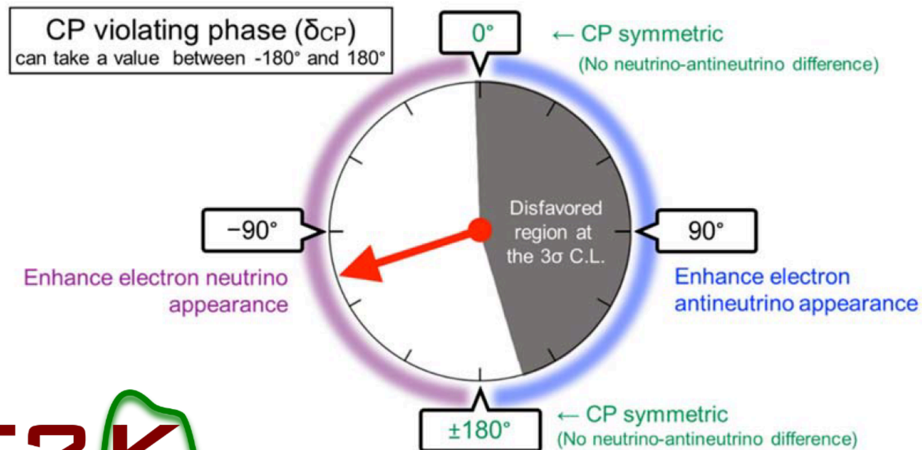
Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

outline

1. Neutrino oscillation experiments
2. Neutrino beam
3. Neutrino detector
4. Neutrino interaction physics
5. Oscillation result
6. SK-Gd, T2K-Upgrade, Hyper-Kamiokande
7. Conclusion



Nature 580 (2020) 339

Teppei Katori @teppeikatori
King's College London

Latin American Webinars on Physics, April 22, 2020

1. **Neutrino oscillation experiments**

2. Neutrino beam

3. Neutrino detector

4. Neutrino interaction physics

5. Oscillation result

6. SK-Gd, T2K-Upgrade, Hyper-Kamiokande

7. Conclusion

Neutrino Physics is center stage!

BREAKTHROUGH PRIZE

2016 Fundamental Physics Breakthrough Prize
- Koichiro Nishikawa (K2K and T2K)
- Atsuto Suzuki (KamLAND)
- Kam-Biu Luk (Daya Bay)
- Yifang Wang (Daya Bay)
- Art McDonald (SNO)
- Yoichiro Suzuki (Super-Kamiokande)
- Takaaki Kajita (Super-Kamiokande)

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this: 1.6K

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

1. Next goal of high energy physics

Establish Neutrino Standard Model (νSM)
- SM + 3 active massive neutrinos

Unknown parameters of νSM
1. Dirac CP phase
2. θ_{23} (θ_{23}=40^o and 50^o are same for sin2θ_{23}, but not for sinθ_{23})
3. normal mass ordering $m_1<m_2<m_3$ or inverted mass ordering $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phases
6. Absolute neutrino mass

(4–6:) not relevant to neutrino oscillation experiments

We need higher precision neutrino oscillation experiments around 1-10 GeV.

1. Neutrino oscillations

Flavour eigenstate = superposition of Hamiltonian eigenstate (mass eigenstate in vacuum)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle,\ \ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

U is PMNS (Pontecovo-Maki-Nakagawa-Sakata) Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Here $c_{23} = cos\theta_{23}$ and $s_{23} = sin\theta_{23}$, δ_{CP} = Dirac phase, α_i = Majorana phase.

Oscillation probability of neutrino flavor ν_α to ν_β with energy *E*, baseline *L* is

$$P_{\alpha\to\beta}(L,E) = 1 - 4\sum_{i>j} Re\left(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}\right) sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j} Im\left(U_{\alpha i}^* U_{\beta i}^* U_{\alpha j} U_{\beta j}\right) sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

After adjusting units, the 2-flavor oscillation can be written in a simple formula.

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. Neutrino oscillations

Keep the first order of CP violation for muon neutrino to electron neutrino oscillation

Jarlskog invariant

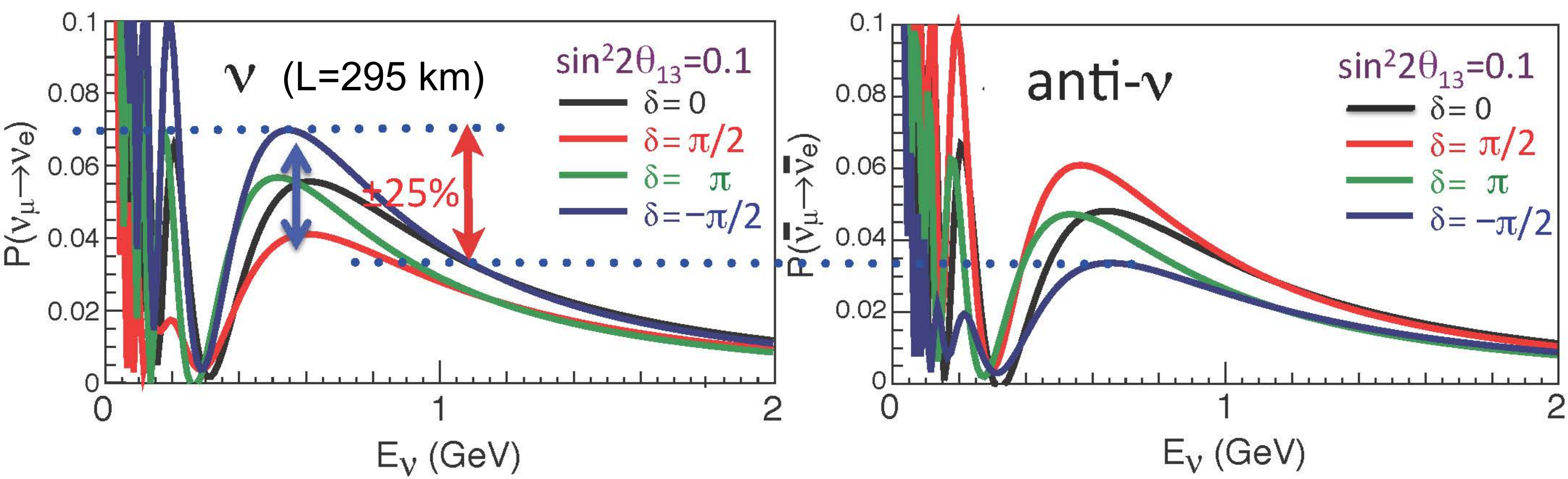
$$J_{CP,1} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP} \quad (1)$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \quad (2)$$

- Neutrino
+ Antineutrino

If there is no CP violation, $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ are the same

Expected oscillation probability to measure δ_{CP} is small



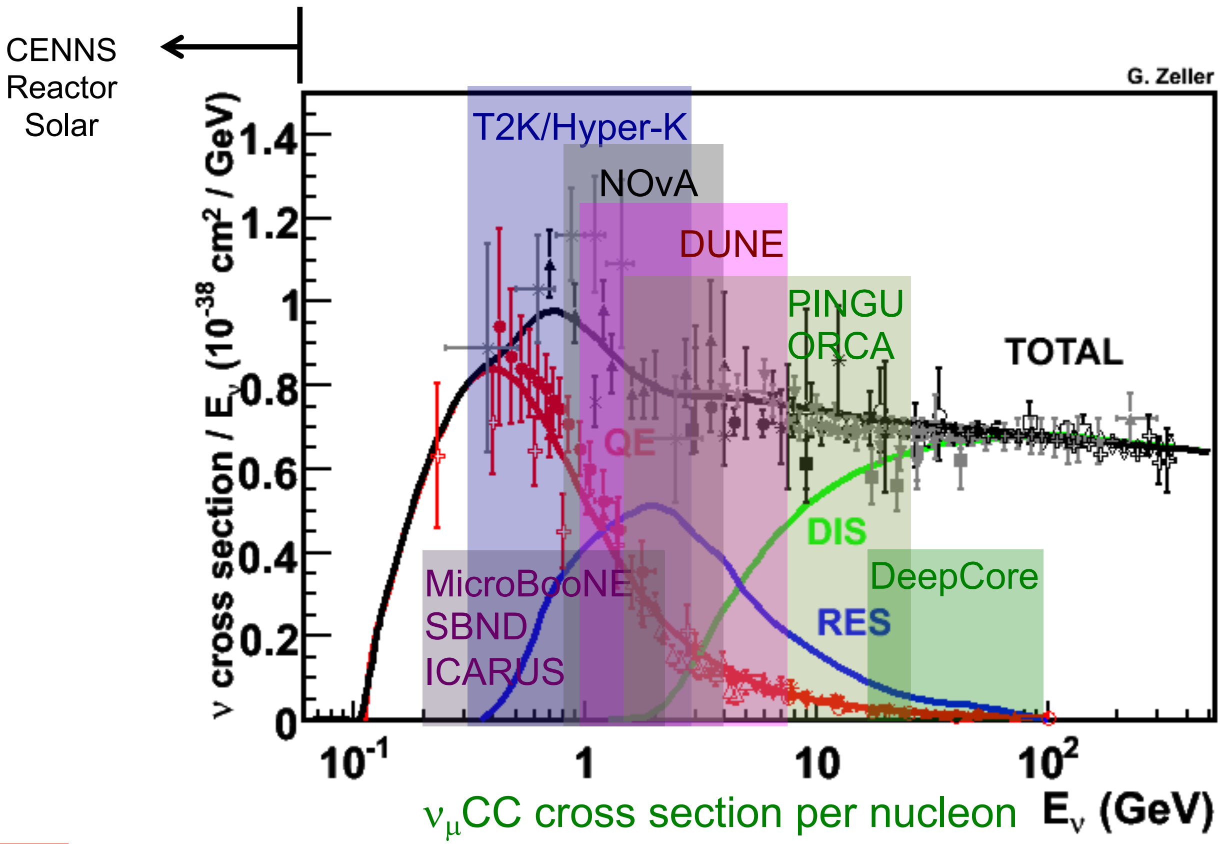
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

KING'S College LONDON

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments
- Present: T2K, NOvA, MicroBooNE, DeepCore...
- Future: Hyper-Kamiokande, DUNE, PINGU, ORCA…

- Most of experiments are 1-10 GeV
- Cross-section data are poor



ν_μCC cross section per nucleon

For Δm^2_{32}~2.5×10^{-3} eV^2, the first oscillation max is L/E ~ 500 km/GeV

ex) T2K
L~300km
E~0.6GeV

ex) NOvA
L~800km
E~2GeV

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. Neutrino oscillation analysis

Data

Create neutrino beam

Measure muon neutrinos at the near detector

Measure electron neutrinos (and muon neutrinos) at the far detector

Simulation

Simulate neutrino flux at the near detector and the far detector

Simulate neutrino interaction at the near detector and the far detector

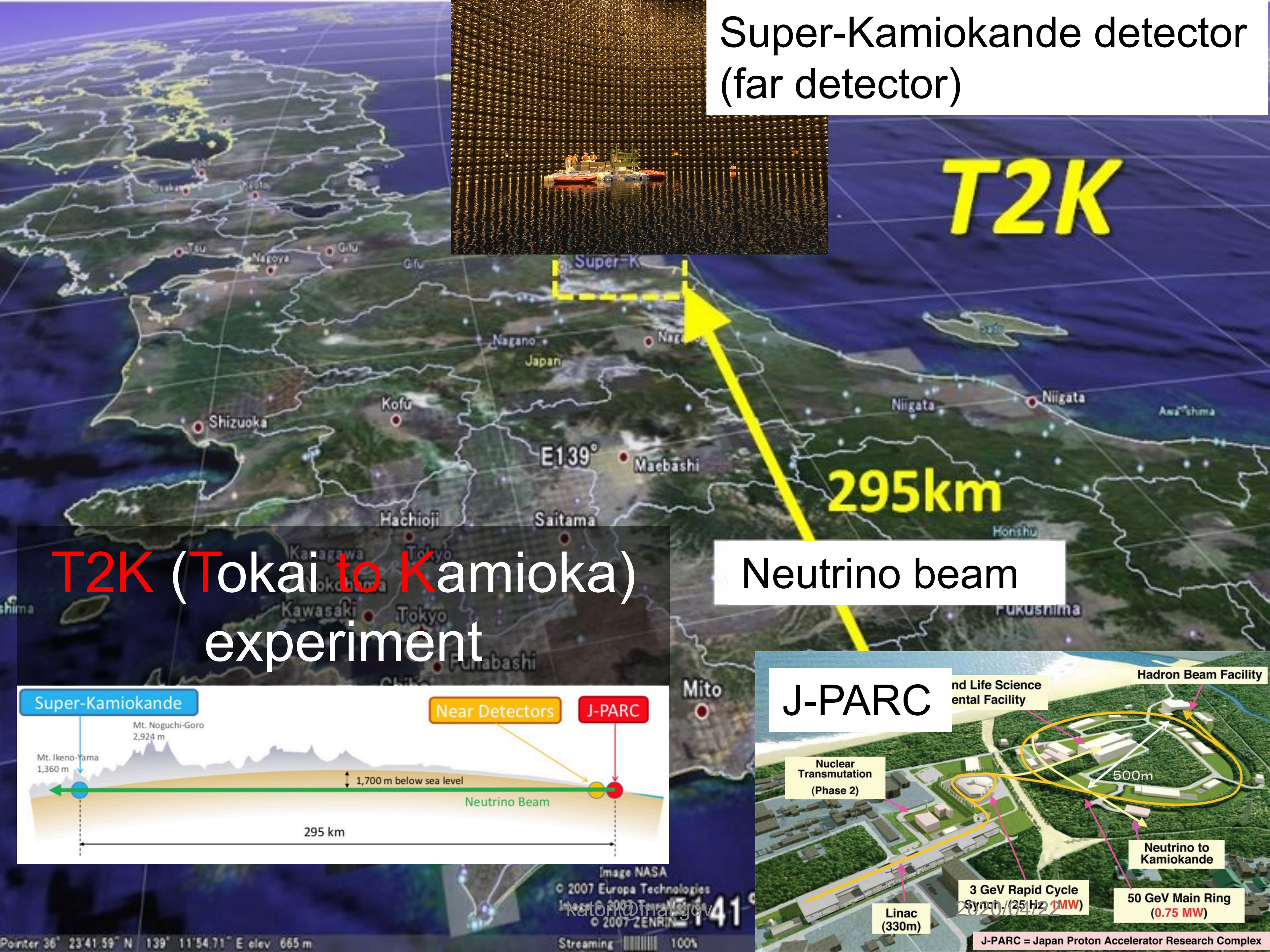
Simulate detector response at the near detector and far detector

Apply oscillation formula to the far event distribution

Oscillation analysis

Compare data and simulation to find oscillation parameters (use near detector information to constrain systematic errors)

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$


Super-Kamiokande detector
(far detector)
T2K
Super-K
295km
Neutrino beam
T2K (Tokai to Kamioka)
experiment
Super-Kamiokande
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
Near Detectors
J-PARC
1,700 m below sea level
Neutrino Beam
295 km
J-PARC
Hadron Beam Facility
Nuclear
Transmutation
(Phase 2)
500m
Neutrino to
Kamiokande
3 GeV Rapid Cycle
Synch. (25 Hz, 1MW)
50 GeV Main Ring
(0.75 MW)
Linac
(330m)
J-PARC = Japan Proton Accelerator Research Complex
Nagano
Japan
Kofu
Shizuoka
E139°
Maebashi
Niigata
Hachioji
Saitama
Honshu
Fukushima
Kawasaki
Tokyo
Funabashi
Mito
Image NASA
© 2007 Europa Technologies

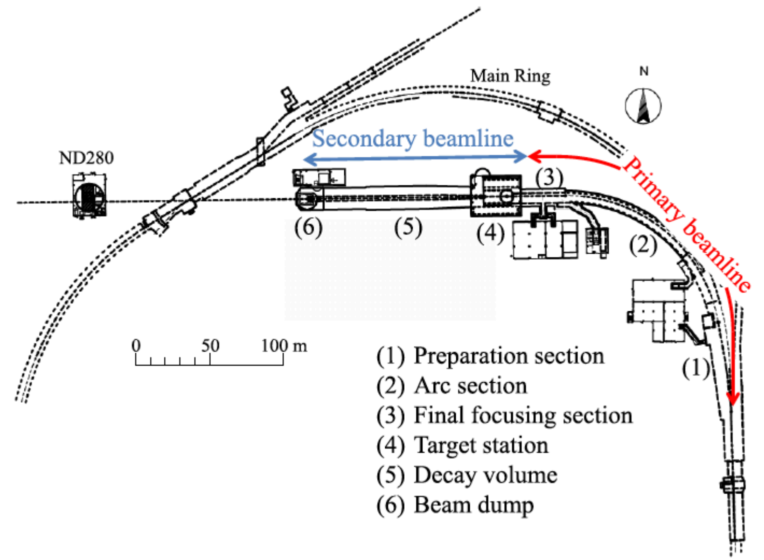
2. J-PARC

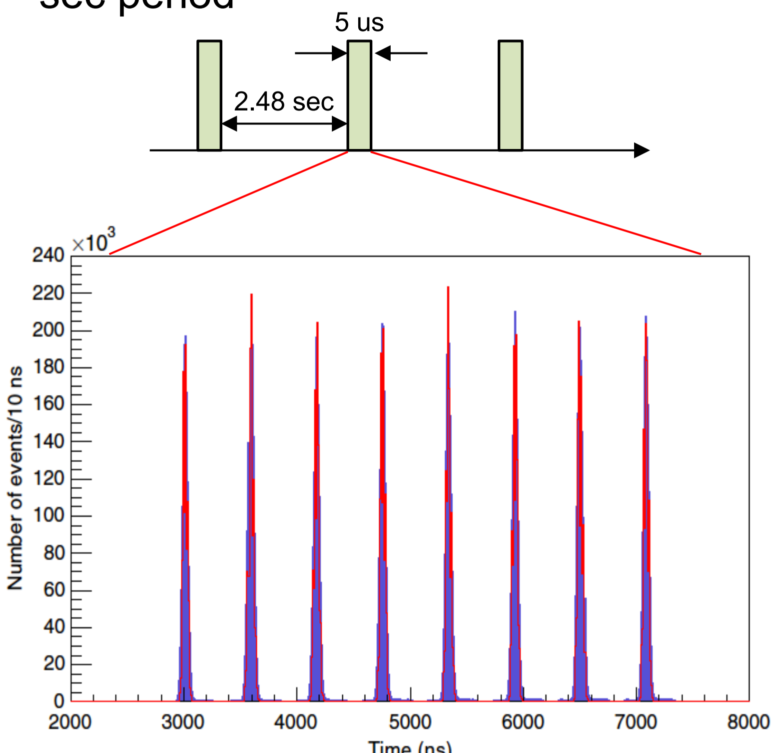
LINAC
- 400 MeV
RCS (Rapid Cycling Synchrotron)
- 3 GeV
To Kamioka
Neutrino
Main Ring
- 30 GeV

2. Neutrino beamline

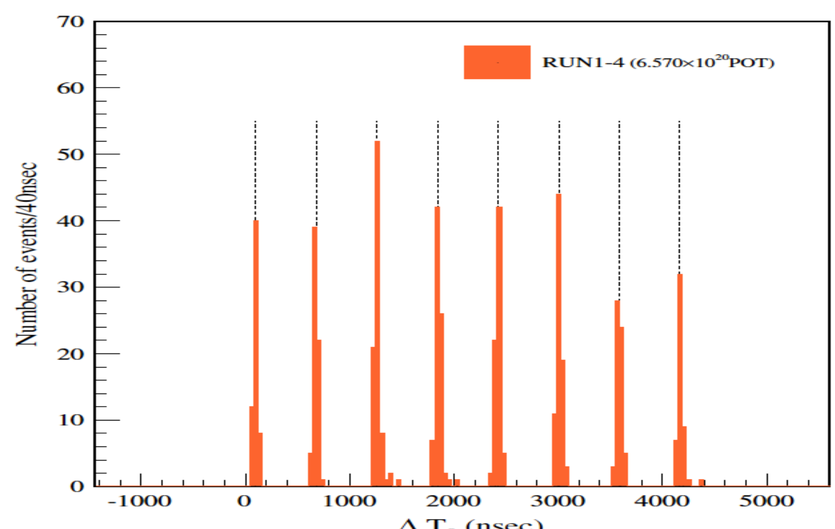
Primary beamline

- 30 GeV protons are extracted from MR by superconducting magnets
- 1 pulse contains 8 bunches in ~5us, about ~2.5E14 ppp (protons per pulse) with 2.48 sec period

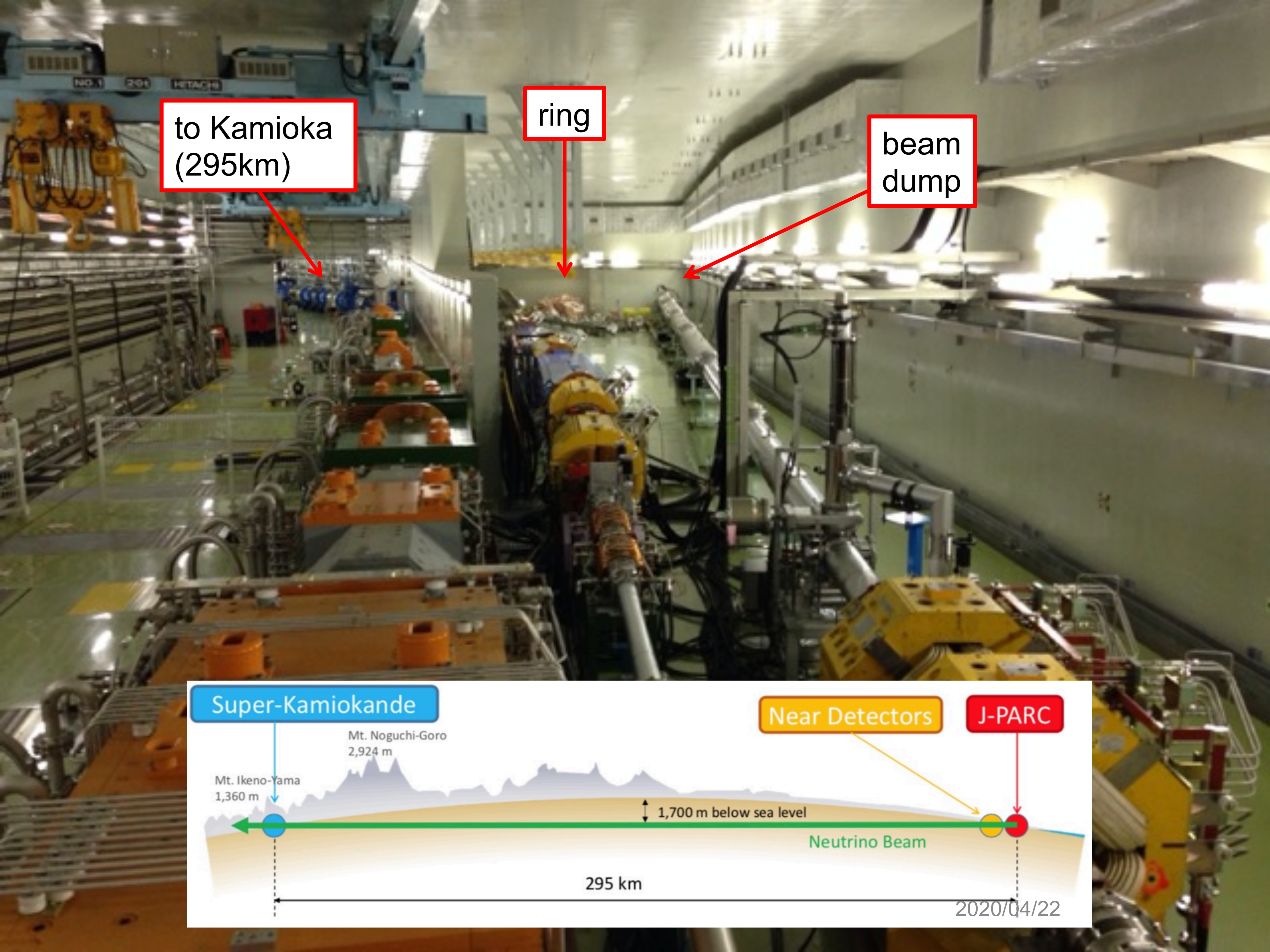




Neutrino events at the near detector



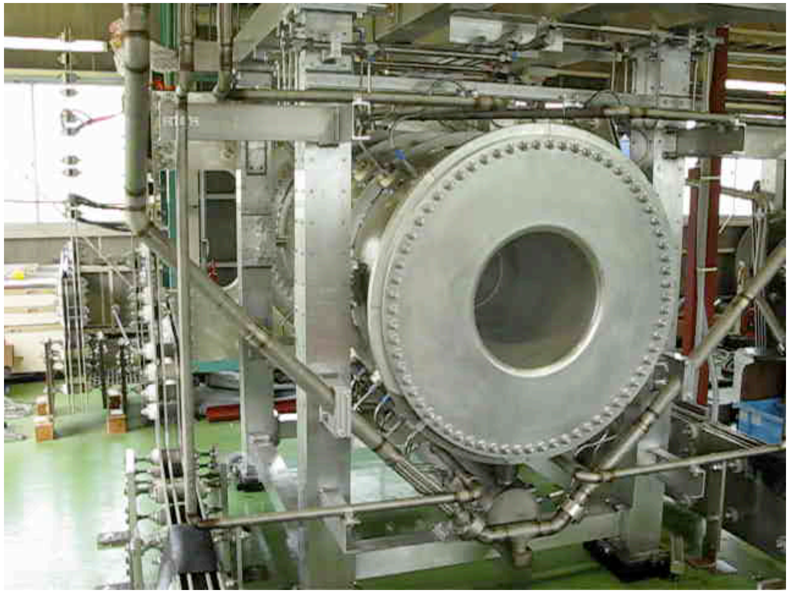
Neutrino events at the far detector


to Kamioka
(295km)
ring
beam
dump
Super-Kamiokande
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
Near Detectors
J-PARC
1,700 m below sea level
Neutrino Beam
295 km

This is the sound of neutrinos!

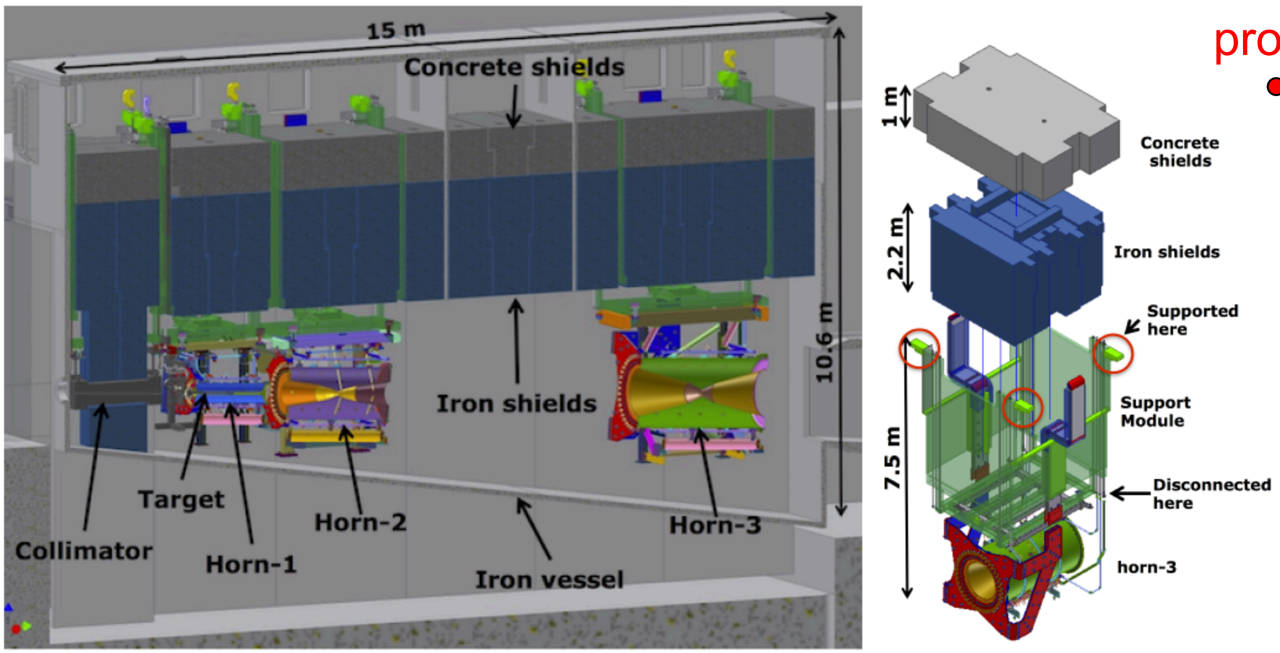
2. Neutrino beamline

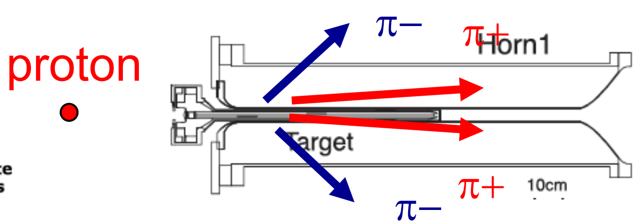
Horn 3 test (250 kA, ~1.7 T)



Secondary beamline

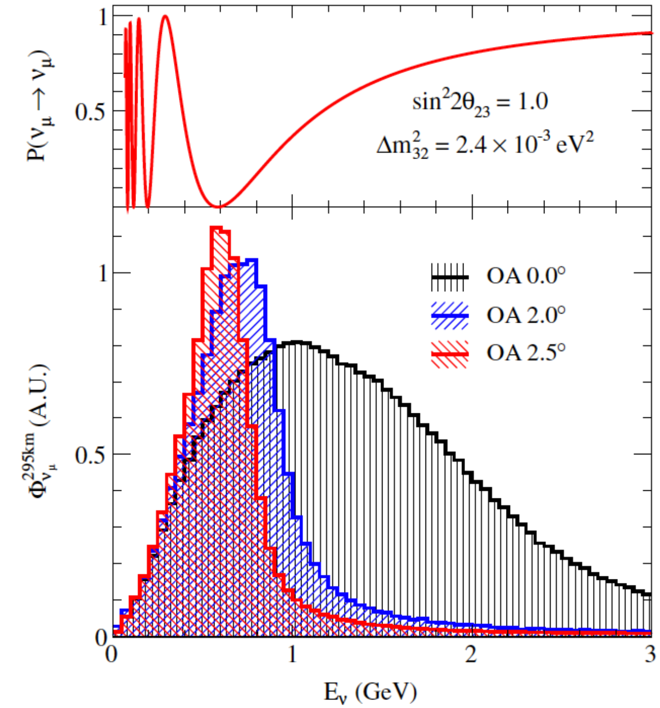
- Protons collide the graphite target (in the Horn 1) to produce mesons, and these mesons decay in the decay volume to produce neutrinos (decay-in-flight).
- In neutrino mode, 3 magnetic horns focus positive mesons and defocus negative mesons to produce neutrino beam (flux ~x17). In antineutrino mode, horn current is reversed to focus negative mesons.





T2K, PRD87(2013)012001
NA61/SHINE, EPJC76(2016)84

2. Neutrino beamline

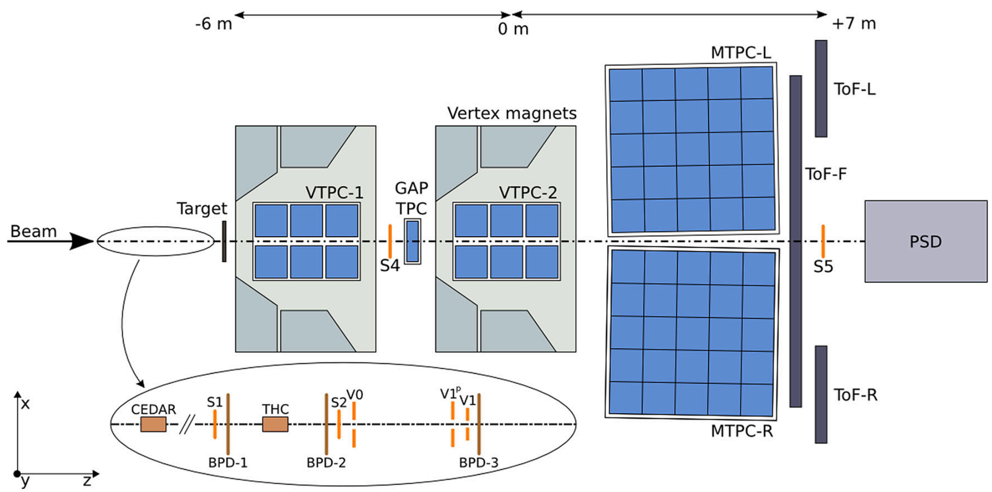


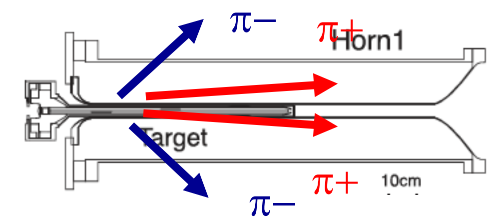
Off-axis beam

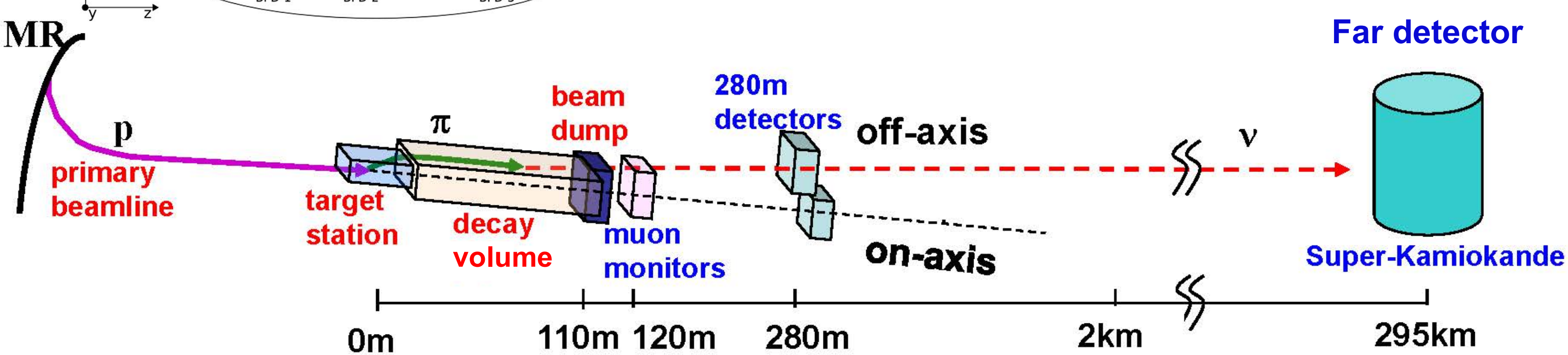
- 2.5° off-axis to make ~0.6 GeV narrow band beam

CERN NA61/SHINE

- Hadron production at the target is simulated with the data from the hadron measurement

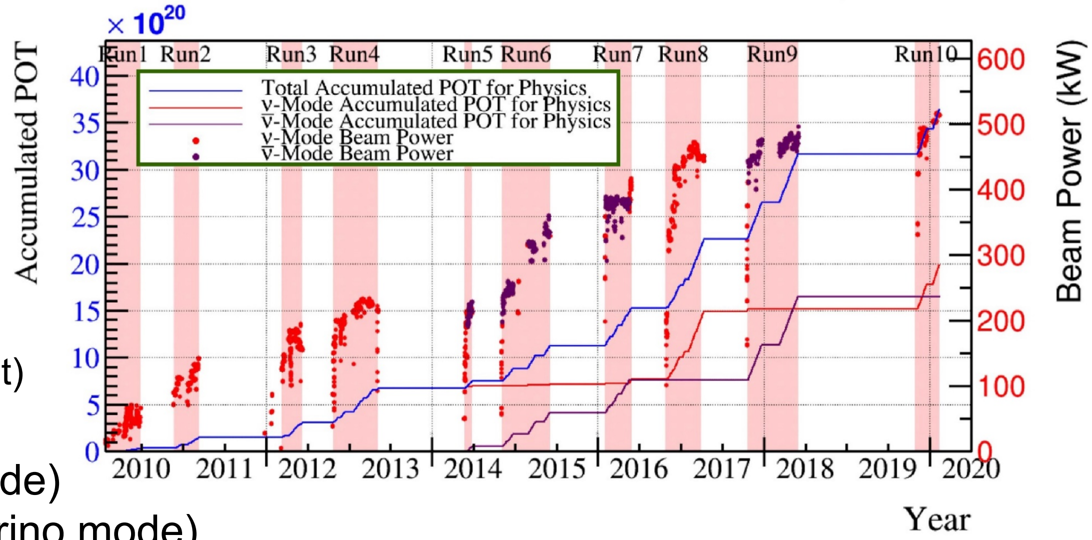






T2K, PRD87(2013)012001
Vladisavljevic (T2K), NuInt18

2. Neutrino beamline



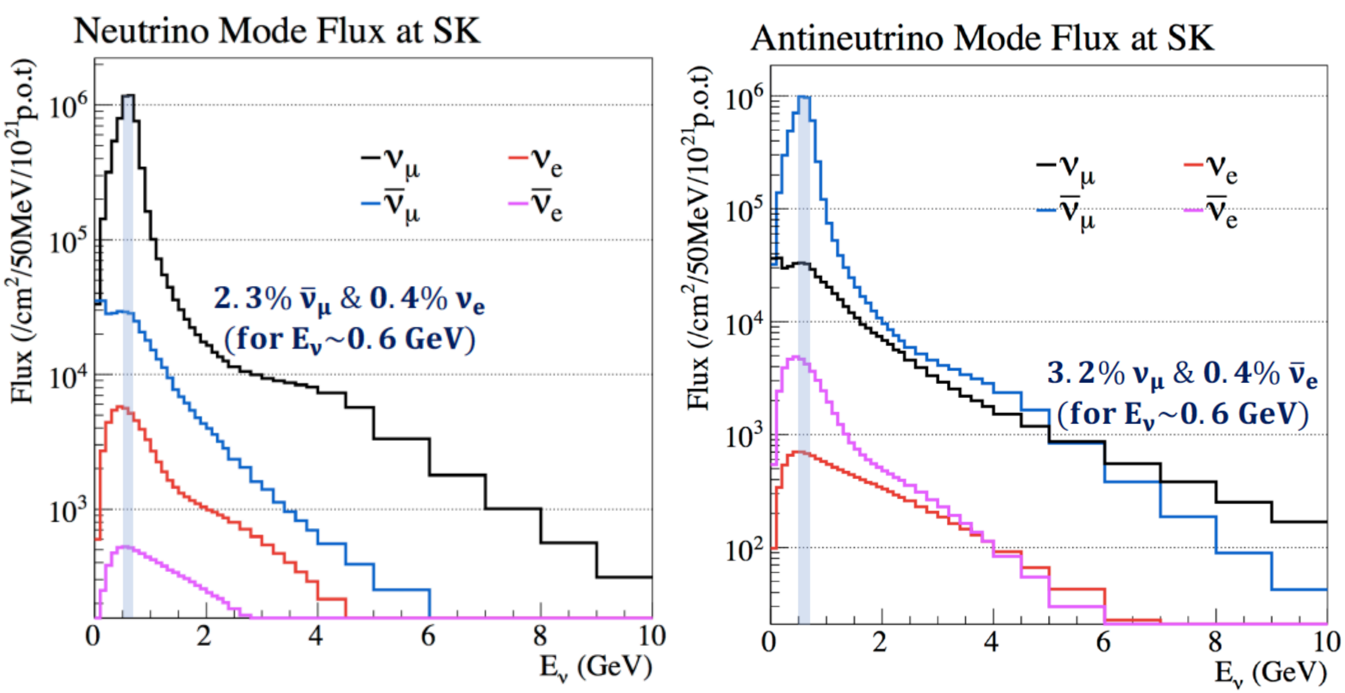
2009 – 2018 data

- Neutrino mode, 1.49E21 POT
- Antineutrino mode, 1.64E21 POT

(POT=protons on target)

Neutrino flux prediction

- muon neutrino dominant (neutrino mode)
- muon antineutrino dominant (antineutrino mode)
- ~9% error at the flux peak
- replica target NA61/SHINE data can reduce error to ~5%

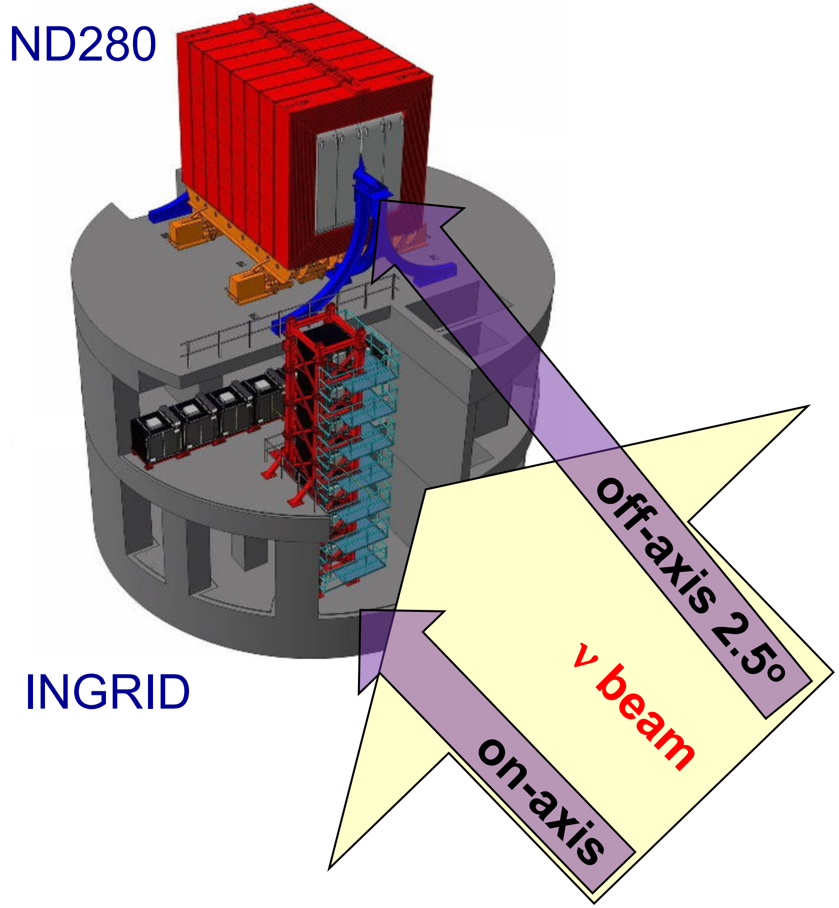


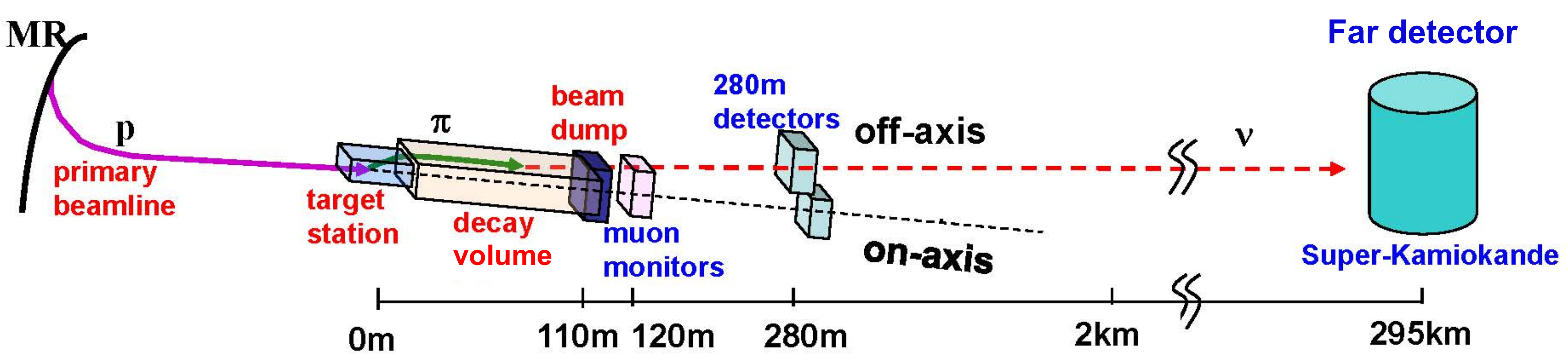
T2K, NIMA659(2011)106
Oyama (T2K), CNNP2020

3. Near detectors

INGRID
- on-axis near detector
- Mainly for neutrino flux monitoring

ND280
- off-axis near detector
- Data are used to constrain various systematics

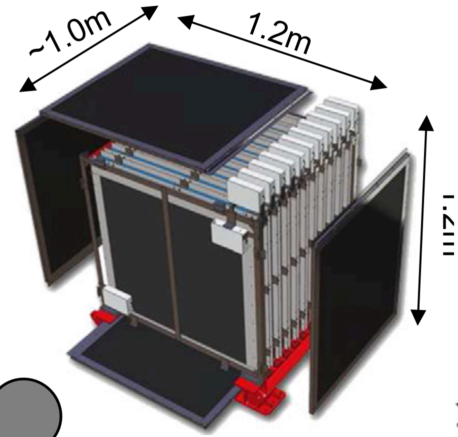


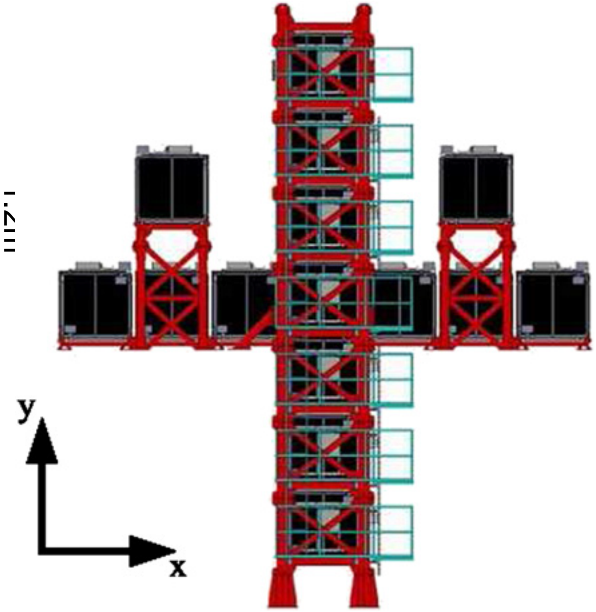


3. On-axis detector

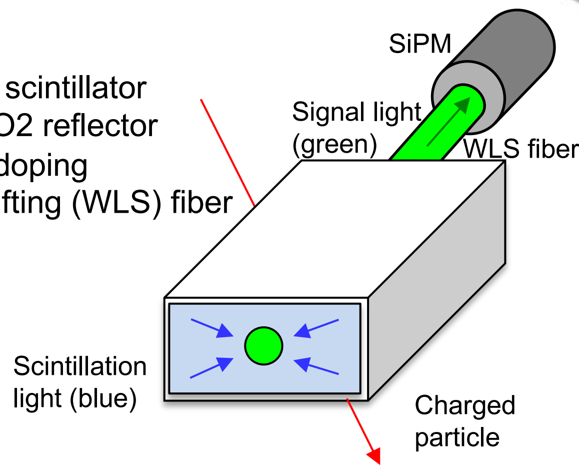
INGRID

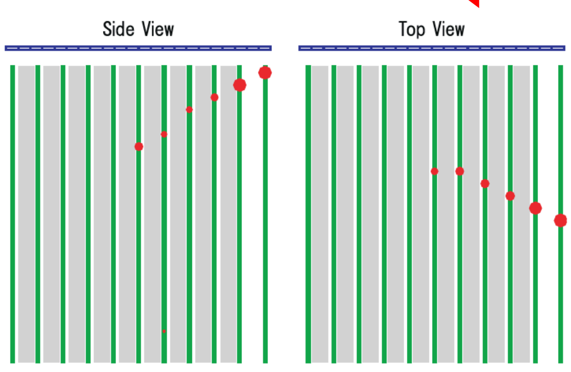
- An array of 16 modules
  - Scintillator-iron tracker
  - nominal accuracy ~ 0.1 mrad

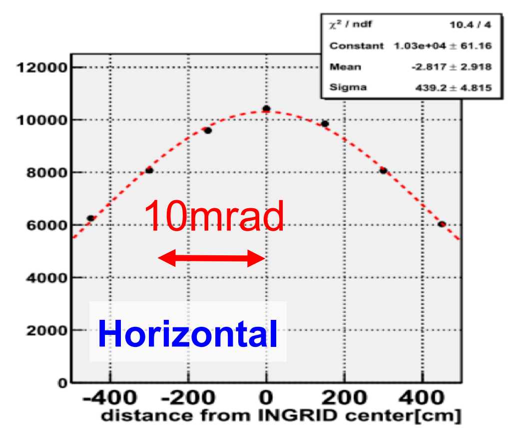


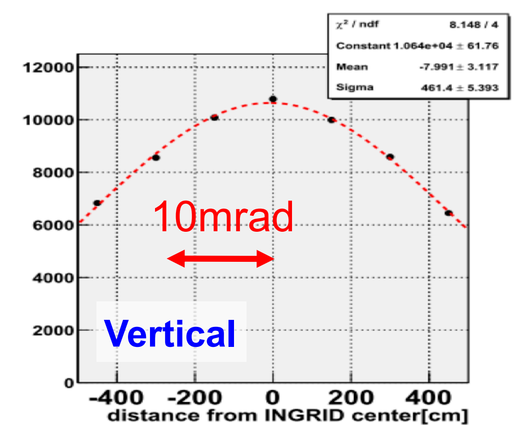


Scintillator
- Organic plastic scintillator
- polystyrene, TiO2 reflector
- PPO, POPOP doping
- Wavelength shifting (WLS) fiber
- SiPM reading









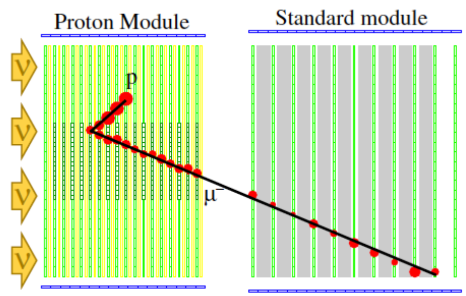
3. On-axis detectors

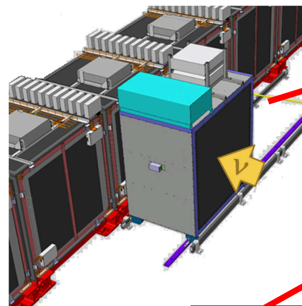
Proton module
- Fully active module

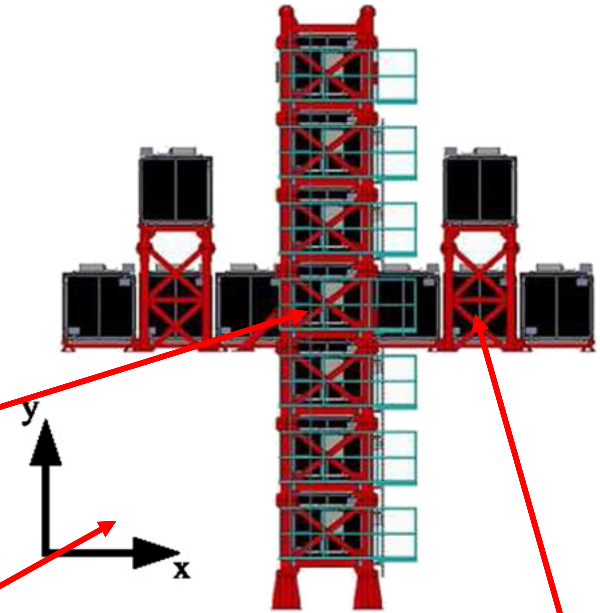
WAGASCI
- Water target 3-d scintillator array

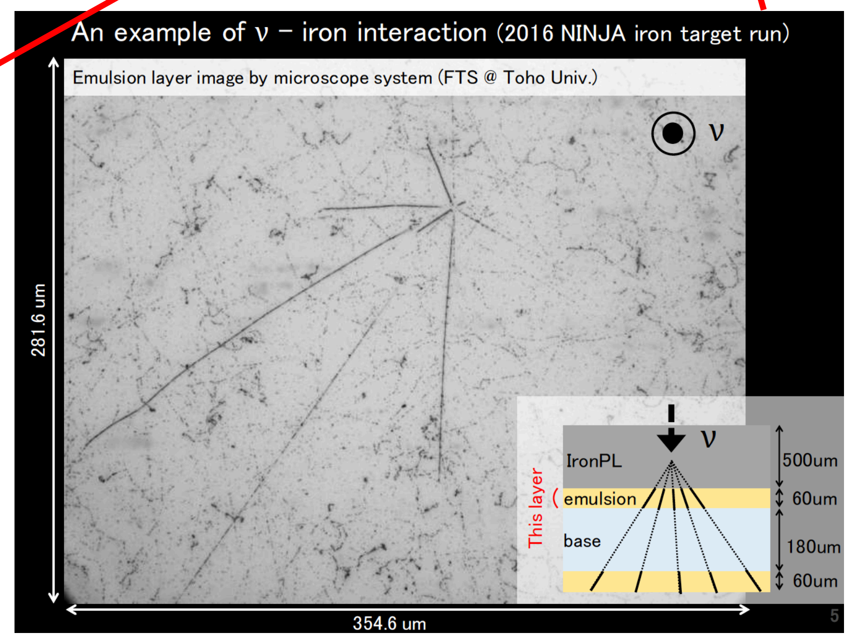
BabyMIND
- Magnetized tracker made at CERN

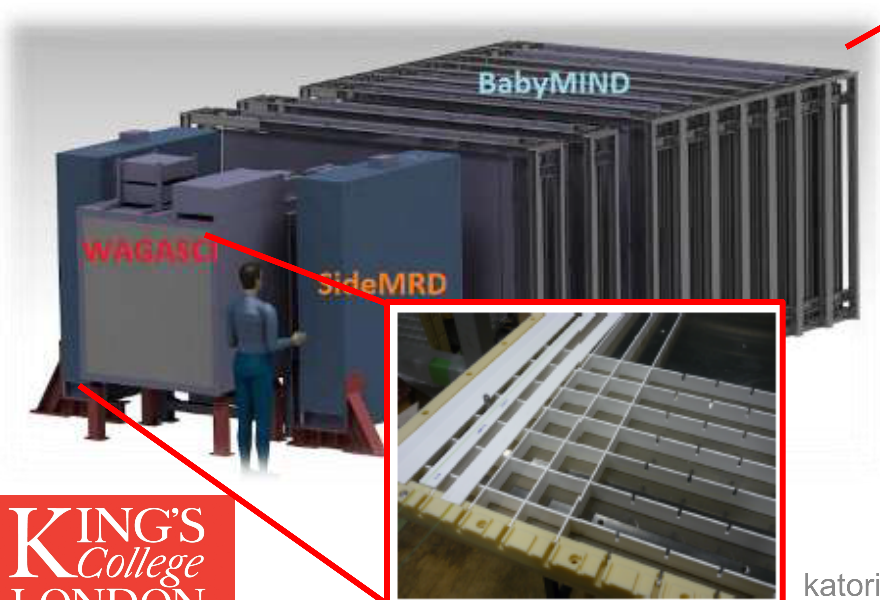
NINJA
- Emulsion neutrino detector





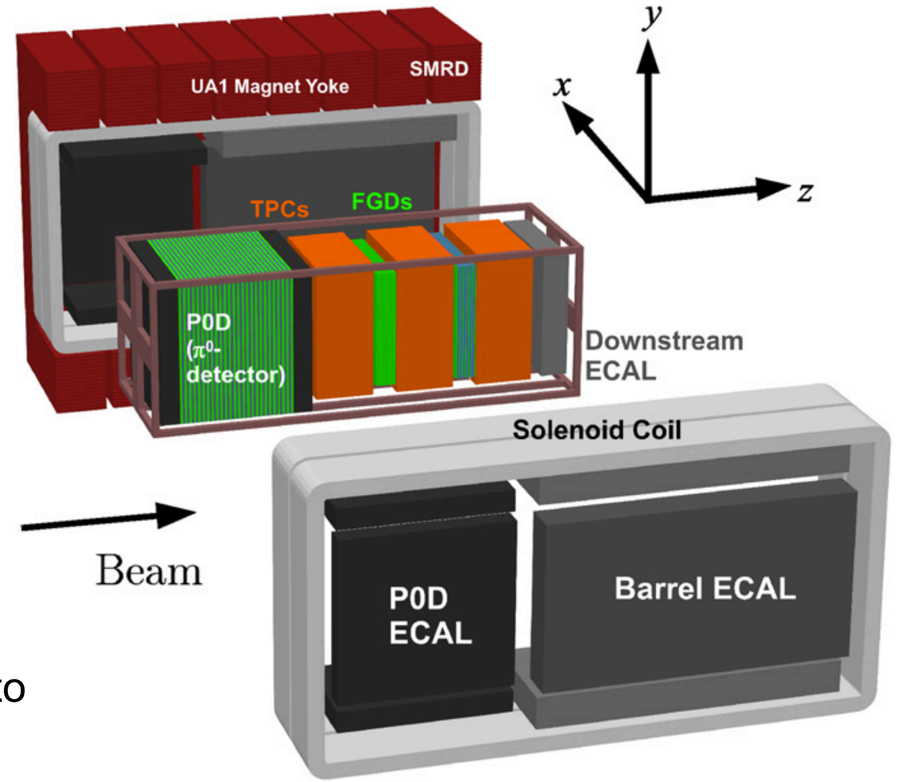






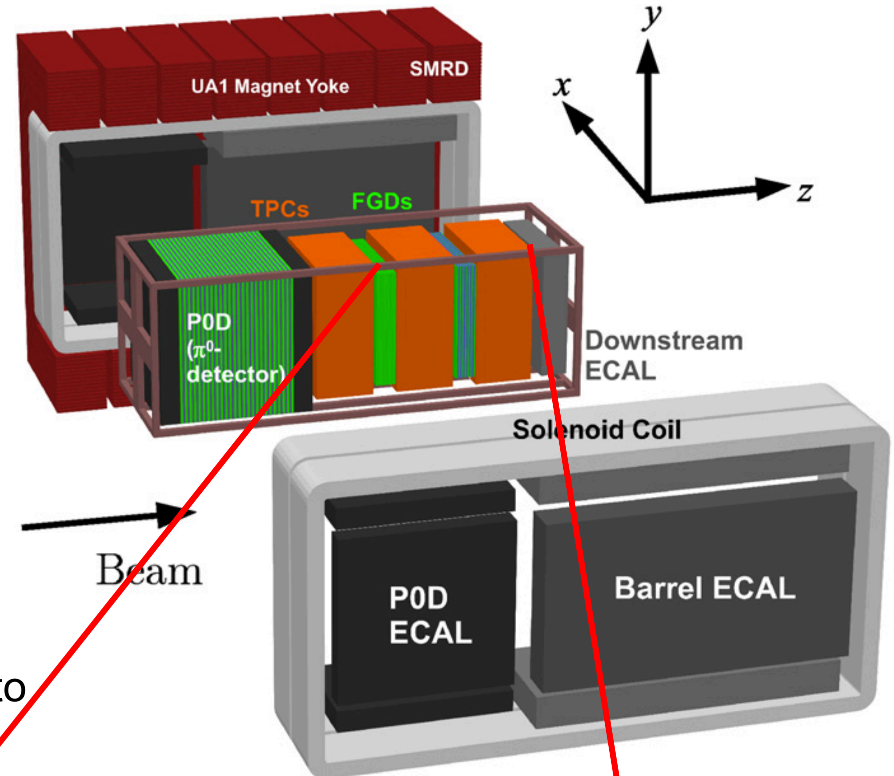
3. Off-axis detector

ND280
- P0D: Water-scintillator tracker
- FGD: Fully active scintillator tracker
- TPC: Ar gas TPC
- ECal: Lead-scintillator calorimeter
- SMRD: Iron-scintillator tracker
- UA1 magnet



Near detector data
- 14 samples are used for the oscillation analysis to constrain flux and cross-section systematic errors

3. Off-axis detector



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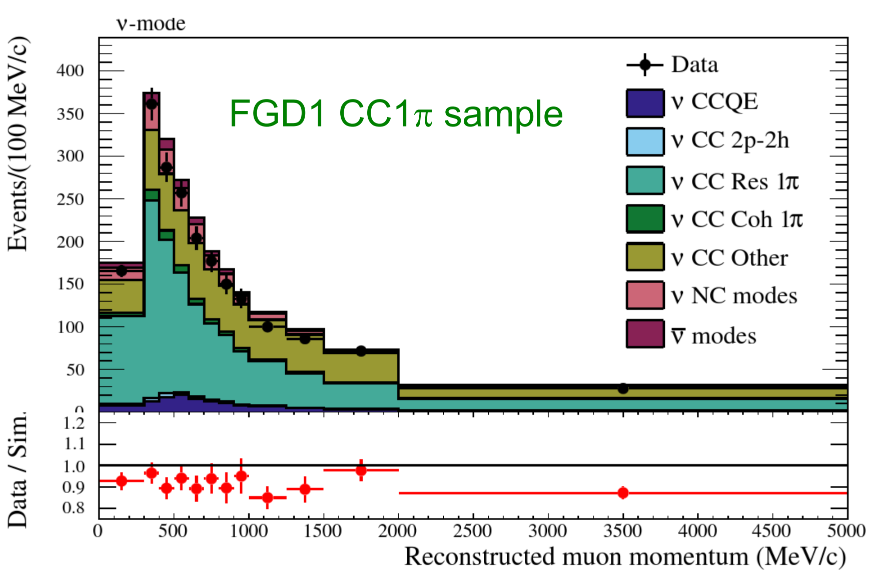
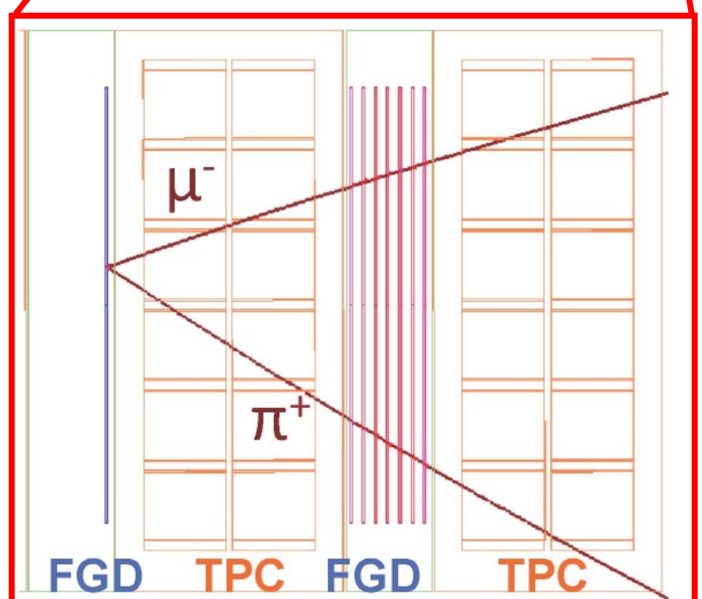


PRELIMINARY



T2K, NIMA659(2011)106, PRL121(2018)171802

3. Off-axis detector

ND280

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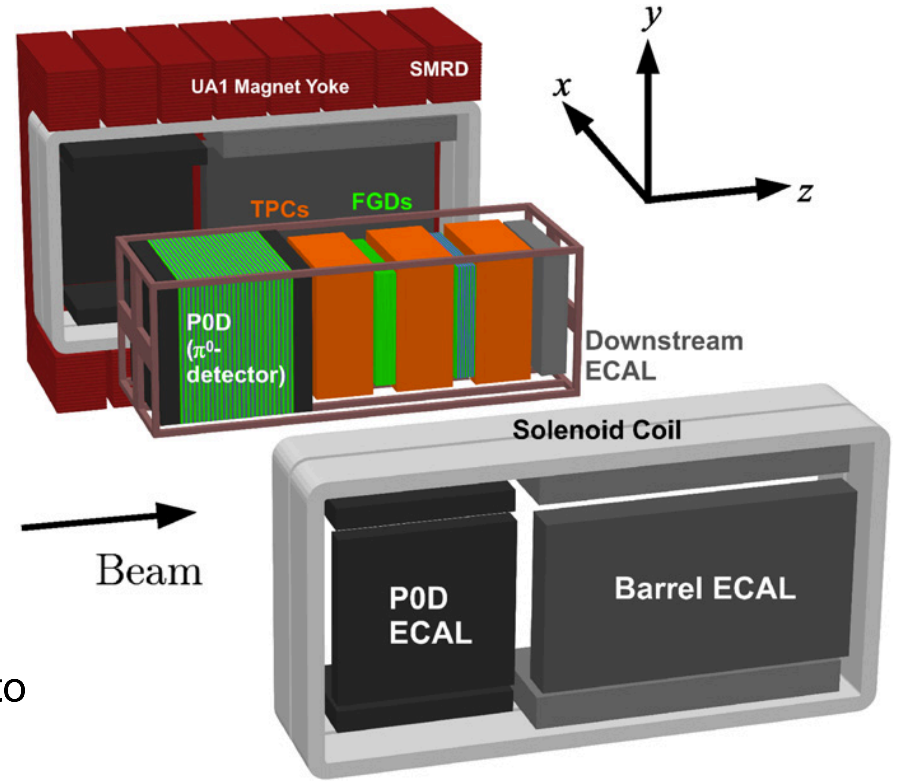

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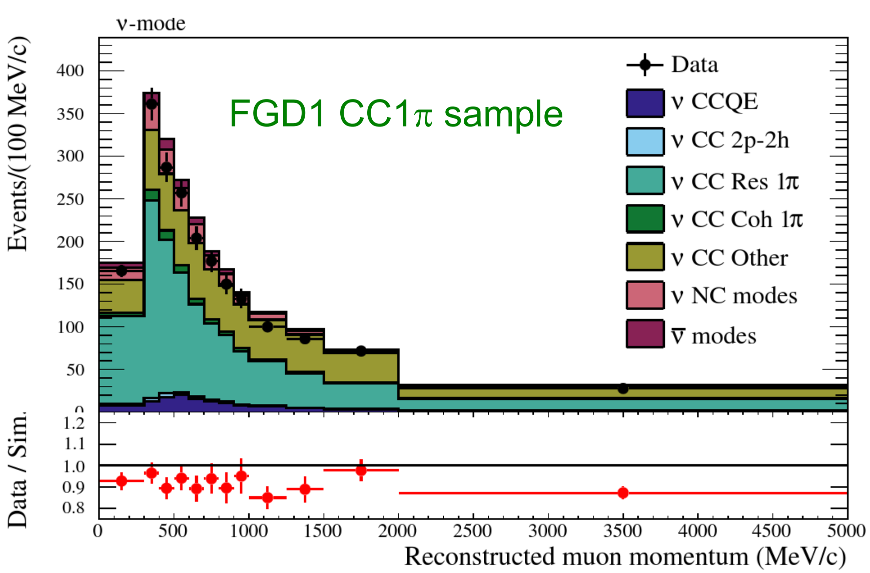
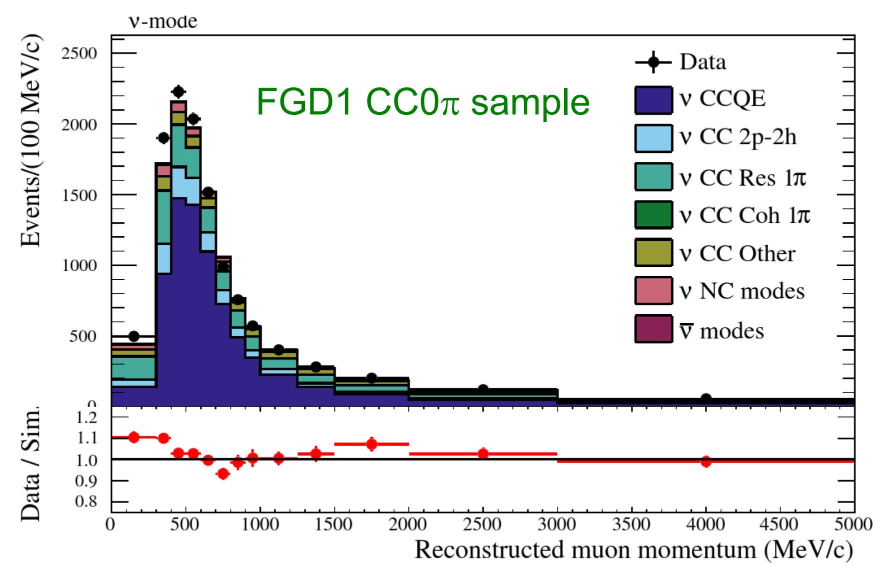


PRELIMINARY



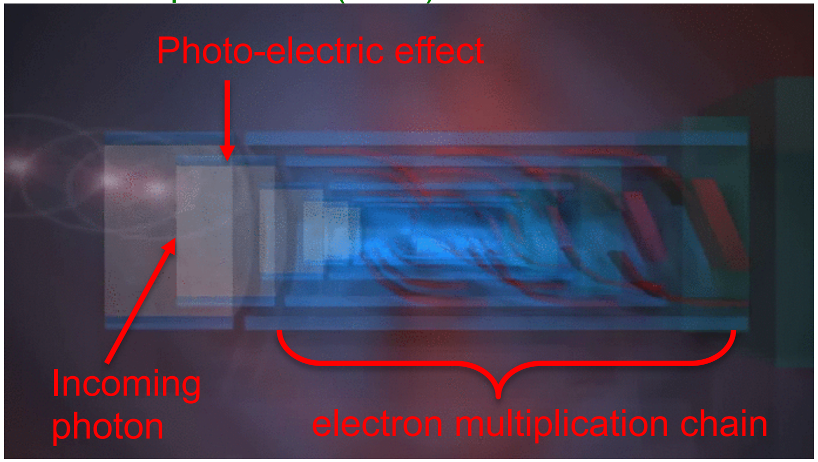
PRELIMINARY

SuperK, NIMA501(2003)418

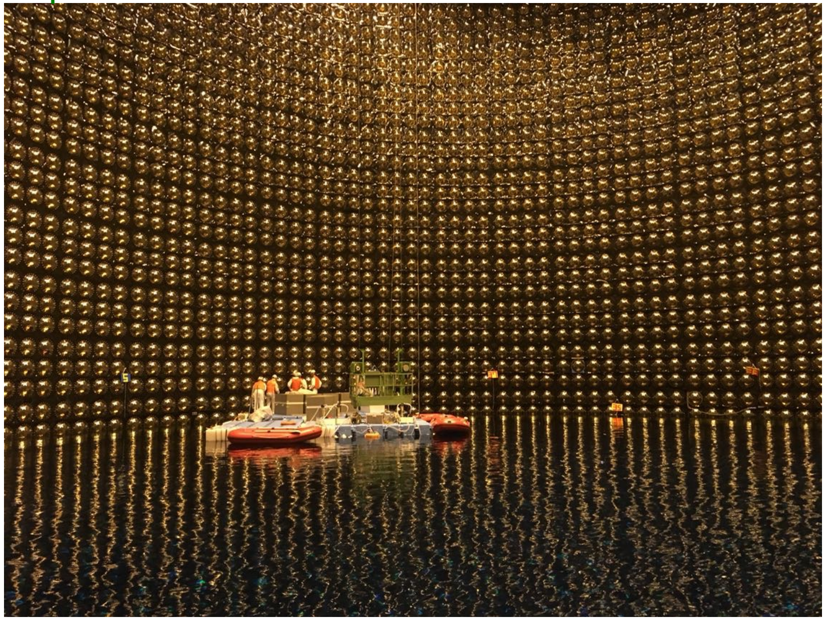
3. Far detector

Super-Kamiokande
- 50 kton water Cherenkov detector
- 2015 Nobel prize
- 11,146 20-inch PMTs (inner detector)
- 1,885 8-inch PMTs (outer detector)

Photo-multiplier tube (PMT)



Super-K inner detector



Super-K outer detector

20-inch PMT is quite big...

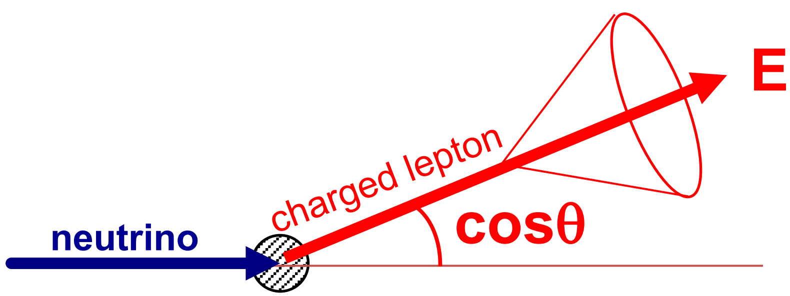
SuperK, NIMA501(2003)418

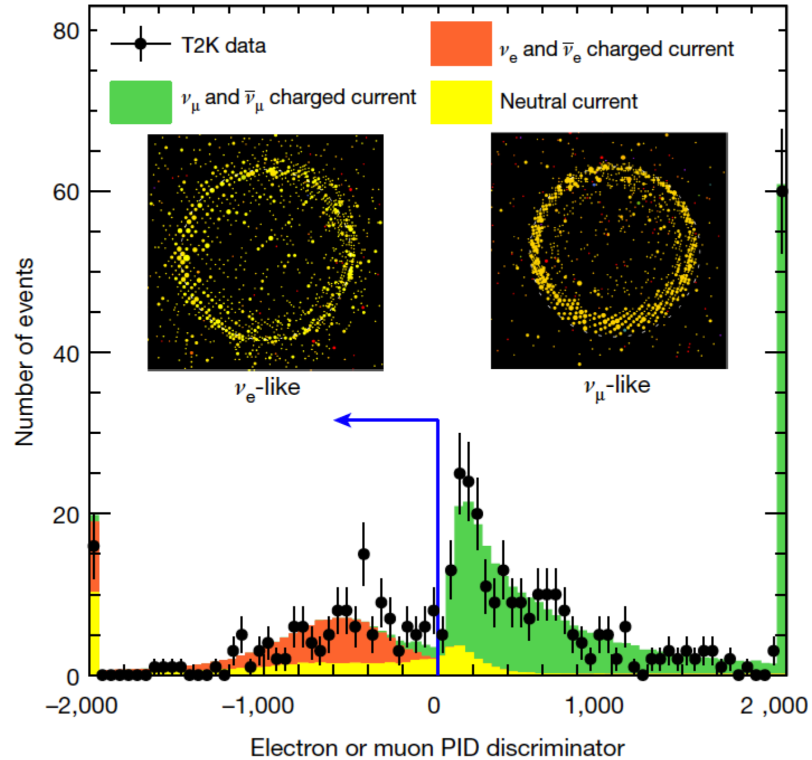
3. Far detector

Event reconstruction

- From measured time and charge information from all PMTs, particle identification (PID) and kinematics are reconstructed
- From reconstructed charged lepton kinematics, neutrino energy is reconstructed

$$E_{\nu}^{QE} = \frac{ME - 0.5m_l^2}{M - E + p\cos\theta}$$





$\nu_e(\bar{\nu}_e)$ measurement has 2 major backgrounds

1. Intrinsic background
$\nu_e(\bar{\nu}_e)$ contamination in the beam (~0.5%)

2. misID background
Gamma rays counted as electron (positron). Majority of them are from neutral current π^o production where one of γ is undetected

$$\nu_\mu + A \rightarrow \nu_\mu + A' + \pi^o, \pi^o \rightarrow \gamma + \gamma$$

KING'S College LONDON

1. Neutrino oscillation experiments

2. Neutrino beam

3. Neutrino detector

4. Neutrino interaction physics

5. Oscillation result

6. SK-Gd, T2K-Upgrade, Hyper-Kamiokande

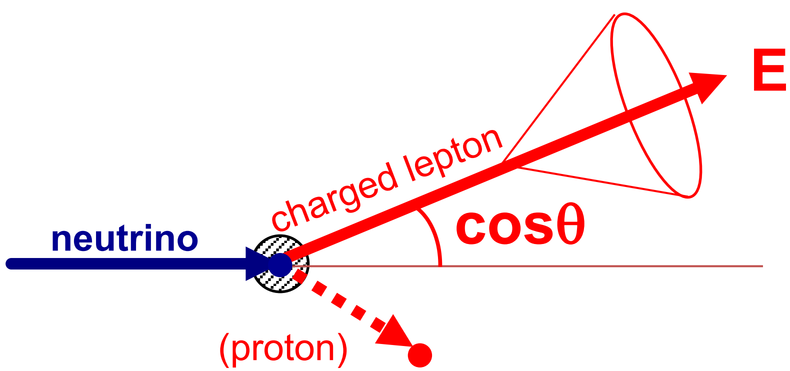
7. Conclusion

4. Charged current quasi-elastic (CCQE) scattering

Event reconstruction

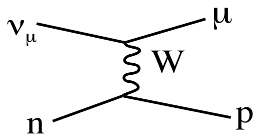
- From measured time and charge information from all PMTs, particle identification (PID) and kinematics are reconstructed
- From reconstructed charged lepton kinematics, neutrino energy is reconstructed

$$E_{\nu}^{QE} = \frac{ME - 0.5m_l^2}{M - E + pcos\theta}$$



CCQE is the most abundant interaction at ~1 GeV.

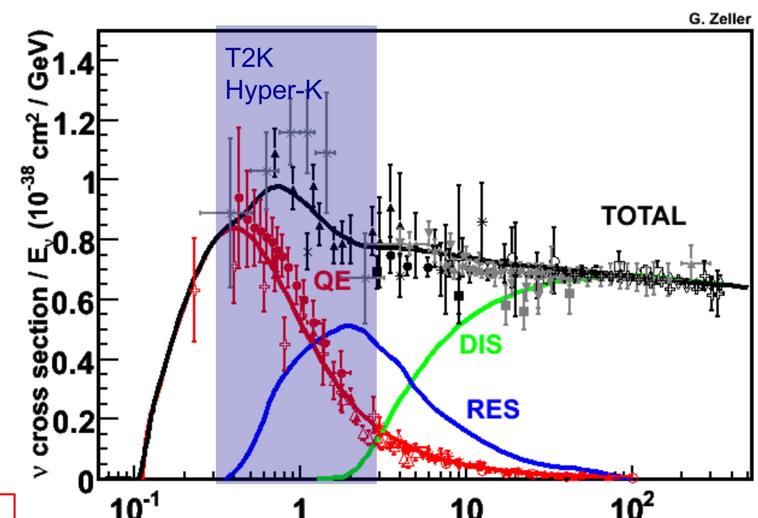
$$\nu_\mu + n \rightarrow \mu^- + p$$
$$(\nu_\mu + X \rightarrow \mu^- + X')$$



Neutrino energy is reconstructed from the observed lepton kinematics

"QE assumption"

1. assuming neutron at rest
2. assuming interaction is CCQE (2-body kinematics)



ν_μCC cross section per nucleon E_ν (GeV)

All neutrino cross-section channels (including CCQE) have large error

Martini et al,PRC80(2009)065501, TK, Martini, JPhysG45(2017)1

4. CCQE puzzle

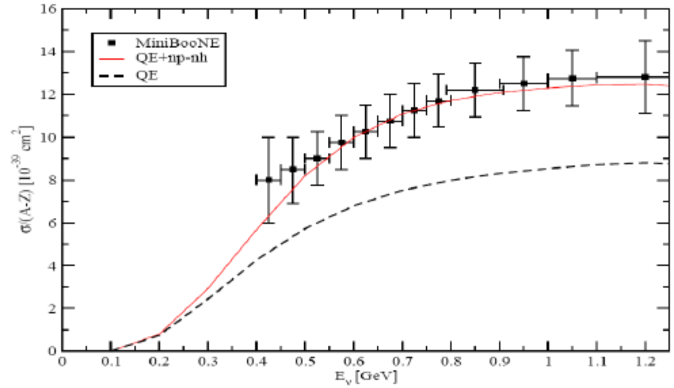
Nuclear correlations

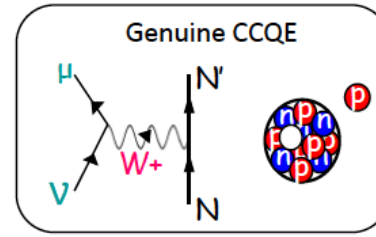
- Martini et al pointed out that neutrino interactions around 1 GeV can be modified ~30% by correlated nucleons (2p2h, 2-body current, meson exchange current, etc)

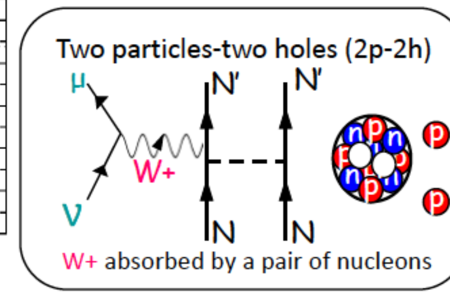
A large community effort (both theorists and experimentalists) to understand the role of nucleon correlations in neutrino interaction physics.

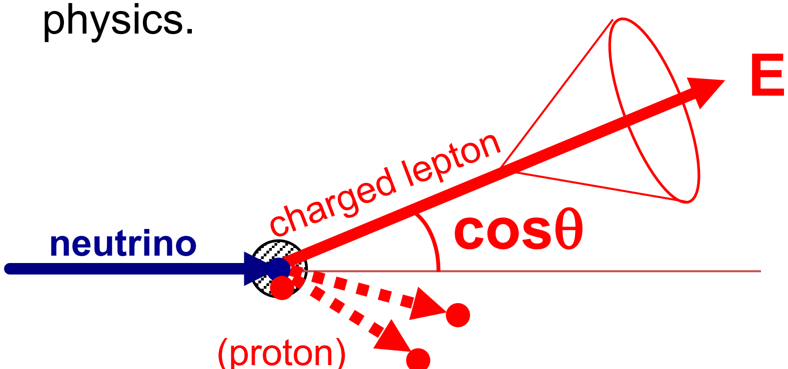
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



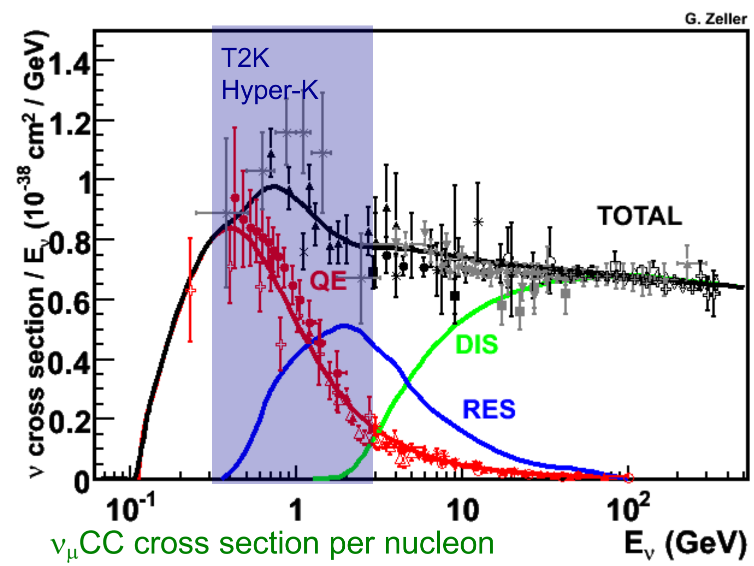






It's not 2-body kinematics

$$E_\nu^{QE} \neq \frac{ME - 0.5m_l^2}{M - E + p\cos\theta}$$



ν_μCC cross section per nucleon

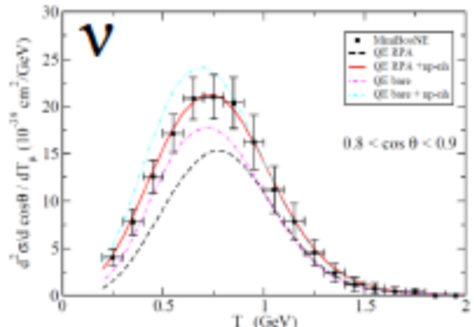
4. CCQE puzzle (2019)

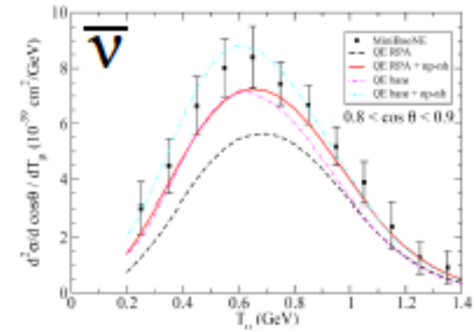
Advanced nuclear models can reproduce MiniBooNE CCQE-like data, but there are large systematics errors on nuclear parameters.

Martini – RPA+2p2h
Nieves – Valencia 2p2h model
SuSA – Superscaling+MEC
Giusti – Relativistic Green's function
Butkevich – RDWIA+MEC

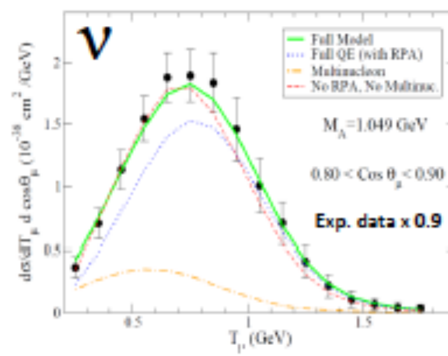
We use Valencia 2p2h model for our simulation

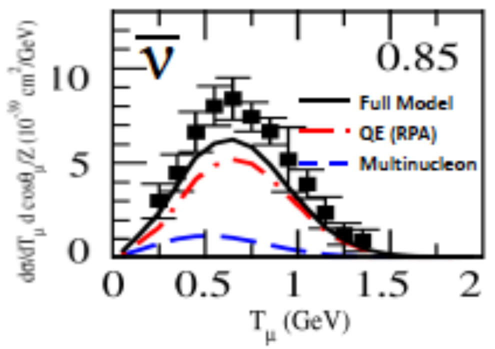
Martini et al



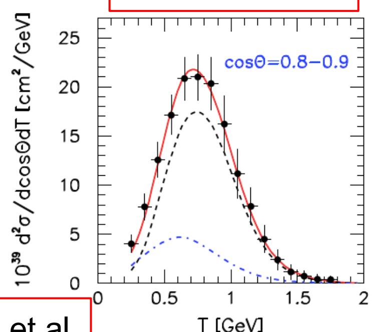


Valencia

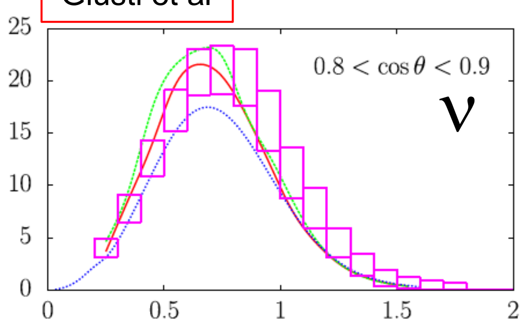




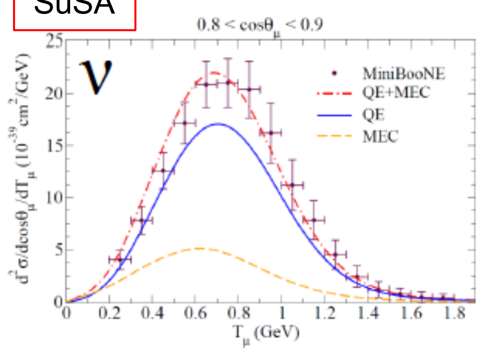
Butkevich et al

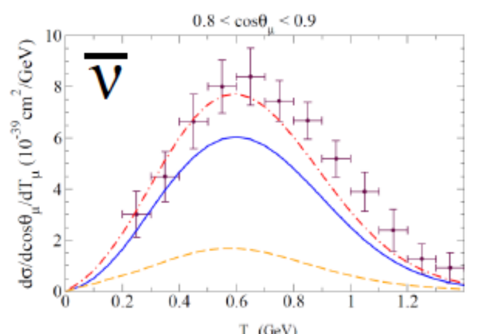


Giusti et al



SuSA





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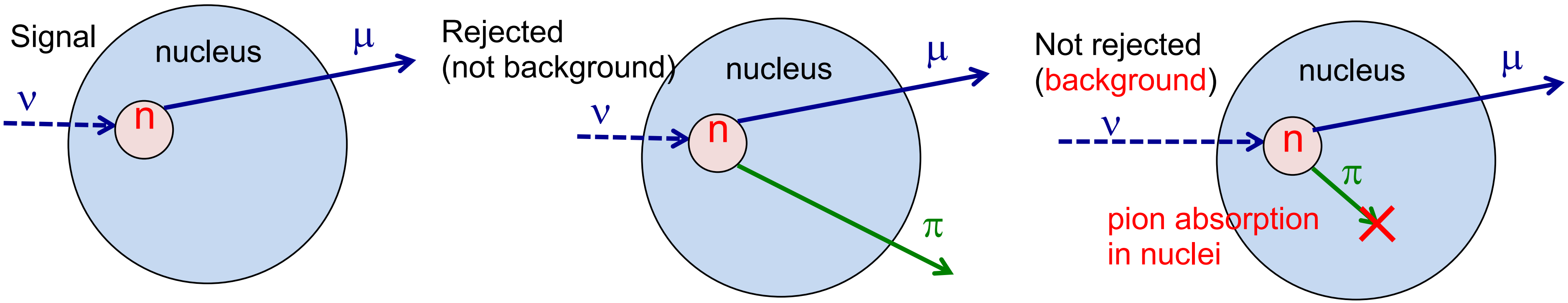
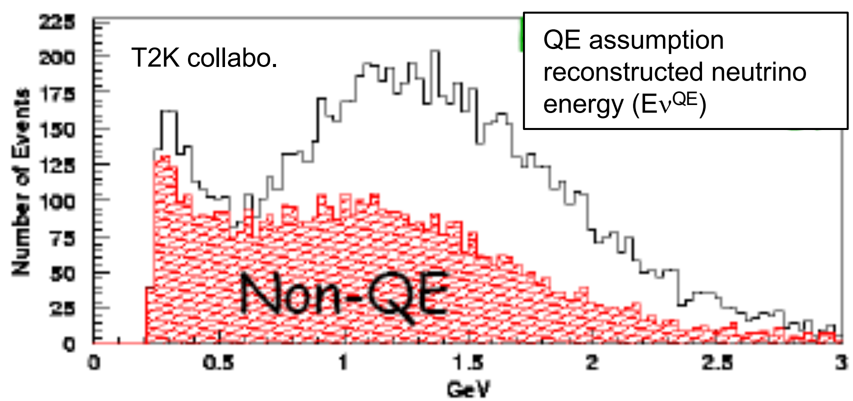
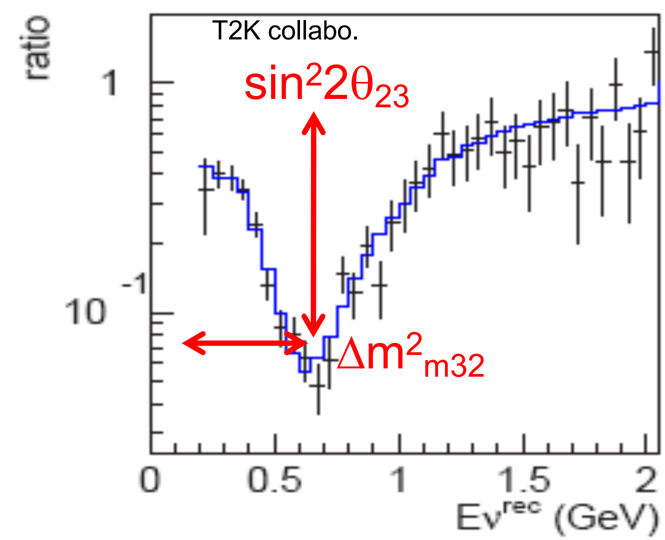
4. Neutrino-induced single pion production

Baryon resonant pion production + final state interaction (FSI)
- Neutrino induced pion productions have large errors
- Final state interaction of hadrons have large errors



muon neutrino disappearance simulation

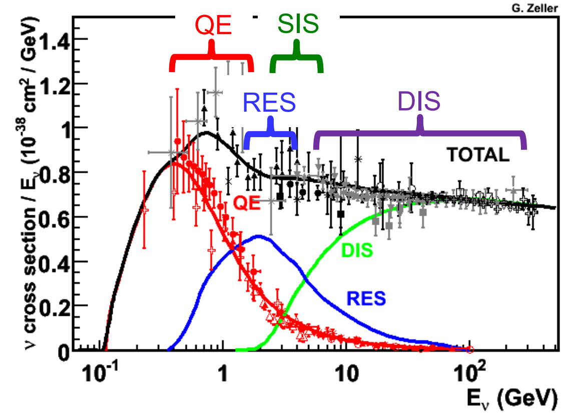




katori@fnal.gov

MINERvA,PRD100(2019)072005
MiniBooNE,PRD83(2011)052009, Lalakulich et al,PRC87(2013)014602

4. Pion puzzle (2019)



MINERvA simultaneous fit for 4 different data set

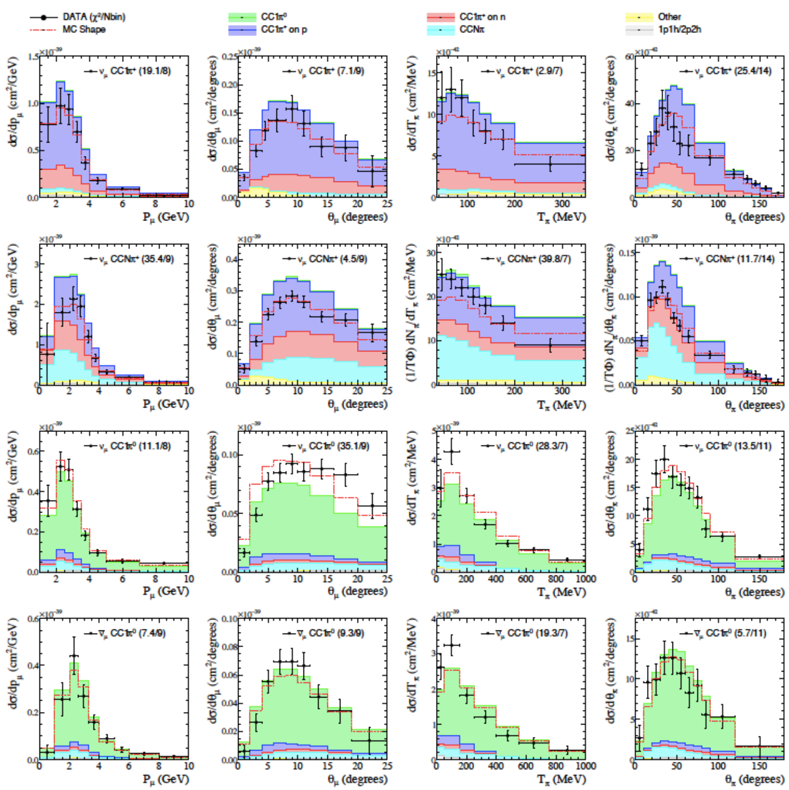
- Most advanced study in this community
- Not conclusive on baryon resonance and FSI models

$\nu_\mu CC1\pi^+$

$\nu_\mu CCN\pi^+$

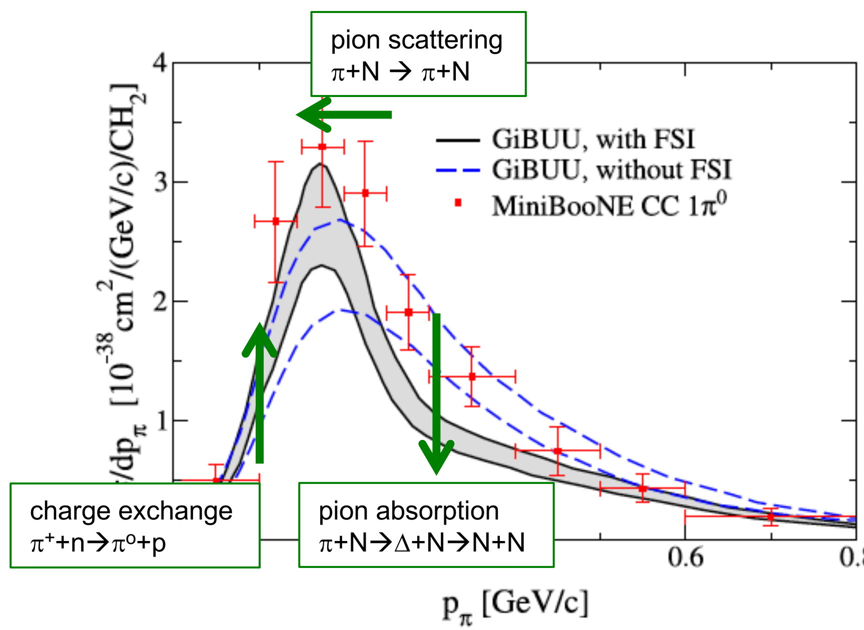
$\nu CC1\pi^o$

$\bar{\nu} CC1\pi^o$



GiBUU vs. MiniBooNE CCπ^o data

- You need to simulate both CCπ^o and CC$\pi^\pm$, and FSI including inelastic scattering, charge exchange, pion absorption



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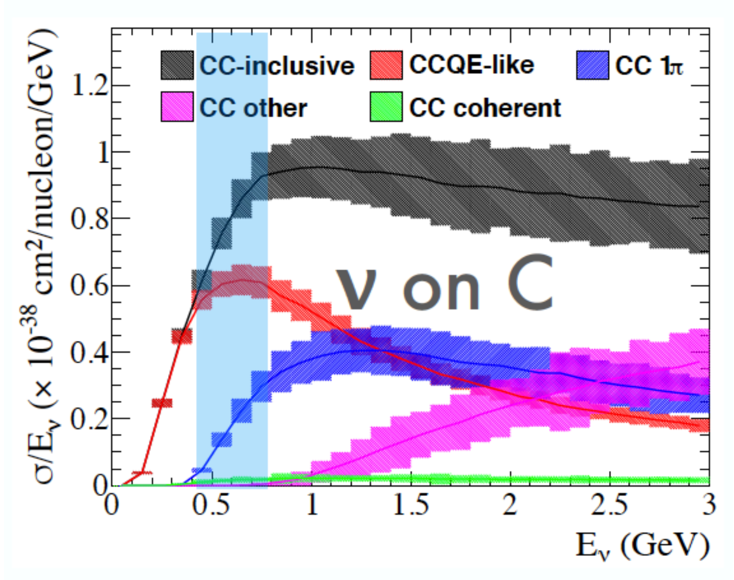
4. Neutrino interaction physics, external data constraints

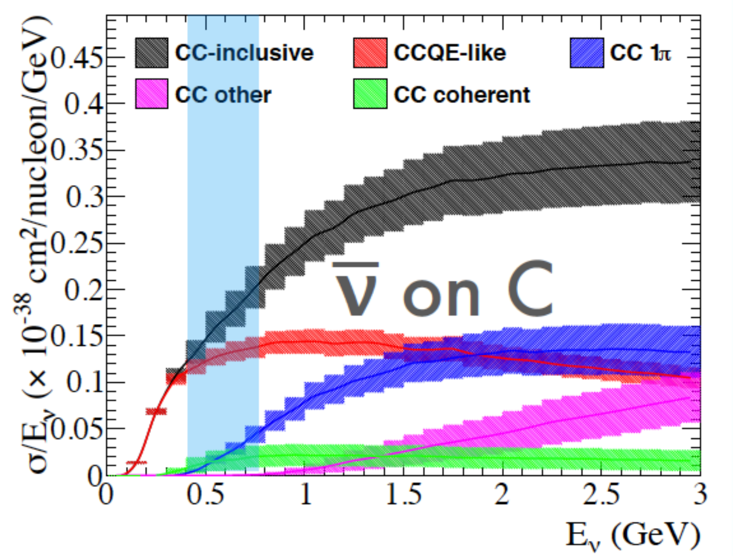
We accept large systematic errors on neutrino interaction models

We need to constrain these errors internally, using the data from the ND280 near detector data

PDG (2019)
Section 42. Monte Carlo Neutrino Generators
Section 50. Neutrino Cross Section Measurements

NuSTEC (https://nustec.fnal.gov/)
New theory-experiment collaboration to promote neutrino interaction physics





1. Neutrino oscillation experiments

2. Neutrino beam

3. Neutrino detector

4. Neutrino interaction physics

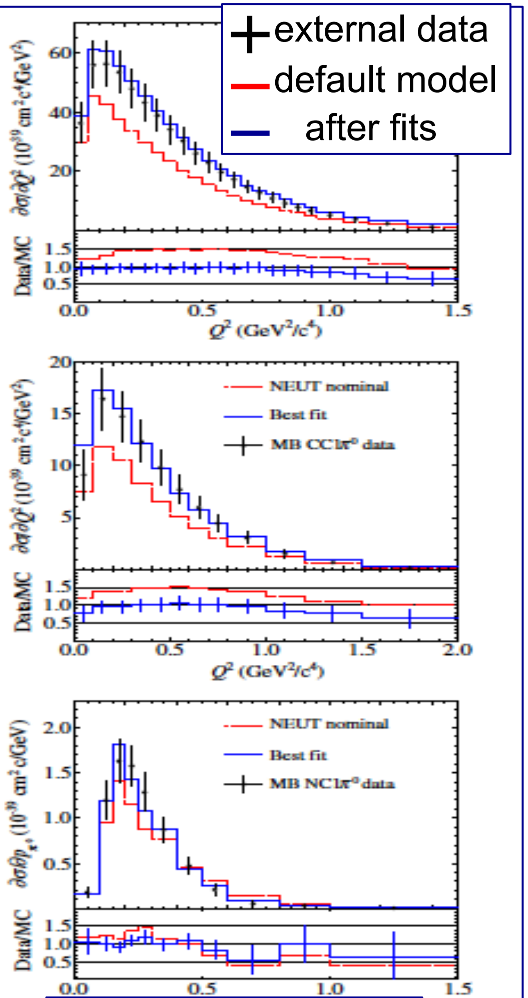
5. Oscillation result

6. SK-Gd, T2K-Upgrade, Hyper-Kamiokande

7. Conclusion

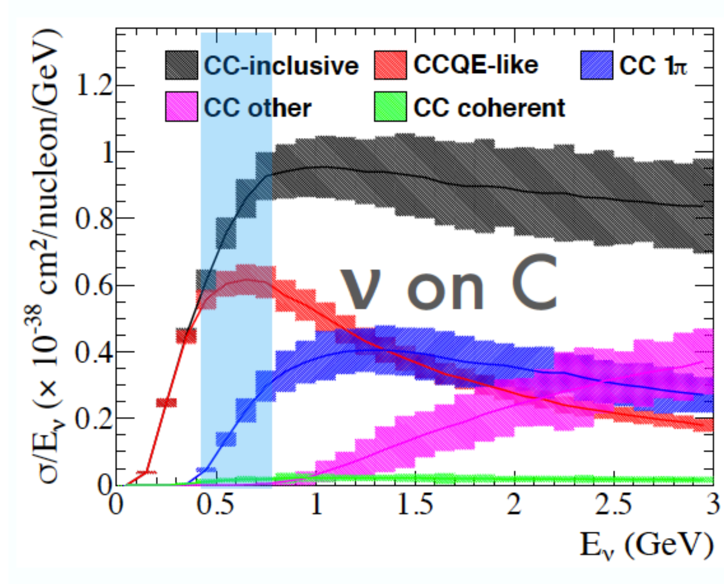
5. T2K oscillation results

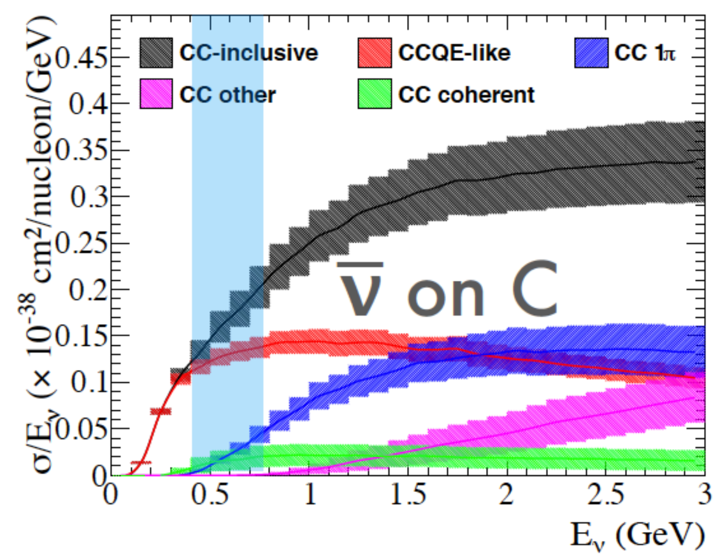
External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics





5. T2K oscillation results

External constraint

MiniBooNE, MINERvA, SciBooNE
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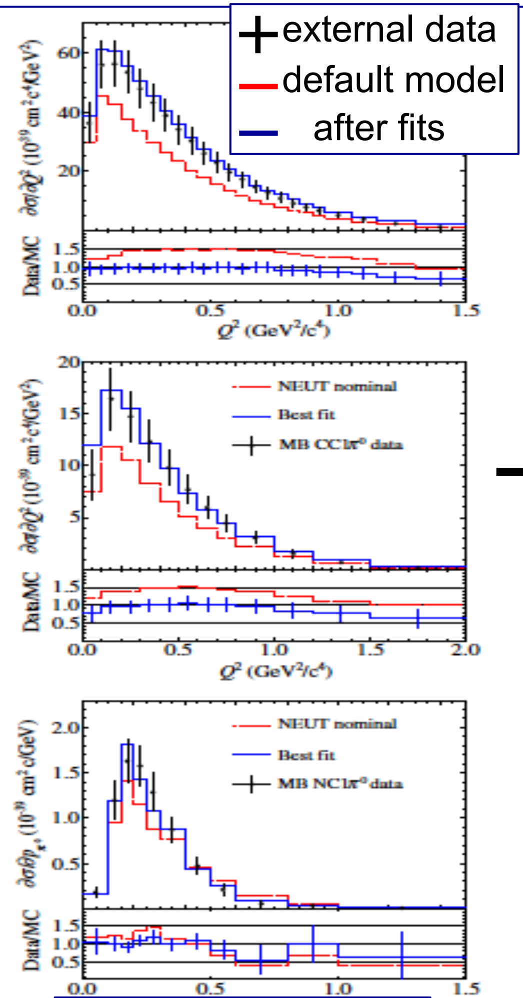
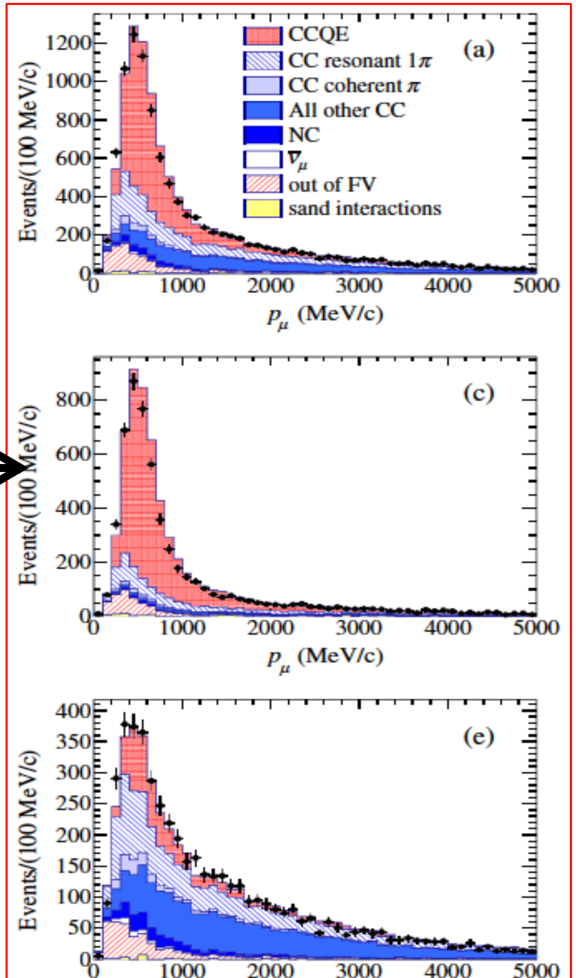


External data fit

Internal constraint

Near detector
oscillation non-sensitive channels

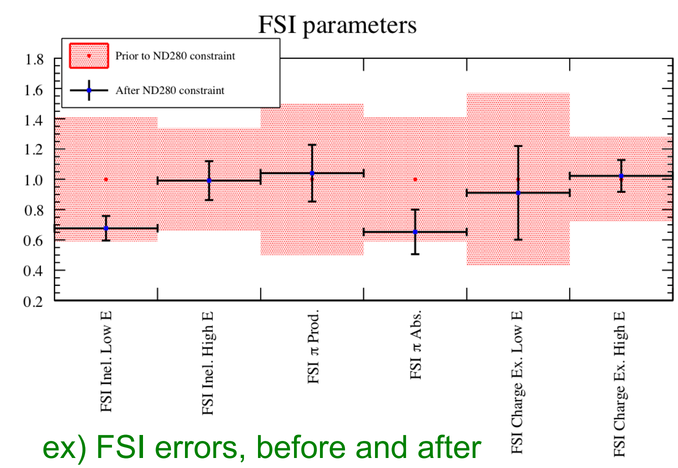


T2K ND280 data fit

Internal data can constrain systematic errors for the event rate (flux x cross-section)

SuperK sample systematic error

sample	Without ND280	With ND280
ν μ-like ring	14.6%	5.1%
ν e-like ring	16.9%	8.8%
$\bar{\nu}$ μ-like ring	12.5%	4.5%
$\bar{\nu}$ e-like ring	14.4%	7.1%



ex) FSI errors, before and after internal constraints

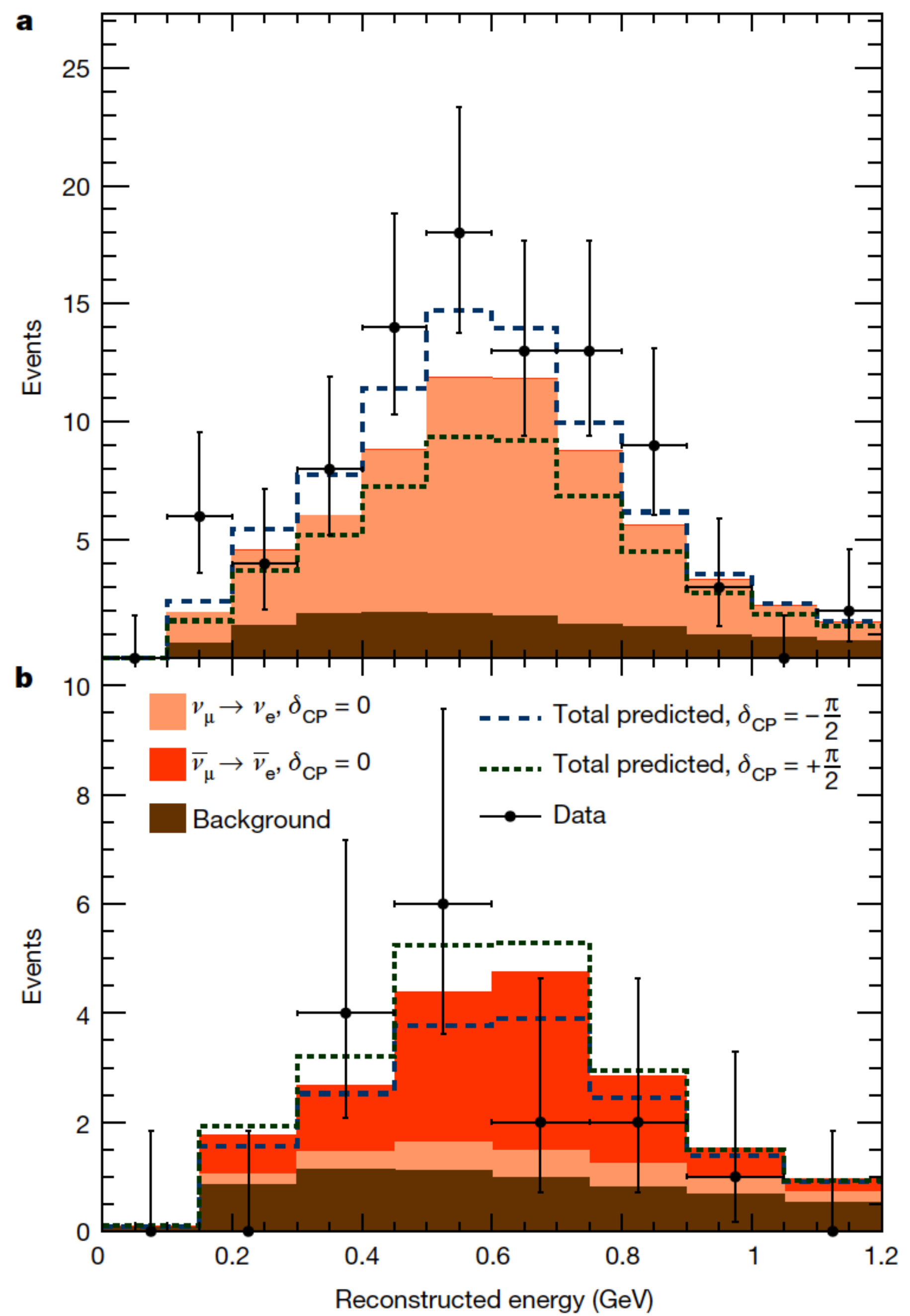
5. T2K oscillation results

SuperK data prefer a model with negative CP violation angle (~-π/2)

- Enhancement of $\mathrm{P}(\nu_\mu \rightarrow \nu_e)$
- Suppression of $\mathrm{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \rightarrow \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15



2009 – 2018 data

- Neutrino mode, 1.49E21 POT
- Antineutrino mode, 1.64E21 POT

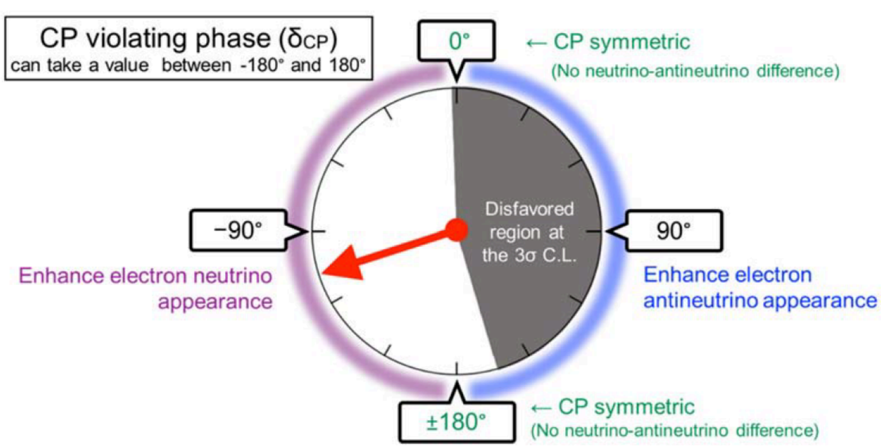
5. T2K oscillation results

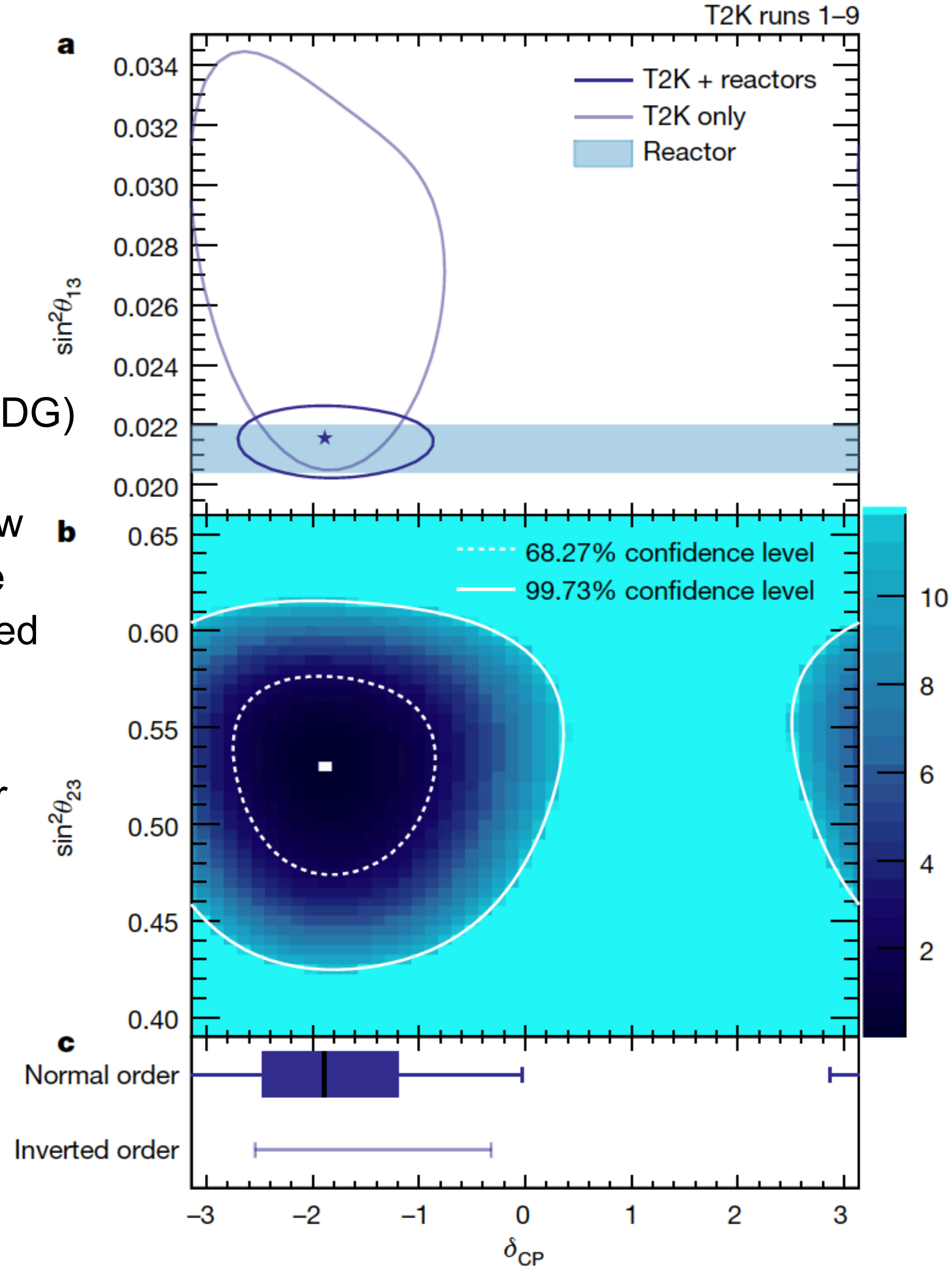
All oscillation parameters are fit by assuming normal or inverted mass ordering.

- δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32} : flat prior
- $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, Δm^2_{21} : external constraint (PDG)

Now the 3σ contour is closed, more data or new generation experiments can find the right value from here (Note, zero CP violation is not rejected with 3σ).

Normal ordering is favoured with 89% posterior probability.





1. Neutrino oscillation experiments

2. Neutrino beam

3. Neutrino detector

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6. SK-Gd, T2K-Upgrade, Hyper-Kamiokande

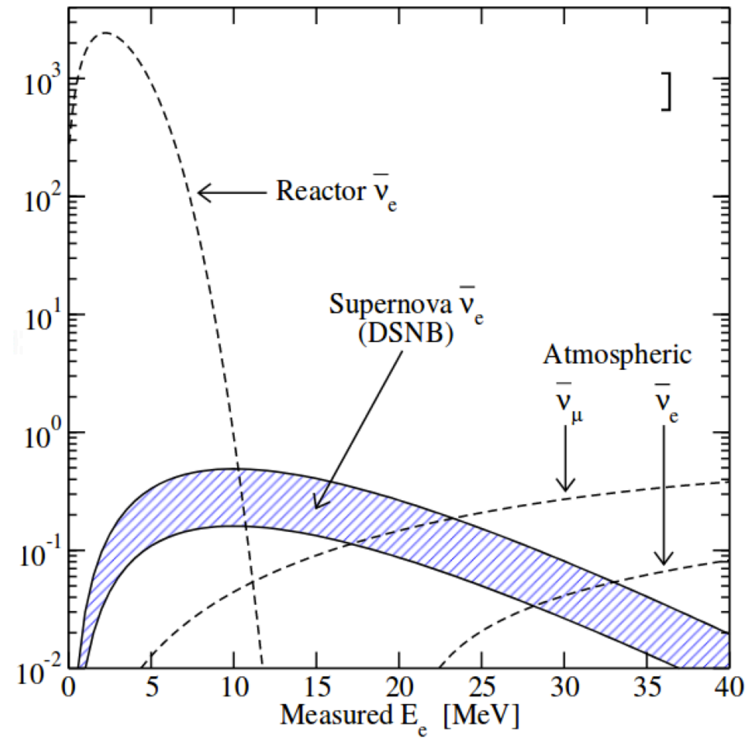
7. Conclusion

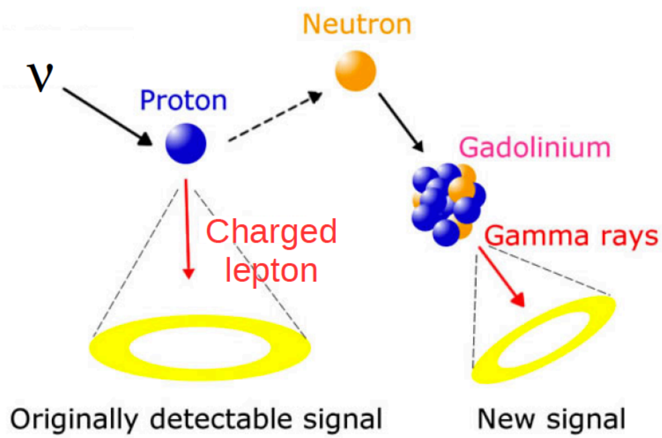
Beacom and Vagins, PRL93(2004)171101
TK, Martini, JPhysG45(2017), TITUS, ArXiv:1606.08114

6. SK-Gd

SuperK is planned to be doped with 0.1% of Gd

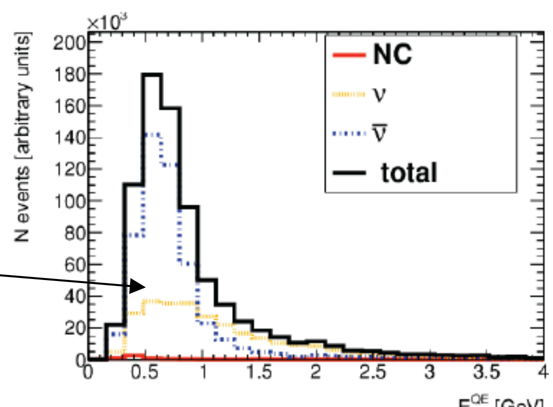
This improves neutron tagging efficiency to be ~90%, making SK-Gd to be visible for DSNB (diffused supernova neutrino background).



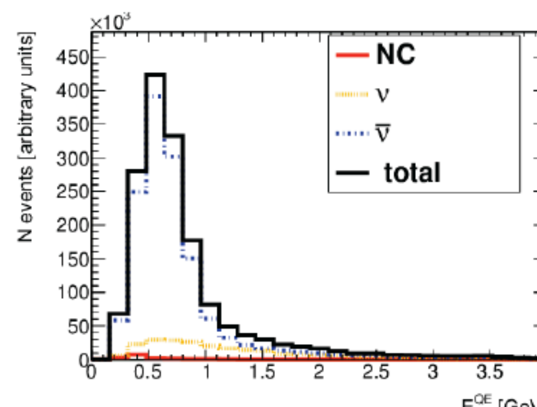


Neutron tagging is also useful to suppress background for antineutrino oscillation measurements.

Antineutrino beam has large background of neutrinos (wrong-sign background)

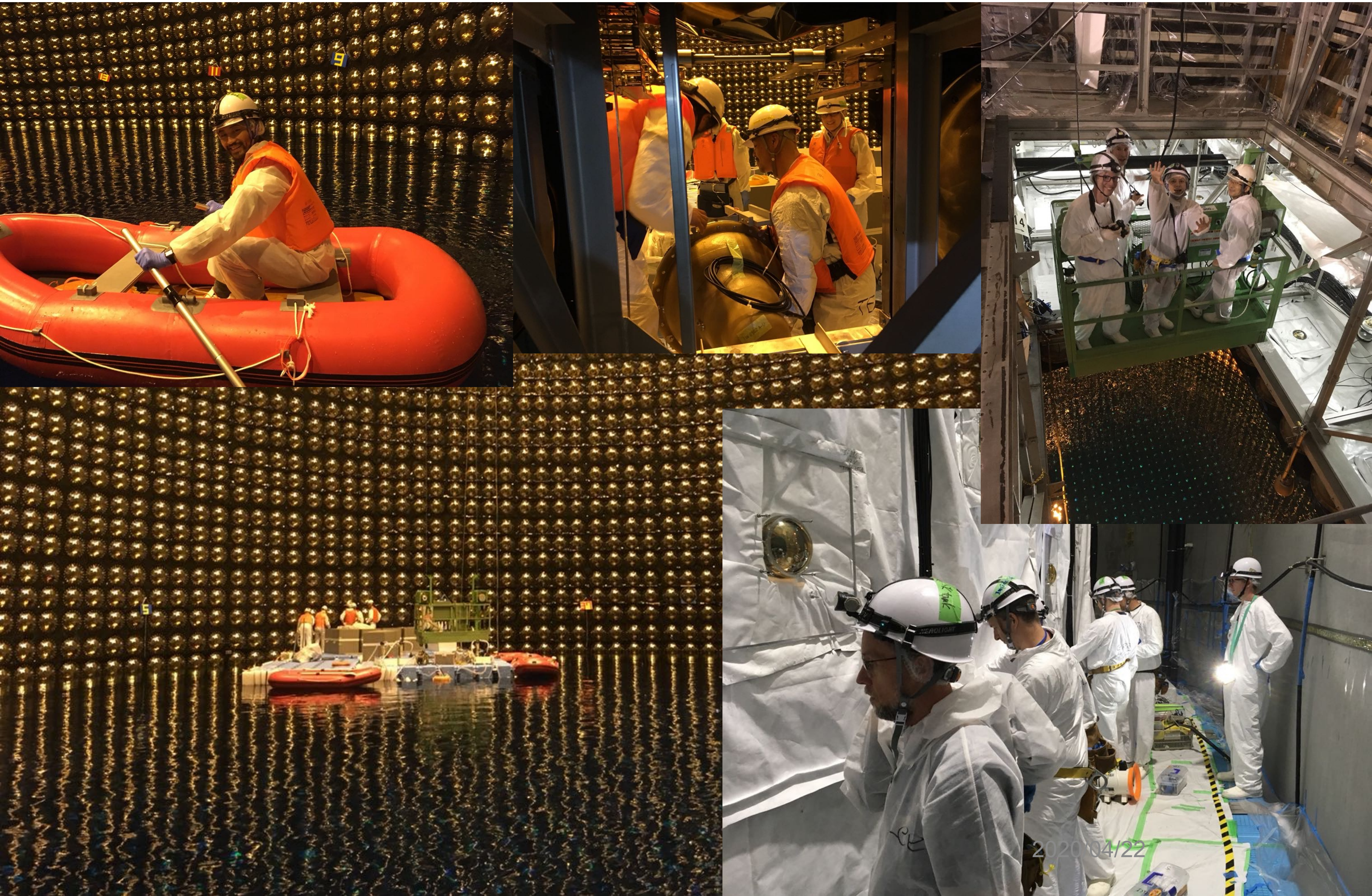


(b) $N_{\mathrm{neutrons}} = 0$



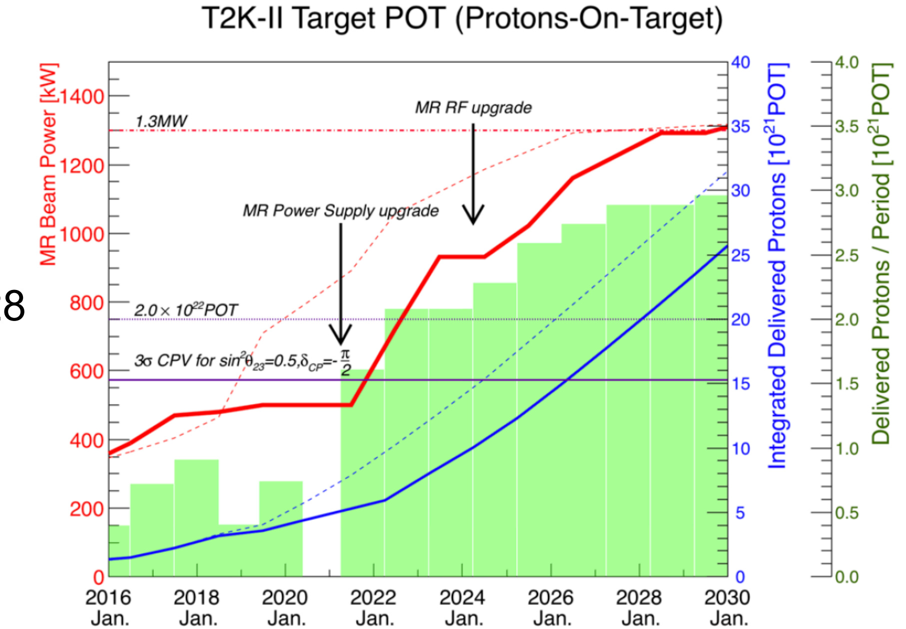
(c) $N_{\mathrm{neutrons}} \geq 1$

Super-Kamiokande detector refurbishment 2018



T2K, ArXiv:1908.05141
Kikutani (T2K), JPS2020

6. T2K upgrade

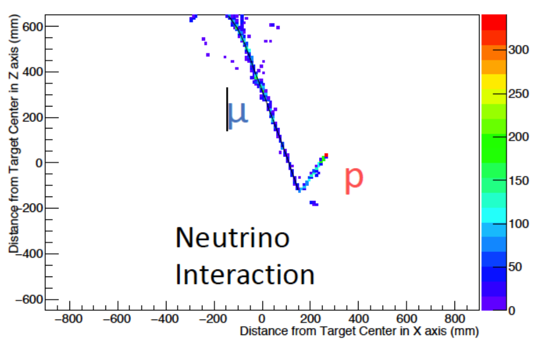


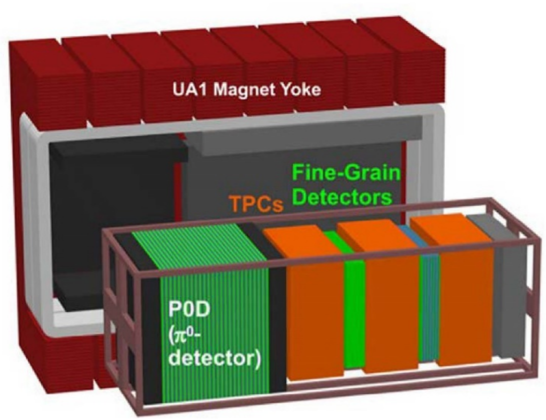
J-PARC neutrino beam upgrade

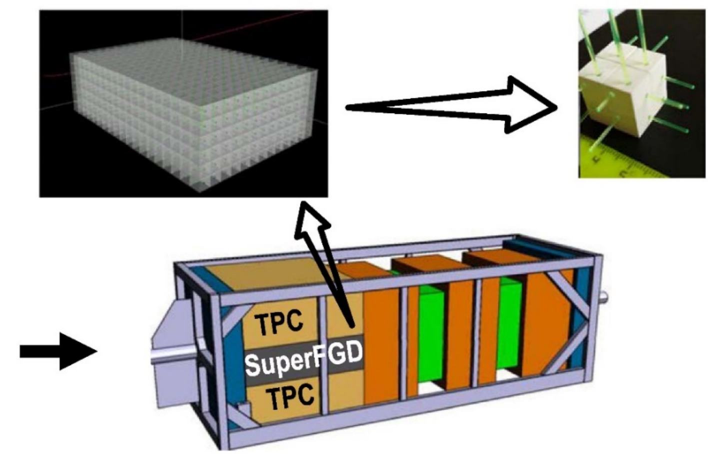
- Current beam power is ~ 500kW
- Beam power will be increased to 1.3MW in ~2028
- 2.48 sec period → 1.16 sec period
- 2.6E14 ppp → 3.2E14 ppp

ND280 detector upgrade

- P0D is replaced with new detectors
- SuperFGD: 3-d scintillator tracker
- High pressure gas TPC: high-angle event measurement





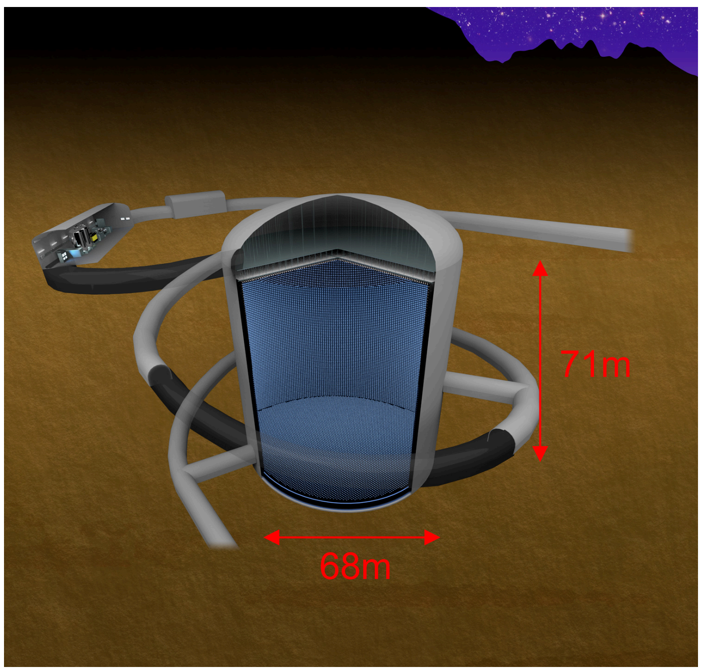


HyperK, ArXiv:1805.04163
Nakayama (HyperK), JPS2020

6. Hyper-Kamiokande

260 kton water Cherenkov tank

- ~x8.4 fiducial volume of SuperK
- Construction starts in this year!
- MeV to TeV physics
- solar, atmospheric, beam neutrinos
- proton decay, new physics search



HiggsTan
https://higgstan.com/

3,000 ton | 50,000 ton | 260,000 ton

~1,000 PMTs | ~11,000 PMTs | ~40,000 PMTs

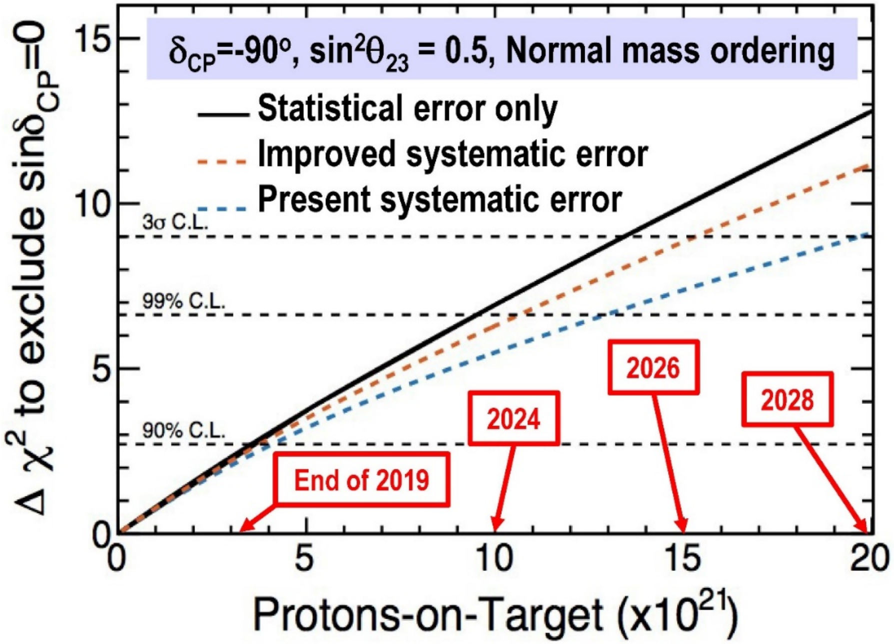
Kamiokande
1983 start
2002

Super-Kamiokande
1996 start
2015

Hyper-Kamiokande
2020 construction start
2027 data taking (plan)
???

HyperK, ArXiv:1805.04163
Nakayama (HyperK), JPS2020, Playfer (HyperK), NuPhys2019

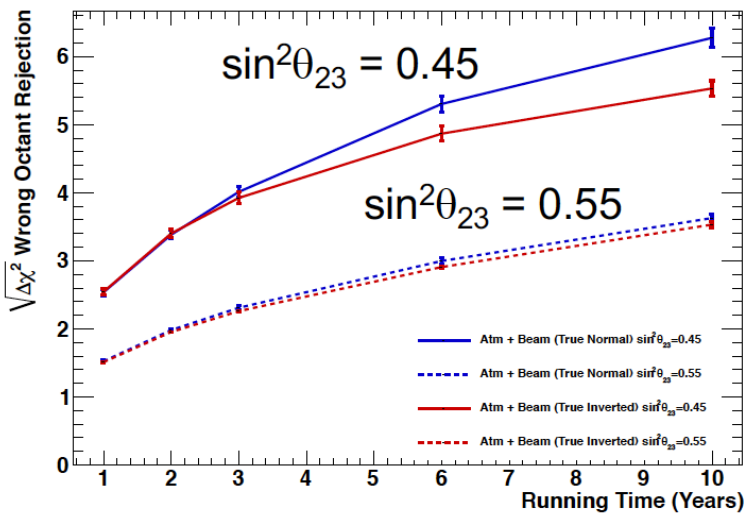
6. Hyper-Kamiokande

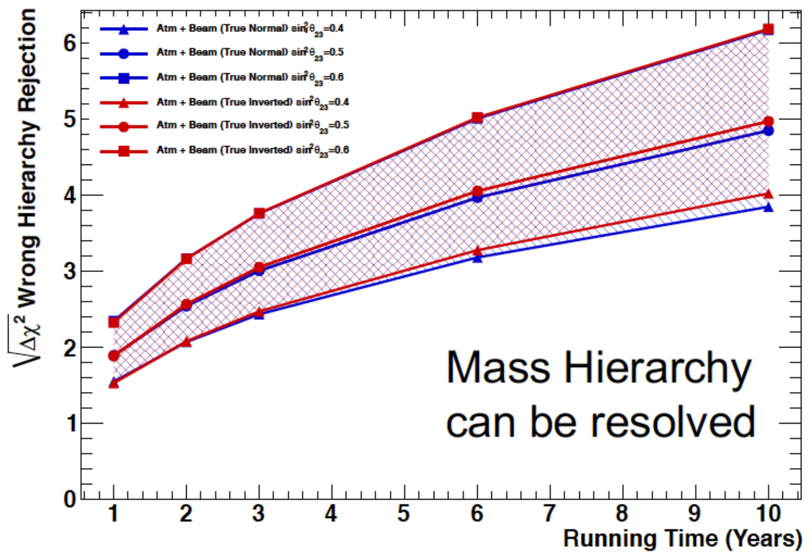


Oscillation program

- 5σ δ_{CP} measurement depends on systematic error reduction
- mass ordering is determined through atmospheric neutrinos
- θ_{23} will be measured

HyperK will find all oscillation parameters!



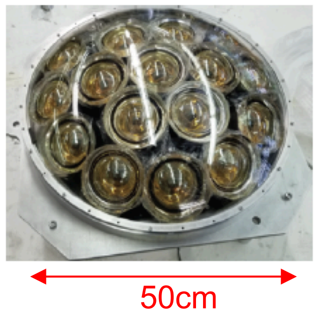


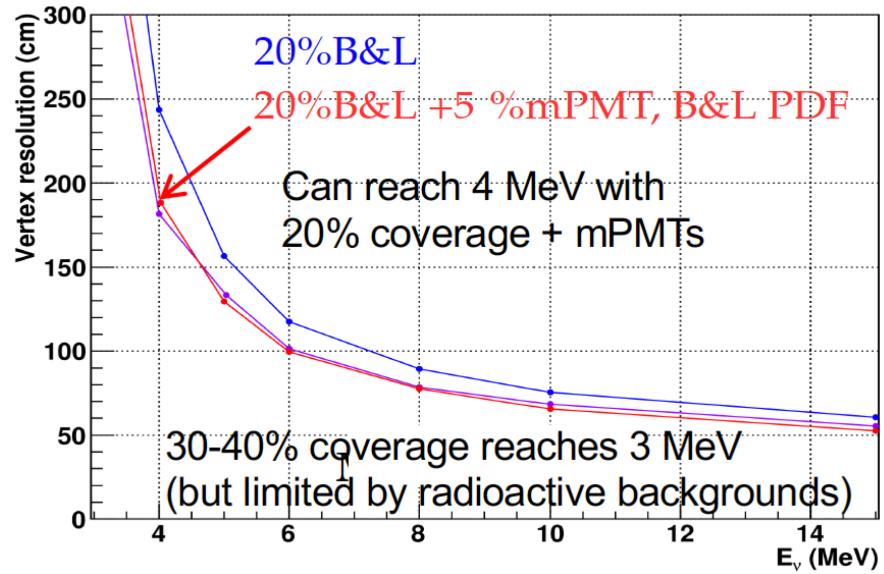
HyperK, ArXiv:1805.04163
Nakayama (HyperK), JPS2020, Playfer (HyperK), NuPhys2019

6. Hyper-Kamiokande

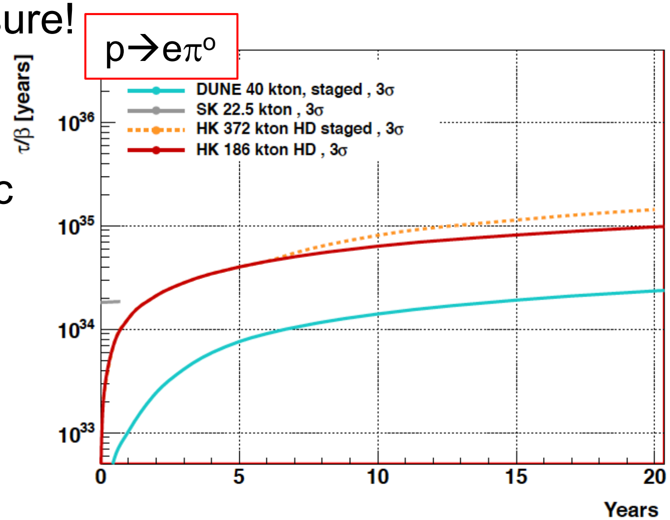
Solar neutrino
- Need low PMT dark rate
- mPMT helps a lot

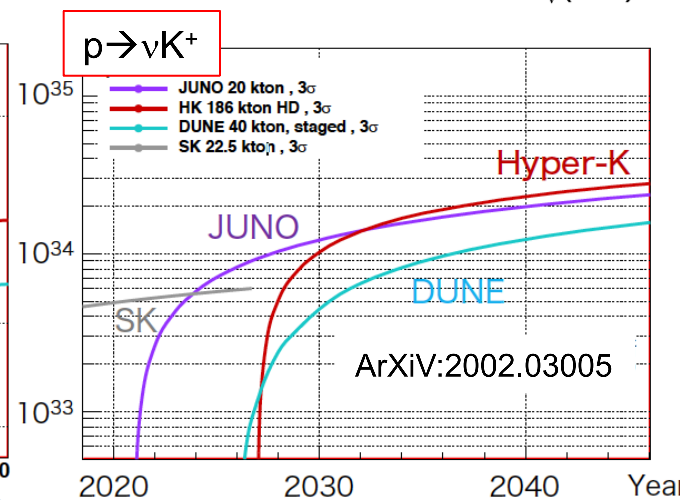
mPMT prototype



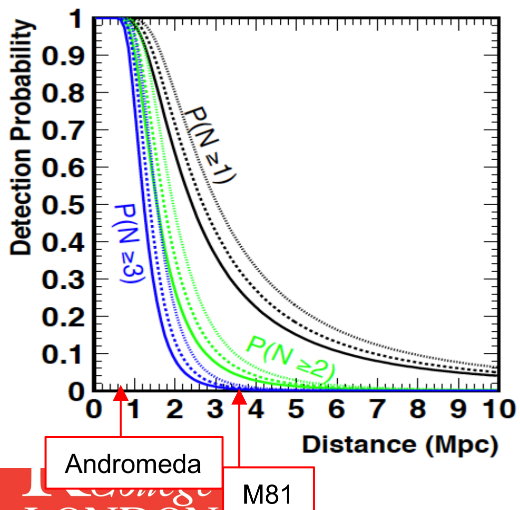


Proton decay
- 3σ sensitivity in 20yrs
- $p \rightarrow e\pi^0$, τ~1E35yr
- $p \rightarrow \nu K^+$, τ~2E34yr
- Many channels to measure!





Supernova neutrinos
- Search extends to ~Mpc



Future of T2K, SK-Gd, T2K-upgrade, and Hyper-Kamiokande are very bright!

Conclusion

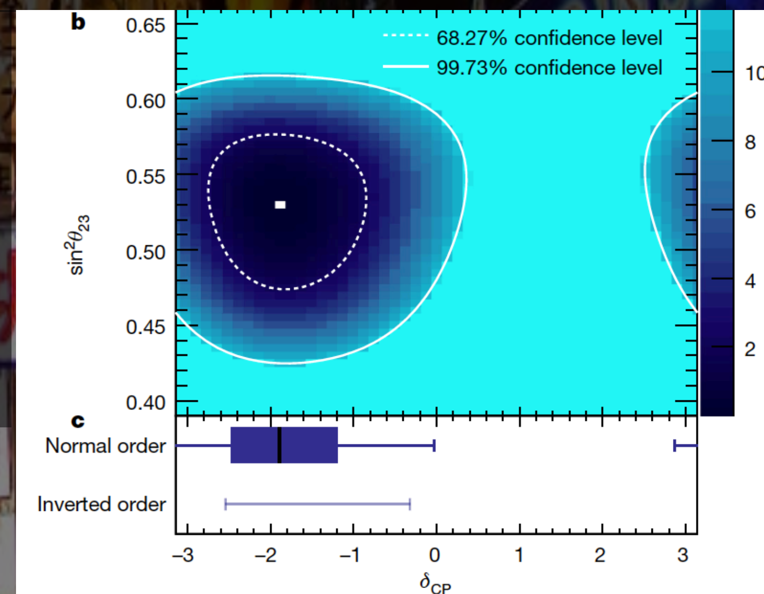
T2K is the second generation long-baseline neutrino oscillation experiment in Japan

Neutrinos from the J-PARC neutrino beam are measured by the Super-Kamiokande detector

2009-2018 data shows asymmetric oscillations, and neutrino oscillation is enhanced, and antineutrino oscillation is suppressed. This can be interpreted as negative CP violation phase.

δCP=0 is rejected more than 2σ, and 3σ interval is [−3.41, −0.03] (normal ordering), and [−2.54, −0.32] (inverted ordering)

The future plans include the SK-Gd, T2K-Upgrade, and Hyper-Kamiokande, and all of them are ongoing projects!



The T2K collaboration

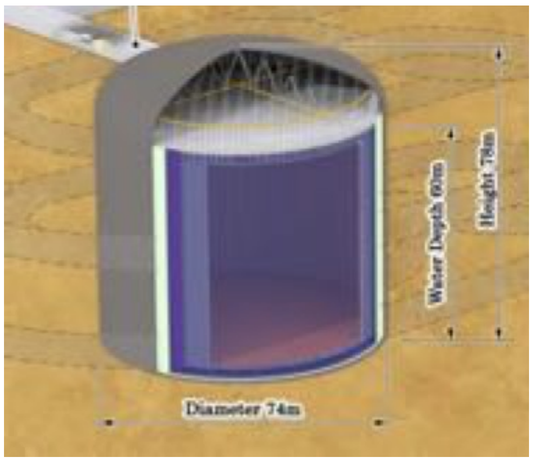
Thank you for your attention!

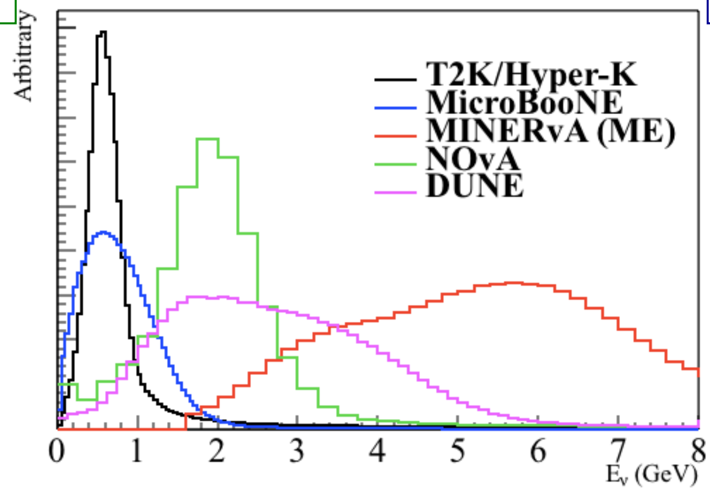
Backup

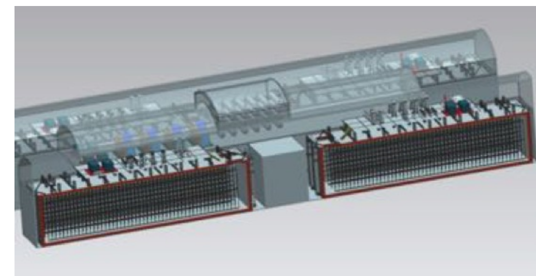
1. Next goal of high energy physics

Hyper-Kamiokande (Japan)
- Water target
- Narrow band 0.6 GeV
- Low spatial resolution
- High time resolution

DUNE (USA)
- Argon target
- wide band 1-4 GeV
- High spatial resolution
- Low time resolution







Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

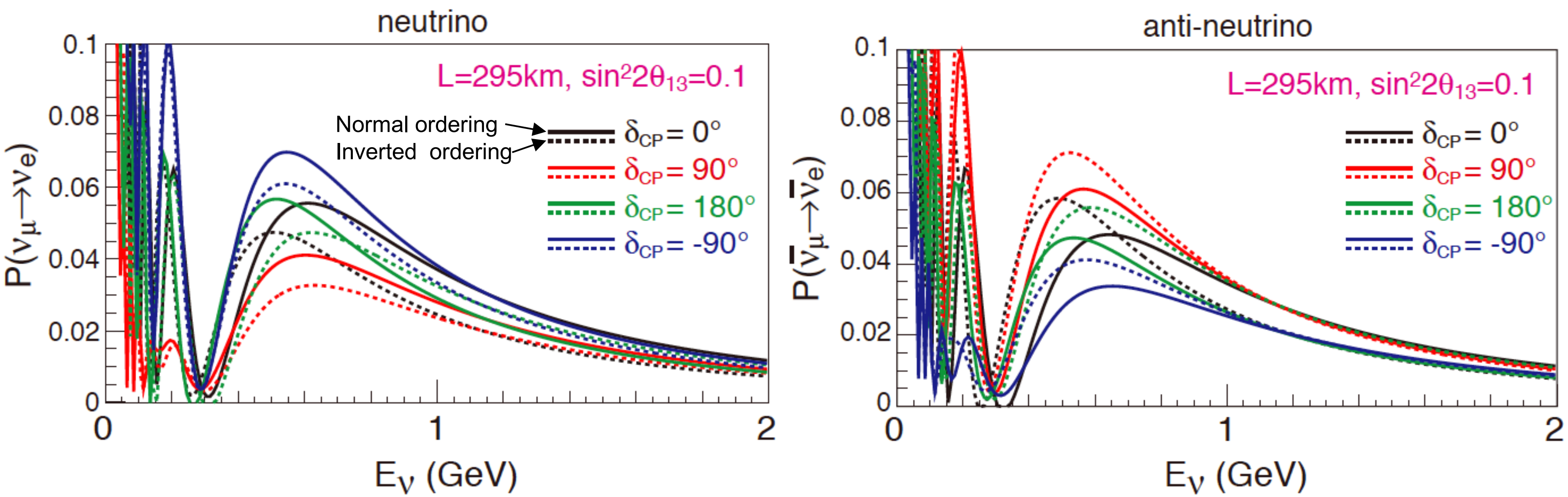
High energy beam (~few GeV)
- longer baseline (higher flux reduction)
- higher neutrino production
- higher interaction
- calorimetric energy reconstruction

$$P_{\mu\rightarrow e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. Neutrino oscillations

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \cdot \sin^2 \Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2s_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

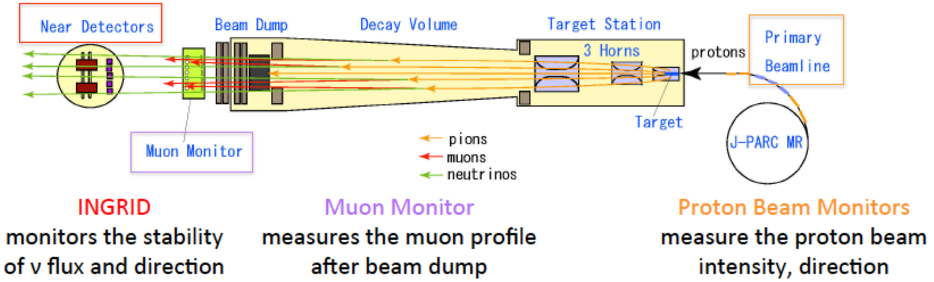
Normal ordering has a higher oscillation probability than inverted ordering for neutrino oscillation

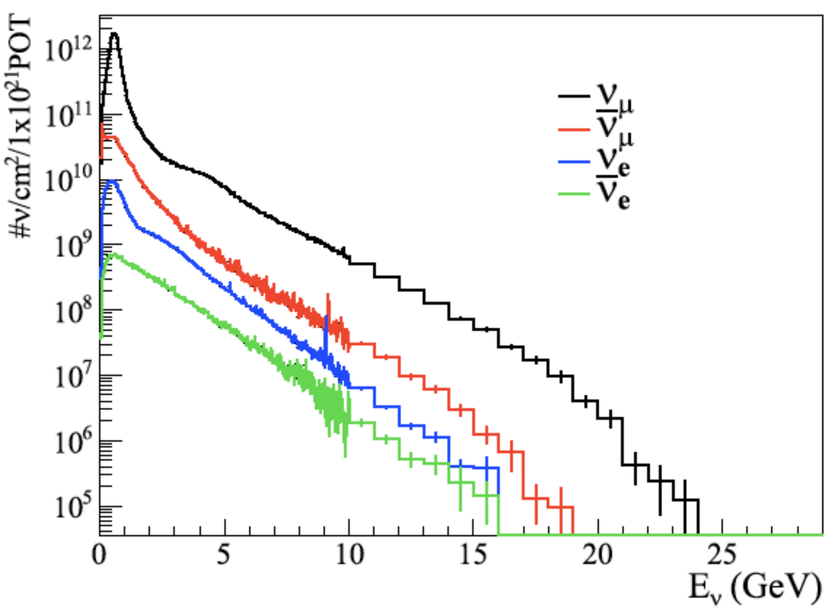


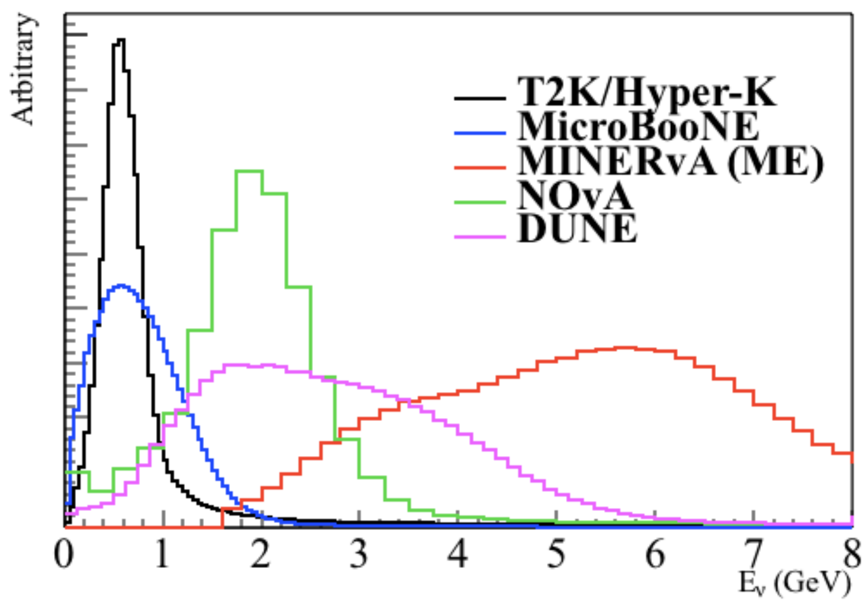
TK, Martini, JPhysG45(2017)1
Kowalik, NuInt16 (Toronto)

2. Typical neutrino beams for oscillation experiments

e.g.) J-PARC neutrino beam (T2K)
- pion decay-in-flight (high flux)
- off-axis beam (narrow band)
- but has components up to ~ 10 GeV
- typical beam 1-10 GeV
- ~5% normalization error (best case)







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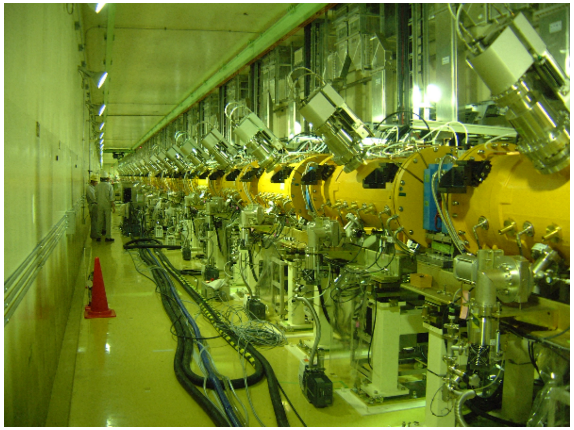
2. LINAC → RCS → MR → extraction



LINAC
- 1st stage
- 400 MeV

RCS (Rapid Cycling Synchrotron)
- 2nd stage
- 3 GeV, 25 Hz
- 4 beam pulse are extracted with 40ms intervals

Main Ring
- 3rd stage
- 30 GeV
- 8 bunches in 1 spill, 2.48 sec interval

Extraction beam line
- Supercoducting bending magnet

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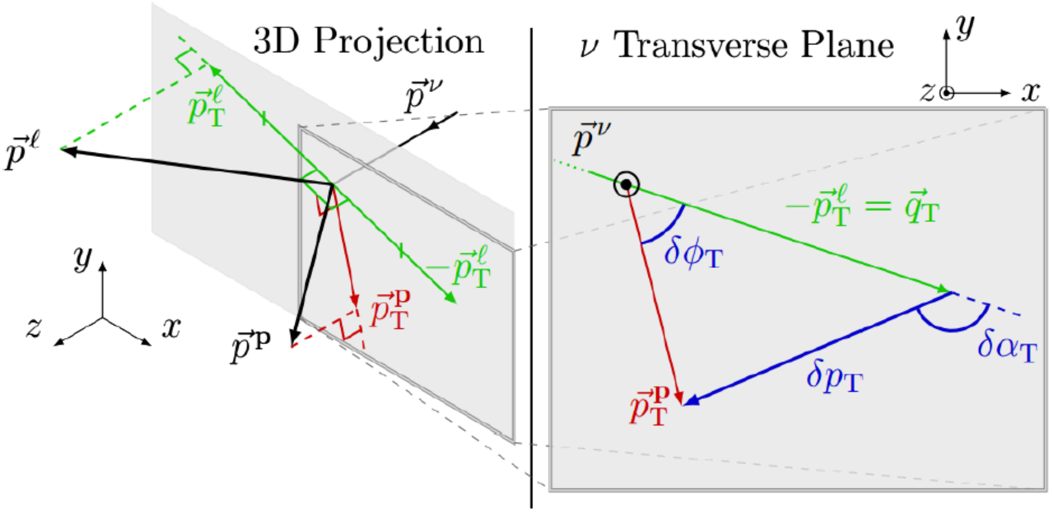
3. Off-axis detector



ND280

- P0D: Water-scintillator tracker
- FGD: Fully active scintillator tracker
- TPC: Ar gas TPC
- ECal: Lead-scintillator calorimeter
- SMRD: Iron-scintillator tracker
- UA1 magnet

Near detector data

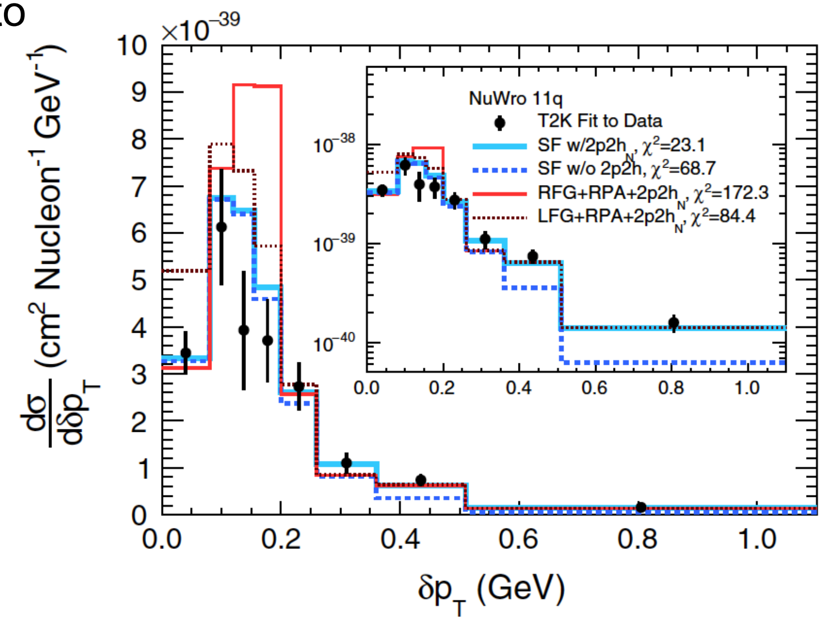
- 14 samples are used for the oscillation analysis to constrain flux and cross-section systematic errors

Neutrino cross section measurements

- many results are published
- neutrino interaction models are studied

ex) 1μ+1p measurement

- Data prefer advanced nuclear models



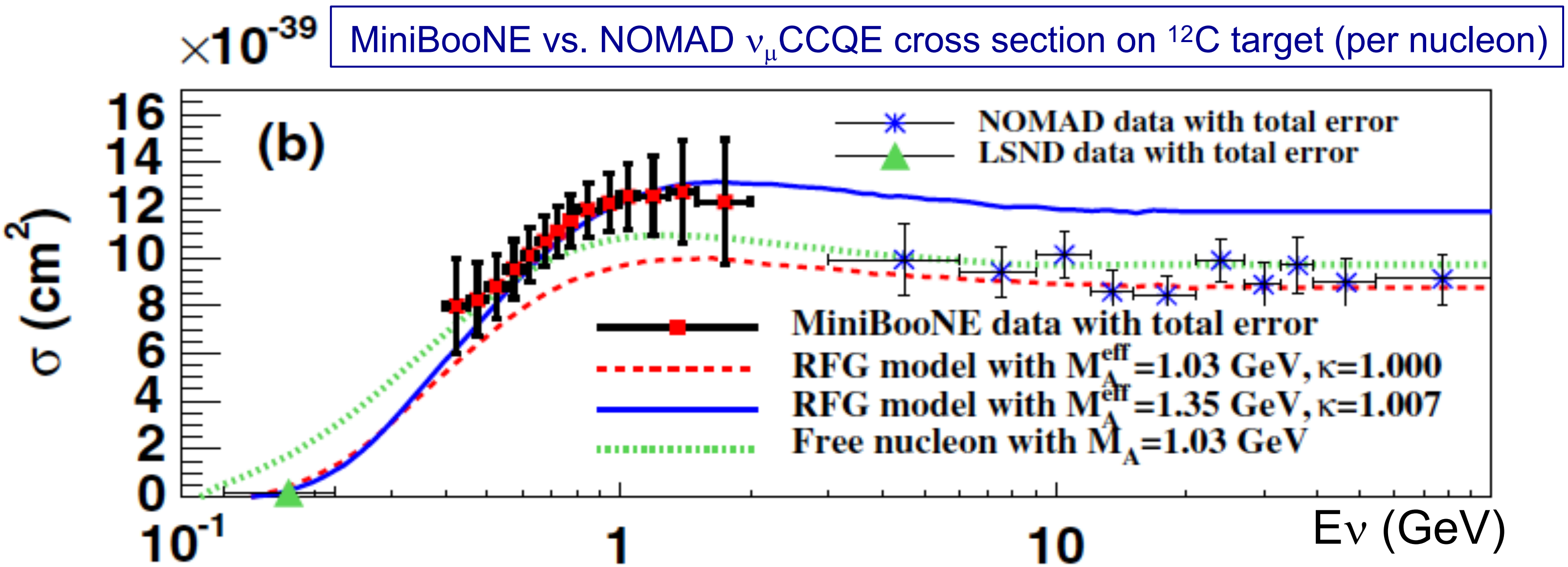
MiniBooNE,PRD81(2010)092005

4. Charged Current Quasi-Elastic scattering (CCQE)

CCQE puzzle

1. low Q2 suppression → Low forward efficiency? (detector?)
2. high Q2 enhancement → Axial mass > 1.0 GeV? (physics?)
3. large normalization → Beam simulation is wrong? (flux?)

CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality = precise prediction for neutrino CCQE cross-section...?



4. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation

This moment…
New nuclear models available in simulations do not quantitatively describe T2K and MINERvA CCQE μ+p data

large M_A error → large 2p2h error

It is crucial to have correct CCQE, 2p2h, pion production models to understand data simultaneously. Otherwise M_A error stays around 20-30%.

We have good theorists who make models, and good experimentalists who measure data, but we are still lacking people between them.

Ankowski et al, PRD92(2015)073014

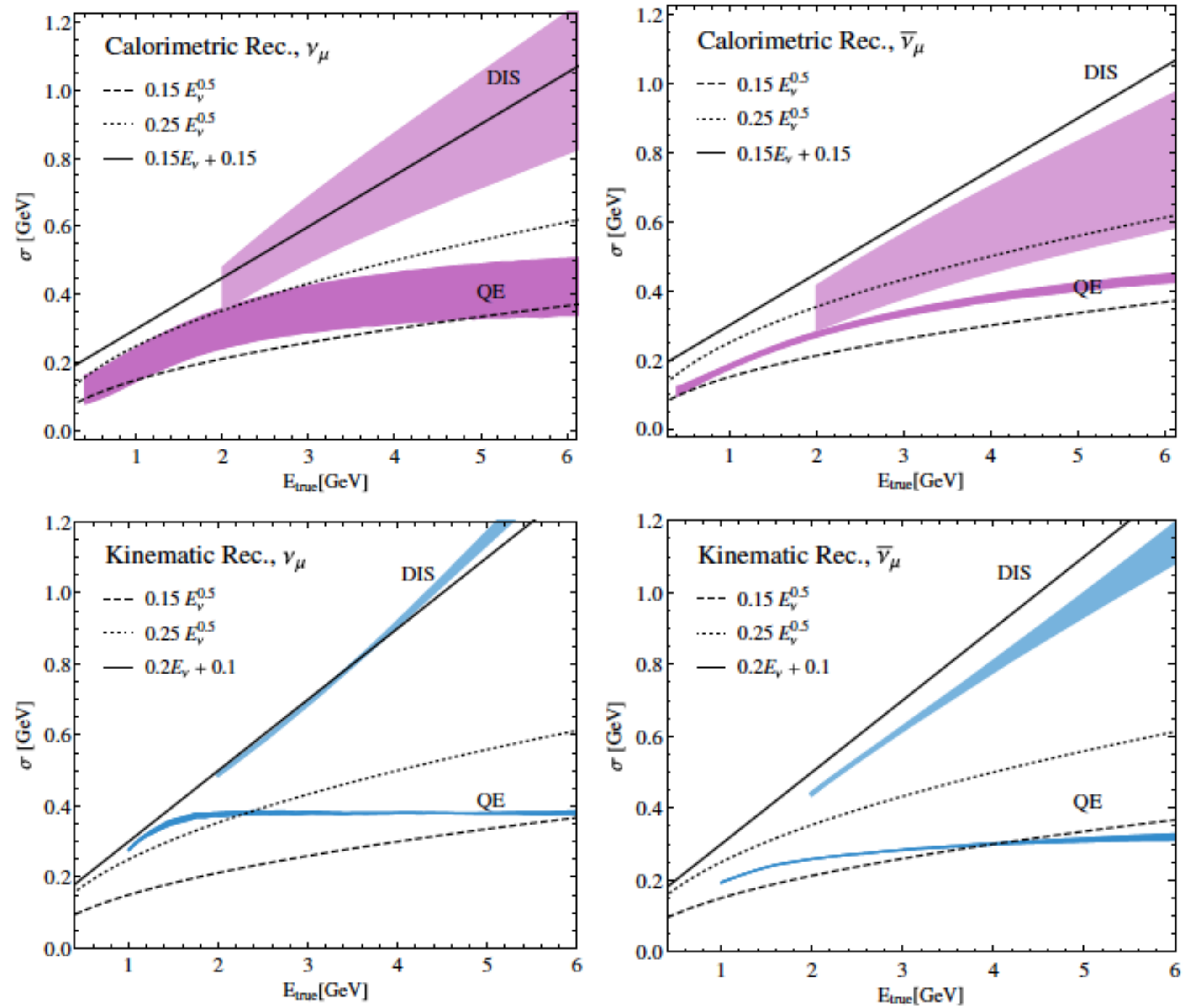
4. Kinematic E reconstruction vs calorimetric E reconstruction

Calorimetric energy reconstruction suffers invisible hadrons (=neutrons)

It largely depends on neutrino interaction and hadron simulation

- multiplicity
- kinematics
- nuclear effect
  - re-scattering
  - charge exchange
  - baryonic resonance
  - nucleon correlation

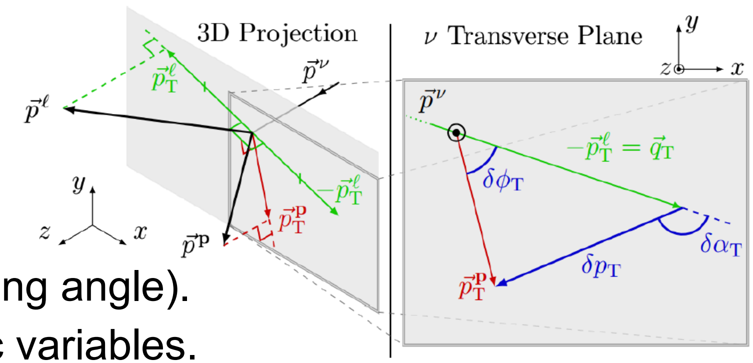
etc



T2K, PRD98(2018)032003
MINERvA,PRD121(2018)022504

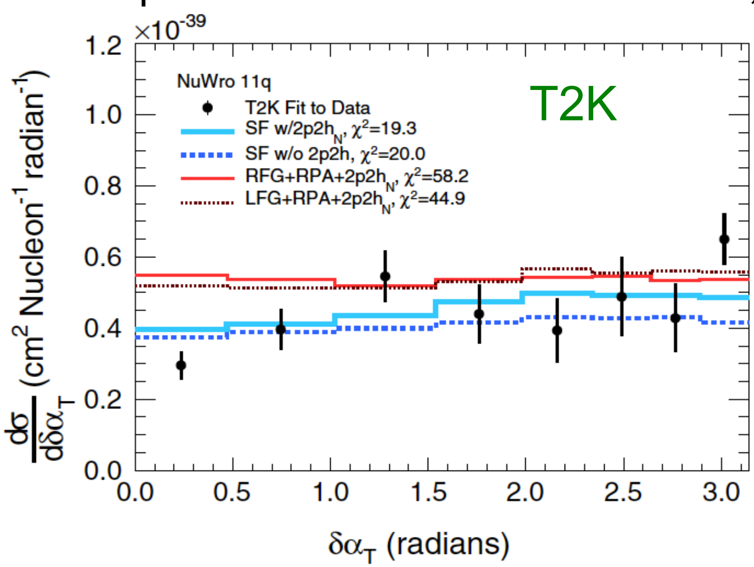
4. Neutrino hadron measurement for nuclear correlations

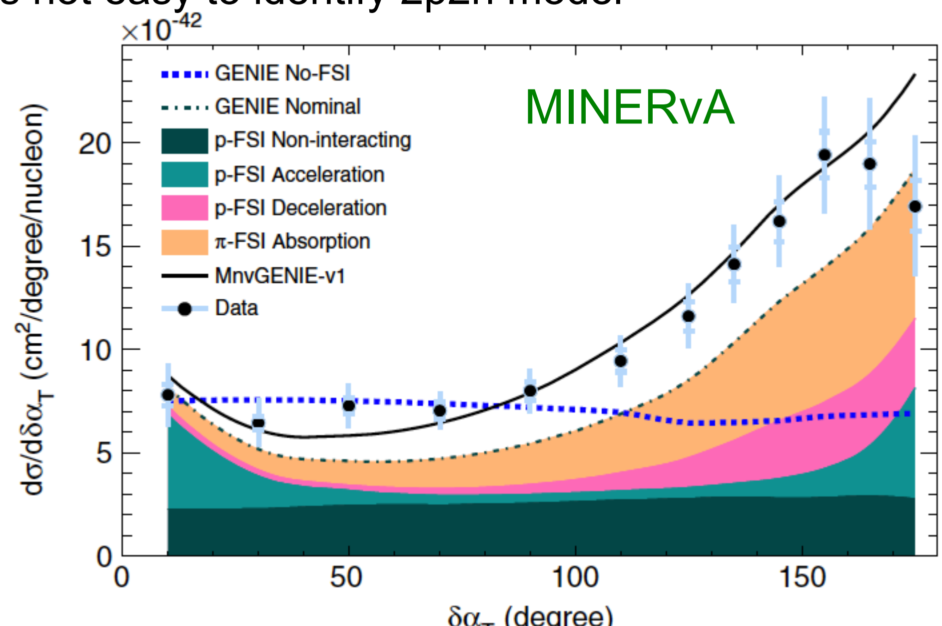
We want to constrain nuclear model from neutrino data
- Final state hadron measurement is the key



1 muon + 1 proton sample
- 5 dof (mu E and cosθ, proton E and cosθ, mu-p opening angle).
- Low statistics, and these are converted to 3 kinematic variables.

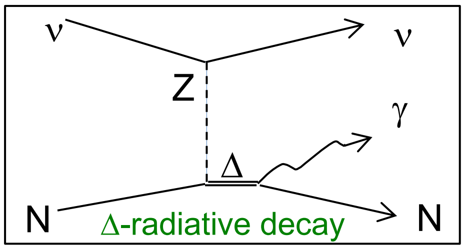
Data prefer advanced nuclear models, but it's not easy to identify 2p2h model

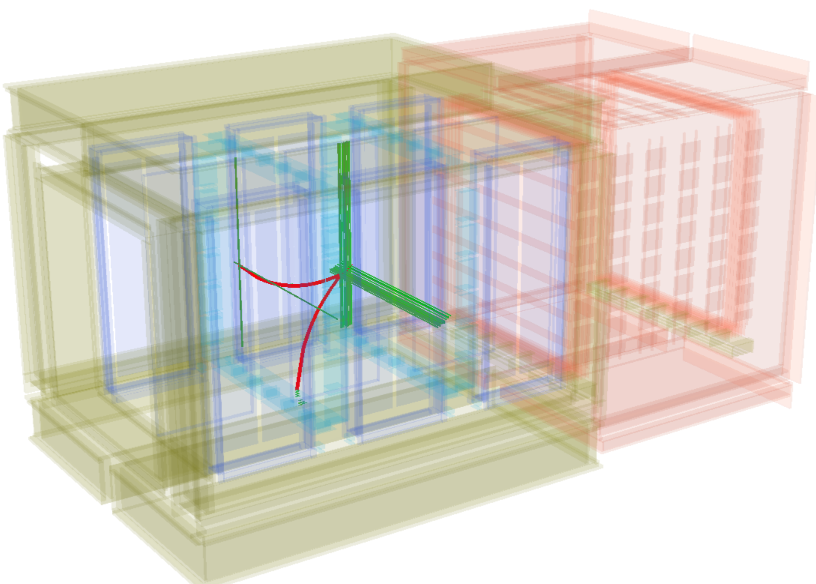




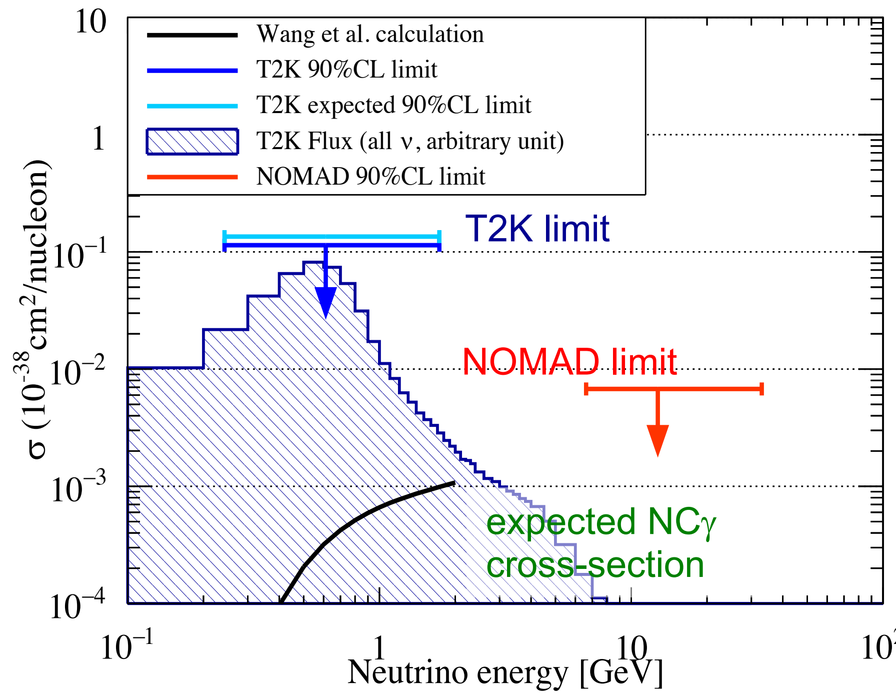
4. T2K Neutrino NC single photon production (NCγ)

Neutrino induced NC single photon production (NCγ) process is not experimentally identified. NCγ is misID background for every electron-neutrino appearance oscillation experiment. T2K and NOMAD set limits on this process, but ~x3 higher cross-section can explain all MiniBooNE excess.





T2K near detector NCγ candidate

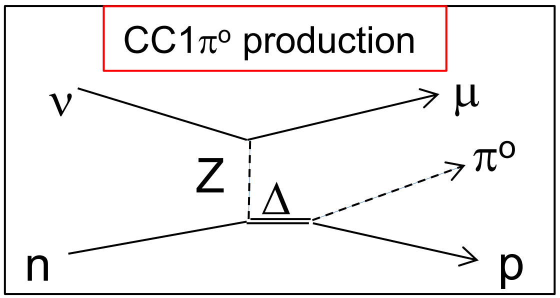


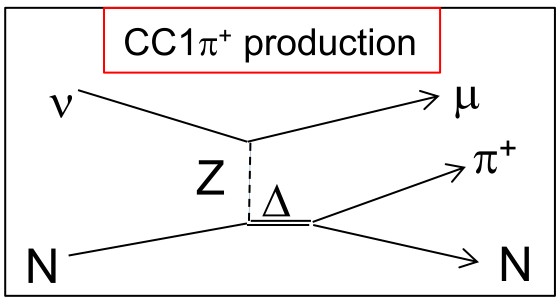
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

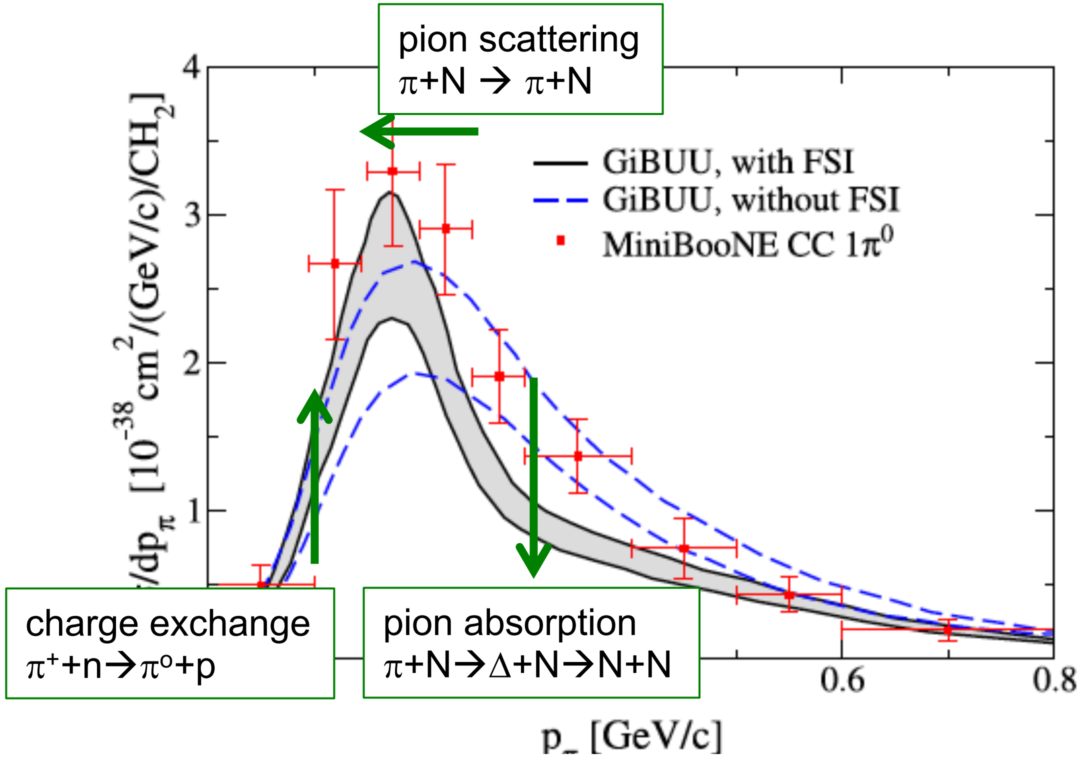
4. Pion puzzle (2019)

Pion production + final state interaction (FSI)

- Neutrino induced pion productions have large errors
- Final state interaction of hadrons have large errors







ex) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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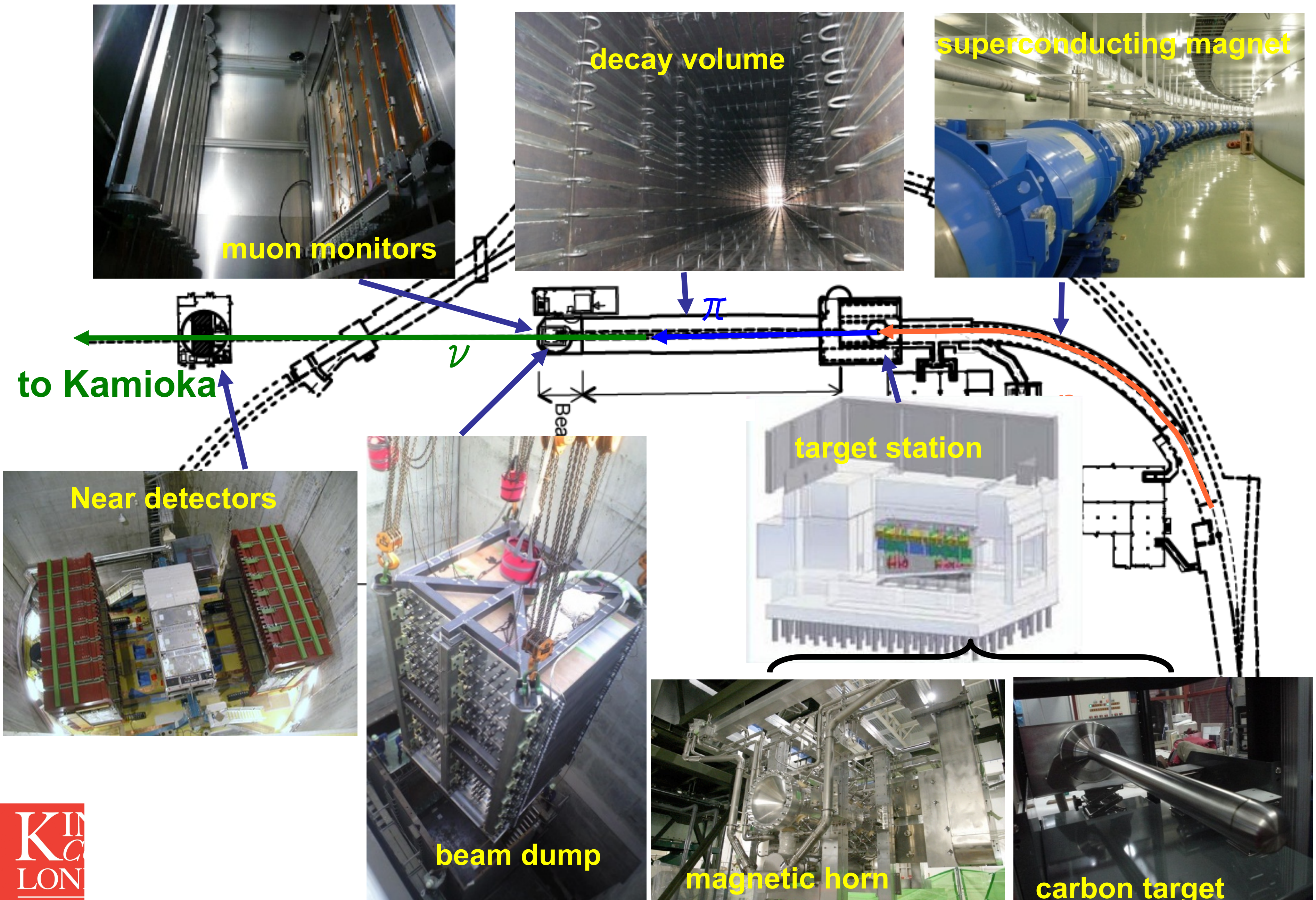
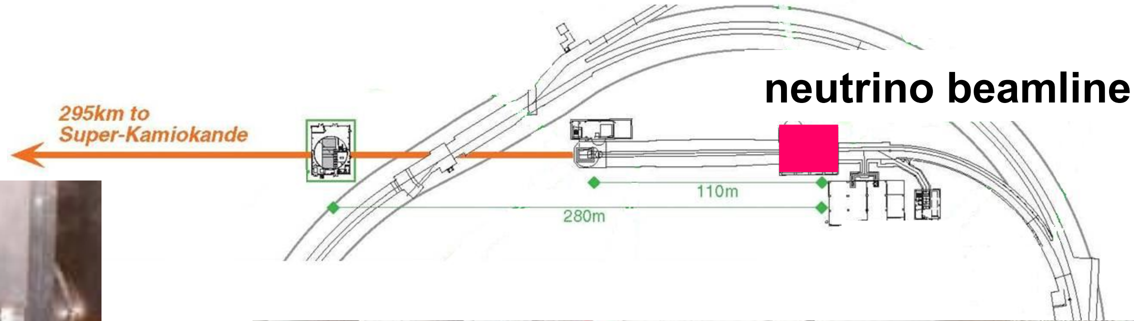
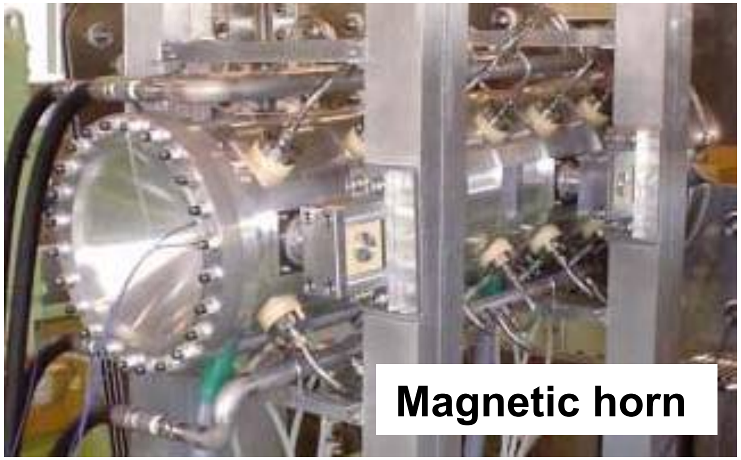
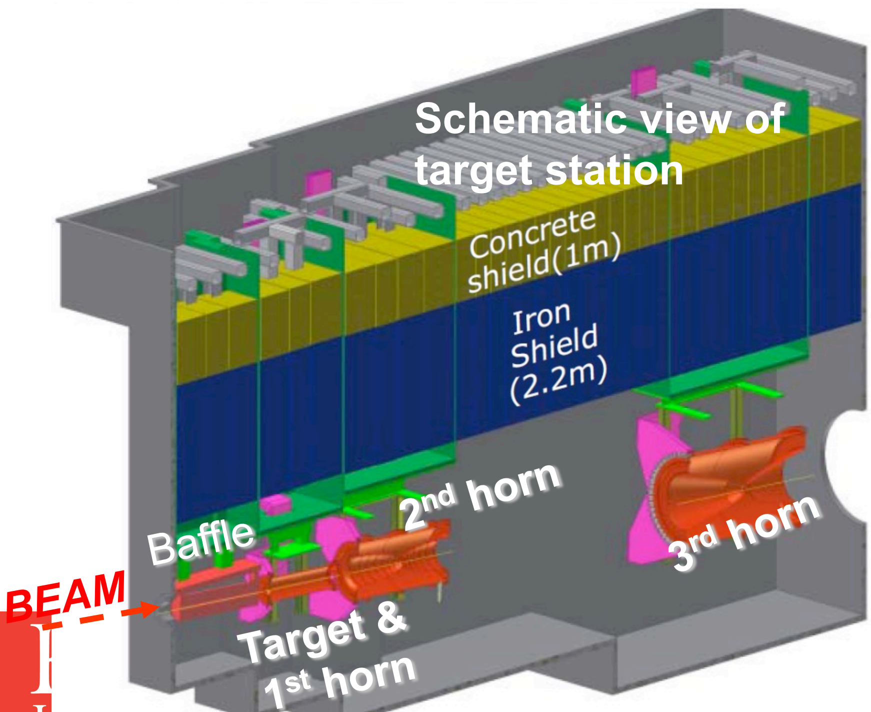
Neutrino beam line and components



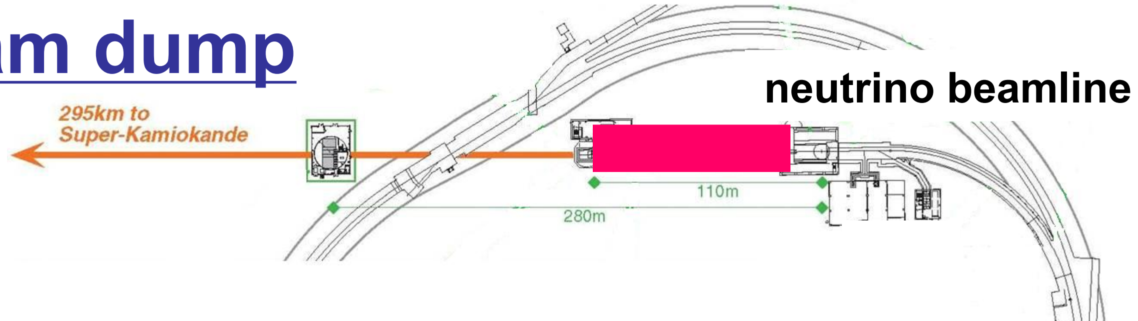
Target Station



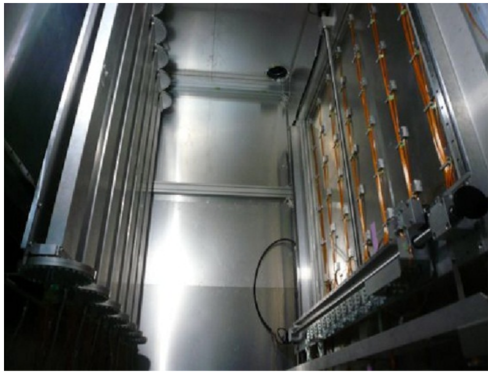


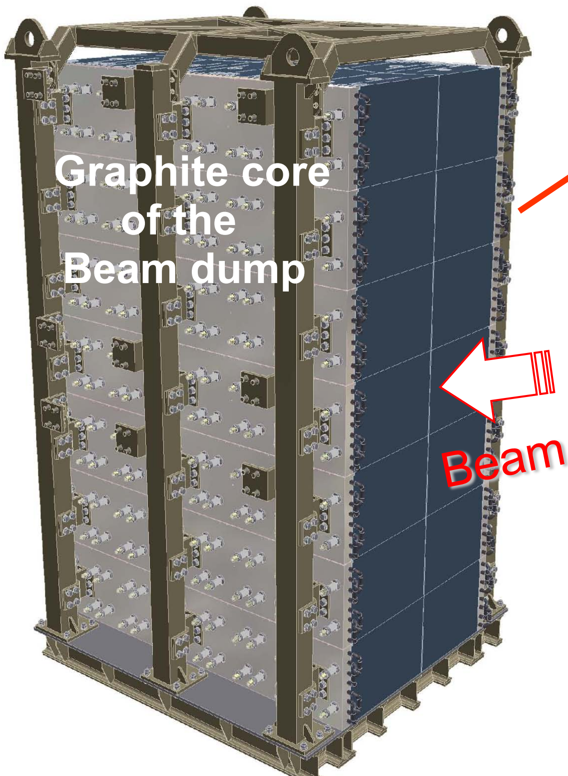


Decay pipe and Beam dump



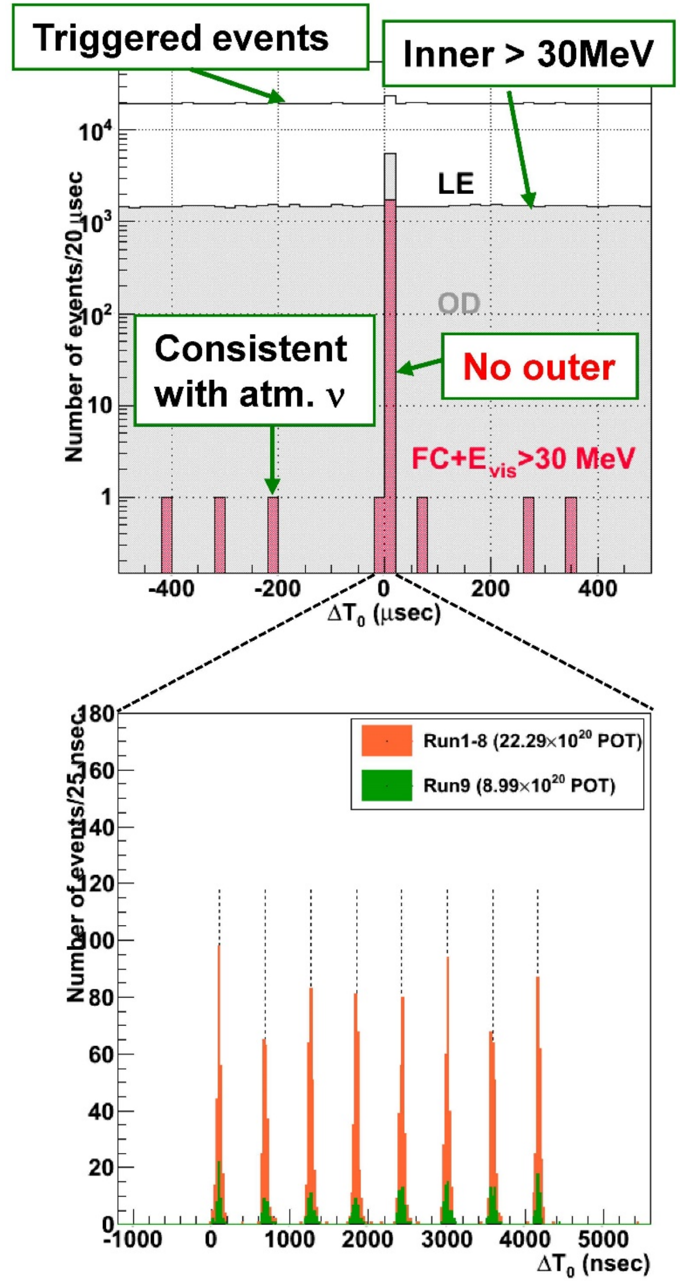
Muon monitors in Muon Pit





Super-Kamiokande Event Selection

- **Data recorded between Jan. 2010 and May 2018 are used. It corresponds to 1.49x10^{21} (ν) + 1.64x10^{21} ($\bar{\nu}$).**



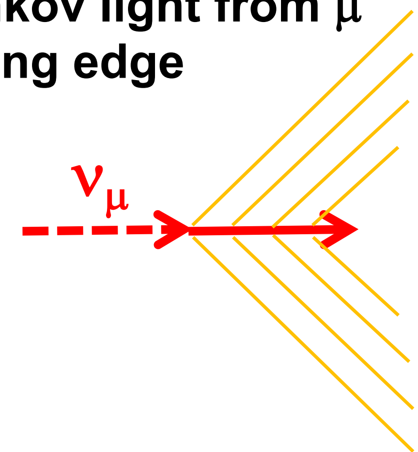
Event Selection Criteria

1. **Total energy deposit in the inner detector is larger than 30 MeV equivalent.**
2. **No outer detector activity**
3. **The event time agrees with ~5 μsec beam period in 2.48 sec accelerator cycle. (8 bunch structure can be found.)**
4. **1 Ring events → μ/e particle identification is applied**

μ/e identification in Super-Kamiokande

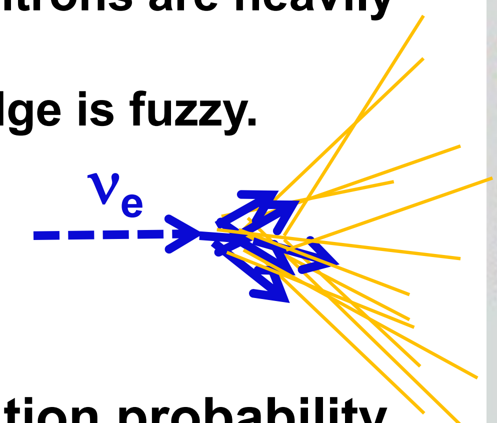
$\nu_\mu \rightarrow \mu$

Only direct Cherenkov light from μ
Clear Cherenkov ring edge

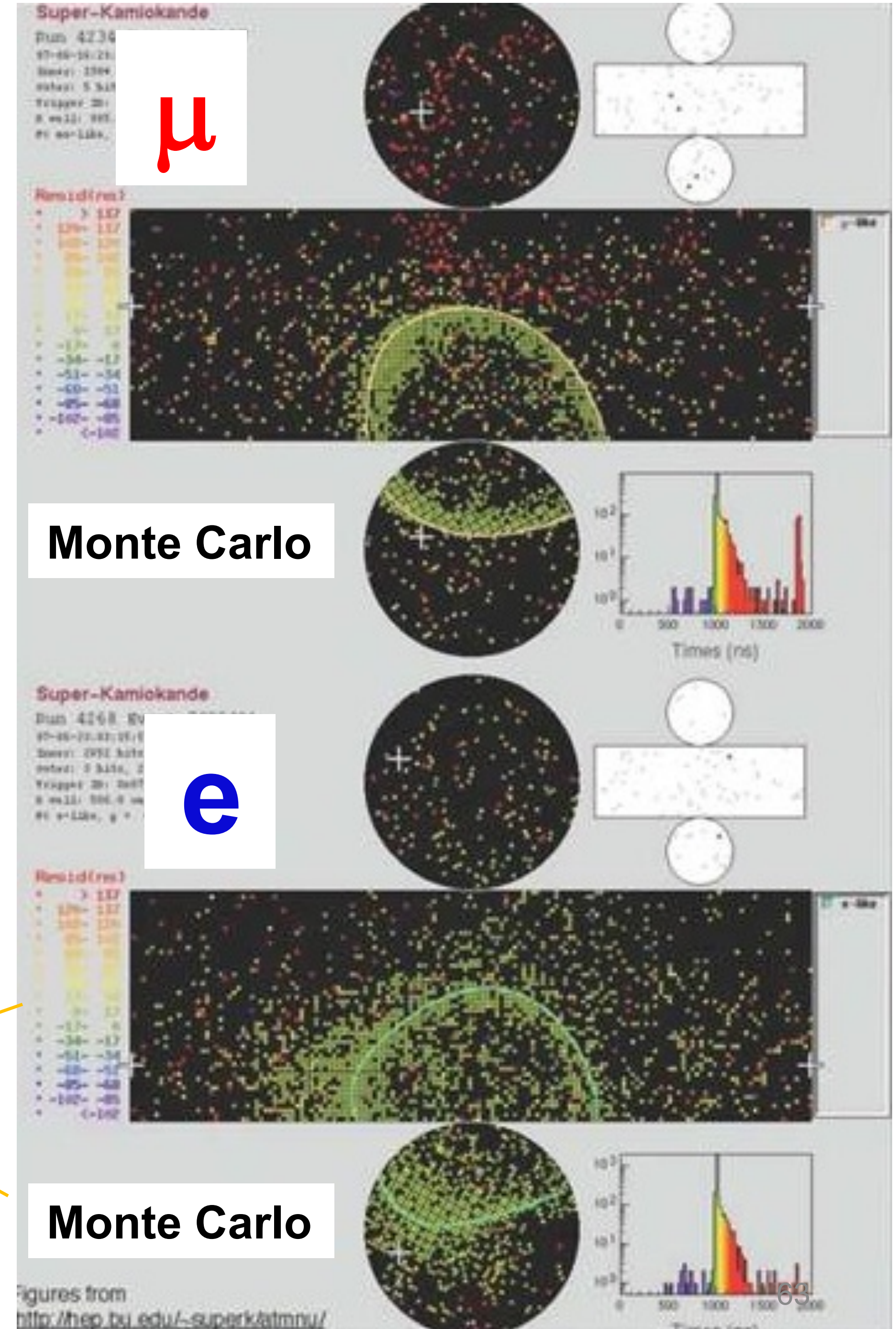


$\nu_e \rightarrow e$

Cherenkov light from e-m shower.
Electrons and positrons are heavily scattered.
Cherenkov ring edge is fuzzy.



- **μ/e misidentification probability is less than 1 %.**

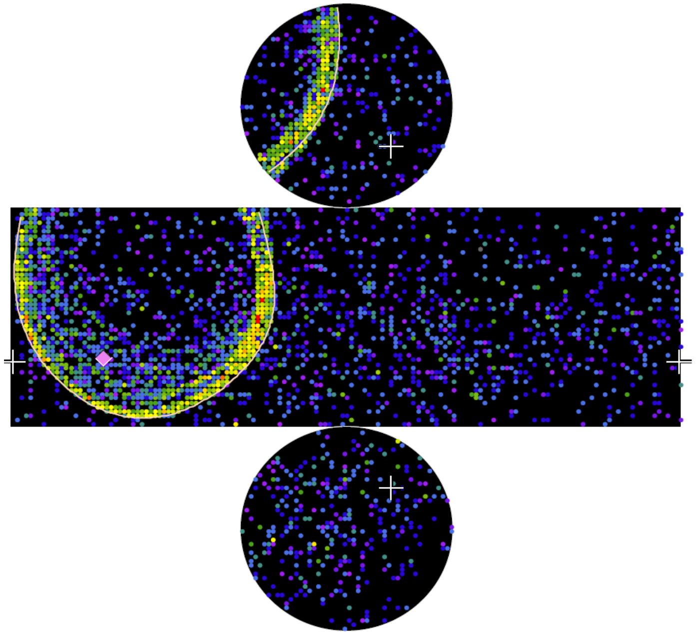


Event Selection

Examine Particle ID of 1 ring events

ν_μ selection

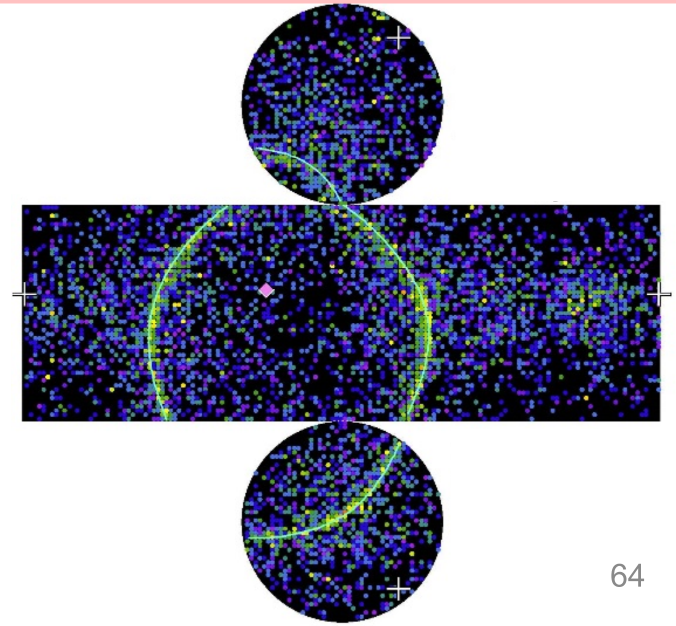
- μ-like PID
- p_μ > 200 MeV/c
- Michel electron 1 or 0



ν_e selection

- e-like PID
- p_e > 100 MeV/c
- E_{rec} < 1250 MeV
- π^0 rejection

π^0 rejection : Forced 2nd ring is assumed. Invariant mass and likelihood for π^0 are examined.

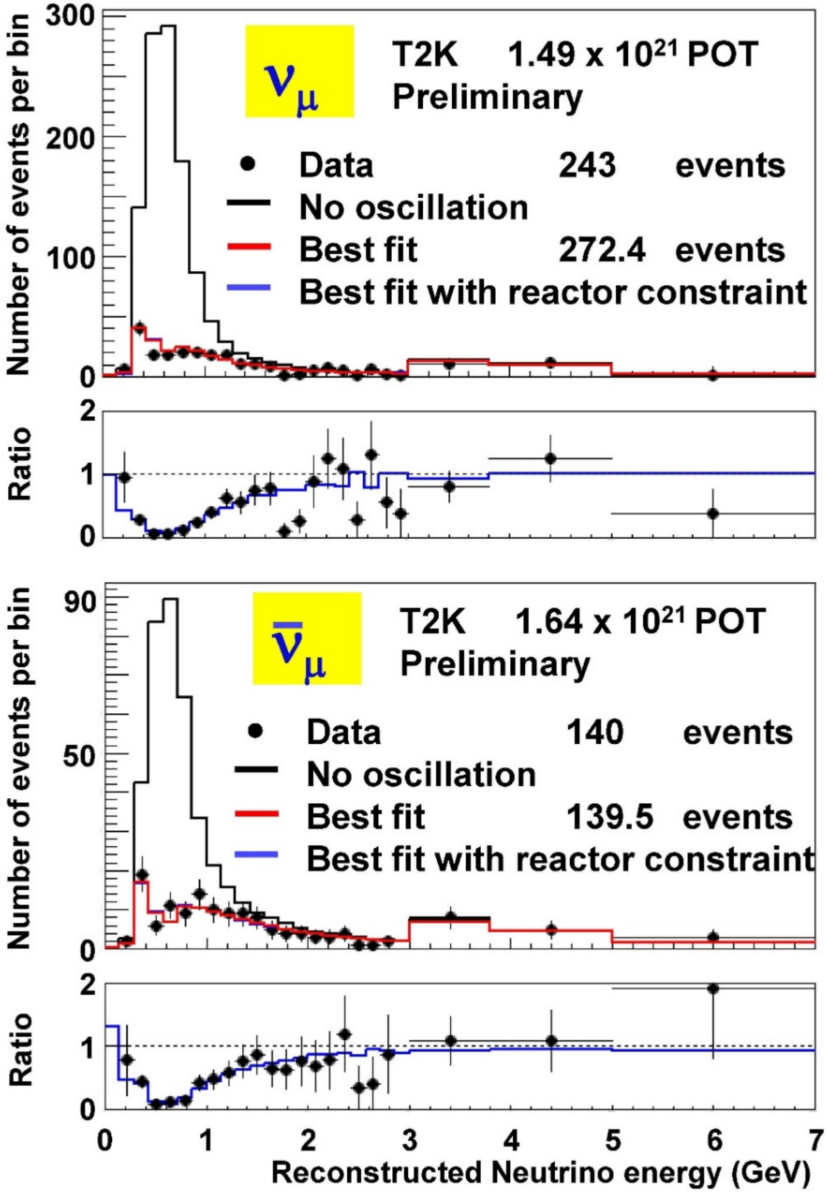


Results of ν_μ and $\bar{\nu}_\mu$ disappearance

- **Disappearance of muon neutrino events as well as a distortion of neutrino energy spectrum is obvious for both ν_μ and $\bar{\nu}_\mu$.**
- **Oscillation parameters for anti-neutrinos well agree with the parameters for neutrinos within statistical errors.**
- **These results are updates of past publications.**

PRL 112, 181801(2014),
PRD 91, 072010(2015)
for 6.57x10[20] POT, **120** ν_μ data

PRL 116, 181801(2016)
for 4.01x10[20] POT, **34** $\bar{\nu}_\mu$ data



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