Neutrino interaction uncertainties in the ν oscillation measurements

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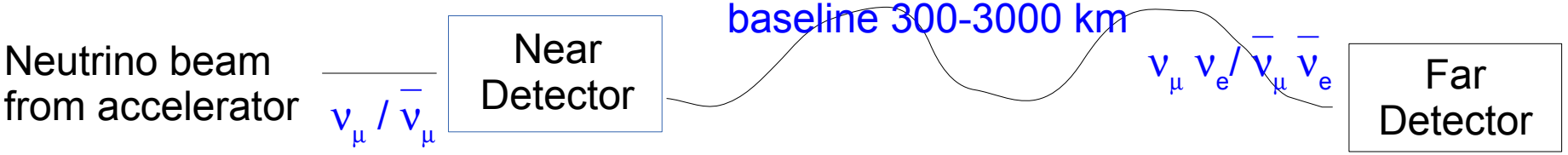
FNAL seminar
16th November 2017

Outline

- Brief introduction about oscillation analysis and the role of near detectors
- Examples of how neutrino interaction uncertainties can affect NOVA-like and T2K-like analyses. What will happen in a LAr TPC?

Long baseline experiments



Oscillation probability estimated by comparing ν_μ and ν_e rate between near and far detectors:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{amplitude}} \sin^2 \underbrace{\left(1.27 \frac{\Delta m^2_{ji}[\text{eV}^2] L[\text{km}]}{E_\nu[\text{GeV}]}\right)}_{\text{frequency}}$$

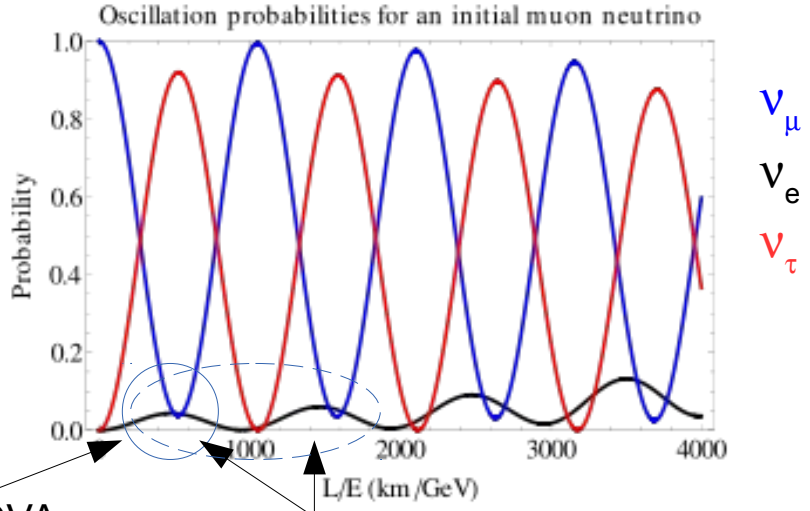
(simplified 2-flavors approximation)

In the atmospheric sector

$$\Delta m^2_{32} = 2.5 \times 10^{-3}\ \text{eV}^2$$

Experiment	Energy	Baseline
T2K (T2HK)	0.6 GeV	295 km
Nova	2 GeV	810 km
DUNE	1-3 GeV	1300 km

(to exploit ν_τ need $E_\nu > m_\tau$ 1.78 GeV)

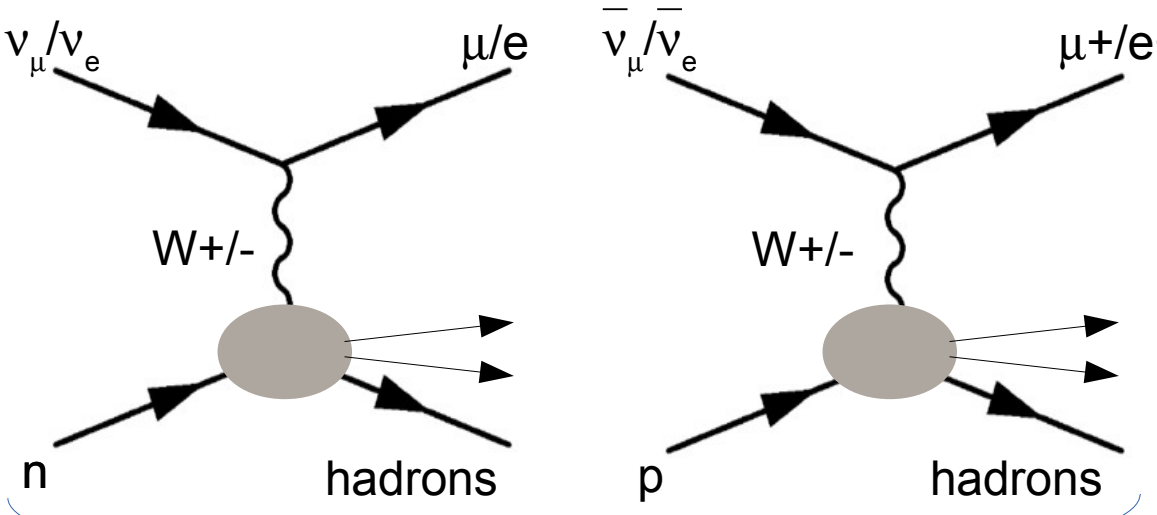


T2K (T2HK) and NOVA working point

DUNE wideband beam covers (at low energy) also the second oscillation maximum

Neutrino “signal” and “background”

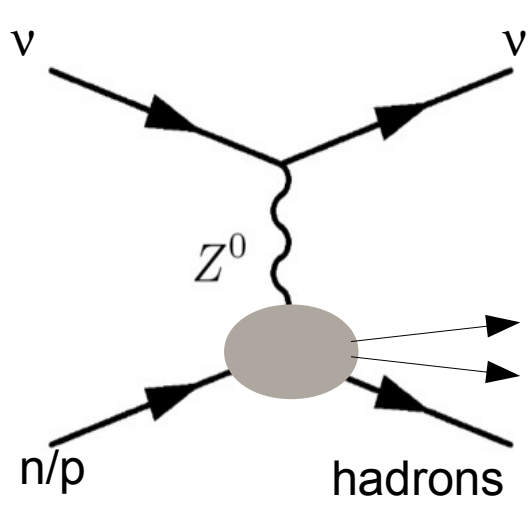
Neutrinos interact with target nucleons in the materials of our detector as



Charged Current (CC) main signal:

- outgoing lepton well visible in the detector to tag interactions → allow to **identify the incoming neutrino flavour and 'charge'**
- full final state can be (in principle) reconstructed in the detector → allow to **estimate the incoming neutrino energy**

(in realistic detectors this actually relies on various approximations)

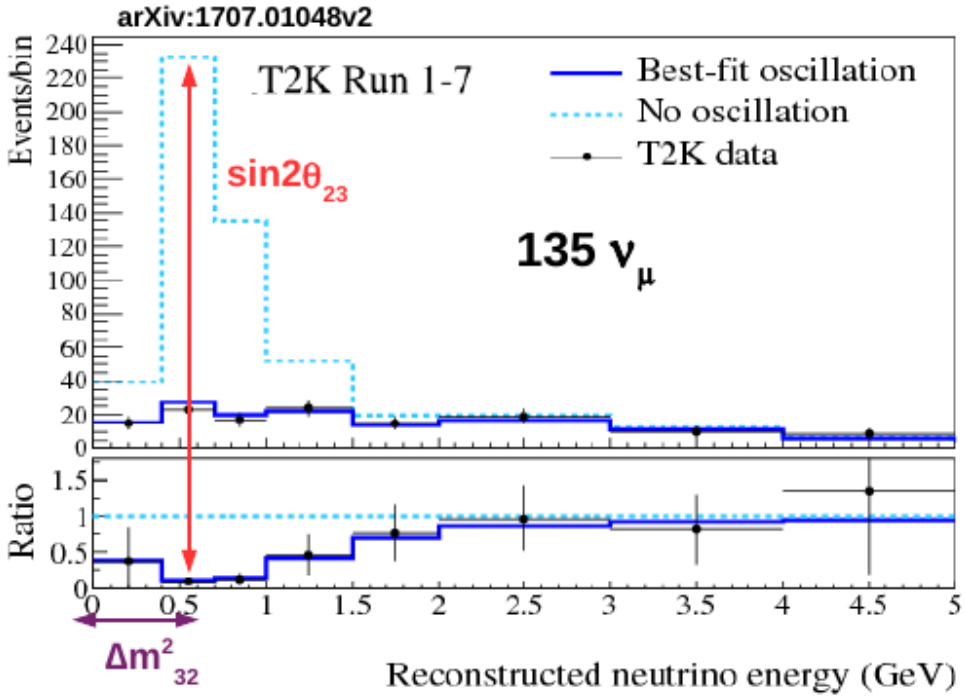


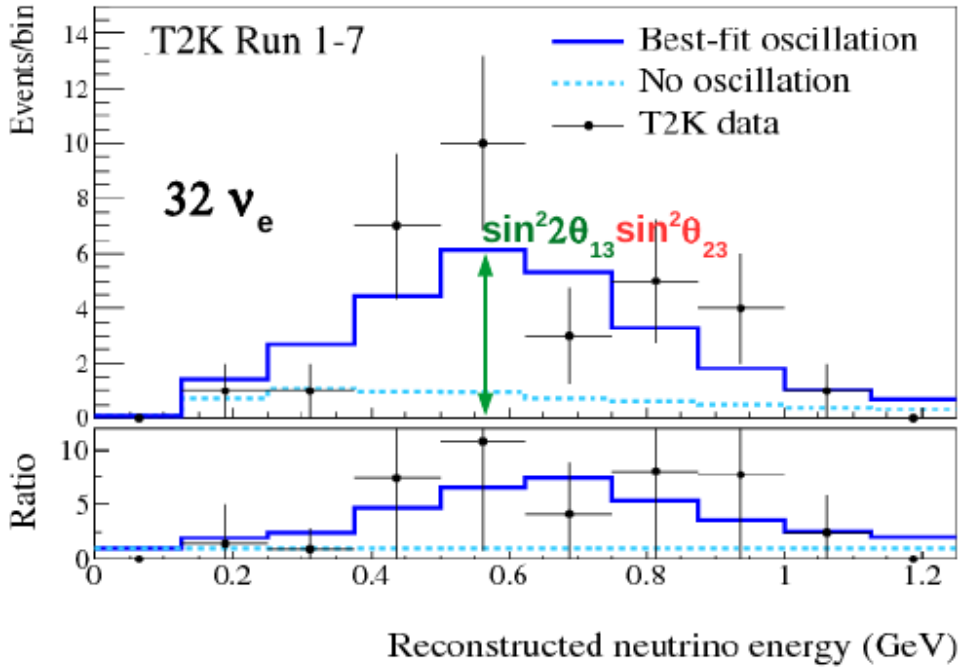
Neutral Current (NC) background

Sometimes the outgoing hadrons can be misidentified as lepton in the detector → background that need to be estimated and subtracted from data distributions

T2K oscillation analyses

(F.Gizzarelli thesis defence)





Disappearance

$$P(\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{\mu}) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- $\sin 2\theta_{23}$ proportional to the depth of the dip
- Δm^2_{32} position of the dip

Appearance

$$P(\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \times \left(\sin^2\theta_{23} \mp \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\left(\frac{\Delta m^2_{21} L}{4E}\right)\right)$$

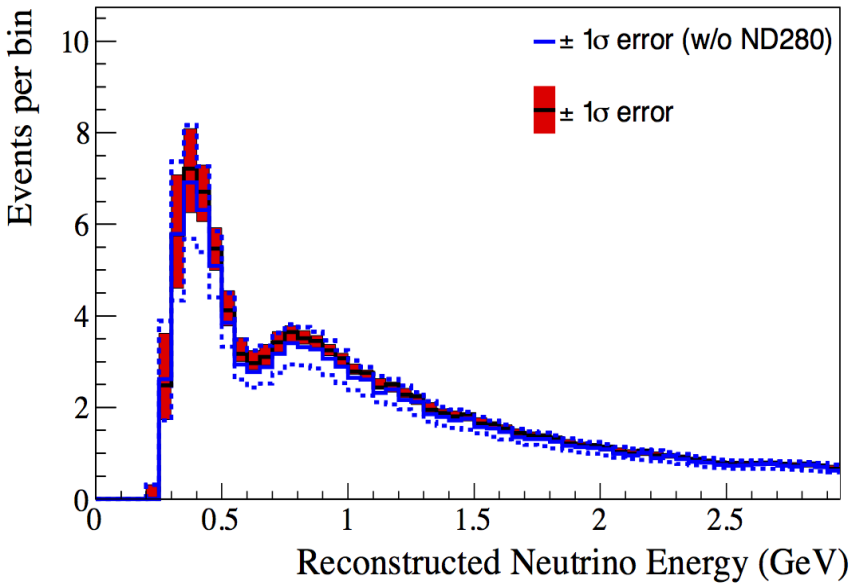
- $\sin^2 2\theta_{13}\sin^2\theta_{23}$ proportional to the oscillation maximum
- δ_{CP} flip sign for ν (-) and $\overline{\nu}$ (+)

Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
e-like ν	28.8	24.2	19.7	24.2	32
e-like $\overline{\nu}$	6.0	6.9	7.7	6.8	4

Why we need ν cross-section

- **Oscillation measurements from N(E_ν) at the Far Detector**

ν_μ at SuperKamiokande in T2K



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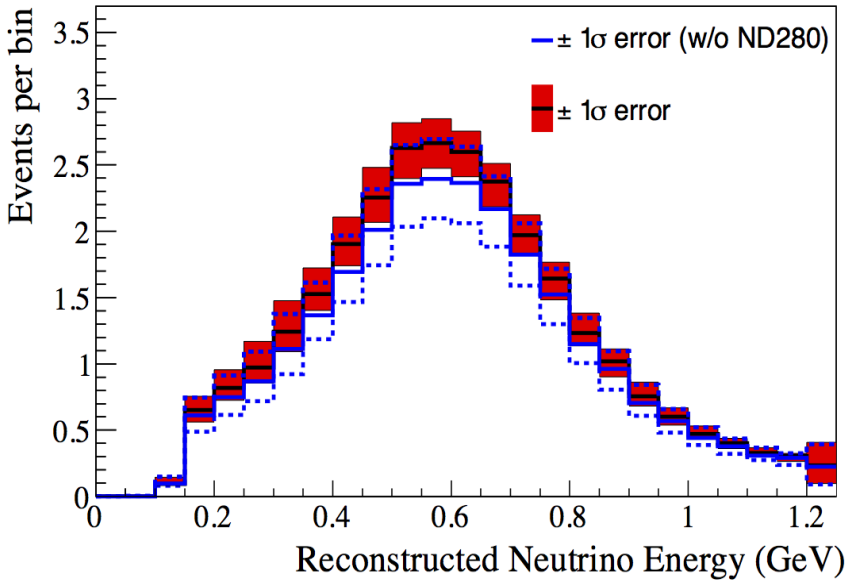


Rate of neutrino events at the far detector is given by

$$N_{FD}^{\nu'} = \int \Phi^{\nu}(E_\nu)\, P_{osc}^{\nu \to \nu'}(E_\nu)\, \frac{d\sigma^{\nu'}}{dE_\nu}\, dE_\nu$$

~same~ flux at ND and FD

what we want to measure: oscillation probability

ν cross-section extrapolation from ND to FD

Does the near detector solve everything???

No! Because of **ND→FD extrapolation :**

- different $E\nu$ distribution
- $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu$
- different acceptance (and target)

→ **rely on models to extrapolate** : neutrino interactions on nuclei (C,O, Ar) → need to model nuclear effects on initial and final states

You can still have a perfect fit to ND data and still be wrong at FD: many systematic effects are **degenerate** at ND but can bias the expected E_ν spectrum at FD
(eg. various theory uncertainties, and theory vs detector and flux uncertainties)

The hard stuff...

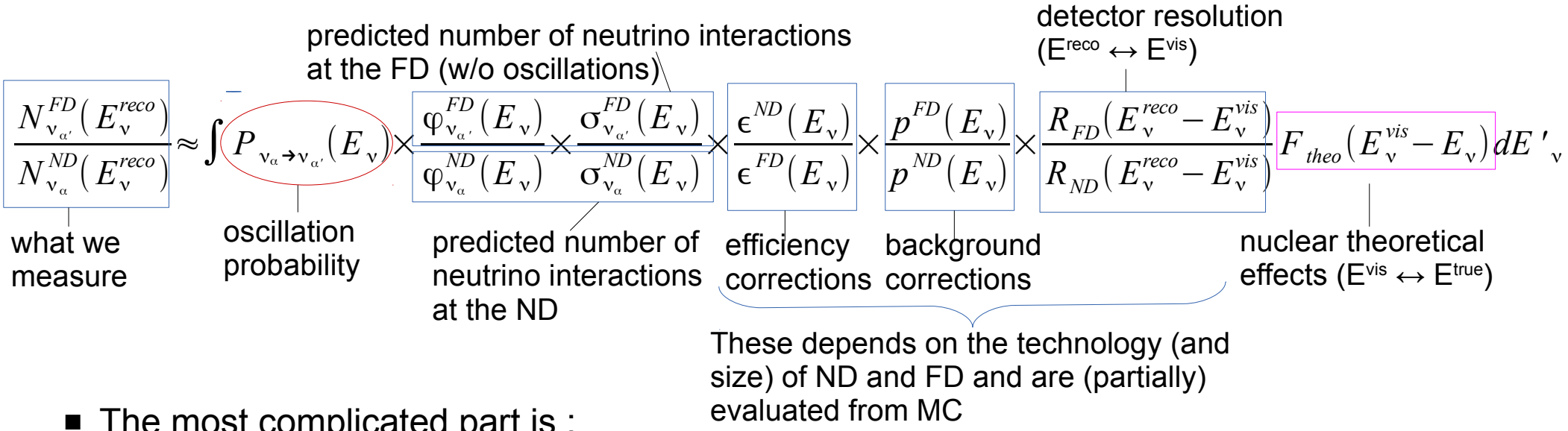
The following issues induce an ***unavoidable model dependency in any oscillation analysis*** and make the evaluation of systematics in oscillation measurements a difficult task:

- extrapolation of xsec to different energy spectrum
- separate flux and xsec evaluation from ND data

The measure of neutrino energy is never exact (even in a 'perfect' detector) because of nuclear effects →
Different detectors have different strategies with different advantages and drawbacks

Flux and cross-section

We measure flux and xsec at the ND and *we use our models to extrapolate* at the far detector, like a ratio measurement convoluted to resolution:



$$\frac{N^{FD}_{\nu_{\alpha'}}(E^{reco}_{\nu})}{N^{ND}_{\nu_{\alpha}}(E^{reco}_{\nu})} \approx \int P_{\nu_{\alpha}\to\nu_{\alpha'}}(E_{\nu}) \times \frac{\varphi^{FD}_{\nu_{\alpha'}}(E_{\nu})}{\varphi^{ND}_{\nu_{\alpha}}(E_{\nu})} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_{\nu})}{\sigma^{ND}_{\nu_{\alpha}}(E_{\nu})} \times \frac{\epsilon^{ND}(E_{\nu})}{\epsilon^{FD}(E_{\nu})} \times \frac{p^{FD}(E_{\nu})}{p^{ND}(E_{\nu})} \times \frac{R_{FD}(E^{reco}_{\nu}-E^{vis}_{\nu})}{R_{ND}(E^{reco}_{\nu}-E^{vis}_{\nu})} F_{theo}(E^{vis}_{\nu}-E_{\nu})\,dE'_{\nu}$$

- The most complicated part is :

1) **We measure rate of events in a given energy range** and the neutrino energy spectrum is different at ND (before oscillation) and at the FD (after oscillation)
→ so we measure the xsec and flux at a given energy and we need to extrapolate to a different energy

2) flux and xsec extrapolation from ND to FD are different → we need to separately estimate flux and xsec at the ND

But **we measure only the product of the two = rate of events** (strong anti-correlation between them)

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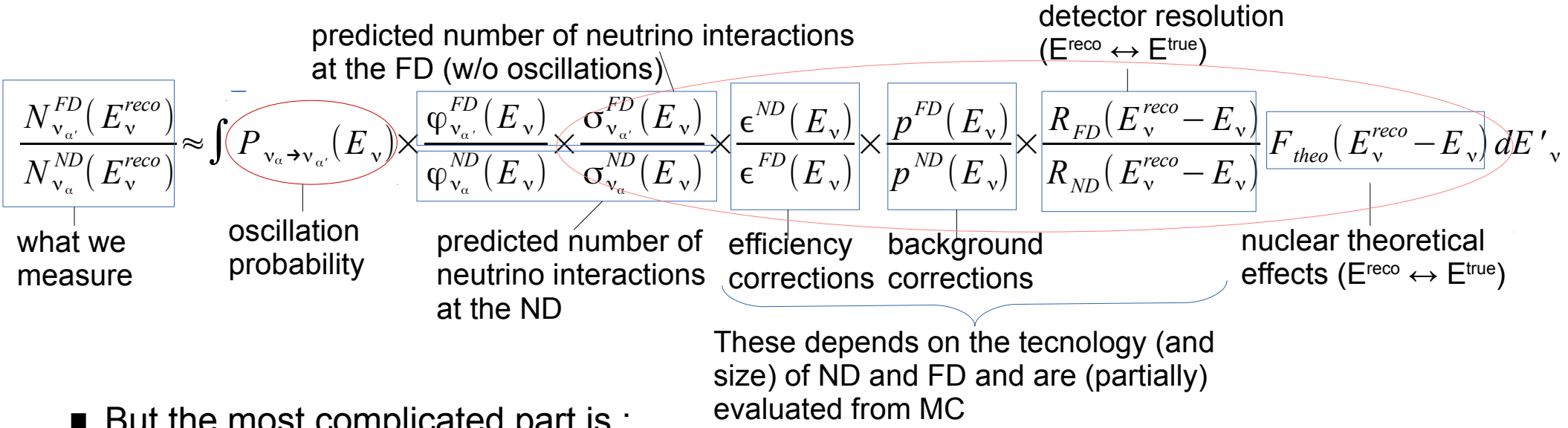

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Statistics

D.Hadley NuFact2017

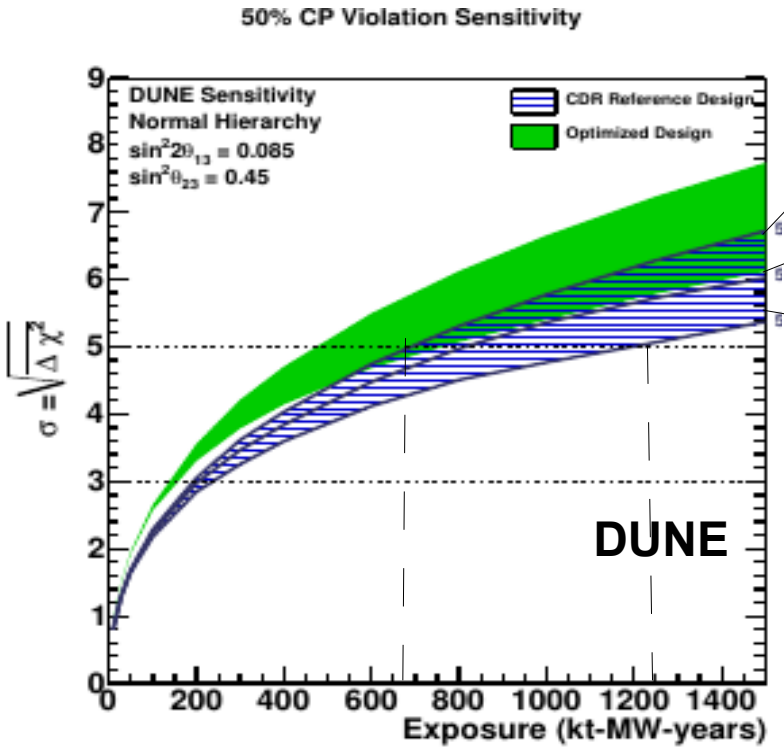
Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 9%	20×10^{21} POT, arXiv1607.08004 [hep-ex]
T2HK	2900 + 2700	2% + 2%	10 yrs 2-tank staged KEK Preprint 2016-21
DUNE	1200 + 350	3% + 5%	3.5+3.5 yrs x 40kt @ 1.07 MW arXiv:1512.06148 [physics.ins-det]

Today stat error ~ 15%

Next generation experiments ~ few 10^3 events → need systematics <2%

The targeted precision

- Oscillation measurements in future long baseline experiments aim to **~1-3% systematic uncertainty on signal normalization**
  (T2K 2017 ~5-6 % dominated by xsec uncertainty)

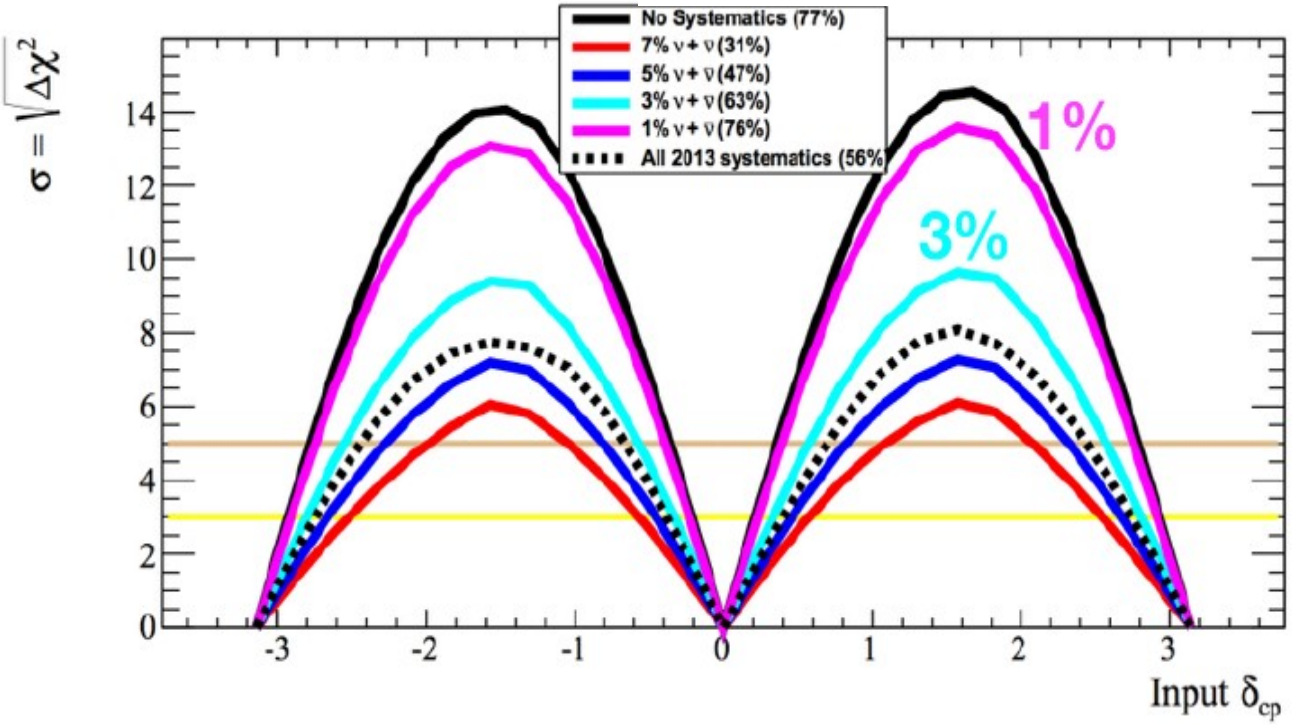


5% ± 1%

5% ± 2%

5% ± 3%

→ equivalent to factor 2 in exposure!



DUNE and HK talks @ NuFact 2015

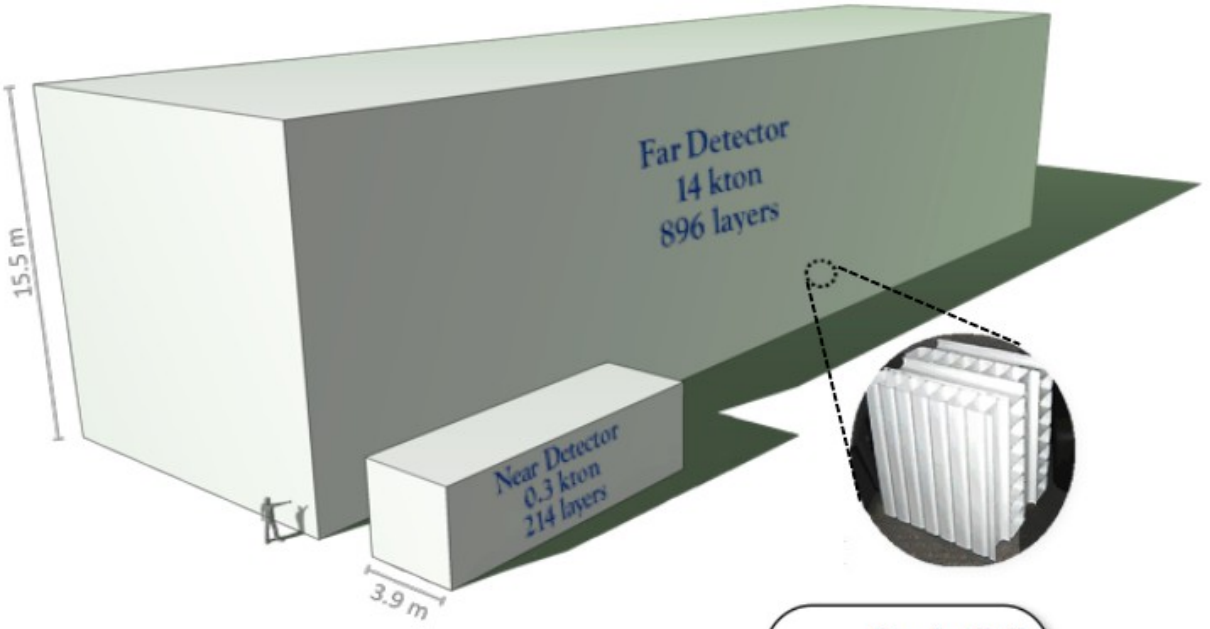
Example of oscillation analysis at T2K and NOVA

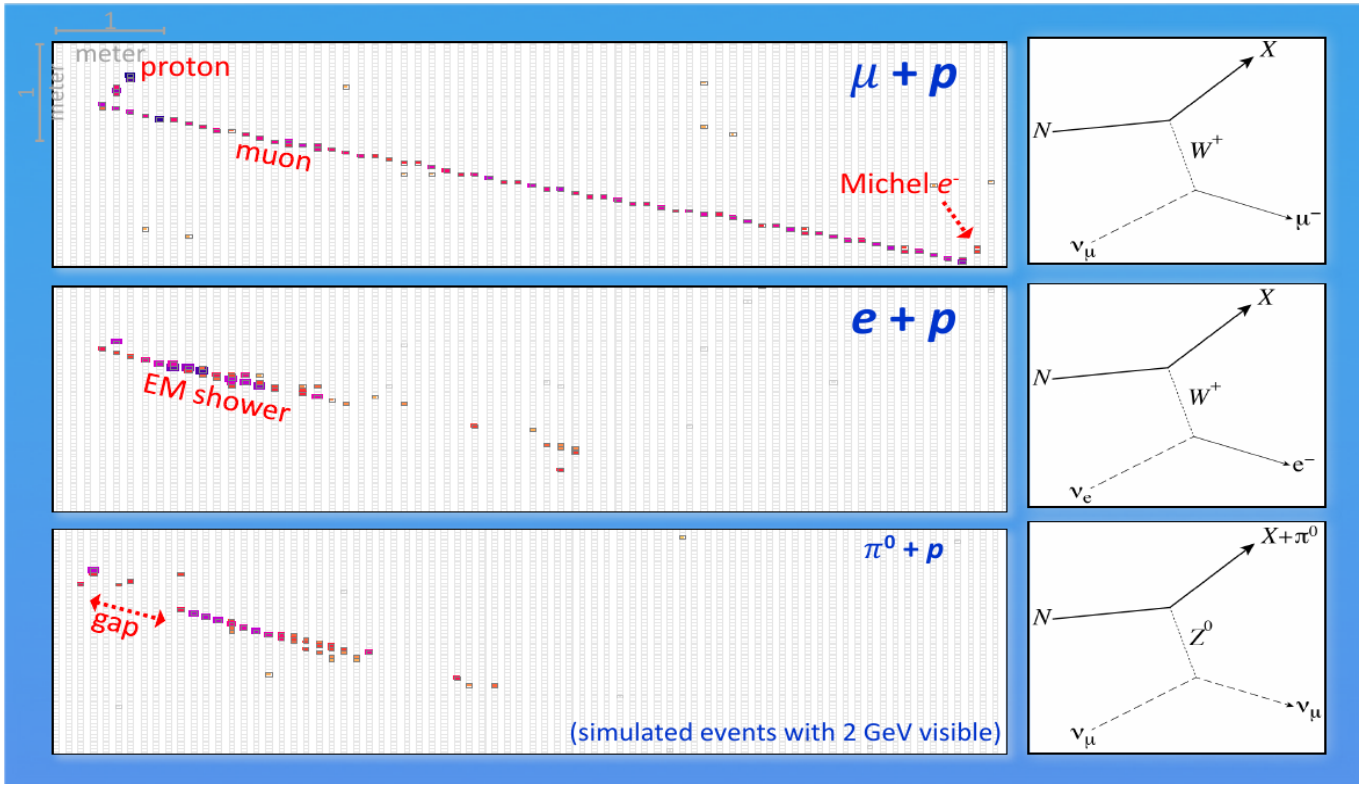
How cross-section uncertainties enter in the game?

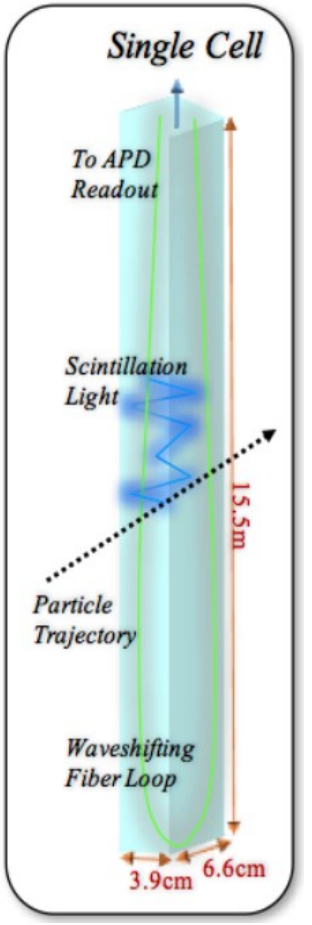
NOVA

Same technology at ND and FD
(not same size → different containment)

Scintillator oil → collect light and use topological info for PID

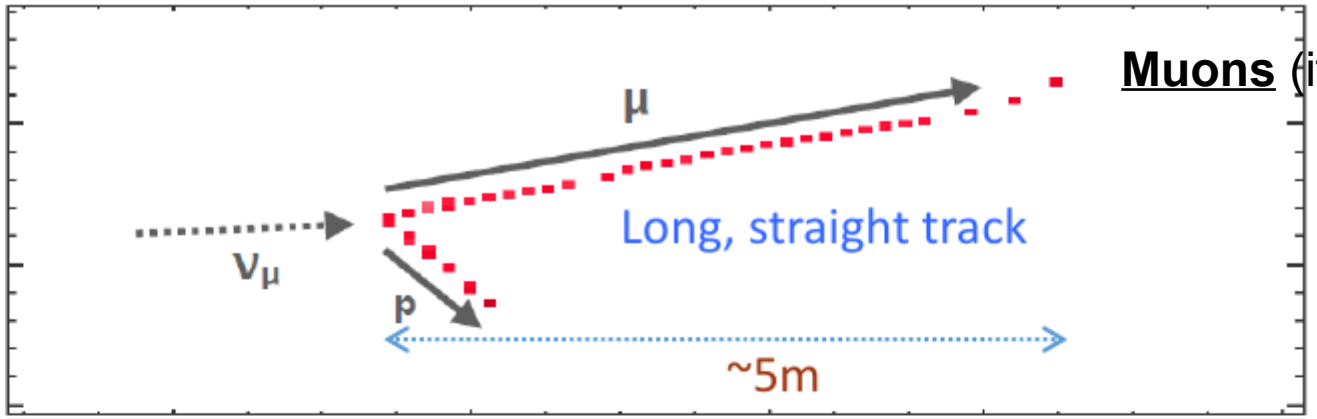






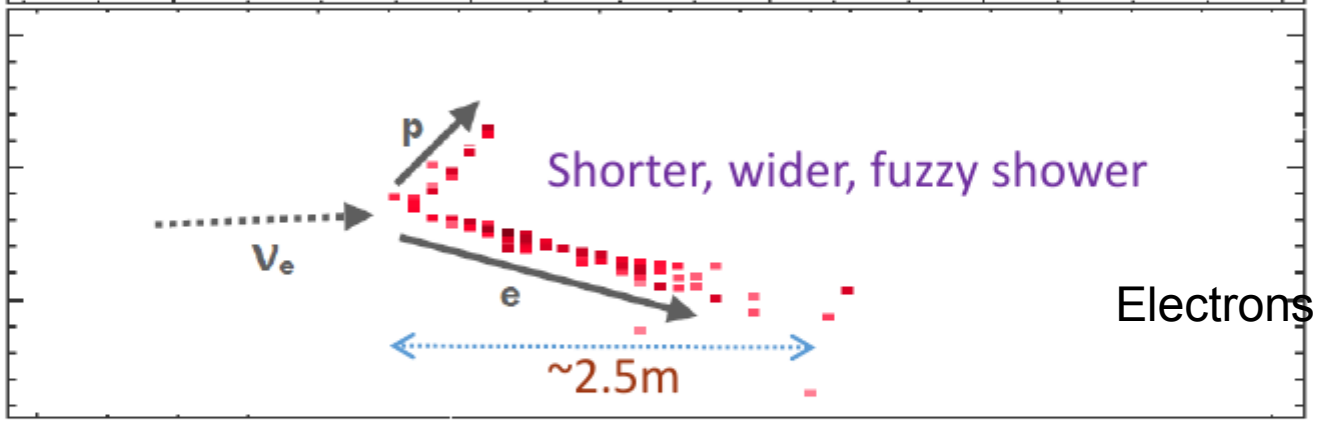
What do we measure?

ν_μ CC



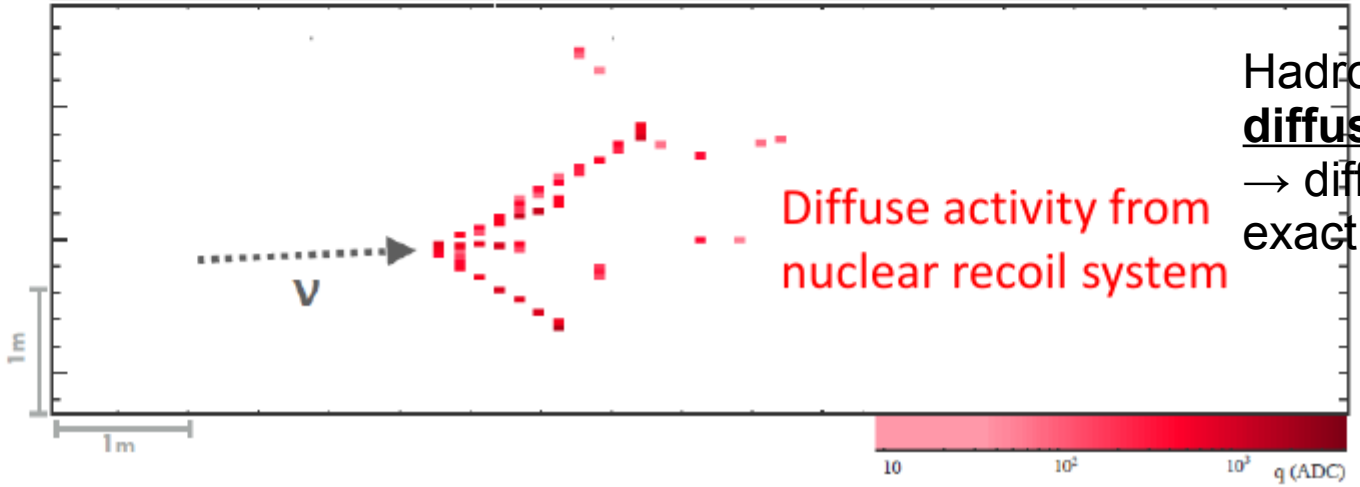
Muons (if contained)

ν_e CC



Electrons as **shower**

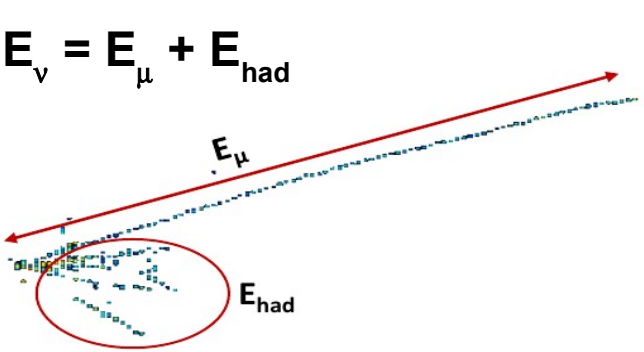
NC

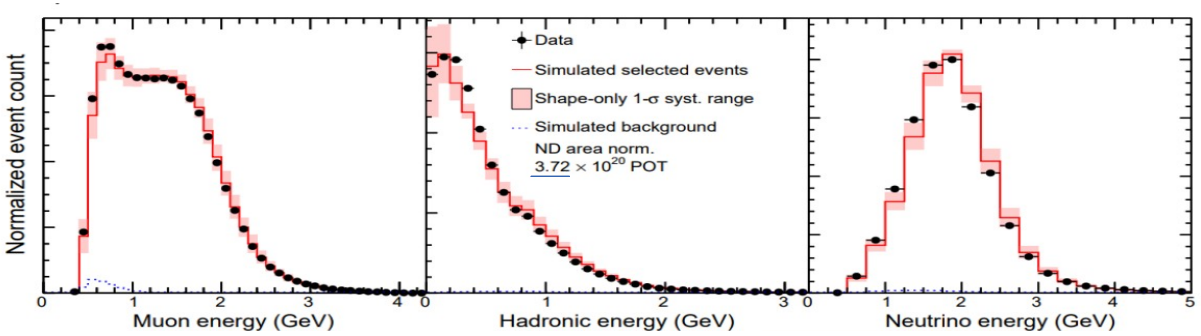


Hadrons (mostly as **diffuse activity + tracks** → difficult to know the exact multiplicity)

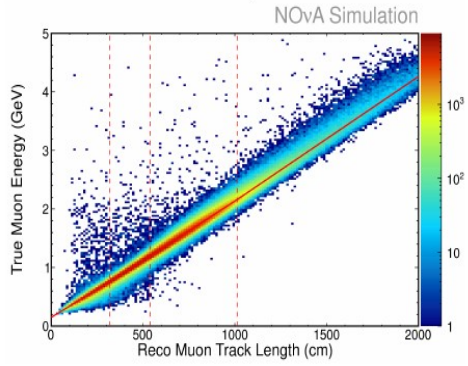
Energy reconstruction

$E_\nu = E_\mu + E_{had}$

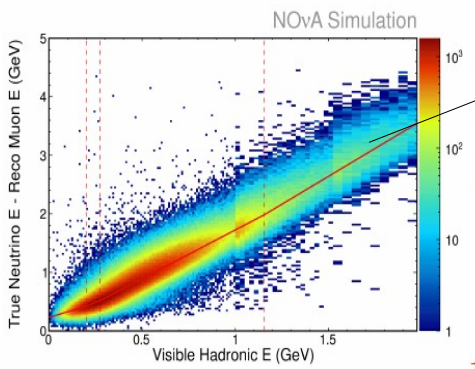




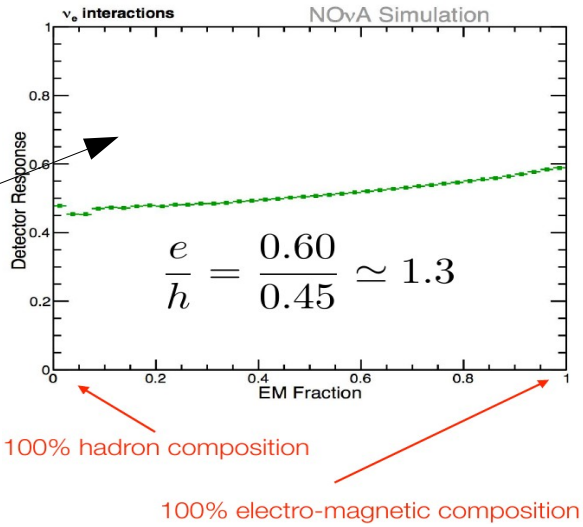
E_ν = E_{lep} + E_{had}



(~3% resolution)

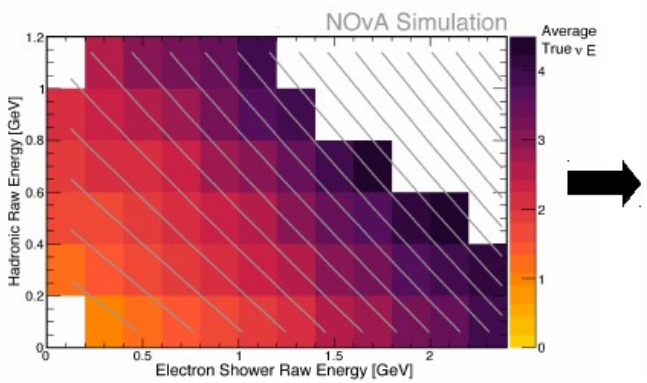


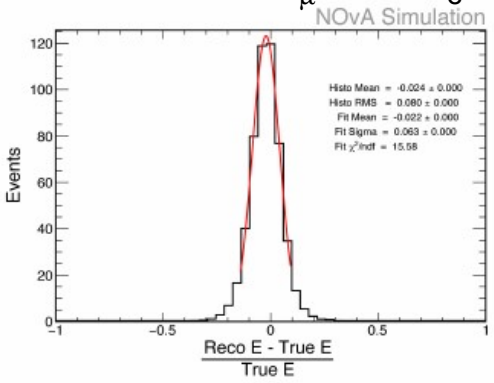
(~15% resolution)



response depend on composition of shower (π^0/hadrons)

Energy reso and detector effects different for ν_μ and ν_e events: different reco and selection

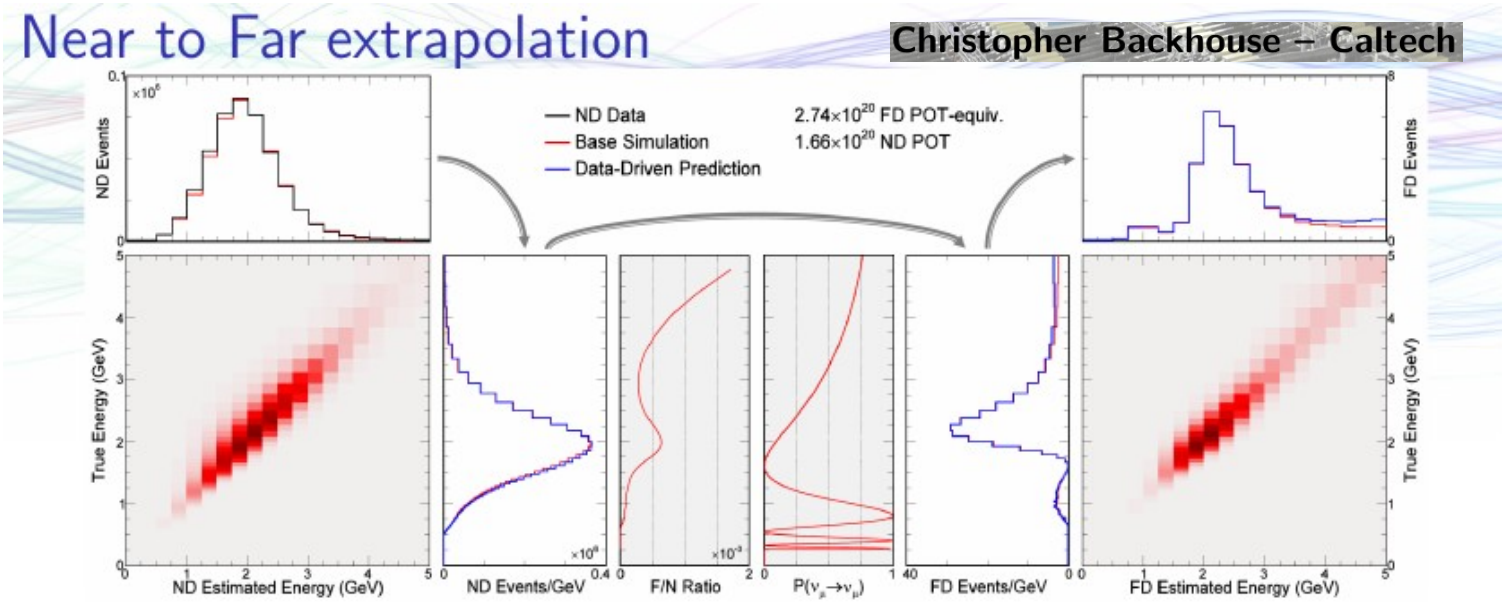




Energy estimator is quadratic function of E_e and E_{had}. ~8% resolution

Calorimetric approach (NOVA)

- Measurement of all the (visible!) energy in the event to estimate the neutrino energy



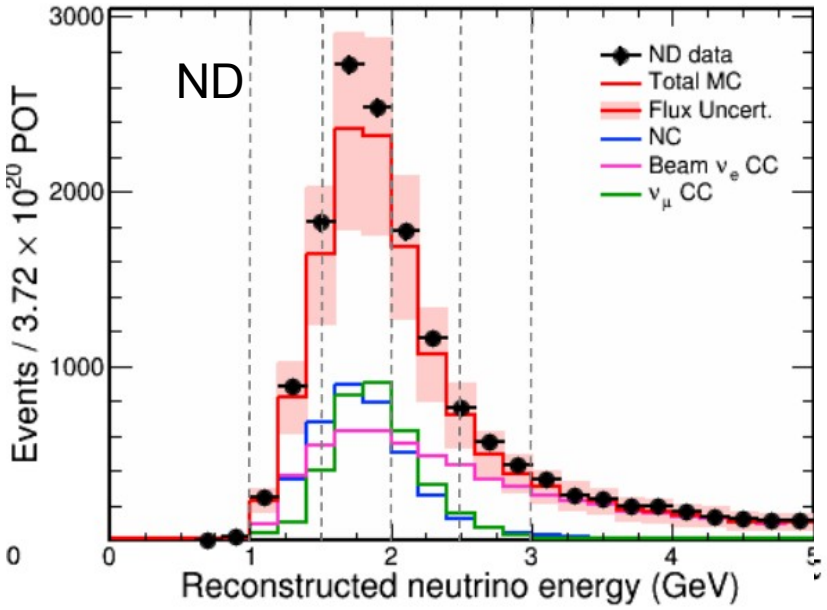
- Subtract NC expectation in ND, reweight MC in reco energy to match
- Transform to true energy, transport to FD with oscillations
- Transform to reco energy, add FD NC expectation back in
- Dependence on MC for background subtraction and true/reco matrix

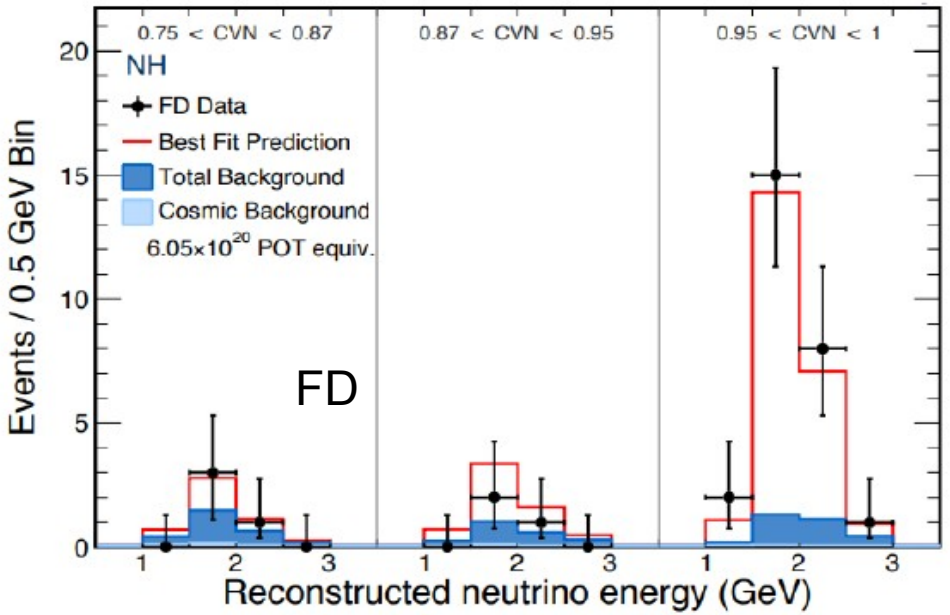
We will see that not only detector systematics but also theoretical uncertainties (FSI, multiplicity in the final state, fraction of neutrons...) do affect the true ↔ reco correspondance

NC background

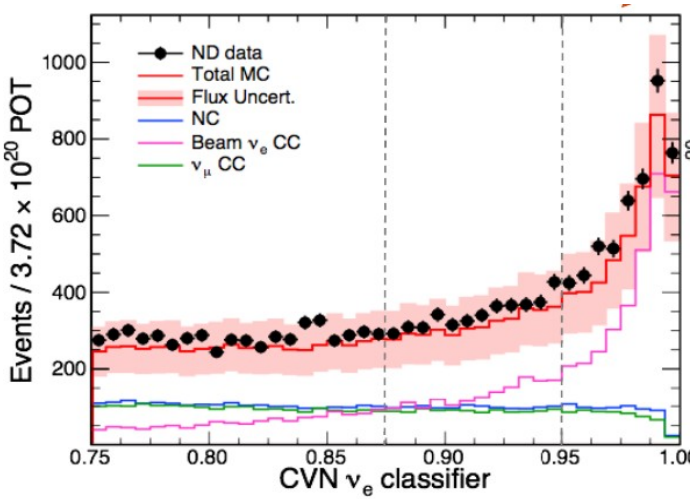
Quite small background for ν_μ since easy to disentangle a muon from an hadron

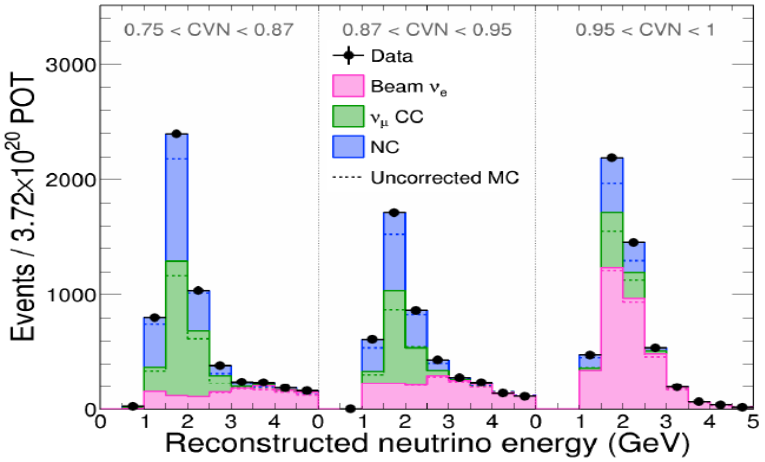
Larger for ν_e:





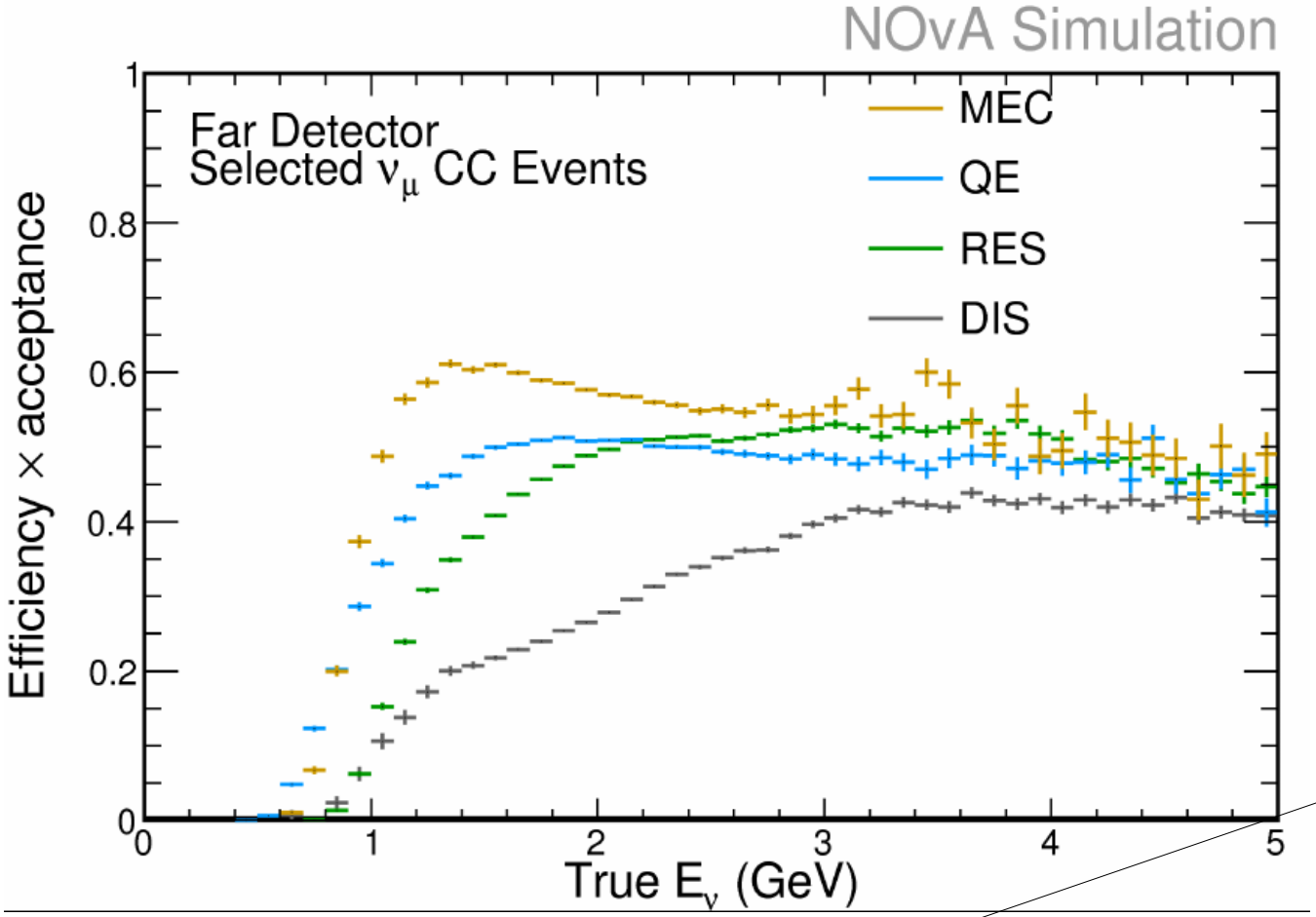
ND data-driven tuning to correct for 10% discrepancy data-MC

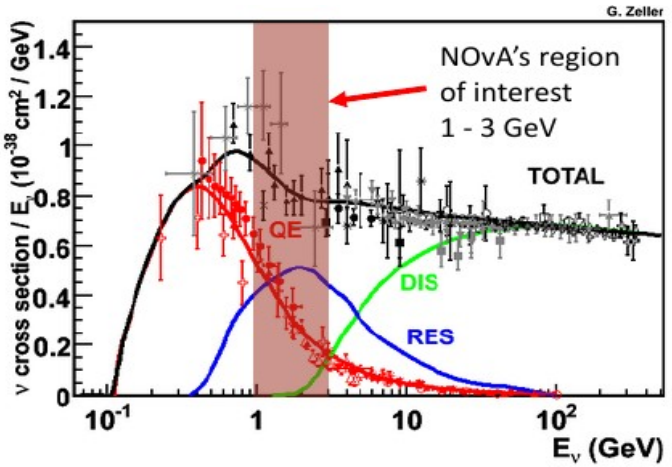




3 regions of electron-classifier with different background fractions

Efficiencies



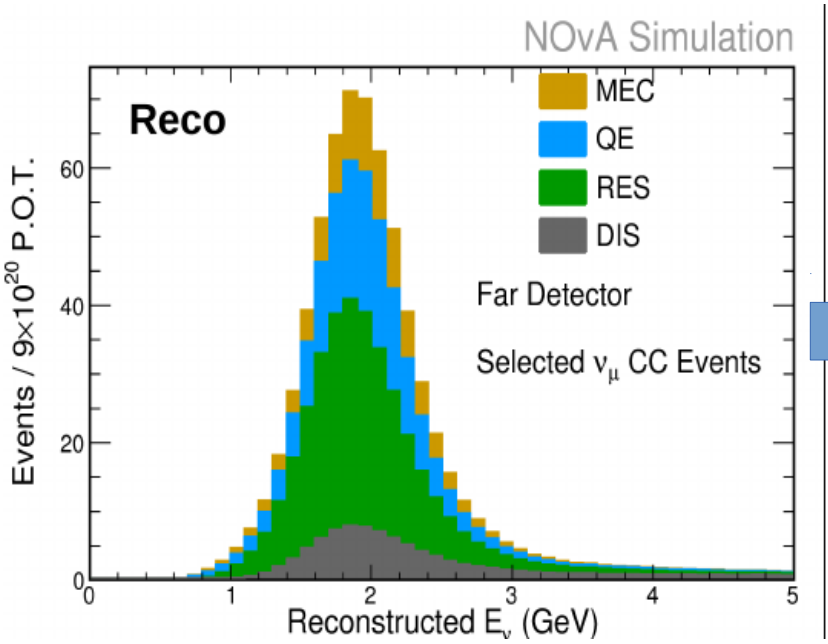


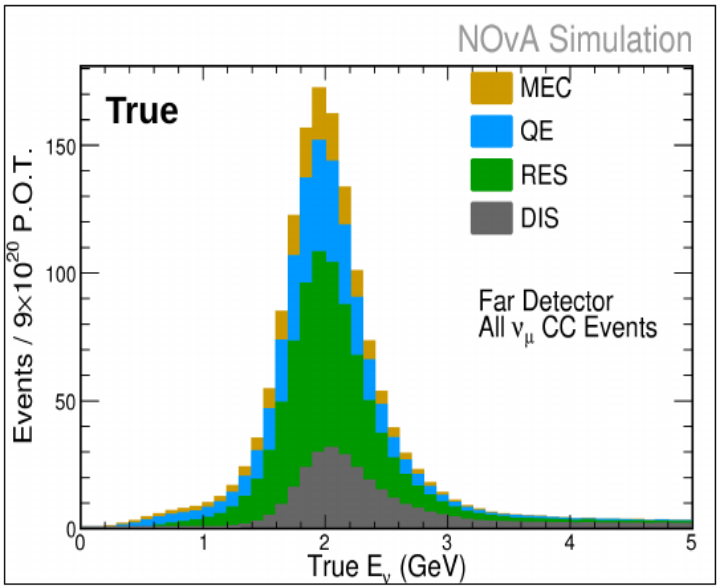
different size of ND and FD → different muon acceptance

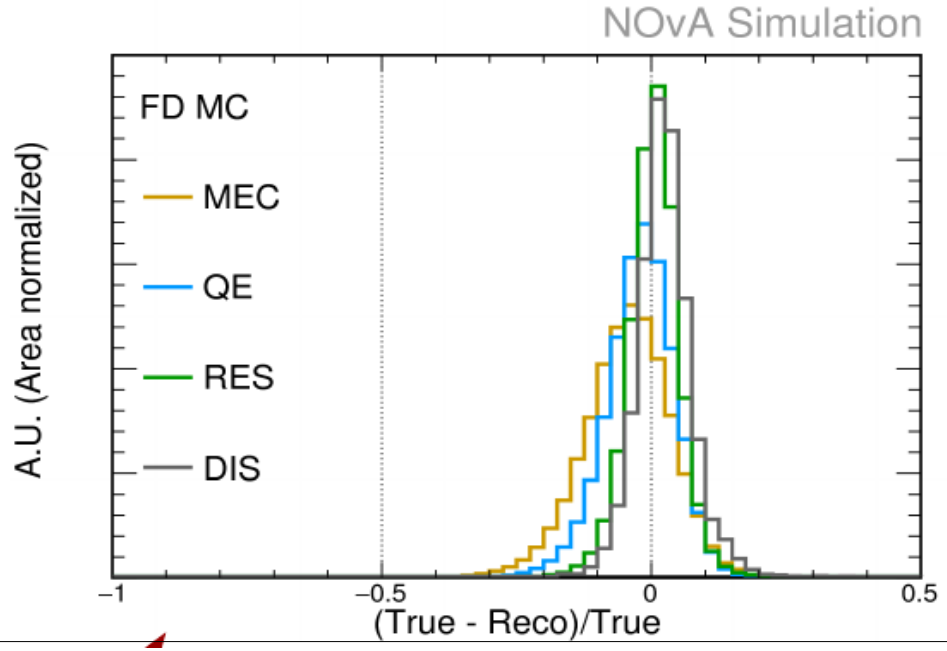
- **Efficiencies sculpted** by containment and background rejections + muon reconstruction more complicated in a high multiplicity environment
- Need to correct back separately for each process to avoid biases in E_ν reconstruction:

correction depend on xsec of each process, hadron multiplicity, lepton kinematics ...

Energy reconstruction







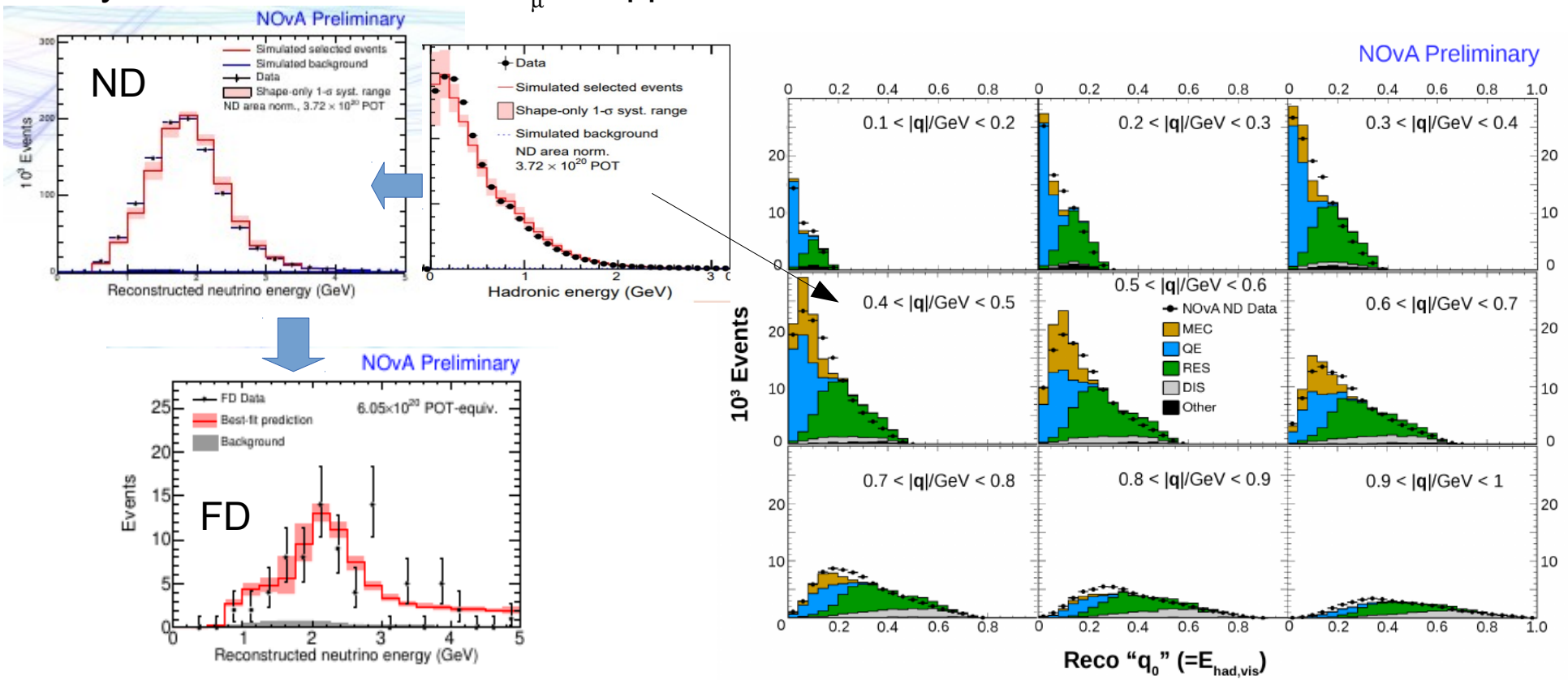
Need to correct from E_{rec} to E_{true}

Correction depends on detector effects + xsec effects (eg neutrals) through efficiencies and resolution

Each process has different resolution + dependence on multiplicity, π^0 fraction, kinematics of leptons ...

2p2h

- **Known mismodeling of hadronic energy in 2p2h (and beyond):** important xsec systematics at NOVA for ν_μ disappearance



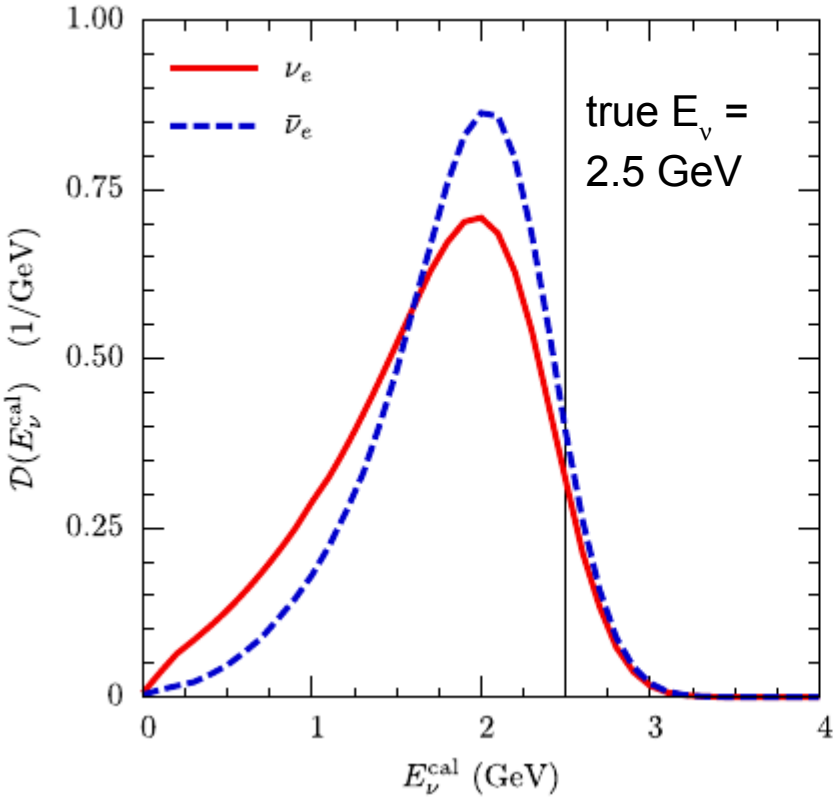
- Another important effect that should be considered is the fraction on neutrons/protons in the final state (depending on the flavor of the correlated pairs in the initial nucleons)

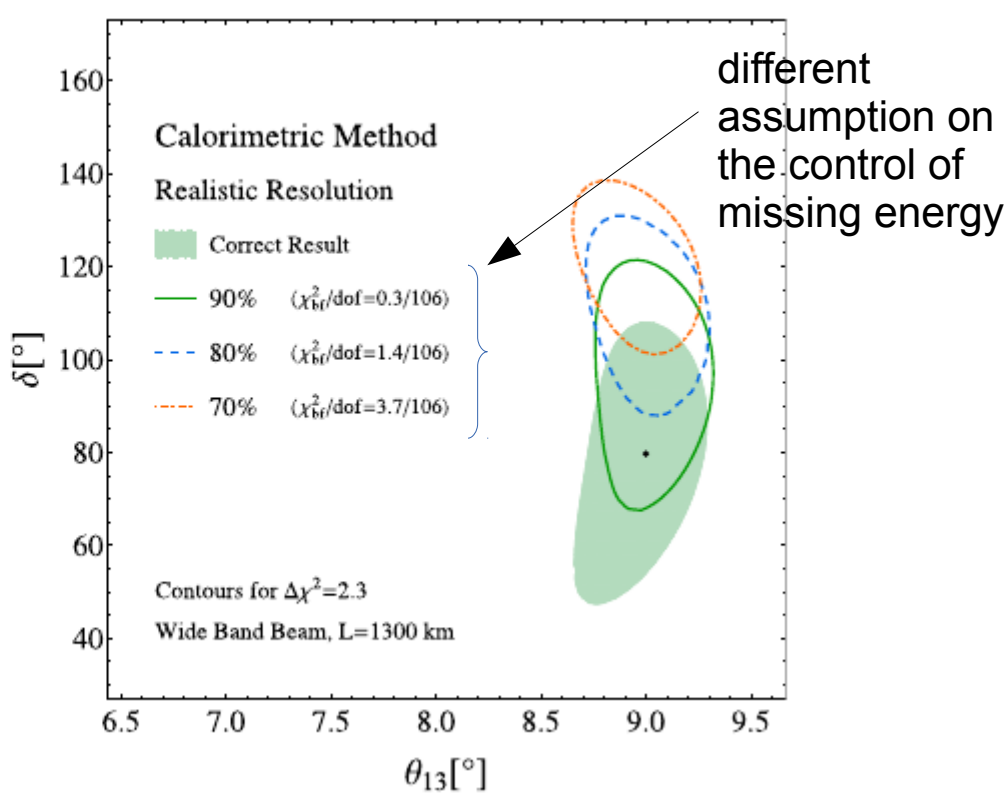
$\nu + nn \rightarrow \mu^- + np$	$\bar{\nu} + pp \rightarrow \mu^+ + pn$
$\nu + pn \rightarrow \mu^- + pp$	$\bar{\nu} + np \rightarrow \mu^+ + nn$

→ **affect $\bar{\nu}/\nu$ differently: important systematics for δ_{CP}**

ν versus $\bar{\nu}$

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054001 A M Ankowski and C Mariani





Smearing and underestimation of neutrino energy due to nuclear effects + detector effects for DIS events

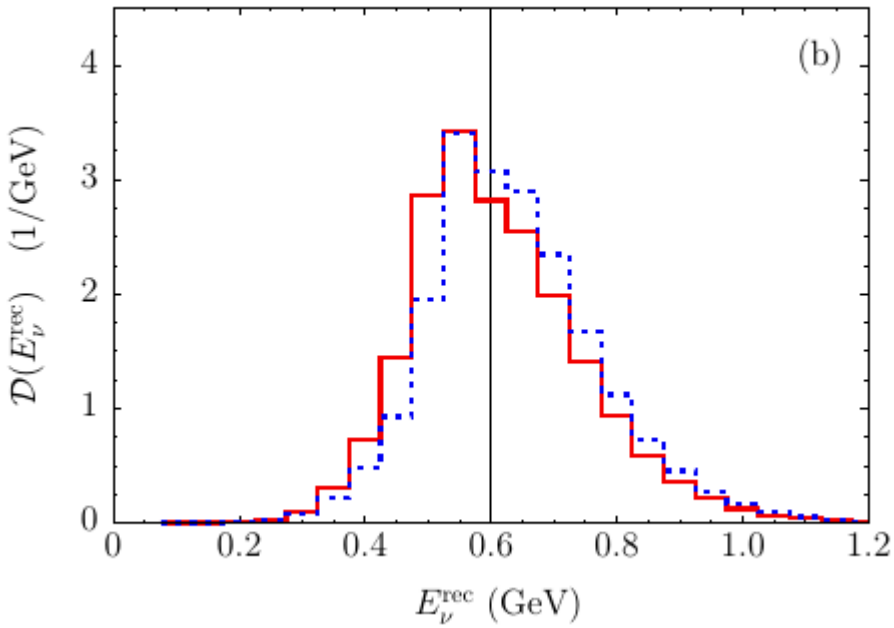
Different response for ν and $\bar{\nu}$ → possible bias on δ_{CP}
(this is due to the convolution of detector effects and nuclear effects)

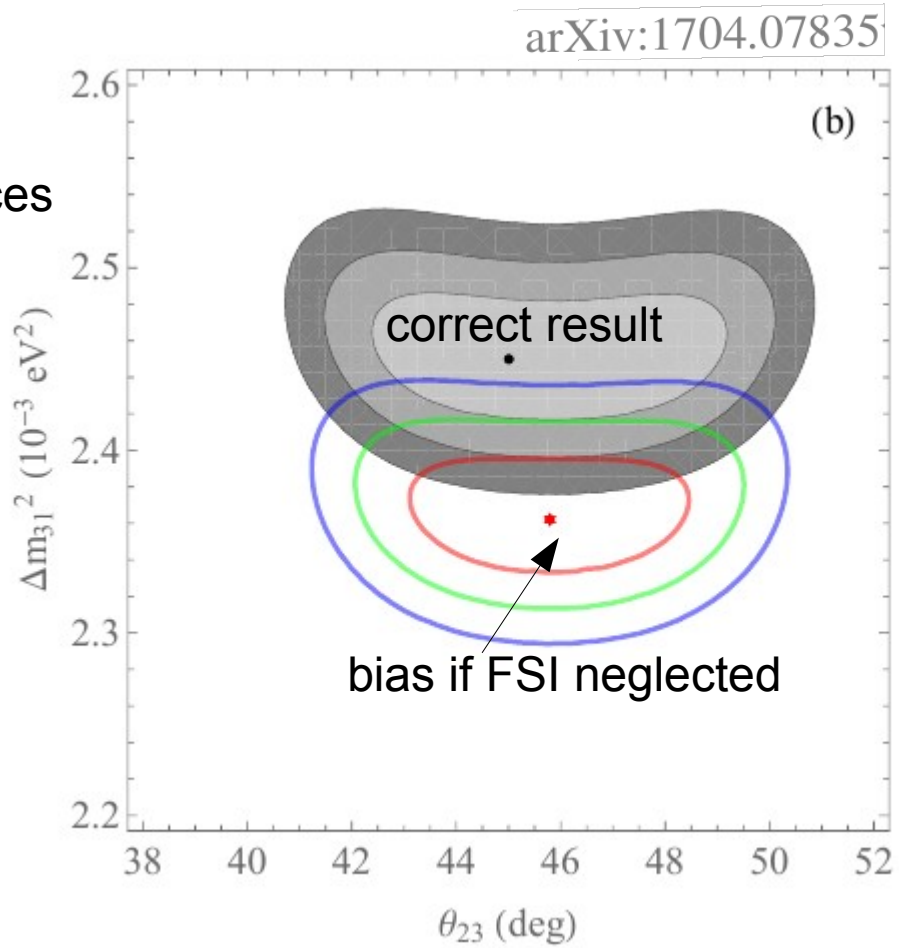
FSI effects on calorimetric energy

→ **Effects on neutrino calorimetric energy reconstruction for oscillation analysis:**

- some energy get lost in the rescattering in the nucleus and cannot be reconstructed
- efficiency corrections for low momentum particles from MC need reliable model of charge, multiplicity and kinematics of outgoing hadrons

Bias in the reconstructed energy if FSI are neglected with 'realistic' detector performances

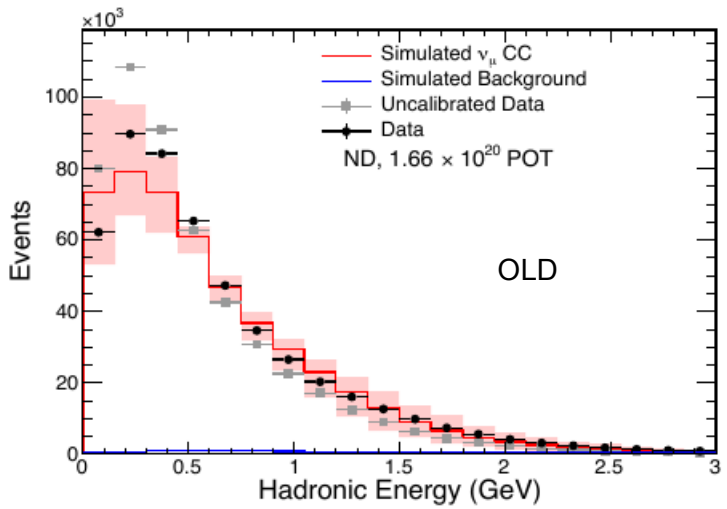


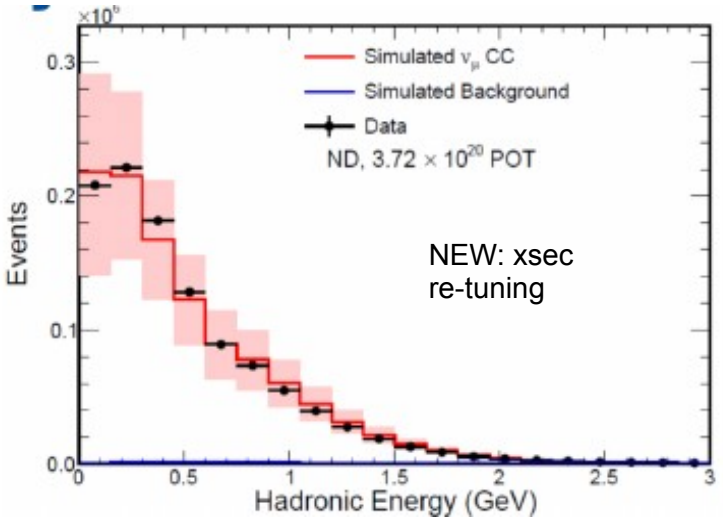


Calorimetric approach: limits

- **Need to correct from reco to true energy.**
  - The detector is not 'perfect': no sensitivity to neutrons, energy threshold... → need to correct from MC knowing (for instance) multiplicity of low momentum hadrons + energy deposits below threshold due to nuclear effects (eg binding energy is 'invisible')
  - Very limited predictivity from models regarding the hadronic final state!
- **Main limitation: convolution of detector calibration and unavoidable nuclear effects**
  The two problems are tightly convoluted and difficult to disentangle

Example from NOVA:





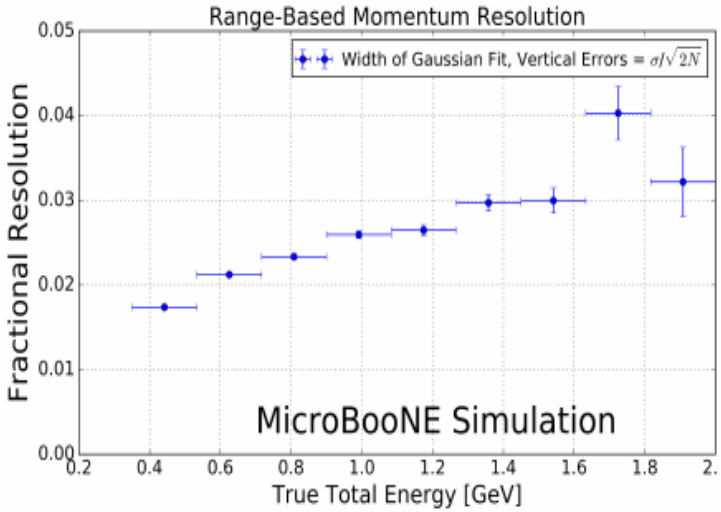
- **A taste of the future → DUNE:**
  - need to reconstruct precise E_ν shape for good sensitivity (two oscillation maxima)
  - capability of full reconstruction of tracks and showers down to very low threshold

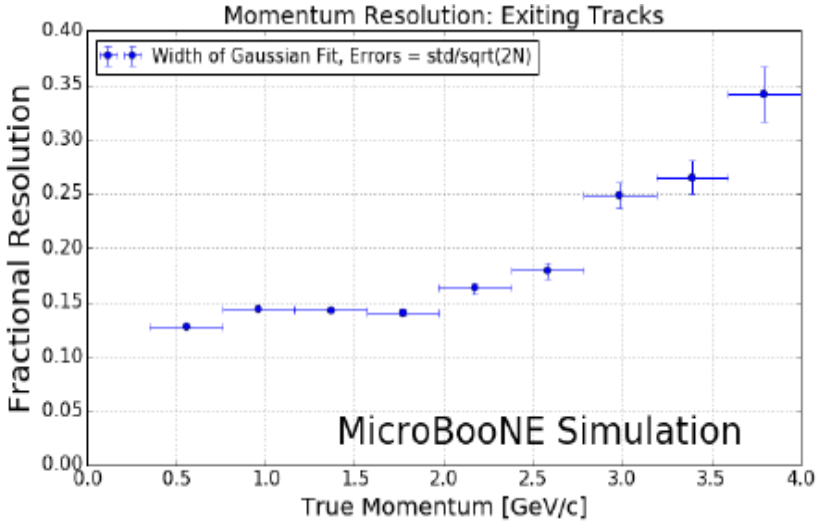
→ need to reach very good control on detector calibration/uniformity *and* on neutrino interaction modelling which have convoluted effected in reco ↔ true E_ν

LAr TPC (MicroBooNE)

- Need to reconstruct muon/electron and hadronic showers to measure the total energy

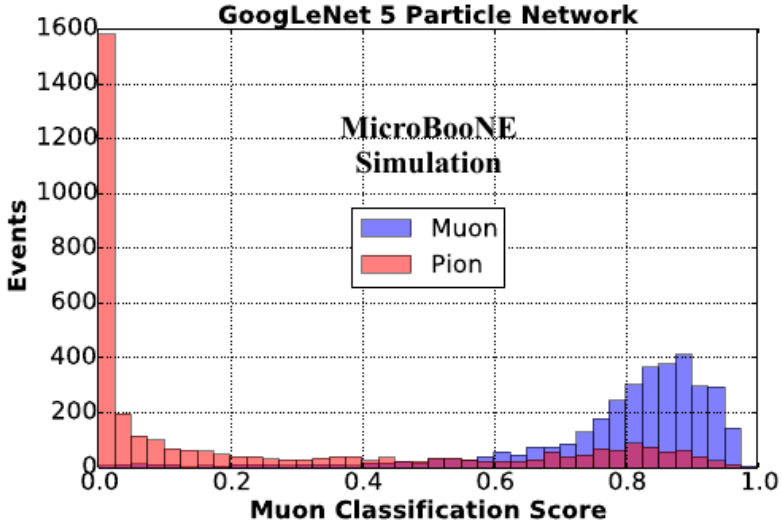
Muon momentum from range (if contained) and multiple scattering

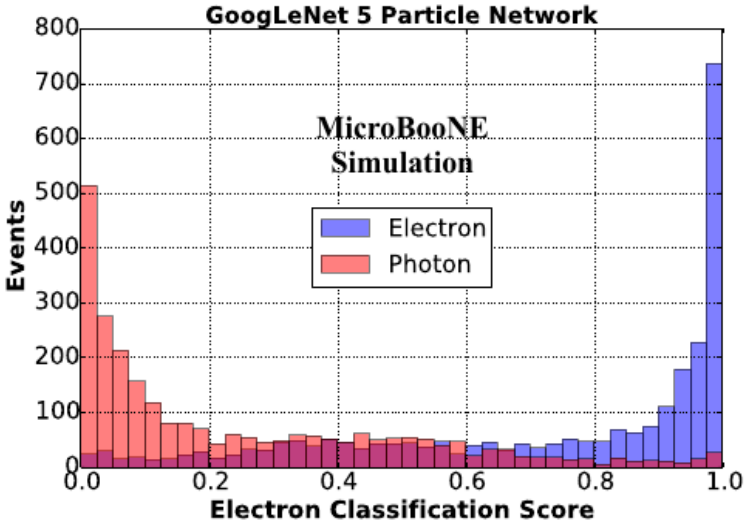




Particle ID from 'visual' Neural Network

Very preliminary simulations from MicroBoone (only single particle simulation, no hadronic side of the interactions)



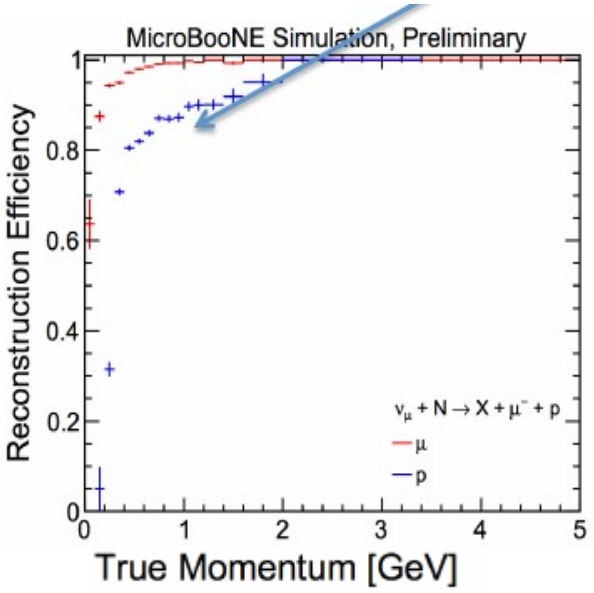


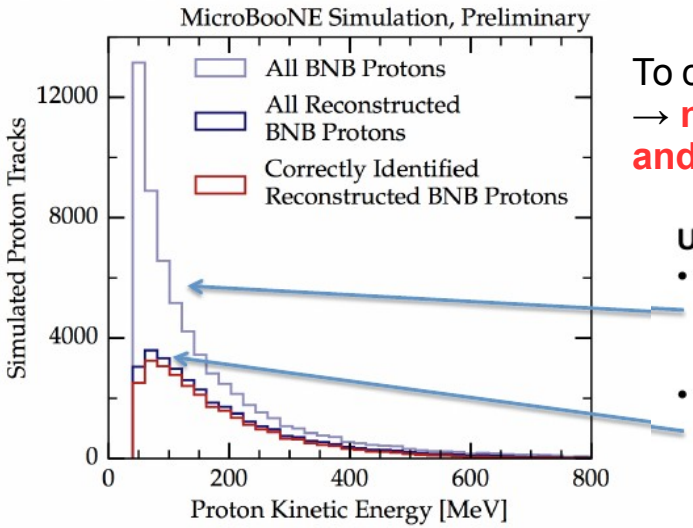
LAr TPC (MicroBooNE)

- Need to reconstruct muon/electron and hadronic showers to measure the total energy

Energy resolution on the hadronic side:

- efficiency of shower clustering reconstruction (vs noise removal)
- π^0/e/γ identification and calibration of EM vs HAD side of the shower ...
- detection threshold of low energy particle





To correct for these effects and go back to total En
→ **need correct MC estimation of multiplicity and momentum of outgoing hadrons**

Uncertainties:

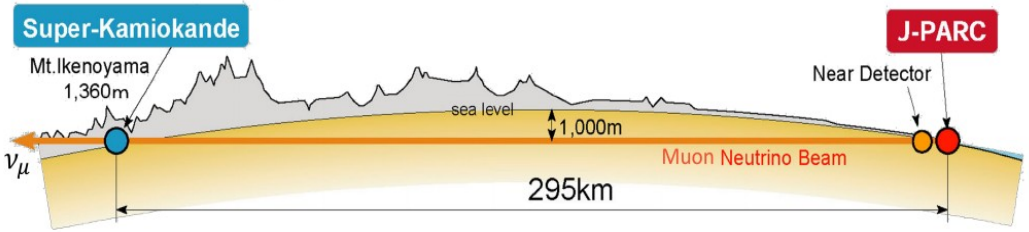
- MC needed to correct for these lost protons
- mis-ID protons counted as pions – energy wrong, or muons – event topology wrong

Full study of these effects to be done at DUNE: how the xsec uncertainties affect the E_ν reco, the efficiency corrections etc...?

(Test benches: MicroBooNE, LArIAT.. and protoDUNEs!!!)

T2K: Tokai (JPARC) to Kamioka (SuperKamiokande)

Long baseline (295 km) neutrino oscillation experiment with off-axis technique:



Far Detector:

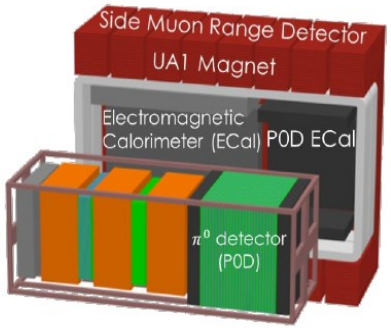
huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

Far Detector

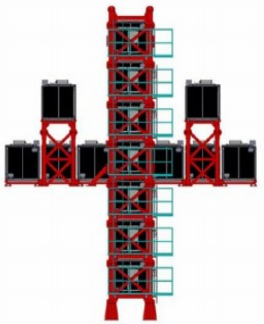
Super-Kamiokande

Near Detectors

Off-Axis: ND280



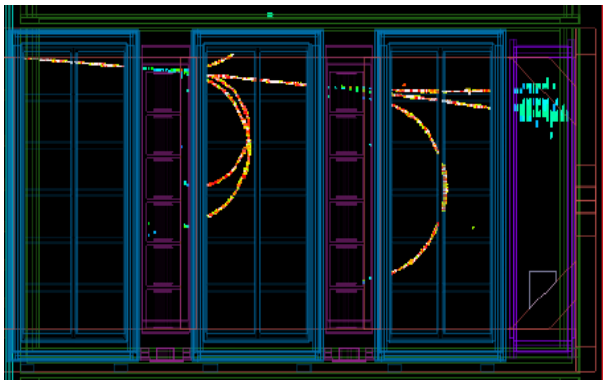
On-Axis: INGRID

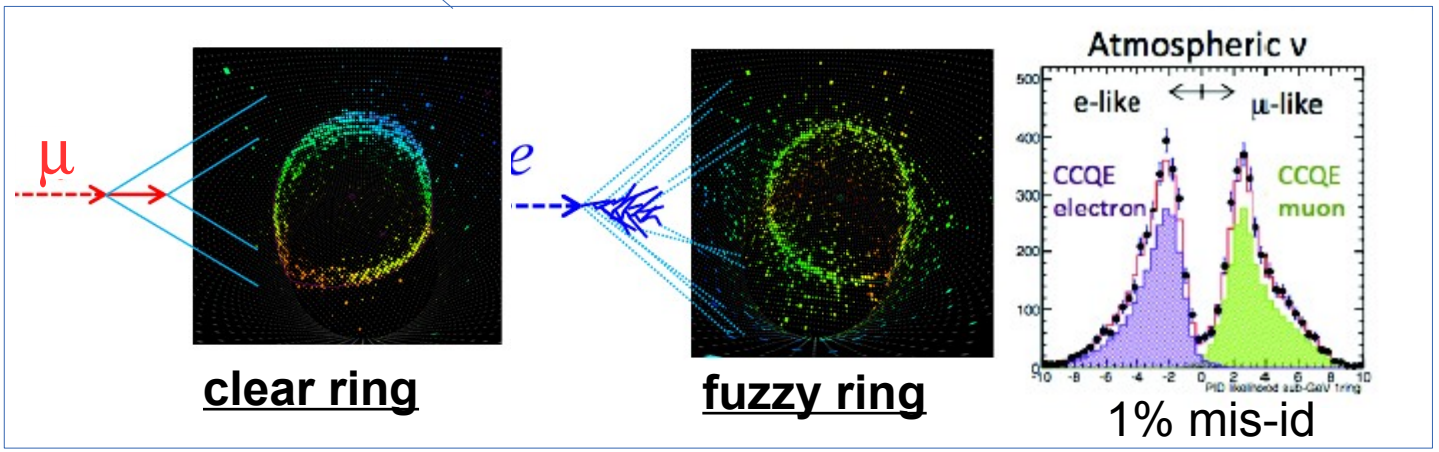


Near Detectors:

On-axis:
iron/CH scintillator
monitoring of beam angle and position

Off-axis:
full tracking and particle reconstruction in near detectors
(magnetized TPC!)





What do we measure?

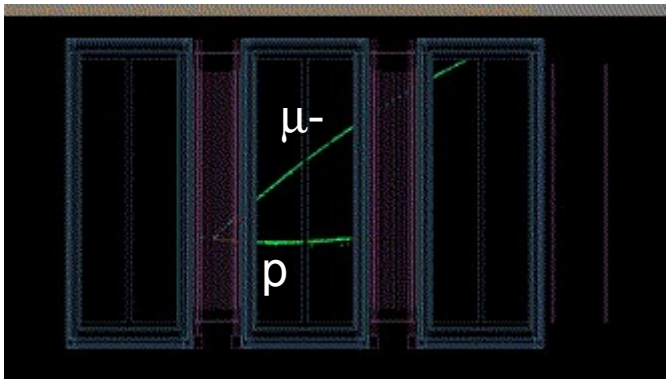
- **Super-Kamiokande:**
  - signal CCQE-only identified as events with only 1-ring from the lepton (proton is below Cherencov threshold)

  → reconstruction of lepton 4-momentum from Cherenkov ring (and μ/e separation)

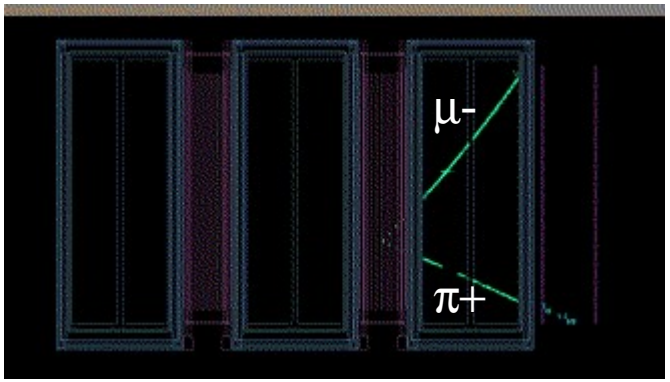
  E_ν estimated from lepton kinematics using nuclear models
  - charged pions rejected if above Cherencov threshold (2-rings events) or by looking at Michel electron.
  - neutral pions ($\pi^0 \rightarrow \gamma\gamma$) give 2-rings

- **ND280 near detector (magnetized):**

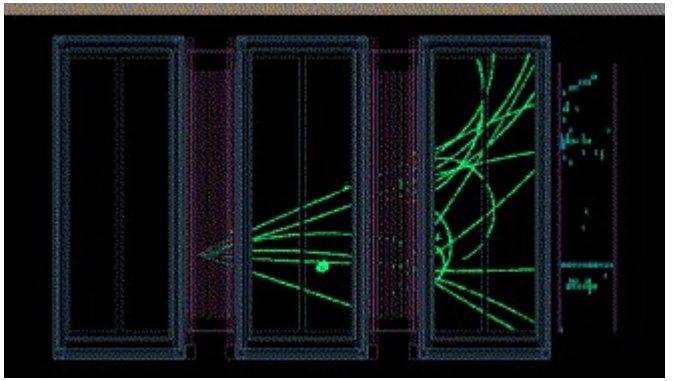
4-momenta, charge reconstruction for all particles reaching the TPC and particle ID to separate the interaction channels:



CCQE event with proton > 500 MeV



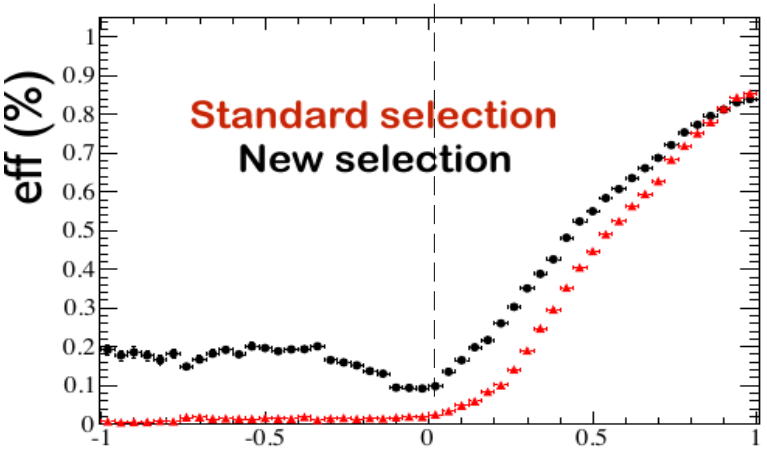
CC1π+: particle ID (p vs μ,π vs e) with dE/dx in TPC



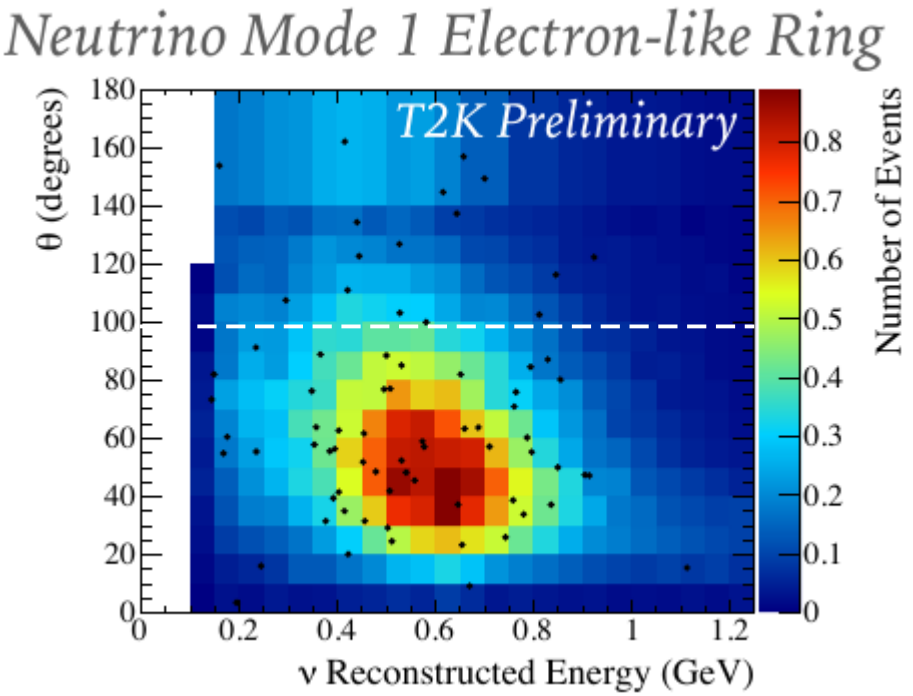
DIS event

Different ND and FD

- ND280 **efficiency**



SuperKamiokande events



- Phenomenological study neglecting the difference between nuclear model in **Carbon and Oxygen**:

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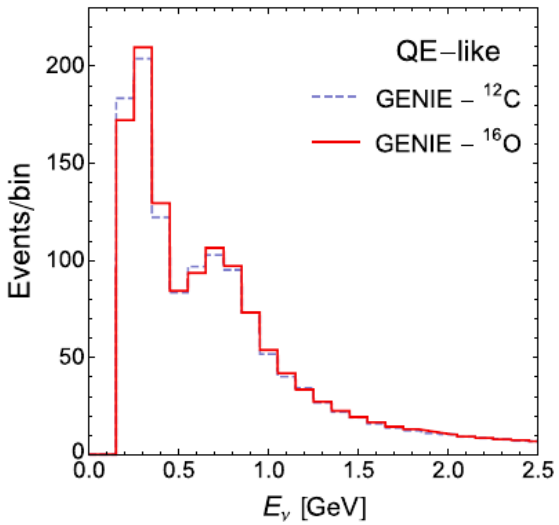
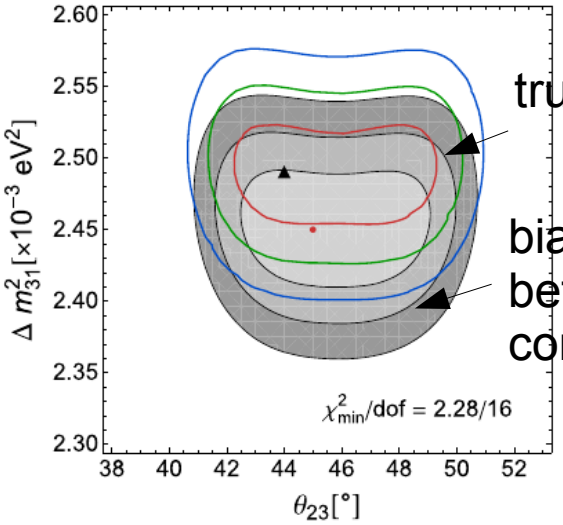
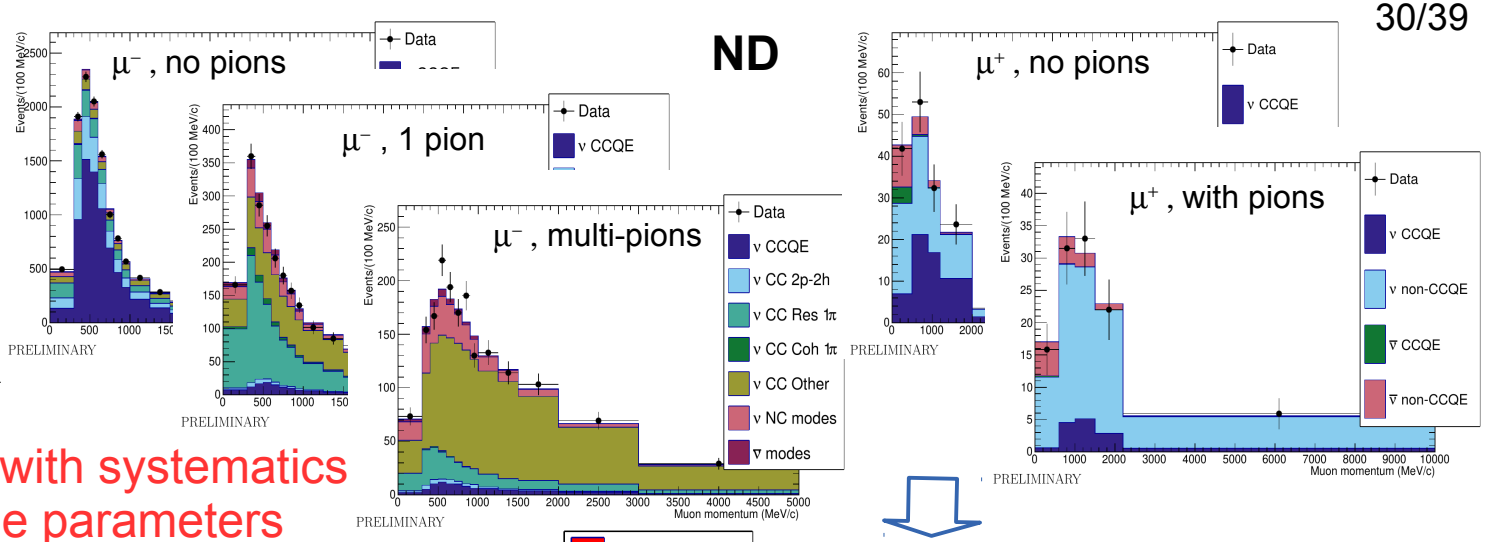




true result (5y data taking)

biased result if difference between C and O are not considered

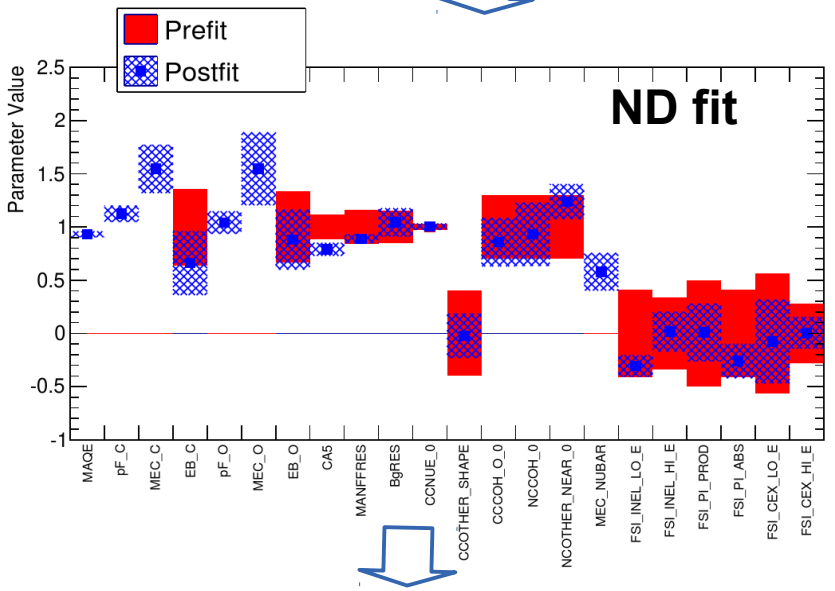
T2K analysis



- Full cross-section model with systematics parametrized with variable parameters

→ ND data divided in samples to **fit cross-section parameters** (+flux)

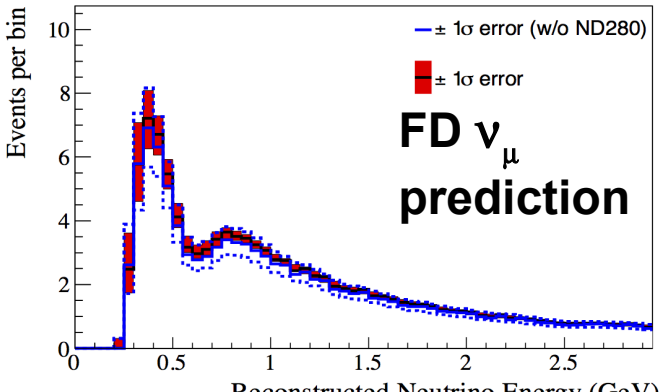
Prediction at FD as a function of muon kinematics



Nuclear effects (initial nucleon momentum or additional final state particle) are estimated from MC **to correct to true neutrino energy (MC fully tuned to fit to ND data!)**

- ND280 allow a precise constrain on nuclear effects which is necessary to estimate E_ν

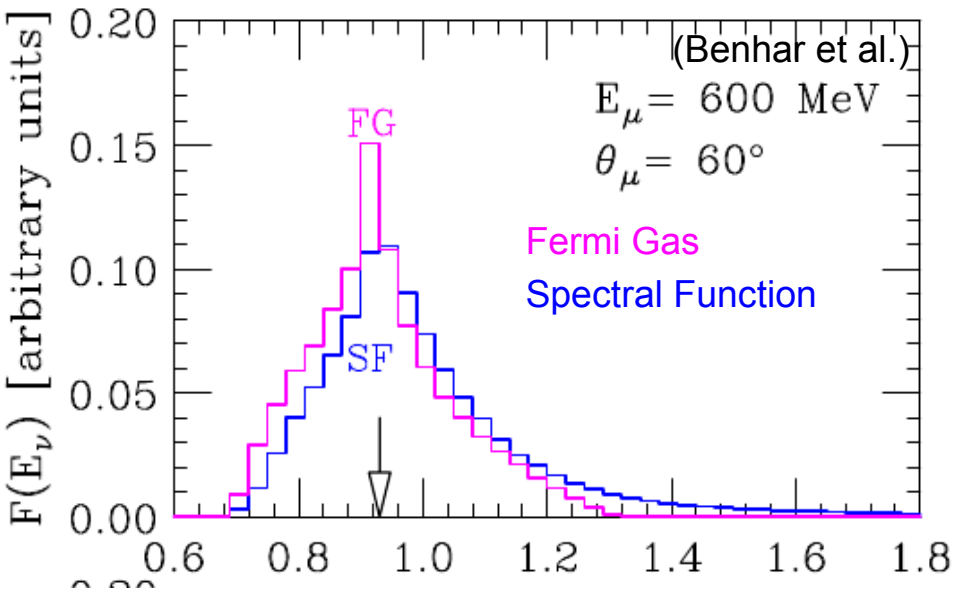
(ND and FD different technology is useful for T2K)



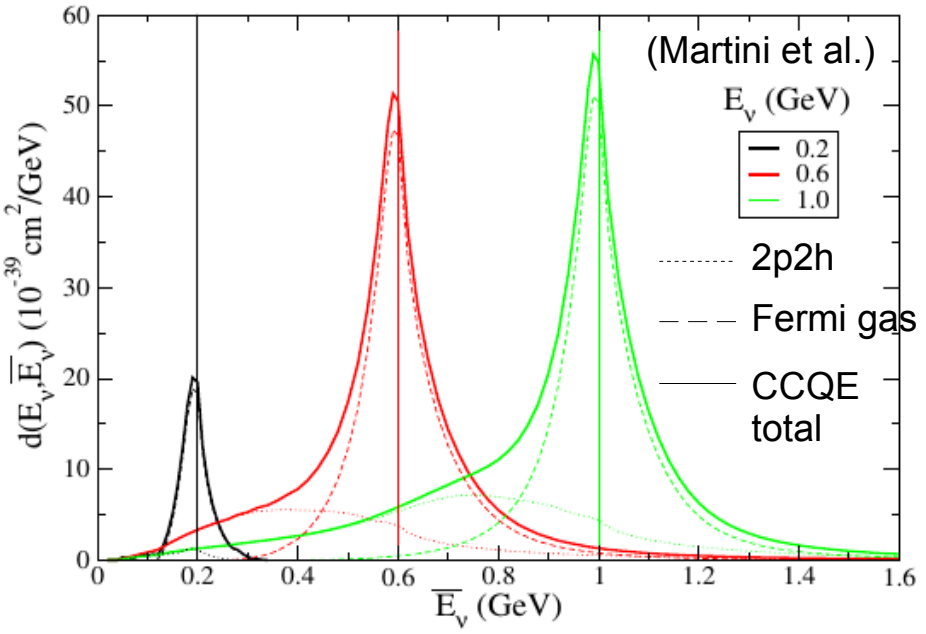
From muon kinematics to E_ν

- **Estimation of neutrino energy from muon kinematics depends on nuclear model**

Spreading of reconstructed E_ν for fixed true E_ν due to nuclear model



Some nuclear effects (scattering on correlated nucleon pairs, aka 2p2h) can also give a bias.



- Very important to have proper parametrization of such effects at ND to correct for them:
  - possible bias **if the model is wrong** and/or underestimation of the uncertainties **if the model is not complete**
  - remaining **unconstrained uncertainties from what cannot be measured at ND** (eg: different acceptance or ν_e xsec)

T2K limitations

Main limitations of the far detector in order of importance regarding xsec uncertainties:

- At SK lepton kinematics only accessible in order to measure the energy (no access to nucleons and low momentum pions)

  → multipurpose ND can be used to ping-down the needed xsec inputs for corrections (and $E_{lep}+E_{had}$ at the ND can be measured)

- Signal for oscillation analysis limited to CCQE only

  → in future pion kinematics will be reconstructed at SK as well (Michel electrons can be used below threshold)

- Different near and far detector: different target and acceptance

  → also Oxygen target and some backward efficiency in ND

- No charge separation (need good control of nu instrinsic pollution in nubar flux and viceversa)

  → ND fully magnetized: precise measurement of wrong sign background in the flux

What do we need to know from nuclear theory?

- Neutrino cross-section as a function of energy (different energy spectrum at ND and FD because of oscillations)
- Neutrino cross-section for different processes CCQE, 2p2h, CCRES, DIS

(since corrections for detector effects like acceptance, efficiency, energy resolution are different for each process)

- Full lepton kinematics outgoing from neutrino interactions → to correct for acceptance and efficiency
- Invisible energy due to nuclear effects (eg. binding energy, final state interactions...)

For E_ν reconstruction different techniques depending on the experiment:

- **NOVA** needs to know the multiplicity of outgoing hadrons and their kinematics in order to correct Ereco ↔ Etrue and because lepton efficiency also depends on this (**DUNE** will have similar needs)
- **T2K (and T2HK)** need to know the correspondence of lepton kinematics and E_ν in CCQE events

What about different neutrino species?

δ_{CP} and $\nu_e/\bar{\nu}_e$ xsec

- Measure of CPV relies on the rate of ν_e and $\bar{\nu}_e$ appearance after oscillation

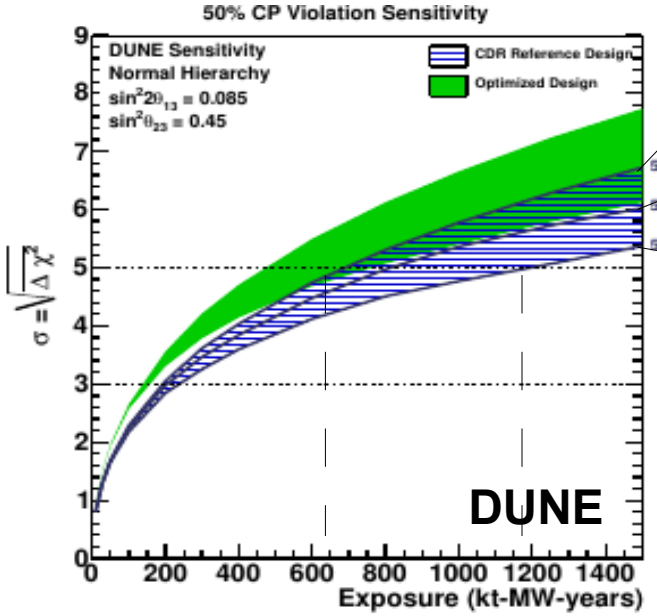
$$\sin(\delta_{CP}) \approx \frac{(\nu_\mu \rightarrow \nu_e) - (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{(\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

→ difference between ν_μ and ν_e / $\bar{\nu}_e$ xsec has a direct impact on δ_{CP}

- Very low statistics of ν_e in 'standard' beam → cannot be constrained at ND

ν_e / $\bar{\nu}_e$ largest systematics for DUNE and HyperKamiokande

- For future long baselines what matter are the uncorrelated uncertainty between different neutrino flavors and 'charge':



5% ± 1%

5% ± 2%

5% ± 3%

5% $\nu_\mu - \bar{\nu}_\mu$ + uncorrelated ν_e - $\bar{\nu}_e$ 1-3%

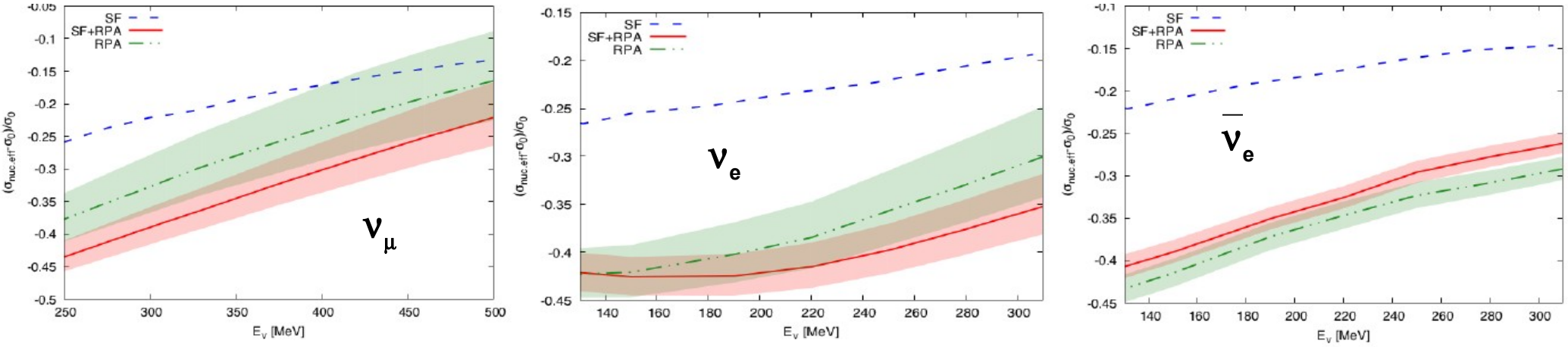
→ equivalent to factor 2 in exposure!

$\nu_e/\bar{\nu}_e$ xsec

- In principle, **if ν_μ xsec is perfectly known, the model can be easily used to extrapolate to $\bar{\nu}_\mu$ and ν_e** (lepton universality and CP symmetry hold in neutrino interactions)

In practice, large uncertainty on ν_μ due to nuclear effects, may affect differently ν_μ, $\bar{\nu}_\mu$ and ν_e
→ **Uncorrelated uncertainty between ν_μ, $\bar{\nu}_\mu$ and ν_e are just a product of our limited knowledge on ν_μ interactions**

Correction to the CC inclusive cross-section due to nuclear effects for different model with theoretical uncertainty band:

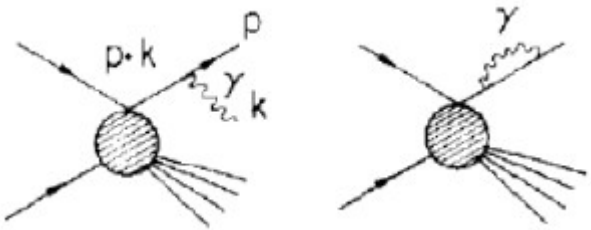


- **Need to control ν_μ *very* precisely** (or find a way to produce a high stat beam of ν_e)

An important missing piece for ν_e

Different radiative corrections for $\nu_e \rightarrow e$ and $\nu_\mu \rightarrow \mu$ (because of different lepton mass)

- The only approximated calculation available is:



Nuclear Physics B154 (1979) 394–426
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RADIATIVE CORRECTIONS TO HIGH-ENERGY NEUTRINO SCATTERING

A. DE RÚJULA * and R. PETRONZIO **
CERN, Geneva, Switzerland

A. SAVOY-NAVARRO
DPhPE, CEN, Saclay, France

Received 19 January 1979

- That formalism has been recently applied to QE cross-section computation:

~10% effect on the difference between ν_μ and ν_e cross-section !

→ **need less approximated calculation?**

(HEP theory expertise!)

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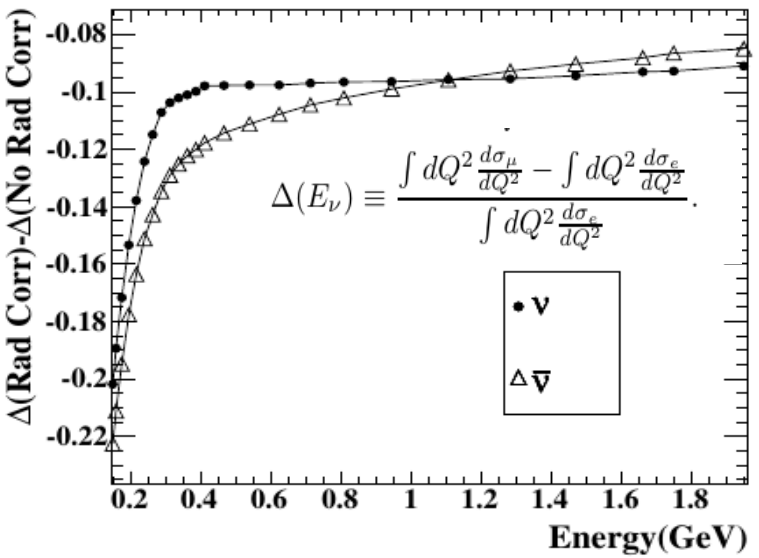


How we are going to improve the ν xsec uncertainty? (1)

- **In a direct way adding new samples at the ND:** eg, improve efficiency for high angle and low momentum particles and include those in the ND fit of oscillation analysis

- **In a indirect way measuring neutrino interactions at ND (and elsewhere):** measure protons, vertex energy, … which are not directly included in oscillation analysis but **help us understanding the goodness of our models and/or constrain the prior uncertainties**

  → **worldwide effort of cross-section measurements!**

Effects on the cross-section which are very small (eg different neutrino flavours or carbon versus oxygen difference) will be very difficult to constrain directly from the data (need very large statistics and/or complex experimental setup/analysis)

But if we do **high precision measurements in ν_μ on a given target** to better constrain the nuclear model then we will know **how to extrapolate to different target and neutrino species**

(... we will never get rid of our models... better to have good ones !!)

How we are going to improve the xsec uncertainty ? (2)

- A lot of room of improvements in the models and their MC implementation: still using relativistic Fermi gas in the simulations !!!

Eg: need models able to describe also electron-scattering data, radiative corrections to ν_e interactions

- A lot of external data available now and in the future to tune such models and simulations:
  - **electron scattering** for nuclear effects (2p2h, binding energy, …)
    → new physics plan (CLAS, JLab) for Argon target in view of DUNE!
  - **neutrino on bubble chamber and pion electro-production data** for nucleon form factors
  - measurement of **pion and proton scattering at protoDUNE** to tune FSI simulations

A joint effort between

- different on-going and future experiments:

  T2K (→ T2K2) + NOVA

  Minerva, LArIAT, protoDUNE...

  DUNE + HK

- and theoreticians (difficult interplay between nuclear and particle physics)

is absolutely imperative to reach the precision needed for the next generation of long baseline experiments!

BACK-UP

Coming back to xsec uncertainties...

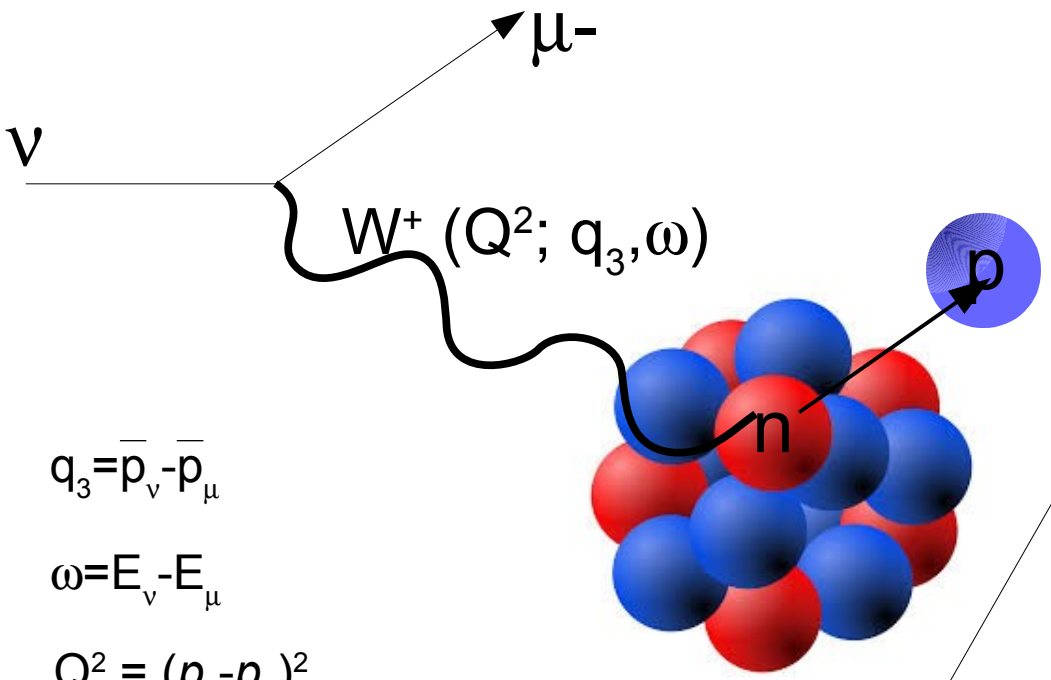
What do we need to control?

Uncertainties in ND→FD extrapolation :

- different E_ν distribution (because of oscillation) ⇒ measure all particles in the final state: threshold and calibration at low energy (neutrons? FSI?)
- 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 and containment at ND
- different neutrino flavor (because of oscillation)
- ν ($\bar{\nu}$) flux has typically a wrong sign component

⇒ 'control' cross-section asymmetries between different neutrino species

The cross-section



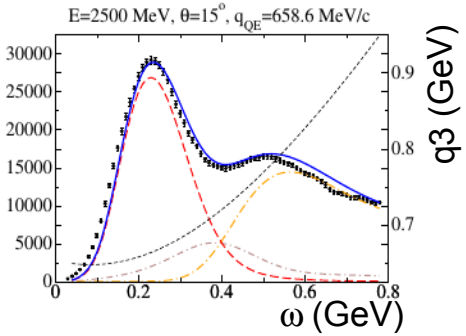
$q_3 = \bar{p}_\nu - \bar{p}_\mu$

$\omega = E_\nu - E_\mu$

$Q^2 = (p_\nu - p_\mu)^2$

- On the leptonic side xsec can be parametrized as a function of q_3,ω

(as in e-scattering data)



but the E_ν is only known on average (flux)

→ q_3, ω cannot be measured directly!

- The νn → lp xsec also depends on the **nucleon initial state momentum, ie nucleus modeling**
(Fermi gas, Spectral Function, and beyond...)

These nuclear effects impact even more directly the hadronic final state

$$\sigma(\nu - Nucleus) \sim |F(Q^2)|^2 \times \sigma_{point-like} \times R(Q^2)$$

Nucleon form factors

collective nuclear effects of xsec screening/enhancement (RPA)

Additional nuclear effects: scattering on correlated pairs (SRC or 2p2h), FSI, ...

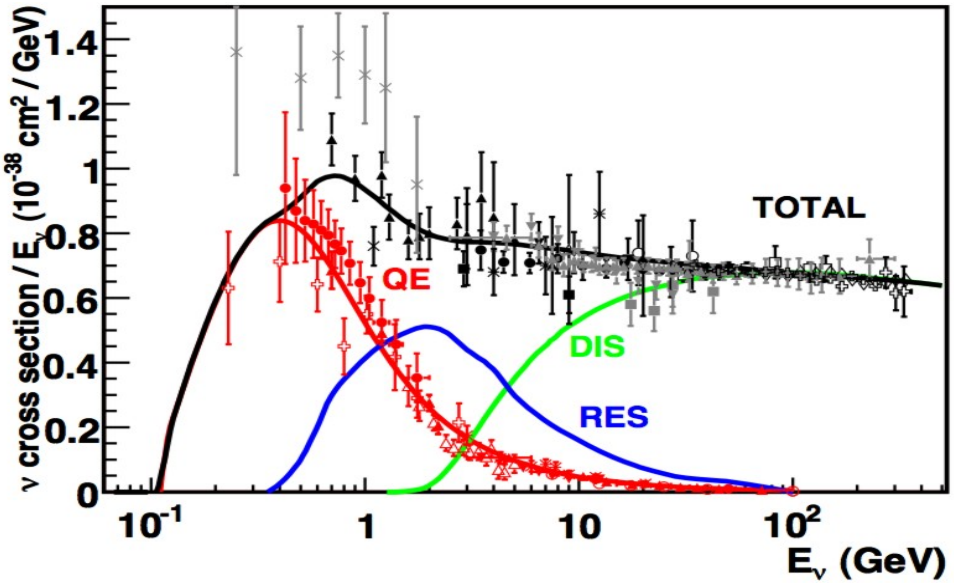
Cross-section vs E_ν

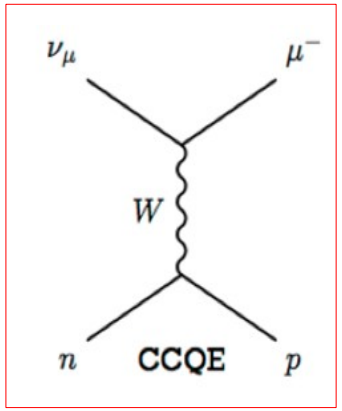
- Can we just measure the inclusive flux x xsec at ND and extrapolate it at the FD?

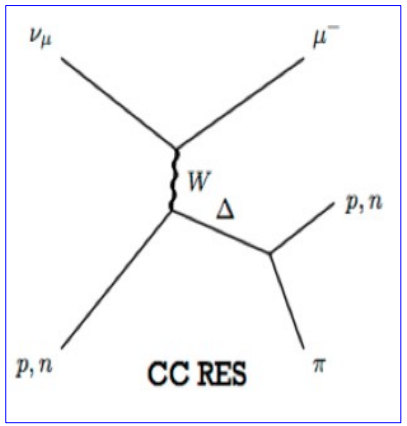
$$R_{FD}^{\nu'} = \int \Phi^{\nu}(E_\nu)\, P_{osc}^{\nu\to\nu'}(E_\nu)\, \frac{d\sigma^{\nu'}}{dE_\nu}\, dE_\nu$$

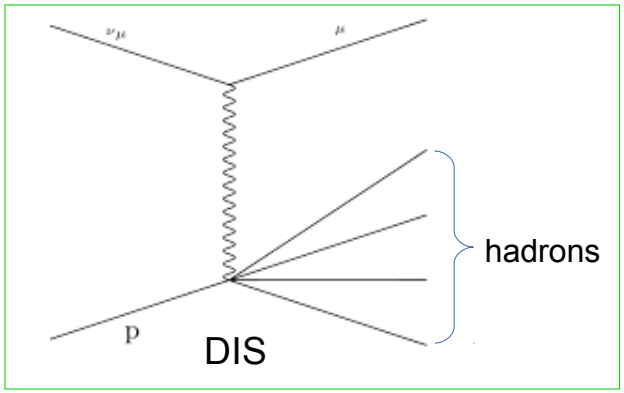
No! Even for identical near and far detector, even if you measure perfectly ALL the energy in the detector → **you still need to propagate the xsec from ND to FD which have different neutrino energy spectrum** (because of the oscillation)

- Need to disentangle the different interactions and propagate to different neutrino energy following their E_ν dependence



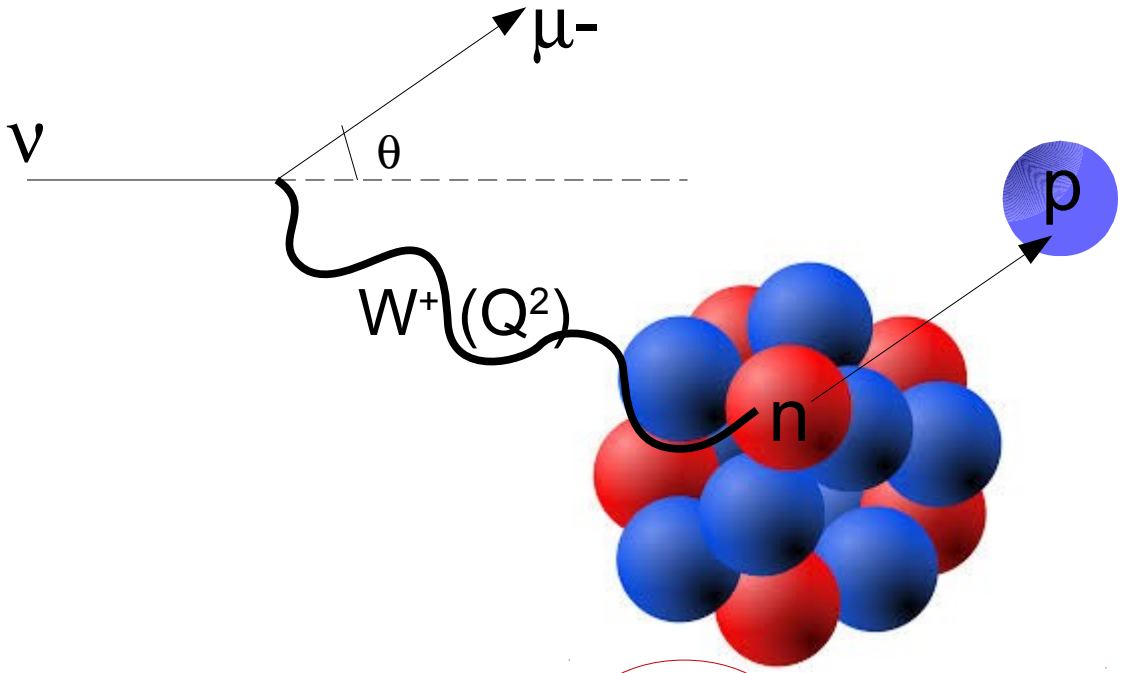






Angular acceptance ↔ Q^2 dependence

The fundamental variable is the transferred 4-momentum to the nucleus (Q^2)



$$Q^2 = (p_\mu - p_\nu)^2 \approx$$
$$\approx 2 E_\mu E_\nu (1 - \cos\theta)$$

$$\sigma(\nu - Nucleus) \sim |F(Q^2)|^2 \times \sigma_{point-like} \times R(Q^2)$$

Nucleon form factors

collective nuclear effects of xsec screening/enhancement (RPA)

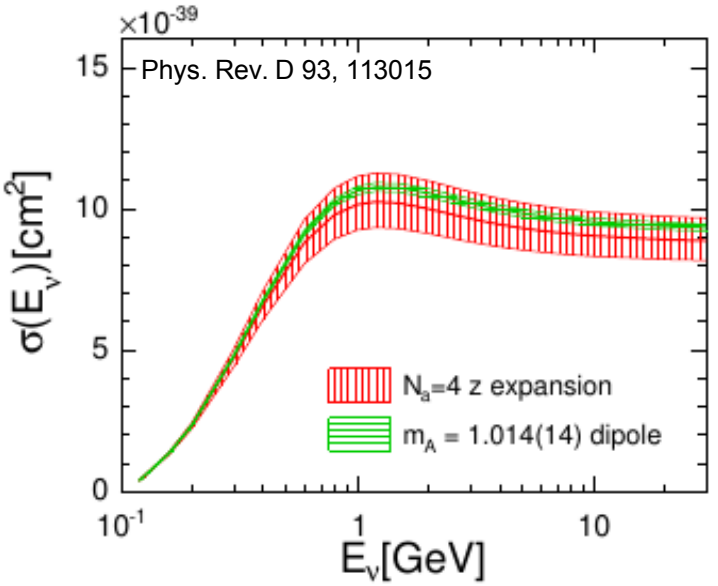
Need to measure the muon in large phase space (high angle and backward) to measure the Q^2 dependence

Nucleon form factors

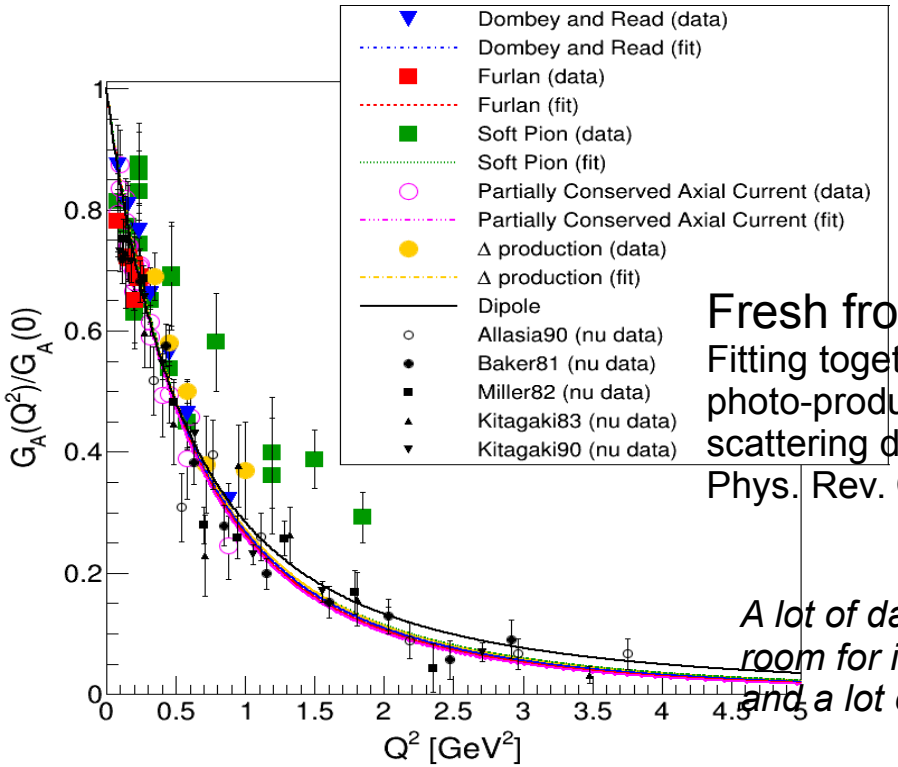
- The vector form factors are well known from electron scattering data → but what about the **axial form factor?**
  Tuned from old bubble chamber data neutrino on deuterium (ANL, BNL, BEBC, FNAL, ...) and old data of pion photo-production

Dipole function usually assumed: $$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^{QE\,2})^2}$$

- Not well motivated! A lot of interest recently: fit to bubble chamber data repeated with other models based on QCD rules ('z expansion') or informed from pion photo-production



Neutrino-nucleon xsec uncertainties re-evaluated



Fresh from my laptop...
Fitting together pion photo-production and neutrino scattering data with model in Phys. Rev. C 78, 031201

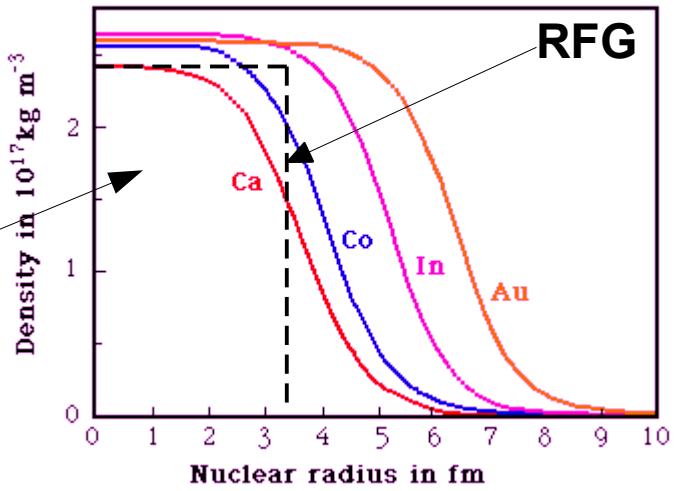
A lot of data available , room for improvements and a lot of fun!

Nuclear model

Various distributions of the momentum and energy of the nucleons in the nucleus

Relativistic Global Fermi Gas (RFG)

all momenta equally probable up to a maximum value which depends on the size of the nucleus.
Fixed binding energy
Nucleus is a box of constant density

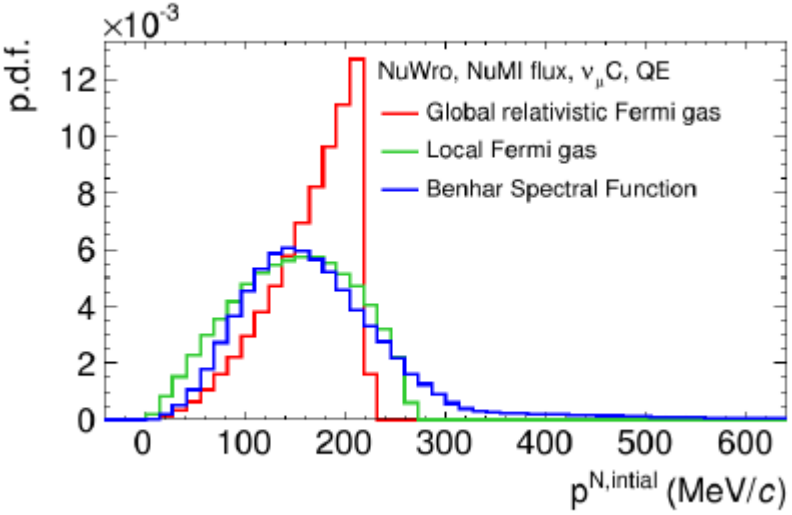


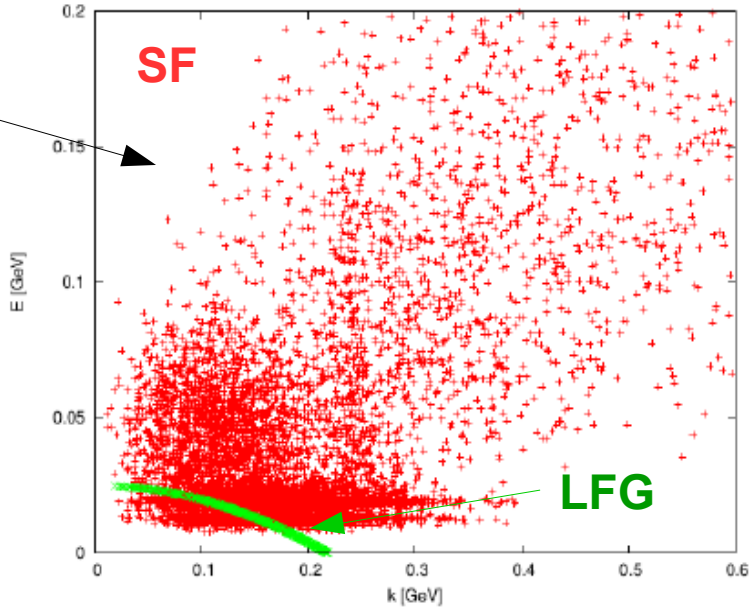
Local Fermi Gas (LFG)

momentum (and binding energy) depends on the radial position in the nucleus, following the density profile of the nuclear matter

Spectral function

More sophisticated 2-dimensional distribution of momentum and binding energy

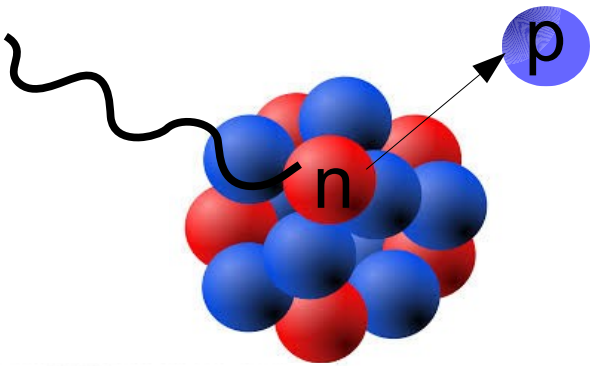




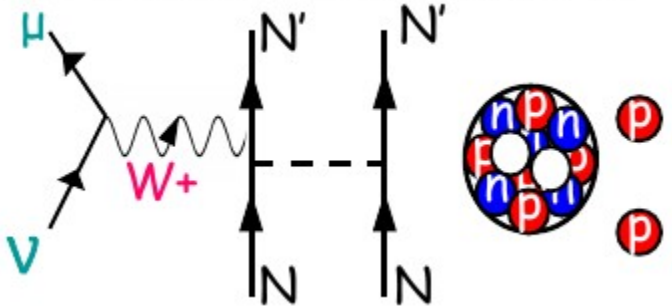
Missing energy

Some modeling uncertainties which affect the neutrino energy reconstruction:

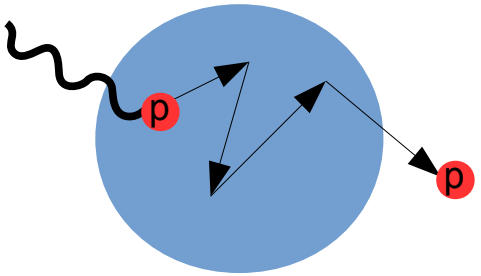
- **Binding energy:** energy needed to extract the nucleon from the nucleus



- **2p2h interactions**: how many neutrons in the final state?



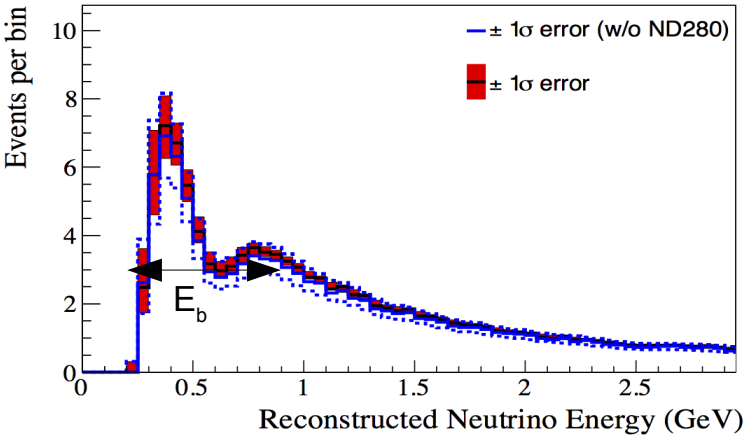
- **Final state interactions of pions and protons** before exiting the nucleus

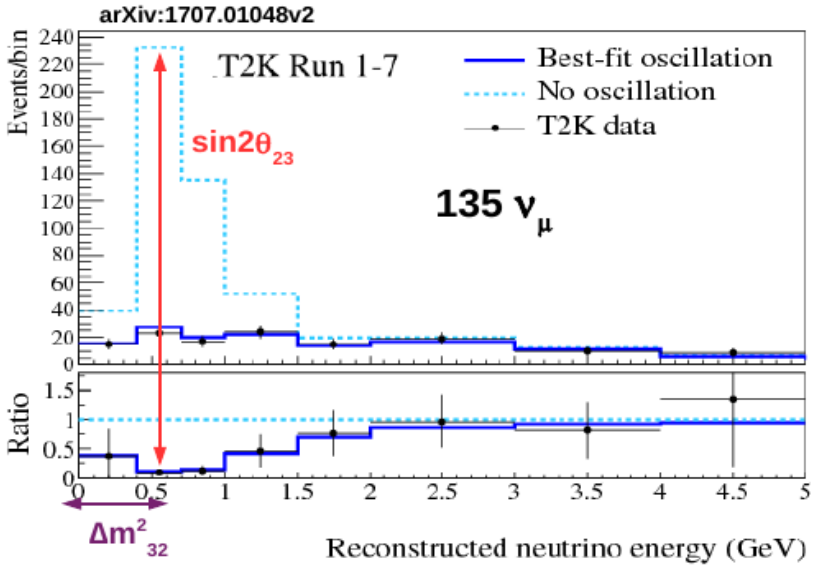


Effect of Eb on estimation of oscillation parameters

- **Binding energy is the energy needed to extract the nucleons from the nucleus** → does not go into the final state but it's 'lost' in the process.

The main effect of a wrong Eb modelling is to move the overall E_ν distribution → bias on Δm^2_{39} which is mostly sensitive to the position of the dip





Reminder from yesterday:

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- $\sin 2\theta_{23}$ proportional to the depth of the dip
- Δm^2_{32} position of the dip

Binding energy (1)

The meaning of binding energy depends on the model.

Example 1:

- **effective parameter tuned from QE interactions in electron scattering data** (E_b determines the position of QE peak)

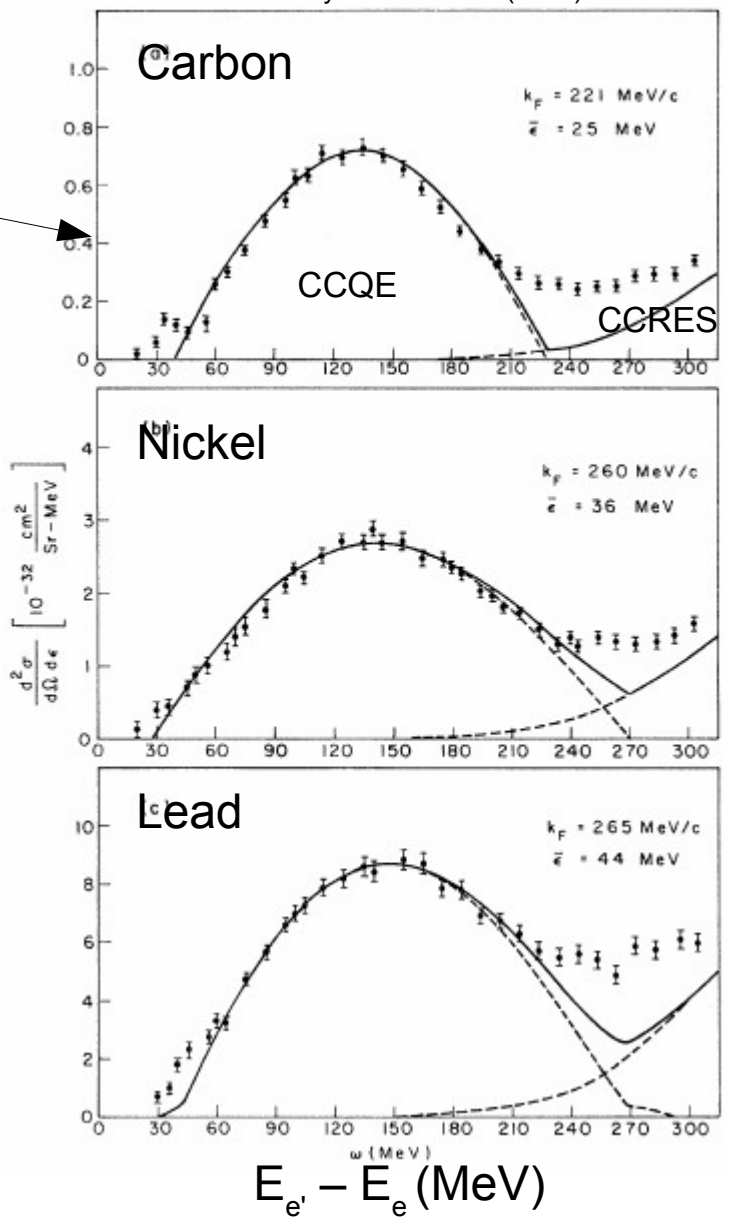
  Evaluated on old data with Fermi gas model and no 2p2h contribution (clear discrepancy in 'dip' region)

- More recent model (eg SuSa v2) is updating this fits → **need to update this** in our MC and oscillation analyses and estimate remaining systematics for different target nuclei

Need models which can predict neutrino but also electron scattering!

electron scattering data

Phys.Rev.Lett. 26 (1971) 445-448



Binding energy (2)

The meaning of binding energy depends on the model.

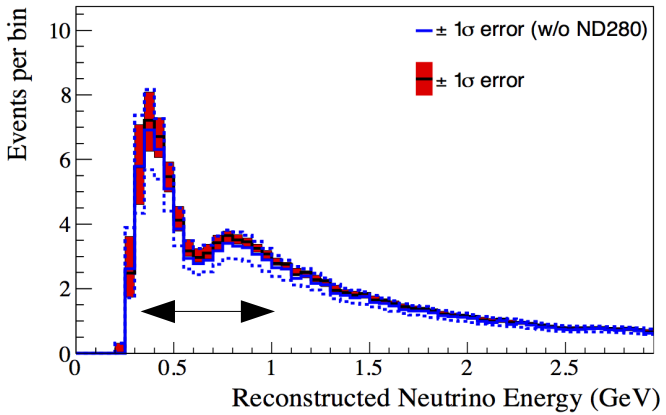
Example 2:

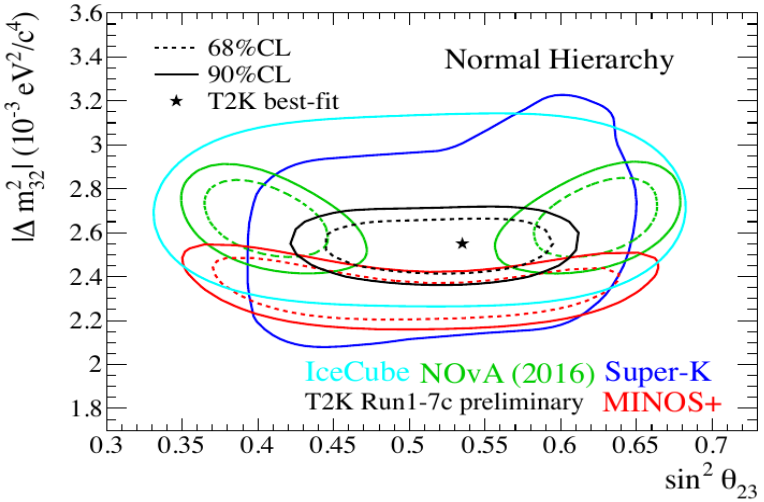
calculation of **difference in energy between the initial and remnant nucleus**

Phys. Rev., C83:045501, 2011.

Target	Nieves ν	Nieves $\bar{\nu}$	approach of previous slide
C	${}^{12}_{6}C \rightarrow {}^{12}_{7}N$ $\Delta E \sim 16.5$ MeV	${}^{12}_{6}C \rightarrow {}^{12}_{5}B$ $\Delta E \sim 14$ MeV	25 MeV
O	${}^{16}_{8}O \rightarrow {}^{16}_{9}F$ $\Delta E \sim 15.5$ MeV	${}^{16}_{8}C \rightarrow {}^{16}_{7}N$ $\Delta E \sim 12.5$ MeV	27 MeV

→ all boils down to E_b uncertainty of ~10 MeV or more: sizable effect on $|\Delta m_{39}|$



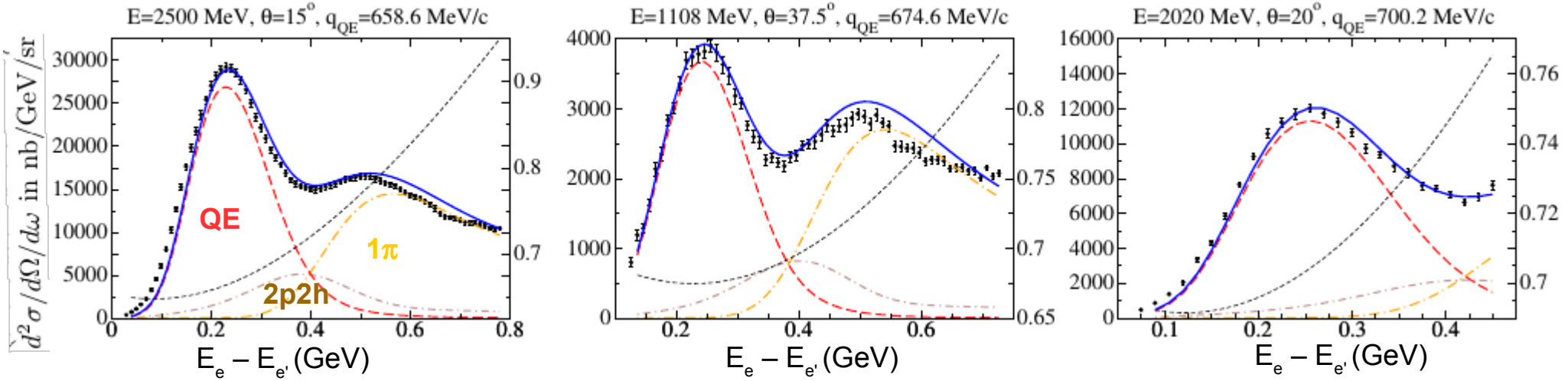


2 particles-2 holes

Interaction with pairs of correlated nucleons in the nucleus and Meson Exchange Currents

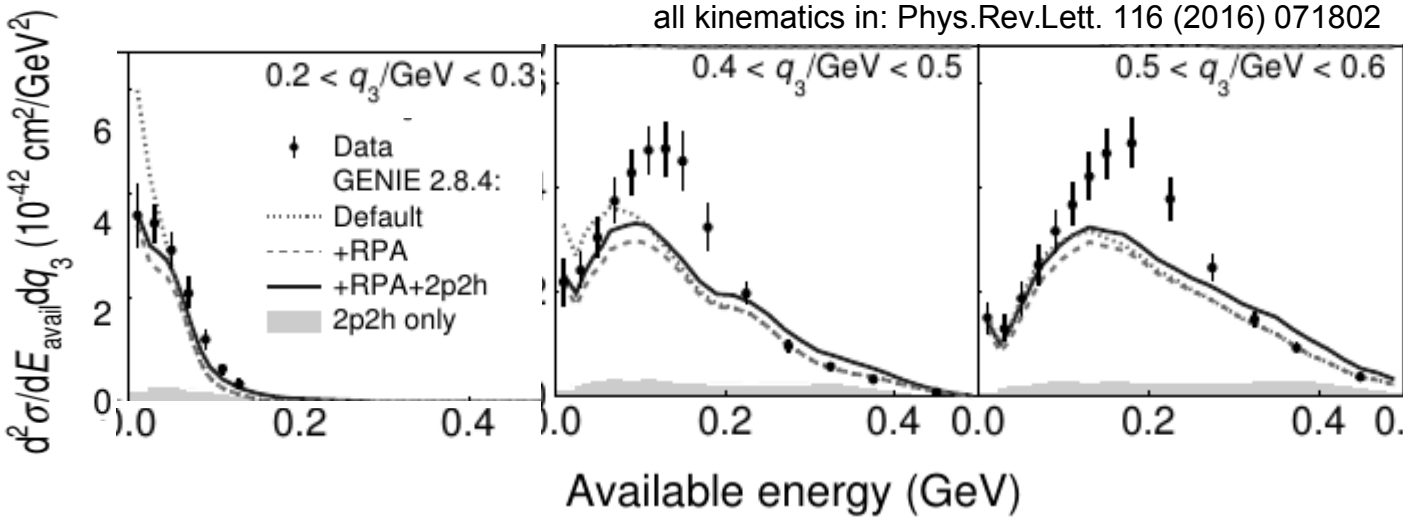
- well established in electron-scattering data:

few examples from SuSav2, all kinematics in: Phys.Rev. D94 (2016) 013012



- **still large uncertainties in neutrino scattering:**

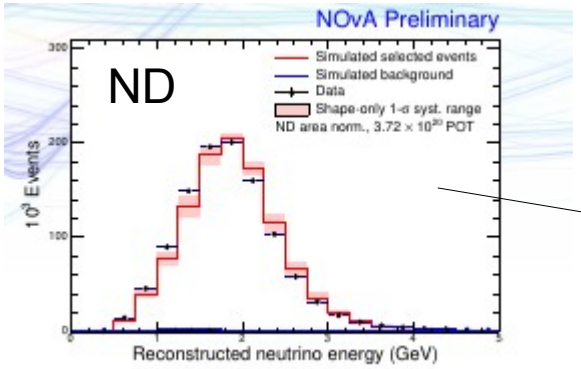
all kinematics in: Phys.Rev.Lett. 116 (2016) 071802

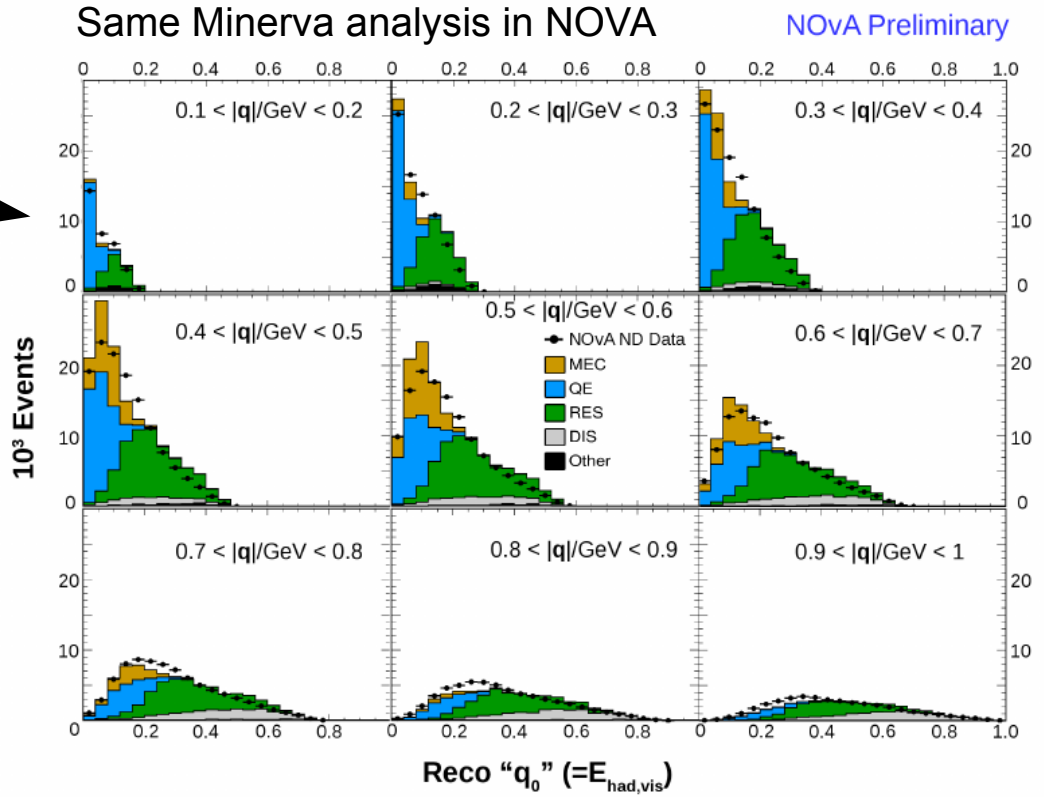


Minerva analysis:
$\omega = E_\nu - E_\mu \sim E_{had}$
reconstructed from hadronic energy in the detector

Impact on reconstructed energy

- From previous Minerva plot, clearly there is a **mismodeling of hadronic energy (in 2p2h and beyond):** important xsec systematics at NOVA for ν_μ disappearance





- Another important effect that should be considered is the fraction on neutrons/protons in the final state (depending on the flavor of the correlated pairs in the initial nucleons)

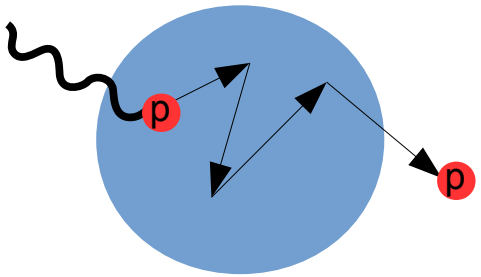
$\nu + nn \rightarrow \mu^- + np$
$\nu + pn \rightarrow \mu^- + pp$

$\bar{\nu} + pp \rightarrow \mu^+ + pn$
$\bar{\nu} + np \rightarrow \mu^+ + nn$

→ **affect $\bar{\nu}/\nu$ differently: important systematics for δ_{CP}**

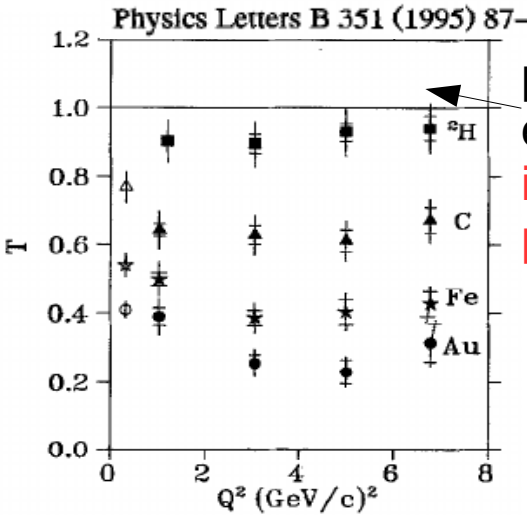
Final state interactions

- Both **pions and protons rescatter before exiting the nucleus:** this change the kinematics, multiplicity and charge of the hadrons in the final state



This process is simulated with approximated 'cascade' models tuned to pion-nucleus and proton-nucleus scattering cross-section

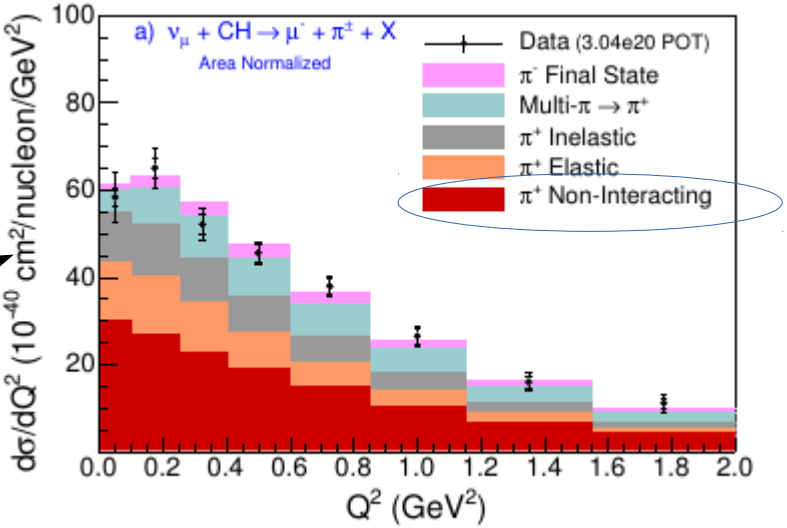
This is not a small effect!



proton transparency in electron scattering:
in Ar FSI corrections for proton production is ~50%

Minerva CC1π sample:
>50% pions re-interacted in the nucleus

Phys.Rev. D94 (2016) no.5, 052005

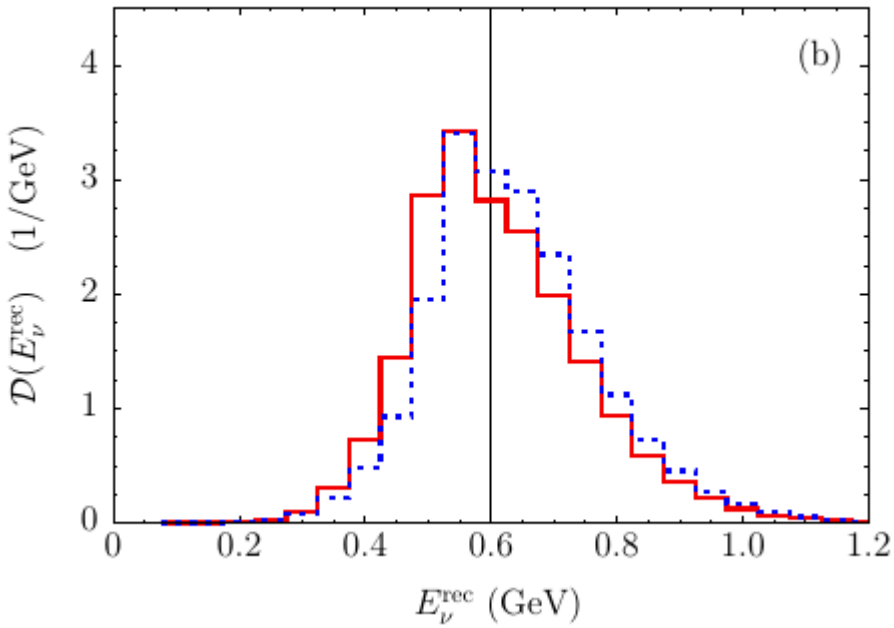


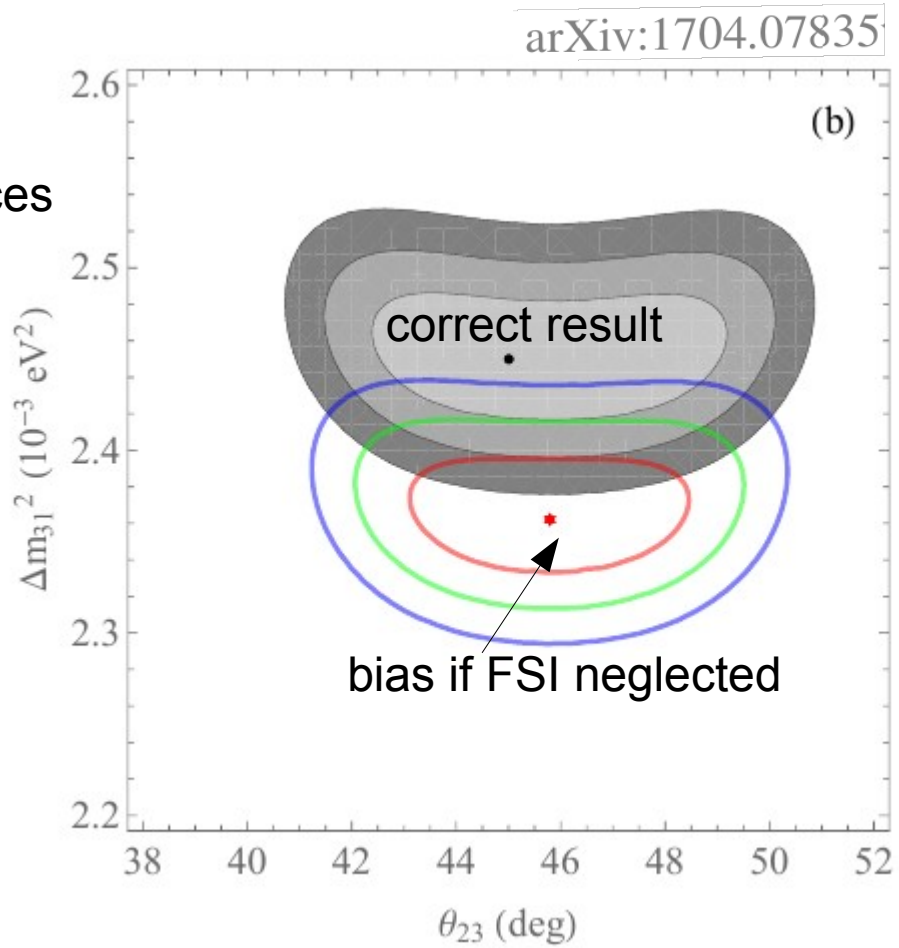
FSI effects on oscillation

→ **Effects on neutrino energy reconstruction for oscillation analysis:**

- efficiency corrections for low momentum particles from MC need reliable model of charge, multiplicity and kinematics of outgoing hadrons
- some energy get lost in the rescattering in the nucleus and cannot be reconstructed

Bias in the reconstructed energy if FSI are neglected with 'realistic' detector performances



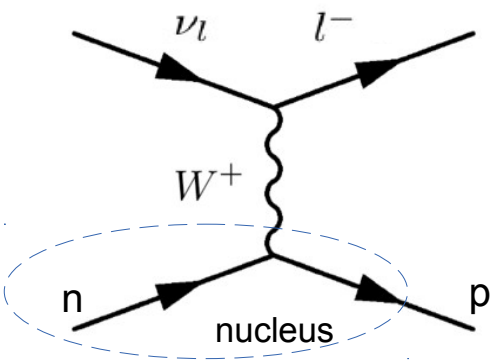


FSI on topology reconstruction

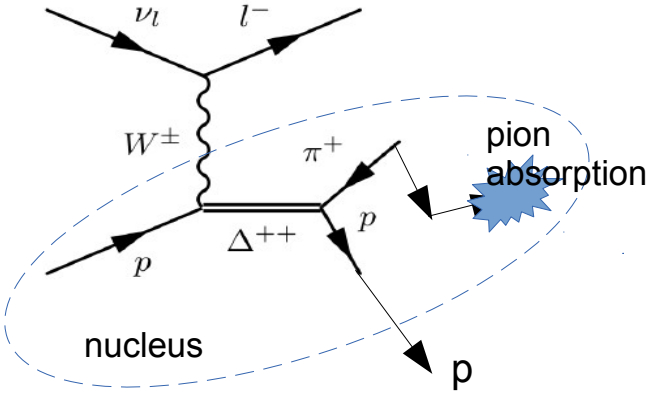
- CC-RES events move into CCQE-like signal (CC0π)

If we observe **a muon and proton in the final state and no pions**, we do not know if that event was:

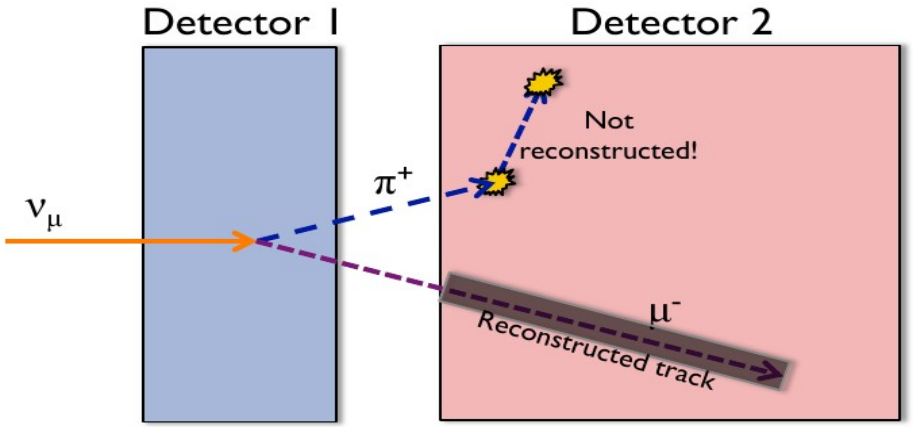
a 'real' CCQE event



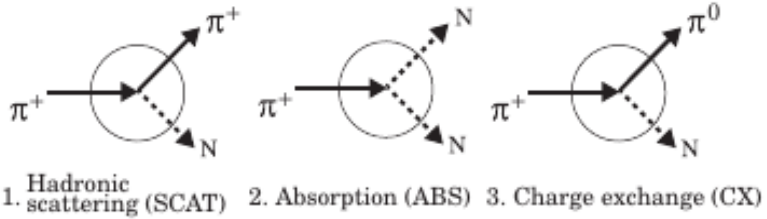
or a RES event where the pion has been reabsorbed in the nucleus



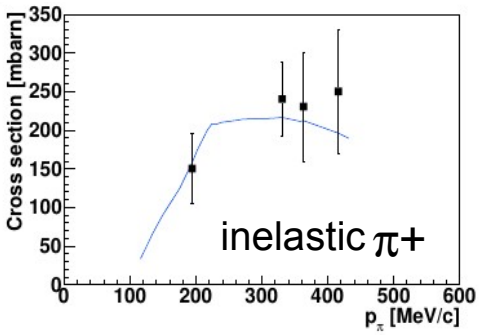
The rescattering of the pion in the detector (outside) the original interacting nucleus is also relevant (**Secondary Interactions**)

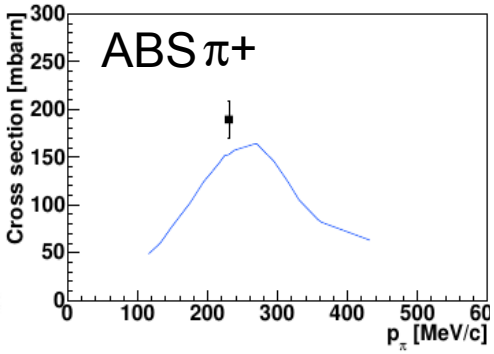


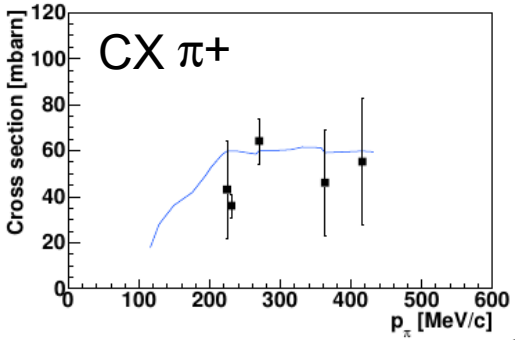
Pions data

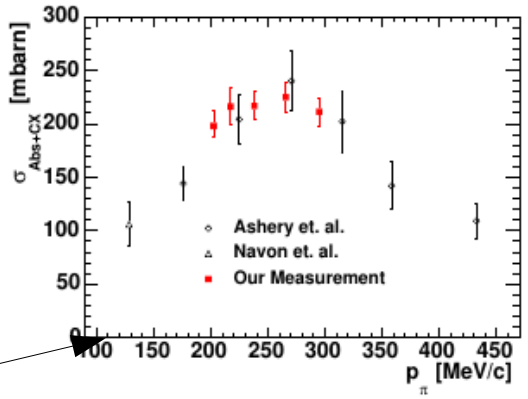


- Pion-nucleus cross-section: **very sparse data available**



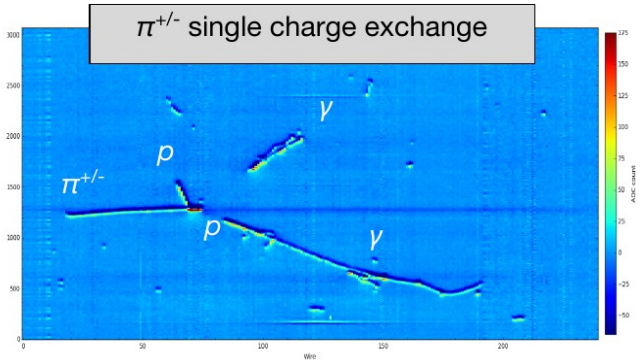


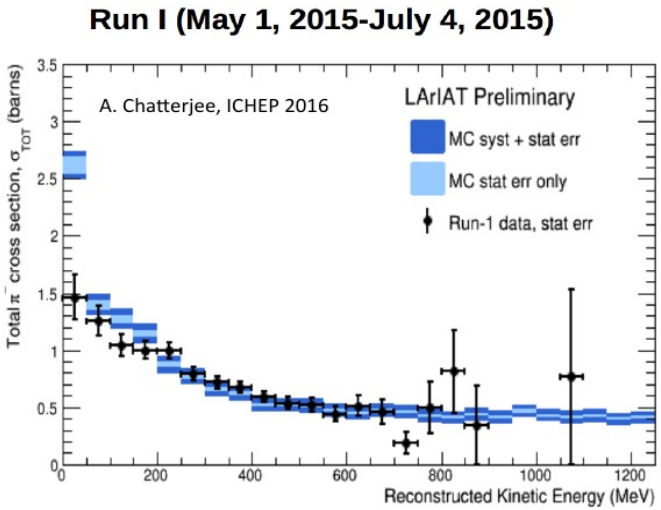




- New measurement from **DUET** experiment at TRIUMF

- **LArIAT:** FNAL LAr on charged test beam



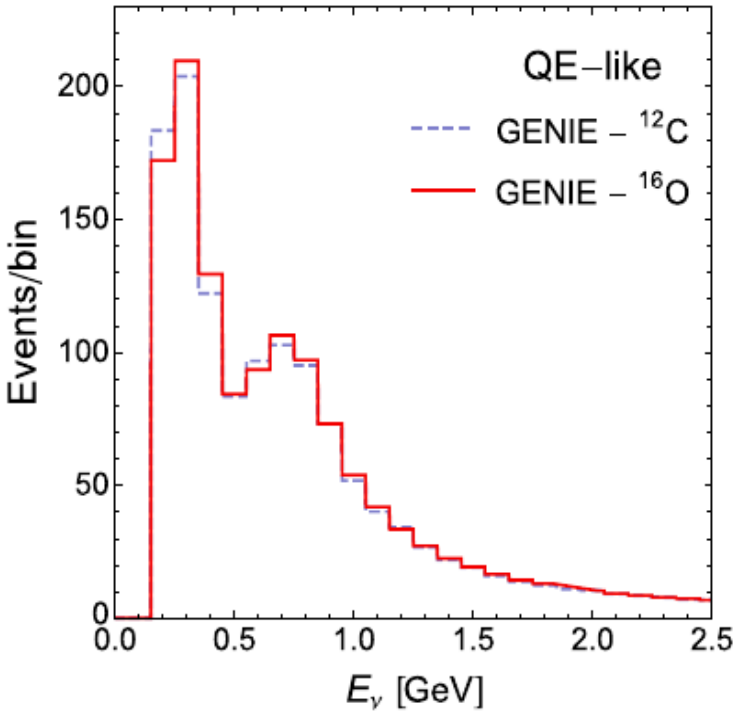


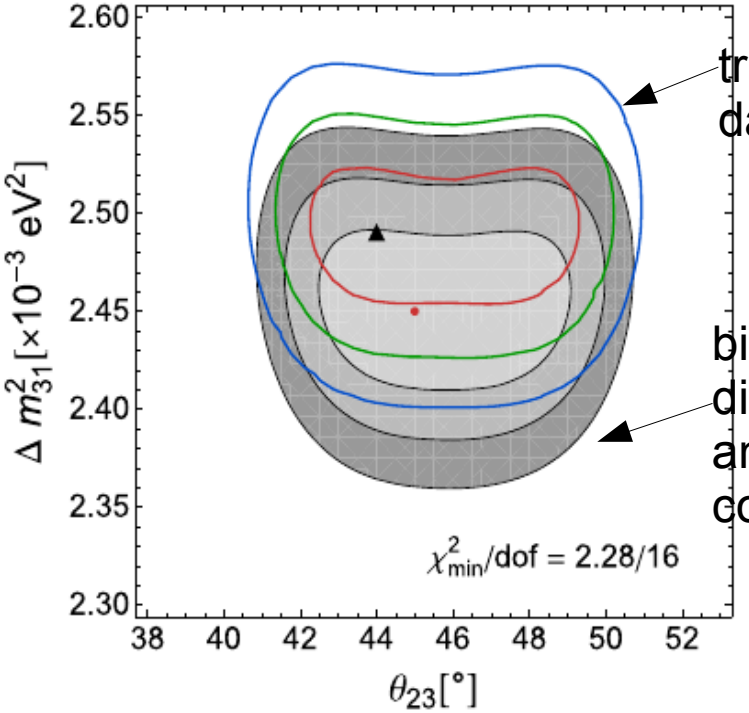
- **Large potential from DUNE prototypes on CERN test beam!**

Multiple targets (C,O) at ND and FD

Phenomenological study neglecting the difference between nuclear model in Carbon and Oxygen:

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054001 A M Ankowski and C Mariani





true result (5y data taking)

biased result if difference between C and O are not considered

Treatment of multiple targets

- **Part of ND280 data are on Carbon while SK is on Water**, we need to know how the cross-section change as a function of A (nucleus size)

  We rely on the **model (NEUT MC) to predict the cross-section on C and O** and when there are effects not well known, we introduce free parameters in the fit

- All the 'physics' is in the estimation of the **correlation between the C and O parameters:**

- if we assume to know perfectly how to extrapolate from C to O, then we have one single parameter for C and O

- if we don't know at all, then two uncorrelated parameters for C and O
(we kill our sensitivity because is like using only FGD2 water data for ND constraints)

- the reality is typically in the middle because C and O have similar A size (large correlation) but the nuclear effects are not well known

T2K 2017 approach: nucleon-level (MAQE) fully correlated between C and O,
BeRPA fully correlated, uncorrelated uncertainty for pF C and O and
20% correlation for 2p2h between C and O (from electron-scattering measurements)

Different targets

Nuclear effects changes as a function of nucleus 'size' (number of nucleons A)

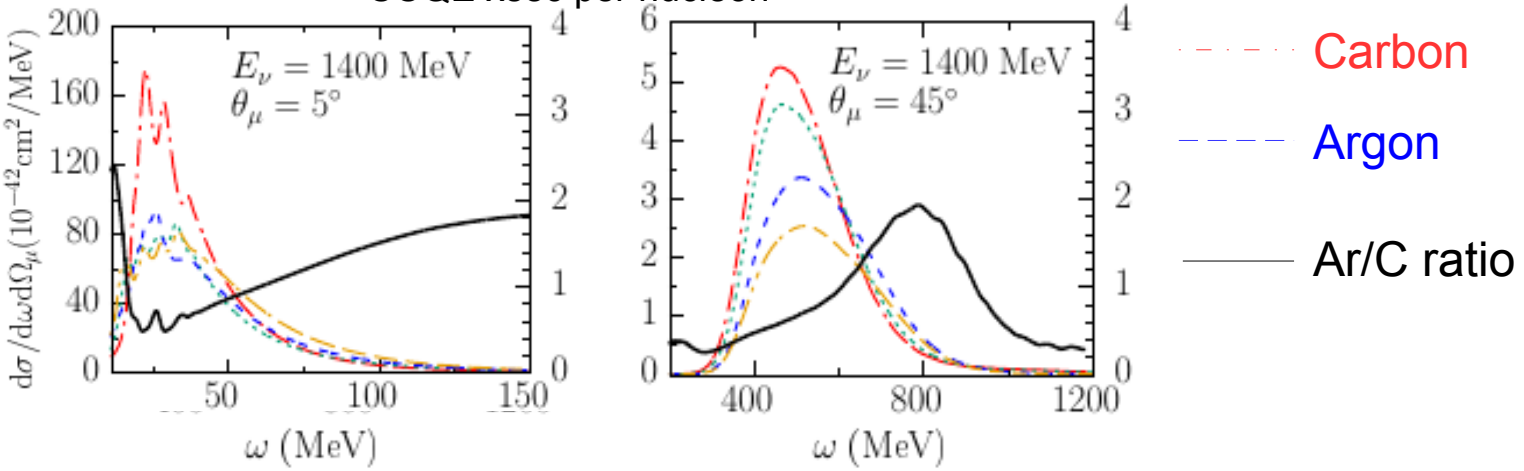
- **binding energy** and Fermi momentum to be tuned vs A

(similarly in more advanced models like Spectral Function the energy-momentum correlation function need to established from electron scattering on Argon → plan at CLAS experiment at JLab)

- **2p2h:** how the number of nn and np correlated pairs scale with A ?

- **C-RPA** = corrections for collective nuclear effects computed down to very low transferred energy → shown very not trivial A-dependency:

CCQE xsec per nucleon



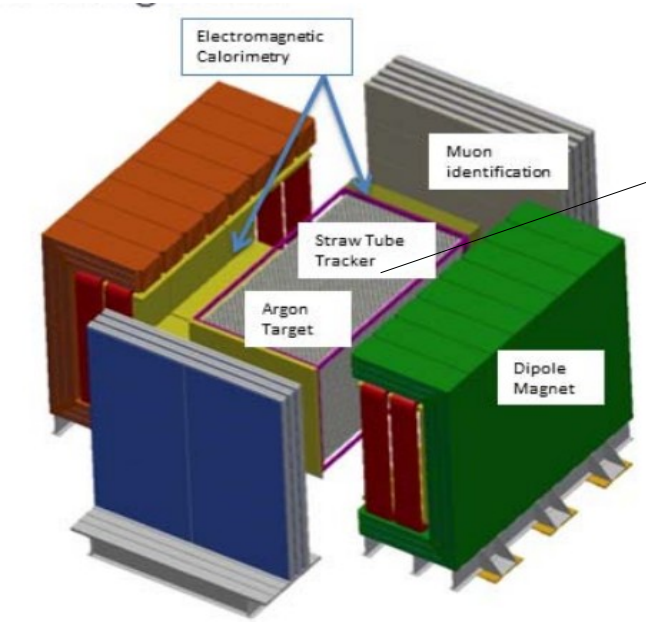
- at higher energy DIS xsec depends on **nuclear PDF**: A-scaling observed in data is not well reproduced by the model

A-scaling and near detector

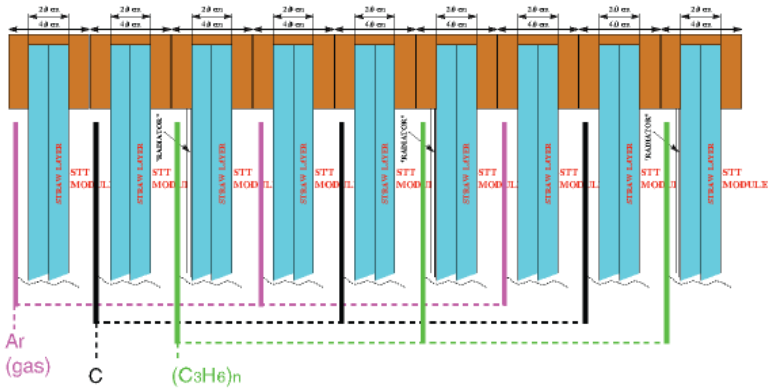
Scaling of nuclear effects with A not straightforward

Importance of large Ar TPC (MicroBooNE, SBND) for DUNE program
Very important to have large Ar target in DUNE near detector

DUNE ND initial design:

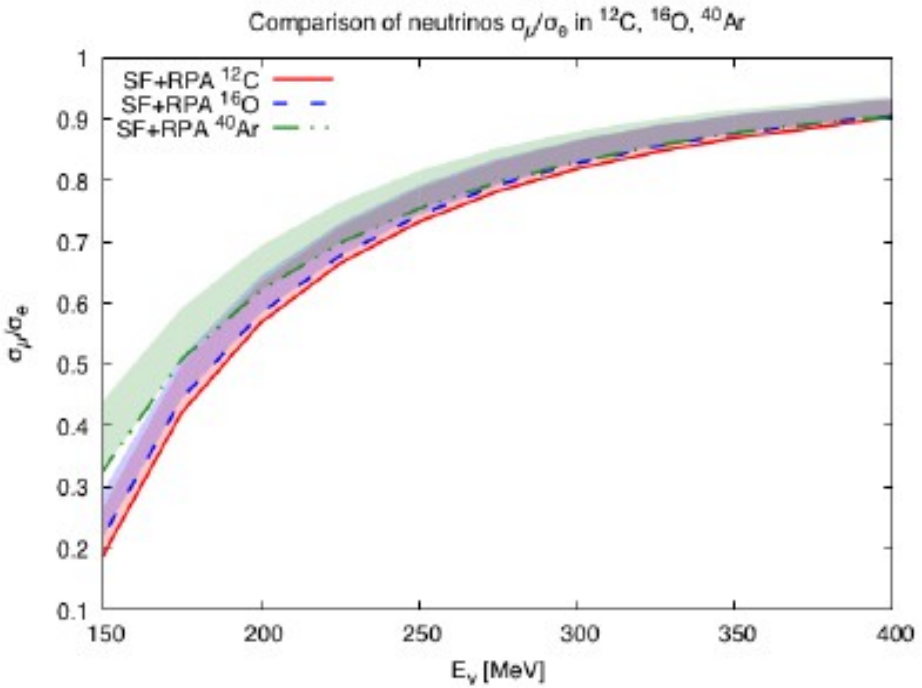


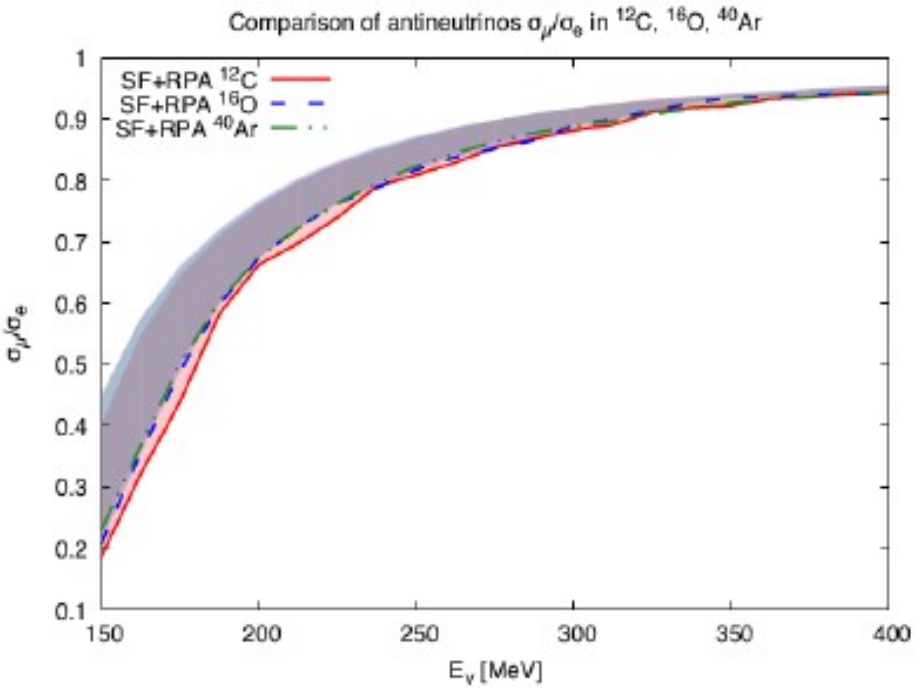
strawtubes (filled with HP Ar) with radiators walls (C_3H_6) interleaved with different targets



- a lot of interactions will not be on Ar
- combined analysis: target subtractions etc. → large systematics due (eg) to uncertainties on acceptance due to xsec modeling

→ HP Ar TPC under discussion


Comparison of neutrinos σ_μ/σ_e in ^{12}C, ^{16}O, ^{40}Ar
SF+RPA ^{12}C
SF+RPA ^{16}O
SF+RPA ^{40}Ar
σ_μ/σ_e
E_ν [MeV]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
150
200
250
300
350
400


Comparison of antineutrinos σ_μ/σ_e in ^{12}C, ^{16}O, ^{40}Ar
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σ_μ/σ_e
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