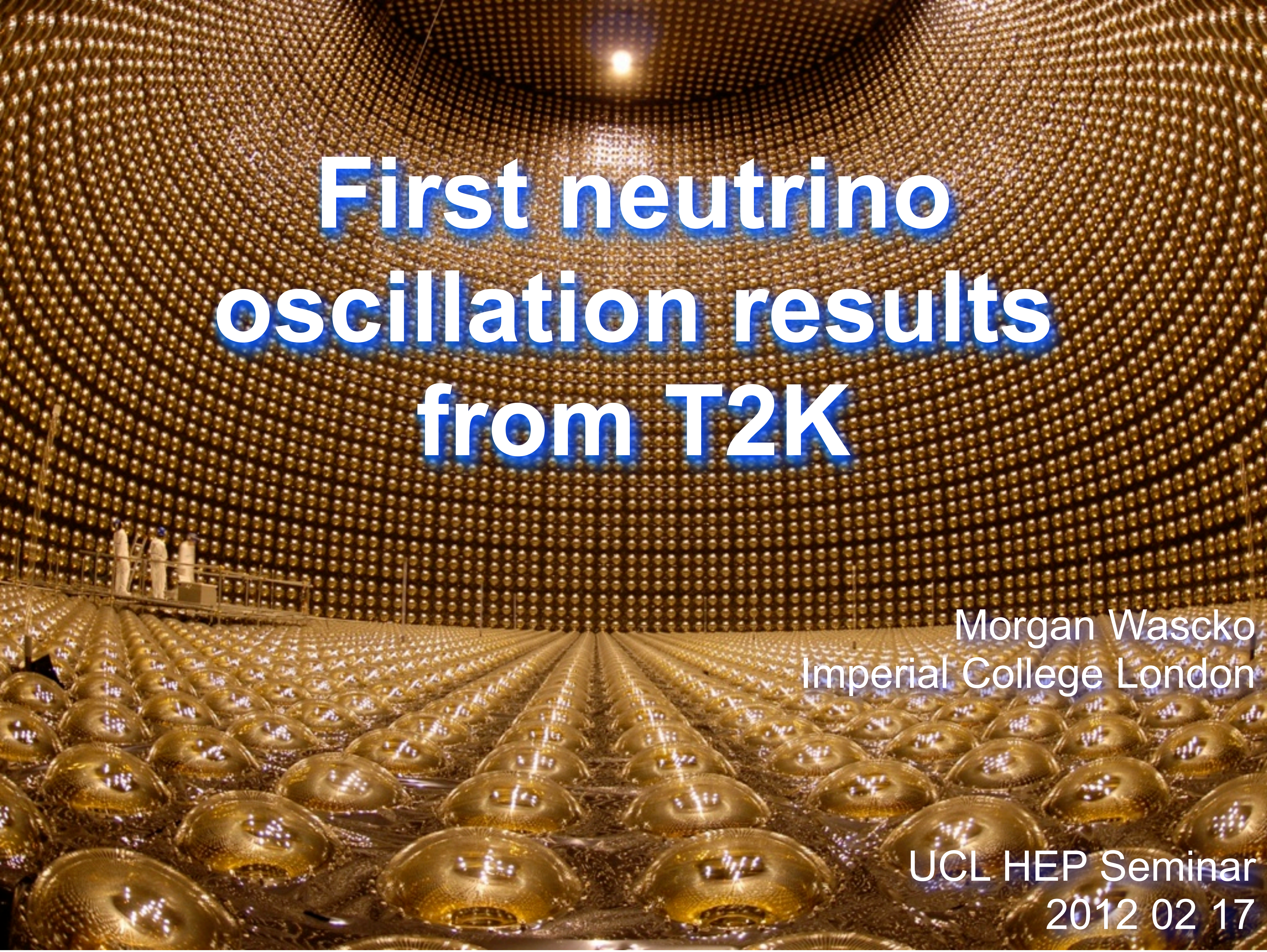


First neutrino oscillation results from T2K

Morgan Wascko
Imperial College London

UCL HEP Seminar
2012 02 17

Outline

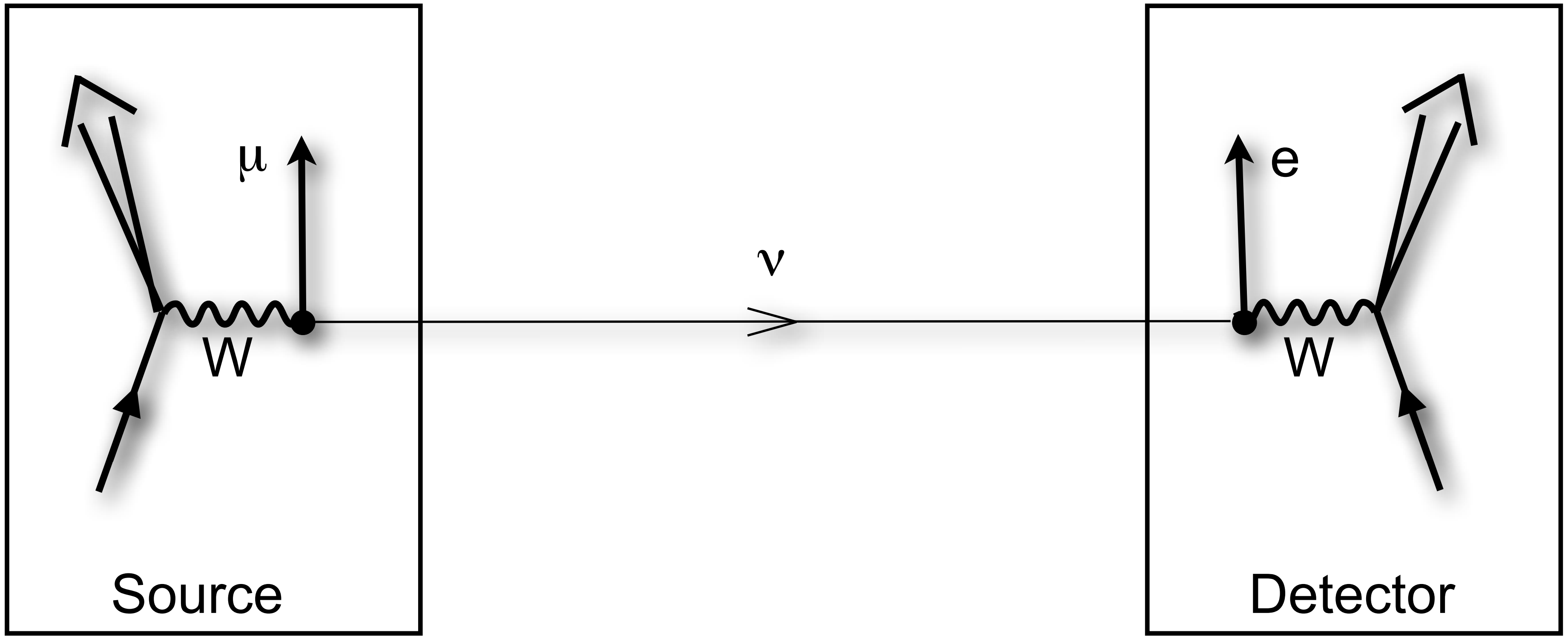
- Introduction to neutrino oscillation
- T2K experimental description
- T2K $\nu_\mu \rightarrow \nu_e$ oscillation
- Conclusions and outlook

Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968



Maki, Nakagawa, Sakata

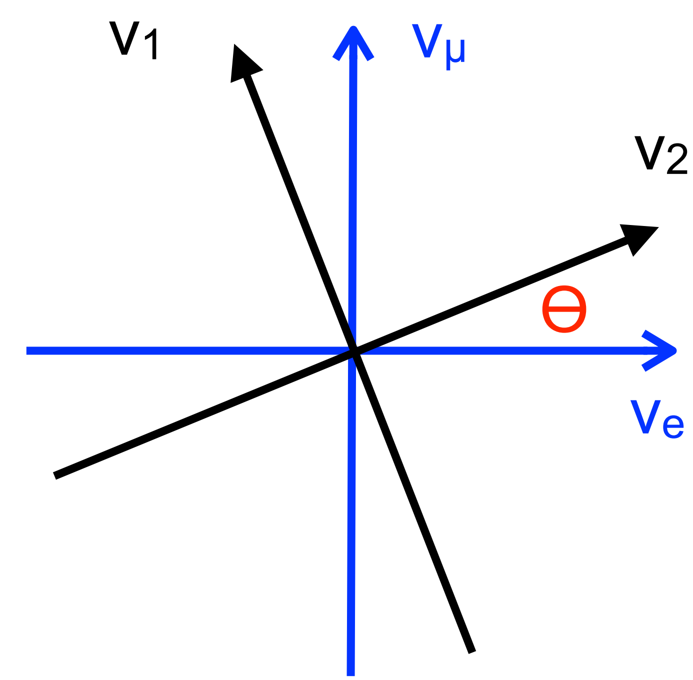
Prog.Theor.Phys. 28, 870 (1962)

- if neutrinos have mass...
  - a neutrino that is produced as a ν_μ
    - (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)
  - might some time later be observed as a ν_e
    - (e.g. $\nu_e\, n \rightarrow e^- p$)

Neutrino oscillation

In a world with 2 neutrinos,
if the weak eigenstates (ν_e, ν_μ)
are different from the mass eigenstates (ν_1, ν_2):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



The weak states are mixtures of the mass states:

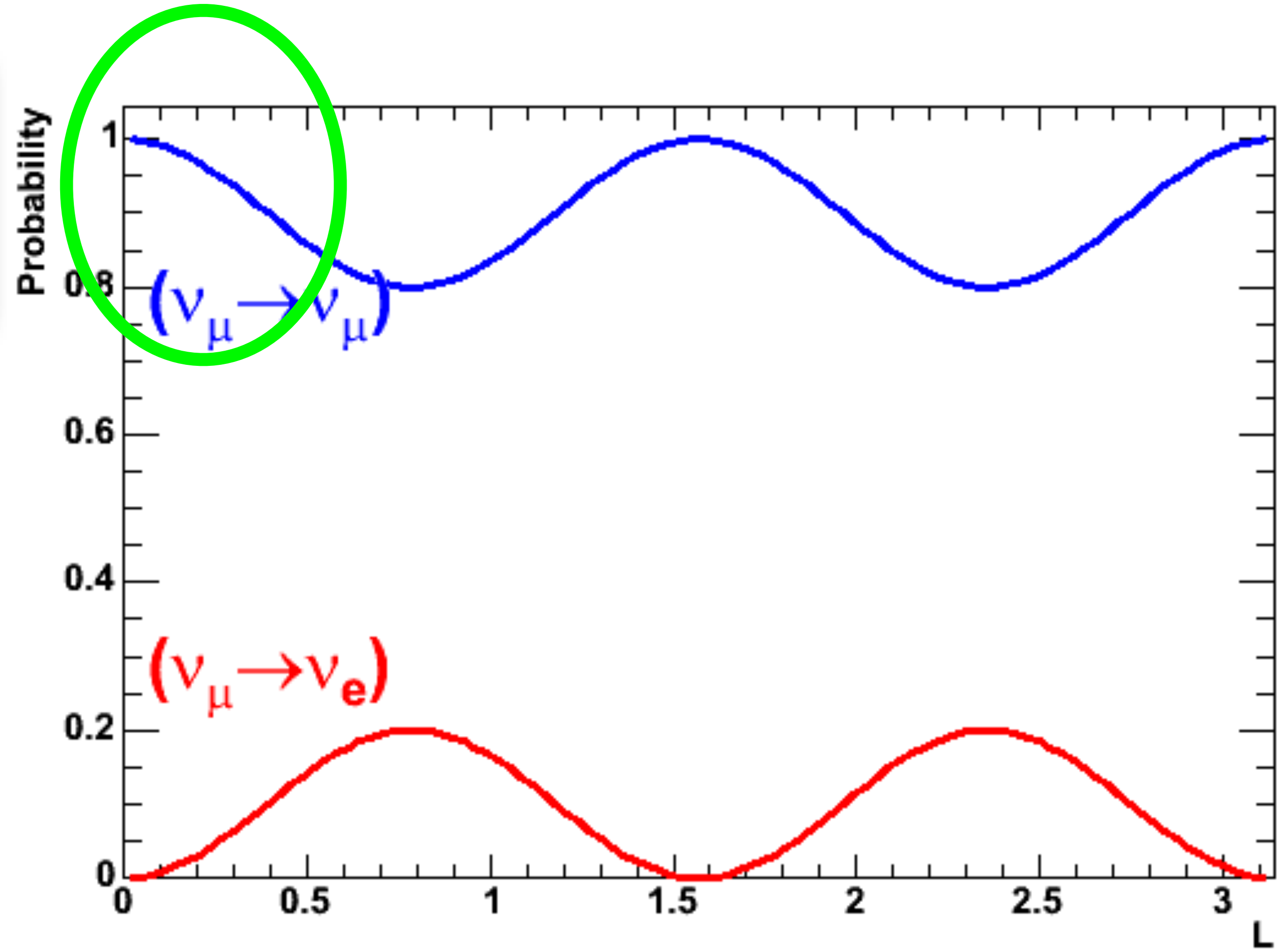
$$|\nu_\mu> = -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

$$|\nu_\mu(t)> = -\sin\theta\left(|\nu_1> e^{-iE_1 t}\right) + \cos\theta\left(|\nu_2> e^{-iE_2 t}\right)$$

The probability to find a ν_e when you started with a ν_μ is:

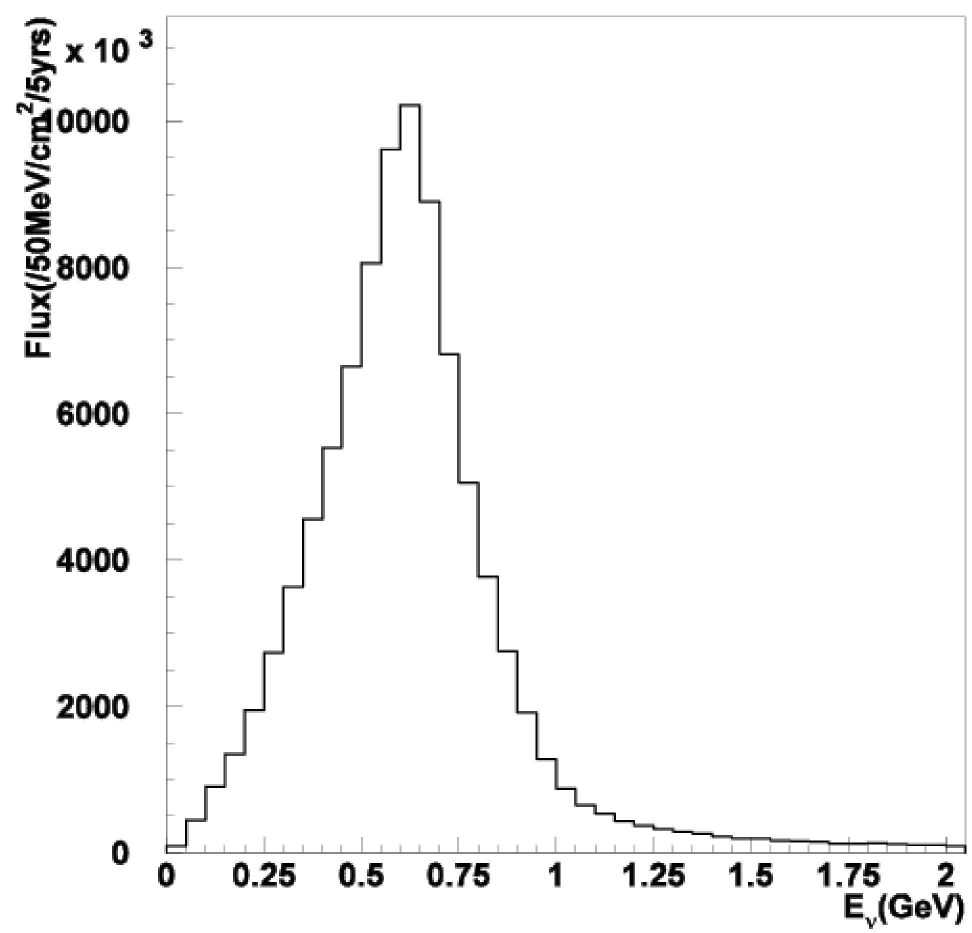
$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = |<\nu_e|\nu_\mu(t)>|^2$$

$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$



- 2 fundamental parameters
  - Δm^2 ↔ period
  - θ_{12} ↔ magnitude

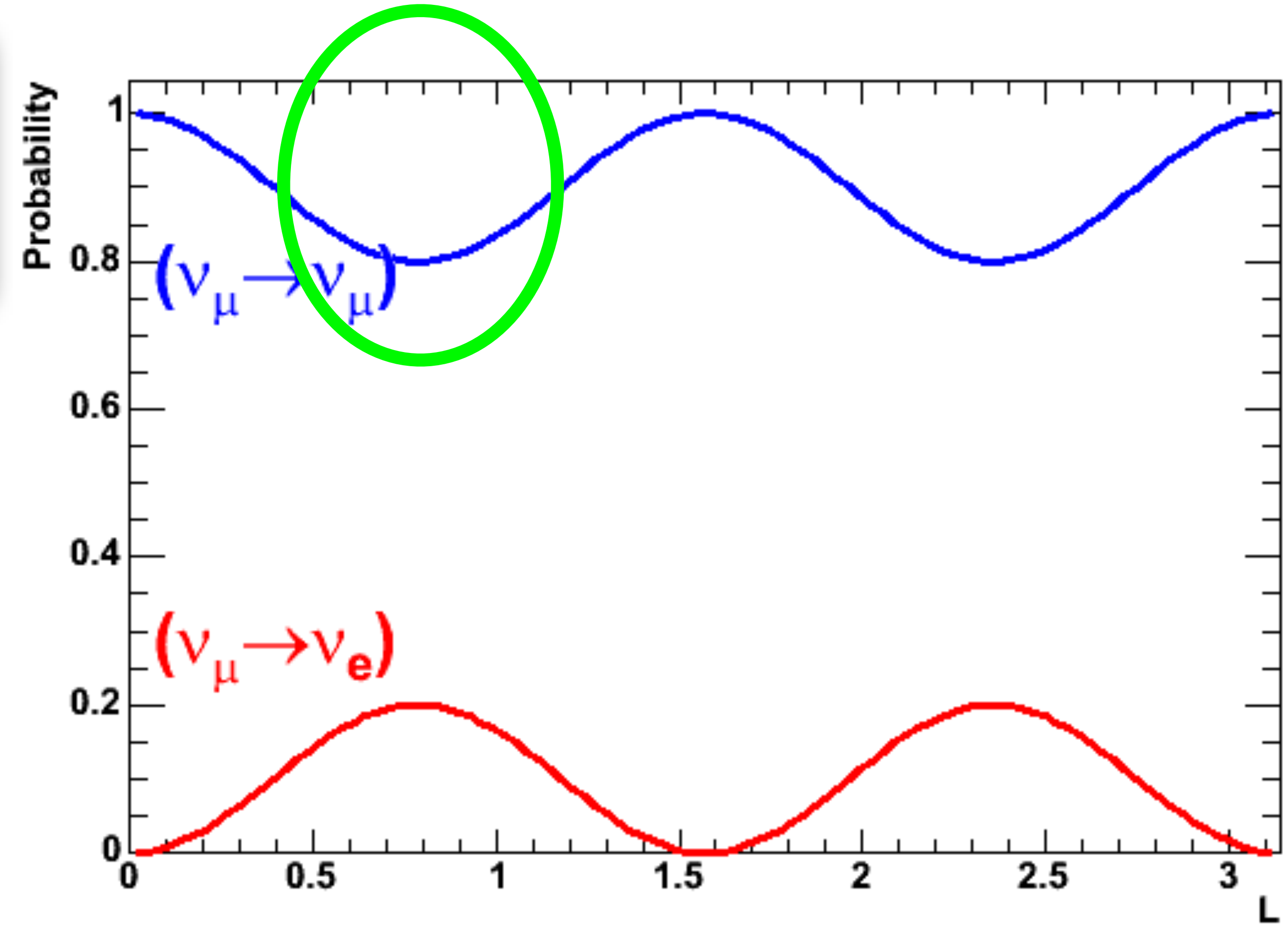
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy

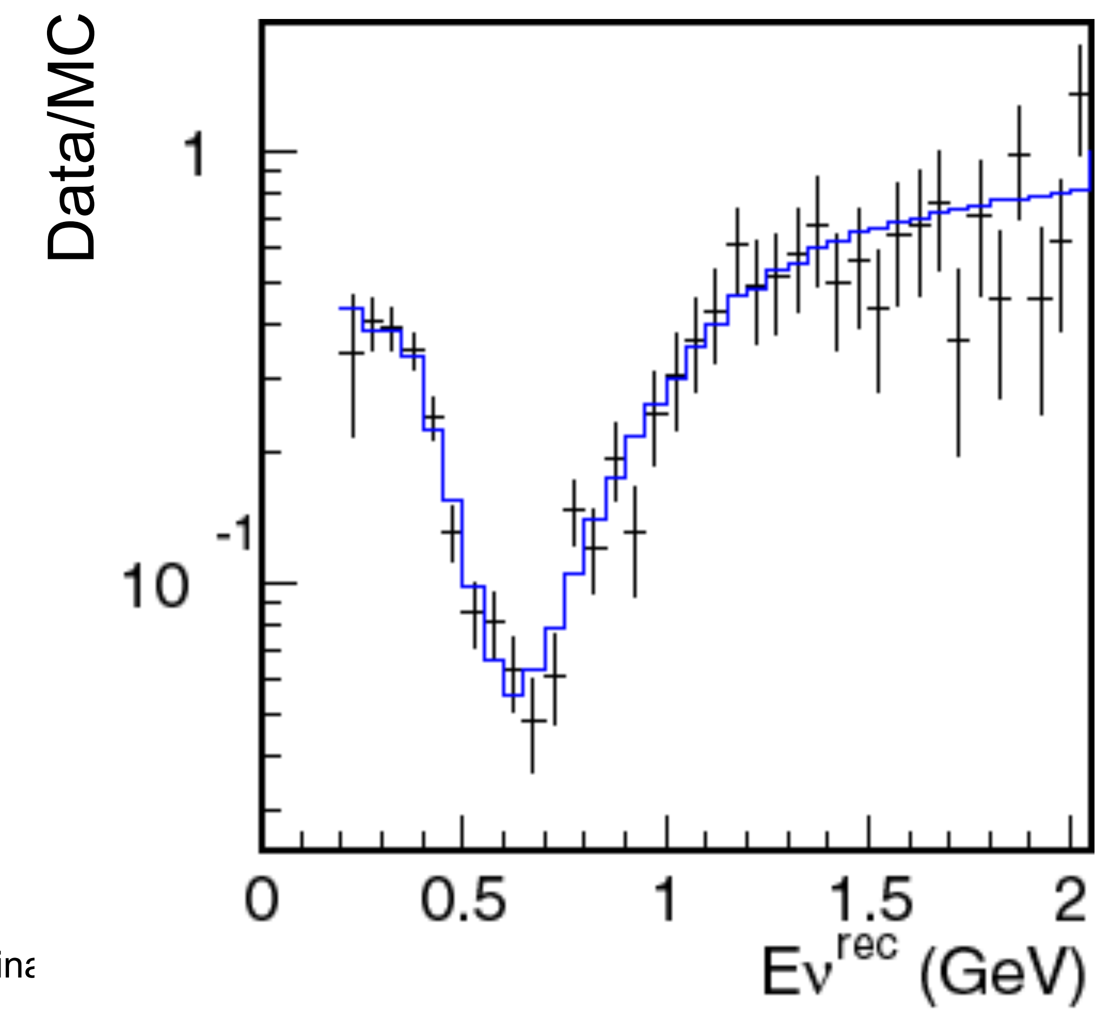


- Choose L&E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear

$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

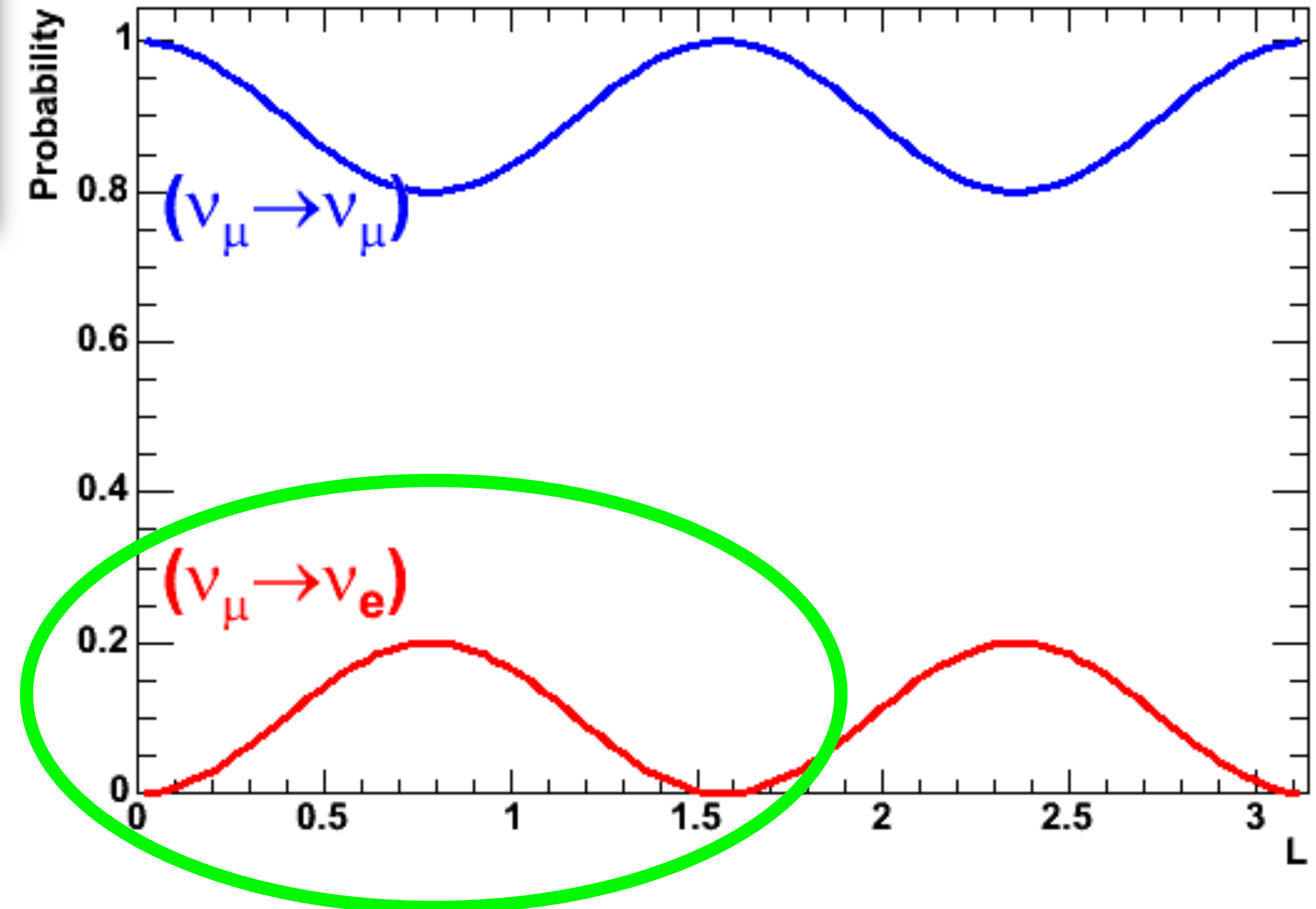
- 2 fundamental parameters
  - $\Delta m^2 \leftrightarrow$ period
  - $\theta_{12} \leftrightarrow$ magnitude
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy
- Choose L&E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear

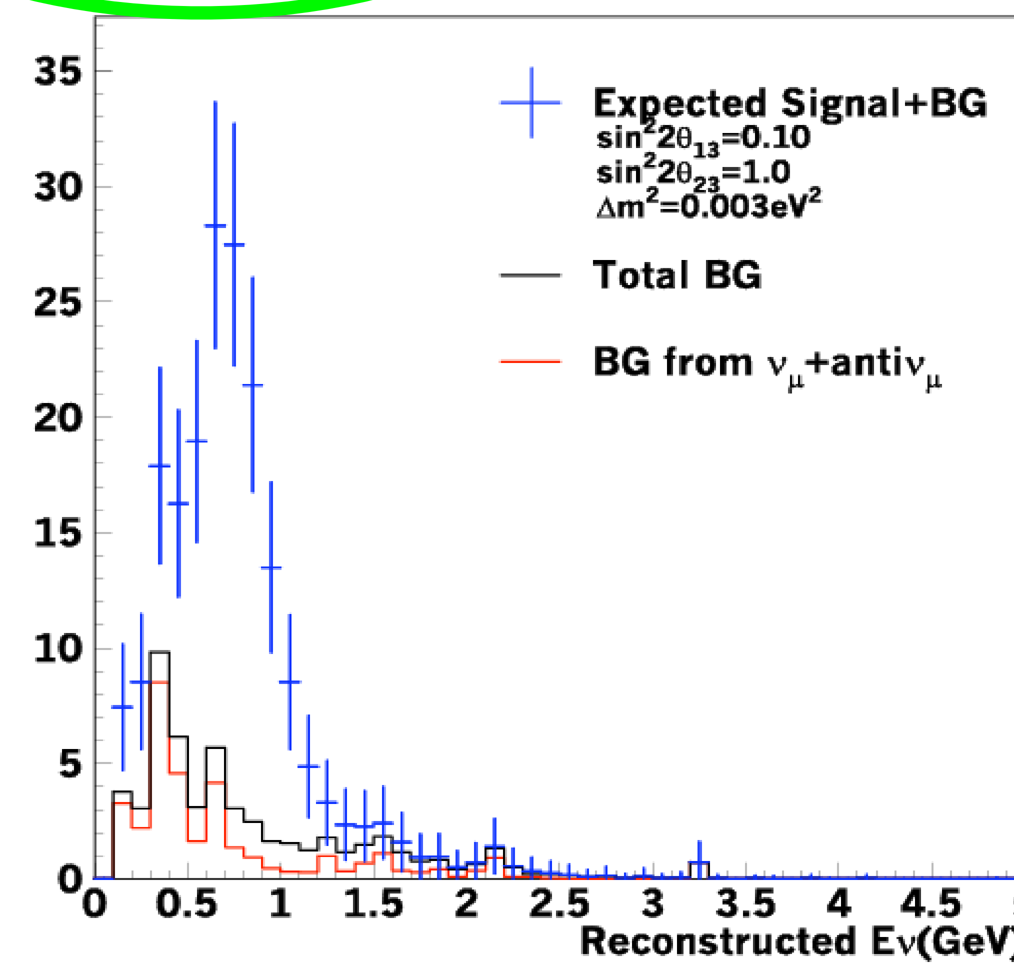




$$P(\nu_\mu \to \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- 2 fundamental parameters
  - $\Delta m^2 \leftrightarrow$ period
  - $\theta_{12} \leftrightarrow$ magnitude
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy
- Choose L&E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear



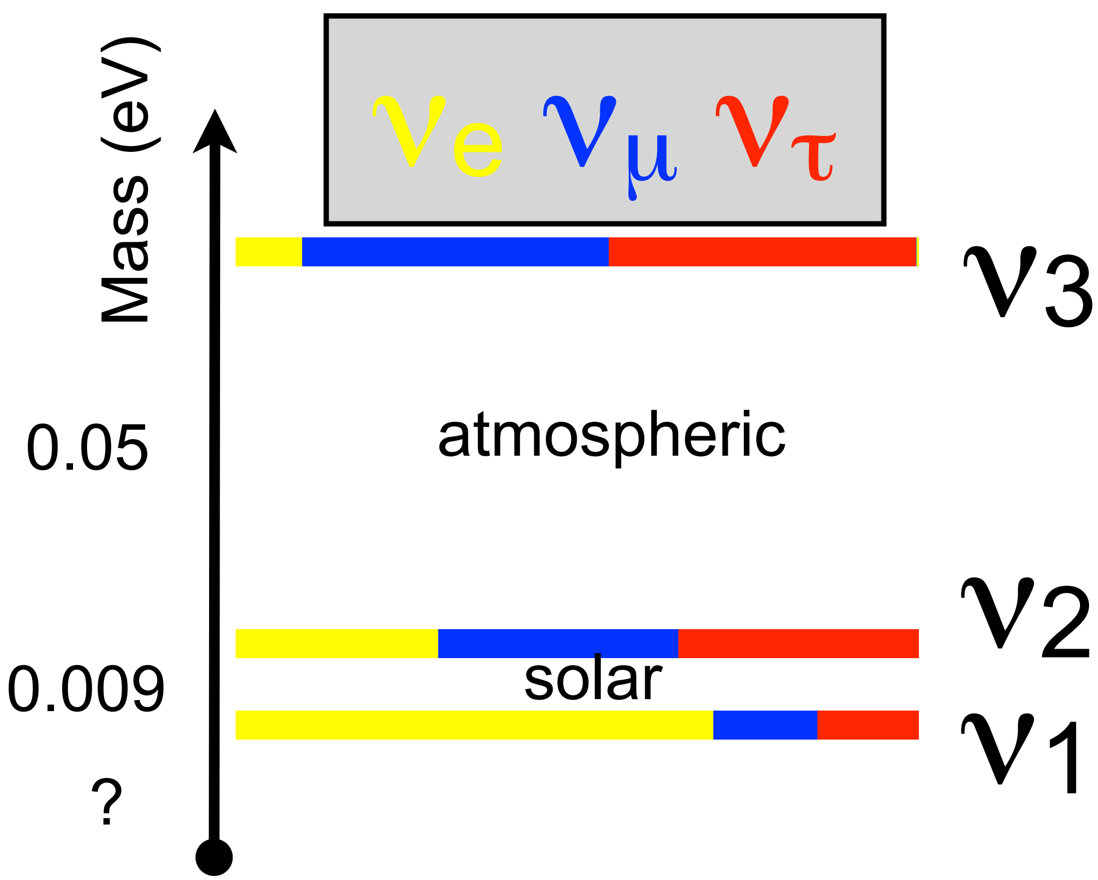


Three flavors

flavor		atmospheric		cross-mixing		solar		**mass**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

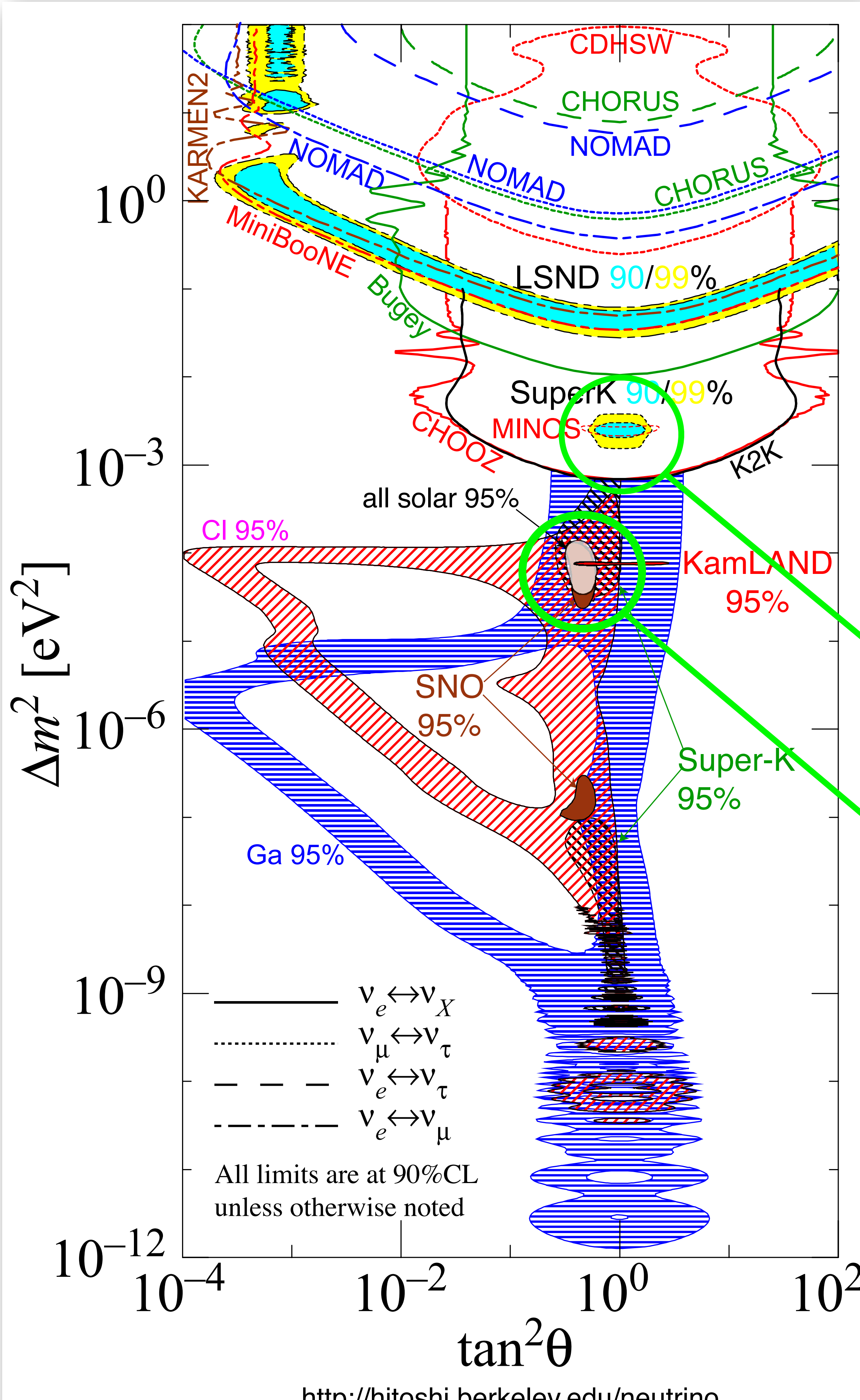
$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

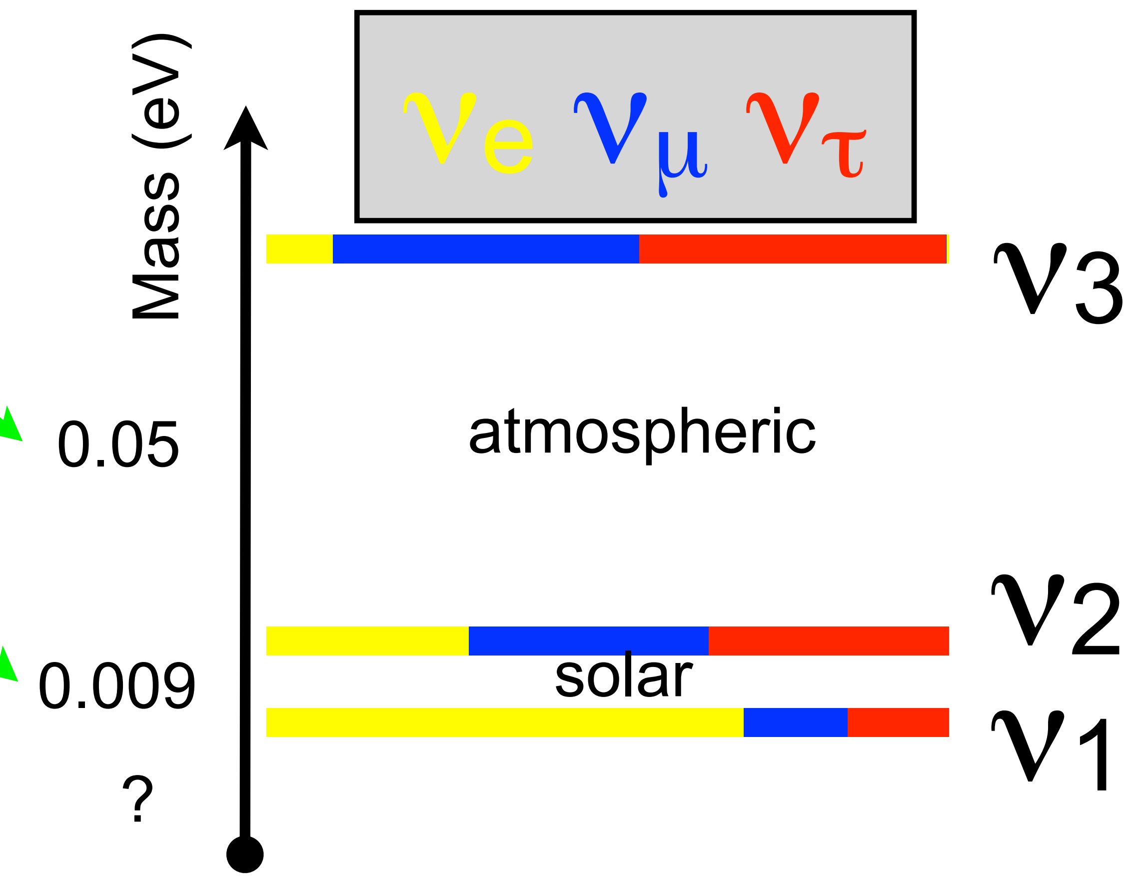


	VALUE
$\lvert\Delta m^2_{32}\rvert$	2.35±0.12 E-03 (eV^2)
Δm^2_{21}	7.58±0.24 E-05 (eV^2)
$\sin^2\theta_{12}$	0.31±0.018
$\sin^2\theta_{23}$	0.42±0.08
$\sin^2\theta_{13}$	~0.02±0.007
δ	?

arXiv:1106.6028 [hep-ph]

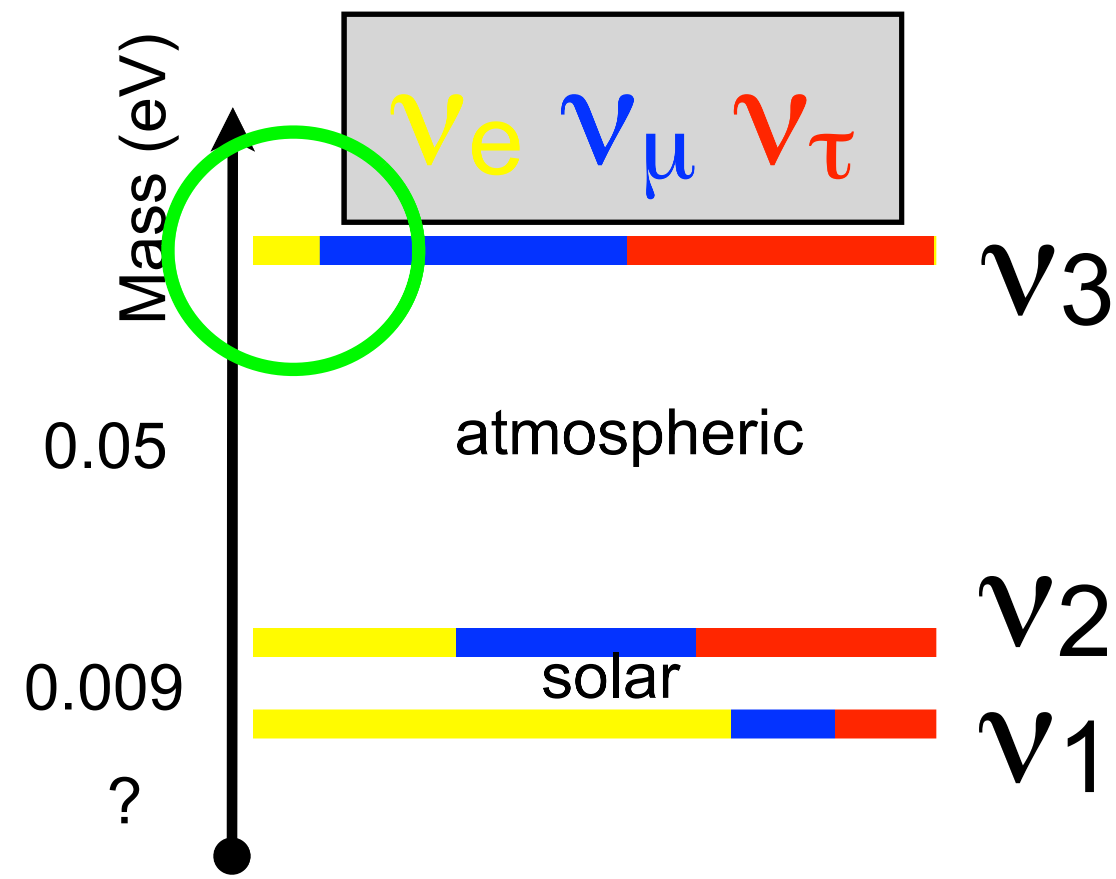
Current picture



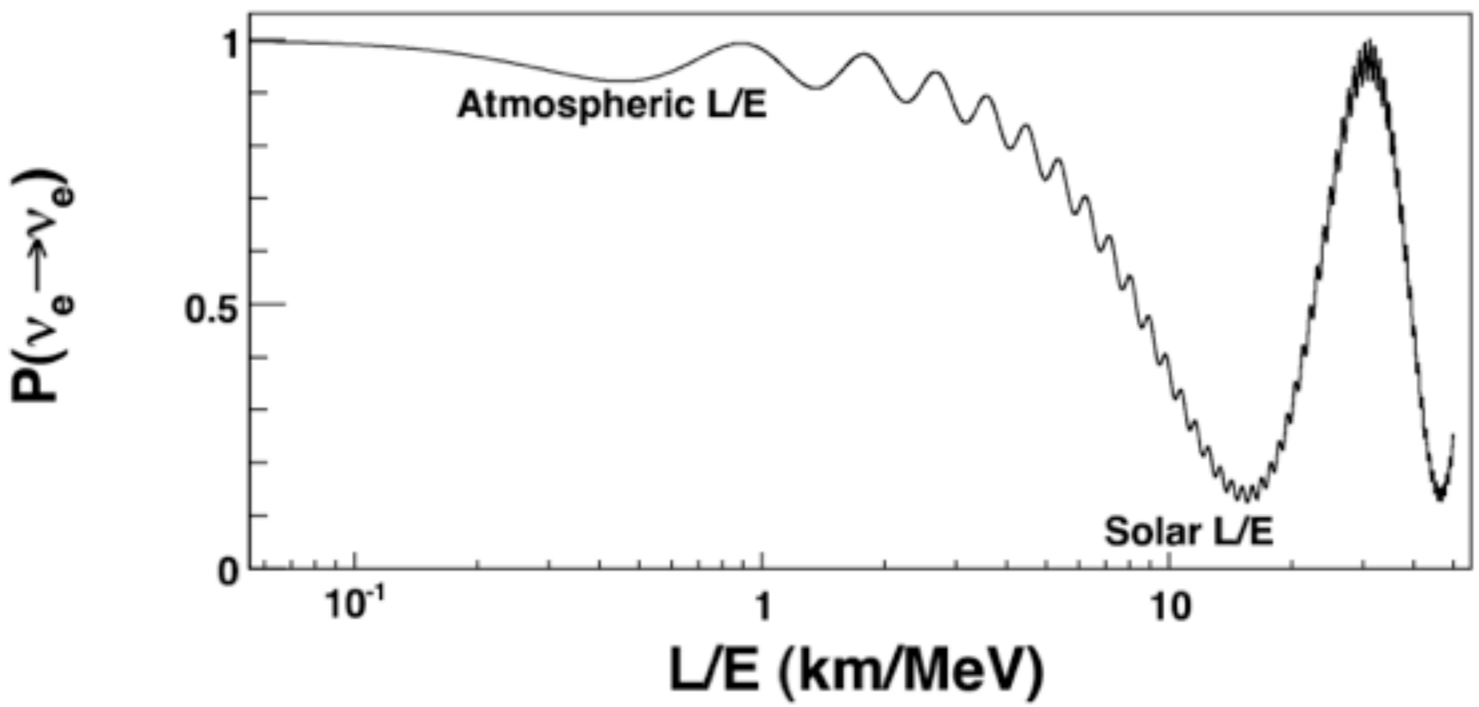


Open Questions

- Important for theories about origins of neutrino mass
  - Relations to flavor? GUTs?
- Cosmological and astrophysical implications
- What is the nature of neutrino mass?
  - Dirac or Majorana?
- What is the absolute mass scale?
- What is the mass hierarchy?
- What is the value of θ_{13}? δ_{CP}??

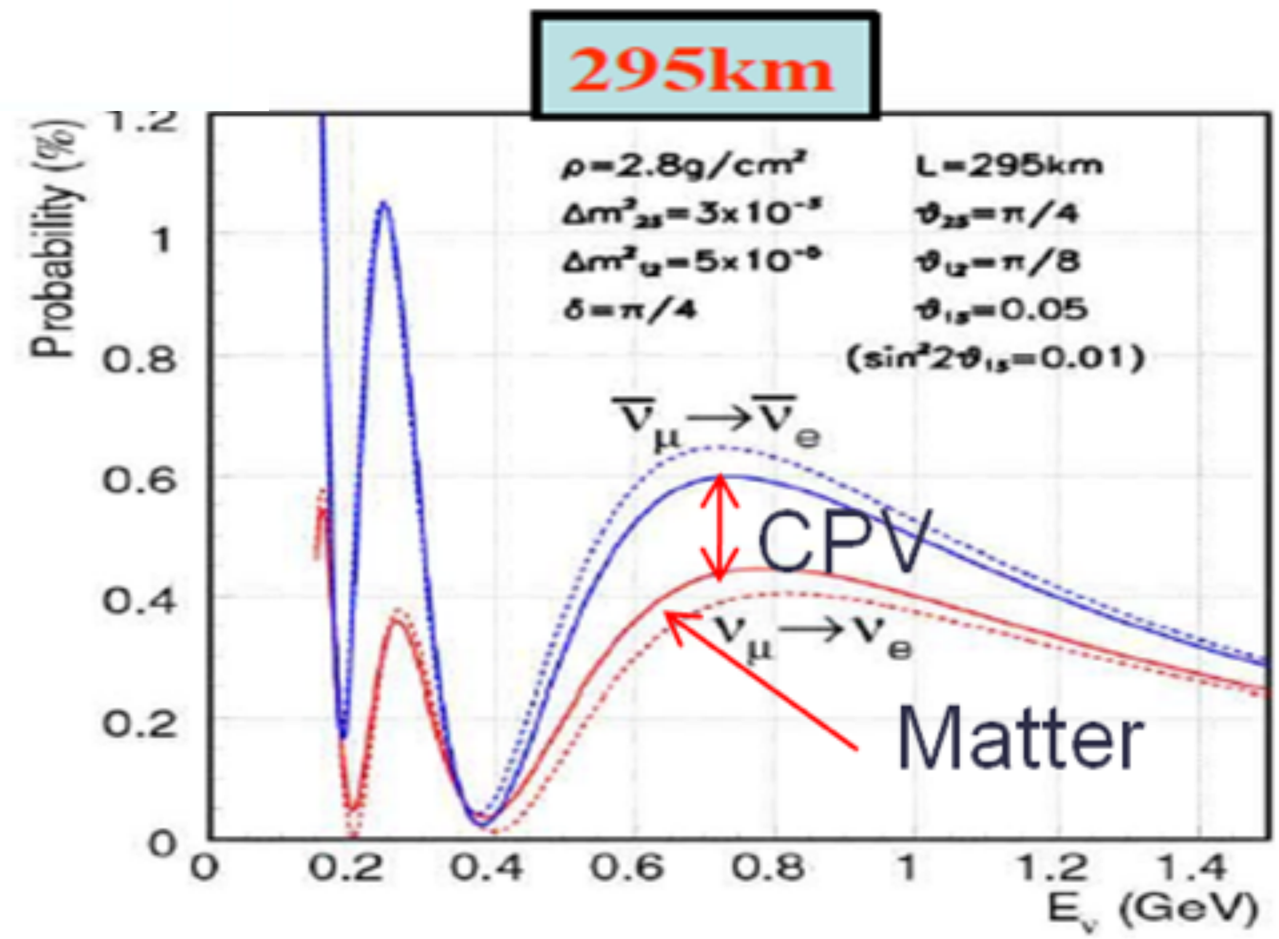


How to measure θ_{13}

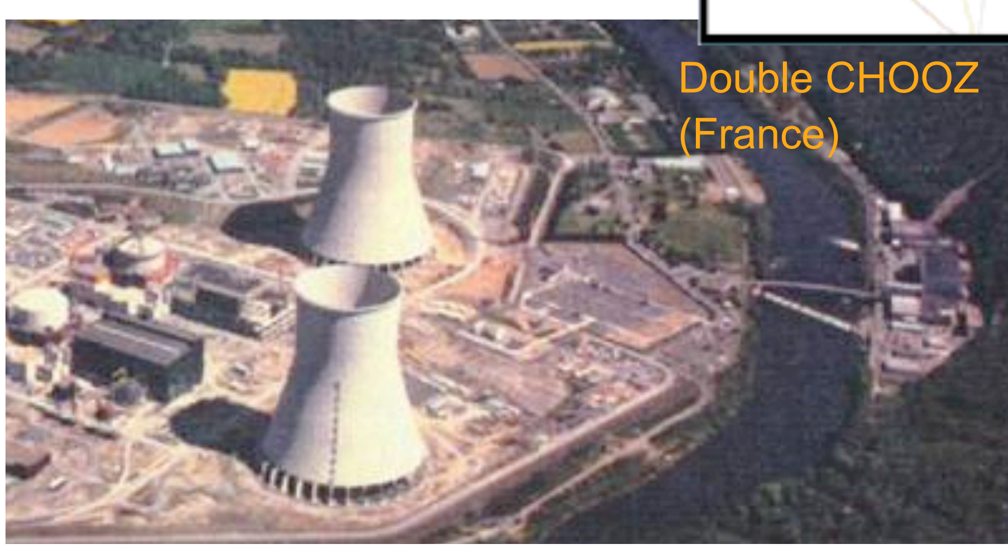


θ_{13} can cause $\bar{\nu}_e$ disappearance in reactor neutrinos

θ_{13} can cause $\nu_\mu \rightarrow \nu_e$ appearance in long baseline experiments



Campaign for θ_{13}



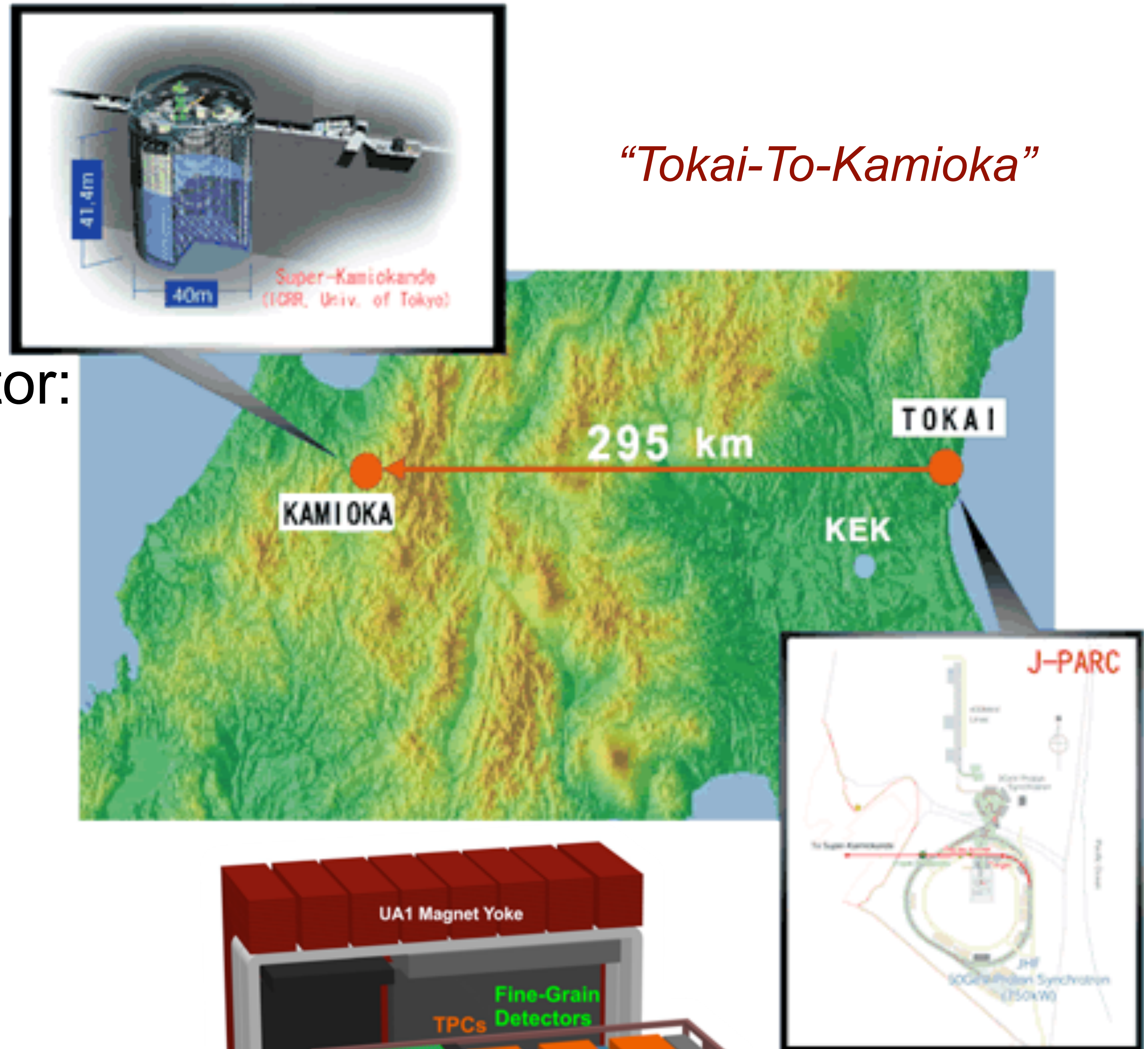
- Phase I (by 2016):
  Accelerators and Reactors
  - T2K & NOvA;
    Daya Bay, Double CHOOZ, RENO
  - Measure value of θ_{13}
    $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_e \to \bar{\nu}_e)$
  - If mixing > ~0.01

- Phase II (farther future):
  Long baseline superbeams and Megaton detectors
  - Measure value of θ_{13}
  - If mixing > ~0.002
  - Search for appearance probability asymmetry

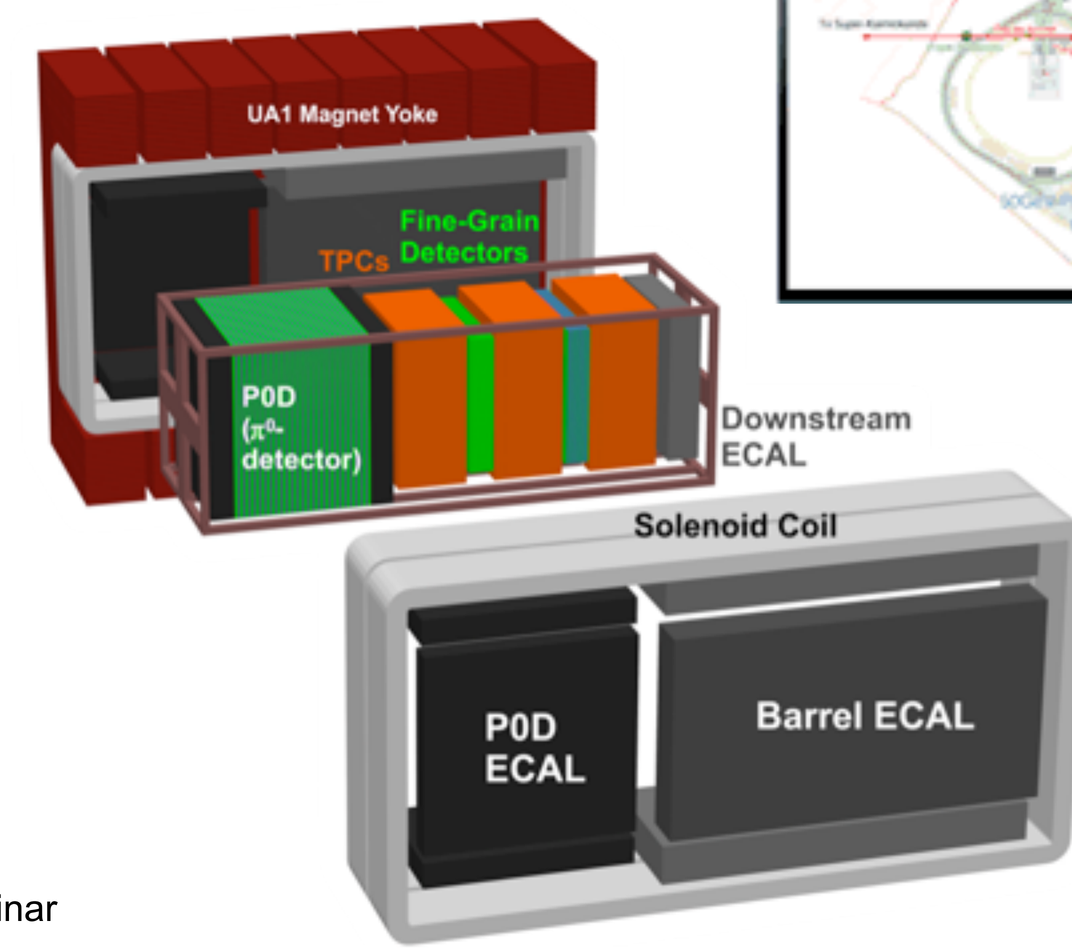

T2K

T2K

"Tokai-To-Kamioka"

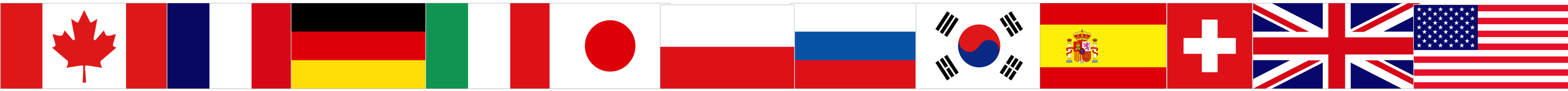


- Start with world's largest detector: Super-Kamiokande
- Build new neutrino beam
- Off-axis beam to Super-K
  - L = 295 km
  - E = 0.6 GeV
- Near detectors at 280m to constrain beam flux

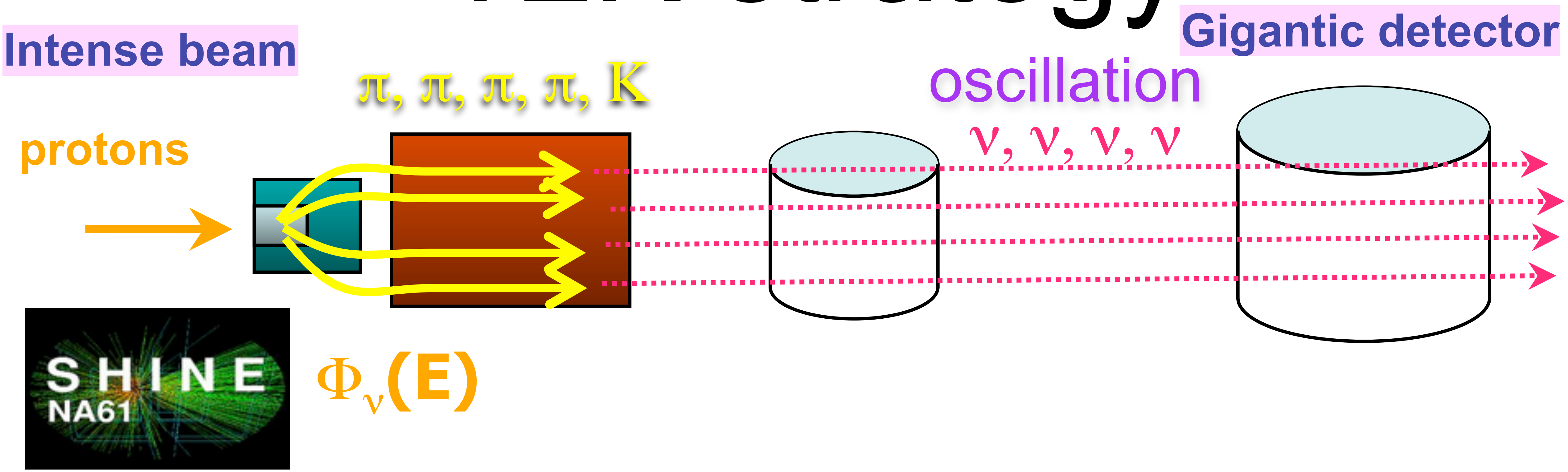


- Physics Goals:
  - precise $\Delta m^2_{32}, \theta_{23}$ measurements
  - search for θ_{13}

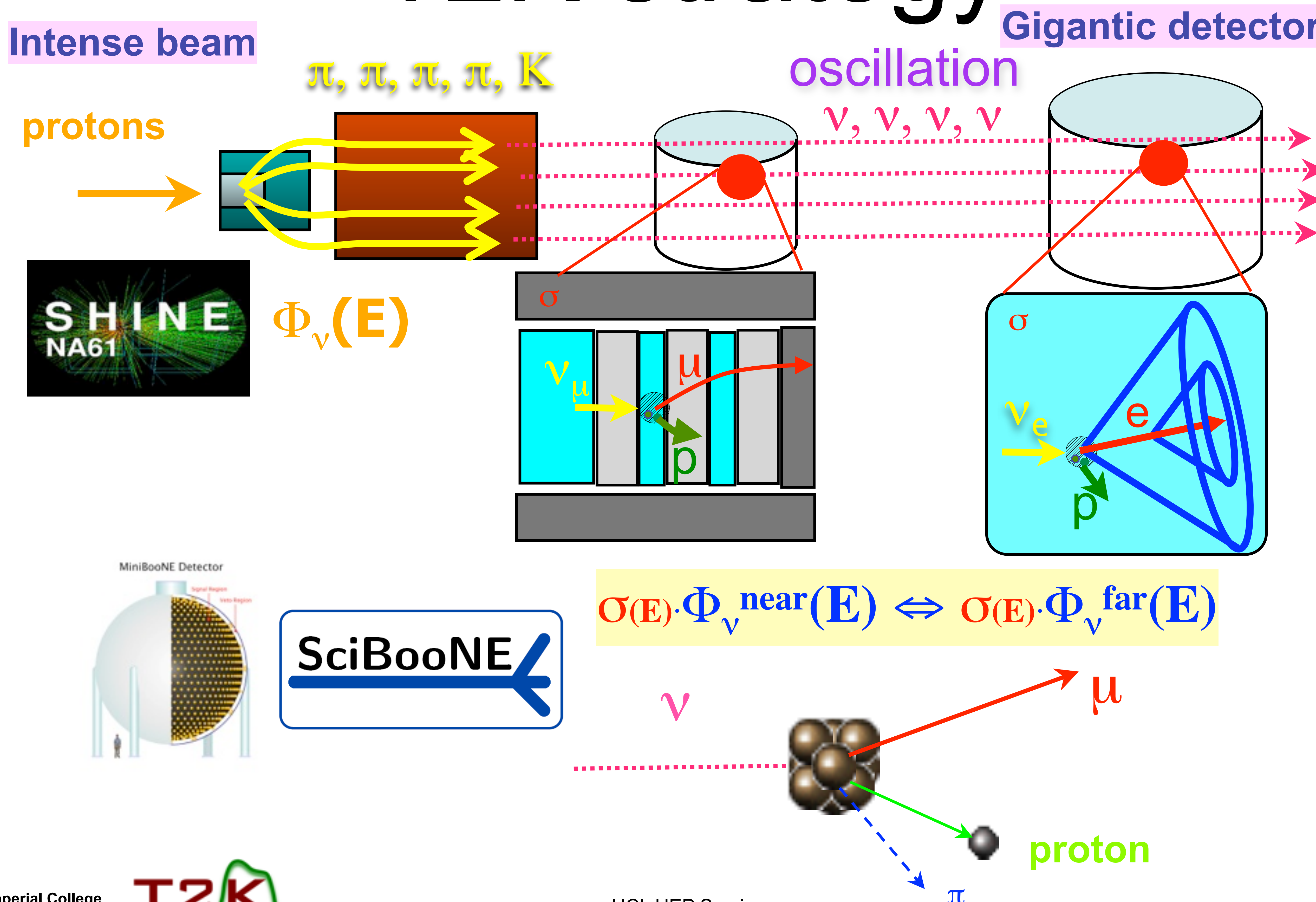
The T2K Collaboration



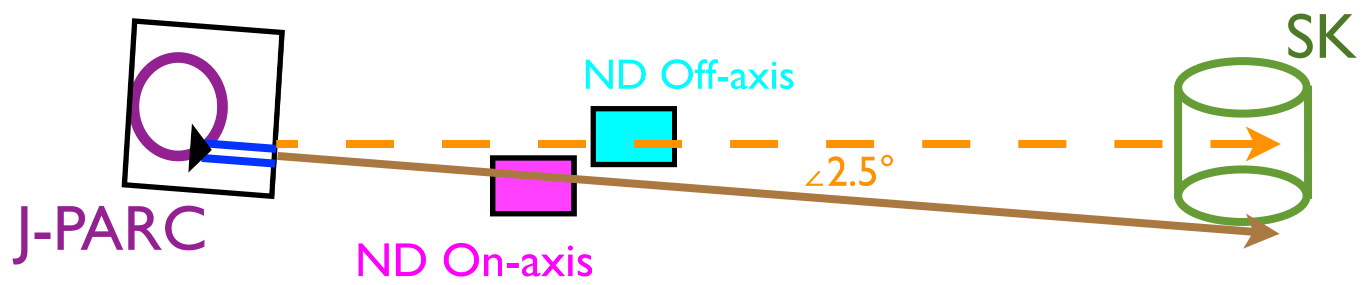
T2K strategy



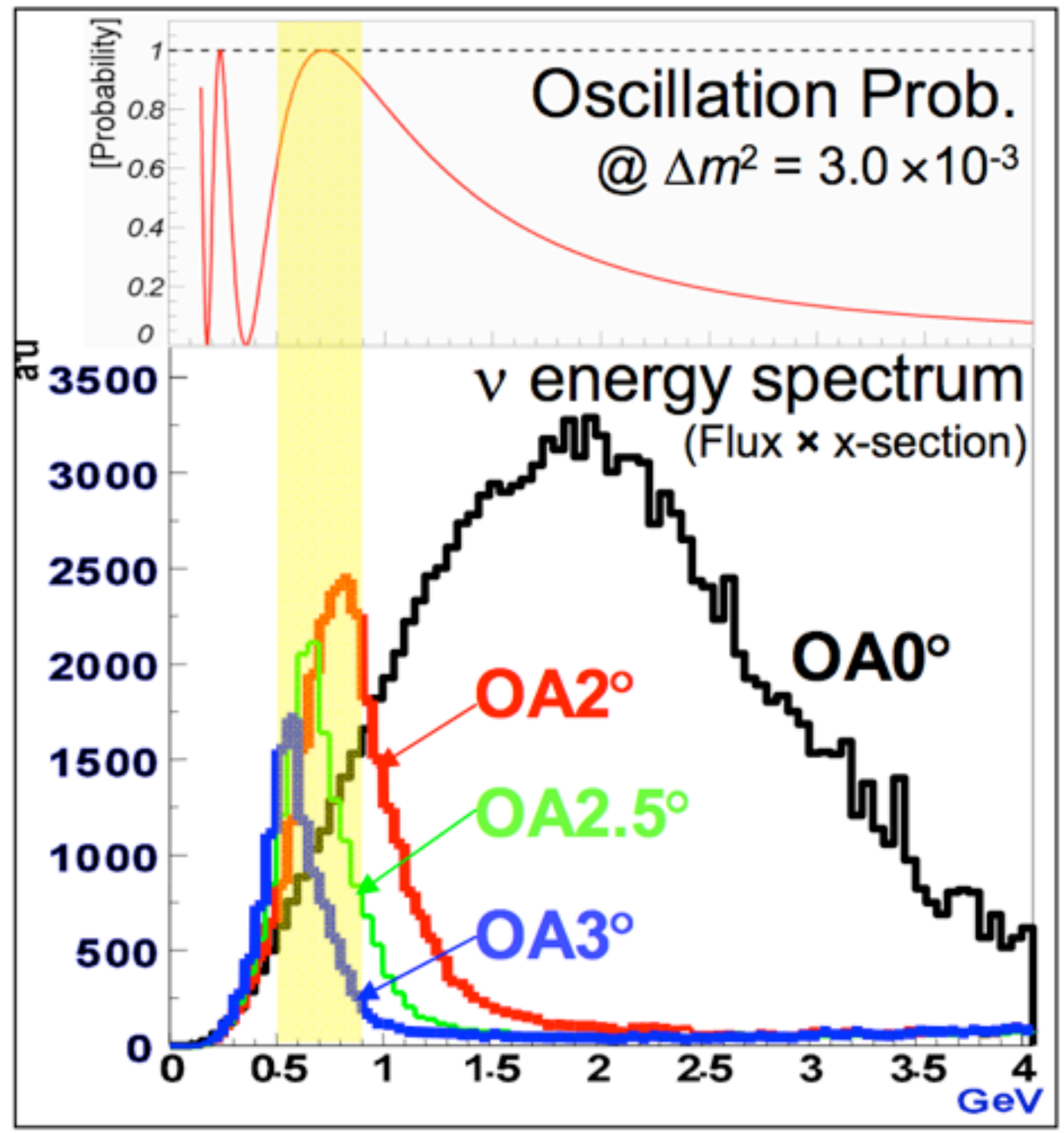
T2K strategy



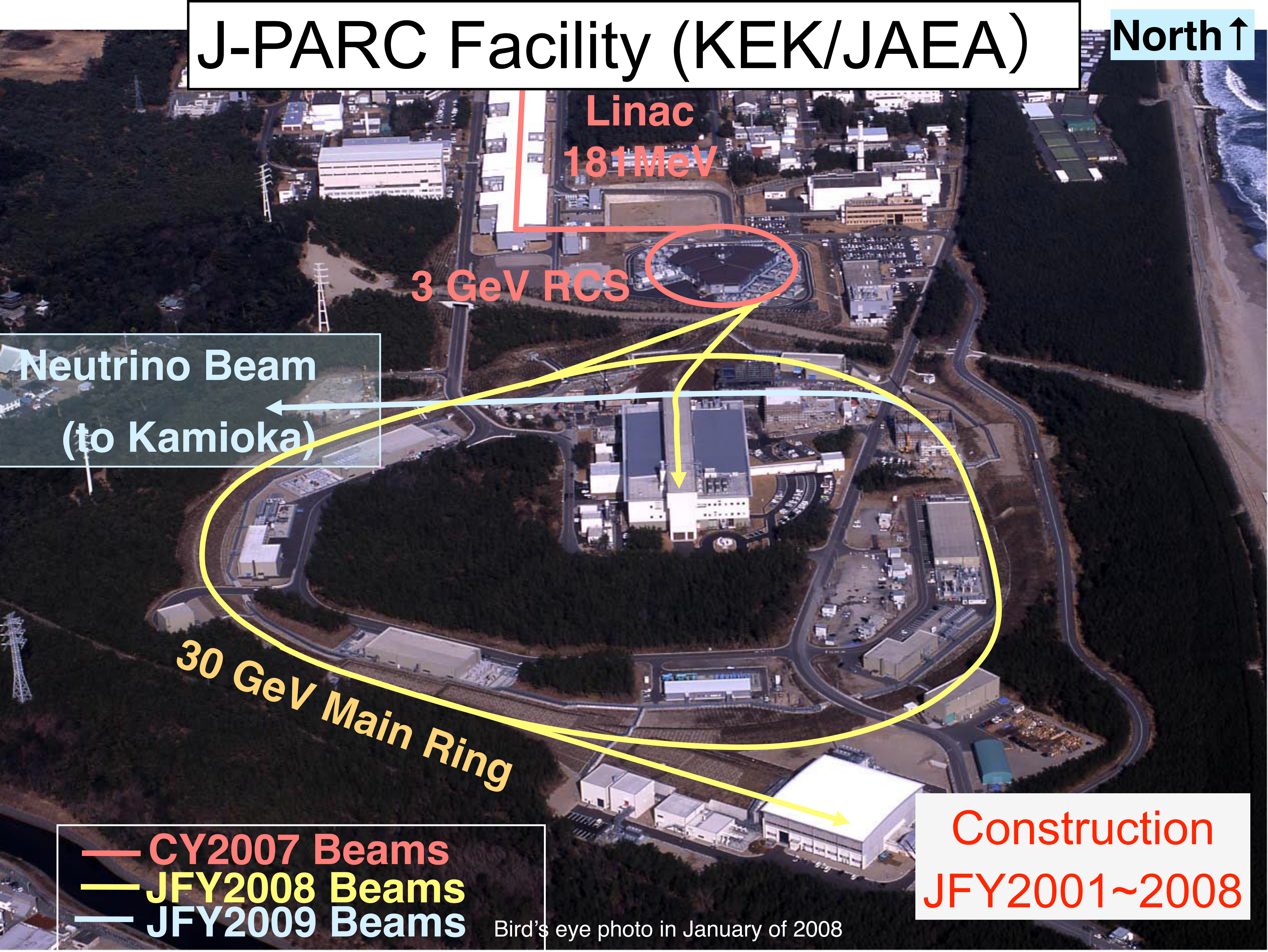
Off-Axis Beam



- Use kinematics of pion decay to tune the neutrino energy
- Flux peak at target energy for desired value of L/E
  - E_ν well matched to Super-K

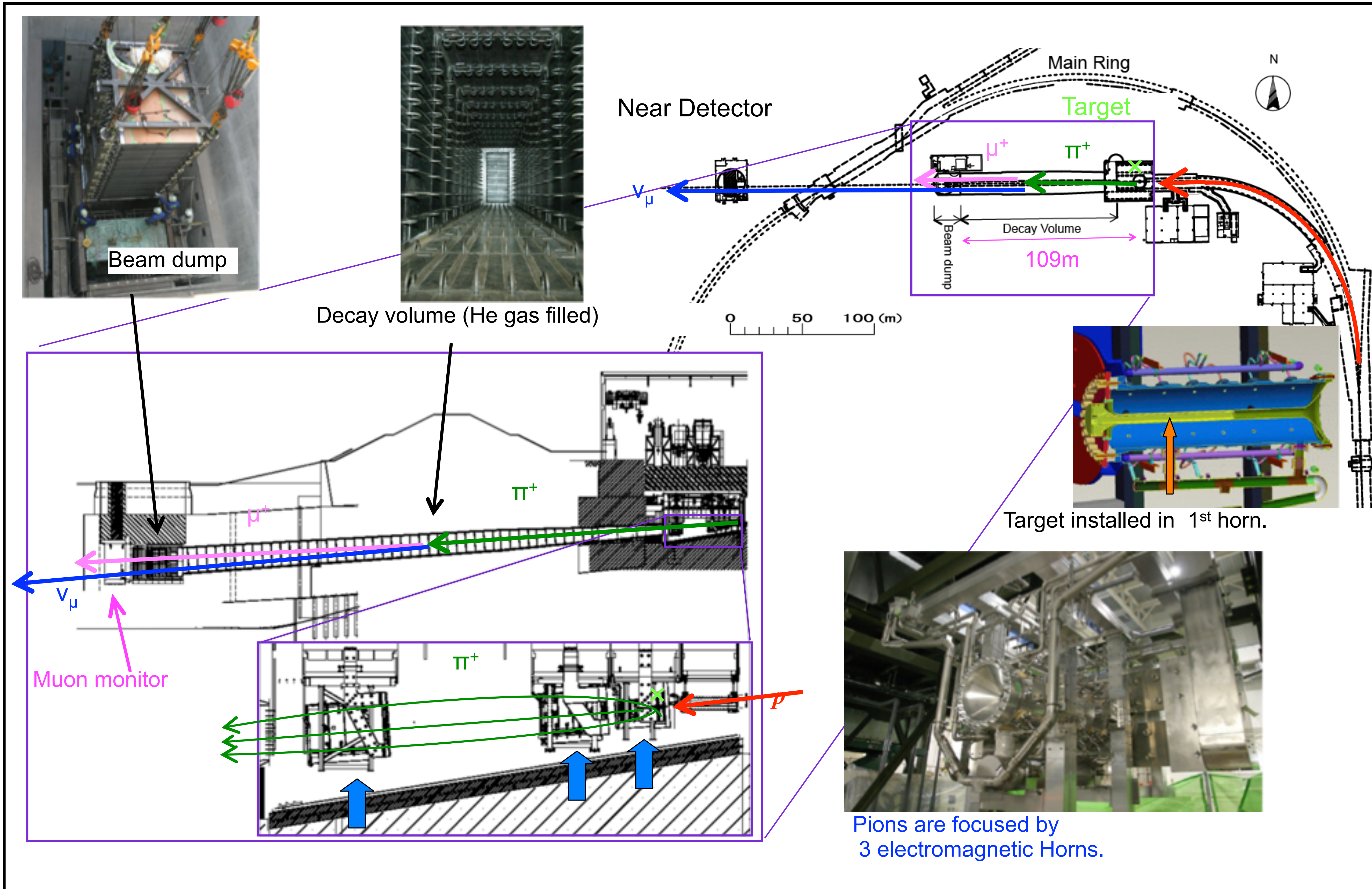


J-PARC Facility (KEK/JAEA)

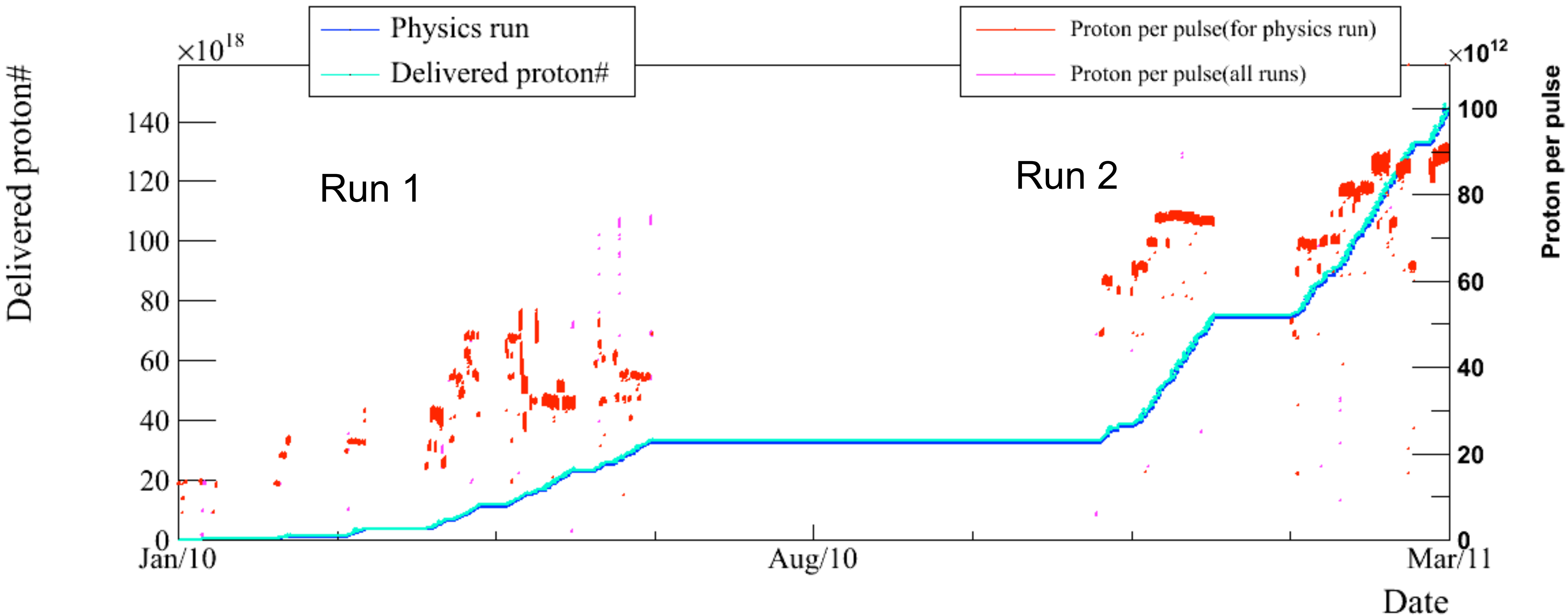


Bird's eye photo in January of 2008

J-PARC neutrino beamline overview

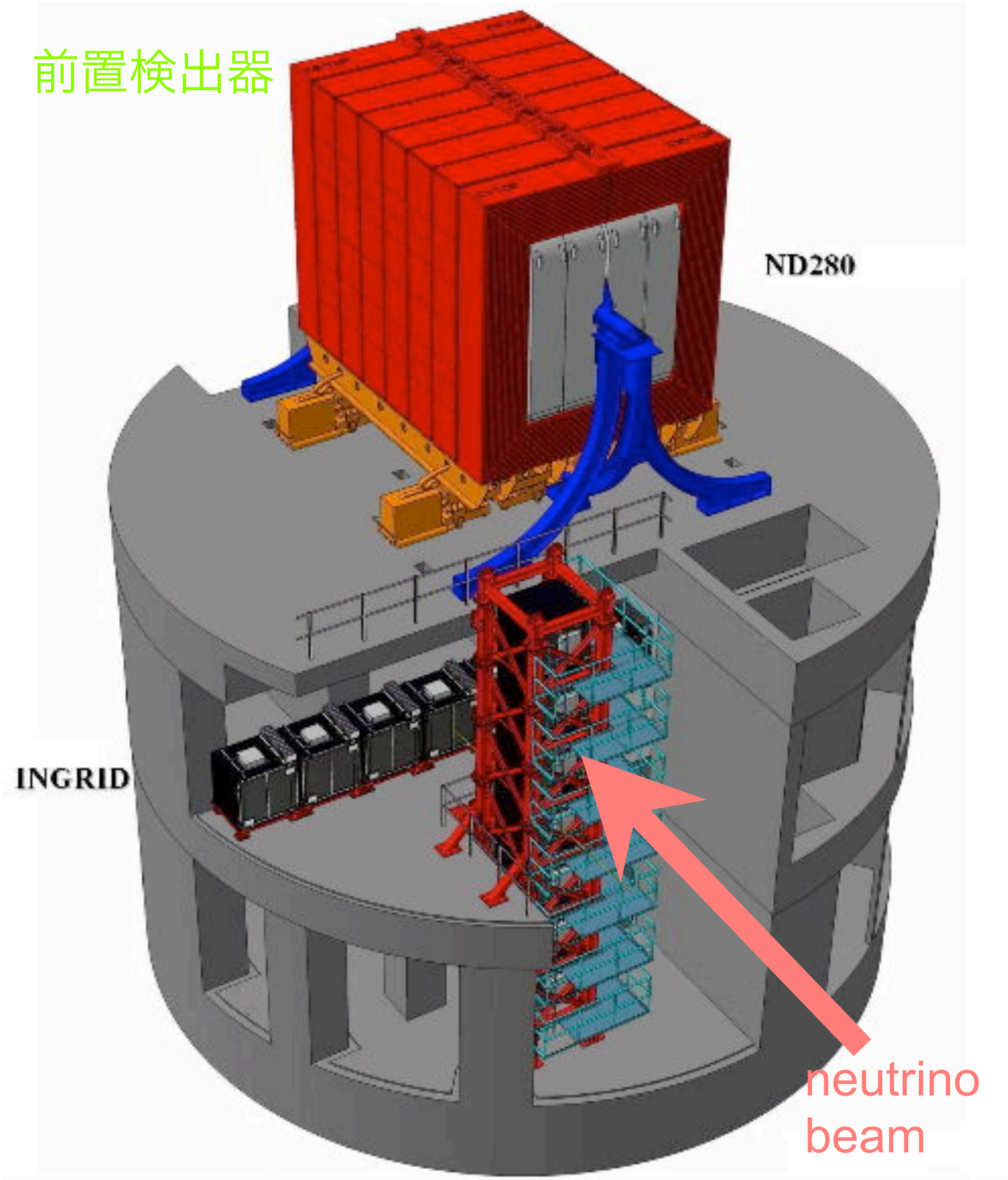


Neutrino Beam Performance



- Total of 1.43×10^{20} POT delivered, less than 2% of final design goal
- Improvements from Run 1 → Run 2: added 2 bunches, more protons/bunch, increased repetition rate.
- Reached 145kW beam power before earthquake shut down beam.

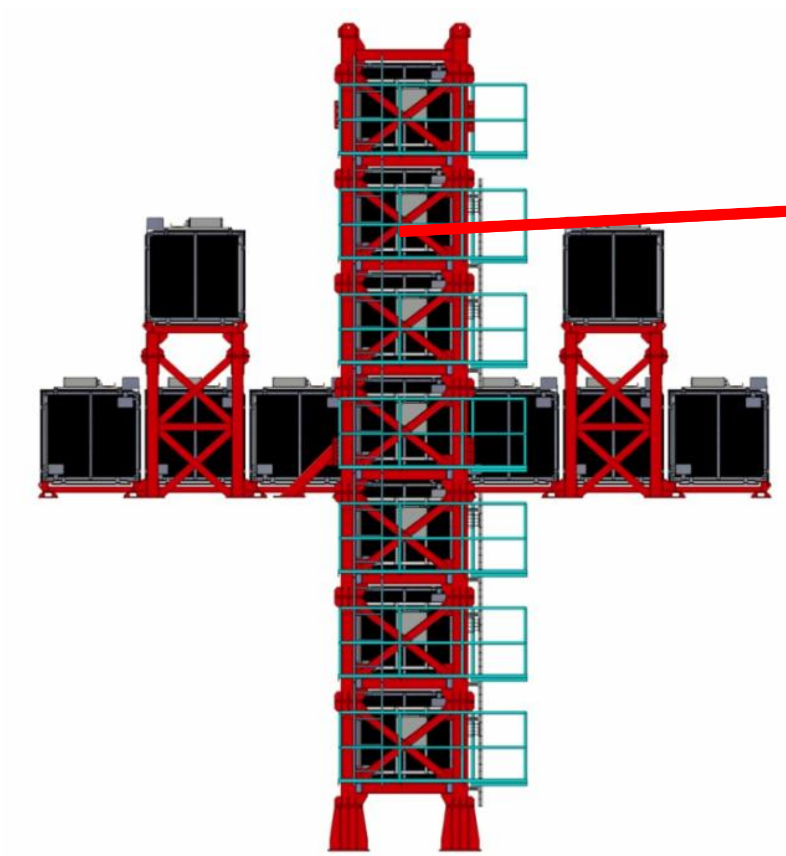
Near Detectors

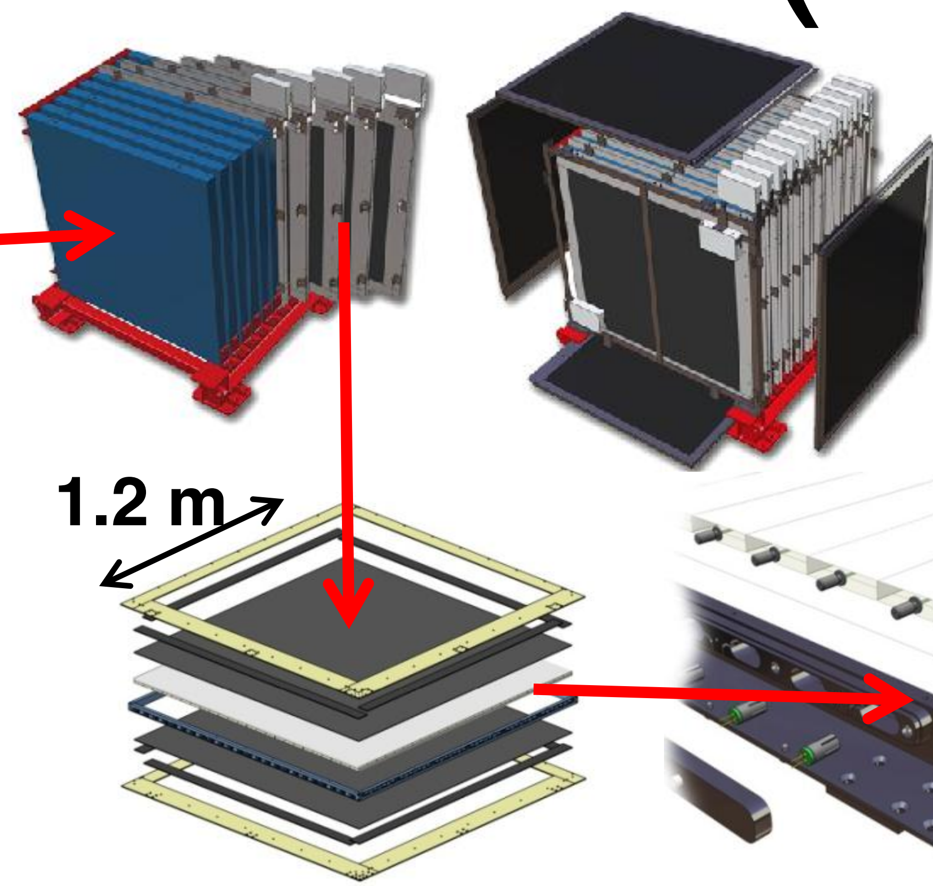


Performance Goals

- INGRID must measure
  - Beam profile and direction
  - High accuracy, short time
- ND280 designed to measure:
  - ν_μ flux: <5%
  - μ energy scale: <2%
  - intrinsic ν_e content: <10%
  - ν_μ CC BGs <10%
- Magnetic field, fine segmentation, excellent tracking

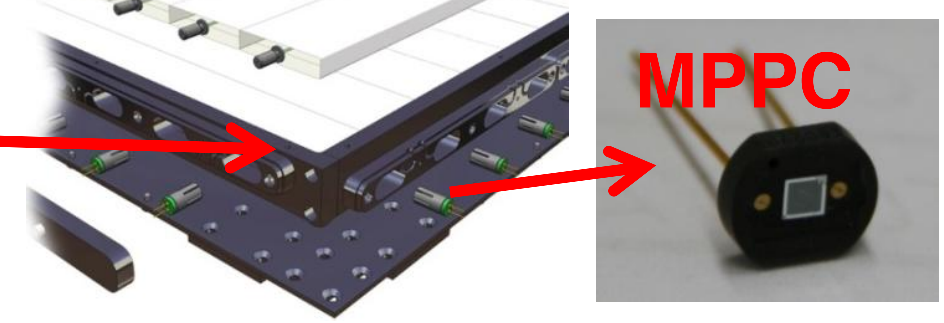
ND280 on-axis (INGRID)



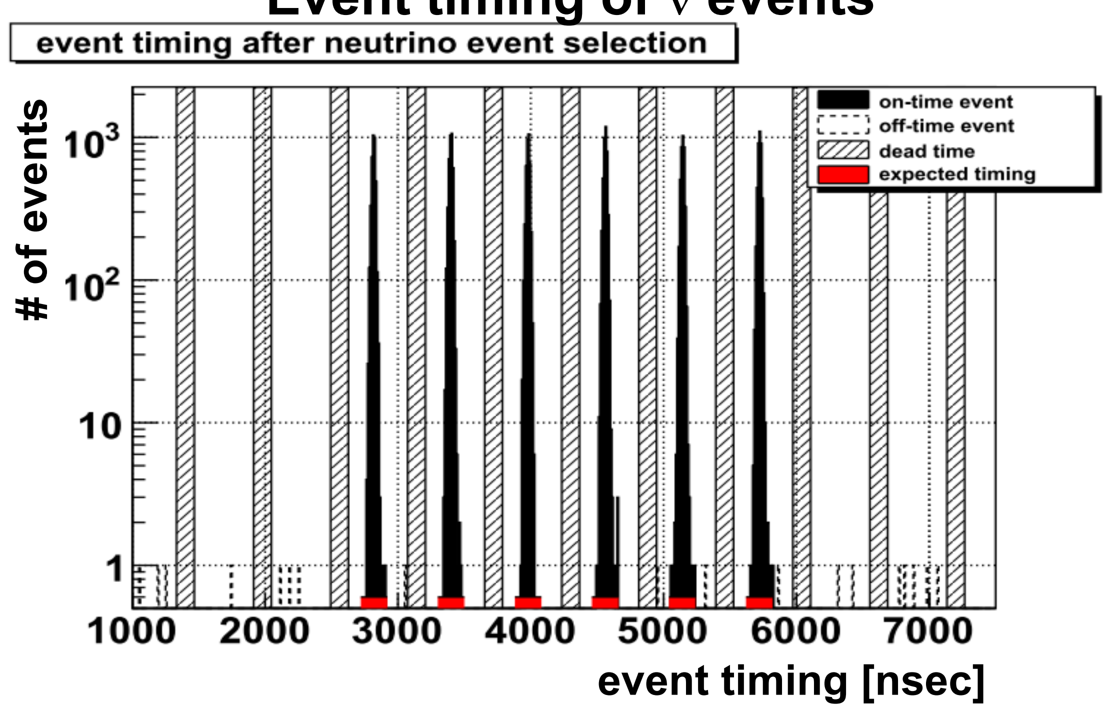


First large scale application of MPPC (~56,000 MPPCs are used for ND280 /INGRID)

~10,800 ch. in INGRID



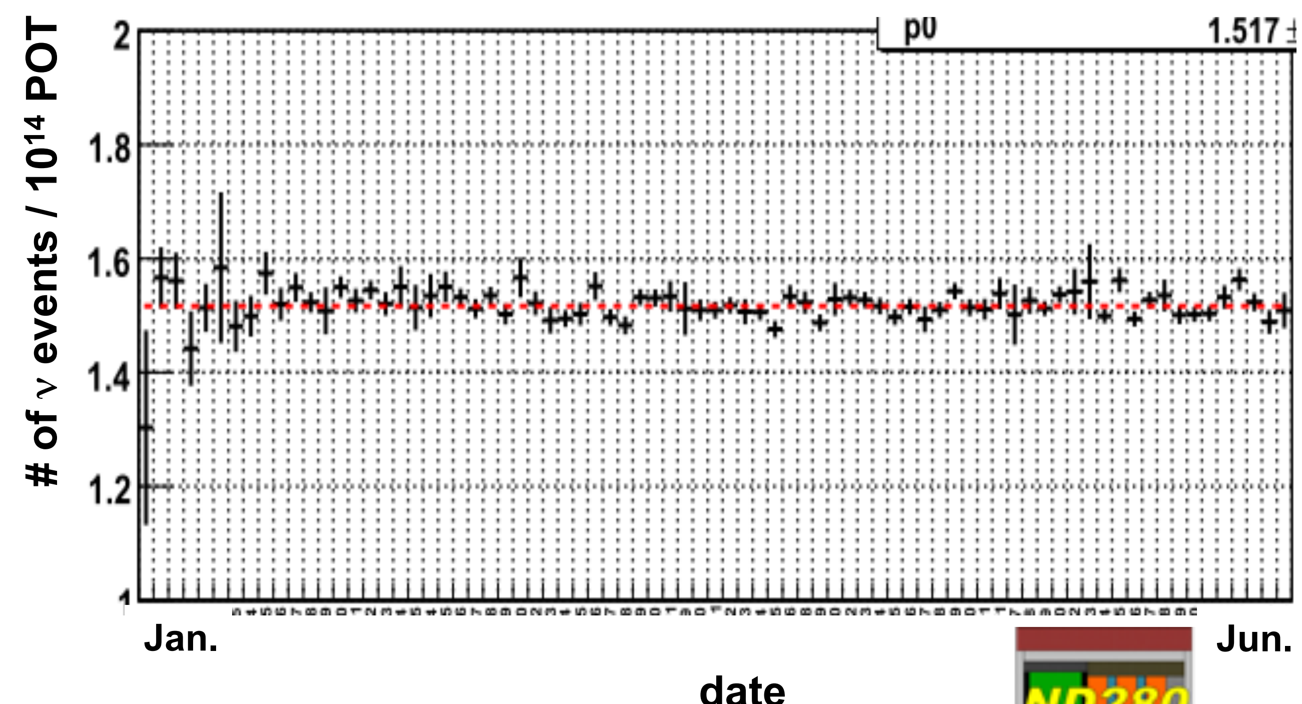
Event timing of ν events



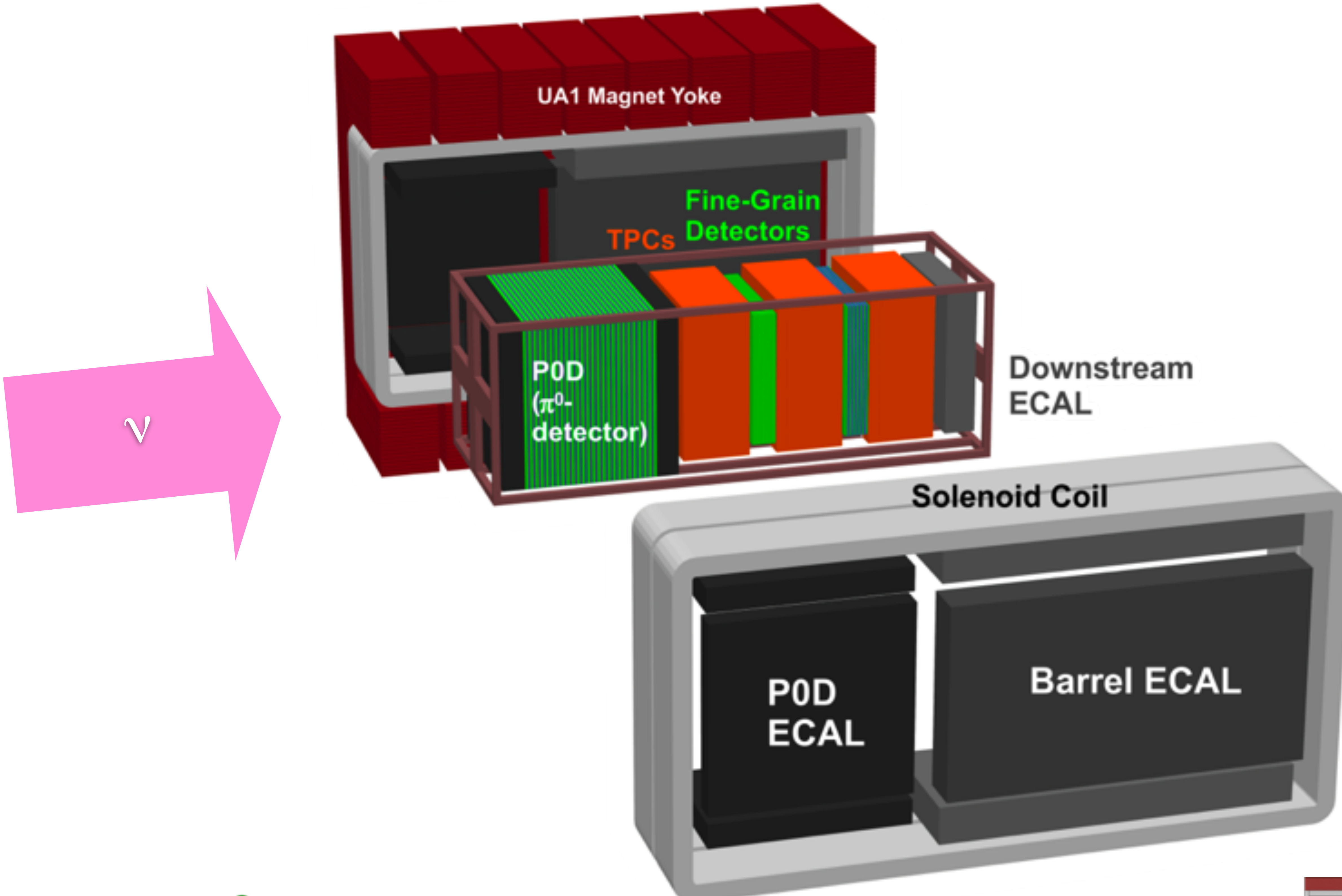
→ Clear 6 bunch structure (581 ns bunch period)

ν beam intensity

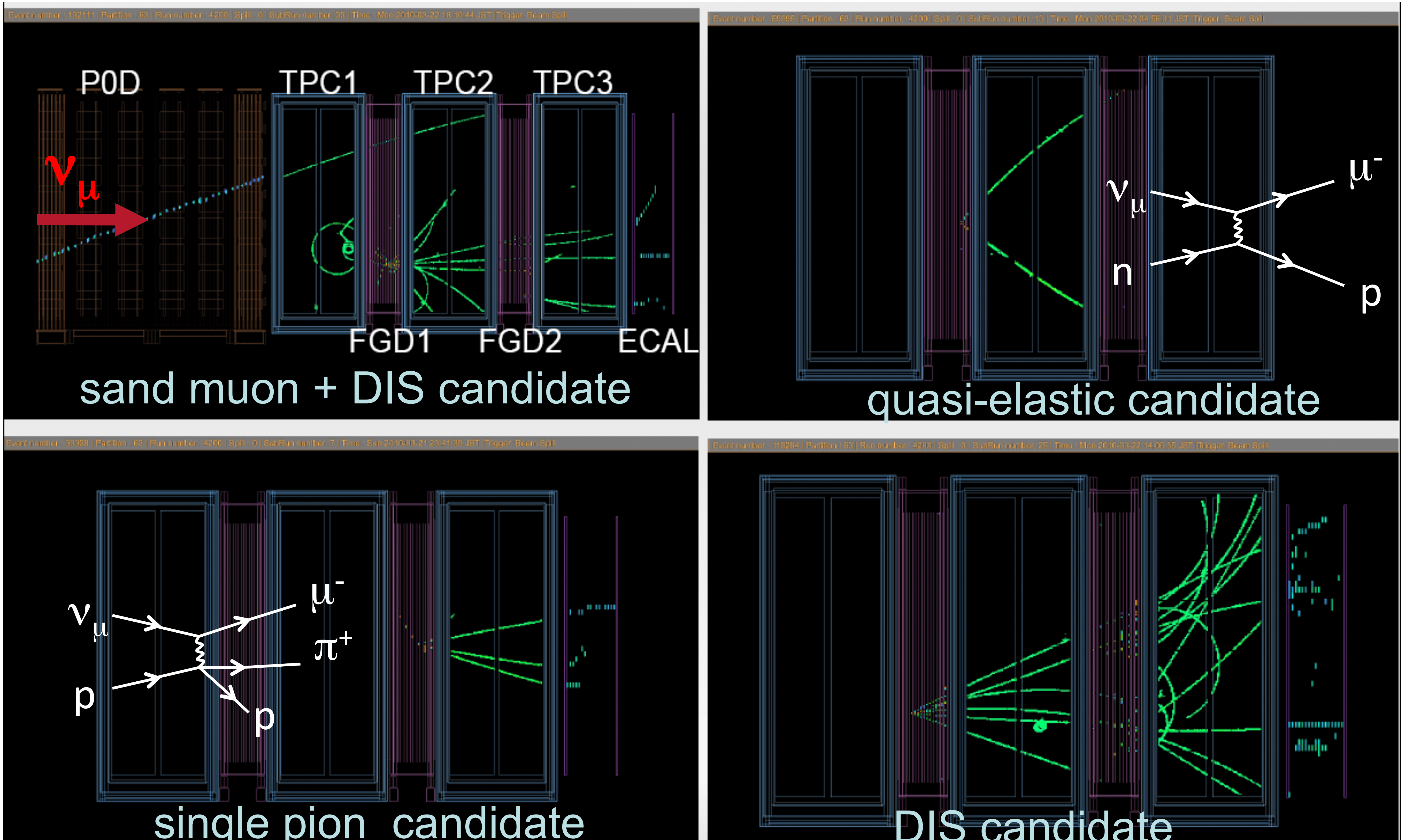
(normalized by proton beam intensity)



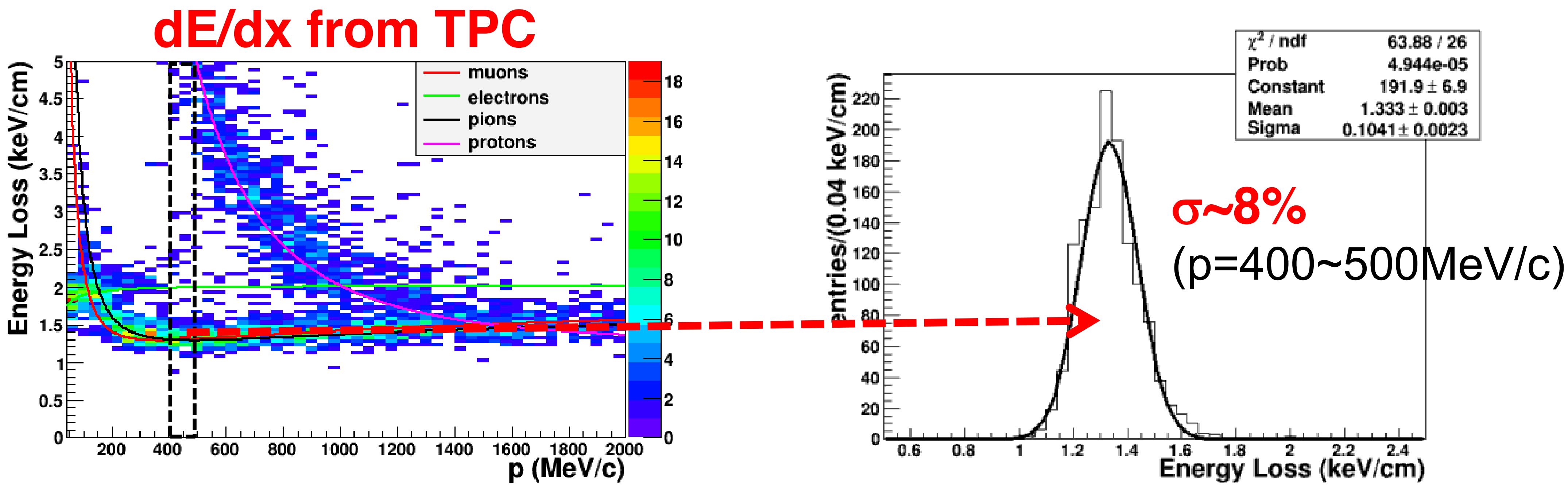
ND280 off-axis detector



ND280 off-axis event gallery

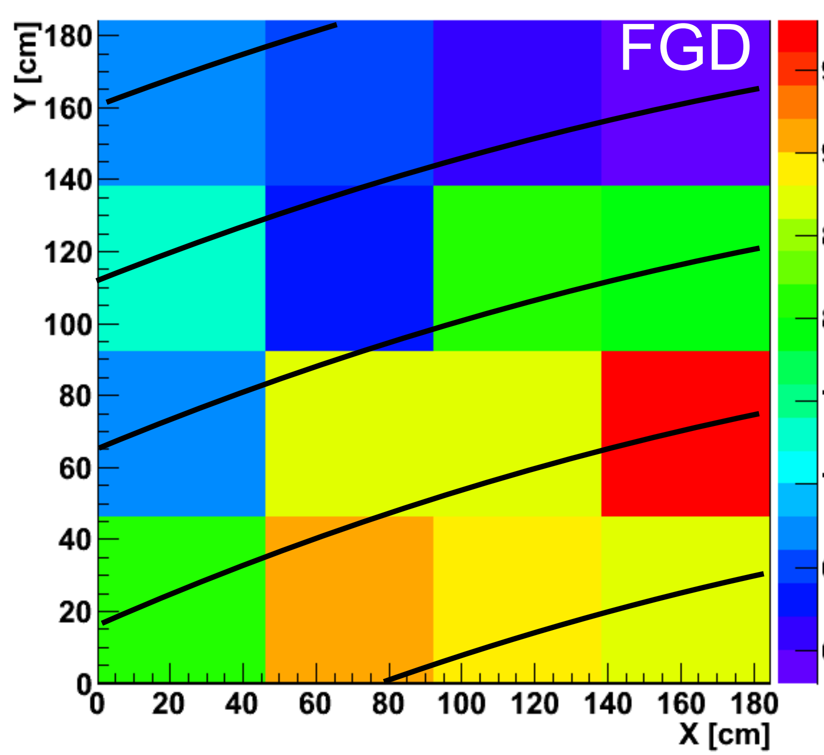


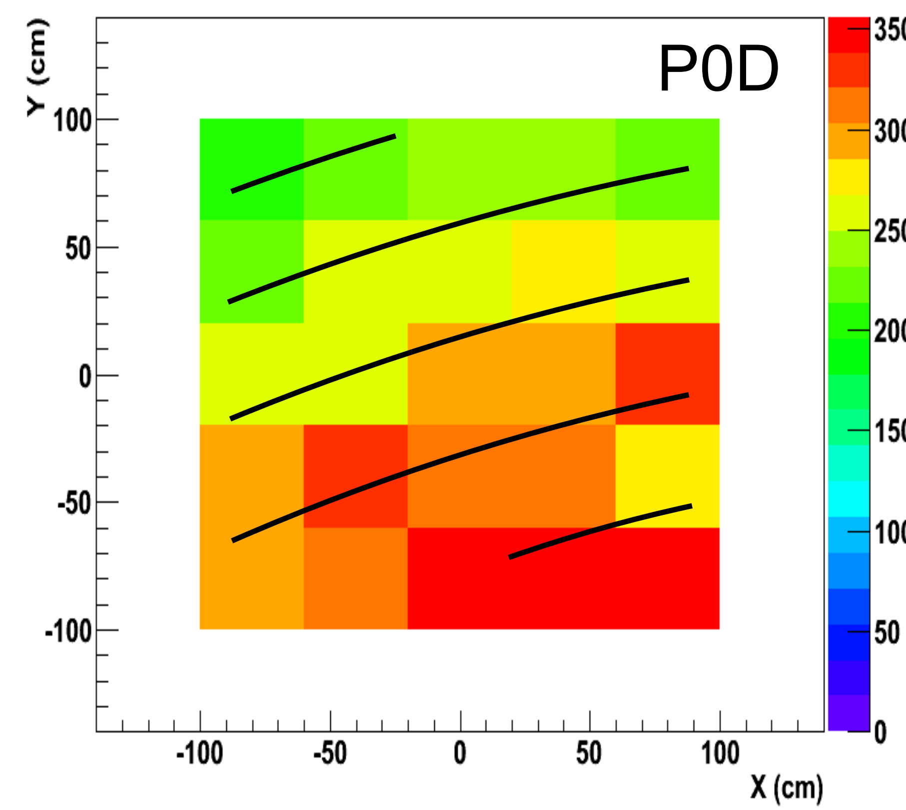
ND280 off-axis performance



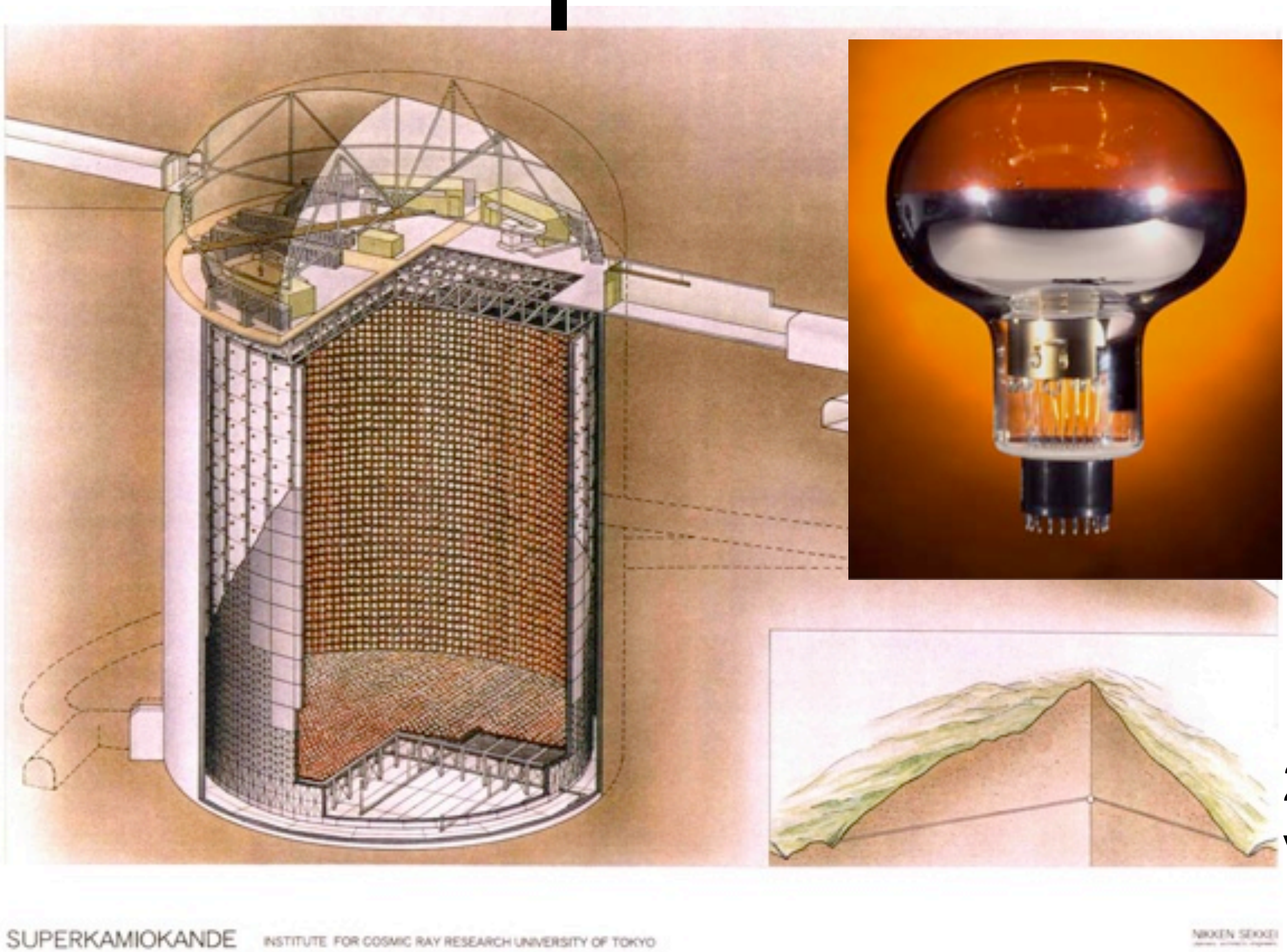
Vertex X-Y distribution

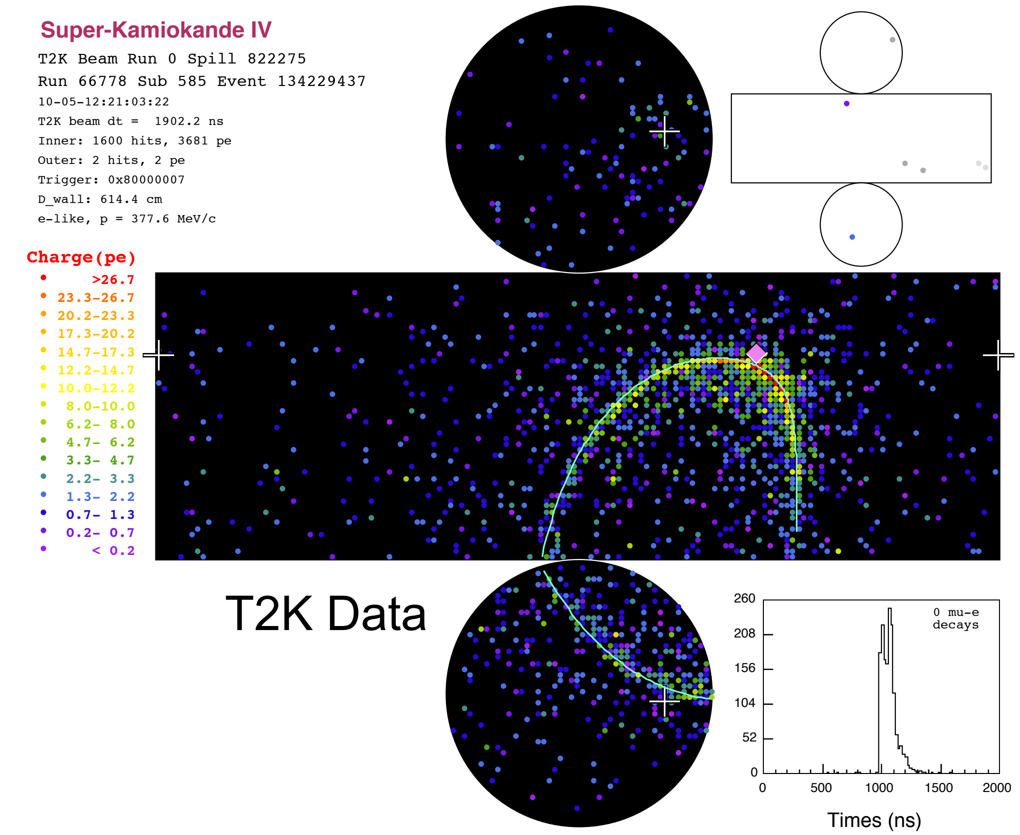
⊙ ν **beam direction**





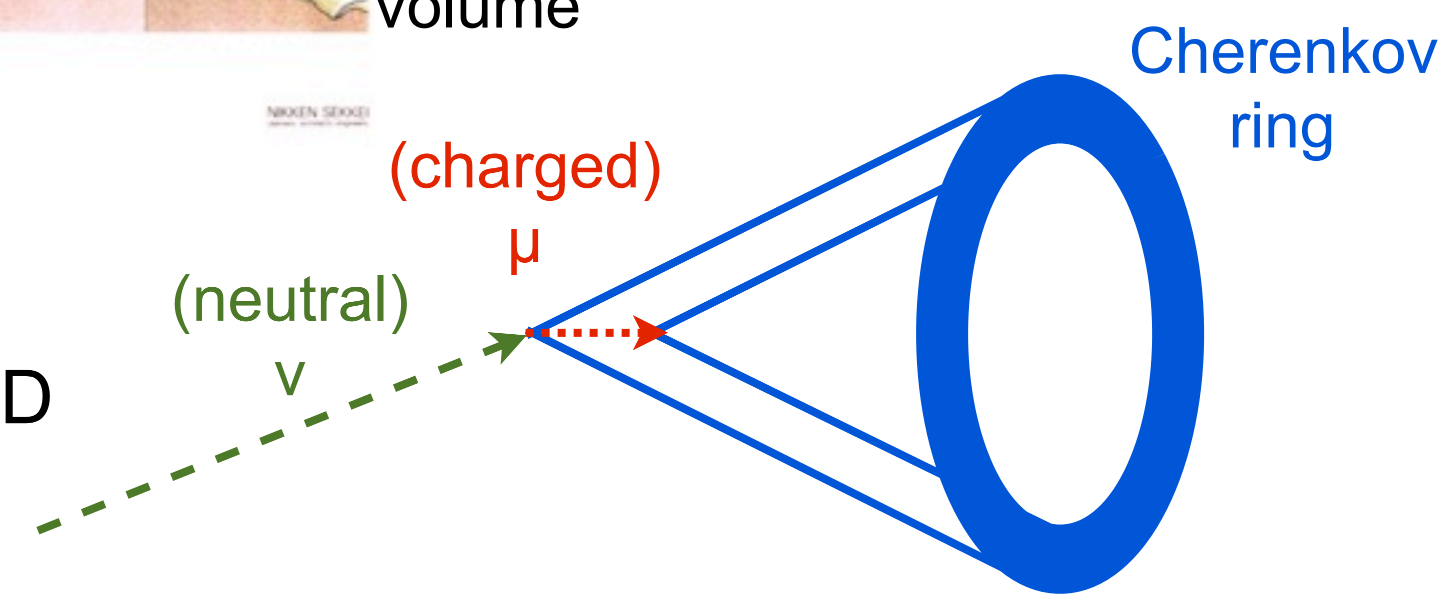
Super-Kamiokande





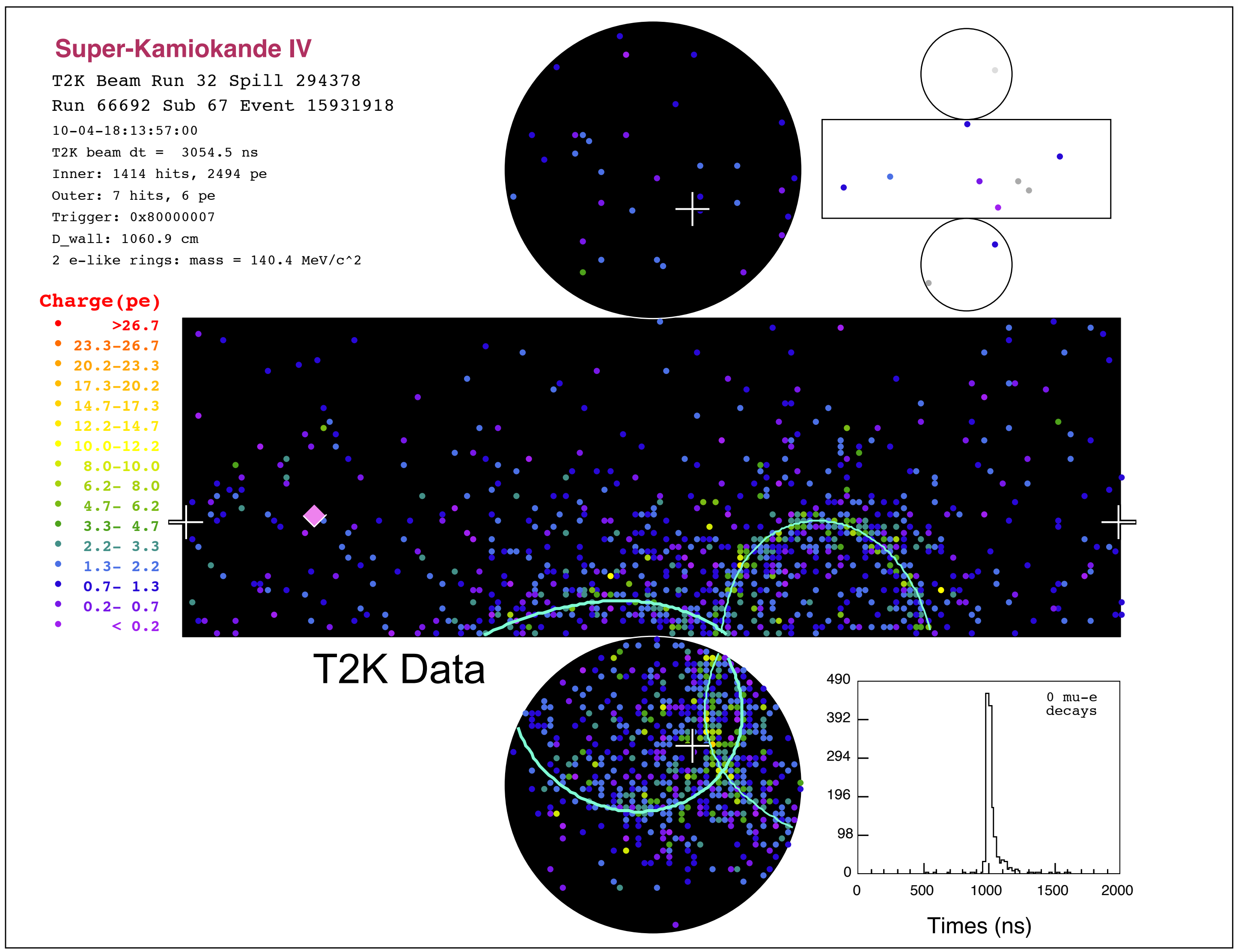
22.5 kton fiducial volume

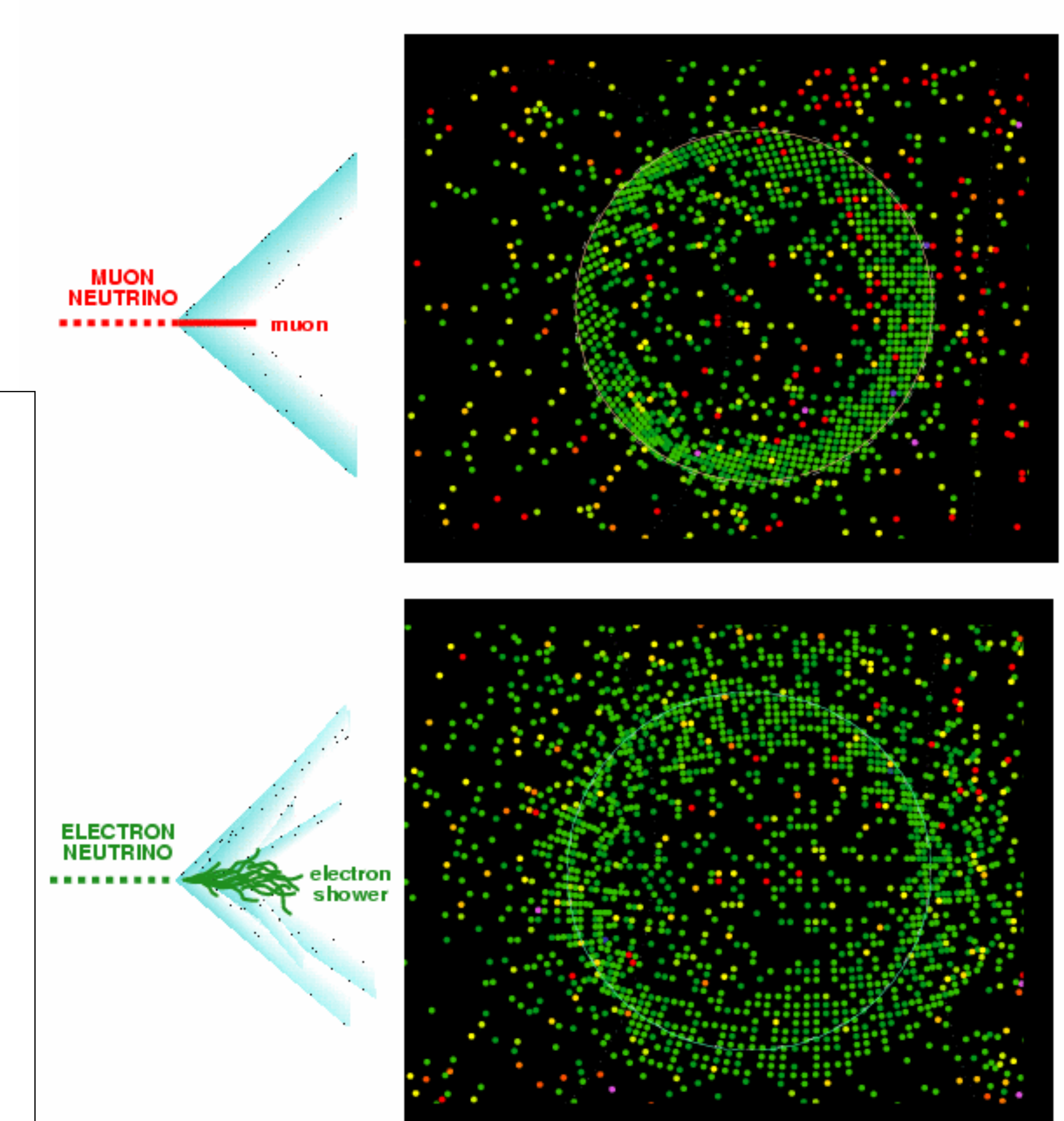
- 50,000 ton water Cherenkov detector
- 11,146 PMTs in ID, 1,885 in OD
- ~1km underneath Ikenoyama



SK Reconstruction

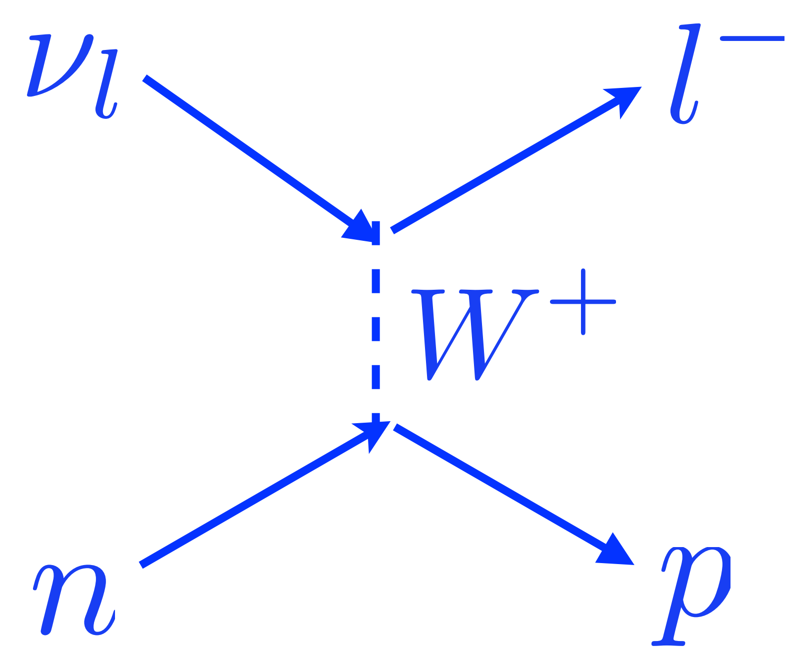
- Find vertex (mostly timing)
- Count rings
- Find momenta
- PID from ring topology (“fuzziness”)





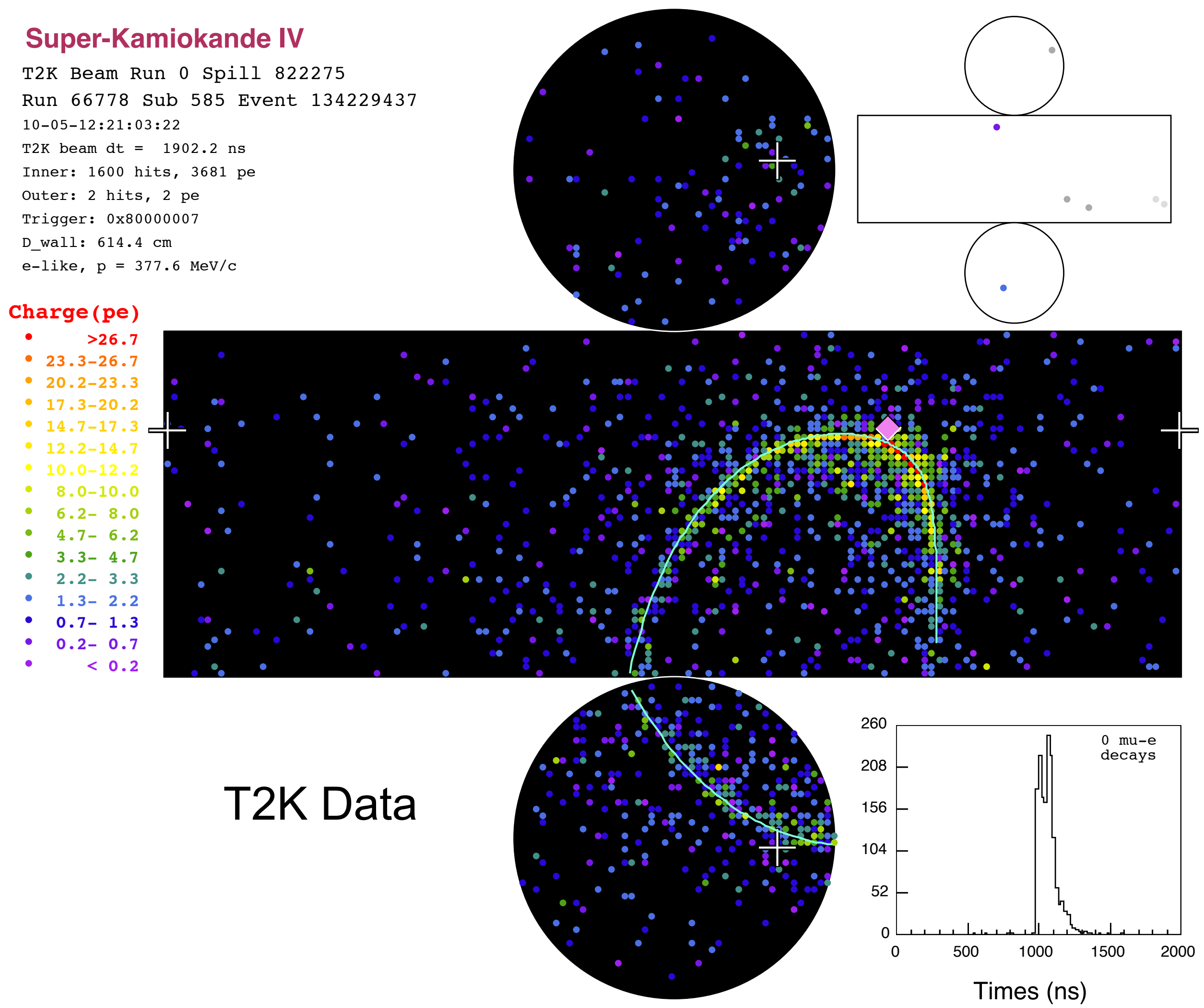
Use atmospheric data vs. MC to check reconstruction and set systematic errors

Signal at SK



- Charged Current Quasi-Elastic Events
- Only single lepton ring visible at SK
- Ring topology indicates ν_e vs. ν_μ

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - El + p_l \cos\theta_l}$$

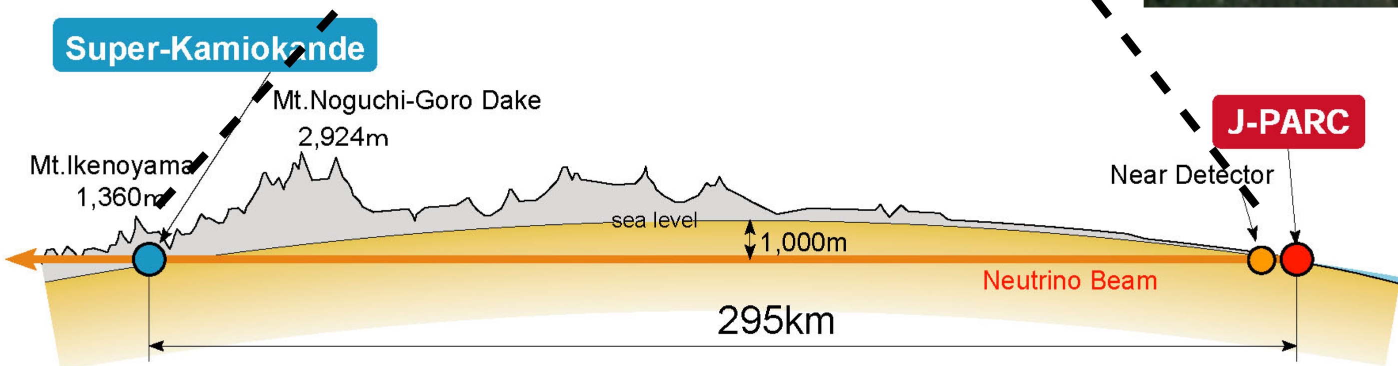


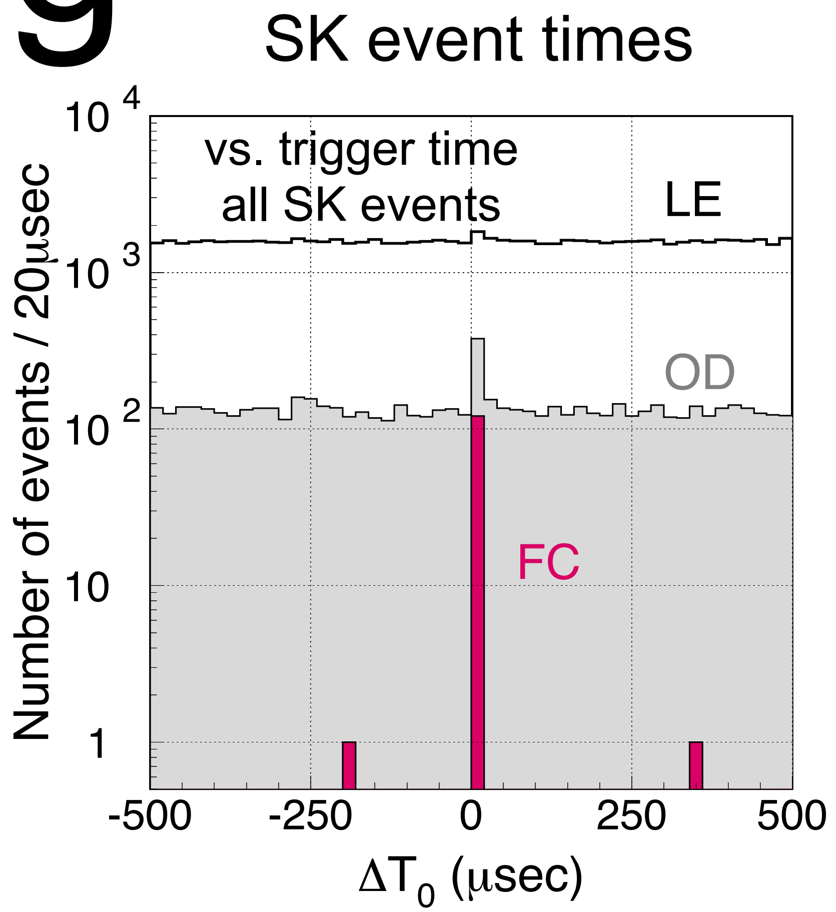
T2K Data

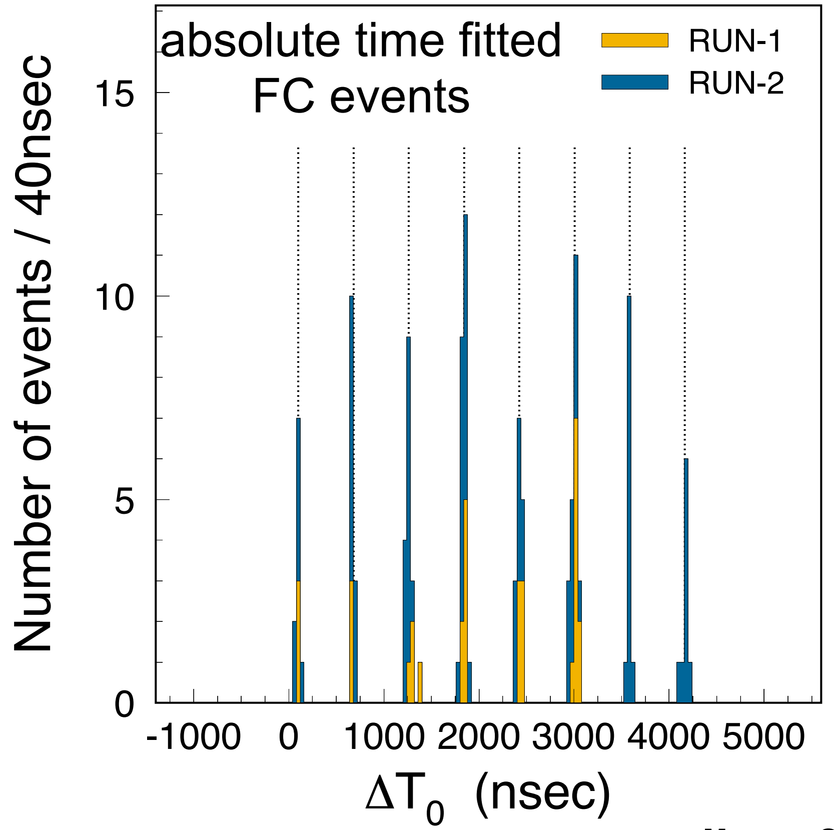
- Incident neutrino energy can be reconstructed (best for CCQE)!
- Recoil proton usually below threshold at T2K beam energy.

Beam Trigger/Timing

- T2K beam trigger from beam extraction
- Commonview GPS mode used



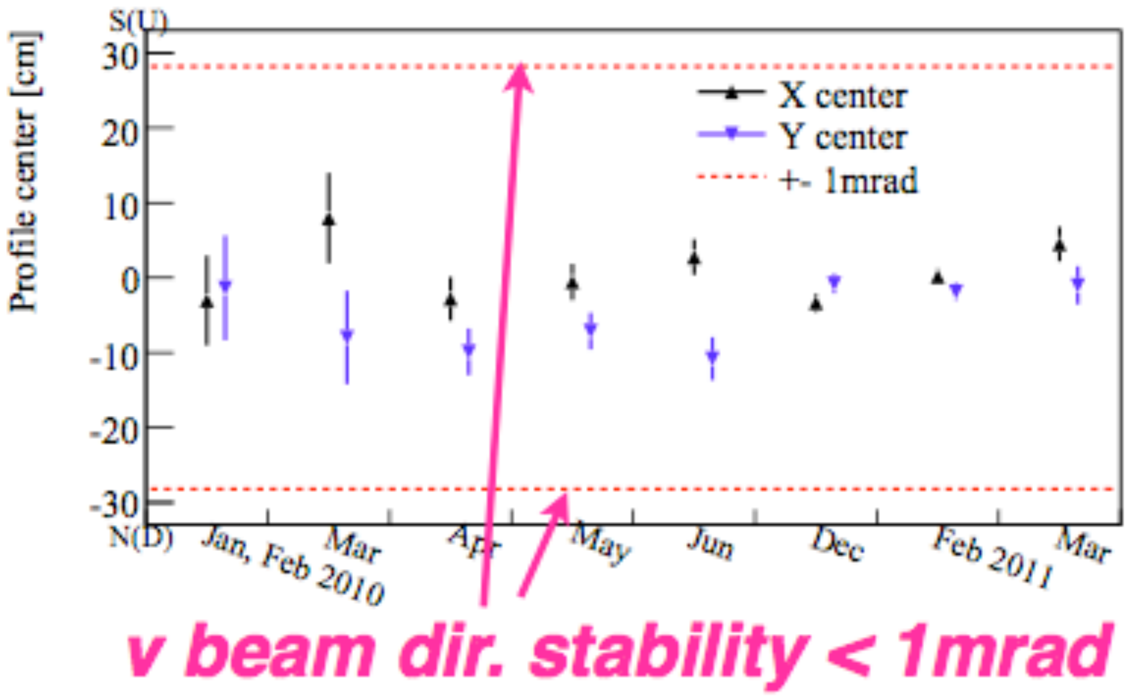




- At SK, 2 GPS units and a Rubidium clock are used to measure and confirm the time stability.

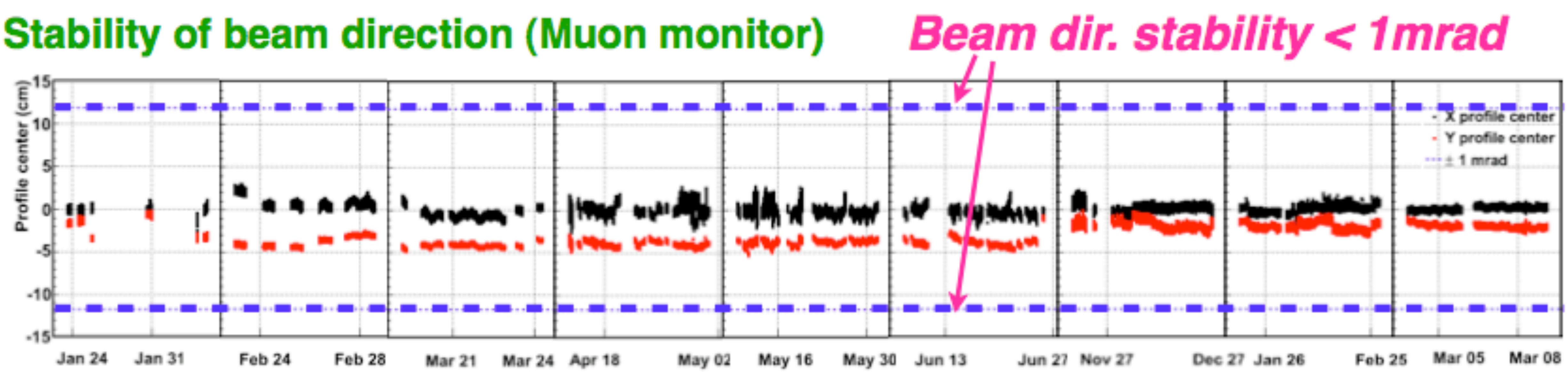
Beam stability

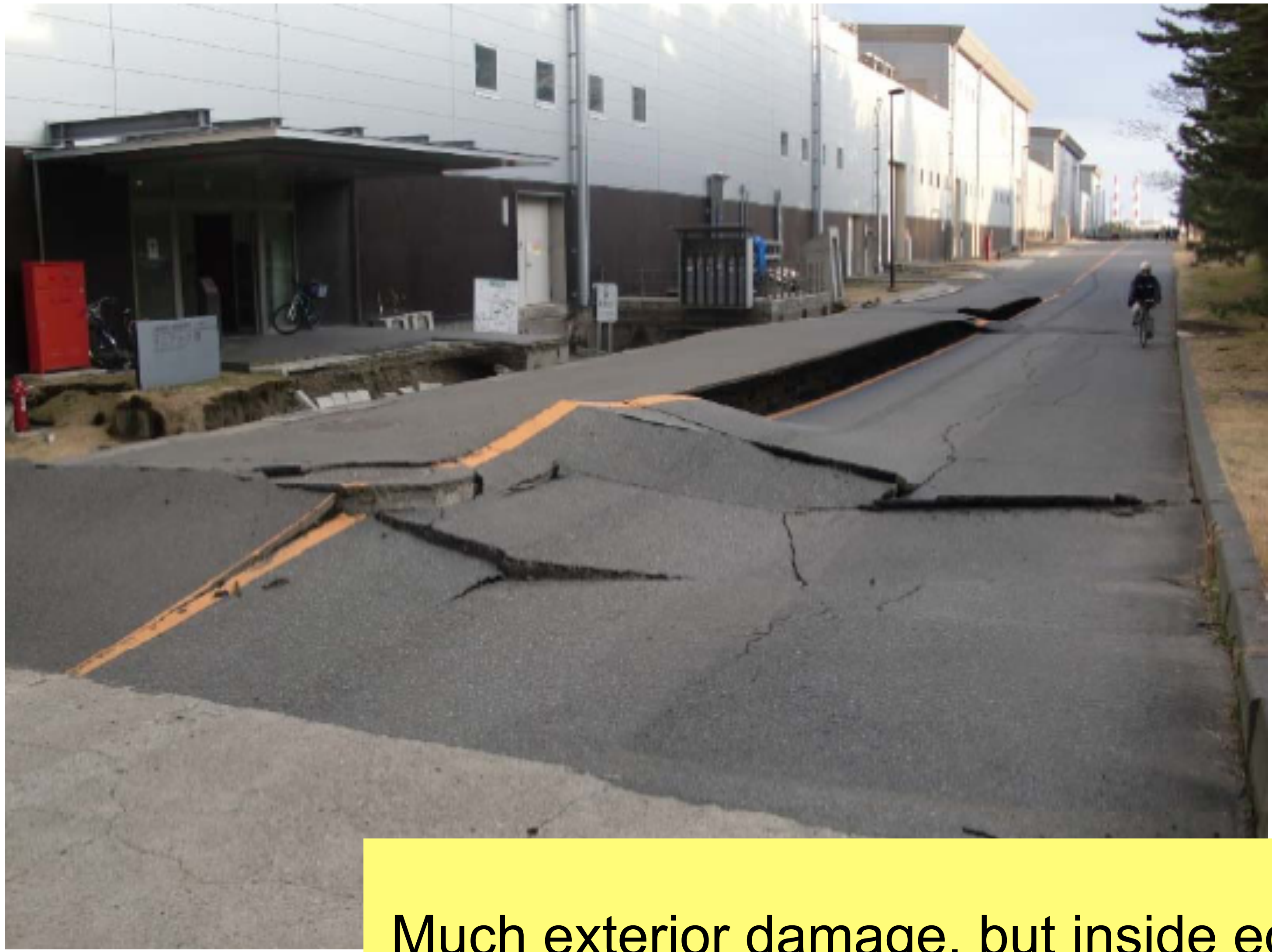
Stability of ν beam direction (INGRID)



Stability of ν interaction rate normalized by # of protons (INGRID)

Stability of beam direction (Muon monitor)





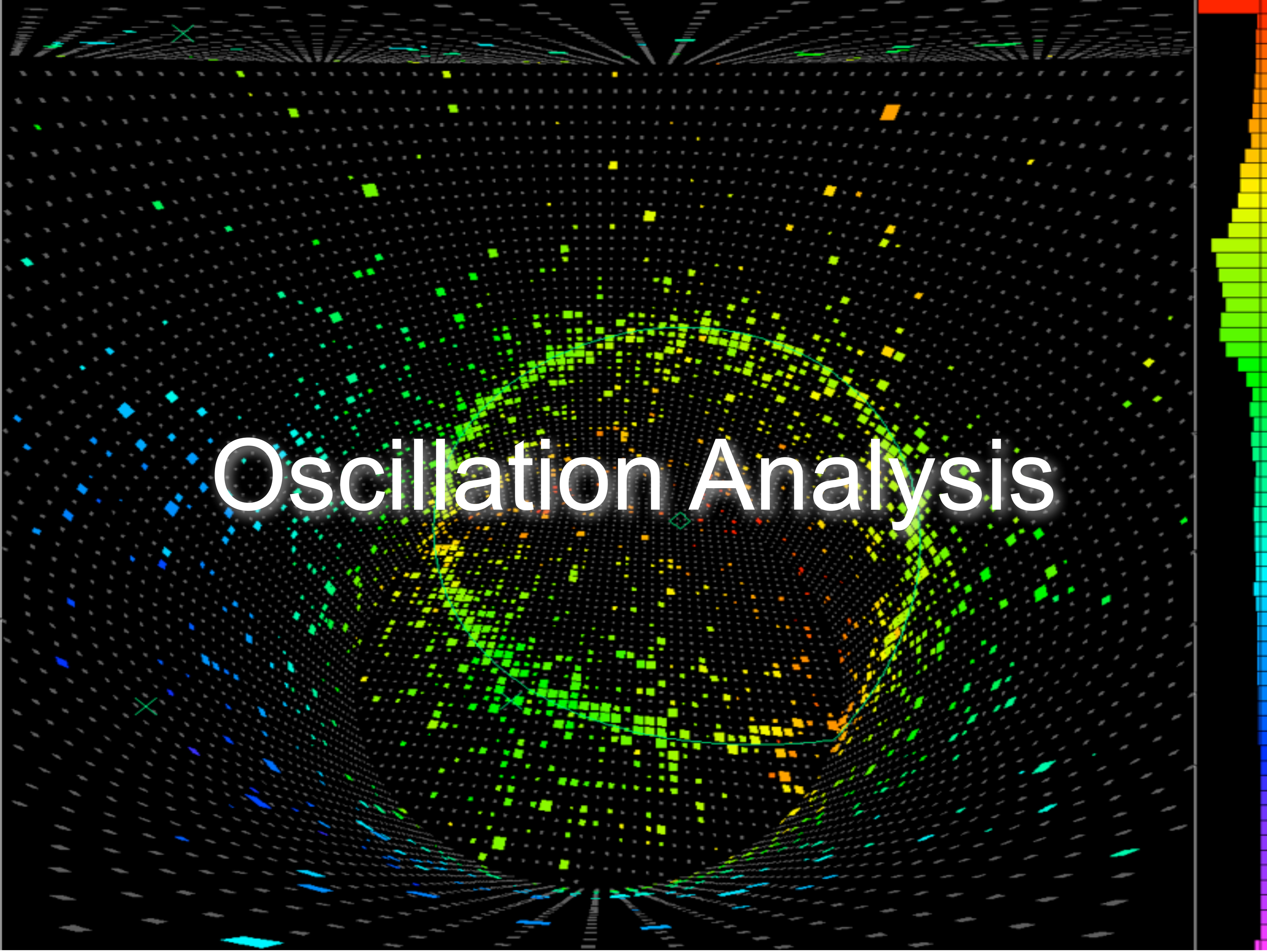
11 March, 14:46...

Much exterior damage, but inside equipment largely undamaged.

Rapidly repaired!

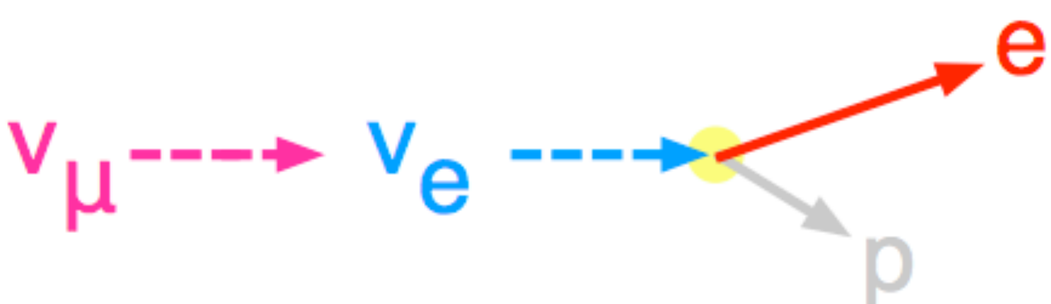
Repairs are basically complete.
Physics data taking resumed in January!

Oscillation Analysis



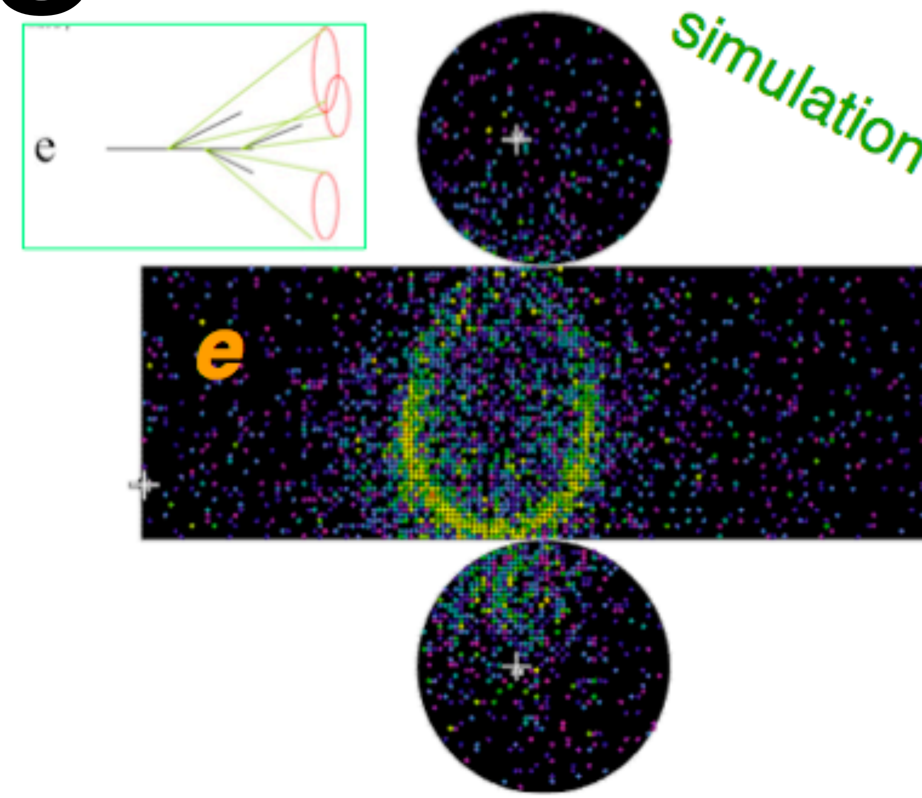
Signal & backgrounds

- Signal = **single electron event**
  - oscillated ν_e interaction :

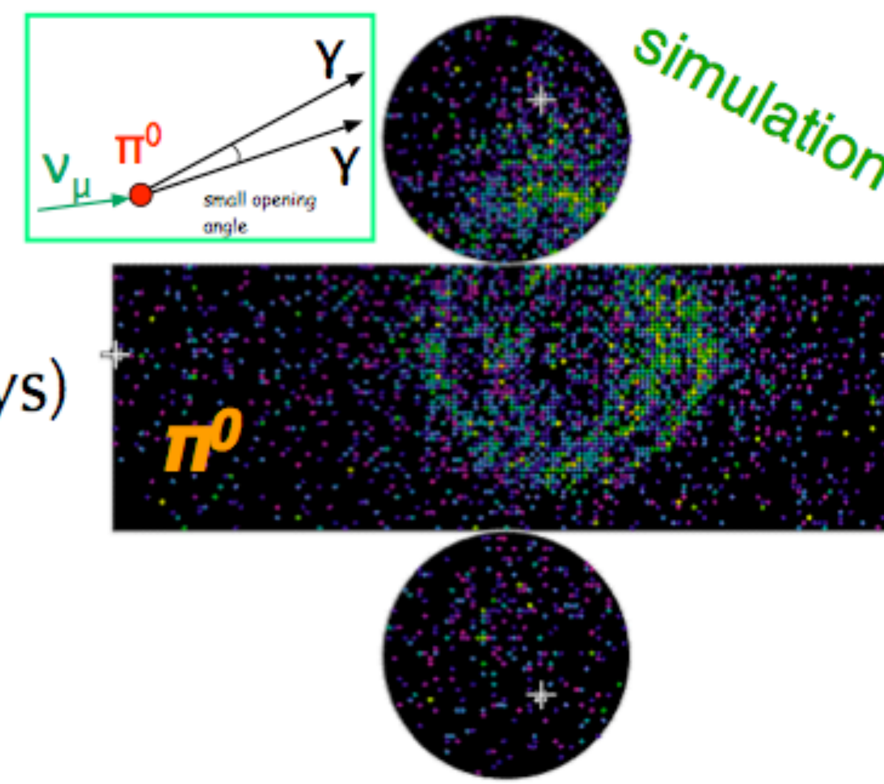


CCQE : $\nu_e + n \rightarrow e + p$

(dominant process at T2K beam energy)



- Background
  - intrinsic ν_e in the beam (from μ, K decays)
  - π^0 from NC interaction



Event rate prediction

$$N_{SK}^{exp} = R_{ND}^{\mu,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,MC}}$$

Measured rate at ND

MC prediction,
tuned with external data

We use the MC to predict the expected event rate at SK, and scale the (flux) expectation using the measured rate of CC events in ND280

Event rate prediction

$$N_{SK}^{exp} = R_{ND}^{\mu,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,MC}}$$

ND ν_μ event rate

Measurement of the number of inclusive ν_μ charged-current events in ND per p.o.t. using data collected in Run 1 (2.88×10^{19} p.o.t.)

Stability of the beam event rate is confirmed by INGRID measurement

INGRID ν int. rate stability Run 1+2 / Run 1 < 1%

F/N ratio for ν_e signal event

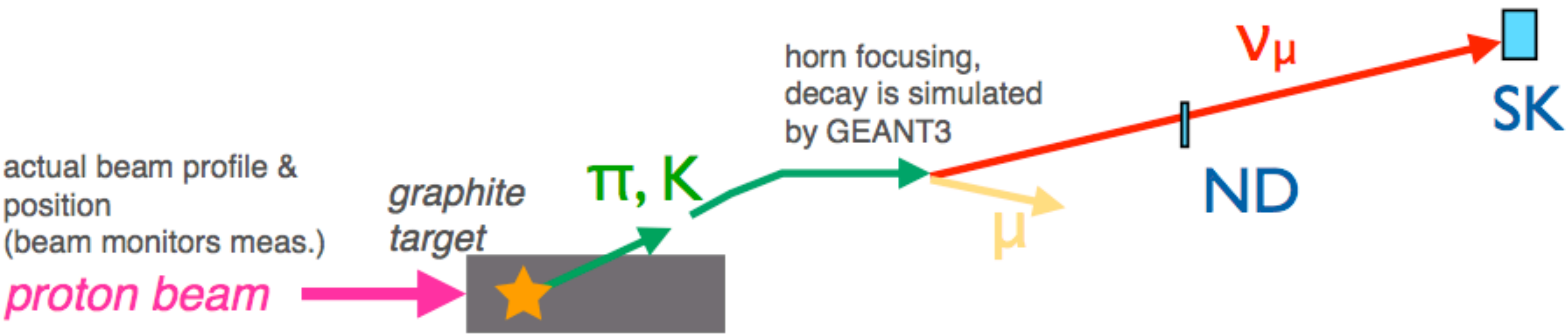
(flux) x (osc. prob.) x (x-section) x (efficiency) x (det. mass)

$$\frac{N^{MC}_{SK\ \nu_e\ sig.}}{R^{\mu,\ MC}_{ND}} = \frac{\int \Phi^{\mathrm{SK}}_{\nu_\mu}(E_\nu) \cdot P_{\nu_\mu \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{\mathrm{ND}}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu} \cdot \frac{M^{SK}}{M^{ND}} \cdot \mathrm{POT}^{SK}$$

Flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

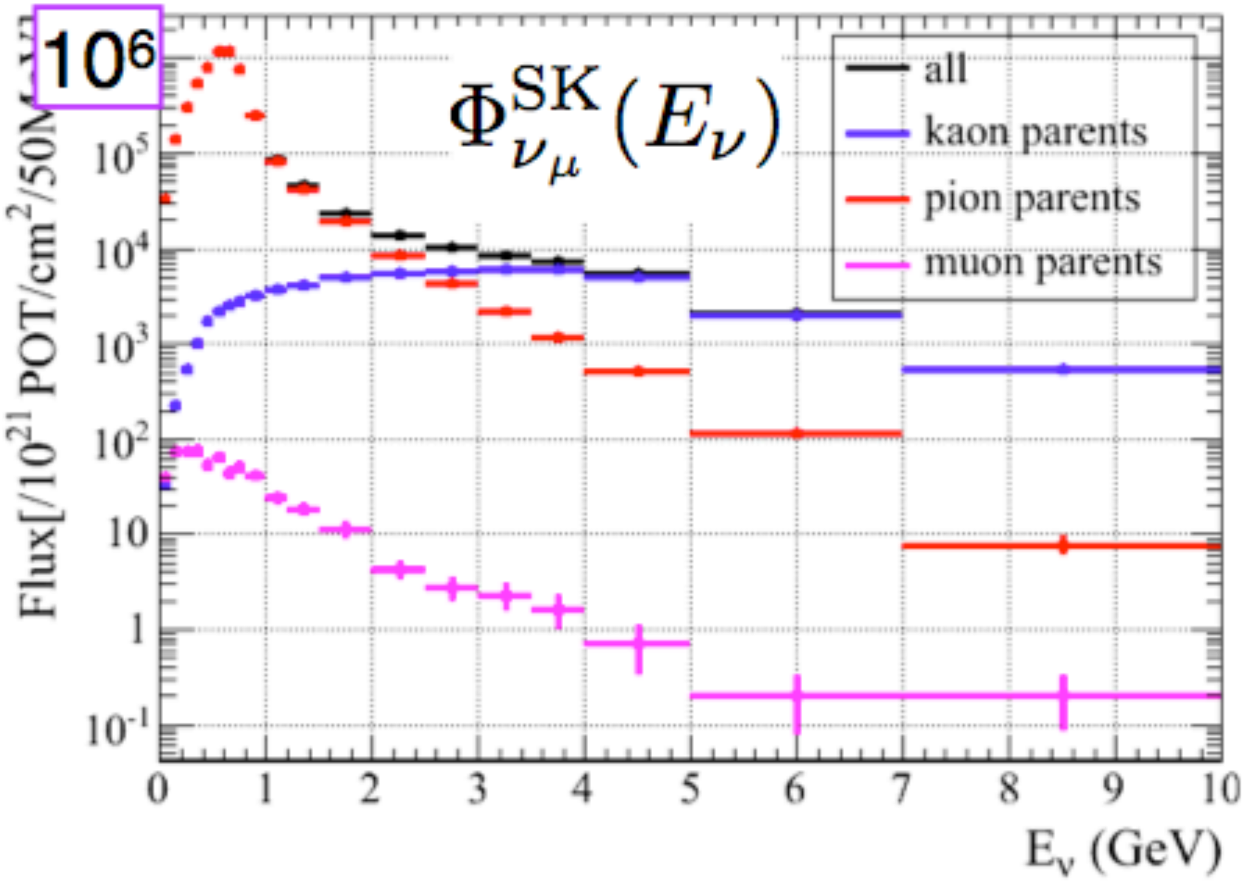
$$\frac{\int \Phi^{SK}_{\nu_\mu}(E_\nu) \cdot P_{\nu_\mu \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

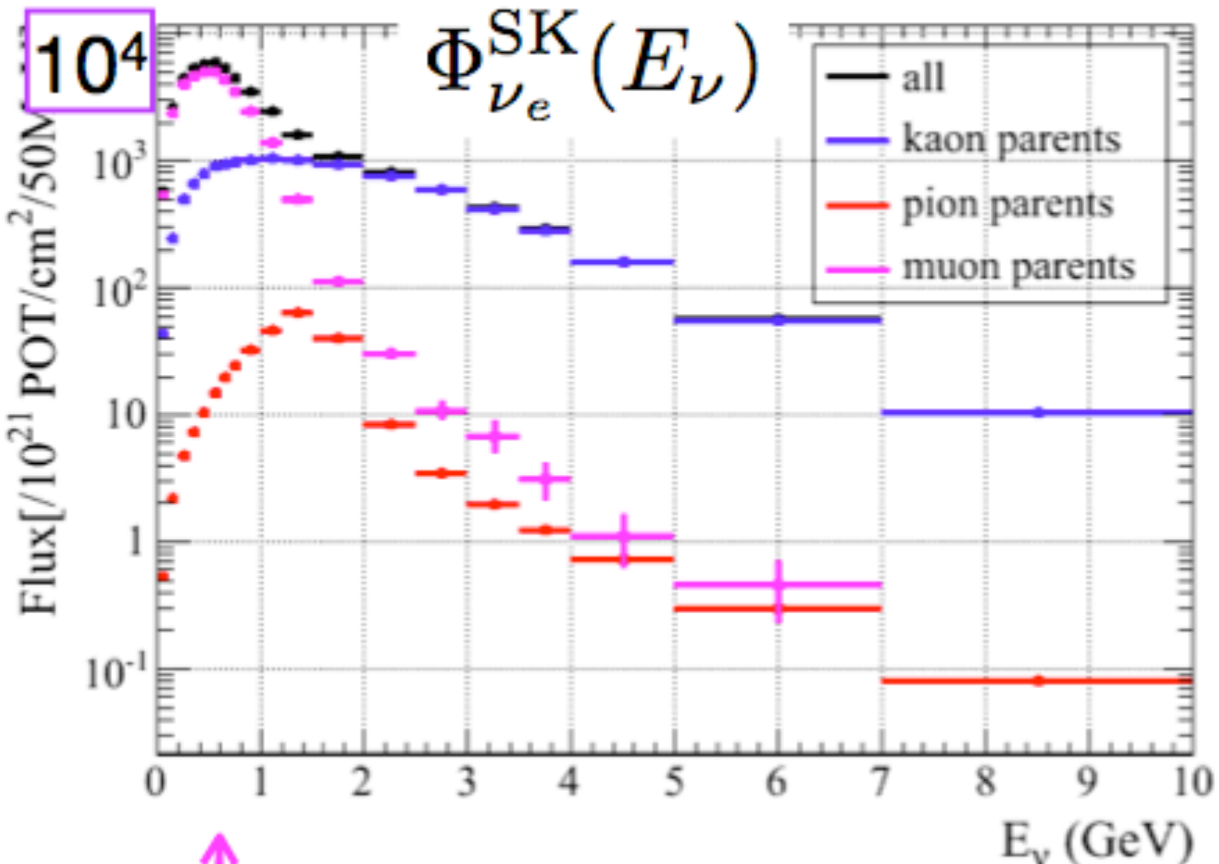


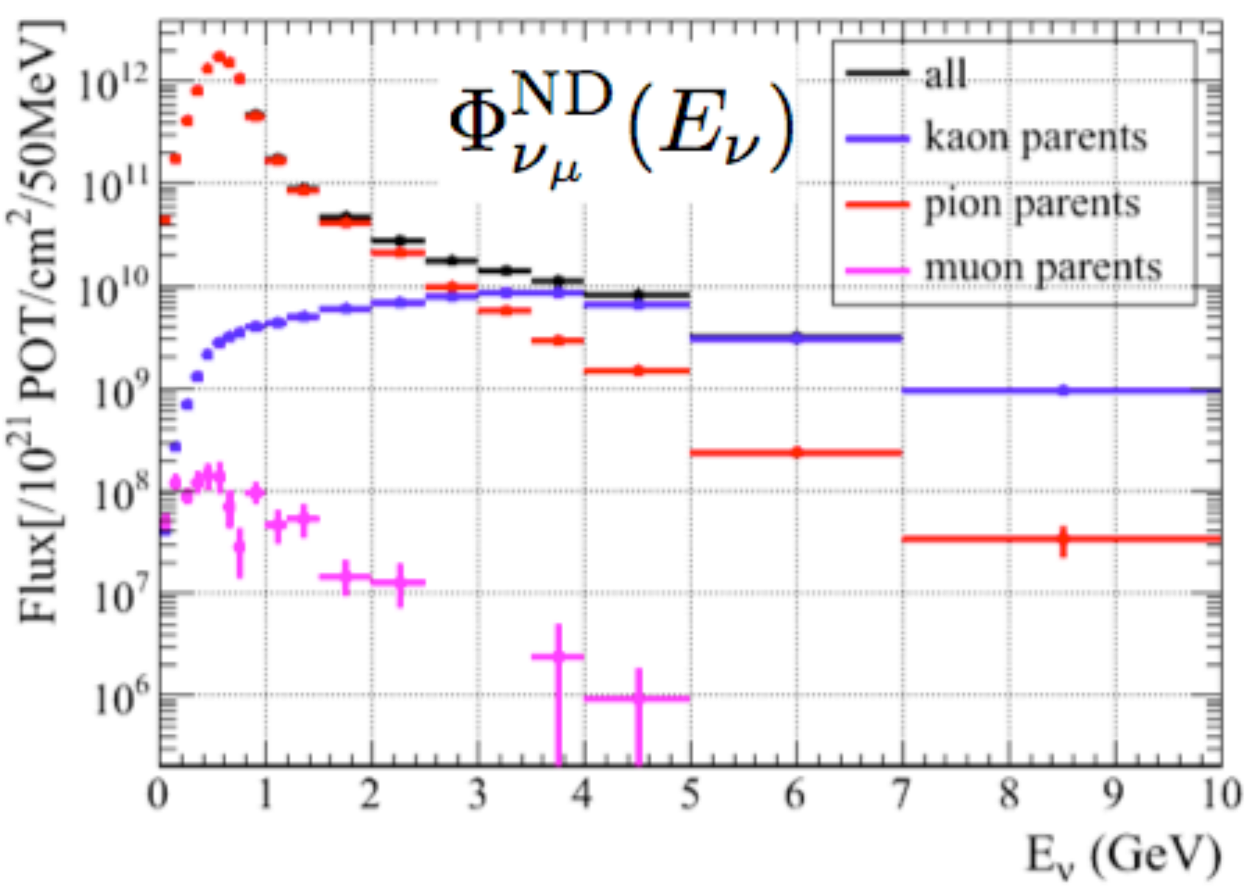
Hadron production in 30GeV proton + C

- ***Use CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)***
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

Predicted neutrino flux (center value)







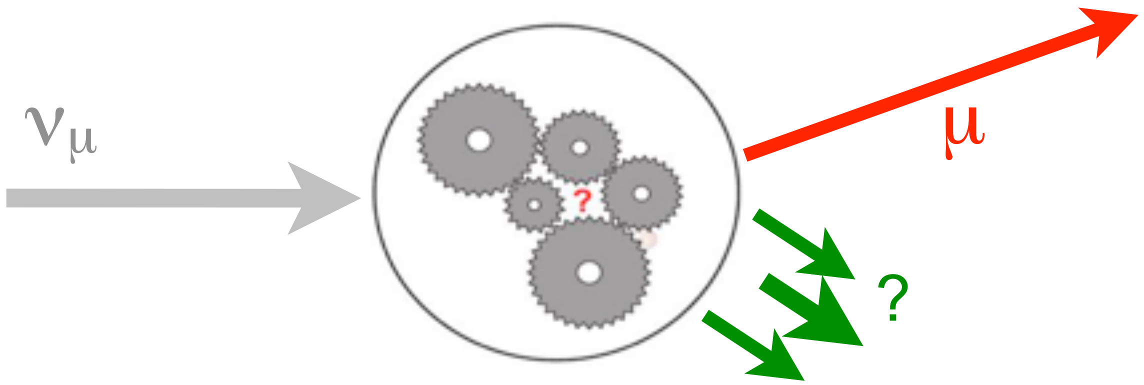
μ decay is dominated at low energy

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

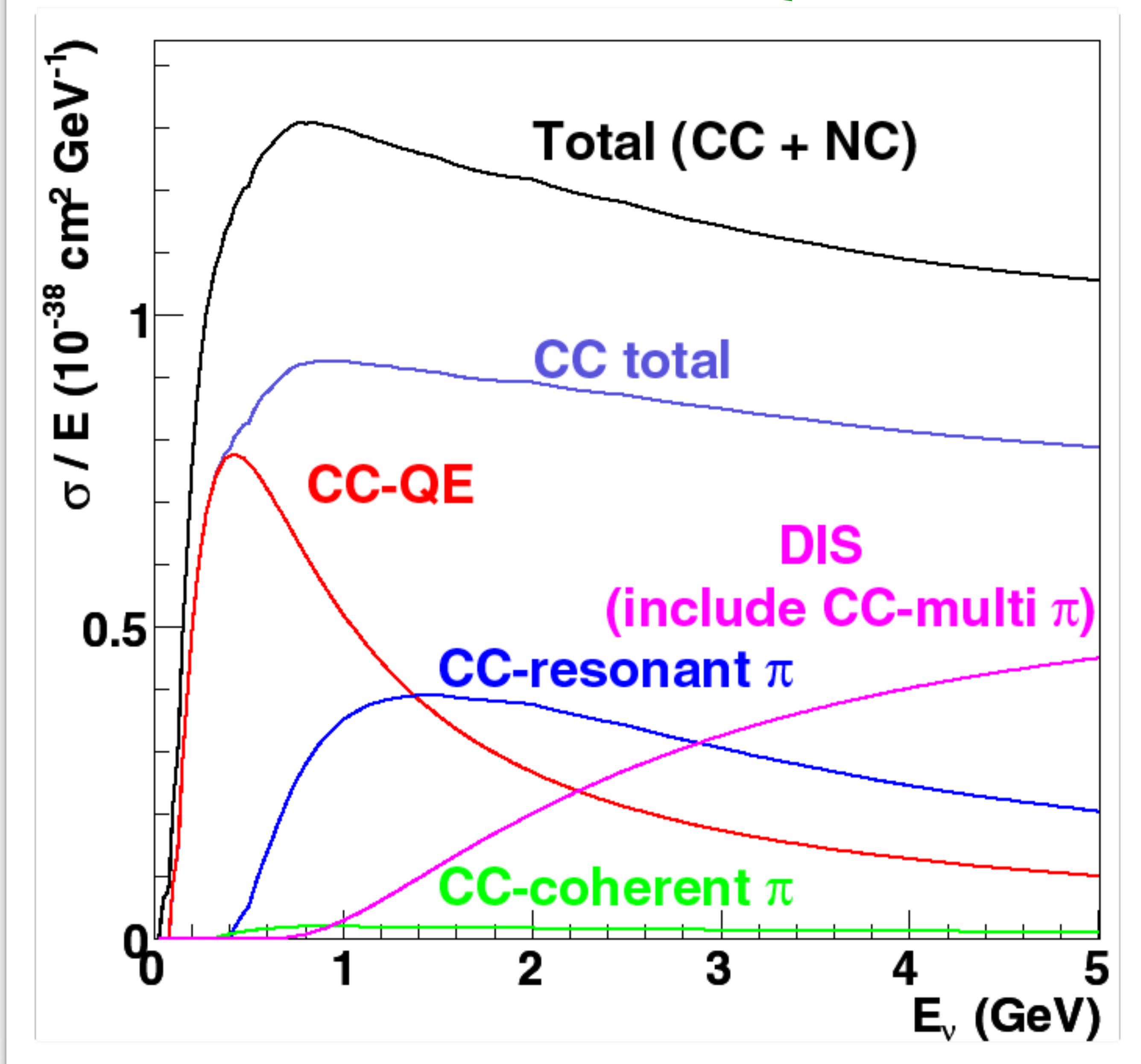
$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

NA61 pion measurement predicts the beam ν_e from pion origin

Neutrino cross section prediction



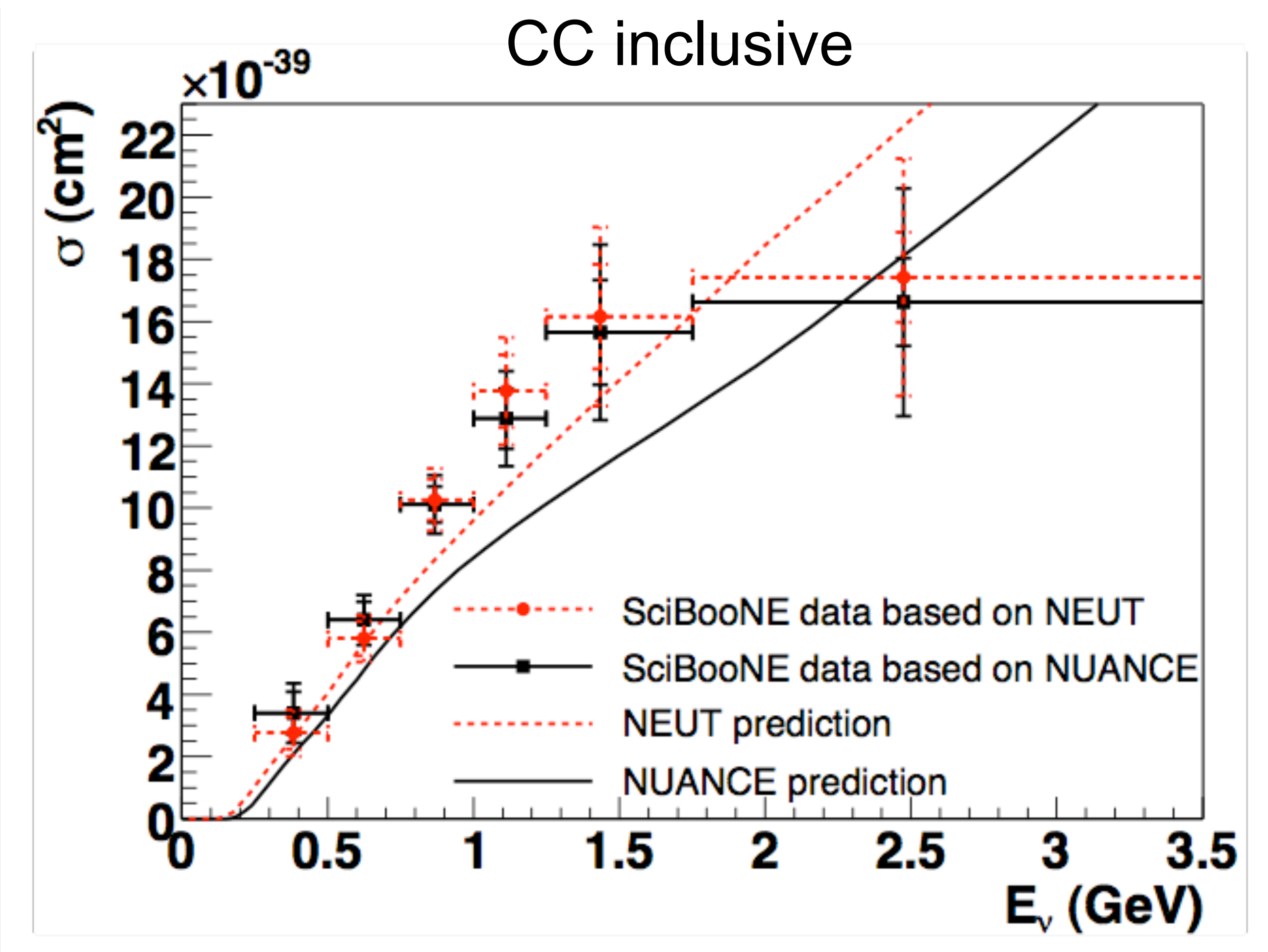
Use NEUT generator (cross-check with GENIE)

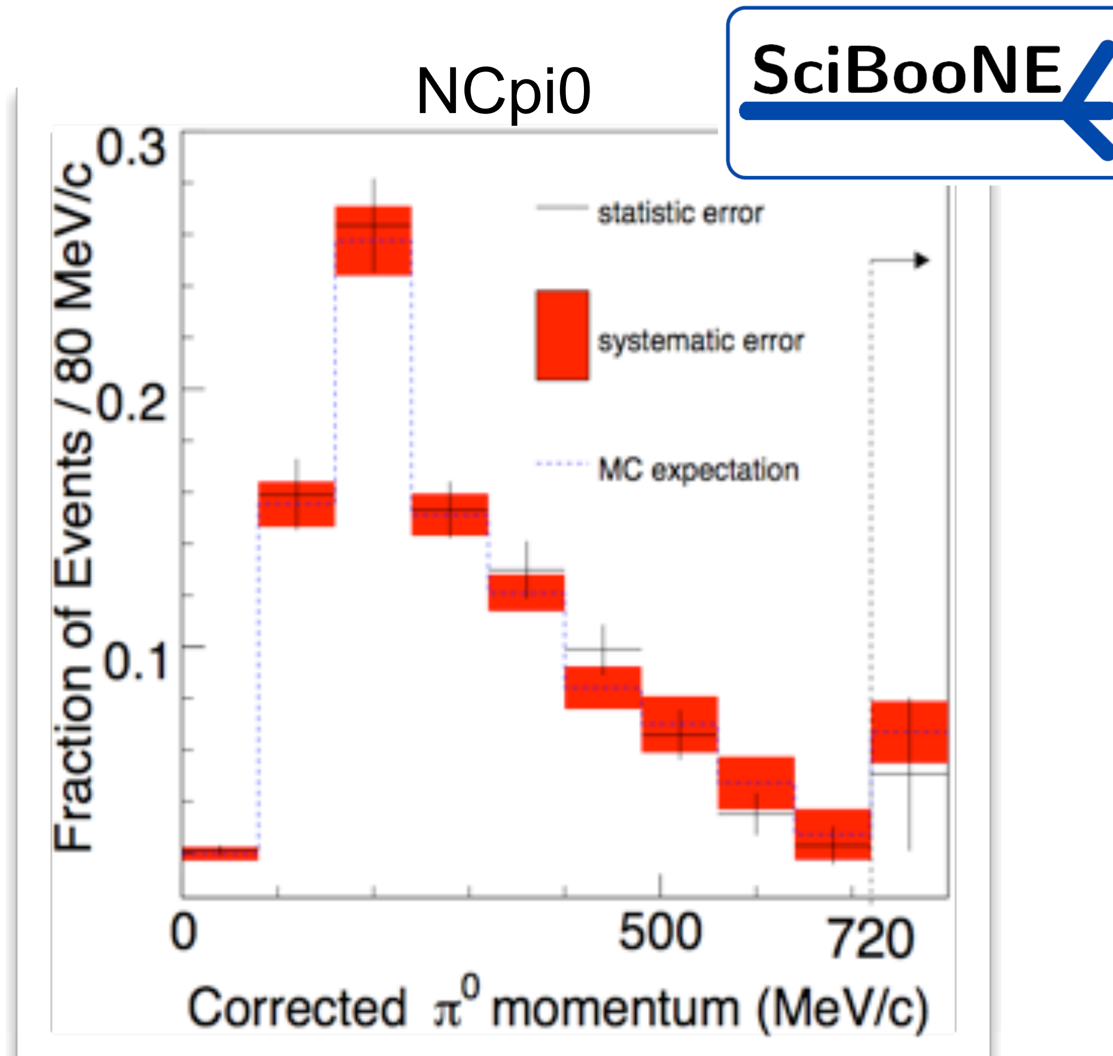


- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2 (GeV/c)^2
  - P_F=217 MeV/c, E_B=27 MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 (GeV/c)^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 (GeV/c)^2
- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

Cross section tuning

- Use external data to tune NEUT
  - Extract values of model parameters with fits to data
- Use mainly SciBooNE and MiniBooNE measurements (carbon)

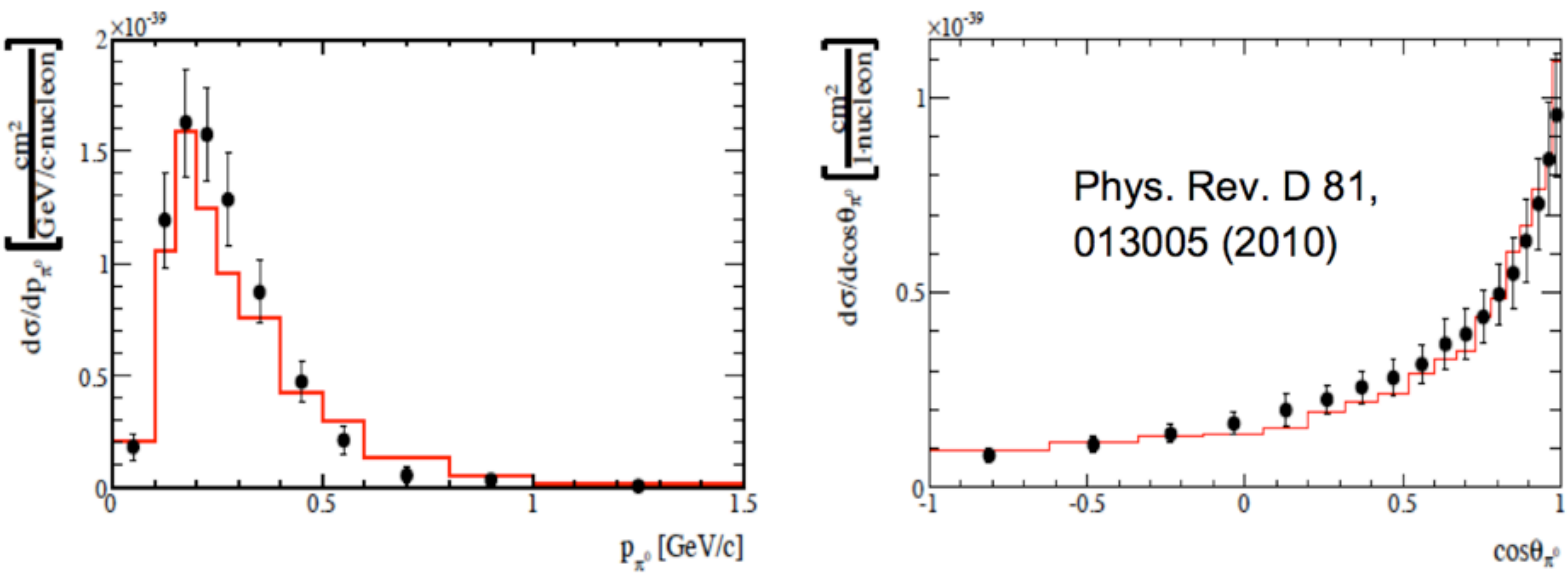




Cross section tuning

- Use external data to tune NEUT
  - Extract values of model parameters with fits to data
- Use mainly SciBooNE and MiniBooNE measurements (carbon)

NEUT comparison to MiniBooNE NCπ^0 diff. cross section



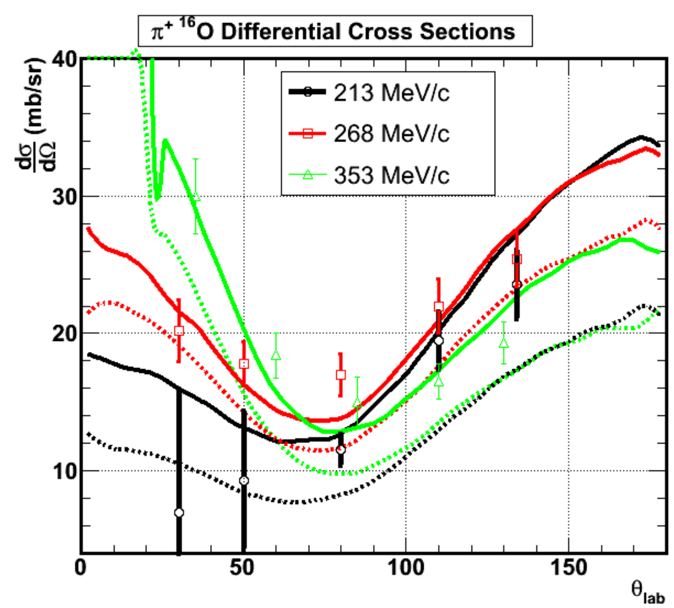
Final State Interactions (FSI)

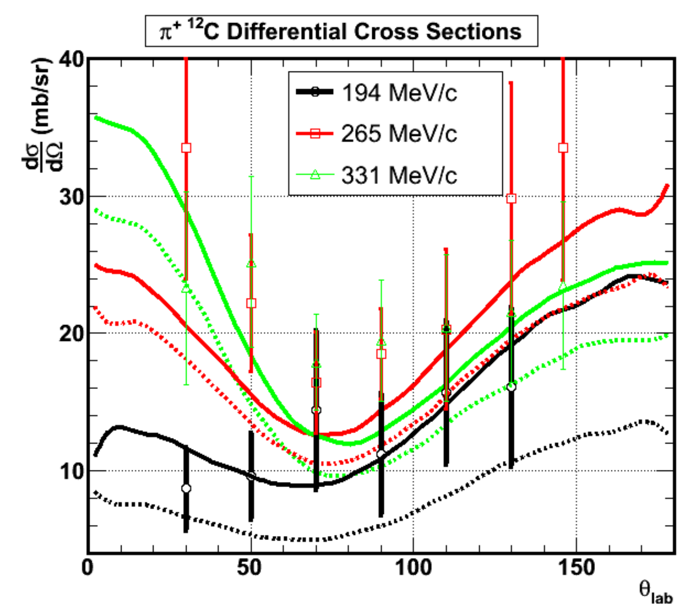
- Use external pion scattering data to tune NEUT
  - Extract values of model parameters with fits to data

π Scattering Differential Cross Sections

- Check how the new tuning affects $\frac{d\sigma}{d\Omega}$ for ^{16}O and ^{12}C
- Nice improvement in these distributions as well

		χ^2/ndf	
Target	***p_π (MeV/c)***	***Default***	***Tuned***
^{16}O	213	4.7	1.1
	268	4.4	1.3
	353	7.6	1.6
^{12}C	194	1.6	0.4
	265	2.3	1.0
	331	2.3	1.0





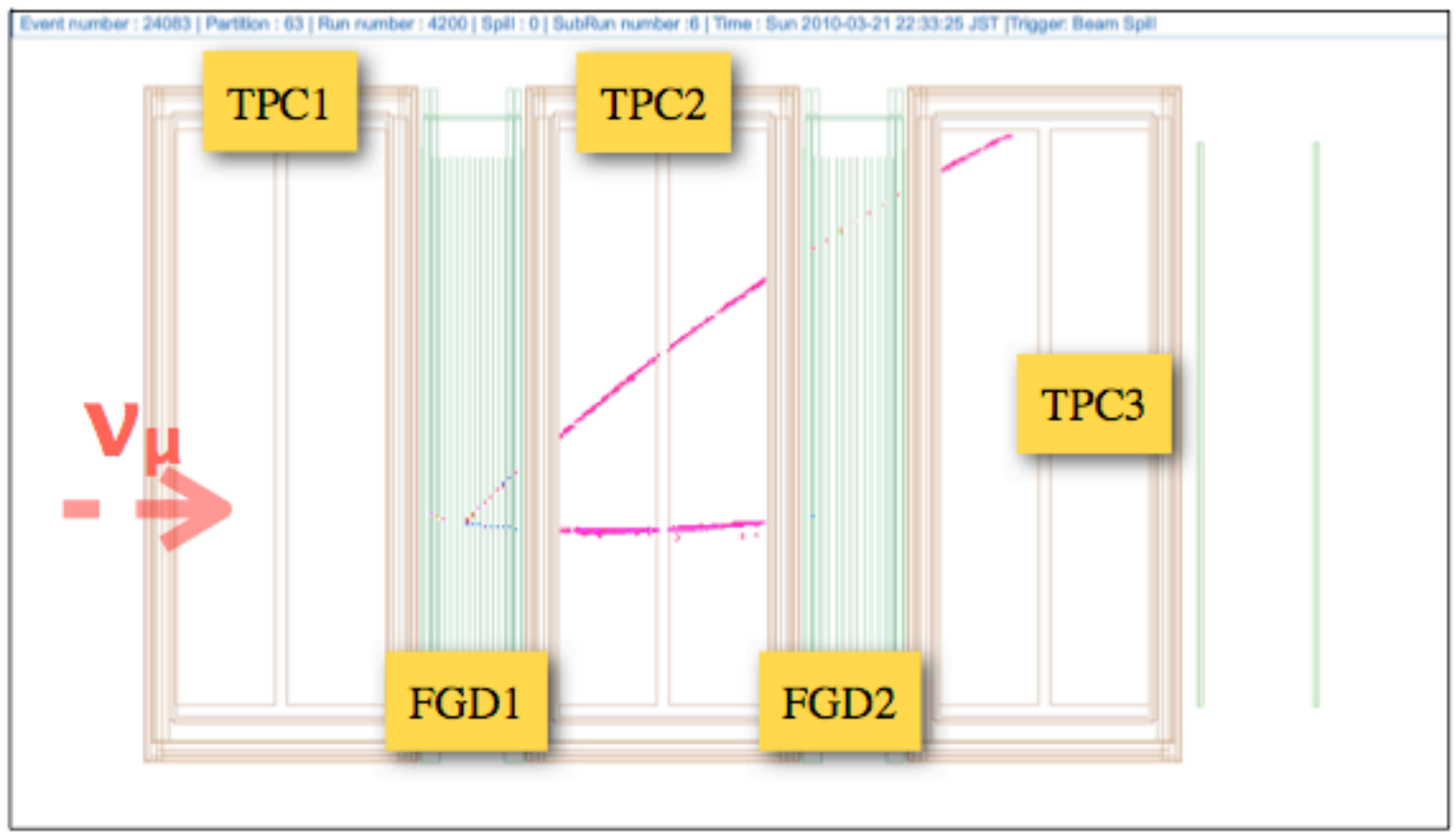
March 11, 2011 NEUT Pion FSI - P. de Perio (U. Toronto) @ NuInt11, Dehradun, India 7

ν_μ events in ND280

- Measure # of inclusive ν_μ charged current interaction (N^{Data}_{ND})

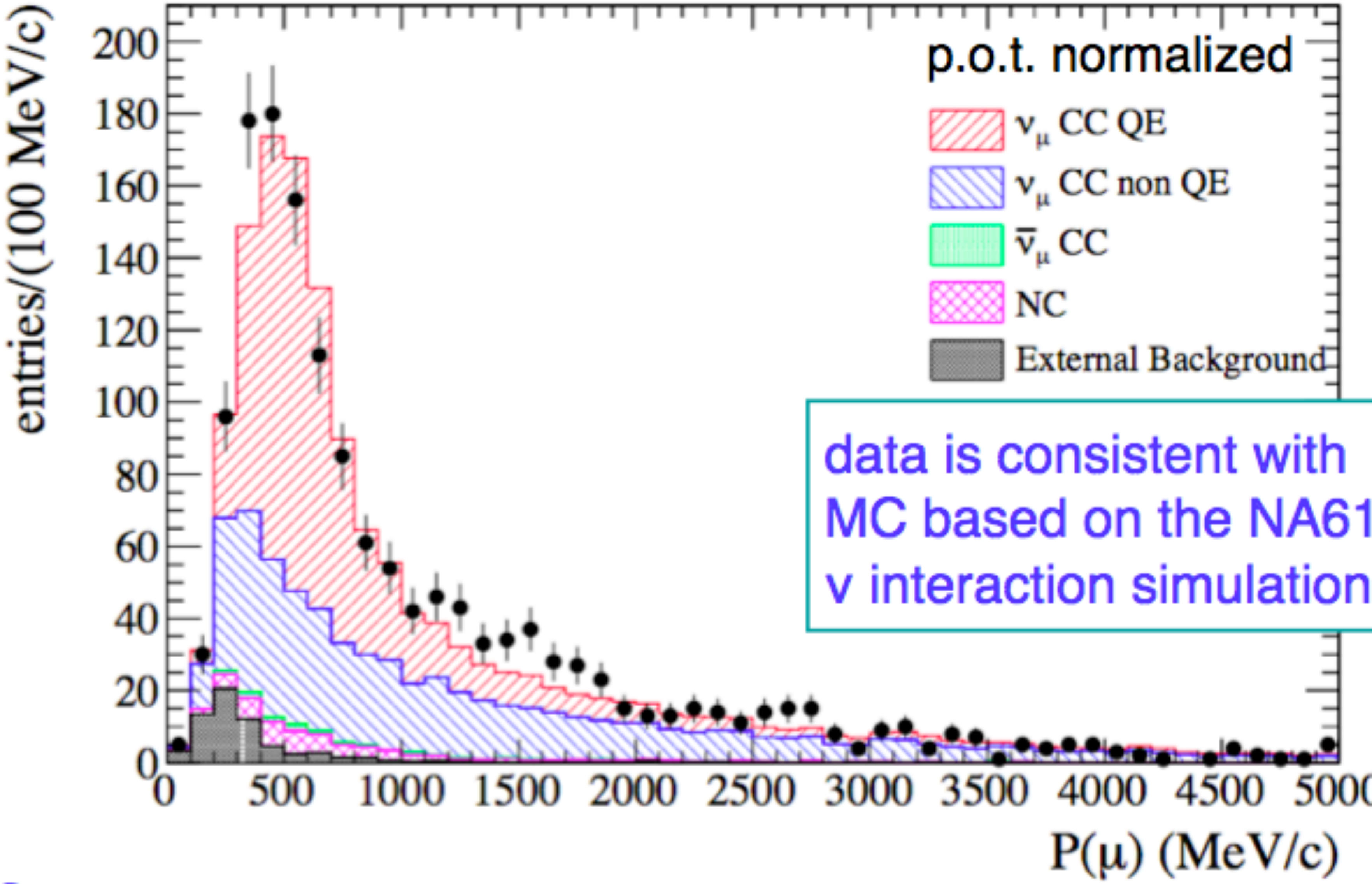
Select events which have FGD hits and μ-like tracks reconstructed in single TPC

Event display (data)



High purity : 90% ν_μ Charged Current int. (50% CCQE)

ND Measurement of muon momentum in inclusive ν_μ CC events ($\nu_\mu + N \rightarrow \mu^+ + X$)



data is consistent with MC based on the NA61 and ν interaction simulation (w/o tuning)

Results

$$R^{\mu,\,Data}_{ND} = 1529 \;\; \text{events} \;/\; 2.9 \times 10^{19} \;\; \text{p.o.t.}$$

$$\frac{R^{\mu,\,Data}_{ND}}{R^{\mu,\,MC}_{ND}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

ν_e Appearance Backgrounds

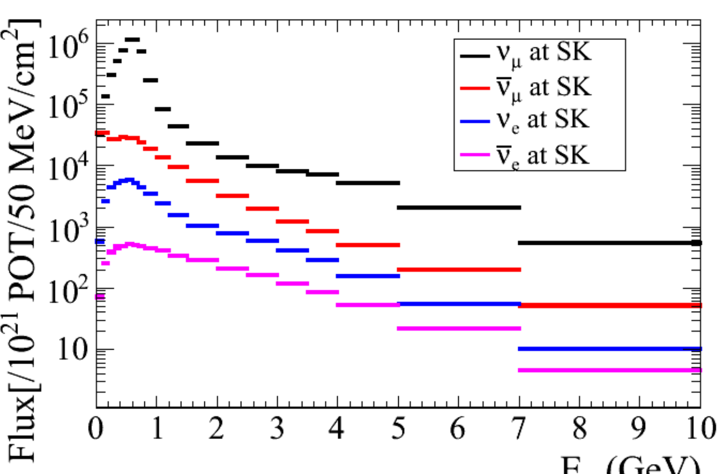
1) Beam ν_e :
ν_μ beam only
~99% pure in signal region

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

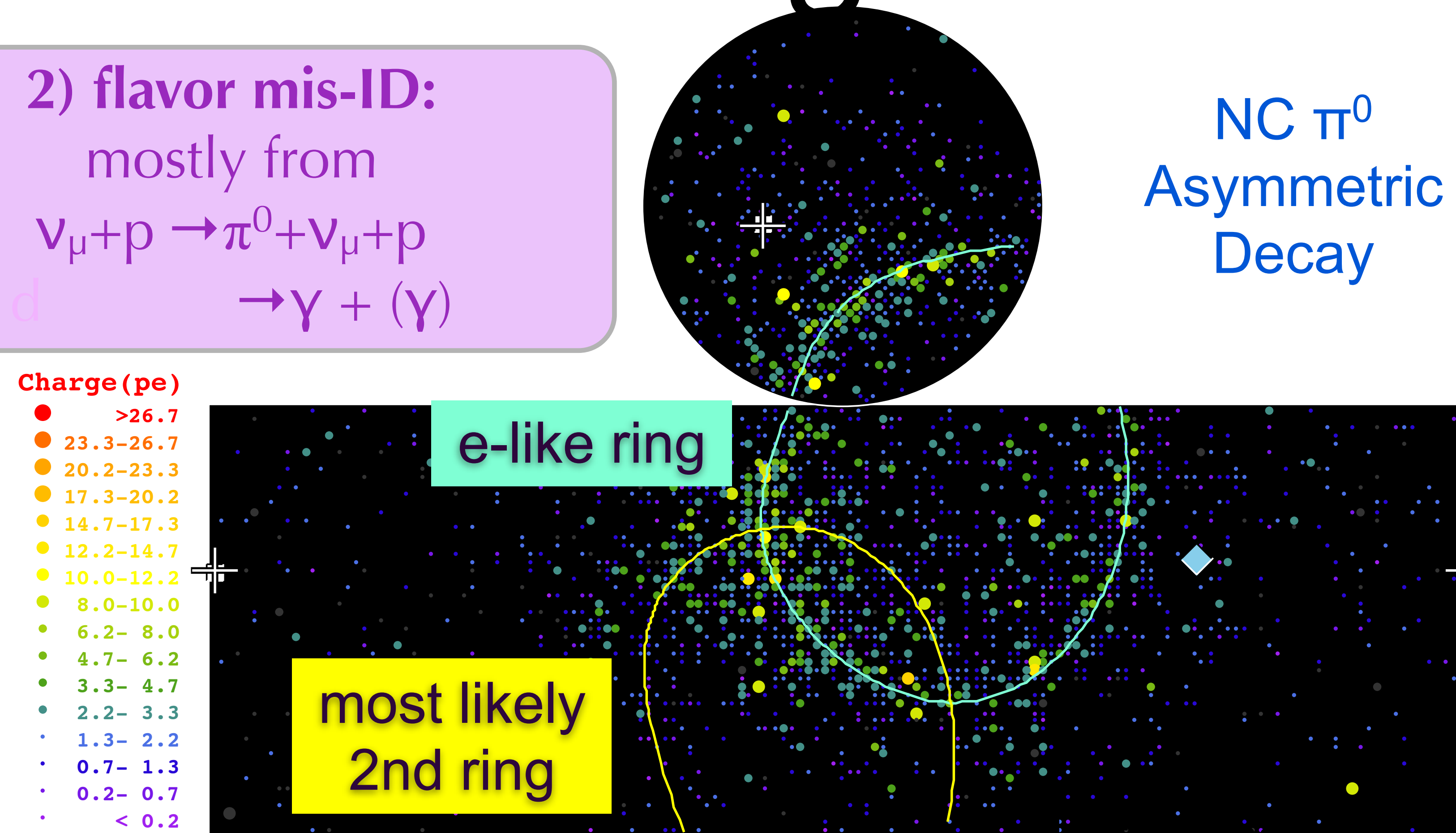
$$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$$

$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$

$$K_L^0 \rightarrow \pi^+ + e^- + \nu_e$$

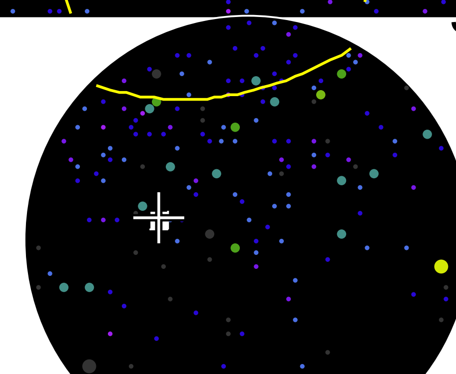


2) flavor mis-ID:
mostly from
ν_μ+p →π^0+ν_μ+p
d →γ + (γ)



NC π^0 Asymmetric Decay

γs either overlap, or one is faint



	Beam nue	numu NC	solar osc signal	Total
N^{exp}_{SK}	0.8	0.6	0.1	1.5

N^{exp}_{SK} systematics

error source	syst. error
(1) ν flux	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$
(5) Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

for $\sin^2 2\theta_{13}=0$

➔ *$N^{exp}_{SK}=1.5\pm0.3$ events*

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\; dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\; dE_\nu}$$

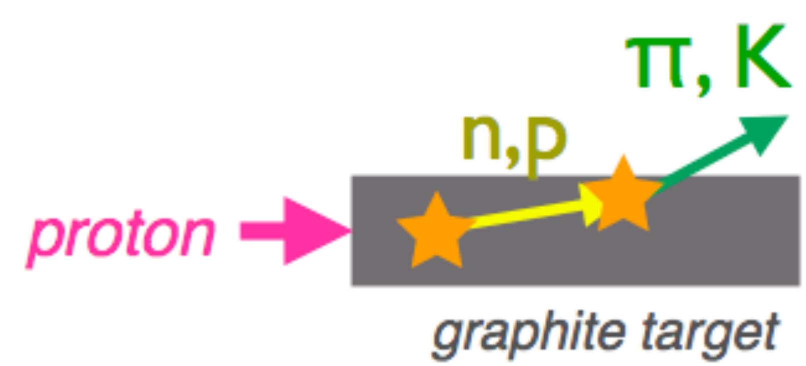
Flux systematic uncertainty

Uncertainties in hadron production and interaction are dominant sources

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu)\cdot P_{osc.}(E_\nu)\cdot \sigma(E_\nu)\cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu)\cdot \sigma(E_\nu)\cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

Error source

- Pion production
  - NA61 systematic uncertainty in each pion's (p,θ) bin
- Kaon production
  - Used model (FLUKA) is compared with the data(Eichten et. al.) in each kaon's (p,θ) bin
- Secondary nucleon production
  - Used model (FLUKA) is compared with the experimental data
- Secondary interaction cross section
  - Used model (FLUKA and GCALOR) is compared with the experimental data of interaction x-section (π, K and nucleon)



Cross section systematics

Evaluate uncertainty on F/N ratio by varying the cross section within its uncertainty

Main ν interaction in each event category

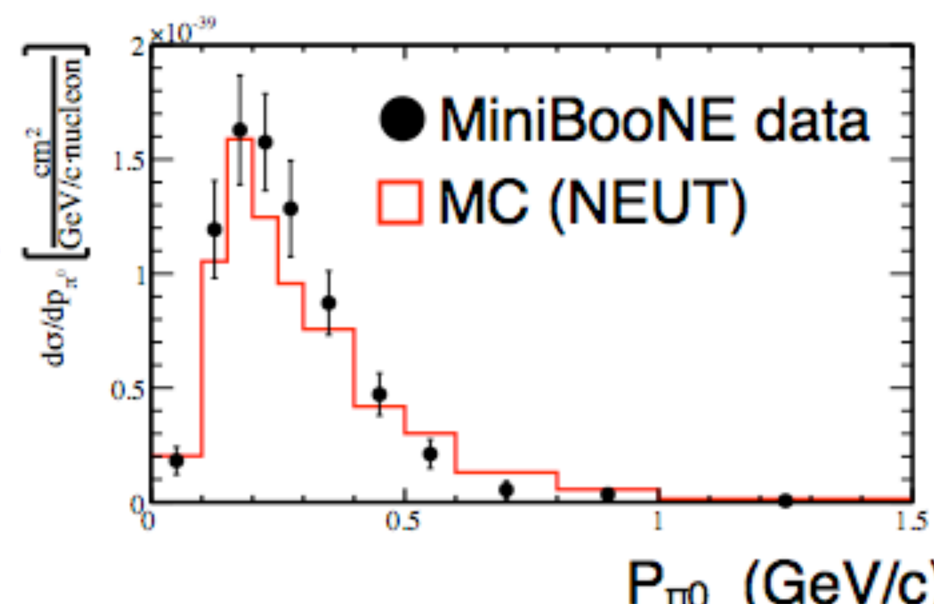
NC background : NC1π^0
Beam ν_e background : ν_e CCQE
Signal : ν_e CCQE
ND CC event : CCQE(50%)
CC1π(23%)

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

Process	Cross section uncertainty relative to the CCQE total x-section
CCQE	energy dependent ($\sim \pm 7\%$ at 500 MeV)
CC 1π	30% ($E_\nu < 2$ GeV) – 20% ($E_\nu > 2$ GeV)
CC coherent π^0	100% (upper limit from [30])
CC other	30% ($E_\nu < 2$ GeV) – 25% ($E_\nu > 2$ GeV)
NC $1\pi^0$	30% ($E_\nu < 1$ GeV) – 20% ($E_\nu > 1$ GeV)
NC coherent π	30%
NC other π	30%
Final State Int.	energy dependent ($\sim \pm 10\%$ at 500 MeV)

Uncertainty of $\sigma(\nu_e)/\sigma(\nu_\mu) = \pm 6\%$

Cross section uncertainties are estimated by Data/MC comparison, model comparison and parameter variation



SK systematics

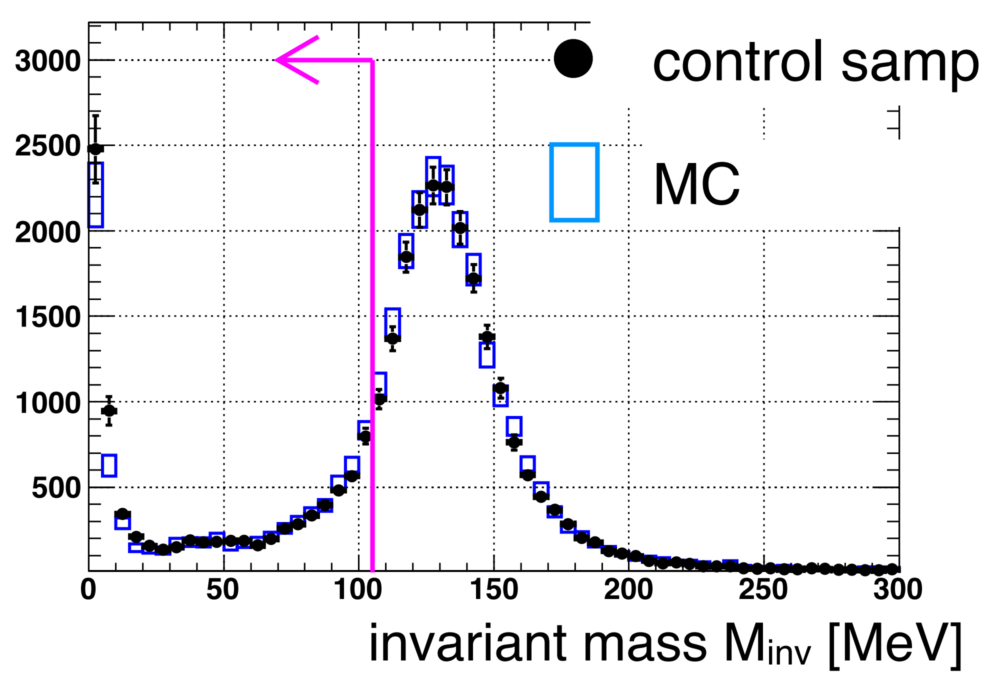
- Uncertainty due to the SK detector uncertainty
- Evaluation using control sample

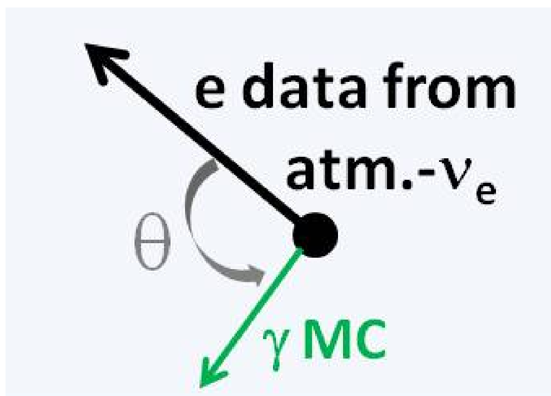
$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

One of big error sources:

detection efficiency of NC 1π^0 background

control sample with one data electron + one simulated γ





apply T2K ν_e selection and compare the cut efficiency between control sample data and its MC
→ difference is assigned as sys. error

Total systematics

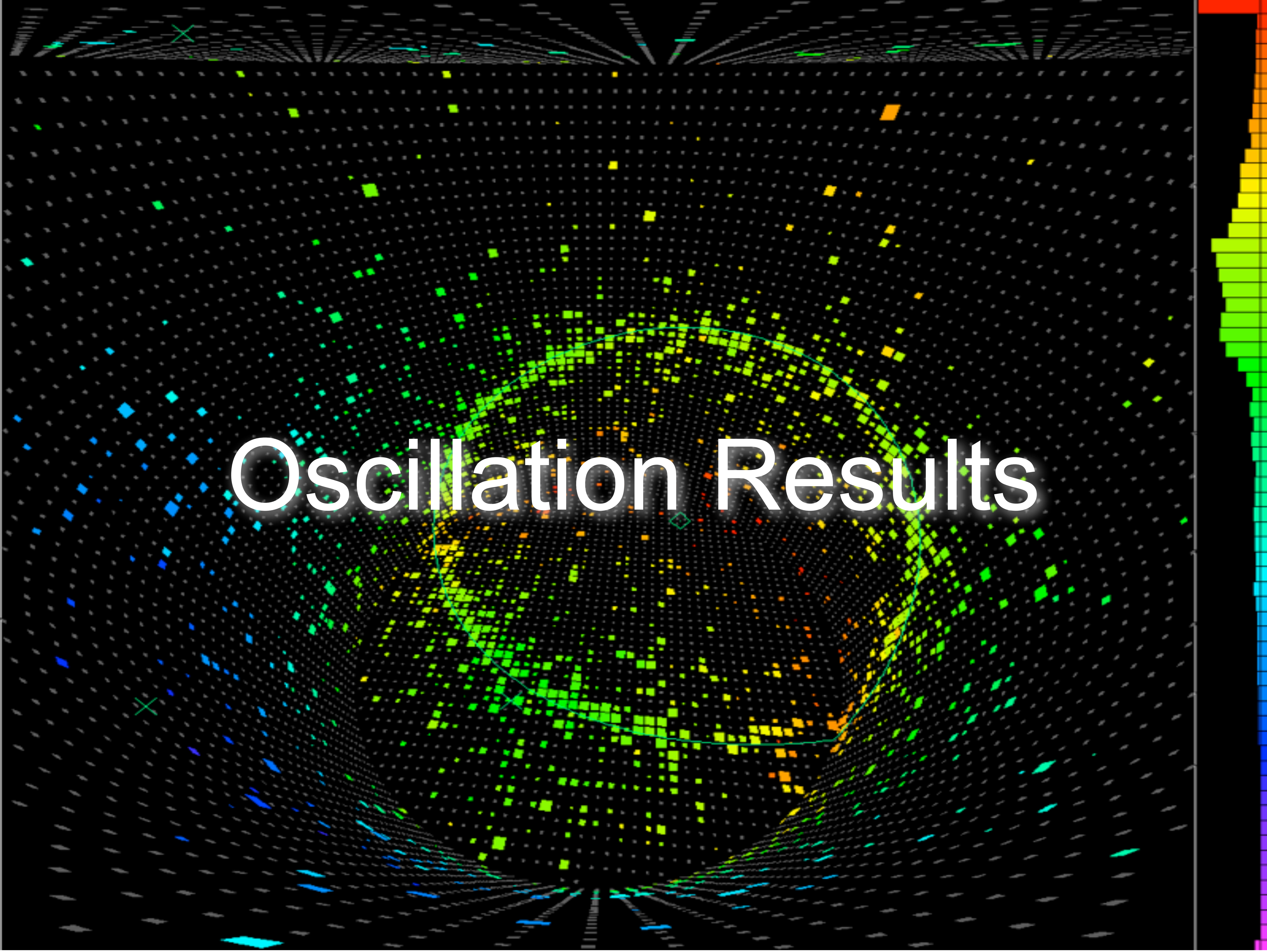
Summary of systematic uncertainties on $N^{exp}_{SK\ total.}$ for $\sin^2 2\theta_{13}$=0 and 0.1

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

(due to small Far det. uncertainty for signal)

$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}$=0 (w/ 1.43 x 10^{20} p.o.t.)

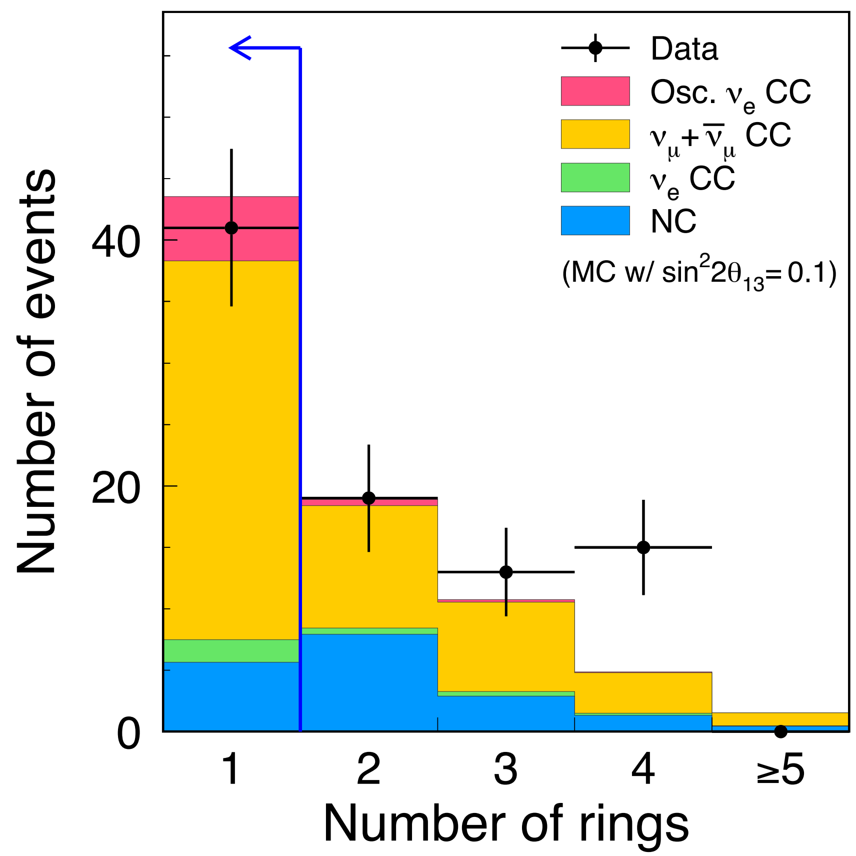
Oscillation Results

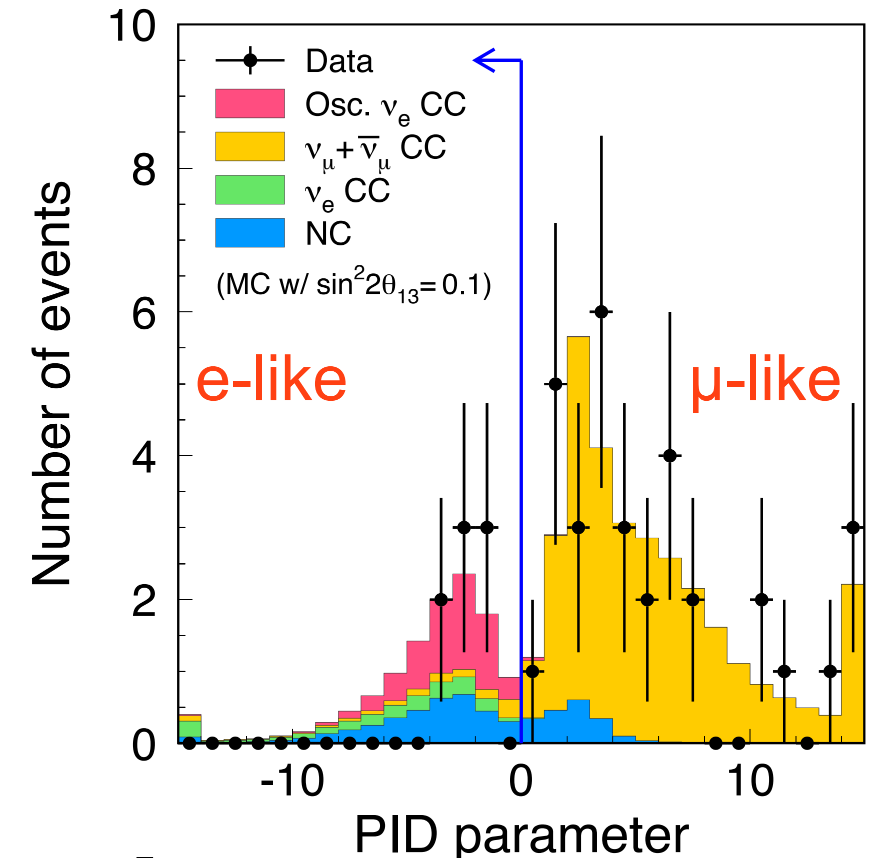


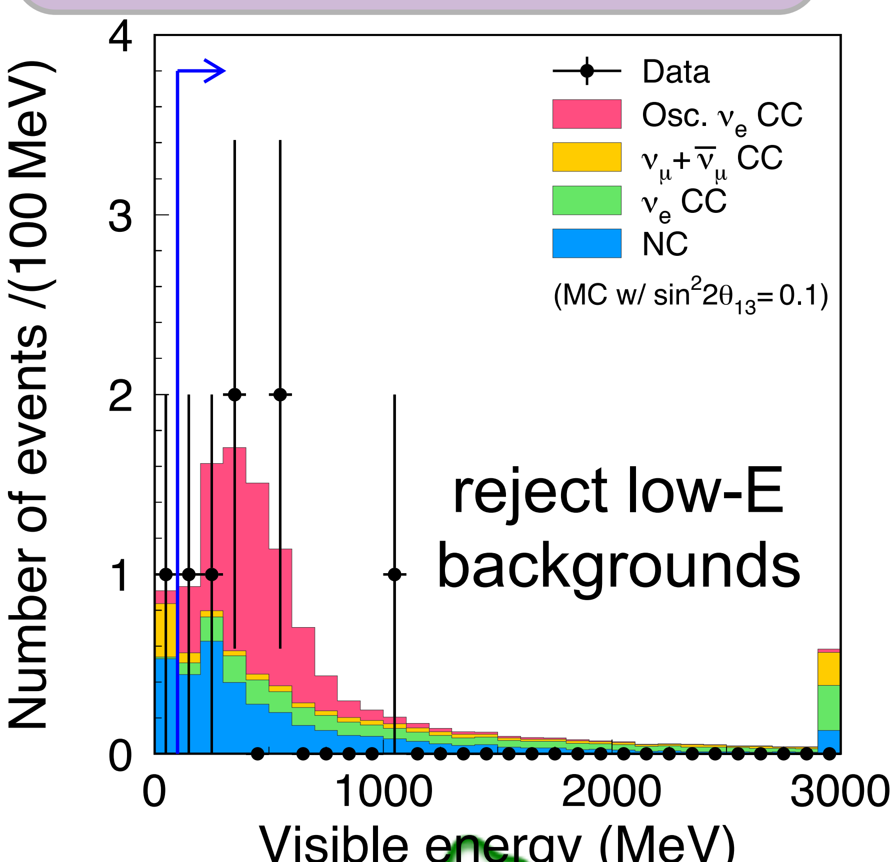
ν_e Appearance

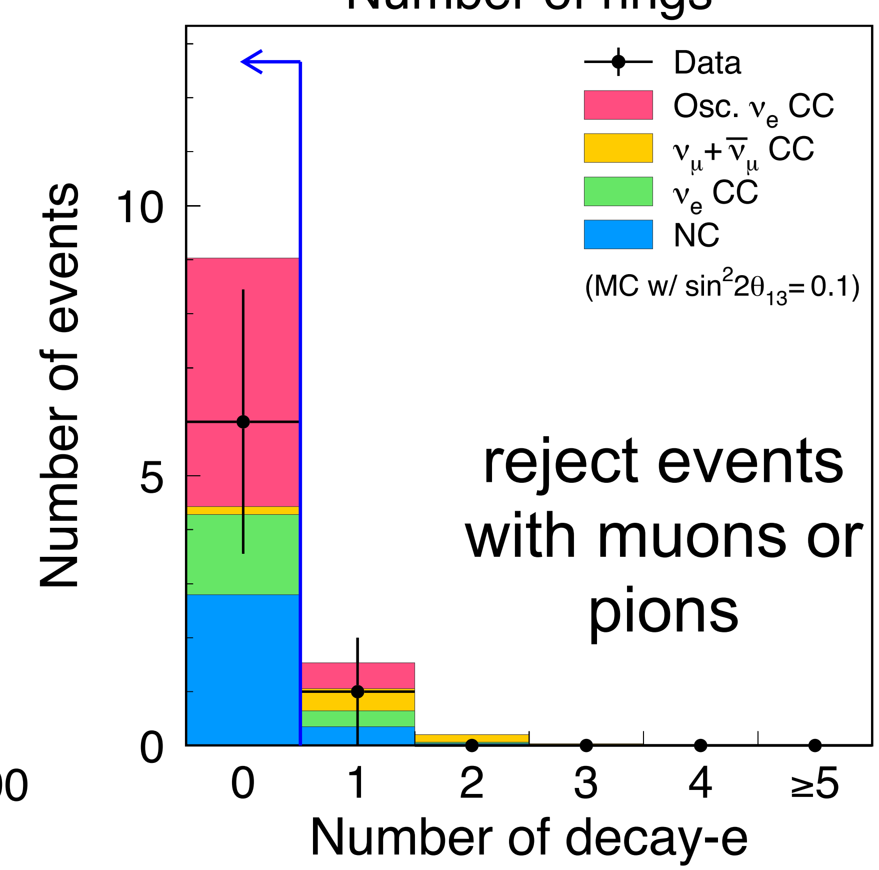
- Fully Contained
- Fiducial Volume
- Single Ring
- e-like
- $E_{visible}$>100 MeV
- N_{decay} = 0
- m_π < 105 MeV

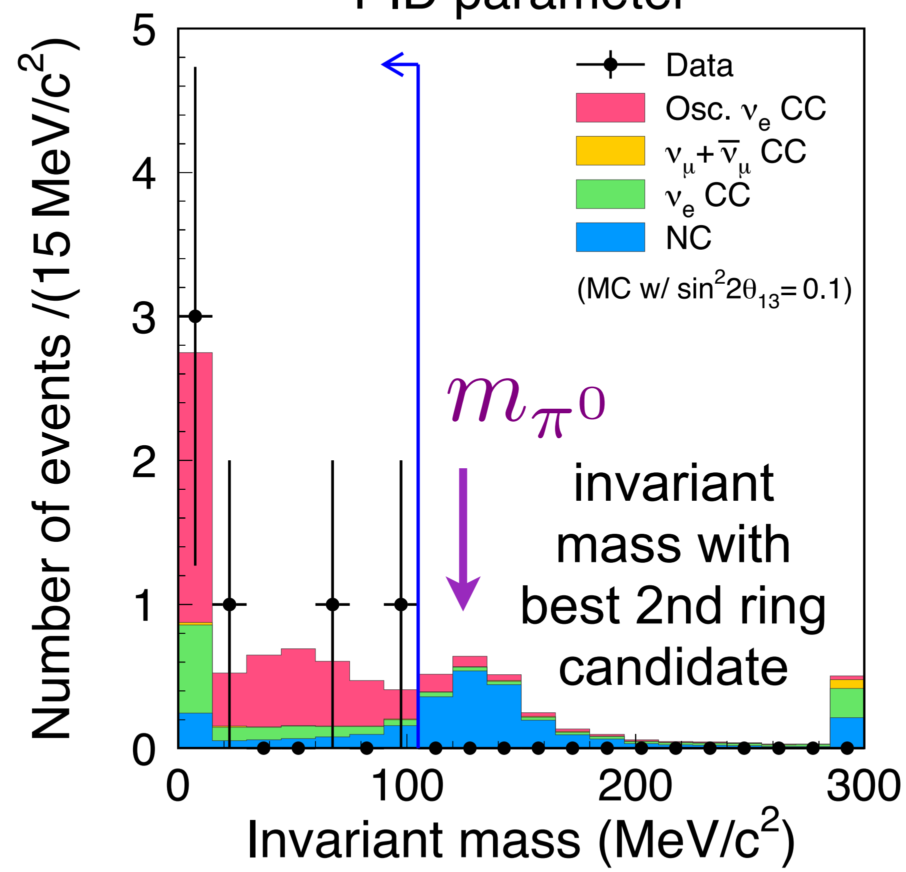
Data: 6 Events...









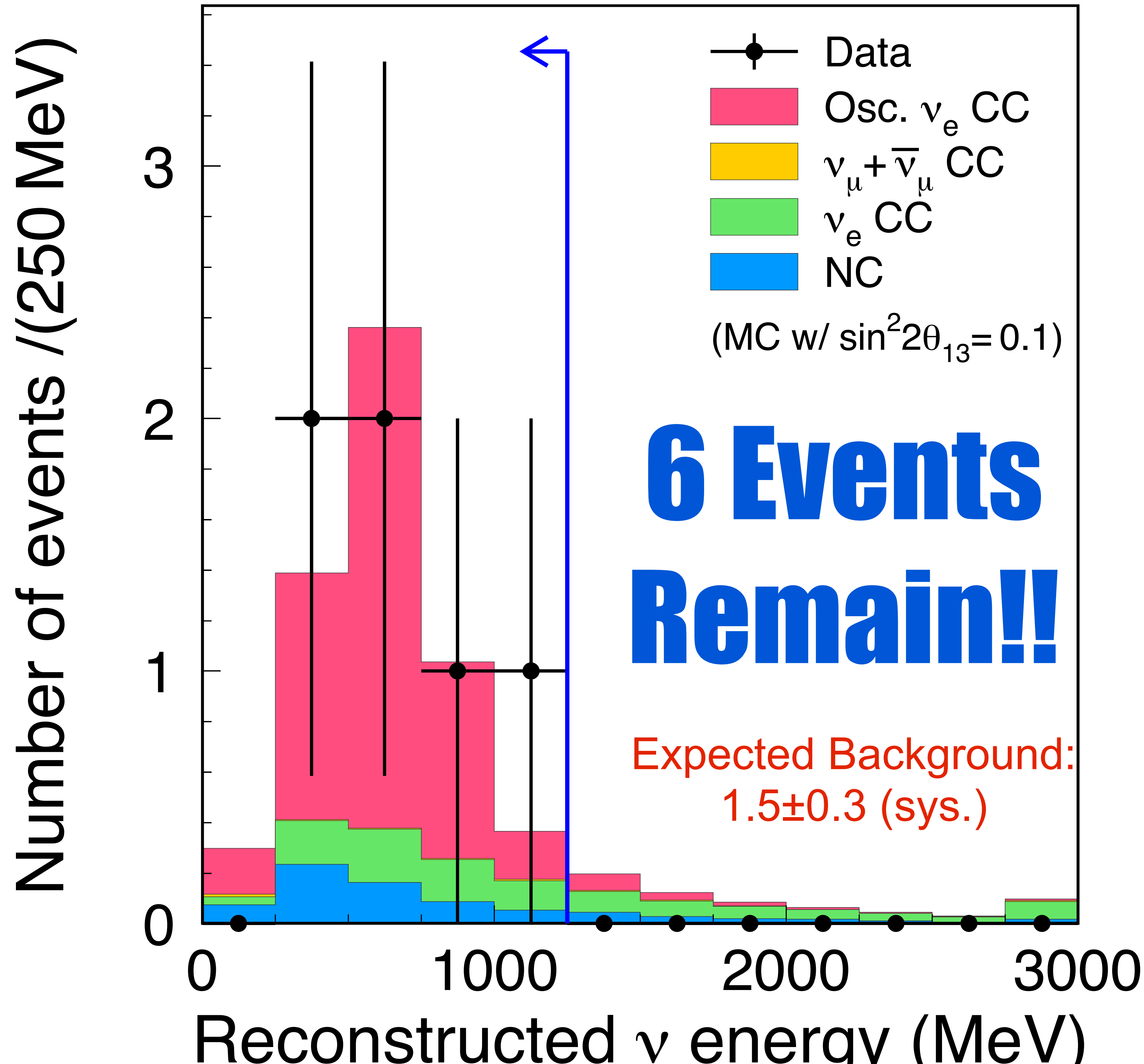


ν_e Appearance Selections

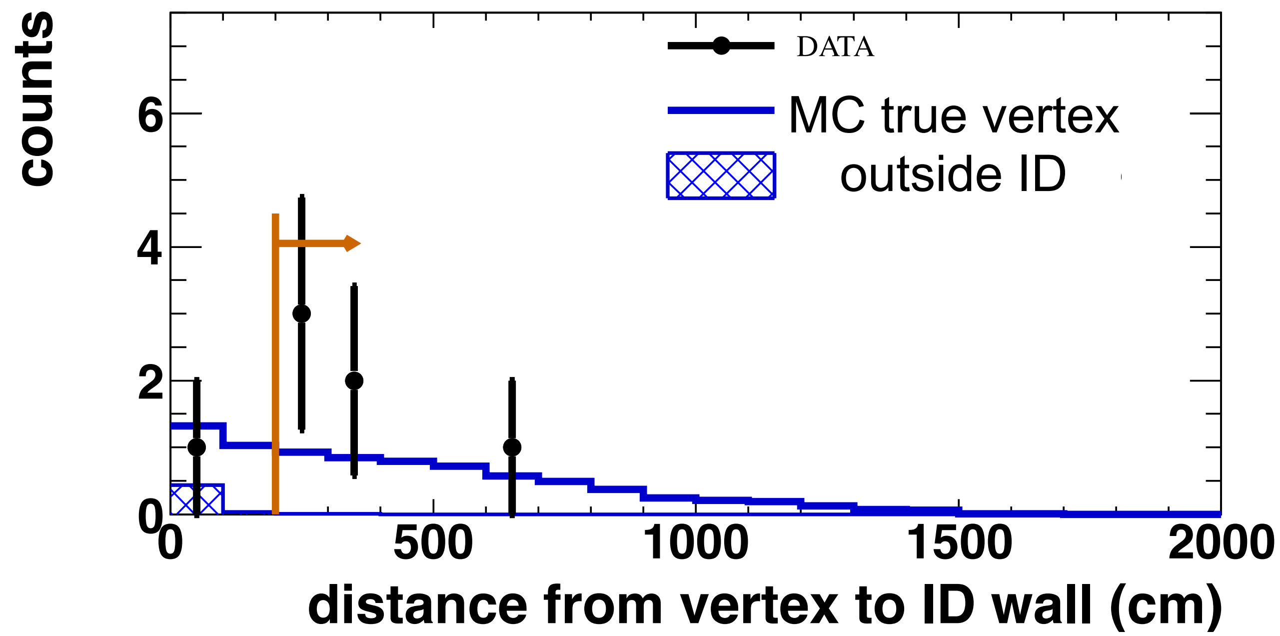
- Fully Contained
- Fiducial Volume
- Single Ring
- e-like
- $E_{visible}$>100 MeV
- $N_{decay} = 0$
- $m_{\pi} < 105$ MeV
- E_{ν}^{rec}<1250 MeV

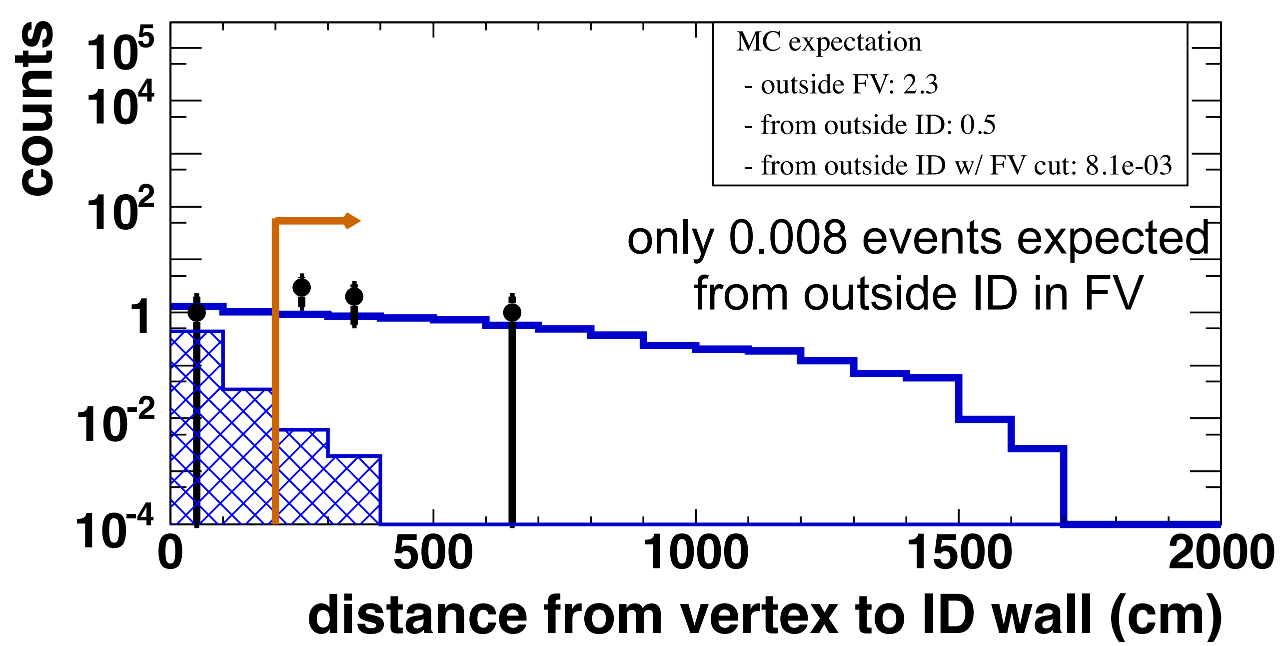
Data: 6 Events

Expect: 1.5

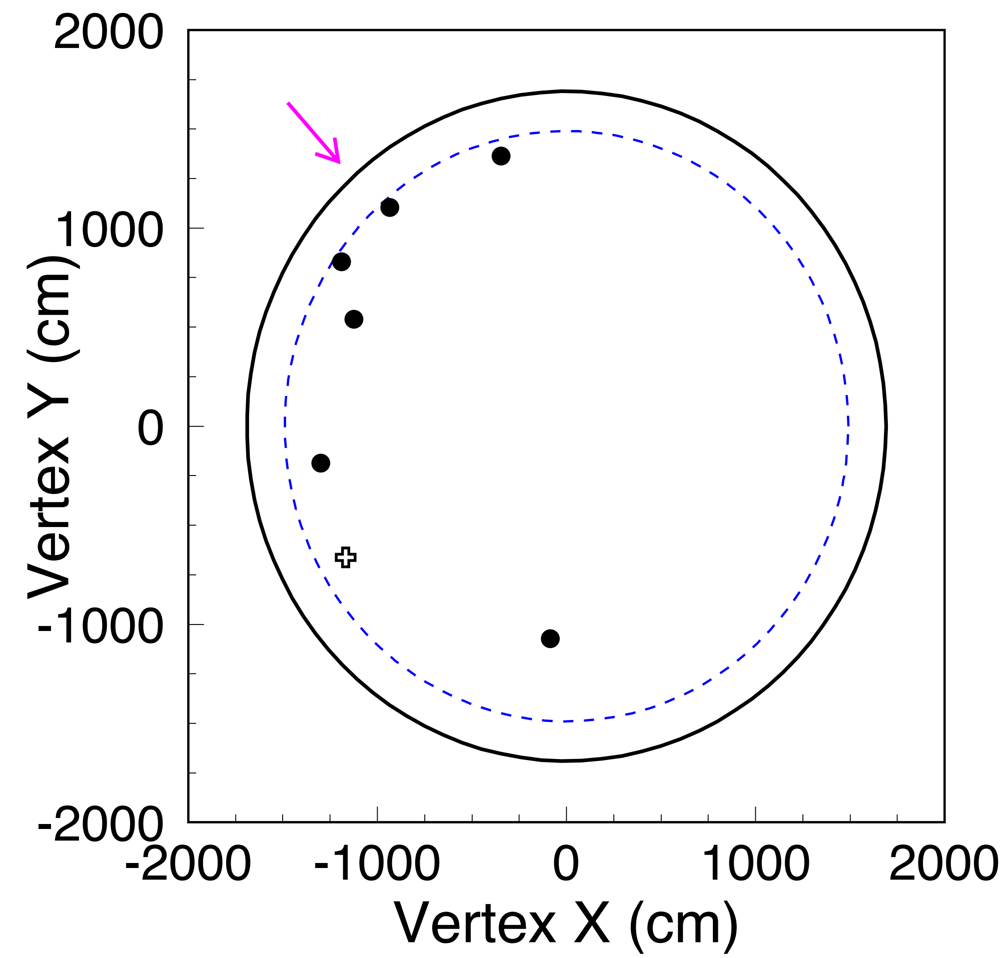


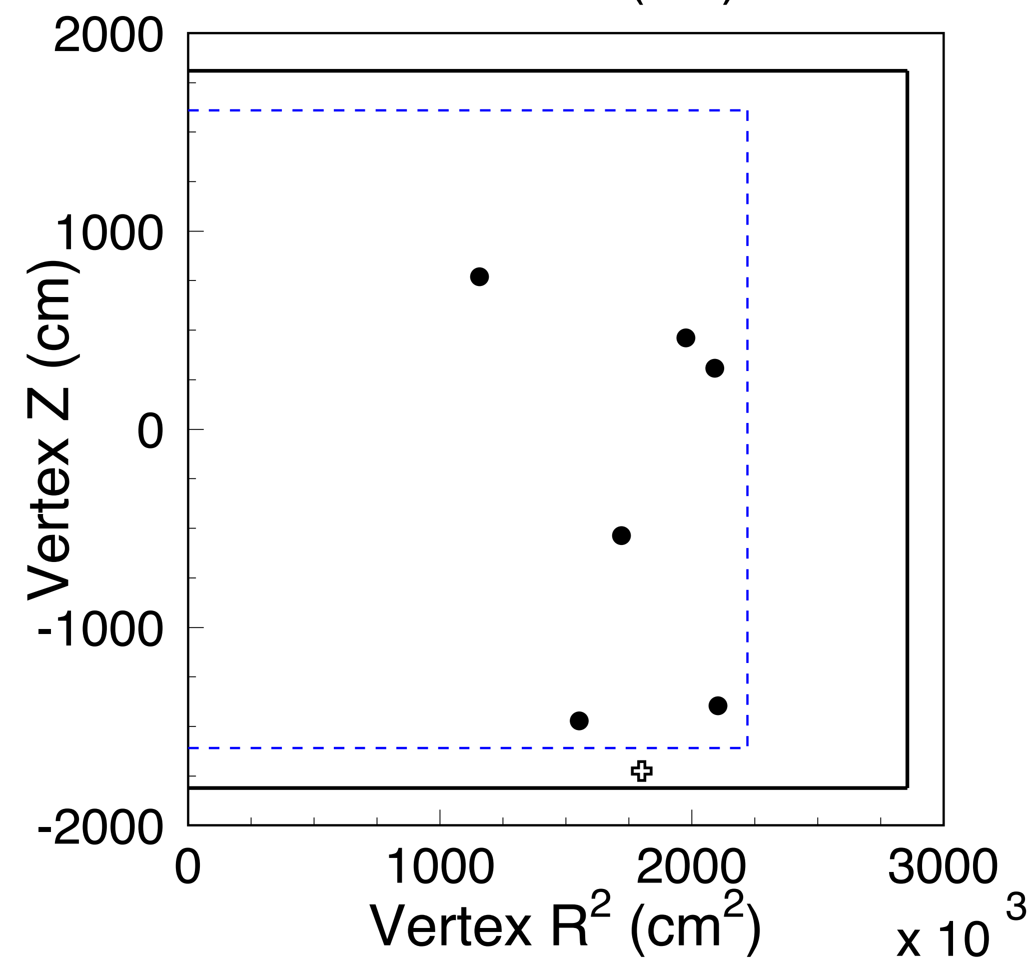
Vertex Distribution





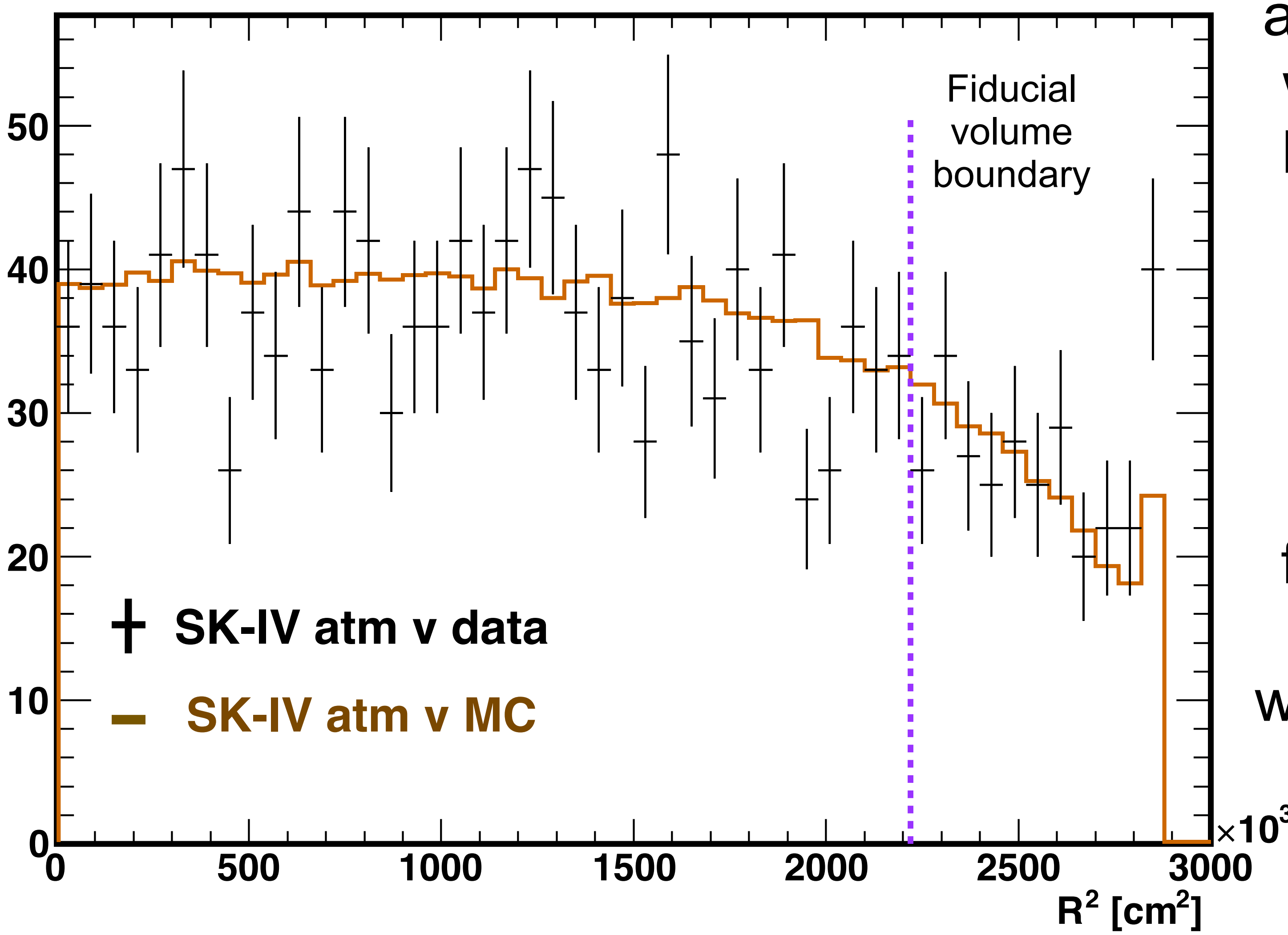
Use MC to test for entering backgrounds



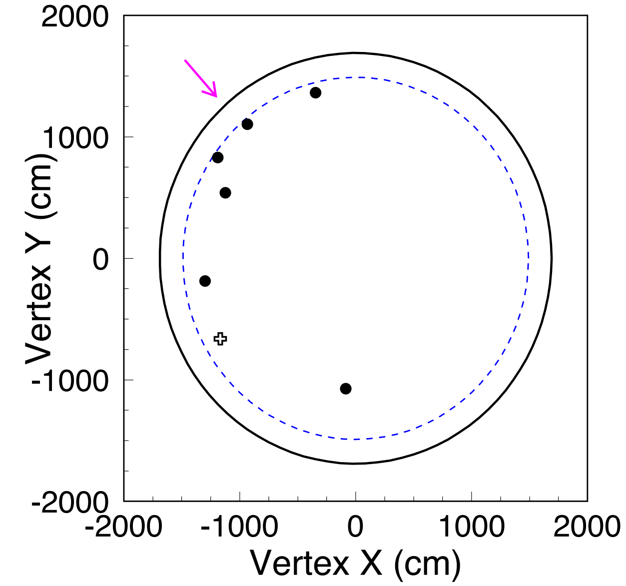


Vertex Distribution Tests

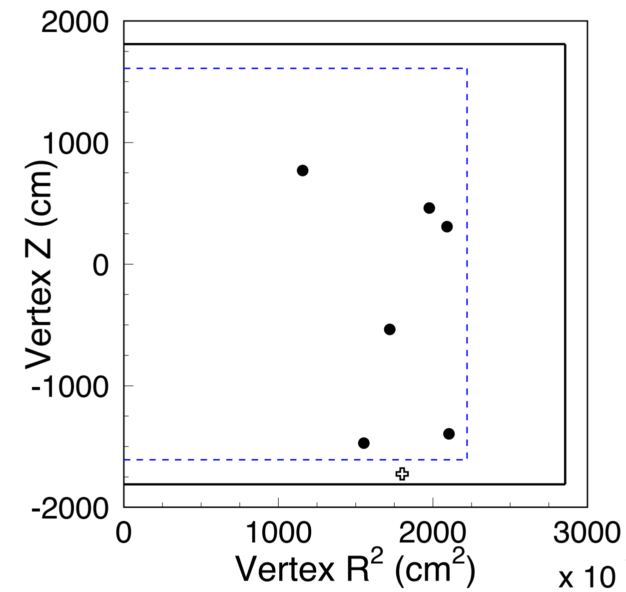
T2K-like event selections used



SK atm. data and MC agree well near the FV boundary



Use KS test for distribution consistency with expectation

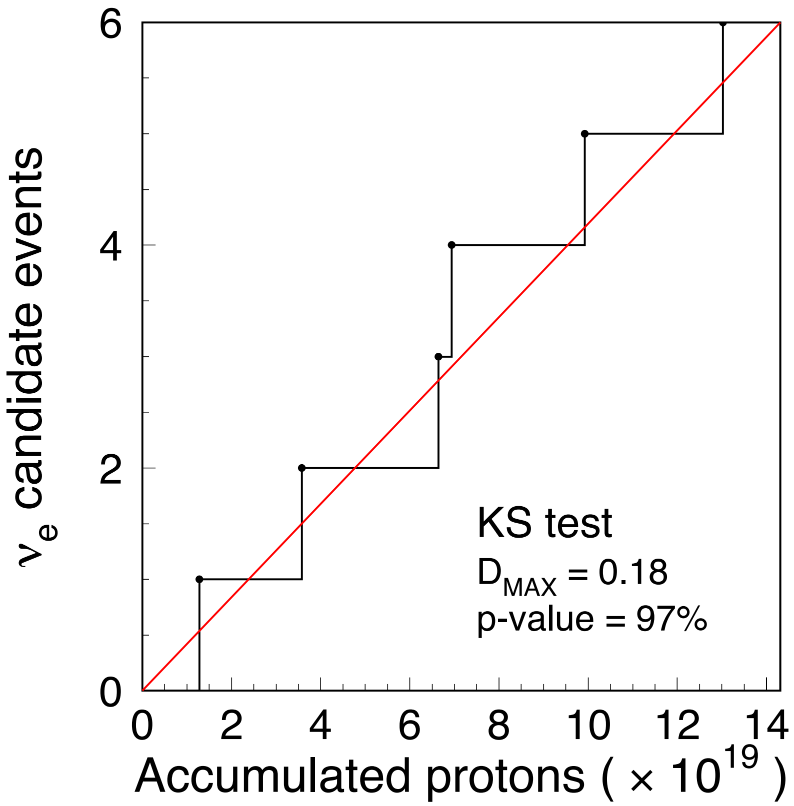


Relative to wall <u>Use 7</u>

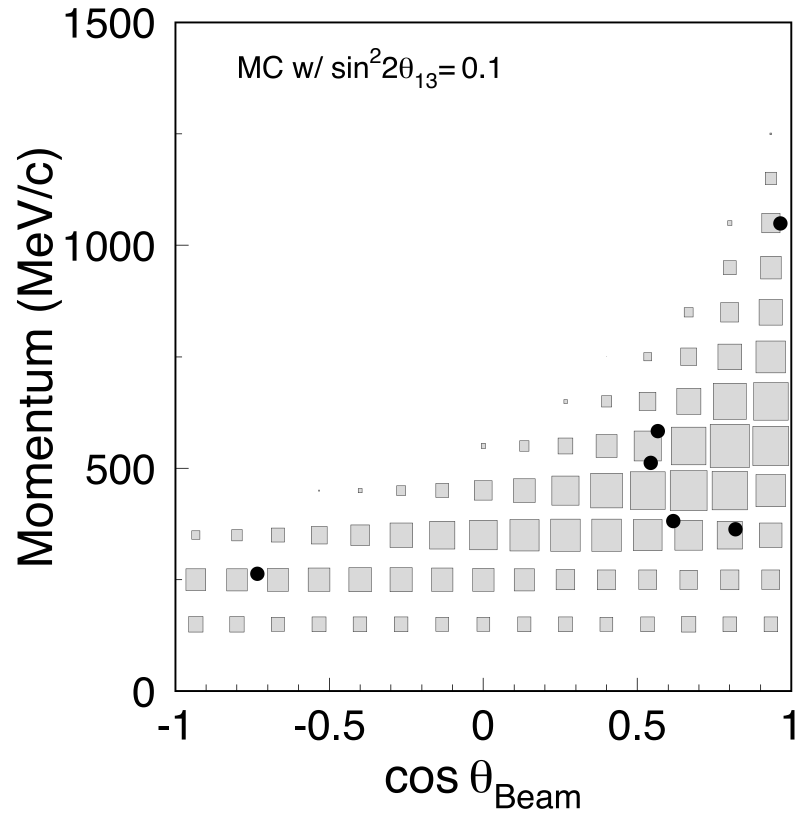
Relative to centre <u>Use 6</u>

Toy MC Probability	7 FC Events	6 FV Events
DWALL	22.7 %	3.7 %
From Wall || Beam	1.4 %	0.14 %
R^2	9.5 %	3.1 %
Z	38.8 %	68.3 %

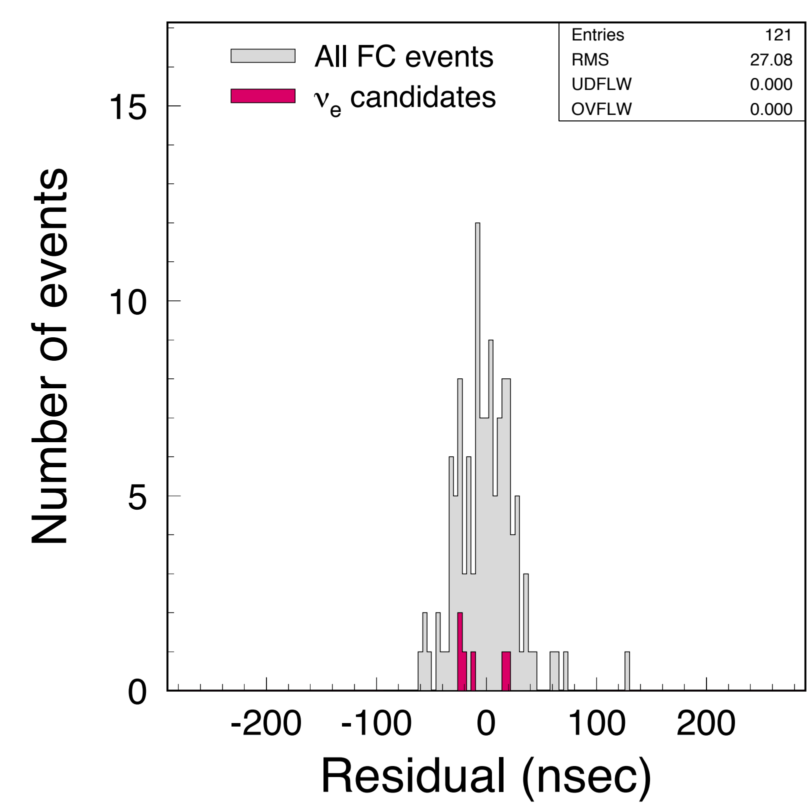
Additional checks



Events distribution over POT



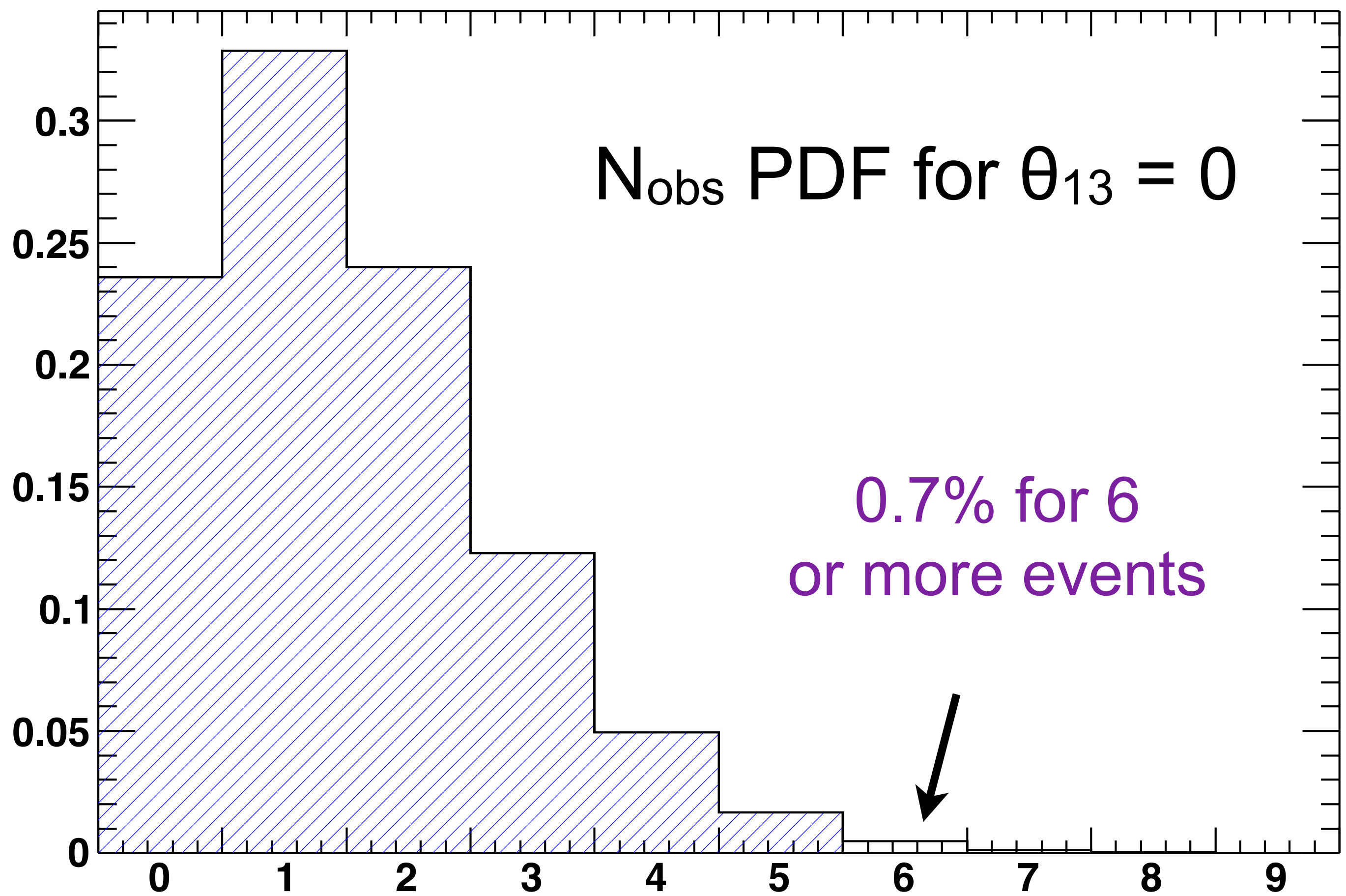
p-θ of produced e



Beam timing

What it Means for θ_{13}

Observed 6 Events, with 1.5±0.3 events background at $\theta_{13} = 0$

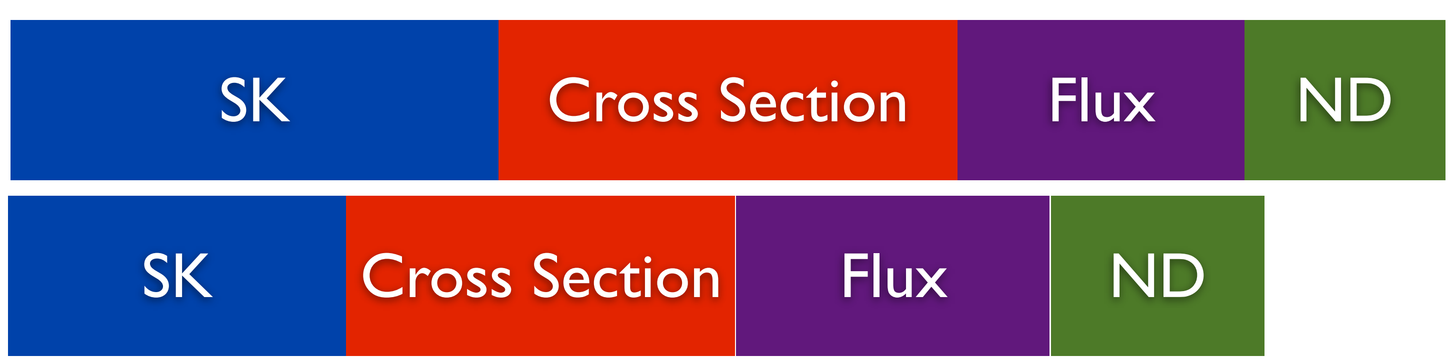


p-value of 0.7%
2.5σ significance

Systematic Errors

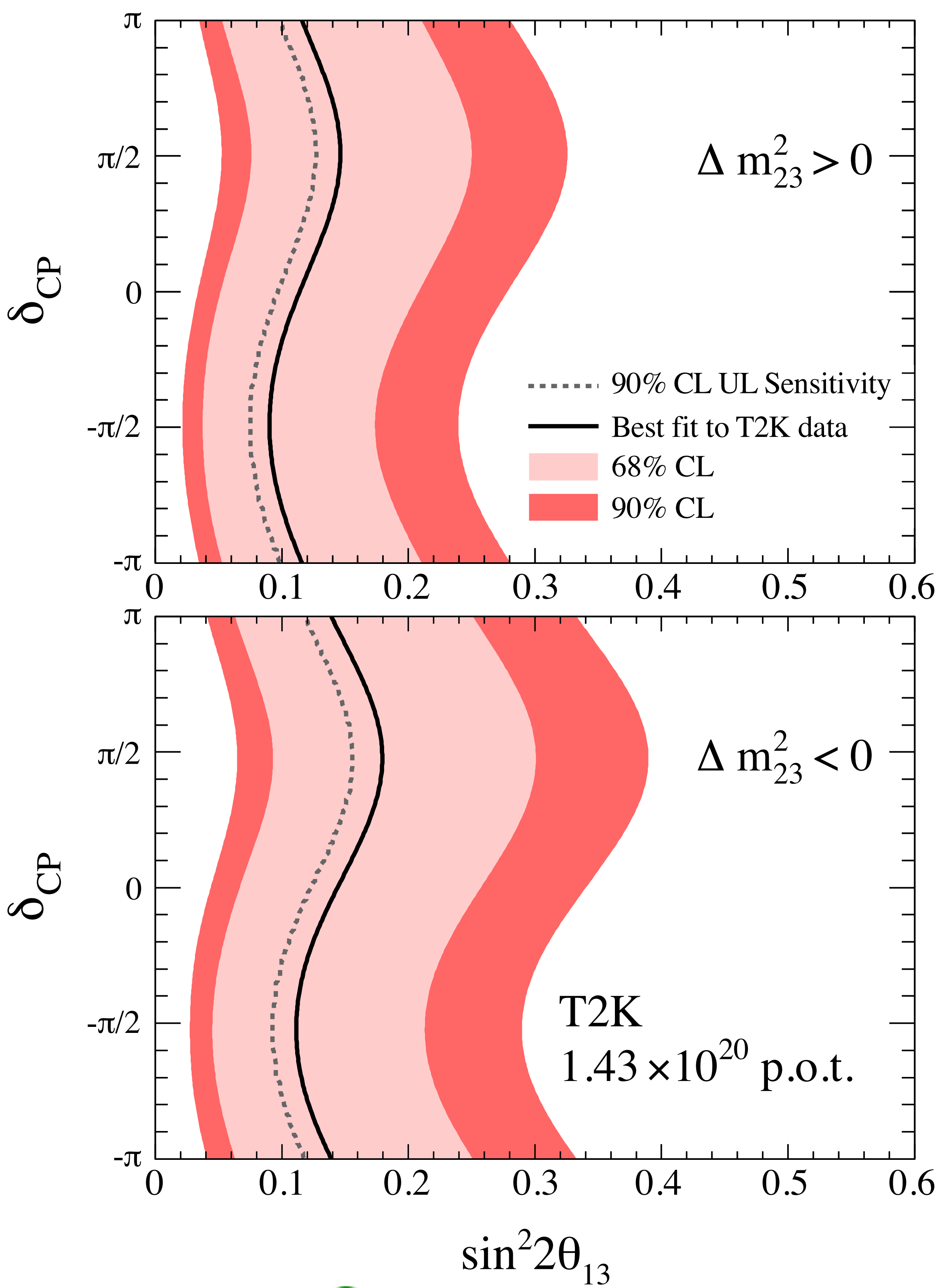
23% Error on Bkg

18% Error on Signal



Combine Poisson distribution + systematics using toy MC

ν_e Appearance Results



- $\theta_{13} = 0$ is not in the 90% CL acceptance region.
- Best fit: $\sin^2 2\theta_{13} = 0.11$
- First non-zero measurement of θ_{13} at the 90% CL!

Normal (Inverted) Hierarchy:

0.03 (0.04) < $\sin^2 2\theta_{13}$ < 0.28 (0.34)

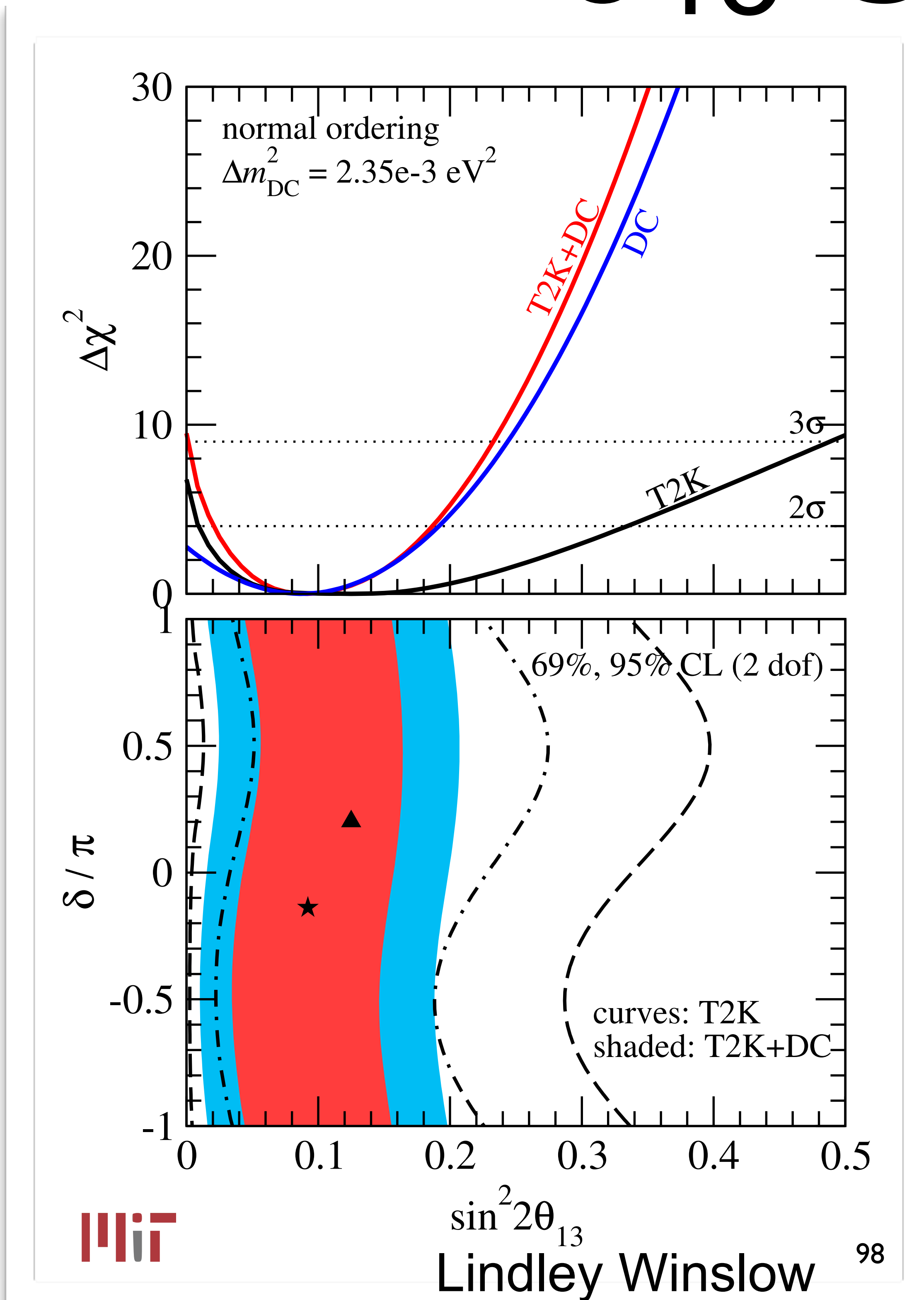
[assuming $|\Delta m^2_{32}| = 2.4\text{e-}3\ eV^2$, $\delta_{CP} = 0$ and $\sin^2 2\theta_{23} = 1$]

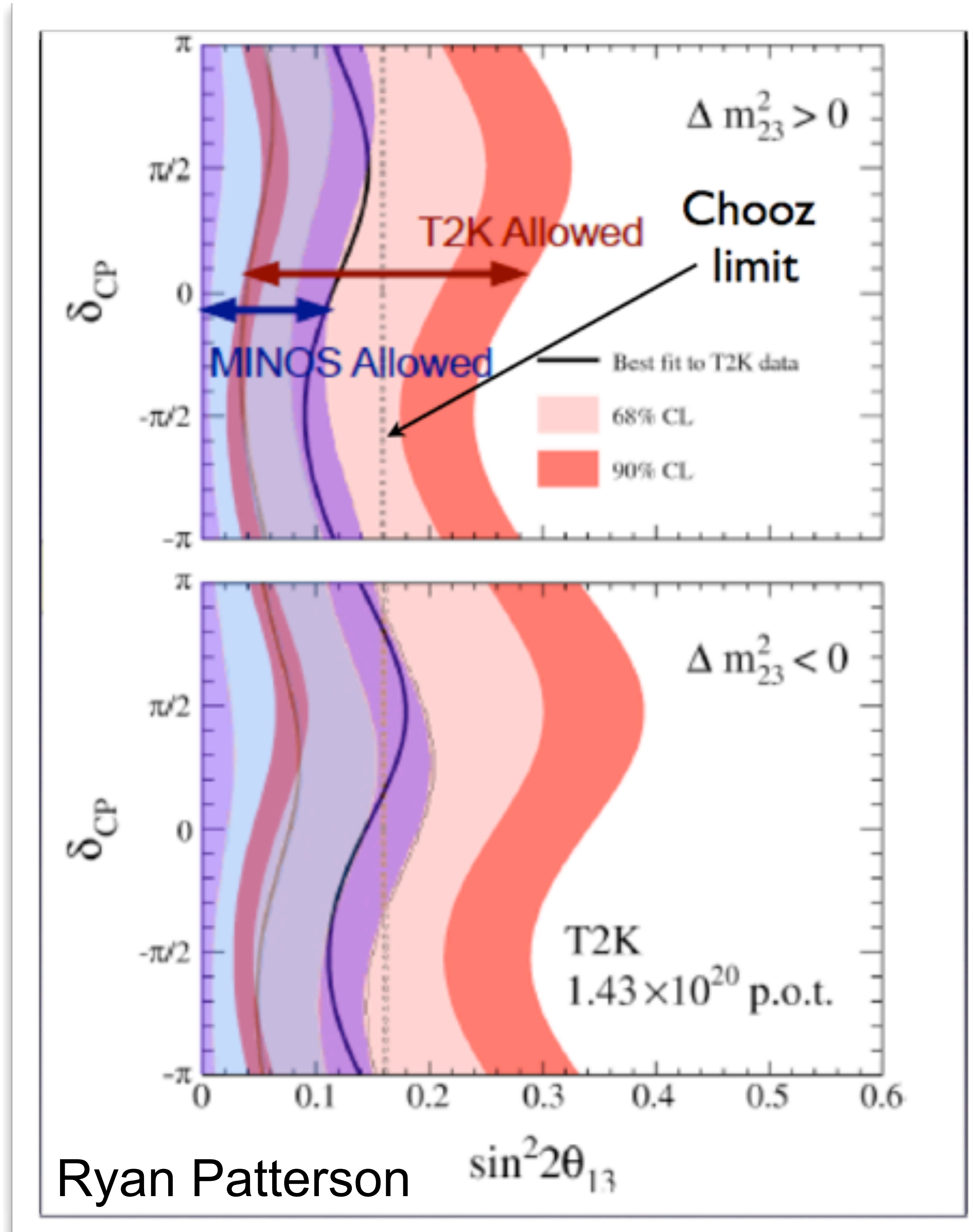
θ_{13} next steps

➡ *Aim to firmly establish ν_e appearance and better determine θ_{13}*

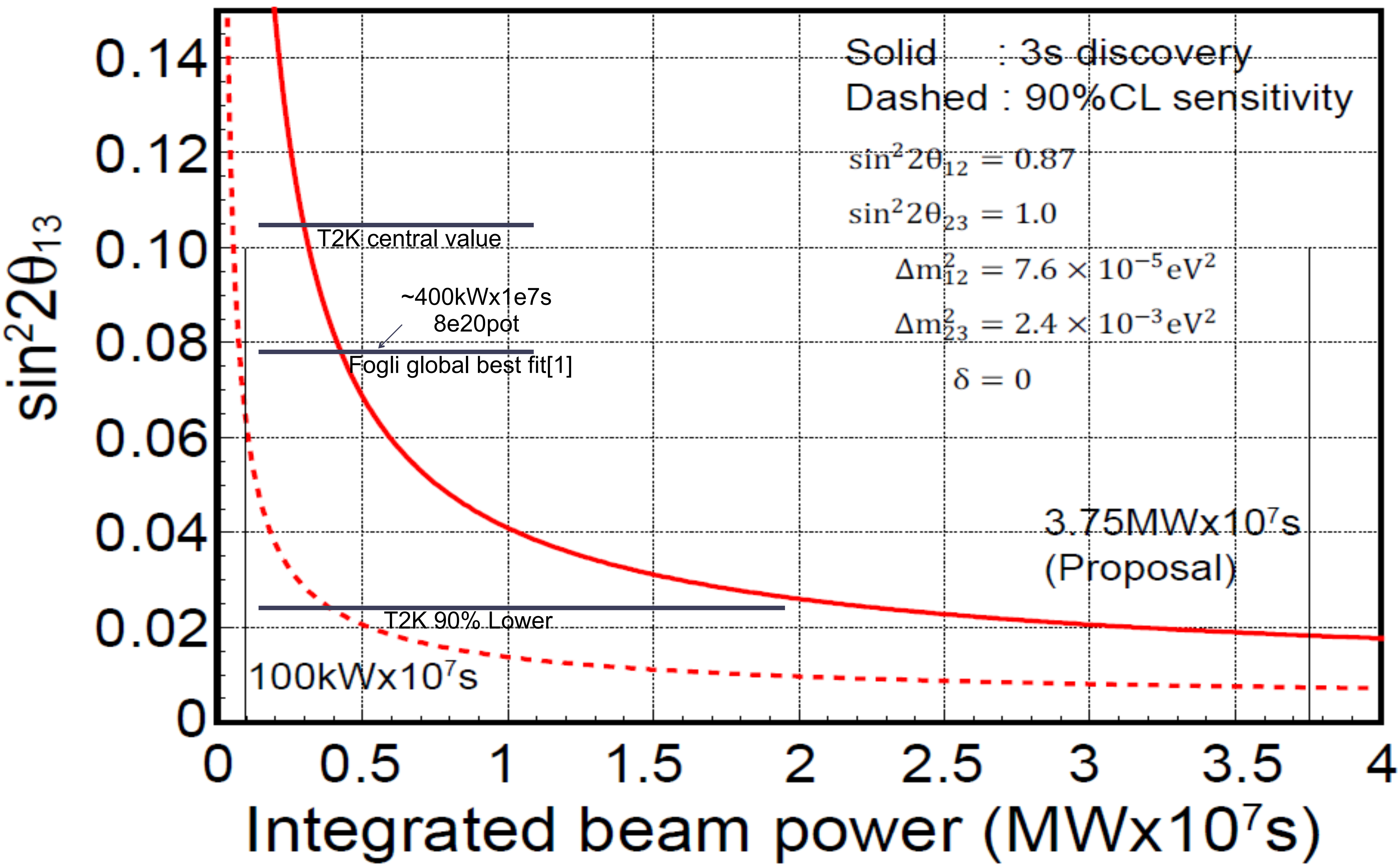
- Resume experiment!
  - Recovery work completed.
  - J-PARC activity in full swing - accelerator operating.
  - Physics running in March - new data for Kyoto
- Improve analysis
  - New methods using more ND280 information under development
  - Long target and kaon data from NA-61
  - Finish external data fitting for cross section tuning
  - Three flavor analysis incorporating our own ν_μ disappearance result

θ_{13} Context





T2K expected sensitivity



[1] G.L.Fogli, et.al, arXiv:1106.6028v1 [hep-ph]

Other T2K Activity

- Several new analyses done in progress with current data set
- ν_μ disappearance result!
  - Fit for atmospheric oscillation parameters
- Cross section analyses
  - CC inclusive cross section (muon momentum and angle)
  - CCQE cross section (E_ν and Q^2)
  - CC pion production

ν_μ Disappearance Analysis

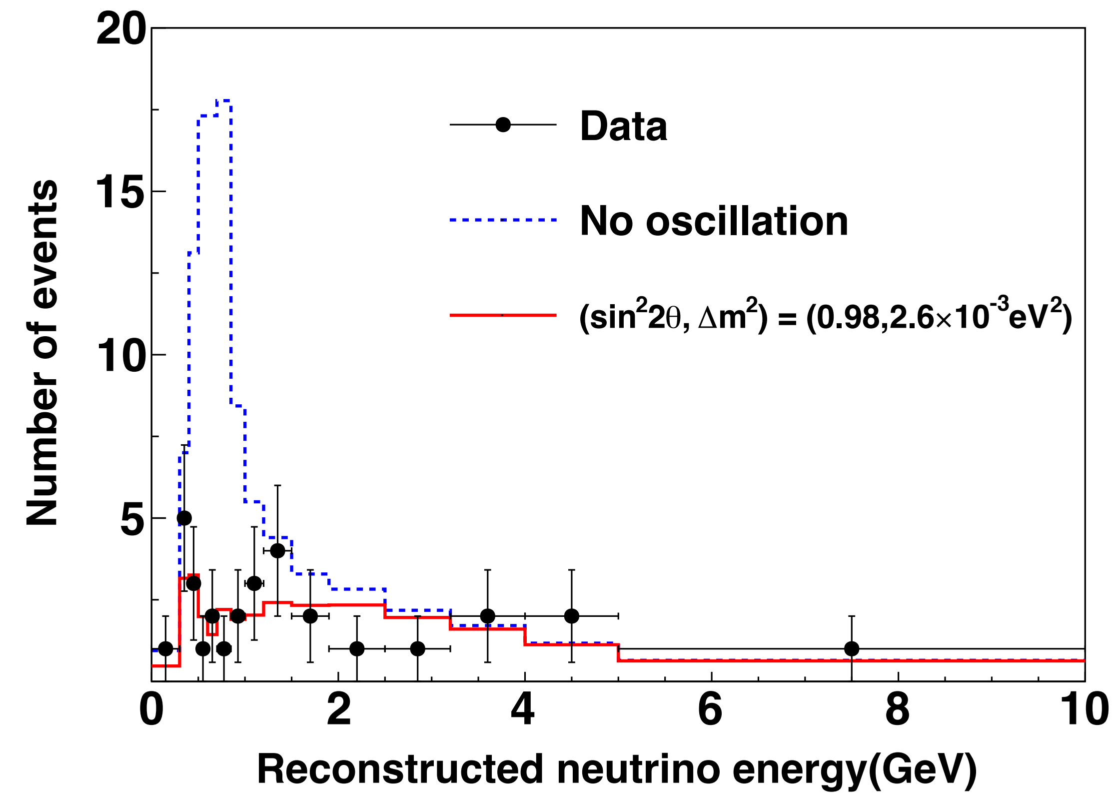
- Fully Contained
- Fiducial Volume
- Single Ring
- μ-like
- $p_\mu > 200$ MeV
- $N_{decay} < 2$

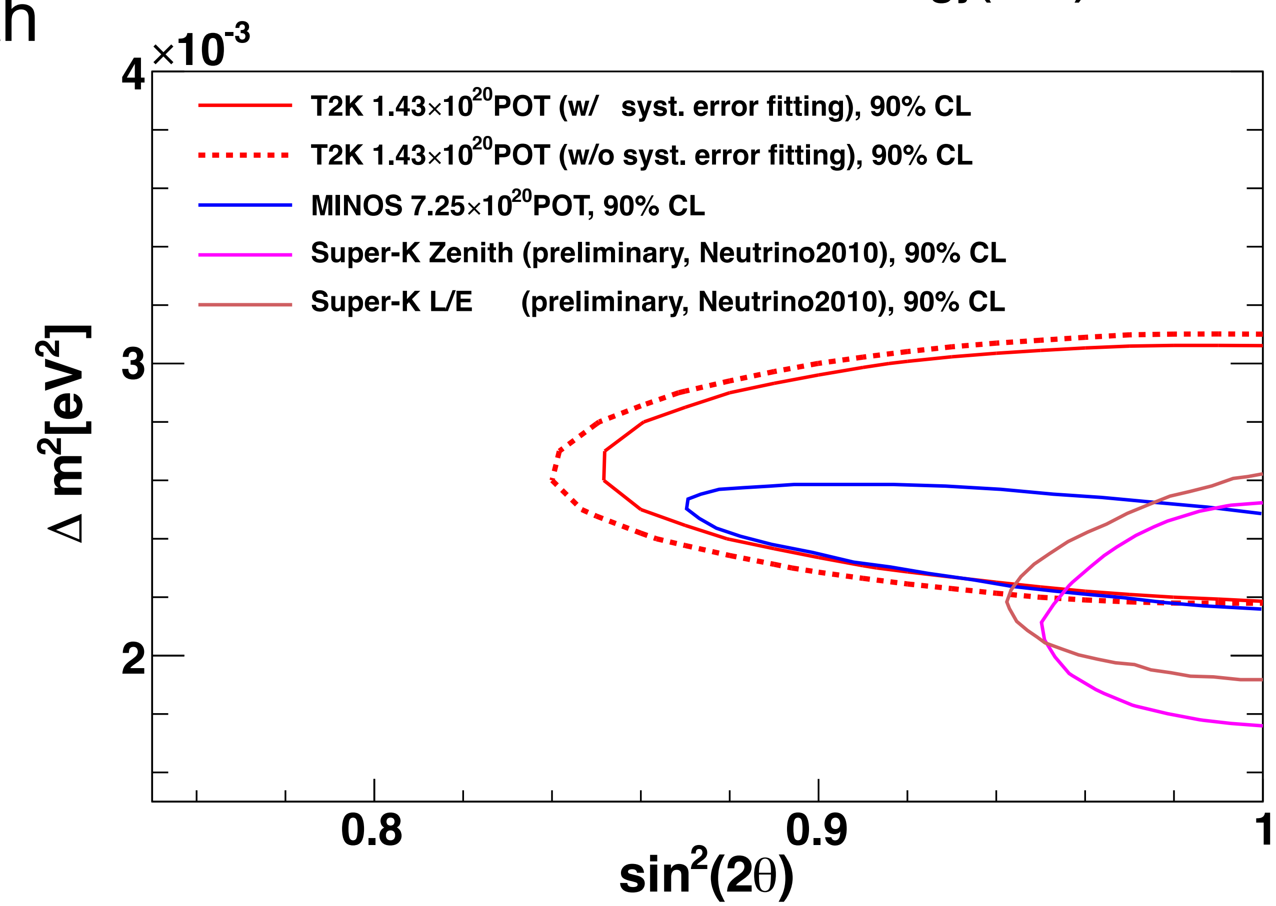
Data: 31 Events

Expect 104 ± 17

Shows power of off-axis technique

Soon be competitive with previous experiments





at 90% CL

$\sin^2 2\theta_{23} > 0.85$

$2.1\text{x}10^{-3} < \Delta m^2_{23}$ (eV) $< 3.1\text{x}10^{-3}$

Conclusion

- T2K reports our first $\nu_\mu \rightarrow \nu_e$ result based on 1.43e20 POT (2% of T2K goal)
- Expected number of events is 1.5±0.3 (for $\sin^2 2\theta_{13} = 0$)
- The probability to observe 6 or more events is 0.007

➡ **Indication of non-zero θ_{13} and ν_e appearance**

- Phys. Rev. Lett. **107** 041801 (2011)

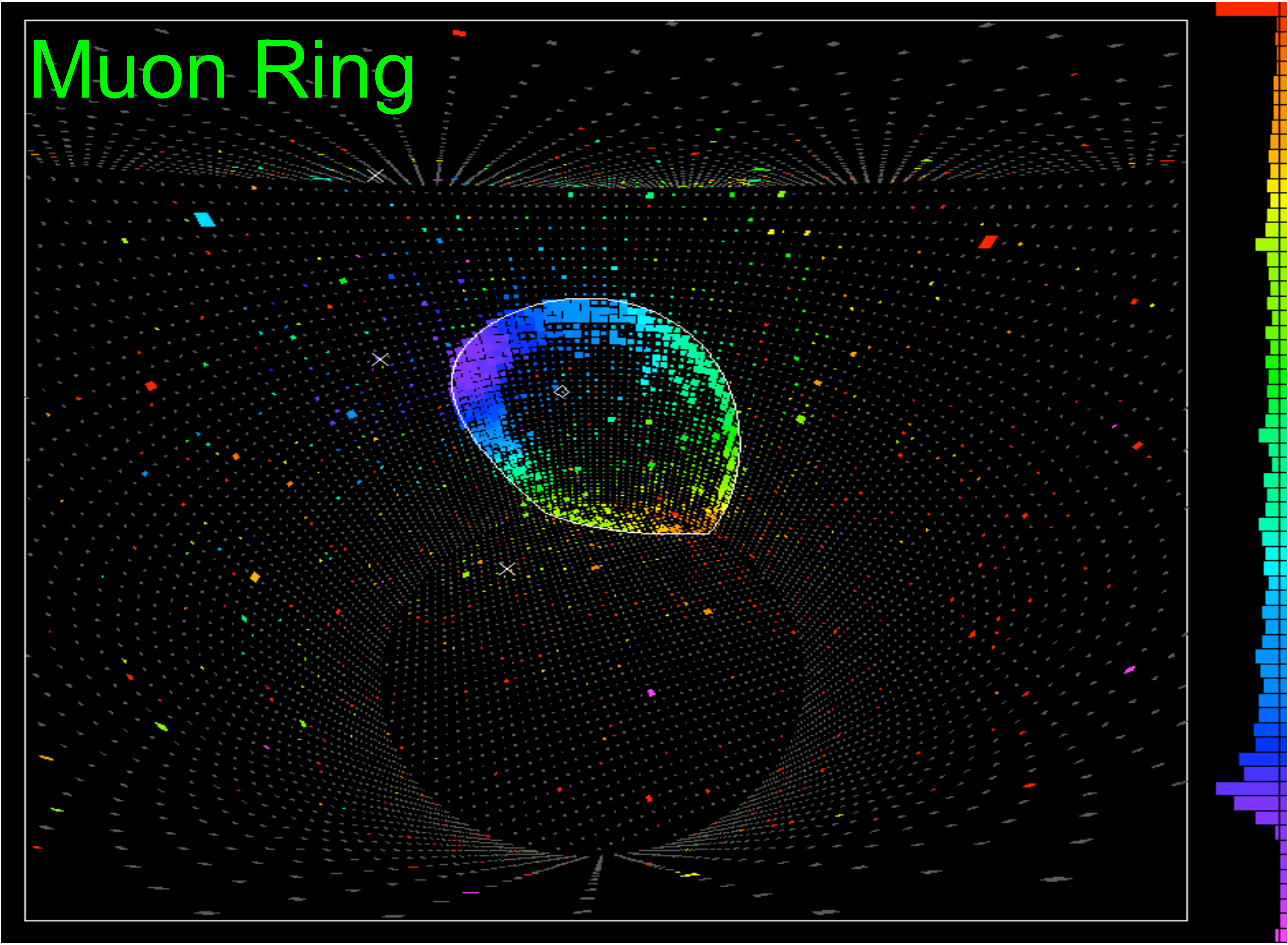
- ν_μ disappearance analysis completed, and paper draft in circulation

- We will show new data at Nu2012!

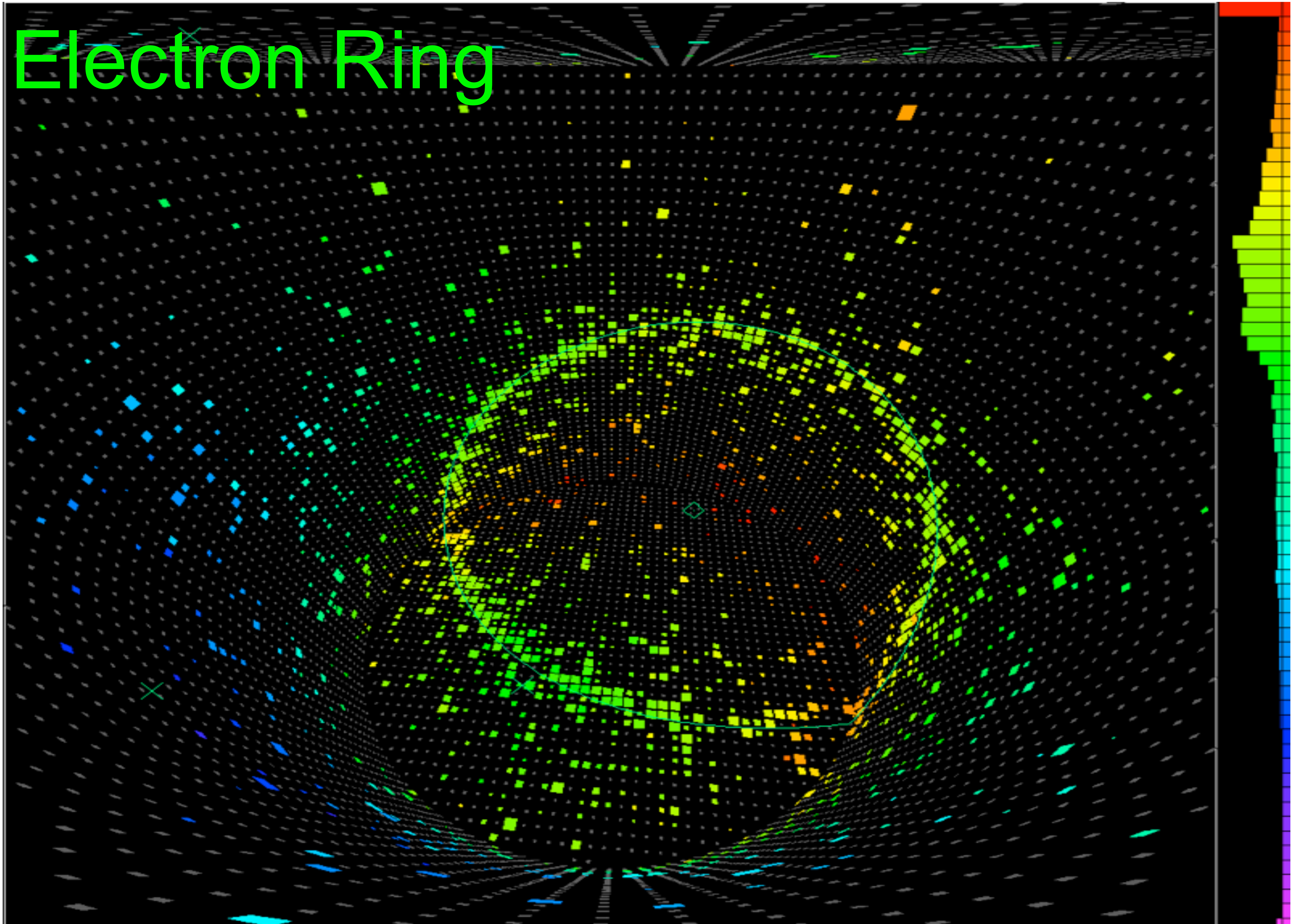
水戸の梅の花


Backup slides

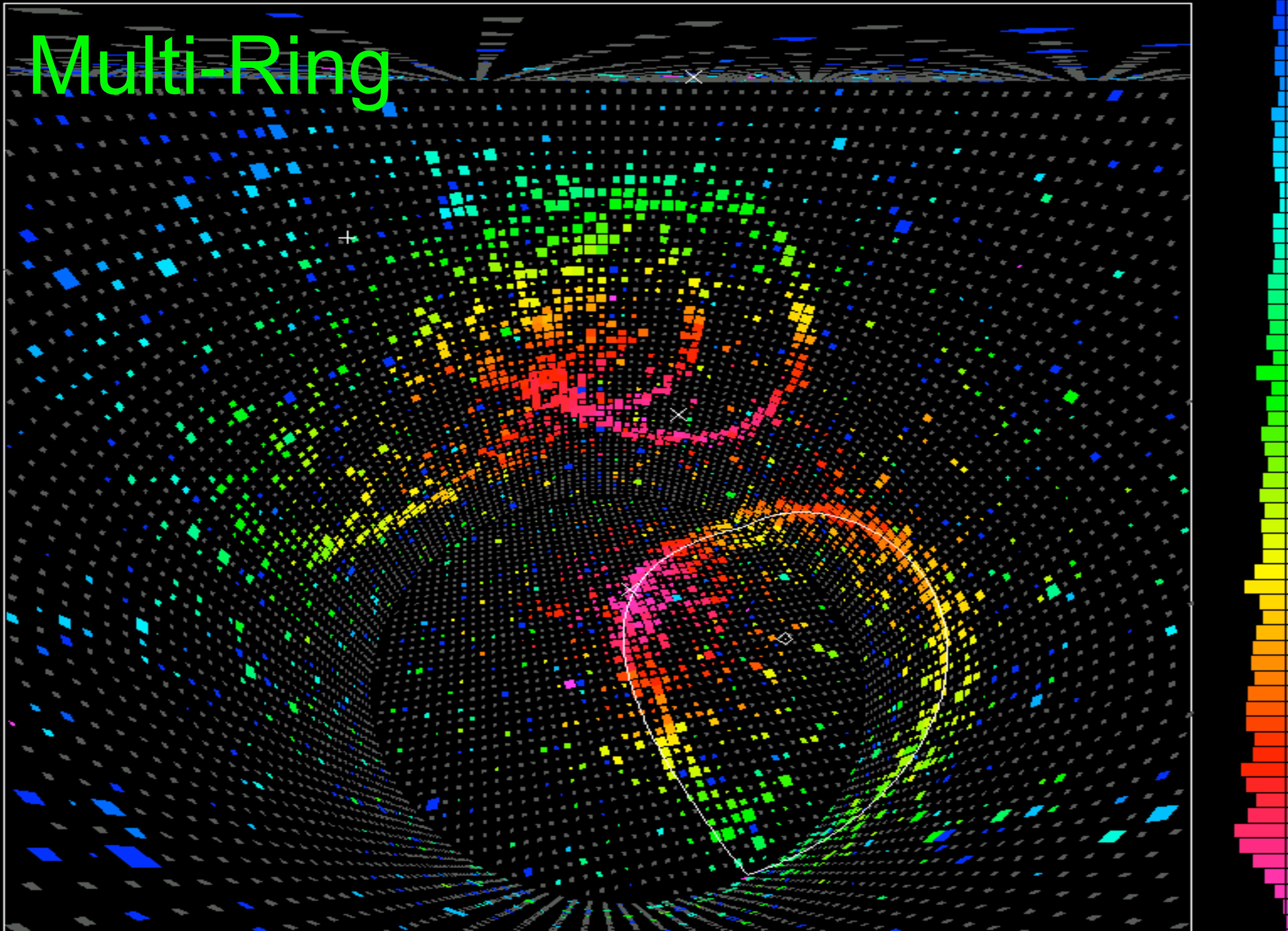
Muon Ring



Electron Ring

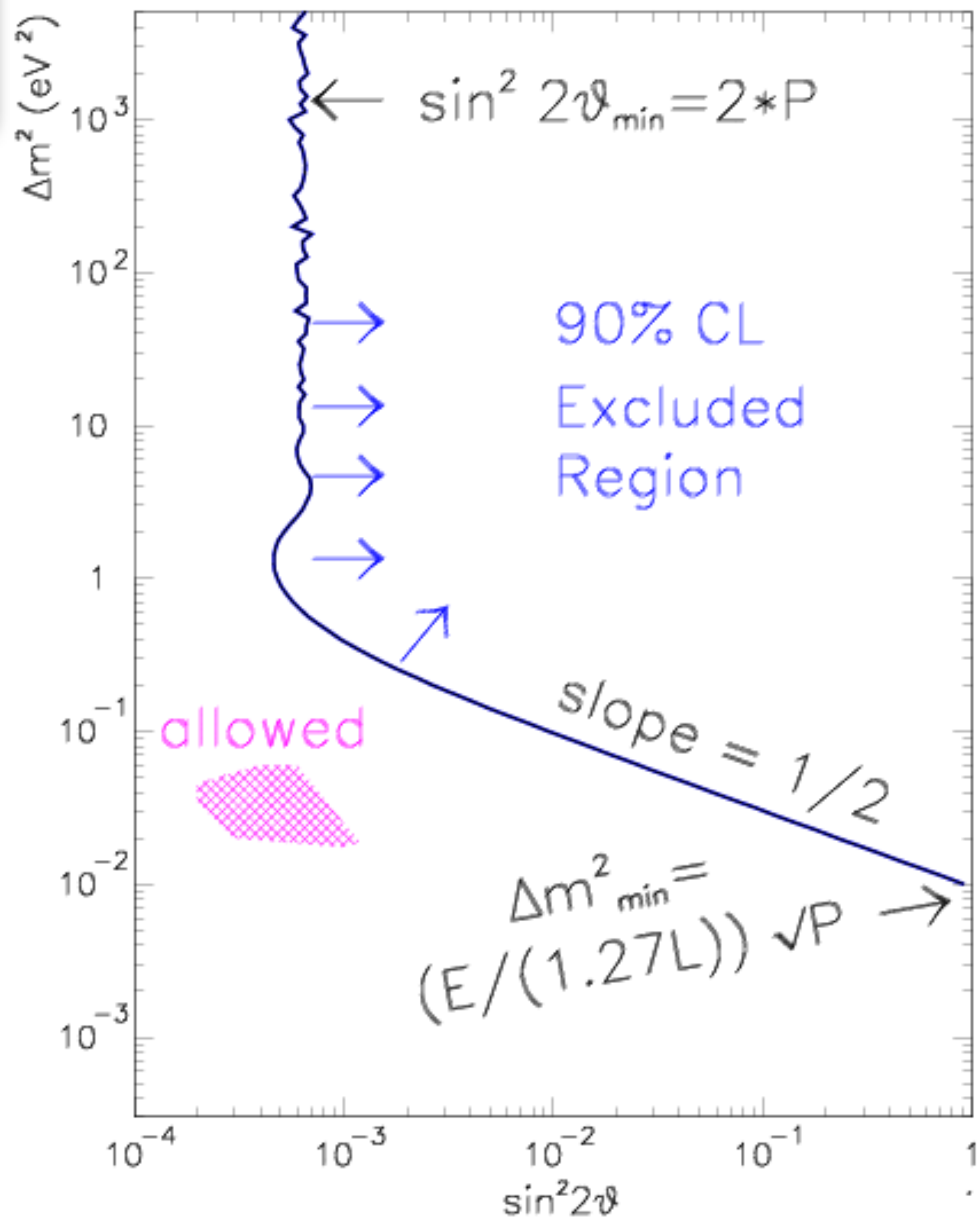


Multi-Ring



$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

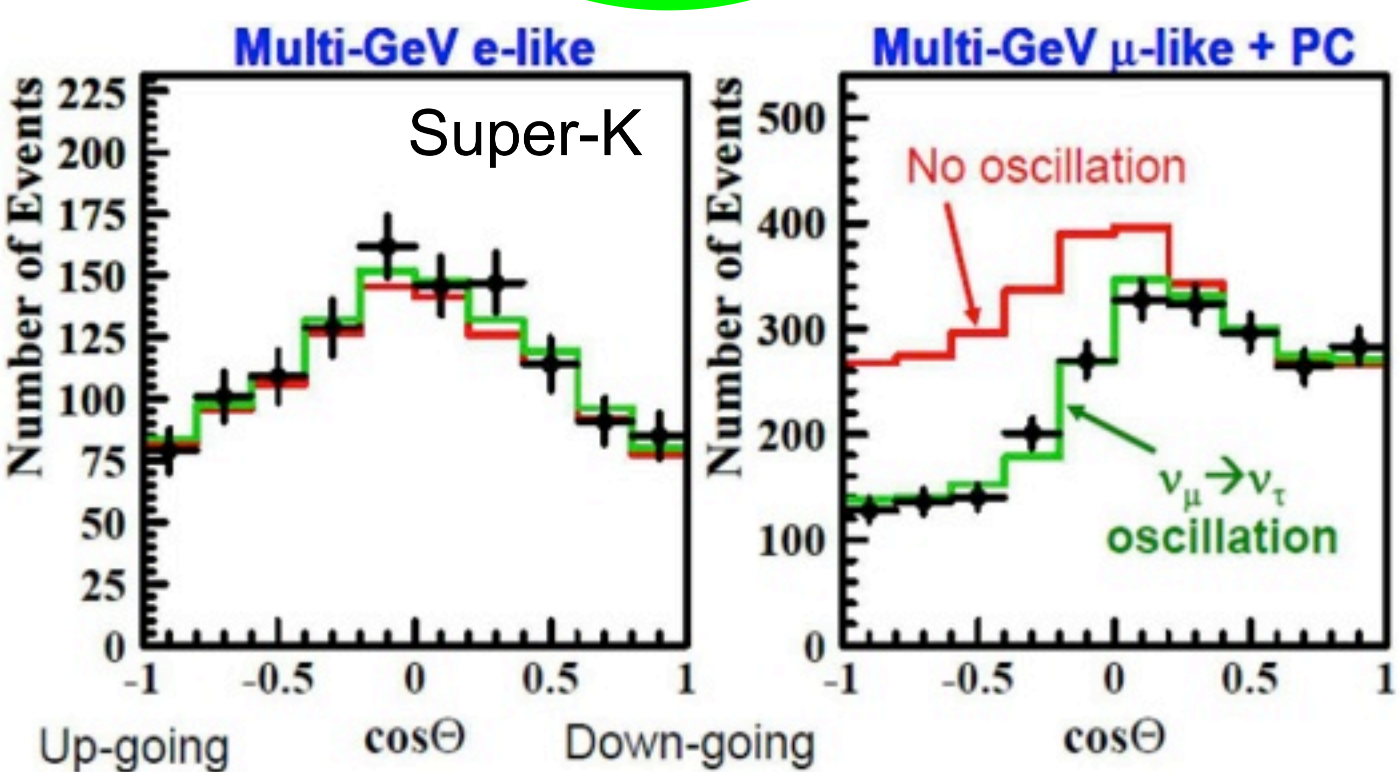
- L and E determine Δm^2 sensitivity
- θ_{12} sensitivity determined by statistics, backgrounds, and uncertainties
- No signal: exclusion curve
- Signal: allowed region



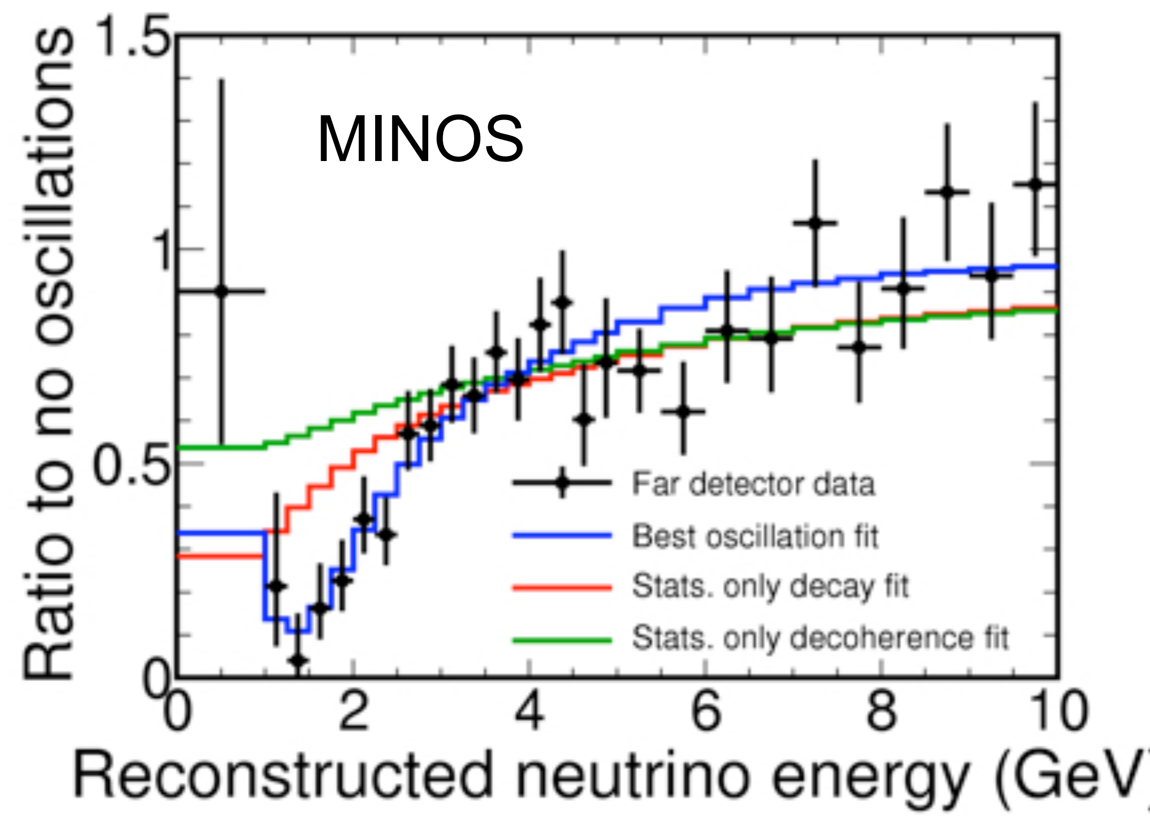
Atmospheric Oscillation

flavor | atmospheric | cross-mixing | solar | mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Phys.Rev.Lett.81.1562(1998)

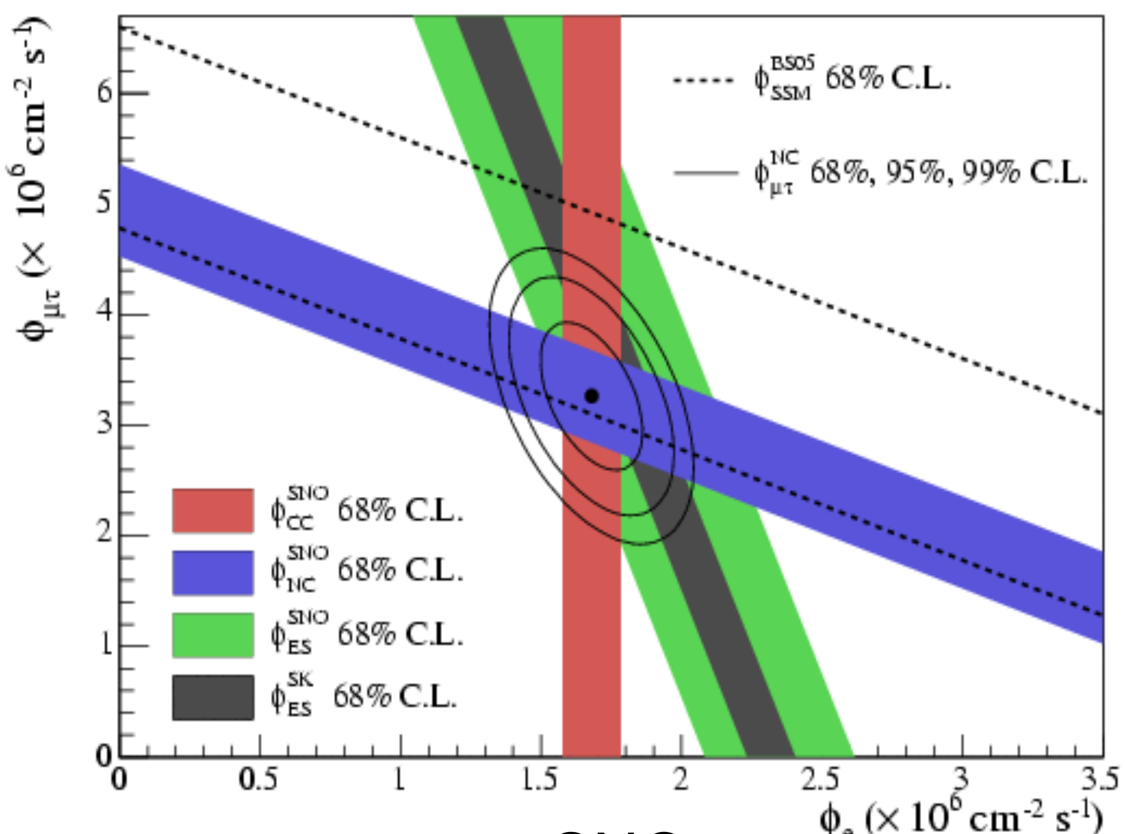


PhysRevLett.101.131802

Solar Oscillation

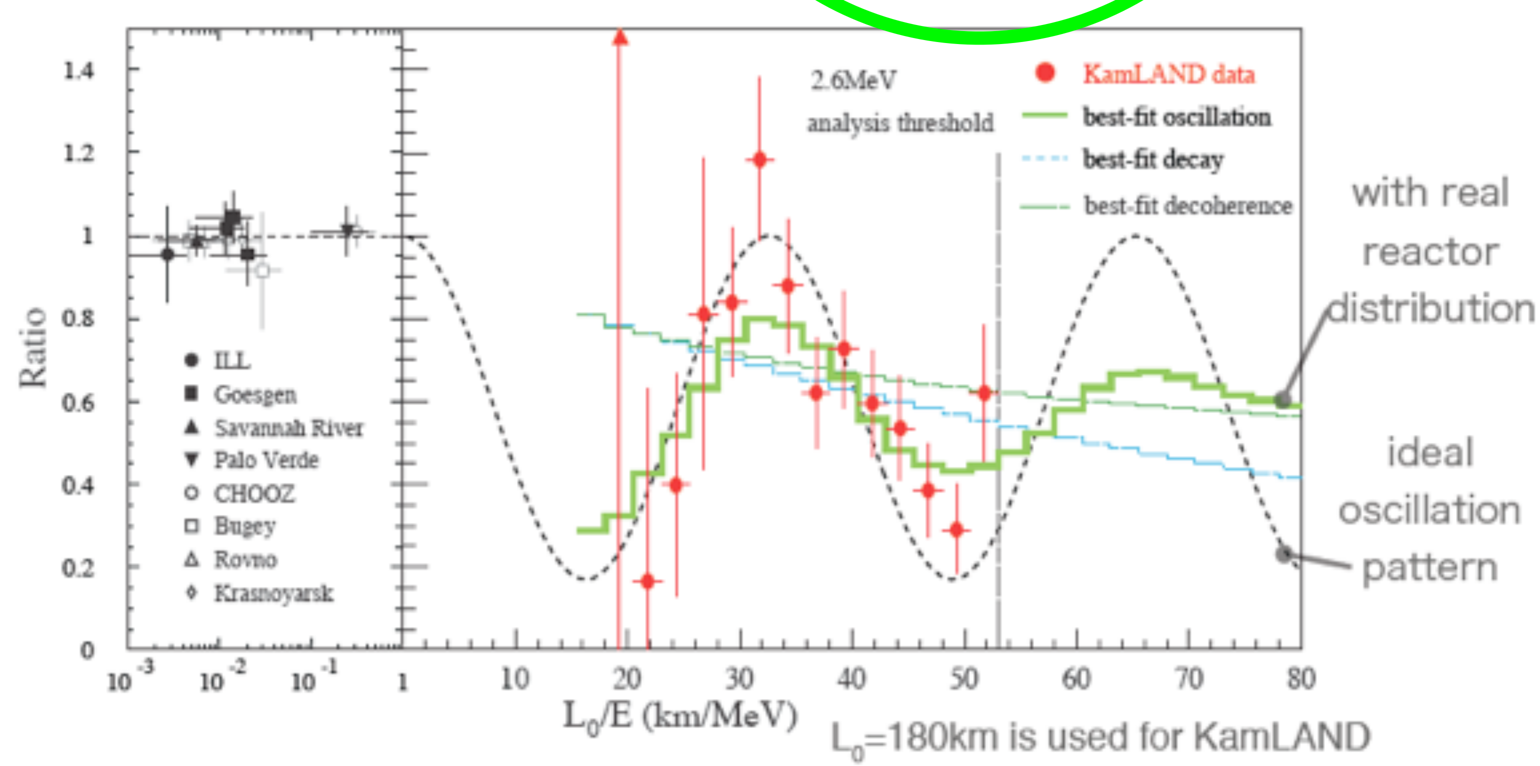
flavor | atmospheric | cross-mixing | solar | mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



SNO

Phys.Rev.Lett.89.011301 (2002)



KamLAND

Phys.Rev.Lett.100.221803 (2008)

Cross Mixing

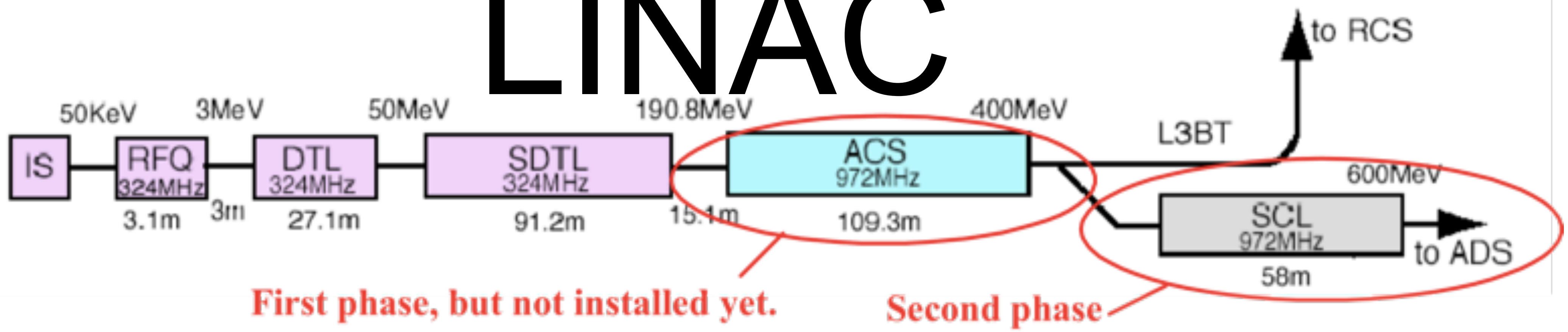
flavor — atmospheric — cross-mixing — solar — mass

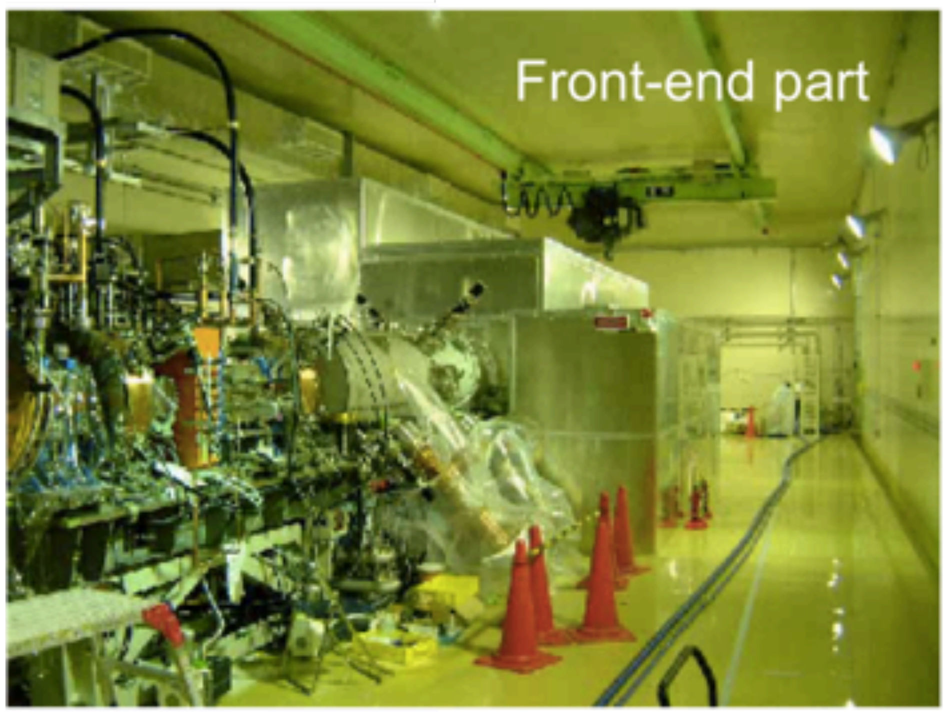
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

10-2

Causes $\bar{\nu}_e$ disappearance in reactors and ν_e appearance in accelerator experiments

LINAC





Ion source, LEBT, RFQ, MEBT(2 choppers, 2 bunchers)

- **Particle:** H^-
- **Energy:**
  - on day-one: 181 MeV
  - with ACS: 400 MeV
- **Peak current:**
  - at 181 MeV: 30 mA
  - at 400 MeV: 50 mA
- **Repetition:** 25 Hz
- **Pulse width:** 0.5 msec

- Stable operation at 15~20mA/500usec pulse width achieved
- Longer continuous operation w/o Ion source maintenance being tried. >1000hr @16mA achieved
- Upgrade 400MeV is delayed to 2013

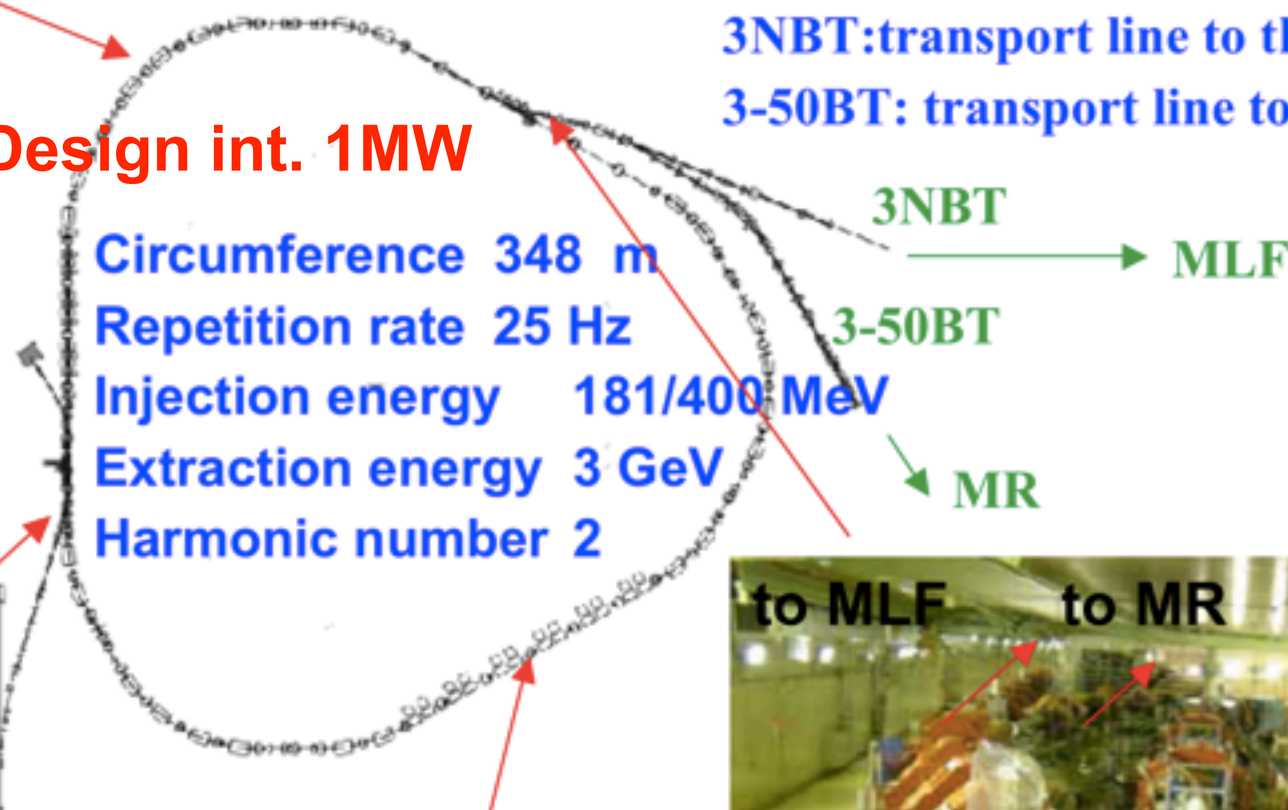
3GeV-RCS

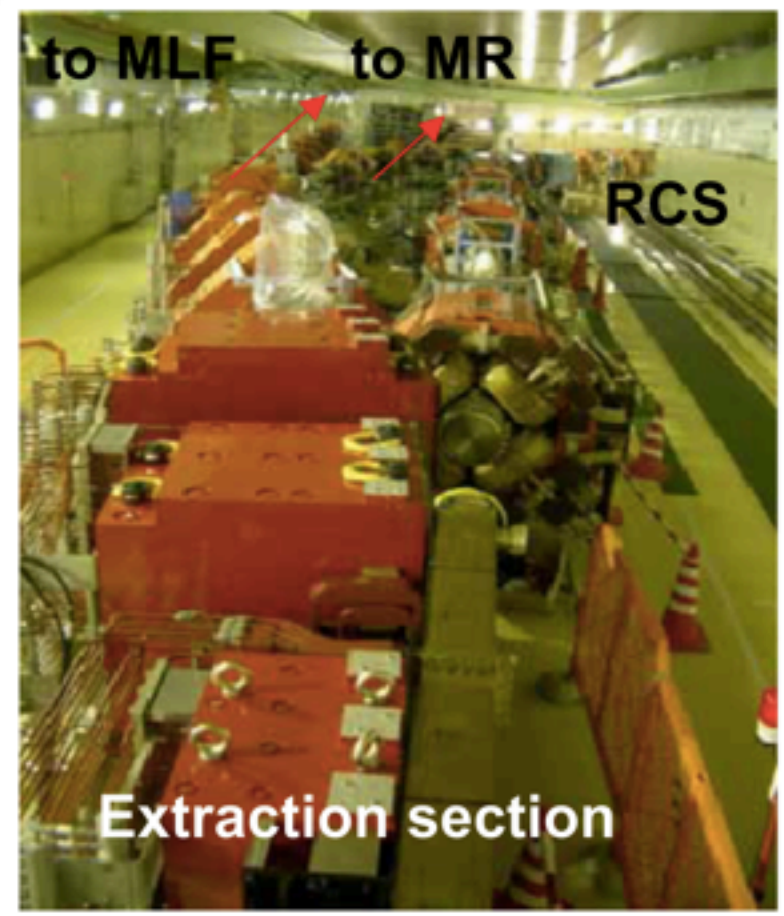
Neutron/Muon source and booster of the MR.

Two beam transport lines

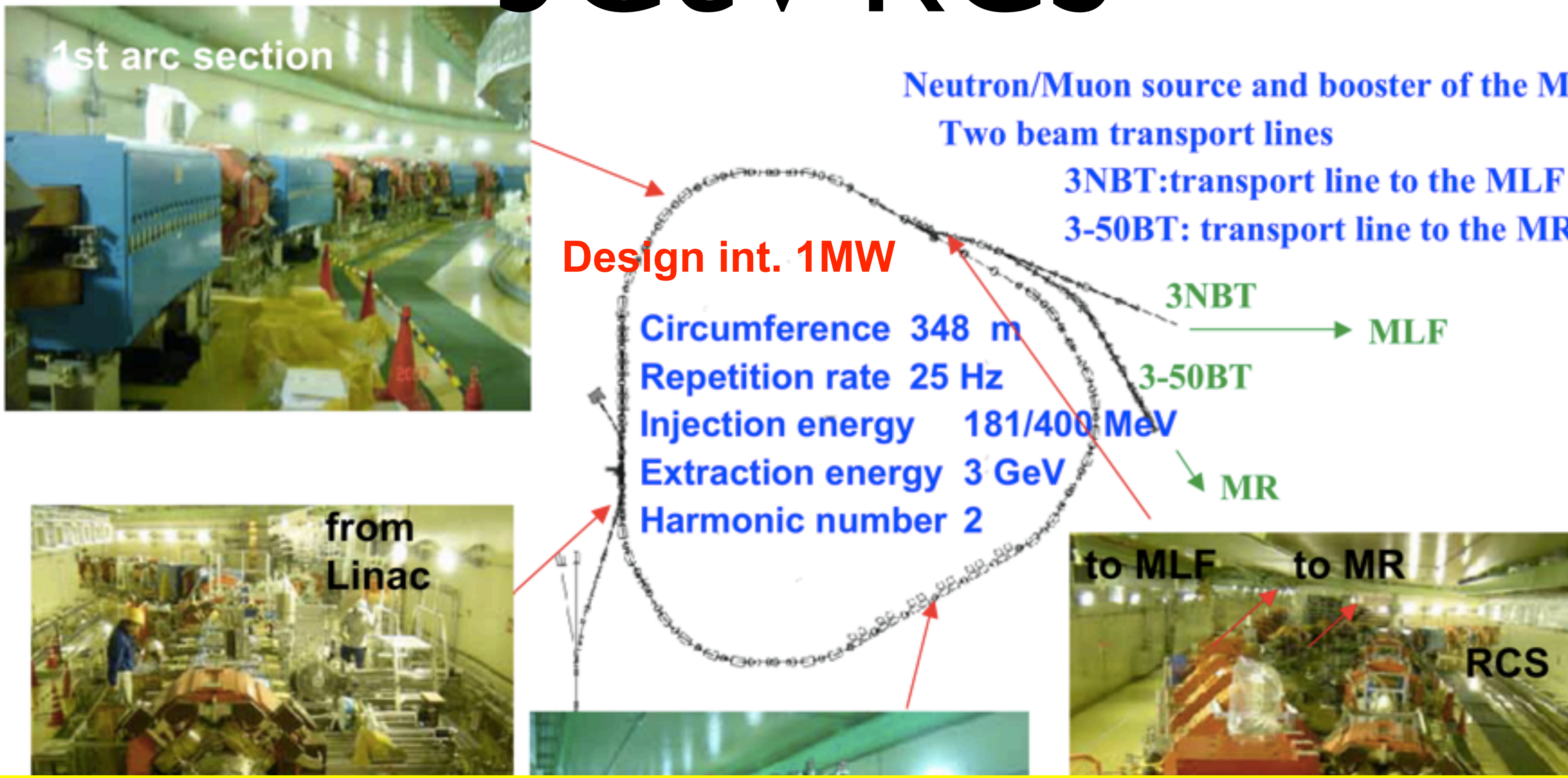
3NBT:transport line to the MLF

3-50BT: transport line to the MR





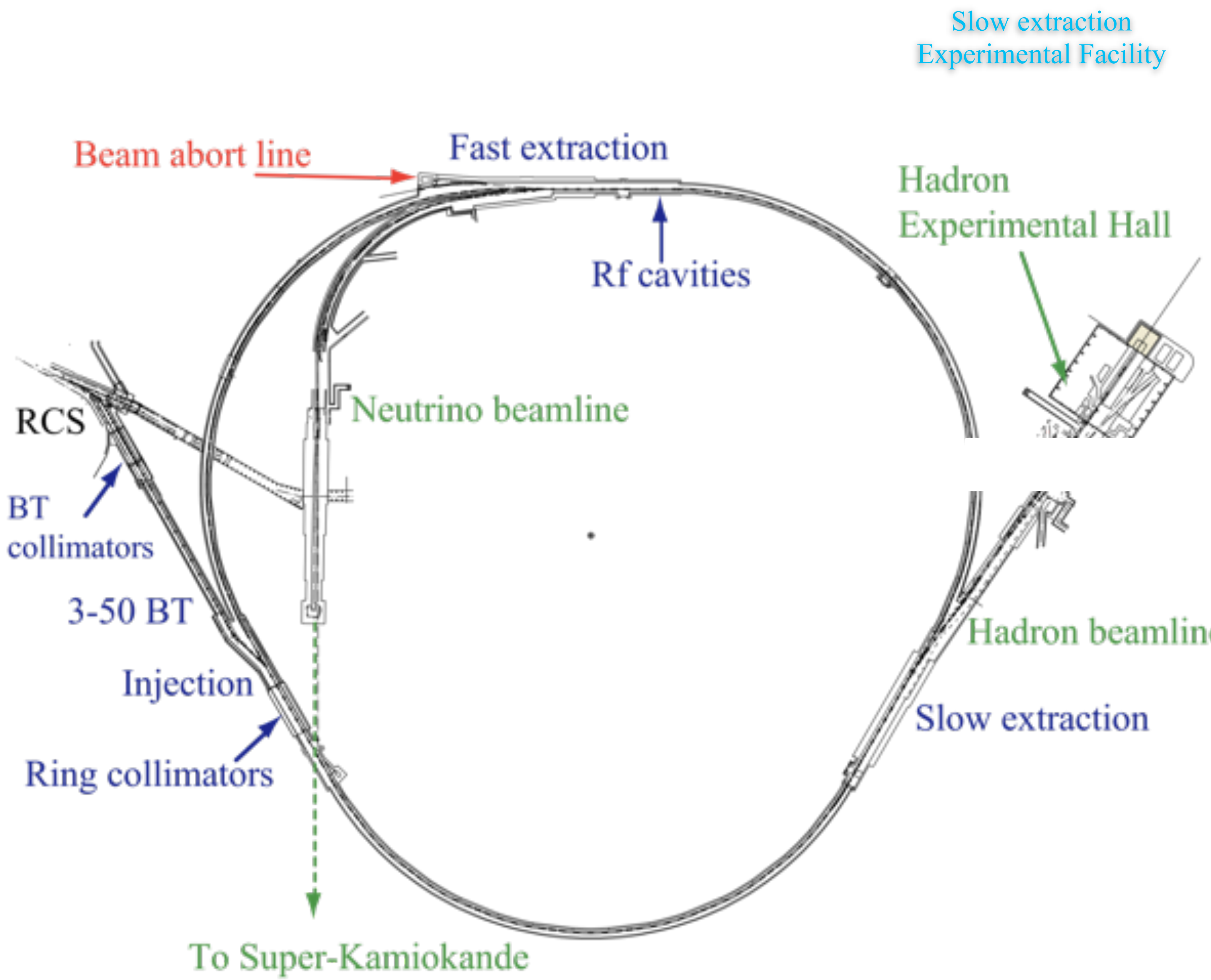
3GeV-RCS



- 200kW stable beam provided for MLF
- 300kW equiv beam provided for MR
- 420kW high power test succeeded (99.5% transmission), ready for providing to MR

MR

Circumference 1567.5 m
Repetition rate ~0.3 Hz@Start Up
Injection energy 3 GeV
Extraction energy 30 GeV
Superperiodicity 3h 9
No. of bunches 8 (6 in day 1)
Transition γ 31.7(imaginary)
Typical tune 22.4, 20.8
Transverse emittance
  At injection ~54 πmm-mrad
  At extraction ~10 πmm-mrad
Beam power 0.75MW



J-PARC Neutrino Beam

Conventional horn focused beam

First application of off-axis beam

Adjustable off-axis angle 2~2.5deg.

2.5 deg at Day1

First MW-capable beamline

Design intensity is 750kW with safety factor

Parts which can never be upgraded later are designed for Multi-MW (3~4MW)

Shielding and cooling capacity of target station, decay volume, beam dump

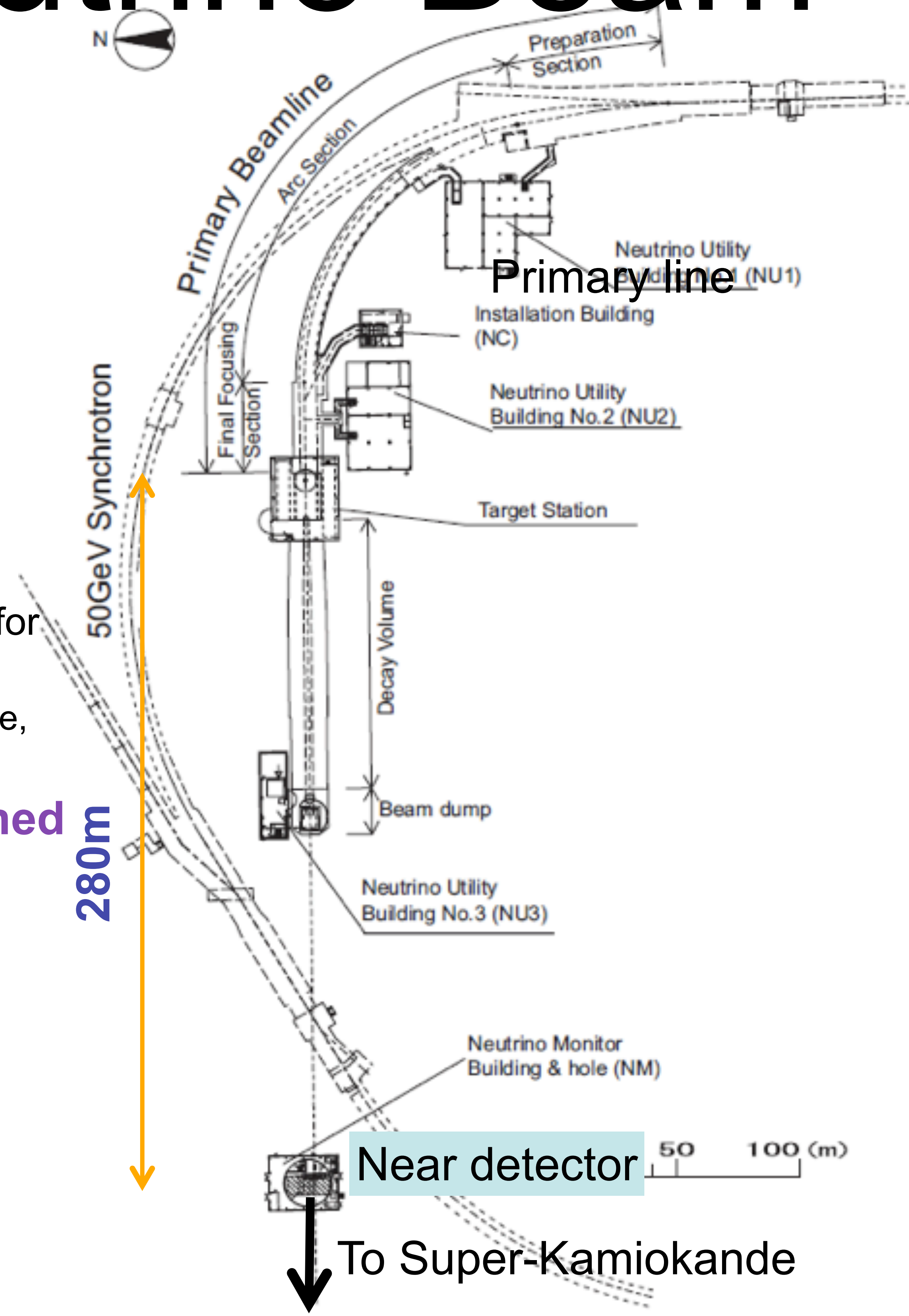
First application of superconducting combined function magnet

Key issues

Beam loss

Remote/quick maintenance of activated components

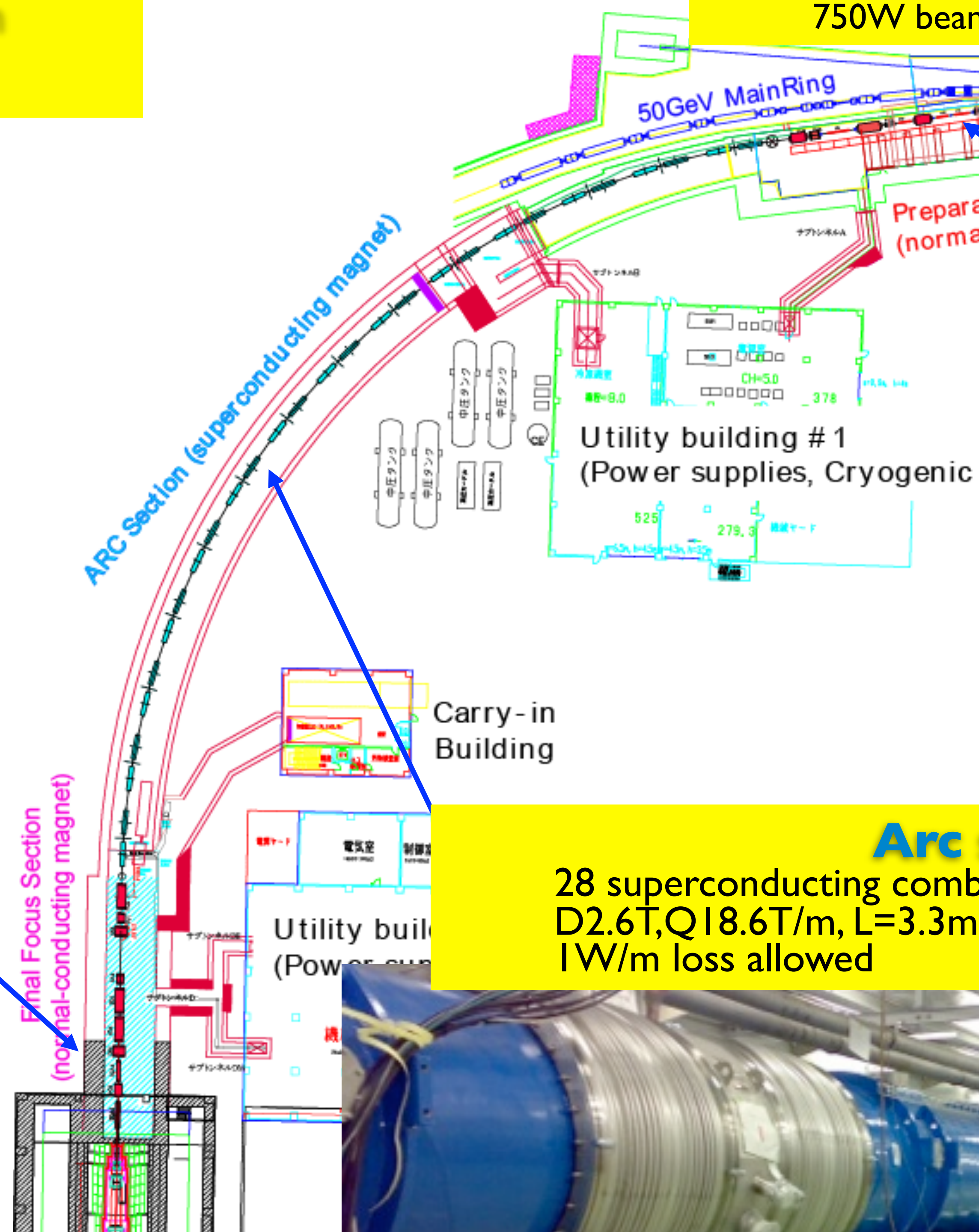
Radio active waste



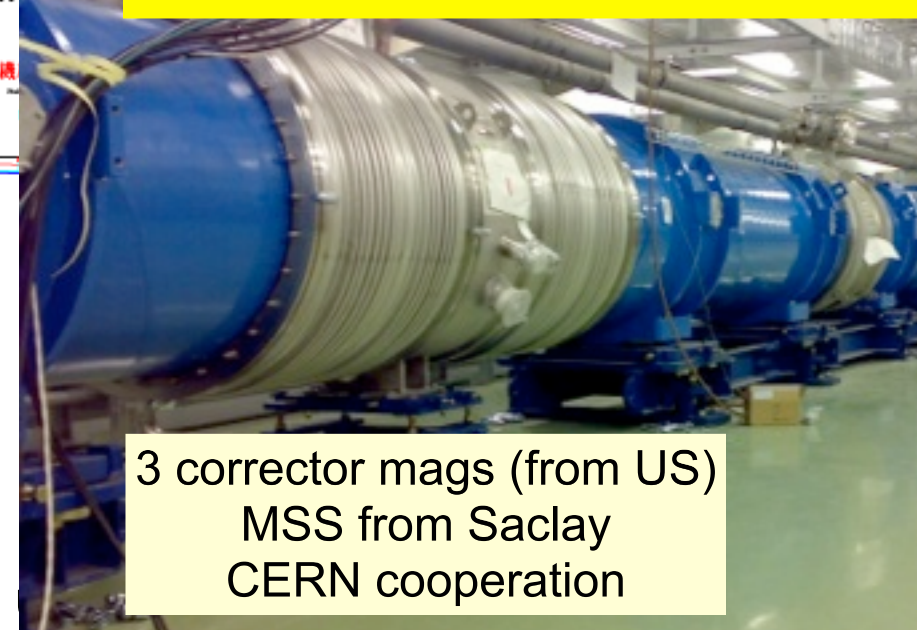
Primary beamline

Final focusing (FF) section
10 normal conducting magnets
250W loss shield

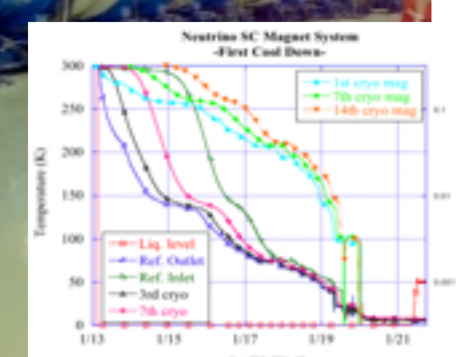
Preparation section
11 normal conducting magnets
750W beam loss shield



Arc section
28 superconducting combined function magnets
D2.6T,Q18.6T/m, L=3.3m
1W/m loss allowed

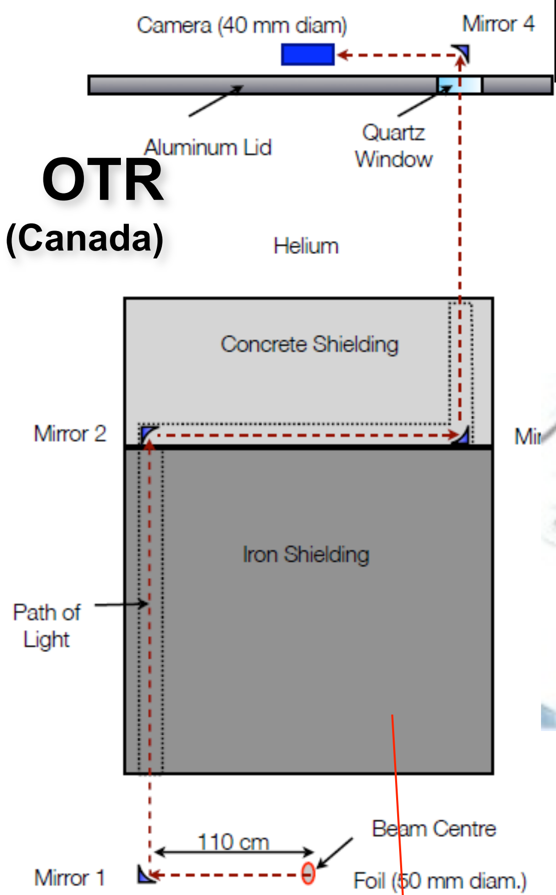


3 corrector mags (from US)
MSS from Saclay
CERN cooperation



Beam Monitors

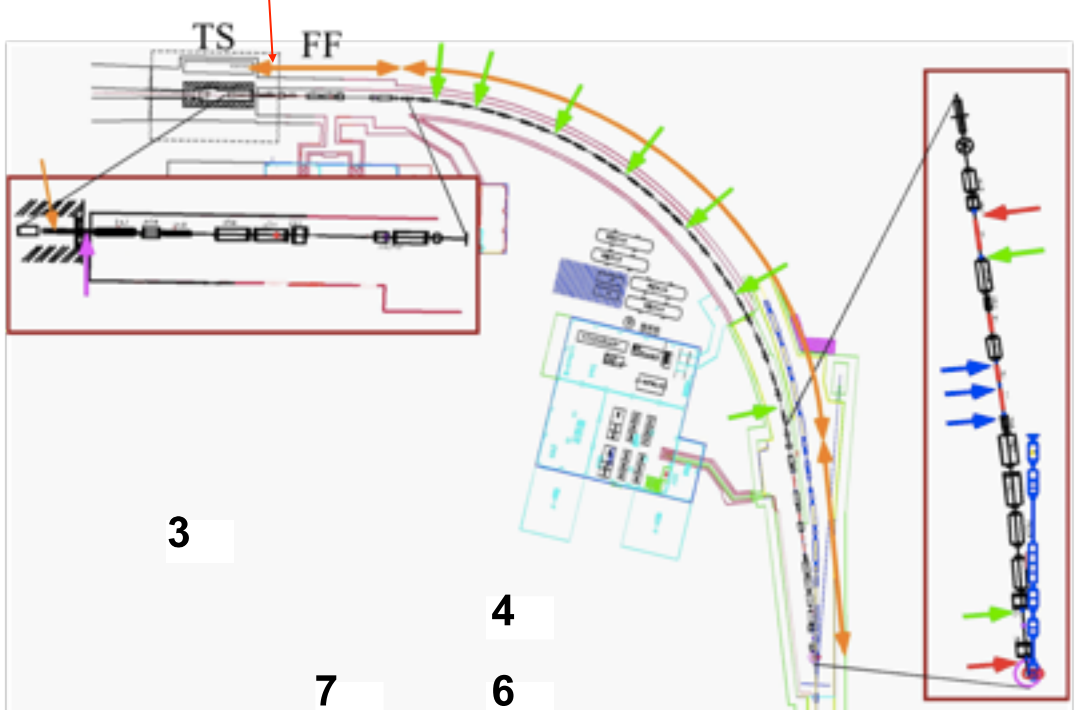
OTR
(Canada)



ESM

CT

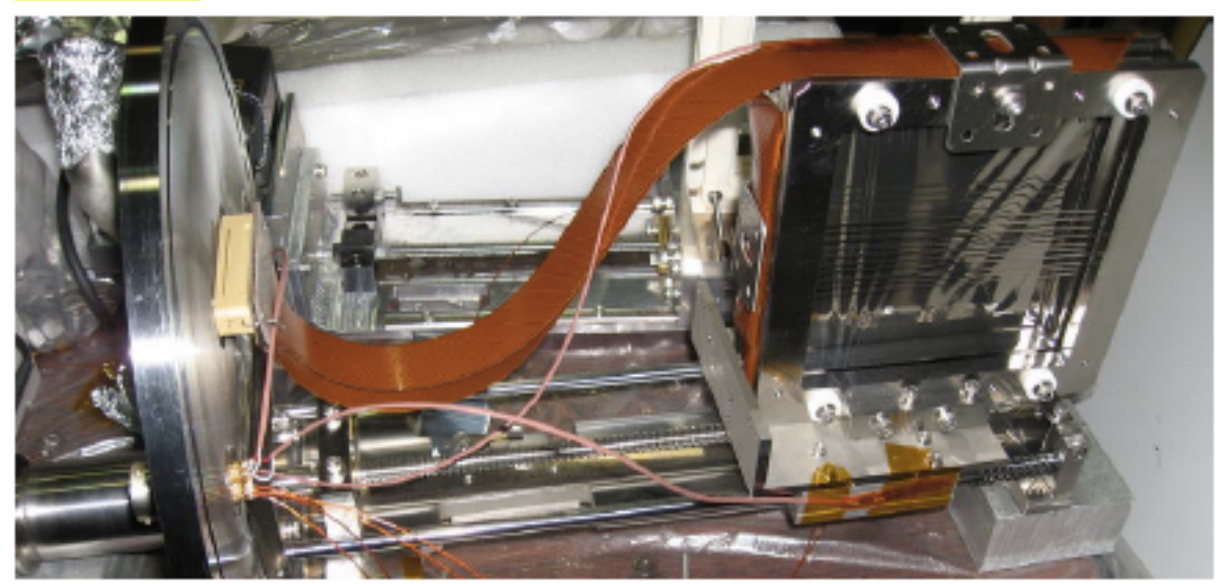
- Position:
  - 21 x Electrostatic monitors
- Profile
  - 19 x Segmented Secondary Emission monitors
- Intensity
  - 5x Current Transformers
- Loss
  - 50 x proportional counters
- Targetting
  - Optical Transition Radiation detector (Canada)
- Elec.: from US/Korea/Jp
- Beam timing: GPS (US)



Beam loss monitor will be placed along the beam line.

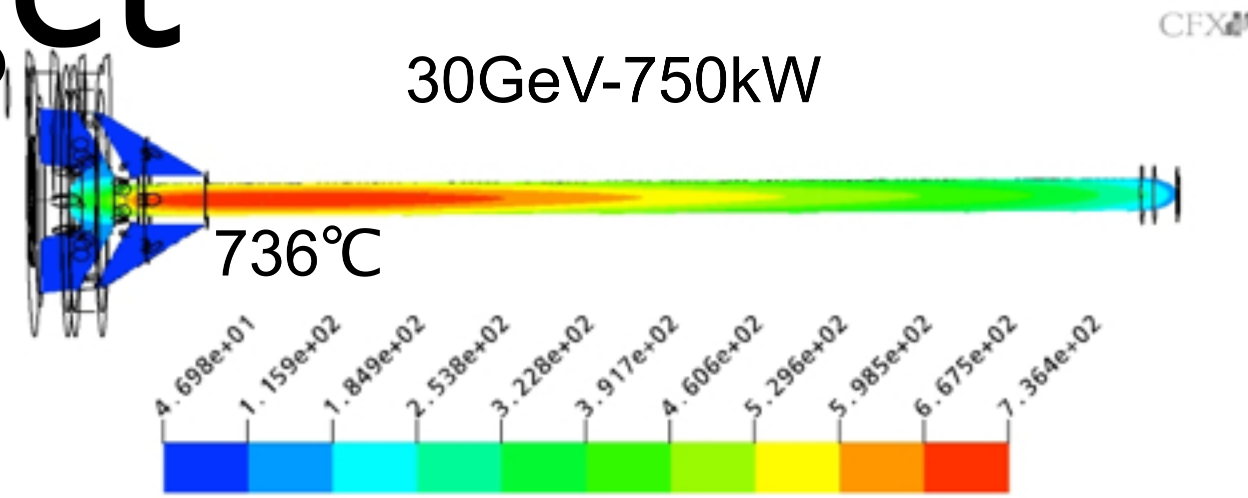
SSEM

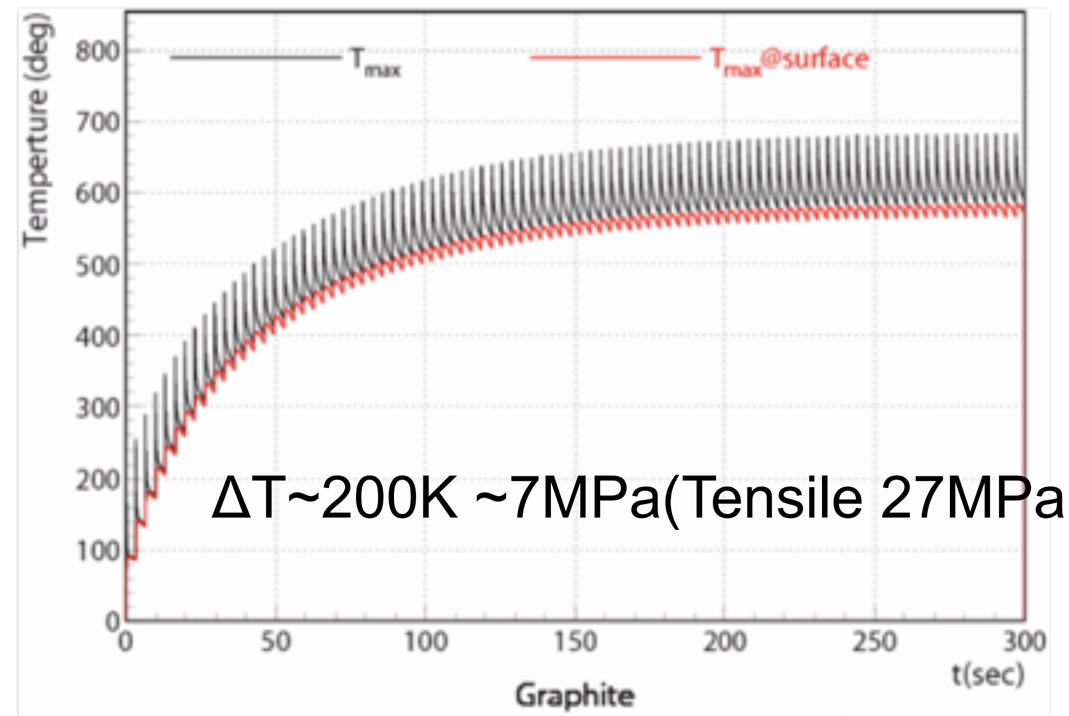
5μm^t Ti foil strips

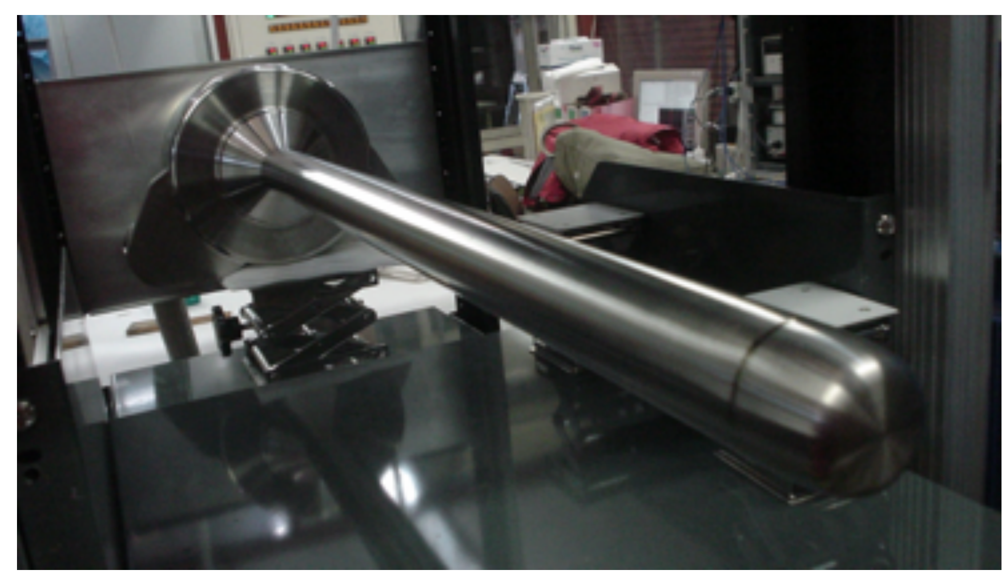


Target

- Isotropic Graphite (IG-430) 1.8g/cm3
- 26mm(D)x900mm(L)
  - 1.9 int len. (70% int.),
- Heat load: 58kJ/spill (~20kW)
- Thermal shock stress (ΔT~200K) ~ 7MPa (< tensile strength 37MPa)
- Forced flow Helium gas cooling in Ti-alloy(Ti-6 A1-4V) container
  - Higher temp = less rad. damage
  - O2 < 100ppm to avoid Oxidization (burn!) → to keep S.F.>2 for 5 yrs
- Remote maintenance
- Design done by KEK/RAL







Electromagnetic horns

- 3 horn system
- 320kA design (now 250kW)
  - 0.7ms for 1st horn
  - 2ms for 2nd/3rd (series)
- Max field: 2.1T
- Al alloy (A6061-T6)
- Heat load ~11kW@1st horn (beam +Joule)
- Water cooled.
- Design max thermal stress: 25MPa (Lorentz+Thermal) (cf. tensile stren. 282MPa)
- Fully remote maintenance

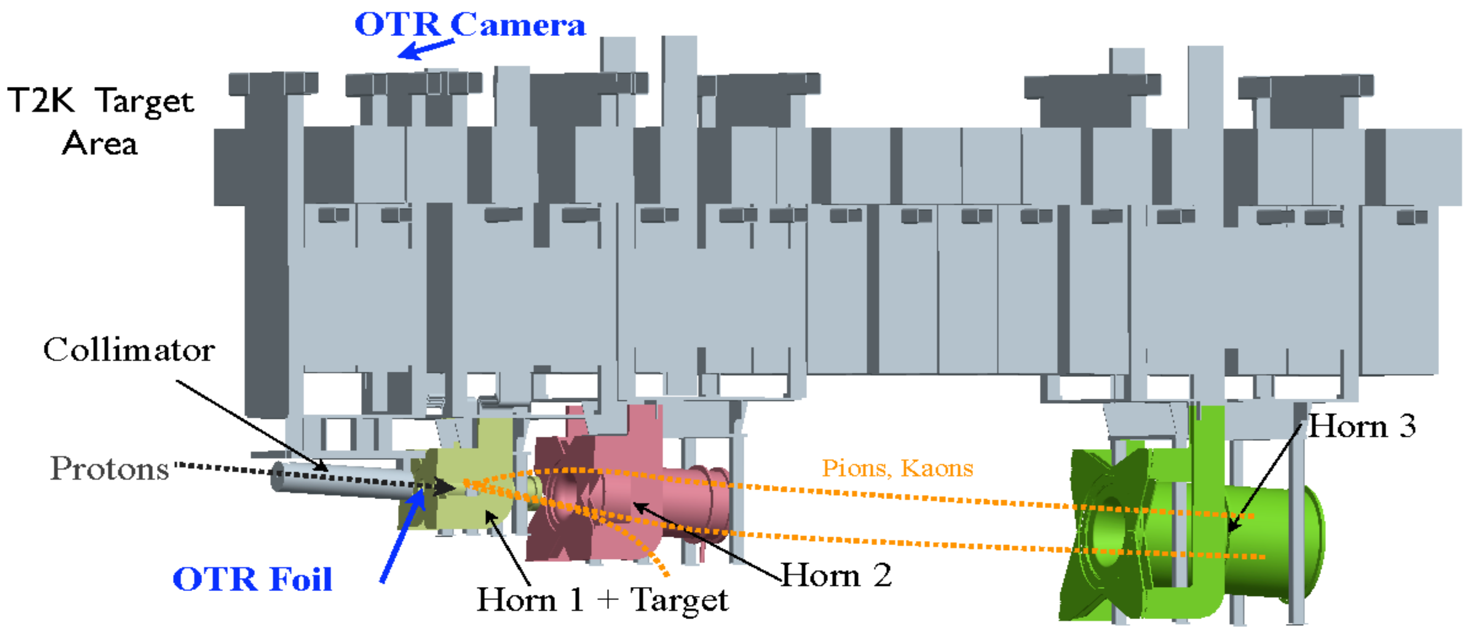
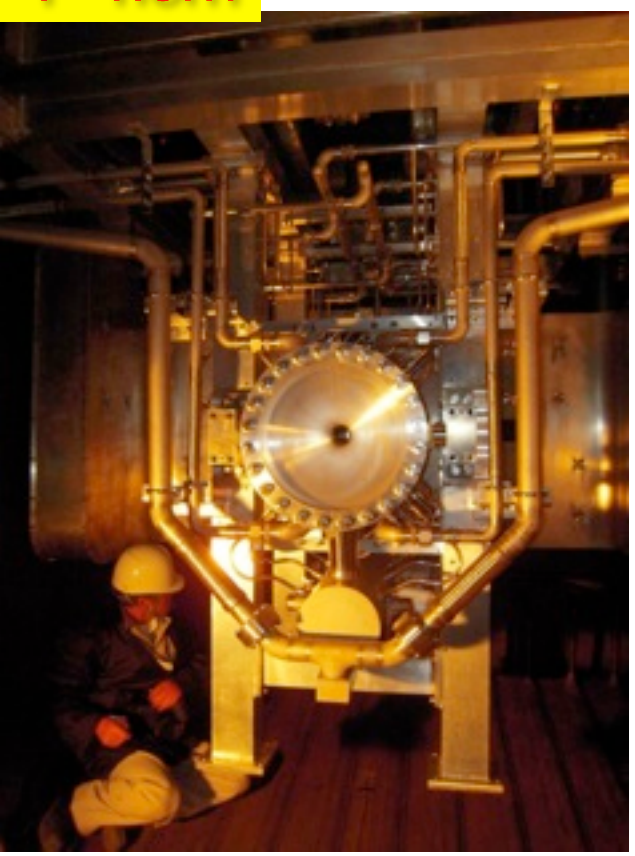


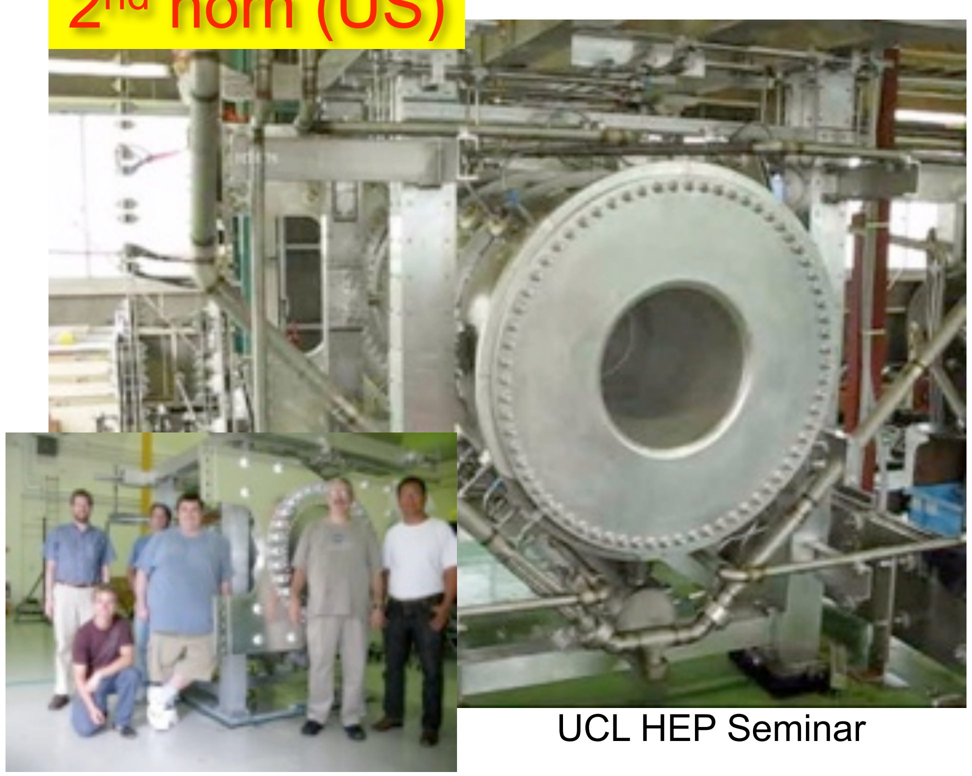
Table 3.8: Heat Load to the horns in unit of kJ/pulse.

	radiaion		Joel's heat	total
	inner-conductor	outer-conductor		
1st horn	23.6	15.6	3.3	42.5(11kW)
2nd horn	6.7	12.3	3.8	22.8(6.3kW)
3rd horn	2.0	4.0	2.5	8.5(2.4kW)

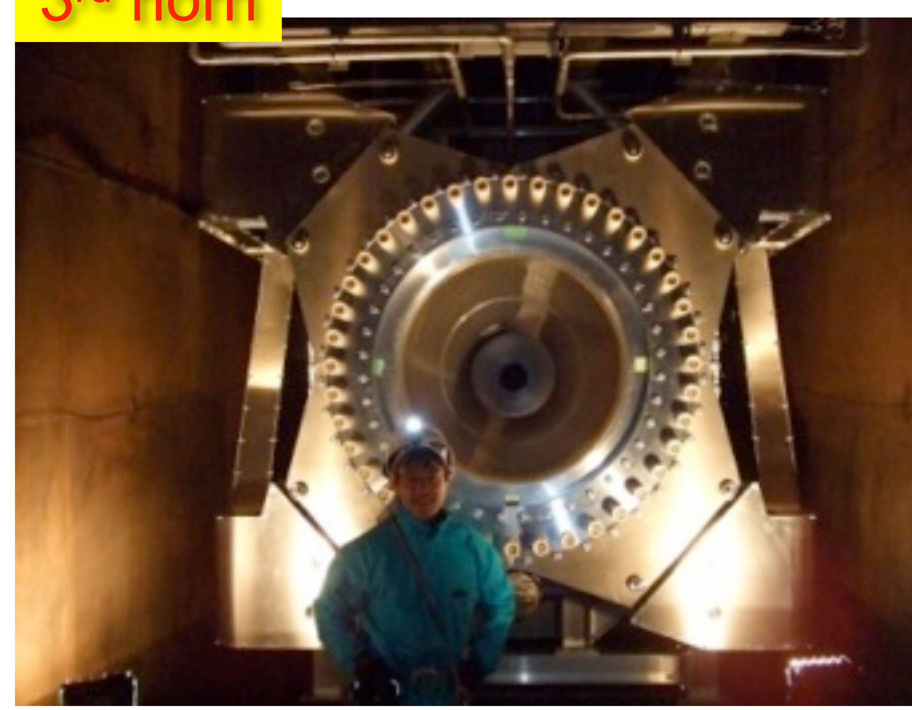
1st horn



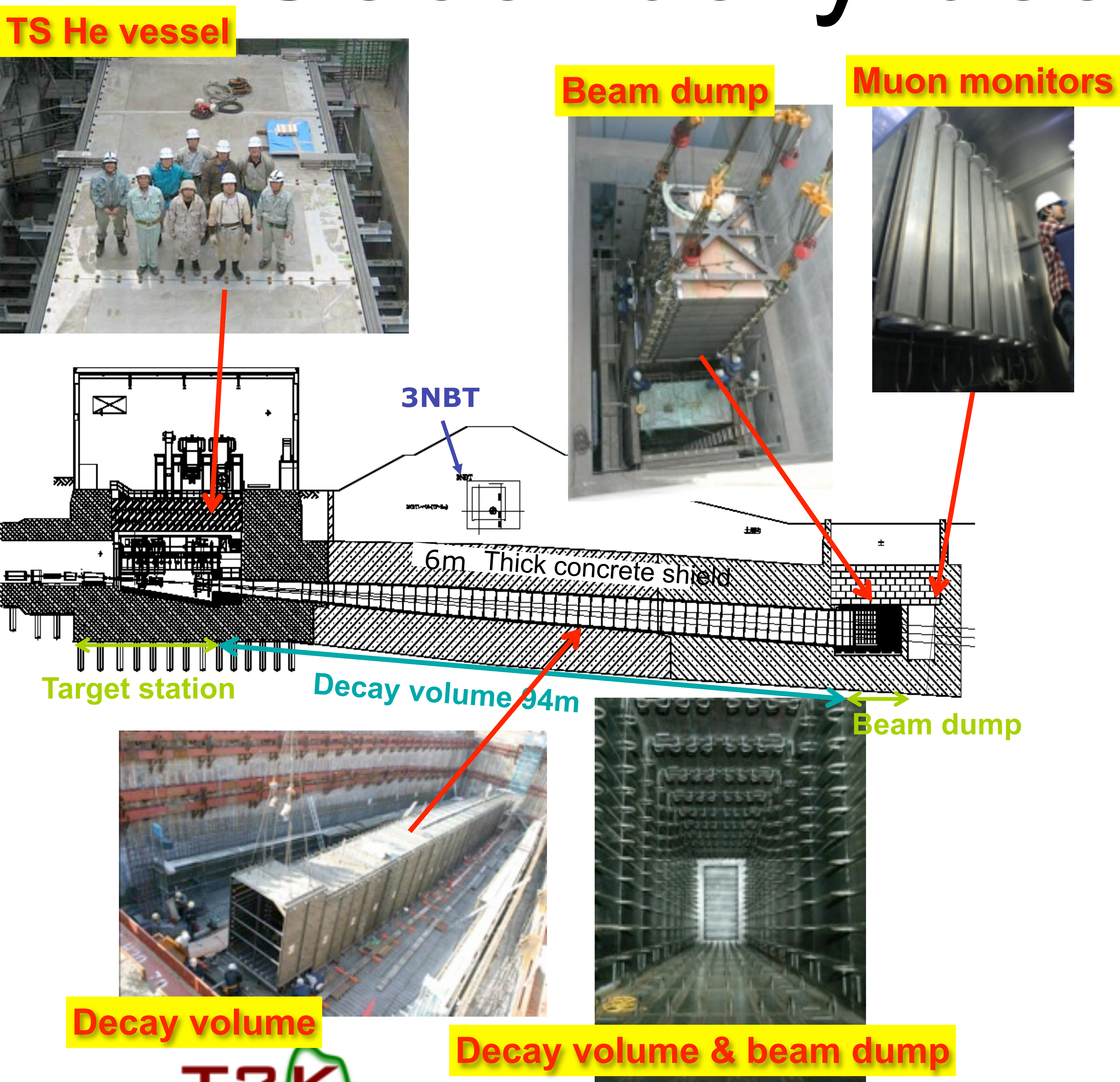
2nd horn (US)



3rd horn

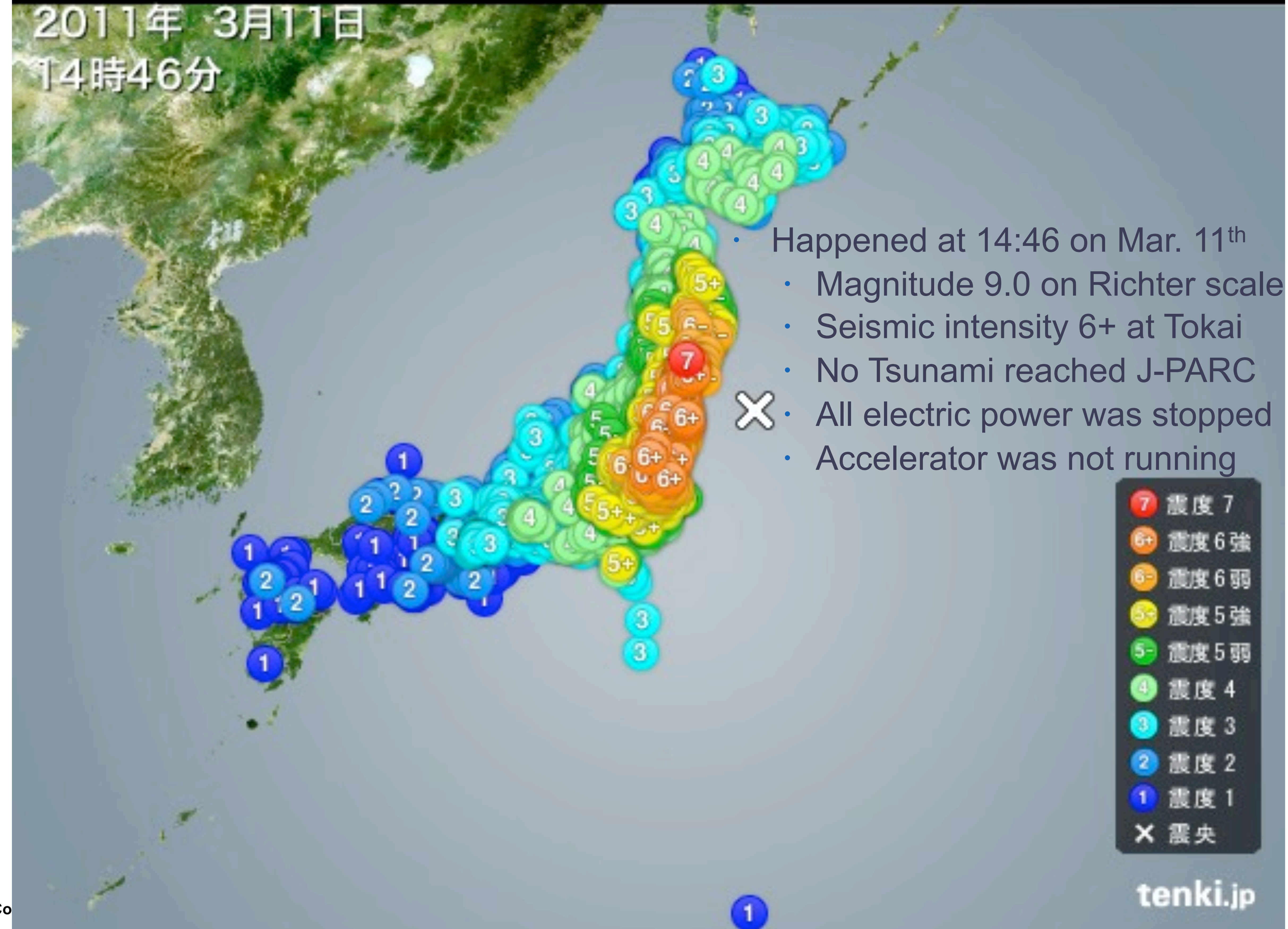


Secondary beamline



- Heat load (@750kW)
  - TS ~300kW
  - DV ~150kW
  - BD ~240kW
- Whole volume filled w/ He gas (~1000m^3)
  - Reduce NOx & ^{3}H
  - Reduce pion abs.
- All inner surfaces water cooled
  - Concrete upto ~100deg
  - Periodically waste with dilution (obey law)
- Beam dump
  - Graphite blocks
  - Water-pipe casted Al block attached to both side
  - Upto 3MW beam
- Muon monitor
  - 5GeV thresh.
  - Ionization chamber & Si
  - 7x7 grid each
  - Monitor dir/int spill-by-spill
  - Emulsion

Earthquake on Mar. 11th



- Happened at 14:46 on Mar. 11th
  - Magnitude 9.0 on Richter scale
  - Seismic intensity 6+ at Tokai
  - No Tsunami reached J-PARC
  - All electric power was stopped
  - Accelerator was not running

Ground level damage

LINAC

RCS (elec yard)

Neutrino (TS)

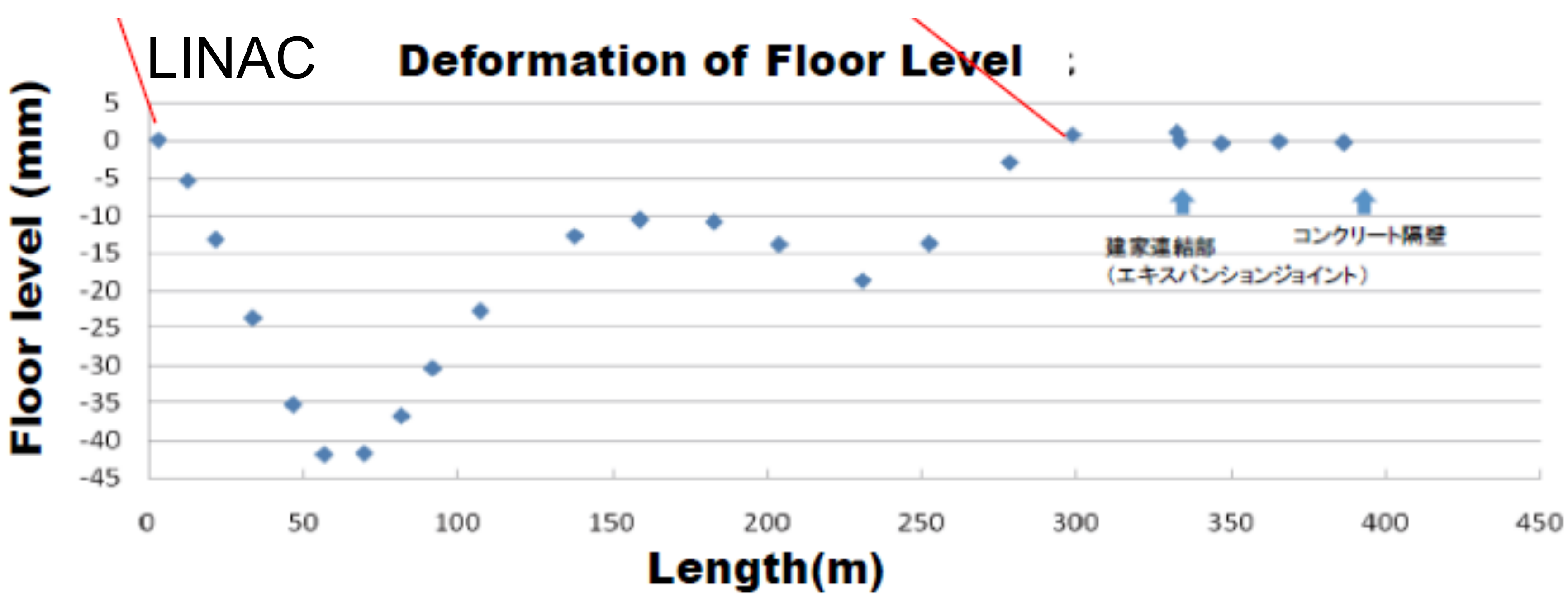
LINAC

Neutrino (Dump)

Neutrino (Dump)

Equipment

- Generally no fatal damage
- LINAC floor, MR tunnel side pit, Near detector bottom floor once submerged under water
    - Fixed in a few weeks
    - No serious damage to components
- Tunnel moved or bent ~ several cm
    - Major alignment of many components needed

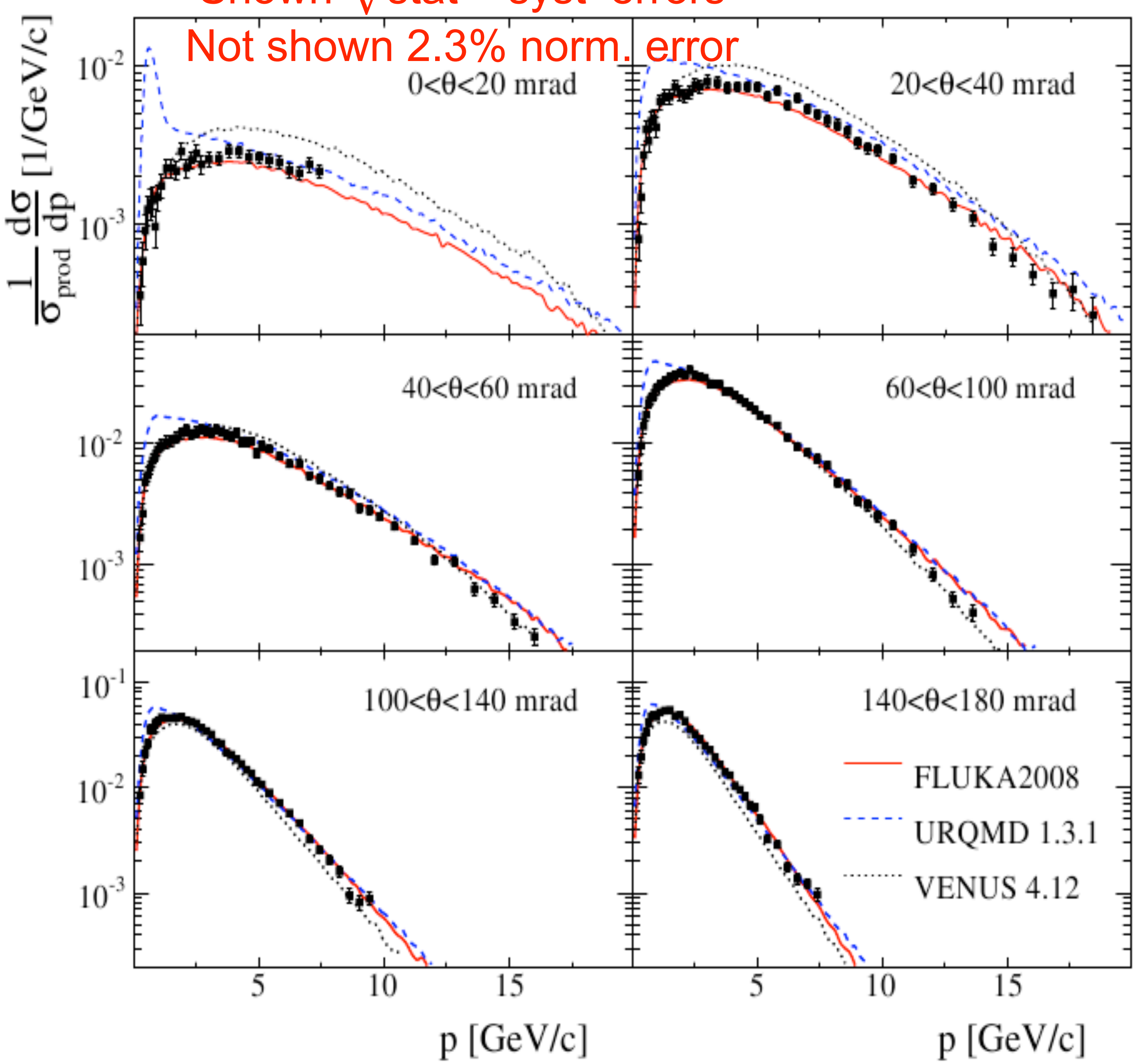


J-PARC Plan

- We will resume J-PARC operation in Dec. 2011
- We will have >2 “cycle”(~month) beam for users within JFY2011 (by the end of Mar,2012)
- LINAC energy recovery from 181MeV to 400MeV originally scheduled in 2012 was delayed to start July 2013
  - User’s need to take longer beam runs after long shutdown by the earthquake
  - Delay of preparation caused by earthquake

NA61 pion data

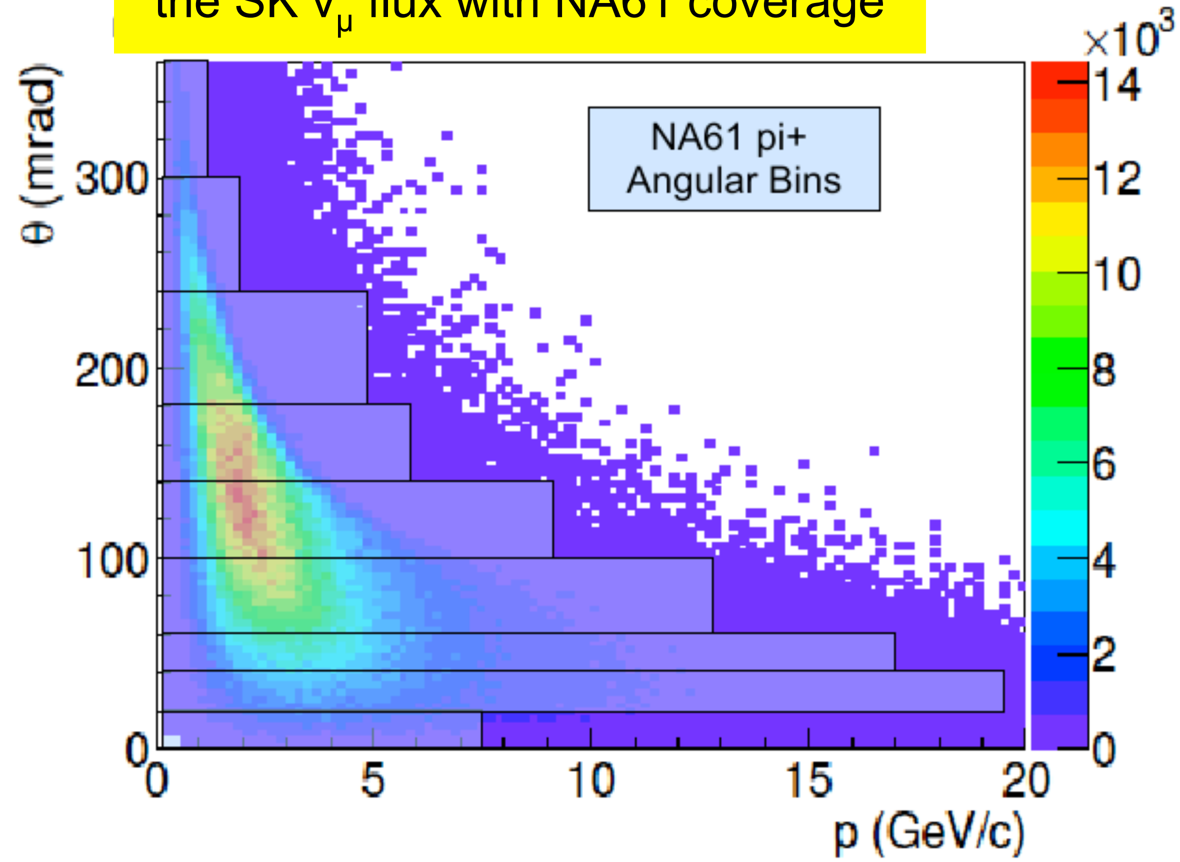
Shown $\sqrt{stat^2 + syst^2}$ errors
Not shown 2.3% norm. error



N. Abgrall et. al., arXiv:1102.0983 [hep-ex]
Accepted by Phys. Rev. C (2011)

NA61 experiment measures particle production from C at T2K beam energy (30 GeV)

Phase-space of pion contributing to the SK ν_μ flux with NA61 coverage



Covers almost all of the relevant pion phase-space for ν_μ production at T2K

Flux uncertainty

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

Error source	$R_{ND}^{\mu,\,MC}$	N_{SK}^{MC}	$\frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Nucleon production	5.9%	6.6%	1.4%
Production x-section	7.7%	6.9%	0.7%
Proton beam position/profile	2.2%	0.0%	2.2%
Beam direction measurement	2.7%	2.0%	0.7%
Target alignment	0.3%	0.0%	0.2%
Horn alignment	0.6%	0.5%	0.1%
Horn abs. current	0.5%	0.7%	0.3%
Total	15.4%	16.1%	8.5%

Hadron production & interaction

The uncertainty on N^{exp}_{SK} due to the beam flux uncertainty is **8.5%**

Error cancellation works for some beam uncertainties

ν int. cross section uncertainty on N^{exp}_{SK} for $\sin^2 2\theta_{13}=0$

error source
(1) ν flux
(2) ν cross section
(3) Near detector
(4) Far detector
(5) Near det. statistics

Error source	syst. error on N_{SK}^{exp}
CC QE shape	3.1%
CC 1π	2.2%
CC Coherentπ	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherentπ	2.3%
NC Other	2.3%
$\sigma(\nu_e)$	3.4%
FSI	10.1%
Total	14.0%

← *Uncertainty in pion's final state interaction is dominant*

The uncertainty on N^{exp}_{SK} due to the ν x-section uncertainty is **14%** ($\sin^2 2\theta_{13}=0$)

Summary of Far detector systematic uncertainty

Error source	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	**7.6%**	**15%**

Evaluated by atmospheric ν_e enriched data

→ The total uncertainty on $N^{MC}{}_{SK\ tot.}$ is **14.7 %** ($\sin^2 2\theta_{13}=0$)
(uncertainty on the background + solar term oscillated ν_e)

Future milestones

- Highest priority is to firmly establish non-zero θ13 and its precise determination as quickly as possible

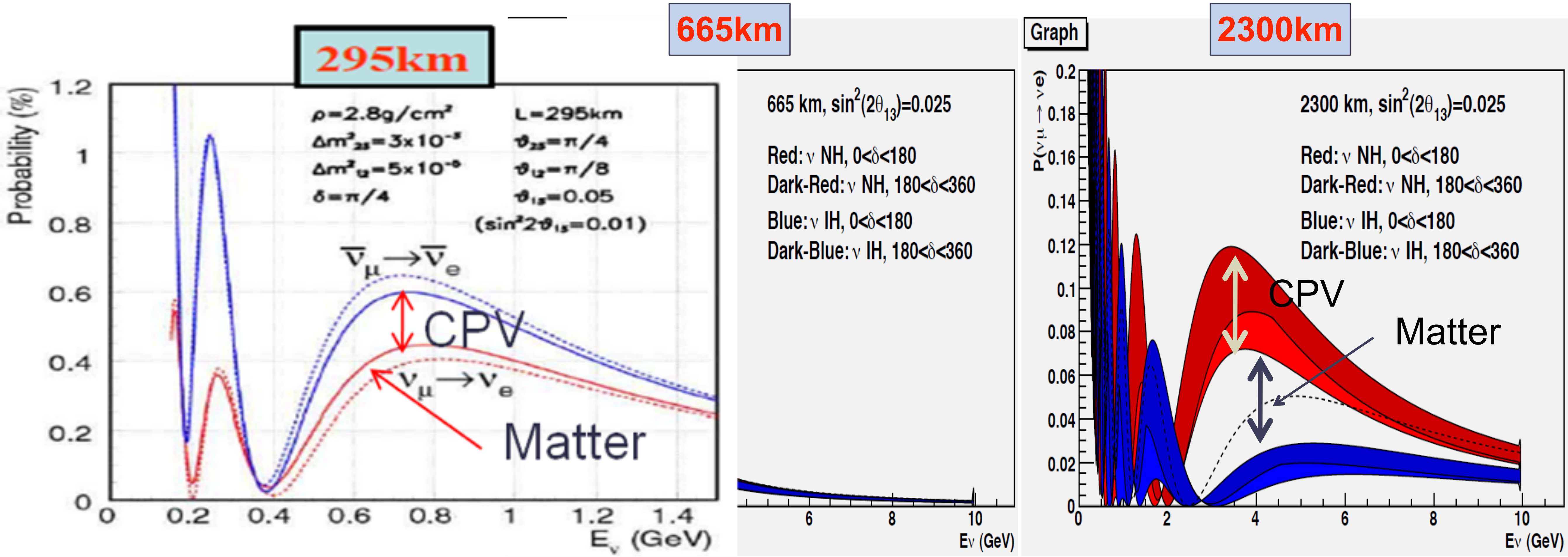
- We have 70 [kWx10^7s] = 1.43e20 pot
- We aim to have:
  - By Summer 2013: ~0.5 [MWx10^7s] ~ 1e21pot
    - Conclude non-zero θ_{13}
    - >5sigma for present T2K central value
  - Within a few yrs : ~ 1 [MWx10^7s] ~ 2e21pot
    - > 3sigma for $\sin^2 2\theta_{13}$ > 0.04
  - Approved goal : 3.8 [MWx10^7s] ~ 8e21pot
    - > 3sigma for $\sin^2 2\theta_{13}$ >~ 0.02

Implications for Future

- If $\sin^2 2\theta_{13}$> ~0.01
  - Conventional Multi-MW super beam long baseline experiment will be really promising to explore CPV in lepton sector
  - We need to put even more effort to formulate the future project in this direction as soon as possible
- IF not
  - Need “ideal” beam such as Neutrino Factory or beta beam to probe CPV

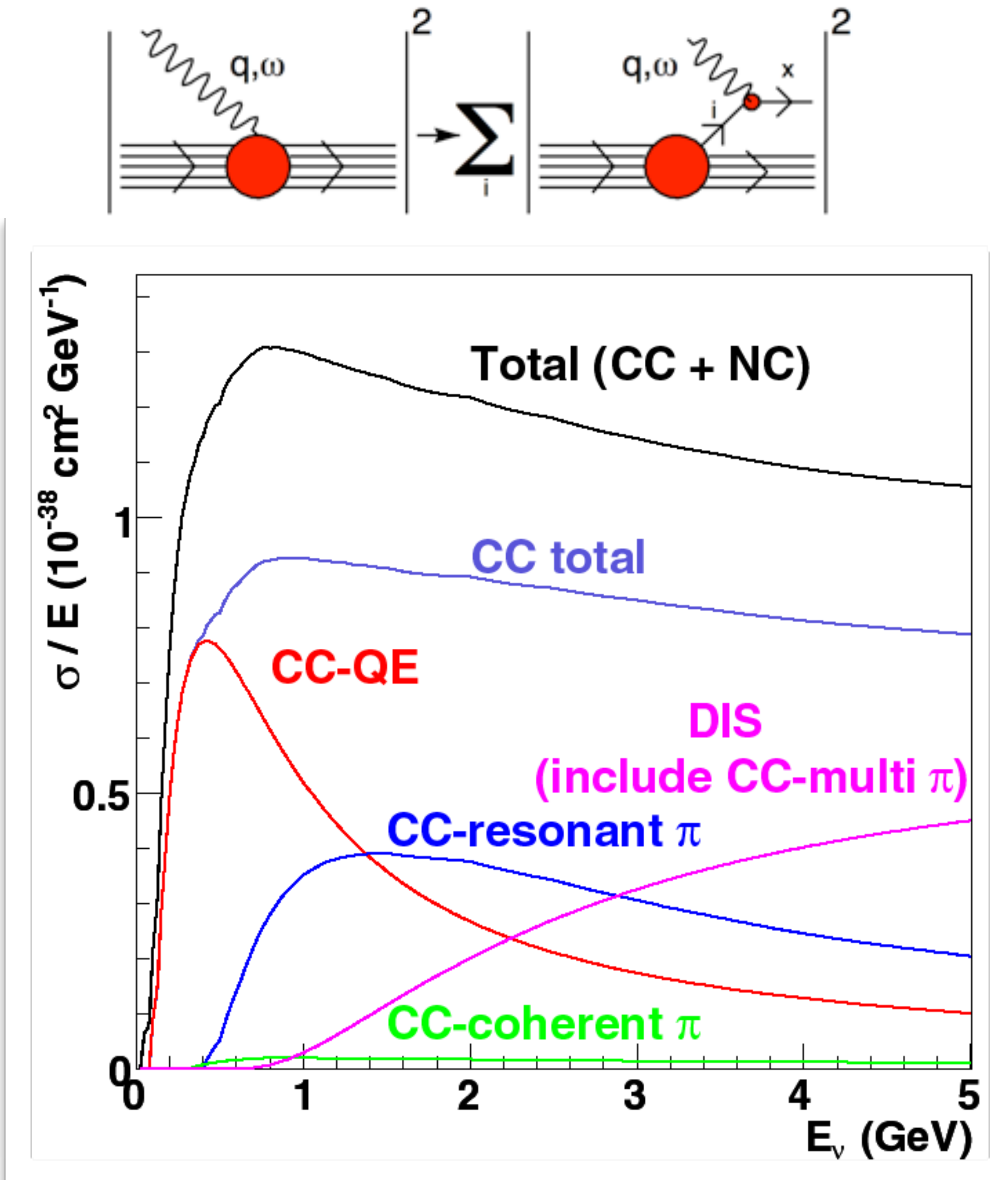
- Therefore, confirming the indication of large θ_{13} by T2K is a very important and urgent issue

How to measure CPV & sign(Δm_{23})



- **νe appearance energy spectrum shape**
  - Peak position and height for 1st, 2nd maximum and minimum
  - Measure both sinδ & cosδ terms ➔ can discriminate 0deg vs 180deg
- **Difference between νe and $\bar{\nu}$e behavior**
  - Sensitive to any mechanism to make asymmetry (No assumption)
  - Basically measure sinδ term
- **Distance:**
  - Larger L Matter effect large ➔ Sensitive to sign(Δm_{23}) too
  - Smaller L (lower E): Purer CPV measurement

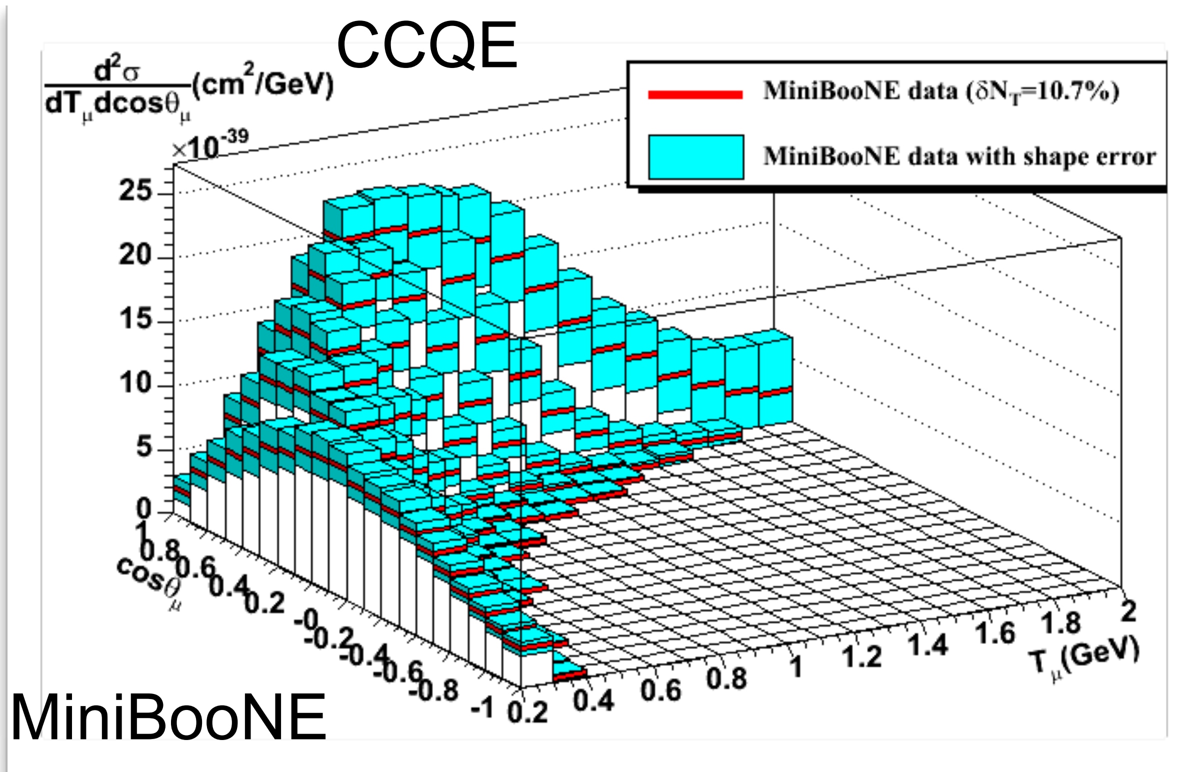
Neutrino cross section prediction

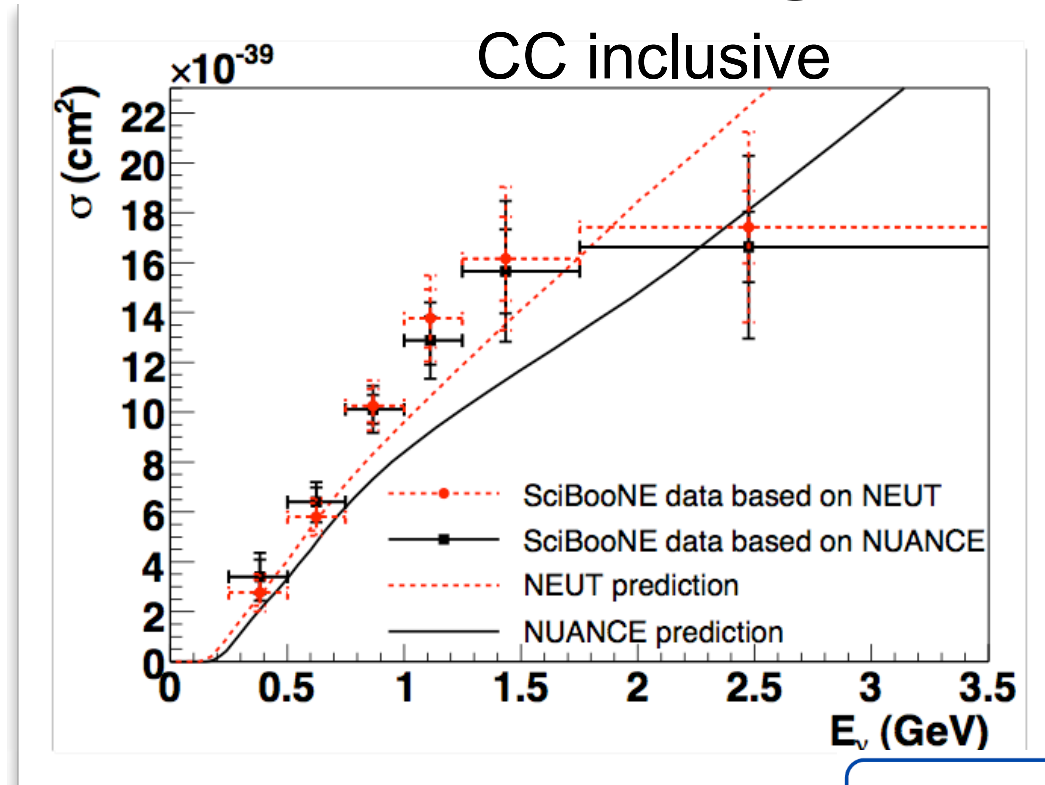


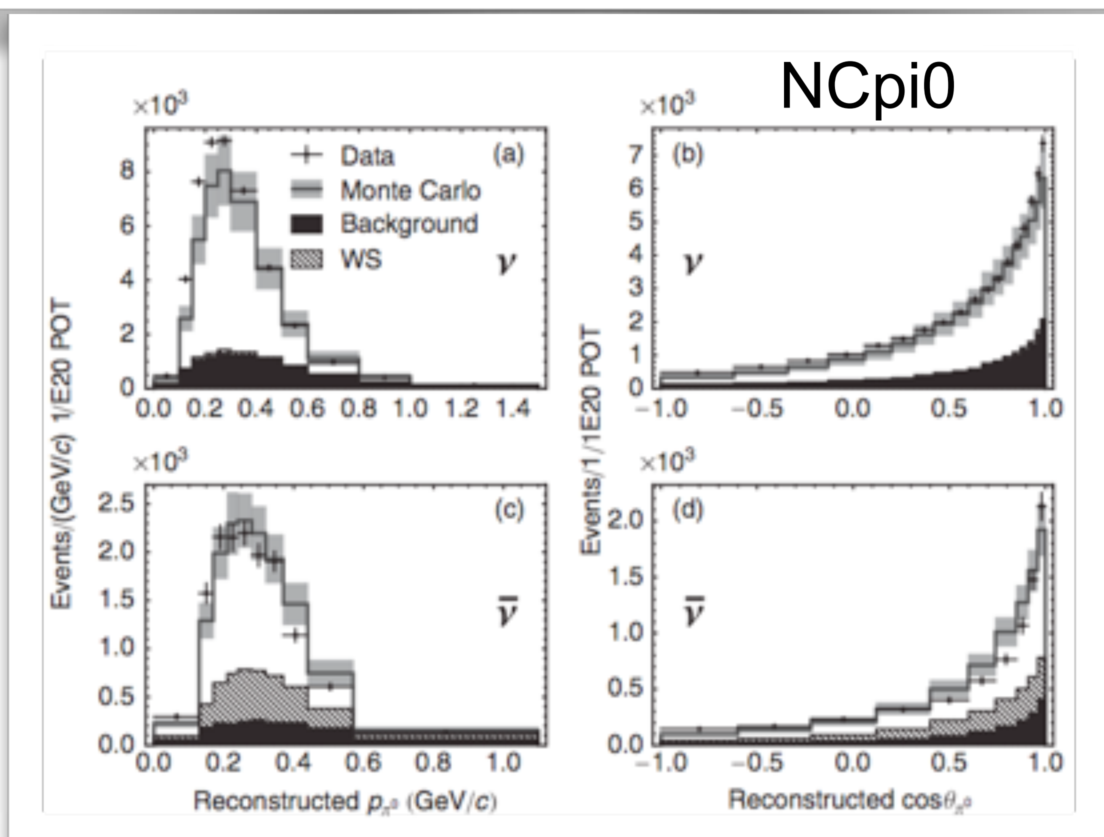
Use NEUT generator
(cross-check with GENIE)

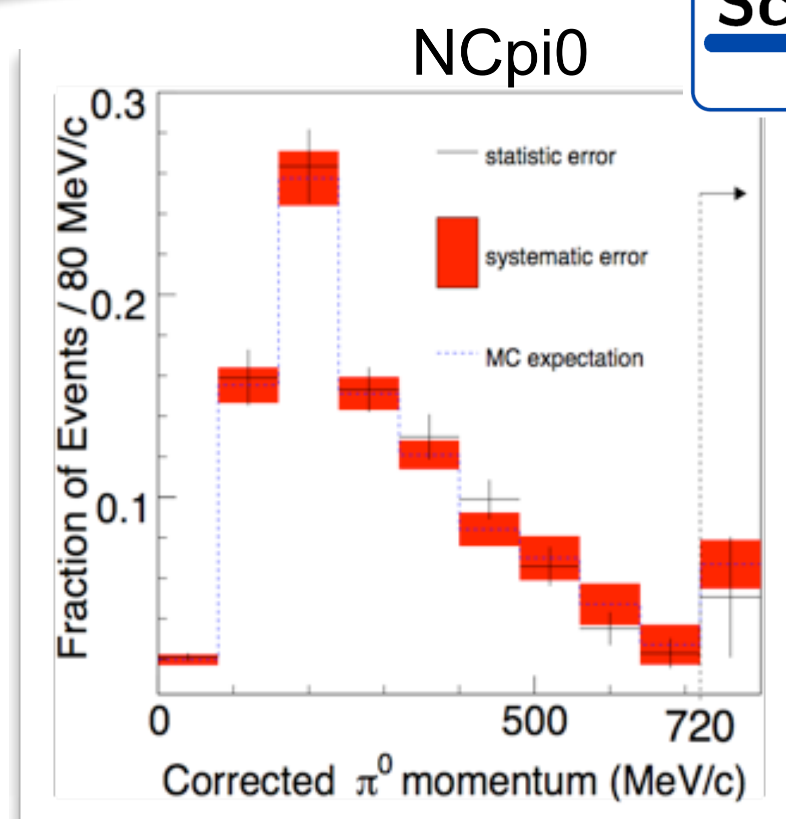
- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2 $(GeV/c)^2$
  - P_F=217 MeV/c, E_B=27 MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 $(GeV/c)^2$
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 $(GeV/c)^2$
- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

Cross section tuning









SciBooNE

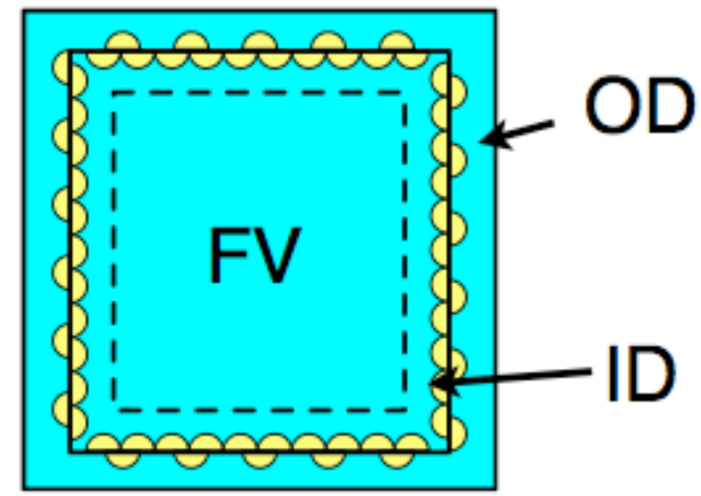
SK ν_e selection

Optimised for initial running conditions

The selection criteria were fixed before data taking started to avoid bias

<ins>7 selection cuts</ins>

1. T2K beam timing & Fully contained (FC)
   (synchronized with the beam timing,
   no activities in the OD)

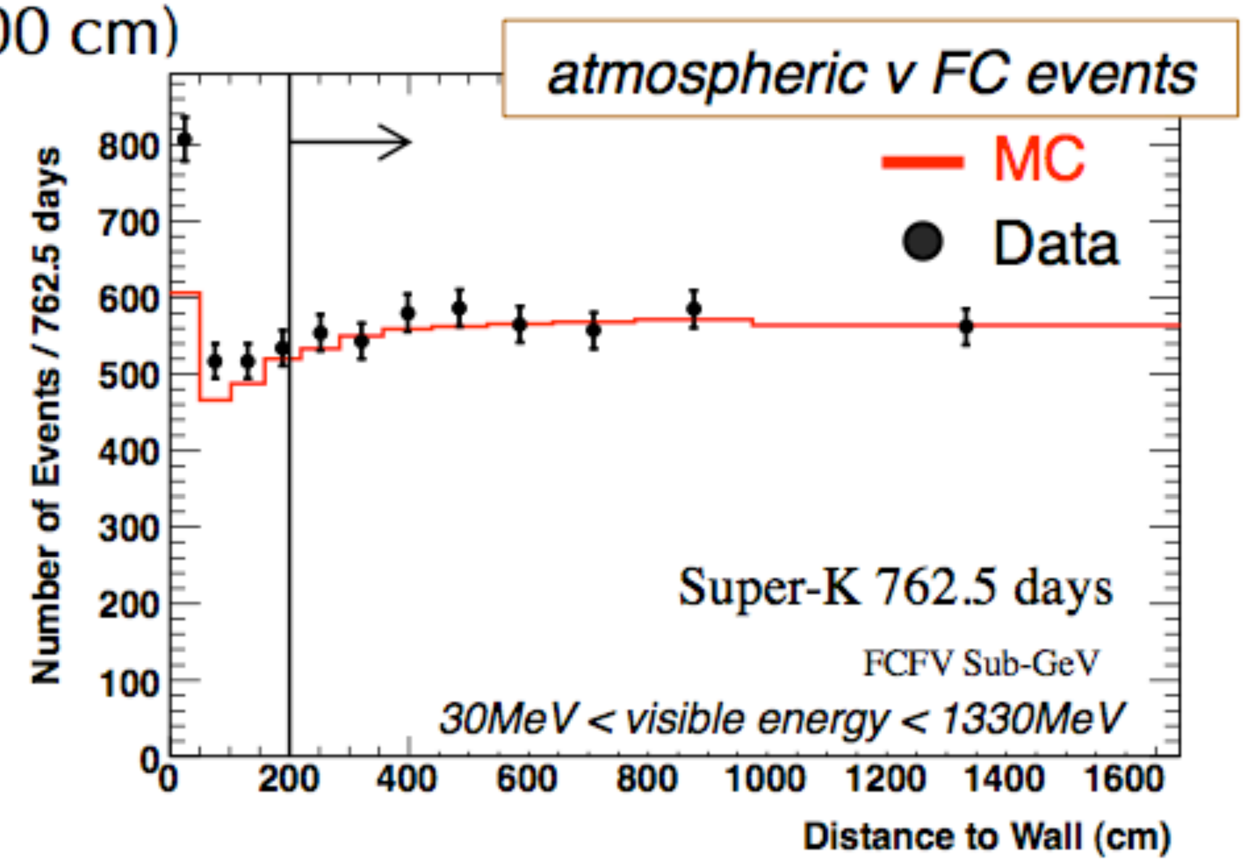


2. In fiducial volume (FV)
   (distance btw recon. vertex and wall > 200 cm)

* Events too close to the wall are difficult to accurately reconstruct vertex

* Reject events which are originated outside the ID

* Define FV 22.5kton



3. Single electron
   (# of ring is one & e-like)

Intrinsic ν_e BG

- **The number of beam ν_e background events at far detector is predicted using the ν beam simulation based on NA61 measurements (pion) and FLUKA (kaon)**
  - ND measurements (μ momentum and event rate) are consistent with MC based on the ν beam simulation

$$N^{exp}_{SK\ beam\ \nu_e\ bkg.} = R^{\mu,\ Data}_{ND} \times \frac{N^{MC}_{SK\ beam\ \nu_e\ bkg.}}{R^{\mu,\ MC}_{ND}}$$

$$\frac{N^{MC}_{SK\ beam\ \nu_e\ bkg.}}{R^{\mu,\ MC}_{ND}} = \frac{\int \Phi^{SK}_{\nu_e}(E_\nu) \cdot P_{\nu_e \to \nu_e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu} \cdot \frac{M^{SK}}{M^{ND}} \cdot \mathrm{POT}^{SK}$$

ν_e event expectation at SK

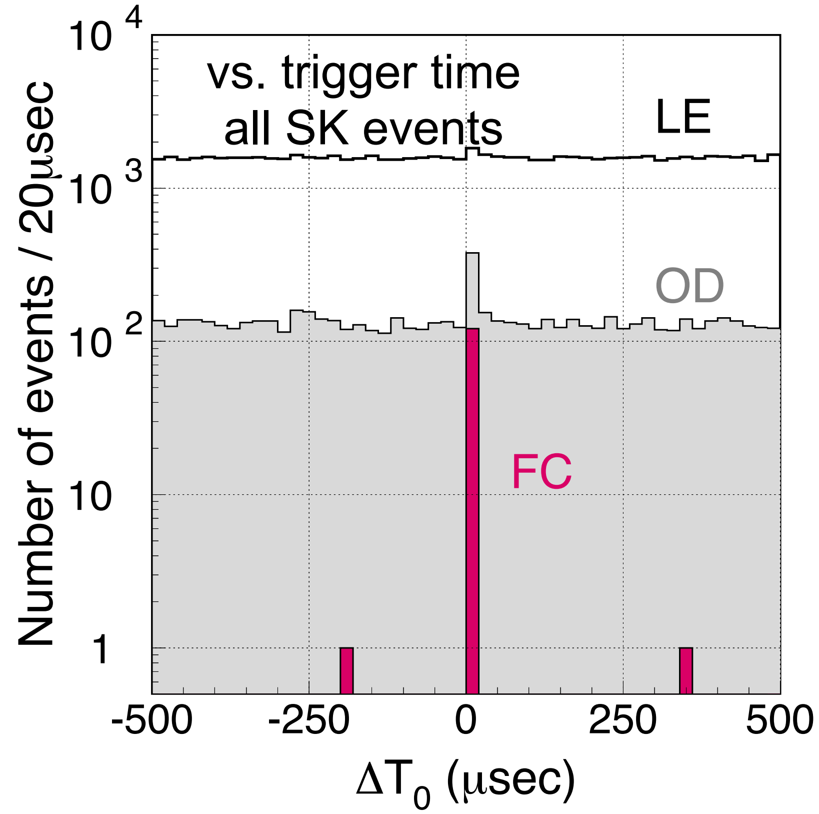
N^{exp}_{SK} = 1.5 events
1.43e20 POT

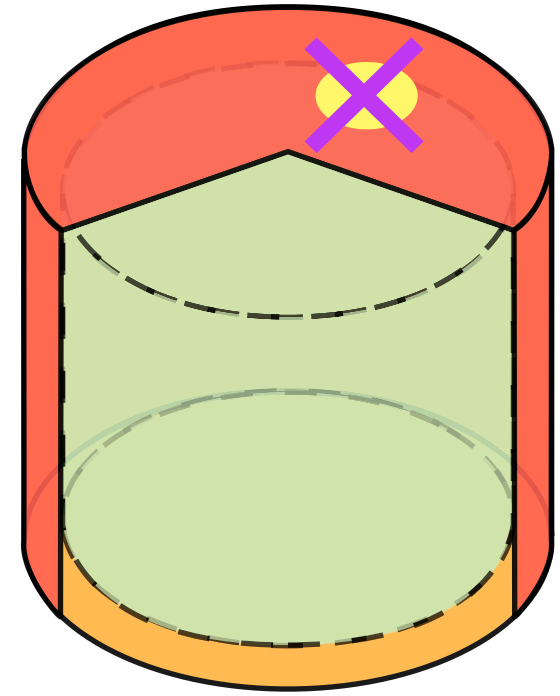
	Beam nue	numu NC	solar osc signal	Total
N^{exp}_{SK}	0.8	0.6	0.1	1.5

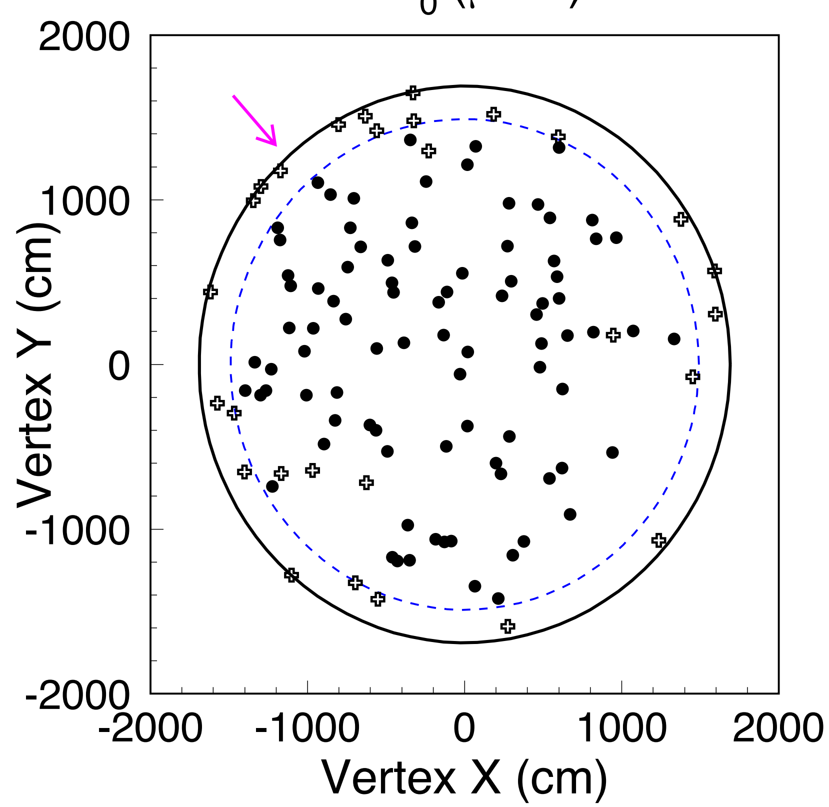
FC FV Selection

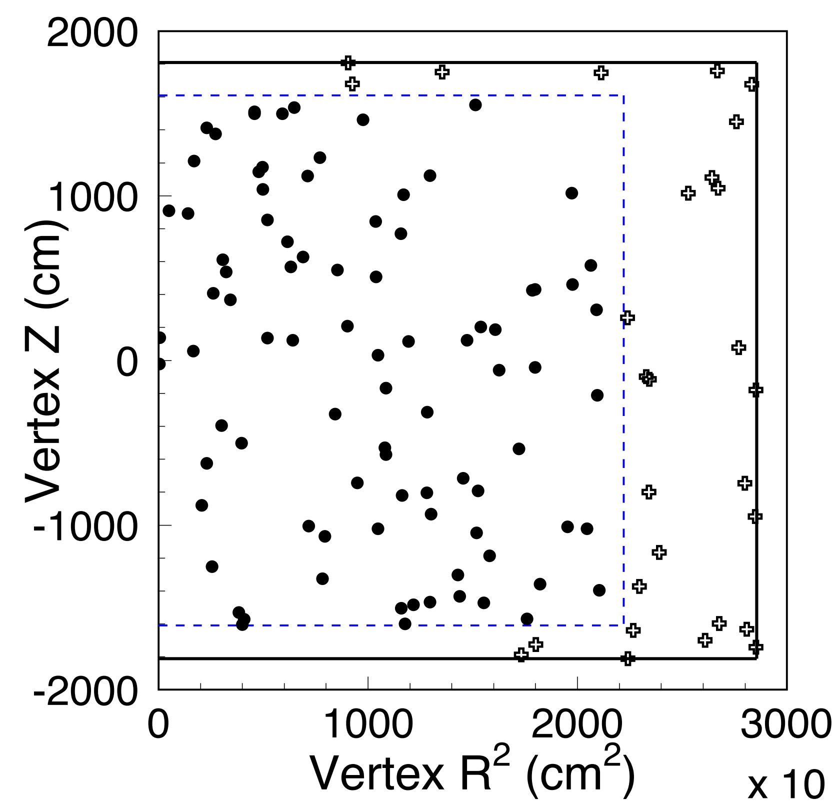
- Fully Contained
- Fiducial Volume
- Single Ring
- μ-like
- p_{μ} > 200 MeV
- N_{decay} < 2

Data: 121 Events









Number of T2K events at far detector

Number of events in on-timing windows (-2 ~ +10 μsec)

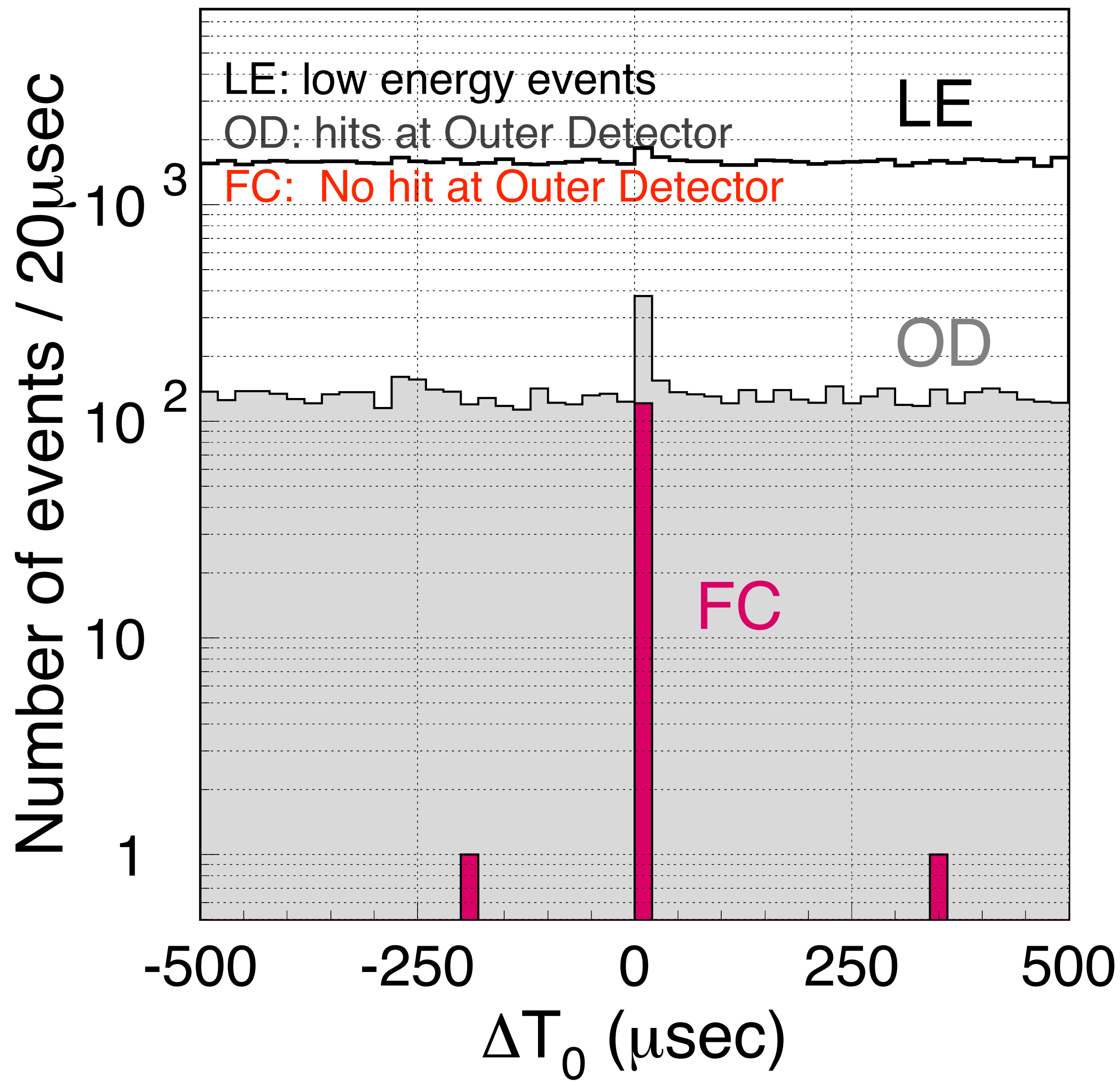
Class / Beam run	RUN-1	RUN-2	Total	non-beam background
POT (x 10^{19})	3.23	11.08	**14.31**	
Fully-Contained (FC)	33	88	**121**	0.023

The accidental contamination from atmospheric ν background is estimated using the sideband events to be 0.023

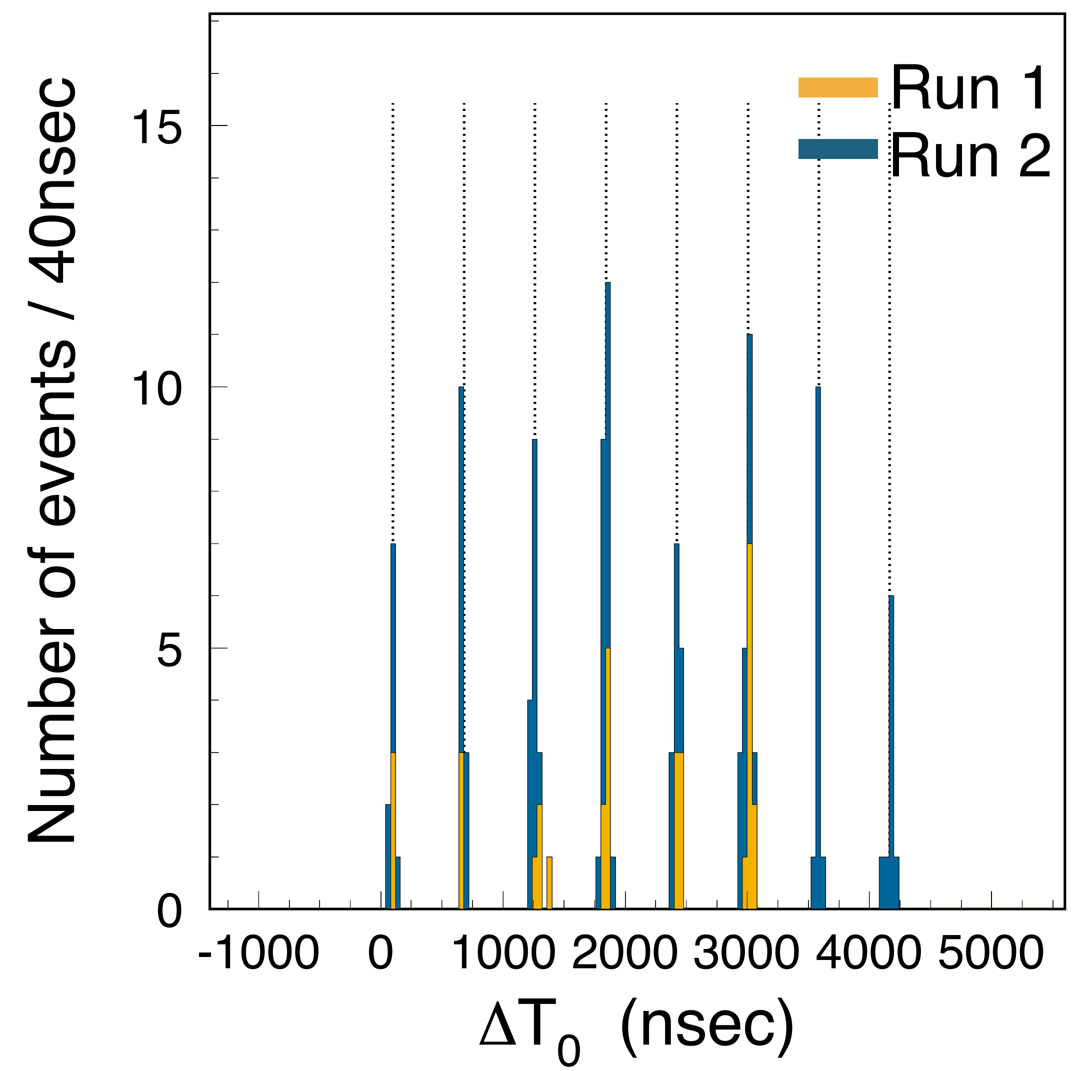
SK events in beam timing

- Events in the T2K beam timing synchronized by GPS

relative event timing to the spill timing

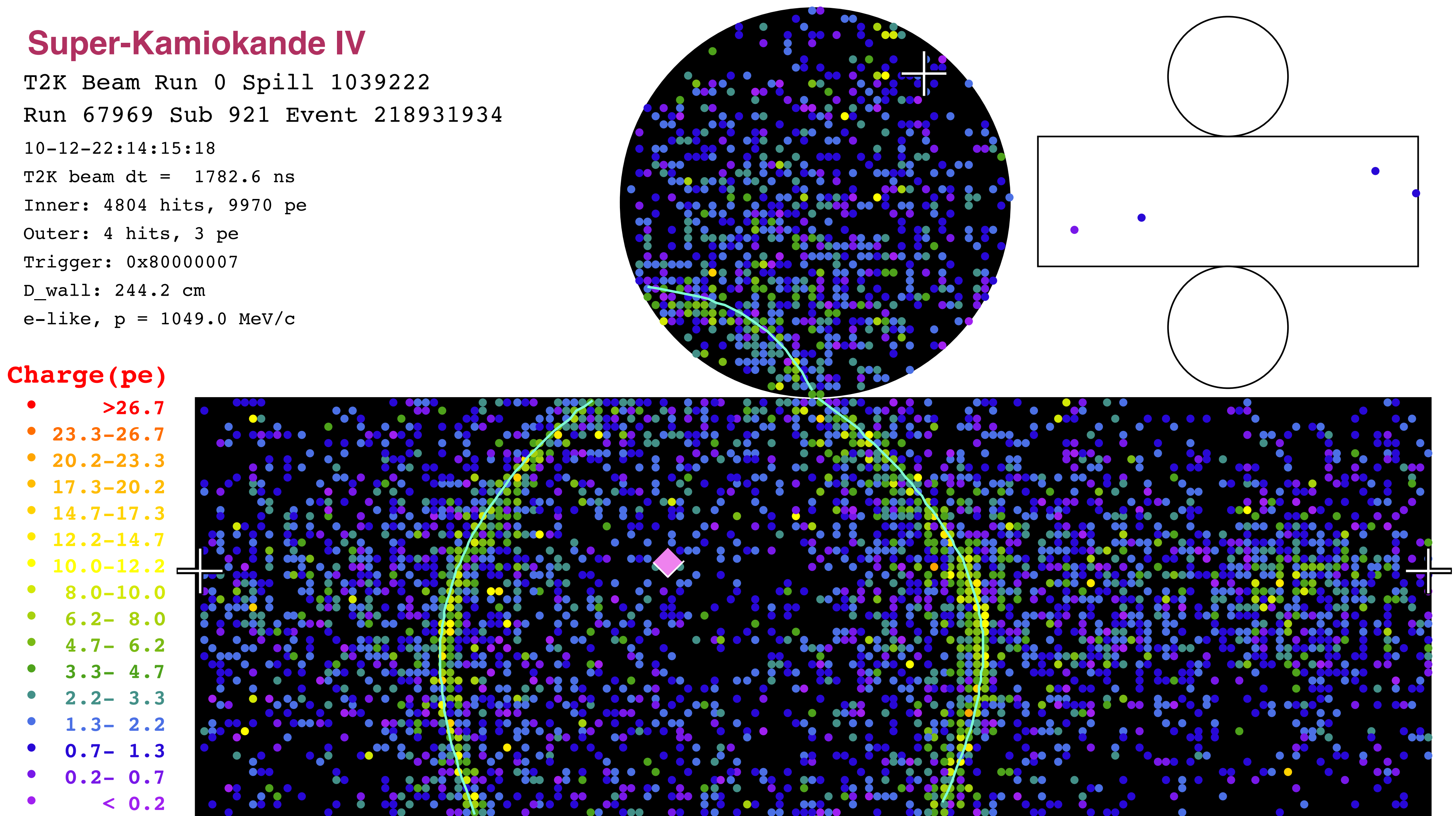


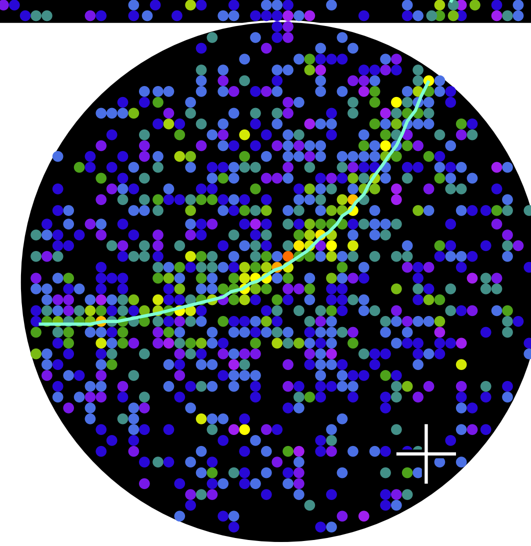
Clear beam structure !



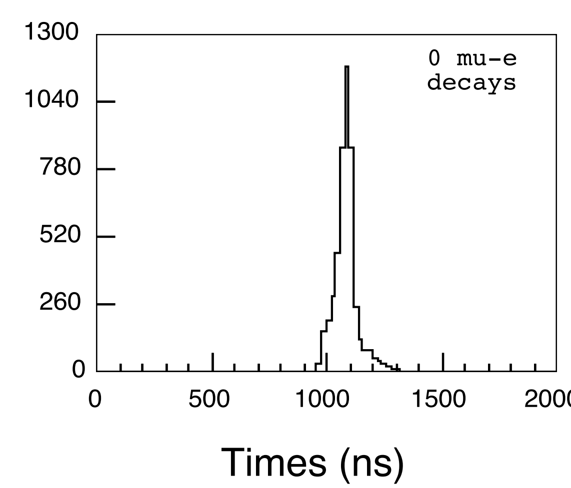
$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

Typical ν_e candidate event

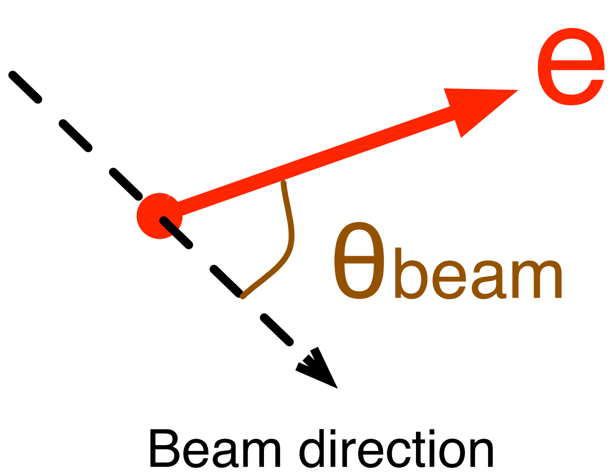


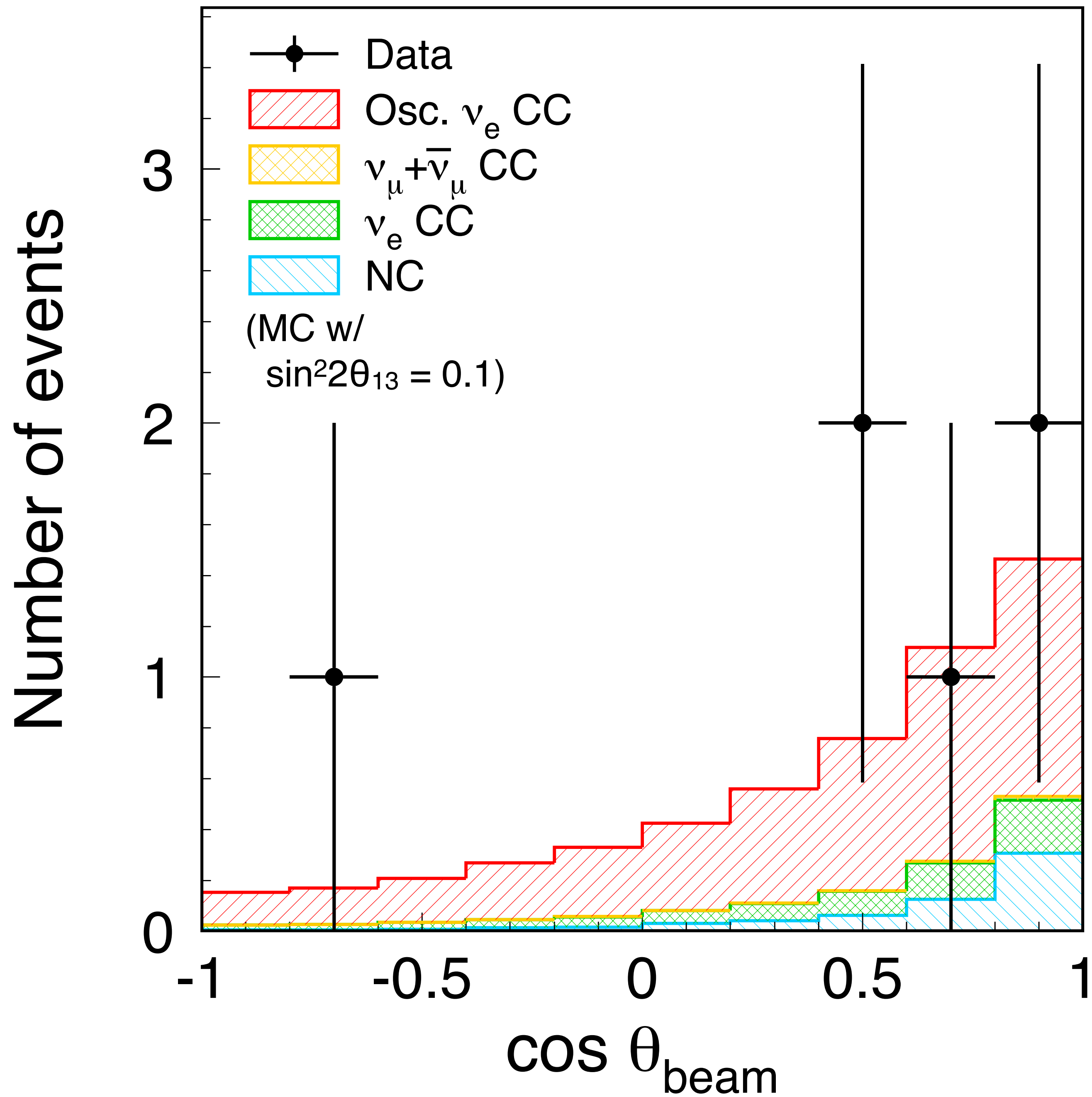


visible energy : 1049 MeV
# of decay-e : 0
2γ Inv. mass : 0.04 MeV/c^2
recon. energy : 1120.9 MeV

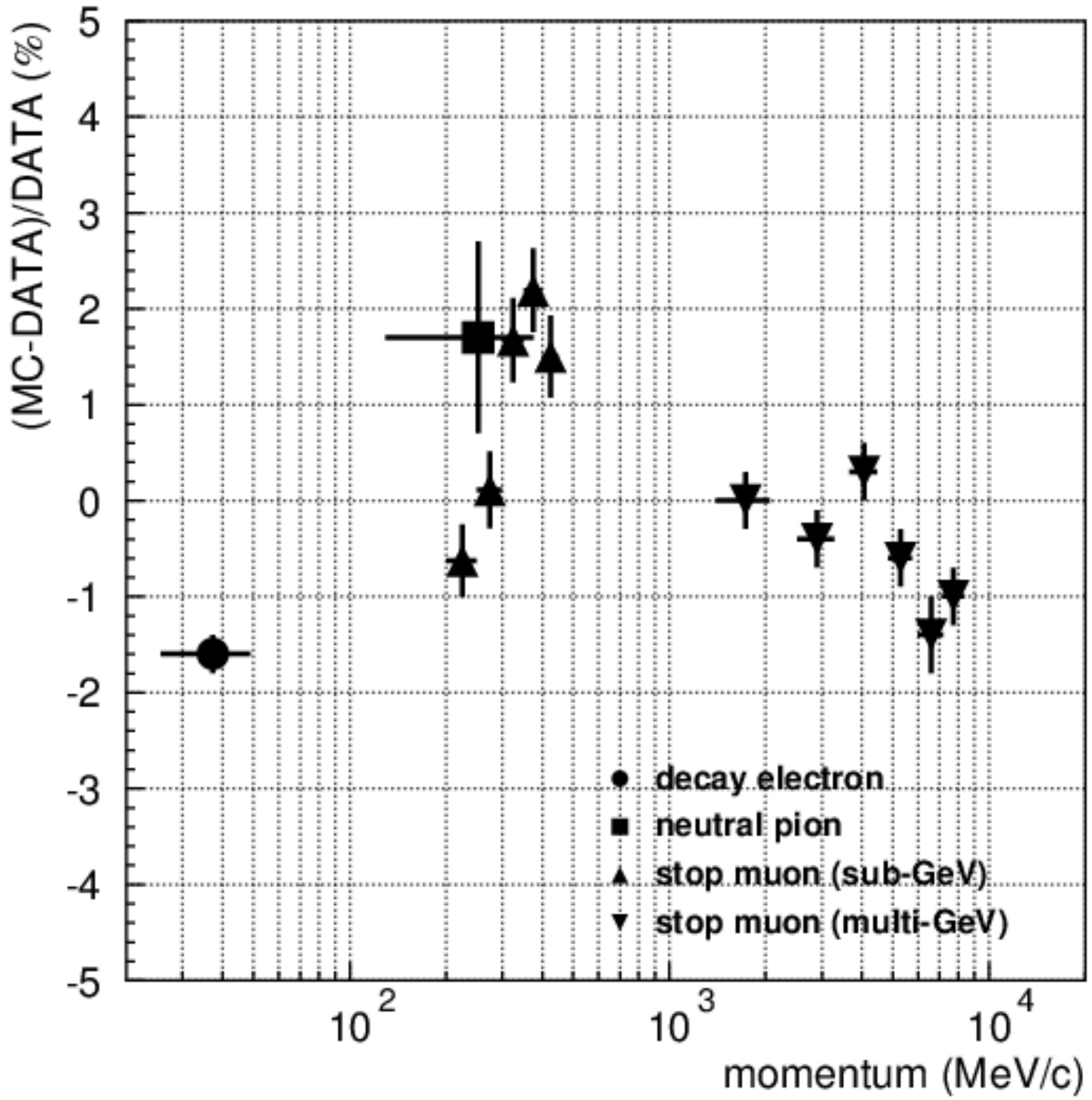


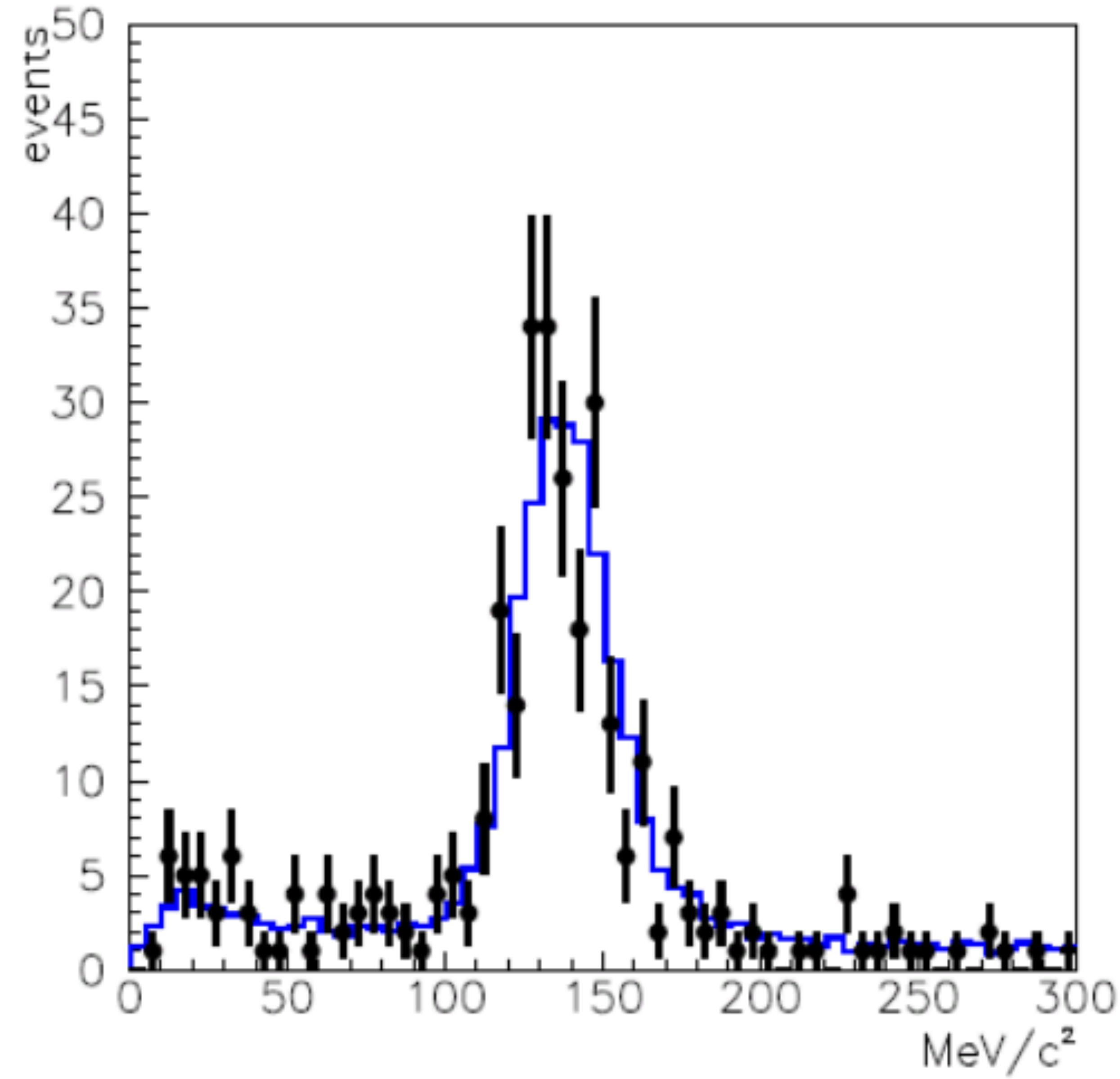
Further checks of data





SK Energy Scale Uncertainty

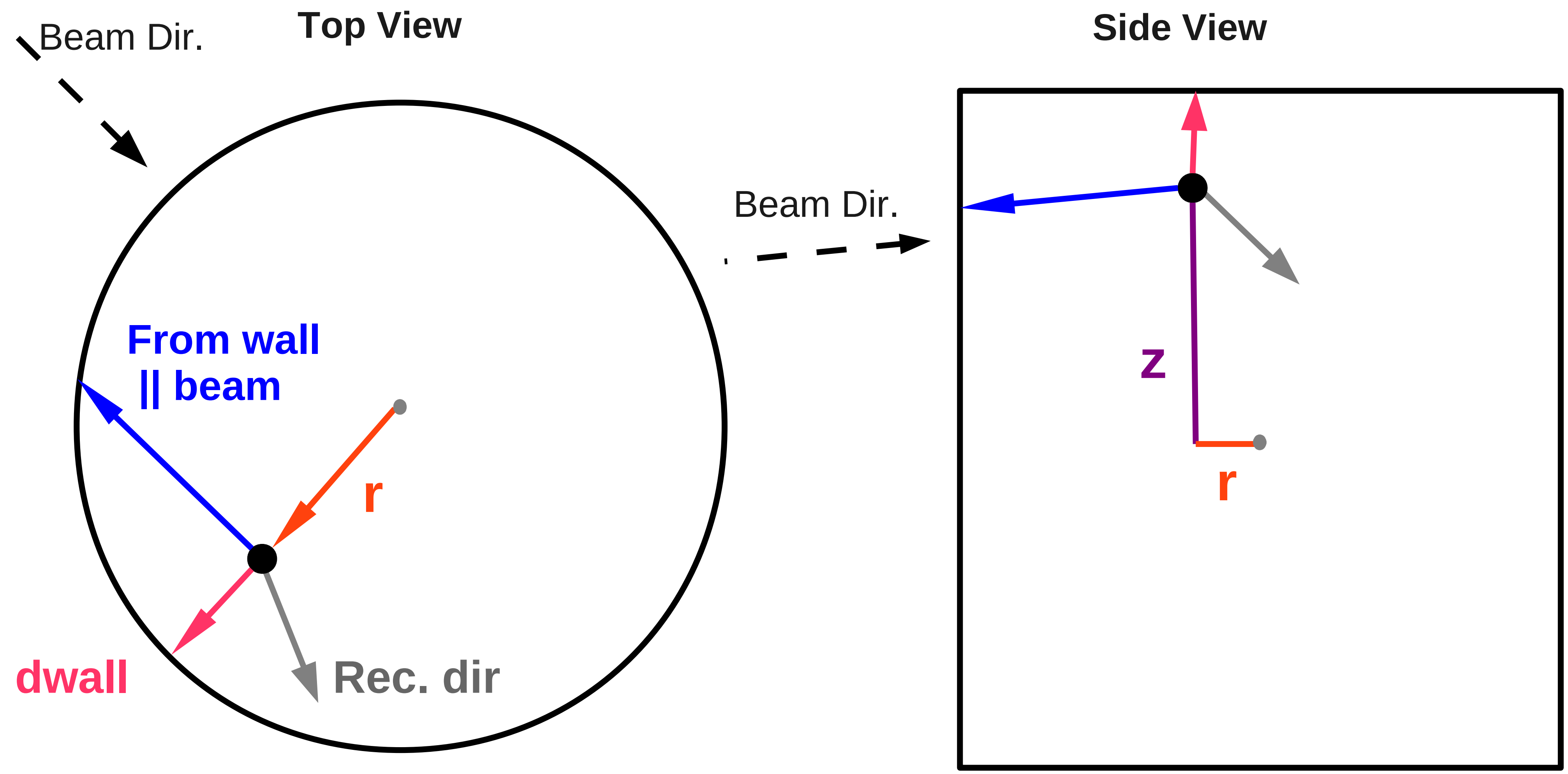




$\theta_{13} = 0$ event expectations

	Data	BG expectation				$\nu_\mu \rightarrow \nu_e$ expect.
		Total	ν_μCC	ν_eCC	NC	
Interaction in FV	-	**141.4**	67.3	3.1	71.0	0.13
FCFV	**88**	**73.8**	52.4	3.0	18.3	0.12
Single-ring	**41**	**38.4**	30.9	1.9	5.7	0.11
e-like	**8**	**6.7**	1.0	1.9	3.7	0.11
E_{vis} > 100 MeV	**7**	**5.8**	0.7	1.9	3.2	0.11
No decay-e	**6**	**4.5**	0.1	1.6	2.8	0.10
M_{inv} < 105 MeV/c^2	**6**	**1.9**	0.04	1.1	0.8	0.09
E_ν^{rec} < 1250 MeV	**6**	**1.4**	0.03	0.8	0.6	0.09
Efficiency	-	**1 %**	< 0.1 %	24 %	1 %	74 %

Parameter Definitions within Super-K (subset)



dwall - Distance to the *closest* ID wall

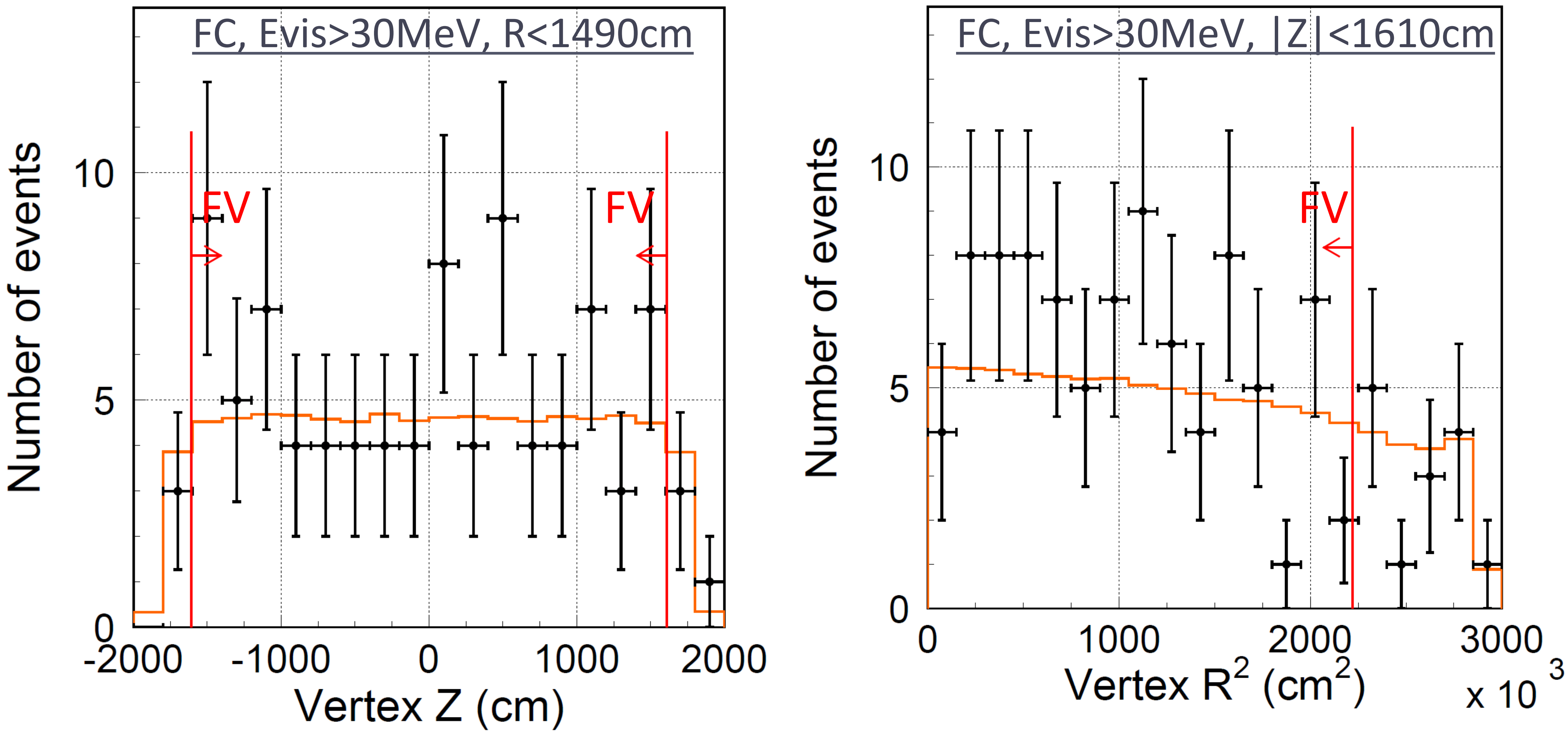
From wall || beam – Distance from vertex in the direction *opposite* the beam

r , z - Radial distance and vertical position

defined before the data collection
6 selection cuts in addition FC cut

Fiducial volume cut

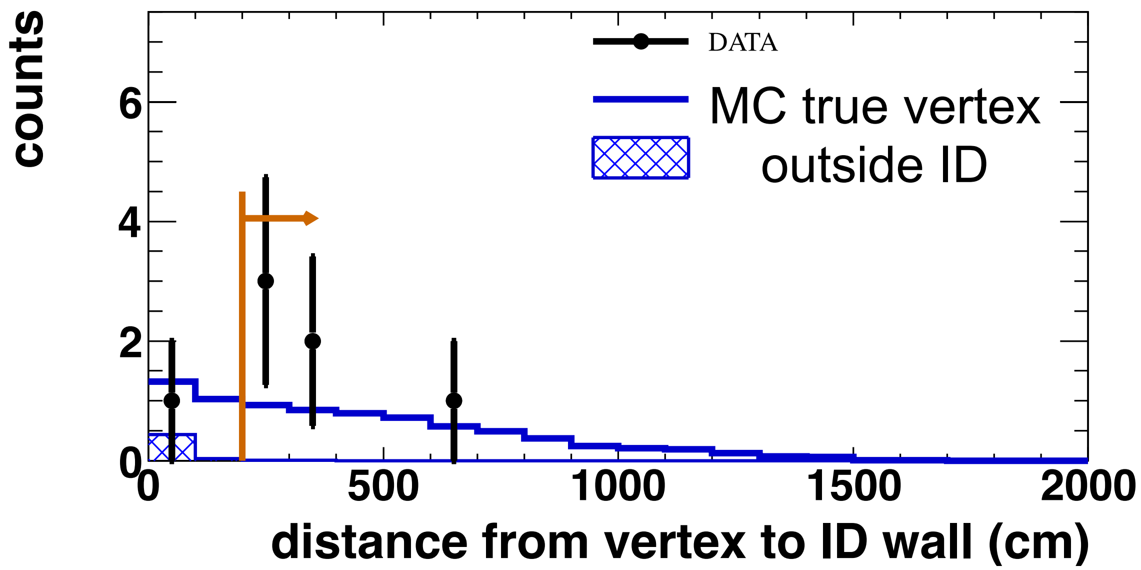
(distance between recon. vertex and wall > 200cm)

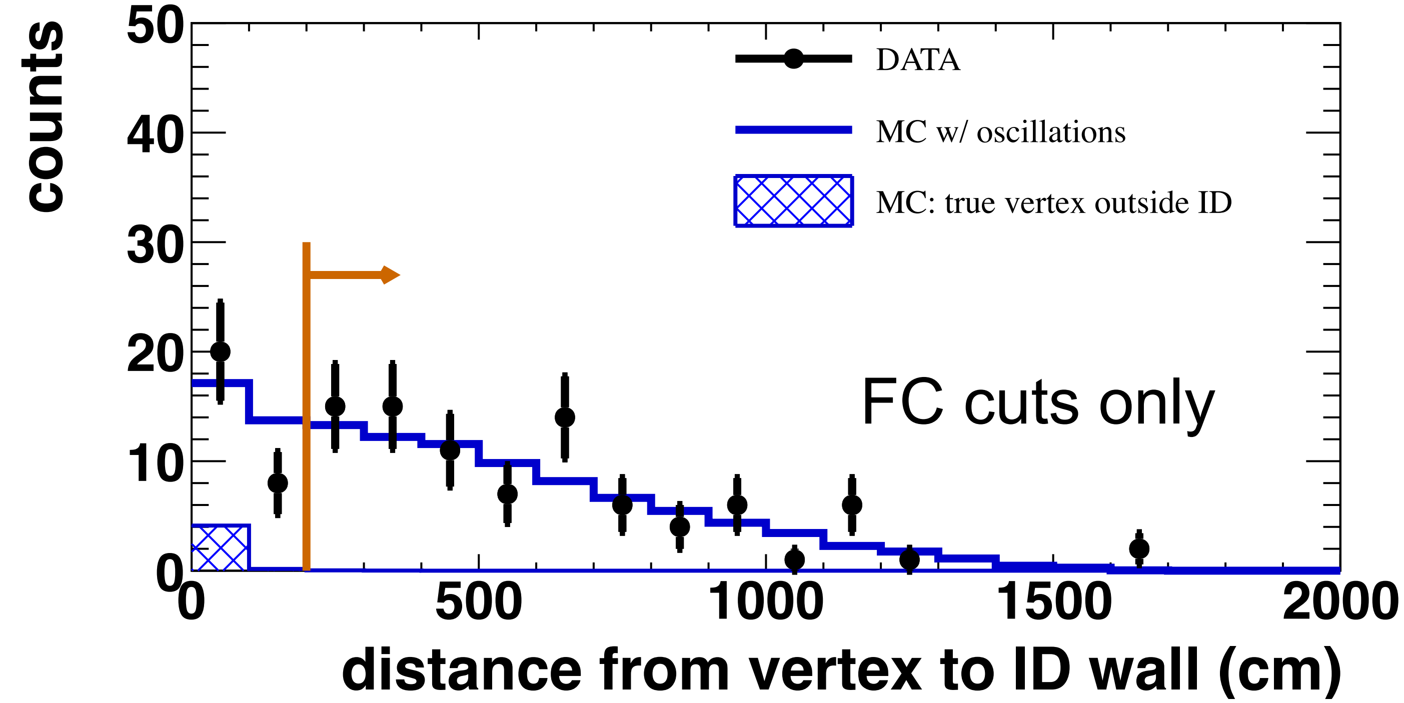


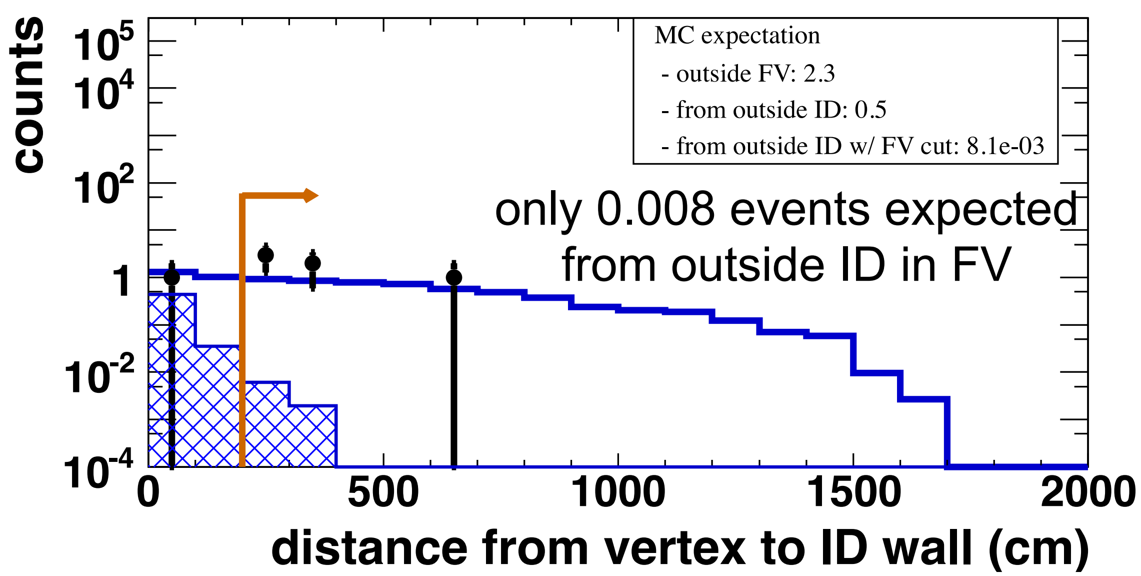
Vertex Distribution Tests

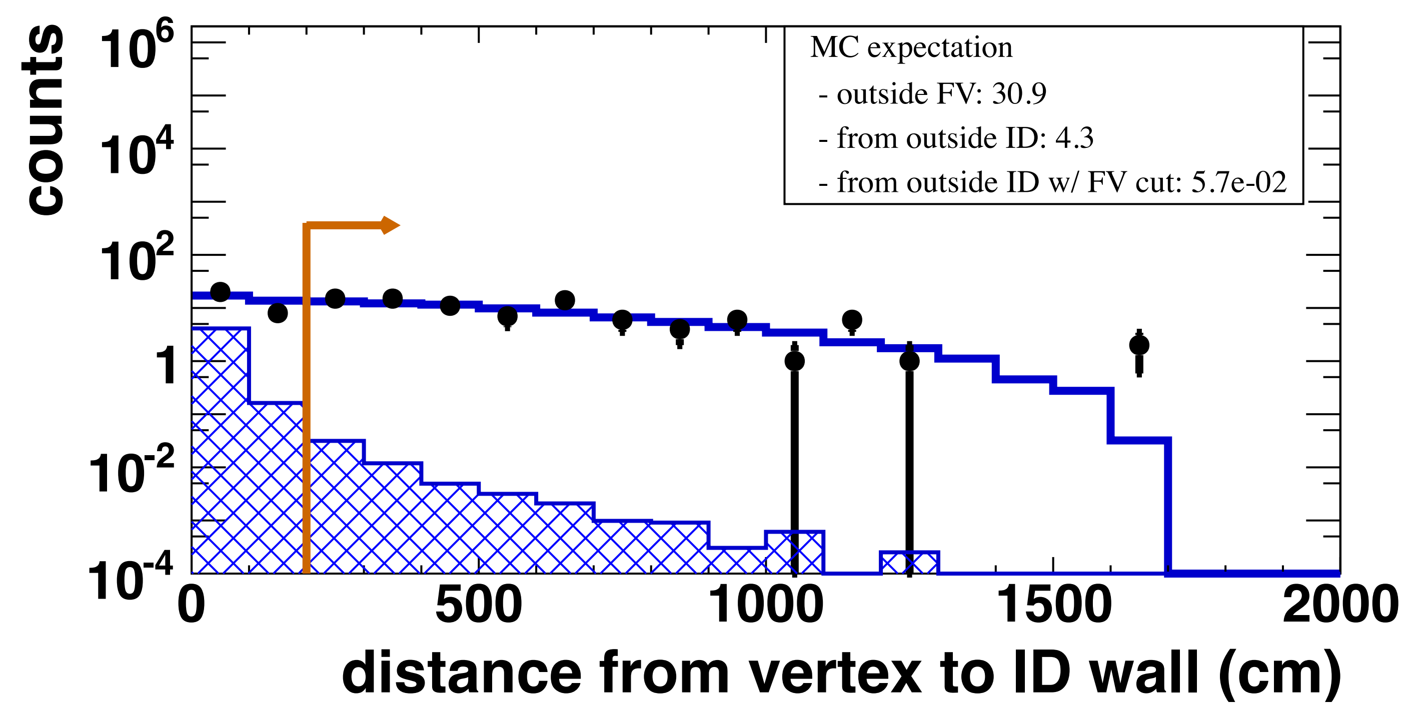
Simulate neutrino events in the rock surrounding SK

Use MC to test for entering backgrounds

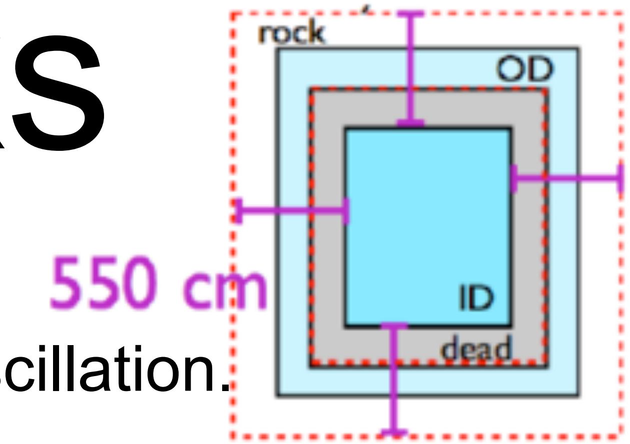




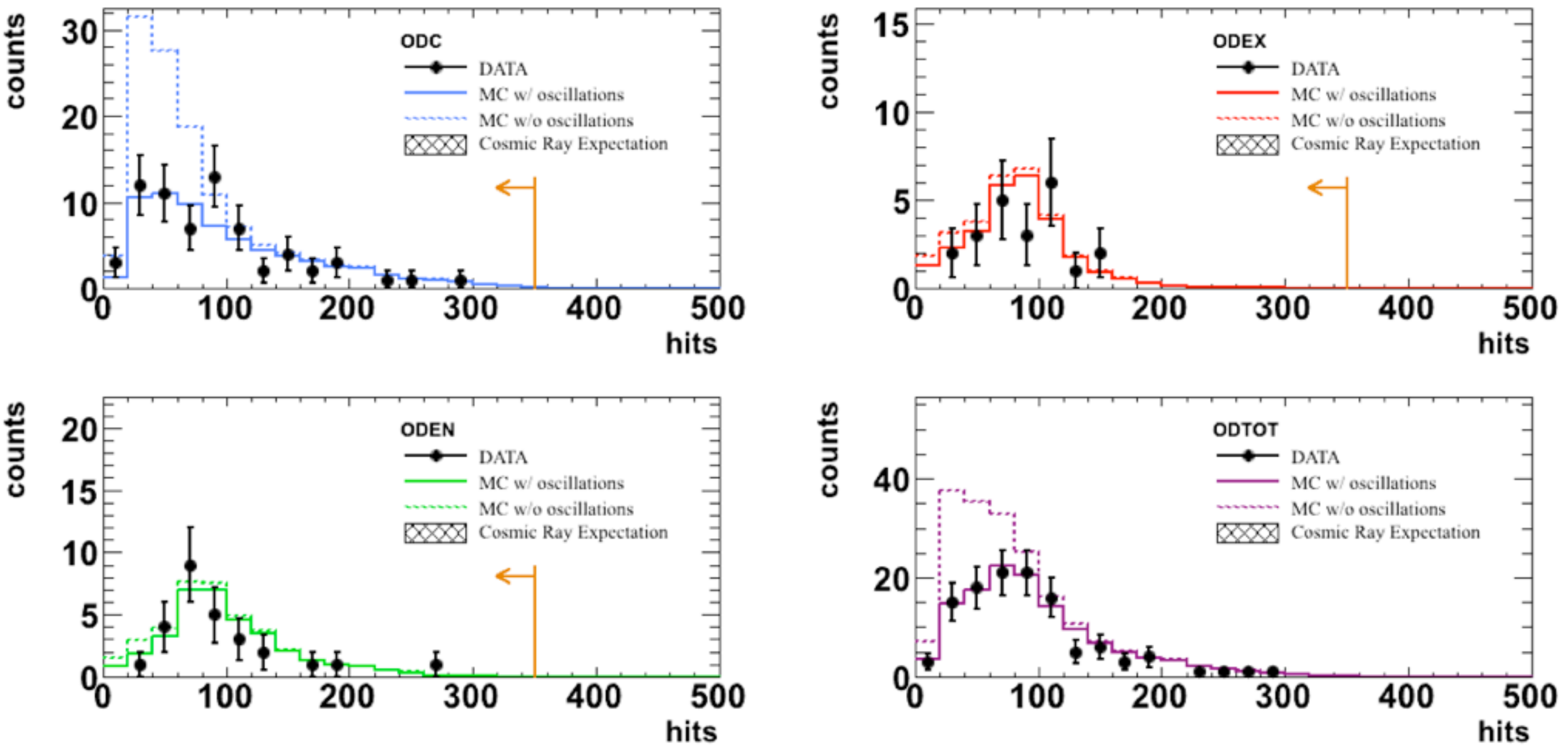




OD Data checks

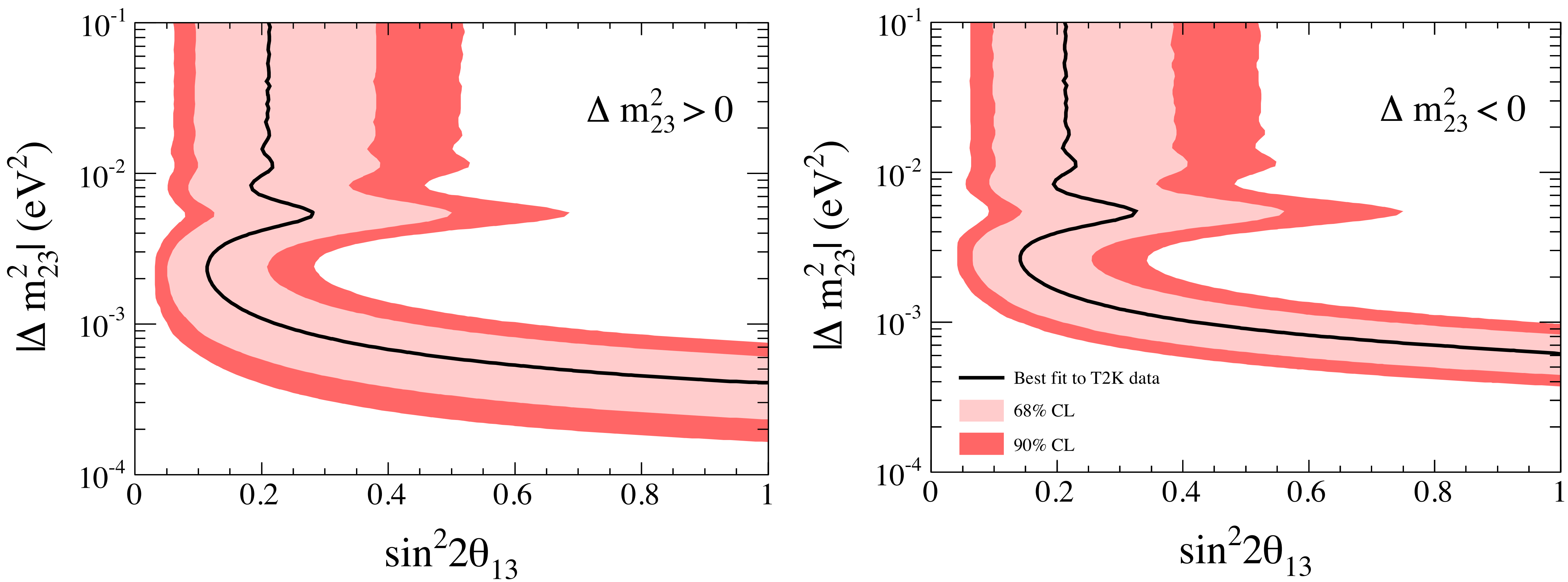


Simulate neutrino events in the rock surrounding SK
Observed OD events agree with MC prediction including effects of oscillation.



Allowed region of $\sin^2 2\theta_{13}$ as a function of Δm^2_{23}

(assuming $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

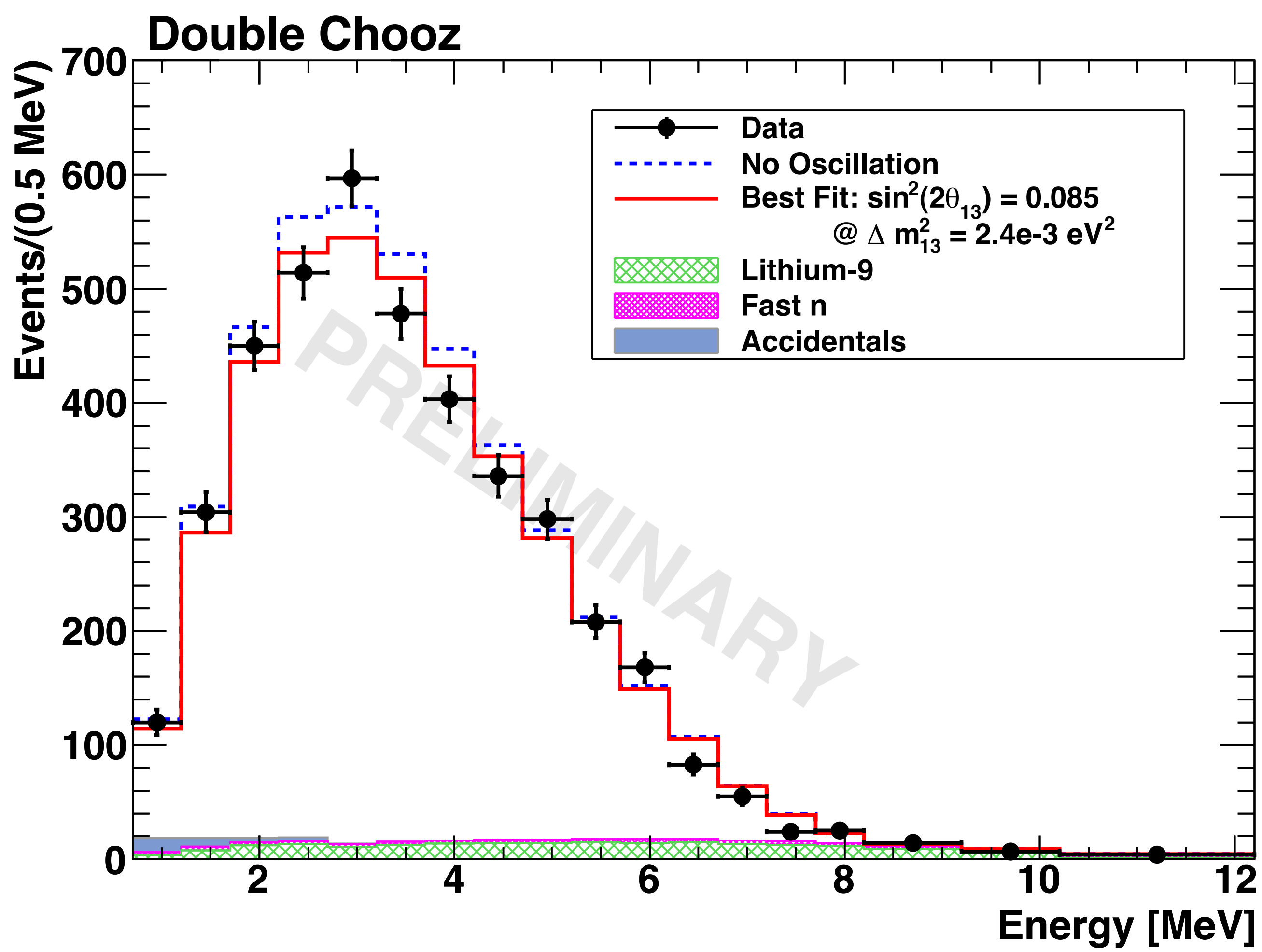


Feldman-Cousins method was used

θ_{13} Context

But what you really want....

Rate and Shape:
$\sin^2 2\theta_{13} = 0.085 \pm 0.051$



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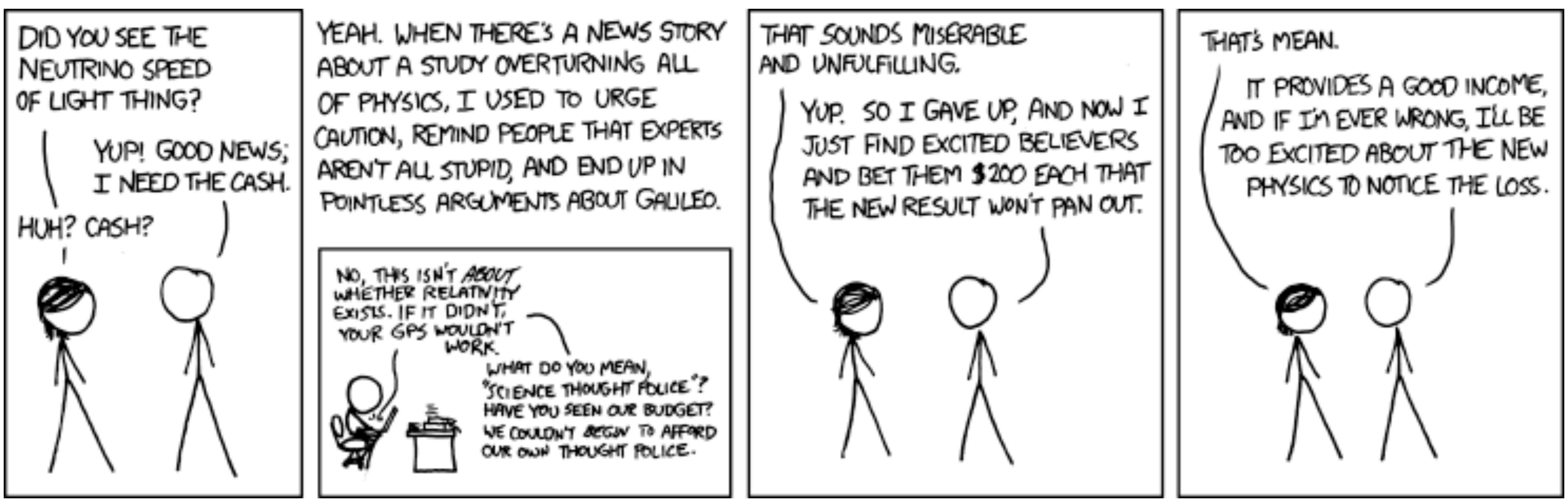
Lindley Winslow

T2K Statement on OPERA

- Based on the initial assessment of our capability, at the moment T2K cannot make any definitive statement to verify the OPERA measurement of the speed of the neutrino (the OPERA anomaly).
- We will assess possibilities to improve our experimental sensitivity for a measurement to cross-check the OPERA anomaly in the future. Such a measurement with an improved system, however, could take a while to achieve.



http://imgs.xkcd.com/comics/neutrinos.png