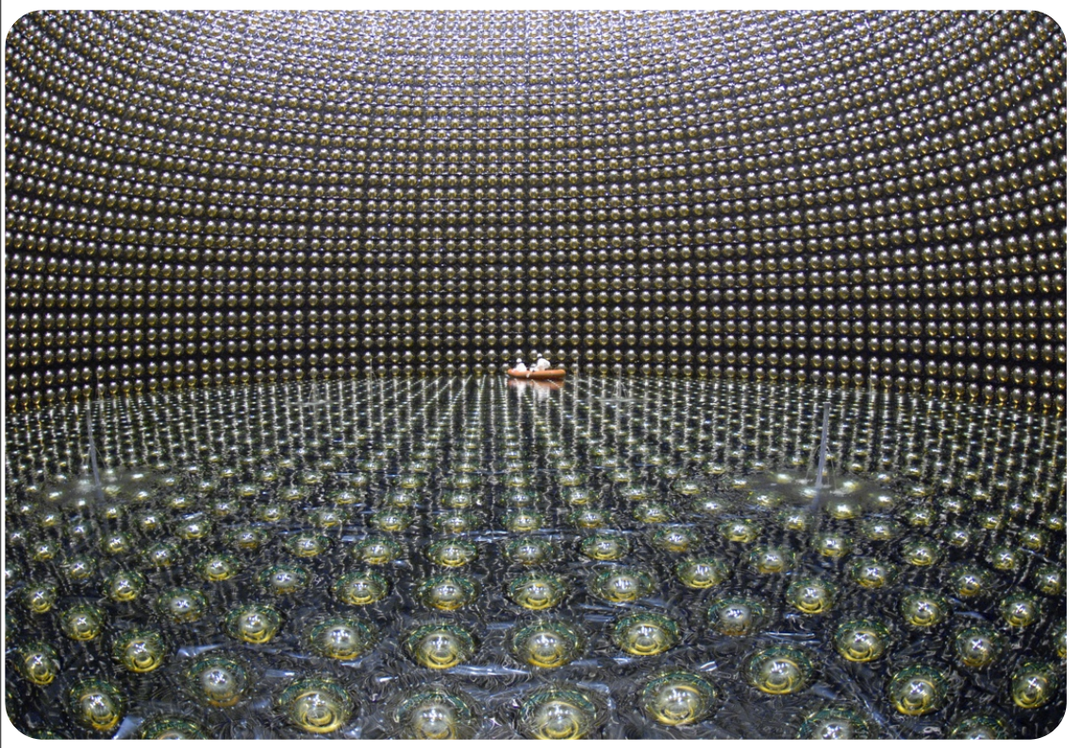


SESAPS 2011: The T2K Experiment

Joshua Albert
Duke University
October 20, 2011

Neutrino Oscillation Review

Flavor — Atmospheric Oscillations — Mass

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

$c_{23} = \cos\theta_{23}$ etc…

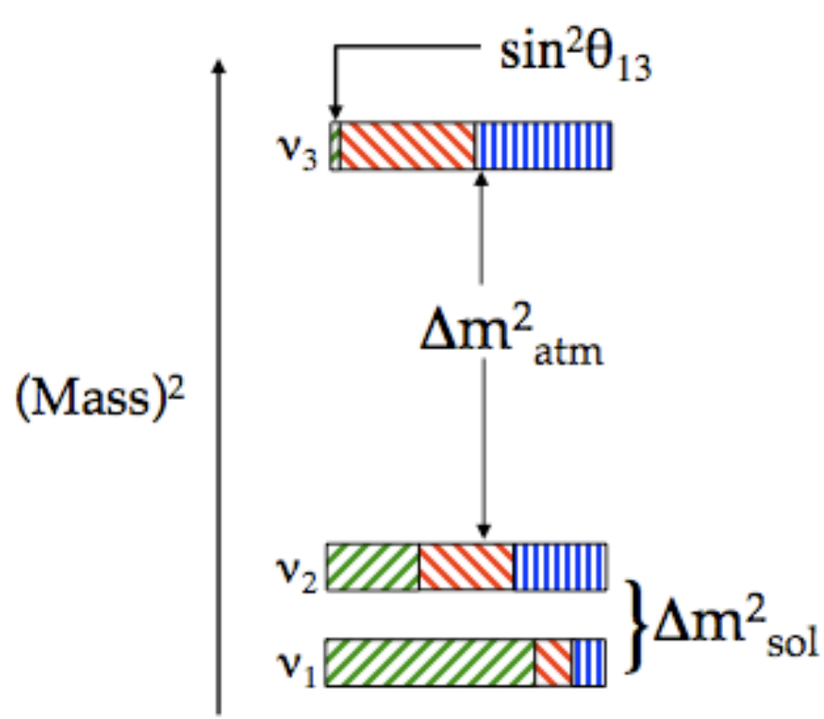
Non-zero?

Solar Oscillations

- In neutrino interactions, we measure weak (flavor) states (e,μ,τ) which are superpositions of the 3 mass states.
- 2-flavor example (good approximation):

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

- Overall, 3-flavor mixing is described by 4 parameters: θ_{12}, θ_{23}, θ_{13}, δ_{CP}.



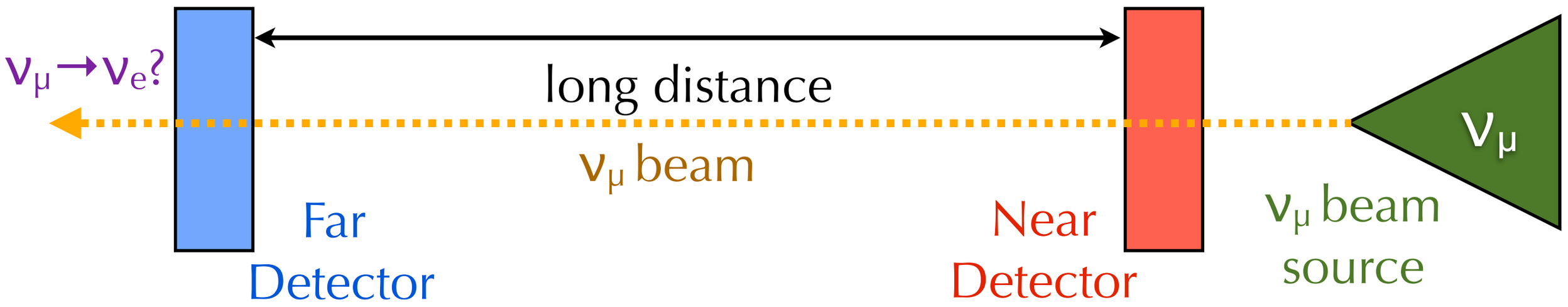
Normal hierarchy eigenstate fractions

How We Measure θ_{13}

- The only unmeasured parameters were θ_{13} (which we know is small) and δ_{CP} (which we know nothing about).
- For technical reasons, we can only hope to measure δ_{CP} if θ_{13} is non-zero. δ_{CP} would be interesting to measure, because it describes whether neutrinos and anti-neutrinos oscillate differently.
- To measure θ_{13}, we can search for $\nu_\mu \rightarrow \nu_e$ oscillation!

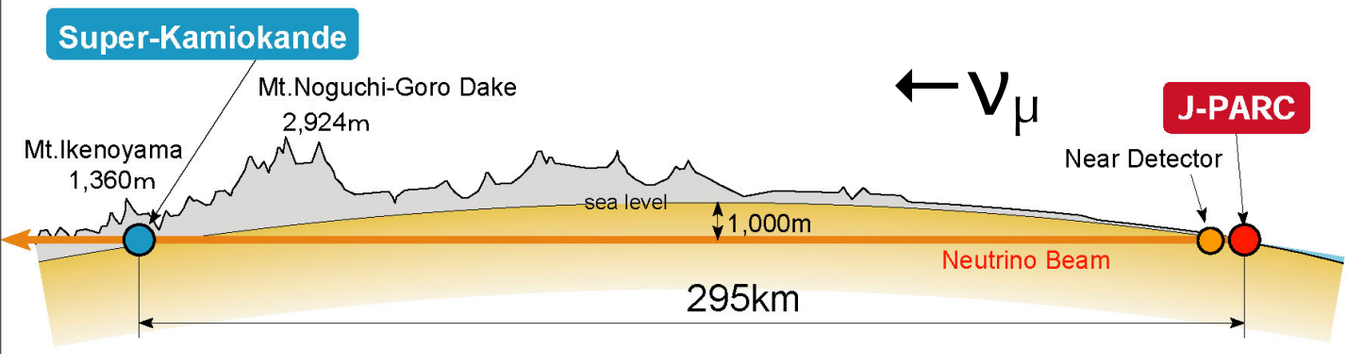
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(1.27 \Delta m^2 (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})} \right)$$

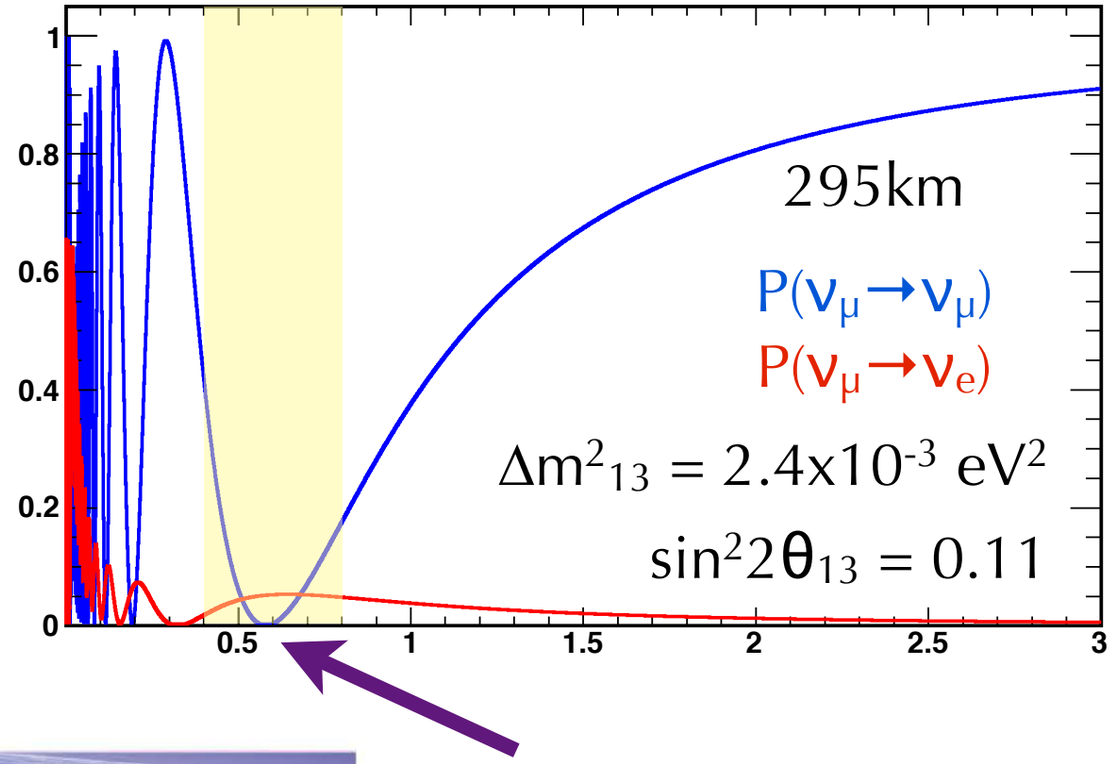
- We know θ_{13} is small, so this will be rare. Build setup like this:



T2K Overview

12 countries, 58 institutions,
512 members



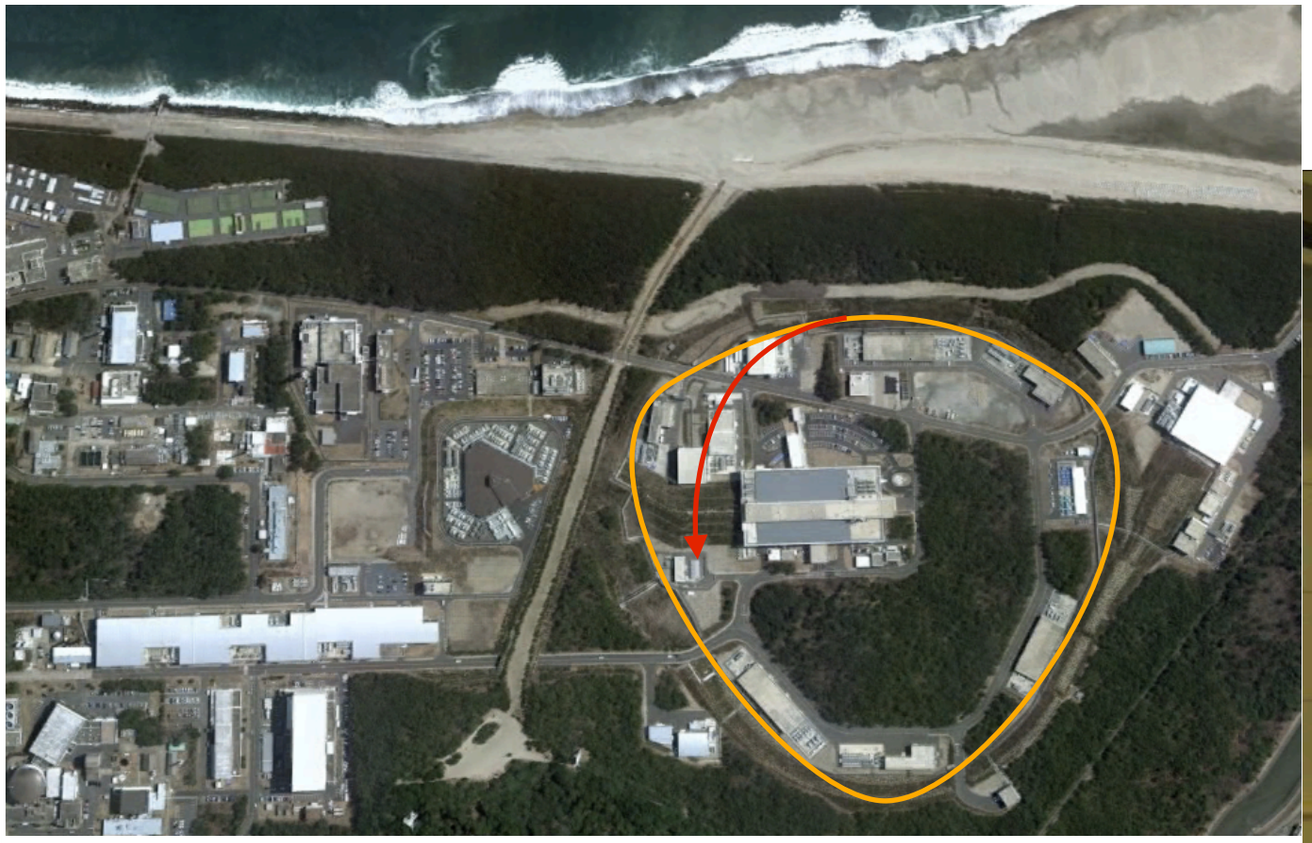


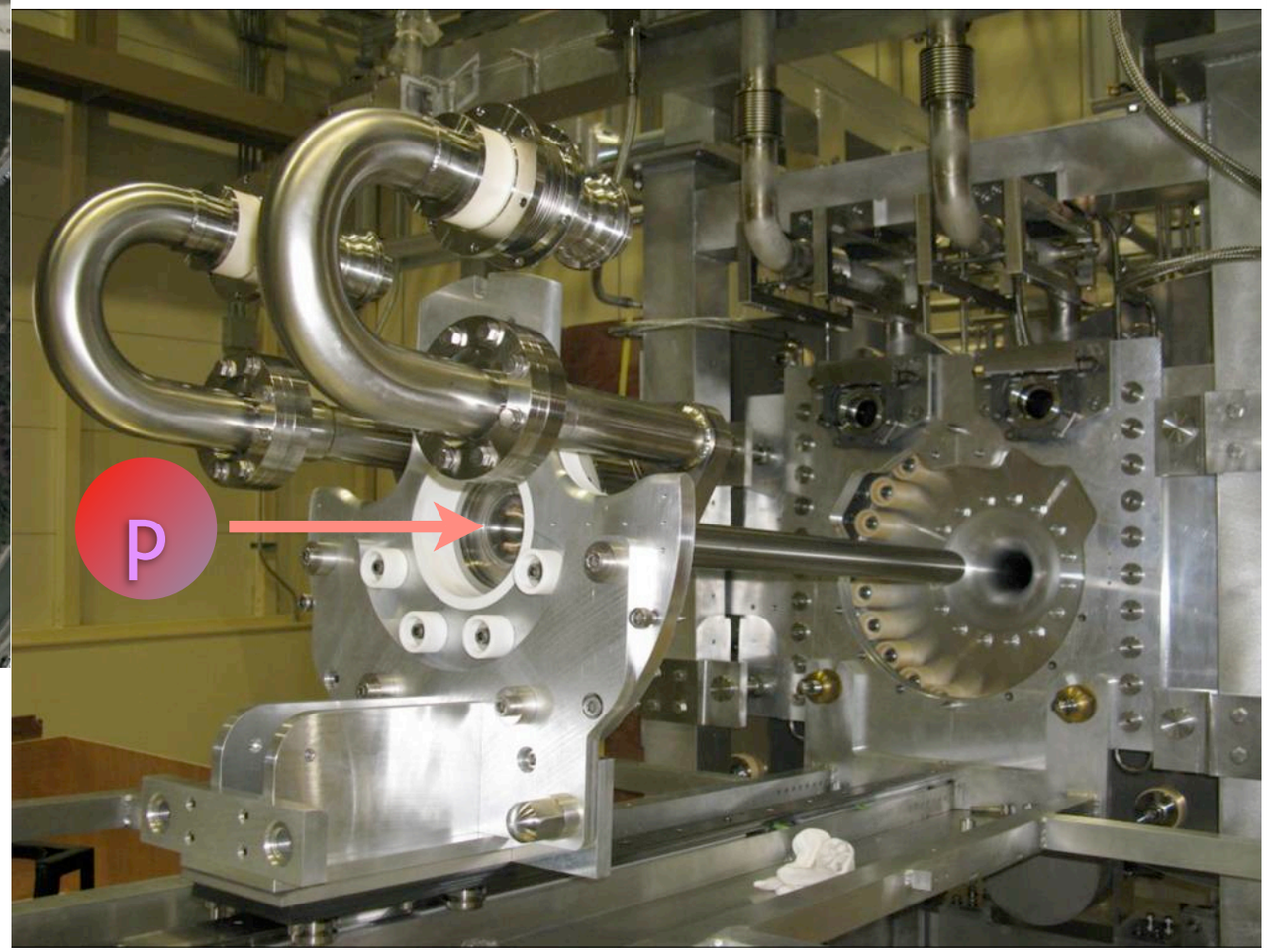
T2K ν_μ beam energy

Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

Neutrino Beam (pt. 1)



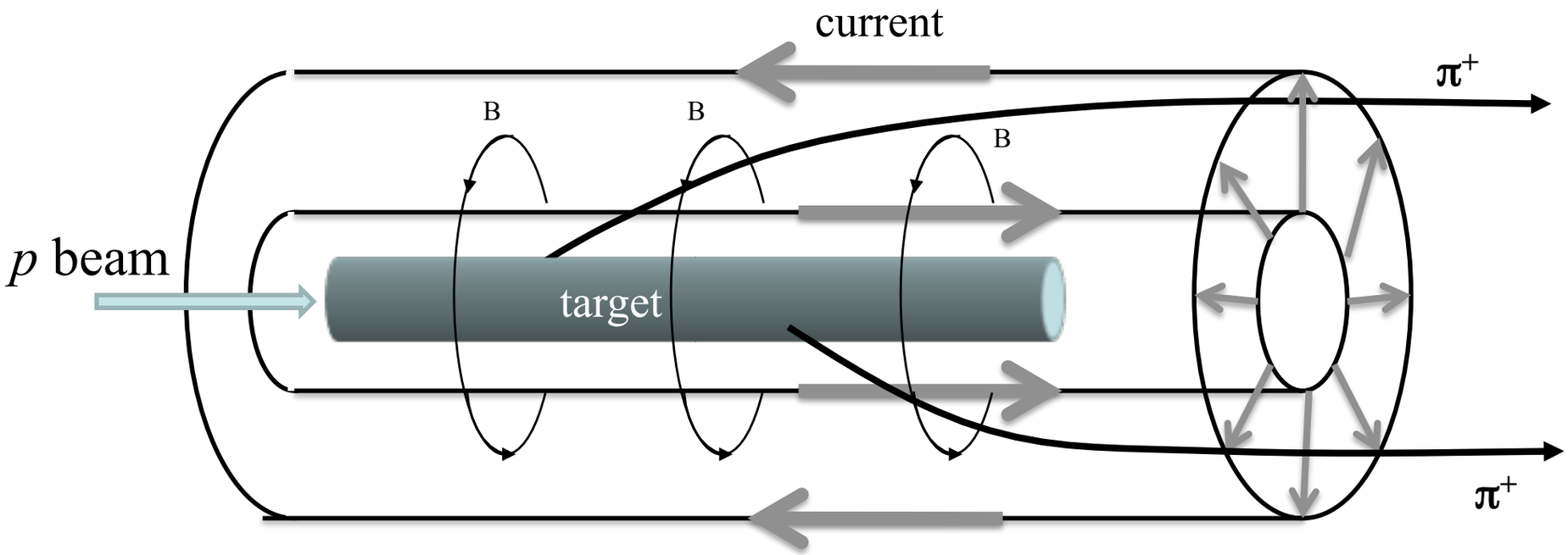


Pulsed beam of 30 GeV protons
from accelerator
Slam into graphite target,
Make pions (and other particles)

$$p + p \rightarrow p + \pi^+ + \ldots$$

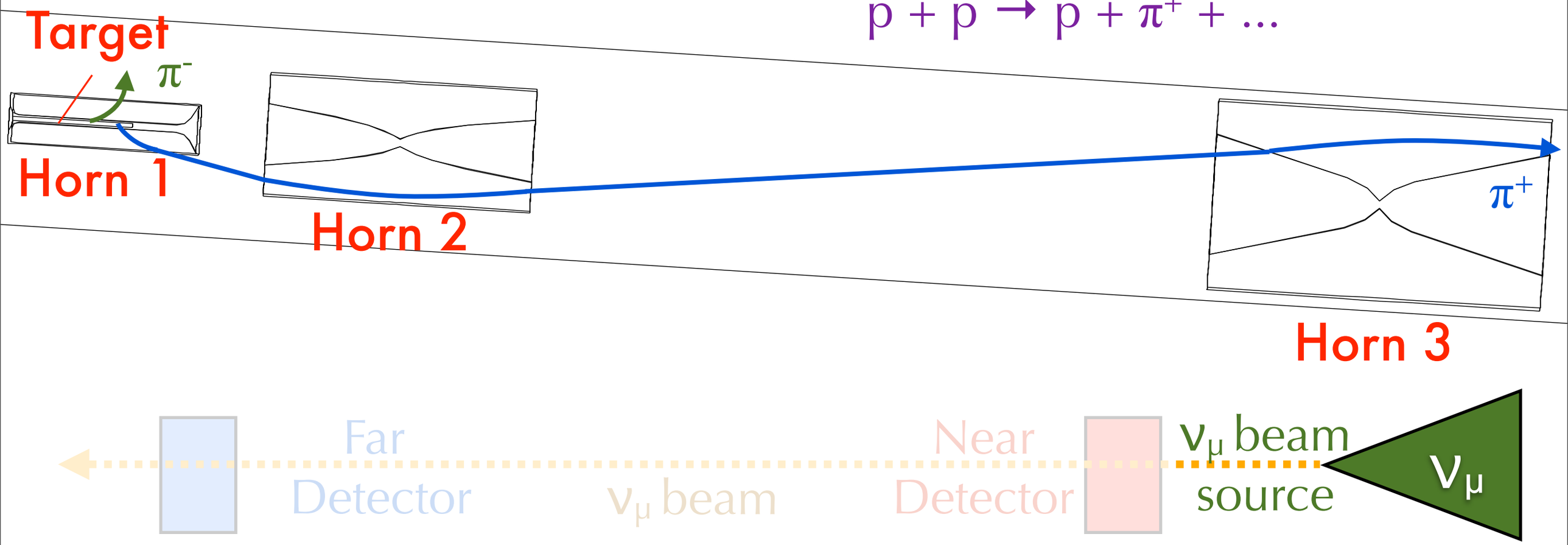
Target is placed inside 1st magnetic horn...

Neutrino Beam (pt. 2)



Positively charged particles focused forward

$p + p \rightarrow p + \pi^+ + \ldots$

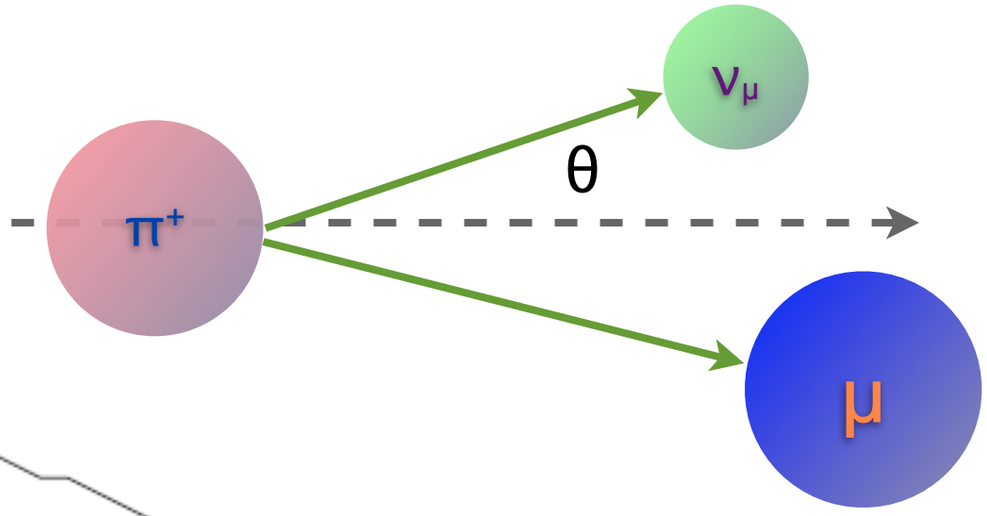


Neutrino Beam (pt. 3)

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

π^+ lifetime: 2.6×10^{-8}s

μ^+ lifetime: 2.2×10^{-6}s

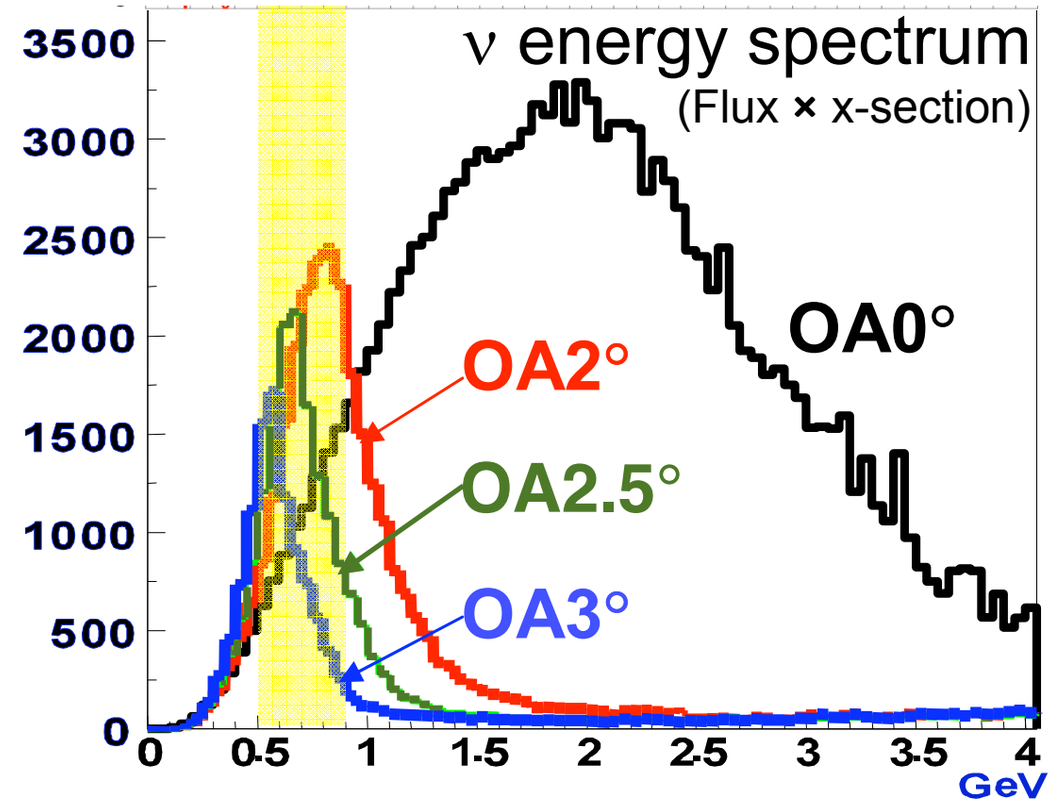


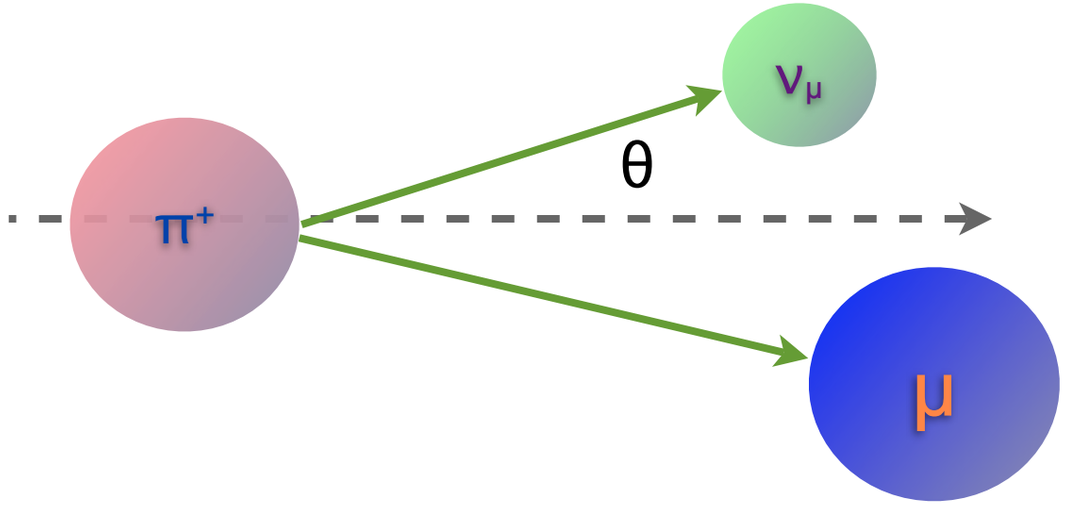
Neutrino Beam (pt. 4)

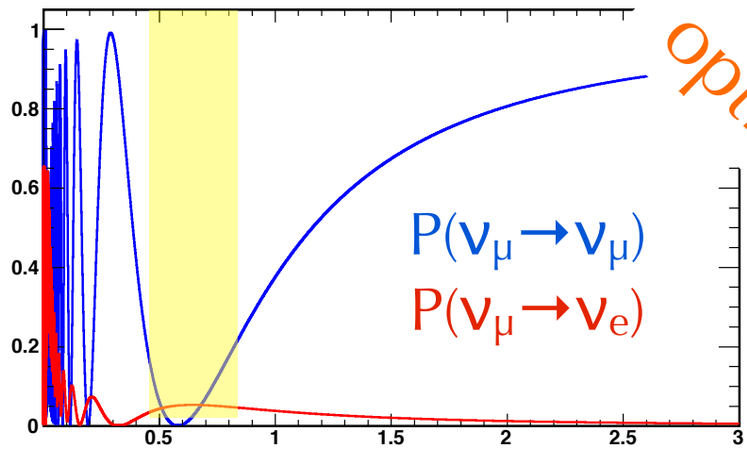
- 2-body decay → exact kinematics

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

$$E_\nu\left(p_\pi, \theta_\nu\right) = \frac{m_\pi^2 - m_\mu^2}{2\left(\sqrt{p_\pi^2 + m_\pi^2} - p_\pi \cos\theta_\nu\right)}$$





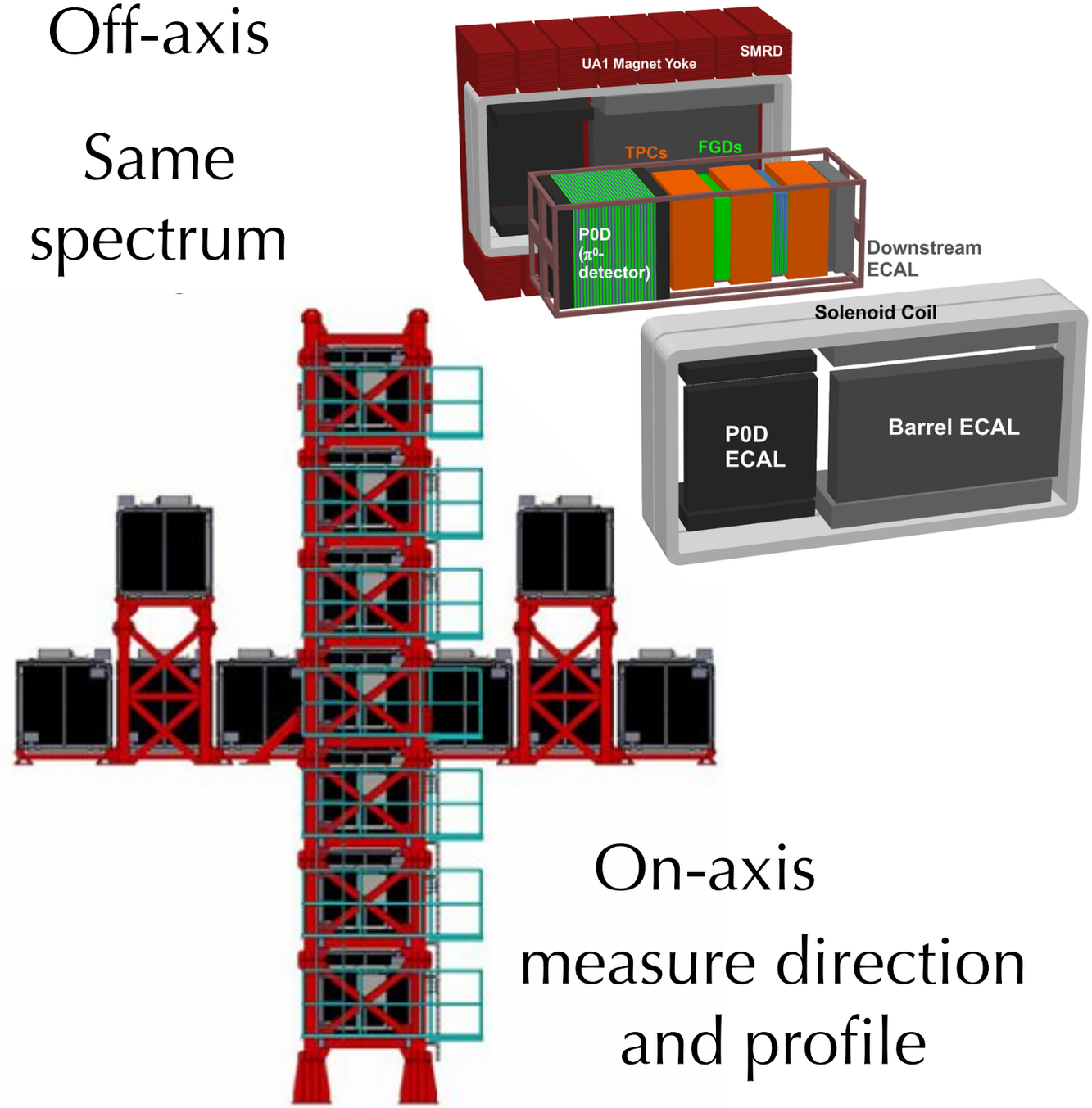


optimized!

Near Detectors

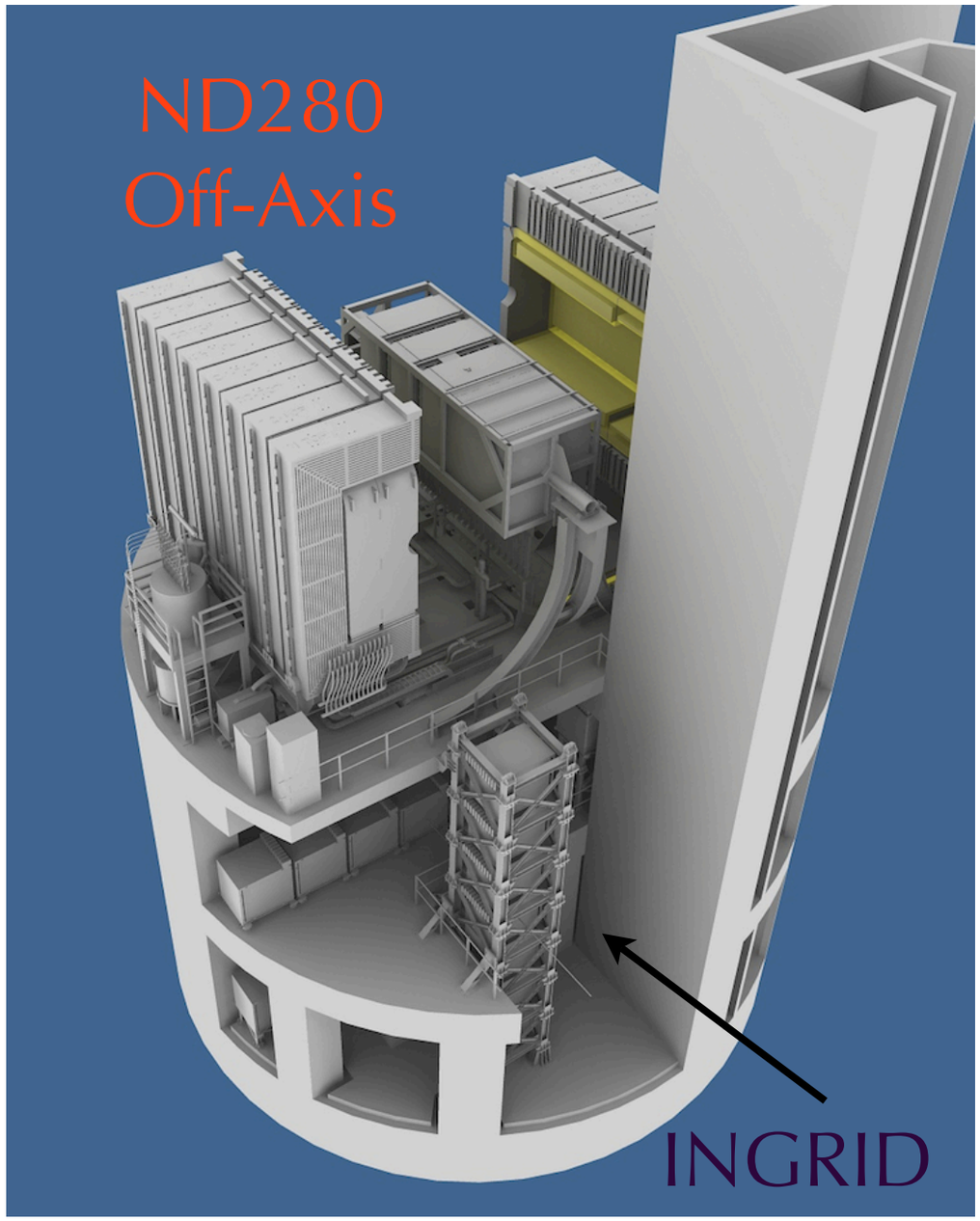
Off-axis

Same spectrum



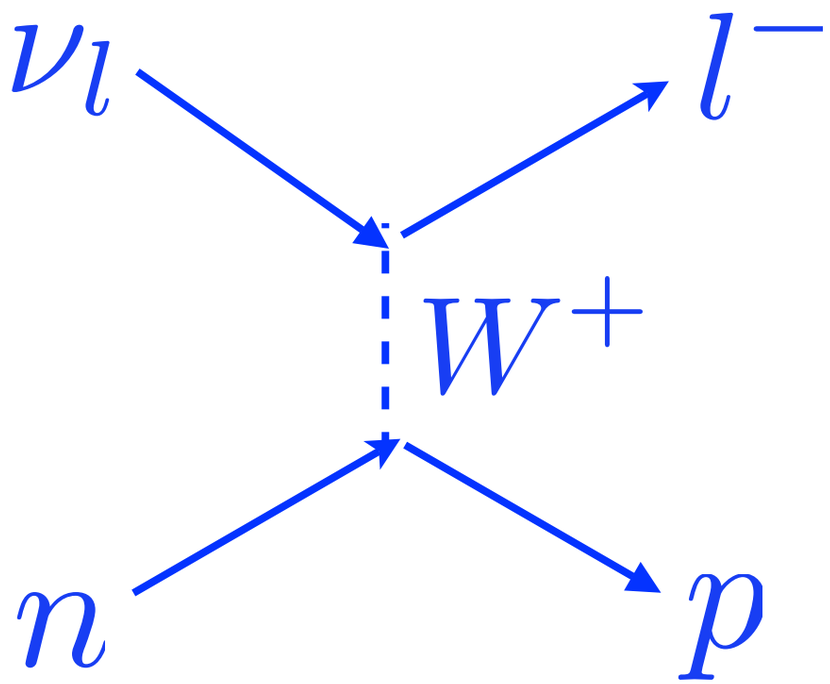
On-axis

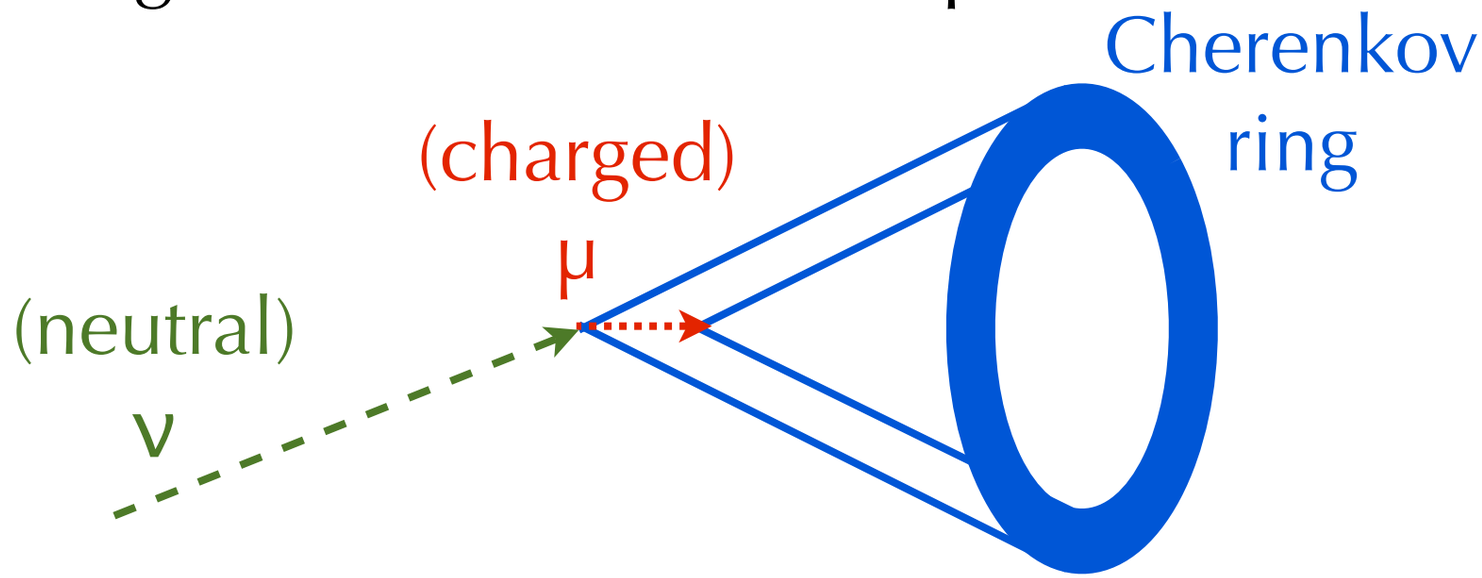
measure direction and profile

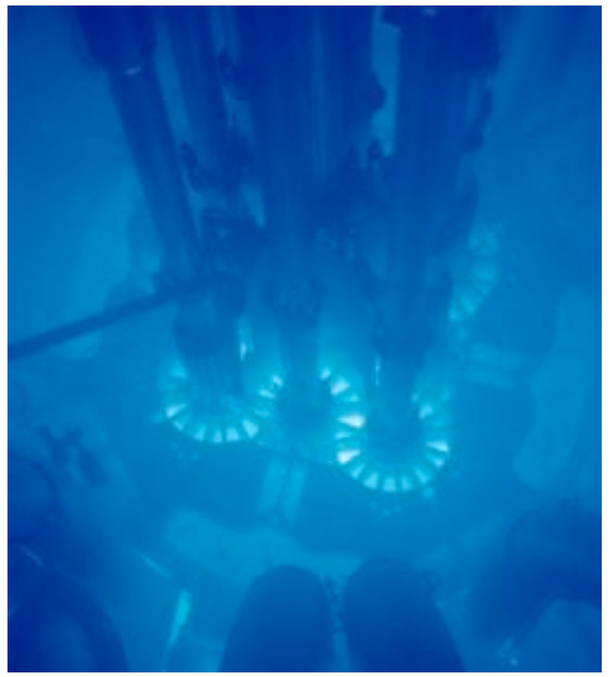


Detecting Neutrinos

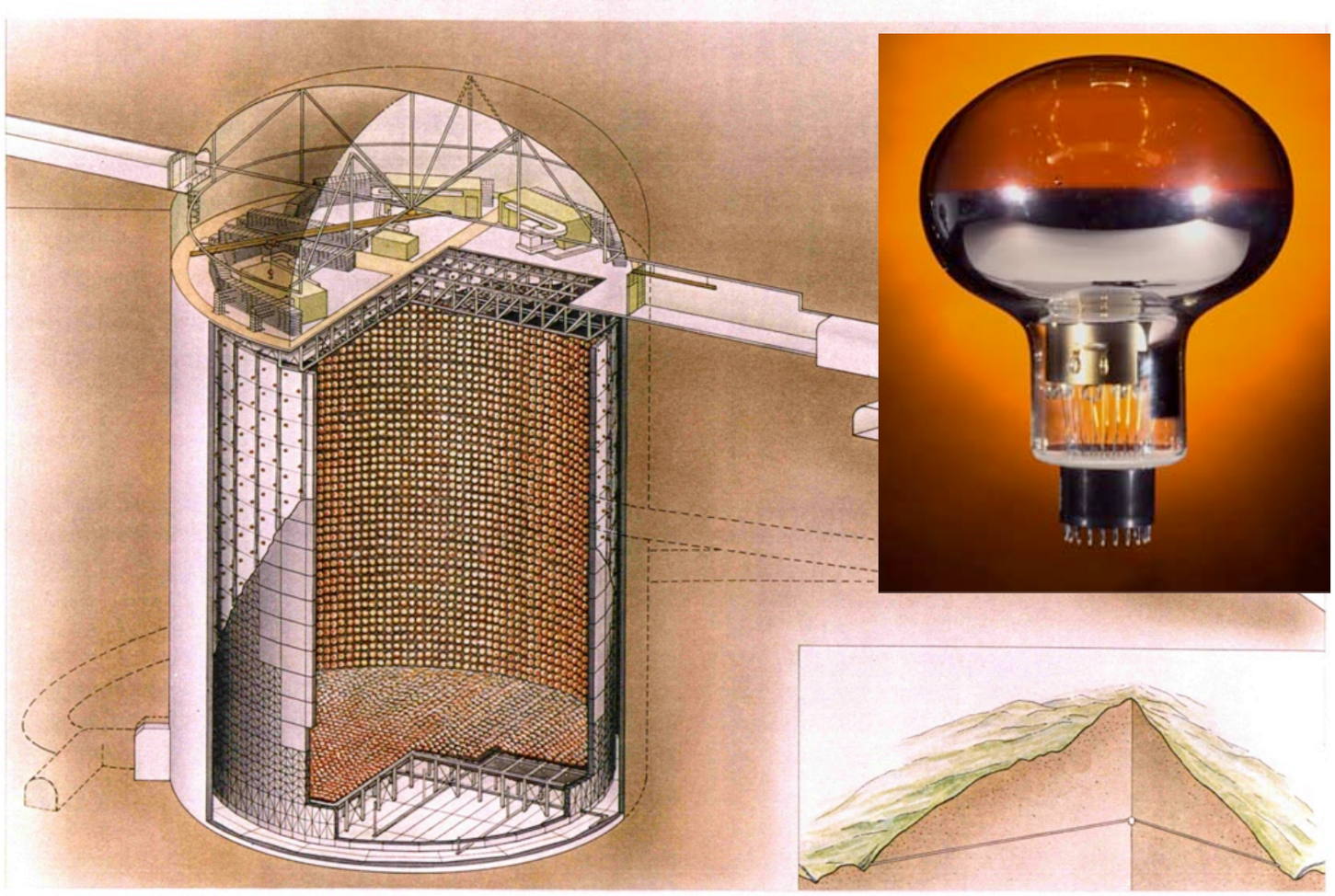
- We only detect the charged products of neutrino interactions!
- Charged particles in traveling faster than the speed of light in some medium (like a sonic boom)
- $v_{light} = c/n$ (n = index of refraction) in water, $v_{light} \approx 0.75c$
- Light emitted in cone shape

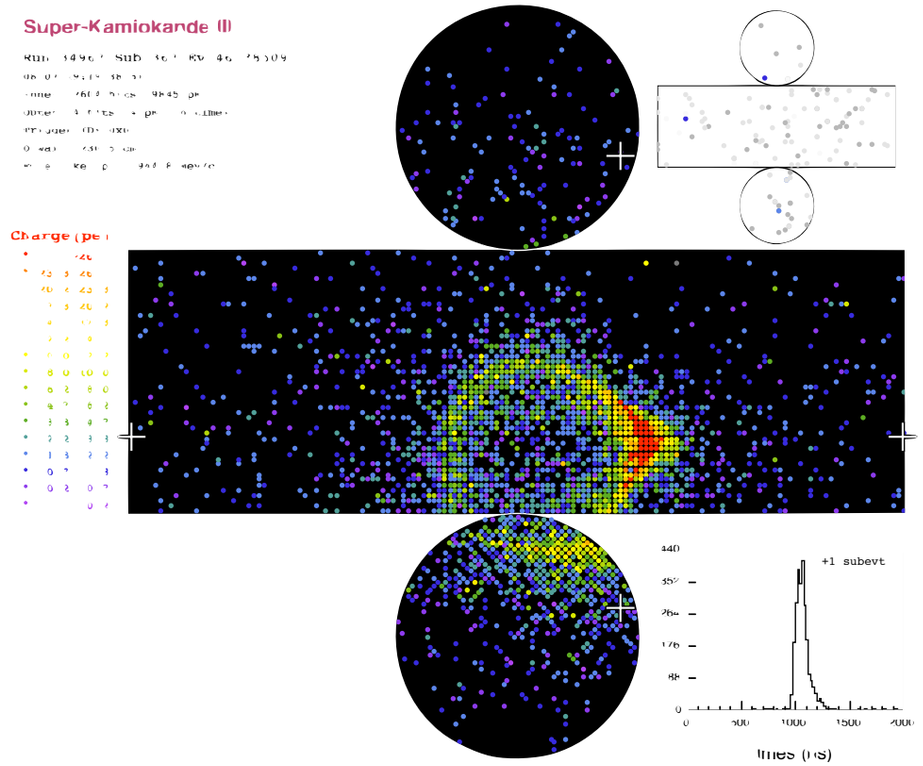






Super-Kamiokande

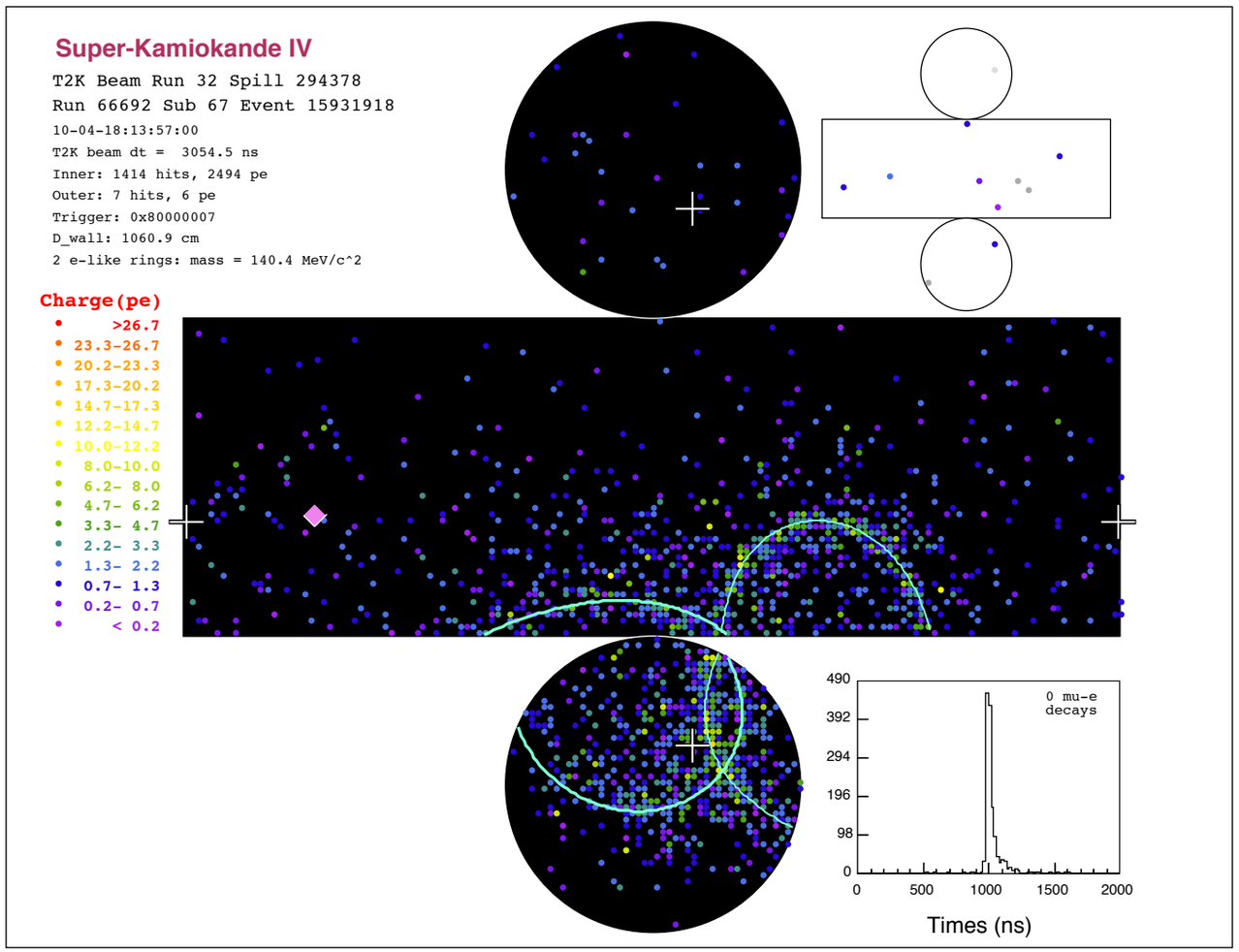


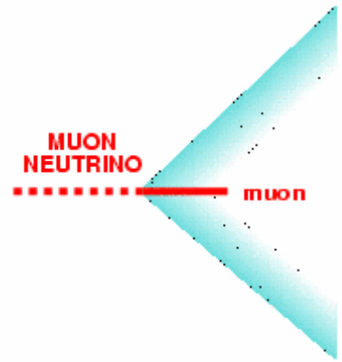


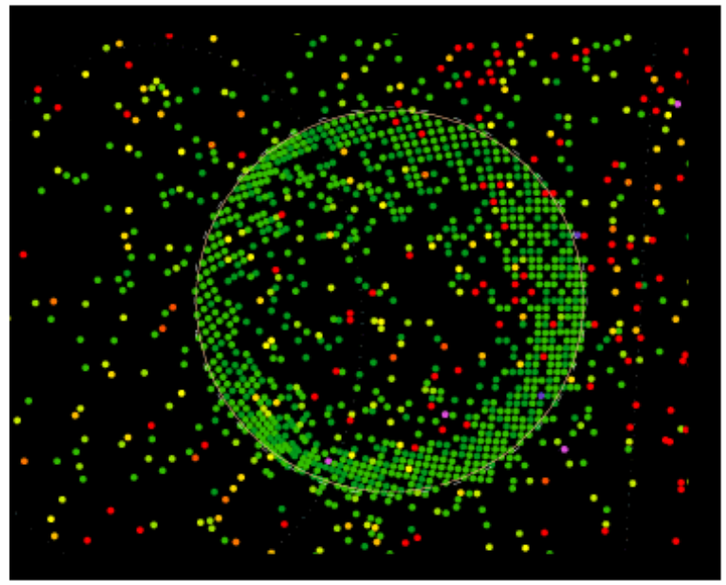
- 50,000 ton water Cherenkov detector
- 11,146 PMTs in ID, 1,885 in OD
- ~1km underground in Mt. Ikenoyama

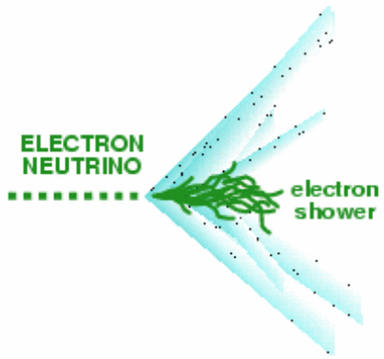
SK Reconstruction

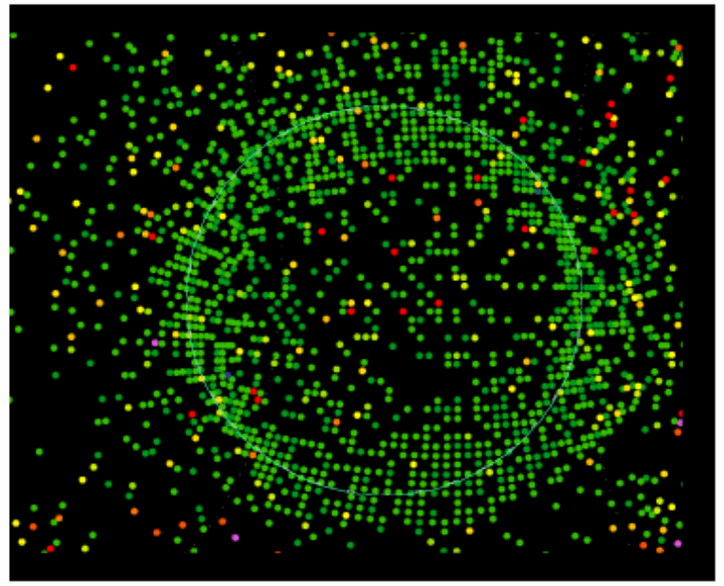
- Find vertex (mostly timing)
- Count rings
- Find momenta
- PID from ring topology (“fuzziness”)





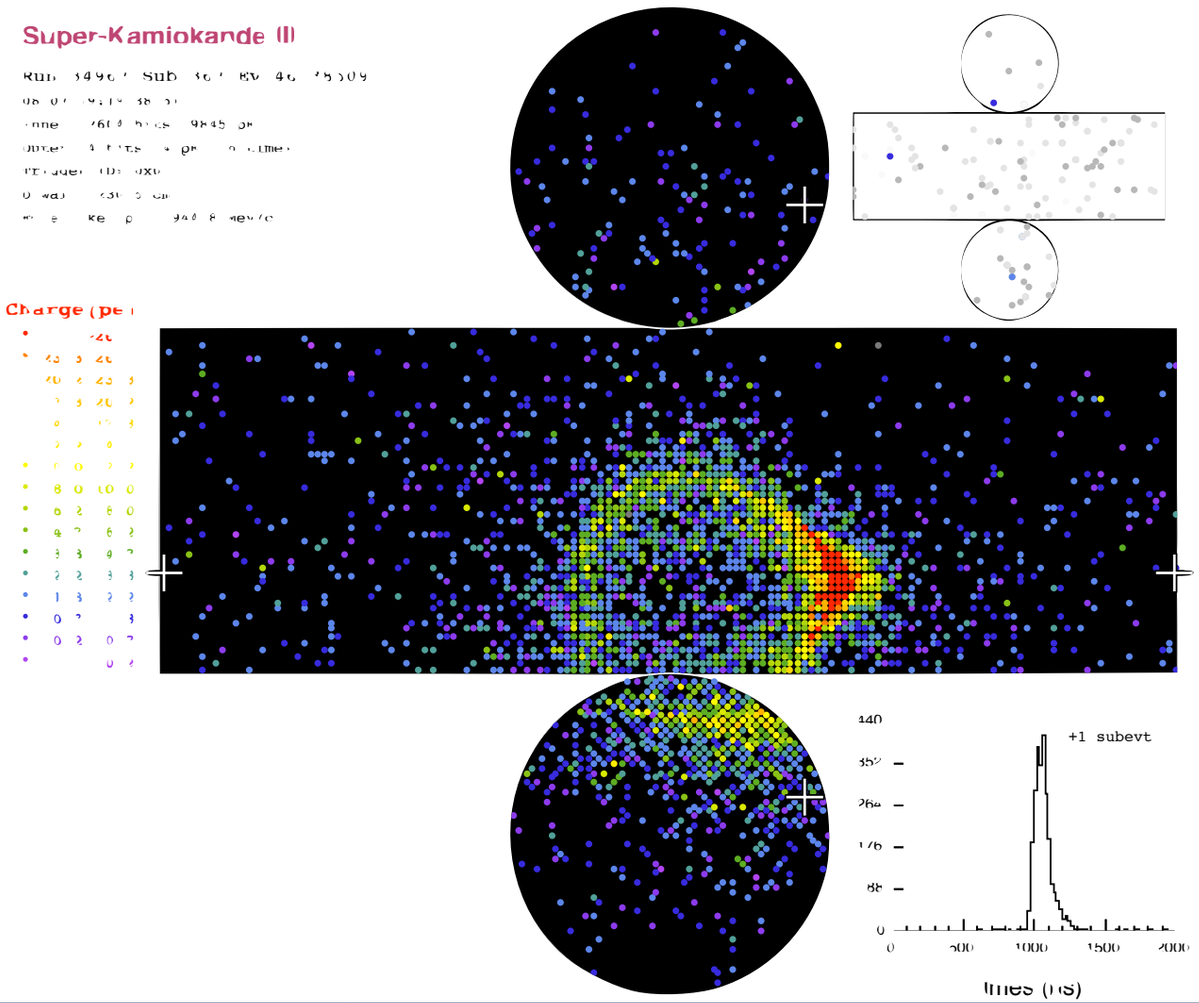


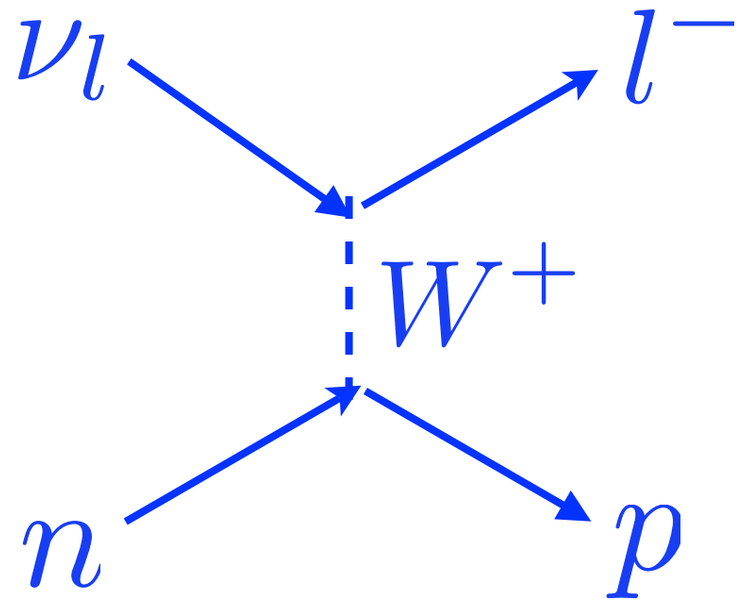




ν_e Appearance Signal

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





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

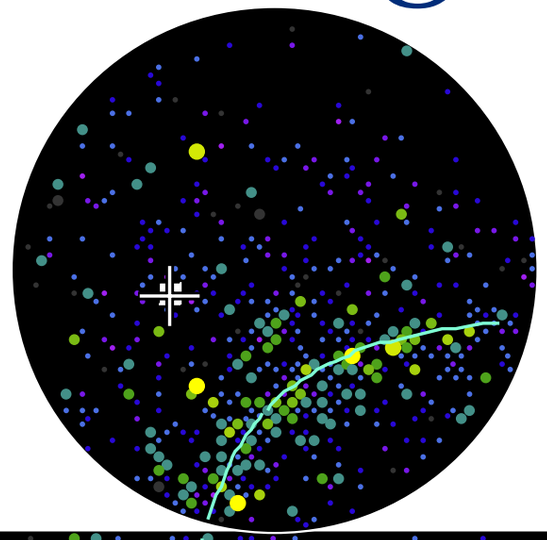
- Incident neutrino energy can be reconstructed!

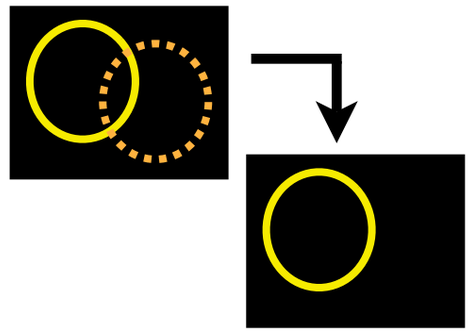
ν_e Appearance Backgrounds

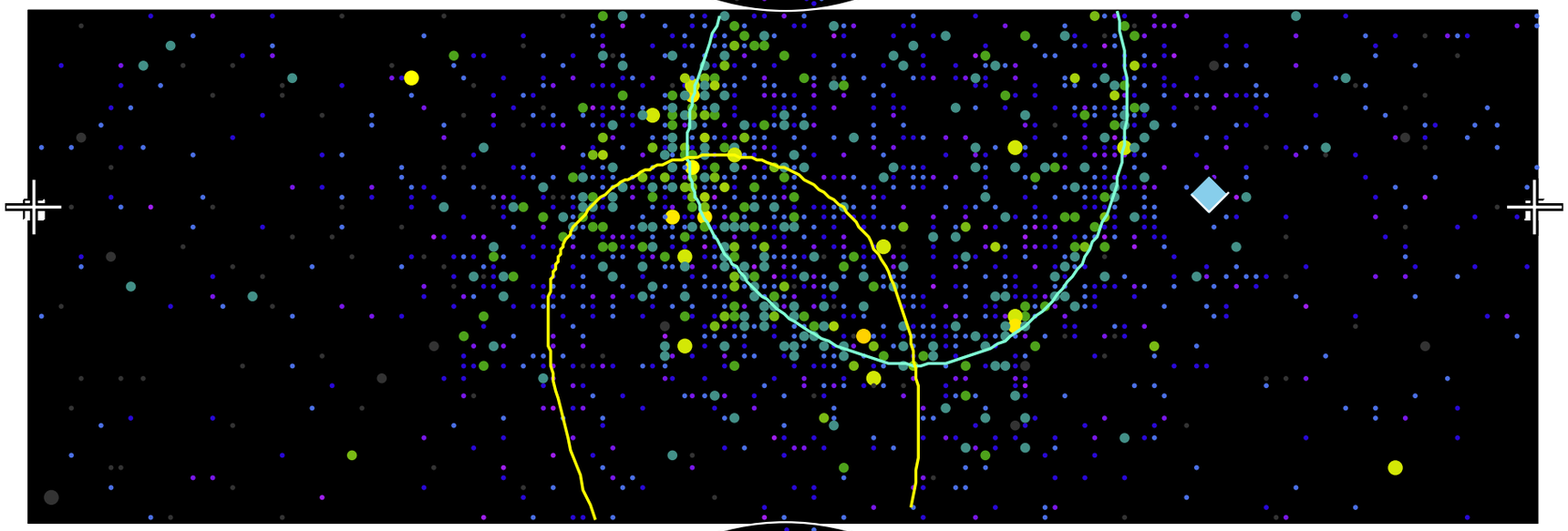
1) Beam ν_e :
ν_μ beam only
~99% pure

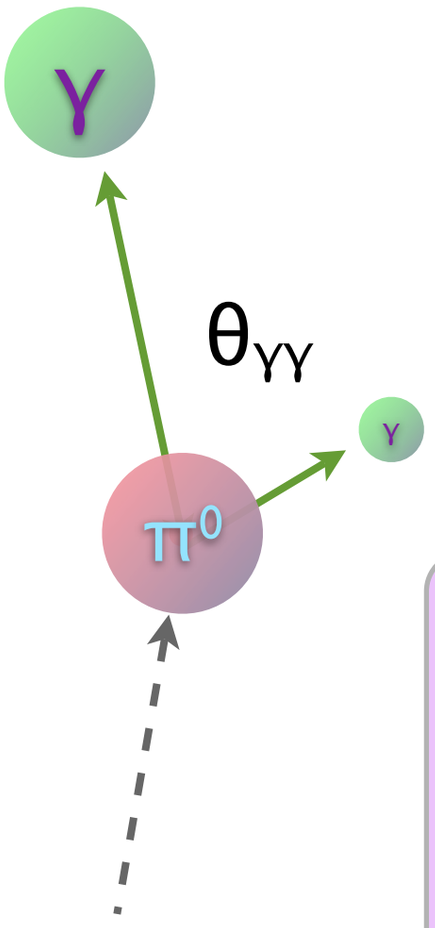
e-like ring

most likely
2nd ring

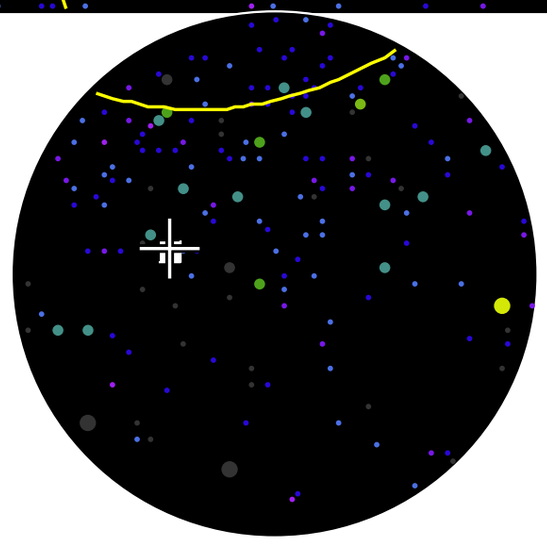








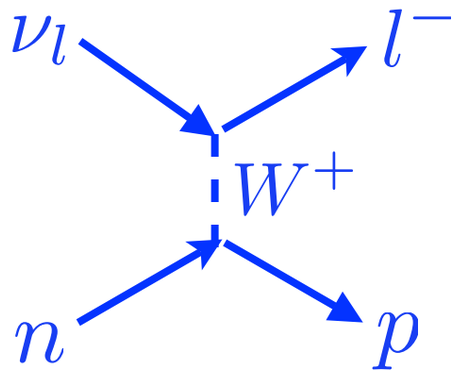
2) flavor mis-ID:
mostly from
$\nu_\mu + p \rightarrow \pi^0 + \nu_\mu + p$
$\hookrightarrow \gamma + (\gamma)$



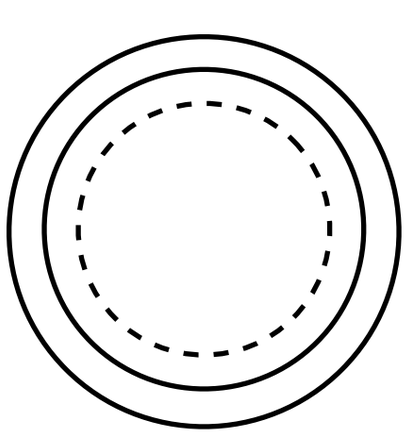
NC π^0
Asymmetric
Decay

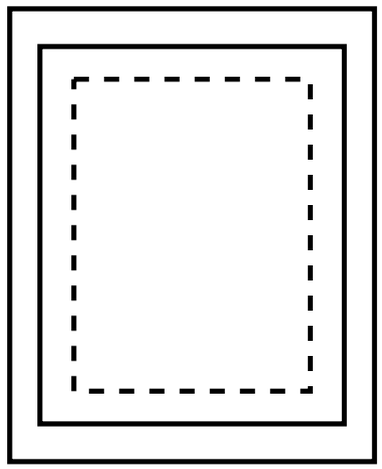
Signal: Single electron ring!

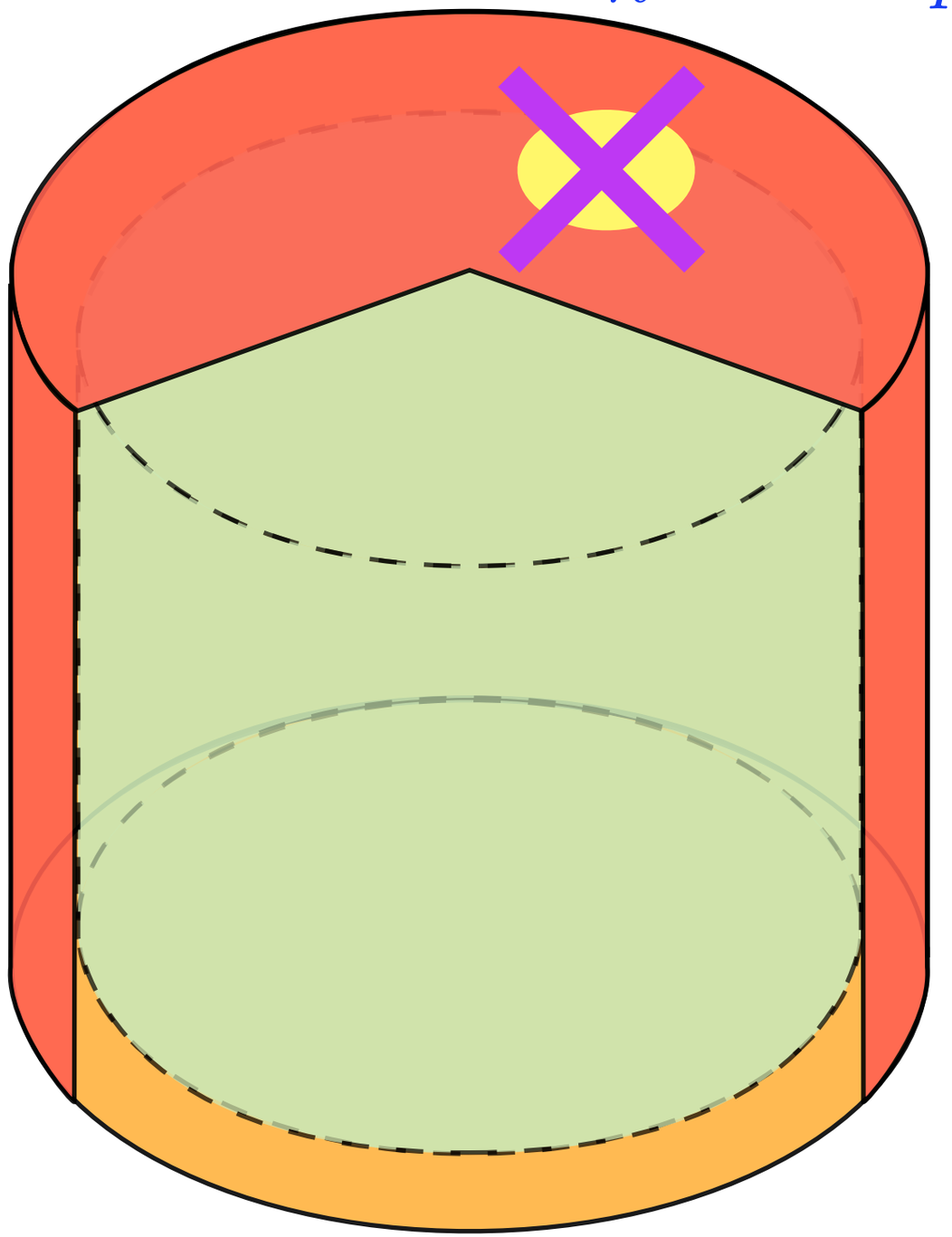
Event Selection



- Fiducial Volume
- Fully Contained

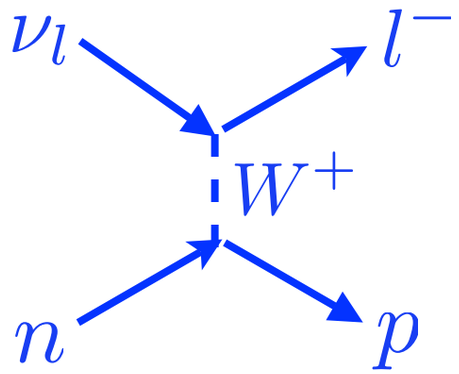




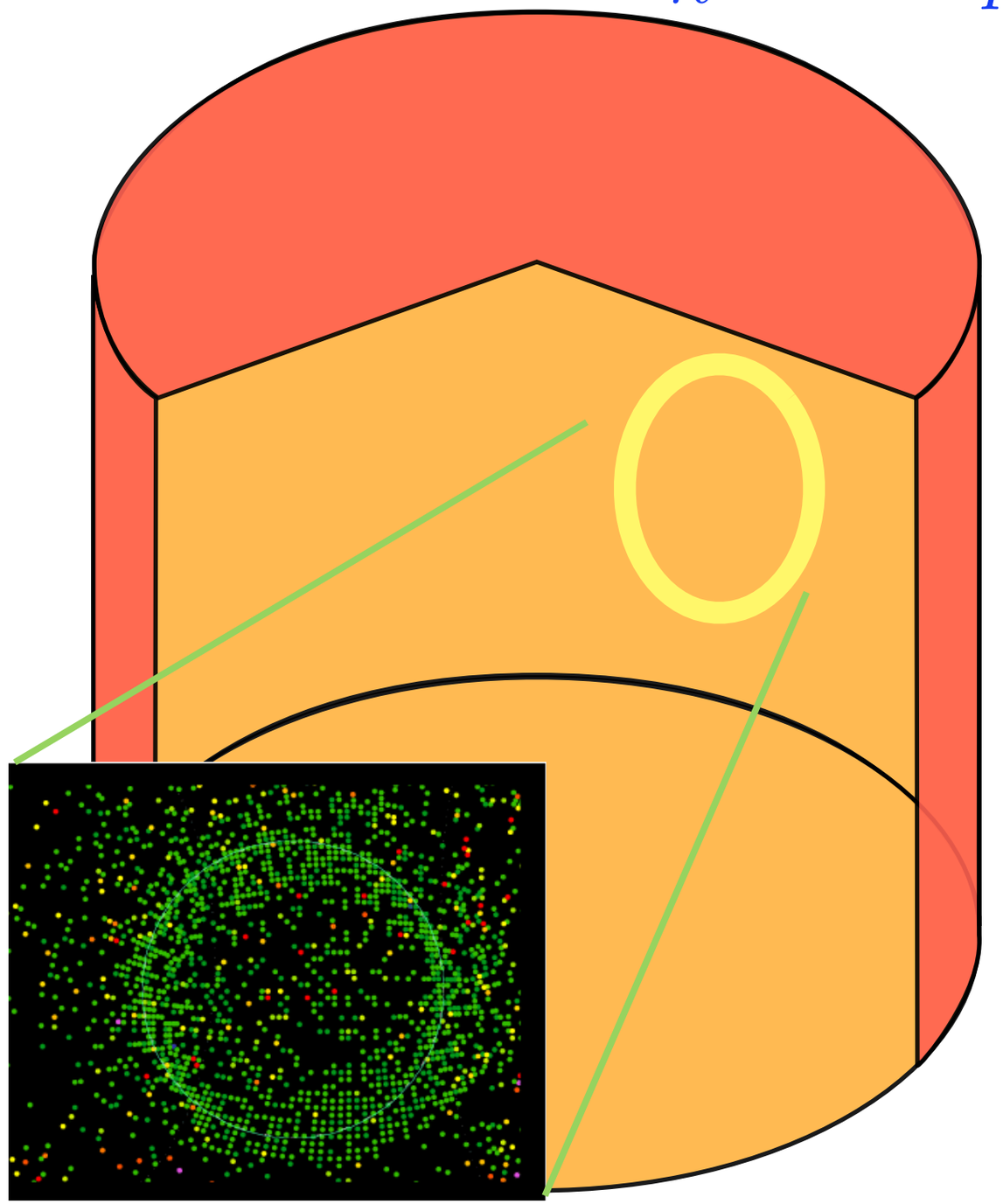


Signal: Single electron ring!

Event Selection

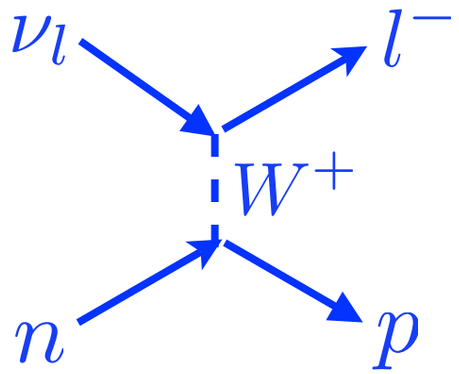


- Fiducial Volume
- Fully Contained
- E_{vis}>100 MeV
- One Ring
- E-like

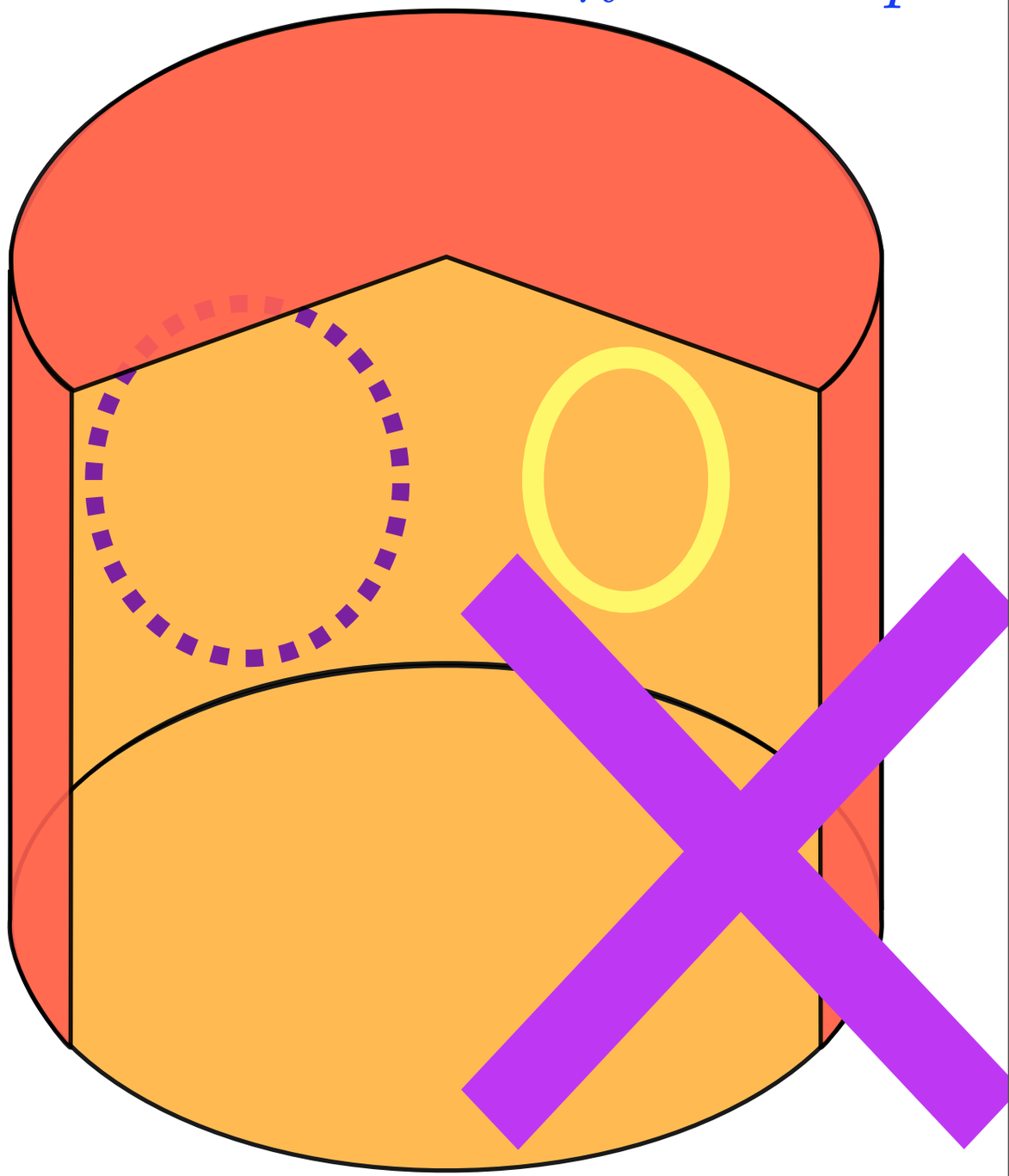


Signal: Single electron ring!

Event Selection

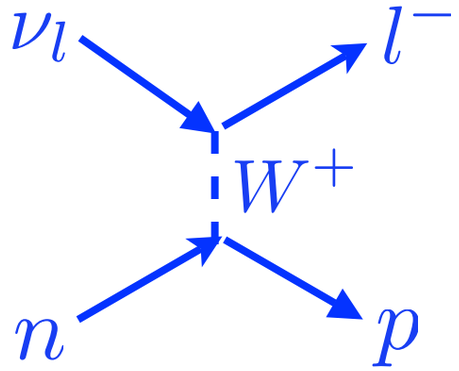


- Fiducial Volume
- Fully Contained
- E_{vis}>100 MeV
- One Ring
- E-like
- No μ→e decay

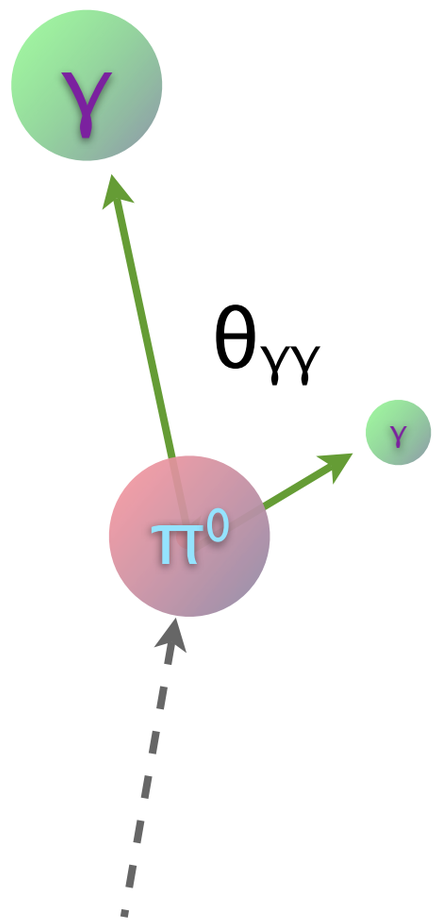


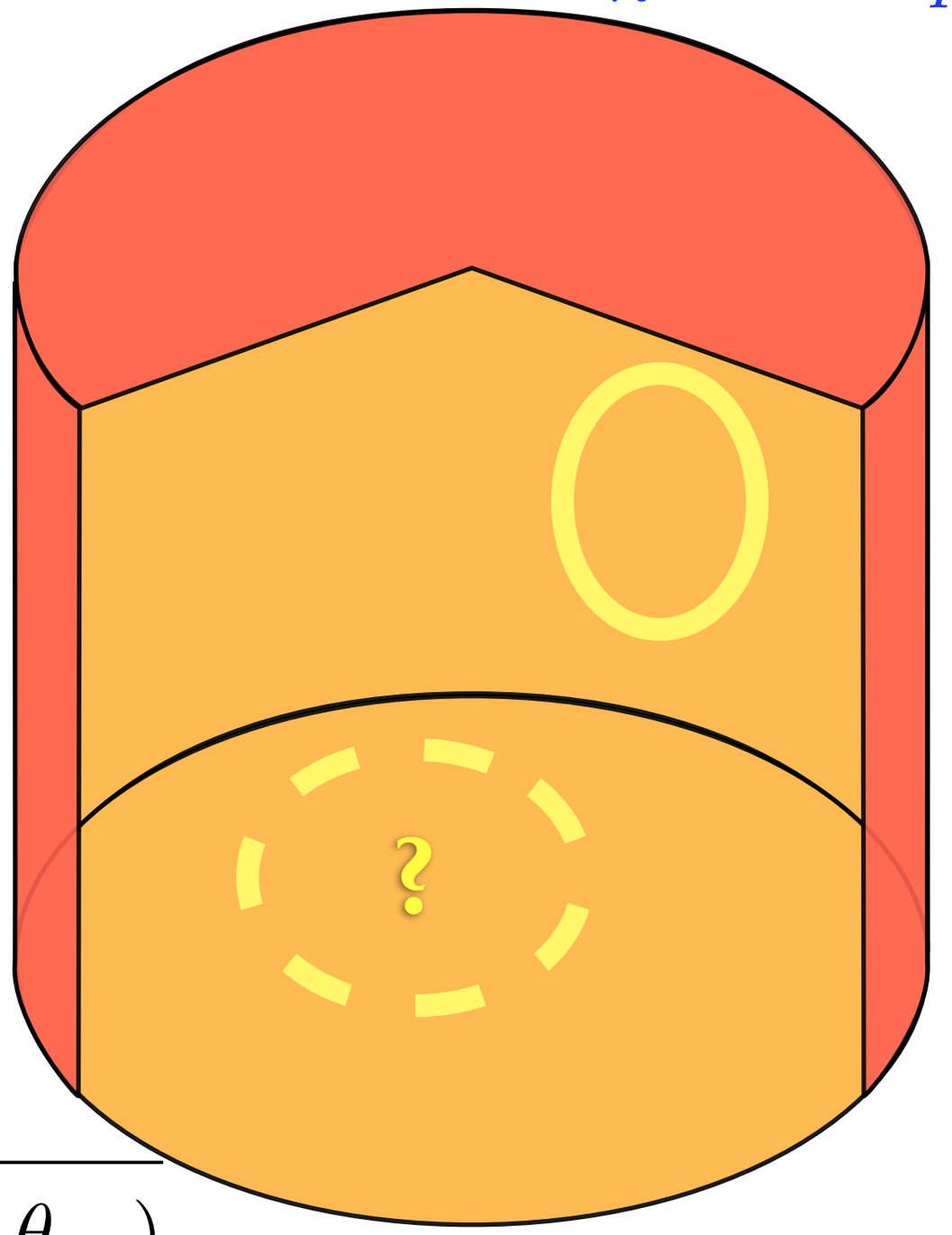
Signal: Single electron ring!

Event Selection



- Fiducial Volume
- Fully Contained
- E_{vis}>100 MeV
- One Ring
- E-like
- No μ→e decay
- POLfit cut (m_π<105 MeV)

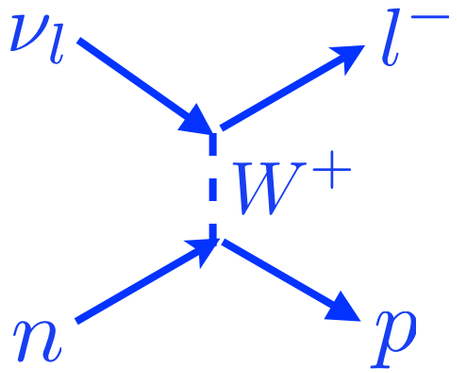




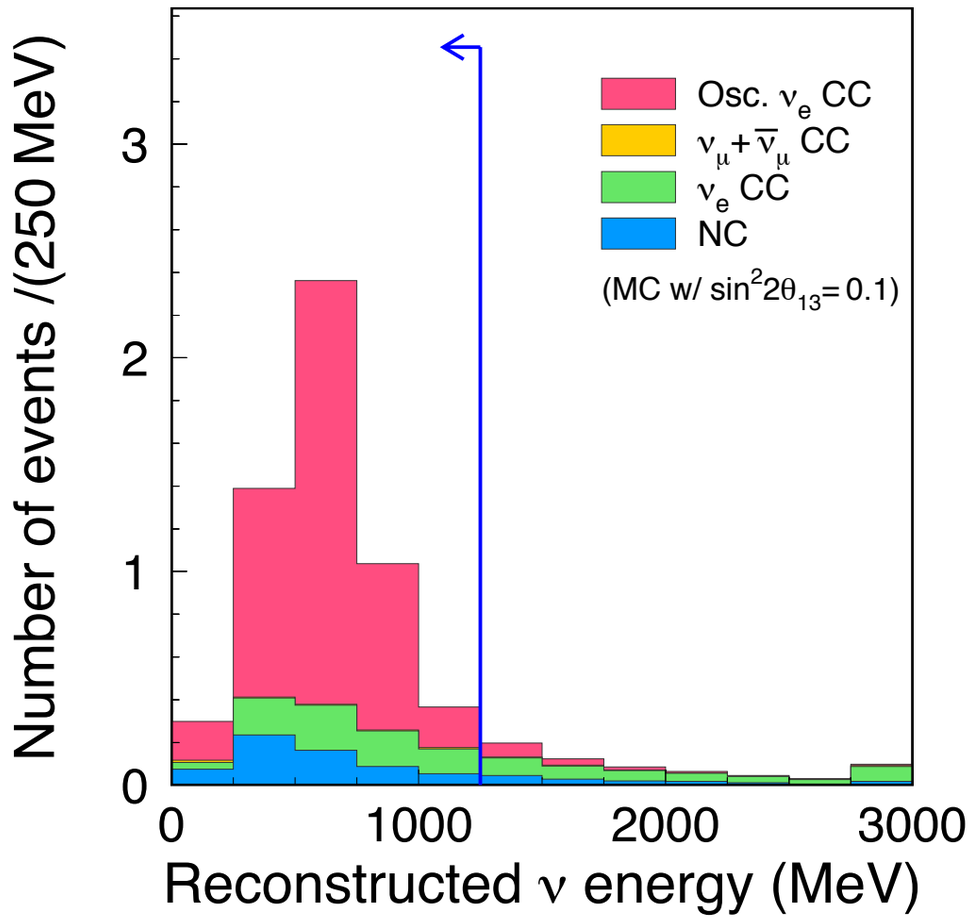
$$m_{\pi^0} = \sqrt{2p_1p_2(1-\cos\theta_{\gamma\gamma})}$$

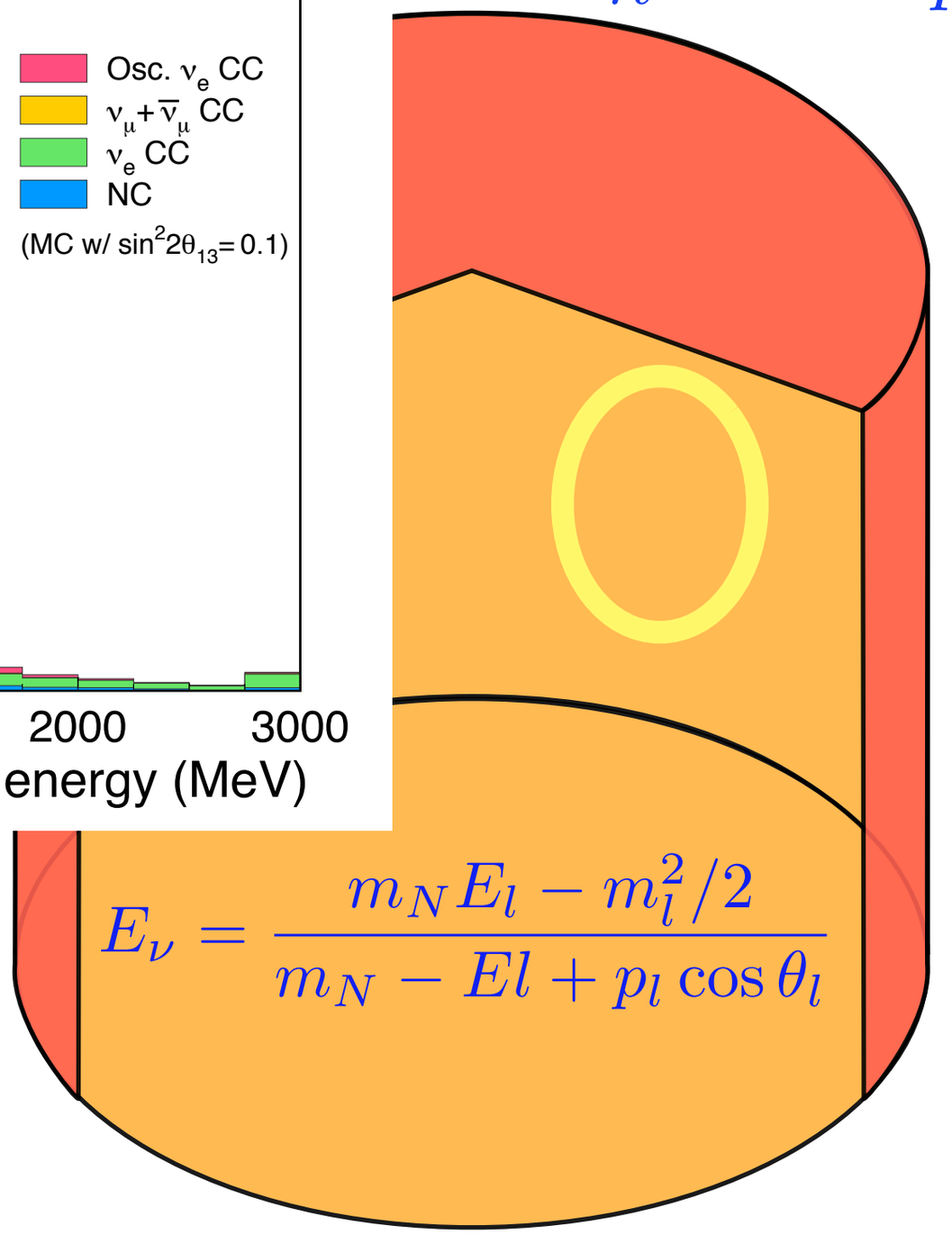
Signal: Single electron ring!

Event Selection



- Fiducial Volume
- Fully Contained
- E_{vis}>100 MeV
- One Ring
- E-like
- No μ→e decay
- POLfit cut (m_π<105 MeV)
- $E_\nu^{rec} < 1250$ MeV



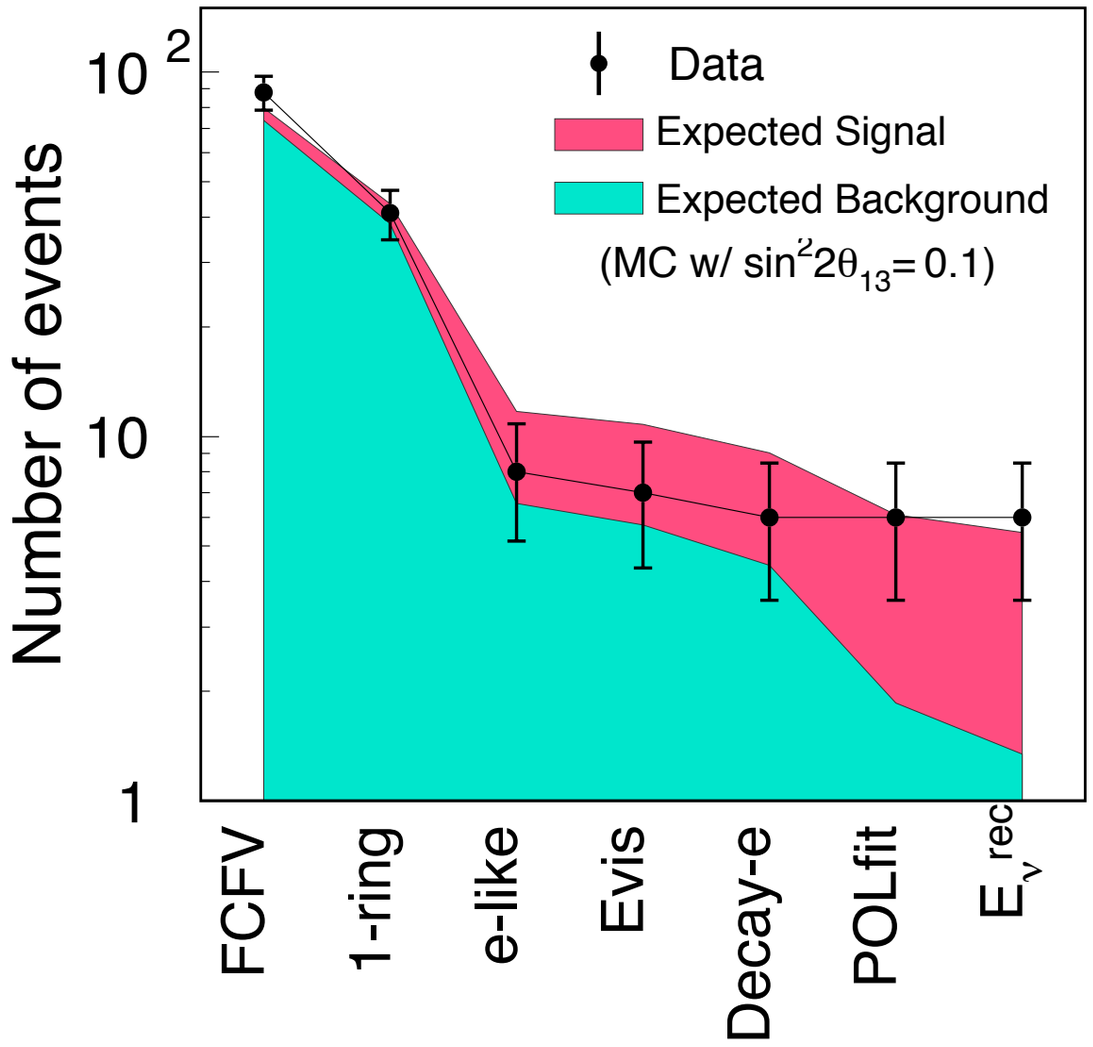


$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - El + p_l \cos\theta_l}$$

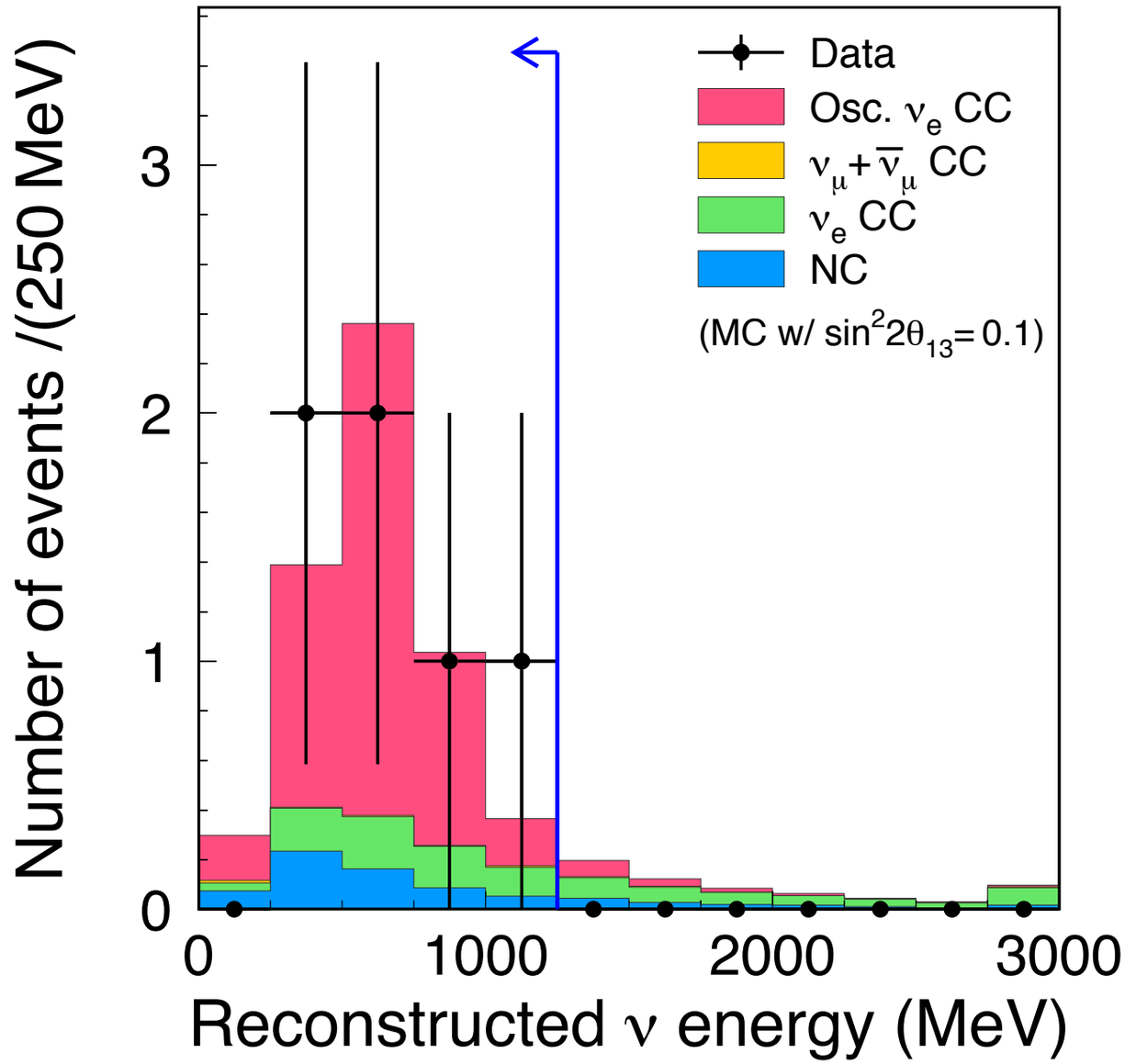
And now,
Let's look at the data!

Six Events Observed!

Applying the selections in sequence

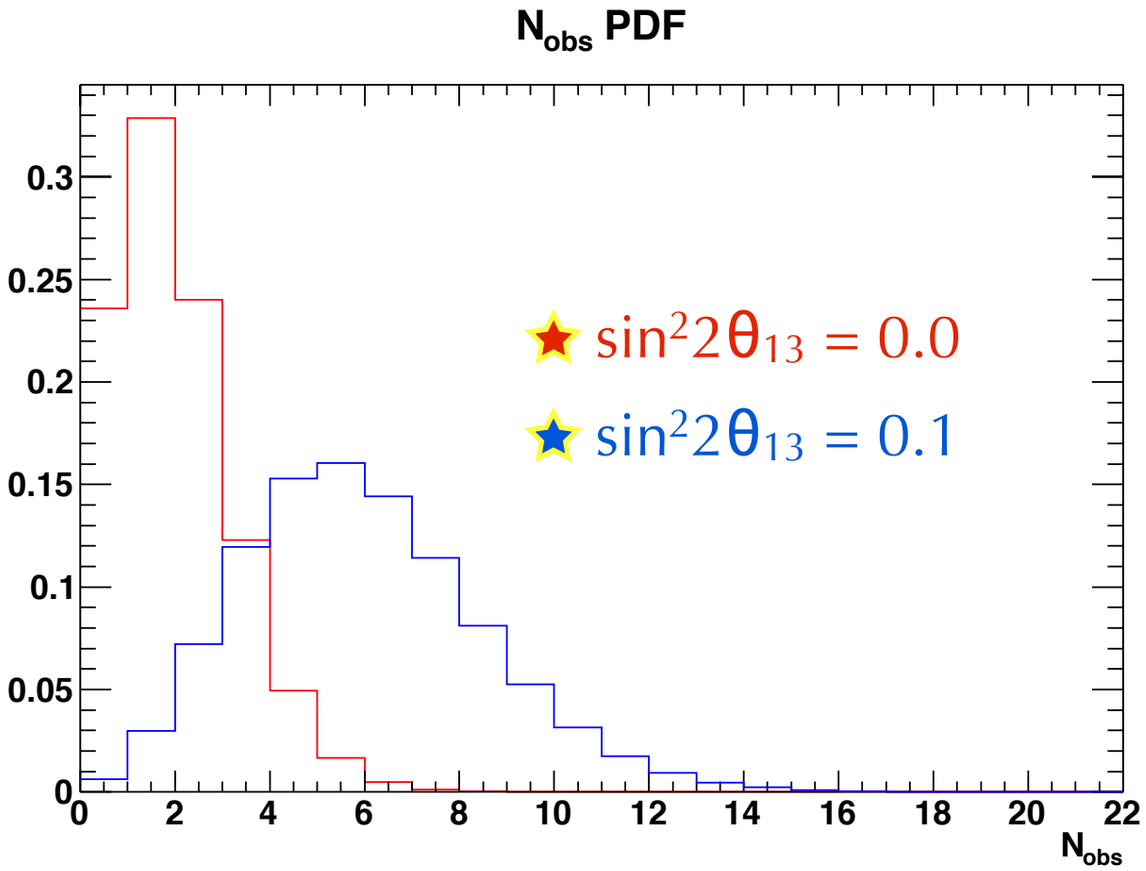


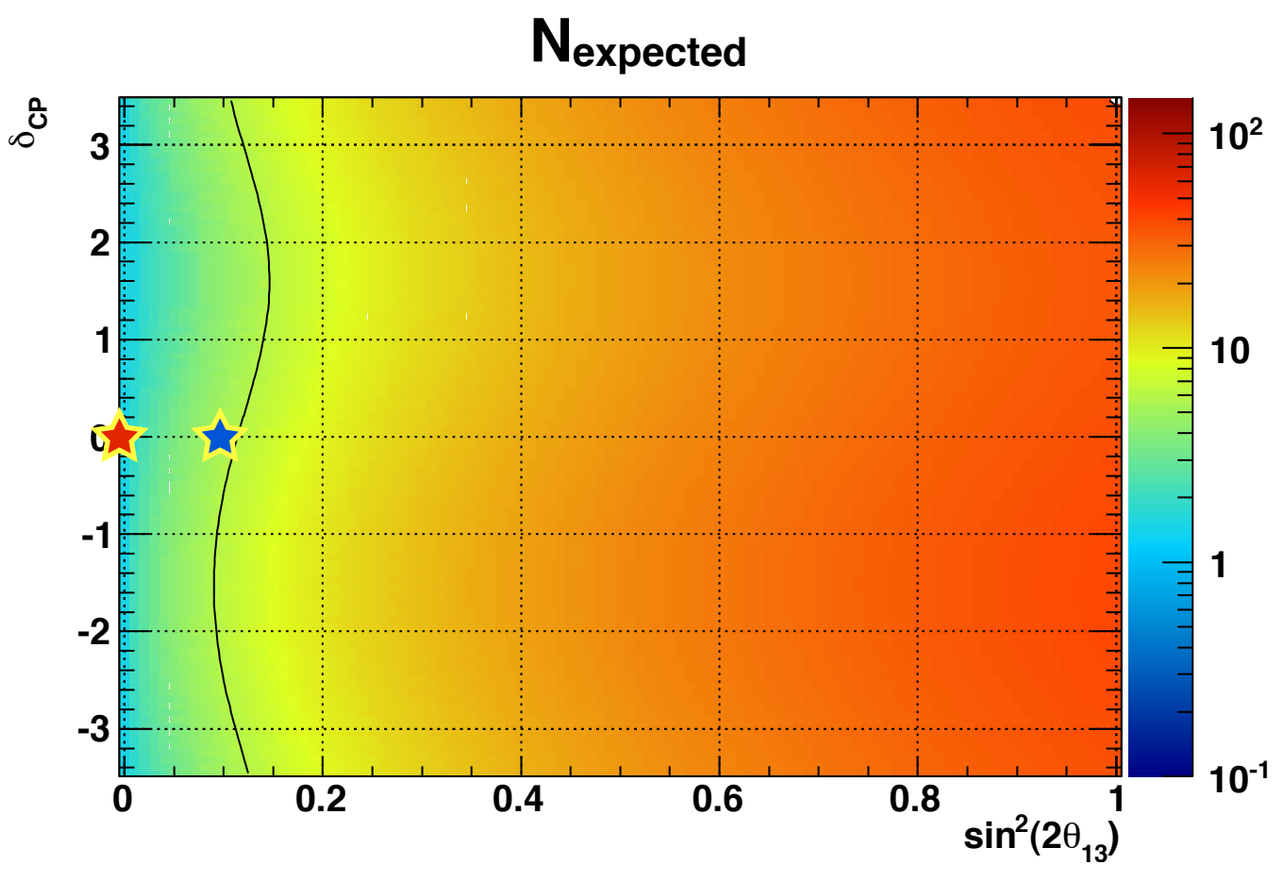
Six events remain, expected background 1.5 evts!



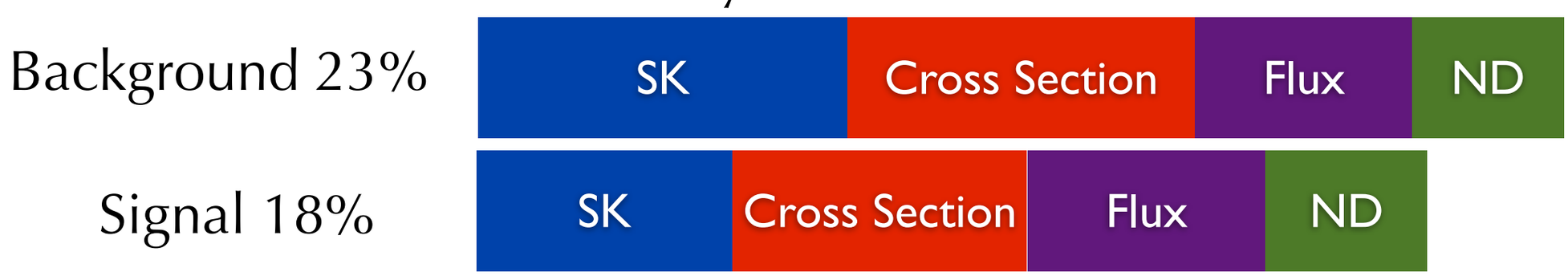
What it Means for θ_{13}

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

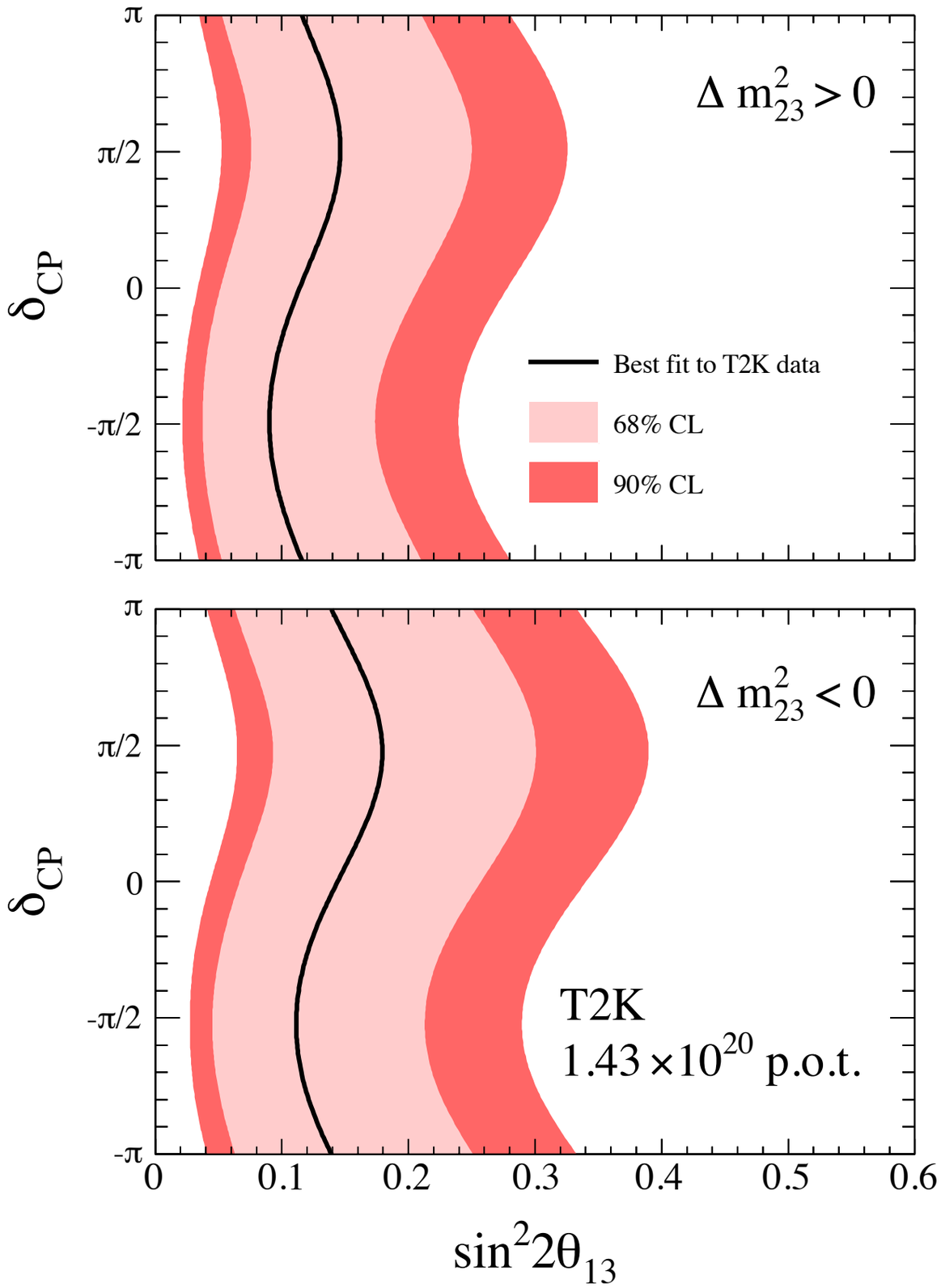




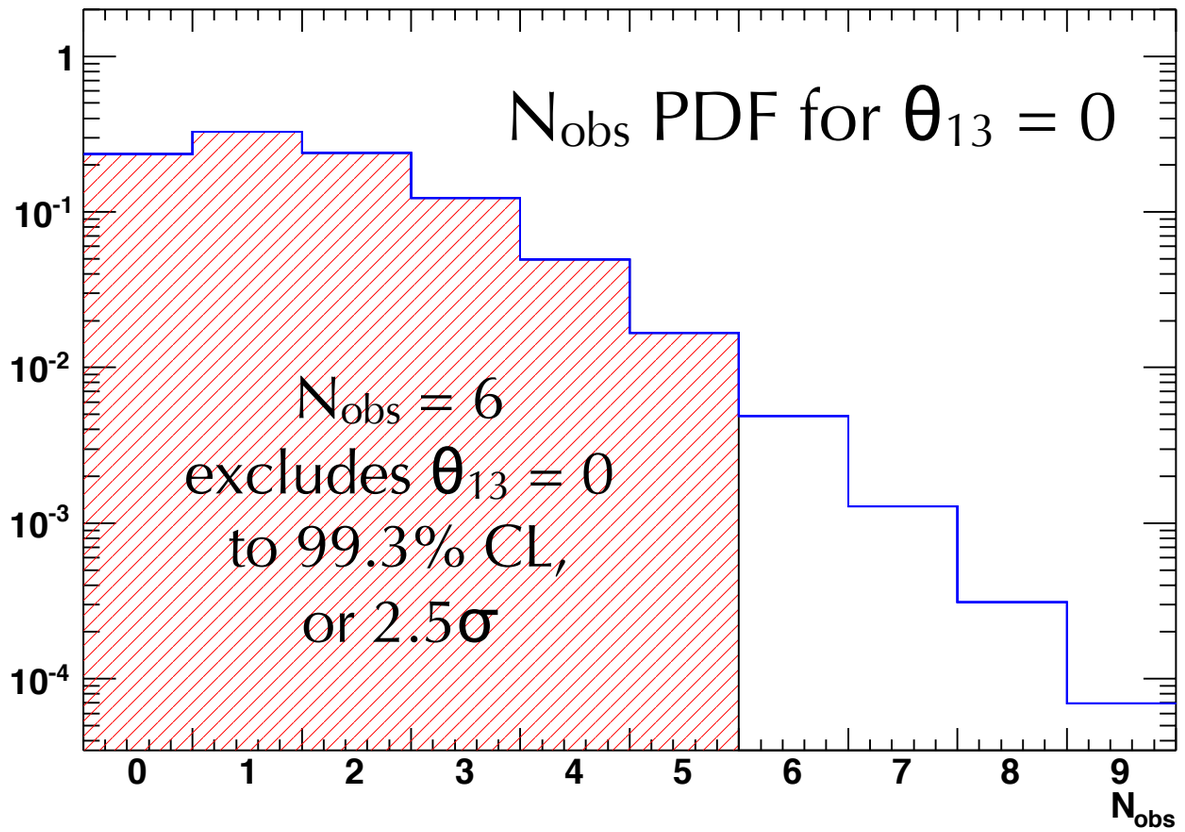
Systematic Errors



Results



- $\theta_{13} = 0$ is excluded to > 90% CL.
- Best fit: $\sin^2 2\theta_{13} = 0.11$
- First non-zero measurement of θ_{13} to better than 90% CL!



Summary/Looking Ahead

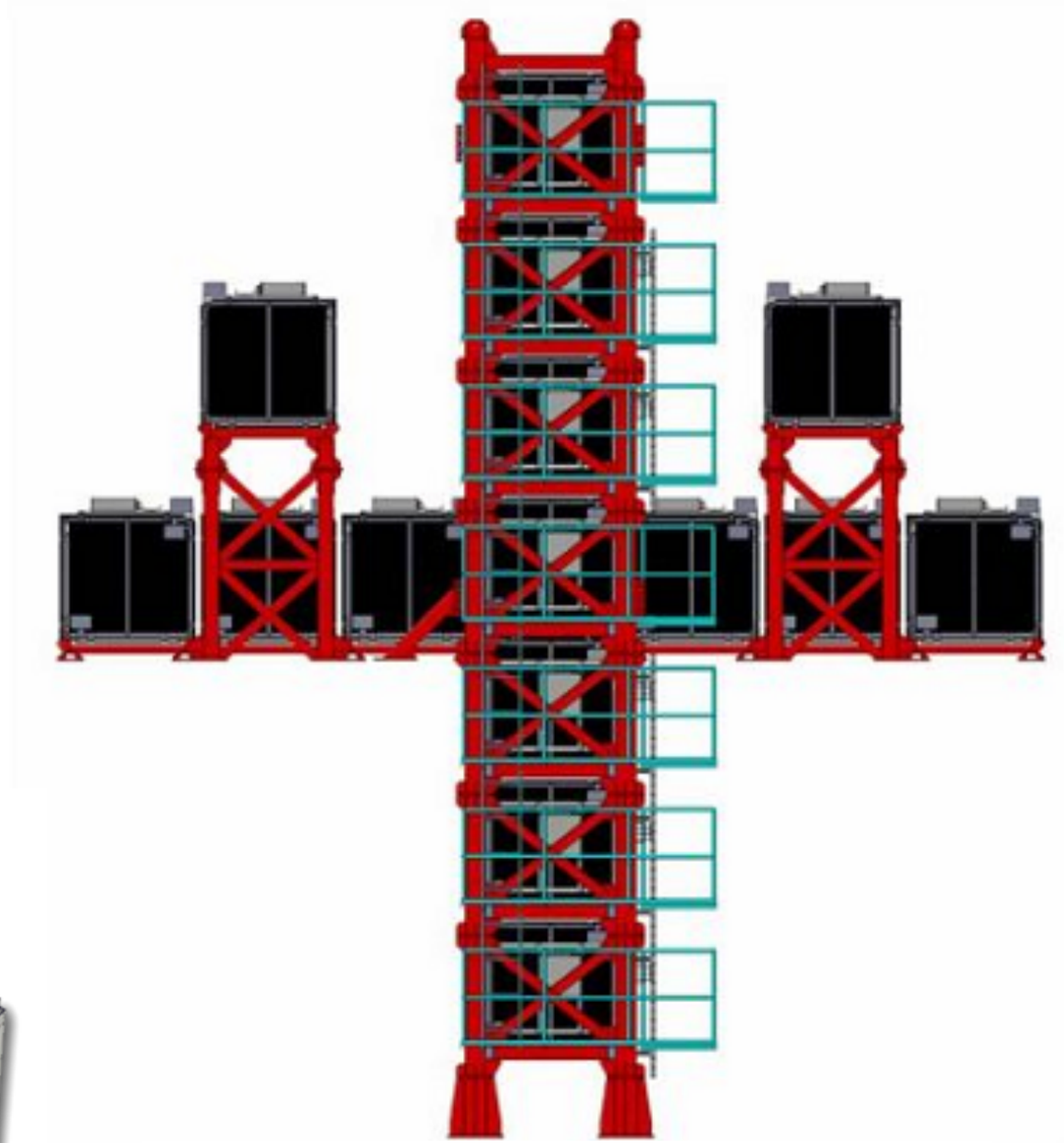
- The T2K experiment features an off-axis beam of ν_μ with near detectors and a far detector, Super-Kamiokande, 295 km away.
- It has found indications of ν_e appearance in a ν_μ beam, and has excluded $\theta_{13} = 0$ at ~ 99.3% CL.
- 6 events were observed on an expected background of 1.5 events.
- Experiment is temporarily disabled due to March 2011 earthquake, but will return in 2012 to deliver stronger results!

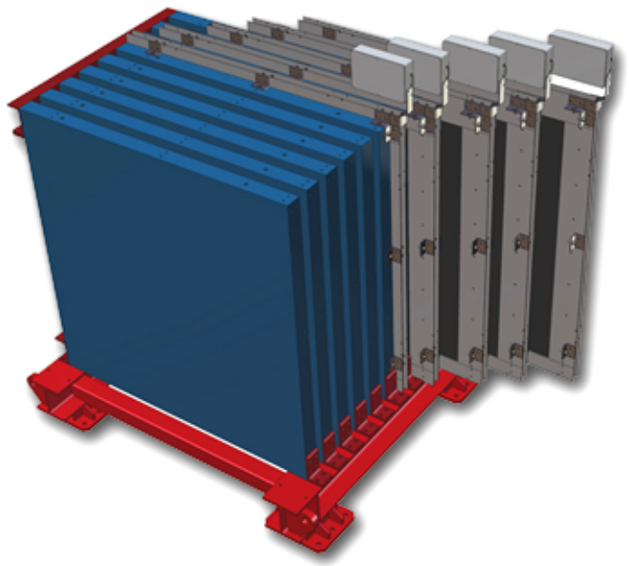
Thank You!

Supplemental Slides

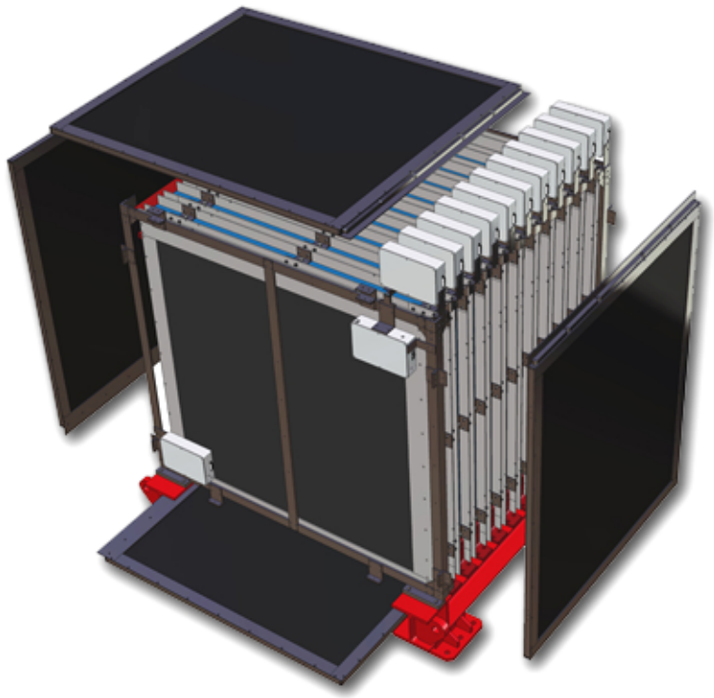
Near Detectors: INGRID

- Measure beam direction and intensity
- On-axis detector
- Iron/scintillator alternating layers, modular design.

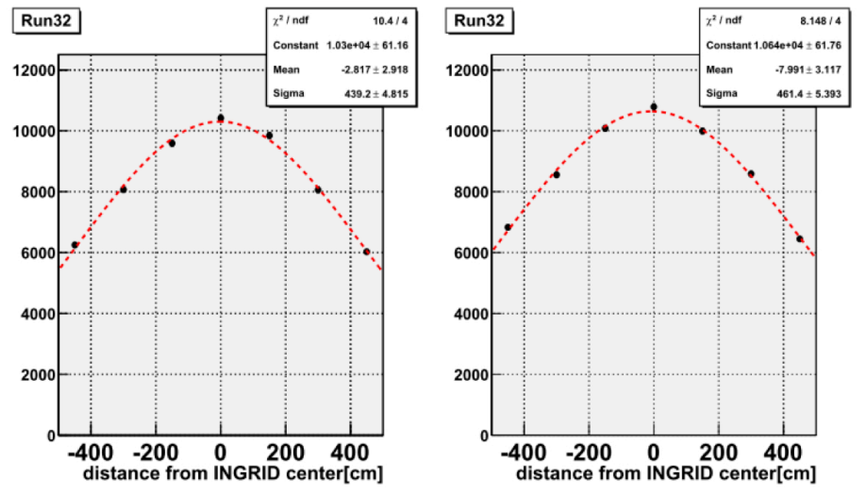




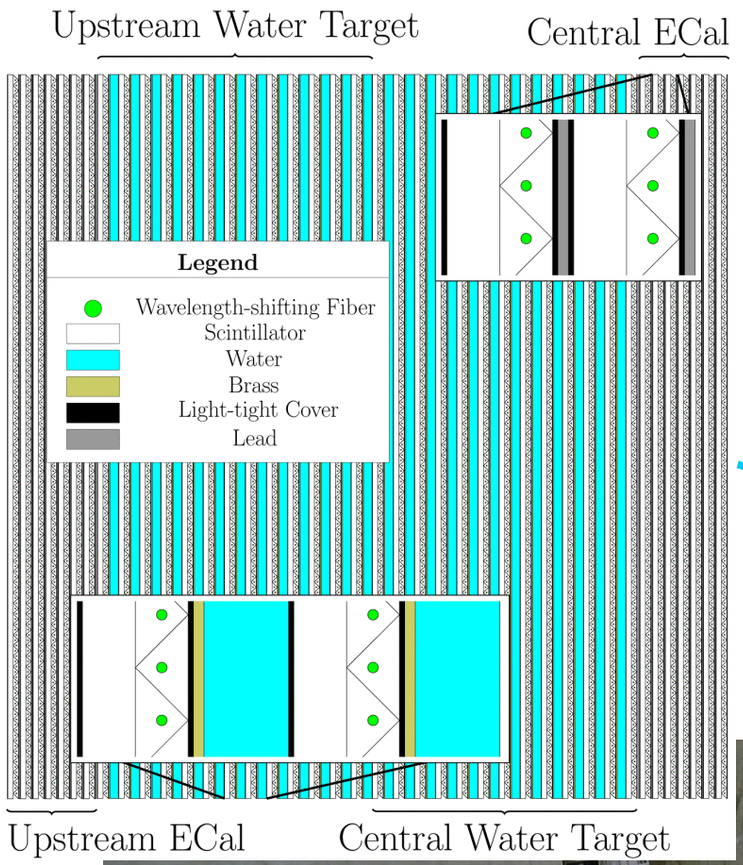
Scintillator Planes
Iron Plates

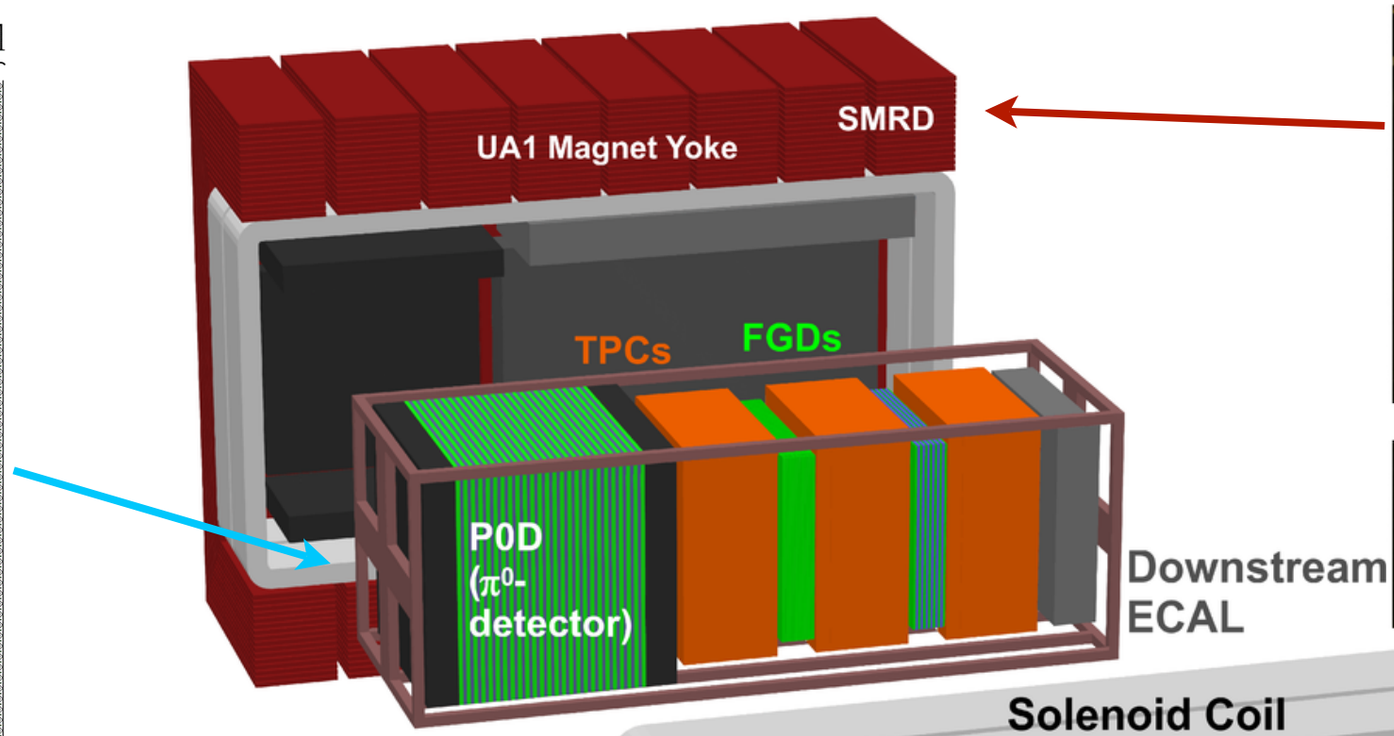


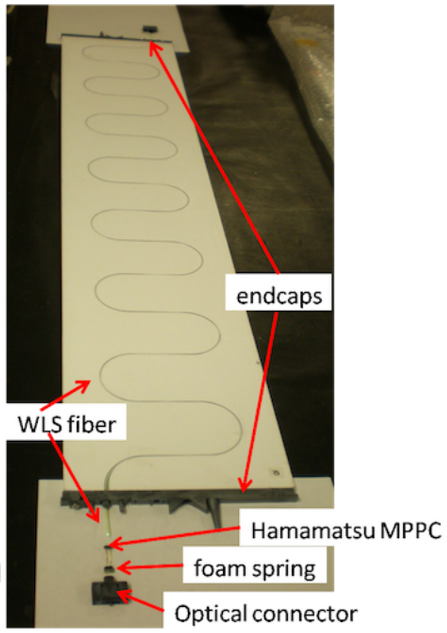
Veto Planes

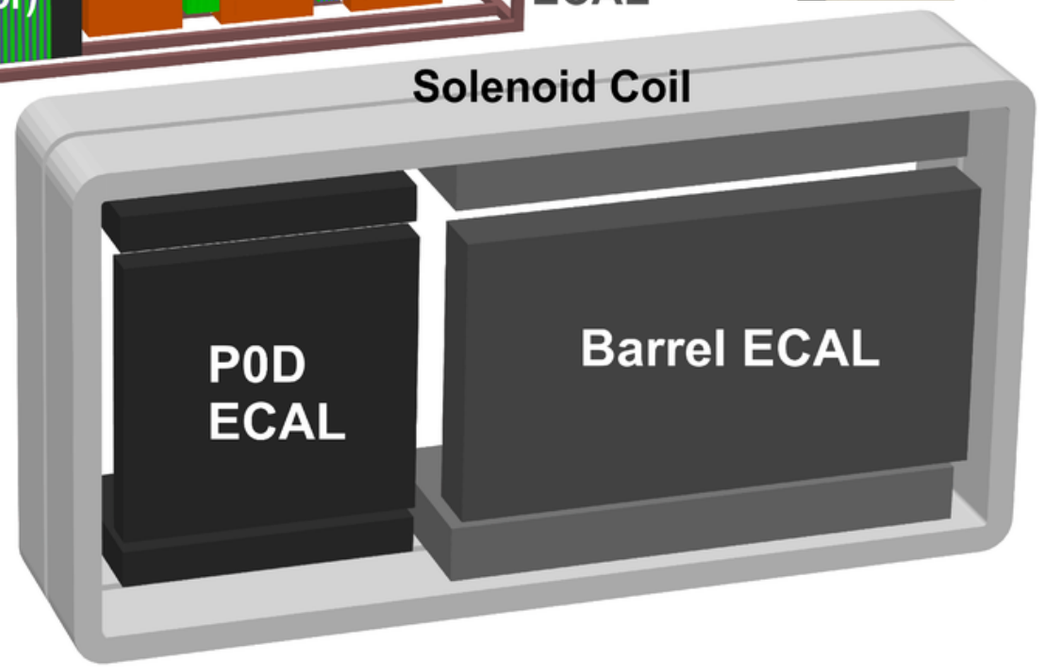


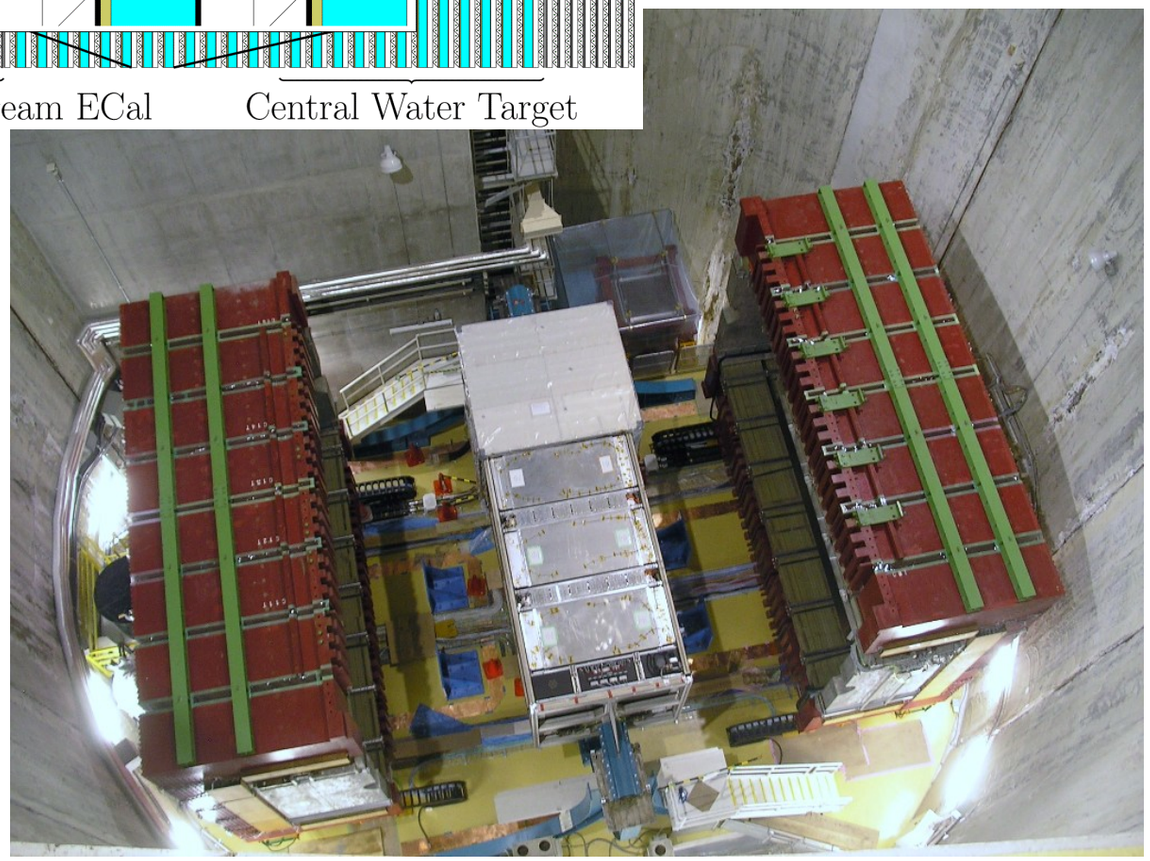
Near Detectors: ND280 Off-Axis



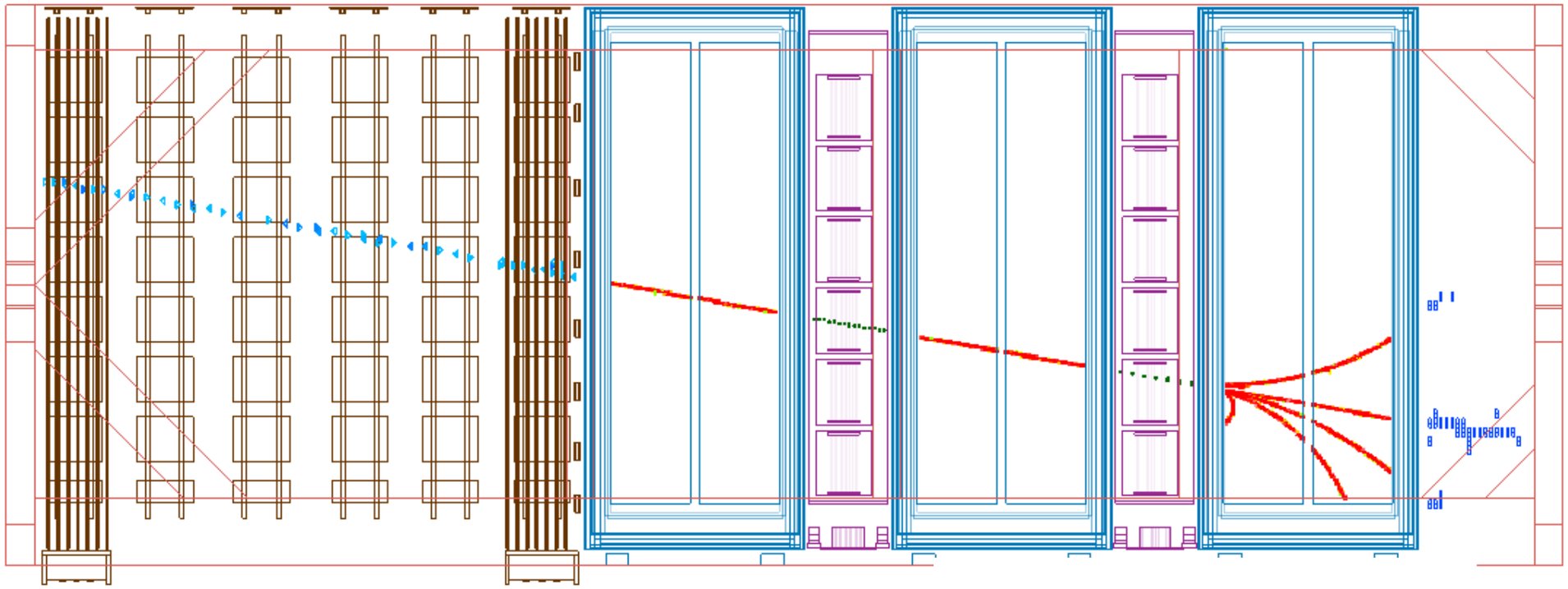


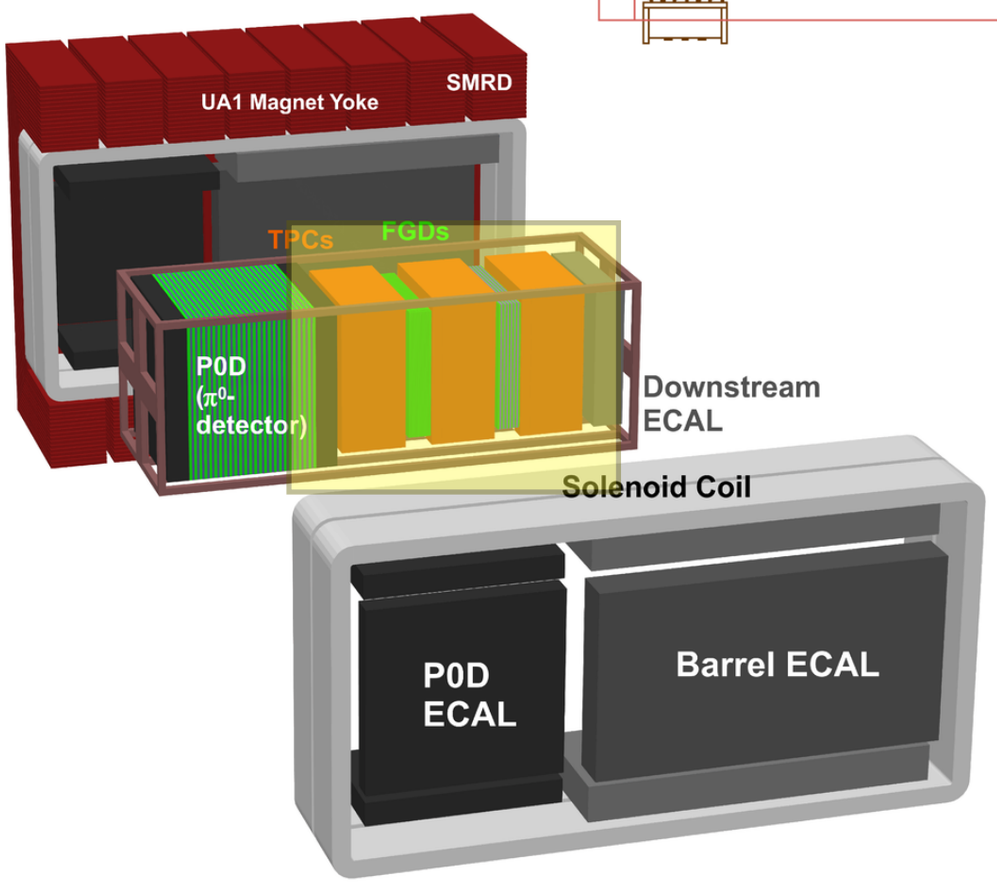


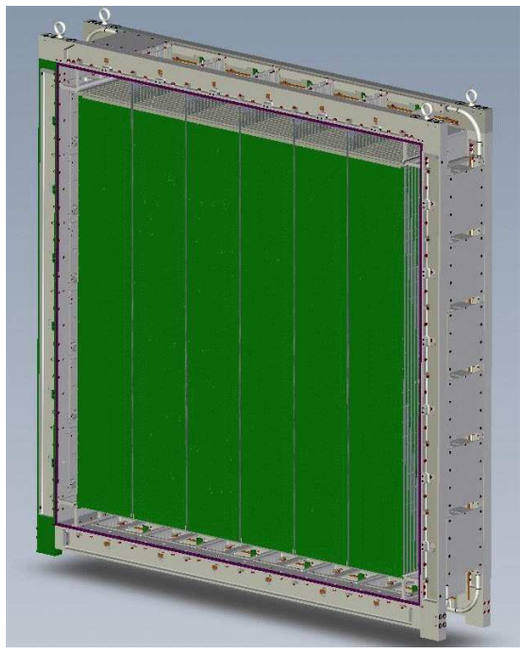


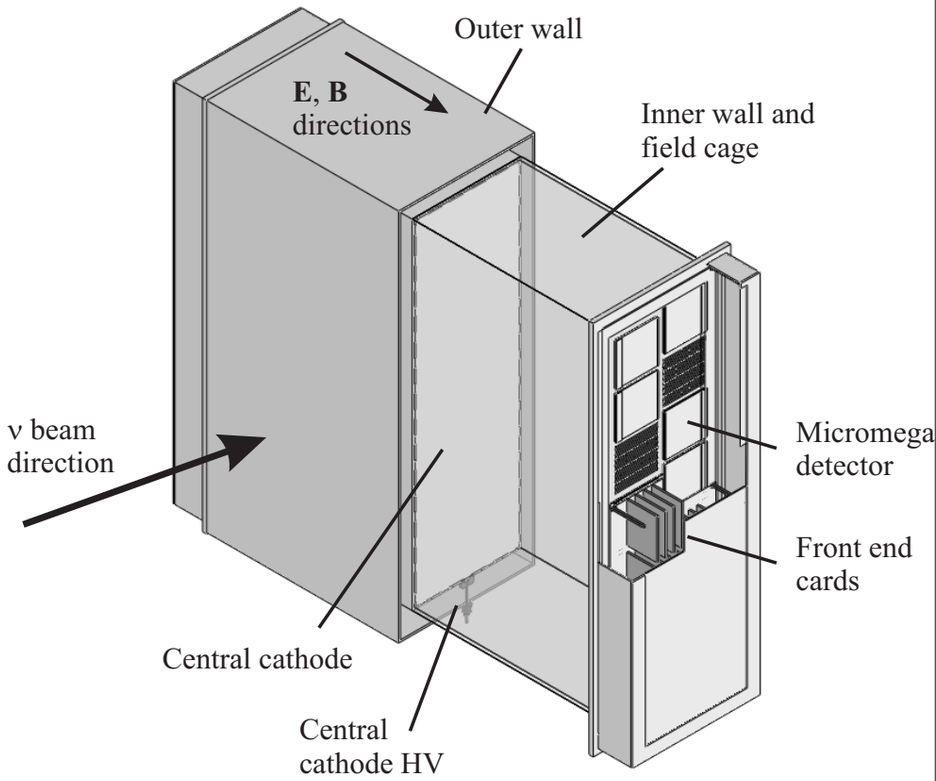


Near Detectors: ND280 Off-Axis









Neutrino Beam (pt. 3)

Beam Dump

Stops all $\pi^{\pm}$, all μ with E<5 GeV

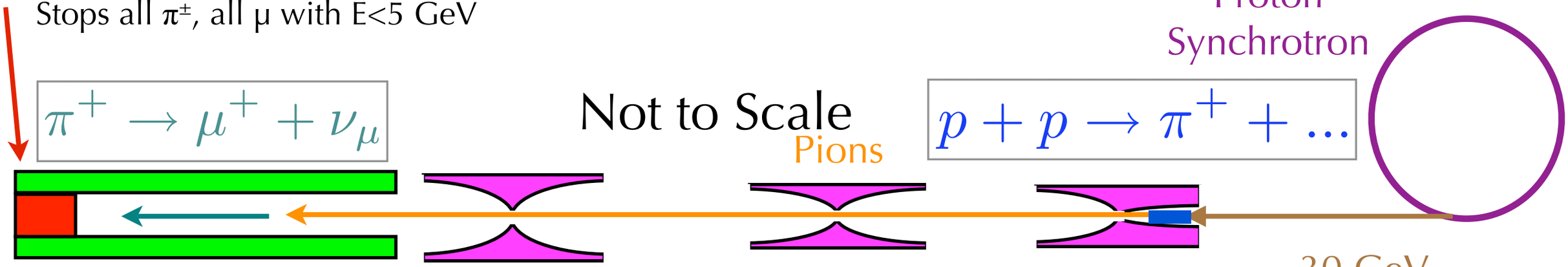
Proton Synchrotron

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

Not to Scale

Pions

$p + p \rightarrow \pi^+ + \ldots$

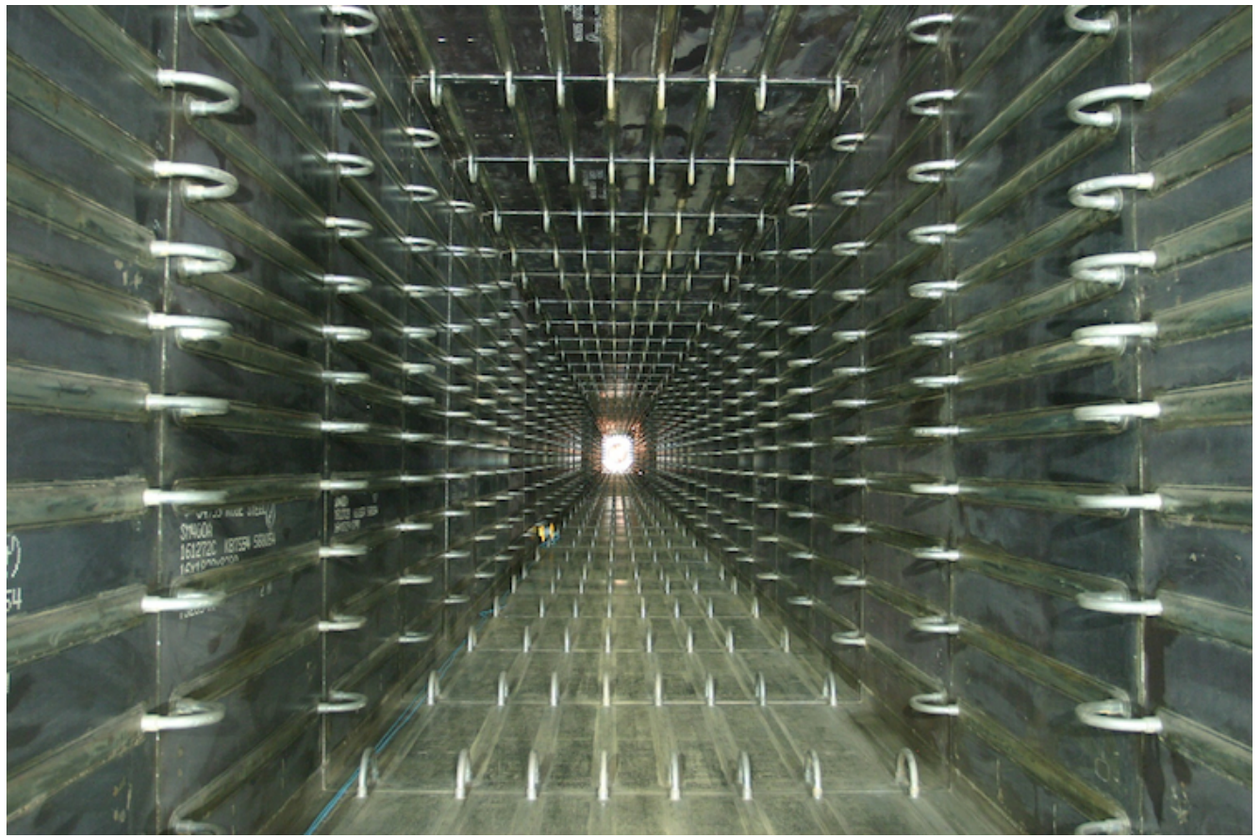


Decay Volume (200m)

Magnetic Focusing Horns

Graphite Target

30 GeV Protons



Main Decay

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

Other Decays

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

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

$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

And many more...

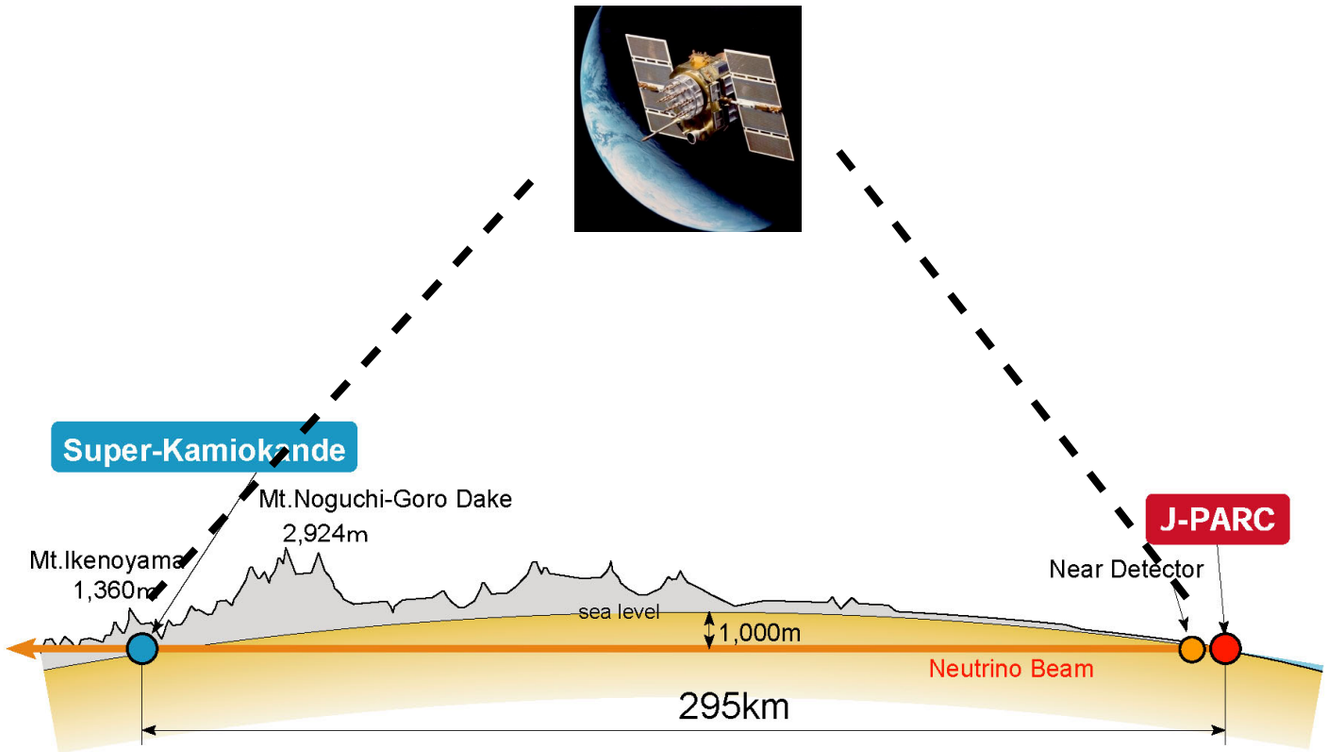
θ_{13} and δ_{CP}

- δ_{CP} observation only possible with all three mixing angles non-zero!
- Non-zero δ_{CP} means neutrinos and anti-neutrinos oscillate differently, this may be related to the matter dominance over anti-matter in the universe.
- To measure δ_{CP}: Perform ν_e appearance experiments with both neutrinos and anti-neutrinos.
- δ_{CP} does not manifest in disappearance experiments!

$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2 \qquad P_{\alpha\to\alpha} = \left|\sum_i |U_{\alpha i}|^2 e^{-im_i^2 L/2E}\right|^2$$

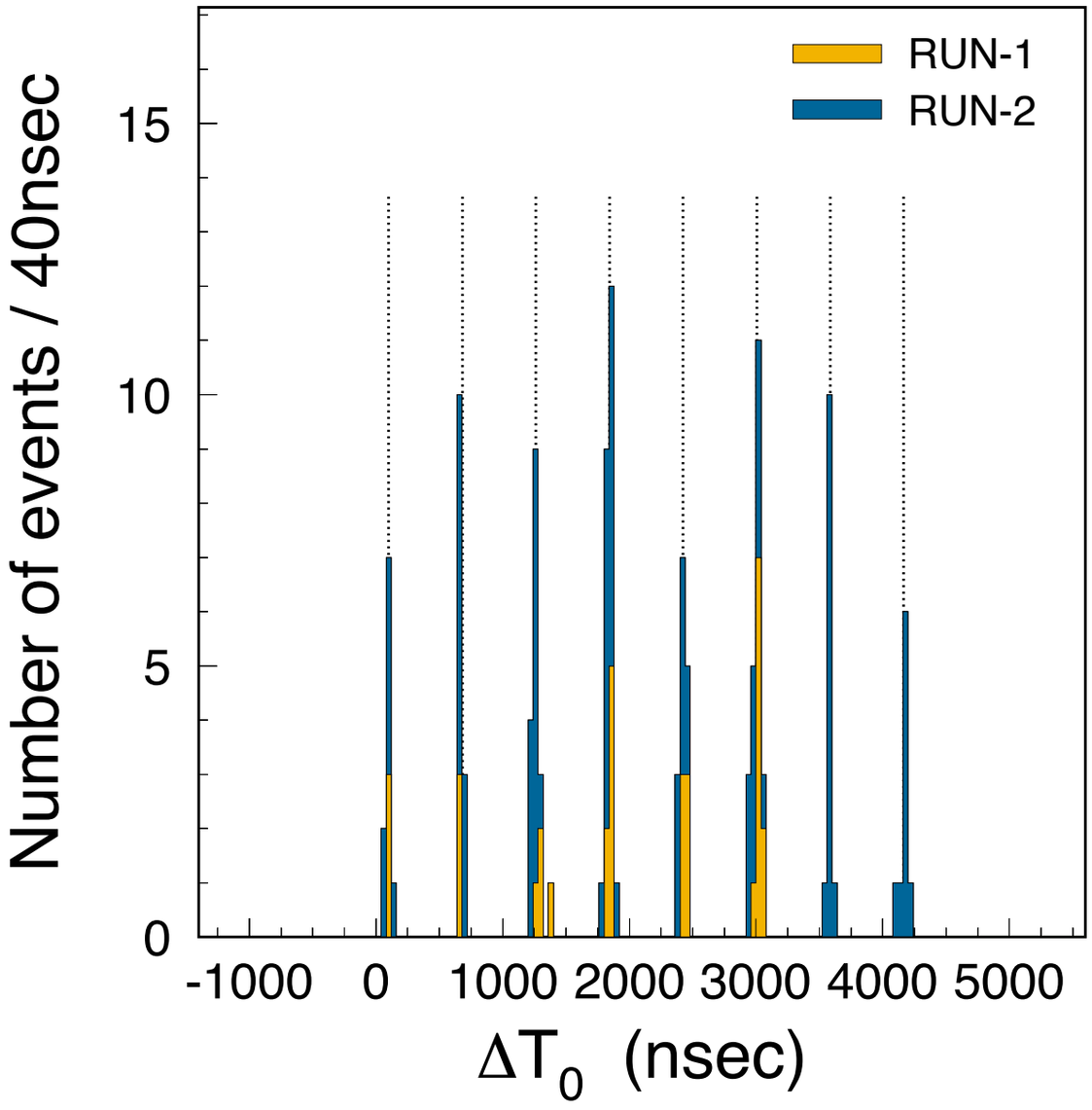
Current T2K Timing System

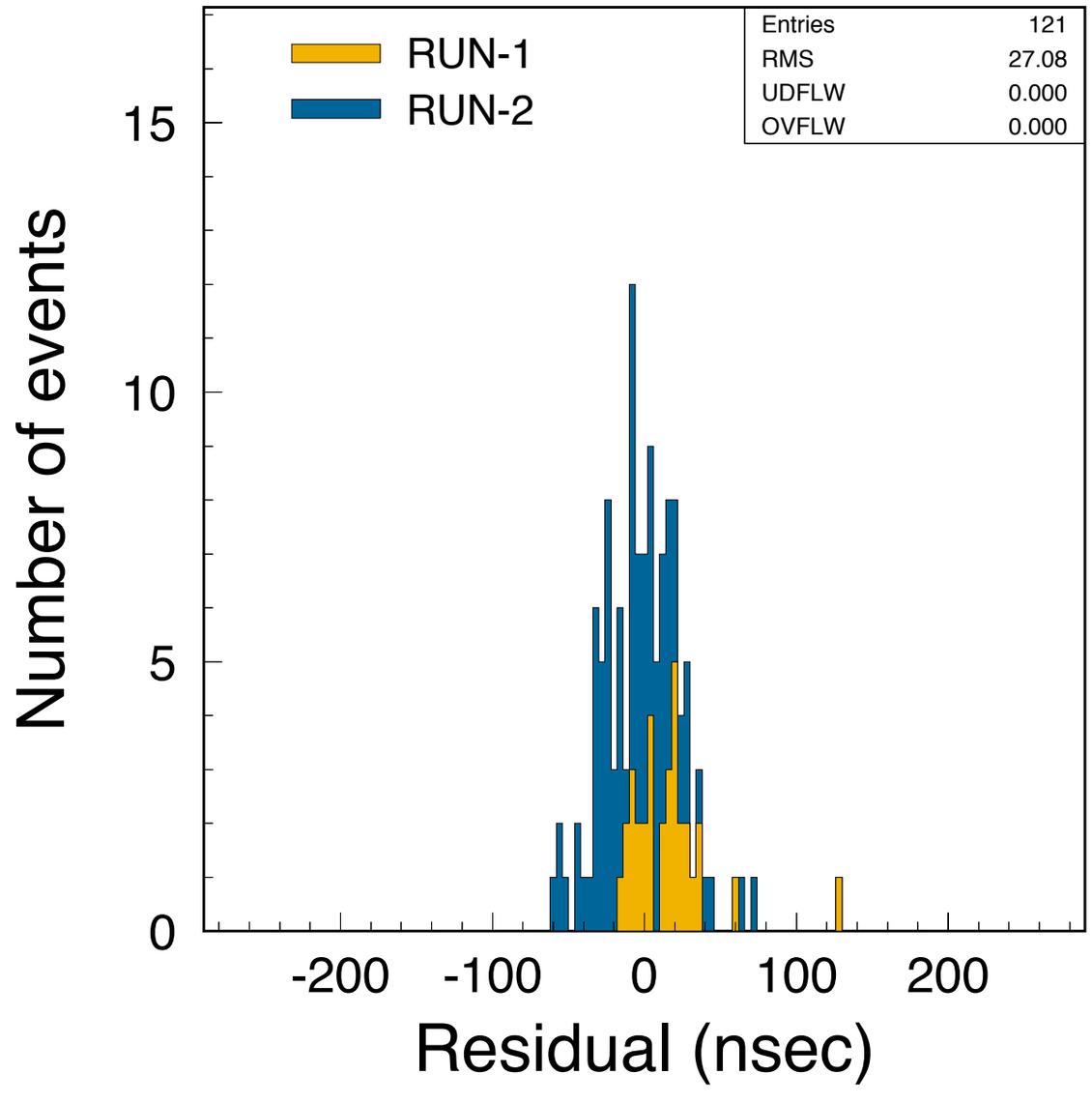
- T2K beam trigger comes from kicker magnets
- "Commonview" GPS mode used



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

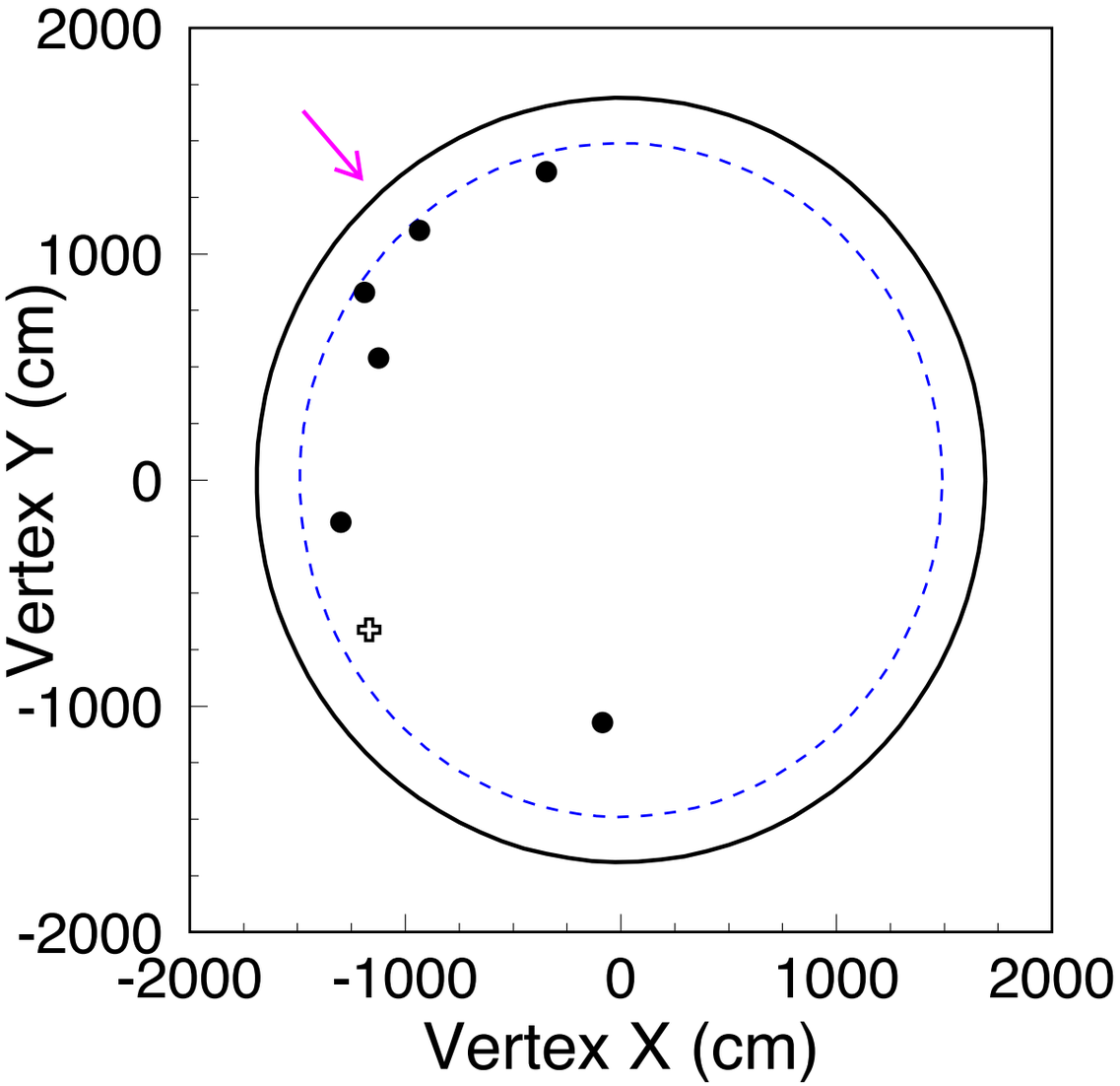
T2K Beam Timing

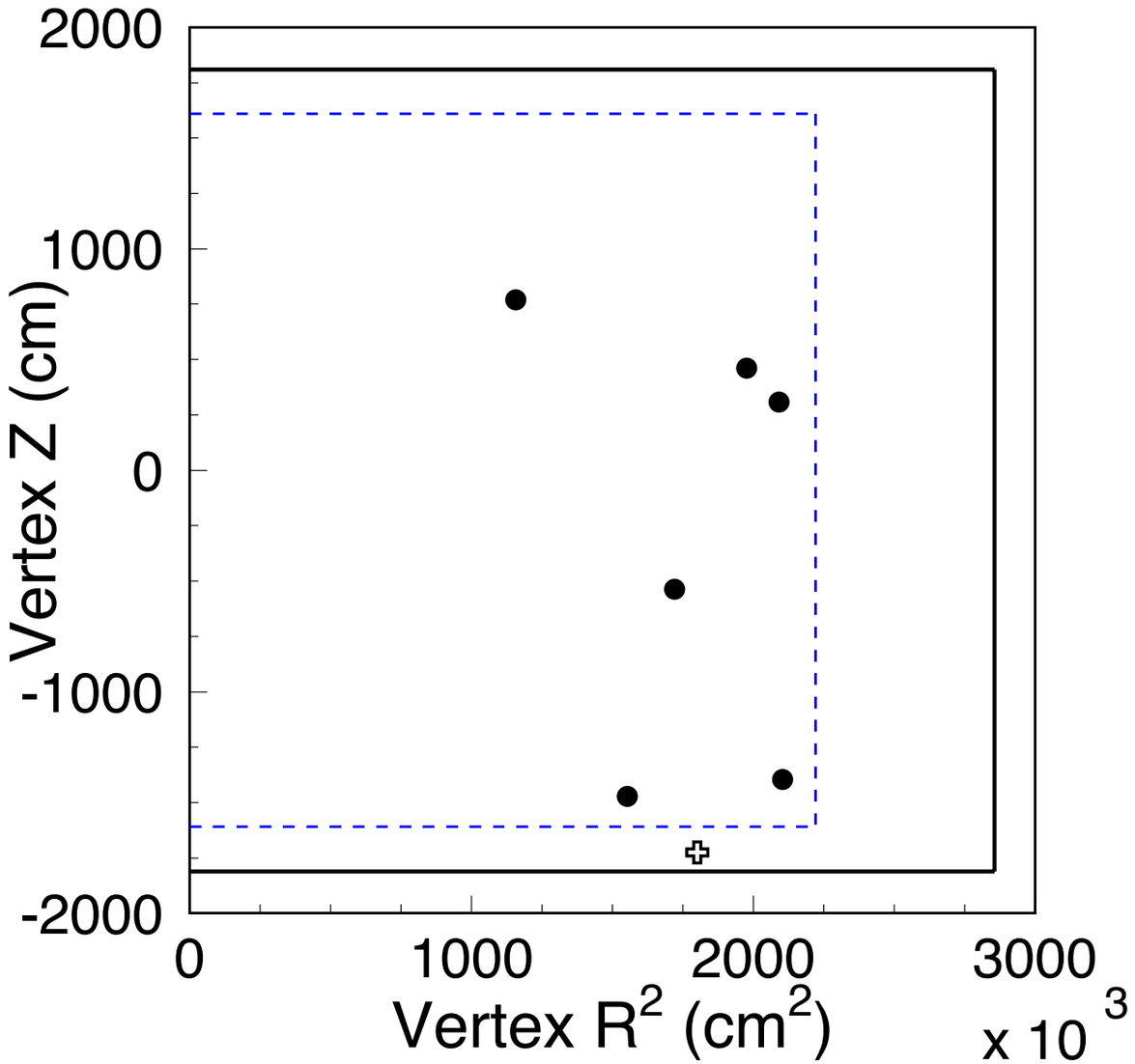




- Bunch structure from protons in beam visible at SK.
- Narrow bunches could be an advantage for T2K for TOF measurement.

Six Events Observed





Vertices appear surprisingly clustered, but extensive studies found no evidence for contamination from outside the detector.

Beam Purity and Spectrum

Main Decay

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

Other Decays

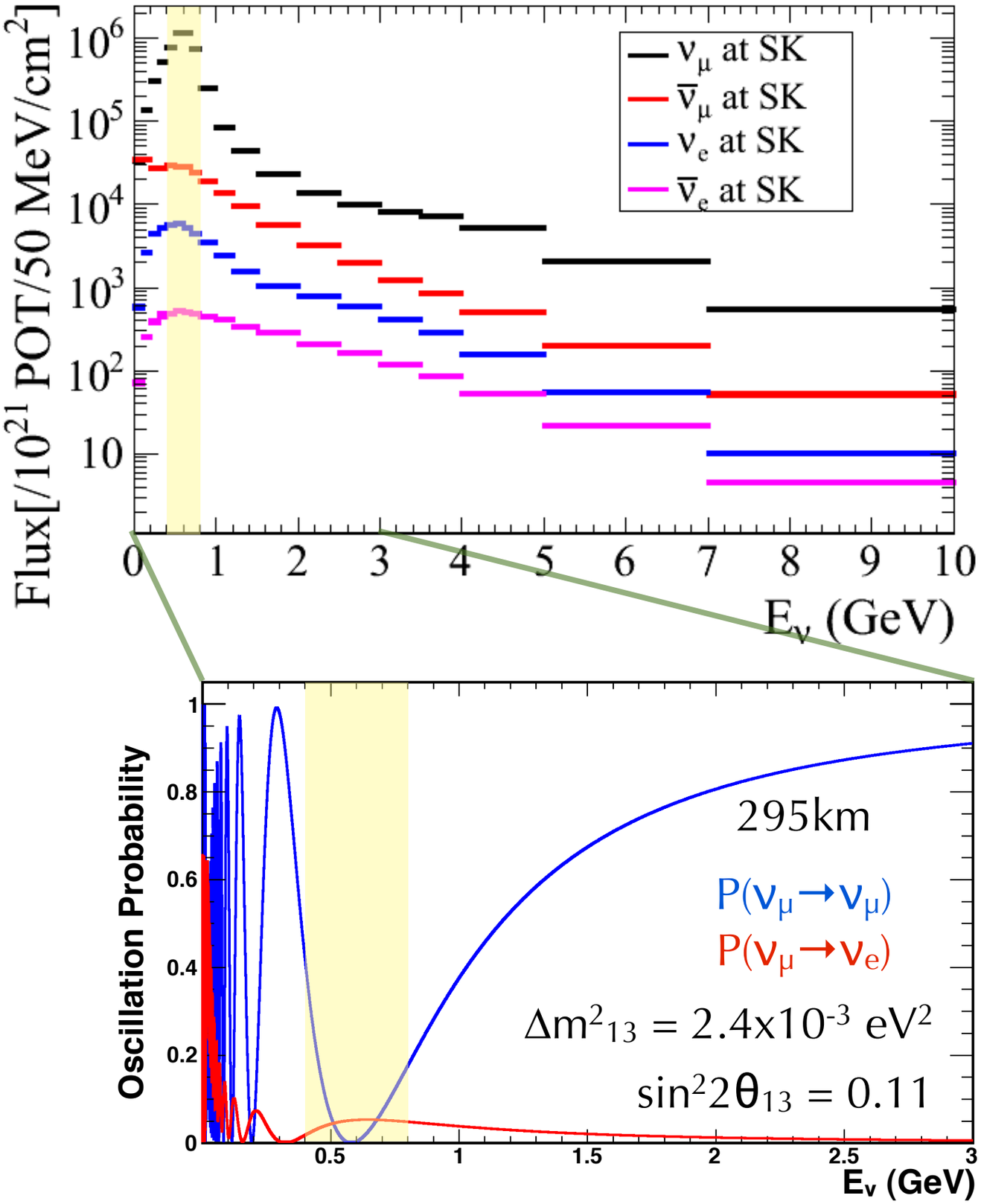
$$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$$

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

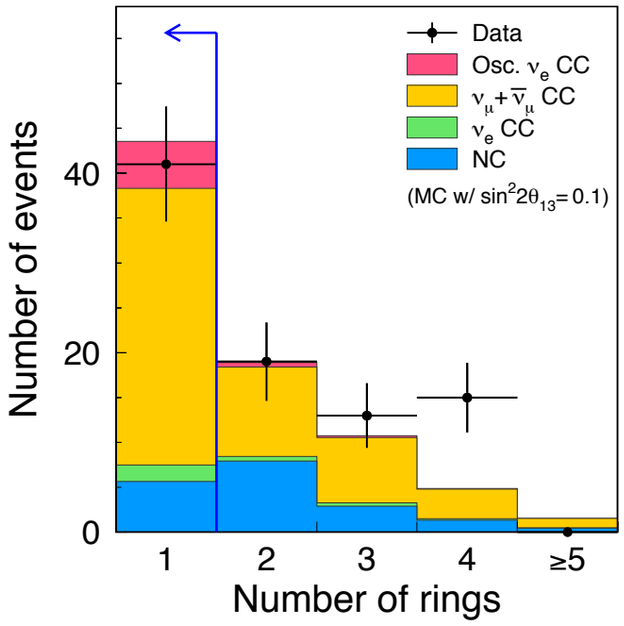
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

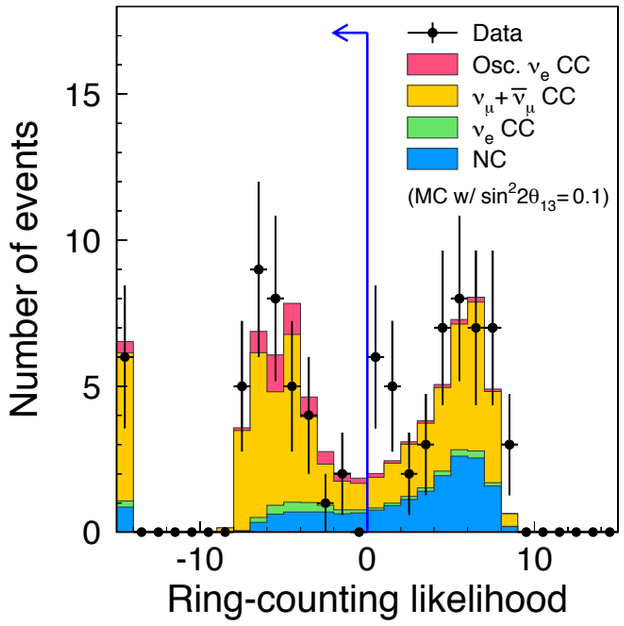
And many more...

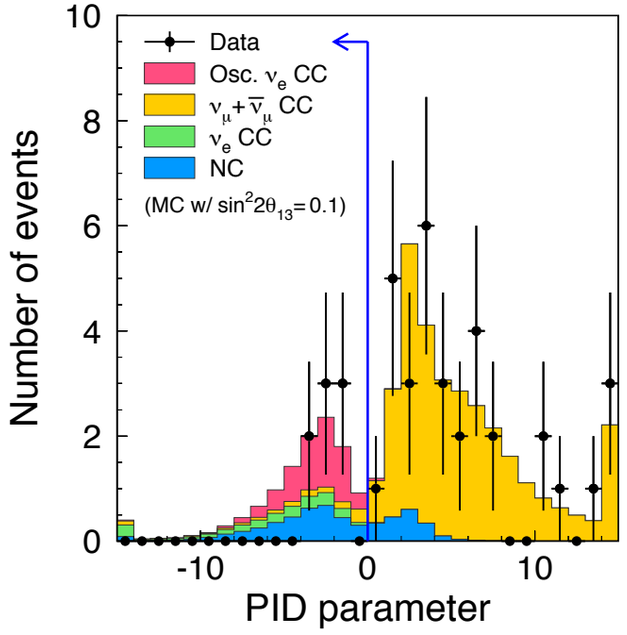
- Beam energy tuned to Δm^2_{13} ($\approx \Delta m^2_{23}$) oscillation maximum.
- Maximum ν_μ disappearance, maximum ν_e appearance.

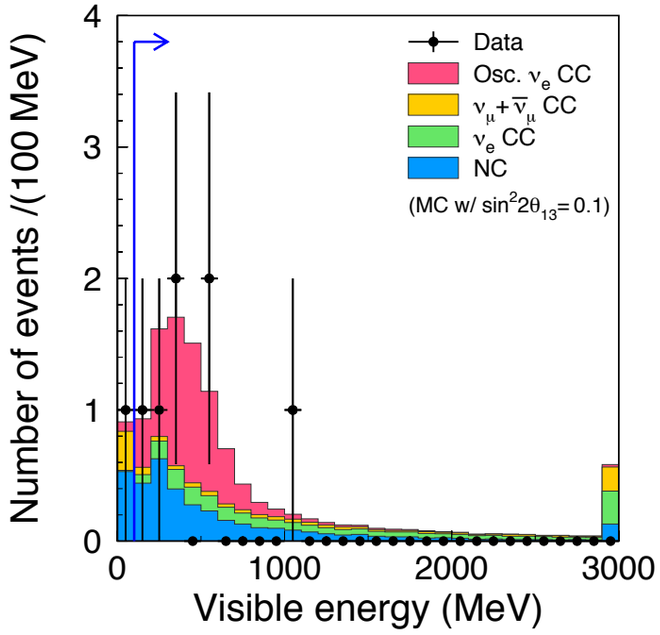


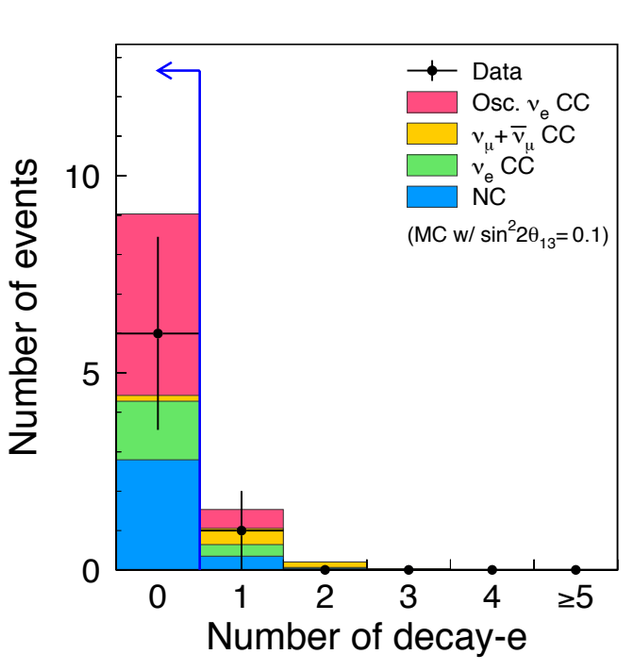
Six Events Observed

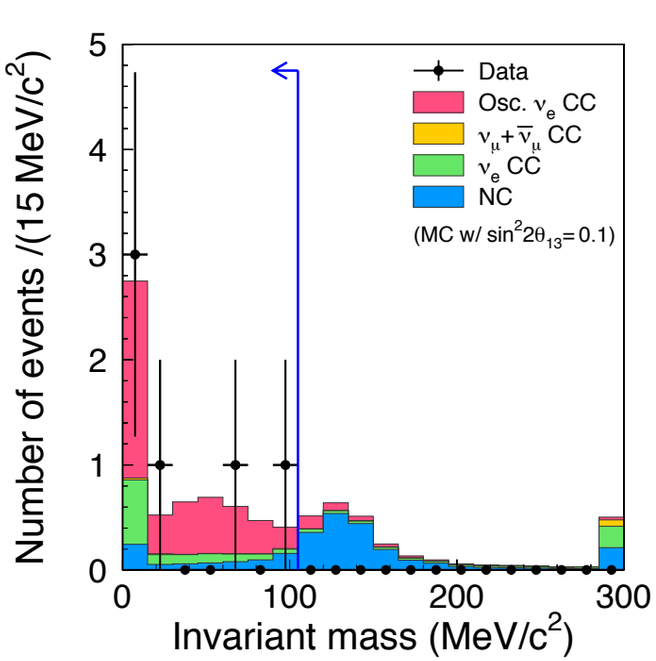












Six events remain, expected background 1.5 evts.