CCEPP Summer School 2021 on Neutrino Physics,
August 20-28, 2021

Accelerator Neutrinos

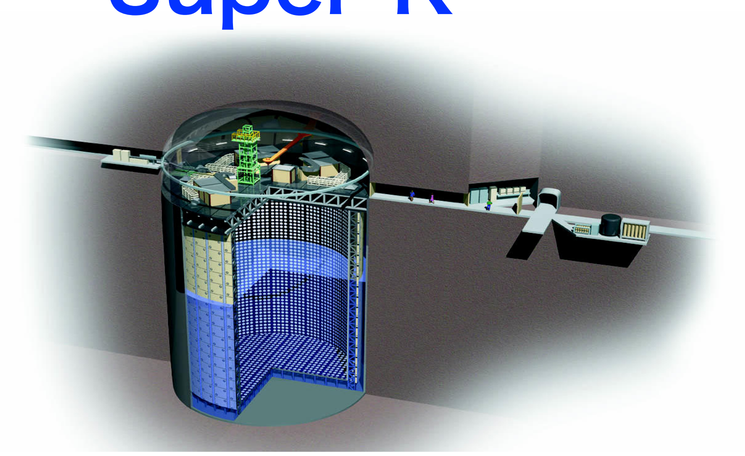
- T2K (and Hyper-K) experiments -

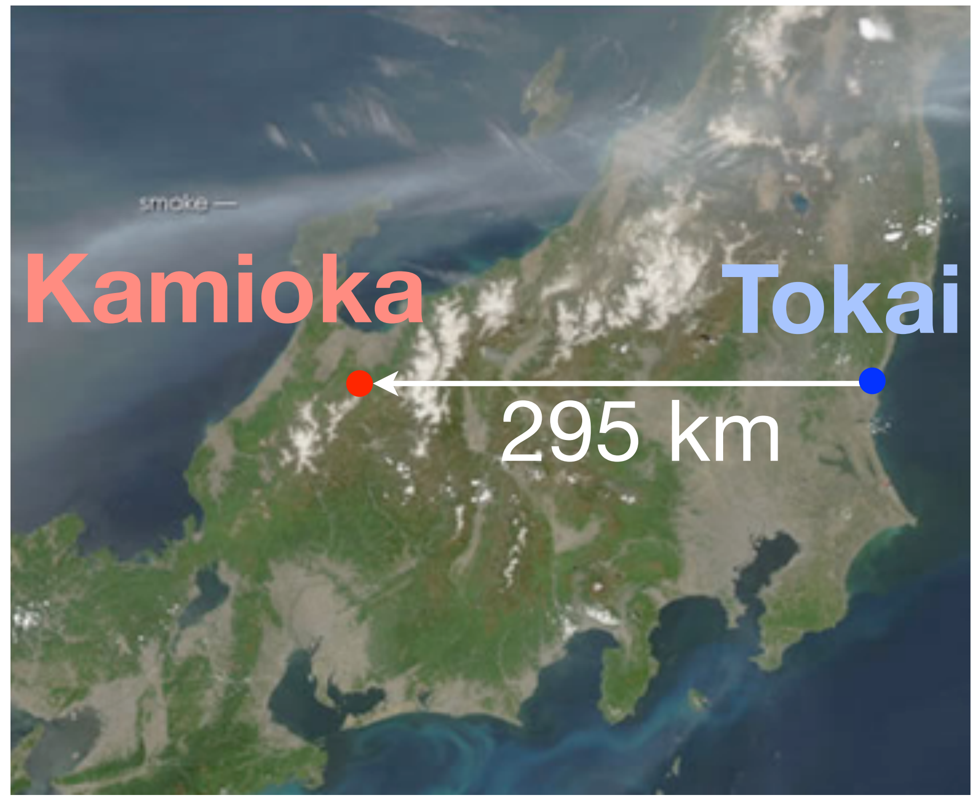
T. Nakaya (Kyoto University)

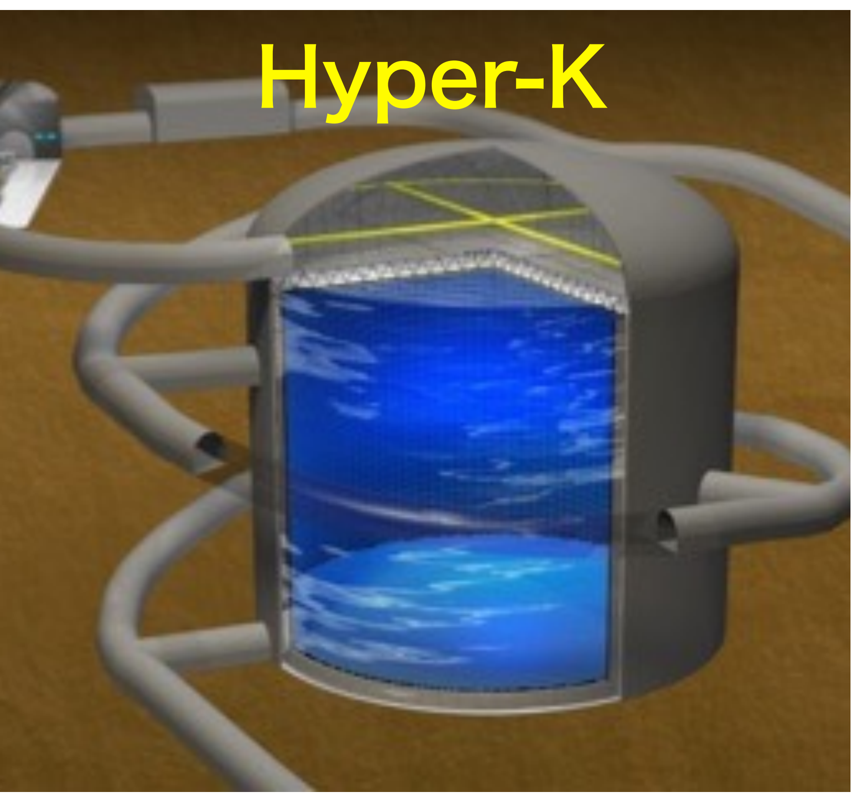
Neutrino Experiments with the J-PARC ν beam

Gigantic detectors with the world-most intense neutrino beam

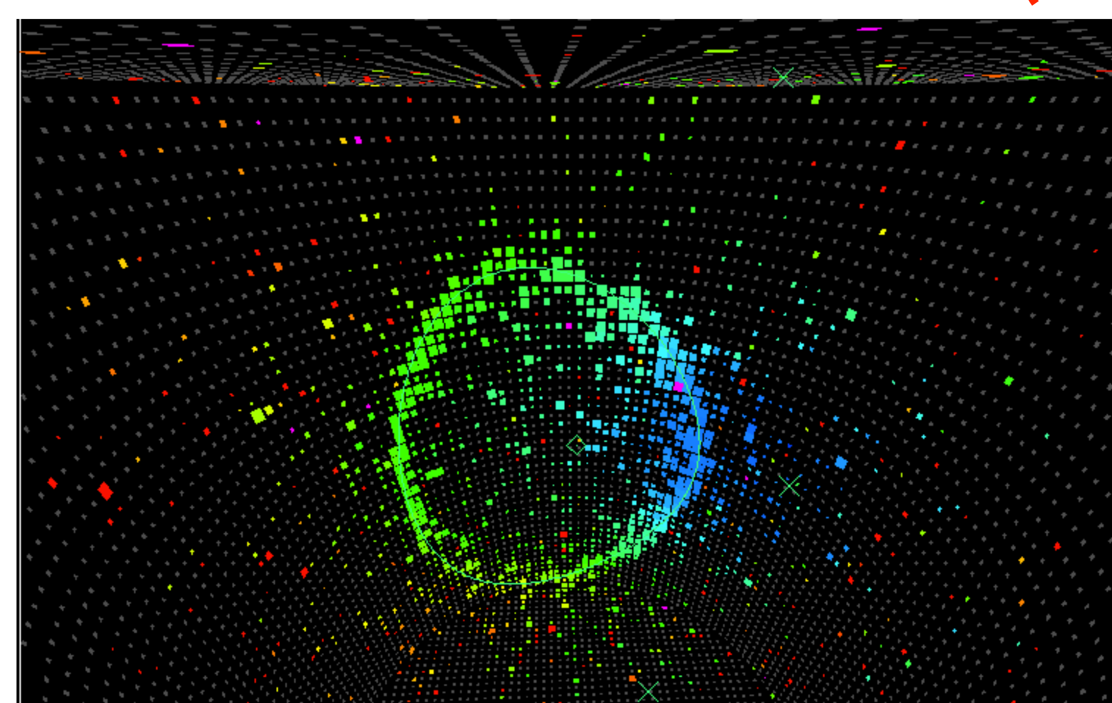
Super-K







- 500 kW (today)
- ~1MW (2025)
- 1.3 MW (2028)



- 22.5 kton (Super-K, ~2027)
- 190 kton (Hyper-K, 2027~)

The T2K Collaboration

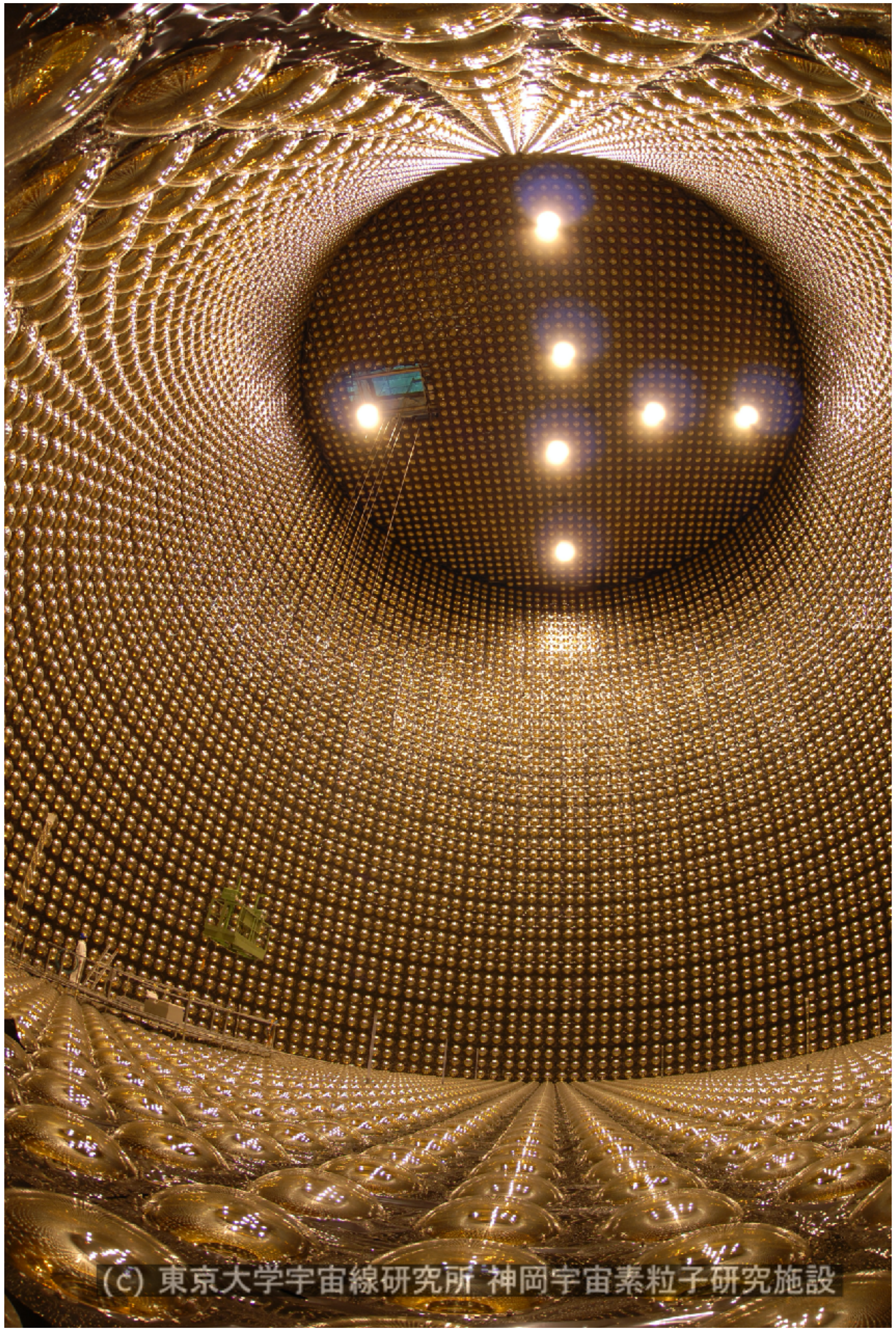
~500 members, 69 Institutes, 12 countries

T2K

J-PARC

Super-K

Super-Kamiokande



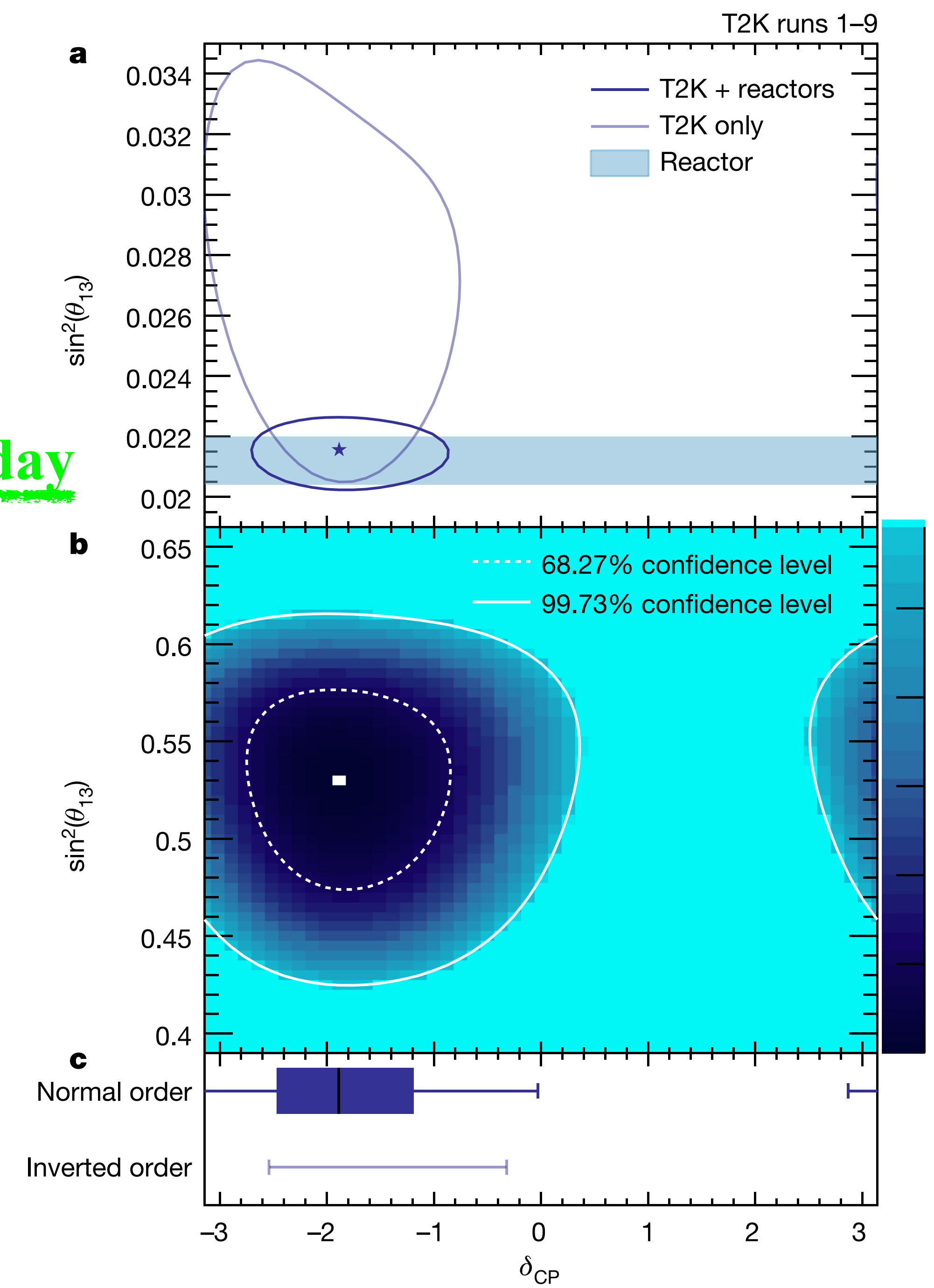
Outline

1. Physics (addressed by the accelerator experiments)
2. Proton Accelerator: J-PARC
3. Neutrino Beam
4. Neutrino Cross section (briefly)
5. Near Detectors: ND280
6. Far Detector: Super-Kamiokande

Today

7. Oscillation Analysis
8. Latest OA results
9. Future Prospect
    1. T2K Upgrade
    2. Hyper-Kamiokande

Nature 580 (2020) 7803, 339-344



Recent references

1. Nature 580 (2020) 7803, 339-344
   - Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations
2. PHYSICAL REVIEW D 103, 112008 (2021)
   - Improved constraints on neutrino mixing from the T2K experiment with 3.13×10^{21} protons on target
3. 1805.04163 [physics.ins-det]
   - Hyper-Kamiokande Design Report

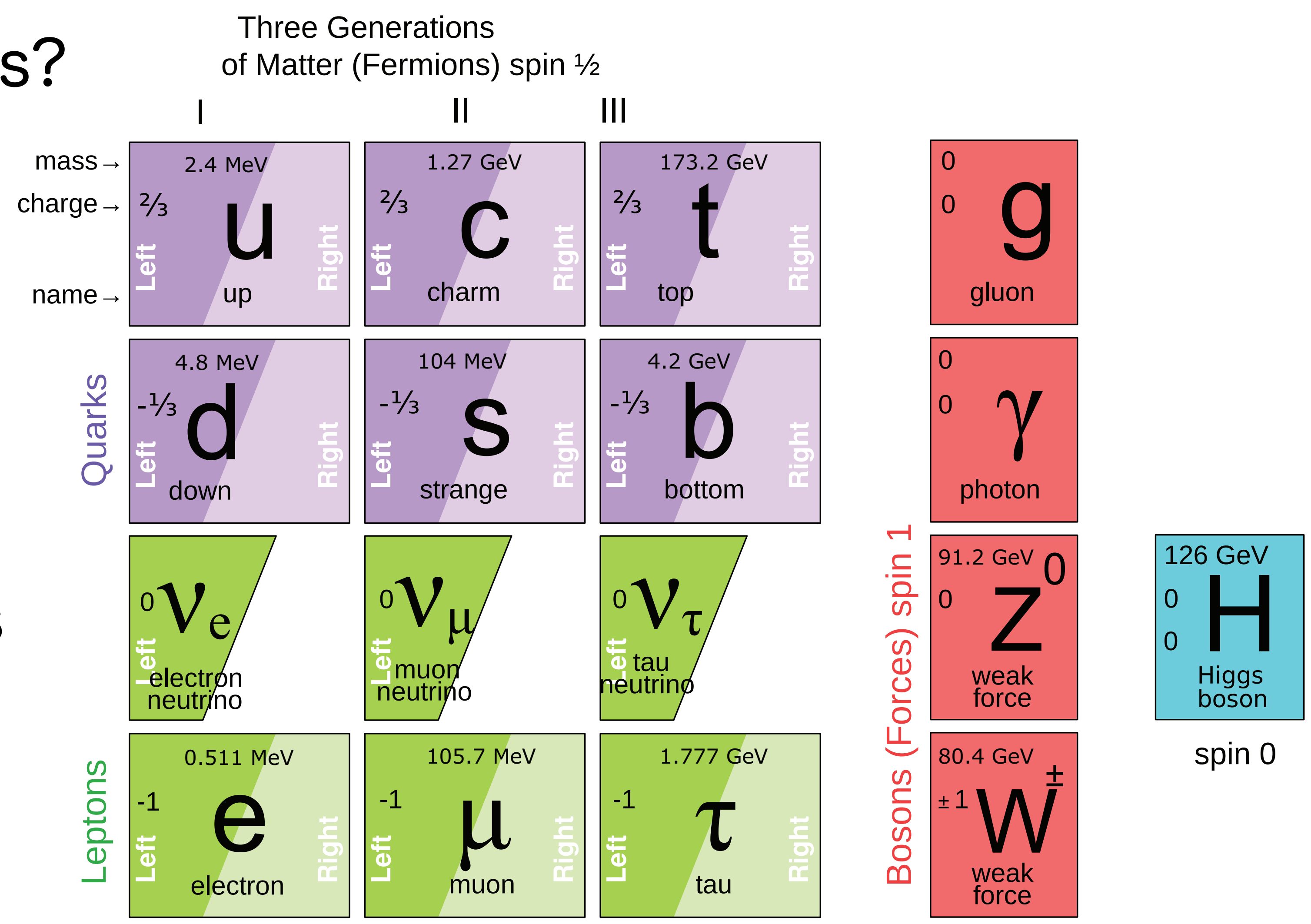
1. Physics

- addressed by the accelerator experiments -

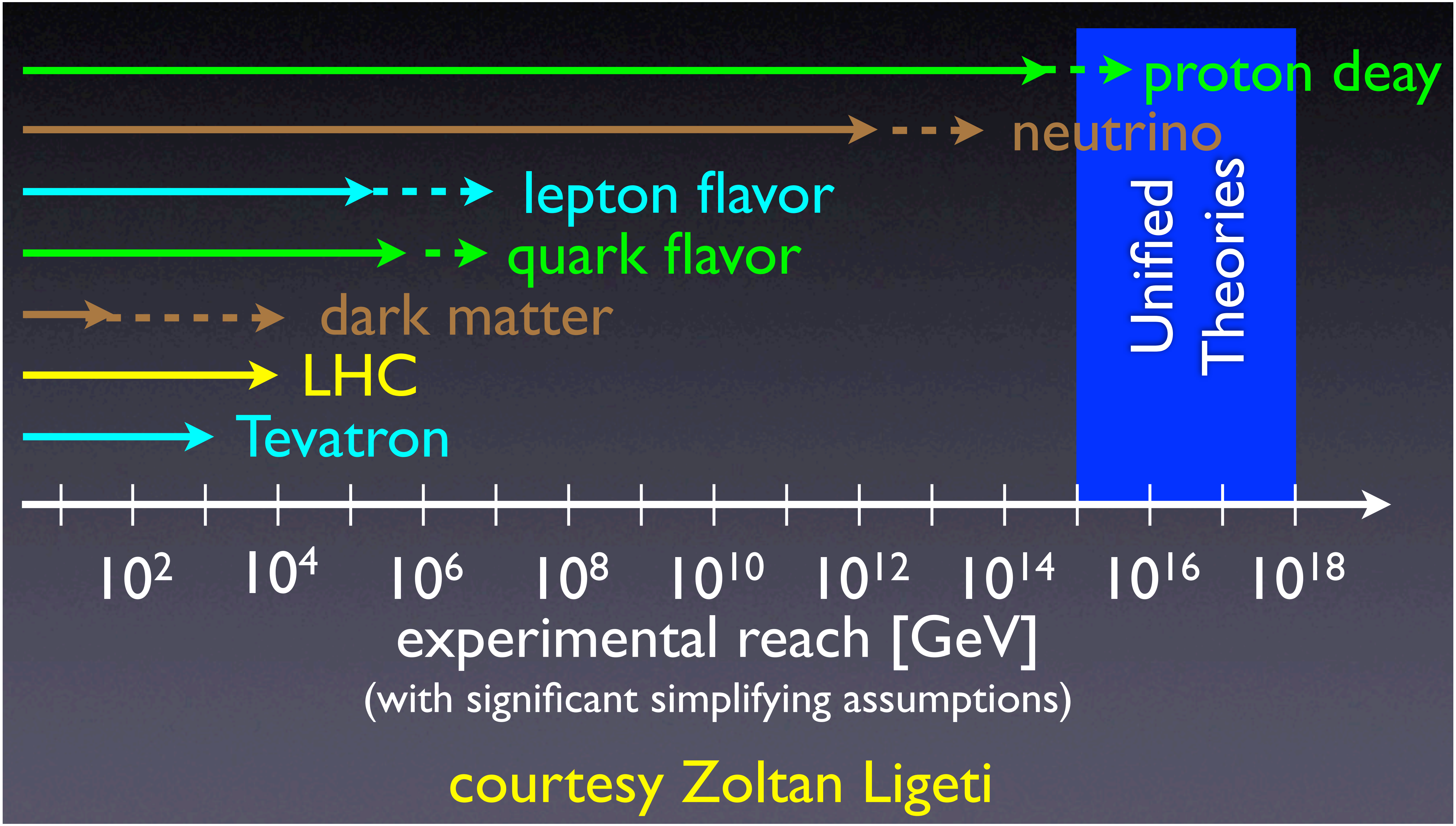
Introduction

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

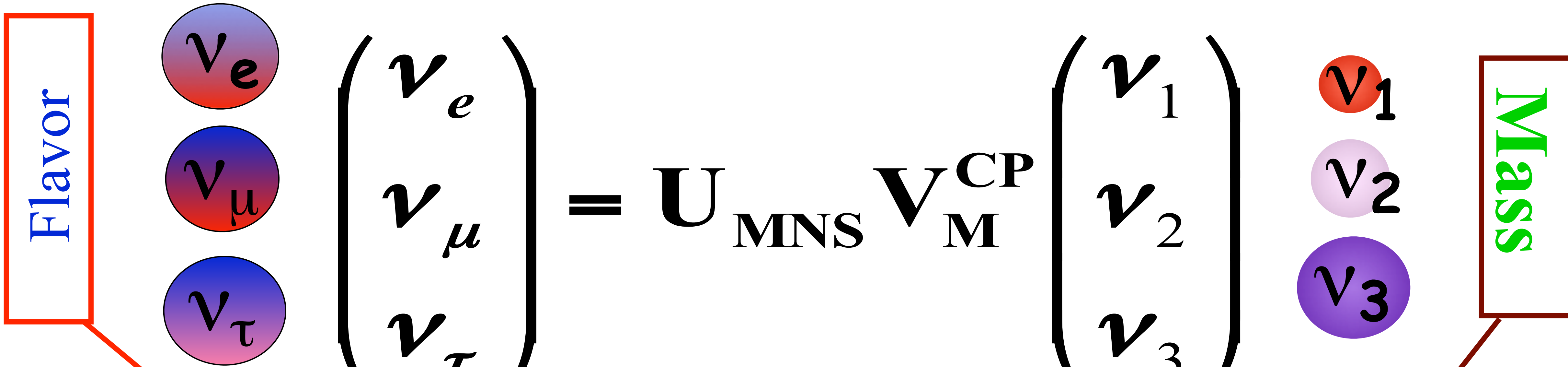
- Tiny Neutrino mass
  - What is the origin of the mass?
- Flavor Symmetry
  - Between leptons and quarks
    - mass pattern
    - mixing pattern
    - the number of generations
- CP violation
  - the origin?
  - matter dominant universe with Leptogenesis



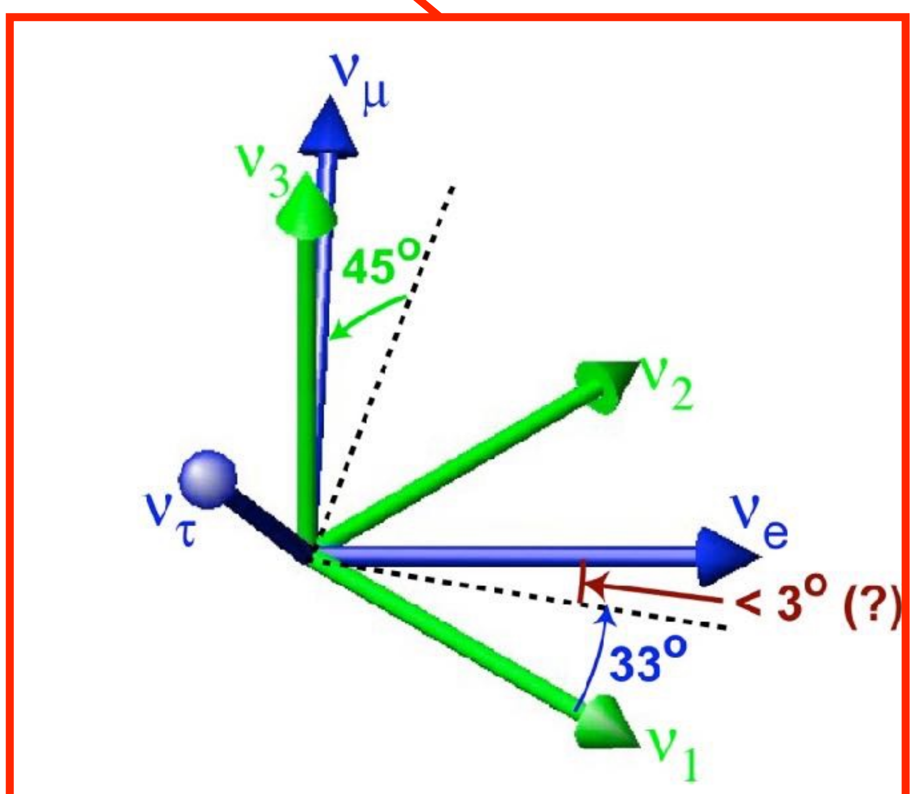
A window to Ultra High Energy



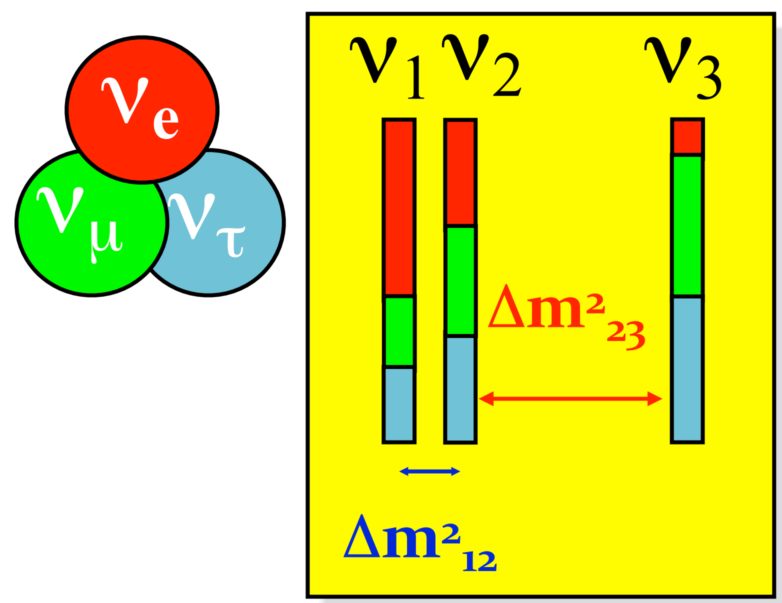
Neutrino Oscillation



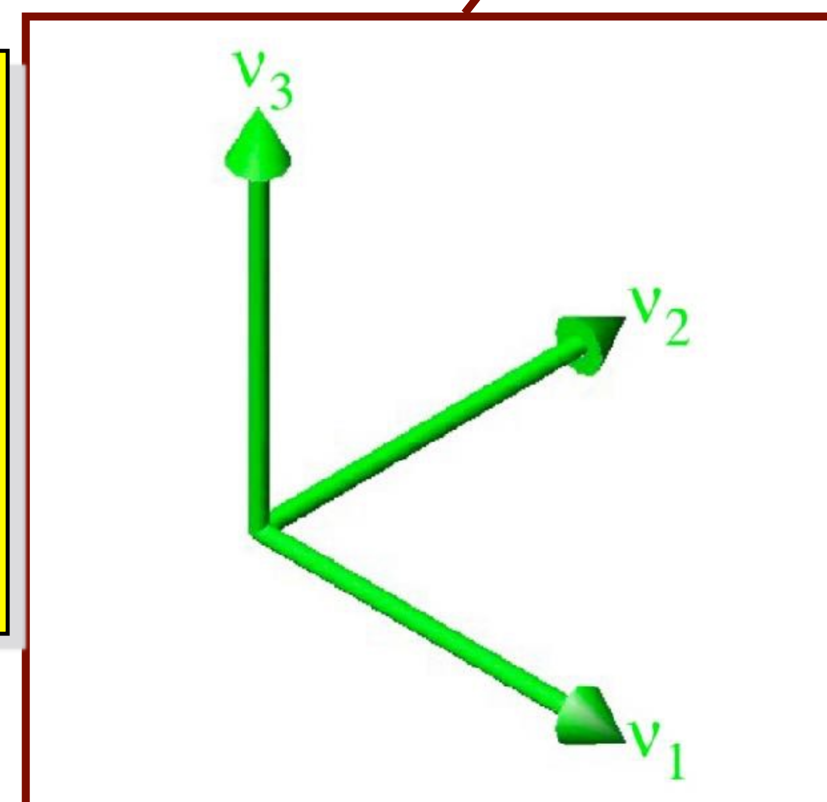
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNS} V_M^{CP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



NH case: $m_3 > m_1, m_2$



IH case: $m_3 < m_1, m_2$



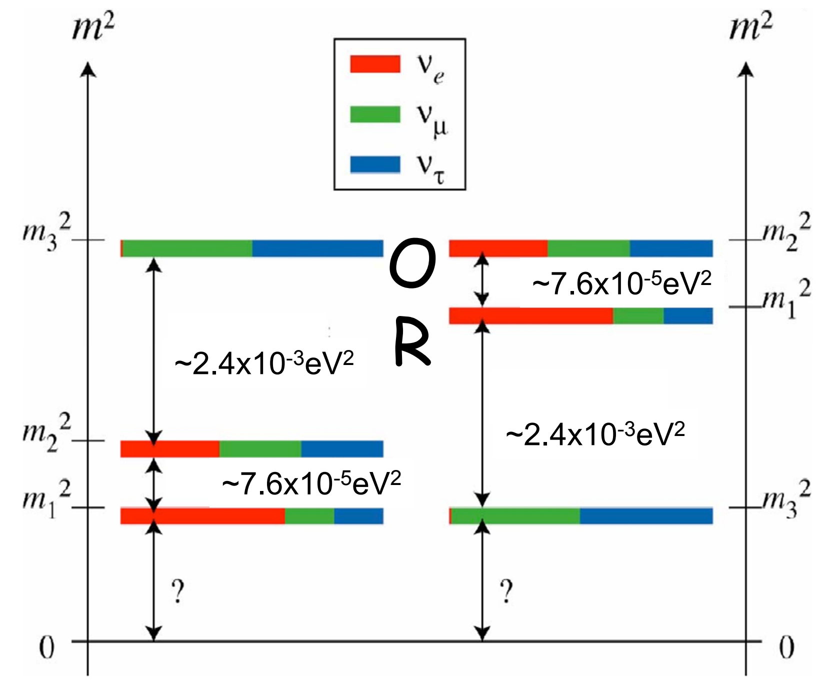
Mass and mixing are addressed by neutrino oscillation

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 (first matrix) — Accelerator, Reactor, Atmospheric (second matrix) — Solar, Reactor (third matrix)

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

δ～unknown

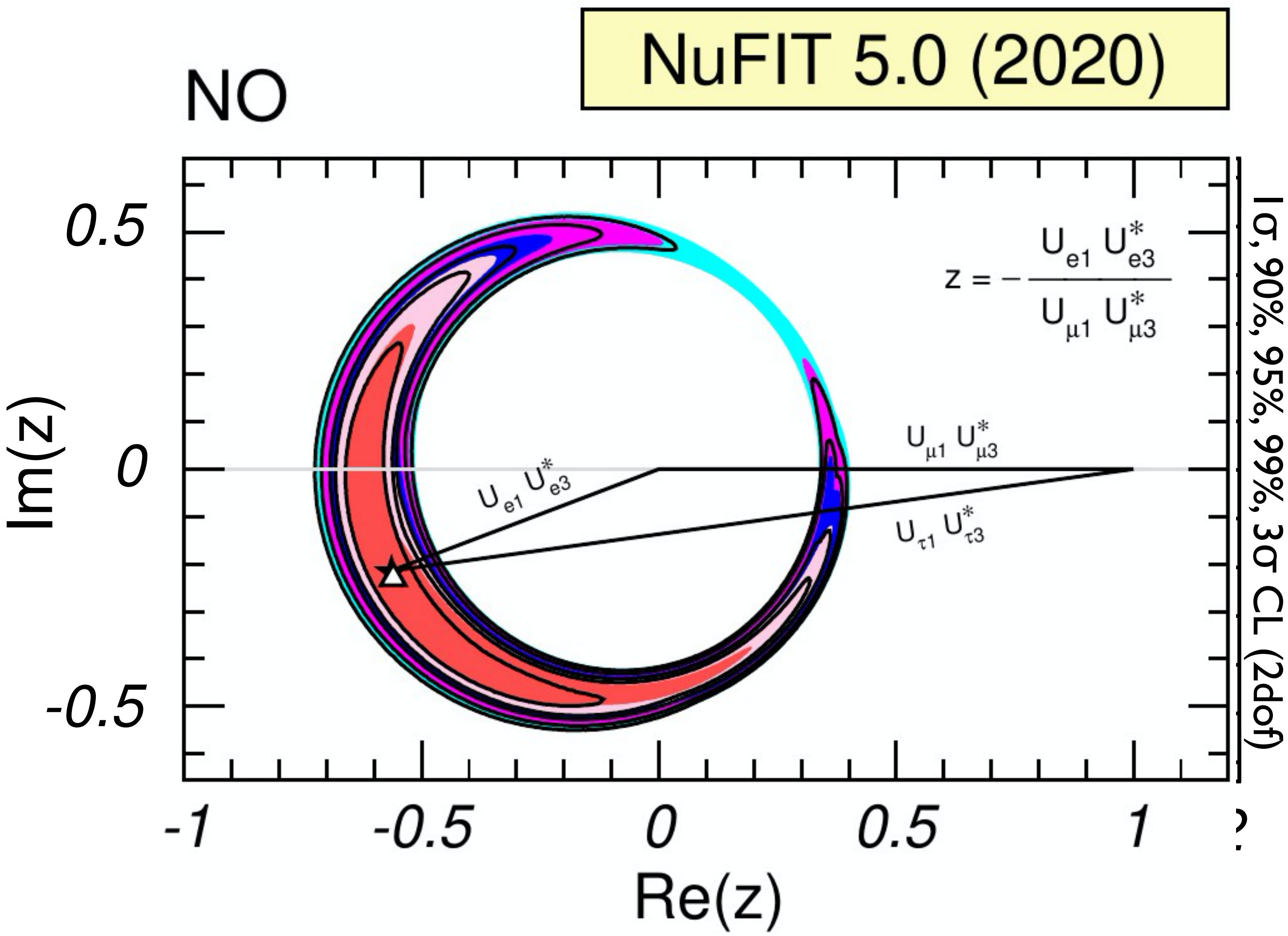
$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

δ=60°

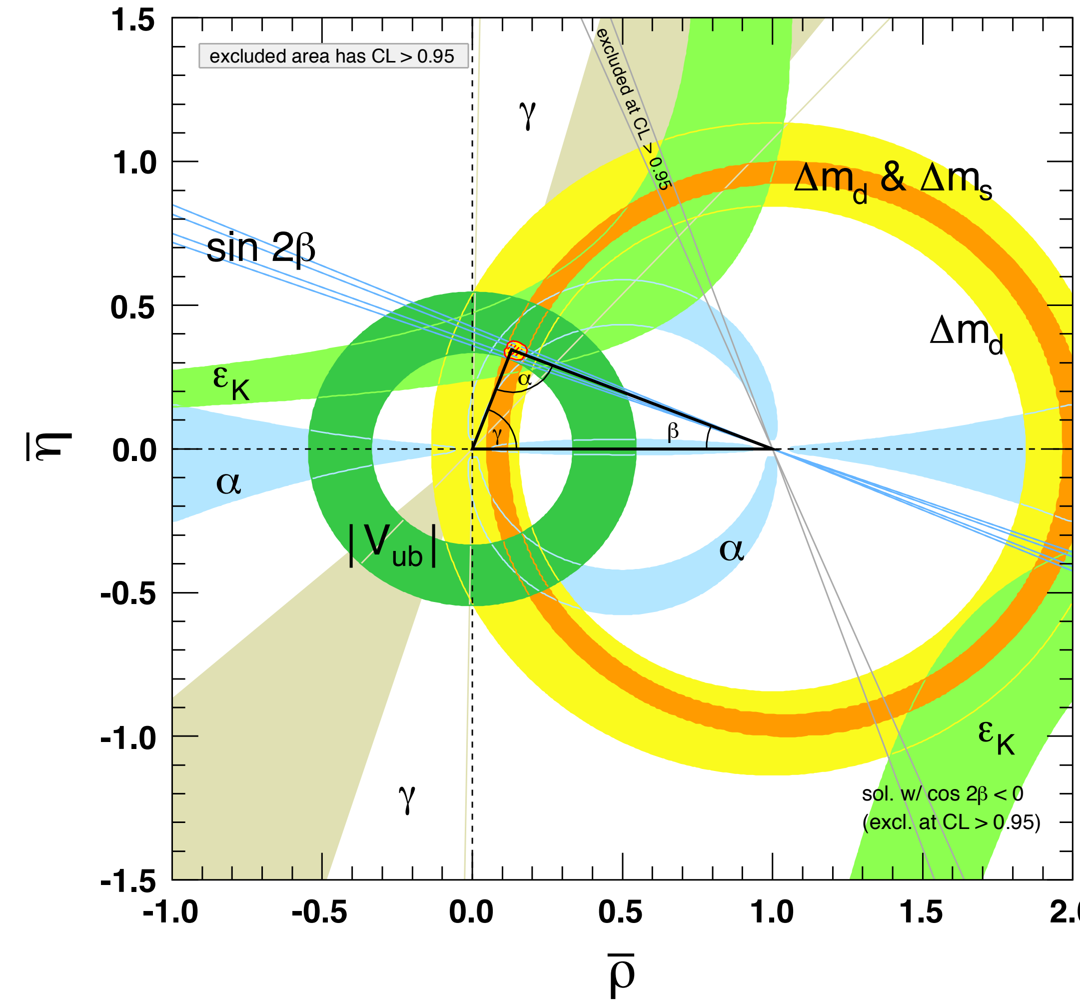
- In the framework of 3 neutrinos, the unknowns are
  - mass ordering
  - CP violation parameter: δ_{CP}

Three neutrinos and Beyond

Leptonic unitarity triangle



Quark



Assuming unitarity (3 neutrinos)

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

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:

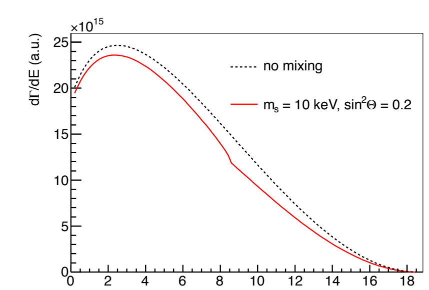
- some theoretical arguments
  - no new scale Asaka/Shaposhnikov
  - classical scale invariance Khoze/Ro, . . .

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)

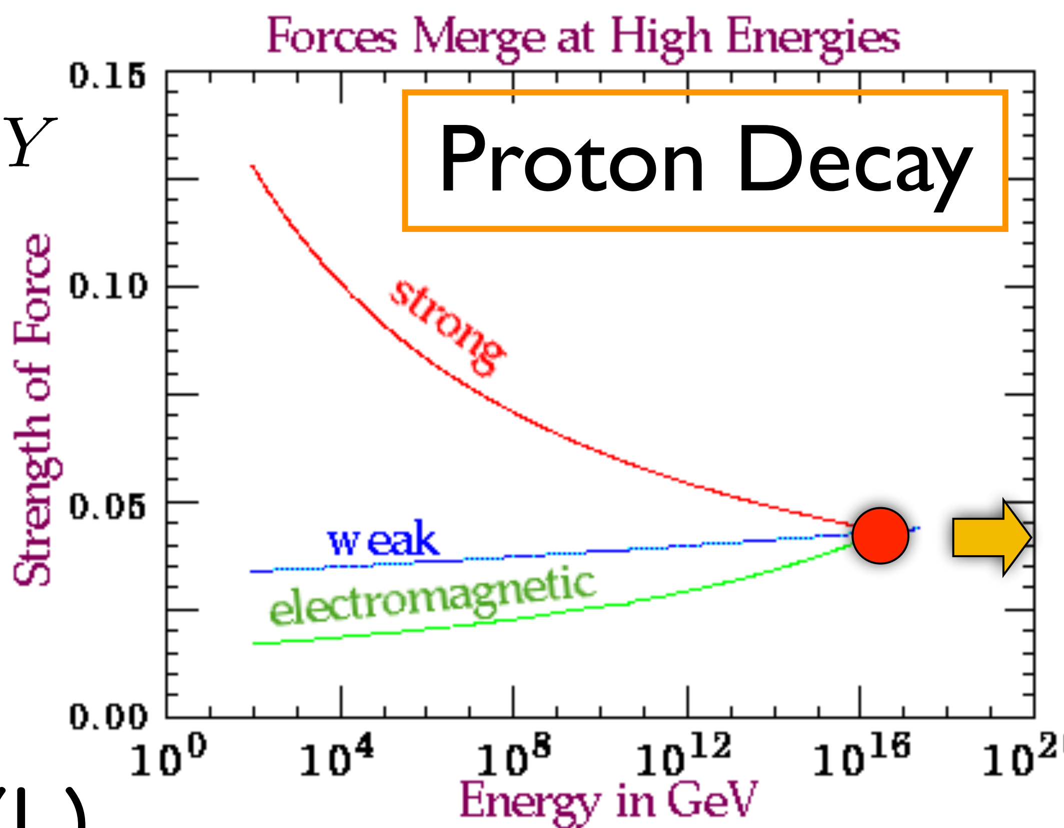
      $SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

   2. Quark and Leptons

      $\boxed{Q \quad U_R^c \quad E_R^c} \; \boxed{D_R^c \quad L} \; \boxed{N_R^c}$

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

      - 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

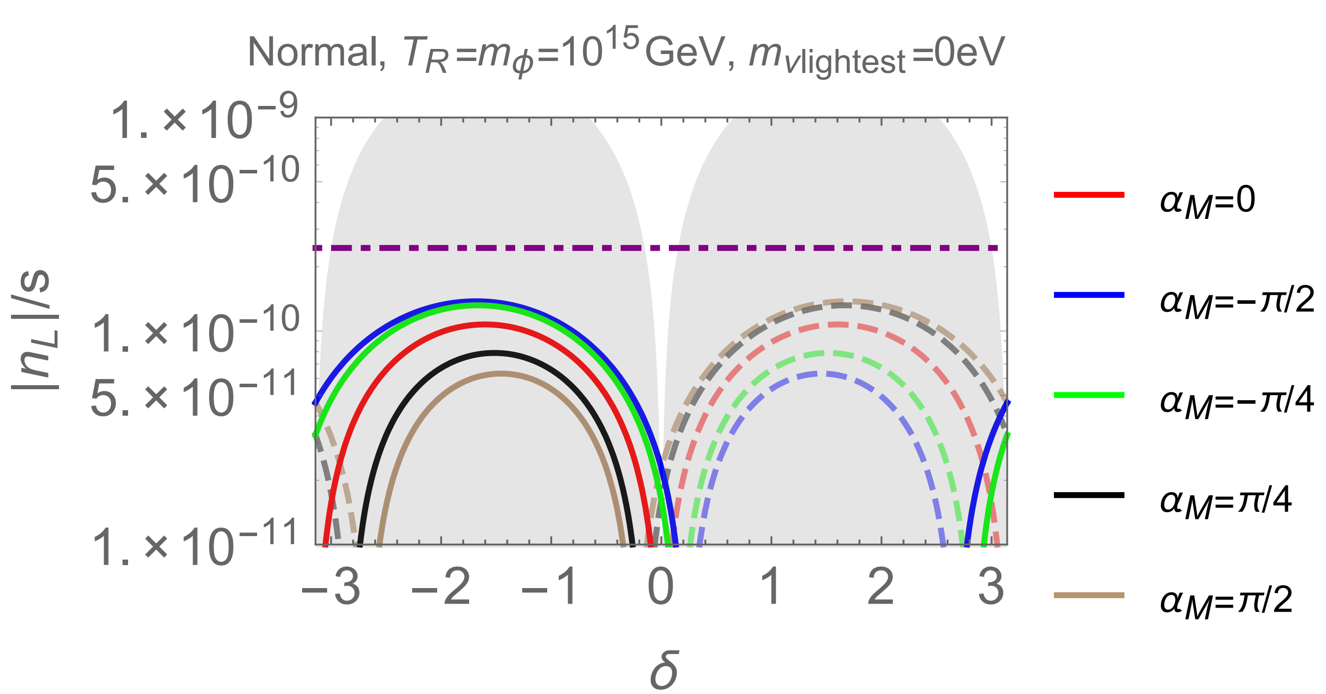
- Leptogenesis and Low Energy CP violation in Neutrinos
  - [B] Sphaleron process for $\Delta(B+L) \neq 0$
  - [CP] Heavy Majorana Neutrino decay and/or Neutrino oscillations
    - $|\sin\theta_{13}\sin\delta|>0.09$ is a necessary condition for a successful "flavoured" leptogenesis with hierarchical 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)].
      - $\sin\theta_{13} \sim 0.15$ ➡ $|\sin\delta|>0.6$

Leptogenesis via neutrino oscillation magic

Yuta Hamada,[a,b] **Ryuichiro Kitano**[a,c] **and Wen Yin**[d]

Abstract: The possibility of generating the baryon asymmetry of the Universe via flavor oscillation in the early Universe is discussed. After the inflation, leptons are born in some states, travel in the medium, and are eventually projected onto flavor eigenstates due to the scattering via the Yukawa interactions. By using the Lagrangian of the Standard Model with the Majorana neutrino mass terms, $llHH$, we follow the time evolution of the density matrices of the leptons in this very first stage of the Universe and show that the CP violation in the flavor oscillation can explain the baryon asymmetry of the Universe. In the scenario where the reheating is caused by the decay of the inflaton into the Higgs bosons, the baryon asymmetry is generated by the CP phases in the Pontecorvo-Maki-Nakagawa-Sakata matrix and thus can be tested by the low energy neutrino experiments.

JHEP10(2018)178



Formula of Oscillation Probability with CP violation

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

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

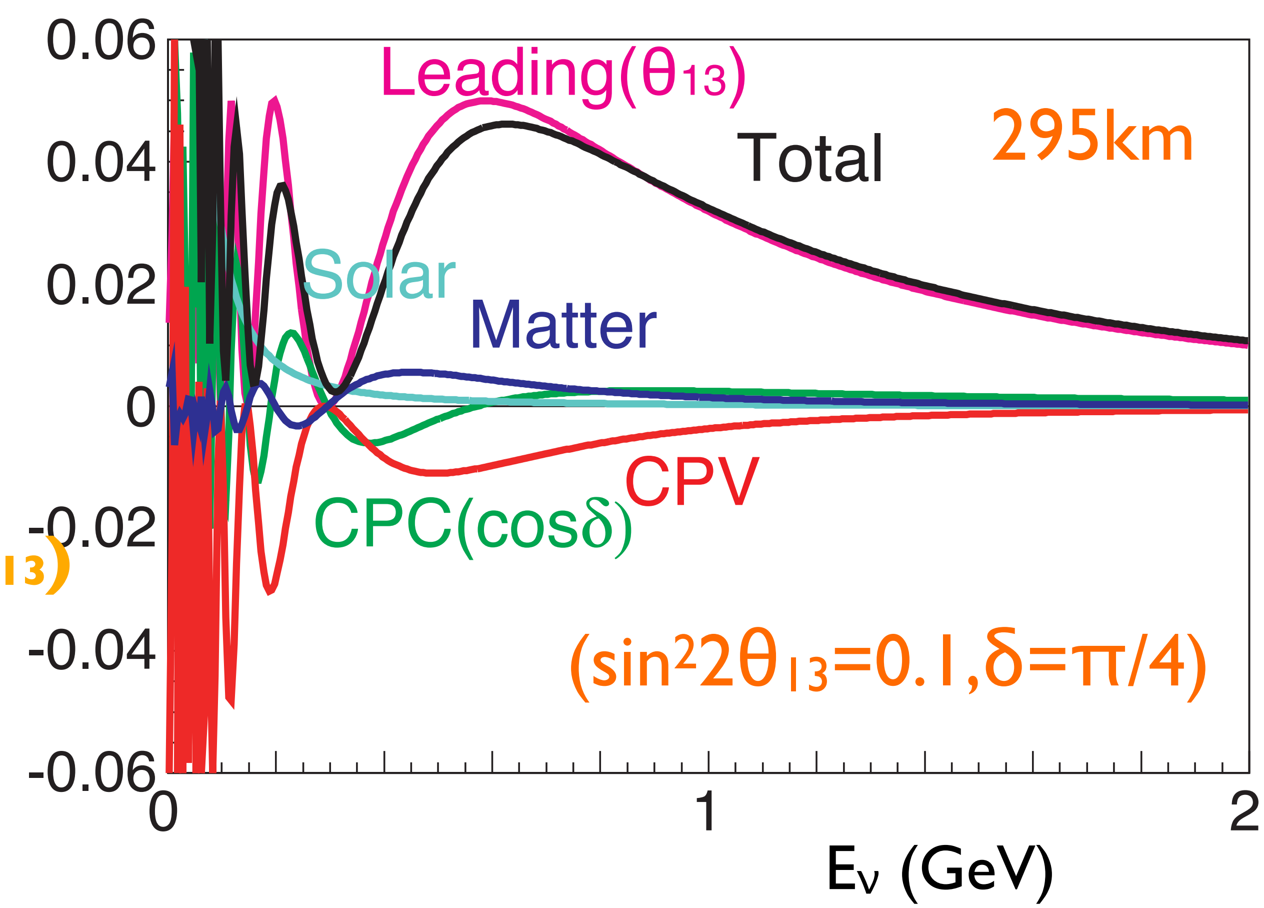
$$\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}\sin\delta$$

~0.03 ~11.8 (6.4 from $1/\sin\theta_{13}$)

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

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

27%

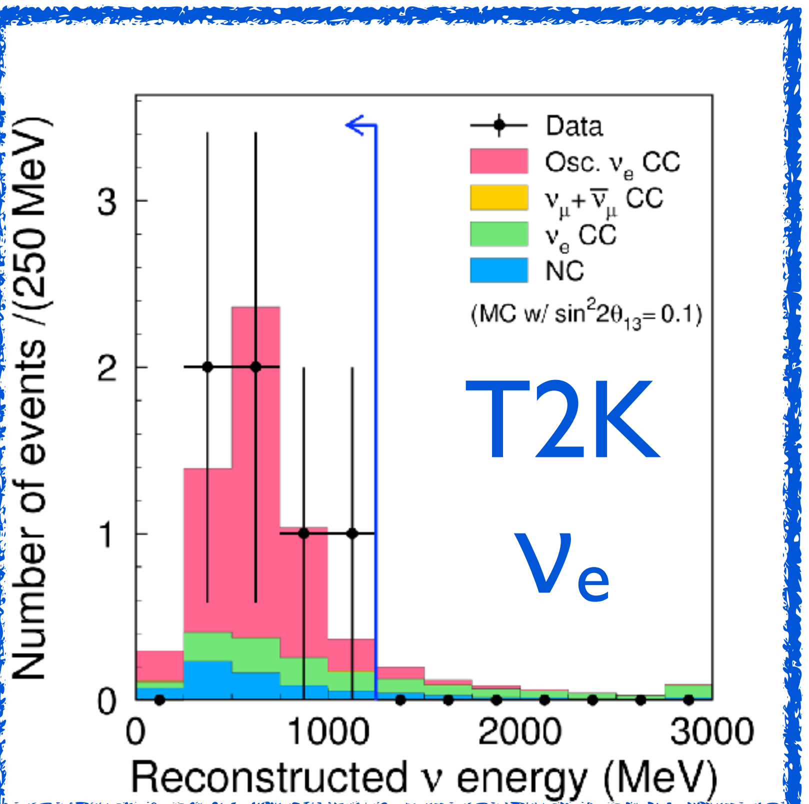


- Energy dependence.

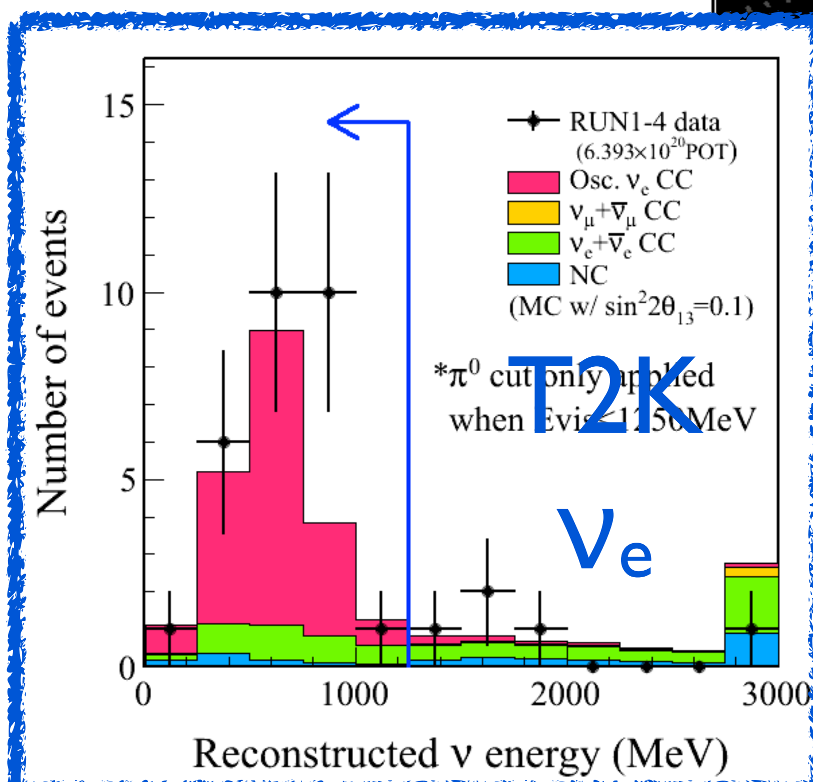
A door to Neutrino CP violation is opened

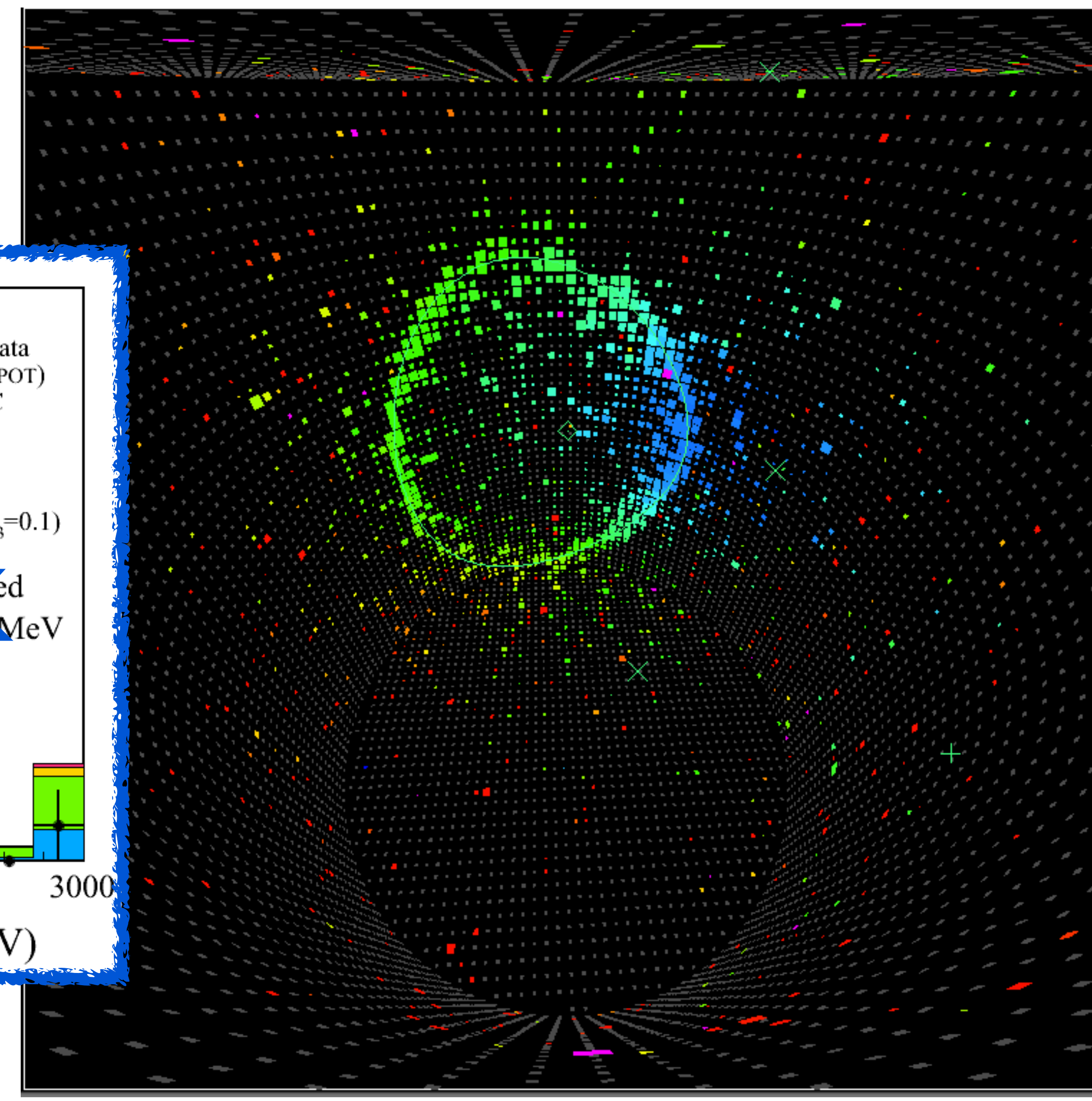
- $\nu_\mu \rightarrow \nu_e$ oscillation w/ Δm_{atm}^2 discovered by the T2K experiment
  - Indication in 2011 [PRL 107, 041801 (2011)]
  - Observation in 2013 [PRL 112, 061802 (2014)]

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

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}$$

constrain by ν_μ disp.

$$-\alpha \sin \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta_{31} \frac{\sin[x\Delta_{31}]}{x} \frac{\sin[(1-x)\Delta_{31}]}{1-x}$$

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

$$+(\text{CP even}) \quad +\mathcal{O}(\alpha^2)$$

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

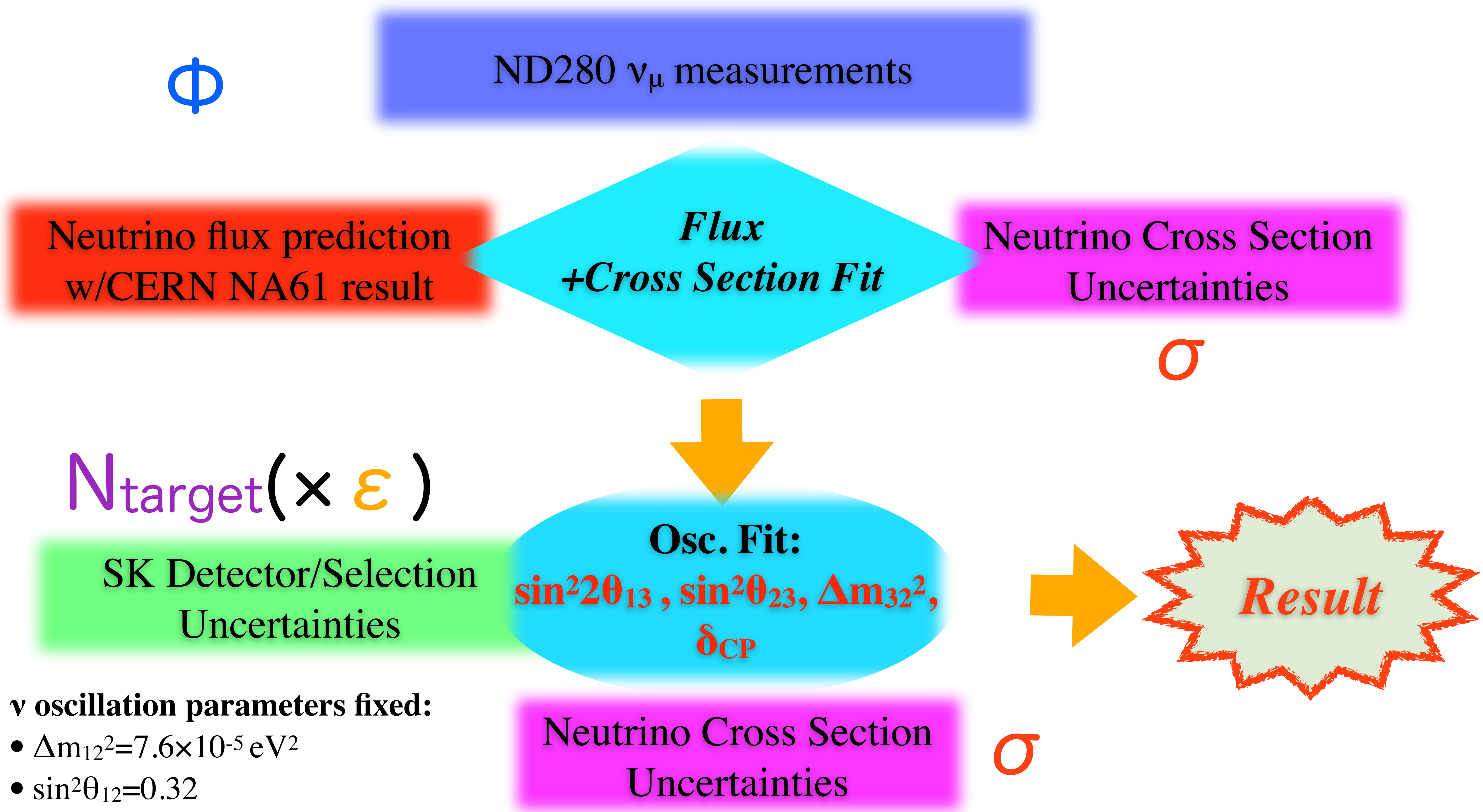
M. Freund, Phys.Rev. D64 (2001) 053003

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

- 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:

- $\Delta m_{12}^2 = 7.6\times10^{-5}$ eV^2
- $\sin^2\theta_{12} = 0.32$

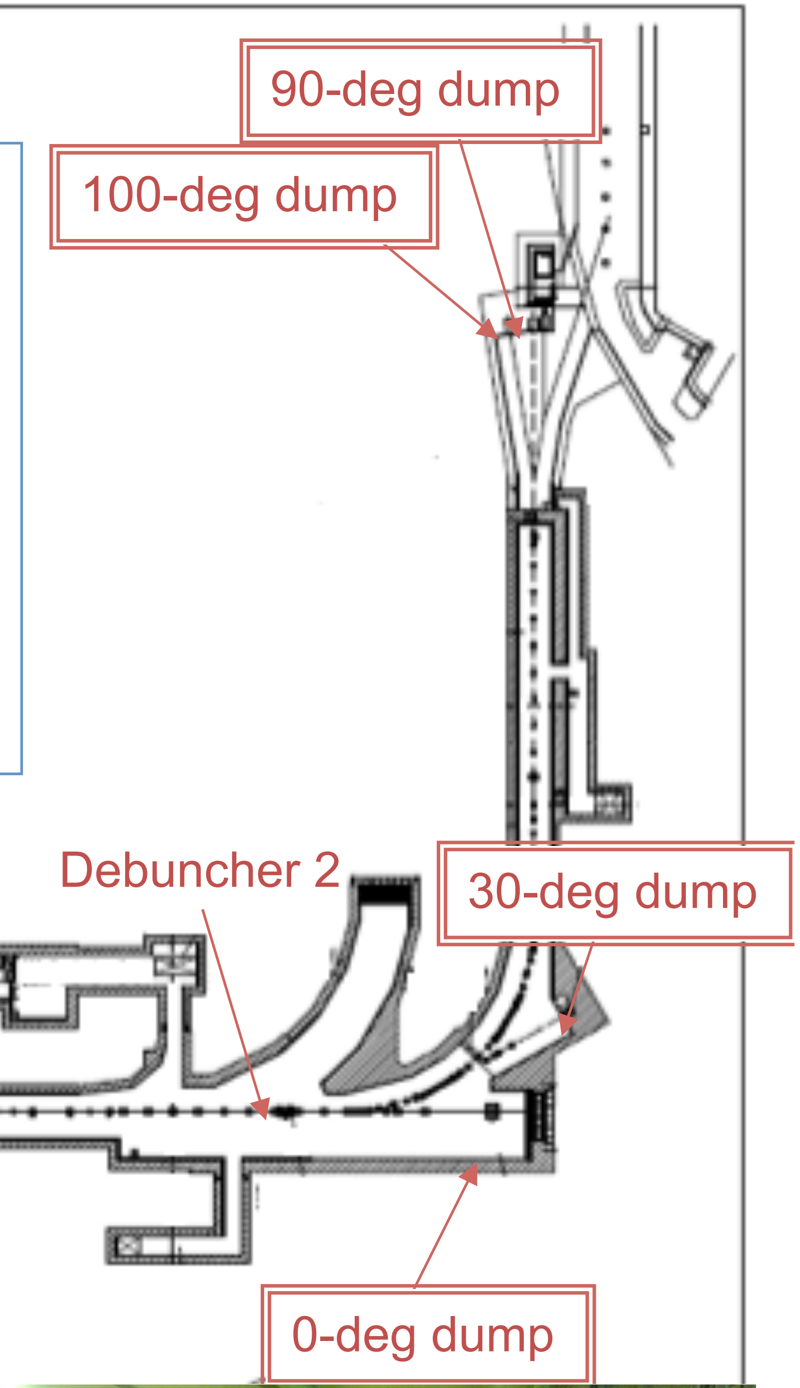
2. J-PARC

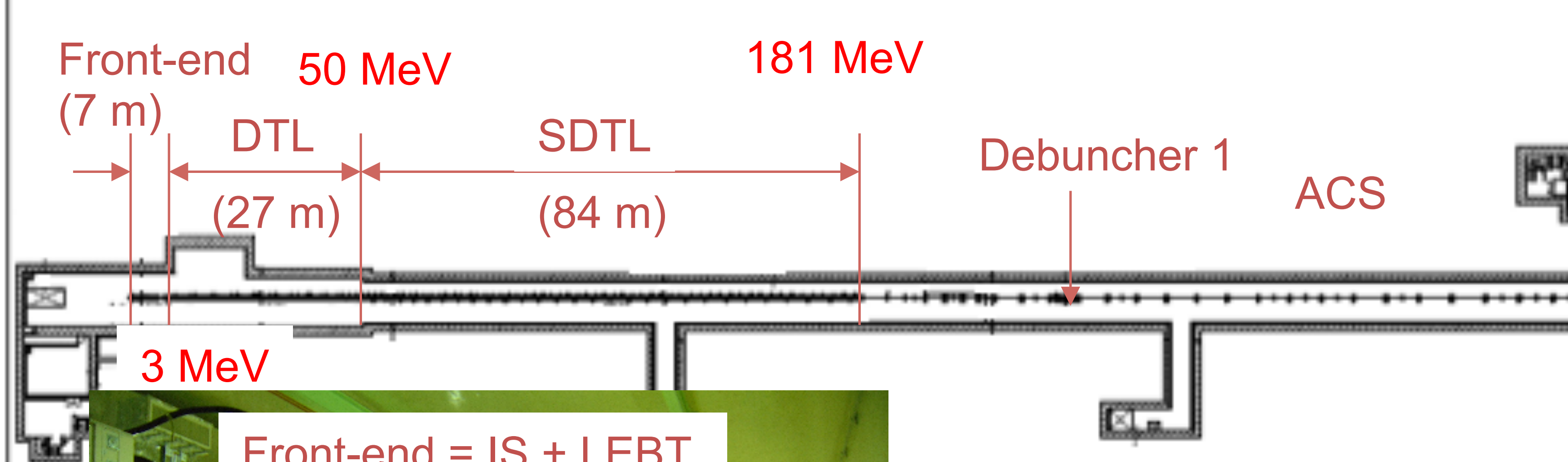
- Proton Accelerator -

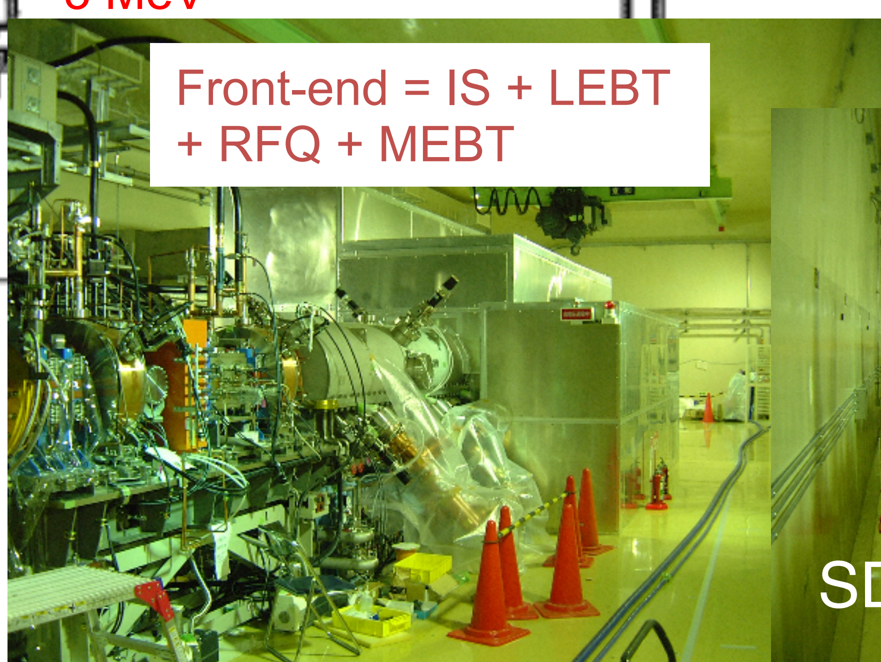
J-PARC
(Japan-Proton-Accelerator Research Complex)

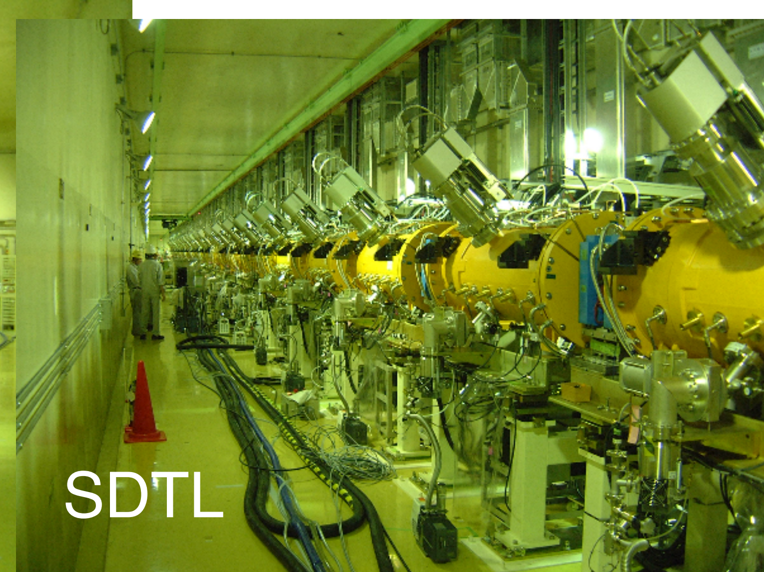
Linac

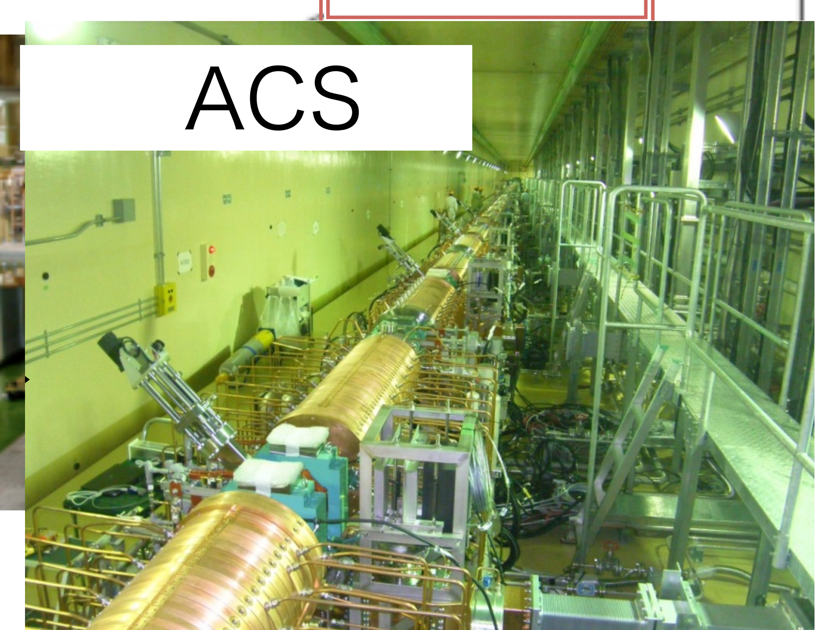
- **Particle:** H⁻
- **Energy:**
  400 MeV by installing ACS
- **Peak current:**
  50 mA at 400 MeV in 2013
- **Repetition:** 25 Hz
- **Pulse width:** 0.5 msec







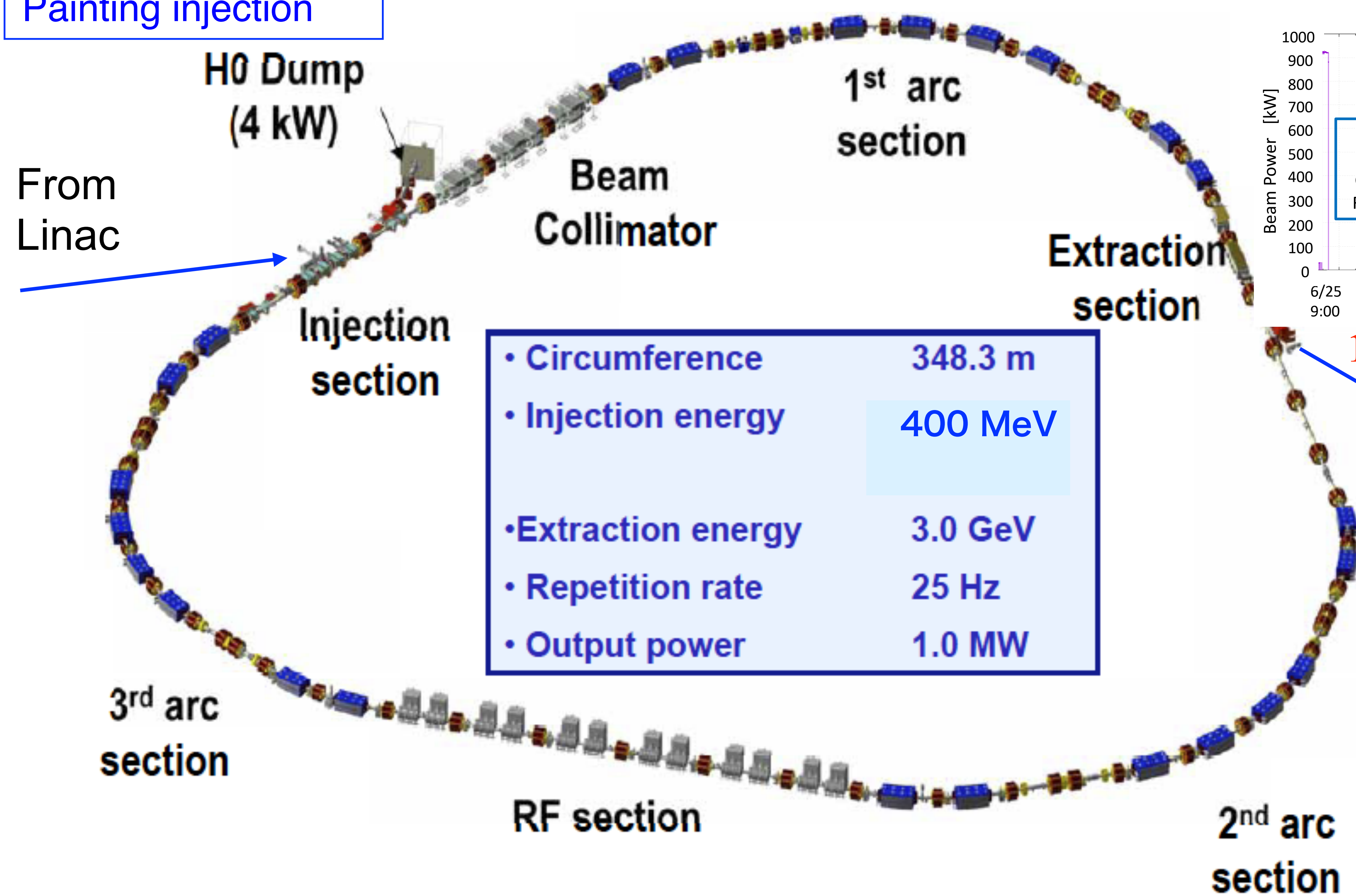


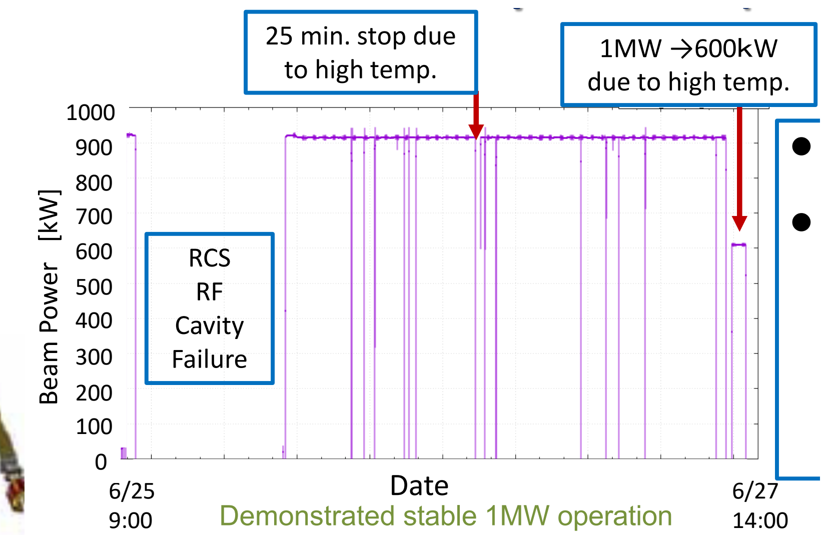


RCS (Rapid Cycling Synchrotron)

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

Charge-exchange & Painting injection





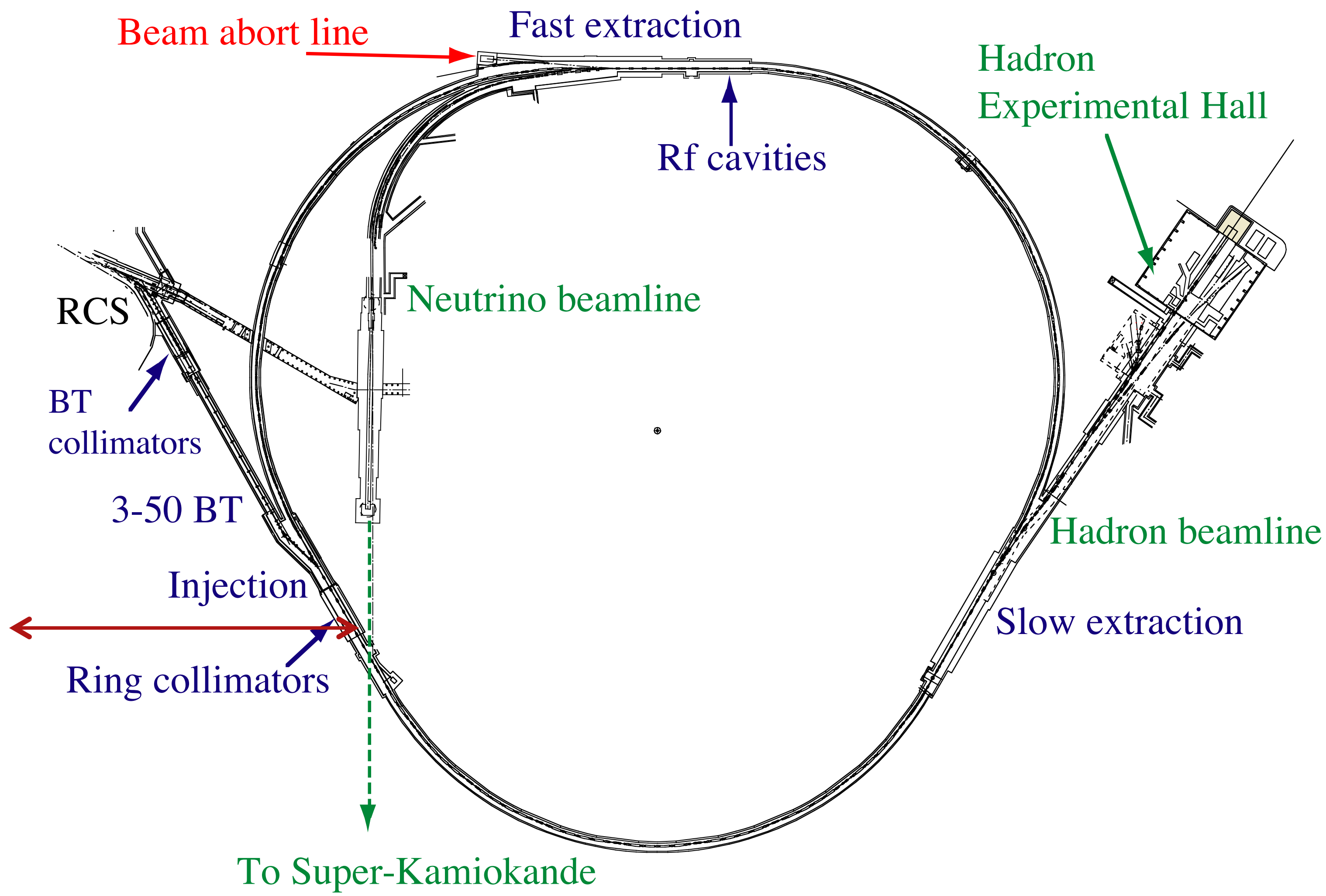
1MW Demonstration

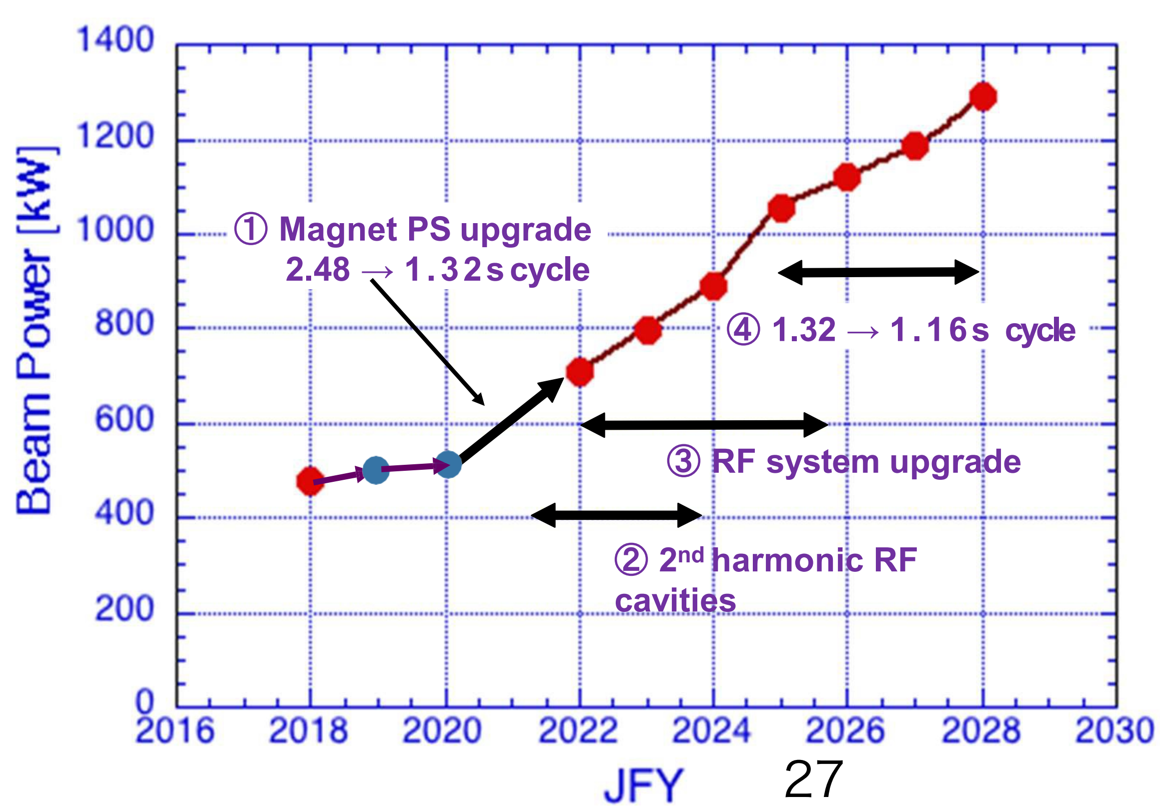
• Circumference	348.3 m
• Injection energy	400 MeV
•Extraction energy	3.0 GeV
• Repetition rate	25 Hz
• Output power	1.0 MW

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

- 515 kW (today)
- 1000 kW (2025)
- 1300 kW (2028)

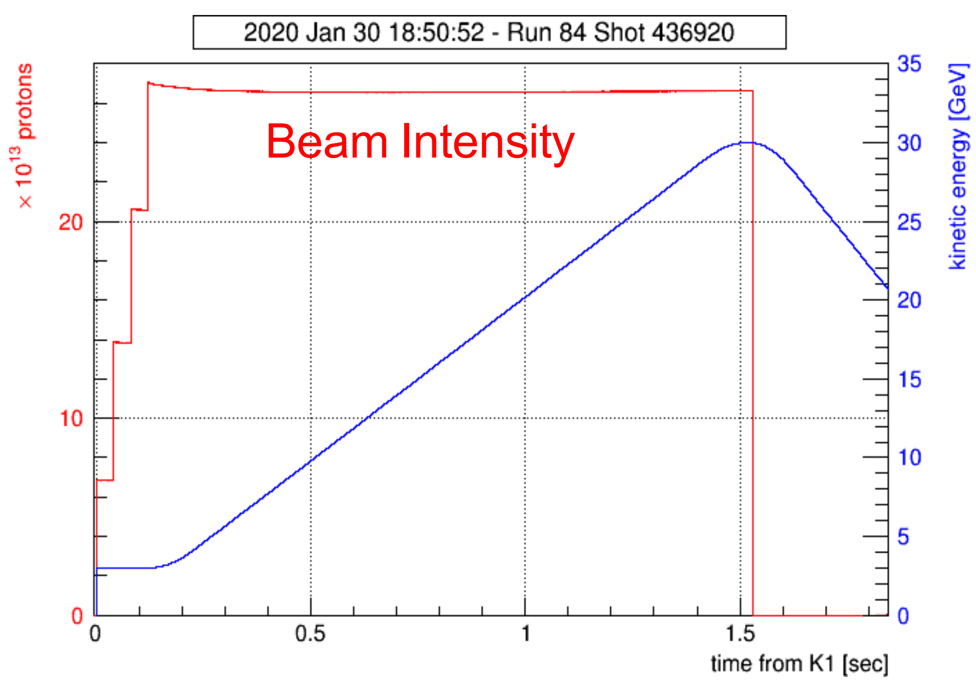
Mid-term Plan of MR

FX: The higher repetition rate scheme : Period 2.48s → 1.32 s for 750 kW
(= shorter repetition period) → 1.16 s for 1.3 MW
SX: Mitigation of the residual activity for the beam power upgrade

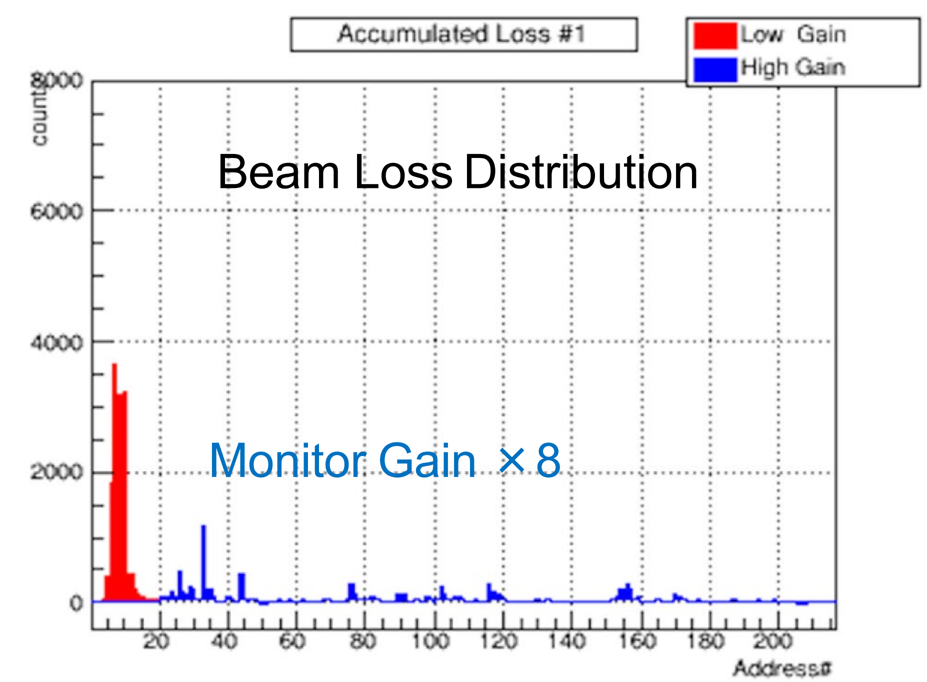
JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		long shutdown							
FX power [kW] SX power [kW]	515 55	- 60~70	>700 >80	800 >80	900 >80	>1000 >80	>1100 ~100	>1200 ~100	1300 ~100
Cycle time for Fast Extraction New Magnet PS	2.48s Mass Production Installation/Test		1.32s	1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
RF system upgrade 2nd harmonic rf system									
Collimator system		Add.colli. (3.5kW)							
Injection system FX system	Kicker PS improvement, Septa manufacture /test								
Beam Monitors (BPM circuits)									
SX Local sheild Diffuser/ Bent crystal/ VHF									

Improvement : High Intensity Beam Study

- The beam power of 515 kW was achieved with the cycle time of 2.48 s.
- The beam power would be 1.1 MW with the beam loss of 1.7 kW if the cycle time is 1.16 s.
- Further beam study is necessary to reduce the beam loss.



Extracted beam: 2.66e14 ppp

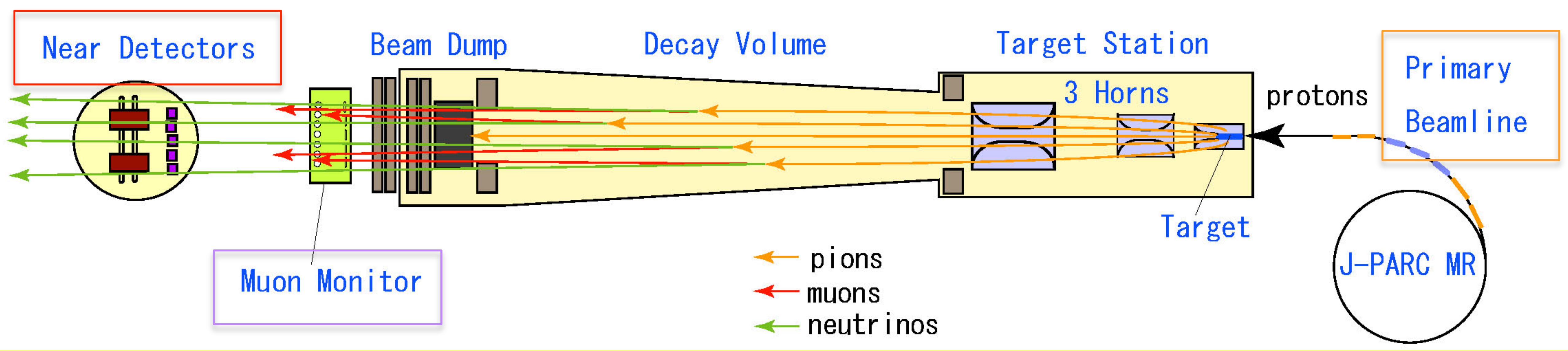


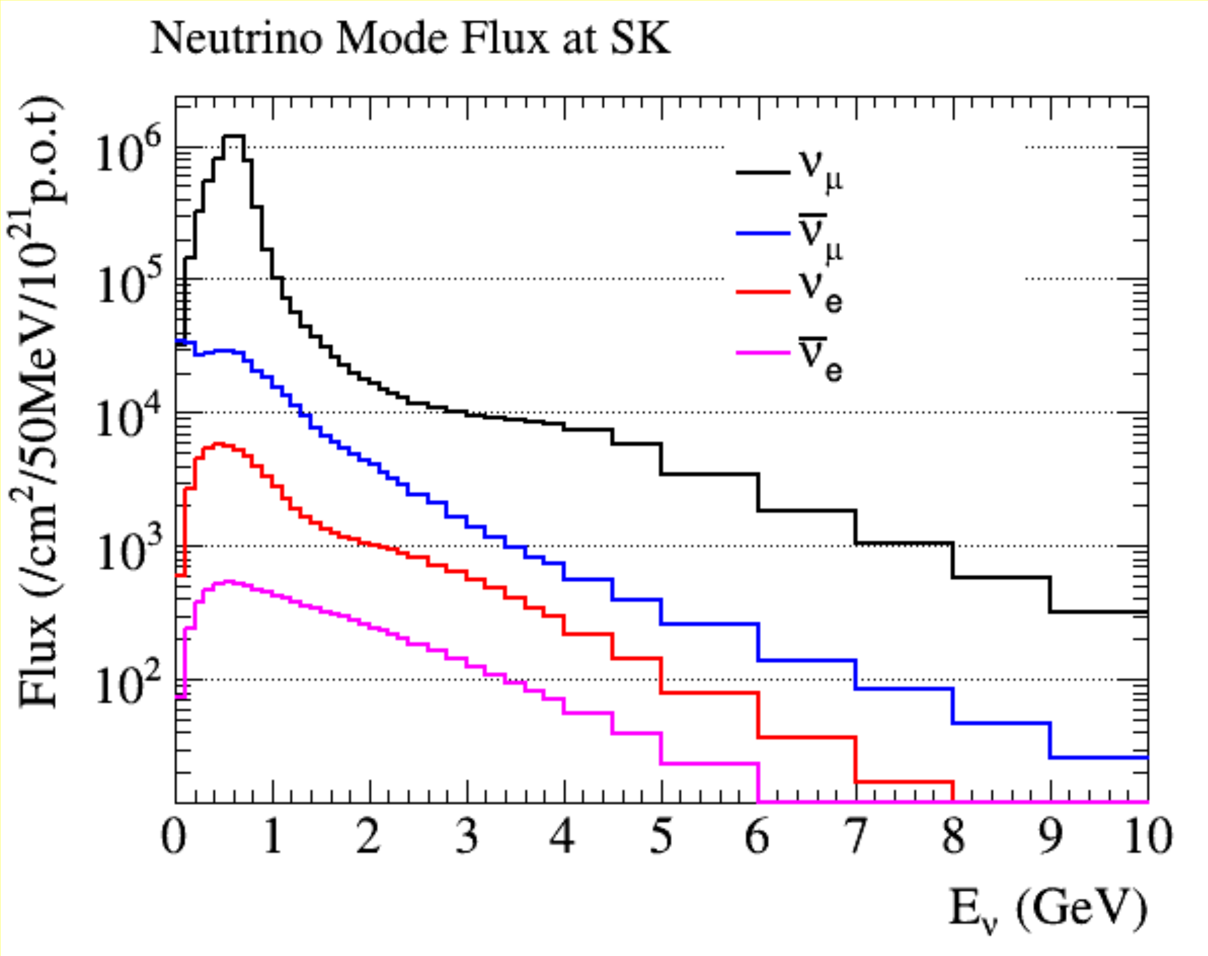
Total beam loss ~ 0.8 kW in the cycle of 2.48 s

	Protons per pulse	Bunch number	Repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
1	2.68e14	8	2.48	515	0.8	measurement
2	2.68e14	8	1.32	967	1.5	estimation
3	2.68e14	8	1.16	1100	1.7	estimation

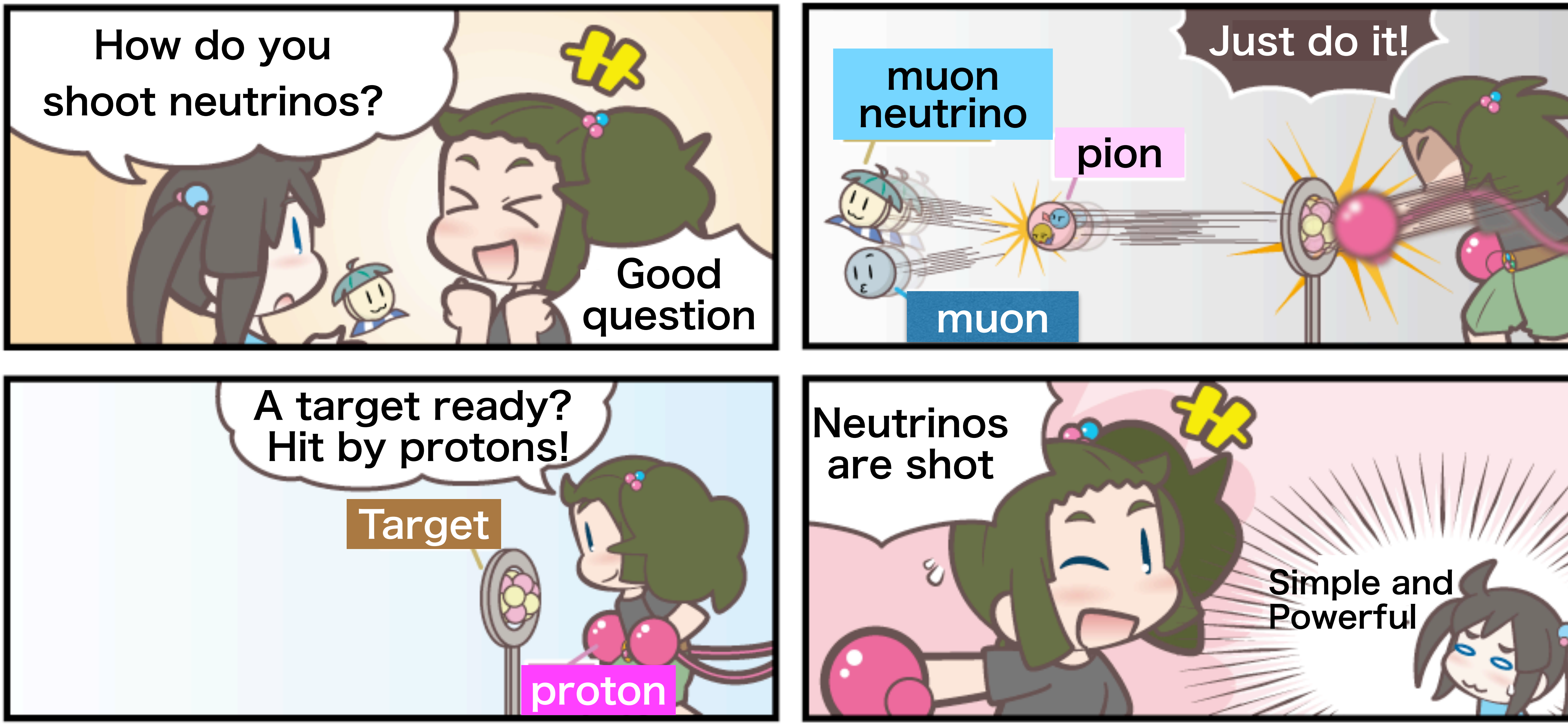
18

3. Neutrino Beam





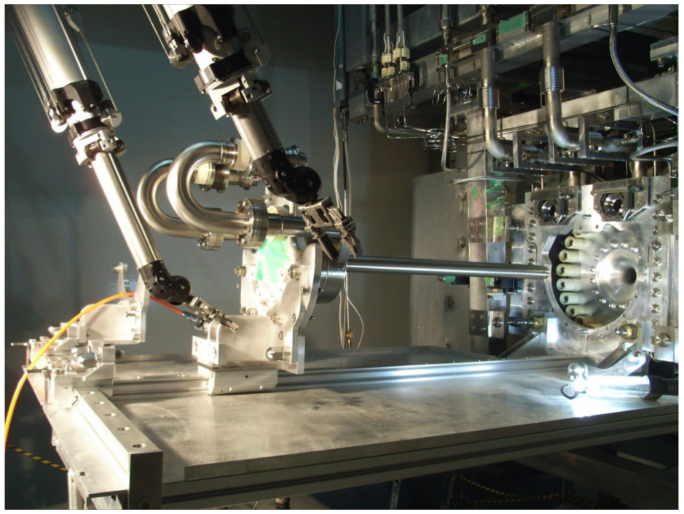
How to make neutrinos



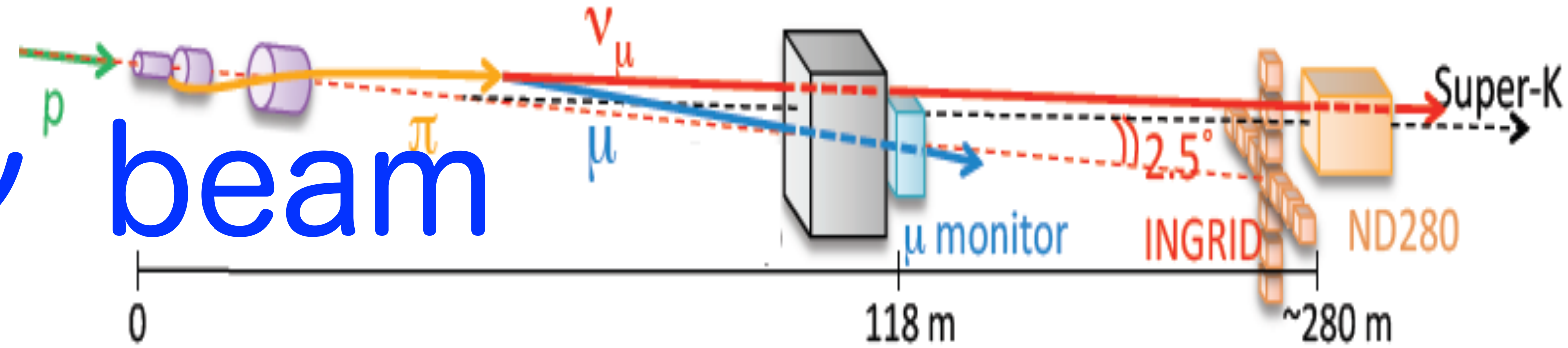
- **Proton Punch**：J-PARC's special.

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

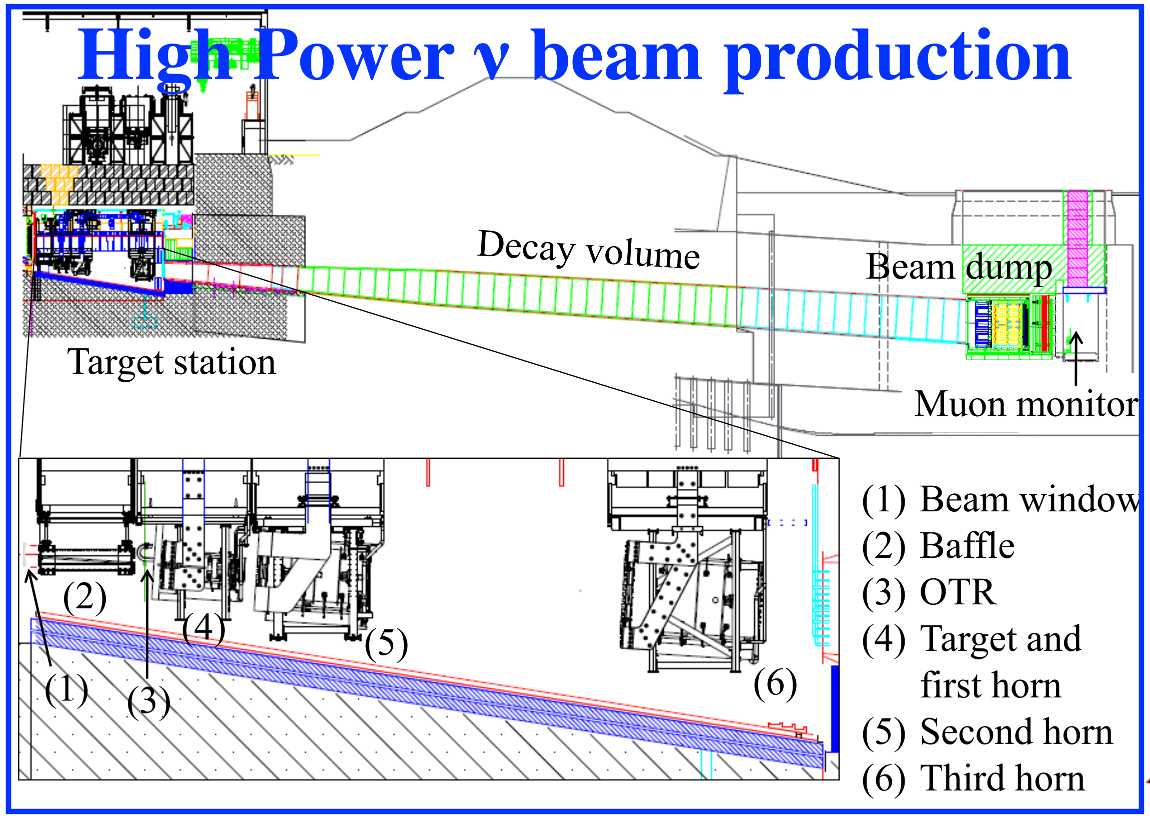
T2K ν beam

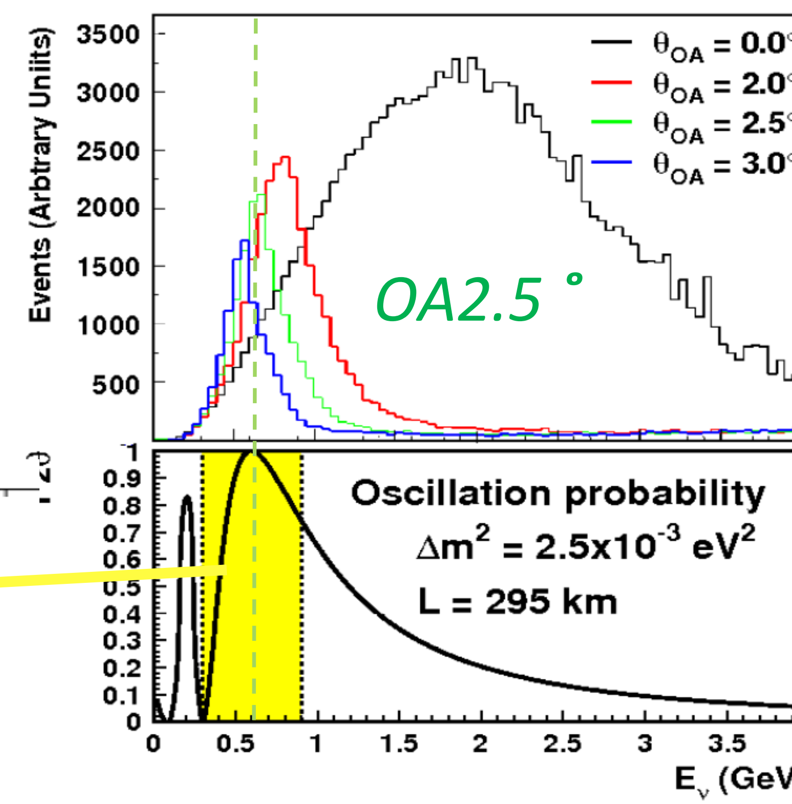


Target + remote handling system

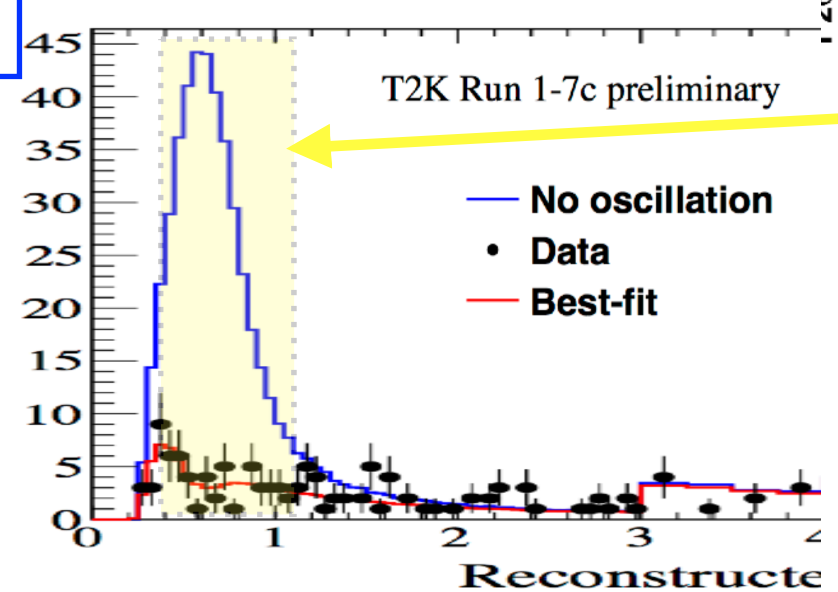


- **Off-axis (2.5 °) ν_μ beam**
  - Intense, low energy narrow-band
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - 1mrad direction shift => ~2% energy shift at peak
  - Small ν_e fraction (~1%)





T2K 2016 ν_μ disappearance



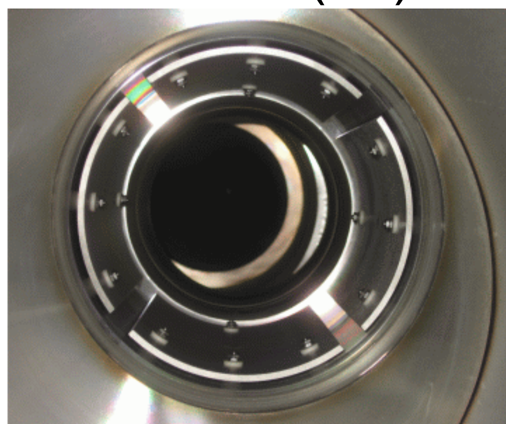
- 30 GeV **~1×10^{14}** protons extracted every 2.5 (1.2) sec. directed to the carbon target.
- Secondary π^+(and K^+) focused by three electromagnetic horns (**250kA (320kA)**)
- ν_μ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e in the beam come from K and μ decays

J-PARC ν beam line :Primary-line

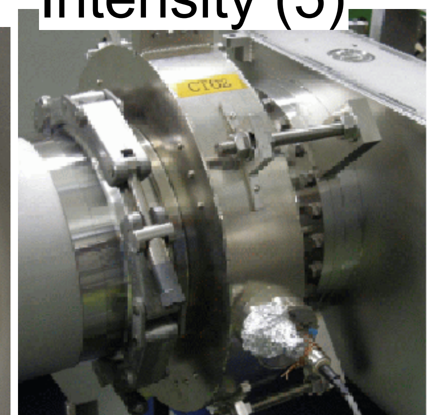
Beam monitors are install along the proton beam transport

Profile (19)

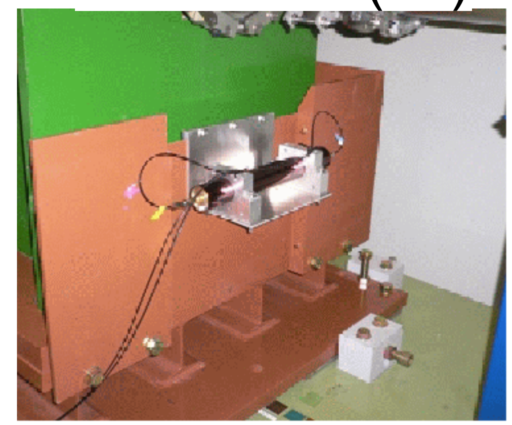
Position (21)



Intensity (5)

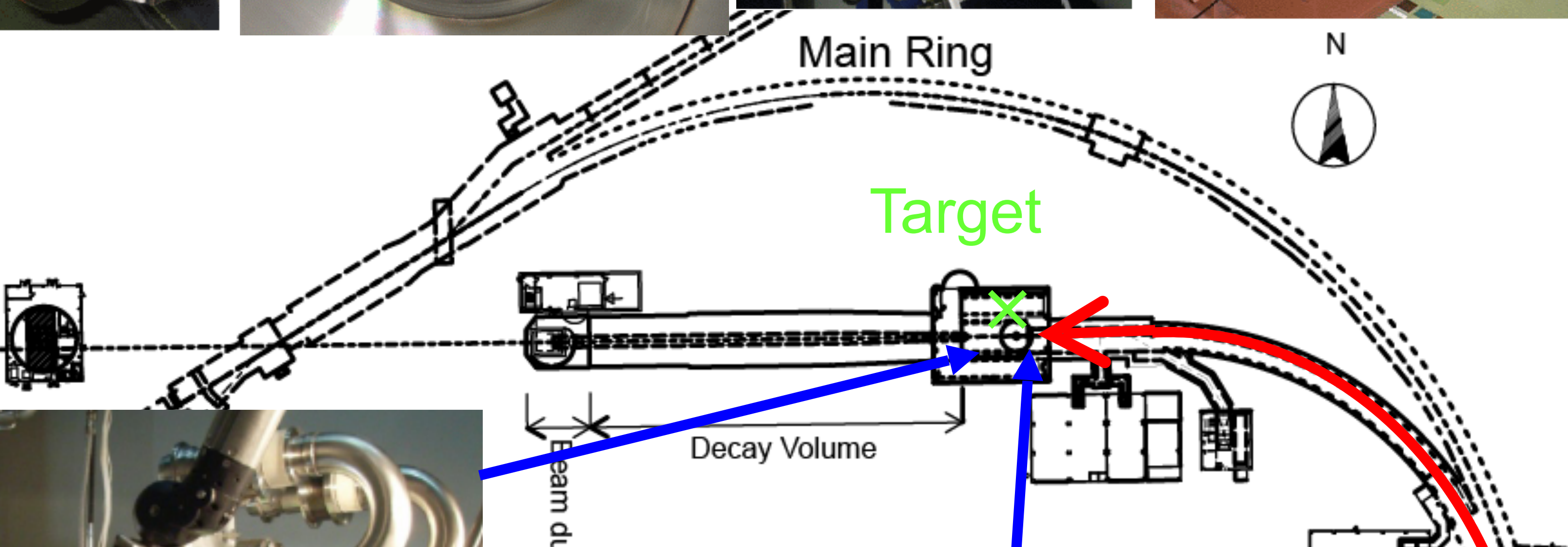


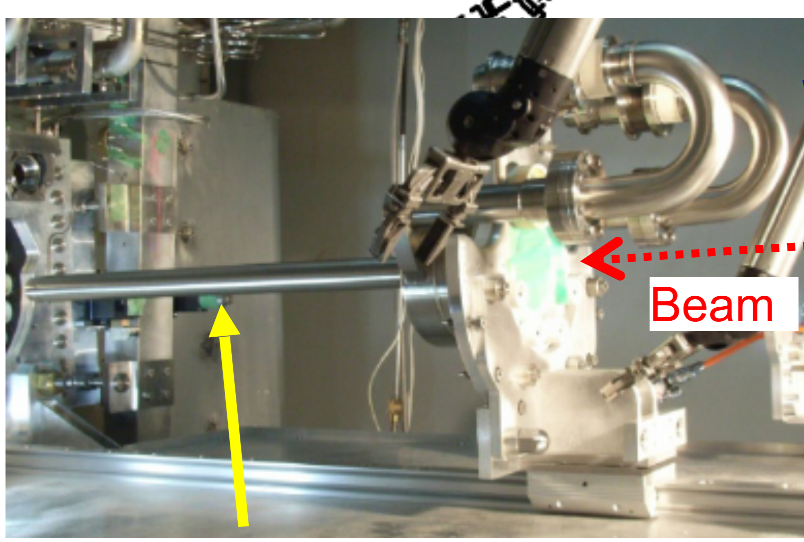
Beam loss (50)



Primary proton transport line

Super-conducting combined-function magnets



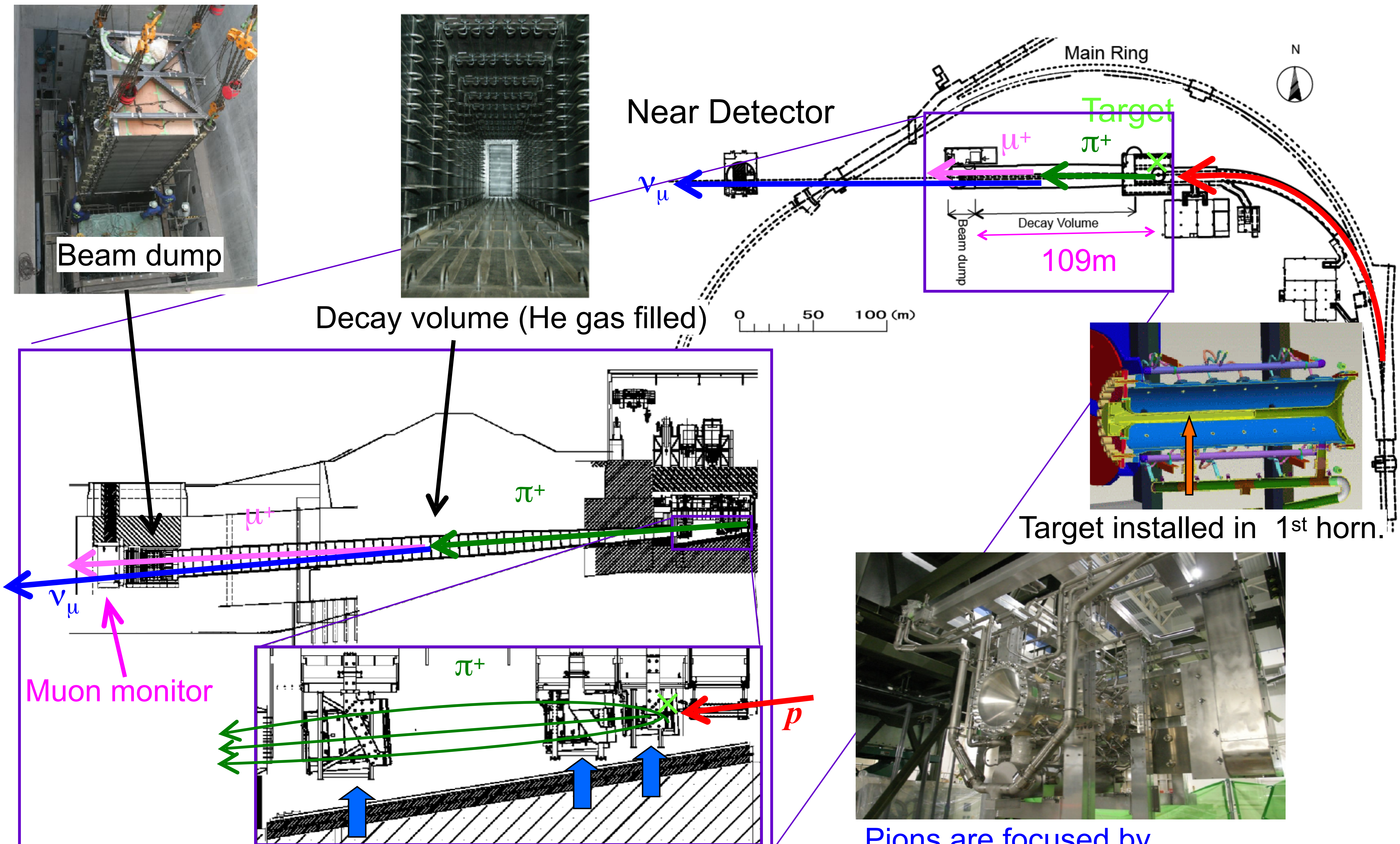


Target :graphite rod
ϕ26mm,L=900mm

Optical Transition Radiation (OTR) Profile monitor

Normal-conducting magnets

J-PARC ν beam line: secondary line

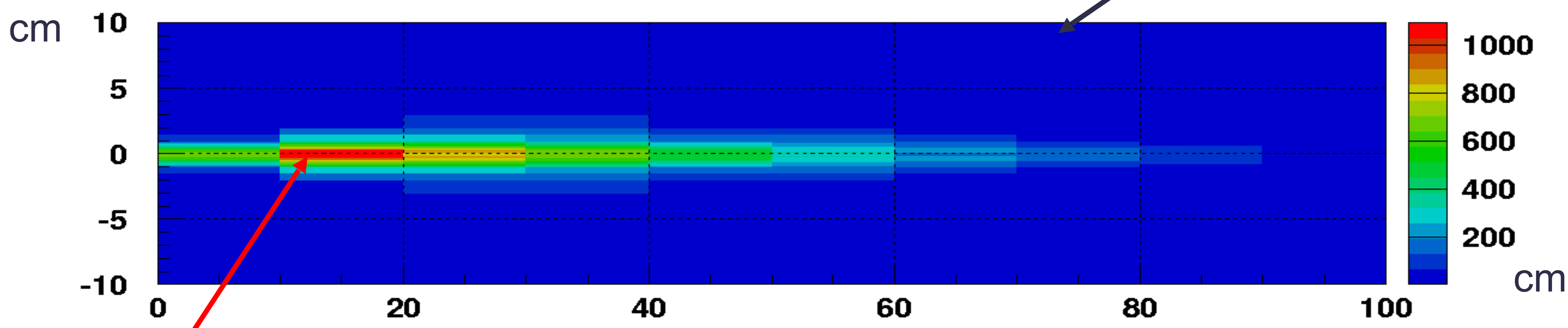


Pions are focused by
3 electromagnetic Horns.

More neutrinos with more beam

Original Design: 7 5 0 k W beam!

- 3×10^{14} Protons-On-Target (POT) every 2.5 sec.
- If the target made of iron,



1100℃

(cf. melting point 1536℃)

✓ melting

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

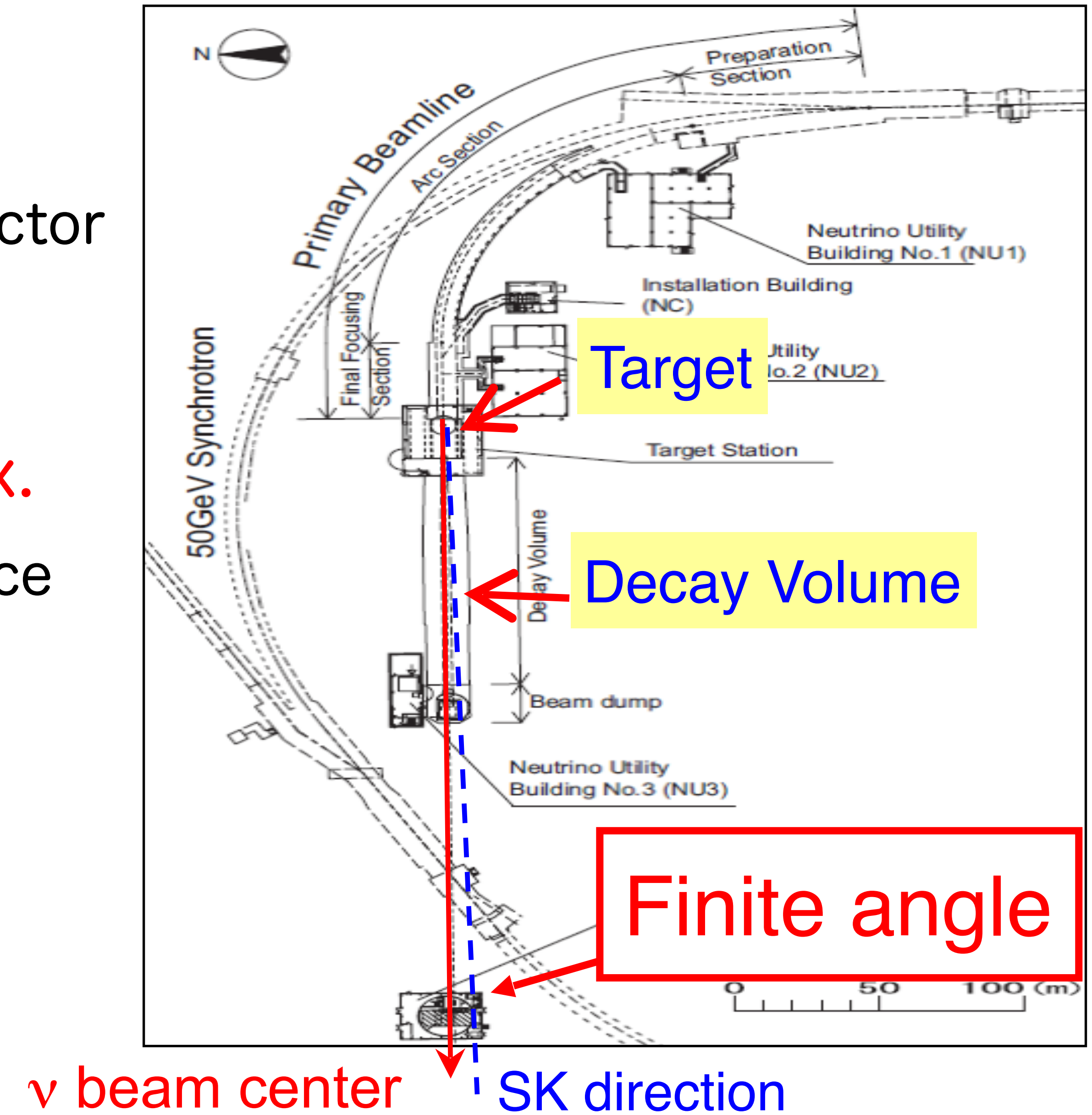
(cf. ~300 MPa)

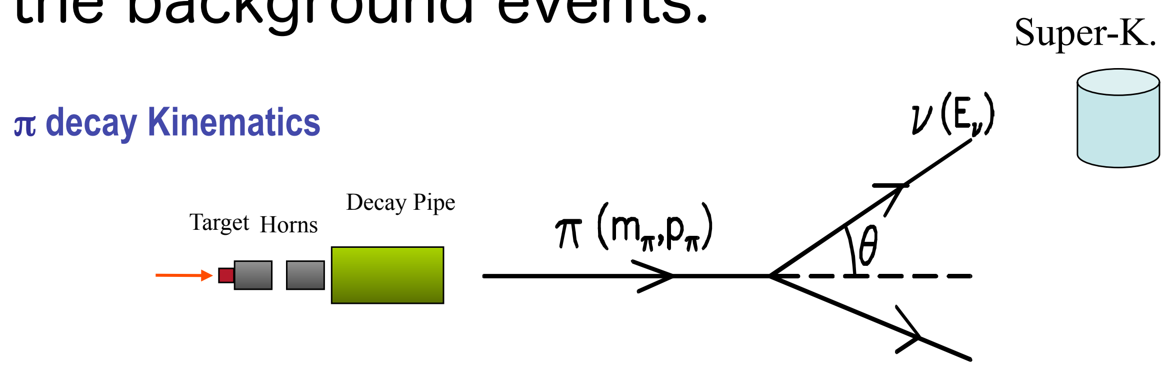
Any metal heavier than Ti will be broken.

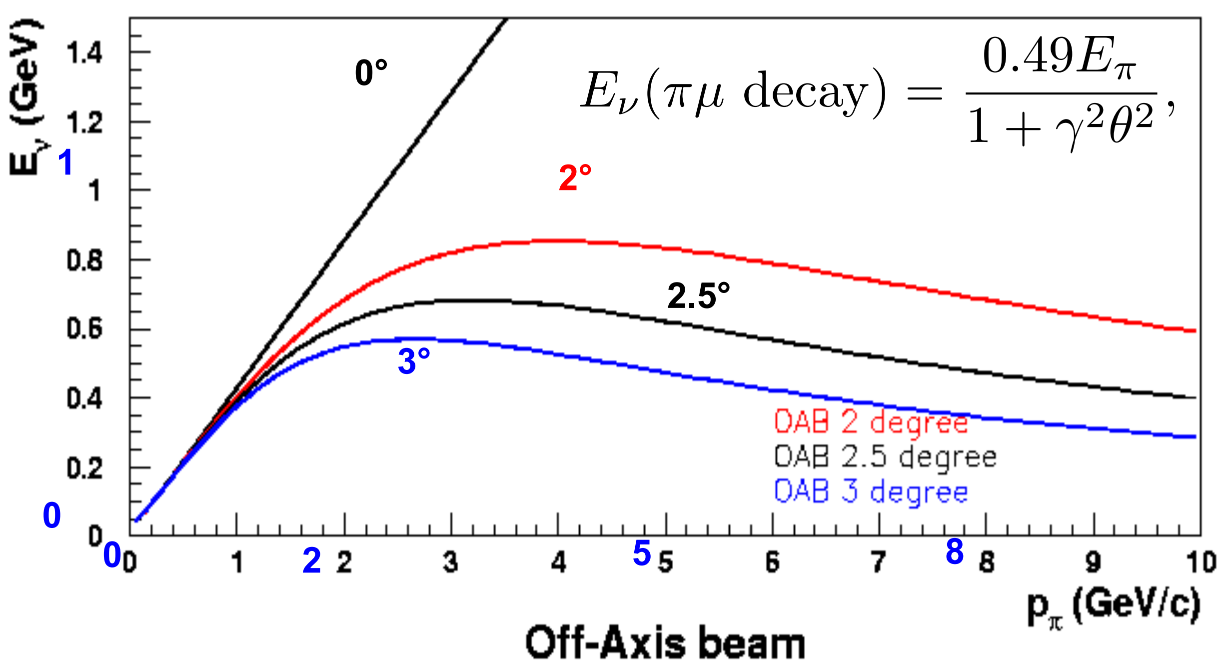
※Beam Power is proportional to #protons/sec × proton Energy

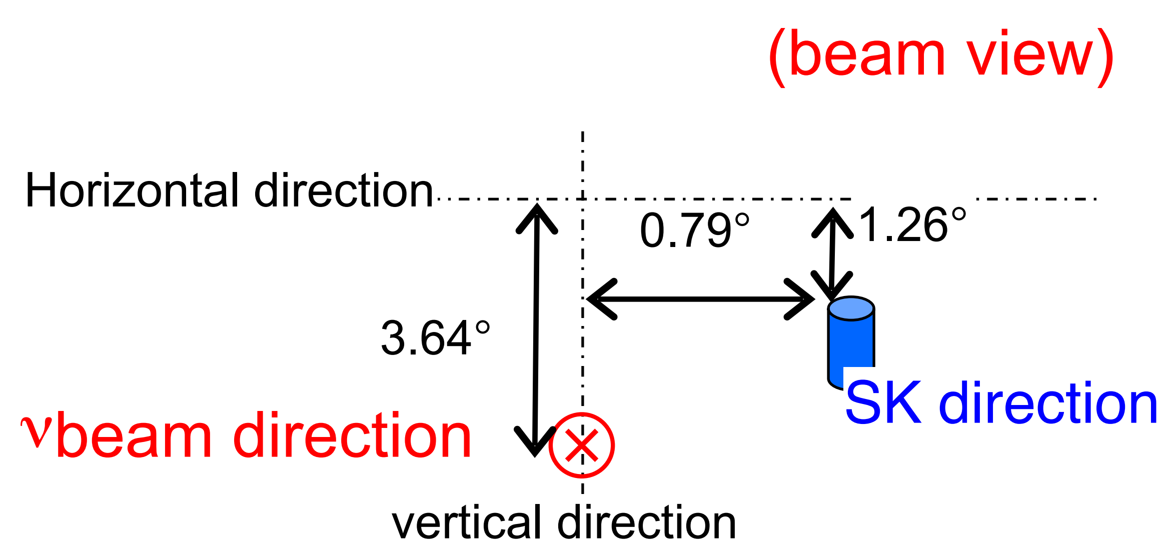
Off axis beam

- 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.

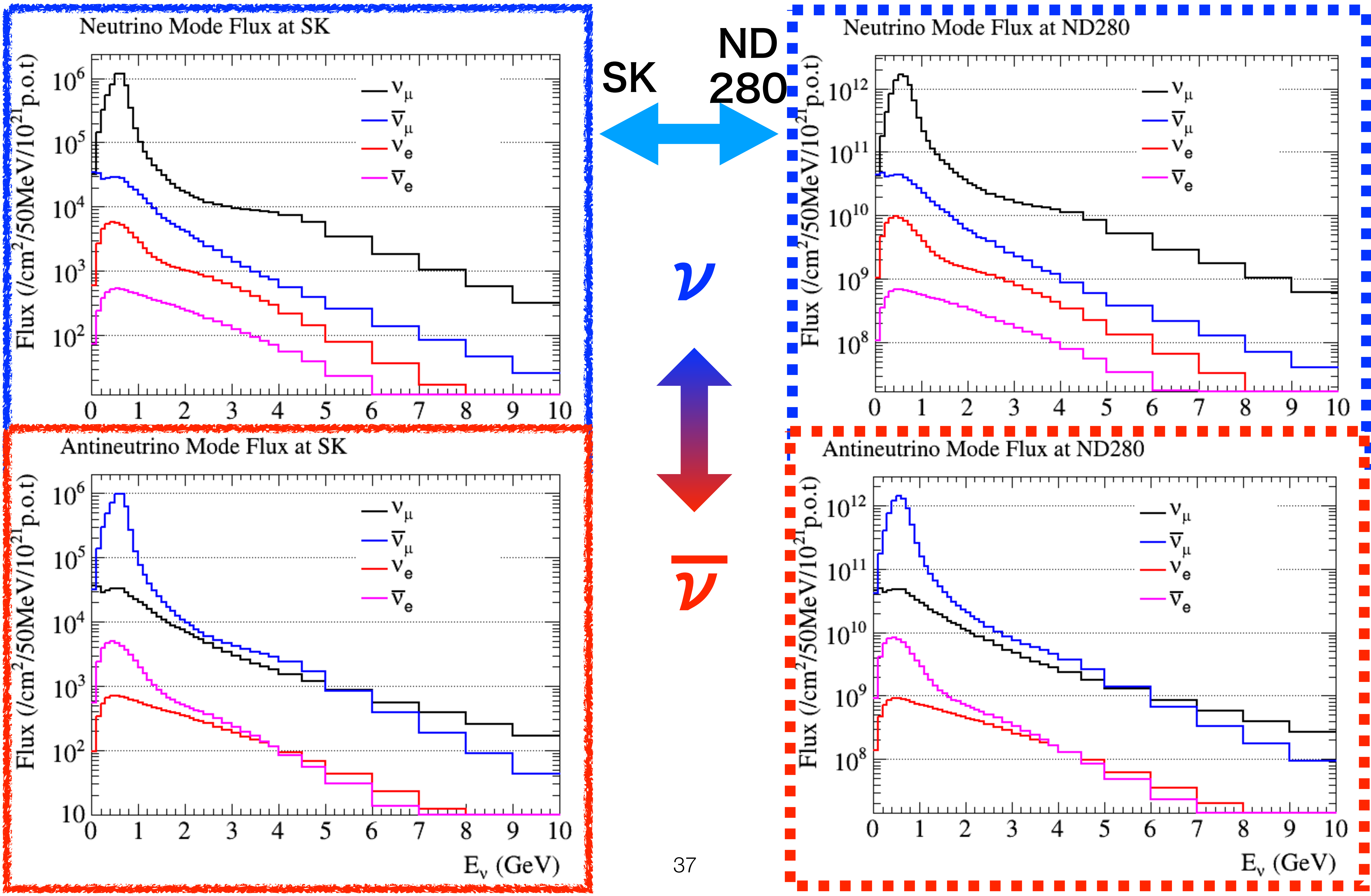


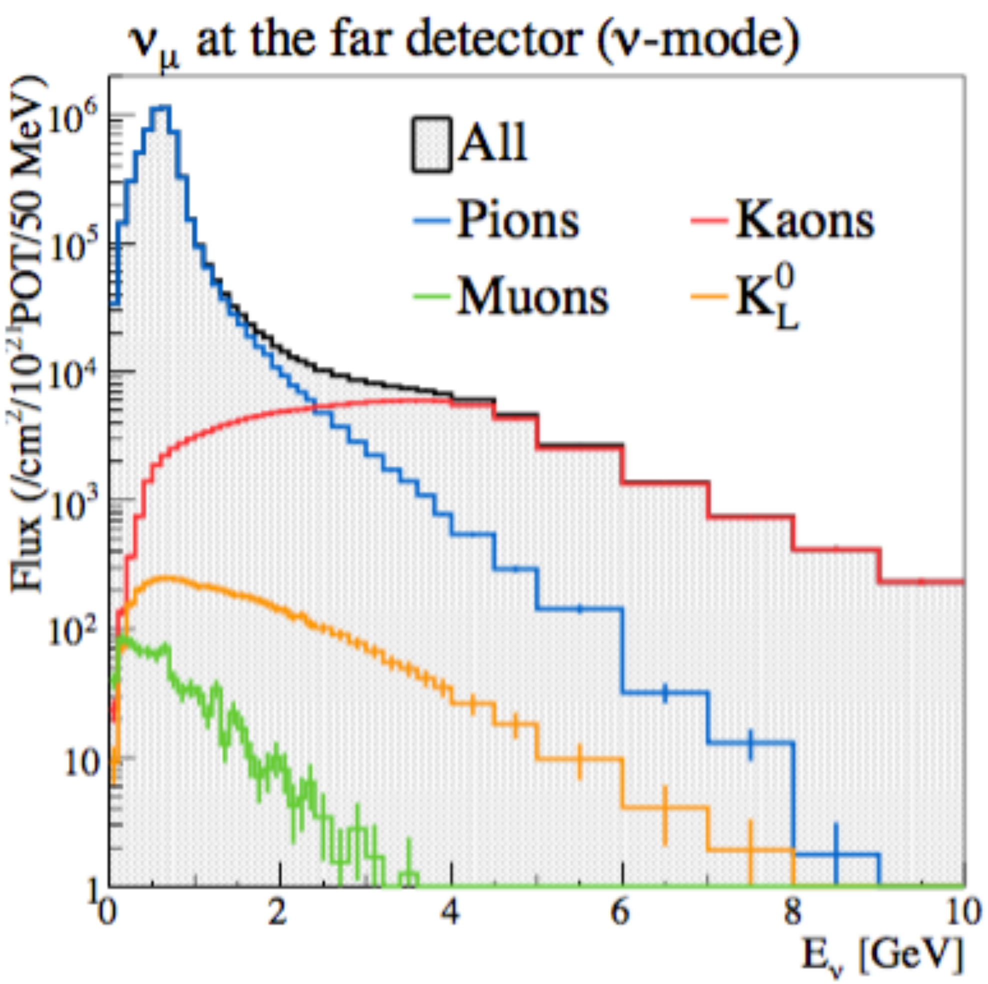


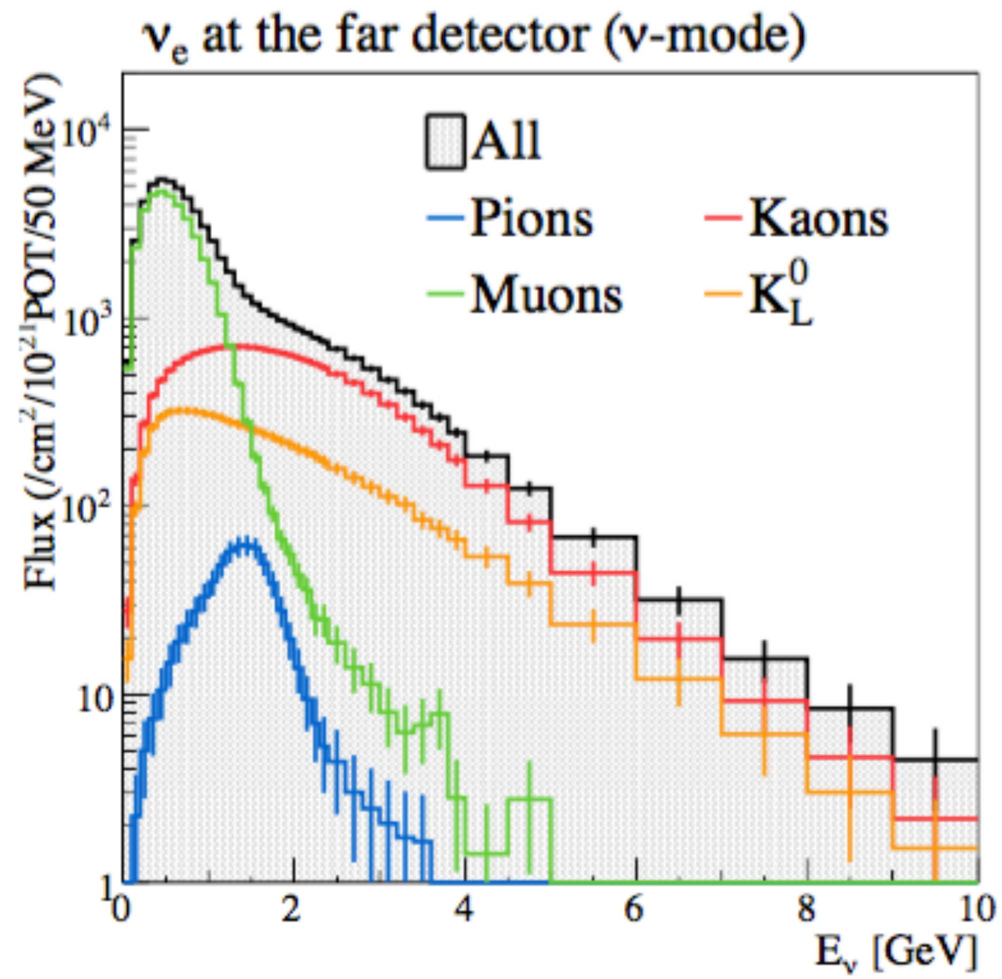




Predicted Neutrino Flux







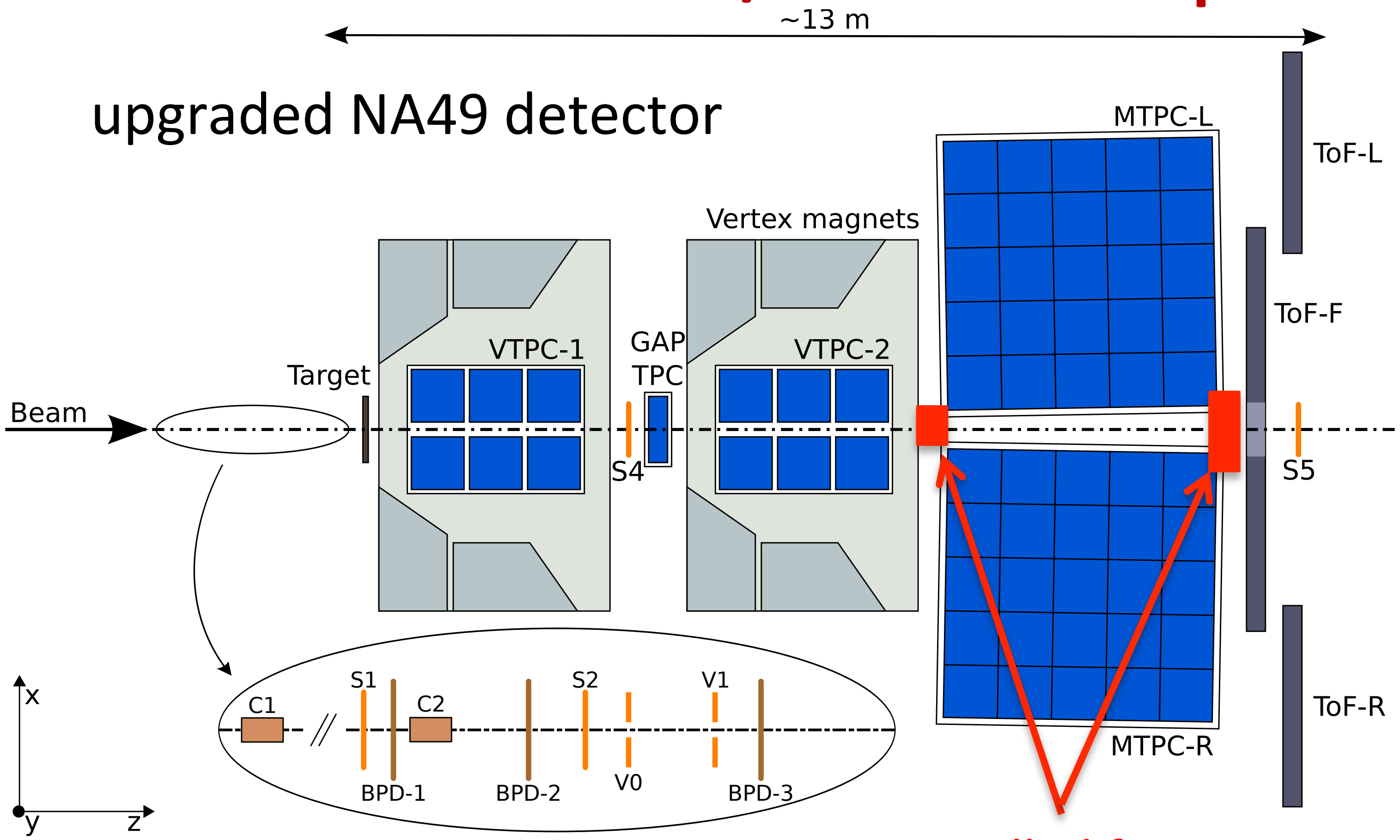
ν_μ (anti-ν_μ) : pions at low E_ν, kaons at large E_ν

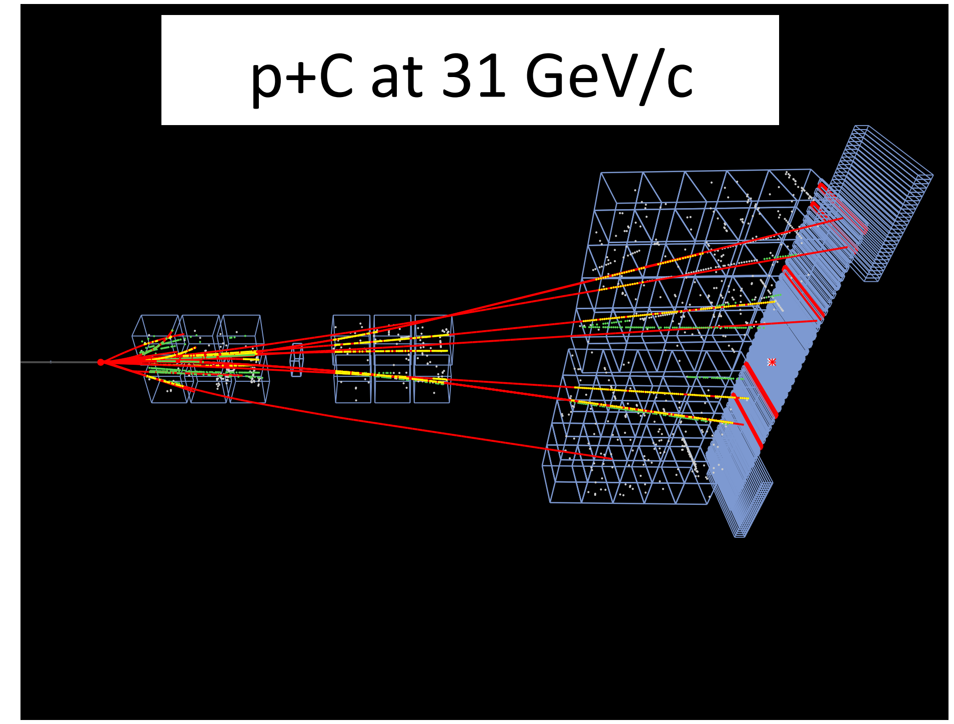
ν_e : muons at at low $E_{\nu,}$ kaons at high E_ν
anti-ν_e : kaons for all E_ν

ν_μ parents:
1. π^+
2. K^+

ν_e parents:
1. μ^+
2. K^+

NA61/SHINE Experimental Setup

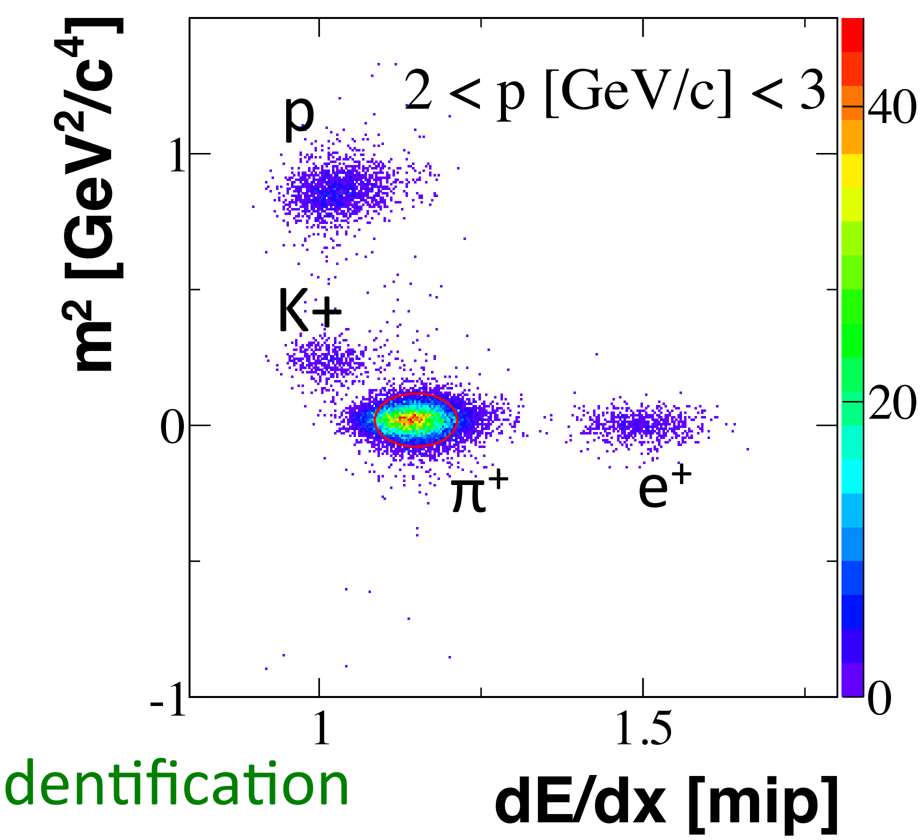




Fixed target experiment at CERN SPS with the large acceptance spectrometer

- **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 $\sigma(t)$ToF-F ≈ 120ps, $\sigma(t)$ToF-L/R ≈ 80ps

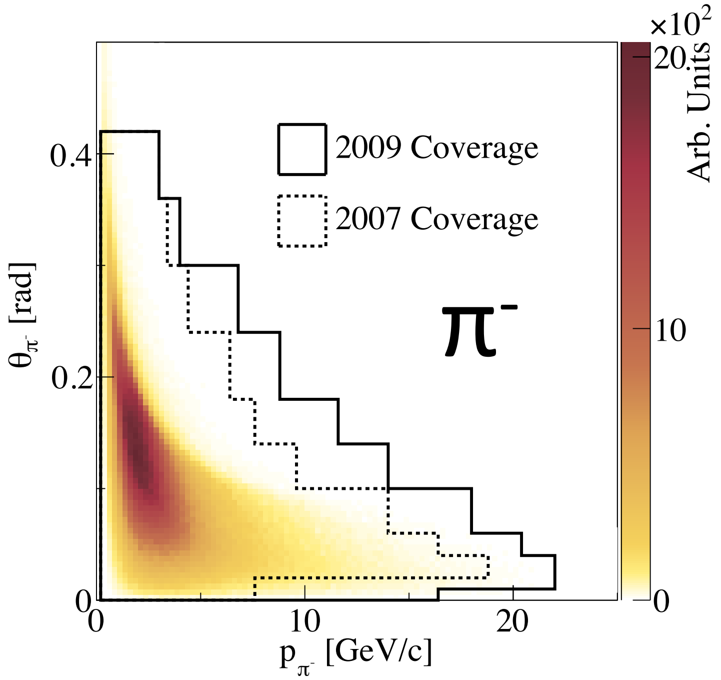
Combined dE/dx + ToF for π^+

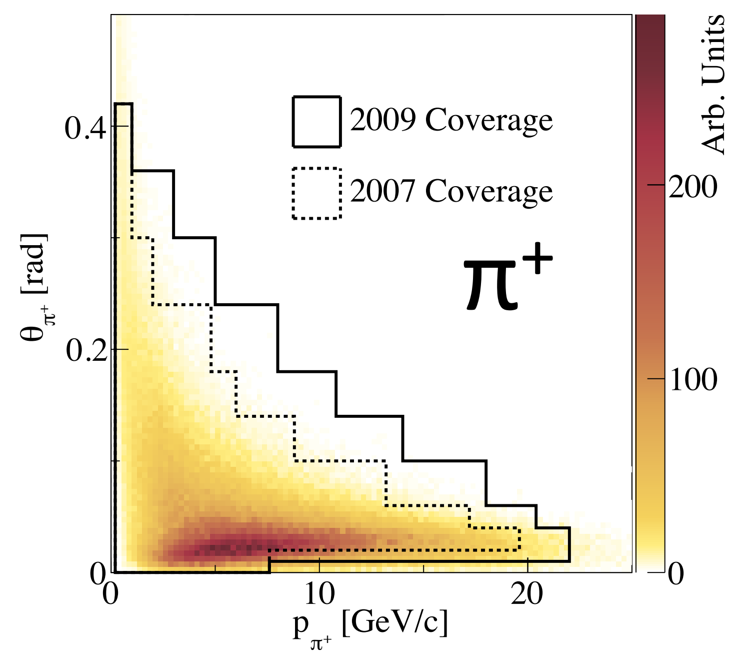


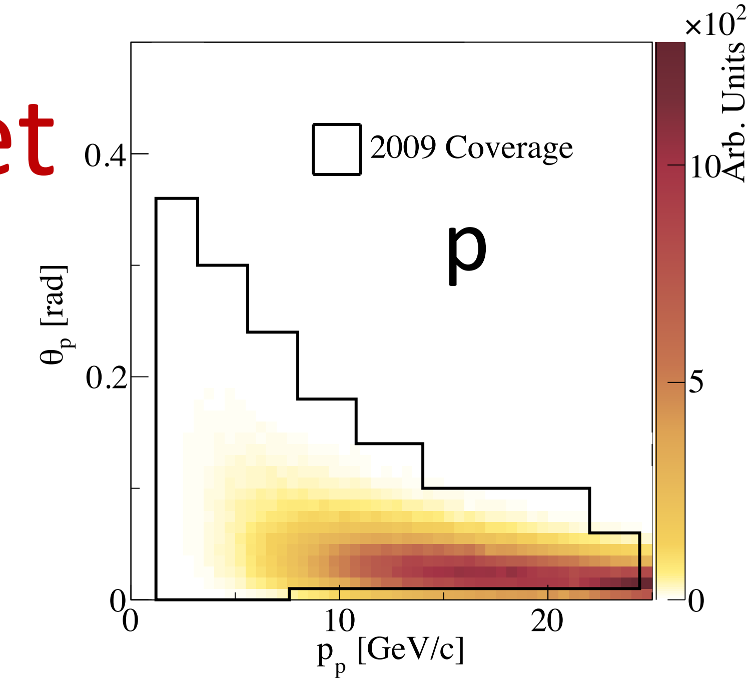
TPC and ToF detectors provide very good particle identification

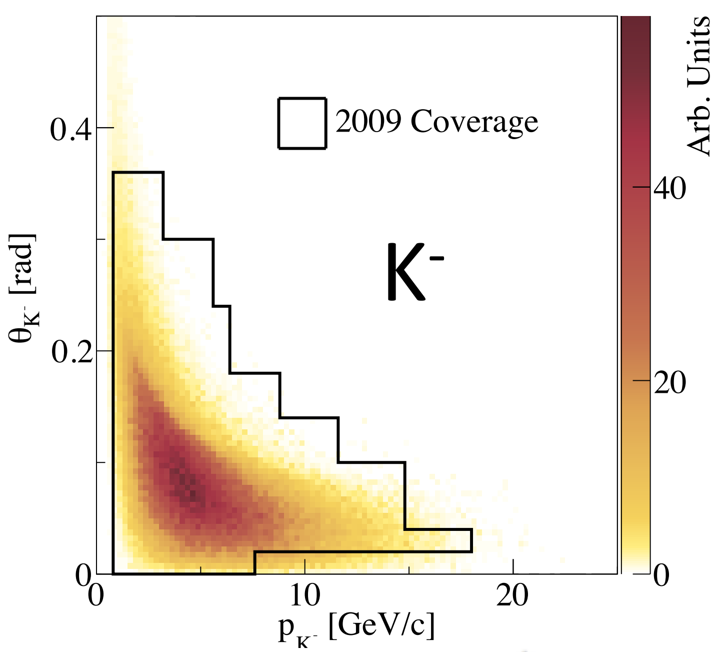
Hadron Measurements on Thin Target

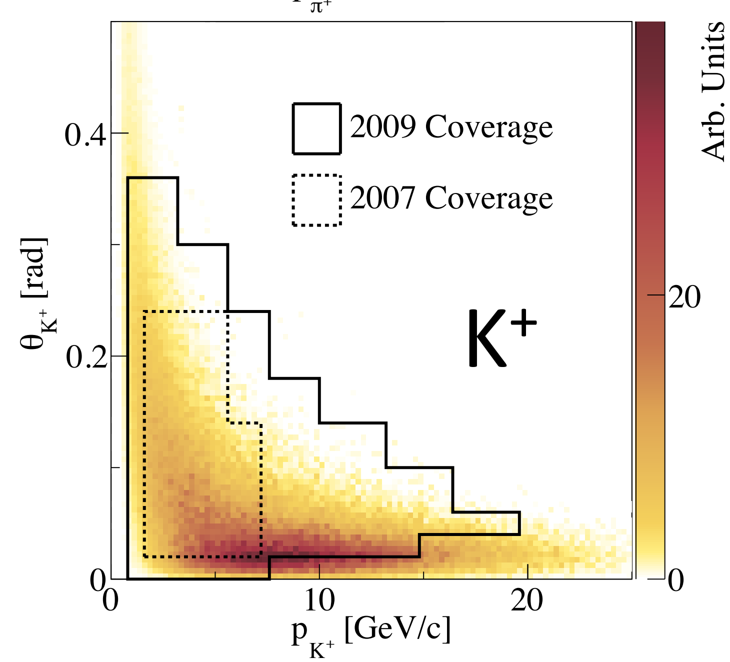
The phase space contributing to the predicted neutrino flux at SK and the NA61 data coverage.

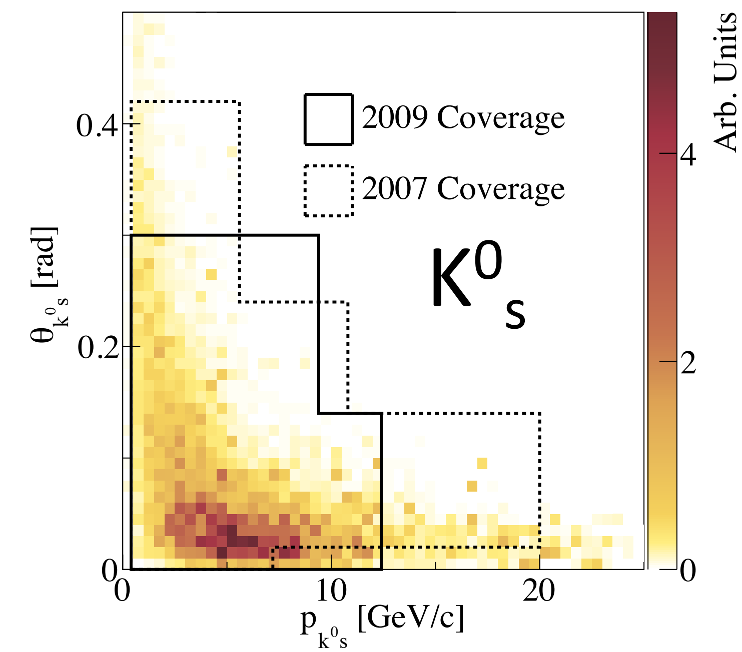


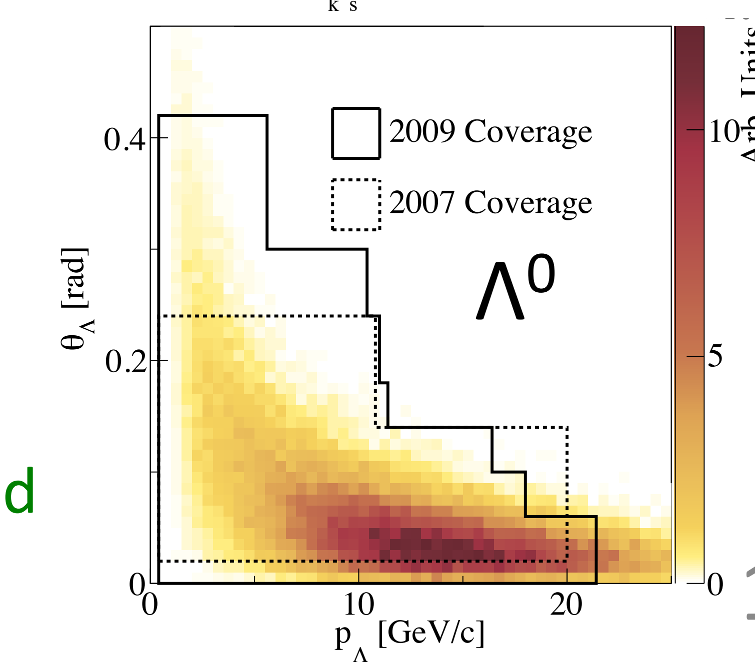


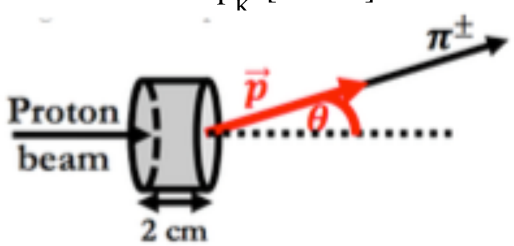








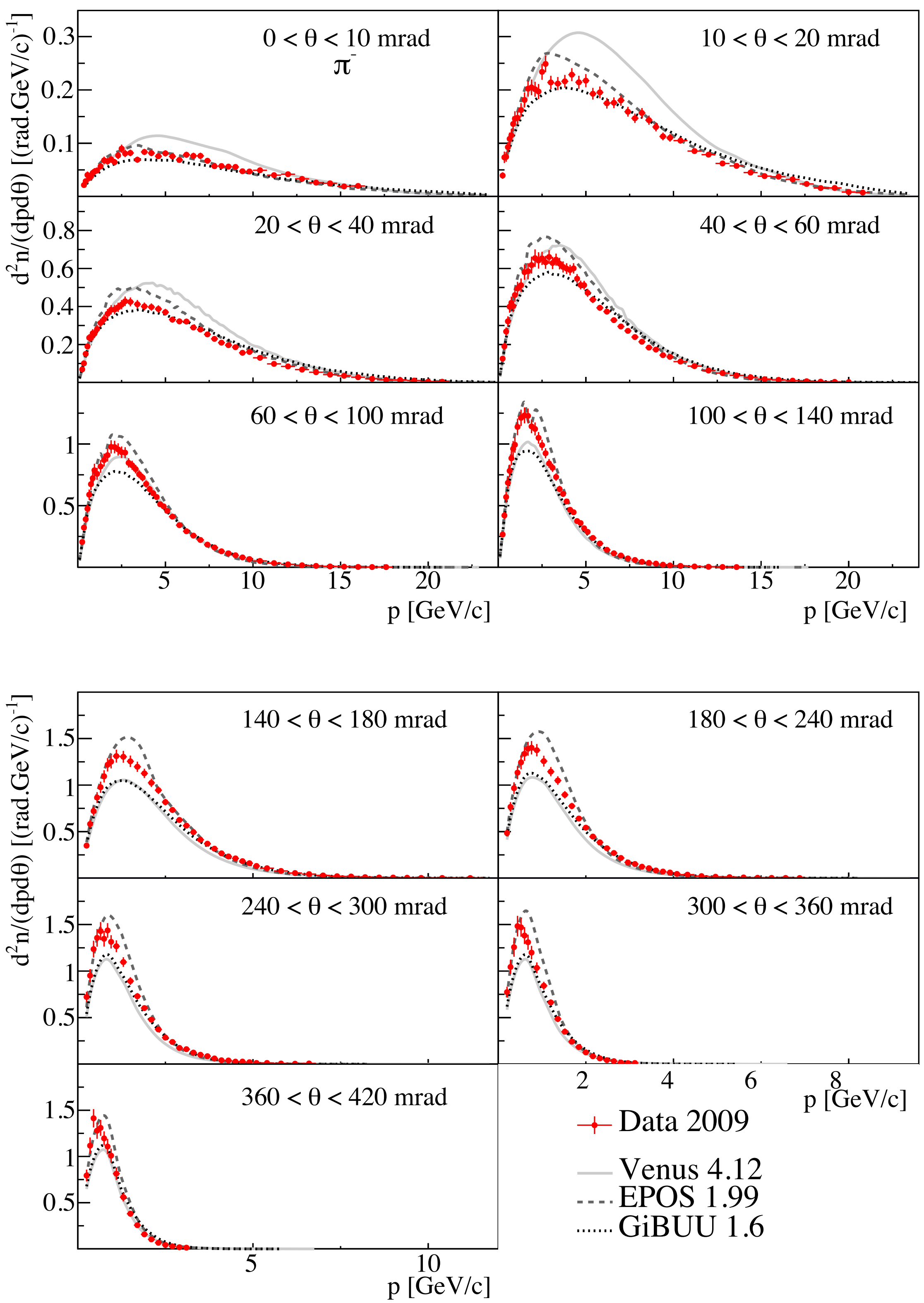




NA61 provides good coverage of required phase-space

Measurements with Thin Target Data

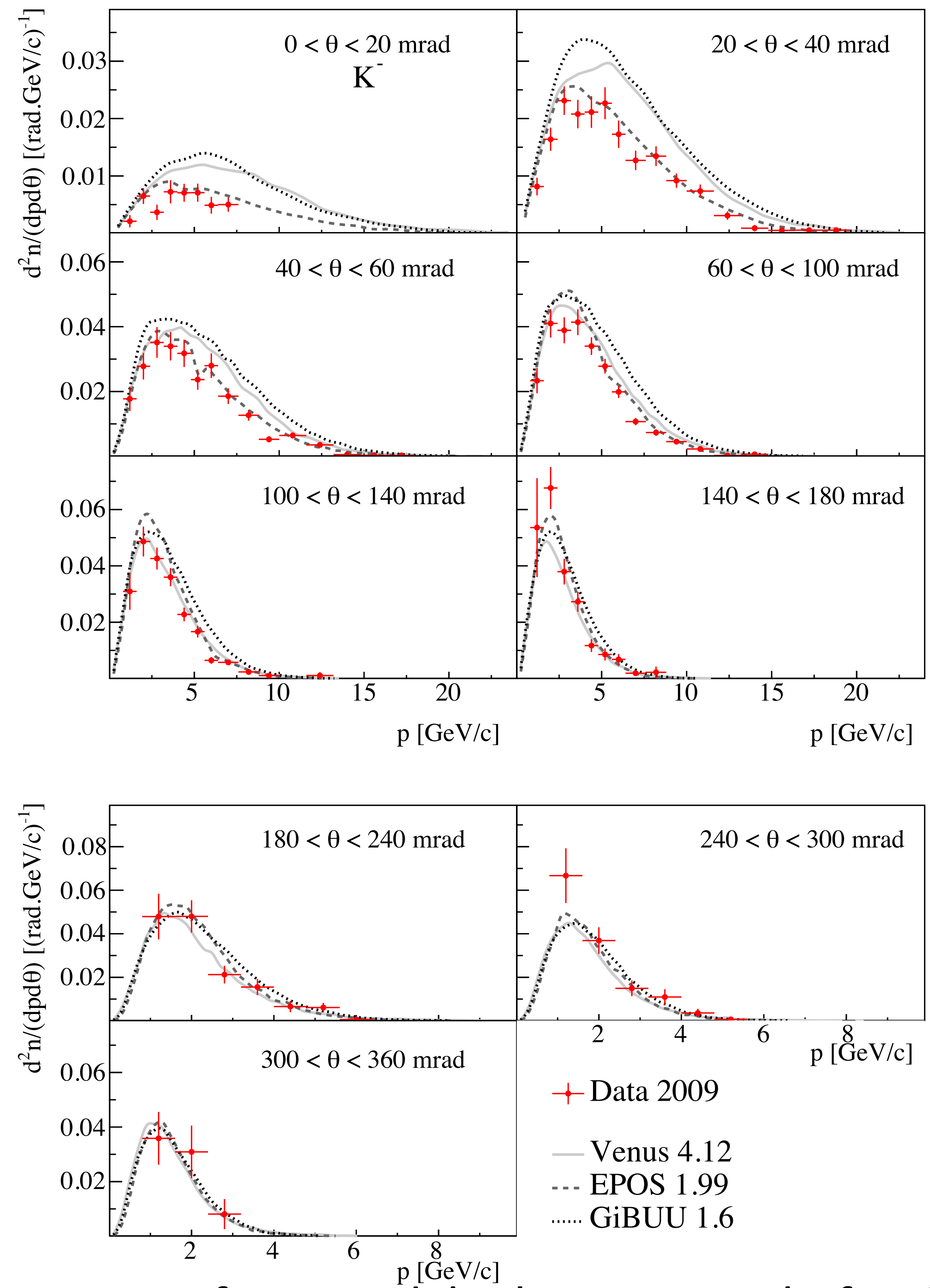
π^- Multiplicities



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%

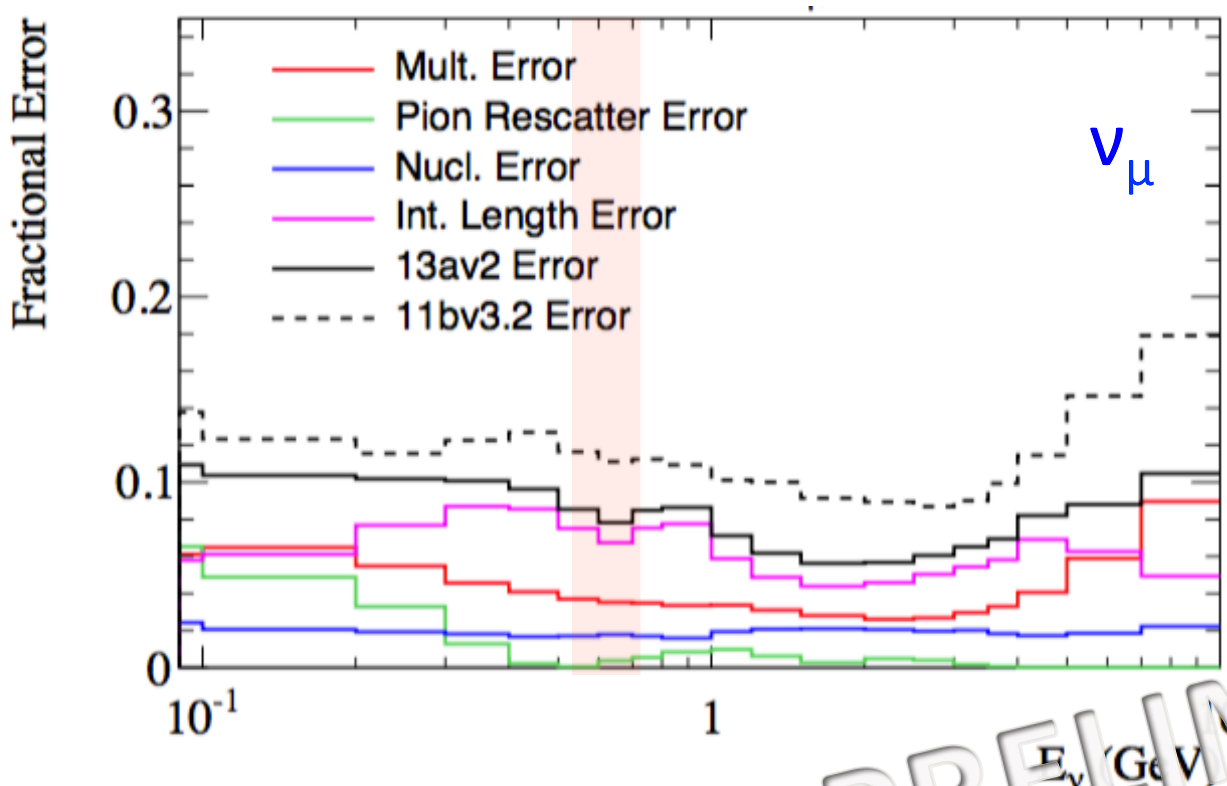
1

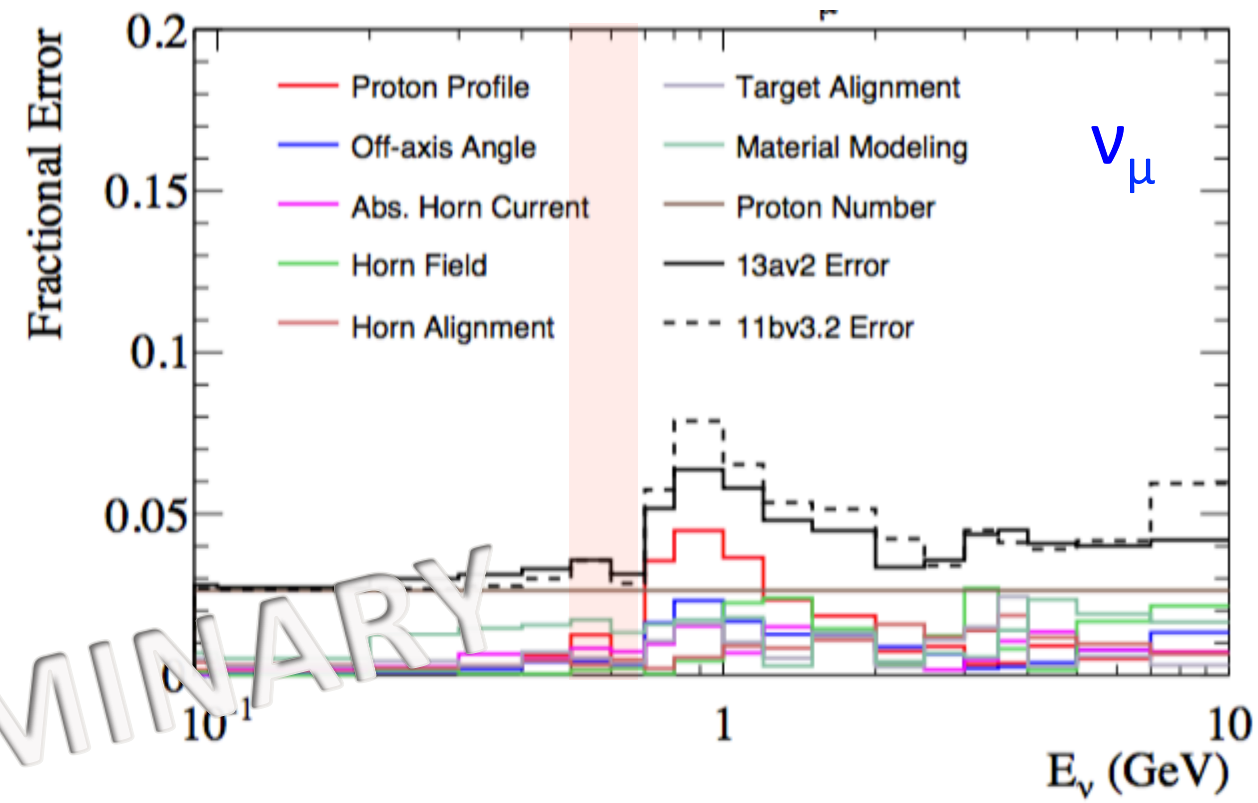
Flux Uncertainties at SK

Hadron Modeling Part

Non-Hadronic Part

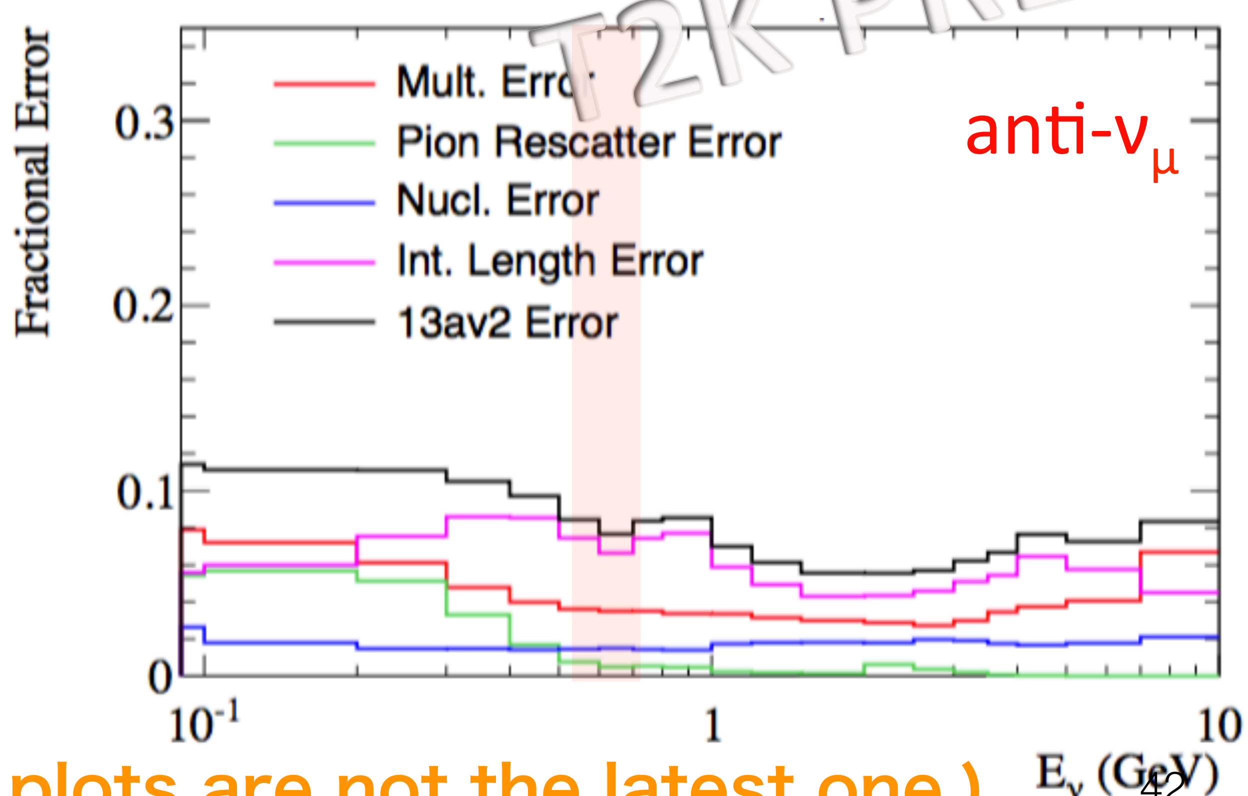
ν_μ at SK

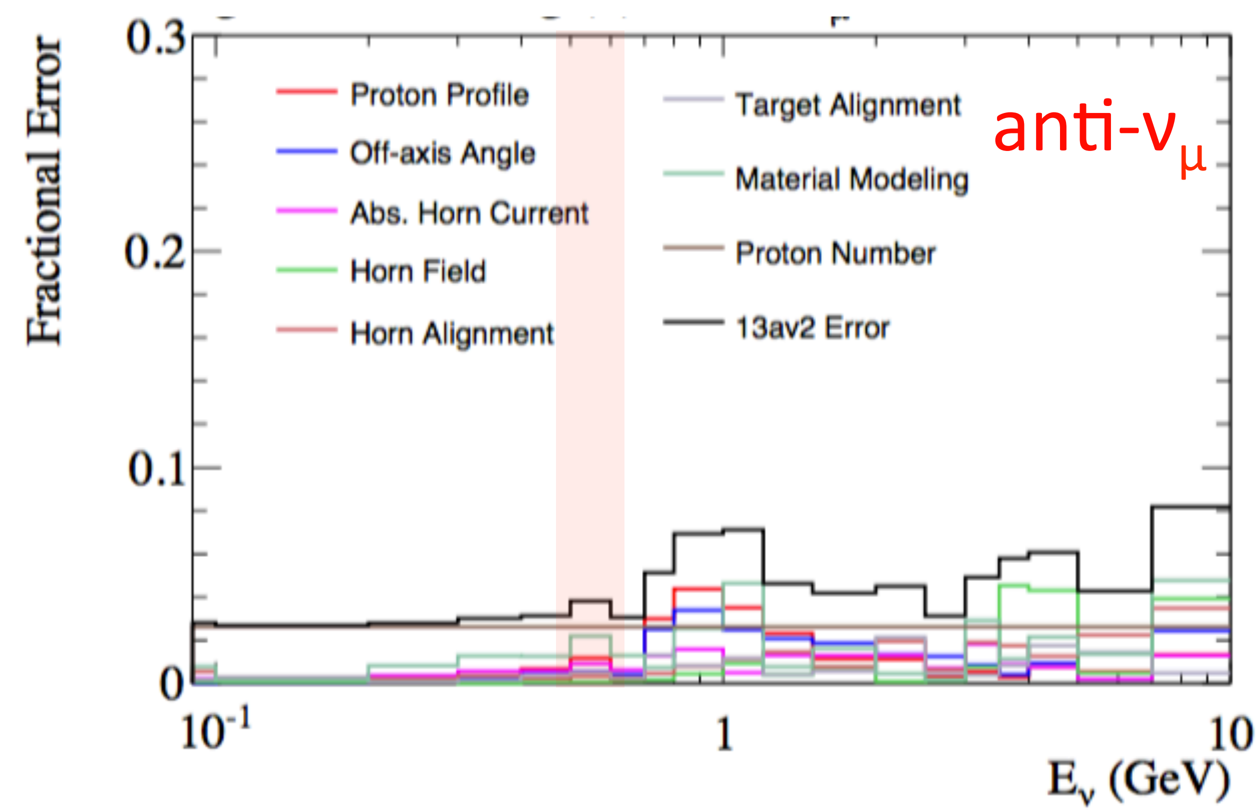




T2K PRELIMINARY

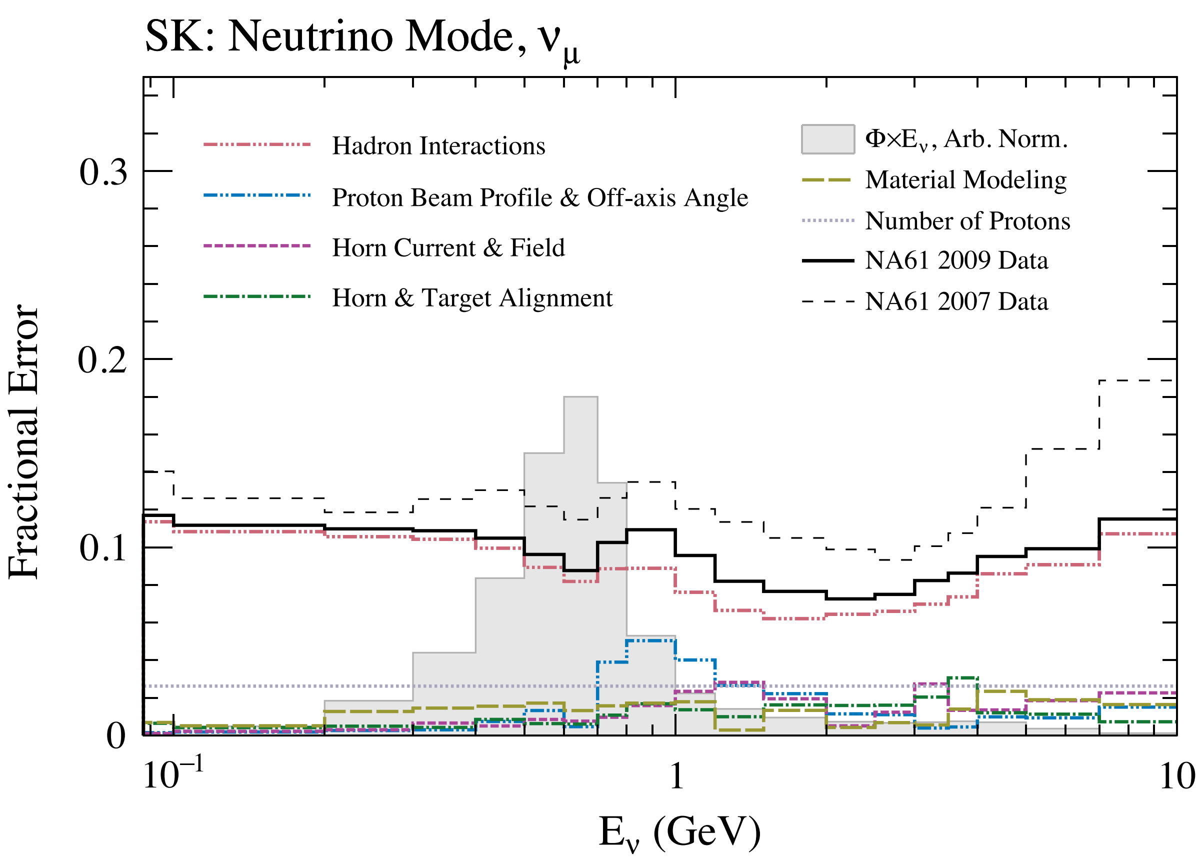
anti-ν_μ at SK

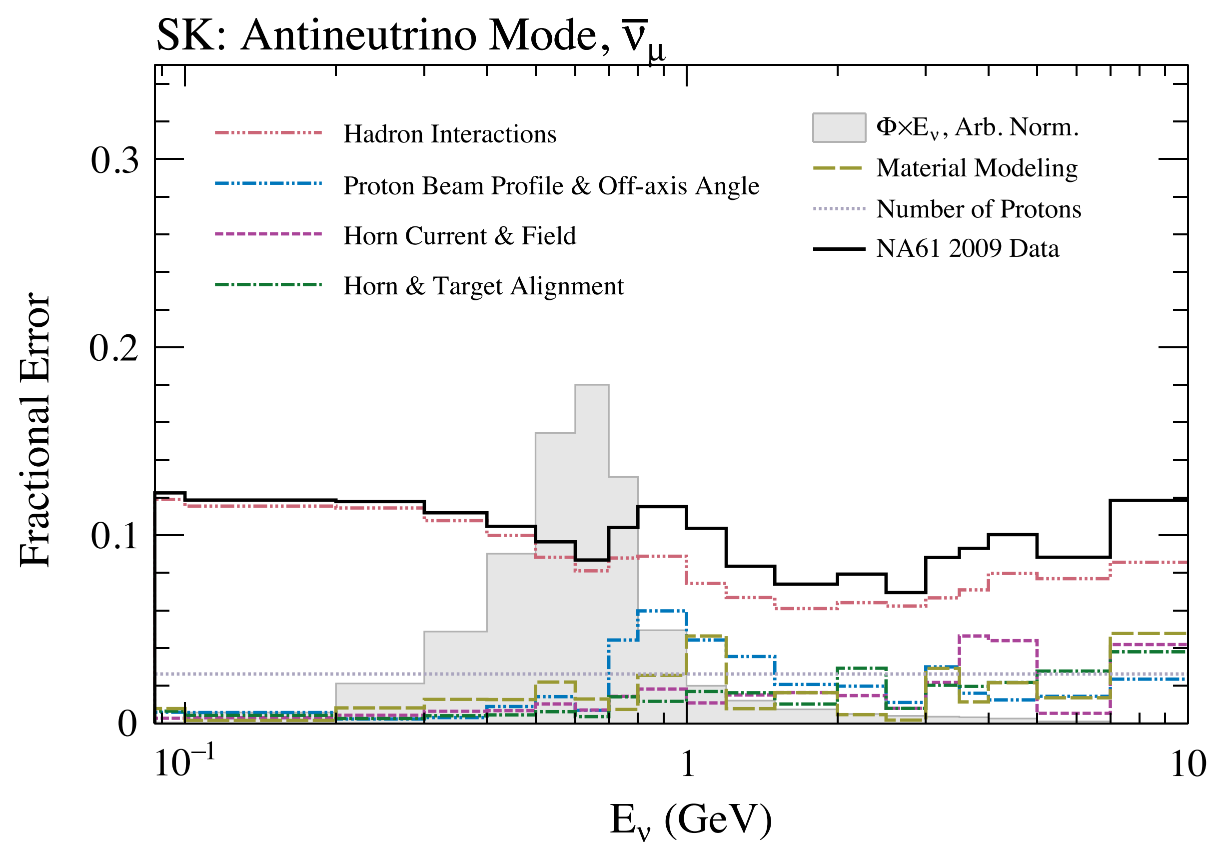


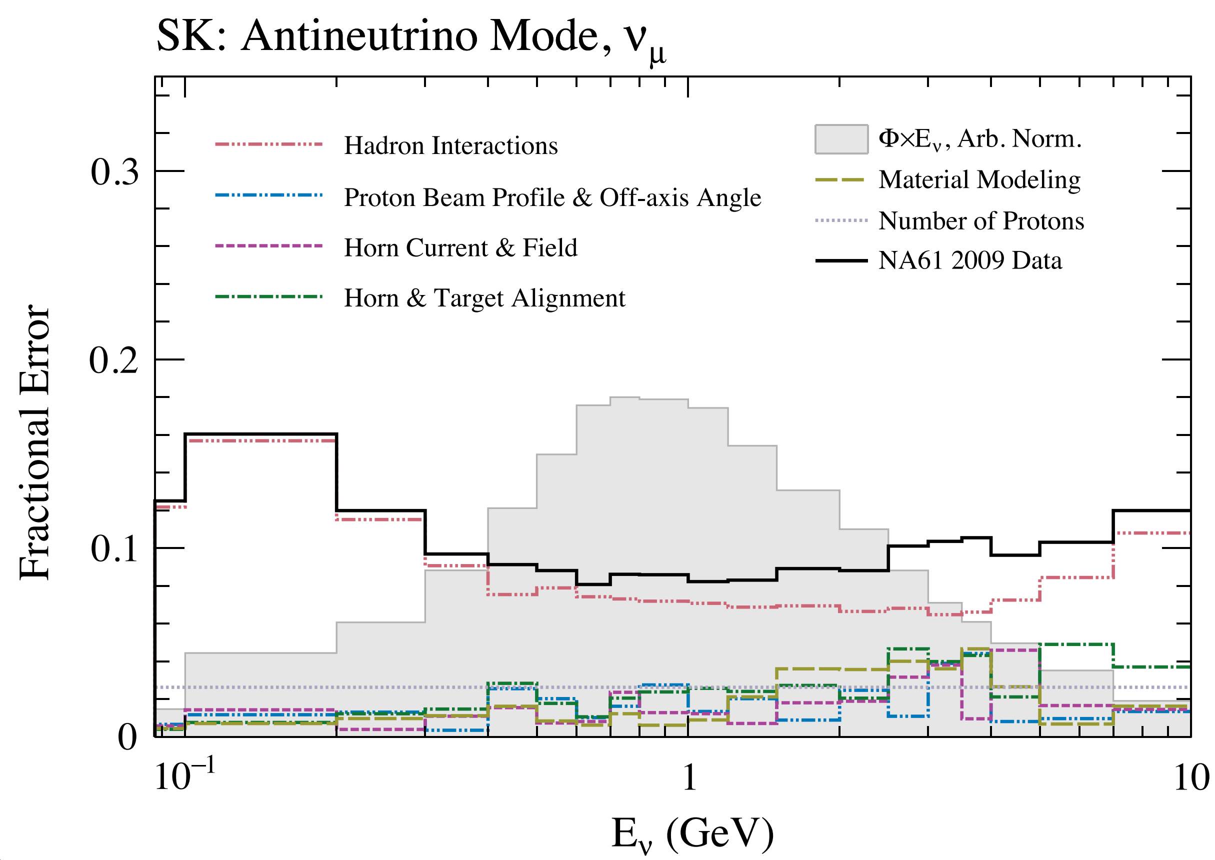


(The plots are not the latest one.)

Flux Uncertainty

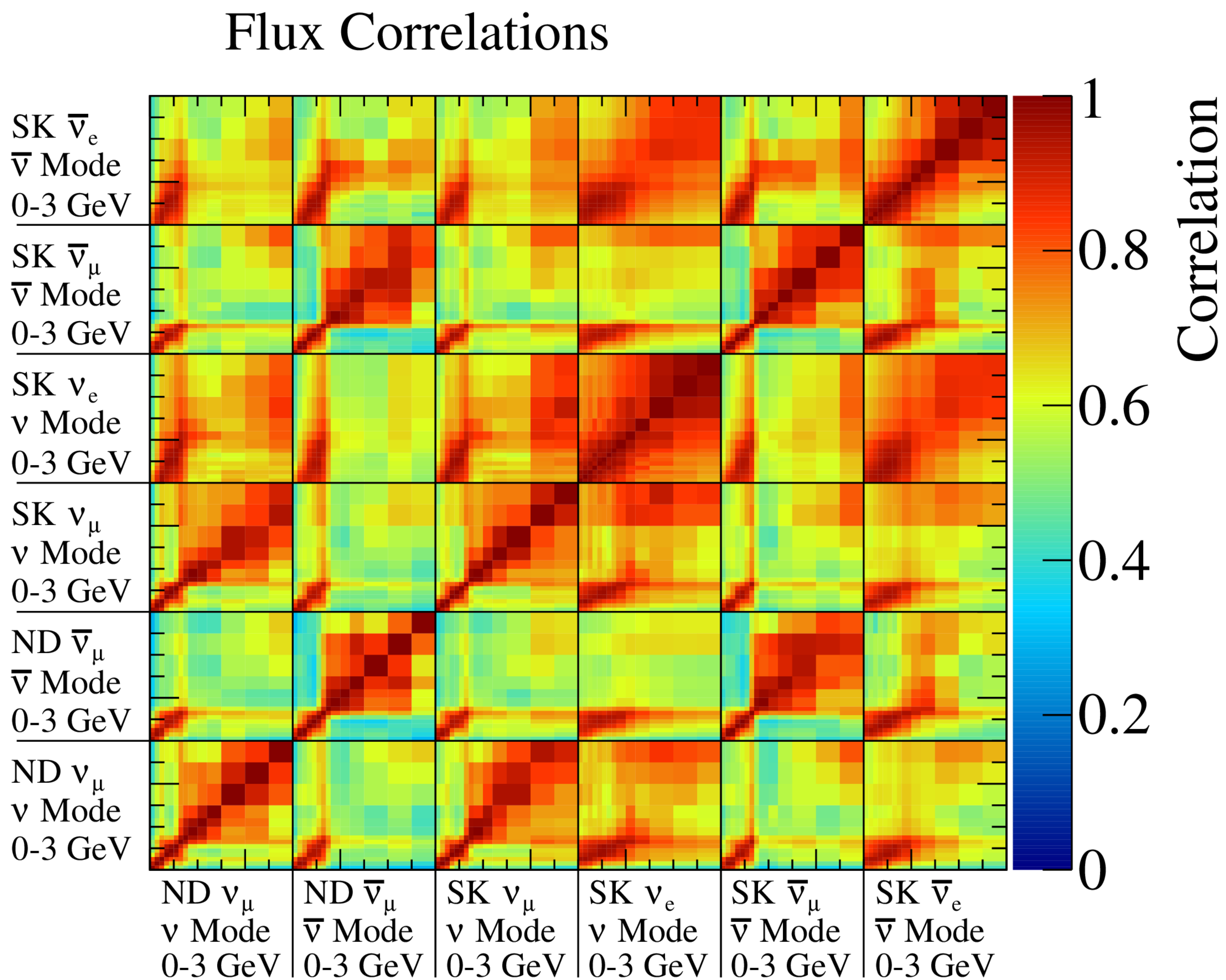




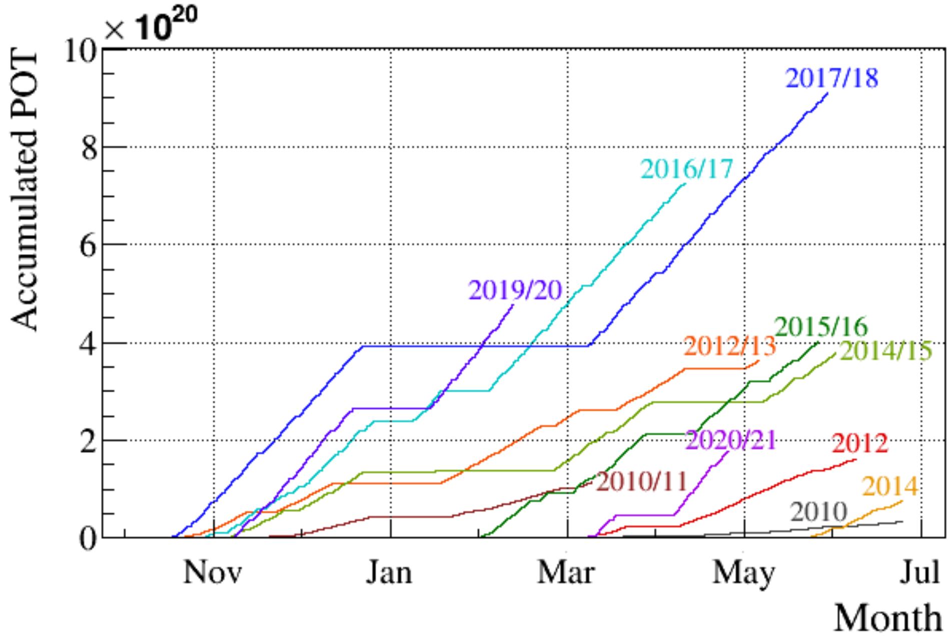


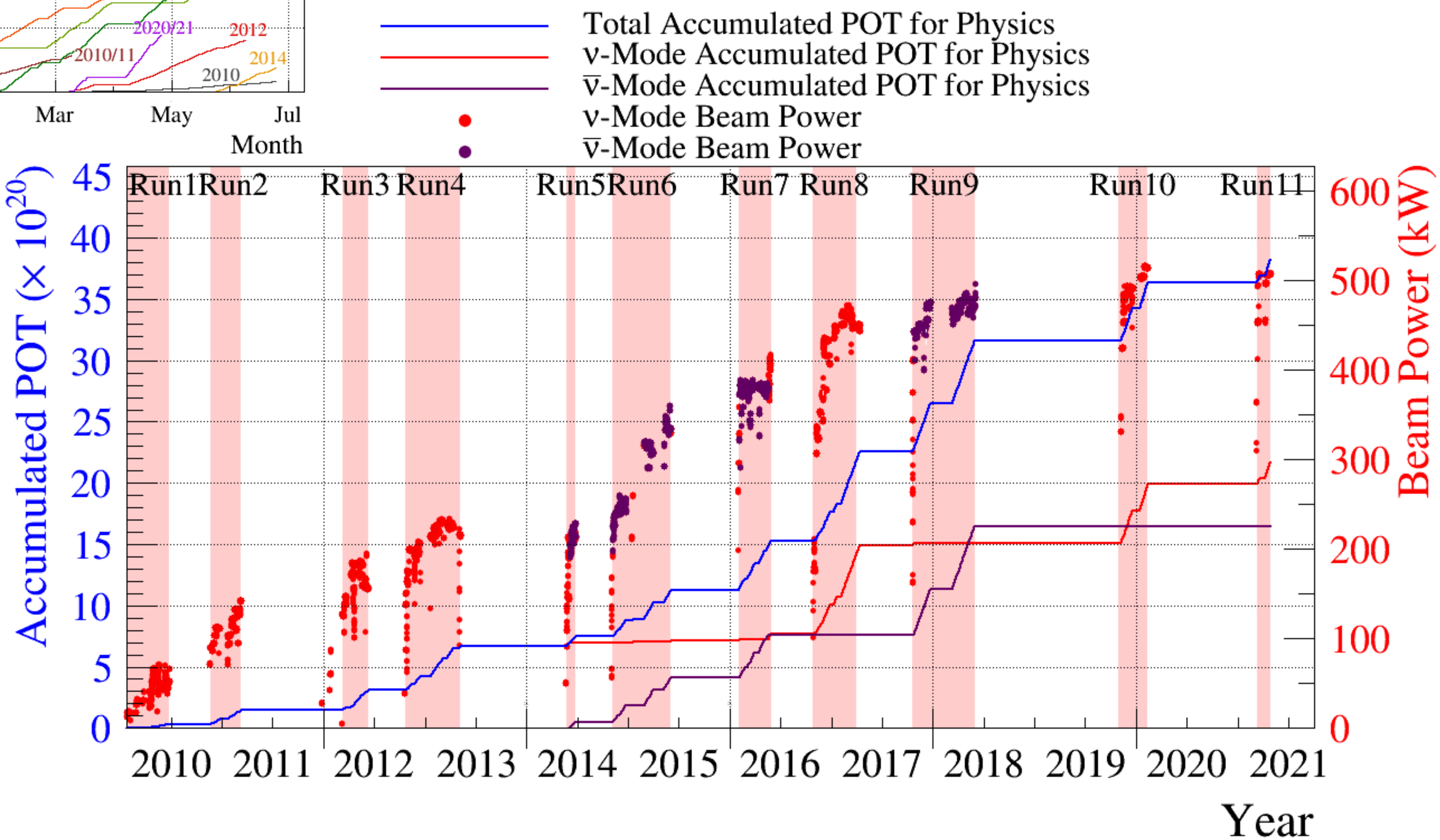
PHYS. REV. D **103,** 112008 (2021)

Flux correlations before ND280 fit : zoom



Data set (in summer 2021)





23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}
(maximum power 522.6 kW)

ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

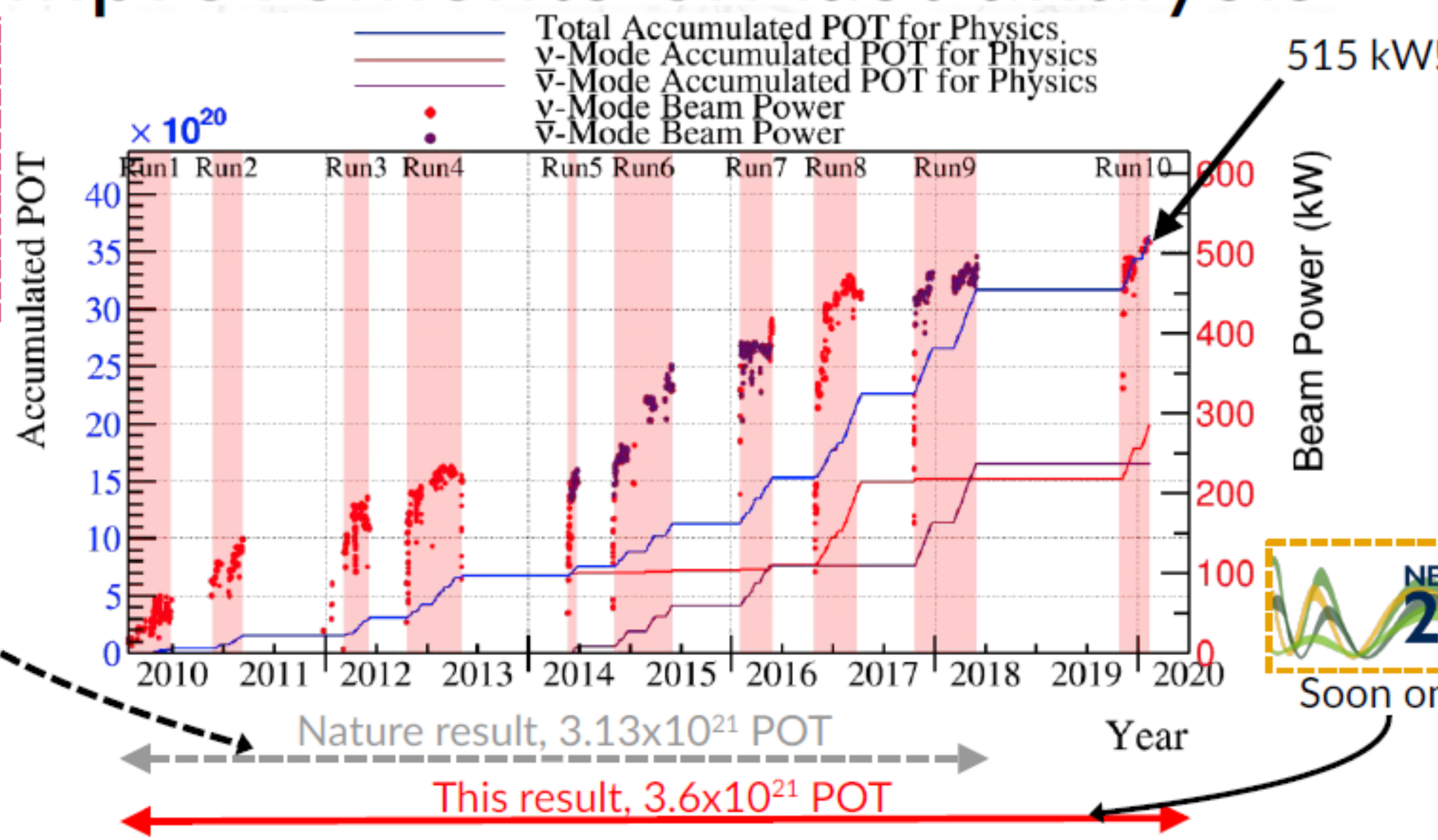
Data set used for analysis (in summer 2021)

Improvements on last analysis

Nature 580, 339-344

arXiv:2101.03779

Phys. Rev. D 103, 011101 (2021)



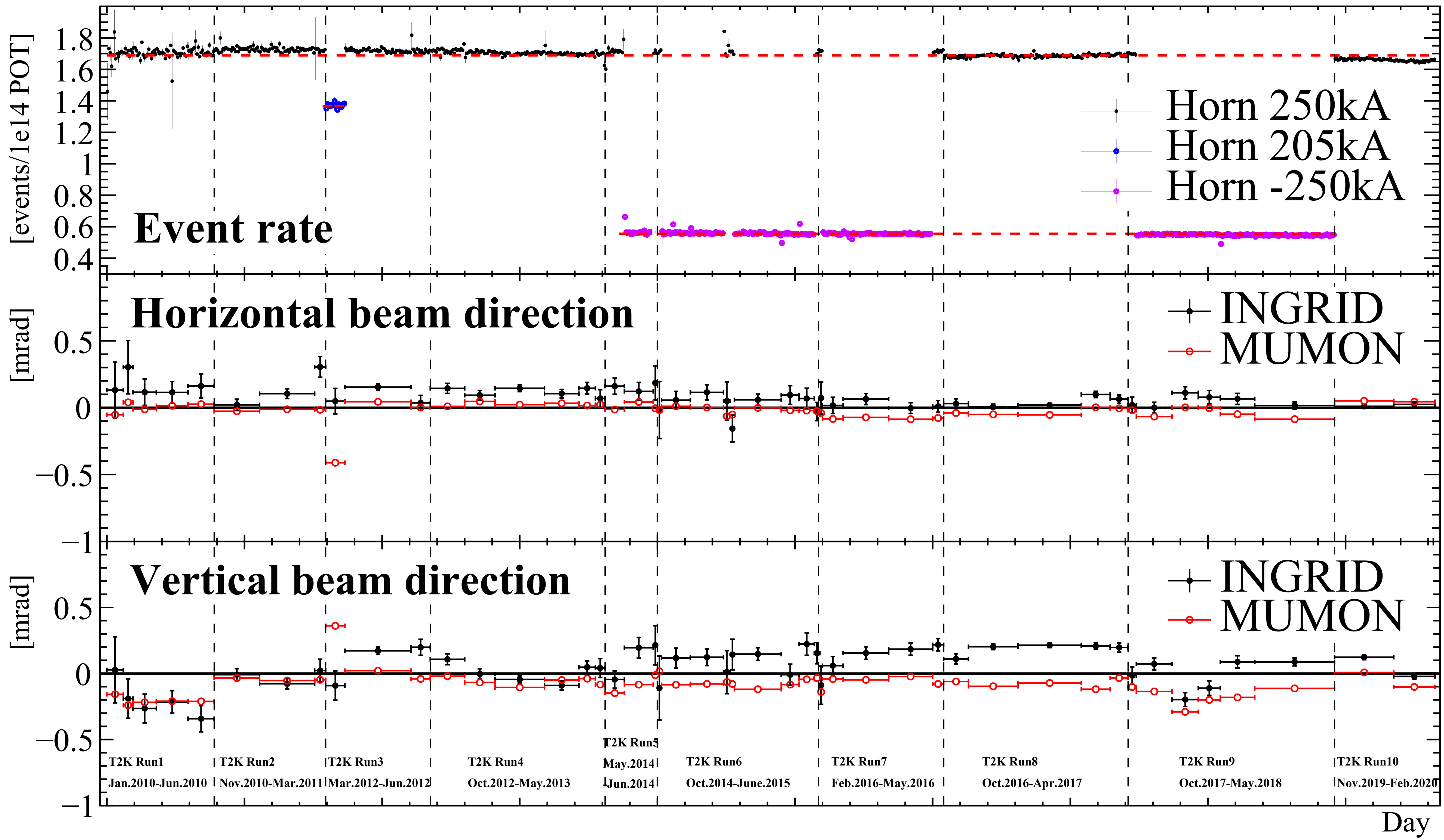
NEUTRINO 2020

Soon on arxiv!

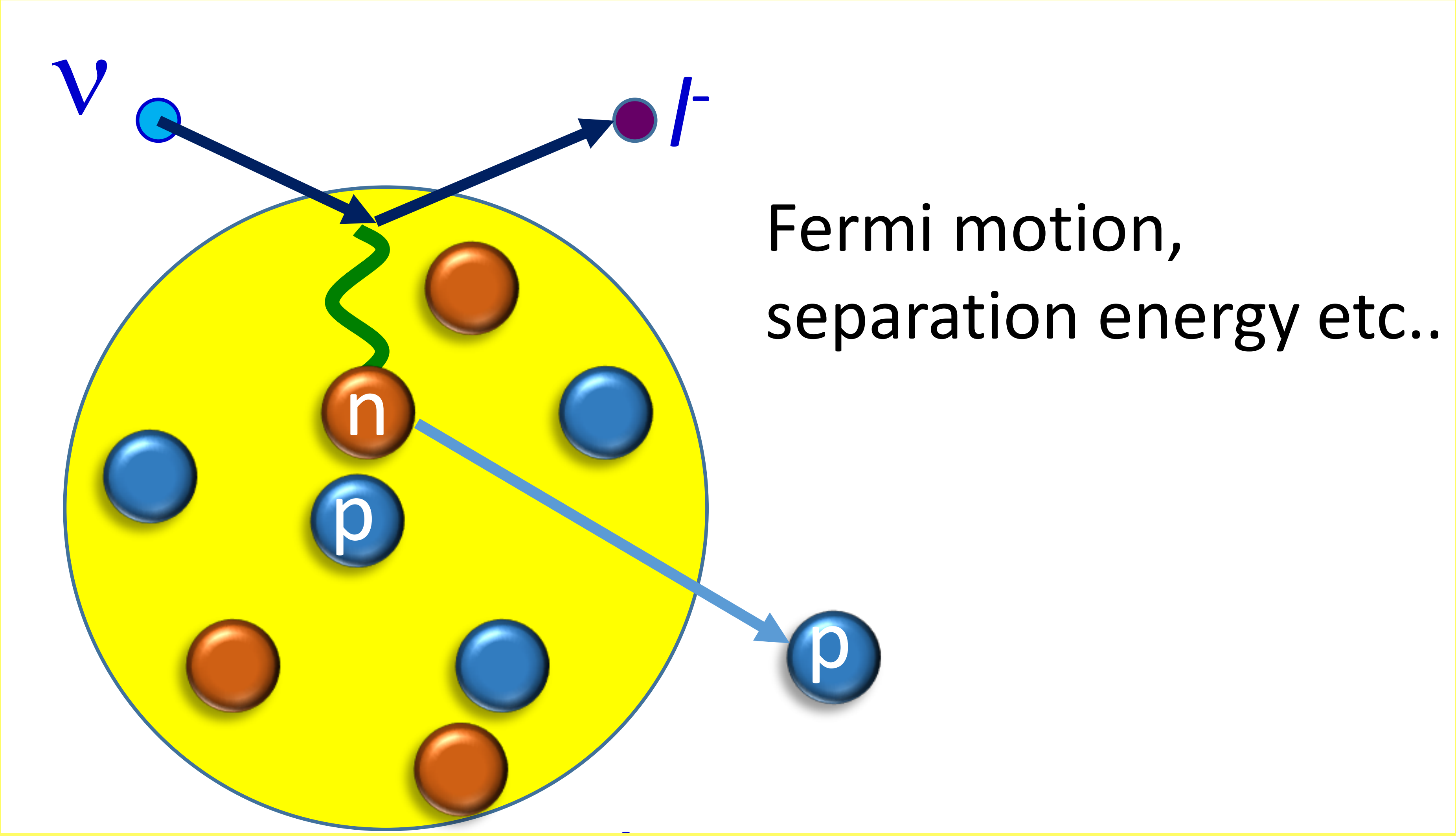
Improvements on Nature paper

- Far detector statistics: +32% ν POT, same anti-ν POT
- Near detector statistics: +98% ν POT, +116% anti-ν POT
- Improved flux constraint, using NA61/SHINE replica target data
- Overhauled interaction model, and updated ND280 selections

Beam quality monitoring

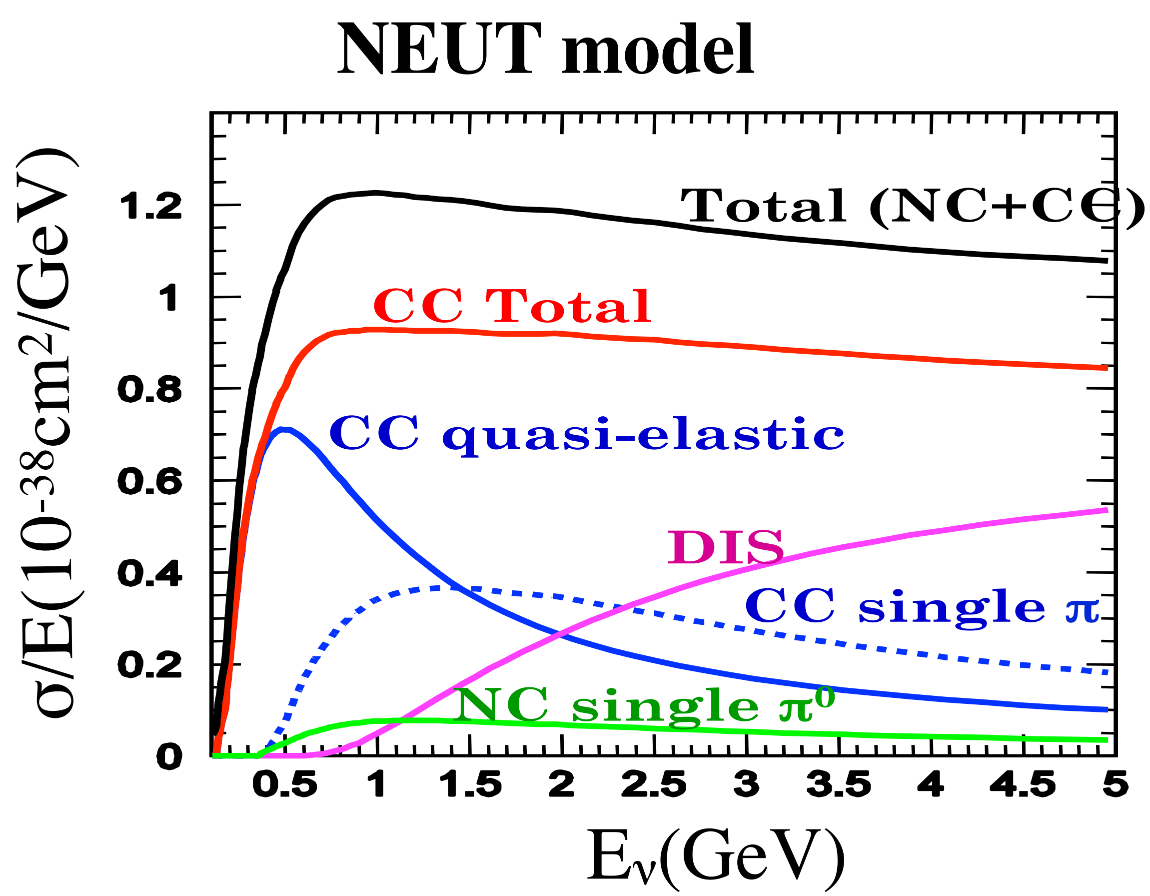


4. Neutrino Cross section



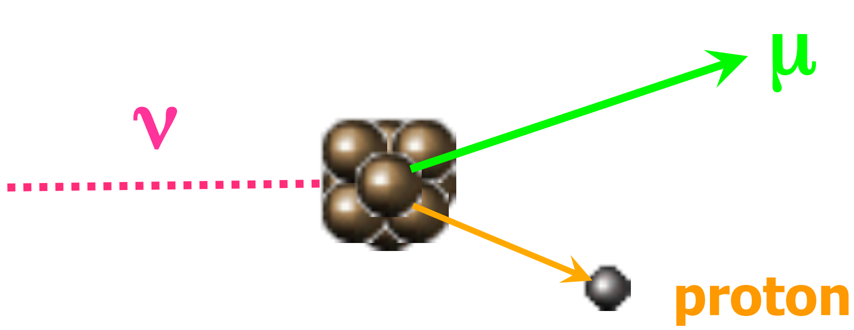
Dedicated lectures will be given by Prof. Kevin McFarland at this CCEPP Summer School.

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

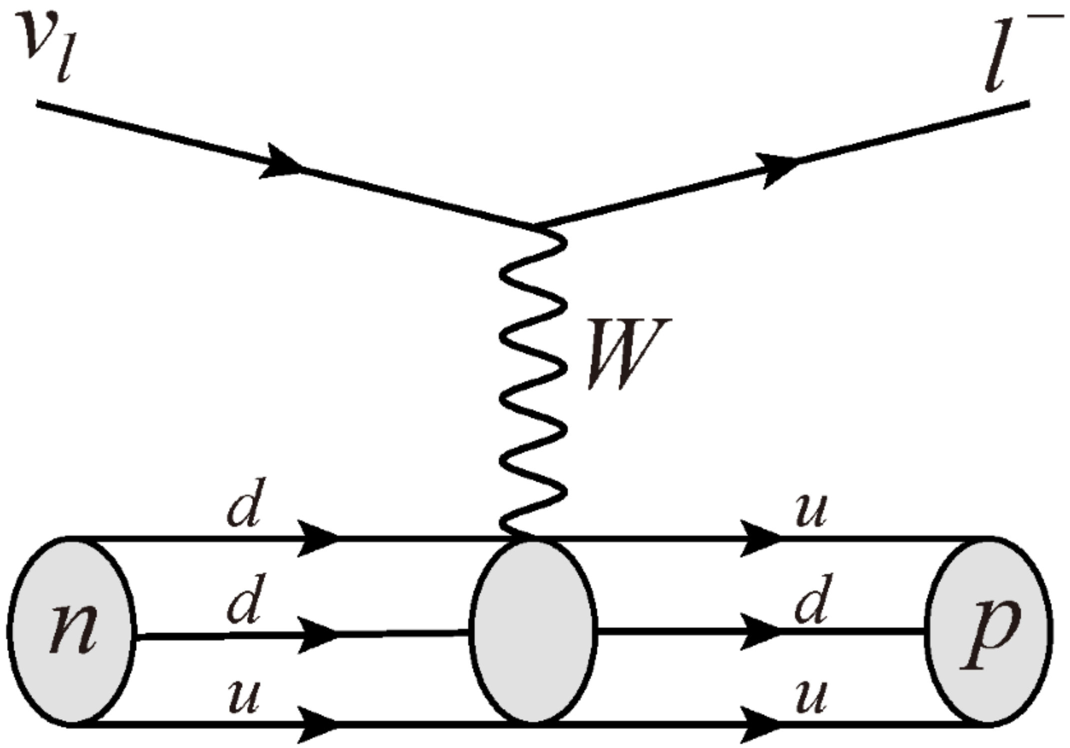


CCQE

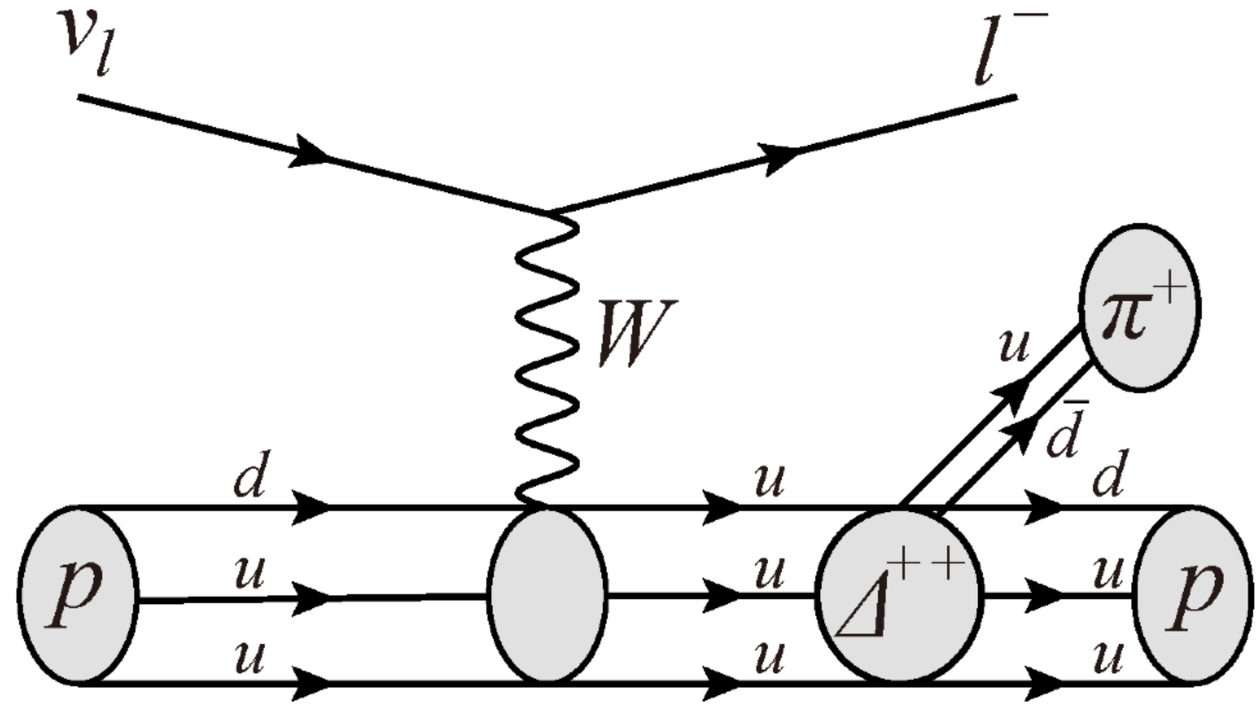
- SIGNAL: reconstruct neutrino energy from lepton momentum and scattering angle.

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

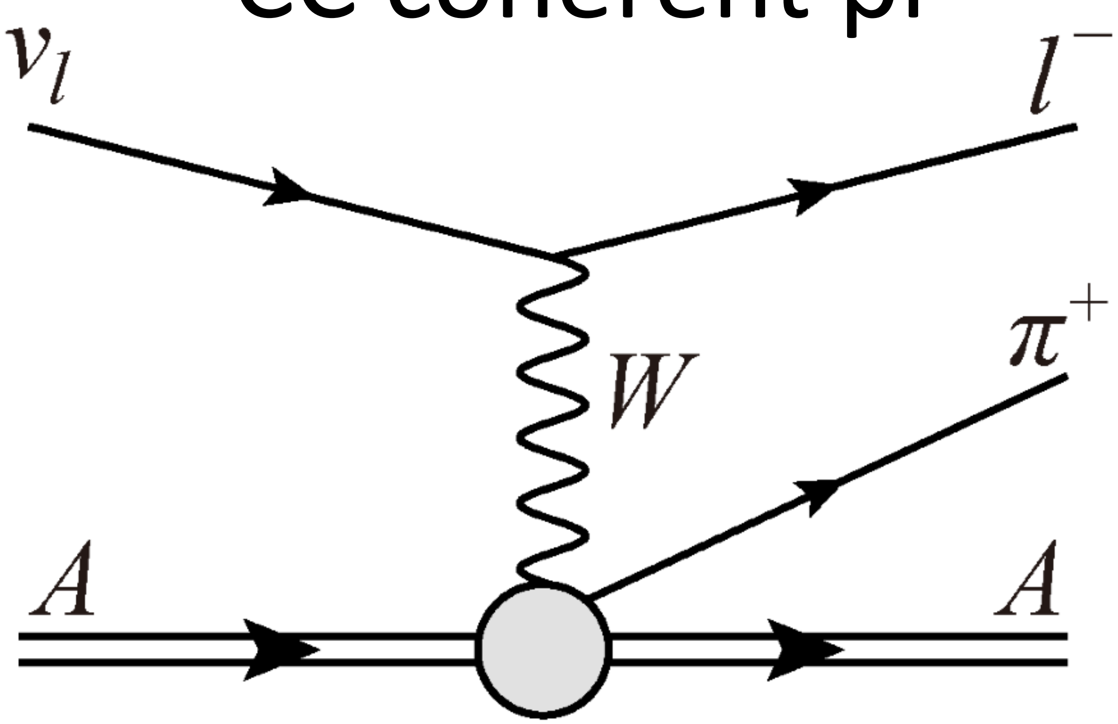
CCQE



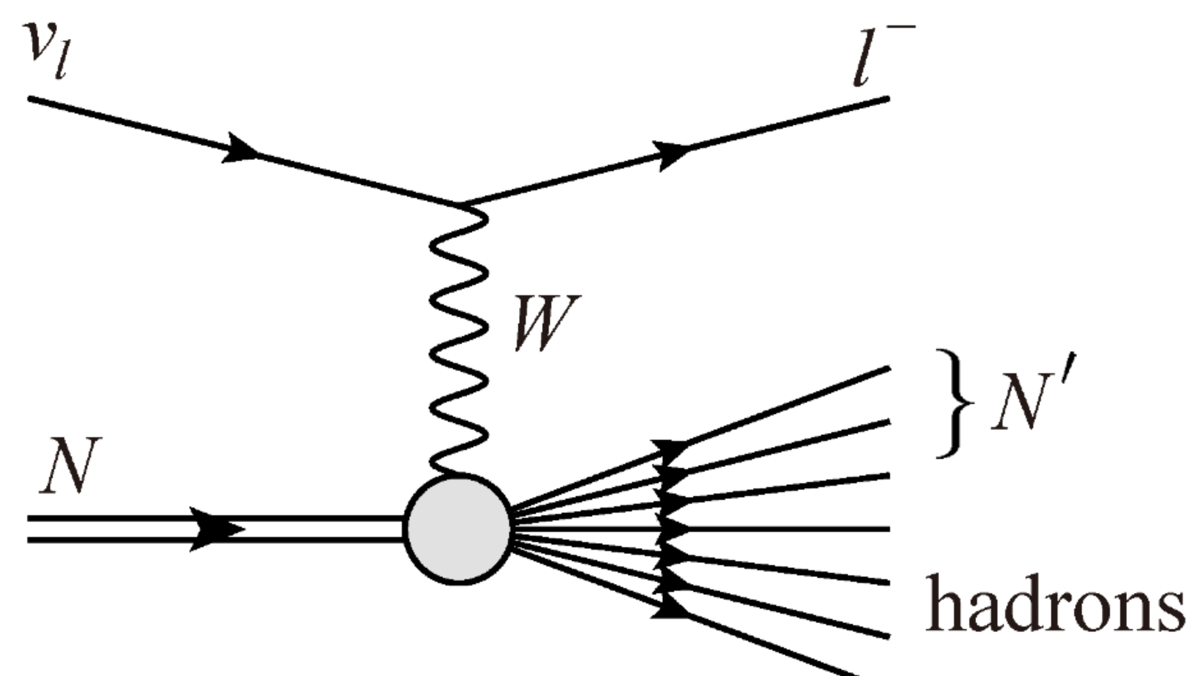
CC1pi



CC coherent pi



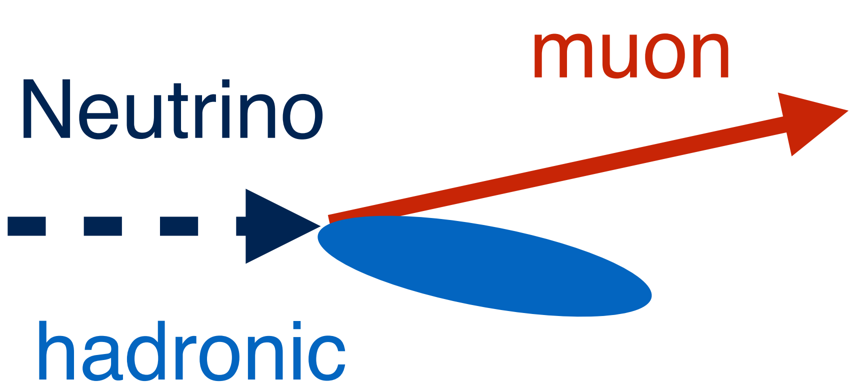
CC Deep-Inelastic-Scattering

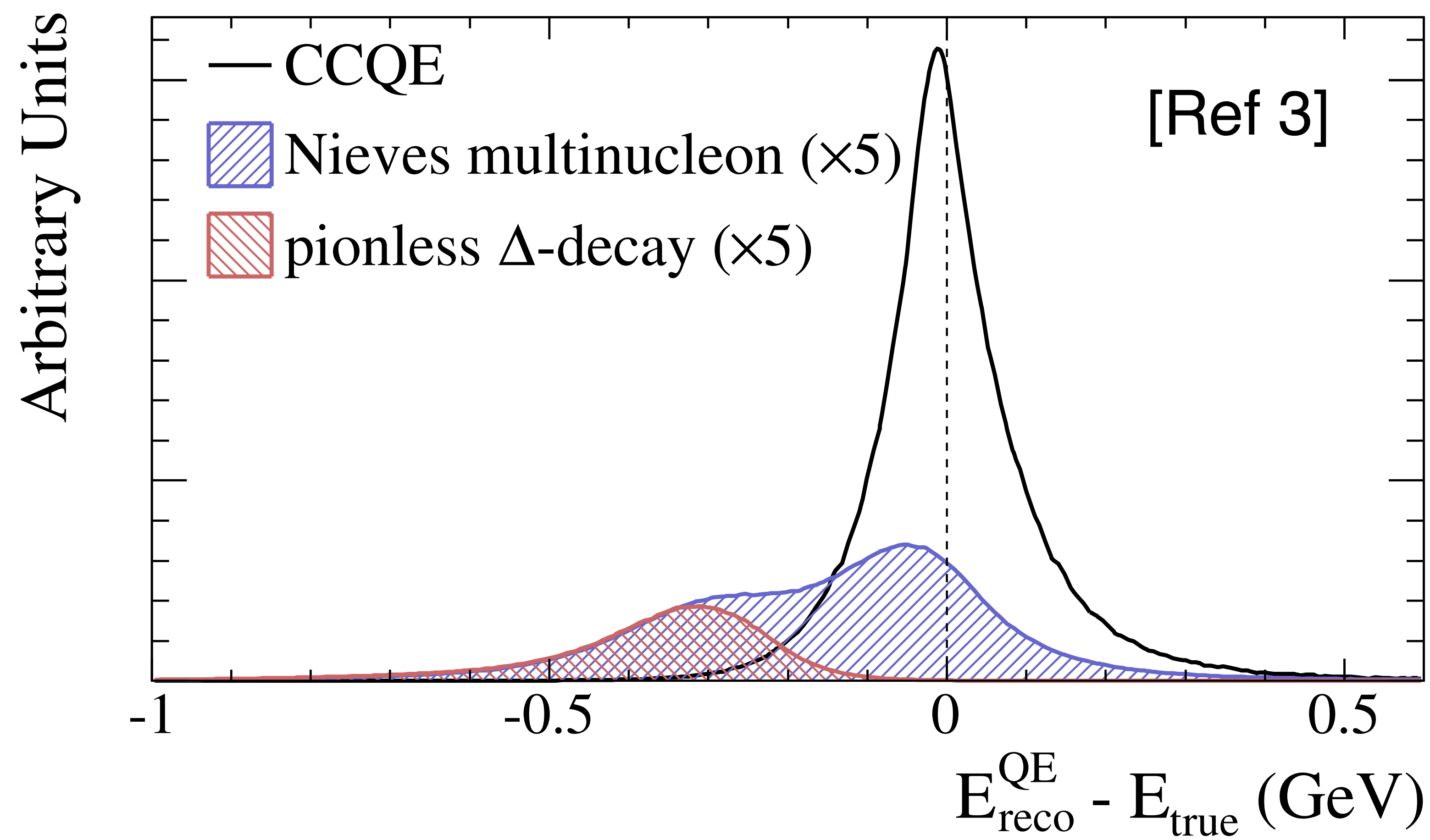


- Oscillation depends on energy
    - Estimate from hadronic and/or leptonic information

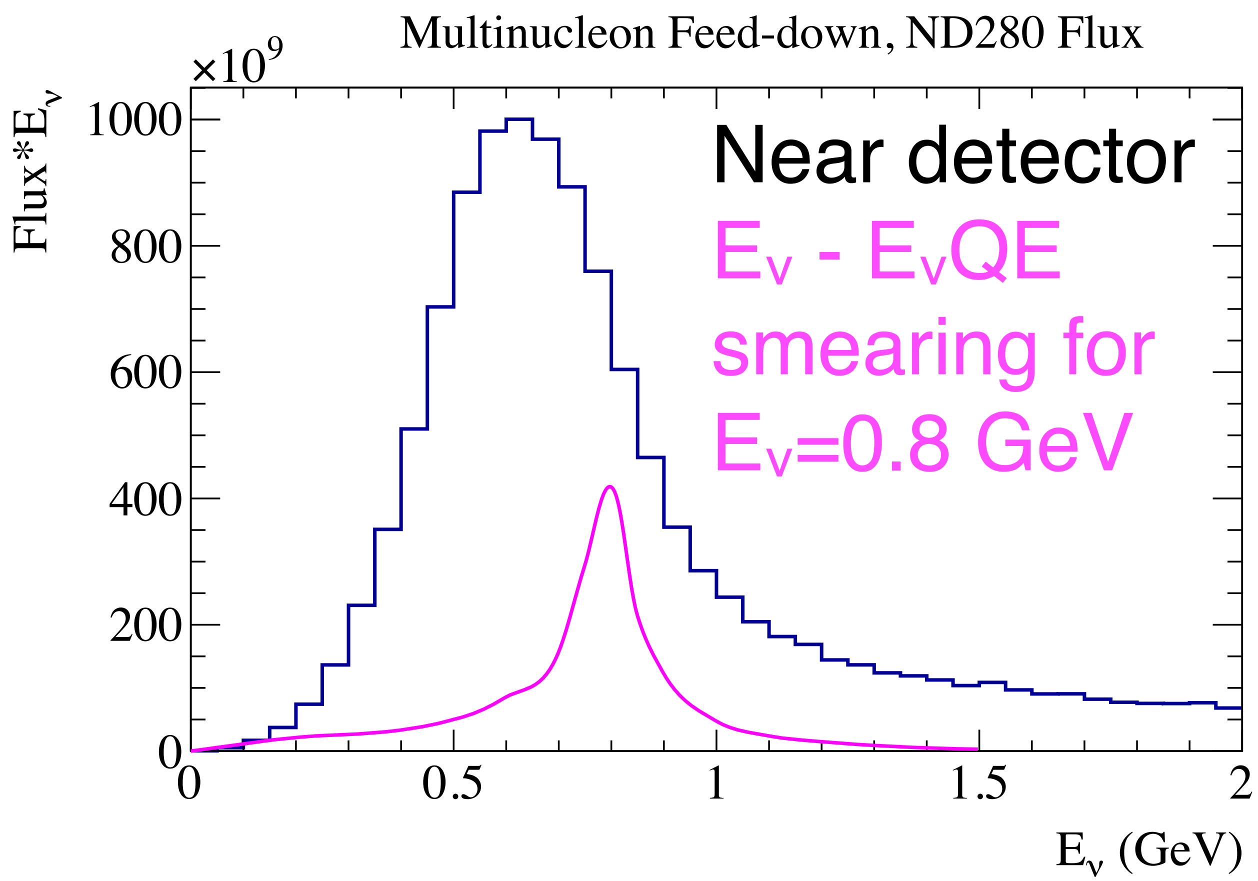
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic}$$

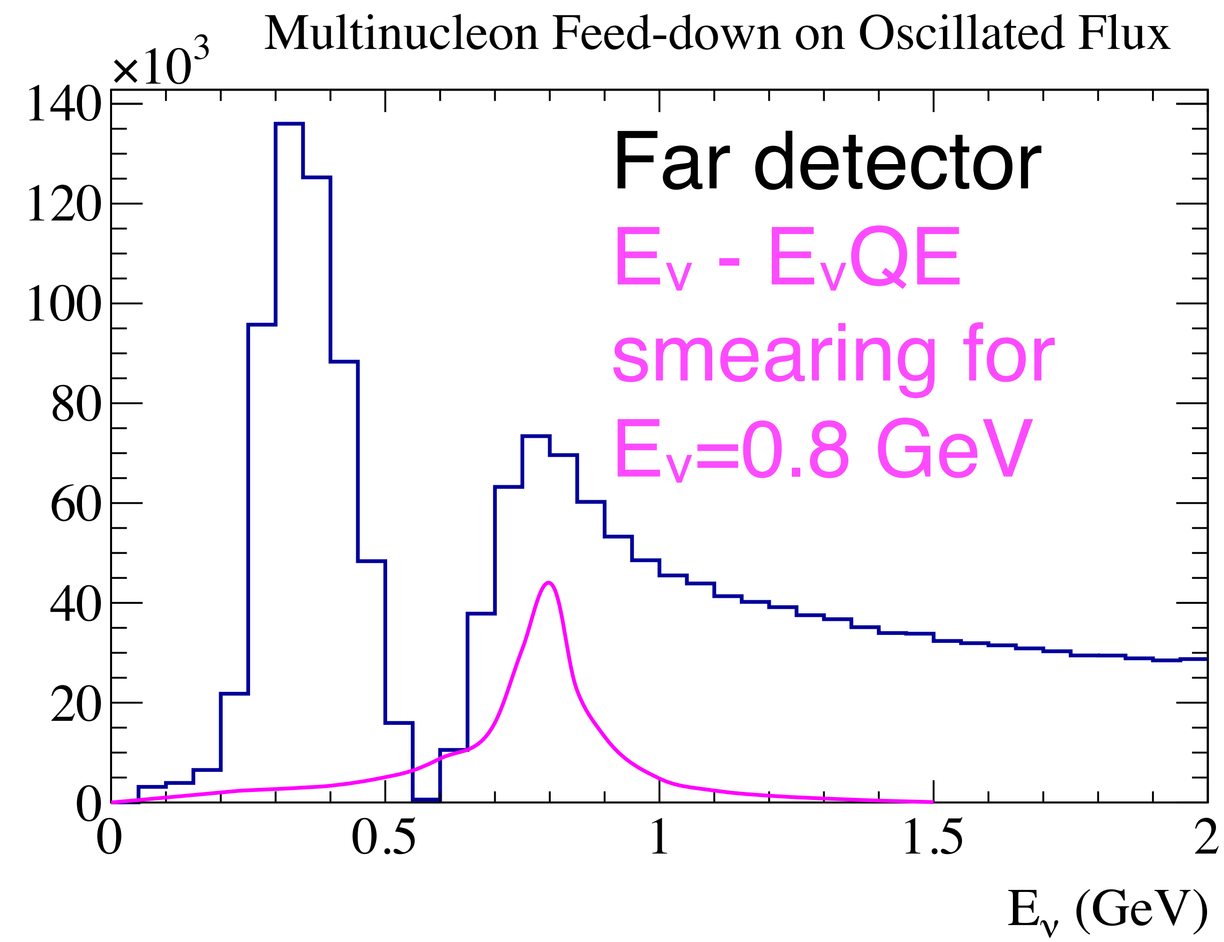
- Nuclear effects bias true and estimated neutrino energy





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



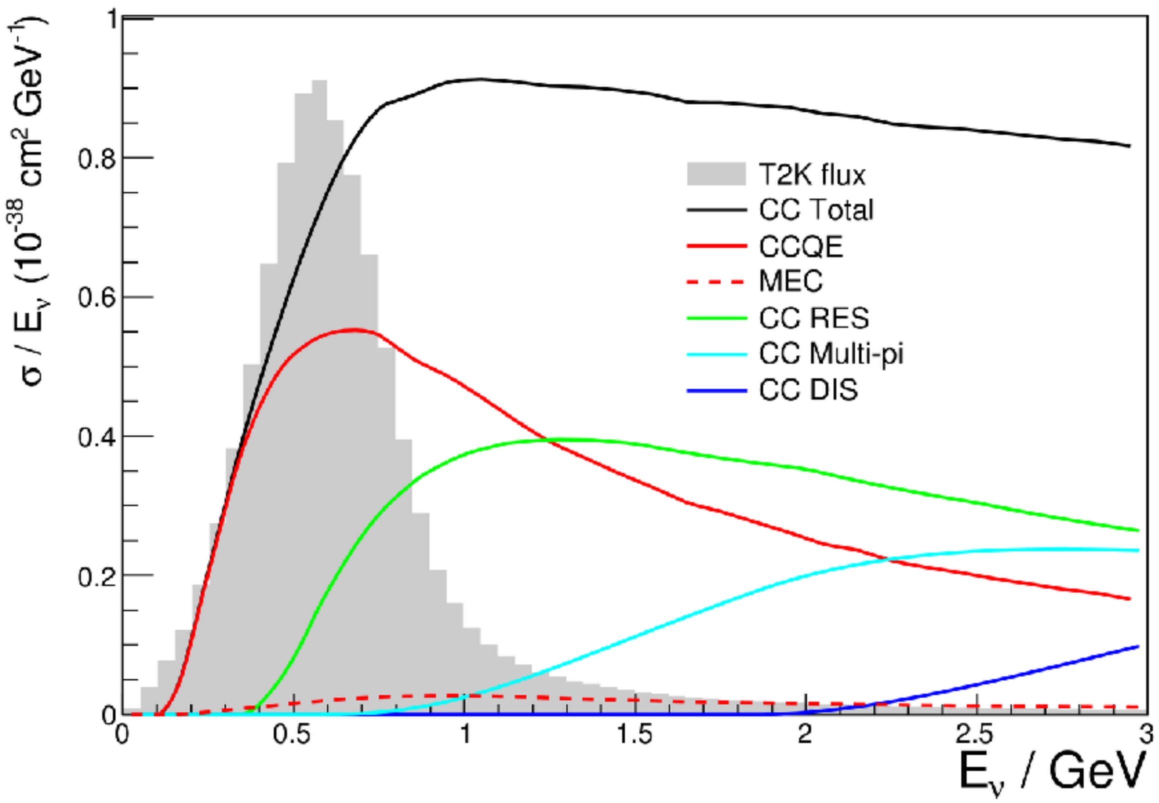


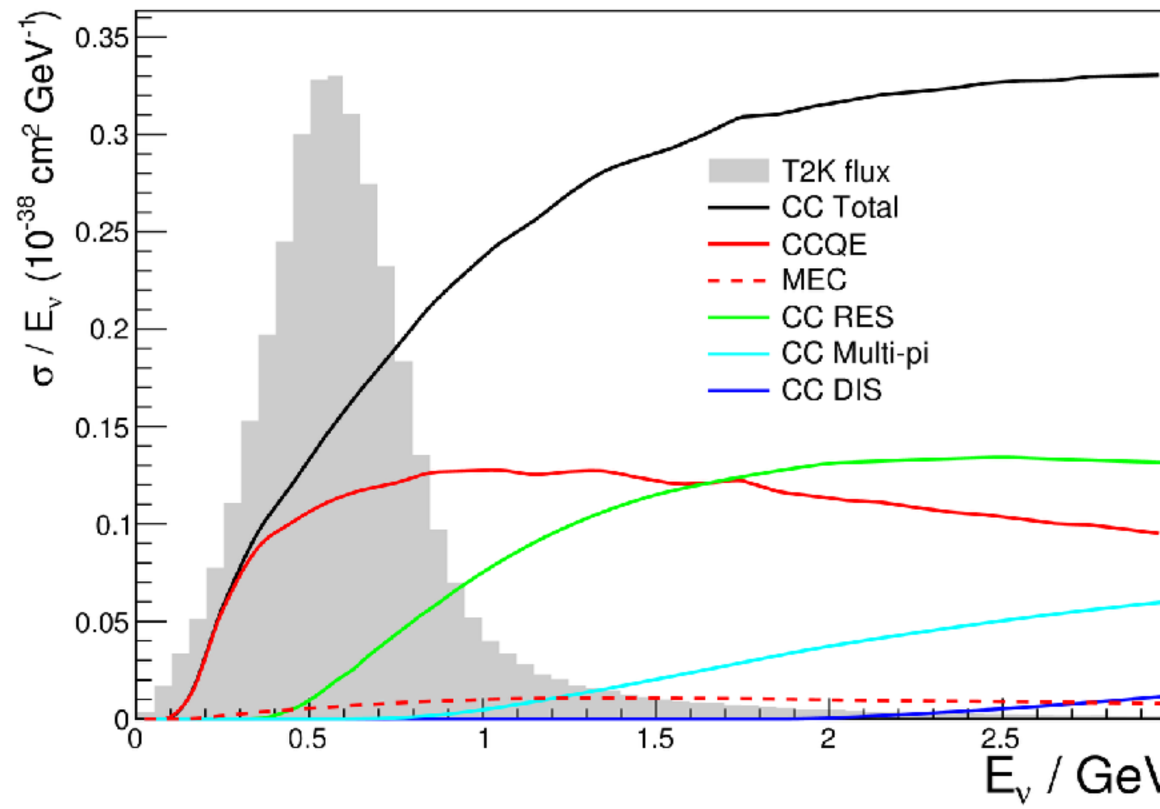
$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P(\nu_\mu \to \nu_e)$$

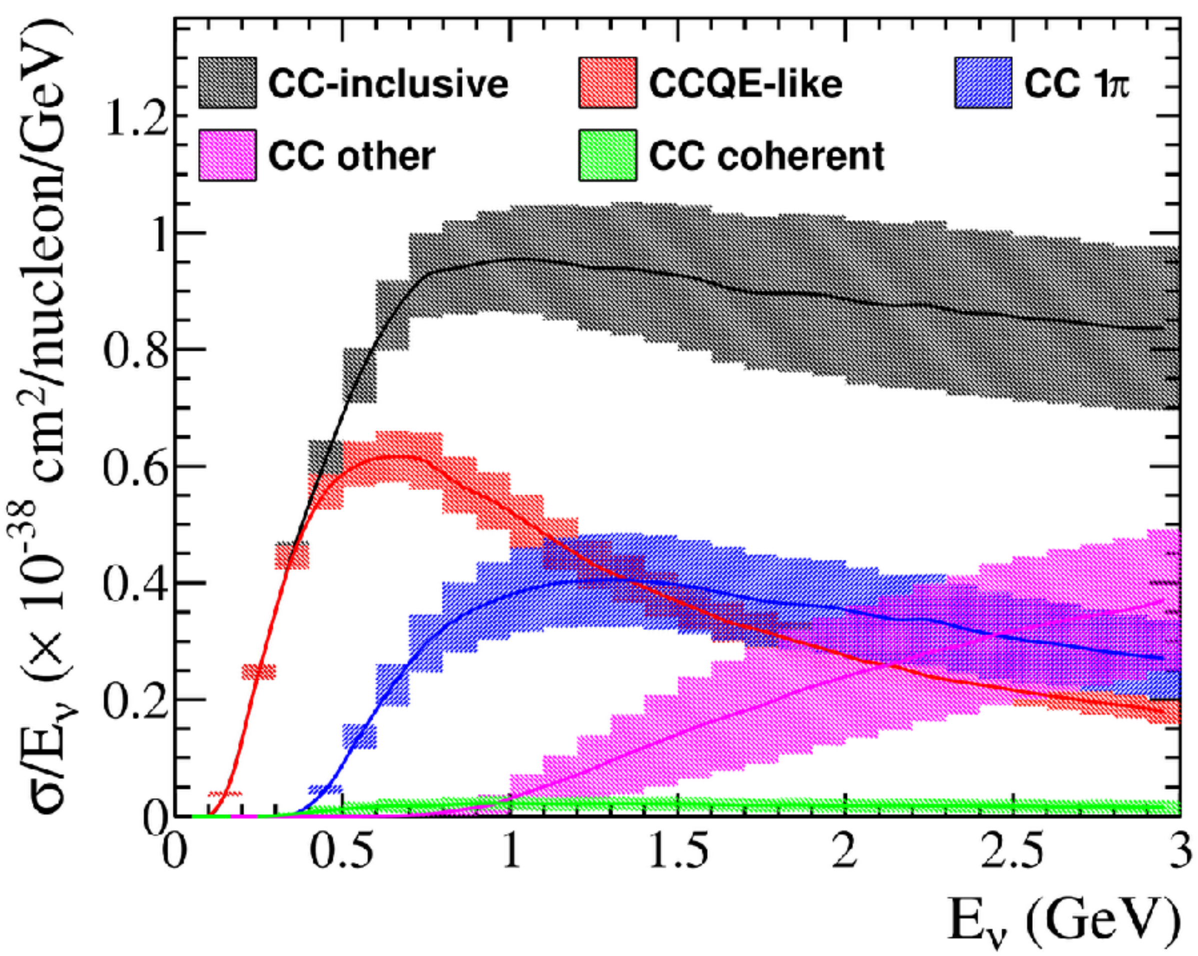
- Even with a near detector, **critical reliance on model**
  - 2p2h feed-down to oscillation peak from [Ref 4]

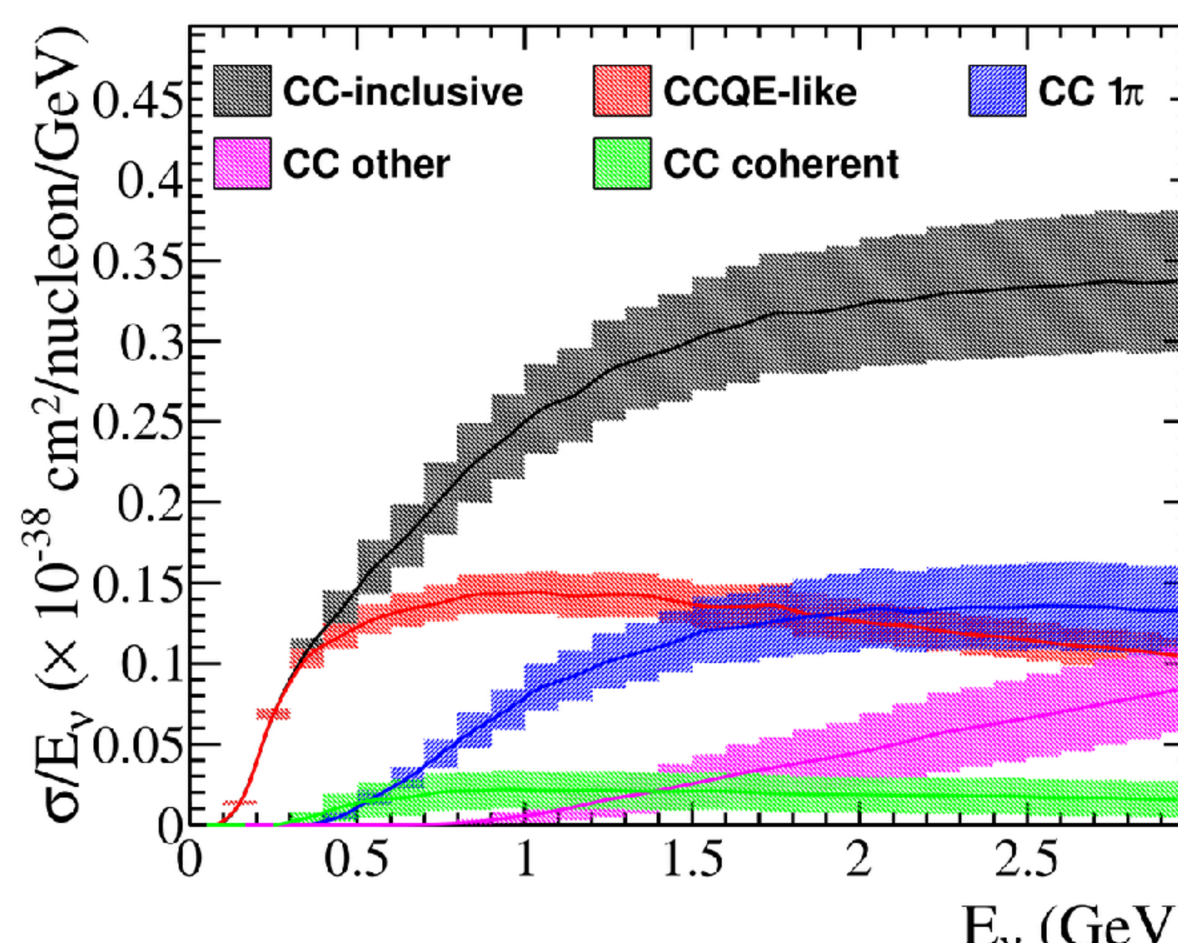
σ ν-CC/E_ν

σ $\bar{\nu}$-CC/$E_{\bar{\nu}}$







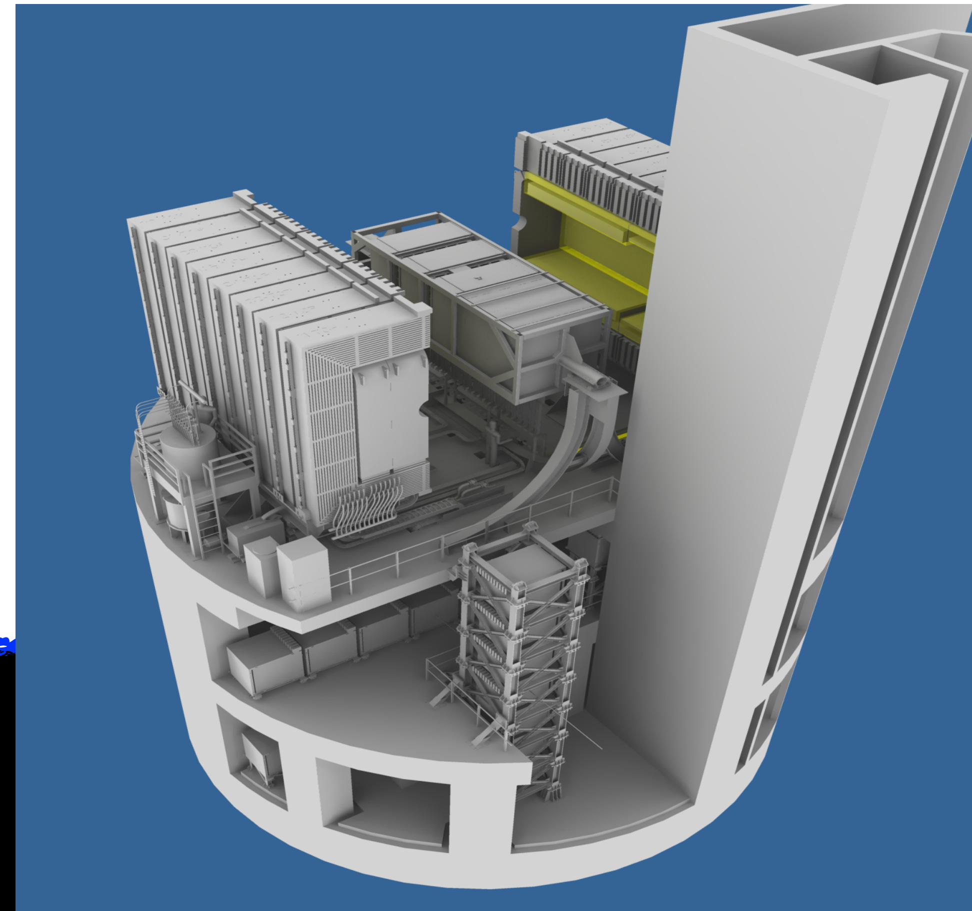


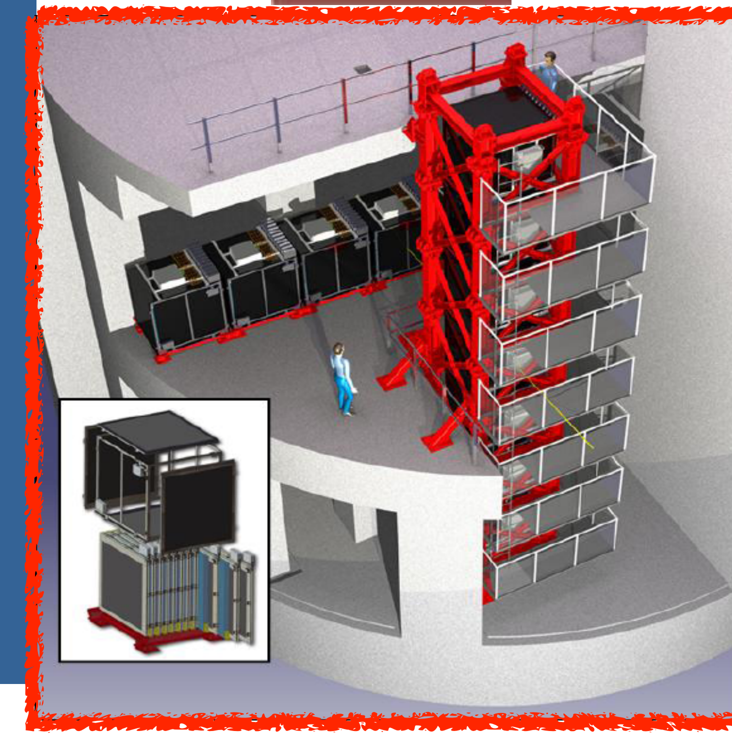
5. ND280

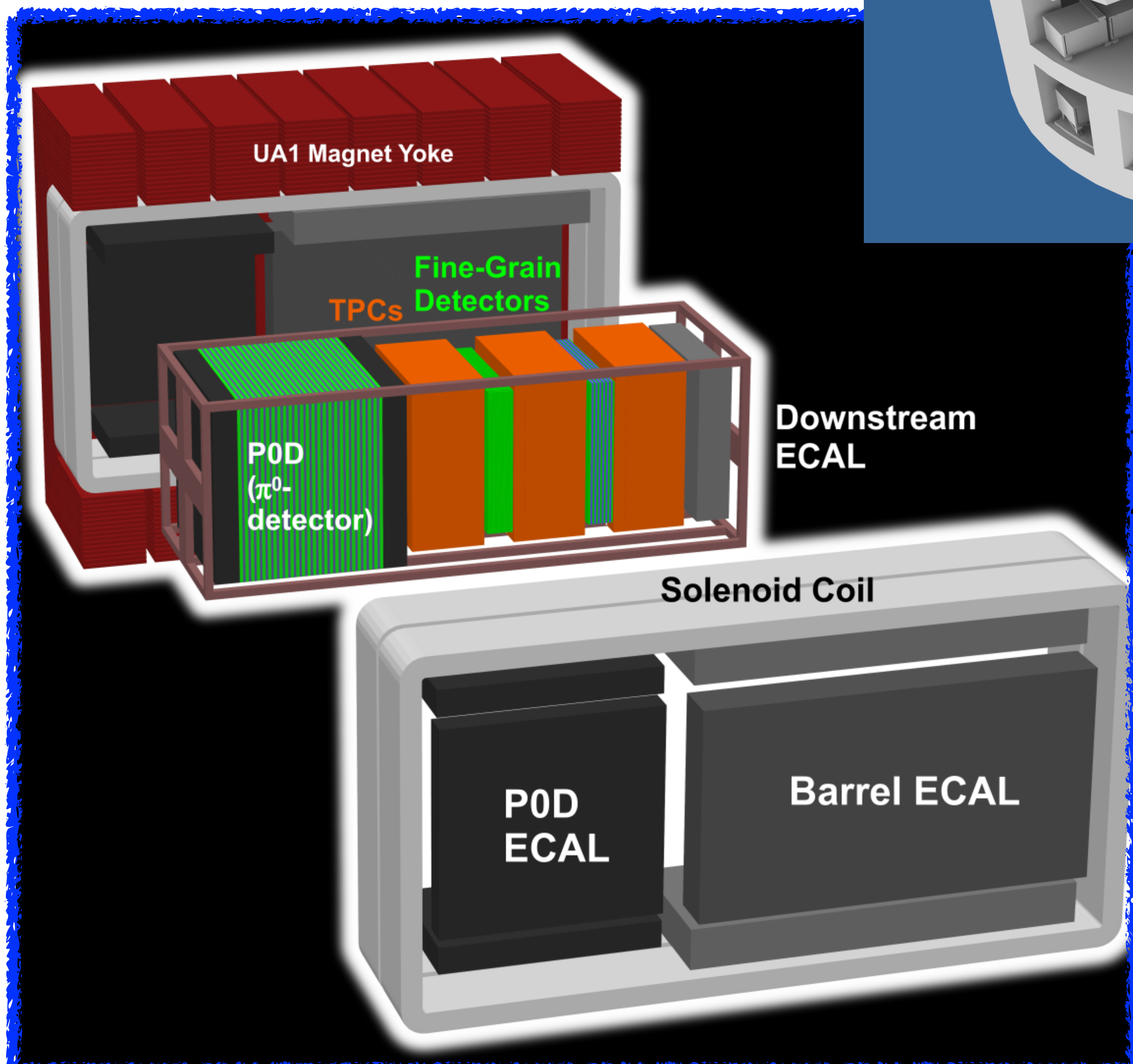
- Near Detectors -

ND280

Near Detector @ 280m from the target



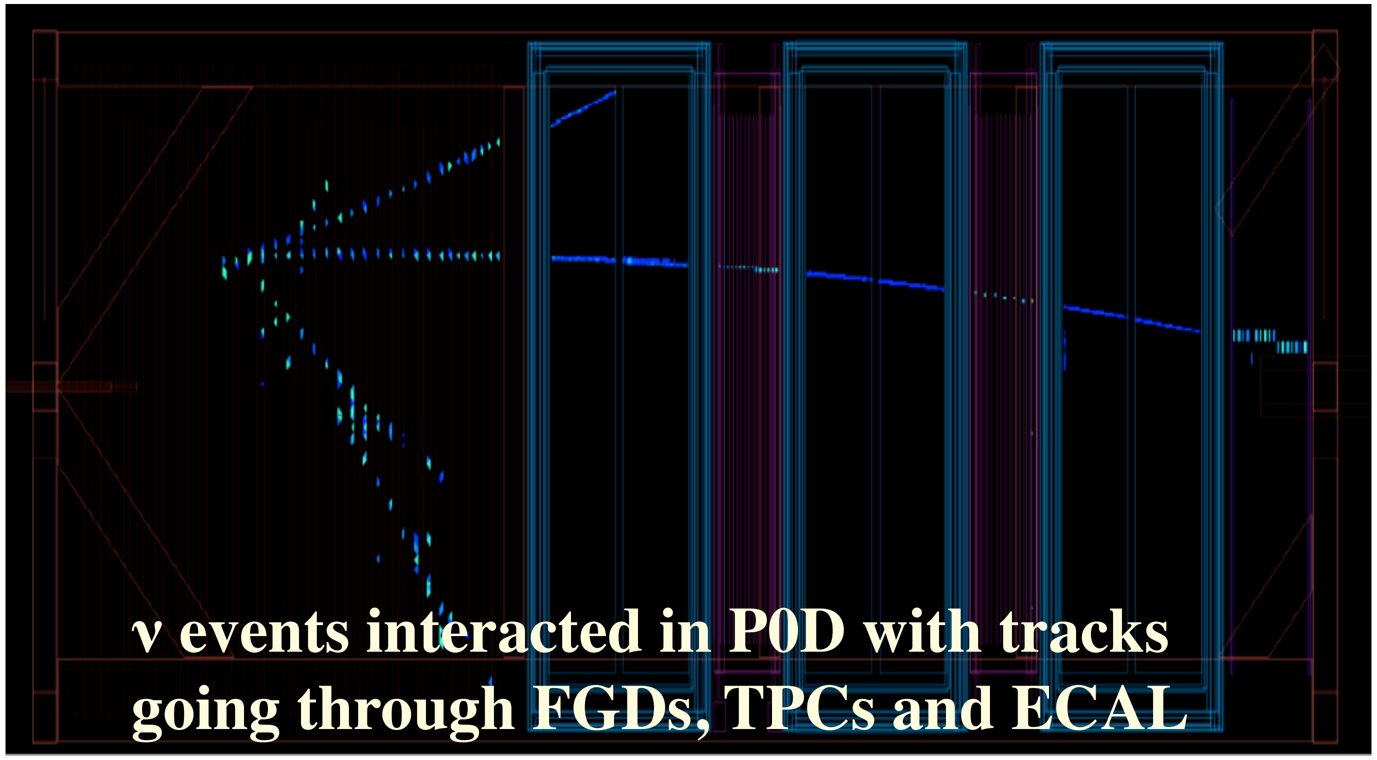




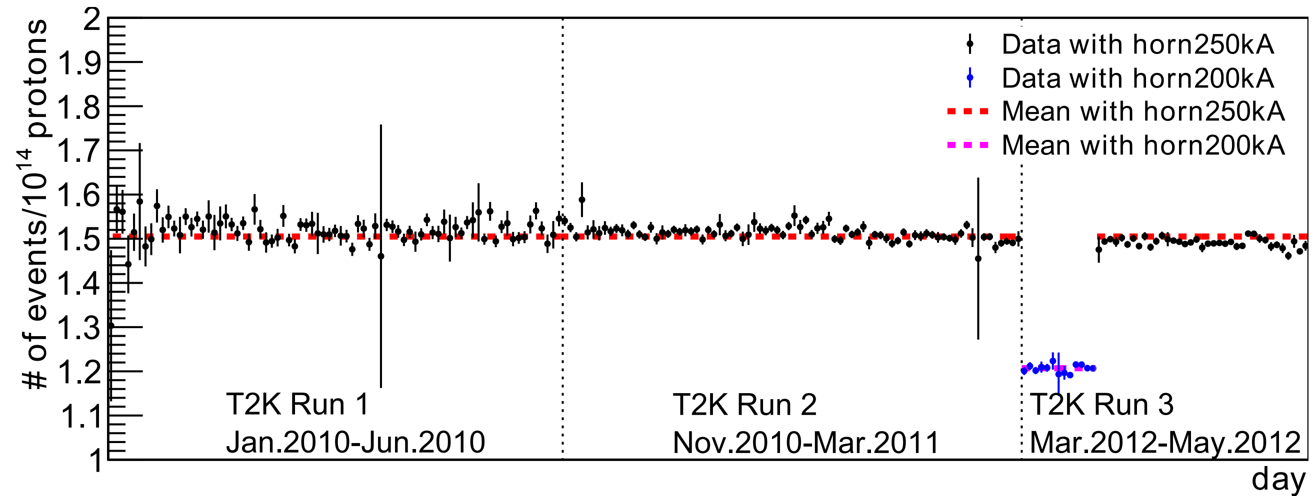
- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]

- **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

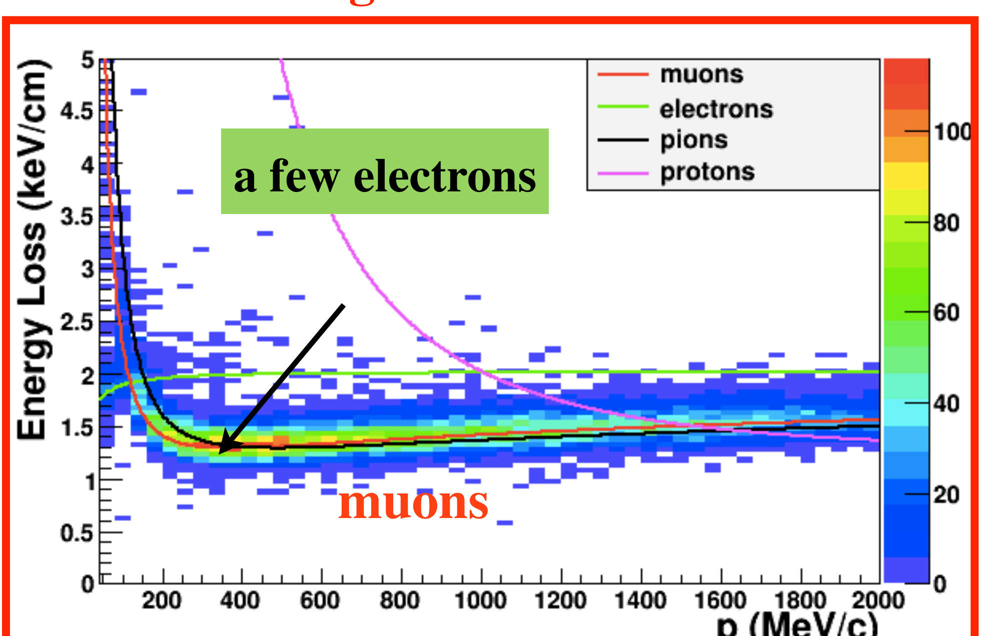


ν event rate stability by INGRID

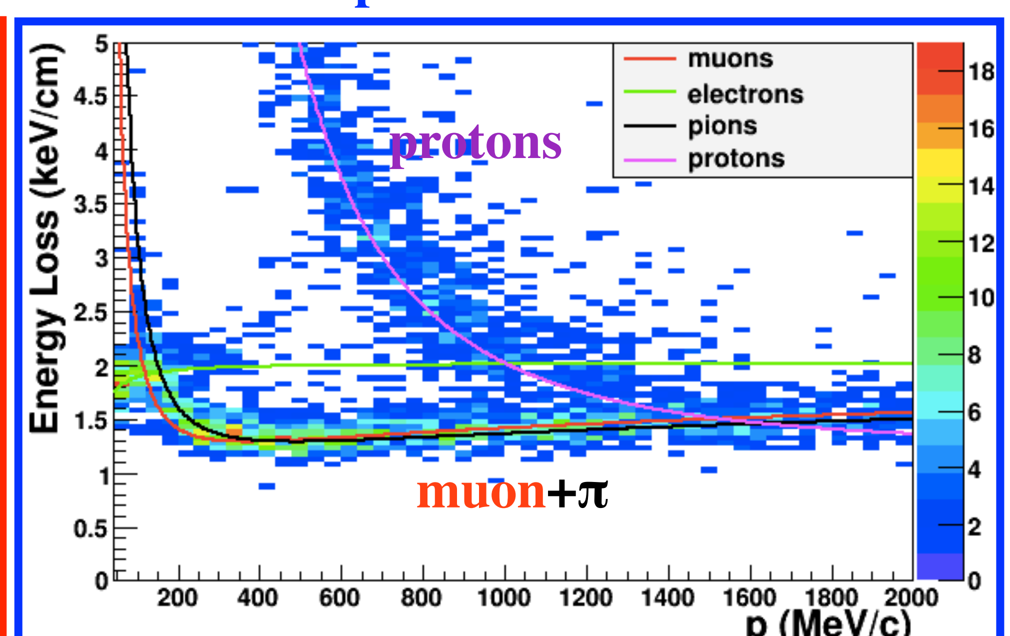


TPC PID

negative track

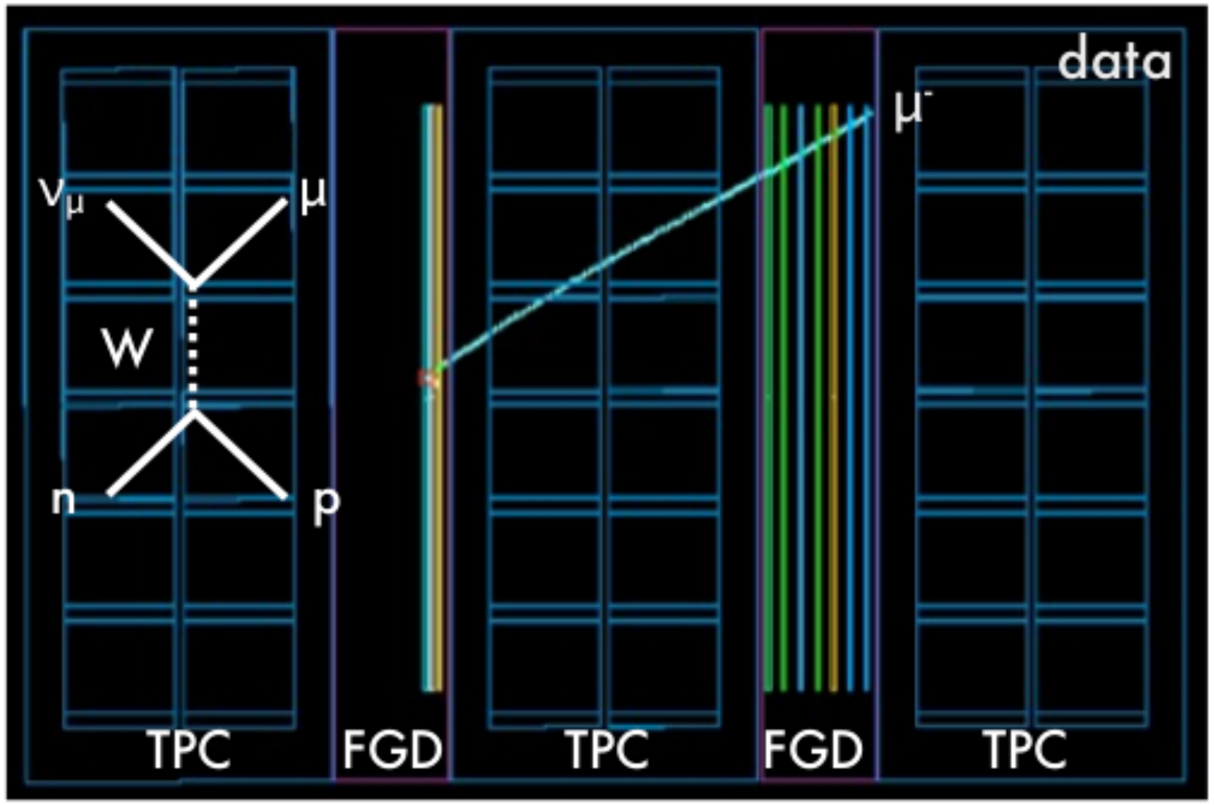


positive track

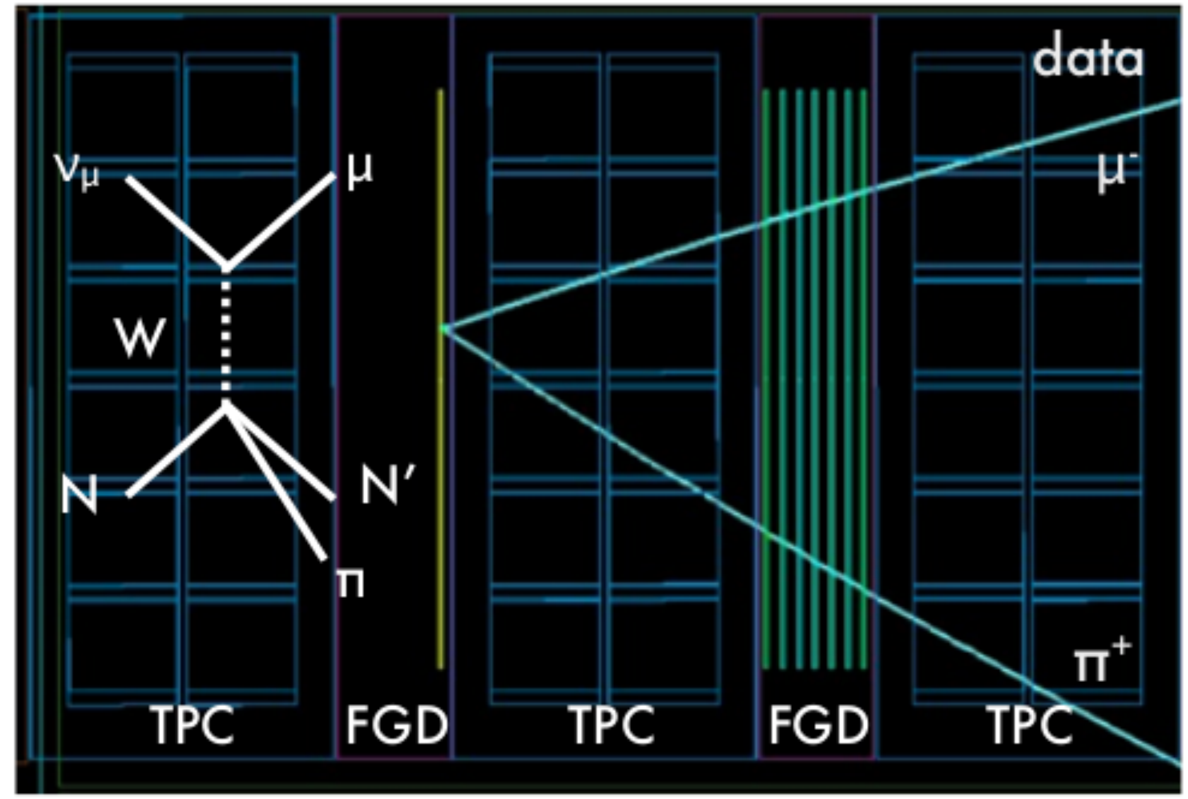


- INGRID
  - ν rate stability
  - beam direction:
    - -0.01±0.33 mrad (x)
    - -0.11±0.37 mrad (y)
- ND280
  - excellent PID and tracking capability
  - measurements of the neutrino interactions.

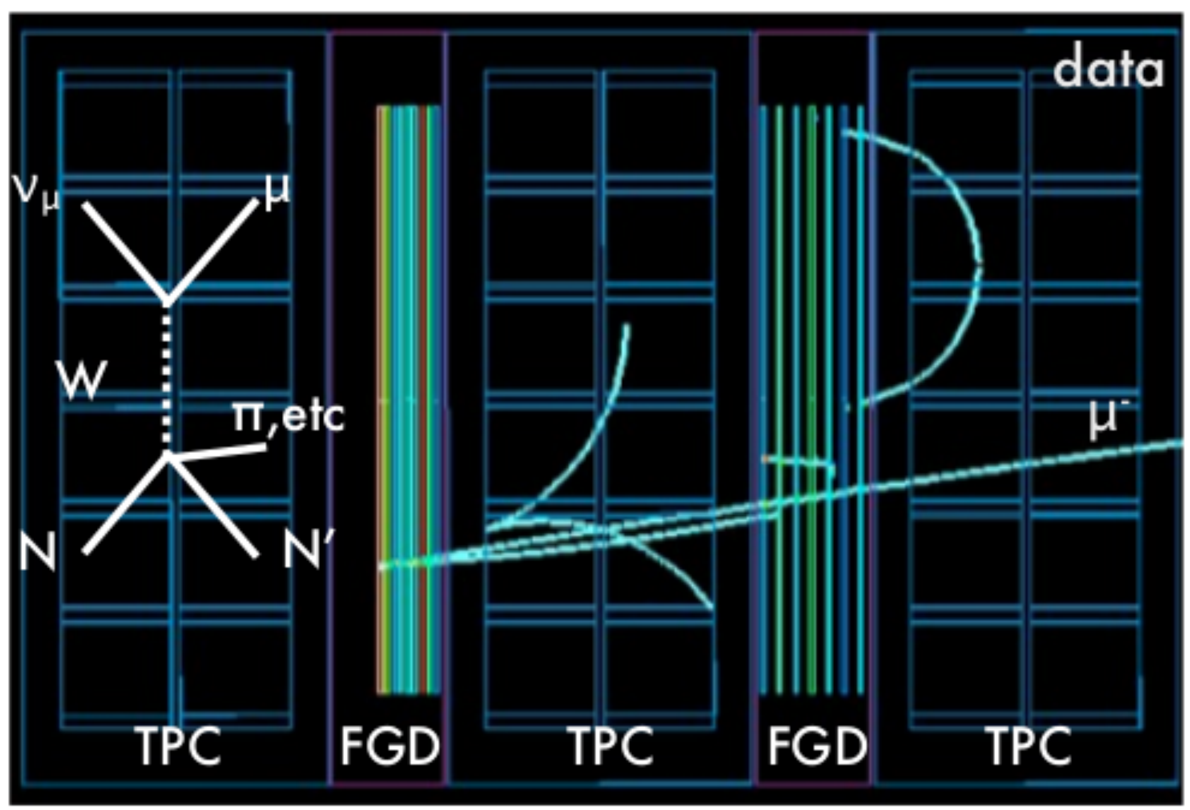
ν_μ CC0π



ν_μ CC1π^+

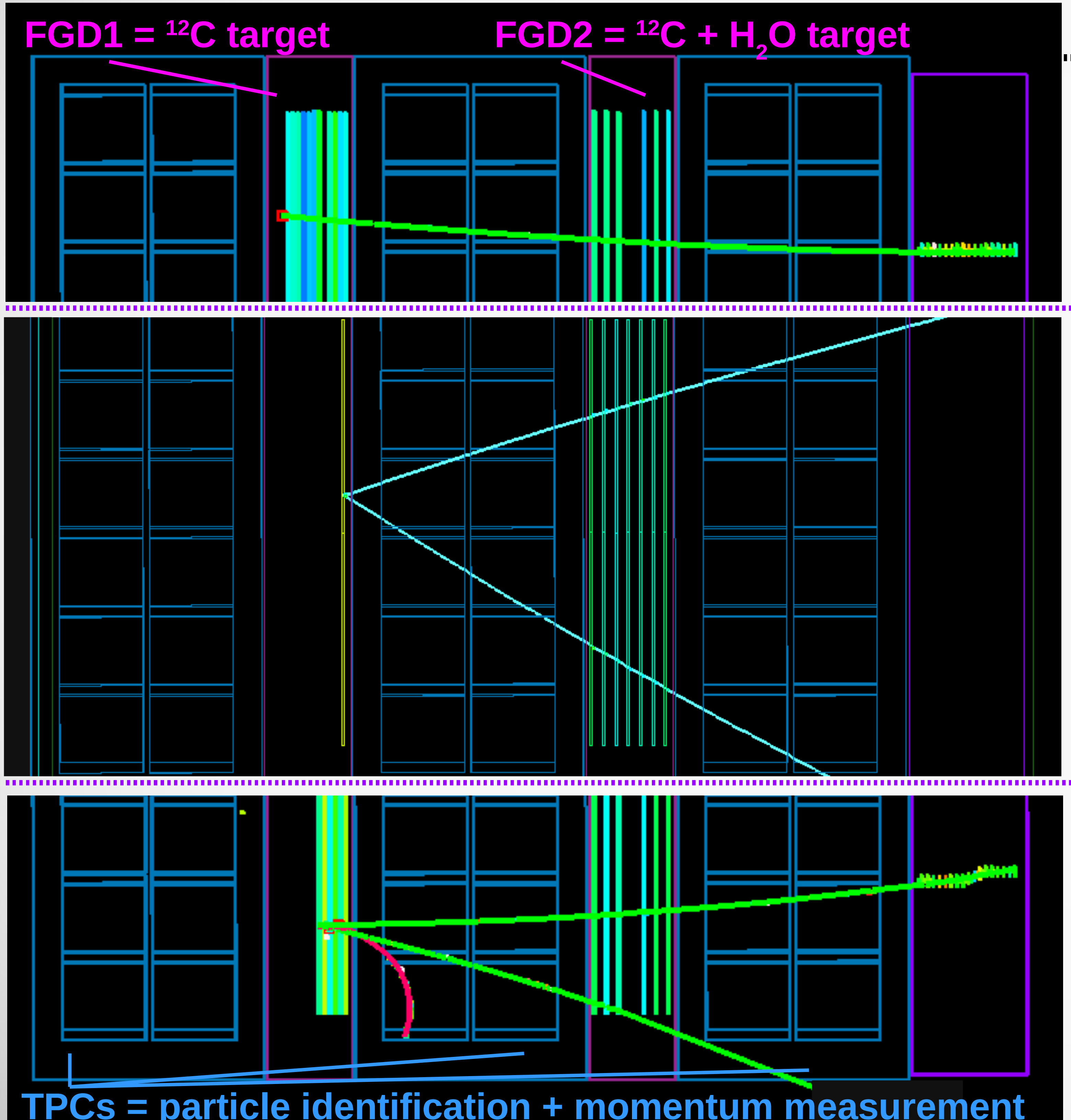


ν_μ CC other



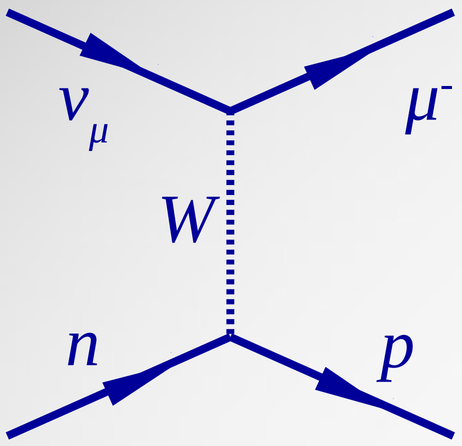
Selection in ND280

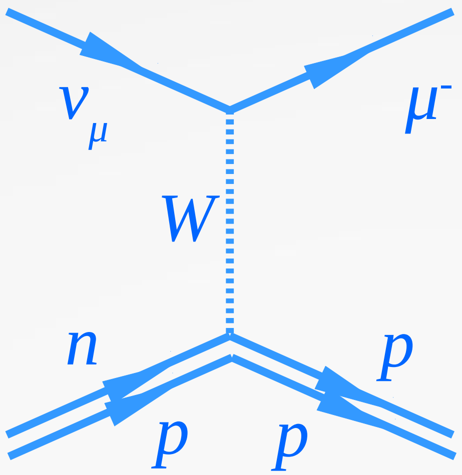
Selection of charged-current (CC) interactions of:



ν_μ in ν mode	$\bar{\nu}_\mu$ in $\bar{\nu}$ mode	ν_μ in $\bar{\nu}$ 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





<u>CCQE: 5 parameters</u>

axial mass M_A^{QE}

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

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

<u>2p2h: 3 parameters</u>

Nieves model

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

(ν / $\bar{\nu}$)

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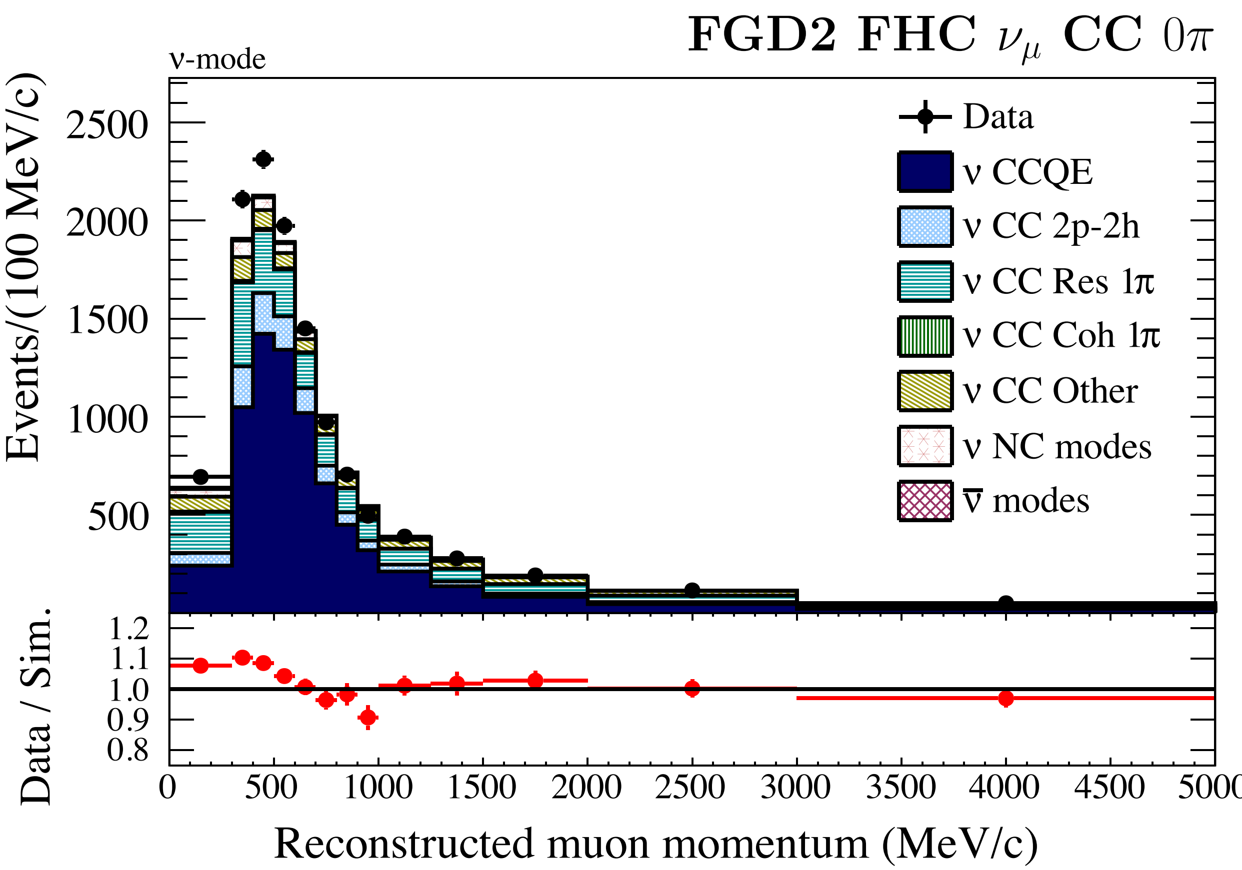

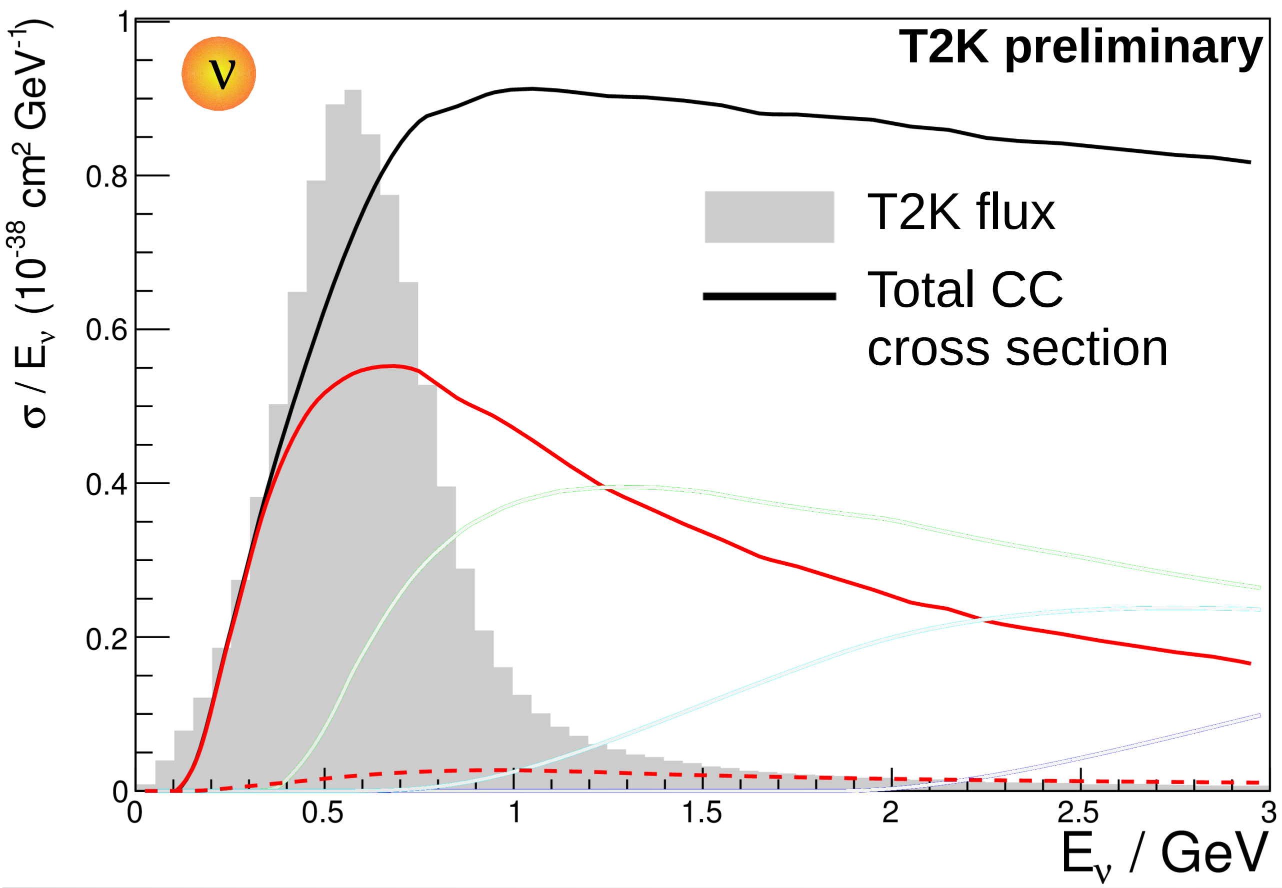

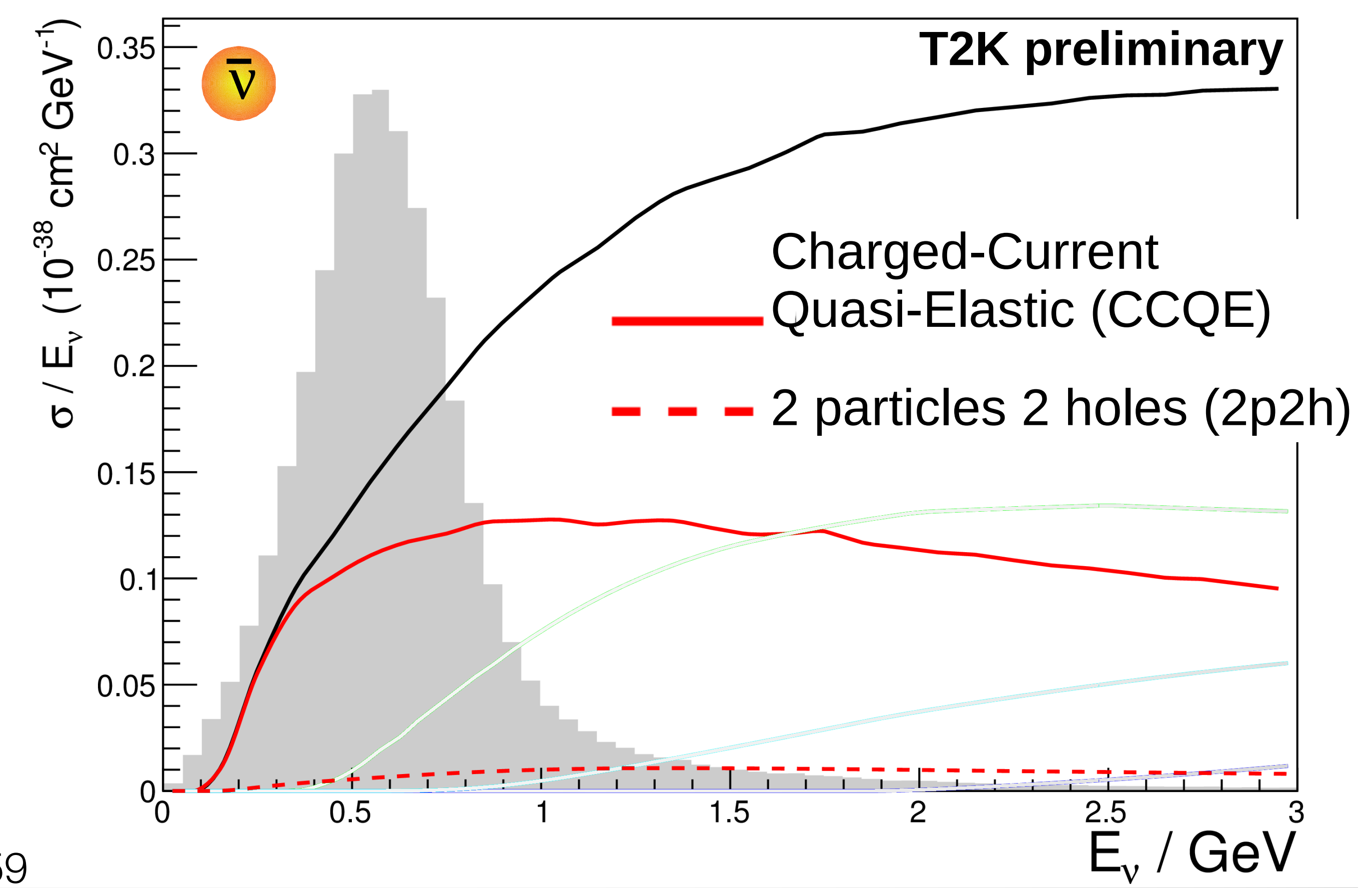

Interaction model: CC-1π

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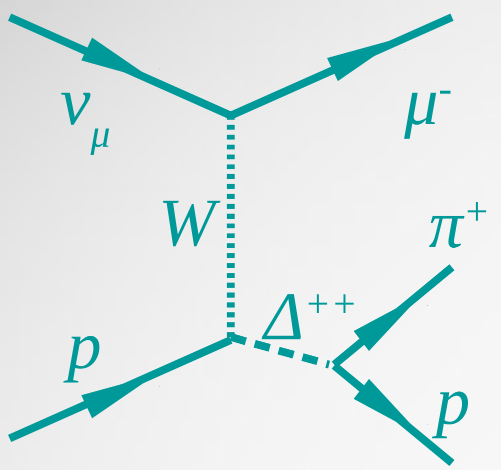
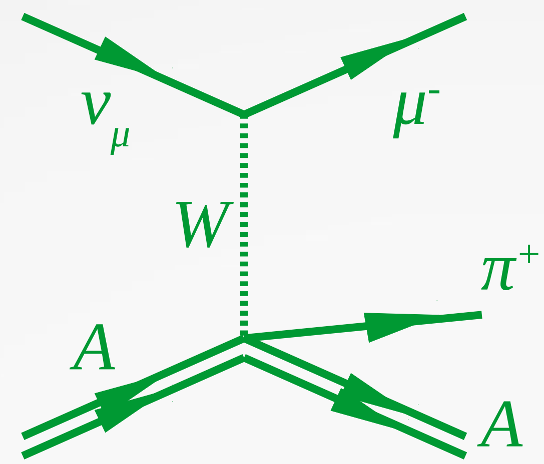




<u>CC-RES: 3 parameters</u>

axial mass M_A^{RES}

norm+shape parameter C_A^5

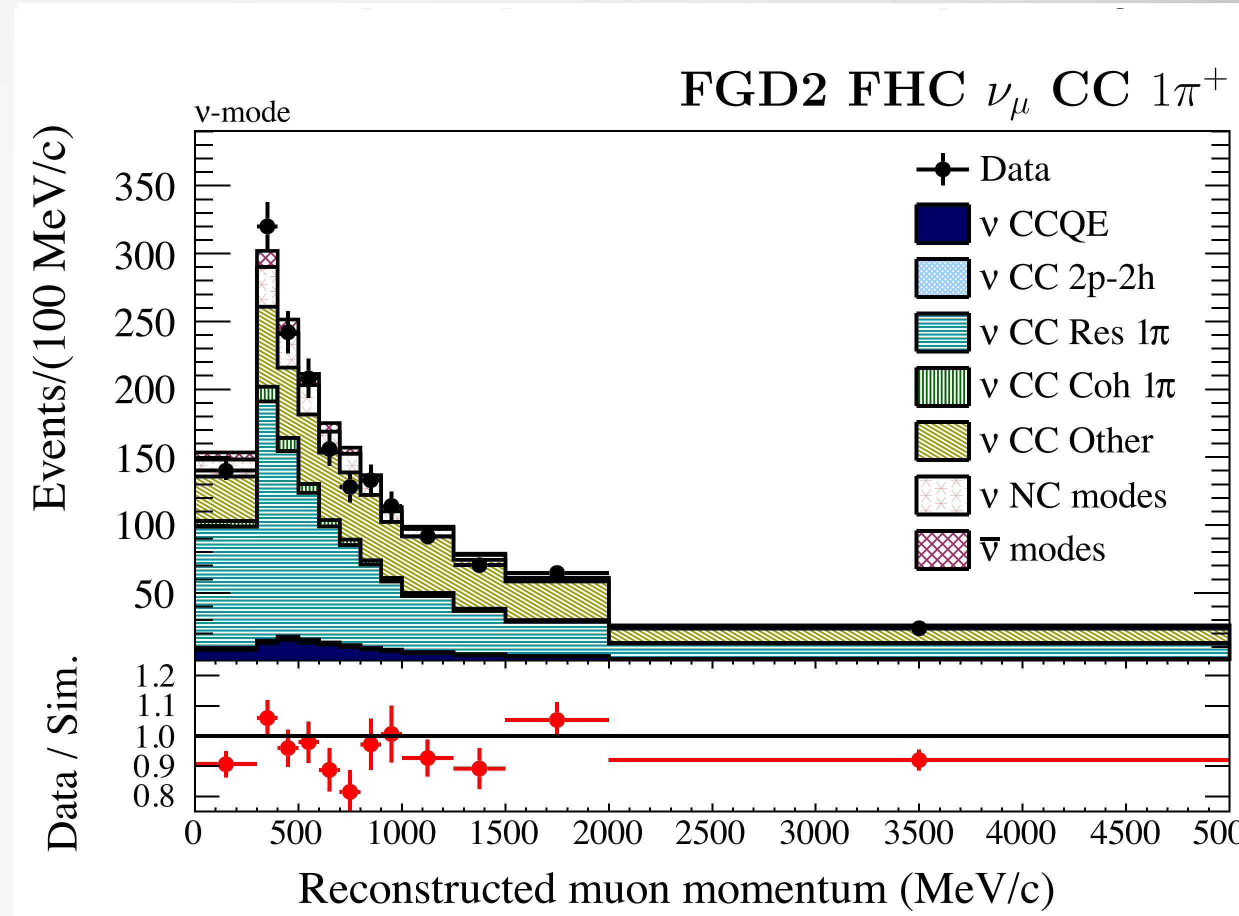
Isospin=1/2 background

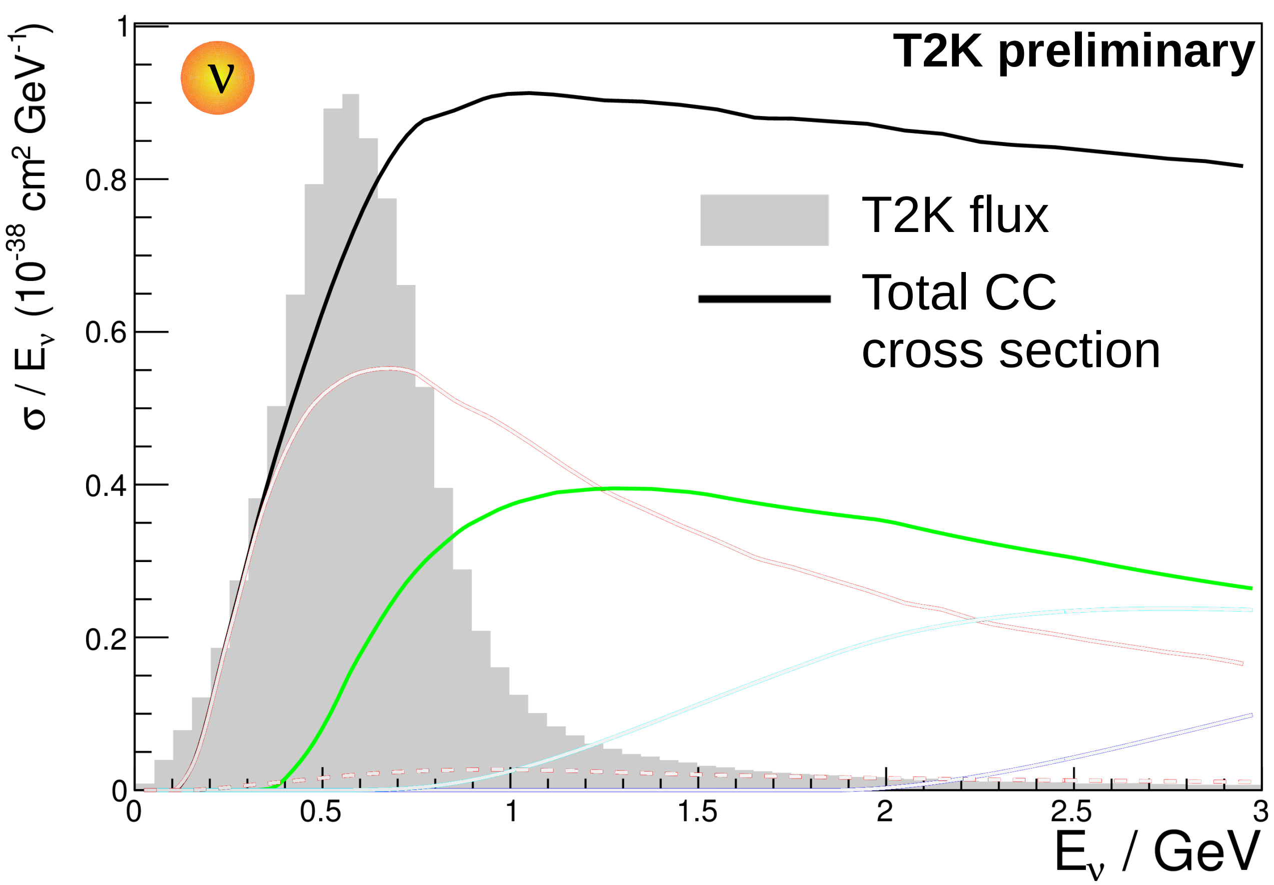
<u>CC-COH: 1 parameter</u>

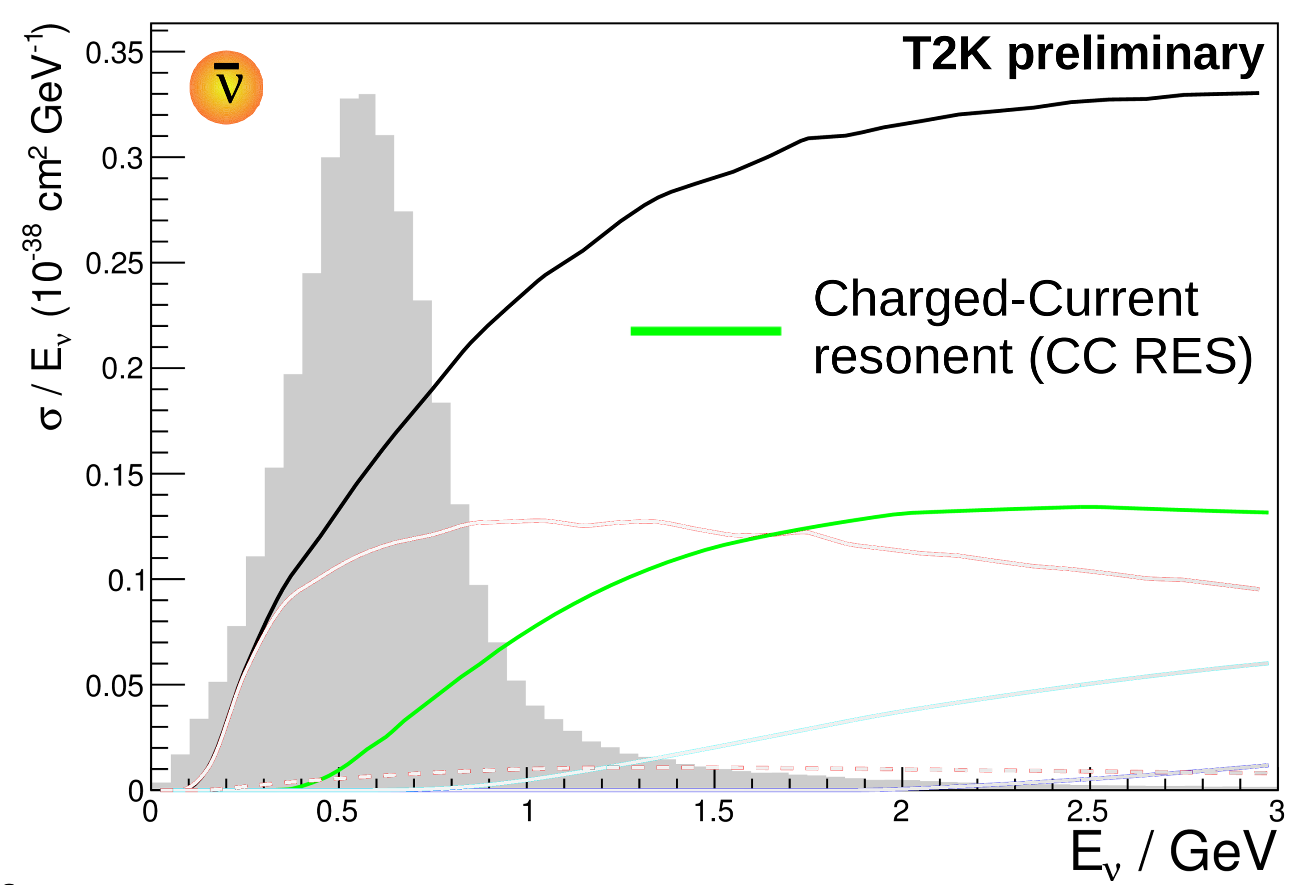
CC-coherent

cross-section

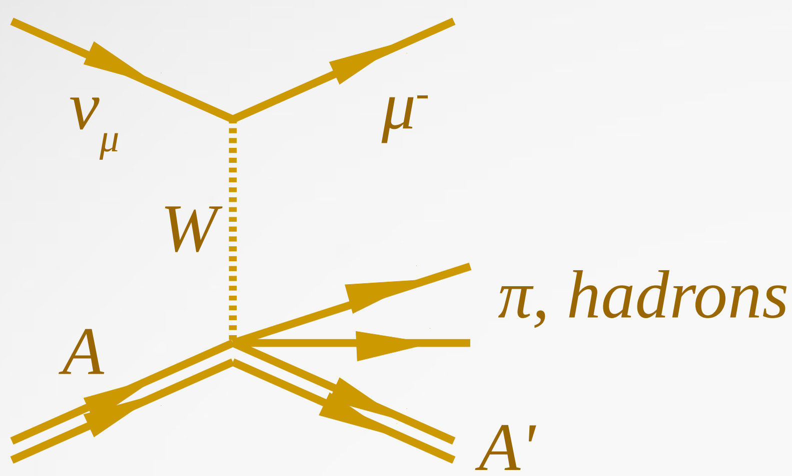
normalisation

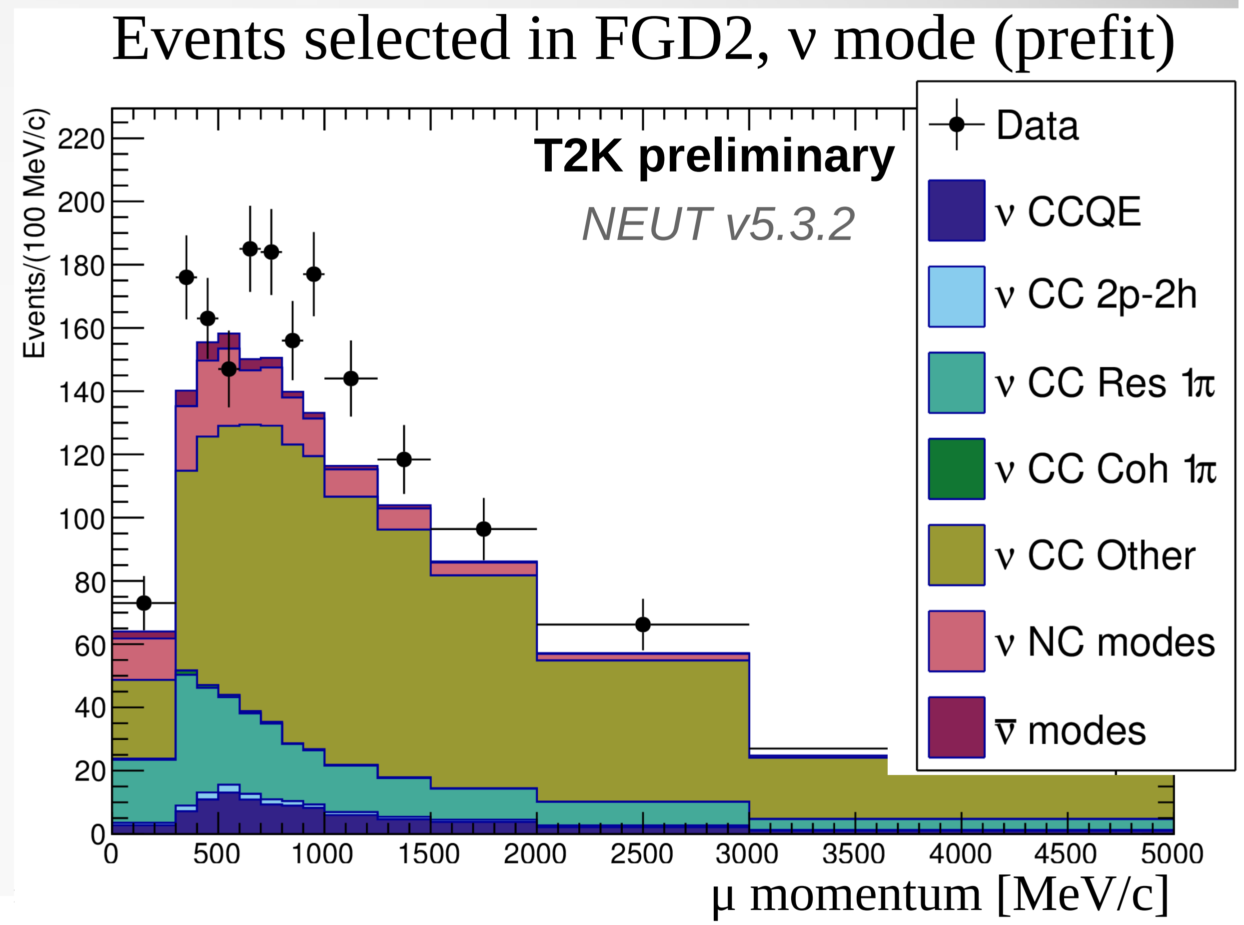






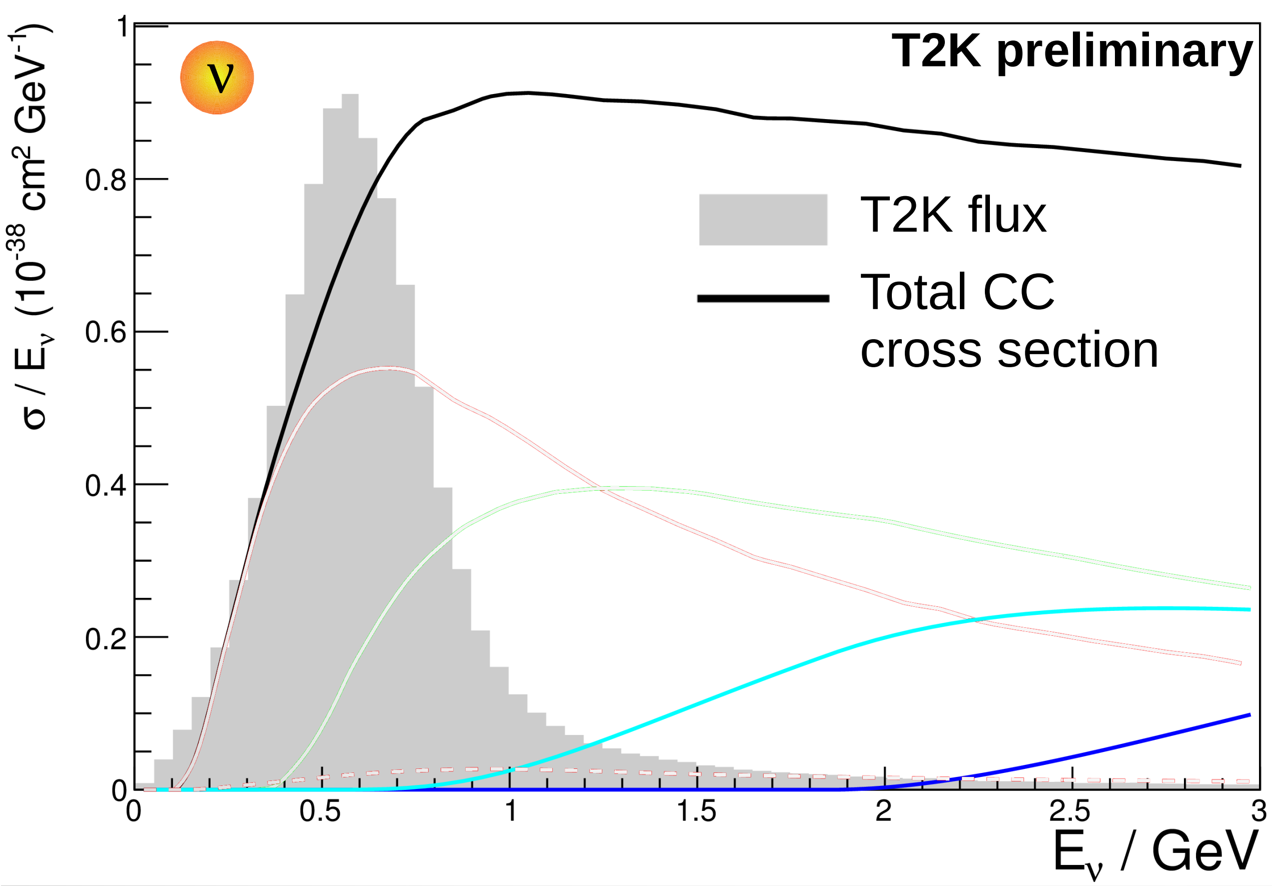
Interaction model: CC-other

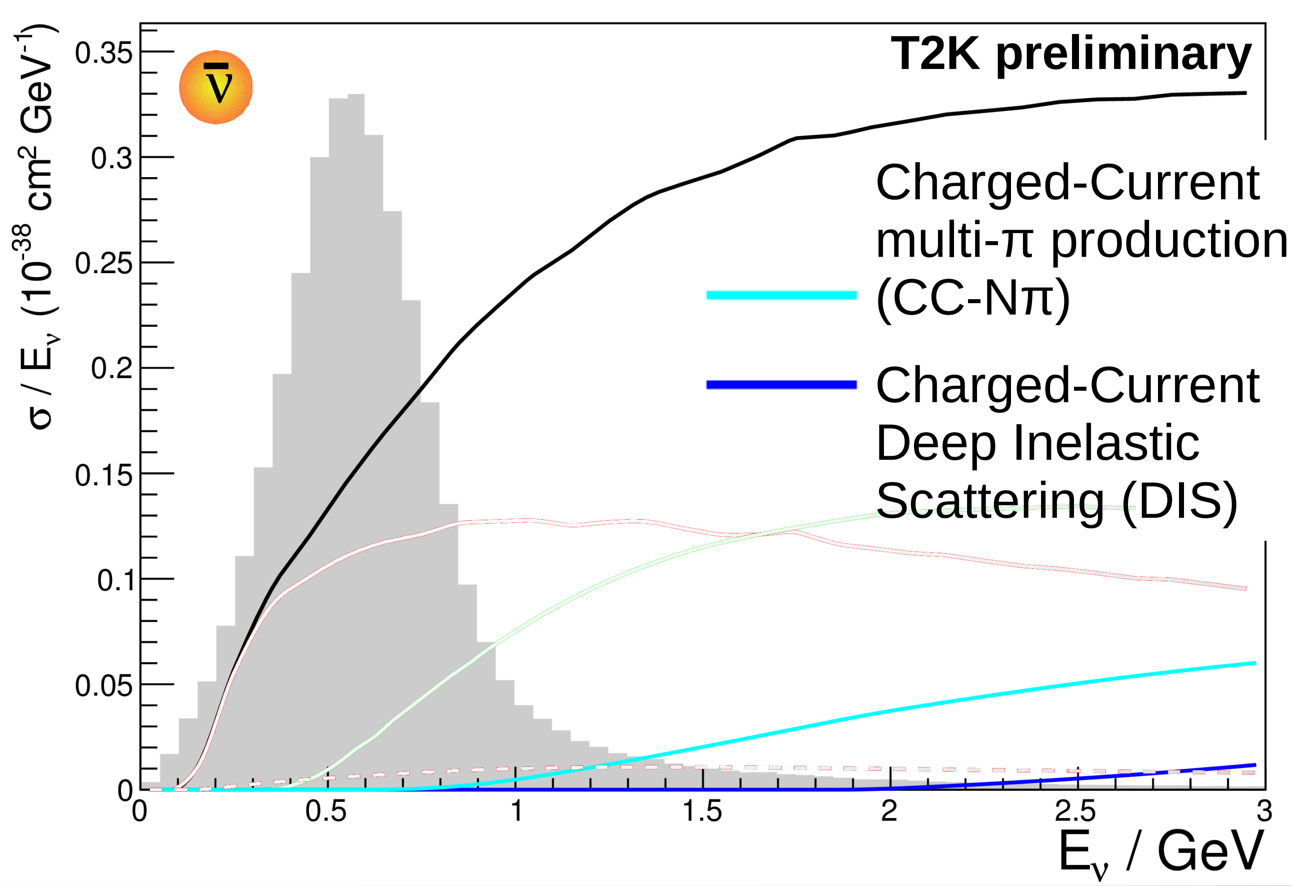




CC-other: 1 parameter

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





Anti-neutrino beam mode

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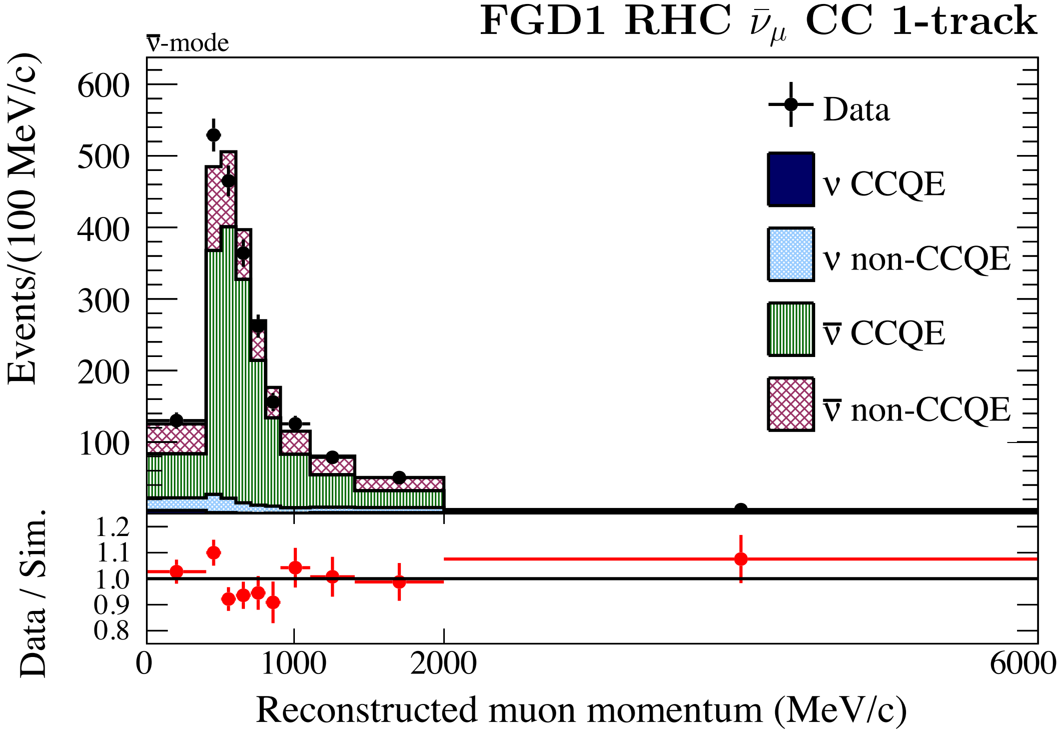
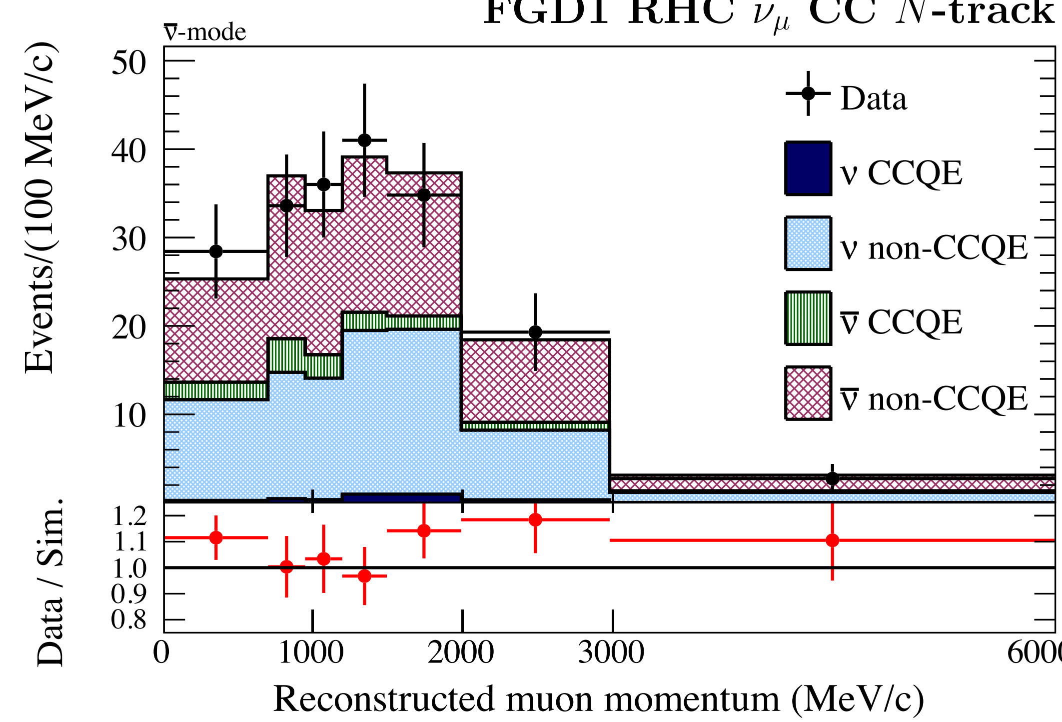
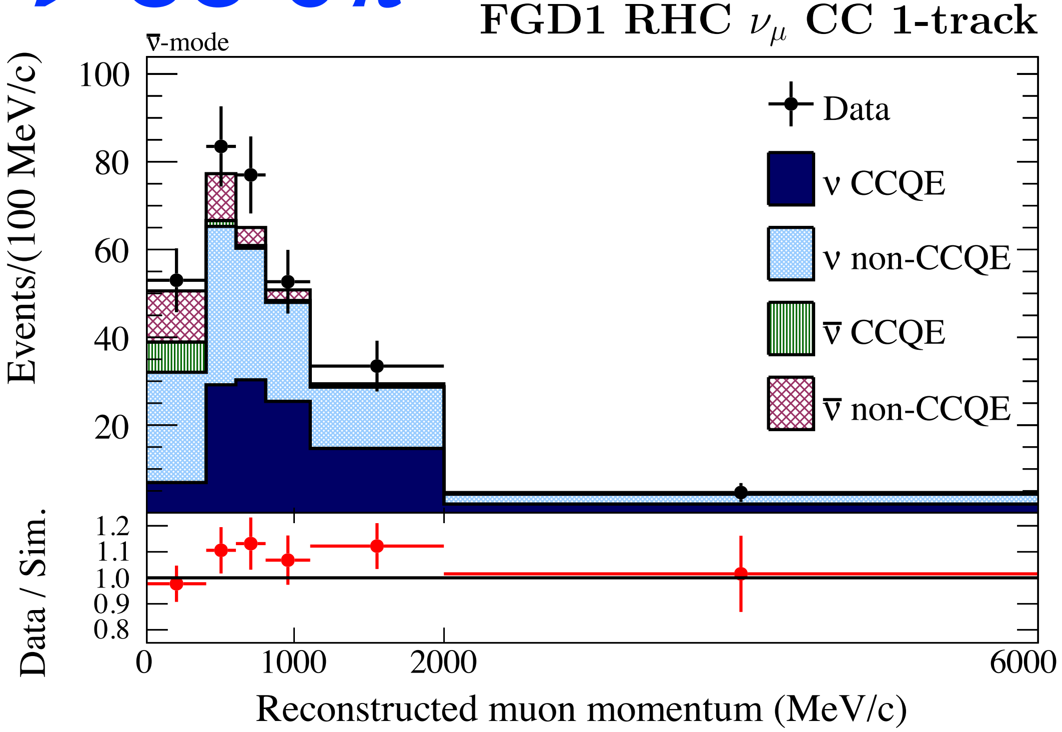
$\overline{\nu}$ CC-0π



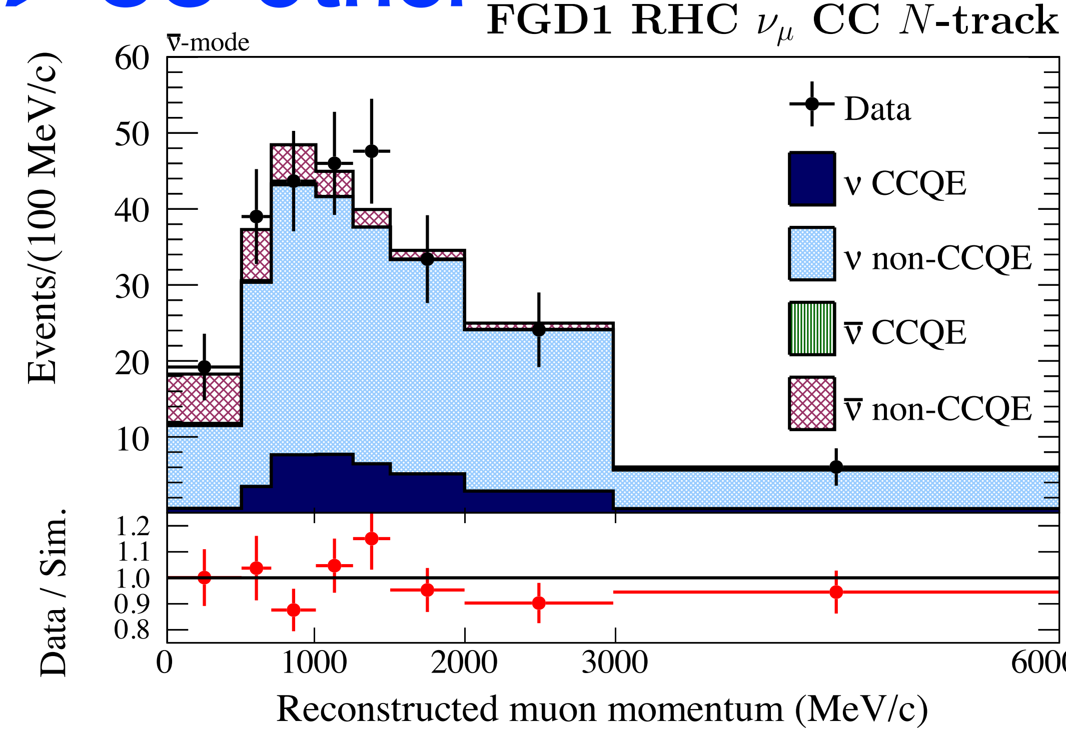
$\overline{\nu}$ CC-other



ν CC-0π



ν CC-other



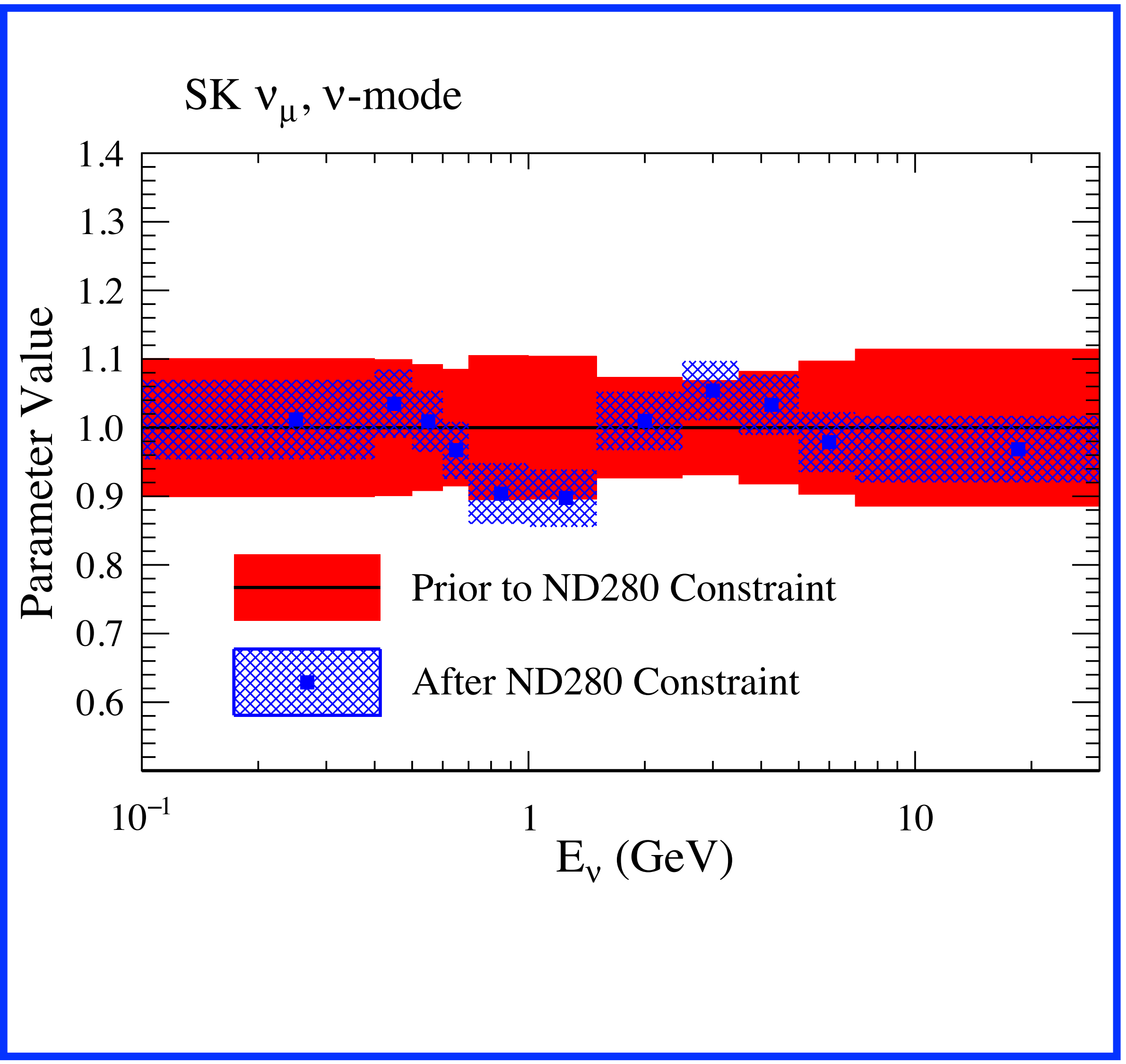
14 ND280 event samples

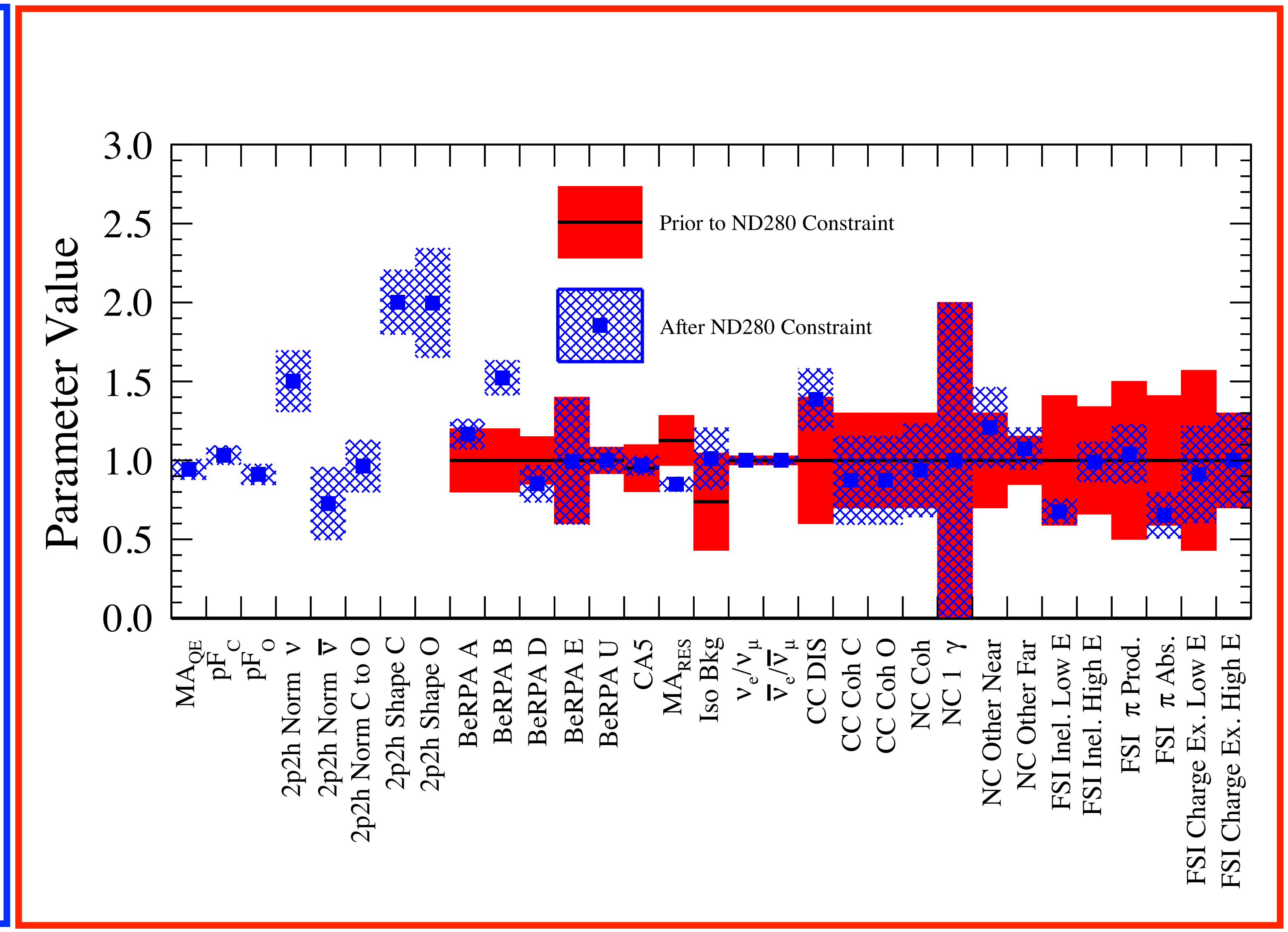
Detector	Beam	CC-0π	CC-1π	CC-other
FGD1	ν	1	2	3
	anti-ν	4	5	
		6	7	
FGD2 (Water)	ν	8	9	10
	anti-ν	11	12	
		13	14	

- Binned Likelihood fit of MC expectations with flux, cross-section and detector parameters to data observation.

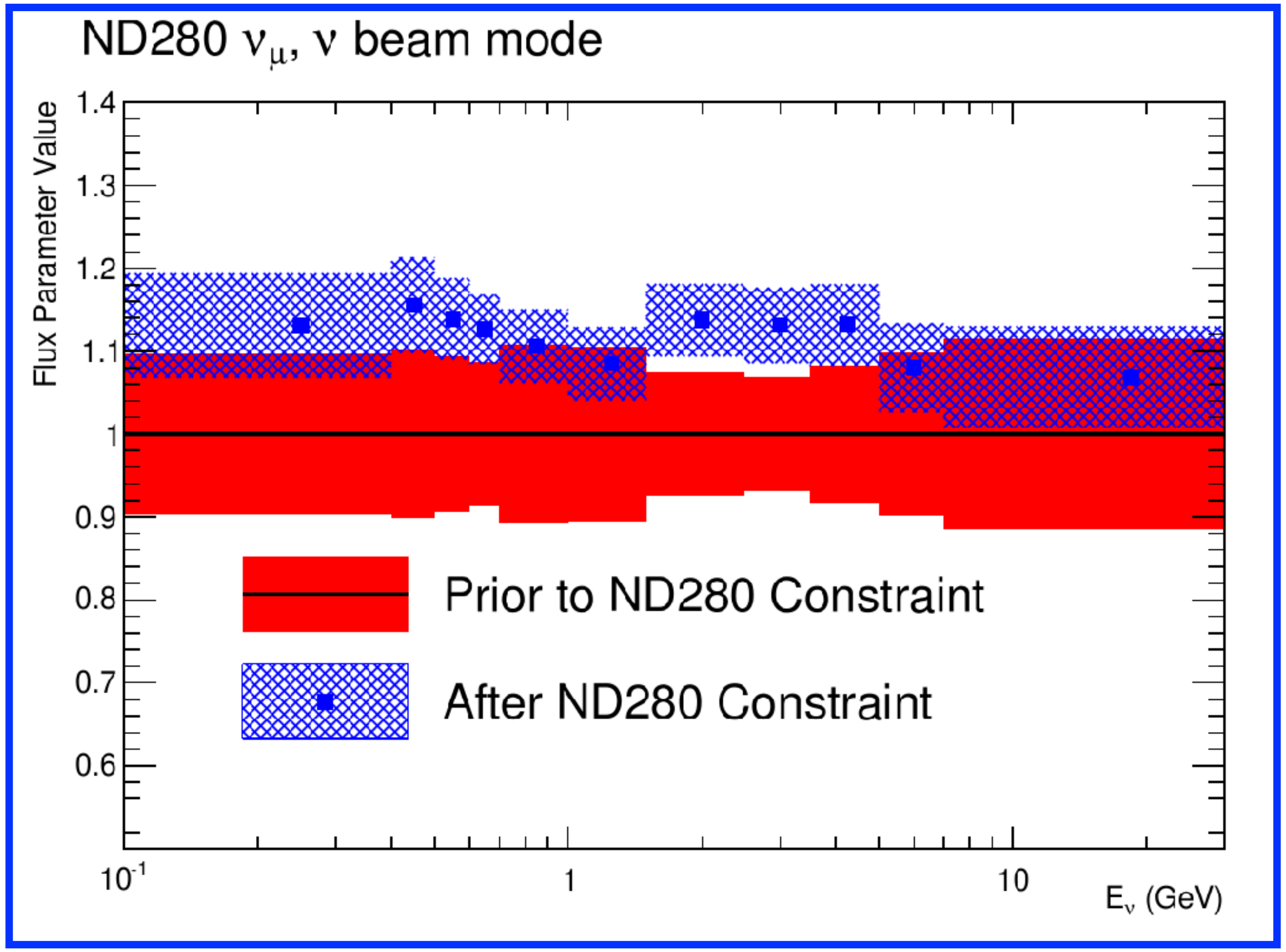
  - P_{μ} vs $\cos\theta_{\mu}$

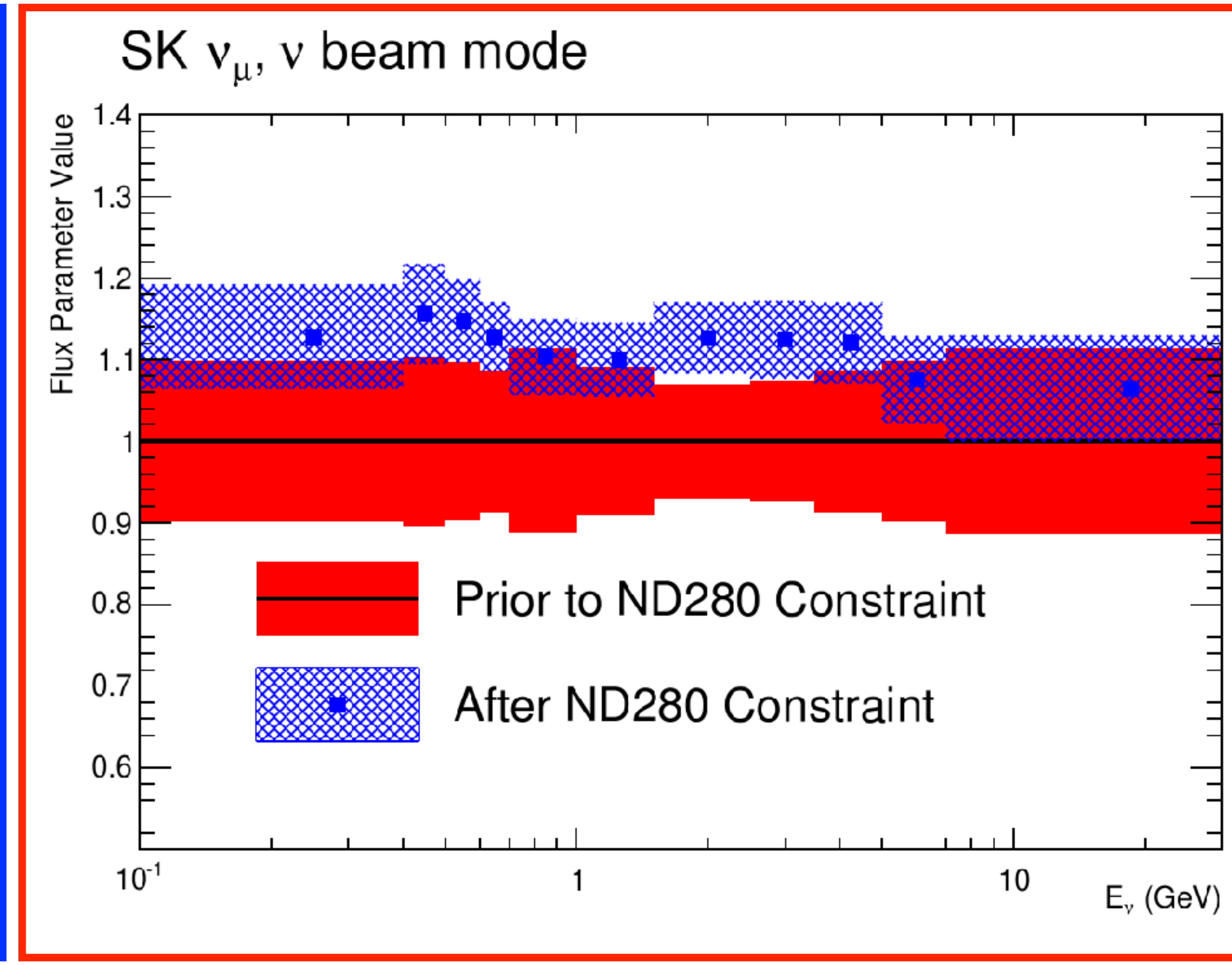
Fit ND280 data with flux and cross-section parameters





How many type of flux parameters?

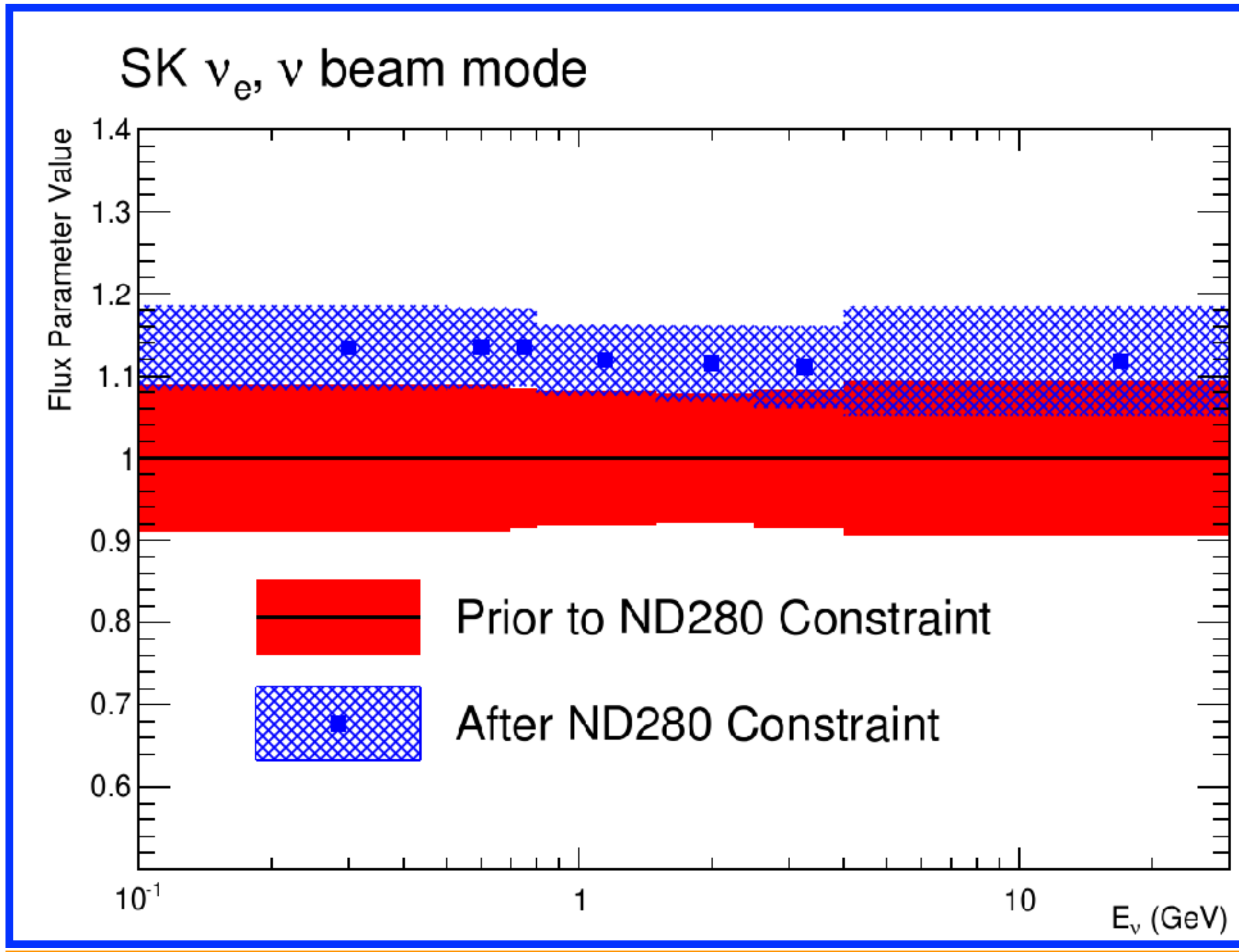


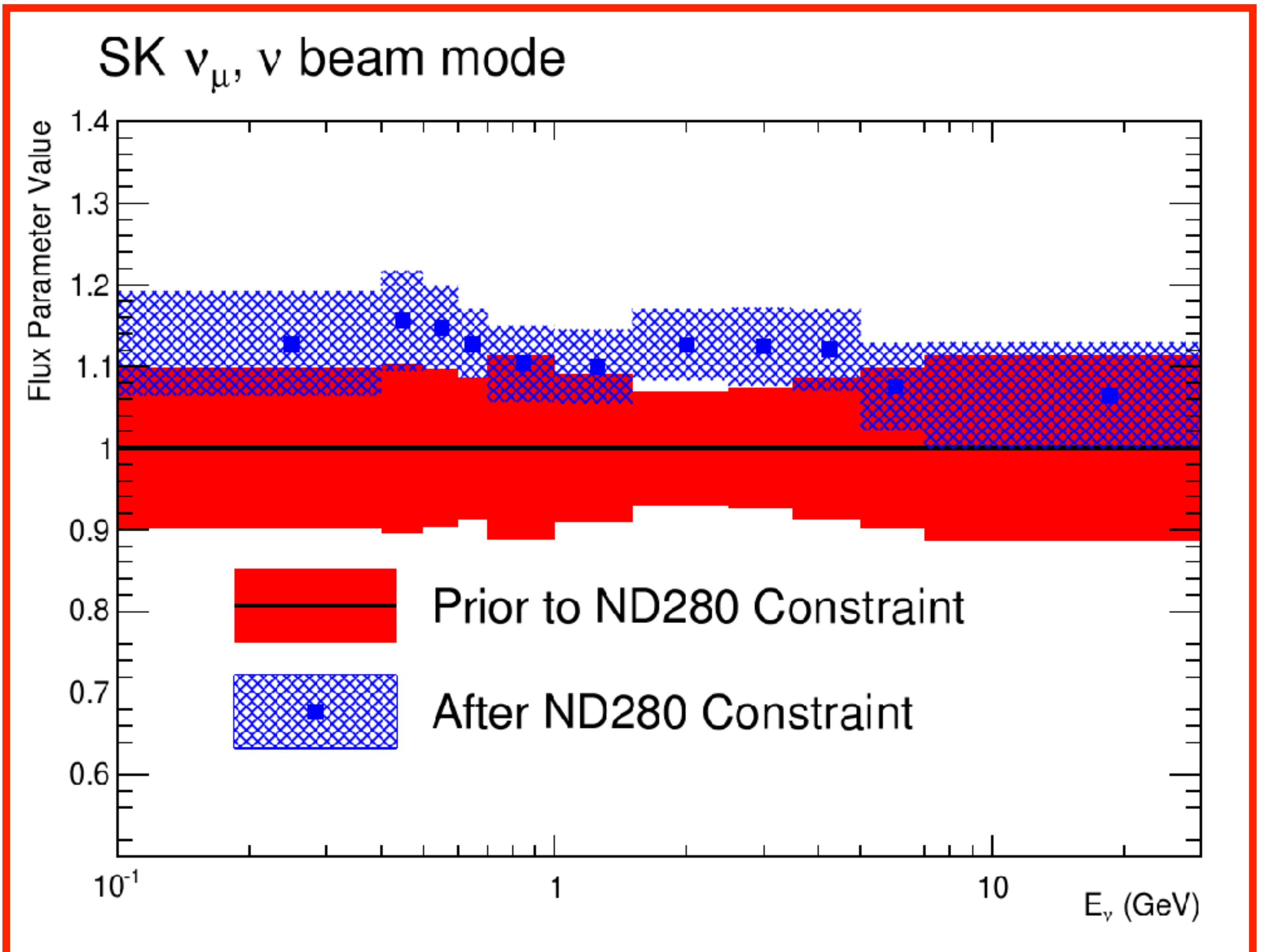


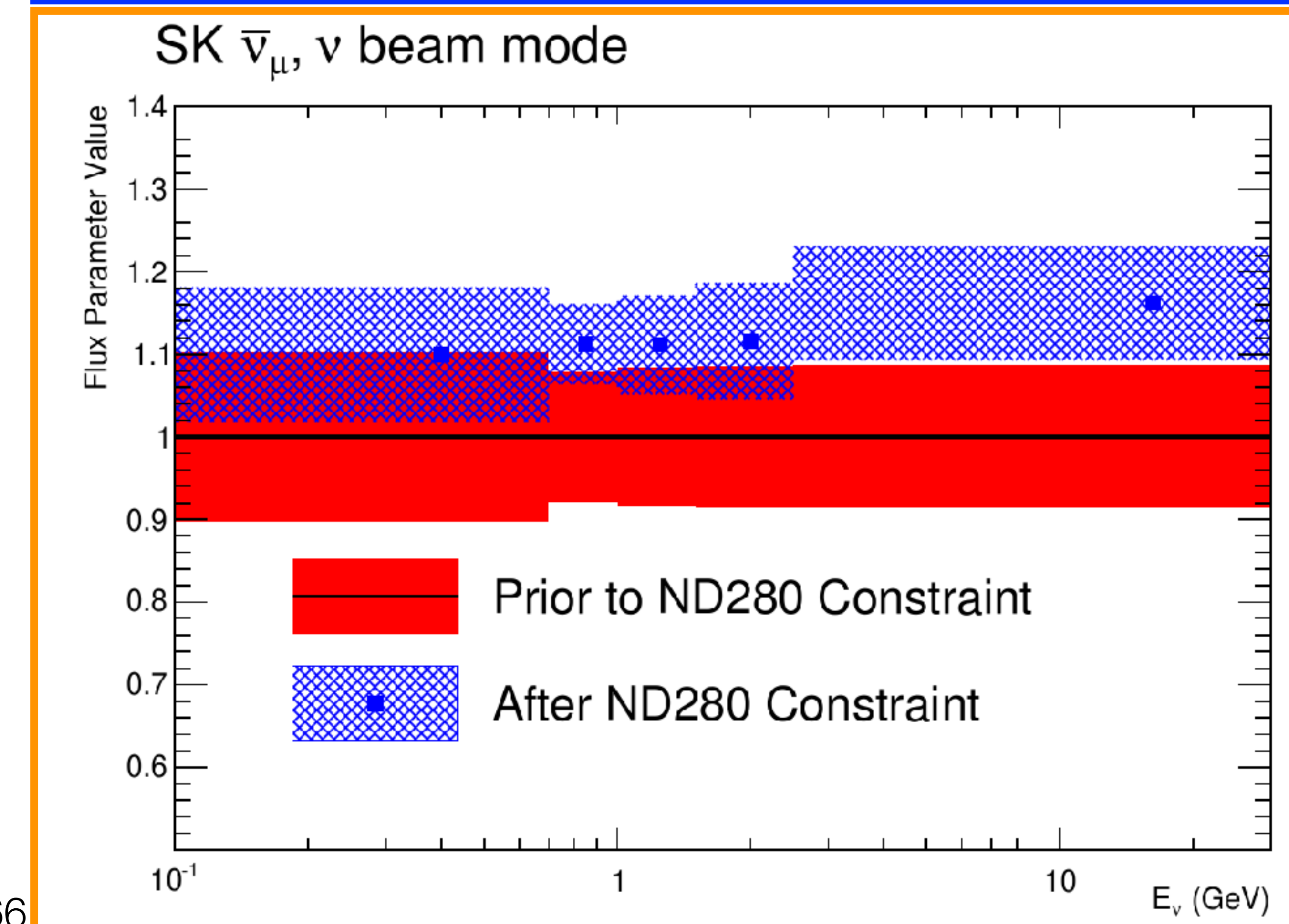
(The plots are not the latest one.)

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

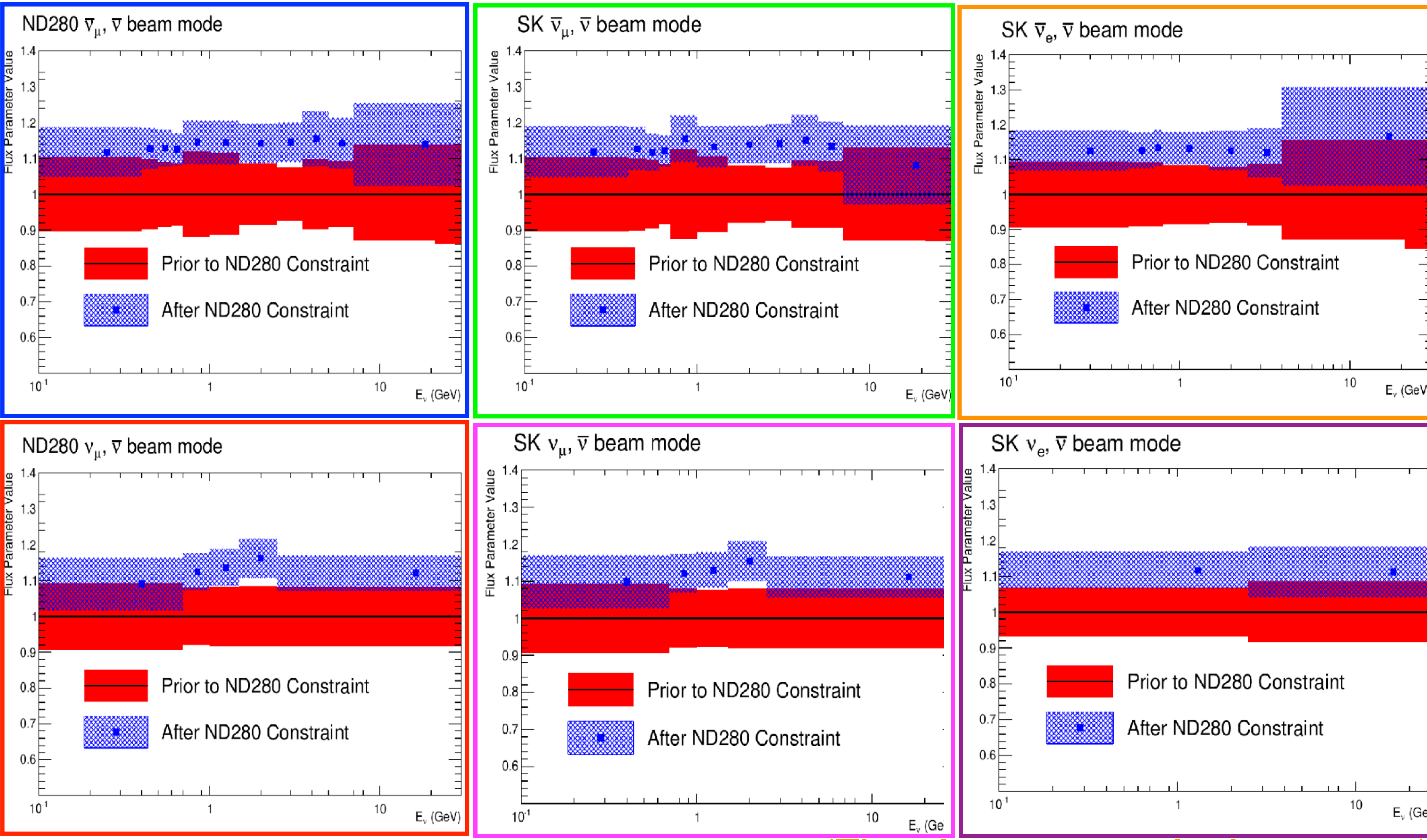
		ν_μ	ν_e	anti-ν_μ
ν	ND280			
	SK	□	□	□







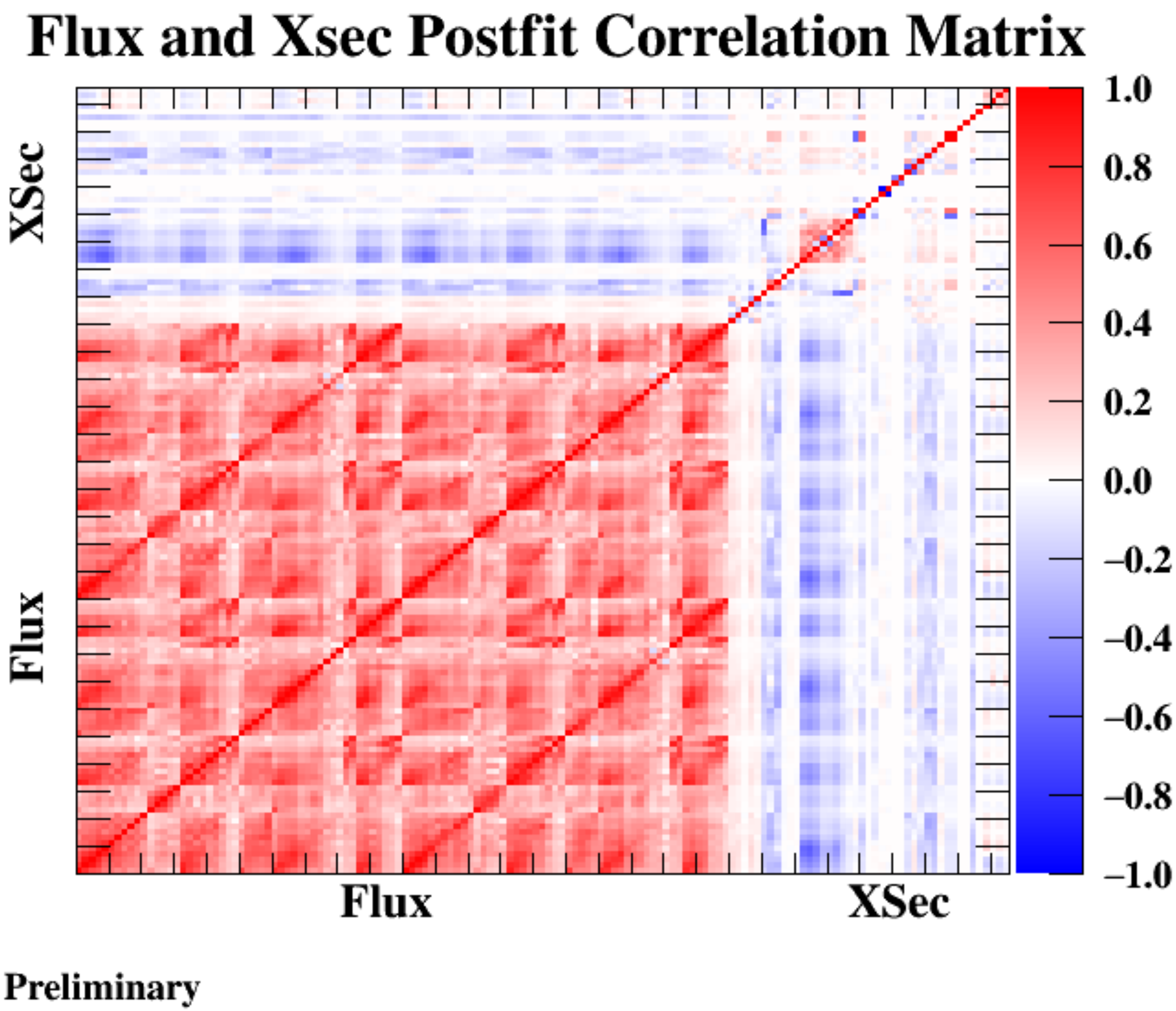
(The plots are not the latest one.)



(The plots are not the latest one.)

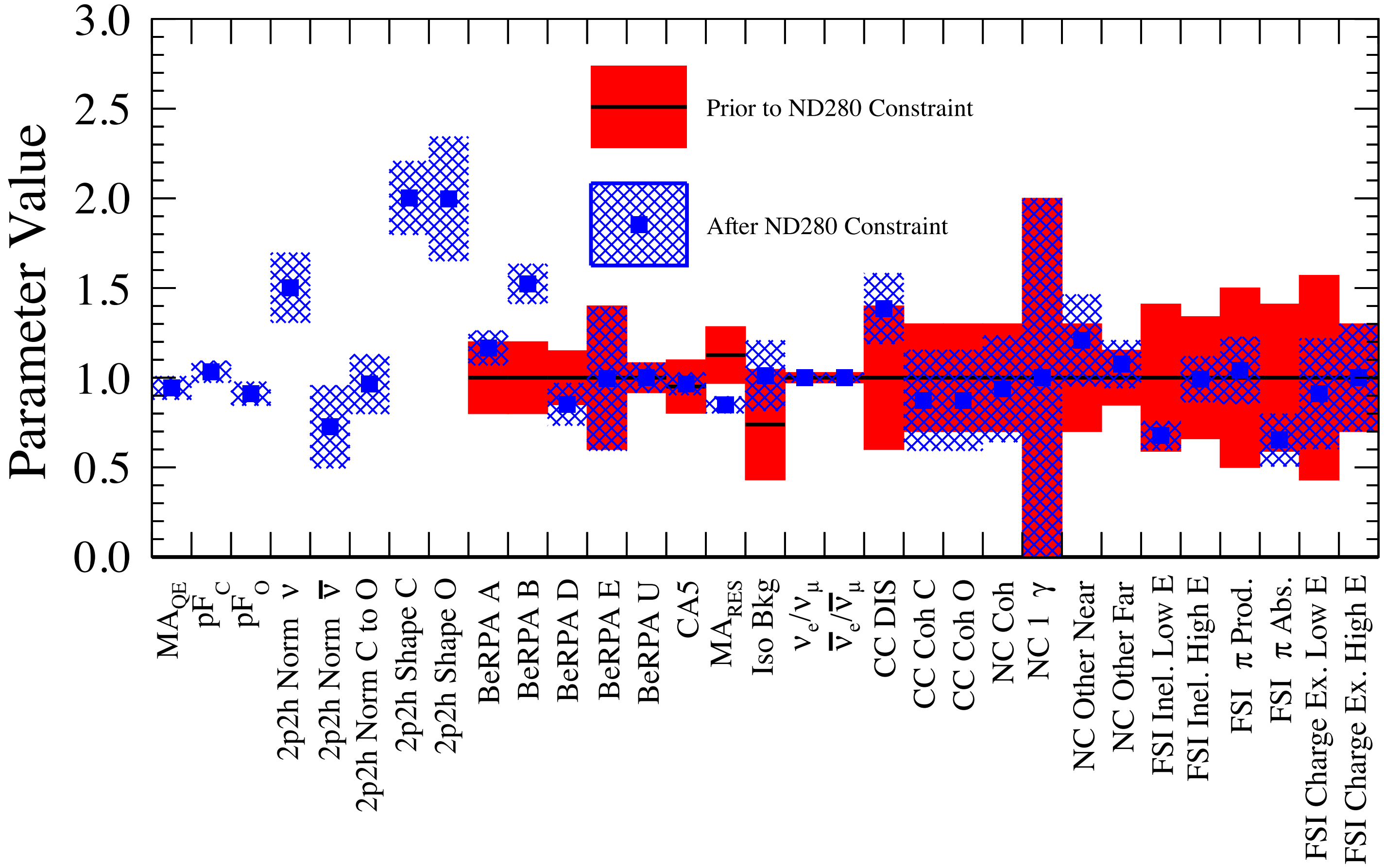
		ν_μ	ν_e	anti-ν_μ	anti-ν_e
anti-ν	ND280	□		□	
	SK	□	□	□	□

SK parameter correlation matrix



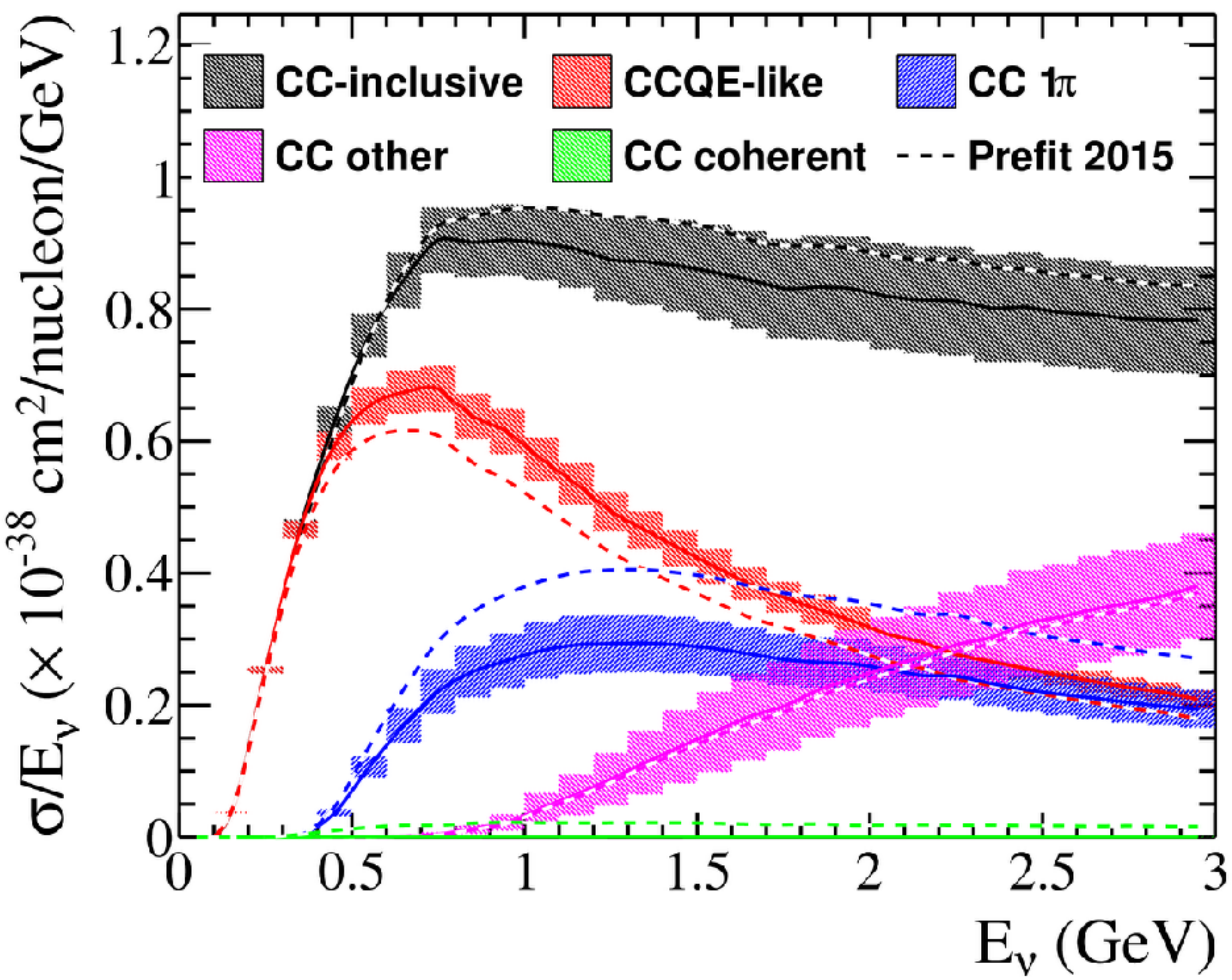
- Flux para[1-50]
  - ν para[1-25]
    - ν_μ[1-11]
    - anti-ν_μ[12-16]
    - ν_e[17-23]
    - anti-ν_e[24-25]
  - anti-ν para[26-50]
    - ν_μ[26-30]
    - anti-ν_μ[31-41]
    - ν_e[42-43]
    - anti-ν_e[44-50]
- Cross-Section Para
  - [51-82] in 2020

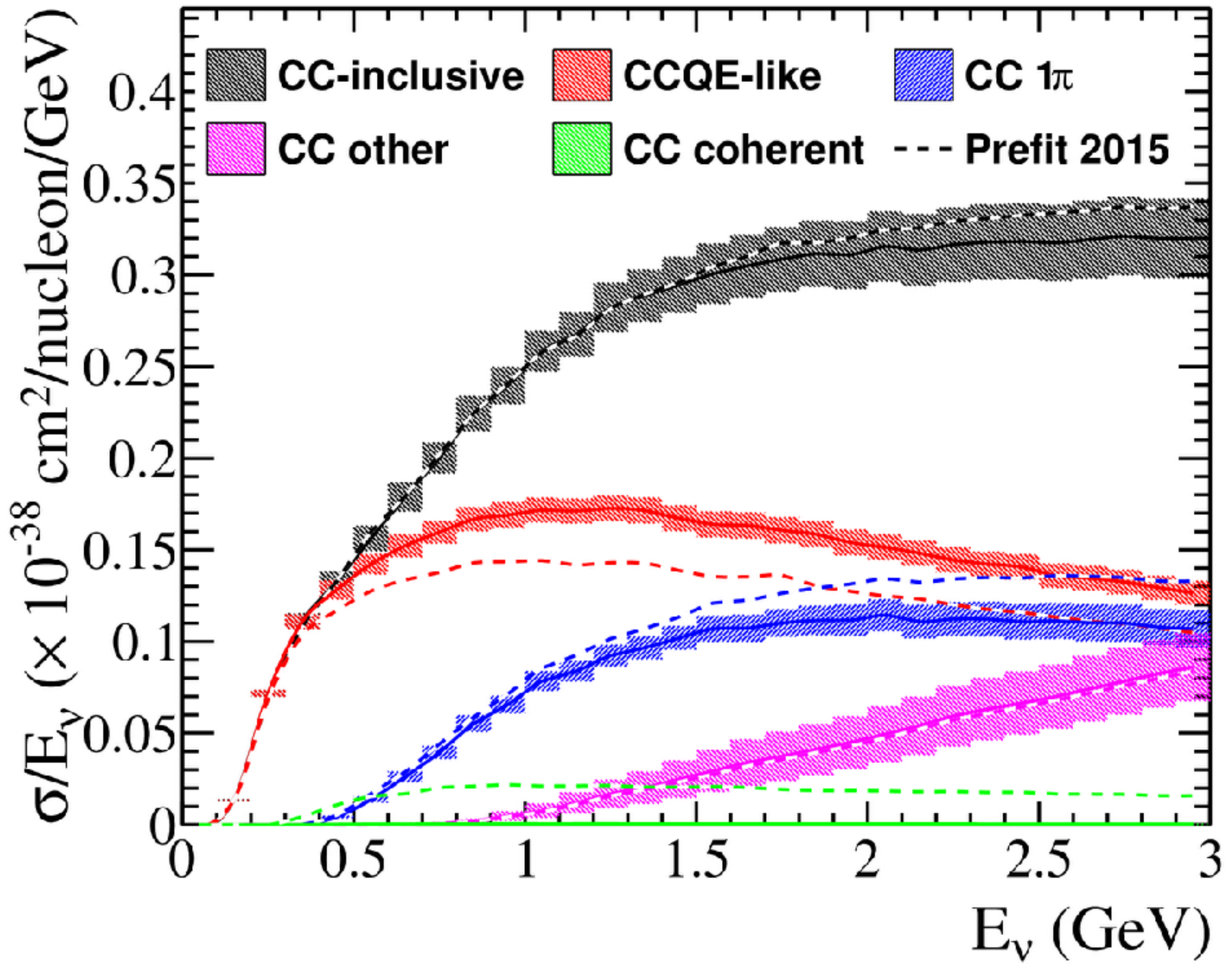
Cross Section Parameters



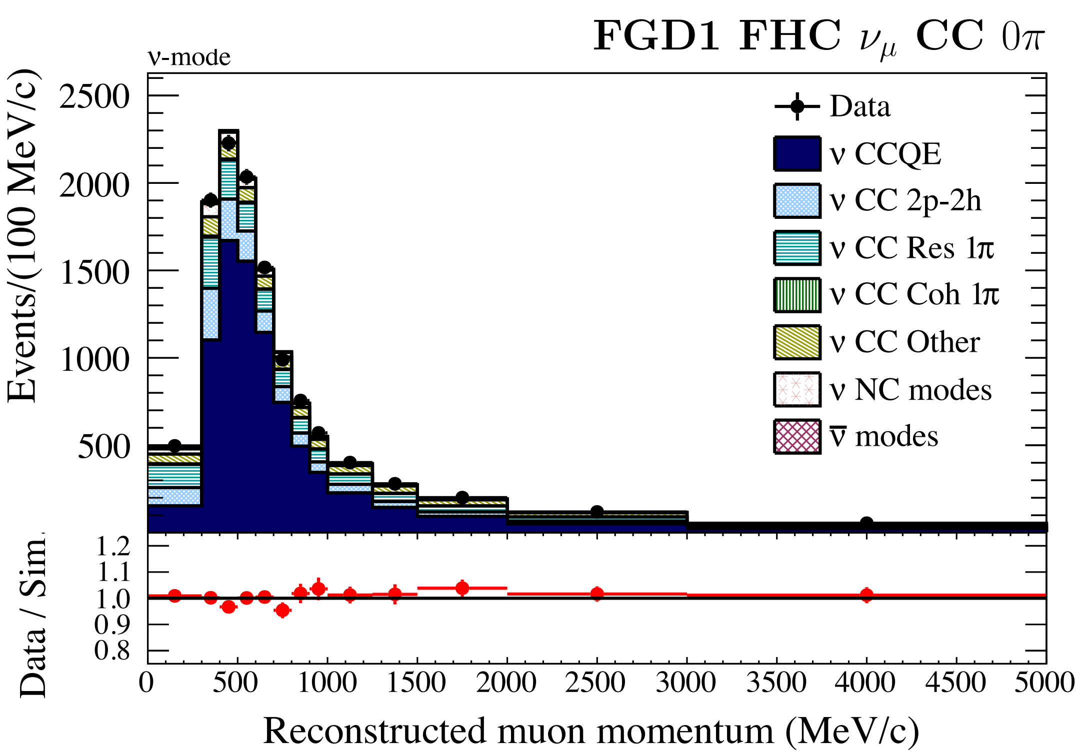
Cross-section parameter	Prefit	ND280 Postfit
M_A^{QE} (GeV/c^2)	1.20 ± 0.03	1.13 ± 0.08
pF ^{12}C(MeV/c)	217 ± 13	224 ± 13
pF ^{16}O(MeV/c)	225 ± 13	205 ± 15
2p2h norm ν	1.00 ± 1.00	1.50 ± 0.20
2p2h norm $\bar{\nu}$	1.00 ± 1.00	0.73 ± 0.23
2p2h norm $^{12}\mathrm{C}/^{16}\mathrm{O}$ ratio	1.00 ± 0.20	0.96 ± 0.17
2p2h shape ^{12}C	1.00 ± 3.00	2.00 ± 0.21
2p2h shape ^{16}O	1.00 ± 3.00	2.00 ± 0.35
BeRPA A	0.59 ± 0.12	0.69 ± 0.06
BeRPA B	1.05 ± 0.21	1.60 ± 0.12
BeRPA D	1.13 ± 0.17	0.96 ± 0.13
BeRPA E	0.88 ± 0.35	0.87 ± 0.35
BeRPA U	1.20 ± 0.10	1.20 ± 0.10
C_A^5	0.96 ± 0.15	0.98 ± 0.06
M_A^{RES} (GeV/c^2)	1.07 ± 0.15	0.81 ± 0.04
$I = \frac{1}{2}$ background	0.96 ± 0.40	1.31 ± 0.26
ν_e/ν_μ	1.00 ± 0.03	1.00 ± 0.03
$\bar{\nu}_e/\bar{\nu}_\mu$	1.00 ± 0.03	1.00 ± 0.03
CC DIS	0.00 ± 0.40	0.39 ± 0.21
CC coherent ^{12}C	1.00 ± 0.30	0.87 ± 0.28
CC coherent ^{16}O	1.00 ± 0.30	0.87 ± 0.28
NC coherent	1.00 ± 0.30	0.94 ± 0.30
NC 1γ	1.00 ± 1.00	1.00 ± 1.00
NC other ND280	1.00 ± 0.30	1.21 ± 0.26
NC other SK	1.00 ± 0.30	1.00 ± 0.30
FSI inelastic low-E	0.00 ± 0.41	-0.32 ± 0.08
FSI inelastic high-E	0.00 ± 0.34	-0.01 ± 0.13
FSI pion production	0.00 ± 0.50	0.04 ± 0.19
FSI pion absorption	0.00 ± 0.41	-0.35 ± 0.15
FSI charge exch. low-E	0.00 ± 0.57	-0.09 ± 0.31
FSI charge exch. high-E	0.00 ± 0.28	0.02 ± 0.10

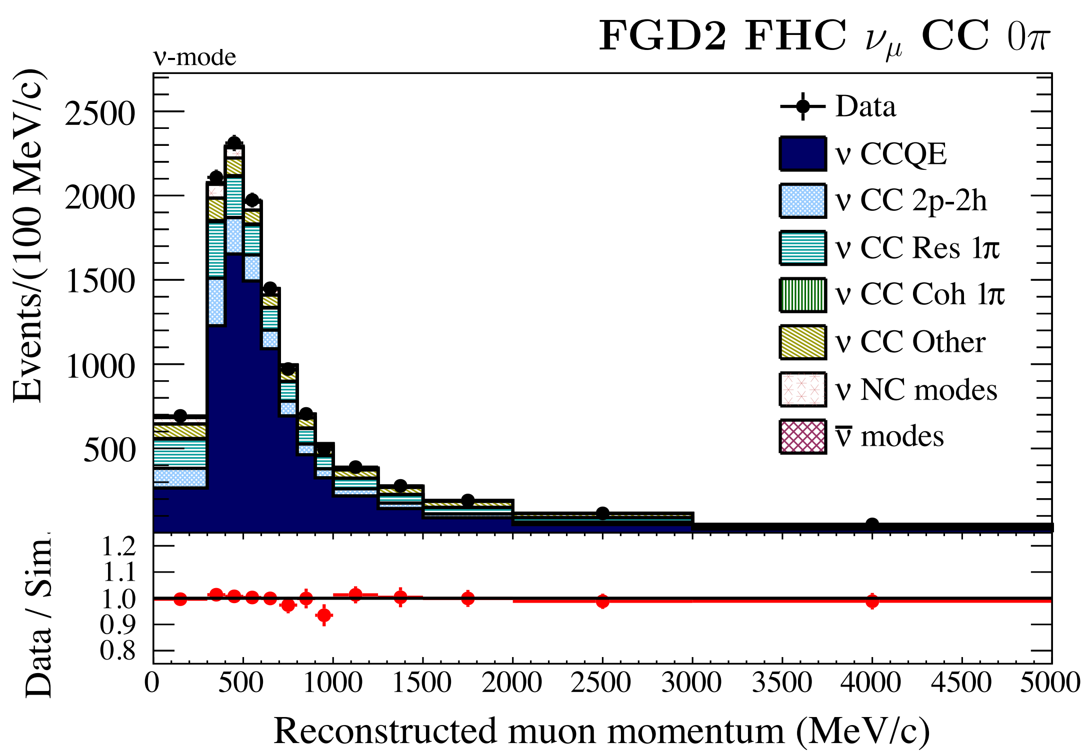
Cross Section tuning

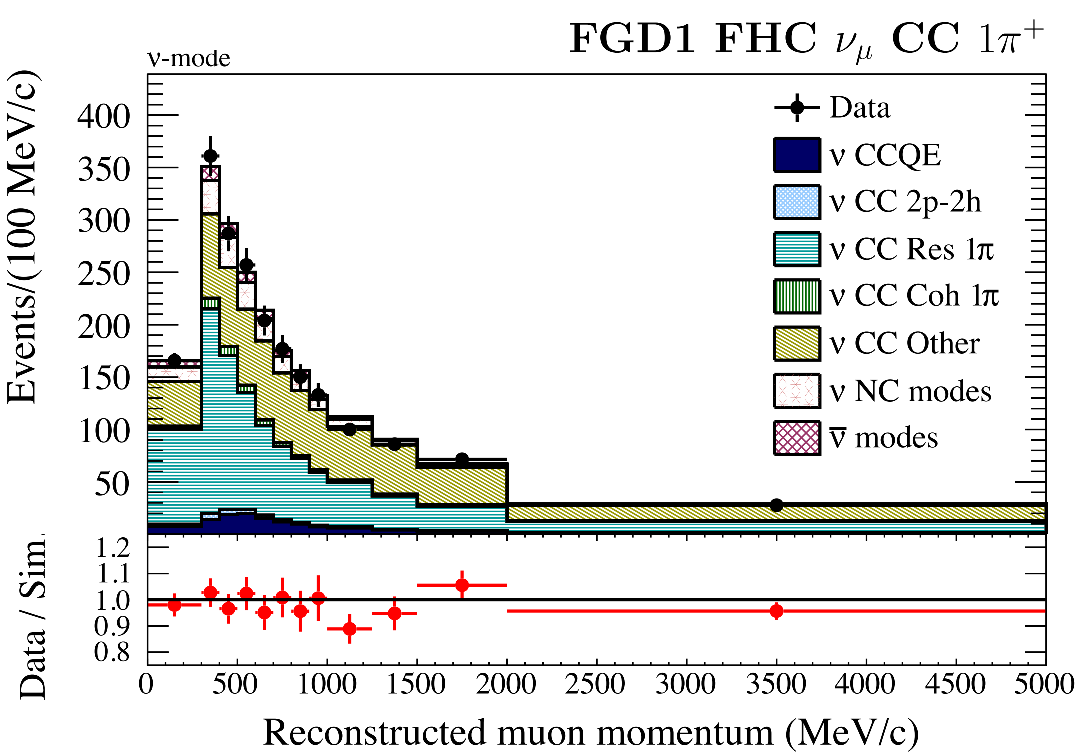


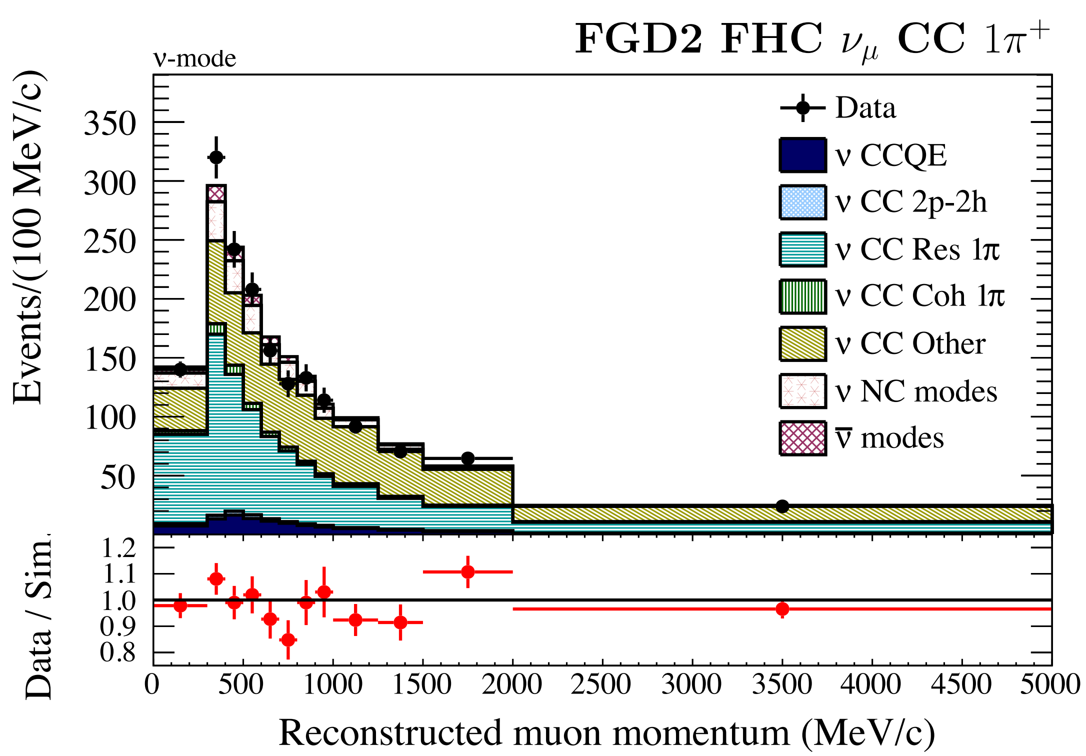


ND280 ν data comparison after FIT









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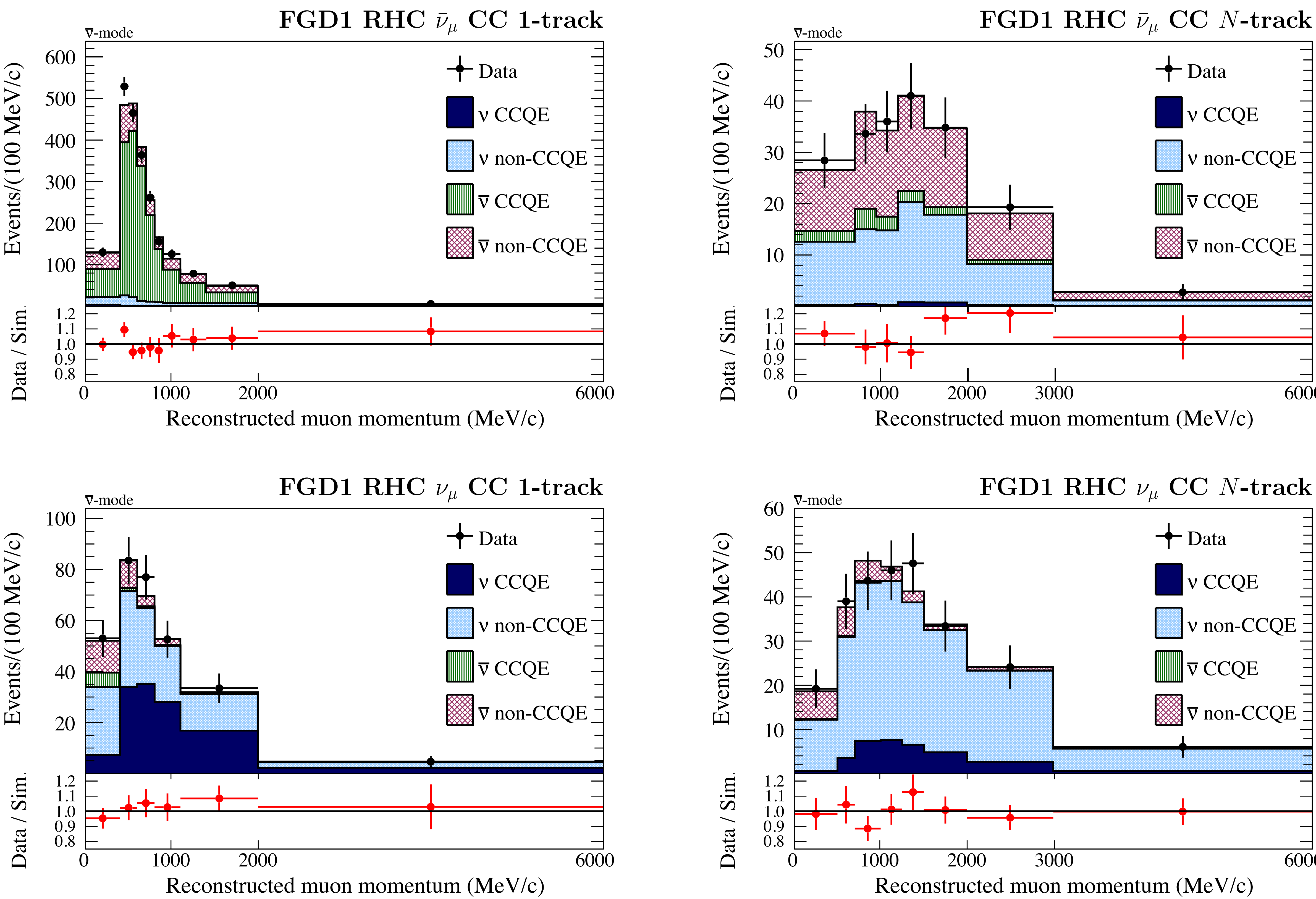
ND280 $\overline{\nu}$ data comparison after FIT



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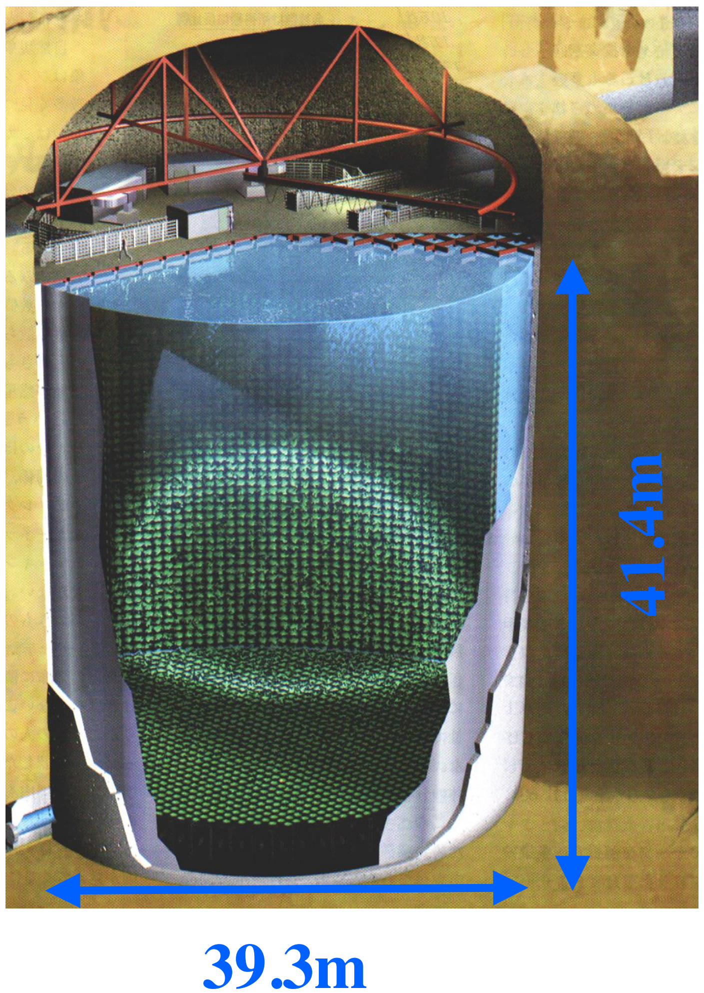
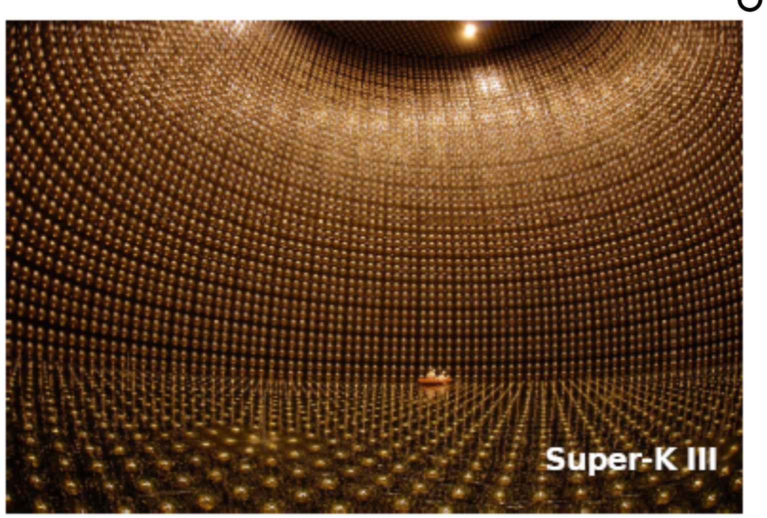
6. Super-Kamiokande

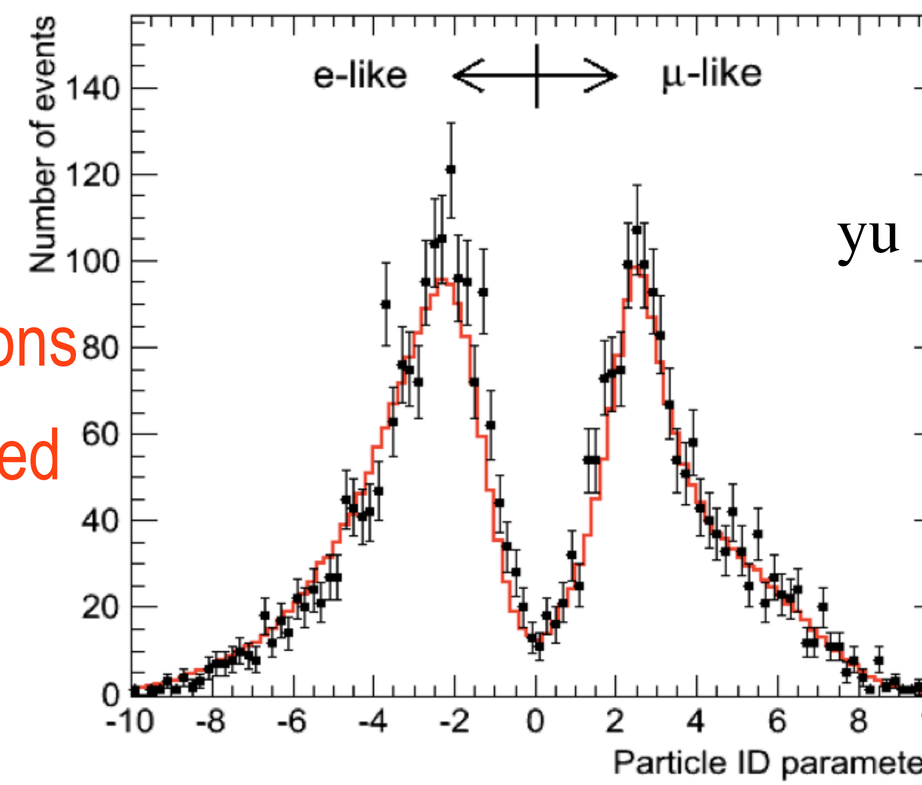
- Far Detector -

T2K-Far Detector: Super-Kamiokande

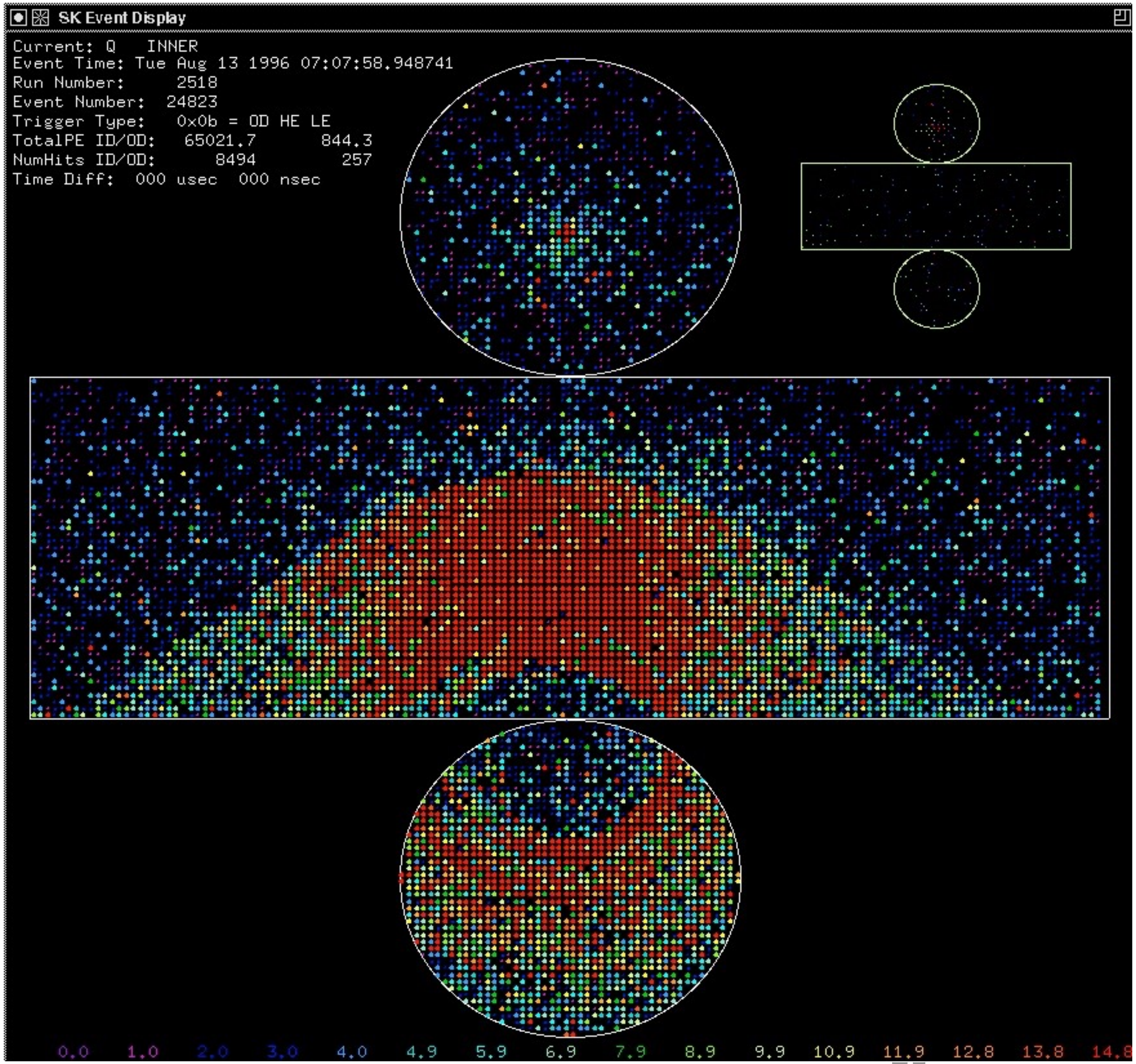


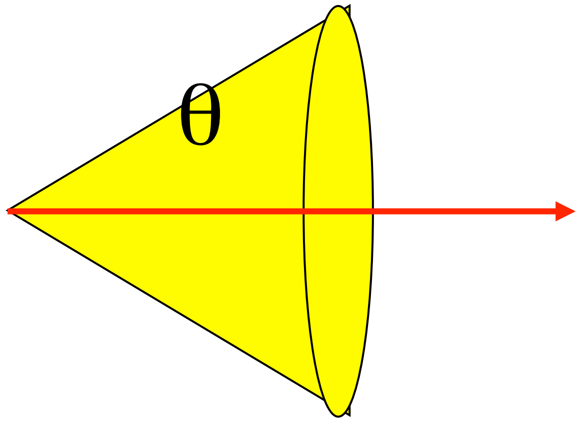


- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with 95% NC-1π^0 rejection
    - Inner tank (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



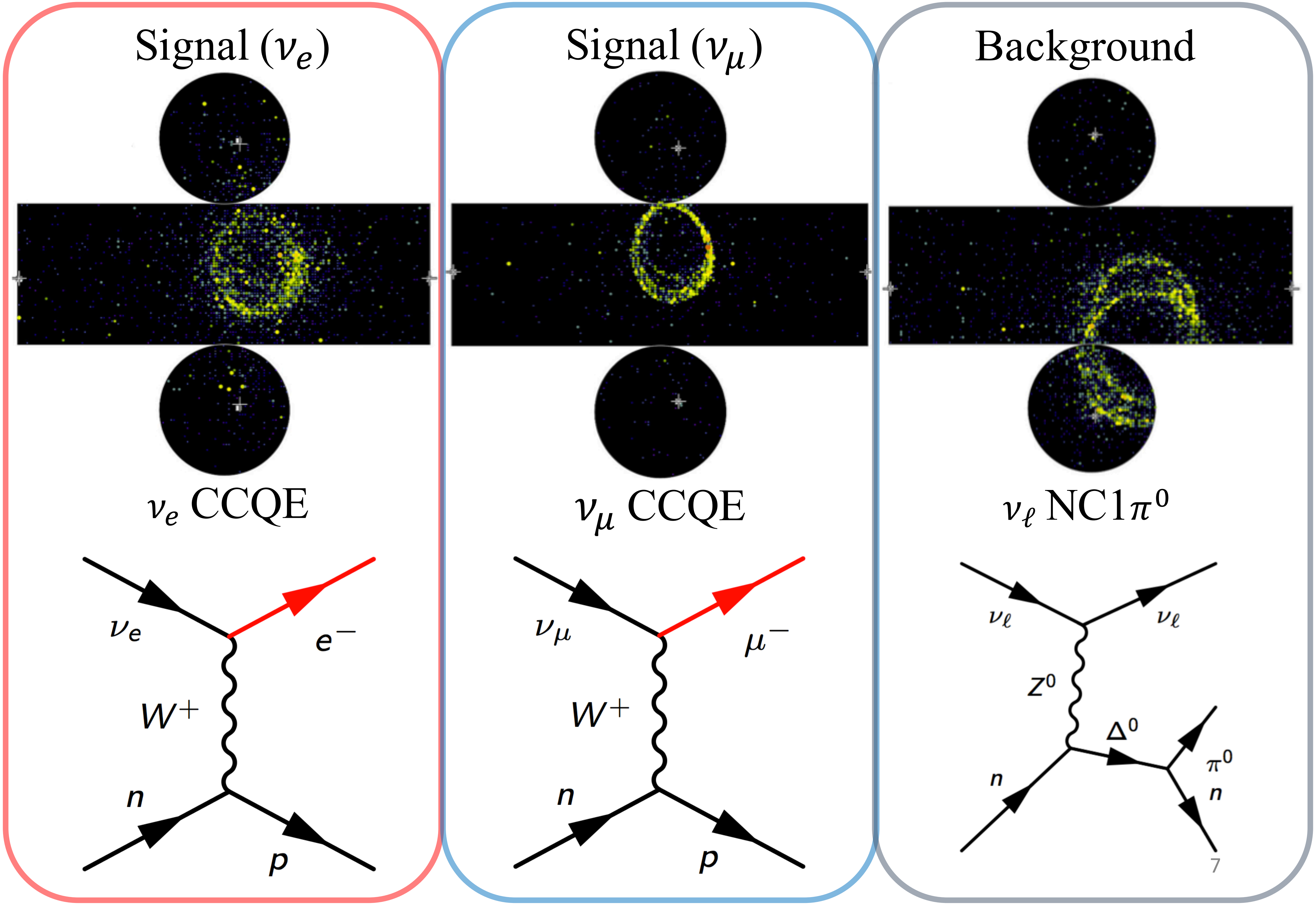


$\beta > 1/n$ (n=1.)

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

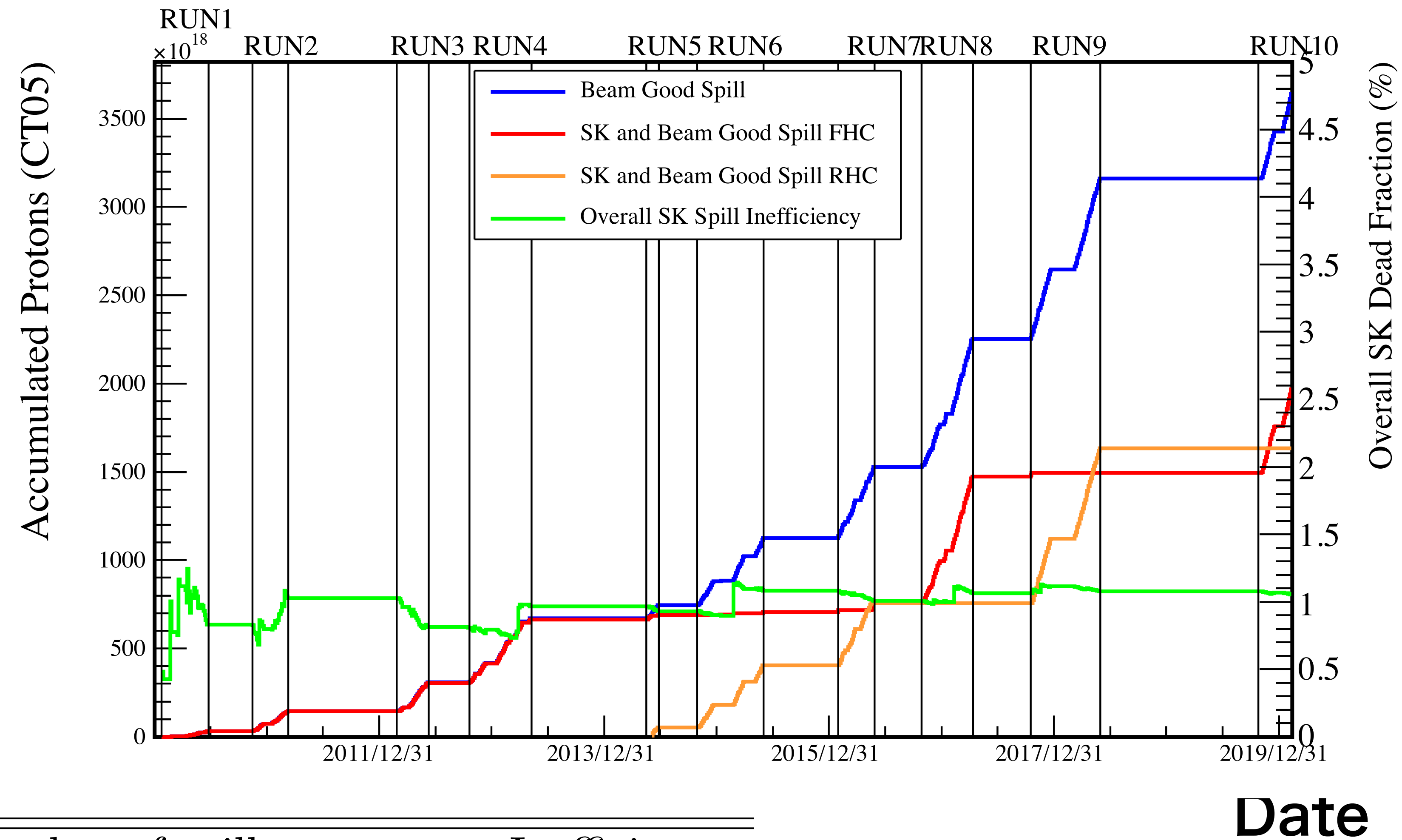
- **Particle ID.**
  - By the Cherenkov ring edge and the opening Angle.
- **Momentum**
  - The amount of light-yield inside a ring with PID
- **Vertex**
  - Timing of the PMT at the ring edge with PID

Neutrino Detection at SK Far Detector



Initial Data Reduction

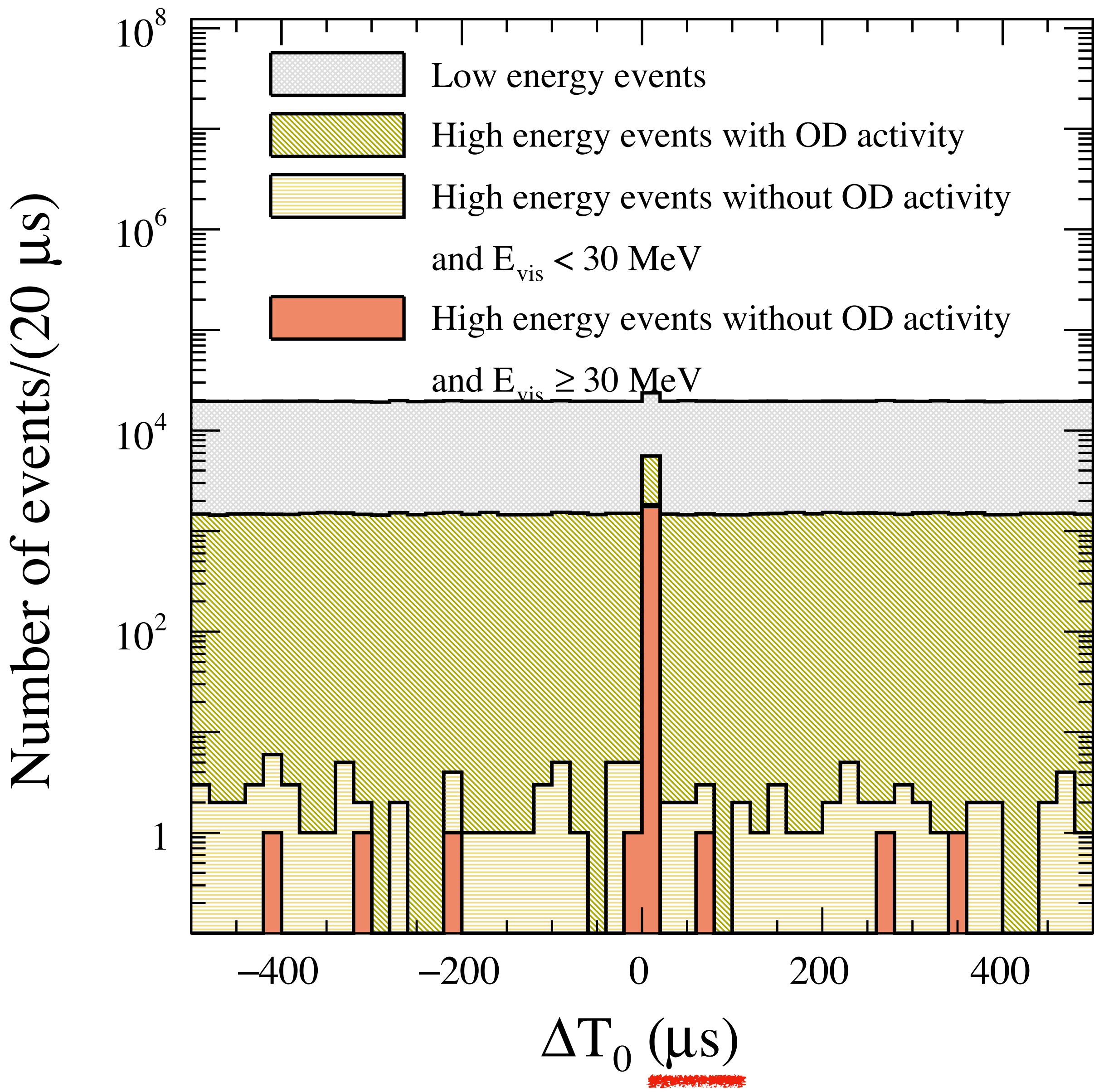
- Total POT
  - Neutrino beam
  - Anti-neutrino beam



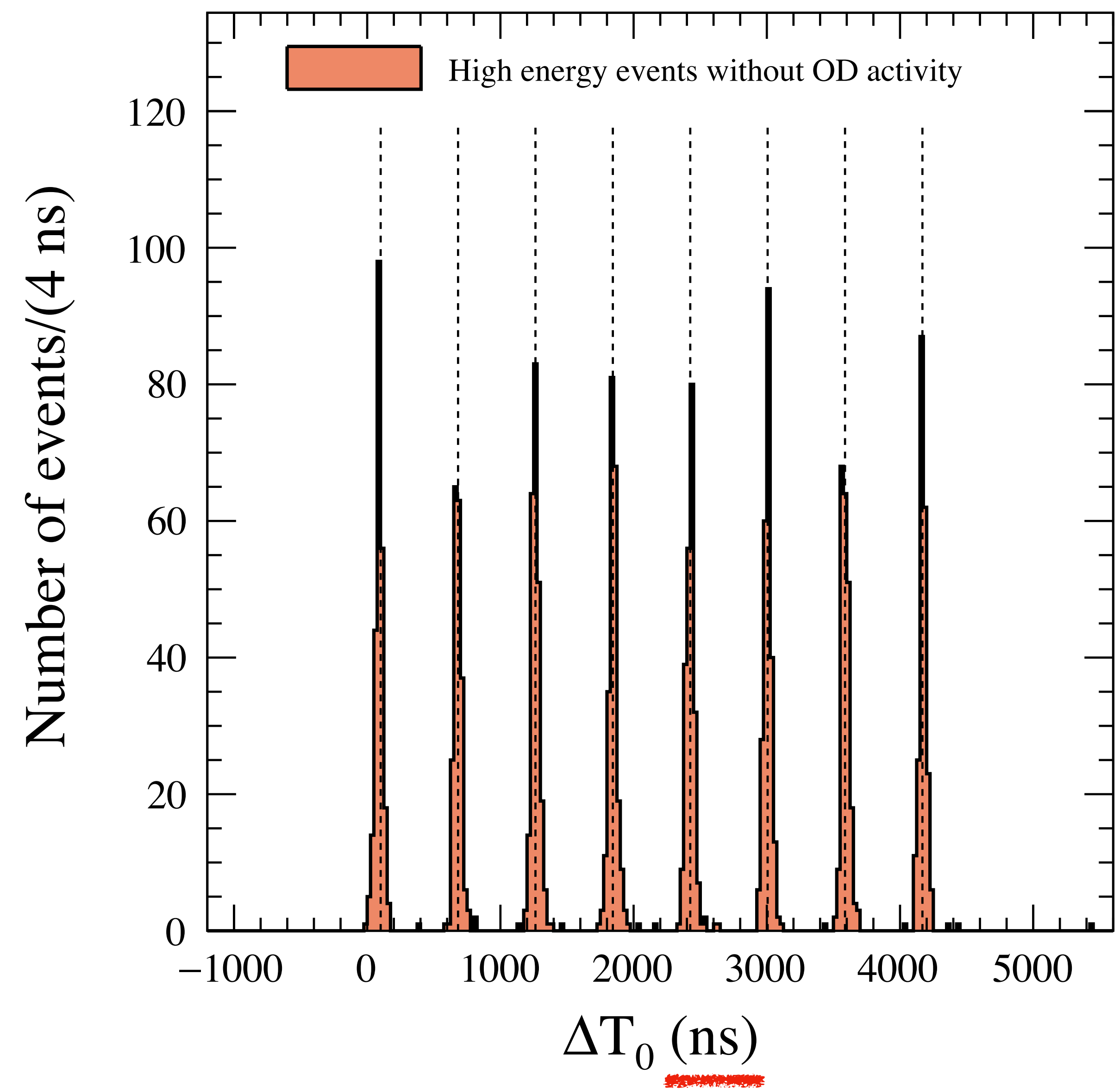
	Number of spills			Inefficiency
	Runs 1-9	Run 10	Total	
Beam good spills	20,122,743	1,883,688	22,006,431	
(1) SK DAQ alive	20,085,525	1,881,924	21,967,449	0.18 %
(2) Bad subrun cut	20,039,874	1,881,636	21,921,510	0.21 %
(3) Incomplete data / GPS error cut	20,030,596	1,880,827	219,11,423	0.05 %
(4) Special data block cut	20,014,244	1,879,260	21,893,504	0.08 %
(5) Pre-activity cut	19,915,932	1,866,252	21,782,184	0.51 %
Total	19,915,932	1,866,252	21,782,184	1.02 %
POT ($\times 10^{20}$)	31.2836	4.7256	36.0092	

Timing Selection of accelerator neutrinos

Timing

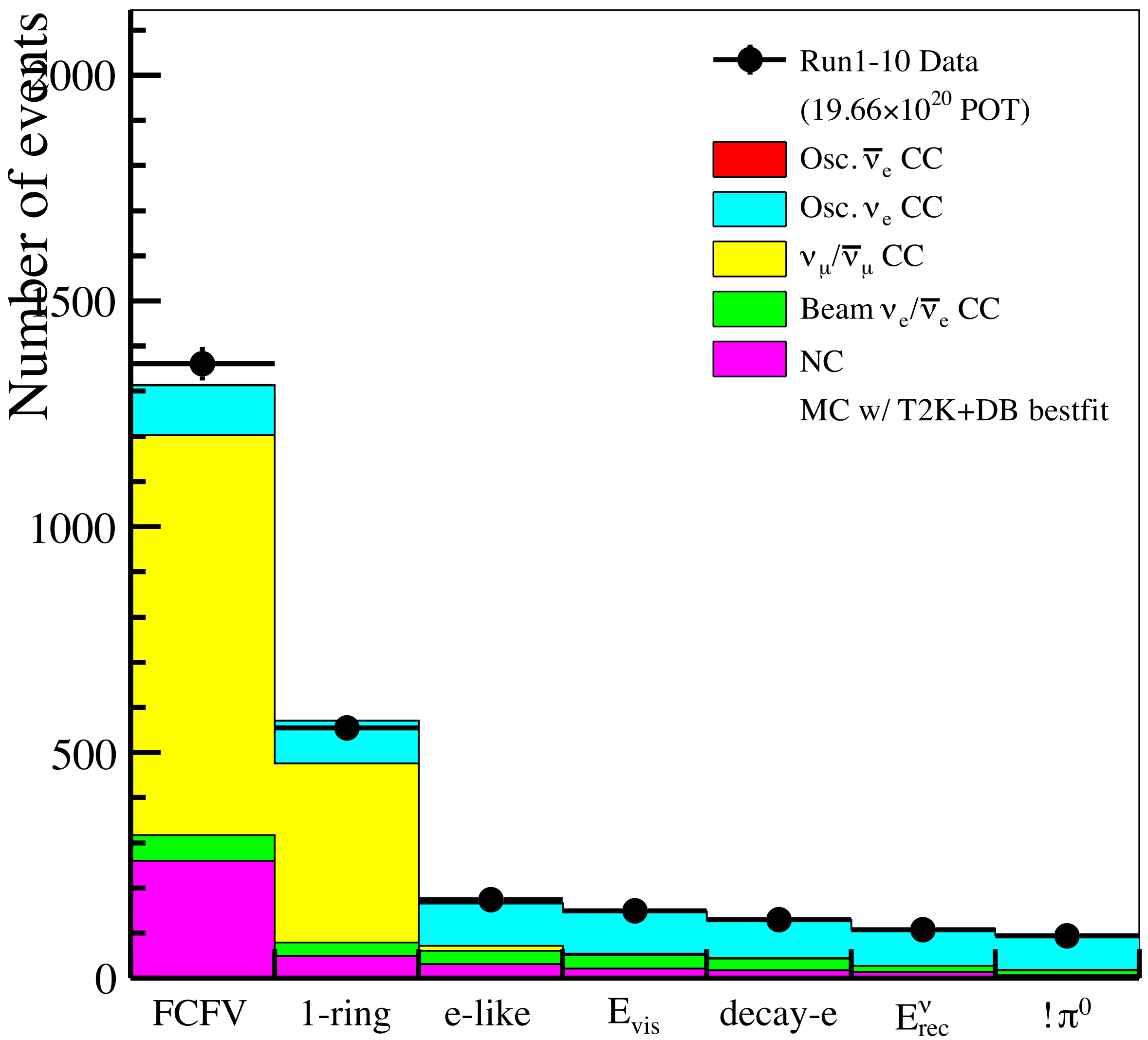


Timing
— Zoom —



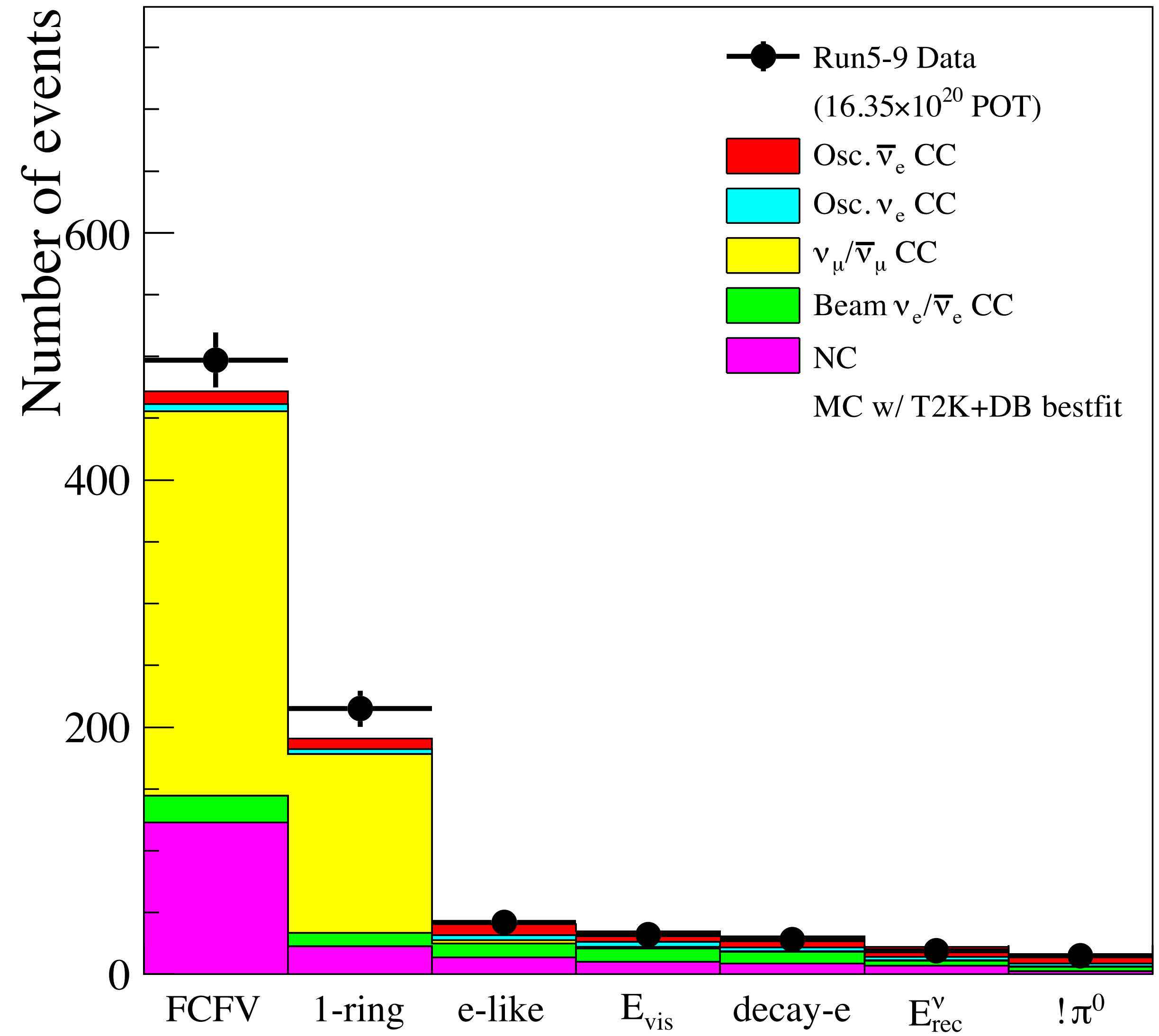
Electron Neutrino Selection

Parameter	Value
Δm^2_{21}	$7.53 \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{23}	$2.54 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{12}$	0.304
$\sin^2\theta_{13}$	0.0219
$\sin^2\theta_{23}$	0.550
δ_{CP}	-1.728
Mass Hierarchy	Normal
ν Travel Length	295 km
Earth Density	$2.6\,\mathrm{g}\cdot\mathrm{cm}^{-3}$



Runs 1-10	Expected							Data
	$\nu_\mu + \bar{\nu}_\mu$ CC	Beam $\nu_e + \bar{\nu}_e$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.359	110.486	0.959	1246.704	1279
FCFV	886.362	56.685	260.508	1203.555	109.753	0.979	1314.287	1361
Single Ring	397.177	29.511	49.246	475.934	94.001	0.765	570.700	554
Electron-like PID	11.353	29.491	30.897	71.740	93.885	0.764	166.389	174
Evis > 100 MeV	4.339	29.317	21.197	54.853	92.680	0.760	148.294	150
No Decay-e	1.196	24.903	18.205	44.304	83.884	0.738	128.927	130
Erec	0.764	13.129	14.137	28.029	81.240	0.540	109.809	107
π^0 rejection cut	0.423	11.661	6.607	18.691	76.164	0.461	95.315	94
Efficiency from FCFV	0.000	0.206	0.025	0.016	0.694	0.470	0.073	-

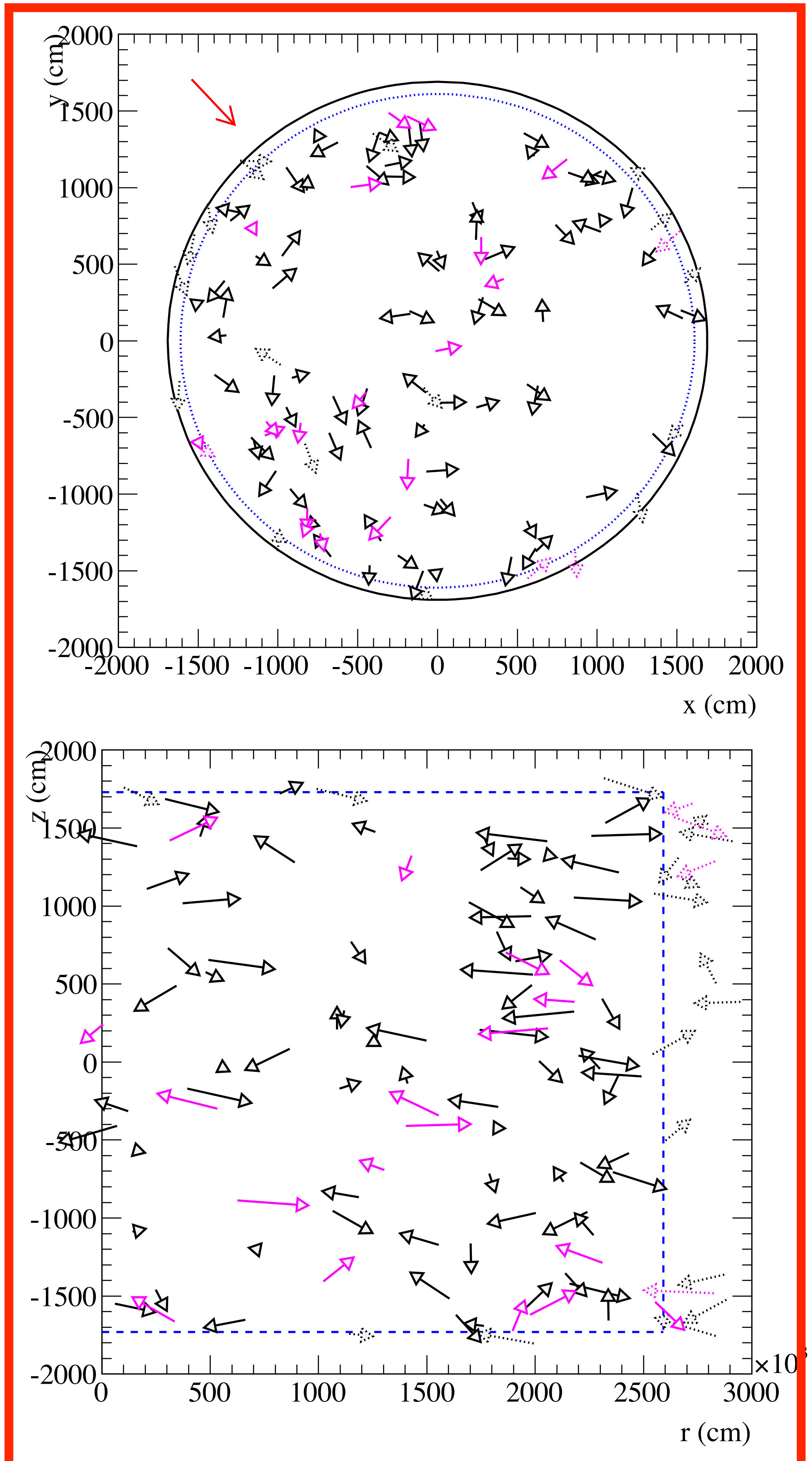
Electron Anti-Neutrino Selection



Parameter	Value
Δm^2_{21}	$7.53 \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{23}	$2.54 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{12}$	0.304
$\sin^2\theta_{13}$	0.0219
$\sin^2\theta_{23}$	0.550
δ_{CP}	-1.728
Mass Hierarchy	Normal
ν Travel Length	295 km
Earth Density	$2.6\,\mathrm{g}\cdot\mathrm{cm}^{-3}$

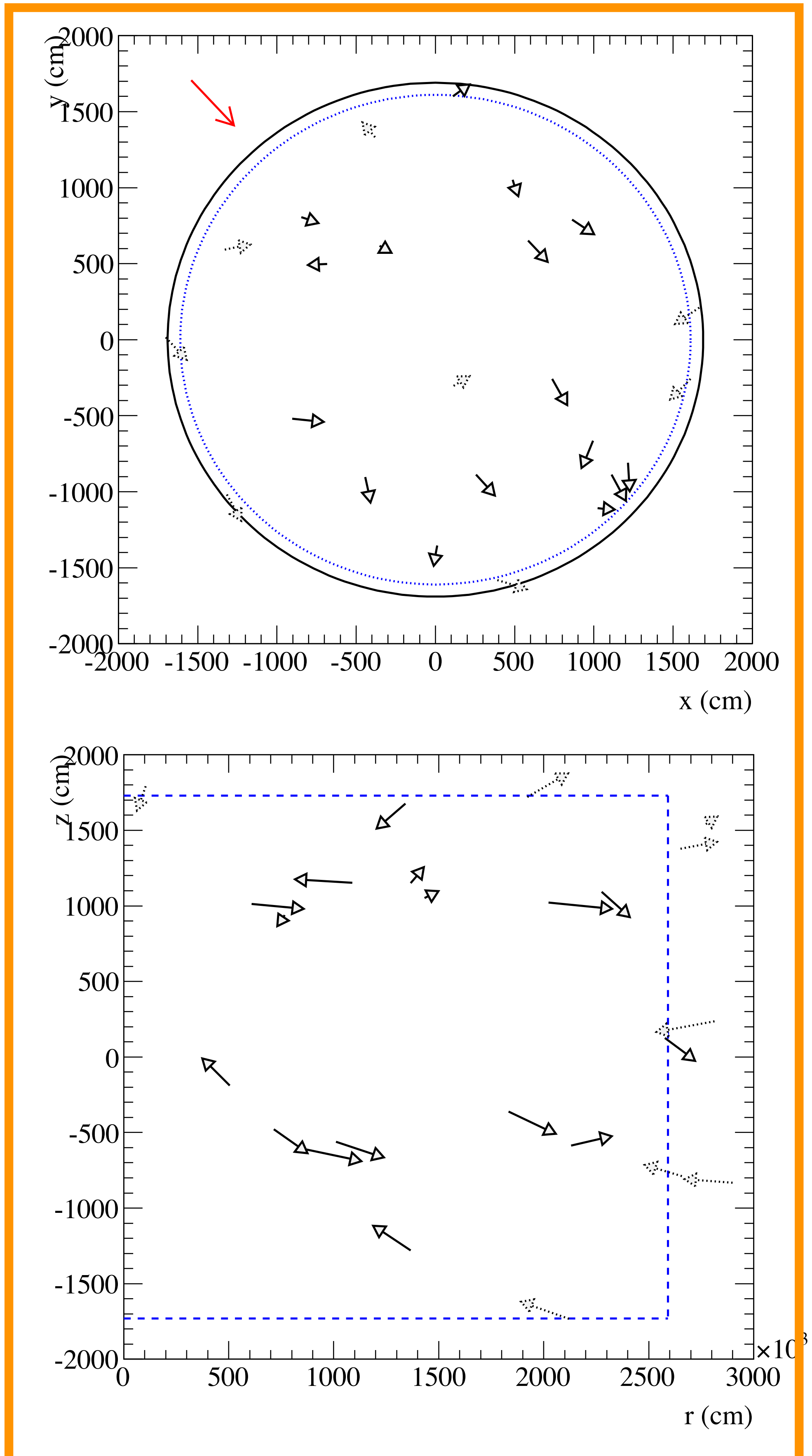
Runs 5-9			Expected					Data
	$\nu_\mu + \bar{\nu_\mu}$ CC	$\nu_e + \bar{\nu_e}$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu_\mu} \to \bar{\nu_e}$	MC total	
Floor-FCFV	290.199	19.106	120.797	430.102	4.202	10.349	444.653	460
Sample-FCFV	311.203	21.476	122.864	455.543	5.810	10.312	471.665	497
Single Ring	144.493	10.884	22.609	177.986	4.133	8.809	190.927	215
Electron-like PID	2.806	10.875	13.831	27.512	4.126	8.802	40.440	42
Evis > 100 MeV	1.410	10.830	9.916	22.156	4.062	8.748	34.966	32
No Decay-e	0.406	9.479	8.600	18.485	3.465	8.581	30.532	28
Erec	0.277	4.272	6.770	11.318	2.914	8.133	22.365	19
π^0 rejection cut	0.130	3.701	2.404	6.235	2.646	7.374	16.255	**16**
Efficiency from FCFV	0.000	0.172	0.020	0.014	0.455	0.715	0.034	-

Fiducial Volume

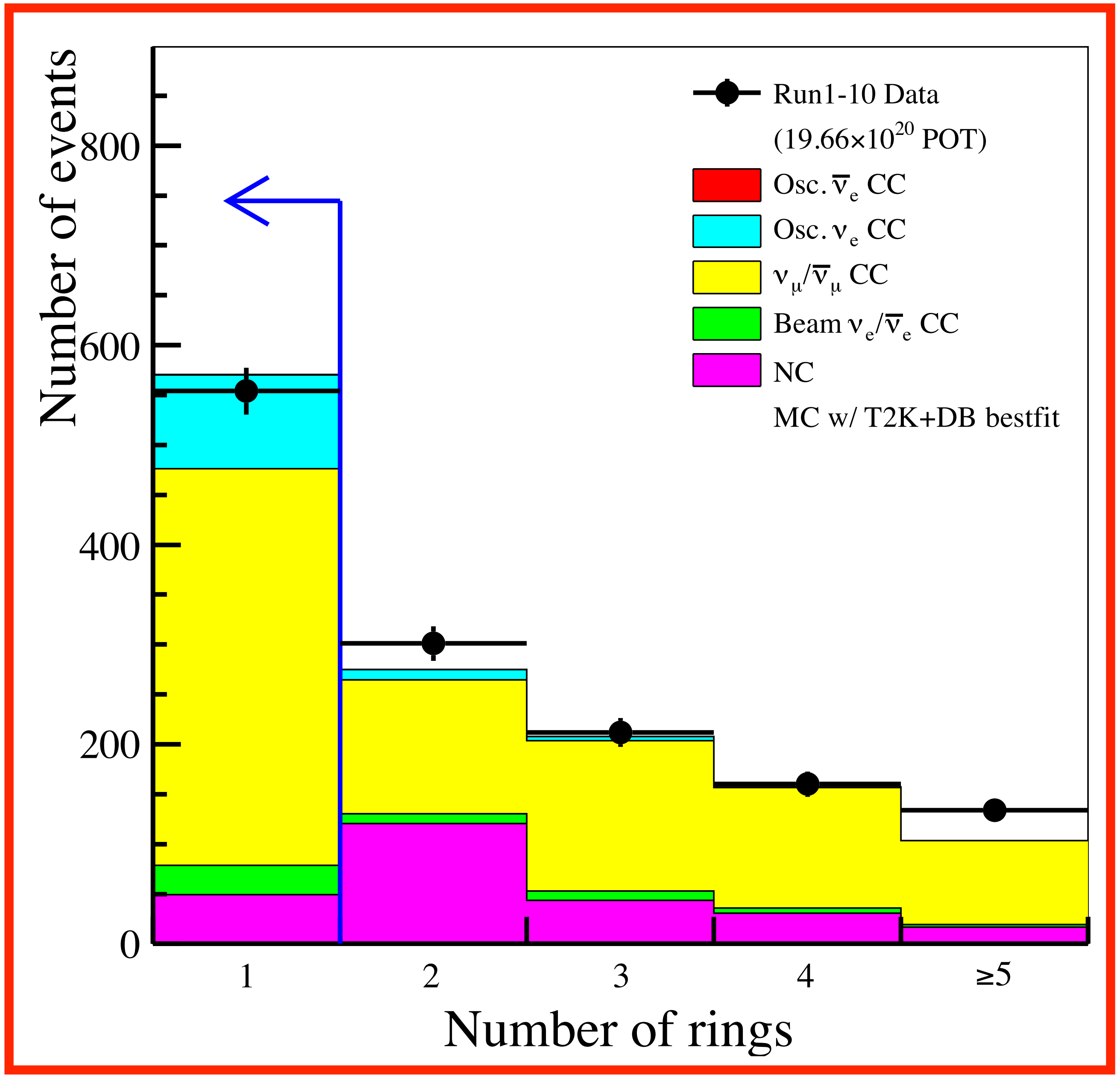


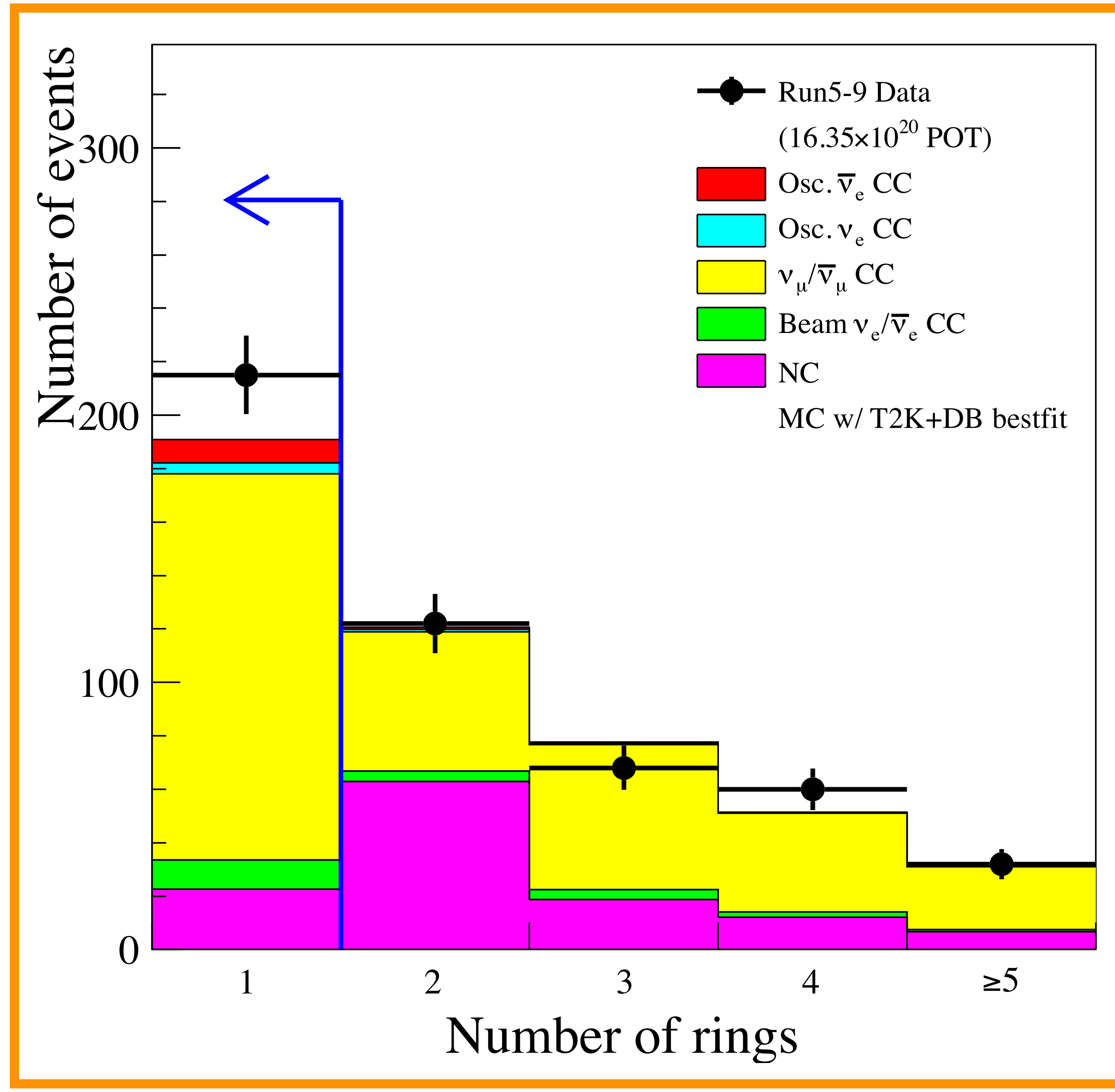
wall > 80 cm

to_wall > 170 cm

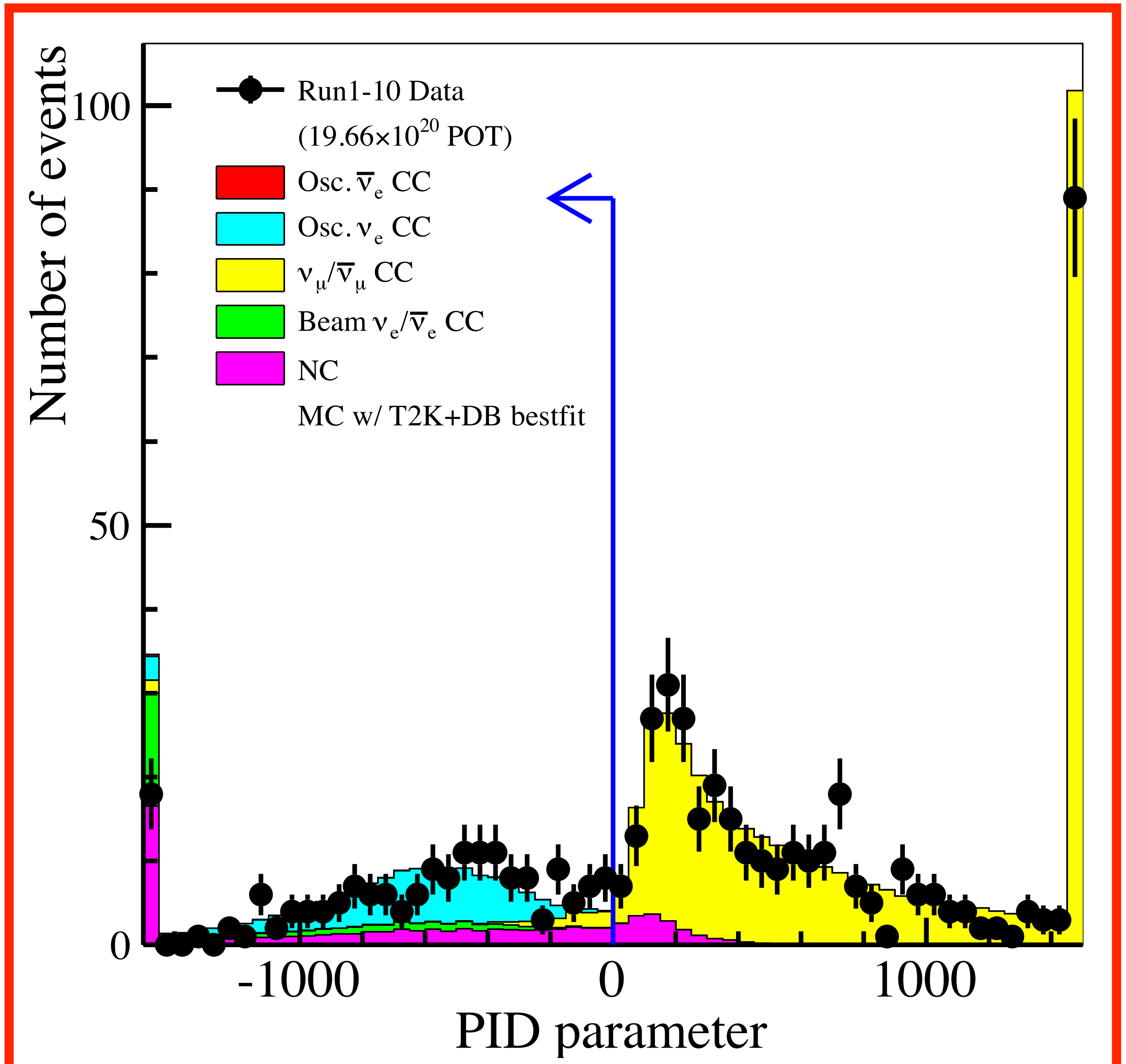


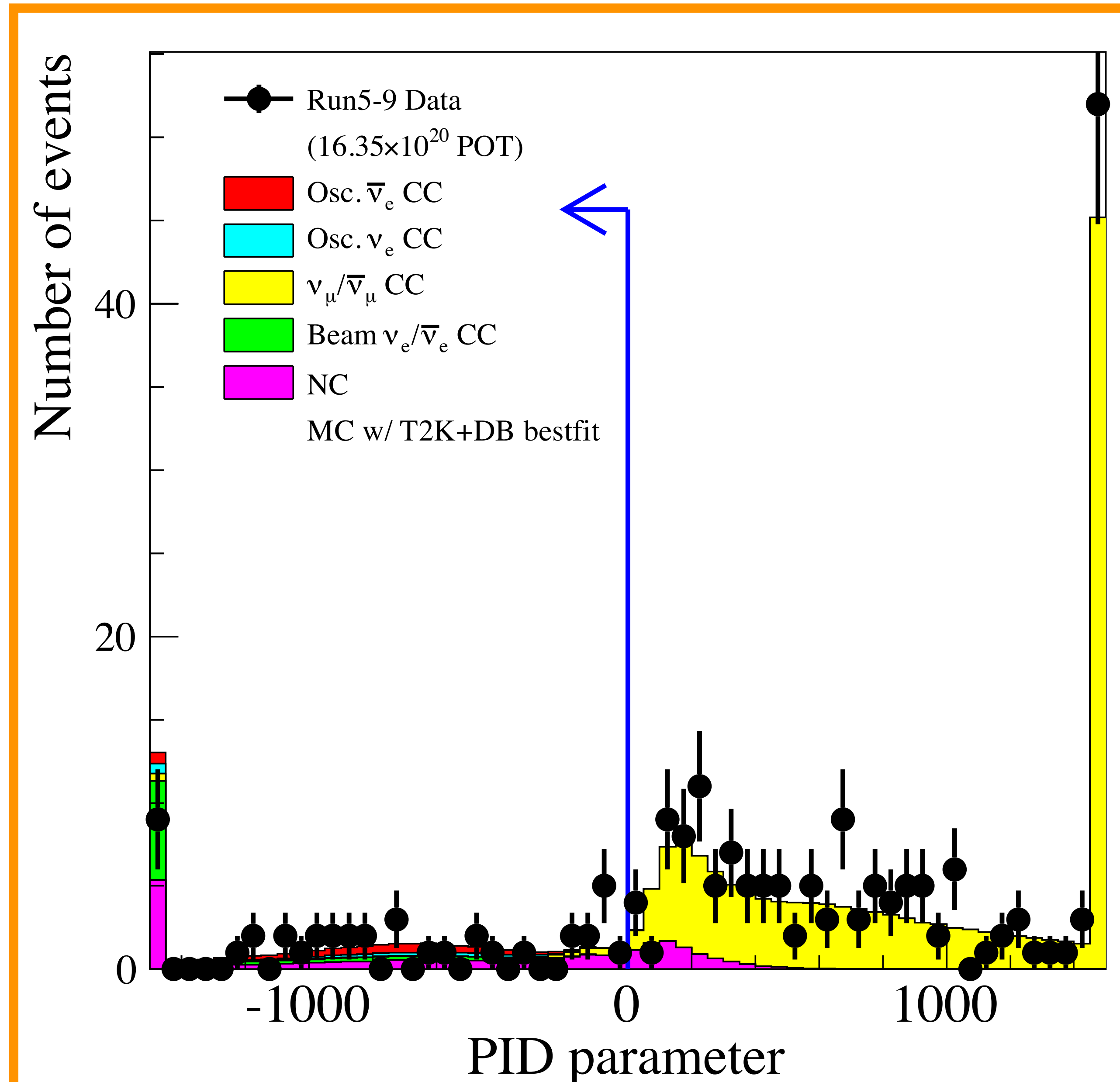
Number of Rings (=1)



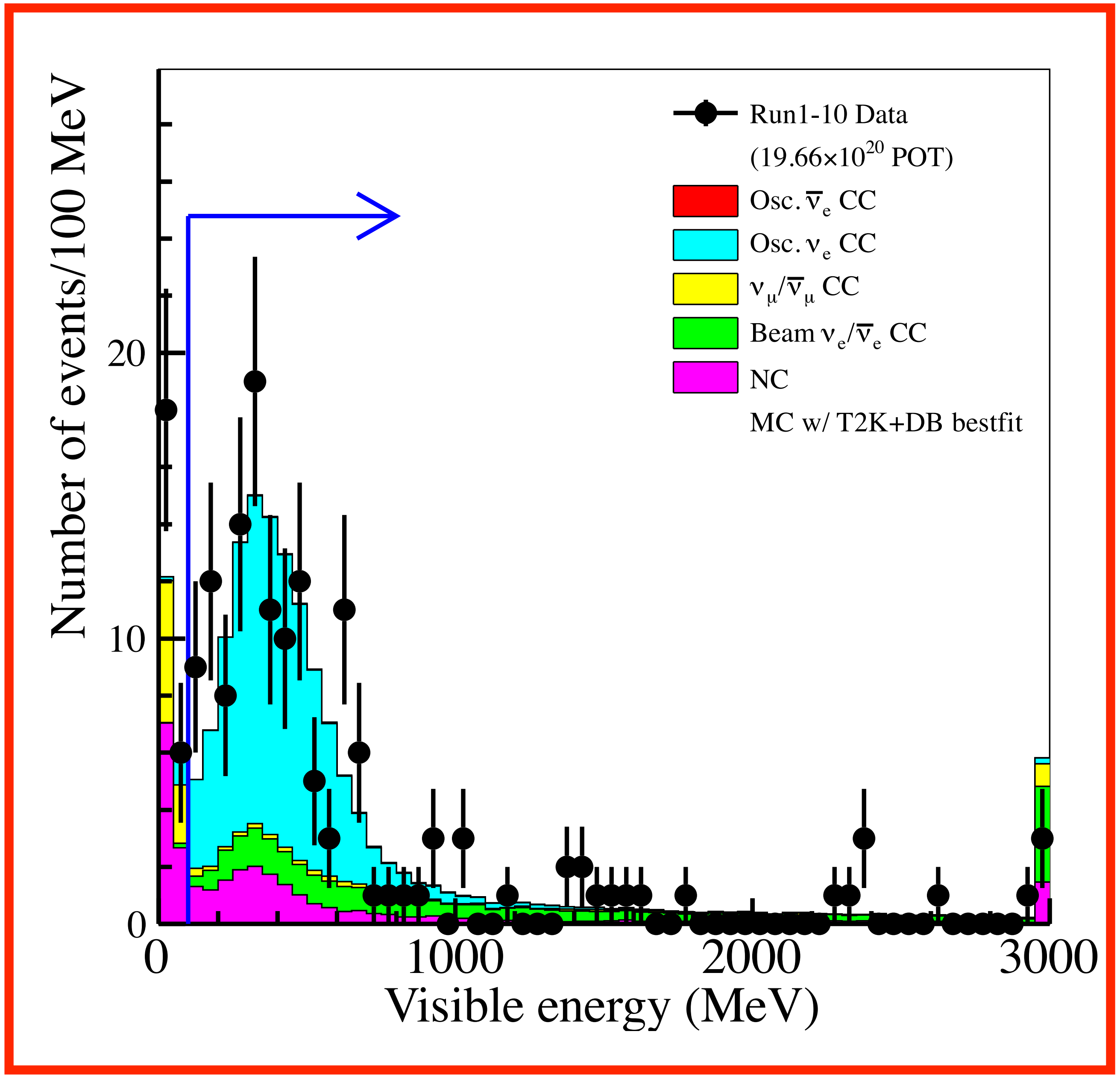


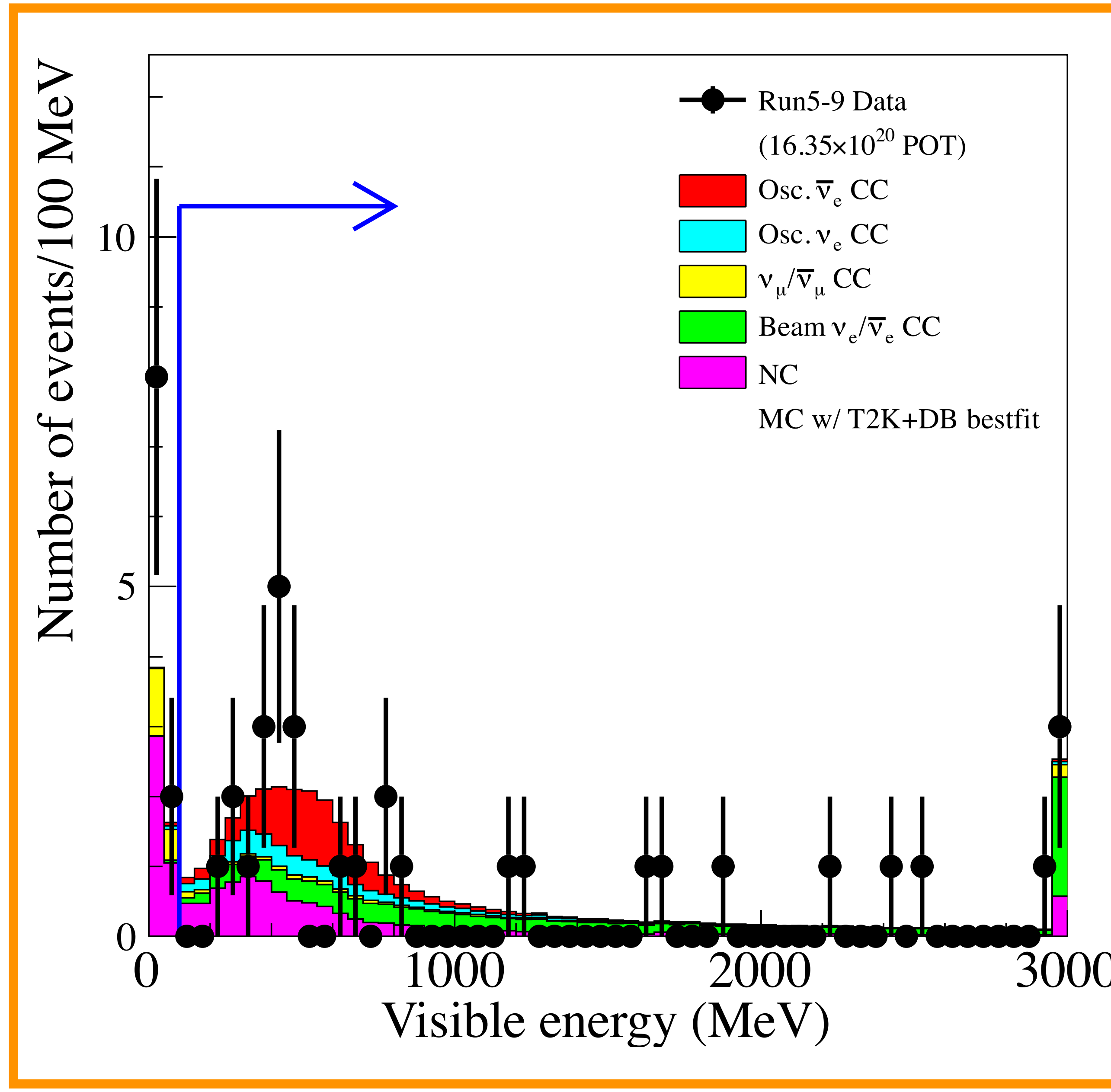
Particle ID (= e-like)



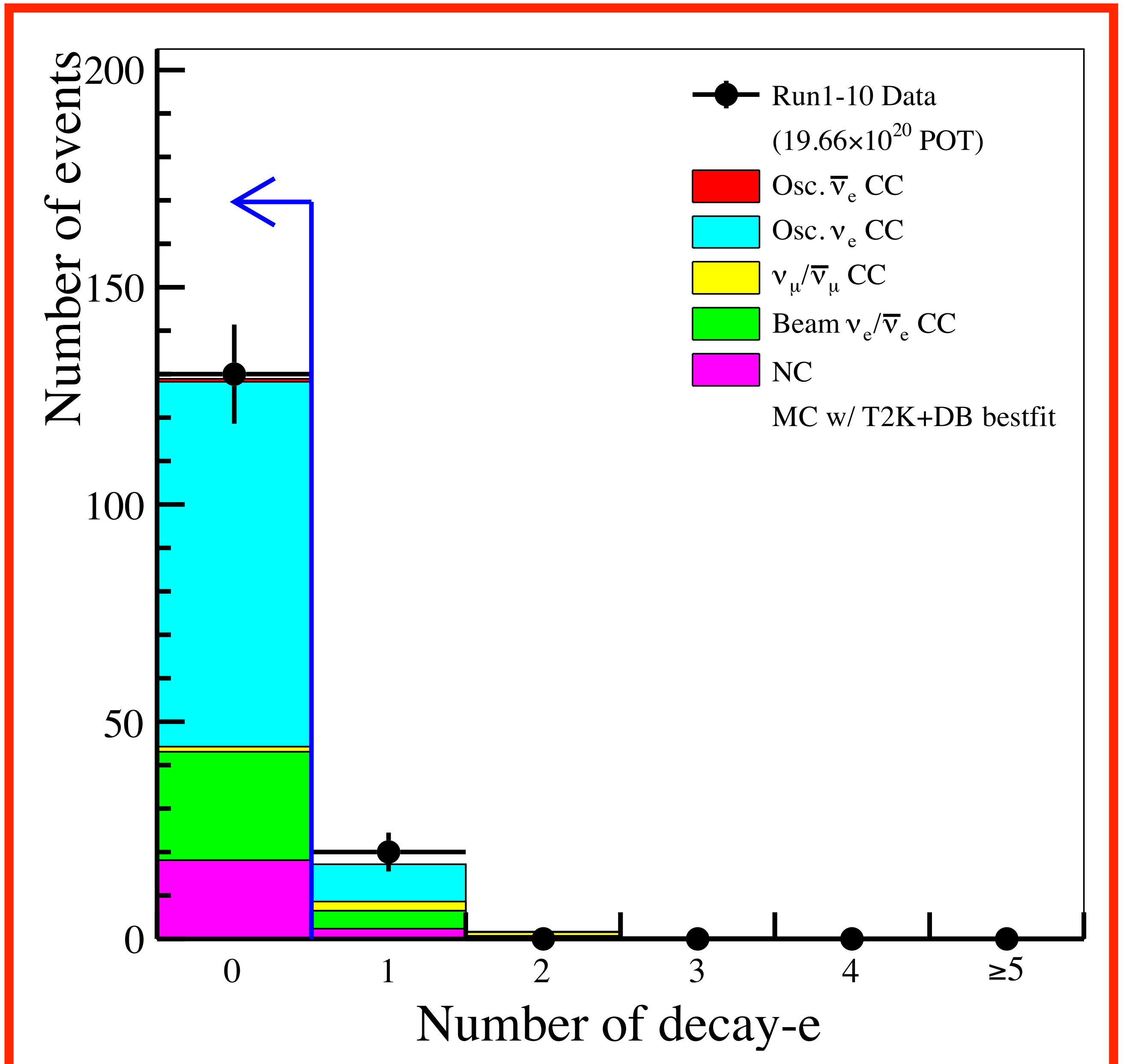


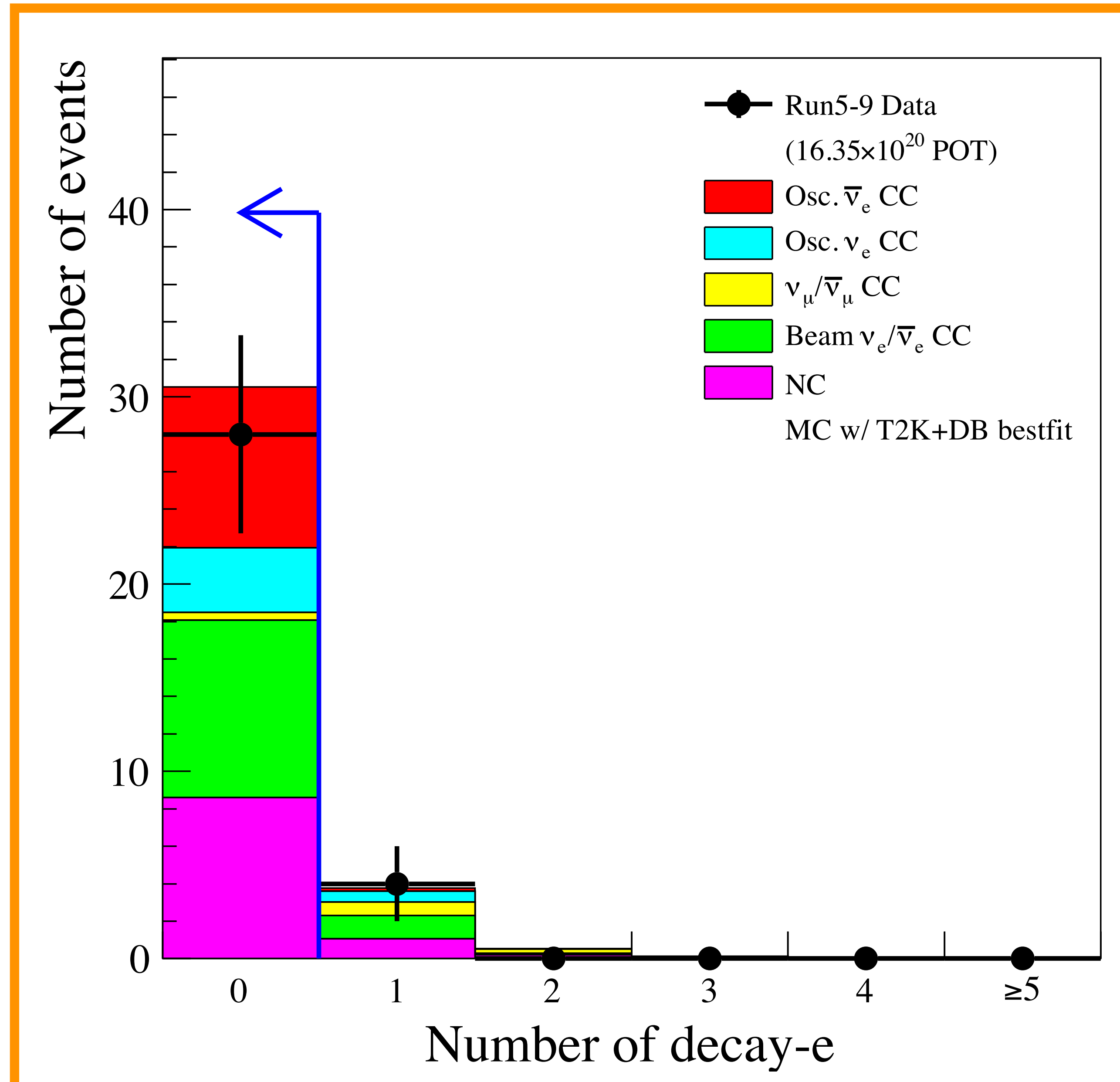
Visible Energy (> 100 MeV)



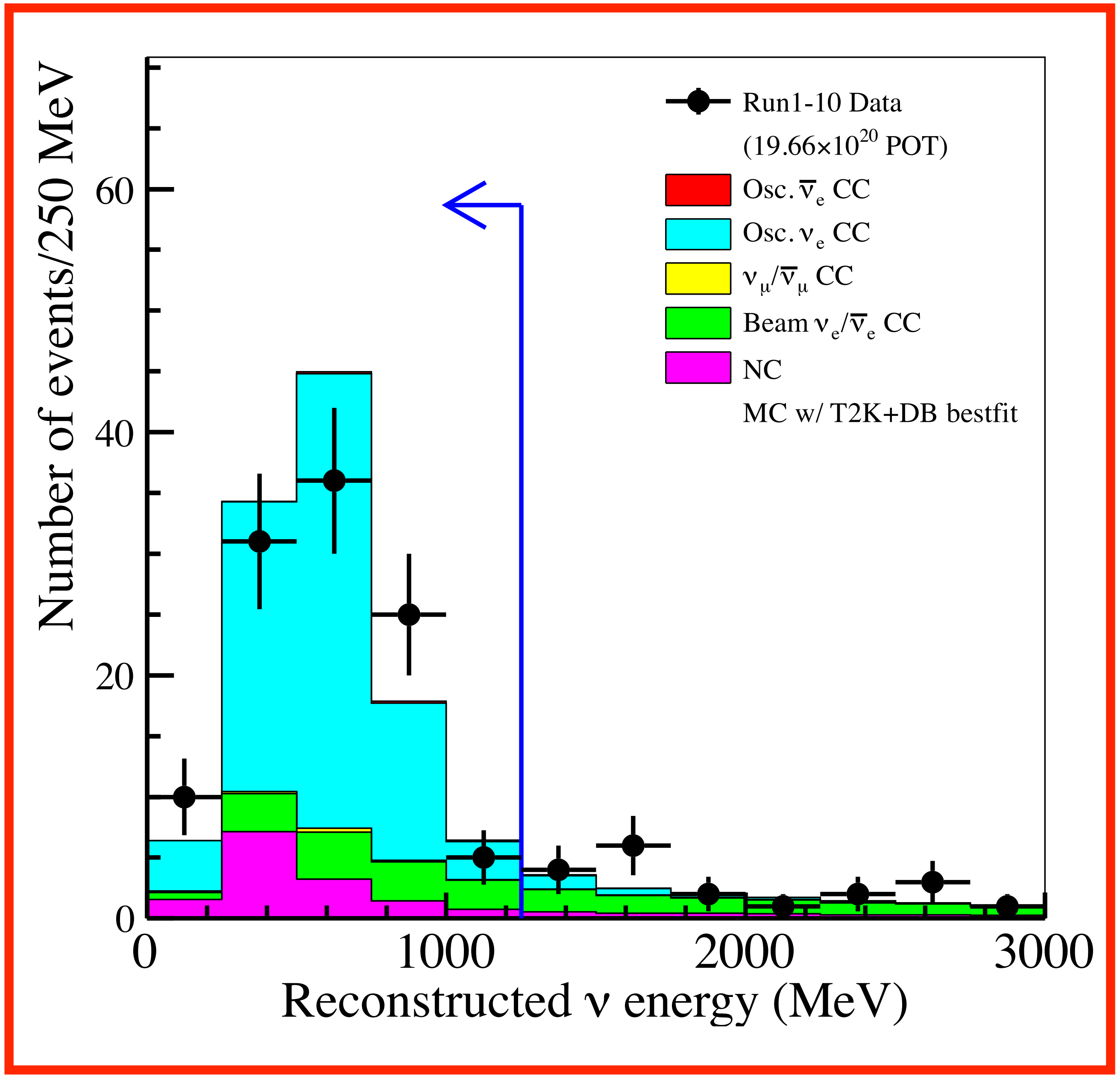


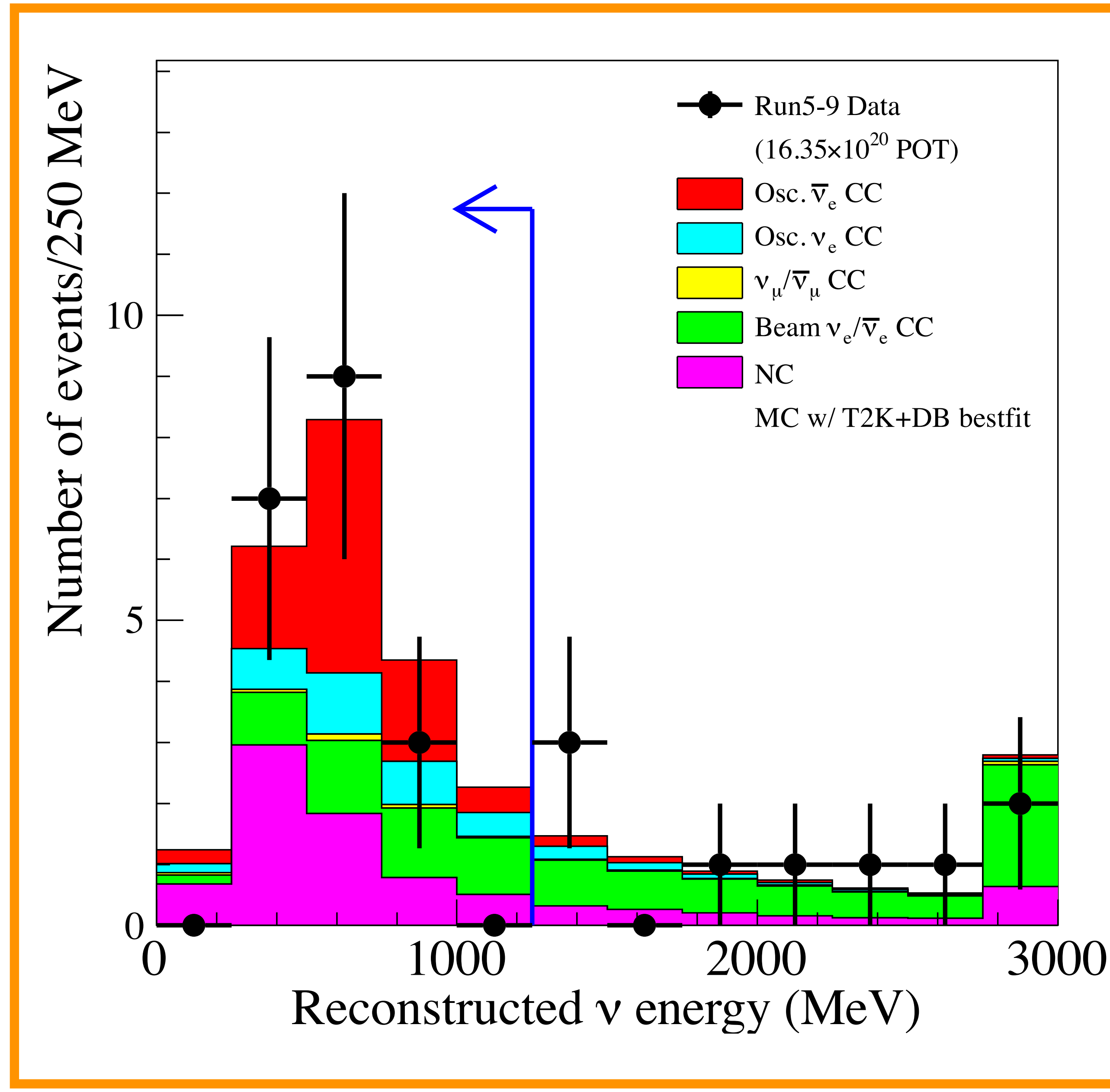
#Decay-electrons (=0)



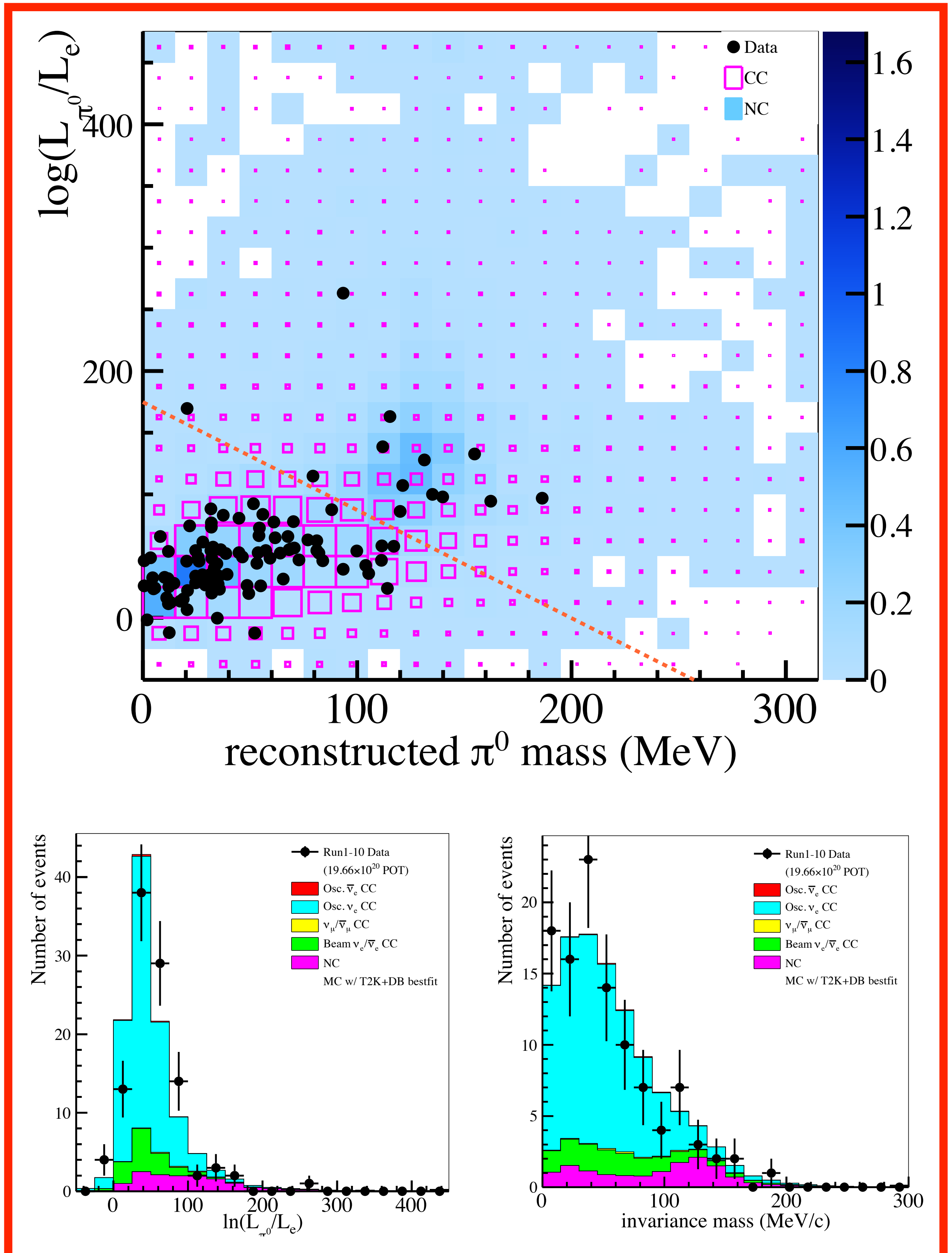


Reconstructed ν energy (<1250 MeV)

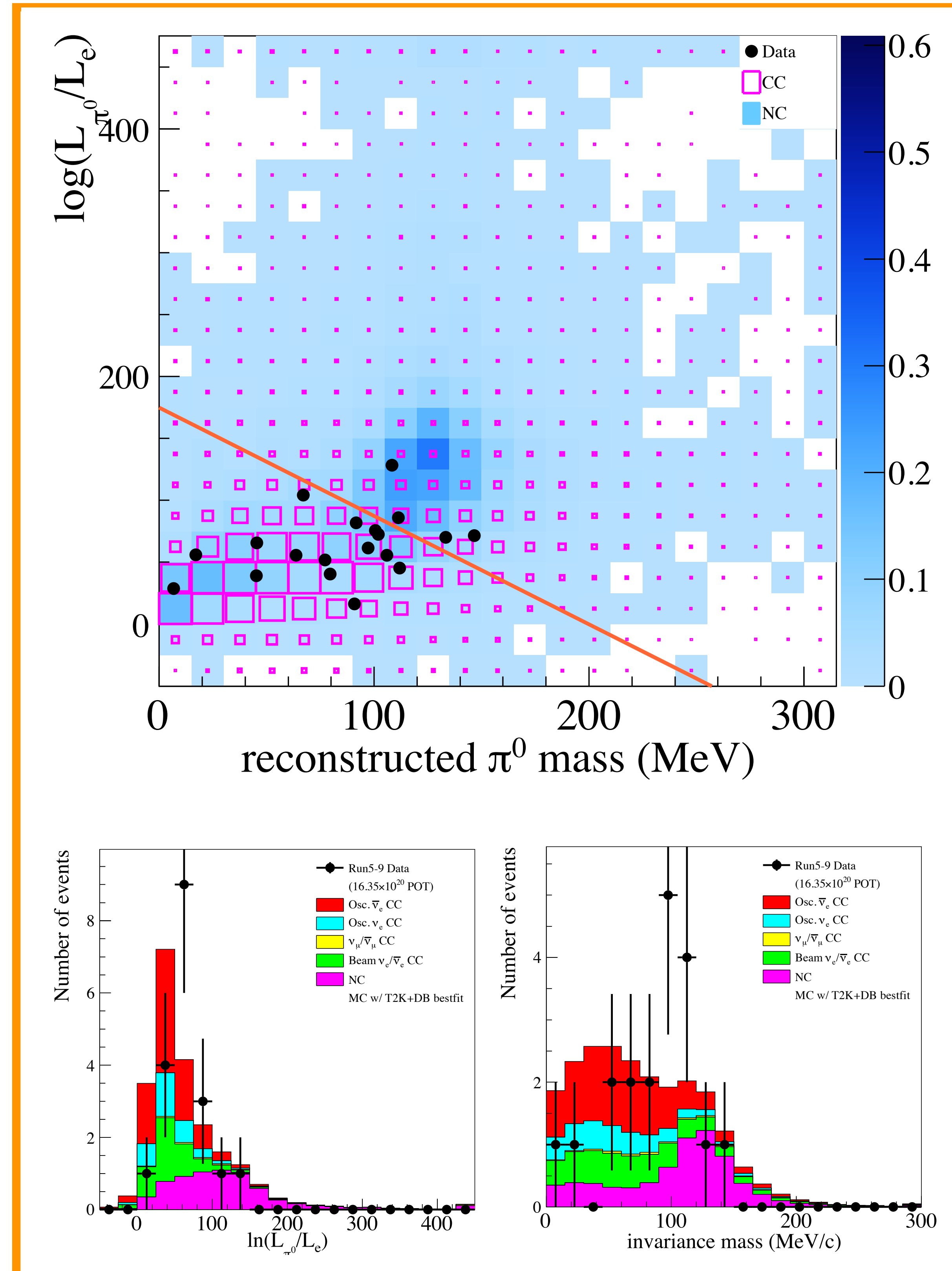




π^0 CUT

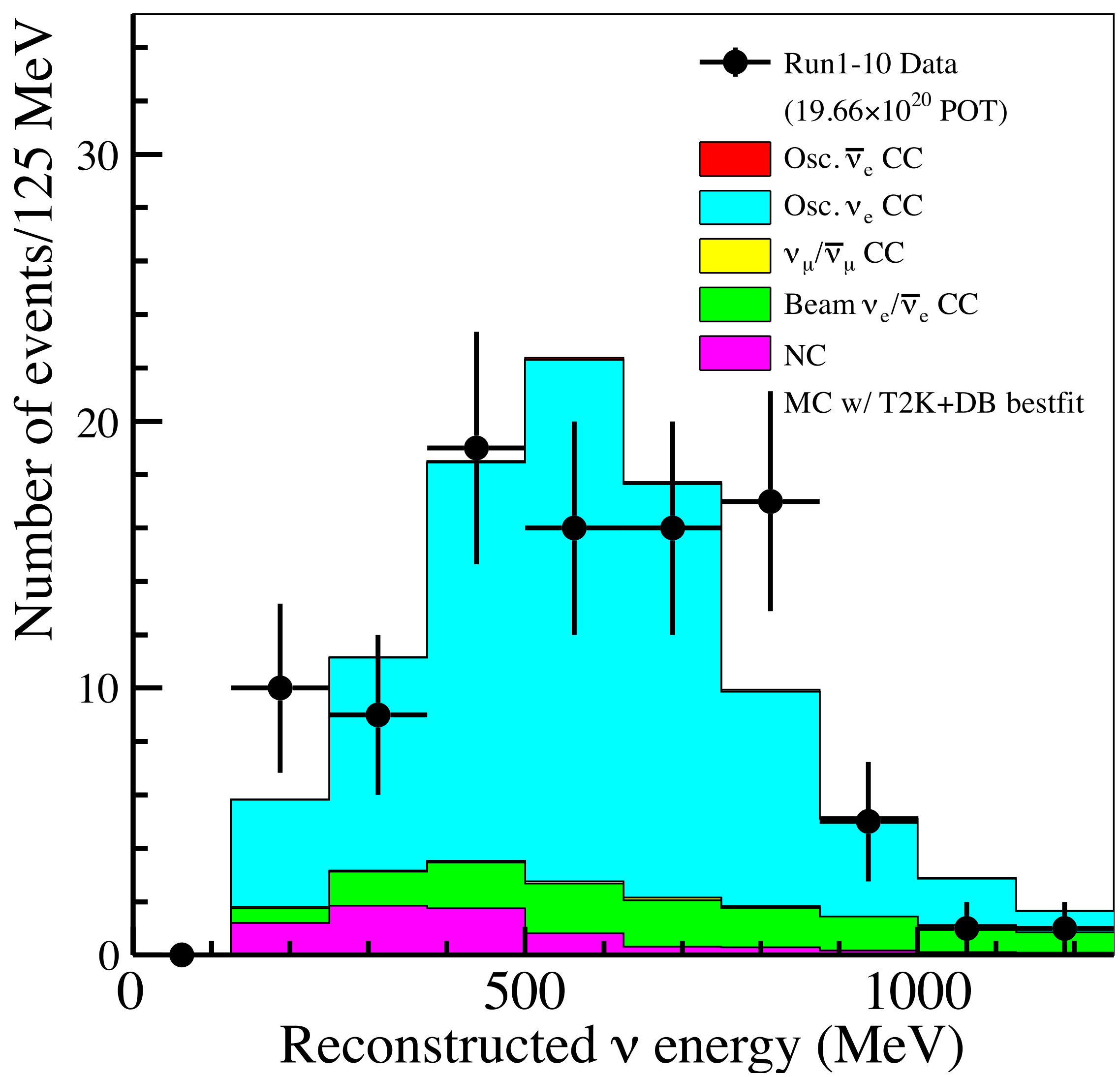


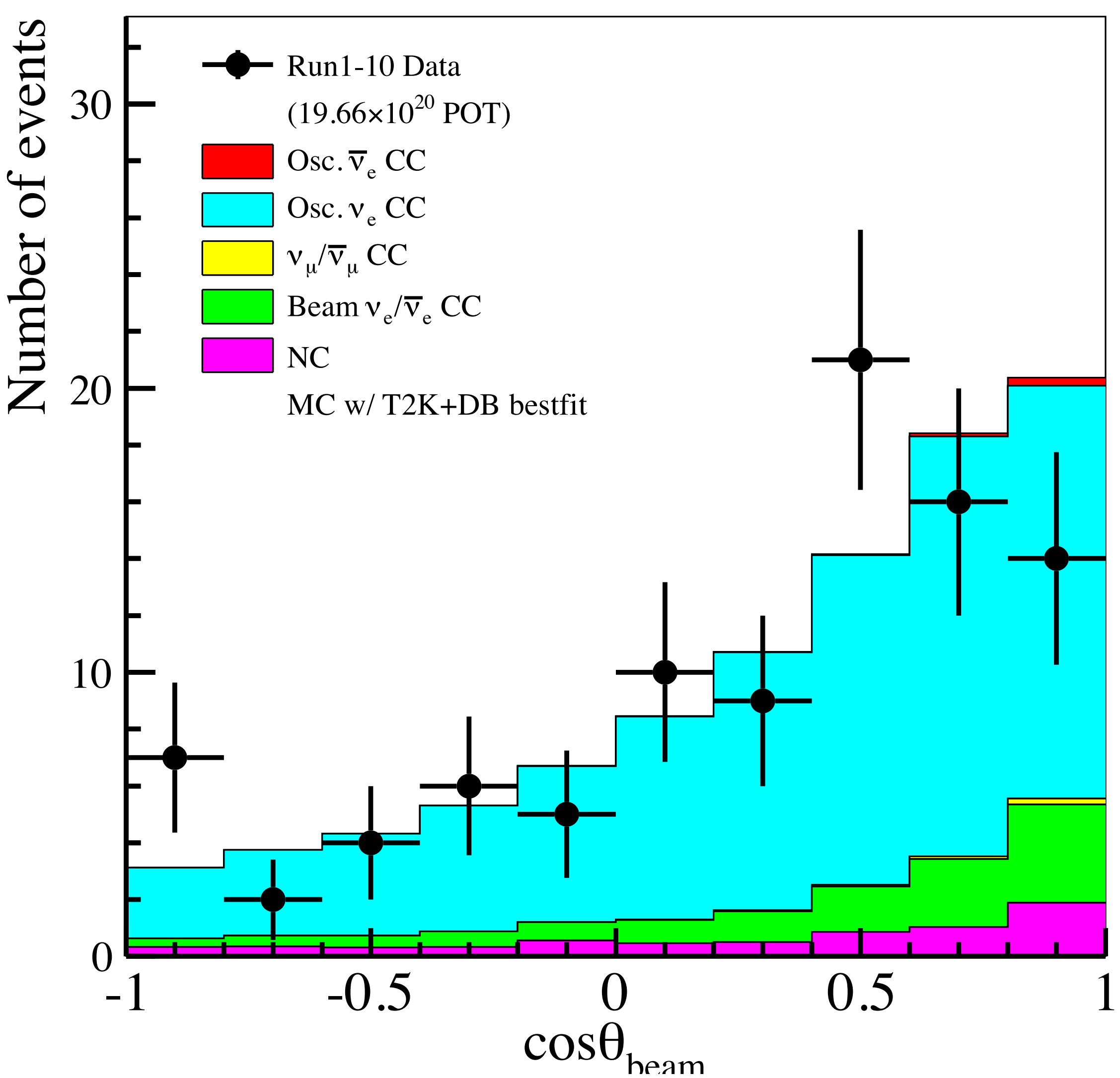
Data
CC
NC
log(L_π0/L_e)
reconstructed π0 mass (MeV)
Number of events
Run1-10 Data
(19.66×10^20 POT)
Osc. ν̄e CC
Osc. νe CC
νμ/ν̄μ CC
Beam νe/ν̄e CC
NC
MC w/ T2K+DB bestfit
ln(L_π0/L_e)
invariance mass (MeV/c)



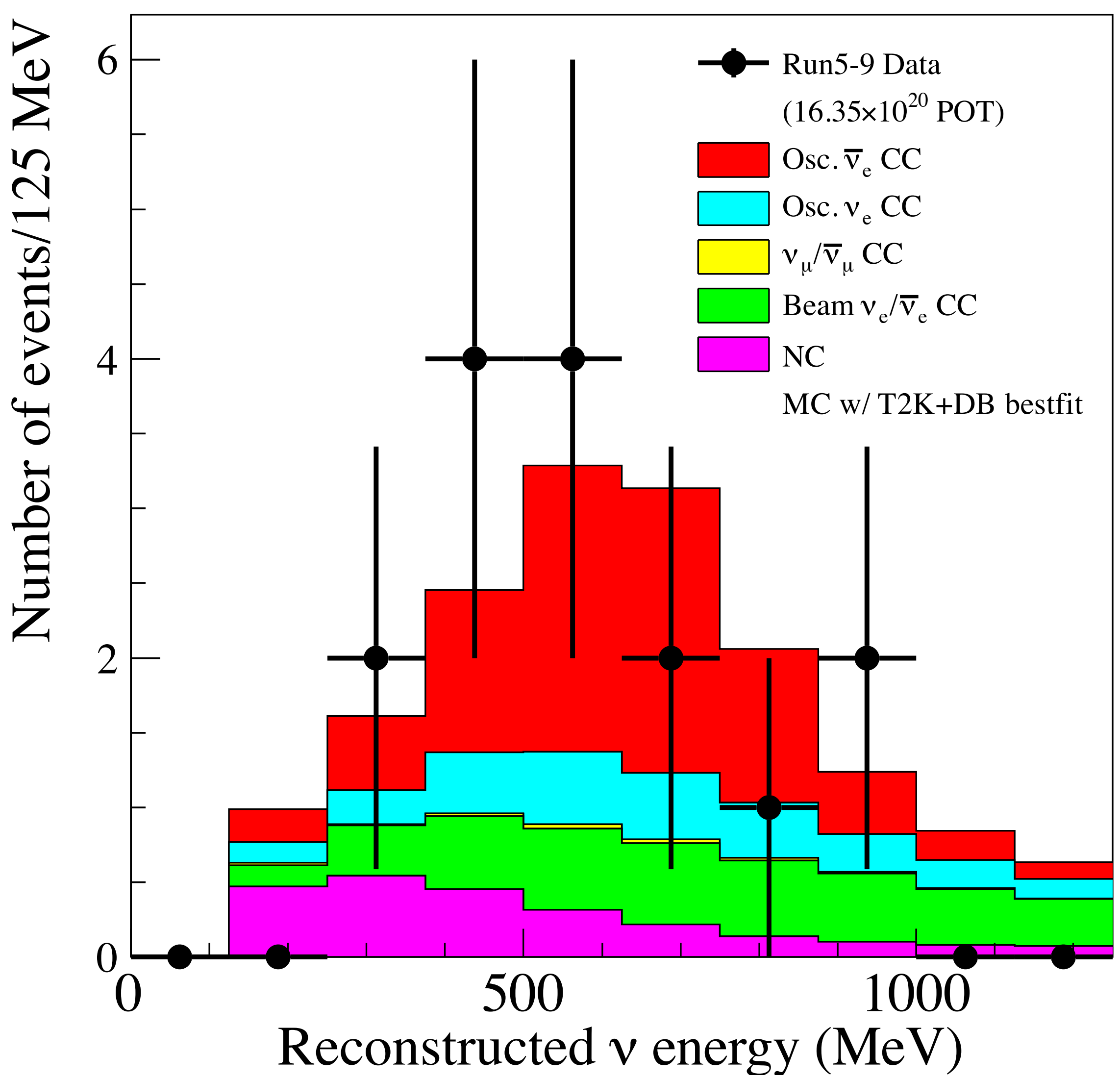
Data
CC
NC
log(L_π0/L_e)
reconstructed π0 mass (MeV)
Number of events
Run5-9 Data
(16.35×10^20 POT)
Osc. ν̄e CC
Osc. νe CC
νμ/ν̄μ CC
Beam νe/ν̄e CC
NC
MC w/ T2K+DB bestfit
ln(L_π0/L_e)
invariance mass (MeV/c)

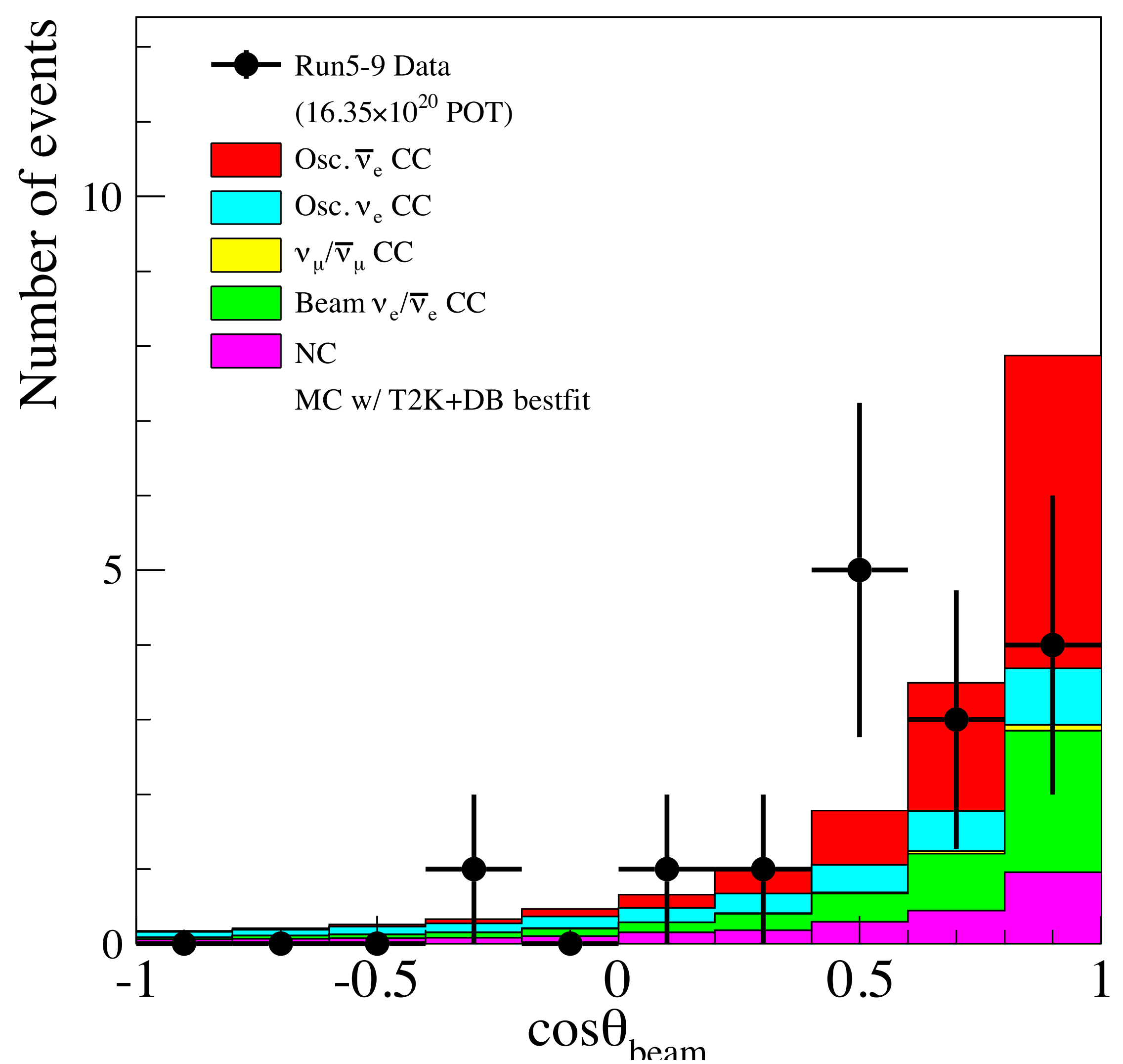
Electron Neutrino events



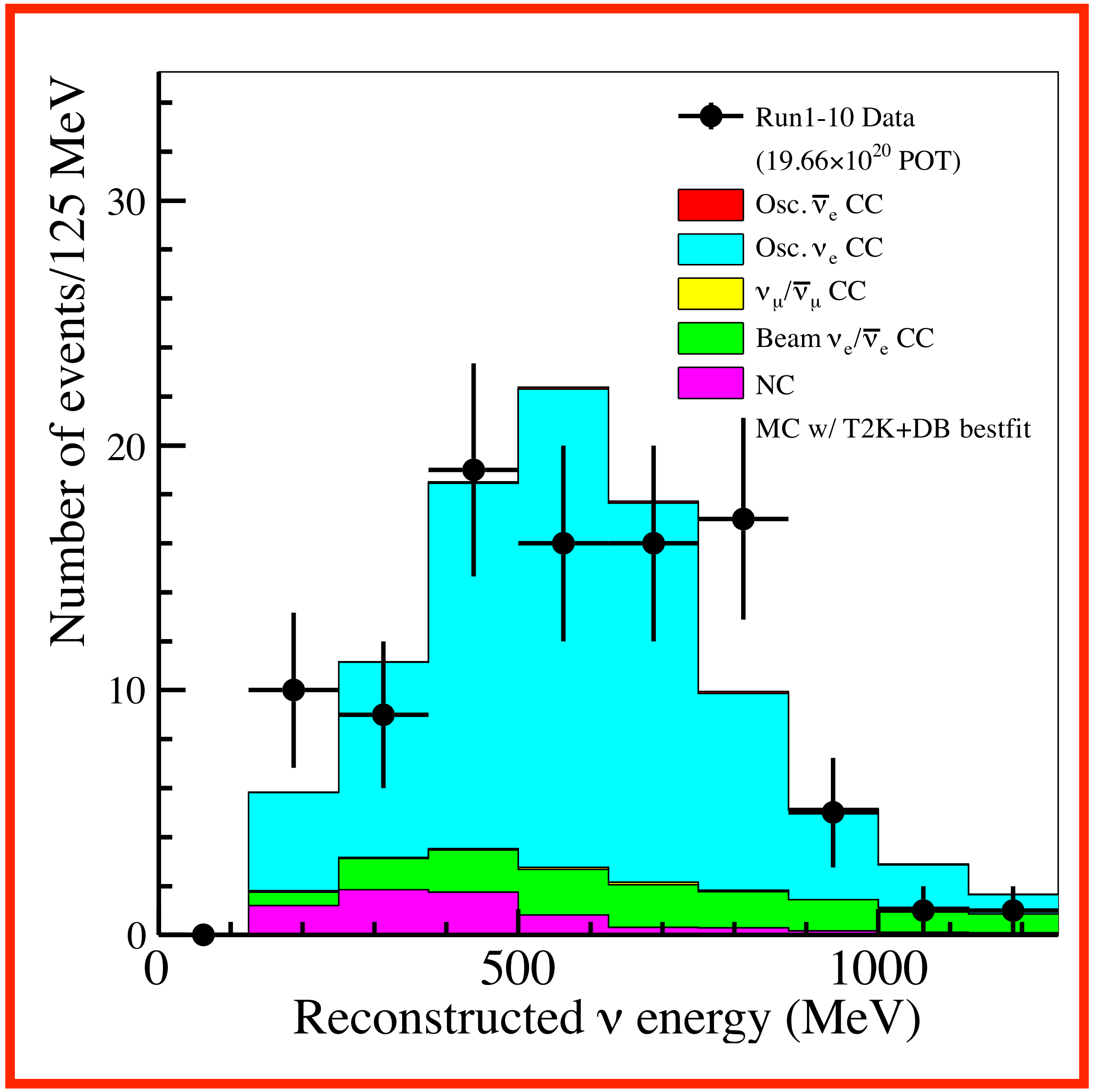


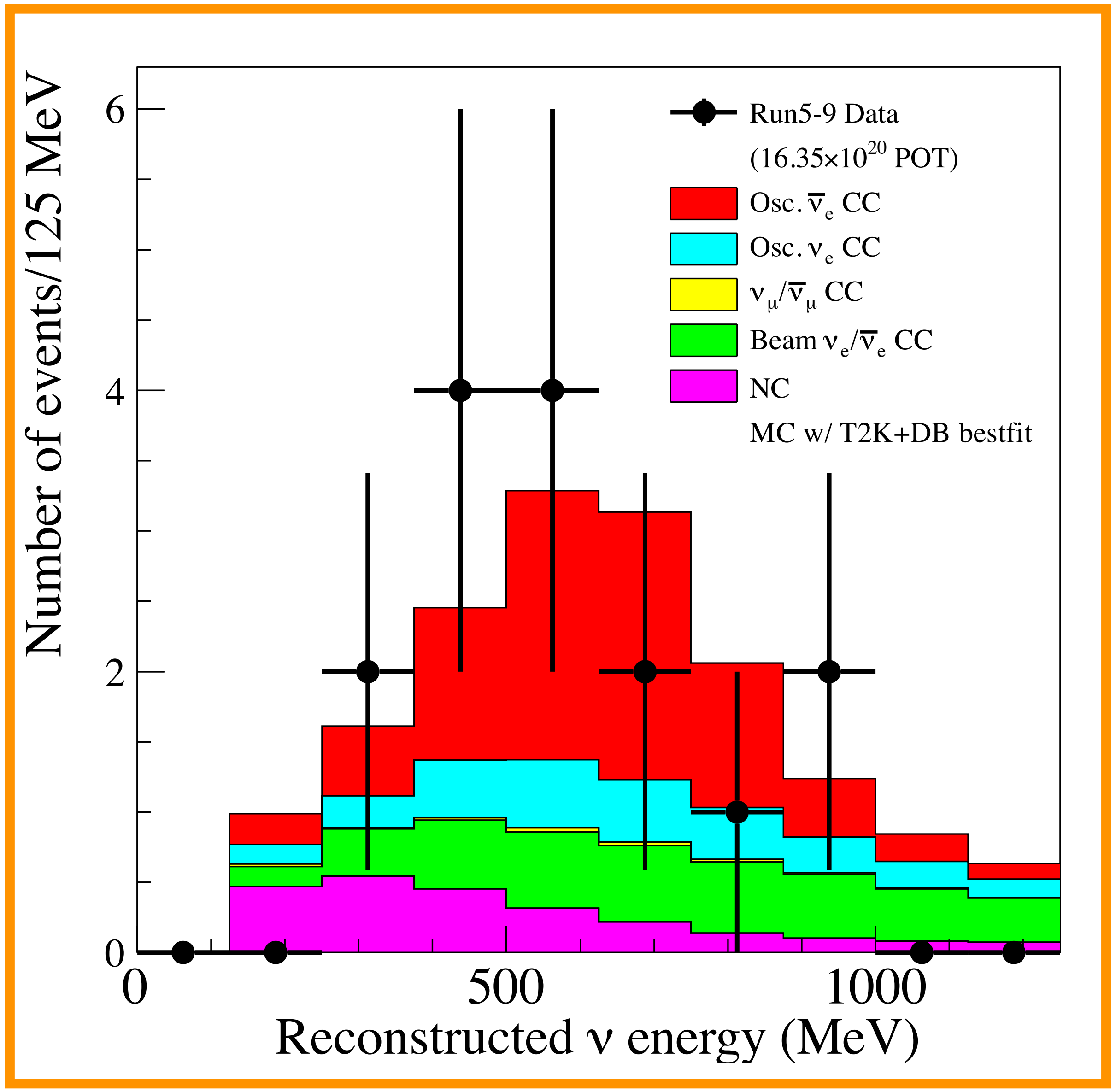
Electron Anti-Neutrino events





FINAL Electron (anti-)neutrino events





- Neutrino:
  - Data: 94
  - MC: 95.315

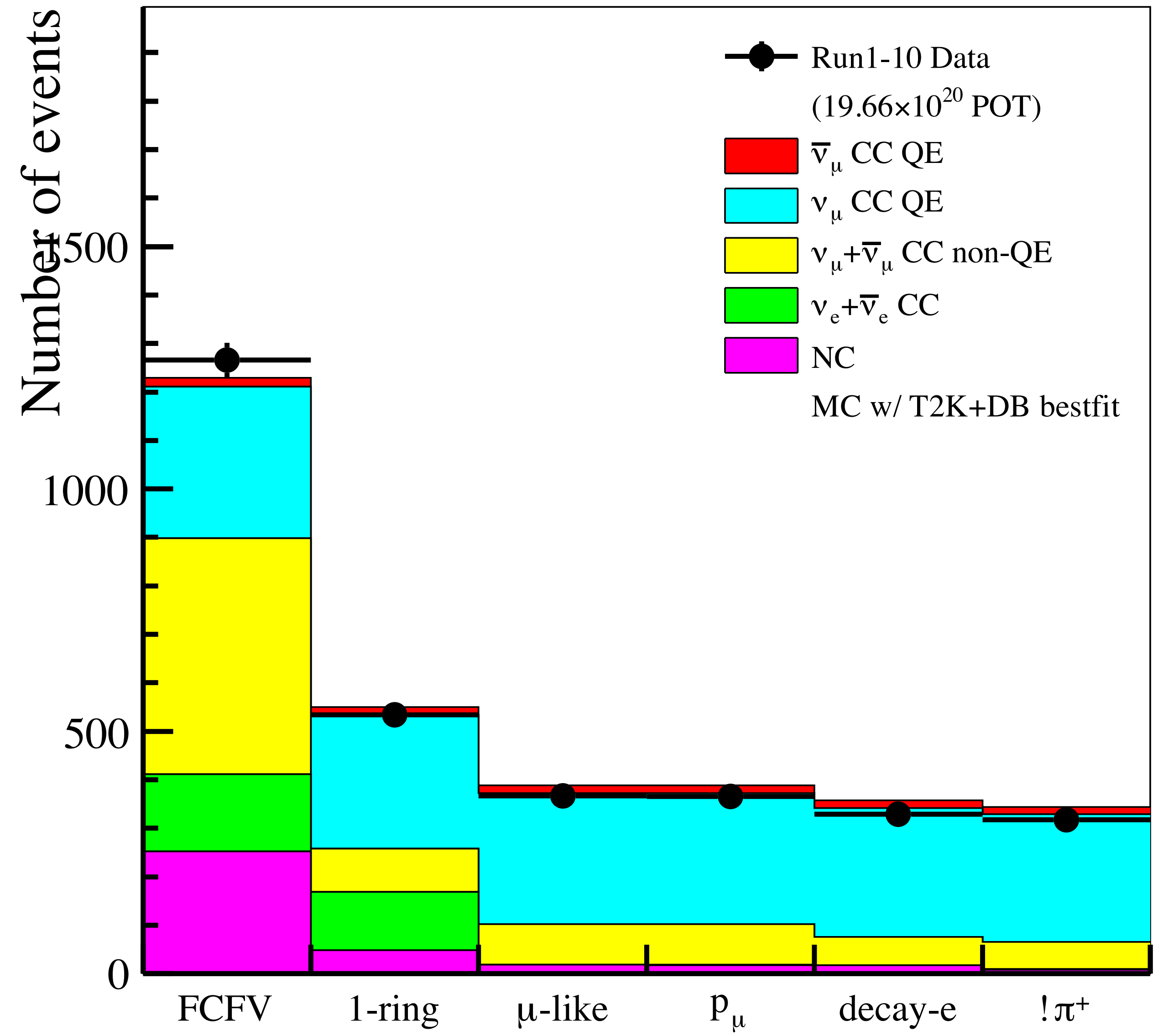
- Anti-neutrino:
  - Data: 16
  - MC: 16.255

FINAL Electron (anti-)neutrino events

Runs 1-10			Expected					Data
	$\nu_\mu + \bar{\nu_\mu}$ CC	Beam $\nu_e + \bar{\nu_e}$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu_\mu} \to \bar{\nu_e}$	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.359	110.486	0.959	1246.704	1279
FCFV	886.362	56.685	260.508	1203.555	109.753	0.979	1314.287	1361
Single Ring	397.177	29.511	49.246	475.934	94.001	0.765	570.700	554
Electron-like PID	11.353	29.491	30.897	71.740	93.885	0.764	166.389	174
Evis > 100 MeV	4.339	29.317	21.197	54.853	92.680	0.760	148.294	150
No Decay-e	1.196	24.903	18.205	44.304	83.884	0.738	128.927	130
Erec	0.764	13.129	14.137	28.029	81.240	0.540	109.809	107
π^0 rejection cut	0.423	11.661	6.607	18.691	76.164	0.461	95.315	94
Efficiency from FCFV	0.000	0.206	0.025	0.016	0.694	0.470	0.073	-

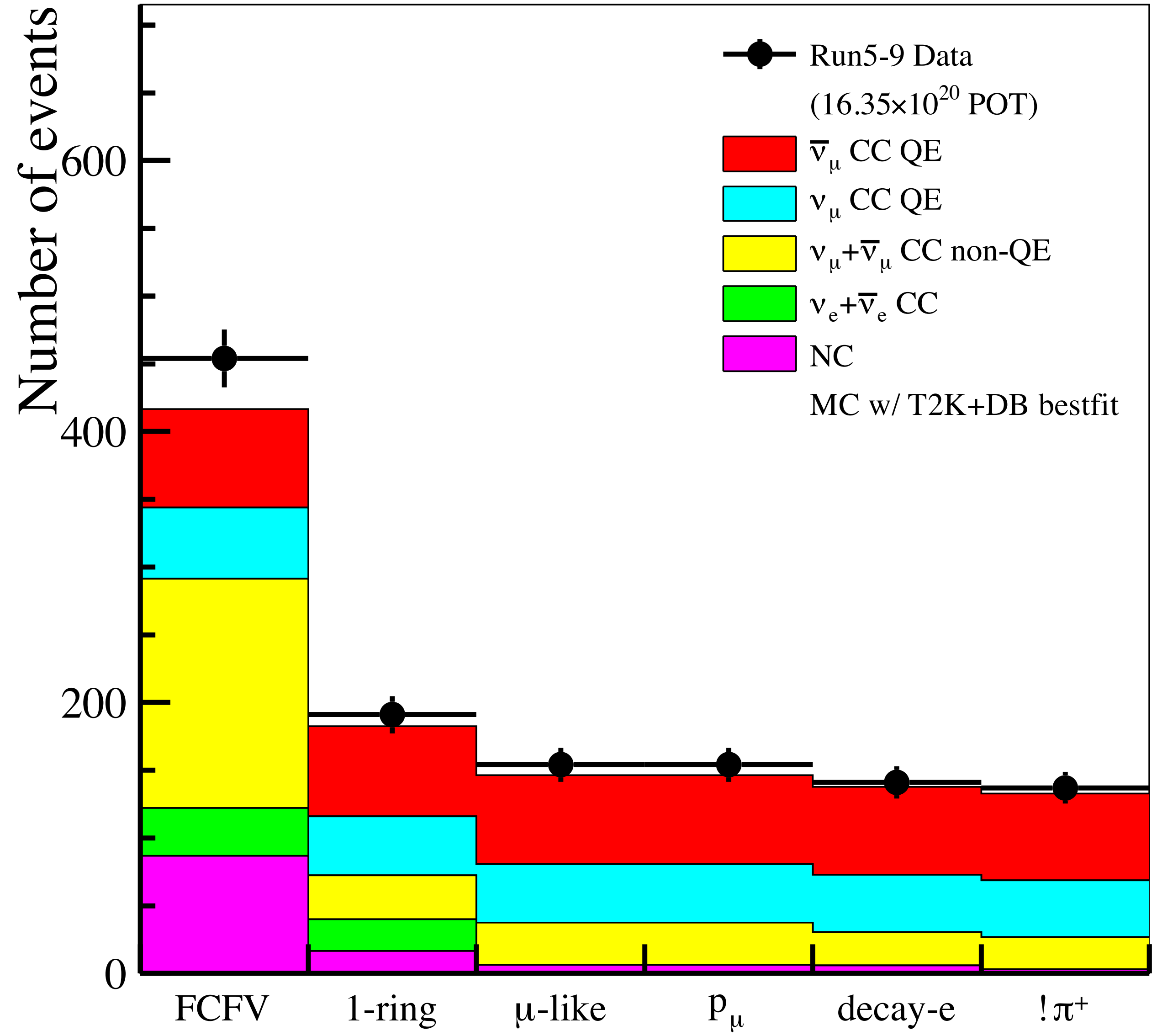
Floor-FCFV	290.199	19.106	120.797	430.102	4.202	10.349	444.653	460
Sample-FCFV	311.203	21.476	122.864	455.543	5.810	10.312	471.665	497
Single Ring	144.493	10.884	22.609	177.986	4.133	8.809	190.927	215
Electron-like PID	2.806	10.875	13.831	27.512	4.126	8.802	40.440	42
Evis > 100 MeV	1.410	10.830	9.916	22.156	4.062	8.748	34.966	32
No Decay-e	0.406	9.479	8.600	18.485	3.465	8.581	30.532	28
Erec	0.277	4.272	6.770	11.318	2.914	8.133	22.365	19
π^0 rejection cut	0.130	3.701	2.404	6.235	2.646	7.374	16.255	**16**
Efficiency from FCFV	0.000	0.172	0.020	0.014	0.455	0.715	0.034	-

Muon Neutrino Selection



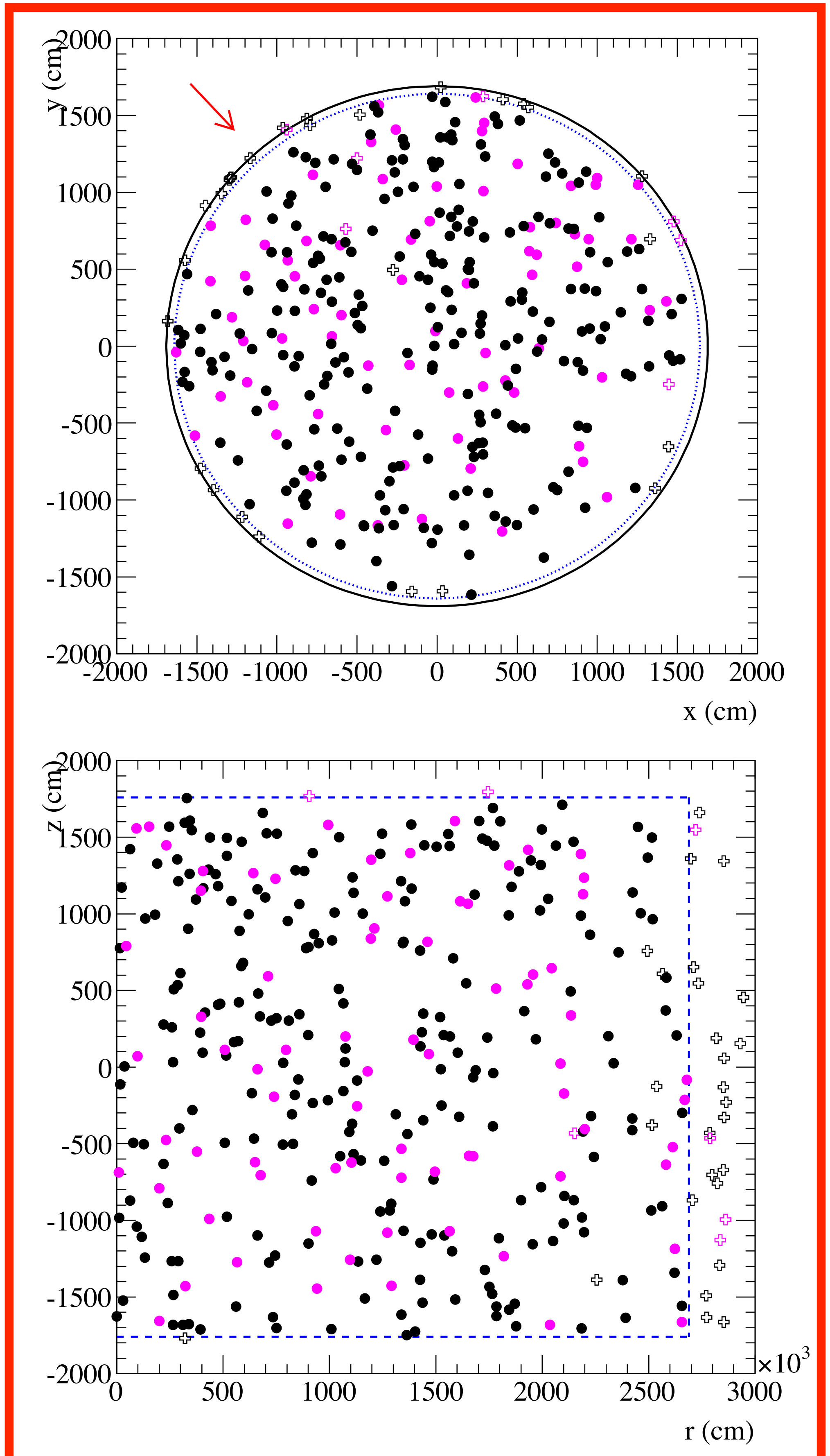
Runs 1-10	Expected							Data
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.259	110.486	0.959	1246.704	1279
FCFV	159.210	252.169	487.223	898.601	312.544	18.239	1229.385	1266
Single Ring	120.241	48.469	89.208	257.919	276.480	16.037	550.436	534
Muon-like PID	0.130	18.270	84.397	102.797	270.330	15.927	389.055	367
Momentum	0.130	18.127	84.351	102.608	269.977	15.924	388.509	366
0 or 1 Decay-e	0.128	17.606	57.972	75.706	266.412	15.751	357.869	329
π^+ rejection cut	0.121	8.896	56.723	65.740	263.084	15.597	344.422	318
Efficiency from FCFV	0.001	0.035	0.116	0.073	0.842	0.855	0.280	-

Muon Anti-Neutrino Selection



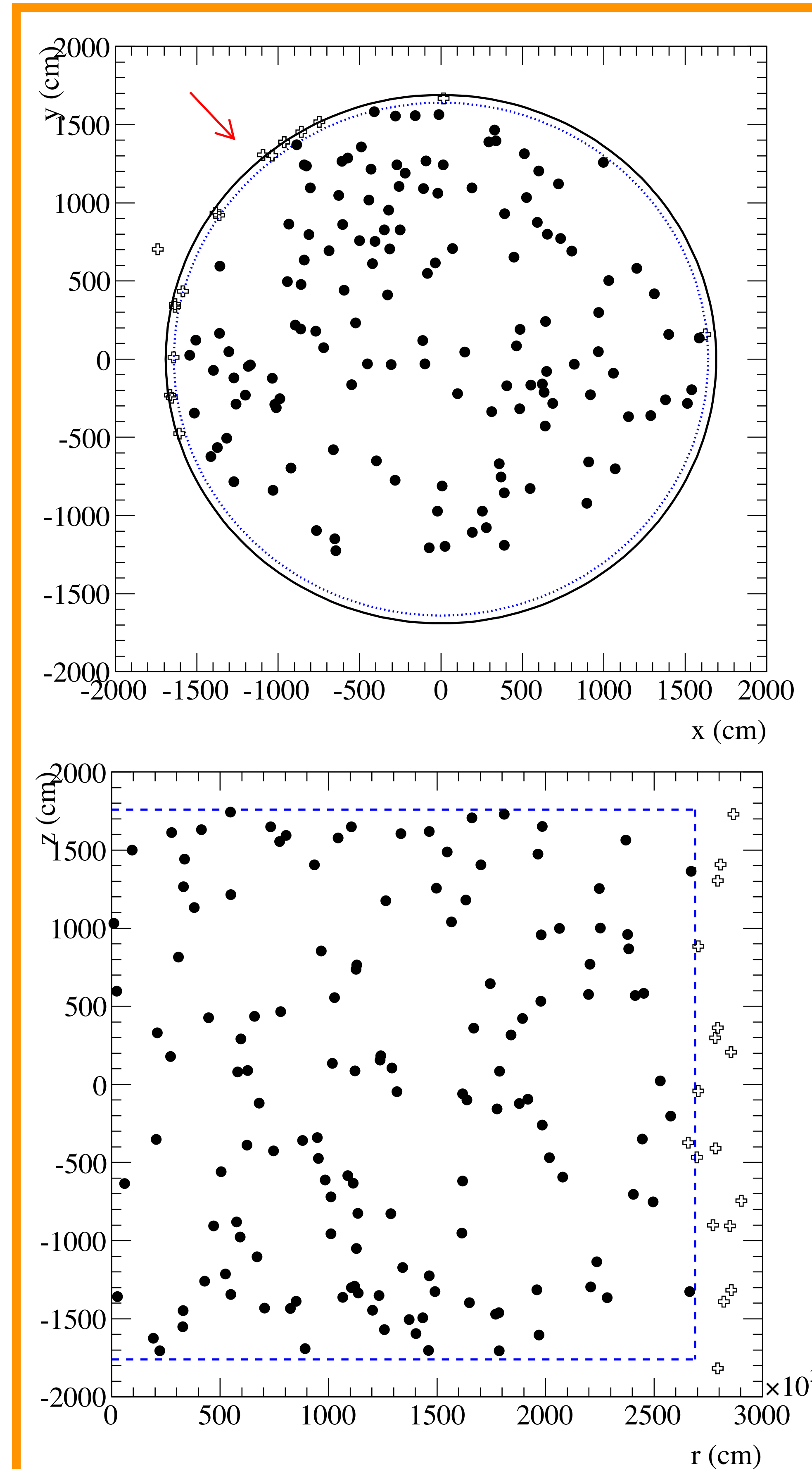
Runs 5-9	Expected							Data
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC total	
Floor-FCFV	19.908	87.827	170.146	277.881	53.225	74.086	405.192	459
FCFV	35.324	86.630	169.259	291.213	52.663	72.699	416.575	454
Single Ring	23.313	16.622	32.691	72.626	43.306	66.692	182.624	191
Muon-like PID	0.013	6.290	31.379	37.682	42.884	65.768	146.333	154
Momentum	0.013	6.232	31.373	37.618	42.865	65.729	146.213	154
0 or 1 Decay-e	0.013	6.031	24.437	30.481	42.160	64.931	137.572	141
π^+ rejection cut	0.011	2.849	24.025	26.885	41.673	64.251	132.809	137
Efficiency from FCFV	0.000	0.033	0.142	0.092	0.791	0.884	0.319	-

Fiducial Volume

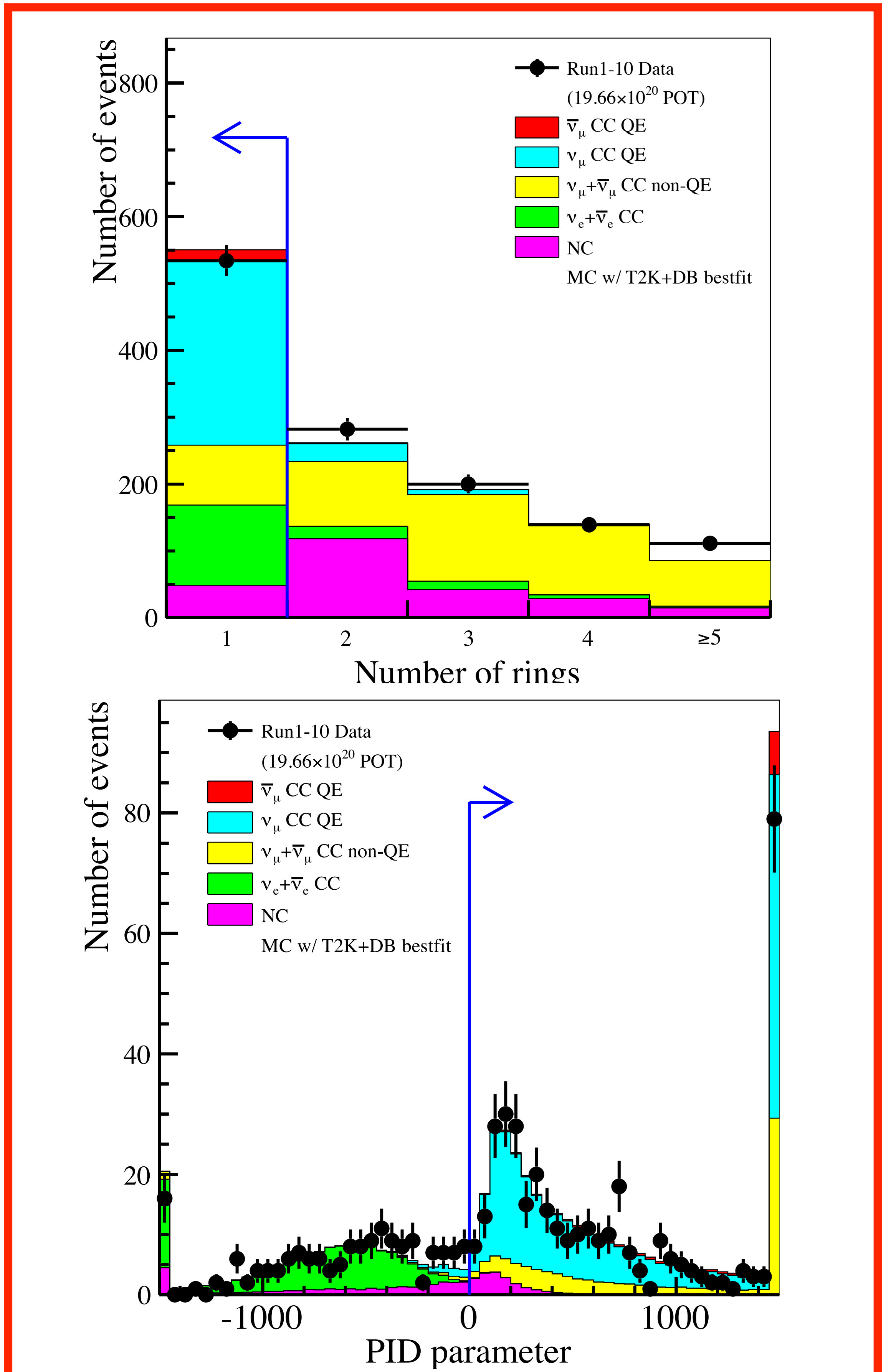


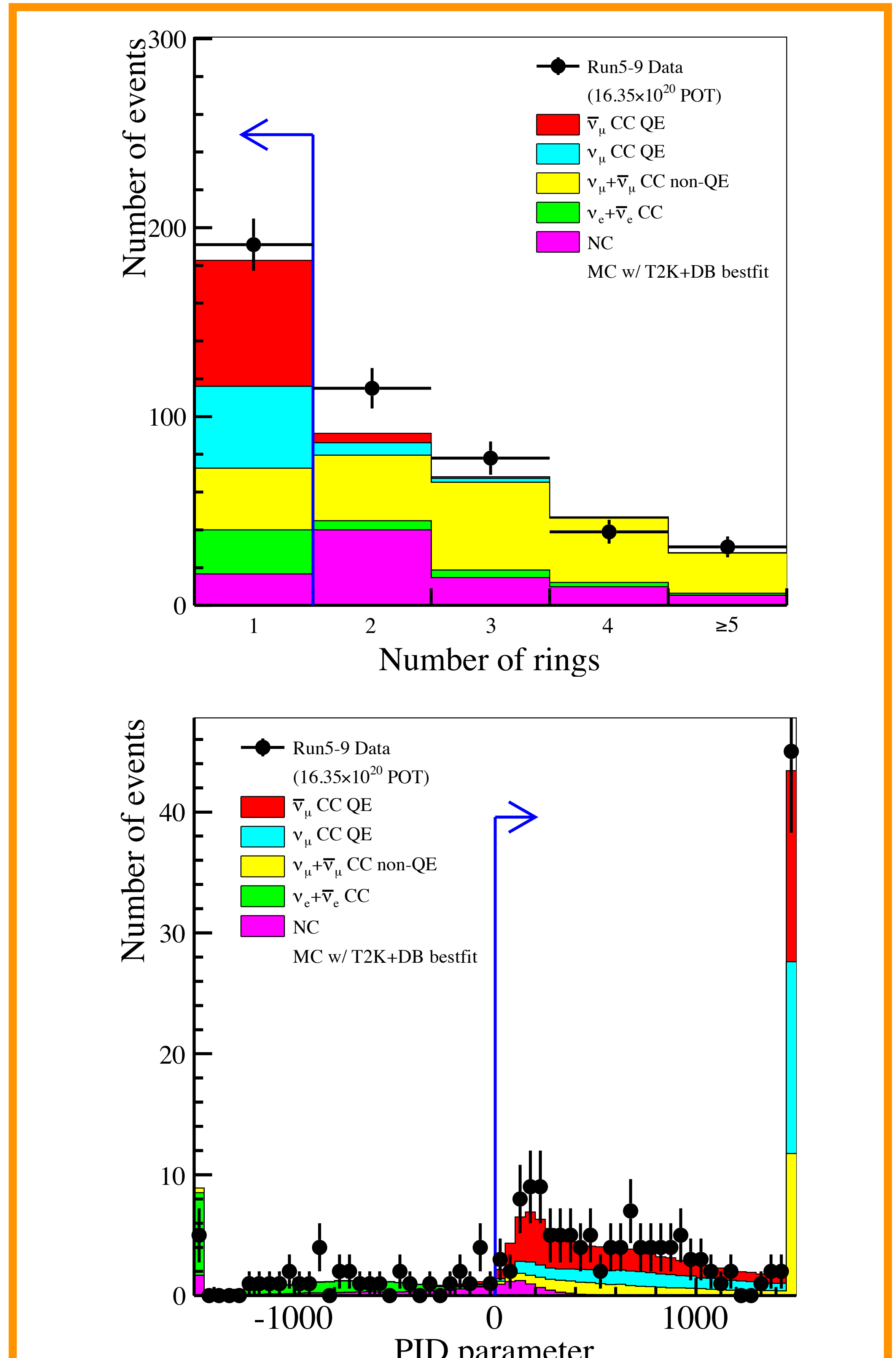
wall > 50 cm

to_wall > 250 cm

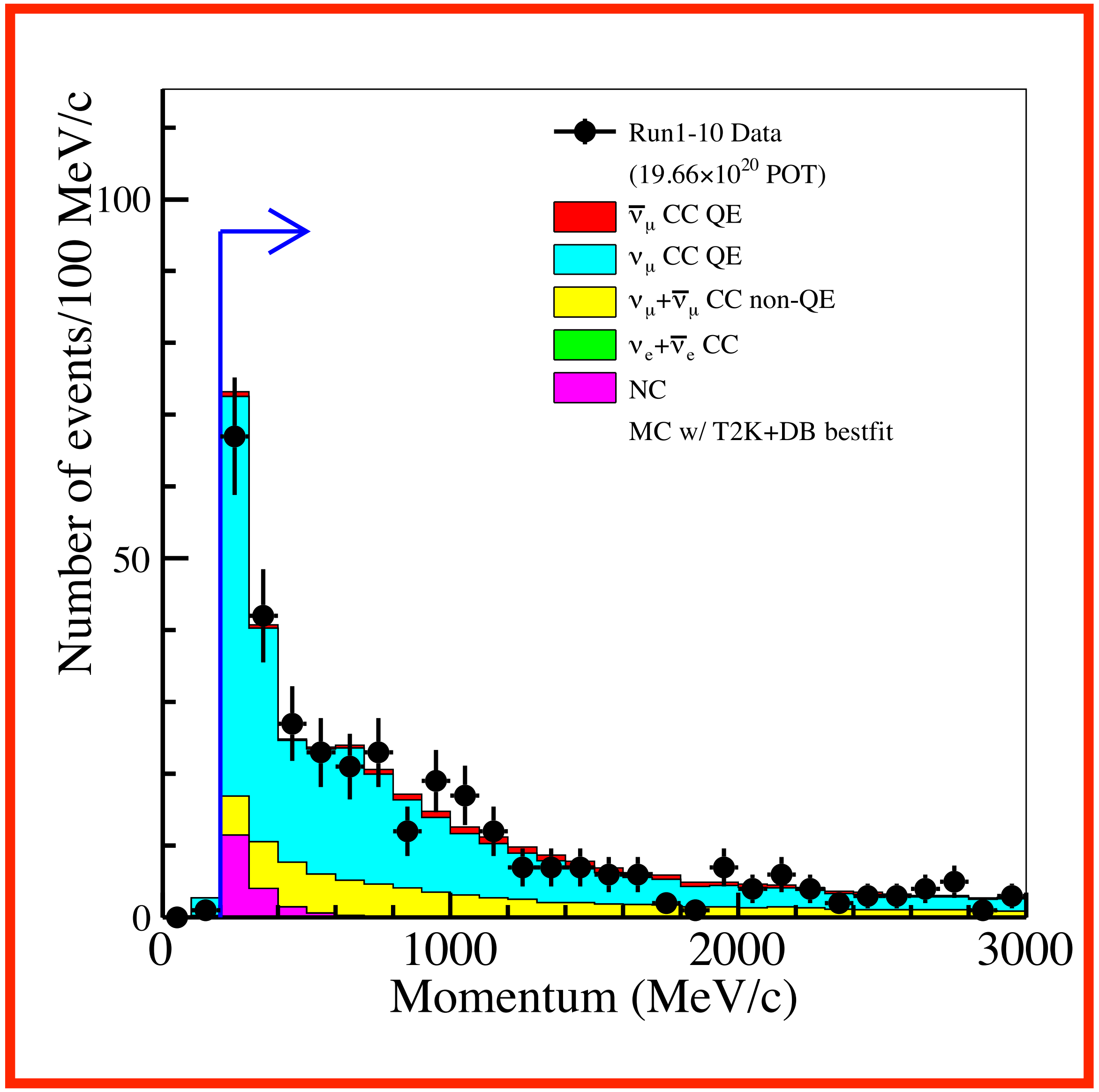


Rings (=1); Particle ID (= μ-like)

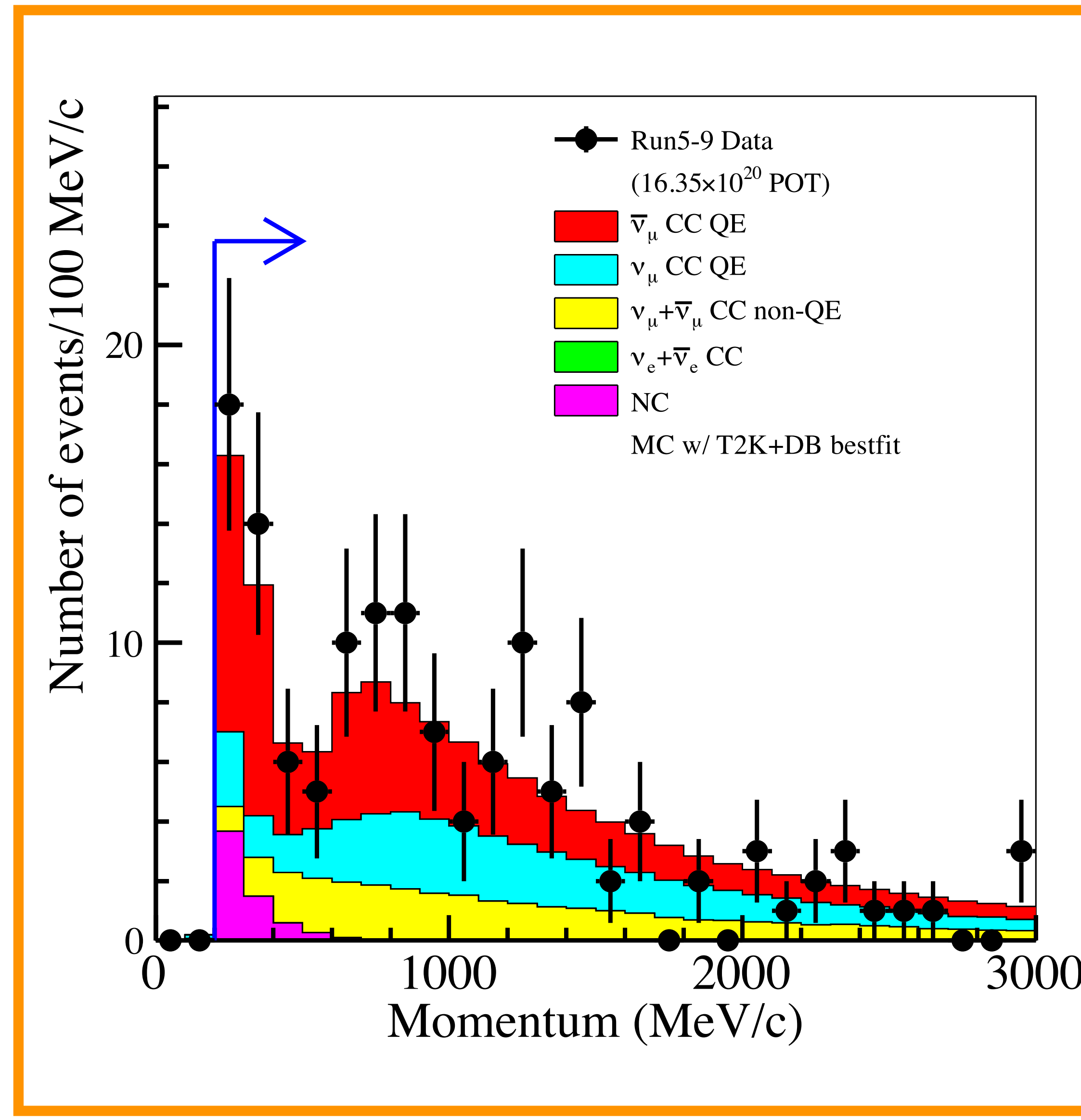




$p_\mu > 200$ MeV/c

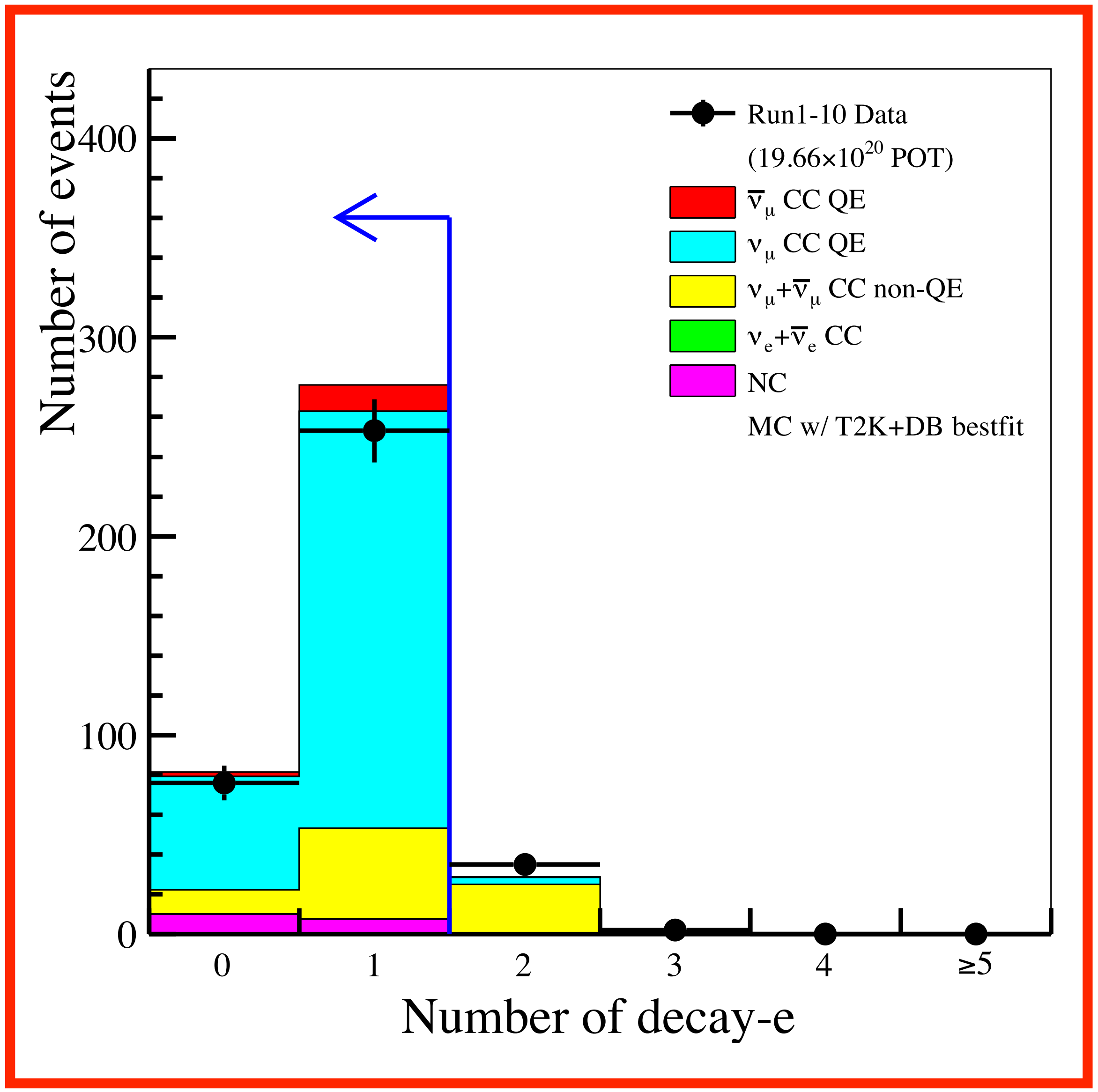


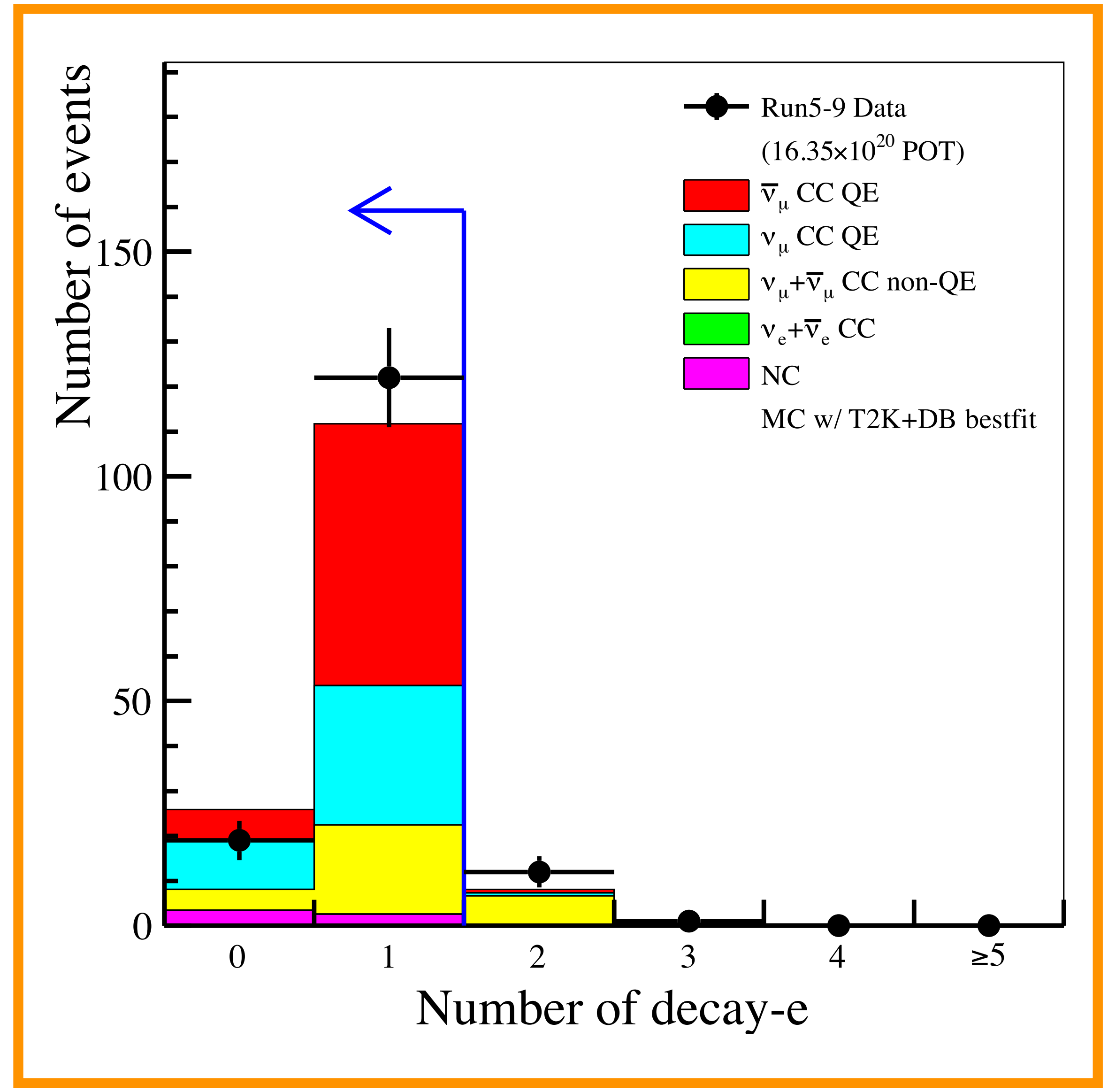
Run1-10 Data
(19.66×10^20 POT)
ν̄μ CC QE
νμ CC QE
νμ+ν̄μ CC non-QE
νe+ν̄e CC
NC
MC w/ T2K+DB bestfit
Number of events/100 MeV/c
Momentum (MeV/c)
0
50
100
0
1000
2000
3000



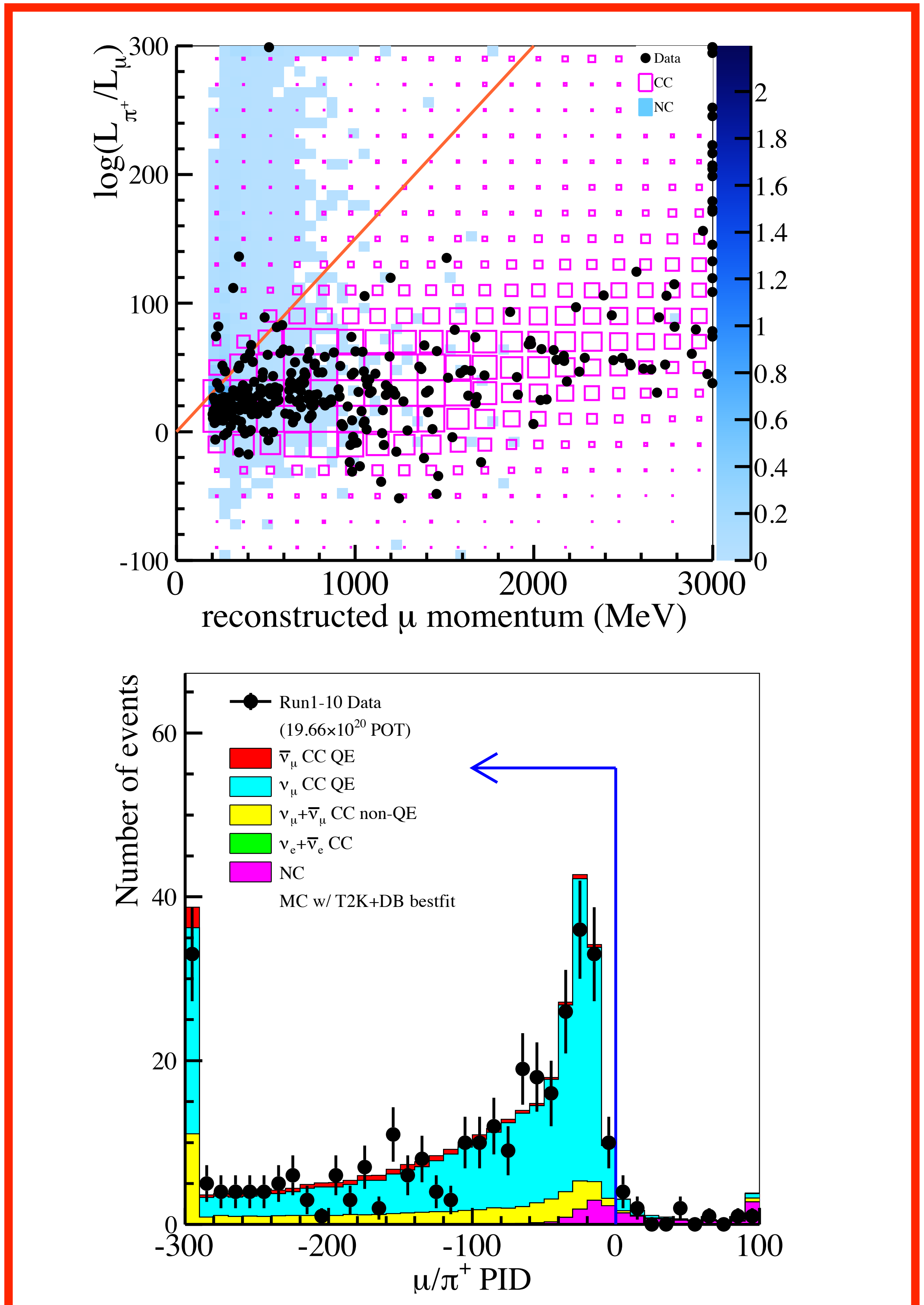
Run5-9 Data
(16.35×10^20 POT)
ν̄μ CC QE
νμ CC QE
νμ+ν̄μ CC non-QE
νe+ν̄e CC
NC
MC w/ T2K+DB bestfit
Number of events/100 MeV/c
Momentum (MeV/c)
0
10
20
0
1000
2000
3000

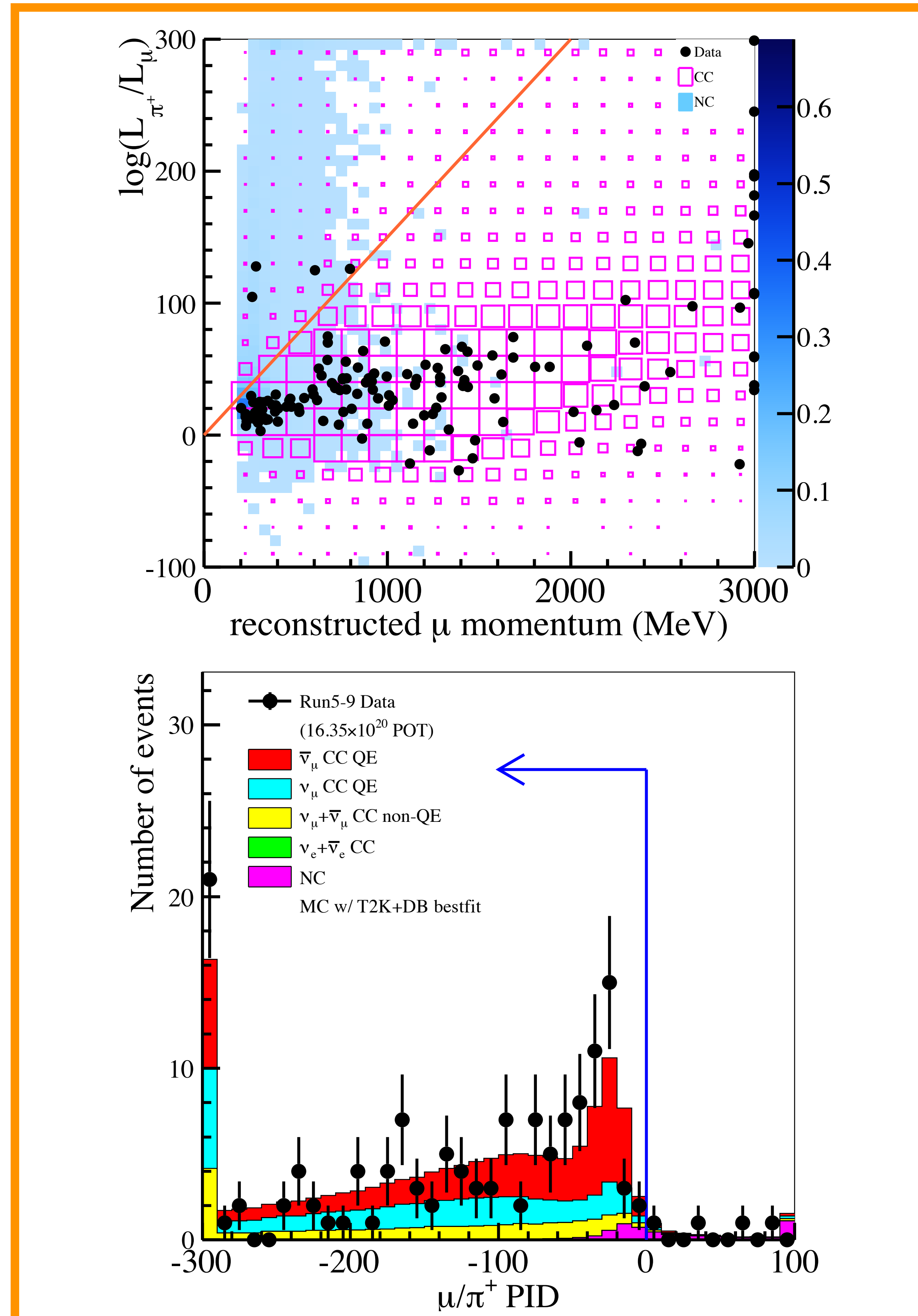
#Decay-electrons (<=1)





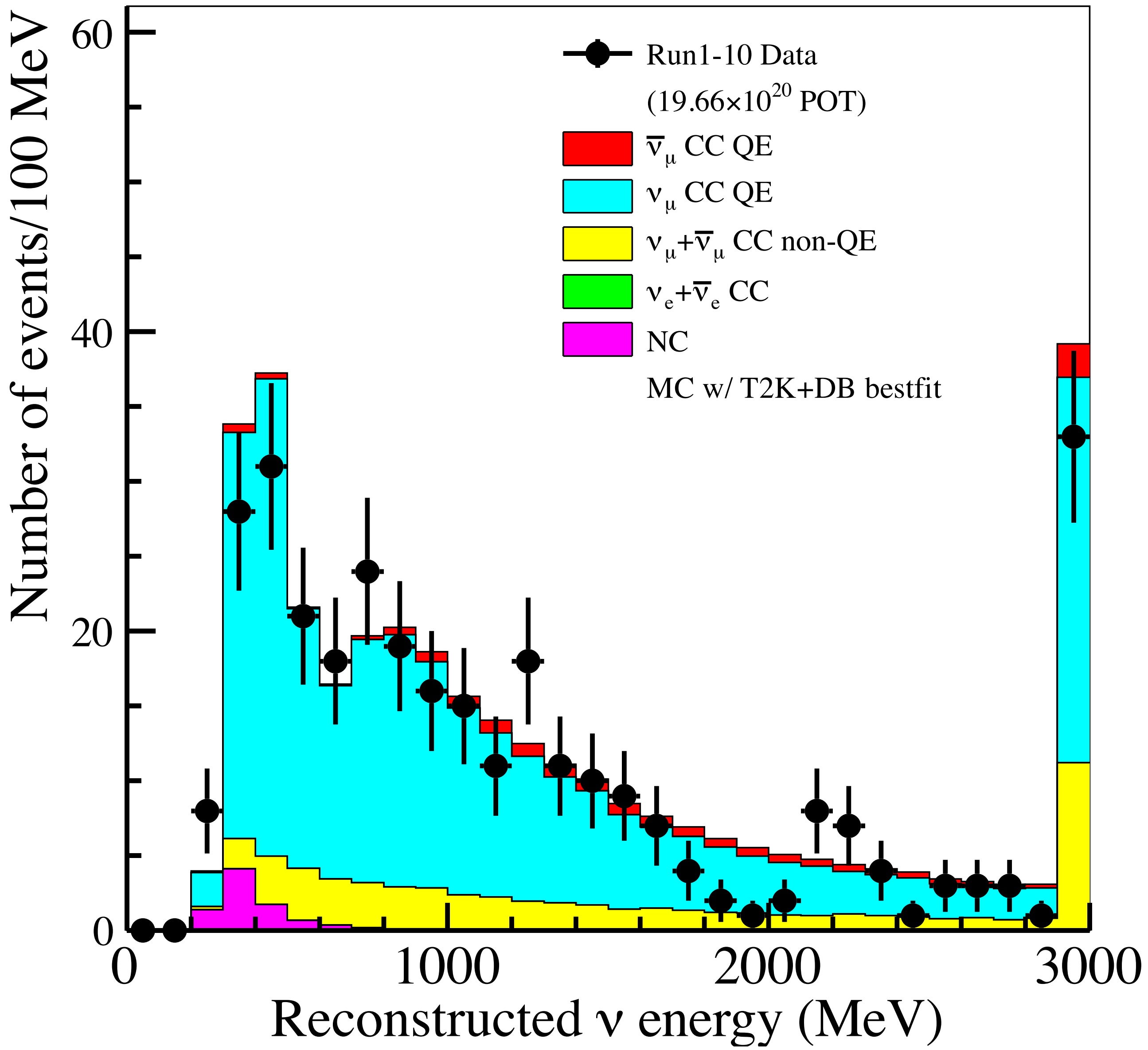
NOT π^+

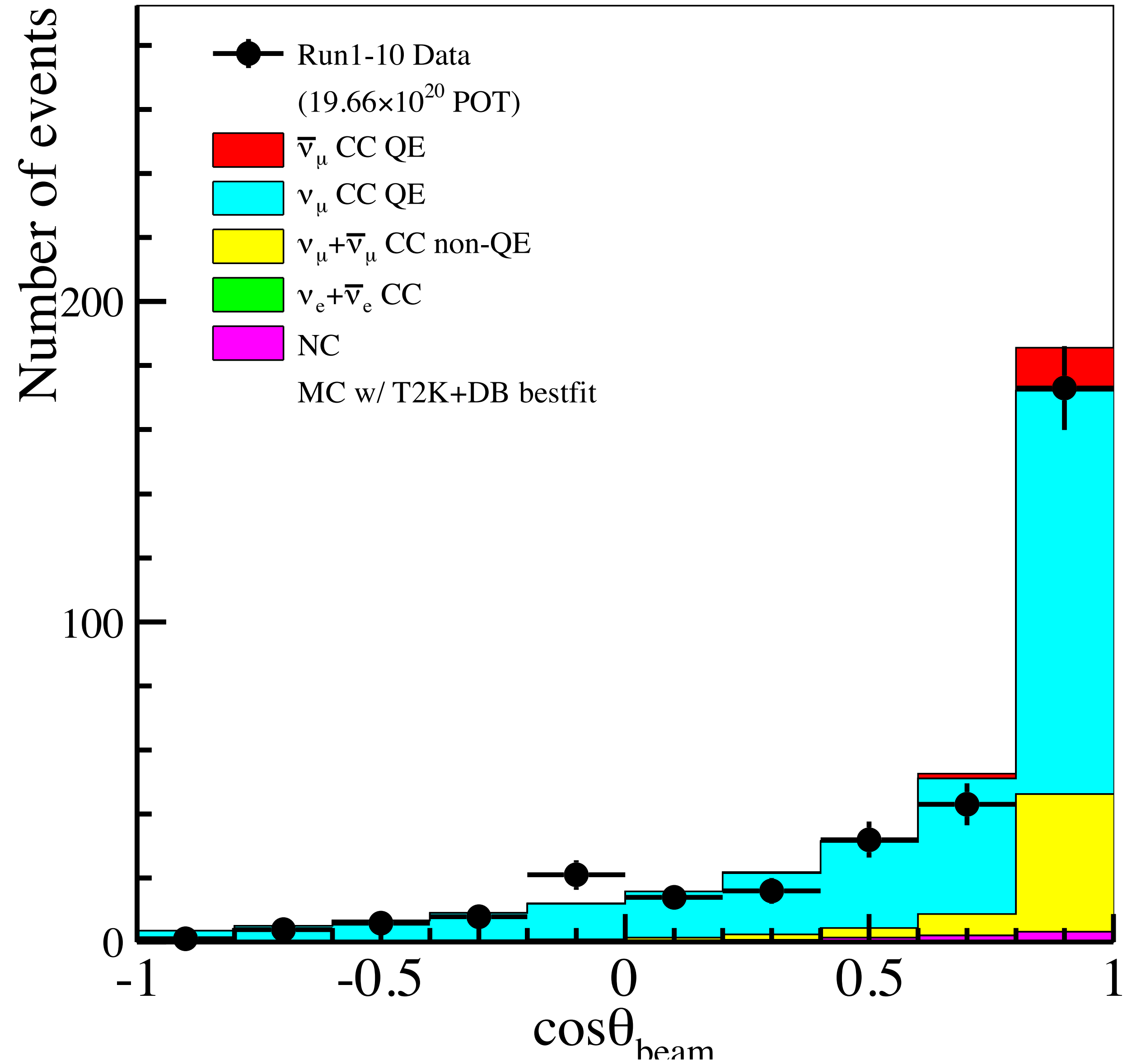

Data
CC
NC
log(L_π+/L_μ)
reconstructed μ momentum (MeV)
Run1-10 Data
(19.66×10^20 POT)
ν̄_μ CC QE
ν_μ CC QE
ν_μ+ν̄_μ CC non-QE
ν_e+ν̄_e CC
NC
MC w/ T2K+DB bestfit
Number of events
μ/π+ PID


Data
CC
NC
log(L_π+/L_μ)
reconstructed μ momentum (MeV)
Run5-9 Data
(16.35×10^20 POT)
ν̄_μ CC QE
ν_μ CC QE
ν_μ+ν̄_μ CC non-QE
ν_e+ν̄_e CC
NC
MC w/ T2K+DB bestfit
Number of events
μ/π+ PID

Muon Neutrino events

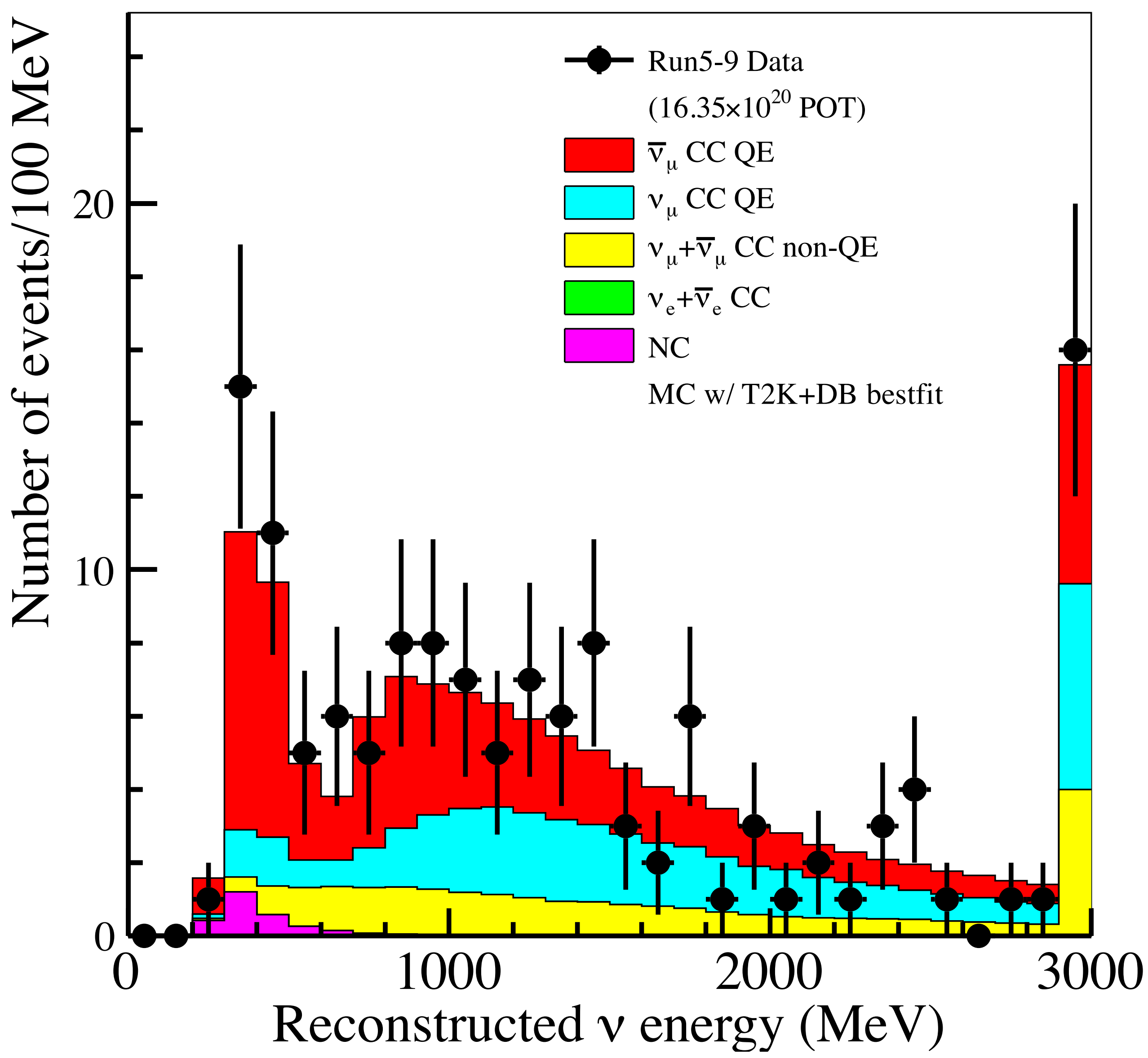
- Neutrino:
  - Data: 318
  - MC: 344.422

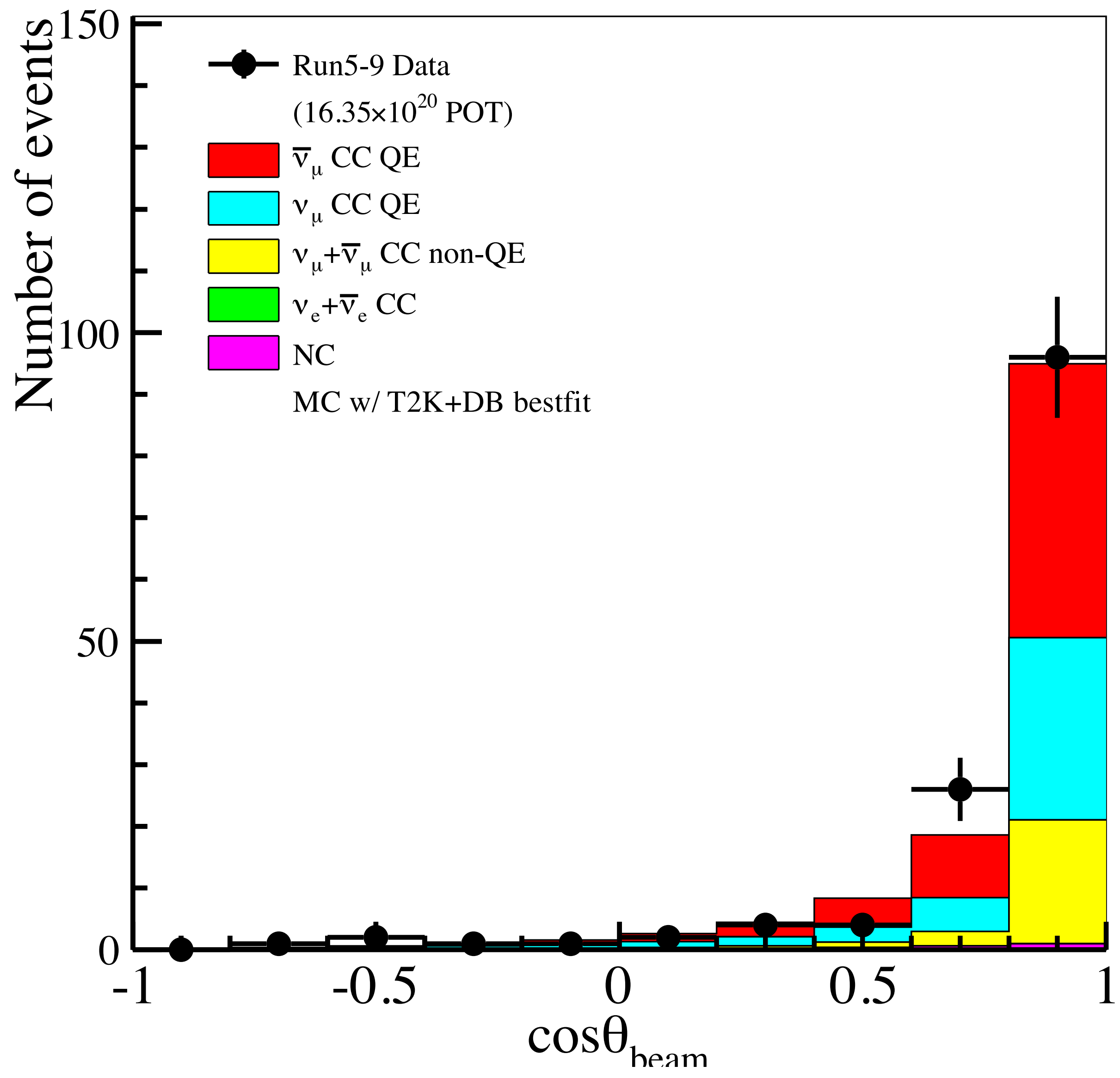




Muon Anti-Neutrino events

- Anti-neutrino:
  - Data: 137
  - MC: 132.809





FINAL muon (anti-)neutrino events

Runs 1-10	Expected							Data
	$\nu_e + \bar{\nu_e}$ CC	NC	$\nu_\mu + \bar{\nu_\mu}$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu_\mu}$ CCQE	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.259	110.486	0.959	1246.704	1279
FCFV	159.210	252.169	487.223	898.601	312.544	18.239	1229.385	1266
Single Ring	120.241	48.469	89.208	257.919	276.480	16.037	550.436	534
Muon-like PID	0.130	18.270	84.397	102.797	270.330	15.927	389.055	367
Momentum	0.130	18.127	84.351	102.608	269.977	15.924	388.509	366
0 or 1 Decay-e	0.128	17.606	57.972	75.706	266.412	15.751	357.869	329
π^+ rejection cut	0.121	8.896	56.723	65.740	263.084	15.597	344.422	318
Efficiency from FCFV	0.001	0.035	0.116	0.073	0.842	0.855	0.280	-

Floor-FCFV	19.908	87.827	170.146	277.881	53.225	74.086	405.192	459
FCFV	35.324	86.630	169.259	291.213	52.663	72.699	416.575	454
Single Ring	23.313	16.622	32.691	72.626	43.306	66.692	182.624	191
Muon-like PID	0.013	6.290	31.379	37.682	42.884	65.768	146.333	154
Momentum	0.013	6.232	31.373	37.618	42.865	65.729	146.213	154
0 or 1 Decay-e	0.013	6.031	24.437	30.481	42.160	64.931	137.572	141
π^+ rejection cut	0.011	2.849	24.025	26.885	41.673	64.251	132.809	137
Efficiency from FCFV	0.000	0.033	0.142	0.092	0.791	0.884	0.319	-

7. Oscillation Analysis