ν-nucleus modeling: priorities for T2K/T2HK

(my personal point of view)

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Some figures for T2HK

From TDR and number of expected events we can evaluate the precision needed:

- **CP-violation discovery** it's mostly about event counting: need to control **cross-section normalizations** (and extrapolation from Near to Far Detector)
  - 3-4% on ν_μ signal
  - <3% on asymmetry (ν_e-$\bar{\nu}_e$/ν_e+$\bar{\nu}_e$) for CPV sensitivity:

    $\nu/\bar{\nu}$ ~1%

    ν_e/ν_μ <3% ($\bar{\nu}_e/\bar{\nu}_\mu$ <3%)

  - Background: wrong sign <10%

    ne instrinsic background from beam 3-15% (depending on ne-nebar correlations)

By combining ND280-like (for ν_μ and $\bar{\nu}_\mu$) + Intermediate Water Cherenkov detector (for ν_e) this looks feasible
The issue comes from the **uncertainties in the extrapolation from ND to FD (see later)**

- **δ_{CP} precision measurement (and Δm_{23}) needs instead very good control of neutrino energy reconstruction:**

~10-15 degree on **δ_{CP}** precision correspond to <1% energy scale (if only one FD)
This is much more challenging: need to control ν_μ modeling ~an order of magnitude better precision than for discovery

From ND to FD

The extrapolation rely on models: how do we validate them? (to the precision of ~2%)

1) **different E_ν spectrum from ND to FD**

→ need to control the cross-section vs E_ν of CCQE, 2p2h and CC1pi (+FSI) separately

2) **different acceptance (FD 4pi)**→ addressed by ND-upgrade

→ different angular distribution of **ν vs $\bar{\nu}$** : uncertainty on forward/backward has direct impact on n/nbar uncertainty

→ need ~5% precision on backward sample (enough stat at ND?)

3) **C to O** : they are very similar targets... issues may rise if they have **different E_ν-dependence or different angular dependency** (initial state nuclear effects but also FSI to consider)

(The extrapolation is not a problem for IWCD but that cannot do ν vs $\bar{\nu}$ and doesn't have the ν_μ precision of a ND in terms of signal purity for different processes)

No precise quantitative studies available yet of the impact of such issues on next generation experiments (or I'm not aware of them). Next slides are my guess...

CCQE, 2p2h

Point 1) in previous slide is in my opinion the most important issue. Already with T2K statistics we see **different models which all fit nicely ND data but give different predictions at the far detector (→ biases on energy spectrum relevant for Δm_{23} and δ_{CP} measurement)**

- CCQE: Muon kinematics alone (i.e. inclusive measurement) can be described by LFG w/RPA, SF (or even RFG) with a suitable set of parameters (pF, Eb...)

- 2p2h: large differences between models but large uncertainties on CCQE 'mask' the 2p2h sensitivity of our measurements

→ **need proton information to break the degeneracy**:

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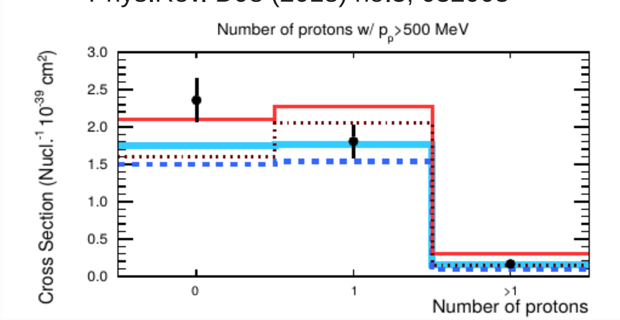
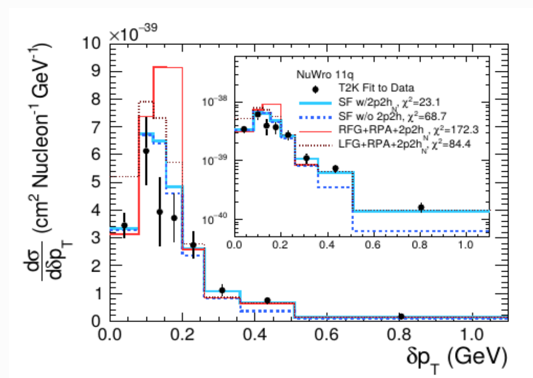
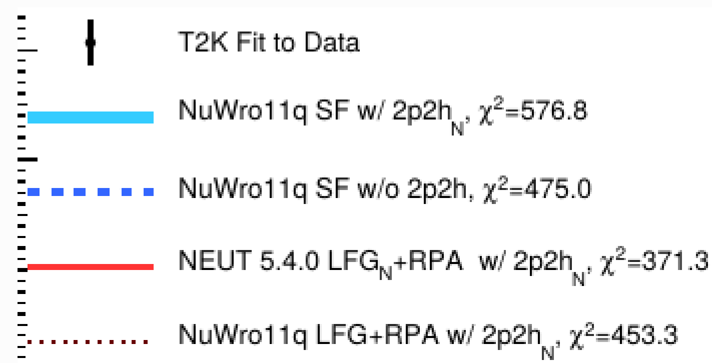






More generally: measuring the outgoing nucleons allow a **more precise E_ν reconstruction** at ND to be tested against muon-only E_ν estimation

We need the models to go beyond the inclusive prediction: prediction for outgoing nucleons (and validation against e → e'p data)
This includes a proper treatment of FSI: need to go beyond semi-classical approximation?

CC1pi

Need to have **FSI** under control to evaluate CC1pi background on CCQE-like selections

If we want to exploit CC1pi as signal then quite a lot of work to be done: we need to control xsec but also **full kinematics of outgoing pions !**

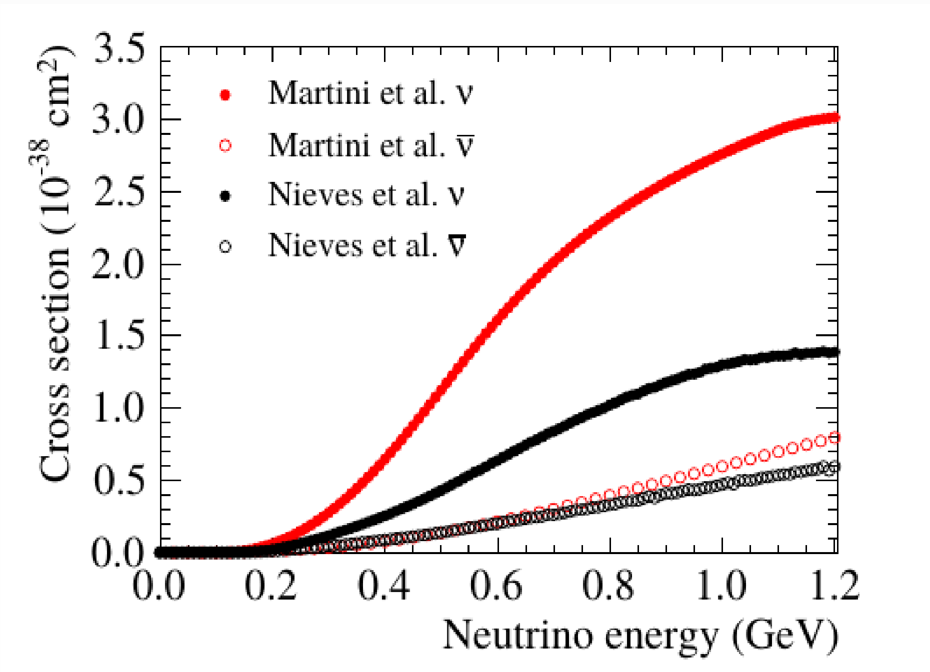
- Experiments use models without nuclear effects (Delta suppression in medium)
- On the other hand more sophisticated models at nucleon level (multiple resonances + interference) have been developed → how to include **nuclear effects** there?
- How **FSI** change the charge, multiplicity and kinematics of the pions? Do we have enough pion-scattering data to tune a semiclassical approximation or we need to go beyond?

(and here I do not even enter in the region of **multipions and DIS** which is not really relevant for T2HK)

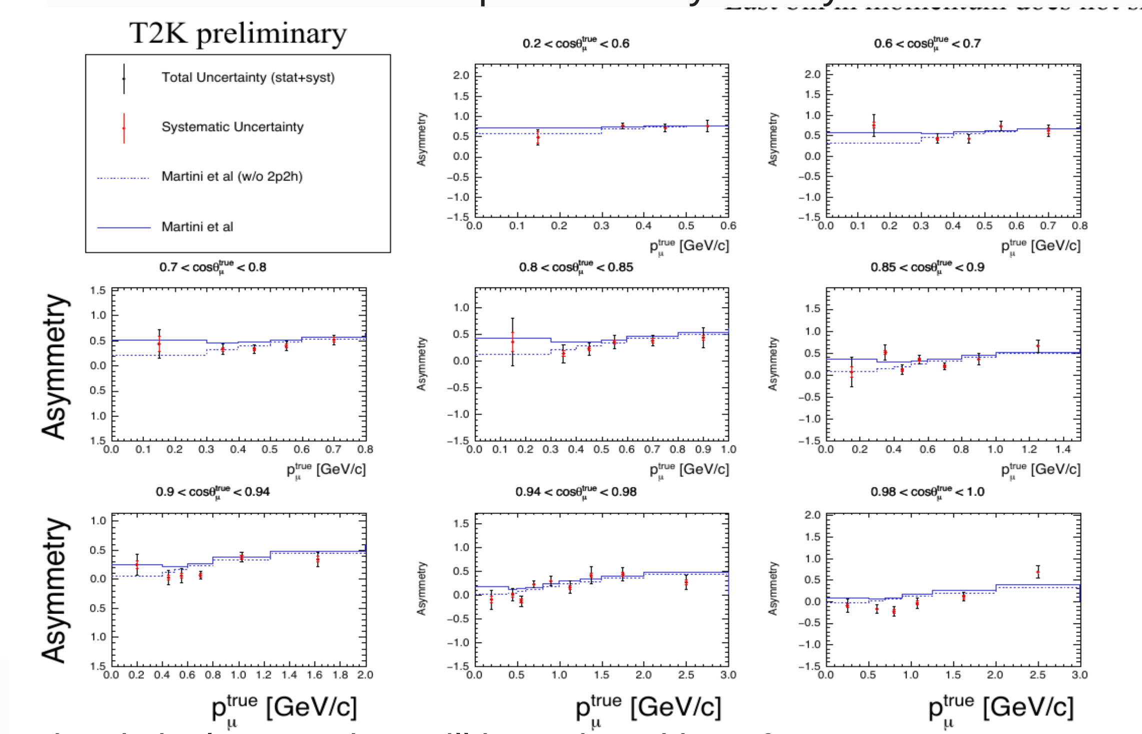
ν vs $\bar{\nu}$

If we control ν well enough (as in previous slide), we should be able to extrapolate to $\bar{\nu}$ + direct $\bar{\nu}$ measurements at ND

We are clearly not there yet ... but there is no other way



C.Riccio NuINT: CC0pi n/nbar asymmetry



(statistical uncertainty will be reduced by a factor ~10 → need to control systematics)

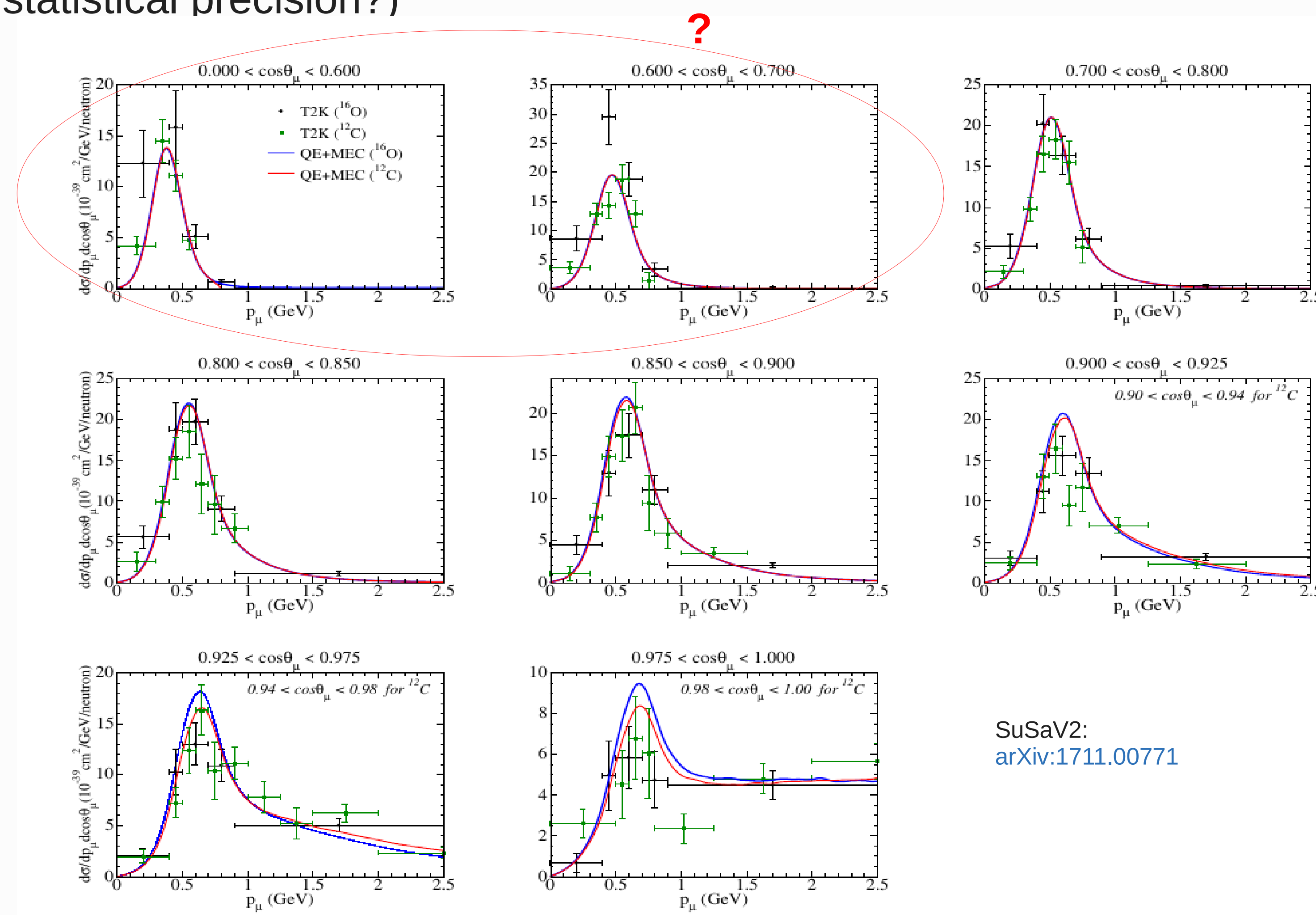
→ **important to master the angular dependence of the cross-section**: which uncertainty at high Q^2? (= backward)

Here is where the nucleon form factors may play a role: no evidence of sizable effect on T2K kinematics (yet?)

C to O

Similar approach:
- precise C sample at ND with model extrapolation to O
- large stat O sample at IWCD: to cover possible differences in E_ν-dependence or backward kinematics (to which statistical precision?)

We do not expect any major surprise … but:



SuSaV2:
arXiv:1711.00771

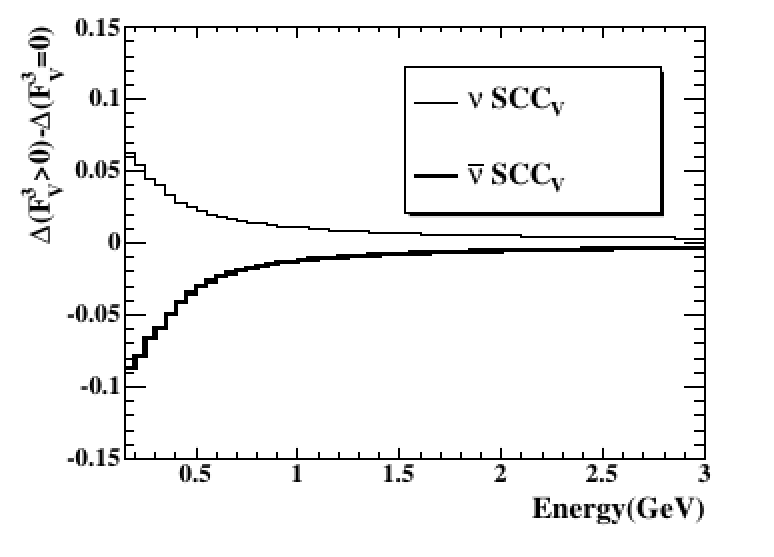
ν_e/ν_μ

Differences come from

- difference in phase space: need to ping down ν_μ to very good precision to extrapolate ν_e.
Which precision is needed on ν_μ in different phase space regions?

- difference in form factors due to subleading terms: present experimental limits on F_3^V gives up to 2-3% on σ at 600 MeV. Is the assumption of $F_3^V=0$ solid? If not, any clear path (reanalysis of existing data or new data)?

$$\Delta(E_\nu) \equiv \frac{\int dQ^2 \frac{d\sigma_\mu}{dQ^2} - \int dQ^2 \frac{d\sigma_e}{dQ^2}}{\int dQ^2 \frac{d\sigma_e}{dQ^2}}.$$



- **radiative corrections -> just need to be done!** Also kinematics of outgoing gamma need to be modeled (most of the effect is 'canceled' because gamma is reconstructed together with electron)

In any case IWCD is targeting a 3% measurement of ν_e with same acceptance and E_ν spectrum of FD

Summary of priorities:

→ beyond inclusive prediction: nucleon kinematics in CCQE and 2p2h + what is the FSI uncertainty in proton and pions due to the semicalssical approximation?

→ forward vs backward (especially for ν vs $\bar{\nu}$ and C vs O)

→ CC1pi modeling: nuclear effects in more recent models and FSI

ν_e: we need input from theoreticians (radiative corrections, $\nu_\mu \rightarrow \nu_e$, F_3^V)
But IWCD can measure ν_e at 3% precision with same E_ν spectrum and acceptance than FD...