T2K Recent Cross-Section Results

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XVIII International Workshop on Neutrino Factories and Future Neutrino Facilities

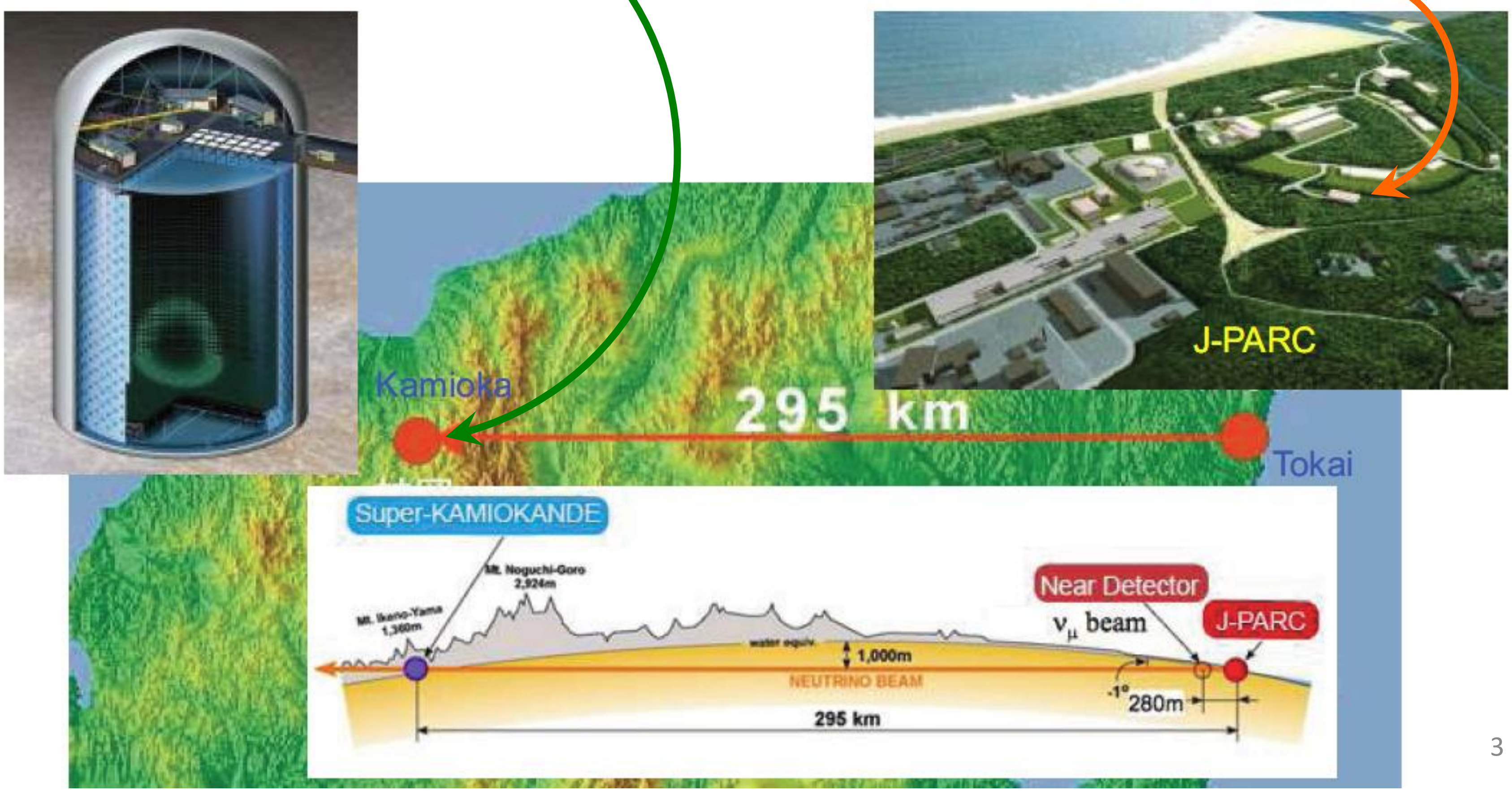
Quy Nhon, Vietnam

Outline

- The T2K experiment
- Neutrino Oscillations and Cross Sections
- T2K Cross-Section Results
- Summary

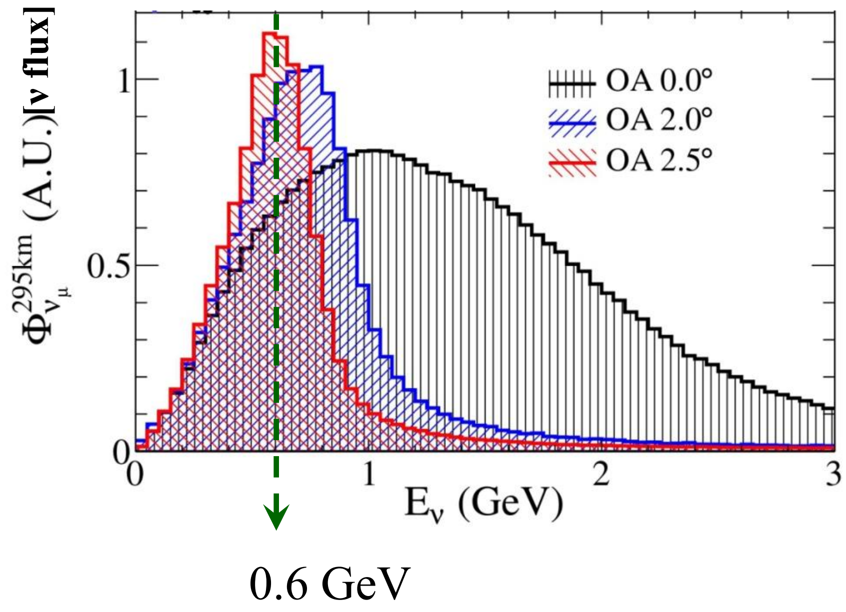
The T2K Experiment

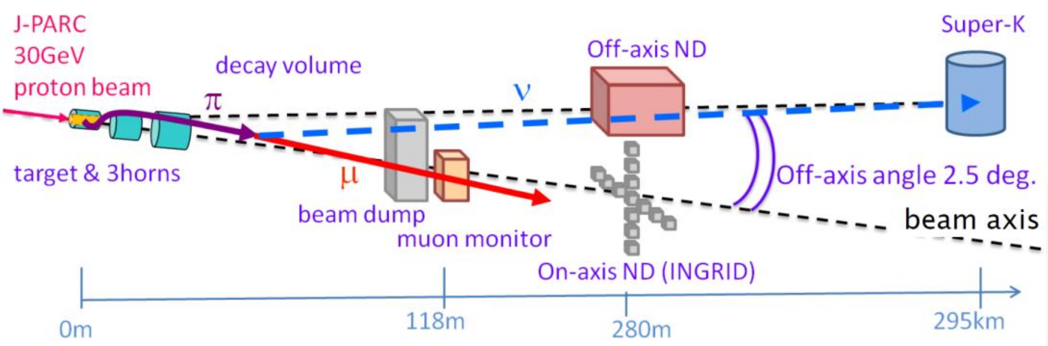
- Tokai-to-Kamioka (T2K): Neutrino Oscillation experiment
  - Location: Japan
  - Baseline: ~295 km
  - Far Detector: Super-Kamiokande
  - Beam: J-PARC Lab 30 GeV proton beam
    Designed to produce ~0.6 GeV ν_μ
  - Near Detectors: In J-PARC campus



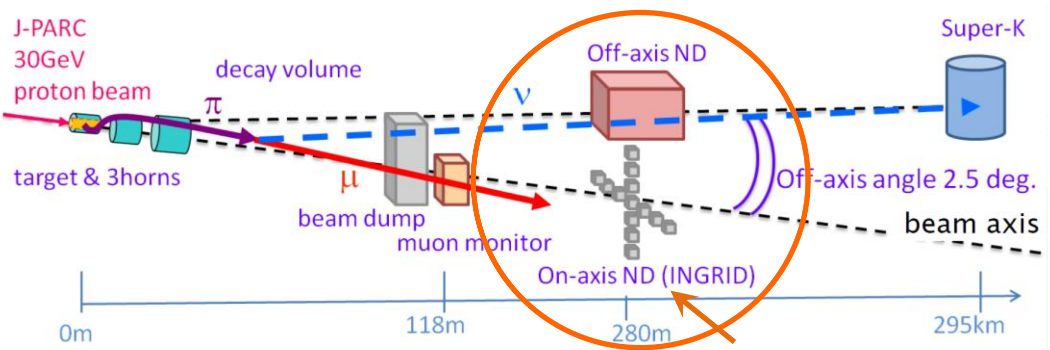
T2K Beam

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



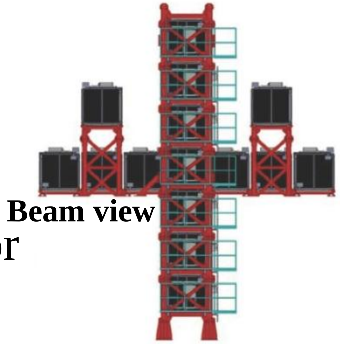


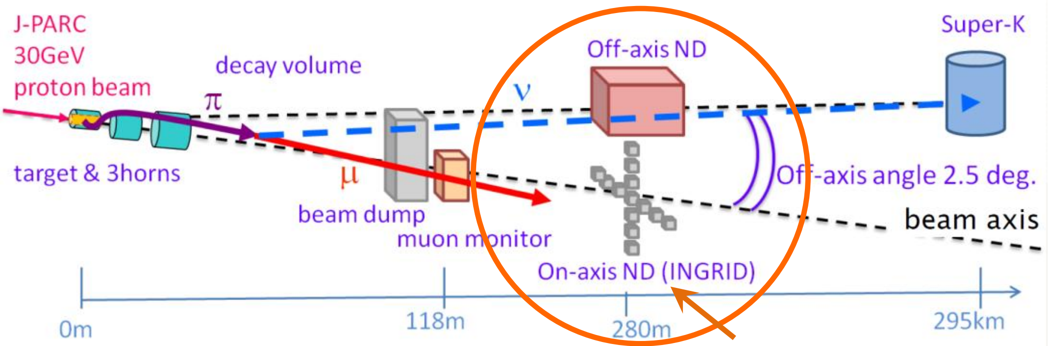
T2K Near Detectors



T2K Near Detectors

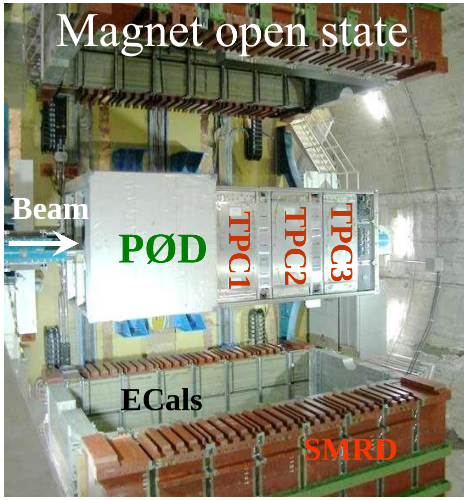
- On-Axis:
  - INGRID
    - 16 Modules of Iron and Scintillator

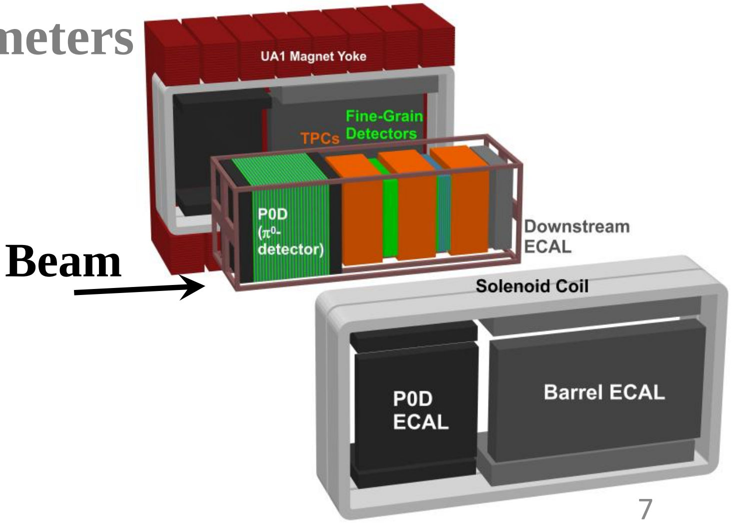


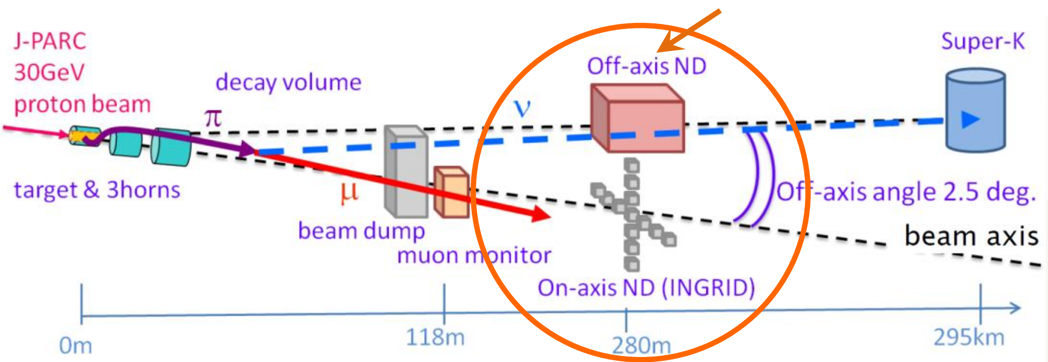


T2K Near Detectors

- 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 a 0.2 T **Magnet**

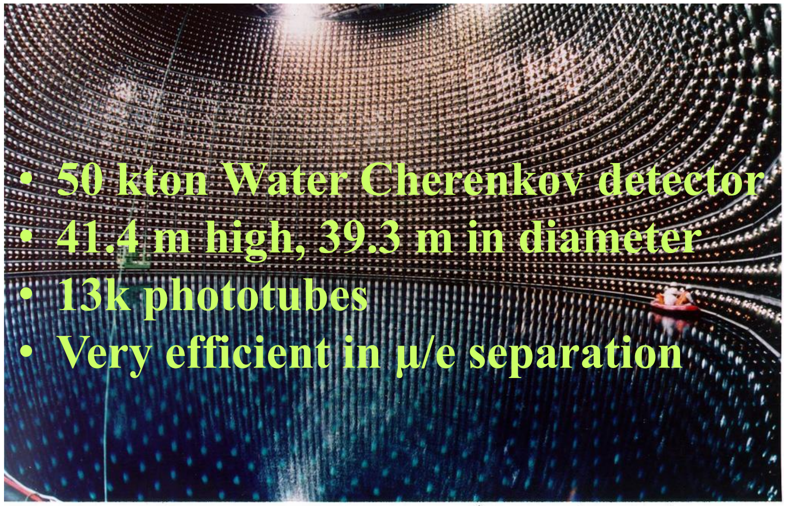


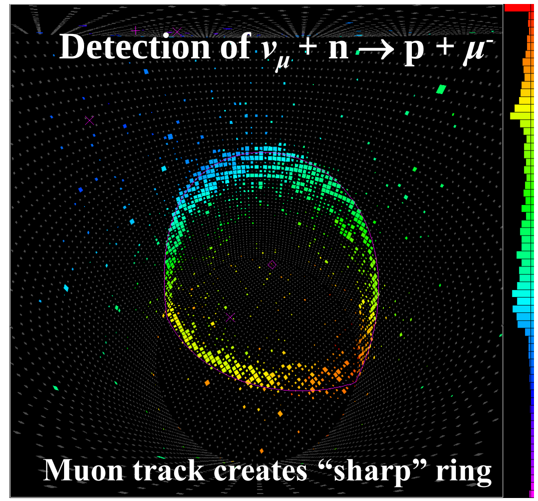


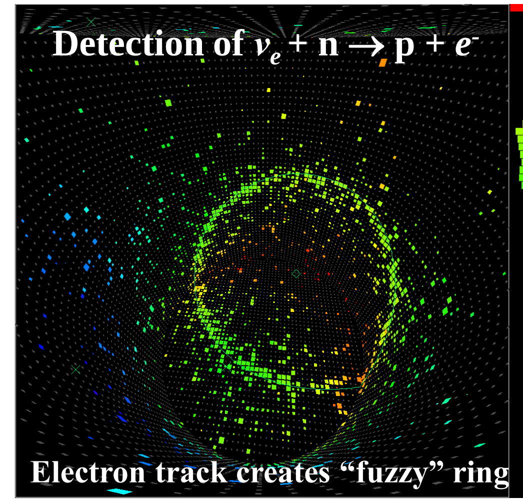


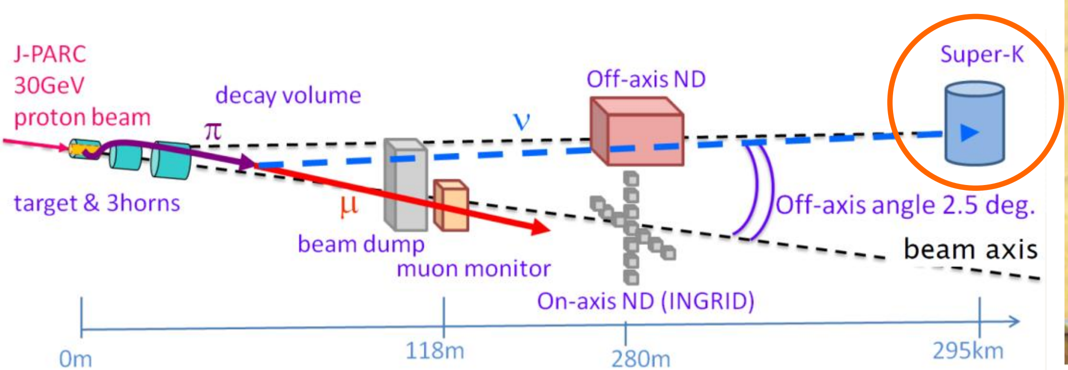
T2K Far Detector

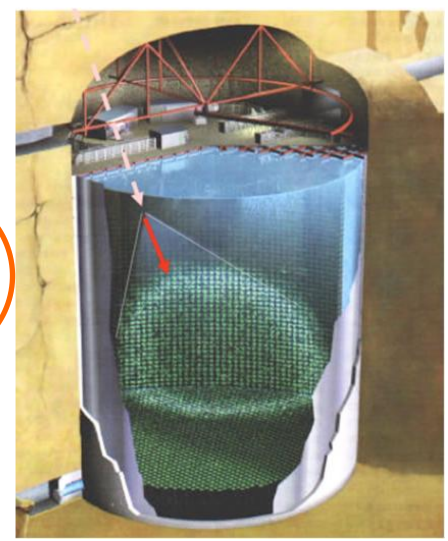
- Super-Kamiokande (SK)

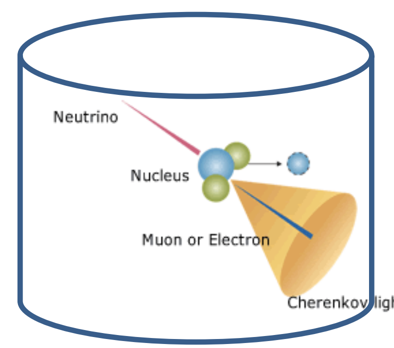












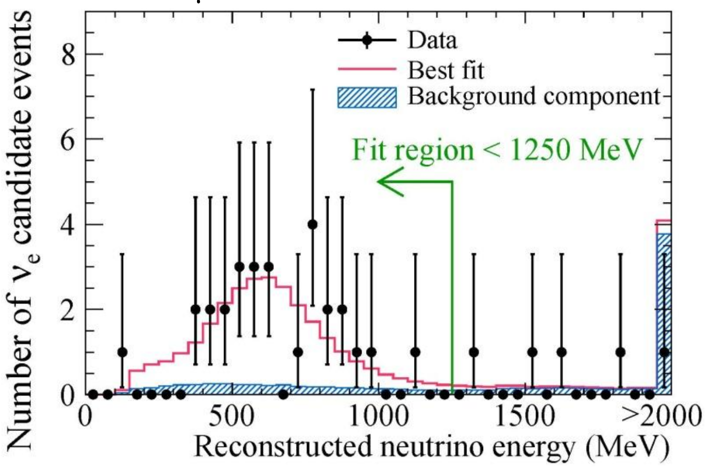
Outline

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

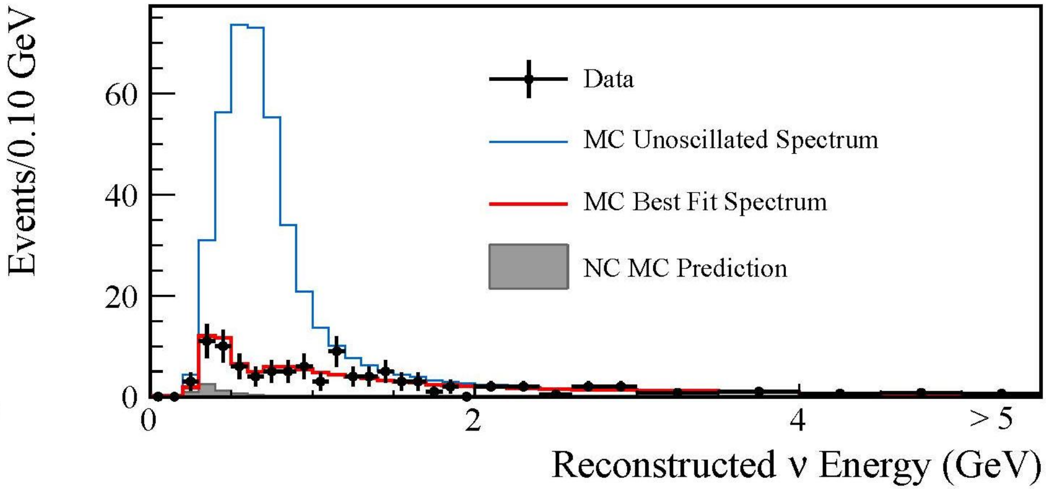
Neutrino Oscillation

- T2K Oscillation results

$\nu_\mu \rightarrow \nu_e$ Appearance



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



Neutrino Oscillation

- T2K Oscillation results

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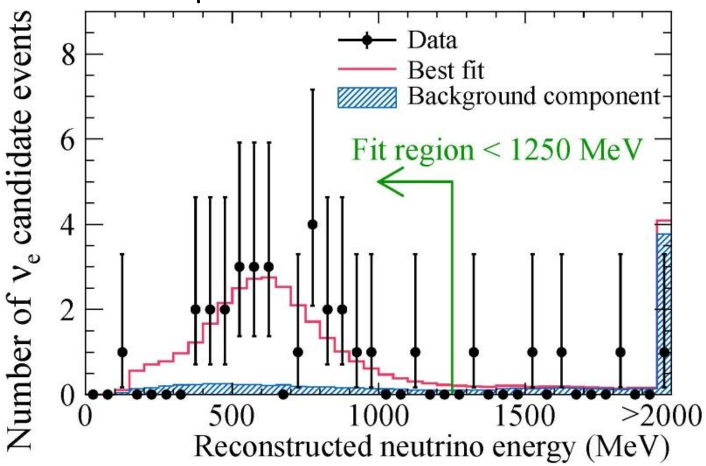

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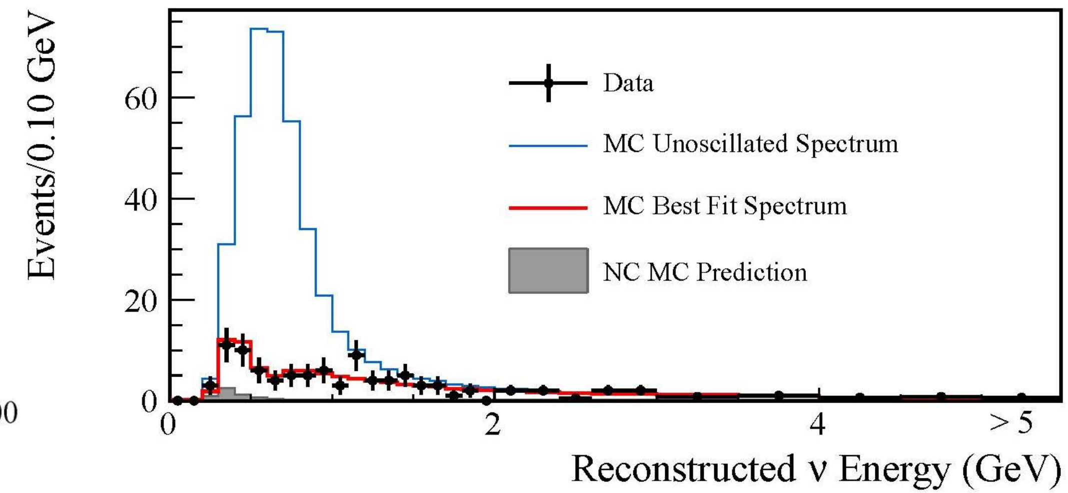

- For "Best fit" and background prediction
  T2K needs: a Near Detector to constrain
  (unoscillated) beam flux × $\overset{(-)}{\nu}$ Cross sections

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

Oscillations and Cross Sections

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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 extract an event rate prediction at the FD

Far Detector data fit

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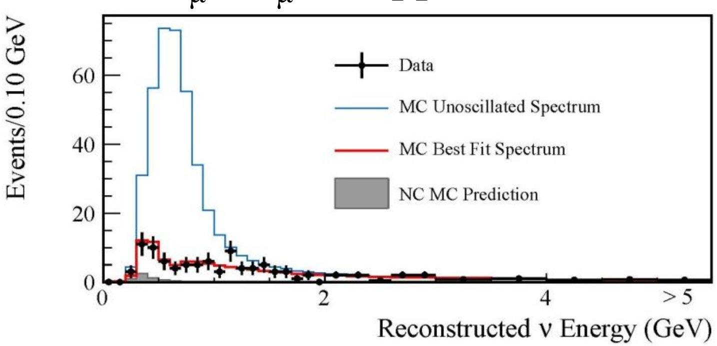
<u>Far Detector data fit</u>
Use the combination of ND and external errors in oscillation fits at FD

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



Oscillations and Cross Sections

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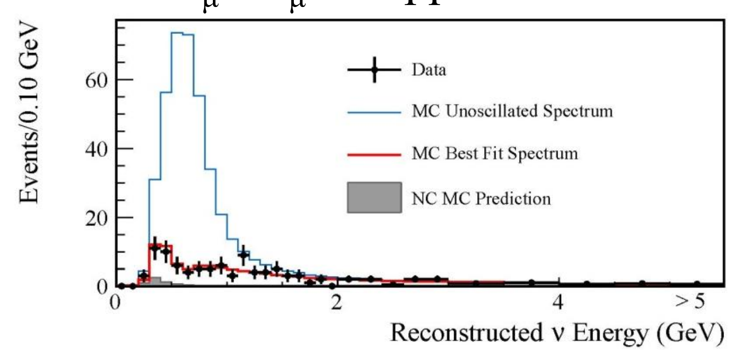
Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets

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

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

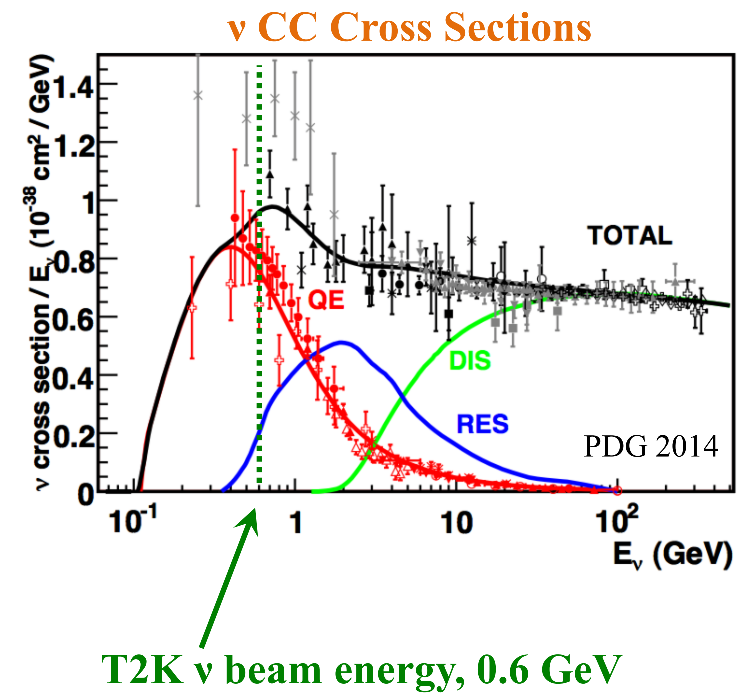
$\overset{(-)}{\nu}$ cross sections are key ingredients

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



T2K Cross Sections

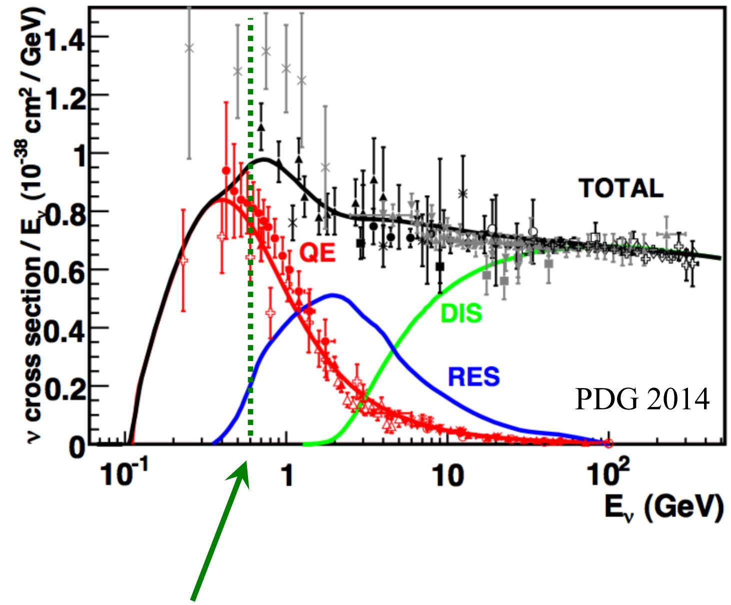
- T2K ν_μ beam energy peaks ~0.6 GeV



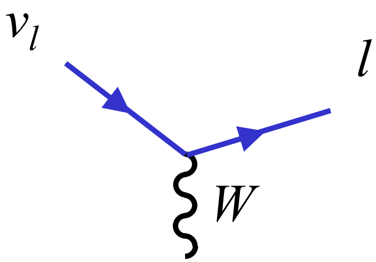
T2K Cross Sections

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

ν CC Cross Sections

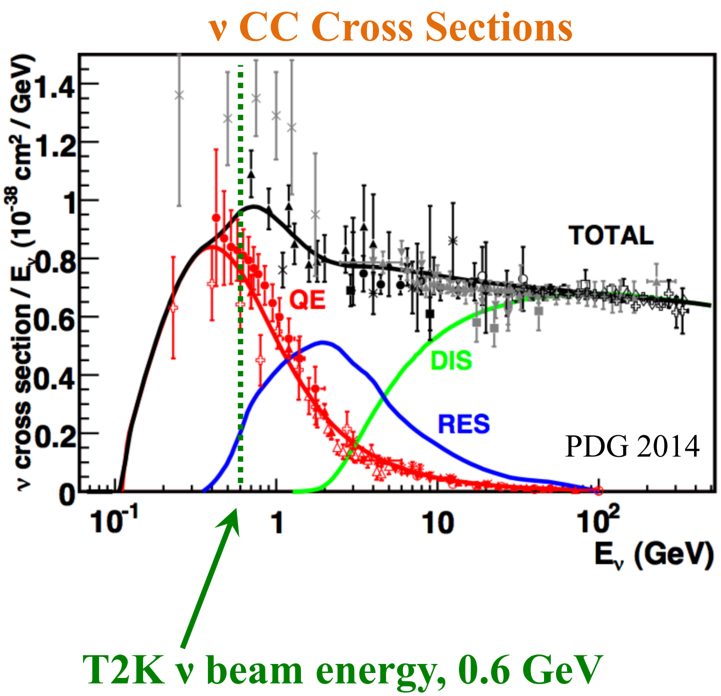


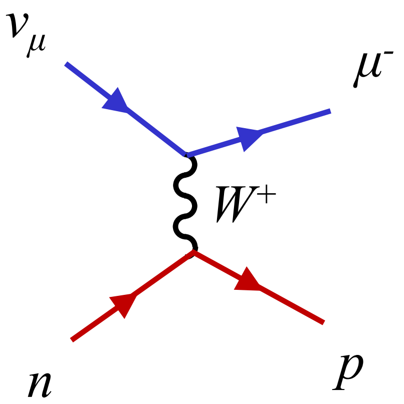
T2K ν beam energy, 0.6 GeV



T2K Cross Sections

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





T2K Cross Sections

- T2K ν_μ beam energy peaks ~0.6 GeV
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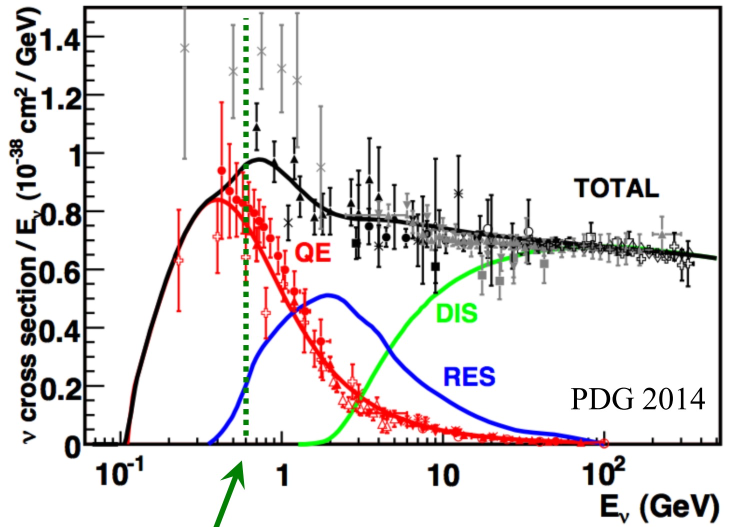
  - CC RESonance or CC 1π

ν CC Cross Sections



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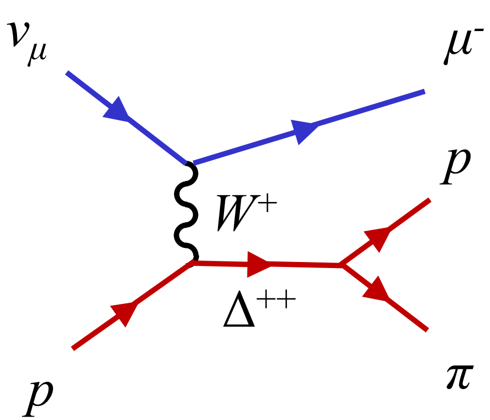

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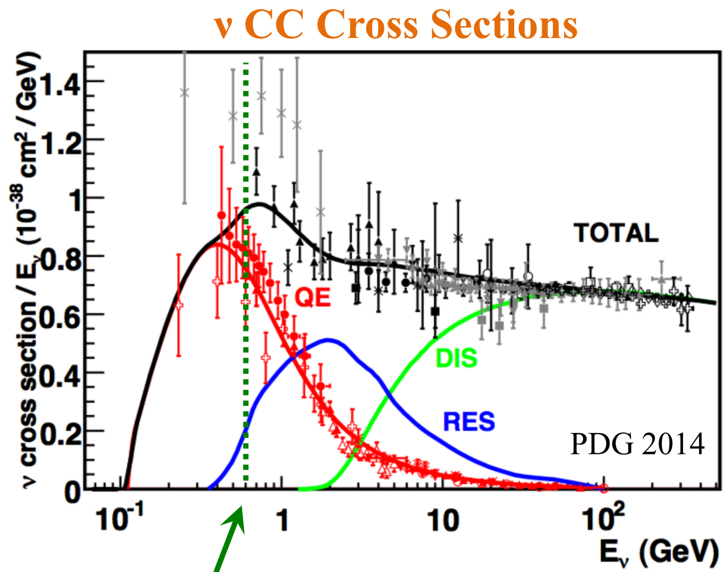

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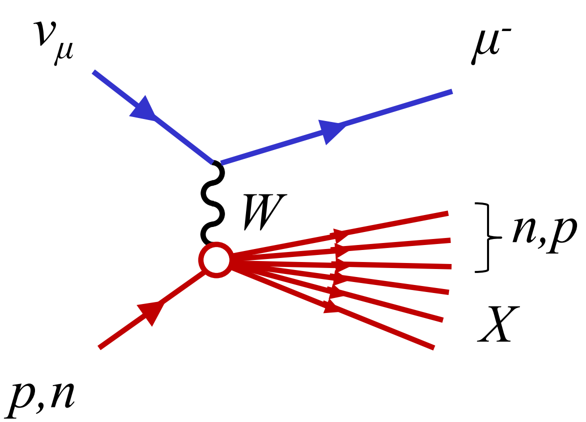

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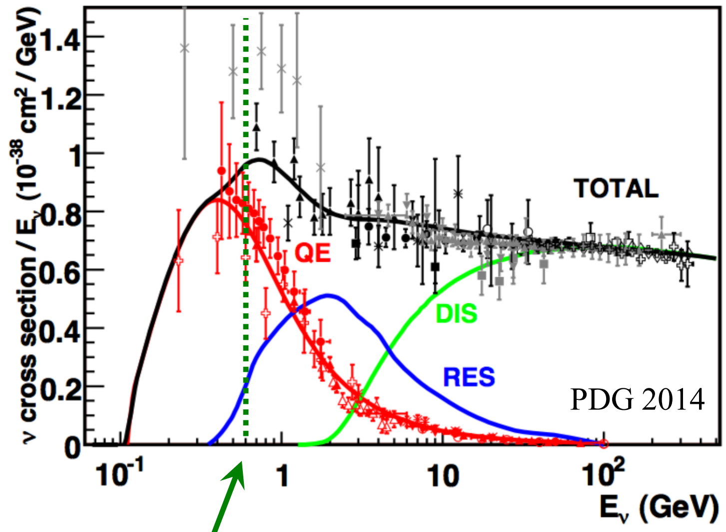
ν CC Cross Sections



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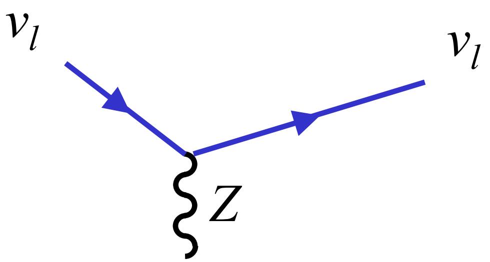

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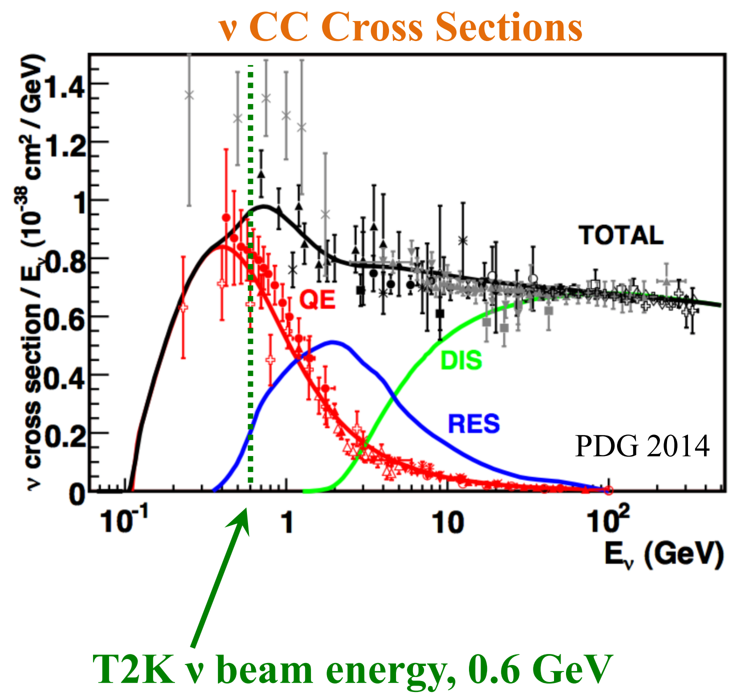

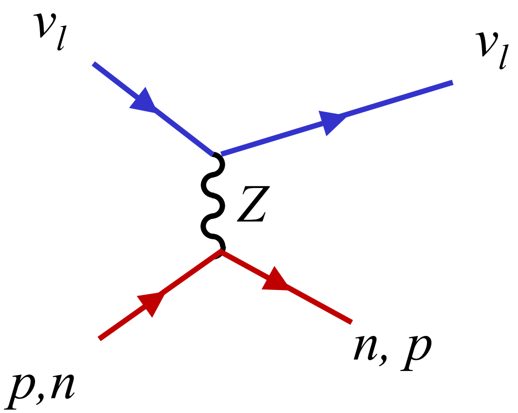

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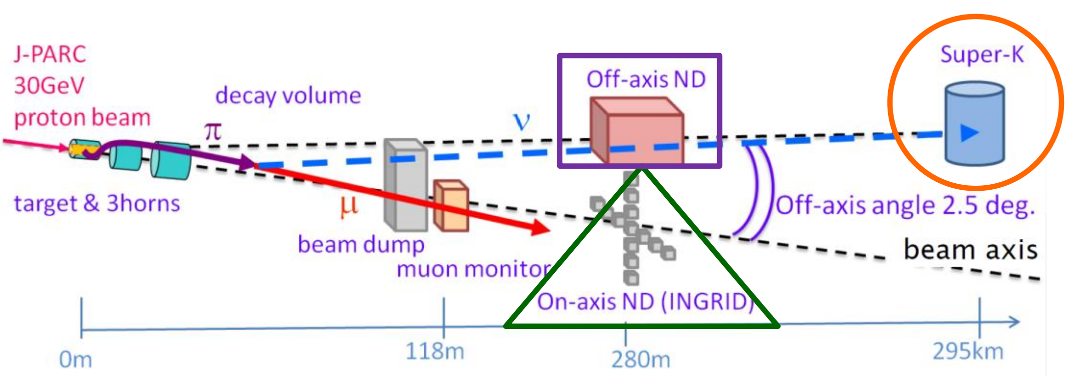
T2K Cross-Section Results

ν
- On-axis near detector
  - ν_μ CC inclusive in E_ν range 1-3 GeV
- Off-axis near detector
  - ν_μ CC $1\pi^+$ (exclusive) on CH
- Far detector
  - ν_μ NCQE (exclusive) on O

$\bar{\nu}$
- Anti-ν_μ: Off-axis near detector
  - Anti-ν_μ CC inclusive on CH and O

Made public recently



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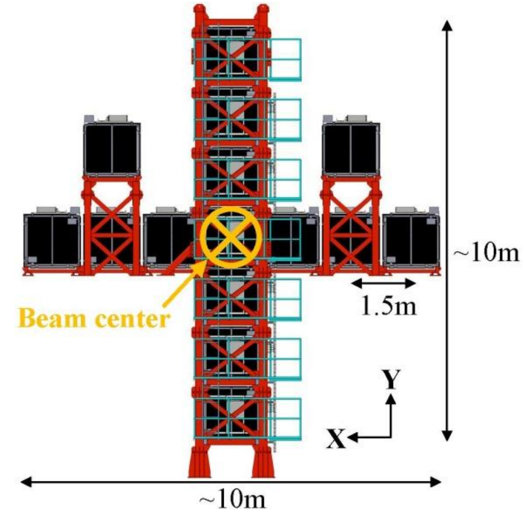

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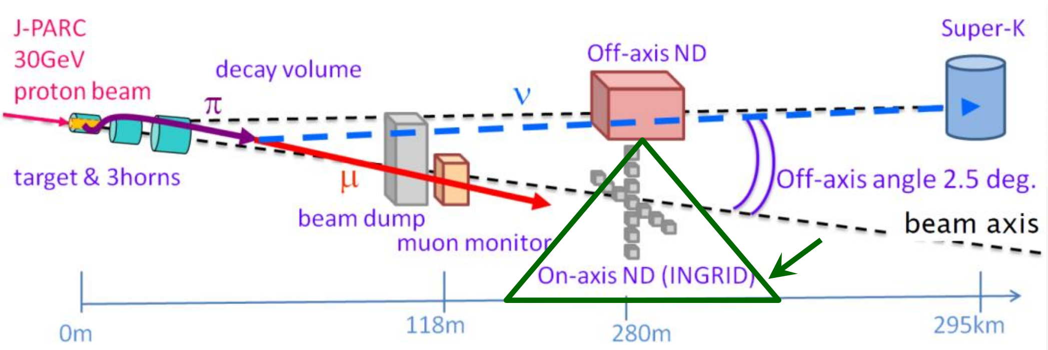
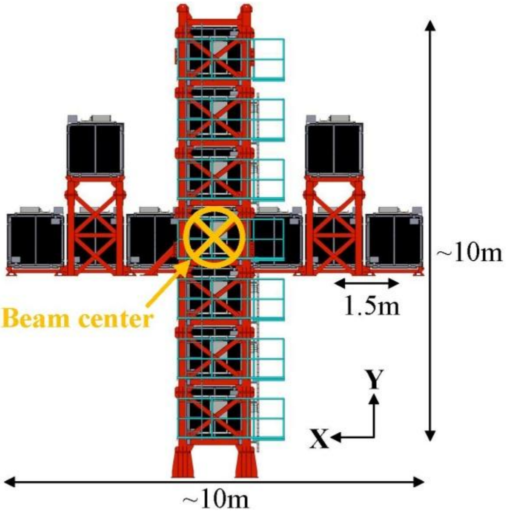


ν_μ CC Inclusive in E_ν range 1-3 GeV

- Motivation
  - Few ν cross-sections measurements on heavy nuclei in this low E_ν range



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ν_μ CC Inclusive in E_ν range 1-3 GeV

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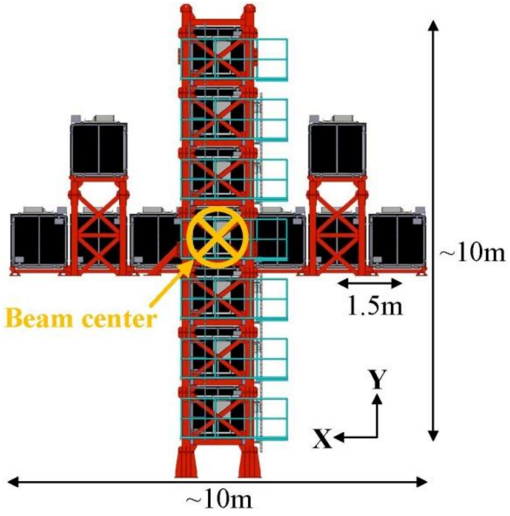
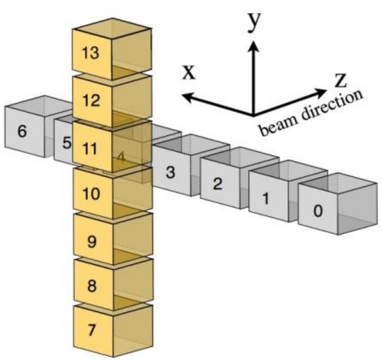
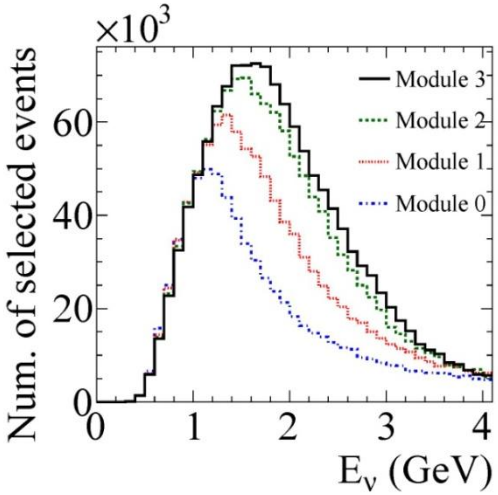
- Energy spectrum
  - "off-axis" angle/E_ν dependence [INGRID: $0^o \rightarrow 1.1^o$]
  - The idea: Group modules by position from center







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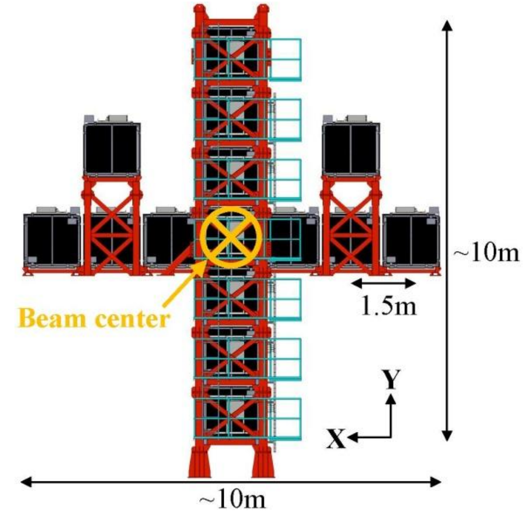
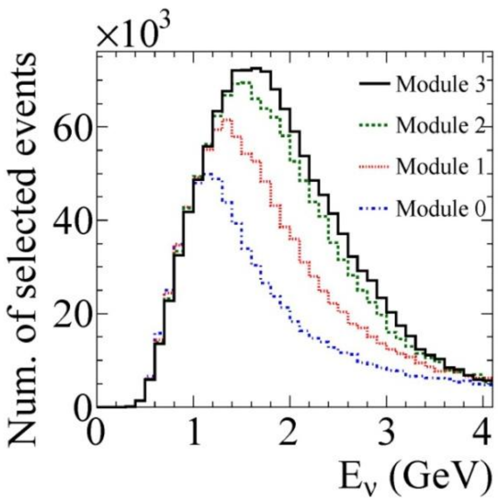
  - The idea: Group modules by position from center
- Neutrino flux
  - Flux prediction, for E_ν < 3 GeV: ~95% ν_μ



	Neutrino energy range [GeV]				
Flavor	0-1	1-2	2-3	3-4	> 4
ν_μ	94.2%	96.8%	95.4%	89.7%	86.5%
$\bar{\nu}_\mu$	4.8%	2.7%	3.8%	7.9%	9.3%
ν_e	0.9%	0.5%	0.7%	2.0%	3.5%
$\bar{\nu}_e$	0.1%	0.0%	0.1%	0.3%	0.6%



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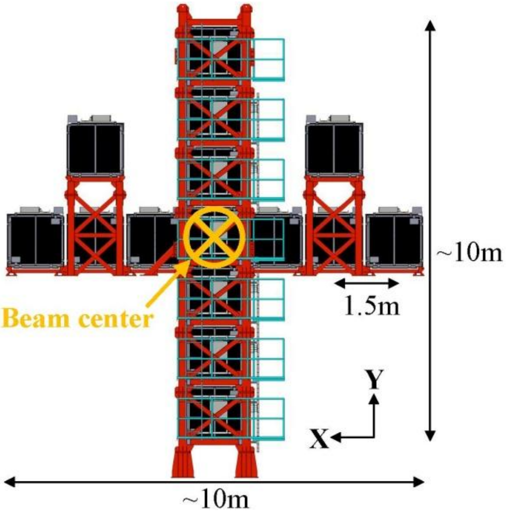
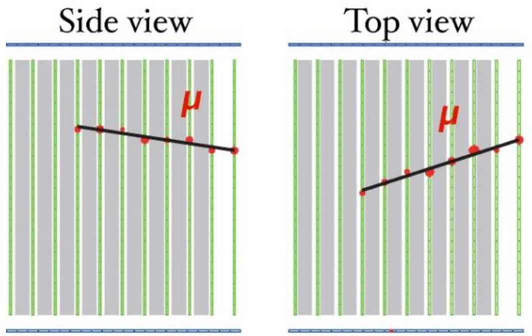
ν_μ CC Inclusive in E_ν range 1-3 GeV

- Event selection (for each module)
  - Identify all 3D tracks in an interaction
  - The tracks should be in-time with the beam bunches
  - μ^- candidate: The longest track in the bunch
  - Tag vertex position (most upstream hit or tracks originating position)
  - Vertex: Should start in the fiducial volume





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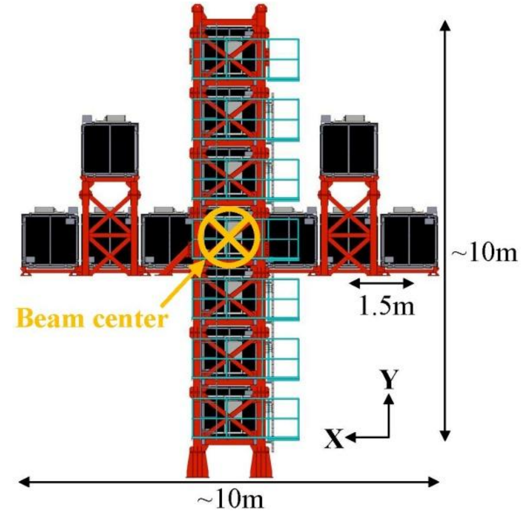
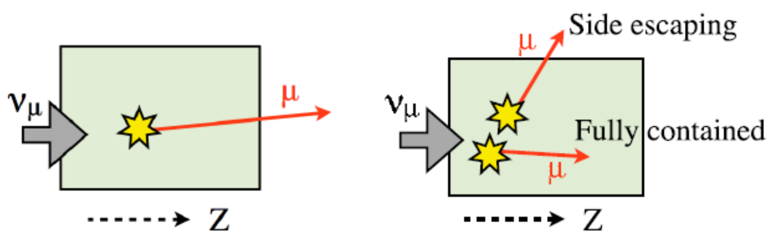
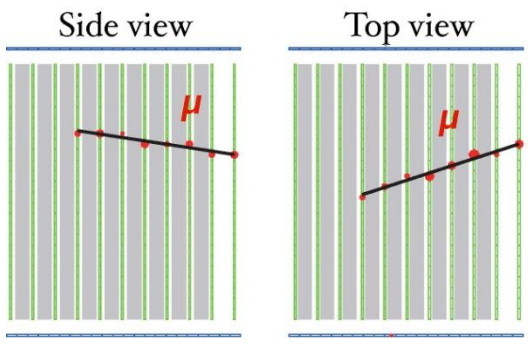
  - Vertex: Should start in the fiducial volume
- Event topology
  - Down Stream (DS)-escaping
  - non-DS-escaping







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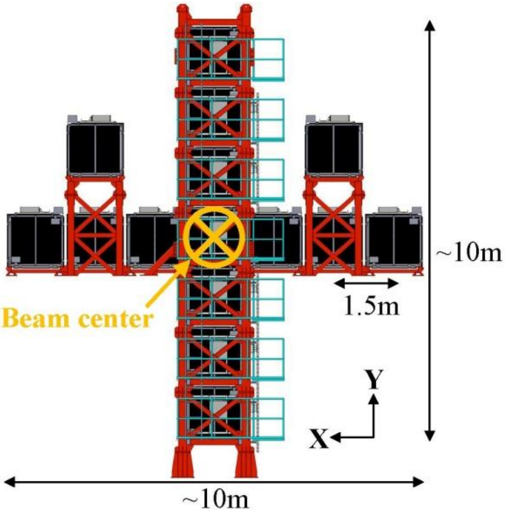
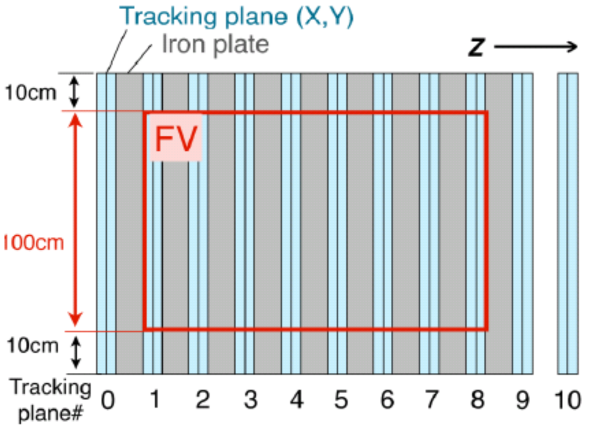
ν_μ CC Inclusive in E_ν range 1-3 GeV

- Measurement method
  - Least χ^2 fit to vertex Z position





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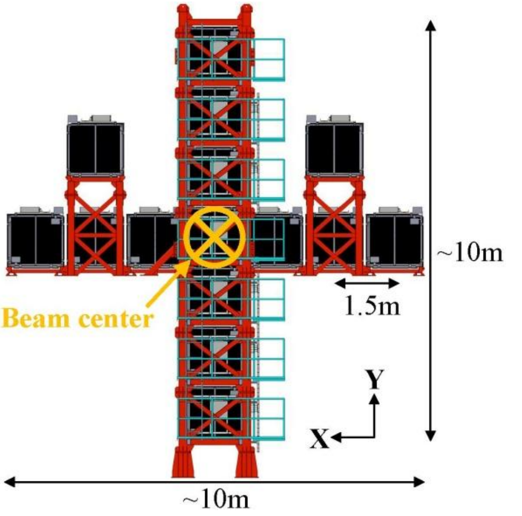
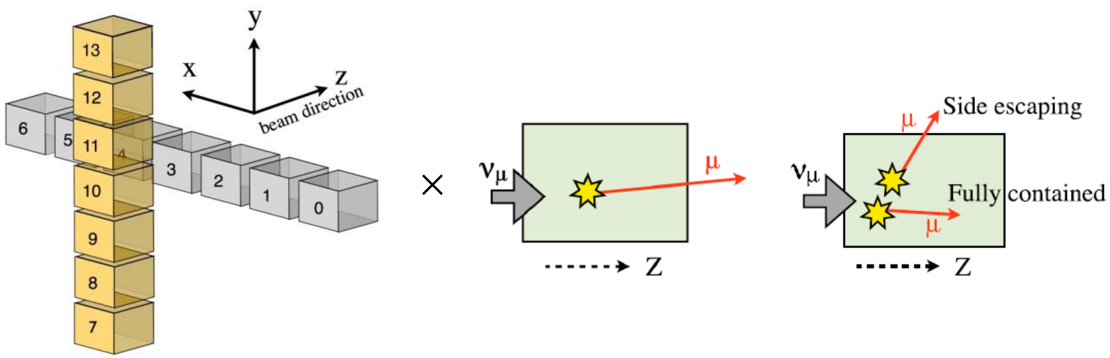
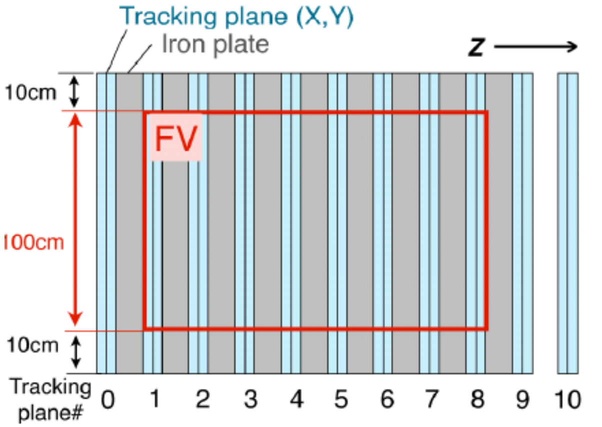
ν_μ CC Inclusive in E_ν range 1-3 GeV

- Measurement method
  - Least χ^2 fit to vertex Z position
  - Fit 14 PDFs
    (7 module groups × 2 topologies)







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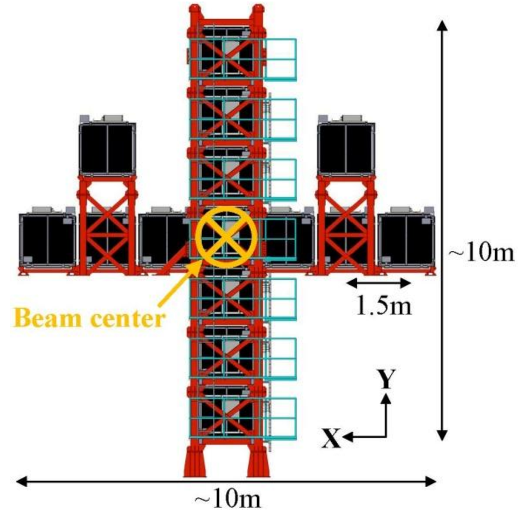
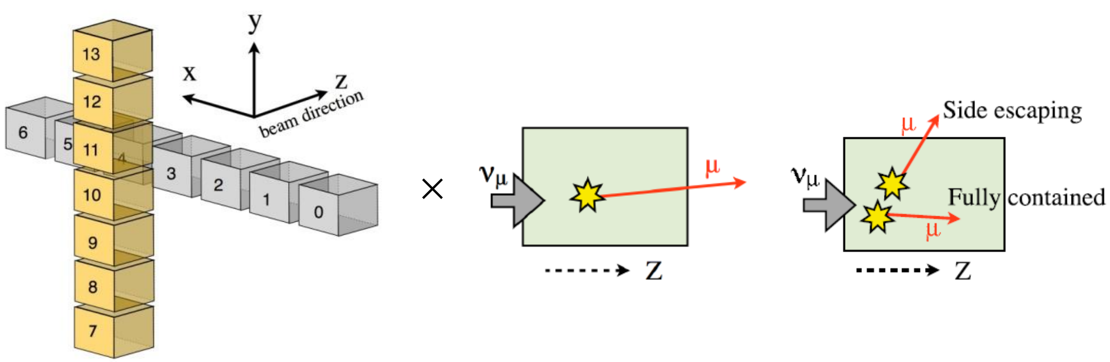
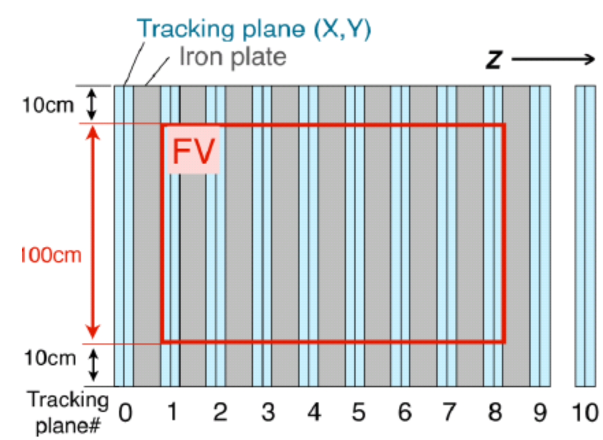
ν_μ CC Inclusive in E_ν range 1-3 GeV

- Measurement method
  - Least χ^2 fit to vertex Z position
  - Fit 14 PDFs
    (7 module groups × 2 topologies)
  - For 4 energy bins
    (0.5-0.8, 0.8-1.4, 1.4-2.6, 2.6-4.0 [GeV])



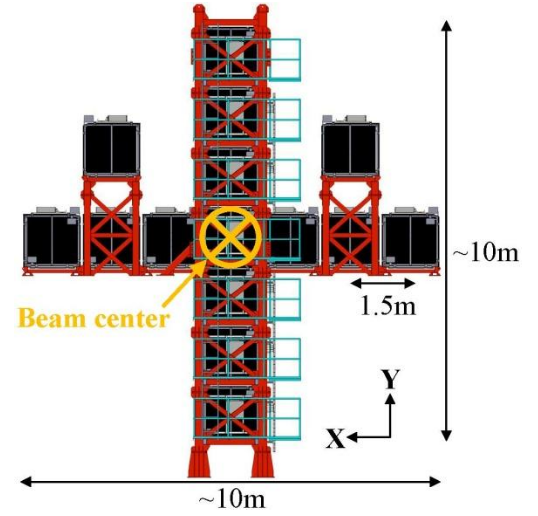


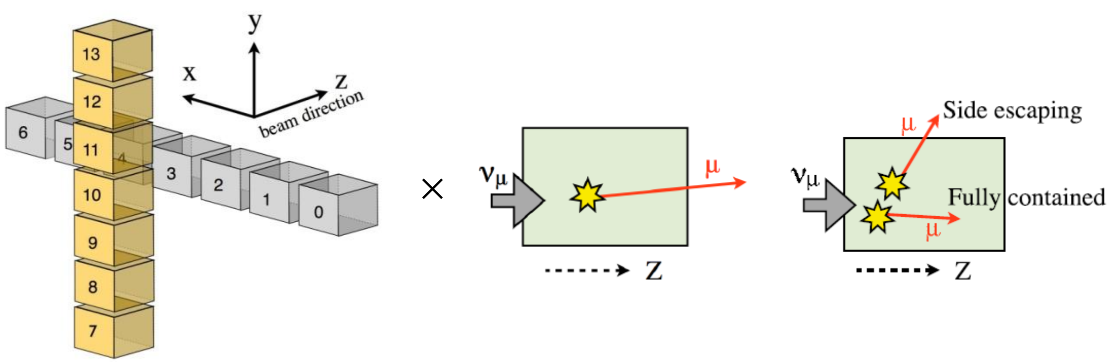


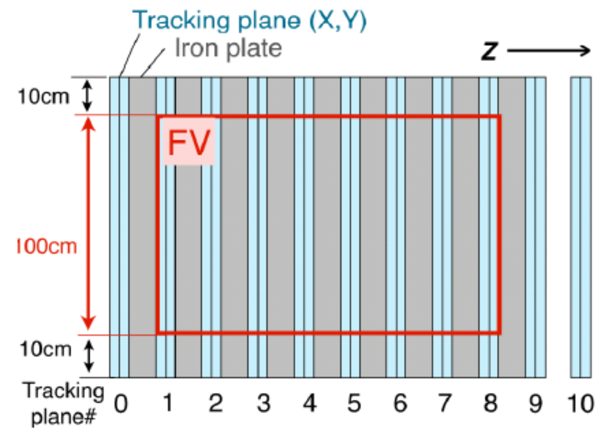
PRD 93 072002

ν_μ CC Inclusive in E_ν range 1-3 GeV

- Measurement method
  - Least χ^2 fit to vertex Z position
  - Fit 14 PDFs
    (7 module groups × 2 topologies)
  - For 4 energy bins
    (0.5-0.8, 0.8-1.4, 1.4-2.6, 2.6-4.0 [GeV])
  - The fit includes uncertainties on:
    beam flux, physics models, detector response
    and pion Final State Interaction (FSI)/Secondary Interaction (SI)



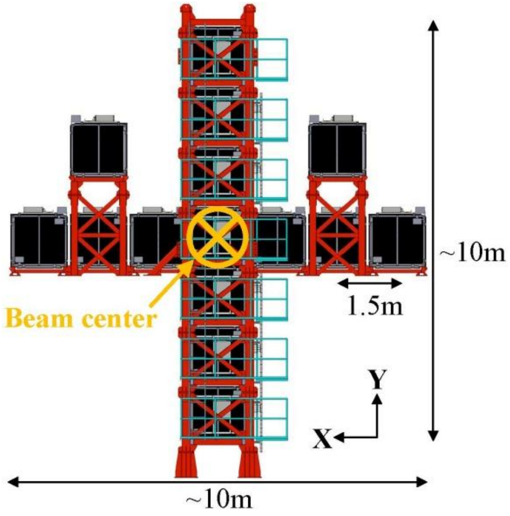




PRD 93 072002

ν_μ CC Inclusive in E_ν range 1-3 GeV

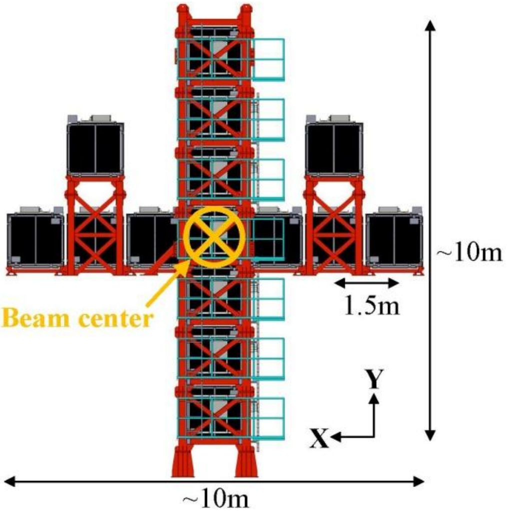
- Results
  - Required continuous at the 4 energy bins edges (linear interpolation)



PRD 93 072002

ν_μ CC Inclusive in E_ν range 1-3 GeV

- Results
  - Required continuous at the 4 energy bins edges (linear interpolation)
  - Final 3 E_ν measurements (averaging on neighboring bins)

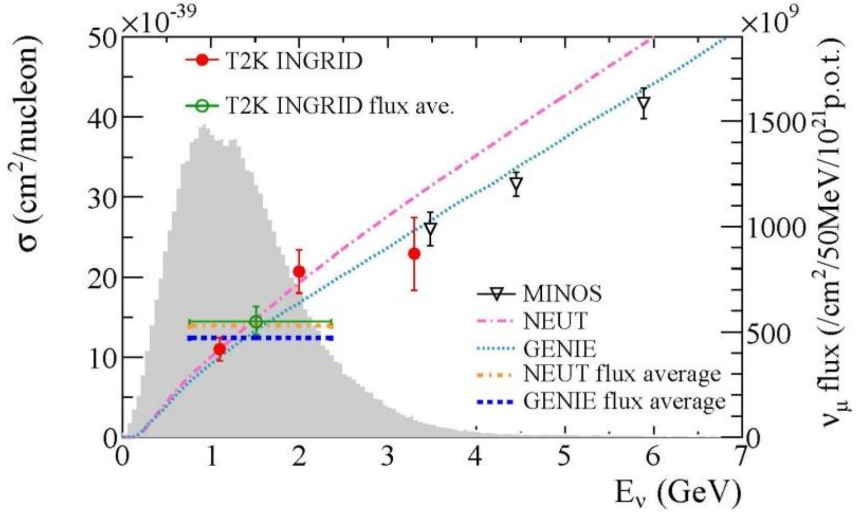


$$\sigma^{CC}(1.1\,\mathrm{GeV}) = (1.10 \pm 0.15)\times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}$$

$$\sigma^{CC}(2.0\,\mathrm{GeV}) = (2.07 \pm 0.27)\times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}$$

$$\sigma^{CC}(3.3\,\mathrm{GeV}) = (2.29 \pm 0.45)\times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}$$

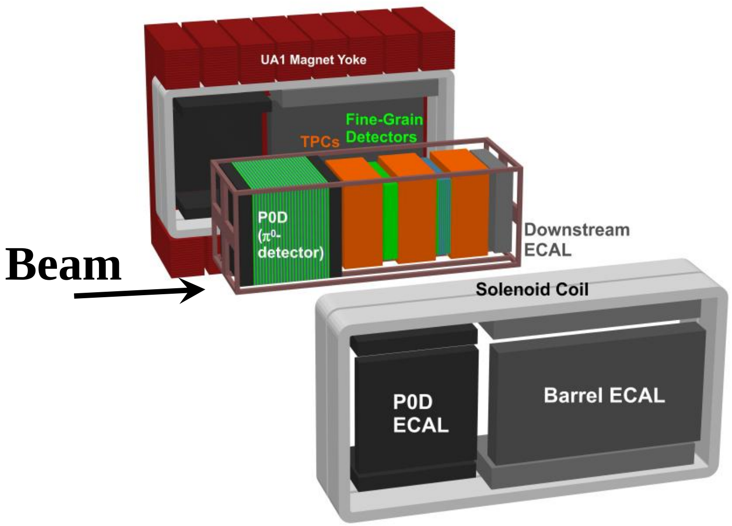
  - Dominant systematics uncertainties Flux (8%-9%), FSI/SI (6%-7%), Detector (~4%)



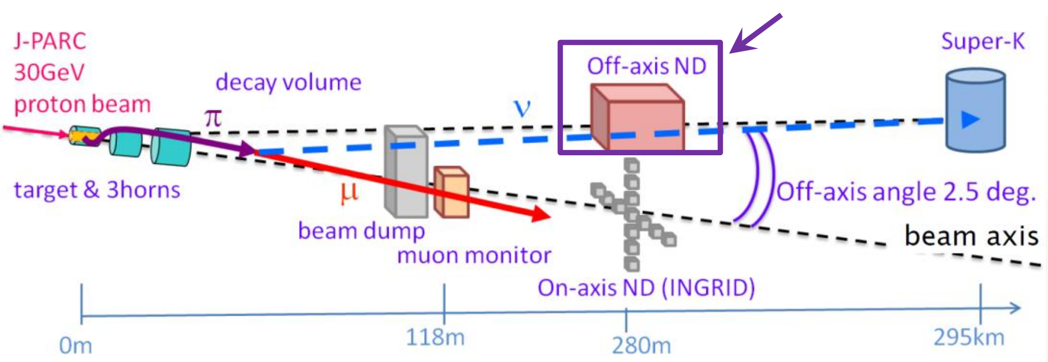
PRD 93 072002

T2K Cross-Section Results

- On-axis near detector
  - ν_μ CC inclusive in E_ν range 1-3 GeV
- Off-axis near detector
  - ν_μ CC $1\pi^+$ (exclusive) on CH
- Far detector
  - ν_μ NCE (exclusive) on O

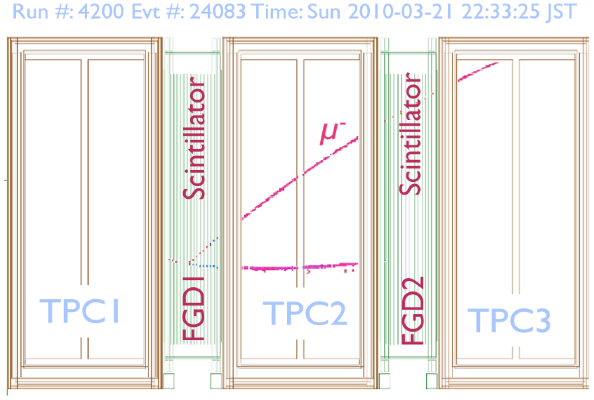


- Anti-ν_μ: Off-axis near detector
  - Anti-ν_μ CC inclusive on CH and O



ν_μ CC $1\pi^+$ on CH

- Motivation
  - One of the main processes in the intermediate energy range (<4 GeV) with large uncertainties
  - The dominant background uncertainties for oscillation analyses (T2K and others...)



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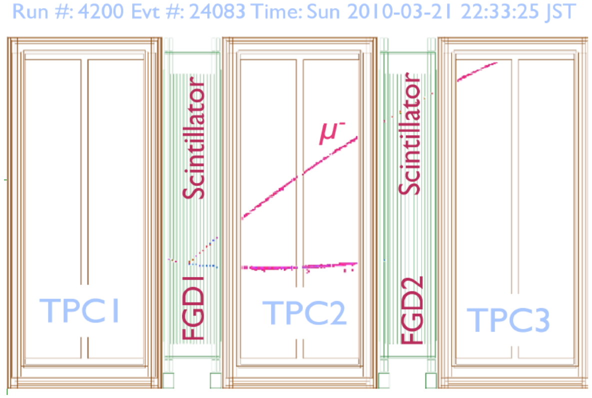
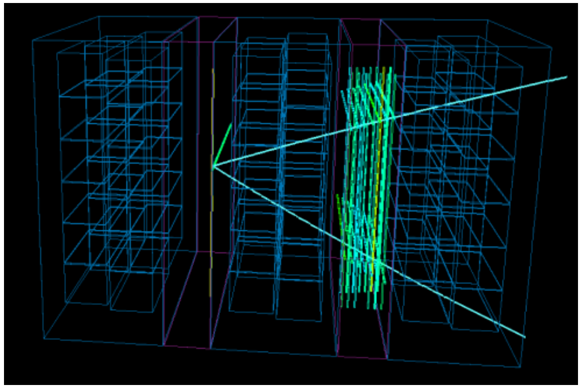
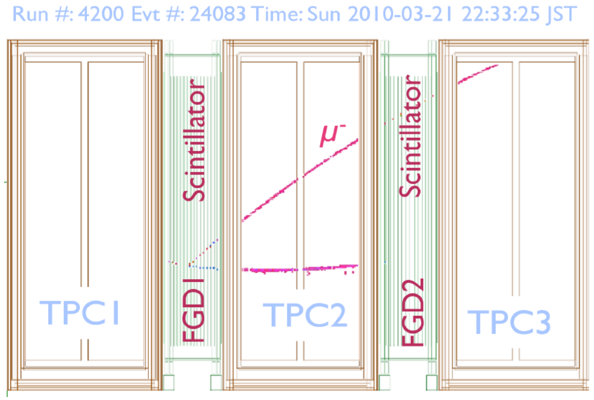


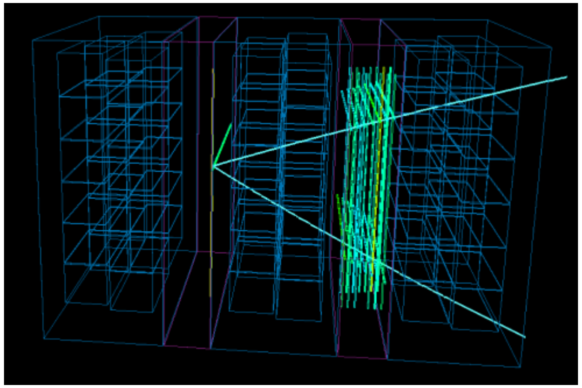
- Motivation
  - One of the main processes in the intermediate energy range (<4 GeV) with large uncertainties
  - The dominant background uncertainties for oscillation analyses (T2K and others...)
- Analysis strategy
  - Measure both outgoing μ and π from the interaction
  - Calculate differential cross sections from the particles kinematics



ν_μ CC $1\pi^+$ on CH

- Event selection
  - Tag the μ^- candidate in the interaction
  - μ^- candidate: in time with beam bunches and in fiducial volume





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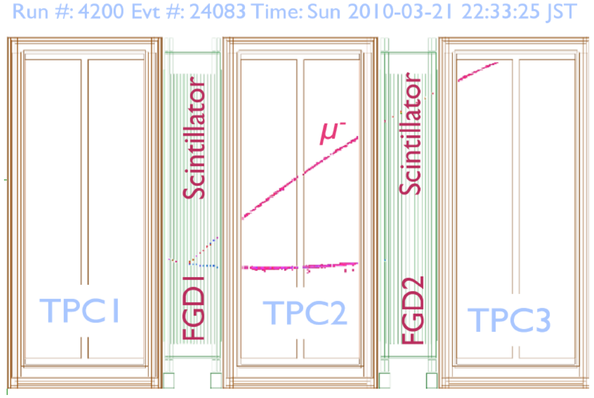
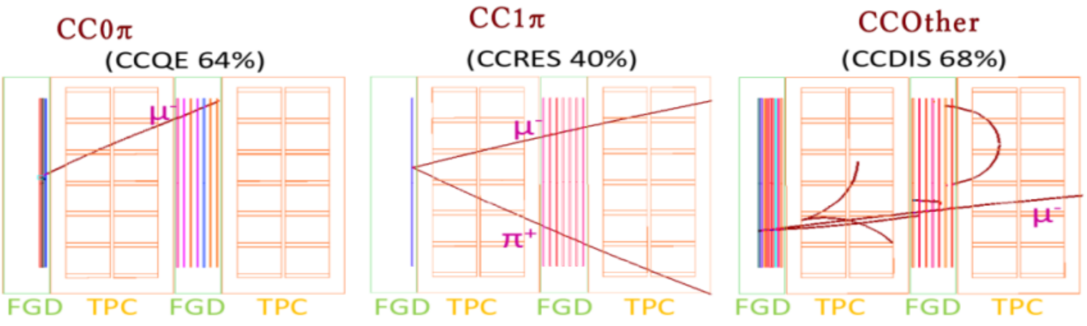
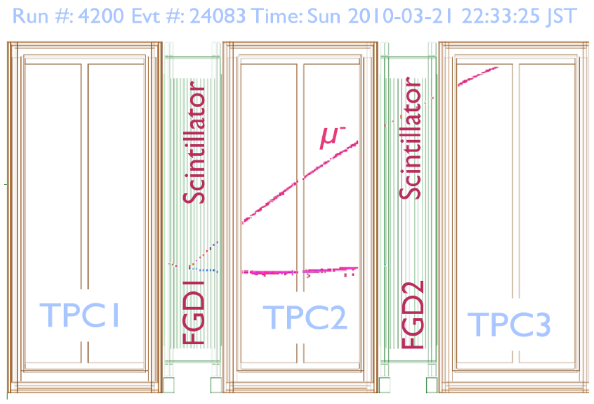
  - Scan the secondary tracks and sort into 3 topologies

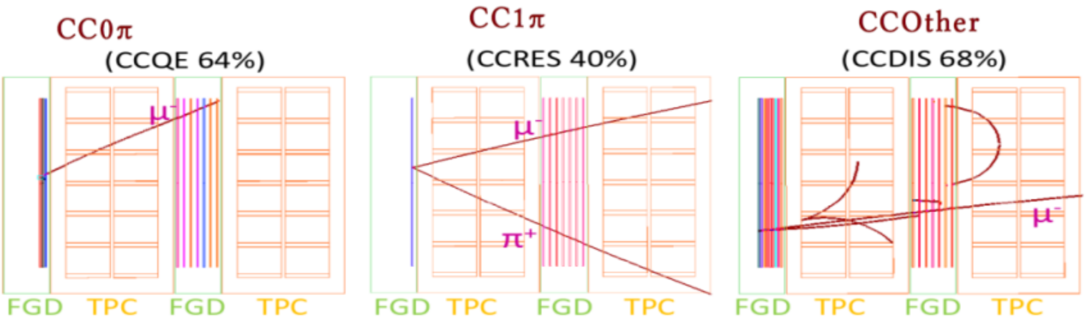


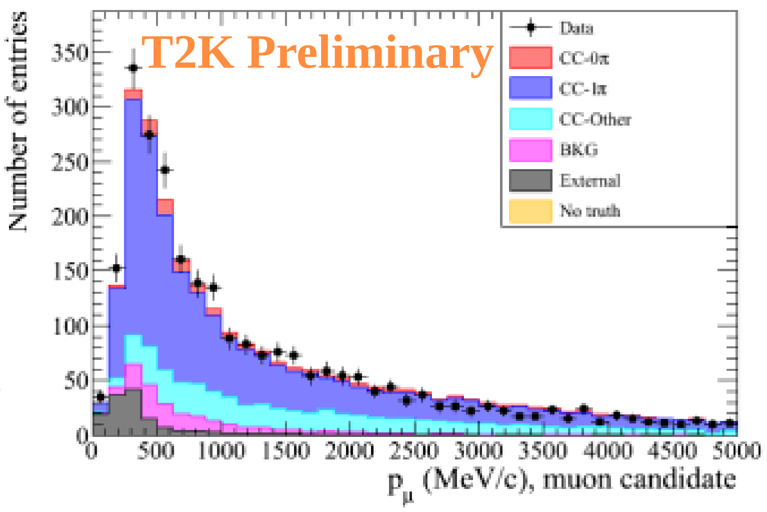


ν_μ CC $1\pi^+$ on CH

- Event selection
  - Tag the μ^- candidate in the interaction
  - μ^- candidate: in time with beam bunches and in fiducial volume
  - Scan the secondary tracks and sort into 3 topologies
  - Improve identify the π candidate (with TPC and FGD PIDs)
  - Select only the interactions with 1 π candidate







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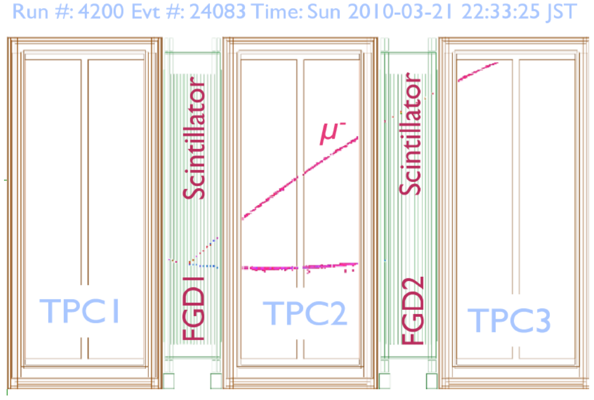
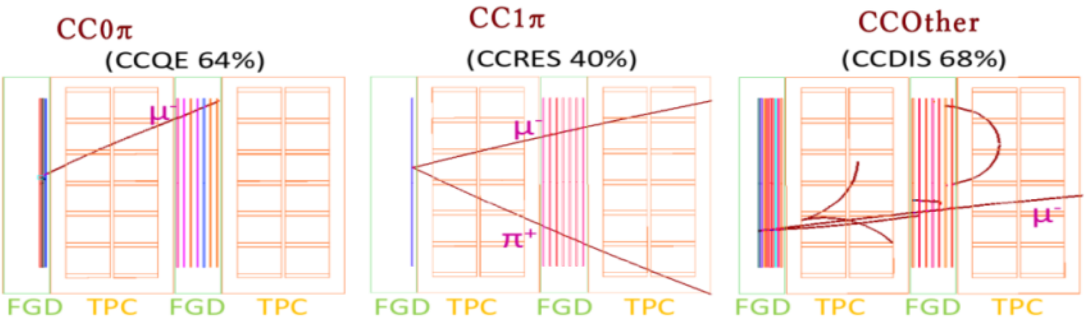
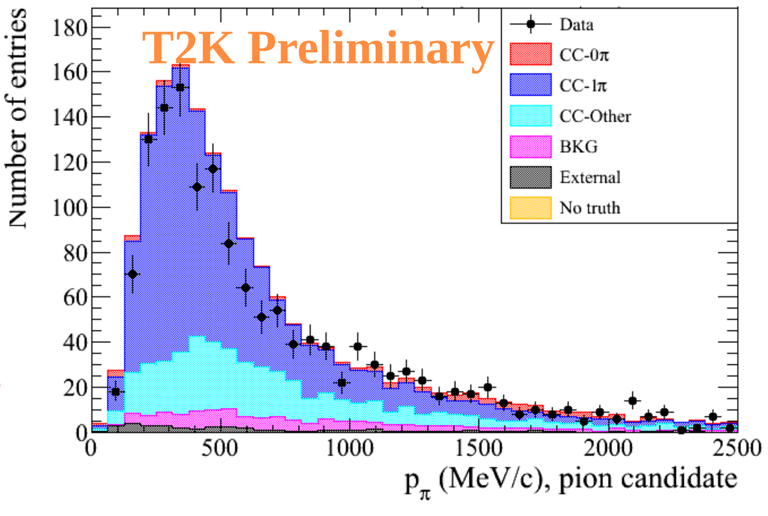
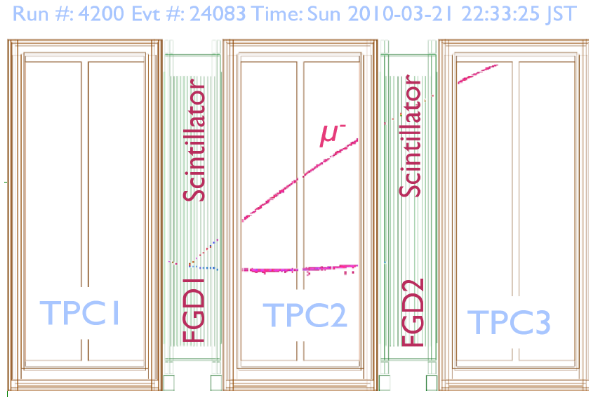




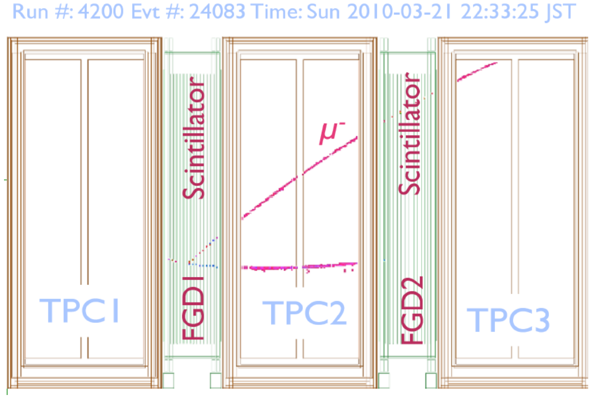


ν_μ CC 1π^+ on CH



- Measurement method
  - Utilize iterative Bayesian unfolding technique

ν_μ CC $1\pi^+$ on CH



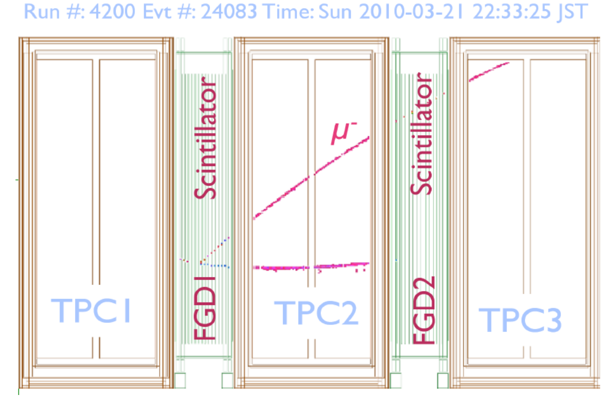
- Measurement method
  - Utilize iterative Bayesian unfolding technique
  - Flux integrated, extract from

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

X = observable,
ΔX = bin width,
N_k = estimated # of true events,
ε_k = efficiency,
ϕ = integrated ν_μ flux,
T = # target nucleons

  - Observables:
    p_μ, $\cos\theta_\mu$, p_π, θ_π, $\theta_{\mu\pi}$, E_ν , Q^2, $|q_3|$, W

ν_μ CC $1\pi^+$ on CH



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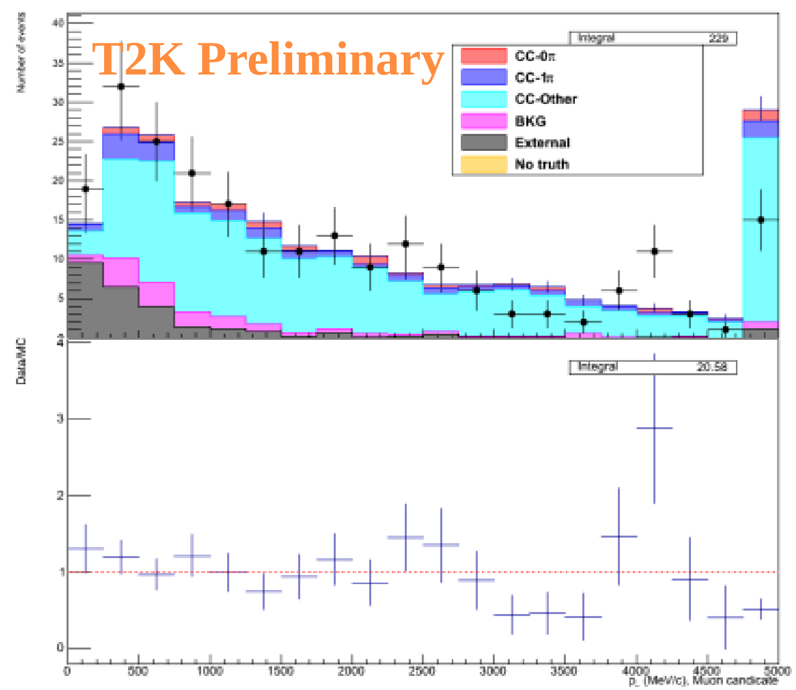
  - Included 2 side-bands to constrain different backgrounds



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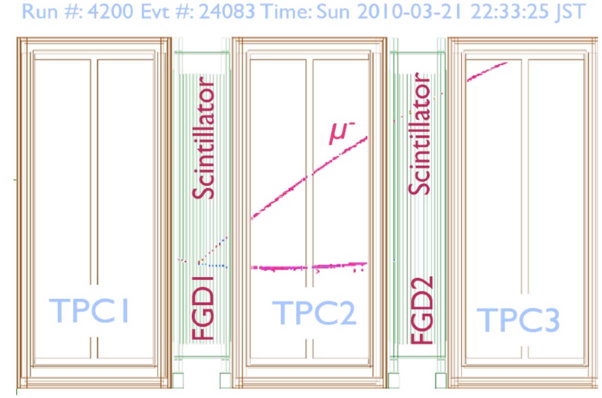

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  - Observables: p_μ, $\cos\theta_\mu$, p_π, θ_π, $\theta_{\mu\pi}$, E_ν , Q^2, $|q_3|$, W
  - Included 2 side-bands to constrain different backgrounds
  - Sources of systematics uncertainties: beam flux, physics models, detector response and pion FSI/SI

Source	with side-bands	without side-bands
XSection parameters	8.07%	9.4%
FSI	1.6%	1.75%
Flux	15.9%	18.14%
B-Field	0.11%	0.093%
Charge confusion	6.24%	6.99%
FGD mass	0.73%	1.02%
FGD PID	0.07%	*negl.*
Michel syst.	0.33%	0.356%
Momentum resolution	0.62%	0.33%
Momentum scale	0.38%	0.38%
OOFV	4.6%	5.17%
Pile-up	0.16%	0.219%
ECal efficiency	0.24%	0.48%
SI Pion	5.04%	5.28%
TPC cluster efficiency	0.0002%	0.001%
TPC-FGD matching efficiency	0.07%	0.096%
TPC PID	0.2%	0.28%
TPC tracker efficiency	*negl.*%	*negl.*

ν_μ CC $1\pi^+$ on CH

- Results
  - Restricted phase-space
    $\theta_\mu, \theta_\pi < 78^0$; $p_\mu, p_\pi > 200$ MeV

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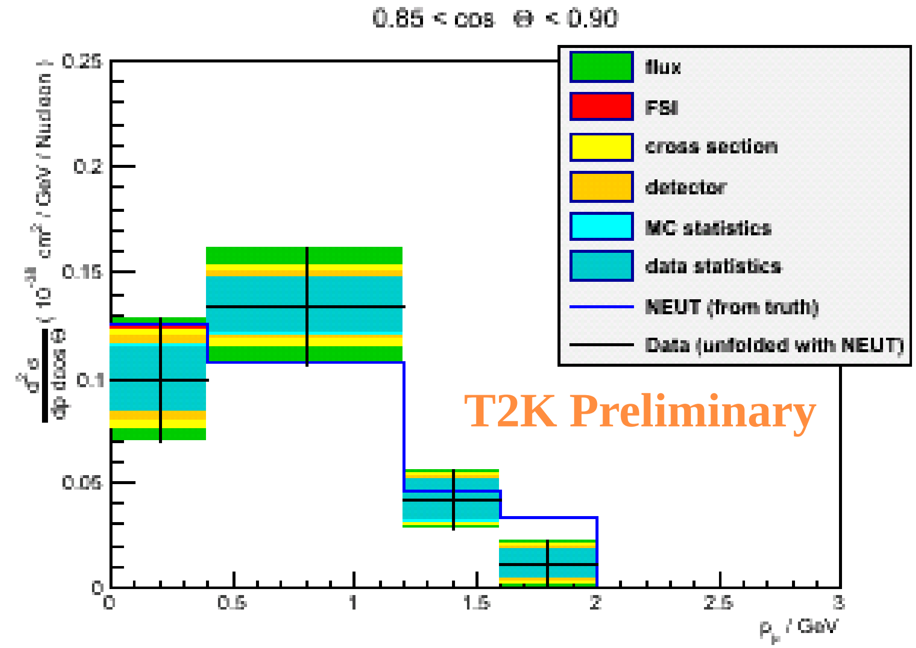
  - $d^2\sigma/dp_\mu d\cos\theta_\mu$



Note: NEUT = ν MC generators

ν_μ CC $1\pi^+$ on CH

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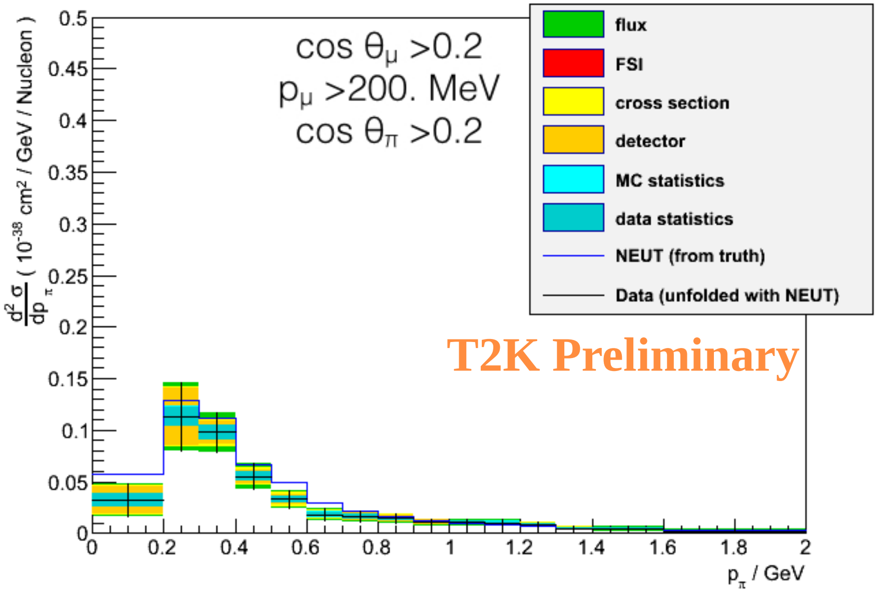
  - Restricted phase-space
    θ_μ, $\theta_\pi < 78^0$; p_μ, $p_\pi > 200$ MeV
  - $d^2\sigma/dp_\mu dcos\theta_\mu$
  - $d\sigma/dp_\pi$



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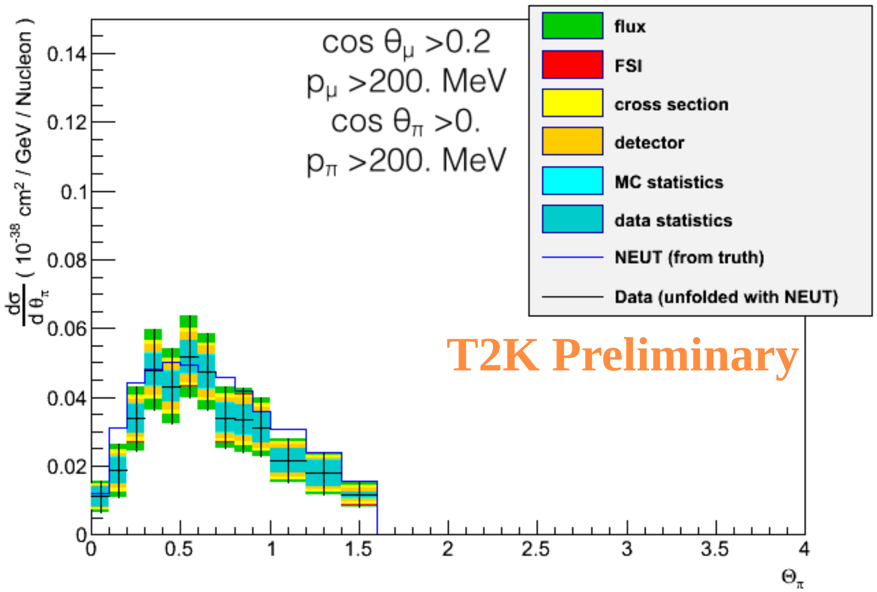

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  - Restricted phase-space
    θ_μ, $\theta_\pi < 78^0$; p_μ, $p_\pi > 200$ MeV
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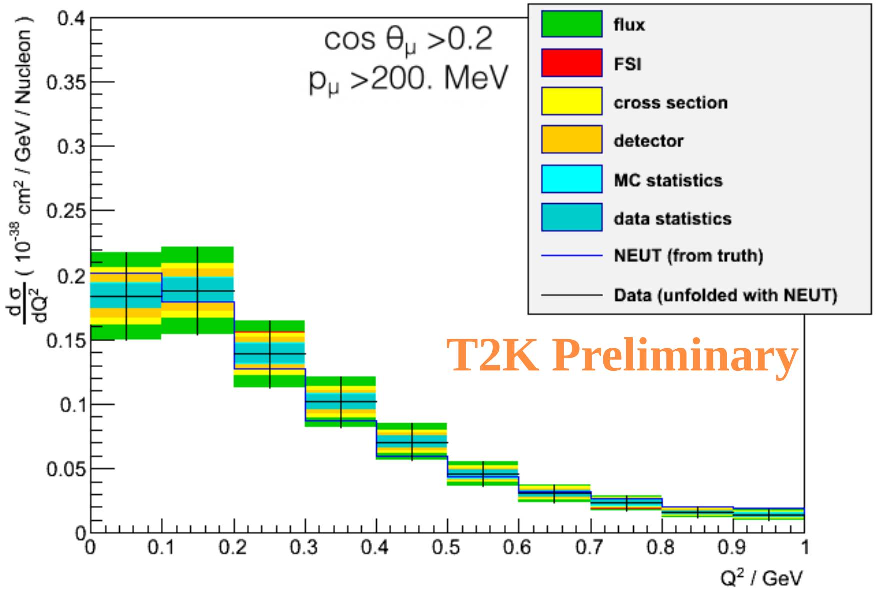
  - $d\sigma/dp_\pi$
  - $d\sigma/d\theta_\pi$
  - $d\sigma/dQ^2$



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ν_μ CC $1\pi^+$ on CH

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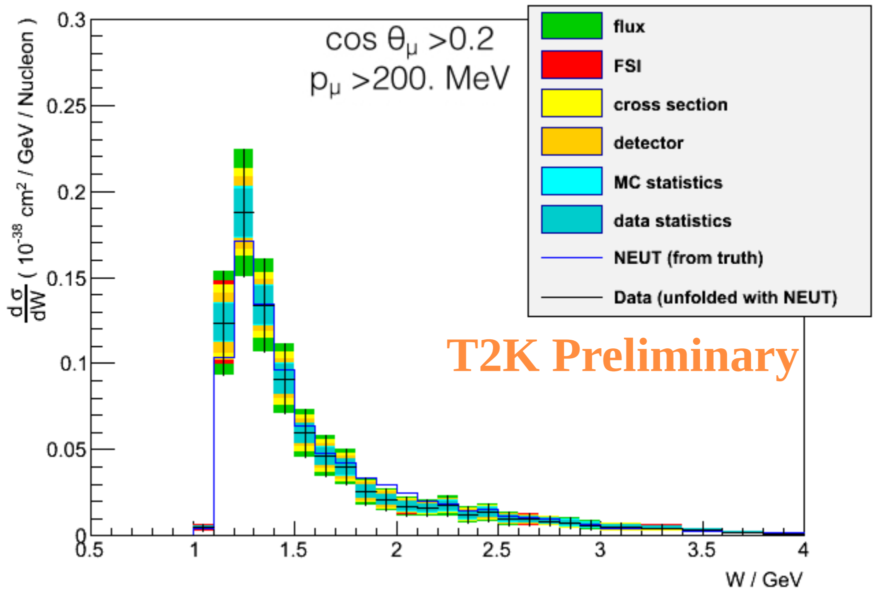
  - Restricted phase-space
    θ_μ, $\theta_\pi < 78^0$; p_μ, $p_\pi > 200$ MeV
  - $d^2\sigma/dp_\mu d\cos\theta_\mu$
  - $d\sigma/dp_\pi$
  - $d\sigma/d\theta_\pi$
  - $d\sigma/dQ^2$
  - $d\sigma/dW$

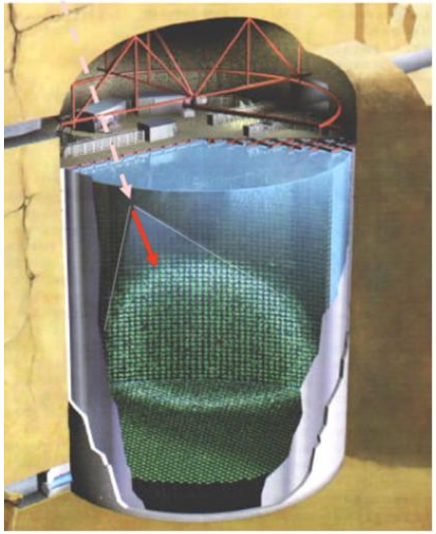


  - Dominant systematic uncertainties:
    Flux (~15%), Detector (~6%) , FSI/SI (~5%)

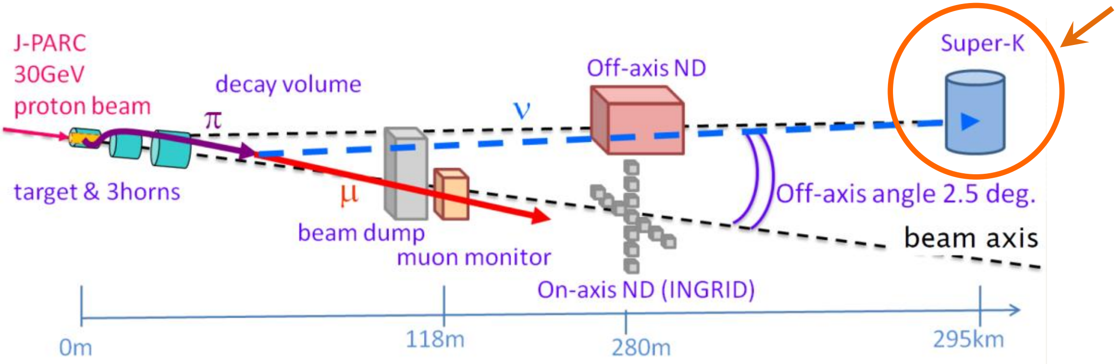
Note: NEUT = ν MC generators

T2K Cross-Section Results

- On-axis near detector
  - ν_μ CC inclusive in E_ν range 1-3 GeV
- Off-axis near detector
  - ν_μ CC $1\pi^+$ (exclusive) on CH
- Far detector
  - ν_μ NCQE (exclusive) on O

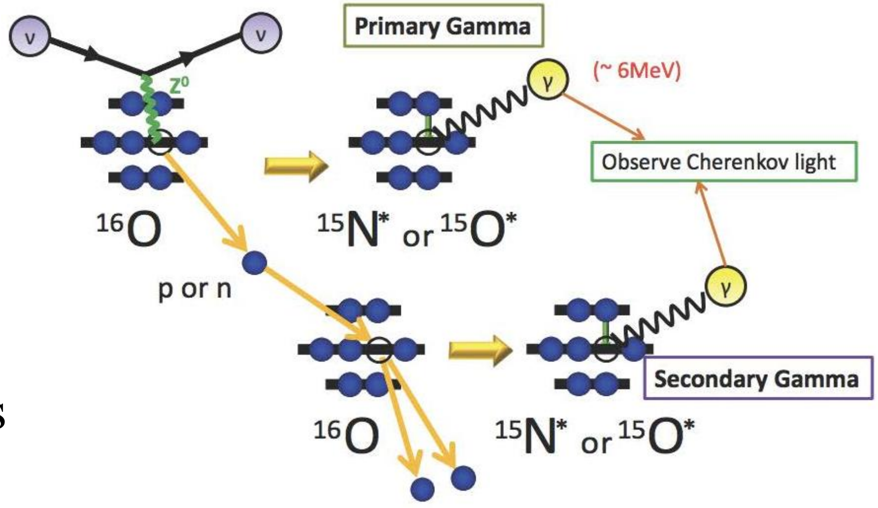


- Anti-ν_μ: Off-axis near detector
  - Anti-ν_μ CC inclusive on CH and O



SK: ν_μ NCQE Cross section on O

- Motivation
  - 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 NCQE interactions on oxygen



PRD 90 072012

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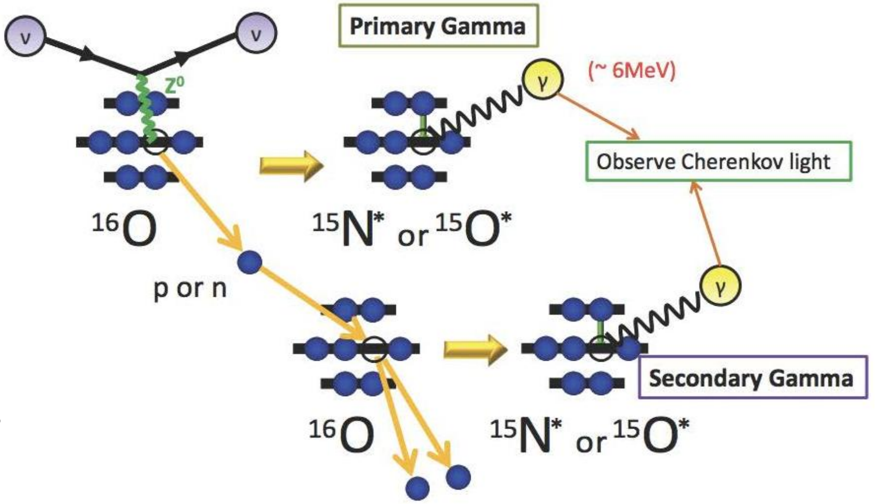
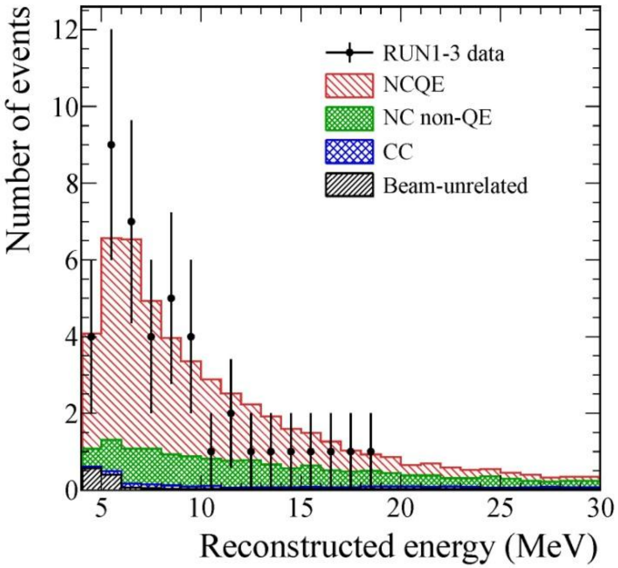
  - Direct impact on the atmospheric background for low-energy phenomena in neutrino experiments
- Topology
  - We look for de-excitation γs in SK's lowest-energy sample (4-30 MeV)
  - To be able to isolate γs from NCQE interactions on oxygen
- Event selection:
  - Tight timing cut (around beam bunch time)
  - 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 072012

SK: ν_μ NCQE Cross section on O

- Measurement method
  - Cross section extracted from

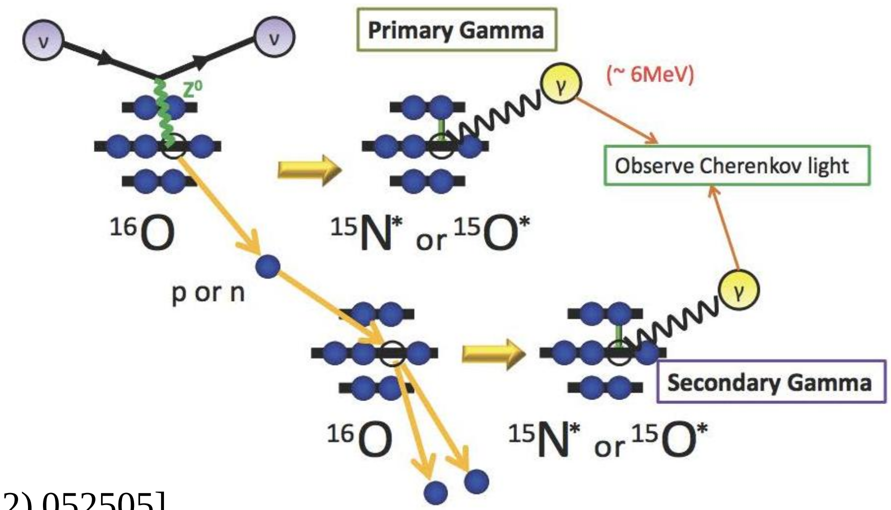
$$\langle \sigma_{NCQE}^{obs} \rangle = \frac{N^{obs} - N_{BG}^{exp}}{N^{exp} - N_{BG}^{exp}} \langle \sigma_{NCQE}^{theory} \rangle$$

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 072012

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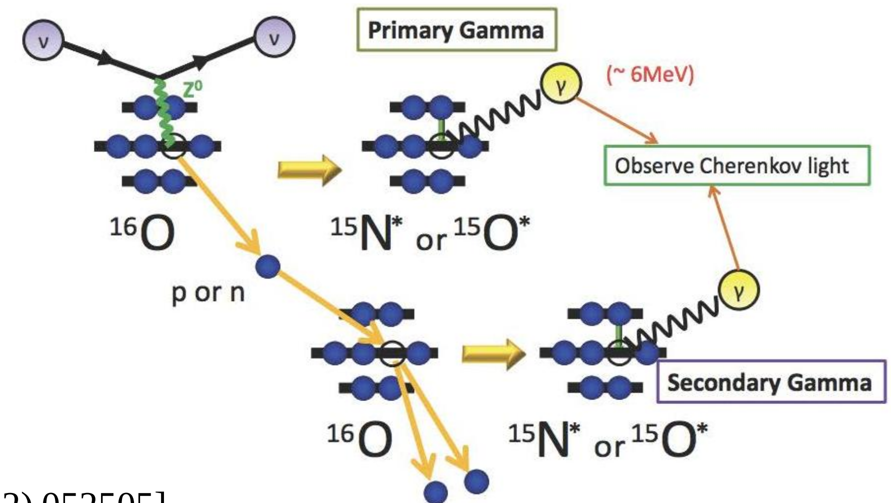
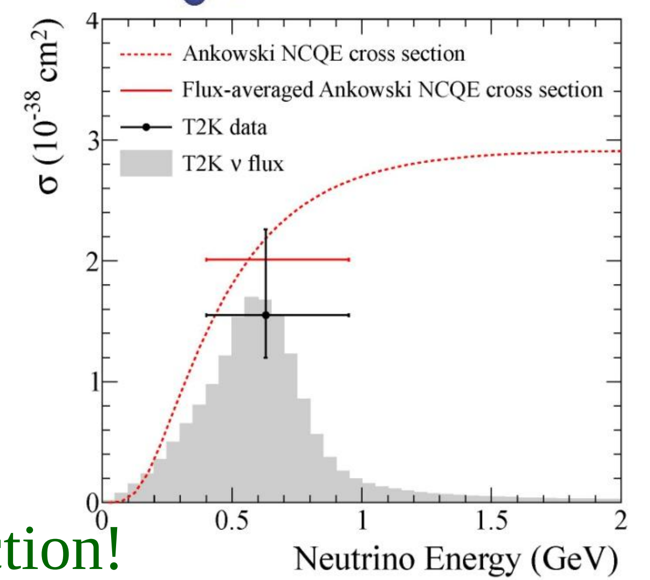


- Results
  - Flux-averaged ν-Oxygen NCQE

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

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



- First measured ν-Oxygen NCQE cross section!

PRD 90 072012

T2K Cross-Section Results

- On-axis near detector
  - ν_μ CC inclusive in E_ν range 1-3 GeV
- Off-axis near detector
  - ν_μ CC $1\pi^+$ (exclusive) on CH
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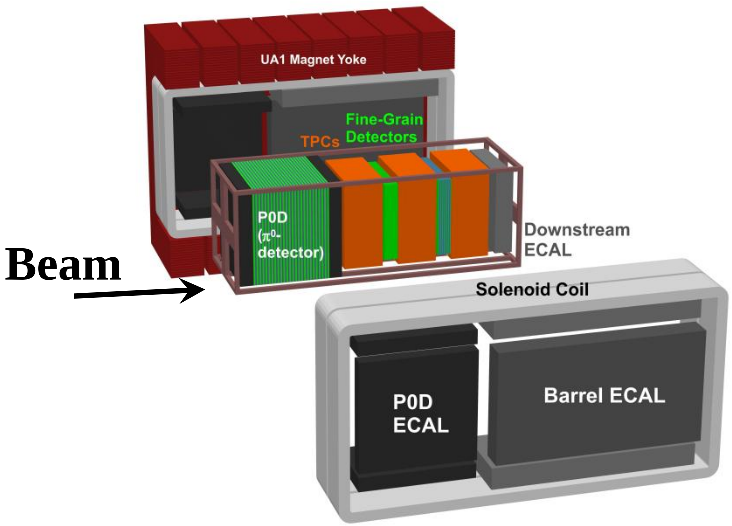
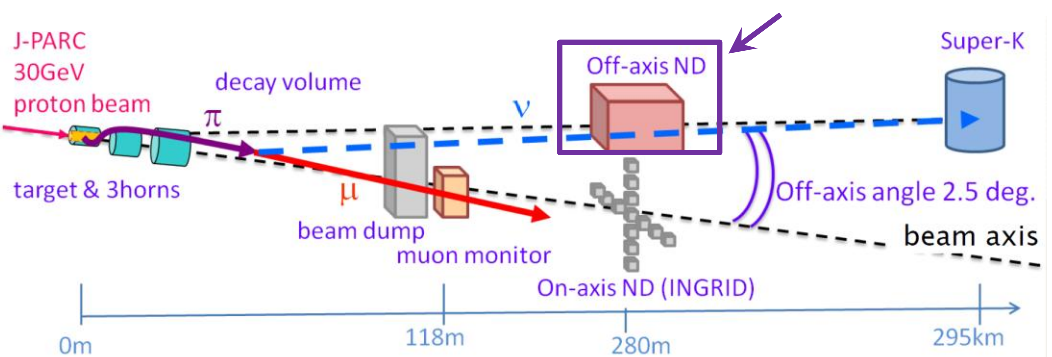
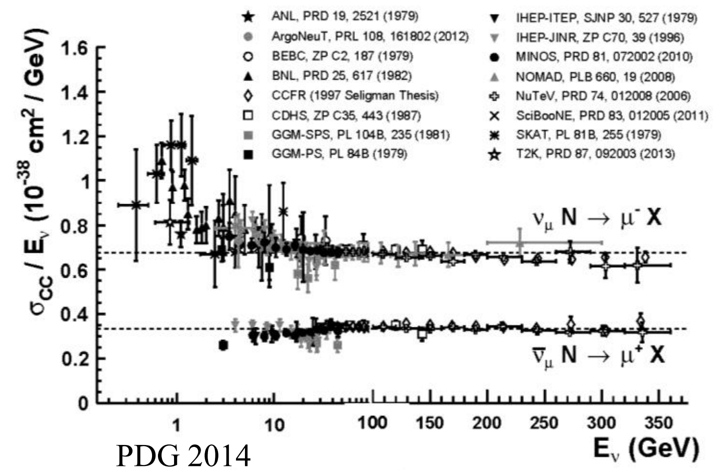


- Anti-ν_μ: Off-axis near detector
  - Anti-ν_μ CC inclusive on CH and O



Anti-ν_μ CC inclusive on CH and O

- Motivation
  - Very few anti-ν measurements in the intermediate energy range (<4 GeV)
  - Important input to anti-ν oscillation analyses and CP measurements



PDG 2014

Anti-ν_μ CC inclusive on CH and O

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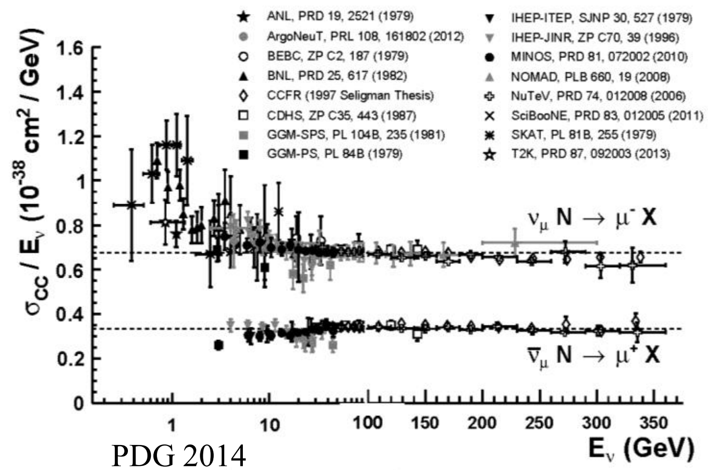
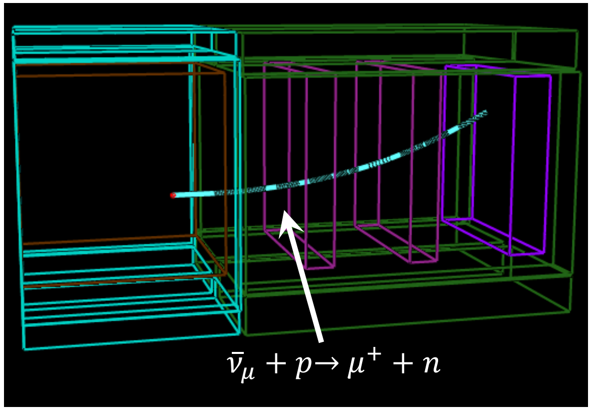


PDG 2014



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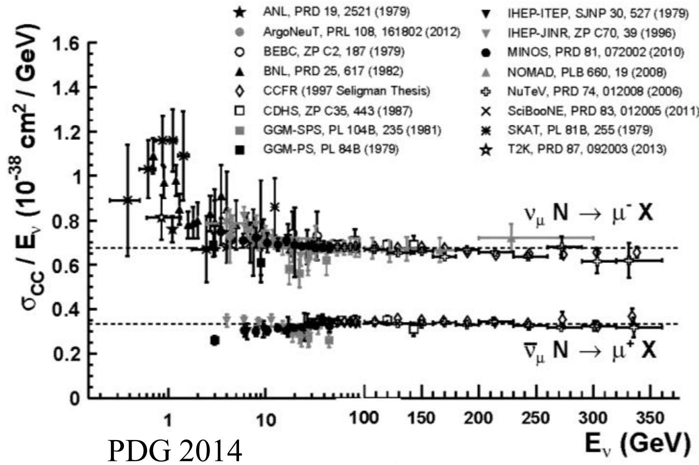

PDG 2014

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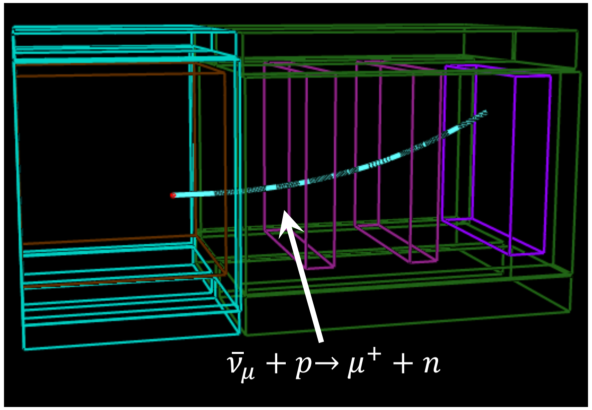

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  - Tag the μ^+ candidate in the interaction
  - μ^+ candidate: in time with beam bunches and in fiducial volume

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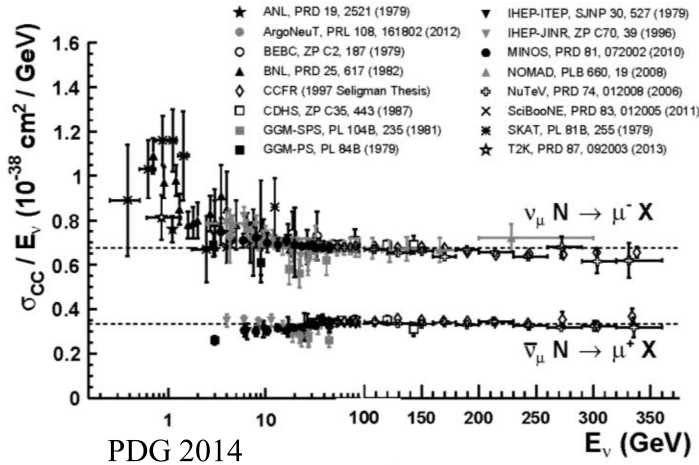
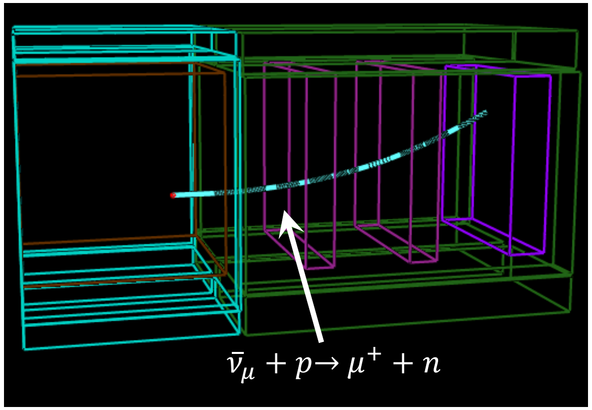


PDG 2014



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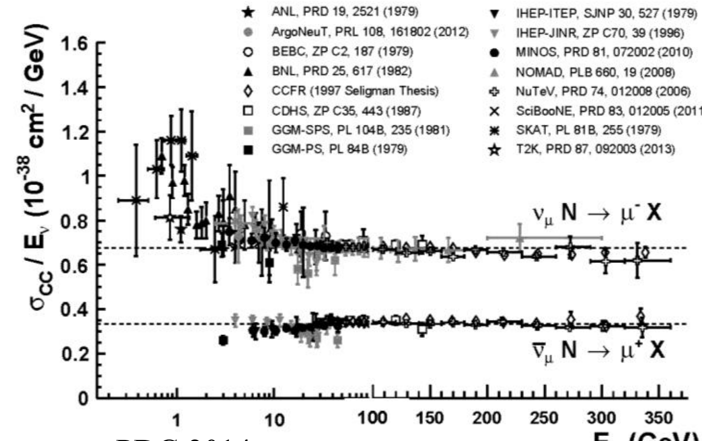
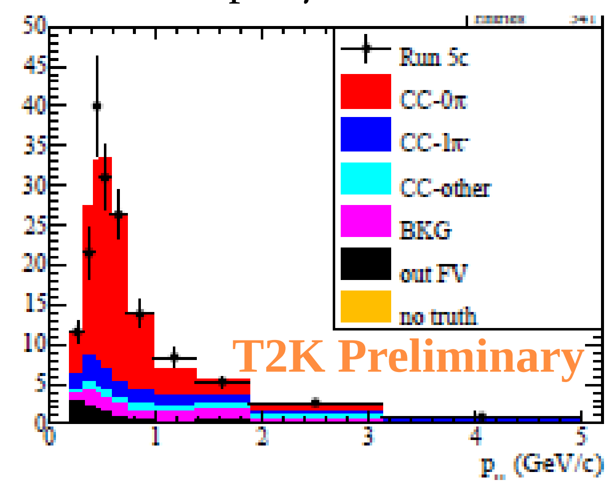


PDG 2014

$\bar{\nu}$ sample: μ^+ candidate



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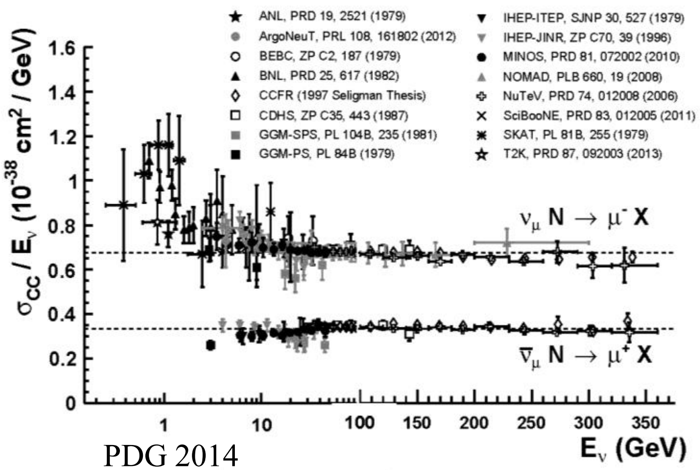

PDG 2014

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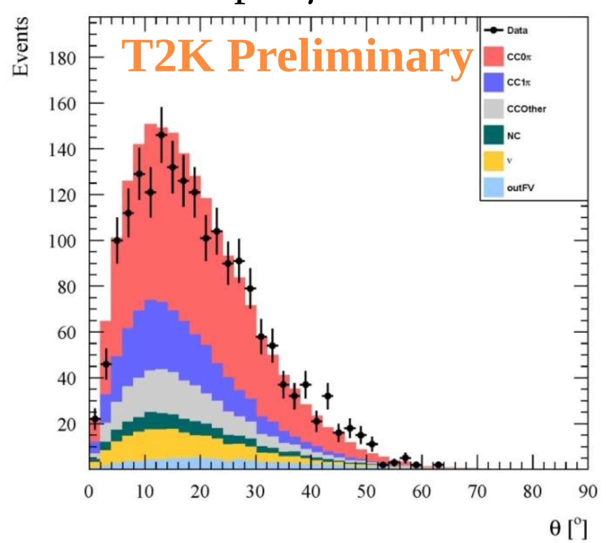

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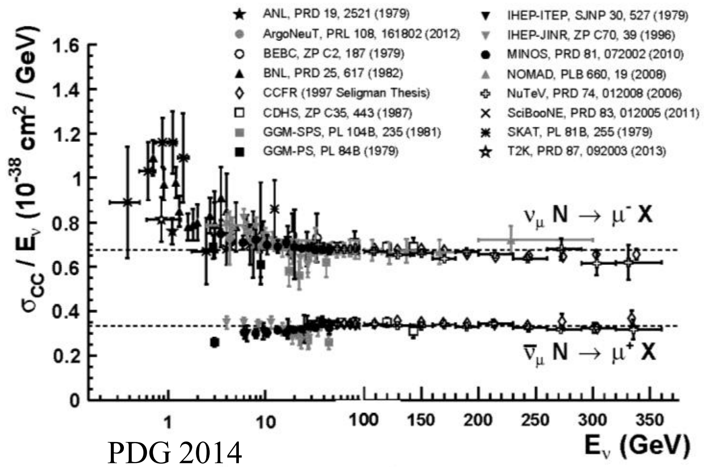
Anti-ν_μ CC inclusive on CH and O

- Measurement method



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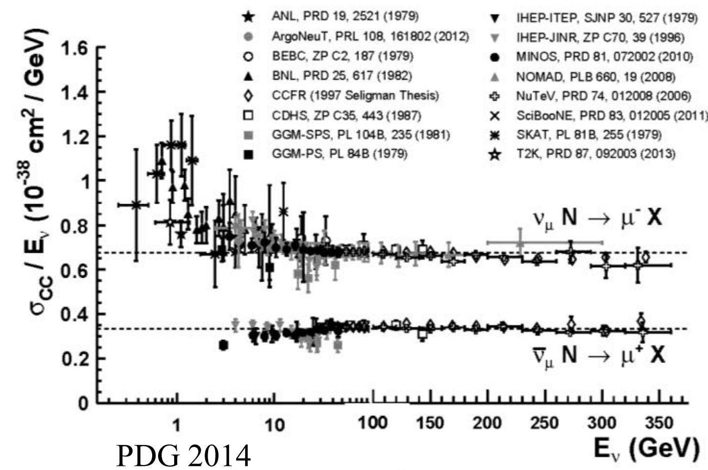
Anti-ν_μ CC inclusive on CH and O

- Measurement method
  - Cross section extracted from

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

X = observable,
ΔX = bin width,
N_k = estimated # of true events,
ε_k = efficiency,
ϕ = integrated flux,
T = # target nucleons

  - N_k via
    - Analysis 1: unfolding
    - Analysis 2: background subtraction



PDG 2014

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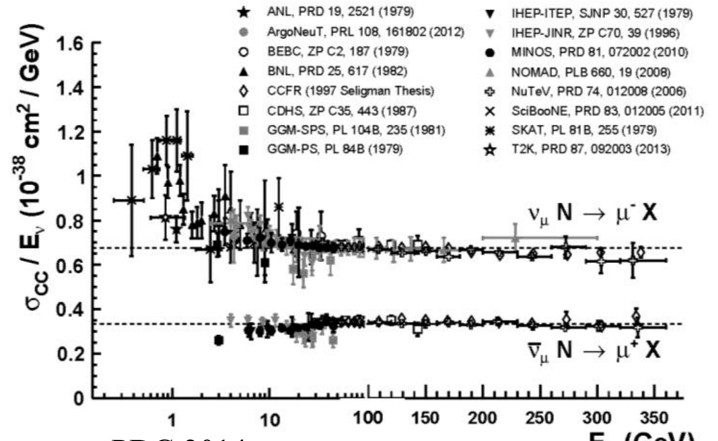

PDG 2014

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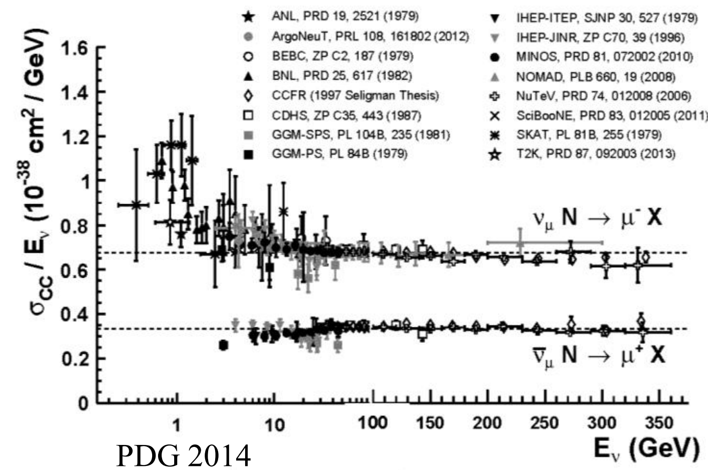
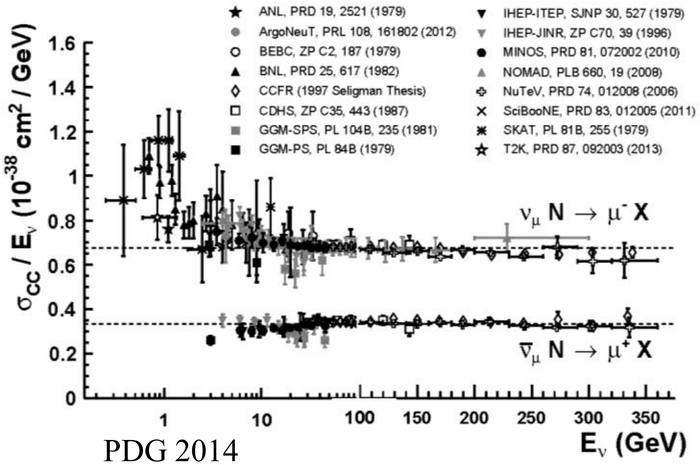
  - Systematics sources of uncertainties:
    beam flux, physics models, detector response and pion FSI/SI



PDG 2014

Anti-ν_μ CC inclusive on CH and O

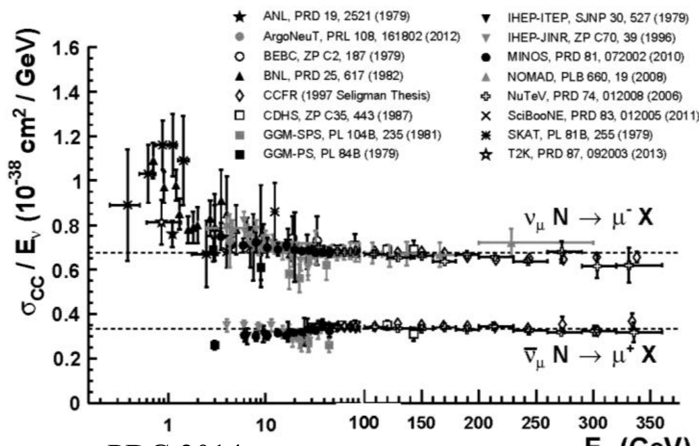
- Results



PDG 2014

Anti-ν_μ CC inclusive on CH and O

- Results
  - Phase-space: (both analyses)
    Restricted measurement → Full extrapolate



PDG 2014

Analysis 1: $\theta_\mu < 78^o$, $p_\mu > 200$ MeV
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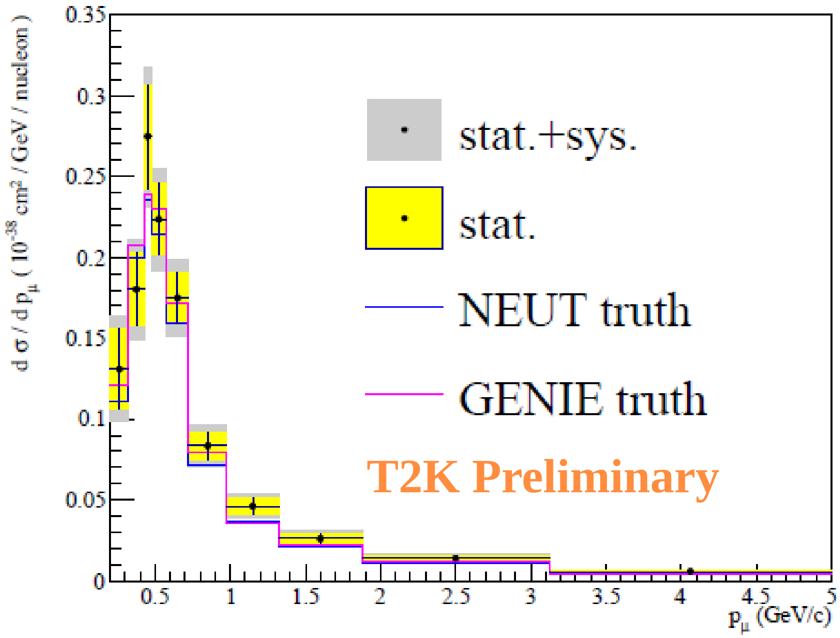

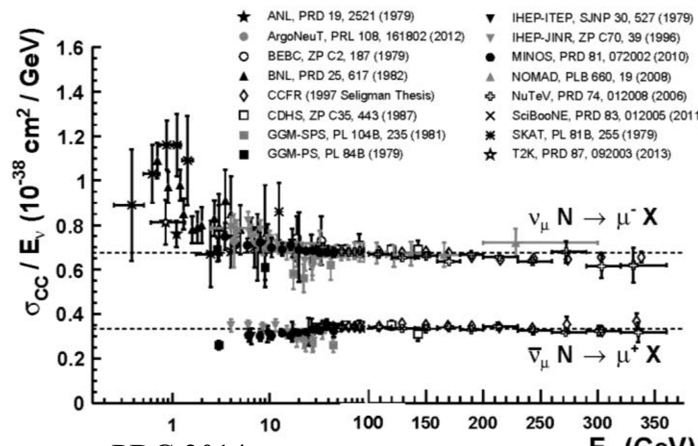

PDG 2014

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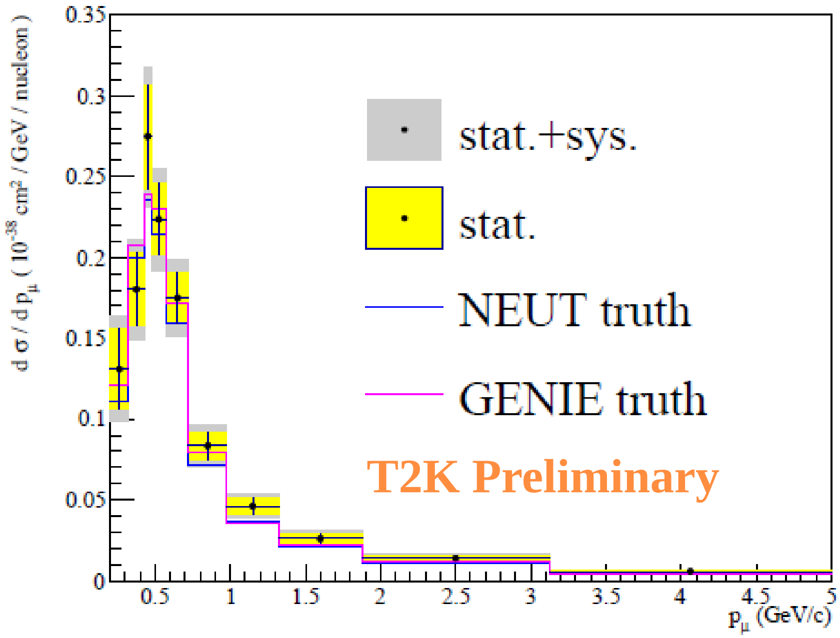

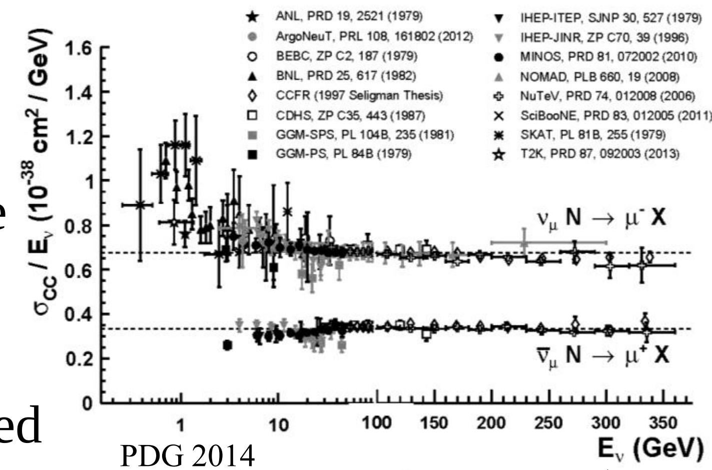

PDG 2014

- Restricted

$$\sigma(\bar{\nu}) = (0.91 \pm 0.03(\text{stat}) \pm 0.09(\text{syst})) \times 10^{-38}\ \text{cm}^2/\text{nucleon}$$

$$\sigma(\bar{\nu}) / \sigma(\nu) = 0.368 \pm 0.011(\text{stat}) \pm 0.019(\text{syst})$$

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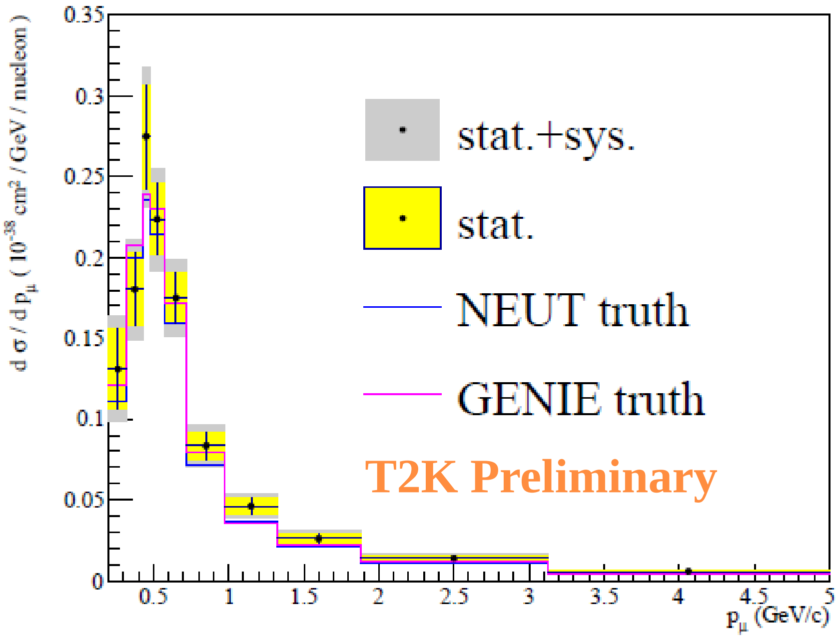

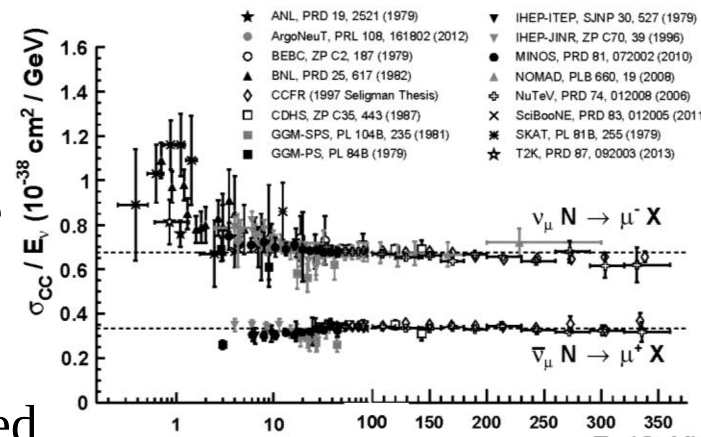

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- Dominant systematics :

	$\sigma(\bar{\nu})$	$\sigma(\bar{\nu})/\sigma(\nu)$
Flux	~9%	~5%
Statistics	~3%	~3%
Physics parameters	~2%	~3%

Note: NEUT and GENIE = ν MC generators

Additional & Upcoming Results

Additional & Upcoming Results

- Additional
  - ν_μ CC-0π (CCQE) cross section on H_2O
  - ν_μ CC-0π (CCQE) cross section on C with proton information

See S. Dolan's talk Parallel #1, WG2

- Upcoming
  - ν_e CC-0π (CCQE) cross section on C
  - ν_μ CC-1π cross section on H_2O
  - Anti-ν_μ CC-0π (CCQE) cross section on H_2O
  - . . .

Summary

- Neutrino Physics has entered its precision measurement era

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- ν-nucleus cross section knowledge – key ingredient
- Better ν-nucleus cross section → Better ν oscillation results

Better physics

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  ↺ Better physics

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  - ν_μ, ν_e and anti-ν
  - Off-axis, on-axis detectors and Far-Detector
  - C, O, Fe and other materials (coming soon)

Summary

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  Better physics

- T2K is making unique measurements with
  - ν_μ, ν_e and anti-ν
  - 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

T2K

ν Cross Sections

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

T2K Recent Cross-Section Results

Erez Reinherz-Aronis
for the T2K Collaboration
Colorado State University

NuFact 2016

XVIII International Workshop on Neutrino Factories and Future Neutrino Facilities

Quy Nhon, Vietnam

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 Sacly
IPN Lyon
LPNHE Paris

Germany
U. Aachen

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

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Okayama U.
Osaka City U.
Tokyo Metro U.
U. Tokyo

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

Russia
INR

Spain
ISIC, Valencia

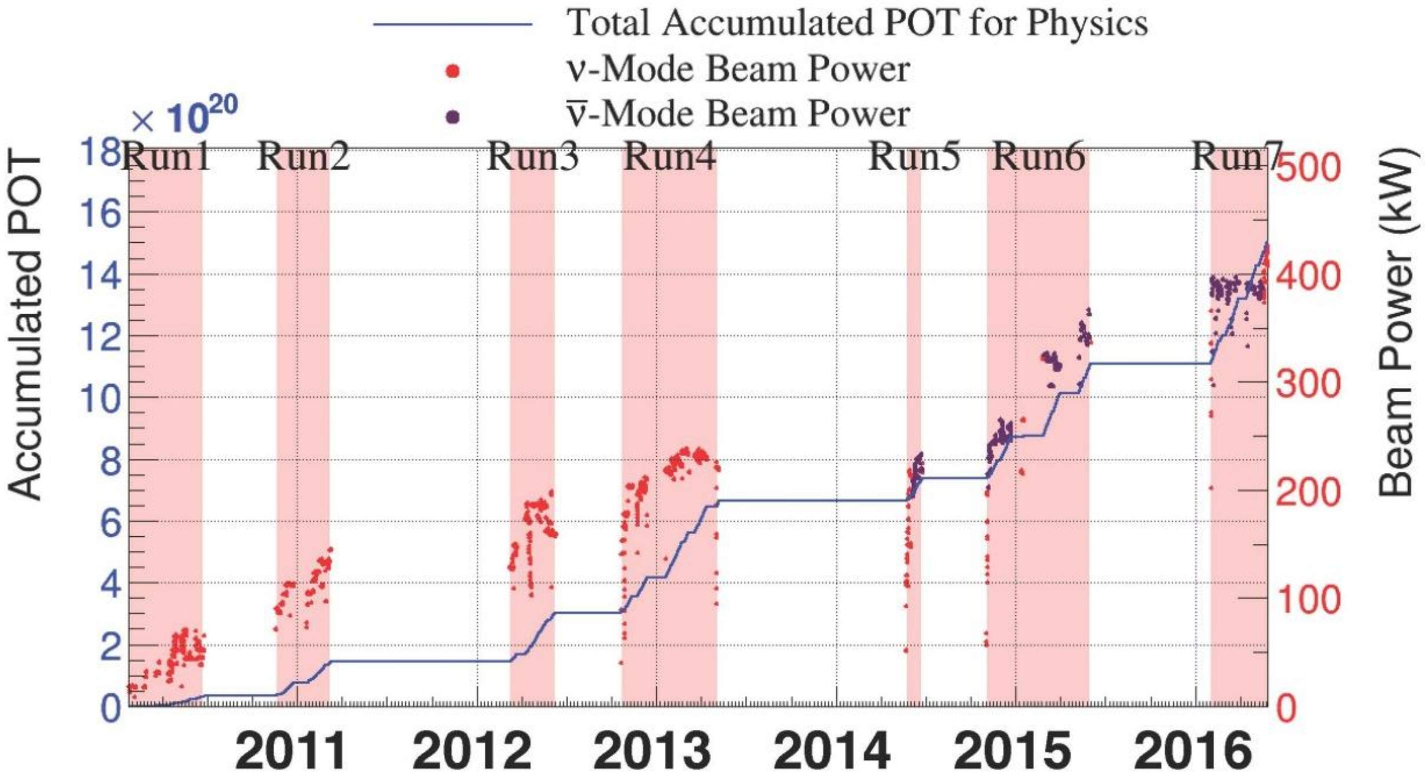
Switzerland
ETH Zurich
U. Bern
U. Geneva

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

USA
Boston U.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburg
U. Rochester
Stony Brook U.
U. Washington

T2K Results: J-PARC/Beam

- Protons-On-Target (POT) for T2K Runs 1-7



27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
$\bar{\nu}$-mode POT: 7.53×10^{20} (49.86%)

(POT = Proton on target)

Oscillations and Cross Sections

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

Flux model
External data from
NA61 (CERN)

Priors to the
ND fit(s)

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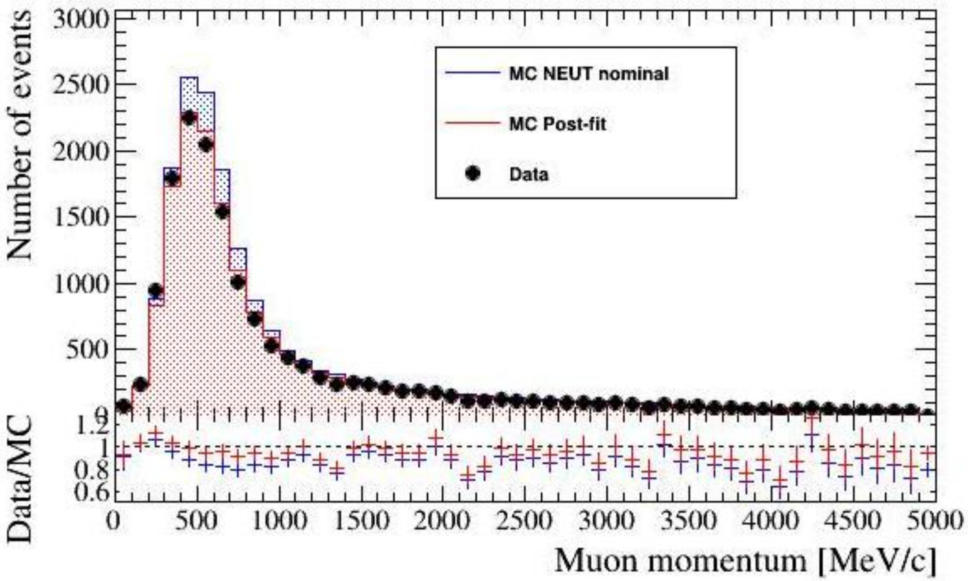
Near Detector data fit
Tune cross section, flux and background parameters to the ND data sets



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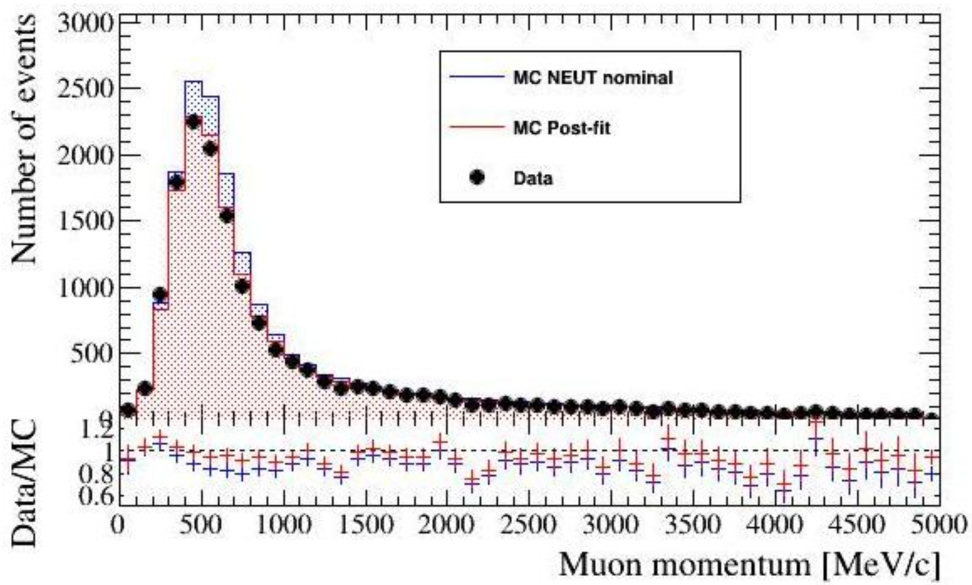

Parameter	Before ND constraint	After ND constraint
M_A^{QE} (GeV/c²)	1.21 ± 0.45	1.24 ± 0.07
E_B (¹²C) (MeV)	25 ± 9	30.9 ± 5.2
p_F (¹²C) (MeV/c)	217 ± 30.0	266.3 ± 10.6
CCQE norm $E\nu < 1.5$ GeV	1.00 ± 0.11	0.97 ± 0.08
CCQE norm $1.5 < E\nu < 3.5$ GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE norm $E\nu > 3.5$ GeV	1.00 ± 0.30	0.93 ± 0.10
M_A^{RES} (GeV/c²)	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

Please see D. Cherdack talk (Plenary #6) for the latest parameters

Oscillations and Cross Sections

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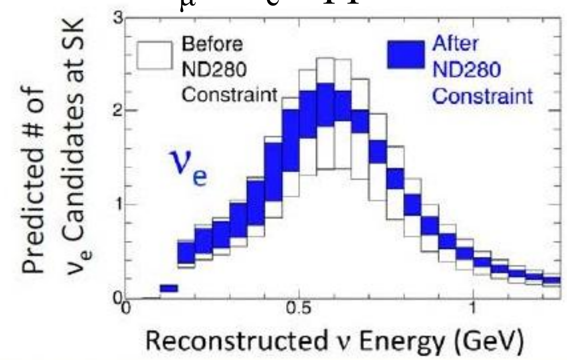
Tune cross section, flux and background parameters to the ND data sets

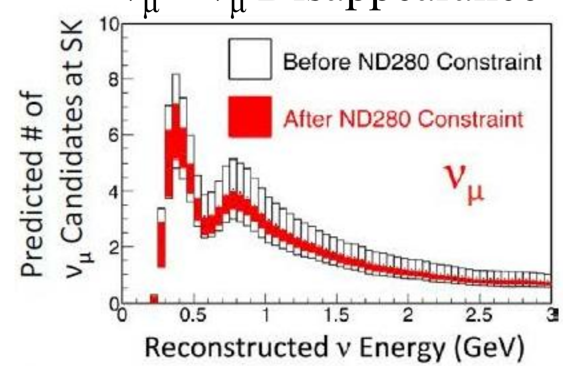
Constrain FD flux and subset of cross-section parameters and extract an event rate prediction at the FD

Priors to the FD fit(s)

$\nu_\mu \rightarrow \nu_e$ Appearance



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



Oscillations and Cross Sections

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(Minerva and/or MiniBooNE)

Flux model
External data from
NA61 (CERN)

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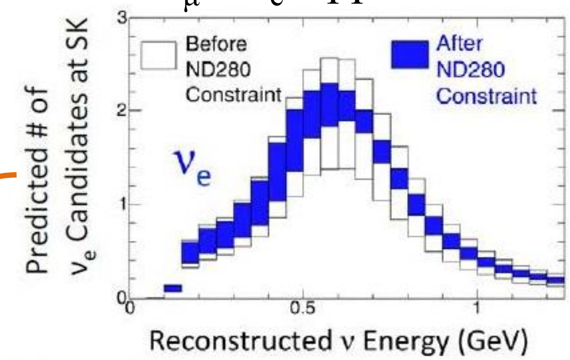
Constrain FD flux and subset of cross-section parameters and extract an event rate prediction at the FD

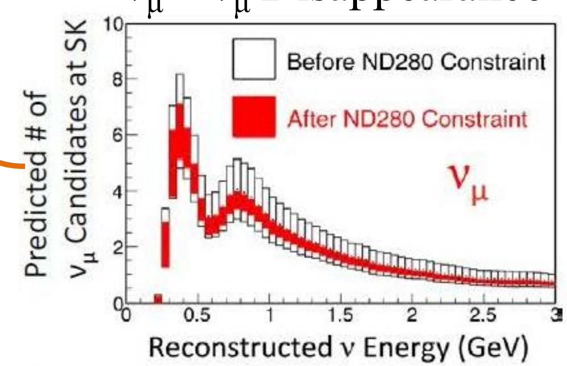
Priors to the FD fit(s)

Errors reduced by a factor of ~3

$\nu_\mu \rightarrow \nu_e$ Appearance



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



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(Minerva and/or MiniBooNE)

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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 extract an event rate prediction at the FD

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

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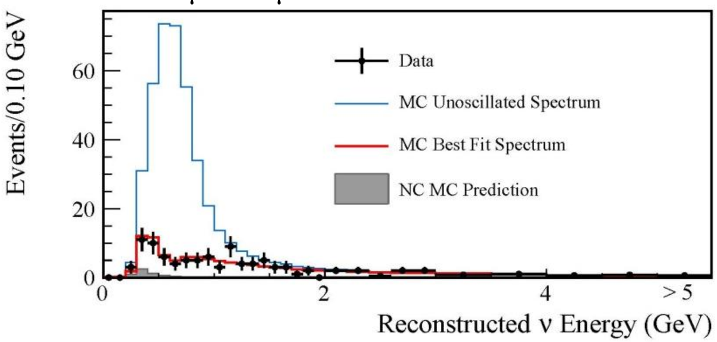

Oscillations and Cross Sections

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$\overset{(-)}{\nu}$ cross sections are key ingredients

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Far Detector data fit
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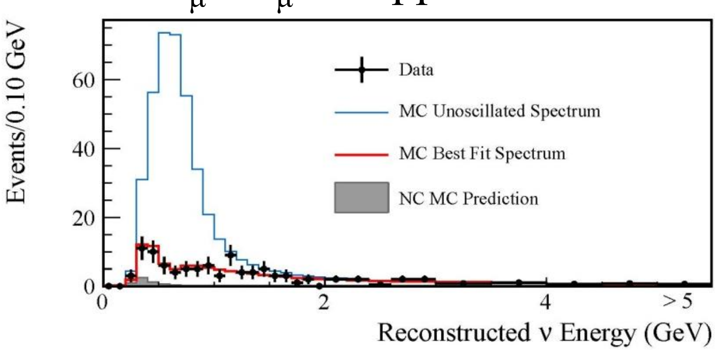

ν_μ CC Inclusive in E_ν range 1-3 GeV

- Final Errors

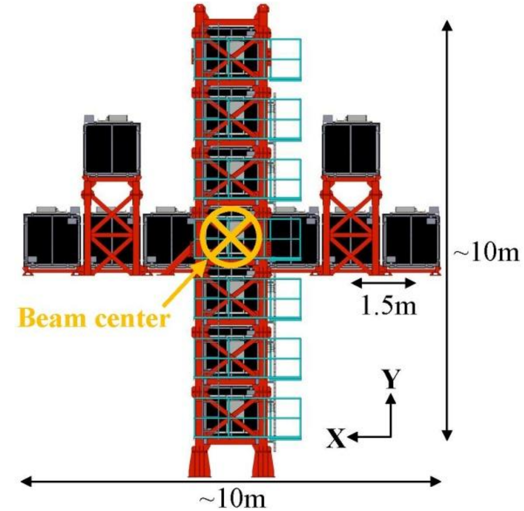

TABLE XI. Contribution to the uncertainty on the cross-section normalization at 1.1, 2.0, and 3.0 GeV from each error source.

Error source	1.1 GeV	2.0 GeV	3.3 GeV
Statistical error	2.0%	0.6%	2.3%
Flux + stat	7.6%	9.0%	8.4%
Detector + stat	4.3%	0.9%	3.9%
Interaction (cc) + stat	3.7%	0.8%	4.8%
Interaction (nc) + stat	2.4%	0.9%	3.2%
Pion FSI	$^{+1.0\%}_{-1.9\%}$	0.5%	$^{+3.7\%}_{-2.9\%}$
Pion multiplicity	3.3%	5.1%	2.1%
Pion SI	5.6%	2.0%	6.9%

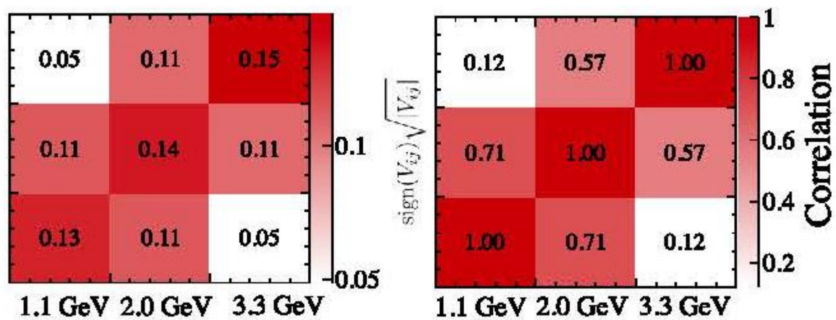

FIG. 26. Error (left) and correlation (right) matrices for the cross-section normalization at 1.1, 2.0, and 3.3 GeV. In both of the matrices, the binning on the y axis is identical to that on the x axis.

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ν_μ CC $1\pi^+$ on CH

- Case A: full phase–space.
- Case B: $\cos\theta_\mu > 0.2, \cos\theta_\pi > 0.2, p_\mu > 200MeV, p_\pi > 200MeV$. Not using the ME sample.
- Case C: $\cos\theta_\mu > 0.2, p_\mu > 200MeV$. If using the ME sample.
- Case D: $\cos\theta_\mu > 0., \cos\theta_\pi > 0.2, p_\mu > 0MeV, p_\pi > 200MeV$. For the double differential measurement on muon kinematical variables, then, low efficiency is covered by bin sizes.
- Case E: $\cos\theta_\mu > 0.2, \cos\theta_\pi > 0., p_\mu > 200MeV, p_\pi > 200MeV$. For the pion angle differential result, then, low efficiency is covered by bin sizes.
- Case F: $\cos\theta_\mu > 0.2, p_\mu > 200MeV, p_\pi > 0MeV$. For the pion momentum differential result, then, low efficiency is covered by bin sizes.
- Case G: $\cos\theta_\mu > 0.2, \cos\theta_\pi > 0.2, p_\mu > 200MeV, p_\pi > 0MeV$. For the pion momentum differential result if no ME sample is used, then, low efficiency is covered by bin sizes.
- Case H: $\cos\theta_\mu > 0.2, \cos\theta_\pi > 0.2, p_\mu > 0MeV, p_\pi > 200MeV$. For the muon momentum differential result, then, low efficiency is covered by bin sizes.

Anti-ν_μ CC inclusive on CH and O

- Efficiencies