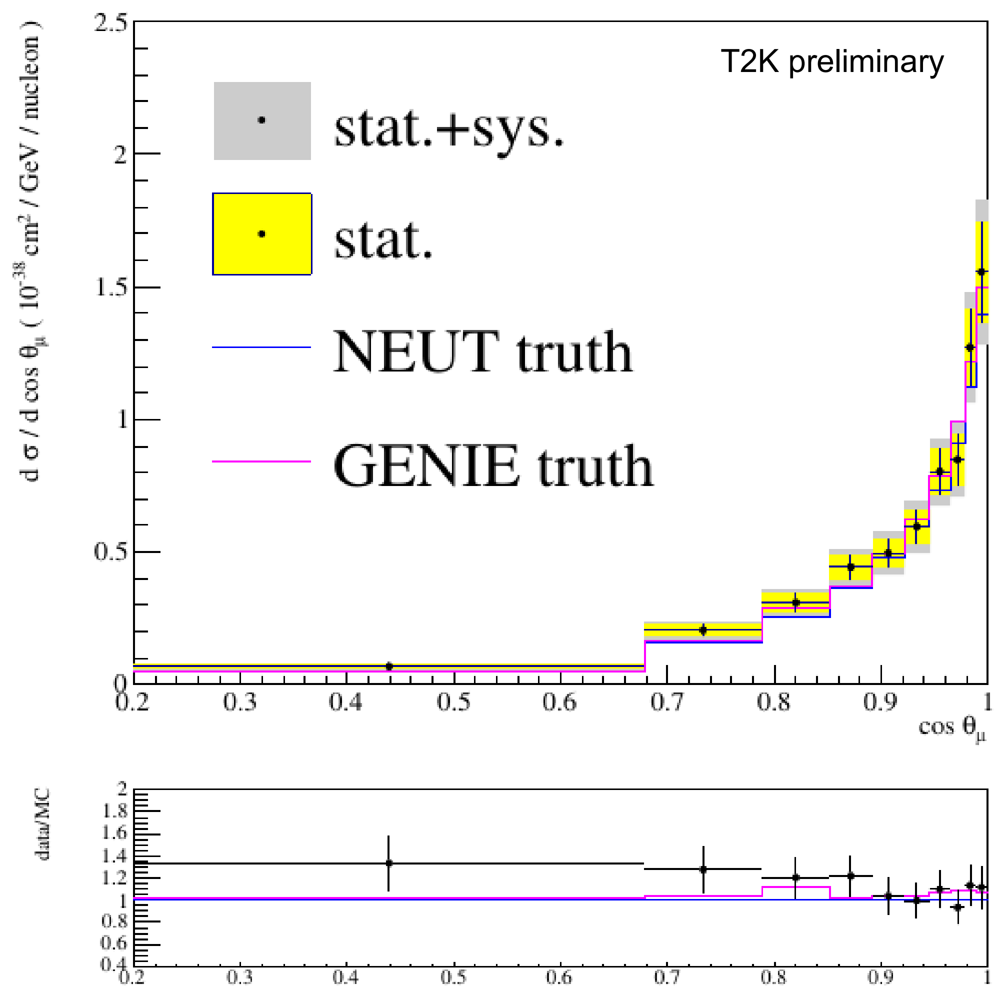


$\bar{\nu}$ cross section measurement

The measurement of δ_{CP} crucially depends on the comparison of ν vs $\bar{\nu}$ oscillation

→ **bias on ν vs $\bar{\nu}$ cross section direct reflect in bias on δ_{CP} measurement**



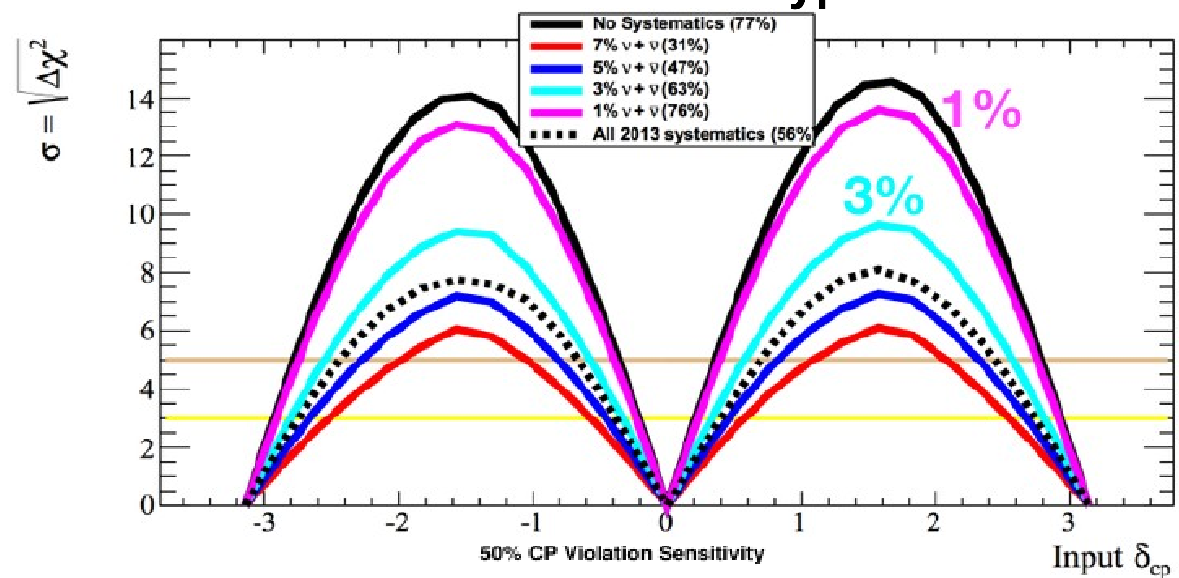


Future experiments: ν_e

- 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.

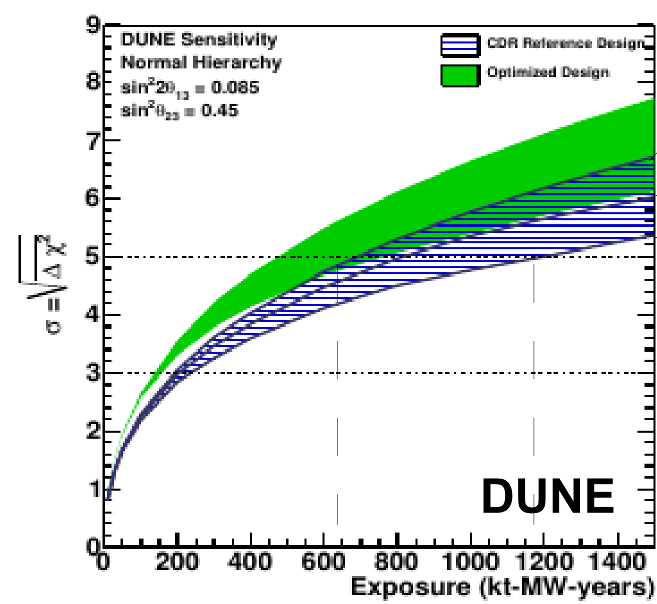
T2K uncertainty today 5-6%
→ ν_e/ν_μ uncorrelated 2.5%
→ $\bar{\nu}/\nu$ uncorrelated 2%

HyperKamiokande



- 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%
  - For **DUNE** assumed: **uncorrelated ν_μ - $\bar{\nu}_\mu$ 5%** and **ν_e - $\bar{\nu}_e$ 2%**

(shape of ν_μ itself may be more important for DUNE: shape analysis and spanning over different xsec)



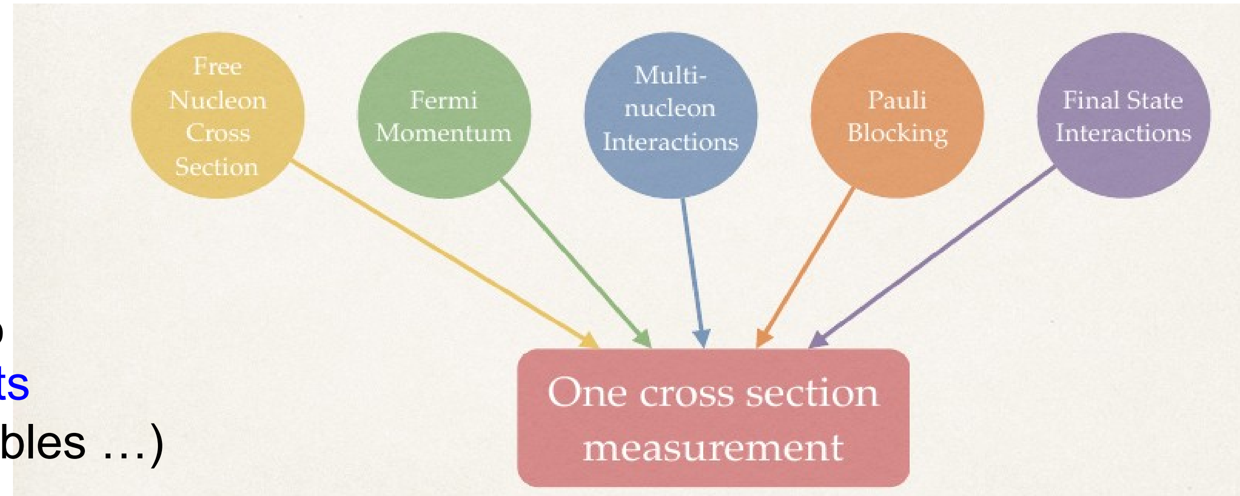
5% ± 1%
5% ± 2%
5% ± 3%

→ equivalent to factor 2 in exposure!

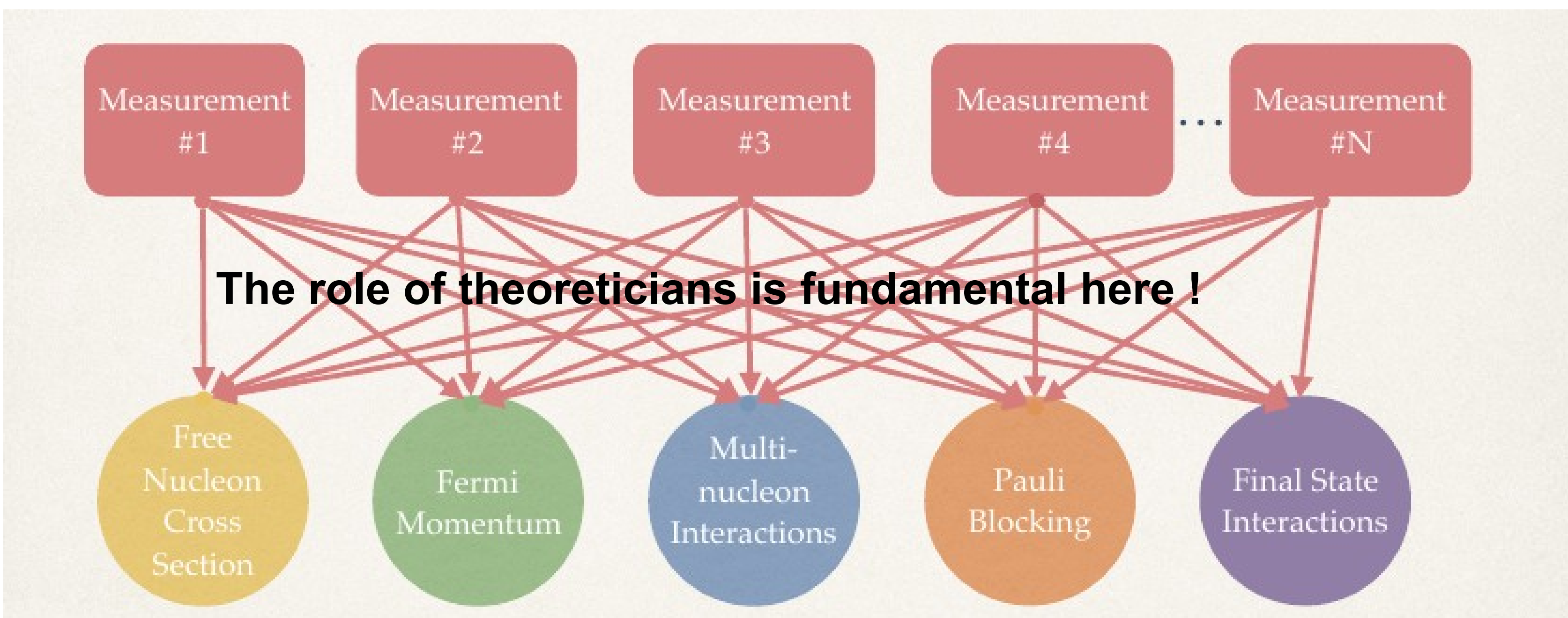
DUNE and HK talks @ NuFact 2015

The way out?

- A given cross-section measurement is affected by many different effects



- To disentangle them we need to compare different measurements (C, O, ν species, different variables …)
  → **long term plan**



The role of theoreticians is fundamental here !

The role of Jennifer

- **All (!!) the measurements presented here have been performed by Jennifer groups**

- Jennifer is allowing to:
  - promote and enhance the European know-how on Near Detector analysis and Neutrino cross-section measurements
  - establish a strict collaboration with Monte Carlo builders in Japan (NEUT)

  → inject measurements into improved Neutrino Interaction modelling
  → implements improved models in MC simulations

Crucial for T2K but also for future generation of long baseline experiments

JENNIFER

BACKUP

Recent **neutrino cross-section** measurements at **T2K**

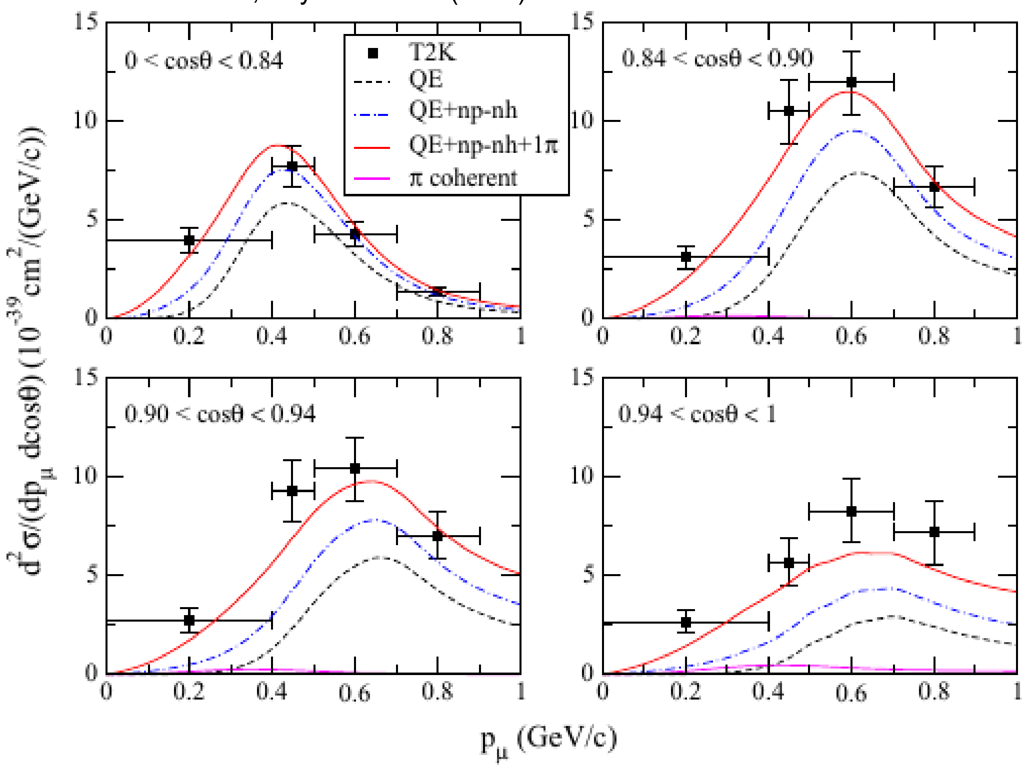
S.Bolognesi
(IRFU, CEA Saclay)

CC inclusive: T2K

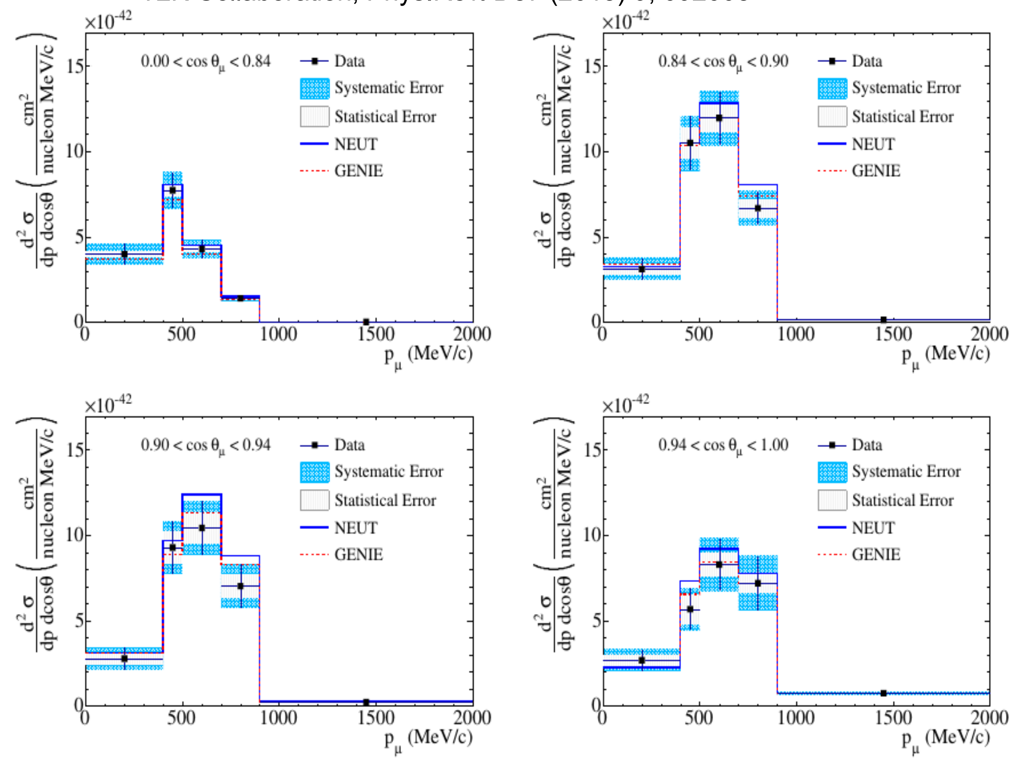
- Simple analysis: require at least one muon (small background from NC and flux pollution ν_{μ})
- **Dominated by CCQE at T2K E_{ν} energy:**

→ indications in favour of new models with 2p2h → agreement also with old tuned models

Martini et al, Phys.Rev. C90 (2014) 025501



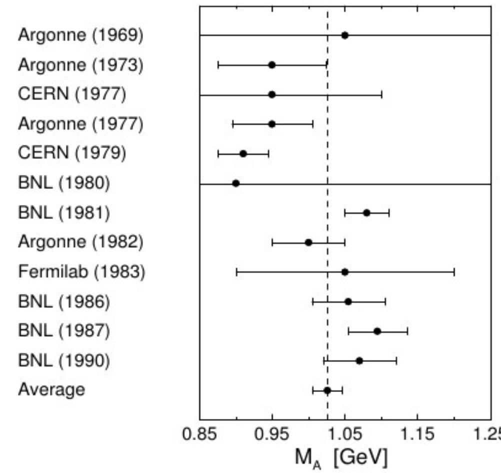
T2K Collaboration, Phys.Rev. D87 (2013) 9, 092003

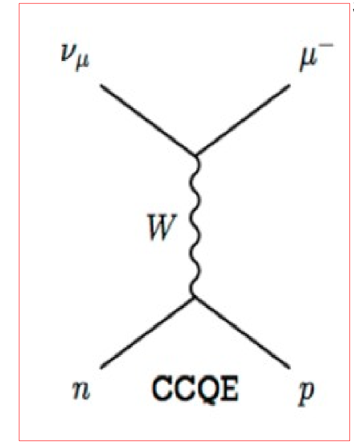


Nuclear physics is the name of the game

- **CCQE model tuned from bubble chambers νH data: M_A^{QE}~1GeV**
  → modern experiments (K2K) include nuclear effects on heavy target (C,O): Fermi Gas

arXiv:hep-ph/0107088



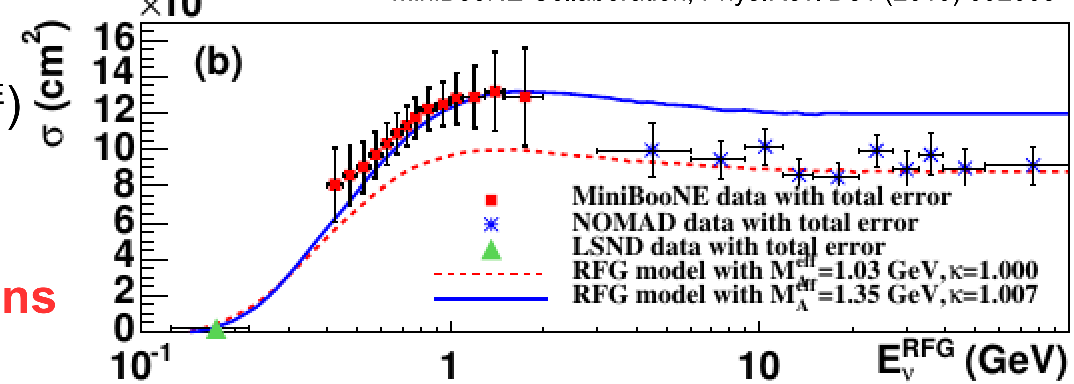


- **MiniBoone measurement shows large discrepancy wrt to this model** (large M_A^{QE})
  → explication from theoretical models including :
  - long range **correlation between nucleons** (aka RPA)
  - possibility of **interactions with NN pairs** (aka 2p2h and MEC effects)

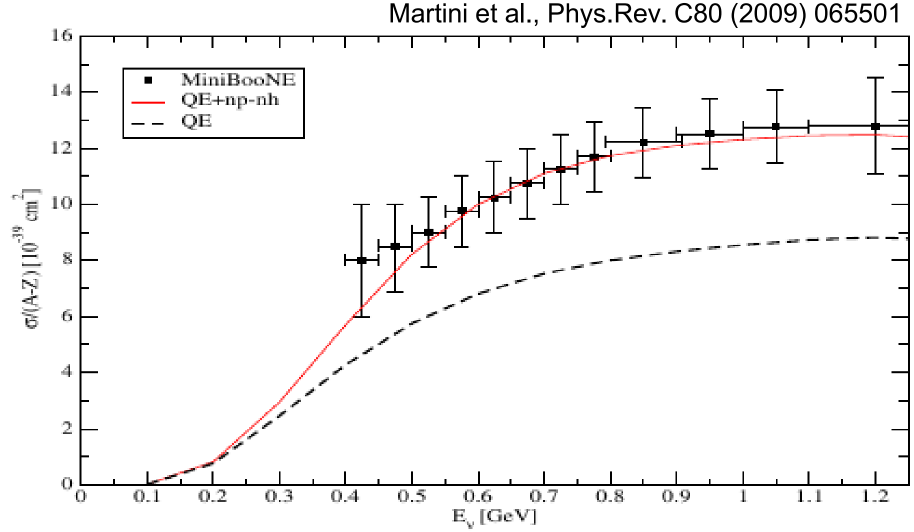
ν_μ n p → μ^- p p
$\bar{\nu}_\mu$ n p → μ^+ n n

(well known in ep scattering but not definitive model)

MiniBooNE Collaboration, Phys.Rev. D81 (2010) 092005



Martini et al., Phys.Rev. C80 (2009) 065501



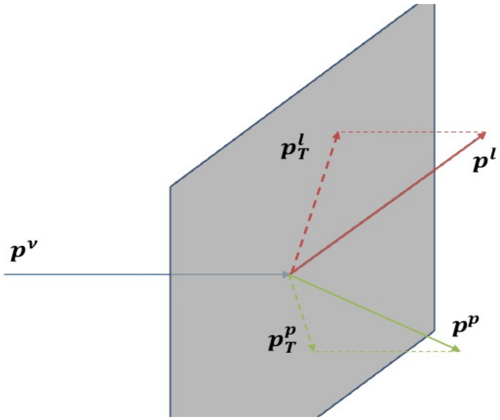
- **Final State Interaction only included in MC models**: CC1π with pion re-absorption included in signal (CC0π)

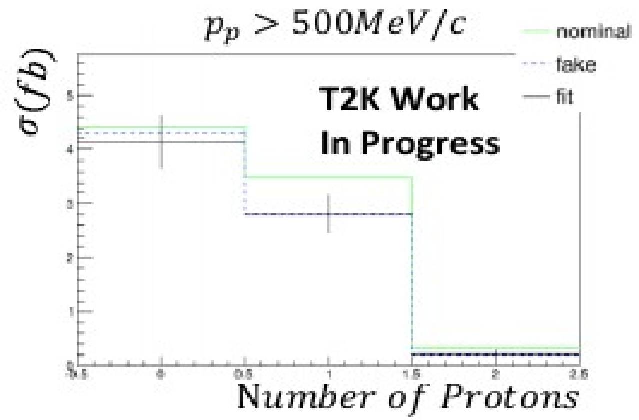
New ways of looking at the data

Look into proton multiplicity and kinematics

for 2p2h events you expect 2 nucleons in the final state

presence of 2p2h induce large asimmetry between the transverse momentum of the outgoing muon and of the outgoing leading proton





- Fake data: GENIE*
- Nominal MC: NEUT