Recent Neutrino Cross Section Results from T2K

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for the T2K Collaboration

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DIS 2015

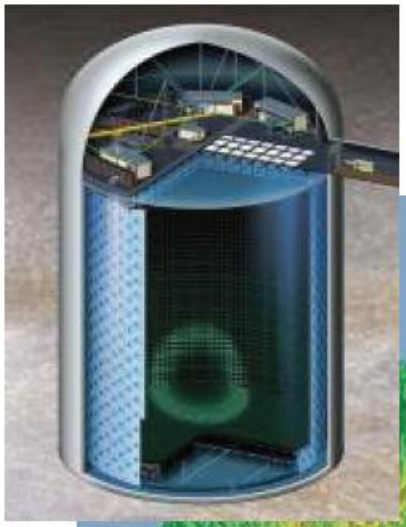
Dallas, Teaxs

Outline

- The T2K experiment
- Neutrino Oscillations and Cross sections
- T2K Cross Section Results
- Upcoming Results
- Summary

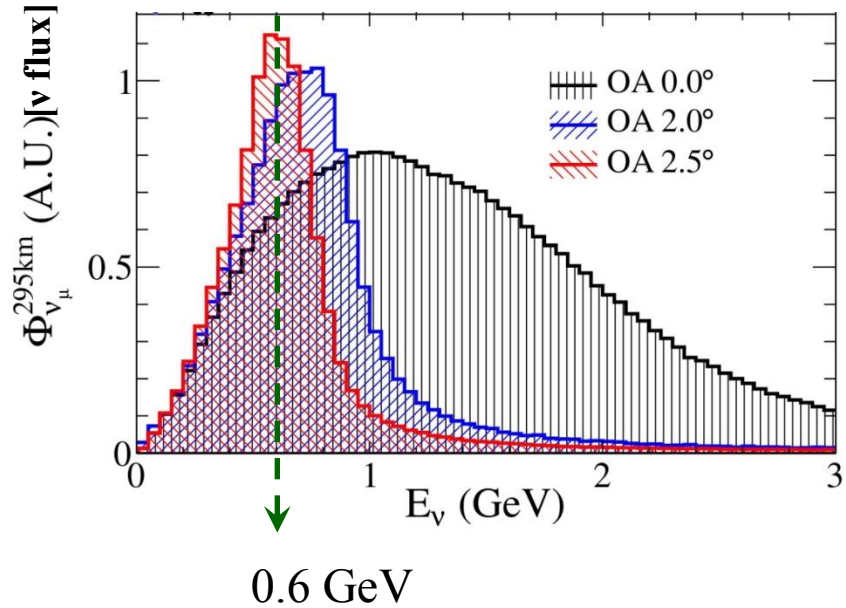
The T2K Experiment

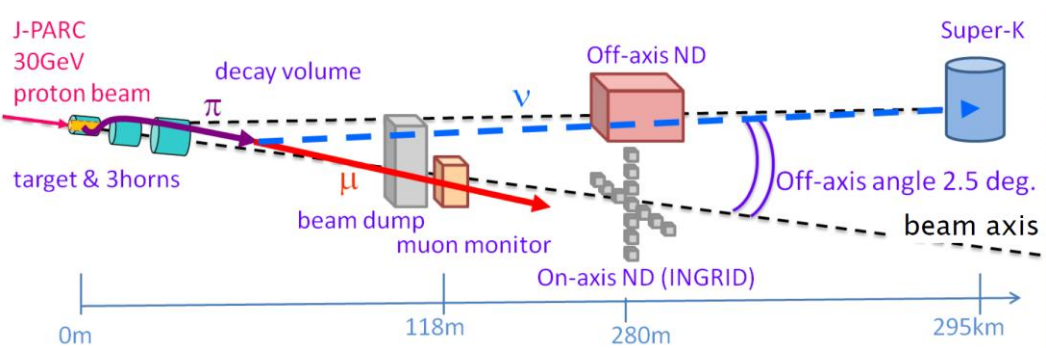
- Tokai-to-Kamioka (T2K): Neutrino Oscillation experiment
  - Location: Japan
  - Baseline: ~295 km
  - Far Detector: Super-Kamiokande
  - Beam: J-PARC Lab — 30 GeV proton beam; Designed to produce ~0.6 GeV ν_μ
  - Near Detectors: In J-PARC campus



T2K Beam

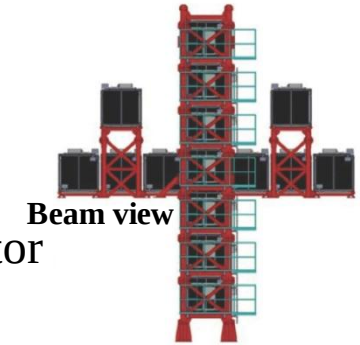
- Off-axis experiment
- Beam is aimed 2.5^0 off the direction to the Super-K (FD)
  - Narrow-band ν beam
  - Reduce background from high energy tail

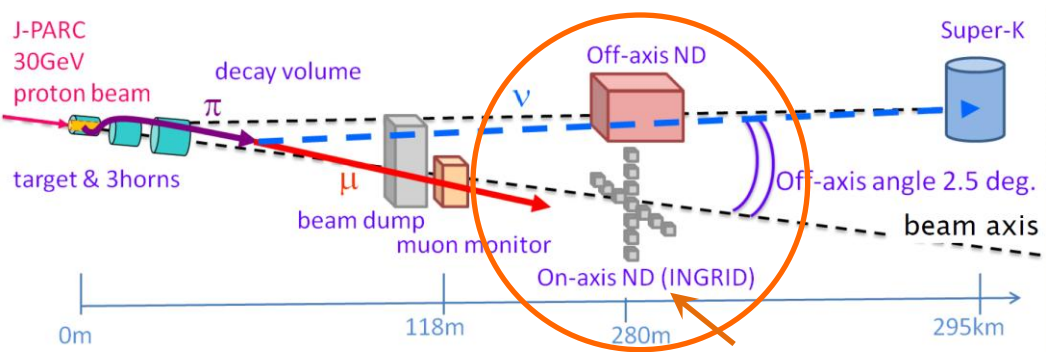




T2K Near Detectors

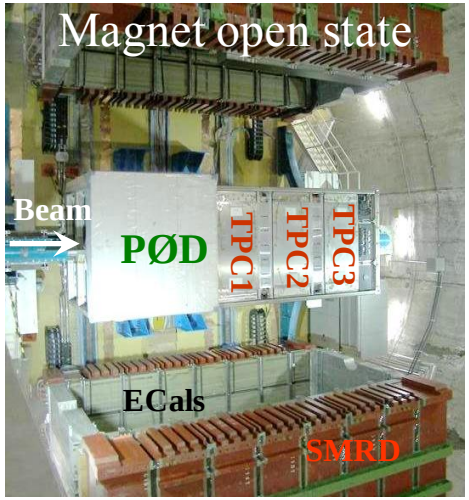
- On-Axis:
  - INGRID
    - 16 Modules of Iron and Scintillator

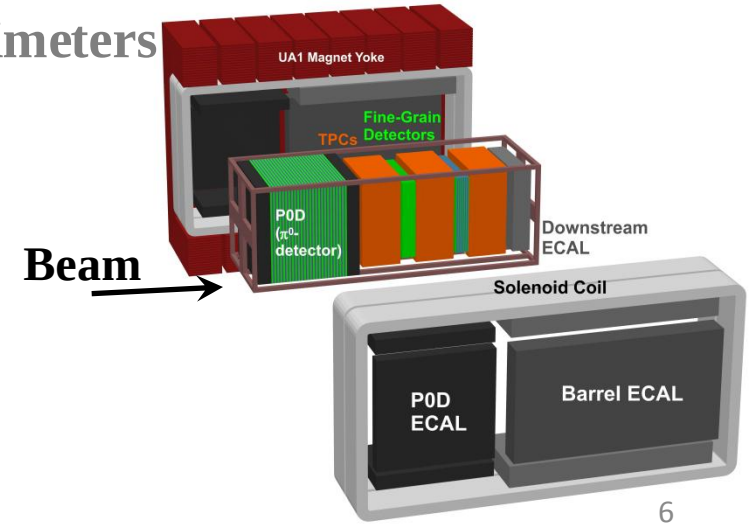


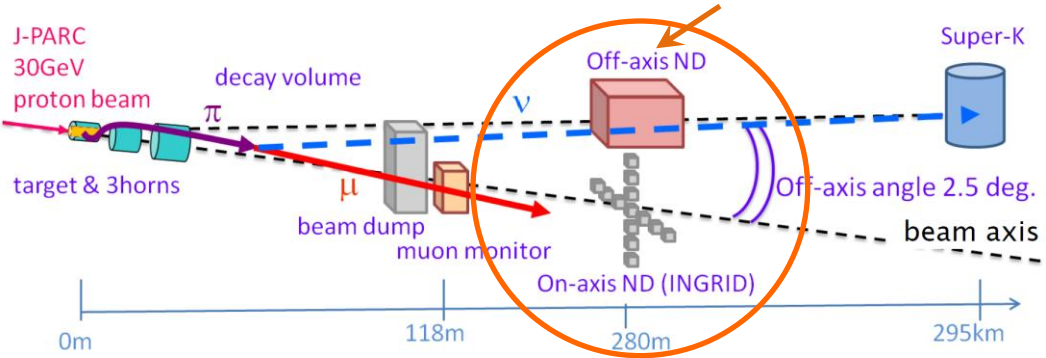


T2K Near Detectors

- On-Axis:
  - INGRID
    - 16 Modules of Iron and Scintillator
- Off-Axis (ND280):
  - Pi-Zero Detector (**PØD**)
  - Tracker
    - 3 Time Projection Chambers (**TPC**)
    - 2 Fine Grain Detectors (**FGD**)
  - Surrounded by **Electromagnetic Calorimeters**
  - Housed inside the **Magnet** of the UA1

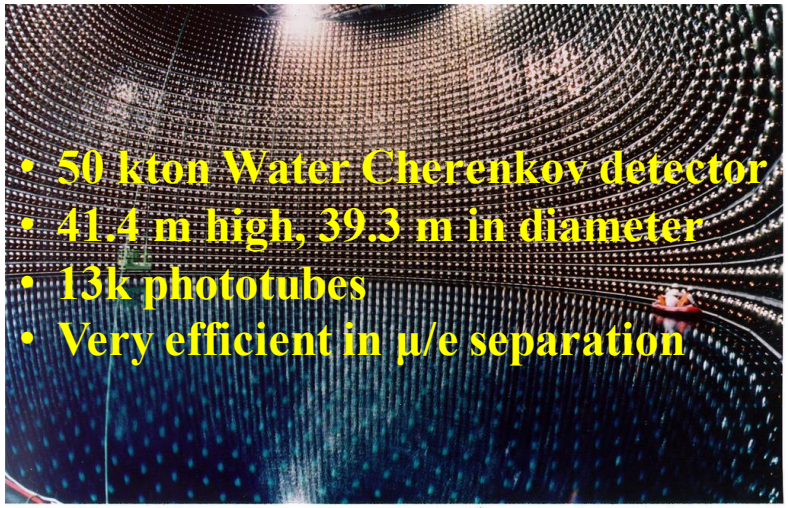


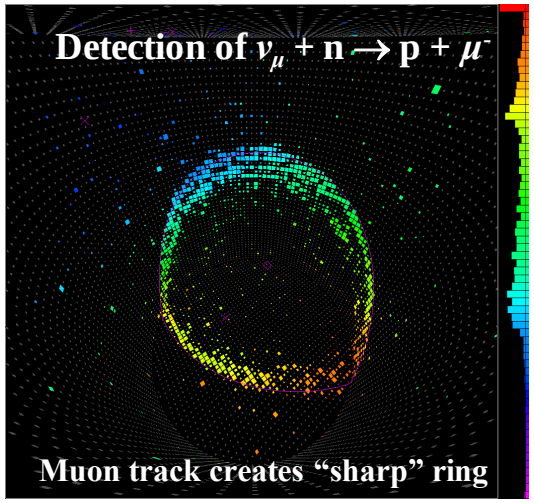


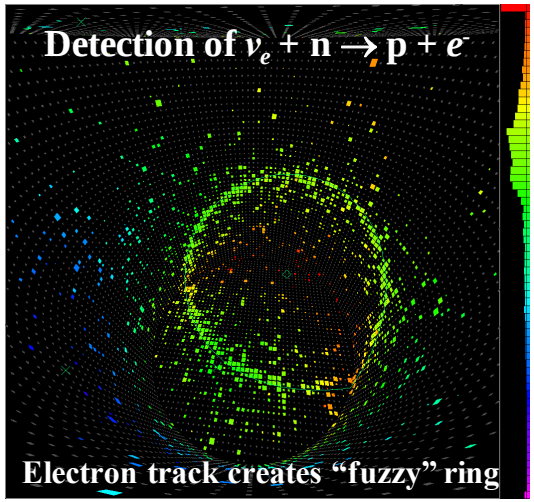


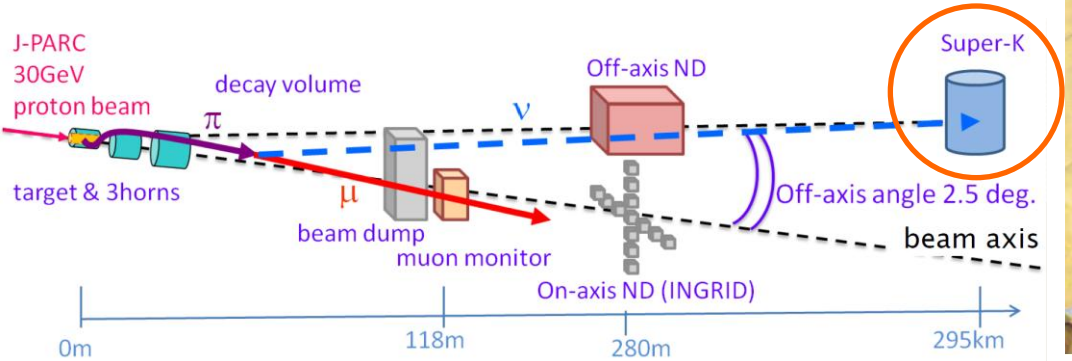
T2K Far Detector

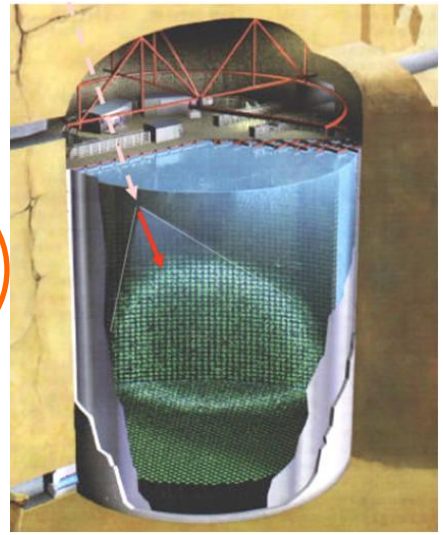
- Super-Kamiokande (SK)

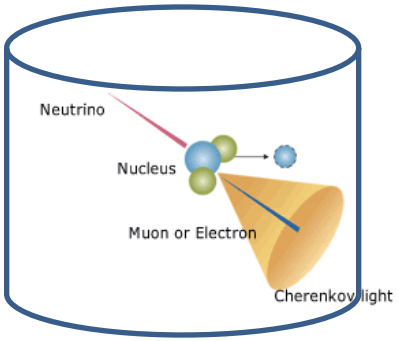












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- **Neutrino Oscillations and Cross sections**
- T2K Cross Section Results
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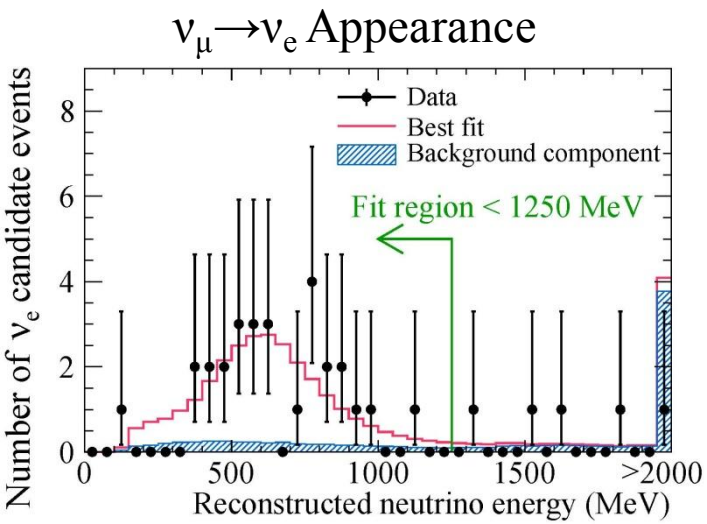
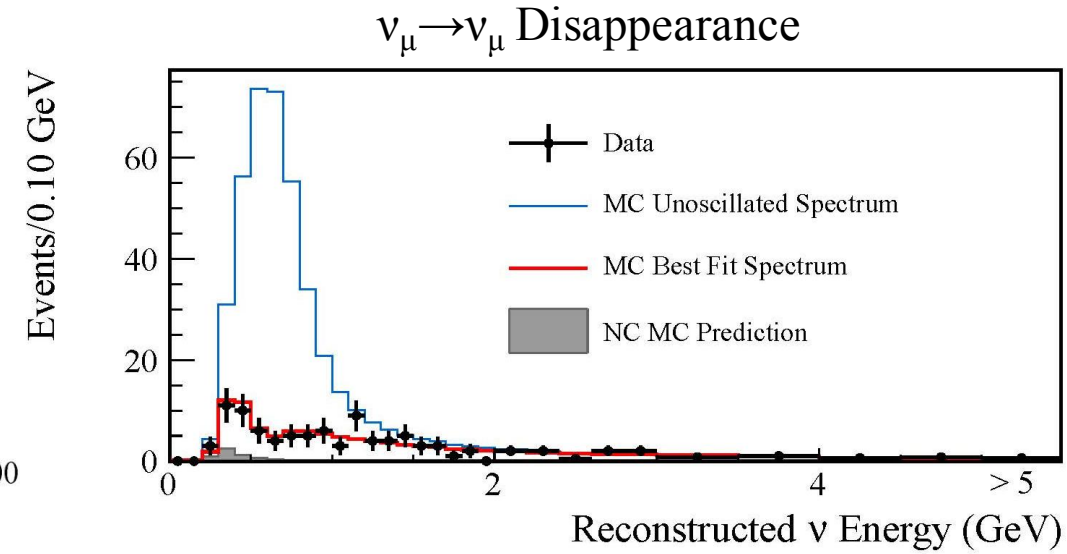
Neutrino Oscillation

- T2K Oscillation results





Neutrino Oscillation

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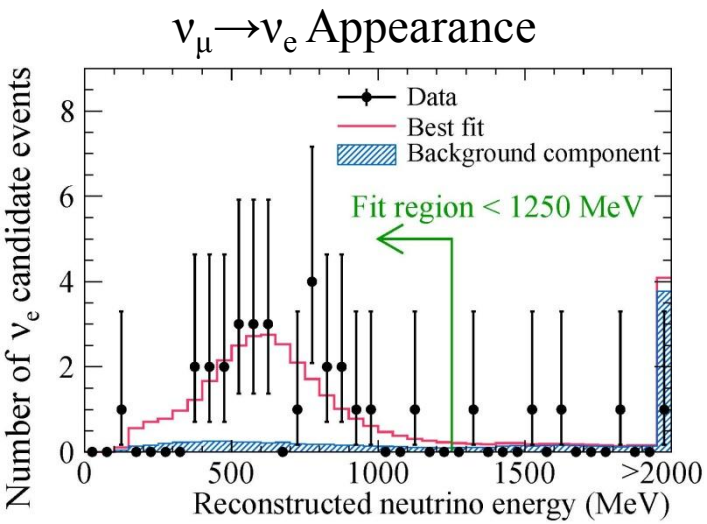

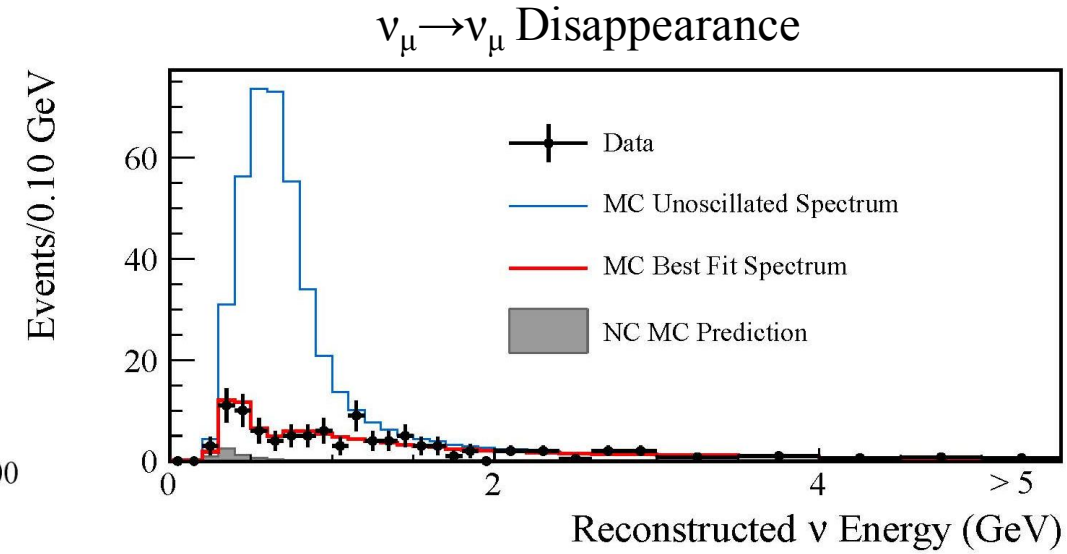

- For "Best fit" and background prediction
  T2K needs: a Near Detector to constrain
  (unoscillated) Beam flux × ν Cross section

Oscillations and Cross Sections

<u>Cross section model</u> (MC)
External data tuning
(Minerva and/or MiniBooNE)

<u>Flux model</u>
External data from
NA61 (CERN)

Priors to the
ND fit(s)

Oscillations and Cross Sections

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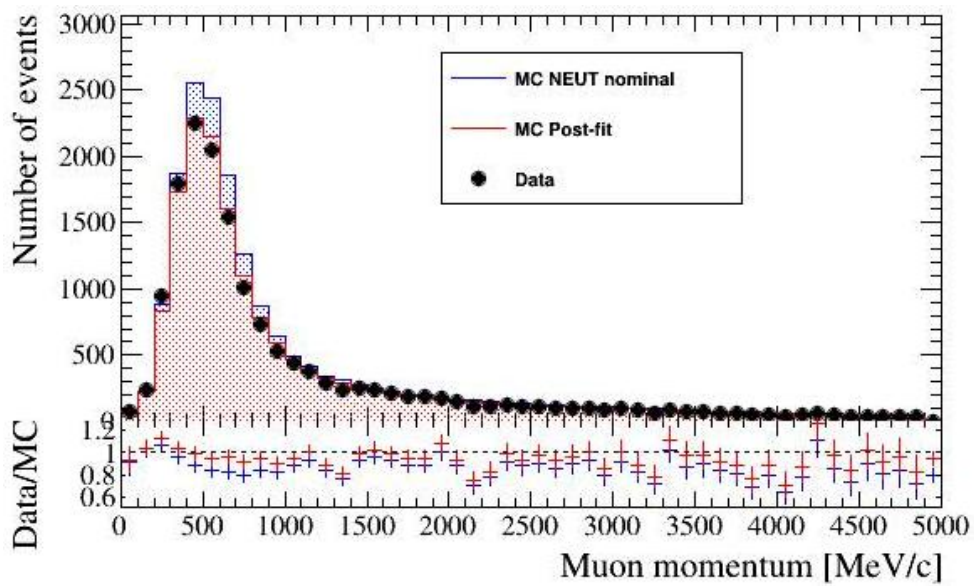
Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets



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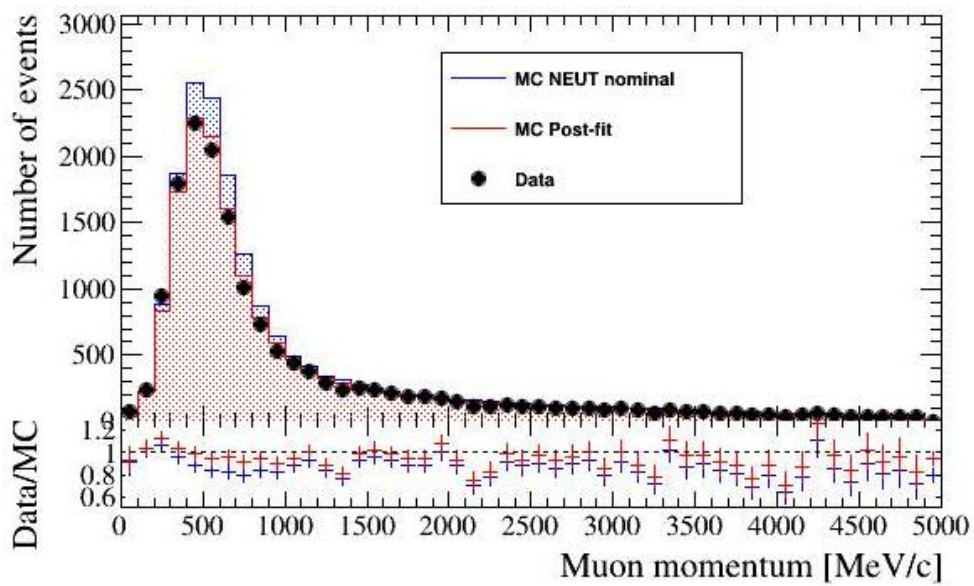

Parameter	Before ND constraint	After ND constraint
M_A^{QE} (GeV/c^2)	1.21 ± 0.45	1.24 ± 0.07
E_B (^{12}C) (MeV)	25 ± 9	30.9 ± 5.2
p_F (^{12}C) (MeV/c)	217 ± 30.0	266.3 ± 10.6
CCQE norm $E\nu < 1.5$ GeV	1.00 ± 0.11	0.97 ± 0.08
CCQE norm $1.5 < E\nu < 3.5$ GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE norm $E\nu > 3.5$ GeV	1.00 ± 0.30	0.93 ± 0.10
M_A^{RES} (GeV/c^2)	1.41 ± 0.11	0.96 ± 0.07
π-less Δ decay fraction	0.20 ± 0.20	0.21 ± 0.08
CC1π^0 norm $E\nu < 2.5$ GeV	1.15 ± 0.43	1.26 ± 0.16
CC1π^0 norm $E\nu > 2.5$ GeV	1.00 ± 0.40	1.12 ± 0.17
CC coherent norm	1.00 ± 1.00	0.45 ± 0.16
NCπ^0 norm	0.96 ± 0.43	1.13 ± 0.25
CC other shape	0.00 ± 0.40	0.23 ± 0.29
NC other norm	1.00 ± 0.30	1.41 ± 0.22

Oscillations and Cross Sections

<u>Cross section model</u> (MC)
External data tuning
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<u>Flux model</u>
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↓

<u>Near Detector data fit</u>
Tune cross section, flux and background
parameters to the ND data sets

↓ Priors to the
FD fit(s)

Oscillations and Cross Sections

Cross section model (MC)
External data tuning
(Minerva and/or MiniBooNE)

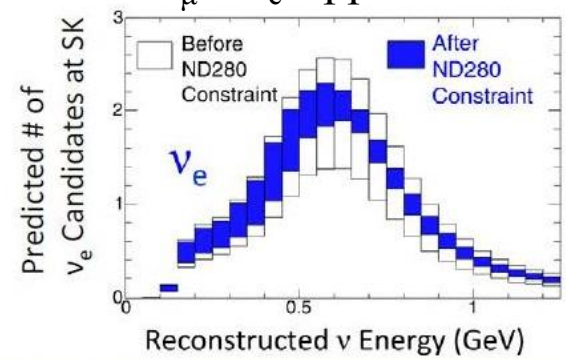
Flux model
External data from
NA61 (CERN)

Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets

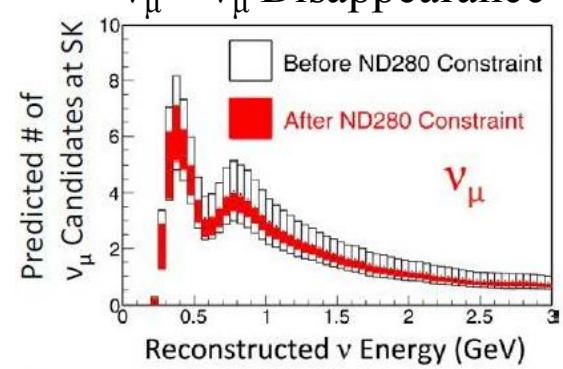
Constrain FD flux and subset of cross section parameters and extracts an event rate prediction at the FD

Priors to the FD fit(s)

$\nu_\mu \rightarrow \nu_e$ Appearance



$\nu_\mu \rightarrow \nu_\mu$ Disappearance



Oscillations and Cross Sections

Cross section model (MC)
External data tuning
(Minerva and/or MiniBooNE)

Flux model
External data from
NA61 (CERN)

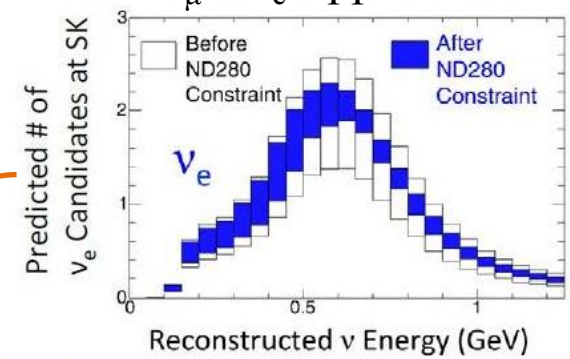
Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets

Constrain FD flux and subset of cross section parameters and extracts an event rate prediction at the FD

Priors to the FD fit(s)

Errors reduced by a factor of ~3-4

$\nu_\mu \rightarrow \nu_e$ Appearance



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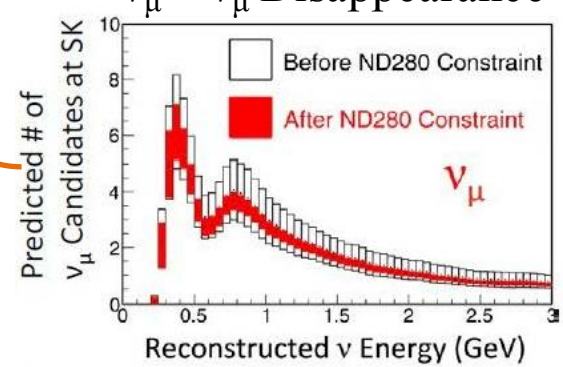

Oscillations and Cross Sections

Cross section model (MC)
External data tuning
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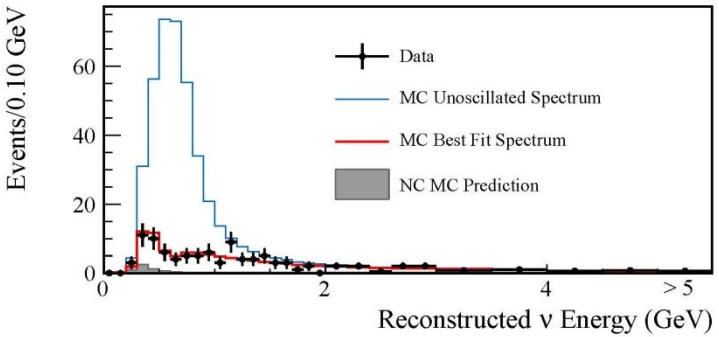
Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets

Constrain FD flux and subset of cross section parameters and extracts an event rate prediction at the FD

Far Detector data fit
Use the combination of ND and external errors in oscillation fits at FD

$\nu_\mu \rightarrow \nu_\mu$ Disappearance



Oscillations and Cross Sections

Cross section model (MC)
External data tuning
(Minerva and/or MiniBooNE)

Flux model
External data from
NA61 (CERN)

ν cross section are key ingredients

Near Detector data fit
Tune cross section, flux and background
parameters to the ND data sets

Constrain FD flux and subset
of cross section parameters
and extracts an event rate
prediction at the FD

Far Detector data fit
Use the combination of ND and
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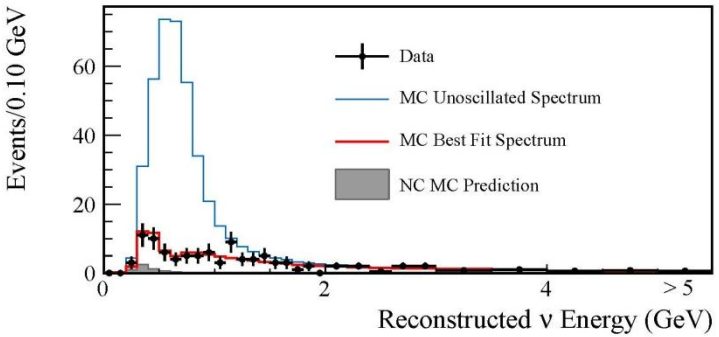
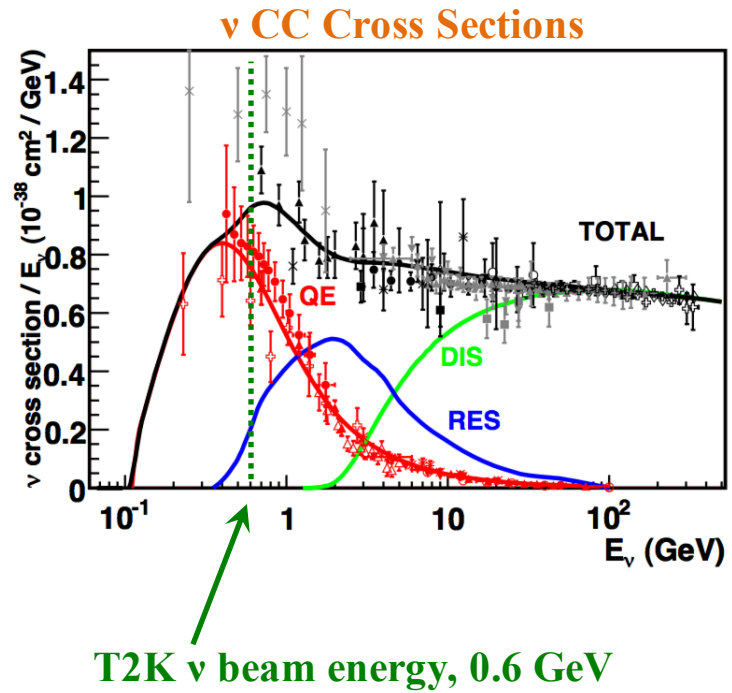
$\nu_\mu \rightarrow \nu_\mu$ Disappearance



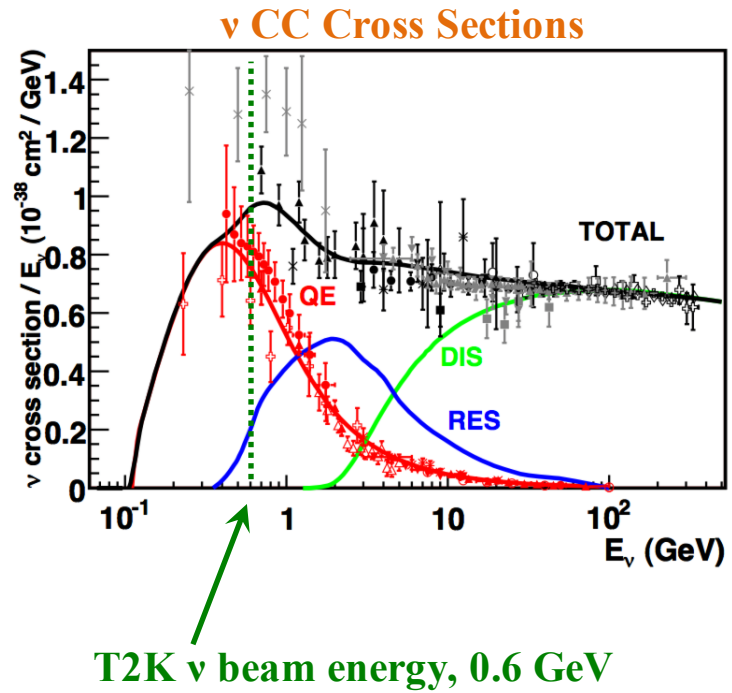
T2K Cross Sections

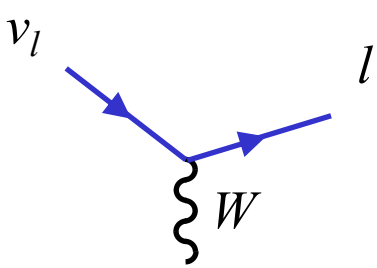
- T2K ν_μ beam energy peaks ~0.6 GeV



T2K Cross Sections

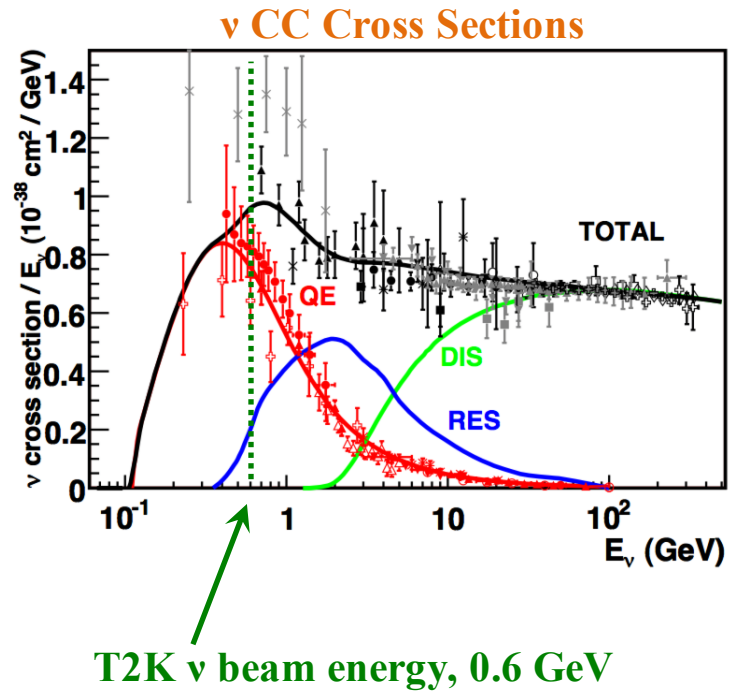
- T2K ν_μ beam energy peaks ~0.6 GeV
- Charge Current (CC)

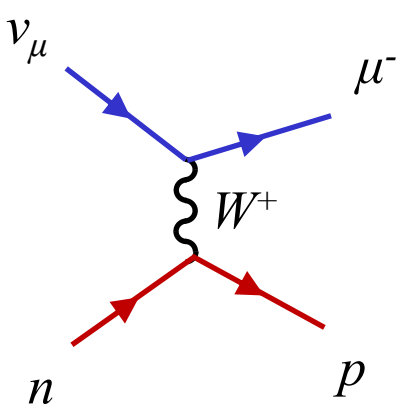




T2K Cross Sections

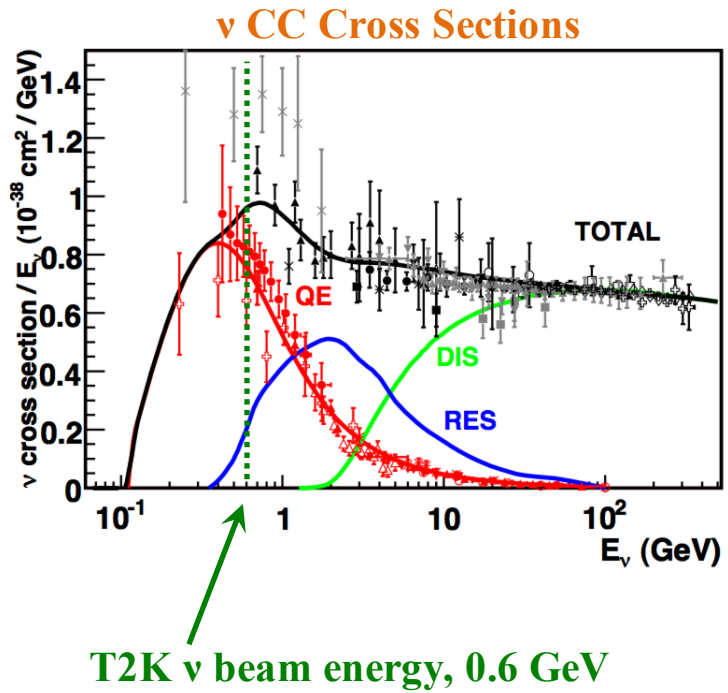
- T2K ν_μ beam energy peaks ~0.6 GeV
- Charge Current (CC)
  - CC Quasi Elastic (CCQE)

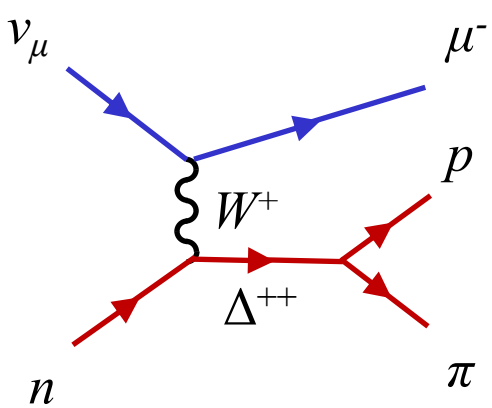




T2K Cross Sections

- T2K ν_μ beam energy peaks ~0.6 GeV
- Charge Current (CC)
  - CC Quasi Elastic (CCQE)
  - CC RESonance or CC 1π





T2K Cross Sections

- T2K ν_μ beam energy peaks ~0.6 GeV
- Charge Current (CC)
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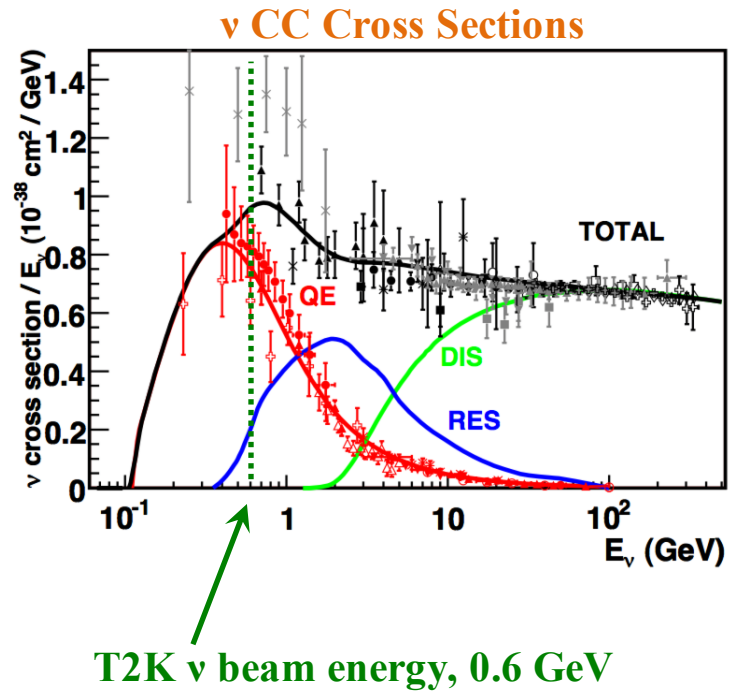
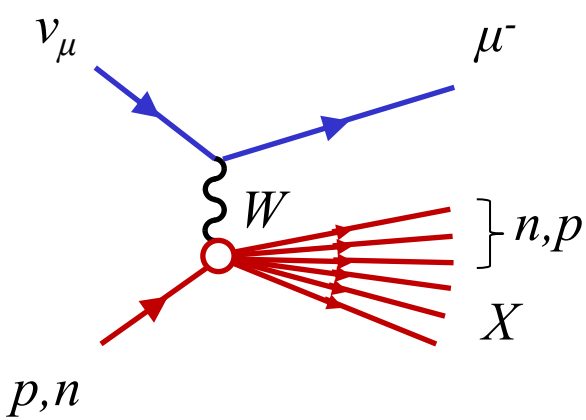
  - CC RESonance or CC 1π
  - > few GeV DIS processes will dominate





T2K Cross Sections

- T2K ν_μ beam energy peaks ~0.6 GeV
- Charge Current (CC)
  - CC Quasi Elastic (CCQE)
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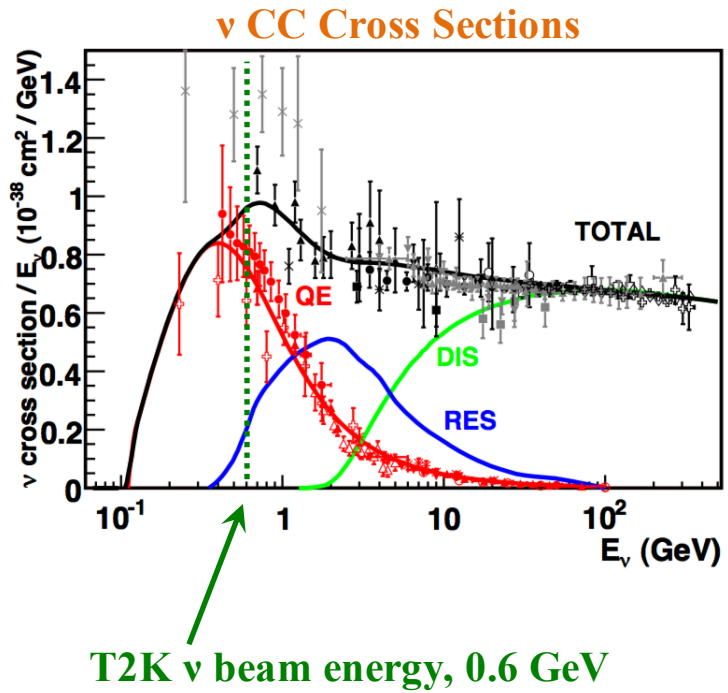
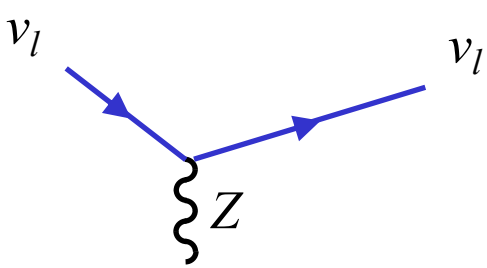
  - > few GeV DIS processes will dominate
- Neutral Current (NC)





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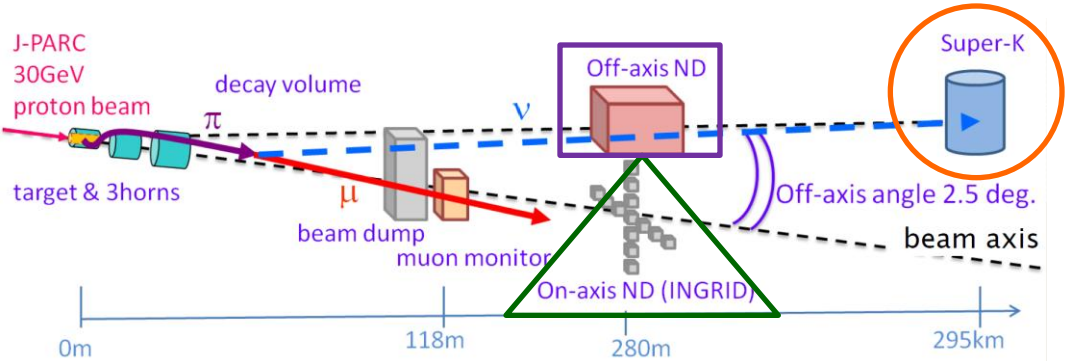
T2K Cross Section Results

- On-axis near detector
  - ν_μ CC inclusive on Fe and on CH
- Off-axis near detector
  - ν_e CC inclusive on C
  - ν_μ NCE (exclusive) on C and O
- Far detector
  - ν_μ NCE (exclusive) on O

T2K cross section publications from the last year



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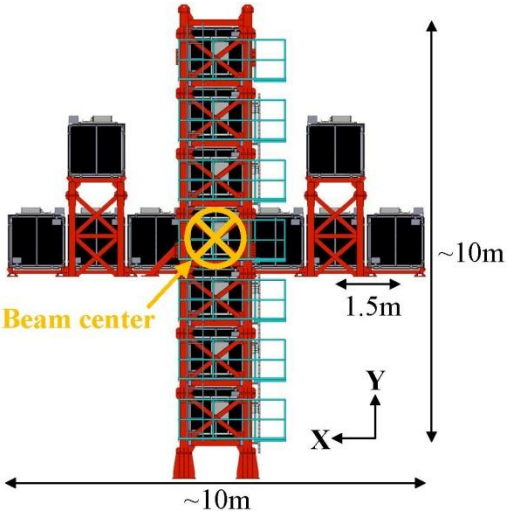
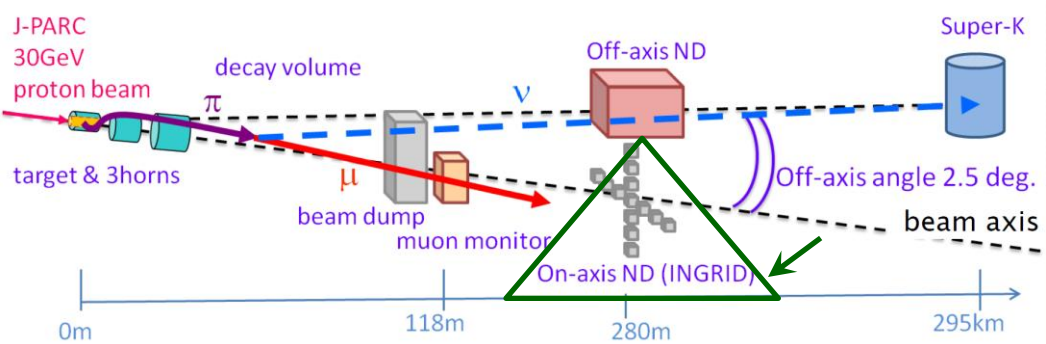
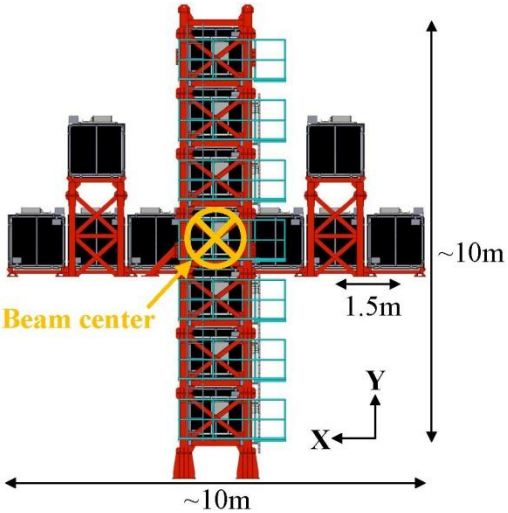




ν_μ CC Inclusive on Fe and on CH

- Motivation
  - Very few ν cross sections on heavy nuclei
  - We have other heavy target material (Pb, Cu-Zn, . .)



PRD 90 (2014) 052010

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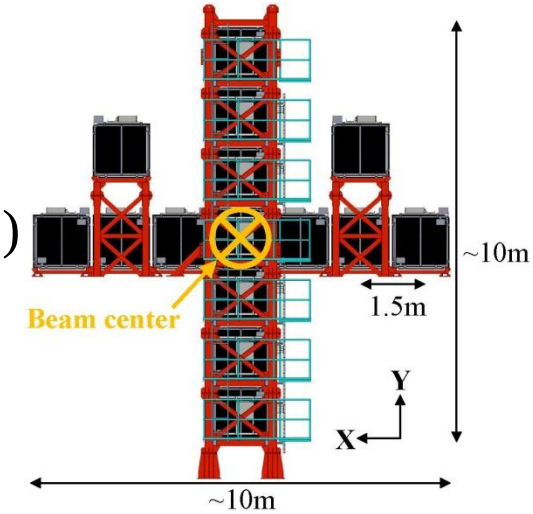
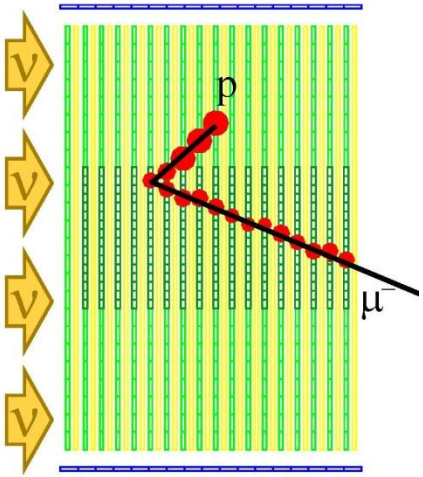
- Events selection
  - Identify the μ^- track in an interaction starting within a central module
  - μ^- candidate: should be in-time with the beam and the longest track.





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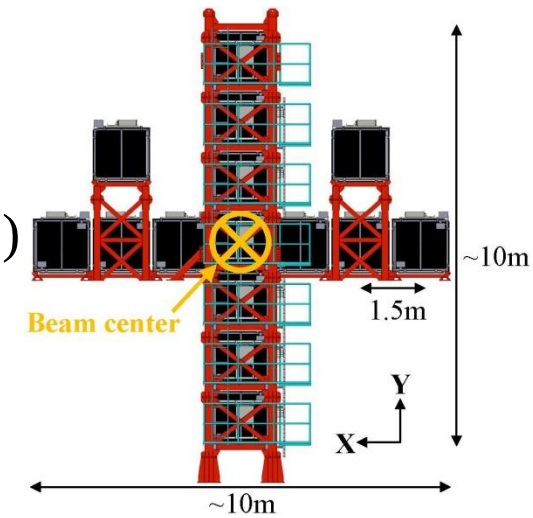
  - μ^- candidate: should be in-time with the beam and the longest track.
- Measurement method
  - Cross section extracted from

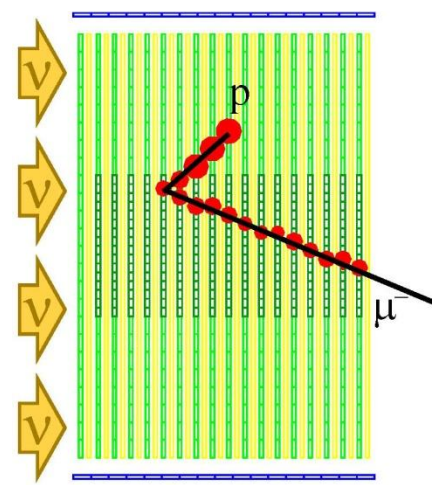
$$\sigma_{CC} = \frac{N_{sel} - N_{BG}}{\phi T \varepsilon}$$

ϕ = integrated ν_μ flux,
T = # target nucleons,
ε = detection efficiency

  - Inputs to the calculations (w/ corrections)

	N_{sel}	N_{BG}	φ [$\times 10^{13}$/cm^2]	T	ε
σ_{CC}^{Fe}	523045	67838	2.999	2.461×10^{30}	0.4270
σ_{CC}^{CH}	36330	5385.5	3.025	1.799×10^{29}	0.4122





PRD 90 (2014) 052010

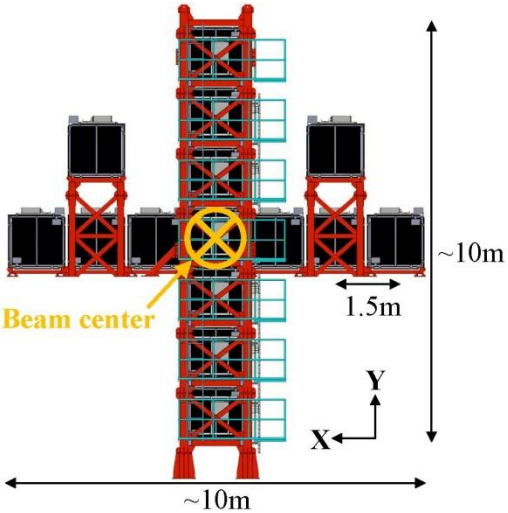
ν_μ CC Inclusive on Fe and on CH

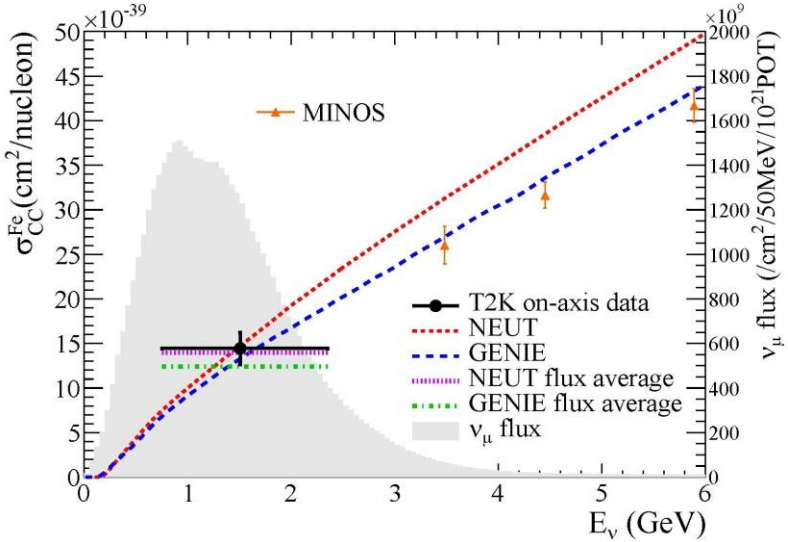
- Results
  - Flux average CC inclusive cross section

$$\sigma_{CC}^{Fe} = \left(1.444 \pm 0.002(\text{stat})\ ^{+0.189}_{-0.157}(\text{syst})\right)\times 10^{-38}\ \text{cm}^2/\text{nucleon}$$

$$\sigma_{CC}^{CH} = \left(1.379 \pm 0.009(\text{stat})\ ^{+0.178}_{-0.147}(\text{syst})\right)\times 10^{-38}\ \text{cm}^2/\text{nucleon}$$

  - Dominated by flux systematic (~11.5%)





Note: NEUT and GENIE = ν MC generators

PRD 90 (2014) 052010

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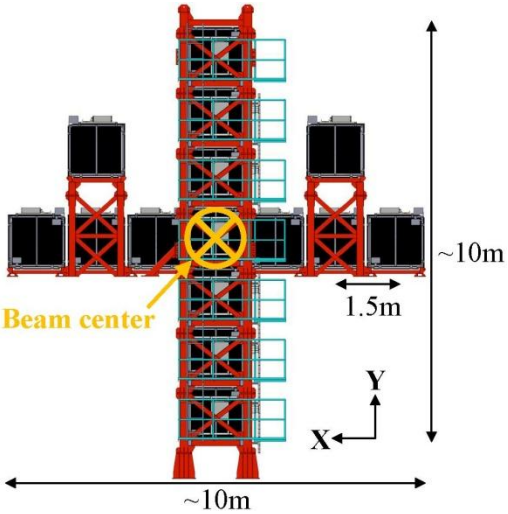
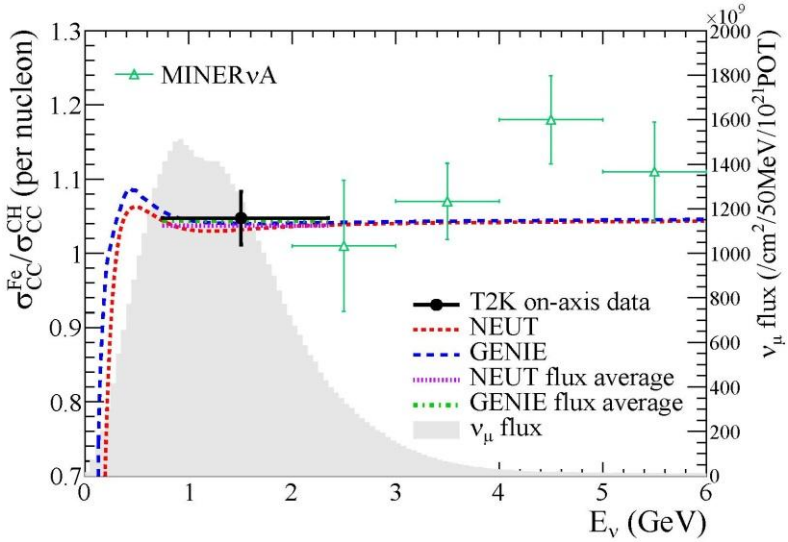
  - Dominated by flux systematic (~11.5%)
  - Cross section ratio

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.047 \pm 0.007(\text{stat}) \pm 0.035(\text{syst})$$

    - Flux systematic mostly cancels out



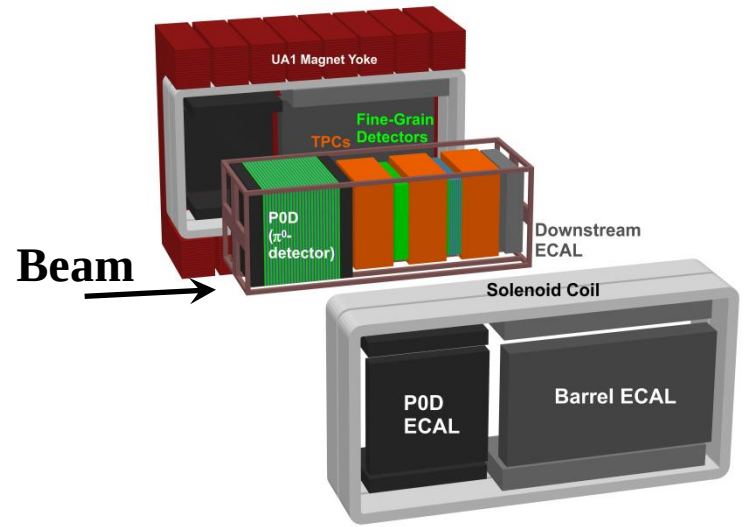


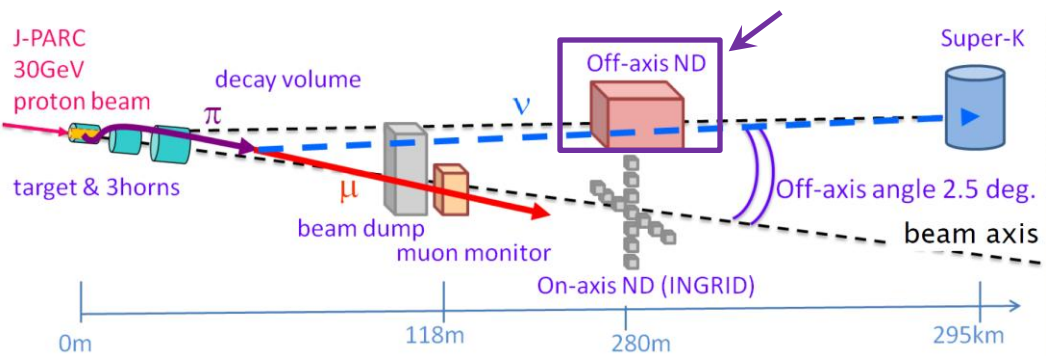
Note: NEUT and GENIE = ν MC generators

PRD 90 (2014) 052010

T2K Cross Section Results

- On-axis near detector
  - ν_μ CC inclusive on Fe and on CH
- Off-axis near detector
  - ν_e CC inclusive on C
  - ν_μ NCE (exclusive) on C and O
- Far detector
  - ν_μ NCE (exclusive) on O





ν_e CC Inclusive Cross Section

- Motivation
  - ν_e contamination is the largest background in $\nu_\mu \rightarrow \nu_e$ Appearance

PRL 113 (2014) 241803

ν_e CC Inclusive Cross Section

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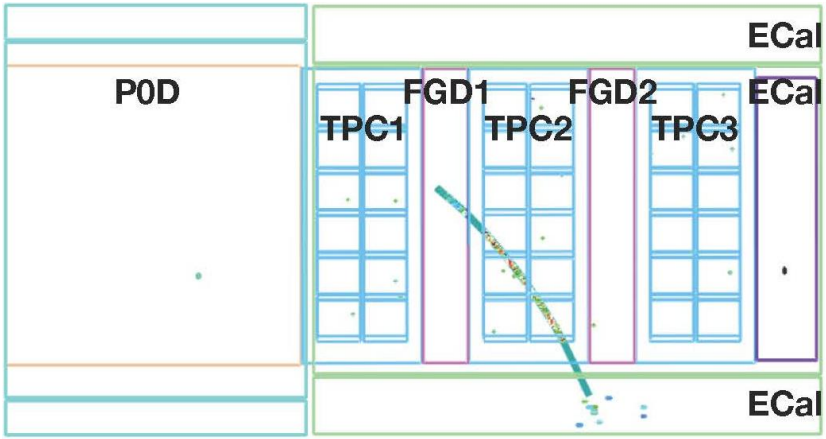
- Events selection
  - Identify the e^- track in an interaction starting within FGD1
  - e^- candidate: Highest momentum, negative charged track that pass electron TPC dE/dx and ECal PID cuts.
  - Main background $\gamma \rightarrow e^+e^-$ treat
    - Veto activity upstream of FGD1
    - e^+e^- invariant mass cut



PRL 113 (2014) 241803

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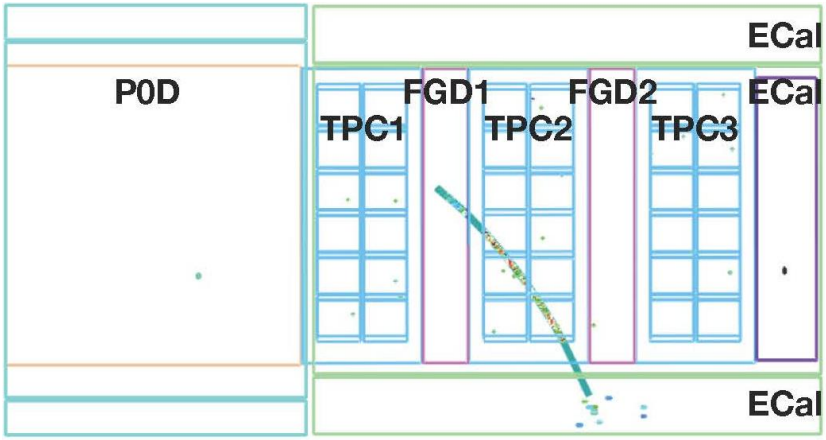
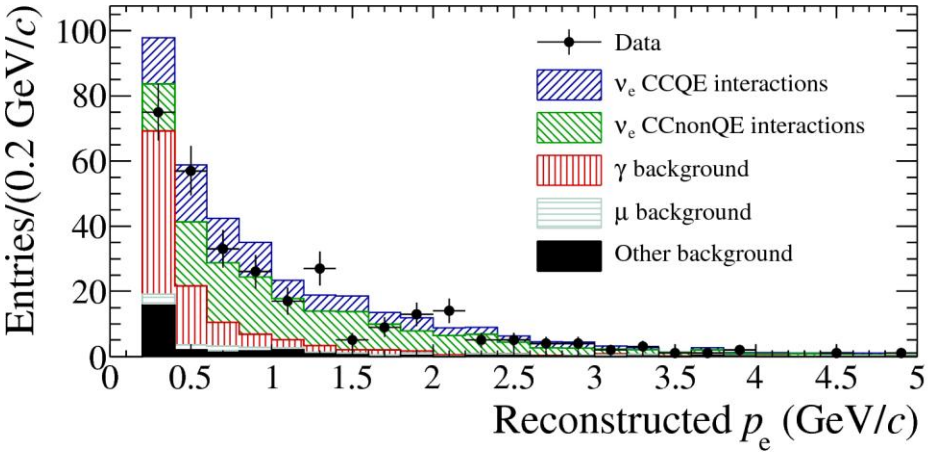
    - e^+e^- invariant mass cut
  - <u>Selected:</u> 315 ν_e CC events





PRL 113 (2014) 241803

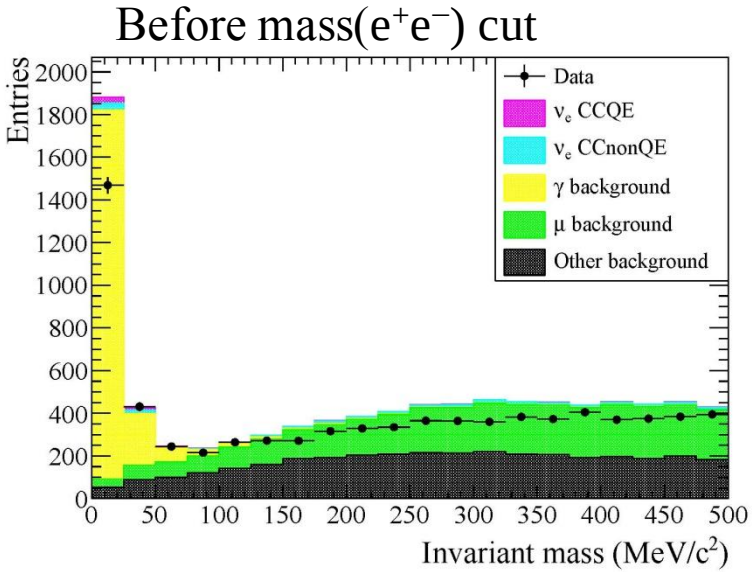
ν_e CC Inclusive Cross Section

- Measurement method
  - Cross section extracted from

$$\left\langle \frac{\partial \langle \sigma \rangle_\phi}{\partial X} \right\rangle_k = \frac{N_k}{\Delta X_k T \phi}$$

$X = p_e$, $\cos\theta_e$ or Q^2,
ΔX = bin width,
N_k = # signal events,
ϕ = integrated ν_μ flux,
T = # target nucleons

  - Background constrained by a γ sideband



Note: $\langle\ \rangle_\varphi$ = average on φ

PRL 113 (2014) 241803

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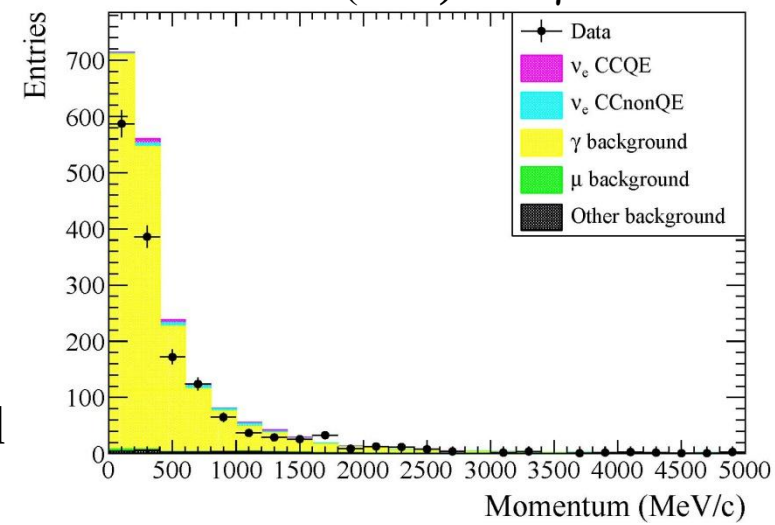
  - Background constrained by a γ sideband

After mass(e^+e^-) cut: γ sideband



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PRL 113 (2014) 241803

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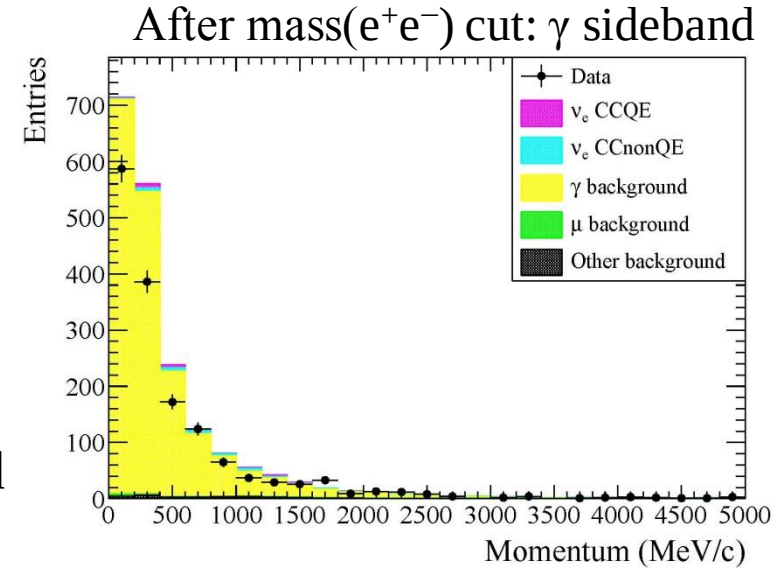
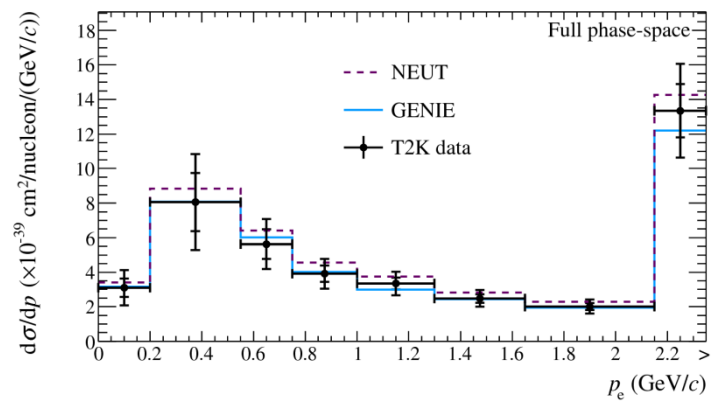
  - Background constrained by a γ sideband
- Results
  - Differential distributions: p_e, $\cos\theta_e$ and Q^2





PRL 113 (2014) 241803

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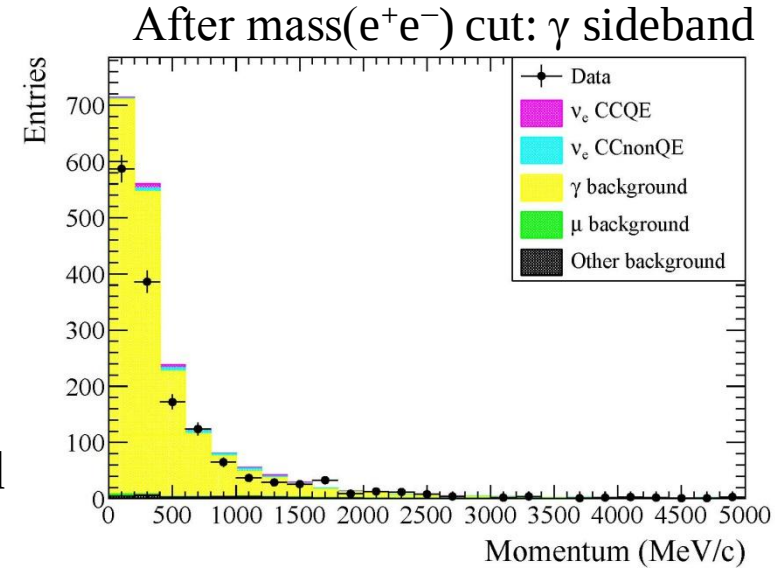
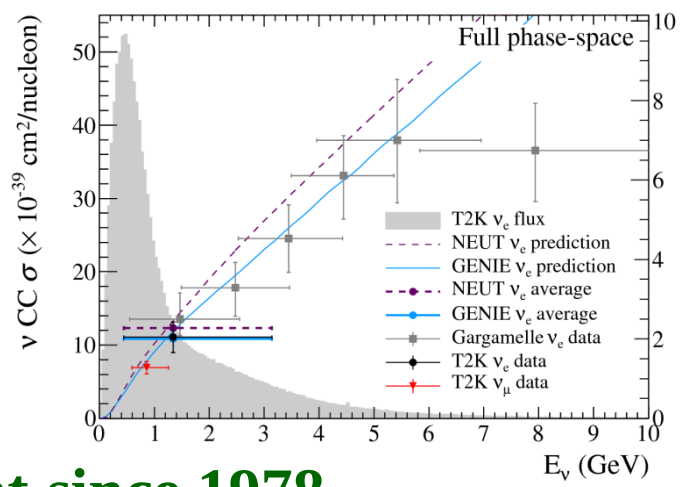


- Results
  - Differential distributions: p_e, $\cos\theta_e$ and Q^2
  - Total ν_e CC inclusive cross section

$\langle\sigma\rangle_\varphi = 1.11 \pm 0.10(\text{stat}) \pm 0.18(\text{syst}) \times 10^{-38}\,\text{cm}^2/\text{nucleon}$

  - Dominant systematics:
    Flux (12.9%), Statistics (8.7%),
    Detector (8.6%)



- **First total ν_e cross section measurement since 1978**

(Gargamelle, Nucl. Phys. B 133, 205)

PRL 113 (2014) 241803

ν_μ NCE on C and O

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- Motivation
  - The NCE is the analogous process to CCQE
  - A test to the hadronic part of QE scattering

D.Ruterbories, NuFact2013 Proceeding

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  - The NCE is the analogous process to CCQE
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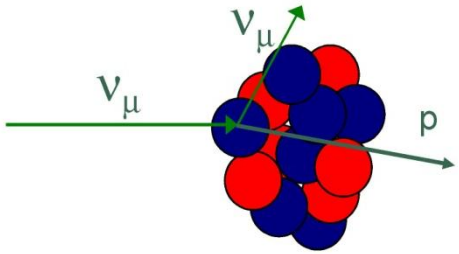
- Topology
  - Elastic interaction $\nu_\mu + p \rightarrow \nu_\mu + p$ where only a proton was produced and nothing else (i.e. a proton "appears")



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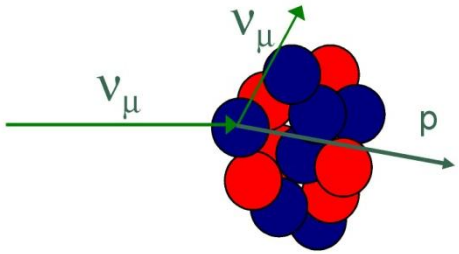

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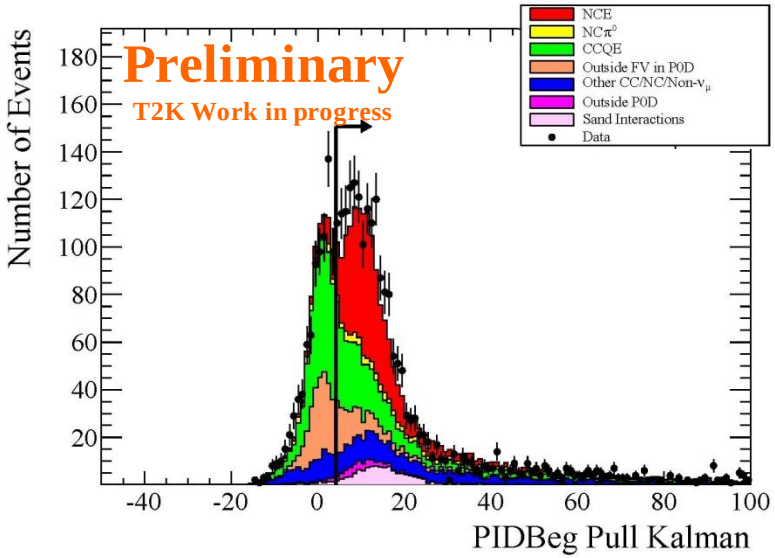


- Events selection
  - Identify the proton track in an interaction starting within the PØD
  - Proton candidate:
    Should pass a Proton dE/dx PID and be the only track in the event.
  - Remove events with a pion or muon decay
  - Main background CCQE (where muon was no reconstructed)

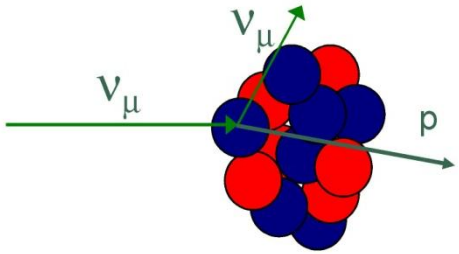
D.Ruterbories, NuFact2013 Proceeding

ν_μ NCE on C and O

- Measurement method
  - Cross section extracted from

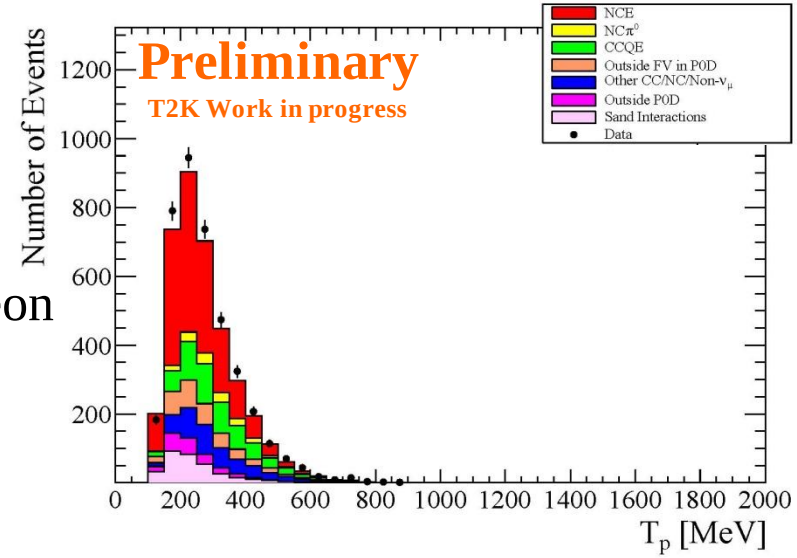
$$\langle\sigma\rangle_\phi = \frac{N_{select} - N_{BG}}{\phi T \varepsilon}$$

ϕ = integrated ν_μ flux,
T = # target nucleons,
ε = selection efficiency



- Results
  - Flux average NCE cross section

$$\langle\sigma\rangle_\phi = 2.24\times10^{-39} \pm 0.07(\text{stat})\ ^{+0.53}_{-0.63}(\text{syst})\ \text{cm}^2/\text{nucleon}$$



  - Dominated systematics:
    Flux (~17%-21%),
    Physics model parameters (14%-16%)

Note: $\langle\ \rangle_\varphi$ = average on φ

D.Ruterbories, NuFact2013 Proceeding

T2K Cross Section Results

- On-axis near detector
  - ν_μ CC inclusive on Fe and on CH
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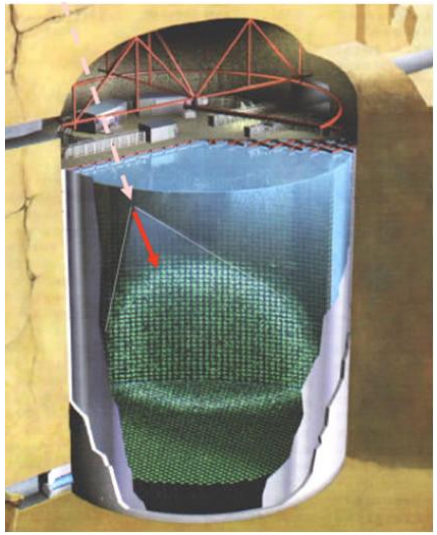

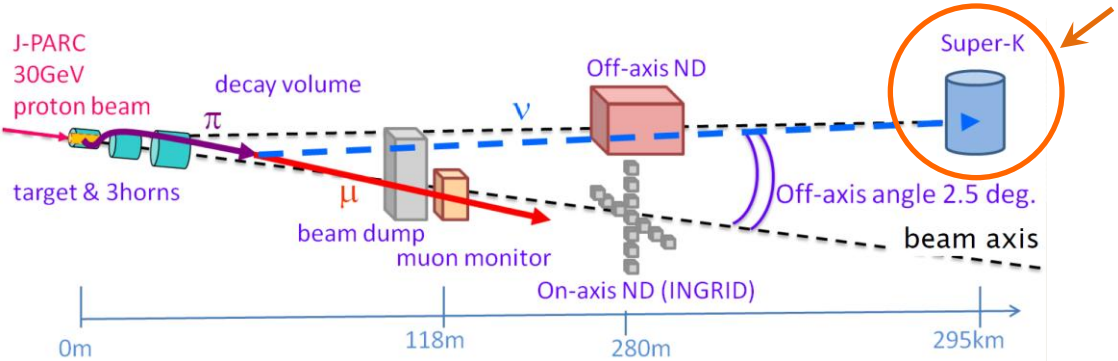

ν_μ NCE Cross section on O

- Motivation
  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments

PRD 90 (2014) 072012

ν_μ NCE Cross section on O

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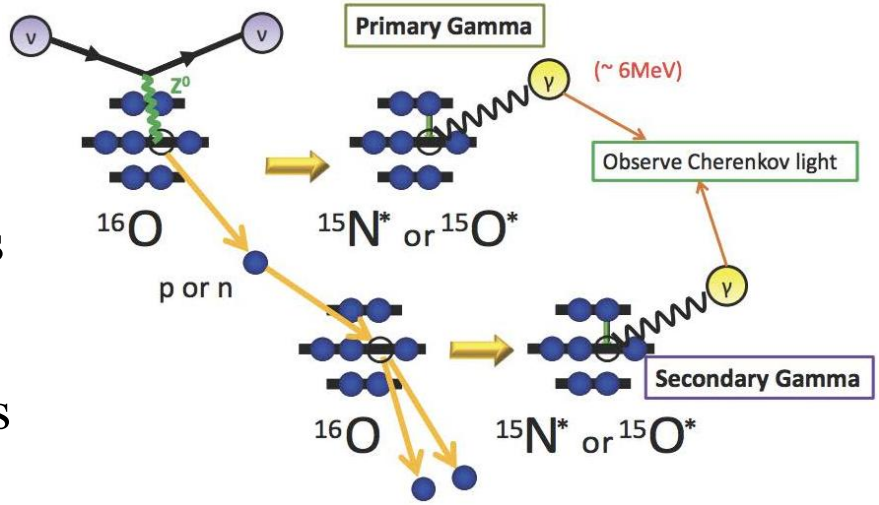
  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments
- Topology
  - We look for de-excitation γs in SK's lowest energy sample (4-30 MeV)
  - To be able to isolate γs from NCE interactions on oxygen



PRD 90 (2014) 072012

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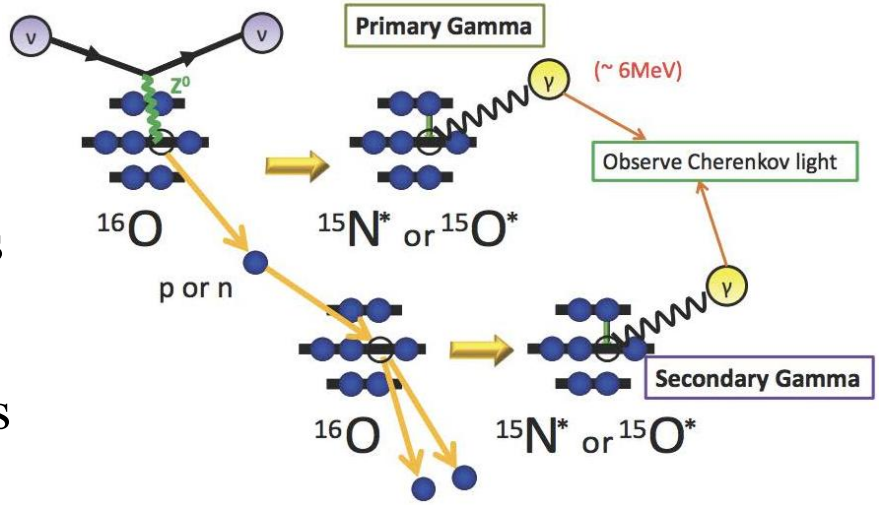
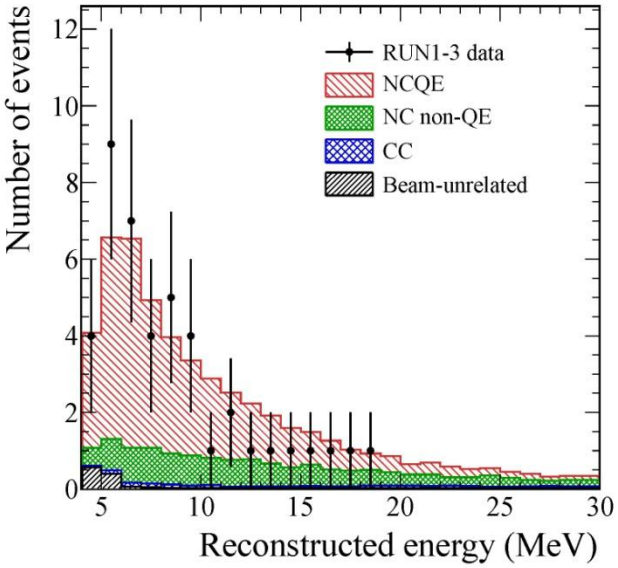
  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments
- Topology
  - We look for de-excitation γs in SK's lowest energy sample (4-30 MeV)
  - To be able to isolate γs from NCE interactions on oxygen
- Events selection:
  - Tight timing cut (around beam bunch time)
  - 4 MeV < E_{Reco} < 30 MeV
  - Remove beam-related background
    - Reject likely decay electron events
    - Cherenkov angle cut > 34^0
  - <u>Observed</u>: 43 electron-like events





PRD 90 (2014) 072012

ν_μ NCE Cross section on O

- Measurement method
  - Cross section extracted from

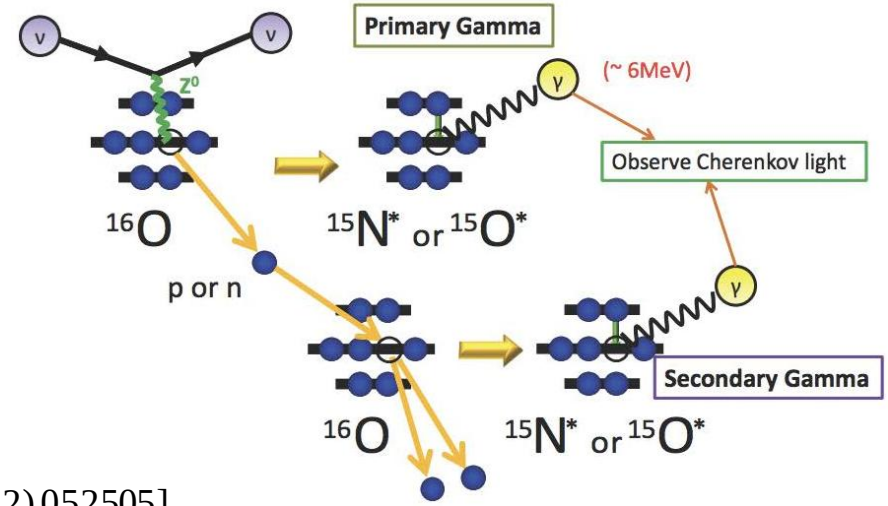
$$\langle \sigma_{NCQE}^{obs} \rangle = \frac{N^{obs} - N_{BG}^{exp}}{N^{exp} - N_{BG}^{exp}} \langle \sigma_{NCQE}^{theory} \rangle$$

obs = observed in data

exp = expected by MC

BG = background

$\langle \sigma_{NCQE}^{theory} \rangle = 2.01 \times 10^{-38} \mathrm{cm}^2$ [PRL 108 (2012) 052505]



PRD 90 (2014) 072012

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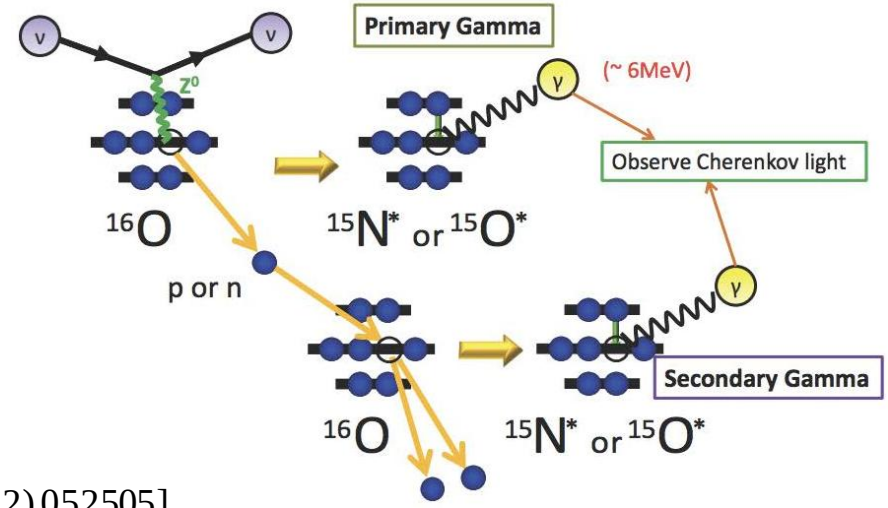
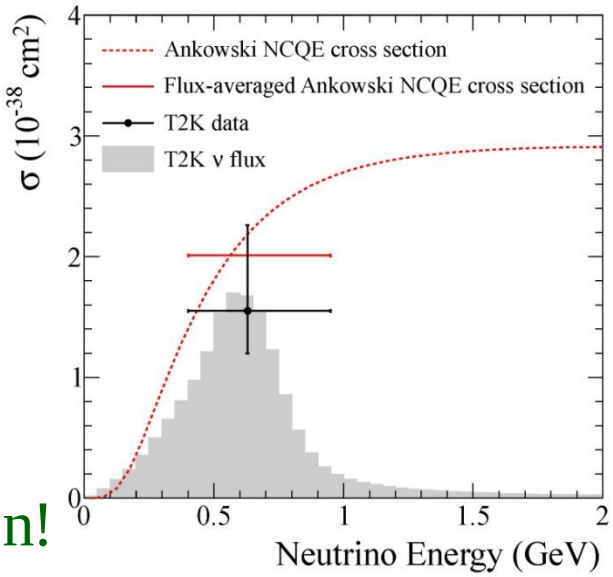


- Results
  - Flux-average ν-Oxygen NCE

$$\langle \sigma_{NCQE}^{obs} \rangle = 1.55^{+0.71}_{-0.35} \times 10^{-38} \mathrm{cm}^2/\mathrm{nucleus}$$

  - Dominant systematics
    - Primary (15%) and secondary (13%) γ productions
    - Flux uncertainty (10%)



- First measured ν-Oxygen NCE cross section!

PRD 90 (2014) 072012

Outline

- The T2K experiment
- Neutrino Oscillations and Cross sections
- T2K Cross Section Results
- **Upcoming Results**
- Summary

Upcoming Results

- T2K ν run measurements
  - ν_μ CC-0π (CCQE) cross section on C
  - ν_μ CC-1π (CCRes) cross sections on C
  - ν_μ NCE differential cross section on O
  - ν_μ-Pb cross section

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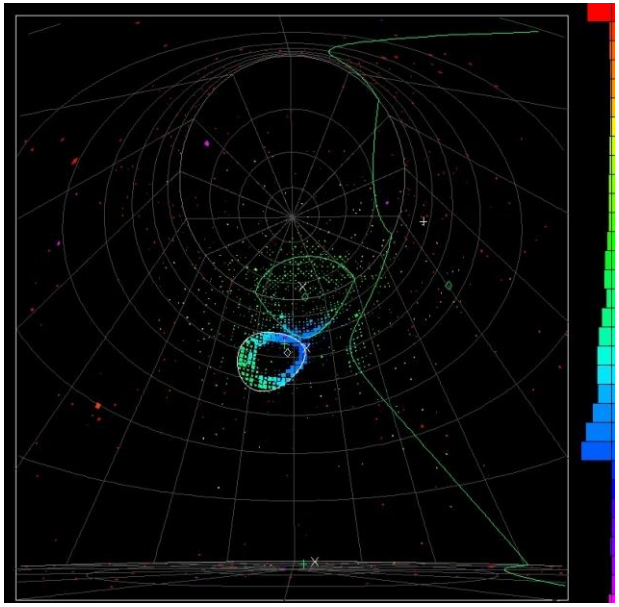
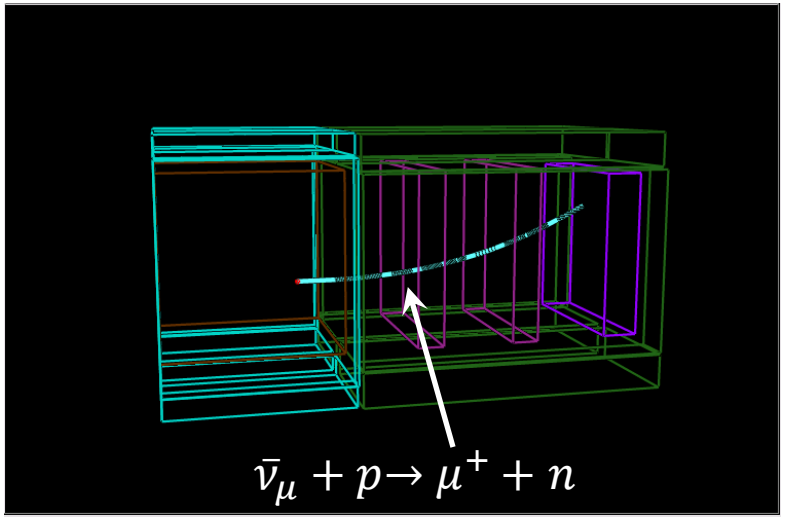
  - ν_μ-Pb cross section
- T2K Anti-ν_μ runs (Started May 2014)

T2K Far Detector



T2K Near Detector



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  - Anti-ν_μ Oscillation results
  - Anti-ν_μ CC inclusive cross section
  - Anti-ν_μ/ν_μ cross sections ratio
- . . .

Summary

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- ν-nucleus cross section knowledge – key ingredient

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  - C, O, Fe and other materials (coming soon)

Summary

- Neutrino Physics has entered its precision measurement era
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  - Off-axis, on-axis detectors and Far-Detector
  - C, O, Fe and other materials (coming soon)
- More
  T2K measurements with better precision are on the horizon

ν Cross Sections

- For more information see http://t2k-experiment.org/results/

Recent Neutrino Cross Section Results from T2K

Erez Reinherz-Aronis

for the T2K Collaboration

Colorado State University

DIS 2015

Dallas, Teaxs

Additional material

T2K Collaboration

~500 members (337 authors), 59 institutes, 11 counters

Canada
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

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U. Aachen

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ICRR RCCN
Kavli IPMU
KEK
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Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metro U.
U. Tokyo

Spain
IFIC, Valencia
IFAE, Barcelona

Poland
NCBJ, Warsaw
IFJ PAN, Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

Switzerland
ETH Zurich
U. Bern
U. Geneva

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Colorado S. U.
U. Colorado
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U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

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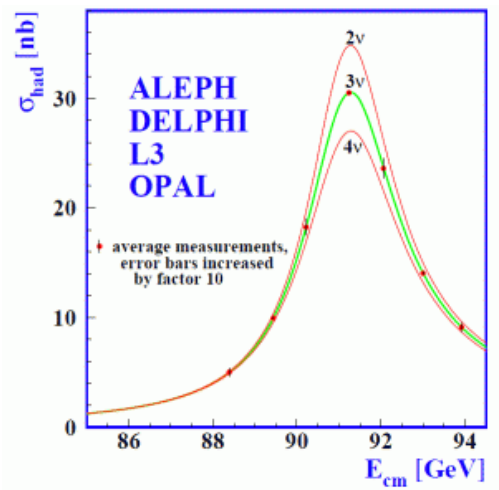
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

Neutrino Oscillations

- In general, a state can be written

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

i = mass state; α = flavor state



- From LEP: At least three neutrino types

- The mixing of flavor and mass eigenstates can be written as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- The PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix

The PMNS Matrix

- A unitary 3x3 matrix → 4 degrees of freedom [assume the 3-flavor paradigm]
- Commonly parameterized by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}) and 1 phase (δ)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{PMNS} = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{"Solar } \nu\text{'s"}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{"Atmospheric } \nu\text{'s"}}$$

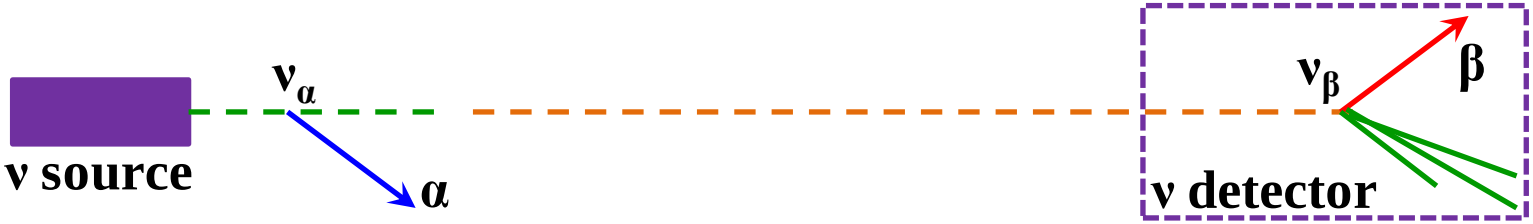
"Solar ν's"		"Atmospheric ν's"
Solar, Reactor	**Reactor, Accelerator**	**Atmospheric, Accelerator**
$\theta_{12} \approx 34^0$	$\theta_{13} \approx 9^0$	$\theta_{23} \approx 45^0$

- Note:
  Large mixing angles compare to the quark section (CKM)

$\theta_{12} \approx 13^0$ $\theta_{13} \approx 0.5^0$ $\theta_{23} \approx 2.3^0$

Oscillation Measurement

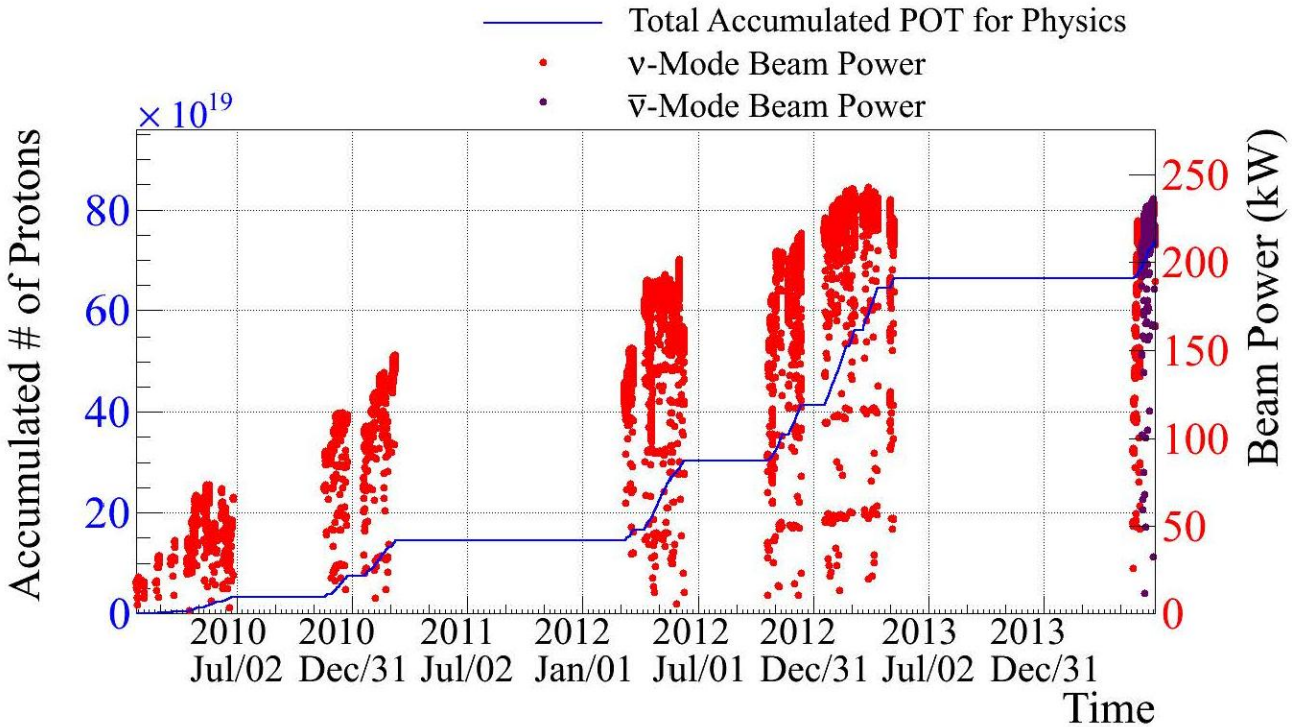
- Neutrino production and detection is determined by their flavor (ν_e, ν_μ, ν_τ) eigenstates
- But propagation through space is determined by their mass (ν_1, ν_2, ν_3) eigenstates
- <u>How</u> do we measure?



- In general the techniques are similar

T2K Results: J-PARC/Beam

- Protons-On-Target (POT) for T2K Runs 1-5



- Integrated nu beam mode: ~6.9×10^{20} POT
- Integrated anti-nu beam mode: ~0.5×10^{20} POT