ETH zürich

Search for CP violation at T2K/Hyper-K and the role of the Near Detector

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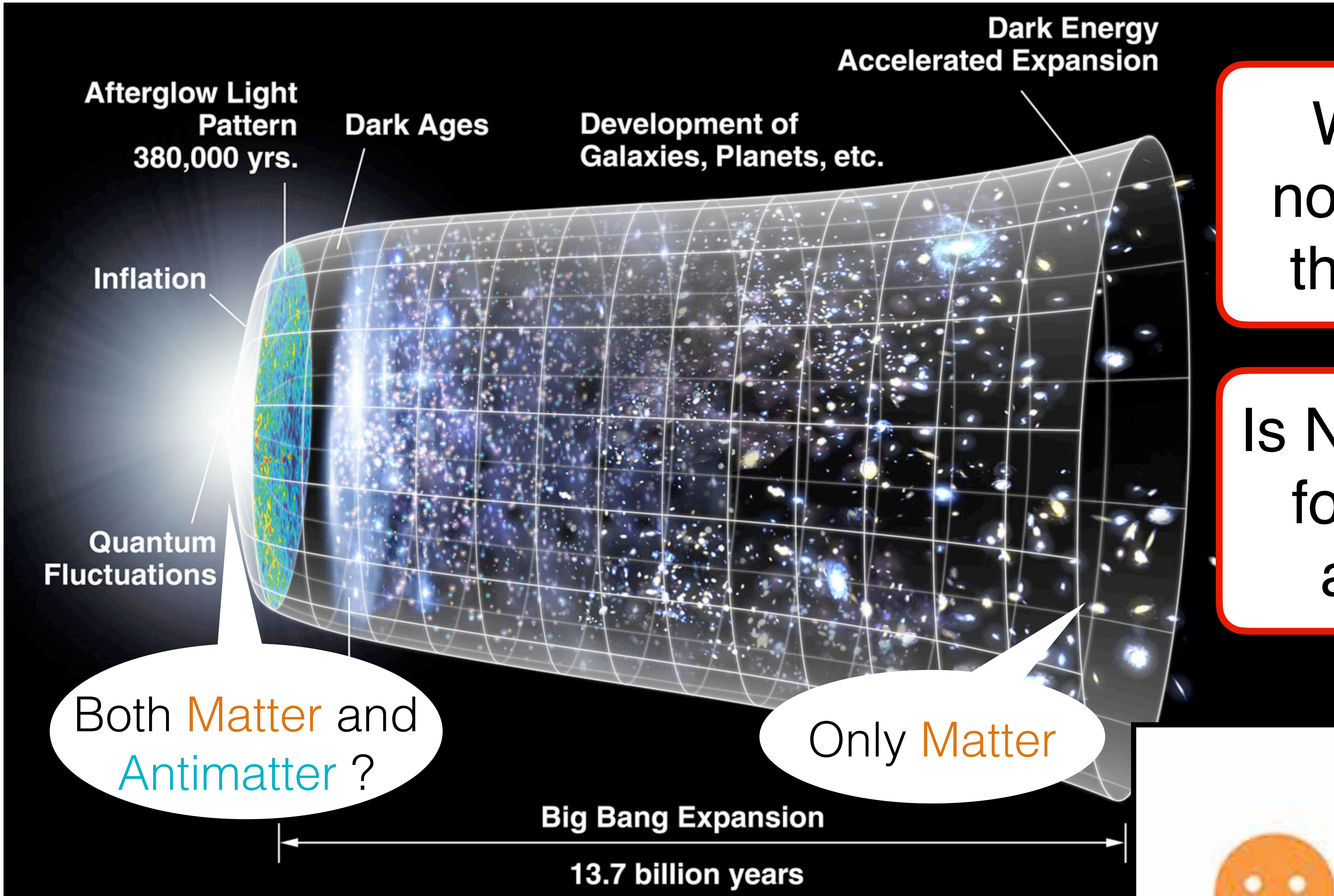
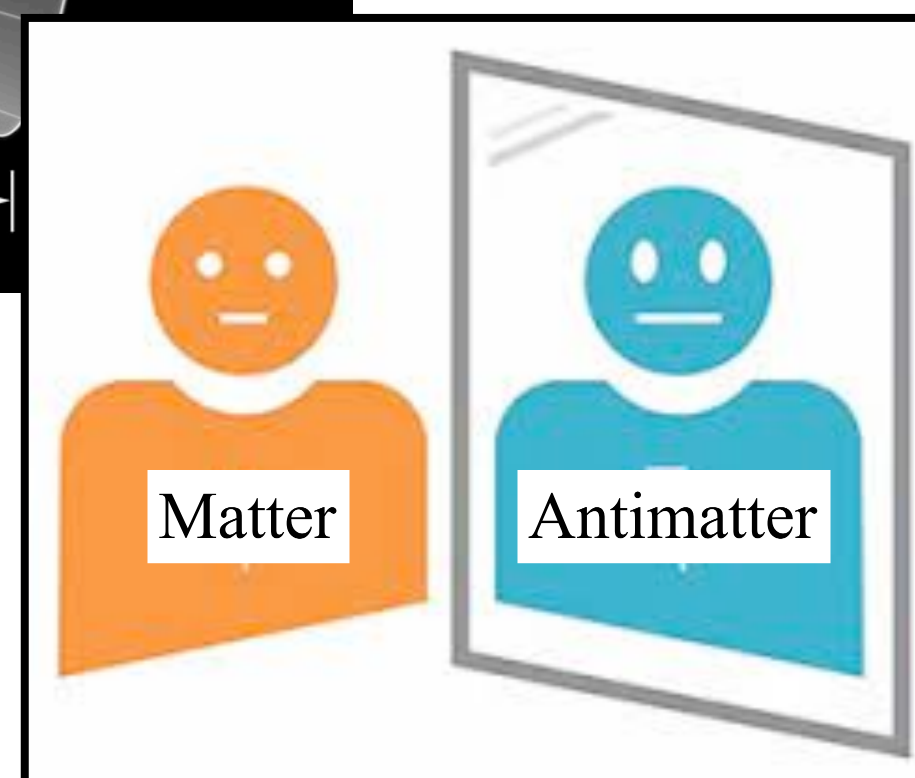
University of Liverpool - Seminar

23rd November 2022



Why there is no antimatter in the universe ?

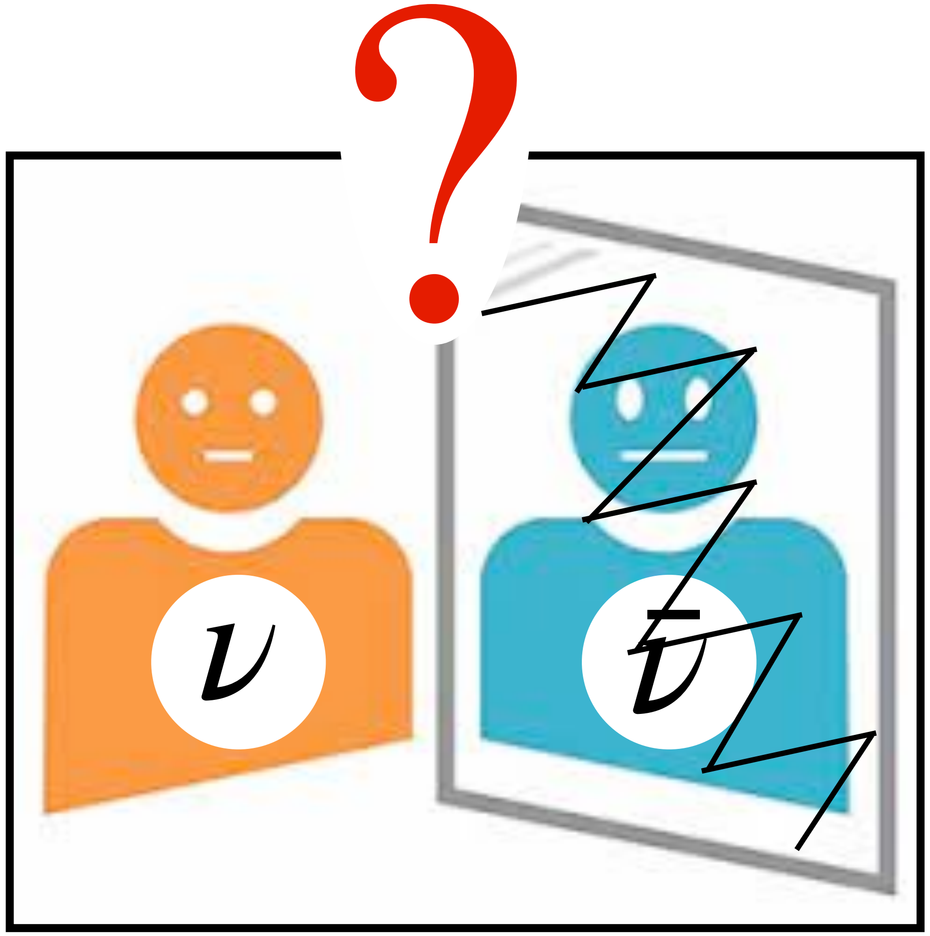
Is Nature different for matter and antimatter ?



Need a mechanism that changes the physics of matter and antimatter

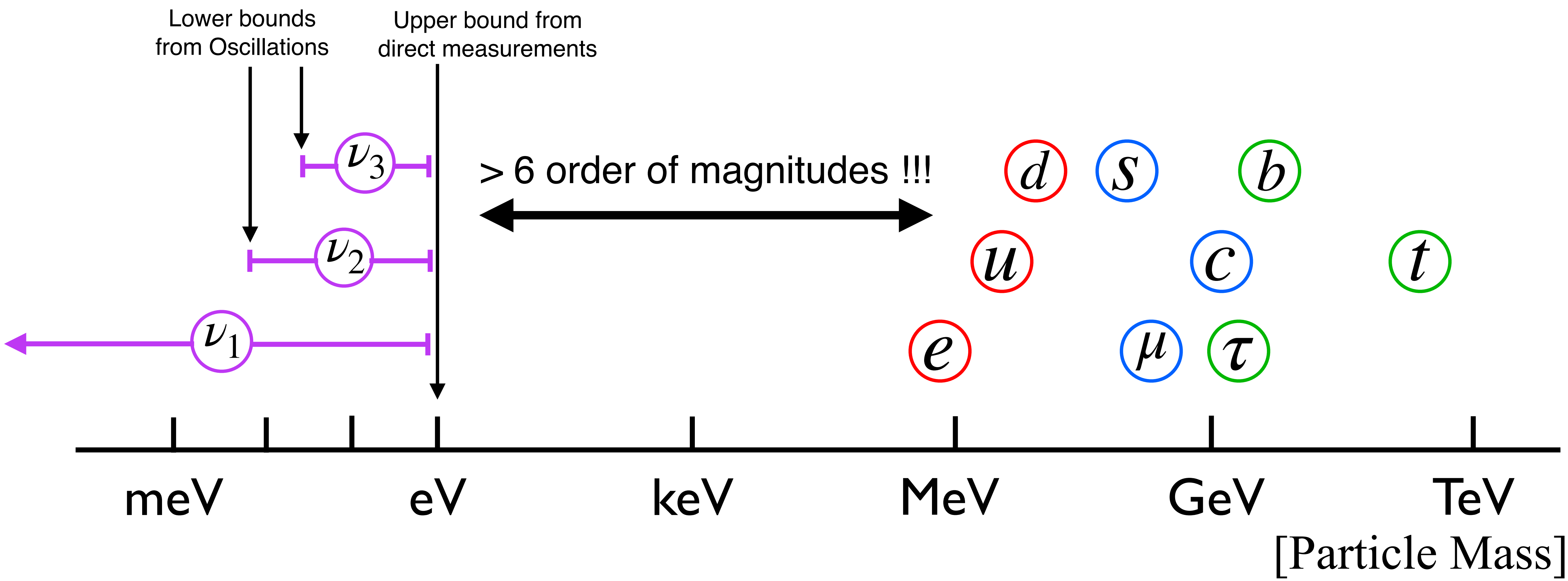
⇒ violate the Charge-Parity symmetry of Nature

What could neutrinos tell us about ?

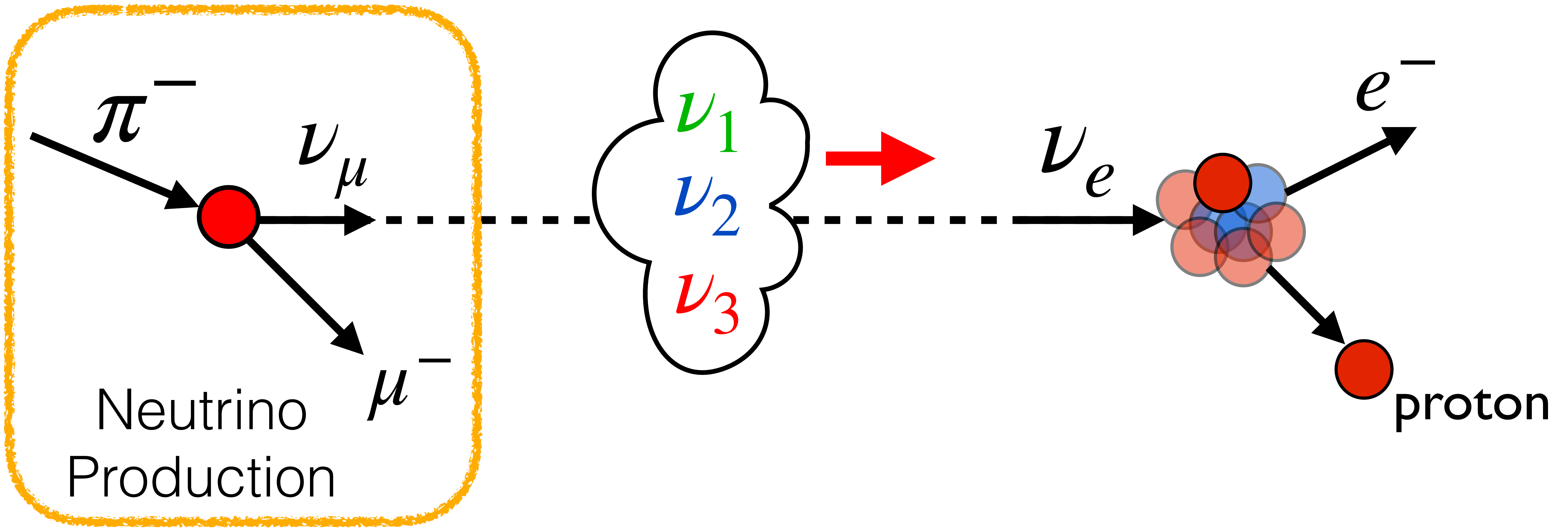


Neutrinos in the Standard Model

- Neutrinos are the most abundant particles in the Universe besides photons. They are neutral and interact weakly
- Neutrinos are mass-less in the Standard Model of particles
- However, we know they oscillate, thus they have mass
  $\Rightarrow$ new physics Beyond the Standard Model of particles



Neutrino Flavor Oscillations

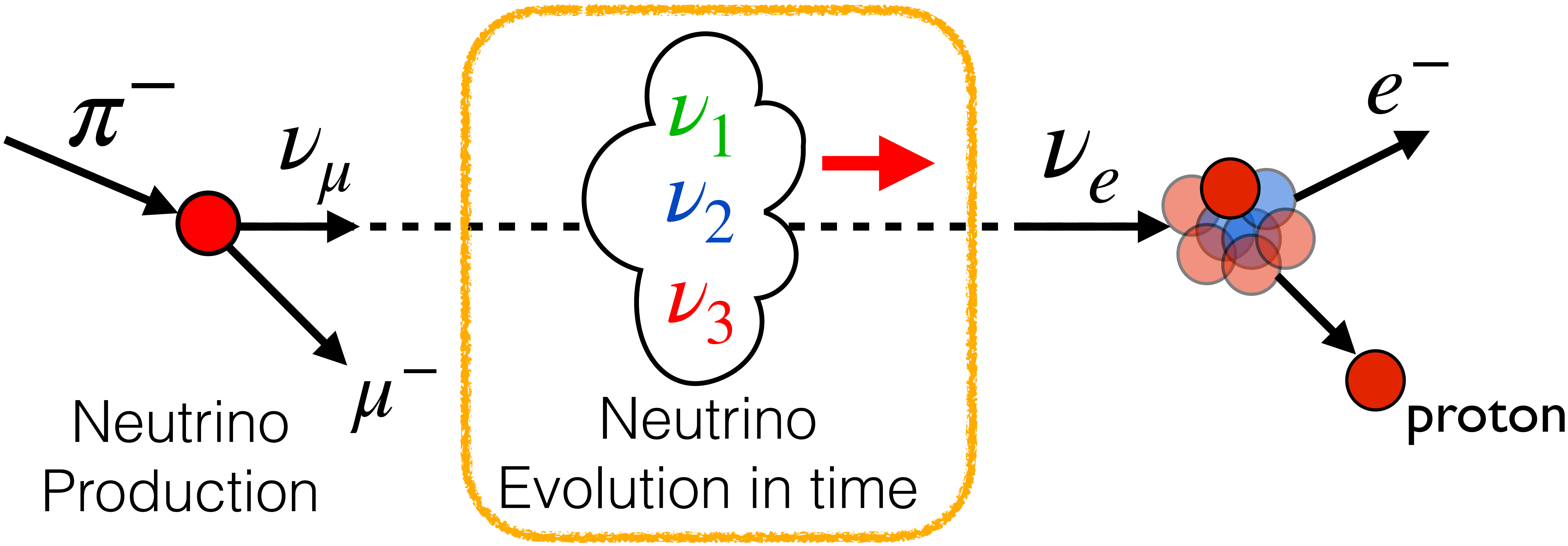


Flavour states: $\nu_e \quad \nu_\mu \quad \nu_\tau$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

The neutrino “flavor” is defined by the lepton produced at the interaction

Neutrino Flavor Oscillations

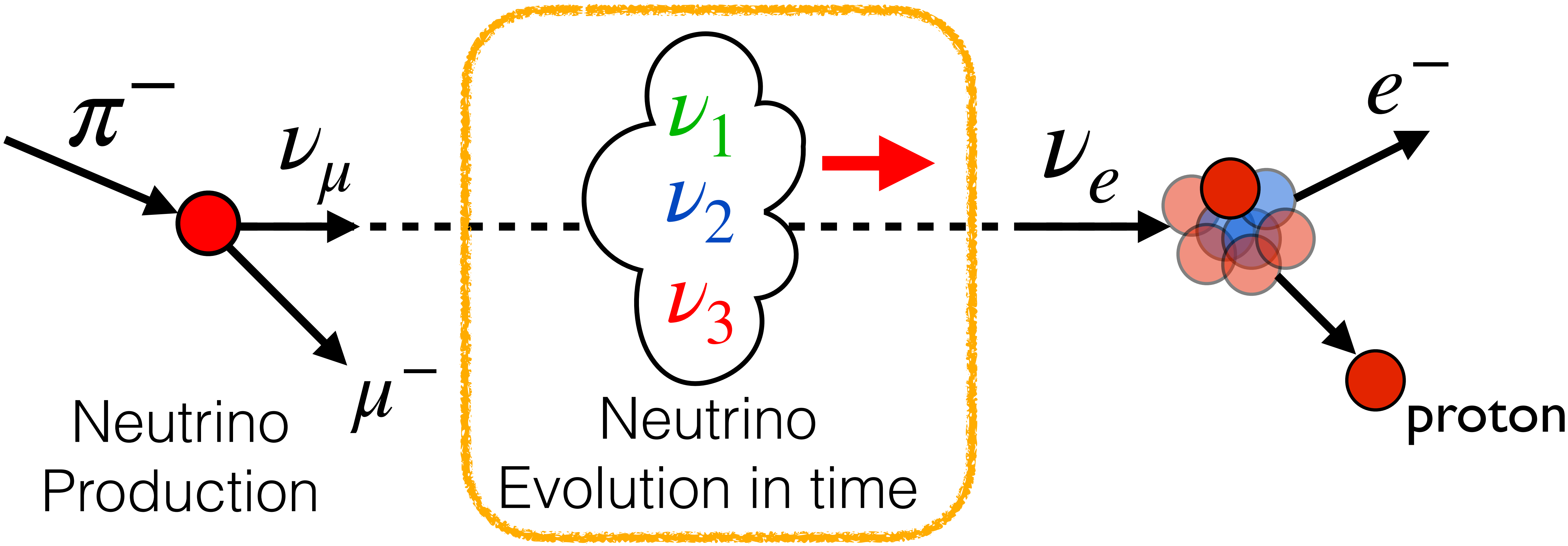


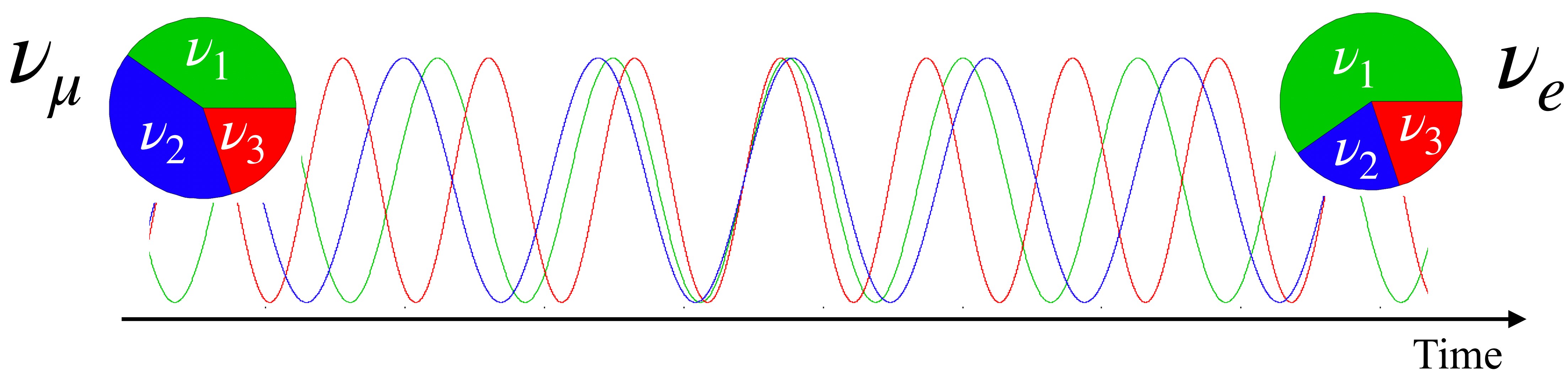
$$|\nu_\mu> = U_{\mu 1} e^{-iE_j t} |\nu_1> + U_{\mu 2} e^{-iE_j t} |\nu_2> + U_{\mu 3} e^{-iE_j t} |\nu_3>$$

The flavor state is a superposition of mass states that evolve in time at different rates

$$m_1 \neq m_2 \neq m_3$$

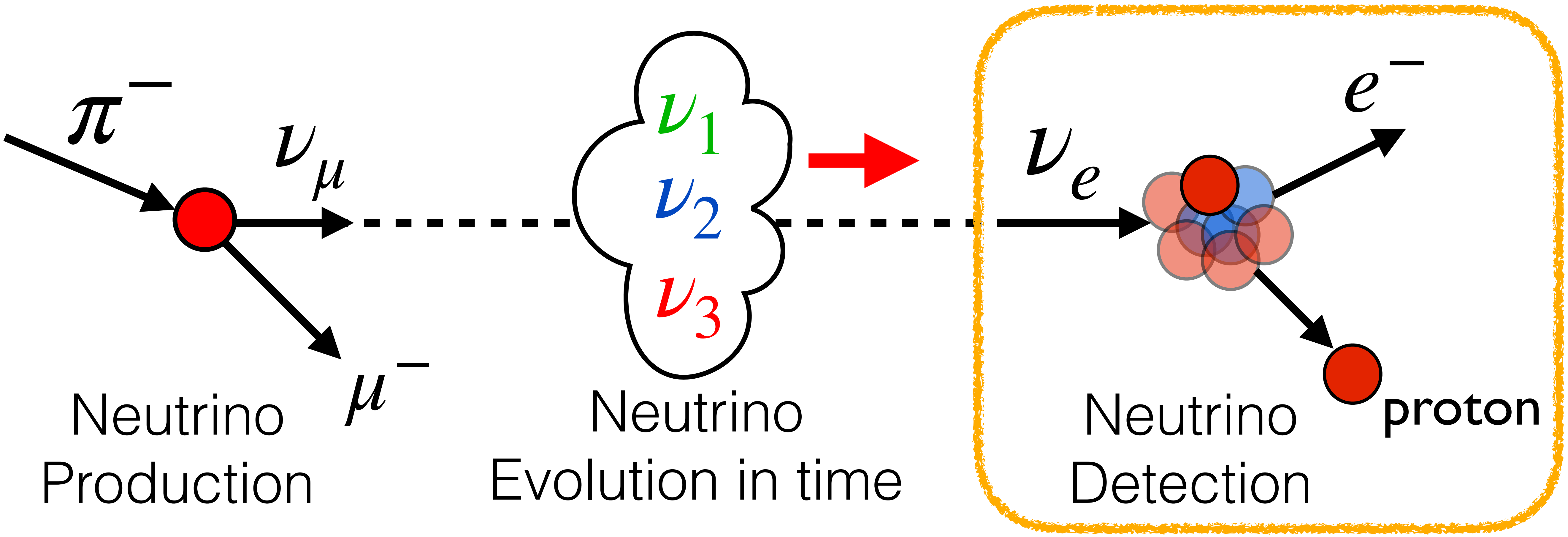
Neutrino Flavor Oscillations





The superposition state can change over time because the components (mass states) evolve differently

Neutrino Flavor Oscillations



Flavour states: $\nu_e \quad \nu_\mu \quad \nu_\tau$

Mass states: $\nu_1 \quad \nu_2 \quad \nu_3$

$m_1 \neq m_2 \neq m_3$

$\Rightarrow$ $\text{Prob}(\nu_\mu \to \nu_e)$

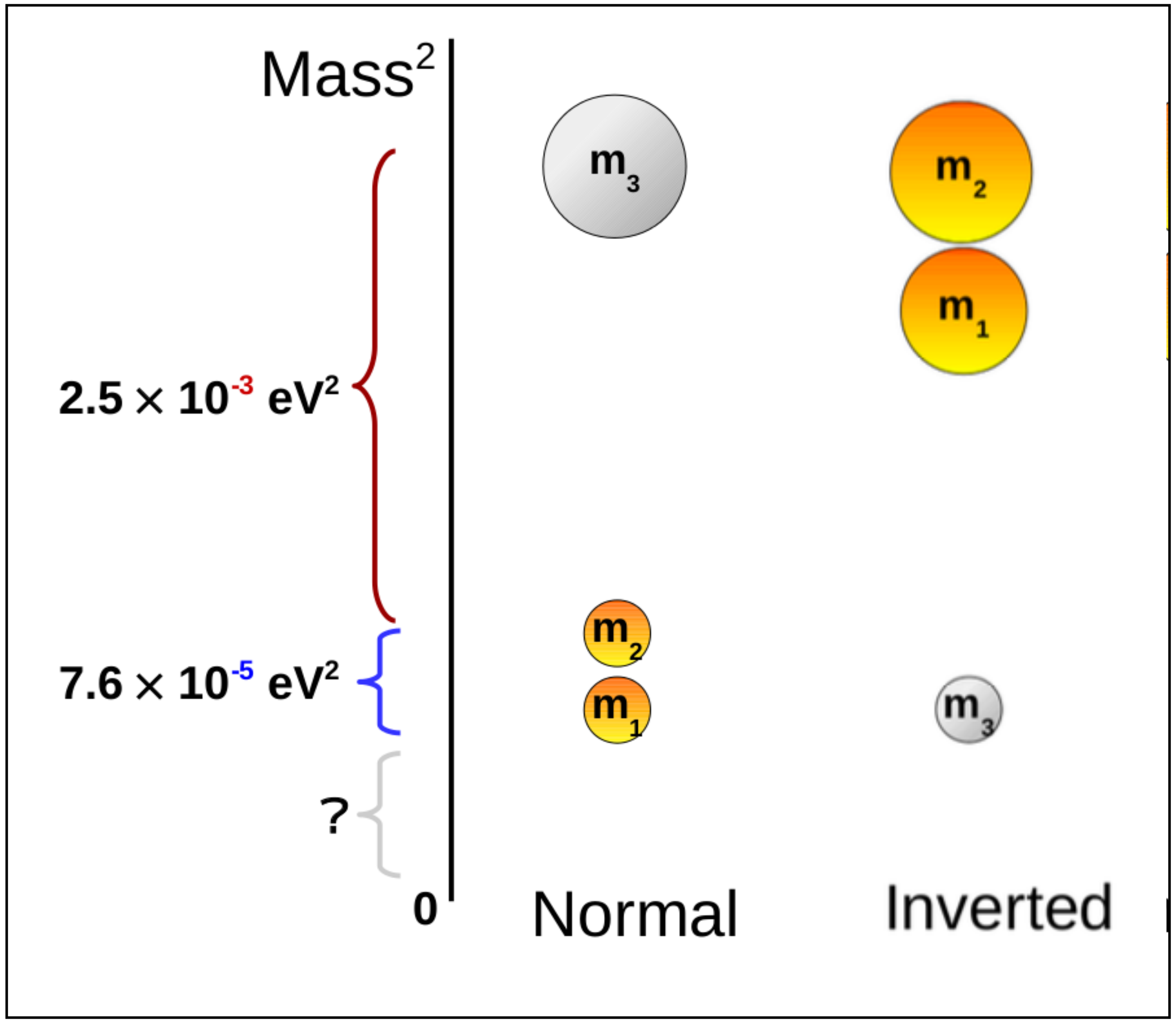
$\text{Prob}(\nu_\mu \to \nu_\tau)$

Neutrino oscillation is a quantum interference phenomenon associated with the fact that neutrinos have non-degenerate mass

The Squared Mass Difference

$$P(\overset{(-)}{\nu_\alpha} \rightarrow \overset{(-)}{\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \qquad \overset{+}{(-)}\, 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\Delta m^2_{ij} \frac{L}{2E}\right)$$



Neutrinos oscillate ($\Delta m^2_{ij} \neq 0$)
$\Rightarrow$ Neutrinos have mass !!!

We don't know yet the Neutrino Mass Hierarchy (sign of $|\Delta m^2_{32}|$)

The Mixing Angles

$$P(\overset{(-)}{\nu_\alpha} \to \overset{(-)}{\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

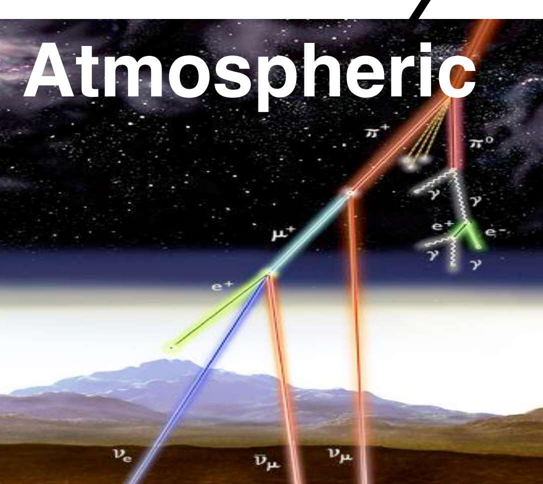
$$\overset{+}{\underset{(-)}{}} 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin(\Delta m^2_{ij}\frac{L}{2E})$$

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

The Mixing Angles have been precisely measured

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



The CP Violating Phase

$$P(\overset{(-)}{\nu_\alpha} \to \overset{(-)}{\nu_\beta}) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$\overset{+}{(-)} 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin(\Delta m^2_{ij}\frac{L}{2E})$$

Jarlskog invariant

δ_{CP} not measured yet

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

New source CP Violation
if $\sin\delta_{CP} \neq 0$
$\Rightarrow$ Oscillations different for
neutrinos and antineutrinos !!!

CP Violation in Quarks and Leptons

$J = U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}$ $\Rightarrow$ Jarlskog invariant generates the CP asymmetry

Quarks: $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$ $\qquad V_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$

$\delta_{CP} \sim 70°$

$J_{CKM} = (3.18 \pm 0.15) \times 10^{-5}$ $\Rightarrow$ small CP asymmetry

Leptons: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ $\qquad U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$

$J_{CP} \sim 0.033 \sin \delta_{CP}$ $\Rightarrow$ potentially large CP asymmetry

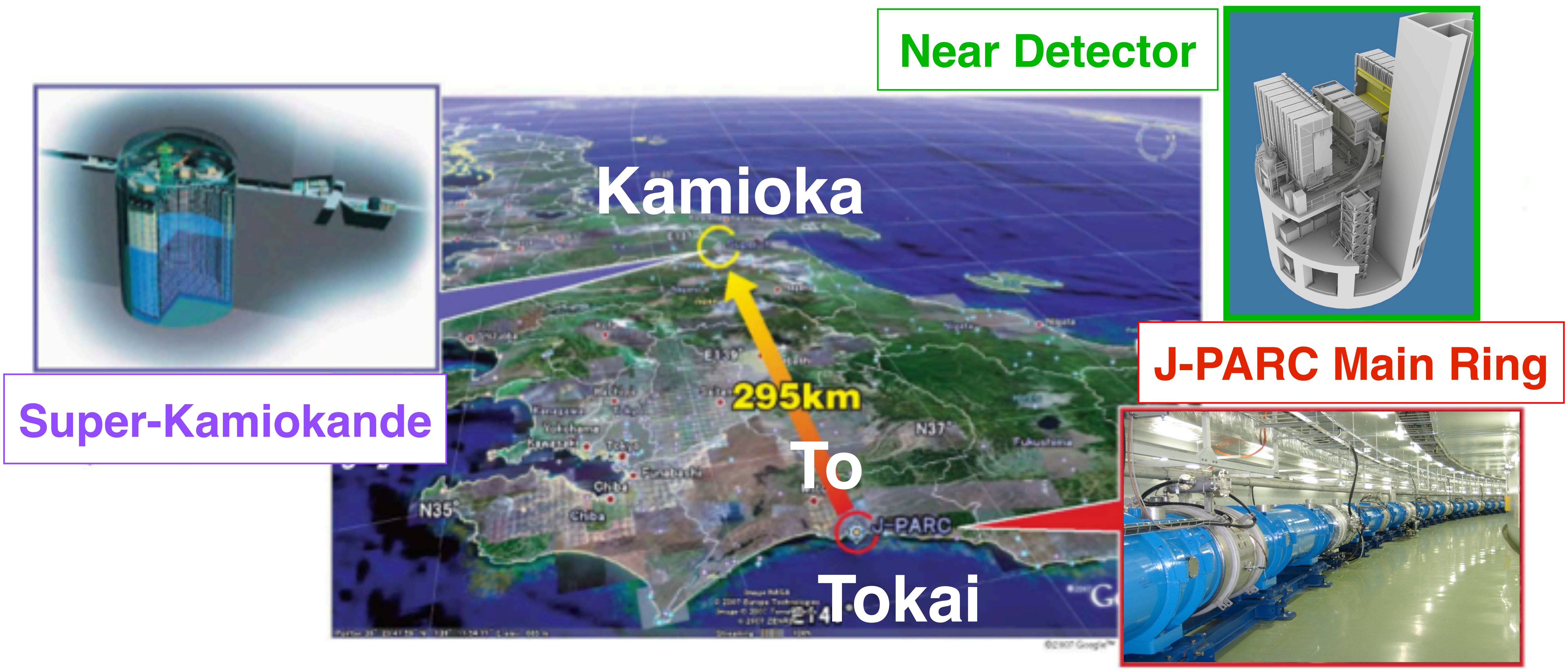
δ_{CP} not measured yet

The T2K neutrino oscillation experiment

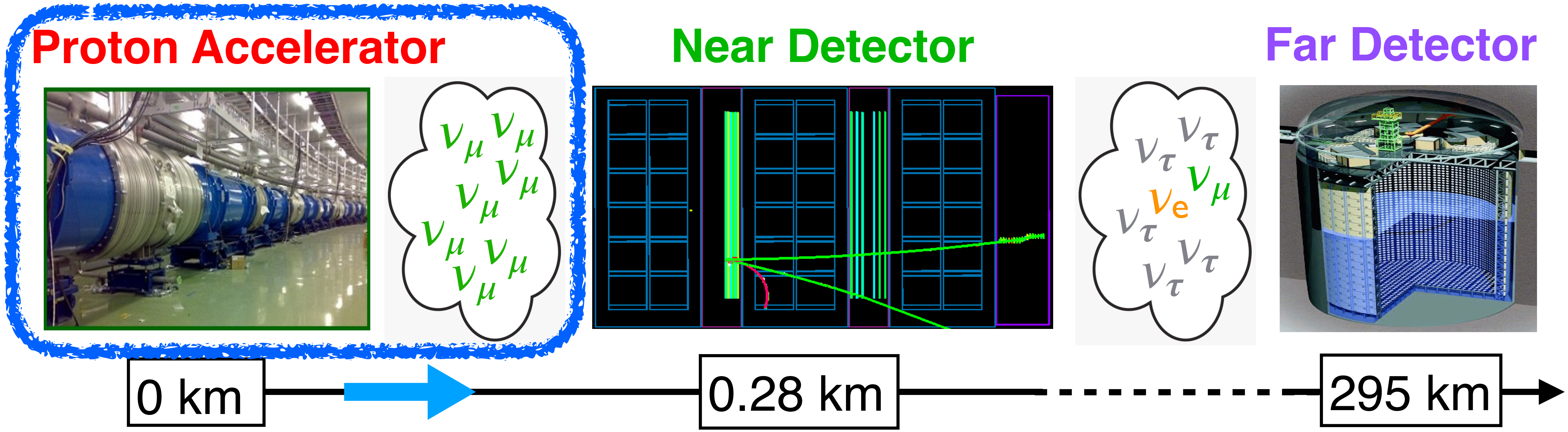
Intense ν_μ / $\bar{\nu}_\mu$ beam from J-PARC to a Near and a Far Detector

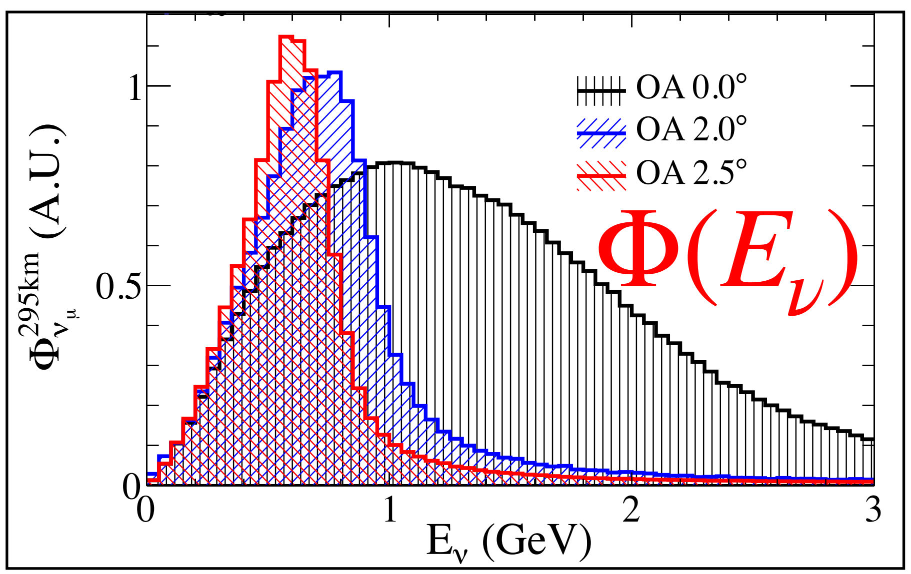
- ν_μ and $\bar{\nu}_\mu$ disappearance $\Rightarrow$ P($\nu_\mu \rightarrow \nu_x$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_x$)
- ν_e and $\bar{\nu}_e$ appearance $\Rightarrow$ P($\nu_\mu \rightarrow \nu_e$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

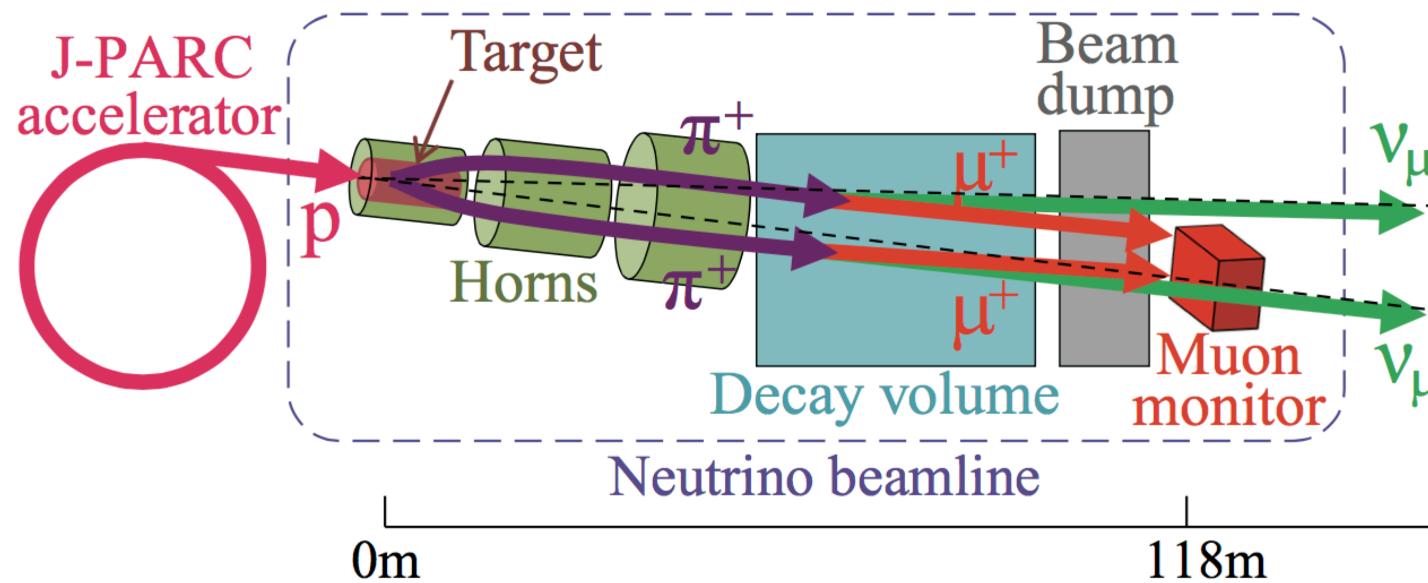
$\nu_x = \nu_e, \nu_\tau$



The T2K neutrino oscillation experiment







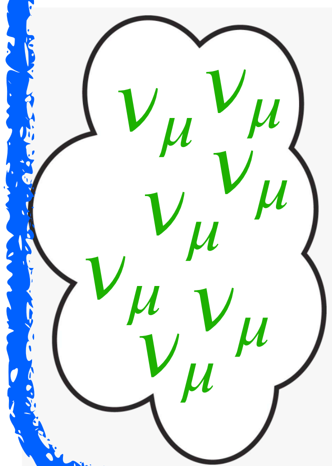
High intensity beam of ν_μ or $\bar{\nu}_\mu$ (only ~1% of ν_e and $\bar{\nu}_e$)

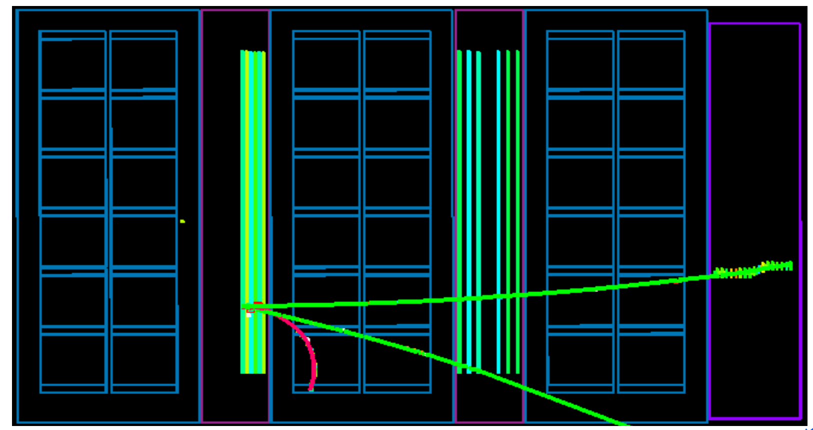
NA61/SHINE@CERN experiment measures the phase space of π/K from pC@30GeV interactions

The T2K neutrino oscillation experiment

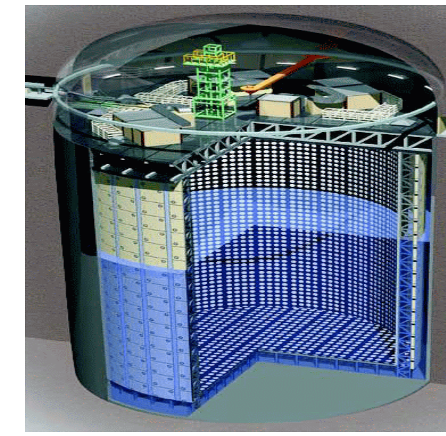
Proton Accelerator

Near Detector

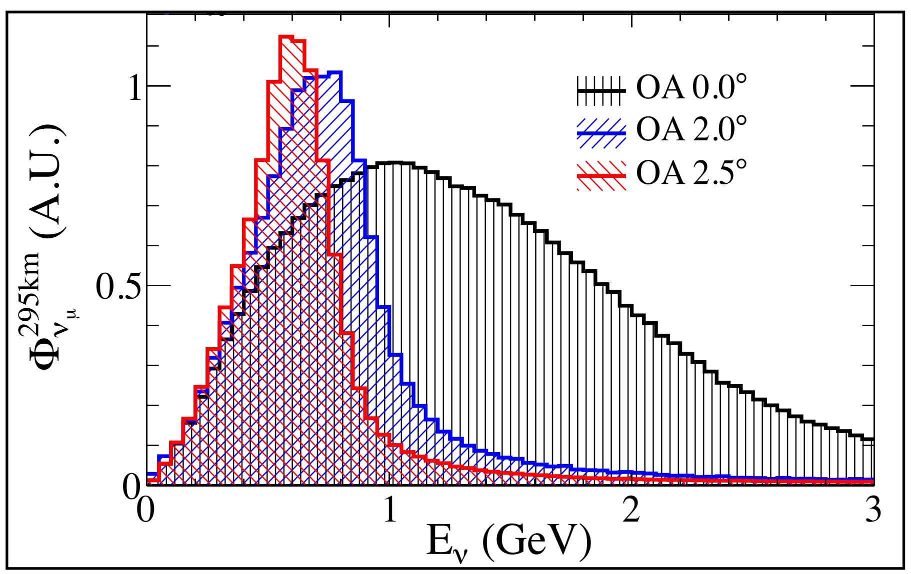




Far Detector

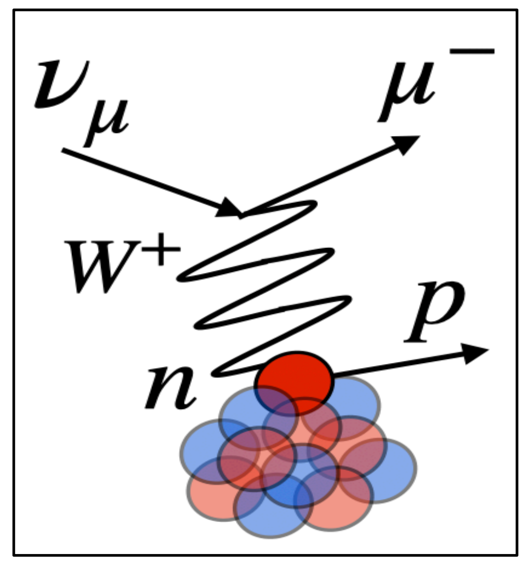


0 km — 0.28 km — 295 km



Flux

$\otimes$

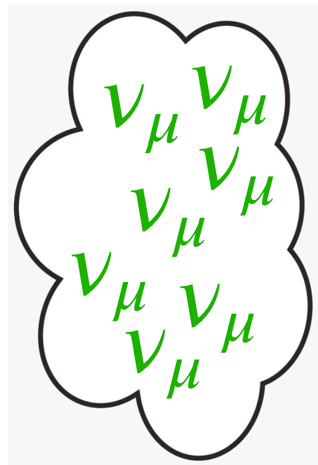


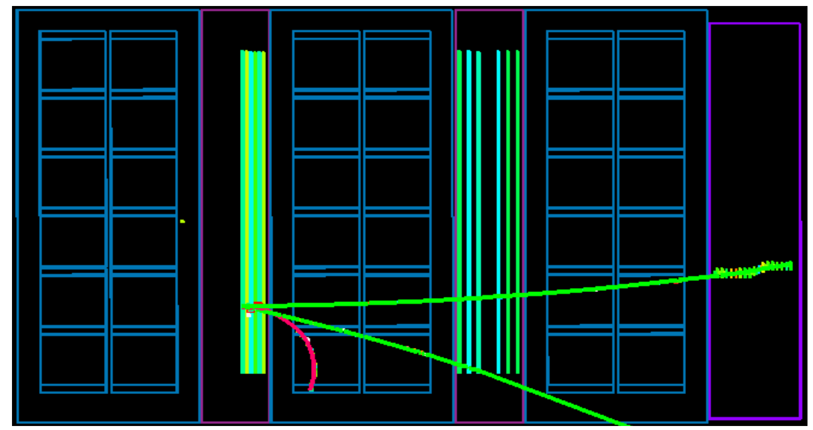
Interaction with Matter

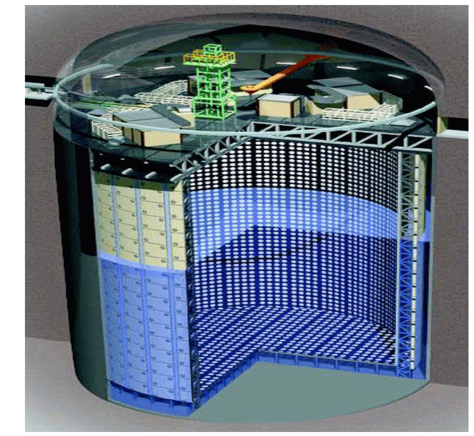
$$N(E_\nu) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma(E_\nu), \vec{r})$$

The T2K neutrino oscillation experiment

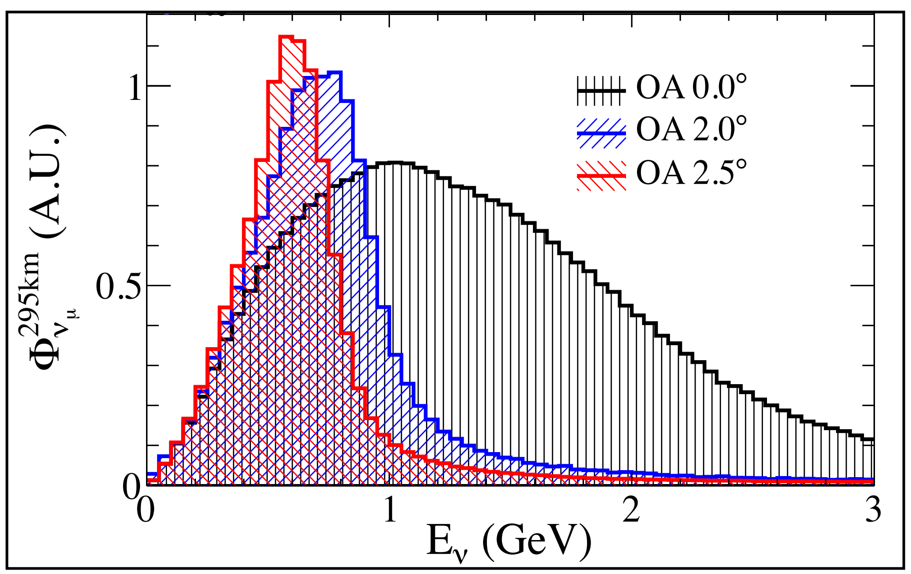
Proton Accelerator | **Near Detector** | **Far Detector**





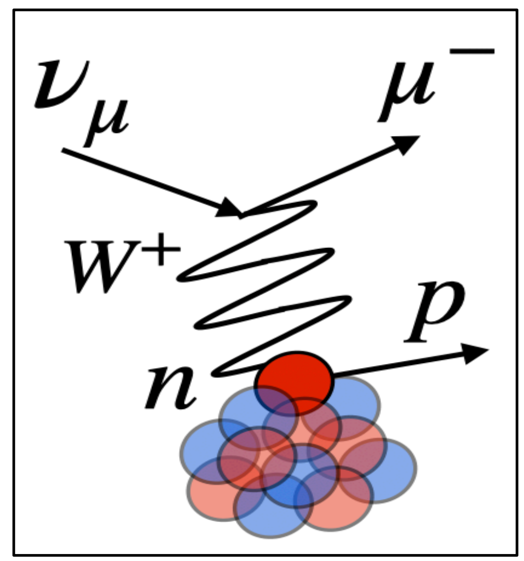


0 km — 0.28 km — 295 km



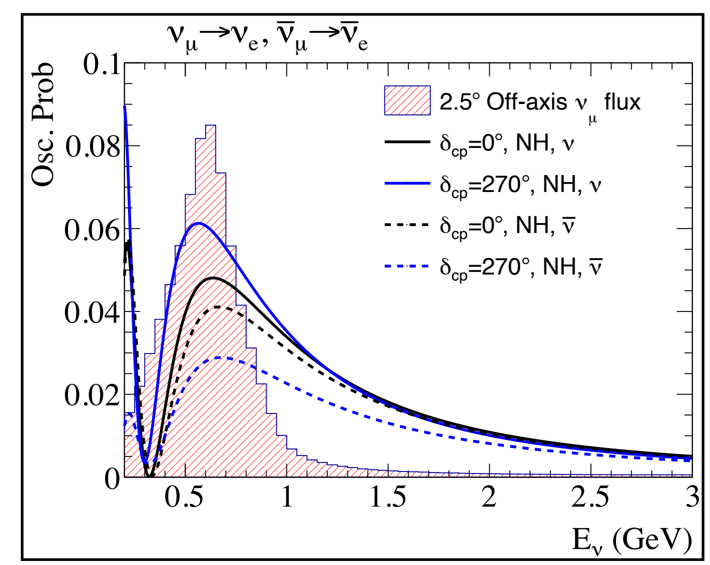
Flux

$\otimes$



Interaction with Matter

$\otimes$

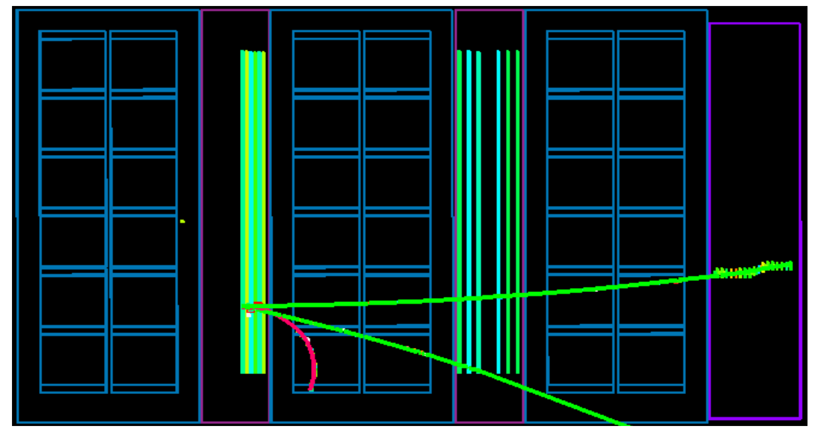


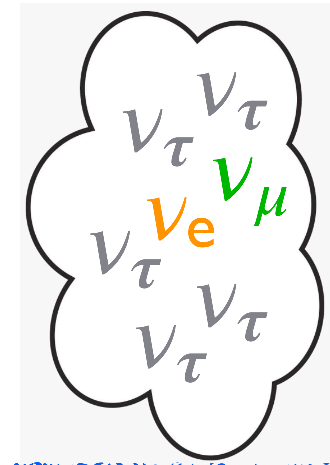
Oscillations

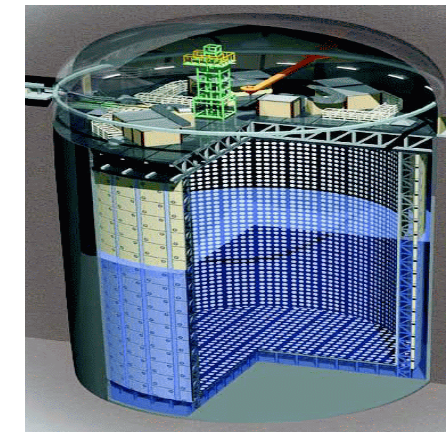
$$N(E_\nu) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma(E_\nu), \vec{r}) \times P_{osc}(E_\nu)$$

The T2K neutrino oscillation experiment

Proton Accelerator **Near Detector** **Far Detector**

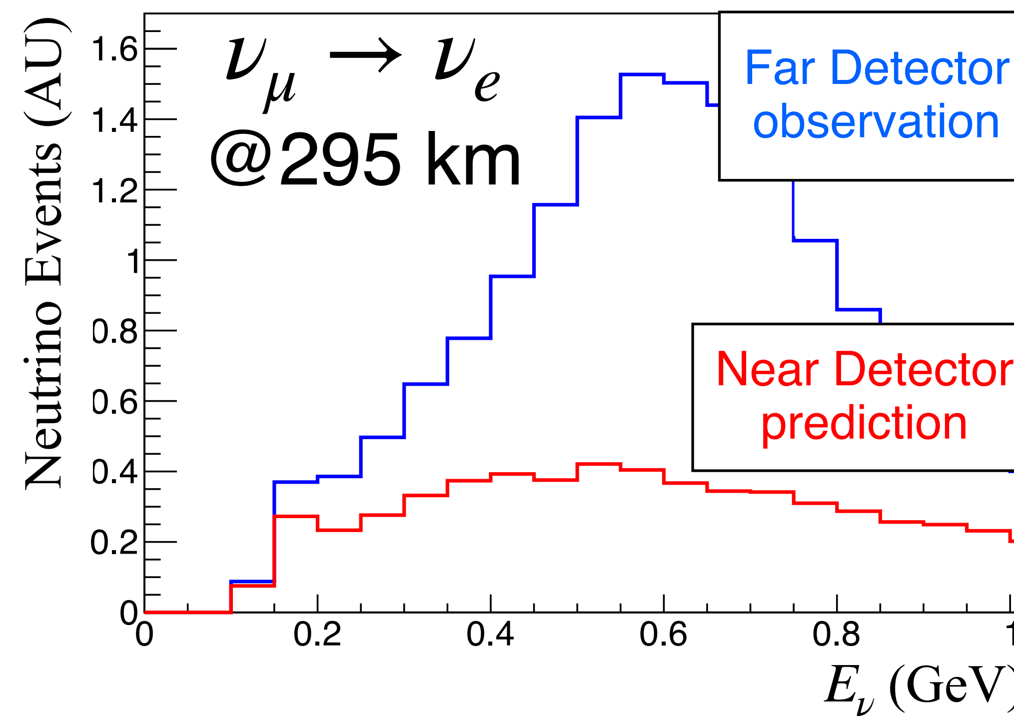






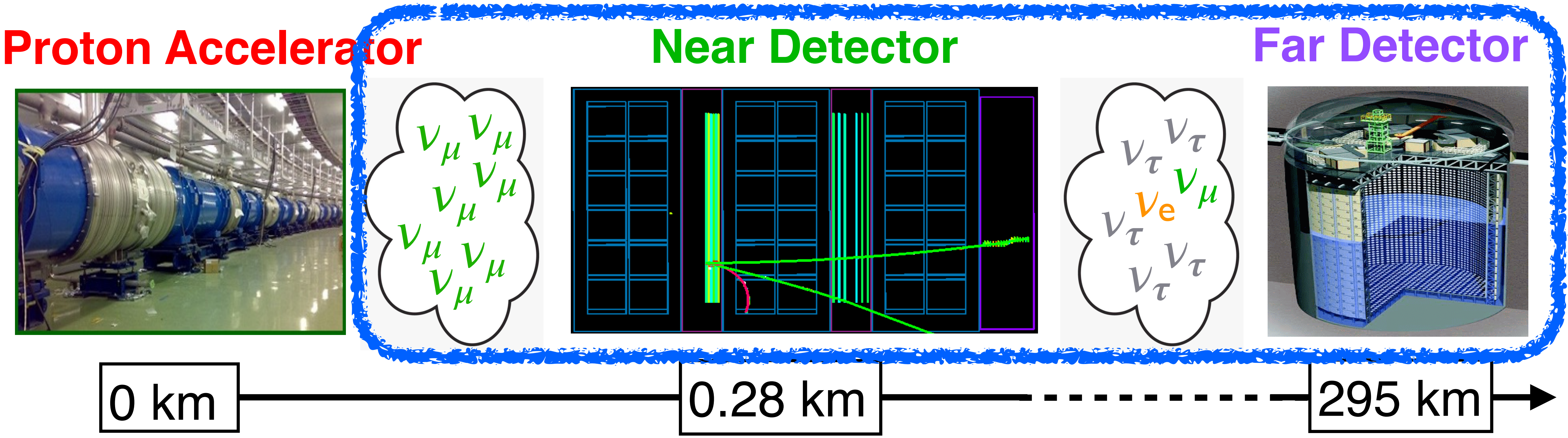
0 km → 0.28 km → 295 km

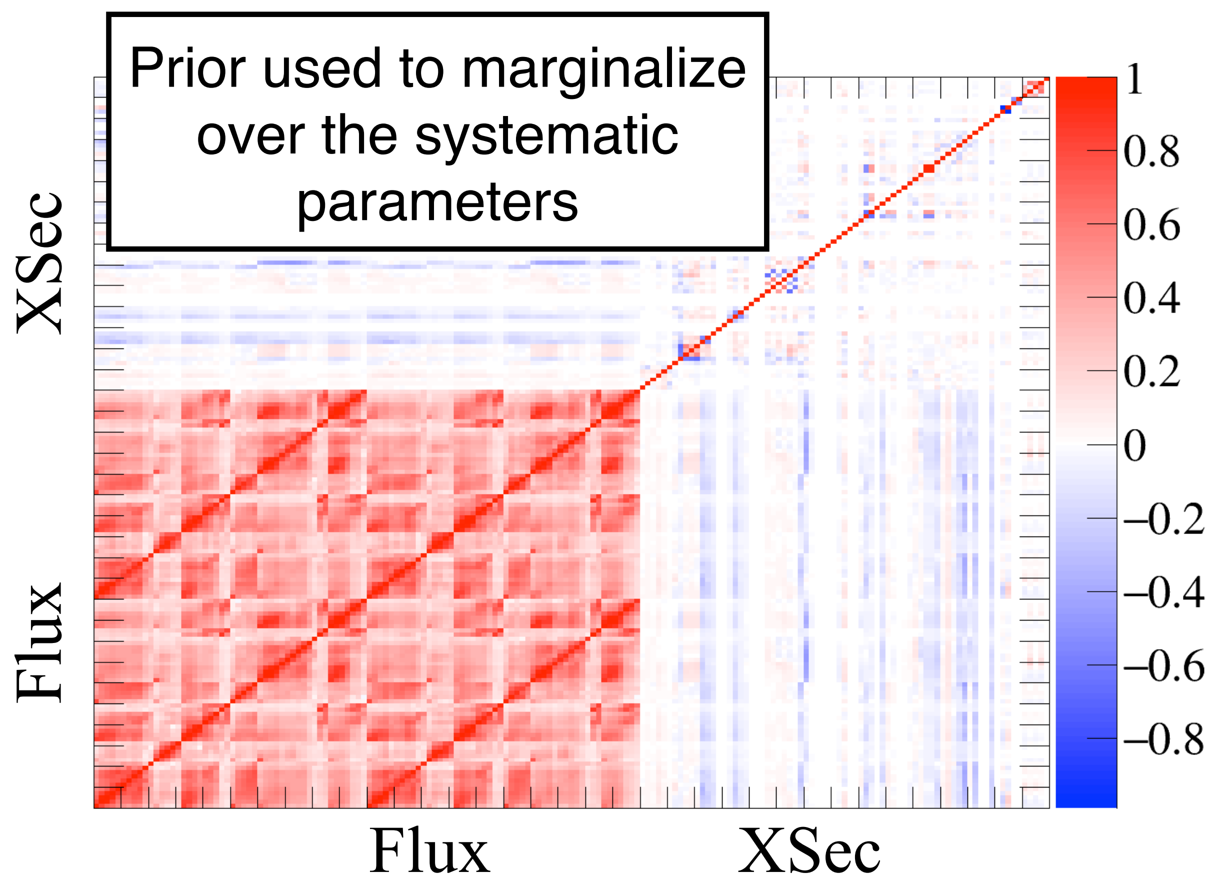
$$N(E_\nu)^{ND} = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma)$$

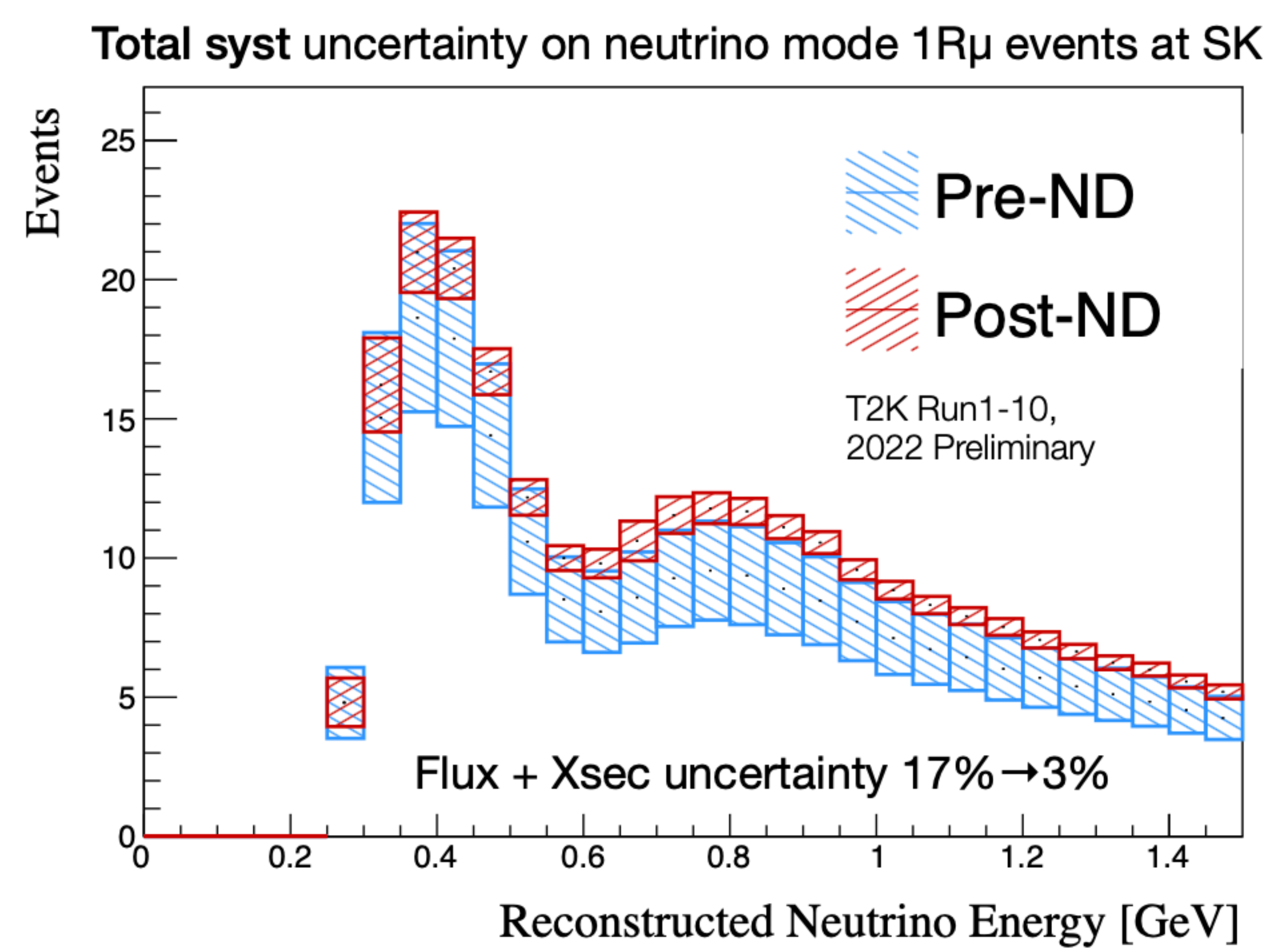


$$N(E_\nu)^{FD} = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma) \times P_{osc}(E_\nu)$$

The T2K neutrino oscillation experiment



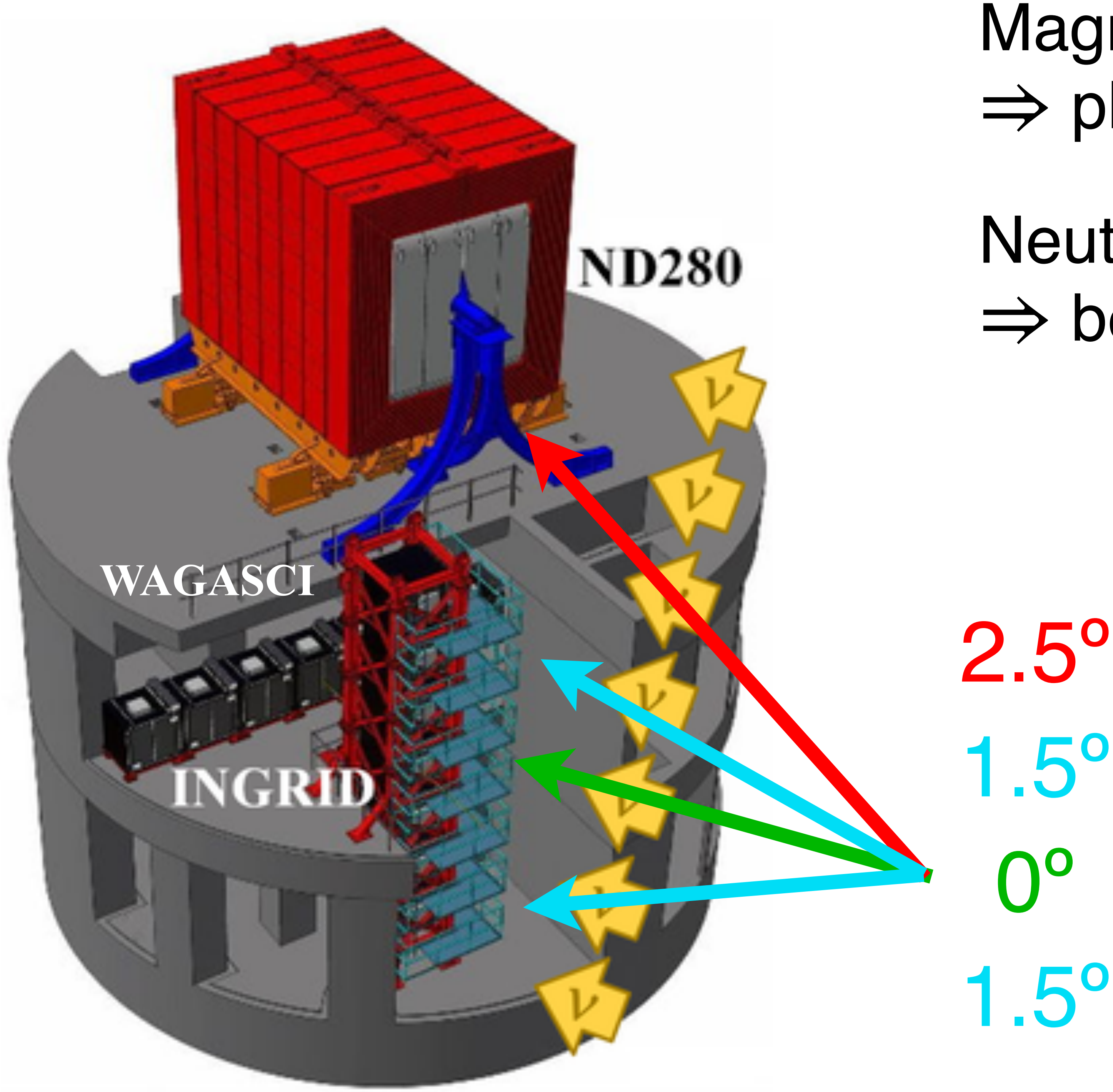


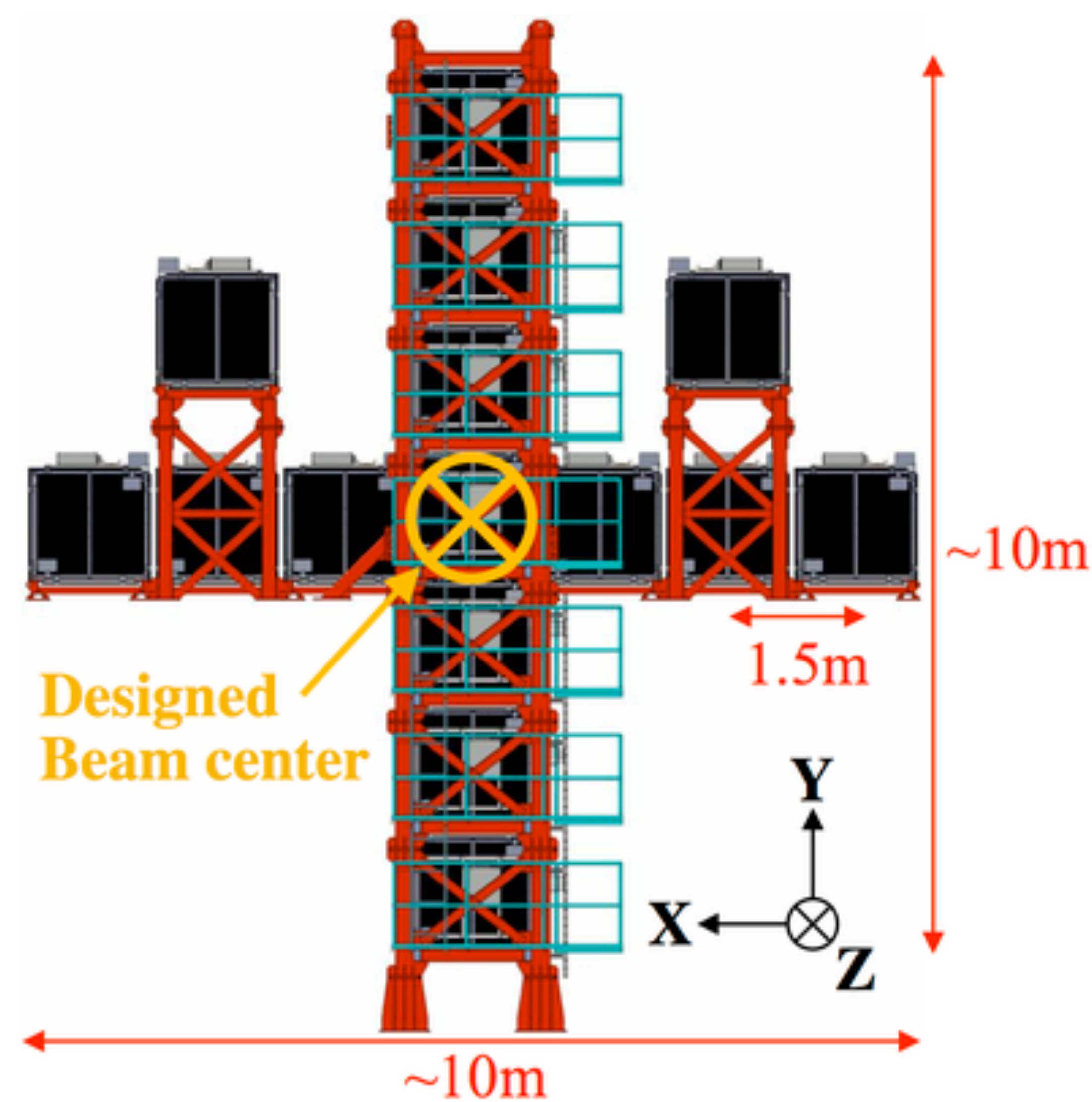


The T2K Near Detector Complex

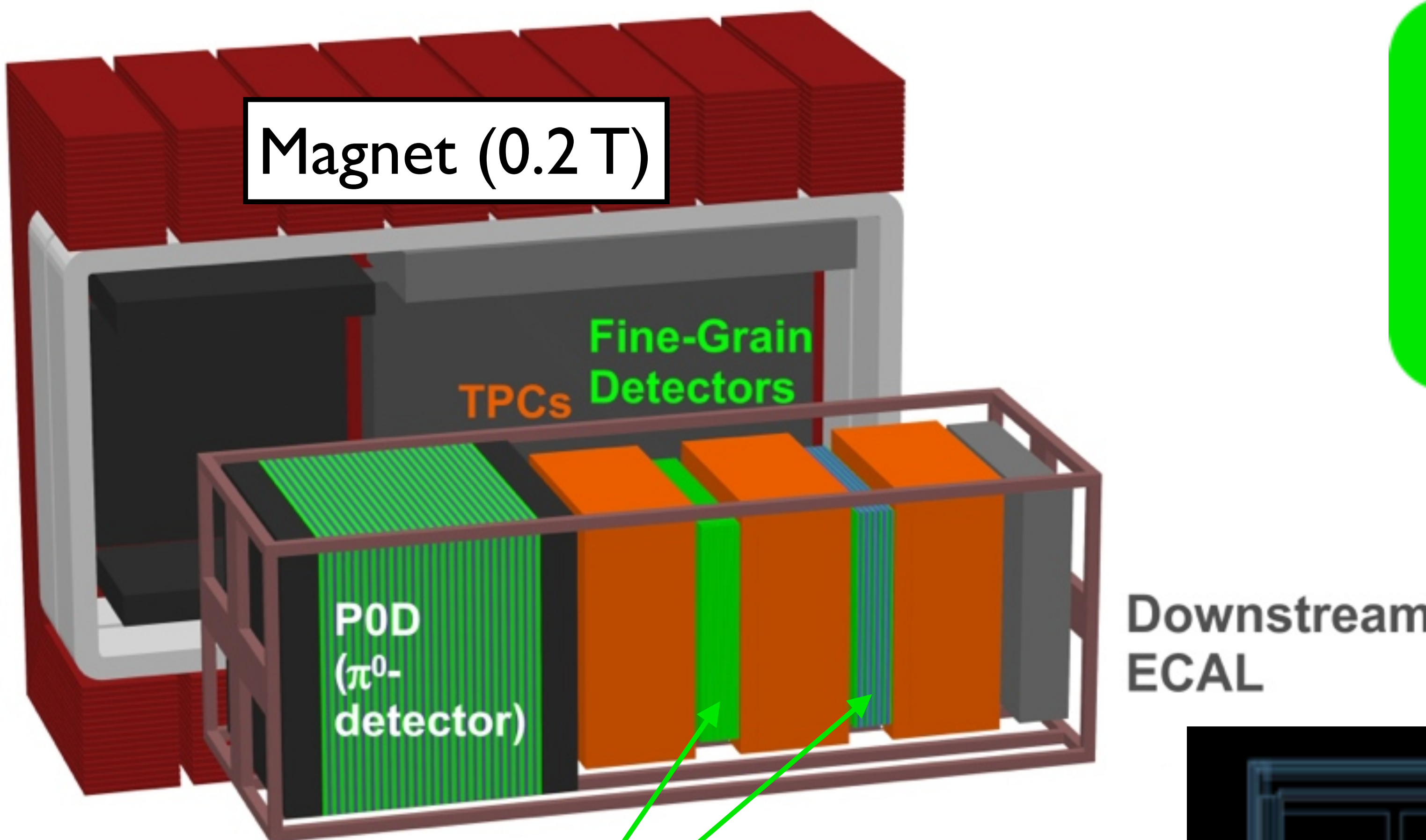
Magnetised Near Detector (ND280)
⇒ physics analysis

Neutrino Beam Monitor (INGRID)
⇒ beam rate, width and direction





The Magnetised Near Detector: ND280

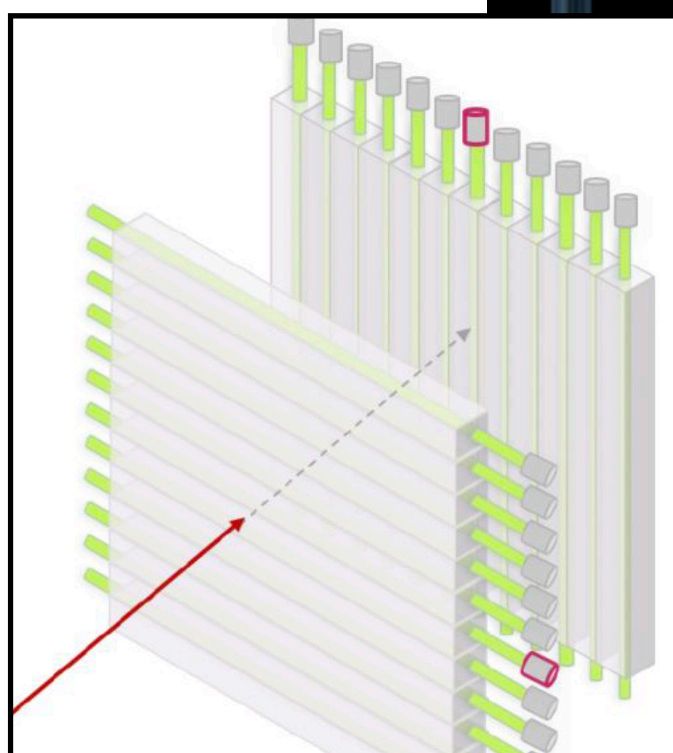


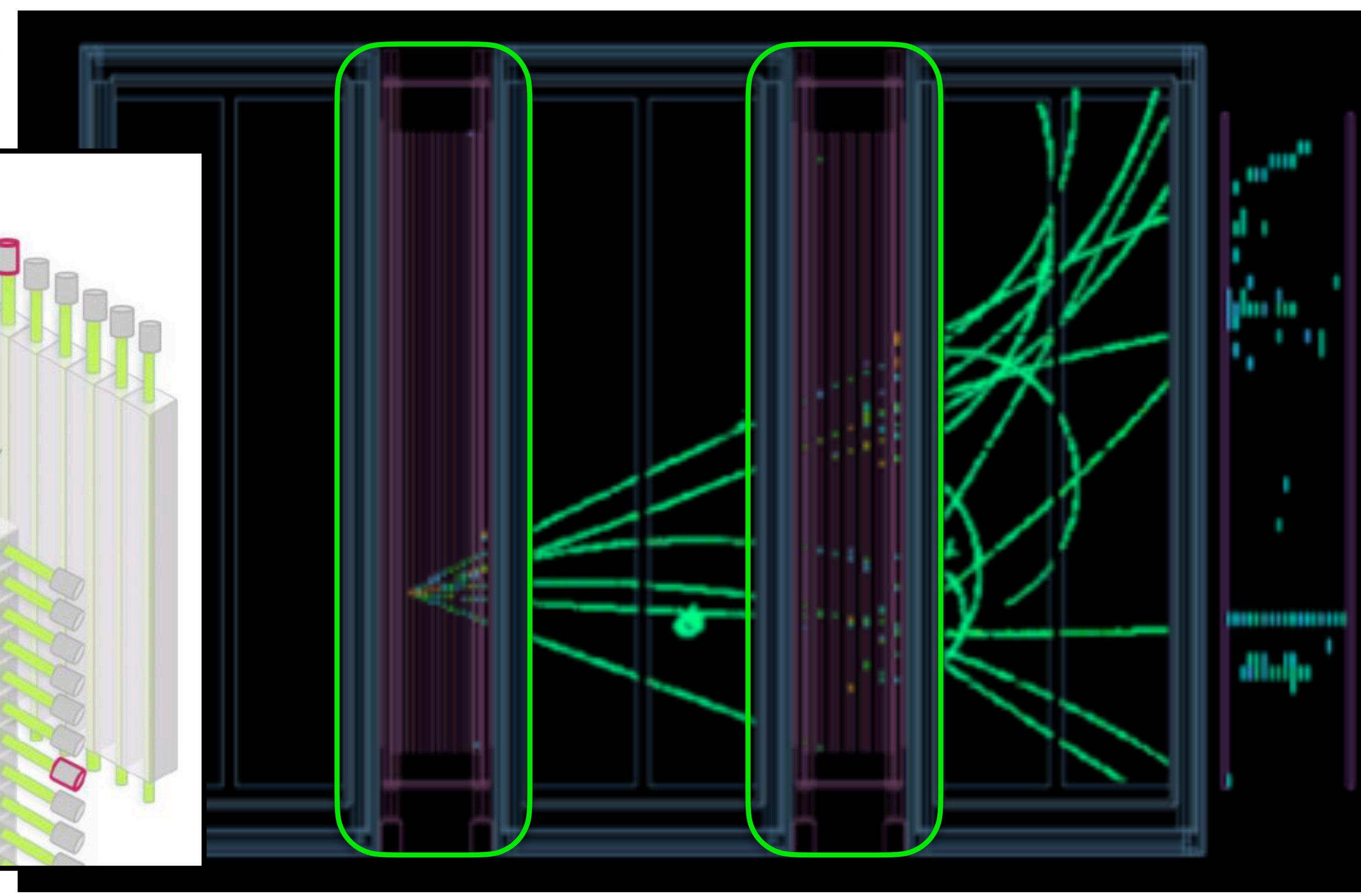
Plastic Scintillator (FGD)

- Vertex reconstruction
- Momentum reconstruction
- Particle Identification

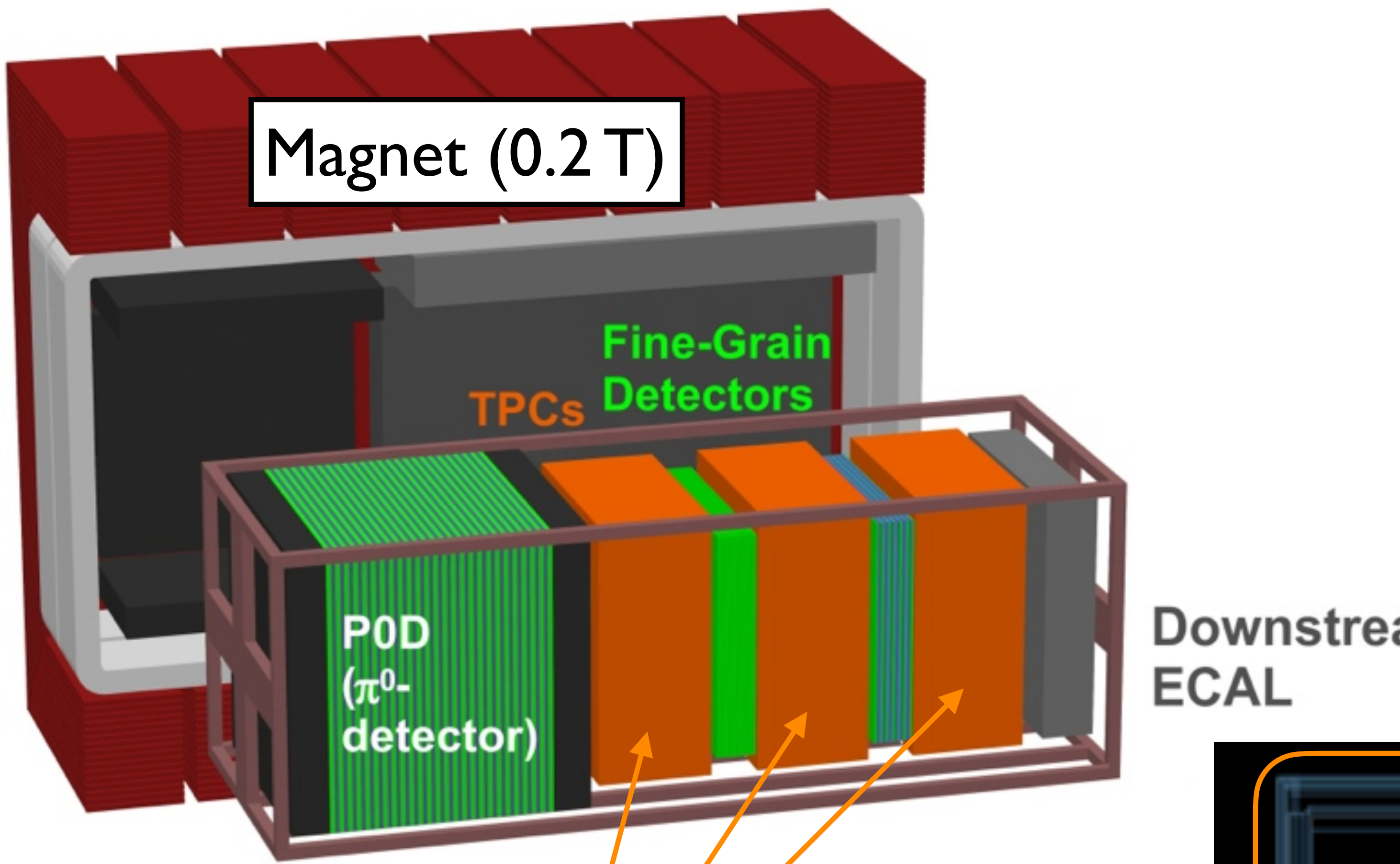
2 tons of plastic and water (nuclei same or similar to Far Detector)

Fine-Grain Detector (FGD)





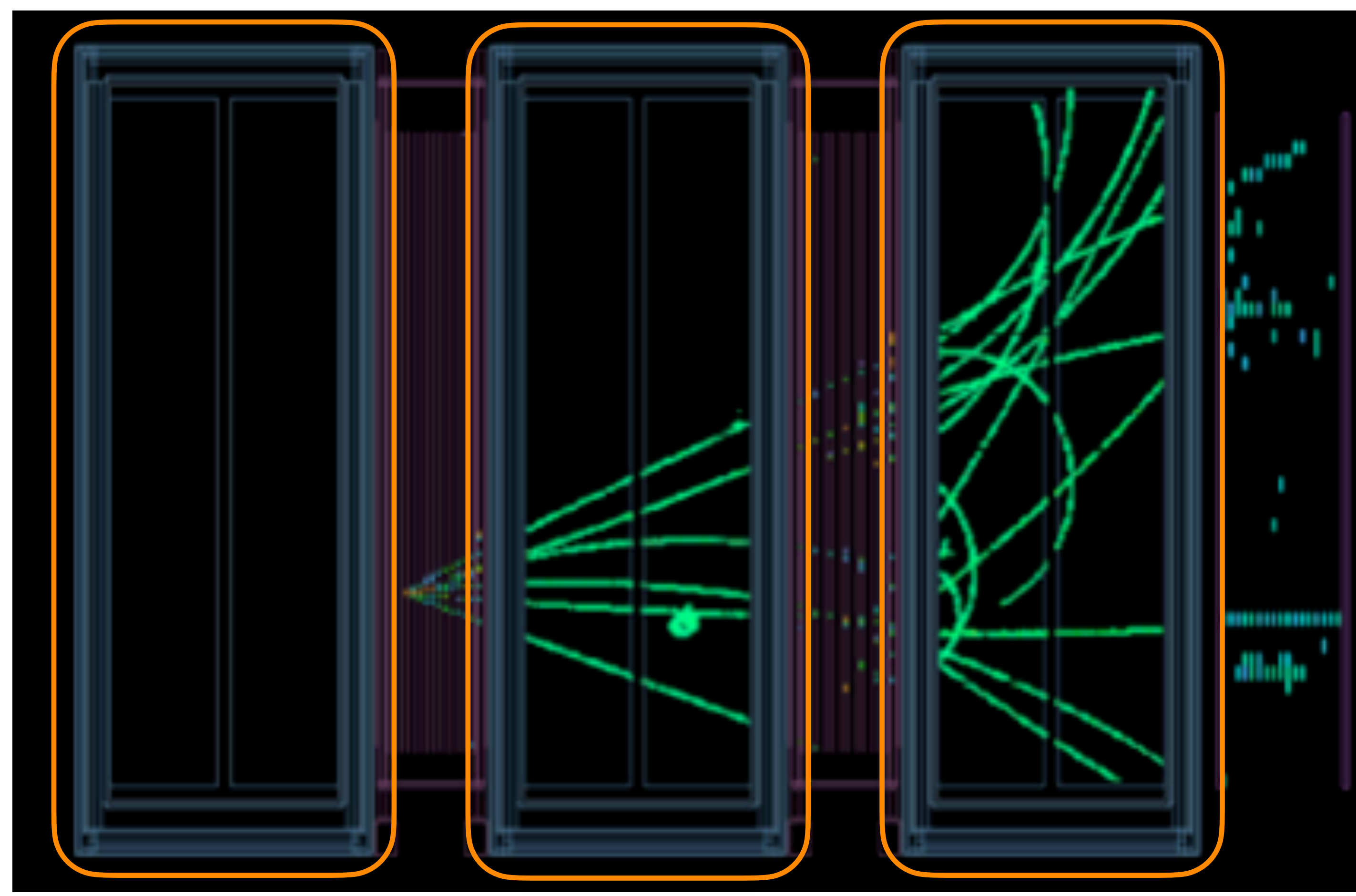
The Magnetised Near Detector: ND280



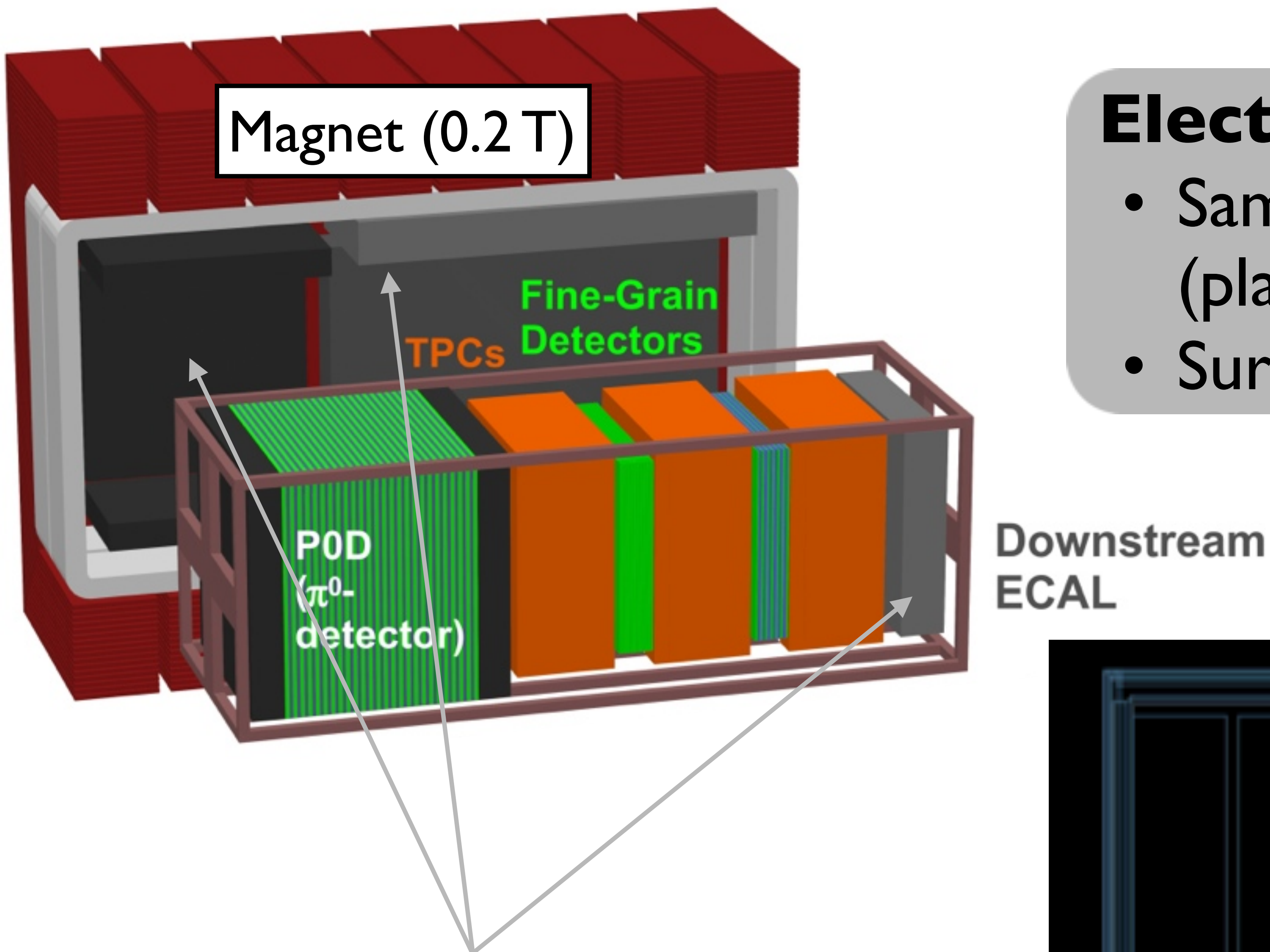
Time Projection Chamber (TPC)

UA1 Solenoid Magnet
- 0.2T uniform magnetic field

Time Projection Chambers
- Tracking detector in B-field
- Momentum reconstruction
- Charged identification
- Particle Identification

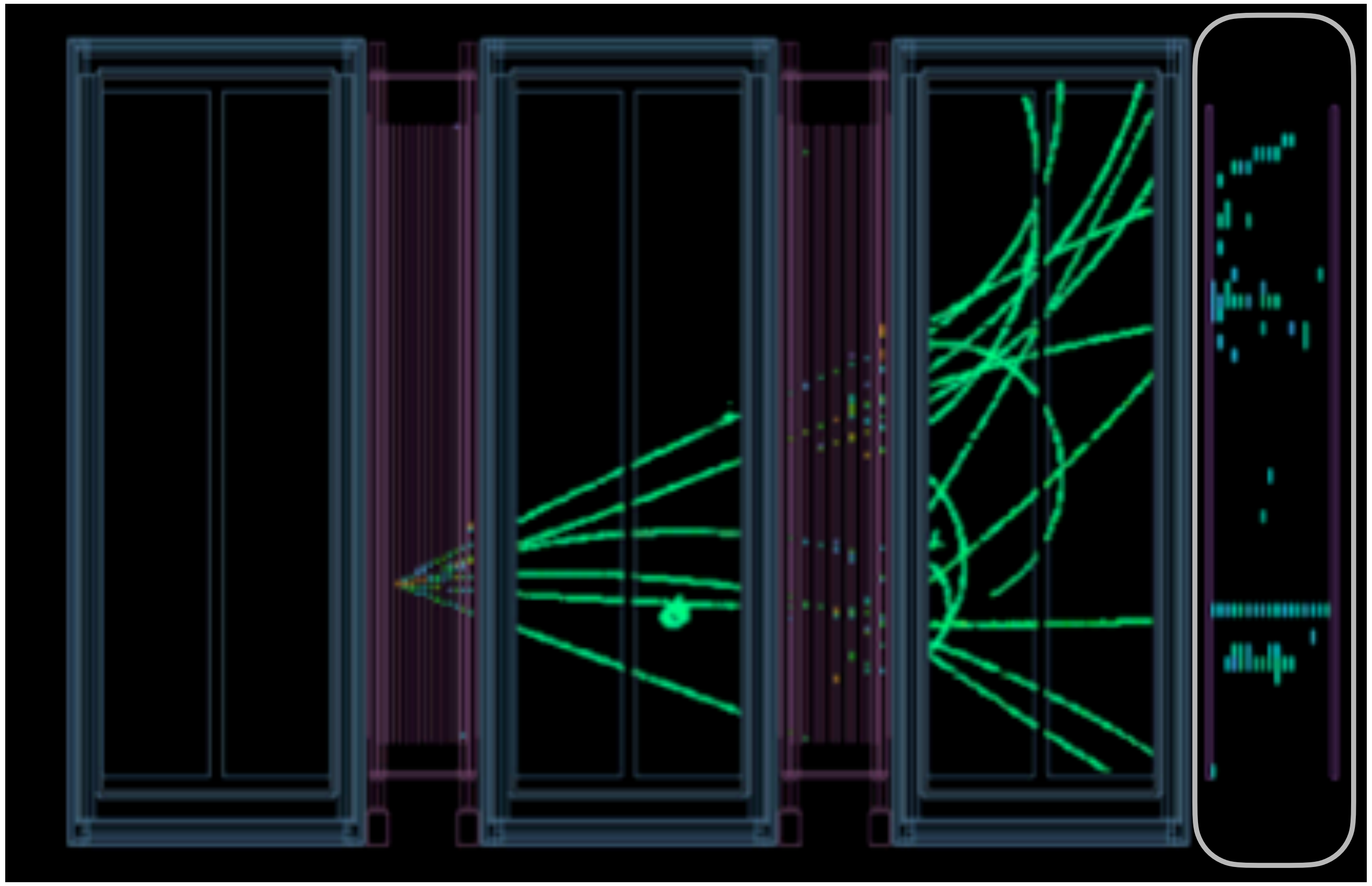


The Magnetised Near Detector: ND280



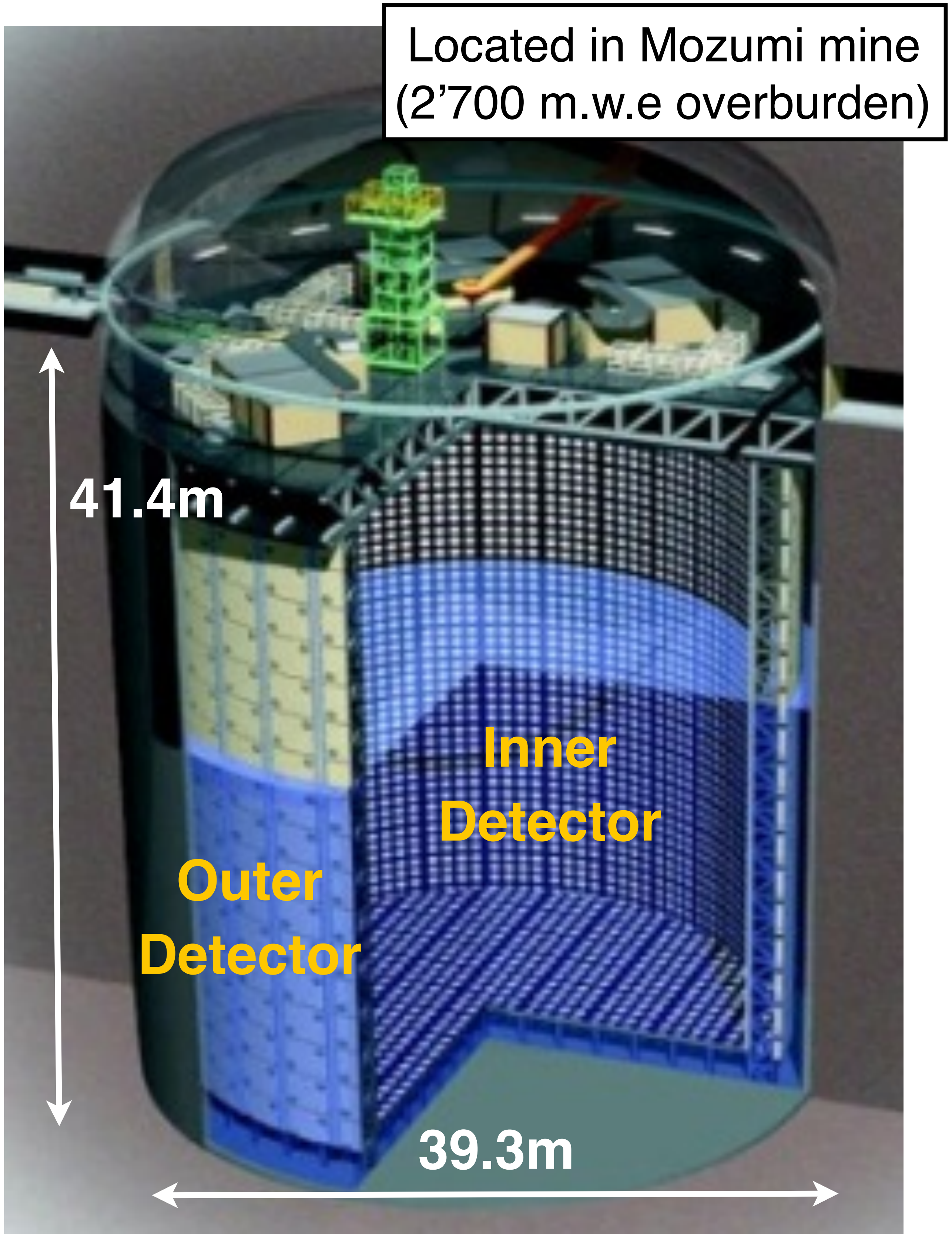
Electromagnetic
Calorimeter (ECAL)

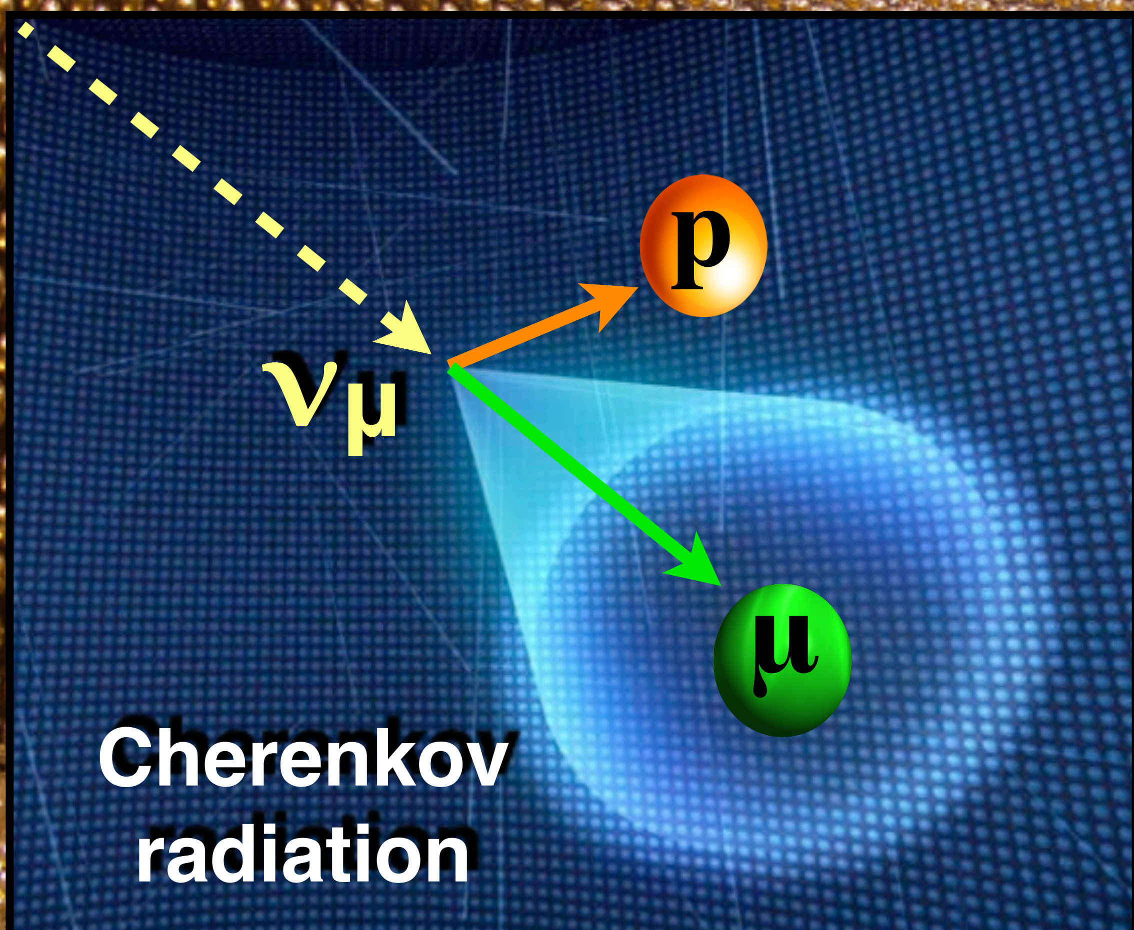
Electromagnetic Calorimeter
- Sampling calorimeter (plastic scintillator / Lead)
- Surrounds all the other detectors

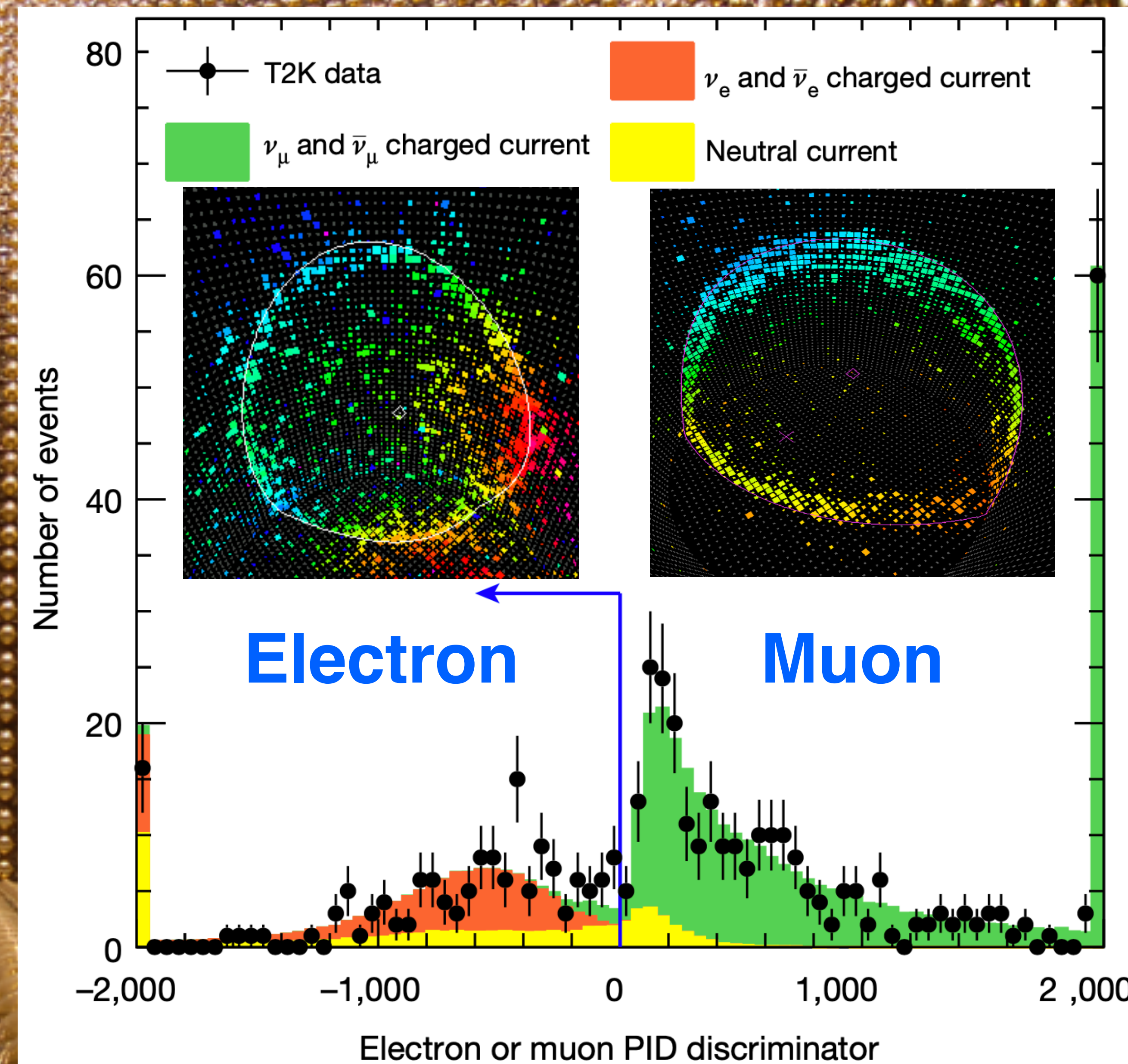


The Far Detector: Super-Kamiokande

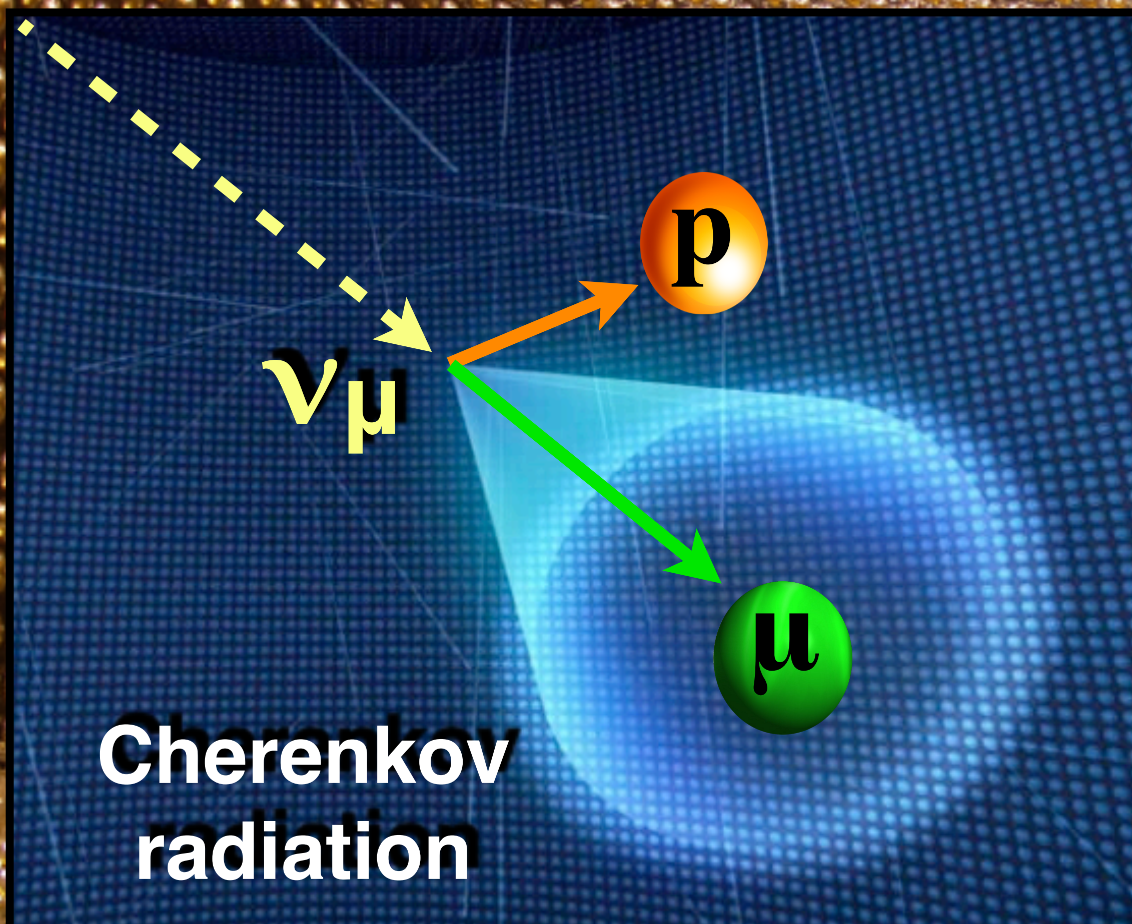
- 50 kton of ultra-pure water (fiducial mass 22.5 kton)
- Detect Cherenkov light with
  - ✓Inner detector with 11’129 20” PMTs
  - ✓ Outer veto detector with 1’885 8” PMTs
- DAQ system with no dead time
- Synchronized with T2K beam by GPS (± 500 µs window)

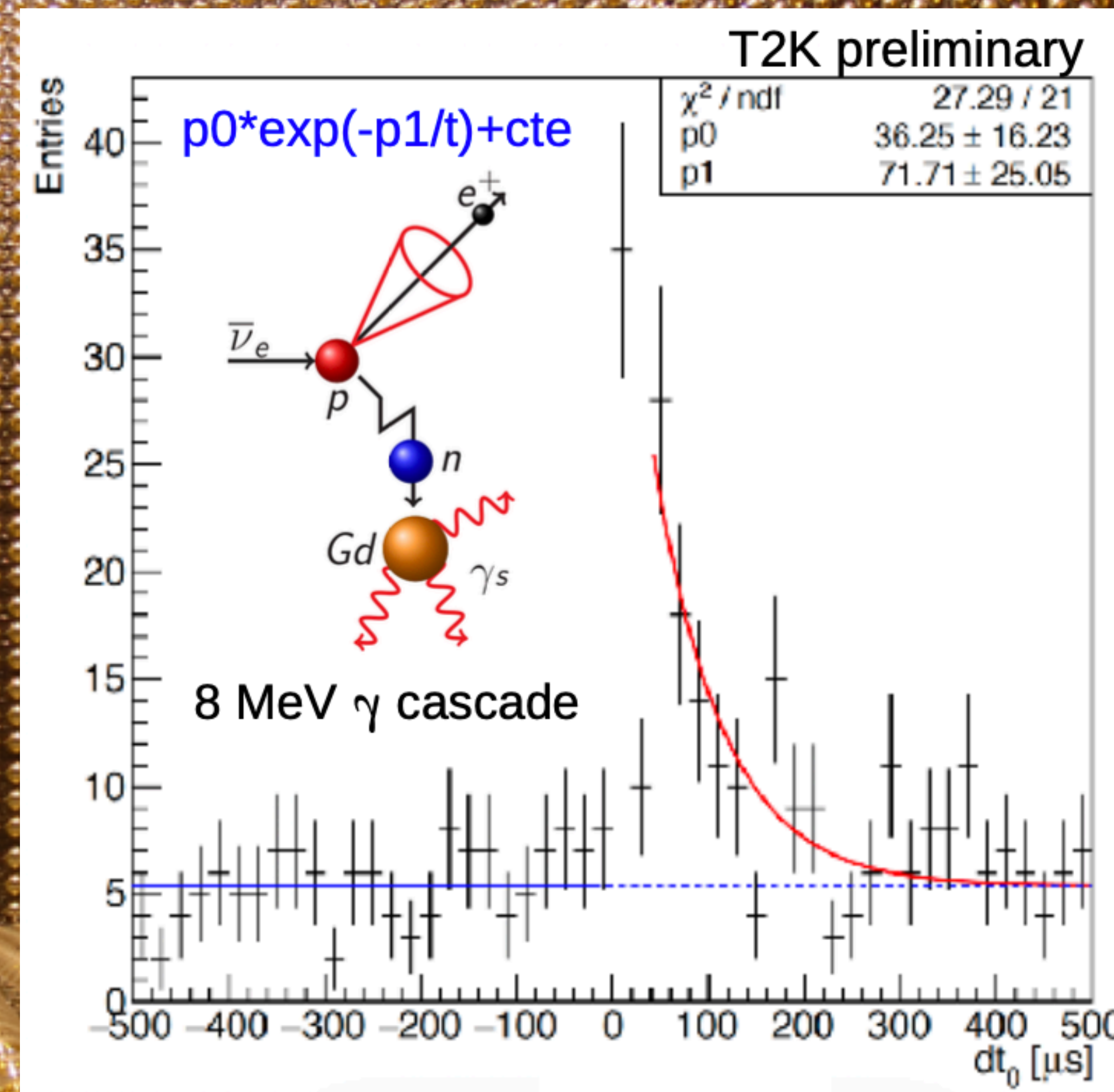






Background from NC $\pi^0 \to \gamma\gamma$ that can fake an electron ring

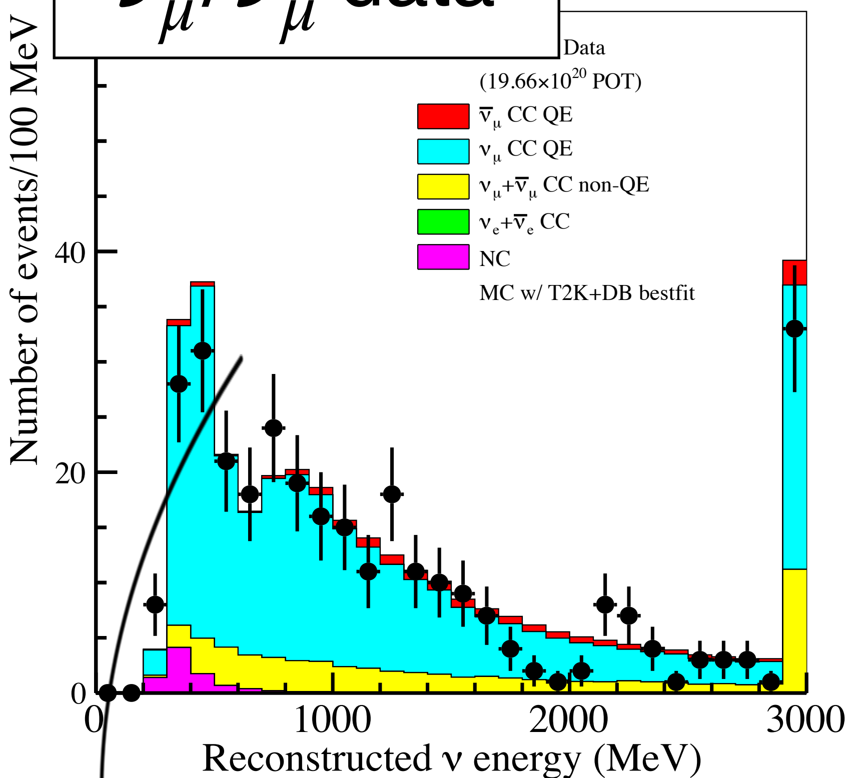




Now loaded with Gadolinium for improved neutron tagging

The oscillation measurement flow

$\nu_\mu/\bar{\nu}_\mu$ data

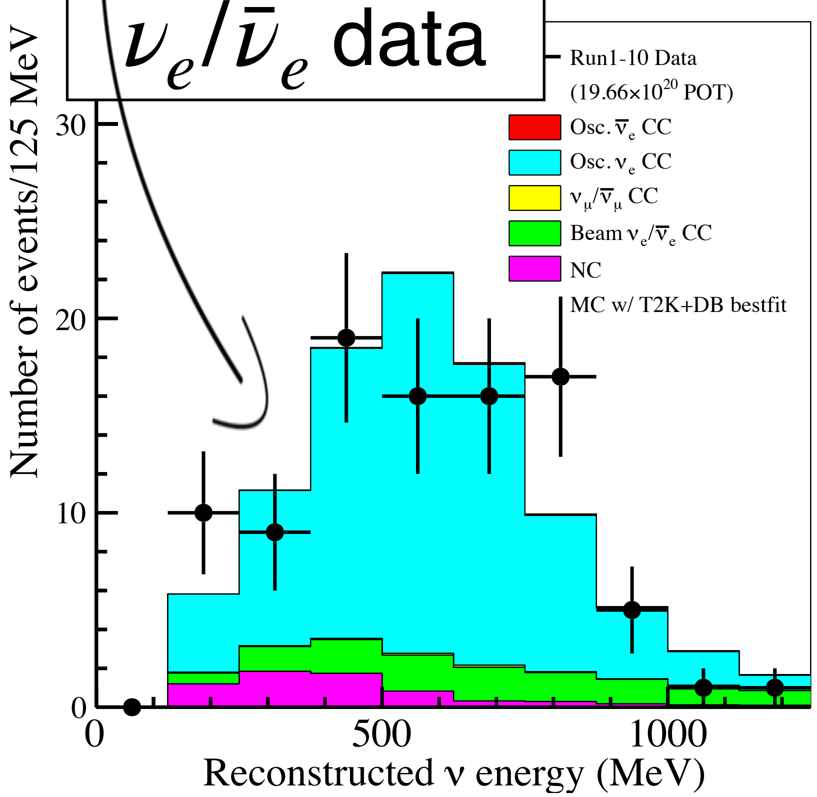


Measure ν_μ and $\bar{\nu}_\mu$ disappearance

$$\phi_{ij} = \left(1.27\frac{L}{E}\Delta m^2_{ij}\right)$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \simeq$$
$$1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23}\right)\sin^2\phi_{32}$$

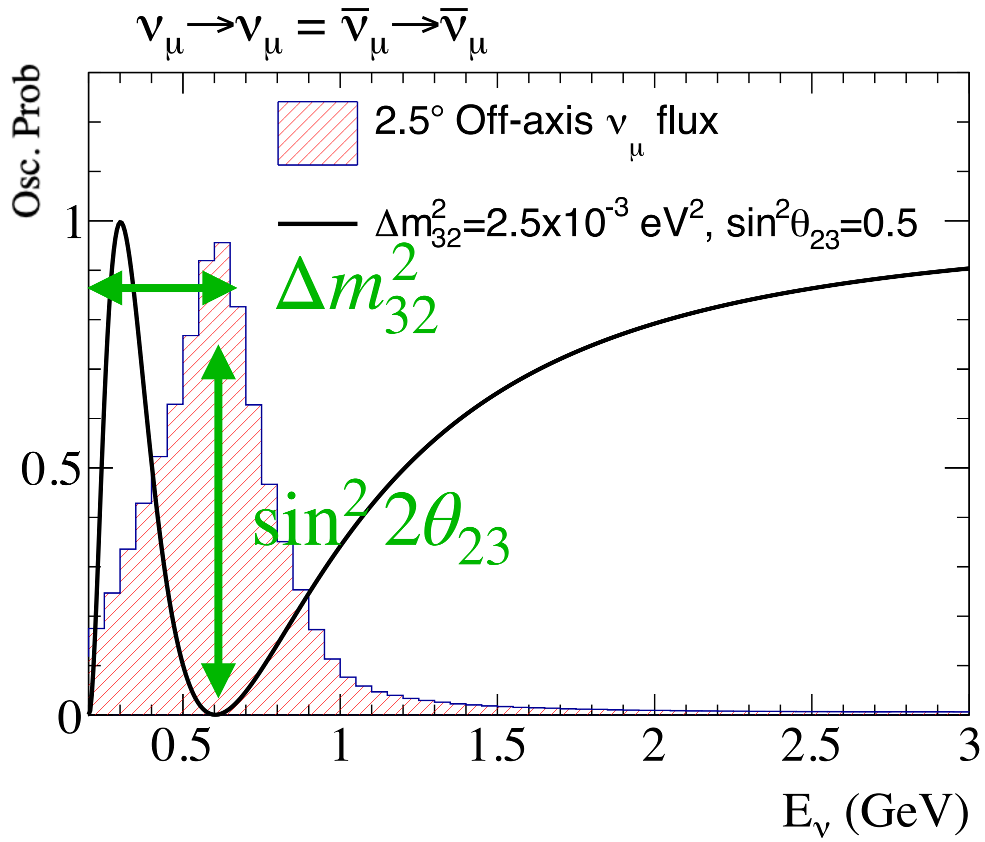
$\nu_e/\bar{\nu}_e$ data



Measure ν_e and $\bar{\nu}_e$ appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\phi_{32}$$
$$\overset{(-)}{+}\, 8J_{CP}\,\phi_{21}\sin^2\phi_{32}$$

The oscillation measurement flow

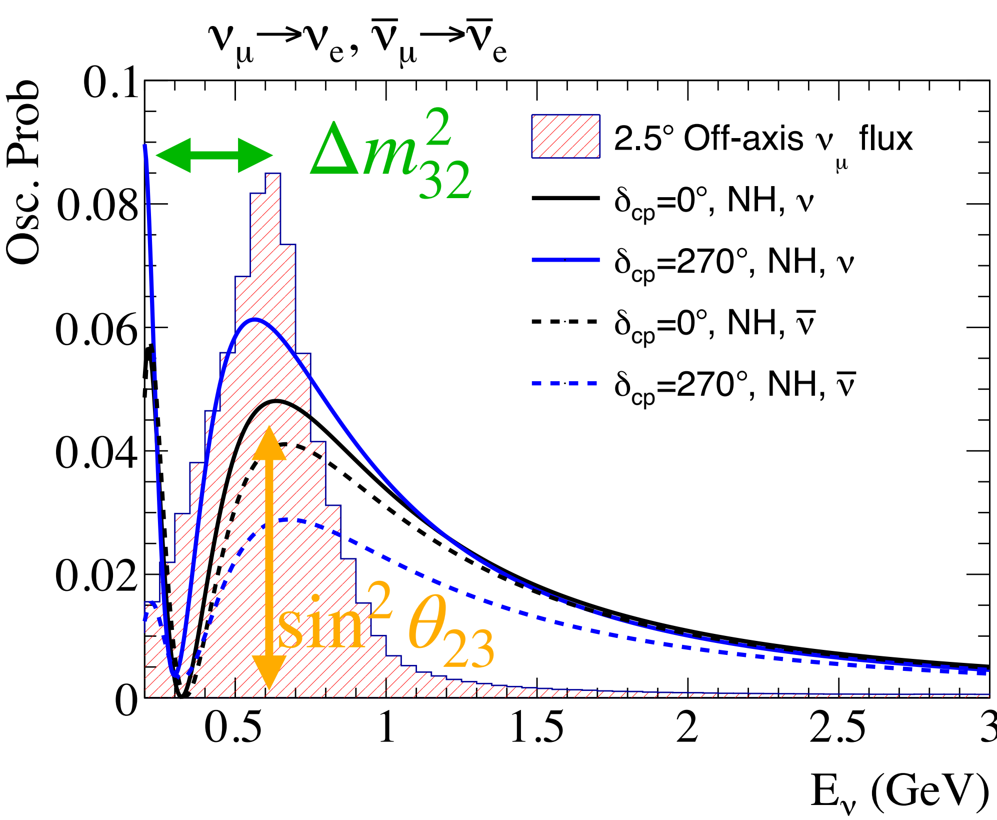


Measure ν_μ and $\bar{\nu}_\mu$ disappearance

$$\phi_{ij} = \left(1.27 \frac{L}{E} \Delta m^2_{ij}\right)$$

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \simeq 1 - \left(\cos^4 \theta_{13} \sin^2 2\theta_{23}\right) \sin^2 \phi_{32}$$

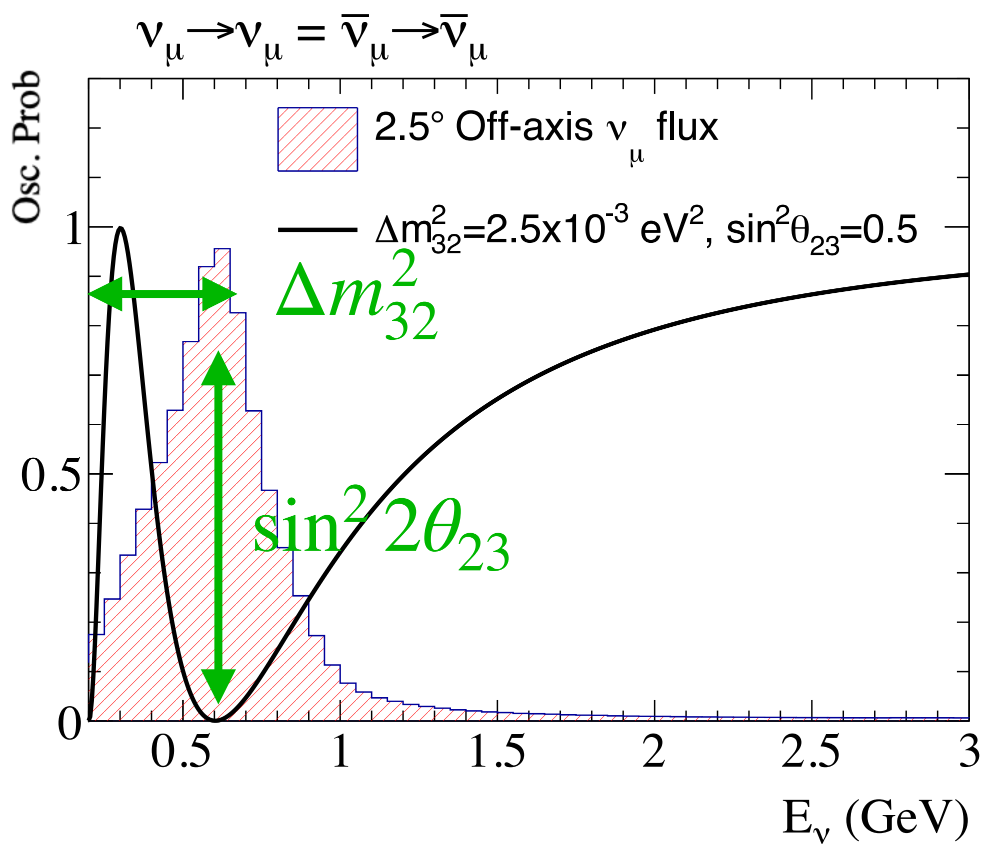
From reactor experiment data



Measure ν_e and $\bar{\nu}_e$ appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \phi_{32} \overset{(-)}{+} 8 J_{CP}\, \phi_{21} \sin^2 \phi_{32}$$

The oscillation measurement flow

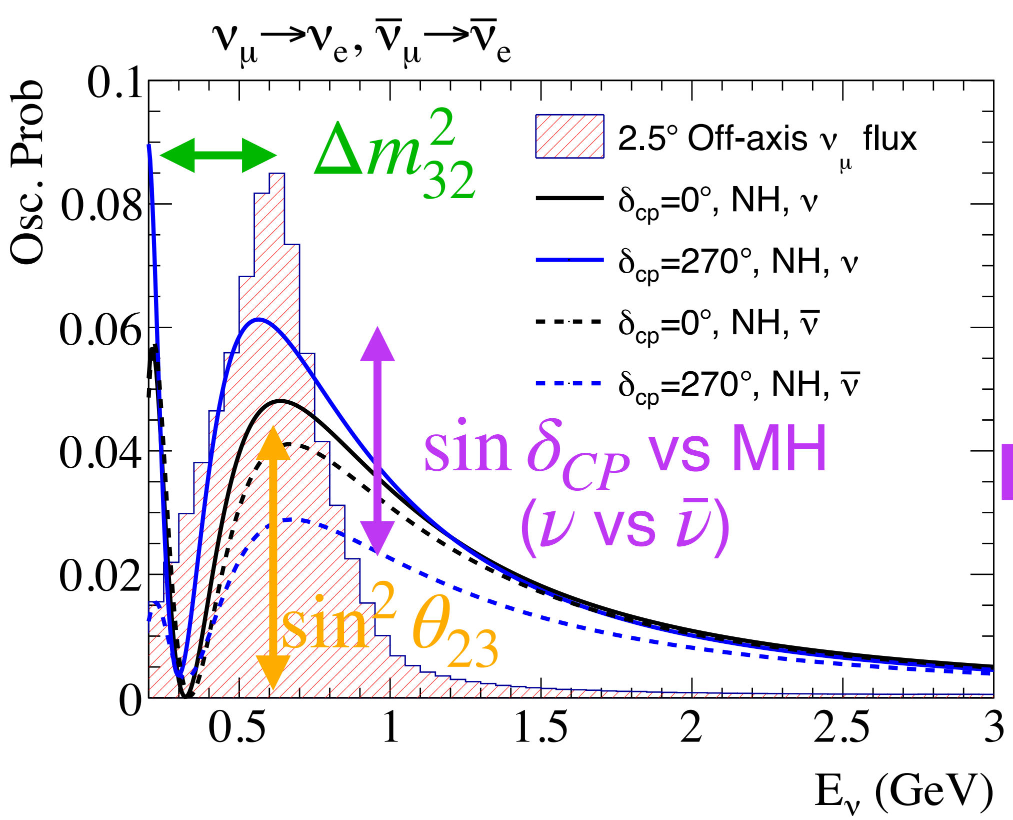


Measure ν_μ and $\bar{\nu}_\mu$ disappearance

$$\phi_{ij} = \left(1.27\frac{L}{E}\Delta m^2_{ij}\right)$$

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \simeq 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23}\right)\sin^2\phi_{32}$$

From reactor experiment data



Measure ν_e and $\bar{\nu}_e$ appearance

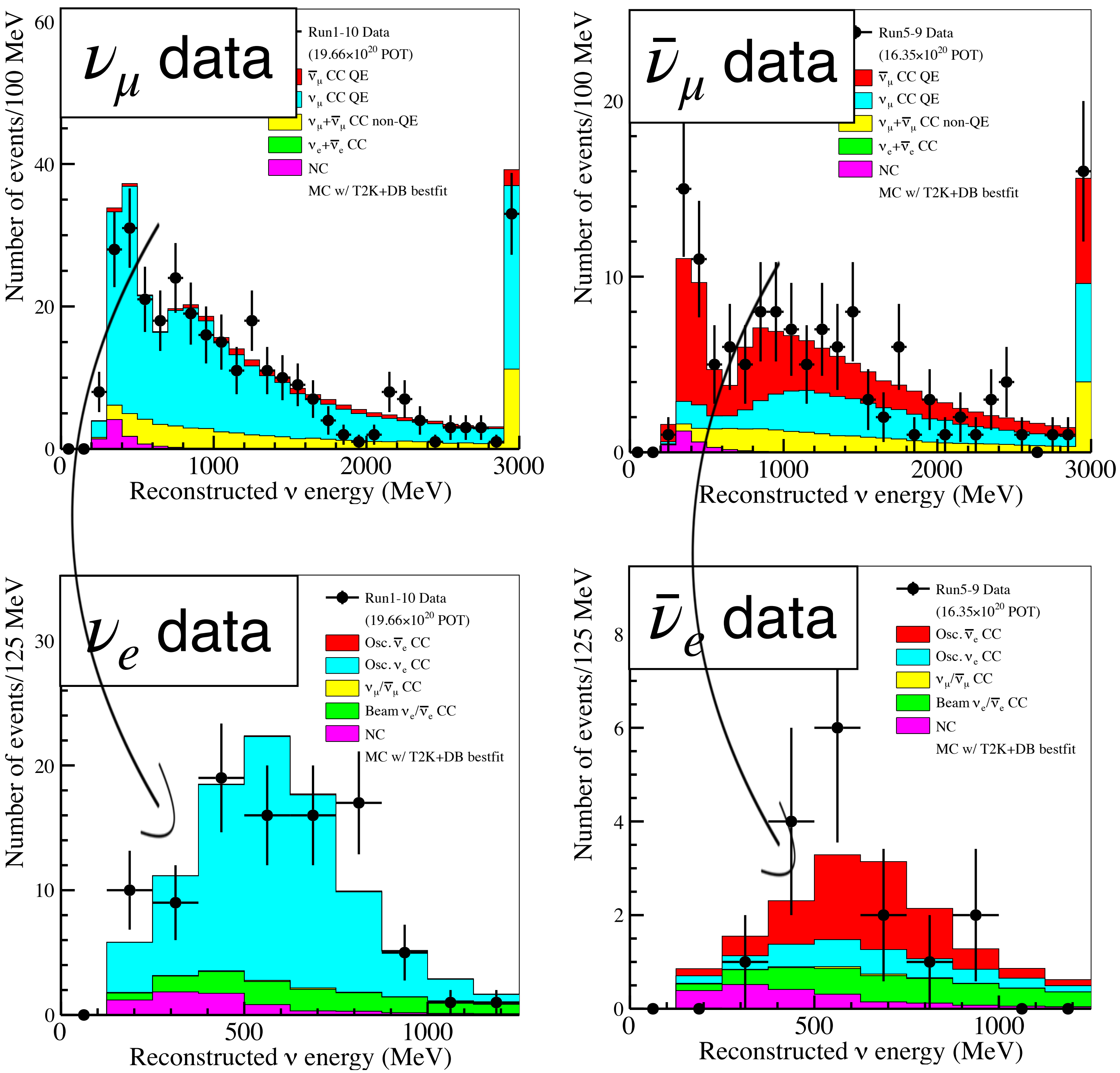
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\phi_{32} \overset{(-)}{+} 8J_{CP}\,\phi_{21}\sin^2\phi_{32}$$

$\Rightarrow \delta_{CP}$ and Mass Hierarchy

T2K results on CP Violation

$\nu_\mu \rightarrow \nu_e$

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



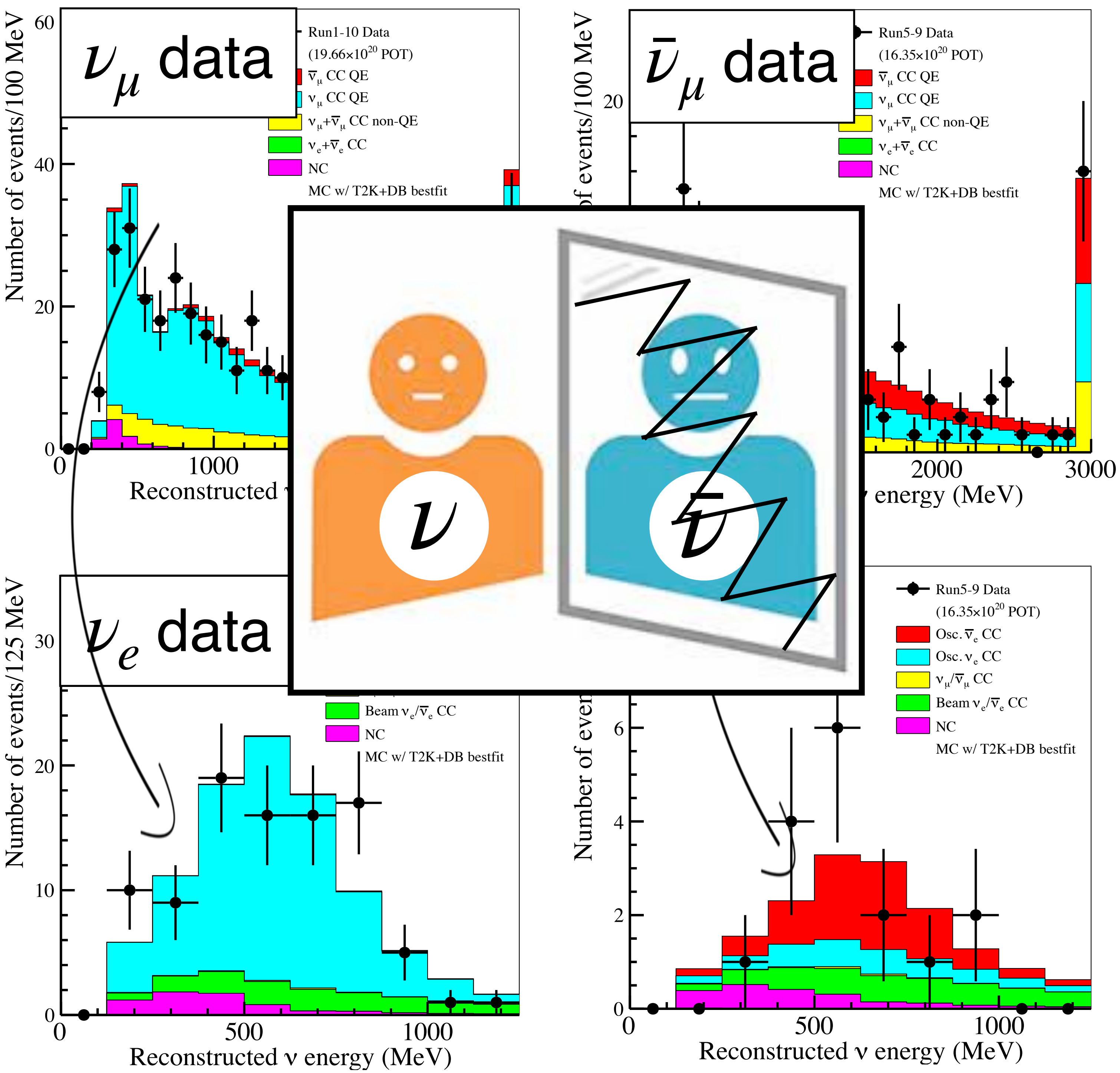
First time 3σ Interval on δ_{CP}

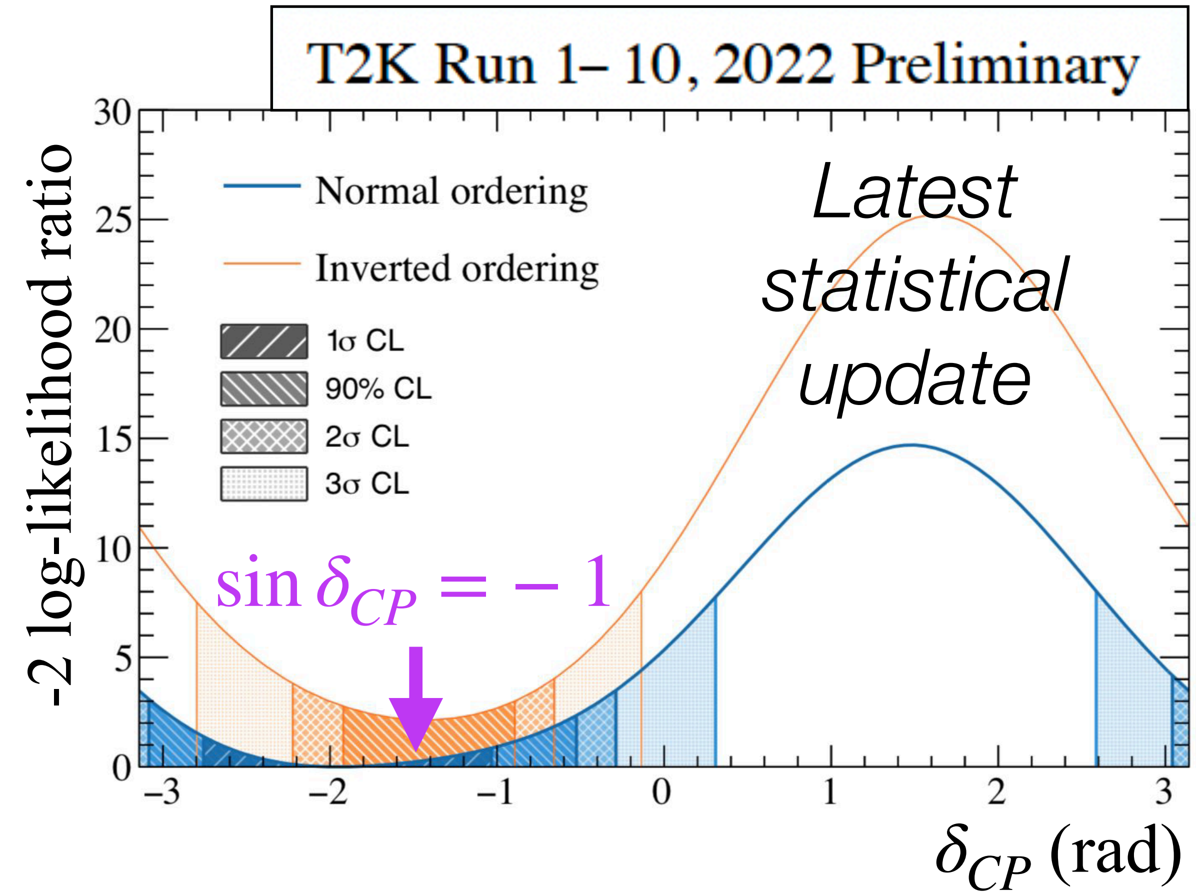
Nature vol. 580, pages 339–344 (2020)

T2K results on CP Violation

$\nu_\mu \rightarrow \nu_e$

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



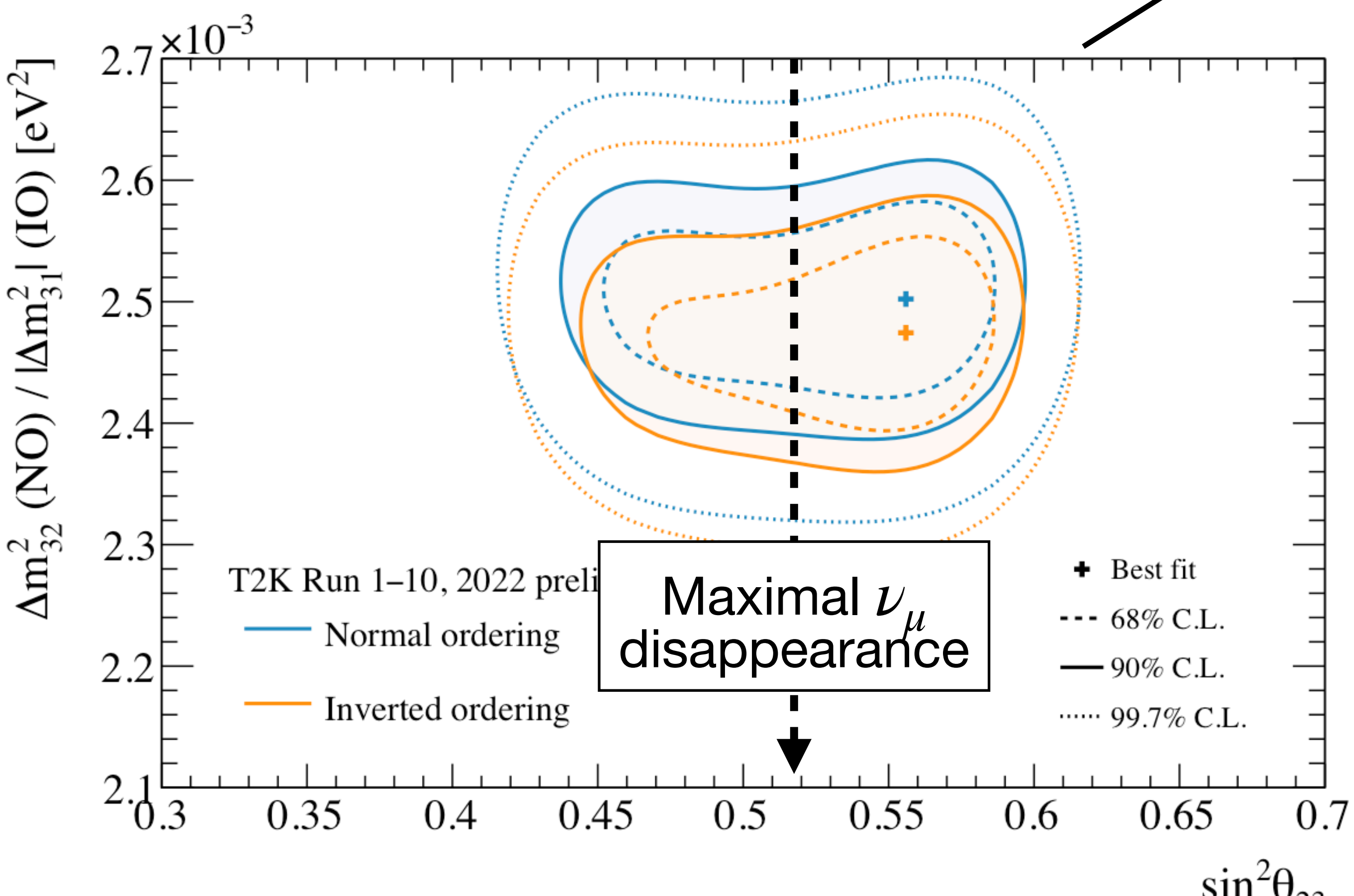


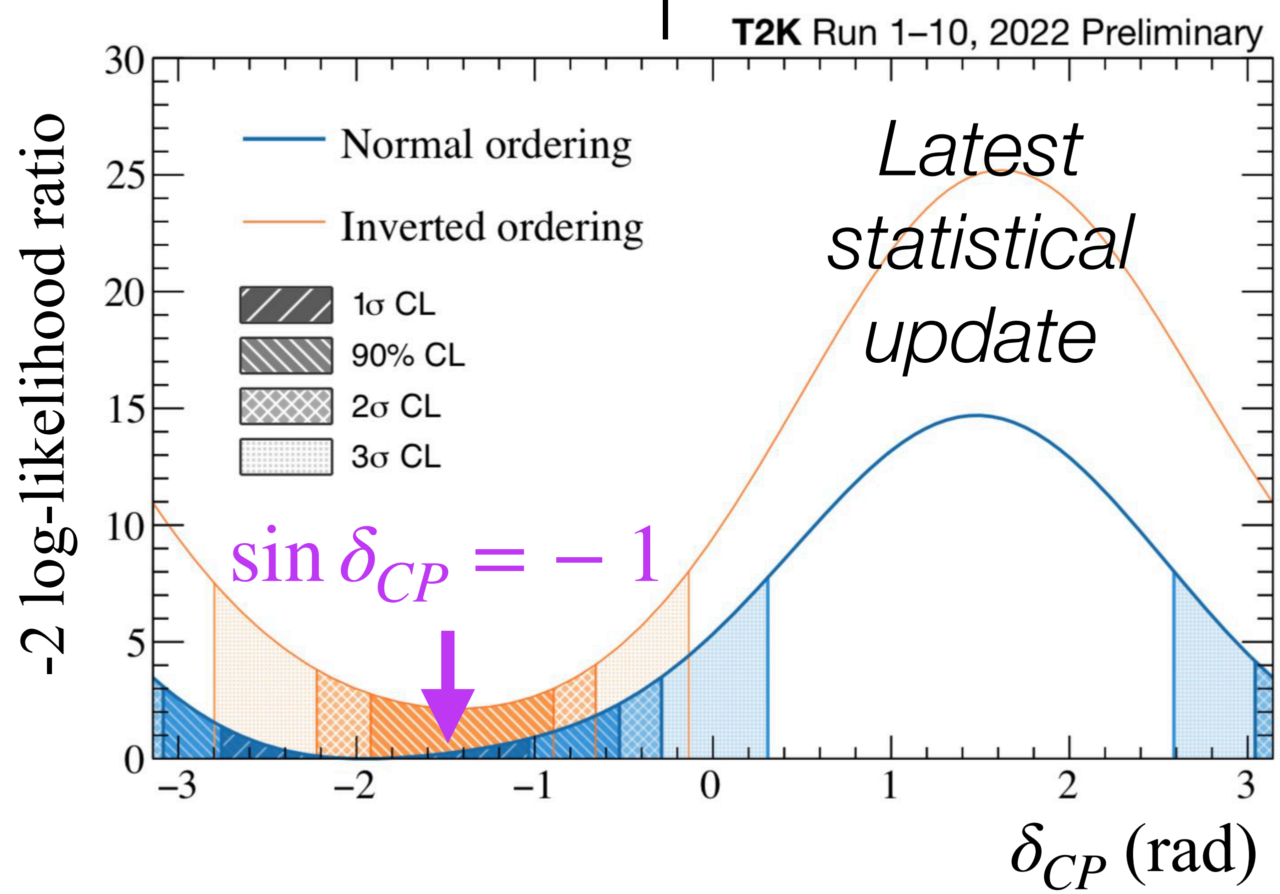
- Large region of δ_{CP} values excluded at 3σ
- CP conservation excluded at 90% C.L.
- $\sin\delta_{CP} \sim 1$ and Normal Hierarchy

Results on other parameters

From reactors/solars (PDG 2022)

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta_{CP} \sim 0.03$$





- Consistent with maximal ν_μ disappearance
- Preference for higher octant

- $\sin\delta_{CP} \sim 1$ and Normal Hierarchy

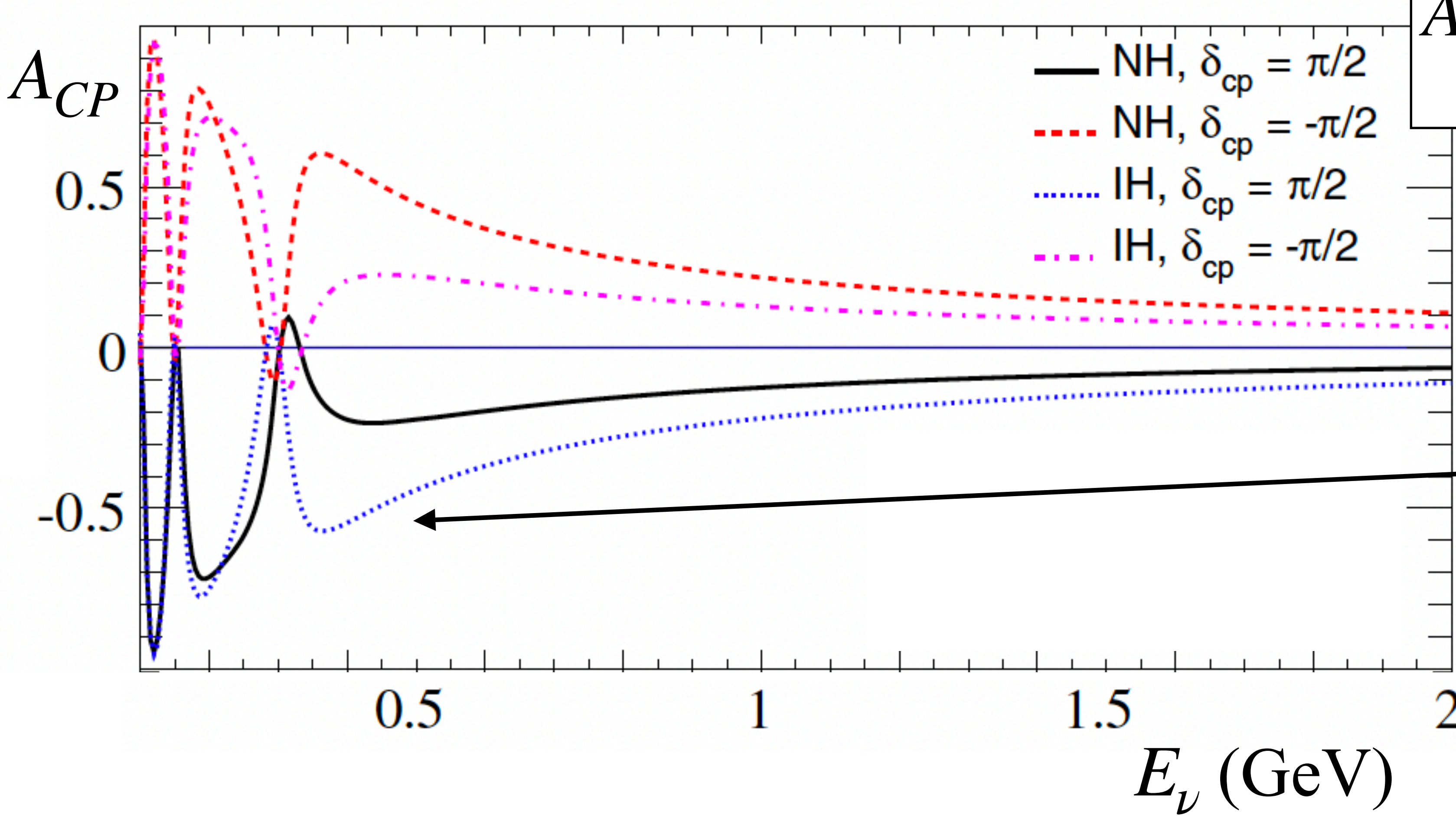
T2K results on CP Violation

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\phi_{32}$$

$$\phi_{ij} = 1.27\frac{L}{E}\Delta m^2_{ij}$$

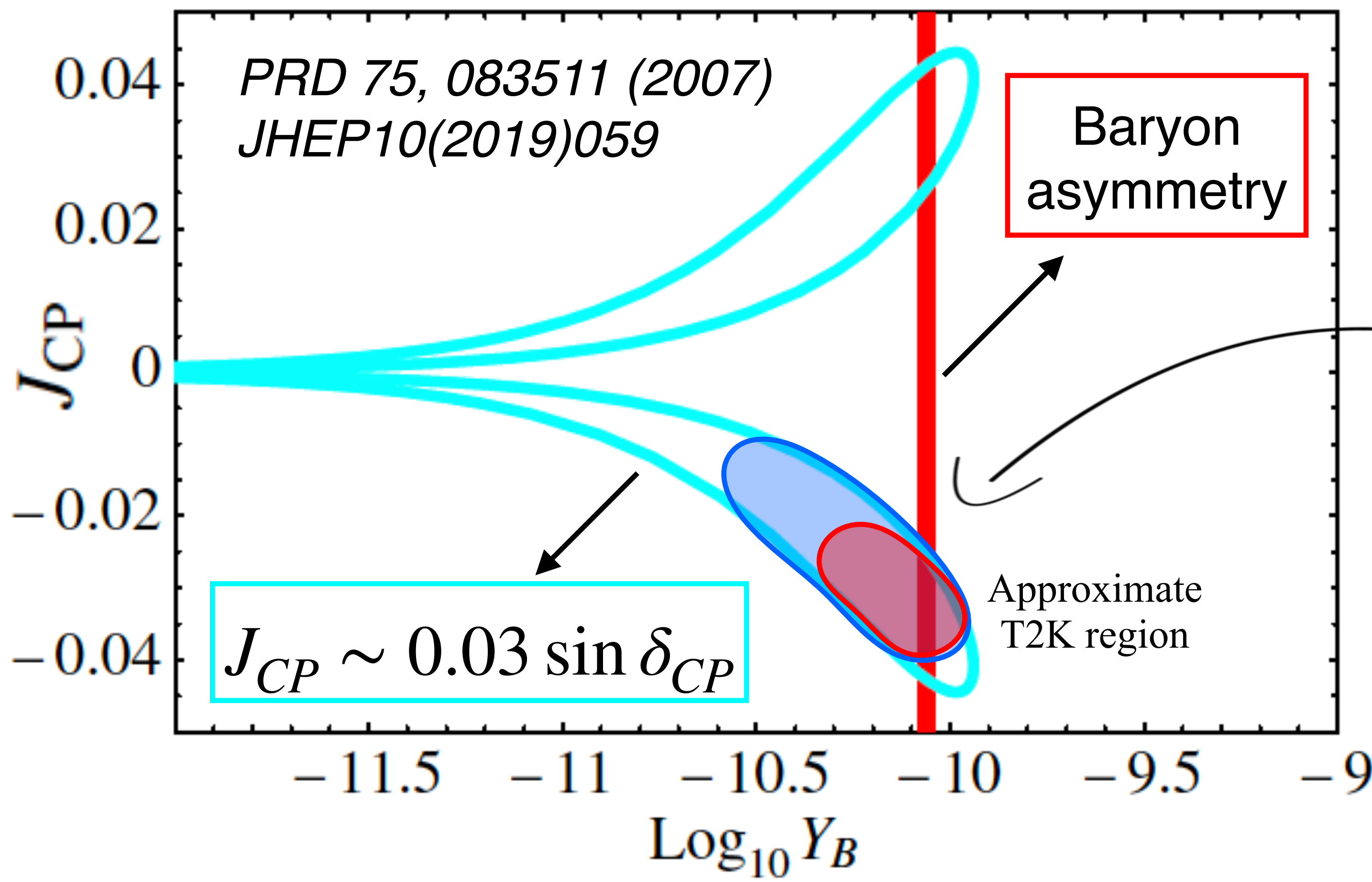
"+" for ν
"-" for $\bar{\nu}$ ⟵ $$\overset{(-)}{+}\, 8J_{CP}\phi_{21}\sin^2\phi_{32}$$

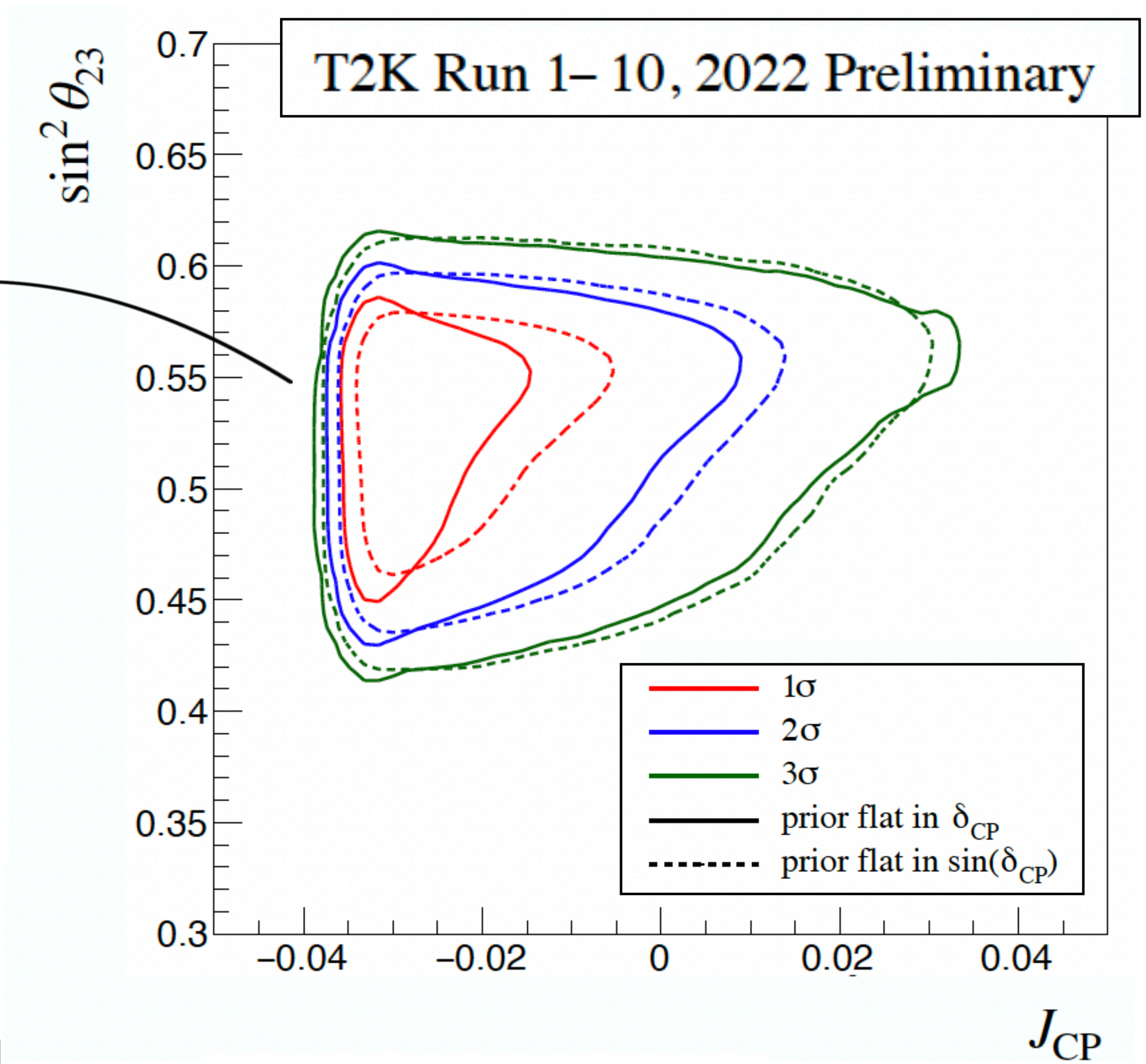
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$



Preference for large CP asymmetry ($\sin\delta_{CP} \sim -1$) and Normal Hierarchy

Matter-Antimatter imbalance in the Universe



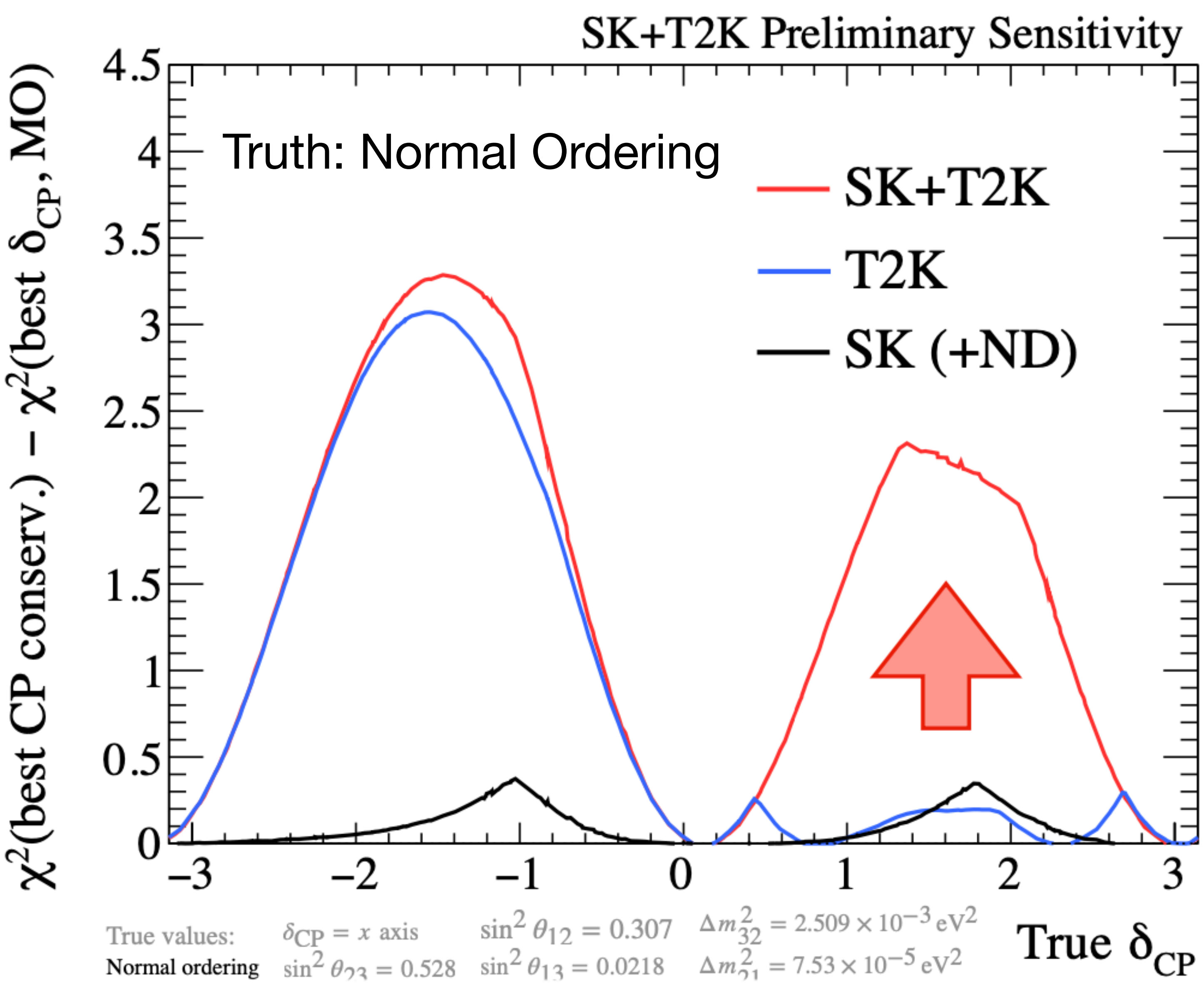


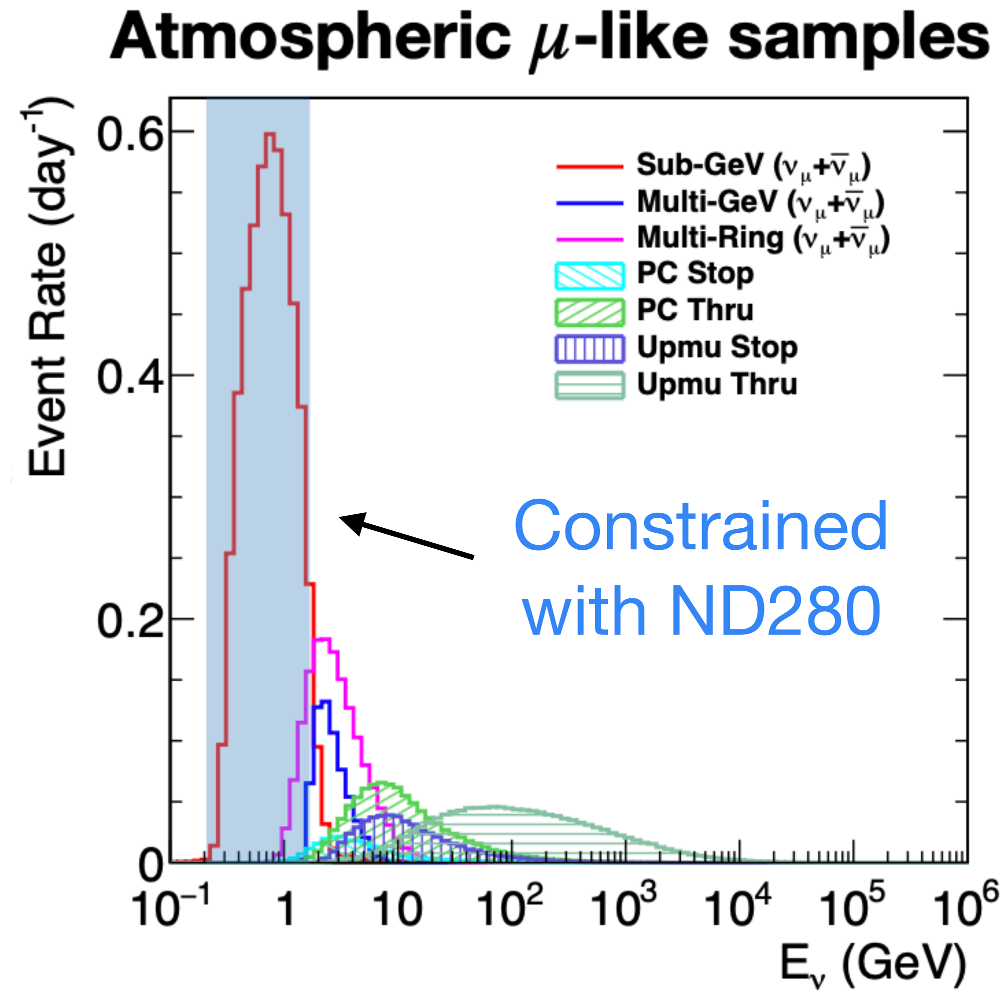
If the results will be confirmed, it is possible that a not-small fraction of the observed matter-antimatter imbalance was generated starting from neutrinos (Leptogenesis)

It is crucial to improve the precision on δ_{CP}

Towards the T2K+SK joint fit

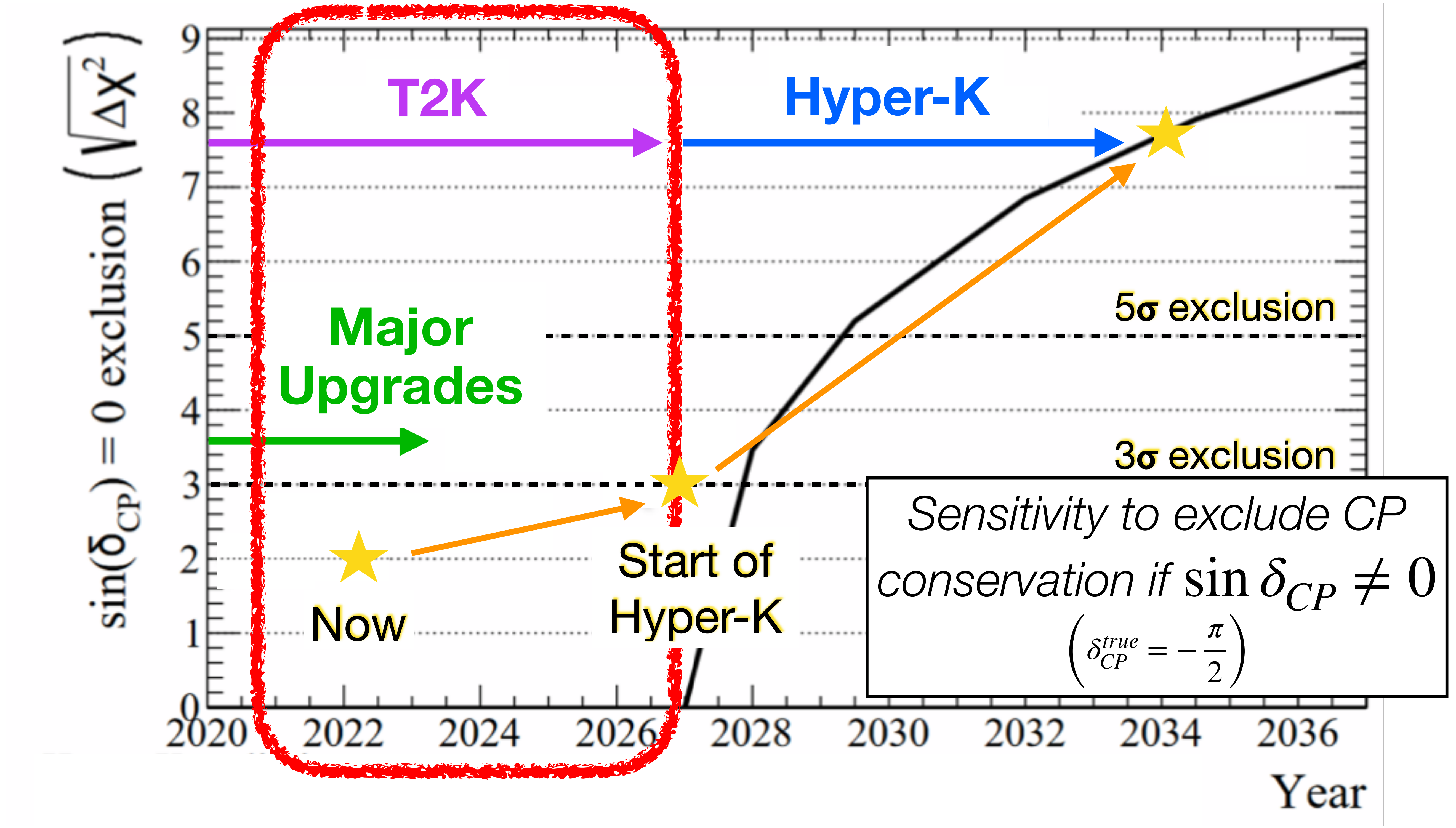
Combining accelerator + atmospheric ν data will enhance the sensitivity to Mass Hierarchy and, consequently, to CP violation



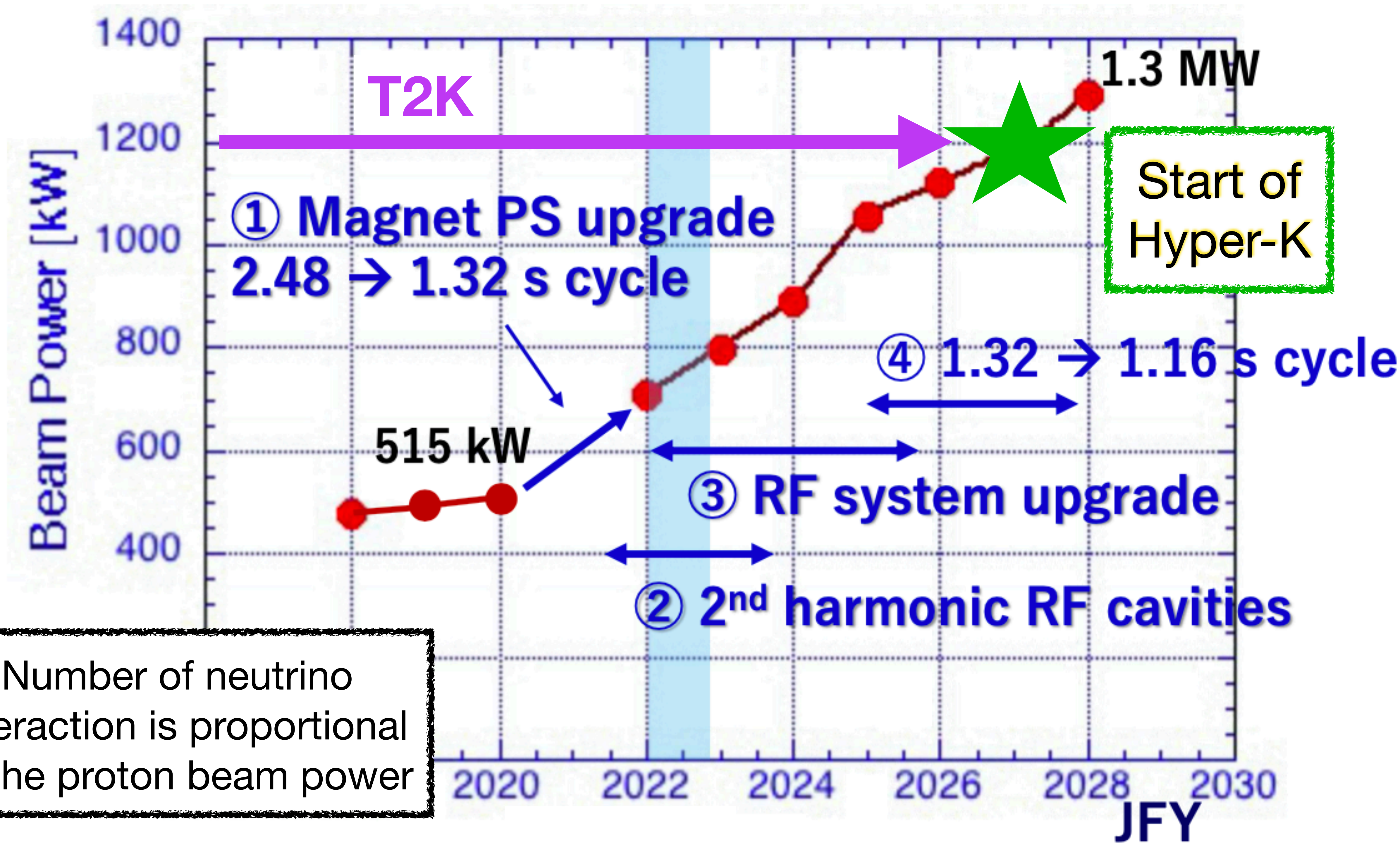


The Near Detector will constrain also cross section model of the ν atmospheric dominant sample

Roadmap for measuring δ_{CP}



The J-PARC proton accelerator upgrade



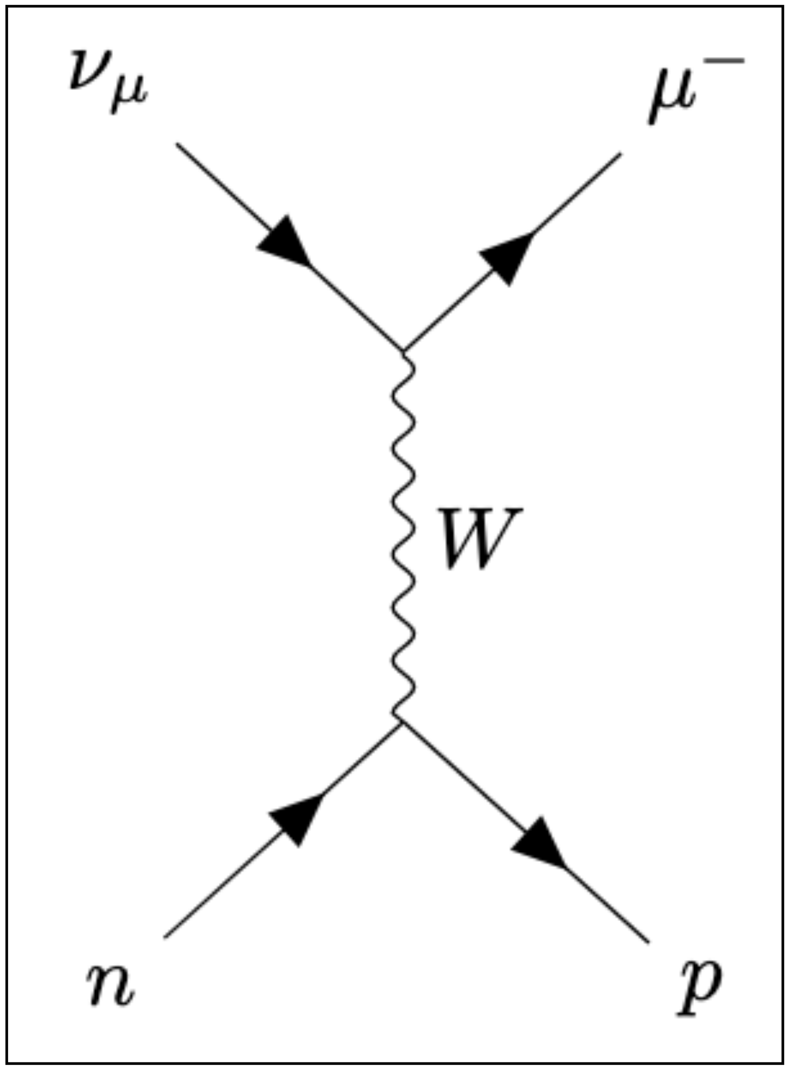
Number of neutrino interaction is proportional to the proton beam power

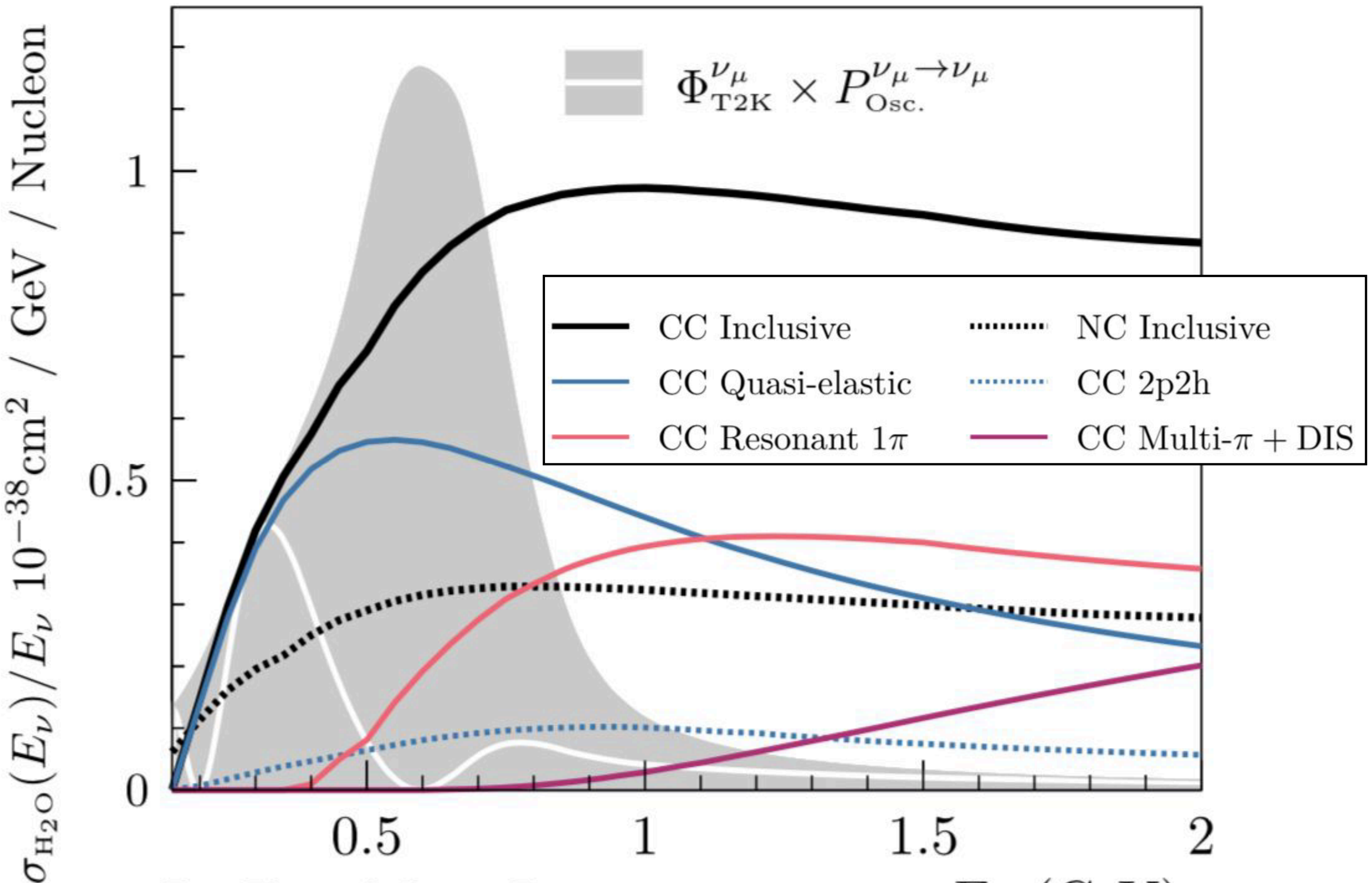
Beam power up from 515 kW to 1.2 MW at the end of T2K

High power beam ready for the start of Hyper-K

Modeling neutrino-nucleus interactions

Charged Current
Quasi-Elastic (CCQE)



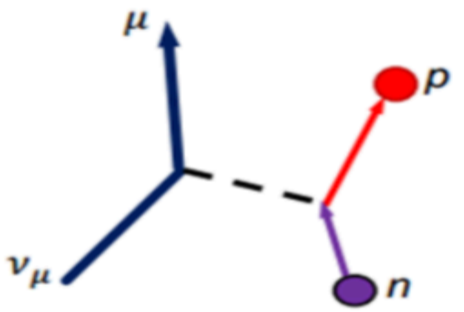


Eur. Phys. J. Spec. Top. (2021) 230:4469–4481

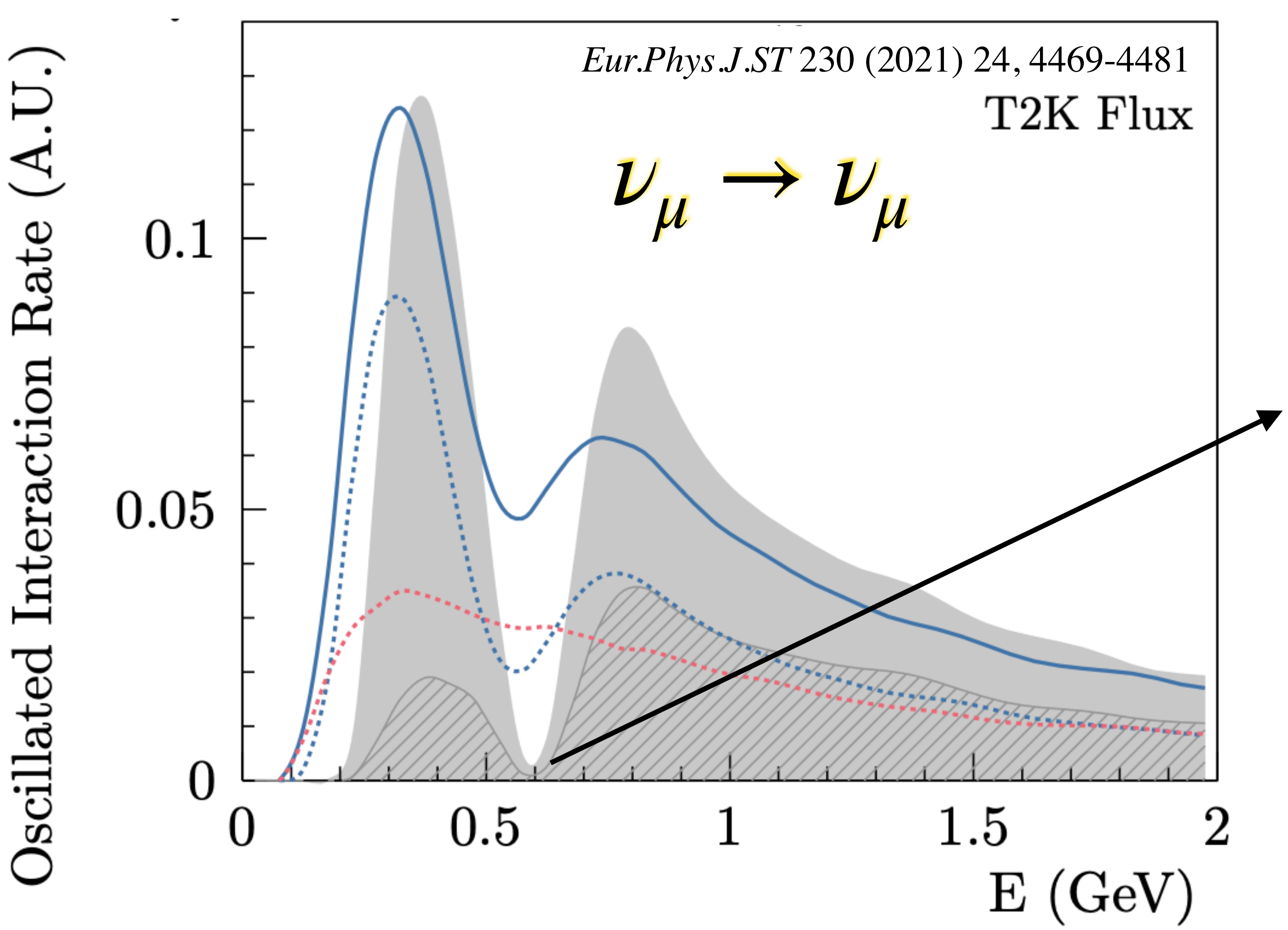
Different cross-section for ν and $\bar{\nu}$ $\Rightarrow$ ambiguity for CP violation search

Other contributions mostly from Neutral Currents and CC π resonances

The impact of nuclear effects

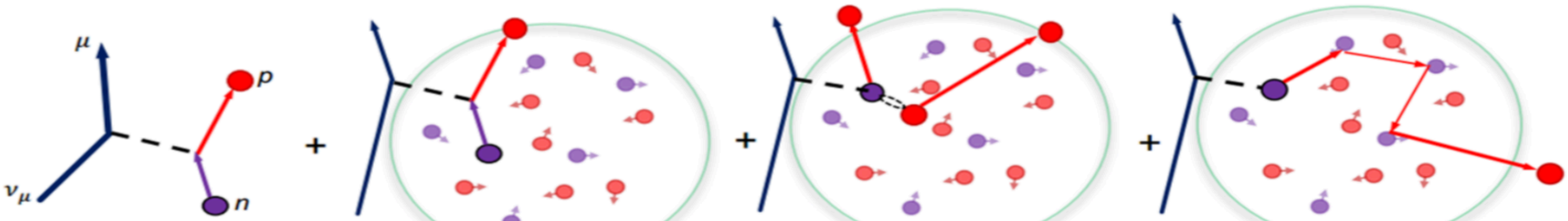


Pure CCQE interaction



Very narrow dip from disappeared ν_μ if the energy is perfectly reconstructed

The impact of nuclear effects

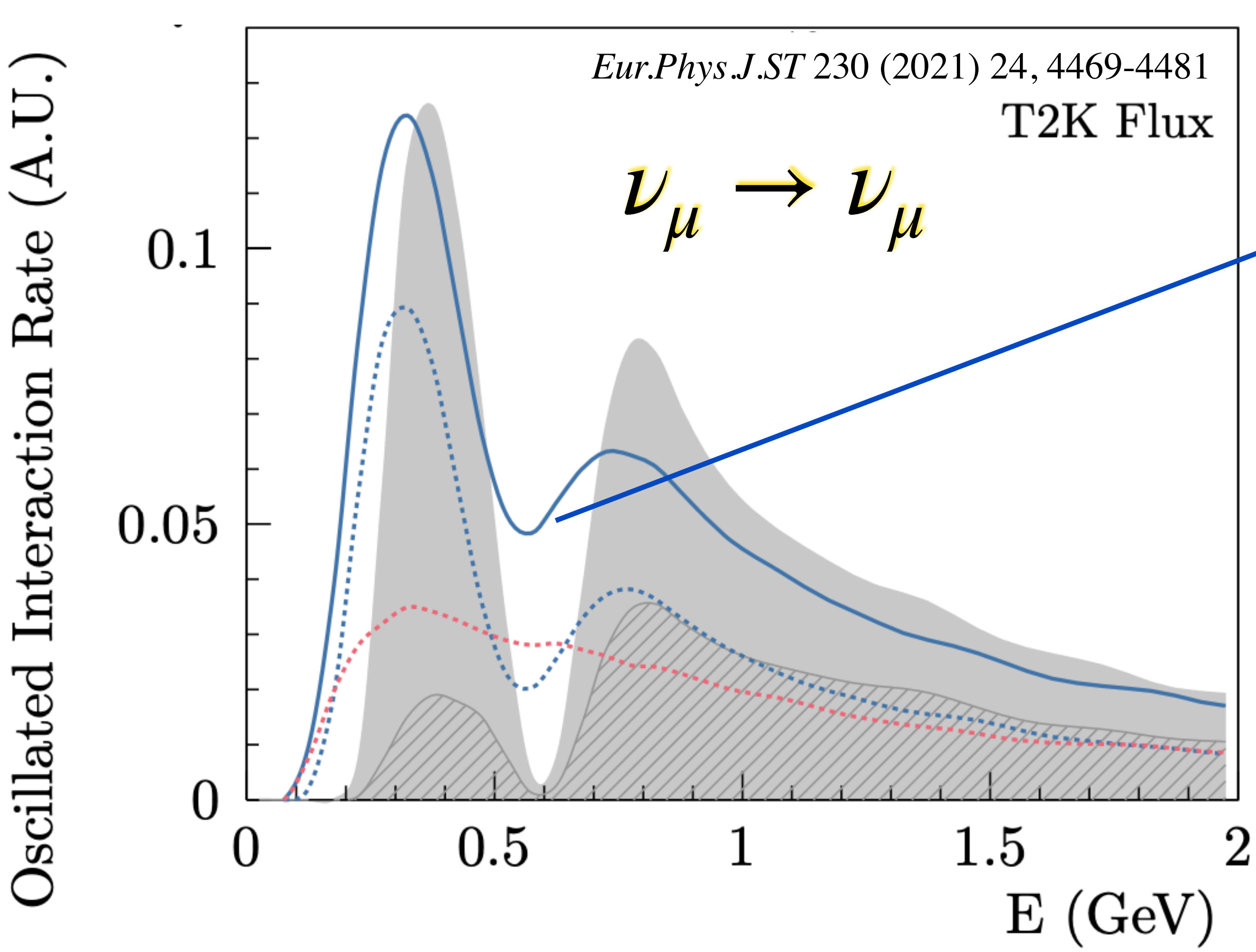


Pure CCQE interaction

Fermi Motion and Binding Energy

Nuclear Correlations

Final State Interactions

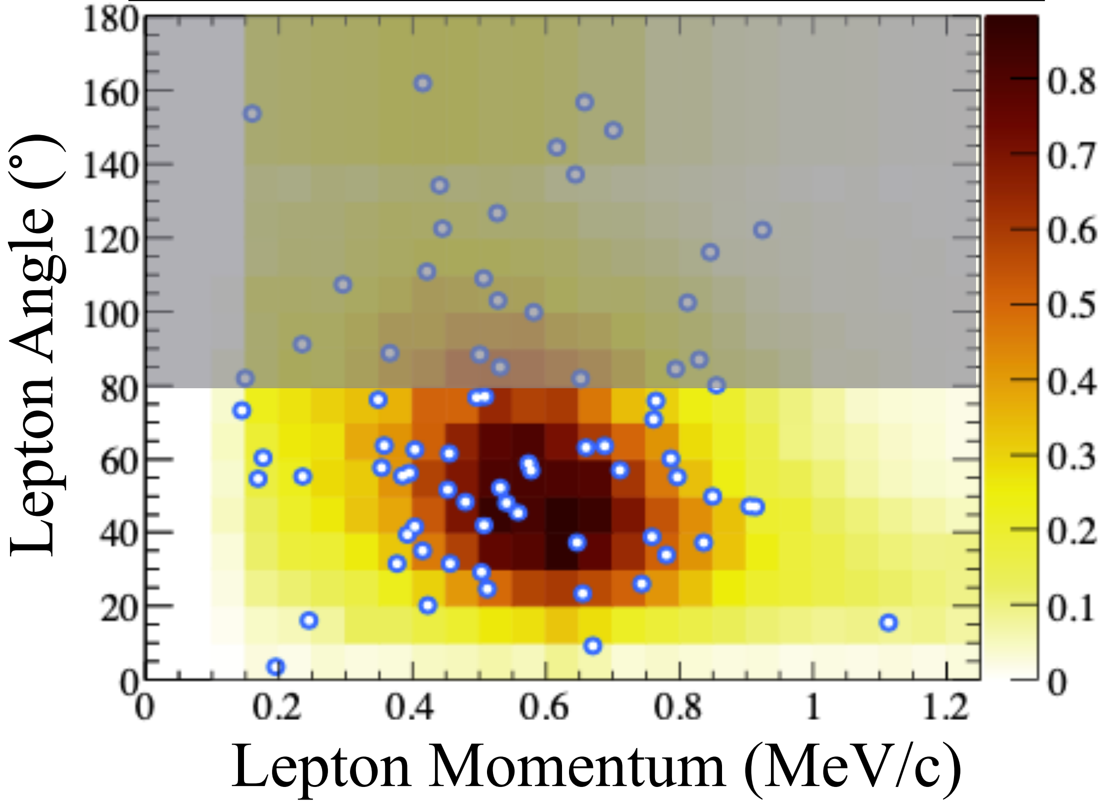


Dip observed in data

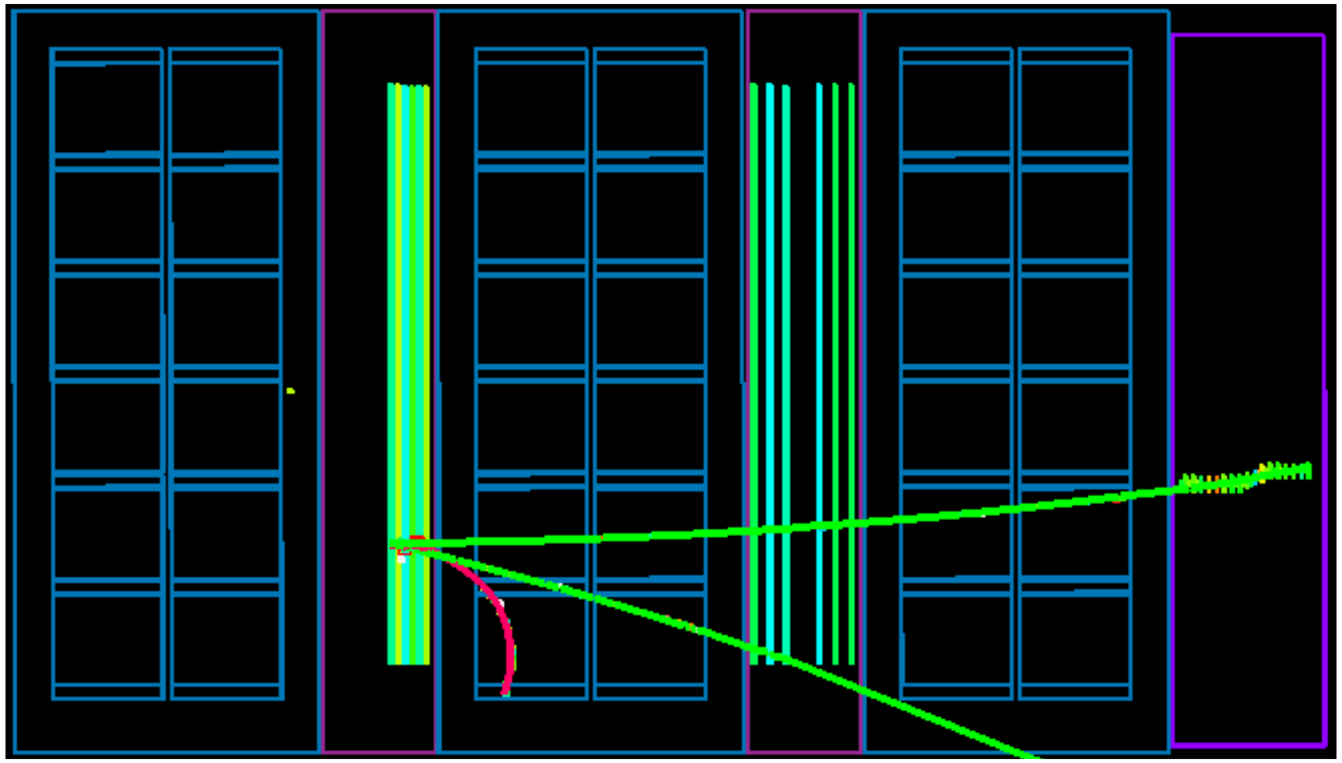
The precise knowledge of the neutrino energy requires an accurate modelling of neutrino interactions

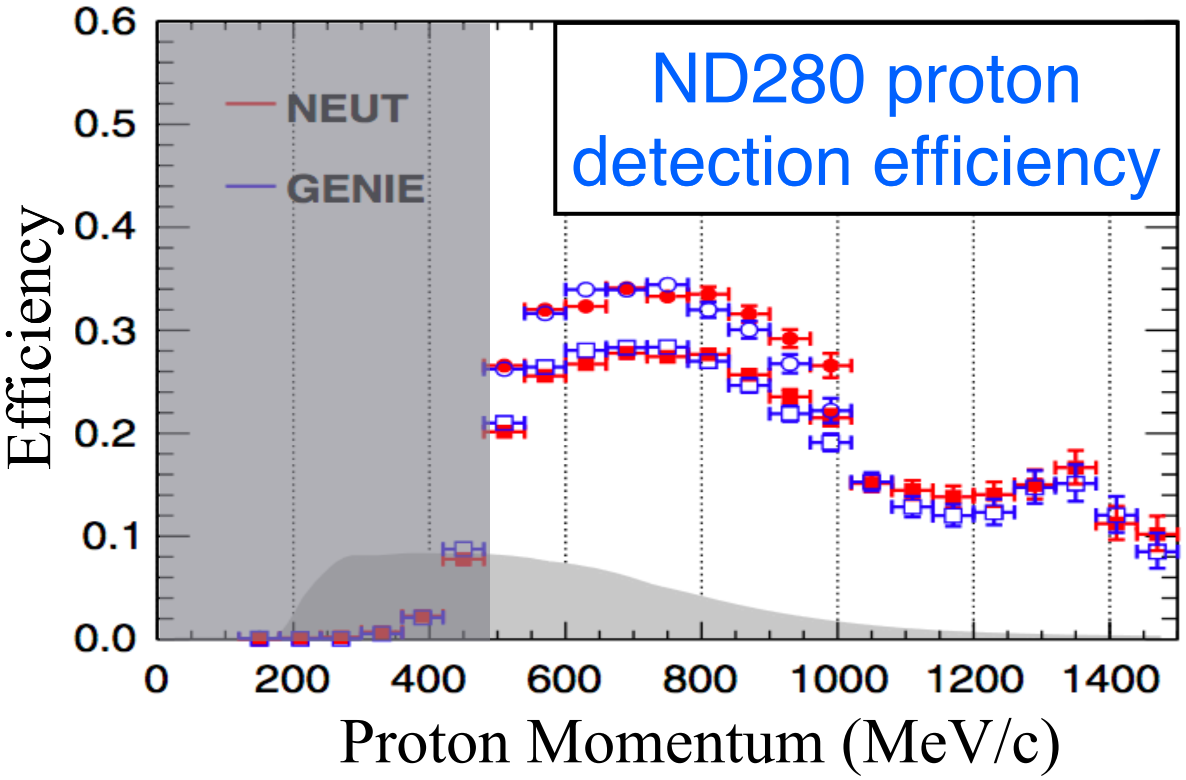
The weaknesses of ND280

ν_e events at the Far Detector



Optimised for forward-going tracks



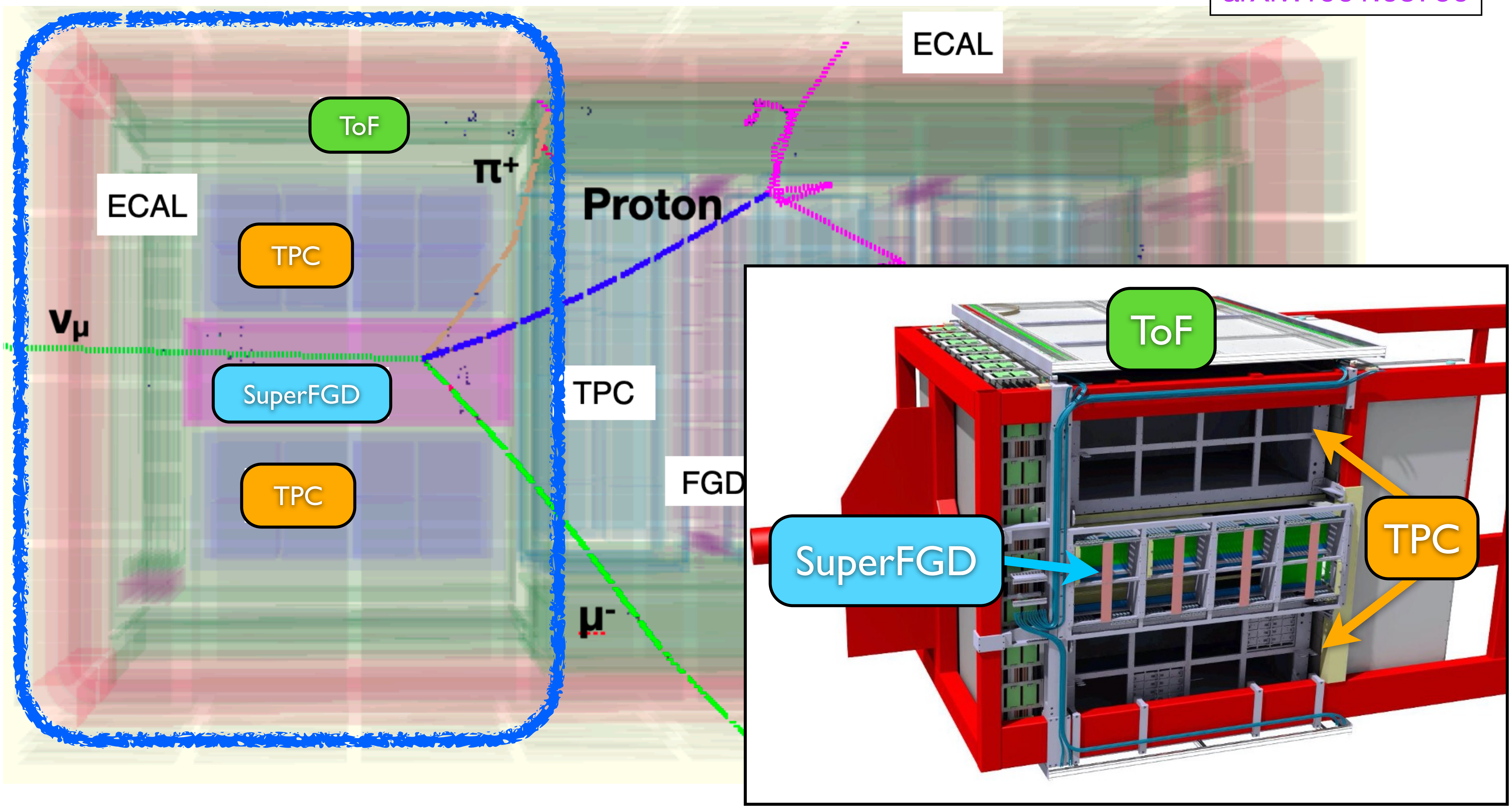


The increase of statistics requires an adequate reduction of the systematics

- Increase the particle detection efficiency as a function of the angle
- Reduce the proton momentum threshold

The ND280 Upgrade

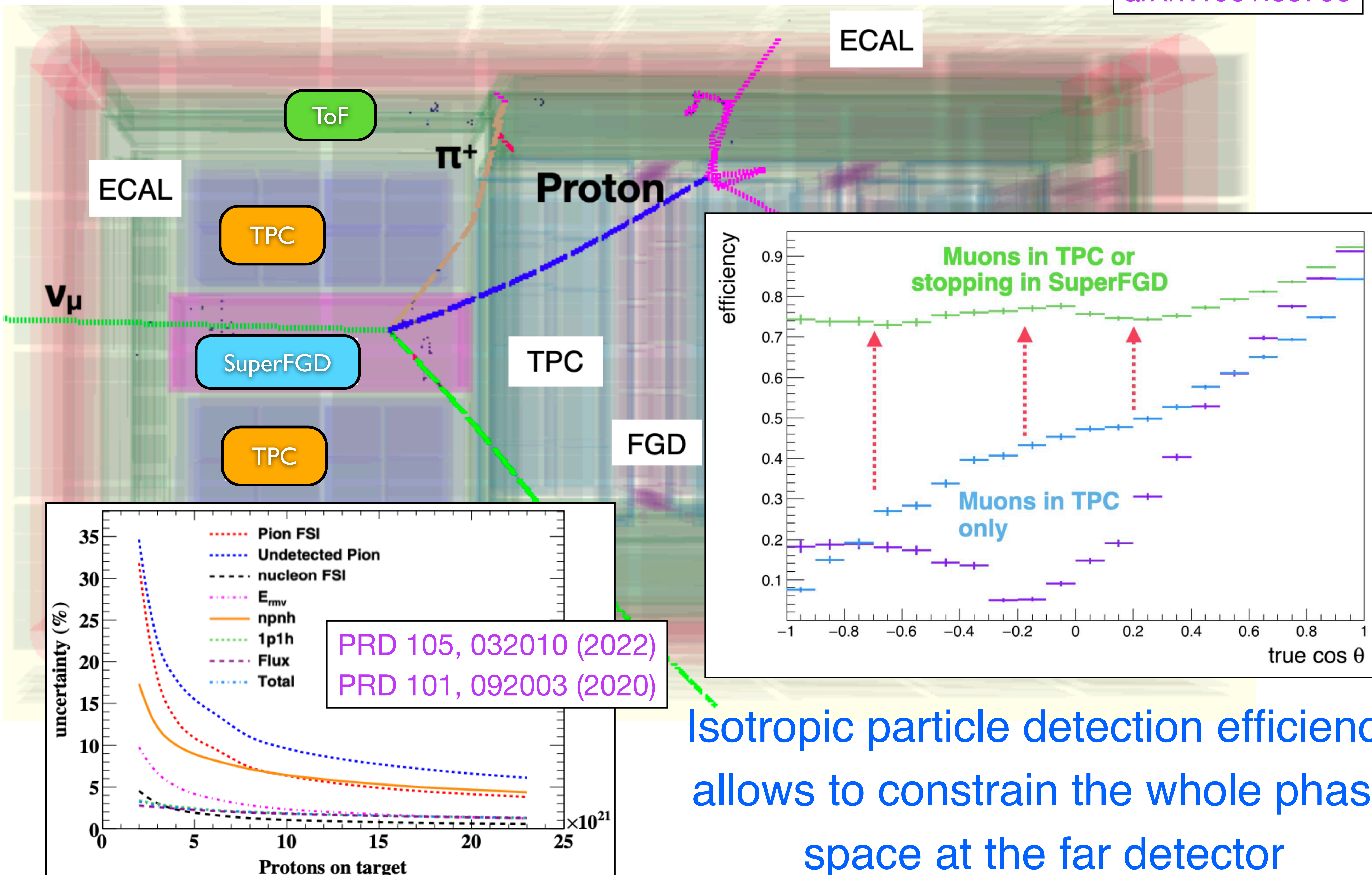
arXiv:1901.03750



Replace part of the P0D detector (measured NC π^0 production) with a new scintillator target (SuperFGD), two TPCs and a ToF detector

The ND280 Upgrade

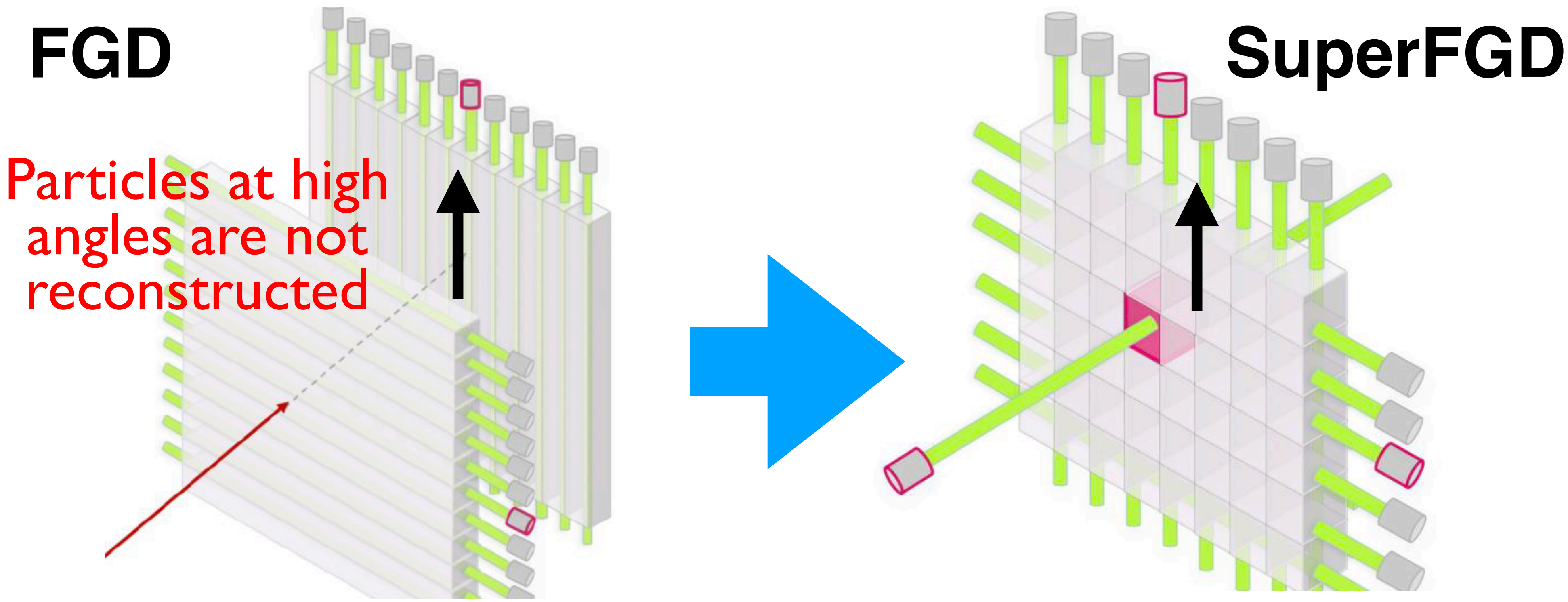
arXiv:1901.03750



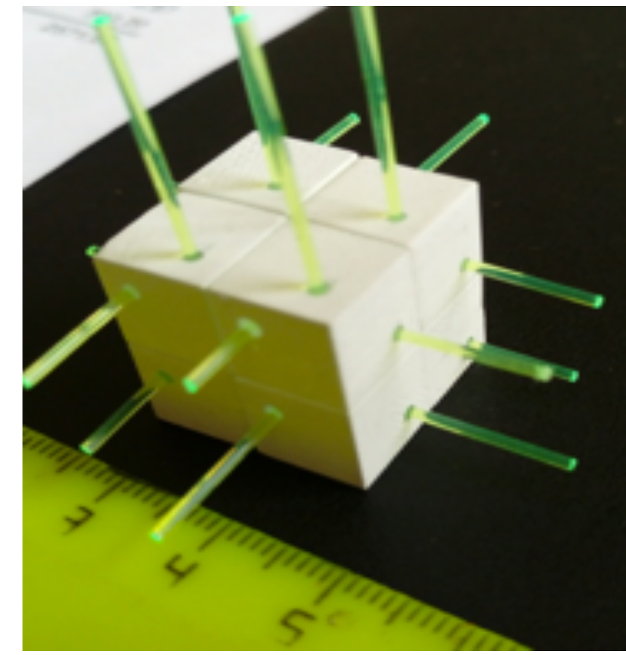
PRD 105, 032010 (2022)
PRD 101, 092003 (2020)

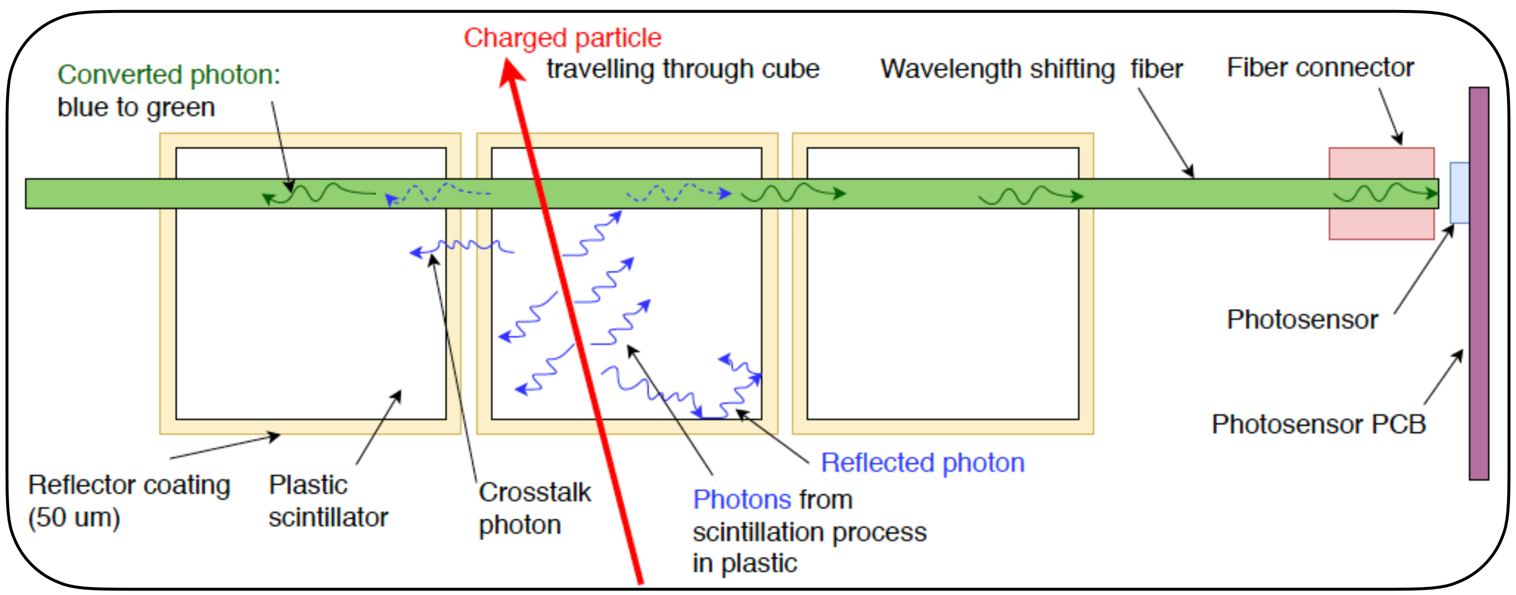
Isotropic particle detection efficiency allows to constrain the whole phase space at the far detector

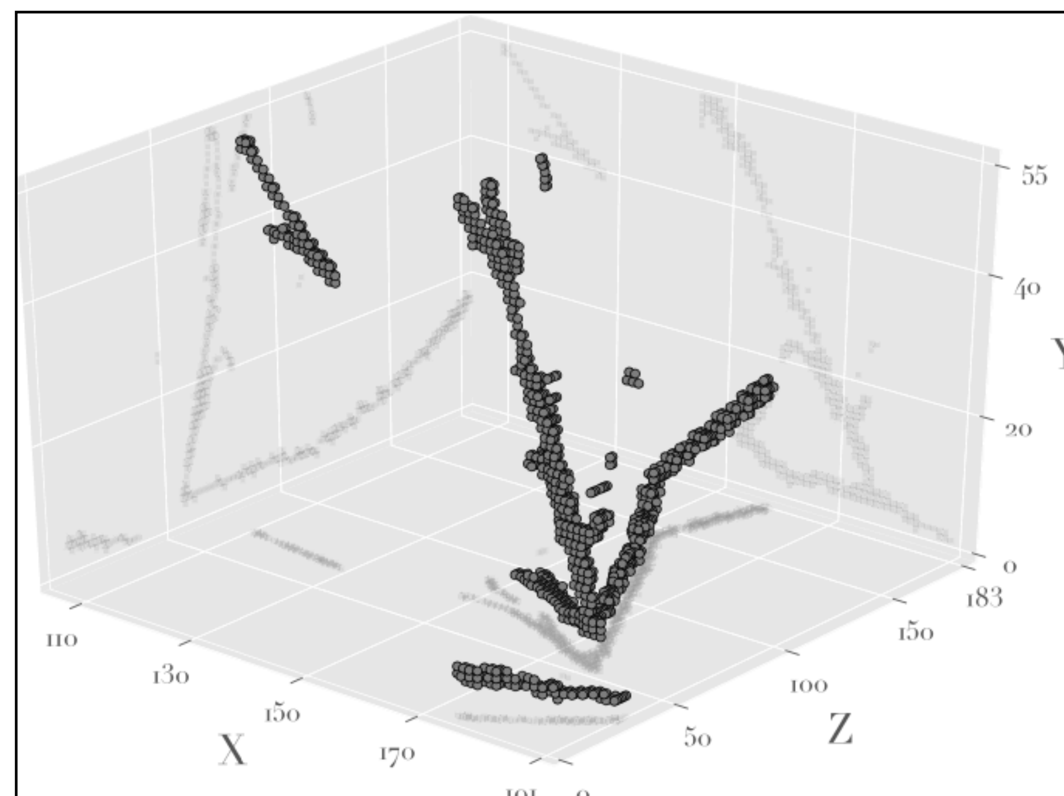
The SuperFGD detector



JINST 13 P02006 (2018)







✓Three projections ⇒ isotropic

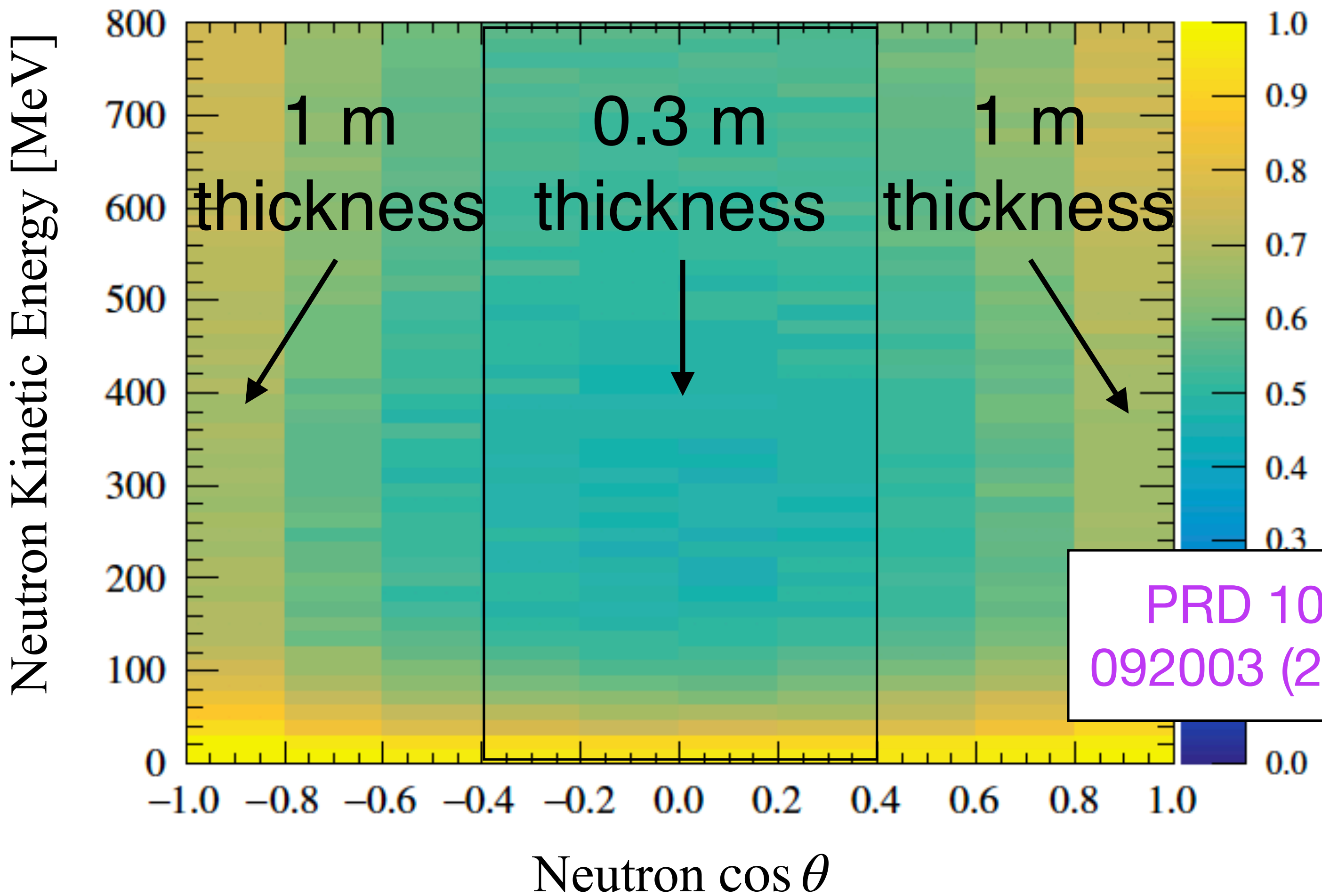
✓3D fine granularity ⇒ short tracks

✓0.6 ns time resolution ⇒ neutron energy

SuperFGD potential for neutron detection

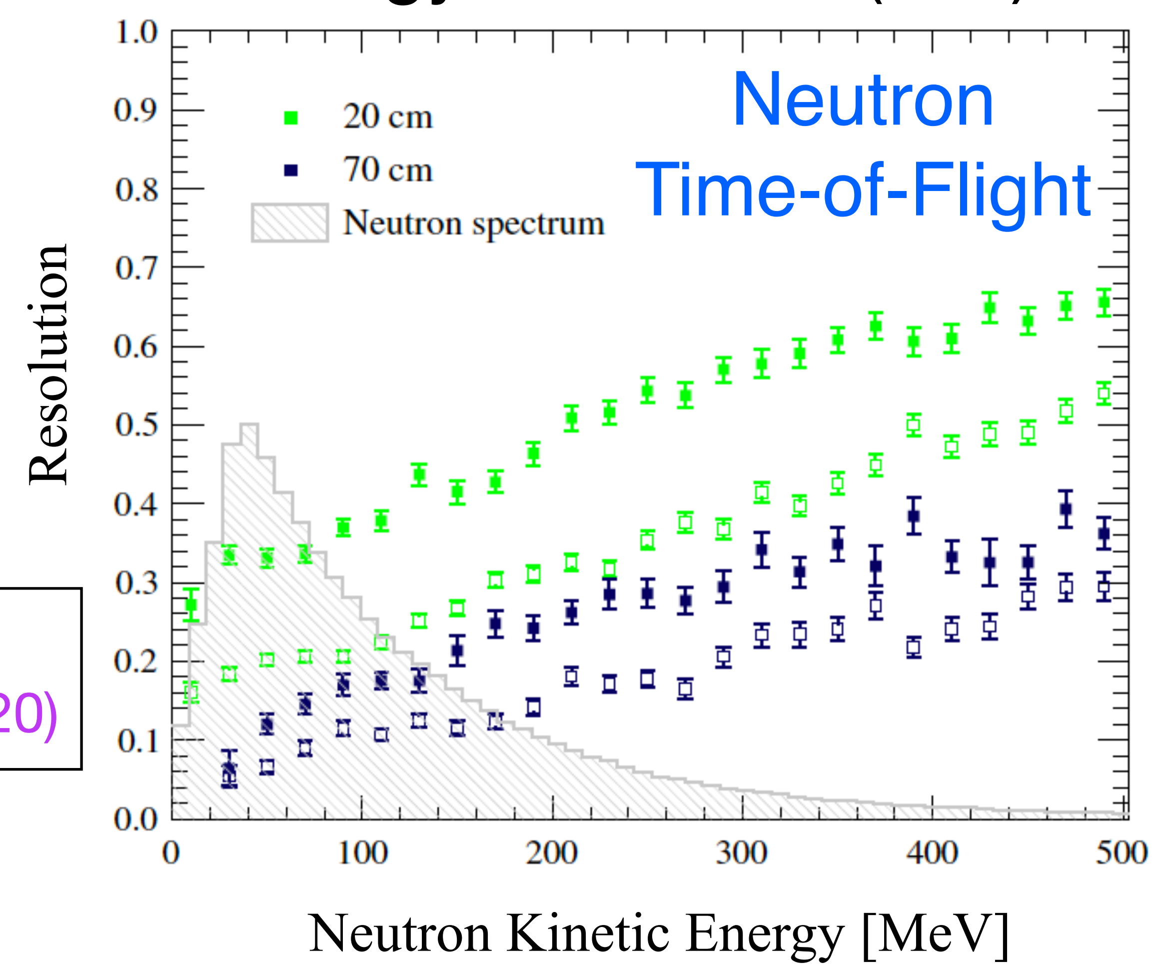
- A fine 3D-granularity fully-active plastic scintillator detector is optimal to detect and measure the ToF of fast neutrons
  - ✦ Sub-ns time resolution
  - ✦ High efficiency (~1% per cm of scintillator)

Detection efficiency (MC)



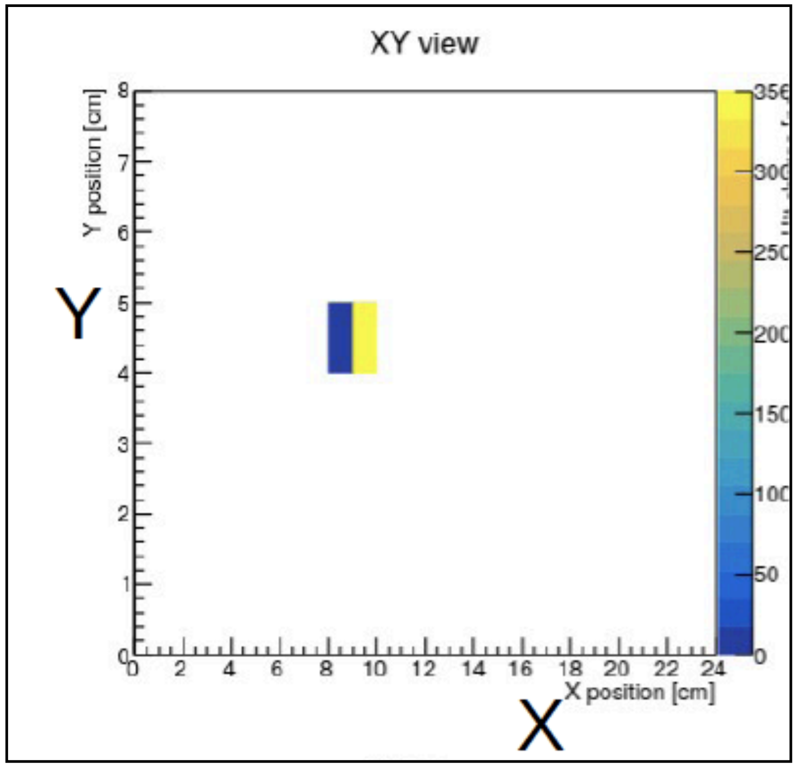
PRD 101, 092003 (2020)

Energy resolution (MC)

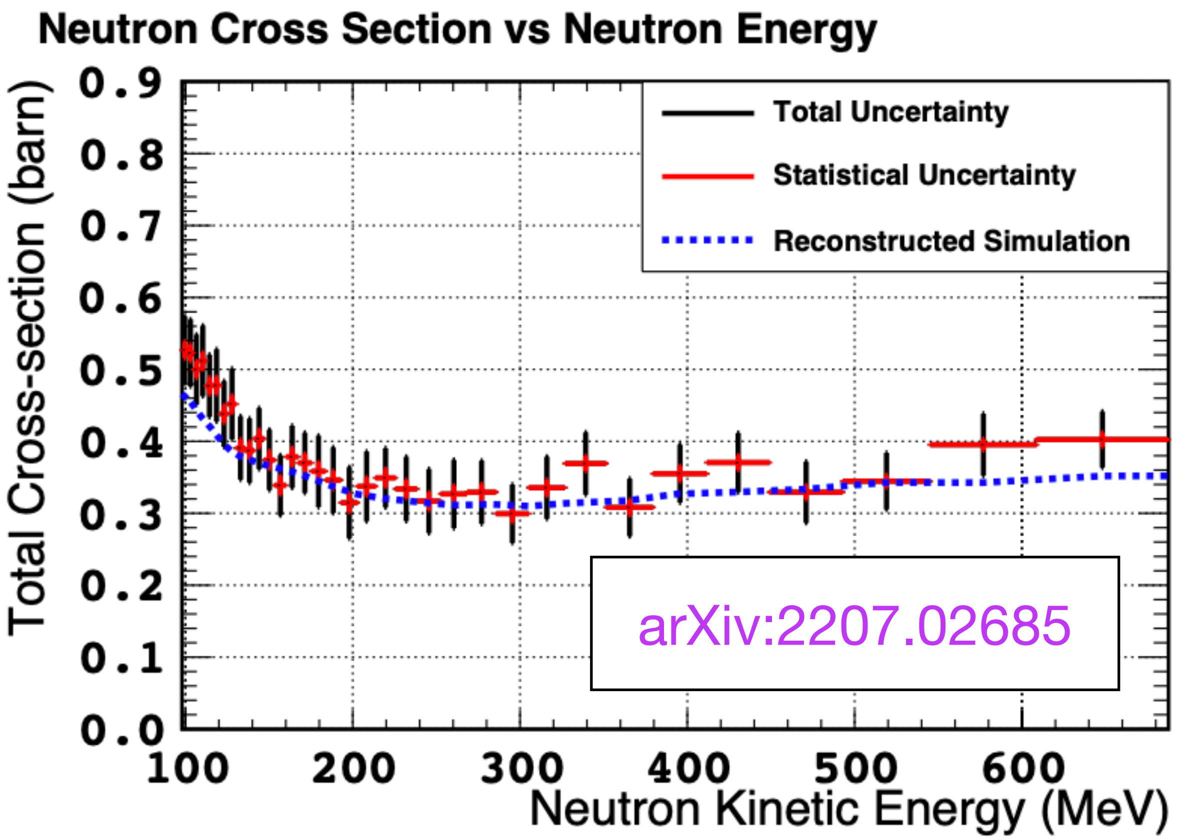


SuperFGD potential for neutron detection

- Two prototypes exposed to neutron test beam at LANL (LANSCE) in 2019 and 2020
  - ✦characterization of detector response to interacting neutrons
  - ✦total cross-section measurement

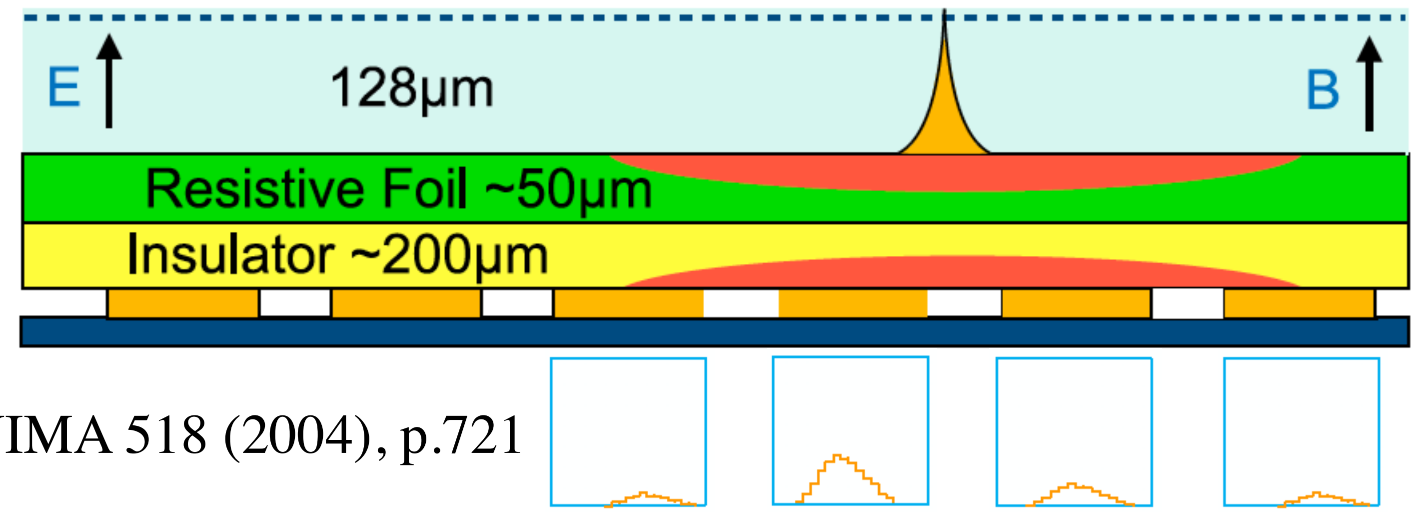


Neutron interaction in SFGD prototype @90m

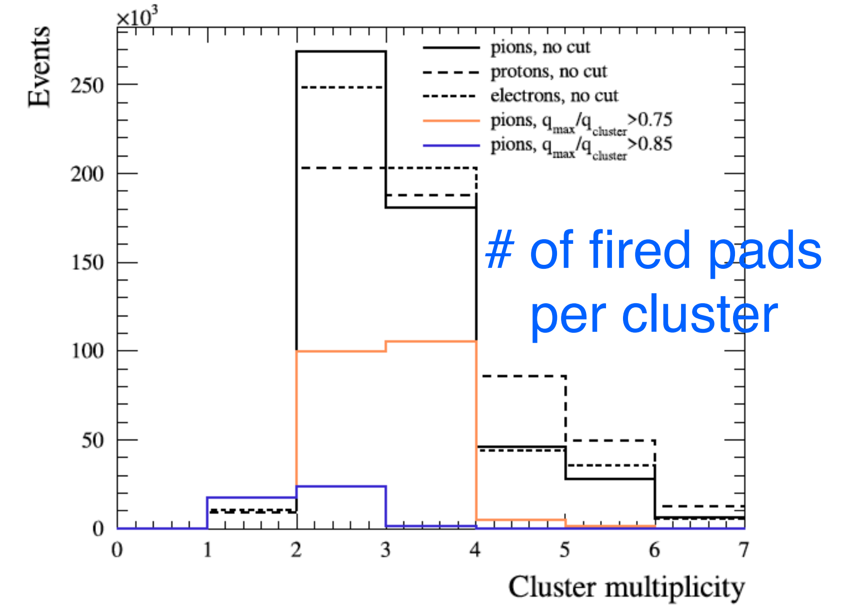


The new Time Projection Chambers

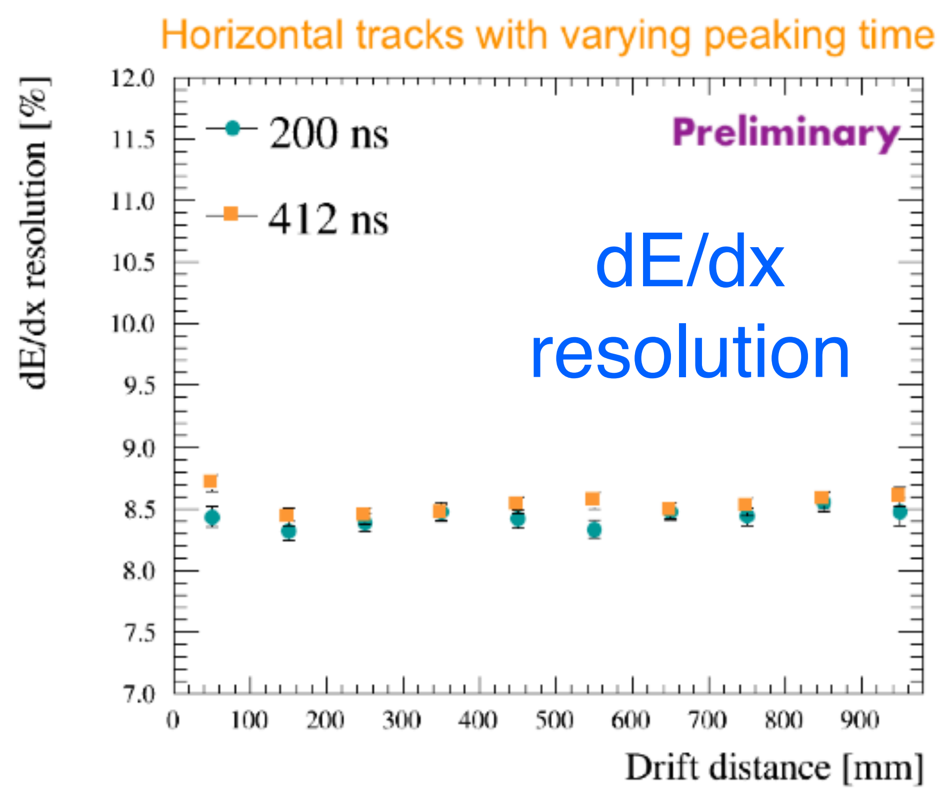
TPC to reconstruct the kinematics of charged particles leaving SuperFGD: muon/electron charge, momentum, PID

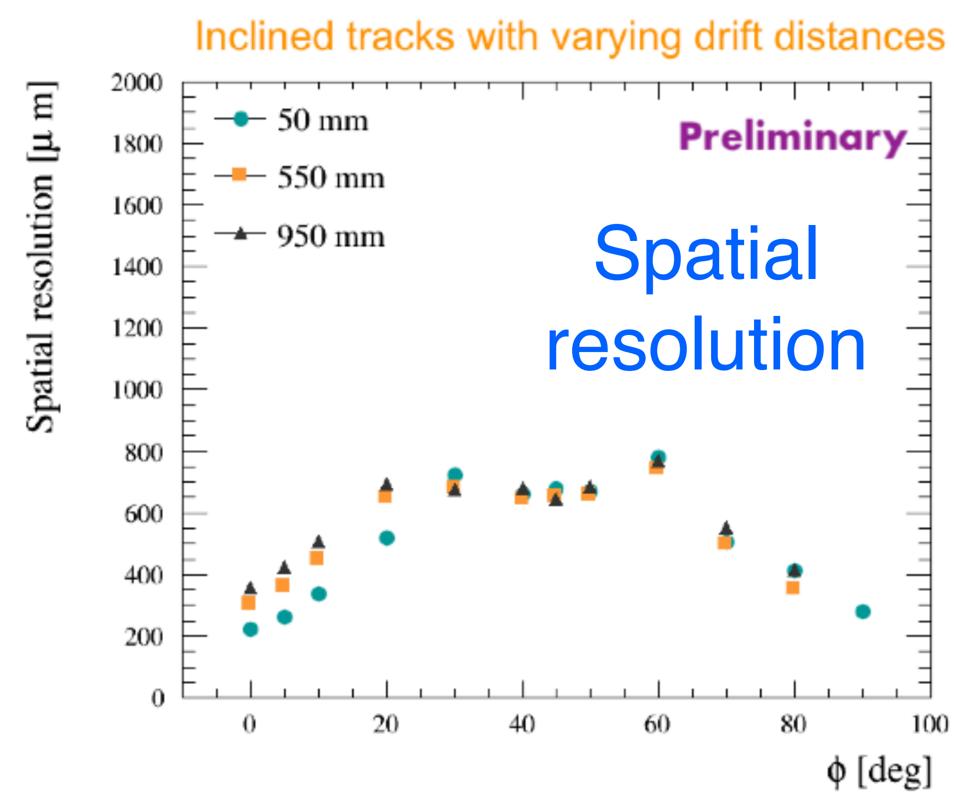


NIMA 518 (2004), p.721

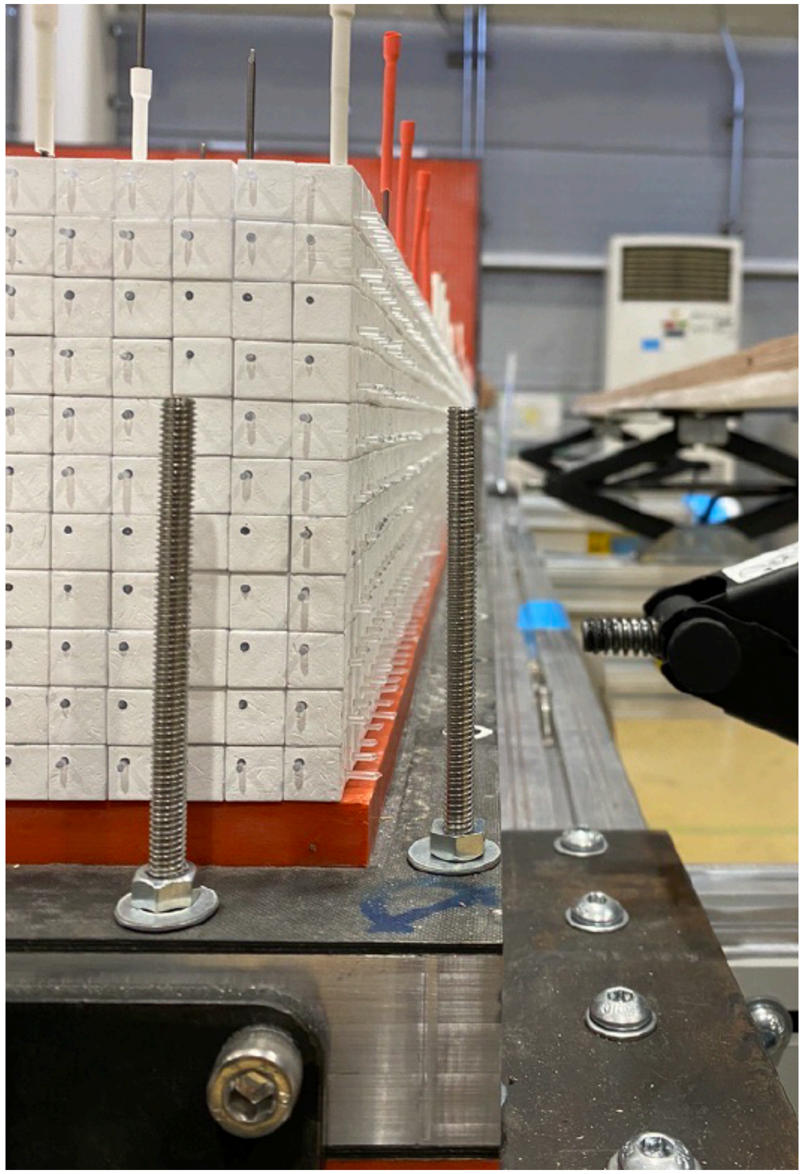


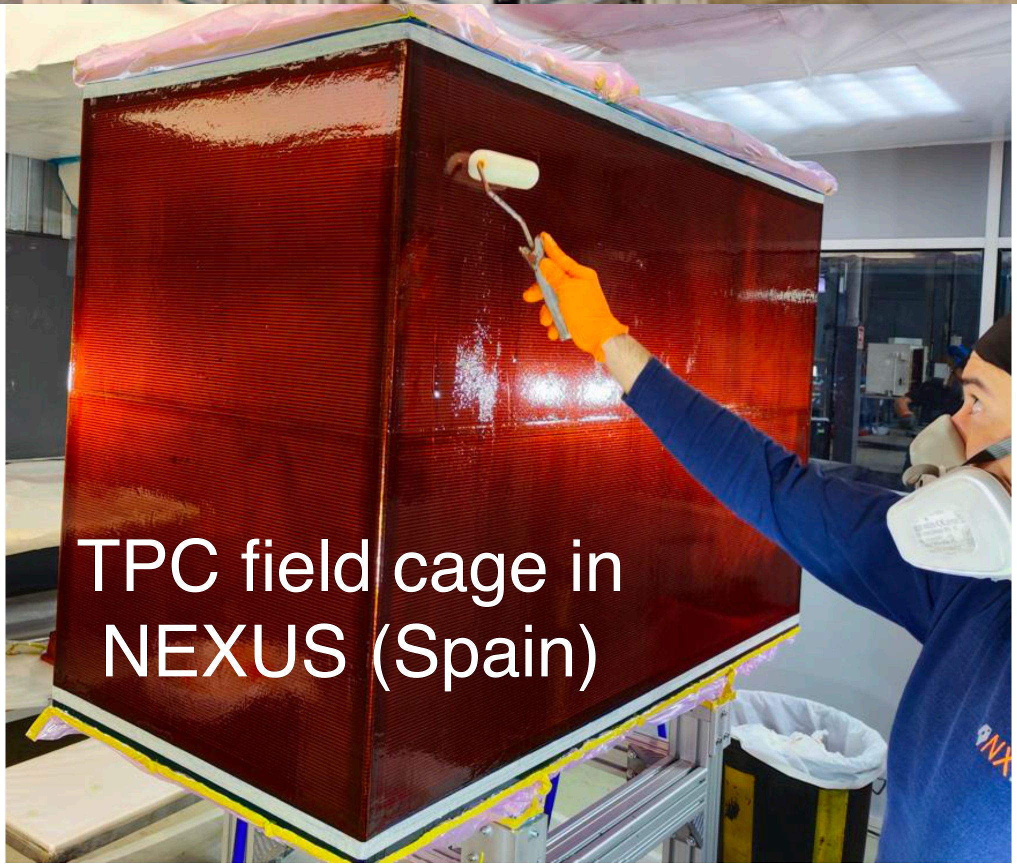
Resistive MicroMegas to improve the spatial resolution





In construction…

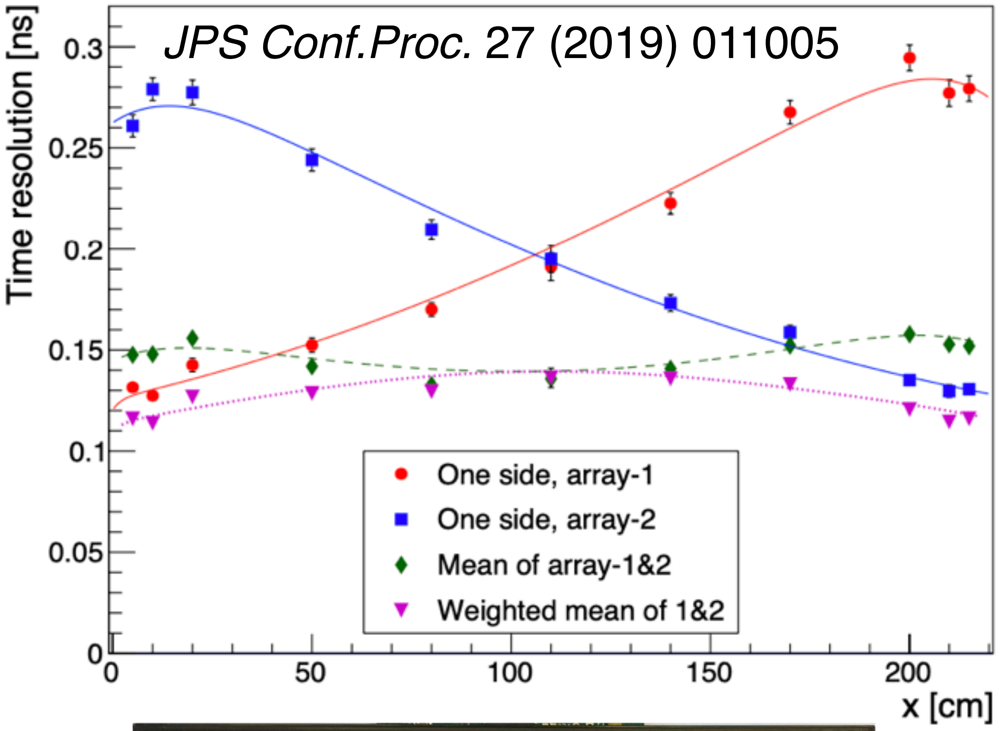


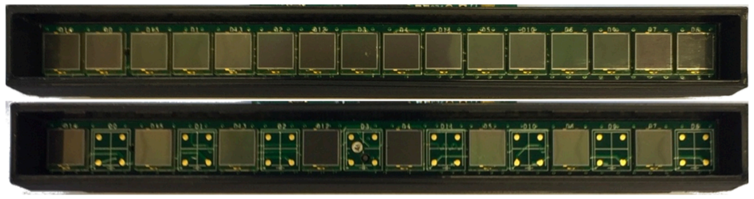


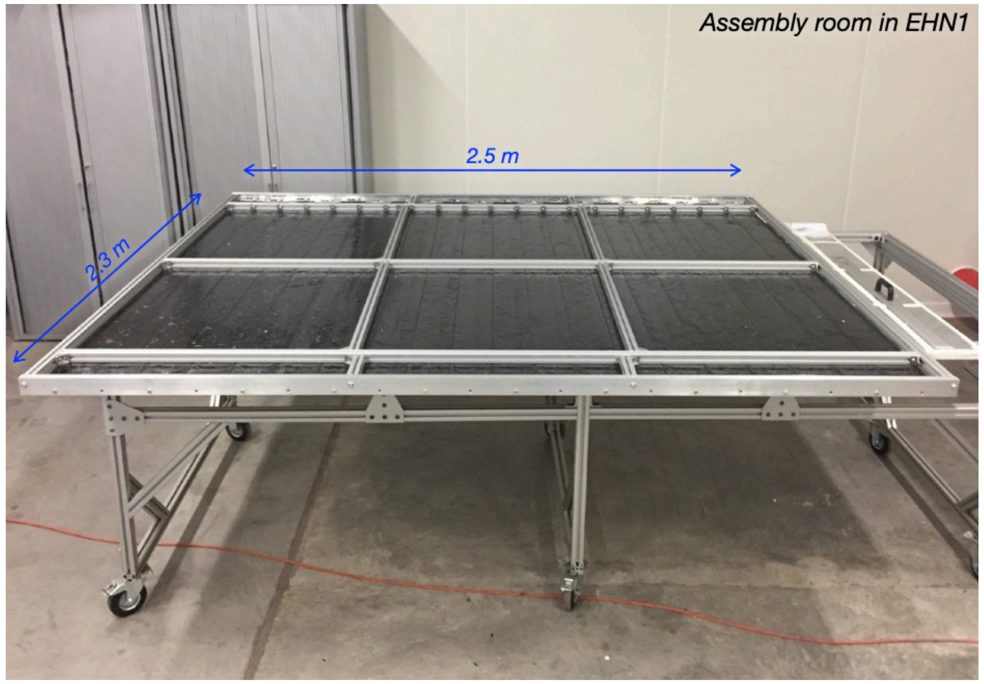
Plan to collect first neutrino data in Japan in 2023

Near Detector of both T2K and Hyper-K experiments

Time-of-Flight Detector: Commissioning at CERN



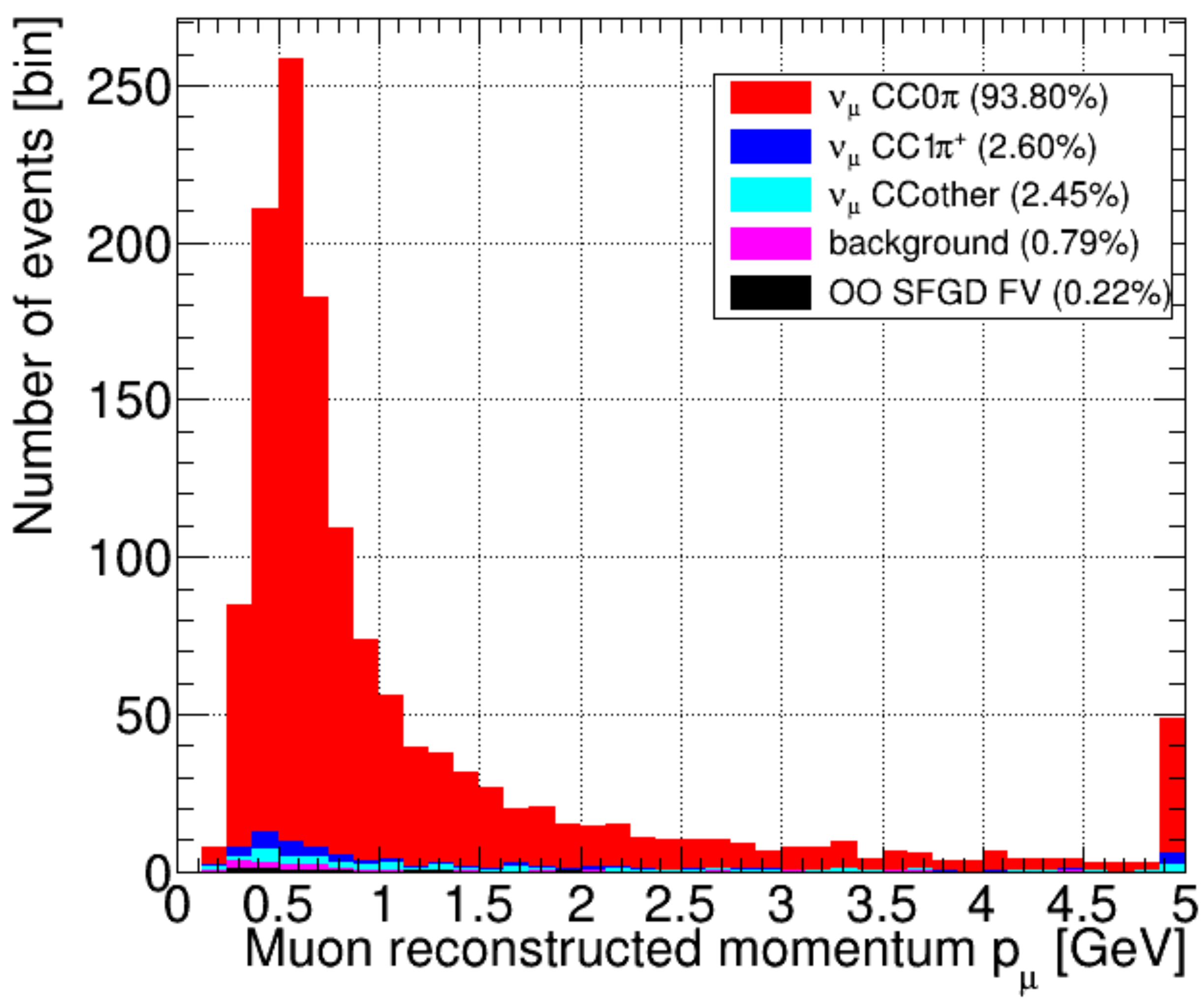


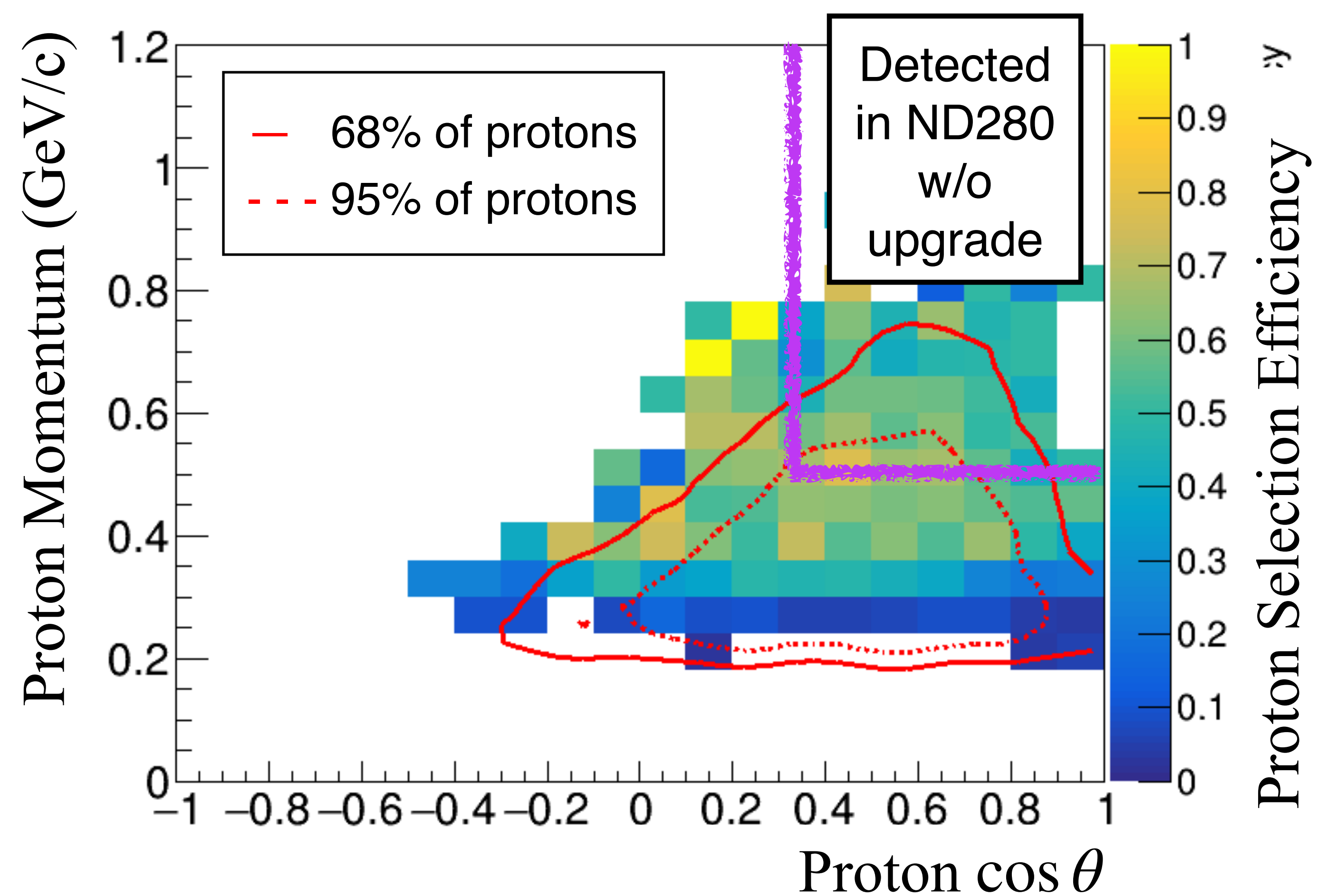


2.3x0.12 m² bars of EJ-200 PVT scintillator read out with Hamamatsu SiPM arrays

Status of Physics Analysis

Simulation and Reconstruction of ND280 upgrade is advancing in order to be ready with the analysis of the first data



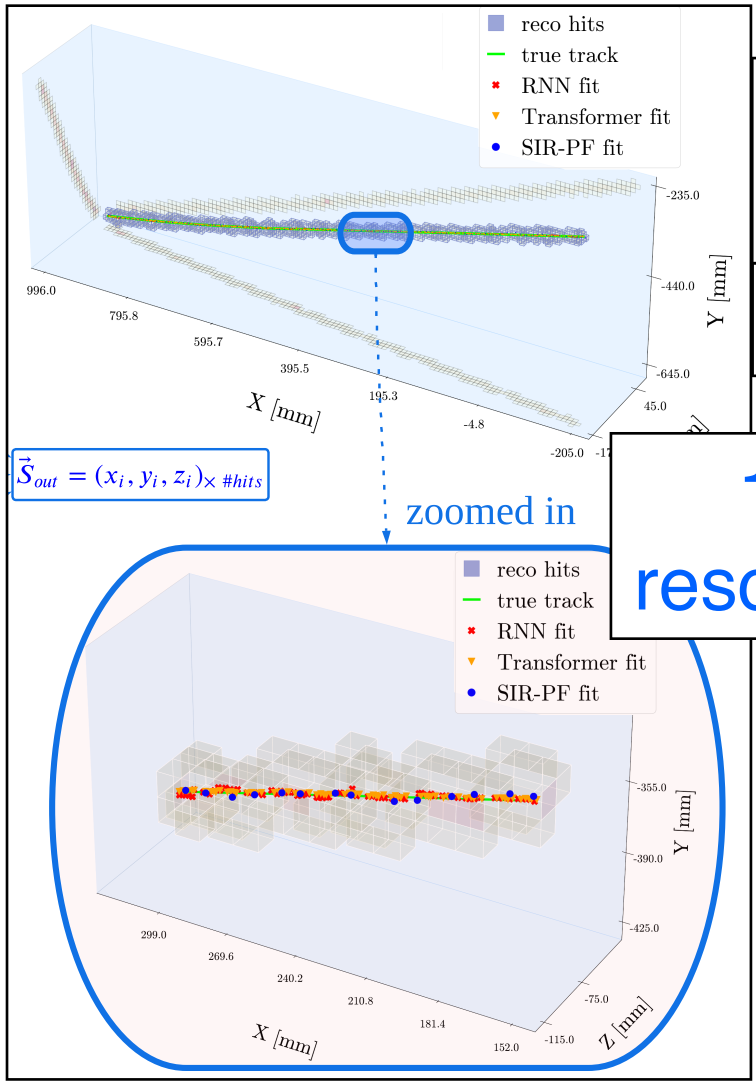


- ν_μ CCQE-like purity improved by more than 10% up to >93%
- Reach a wider portion of the proton phase space
- New physics (sterile neutrinos, heavy neutral leptons,…)

Data exploitation with Artificial Intelligence

Deep Learning to enhance the performance of SuperFGD

Strategy: assist traditional the reconstruction in its various steps towards a model-independent approach

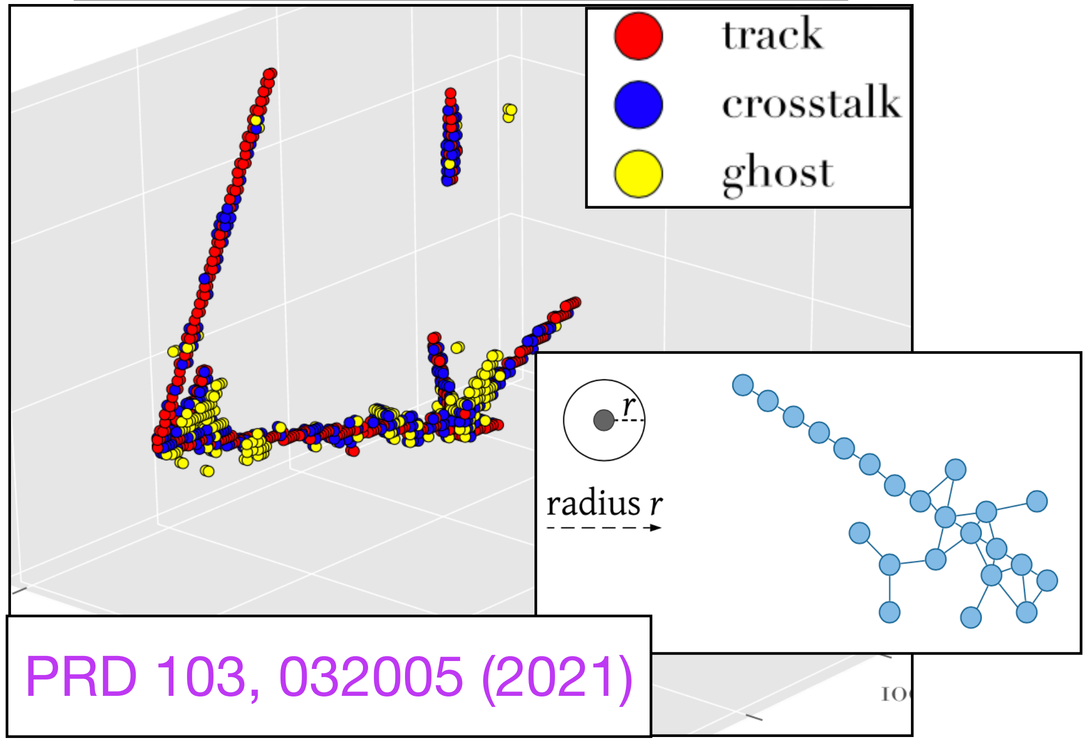


Deep Learning based particle Track Fitting

arXiv:2211.04890

1-2mm spatial resolution for muons

Graph Neural Network to identify ambiguities

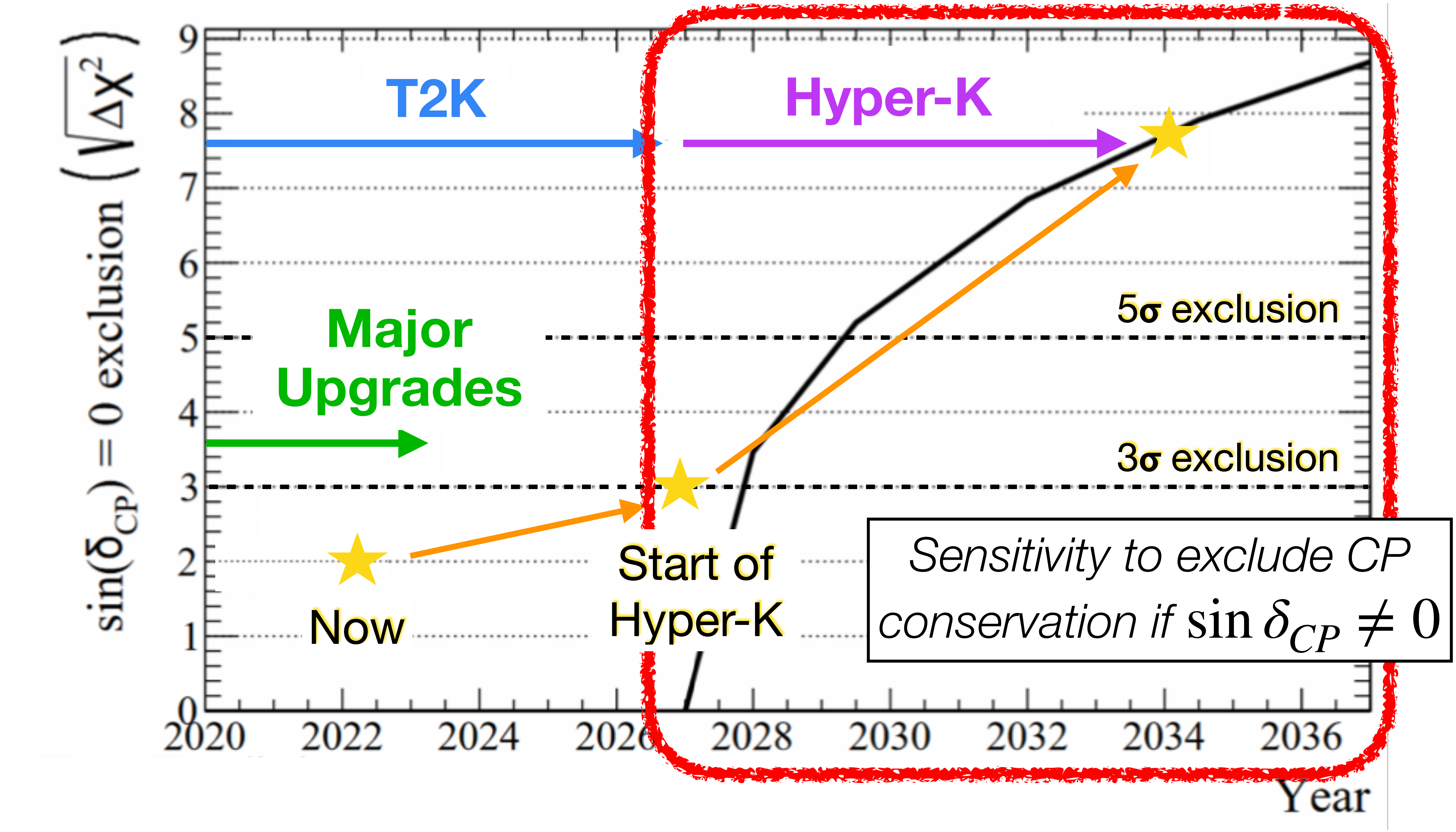


PRD 103, 032005 (2021)

Multi-particle hit tagging (Work in progress)

Generative Adversarial Networks for particle fast simulations (Work in progress)

Roadmap for measuring δ_{CP}



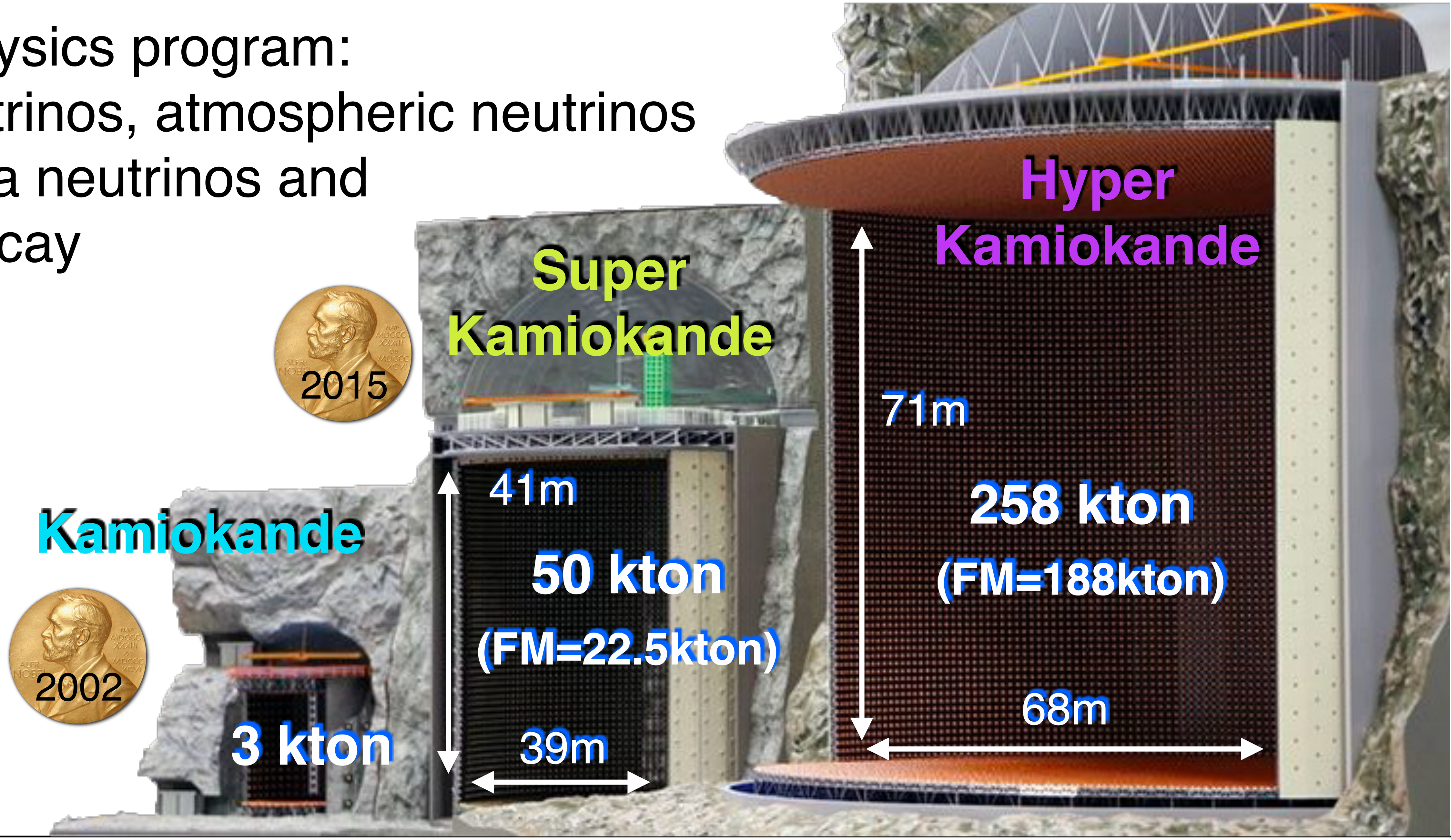
The Hyper-Kamiokande experiment

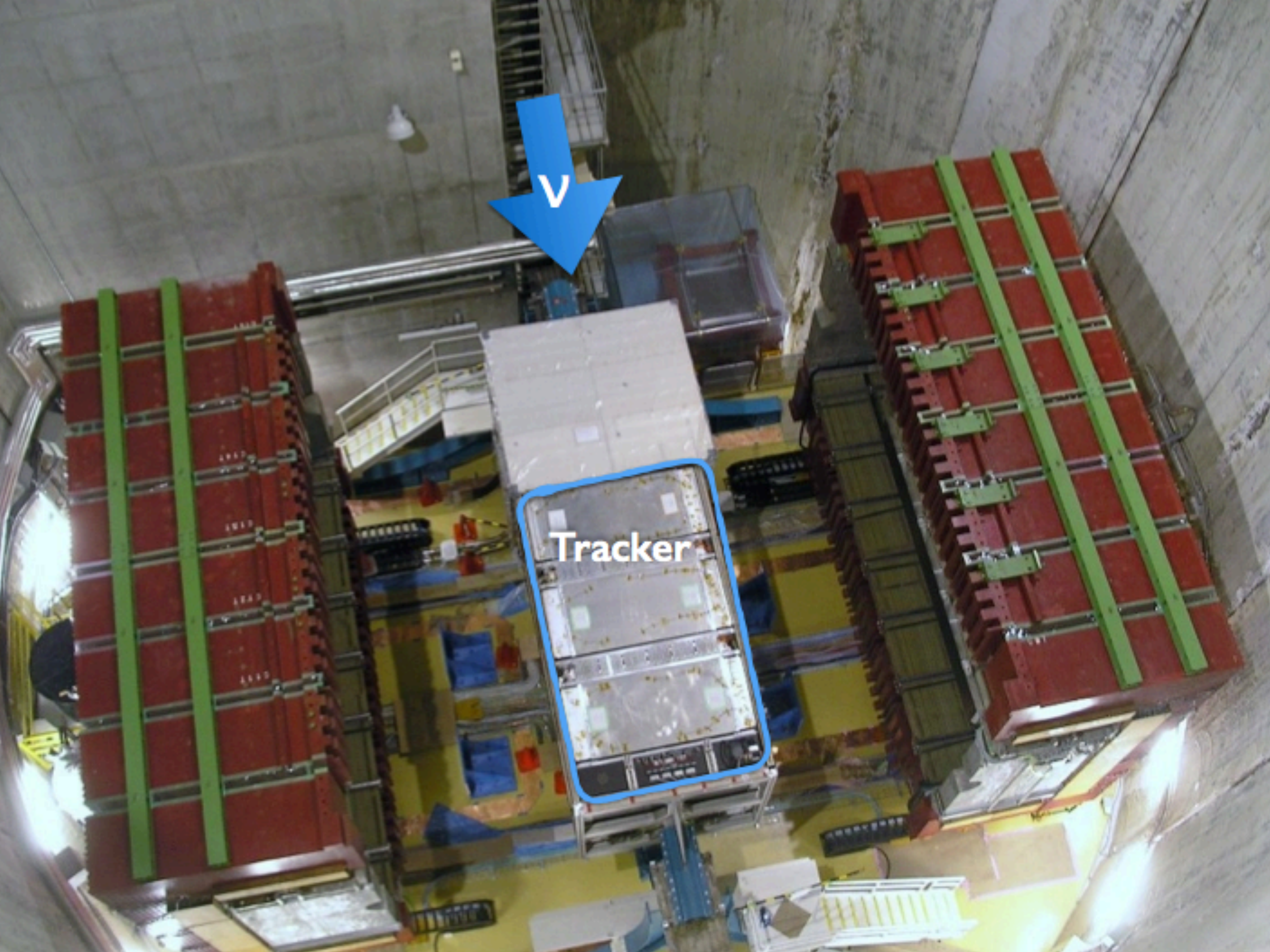
Exactly the same experimental configuration as T2K

✓Inherit the neutrino beam line and ND280 detector complex

✓Additional water Cherenkov detector at the near site (~1 km)

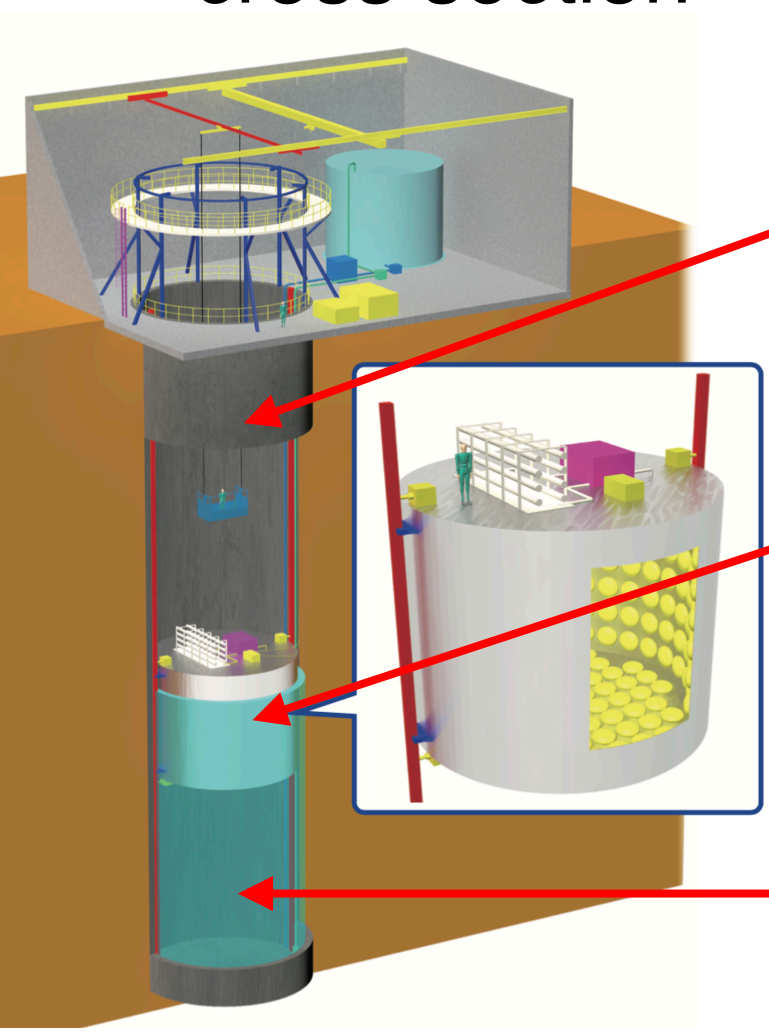
✓Broad physics program:
solar neutrinos, atmospheric neutrinos
supernova neutrinos and
proton decay

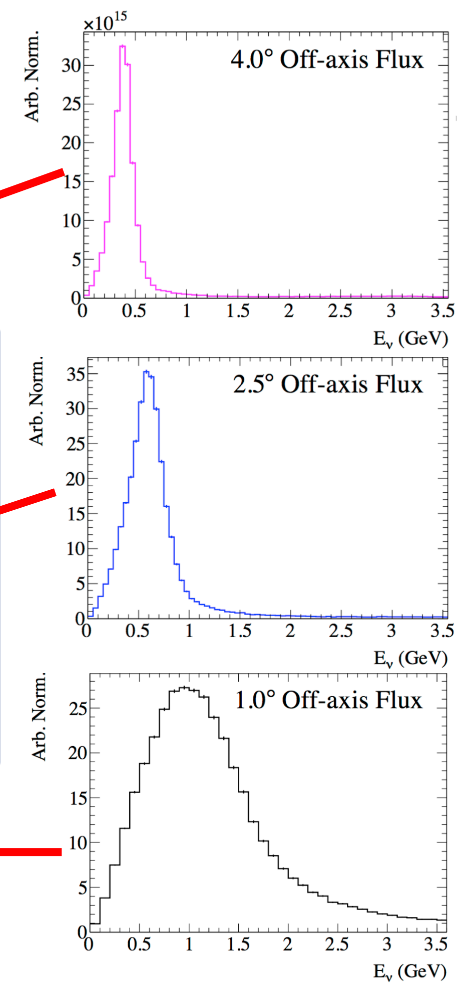


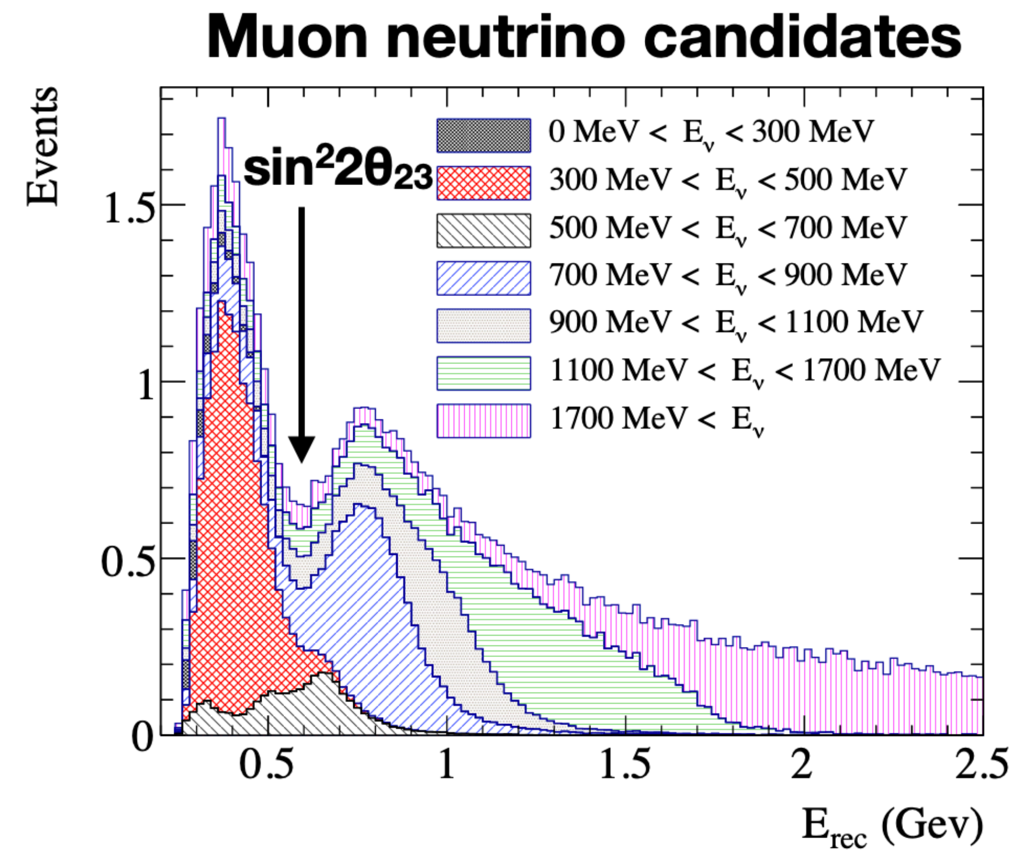

ν
Tracker

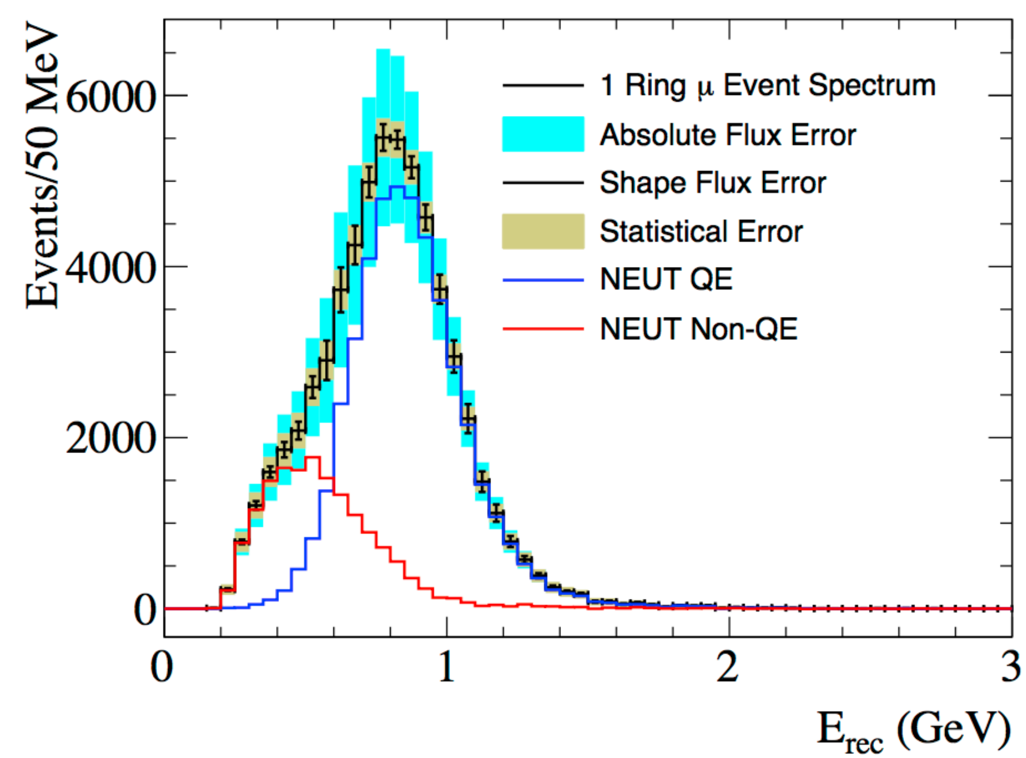
Intermediate Water Cherenkov Detector

- ~1 km from ν source, Fiducial Mass ~ 60 ton for $\nu_e/\bar{\nu}_e$, Gd-loading option
- Low statistical uncertainty in ν_e cross section



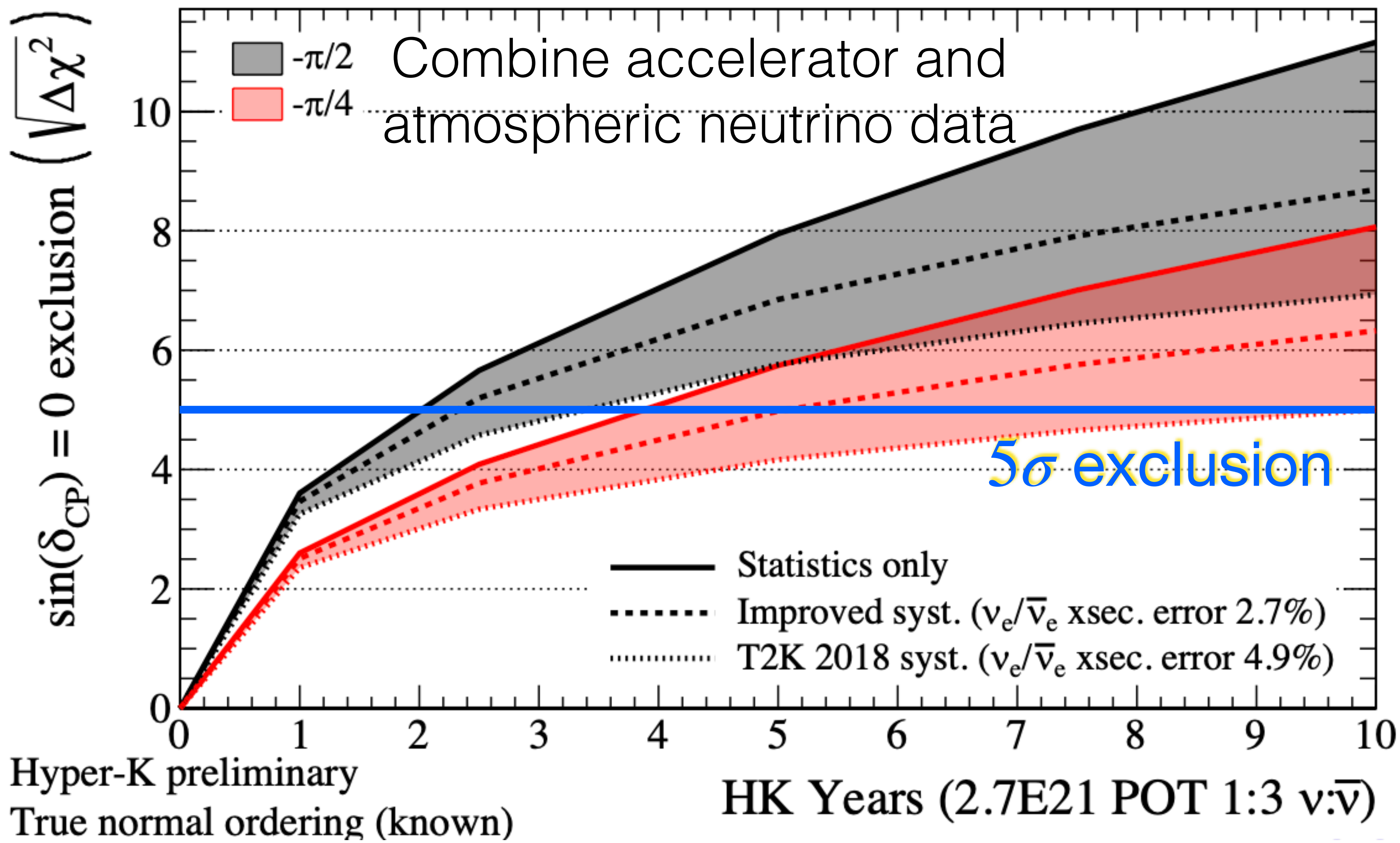






Obtain the relation between ν energy and observed final state in water

Sensitivity to CP Violation



Hyper-K will measure δ_{CP} with resolution $< 20°$

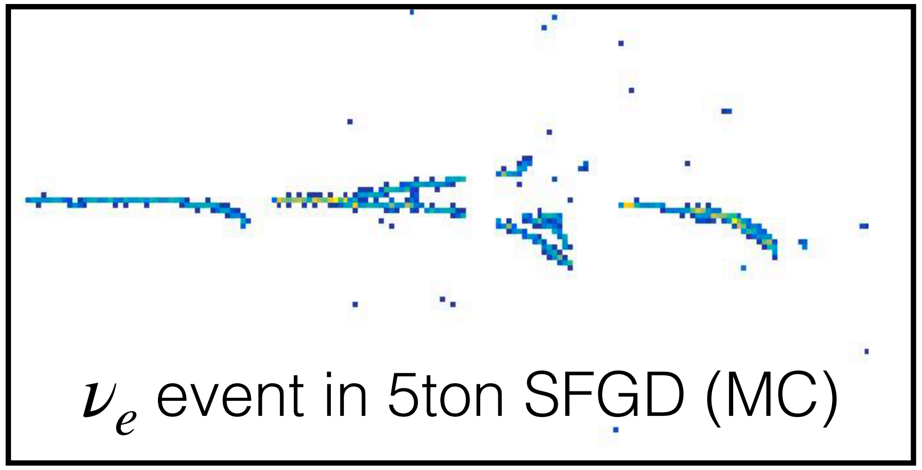
Potential for CP violation discovery after less than 3 years if $\delta_{cp} = -\frac{\pi}{2}$

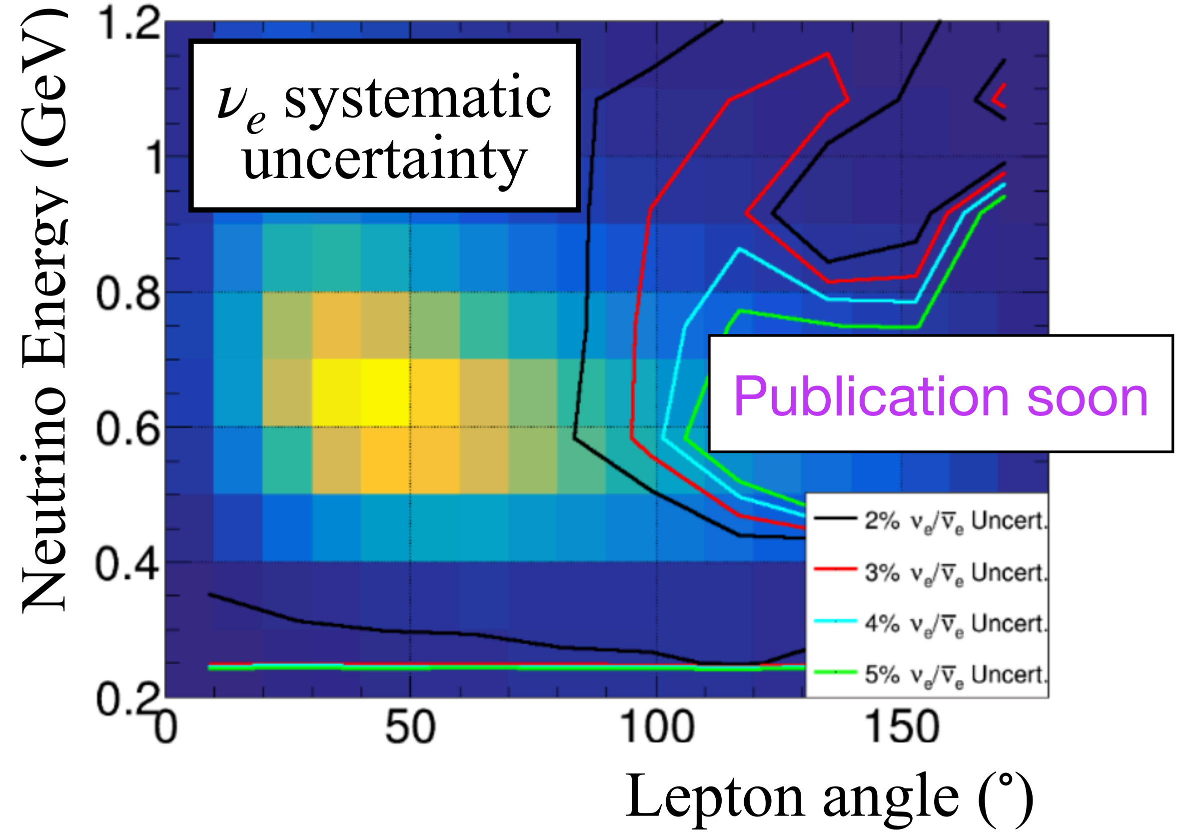
and determination of Mass Hierarchy with $> 4\sigma$ significance

Systematics goal at Hyper-K late phase

- ν_e cross section at 3% level

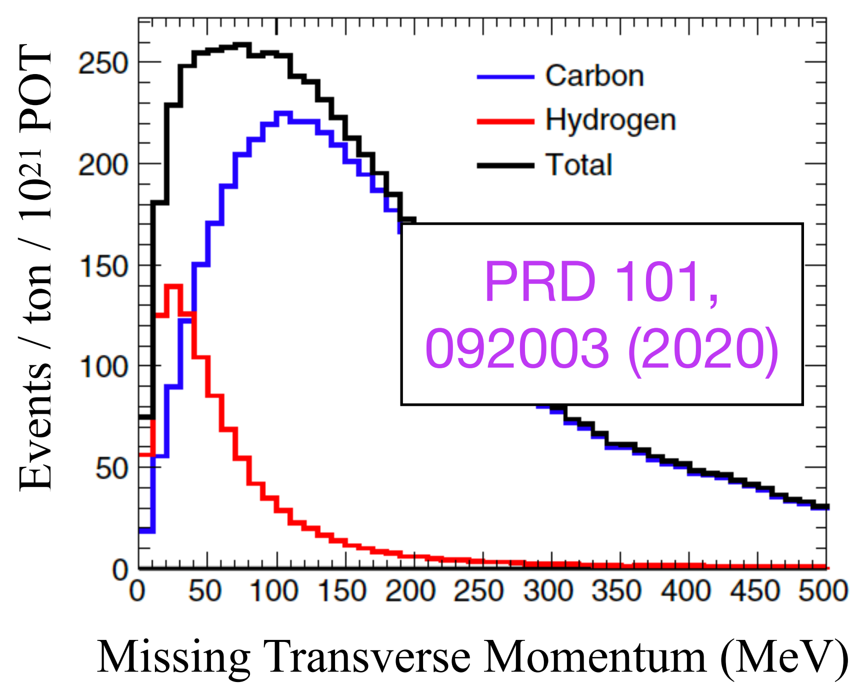
Nuclear Effects change the ratio between ν_μ and ν_e in a non-trivial way

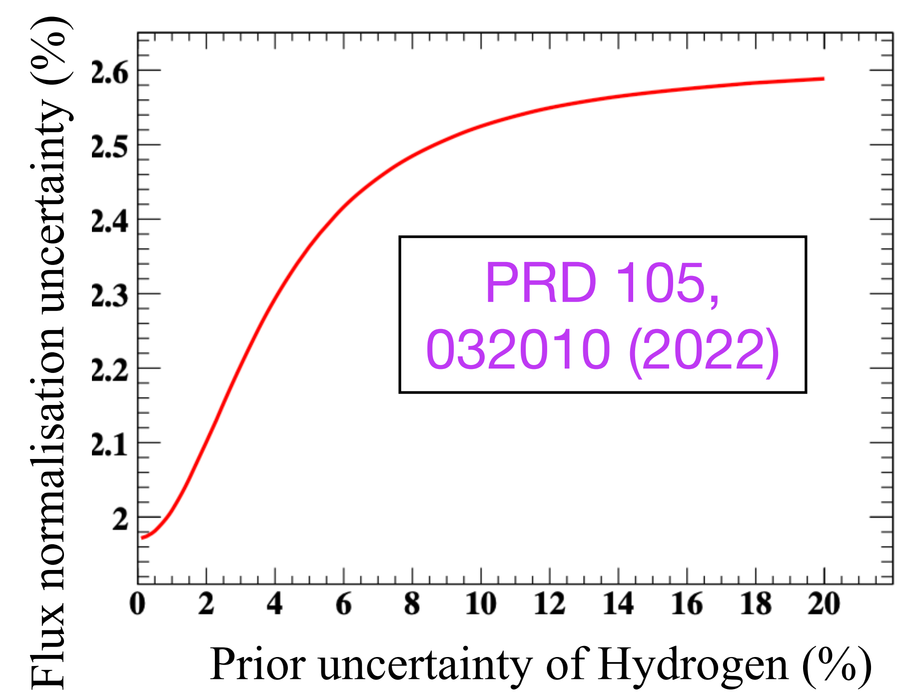




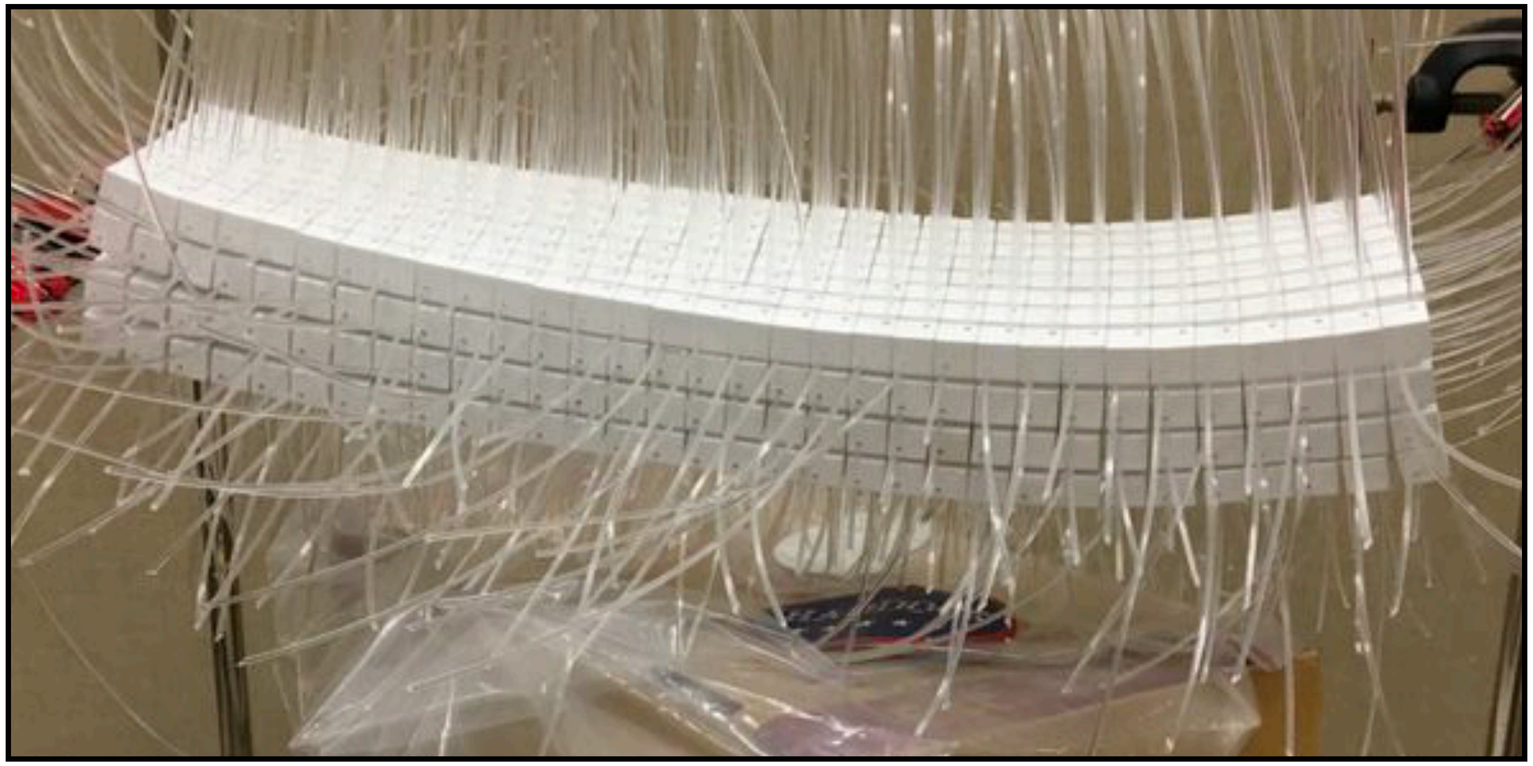
- Select $\bar{\nu}_\mu$ interactions on hydrogen (no nuclear effects)

Large sample (~10'000 events) to directly infer the neutrino flux





Systematics goal at Hyper-K late phase



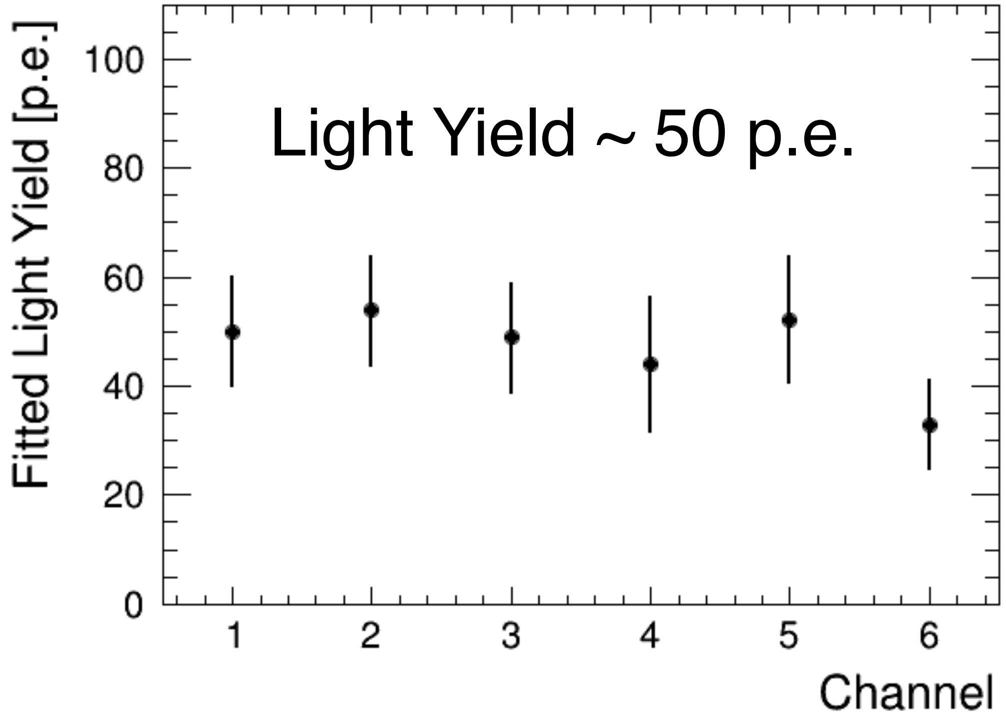
Need a method to make a unique block of plastic scintillator with all the cubes optically isolated ready just for inserting WLS fibers

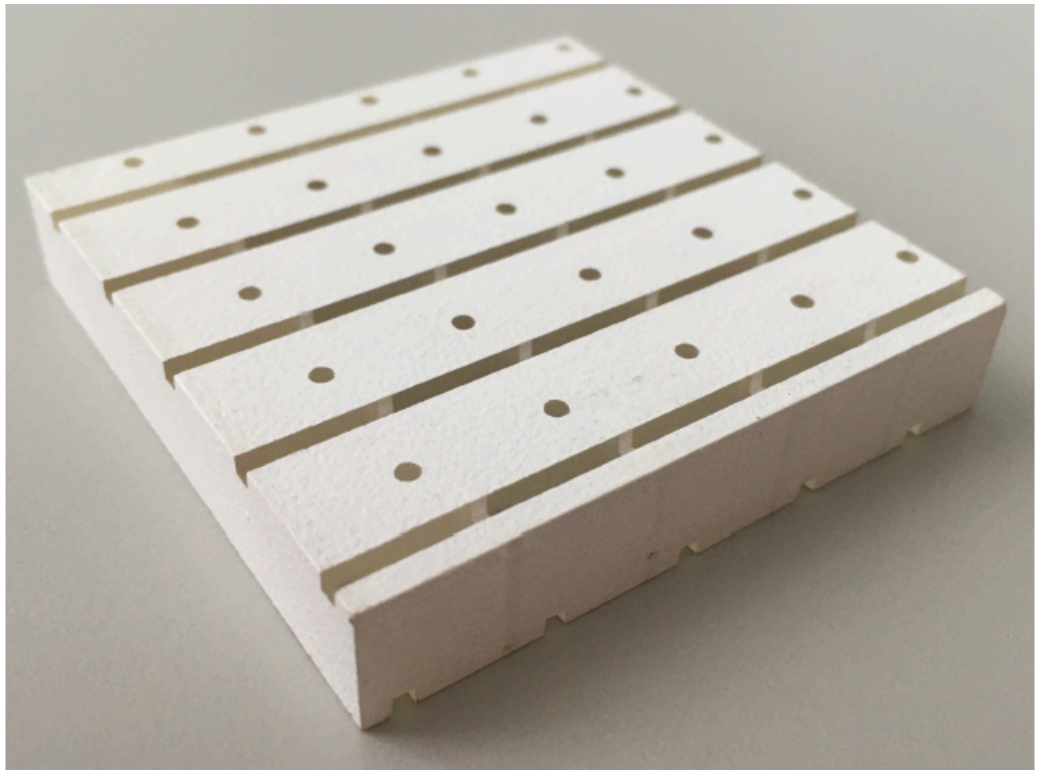
⇒Not straightforward to scale SuperFGD to several tonnes

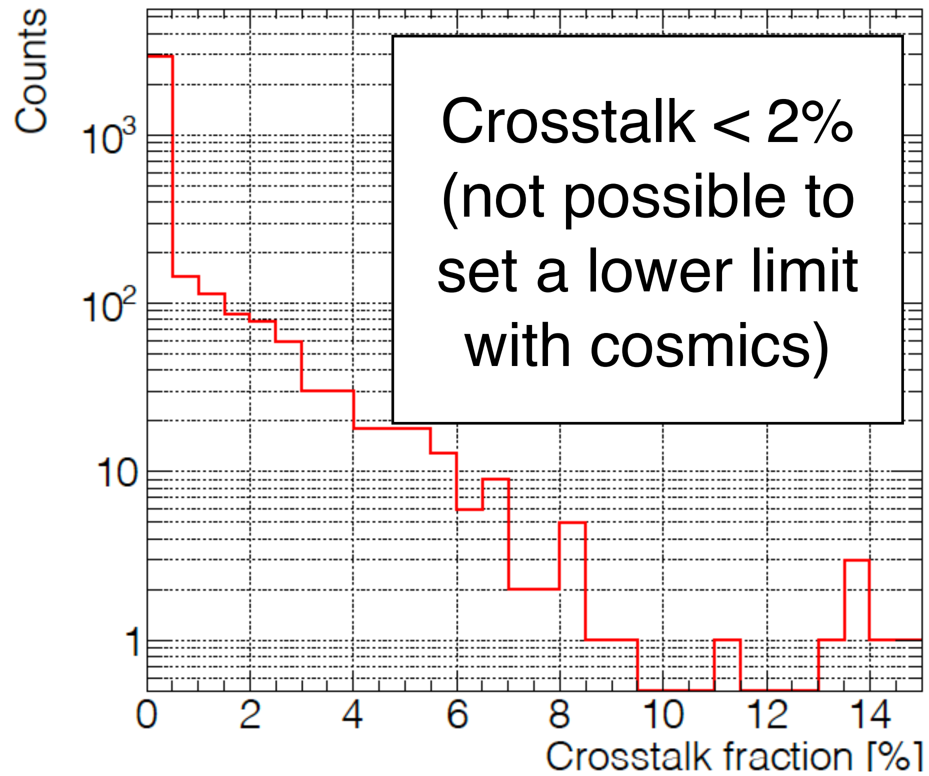
Plastic Scintillator: 3D-glued cubes

- Developed a production process to scale SuperFGD to several tonnes
  - ✦ Successfully built a SuperLayer: glued optically-isolated 1cm³ cubes made of polystyrene scintillator
  - ✦ We can reach sizes up to 50x100 cm² (potentially 50x200 cm²)

JINST 16 (2021), P12010



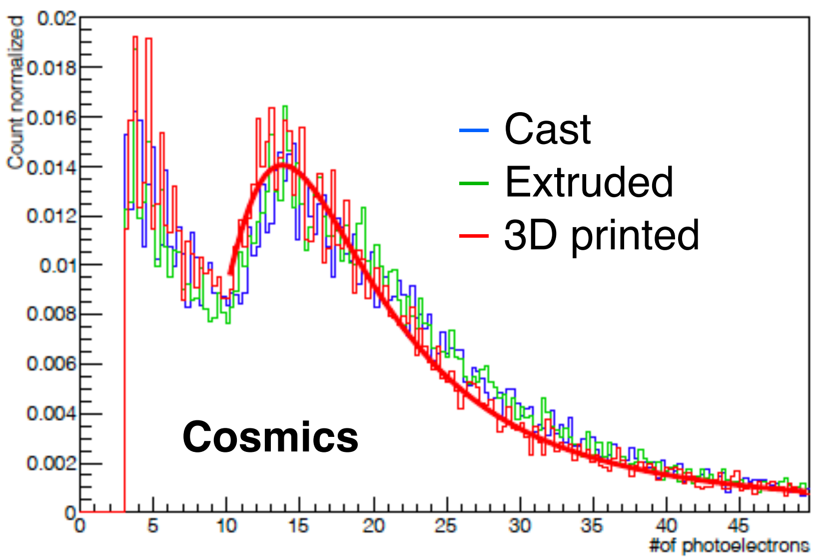


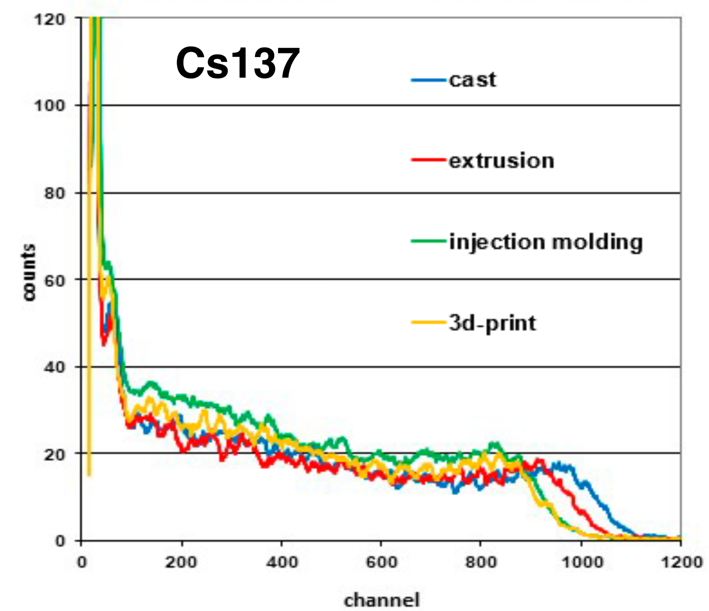


3D printing of Plastic Scintillator

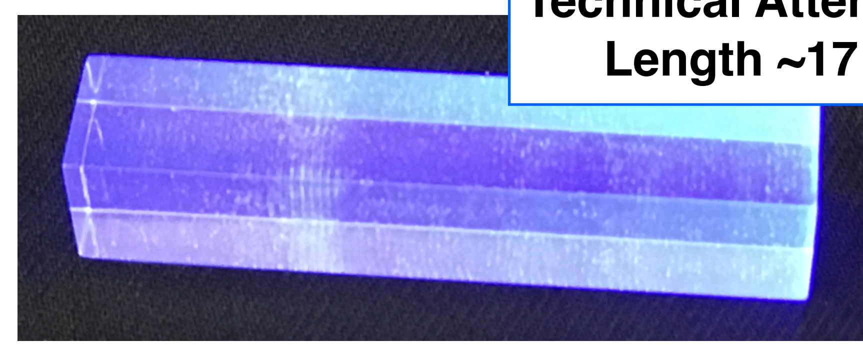
Formed an R&D collaboration (CERN, ETH Zurich, HEIG-VD, ISMA) for 3D printing plastic scintillator⇒ 3DET

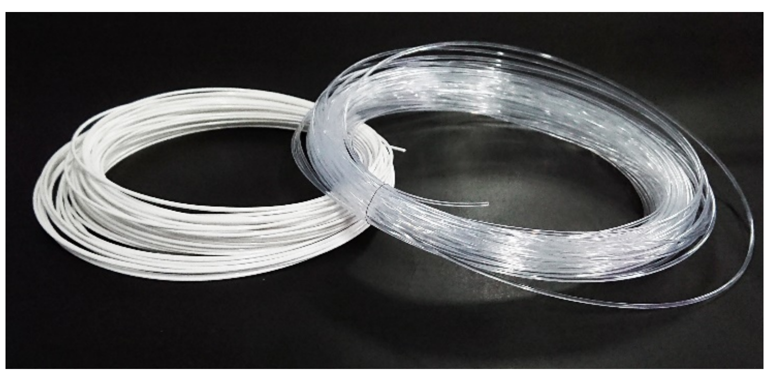
Proof of Concept in:
JINST 15 (2020) 10, P10019
JINST 17 (2022) 10, P10045

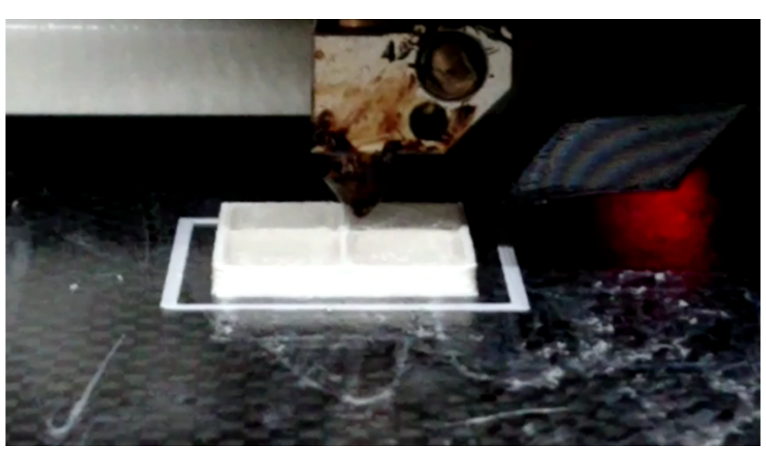


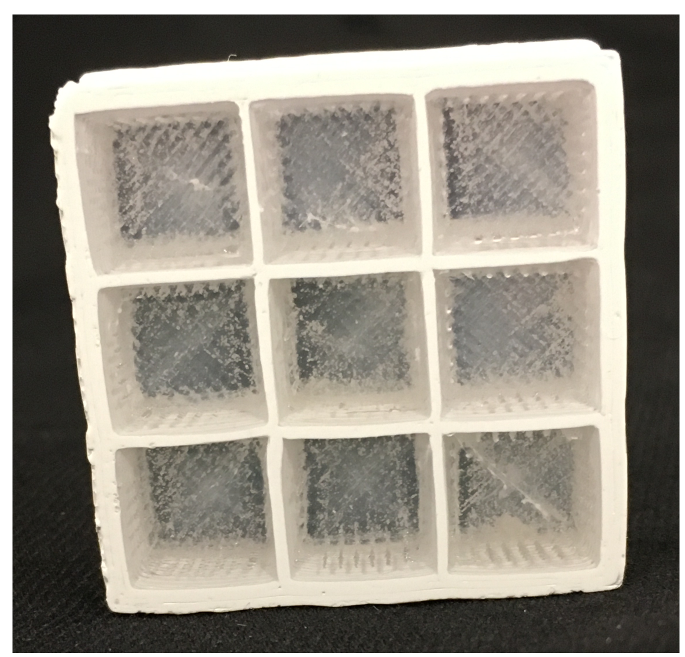


Technical Attenuation Length ~17 cm

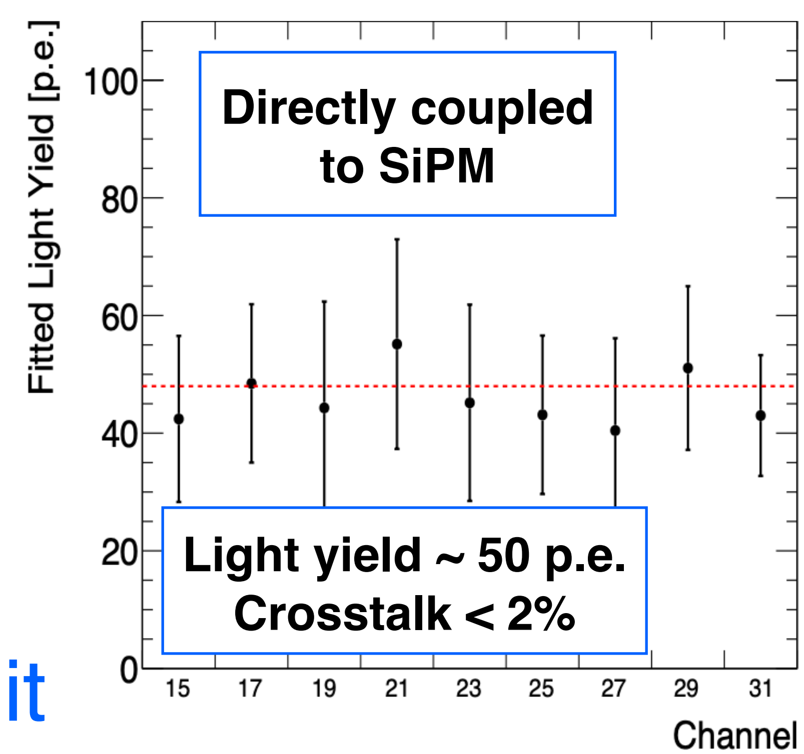






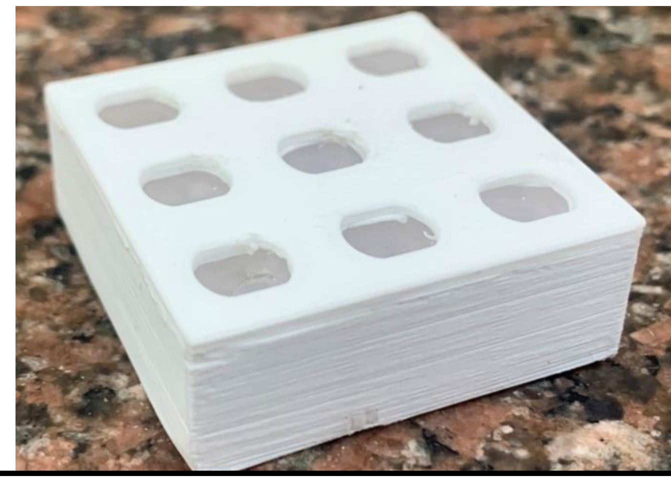


However, we had to polish it

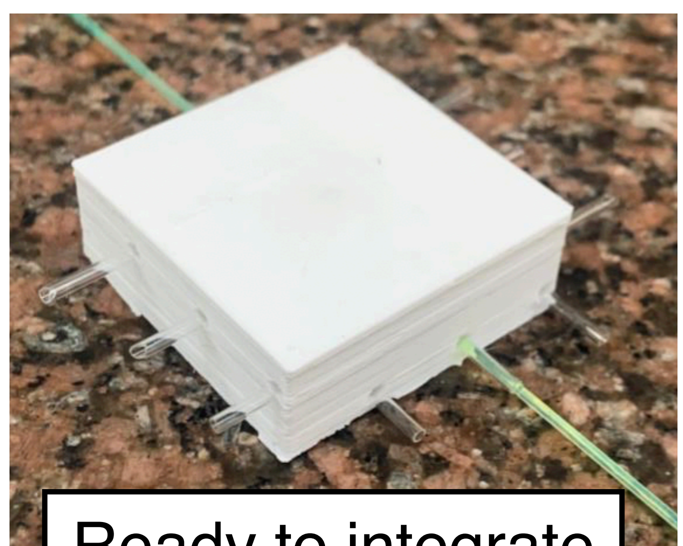


3D printing of Plastic Scintillator

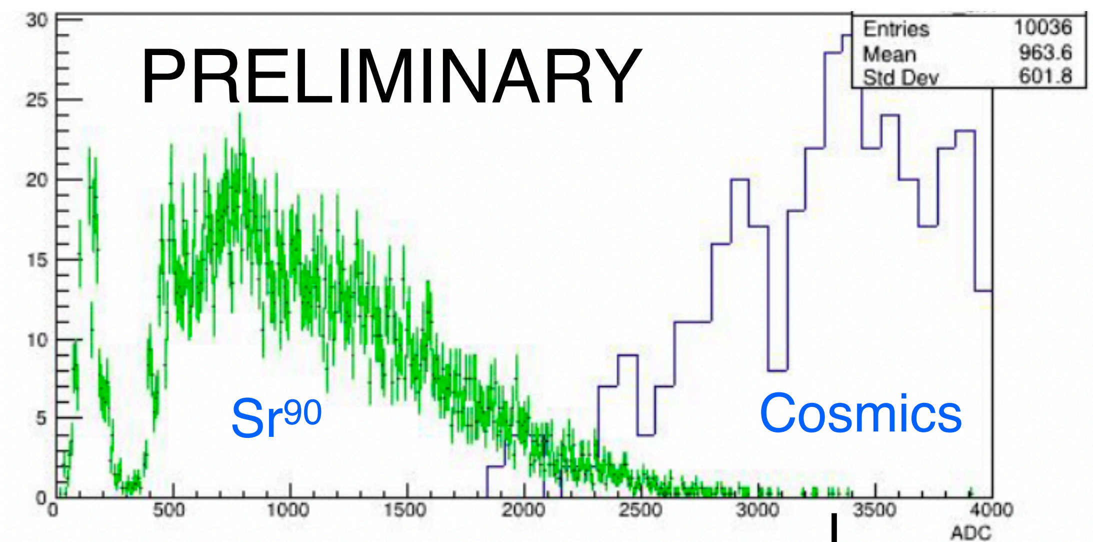
Over the last year we worked on improving the production
no post-processing, improve geometrical tolerance and make holes



Ready to integrate SiPM



Ready to integrate
WLS fibers



~60-70 p.e. / MIP

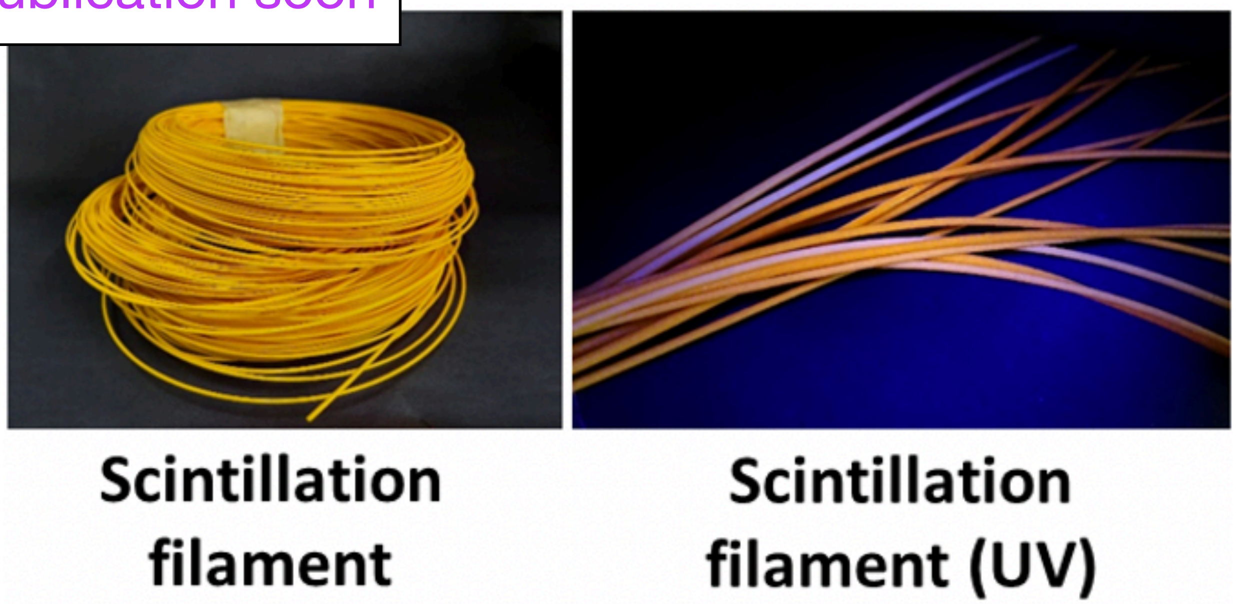
Ready for application
right after the printing
w/o post-processing

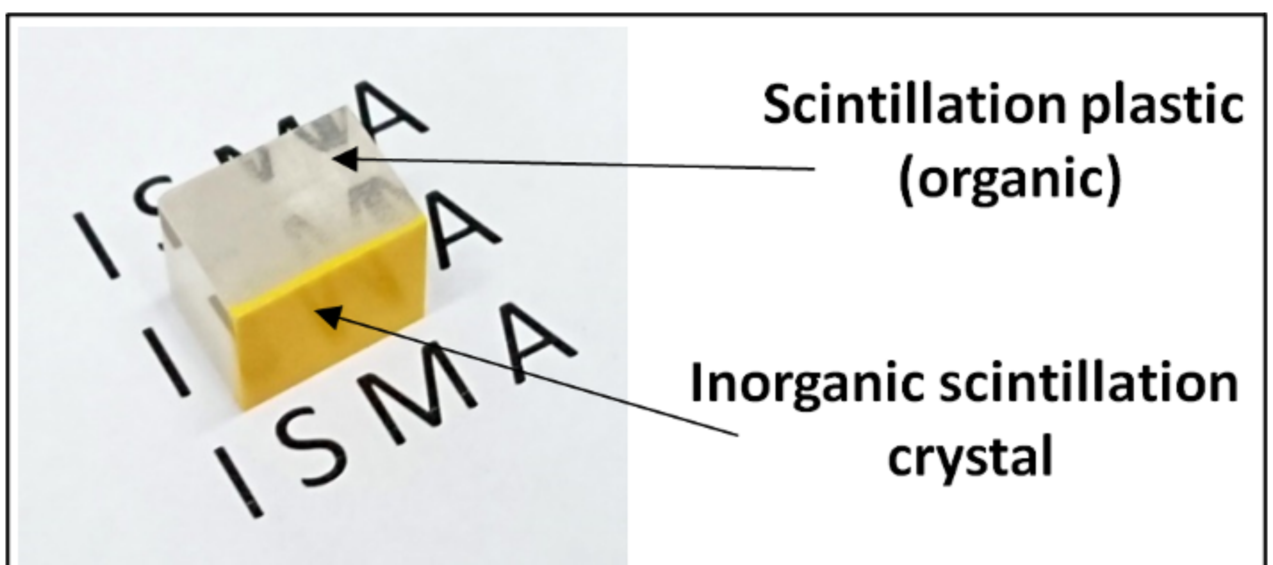
Work in progress…

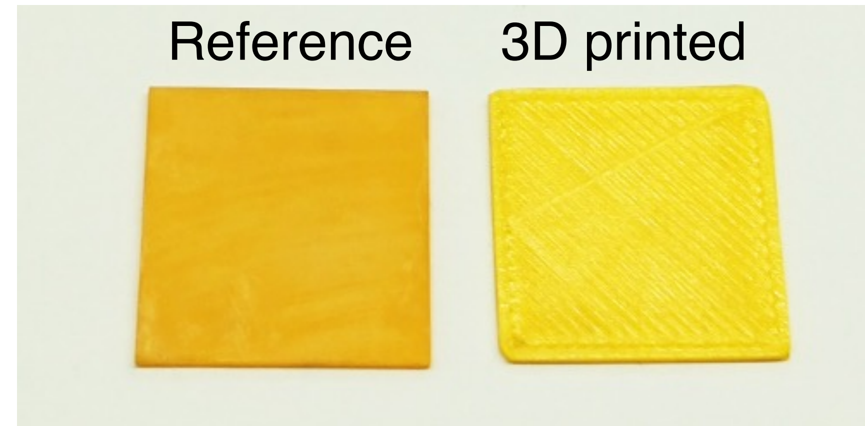
Inorganic Scintillator

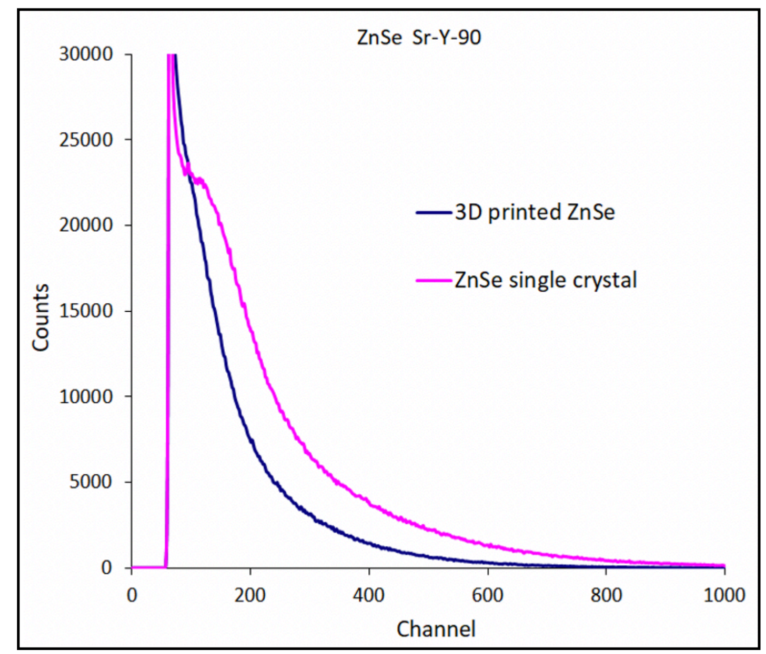
Filament of inorganic scintillator crystal based on ZnS:Ag for α, β and X-ray detection

Publication soon





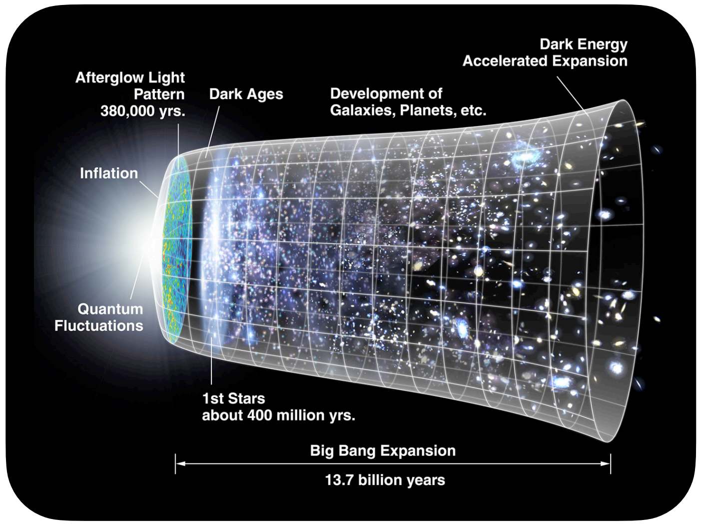




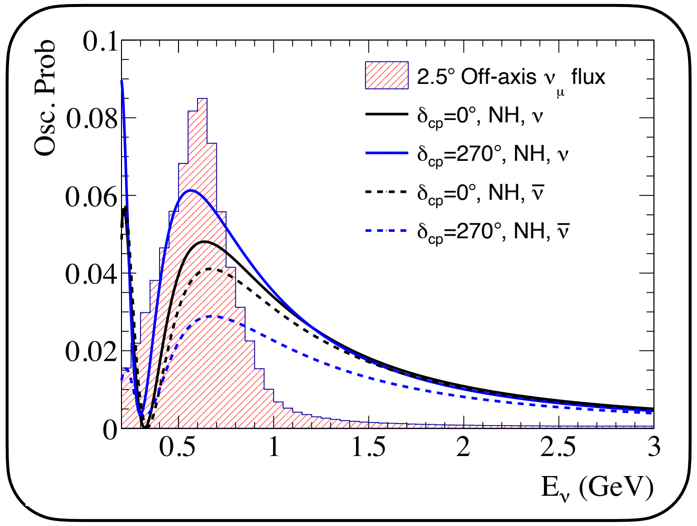
Succeeded to 3D print a "sampling" element of organic plastic + inorganic crystal scintillators

Conclusions

- The discovery of a source of large CP asymmetry could help understanding the observed matter-antimatter imbalance



- The T2K and Hyper-K neutrino oscillation experiments aim to measure δ_{CP}



- The Near Detector upgrade program aim to improve the modeling of neutrino-nucleus interactions