T2K antineutrinos oscillation results

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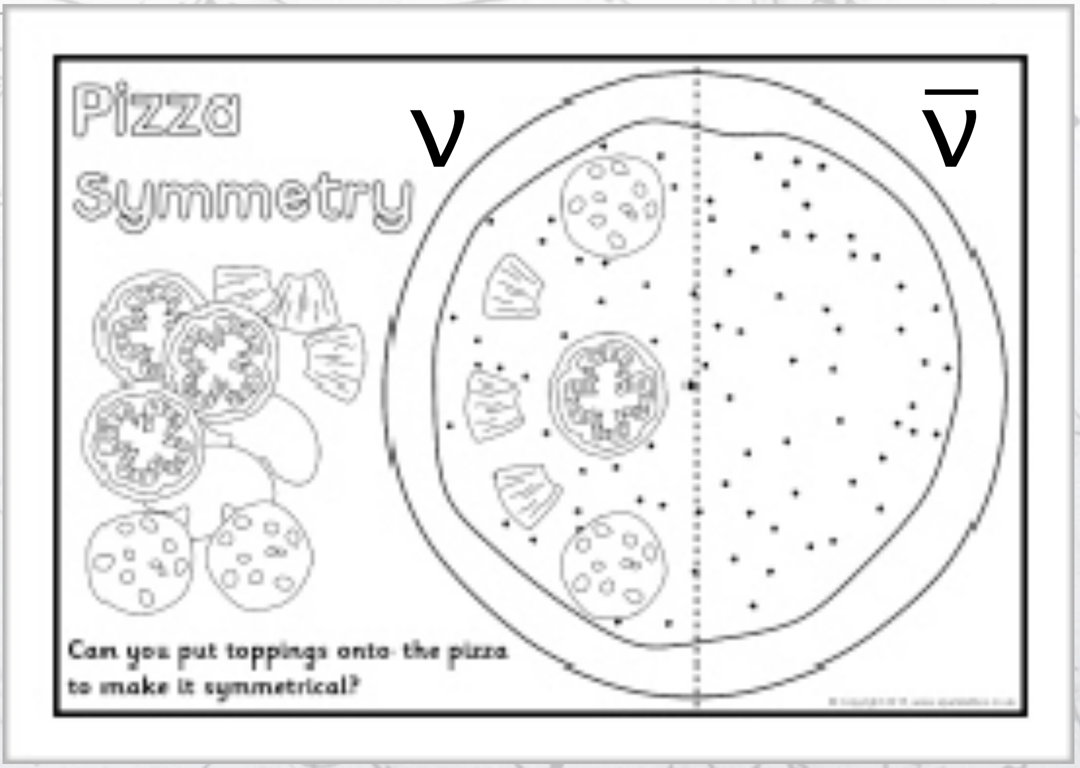
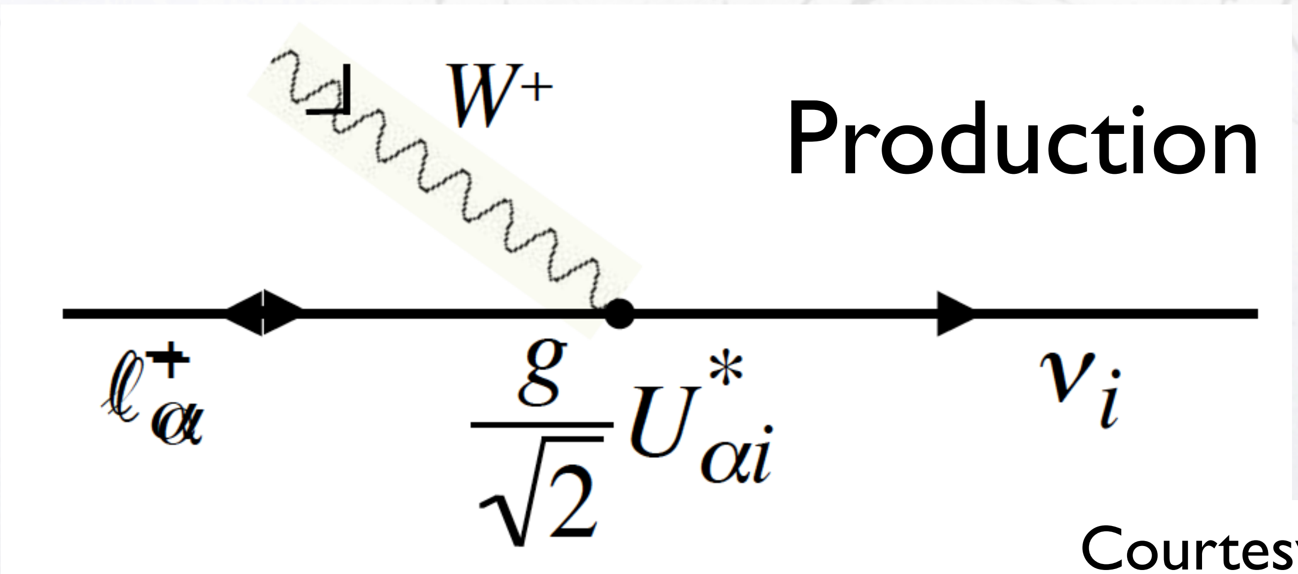


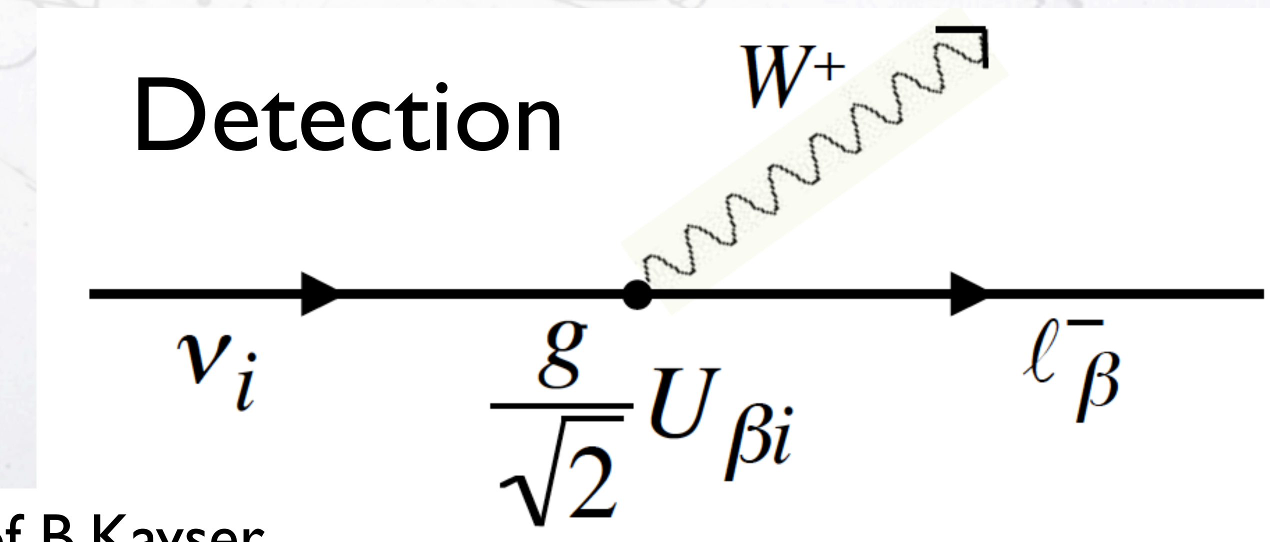
ν oscillations

Similar to quarks, flavour and Lorentz eigenstates of massive neutrinos are not identical.

The two eigenbases are related through the Pontecorvo-Maki-Nakagawa-Sakata matrix (U_{PNMS}).

$$U_{PNMS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$





Courtesy of B.Kayser

ν oscillations

atmospheric | solar

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{21} & \sin\theta_{21} & 0 \\ -\sin\theta_{21} & \cos\theta_{21} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2: traditionally Δm^2_{12} & Δm^2_{23}.

ν vs. $\bar{\nu}$

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \; (1 - 2S_{13}^2)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

$$\boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}}$$

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)$$

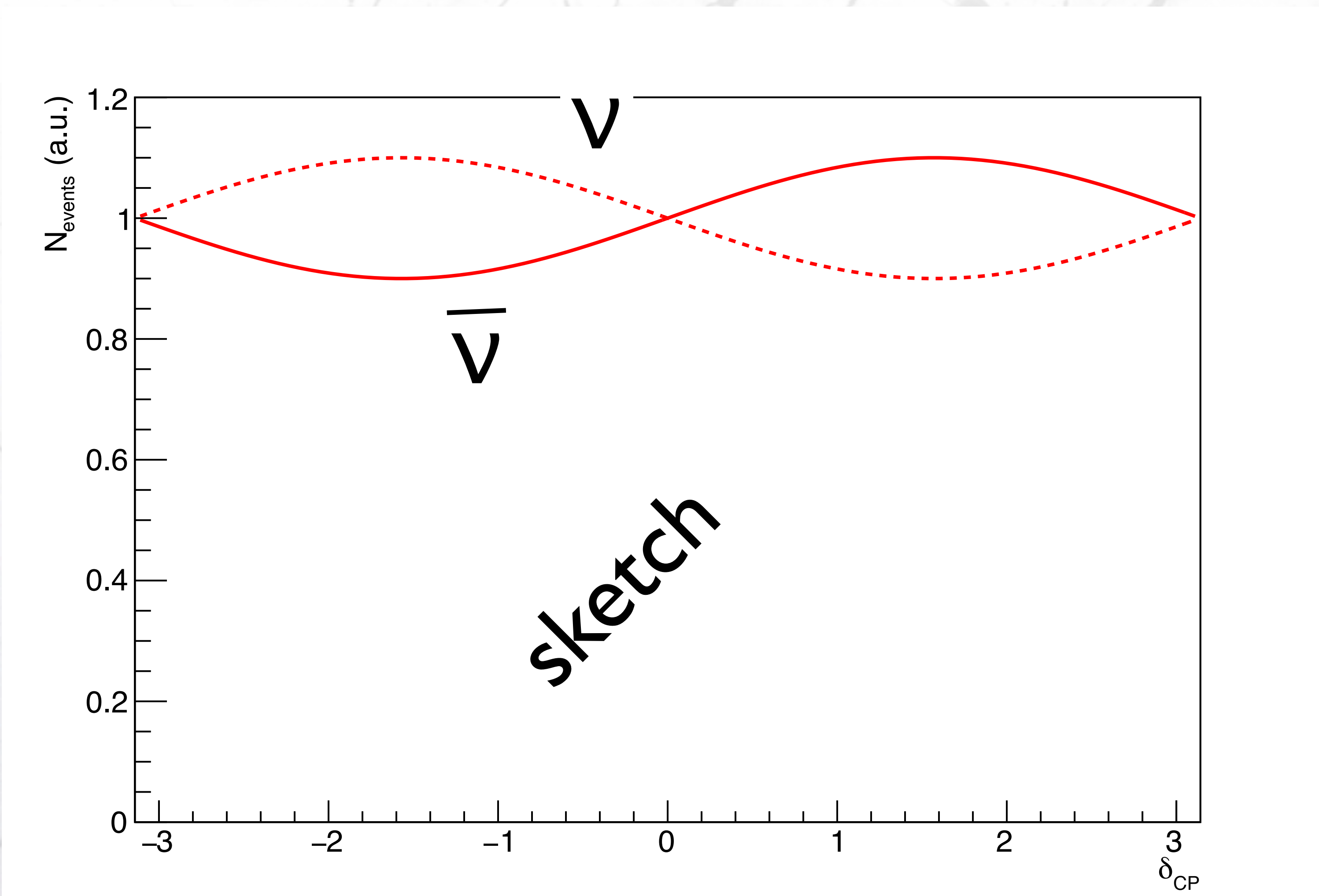
#delta_{CP}

- From neutrinos to antineutrinos the boxed terms change the sign.

$$\frac{N(\nu_\mu \rightarrow \nu_e) - N(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{N(\nu_\mu \rightarrow \nu_e) + N(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx 2 \frac{C_{12} C_{23} S_{12} sin \frac{\Delta m_{21}^2 L}{4\Delta E}}{S_{13} S_{23}} \sin\delta$$

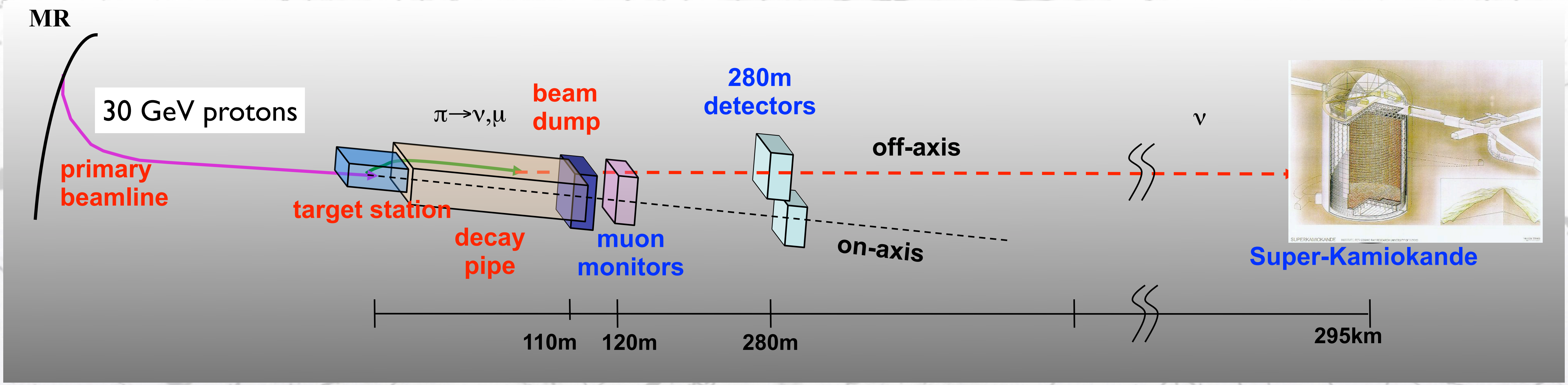
ν vs. $\bar{\nu}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)
\end{aligned}
$$



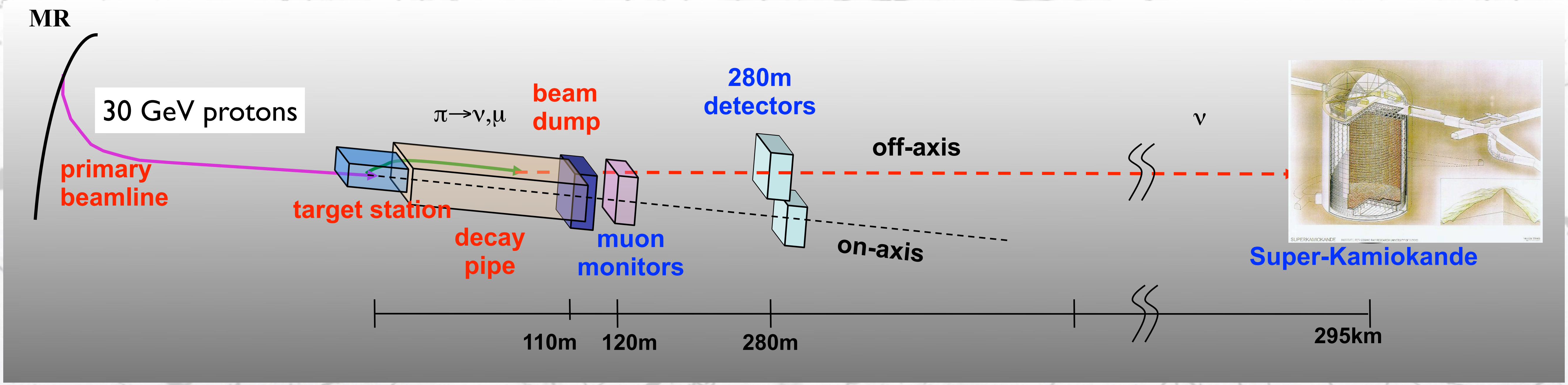
Assuming flux and cross-section to be the same

- $\delta_{CP} = 0$
  - Rate ν = Rate $\bar{\nu}$
- $\delta_{CP} = -\pi/2$
  - Rate ν > Rate $\bar{\nu}$
- $\delta_{CP} = -\pi/2$
  - Rate ν < Rate $\bar{\nu}$



Beam ND280 Super-Kamiokande

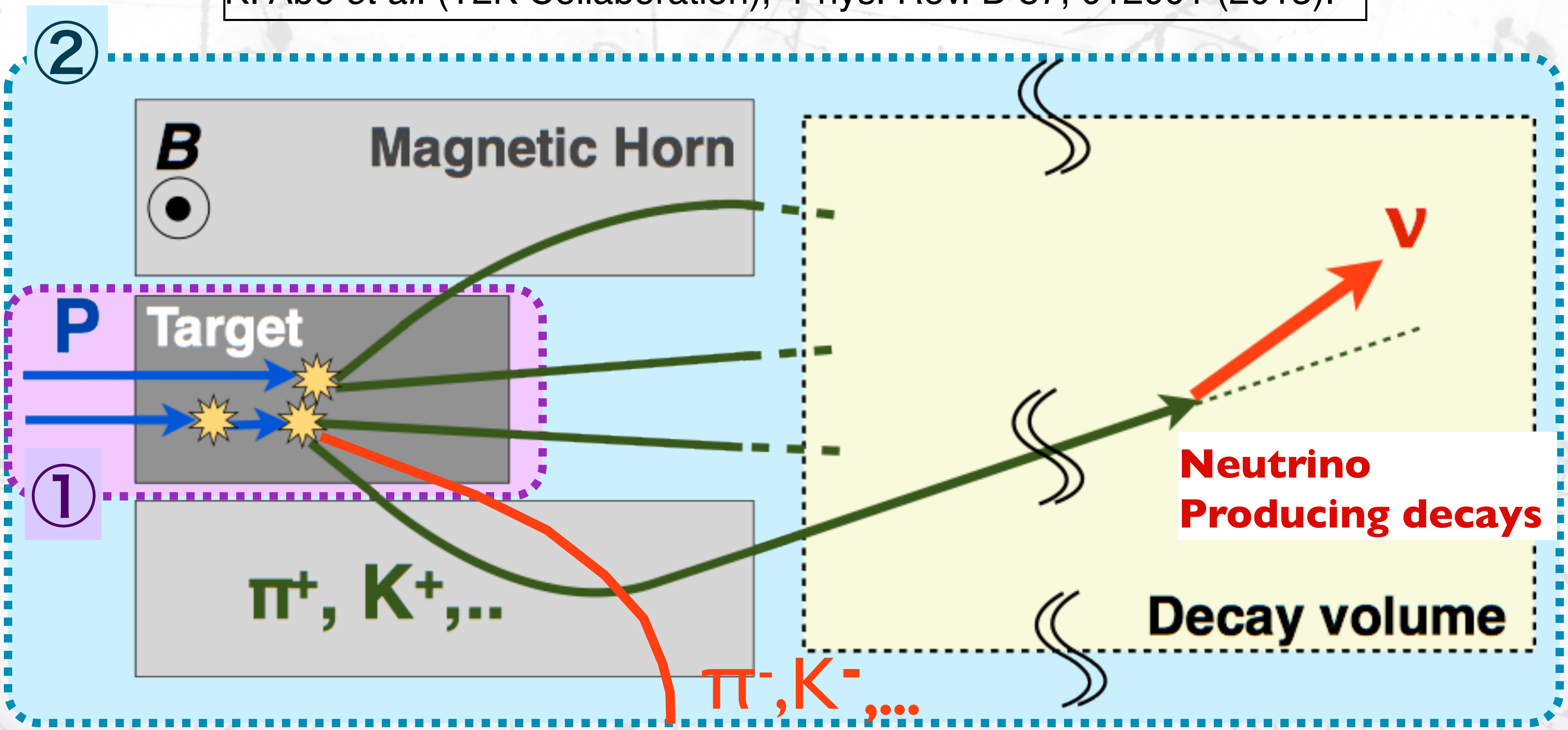
T2K



Beam ND280 Super-Kamiokande

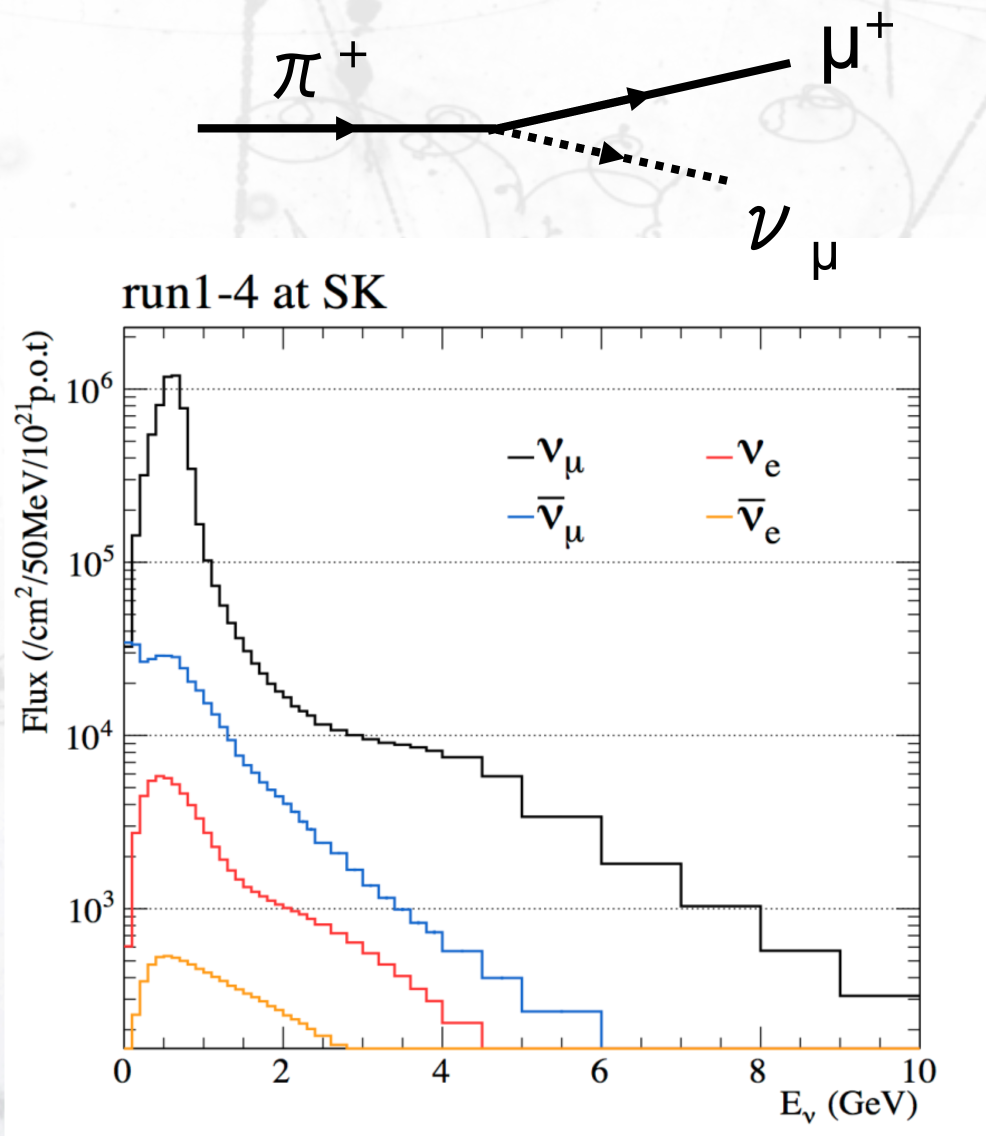
Antineutrinos

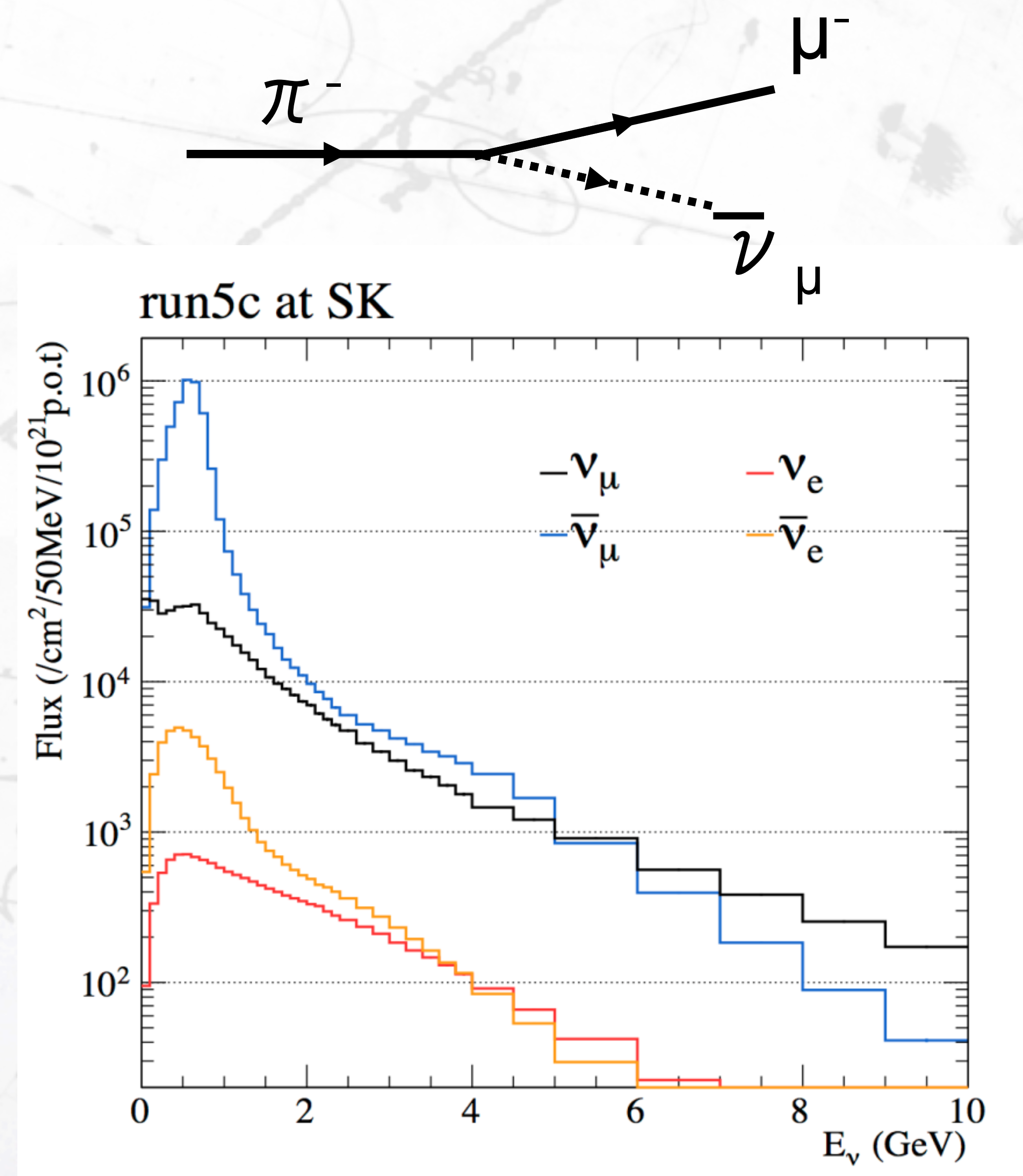
K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



To make antineutrinos we simply reverse the B field changing the horn current pulse polarity.

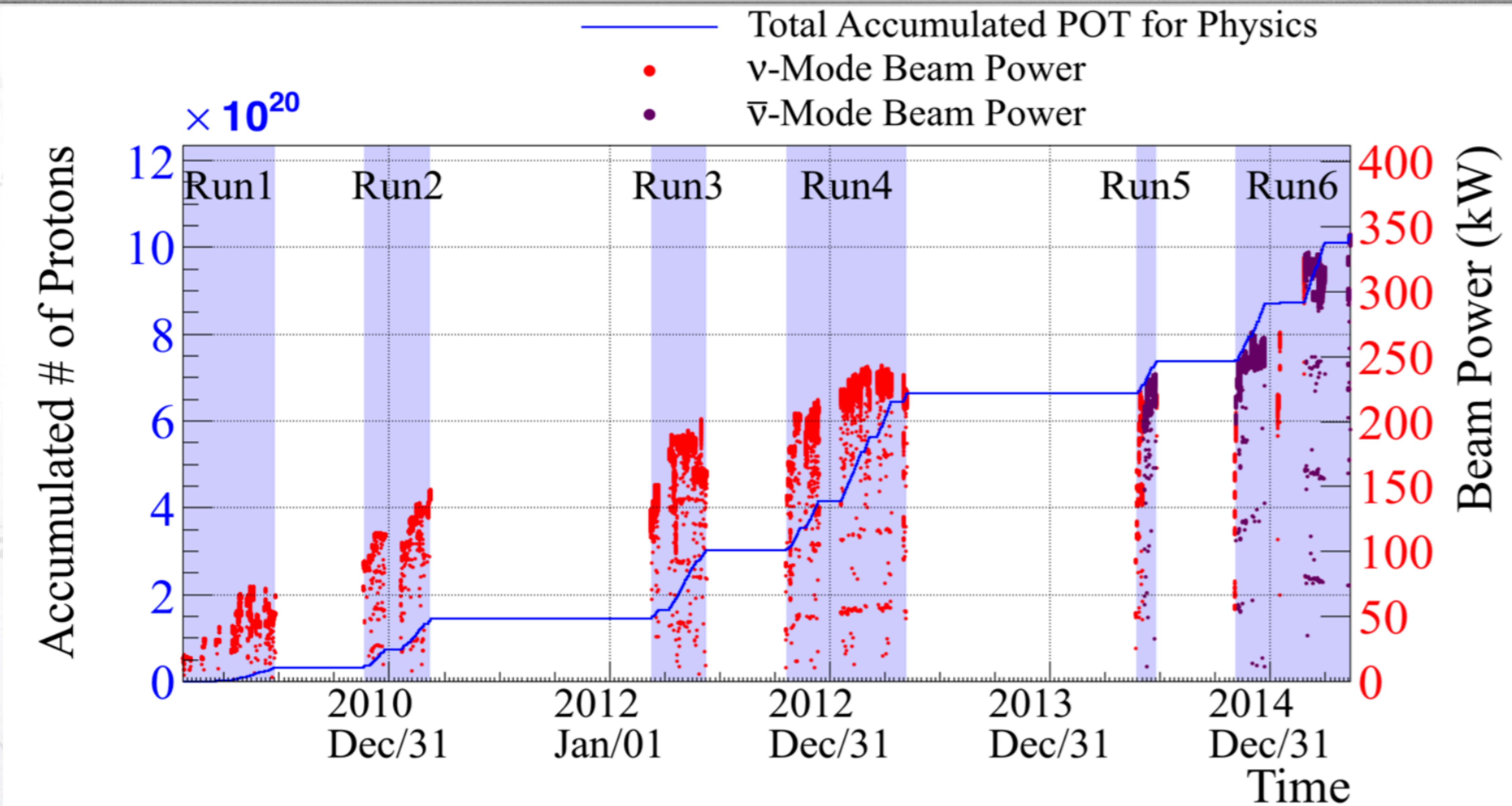
Flux prediction





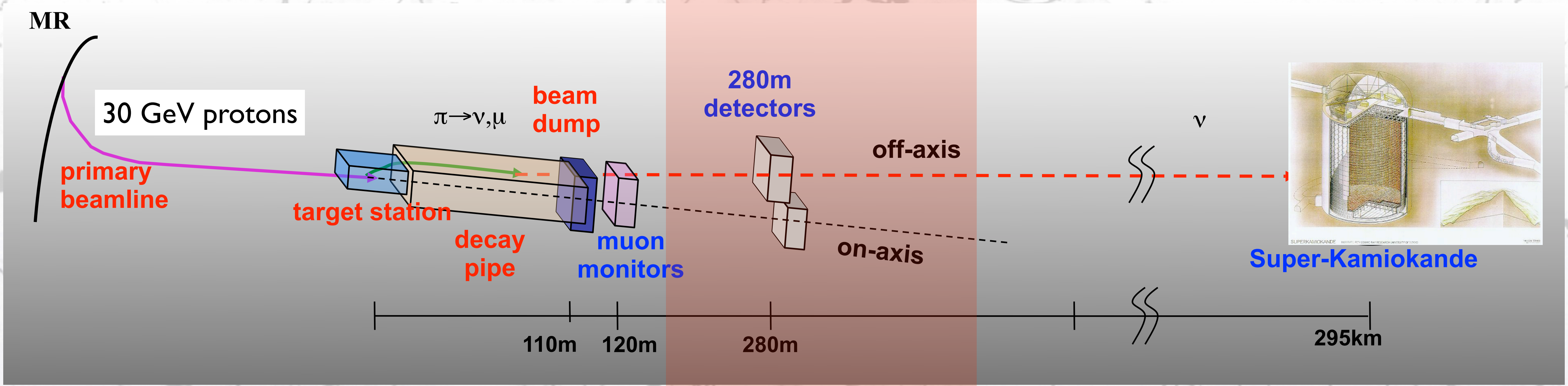
In pA interaction we produce more π^+ than π^-

Data sets



- Total delivered beam:
  - 4×10^{20} protons on target for anti-neutrinos
  - 6.6×10^{20} protons on target for anti-neutrinos

ND280

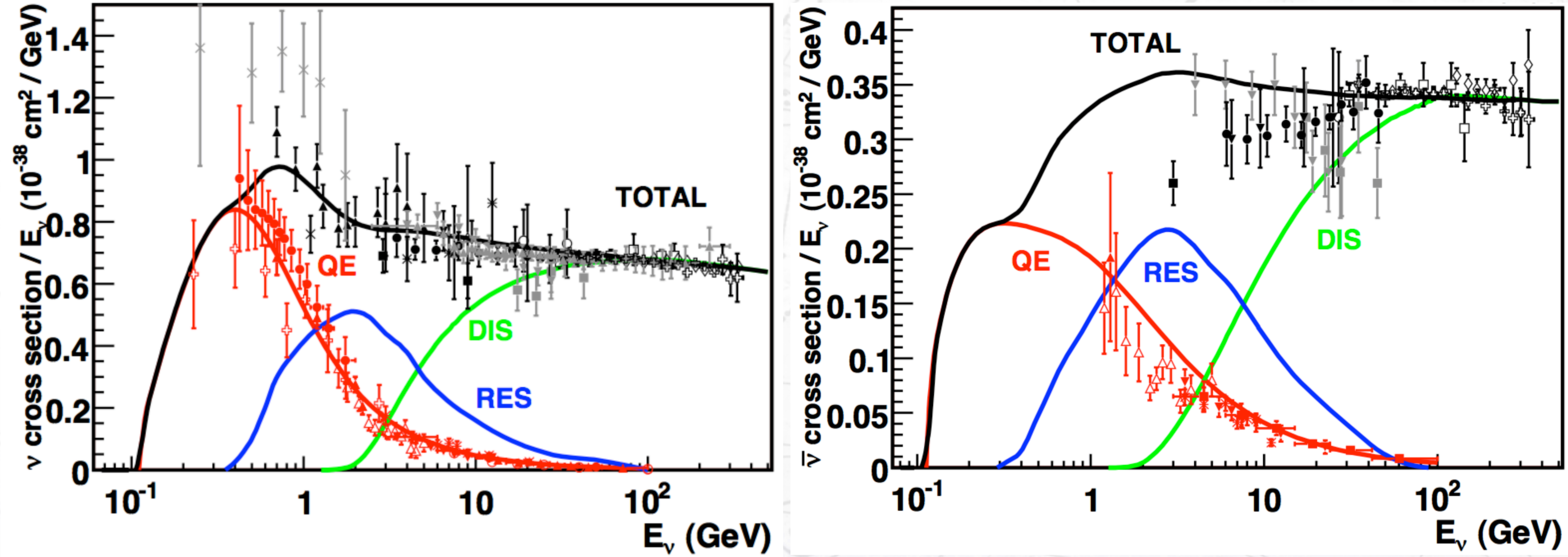


Beam

ND280

Super-Kamiokande

ν cross-section



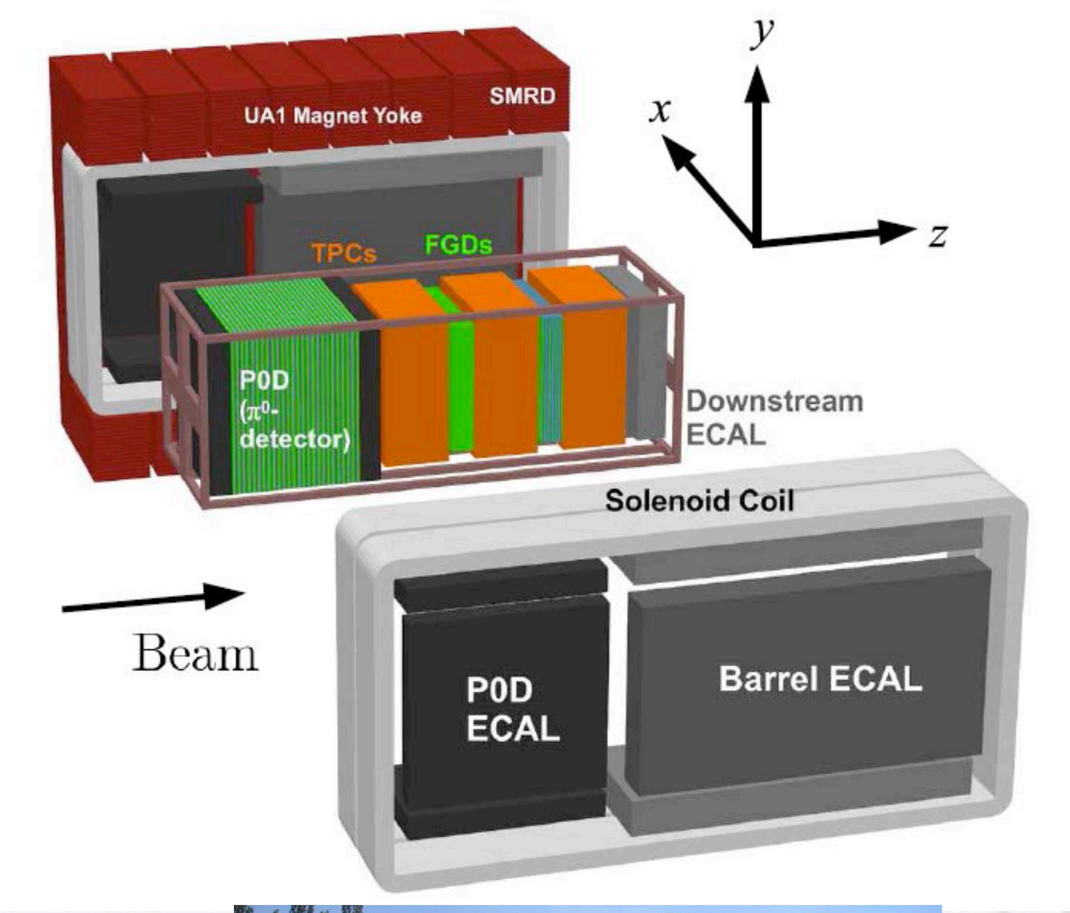
- νA cross-section is a factor of ~3 larger than the $\bar{\nu}$A cross-section

Off-axis: ND280

- Off-axis ND280 is a detector complex with tracking calorimeters, time projection chambers and Electromagnetic calorimeters in the UA1/Nomad 0.2T magnet.
  - ν interaction target polystyrene (CH) and water.
  - Particle ID by dE/dx and calorimetry.
  - Charge sign by curvature.

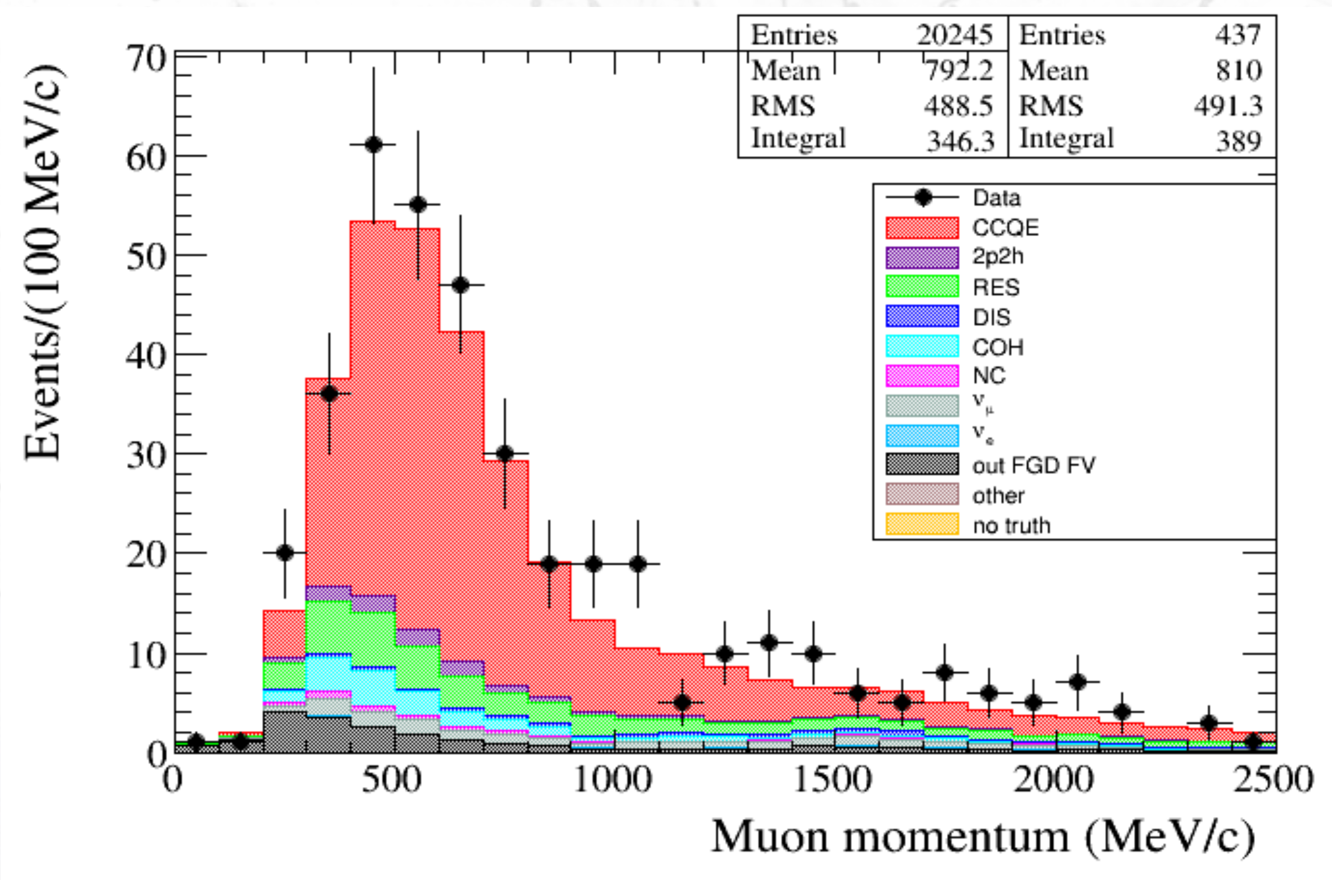
- Specific π^0 detector (P0D) made of water, CH and brass optimised for NC π^0 measurement.

Magnet was granted by CERN

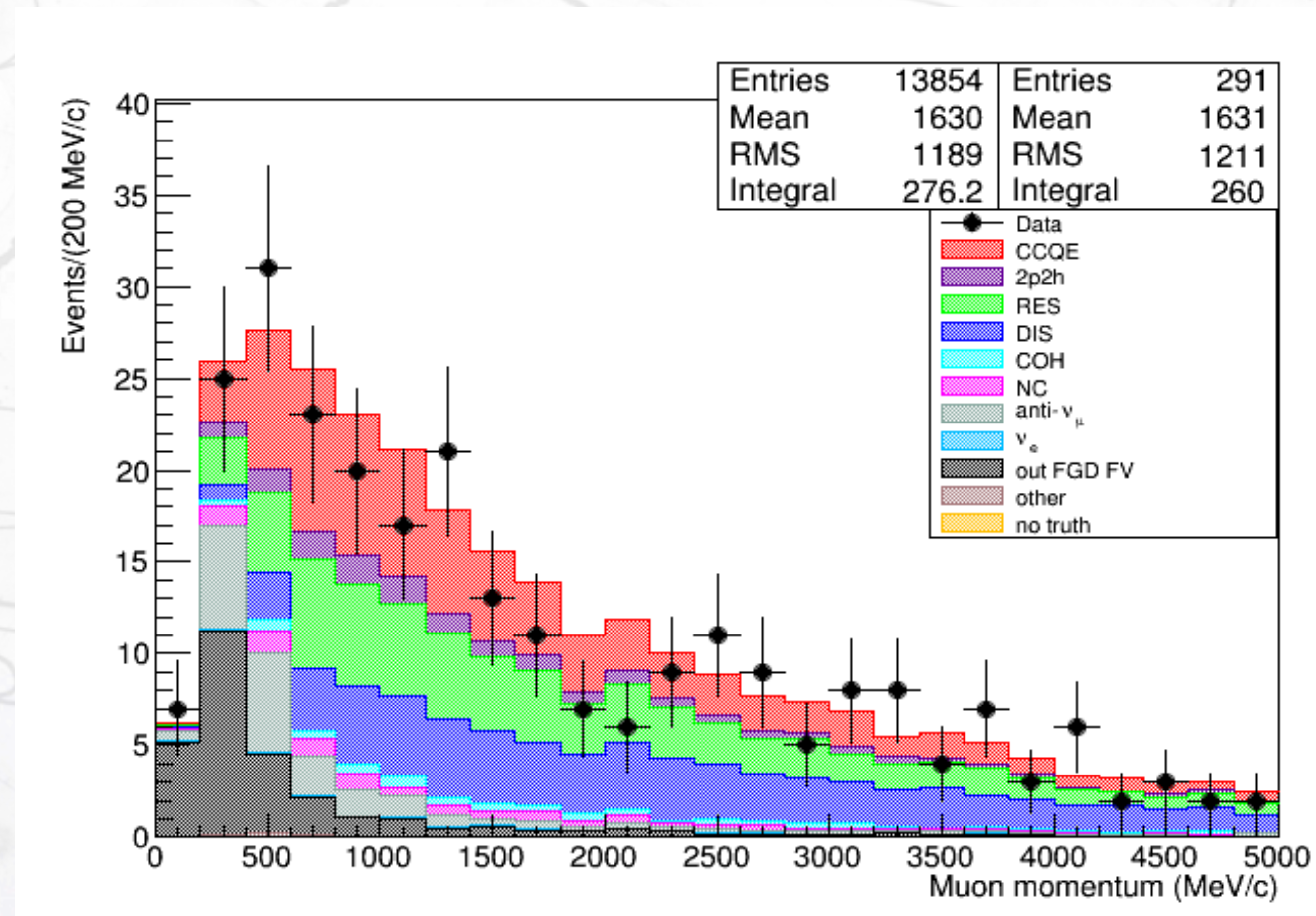


Off-axis: ν_μ analysis

$\bar{\nu}$ in $\bar{\nu}$ beam

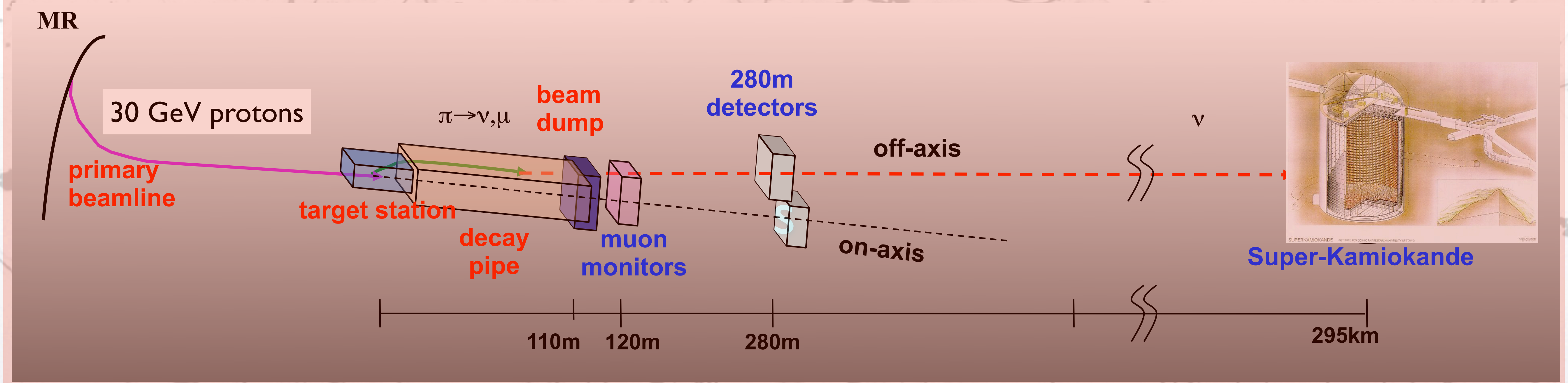


ν in $\bar{\nu}$ beam



- The T2K Near Detector helps controlling the wrong-sign background.

ν oscillation analysis



Beam ND280 Super-Kamiokande

Procedure

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

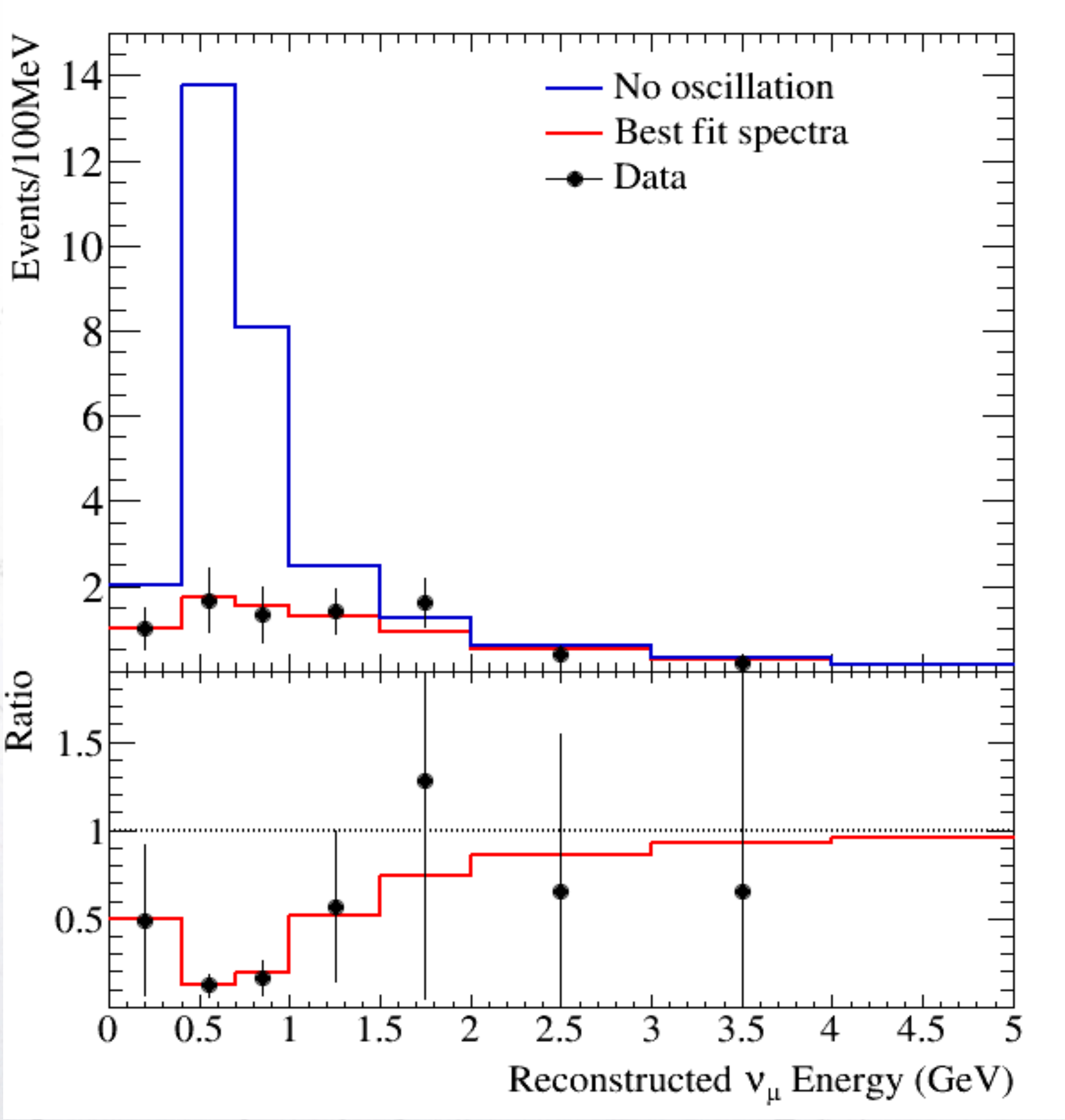
- Fit for $\bar{\theta}_{23}$ and $\overline{\Delta m^2}_{32}$
- Use separate parameters for neutrino oscillations and marginalize.
- The solar parameters and θ_{13} are fixed to PDG world average.

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Very little number of events expected.
- The main goal is to establish the appearance of $\bar{\nu}_e$

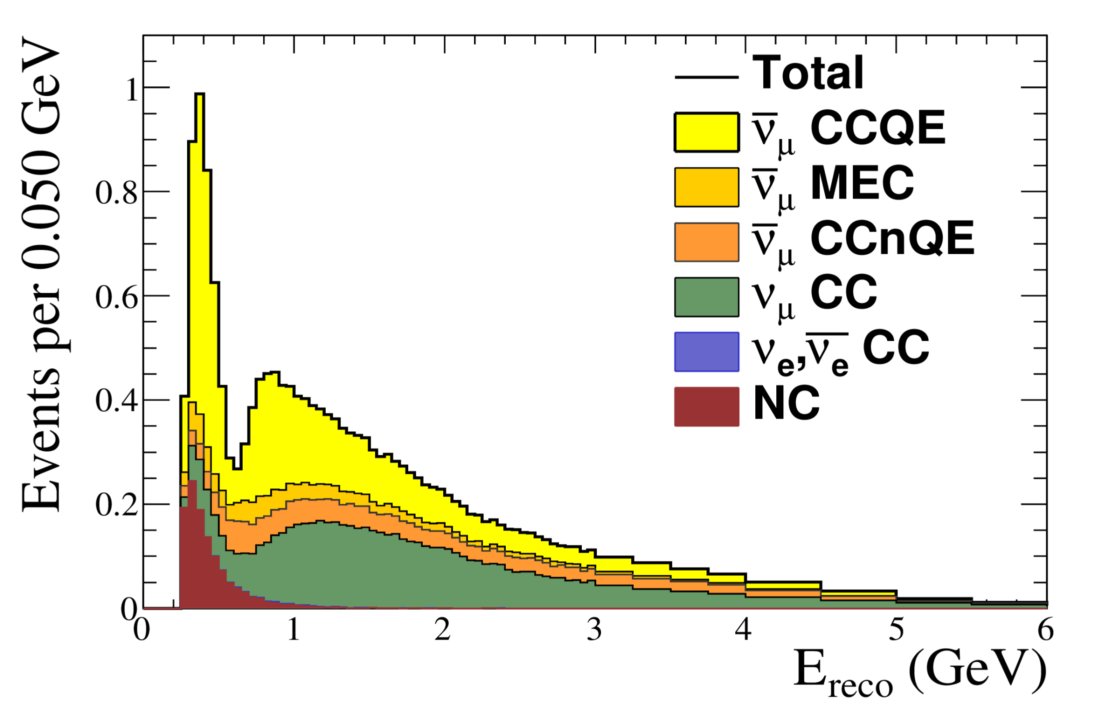
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

ν_μ disappearance



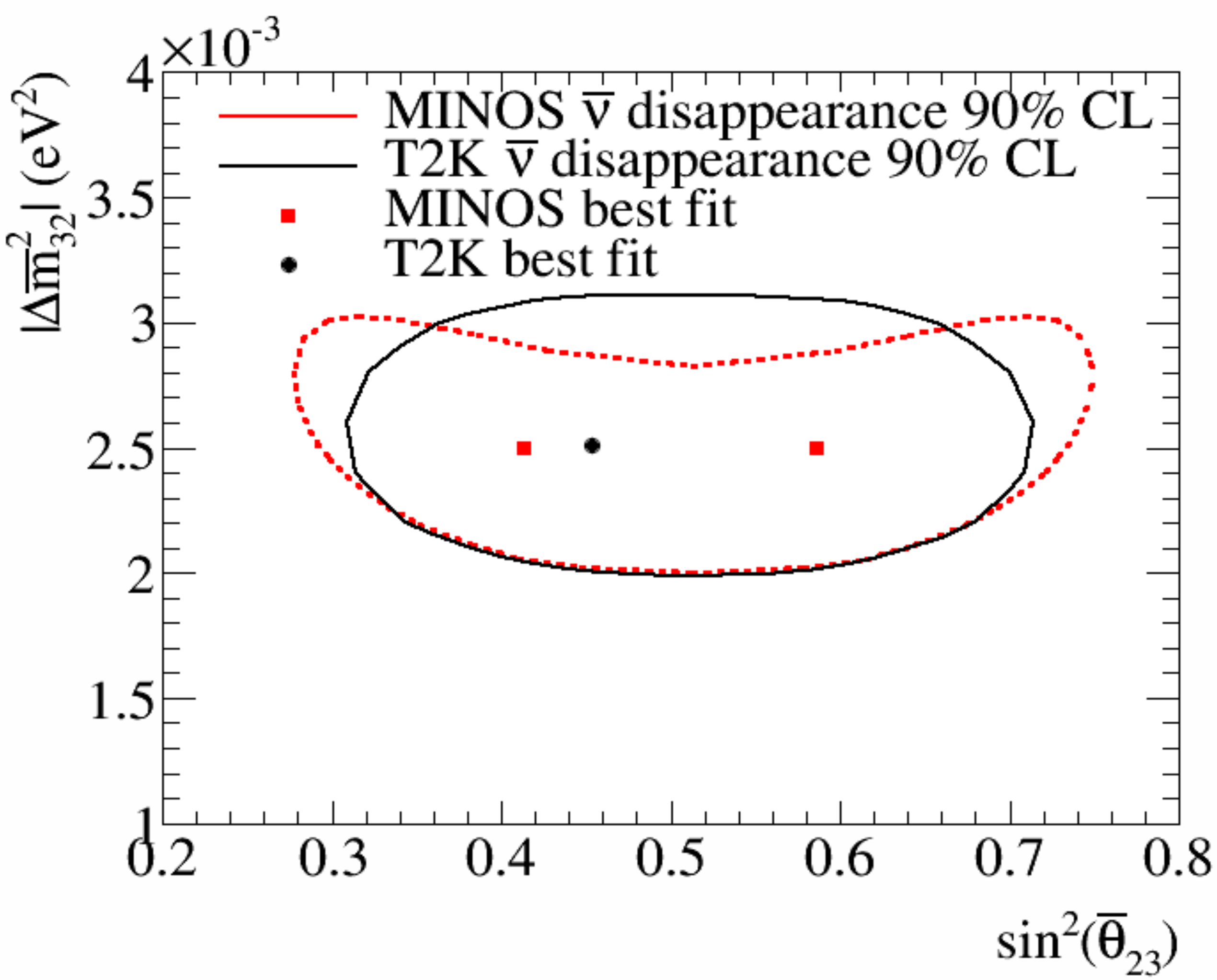
- Expected number of events in absence of oscillations: 103.6
- Observed number of events: 34

Energy reconstruction assuming CCQE



Results

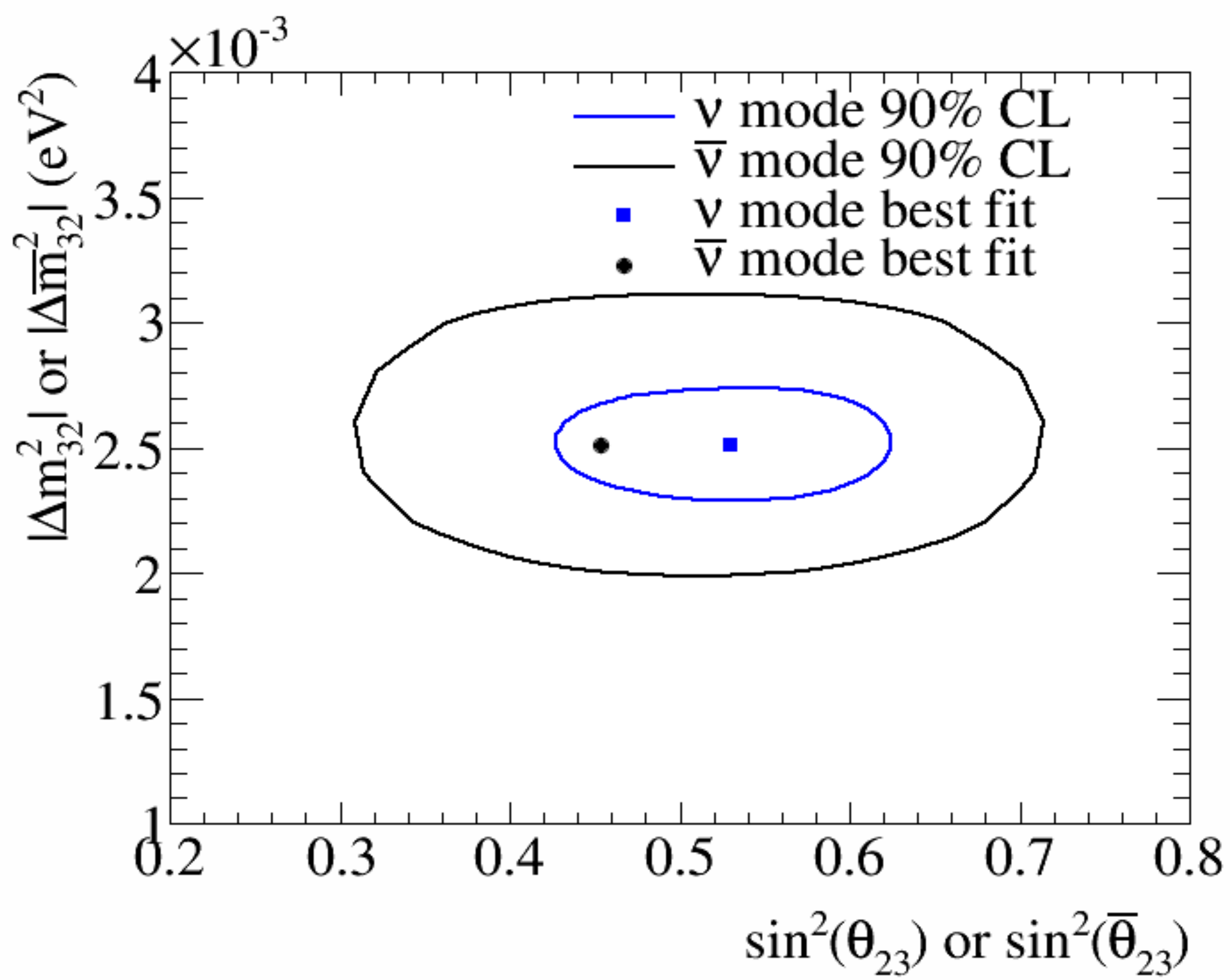
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ T2K vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Minos



Better determination of $\bar{\theta}_{23}$

T2K

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ vs. $\nu_\mu \rightarrow \nu_\mu$

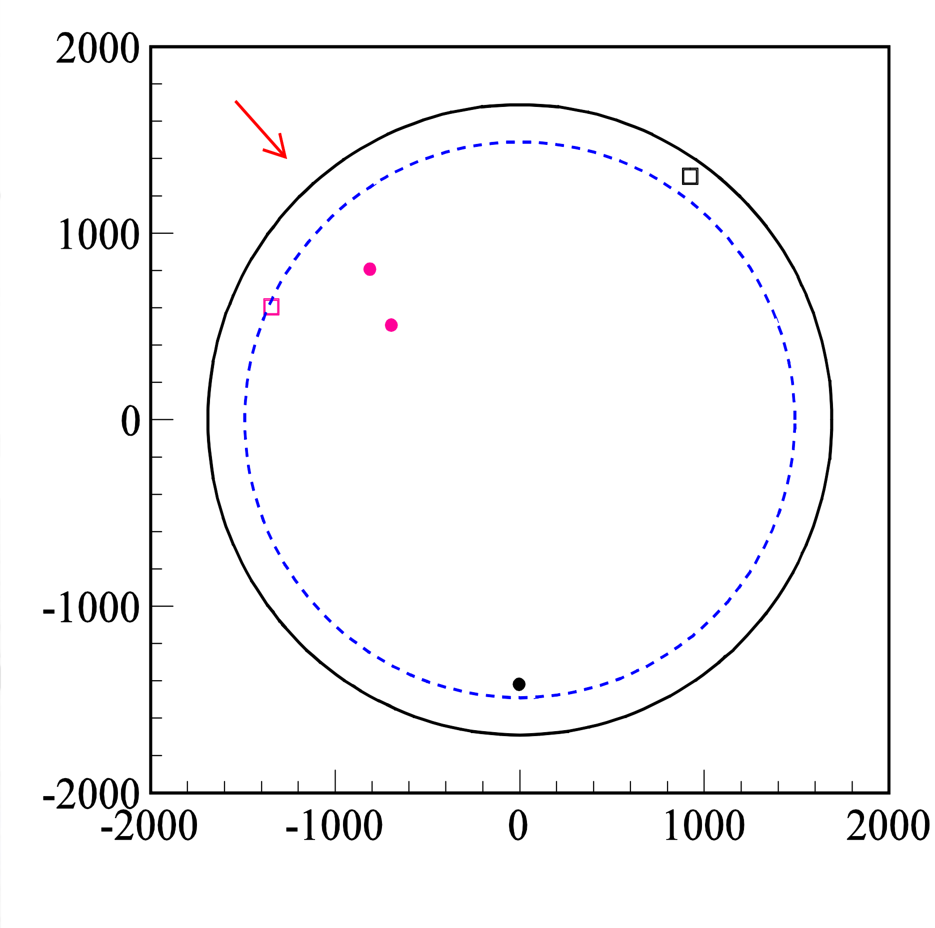


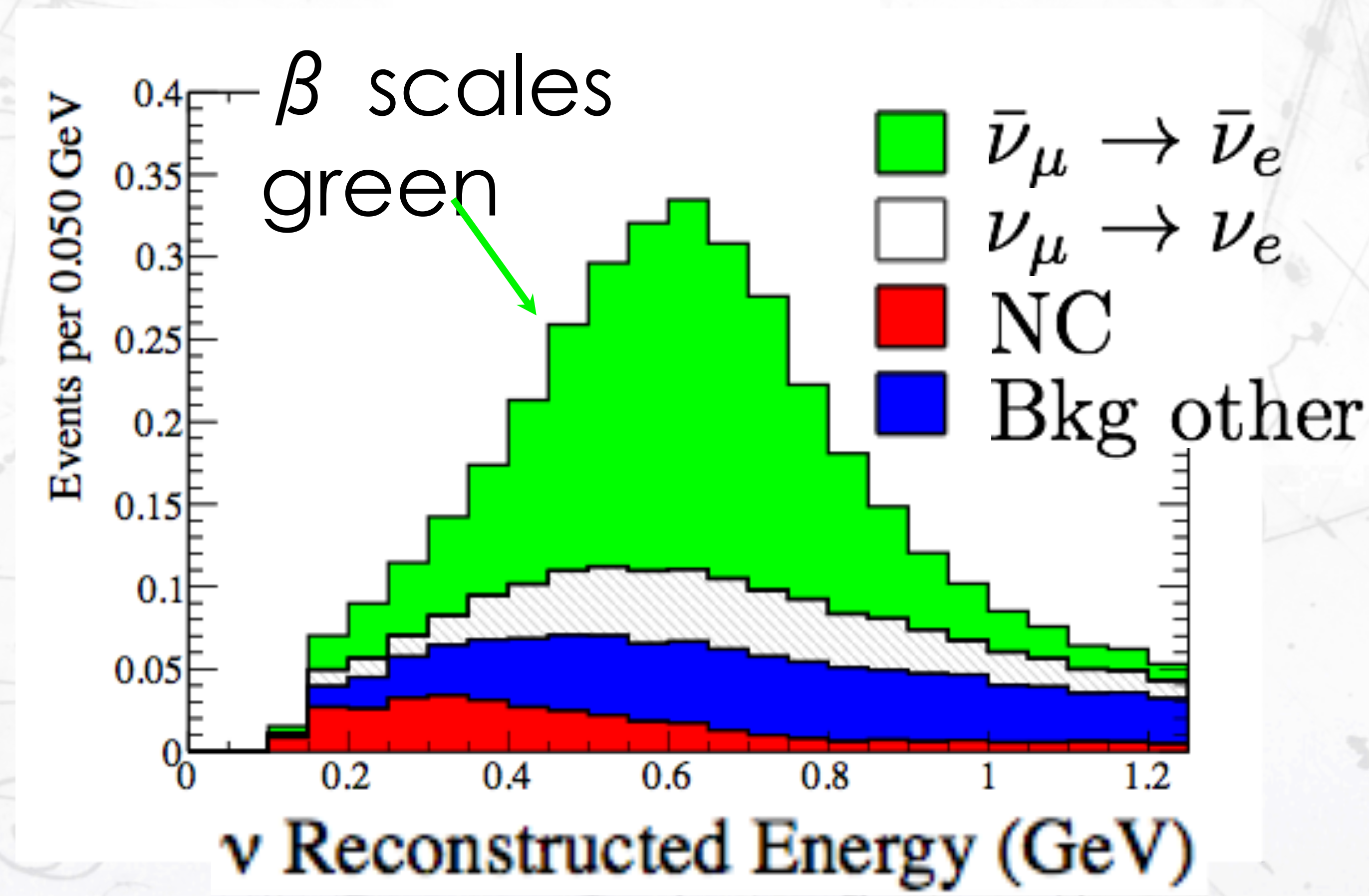
CPT is conserved!

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

ν_e appearance

3 events!



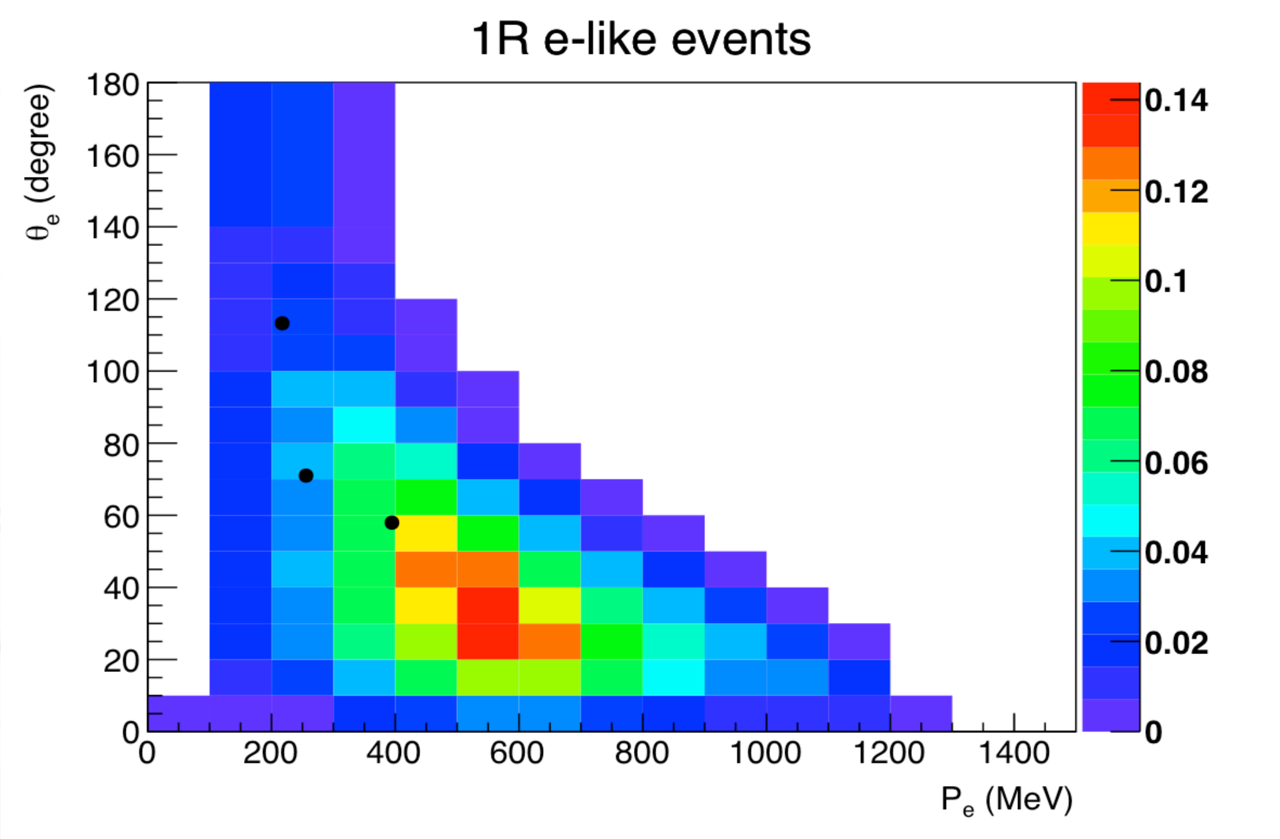


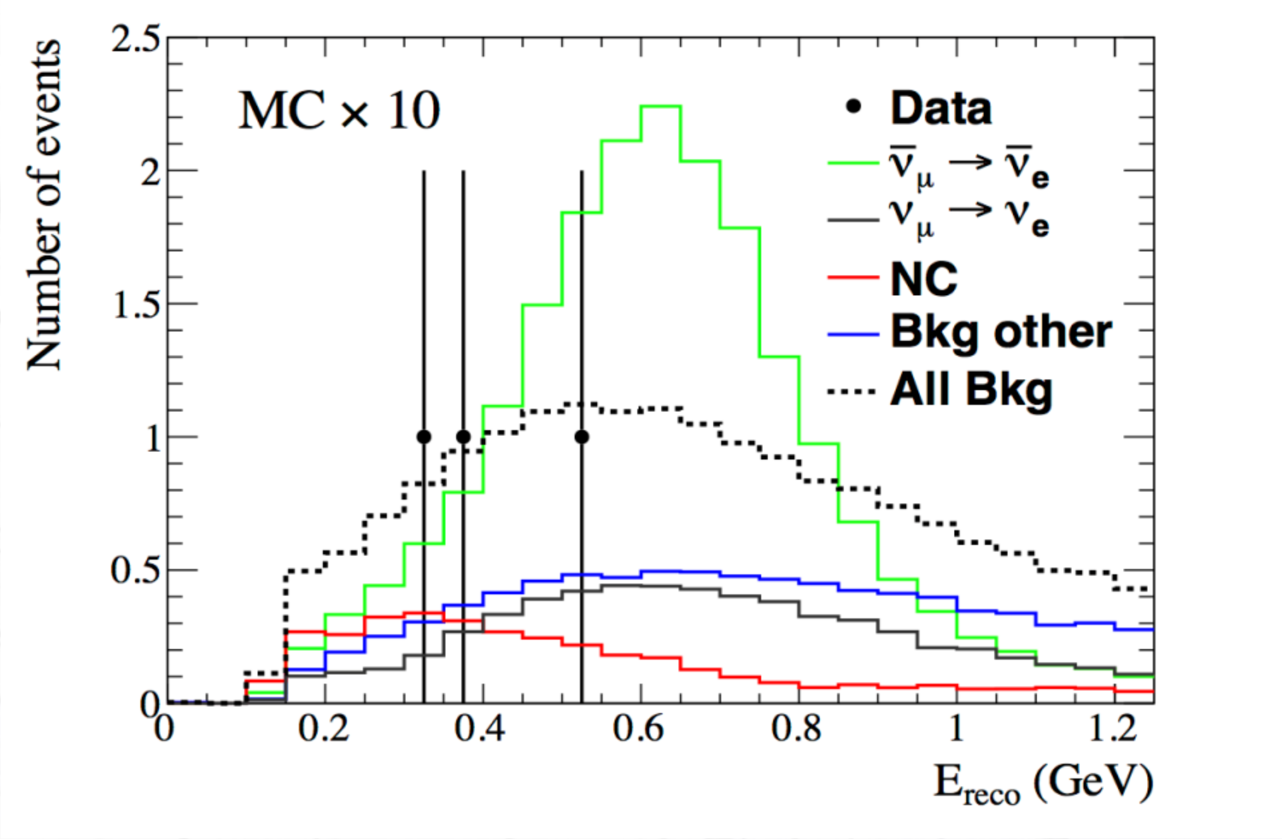
Expectations

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1.961	2.636	3.288	2.481	3.254	3.939
Bkg $\nu_\mu \rightarrow \nu_e$	0.592	0.505	0.389	0.531	0.423	0.341
Bkg NC	0.349	0.349	0.349	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826	0.821	0.821	0.821
Total	3.729	4.315	4.851	4.181	4.848	5.450

ν_e appearance

- Kinematical properties of the events. Distribution shape will help!

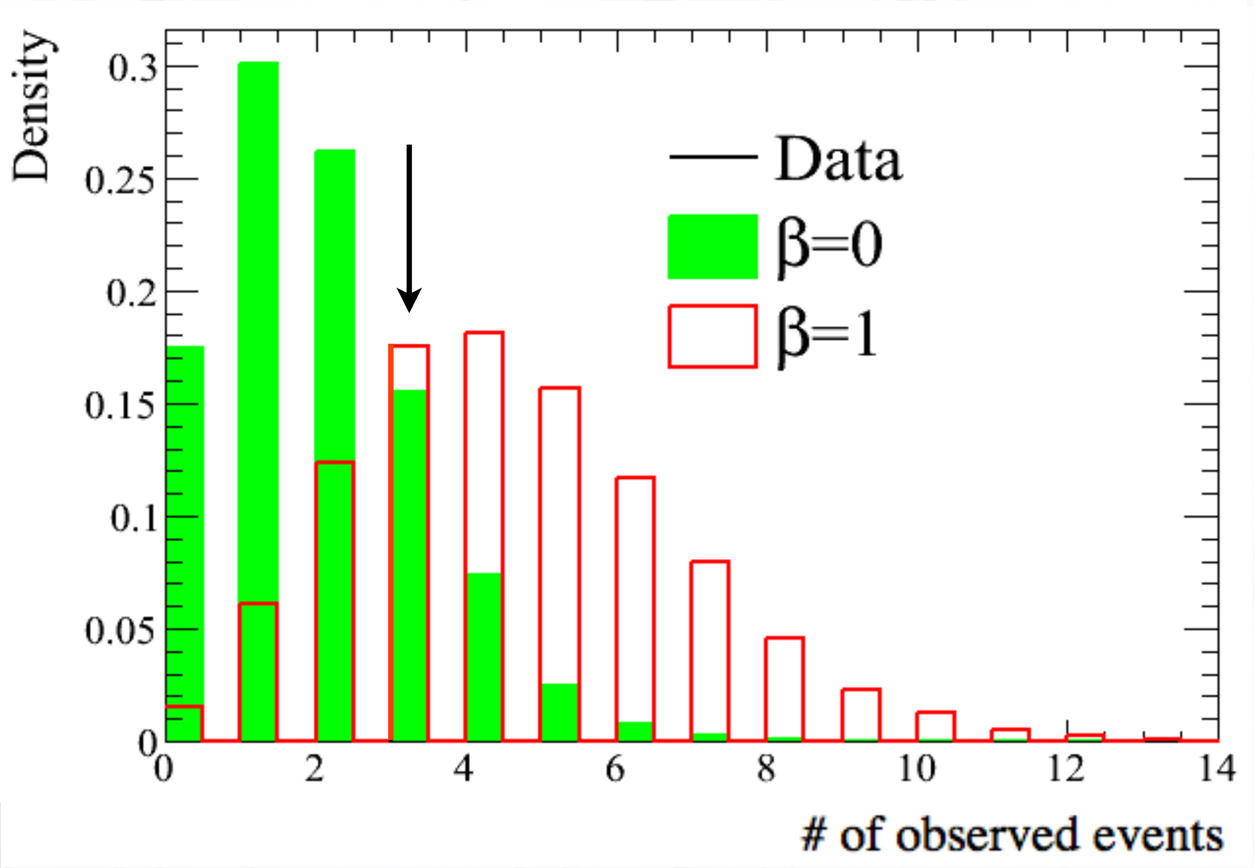




- Relative weight between the neutrinos and antineutrinos depend on δ_{CP}.
  - $\delta_{CP} = -\pi/2$ gives the worst ratio of antineutrinos/neutrinos.
  - $\delta_{CP} = +\pi/2$ gives the best ratio of antineutrinos/neutrinos.

Result

- We are interested in detecting the transition $\bar{\nu}_\mu \to \bar{\nu}_e$.
- We model the data a $N = N_{\nu_e} + \beta N_{\bar{\nu}_e}$



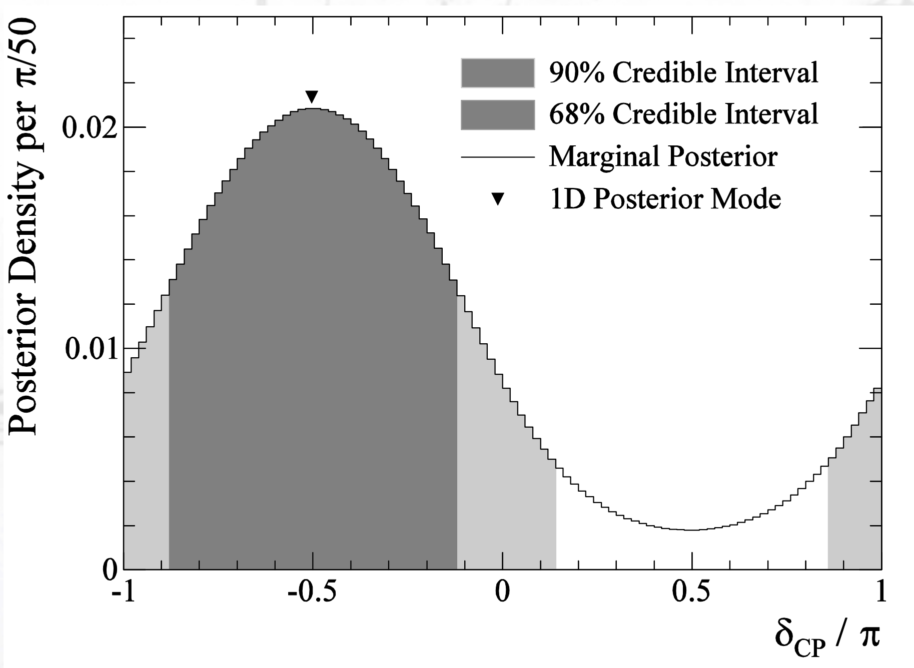
Rate	p-value	$\mathscr{L}$-ratio
3	0.26	0.9

p-value: fraction of test experiments that have as many or more candidate events as T2K data.

Comparing to $\bar{\nu}$

- Analysis of the 4 samples in T2K in a single analysis:
  - The goal is to improve on the δ_{CP} limit.

T2K $\nu_\mu \rightarrow \nu_e$



	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	1.961	2.636	3.288
Bkg $\nu_\mu \rightarrow \nu_e$	0.592	0.505	0.389
Bkg NC	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826
Total	3.729	4.315	4.851

3 evts

- More and more (and more) data:
  - improvement in accelerator performance.(>400 MW in 2016).
  - Run in antineutrinos until POT is equal to neutrinos.

What's next ?

- Analysis of the 4 samples in T2K in a single analysis:

$$\nu_\mu \to \nu_e,\ \nu_\mu \to \nu_\mu,\ \bar{\nu}_\mu \to \bar{\nu}_e,\ \bar{\nu}_\mu \to \bar{\nu}_\mu$$

  - The goal is to improve on the δ_{CP} limit.
- Nedd more and more (and more, and more...) data:
  - improvement in accelerator performance.(>400 MW in 2016).
  - Run in antineutrinos until POT is equal to neutrinos.
    - Then alternate forward and reverse horn operation.