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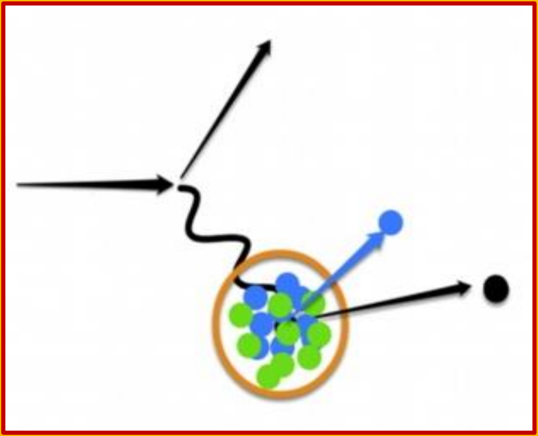
FOR FUNDAMENTAL PHYSICS

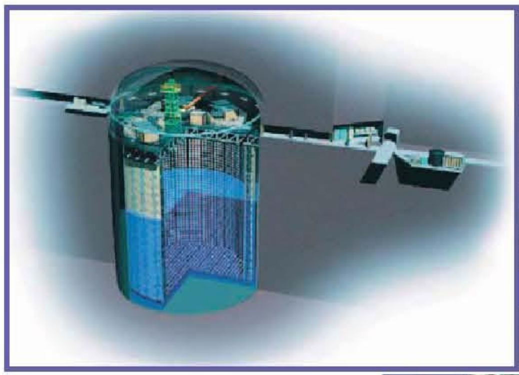
CC0π CROSS SECTION MEASUREMENTS AT THE T2K NEAR DETECTOR



Asmita Redij
University of Bern
for the T2K collaboration

10th NuInt workshop,
16-21 November 2015, Osaka University Suita Campus

Tokai 2 Kamioka



Super-Kamiokande
(ICRR, Univ. Tokyo)

2013 SUWA Award

J-PARC Main Ring
(KEK-JAEA, Tokai)

Long-baseline neutrino oscillation experiment

2015 Nobel Prize

T2K: Oscillation physics

- Appearance: $\boldsymbol{\nu_\mu}$ −> $\boldsymbol{\nu}_e$
  First evidence of $\boldsymbol{\nu}_e$ appearance from $\boldsymbol{\nu_\mu}$,
  followed by measurement with 7.3σ significance.

- Disappearance: $\boldsymbol{\nu_\mu}$ −> $\boldsymbol{\nu_\mu}$
  Precise measurement of atm. neutrino parameters.
  World's most precise measurement of $\sin^2\theta_{23}$.

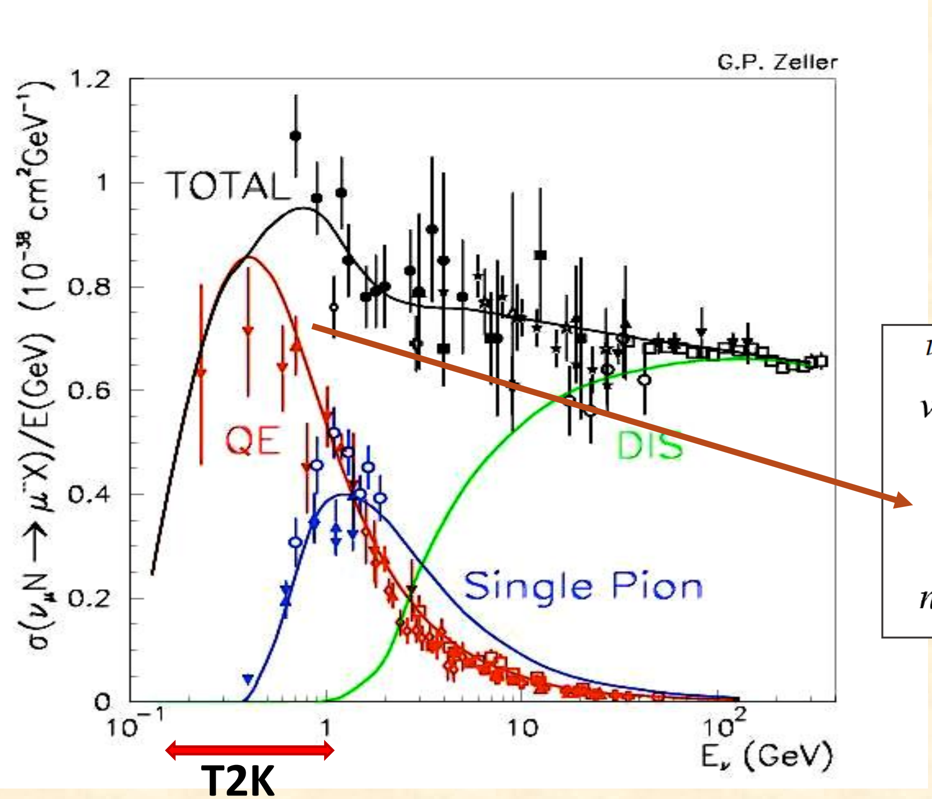
- Antineutrino mode: $\overline{\boldsymbol{\nu_\mu}}$−>$\overline{\boldsymbol{\nu_e}}$ & $\overline{\boldsymbol{\nu_\mu}}$ −> $\overline{\boldsymbol{\nu_\mu}}$
  Started data taking in anti-neutrino mode and first measurements presented.

- CP violation in neutrino sector: δ_{CP}
  Along with constraints from reactor experiments, exclude region of $\delta_{CP} = 0$ with 90% C.L.

PRL 112, 061802 (2014) PRL. 112, 181801 (2014)

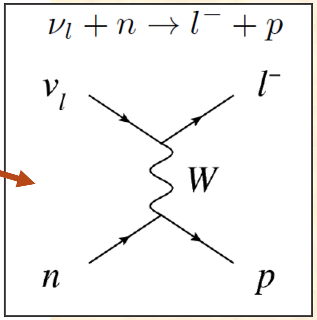
T2K @ NuInt

Oscillation physics relies on the understanding of neutrino interactions.



At low energies CCQE is the dominant signal.

Experimentally, an event with a muon and no pion is CCQE



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

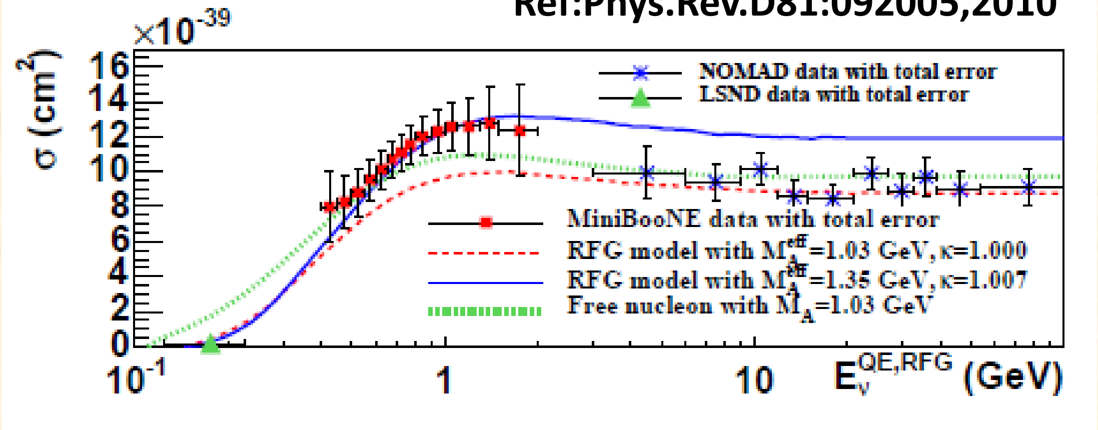
Easy…

T2K @ NuInt

… but it isn't that simple.

In the presence of nuclear effects, other interactions contribute to this signal definition.

Ref:Phys.Rev.D81:092005,2010

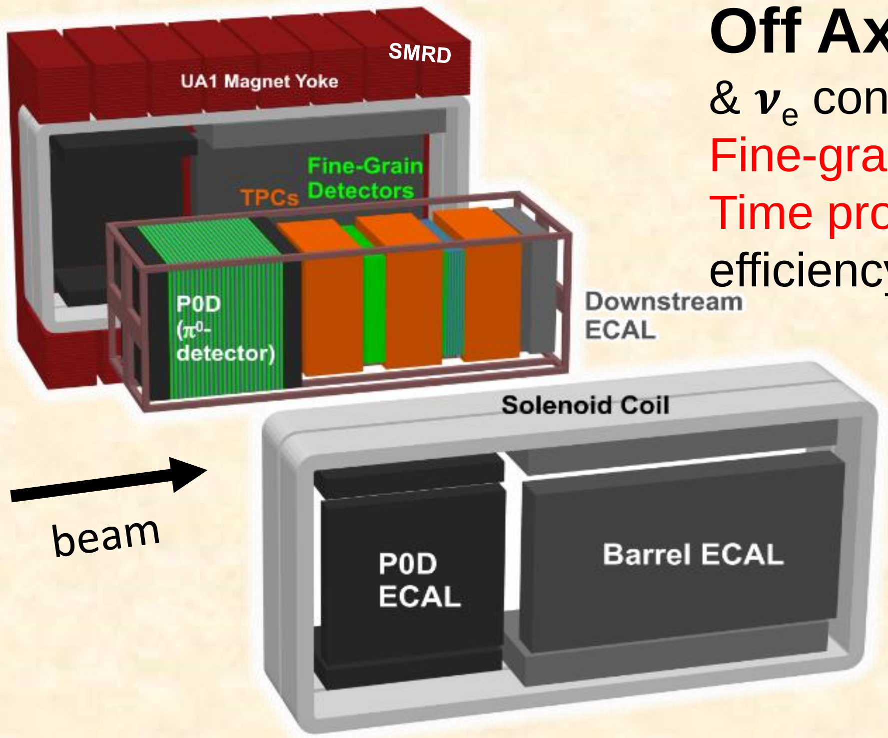


We now call it,
CC0π =
  CCQE (with RPA)
  + 2p2h + CC1π-abs

Need new models and model-independent CC0π measurements to test them.

In this talk: CC0π measurements @ T2K near detectors

Near Detector



Off Axis: constrain flux and cross section & ν_e contamination

Fine-grained detector (FGD) : CH and H_2O

Time projection chamber (TPC): good tracking efficiency + resolution + particle identification

π^0 detector (POD): scintillator CH with H_2O

Electromagnetic calorimeter (ECAL) : Pb

Side muon range detector (SMRD)

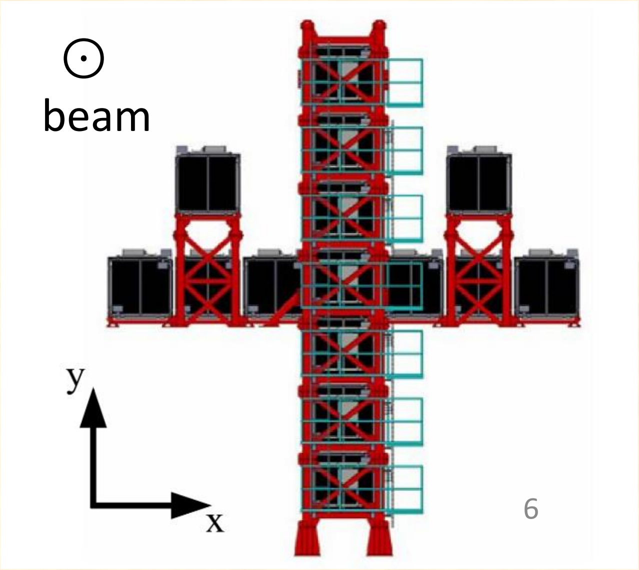
Other targets: Ar, Cu, Zn

Placed in 0.2 Tesla magnetic field

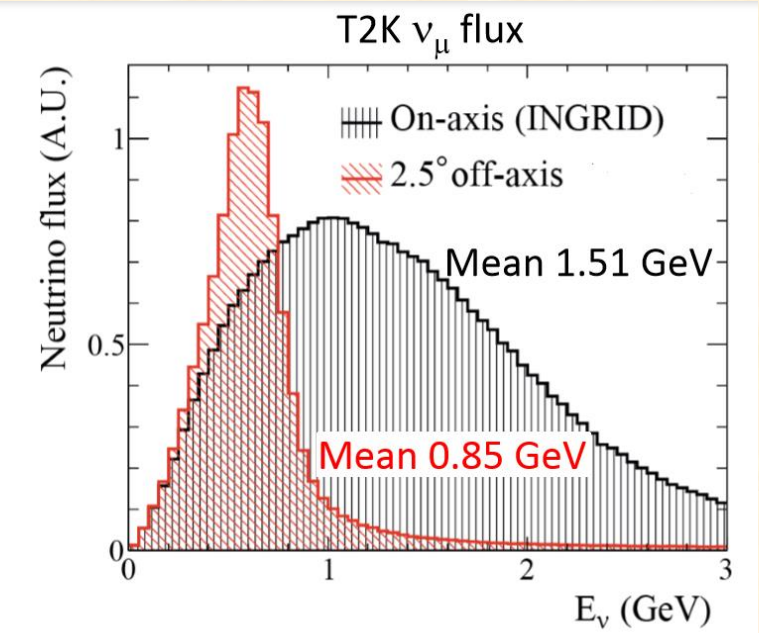
On Axis: to measure beam direction, beam profile, beam stability and rates

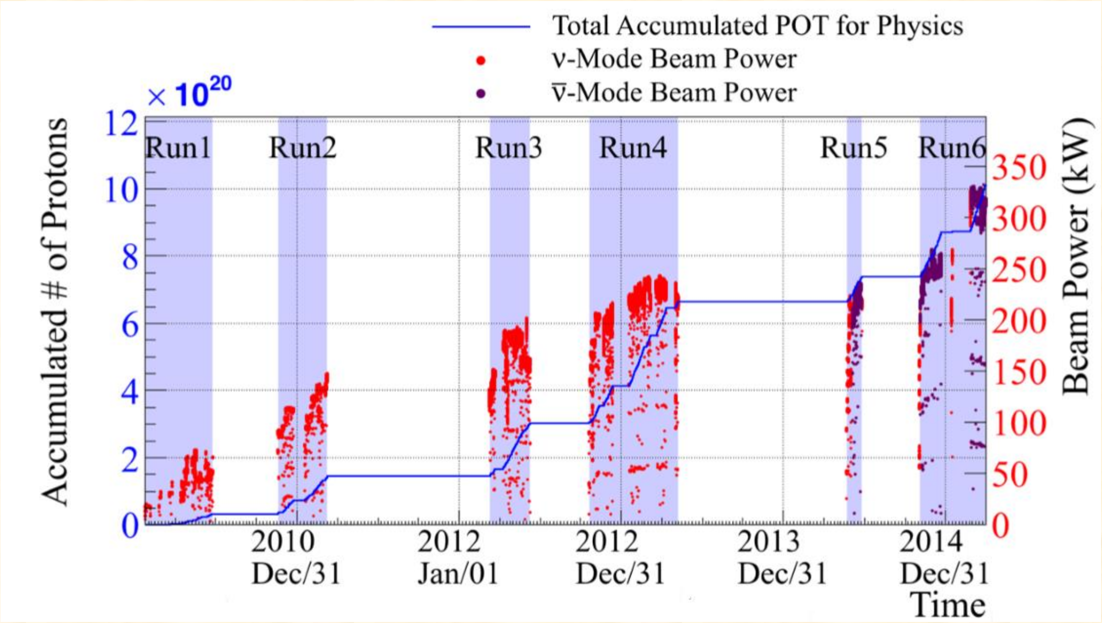
INGRID: 16 modules, each with alternating scintillator (CH) & Iron (Fe) plates

Proton Module: only scintillator (CH) plates



Flux





On-axis beam: wide energy spectrum.

Off-axis beam: narrower band, peaks at 0.6 GeV.

Cumulative Proton on Target (POT)

Total : 11.04 x 10^{20} POT

Run 1 - 4 in neutrino mode : 7.00 x 10^{20} POT

Run 5 - 6 in antineutrino mode : 4.04 x 10^{20} POT

Cross section measurements

T2K is producing world class measurements for a variety of neutrino interaction channels at few-GeV energies:

CC0π

On-Axis

- ✓ **ν_μ CCQE (C)**

Off-Axis

- ✓ **ν_μ CCQE vs E_ν (C)**
- ✓ **ν_μ CC0π differential (2 methods) (C)**
- ν_μ **CC0π** on H_2O
- $\bar{\nu}_\mu$ **CC0π** on C
- ν_μ / $\bar{\nu}_\mu$ **CC0π** on C

✓ **Shown in this talk**

Other

ν_μ and ν_e CC inclusive C & H_2O

ν_μ CC1π^+ on C & H_2O

ν_μ CC1π^+ coherent on C

$\bar{\nu}_\mu$ CC1π^+ on C

NCE on C

CC1K^+ on C

NC 1gamma on C

2p2h searches and more

Green & Red => Analysis complete

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Talk by Dr. Son Cov on Wednesday

$\bar{\nu}_\mu$ CC1π^+ on C

NCE on C

CC1K^+ on C

NC 1gamma on C

2p2h searches and more

Green & Red => Analysis complete

ν_μ CCQE model-dependent measurements

Published results

Published: Phy Rev D91. 112002 (2015)

ν_μ CCQE on carbon @ Proton Module

Measurement of CCQE on carbon per neutron.

- POT 6.042 x 10^{20} (Run 2-4)

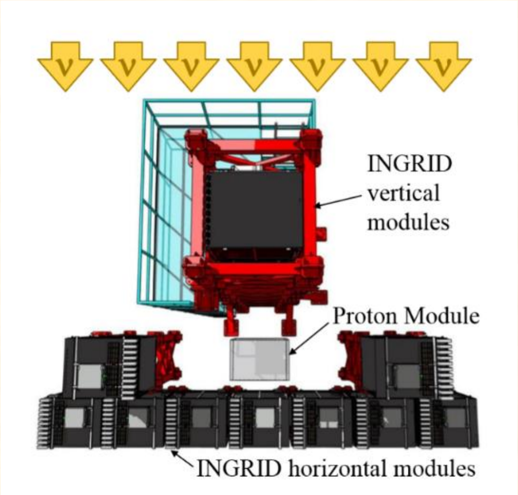
Detector: **Proton module (target) + INGRID**

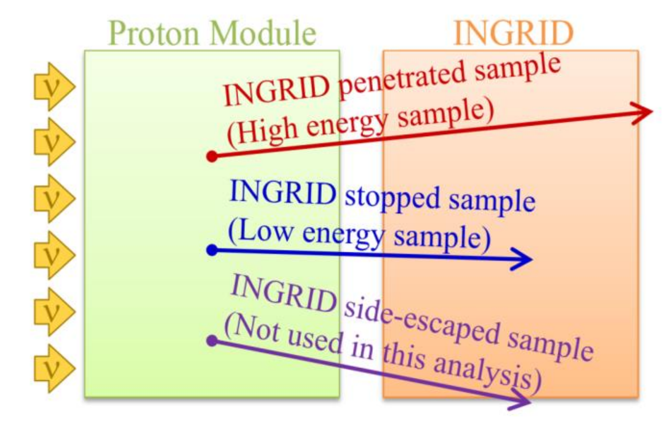
Selection: Topological selection, (kinematic cut with CCQE assumption)

- 1 muon-like track
- 2 tracks, one muon-like and other proton-like sample.

Each sample further divided into:

- low energy sample
- high energy sample





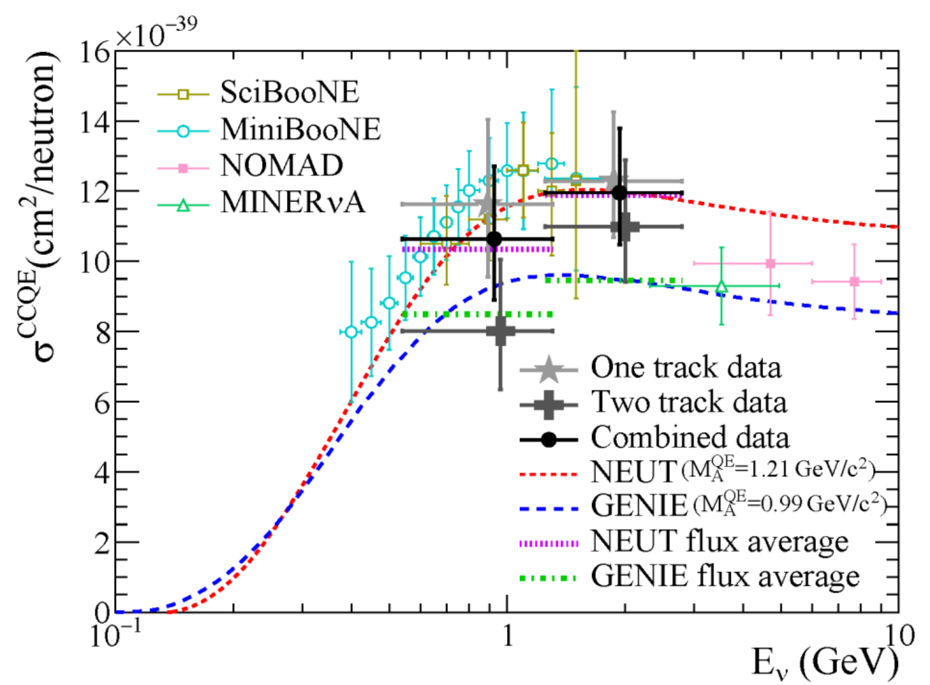
Published: Phy Rev D91. 112002 (2015)

ν_μ CCQE on carbon @ Proton Module

Measured cross section for each energy bin in each topology, using

$$\sigma_{CCQE} = \frac{N_{selected} - N_{backgrd}}{Flux\,.\,Target\,.\,\varepsilon}$$

$$\varepsilon \rightarrow Efficiency\ of\ selection$$



	One-track sample	Two-track sample
High energy region	$(12.286 \pm 0.221(stat.)+1.963-1.595(syst.)) \times 10^{-39} cm^2/neutron$	$(10.981 \pm 0.348(stat.)+1.876-1.546(syst.)) \times 10^{-39} cm^2/neutron$
Low energy region	$(11.629 \pm 0.454(stat.)+2.377-2.030(syst.)) \times 10^{-39} cm^2/neutron$	$(8.008 \pm 0.638(stat.)+1.951-1.550(syst.)) \times 10^{-39} cm^2/neutron$

ν_μ CCQE on carbon @ Proton Module

Measured cross section for each energy bin in each topology, using

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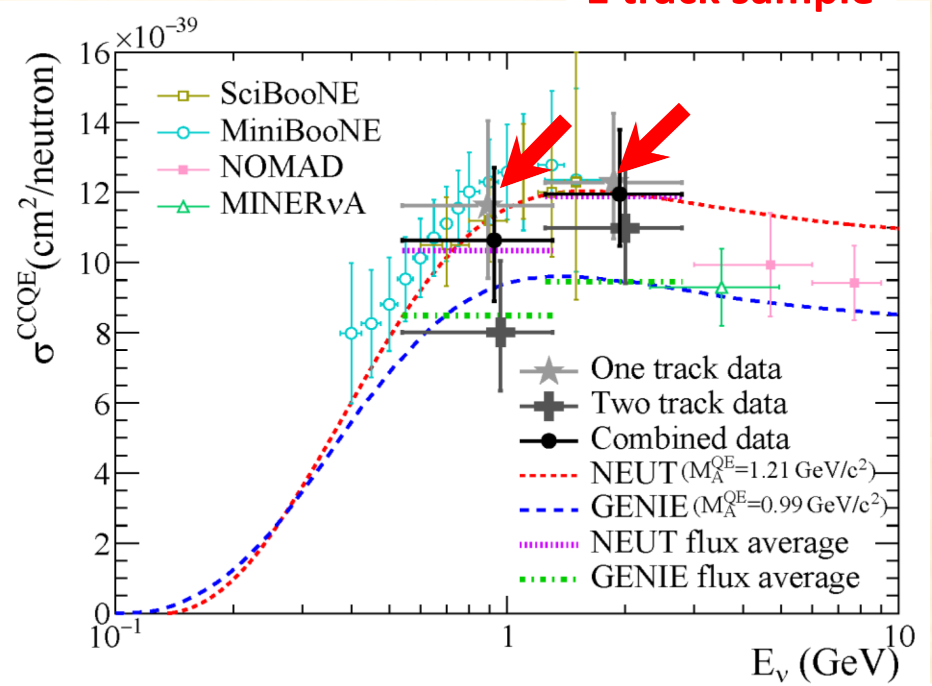
1 track sample



	One-track sample	Two-track sample
High energy region	(12.286 ± 0.221(stat.)+1.963-1.595(syst.)) × 10^{-39}cm^2/neutron	(10.981 ± 0.348(stat.)+1.876-1.546(syst.)) × 10^{-39}cm^2/neutron
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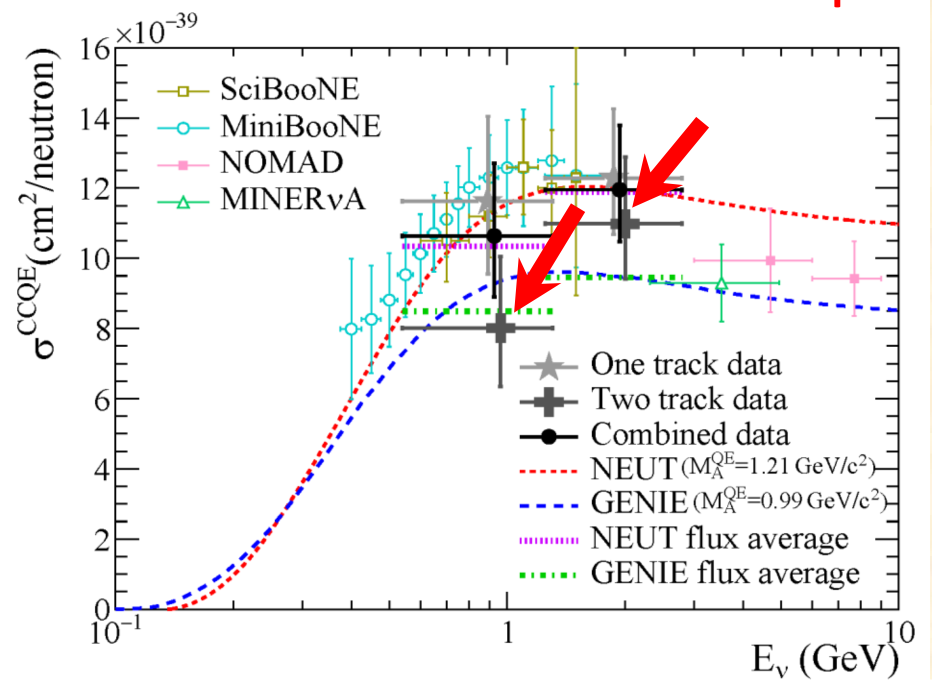
$$\sigma_{CCQE} = \frac{N_{selected} - N_{backgrd}}{Flux \, . Target \, . \varepsilon}$$

$$\varepsilon \rightarrow Efficiency \ of \ selection$$

2 tracks sample



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High energy region	(12.286 ± 0.221(stat.)+1.963-1.595(syst.)) × 10^{-39}cm^2/neutron	(10.981 ± 0.348(stat.)+1.876-1.546(syst.)) × 10^{-39}cm^2/neutron
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accepted by Phy.Rev. D

ν_μ CCQE on carbon @ FGD1

Model-dependent likelihood fit to extract flux-averaged cross section and model parameter fits

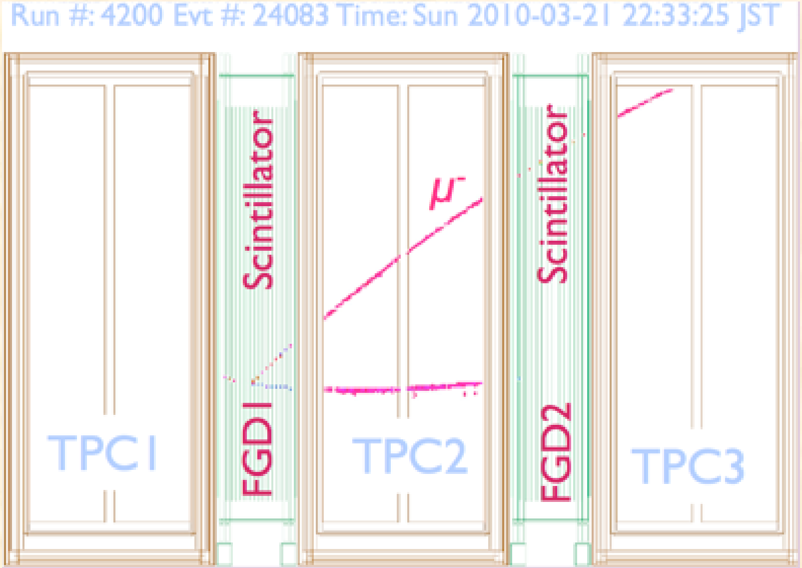
POT 2.6 x 10^{20} (Run 1-3)

Detector: **Fine-grained detector (FGD1) as target + TPC**

Selection: (same as MiniBooNE)

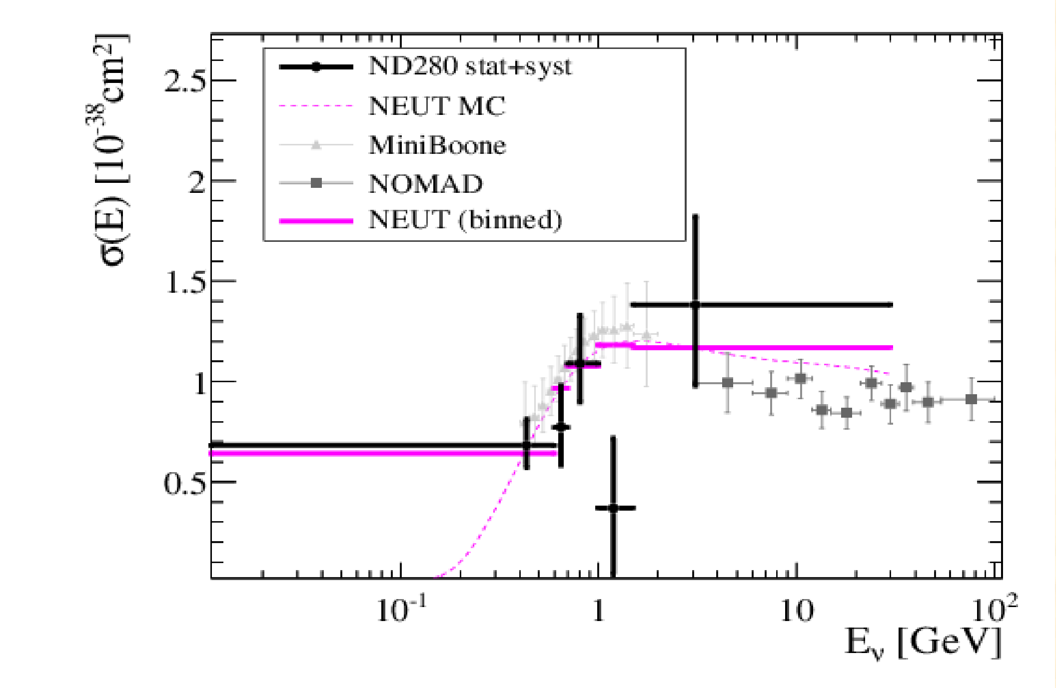
Interaction in FGD1 with associated muon-like track in TPC2 and no pion track

- Include 2p2h interaction
- **Corrected for** CC1π^+ **absorption**

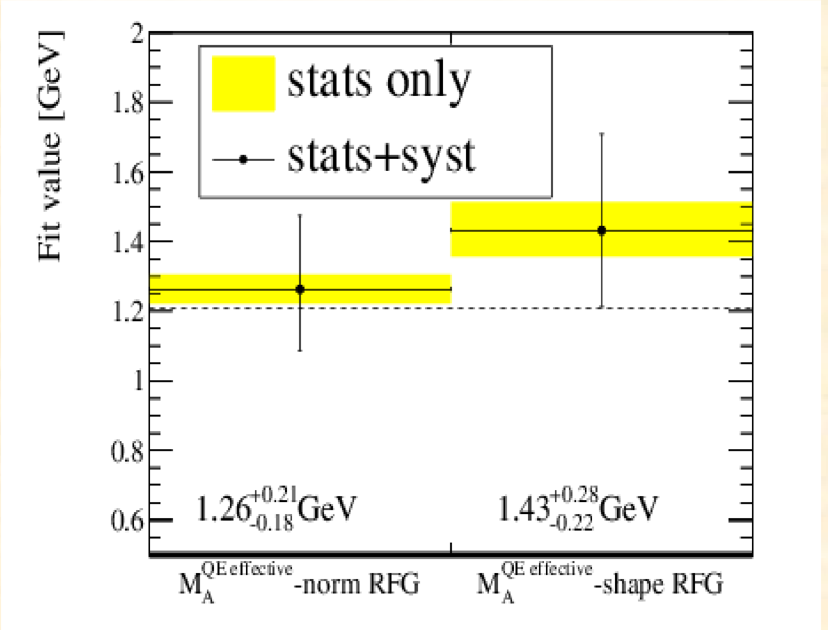


ν_μ CCQE on carbon @ FGD1: Results

Flux-averaged cross section



Best fit M_A^{QE} Parameters



- Energy calculated from muon kinematic with CCQE assumption
- A χ^2 test to compare the fitted result with the nominal NEUT MC (M_A = 1.21 GeV) gave a p-value of 17%.

ν_μ CC0π model-independent measurements

New results

Paper in preparation

ν_μ CC0π on carbon @ FGD1

Model-independent measurement of CC0π on CH as function of muon kinematics

- POT 5.73 x 10^{20} (Run 2-4)

Detector: Fine-grained detector (FGD1) as target + TPC

Carried out two separate measurements with two different analyses and two different methods.

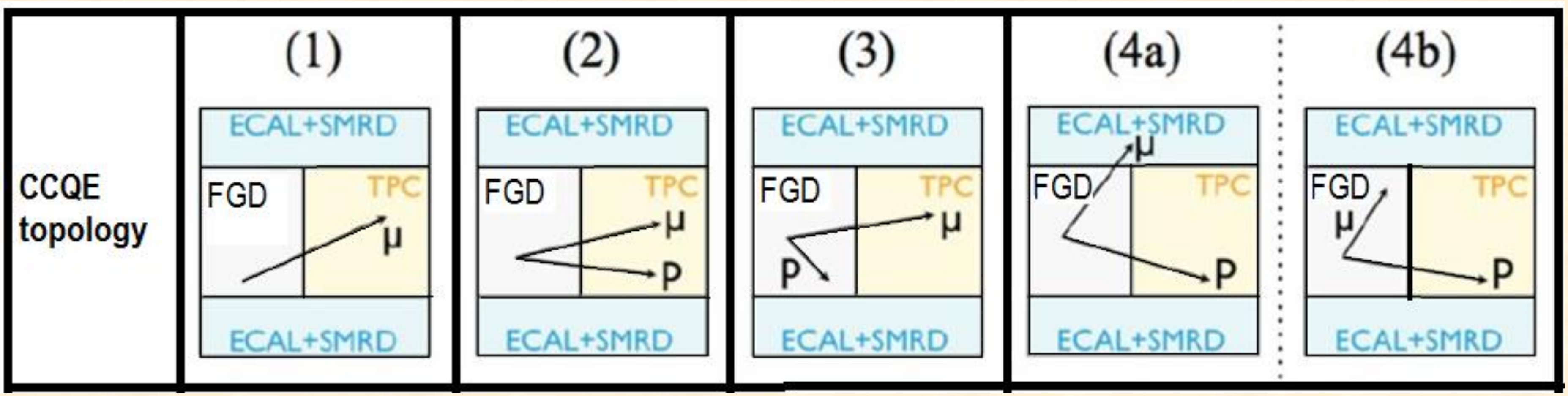
Selection: Both used CC0Pi sample with no pion in final state.

Analysis I : proton information included

Analysis II : no proton information used

ν_μ CC0π: Selection

Analysis I: A muon track \w and \wo additional proton track. Good purity and high angle acceptance.

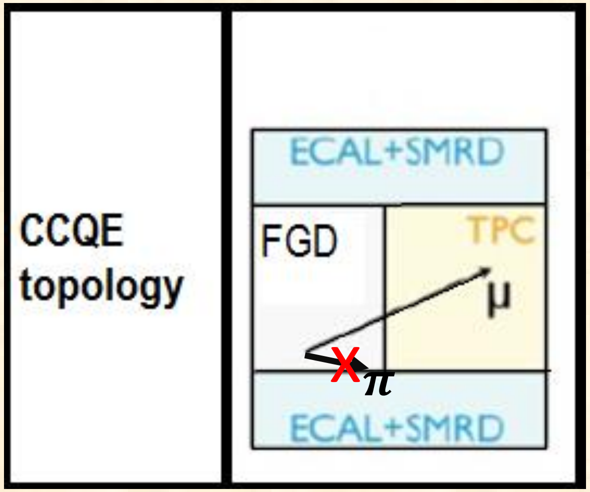


Background: pion production process.

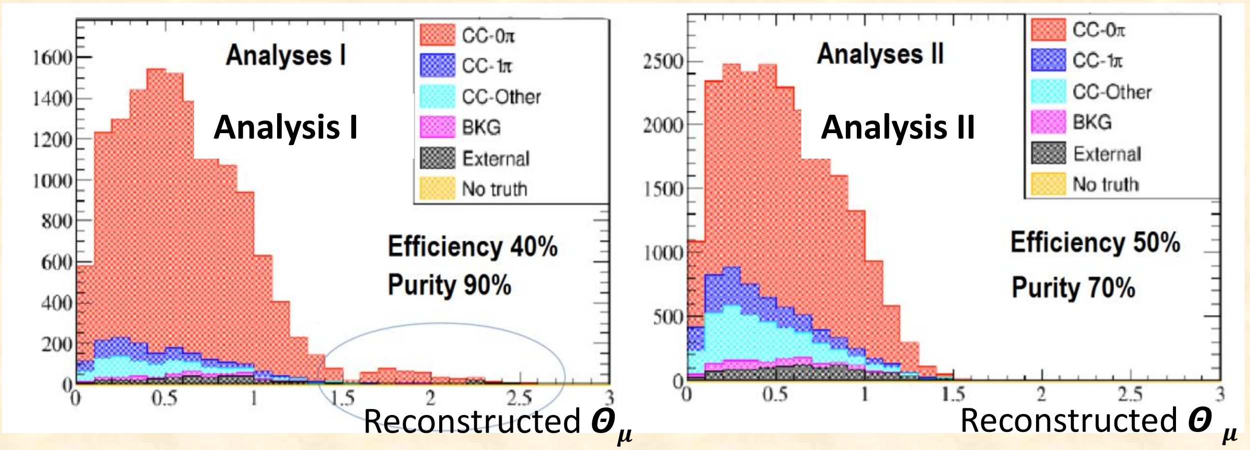
- Control regions are used to fit the background from the data.

ν_μ CC0π: Selection

Analysis II: only muon track in TPC and no pion in final state (no proton information used).



Good efficiency. Less purity compared to Analysis I



<u>Background:</u> pion production process.

- Monte Carlo tuned to fits to MiniBooNE and MINERvA data.

Used limited phase space to avoid region of smaller signal to background ratio.

ν_μ CC0π: Extraction method

Likelihood fit (Analysis I)

- To predict true spectrum from reconstructed spectrum

# of events in true bin = [Signal events in reco bin + bkgd events in reco bin] x MC based reco -> true

$$N_i = \sum_j^{bins\ by\ topo} \left[c_i \left(N_j^{MC\ CC0\pi} \prod_a^{model} w(a)_{ij}^{CC0\pi} \right) + \sum_k^{bkg\ reactions} N_j^{MC\ bkg\ k} \prod_a^{model} w(a)_{ij}^{k} \right] t_{ij}^{det} r_j^{det}$$

- Simultaneously fit four topologies and two control samples.

- Extract flux integrated cross section

ν_μ CC0π: Extraction method

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DATA/MC: parameter fitted

Free nuisance parameter (theory + detector)

- Simultaneously fit four topologies and two control samples.

- Extract flux integrated cross section

ν_μ CC0π: Extraction method

Likelihood fit (Analysis I)

- To predict true spectrum from reconstructed spectrum

# of events in true bin = [**Signal events in reco bin** + **bkgd events in reco bin**] x **MC based reco -> true**

$$N_i = \sum_j^{bins\ by\ topo} \left[c_i \left(N_j^{MC\ CC0\pi} \prod_a^{model} w(a)_{ij}^{CC0\pi} \right) + \sum_k^{bkg\ reactions} N_j^{MC\ bkg\ k} \prod_a^{model} w(a)_{ij}^{k} \right] t_{ij}^{det} r_j^{det}$$

DATA/MC: parameter fitted (c_i)

Free nuisance parameter (theory + detector) ($w(a)$, r_j^{det})

- Simultaneously fit four topologies and two control samples.

Minimizer:

$$\chi^2 = \chi^2_{stat} + \chi^2_{syst} = \sum_j^{reco\ bins} 2(N_j - N_j^{obs} + N_j^{obs} \ln \frac{N_j^{obs}}{N_j}) + \chi^2_{syst}$$

- Extract flux integrated cross section

$$\begin{aligned} \chi^2_{syst} &= (\vec{r}^{det} - \vec{r}^{det}_{prior})(V^{det}_{cov})^{-1}(\vec{r}^{det} - \vec{r}^{det}_{prior}) \\ &+ (\vec{a}^{theory} - \vec{a}^{theory}_{prior})(V^{theory}_{cov})^{-1}(\vec{a}^{theory} - \vec{a}^{theory}_{prior}) \end{aligned}$$

ν_μ CC0π: Extraction method

Bayesian unfolding (Analysis II)

- To predict true spectrum from reconstructed spectrum

Prediction in true bin:

$$N_{t_j}^{unfolded} = \frac{1}{\epsilon_j} \sum_i P(t_j|r_i)(N_{r_i} - B_{r_i})$$

Signal - Background

Reconstructed bins

Unsmearing matrix:

Smearing matrix

$$P(t_j|r_i) = \frac{P(r_i|t_j)P(t_j)}{P(r_i)}$$

Probability of event being in reco and true bin

Extracted from MC

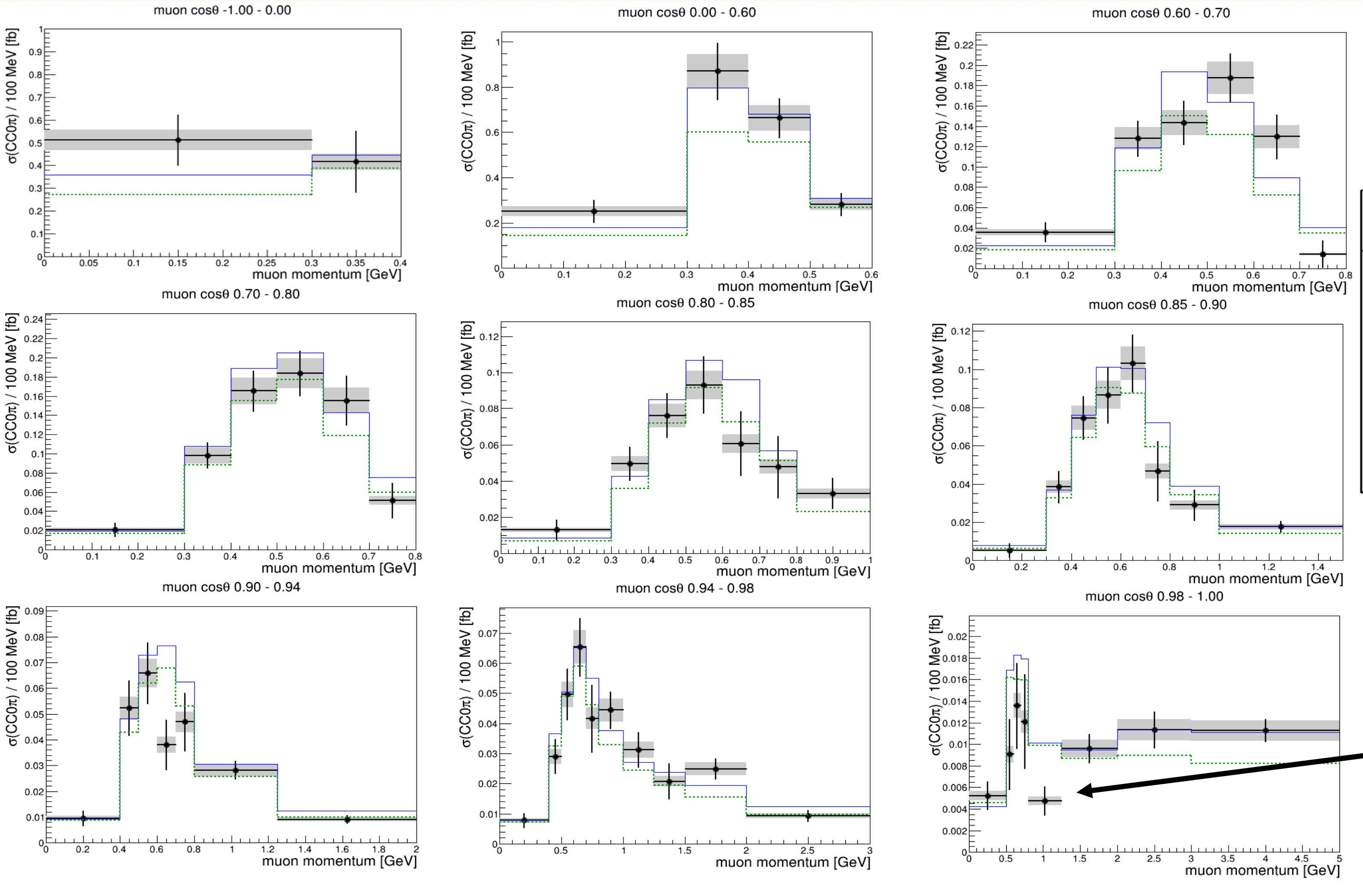
- Extract flux-integrated cross section from the true prediction

ν_μ CC0π: Uncertainty

1. **Flux:**
   10% normalization (dominant)
   Constrained by NA61 and T2K beam measurements
2. **Cross-section:**
   Used NEUT default model
   Constrained by fits to external data
   Signal systematics is important in the low-efficiency region
   For Analysis I: Background systematics is negligible.
3. **Detector:**
   Vary detector parameters such as magnetic fields etc.

Analysis I has lower flux and cross section systematic while Analysis II had lower statistical uncertainty.

CC0π: differential cross section



Analysis I

NEUT M_a = 1.21

GENIE M_a= 0.99 (GeV)

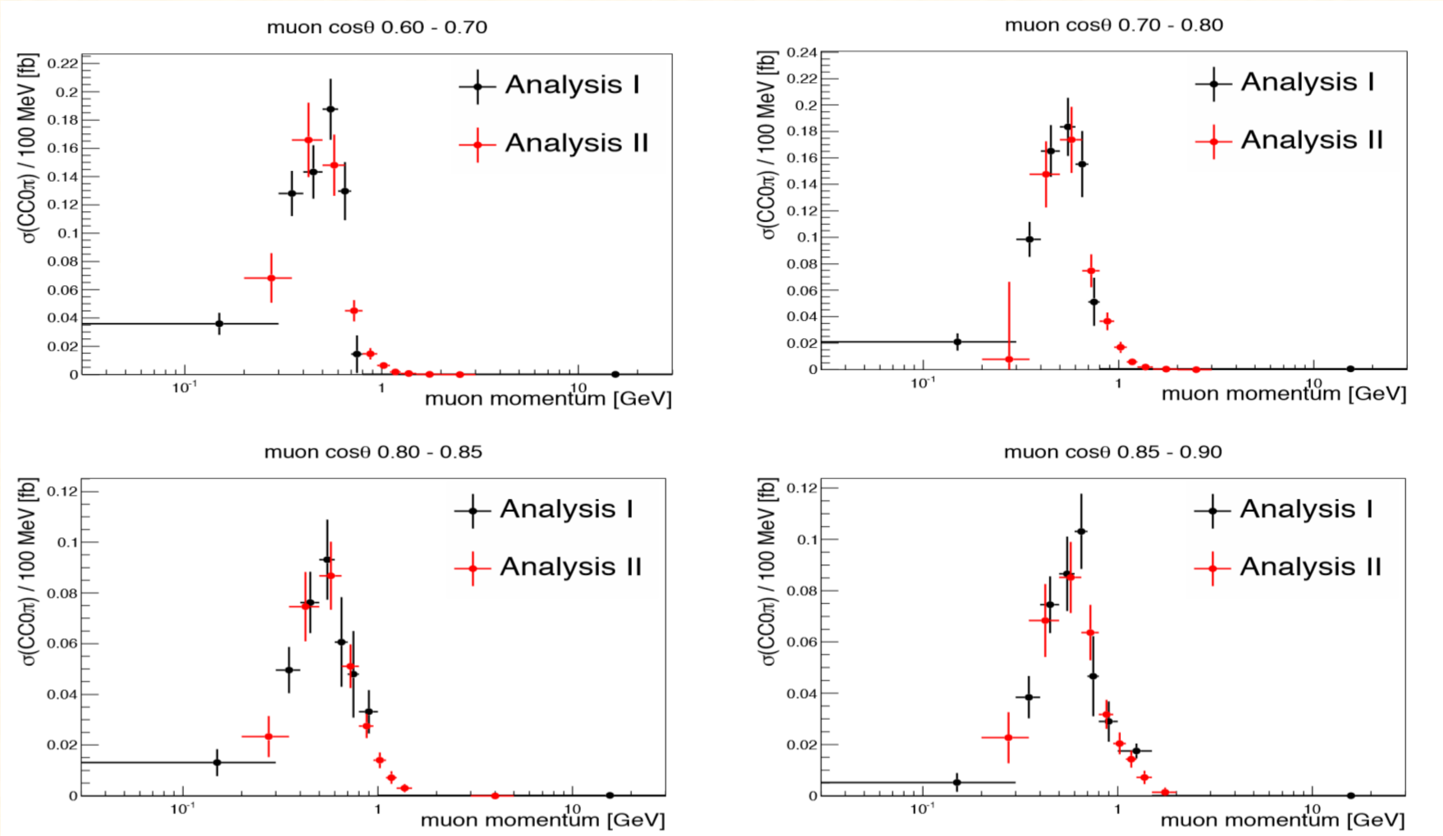
Norm

+ Shape

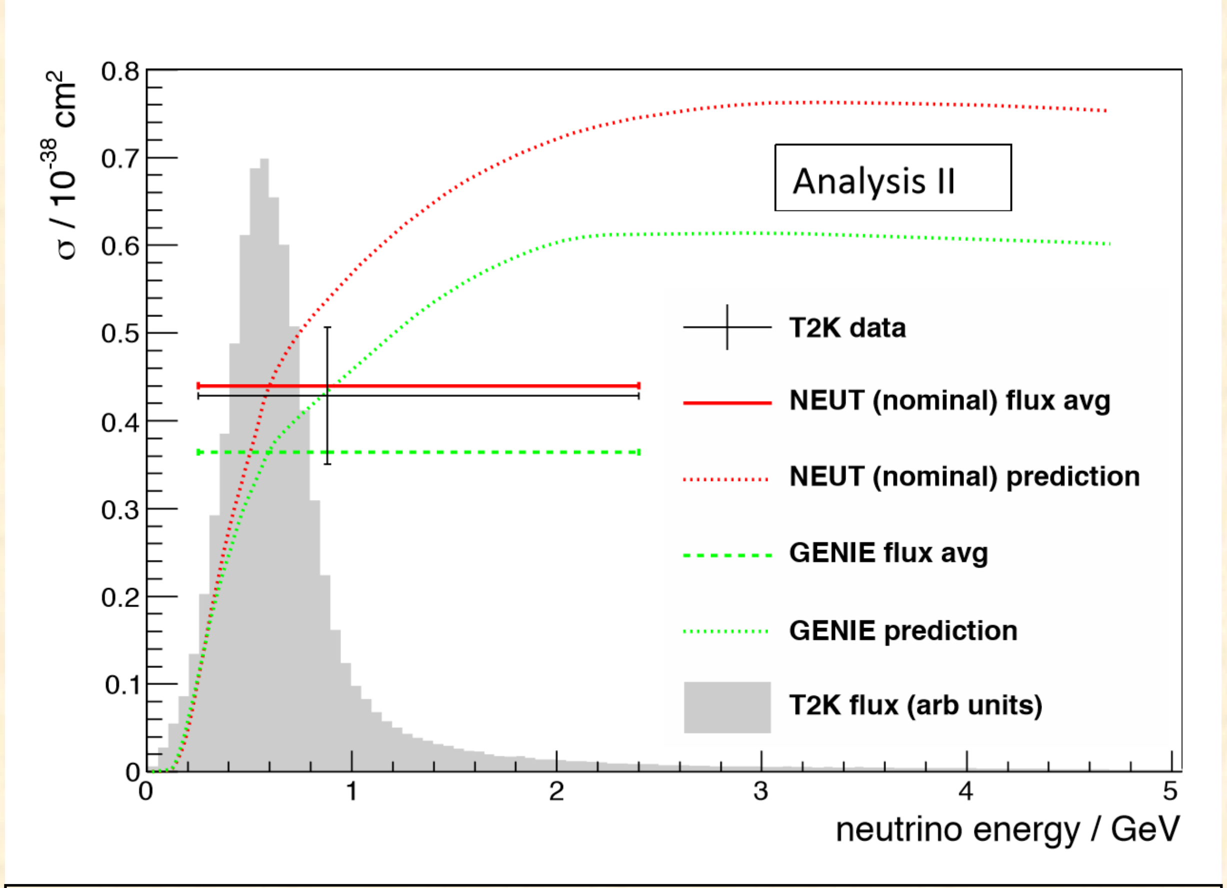
Dip seen in both analyses, not in the prediction

CC0π: comparing both analyses

- Results from both analyses match, despite different binning, selection and analysis methods.
- Cross check of model independence.



CC0π: integrated cross section



Same for both the analyses

For Analysis I:

$\sigma = 4.17 \pm 0.47\ (\text{syst.}) \pm 0.05\ (\text{stat.})\ \ 10^{-39}\ \text{cm}^2$

Comparison with nuclear models

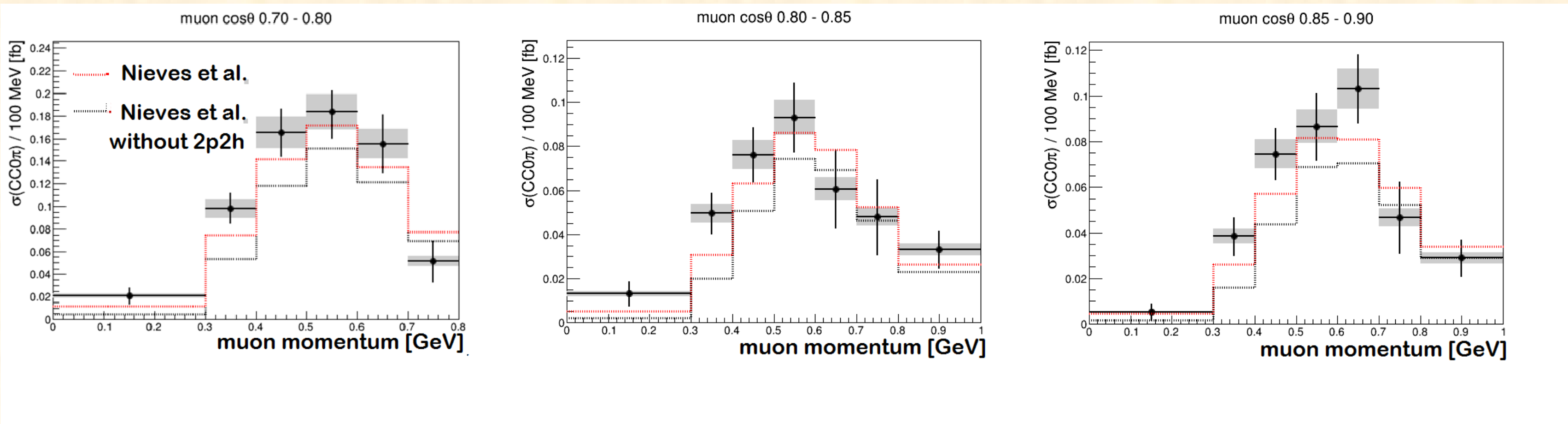
Lots of work within T2K to keep NEUT up to date as new models become available.

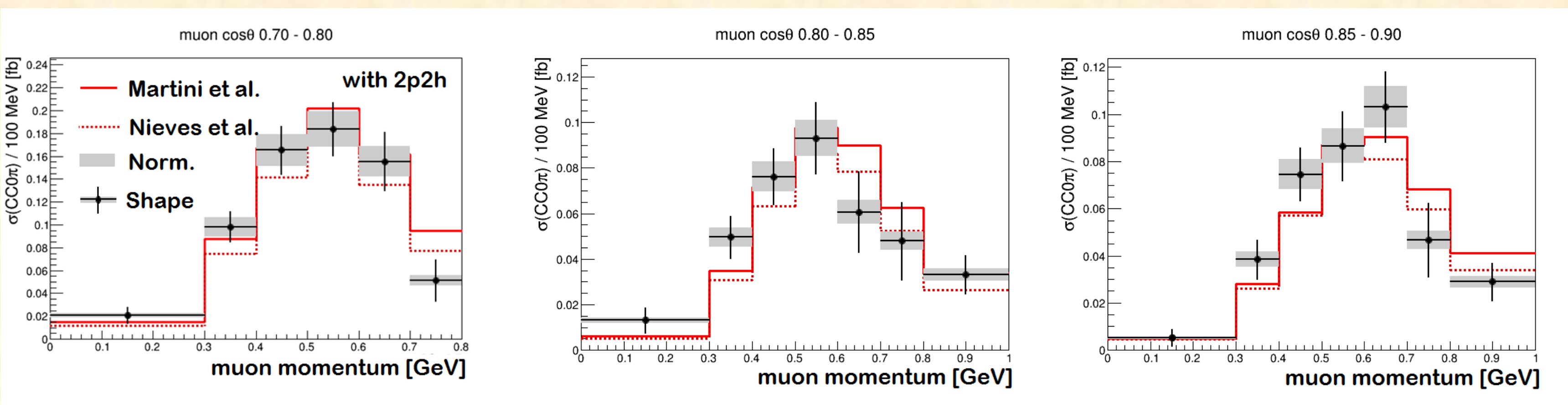
First opportunity to test these models with full detector MC simulation and systematic uncertainties.

CC0π measurements from T2K and other experiments are used to:

- test the theory models in the market.
- introduce new data-based models to determine unknown model uncertainty.

Comparison with nuclear models





Measurement favor presence of 2p2h interactions.

Summary & Prospects

T2K continues to make world-class neutrino cross section measurements.

- Now moved to topology-based model-independent measurements.
- Measurements clearly show excess coming from nuclear effects.
- Other ongoing extensions of the presented analysis
  - Including more than two tracks sample
  - Increasing the phase space
  - Measurements on water target and ratio of neutrino/ antineutrino
  - 2p2h searches

Have an up-to-date neutrino generator and MC framework to test new models with full sys. uncertainties and to incorporate them in oscillation analysis.

Thank you

500 people, 59 institute, 11 countries

Back up

Llewellyn Smith formula for QE scattering

- Present neutrino generators use scattering cross-section of neutrinos off the nucleon, given by the Llewellyn Smith formula / Smith Moniz (RFG).
  - Impulse Approximation : gauge boson is absorbed by just one nucleon .
  - Use Fermi Gas model , free nucleon in mean field, with P (nucleon) < Fermi surface momentum

$$\frac{\partial \sigma}{\partial Q^2} = \frac{M^2 G_F^2 \cos\theta_C}{8E_\nu^2}\left(A(Q^2) \pm \frac{B(Q^2)(s-u)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^4}\right)$$

G_F is the Fermi constant, M is the average nucleon mass, θ_C is the Cabbibo angle, E is the neutrino energy, s and u are Mandelstam variables,

A, B, C are functions of Q^2, with coefficients called form-factor.

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261

Form Factors

- Form factors parameterize hadronic information and are measured experimentally.
  - Two vector form factors are know from electron scattering experiments.
  - Pseudo-scalar form factors contribution is negligible.
  - Only unknown is axial form factor, and is measured using neutrino scattering.
- Axial form factor in the dipole form is dependent on two parameters.
  - F_A (0) is precisely known from beta decay experiment.
  - **So the only parameter left was axial mass form factor M_a**

Nominal value of M_a = 1.02

(from pre-MiniBooNE era, from fit to BNL, ANL, FNAL data)

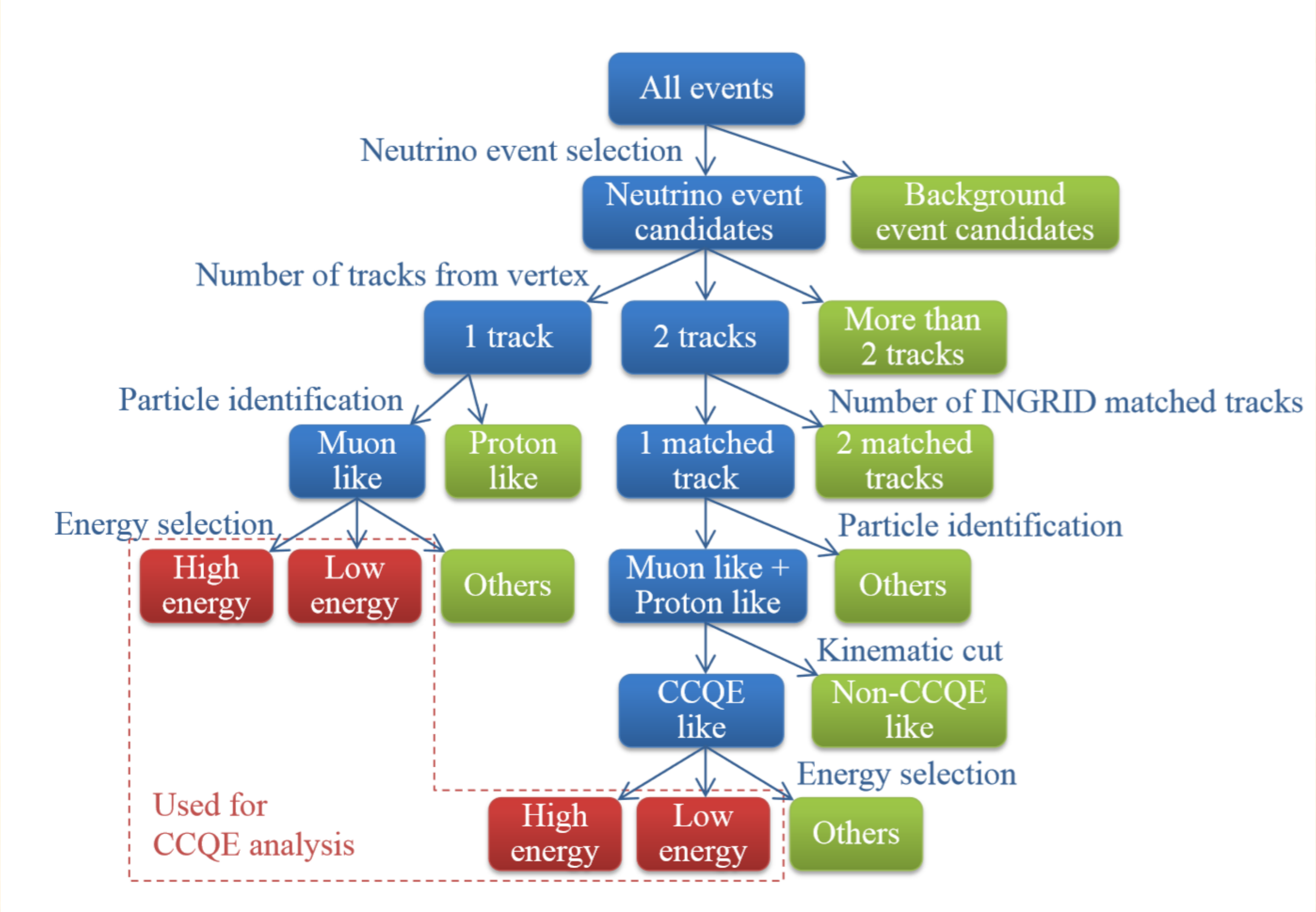
$$F_A^{dipole} = \frac{F_A(0)}{(1 - \frac{q^2}{M_a^2})^2}$$

BNL: Baker, PRD **23**, 2499 (1981)

ANL: Miller, PRD **26**, 537 (1982)

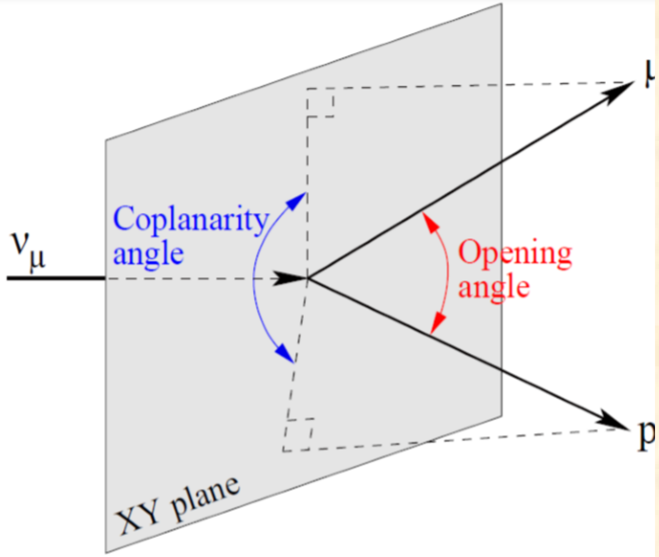
FNAL: Kitagaki, PRD **28**, 436 (1983)

CCQE at Proton Module: Selection

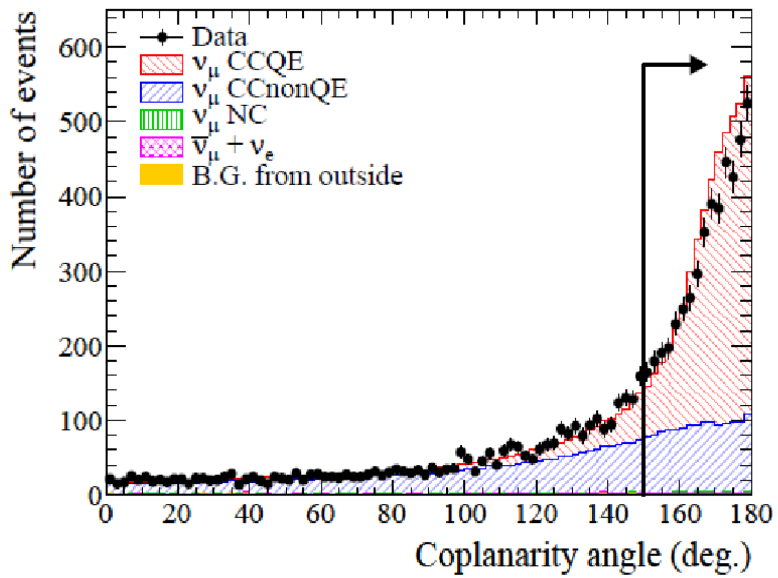


Talk by T. Kikawa @NuInt 2014

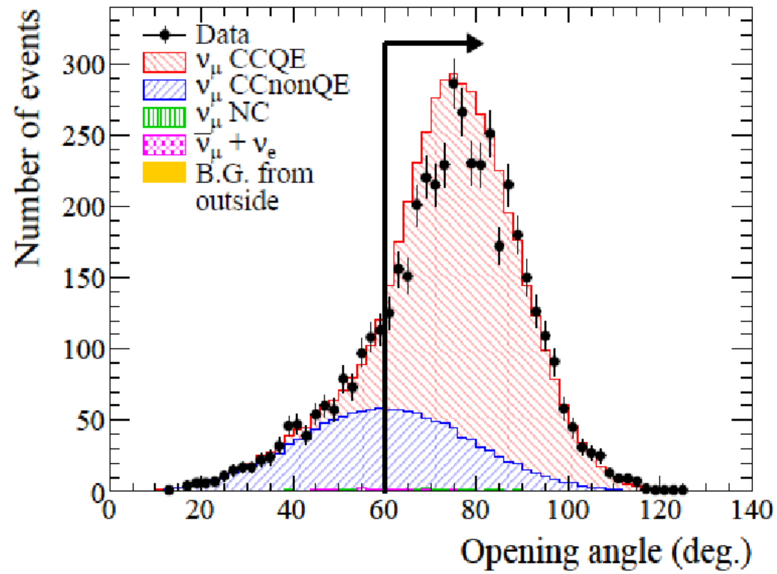
- Coplanarity angle
  - Angle between $\vec{\mu}$ and $\vec{p}$ projected to a plane which is perpendicular to $\vec{\nu}$.
  - Should be around 180 deg. for CCQE.
- Opening angle
  - Angle between $\vec{\mu}$ and $\vec{p}$.
  - Generally large for CCQE.



Coplanarity angle cut



Opening angle cut



Selection of CC0pi @ FGD1

- Data quality
- Highest momentum negative track selection
- Starts in FGD Fiducial volume
- Broken track cut
- Muon PID

Analysis I

- Proton topologies
  - Muon-only
  - Muon + TPC proton
  - Muon + FGD proton
  - TPC proton + FGD muon
- No dependence on pion rejection
- Additional high-angle tracks
- High purity

Analysis II

- Pion rejection:
  - Pion-like TPC tracks
  - Pion-like FGD-only tracks
  - Michel electron (delayed)
  - Electron-like TPC tracks (due to π^0 decay)
- Fully proton-inclusive
- Higher efficiency