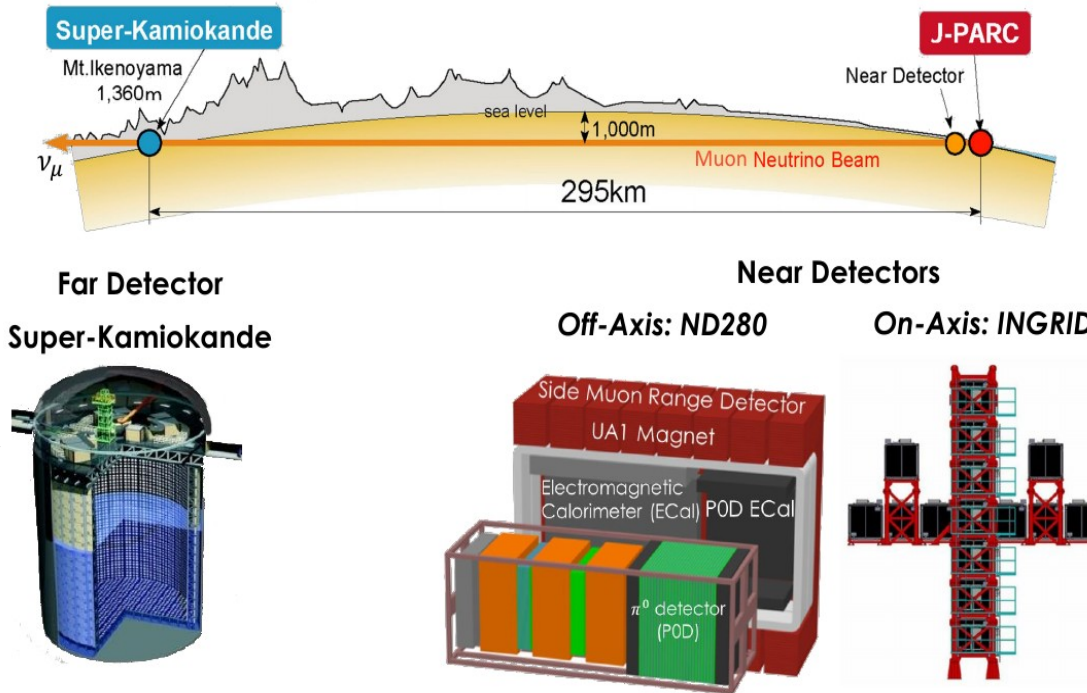# Systematics on (long-baseline) neutrino oscillation measurements

- **Introduction on oscillation measurements:** present results from T2K and NOVA and precision needed for next generation HyperKamiokande, DUNE

- Overview of the systematics:

    - How **neutrino flux and cross-section** affect neutrino oscillation measurements ?

    - **Flux** simulation and tuning

    - Main neutrino **cross-section uncertainties** (from an experimentalist point of view)

- Neutrino oscillation analyses and xsec systematics in details: **the T2K and NOVA examples**

S.Bolognesi (CEA Saclay) - T2K

Neutrino oscillation analyses and xsec systematics in details

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

Super-Kamiokande
Mt.Ikenoyama 1,360m
sea level
ν_μ
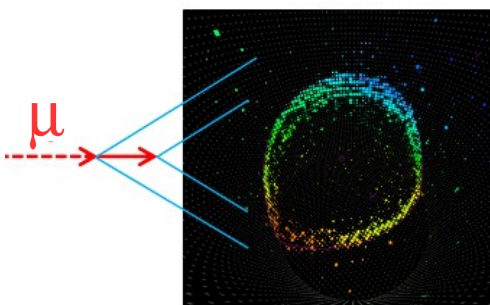1,000m
Muon Neutrino Beam
295km
J-PARC
Near Detector

Near Detectors:

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

Far Detector:

Far Detector:
Super-Kamiokande

Near Detectors
Off-Axis: ND280   On-Axis: INGRID

Side Muon Range Detector
UA1 Magnet
Electromagnetic Calorimeter (ECal) P0D ECal
π^0 detector (P0D)

huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ
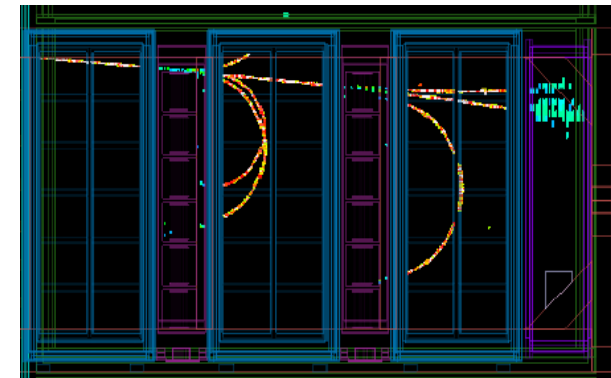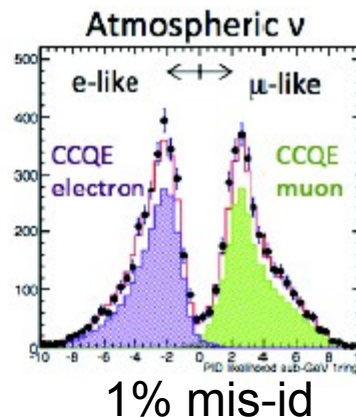
Off-axis:
full tracking and particle reconstruction in near detectors (magnetized TPC!)

Atmospheric ν
e-like ↔ μ-like
CCQE electron
CCQE muon

μ   e

clear ring   **fuzzy ring**   1% mis-id

3

Super-Kamiokande:
ν_e vs ν_μ

Super-Kamiokande: background

CC1π :

if pion above Cherencov threshold 'easy' to reject (ask for 1 only ring)
if below threshold (~150 MeV) look for Michel electrons
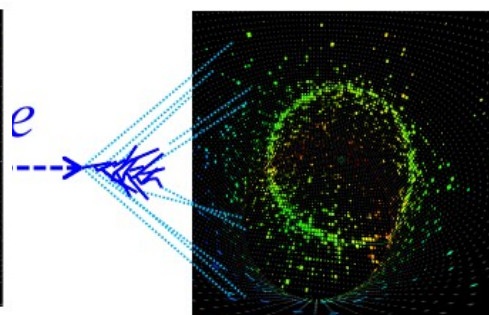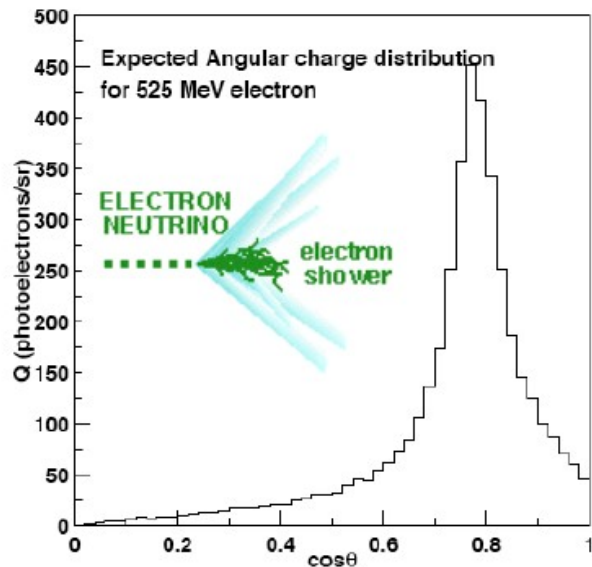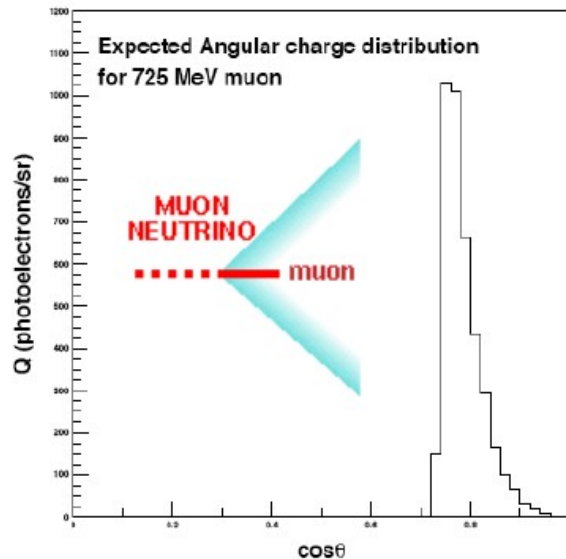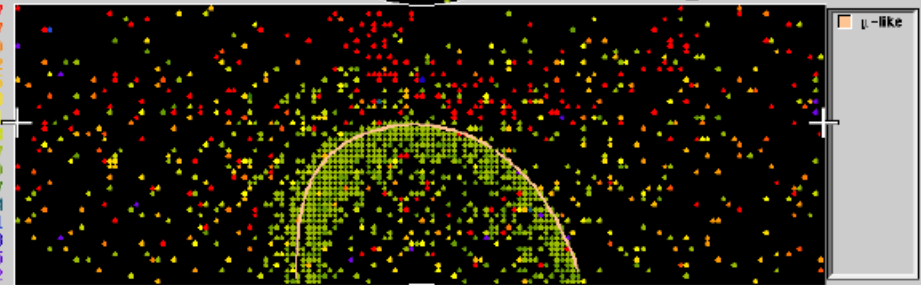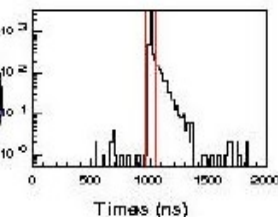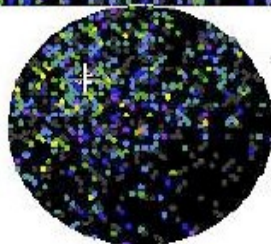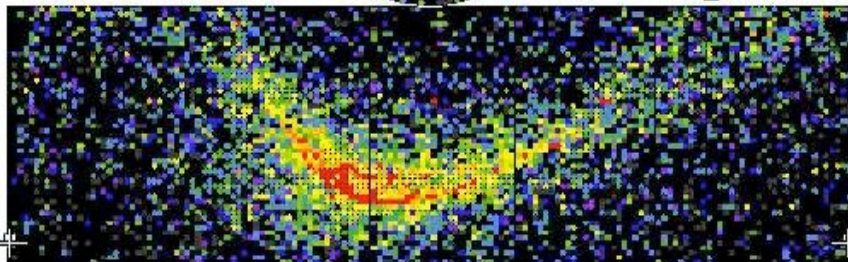

Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 995.0 cm
rc mu-like, p = 766.0 MeV/c

Resid(ns)
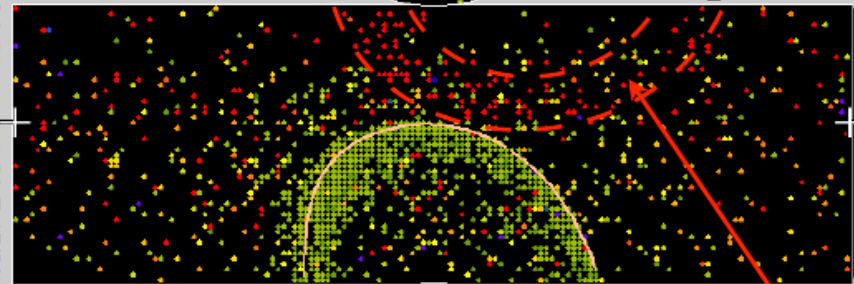
Useful trick: Count decay electrons from π→µ→e decay. Good way to count π's and µ's that are below threshold
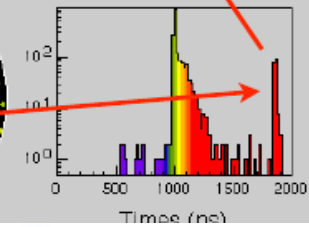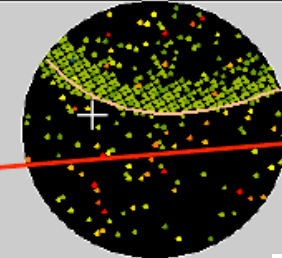
NC π⁰ at high energy very similar to ν_e
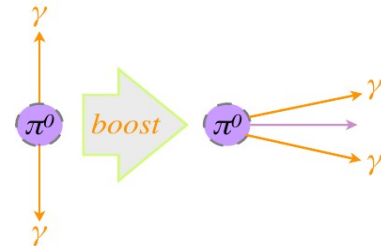
Still good separation using $m_{\gamma\gamma}$ and vertex time, position, momentum, direction: 1-ring vs 2-rings hypothesis (90% π^0 rejection with 80% ν_e efficiency)

5

Super-Kamiokande spectra
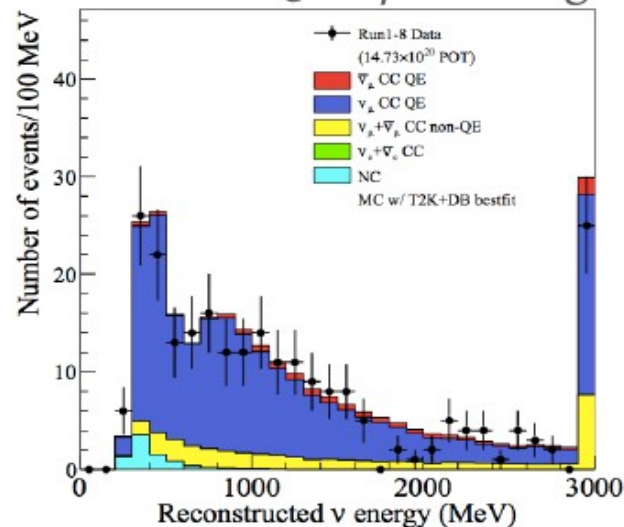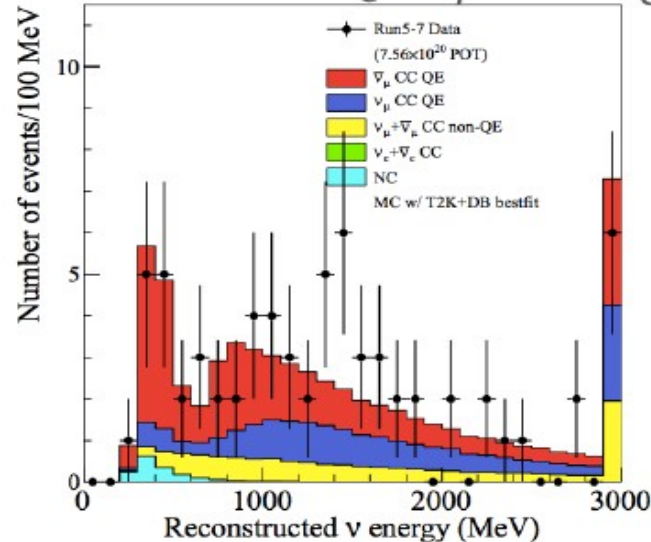
T2K Preliminary

(not tuned MC)
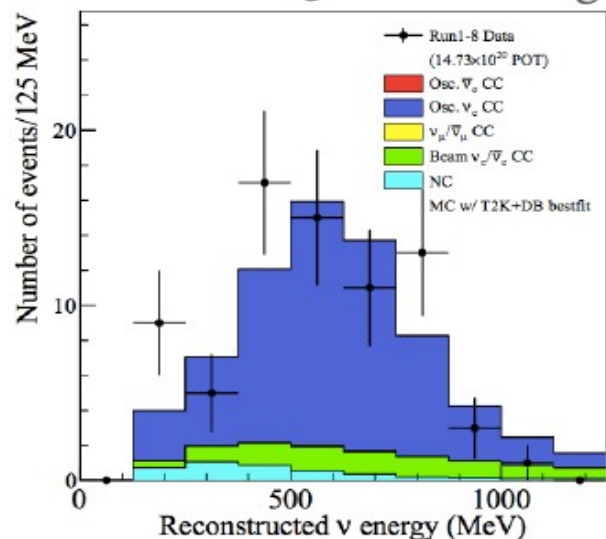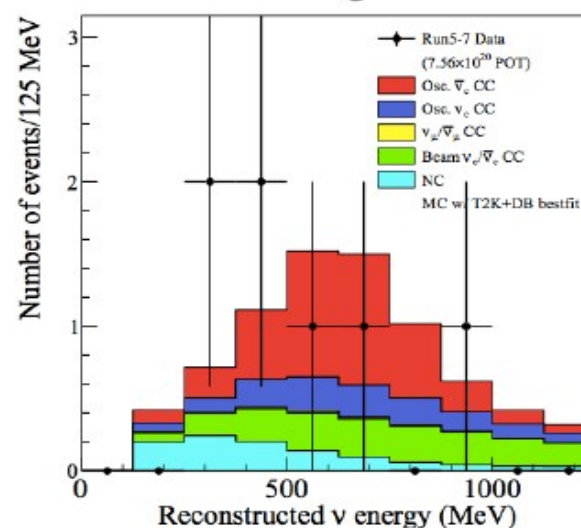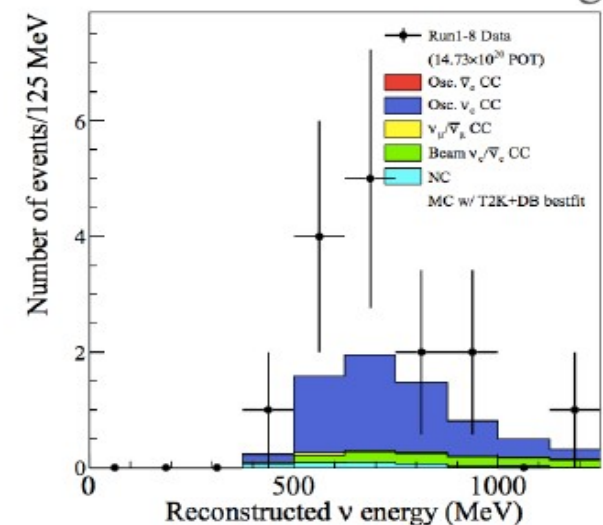
T2K near detector: ND280

Multipurpose detector for full characterization of neutrino interactions:
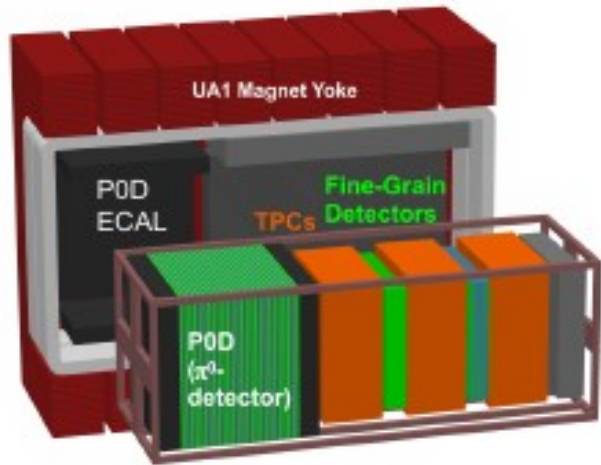
- FGD scintillators : main target for neutrino interaction ($CH + H_2O$)
  → vertex position and energy deposition around the vertex

- fully magnetized (0.2 T)

- TPC → **good tracking efficiency**, **resolution** (6% p_T<1GeV) **and particle identification**

- Ecal all around tracker region to measure γ from π^0 and electrons

- Side Muon Range Detector in the magnet for escaping particles

- P0D scintillator with water target (not yet used for oscillation analysis)
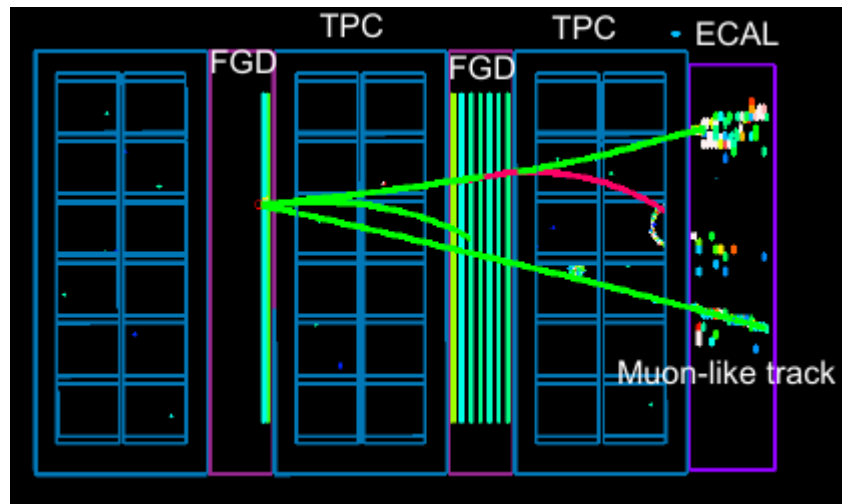
Neutrinos at ND280

Muon reconstruction (same for all CC processes) and particle ID to separate the interaction channels:
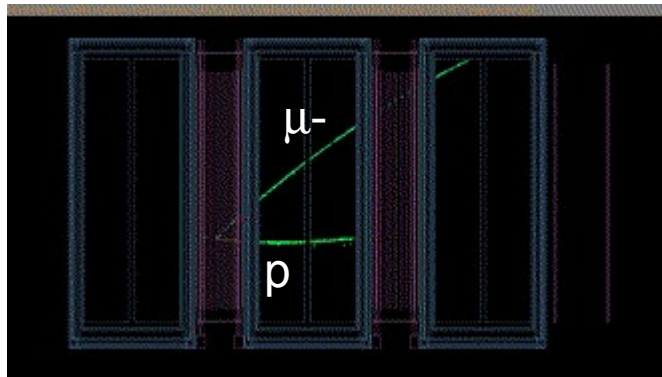
CCQE event with proton > 500 MeV
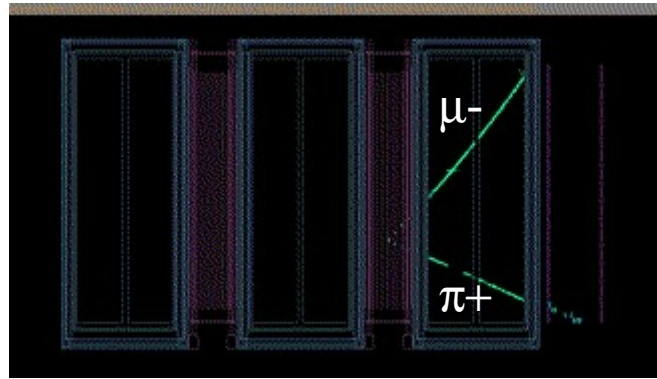
CC1π+: particle ID (p vs μ,π vs e) with dE/dx in TPC

DIS event

Muon p_T resolution

Muon reco efficiency

Particle ID in TPC

ND280 spectra

- **Neutrino beam mode**: selected interactions in FGD1

Same selection also available for interactions in **FGD2 (CH + Water)**

- **Antineutrino beam mode:**

Same selection also for μ- in antineutrino beam mode to measure the **wrong ν sign background in the flux**

Neutrino cross-sections uncertainties measured separately for each process using the muon kinematics

Future: more variables (pion kinematics, protons, E_{had} ...)

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ND280 spectra

- **Neutrino beam mode**: selected interactions in FGD1

Same selection also available for interactions in **FGD2 (CH + Water)**

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Same selection also for µ- in antineutrino beam mode to measure the **wrong ν sign background in the flux**

Neutrino cross-sections uncertainties measured separately for each process using the muon kinematics

Future: more variables (pion kinematics, protons, Ehad ...)

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Muon kinematics (T2K)

ND

Full cross-section model with systematics parametrized with variable parameters

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

ND fit

Prediction at FD: neutrino energy estimated from approximated formula

$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

(valid for 2-body scattering with nucleon at rest + correction for binding energy of nucleon)

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)

FD ν_μ prediction

11
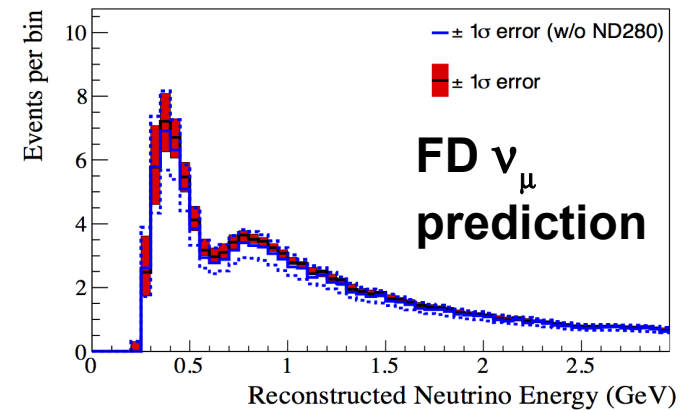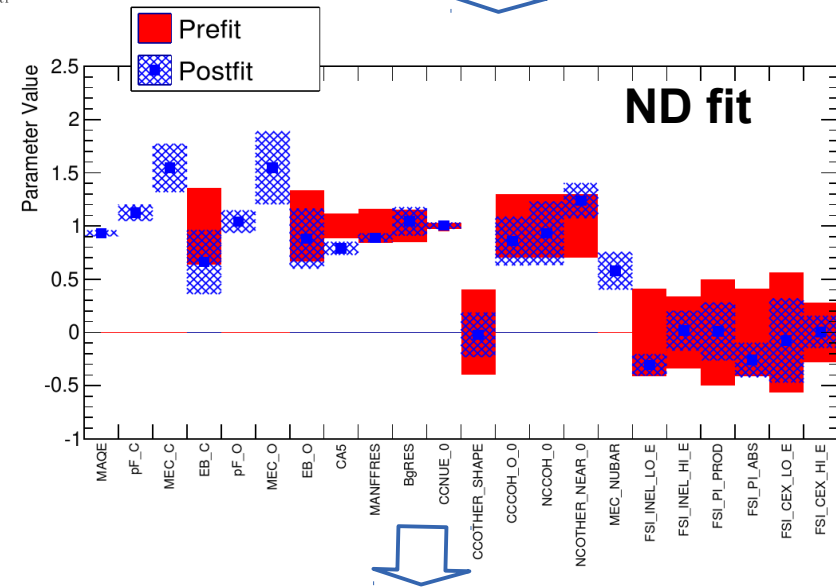
Tuning of cross-section model
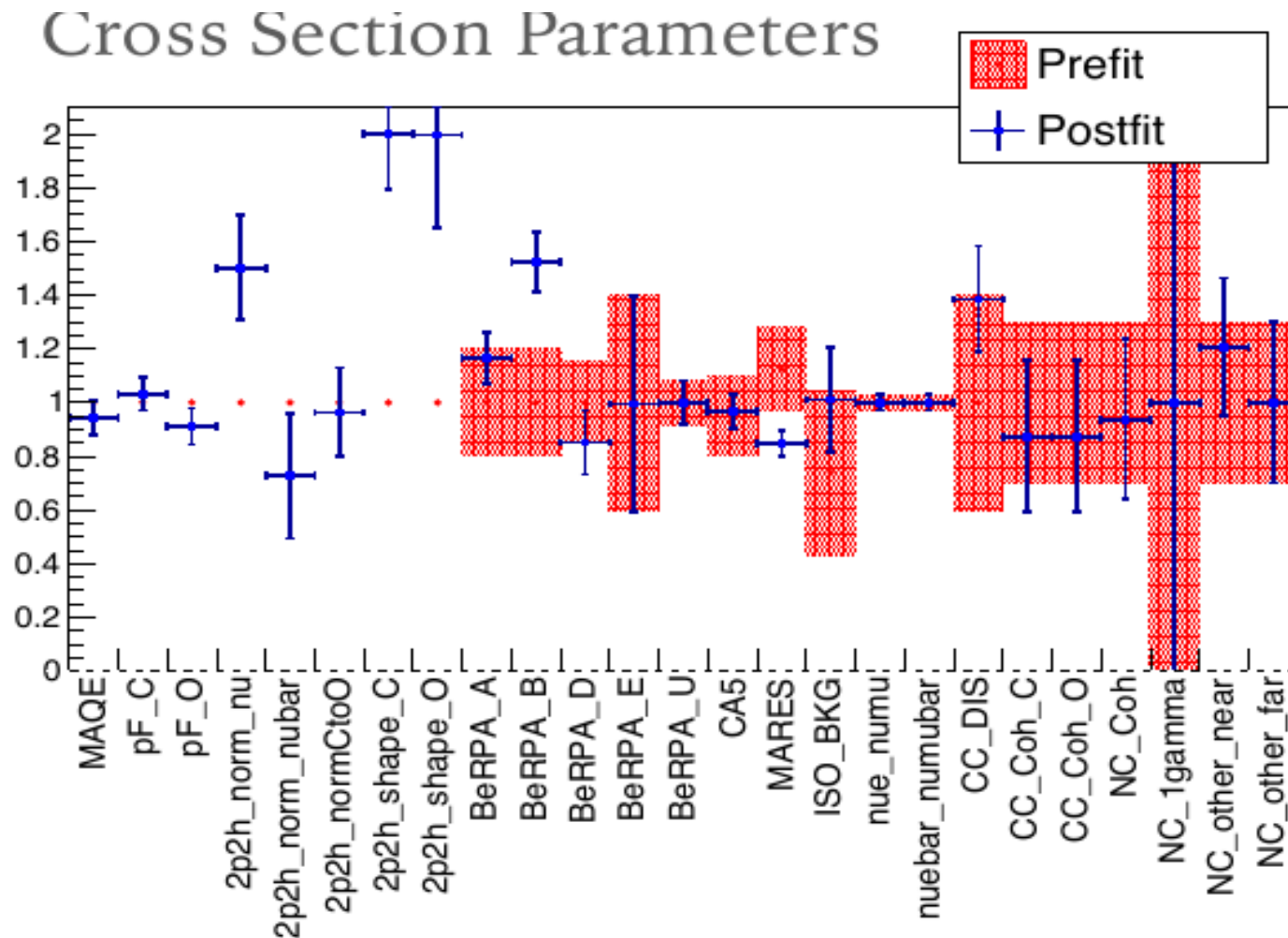
T2K limitations

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

Angular acceptance
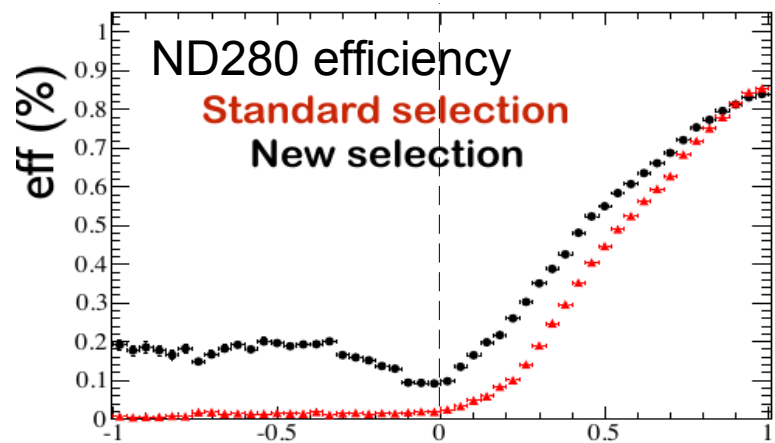
SuperKamiokande events

ND280 efficiency
Standard selection
New selection

Neutrino Mode 1 Electron-like Ring

T2K Preliminary
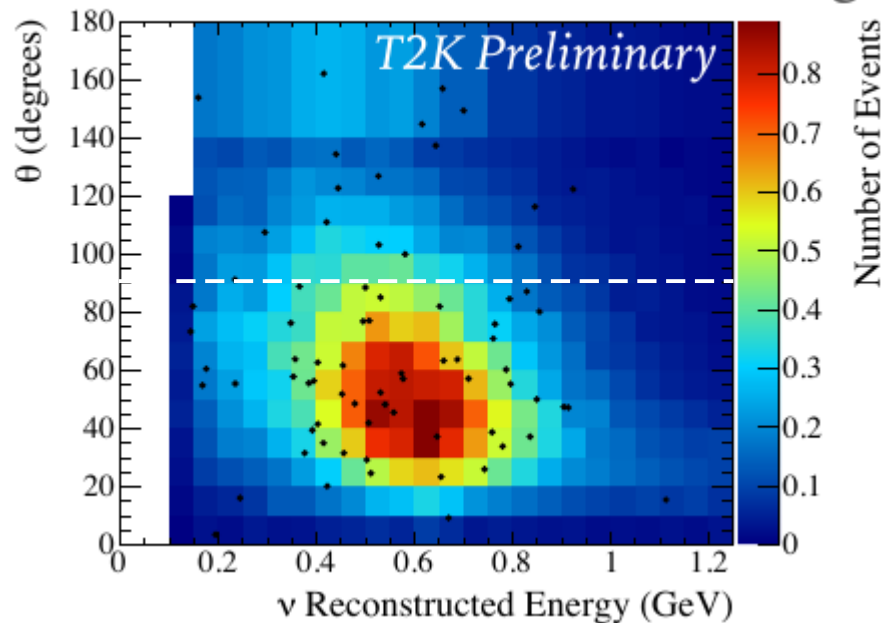
- **T2K-2: new horizontal target and TPCs to enlarge high angle acceptance**

ND280 Upgrade

same as today

new TPC
new target
new TPC

ν

FGD1
FGD2
new target
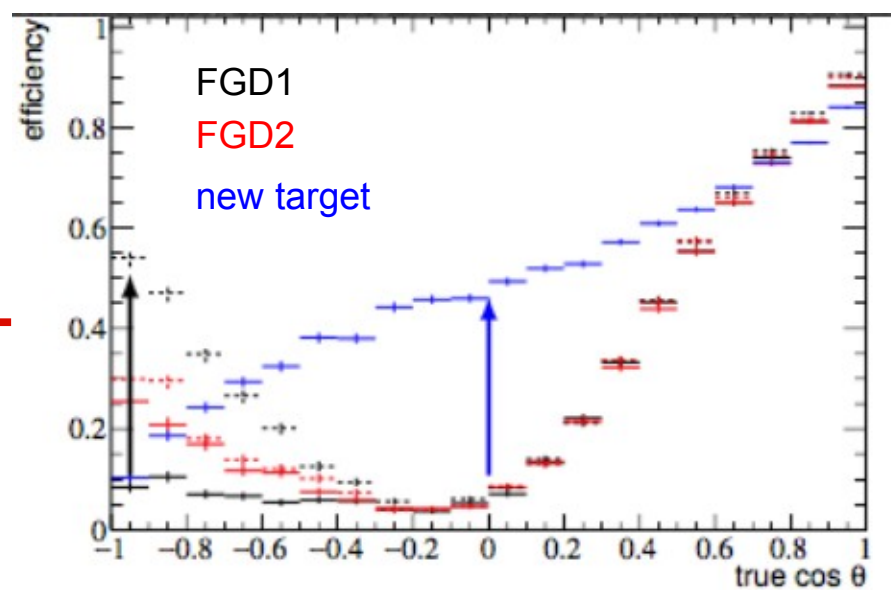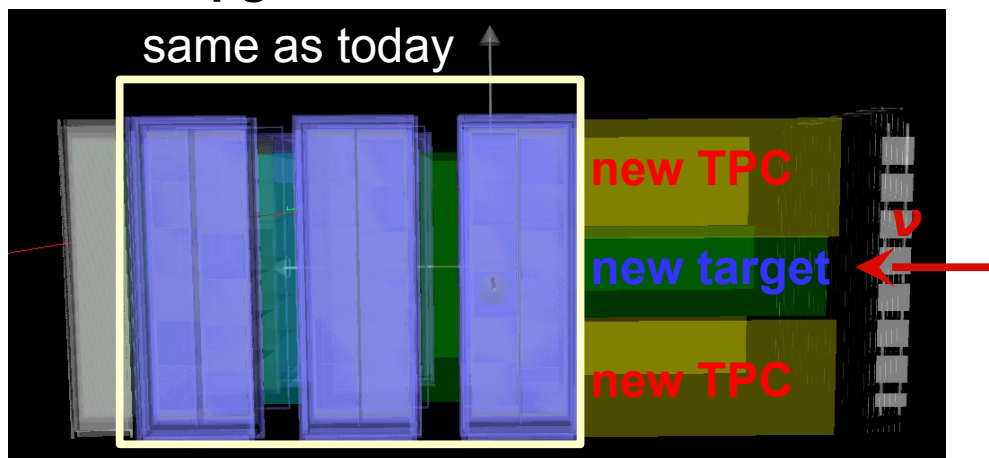
Multiple targets (C,O) at ND and FD

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

                    A M Ankowski and C Mariani

true result (5y data taking)

biased result if difference between C and O are not considered

15
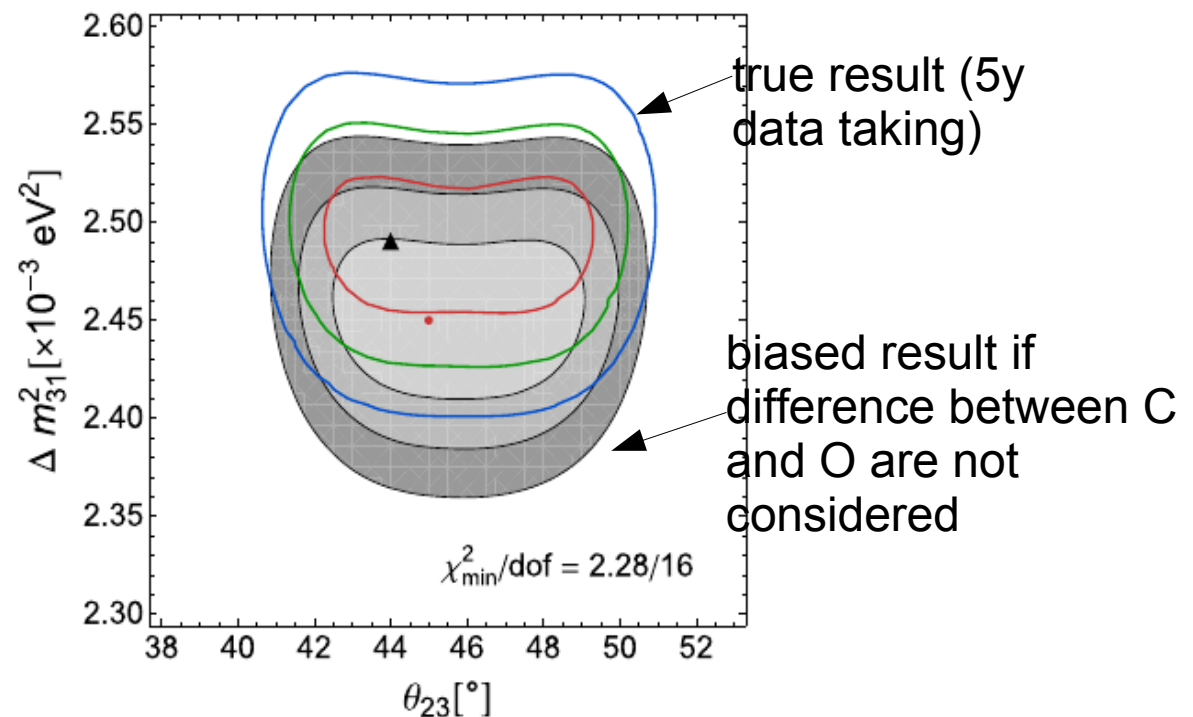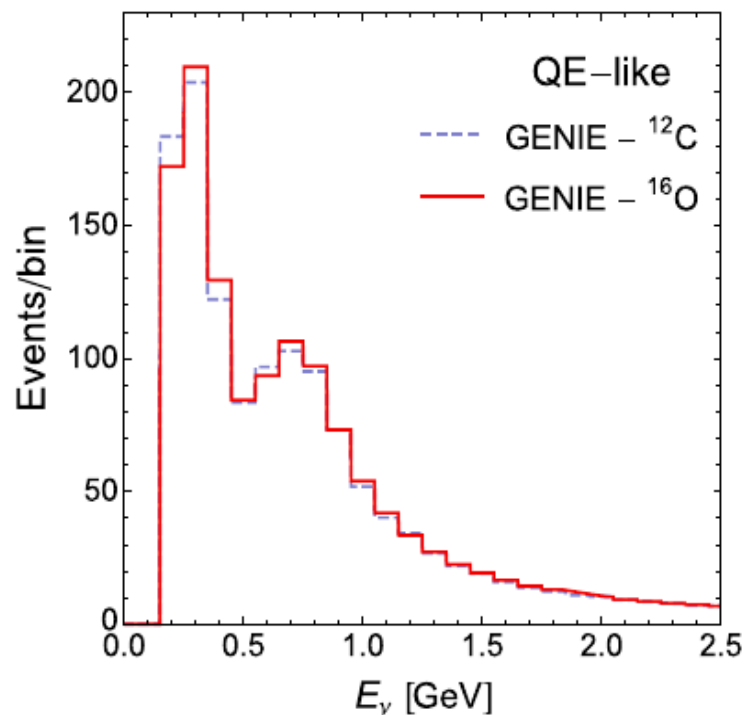
Treatment of multiple targets

- **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)

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Multiple targets: FSI and SI

FSI and Secondary Interactions: today: 2-3% uncertainty on signal at SuperKamiokande assuming NO correlation between C and O (no ND constraints)

Next analysis: full fit to pion scattering data over multiple targets → tune of NEUT FSI/SI model for all targets

(E.Pinzon, NuINT2017)

C only
light nuclei
all nuclei (up to Fe, Pb, ...)

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Example: 2p2h normalization C vs O

- **2p2h interactions are due to correlated proton-proton and neutron-proton pairs in the initial nucleus: how their number changes with A ?**

- **Electron scattering data**

  number of Short Range Correlated pairs is extracted from the comparison of $\sigma(e \to e'p)$ and $\sigma(e \to e'pp)$ measurement
  +
  corrected for FSI effects (large uncertainty)

- Measurements on C, Al, Fe, Pb ($\to$ plot as ratio to C) compared to simple model

- 1σ uncertainty on the measurements gives **20% uncertainty on O prediction** $\to$ C to O extrapolation known at 20% (i.e. 2p2h normalization parameter is correlated at 20%)

E$_\nu$ reconstruction: 2p2h bias

■ CCQE formula to reconstruct E$_\nu$ does not hold for 2p2h

$$\overline{E_\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Different 2p2h components give different E$_\nu$ biases

Nucleon-Nucleon correlations

Pion in flight   Contact   Delta

E$_{true}$ 600 MeV

...... CCQE (w/ RPA)
...... 2p2h
——— total

σ / Z (fb/GeV)

Delta-like   NN correlation (not Delta)

Nieves

E$^{QE}_{reco}$ (GeV)
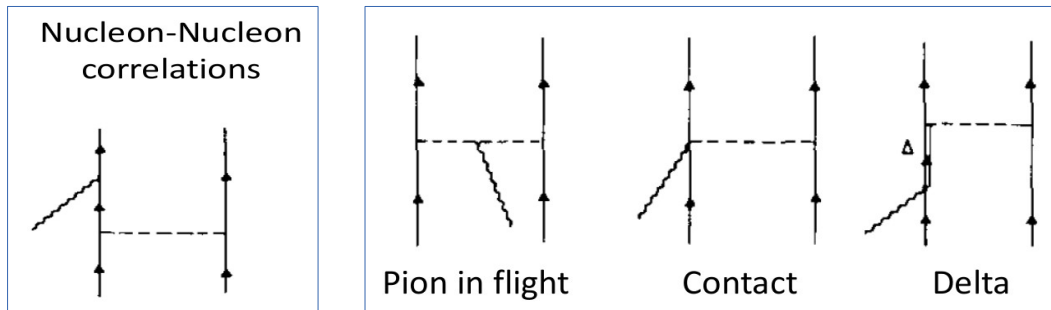
■ OA approach: let free in ND fit 2p2h total xsec and Delta/notDelta fraction

Martini

reconstructed energy (GeV)
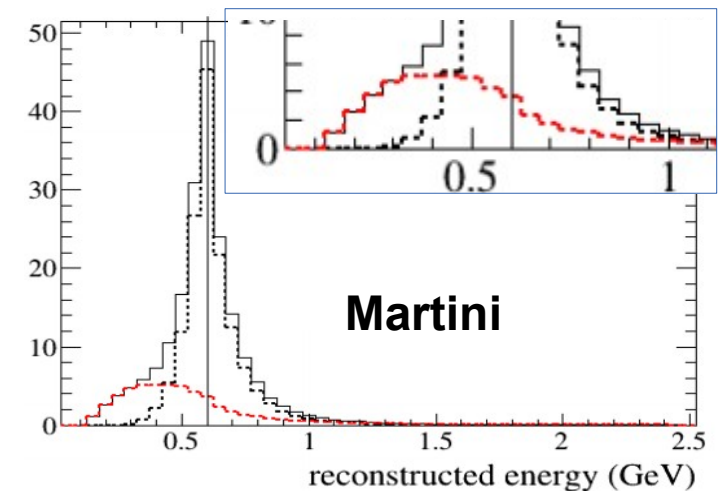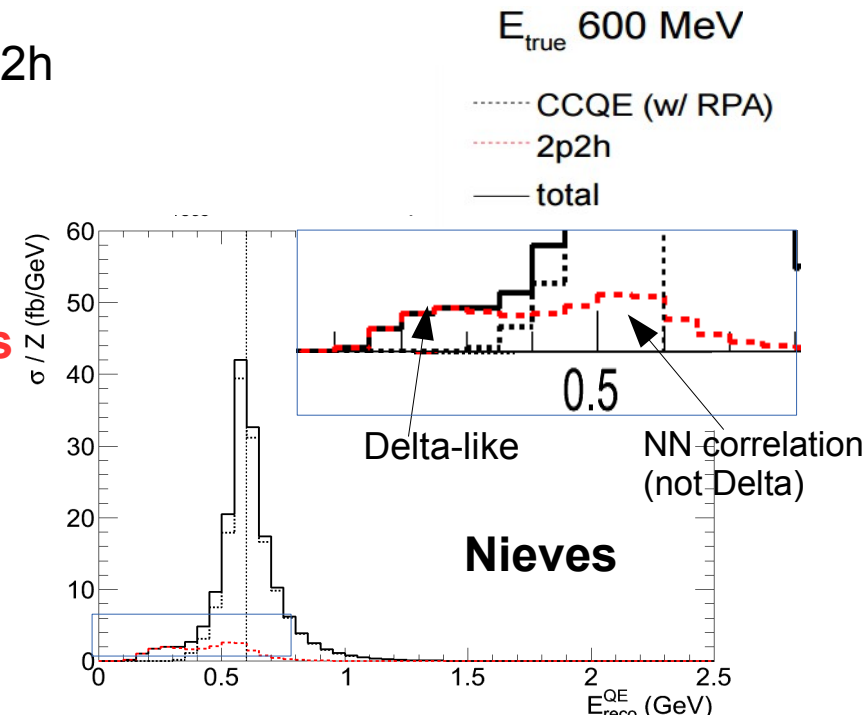
Muon kinematics: limitations

- **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
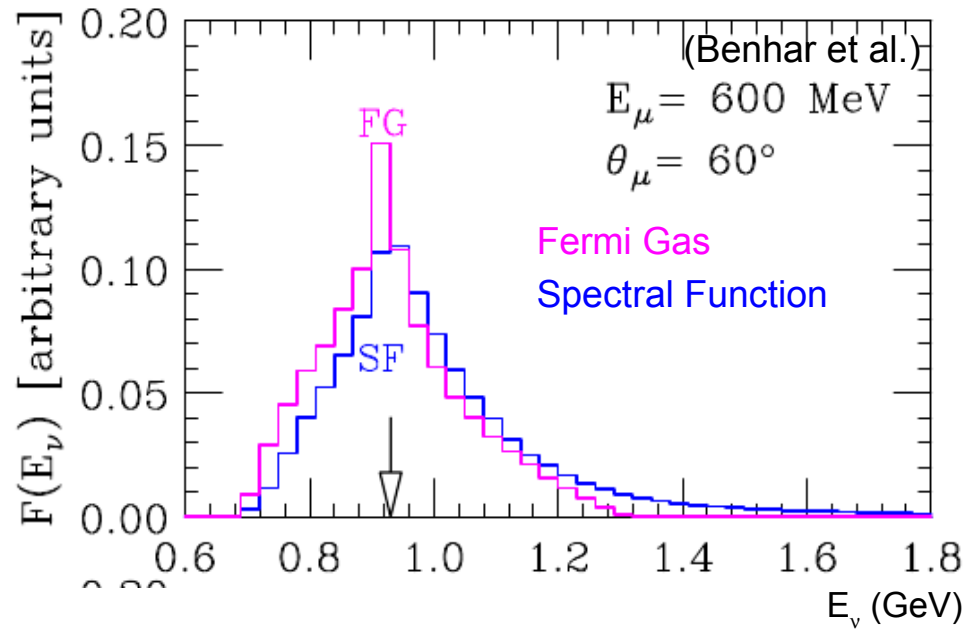
Some nuclear effects (scattering on correlated nucleon pairs, aka 2p2h) can also give a bias.
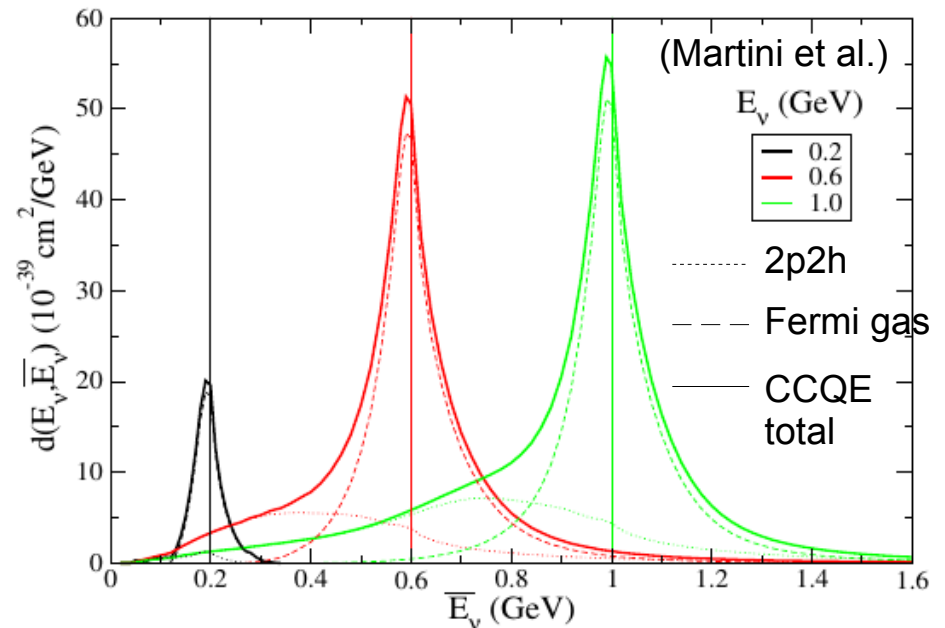
- Very important to have proper parametrization of such effects at ND to correct for them:

  - 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)

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NOVA

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

Scintillator oil → collect light and use topological info for PID

Far Detector
14 kton
896 layers

15.5 m

Near Detector
0.3 kton
214 layers

3.9 m

$\mu + p$

proton

muon

Michel e^-

$e + p$

EM shower

$\pi^0 + p$

gap

(simulated events with 2 GeV visible)

N — W^+ — X, ν_μ, μ^-

N — W^+ — X, ν_e, e^-

N — Z^0 — $X + \pi^0$, ν_μ, ν_μ

Single Cell

To APD Readout

Scintillation Light

Particle Trajectory

15.5m

Waveshifting Fiber Loop

3.9cm   6.6cm
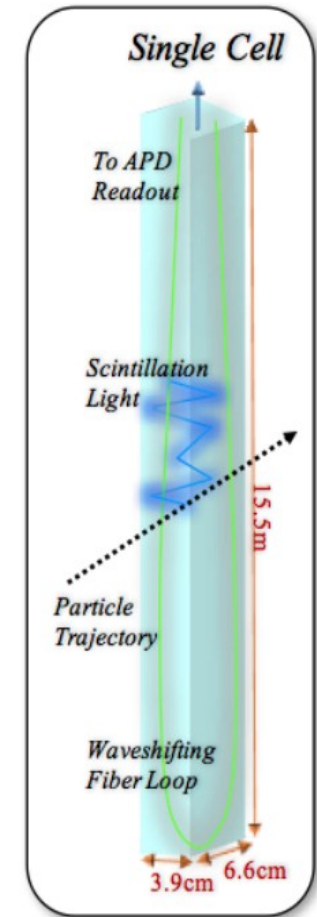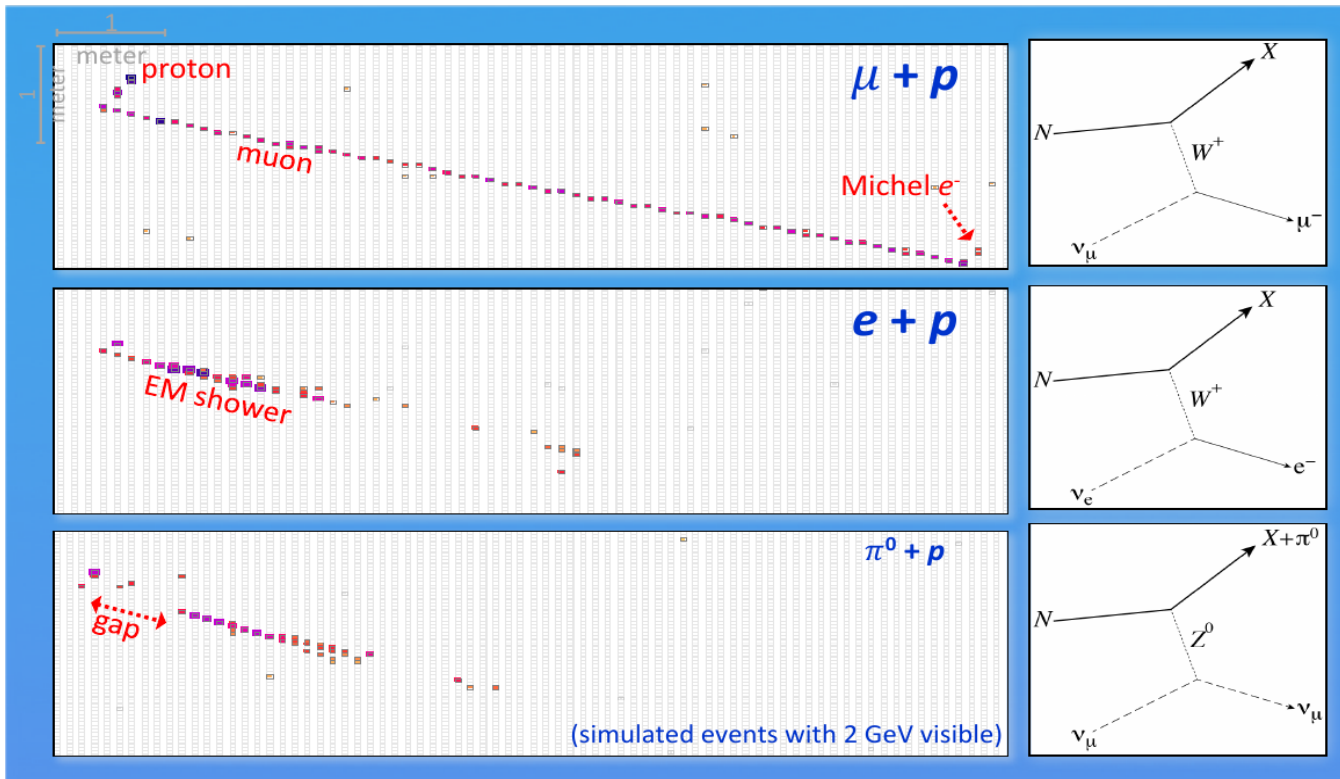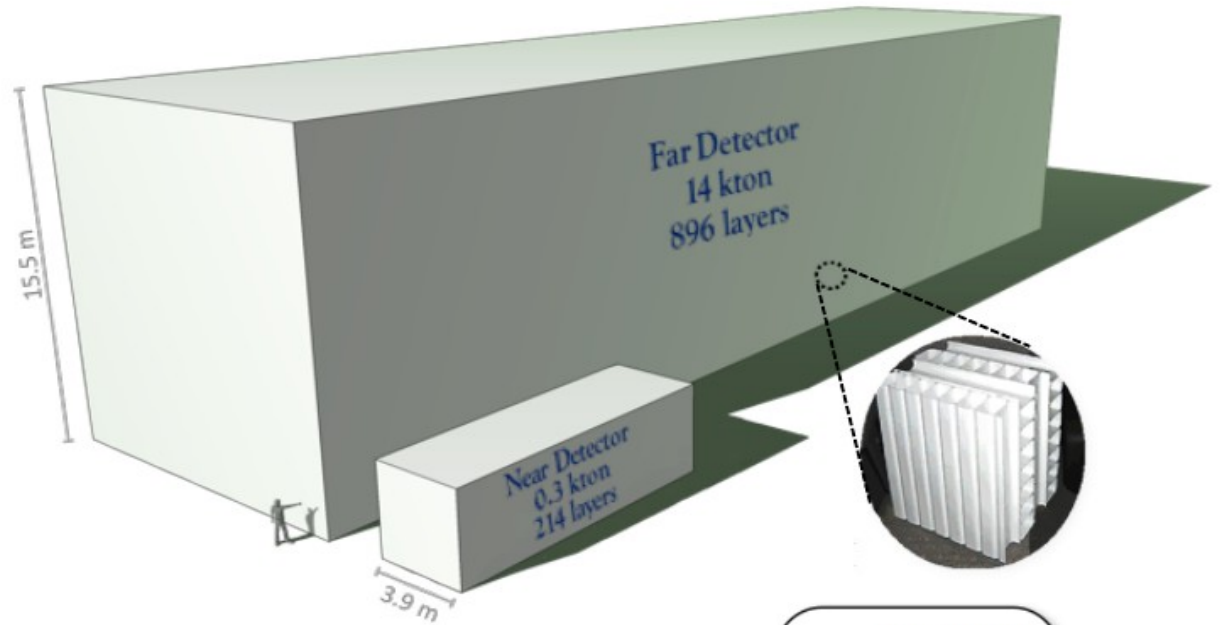
Example of events in NOVA

ν_μ CC

μ

ν_μ

p

Long, straight track

~5m

ν_e CC

p

ν_e

e

Shorter, wider, fuzzy shower

~2.5m

NC

ν

Diffuse activity from nuclear recoil system

1m

1m

10   10^2 10^3 q (ADC)

22
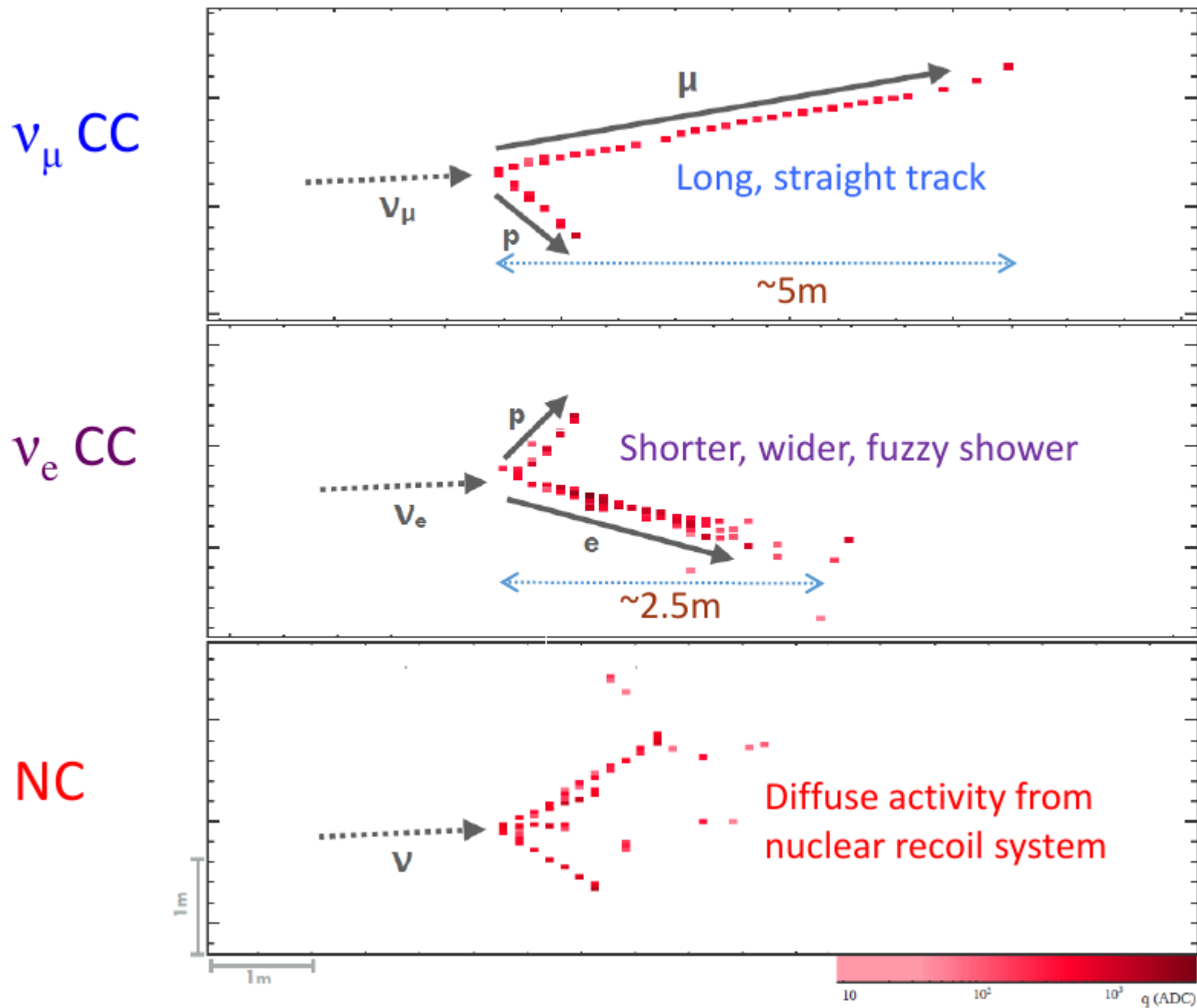
Cosmics

Surface far detector, rate is driven by cosmic ray muons. Rate of 148 kHz

Beam

15 meters

15 meters

60 meters

Record 10 µs beam window ± 270 µs side band

NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608

Top view

13 meters

6 meters

Beam direction

Side view

Color denotes deposited charge
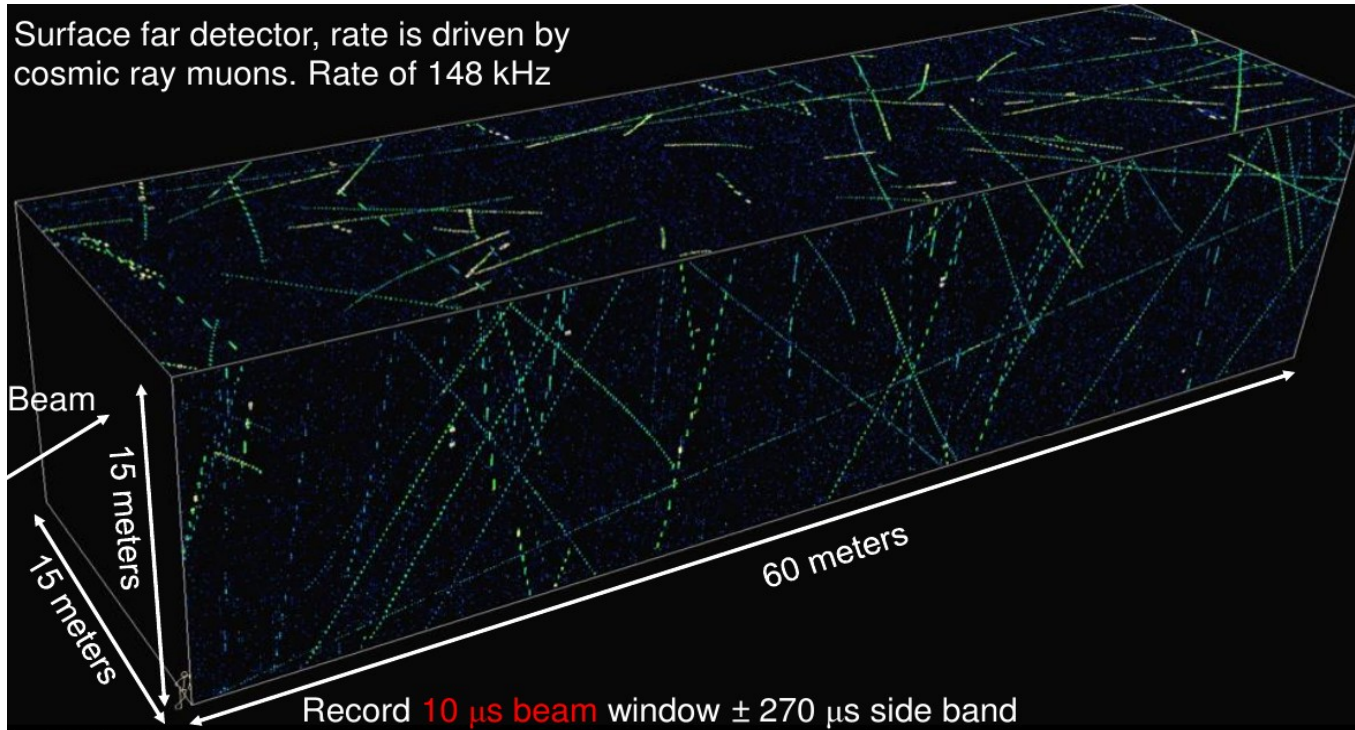
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
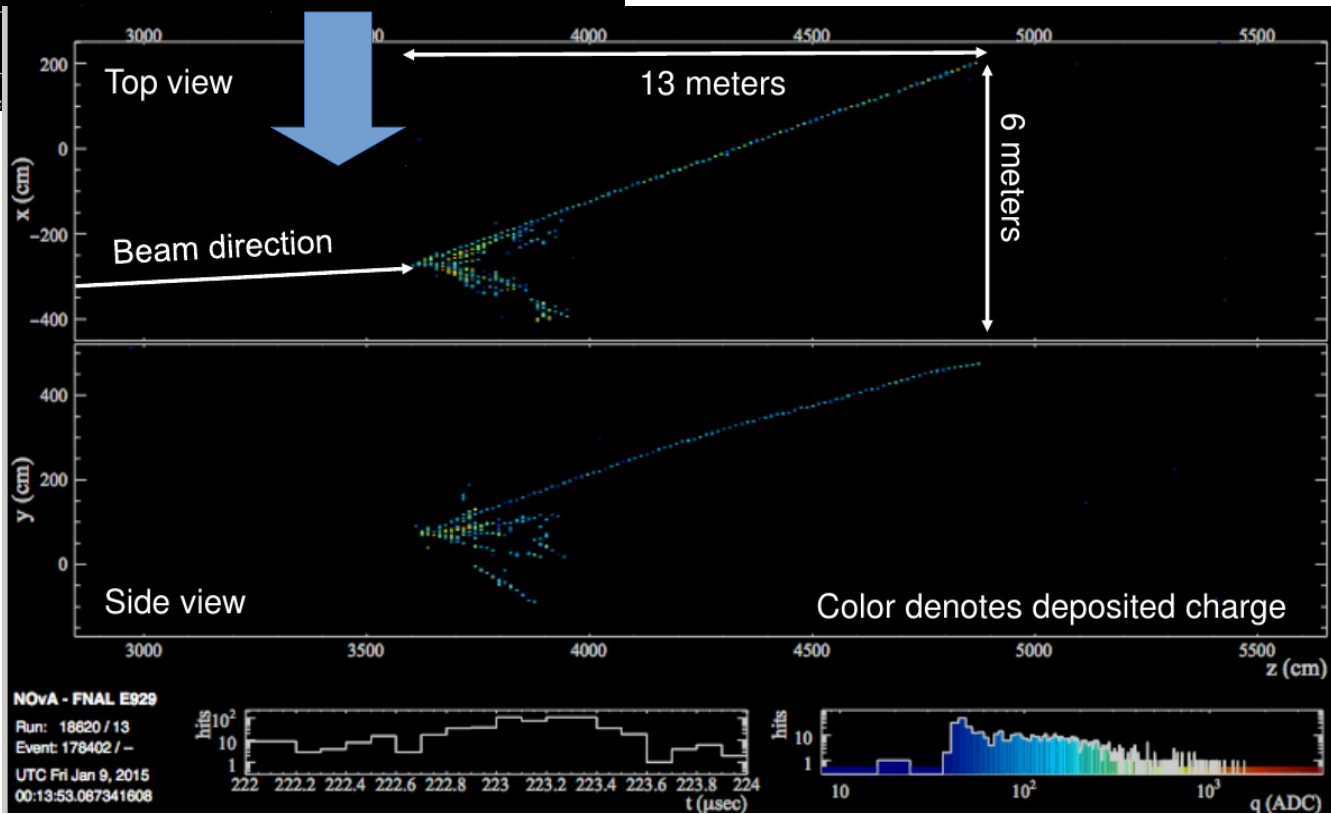
Electrons vs muons and muon containement
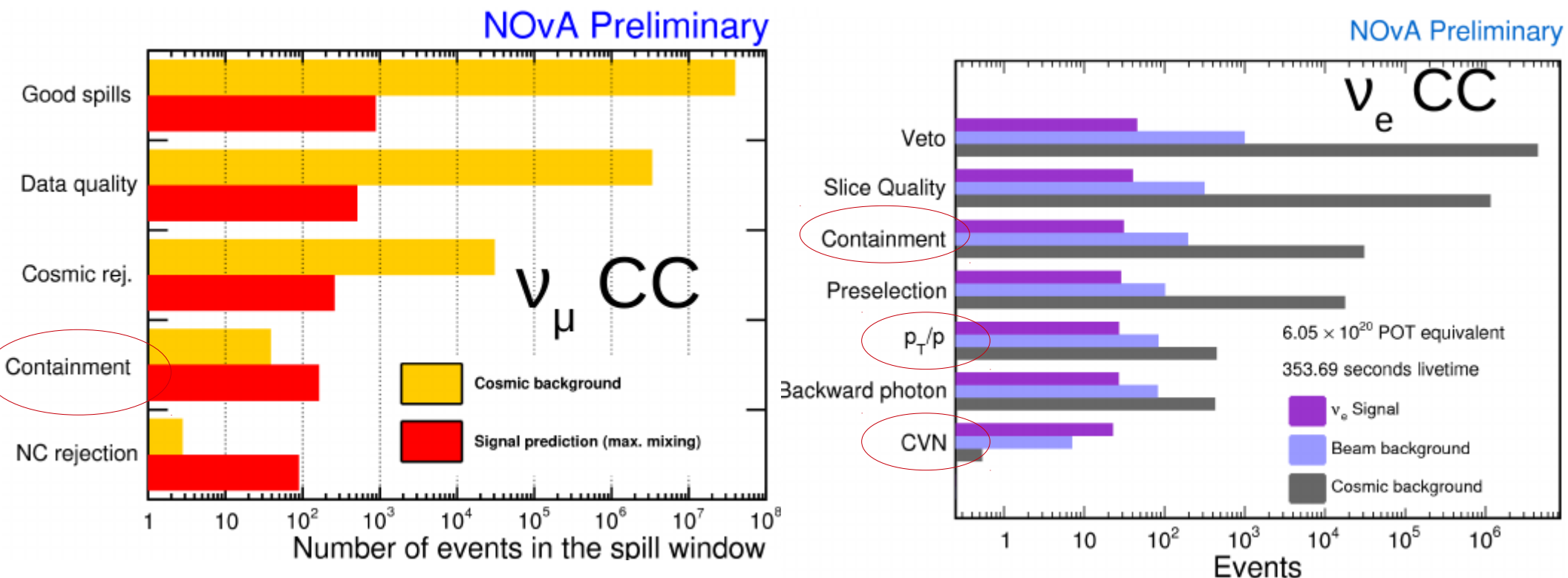
- Need the muon to be contained to measure the momentum using the energy range
  → different efficiency for μ and e, different efficiency for ND and FD

(different size → different E_ν,Q2 phase space for ND and FD)

- ν_e vs ν_μ with visual neural network: not straightforward efficiency and different for electron and muons

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Energy reconstruction

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

$$E_\nu = \quad E_{lep} \quad + \quad E_{had}$$

(~3% resolution)   (~15% resolution)

ν_e interactions   NOvA Simulation

$$\frac{e}{h} = \frac{0.60}{0.45} \simeq 1.3$$
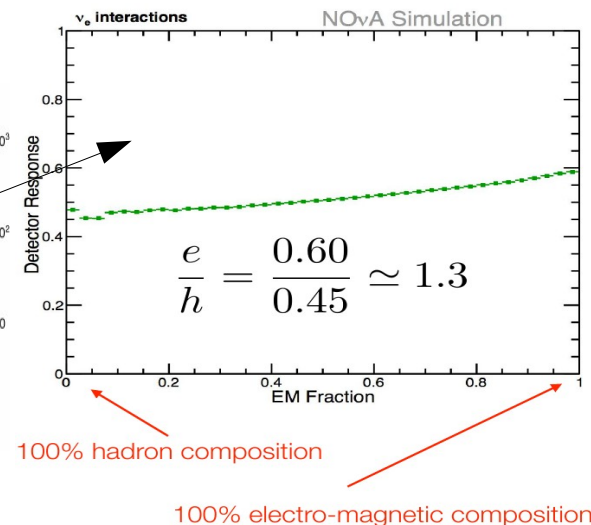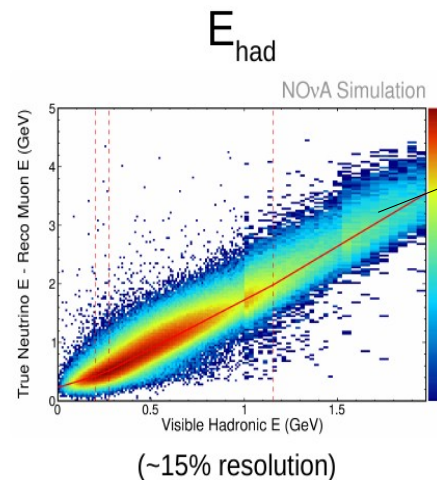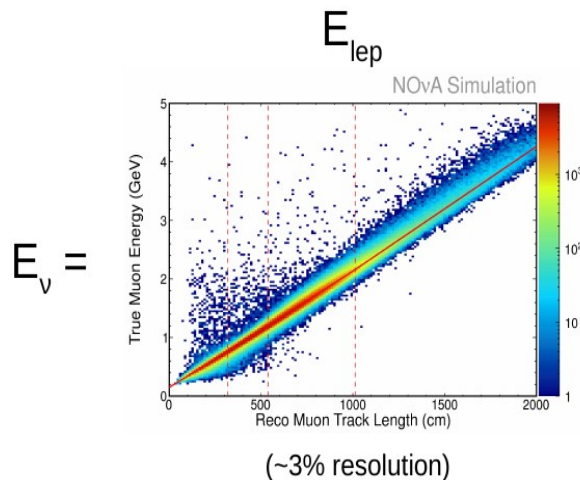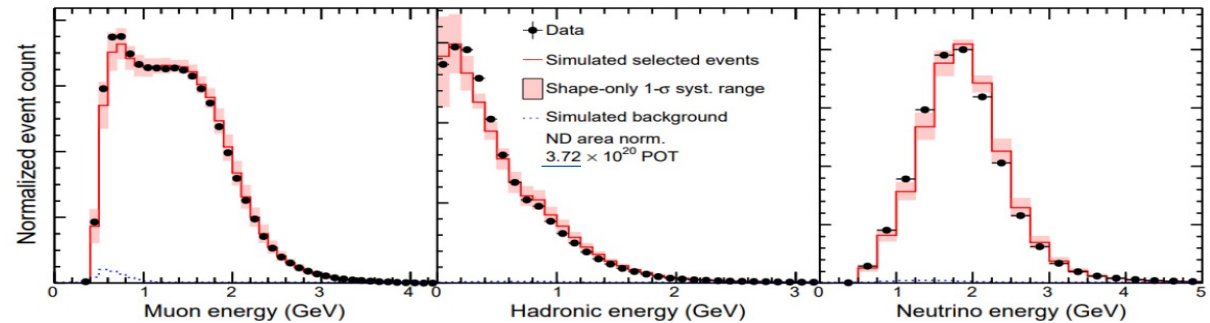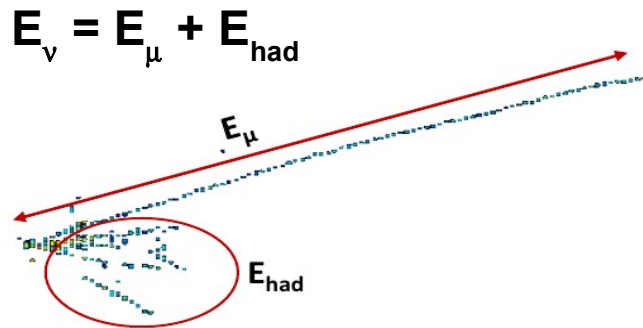
response depend on composition of shower (π^0/hadrons)

100% hadron composition

100% electro-magnetic composition

Energy reso and detector effects different for ν_μ and ν_e events: different reco and selection
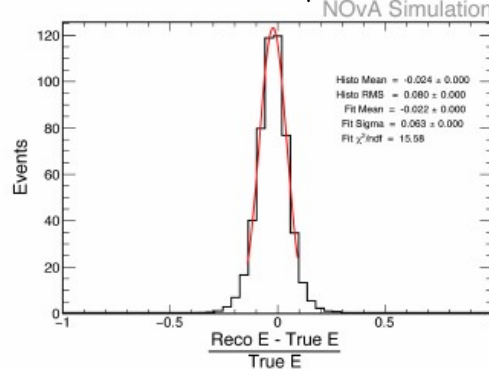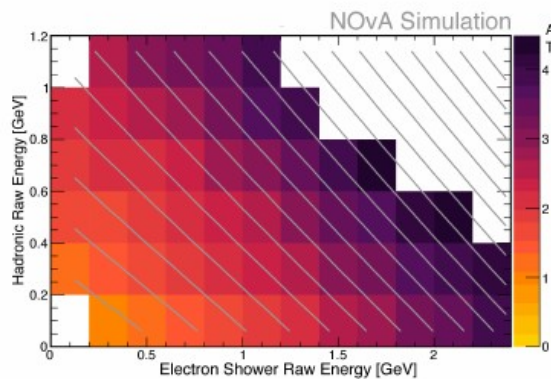
Energy estimator is quadratic function of E_e and E_{had}. ~8% resolution

NOVA spectra

ν_μ disappearance
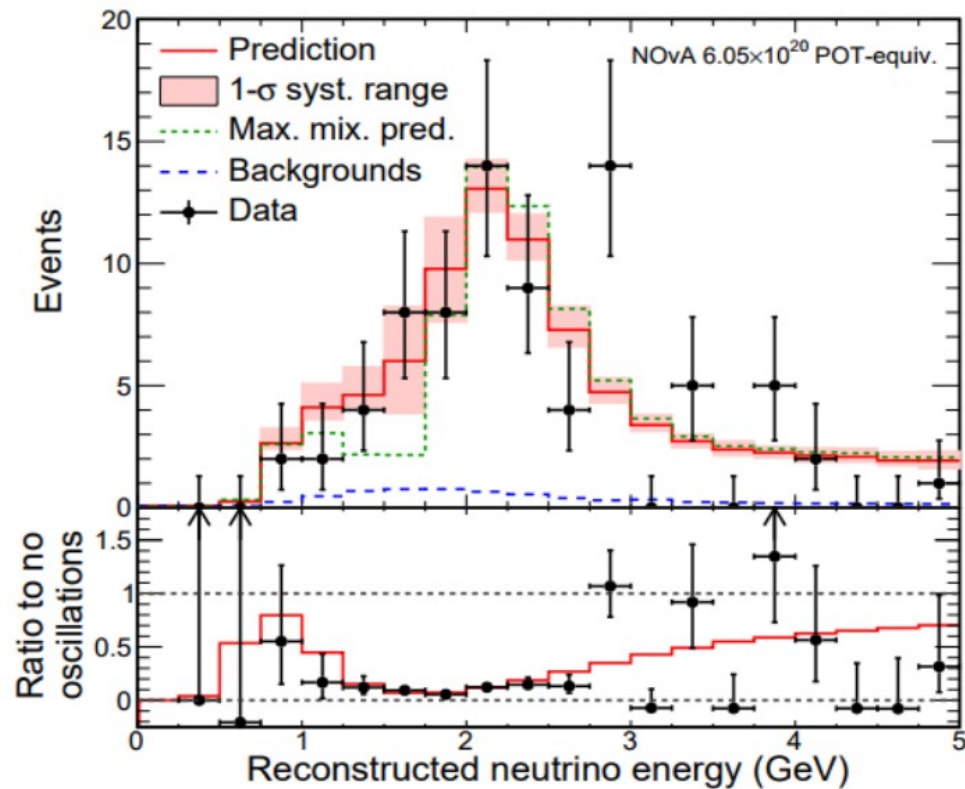
ν_e appearance
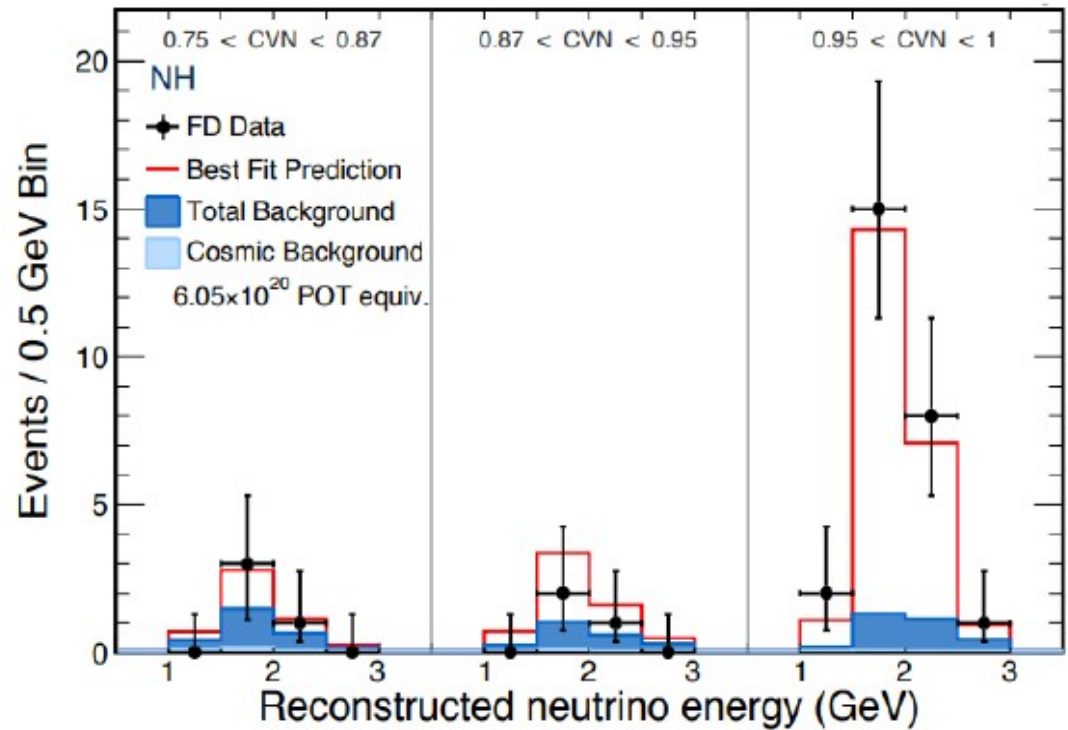
NOVA limitations

Main limitations in order of importance for xsec systematics:

- Calorimetric energy reconstruction: entangling of detector effects (e.g. e/h) and xsec effects: neutrals + nuclear effects (Eb, ...)

- As a consequence: different energy response for ν_e, ν_μ and ν vs $\bar{\nu}$

- 'Complicated' muon and electron ID and efficiency: dependence on kinematics of lepton and on topology (multiplicity)

- NC background and wrong flavor (ν_e/ν_μ) background larger than SK?

The impact of most of these problems are highly suppressed by using the same technology at ND and FD
But... the cancellation is not complete because of

different neutrino energy spectrum before and after oscillation
($\rightarrow$ eg different fraction of neutrals)

Oscillation analysis in NOVA

■ Measurement of all the (visible!) energy in the event to estimate the neutrino energy
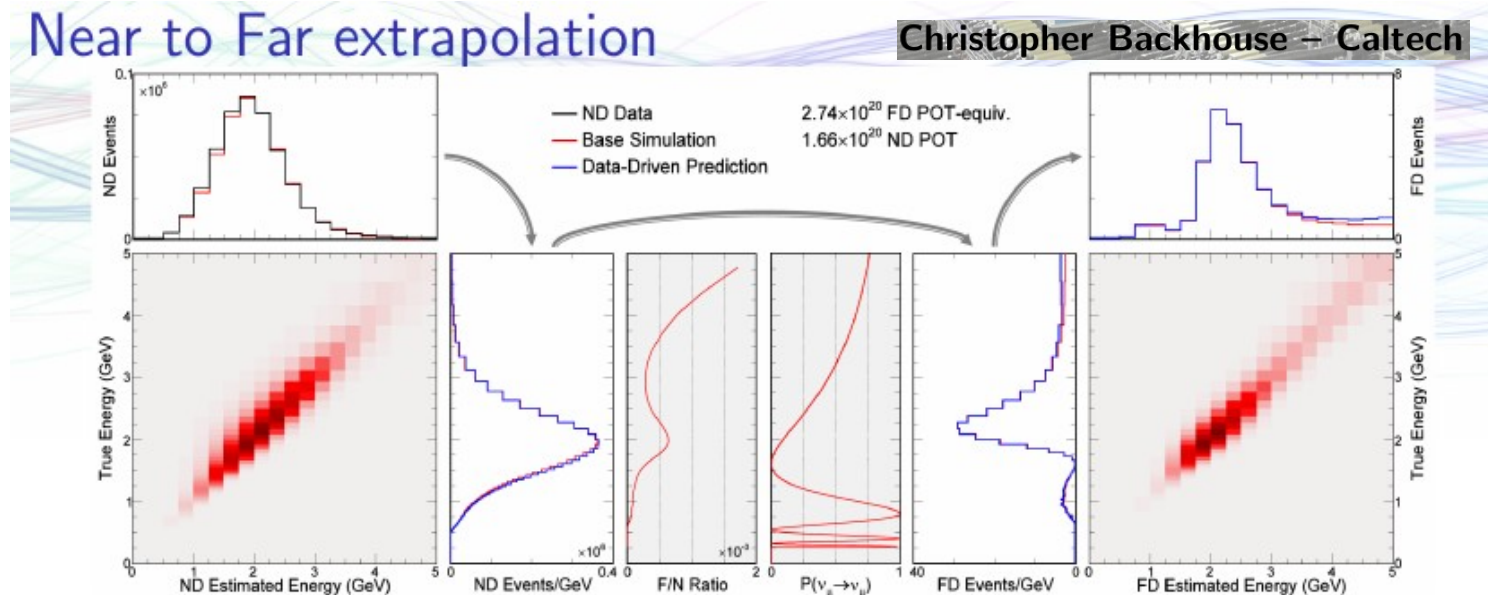
- ▶ Subtract NC expectation in ND, reweight MC in reco energy to match
- ▶ Transform to true energy, transport to FD with oscillations
- ▶ Transform to reco energy, add FD NC expectation back in
- ▶ Dependence on MC for background subtraction and true/reco matrix

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

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Efficiencies

NOvA Simulation

Far Detector
Selected ν_μ CC Events

- MEC
- QE
- RES
- DIS

Efficiency × acceptance vs True E_ν (GeV)

G. Zeller

ν cross section / E_ν (10^{-38} cm^2 / GeV)

NOvA's region of interest 1 - 3 GeV

TOTAL

QE

DIS

RES

E_ν (GeV)
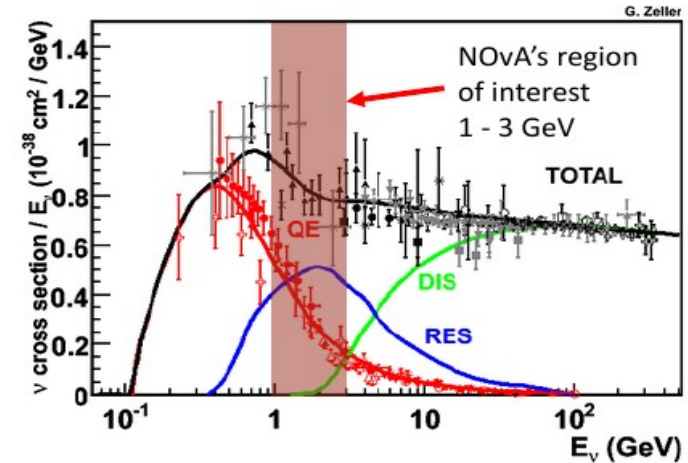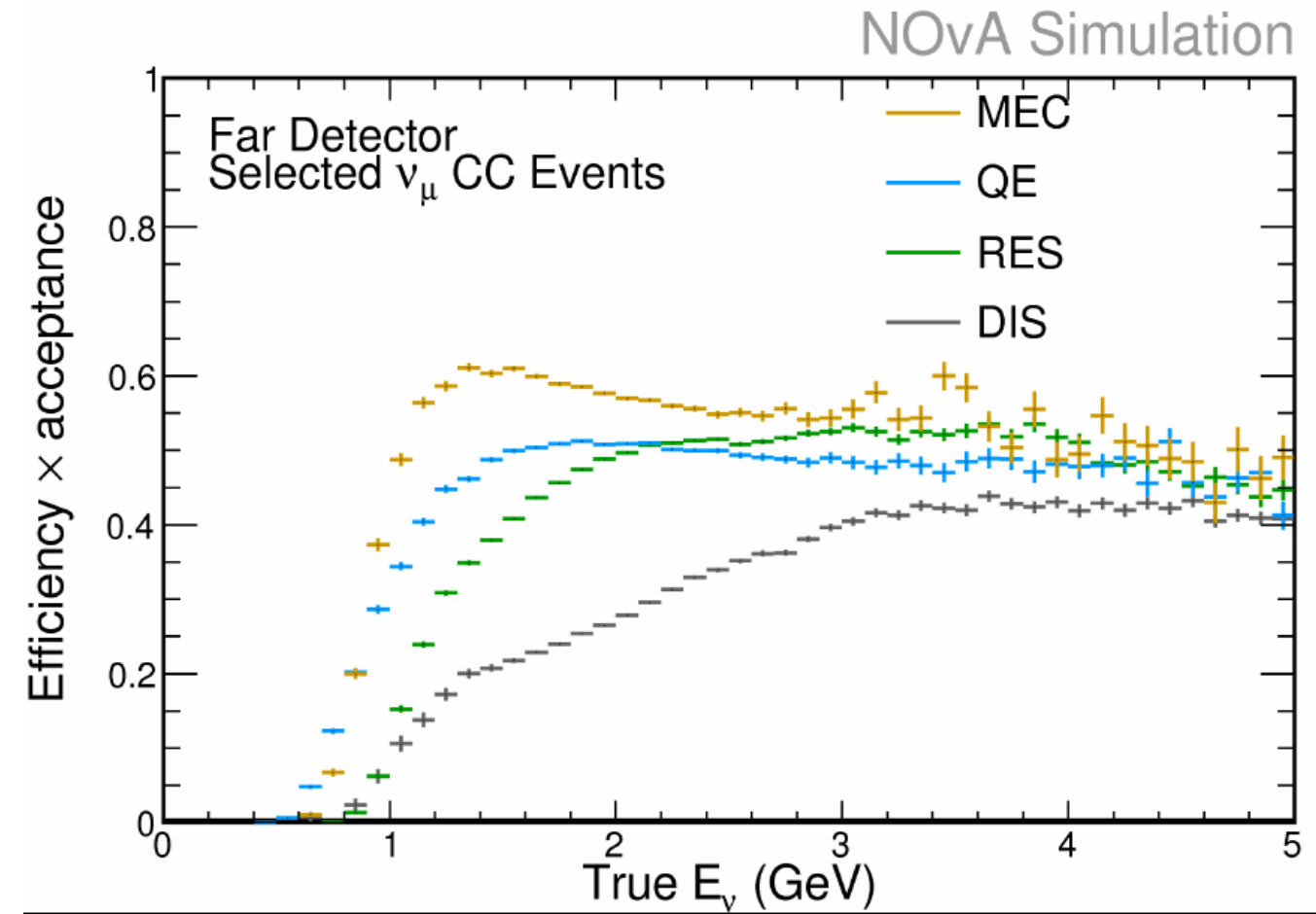
- **Efficiencies sculpted** by containment and background rejections + muon reconstruction more complicated in a high multiplicity environment

- 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...**

NC background

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

Larger for ν_e:
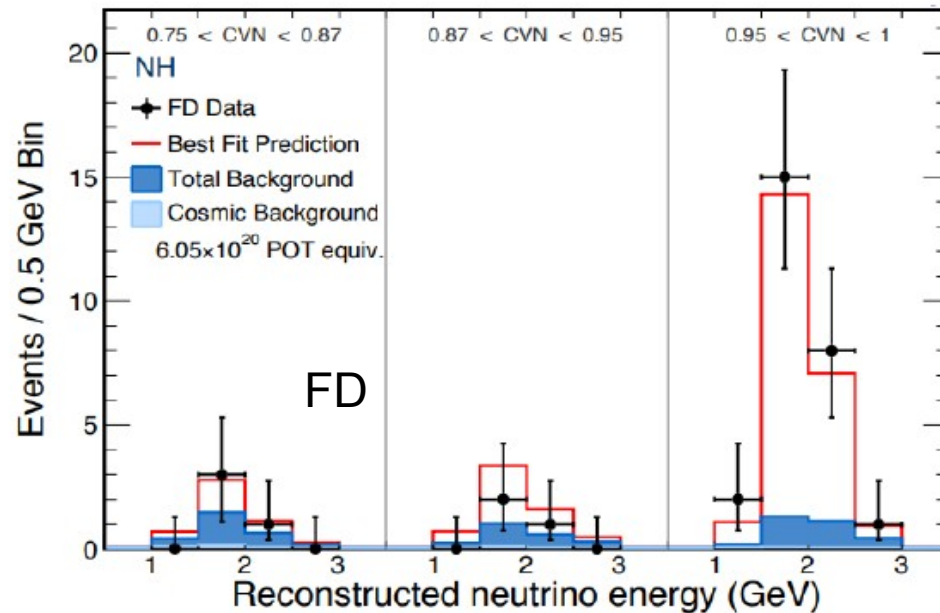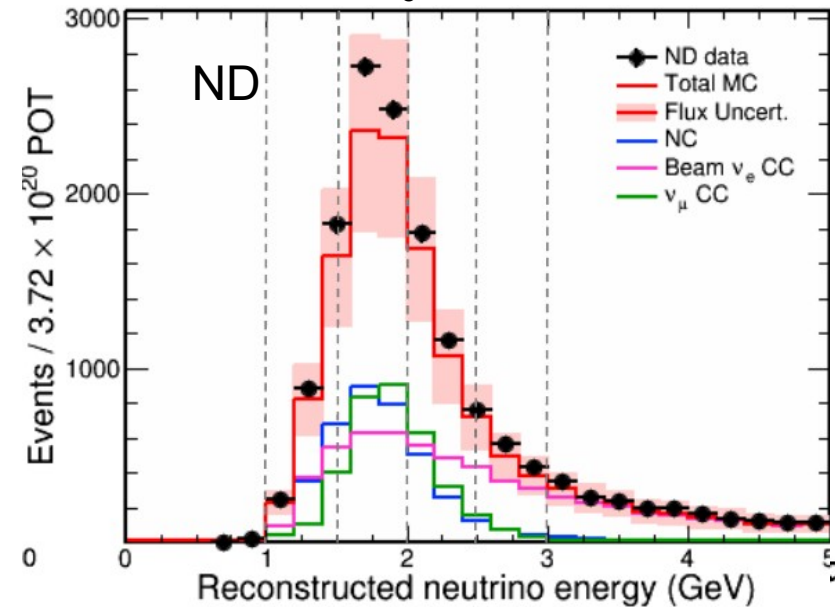
ND data-driven tuning to correct for 10% discrepancy data-MC
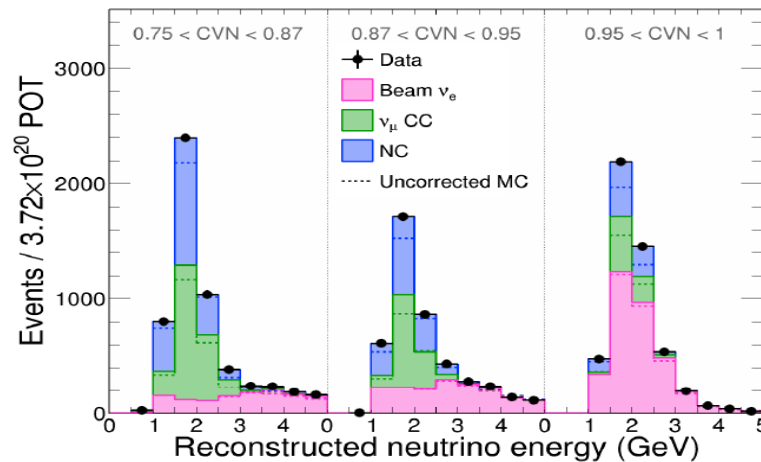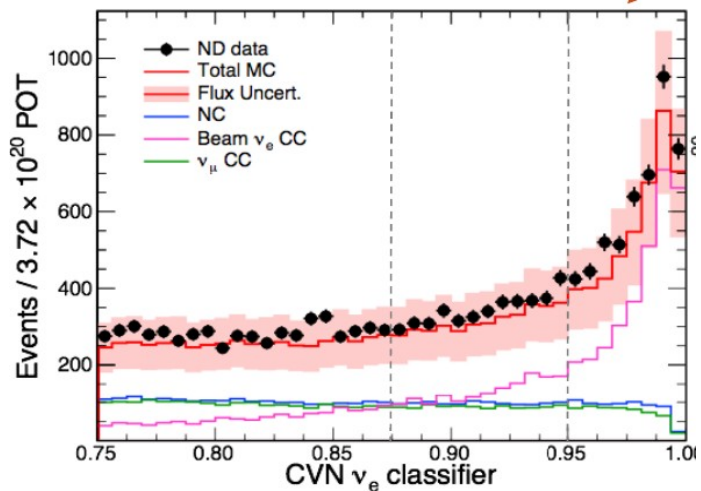
3 regions of electron-classifier with different background fractions

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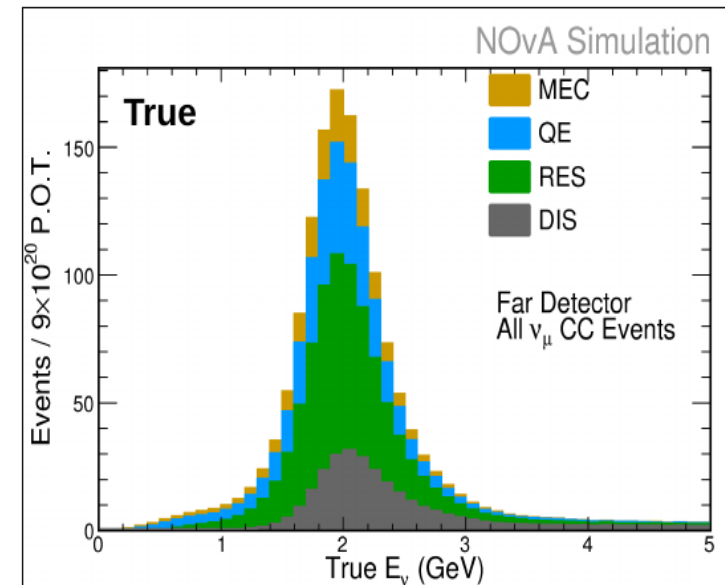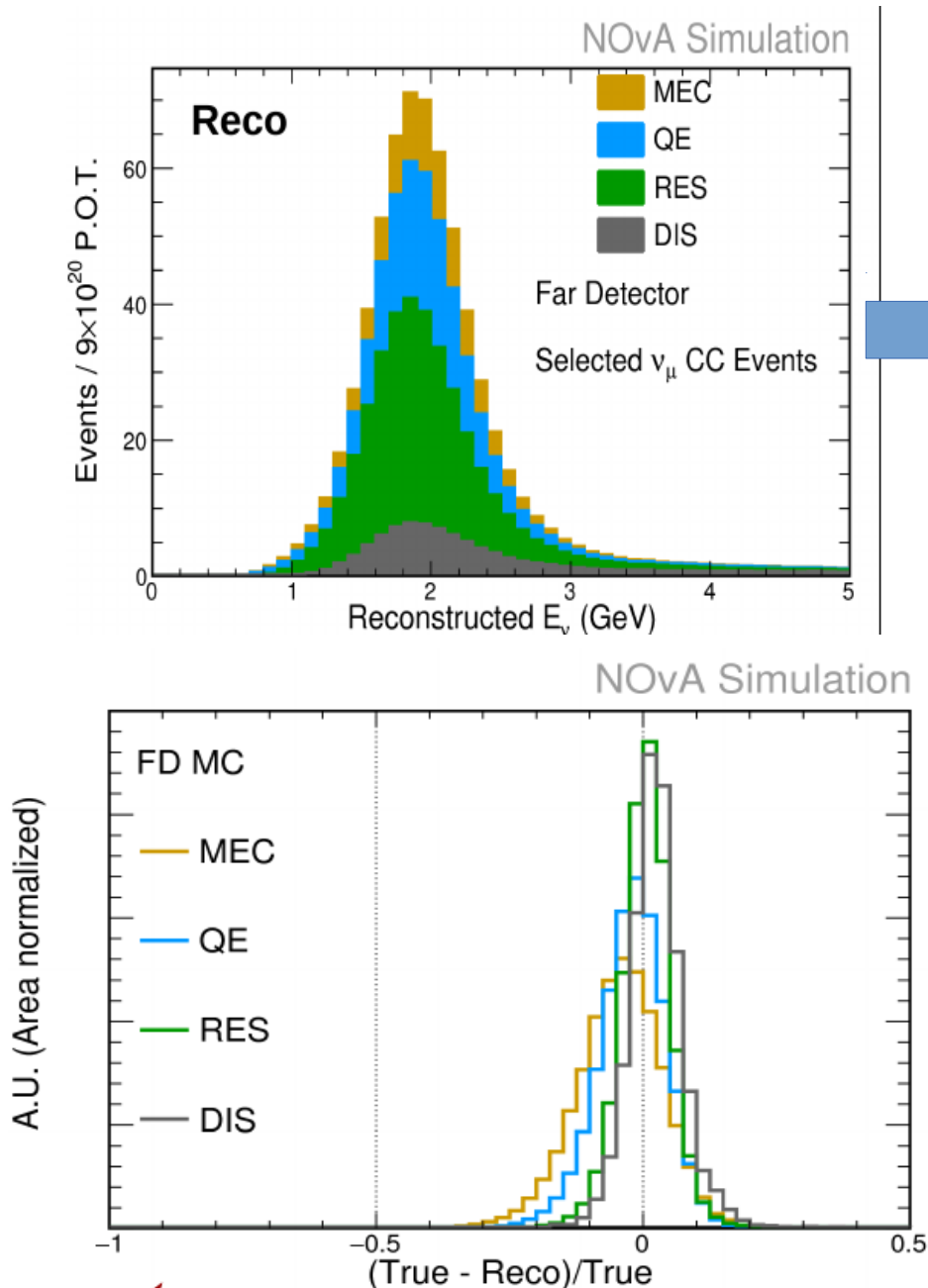
Need to correct from E_{rec} to E_{true}

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 ...

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ν versus $\bar{\nu}$

A M Ankowski and C Mariani

true E_ν = 2.5 GeV

different assumption on the control of missing energy
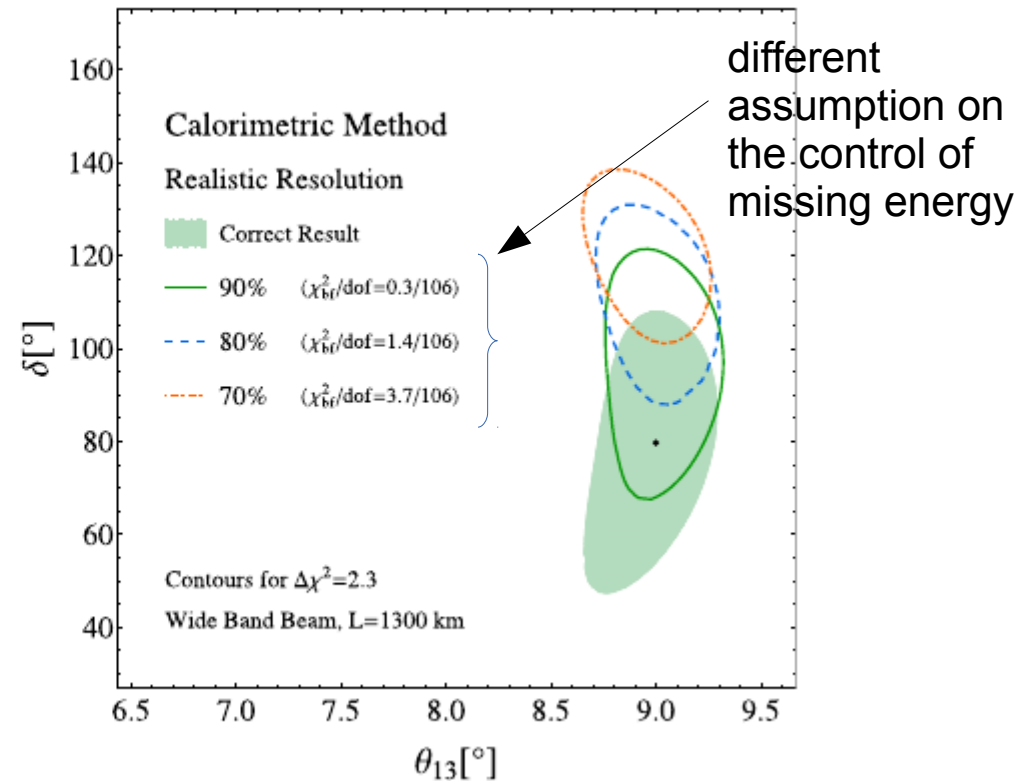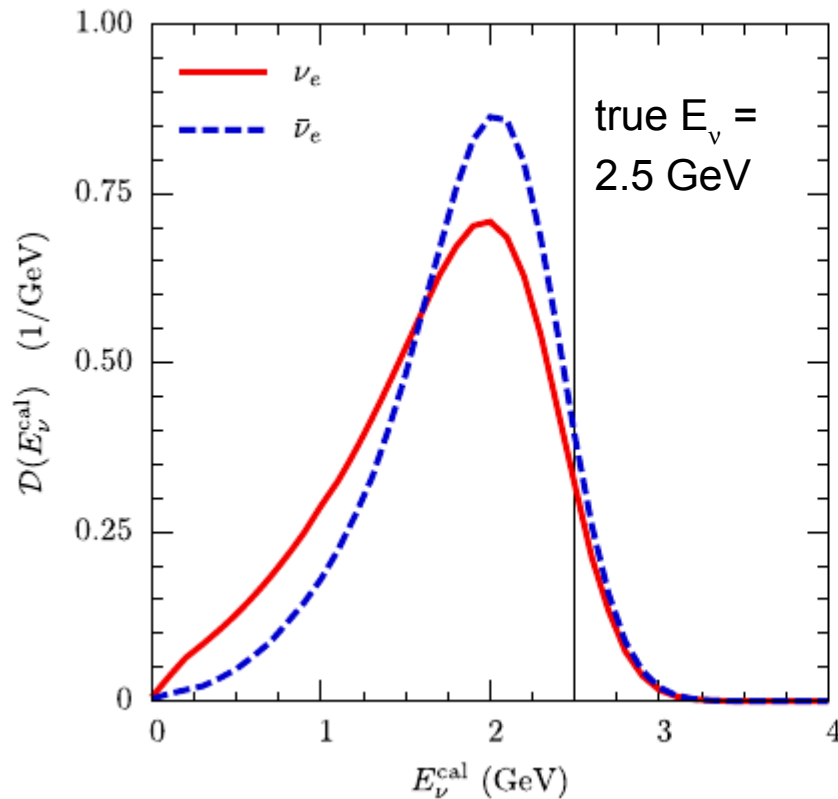
Smearing and underestimation of neutrino energy due to nuclear effects + detector effects for DIS events

Different response for ν and $\bar{\nu}$ → possible bias on δ_{CP}

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2p2h

- **Known mismodeling of hadronic energy in 2p2h (and beyond):** important xsec systematics at NOVA for ν_μ disappearance
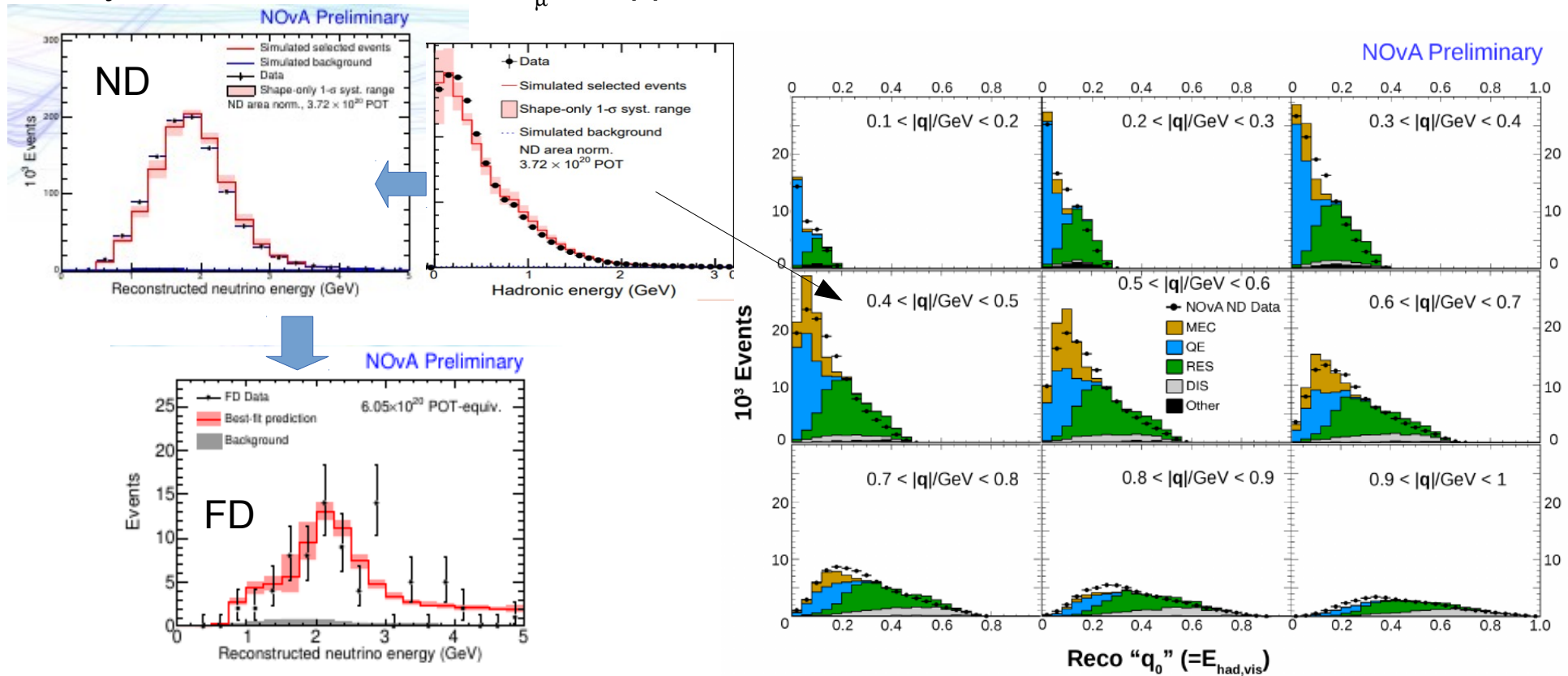
- Another important effect that should be considered is the fraction on neutrons/protons in the final state (depending on the flavor of the correlated pairs in the initial nucleons)

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

$$\bar{\nu} + pp \rightarrow \mu^+ + pn$$
$$\bar{\nu} + np \rightarrow \mu^+ + nn$$
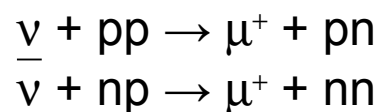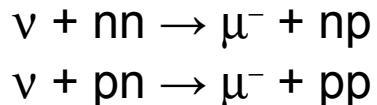
$\rightarrow$ **affect $\bar{\nu}/\nu$ differently: important systematics for δ_{CP}**

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Calorimetric approach: limits

- **Main limitation:**

- Calibration issues (no sensitivity to neutrons, energy threshold...)

- Very limited predictivity from models regarding the hadronic final state!

The two problems are tightly convoluted and difficult to disentangle

Example from NOVA:
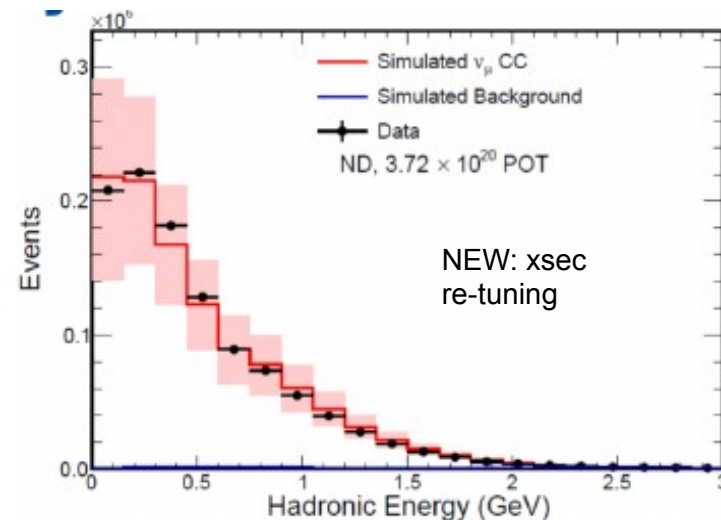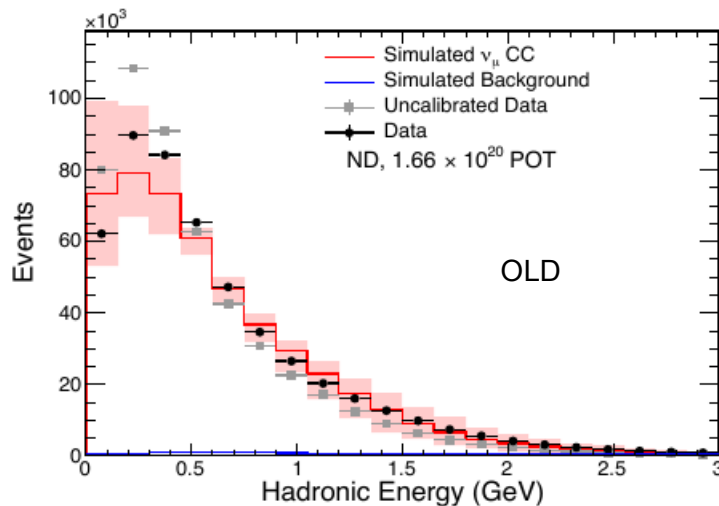
- **A taste of the future → DUNE:**

  - need to reconstruct precise E_ν shape for good sensitivity (two oscillation maxima)

  - capability of full reconstruction of tracks and showers down to very low threshold

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

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LAr TPC (MicroBooNE)

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

- **Muon momentum from multiple scattering**
  (+ correction for Michel electrons)

Selected, Well Reconstructed Tracks from ν_μ CC Data

arXiv:1703.06187

MicroBooNE Data

MCS Momentum [GeV/c] vs Range-Based Momentum [GeV/c]

- **Energy resolution on the hadronic side:**

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

  Full study of these effects to be done: how the xsec uncertainties interplay with all of these effects?
  (Test benches: MicroBooNE, LArIAT.. and protoDUNEs!!!)

MicroBooNE Simulation, Preliminary

Reconstruction Efficiency vs True Momentum [GeV]

$\nu_\mu + N \rightarrow X + \mu^- + p$
— μ
— p

MicroBooNE Simulation, Preliminary

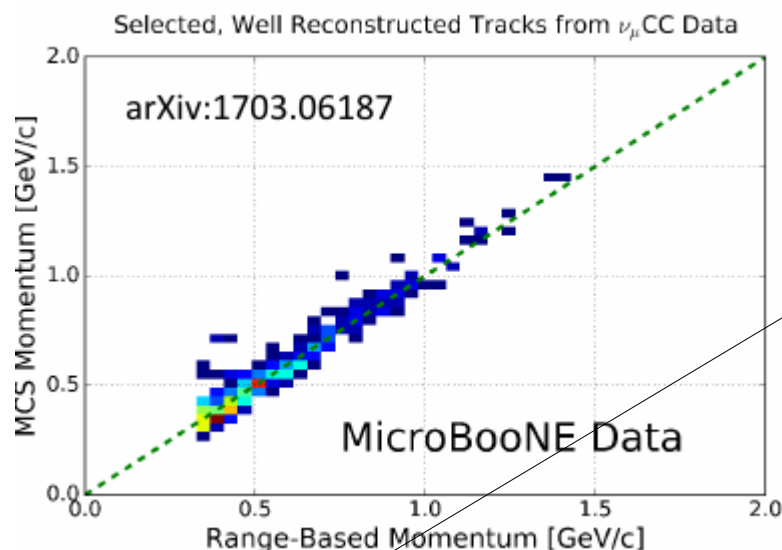| | All BNB Protons |
| | All Reconstructed BNB Protons |
| | Correctly Identified Reconstructed BNB Protons |

Simulated Proton Tracks vs Proton Kinetic Energy [MeV]
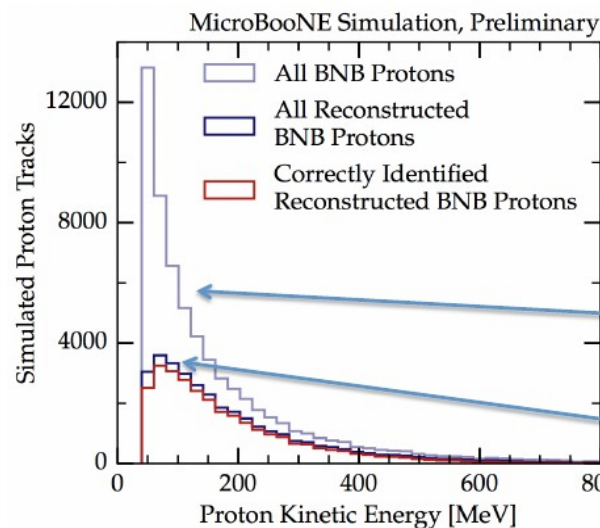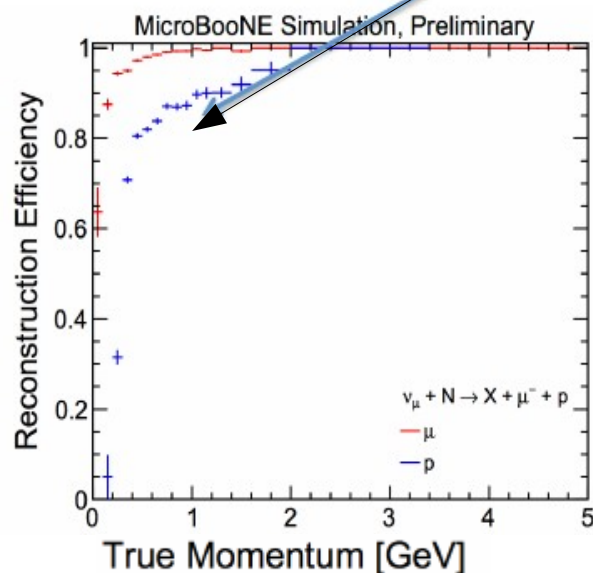
To correct for these effects and go back to total En
→ **need correct MC estimation of multiplicity and momentum of outgoing hadrons**

Uncertainties:
- MC needed to correct for these lost protons

- mis-ID protons counted as pions – energy wrong, or muons – event topology wrong

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No perfect solution

■ Impact of neutrino cross-section uncertainties on oscillation measurements is a complicated problem!

■ There is no perfect solution!

■ Having two very different detectors (SuperKamiokande and NOVA) where the same systematics gives different effects is very valuable in order to:

- check for possible bias on the results

- better understand possible problems in the neutrino interactions

(hopefully this will be true also for HyperKamiokande and DUNE!)

How we are going to improve the xsec model uncertainty for the OA?

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

- **In a indirect way measuring neutrino interactions at ND (and elsewhere):** measure protons, vertex energy, … which are not directly included in OA 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**

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

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BACK-UP

Near detector constraints

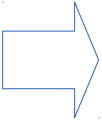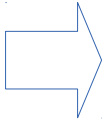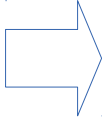Near detector is used to tune the xsec model but...
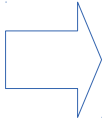
- some nuclear effects can be degenerate (indistinguishable) with near detector data but still give you different spectrum at far detector

- detector effects (calibration and threshold) can also be degenerate with nuclear effects

- anticorrelation between the xsec and the flux → difficult to constrain them separately (and they propagate differently at FD)

you can perfectly describe ND data and still be wrong in FD prediction

Impact of such problems on the oscillation analysis depends on the detector and how the analysis is done

What we need to control?

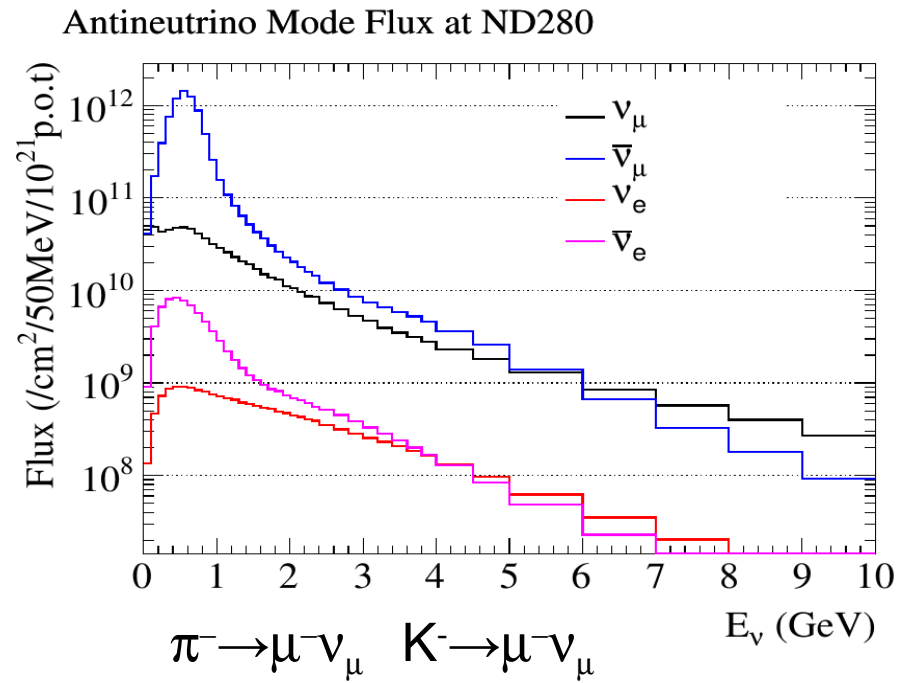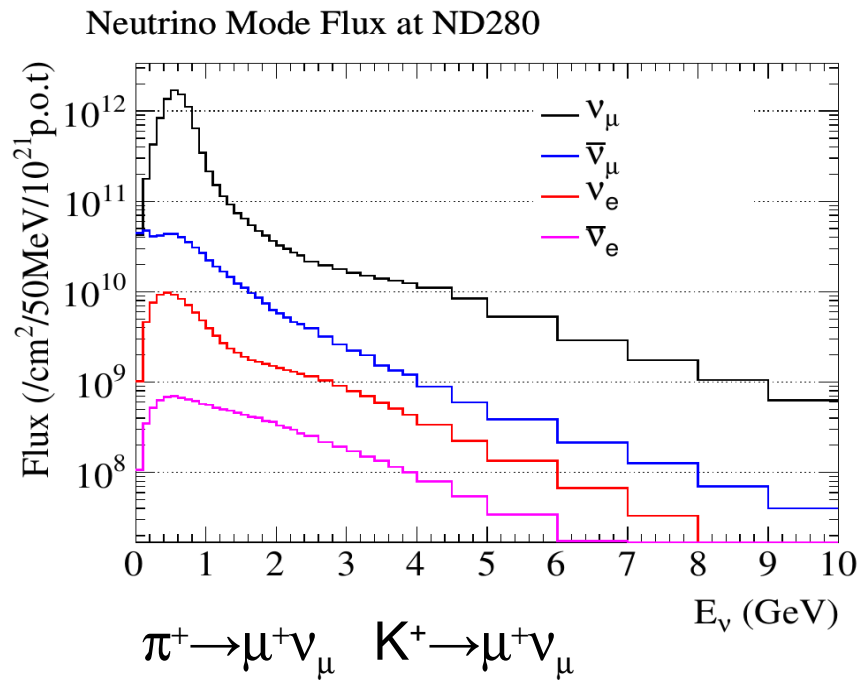**Uncertainties in ND→FD extrapolation :**

- 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

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Question from yesterday (1)

Neutrino Mode Flux at ND280

Antineutrino Mode Flux at ND280

$$\pi^+ \to \mu^+ \nu_\mu \quad K^+ \to \mu^+ \nu_\mu$$

$$\pi^- \to \mu^- \nu_\mu \quad K^- \to \mu^- \nu_\mu$$
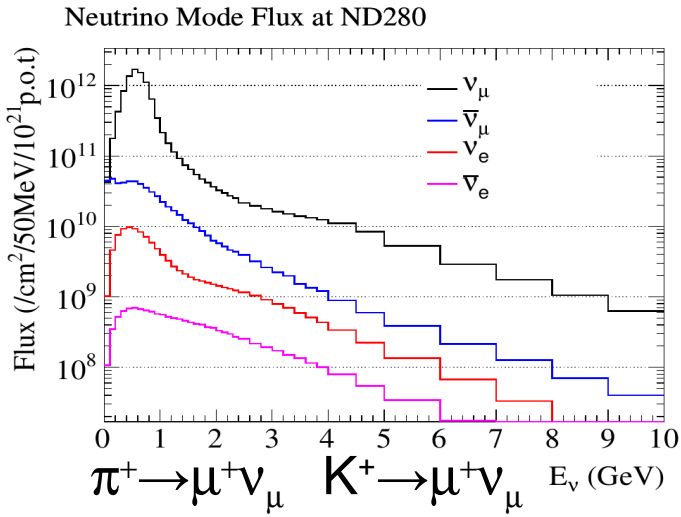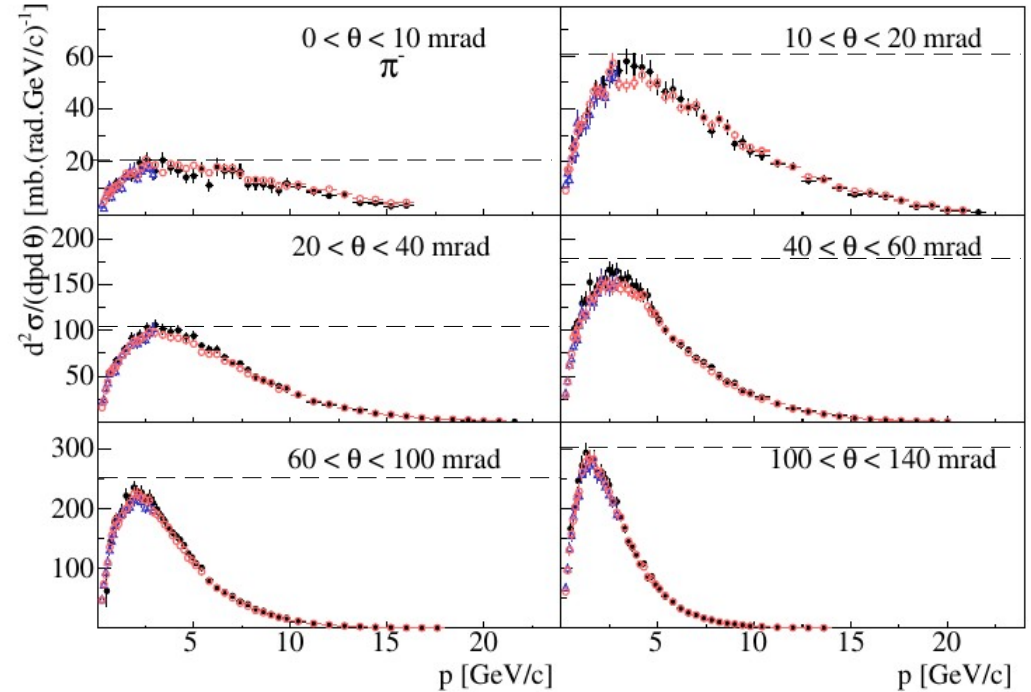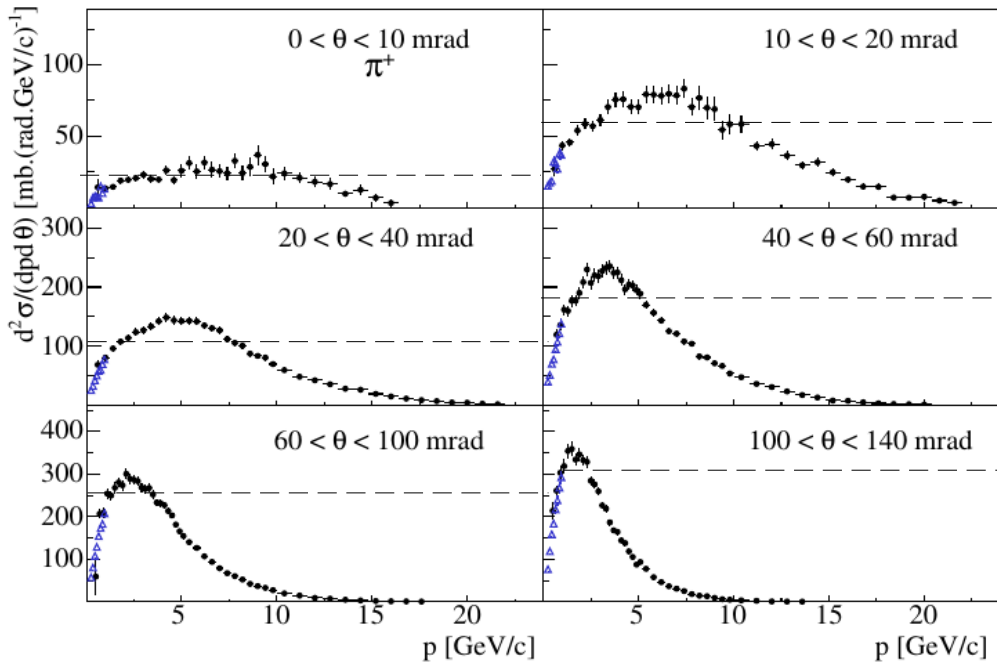
The 'wrong sign' background comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns

Question from yesterday (2)

Neutrino Mode Flux at ND280

Antineutrino Mode Flux at ND280
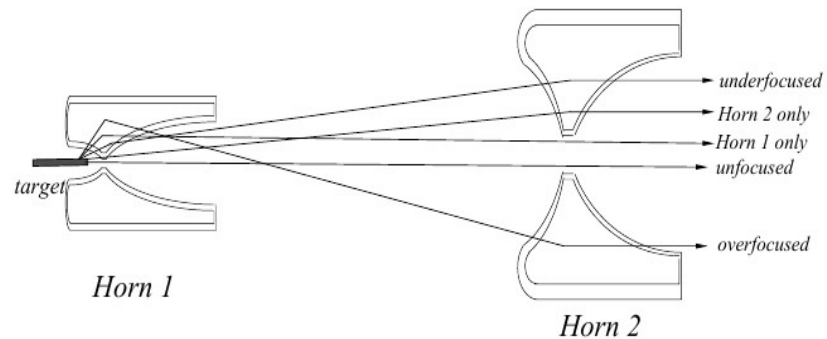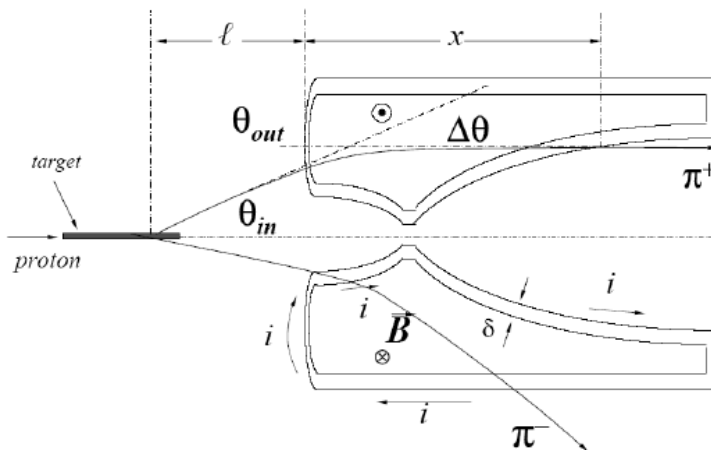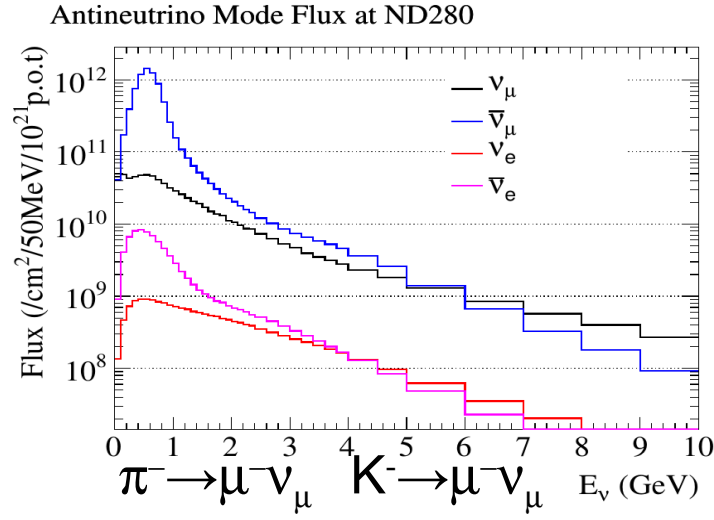
When proton hits the target it is more probable to create positive charged hadrons than negative ones

Cross-section normalization

$$\sigma_{hadroprod} = \sigma_{tot} - \sigma_{el} - \sigma_{qe}$$

$\boxed{\sigma_{tot}}$ can be extracted from beam instrumentation in anti-coincidence with S4

(normalized to number of carbon nuclei in the target)

Need to correct for events with actual interactions in S4 using model

$\boxed{\sigma_{el}}$ elastic scattering on carbon nucleus
(from previous measurements compared to GEANT → largest uncertainty)

$\boxed{\sigma_{qe}}$ quasi-elastic scattering on single nucleon in the carbon nucleus which get ejected (from GEANT)
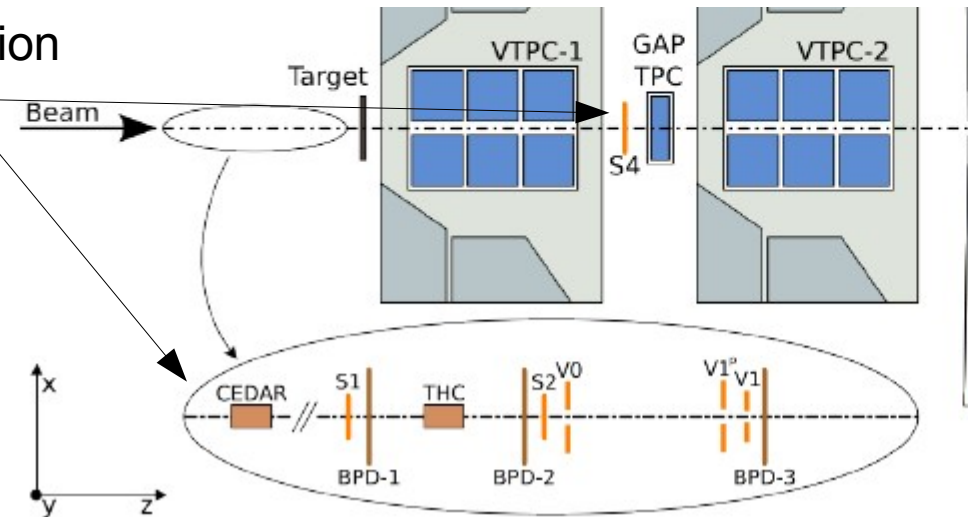
$$\sigma_{\mathrm{prod}} = 230.7 \pm 2.8(\mathrm{stat}) \pm 1.2(\mathrm{det}) {}^{+6.3}_{-3.5}(\mathrm{mod})\,\mathrm{mb}$$

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RPA

Random Phase Approximation is a non-perturbative method to describe microscopic quantum mechanical interactions in complex systems of many bodies.

The many-body system constituted by the mutual interactions of nucleons inside the nucleus cannot be resolved exactly → approximated calculation which parametrize the impact of such collective effects on the ν-N cross-section
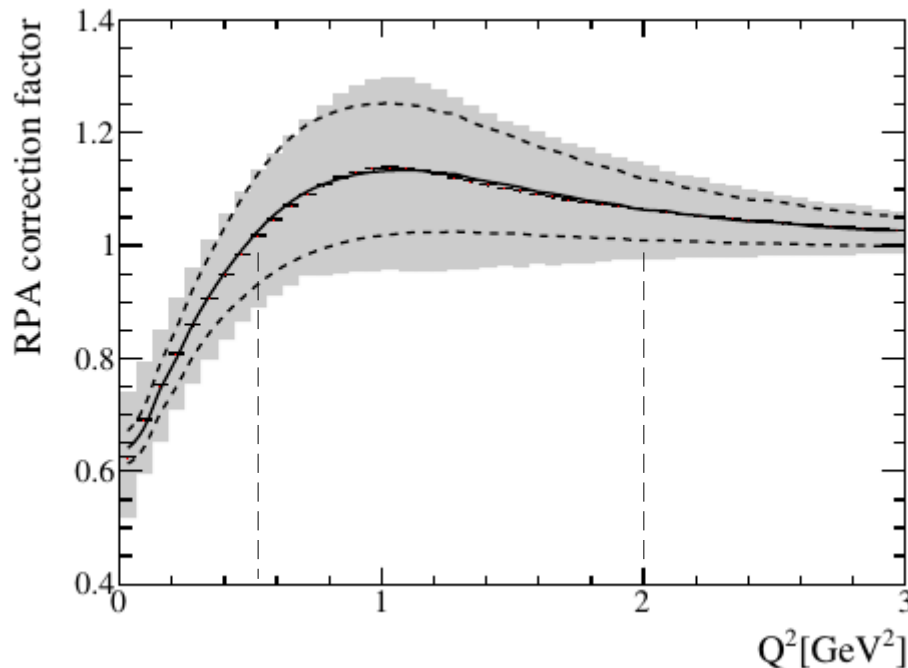

- **$Q^2 < 0.5$ GeV^2 screening:**
  nucleons embedded in nuclear potential

- **$Q^2 \to$ inf no RPA effect:**
  if high energy transferred to nucleus than nucleons (→ quarks) ~ free

C-RPA

RPA is an ***approximation*** → a more sophisticated computation **Continuum-RPA** describes the very reach details of the nuclear structure

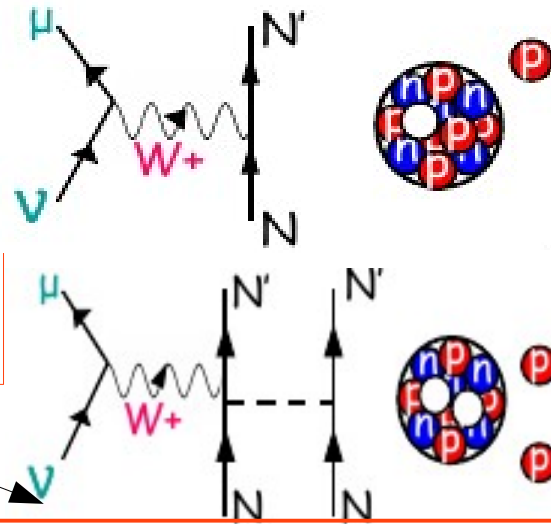Resonances at low energy transferred to the nucleus (ω), ie low E_ν or very forward muon
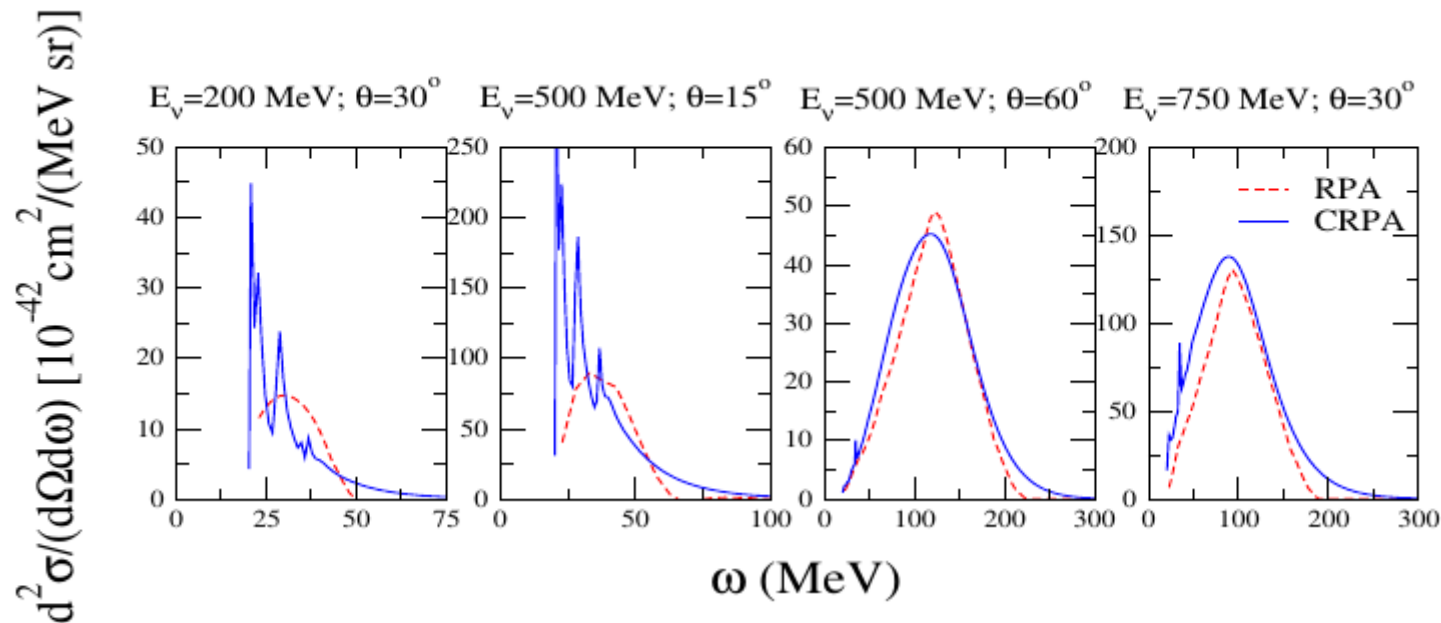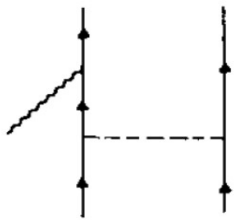
Additional process: 2particles-2holes (only in nuclei)

CCQE (aka **1p1h**)

+

2p2h : interaction with correlated nucleons

Nucleon-Nucleon correlations

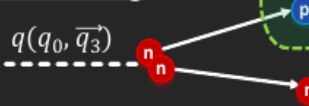Meson Exchange Currents (MEC)

Pion in flight   Contact   Delta
Dominant in MEC
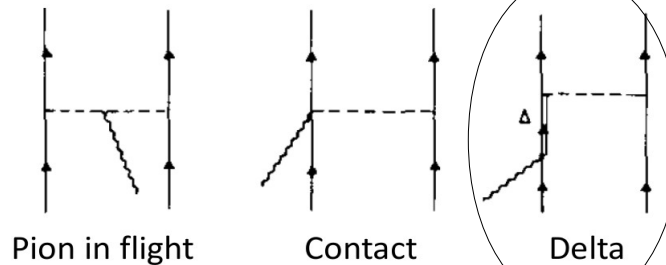
+ interference

Experimentally difficult to disentangle: final state can be pn or pp with low energy protons

CCQE + CC1pi (+DIS)
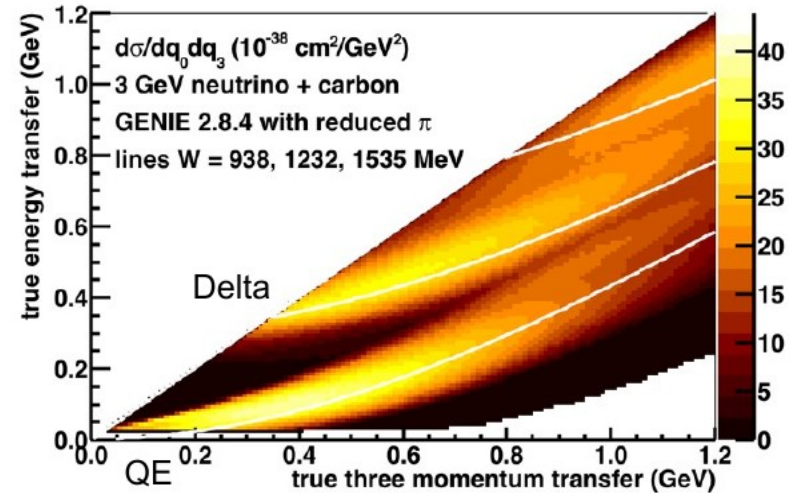
$d\sigma/dq_0 dq_3$ (10^{-38} cm^2/GeV^2)
3 GeV neutrino + carbon
GENIE 2.8.4 with reduced π
lines W = 938, 1232, 1535 MeV

Delta

QE

true three momentum transfer (GeV)

2p2h (Nieves)

$d\sigma/dq_0 dq_3$ (10^{-38} cm^2/GeV^2)
3 GeV neutrino + carbon
Nieves CCQE-like 2p2h
lines W = 938, 1232, 1535 MeV

MEC region

NN region

$q_3 = |q_3|$ true three momentum transfer (GeV)

PN Scattering
$q(q_0, \vec{q_3})$ E_{av}^{pn}

NN Scattering
$q(q_0, \vec{q_3})$ E_{av}^{nn}