Neutrino school at Daya Bay,
July 1-2, 2017

T2K Experiment

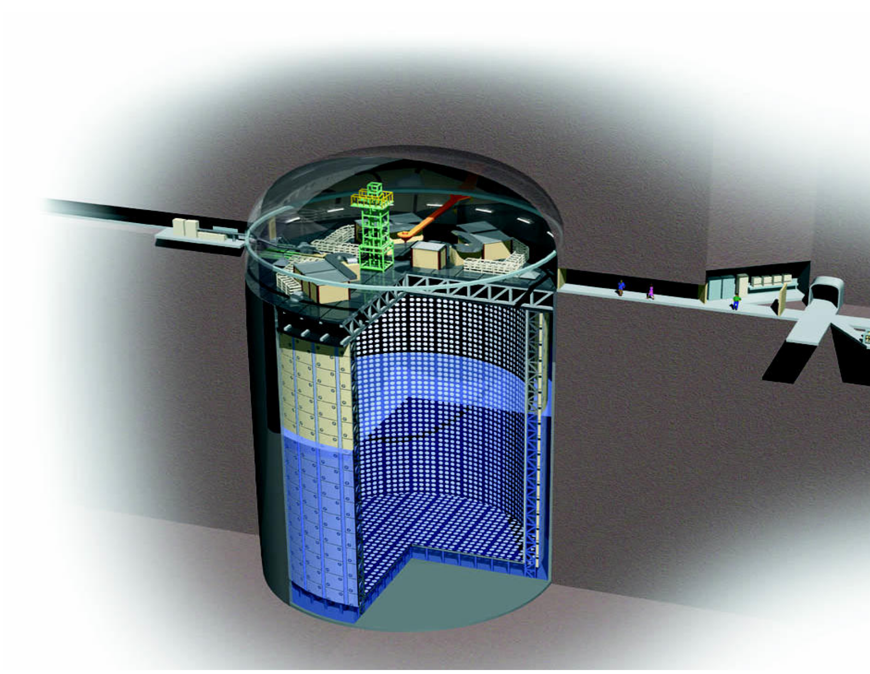
- The accelerator neutrino oscillation experiment -

T. Nakaya (Kyoto University)

T2K Neutrino Oscillation Experiment

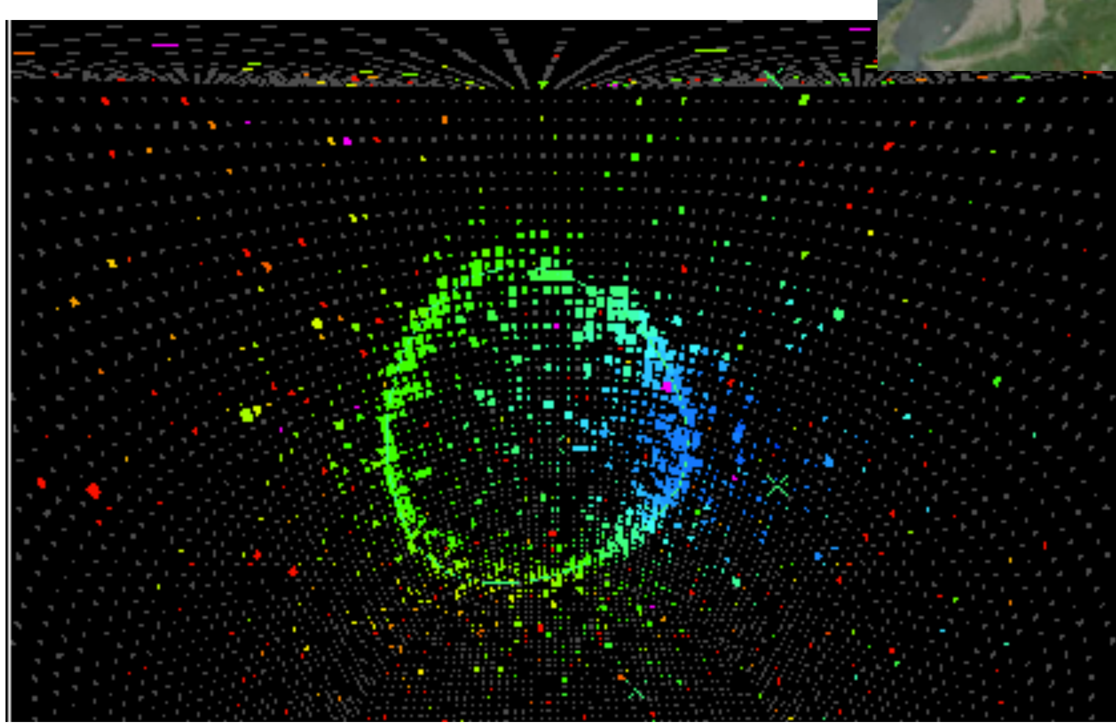
Very Intense Neutrino Beam for $\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}$ study

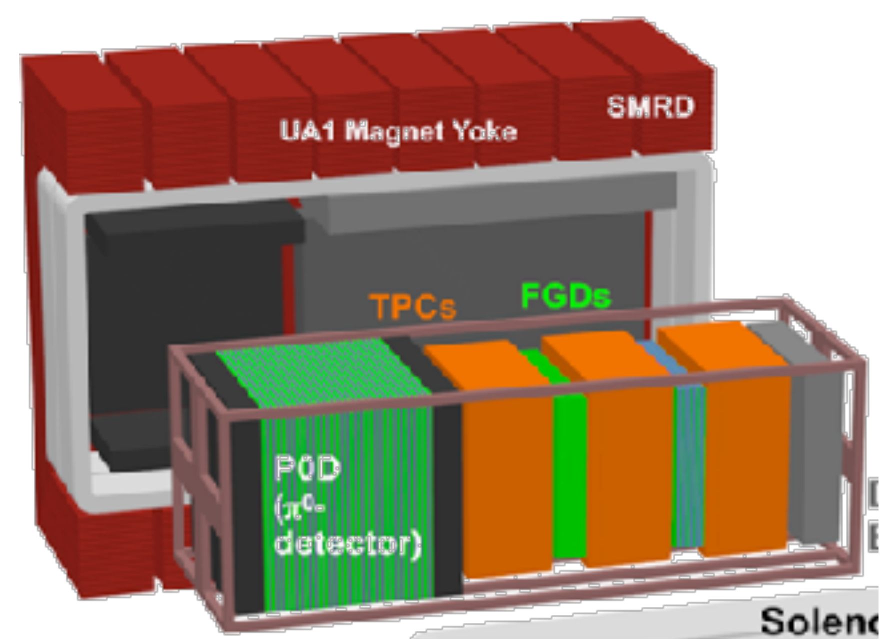
Super-K



J-PARC

- 470 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)






~500 members, 59 Institutes, 11 countries

The T2K Collaboration

~500 members, 59 Institutes, 11 countries

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

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

Germany
Aachen

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

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute of Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.

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

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

T2K

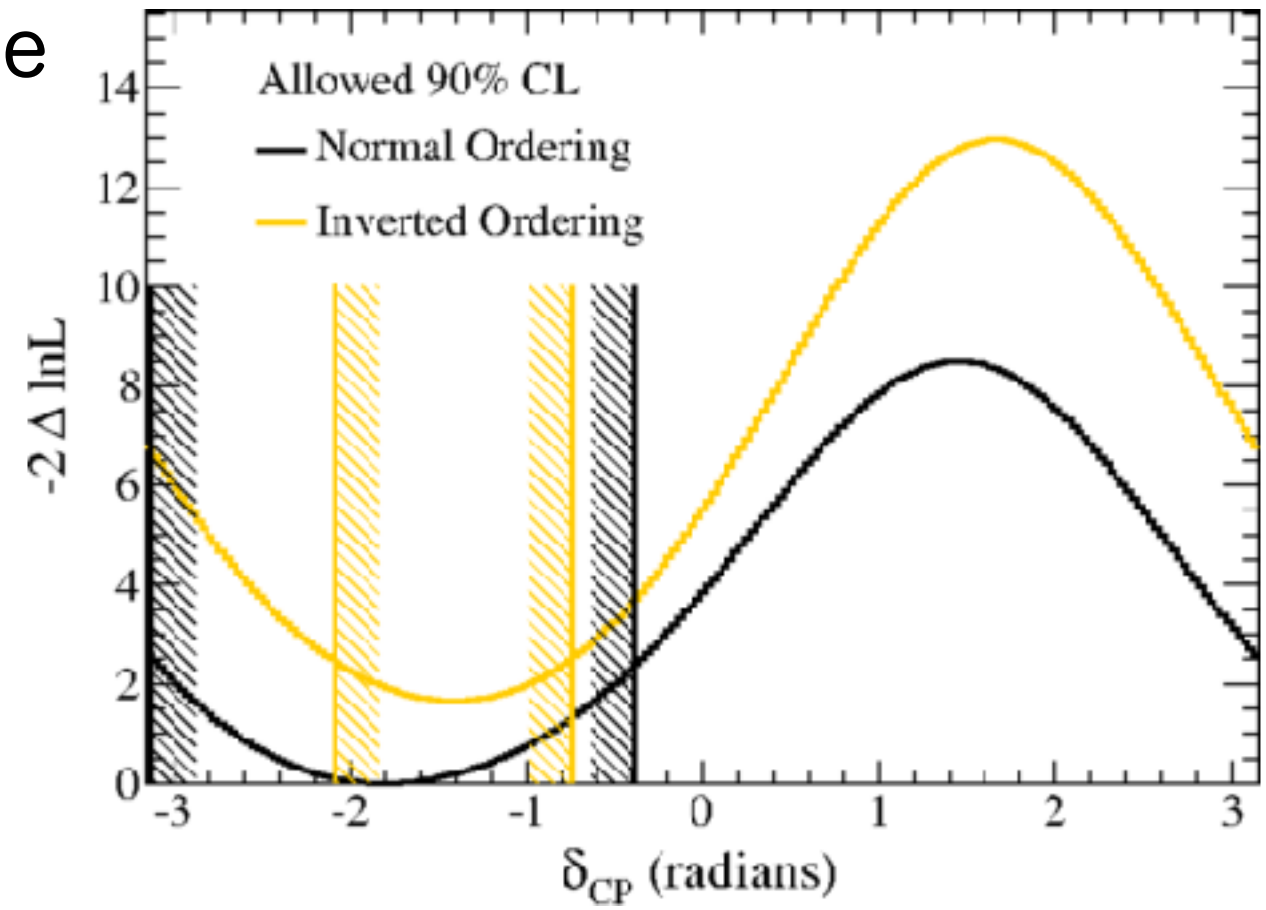
J-PARC

Super-K

Outline

1. Physics (addressed by the accelerator experiment)
2. Proton Accelerator: J-PARC
3. Neutrino Beam
4. Neutrino Cross section
5. Near Detectors: ND280
6. Far Detector: Super-Kamiokande
7. Oscillation Analysis
8. Latest OA results
9. Future Prospect

Pays. Rev. Lett. 118, 151801 (2017)



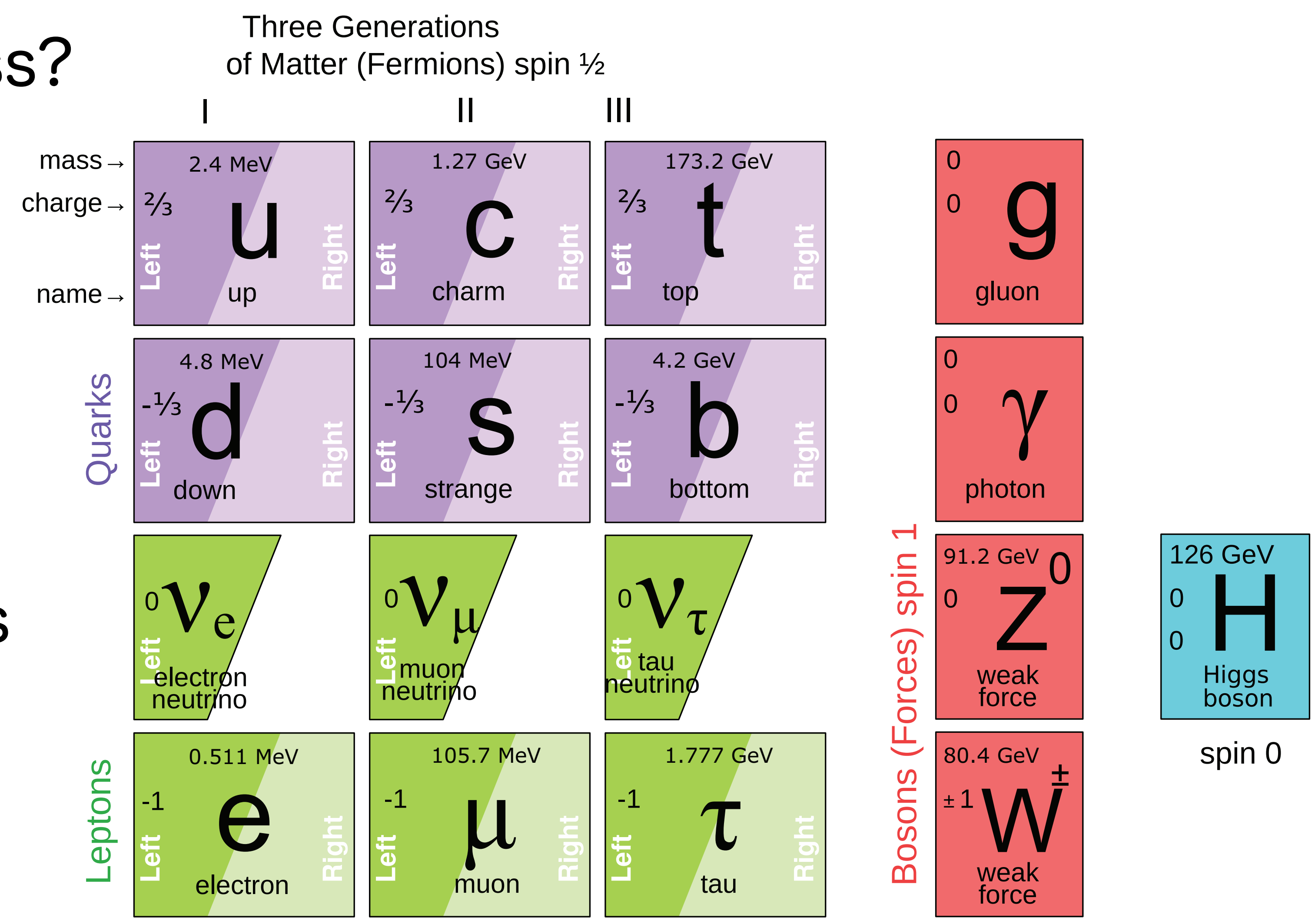
1. Physics

- addressed by the accelerator experiment -

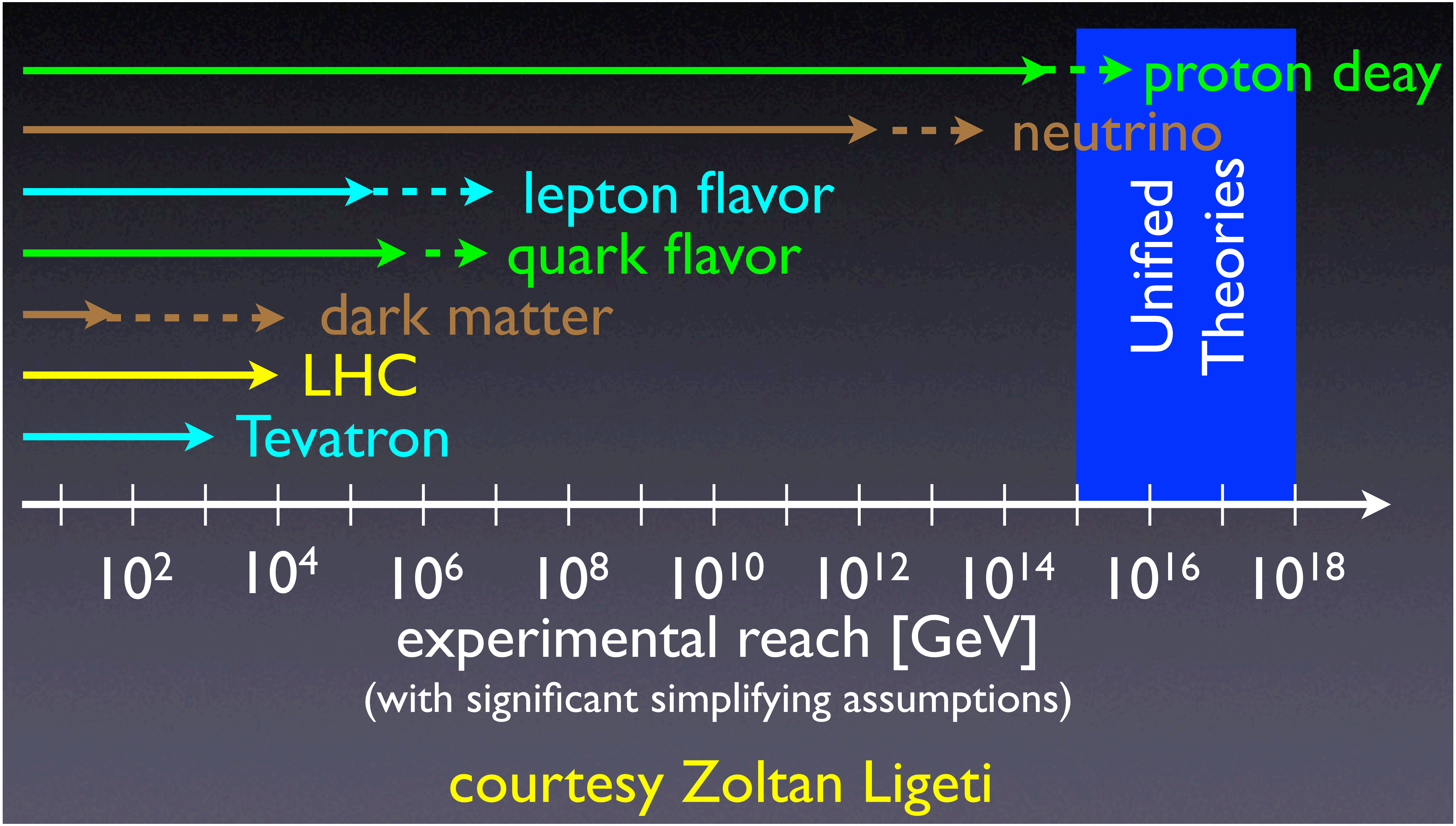
Introduction

- Neutrino mass and mixing (right handed neutrinos) are physics beyond the standard model.

- Tiny Neutrino mass
  - What is the origin of the mass?
- Flavor Symmetry
  - Between leptons and quarks
    - mass pattern
    - mixing pattern
    - the number of generations
- CP violation
  - the origin?
  - matter dominant universe with Leptogenesis



A window to Ultra High Energy



Neutrino Oscillation

Flavor

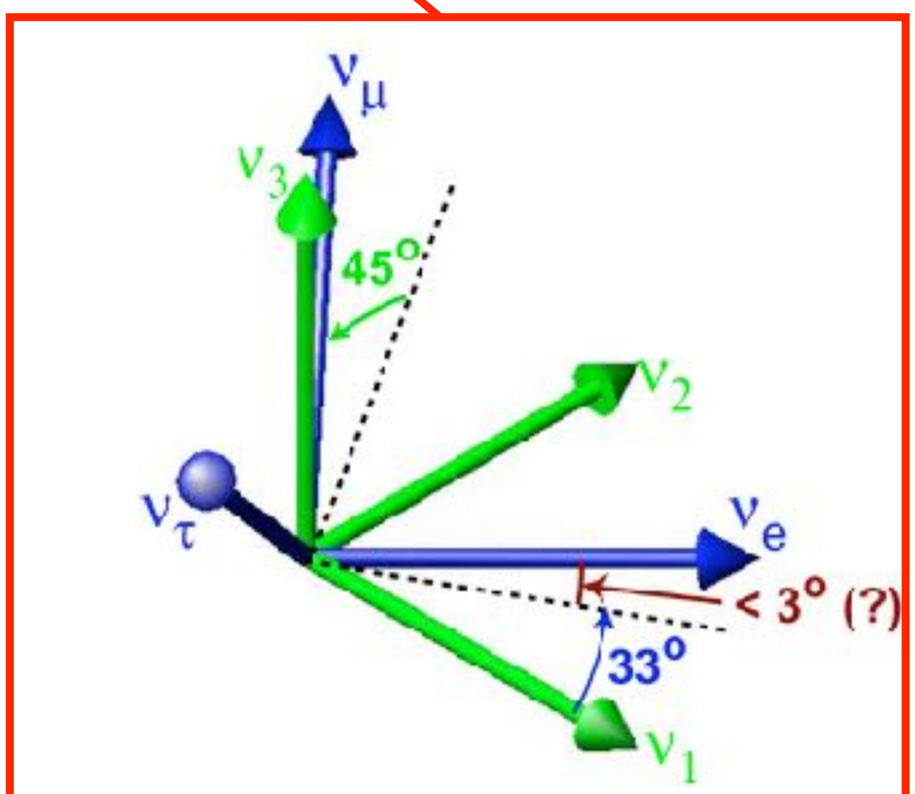
ν_e ν_μ ν_τ

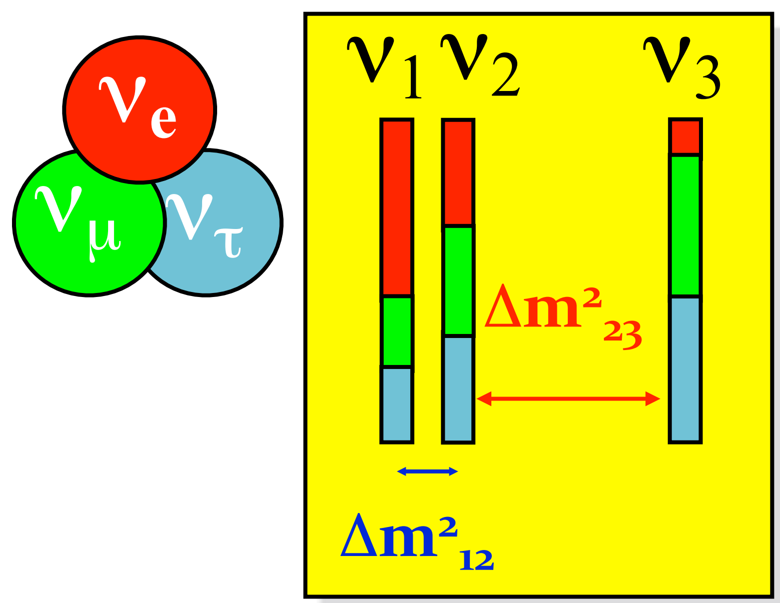
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathbf{U}_{\mathbf{MNS}}\mathbf{V}_{\mathbf{M}}^{\mathbf{CP}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

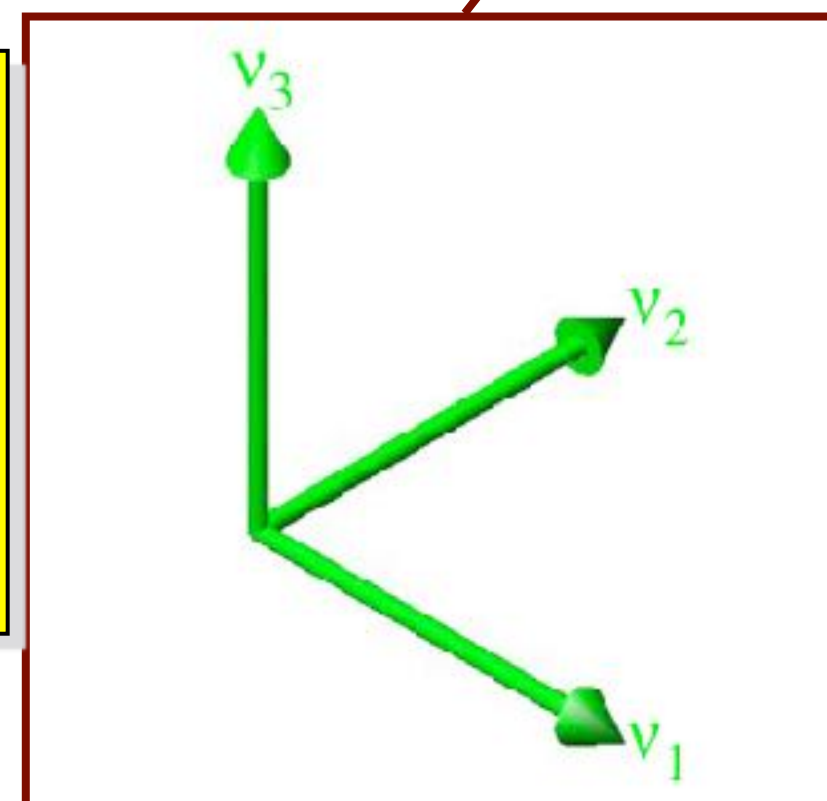
ν_1 ν_2 ν_3

Mass

NH case: $m_3 > m_1, m_2$



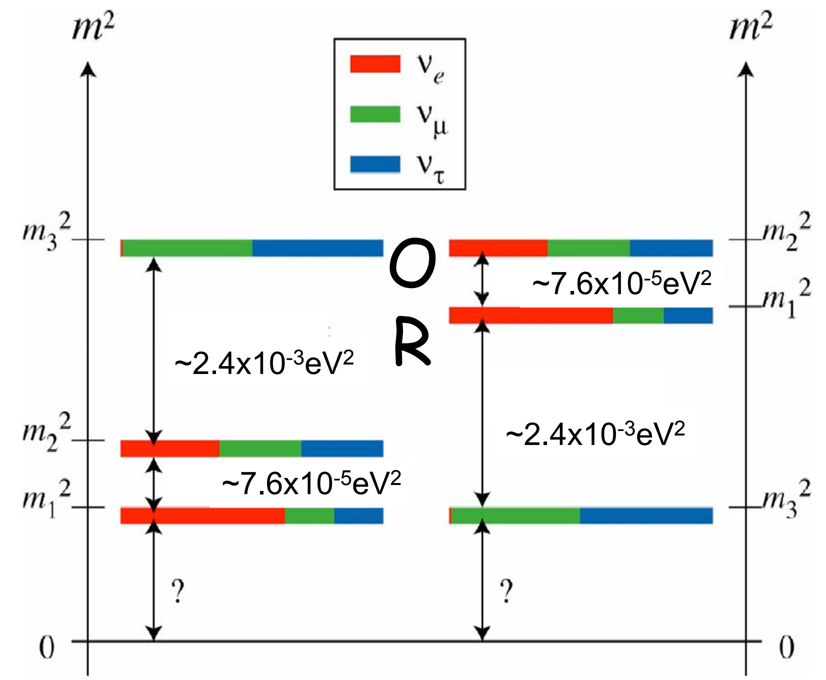




IH case: $m_3 < m_1, m_2$

Mass and mixing are addressed by neutrino oscillation

Neutrino Oscillation



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

Solar, Reactor (ν_1, ν_2)

Atmospheric, Accelerator (ν_2, ν_3)

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

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
Accelerator

Accelerator
Reactor
Atmospheric

Solar
Reactor

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

δ〜unknown

$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

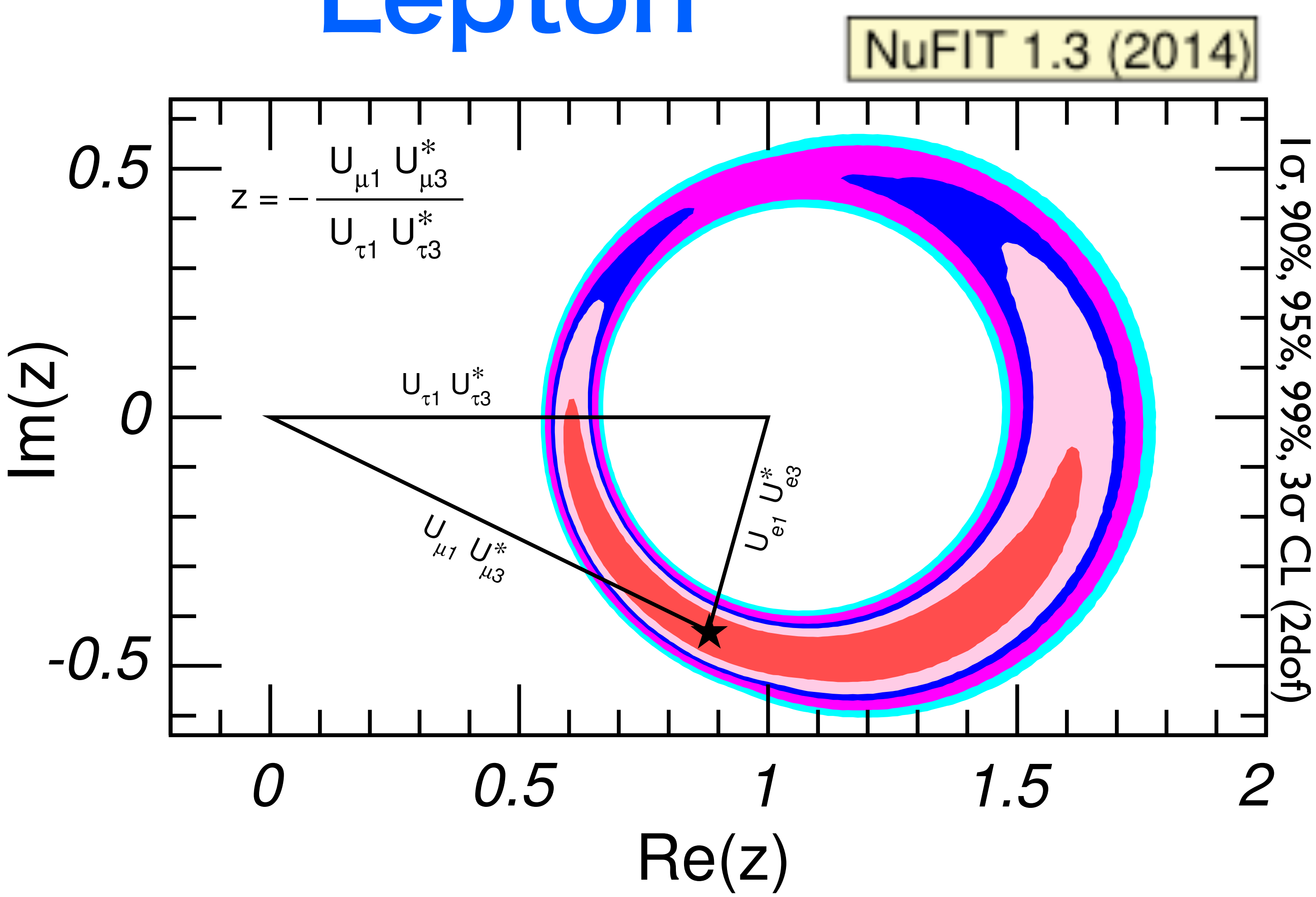
δ=60°

- In the framework of 3 neutrinos, the unknowns are
  - mass ordering
  - CP violation parameter: δ_{CP}

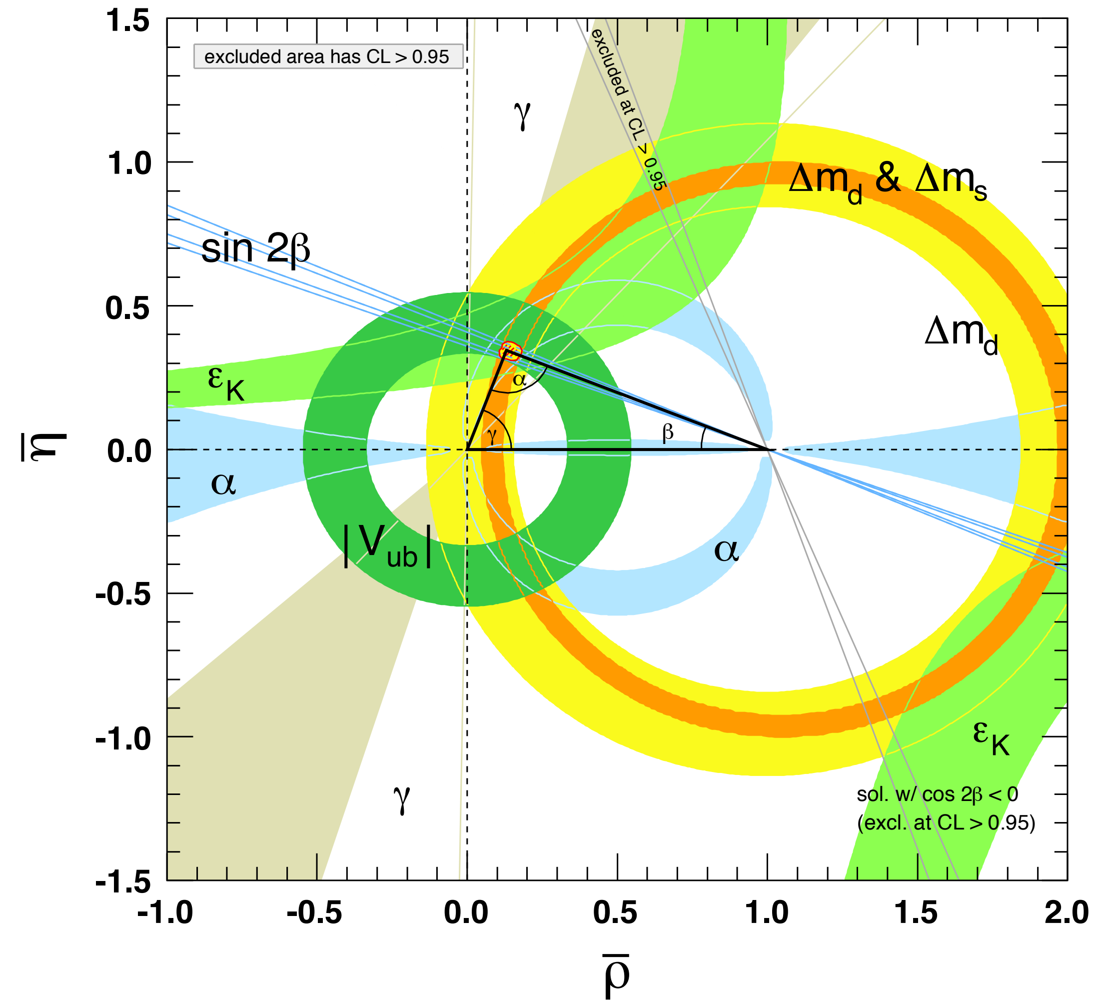
Three neutrinos and Beyond

Leptonic unitarity triangle

Lepton



Quark



Assuming unitarity (3 neutrinos)

by T. Schwetz @ NuFact2014

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L y \nu_R \tilde{H} - \bar{\nu}_R y^\dagger L \tilde{H}^\dagger - \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

Minkowski 1979, Gell-Mann/Ramond/Slansky 1979, Mohapatra/Senjanovic 1979, Yanagida 1980

$$\Rightarrow \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

The GUT seesaw

Pros:

- theoretically well-motivatedin GUTs, e.g. SO(10)
- “naturally” explains small neutrino masses
- “naturally” leads to leptogenesis Fukugita/Yanagida
- indirect experimental access to very high scales

Cons:

- new states experimentally inaccessible
- adds to hierarchy problem

by M. Draws @ NuFact2014

The electroweak / TeV seesaw

Pros:

- some theoretical arguments
  - no new scale Asaka/Shaposhnikov
  - classical scale invariance Khoze/Ro,. . .
- allows for leptogenesis

The GeV seesaw

Pros:

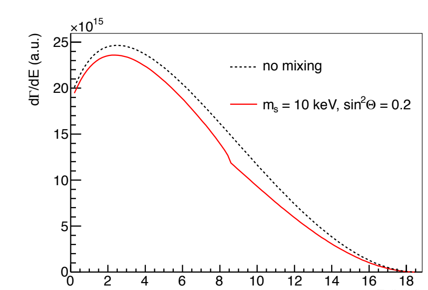
- some theoretical arguments
  - no new scale Asaka/Shaposhnikov
  - classical scale invariance Khoze/Ro,. . .

The keV seesaw

Pros:

- can in principle explain neutrino masses
- can be Dark Matter (cold, warm, non-thermal. . .)
- can be tested
  - KATRIN type experiments
  - astrophysics / cosmology

courtesy S. Martens



Cons:

- very tiny Yukawa couplings y, cancellations
- a state can only **either** be DM **or** contribute to neutrino mass
- simplest scenario (Dodelson/Widrow) disfavoured by data

$E_6 \longrightarrow SO(10) \longrightarrow SU(5)$

Example *a GUT* by N. Maekawa

1. Unification
   1. Force (w/ SUSY)

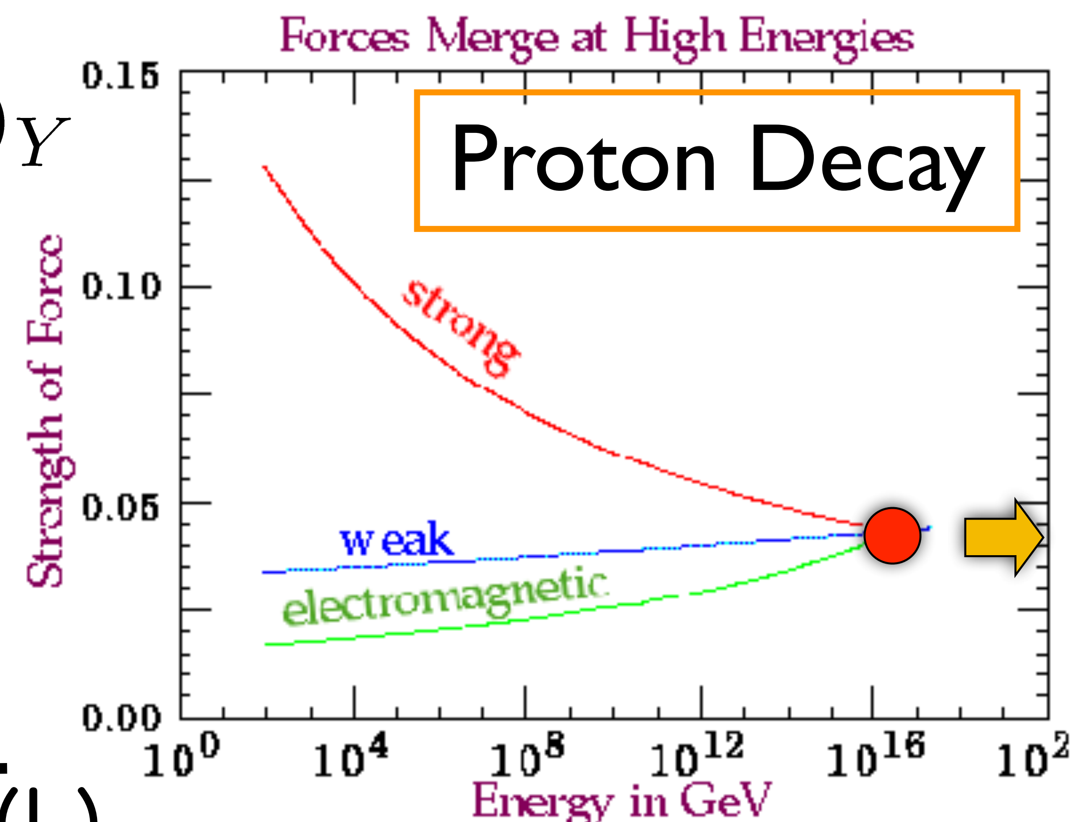
   $SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

   2. Quark and Leptons

   $Q \quad U_R^c \quad E_R^c \quad | \quad D_R^c \quad L \quad | \quad N_R^c$

   $$\mathbf{10} + \bar{\mathbf{5}} + \mathbf{1} = \mathbf{16}$$

   · 10(Q_i) has more hierarchy than $\overline{5}$(L)



2. Hierarchy
   1. mixing: lepton (large) >> quark (small)
   2. mass: u-type quark >> d-type quark, charged lepton >> neutrino

Neutrino CPV

- Neutrino Oscillations with CP violation
  - Weak (flavor) state ≠ Mass state
  - 3 generations ➡ Imaginary Phase in a mixing matrix
    - [Neutrino] MNS matrix ~ [Quark] CKM matrix
  - Example: Prob.($\nu_\mu \rightarrow \nu_e$) ≠ Prob.($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)
- Heavy Majorana Neutrino (N) [if exists] with CP violation
  - NOT easy to access (very very difficult)
  - The decay of N
    - Prob.($N \rightarrow \overline{l_L} + \phi$) ≠ Prob.($N \rightarrow l_L + \overline{\phi}$)
  - Or, the oscillations of N

Leptogenesis and Neutrino CPV

- Saharov conditions for Baryon Asymmetry
  - [B] Baryon Number Violation
  - [CP] C and CP violation
  - [T] Interactions out of thermal equilibrium

- Leptogenesis and Low Energy CP violation in Neutrinos
  - [B] Sphaleron process for $\Delta(B+L)\neq 0$
  - [CP] Heavy Majorana Neutrino decay and/or Neutrino oscillations
    - $|\sin\theta_{13}\sin\delta|>0.09$ is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix [Phys. Rev. D75, 083511 (2007)].
      - $\sin\theta_{13}\sim 0.15$ ➡ $|\sin\delta|>0.6$

Formula of Oscillation Probability with CP violation

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{13_{2}}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

Leading

$$\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

CPV

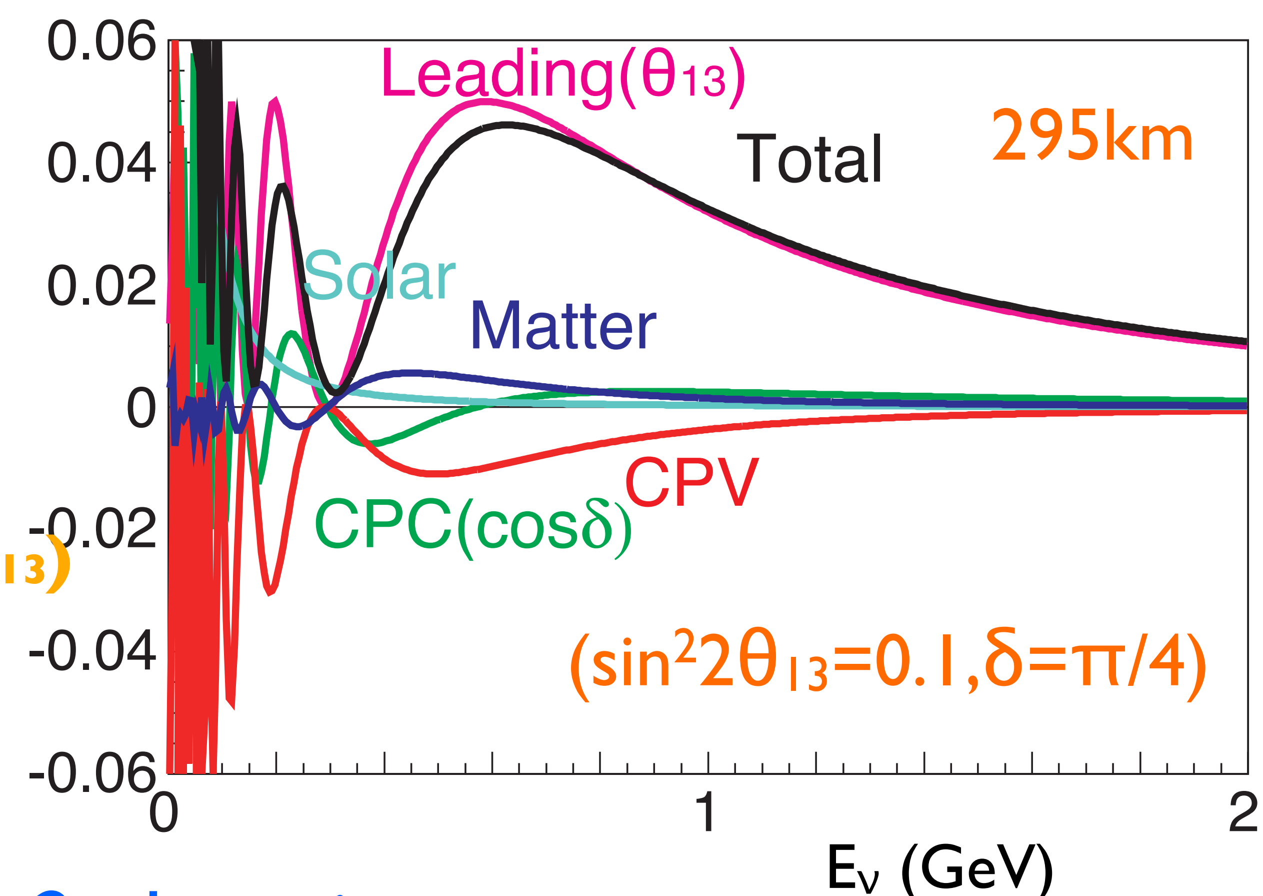
$$\frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \sin\delta$$

~0.03 **~11.8 (6.4 from 1/sinθ$_{13}$)**

$$\sim \frac{\pi}{4} \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{\sin^2\theta_{23} \sin\theta_{13}} \frac{E_{1st\max}}{E} [leading] \sin\delta$$

$$\sim 0.27 \times [leading] \times \frac{E_{1st\max}}{E} \times \sin\delta$$

27%

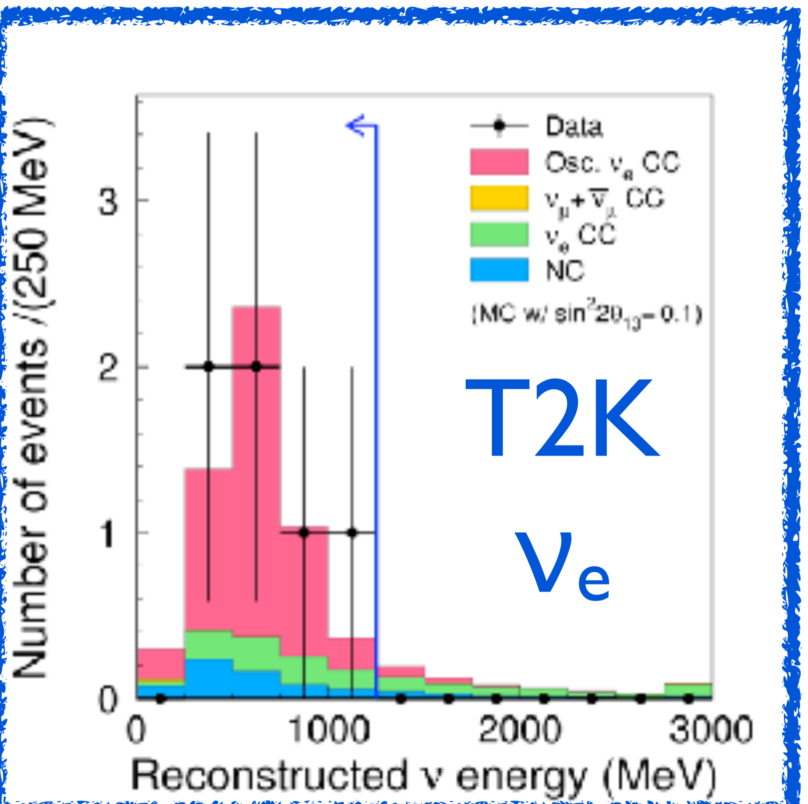


- No magic for the 2nd maximum.
- Energy dependence is important.

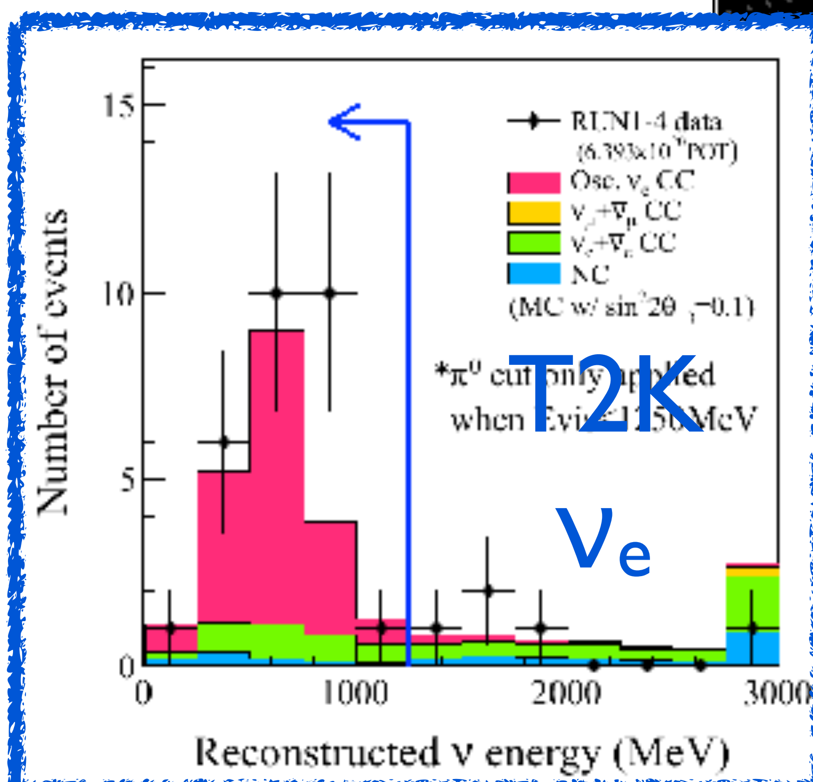
A door to Neutrino CP violation is opened

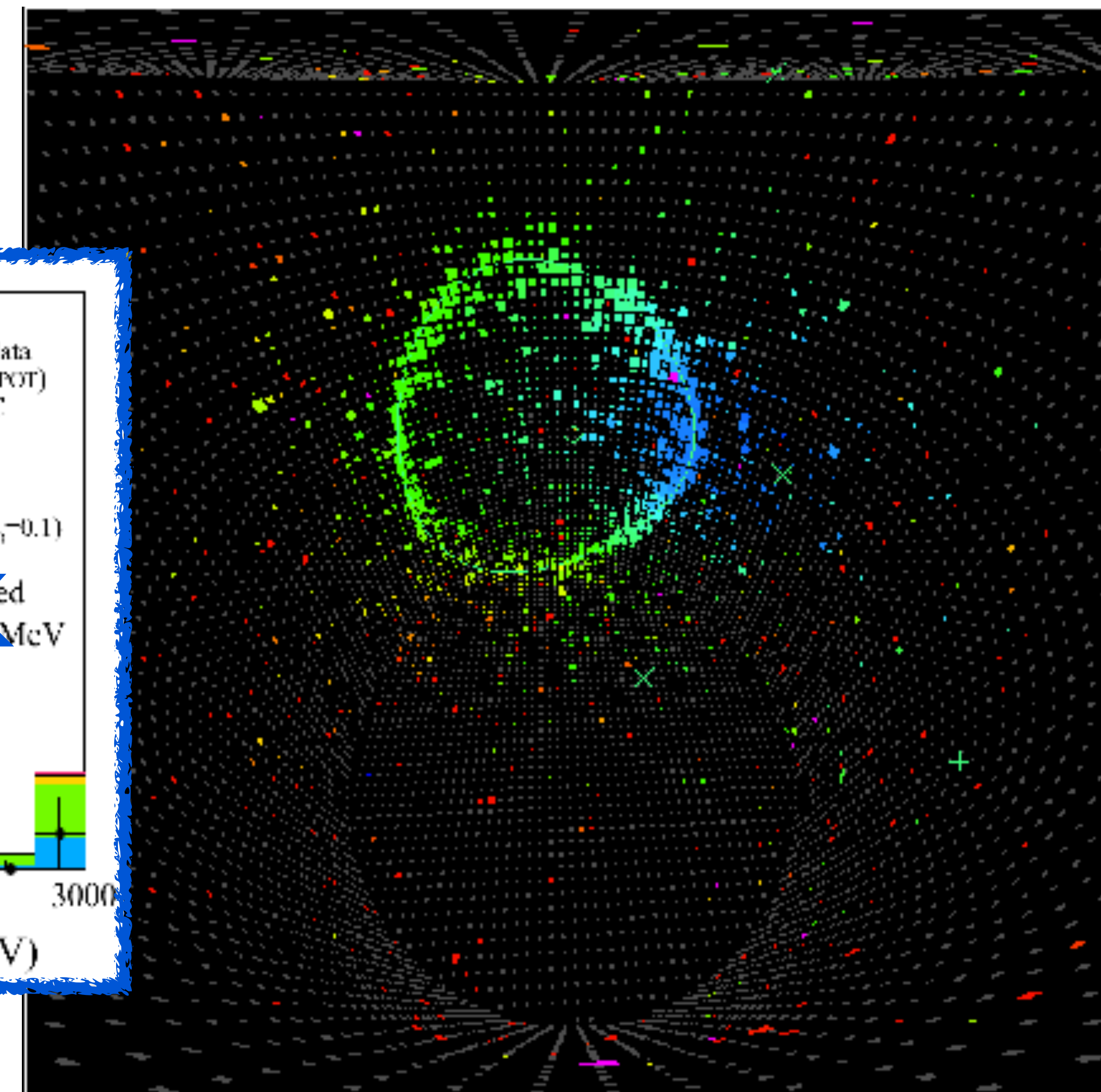
- $\nu_\mu \to \nu_e$ oscillation w/ Δm_{atm}^2 discovered by the T2K experiment
  - Indication in 2011 [PRL 107, 041801 (2011)]
  - Observation in 2013 [PRL 112, 061802 (2014)]

2011



2013





FRAMEWORK

Parameters	Asimov A
$sin^2 2\theta_{12}$	0.846
$sin^2 2\theta_{13}$	0.0849
$sin^2 \theta_{23}$	0.528
Δm^2_{21}	7.53×10^{-5}
Δm^2_{32}	2.509×10^{-3}
δ_{cp}	-1.601

- Four modes of observation observed at T2K
  - $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
  - $\nu_\mu \nrightarrow \nu_\mu$, $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$ disappearance
  - use all information to constrain oscillation parameters

constrain by reactor

constrain by ν_μ disp.

switches sign for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$
$$-\alpha \sin\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta_{31} \frac{\sin[x\Delta_{31}]}{x} \frac{\sin[(1-x)\Delta_{31}]}{1-x}$$
$$+(\text{CP even}) \quad +\mathcal{O}(\alpha^2)$$

M. Freund, Phys.Rev. D64 (2001) 053003

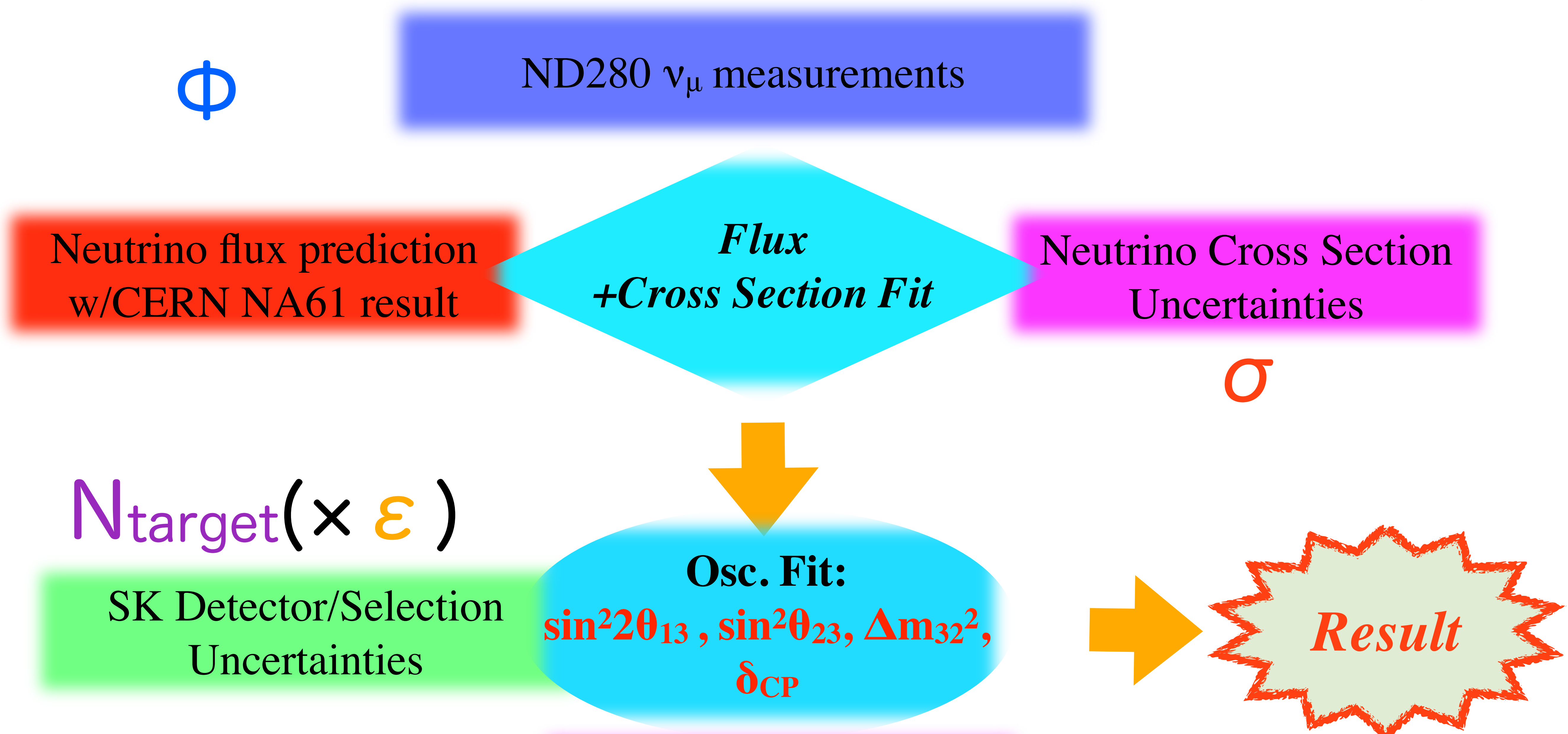
$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2\theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

- Large θ_{23}: enhances both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- δ_{CP} =-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Δm^2_{31}>0 (normal hierarchy): enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$N_{signal} = \Phi \times \sigma \times N_{target} (\times \varepsilon)$$

Oscillation Analysis in T2K



ν oscillation parameters fixed:

- $\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV^2
- $\sin^2\theta_{12} = 0.32$

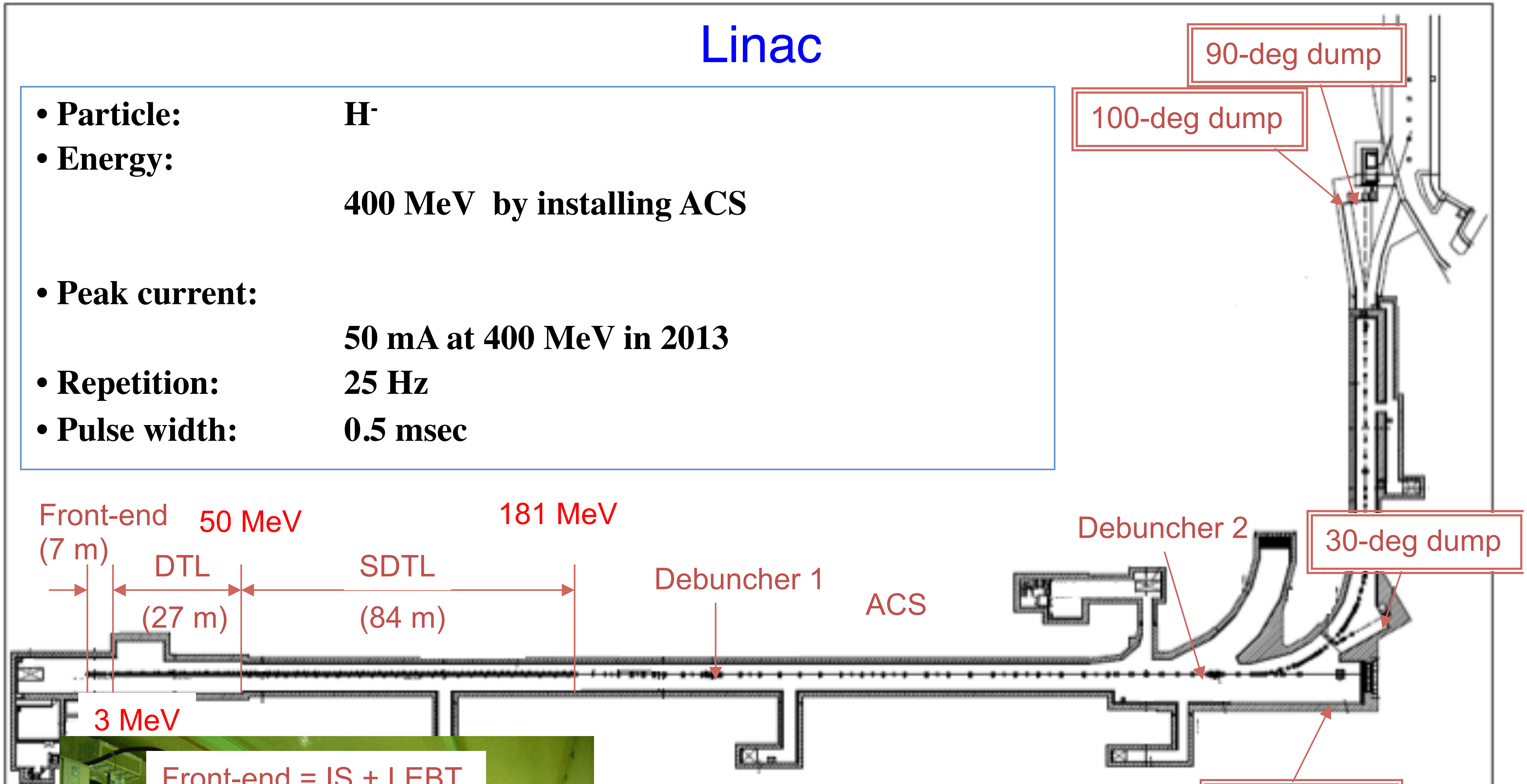
2. J-PARC

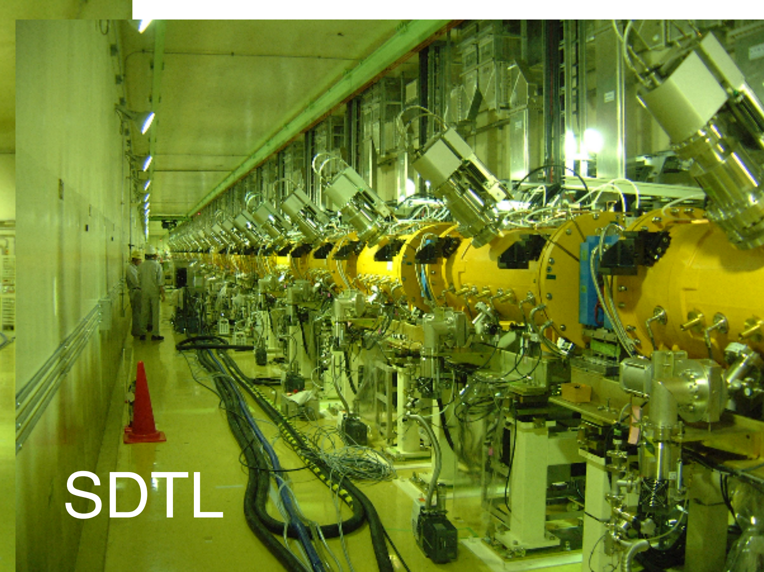
- Proton Accelerator -

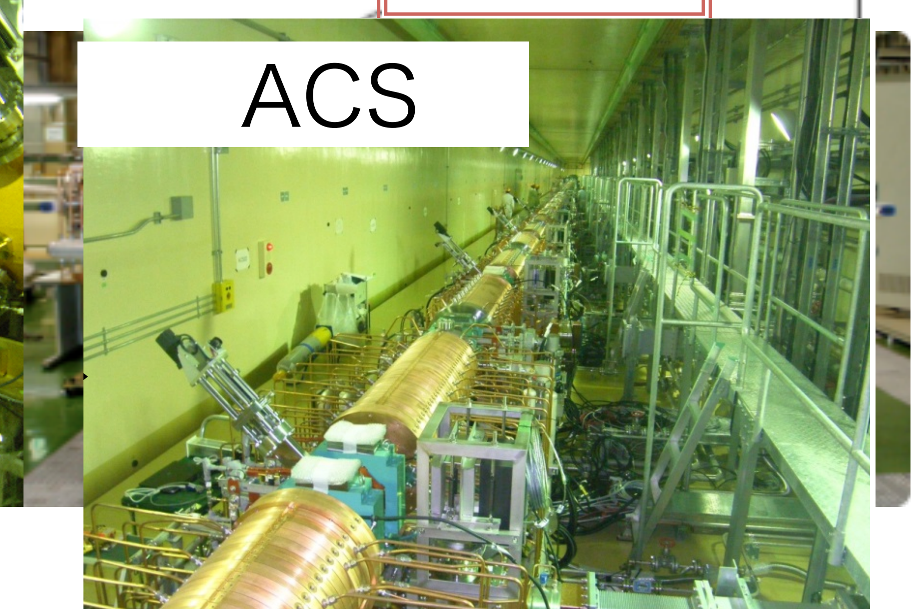
J-PARC
(Japan-Proton-Accelerator Research Complex)

Linac

- **Particle:** **H^-**
- **Energy:**
  400 MeV by installing ACS
- **Peak current:**
  50 mA at 400 MeV in 2013
- **Repetition:** **25 Hz**
- **Pulse width:** **0.5 msec**



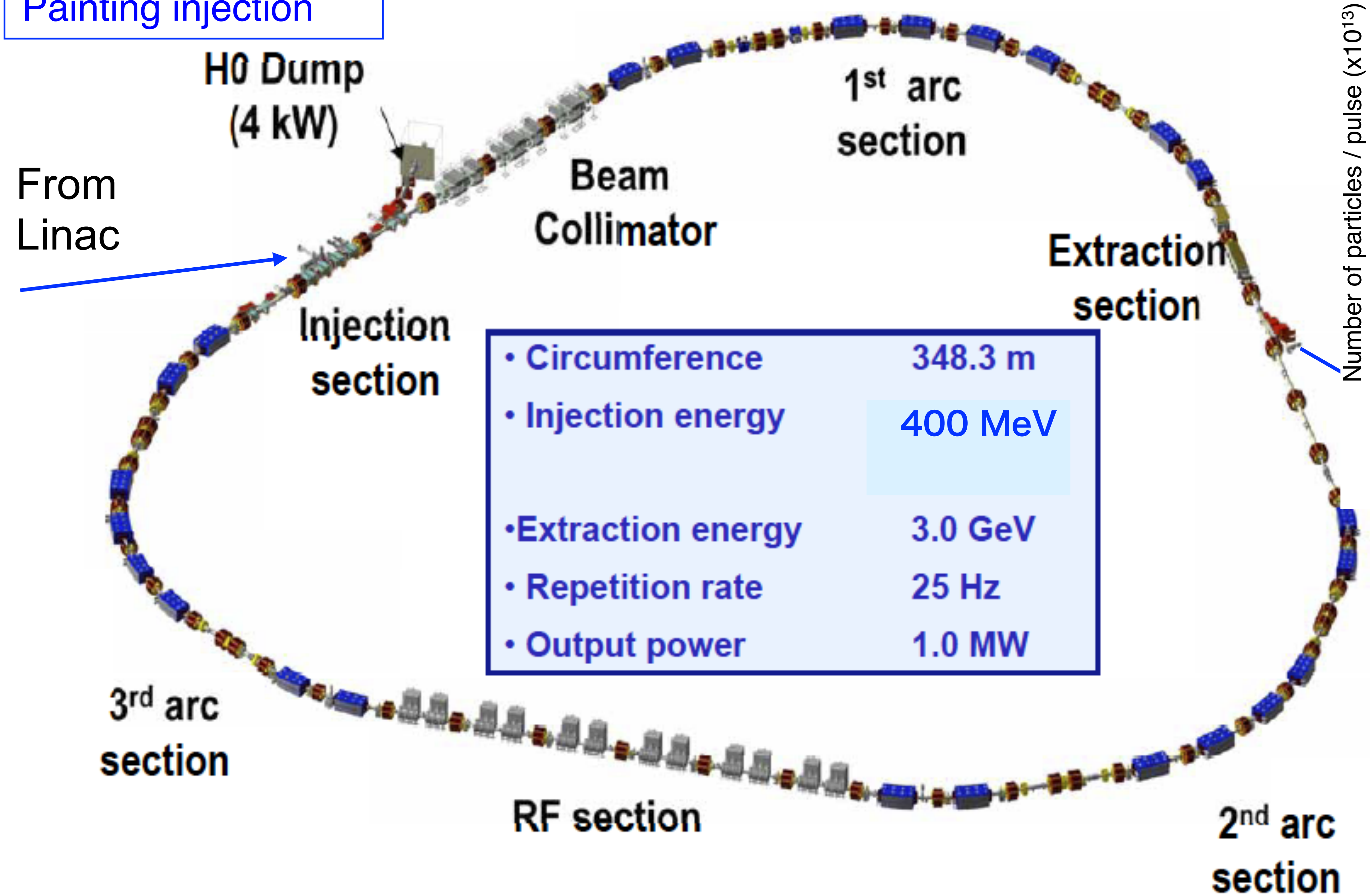




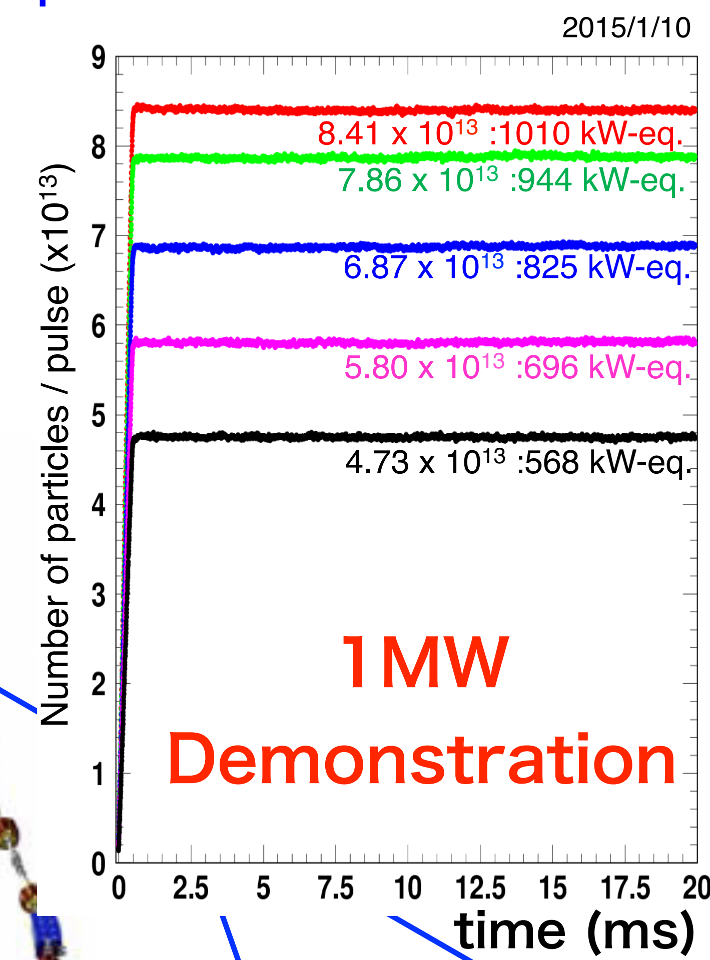
RCS (Rapid Cycling Synchrotron)

Multi-purpose machine:
-Proton driver for neutron/muon production
-Booster of the MR injection

Charge-exchange & Painting injection



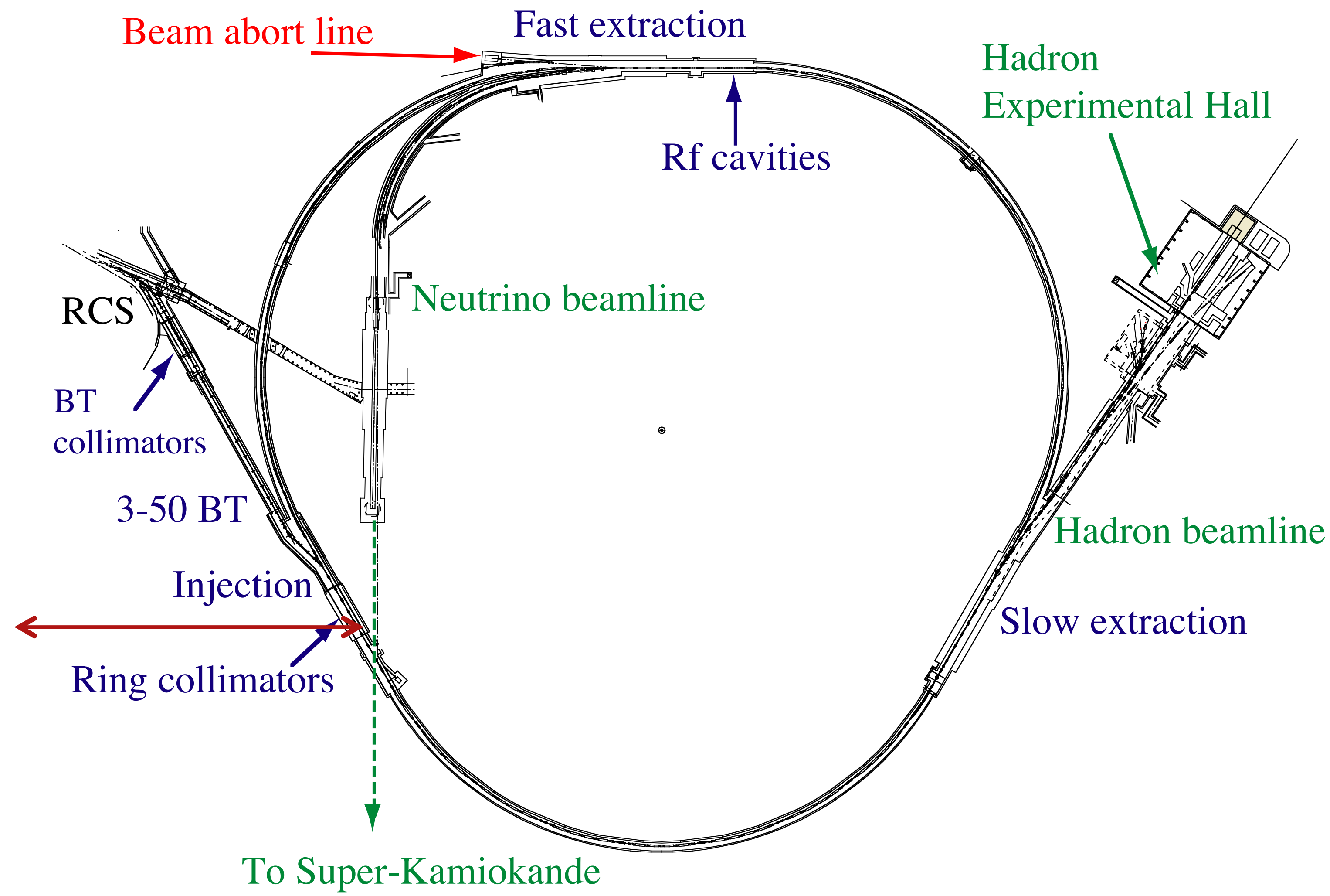
• Circumference	348.3 m
• Injection energy	400 MeV
•Extraction energy	3.0 GeV
• Repetition rate	25 Hz
• Output power	1.0 MW

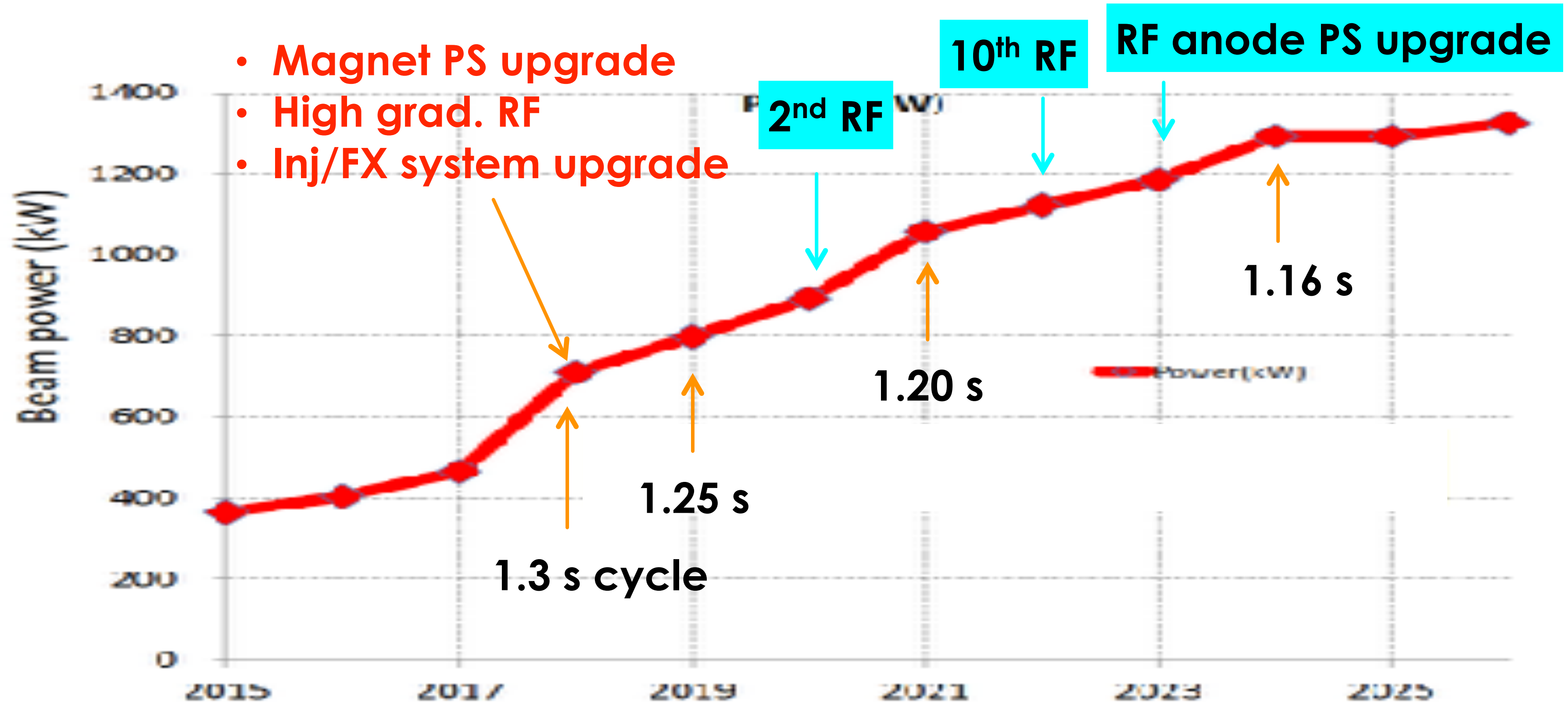


Main parameters of MR

Circumference	**1567.5 m**
Repetition rate	**~ 0.17 Hz for SX** **0.3 ~ 0.4 Hz for FX**
Injection energy	**3 GeV**
Extraction energy	**30 GeV**
Superperiodicity	**3**
h	**9**
Number of bunches	**8**
Rf frequency	**1.67 - 1.72 MHz**
Transition γ	**j 31.7 (typical)**

Physical Aperture	
3-50 BT Collimator	**54-65 π.mm.mrad**
3-50 BT physical ap.	**> 120 π.mm.mrad**
Ring Collimator	**54-65 π.mm.mrad**
Ring physical ap.	**> 81 π.mm.mrad**





Beam Power Plan

- 470 kW (today)
- 800 kW (2019)
- 1300 kW (2024)

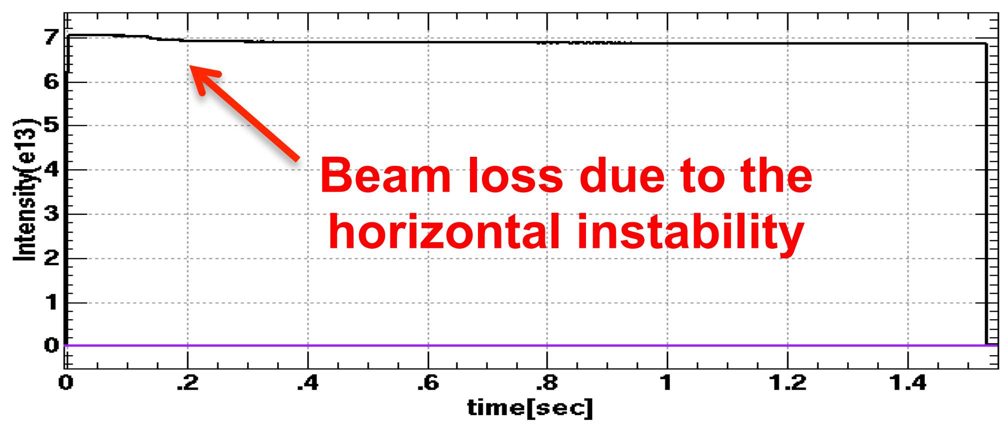
Mid-term plan of MR (Revised in Jan. 2017)

JFY	2015	2016	2017	2018	2019	2020	2021	2022
		New buildings →		HD Target	Long shutdown		Goal of RM2013	
FX power [kW]	390	470	480-500	> 500	700	800	900	1060
SX power [kW]	42	42	50	50-60	60-80	80	80-100	100
Cycle time of main magnet PS New magnet PS	2.48 s Mass production installation/test →			2.48 s	1.3 s	1.3 s	1.3 s	1.3 s
High gradient rf system 2nd harmonic rf system	Installation → Manufacture, installation/test →						- - →	- - →
Ring collimators	Add.coll imators (2 kW)				Add.colli. (3.5kW)			
Injection system FX system	Kicker PS improvement, Septa manufacture /test → Kicker PS improvement, FX septa manufacture /test →						- - →	- - →
SX collimator / Local shields					Local shields →			
Ti ducts and SX devices with Ti chamber			ESS					

High Intensity beam study in June 2015 (cont'd)

- at the new betatron tune (22.239, 21.310) -

High power trial with two bunches



Extracted beam : 3.41e13 ppb
6.82e13 ppp (132 kW eq. ,2 bunches)

	Beam loss[Watt]	
INJ(K1+K2+K3+K4)	144	7.43e+11
P2 --> +90ms	241	1.00e+12
P2+90ms --> +120ms	31	1.30e+11
P2+100ms ---> EXT		1.83e+11

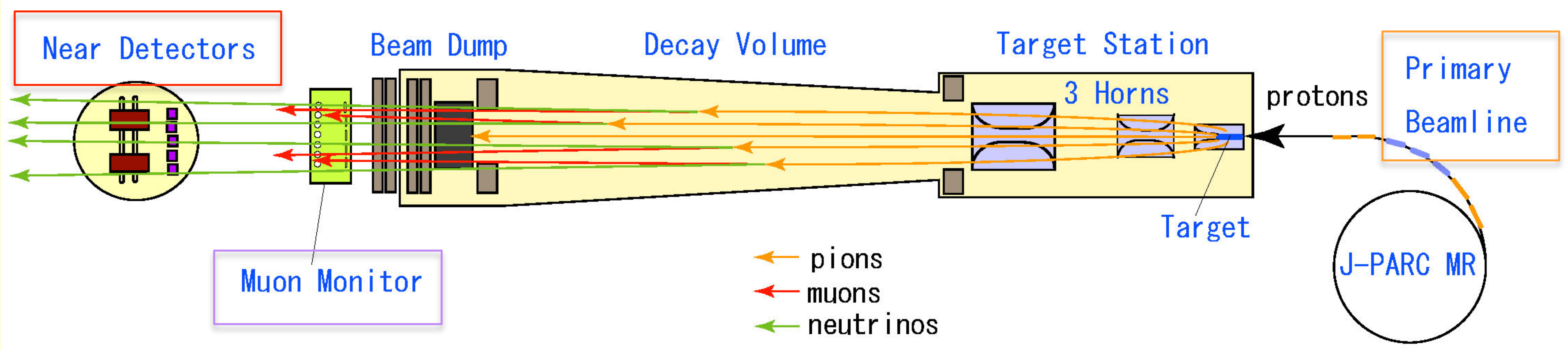
Total beam loss ~ 420 W

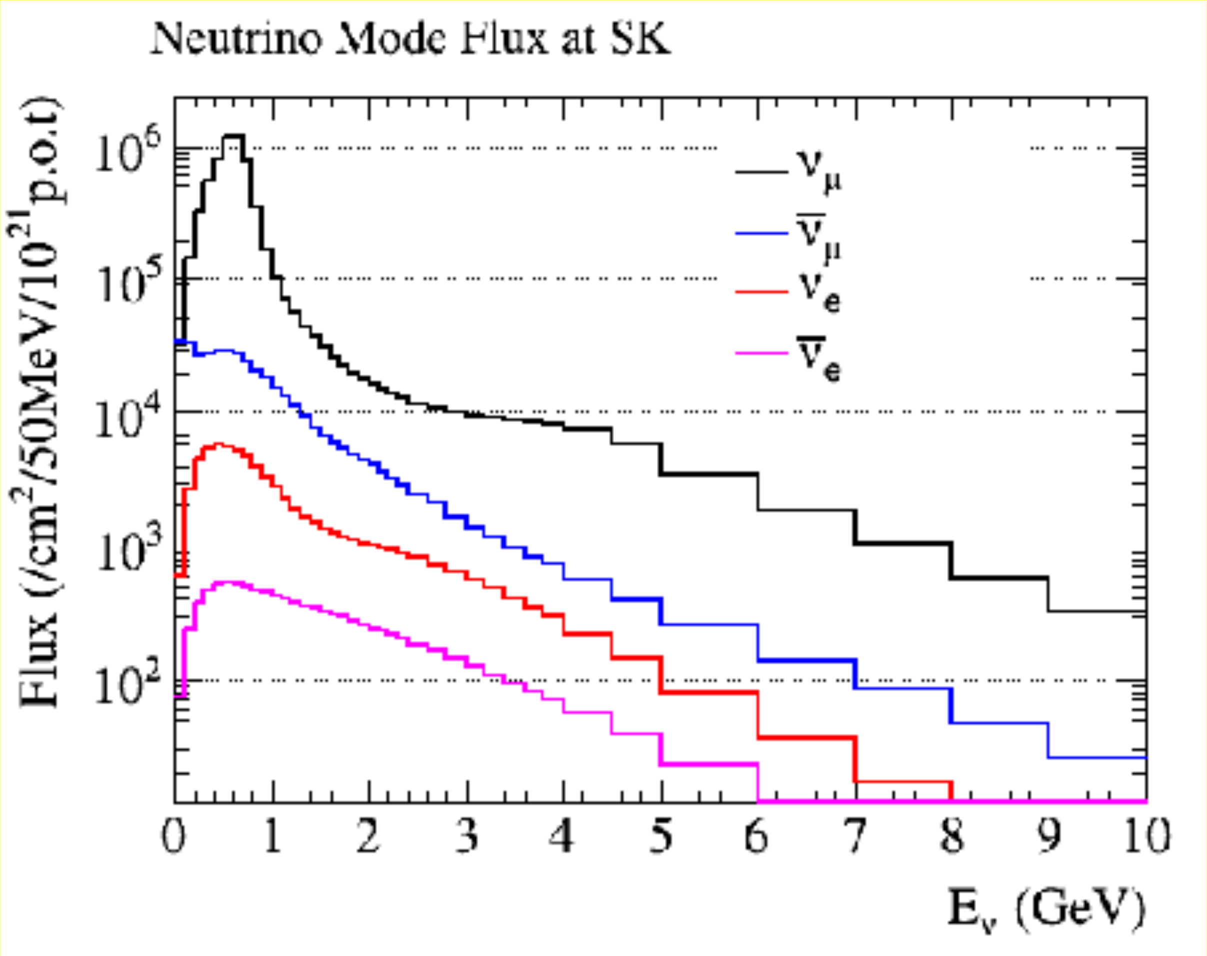
Near future tunable knobs to reduce the beam loss:
Injection kicker, BxB feed-back,
2nd harmonic cavity, VHF cavity, etc.

	Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
1	2	2.48	132	0.42	measurement
2	8	2.48	529	1.7	estimation
3	8	1.3	1009	3.2	estimation

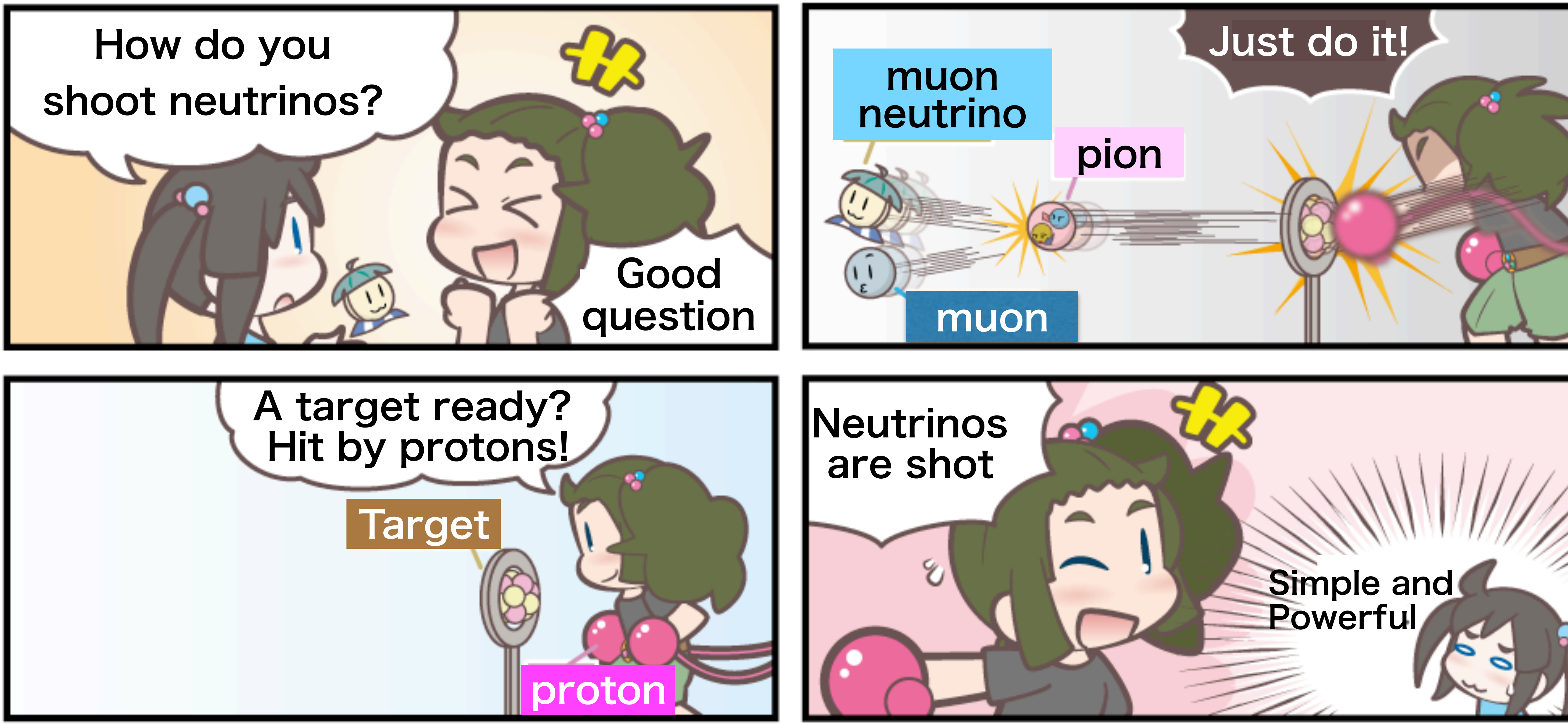
The MR has capability to reach 1MW with the high repetition rate operation.

3. Neutrino Beam



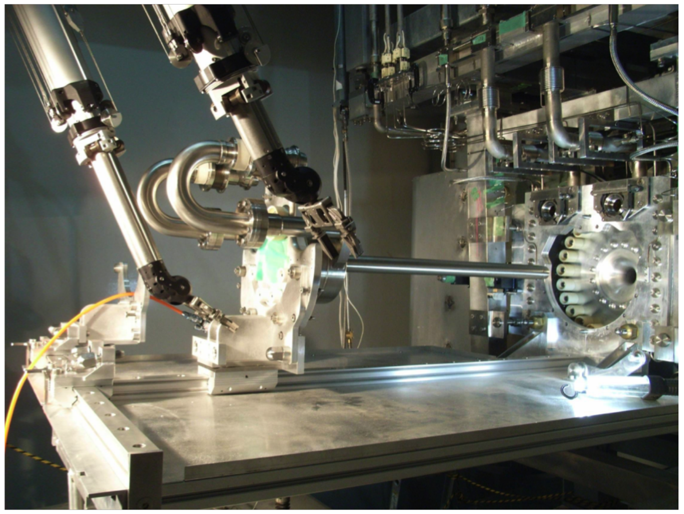


How to make neutrinos



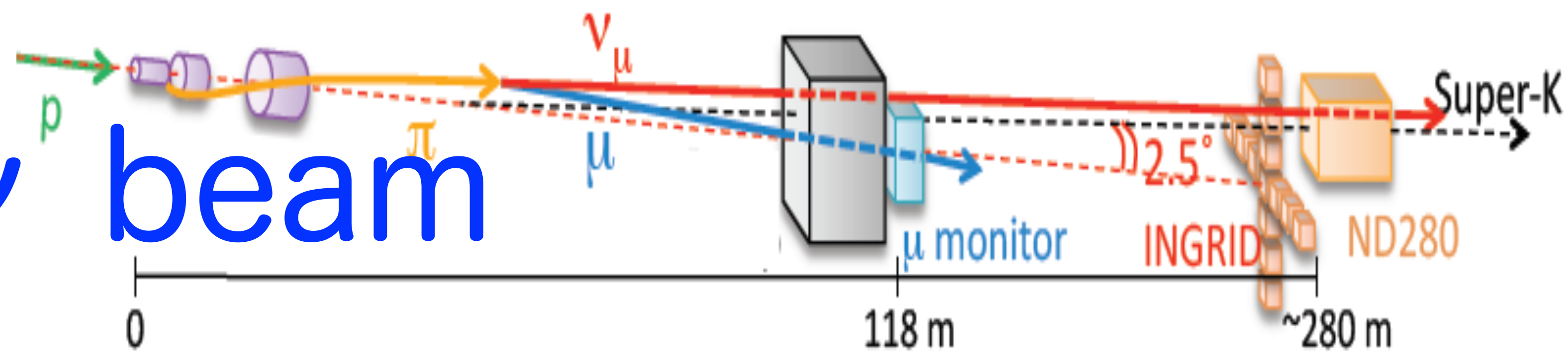
- **Proton Punch**：J-PARC's special.

- **Target**：will be hit by powerful protons

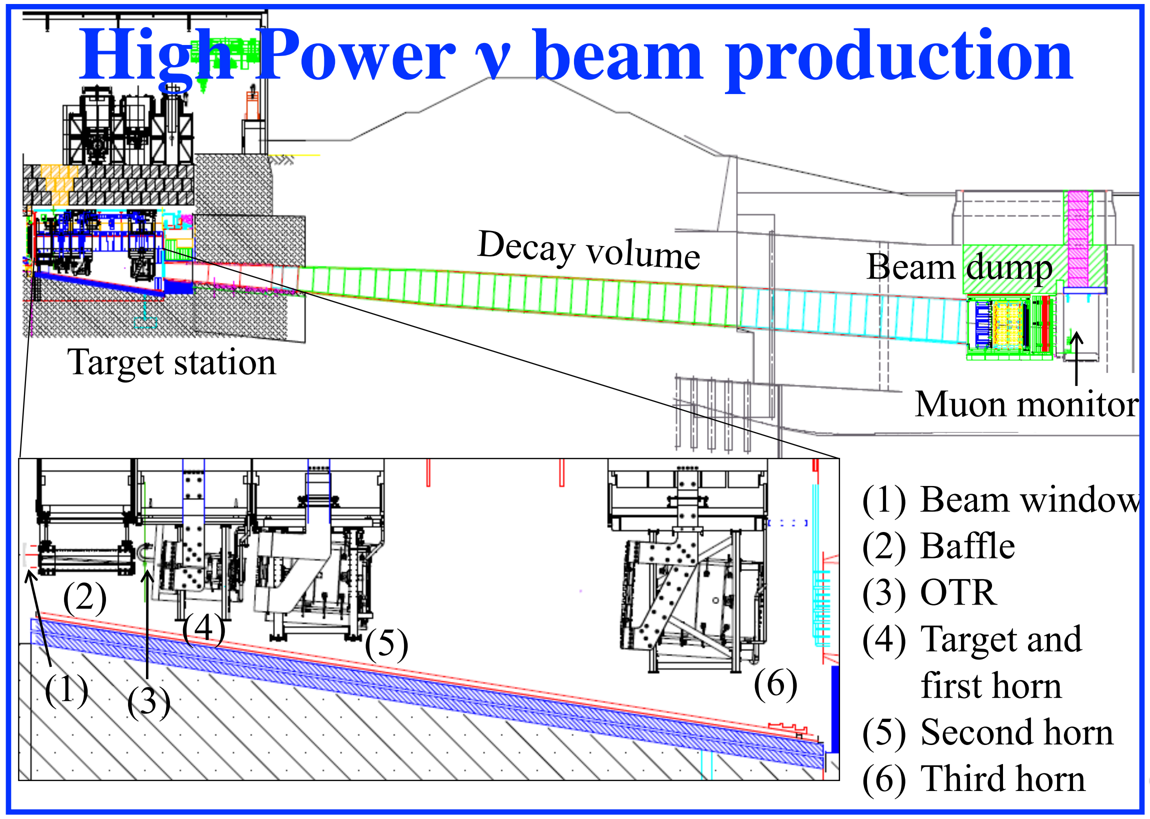


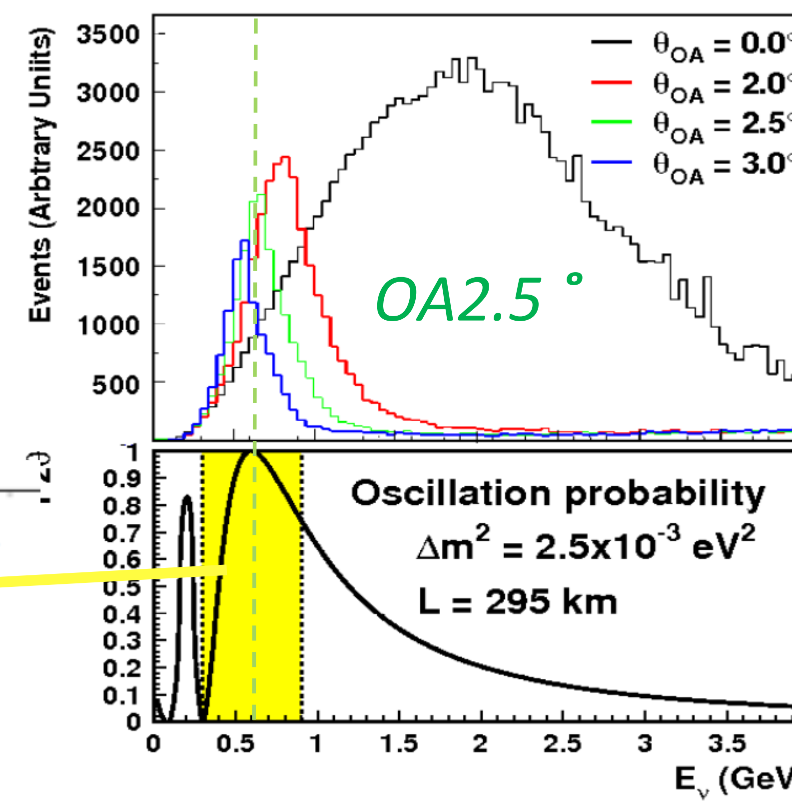
Target + remote handling system

T2K ν beam

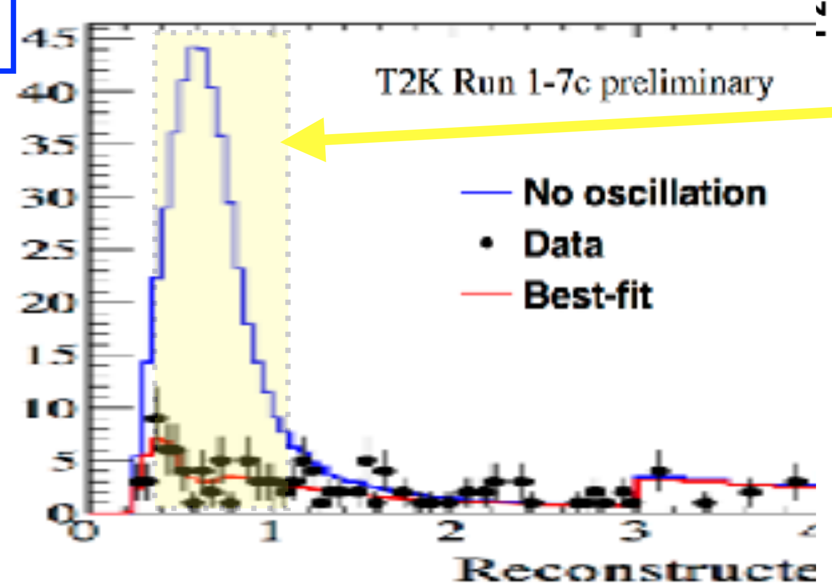


- **Off-axis (2.5 °) ν_μ beam**
  - Intense, low energy narrow-band
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - 1mrad direction shift => ~2% energy shift at peak
  - Small ν_e fraction (~1%)





T2K 2016 ν_μ disappearance



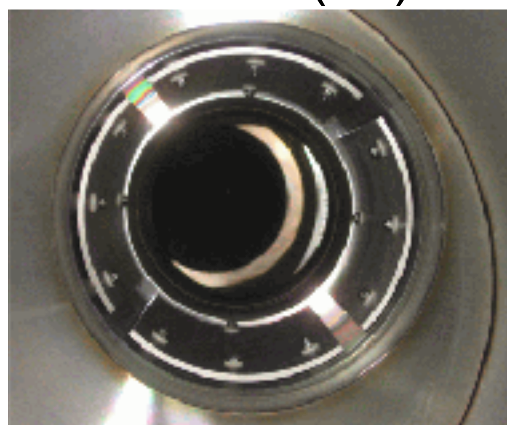
- 30 GeV **~1×10^{14}** protons extracted every 2.5/1.3 sec. directed to the carbon target.
- Secondary π^+(and K^+) focused by three electromagnetic horns (**250kA/320kA**)
- ν_μ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e in the beam come from K and μ decays

J-PARC ν beam line :Primary-line

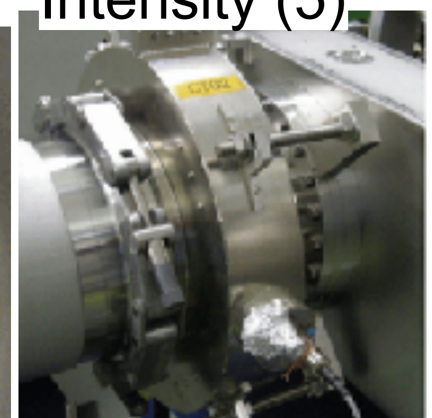
Beam monitors are install along the proton beam transport

Profile (19)

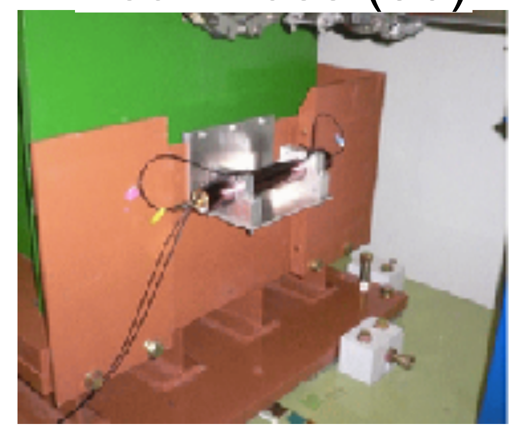
Position (21)



Intensity (5)

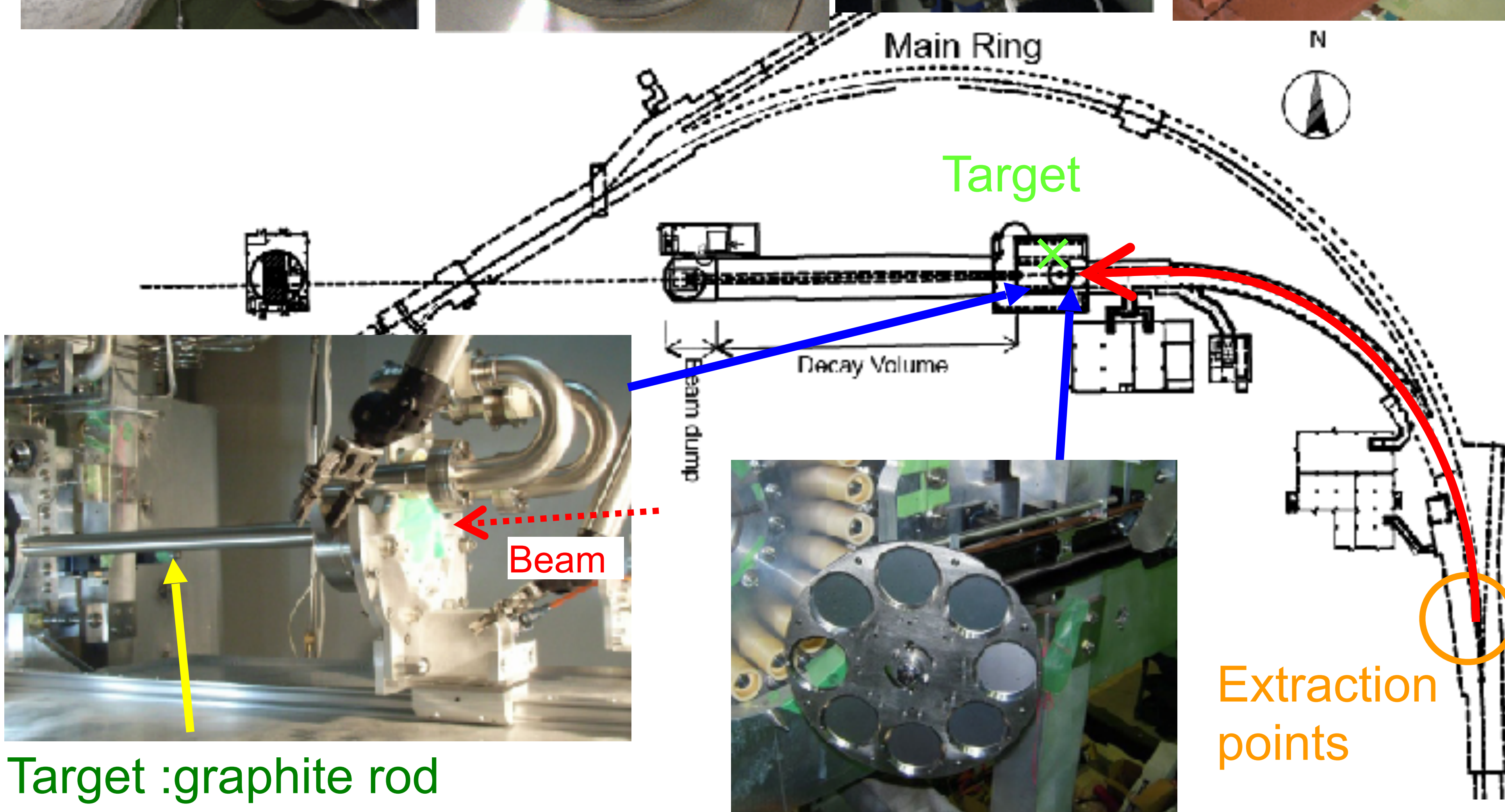


Beam loss (50)



Primary proton transport line

Super-conducting combined-function magnets

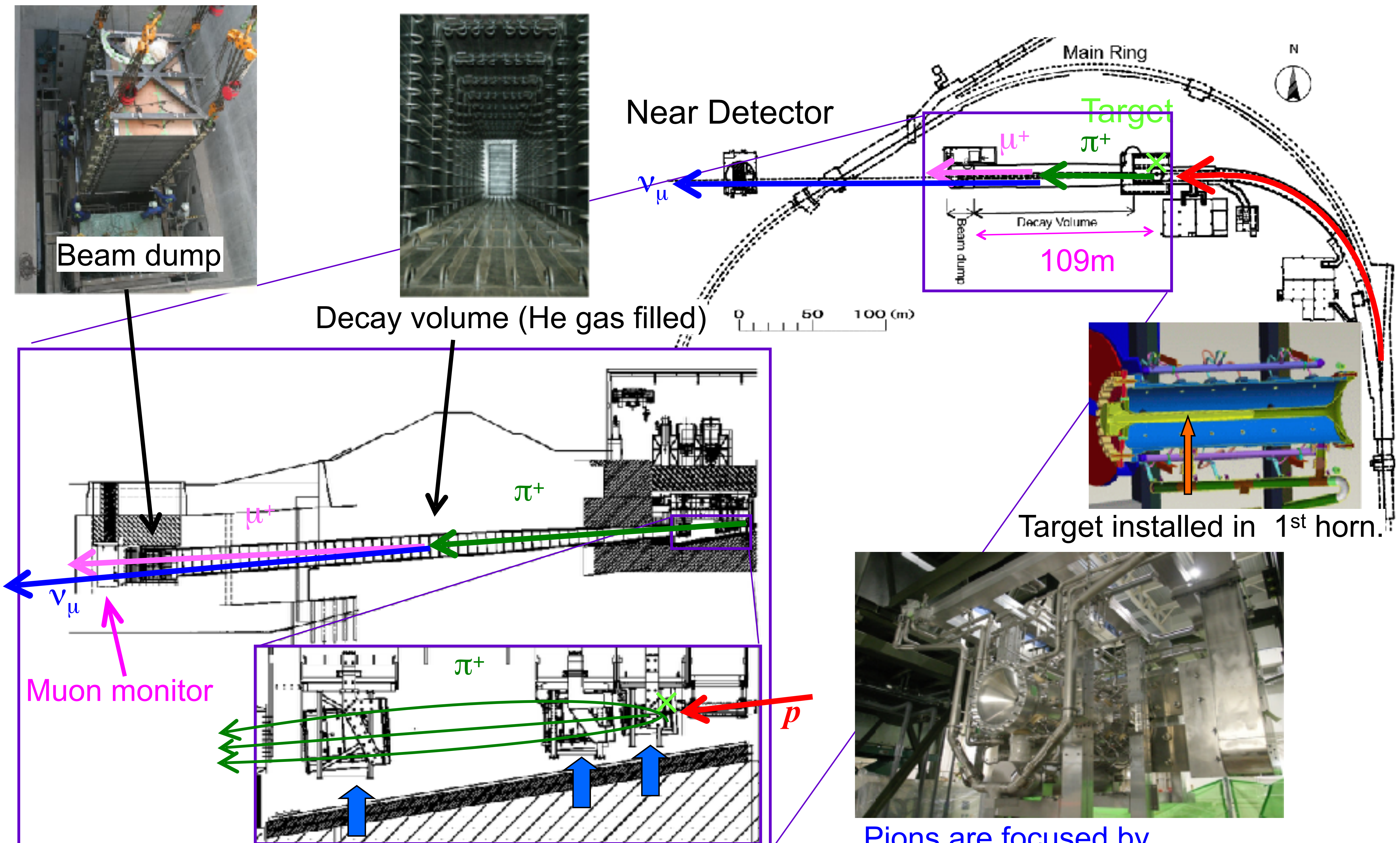


Target :graphite rod
ϕ26mm,L=900mm

Optical Transition Radiation (OTR) Profile monitor

Normal-conducting magnets

J-PARC ν beam line: secondary line



Pions are focused by 3 electromagnetic Horns.

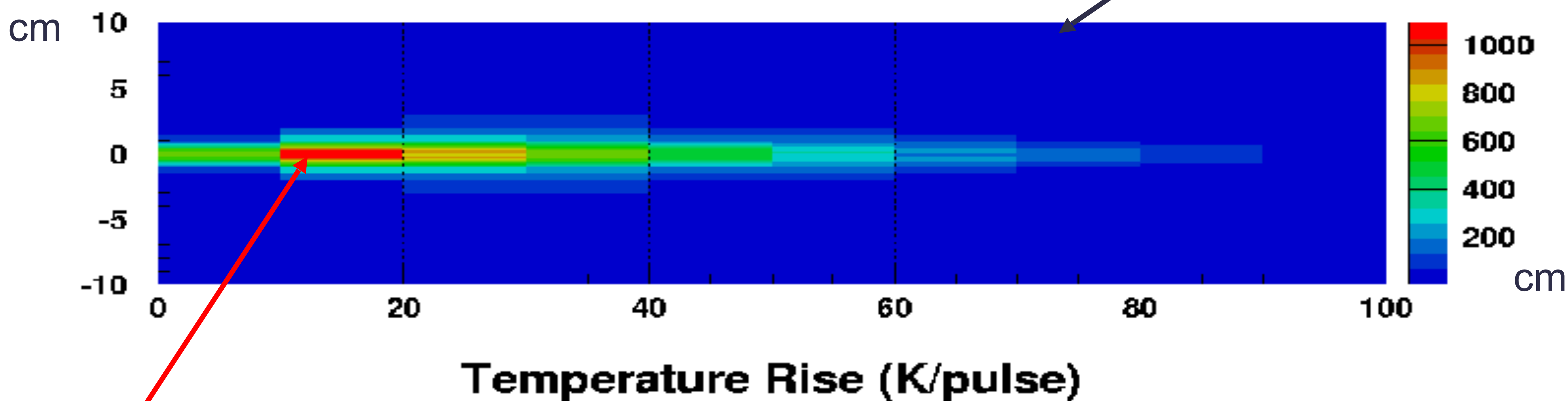
More neutrinos with more beam

Original Design: 7 5 0 k W beam!

- 3×1014 Protons-On-Target (POT) every 2.5 sec.
- If the target made of iron,

radiation

> 1000Sv/h



1100℃

(cf. melting point 1536℃)

✓ melting

✓ broken $\approx E\alpha\Delta T \approx 3GPa$

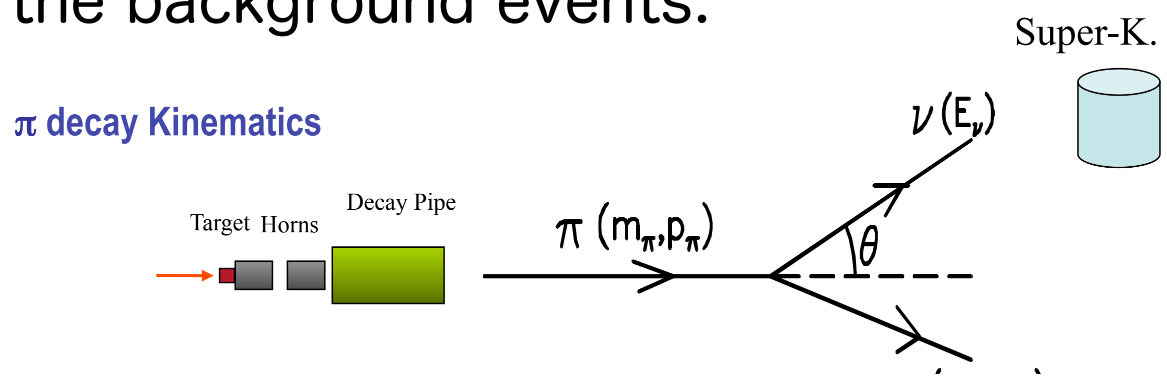
(cf. ~300 MPa)

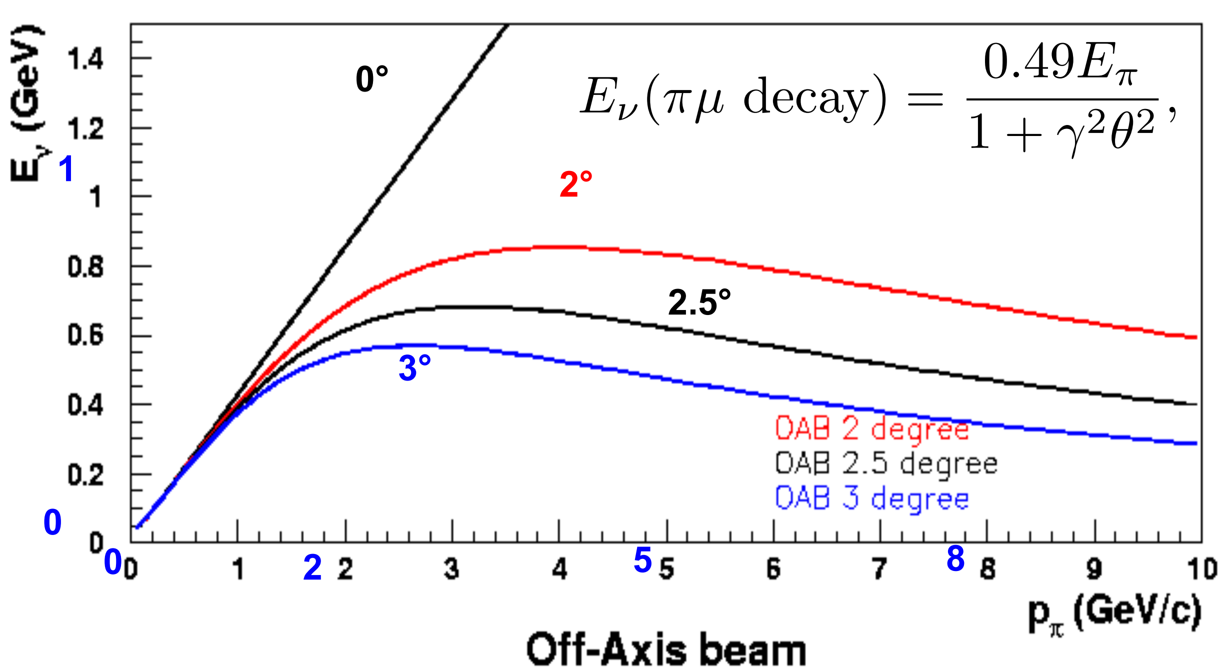
Any metal heavier than Ti will be broken.

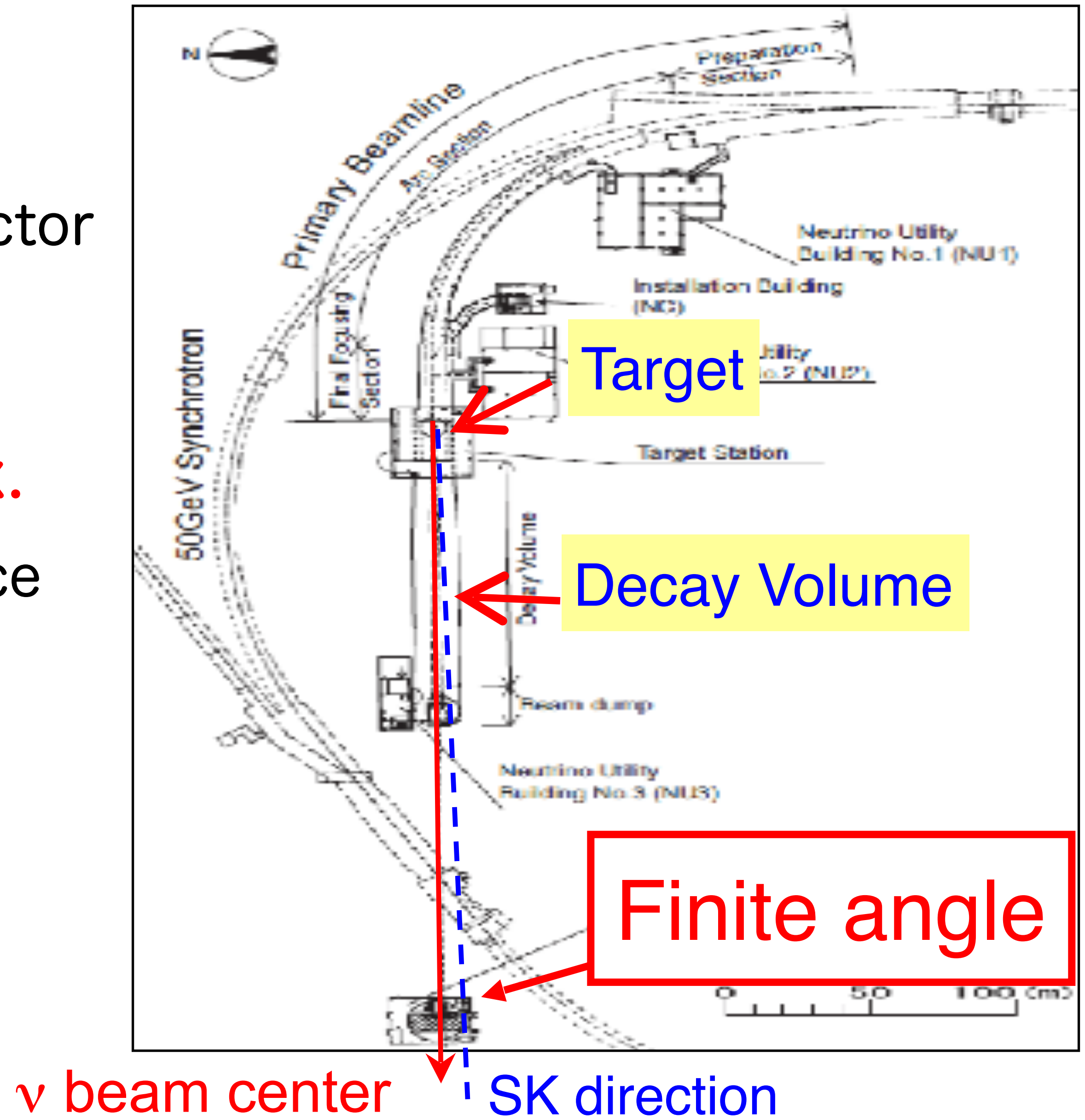
※Beam Power is proportional to #protons/sec × proton Energy

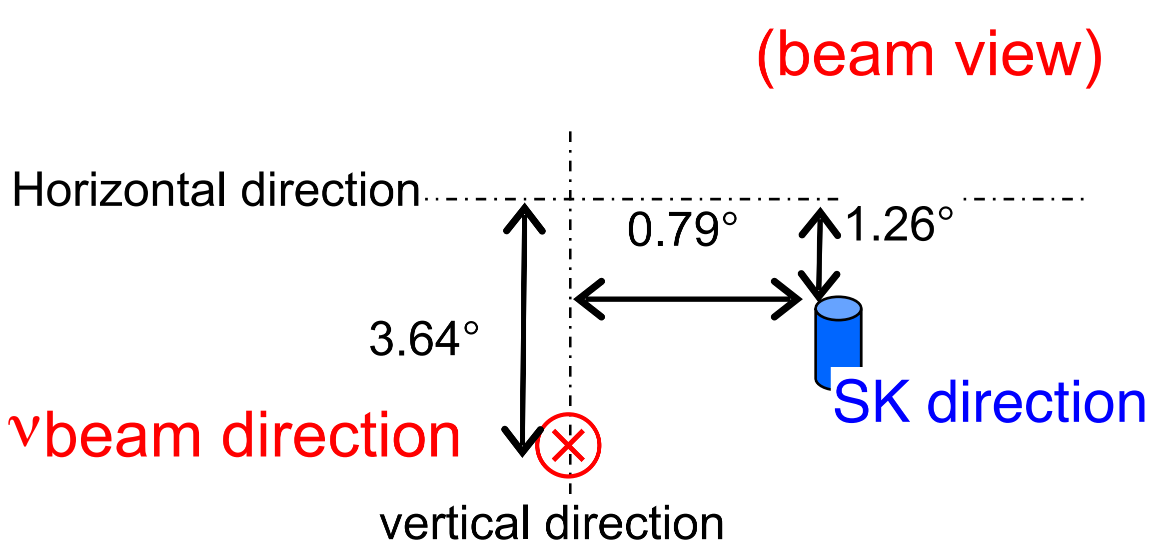
Off axis beam

- Pseudo-Monochromatic beam by Off-Axis method (ref. BNL E899)
  - ν_μ beam direction is different from Far detector direction.
  - Current Off axis angle is 2.504°
- Set peak of (flux × σ_{CC}) @ oscillation max.
  - Minimize the high energy neutrino flux to reduce the background events.

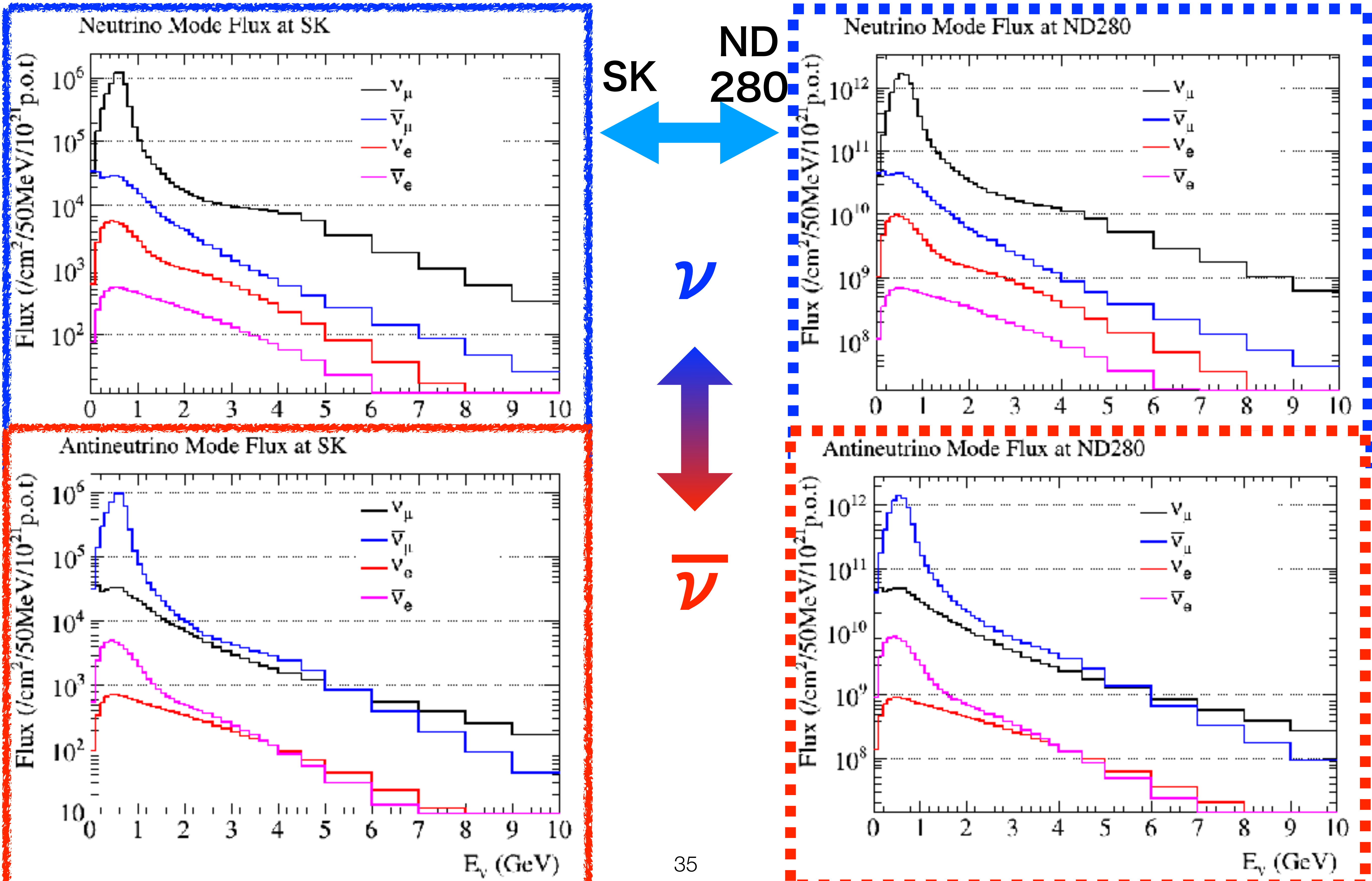


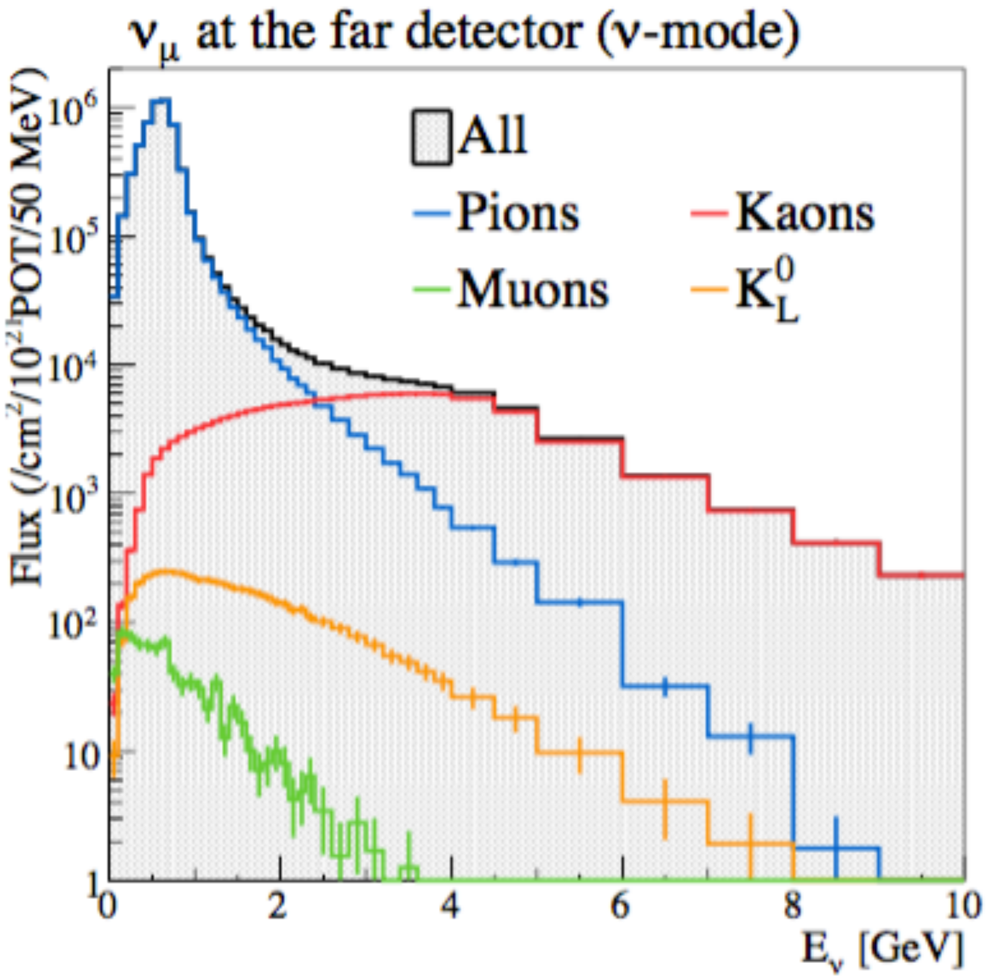




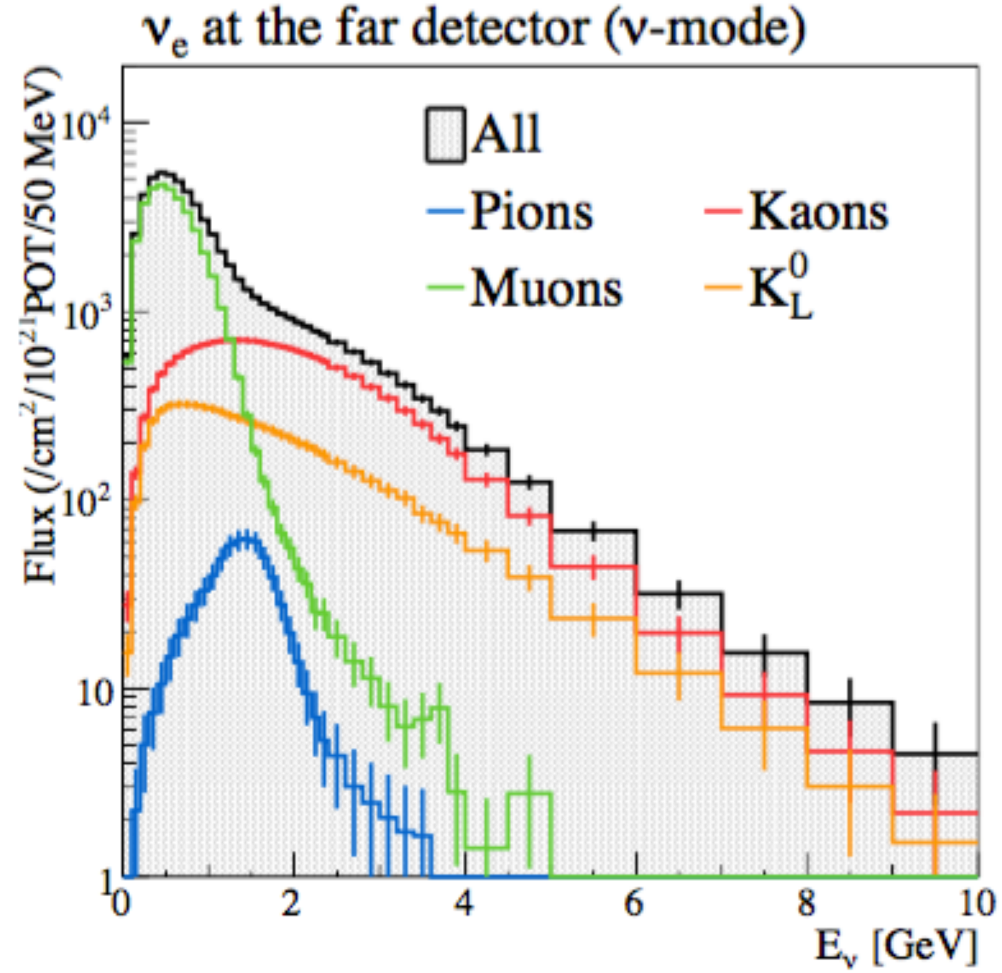


Predicted Neutrino Flux





ν_μ (anti-ν_μ) : pions at low E_ν, kaons at large E_ν



ν_e : muons at at low E_ν, kaons at high E_ν
anti-ν_e : kaons for all E_ν

ν_μ parents:

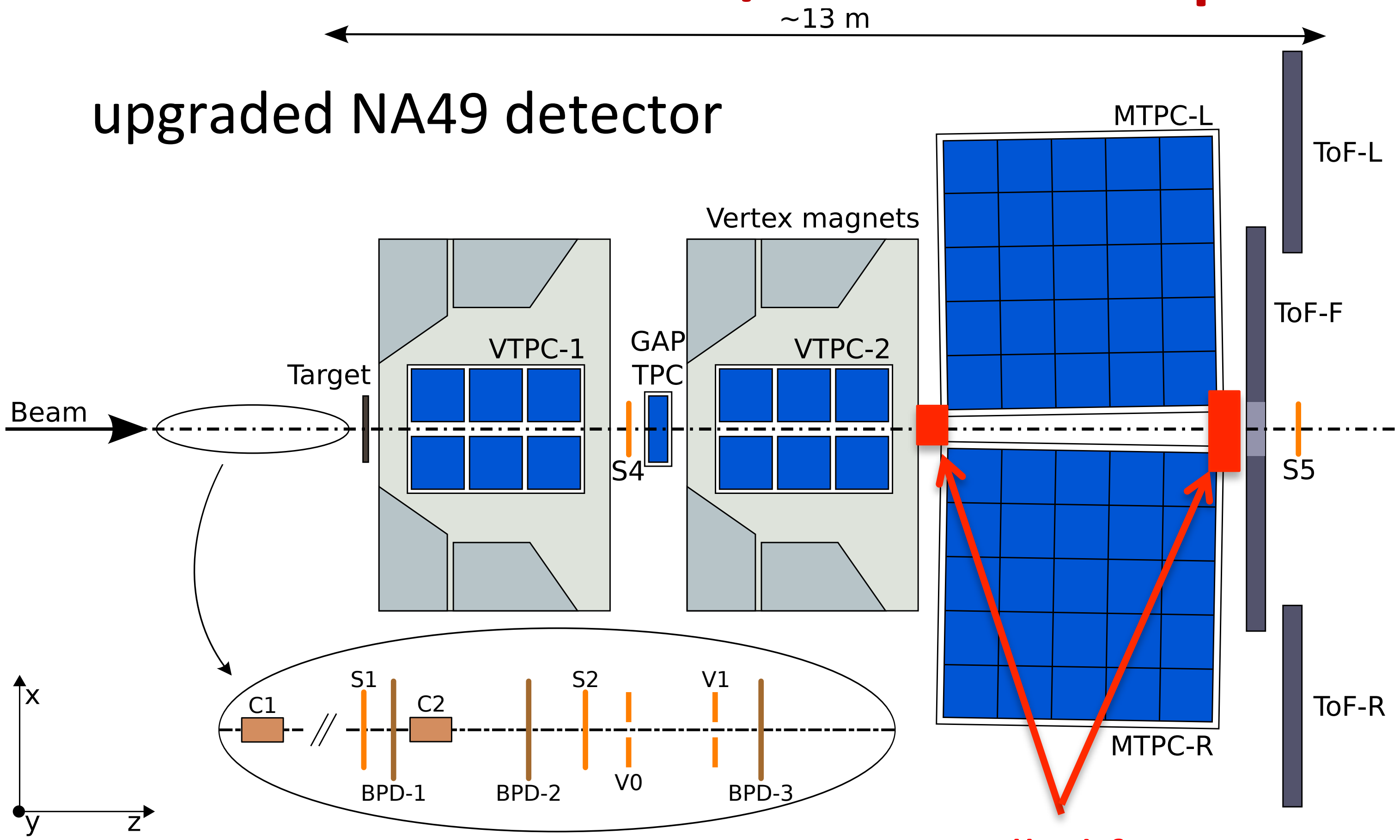
1. π
2. K^+

ν_e parents:

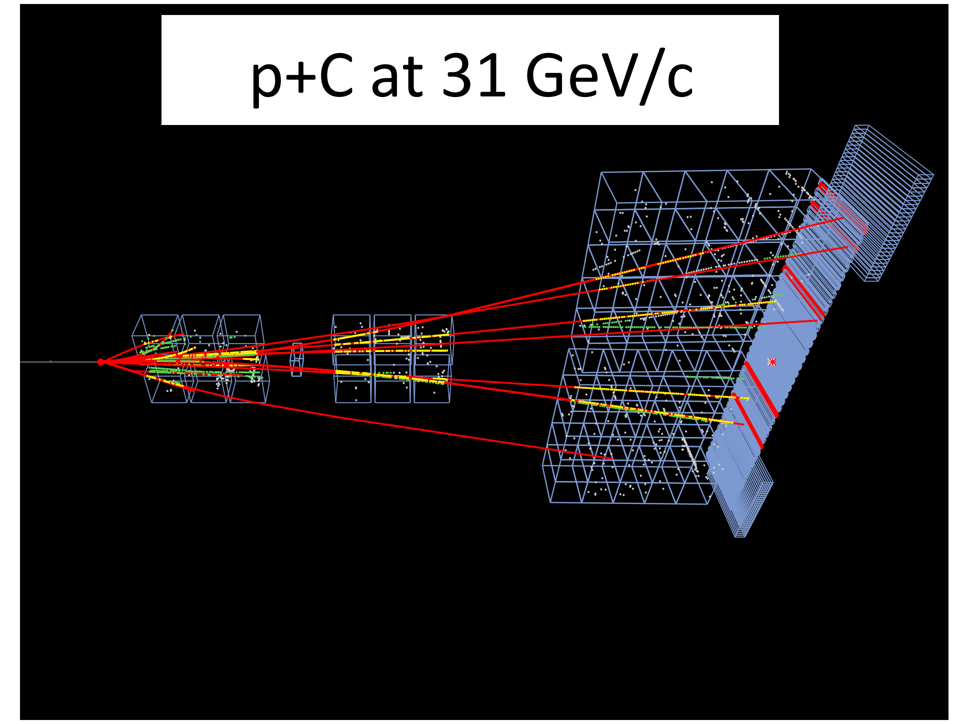
1. μ
2. K^+

NA61/SHINE Experimental Setup

upgraded NA49 detector



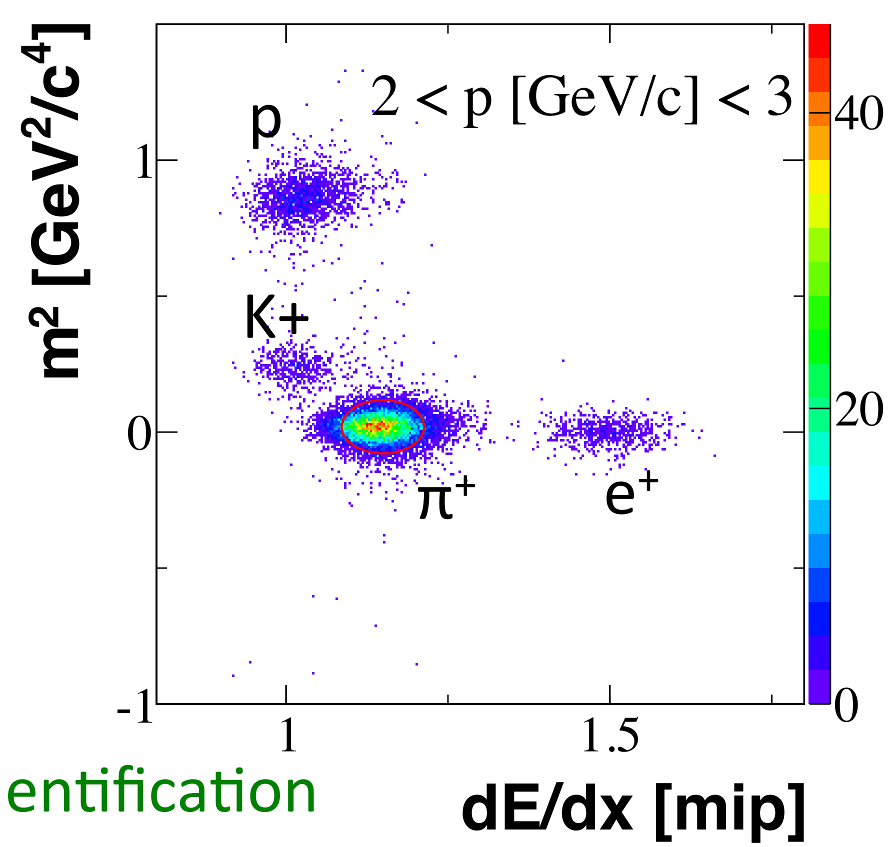
new FTPC installed for 2017 run



Fixed target experiment at CERN SPS with the large acceptance spectrometer

- **Time Projection Chambers** : tracking and particle identification
  - Momentum resolution $\sigma(p)/p^2 \approx 10^{-4}$ $(GeV/c)^{-1}$
  - Particle identification : $\sigma(dE/dx)/ \langle dE/dx \rangle \approx 4\%$
- **Time of Flight :** particle identification
  - New ToF-F array installed to fully cover T2K acceptance
  - Time resolution σ(t)ToF-F ≈ 120ps, σ(t)ToF-L/R ≈ 80ps

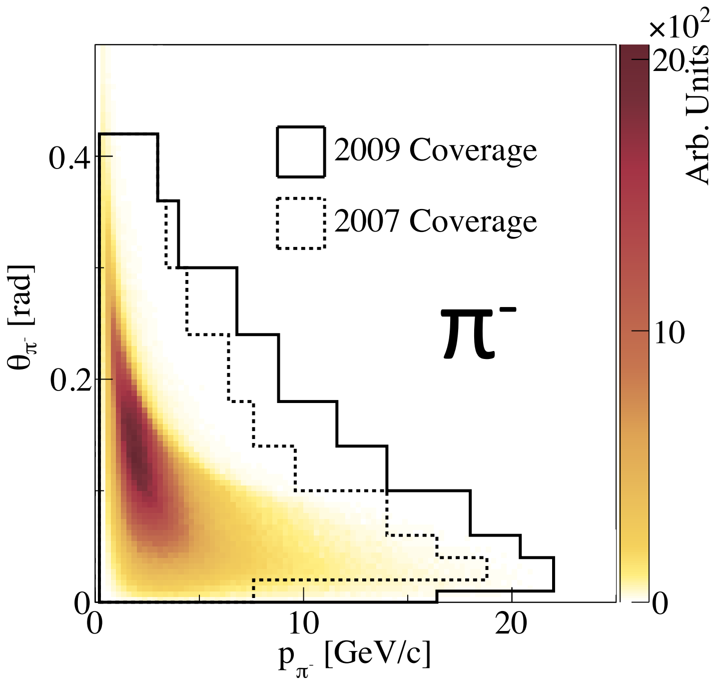
Combined dE/dx + ToF for π^+

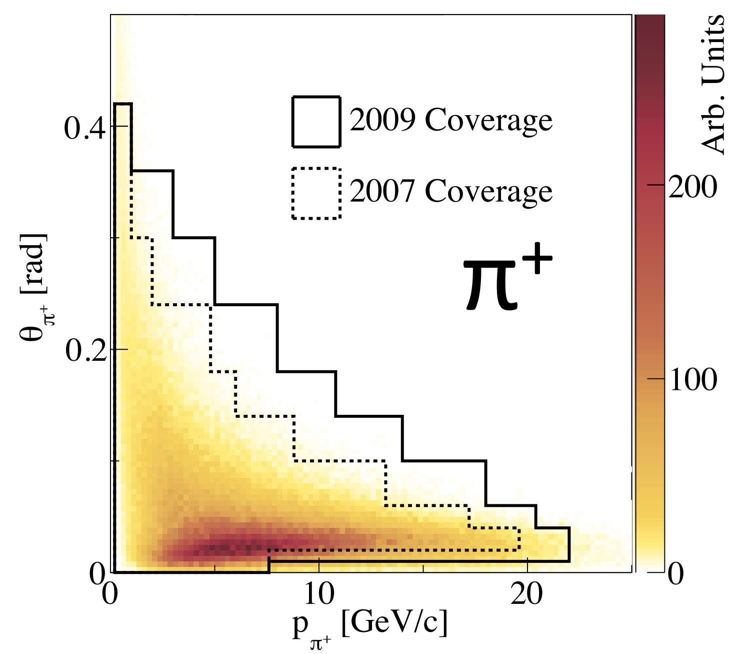


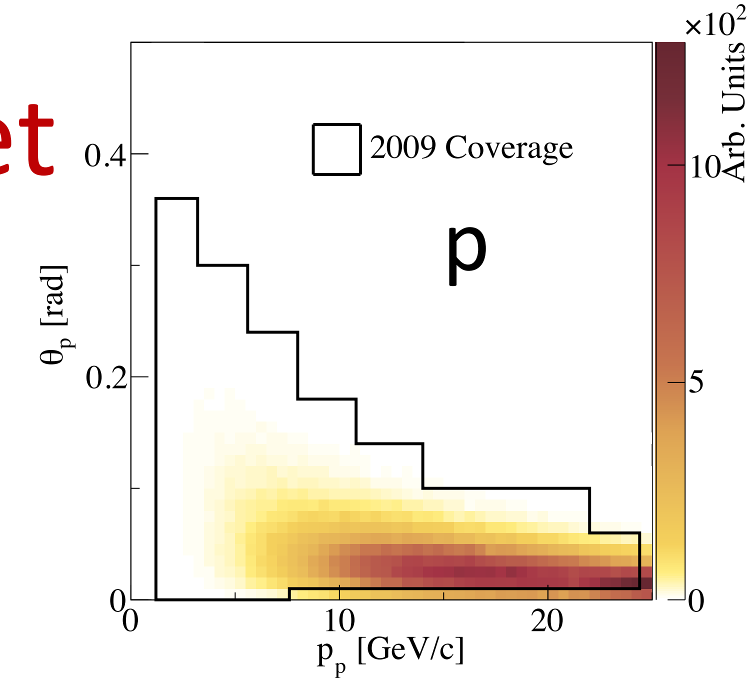
TPC and ToF detectors provide very good particle identification

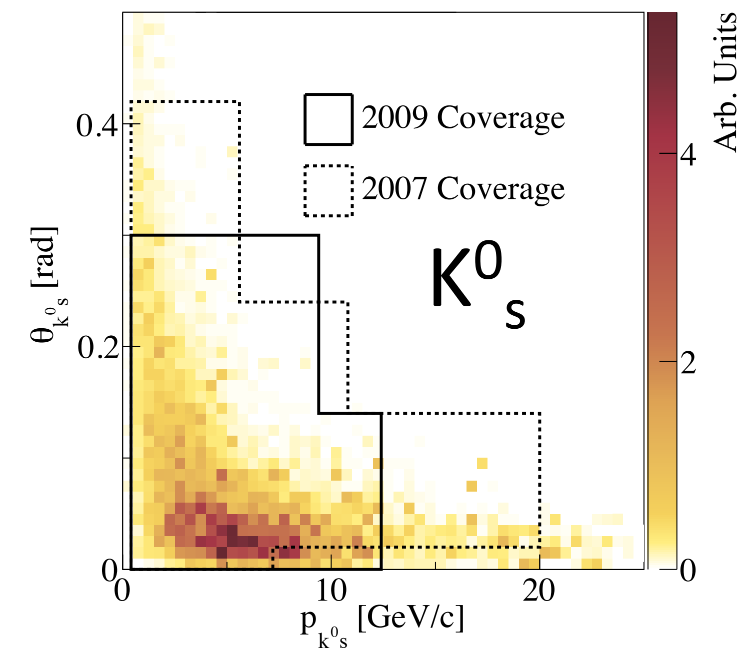
Hadron Measurements on Thin Target

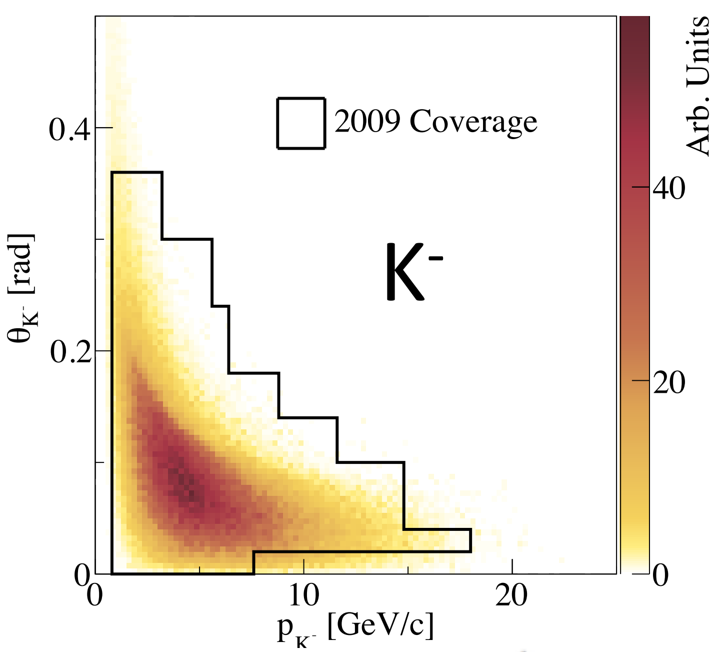
The phase space contributing to the predicted neutrino flux at SK and the NA61 data coverage.

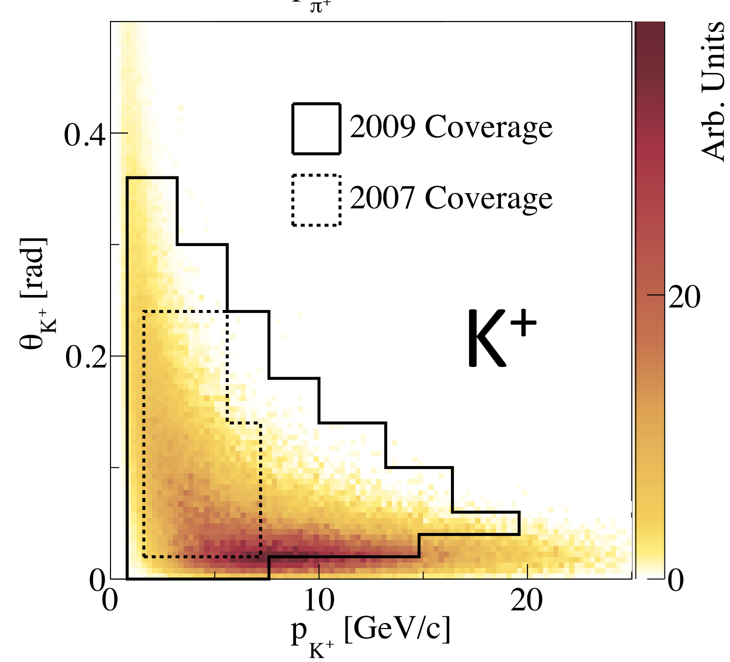


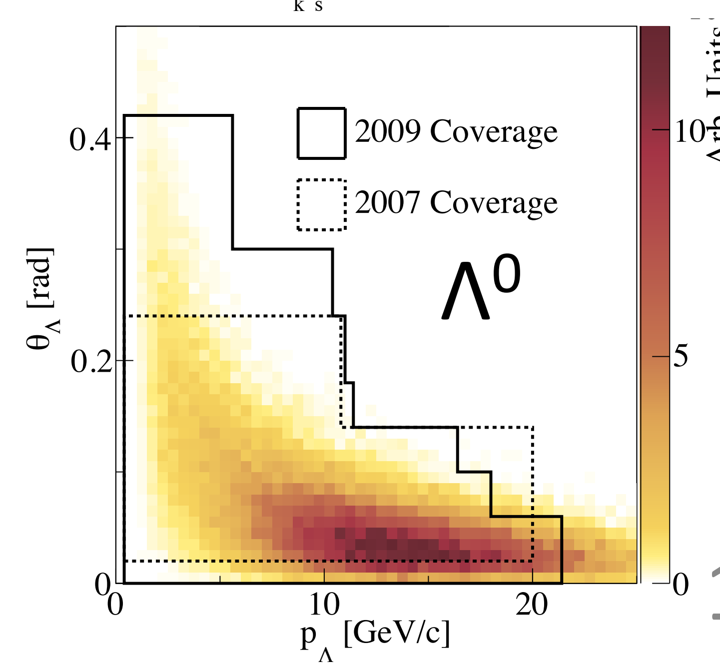


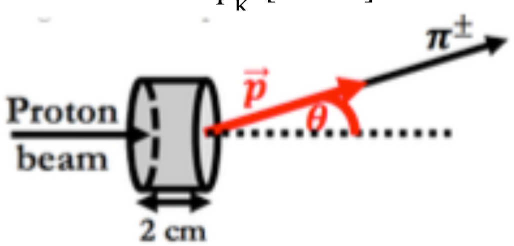








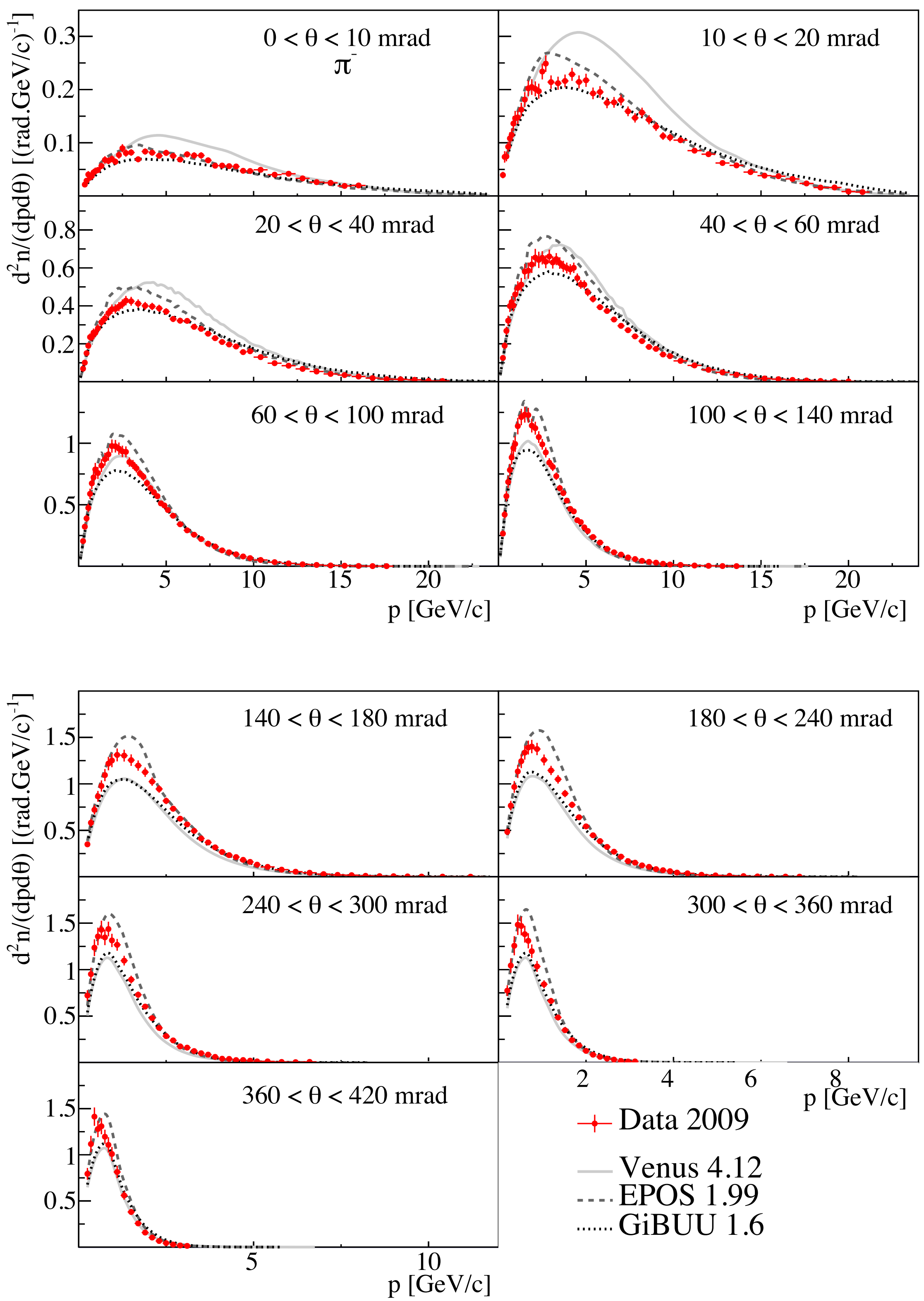




NA61 provides good coverage of required phase-space

Measurements with Thin Target Data

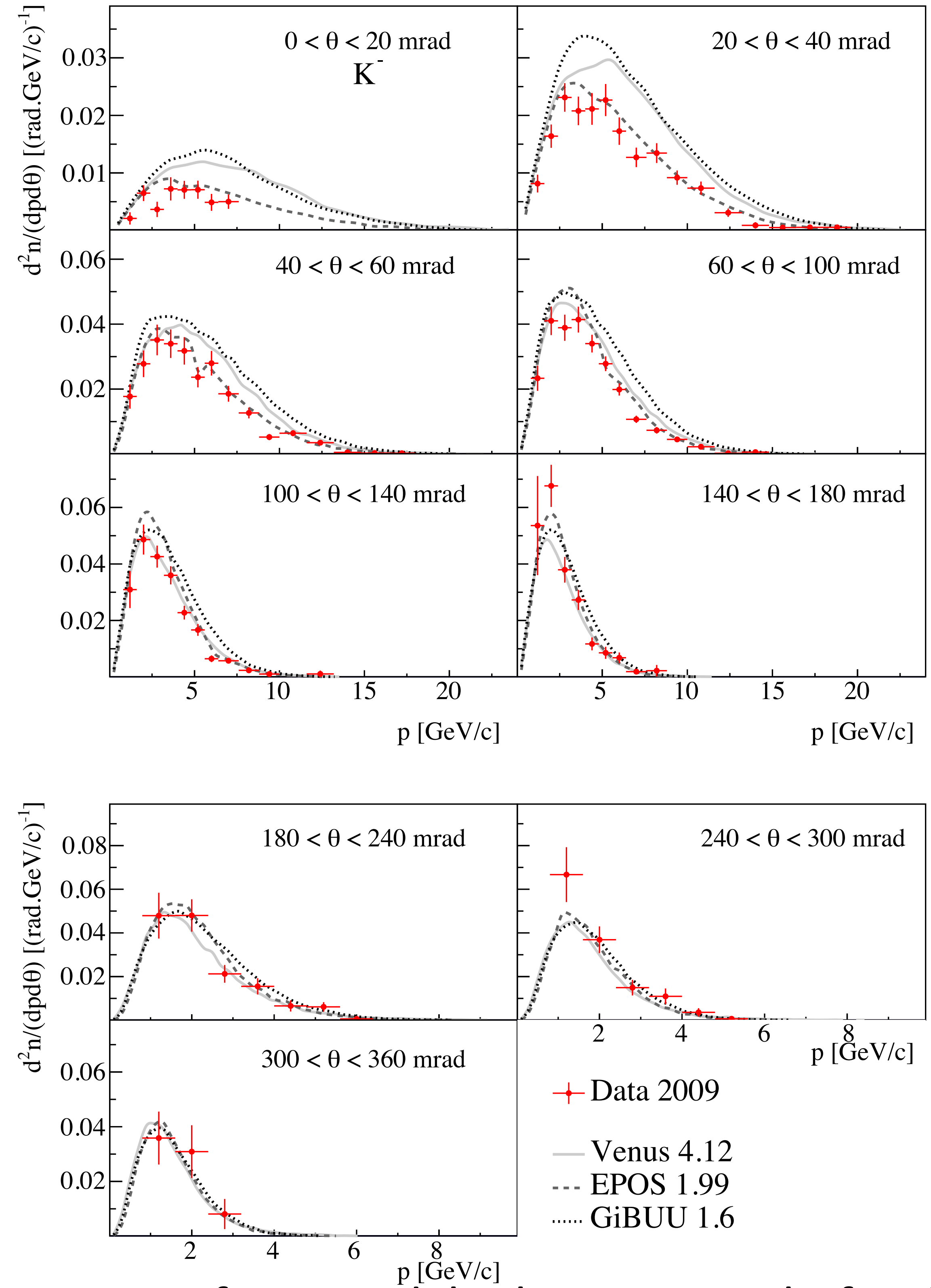
π^- Multiplicities



Relative errors ~4%

Published: Eur.Phys.J.C76 (2016) no.2, 84

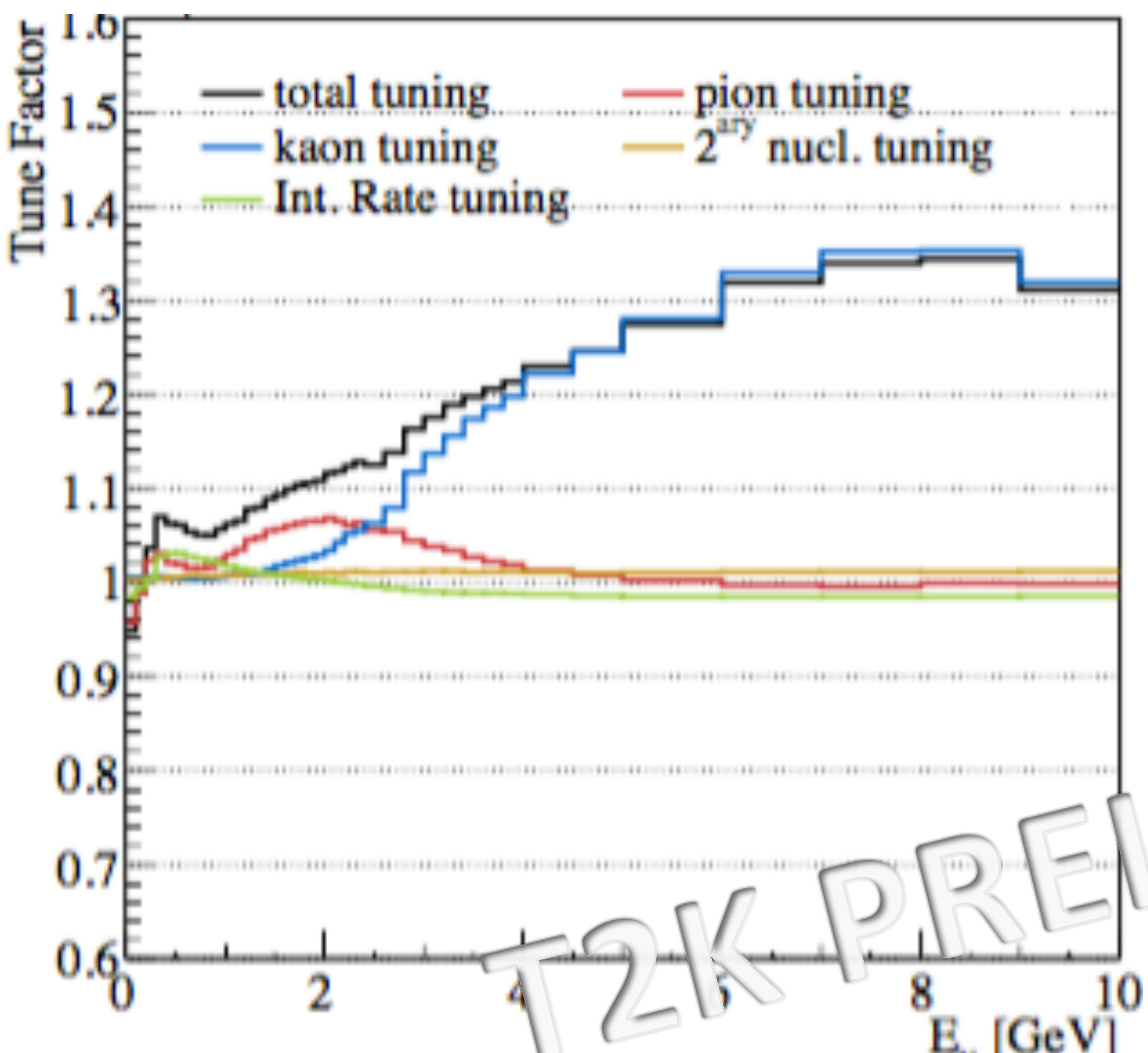
K^- Multiplicities



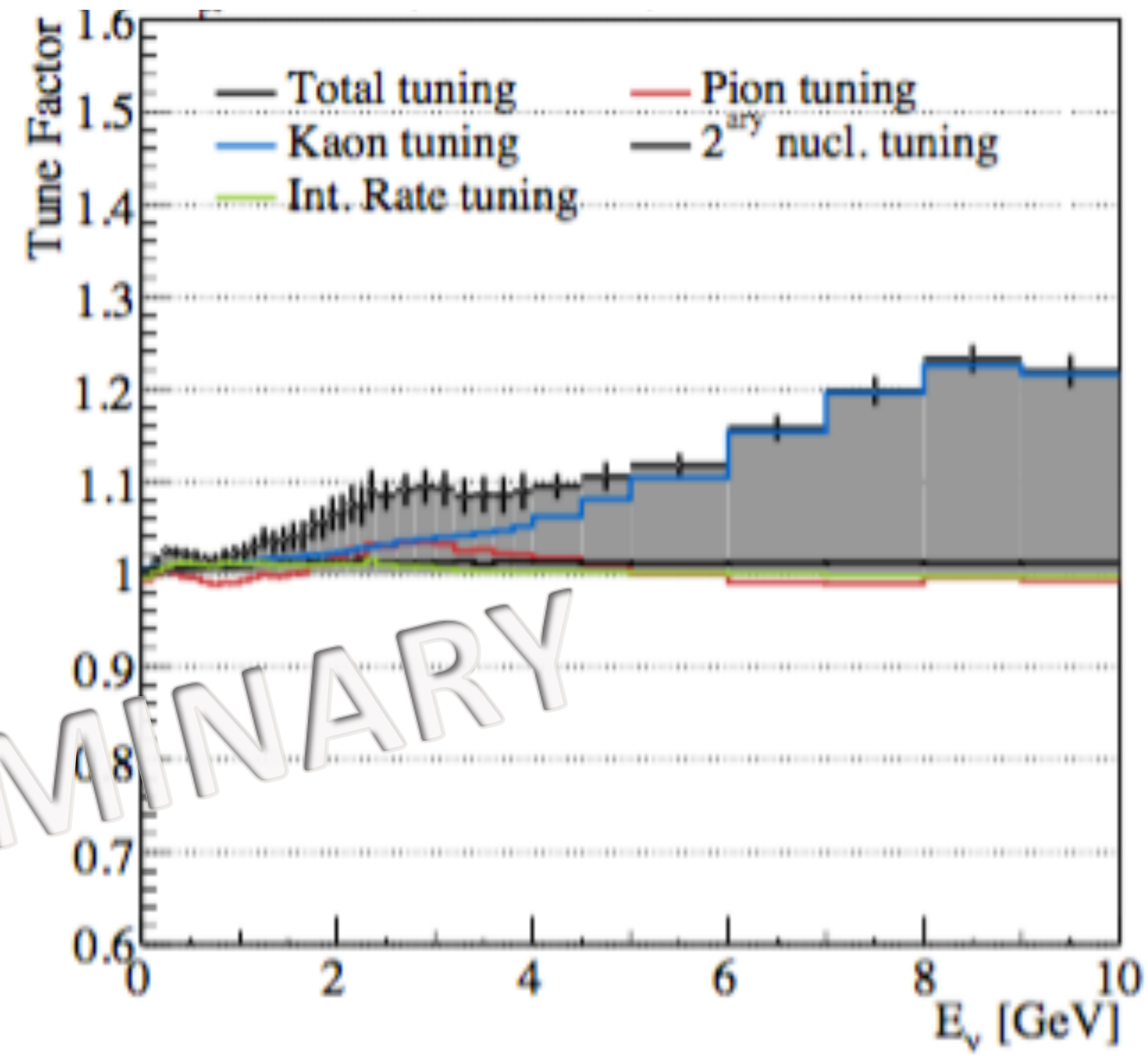
Important for ν_e and high-energy tail of ν_μ flux

Relative errors ~15%

ν_μ at SK



anti-ν_μ at SK

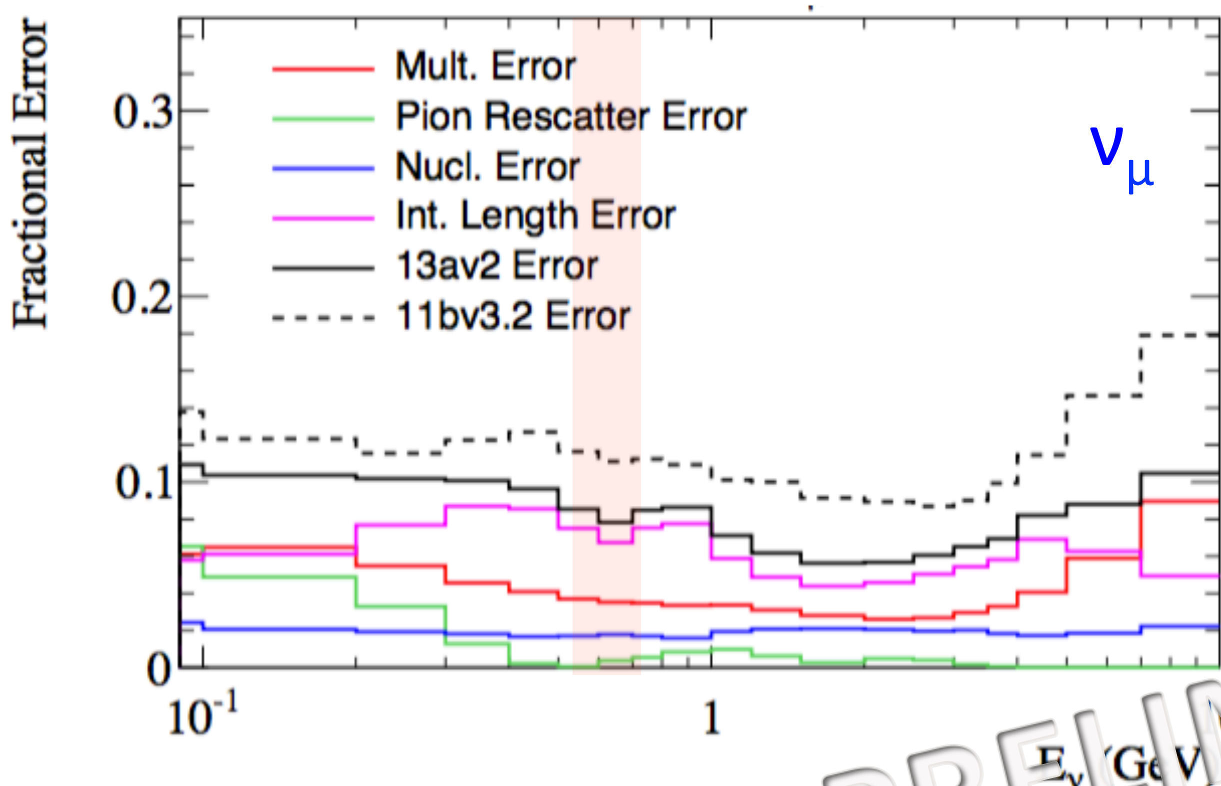


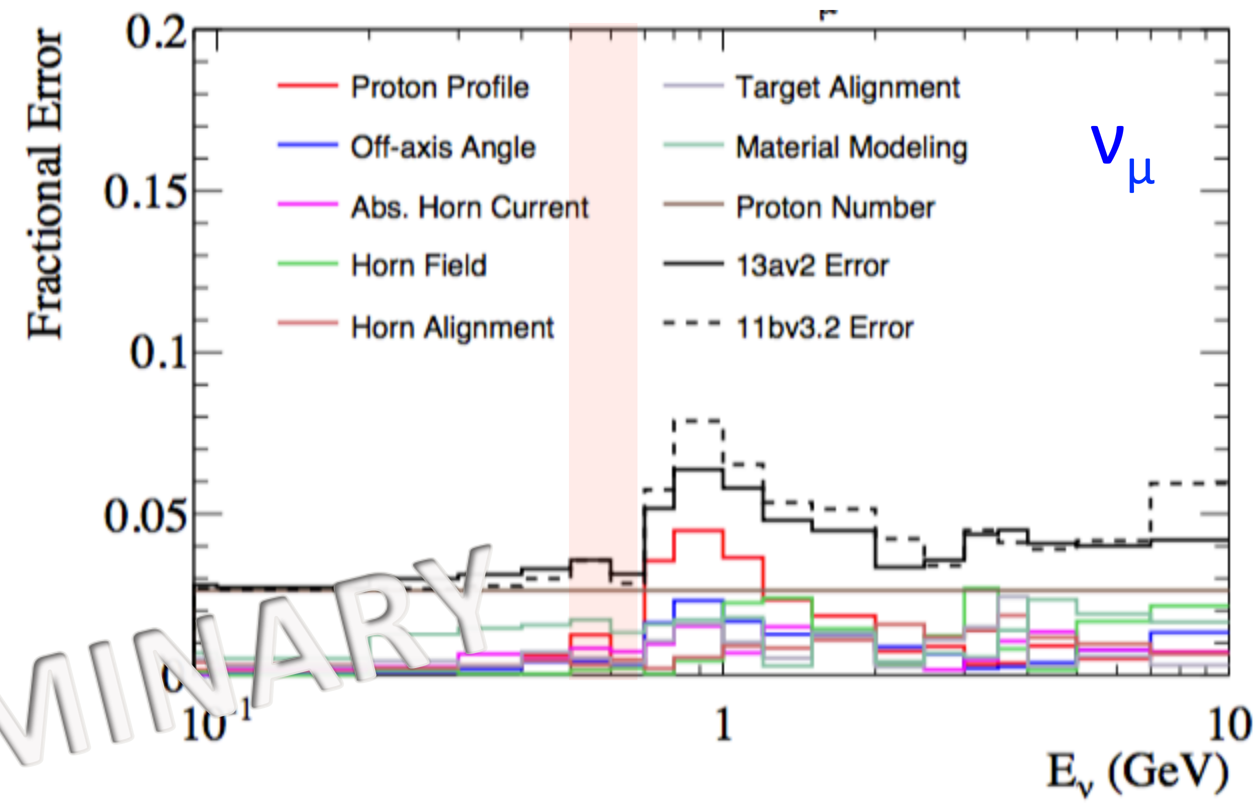
Flux Uncertainties at SK

Hadron Modeling Part

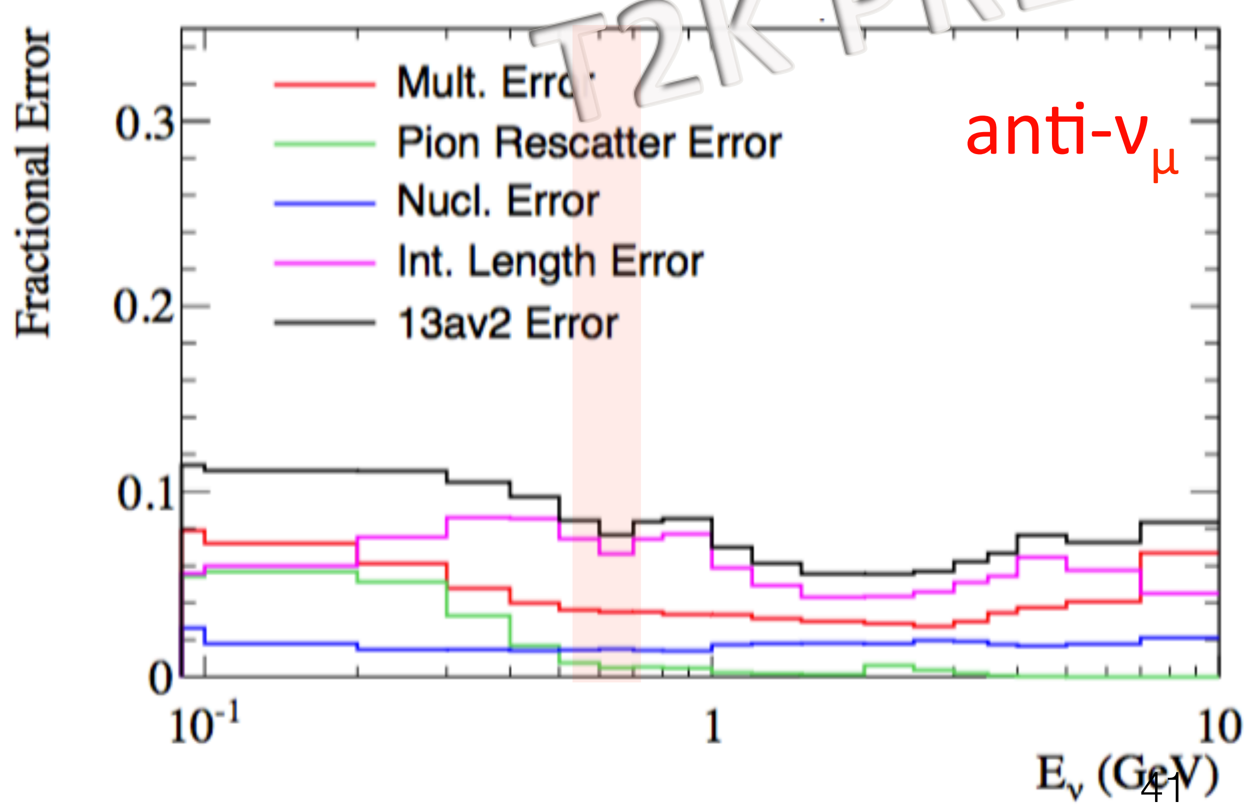
Non-Hadronic Part

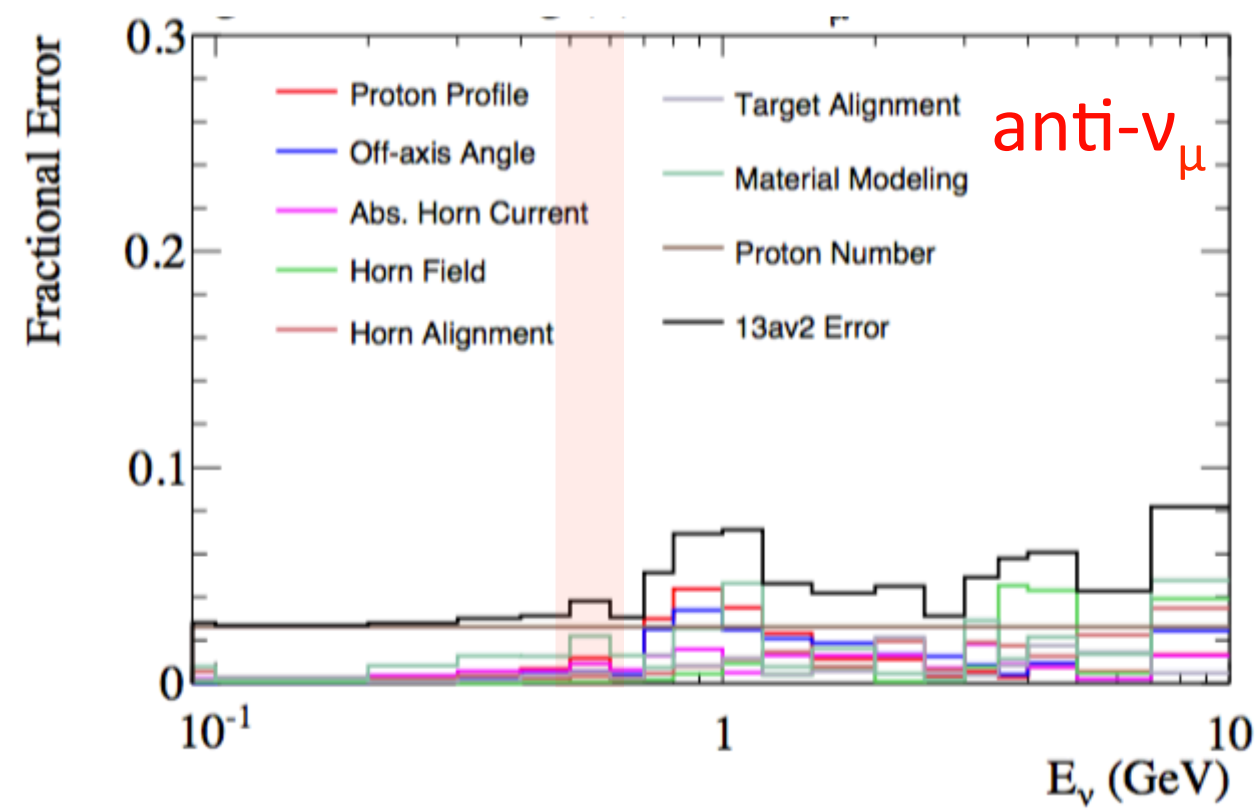
ν_μ at SK

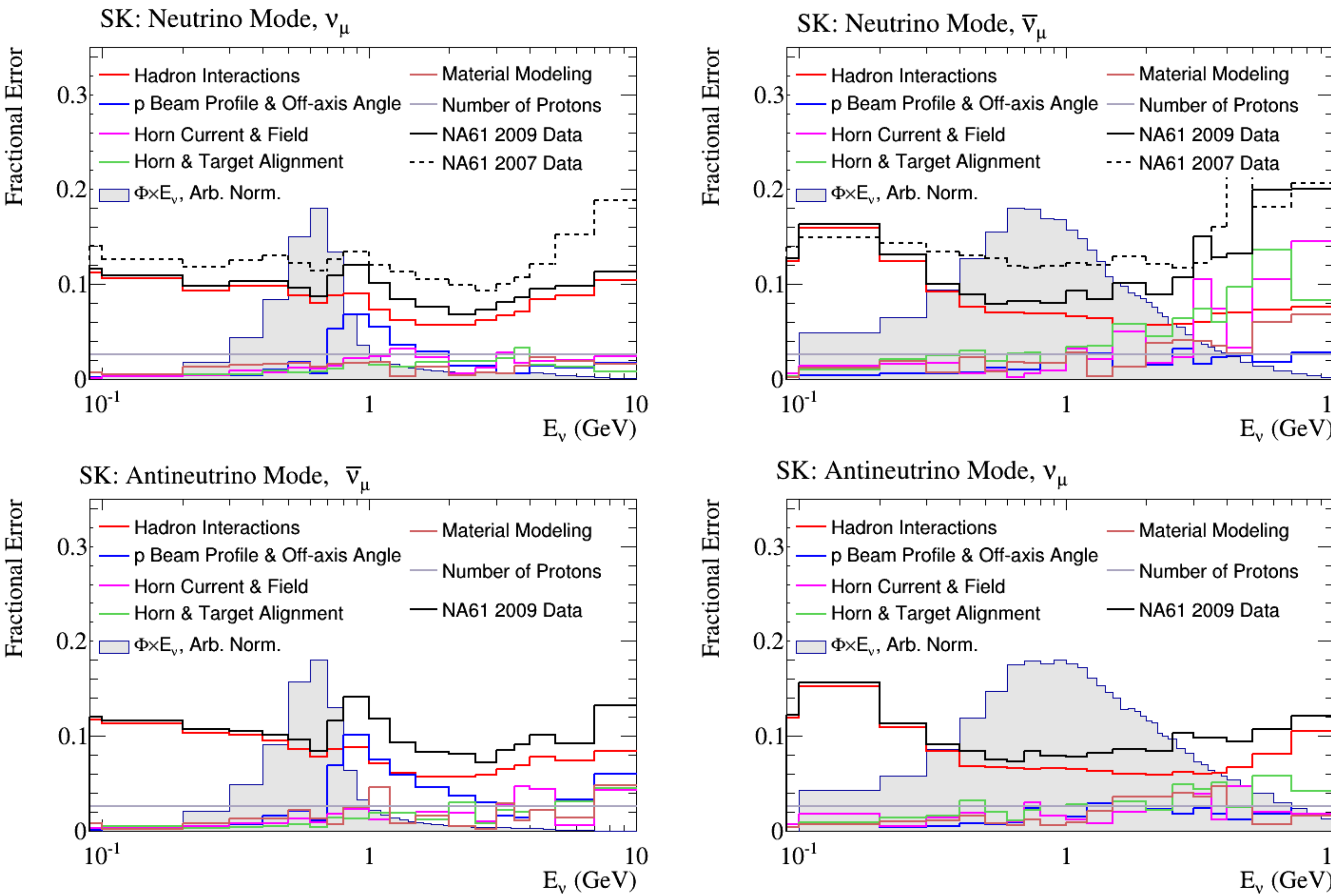




anti-ν_μ at SK

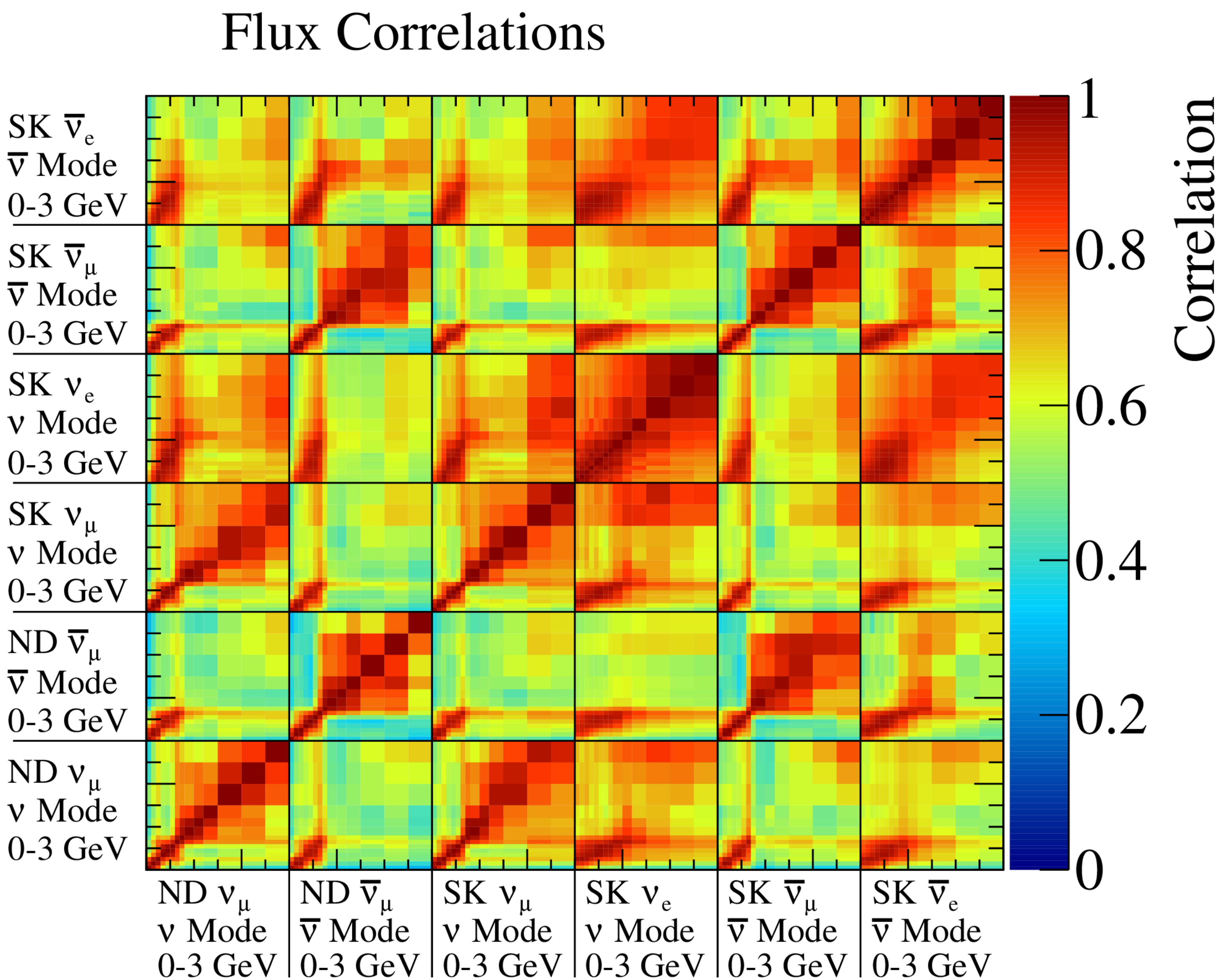


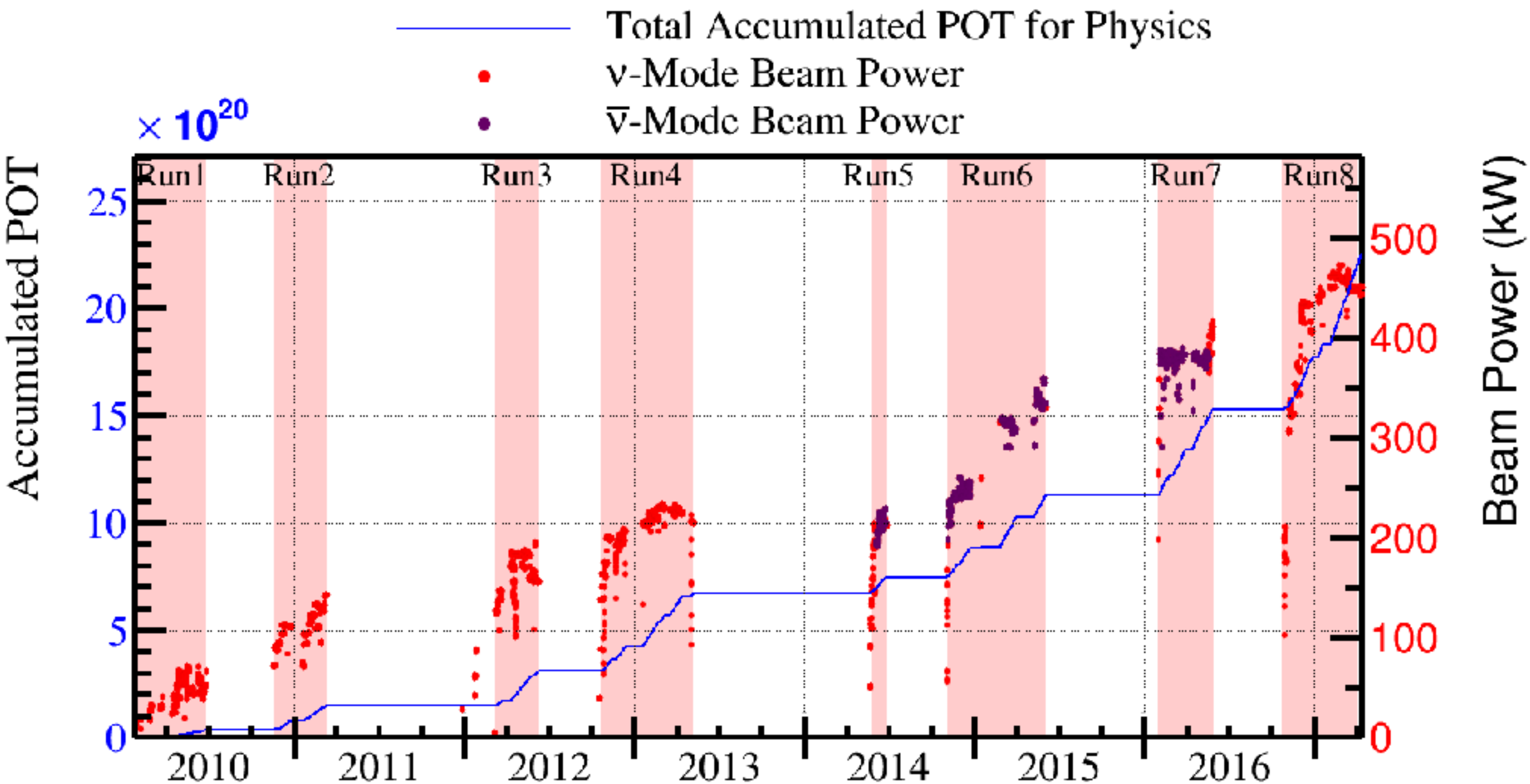


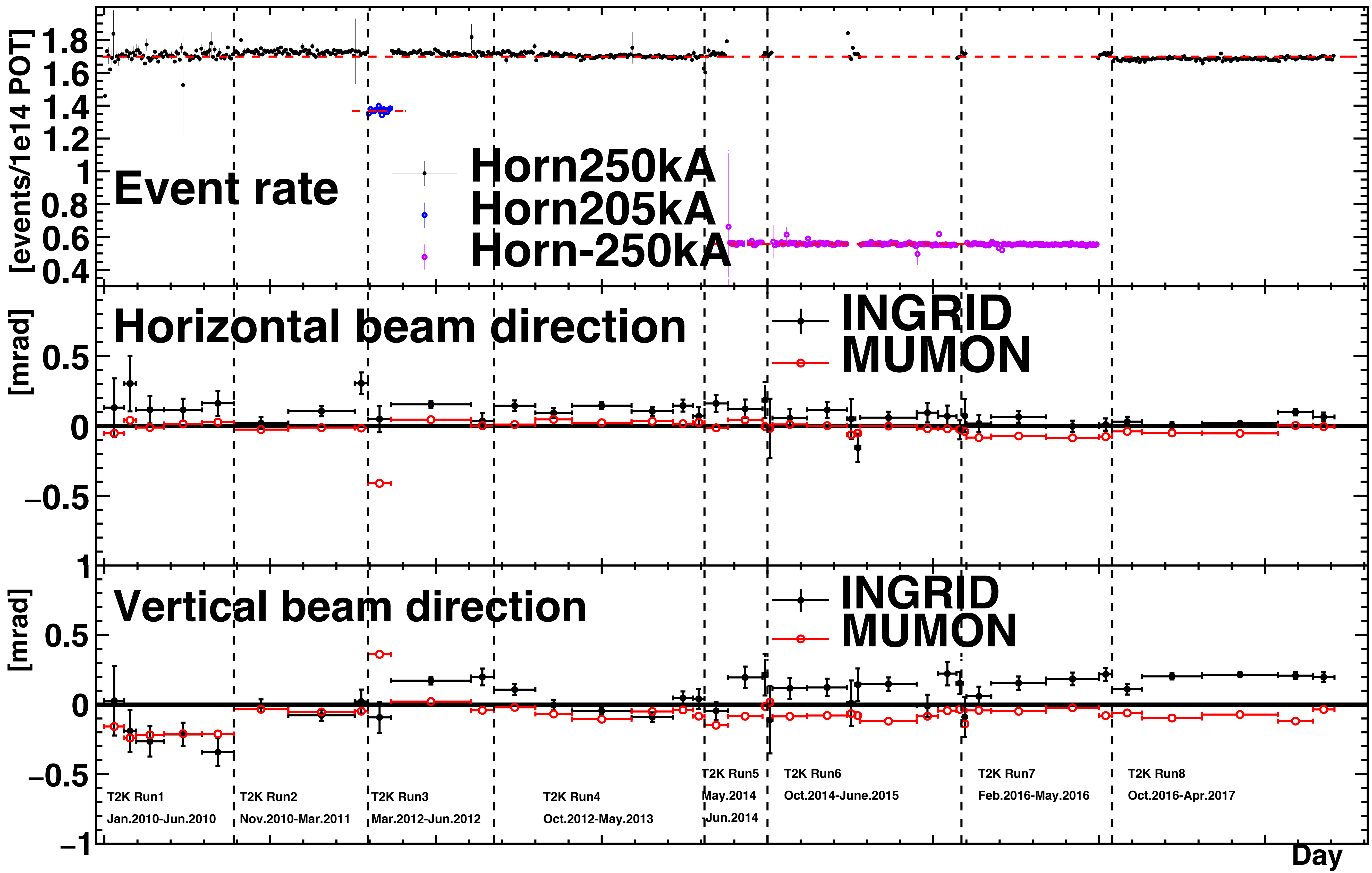


SK: Neutrino Mode, ν_μ
Fractional Error
Hadron Interactions
p Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
NA61 2009 Data
NA61 2007 Data
0
0.1
0.2
0.3
10^{-1}
1
10
E_ν (GeV)
SK: Neutrino Mode, $\bar{\nu}_\mu$
Fractional Error
Hadron Interactions
p Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
NA61 2009 Data
NA61 2007 Data
0
0.1
0.2
0.3
10^{-1}
1
10
E_ν (GeV)
SK: Antineutrino Mode, $\bar{\nu}_\mu$
Fractional Error
Hadron Interactions
p Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
NA61 2009 Data
0
0.1
0.2
0.3
10^{-1}
1
10
E_ν (GeV)
SK: Antineutrino Mode, ν_μ
Fractional Error
Hadron Interactions
p Beam Profile & Off-axis Angle
Horn Current & Field
Horn & Target Alignment
$\Phi\times E_\nu$, Arb. Norm.
Material Modeling
Number of Protons
NA61 2009 Data
0
0.1
0.2
0.3
10^{-1}
1
10
E_ν (GeV)

Flux correlations before ND280 fit : zoom

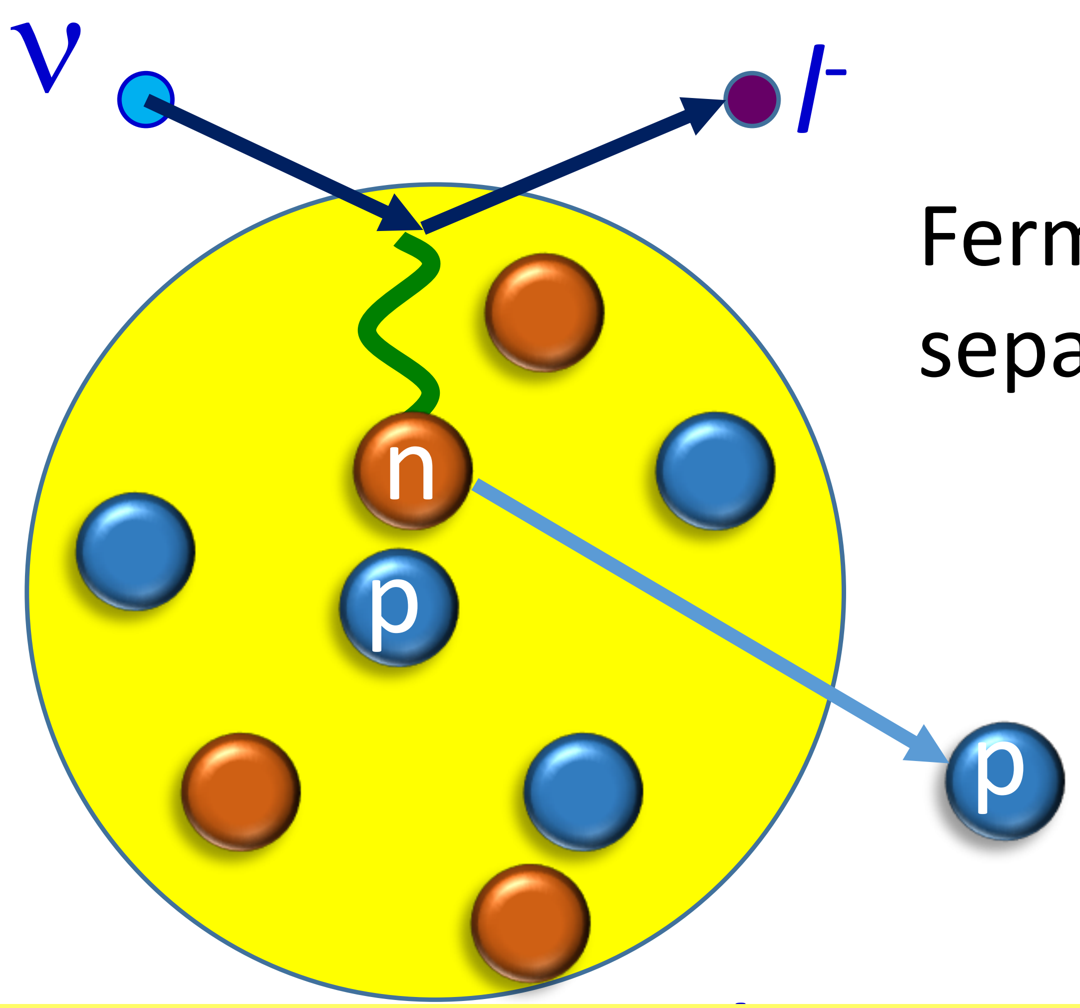



Total Accumulated POT for Physics
ν-Mode Beam Power
ν̄-Mode Beam Power
× 10^20
Accumulated POT
Beam Power (kW)
Run1
Run2
Run3
Run4
Run5
Run6
Run7
Run8
0
5
10
15
20
25
0
100
200
300
400
500
2010
2011
2012
2013
2014
2015
2016



[events/1e14 POT]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
Event rate
Horn250kA
Horn205kA
Horn-250kA
Horizontal beam direction
[mrad]
0.5
0
−0.5
INGRID
MUMON
1
Vertical beam direction
[mrad]
0.5
0
−0.5
−1
INGRID
MUMON
T2K Run1
Jan.2010-Jun.2010
T2K Run2
Nov.2010-Mar.2011
T2K Run3
Mar.2012-Jun.2012
T2K Run4
Oct.2012-May.2013
T2K Run5
May.2014
-Jun.2014
T2K Run6
Oct.2014-June.2015
T2K Run7
Feb.2016-May.2016
T2K Run8
Oct.2016-Apr.2017
Day

4. Neutrino Cross section



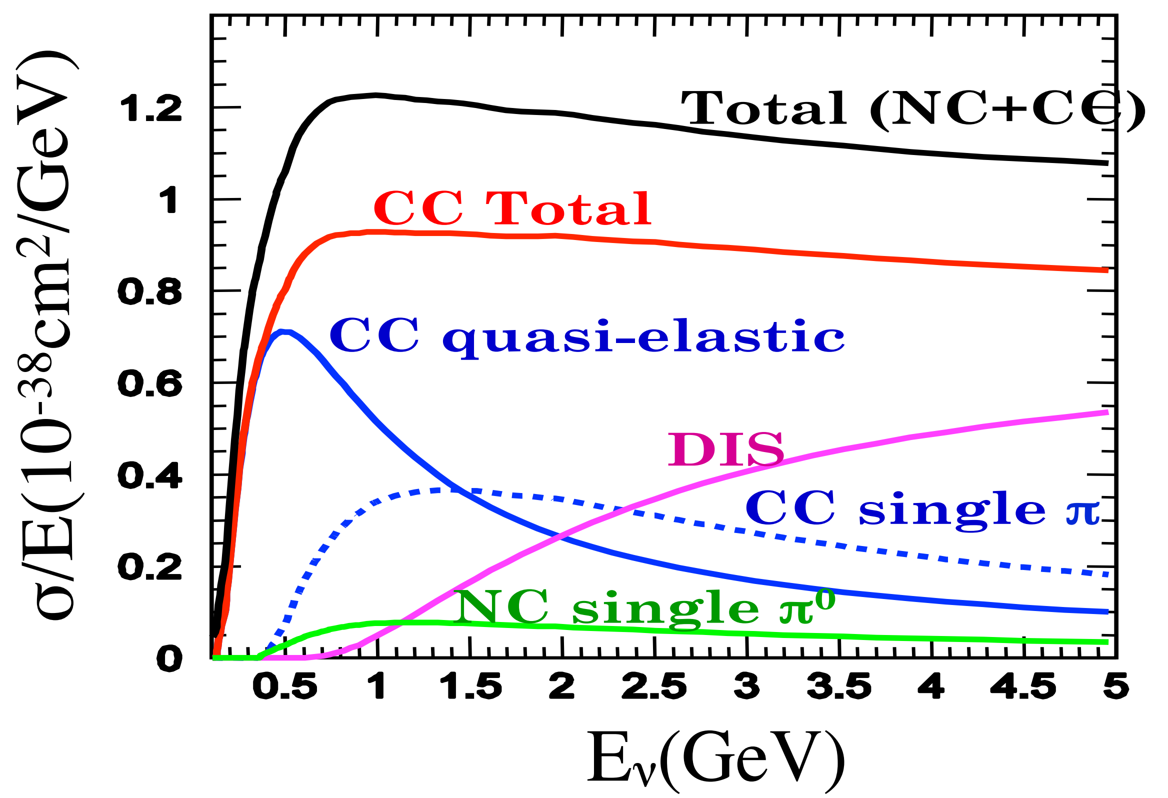
Fermi motion,
separation energy etc..

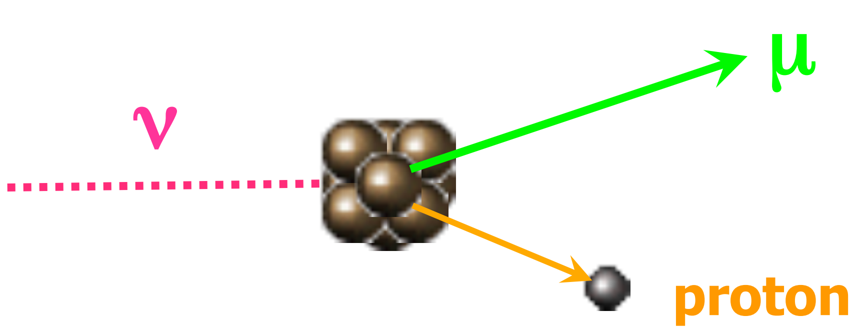
Neutrino Interactions in T2K (NEUT and GENIE)

- CC (Charged-Current) quasi elastic (CCQE)
  - $\nu + n \rightarrow \mu^- + p$ (n in N)
- CC (resonance) single π(CC-1π)
  - $\nu + n(p) \rightarrow \mu^- + \pi^+ + p(n)$ (n,p in N)
- DIS (Deep Inelastic Scattering)
  - $\nu + N \rightarrow \mu^- + m\pi^{+/-/0} + N'$
- CC coherent π ($\nu + A \rightarrow \mu^- + \pi^+ + A$)
- NC (Neutral-Current) copious process (NC-1π^0, etc..)

  + Nuclear Effects

NEUT model



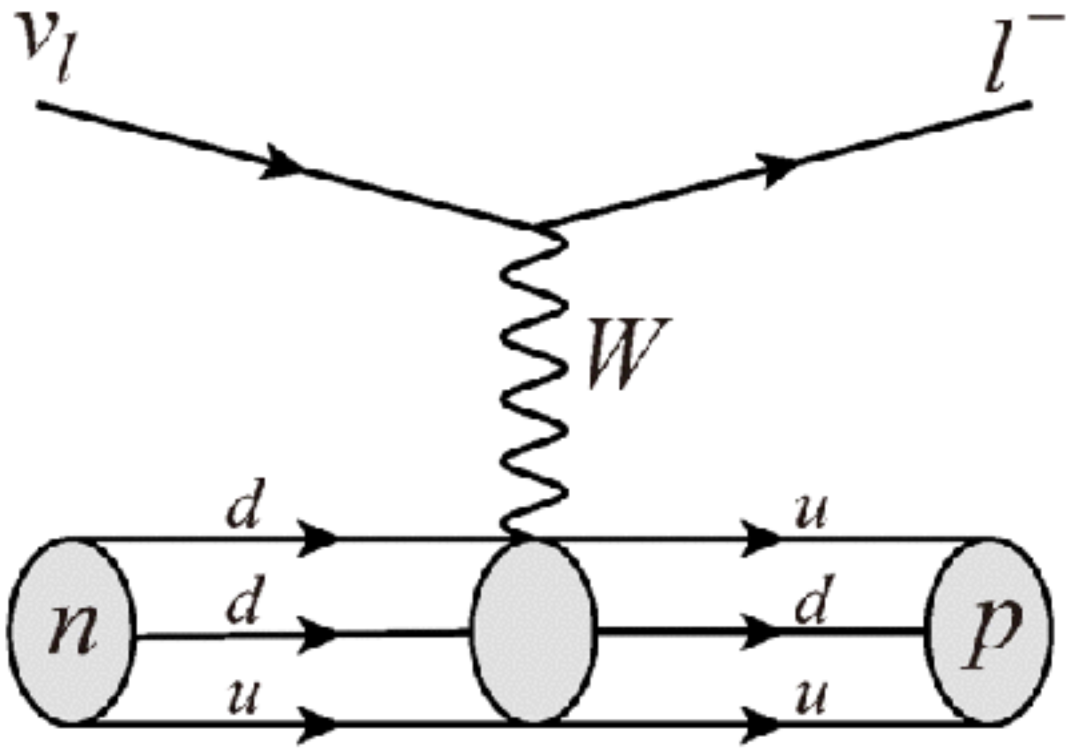


CCQE

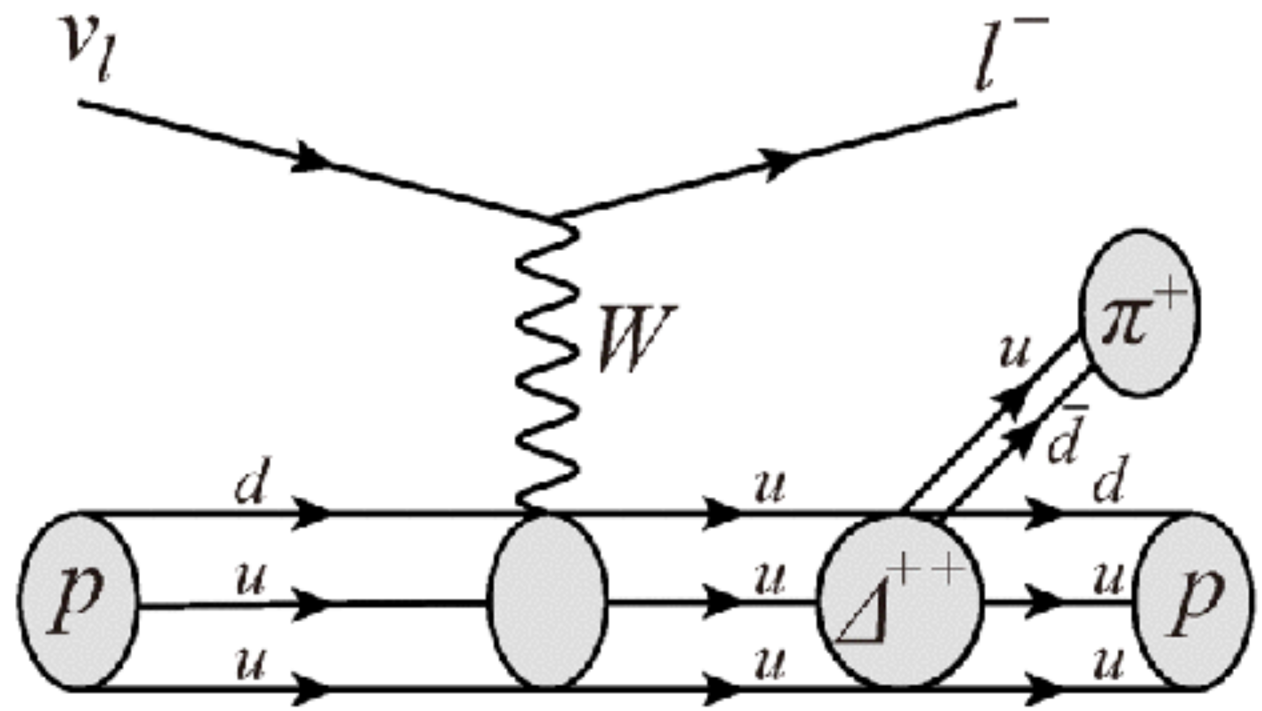
- SIGNAL: reconstruct neutrino energy from lepton momentum and scattering angle.

$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

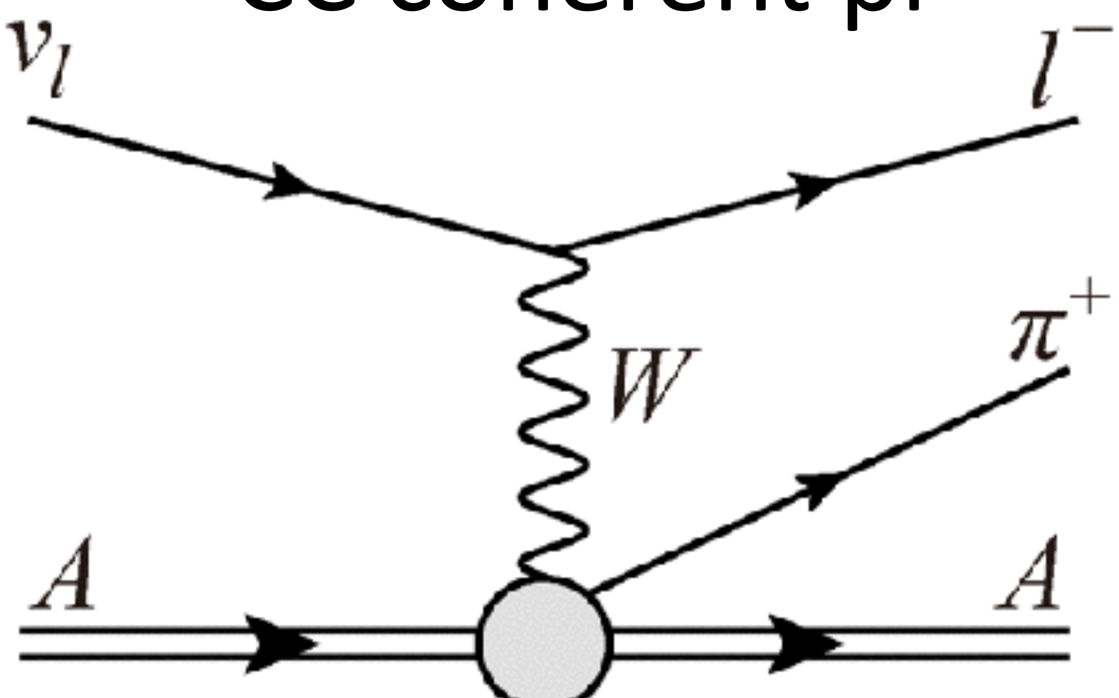
CCQE



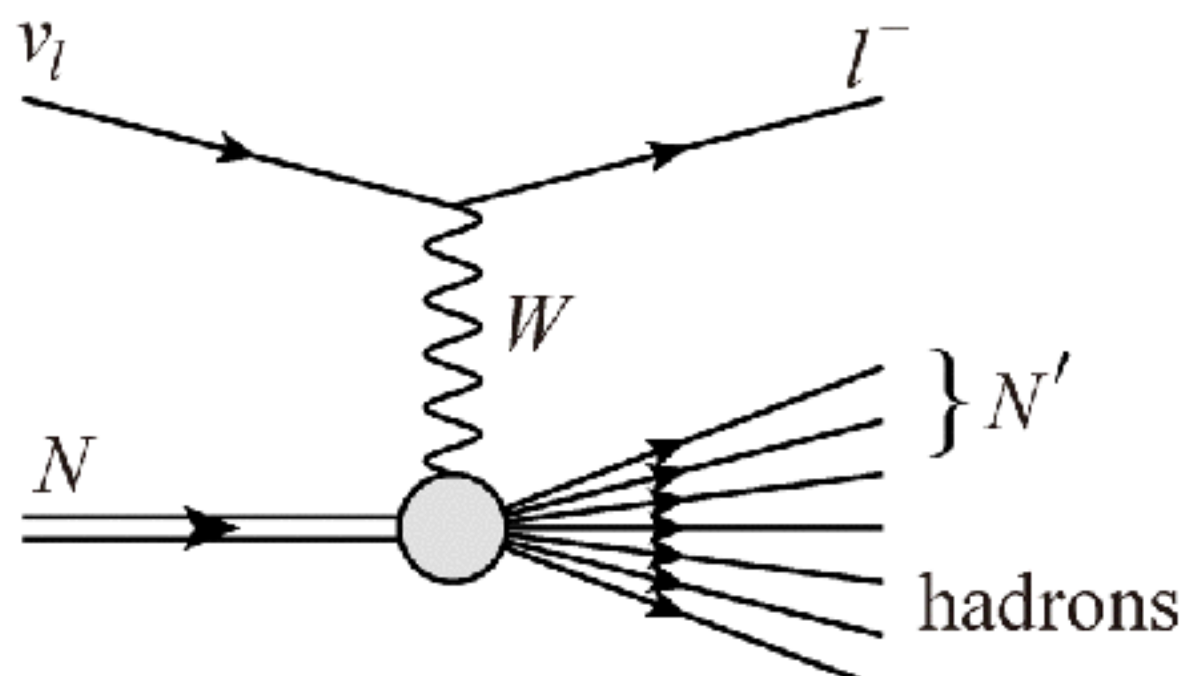
CC1pi



CC coherent pi



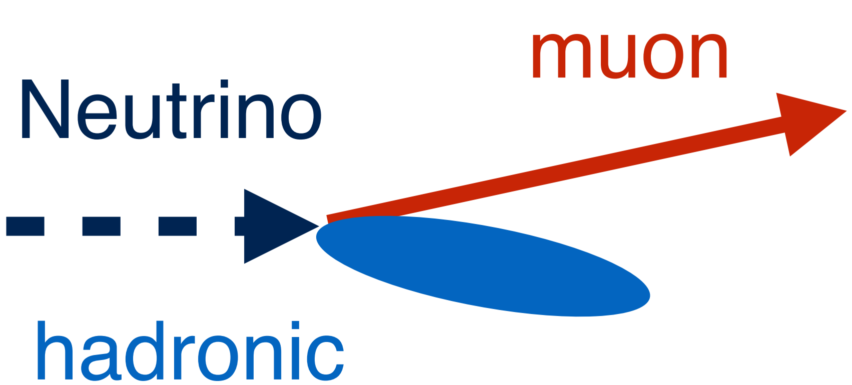
CC Deep-Inelastic-Scattering

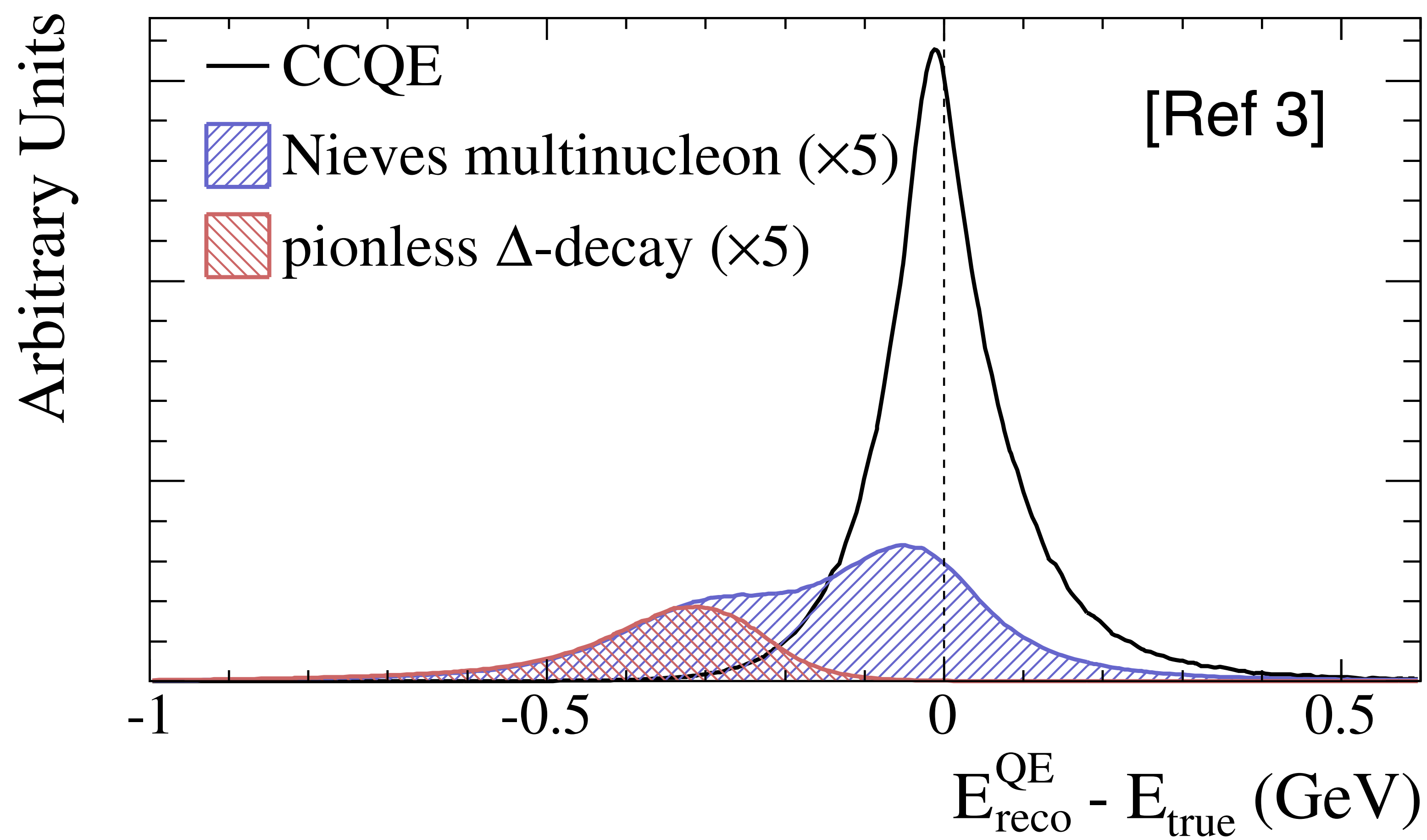


- Oscillation depends on energy
  - Estimate from hadronic and/or leptonic information

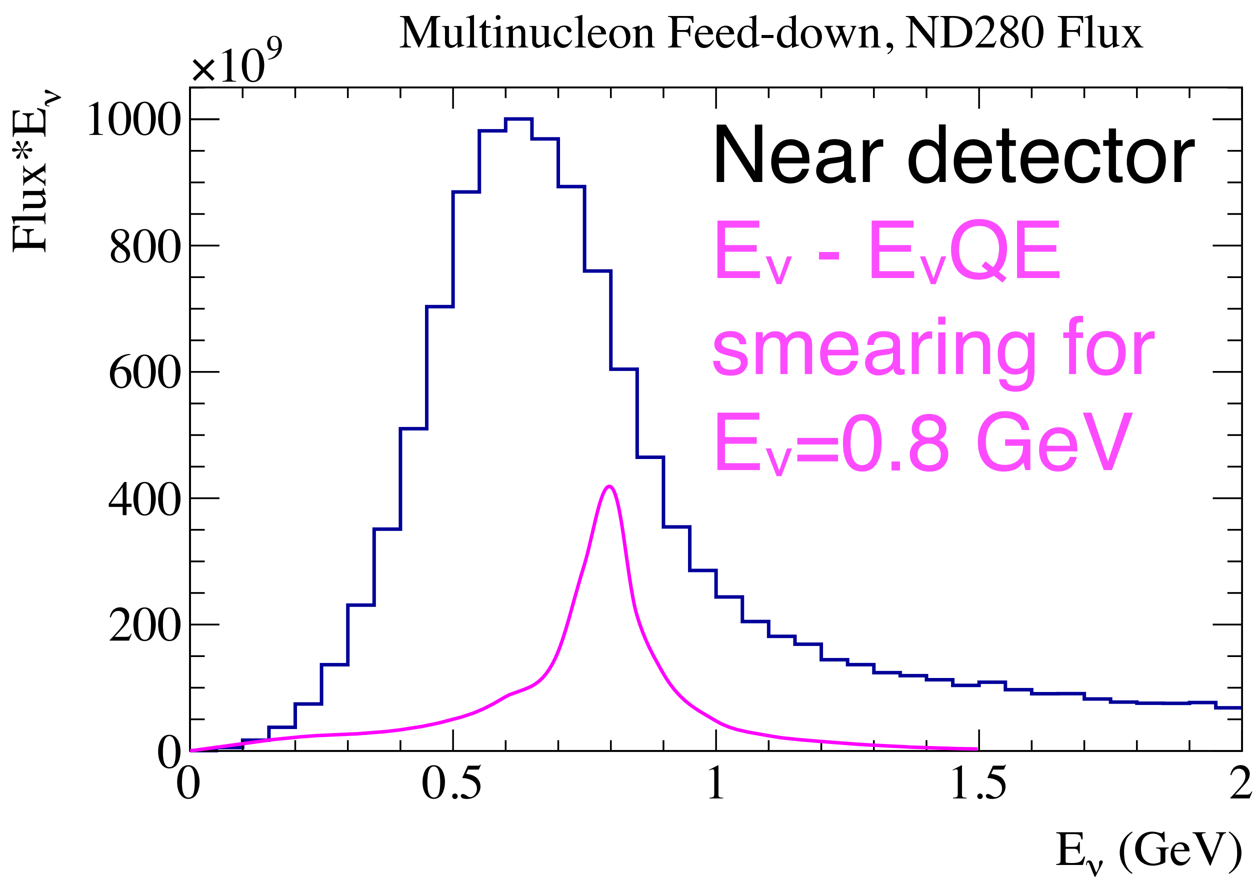
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic}$$

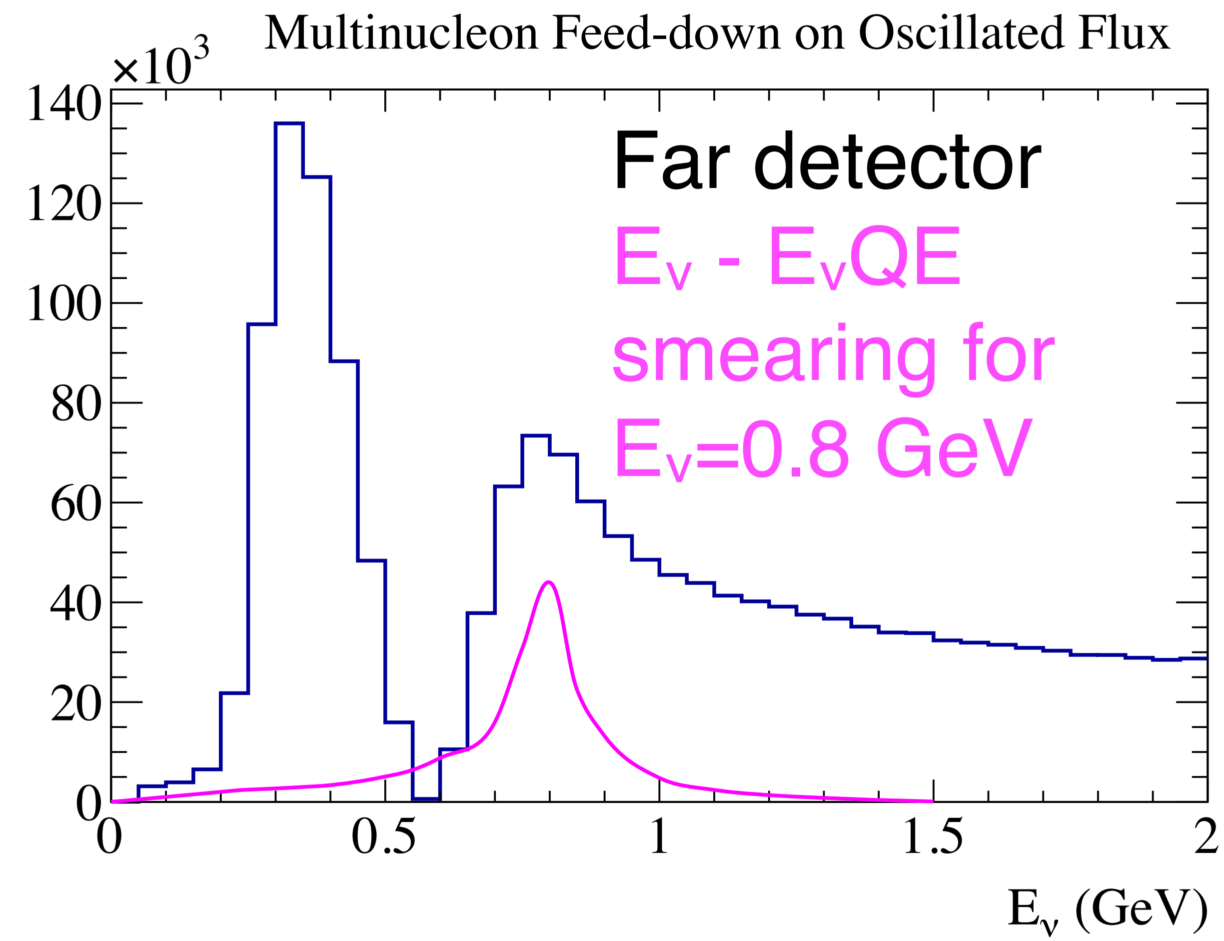
- Nuclear effects bias true and estimated neutrino energy





Near Detector (ND280) Far Detector (Super-K)



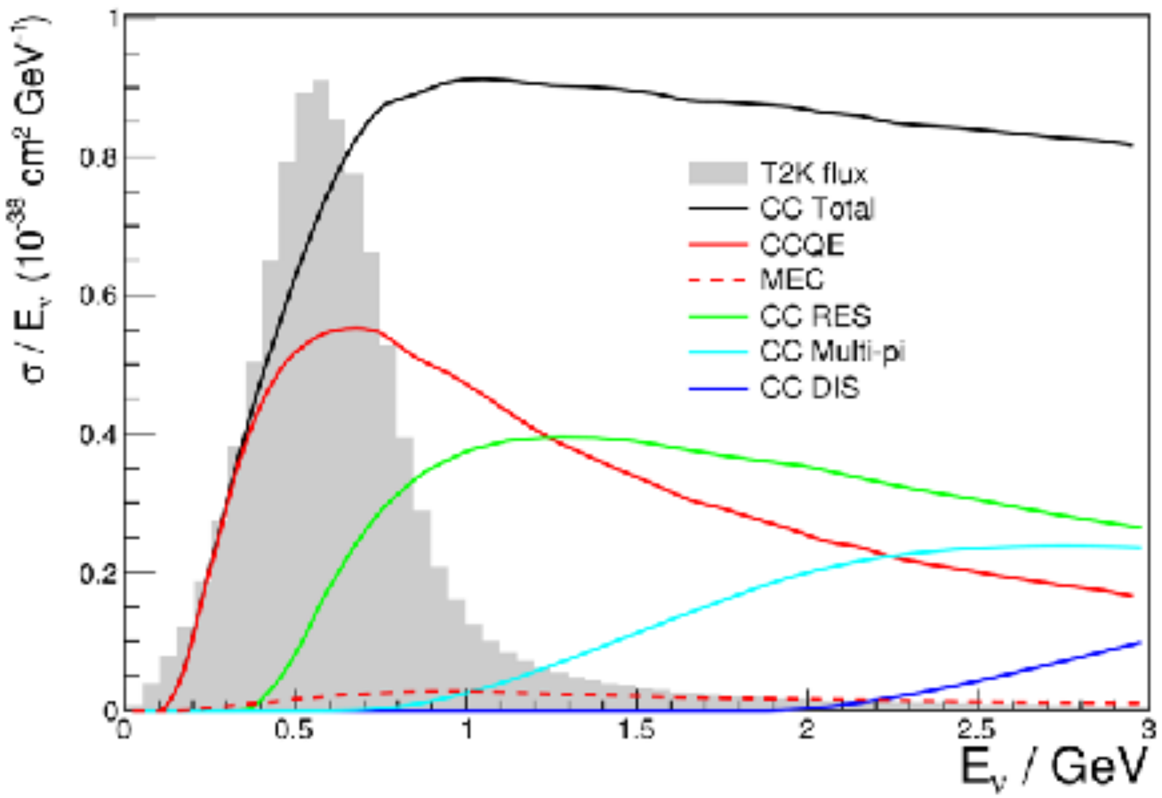


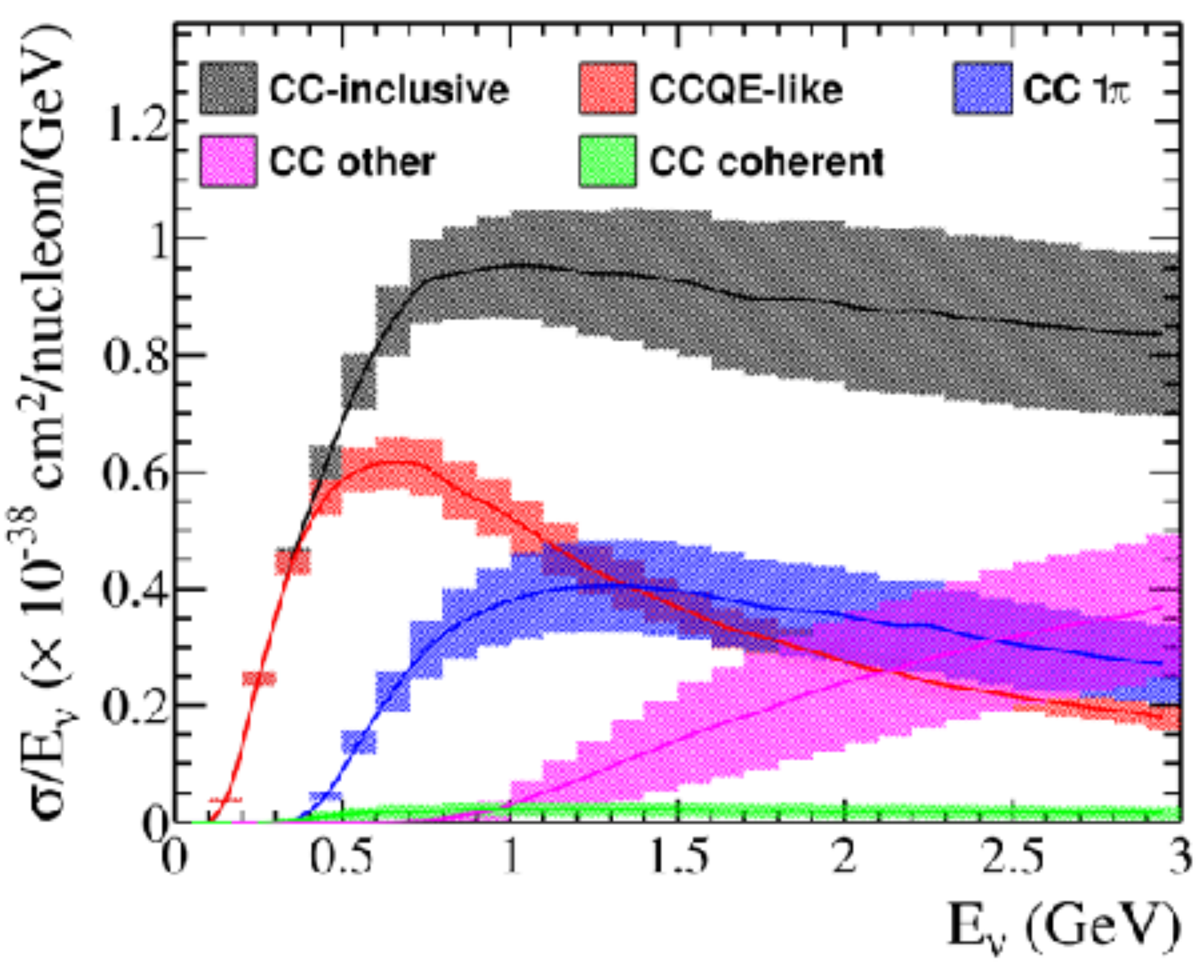
$$ND(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND}$$

$$FD(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P(\nu_\mu \to \nu_e)$$

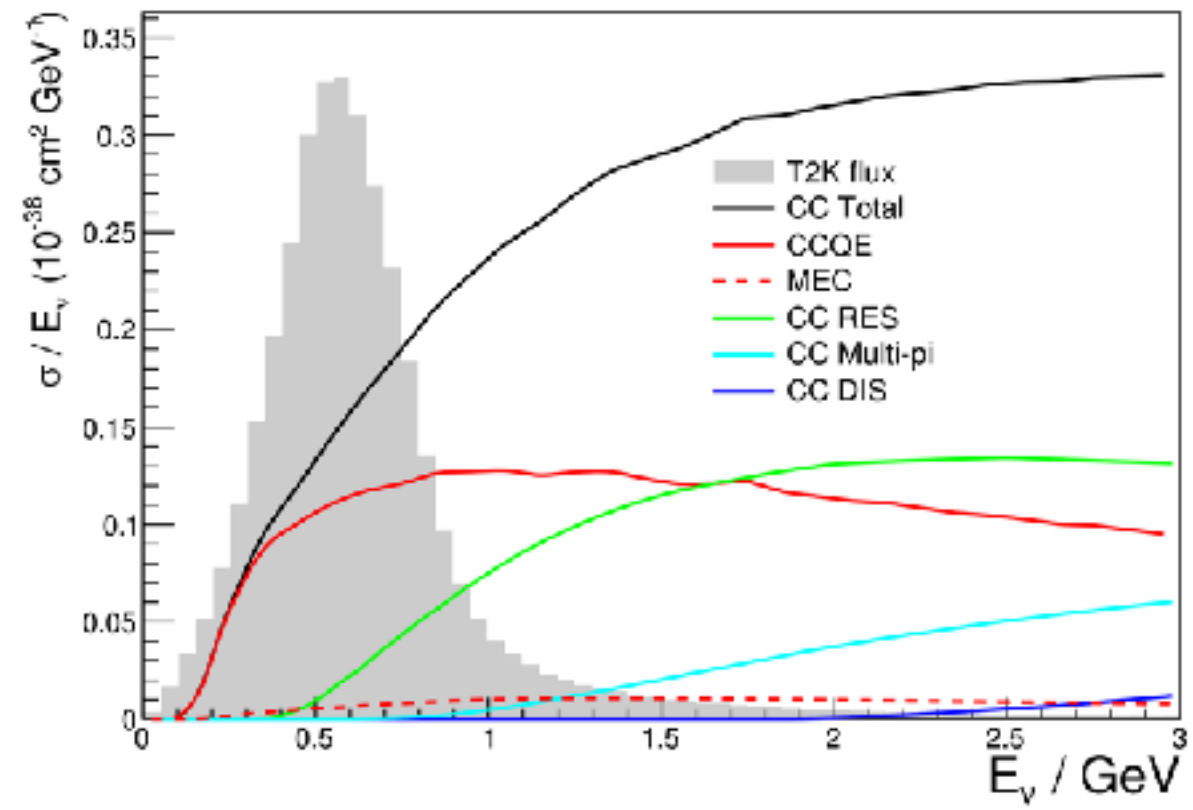
- Even with a near detector, **critical reliance on model**
  - 2p2h feed-down to oscillation peak from [Ref 4]

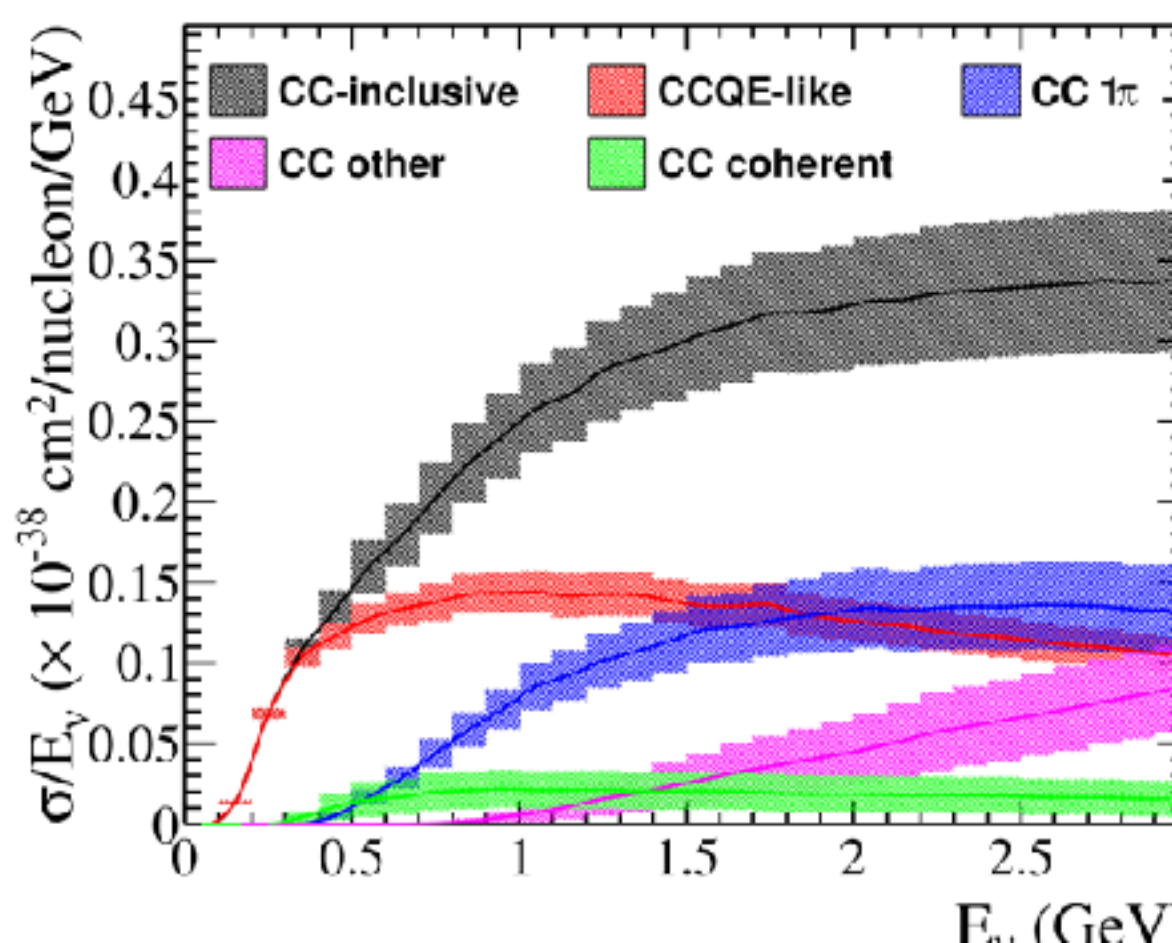
σ ν-CC/Eν





σ $\bar{\nu}$-CC/E$\bar{\nu}$



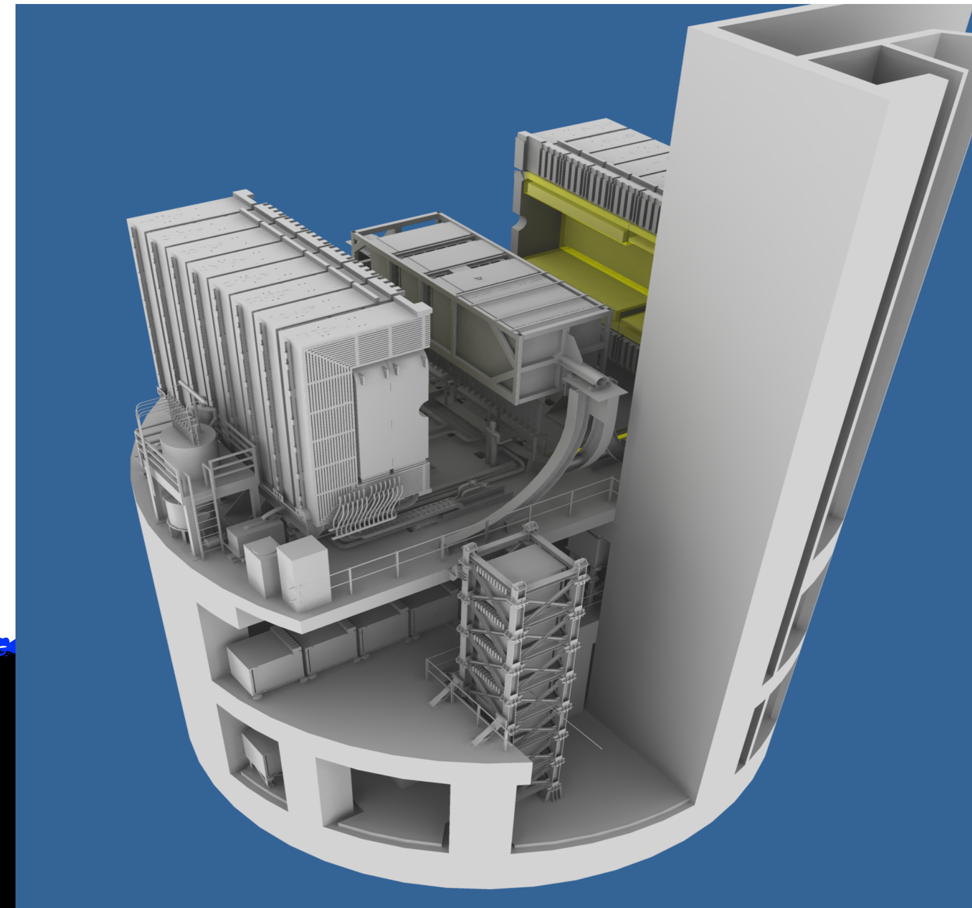


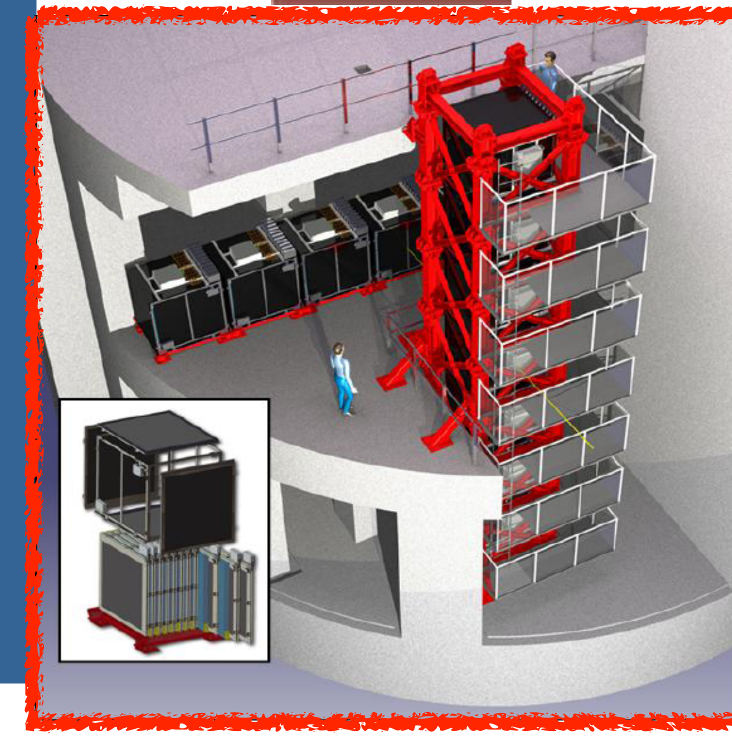
5. ND280

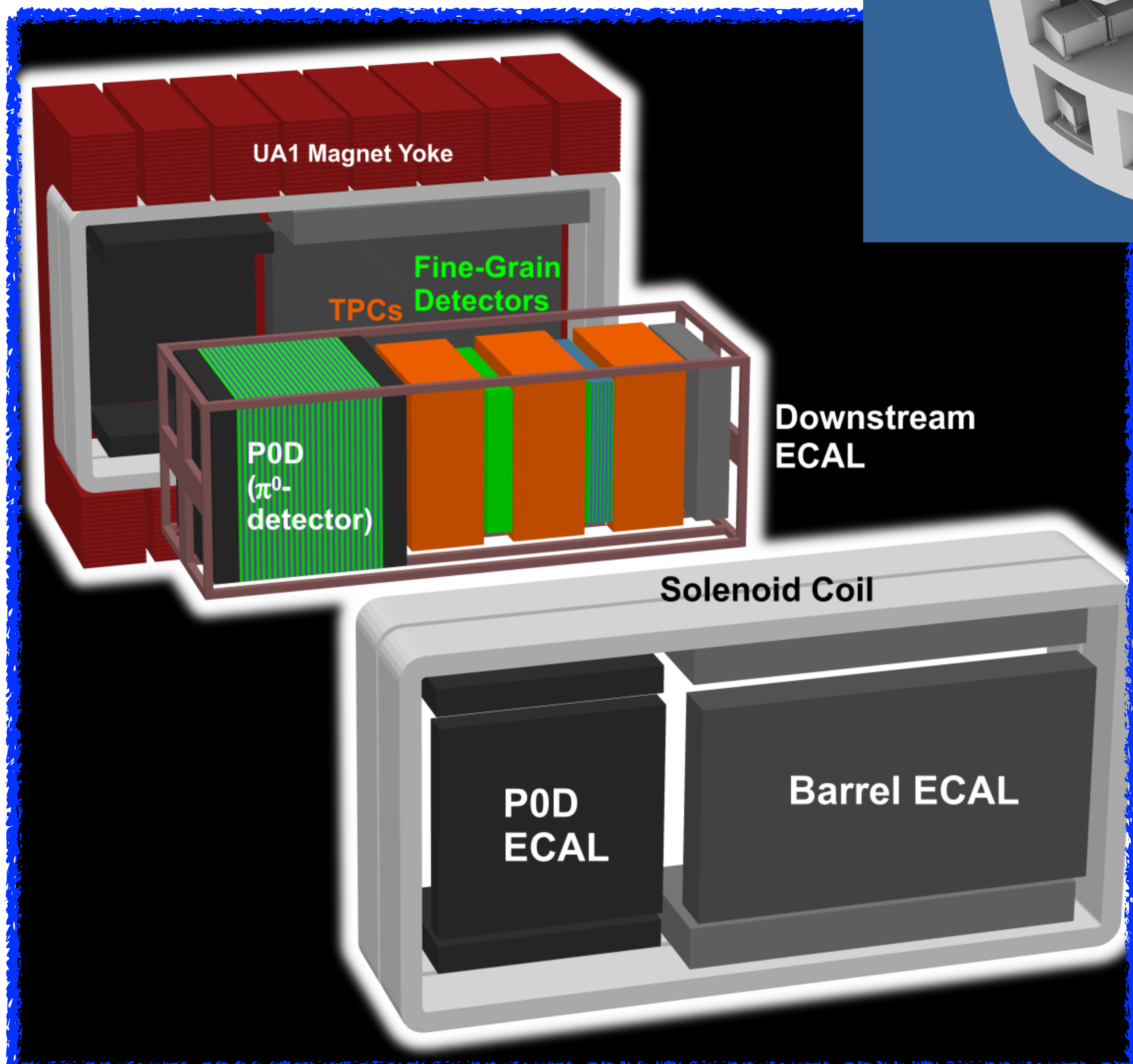
- Near Detectors -

ND280

Near Detector @ 280m from the target



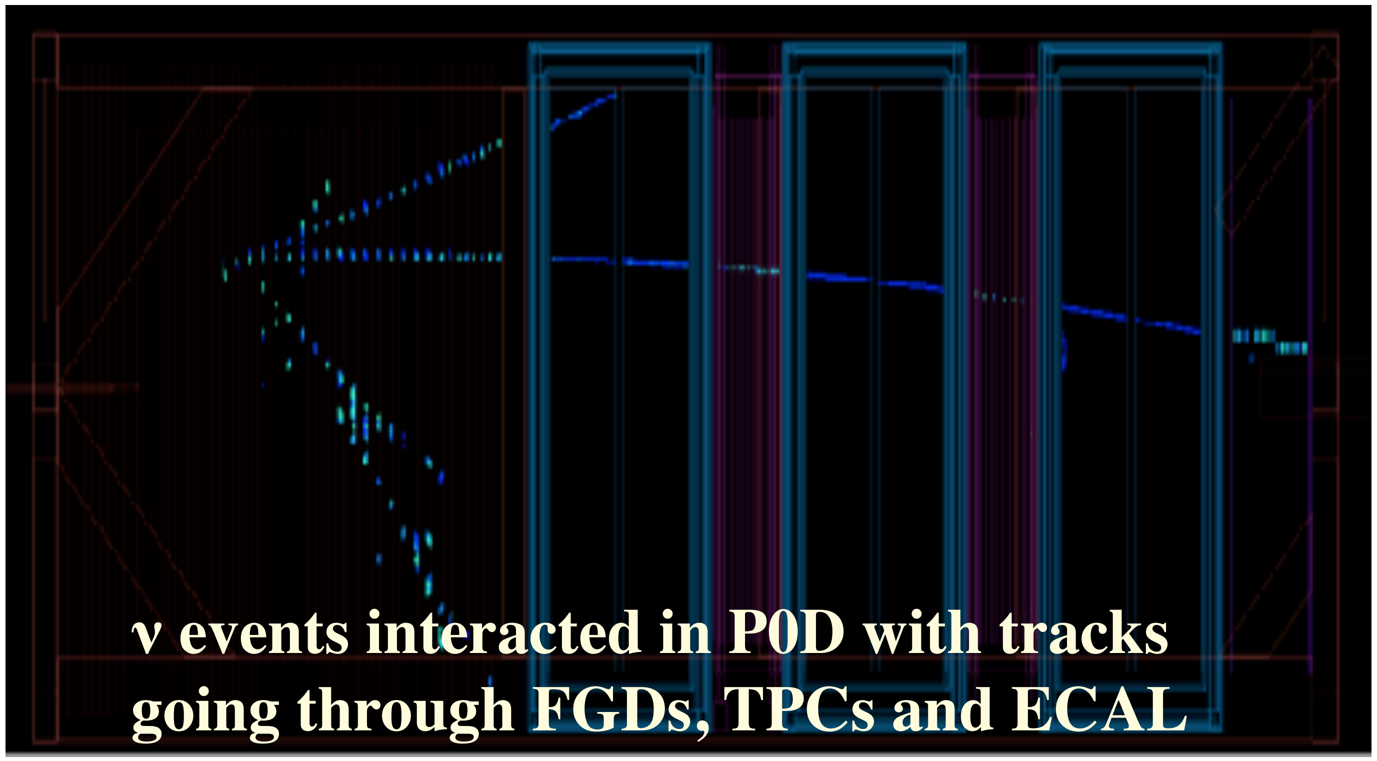




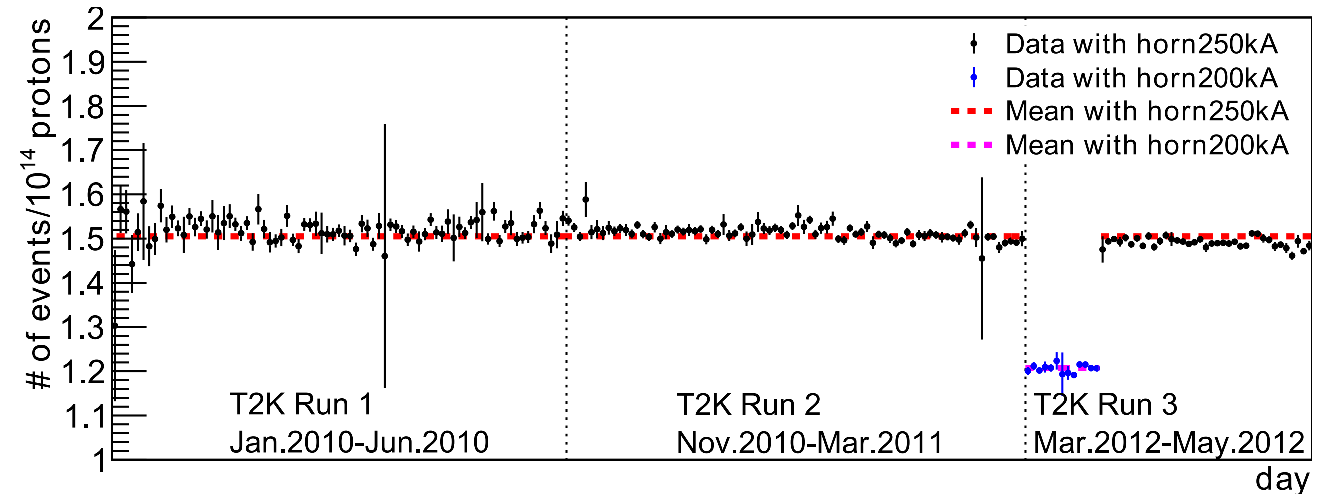
- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]

- **ND280** @ 2.5 degree off-axis
  - ✦ Normalization of Neutrino Flux
  - ✦ Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - **P0D:** π^0 Detector
    - **FGD+TPC:** Target + Particle tracking
    - **EM calorimeter**
    - **Side-Muon-Range Detector**

Performance of ND280

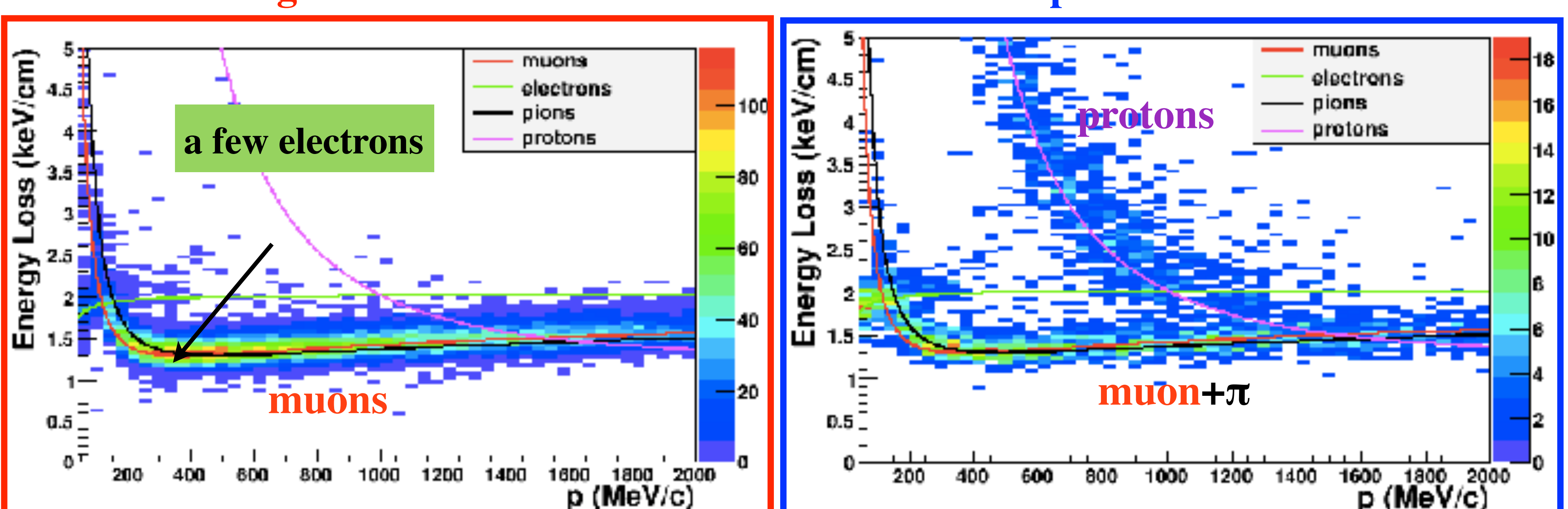


ν event rate stability by INGRID



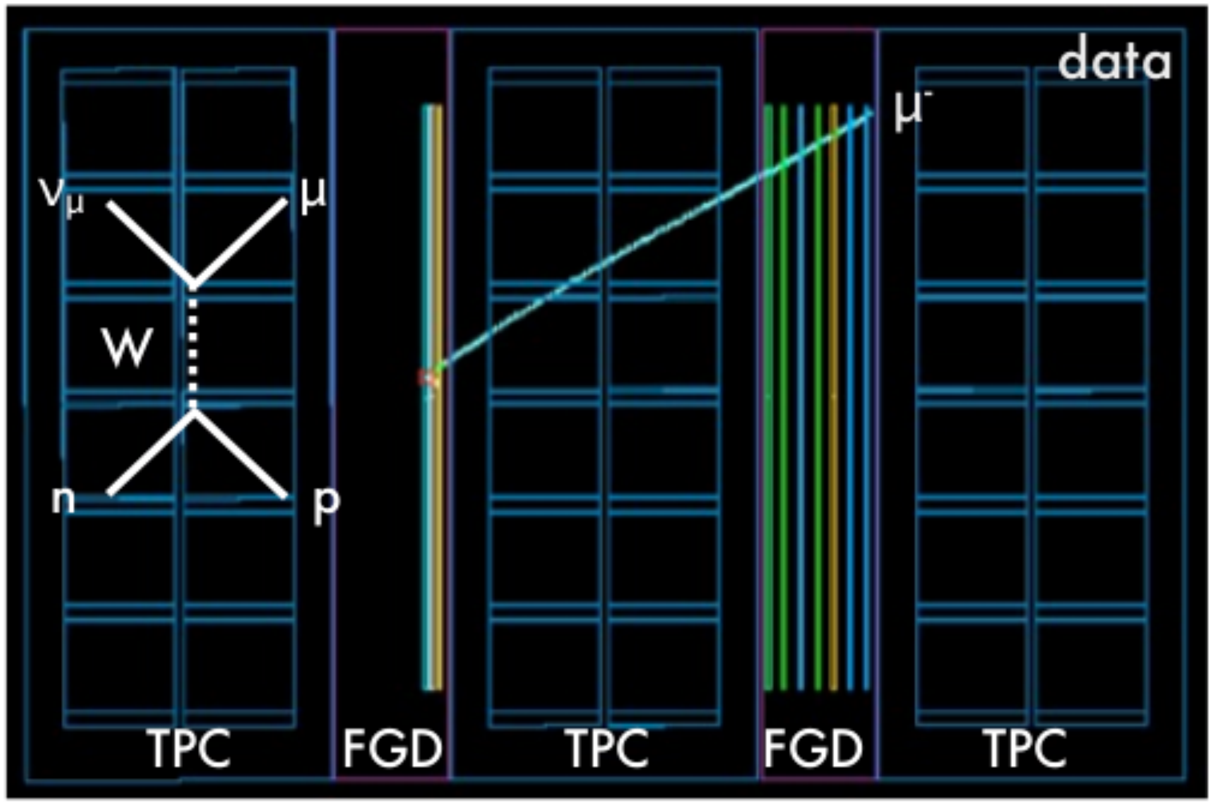
TPC PID

negative track **positive track**

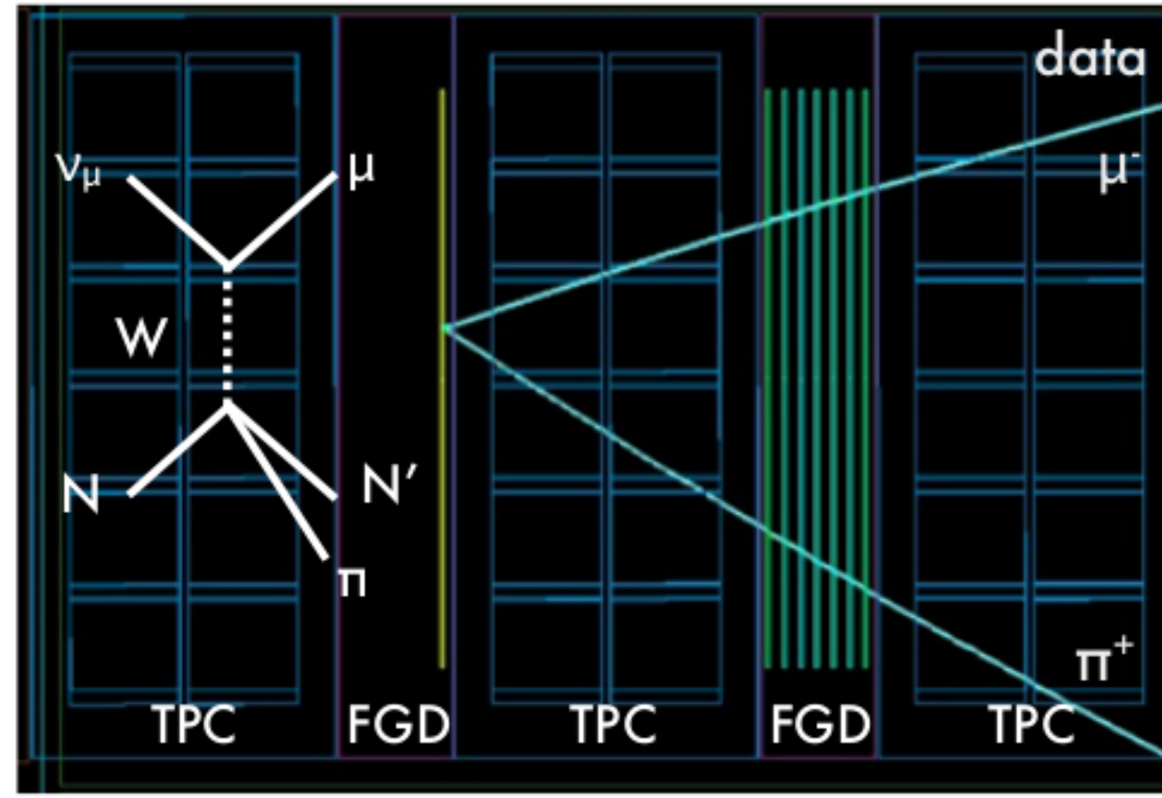


- INGRID
  - ν rate stability
  - beam direction:
    - -0.01±0.33 mrad (x)
    - -0.11±0.37 mrad (y)
- ND280
  - excellent PID and tracking capability
  - measurements of the neutrino interactions.

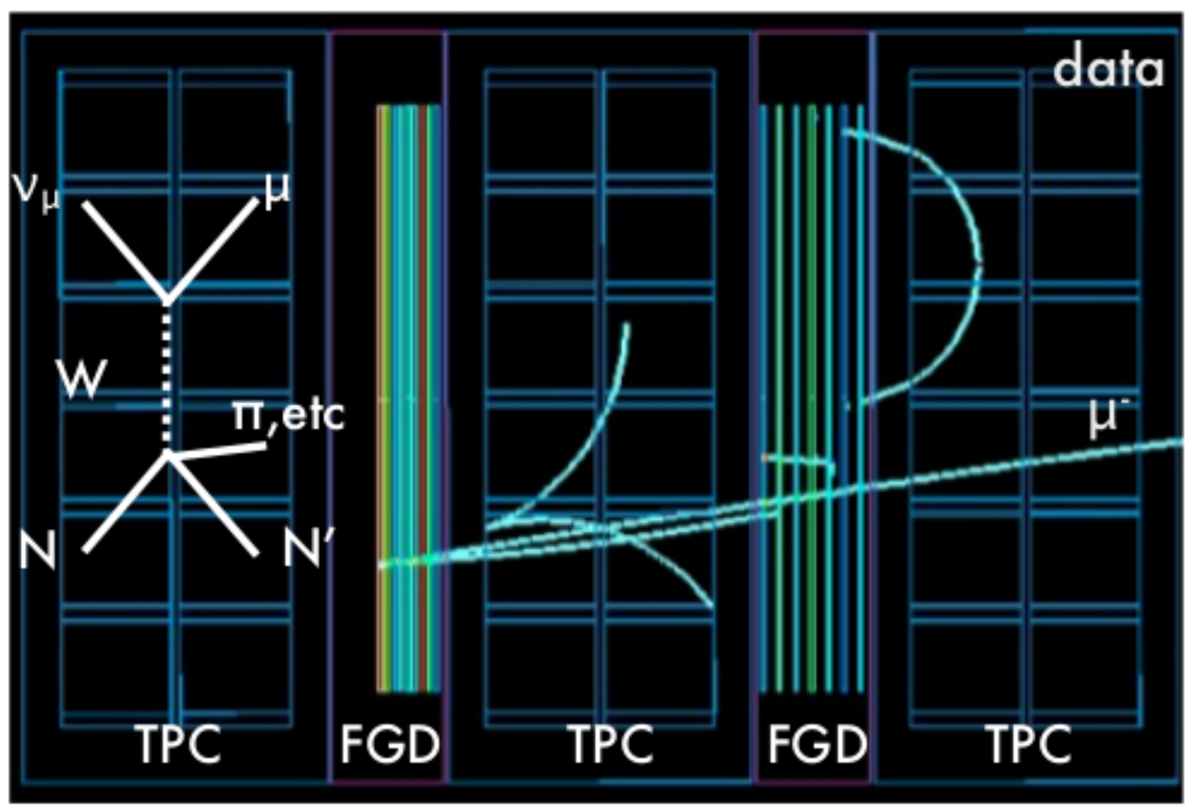
ν_μ CC0π



ν_μ CC1π^+

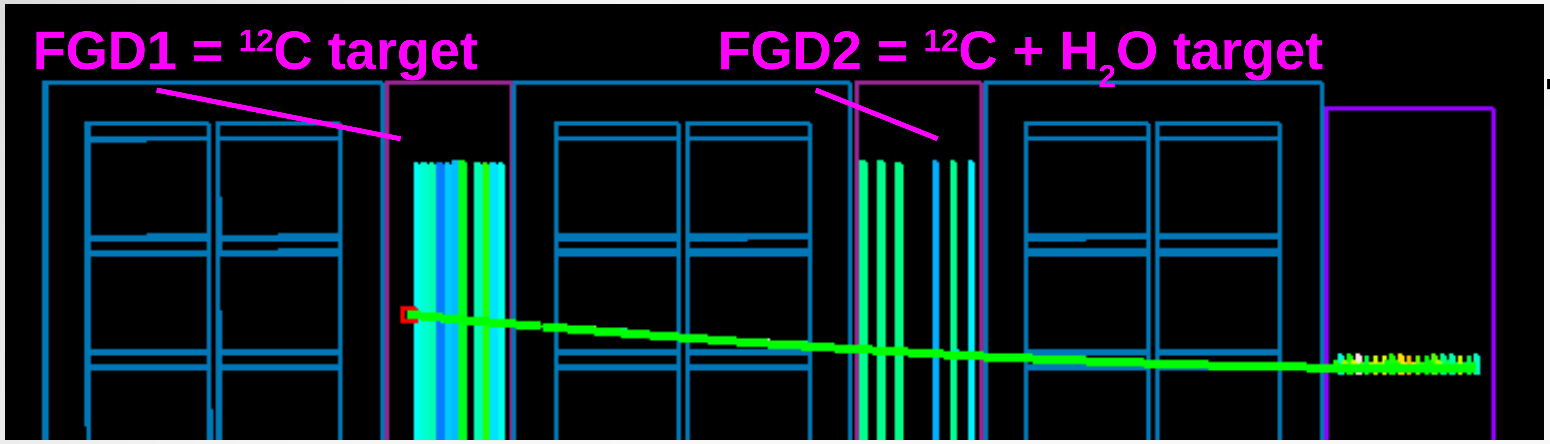


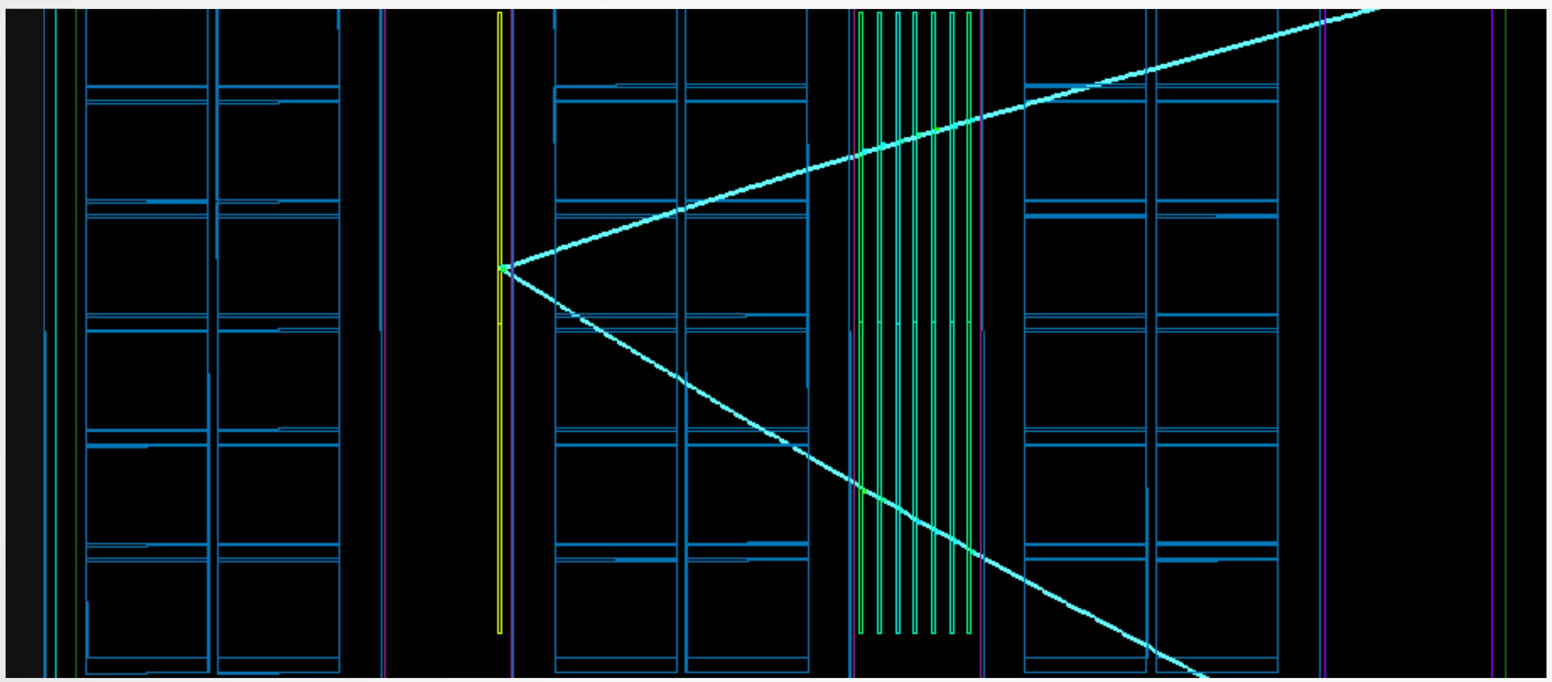
ν_μ CC other

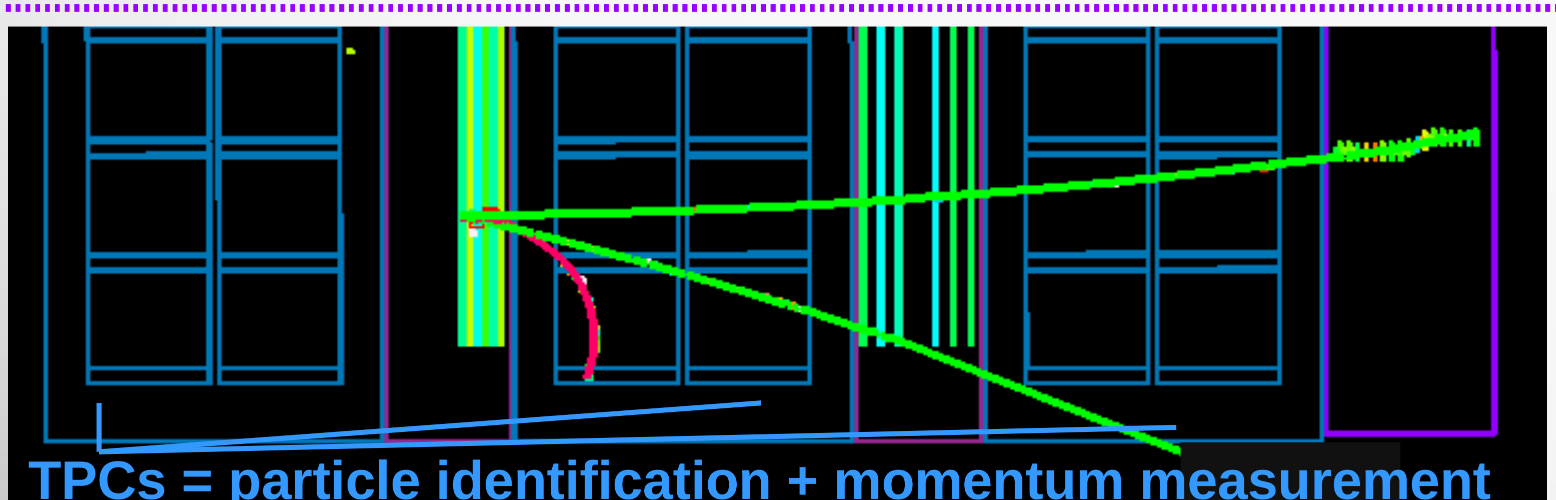


Selection in ND280

Selection of charged-current (CC) interactions of:

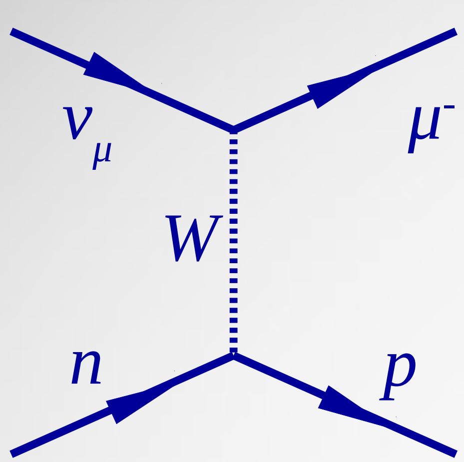


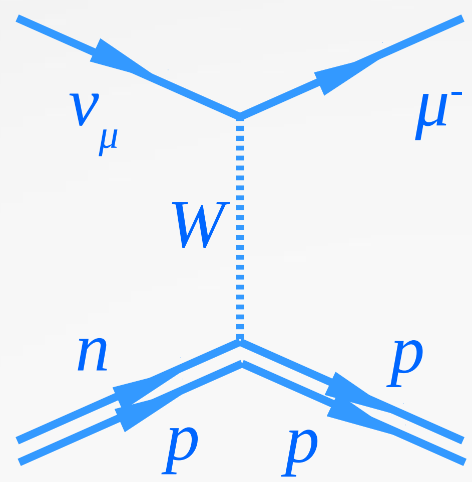


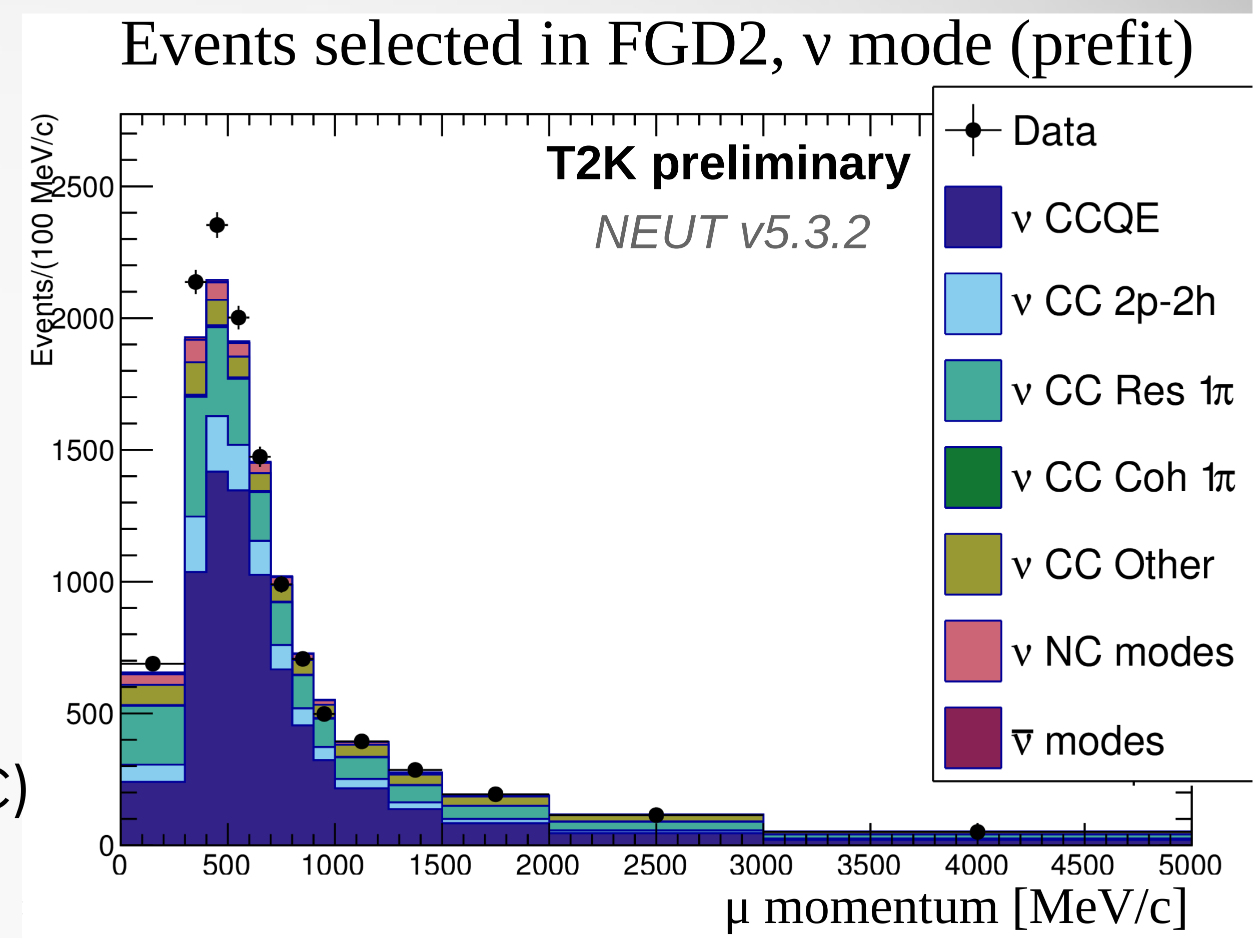


ν_μ in ν mode	$\overline{\nu}_\mu$ in $\overline{\nu}$ mode	ν_μ in $\overline{\nu}$ mode (oscillation background)
CC-0π: only 1 μ^- detected	CC-0π: only 1 μ^+ detected	CC-0π: only 1 μ^- detected
CC-1π: 1 μ^- + 1 π^+ detected	CC-other: 1 μ^+ +something other detected	CC-other: 1 μ^- +something other detected
CC-other: 1 μ^- + something other than 1π^+ detected		

Interaction model: CC-0π







CCQE: 5 parameters

axial mass M_A^{QE}

Fermi momentum p_F (^{16}O; ^{12}C)

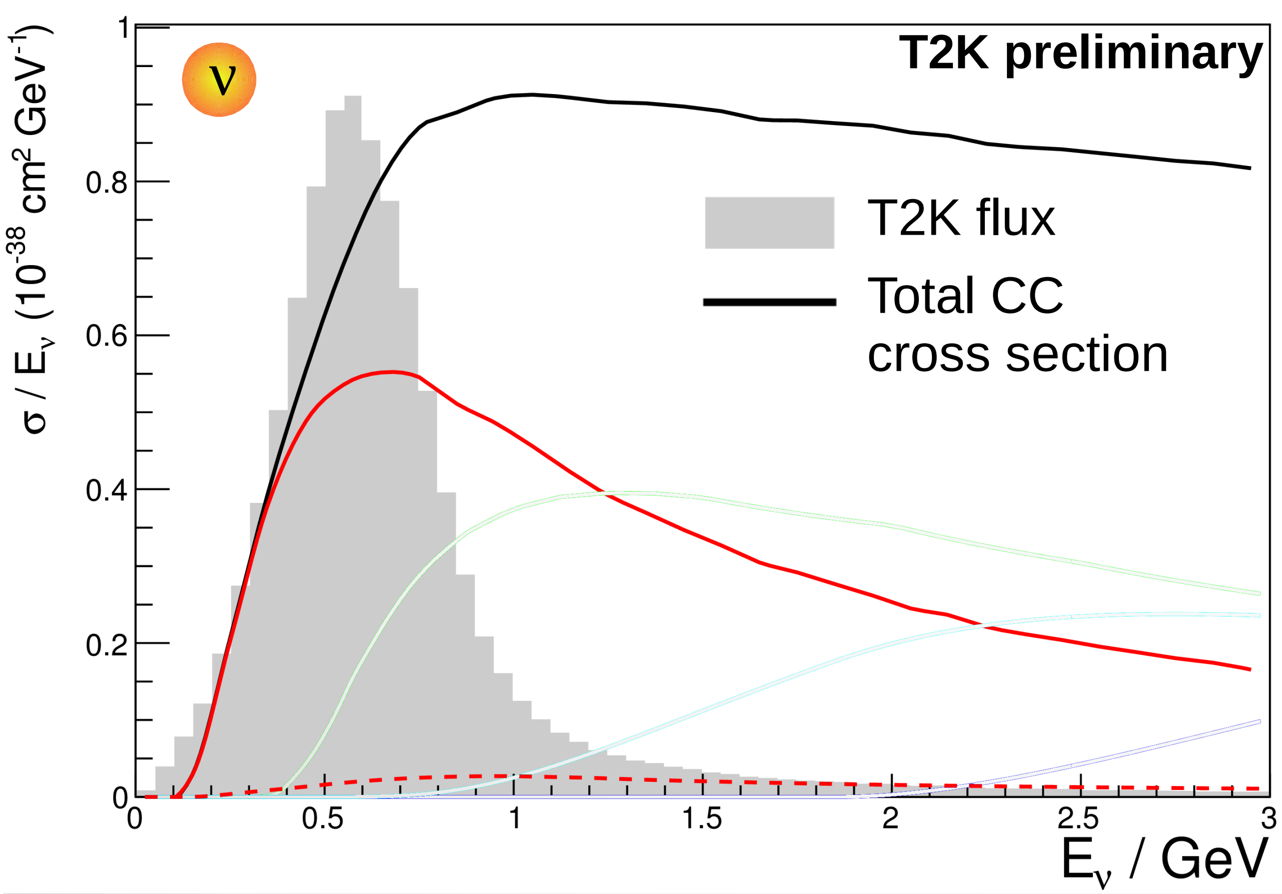
binding energy E_b (^{16}O; ^{12}C)

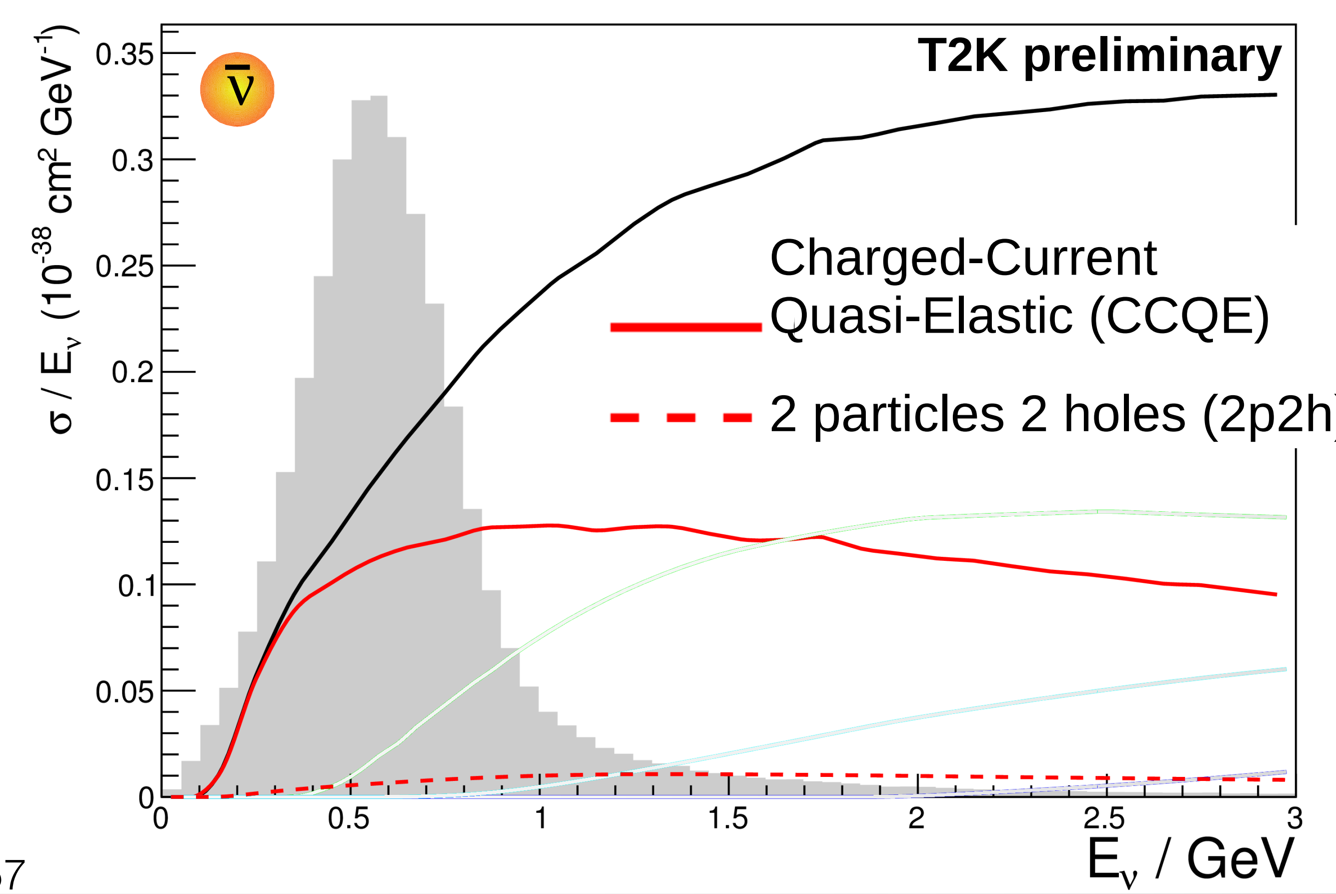
2p2h: 3 parameters

Nieves model

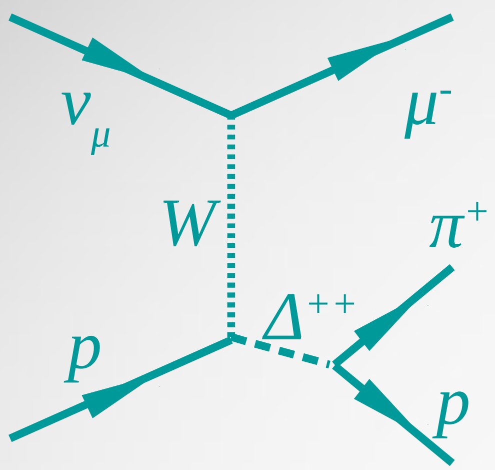
normalisation (^{16}O; ^{12}C)

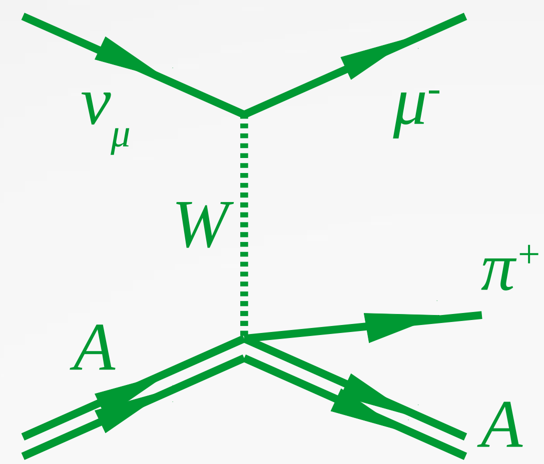
(ν / ν̄)

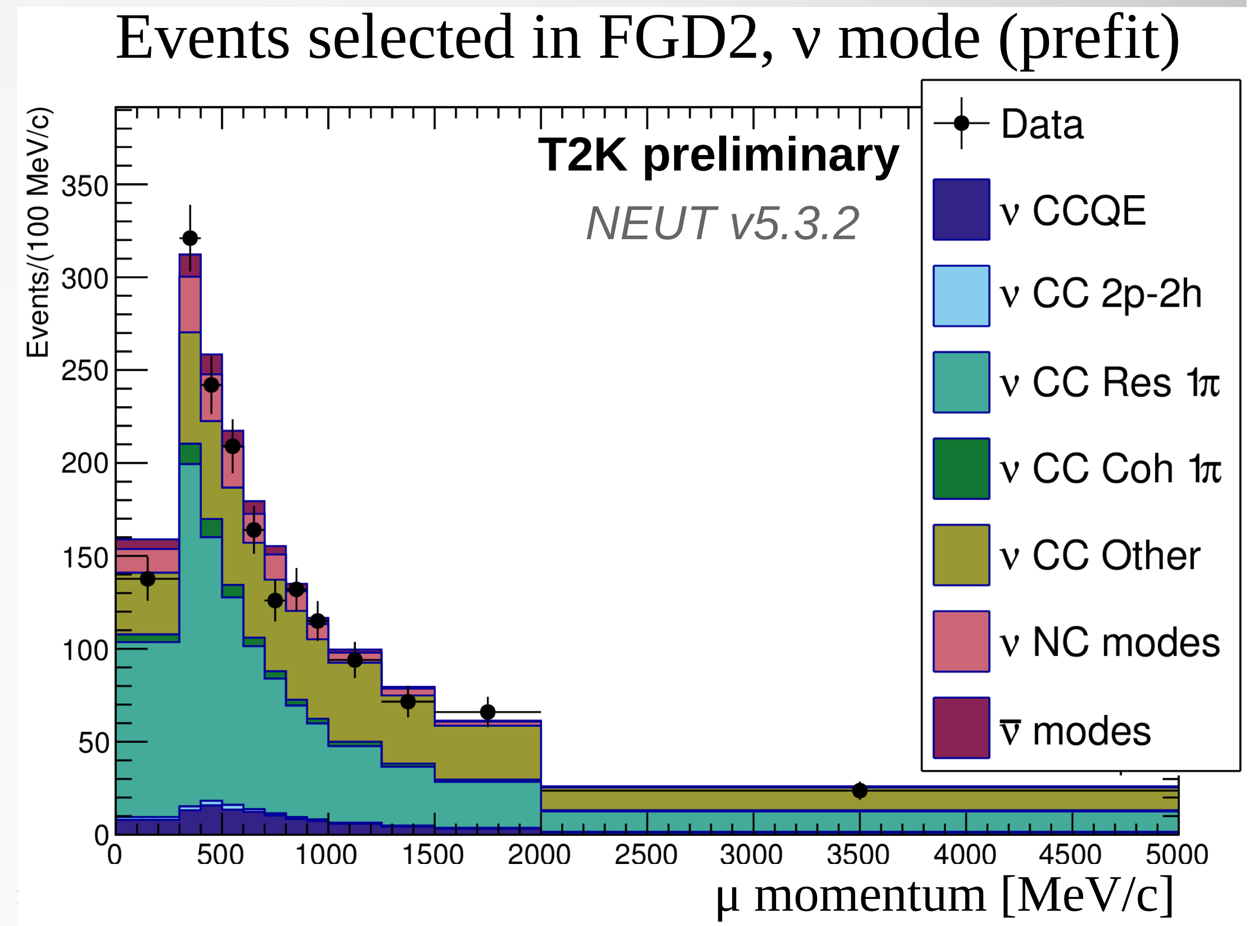




Interaction model: CC-1π







<u>CC-RES: 3 parameters</u>

axial mass M_A^{RES}

norm+shape parameter C_A^5

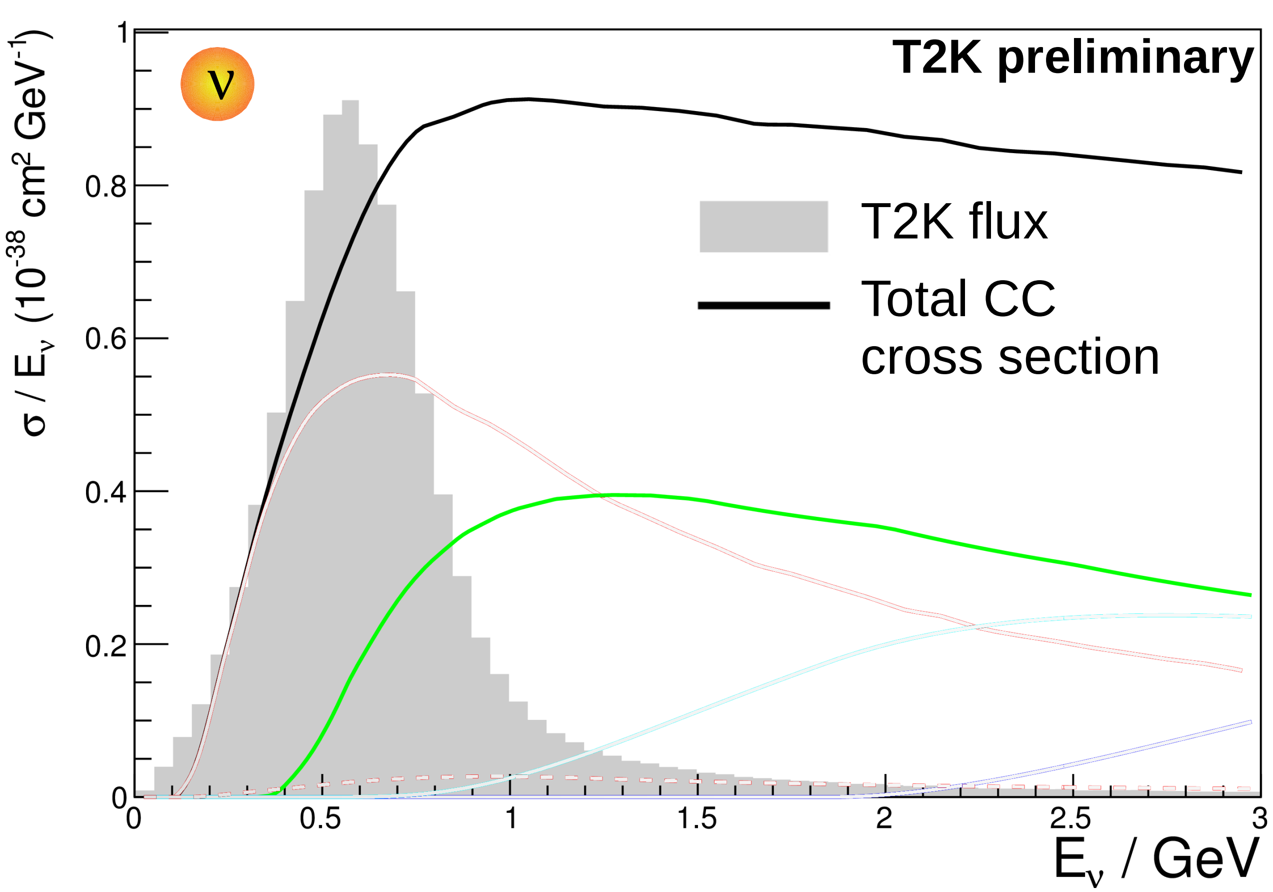
Isospin=1/2 background

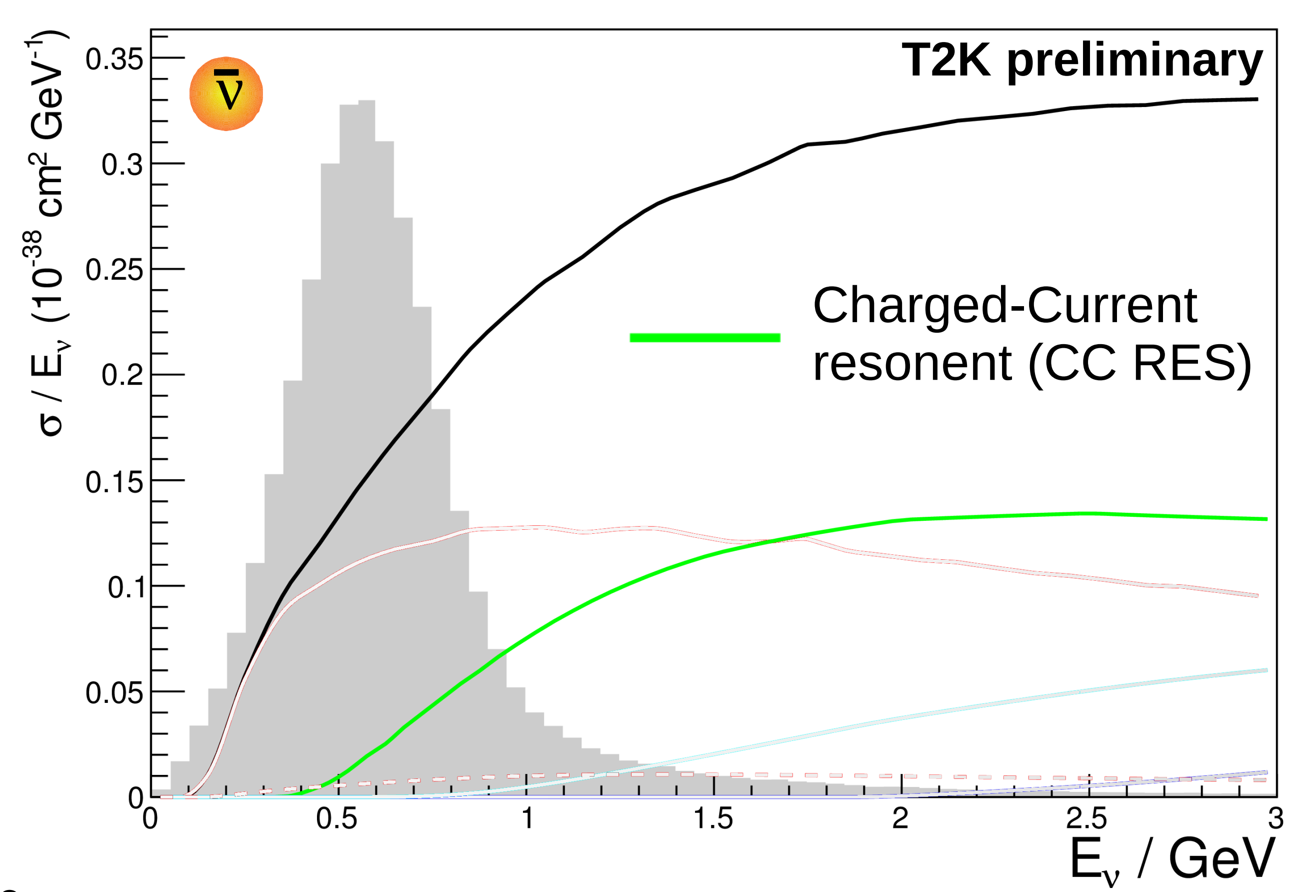
<u>CC-COH: 1 parameter</u>

CC-coherent

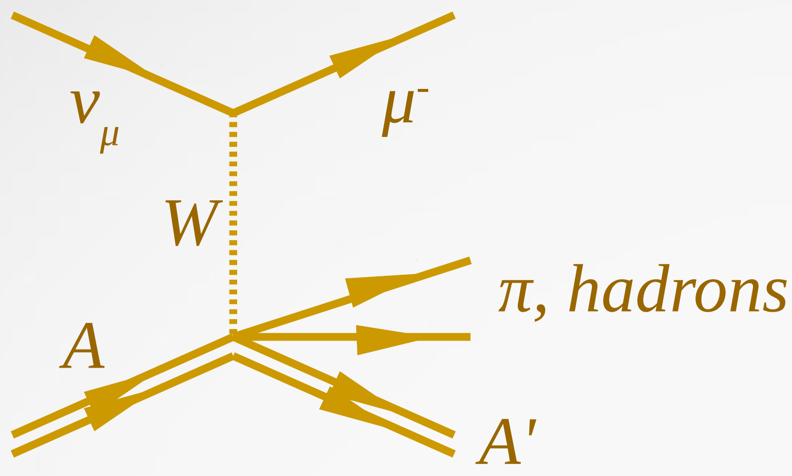
cross-section

normalisation



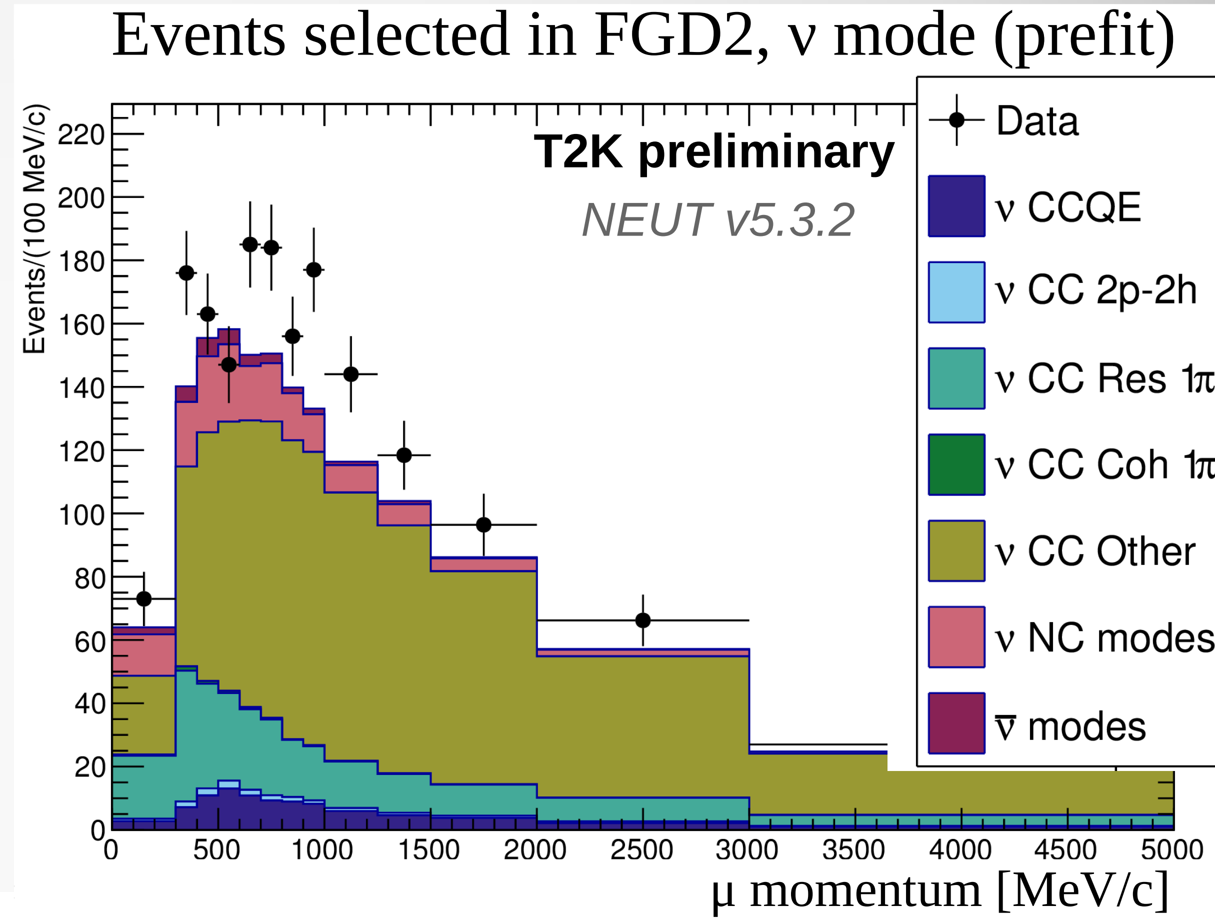


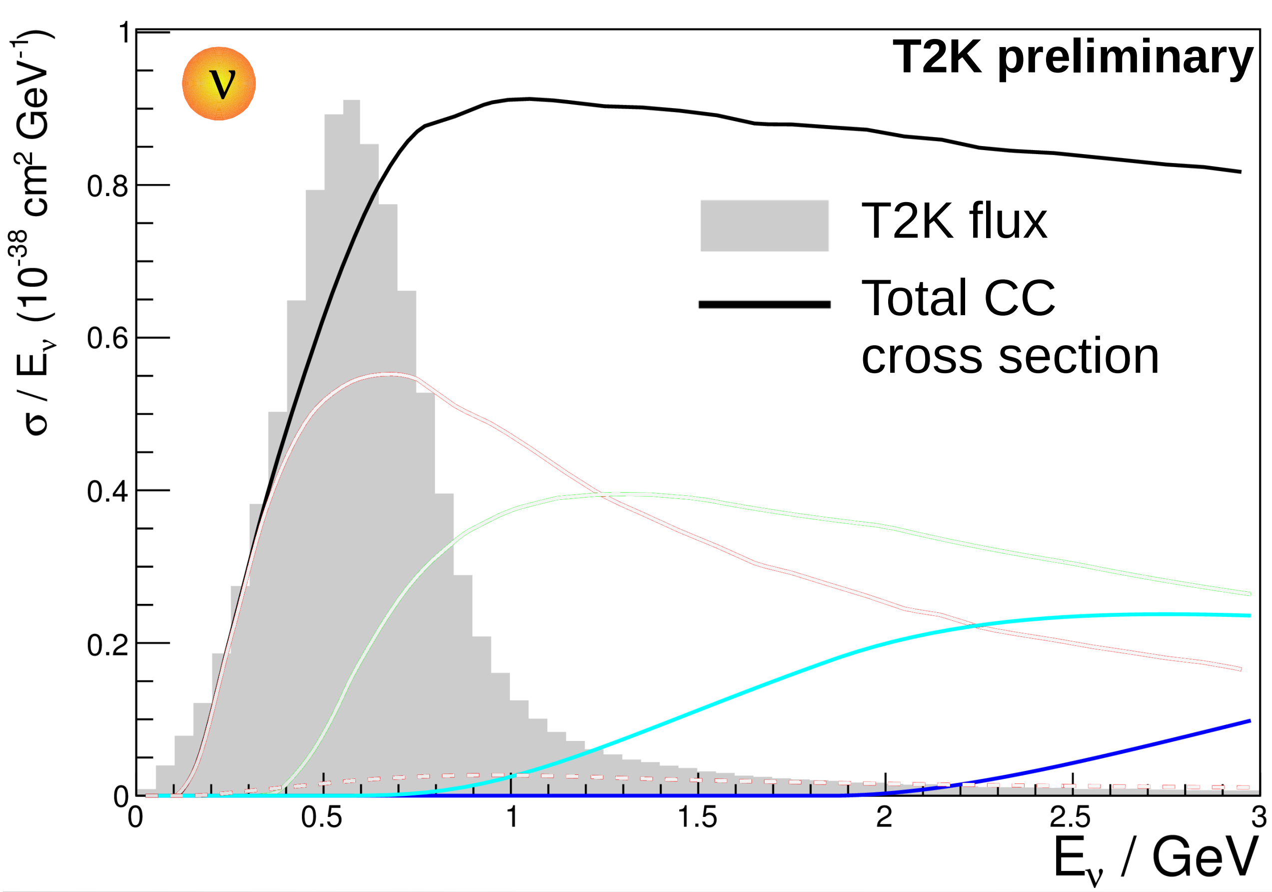
Interaction model: CC-other

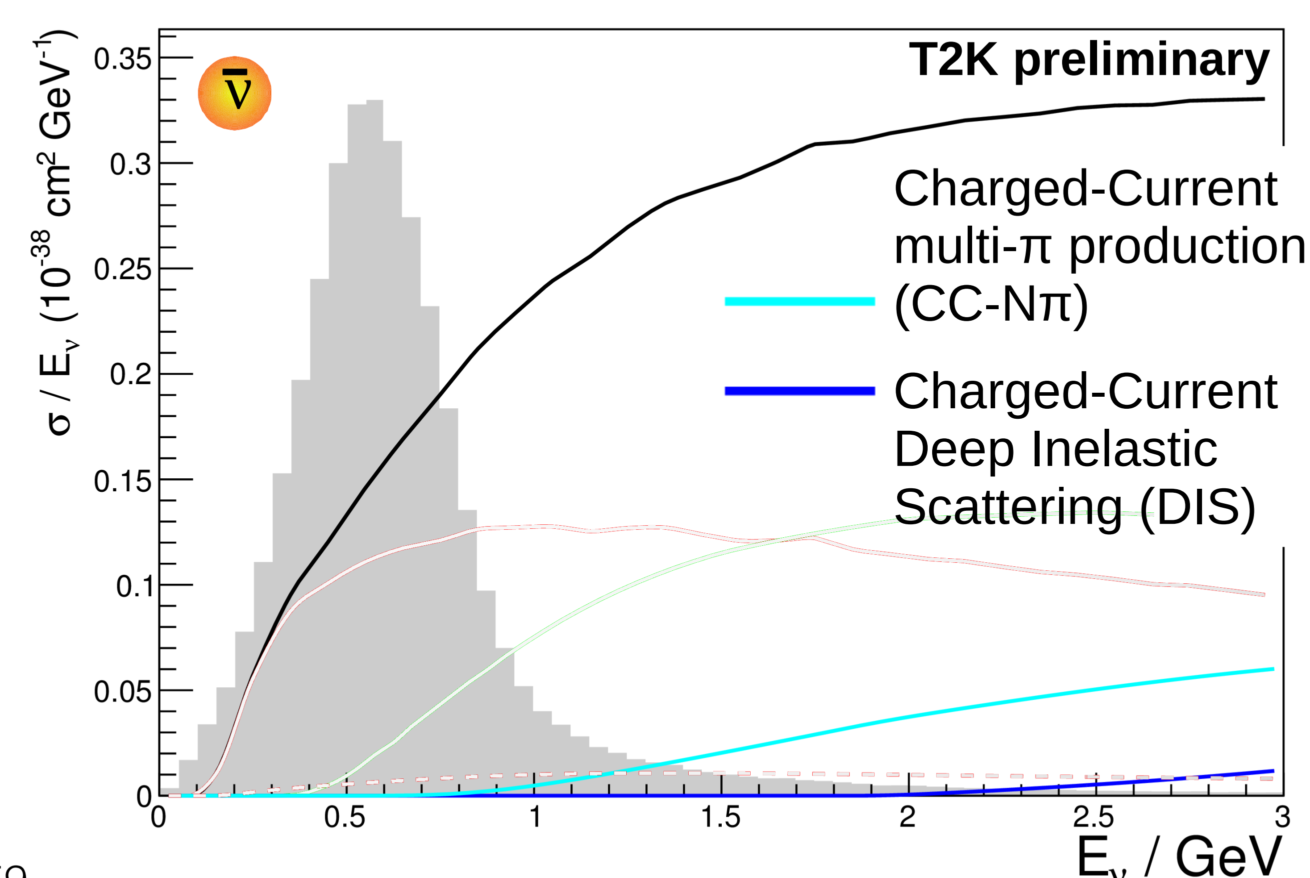


CC-other: 1 parameter

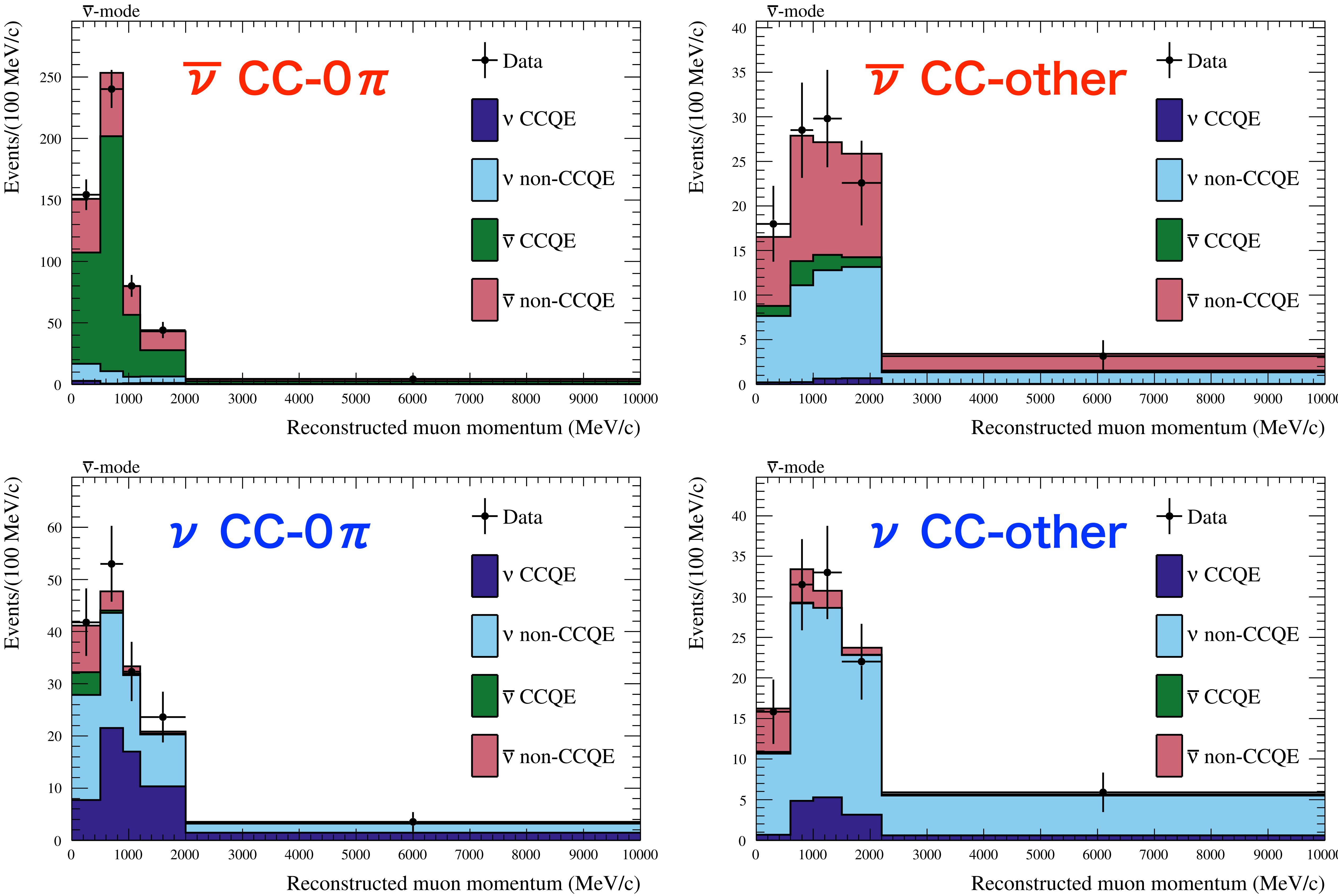
shape of CC-Nπ and DIS cross sections (merged)







Anti-neutrino beam mode

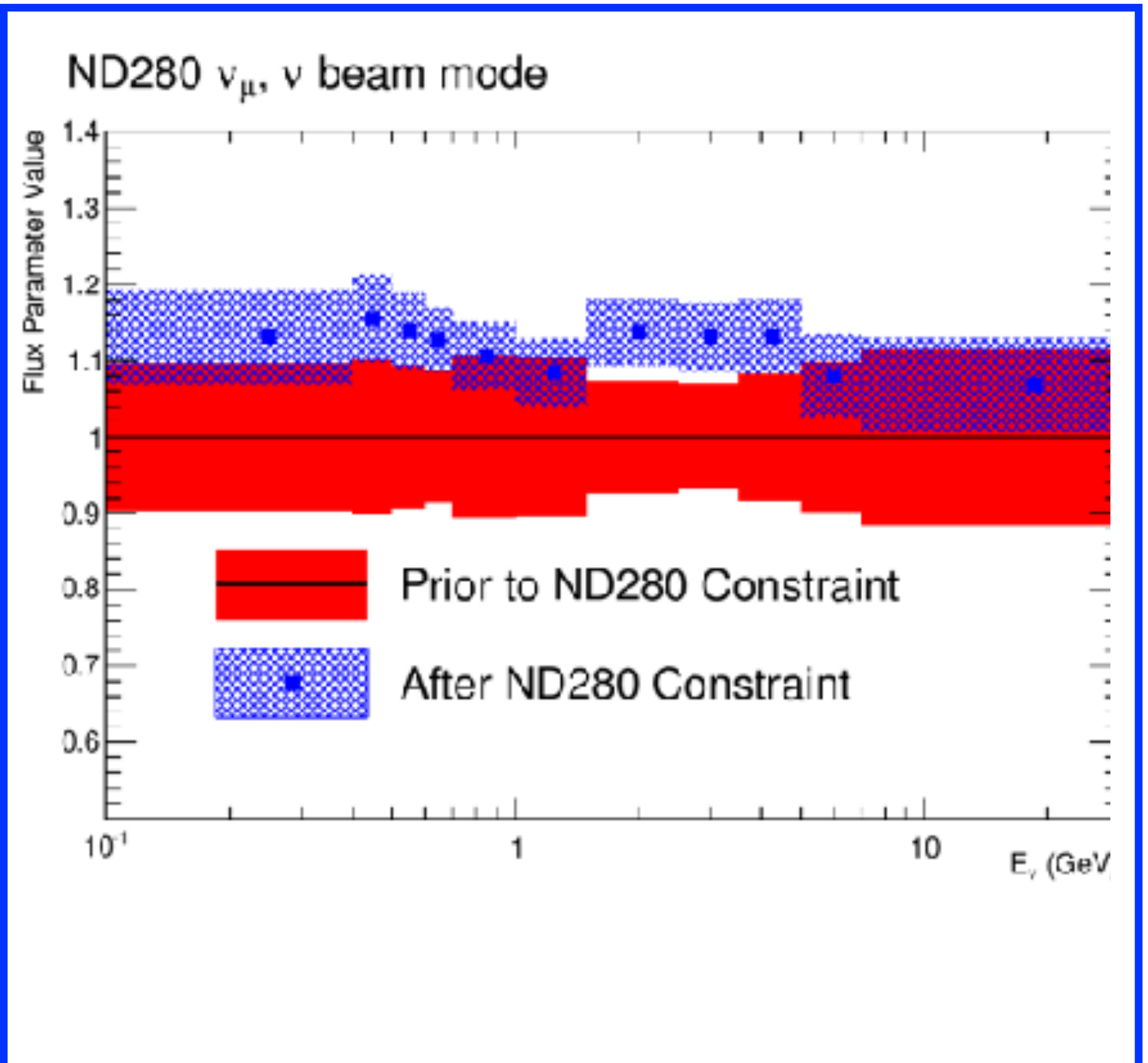


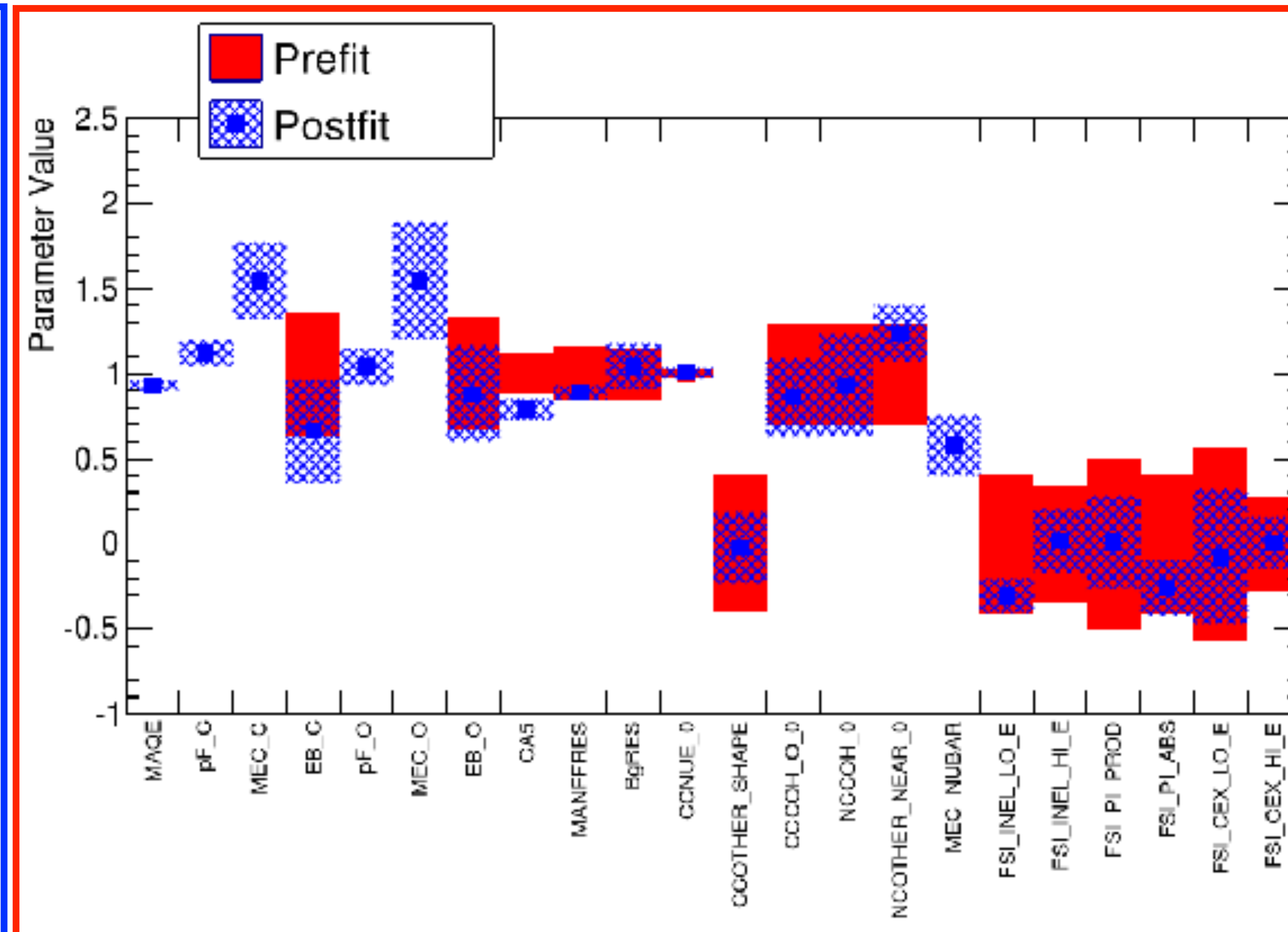
14 ND280 event samples

Detector	Beam	CC-0π	CC-1π	CC-other
FGD1	ν	1	2	3
	anti-ν	4	5	
		6	7	
FGD2 (Water)	ν	8	9	10
	anti-ν	11	12	
		13	14	

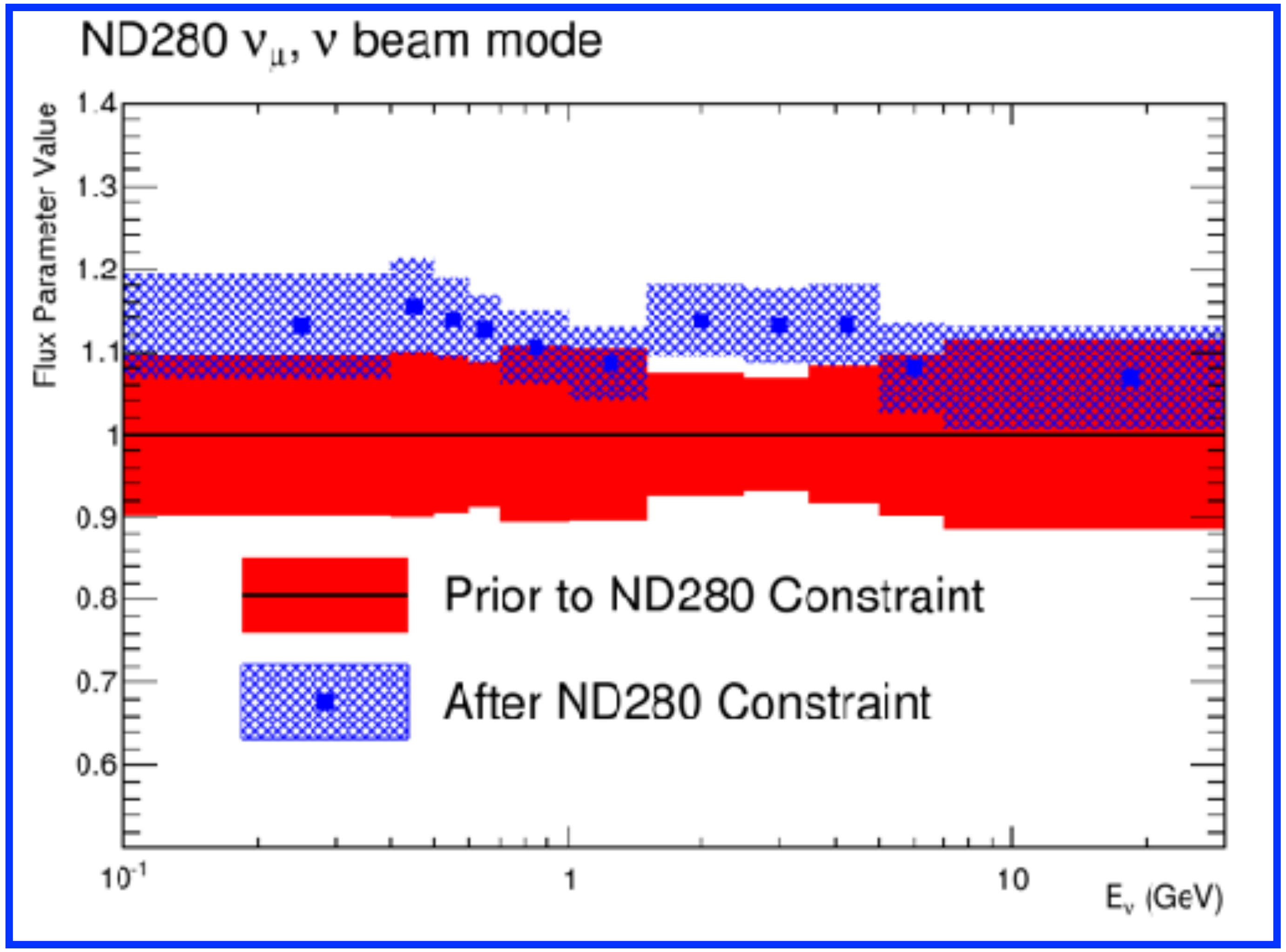
- Binned Likelihood fit of MC expectations with flux, cross-section and detector parameters to data **observation.**
  - P_μ vs $\cos\theta_\mu$

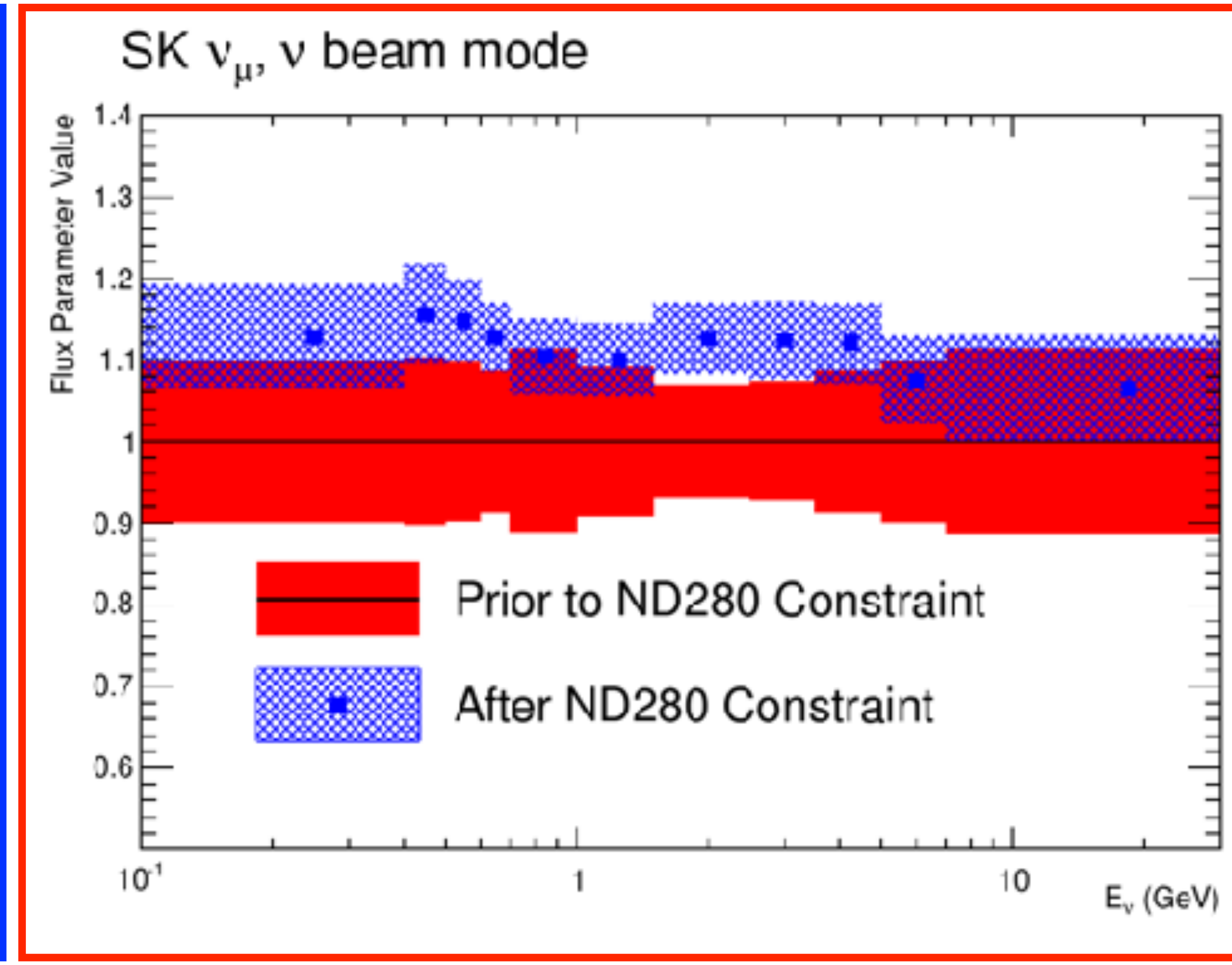
Fit ND280 data with flux and cross-section parameters





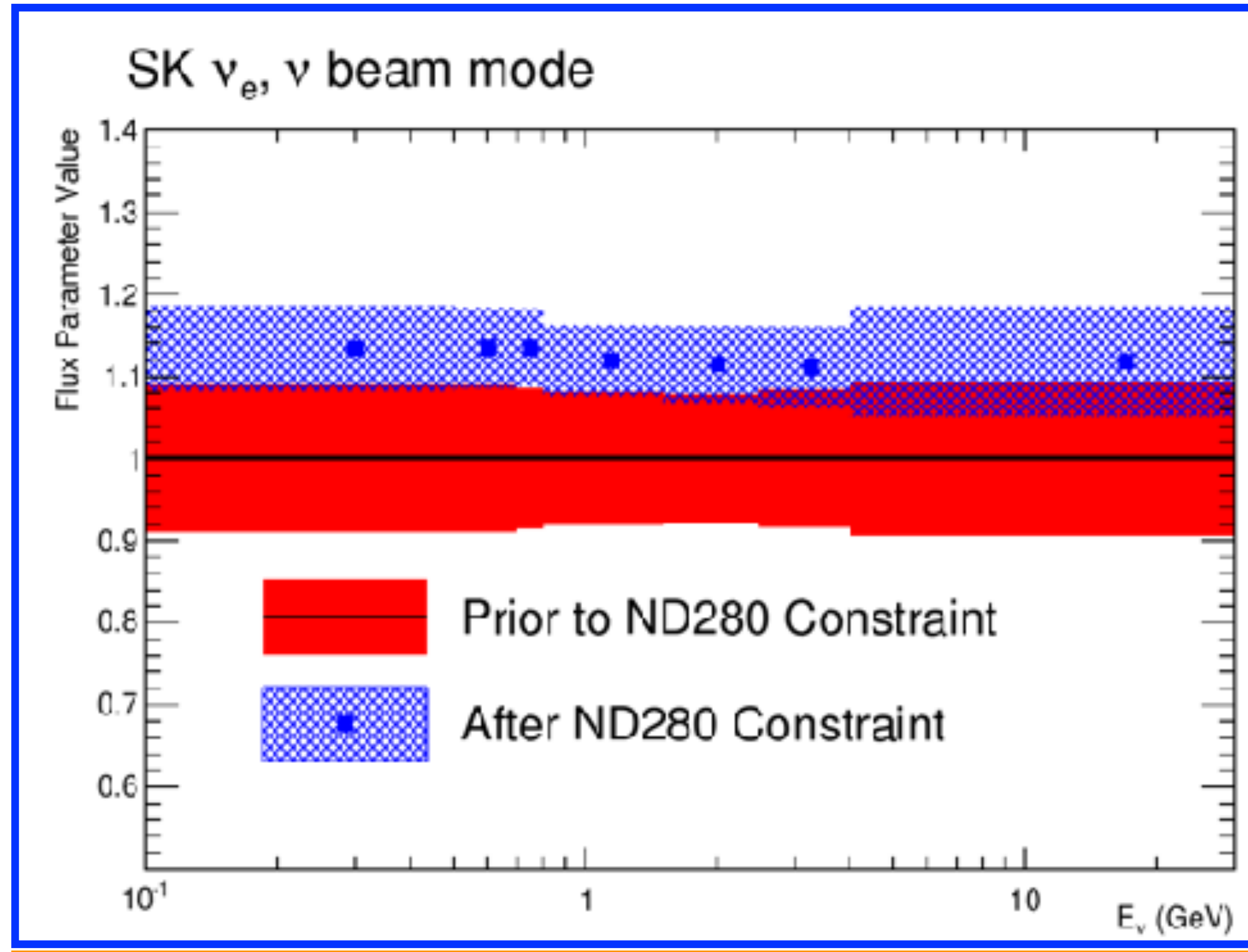
How many type of flux parameters?

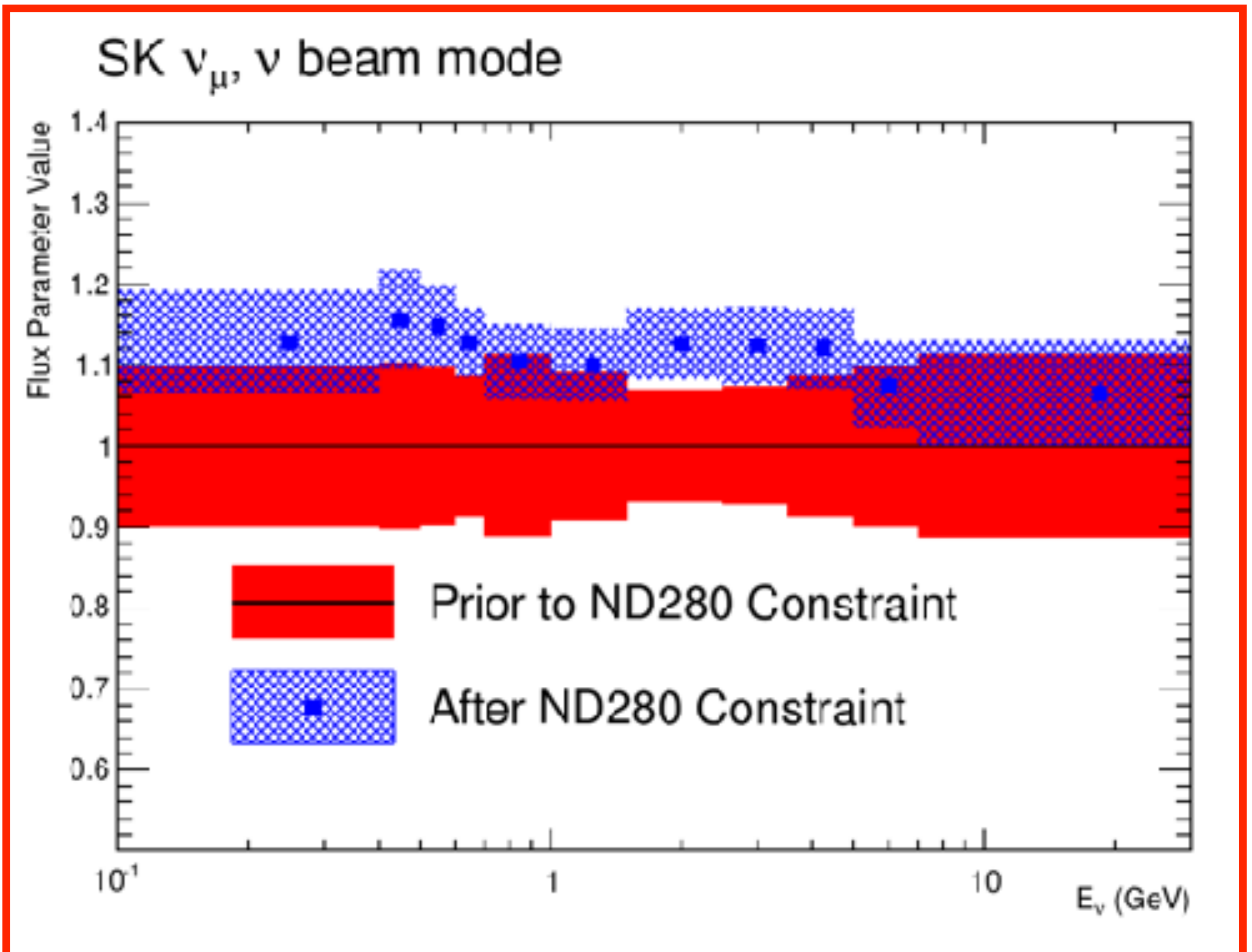


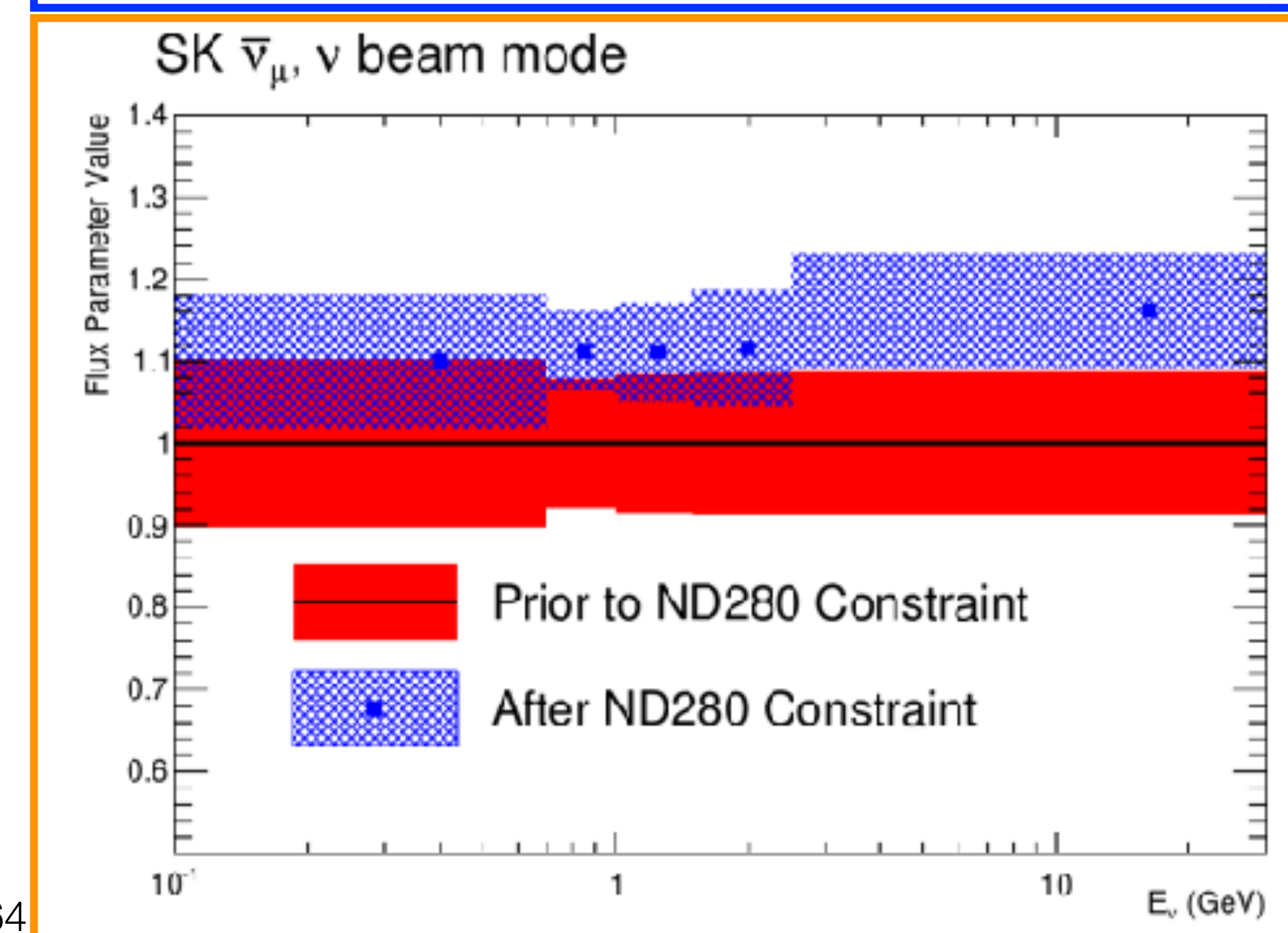


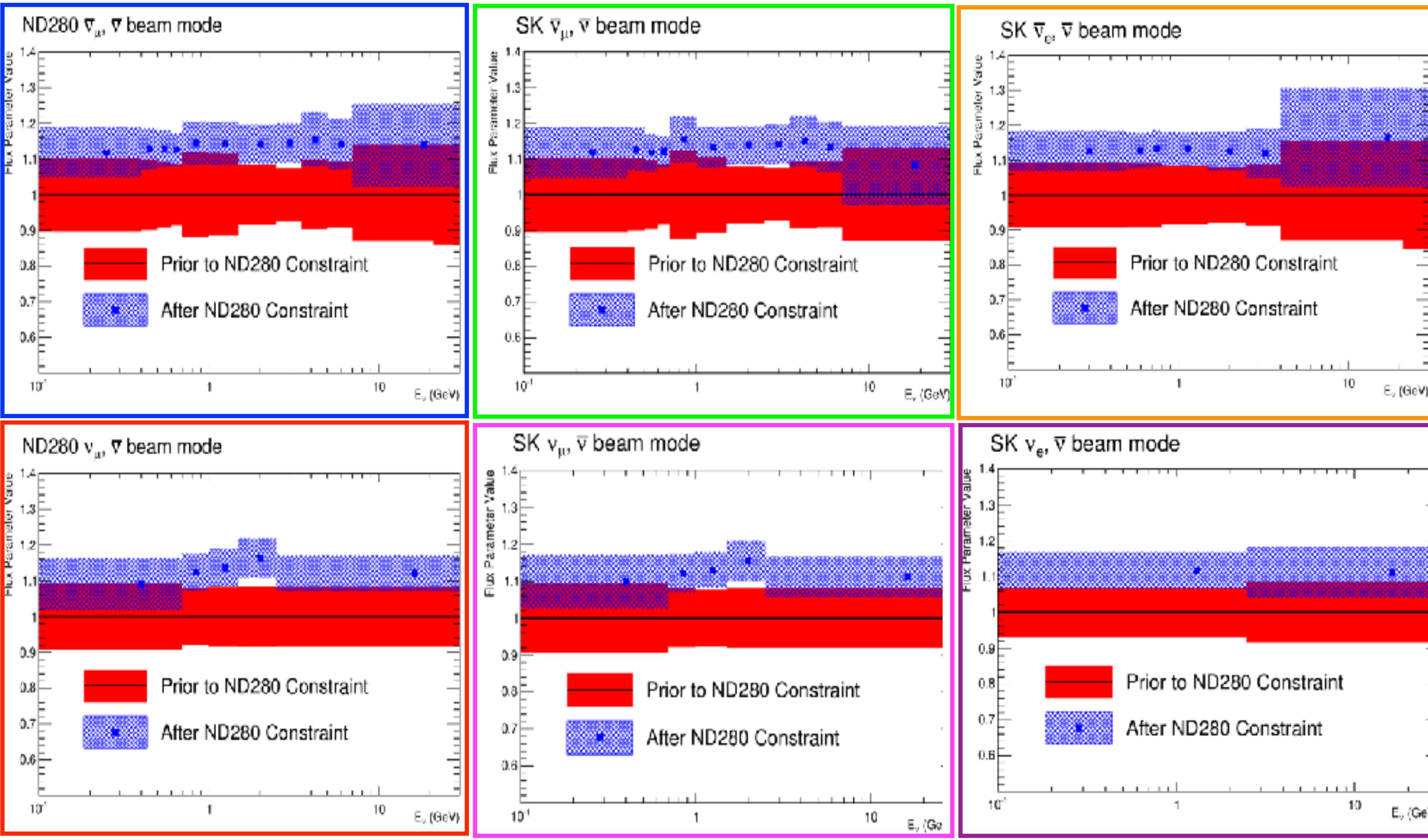
		ν_μ	ν_e	anti-ν_μ	anti-ν_e
ν	ND280	□			
	SK	□			
anti-ν	ND280				
	SK				

		ν_μ	ν_e	anti-ν_μ
ν	ND280			
	SK	□	□	□



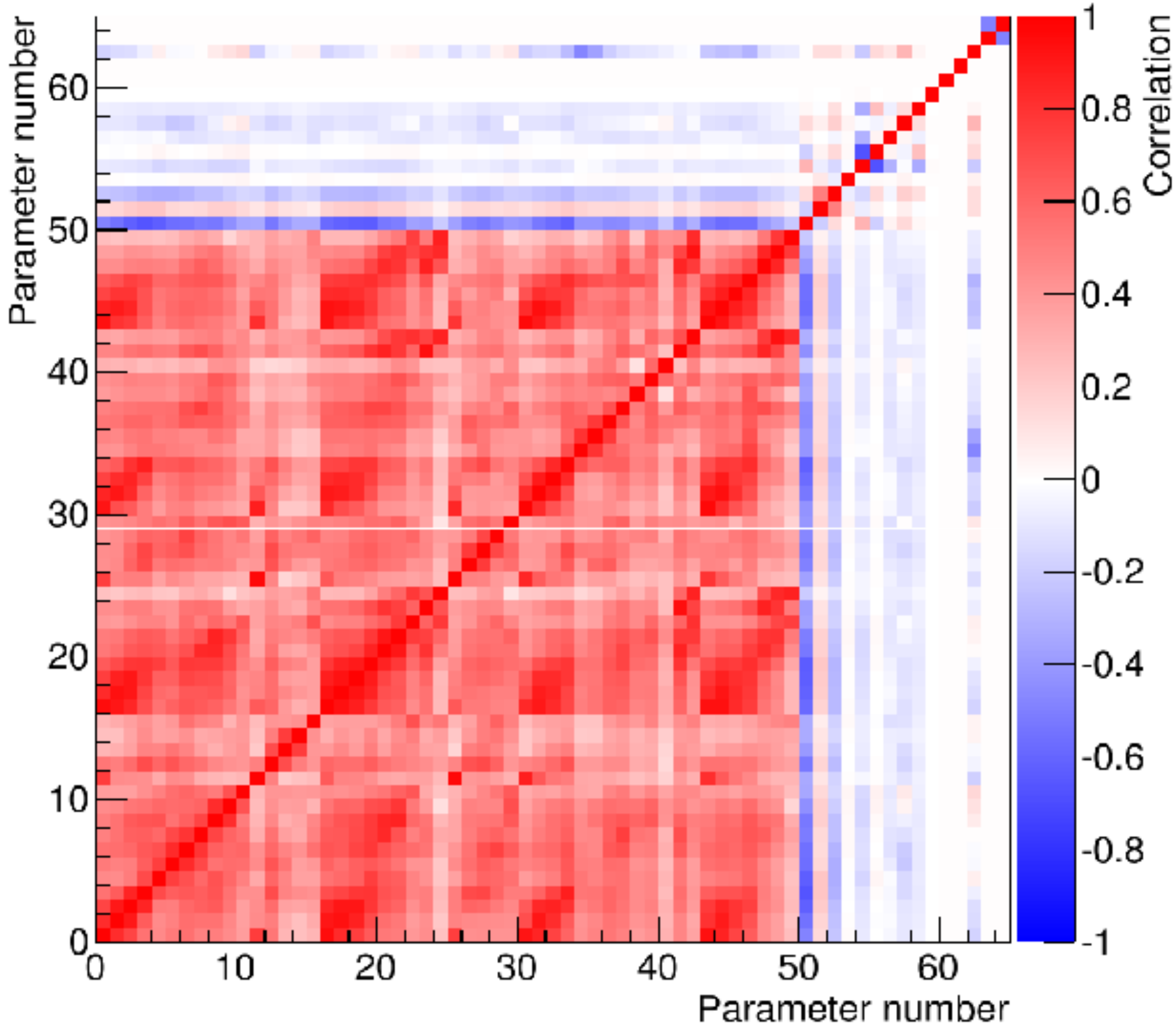






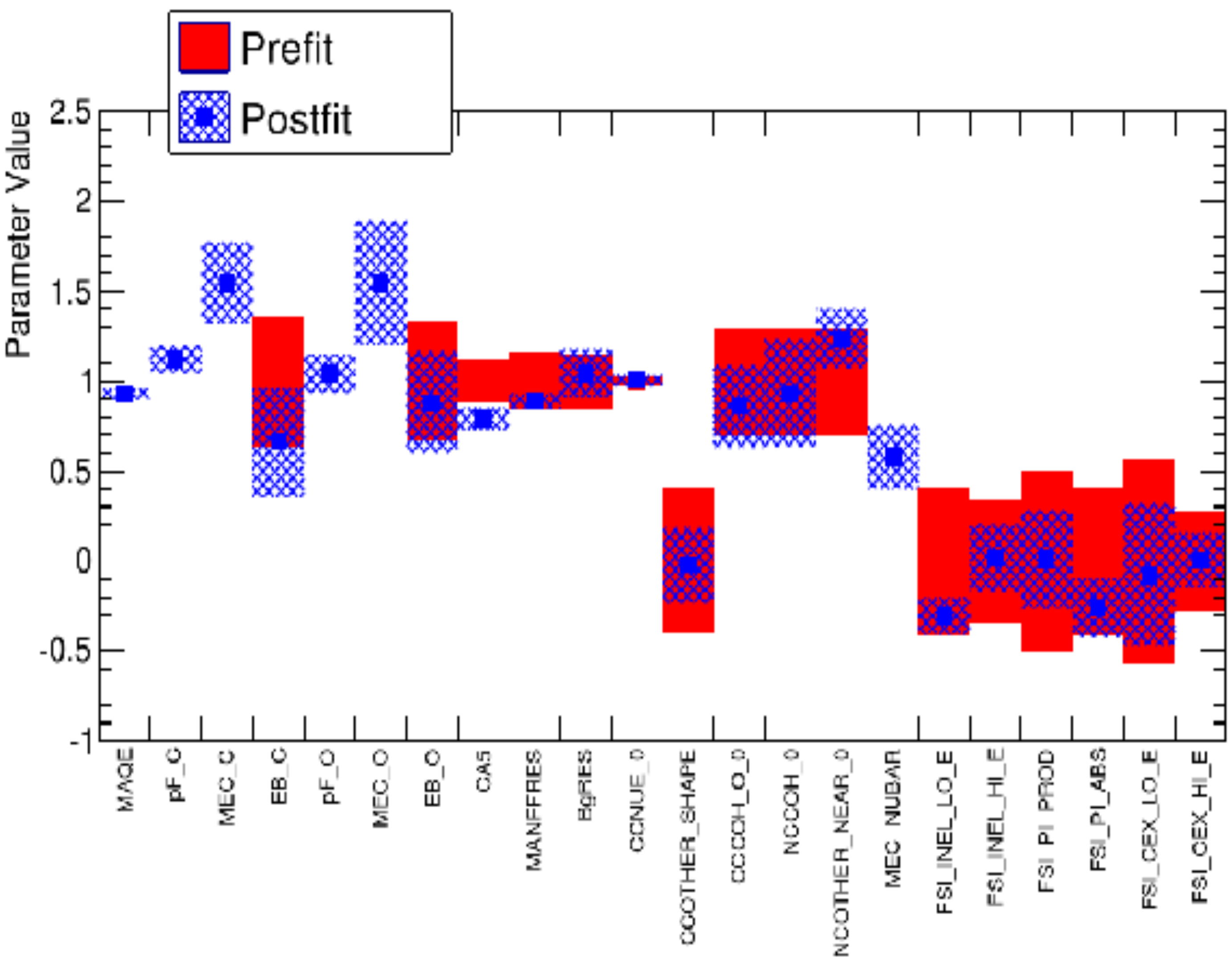
		ν_μ	ν_e	anti-ν_μ	anti-ν_e
anti-ν	ND280	□		□	
	SK	□	□	□	□

SK parameter correlation matrix



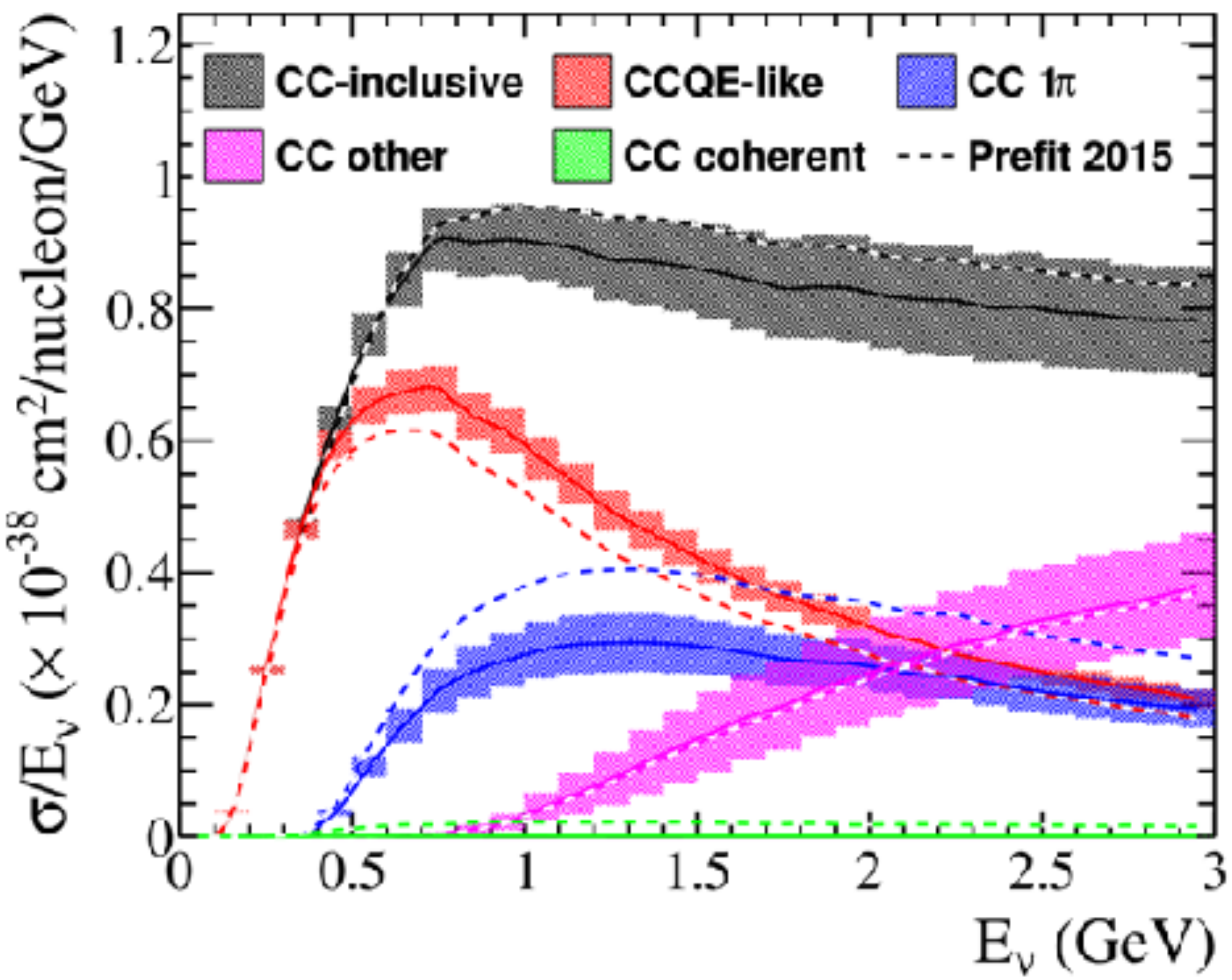
- Flux para[1-50]
  - ν para[1-25]
    - ν_μ[1-11]
    - anti-ν_μ[12-16]
    - ν_e[17-23]
    - anti-ν_e[24-25]
  - anti-ν para[26-50]
    - ν_μ[26-30]
    - anti-ν_μ[31-41]
    - ν_e[42-43]
    - anti-ν_e[44-50]
- Cross-Section Para[51-65]

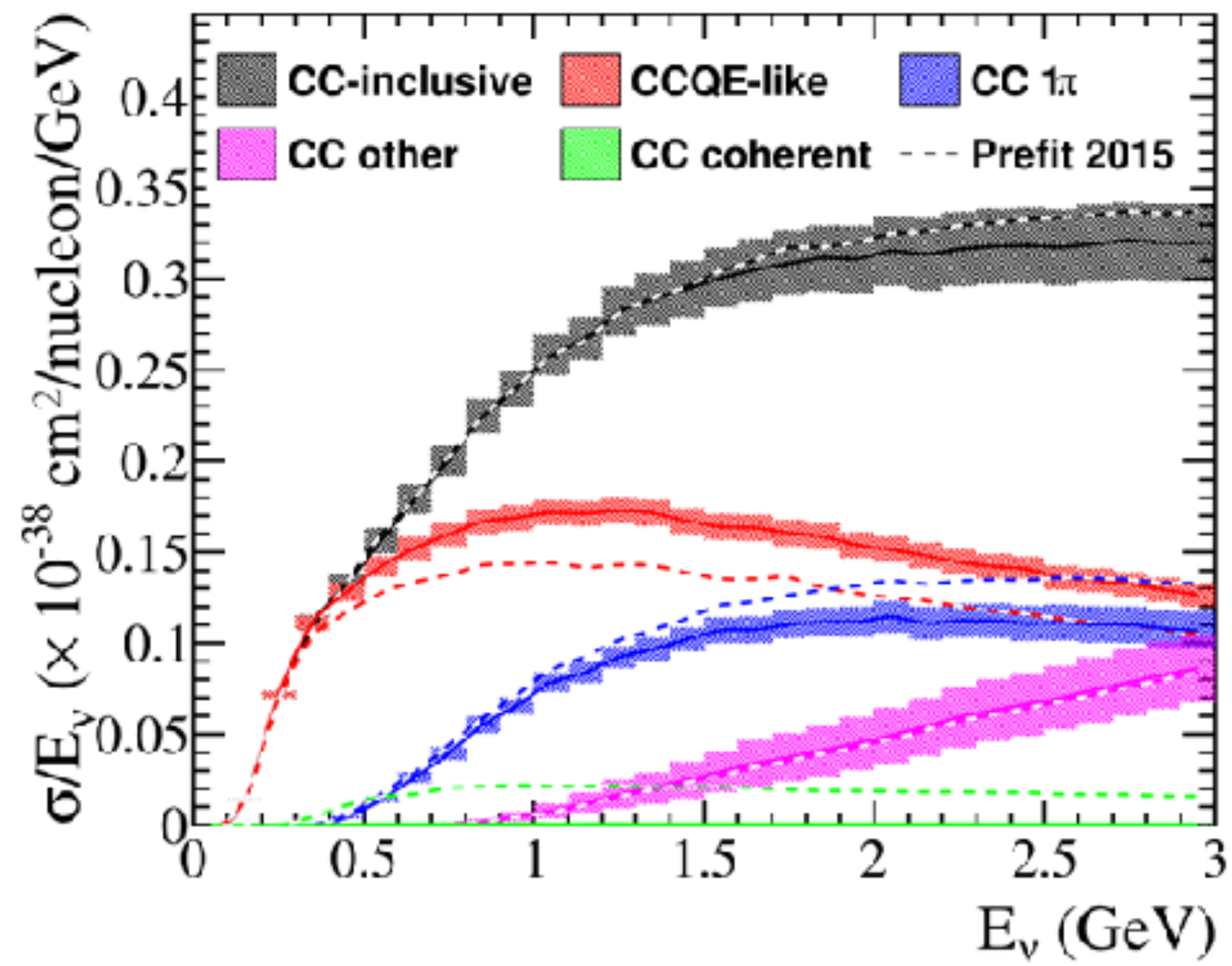
Cross Section Parameters



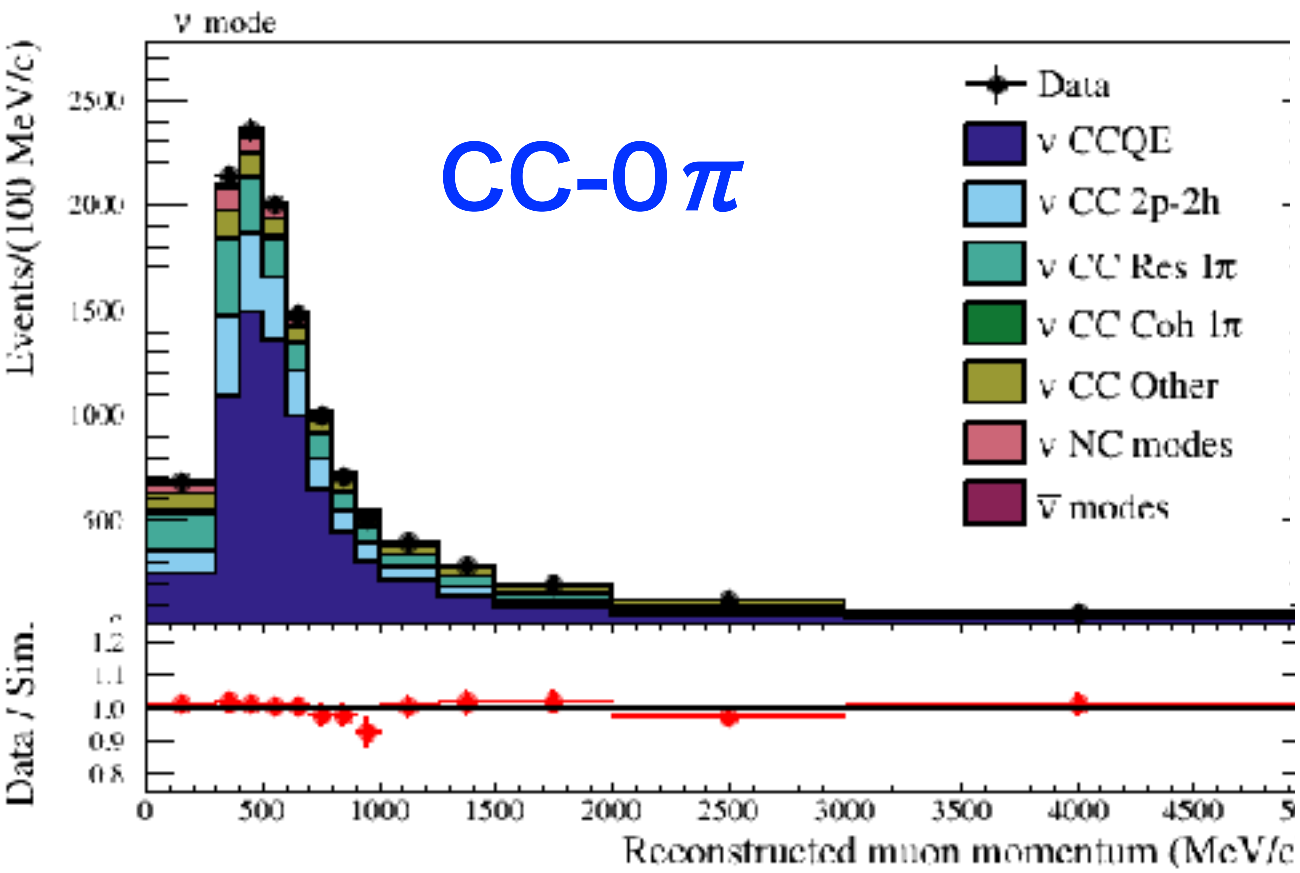
Cross section parameter	Prefit	ND280 postfit
M_A^{QE} (GeV/c^2)	1.20	1.12 ± 0.03
p_F ^{12}C (MeV/c)	217.0	243.9 ± 16.6
2p2h ^{12}C	100.0	154.5 ± 22.7
E_b ^{12}C (MeV)	25.0 ± 9.00	16.5 ± 7.53
p_F ^{16}O (MeV/c)	225.0	234.2 ± 23.7
2p2h ^{16}O	100.0	154.6 ± 34.3
E_b ^{16}O (MeV)	27.0 ± 9.00	23.8 ± 7.61
C_A^5	1.01 ± 0.12	0.80 ± 0.06
M_A^{RES} (GeV/c^2)	0.95 ± 0.15	0.84 ± 0.04
$I_{\frac{1}{2}}$ background	1.30 ± 0.20	1.36 ± 0.17
CC other shape	0.00 ± 0.40	-0.02 ± 0.21
CC coherent	1.00 ± 0.30	0.86 ± 0.23
NC coherent	1.00 ± 0.30	0.93 ± 0.30
2p2h $\bar{\nu}$	1.00	0.58 ± 0.18
NC other	1.00 ± 0.30	Not constrained
NC 1-γ	1.00 ± 1.00	Not constrained
ν_e/ν_μ ratio	1.00 ± 0.02	Not constrained
$\bar{\nu}_e/\bar{\nu}_\mu$ ratio	1.00 ± 0.02	Not constrained
FSI elastic low-E	0.00 ± 0.41	Not constrained
FSI elastic high-E	0.00 ± 0.34	Not constrained
FSI pion production	0.00 ± 0.50	Not constrained
FSI pion absorption	0.00 ± 0.41	Not constrained
FSI charge exchange low-E	0.00 ± 0.57	Not constrained
FSI charge exchange high-E	0.00 ± 0.28	Not constrained

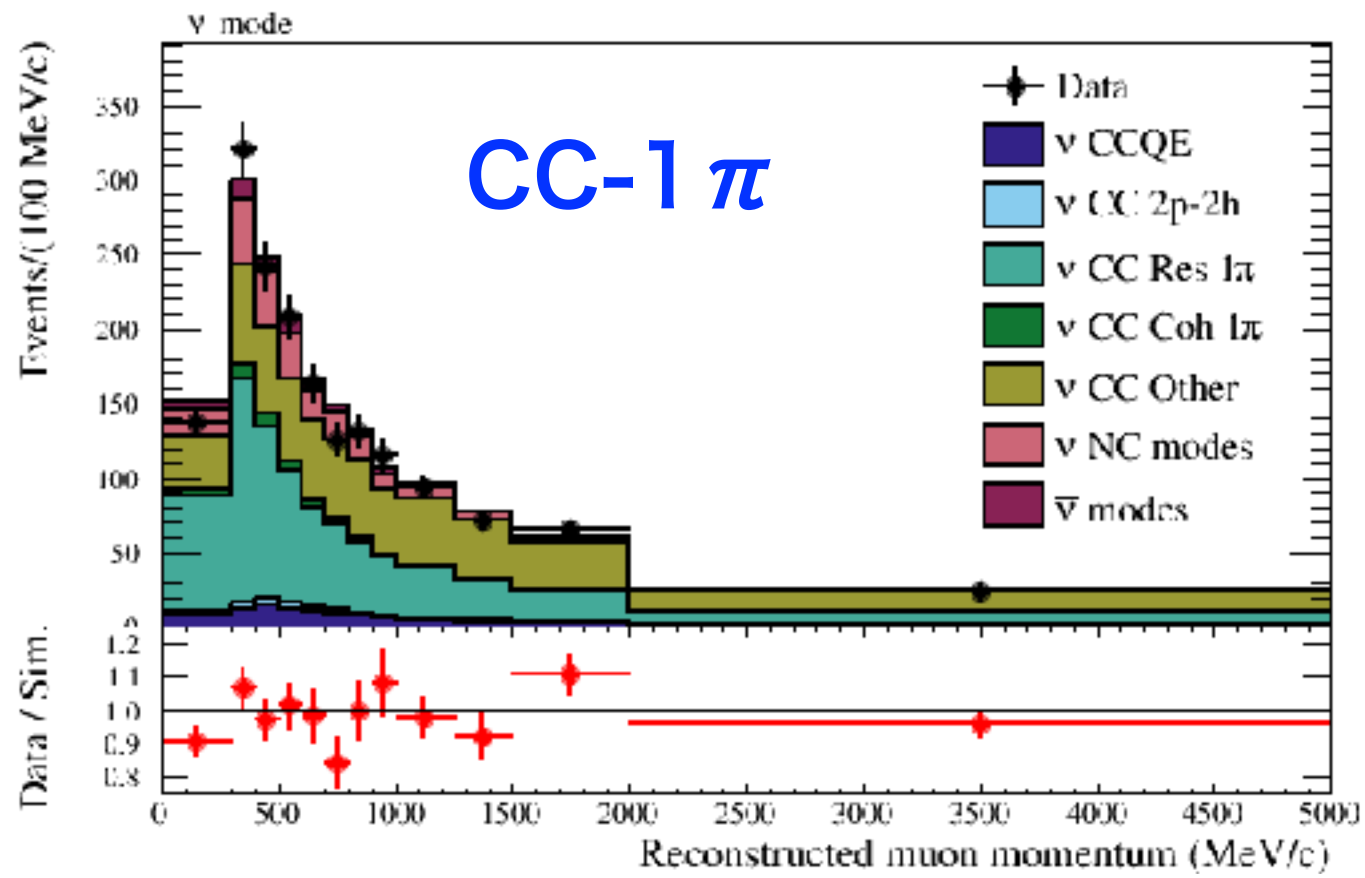
Cross Section tuning

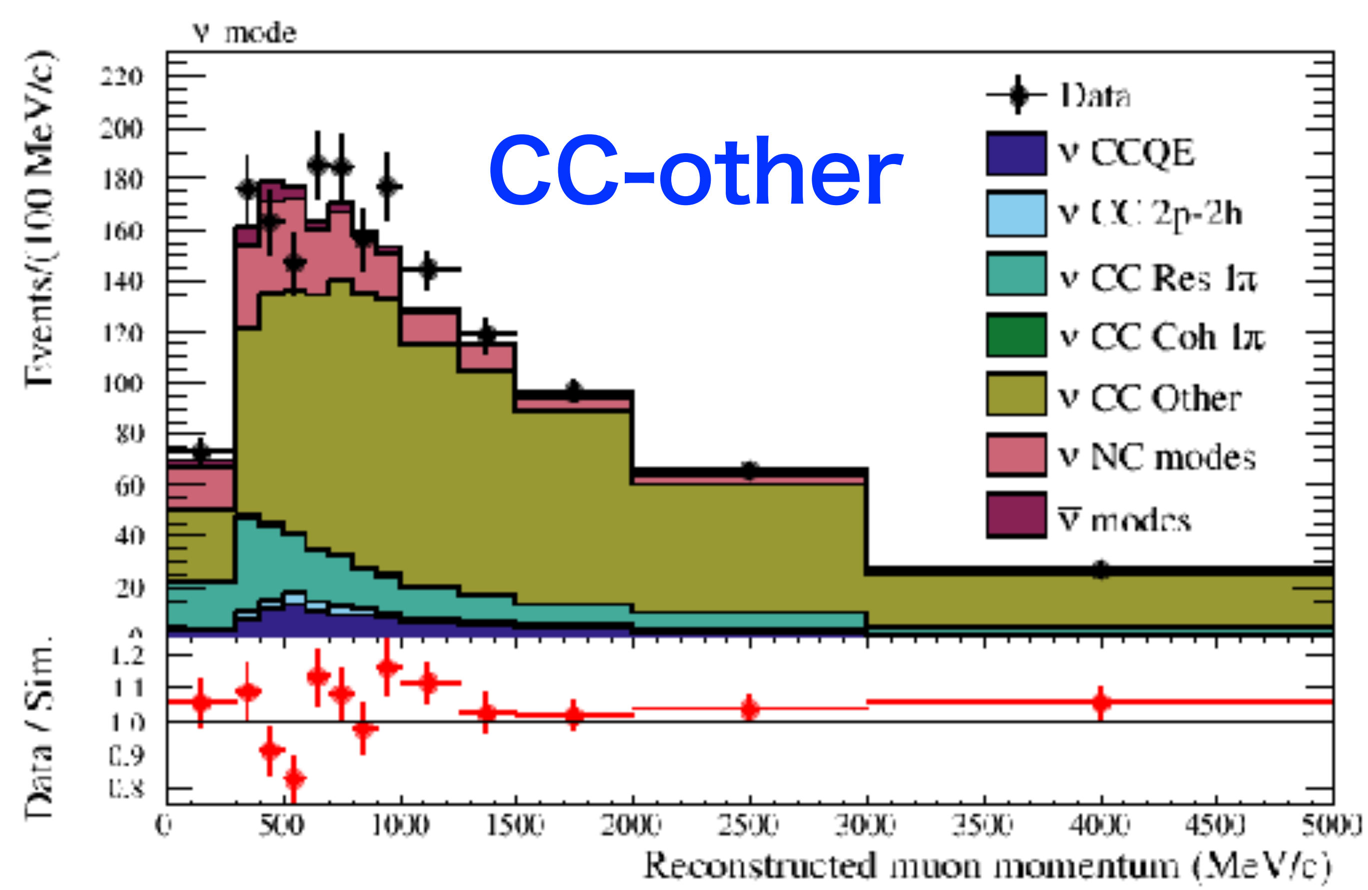




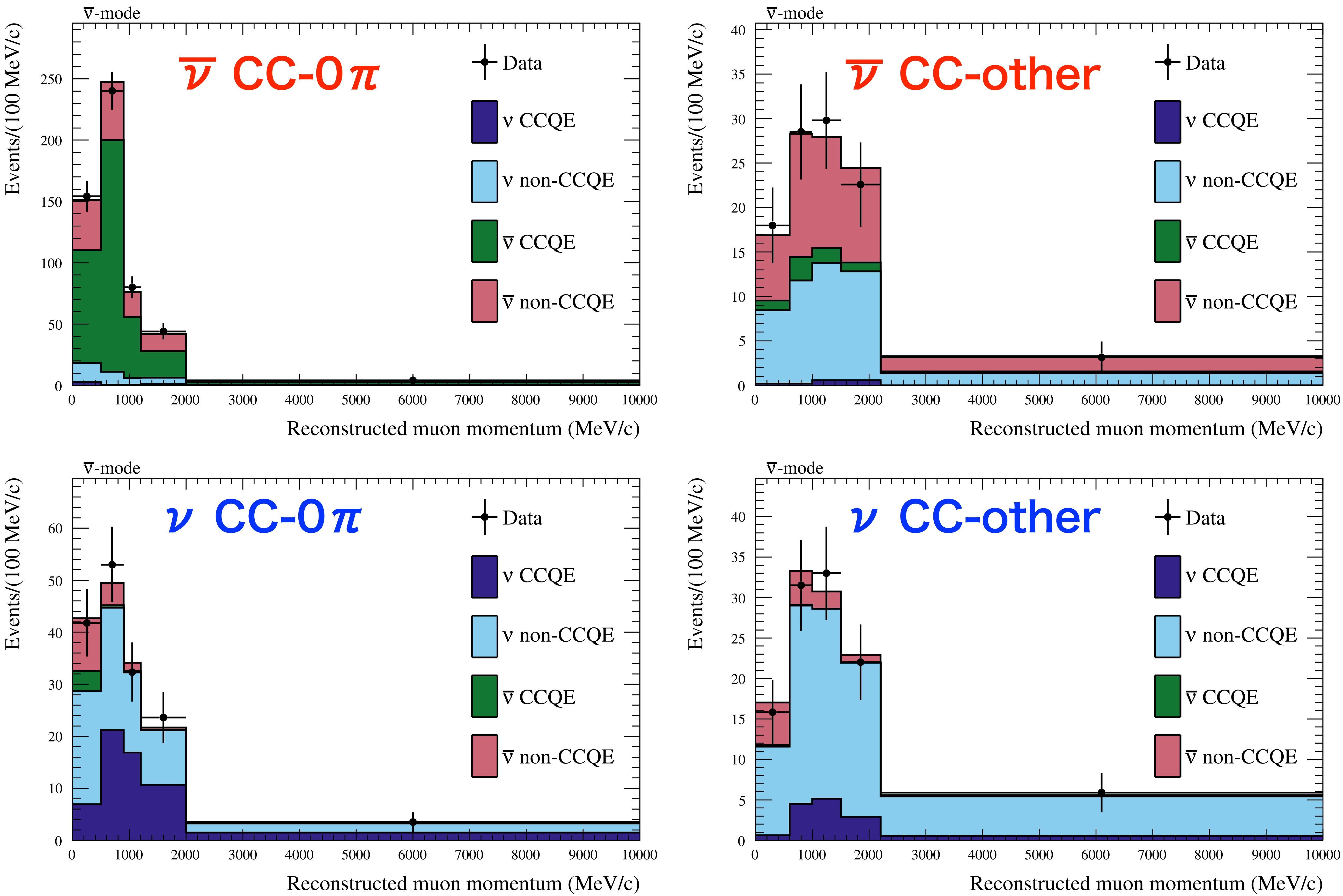
ND280 ν data comparison after FIT







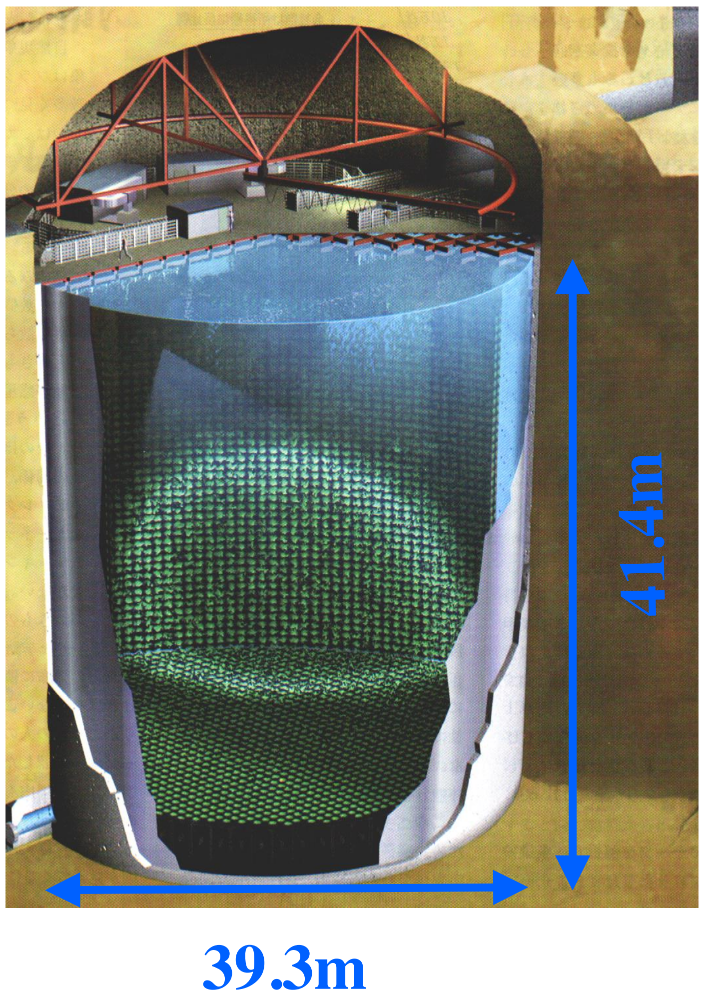
ND280 $\overline{\nu}$ data comparison after FIT

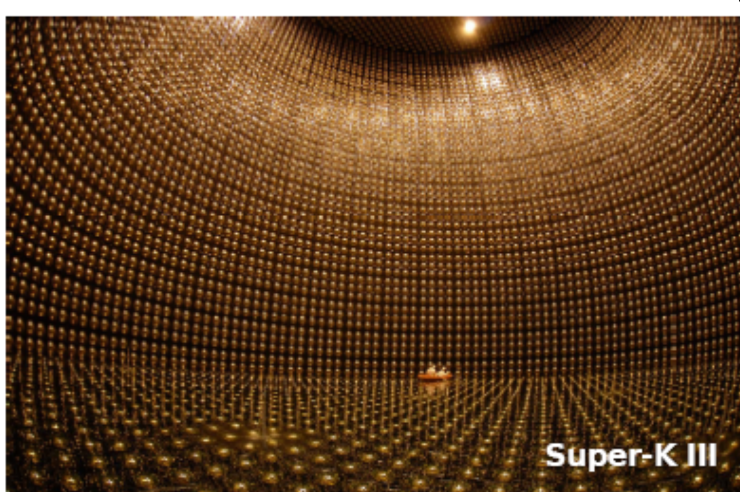


6. Super-Kamiokande

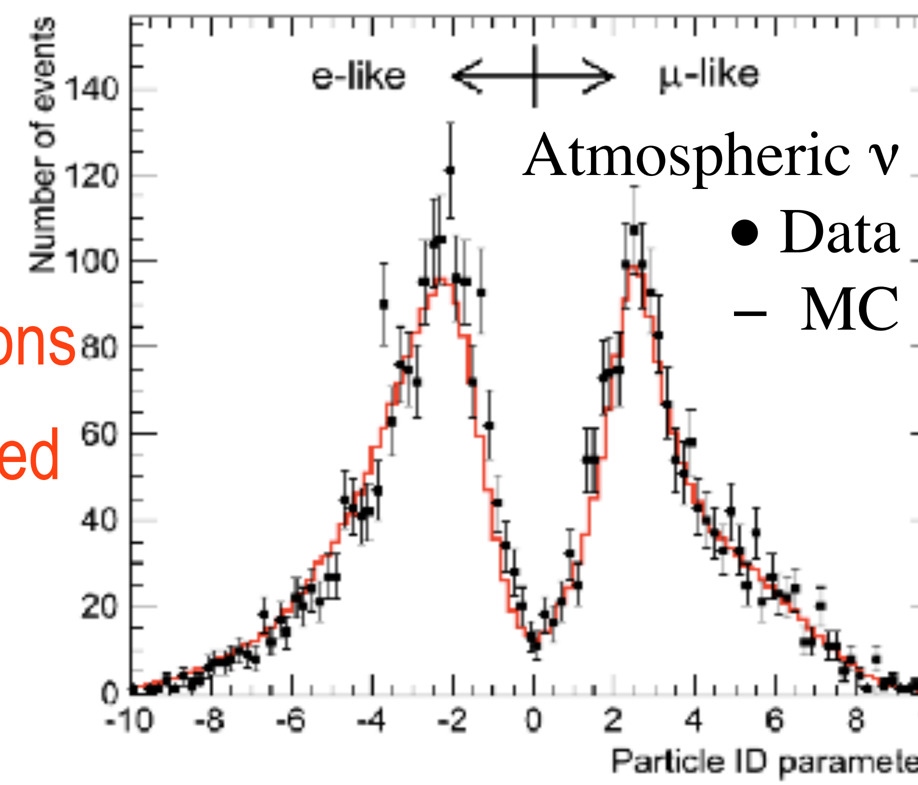
- Far Detector -

T2K-Far Detector: Super-Kamiokande

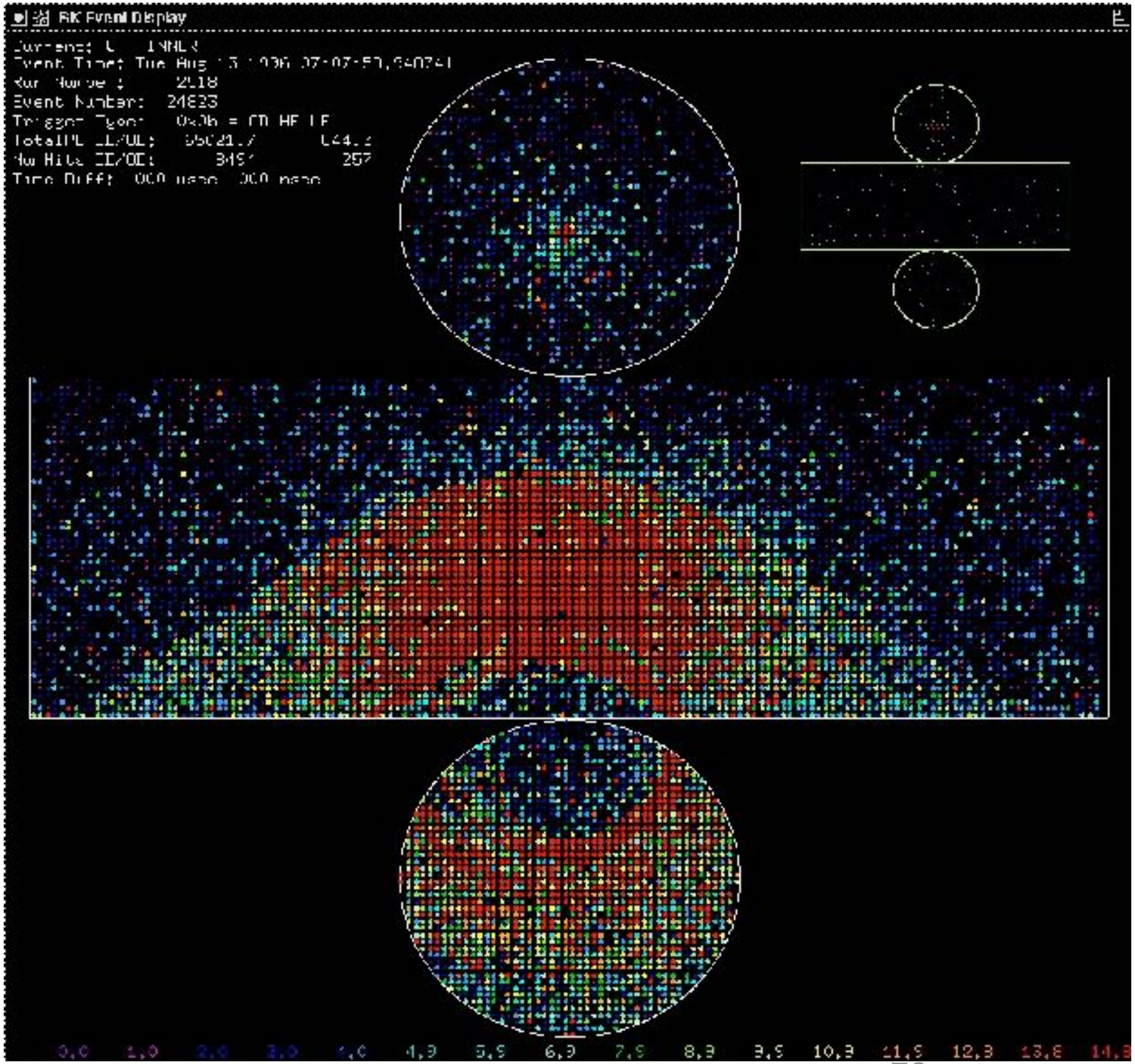


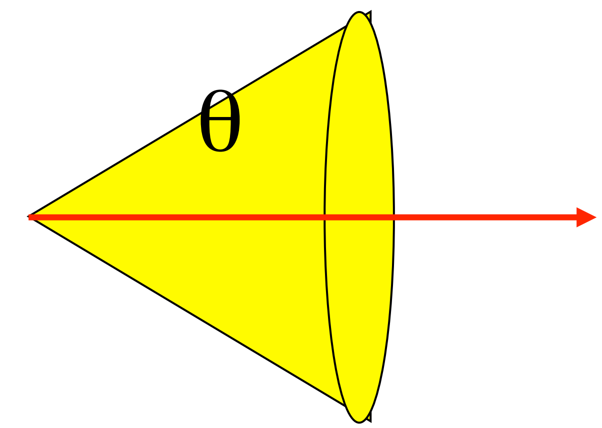


- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with 95% NC-1π^0 rejection
    - Inner tank (32 kton) :11,129 20inch PMT
    - Outer tank:1,885 8inch PMT
- Dead-time-less DAQ
- GPS timing information is recorded real-time at every accelerator spill
  - T2K recorded events: All interactions within a ±500μsec window centered on the the neutrino arrival time.



• Cherenkov Imaging





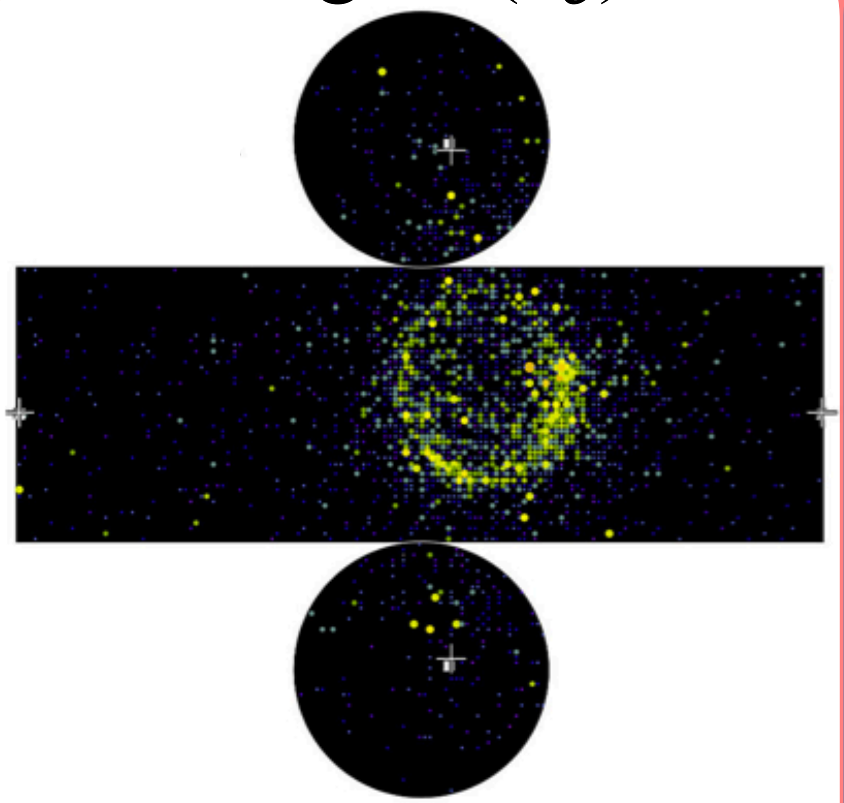
$\beta > 1/n$ (n=1.)

$\cos\theta = 1/n\beta$

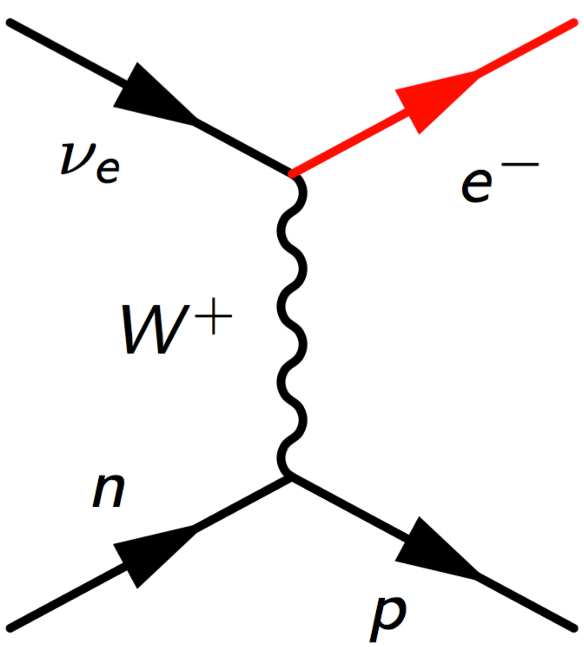
- **Particle ID.**
  - By the Cherenkov ring edge and the opening Angle.
- **Momentum**
  - The amount of light-yield inside a ring with PID
- **Vertex**
  - Timing of the PMT at the ring edge with PID

Neutrino Detection at SK Far Detector

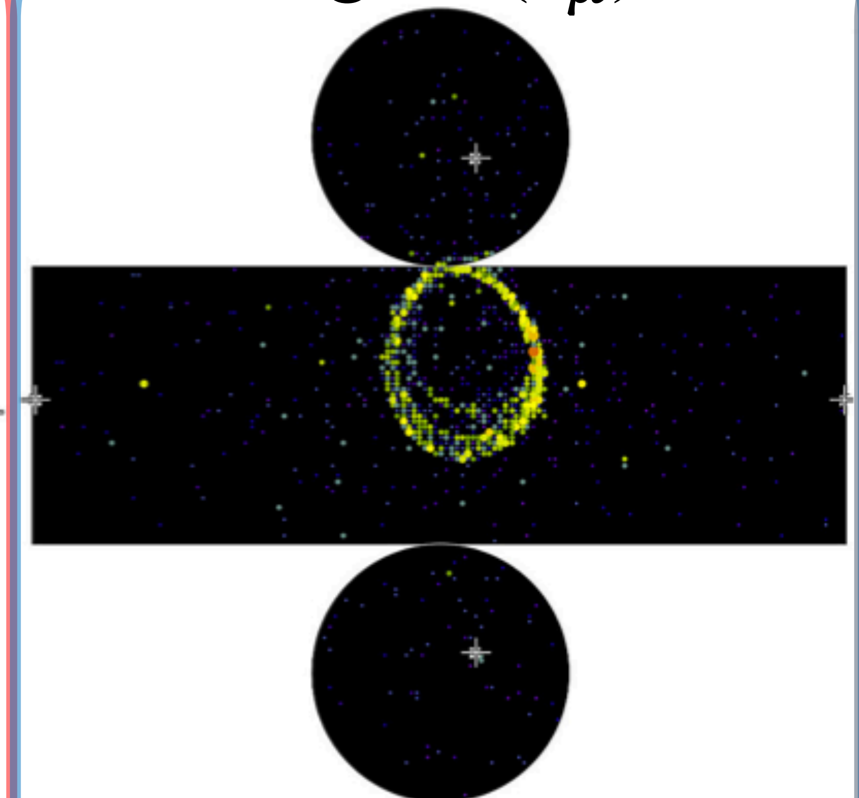
Signal (ν_e)



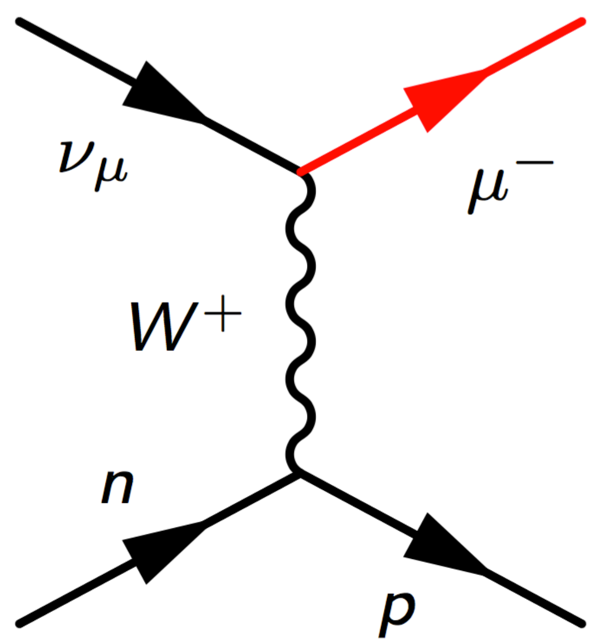
ν_e CCQE



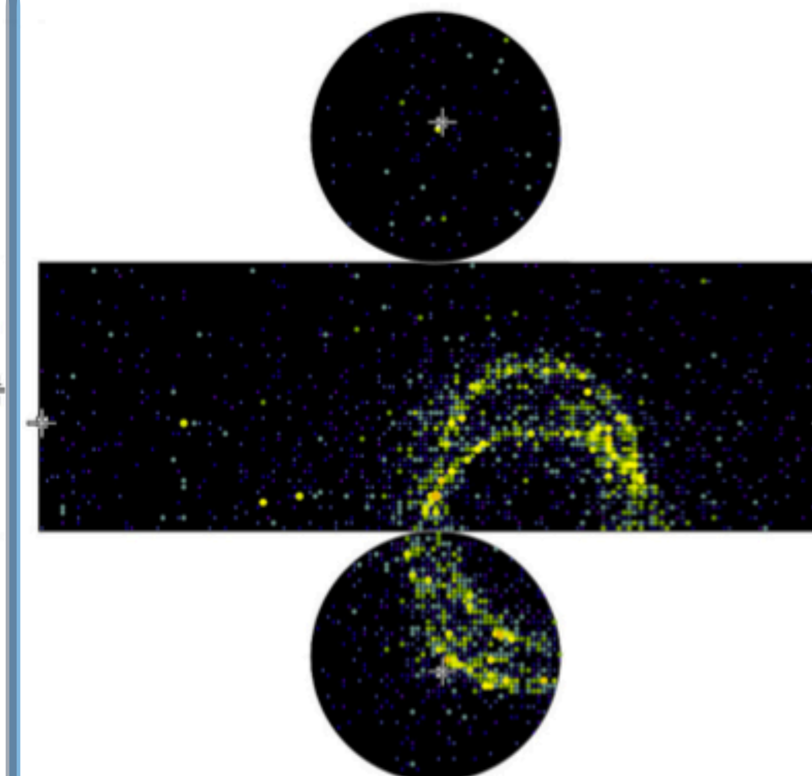
Signal (ν_μ)



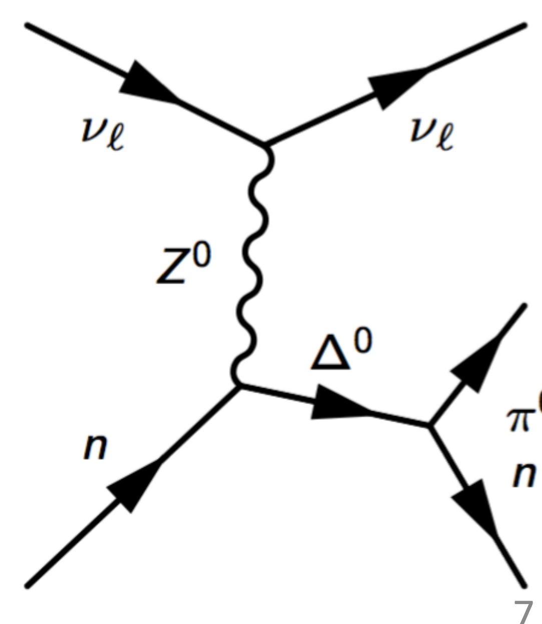
ν_μ CCQE



Background

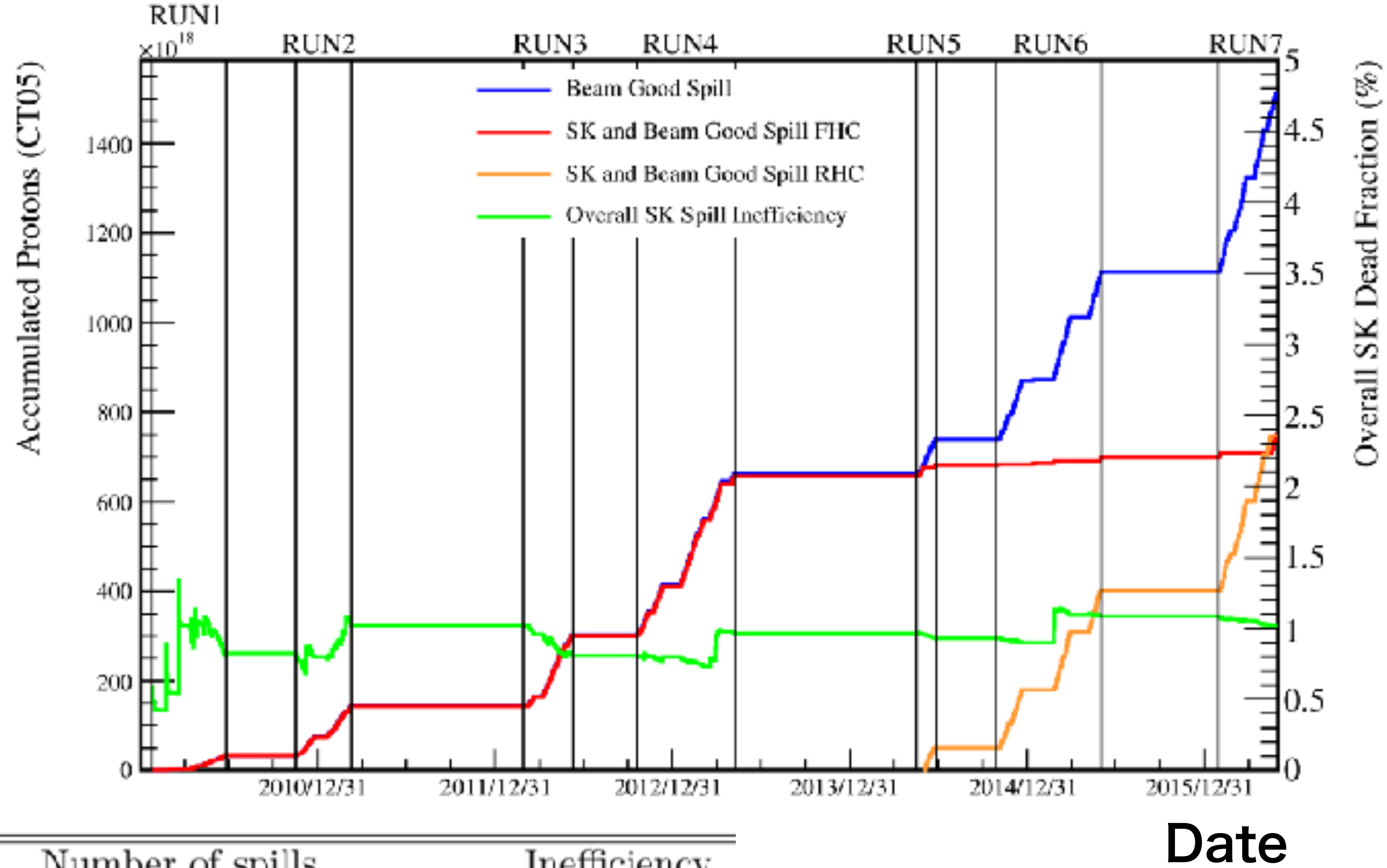


ν_ℓ NC1π^0



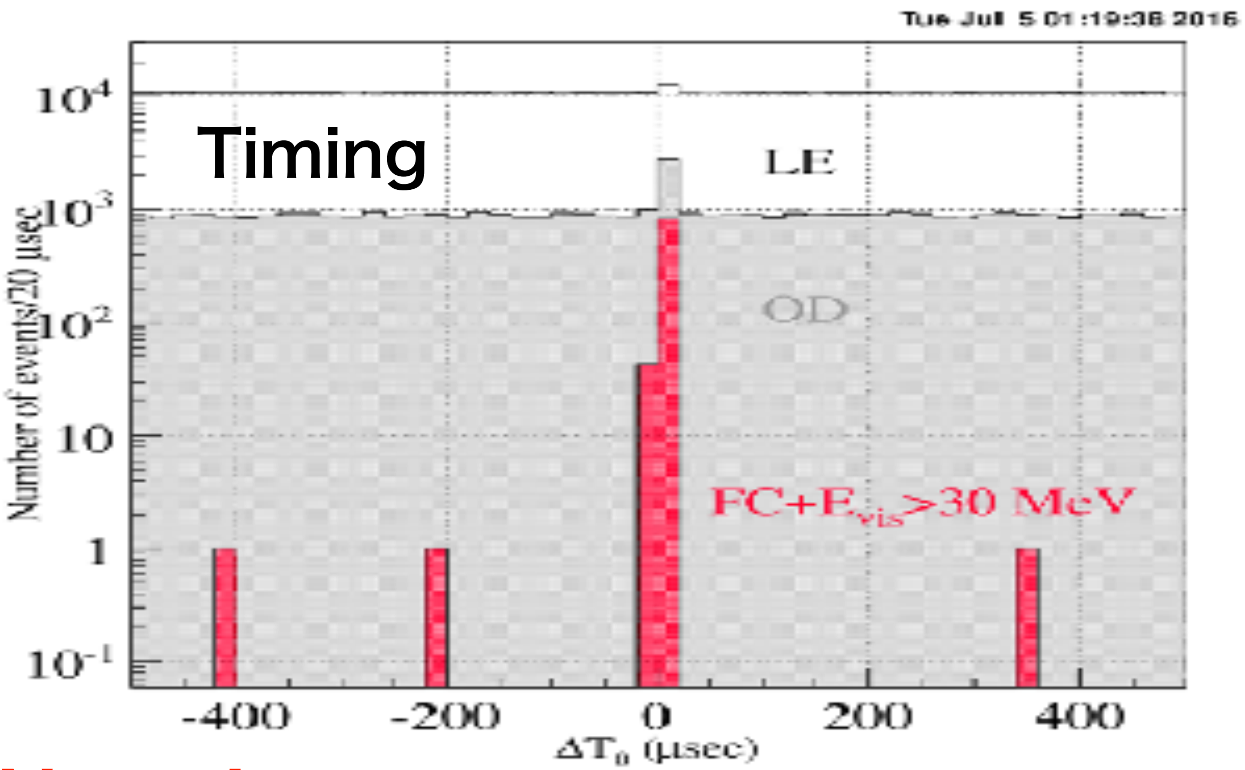
Initial Data Reduction

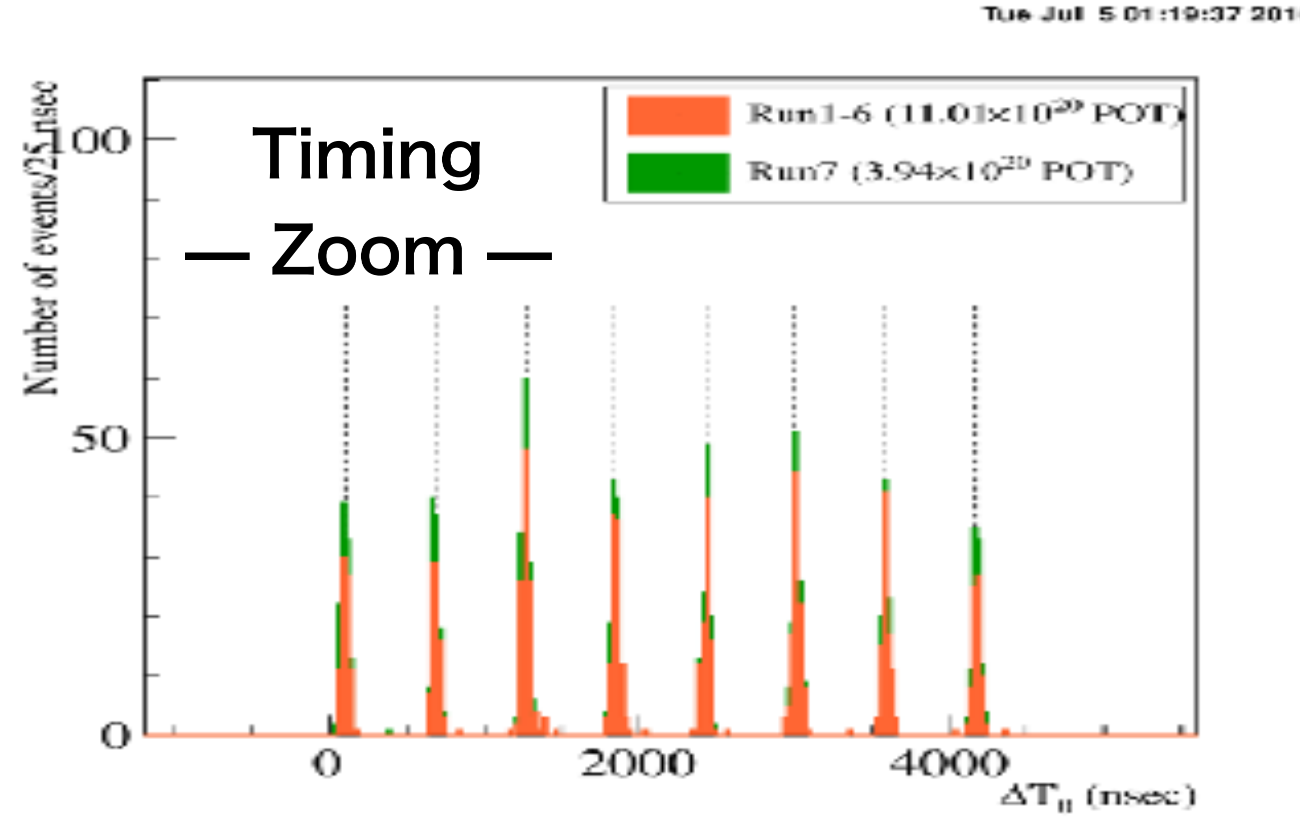
- Total POT
  - Neutrino beam
  - Anti-neutrino beam



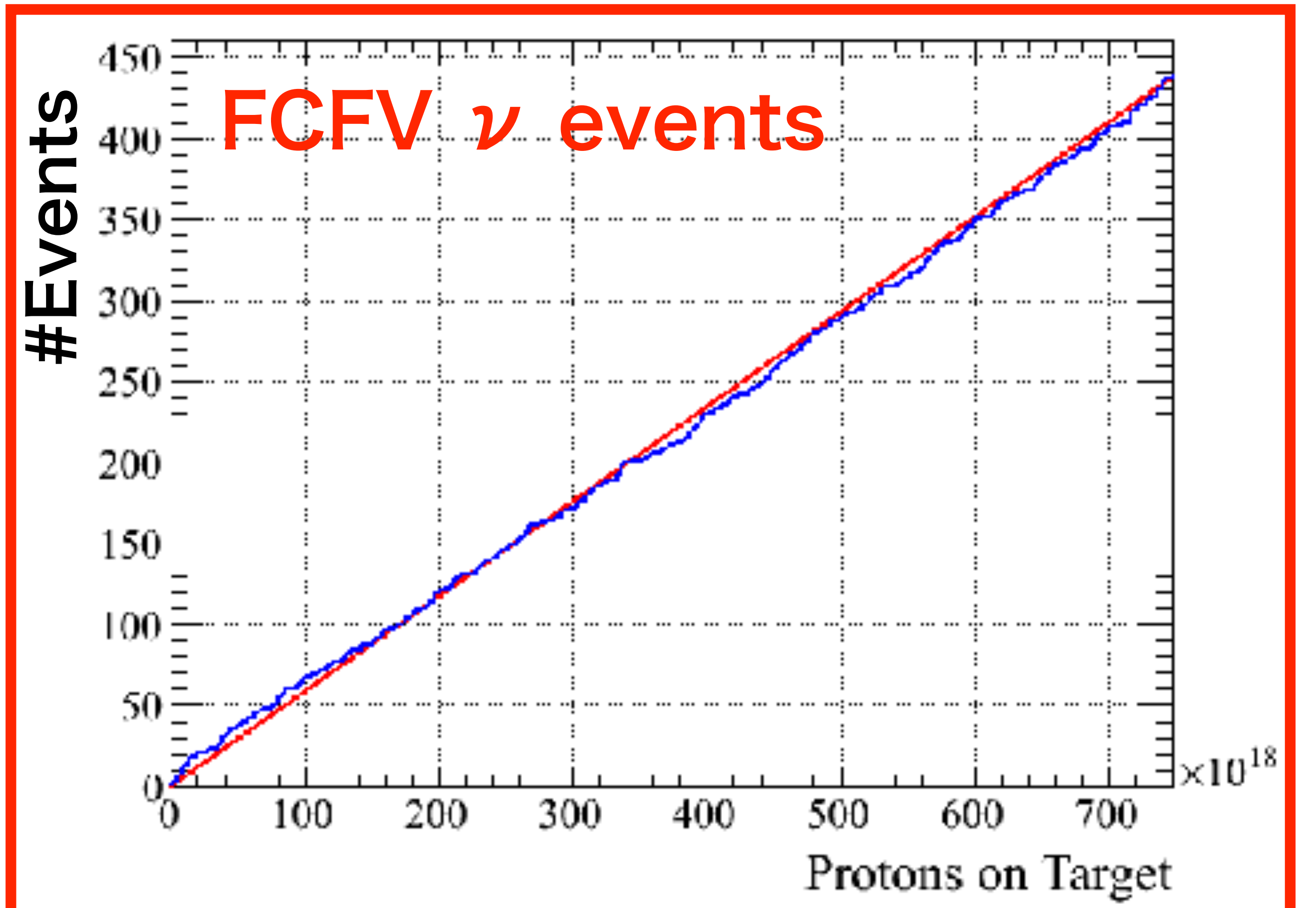
	Number of spills			Inefficiency
	Runs 1-6	Run 7	Total	
Beam good spills	10,901,102	2,056,066	12,957,168	
(1) SK DAQ alive	10,877,078	2,054,214	12,931,292	0.20 %
(2) Bad subrun cut	10,852,539	2,052,044	12,904,583	0.21 %
(3) Incomplete data / GPS error cut	10,843,262	2,052,043	12,895,305	0.07 %
(4) Special data block cut	10,834,275	2,050,337	12,884,612	0.08 %
(5) Pre-activity cut	10,791,744	2,039,626	12,831,370	0.41 %
Total	10,791,744	2,039,626	12,831,371	0.97 %
POT ($\times 10^{20}$)	11.013	3.940	14.953	

Timing Selection of accelerator neutrinos

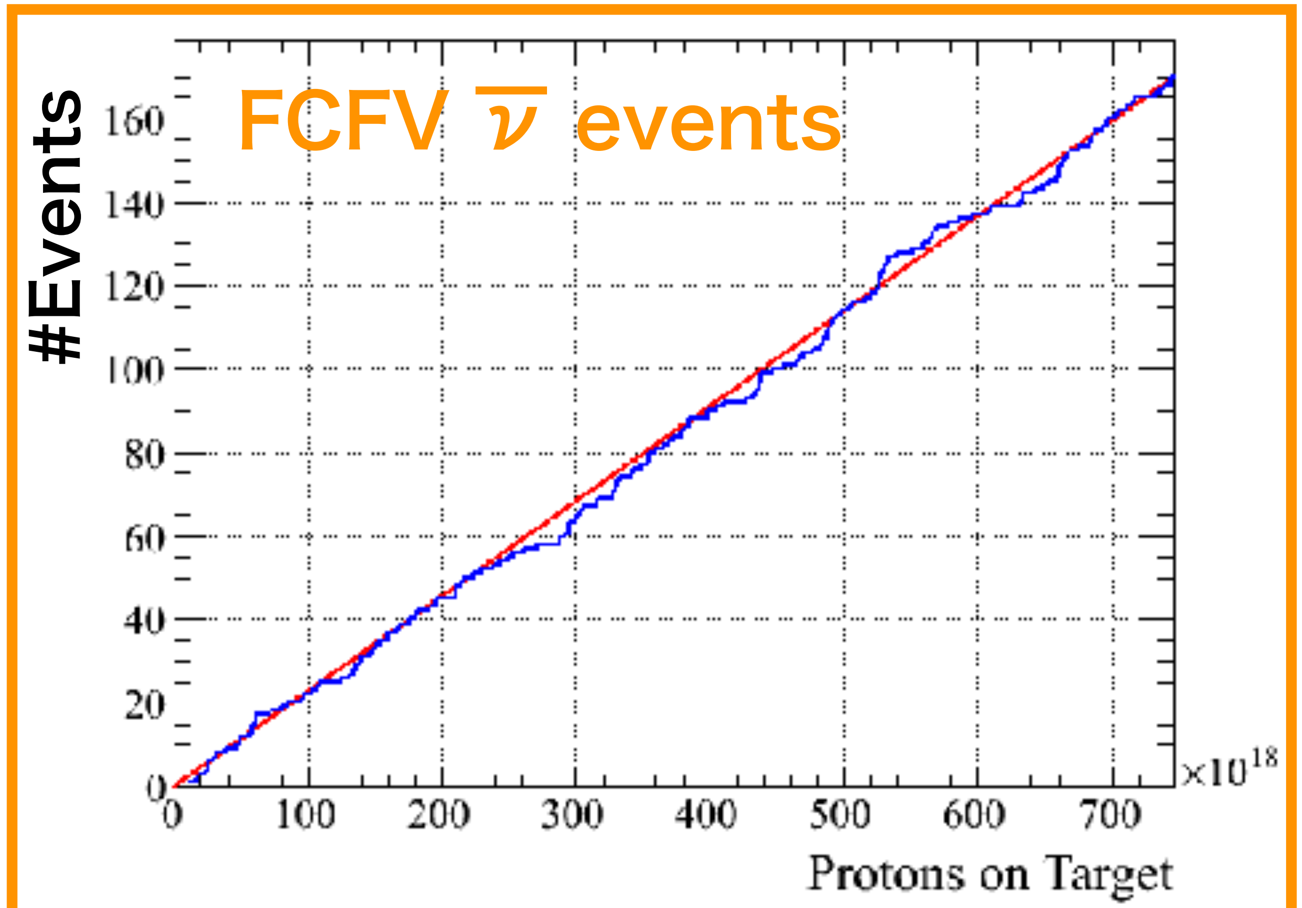




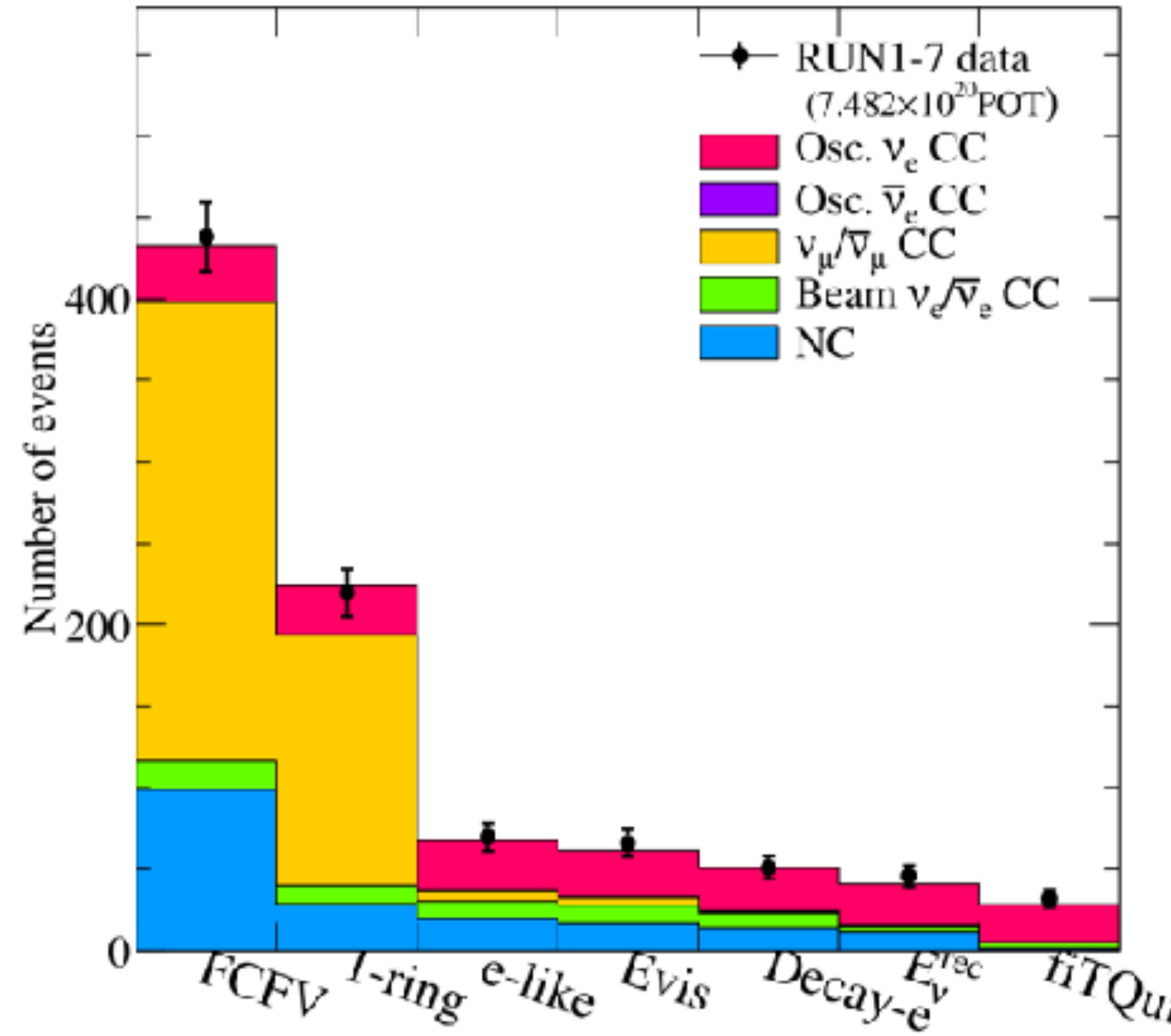
Neutrino



Anti-neutrino

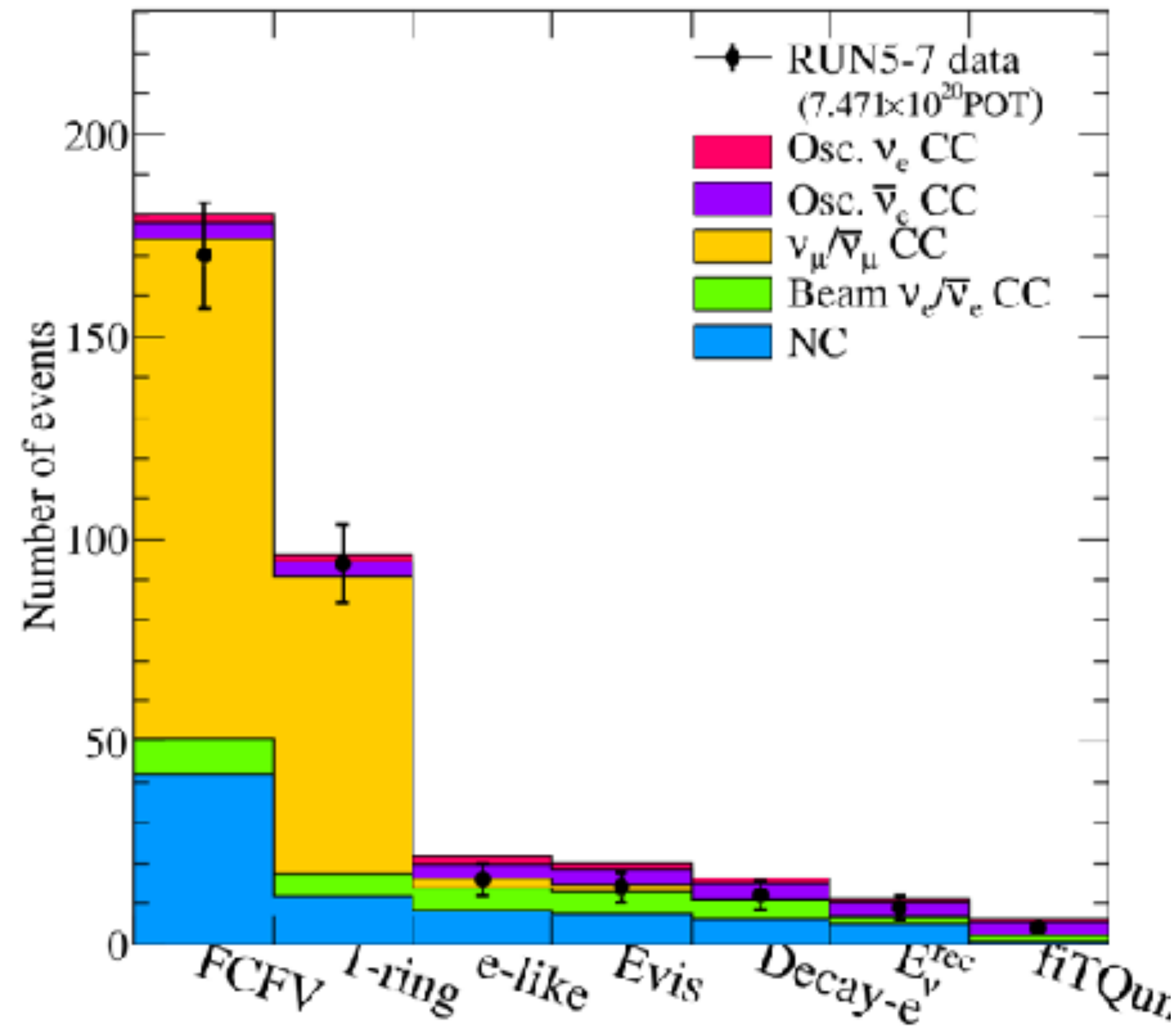


Electron Neutrino Selection



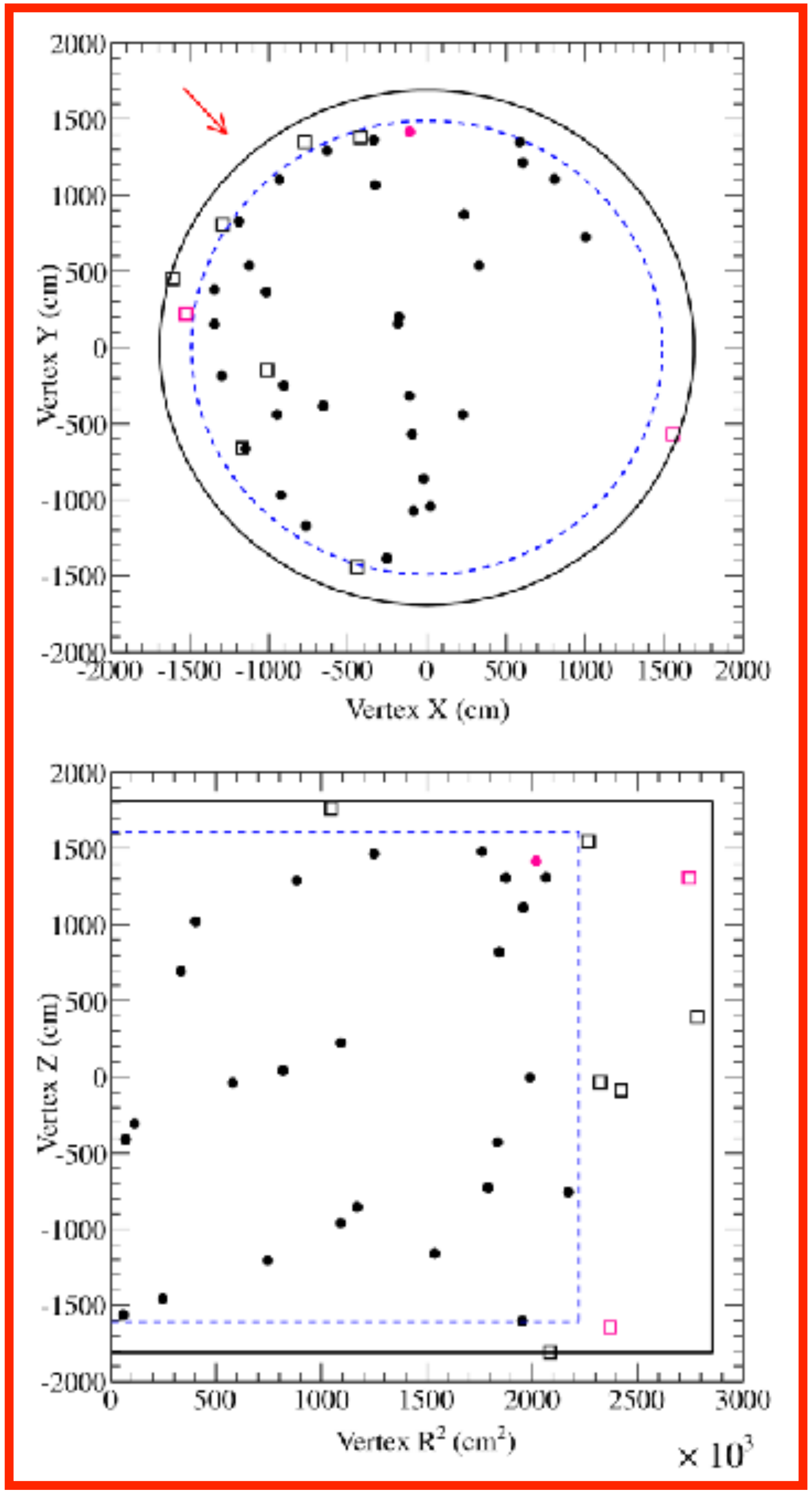
Runs 1-7	Expected						Data
	$\nu_\mu + \bar{\nu_\mu}$ CC	$\nu_e + \bar{\nu_e}$ CC	NC	$\bar{\nu_\mu} \to \bar{\nu_e}$	BG Total	$\nu_\mu \to \nu_e$	
Interactions in FV	365.2332	18.5971	326.9786	0.3919	711.2008	35.5567	654
FCFV	280.5837	18.1317	98.9675	0.3825	398.0655	34.8647	438
Single ring	153.7866	11.1750	28.7556	0.3161	194.0334	30.0231	220
Electron-like PID	6.4809	11.0915	19.5762	0.3138	37.4625	29.6420	70
Evis >100 MeV	4.6030	11.0352	16.8511	0.3122	32.8016	29.1320	66
No Decay-e	0.9714	8.9912	14.2791	0.3070	24.5487	26.1802	51
E_ν^{rec}	0.2532	4.2693	10.8768	0.2168	15.6161	25.1998	46
fiTQun π^0 cut	0.0892	3.6846	1.3528	0.1812	5.3078	23.3110	32
Efficiency from Interactions [%]	0.0	19.8	0.4	46.2	0.7	65.6	-
Efficiency from FCFV [%]	0.0	20.3	1.4	47.4	1.3	66.9	-

Electron Anti-Neutrino Selection

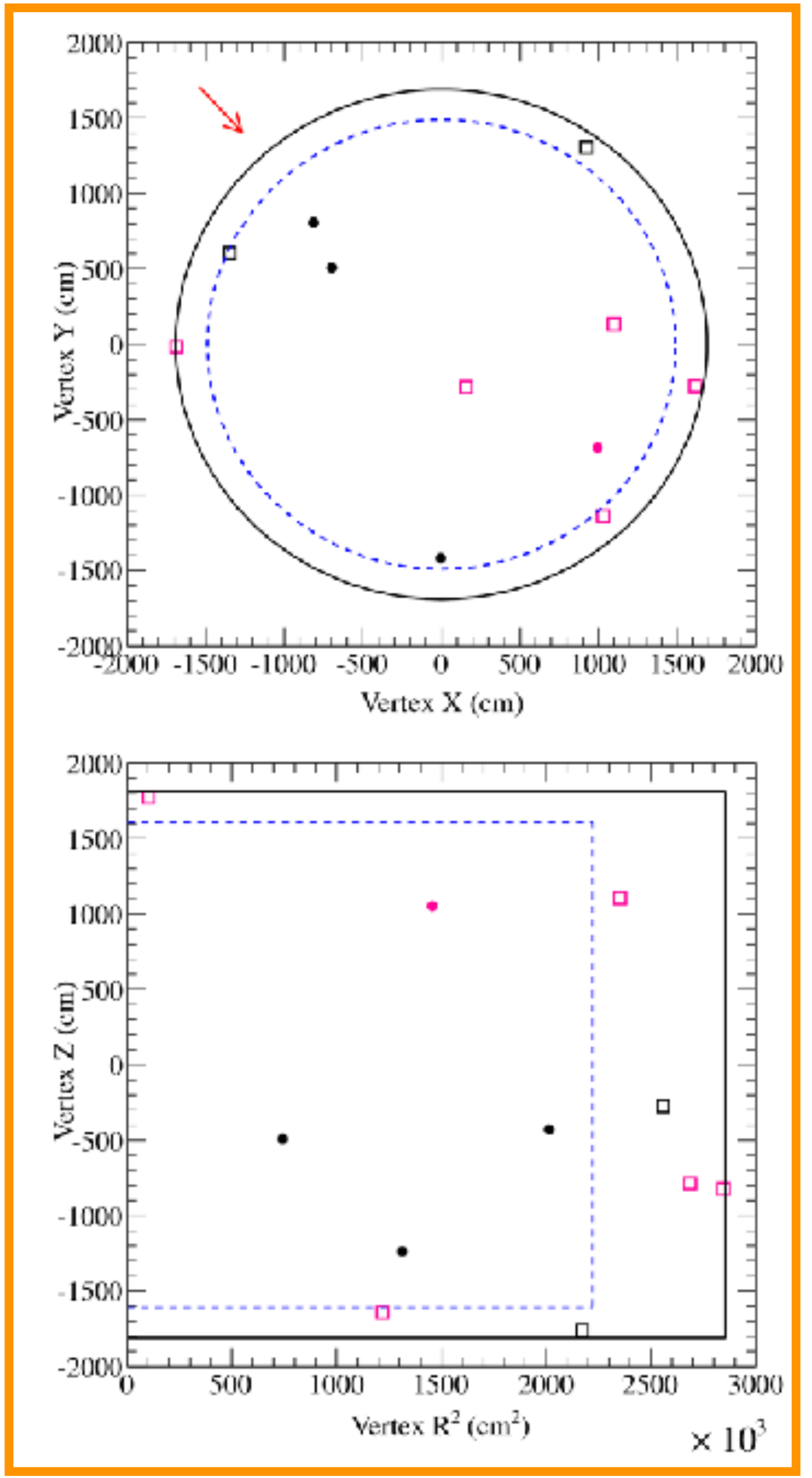


Runs 5-7	Expected						Data
	$\nu_\mu + \bar{\nu_\mu}$ CC	$\nu_e + \bar{\nu_e}$ CC	NC	$\bar{\nu_\mu} \to \bar{\nu_e}$	BG Total	$\nu_\mu \to \nu_e$	
Interactions in FV	164.0430	9.0049	132.7521	2.2885	308.0886	4.2956	263
FCFV	123.2438	8.7503	42.0523	2.2411	176.2875	4.1961	170
Single ring	73.2145	5.5119	11.8747	1.7265	92.3276	3.7371	94
Electron-like PID	2.3068	5.4784	8.3577	1.7060	17.8489	3.6989	16
Evis >100 MeV	1.8266	5.4625	7.3923	1.6866	16.3680	3.6791	14
No Decay e	0.3284	4.7127	6.2416	1.4595	12.7421	3.6571	12
E_ν^{rec}	0.0828	1.8870	4.8261	1.1858	7.9816	3.4192	9
fiTQun π^0 cut	0.0190	1.5754	0.5968	1.0456	3.2368	3.0432	4
Efficiency from Interactions [%]	0.0	17.5	0.4	45.7	1.1	70.8	-
Efficiency from FCFV [%]	0.0	18.0	1.4	46.7	1.8	72.5	-

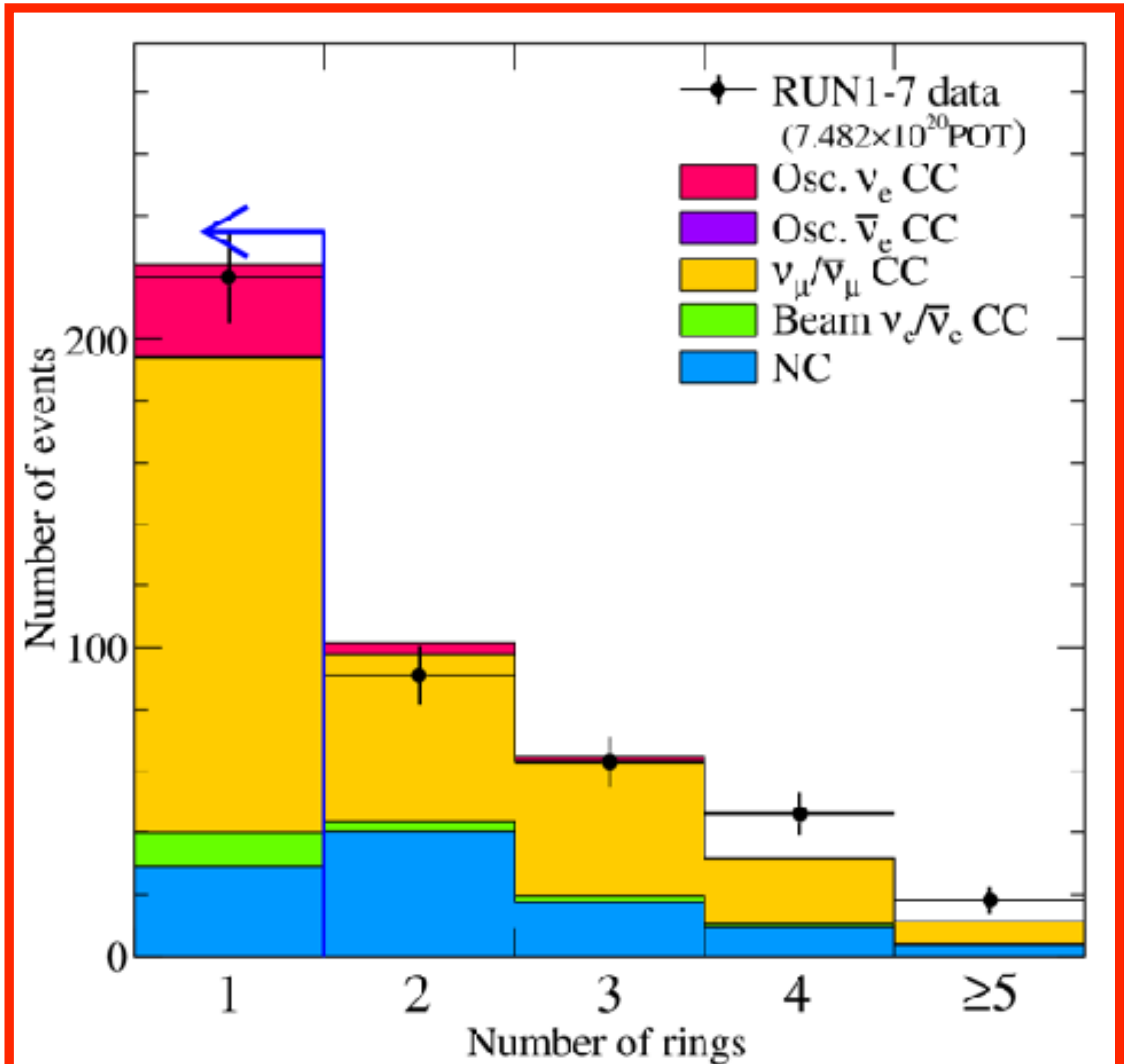
Fiducial Volume

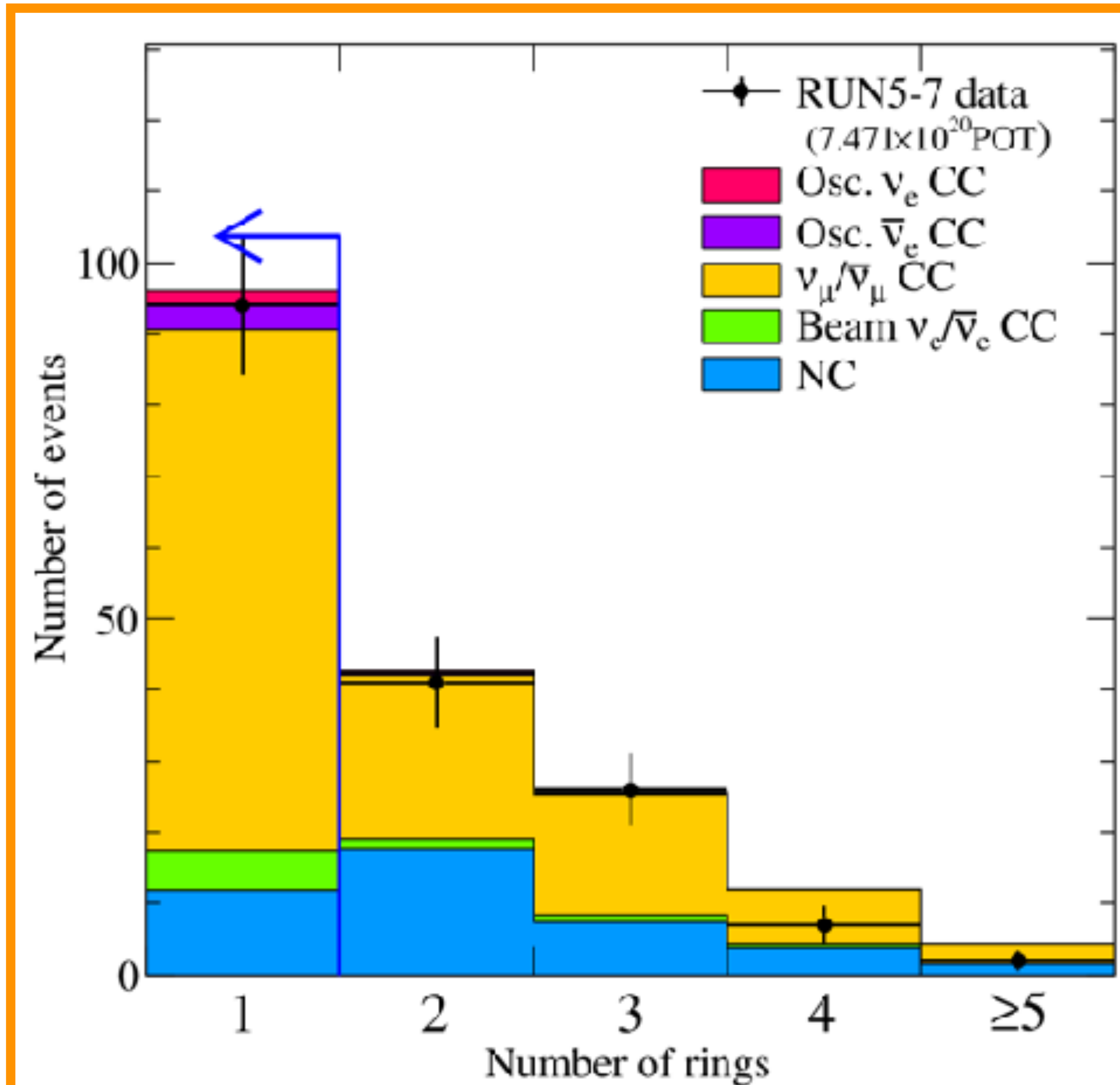


2m away from the wall

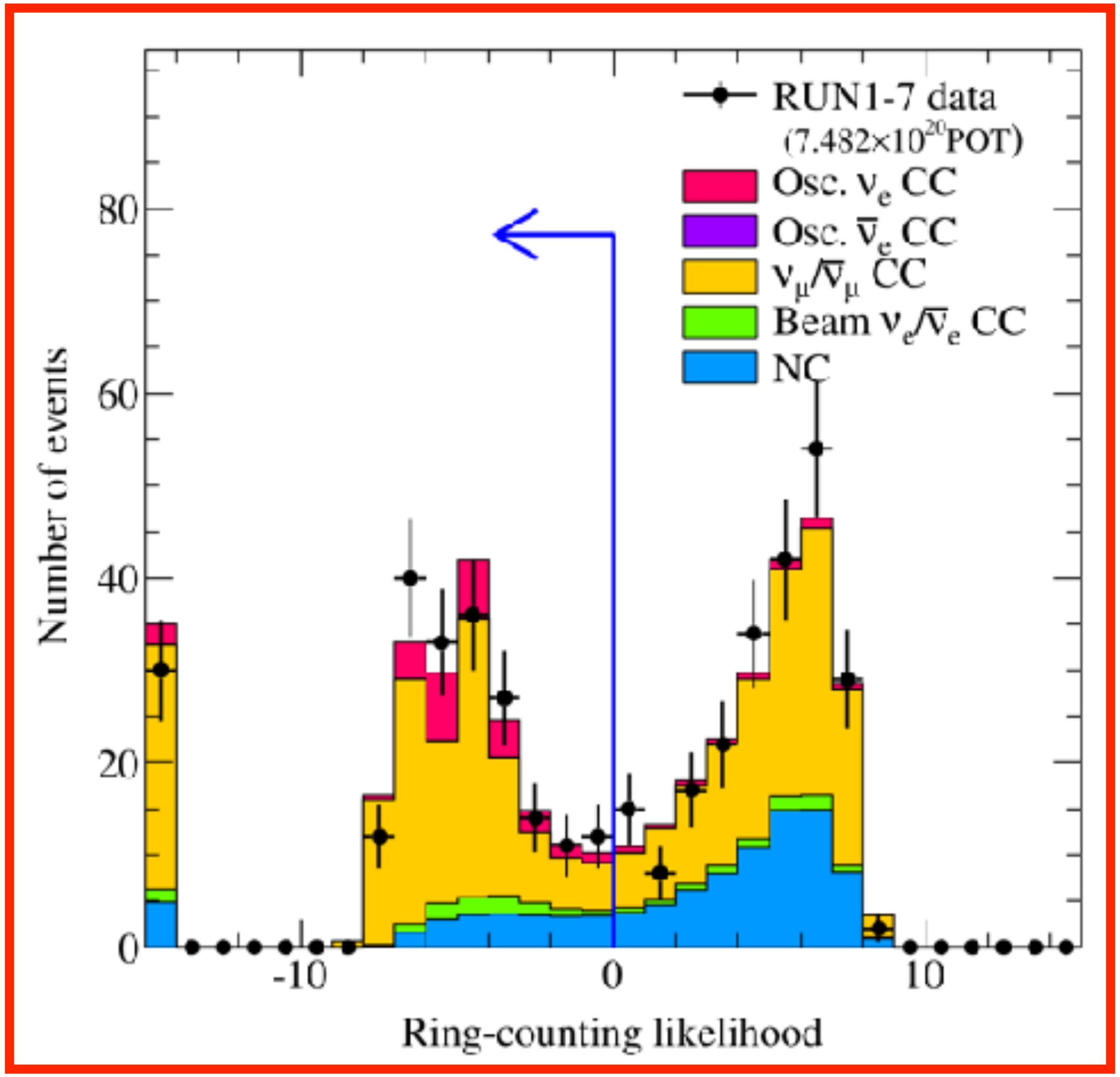


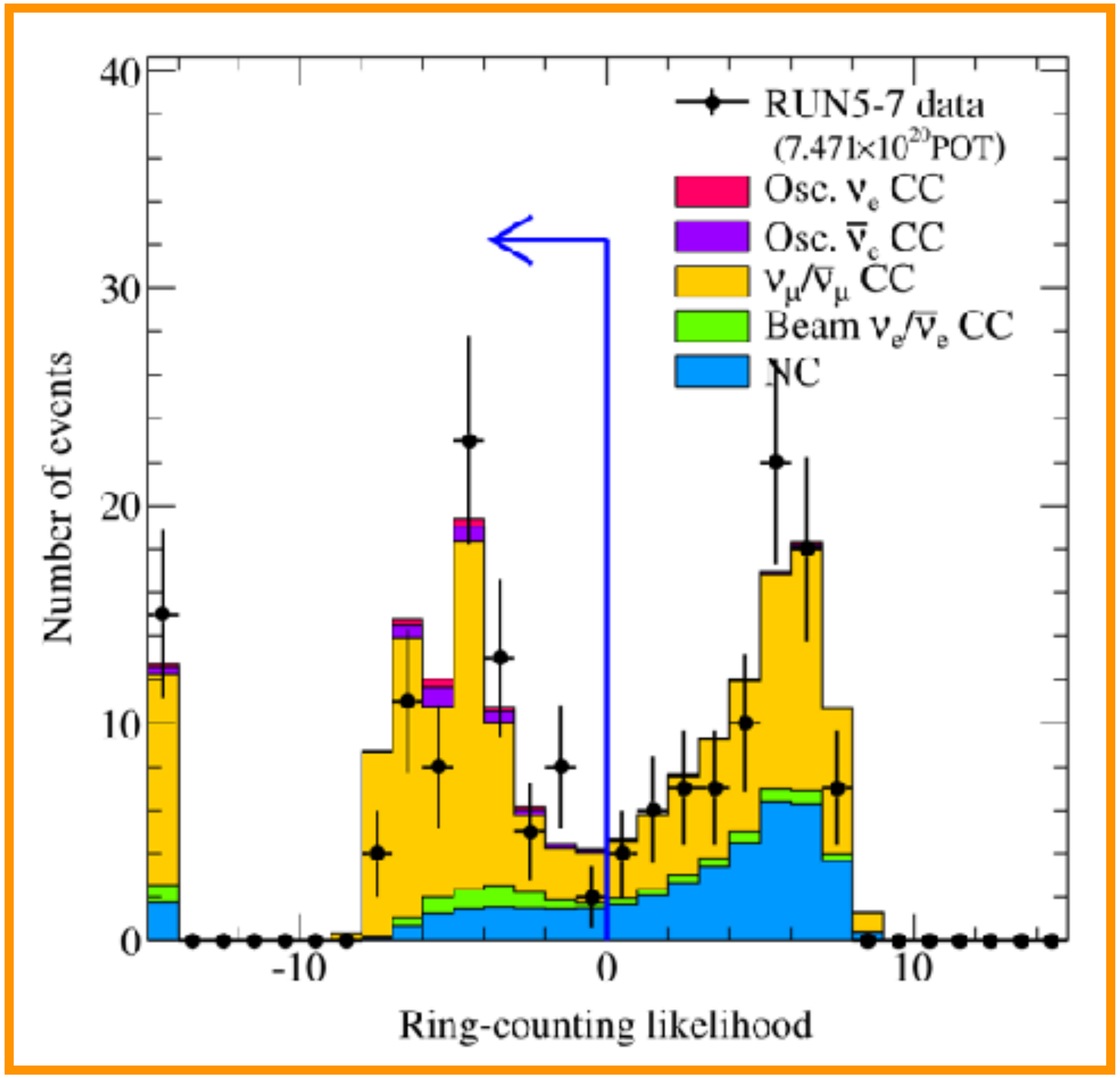
Number of Rings (=1)



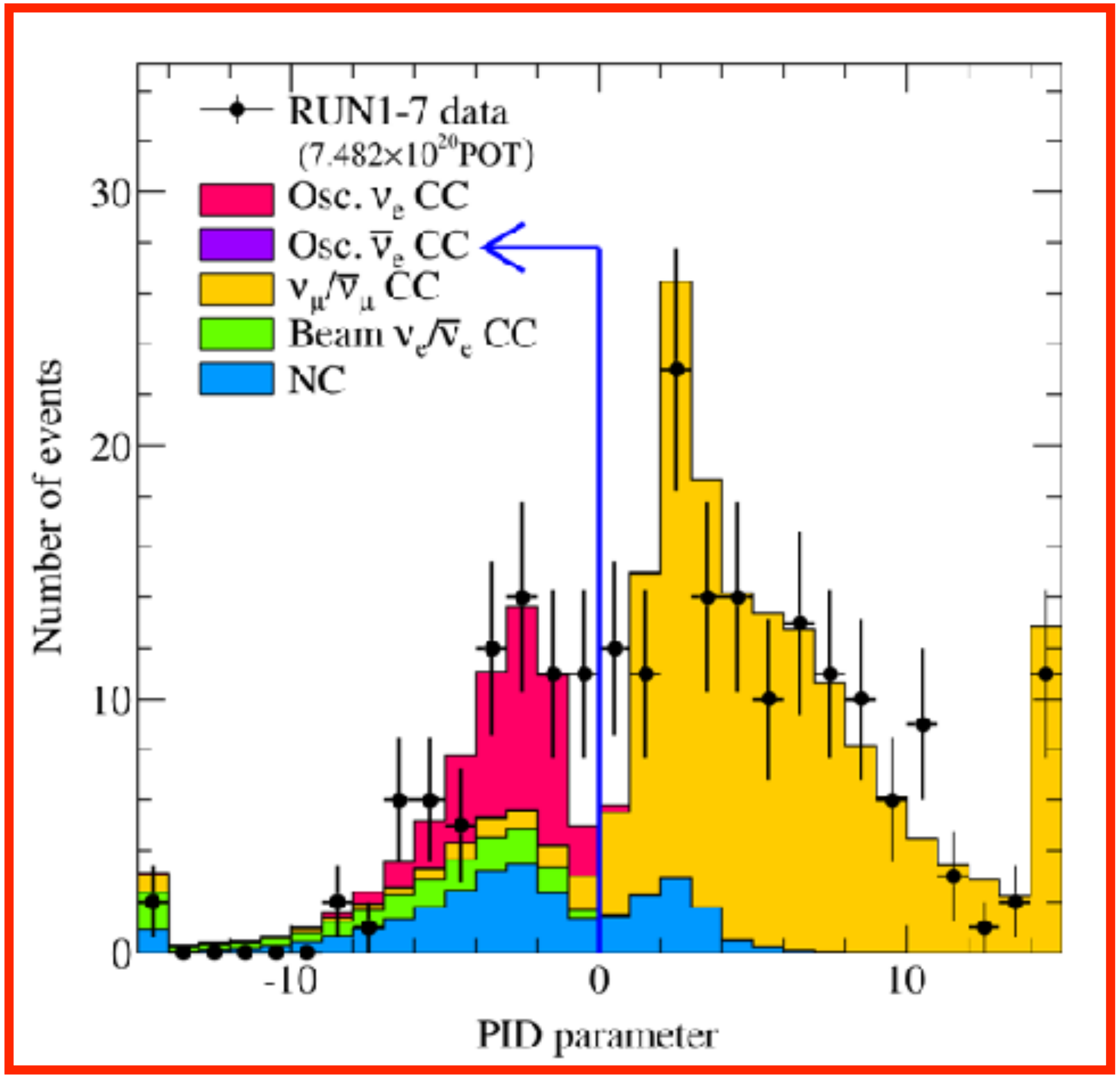


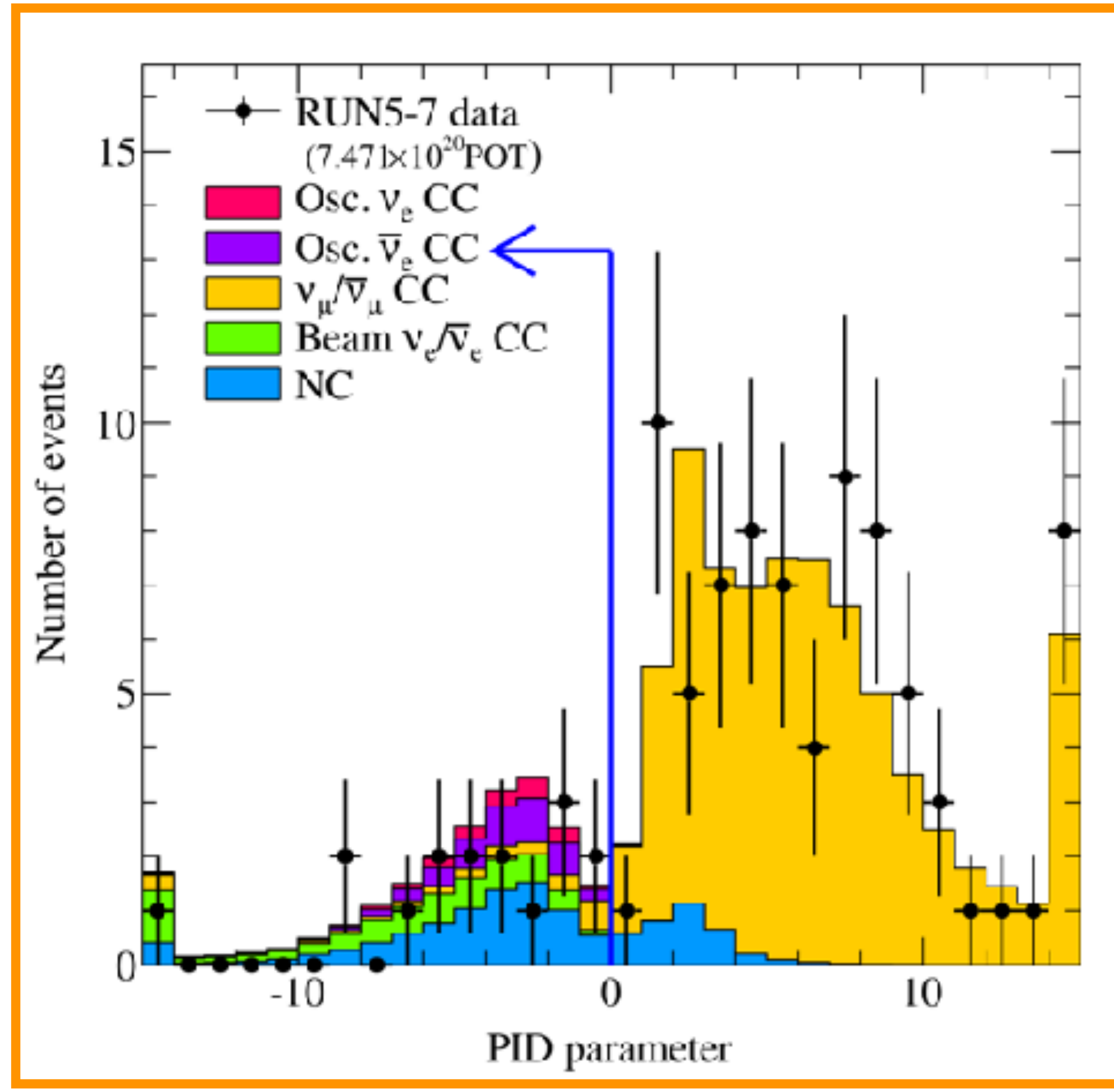
Ring-counting Likelihood



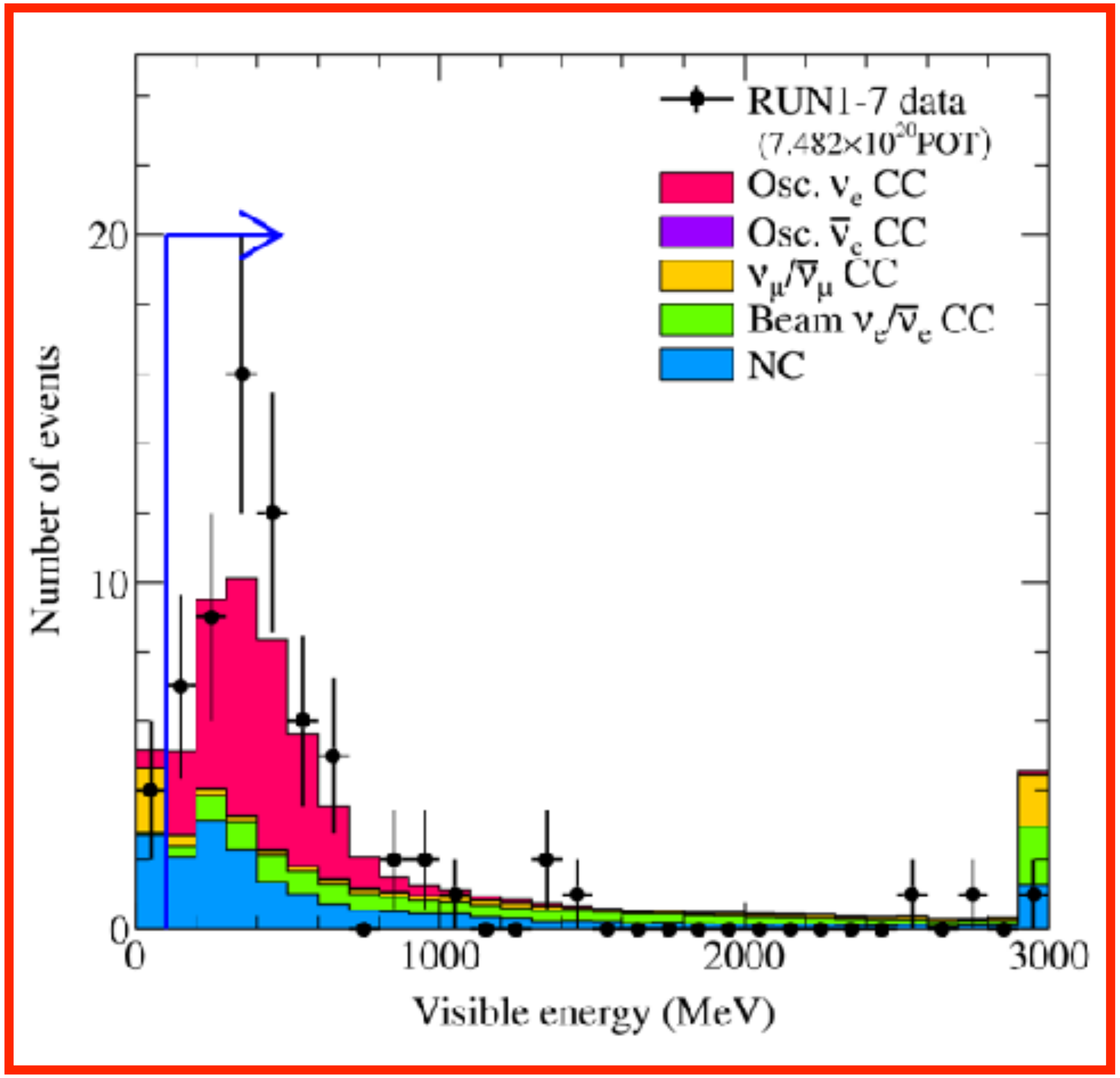


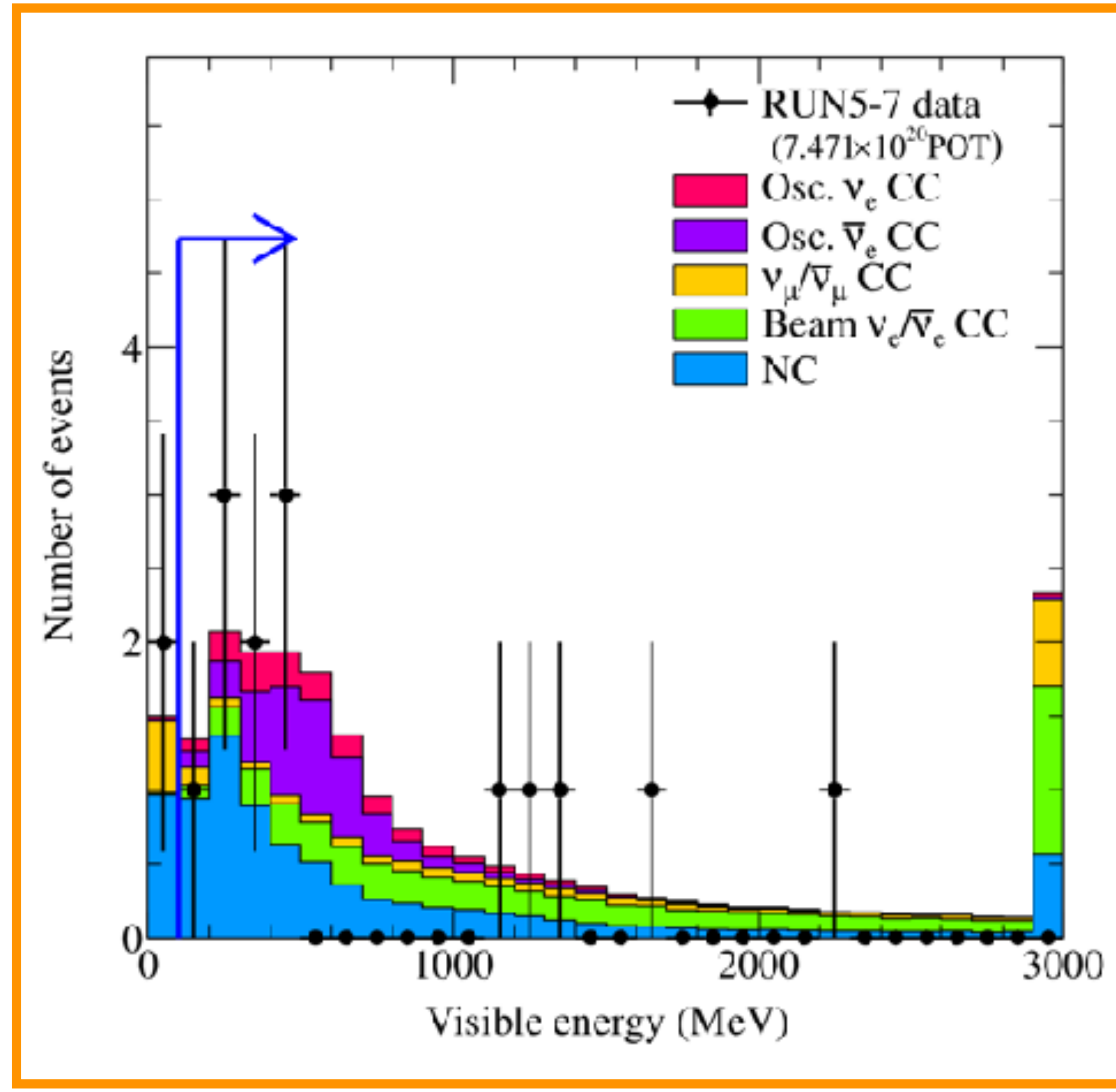
Particle ID (= e-like)



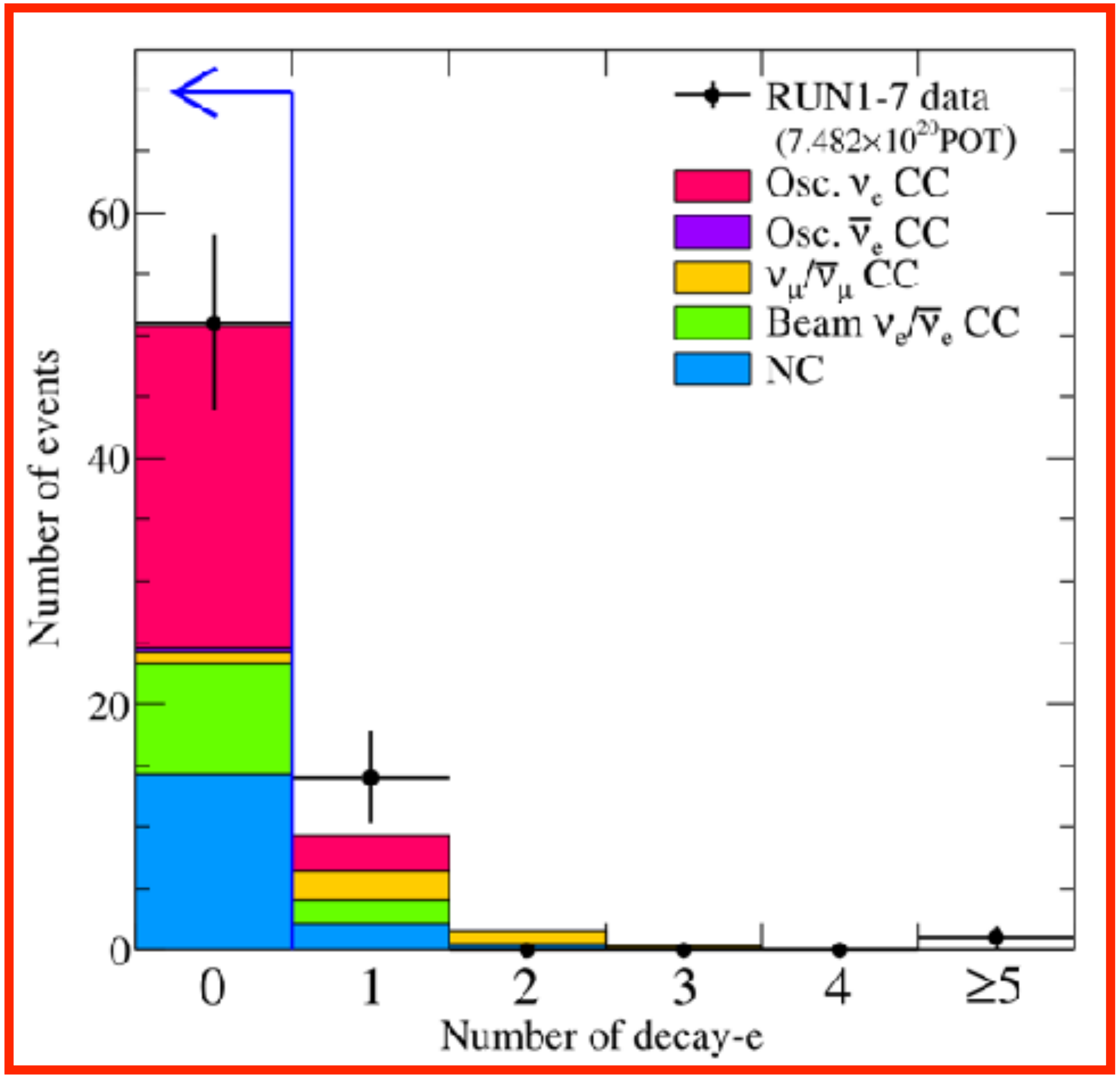


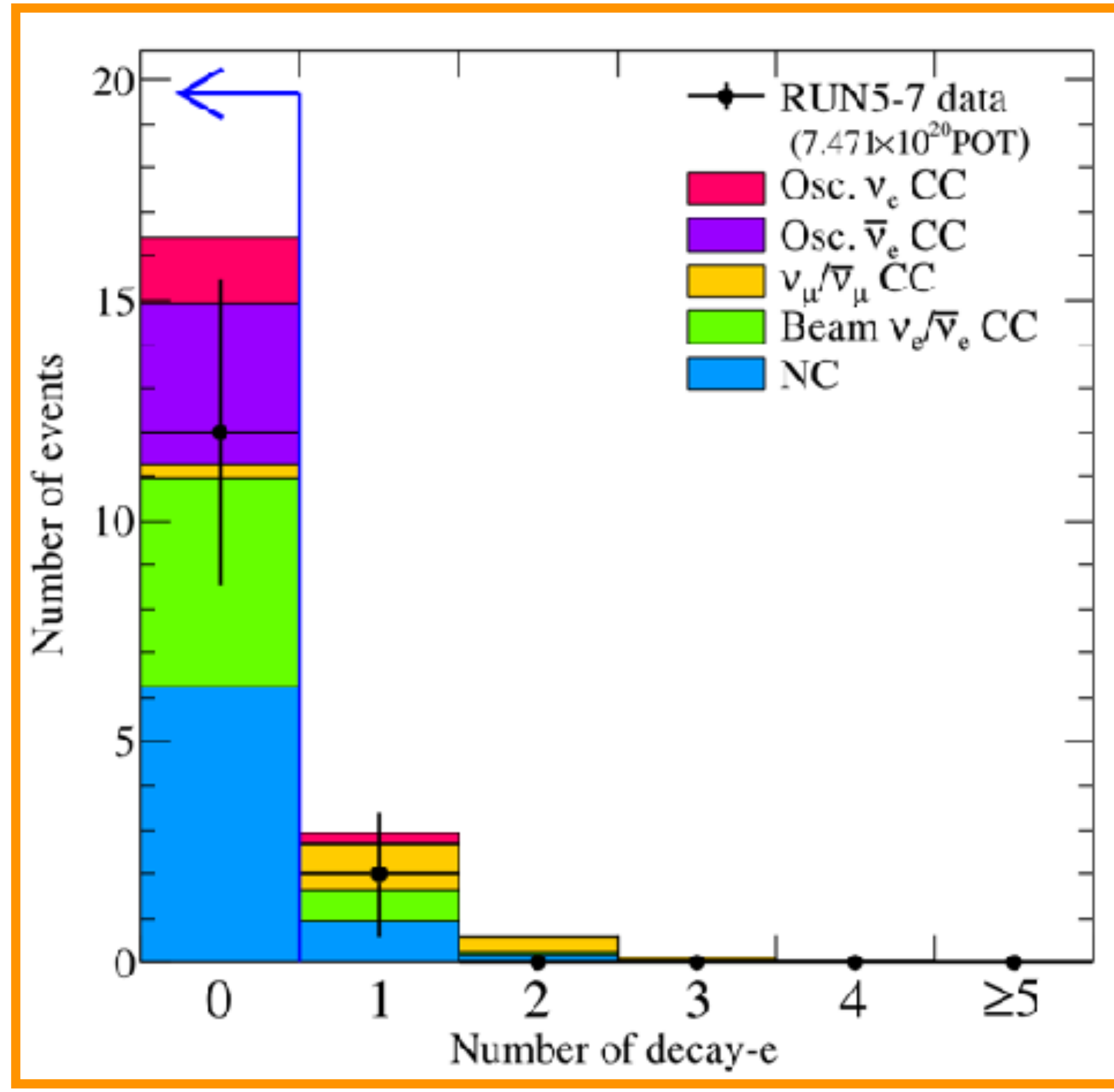
Visible Energy (> 100 MeV)



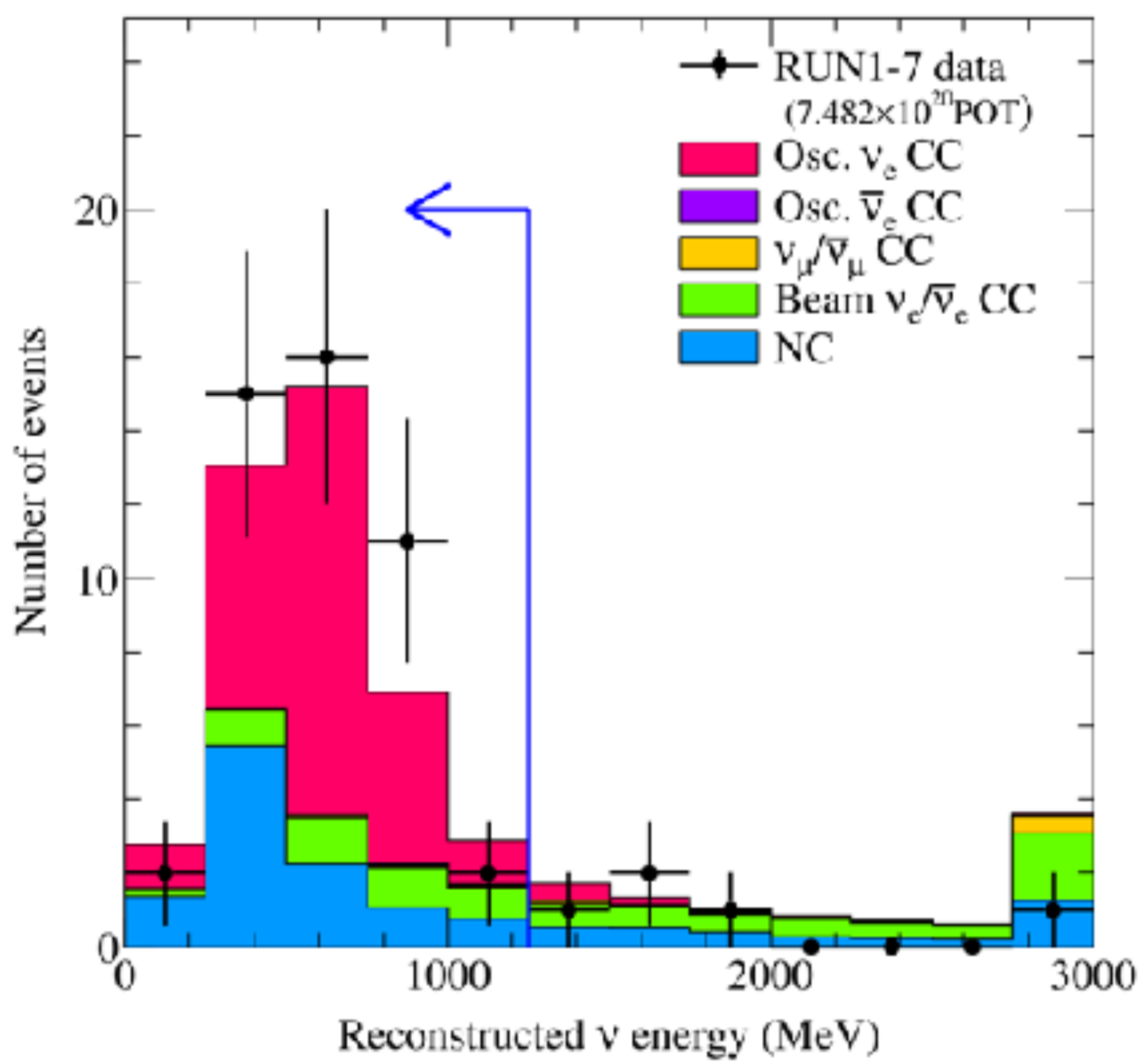


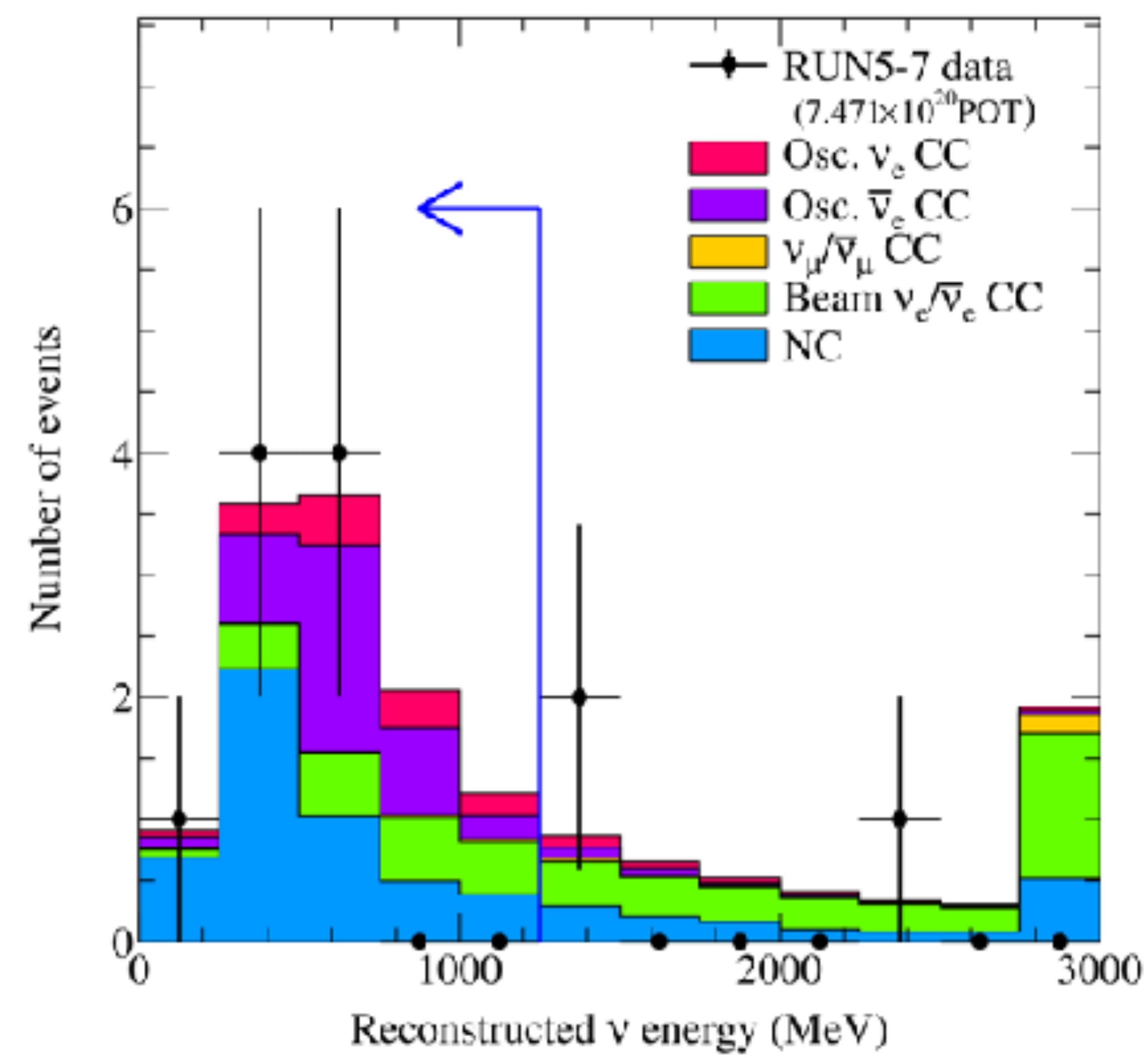
#Decay-electrons (=0)



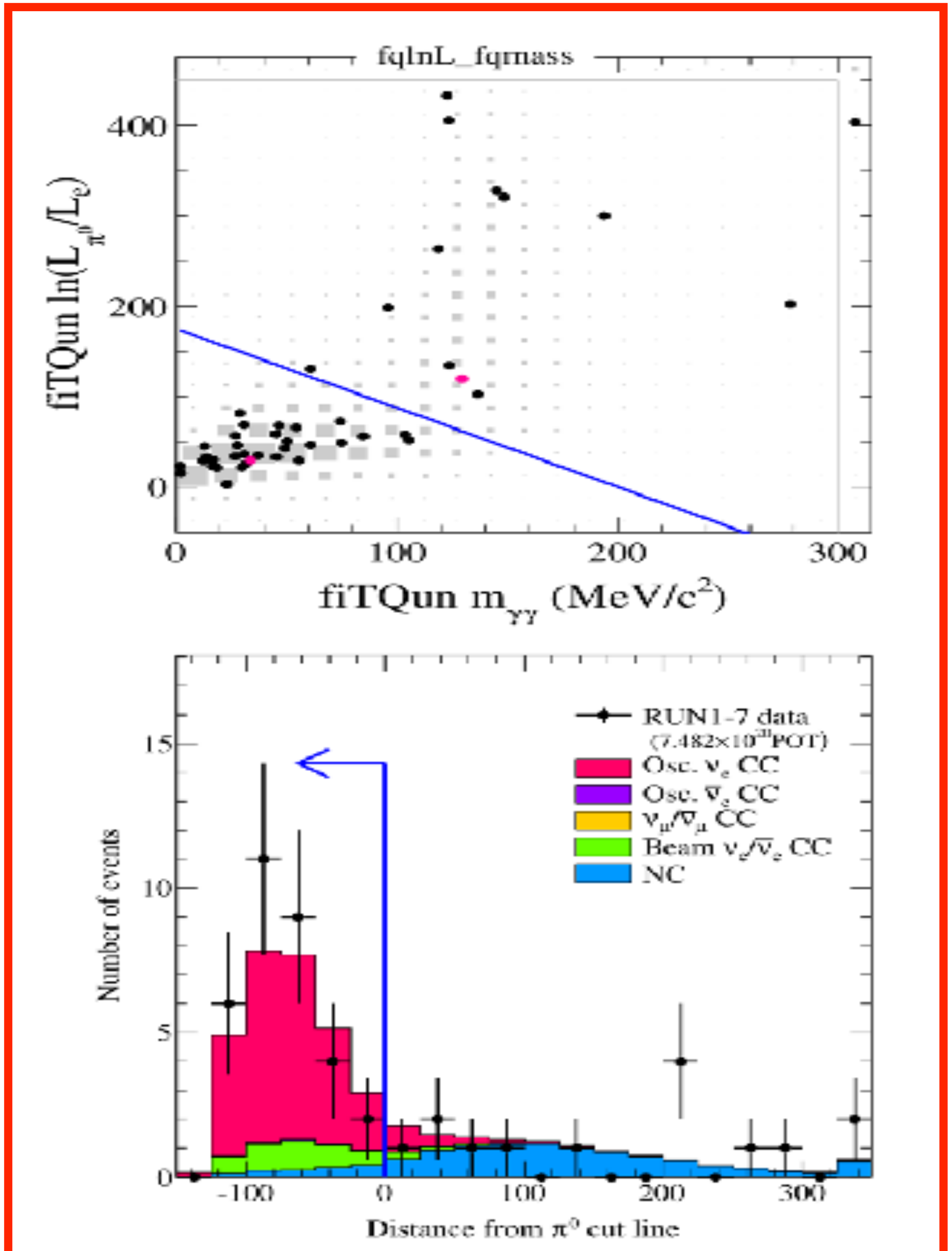


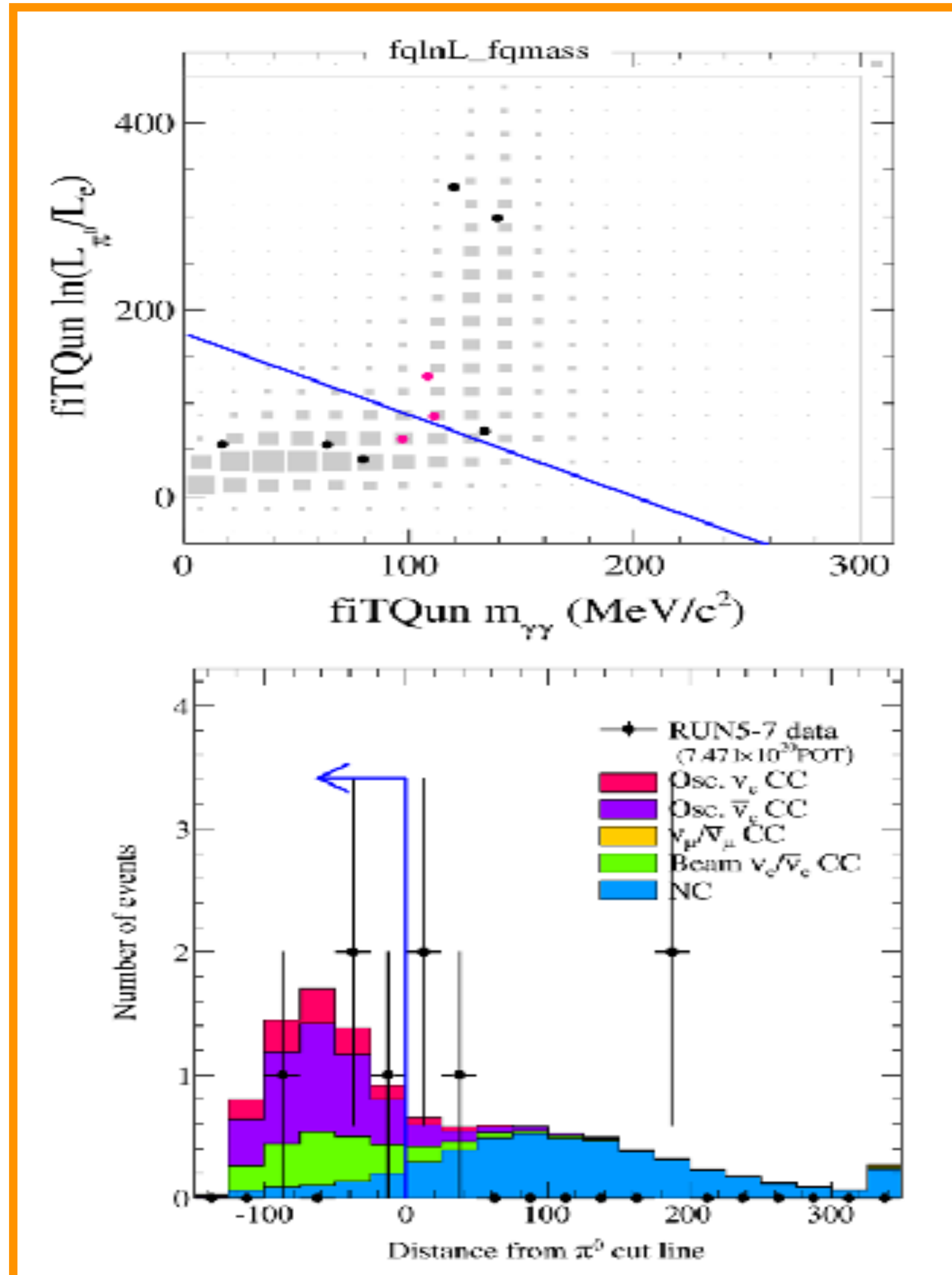
Reconstructed ν energy (<1250 MeV)



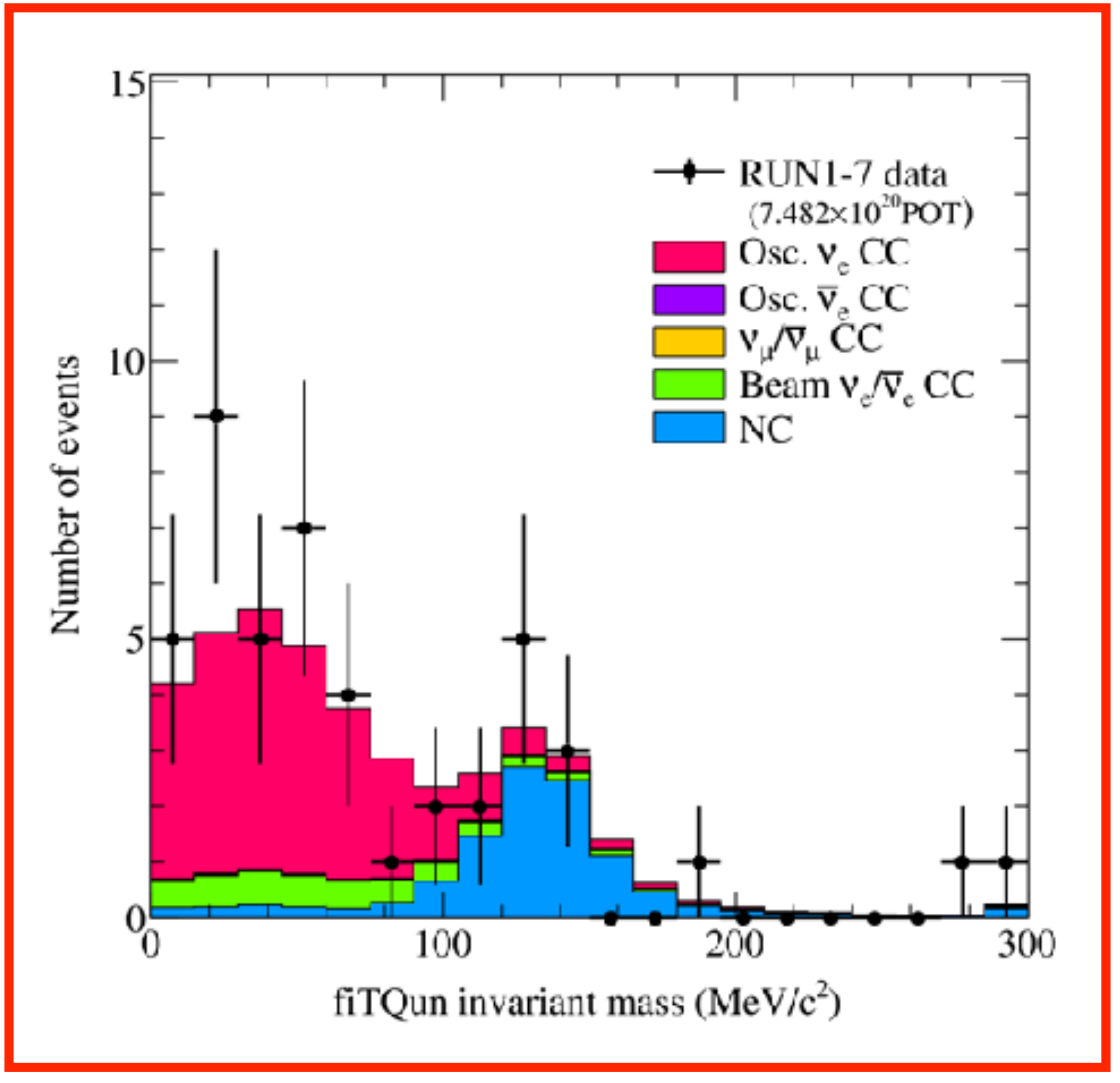


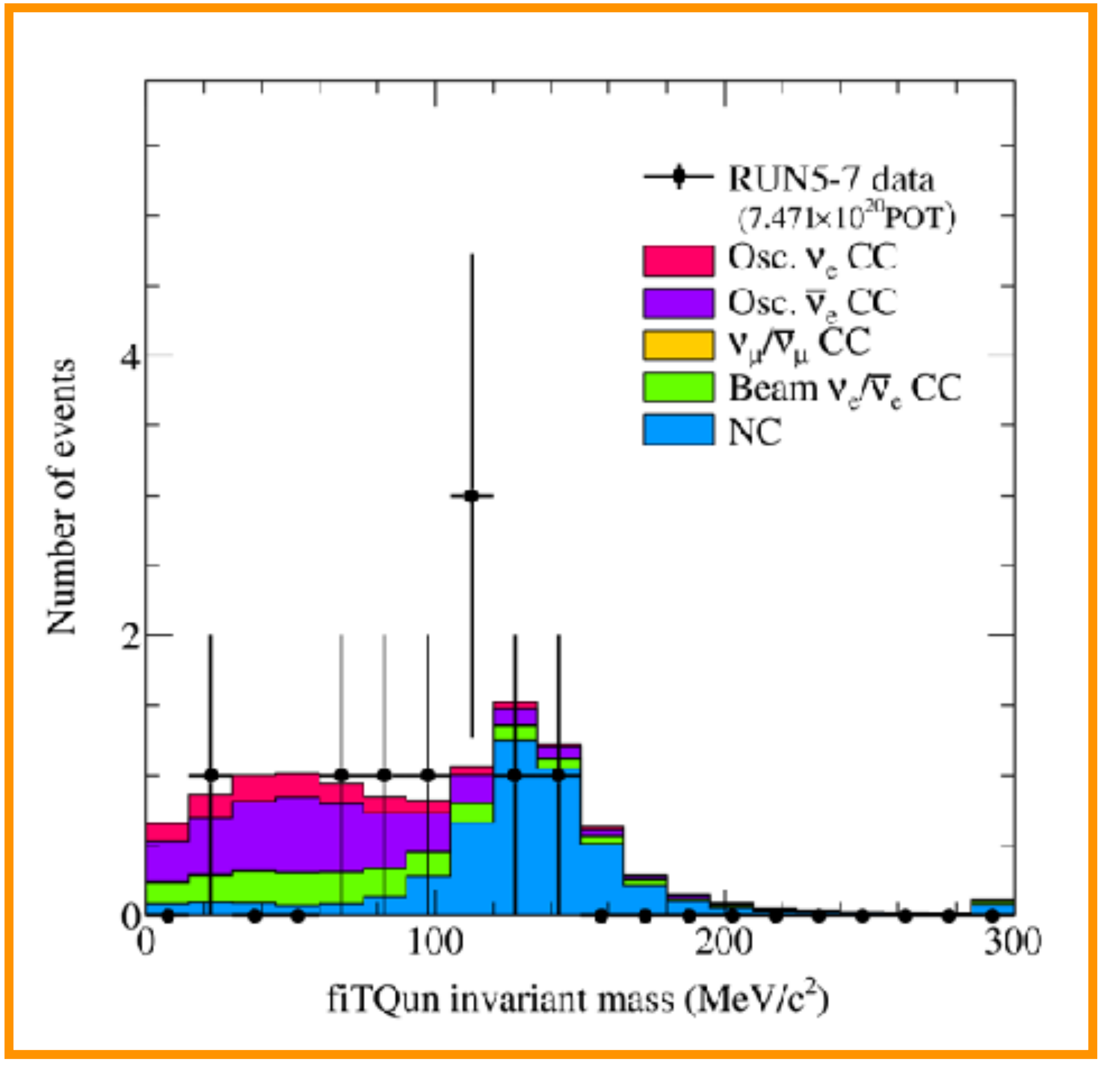
fiTQun π^0 CUT



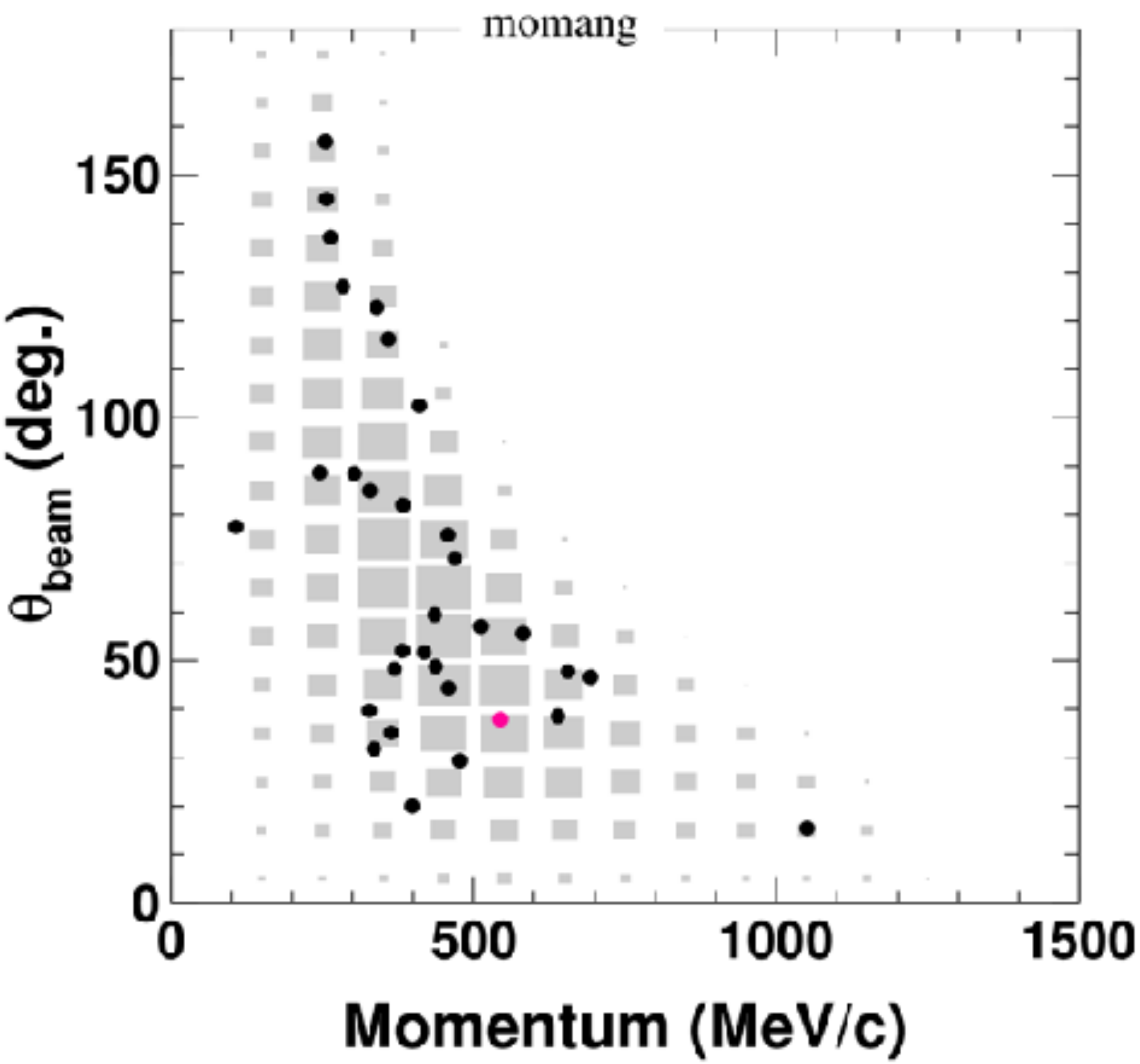


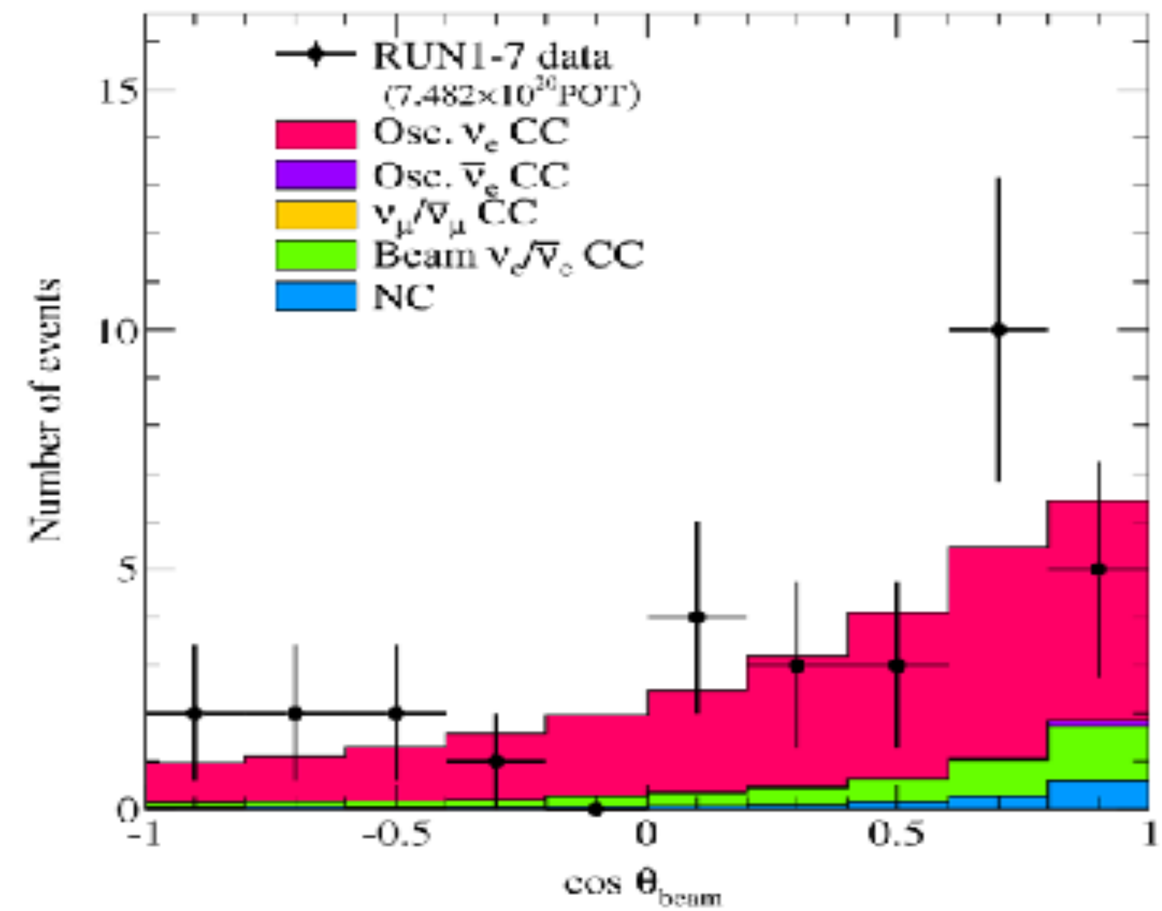
fiTQun π^0 CUT (before)

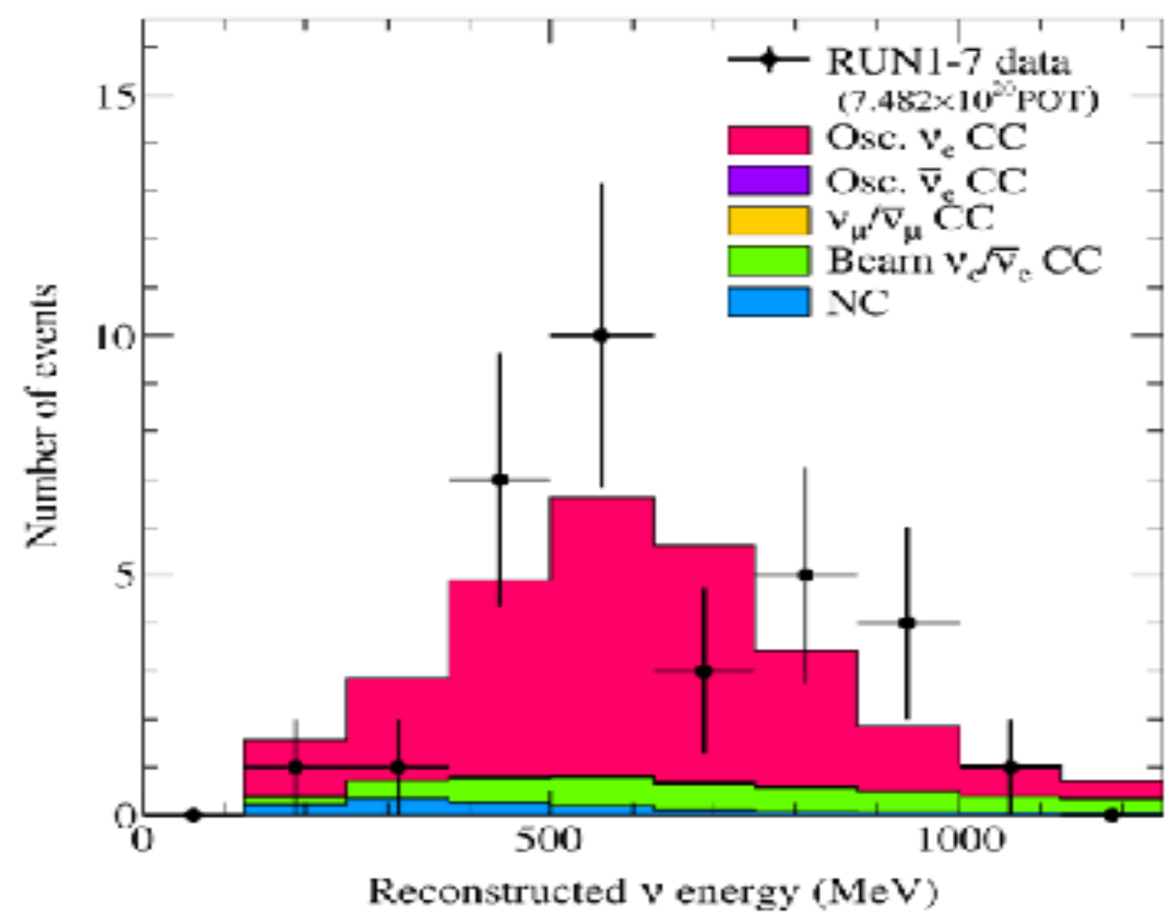




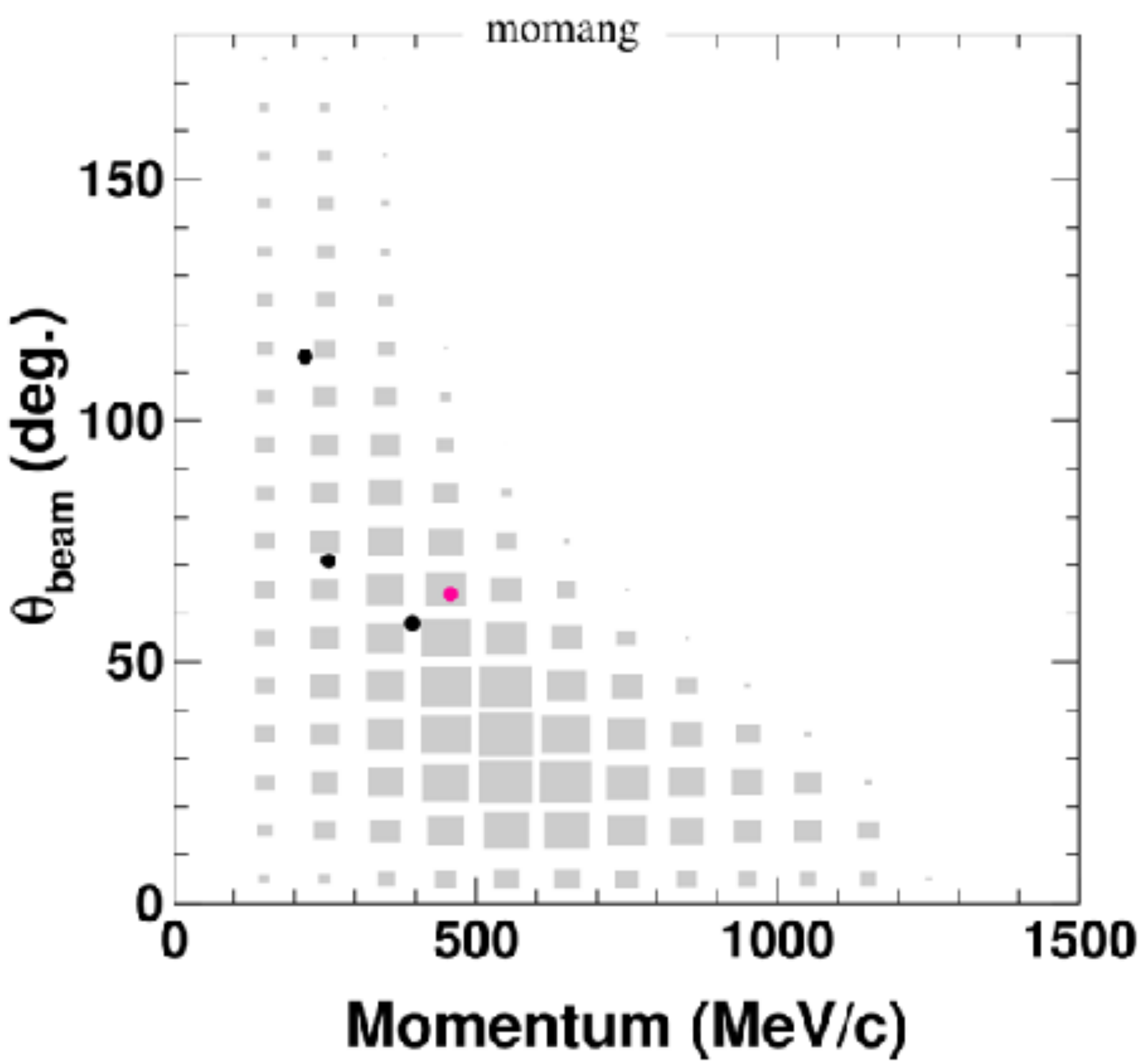
Electron Neutrino events

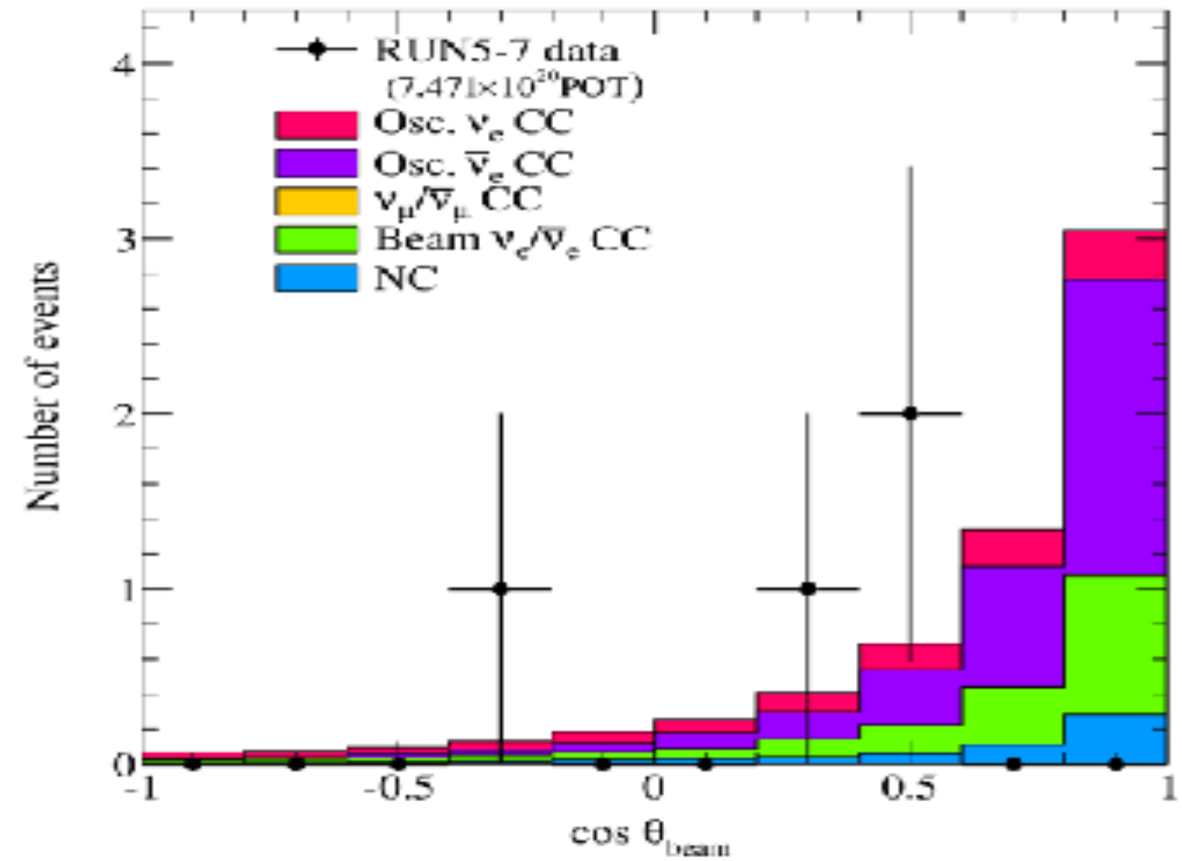


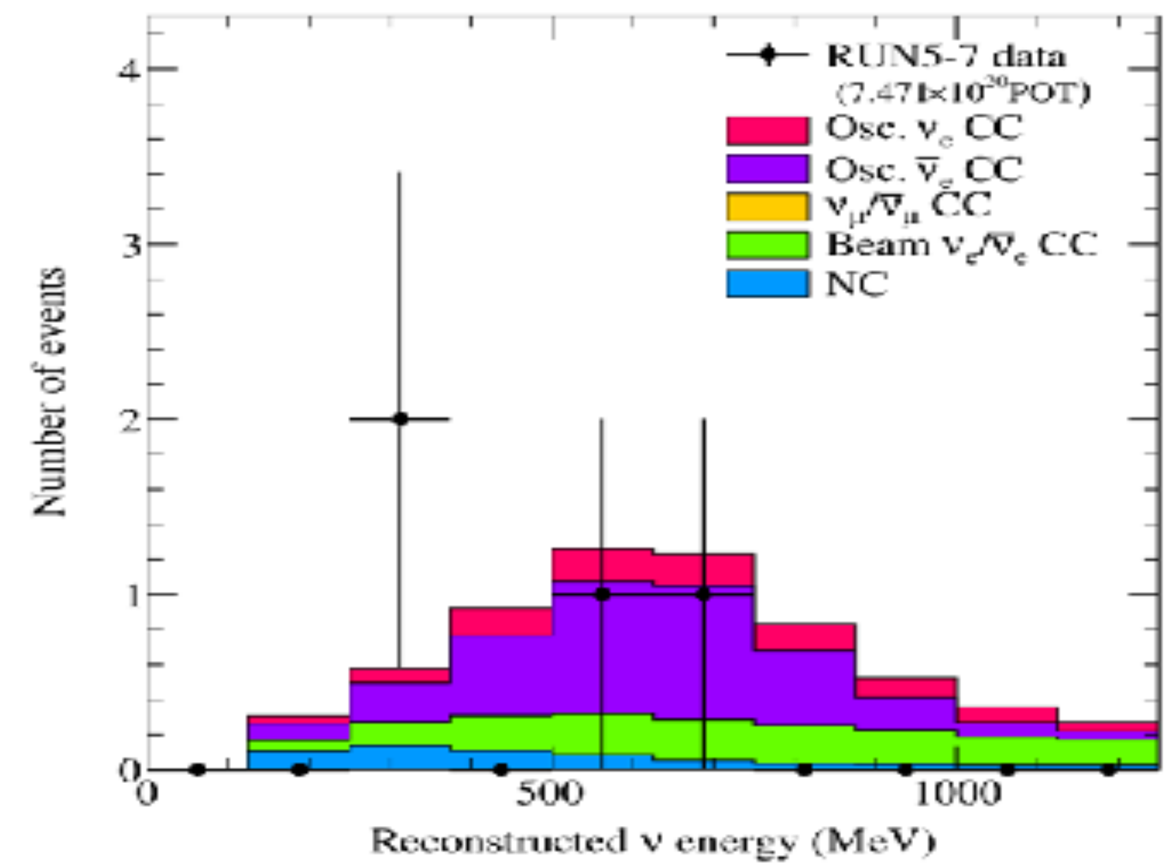




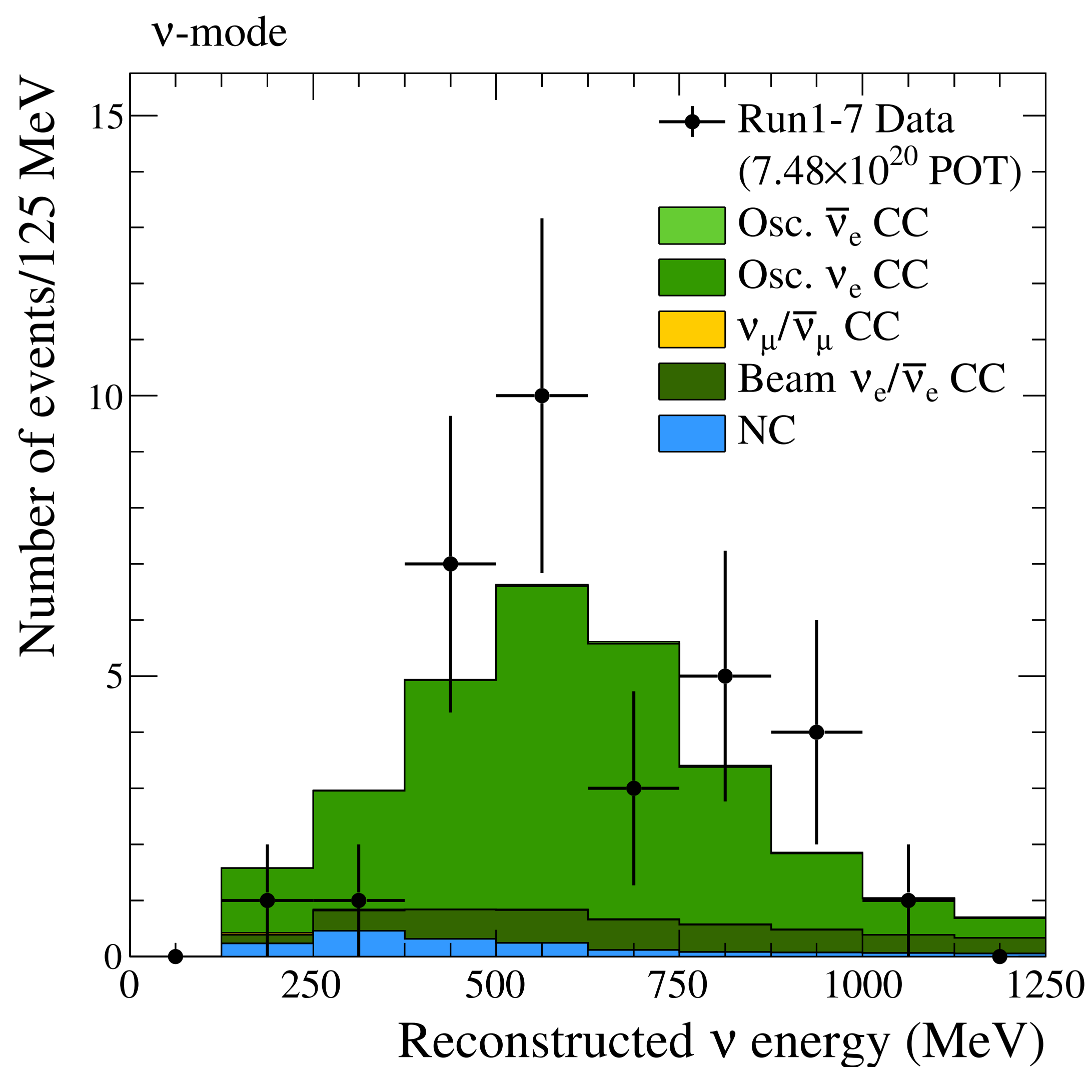
Electron Anti-Neutrino events

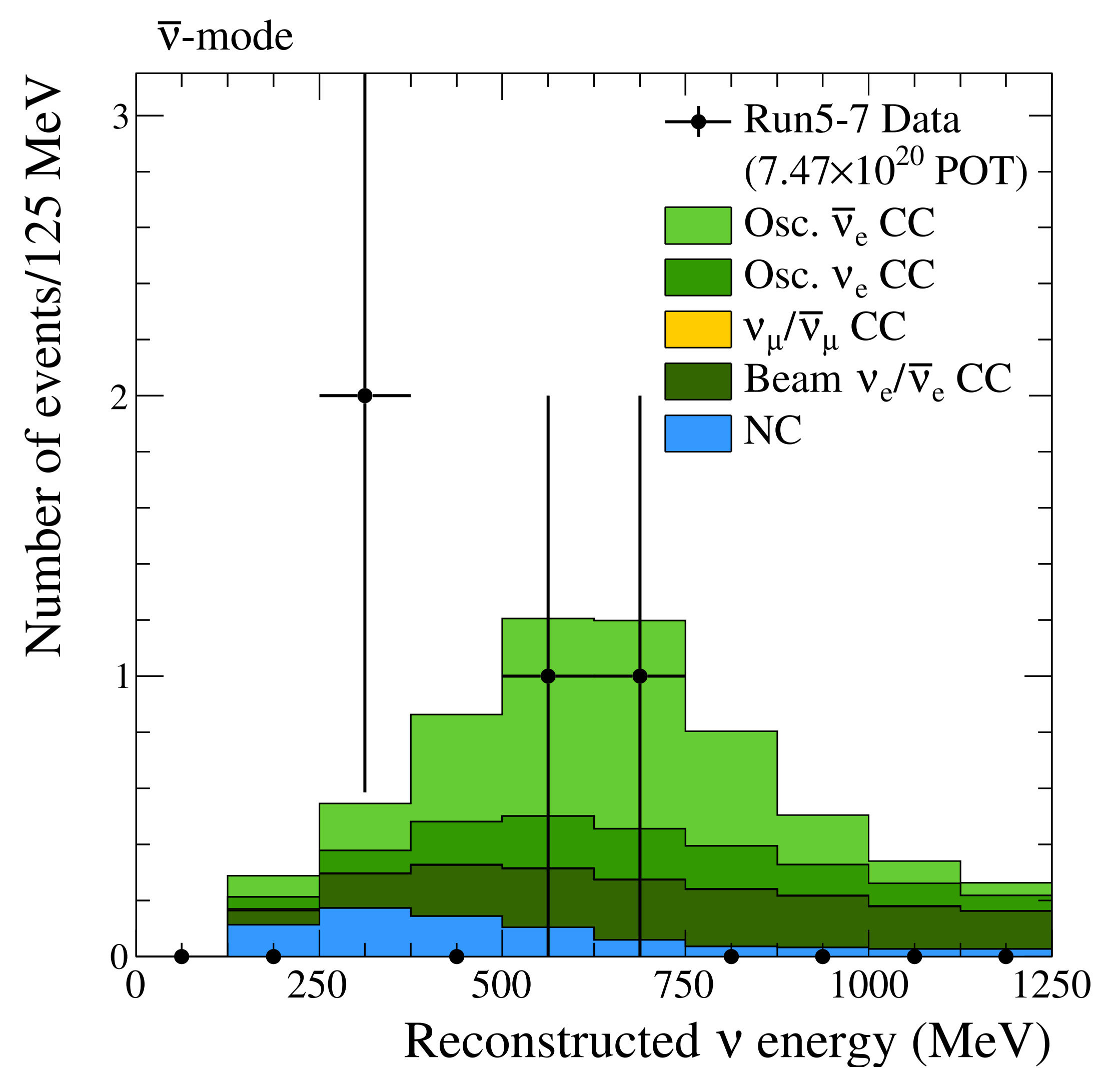






FINAL Electron (anti-)neutrino events





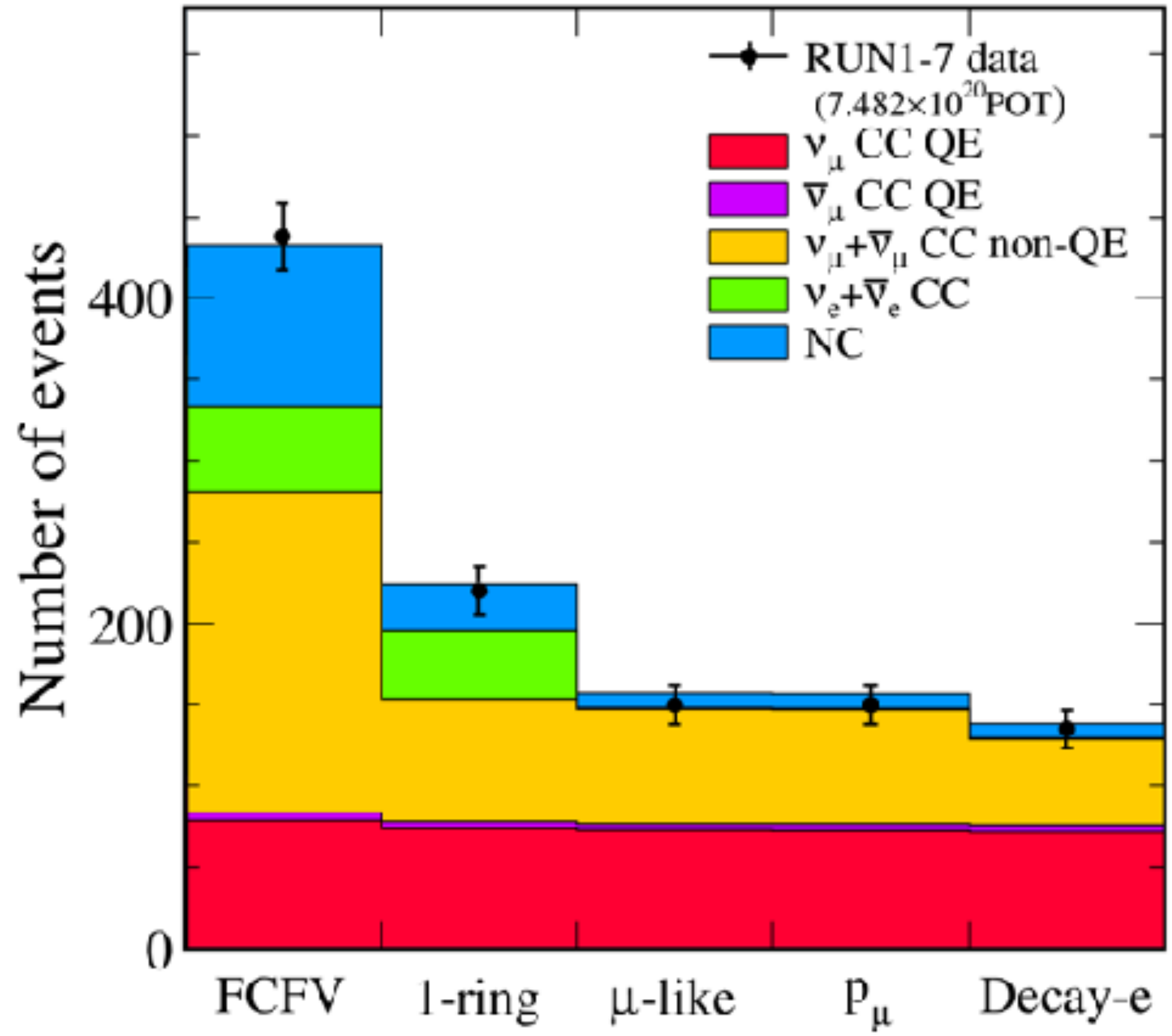
- Neutrino:
  - Data: 32
  - MC: 28.55

- Anti-neutrino:
  - Data: 4
  - MC: 6.28

FINAL Electron (anti-)neutrino events

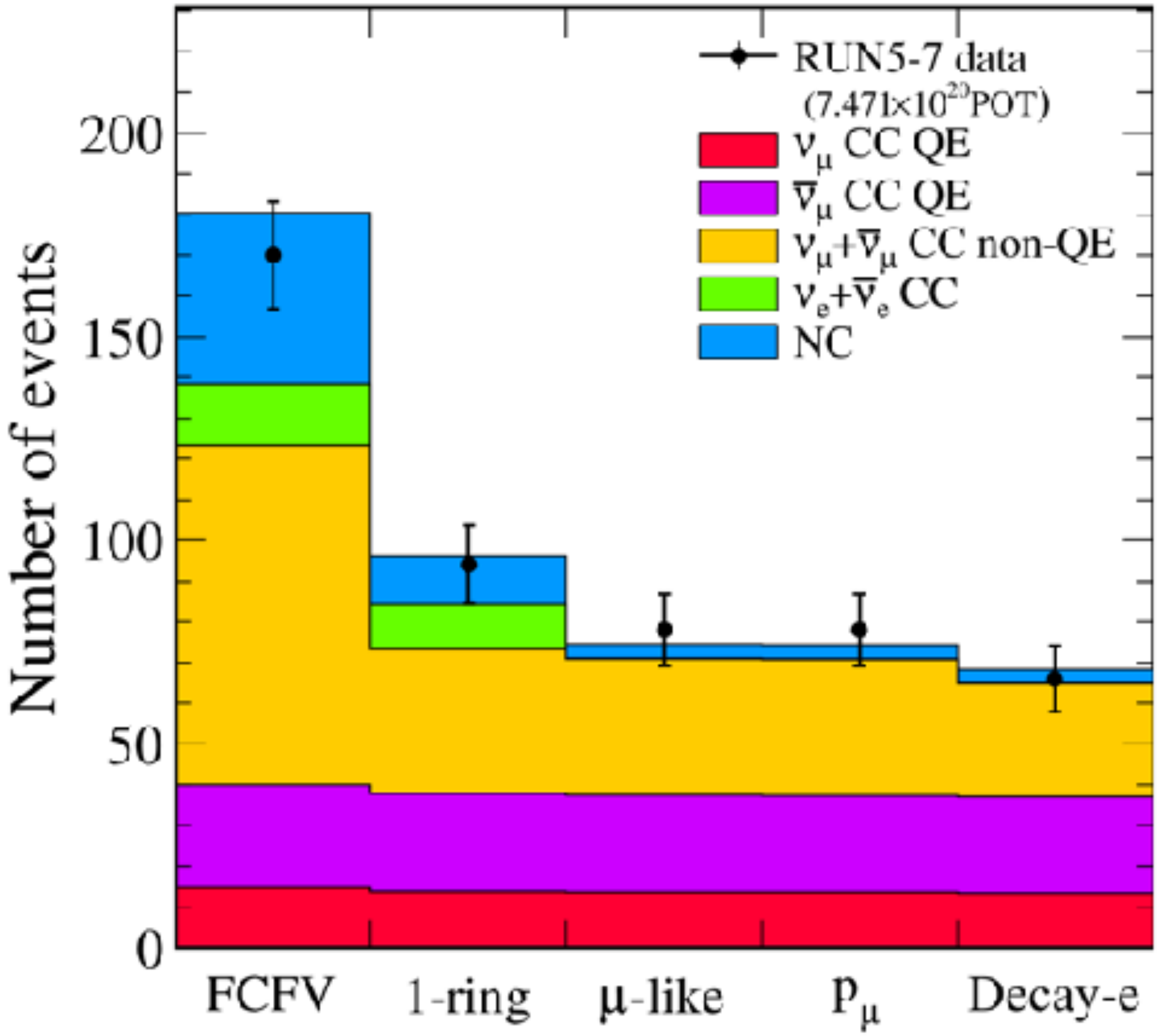
ν-beam mode	MC total	$\nu_\mu + \overline{\nu}_\mu$ CC	$\nu_e + \overline{\nu}_e$ CC	$\nu + \bar{\nu}$ NC	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ CC	$\nu_\mu \rightarrow \nu_e$ CC	Data
interactions in FV	744.89	364.32	18.55	326.16	0.39	35.47	-
FCFV	431.85	279.88	18.09	98.72	0.38	34.78	438
single ring[a]	223.49	153.40	11.15	28.68	0.32	29.95	220
electron-like[b]	66.94	6.46	11.06	19.53	0.31	29.57	70
$E_{\mathrm{vis}} > 100\,\mathrm{MeV}$[c]	61.78	4.59	11.01	16.81	0.31	29.06	66
$N_{\mathrm{Michel-e}} = 0$[d]	50.60	0.97	8.97	14.24	0.31	26.11	51
$E_\nu^{\mathrm{rec}} < 1250\,\mathrm{MeV}$[e]	40.71	0.25	4.26	10.85	0.22	25.14	46
not π^0-like[f]	28.55	0.09	3.68	1.35	0.18	23.25	32
$\bar{\nu}$-beam mode							
interactions in FV	312.38	164.04	9.00	132.75	4.30	2.29	-
FCFV	180.48	123.24	8.75	42.05	4.20	2.24	170
single ring	96.06	73.21	5.51	11.87	3.74	1.73	94
electron-like	21.55	2.31	5.48	8.36	3.70	1.71	16
$E_{\mathrm{vis}} > 100\,\mathrm{MeV}$	20.05	1.83	5.46	7.39	3.68	1.69	14
$N_{\mathrm{Michel-e}} = 0$	16.40	0.33	4.71	6.24	3.66	1.46	12
$E_\nu^{rec} < 1250\,\mathrm{MeV}$	11.40	0.08	1.89	4.83	3.42	1.19	9
not π^0-like	6.28	0.02	1.58	0.60	3.04	1.05	4

Muon Neutrino Selection



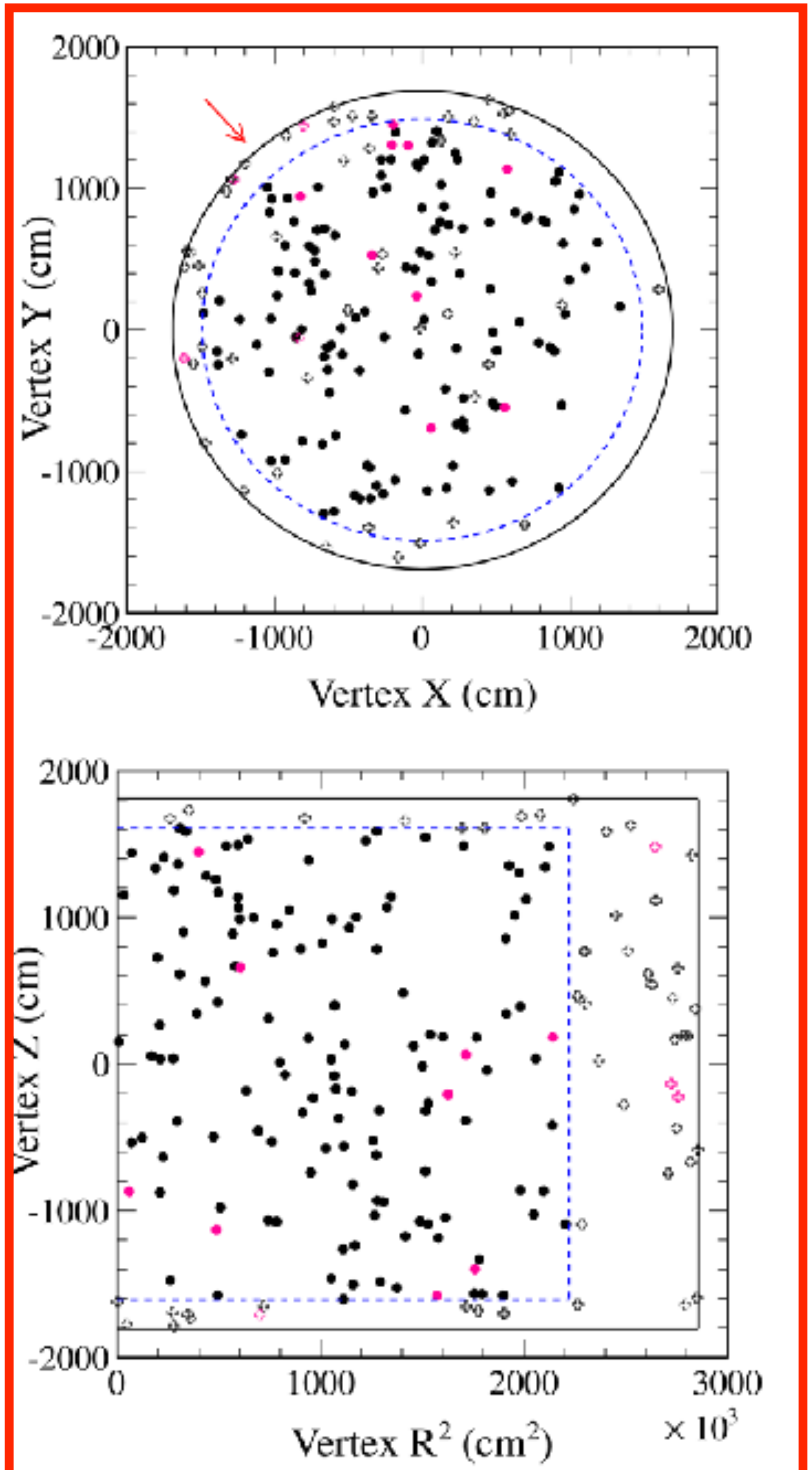
Runs 1-7	Data	Expected					
		MC Total	ν_μ CCQE	$\bar{\nu_\mu}$ CCQE	$\nu_\mu + \bar{\nu_\mu}$ CC non-QE	$\nu_e + \bar{\nu_e}$ CC	NC
Interactions in FV	654	746.7575	100.4284	6.4638	258.3411	54.5457	326.9786
FCFV	438	432.9301	78.9518	4.8621	196.7698	53.3789	98.9675
Single ring	220	224.0565	73.6820	4.7067	75.3979	41.5143	28.7556
Muon-like PID	150	156.9520	72.4042	4.6641	70.2374	0.4669	9.1794
p_μ >200 MeV/c	150	156.6329	72.2183	4.6613	70.1791	0.4669	9.1073
$N_{decay-e} \leq 1$	135	138.1053	71.4660	4.6381	52.7374	0.4657	8.7981
Efficiency from Interactions [%]	-	18.5	71.2	71.8	20.4	0.8	2.7
Efficiency from FCFV [%]	-	31.9	90.5	95.4	26.8	0.9	8.9

Muon Anti-Neutrino Selection

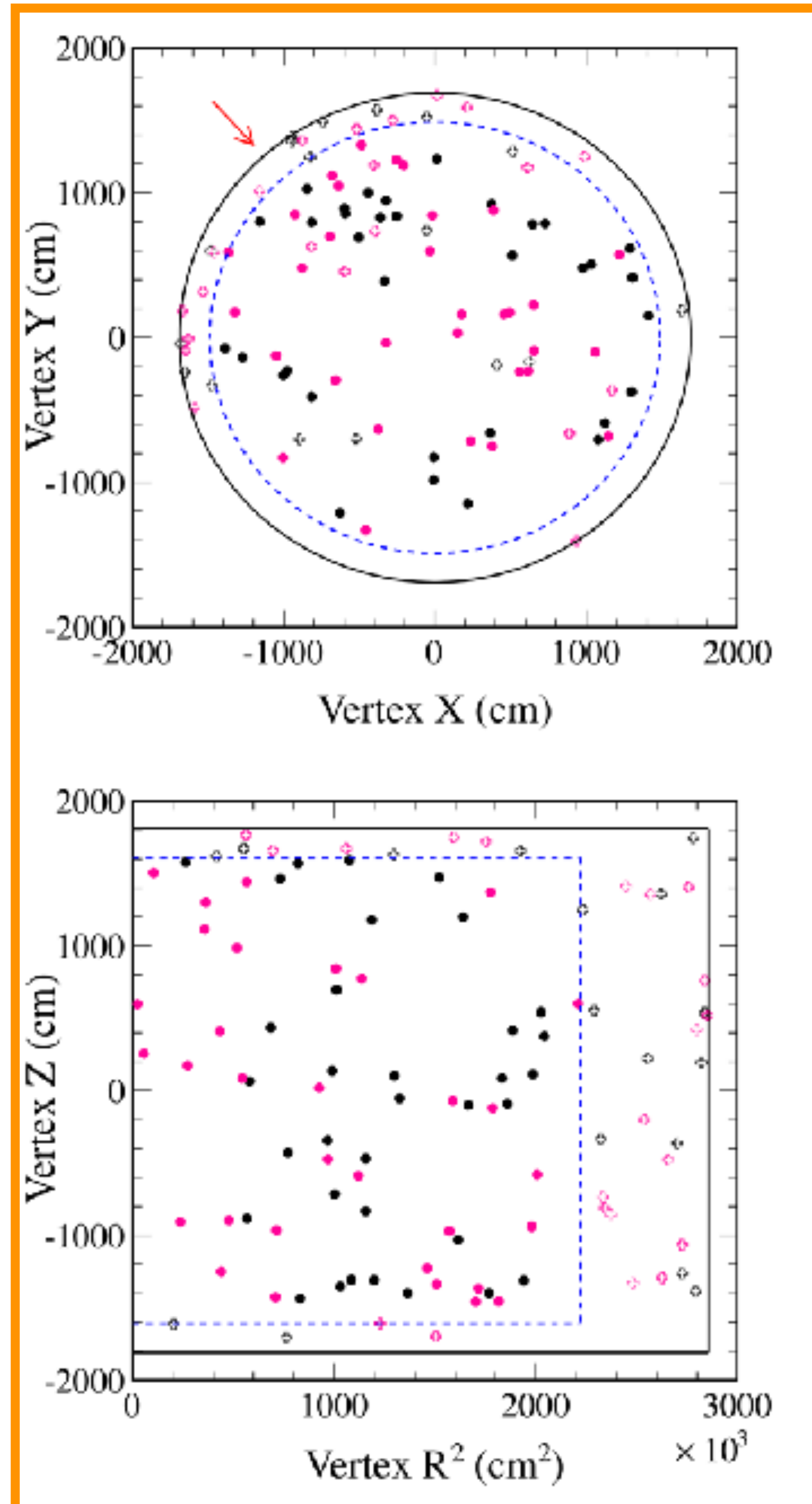


Runs 5-7	Data	Expected					
		MC Total	ν_μ CCQE	$\bar{\nu_\mu}$ CCQE	$\nu_\mu + \bar{\nu_\mu}$ CC non-QE	$\nu_e + \bar{\nu_e}$ CC	NC
Interactions in FV	263	312.3842	20.0413	30.7730	113.2287	15.5890	132.7521
FCFV	170	180.4835	15.0375	24.9456	83.2607	15.1875	42.0523
Single ring	94	96.0647	13.5195	24.2846	35.4103	10.9755	11.8747
Muon-like PID	78	74.5169	13.3959	23.9567	33.5551	0.0922	3.5170
p_μ >200 MeV/c	78	74.4175	13.3862	23.9221	33.5368	0.0922	3.4802
$N_{decay-e}$ ≤ 1	66	68.2621	13.1816	23.8472	27.7887	0.0917	3.3528
Efficiency from Interactions [%]	-	21.9	65.8	77.5	24.5	0.6	2.5
Efficiency from FCFV [%]	-	37.8	87.7	95.6	33.4	0.6	8.0

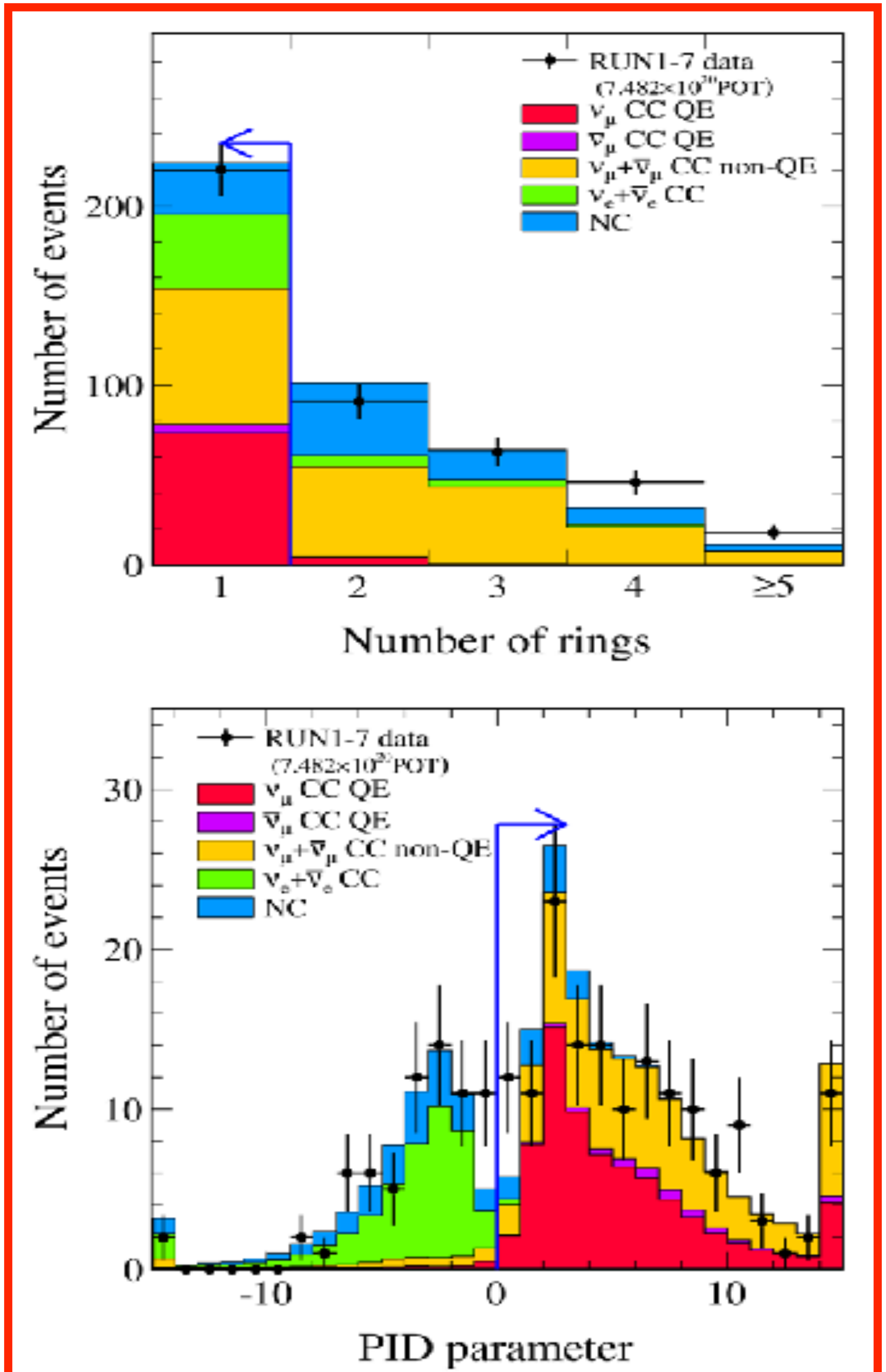
Fiducial Volume

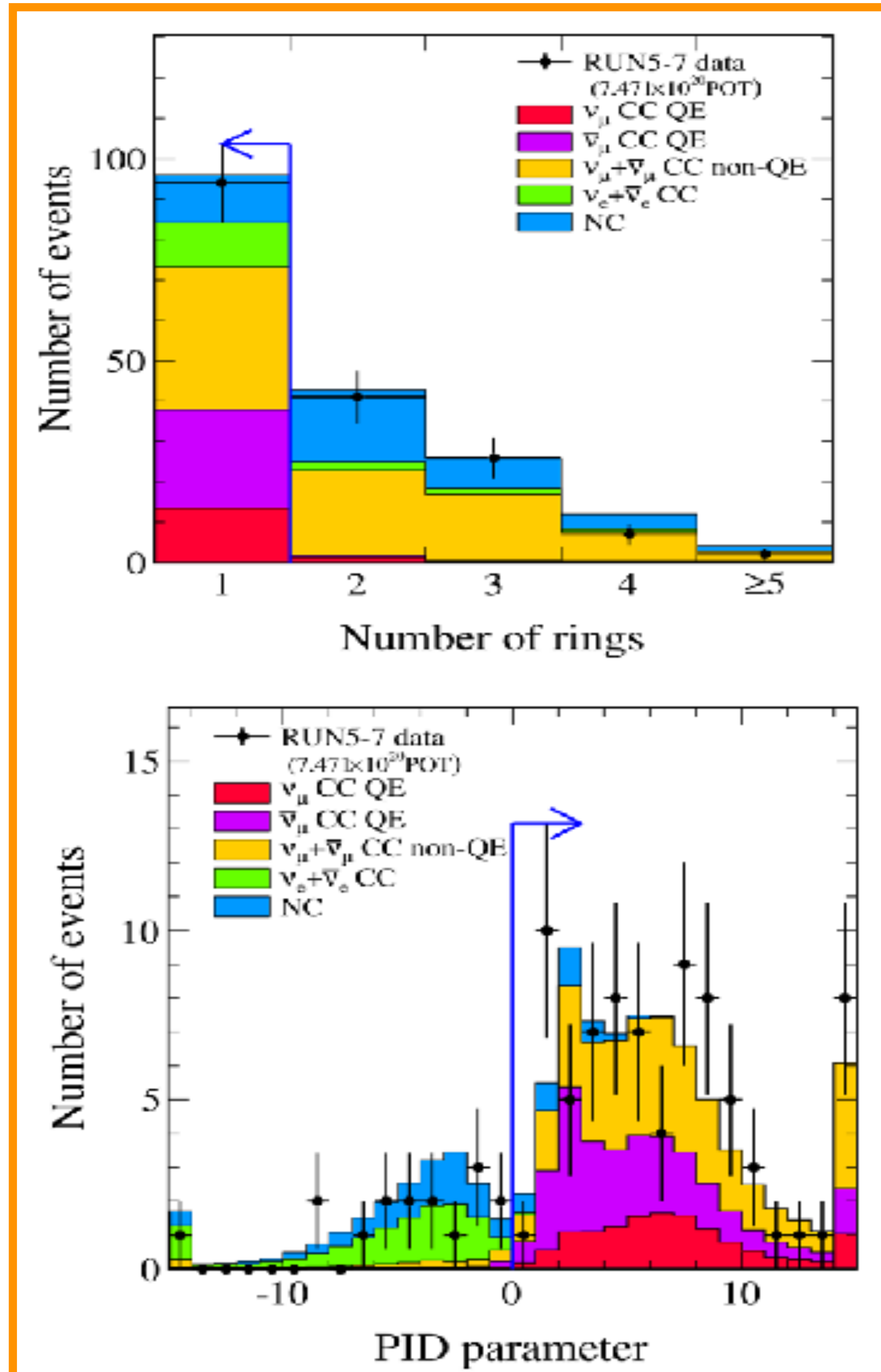


2m away from the wall

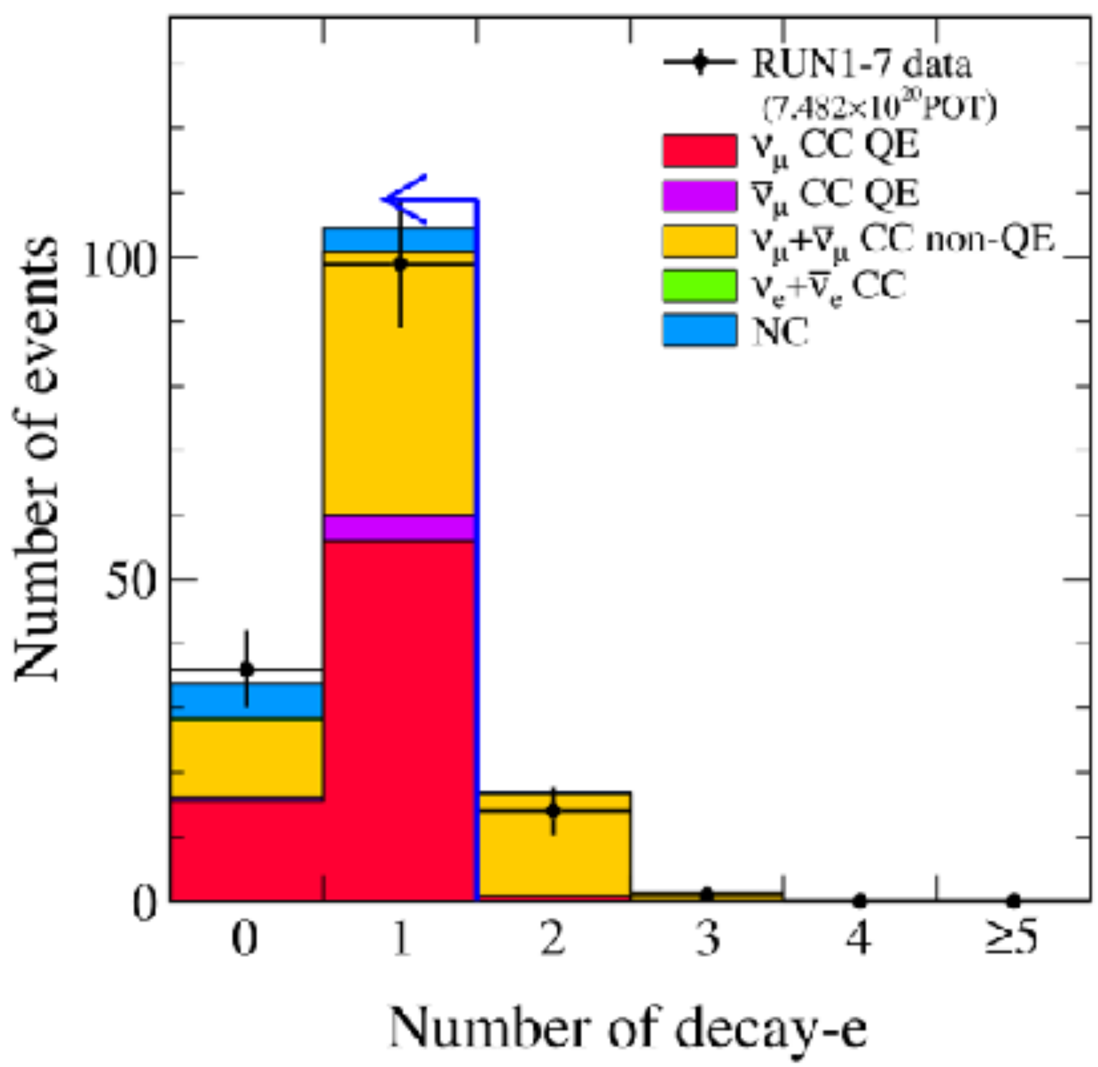


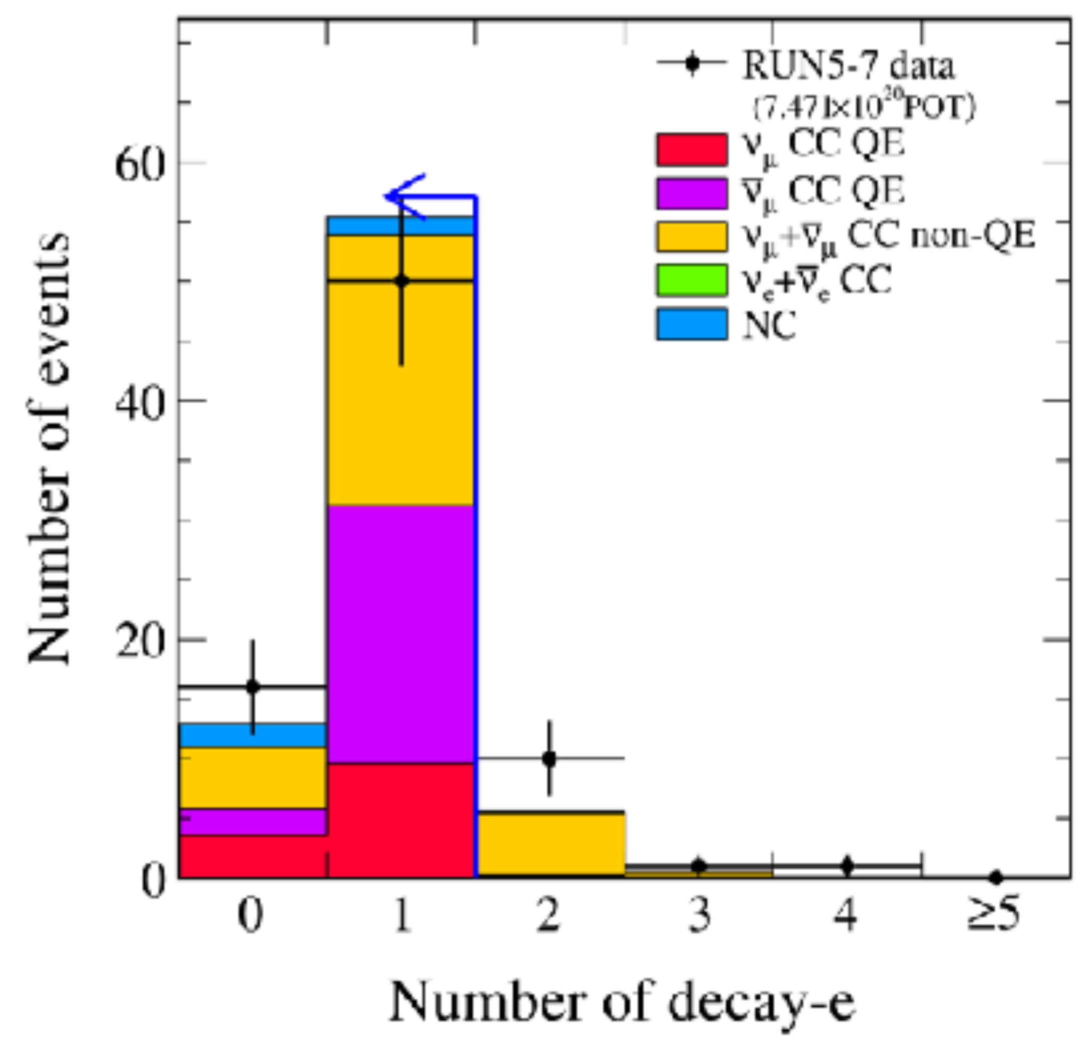
Rings (=1); Particle ID (= μ-like)



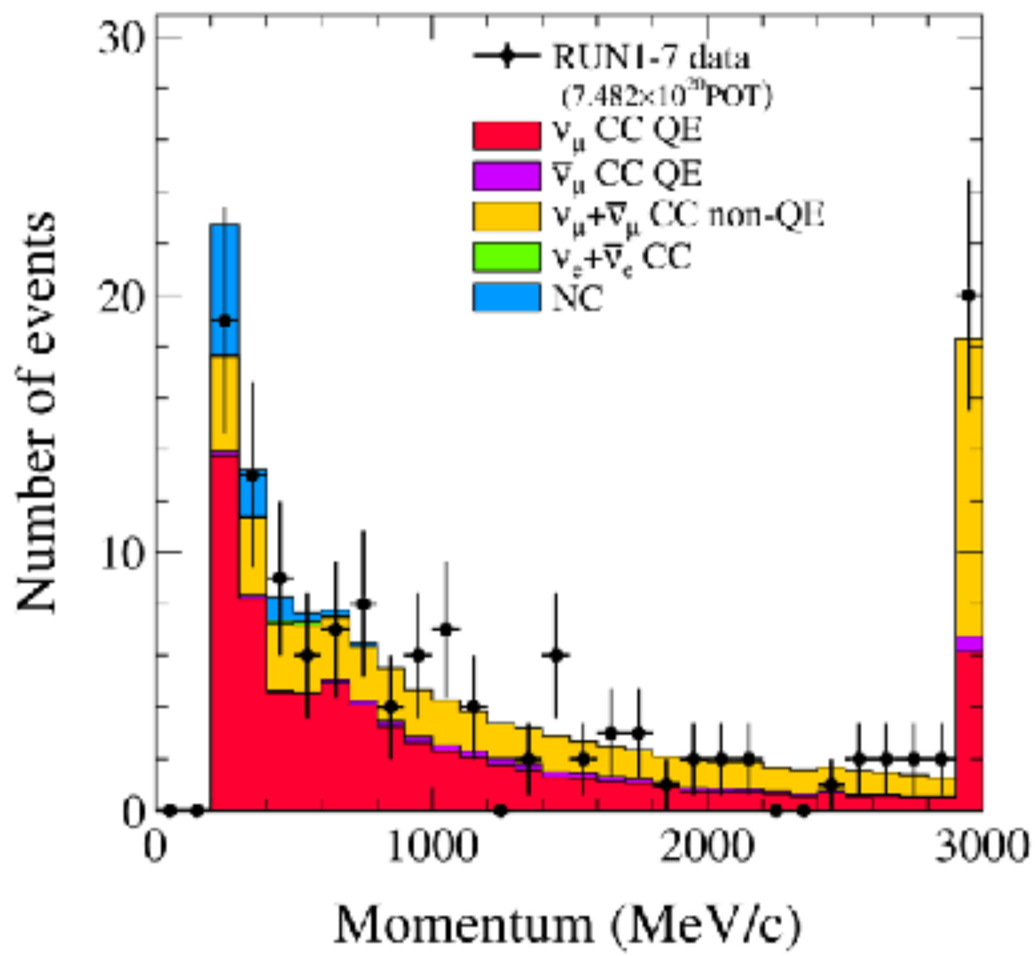


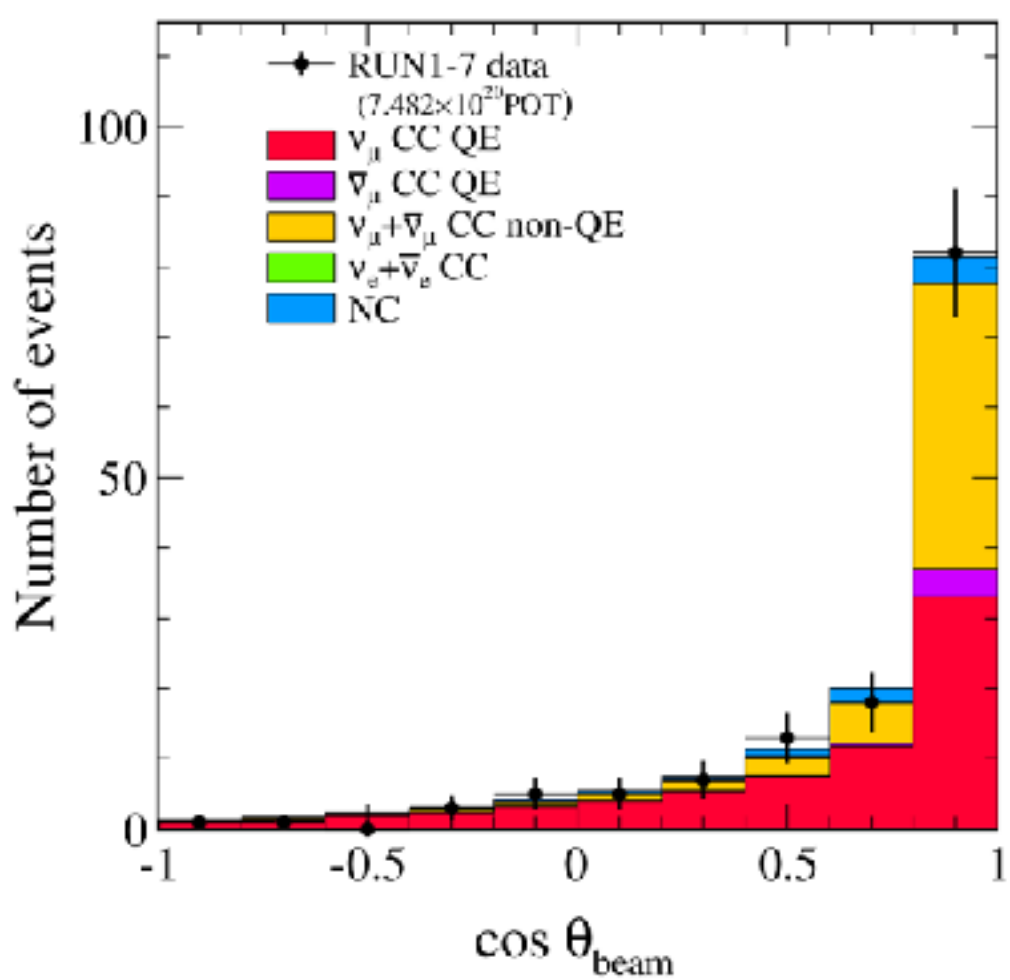
#Decay-electrons (<=1)

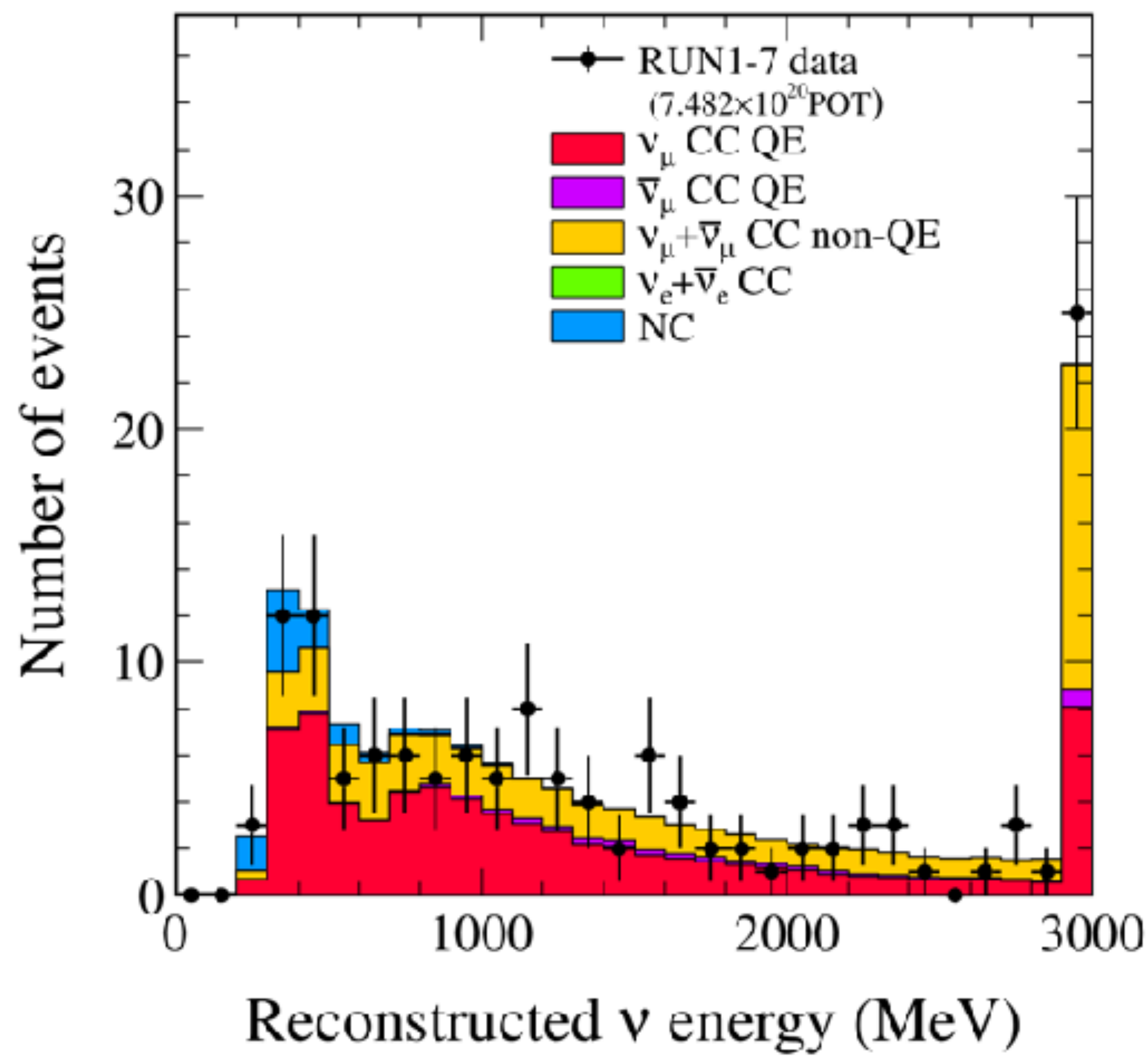




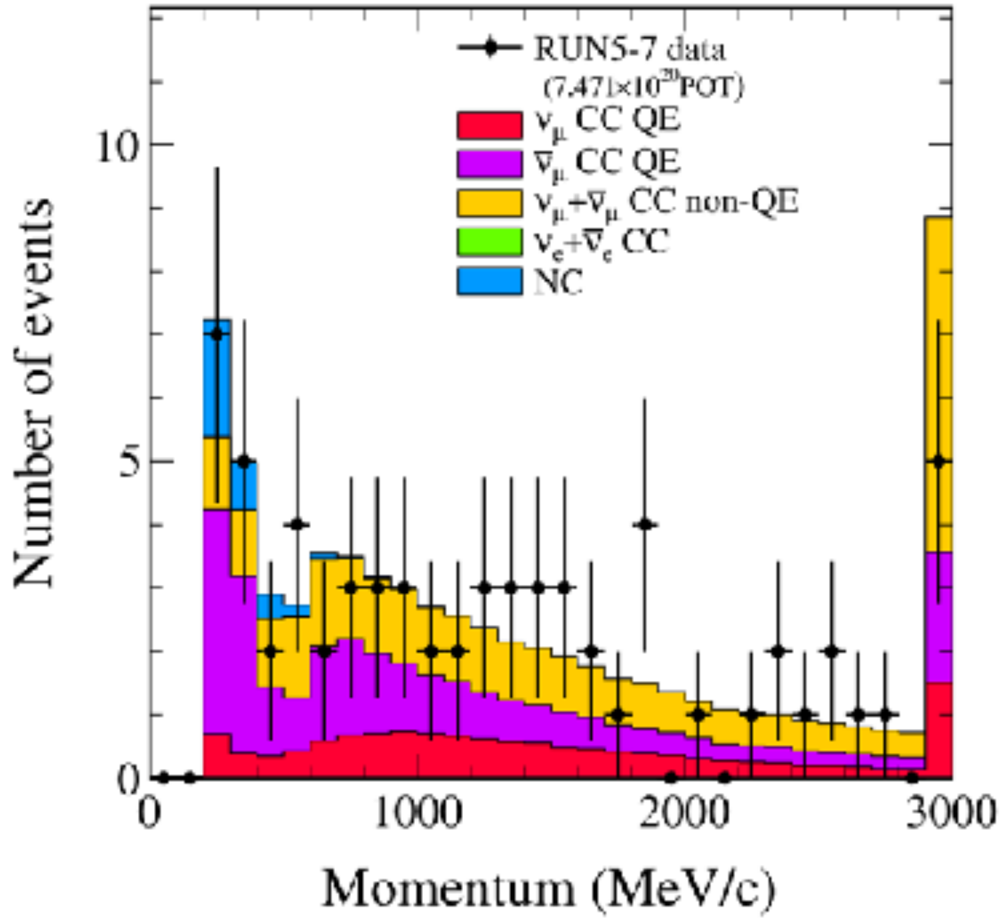
Muon Neutrino events

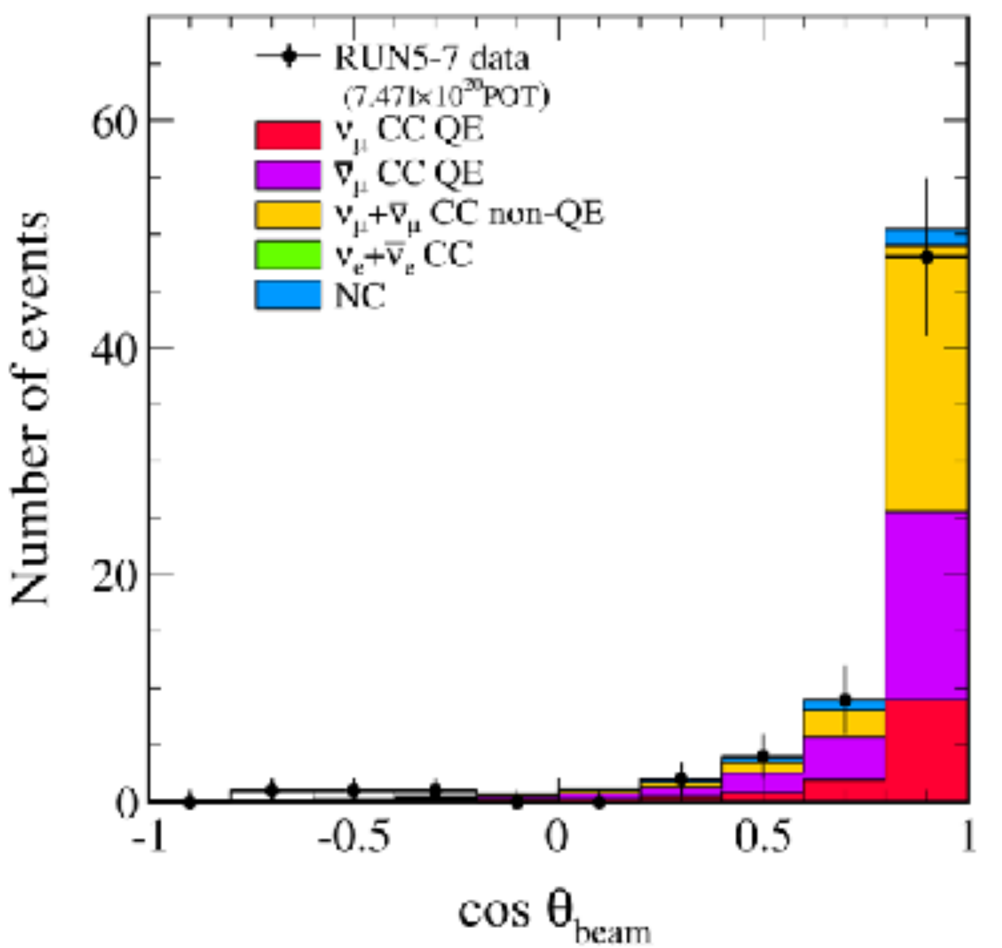


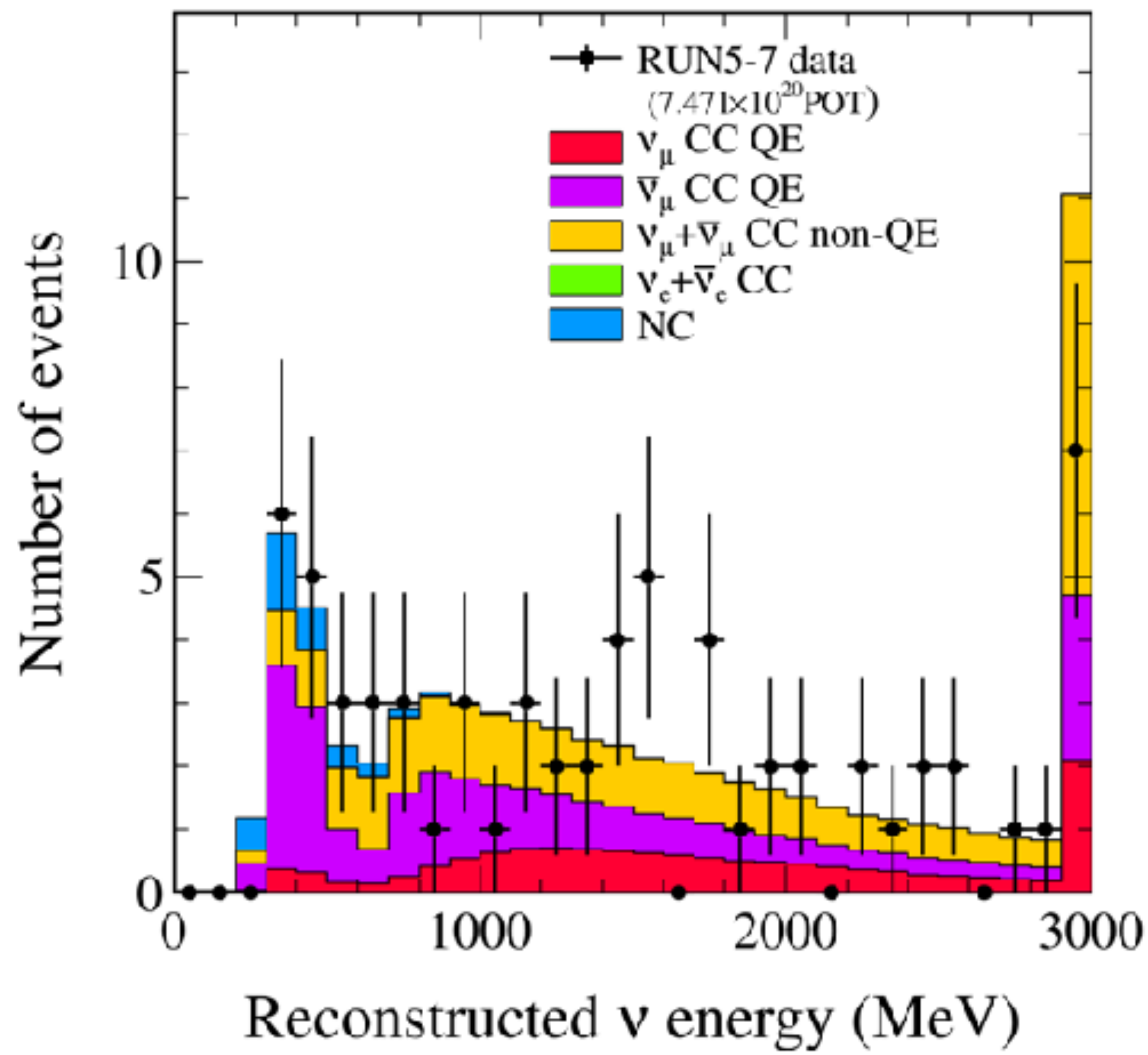




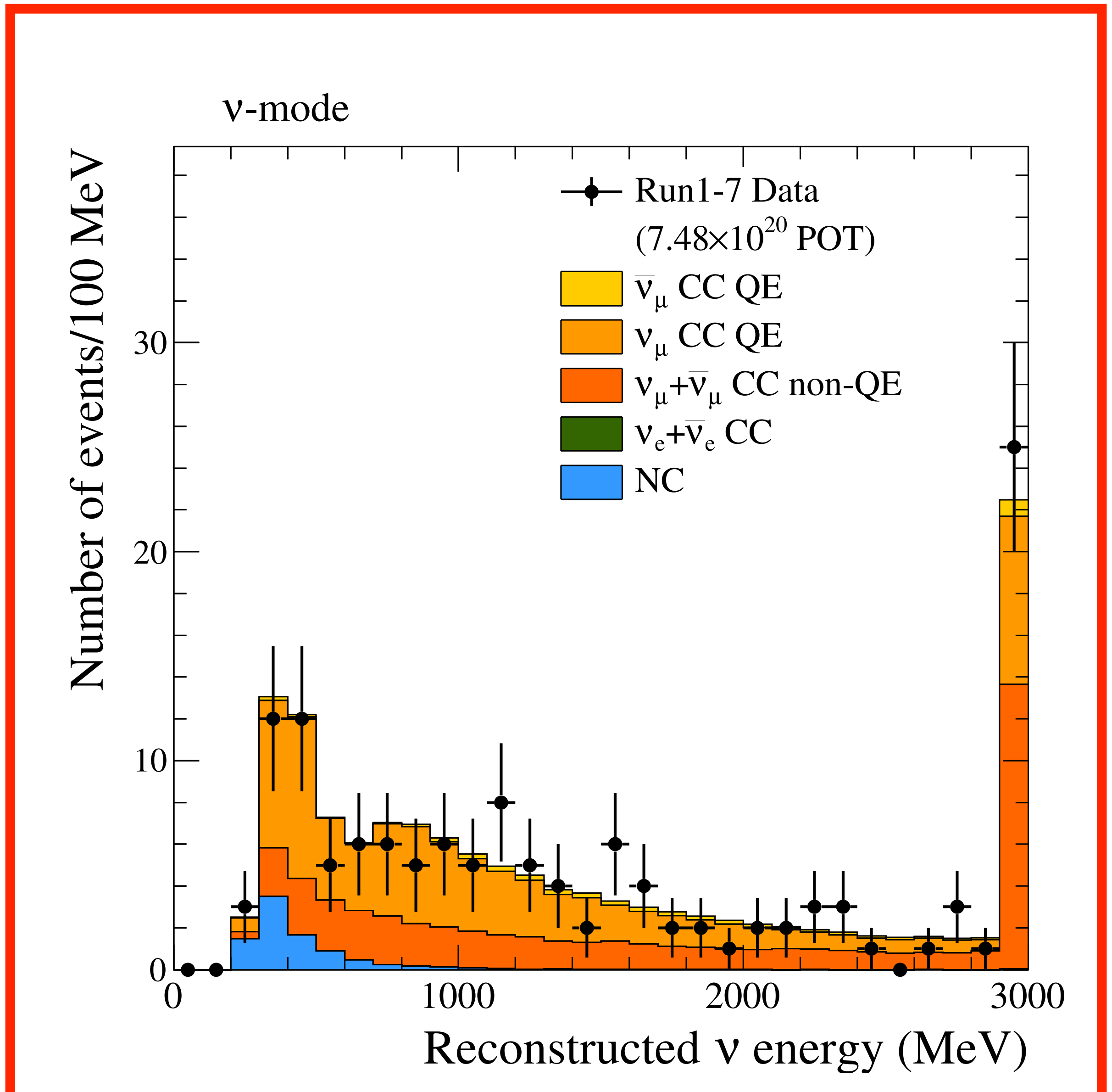
Muon Anti-Neutrino events

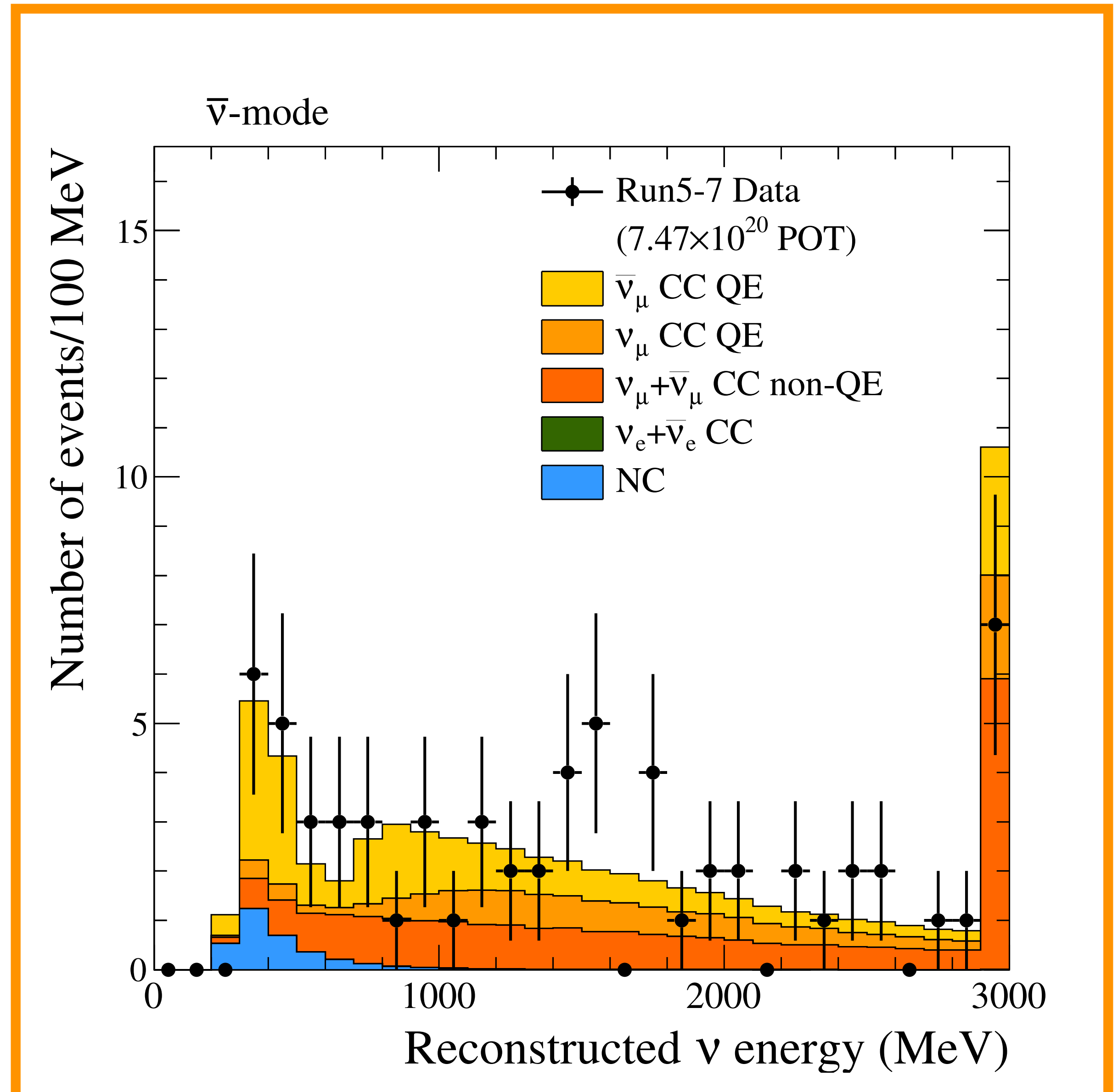






FINAL muon (anti-)neutrino events





- Neutrino:
  - Data: 135
  - MC: 137.76

- Anti-neutrino:
  - Data: 66
  - MC: 68.26

FINAL muon (anti-)neutrino events

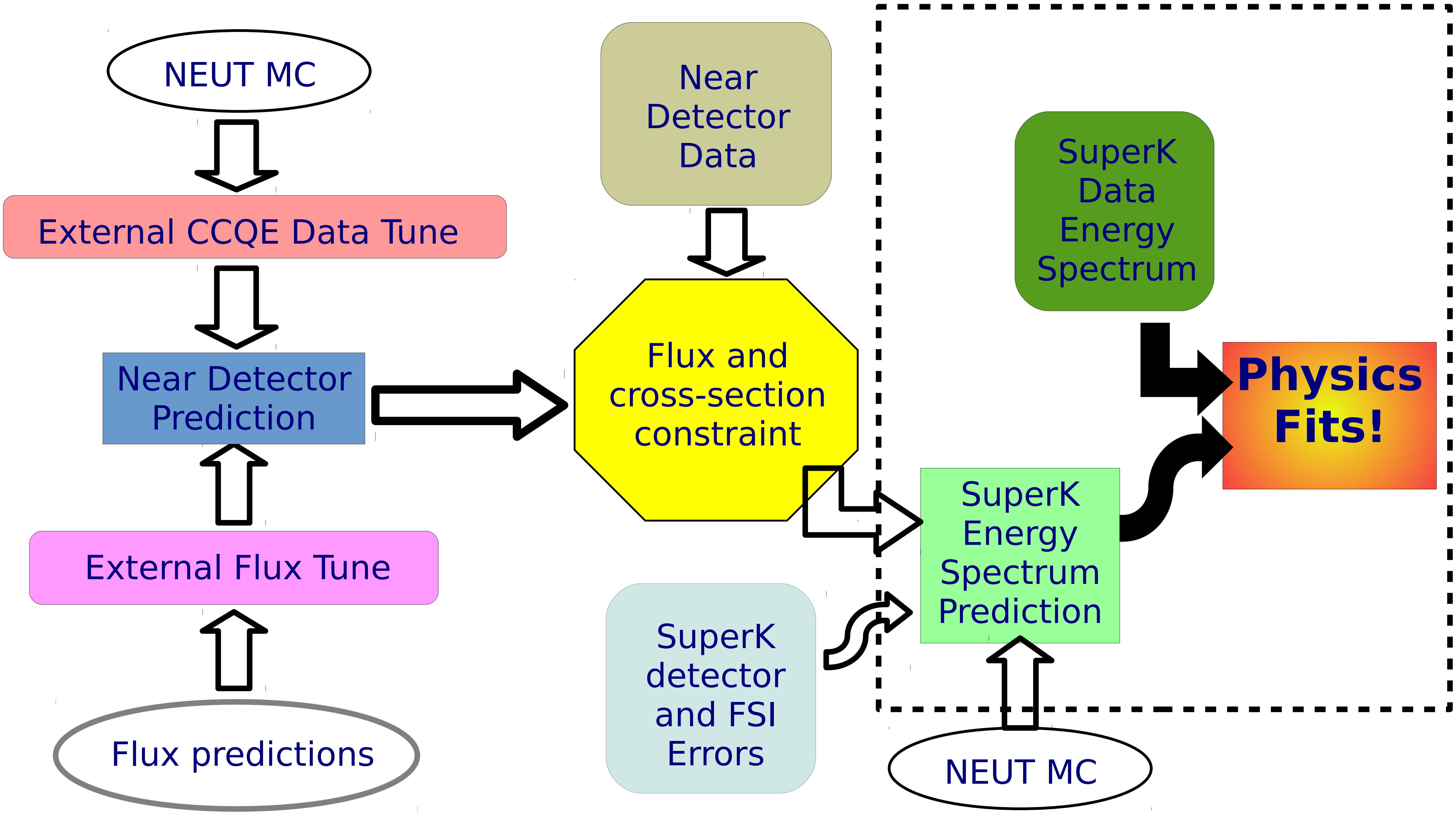
ν-beam mode	MC total	ν_μ CCQE	$\overline{\nu}_\mu$ CCQE	$\nu_\mu + \overline{\nu}_\mu$ CC nonQE	$\nu_e + \overline{\nu}_e$ CC	$\nu + \bar{\nu}$ NC	Data
interactions in FV	744.89	100.17	6.45	257.70	54.41	326.16	-
FCFV	431.85	78.75	4.85	196.28	53.25	98.72	438
single ring[g]	223.49	73.49	4.70	75.21	41.41	28.68	220
muon-like[h]	156.56	72.22	4.65	70.06	0.47	9.16	150
$p_\mu > 200\,\mathrm{MeV}/c$[i]	156.24	72.03	4.65	70.00	0.47	9.08	150
$N_{\mathrm{Michel-e}} \leq 1$[j]	137.76	71.28	4.63	52.61	0.46	8.78	135
$\bar{\nu}$-beam mode							
interactions in FV	312.38	20.04	30.77	113.23	15.59	132.75	-
FCFV	180.48	15.04	24.95	83.26	15.19	42.05	170
single ring	96.06	13.52	24.28	35.41	10.98	11.87	94
muon-like	74.52	13.40	23.96	33.56	0.09	3.52	78
$p_\mu > 200\,\mathrm{MeV}/c$	74.42	13.39	23.92	33.54	0.09	3.48	78
$N_{\mathrm{Michel-e}} \leq 1$	68.26	13.18	23.85	27.79	0.09	3.35	66

FINAL ν and $\overline{\nu}$ events

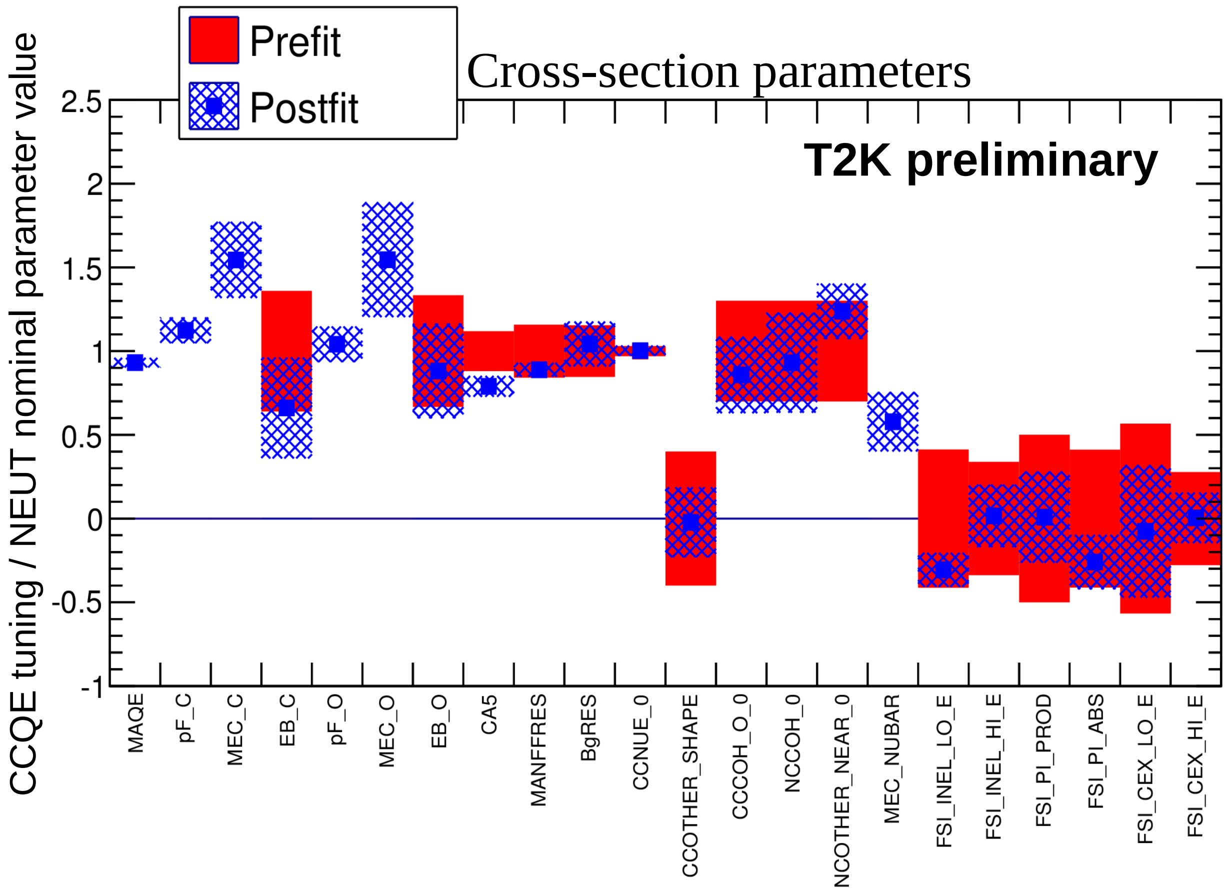
Beam mode	Sample	$\delta_{CP} = -1.601$	$\delta_{CP} = 0$	Exp. Not Osc	Observed
neutrino	μ-like	135.815	135.459	521.777	135
neutrino	e-like	28.687	24.170	6.147	32
antineutrino	μ-like	64.205	64.059	184.837	66
antineutrino	e-like	6.004	6.902	2.335	4
neutrino	CC1π^+-like	3.126	2.744	3.258	5

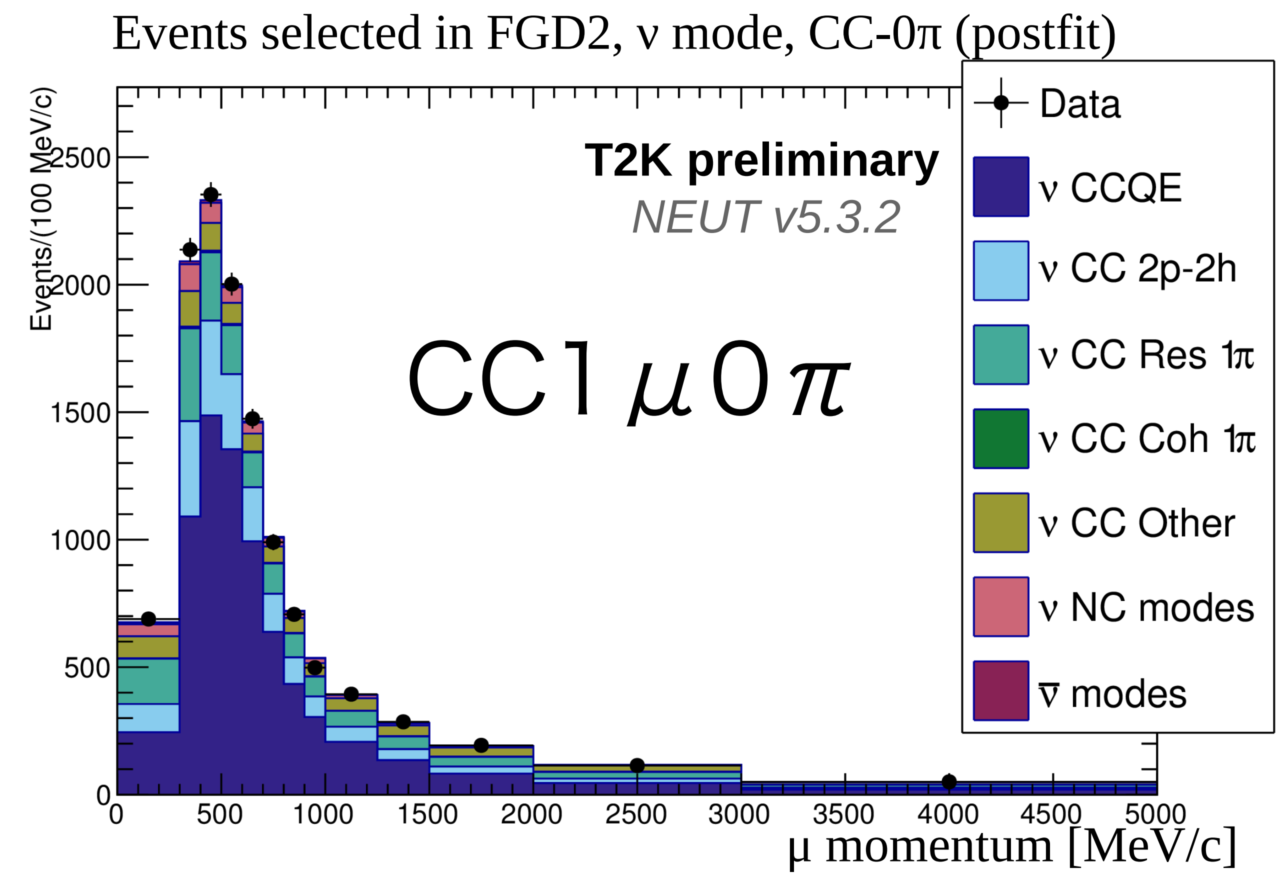
New in 2017

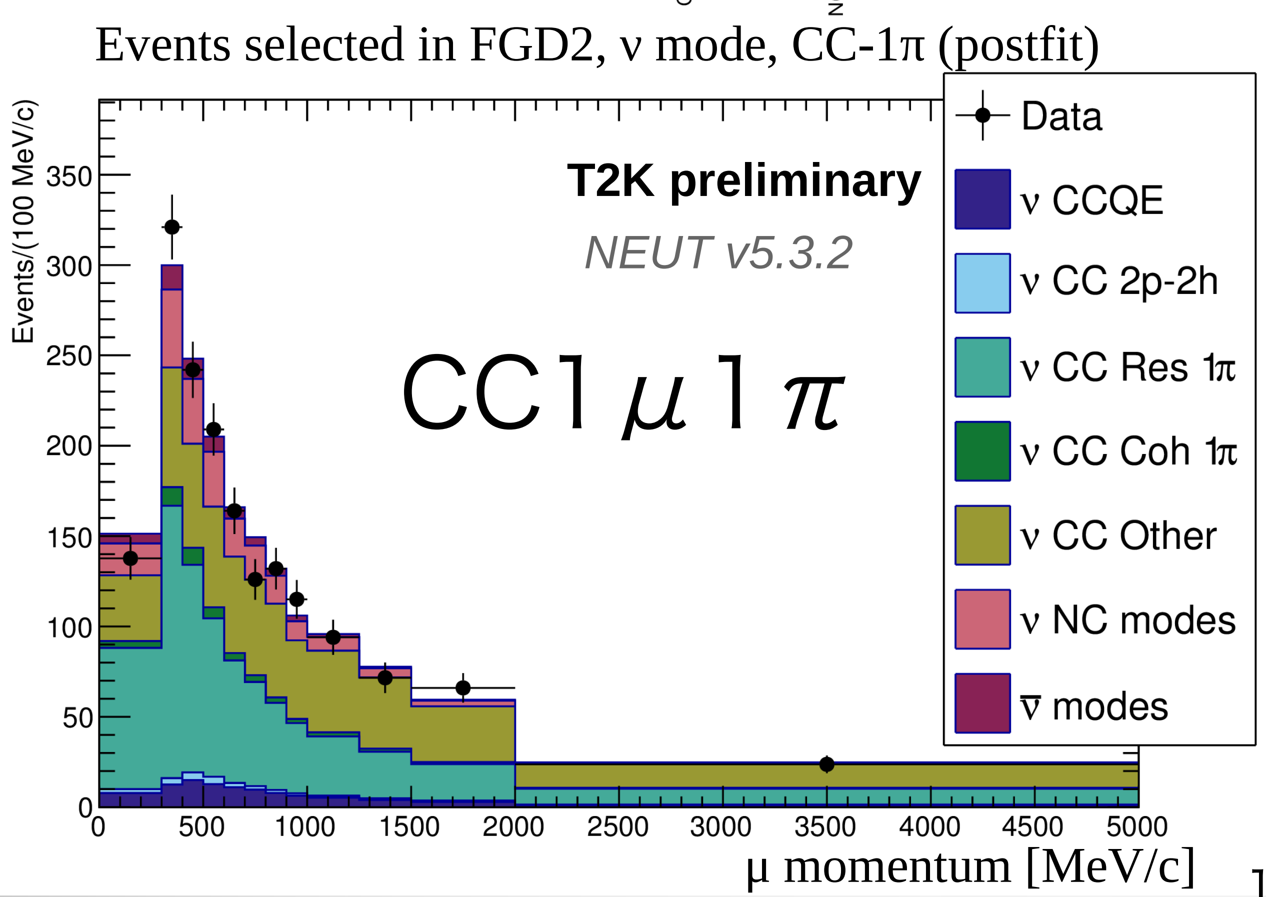
7. Oscillation Analysis

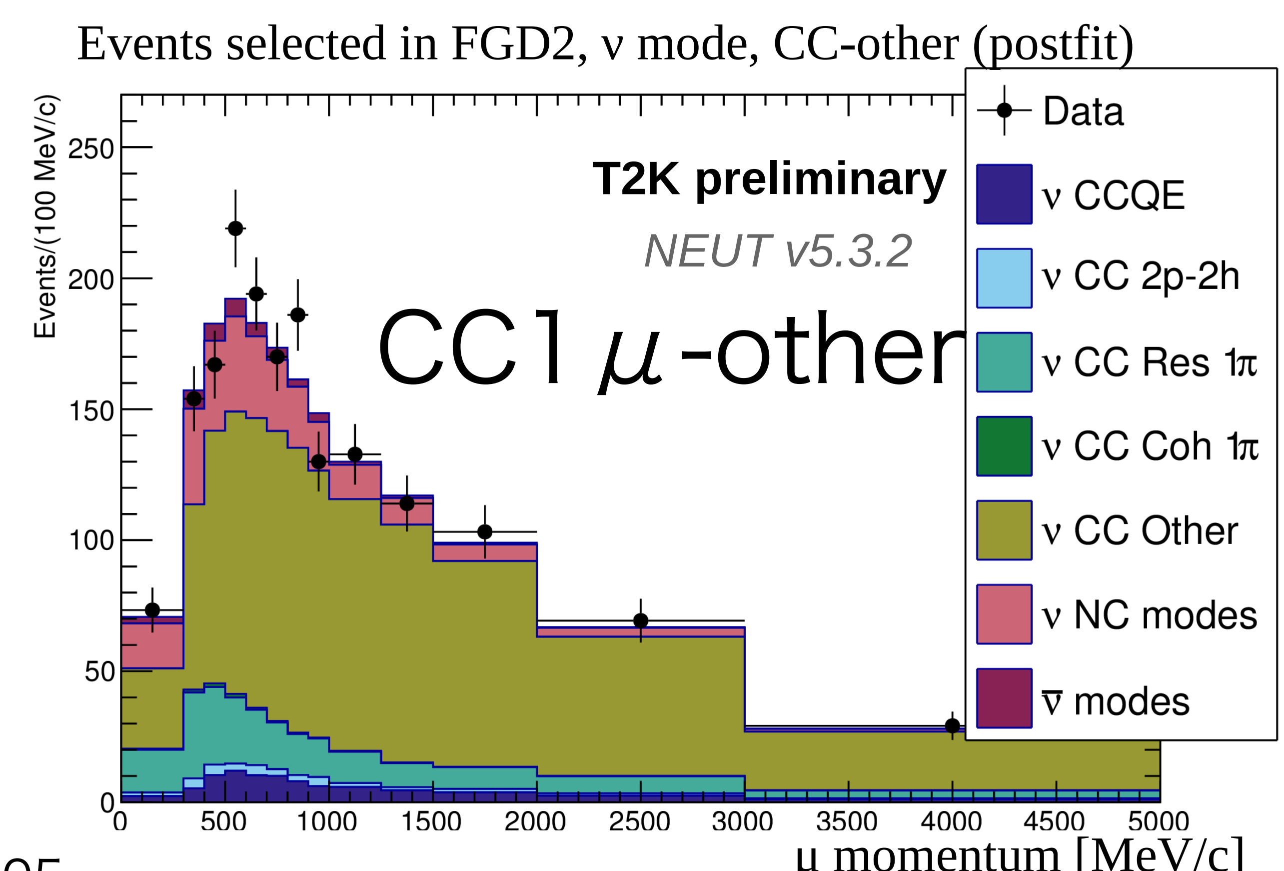

NEUT MC
External CCQE Data Tune
Near Detector Prediction
External Flux Tune
Flux predictions
Near Detector Data
Flux and cross-section constraint
SuperK detector and FSI Errors
SuperK Data Energy Spectrum
Physics Fits!
SuperK Energy Spectrum Prediction
NEUT MC

Near Detector measurements → constraints

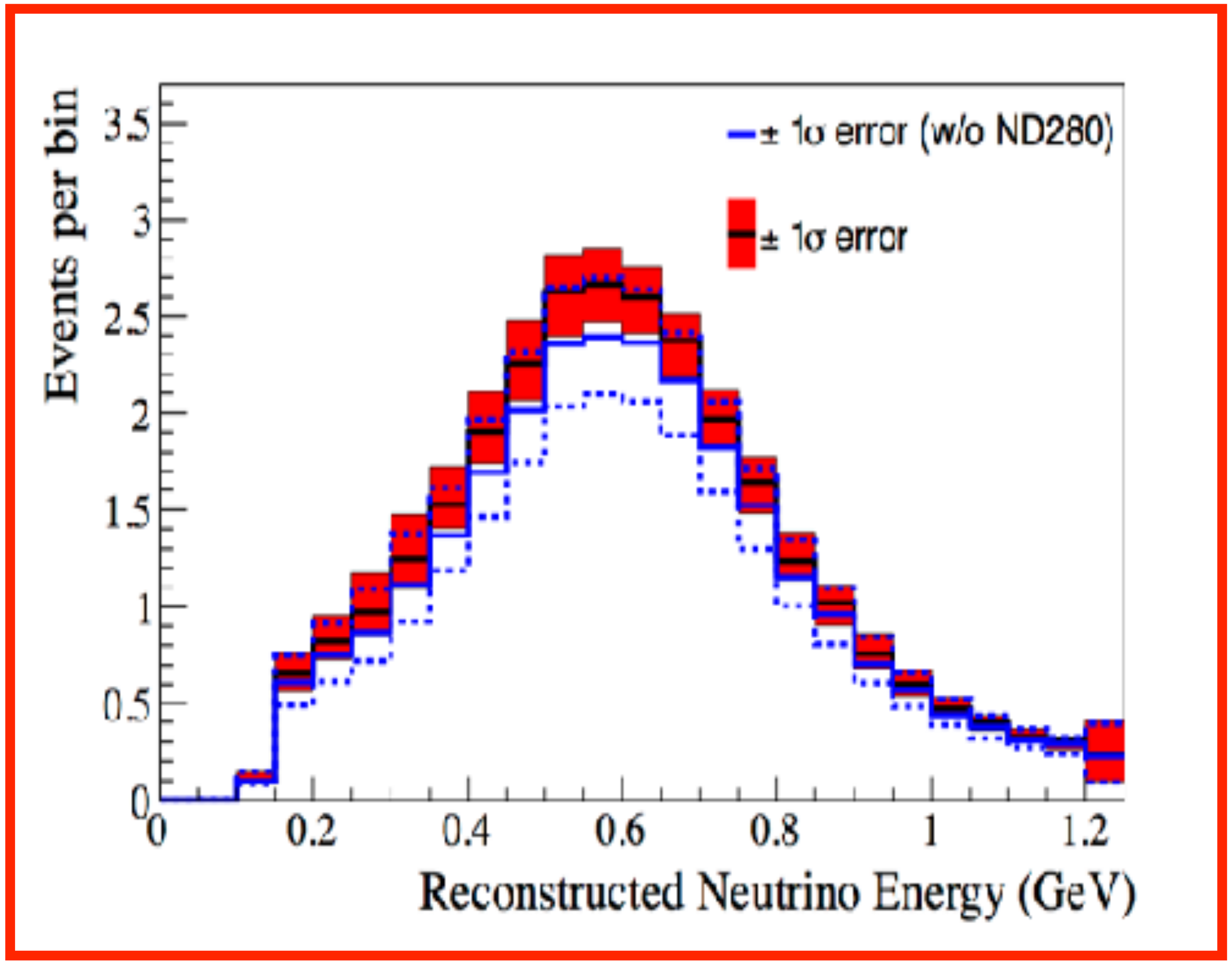


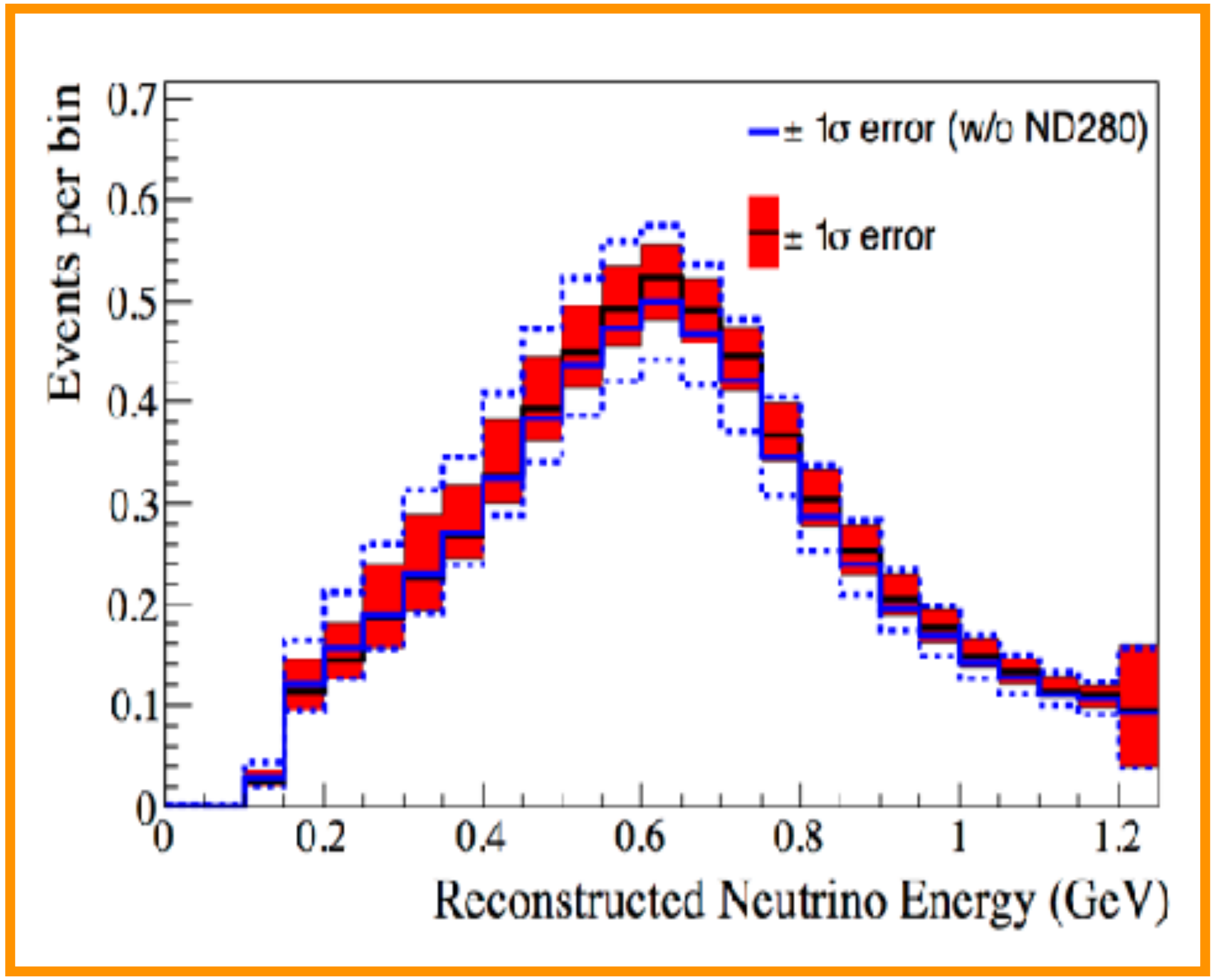




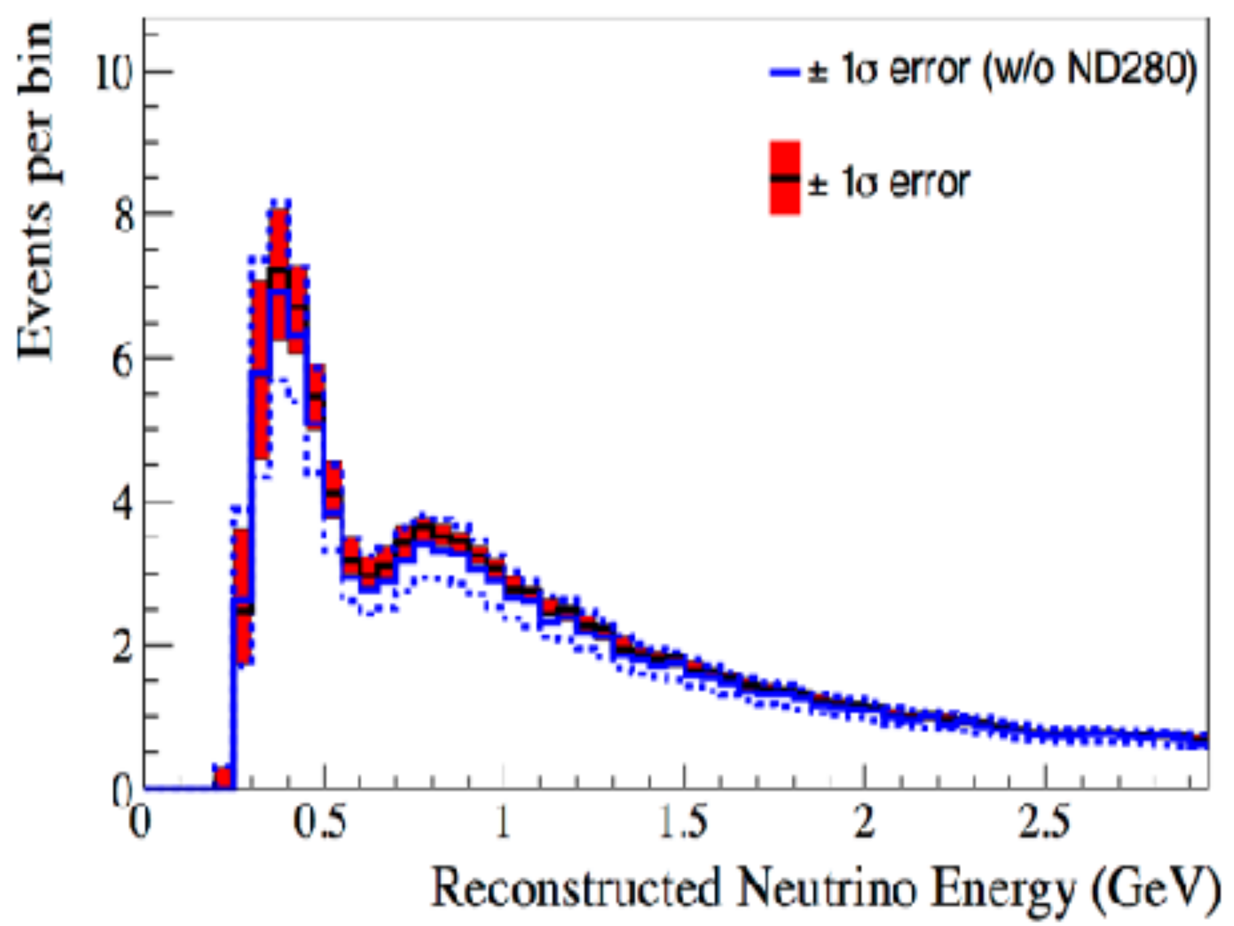


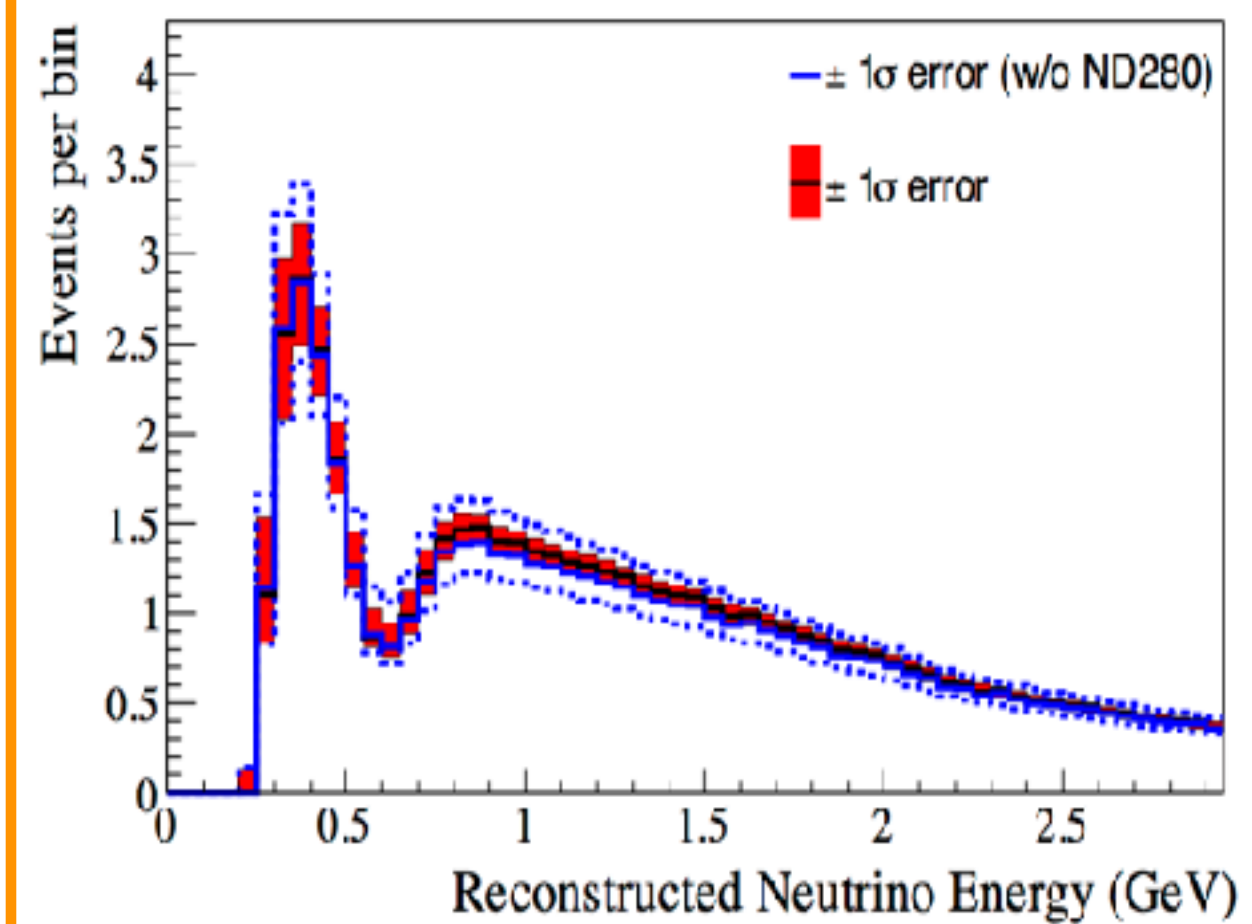
Electron Neutrino Predictions





Muon Neutrino Predictions





Systematic uncertainties

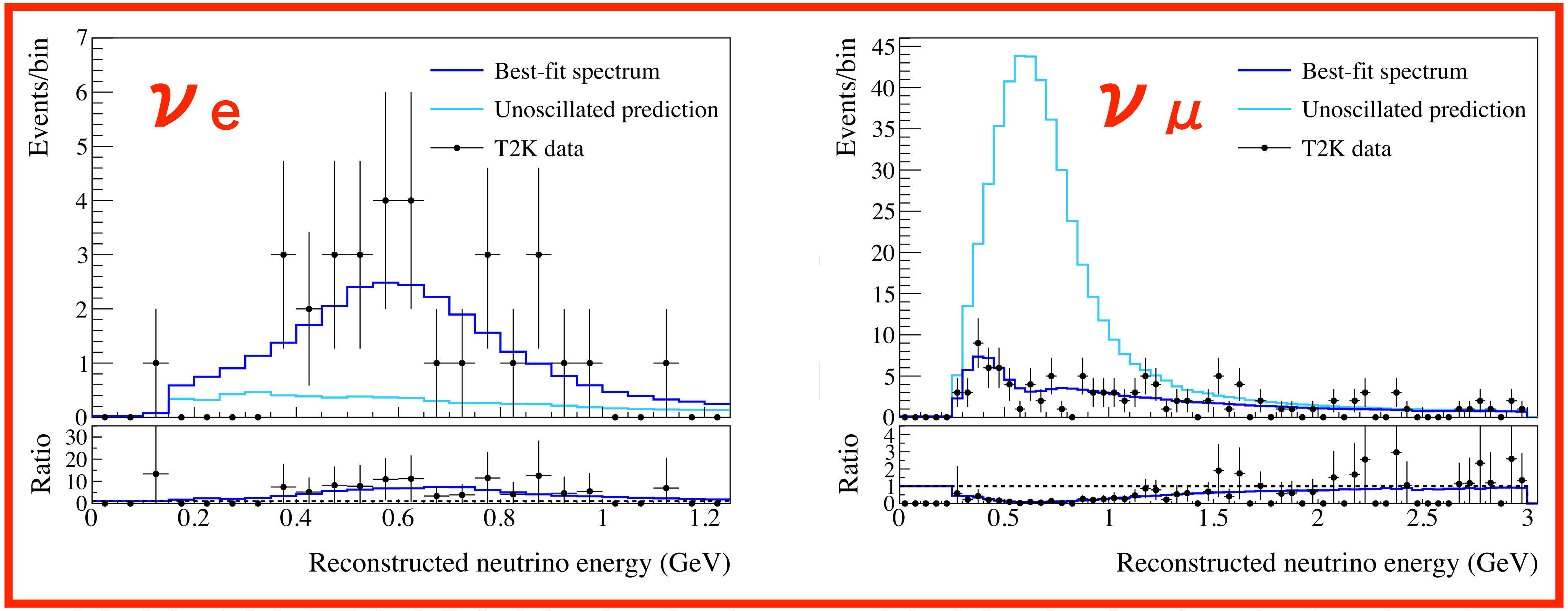
Total $\delta N_{SK}/N_{SK}$			
Beam mode	sample	ND280 constrained	W/o ND280
neutrino	μ-like	5.11%	12.02%
neutrino	e-like	5.53%	12.06%
antineutrino	μ-like	5.19%	12.88%
antineutrino	e-like	6.31%	14.06%
neutrino	CC1π^+-like	14.84%	21.84%

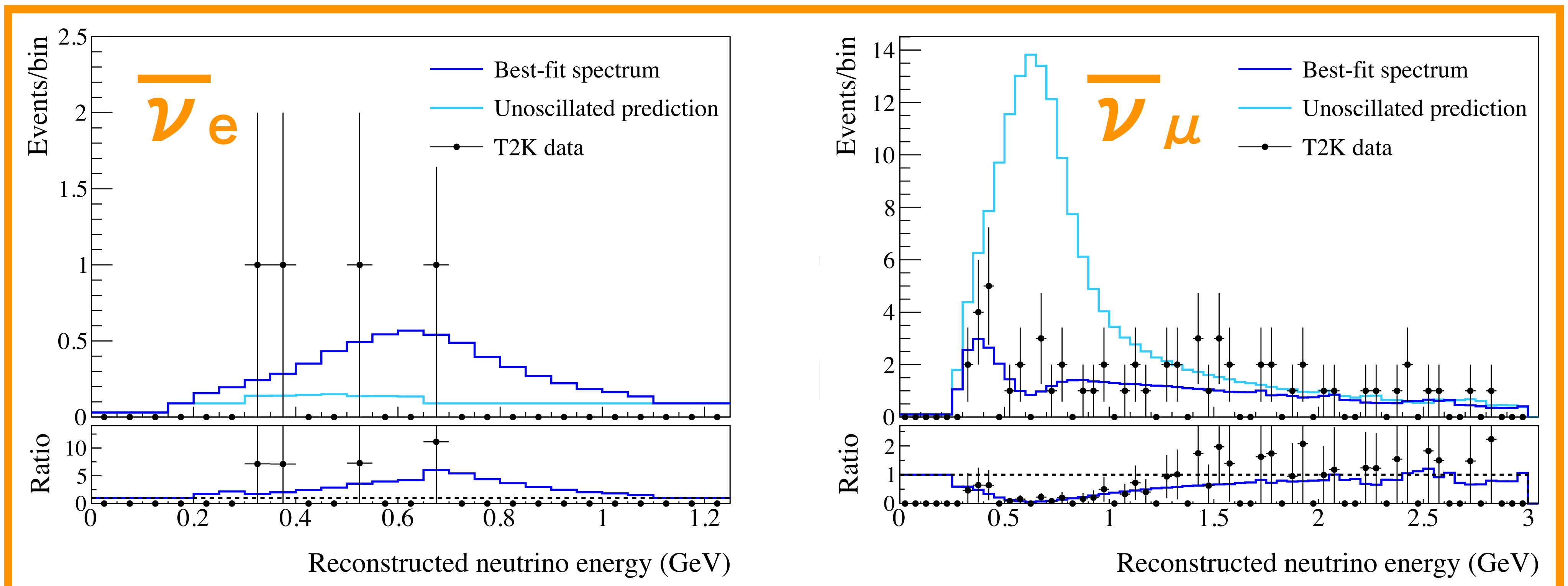
Systematic uncertainties

Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	ν_e CC1π^+ $\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross-section			
(w/o ND280 constraint)	11.3%	10.8%	16.4%
(w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI+SI+PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All			
(w/o ND280 constraint)	12.7%	12.0%	21.9%
(w/ ND280 constraint)	5.5%	5.1%	14.8%

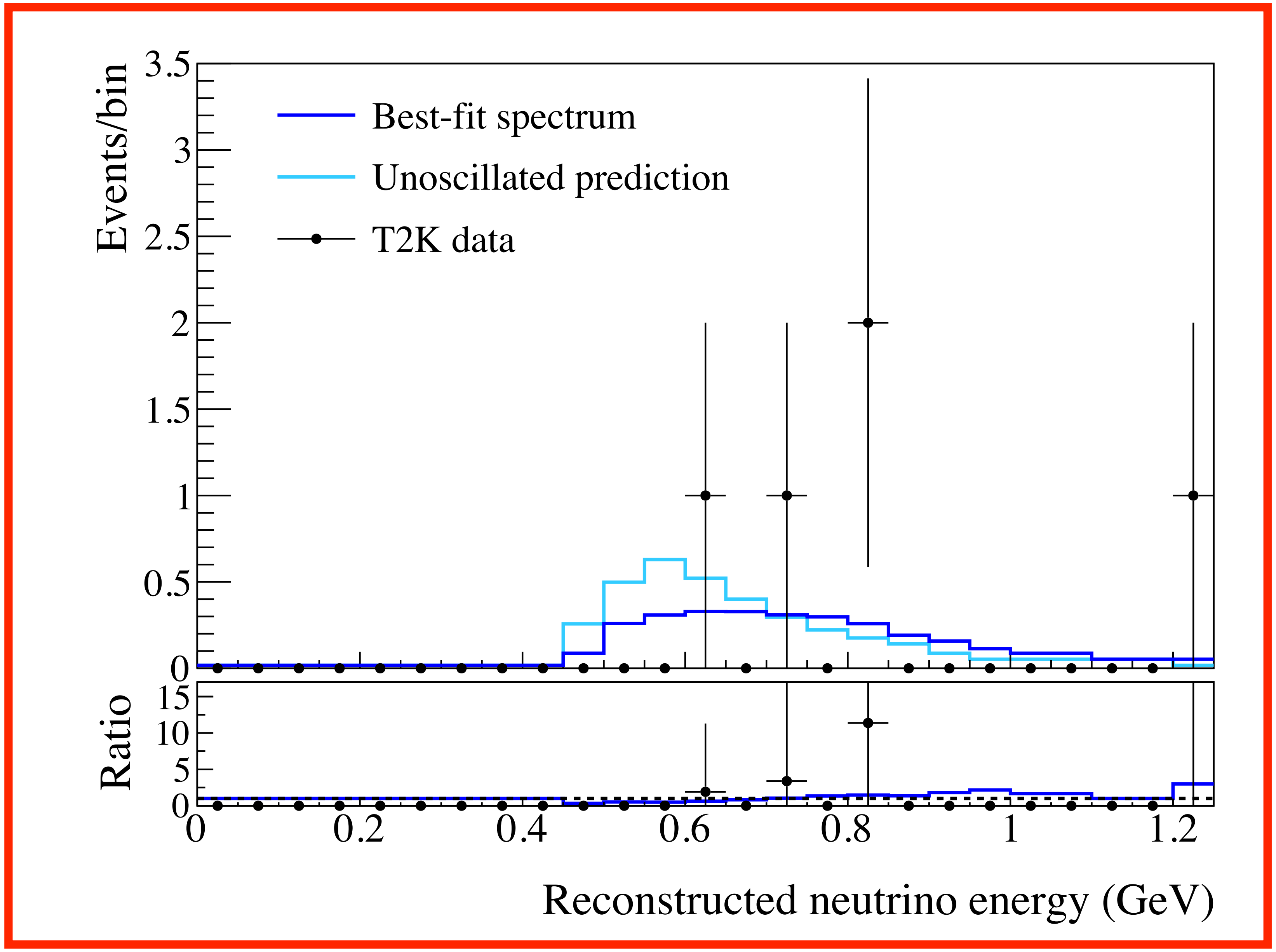
Source of uncertainty	$\overline{\nu}_e$ CCQE-like $\delta N/N$	$\overline{\nu}_\mu$ $\delta N/N$
Flux (w/ ND280 constraint)	3.8%	3.8%
Cross section (w/ ND280 constraint)	5.5%	4.2%
Flux+cross-section		
(w/o ND280 constraint)	12.9%	11.3%
(w/ ND280 constraint)	4.7%	3.5%
FSI+SI+PN at SK	3.0%	2.1%
SK detector	2.5%	3.4%
All		
(w/o ND280 constraint)	14.5%	12.5%
(w/ ND280 constraint)	6.5%	5.3%

Oscillation FIT





Oscillation FIT w/ CCν_e-1π^+

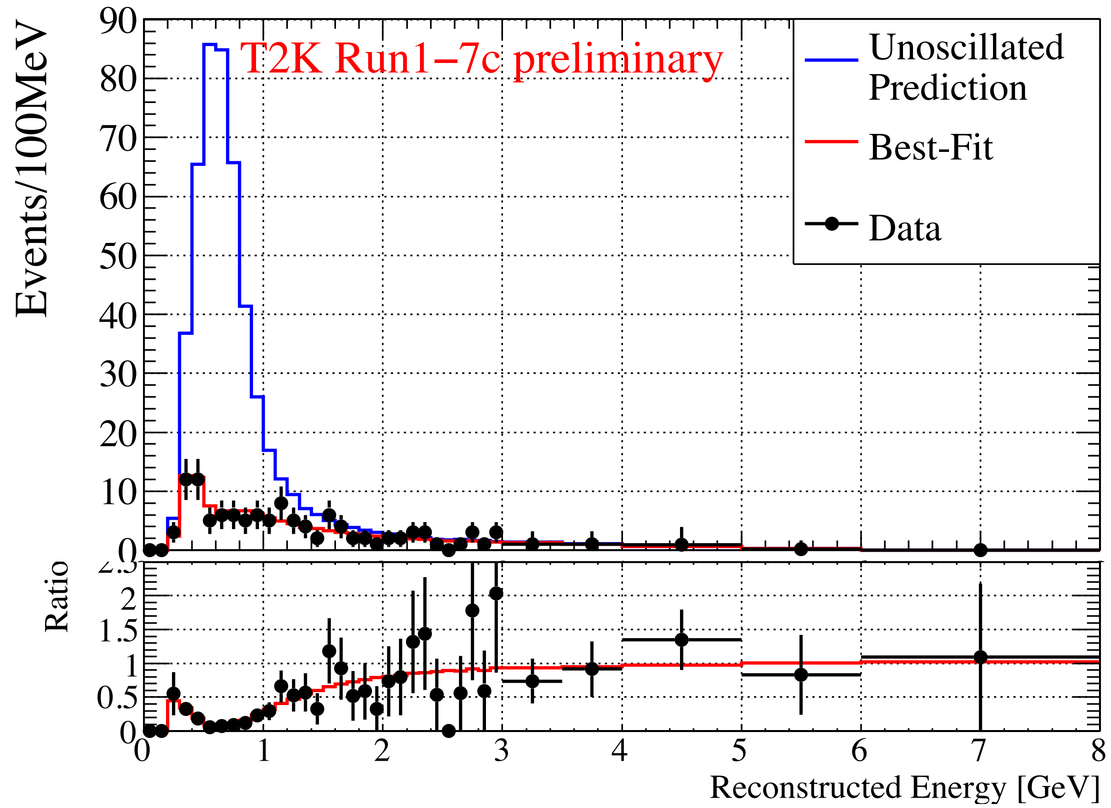


9. Latest OA results

$\nu_\mu/\bar{\nu}_\mu$ Disappearance Analysis

- CPT test by comparing $(\nu_\mu \rightarrow \nu_\mu)$ and $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ modes

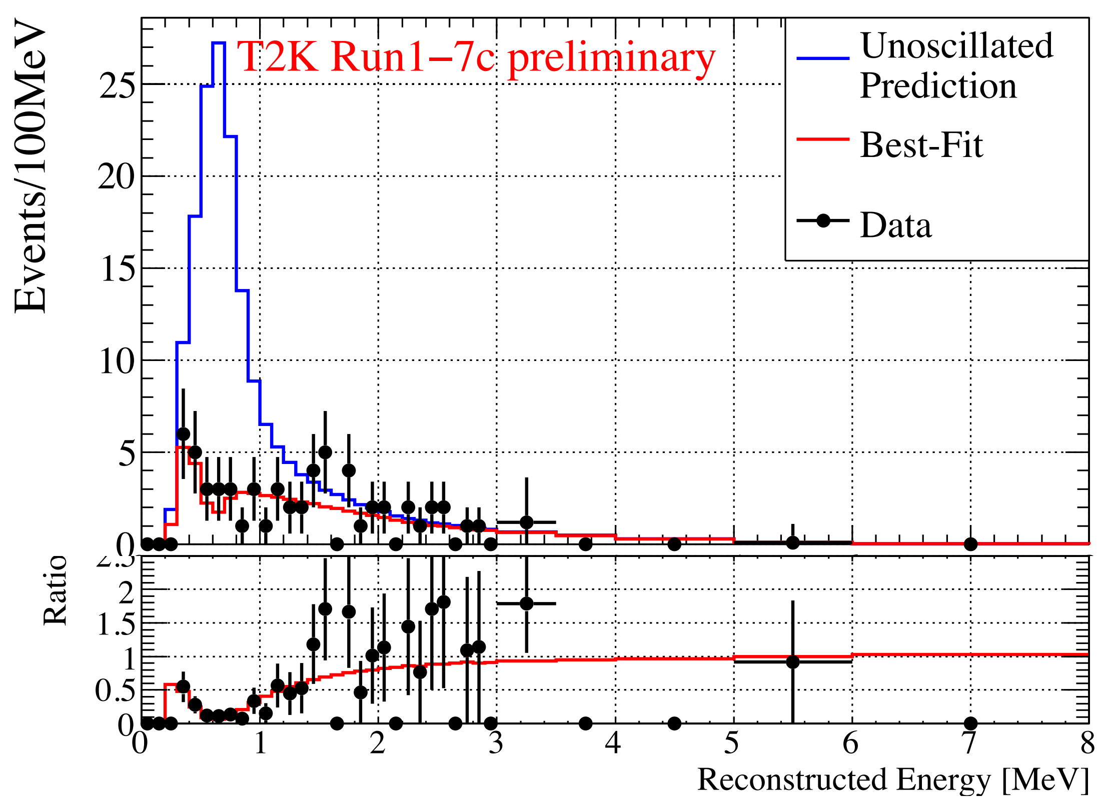
ν_μ



135 events observed

(135.8 events expected)

$\bar{\nu}_\mu$

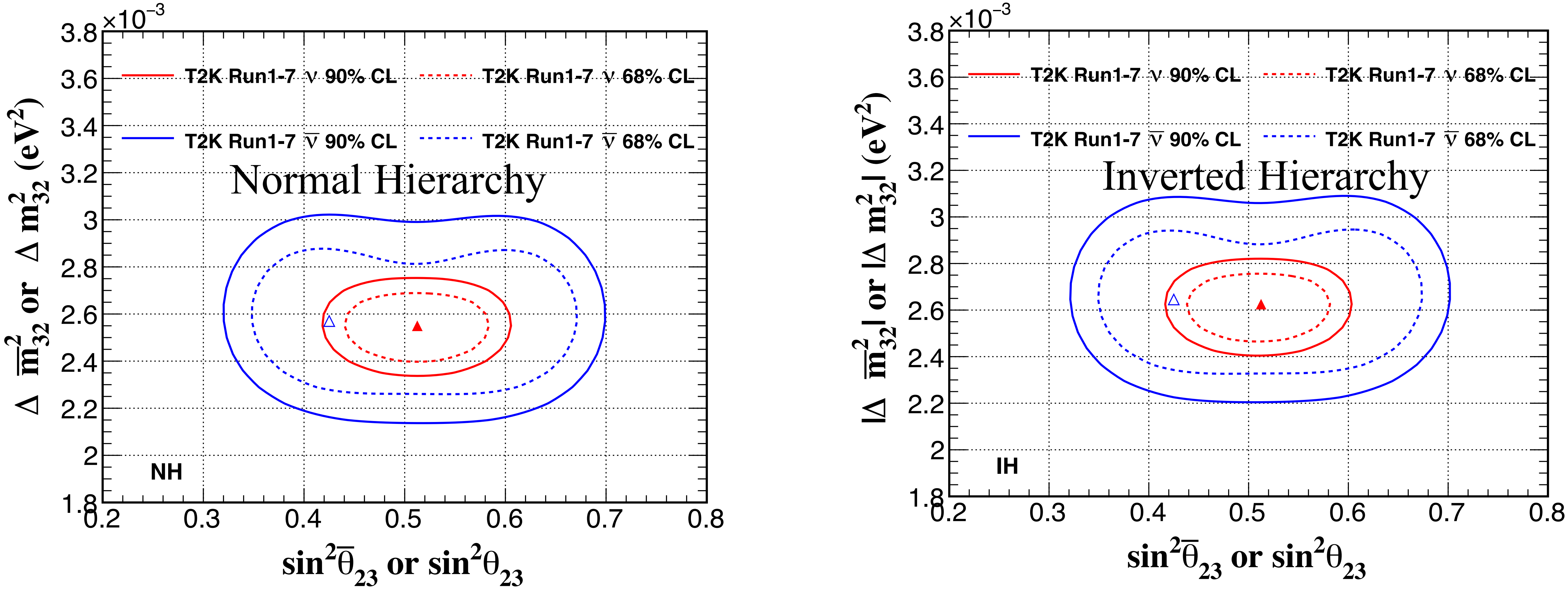


66 events observed

(64.2 events expected)

θ_{23} and Δm^2_{32} Comparison

- No hint of CPT violation



$\Delta \overline{m}^2_{32} = [2.16, 3.02]\times 10^{-3} eV^2 (NH)$ at 90% CL

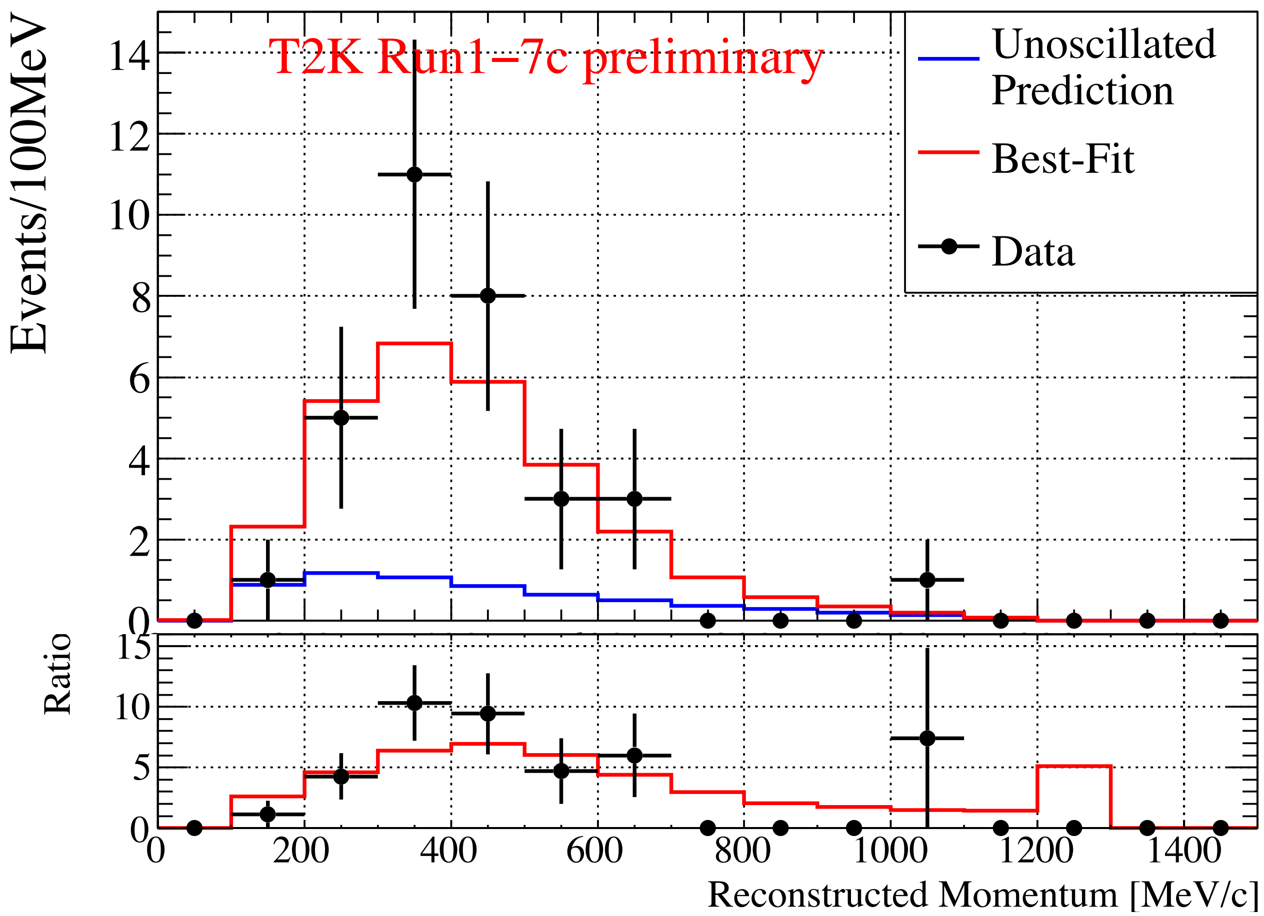
$\sin^2 \overline{\theta}_{23} = [0.32, 0.70](NH)$ at 90% CL

$\Delta m^2_{32} = [2.34, 2.75]\times 10^{-3} eV^2 (NH)$ at 90% CL

$\sin^2 \theta_{23} = [0.42, 0.61](NH)$ at 90% CL

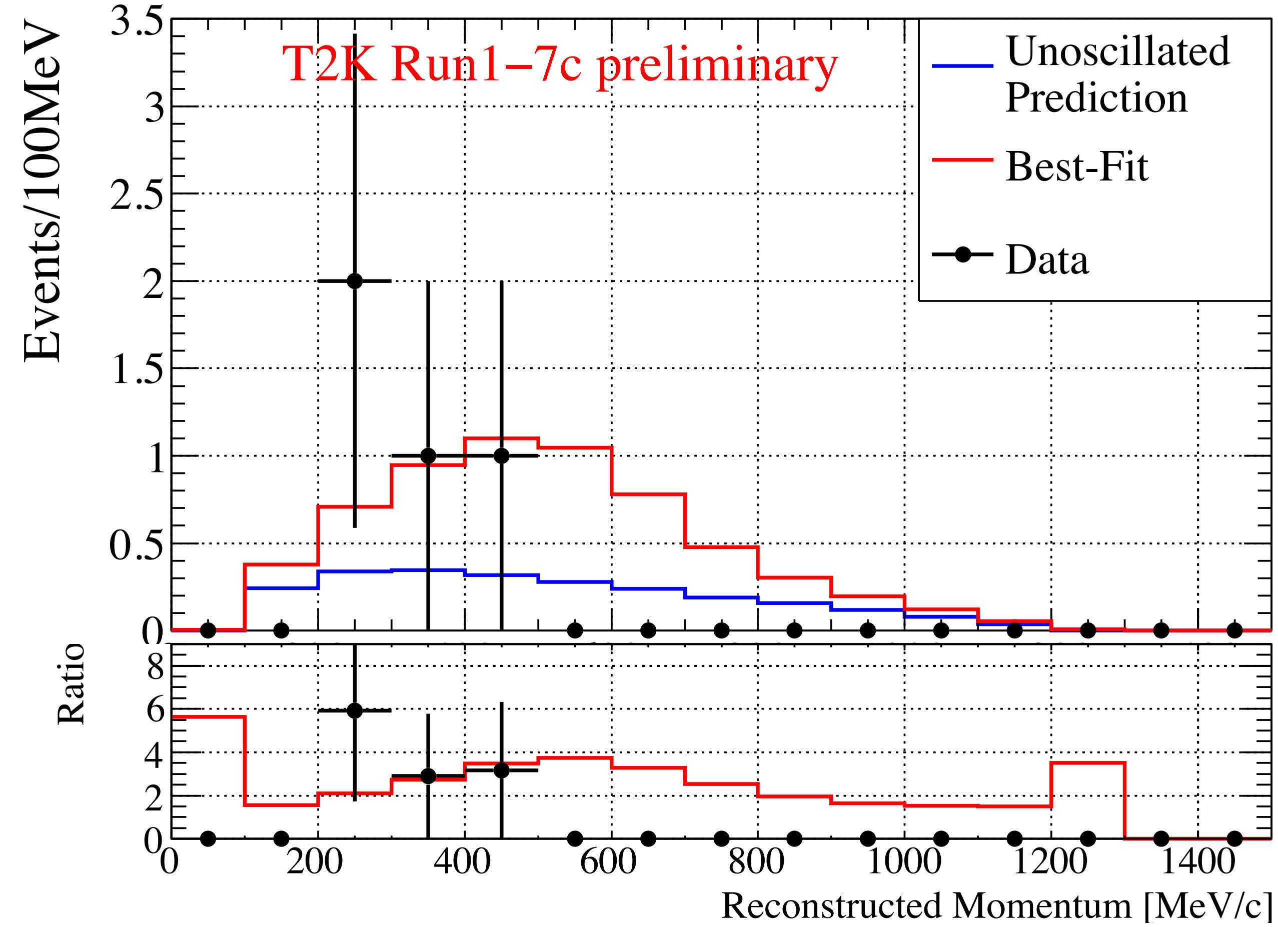
Full Joint Fit Analysis

ν_e



32 events observed

$\bar{\nu}_e$

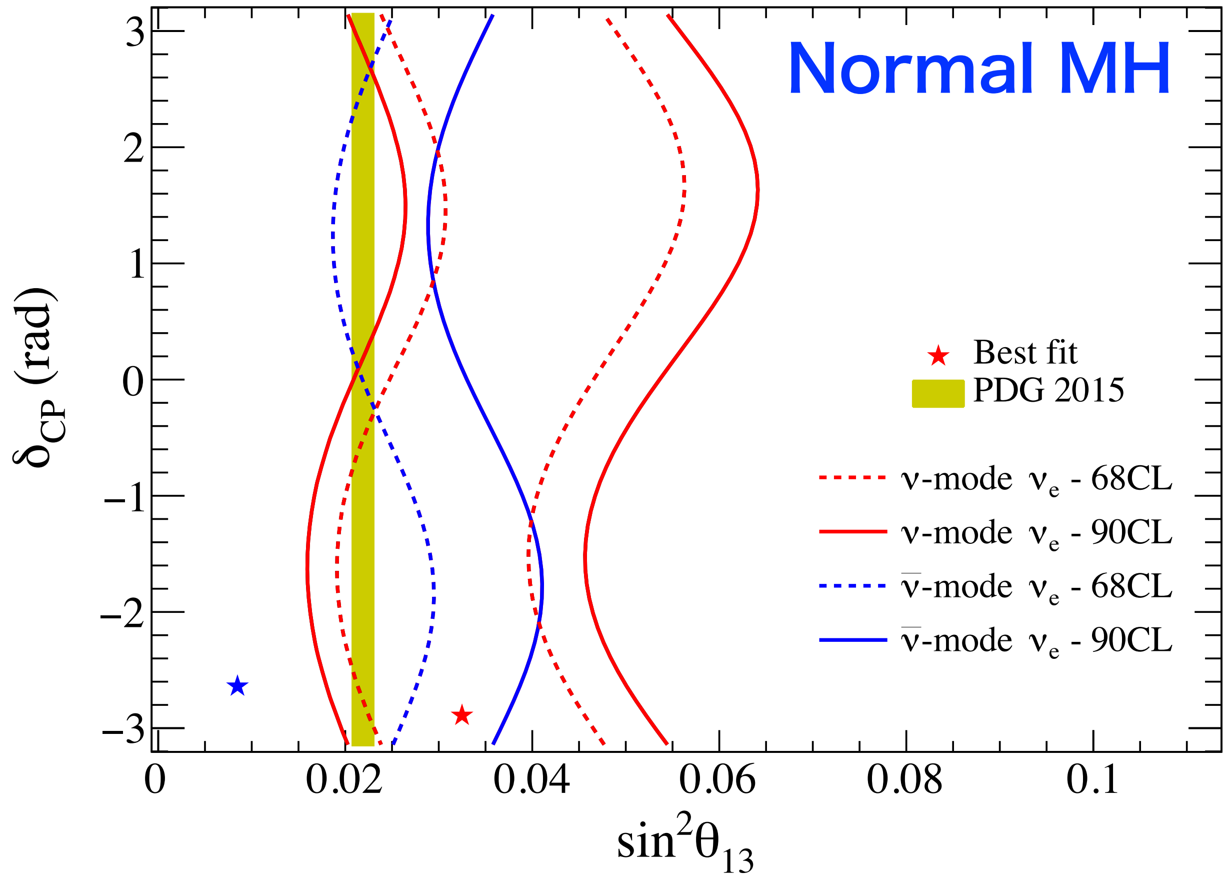


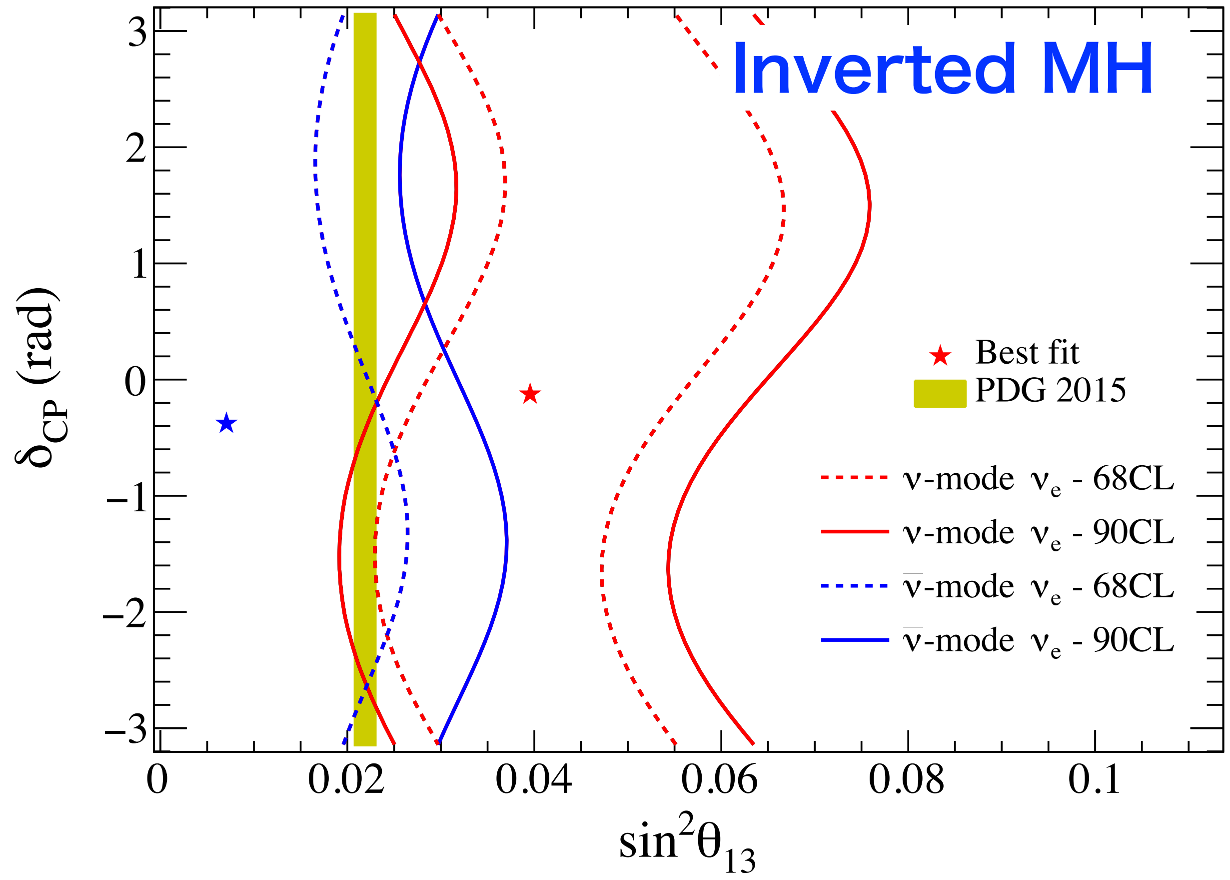
4 events observed

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

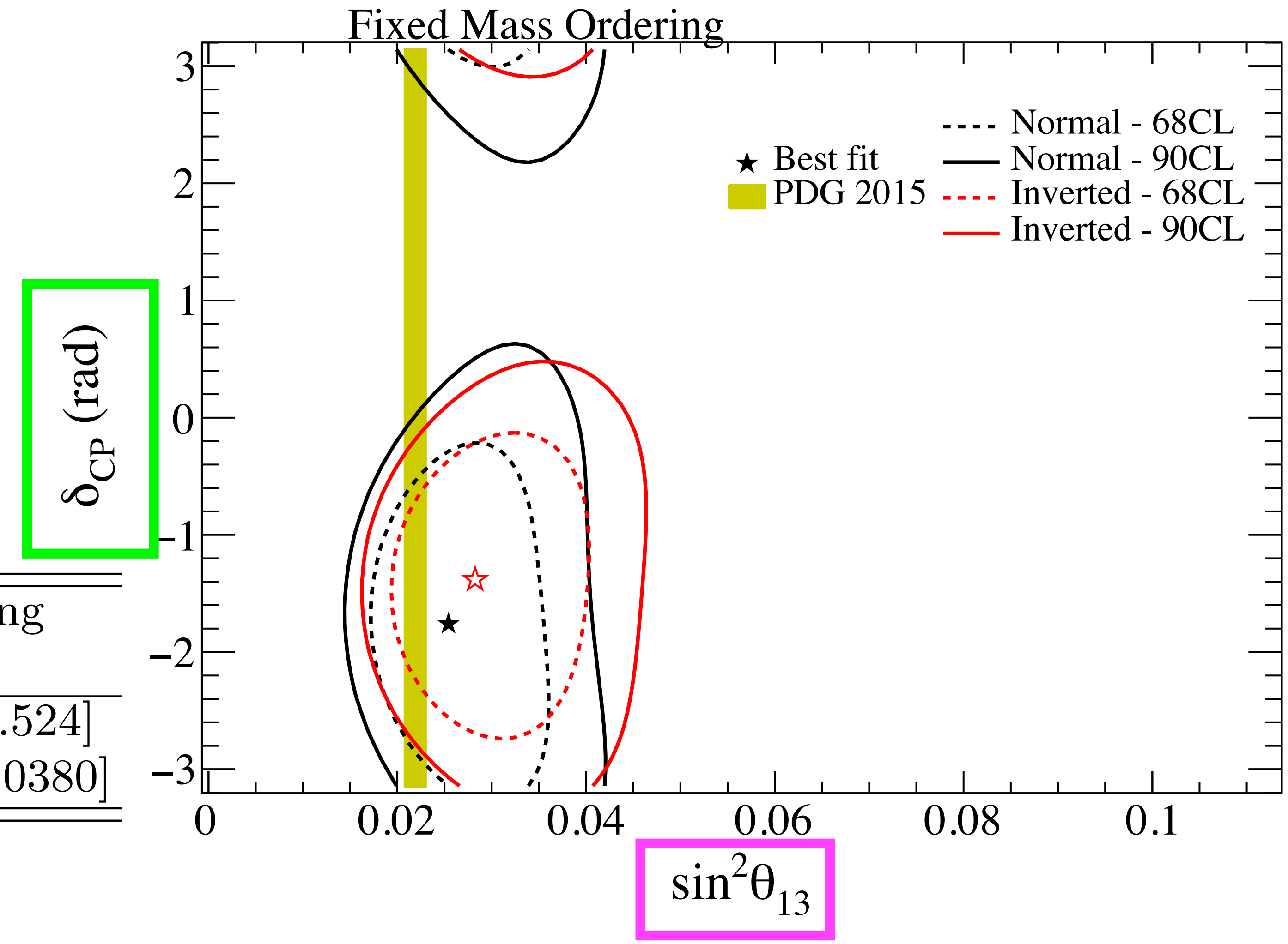
OA Fit results with T2K only data

- FIT neutrino and anti-neutrino data separately.

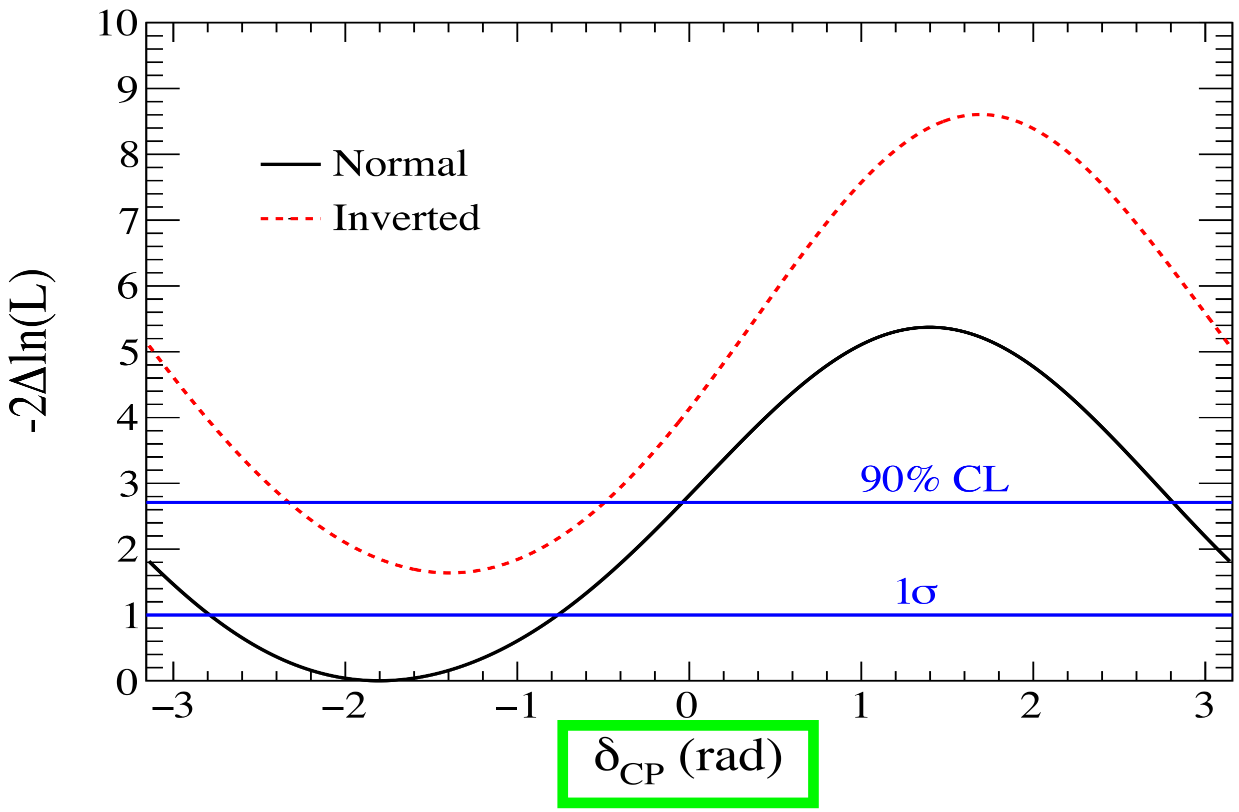


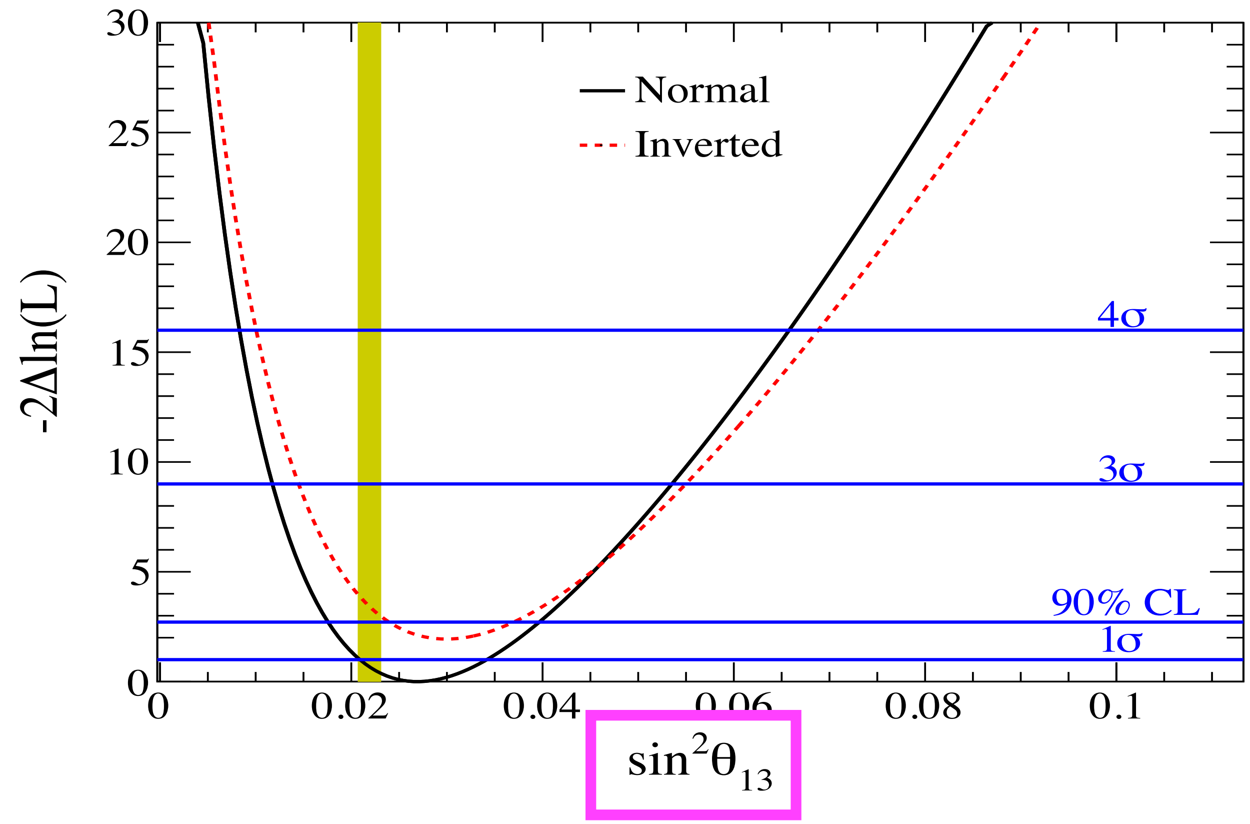


OA Fit results with T2K only data

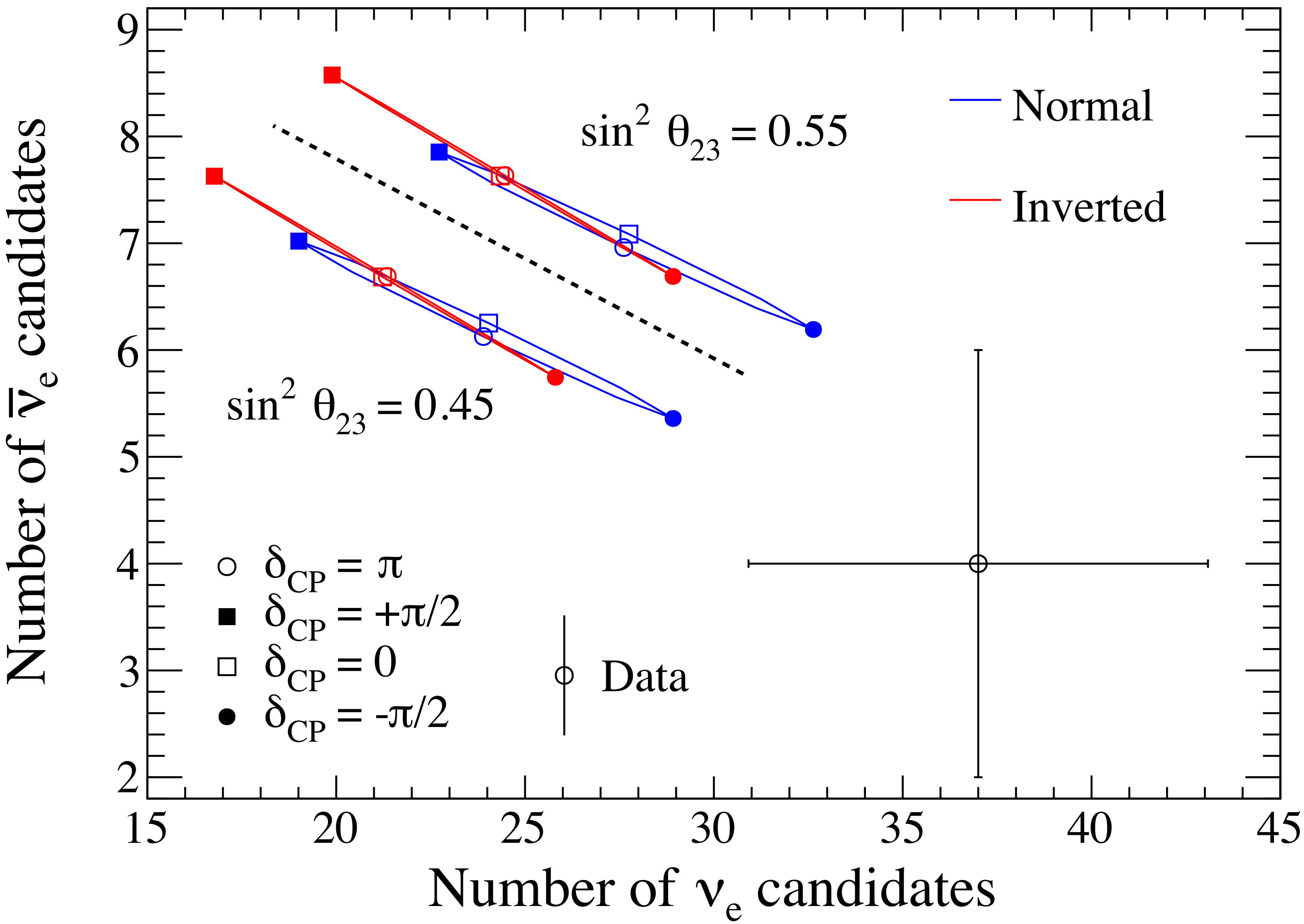


Parameter	Normal ordering		Inverted ordering	
	Best-fit	$\pm 1\sigma$	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.791	[-2.789; -0.764]	-1.382	[-2.296;-0.524]
$\sin^2\theta_{13}$	0.0271	[0.0209; 0.0342]	0.0299	[0.0232; 0.0380]



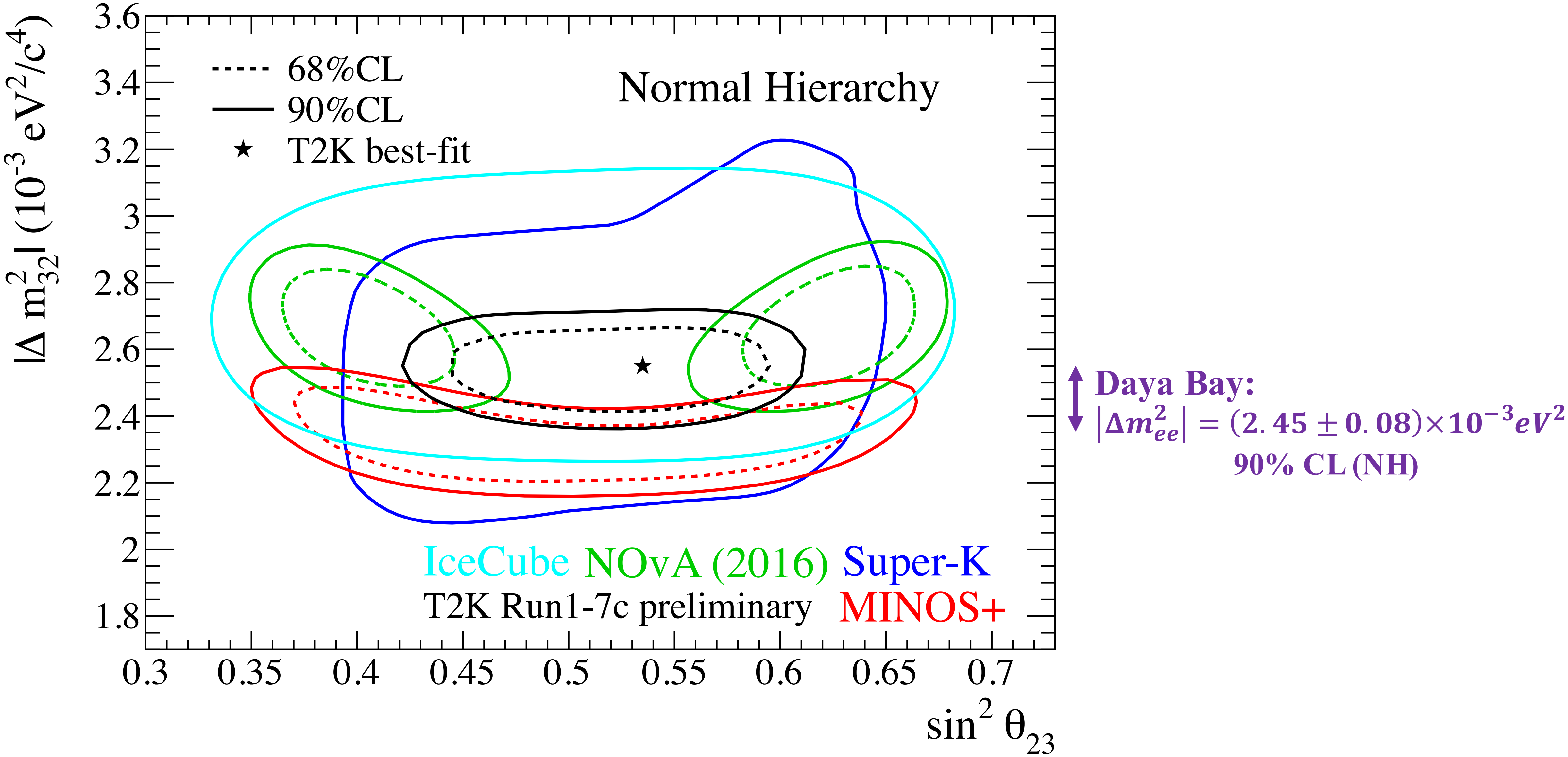


Number of events as a function of θ_{23}



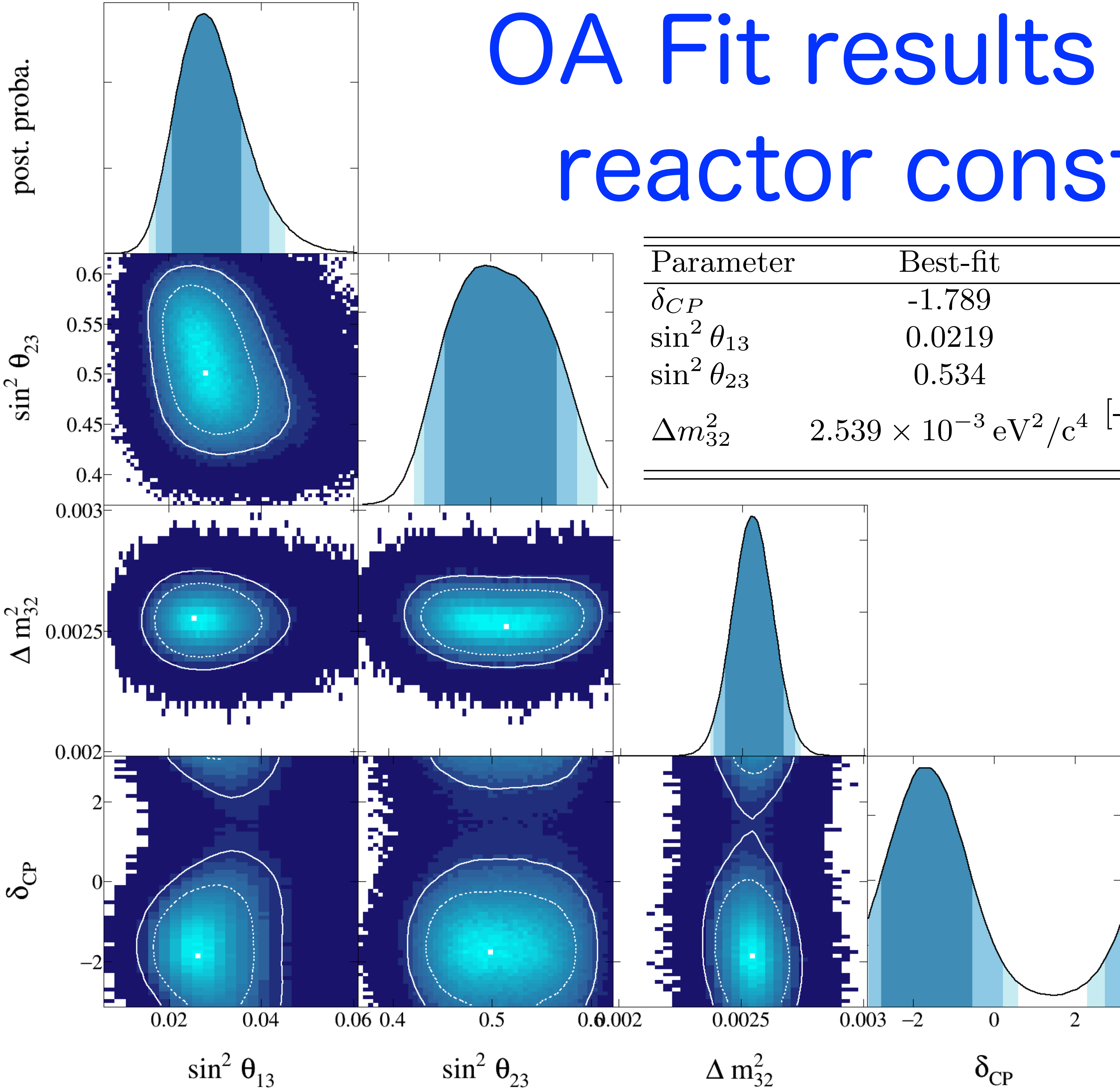
θ_{23} and Δm^2_{32}

- Consistent with maximal mixing



	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}eV^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

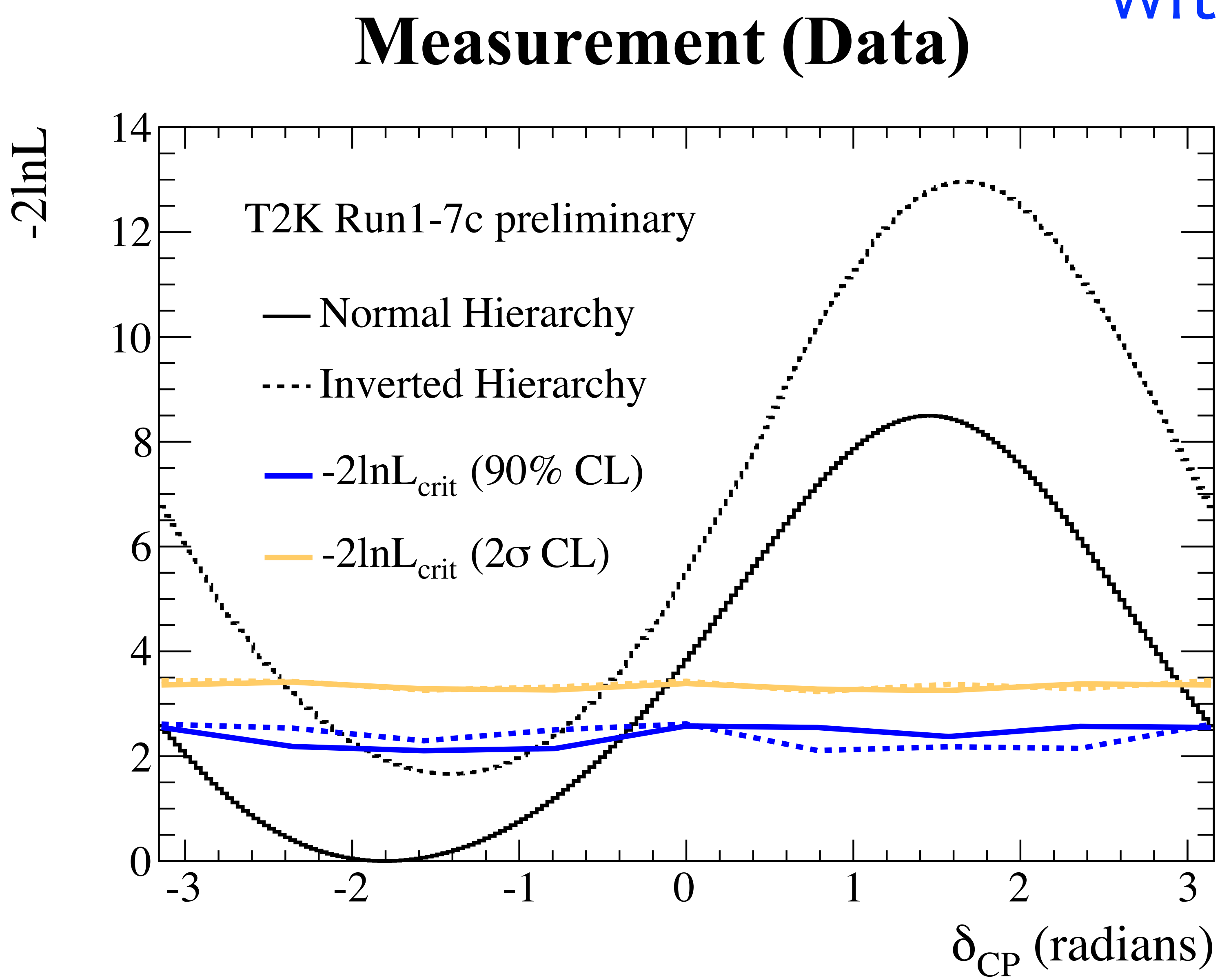
OA Fit results w/ the reactor constraint



Parameter	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.789	[-2.450; -0.880]
$\sin^2\theta_{13}$	0.0219	[0.0208; 0.0233]
$\sin^2\theta_{23}$	0.534	[0.490 ; 0.580]
Δm^2_{32}	$2.539\times 10^{-3}\,\mathrm{eV}^2/\mathrm{c}^4$	[-3.000; -2.952] $\times 10^{-3} eV^2/c^4$ [2.424; 2.664] $\times 10^{-3} eV^2/c^4$

δ_{CP} with reactor θ_{13}

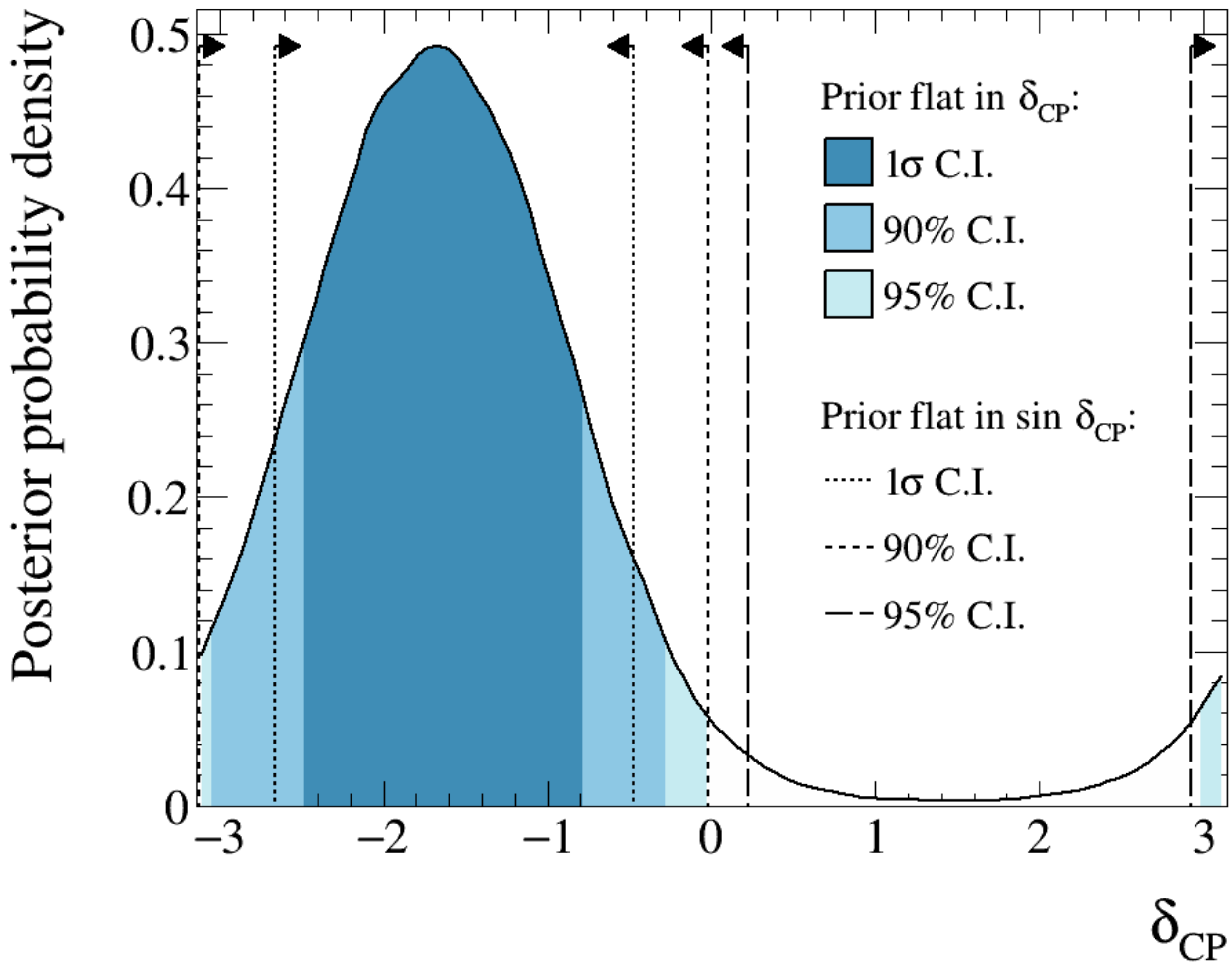
with $\sin^2 2\theta_{13}$=0.085±0.005



True: $\delta_{CP} = -\pi/2$ — normal ordering			
δ_{CP}	Ordering	90% CL	2σ CL
0	Normal	0.243	0.131
π	Normal	0.216	0.105
0	Inverted	0.542	0.425
π	Inverted	0.559	0.436
True: $\delta_{CP} = 0$ — normal ordering			
δ_{CP}	Ordering	90% CL	2σ CL
0	Normal	0.104	0.0490
π	Normal	0.130	0.0591
0	Inverted	0.229	0.137
π	Inverted	0.205	0.122
True: $\delta_{CP} = -\pi/2$ — inverted ordering			
δ_{CP}	Ordering	90% CL	2σ CL
0	Normal	0.124	0.0515
π	Normal	0.102	0.0413
0	Inverted	0.290	0.194
π	Inverted	0.308	0.207

- A constraint of neutrino CPV at 90% CL
  - δ_{CP} = [-3.13, -0.39] (NH), [-2.09, -0.74] (IH) at 90% CL

Posterior probability on δ_{CP}



Posterior probabilities for the mass ordering and $\sin^2\theta_{23}$

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line Total
Inverted ordering	0.060	0.152	0.212
Normal ordering	0.235	0.553	0.788
Column total	0.295	0.705	1

10. Future Prospect

Seamless program to ν CPV

From T2K to T2K-II and Hyper-Kamiokande

CP Violation Sensitivity in T2K-II

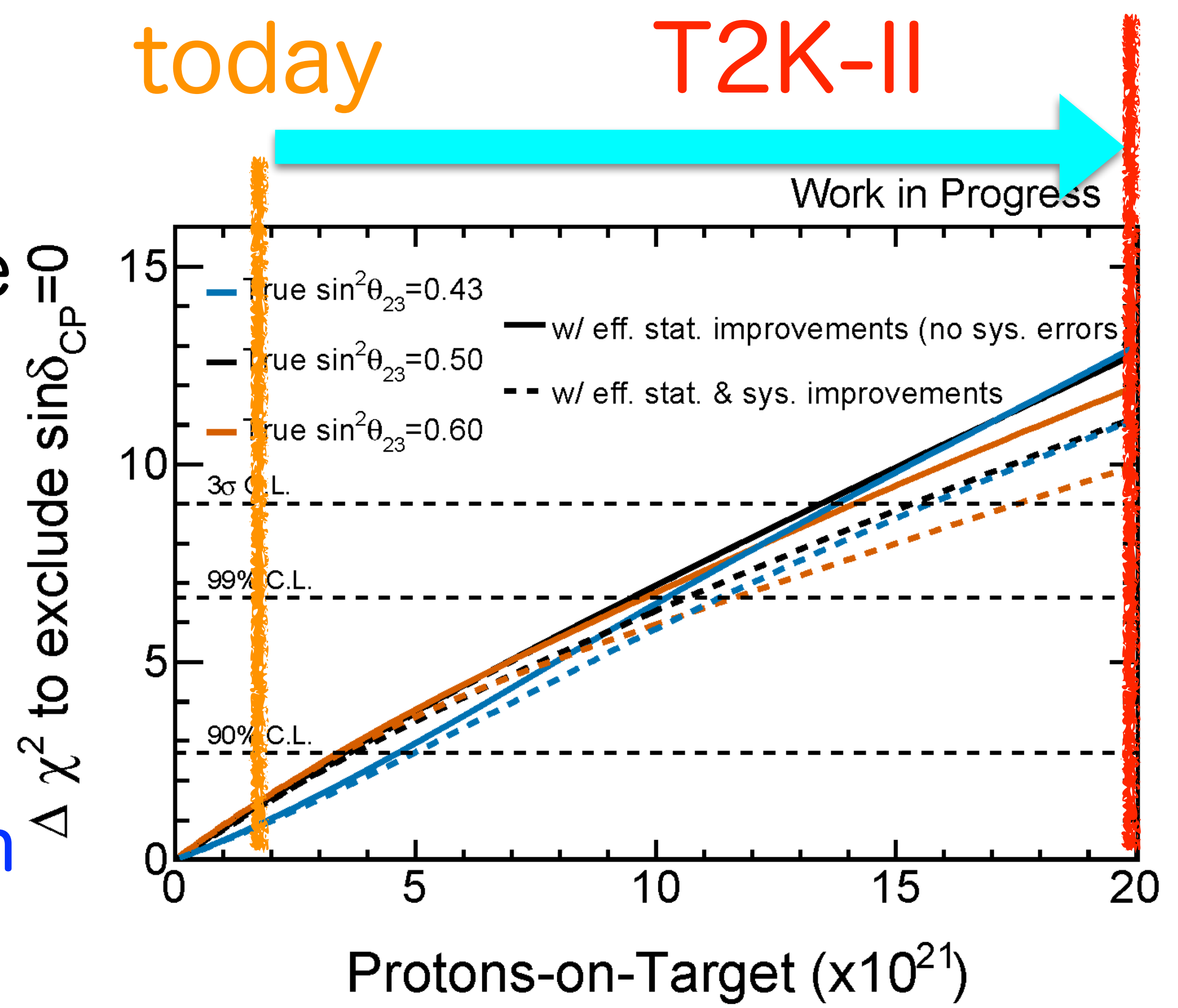
T2K-II w/ improved stat. (10E21 POT for nu and 10E21 POT for anti-nu)

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

3σ sensitivity to CP violation for favorable parameters based on

- 20×10^{21} Protons on Target with the upgrade of J-PARC to 1.3MW (~10 year long run) before year 2026.

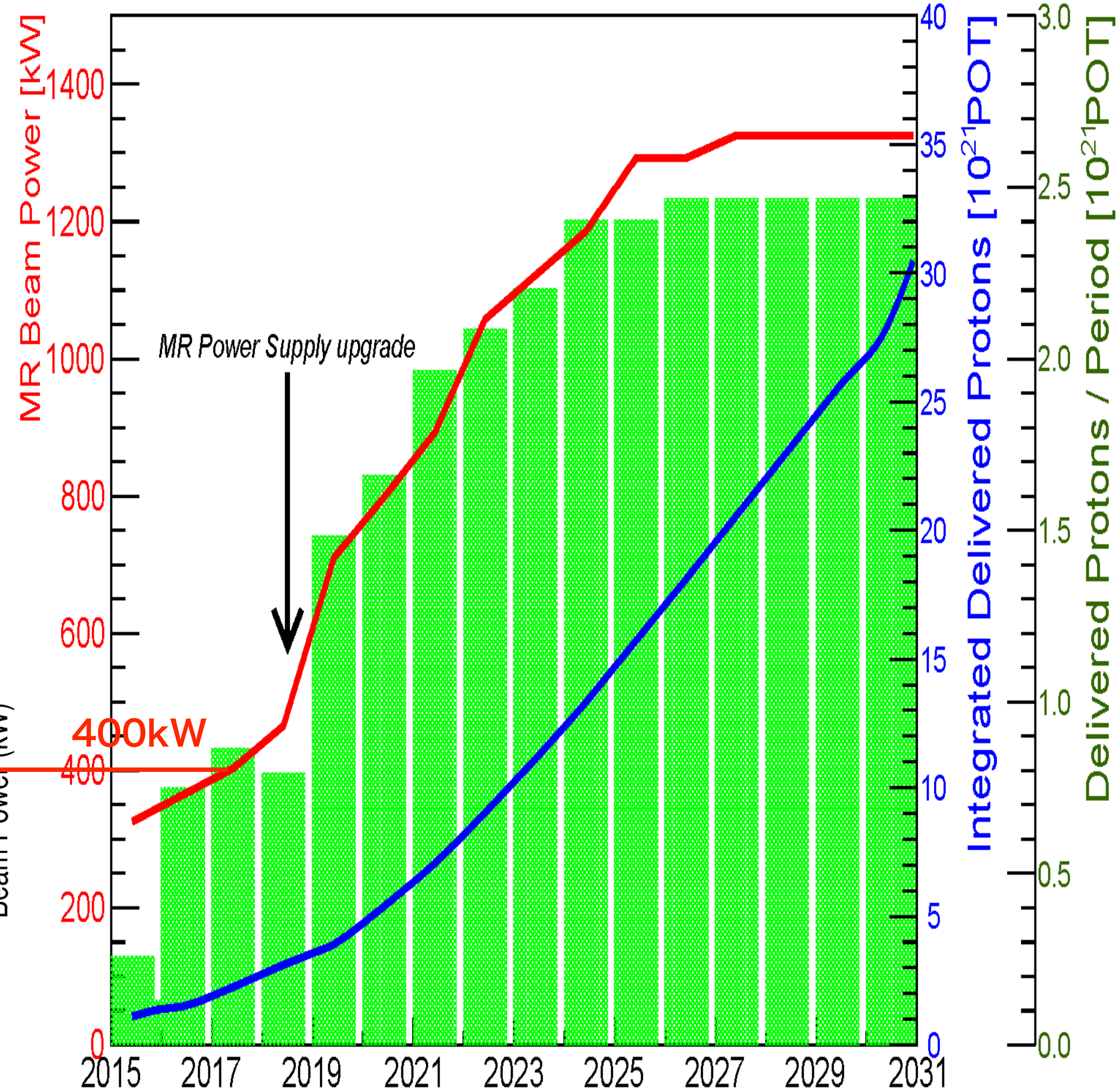
J-PARC PAC gives Stage 1 approval.
We are preparing the Technical Design Report.



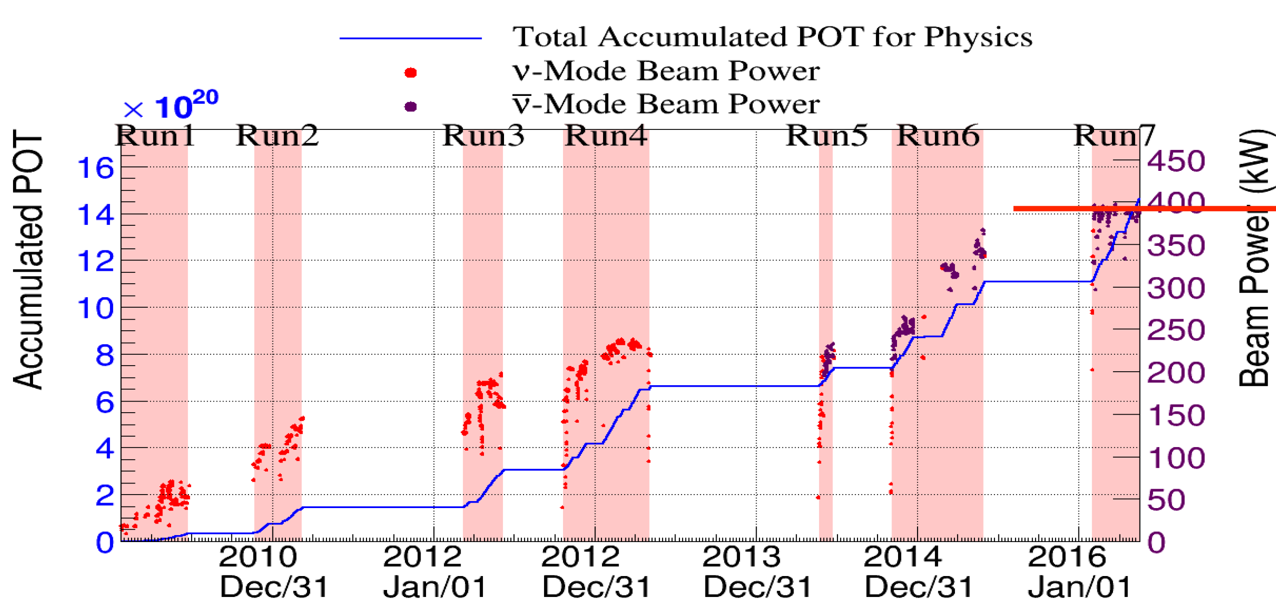
Accelerator Improvement

- J-PARC MR has achieved **420 kW** operation
- **MR Power Supply Upgrade** is scheduled on 2018.
- J-PARC demonstrated 3.41E13 ppb operation [1 MW equivalent]
- After the upgrade, the aim is **1.3MW or higher**.

T2K-II to Hyper-K



Today



T2K

T2K-II

Hyper-K

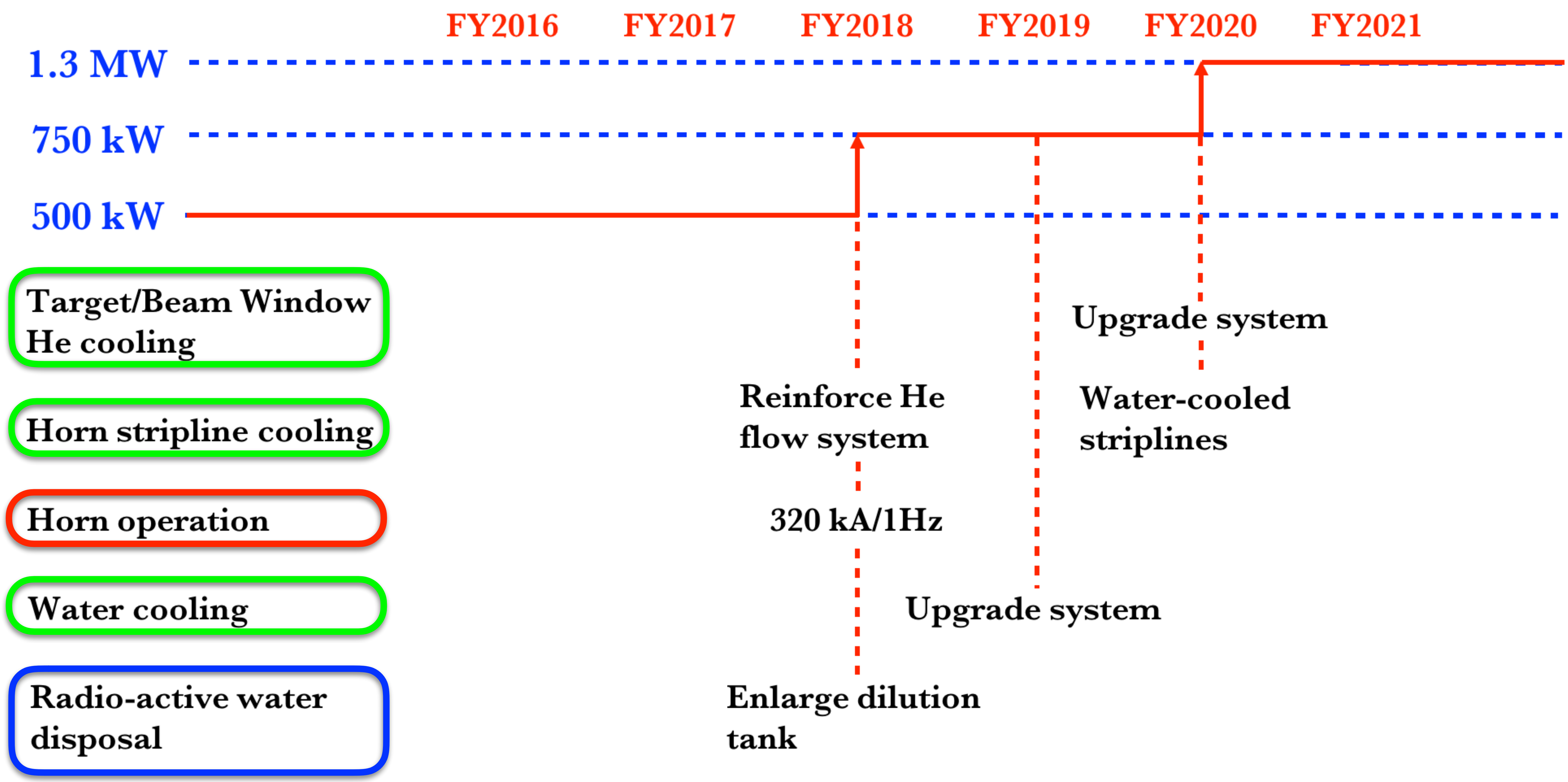
J-PARC Secondary Beamline Upgrades

However, need upgrades to improve cooling capacity, radiation containment, and irradiated cooling water disposal for 1+ MW

Component	Limiting Factor	Current Acceptable Value	Upgraded Acceptable Value
Target	Thermal Shock	3.3×10^{14} ppp	3.3×10^{14} ppp
	Cooling Capacity	0.75 MW	$>$1.5 MW
Horn	Conductor Cooling	2 MW	2 MW
	Stripline Cooling	0.54 MW	$>$1.25 MW
	Hydrogen Production	1 MW	$>$1 MW
	Operation	2.48 s & 250 kA	1 s & 320 kA
He Vessel	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	$>$1.5 MW
Decay Volume	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	$>$1.5 MW
Beam Dump	Thermal Stress	3 MW	3 MW
	Cooling Capacity	0.75 MW	$>$1.5 MW
Radiation	Radioactive Air Disposal	1 MW	$>$1 MW
	Radioactive Water	0.5 MW	0.75$\rightarrow$1.3 or 2 MW

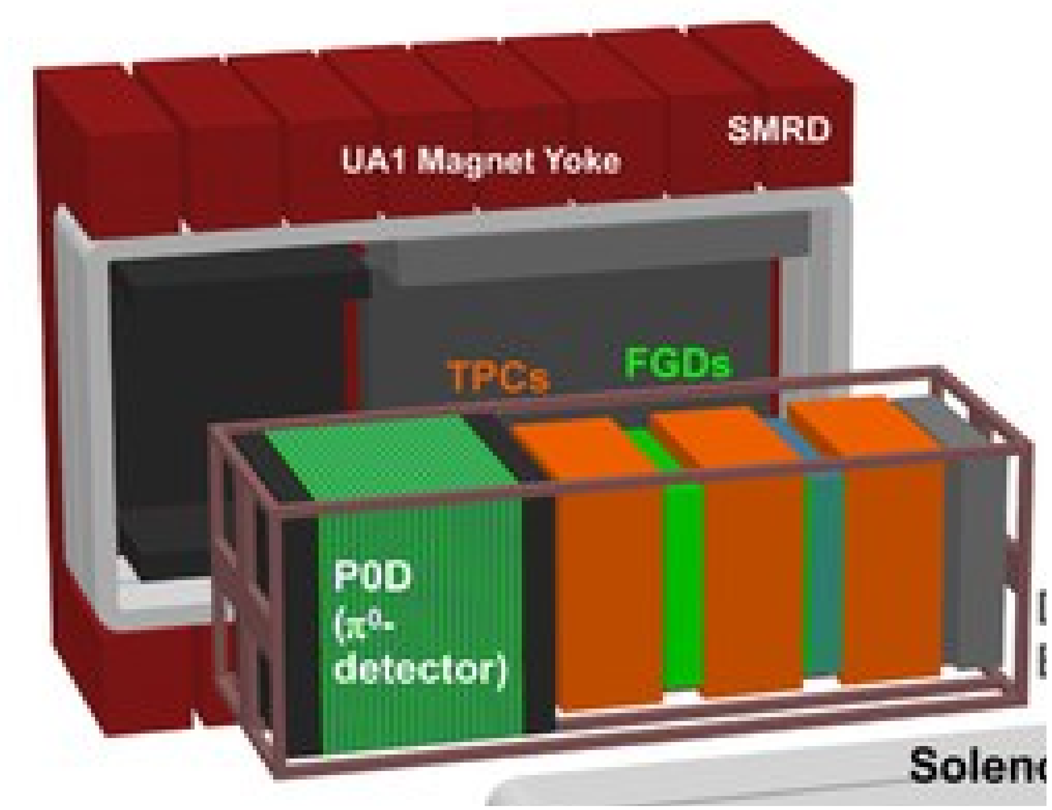
Improvement of Neutrino Flux with Upgrade

- 320kA horn current, Radio-active water disposal, cooling, cooling, and cooling
  - +10% more neutrino flux expected

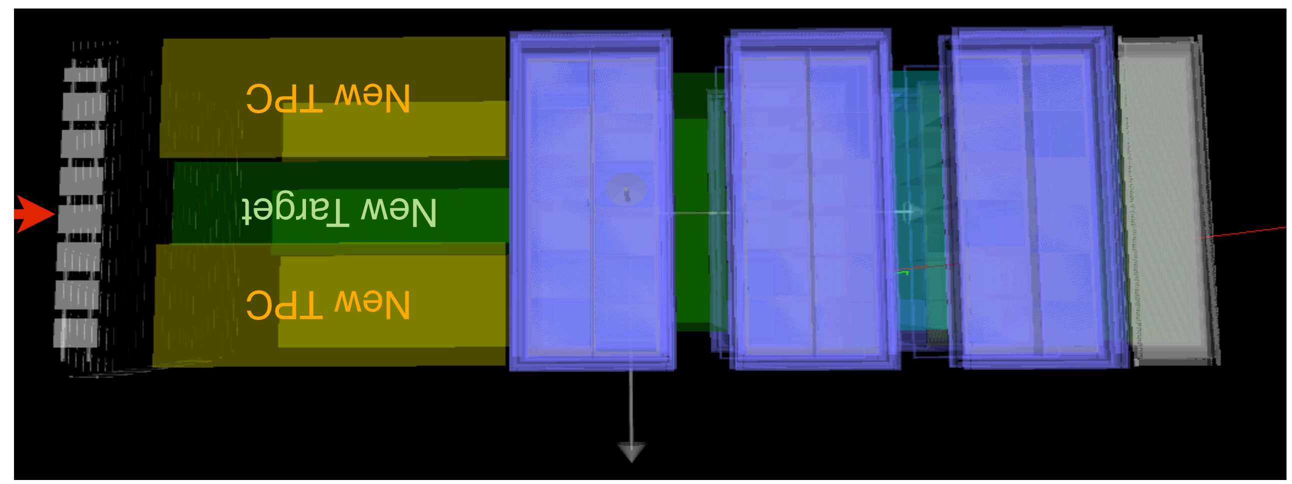


Near Detector Upgrade

ND280 (NOW)



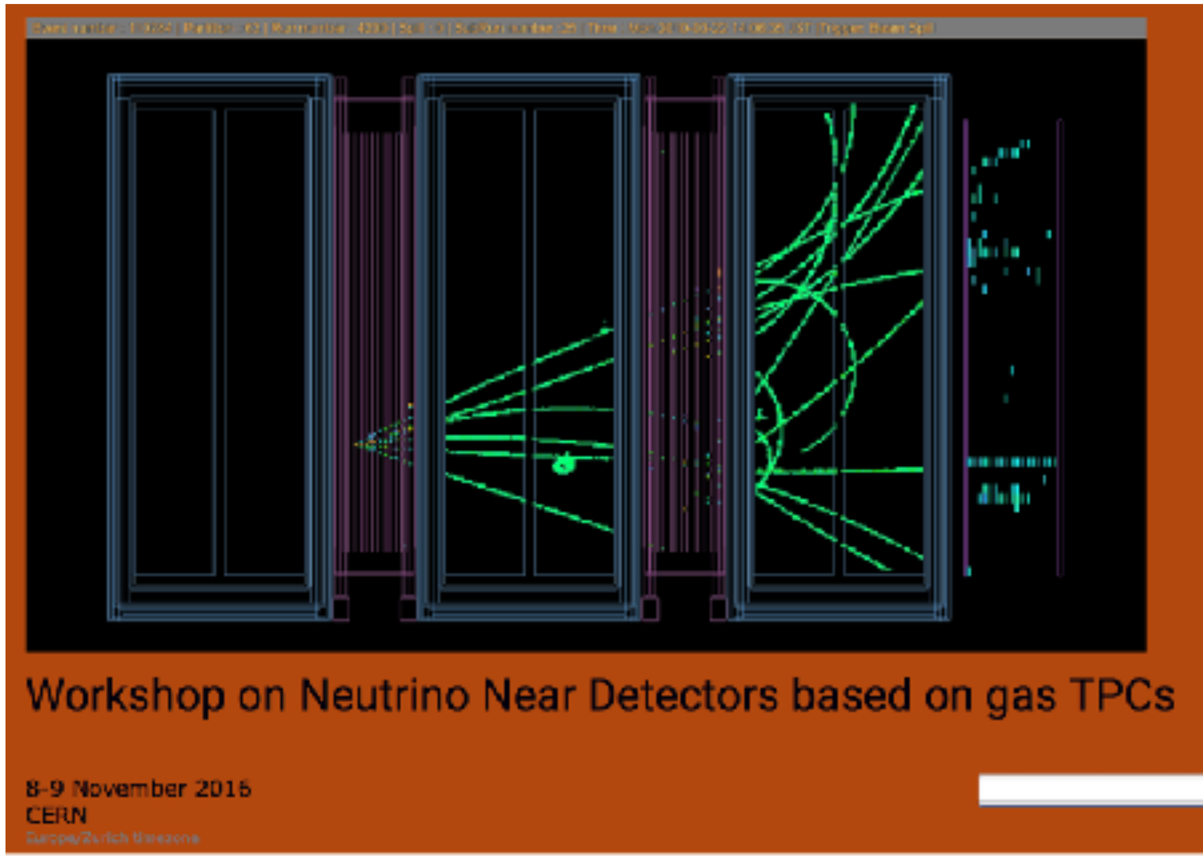
ND280 (Upgrade)



This is just an image, and the details are under discussions in the T2K collaboration.

- T2K steadily improves the systematic uncertainty.
  - **~18% (2011) → ~9% (2014) → ~6% (2016) [→ ~3% (2020)]**
- Understanding of Neutrino Interactions is essential for future experiments (T2K-II and Hyper-K)

Systematic errors

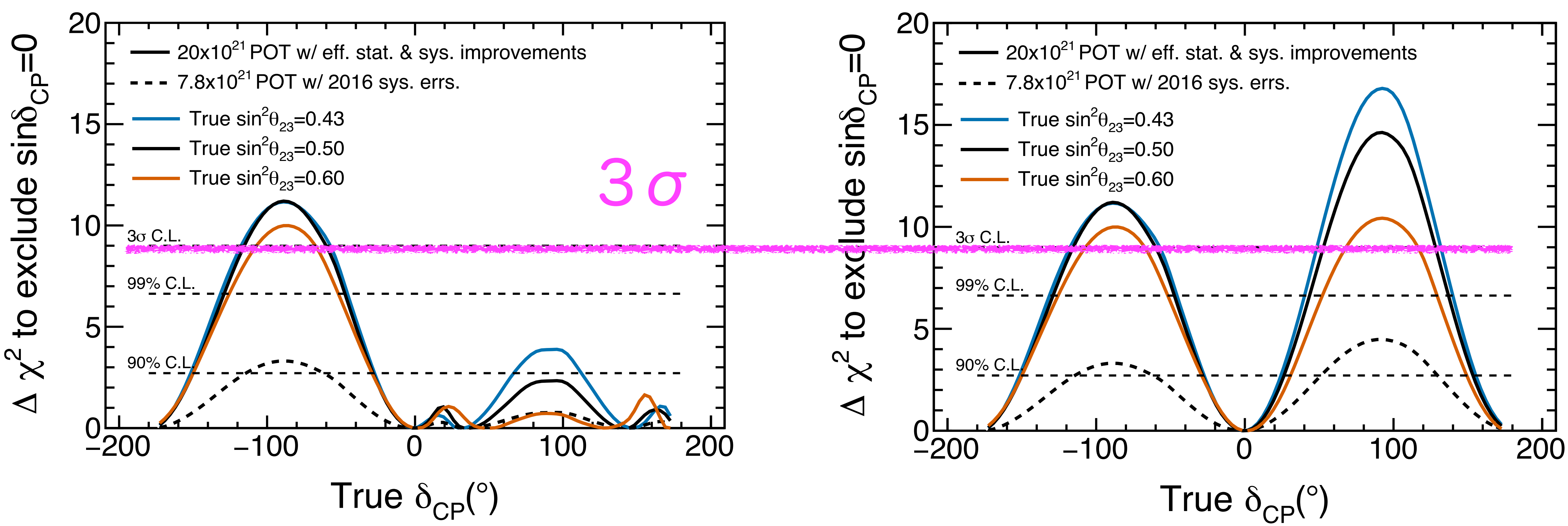


- Neutrino Interactions
  - We will improve the near detector performance
    - with the better efficiency (and purity)
    - with the lower threshold to detector all hadrons, mainly protons.
  - A plan is to install new horizontal TPCs which will be developed by utilizing the CERN neutrino plat form.

T2K-II Physics Sensitivity

- For which true δ_{CP} values can we find CP violation assuming true $\sin^2\theta_{23}$=0.43, 0.50, 0.60?
  - The fractional region for which $\sin\delta_{CP}$=0 can be excluded at the 99% (3σ) C.L. is 49% (36%) of possible true values of δ_{CP} assuming the MH is known.

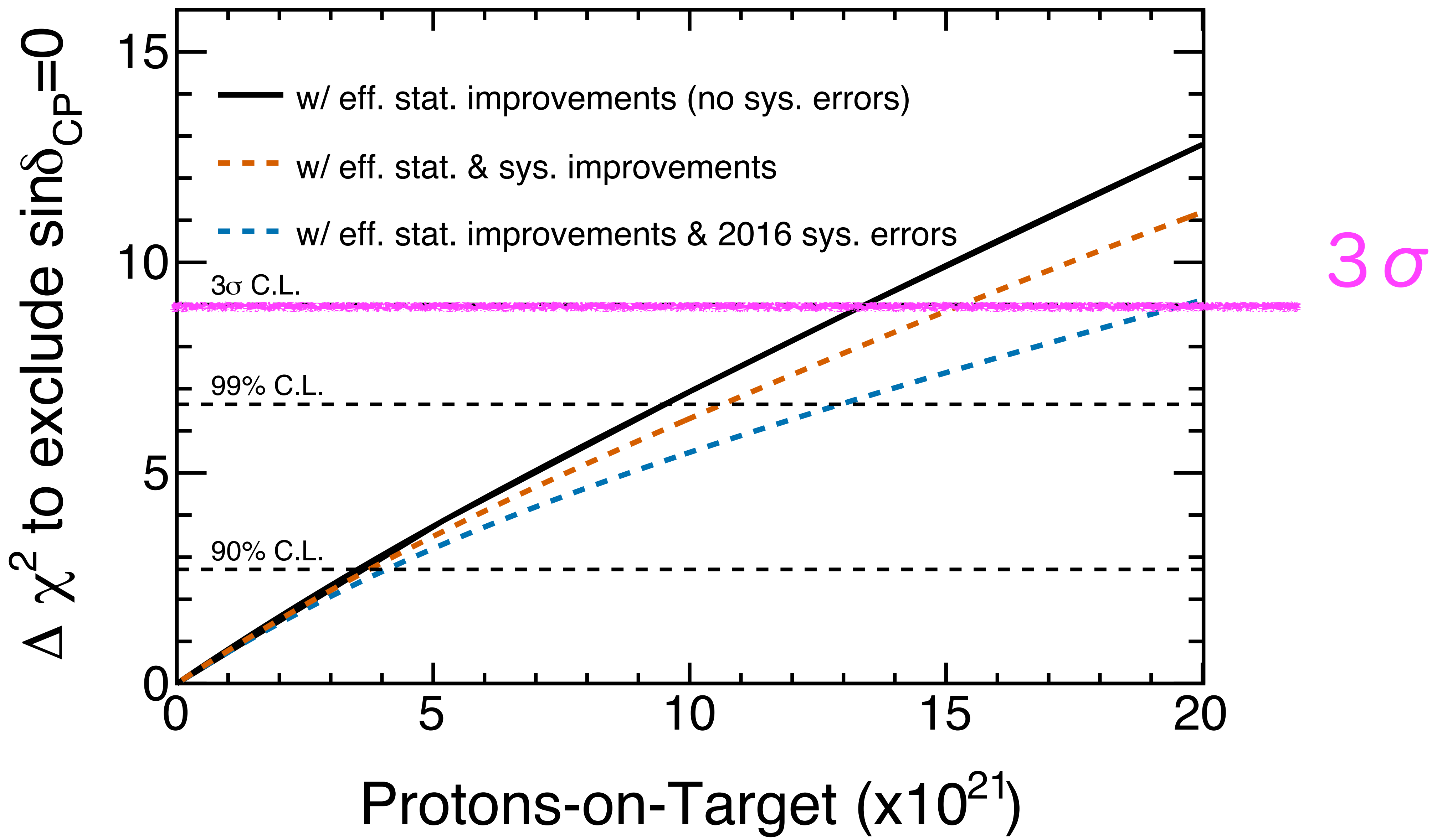
assuming MH unknown   assuming MH known



(Note) Although T2K alone can't measure MH, we can help with the MH measurement by, ie, combining T2K + NOVA

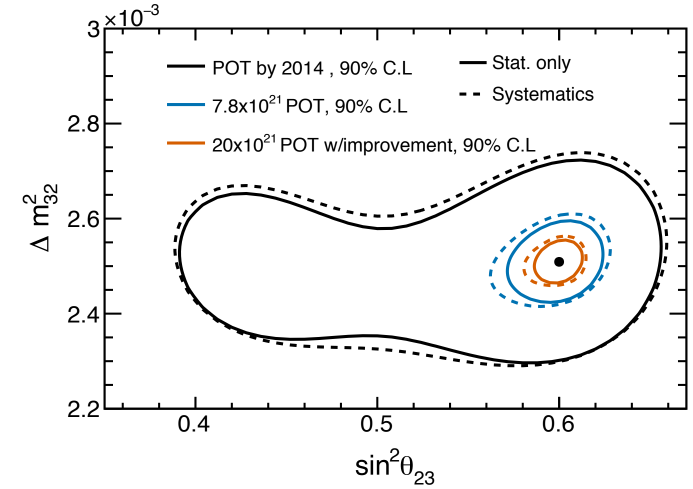
T2K-II Physics Sensitivity

- As a function of POT in the case of $\sin^2\theta_{23}$=0.5, δ_{CP}=-π/2 and normal MH

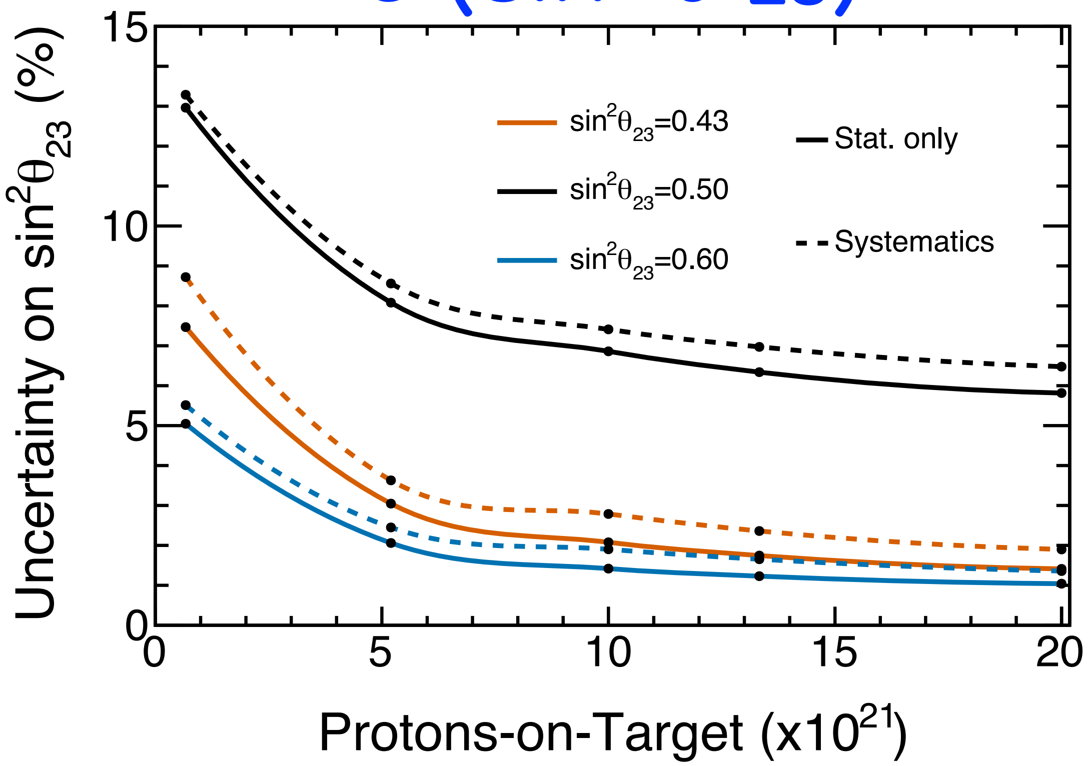


T2K-II Physics Sensitivity

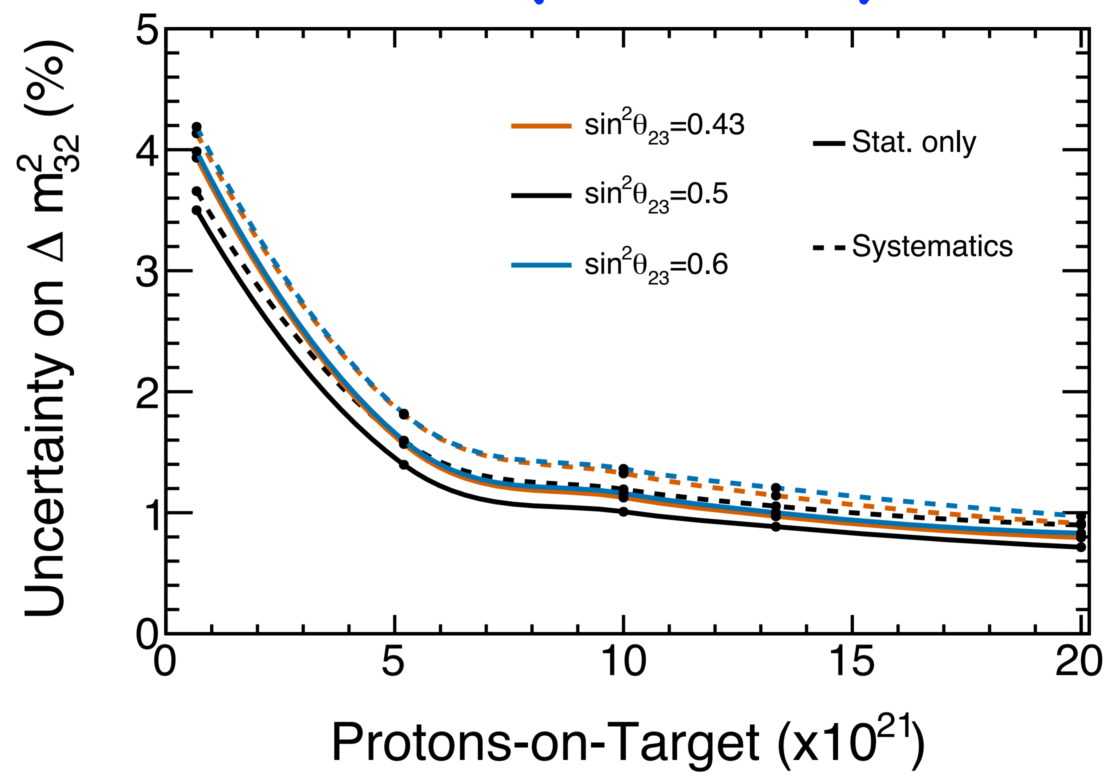
- Precisions of $\sin^2\theta_{23}$ and Δm_{32}^2



$\delta(\sin^2\theta_{23})$



$\delta(\Delta m_{32}^2)$

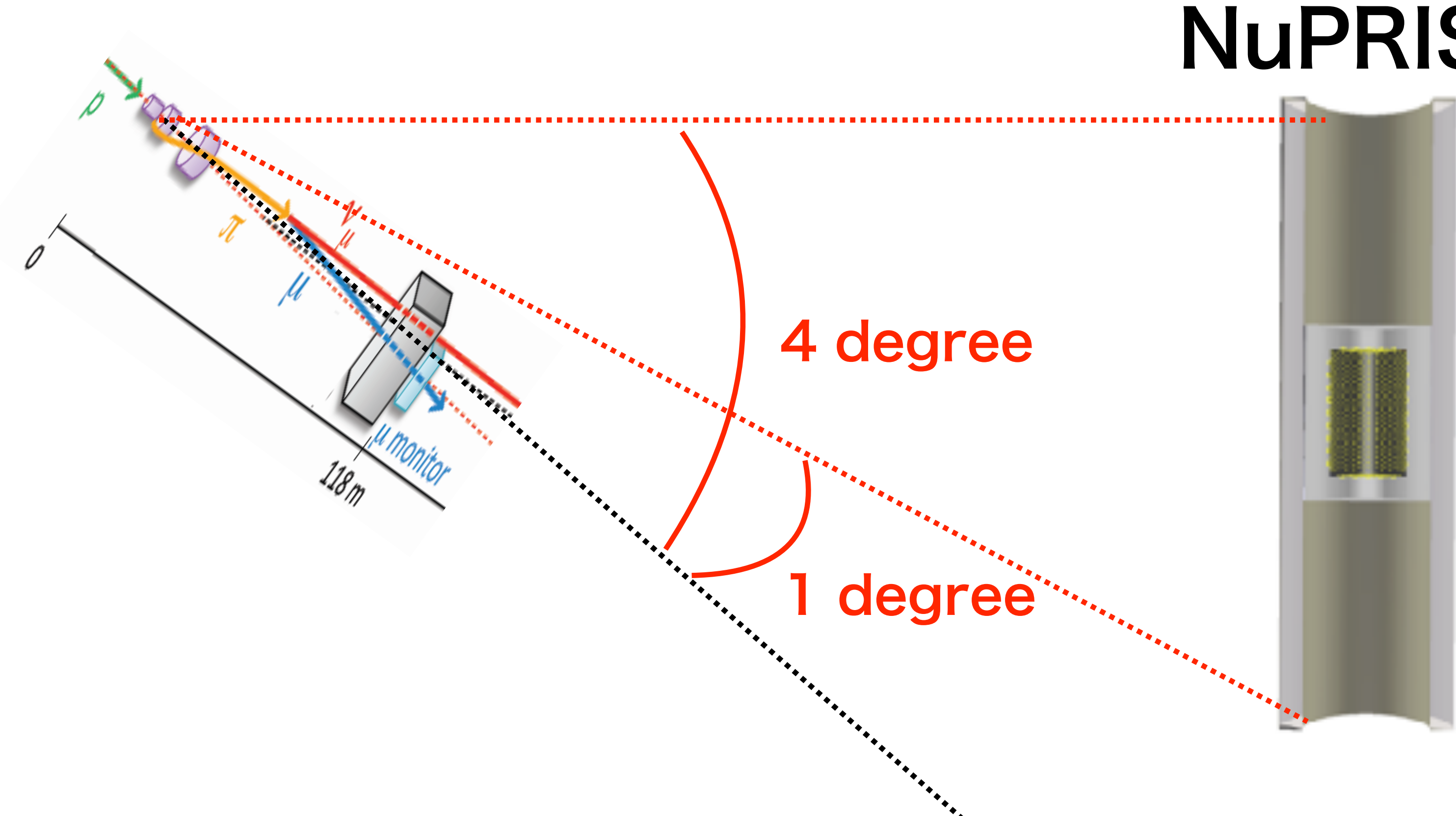


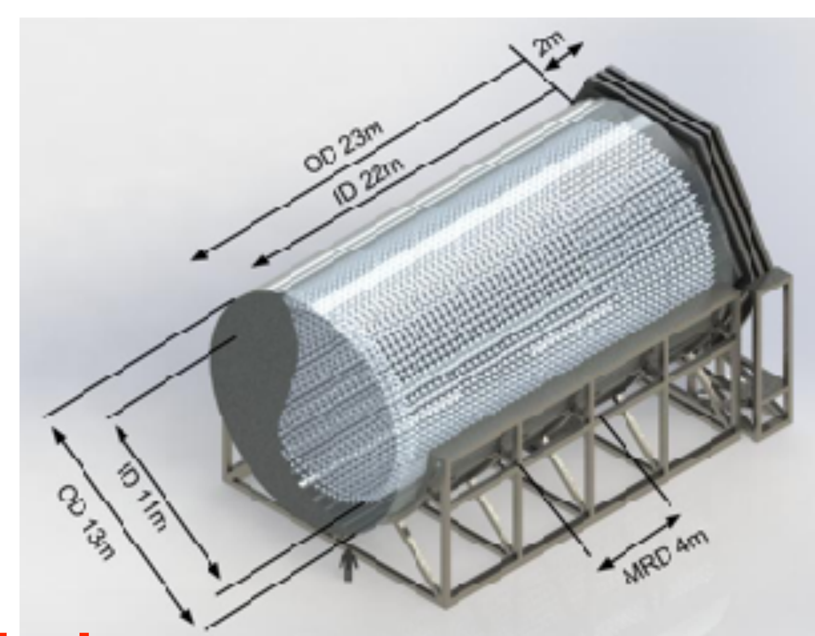
- More physics for Neutrino Interactions and non-standard models

New Intermediate Detector

- Good Near/Far flux ratio to predict the neutrino events at Kamioka (TITUS)
- A new technique to predict the neutrino events at Kamioka (NuPRISM).
- **Under design intensively and being combined!**

  - With the intense neutrino beam, a Water Cherenkov detector can be only operable in the intermediate distance (> ~1km from the target).

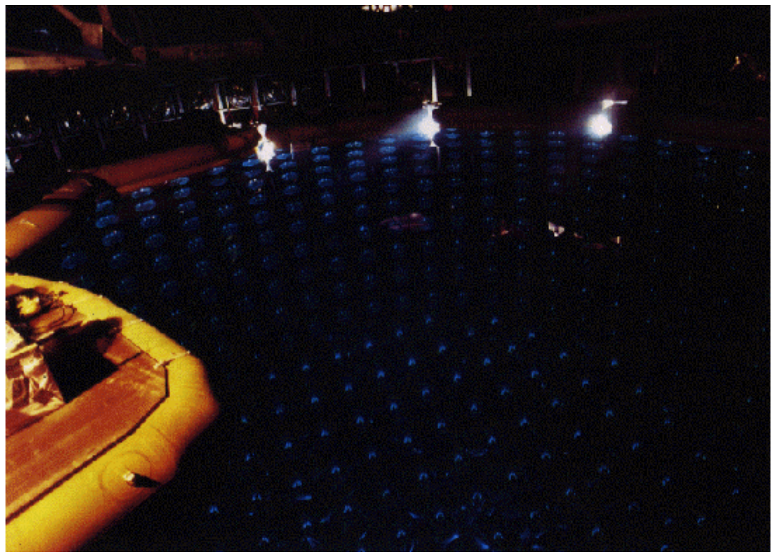




+ combining

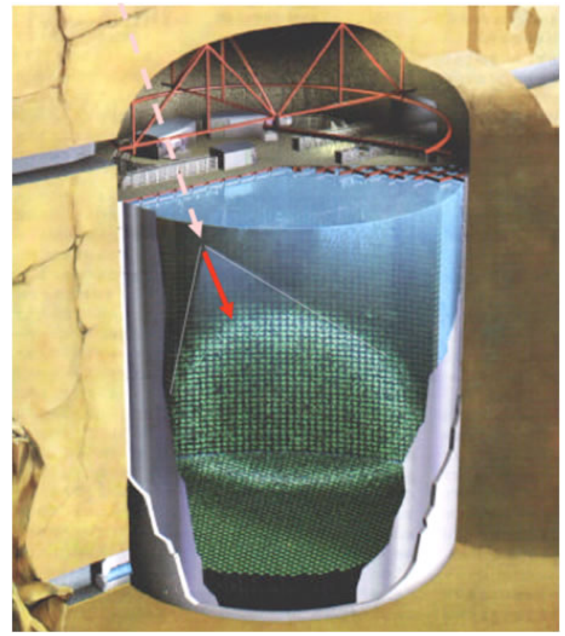
Kamiokande family

Kamiokande (1983-1996)
3000 ton



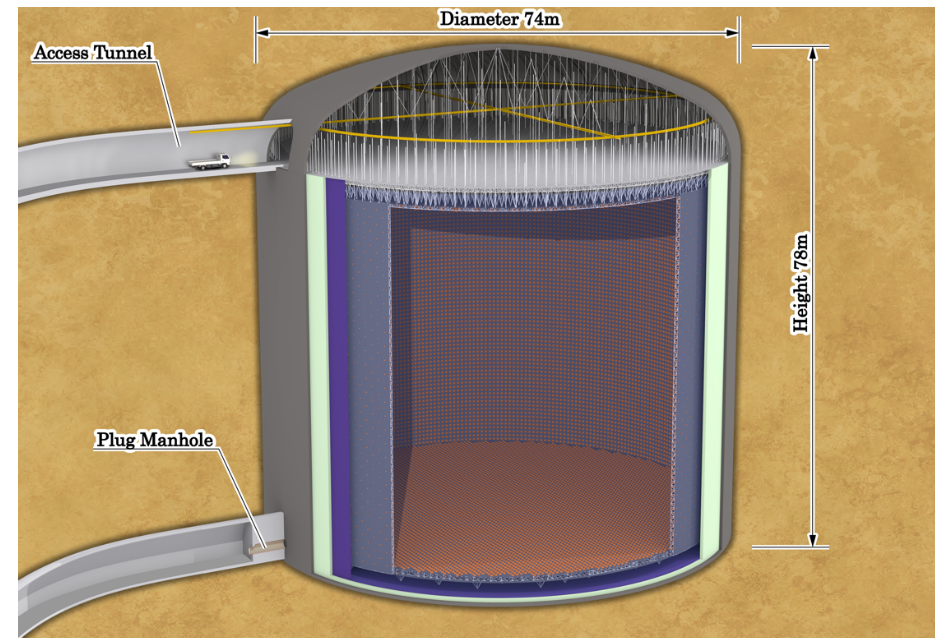
- Neutrinos from SN1987a.
- Atmospheric neutrino deficit.
- Solar neutrinos.

Super-Kamiokande (1996-)
50,000 ton



- Atmospheric neutrino oscillation.
- Solar neutrino oscillation with SNO.
- Far detector for KEK-PS (K2K) and J-PARC beam (T2K): electron neutrino appearance.
- World leading limit on proton lifetime $> 10^{34}$ years.

Hyper-Kamiokande ($\sim$2026-)
$2\times$260,000 ton



Physics programme:

- Neutrino oscillations: Mass Hierarchy, Leptonic CP violation, θ_{23} Octant,...
- Nucleon decay: $p\to e^+\pi^0$, $p\to K^+\bar{\nu}$,...
- Neutrino astrophysics: Solar neutrinos, Supernova neutrinos, WIMP searches

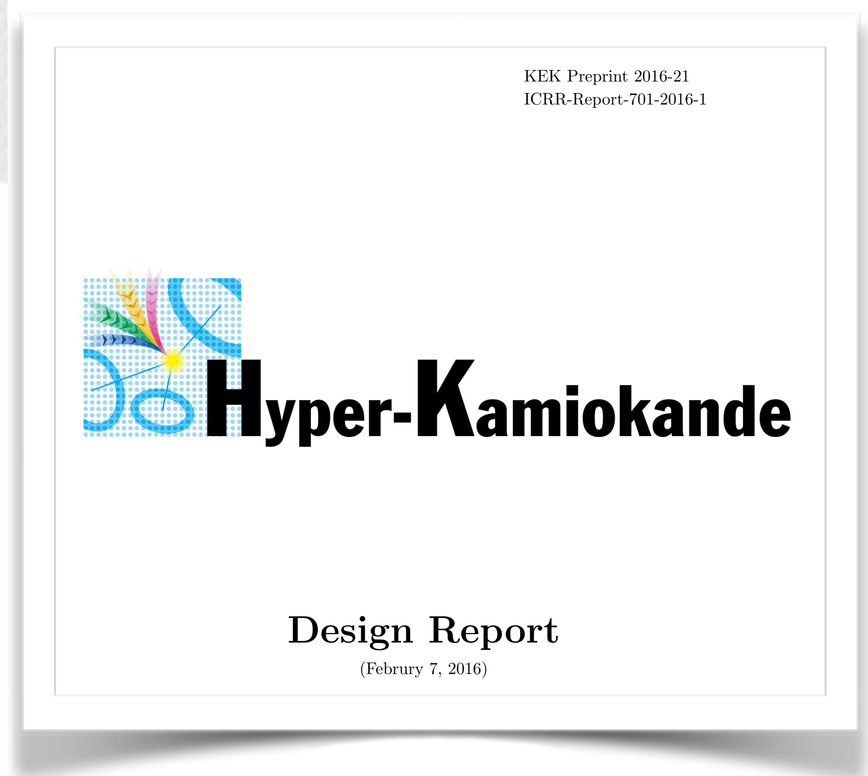
Hyper-Kamiokande (New Design)

http://www.hyperk.org

One tank

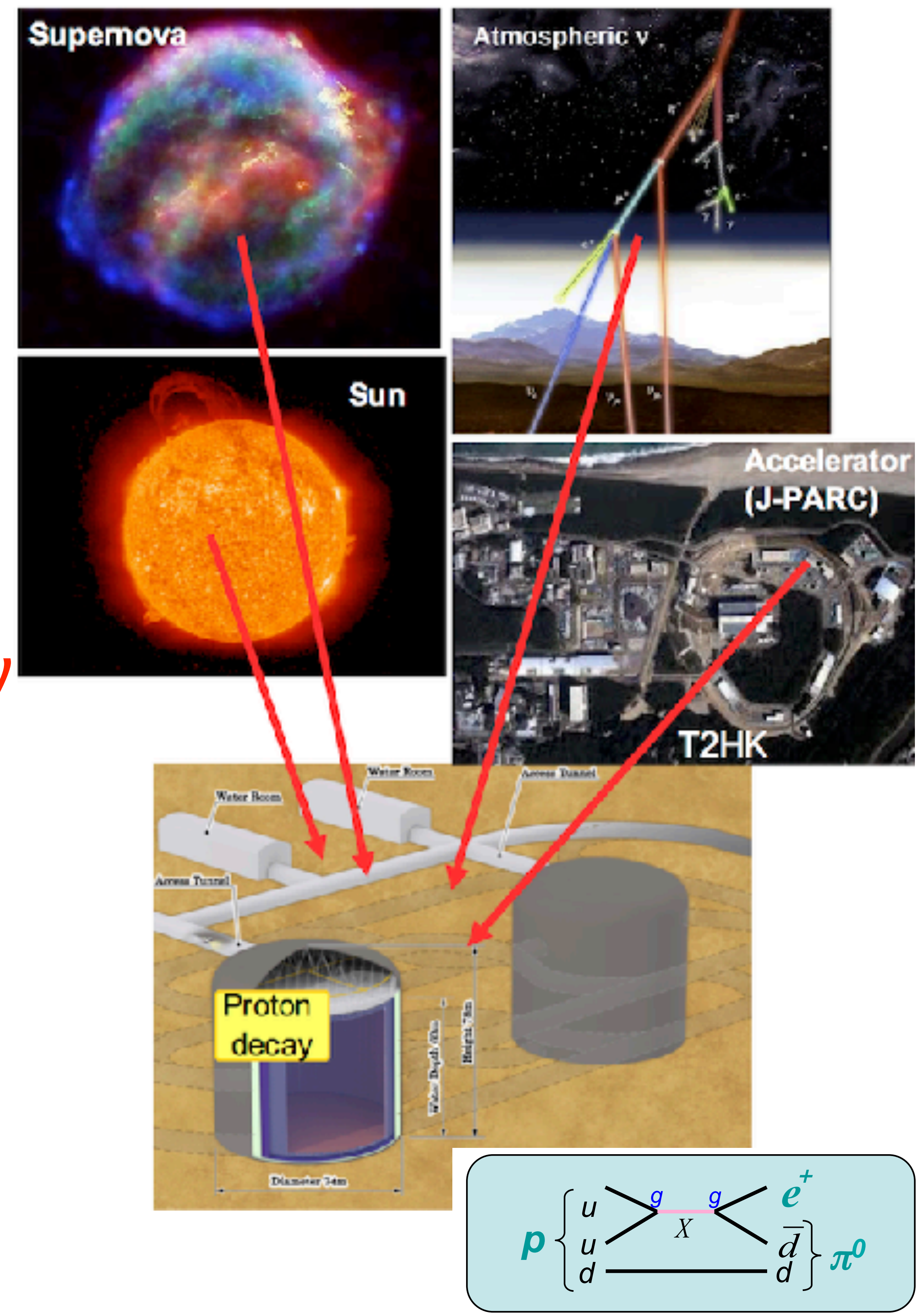
- 60m (high) × 74m (diameter)
- Total Volume: 260 kton.
- Fiducial Volume: 190 kton (∼ 10× Super-K).
- 40% PMT coverage.
- 40,000 50cm ID PMTs, 6,700 20cm OD PMTs.

- Cost saving and quick start with one tank first
- Improving the performance
  - A new PMT has x2 better Photon sensitivity
- A new design was reviewed by the international advisory committee, and endorsed.



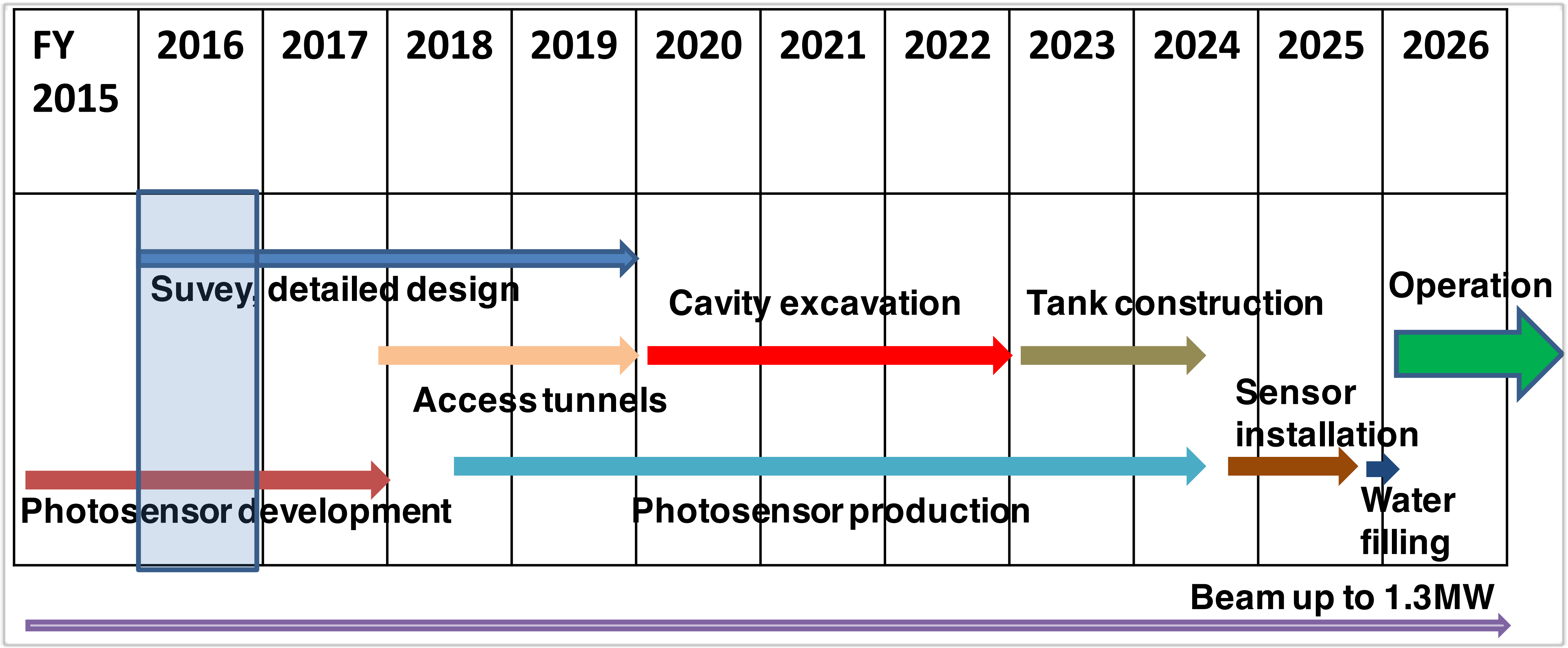
Broad science program with Hyper-K

- Neutrino oscillation physics
  - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
  - Possible discovery with ~×10 better sensitivity than Super-K
- Neutrino astrophysics
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- Geophysics (neutrinography of interior of the Earth)
- Maybe more (unexpected)



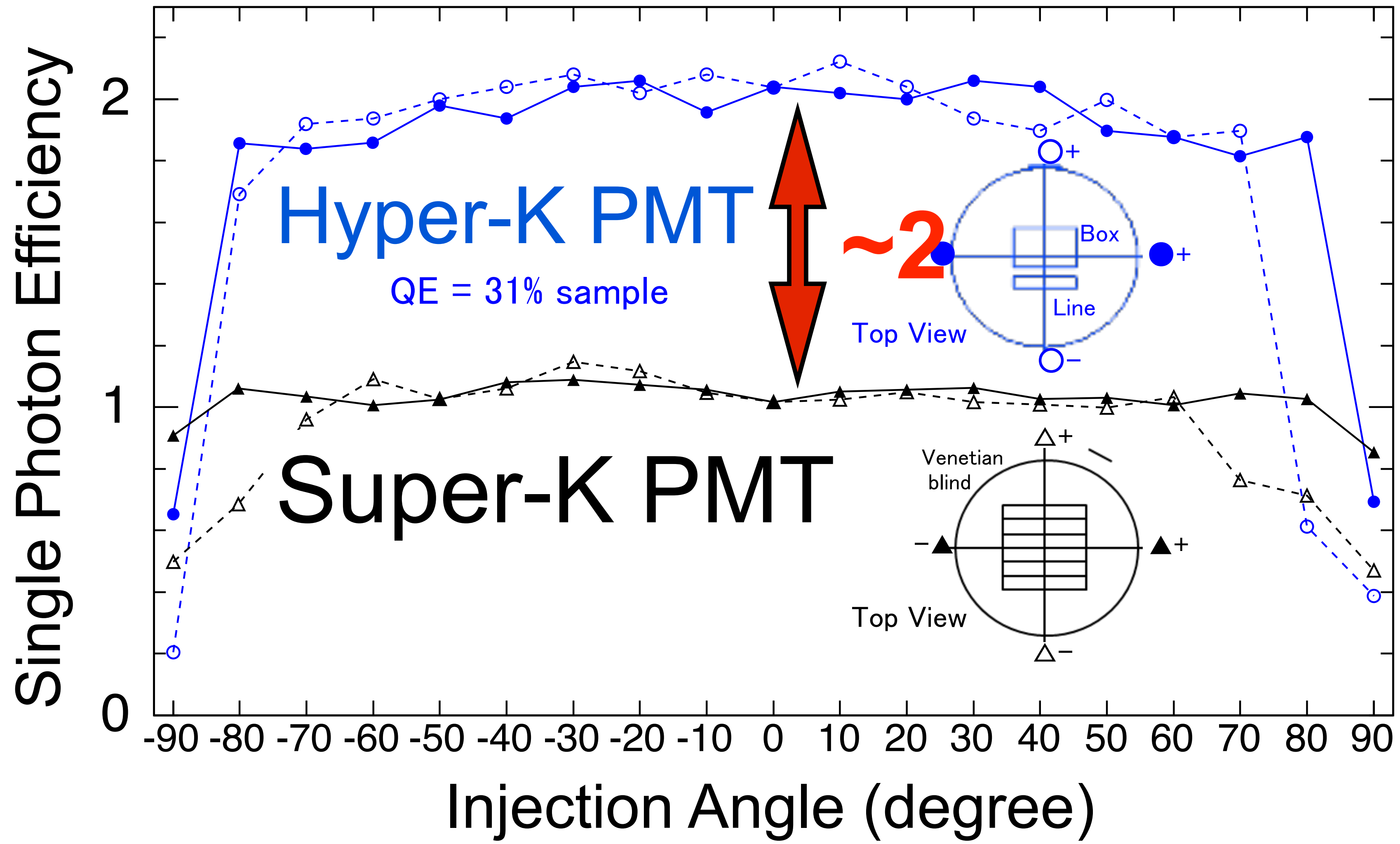
$p \to e^+\pi^0$

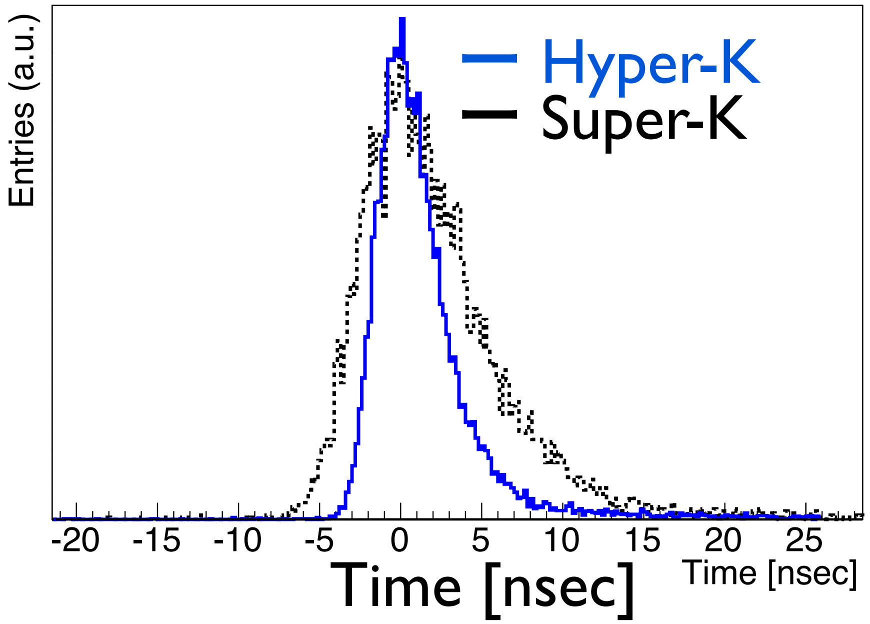
Hyper-K construction timeline

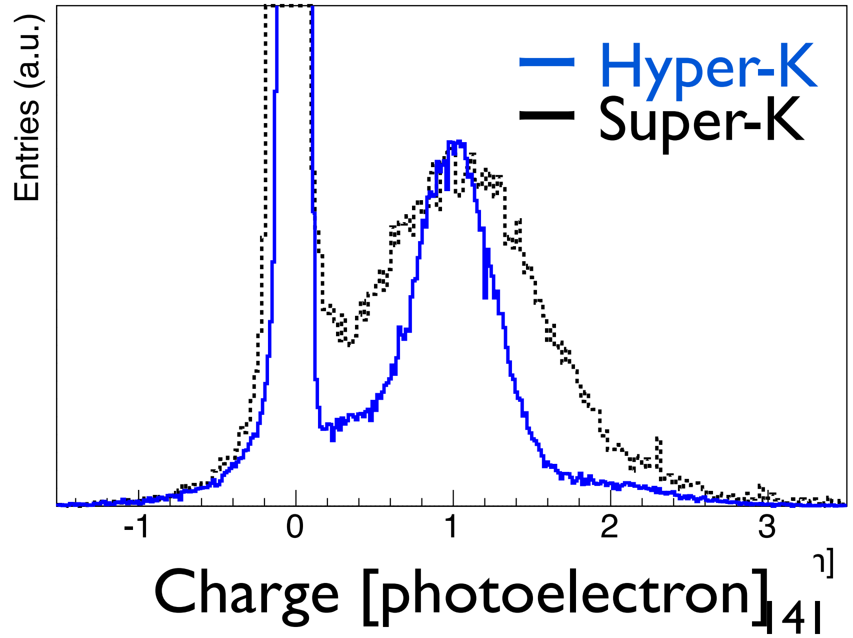


- Assuming funding from 2018
- The 1st detector construction in 2018~2025
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years

Hyper-K New Technology







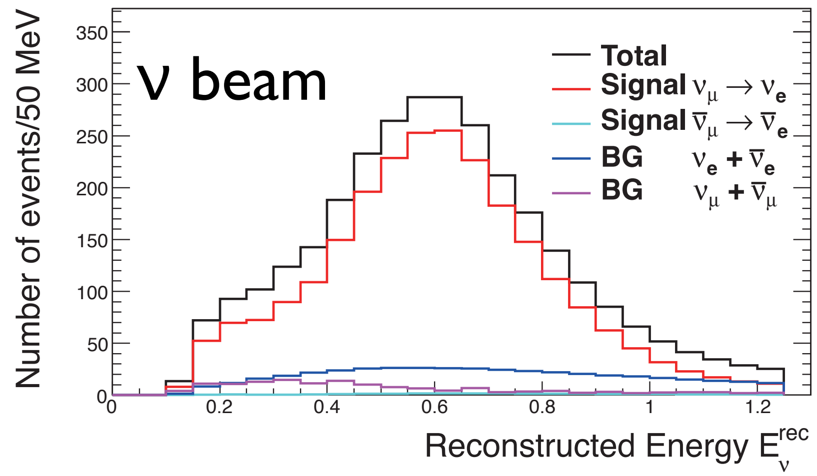
- Single Photon Efficiency: **x2**
- Time Resolution: **x2**
- Charge Resolution: **x2**
- Better Physics Sensitivity with the improved detector performance

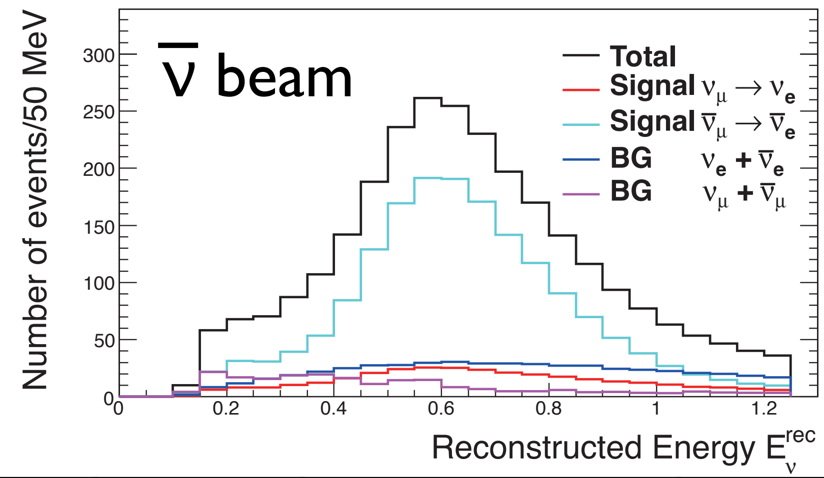
Expected events

1.3MW, 10×10^{7}sec, $\nu:\bar{\nu}$=1.3

ν_e candidates

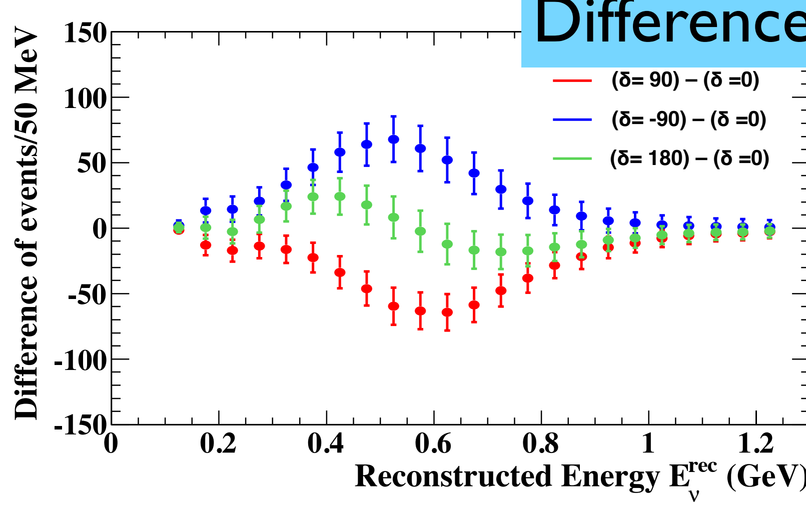
Using fiTQun for π^0 rejection

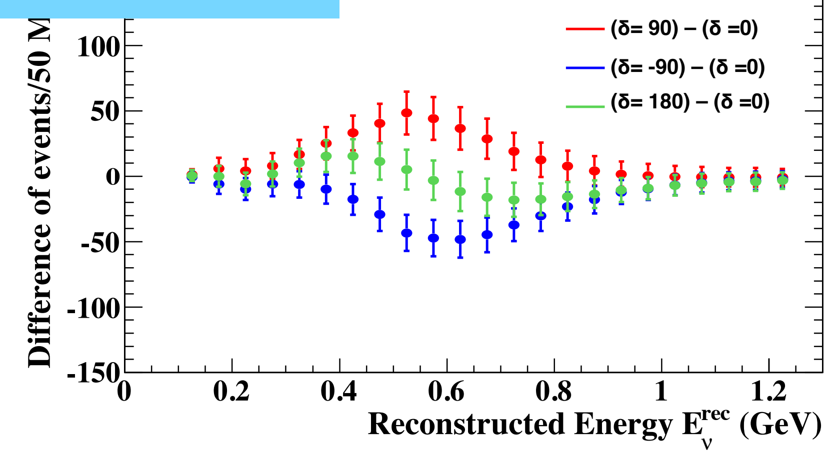




for δ=0	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

Difference from δ_{CP}=0





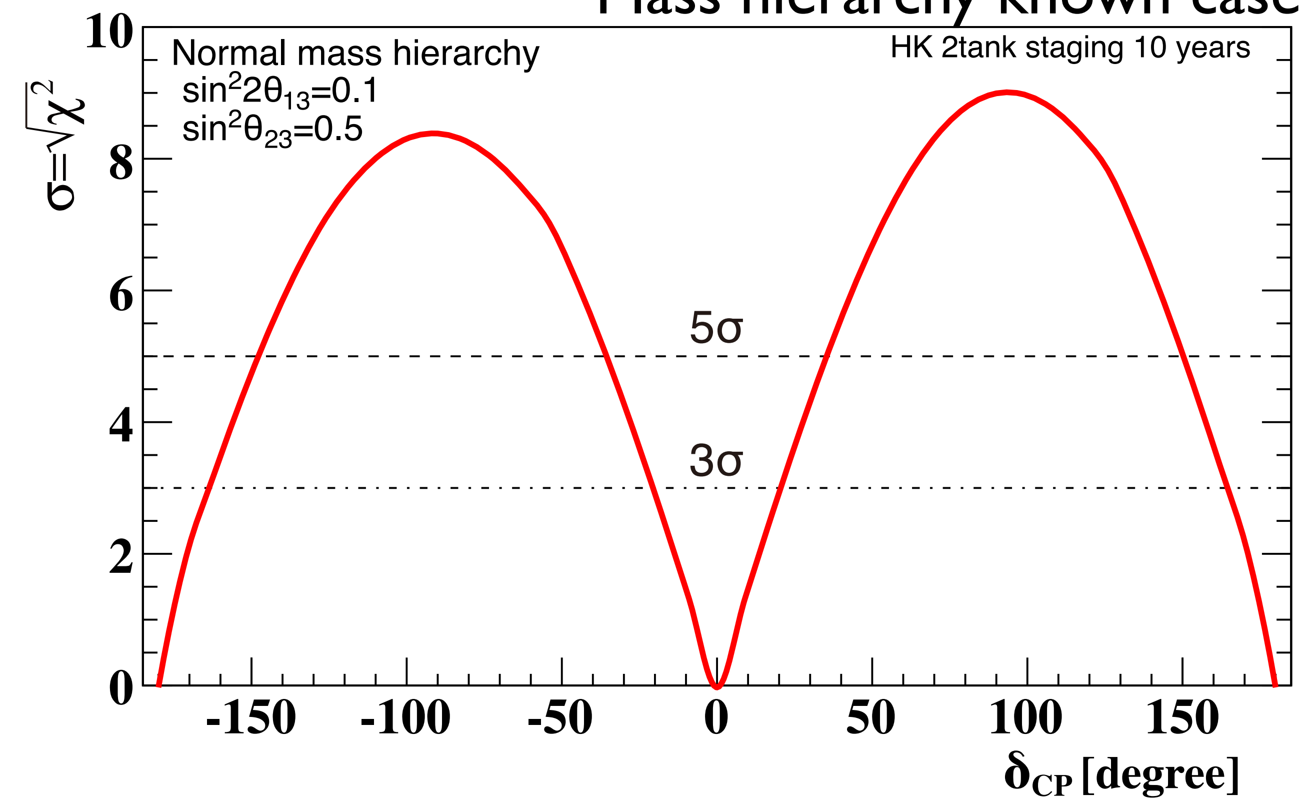
δ=0 and 180° can be distinguished using shape information

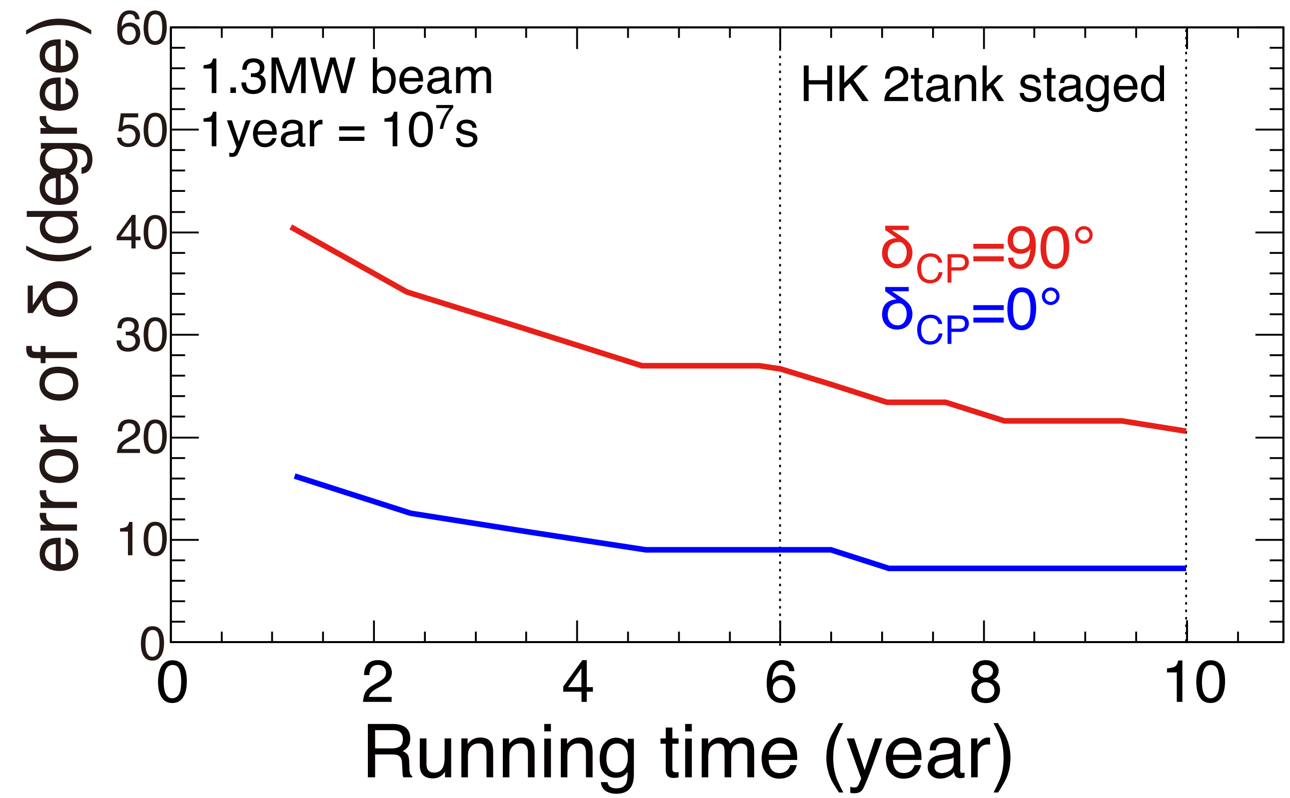
CPV sensitivity

- Exclusion of sinδ$_{CP}$=0
  - >8σ(6σ) for δ=-90°(-45°)
  - ~80% coverage of δ parameter space with >3σ
- From discovery to δ$_{CP}$ measurement:
  - ~7° precision possible

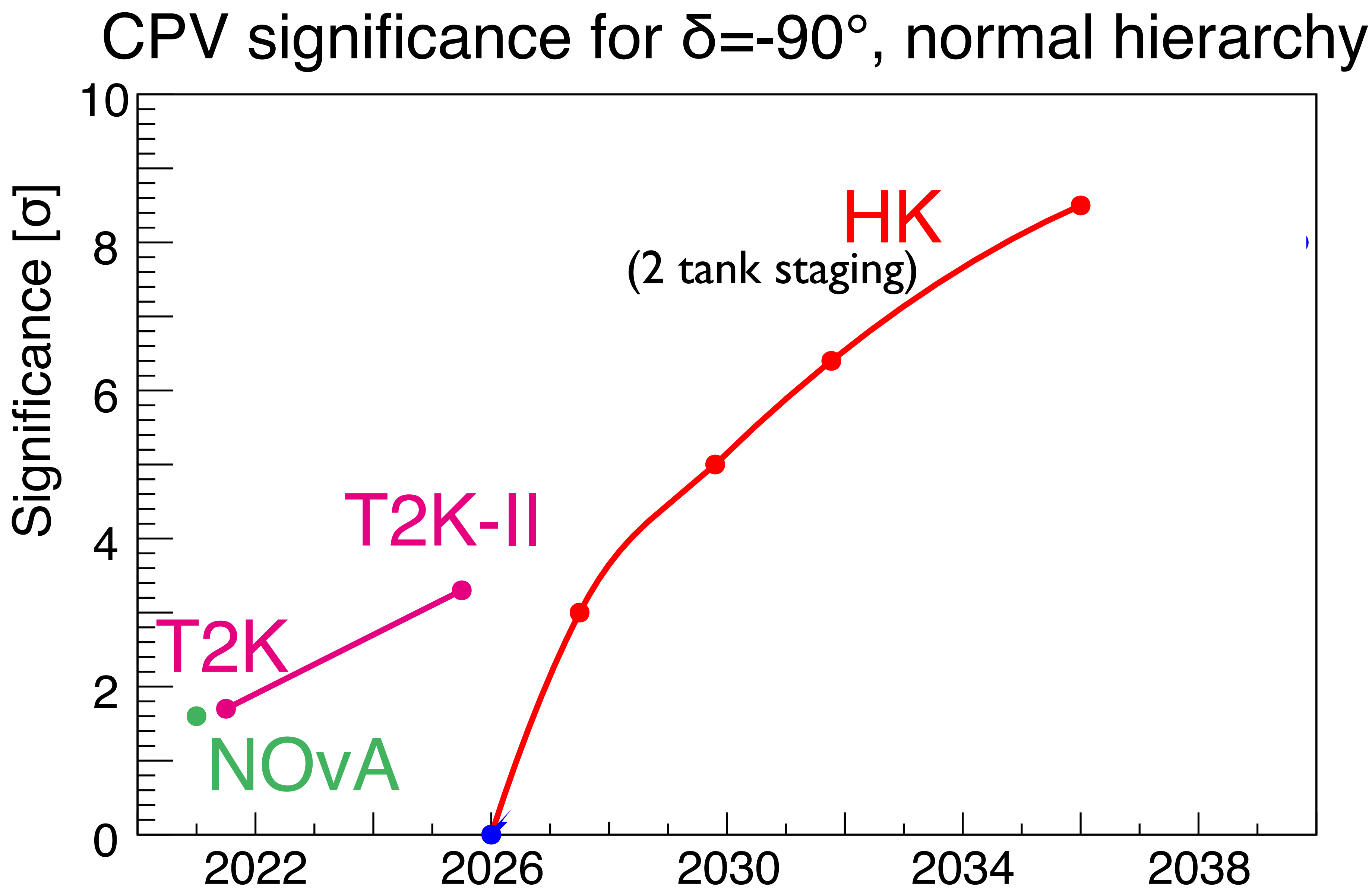
sinδ=0 exclusion		error	
>3σ	>5σ	δ=0°	δ=90°
78%	62%	7.2°	21°

Mass hierarchy known case





Towards leptonic CP asymmetry



Strategy of Japan-based program

~3σ evidence with T2K→T2K-II,

>5σ discovery and measurement with HK

Note: "exact" comparison sometimes difficult due to different assumptions

θ_{23} and Δm^2_{32}

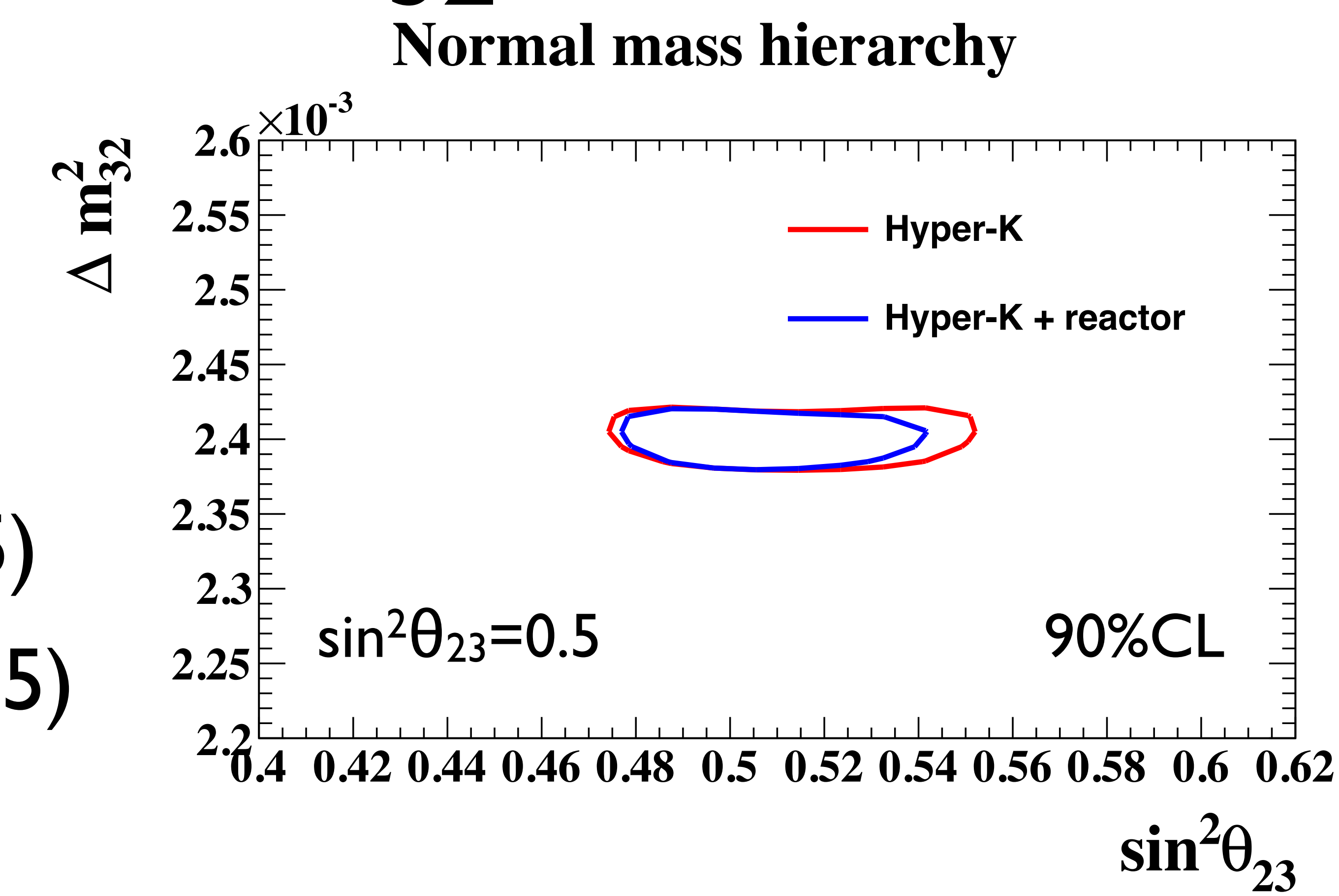
$\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5} eV^2$

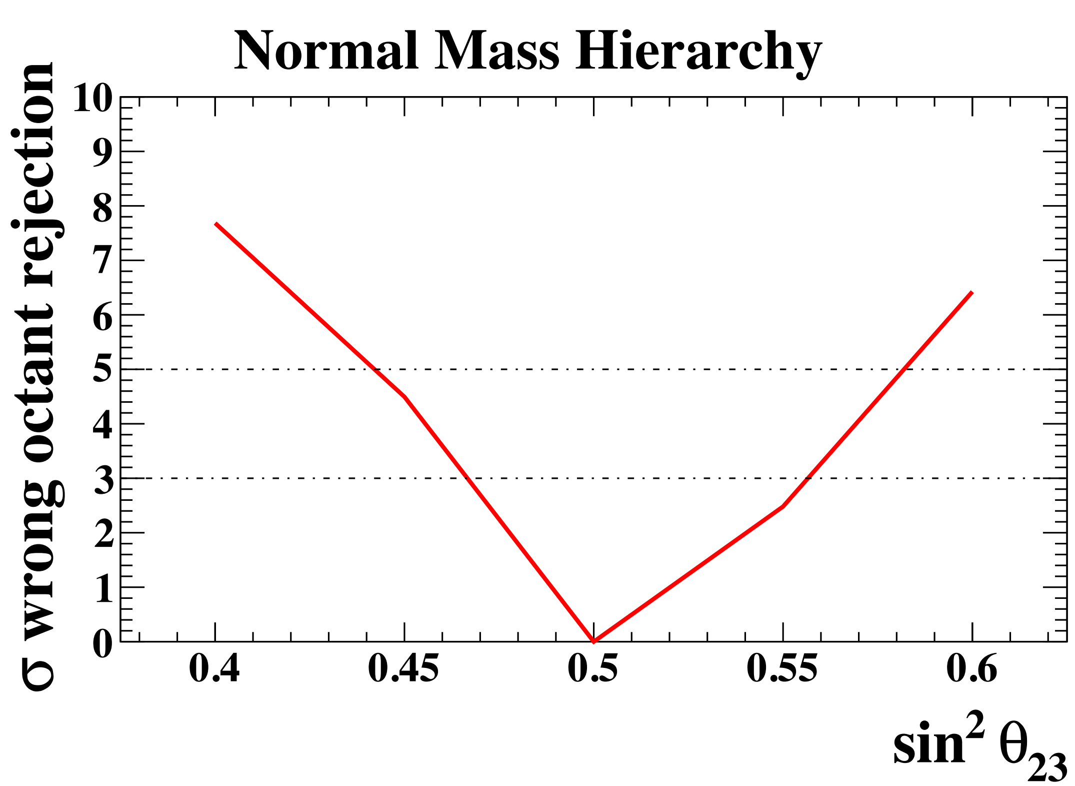
→ Mass hierarchy sensitivity in combination with reactor

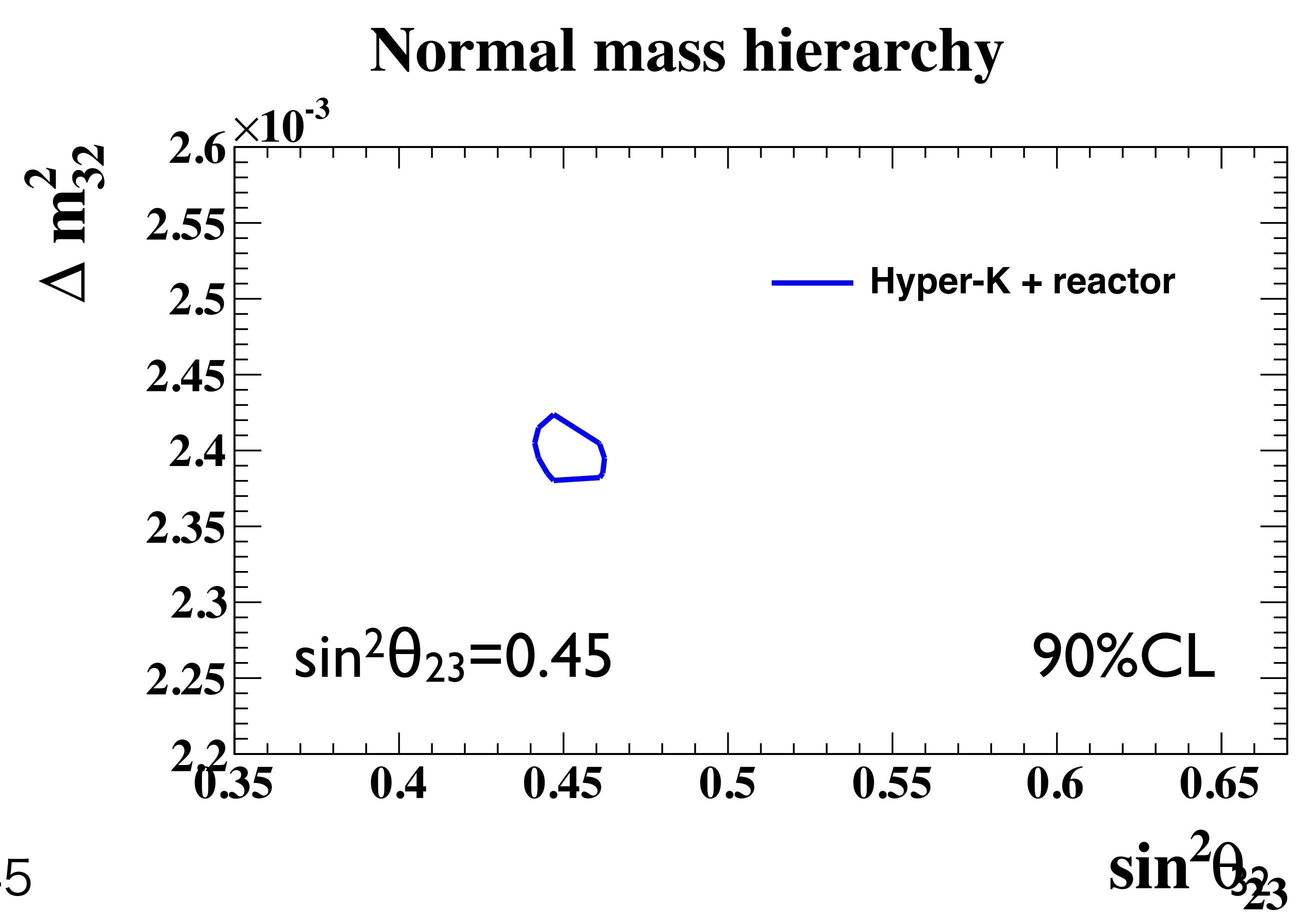
$\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}=0.5$)

~ 0.006 (for $\sin^2\theta_{23}=0.45$)

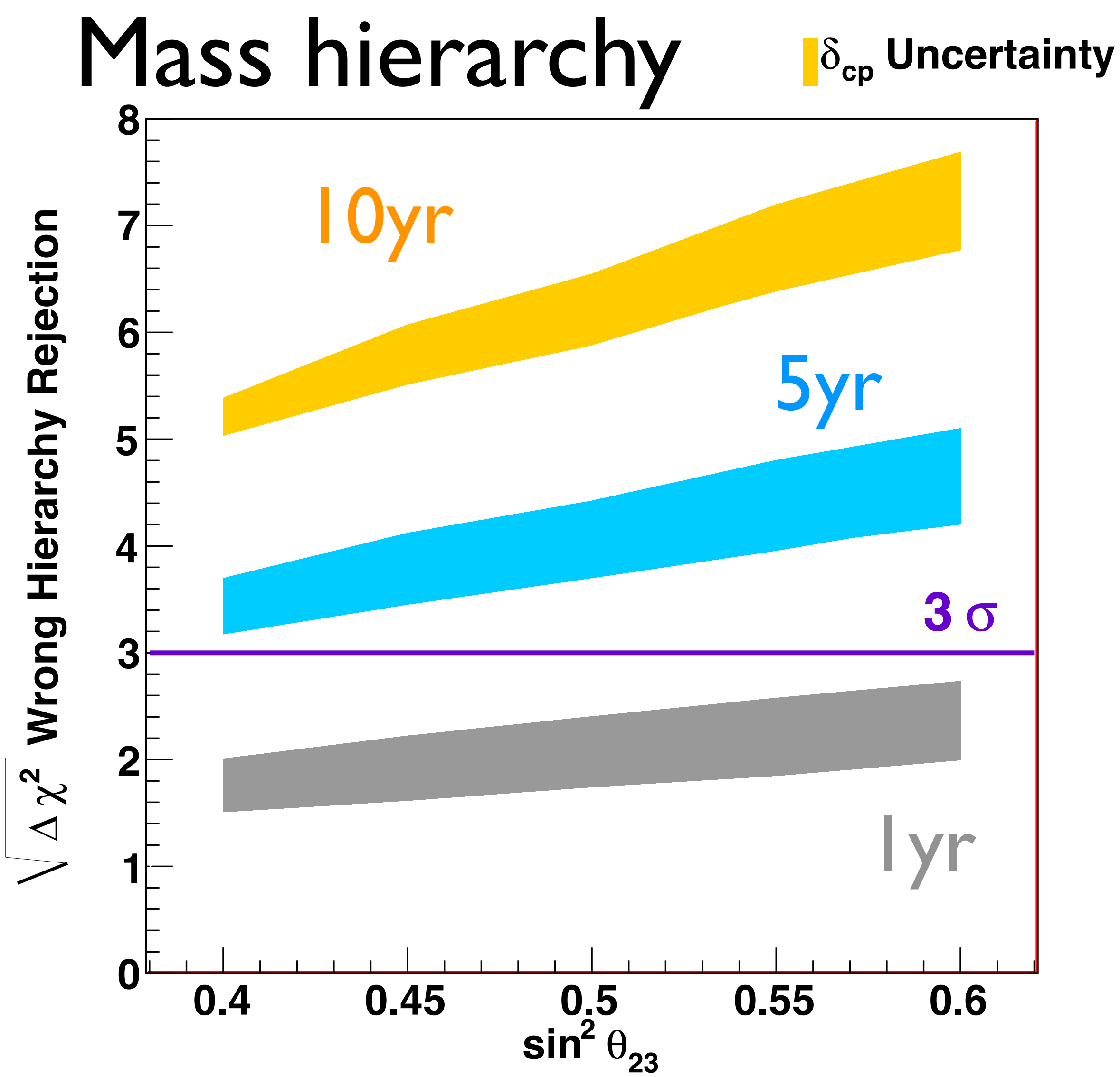
→ Octant determination, input to models

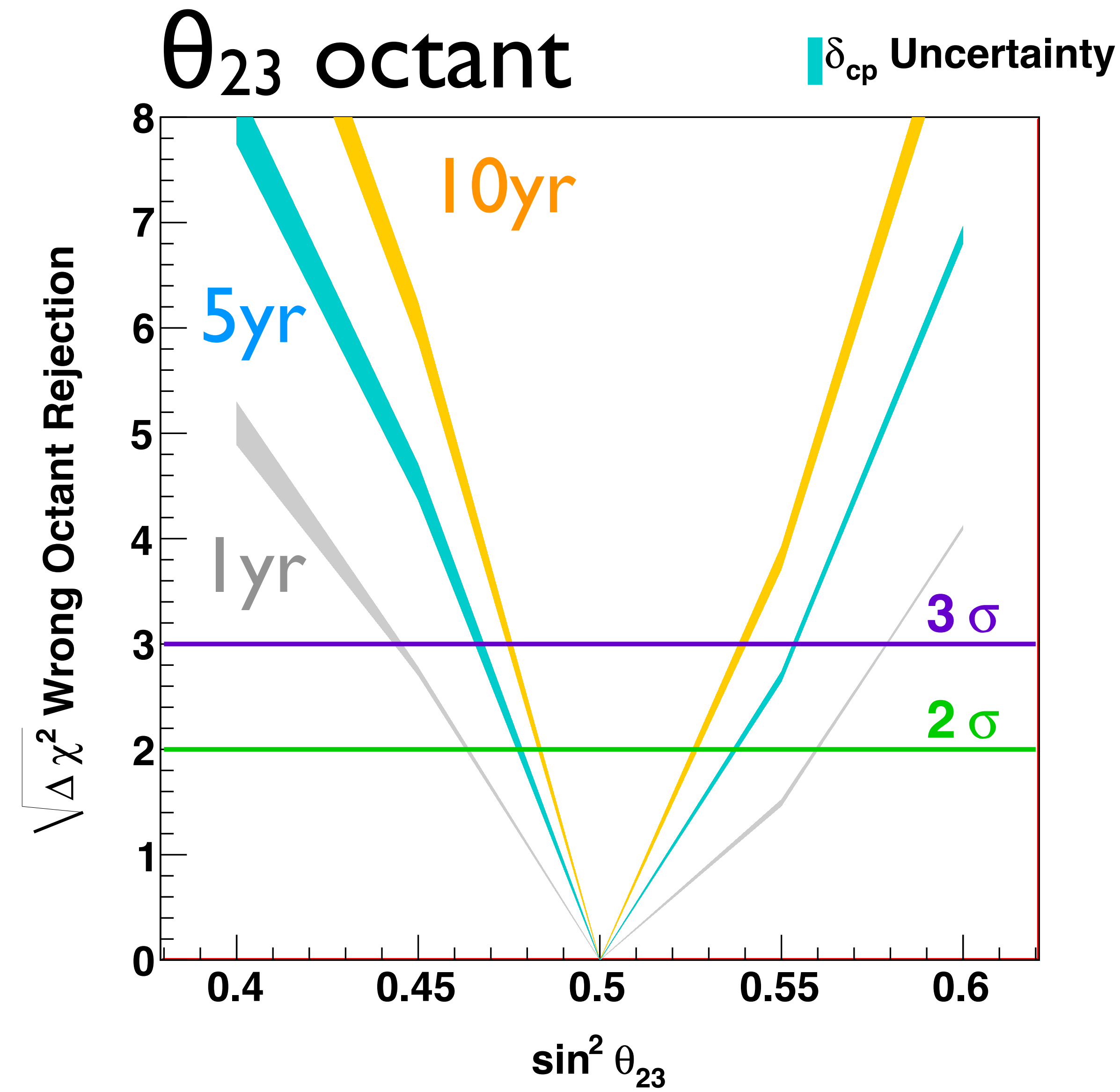






Beam + Atm ν combination



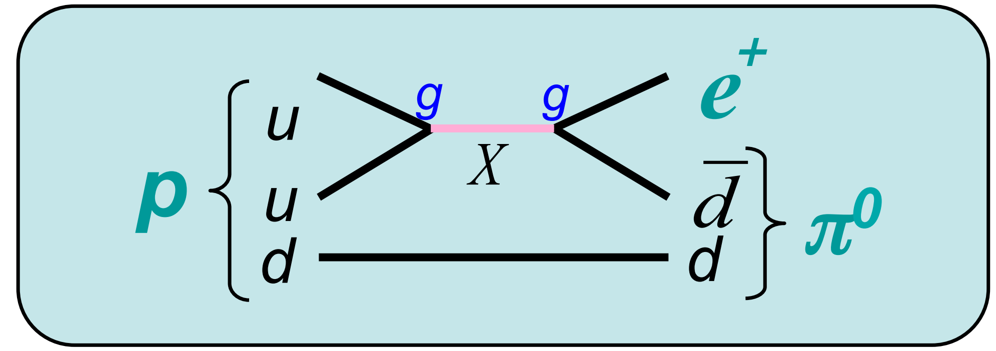


- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

Proton Decay

- **Keep looking for GUT with neutrinos.**
- Example: $p \rightarrow e^+\pi^0$ in Hyper-K

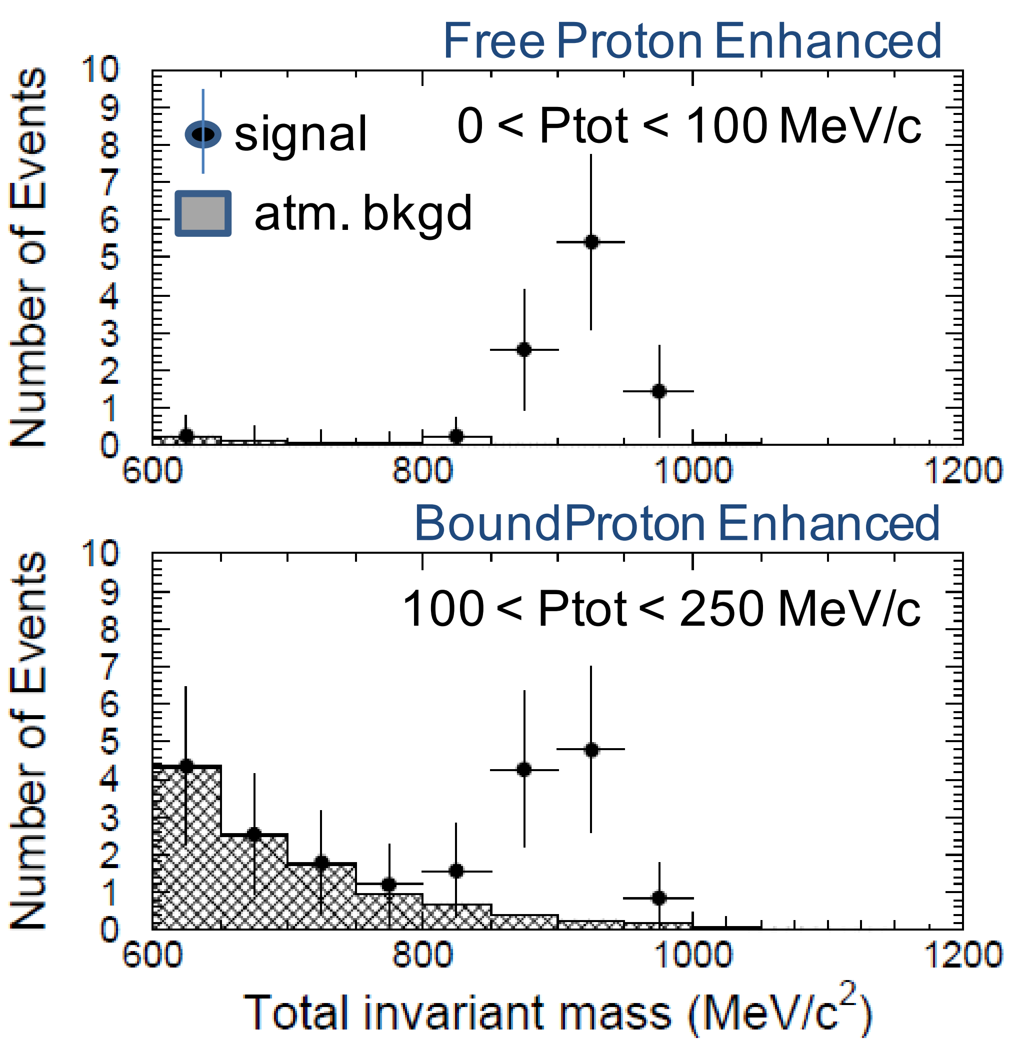
Mediated by gauge bosons

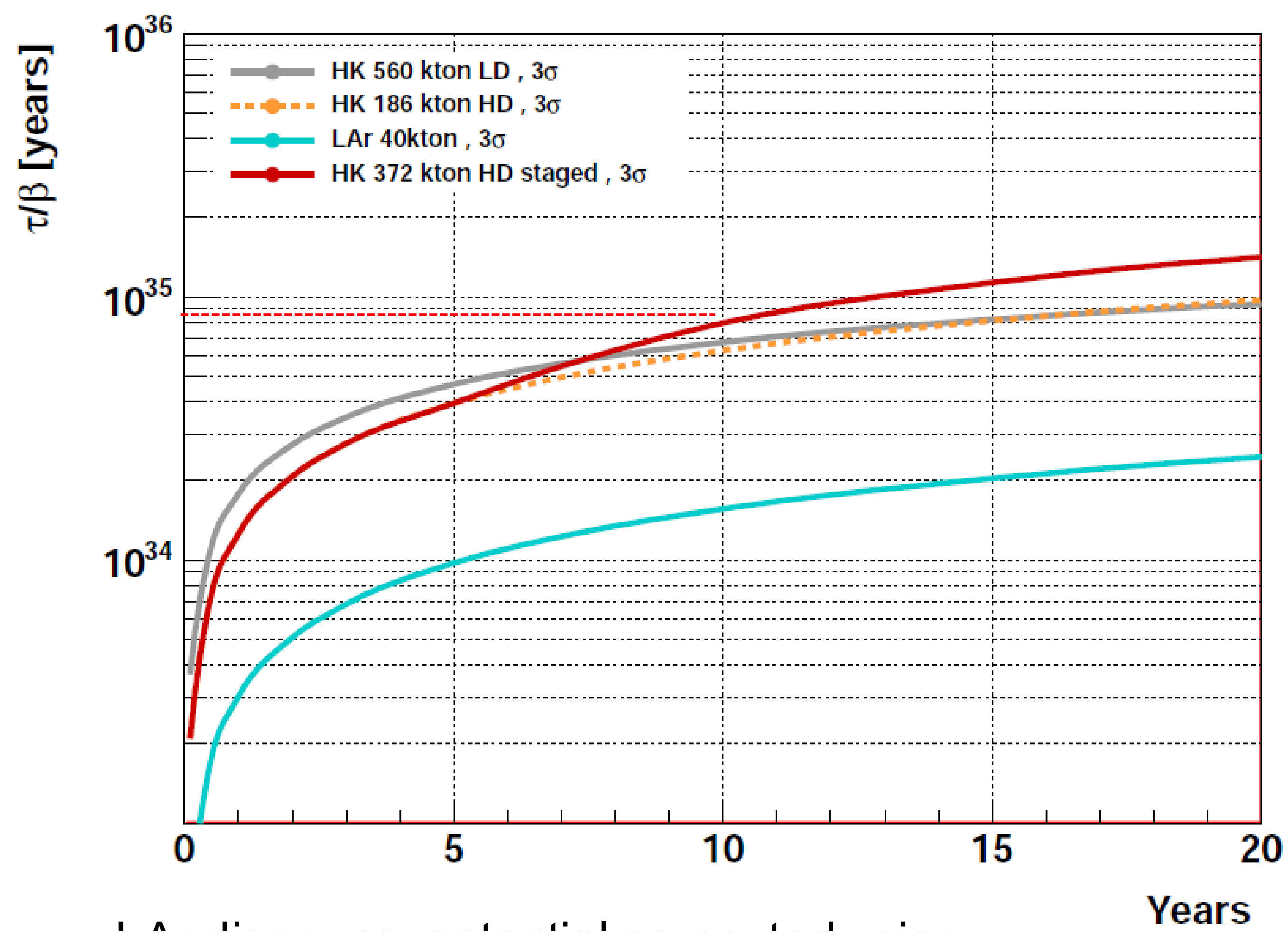


$p \rightarrow e^+\pi^0$

$$\Gamma(p \rightarrow e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

$\tau_{proton} = 1.4\times10^{34}$ years (SK 90% CL limit)





Hyper-K Status in Japan

- J-PARC upgrade for Hyper-K is the first priorities in KEK (KEK PIP).
- A proposal of the Hyper-K project is under review by several council, managements and committees in Japan.
  - Science Council of Japan (SCJ)
    - The result will be in public around the beginning of year 2017.
  - MEXT (funding agency) will make the roadmap based on the SCJ report around the middle of 2017.
- The budget request of the far detector is under preparation for 2017.

END

HiggsTan
http://higgstan.com

HiggsTan Cartoon

登録情報

単行本（ソフトカバー）： 143ページ

出版社: 洋泉社 (2016/5/24)

言語: 日本語

ISBN-10: 4800309174

ISBN-13: 978-4800309174

発売日： 2016/5/24

商品パッケージの寸法: 21 x 14.8 x 1.6 cm

おすすめ度： ★★★★★ 2件のカスタマーレビュー

Supplement

$$N_{signal} = \Phi \times \sigma \times N_{target} (\times \varepsilon)$$

- Φ : Intense Neutrino Source
- σ: cannot be made larger for fixed neutrino energy.
- N_{target}: Gigantic Detector
- ε : High Efficiency.

- Background to be under control: $N_{background}$

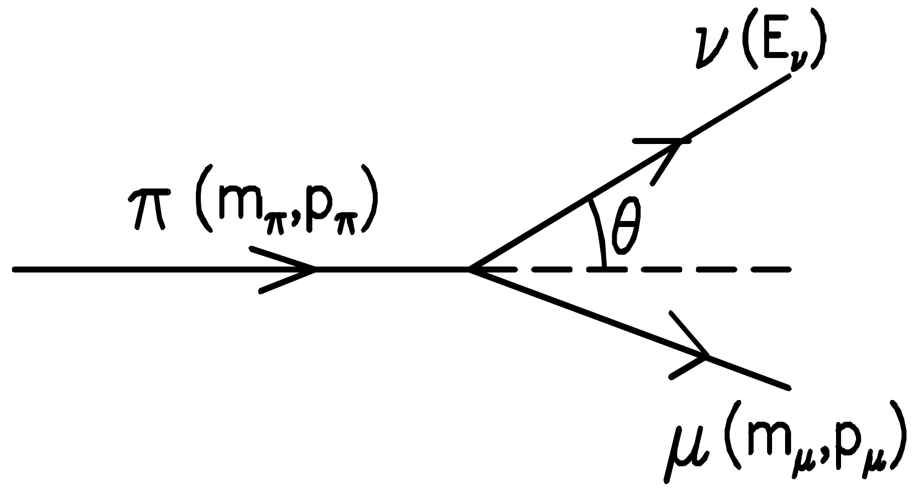
N_{signal}

- Examples
  - $N_{signal} = \Phi \times \sigma \times N_{target} (\times \varepsilon)$
    - LHC@7TeV/ATLAS(7kton): $W \to \mu(e) \nu_{\mu(e)}$
      - Φ~100Hz $W \to \mu(e) \nu_{\mu(e)}$ production÷Surface area $(22\times22\times44m^3)$~$5\times10^{-9}\ \nu/cm^2/sec$
      - σ~$10^{-36}\ cm^2$/nucleon@100GeV
      - $N_{target} = 4\times10^{33}$ nucleon/ATLAS
      - $N_{signal} = 2\times10^{-11}$ events/s = 6×10^{-4} events/year
    - Solar ν (^8B)+ Super-K (22.5kton)
      - Φ~$5\times10^6/cm^2/s$
      - σ~$10^{-43}\ cm^2$/electron@10MeV
      - $N_{target} = 7\times10^{33}$ electron/Super-K
      - $N_{signal} = 3.5\times10^{-3}$ events/s = 300 events/day [Reality: ~30 events/day]
    - [HW1]: Find the source of neutrinos and define the target, and calculate the event rate.
      - Daya Bay, T2K, Super-K atmospheric, SNO solar neutrino

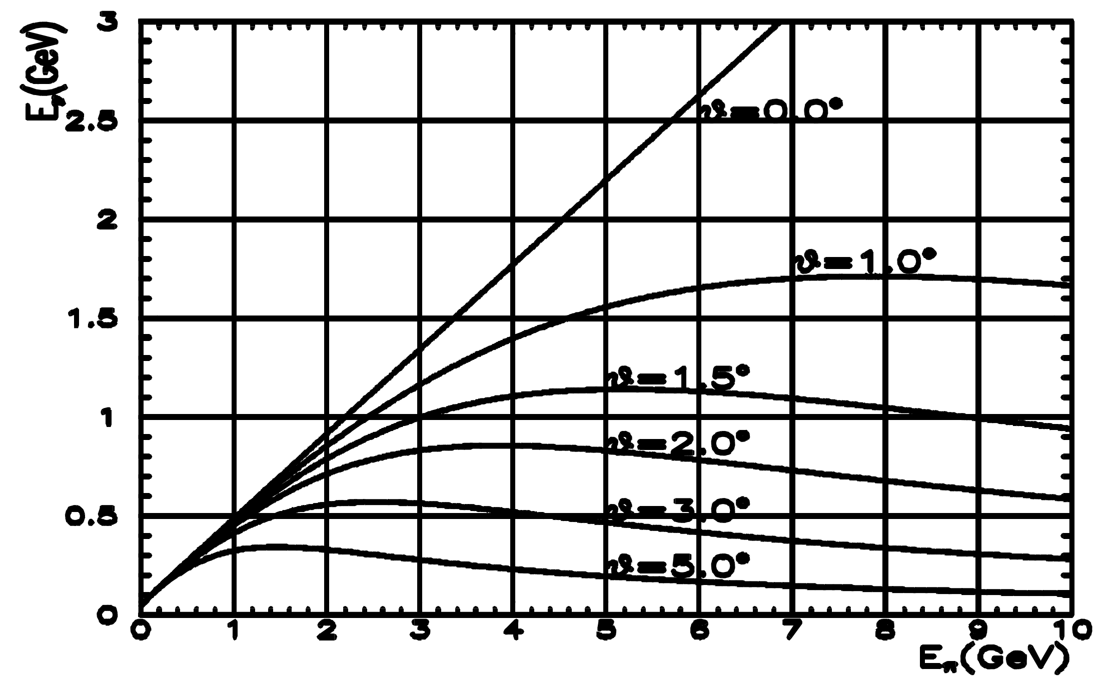
Exercise 1

- Calculate the neutrino event rate in a day by assuming the source of neutrinos, the target mass and distance from the source.

Exercise 2



$$E_\nu = \frac{m_\pi^{\ 2} - m_\mu^{\ 2}}{2(E_\pi - p_\pi \cos\theta)}$$



(1) Calculate the neutrino beam energy as a function of the parent pion energy, momentum and the emitting angle of neutrino relative to the pion direction.

(2) Calculate the maximum neutrino energy as a function of the parent pion energy.

(3)Explain the off-axis effect with small θ (such as θ=2.5 degrees in the case of T2K).

TABLE I. T2K data-taking periods and collected POT used in the analyses presented in this paper.

Run Period	Dates	ν-mode POT ($\times 10^{20}$)	$\bar{\nu}$-mode POT ($\times 10^{20}$)
Run 1	Jan. 2010-Jun. 2010	0.323	–
Run 2	Nov. 2010-Mar. 2011	1.108	–
Run 3	Mar. 2012-Jun. 2012	1.579	–
Run 4	Oct. 2012-May 2013	3.560	–
Run 5	May 2014-Jun. 2014	0.242	0.506
Run 6	Nov. 2014-Jun. 2015	0.190	3.505
Run 7	Feb. 2016-May 2016	0.480	3.460
Total	Jan. 2010-May 2016	7.482	7.471