High-Angle TPCs of the upgraded ND280 for T2K-II and HK

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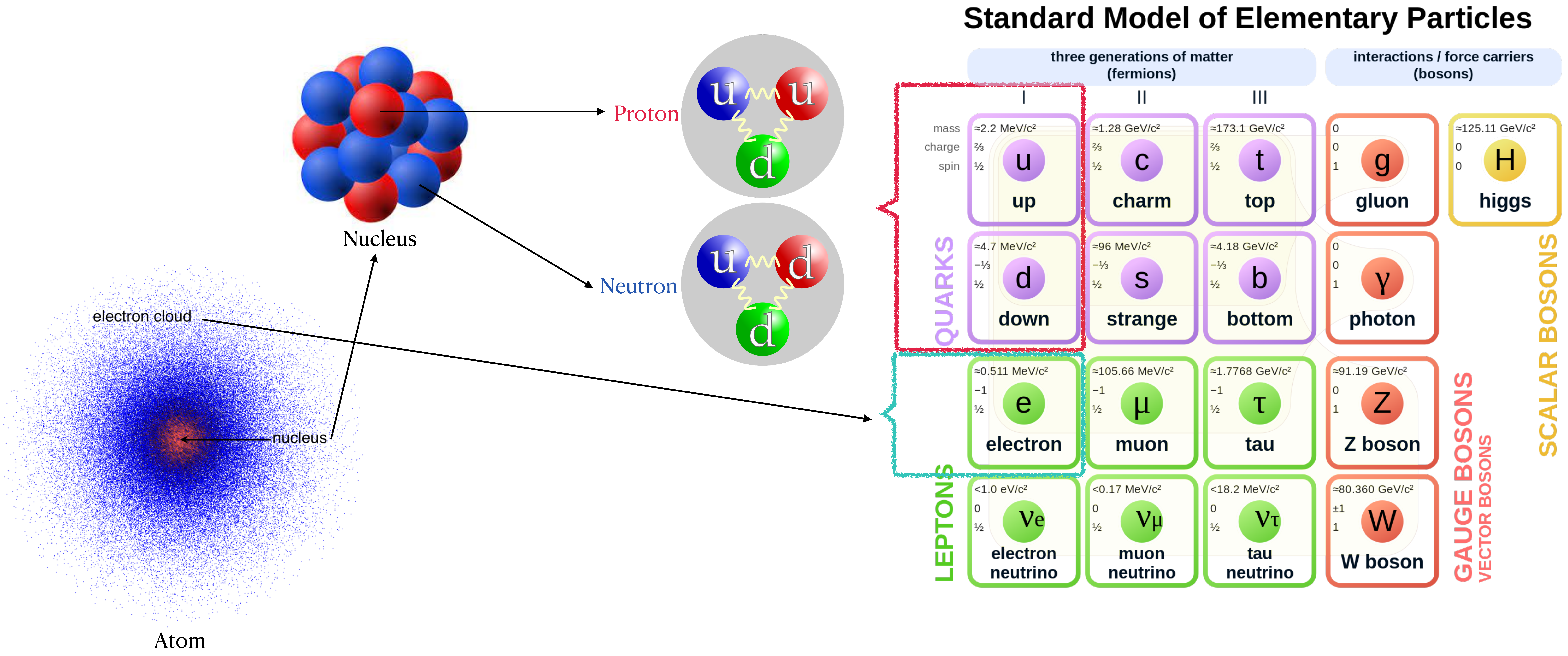
Ulysse VIRGINET - Réunion du Vendredi du LPNHE - 26/01/2024

Summary

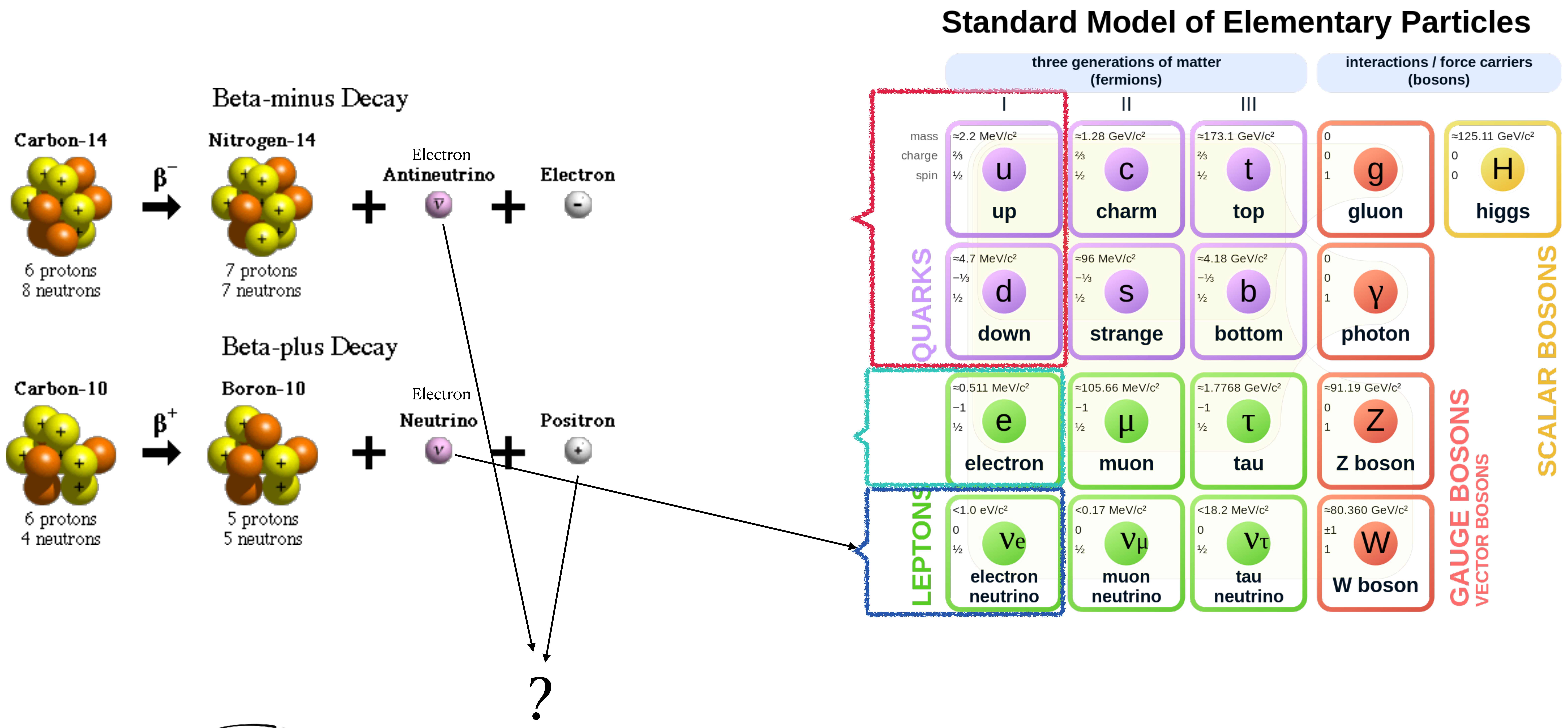
- Contextual introduction
- T2K(-II) experiment
- Fit of ν_e and $\bar{\nu}_e$ samples at ND280 and study of their impact for HyperKamiokande
- Reconstruction in the HA-TPCs of the upgraded ND280

Contextual introduction

The Standard Model

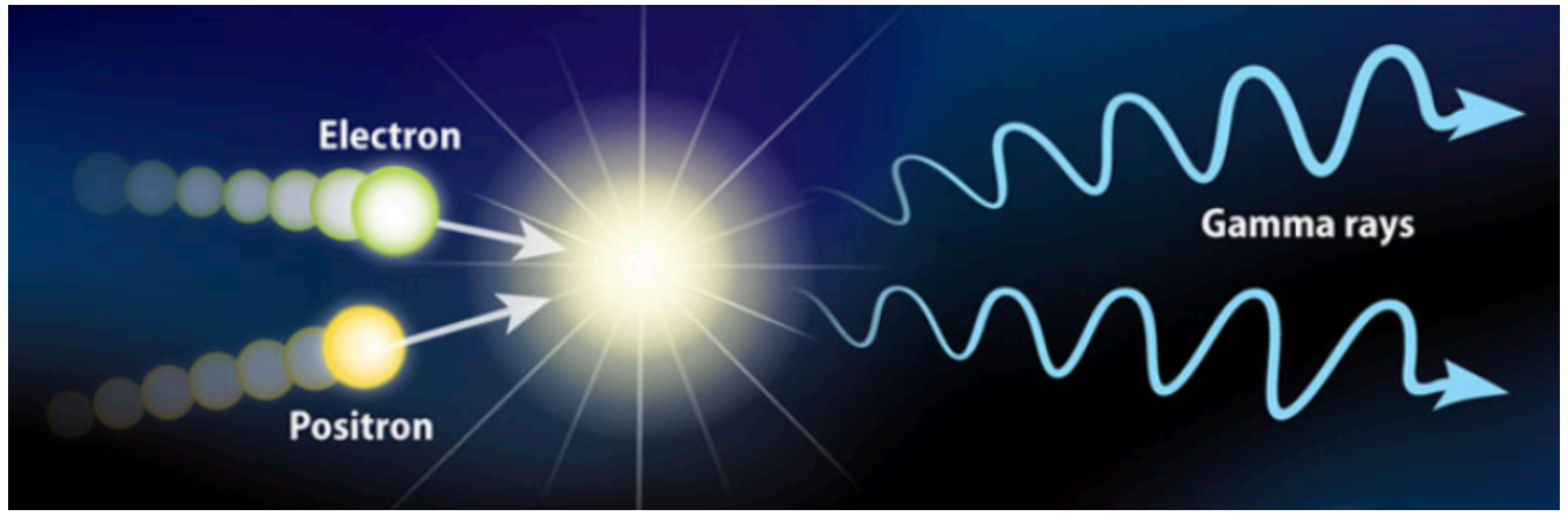


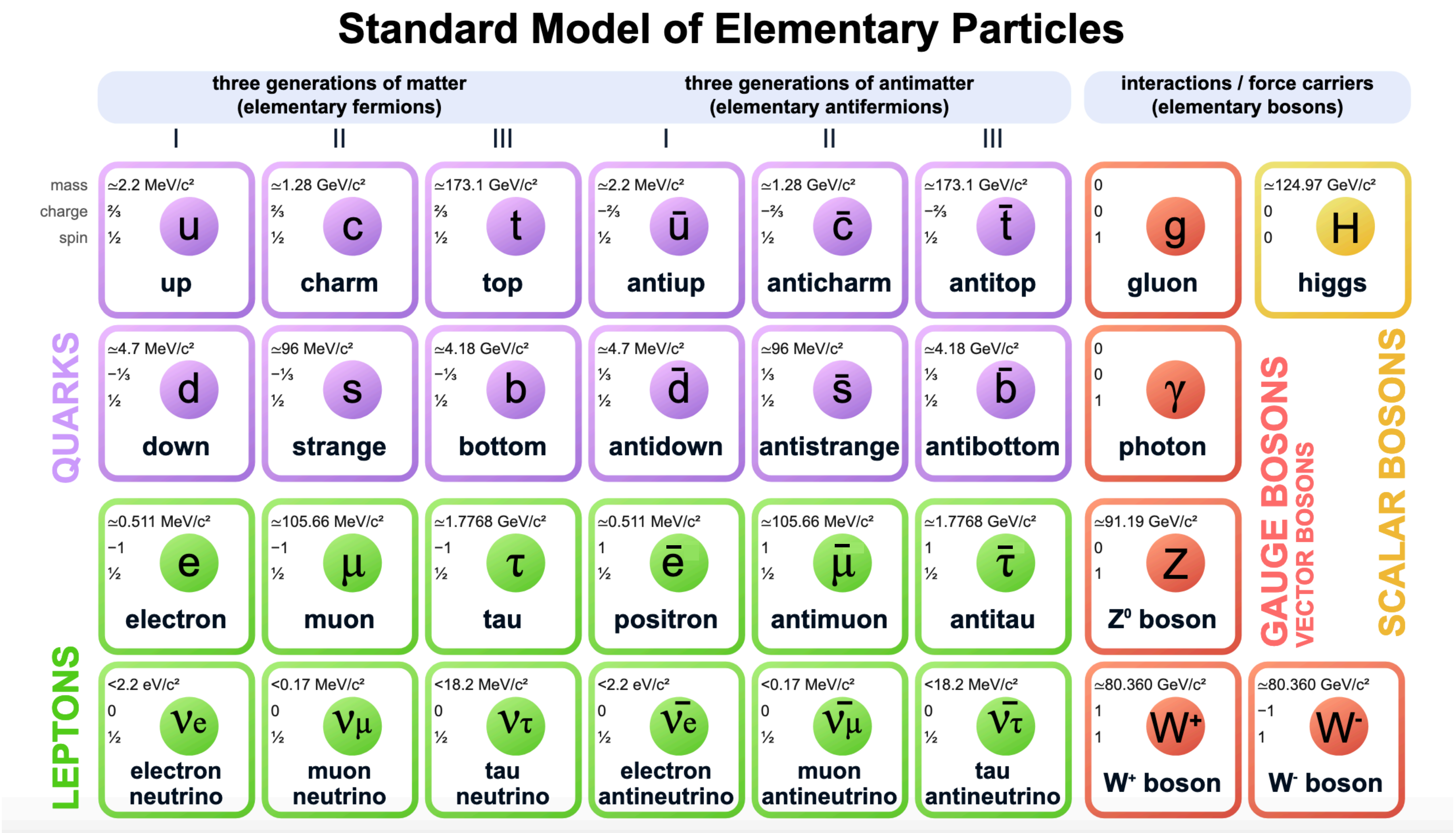
The $\beta^{\pm}$ radioactivity



The Antimatter

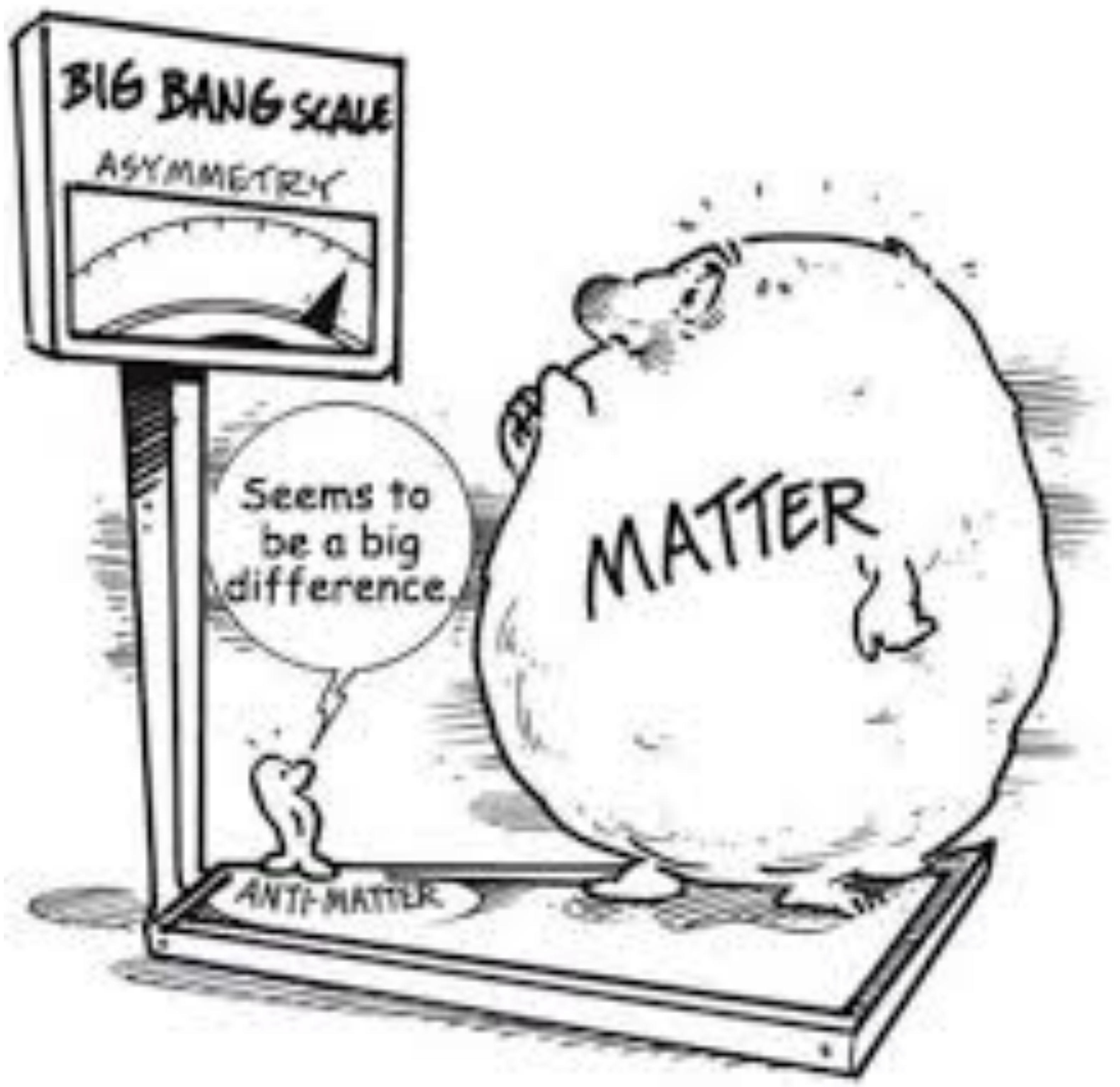
- **Same** as matter (mass and interactions are identical)
- **But** electric charge is opposite
- Produced in some radioactive processes or reactions at high energy (supernovae, cosmic rays…)
- Life-time very short, annihilates with its associate « usual matter » partner





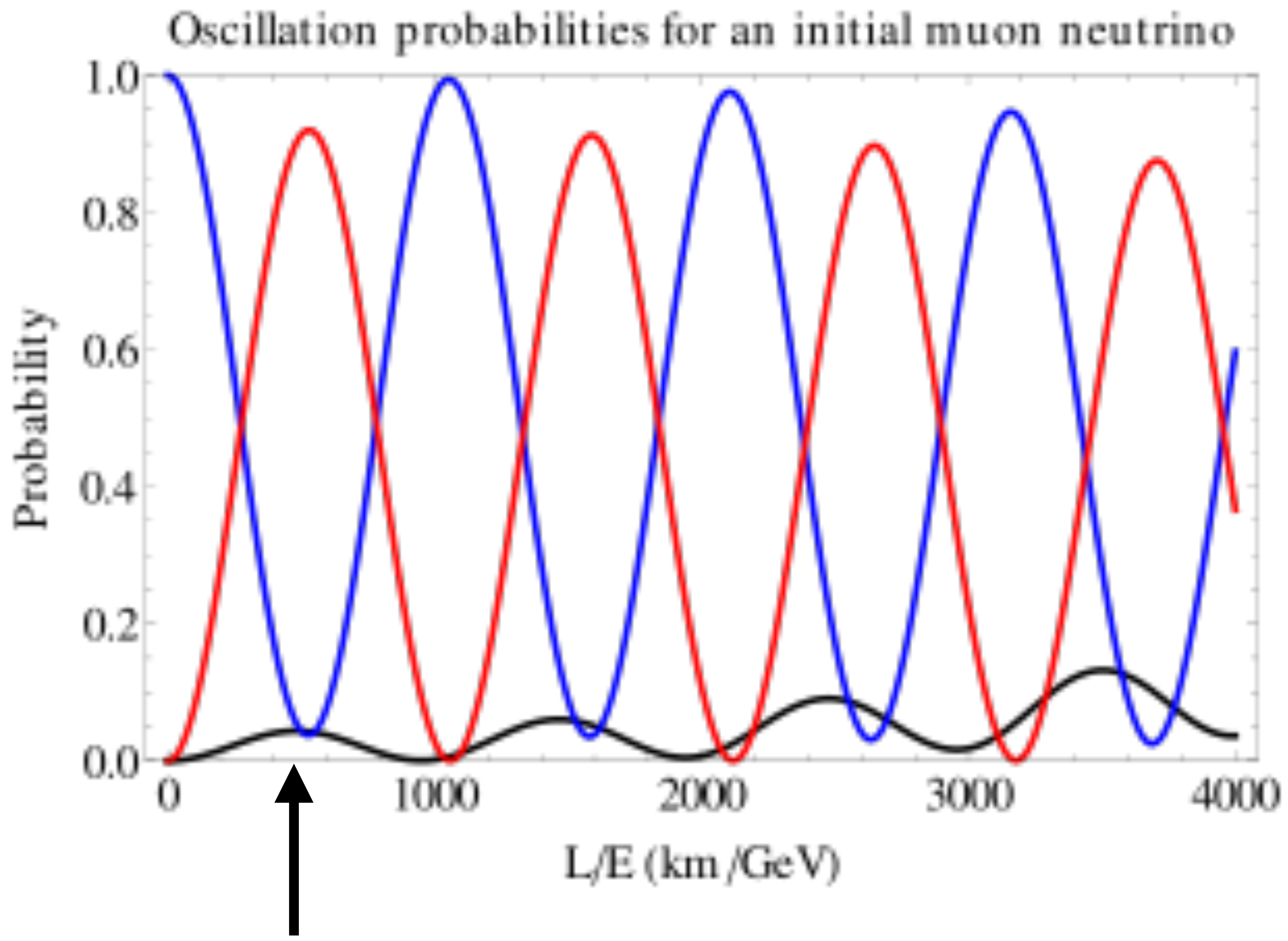
The matter-antimatter asymmetry

- Matter + Antimatter —> « Vacuum » + Energy
- « Vacuum » + Energy —> Matter + Antimatter
- Big Bang should have produced an **equal** amount of **matter** and **antimatter**
- Where did **the latter** go ?
- One of the (very!) numerous necessary ingredients to explain the observed asymmetry: **CP symmetry violation,** which means a **difference** of behavior between **matter** and **antimatter**



Neutrino oscillations

- When a neutrino is produced in a given flavor, there's a non-null probability for it to be detected in another flavor
- This « oscillation probability » depends on its energy E and the distance it travelled L
- Two effects could explain neutrino and antineutrino oscillations which would not be identical: $\mathscr{P}(\nu_\mu \to \nu_e) \neq \mathscr{P}(\bar{\nu}_\mu \to \bar{\nu}_e)$:
  - Matter effects (to be excluded because T2K baseline is to short) ❌
  - **CP** symmetry is **violated** ✅



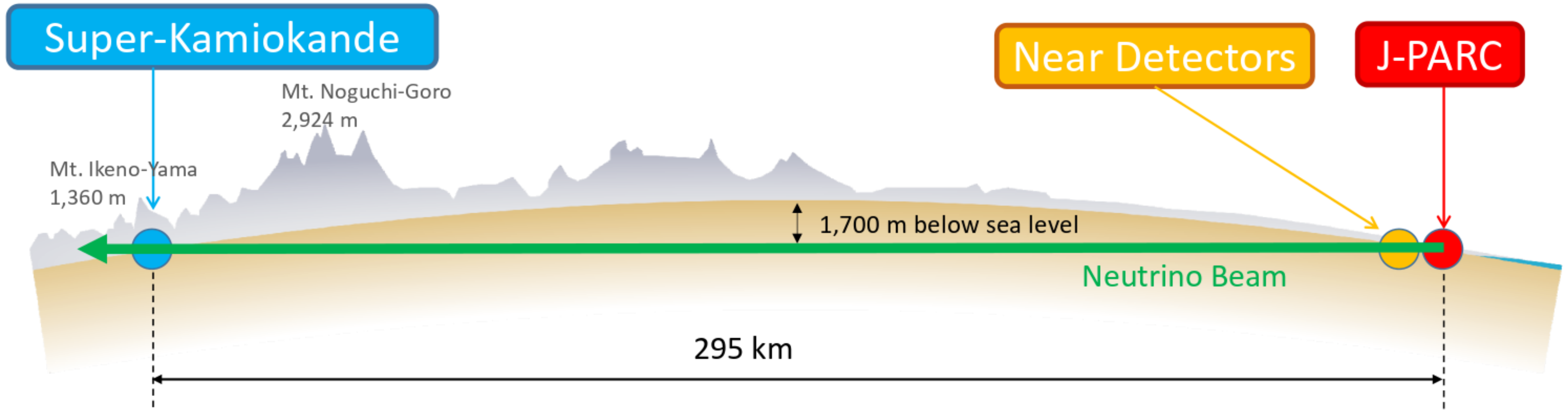
T2K
L/E $\simeq$ 492 km/GeV

ν_μ, ν_e, ν_τ

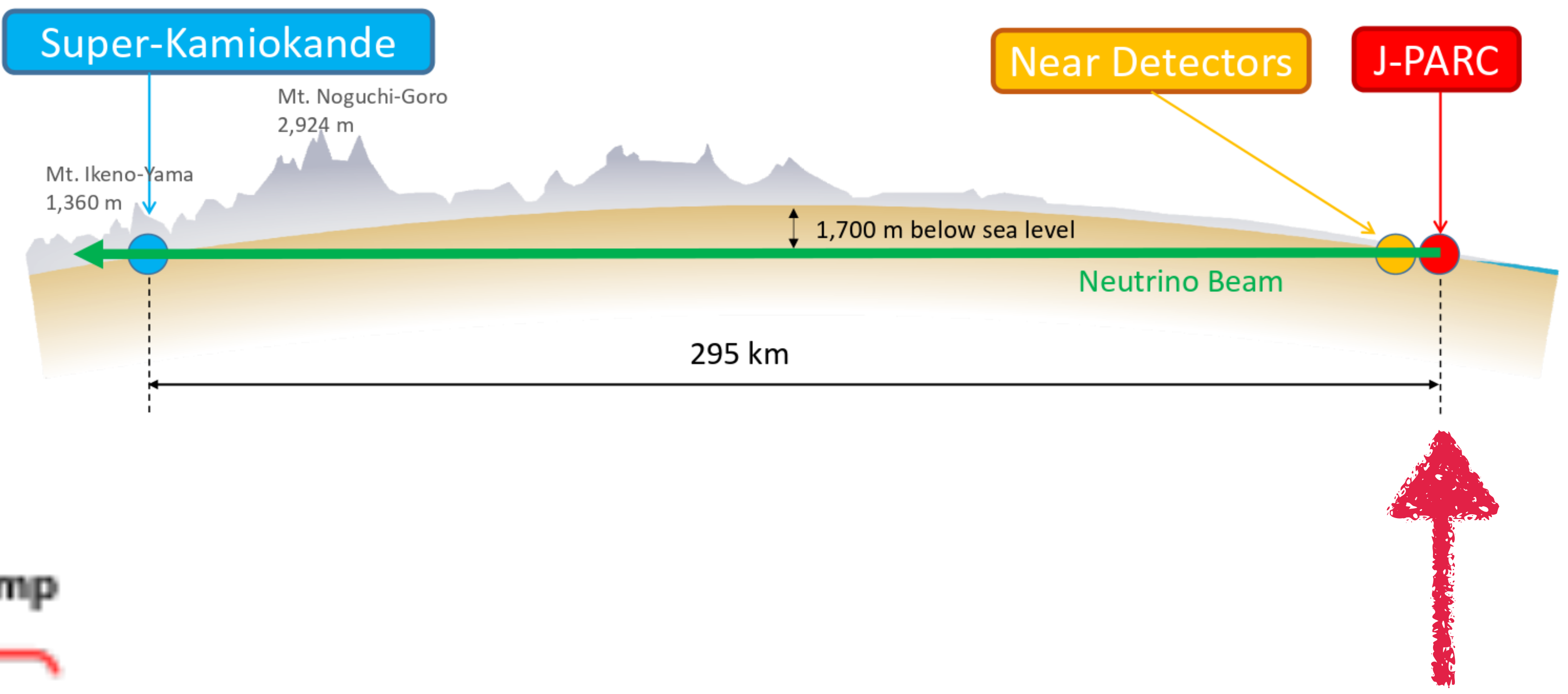
T2K(-II) experiment

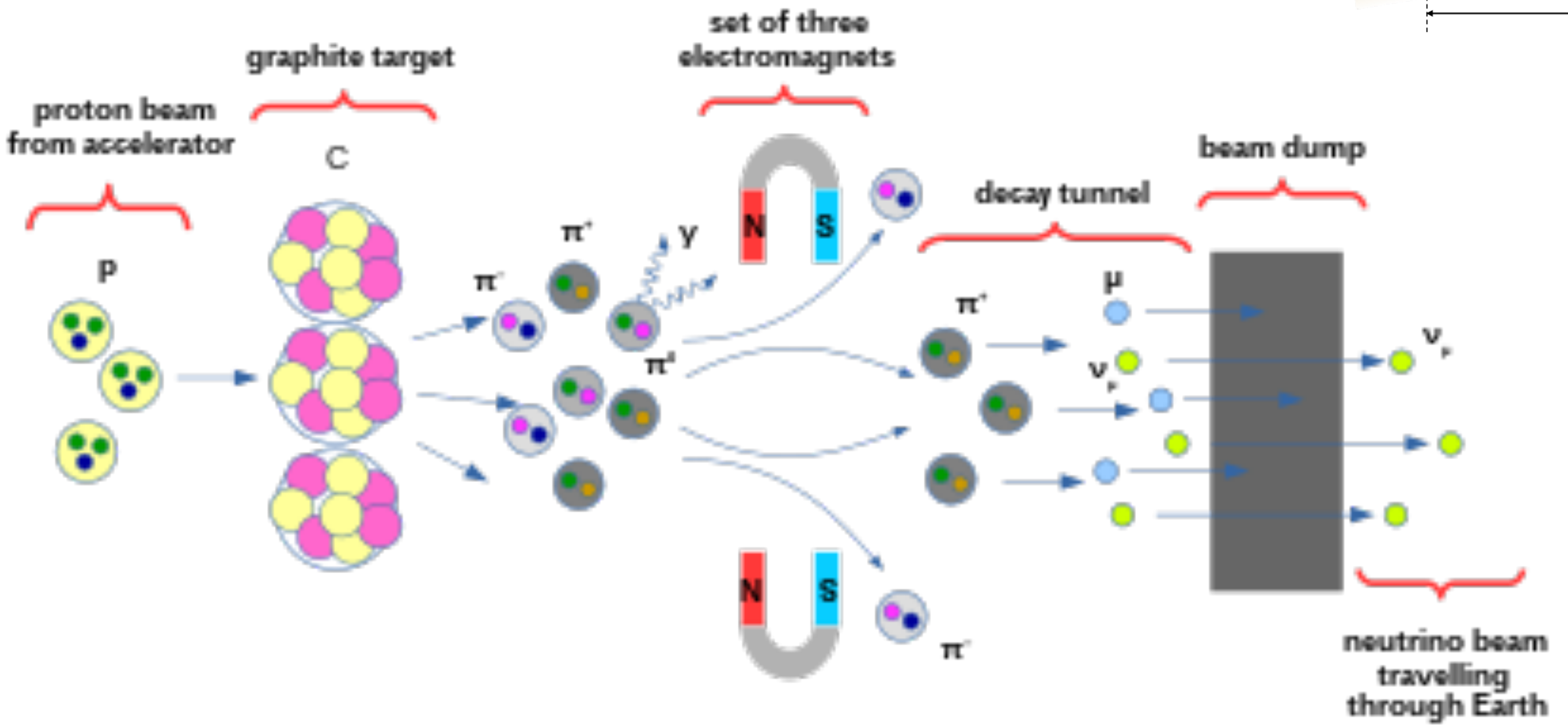
The T2K experiment

- Long-baseline neutrino oscillation experiment
- Has taken data in Japan since 2010

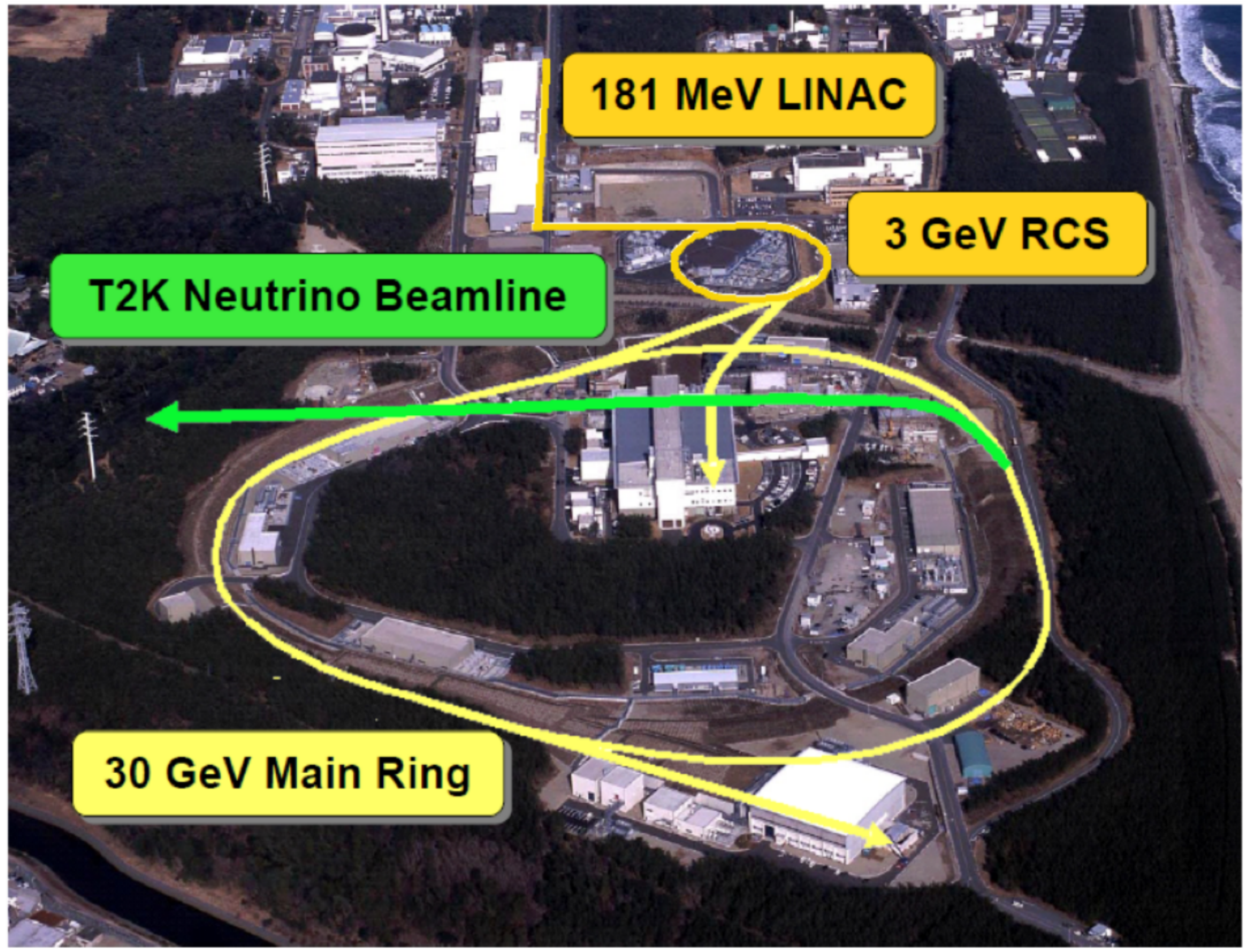


The T2K experiment: J-PARC

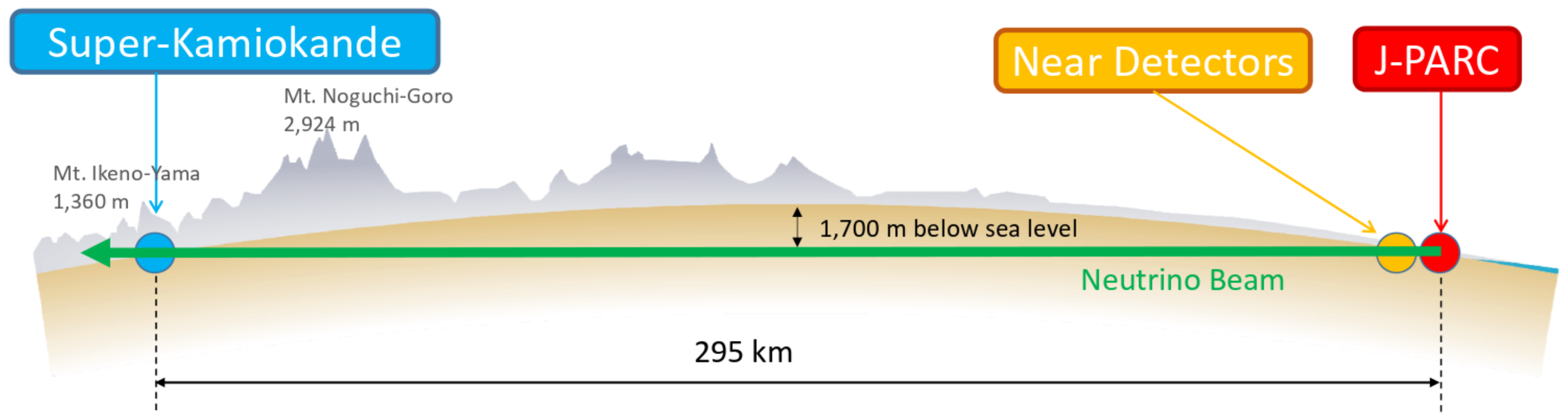




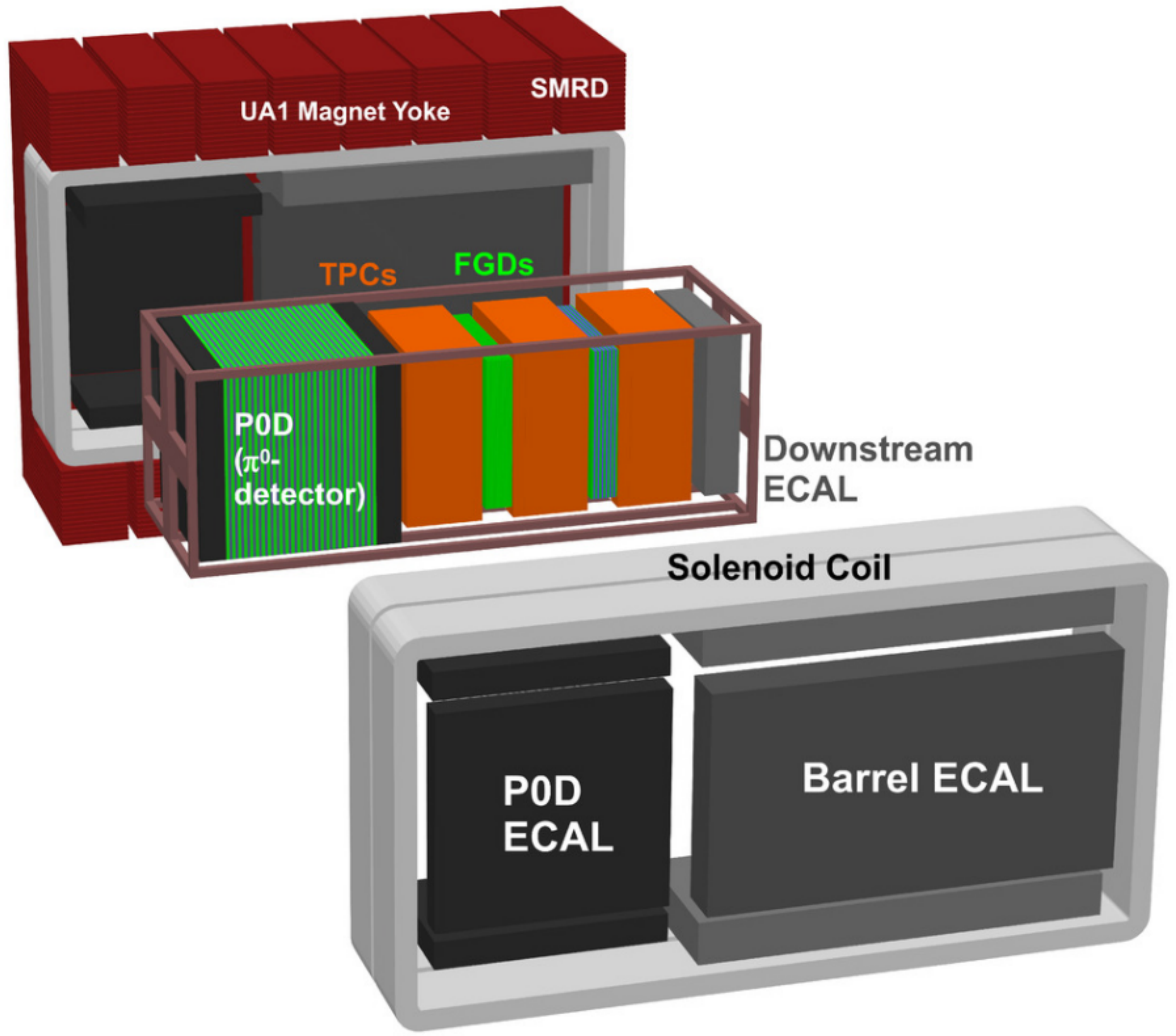
- Japan Proton Accelerator Research Complex: Acceleration of protons
- Collisions on a graphite target produce mainly mesons: $\pi^{\pm}, K^{\pm}$
- Thanks to magnetic horns, select:
  - Either π^{+}, K^{+} which decay mainly in $\mu^{+} + \nu_{\mu}$ —> ν_{μ} **beam**
  - Or π^{-}, K^{-} which decay mainly in $\mu^{-} + \bar{\nu}_{\mu}$ —> $\bar{\nu}_{\mu}$ **beam**



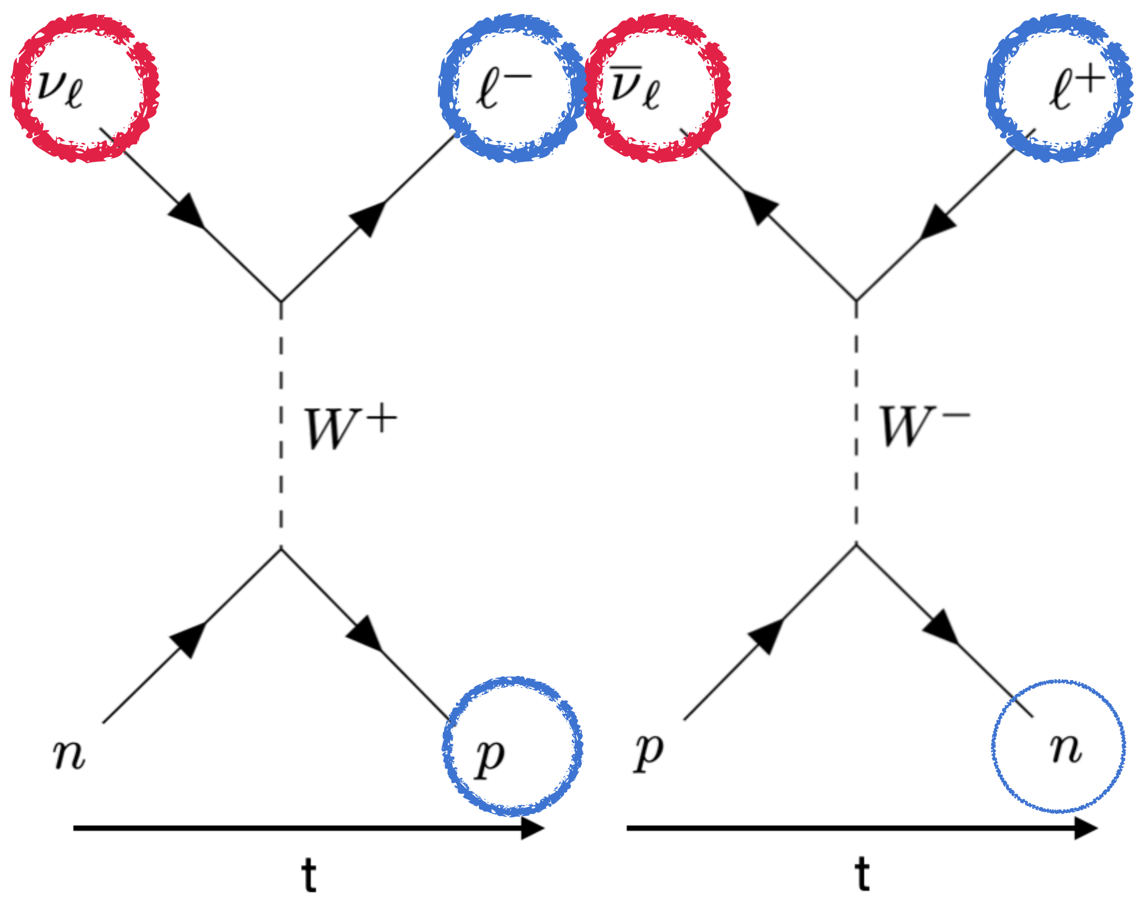
The T2K experiment: ND280



- Magnetized (thanks to **magnet yoke** coming from CERN UA1 experiment) series of detectors, located 280m downstream of the J-PARC graphite target
- **PoD** (π^0 detector): measurement of π^0 production ($\pi^0 \rightarrow \gamma + \gamma$ mimics ν_e interaction)
- **FGDs** (Fine Grain Detectors): plastic scintillator bars planes where (anti)neutrino interaction (most probably) takes place: target (+ tracker)
- **TPCs** (Time Projection Chambers): highly accurate reconstruction of particle's momentum: very precise tracker
- **ECAL** (Electromagnetic calorimeter): measures energy deposit



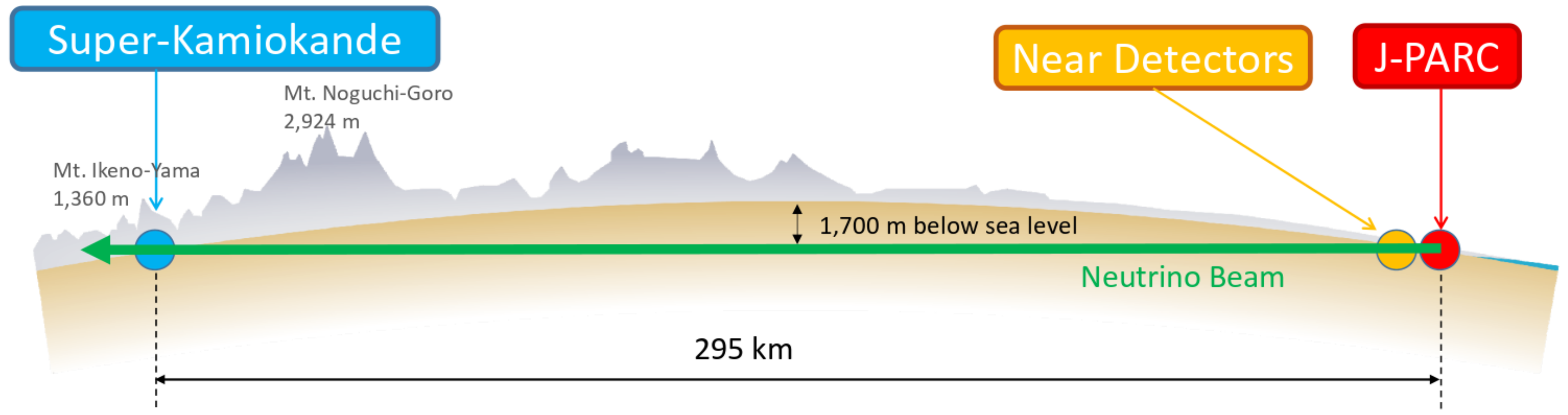
Schematic view of ND280 original configuration (2010-2022)

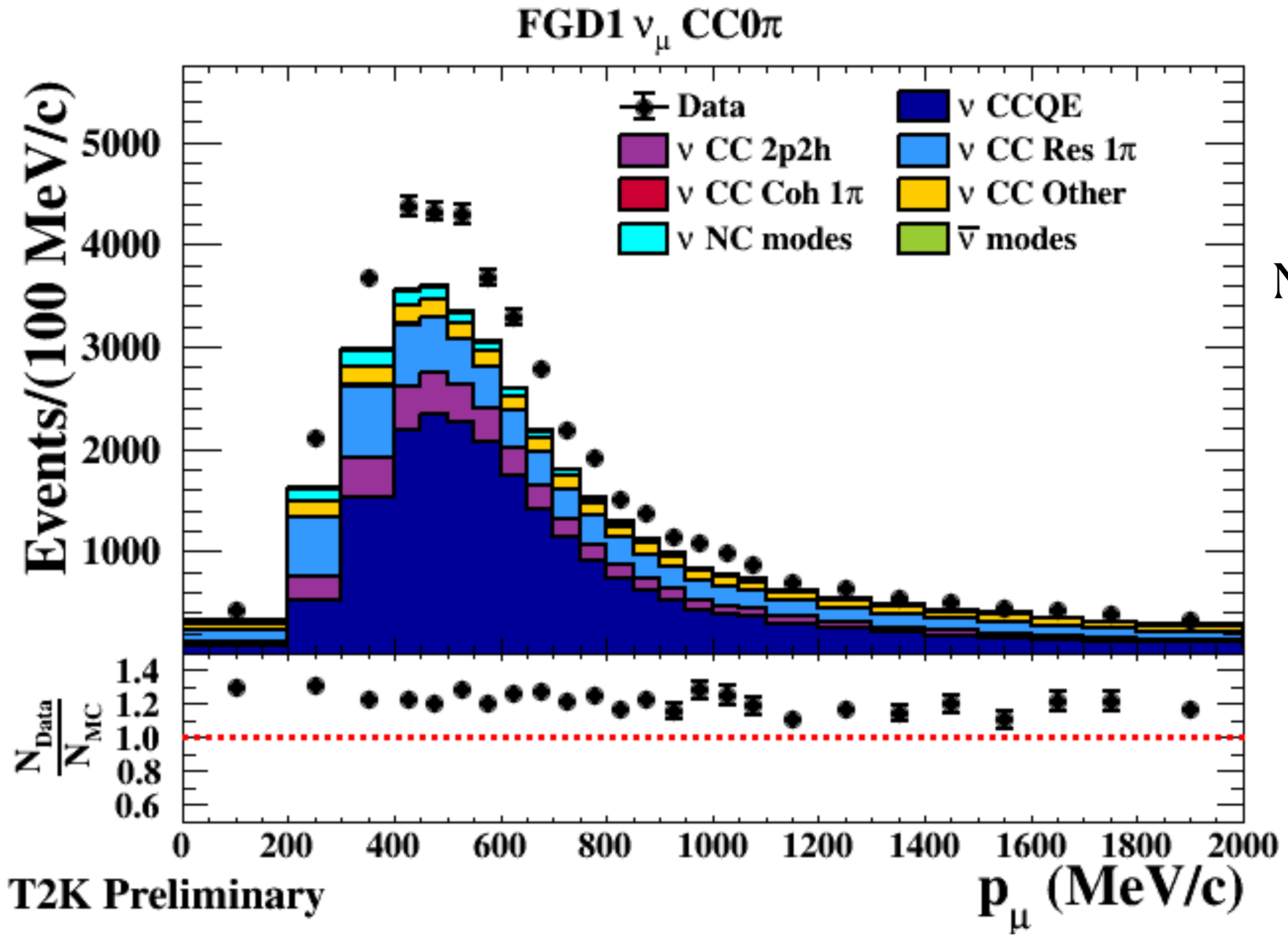


$\ell \in \{e, \mu, \tau\}$

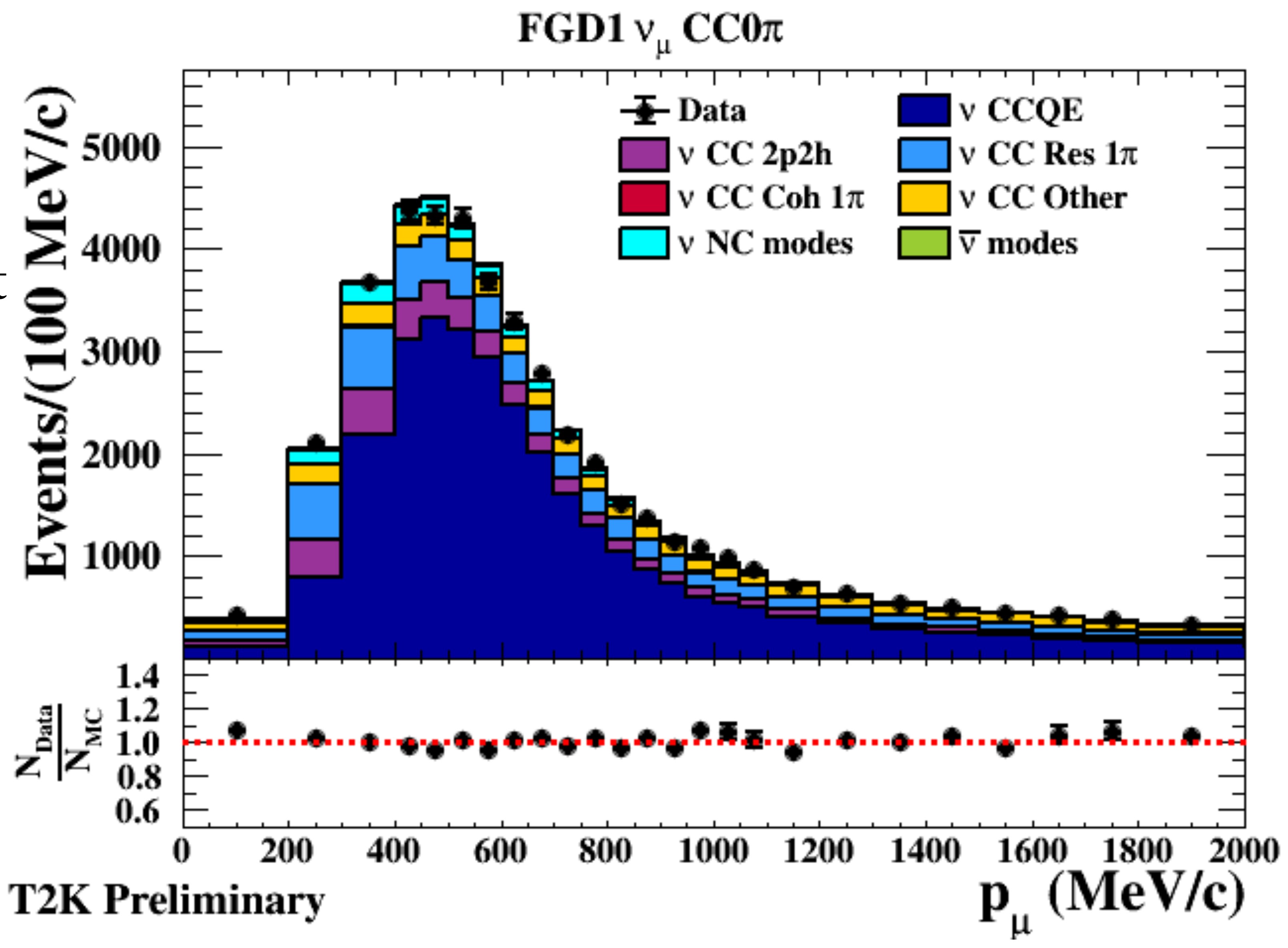
The T2K experiment: ND280

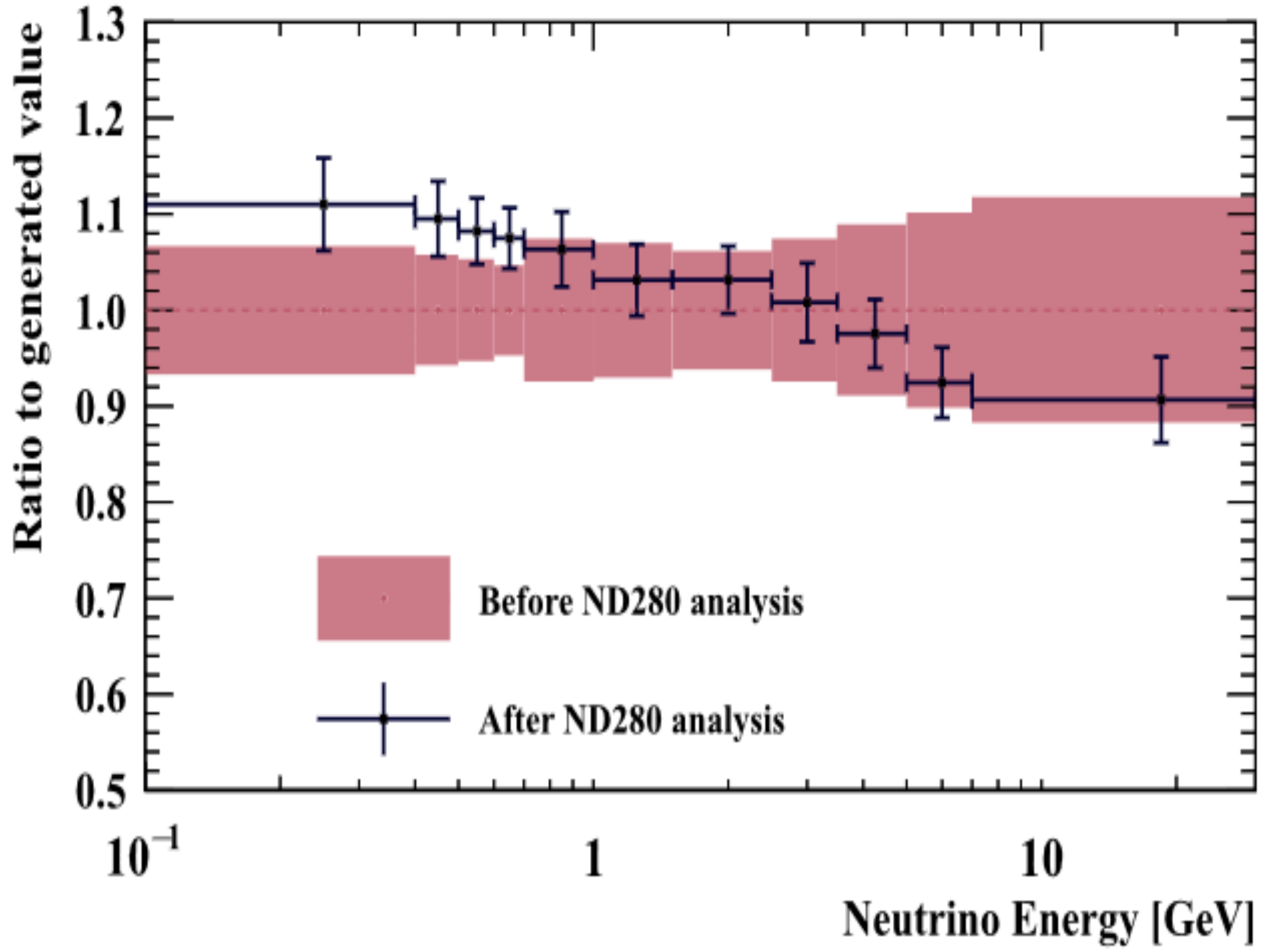
- Fit non-oscillated ν_μ ($\overline{\nu}_\mu$) spectrum
- Reduction of flux and cross-section systematic uncertainties





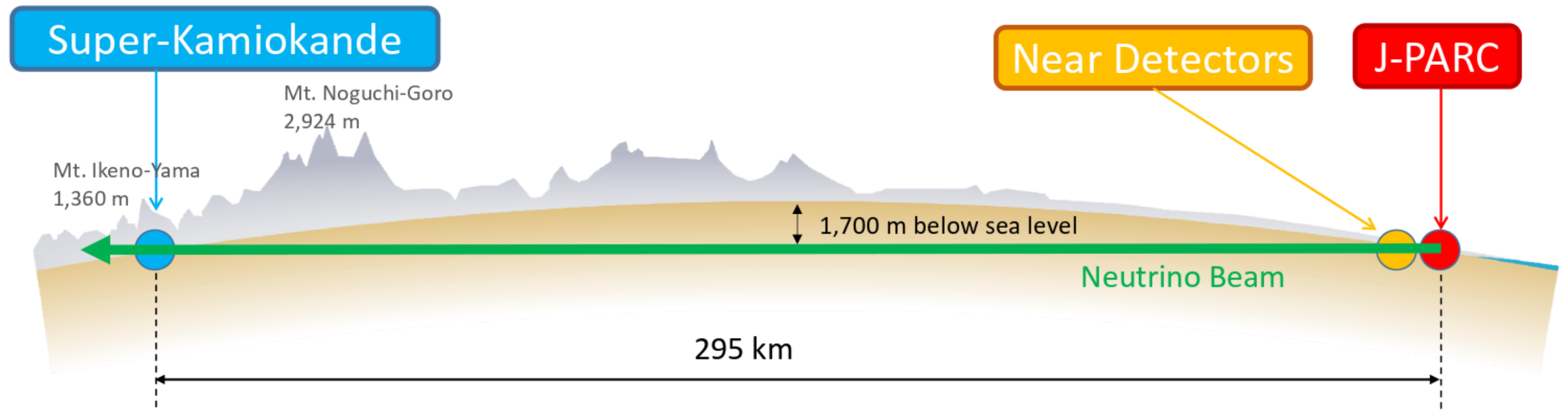
ND280 Fit



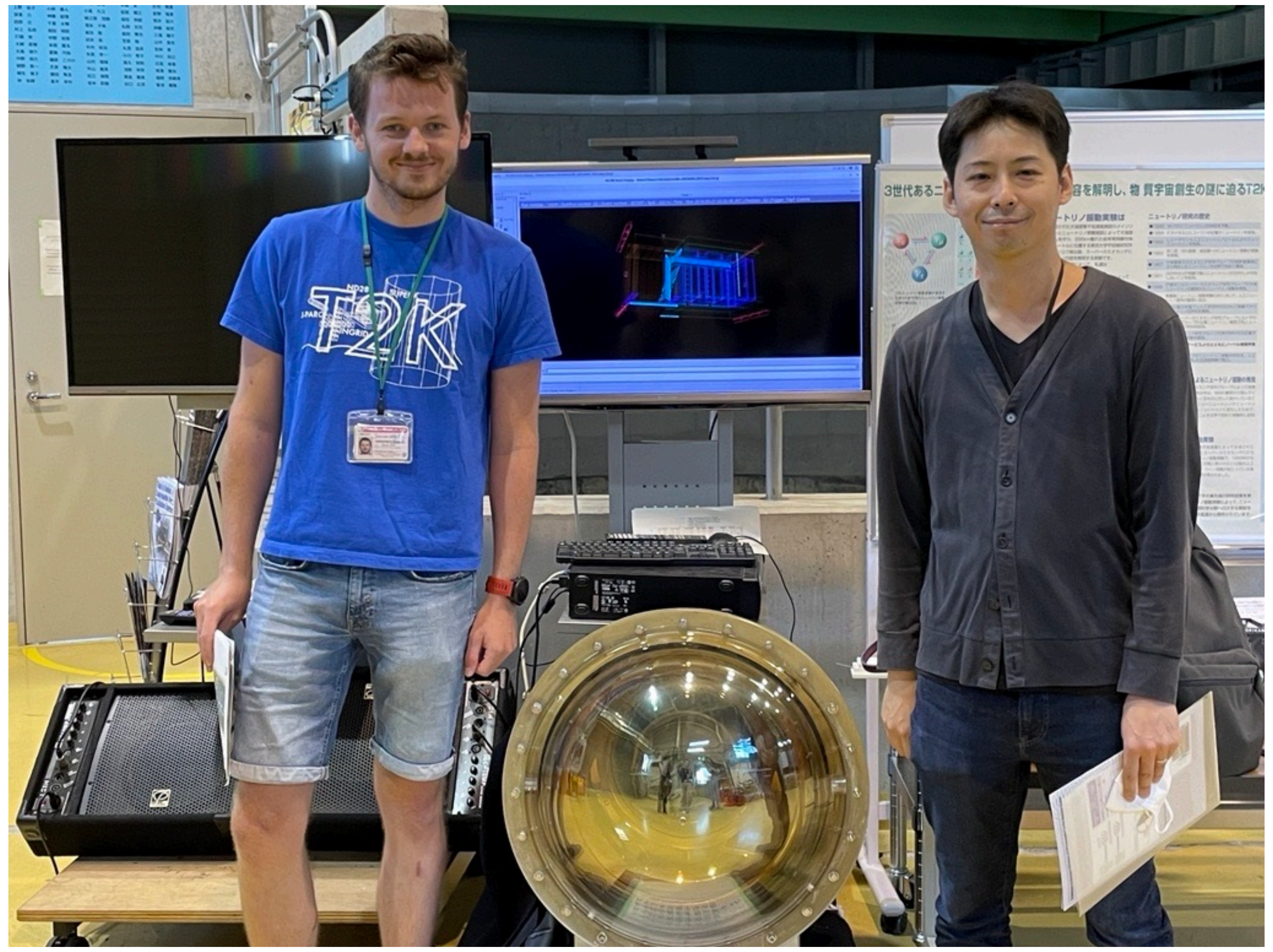


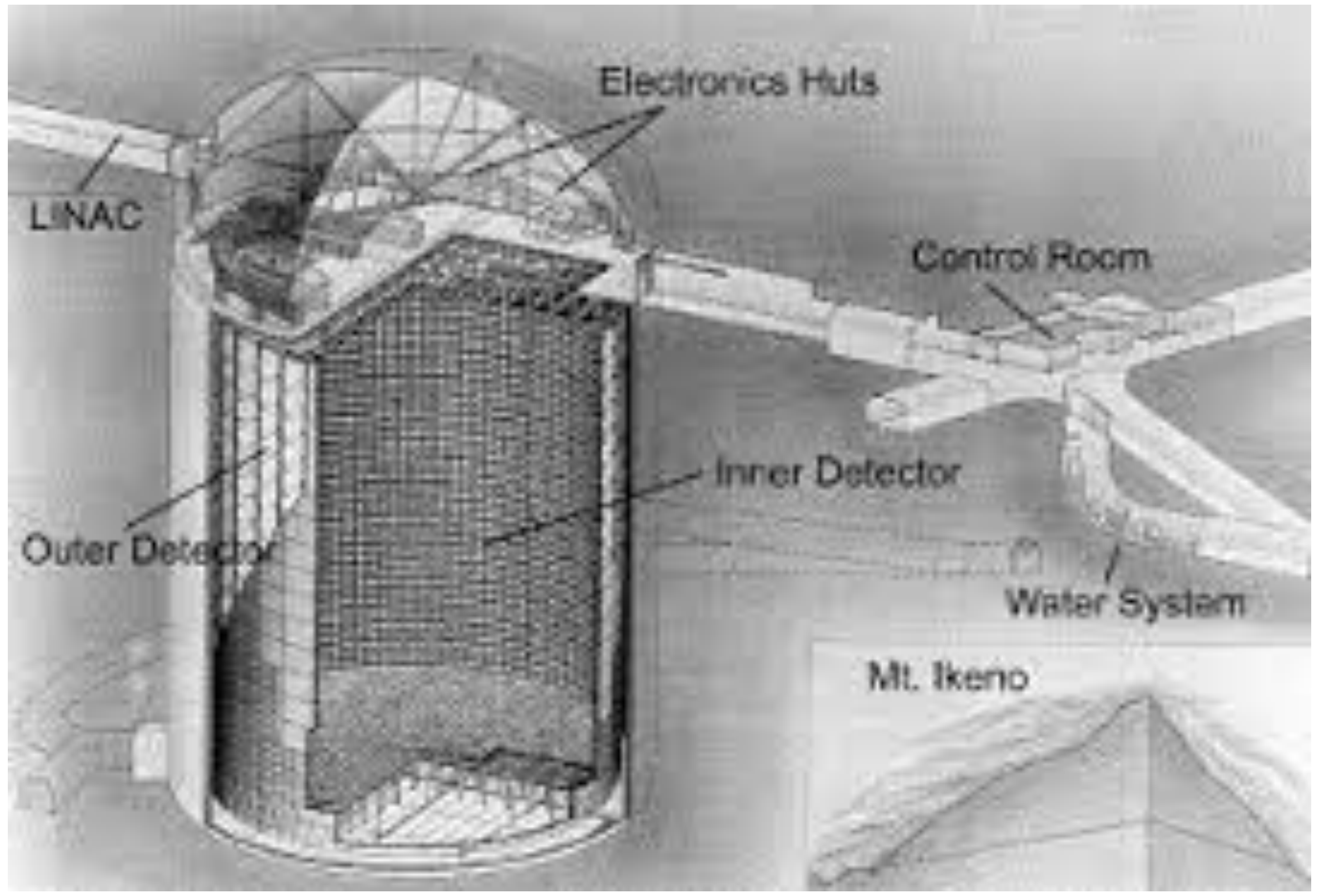
Flux uncertainties
Before vs After ND fit

The T2K experiment: SK

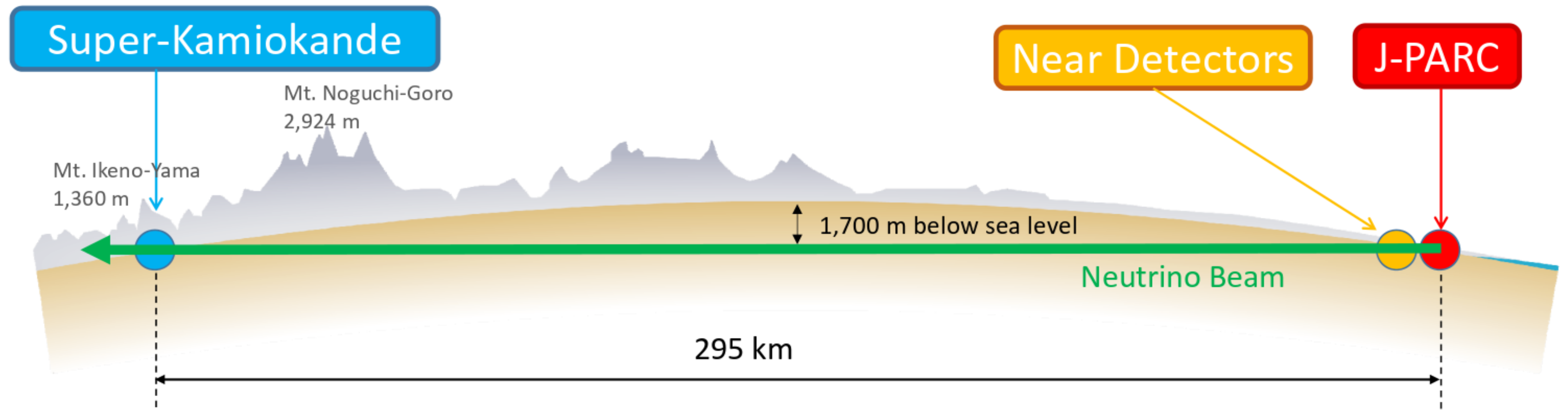


- 40m diameter × 40m height cylinder
- Filled with 50000 tons of ultra pure water
- More than 10000 PMT aim to detect Cherenkov light emitted by charged lepton coming from ν interaction

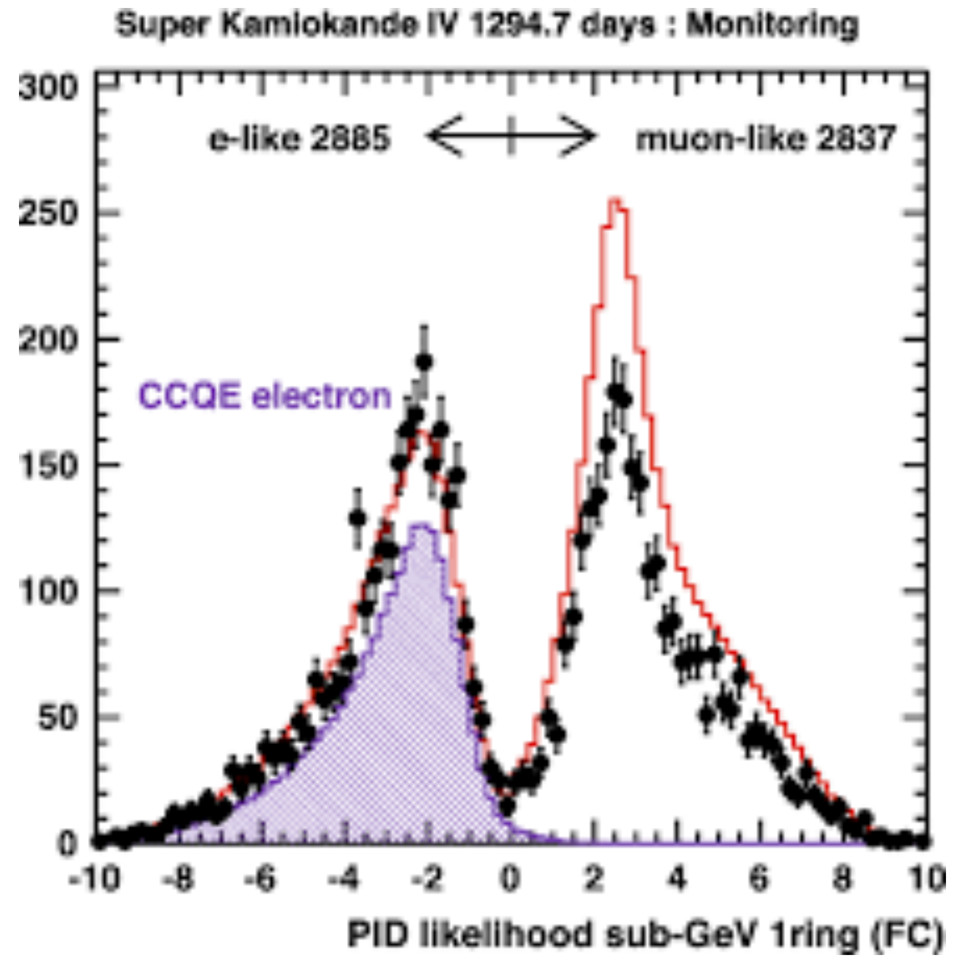


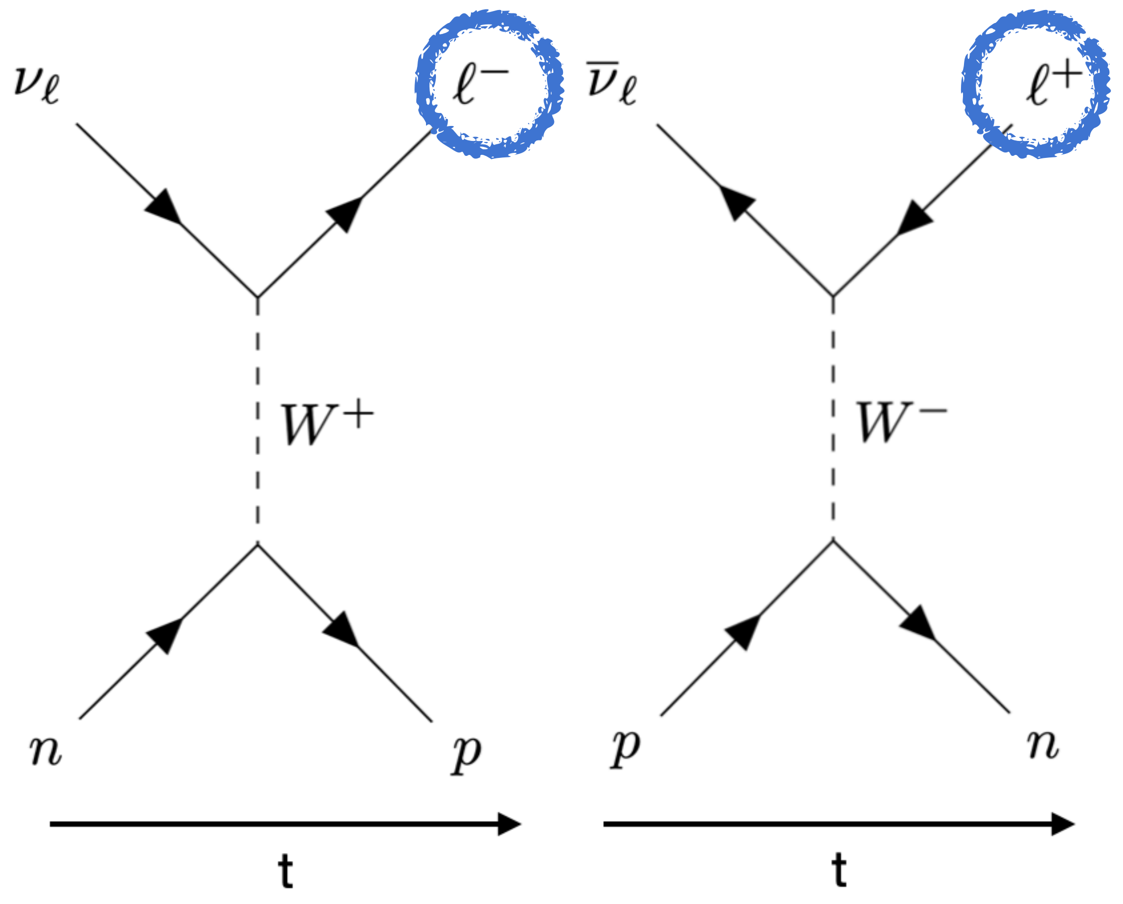


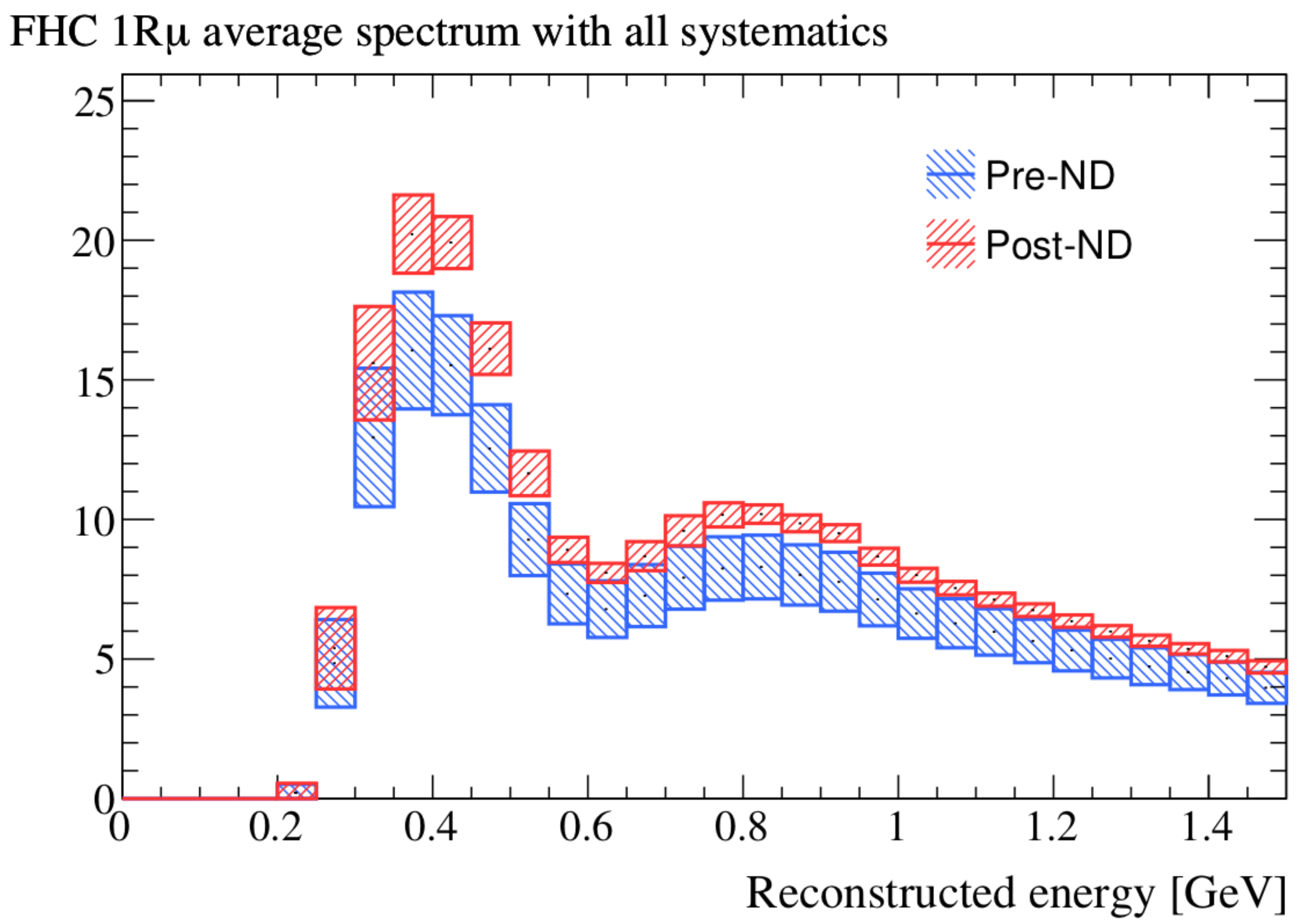
The T2K experiment: SK

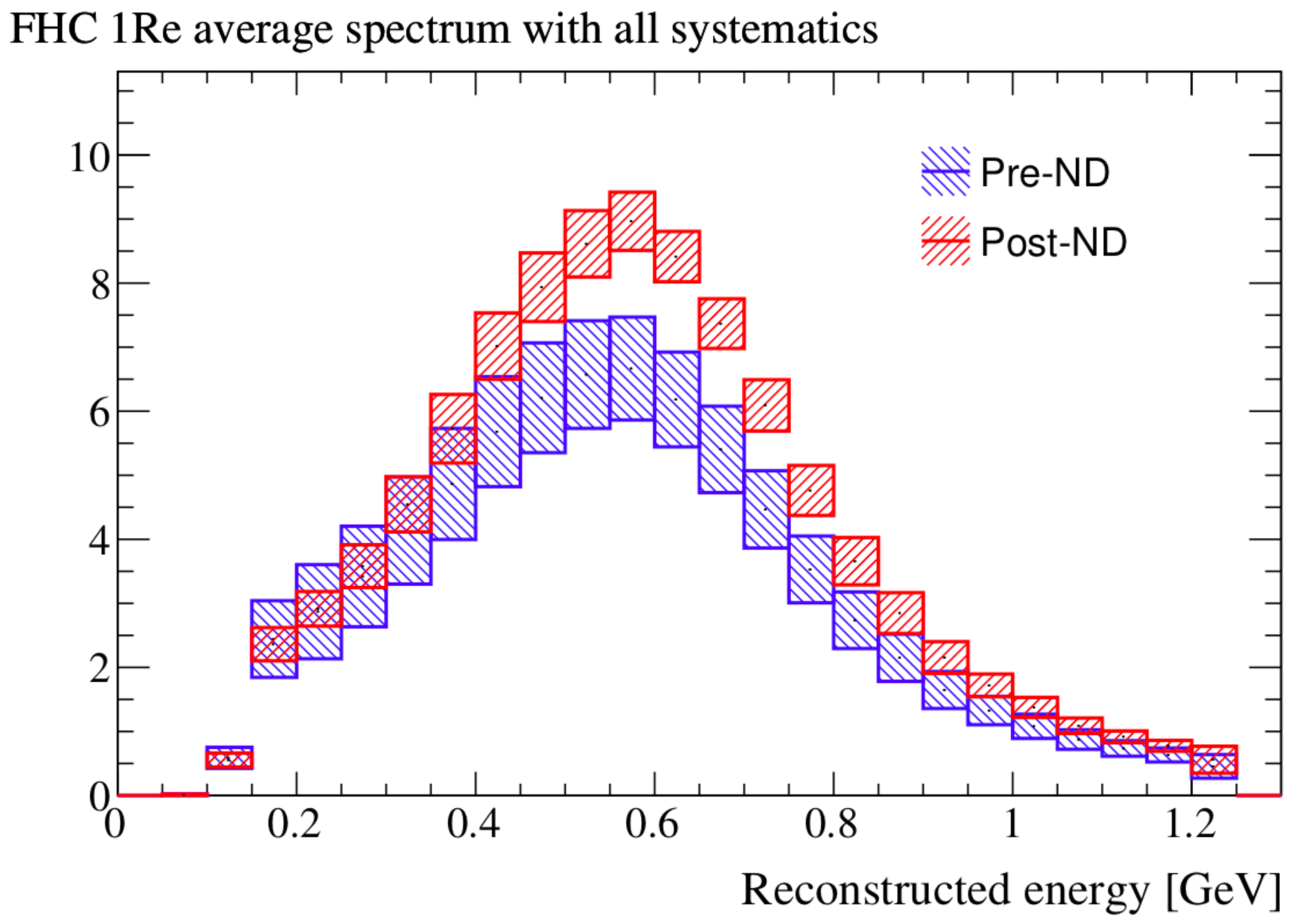


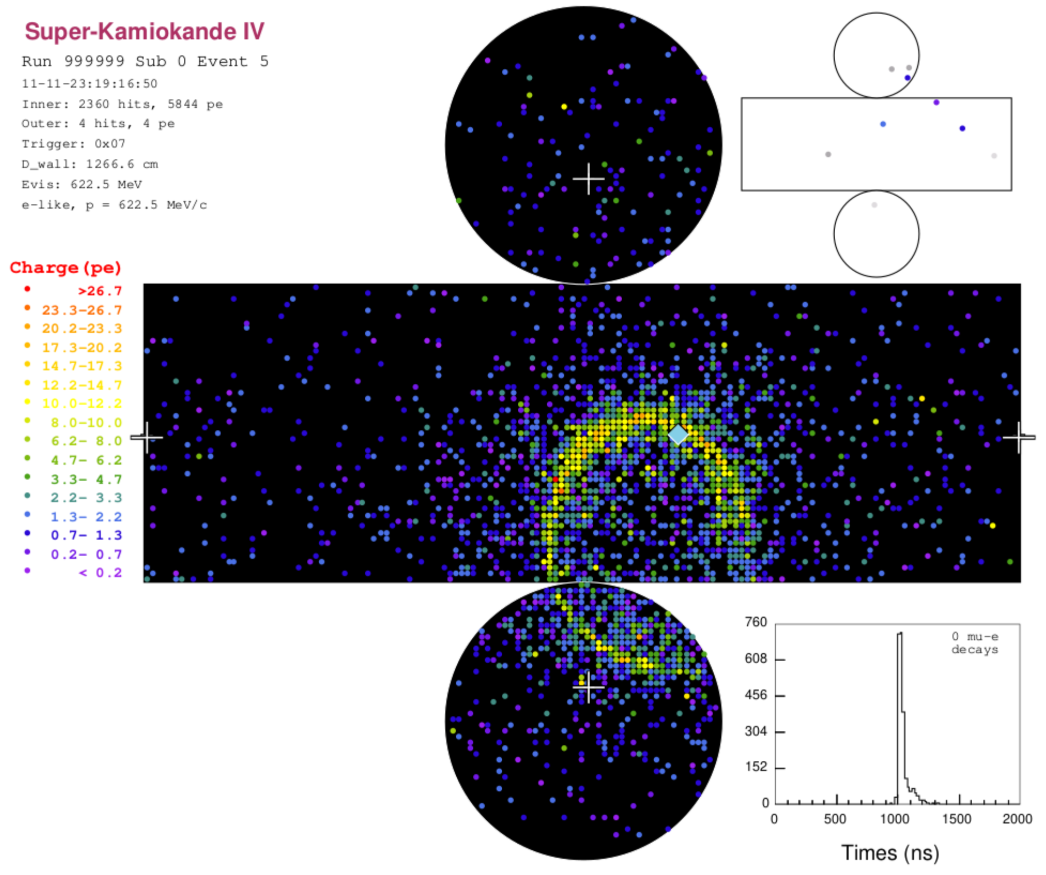
- Fit ν_μ ($\bar{\nu}_\mu$) spectrum but also ν_e ($\bar{\nu}_e$) one
- Constrain ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance to measure oscillation parameters

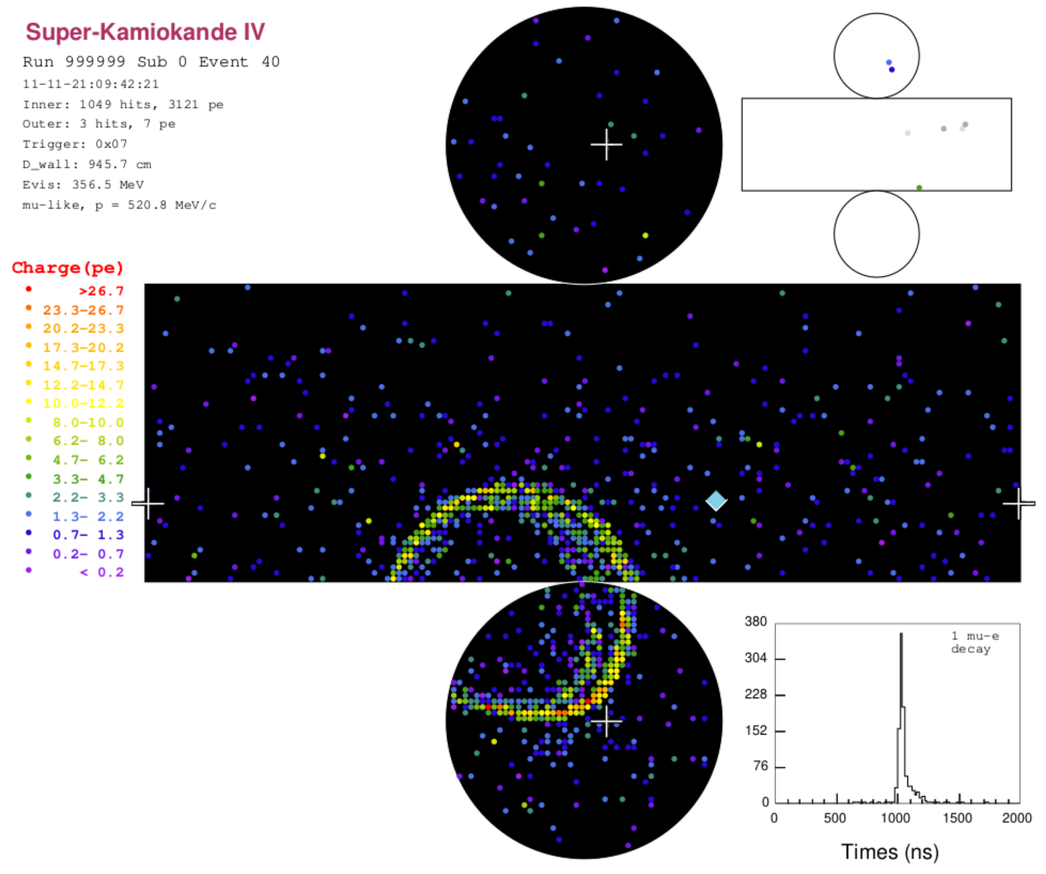






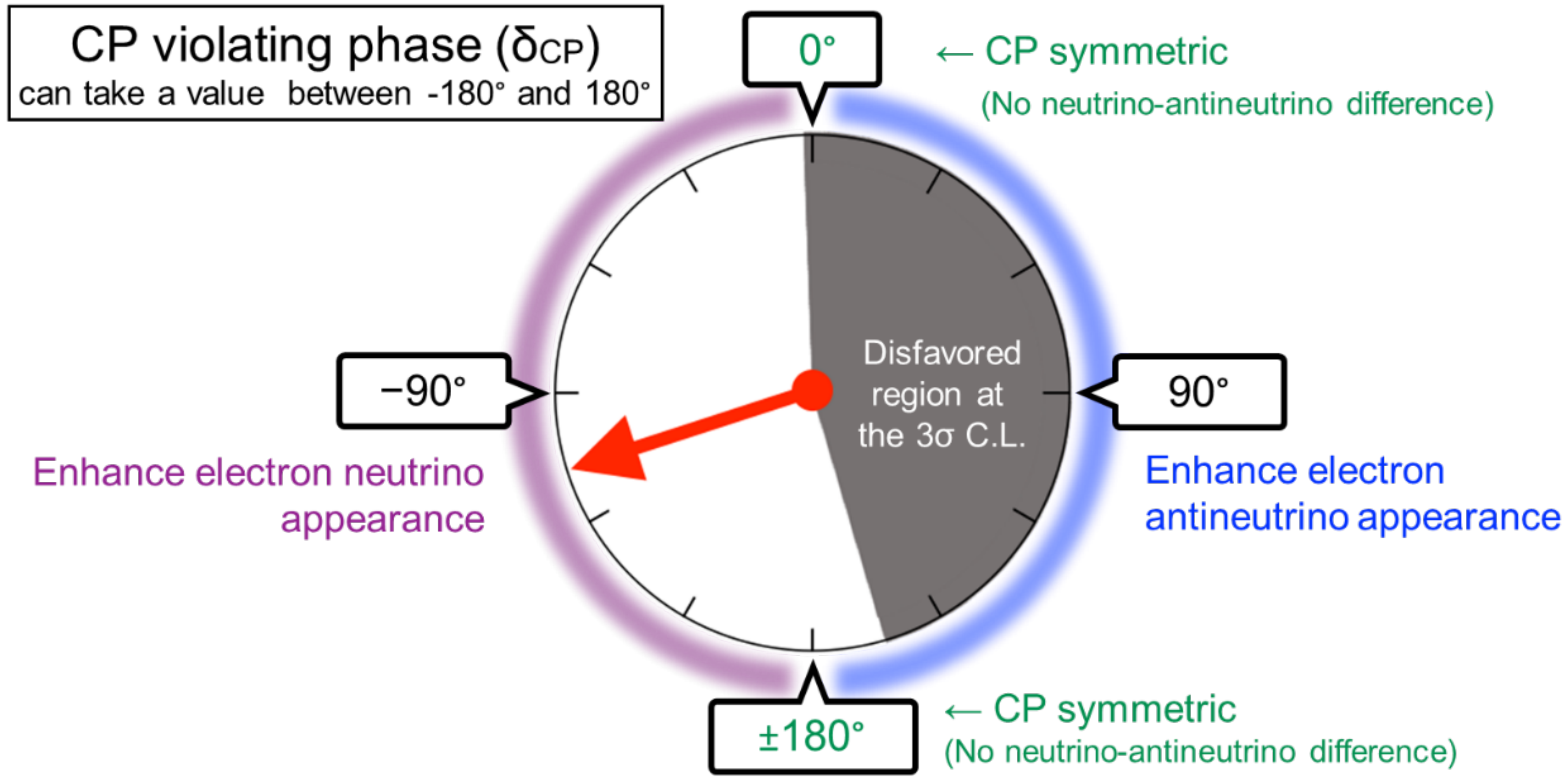


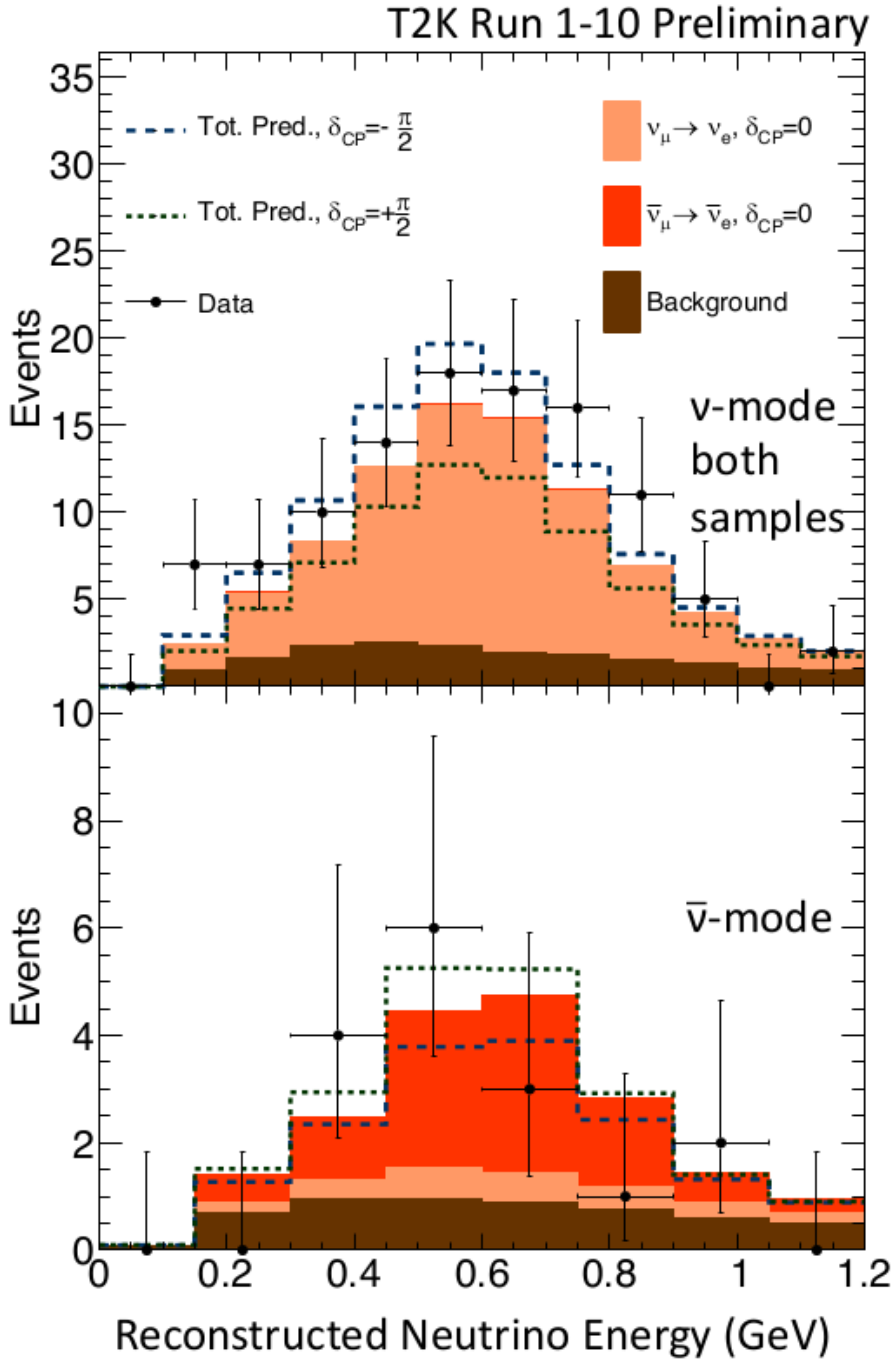




First hints of CP symmetry violation in leptonic sector

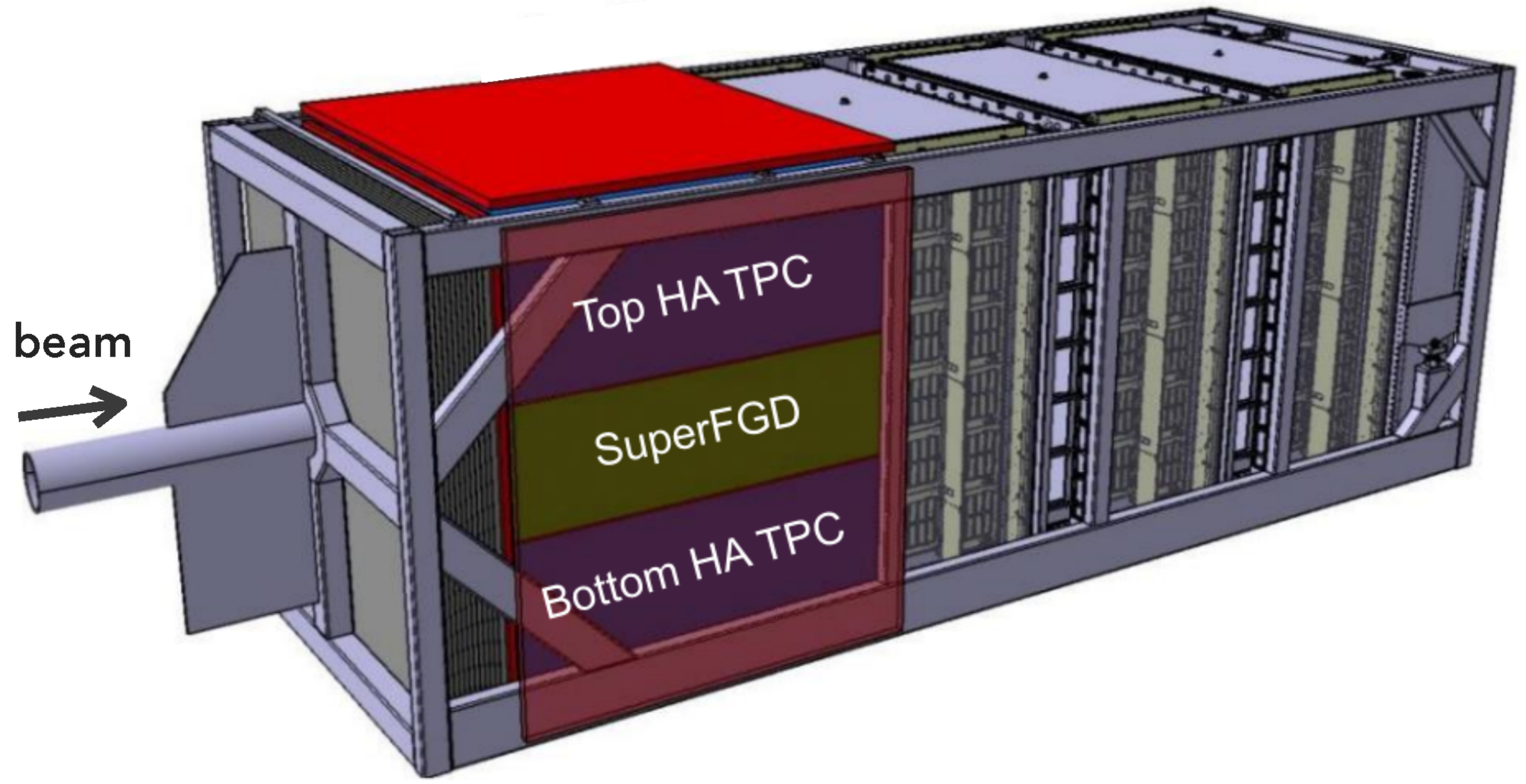
- Published in *Nature* in 2020
- CP symmetry conserving points ruled out at the 2σ confidence level
- Need more data and less uncertainties to confirm those first hints: —> T2K-II !

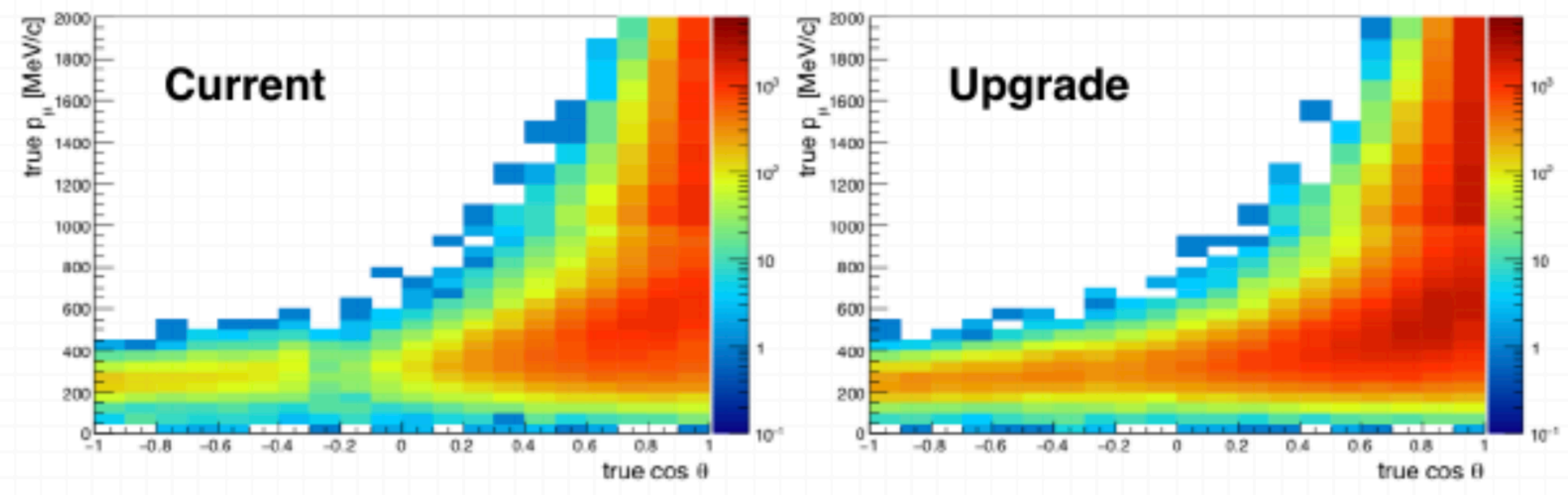




T2K-II

- Upgrade of J-PARC neutrino beam line: proton **beam power** gradually **increase** from $\simeq$ 500kW to 1.3MW (in 2027)
- Upgrade of the ND280: replacement of PoD by:
  - **SFGD** (Super Fine Grain Detector): 2 millions of 1cm^3 plastic scintillator cubes —> target + tracker, better reconstruction of hadronic part
  - **2 HA-TPC** (High-Angle TPC): TPCs at the top and the bottom of the SFGD, equipped with the new Resistive Micromegas technology: huge increase of angle acceptance
  - 6 **TOF** planes surrounding this structure





Angular acceptance

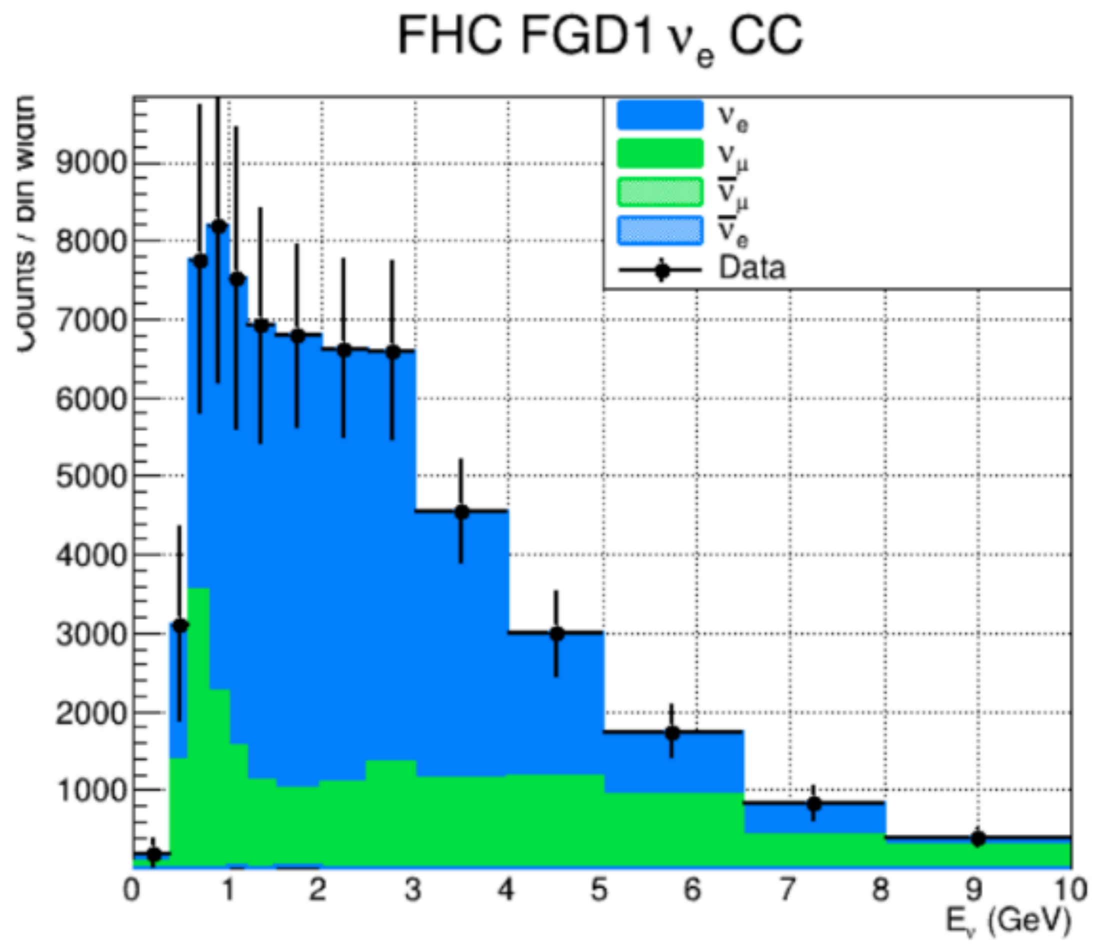
Fit of ν_e and $\bar{\nu}_e$ samples at ND280 and study of their impact for HyperKamiokande

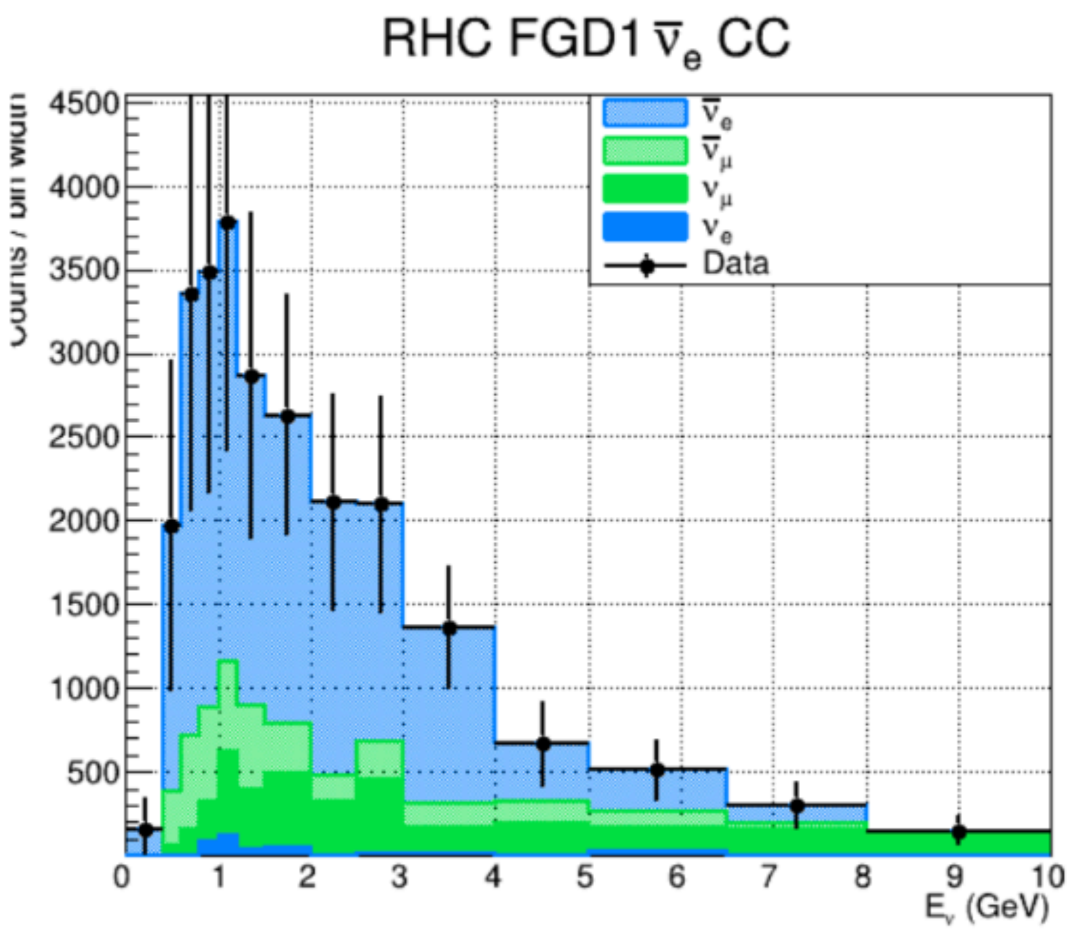
Fit of ν_e and $\bar{\nu}_e$ samples with GUNDAM

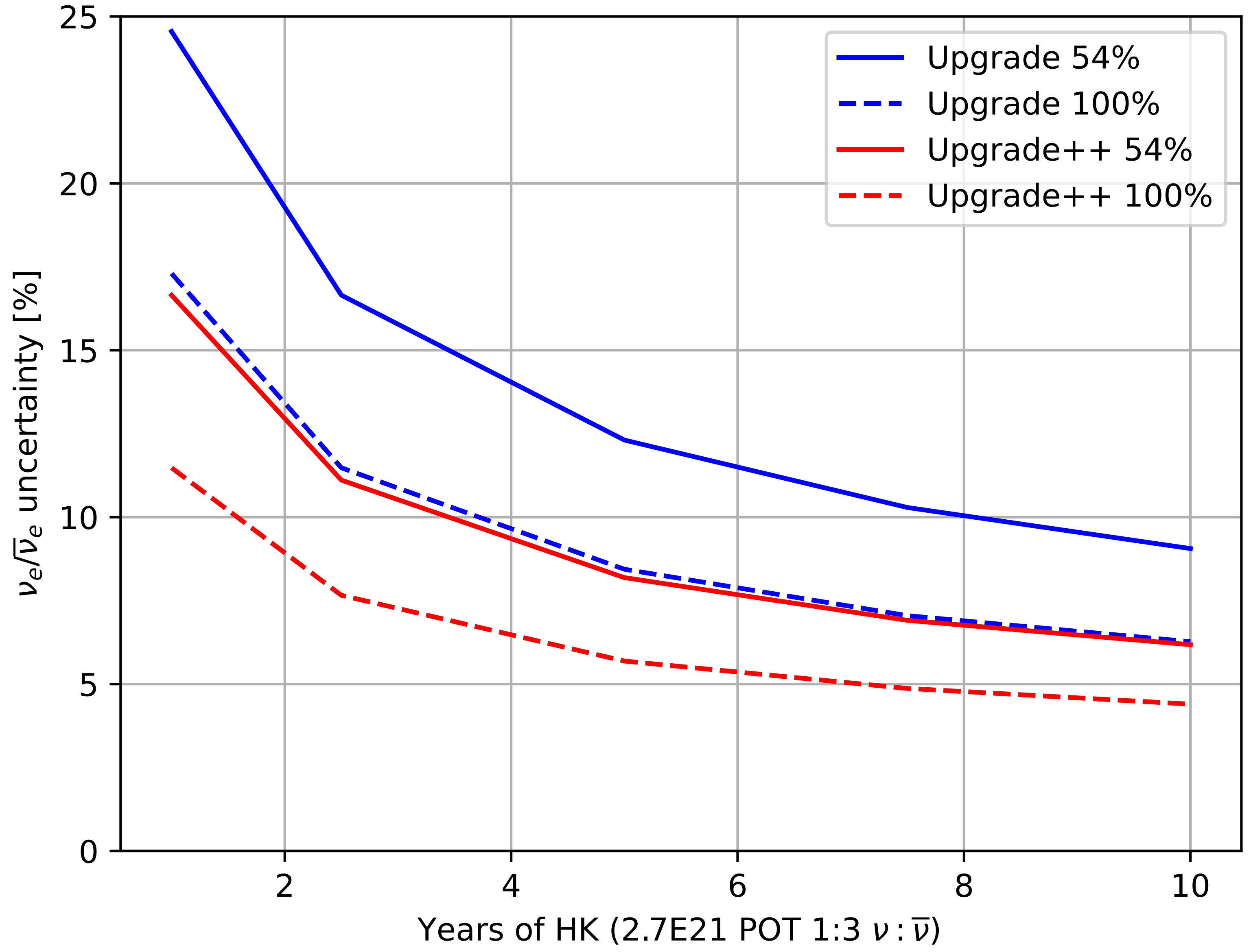
- GUNDAM (a Generic Fitter for Upgraded Near Detector Analysis Methods): new ND280 fitter

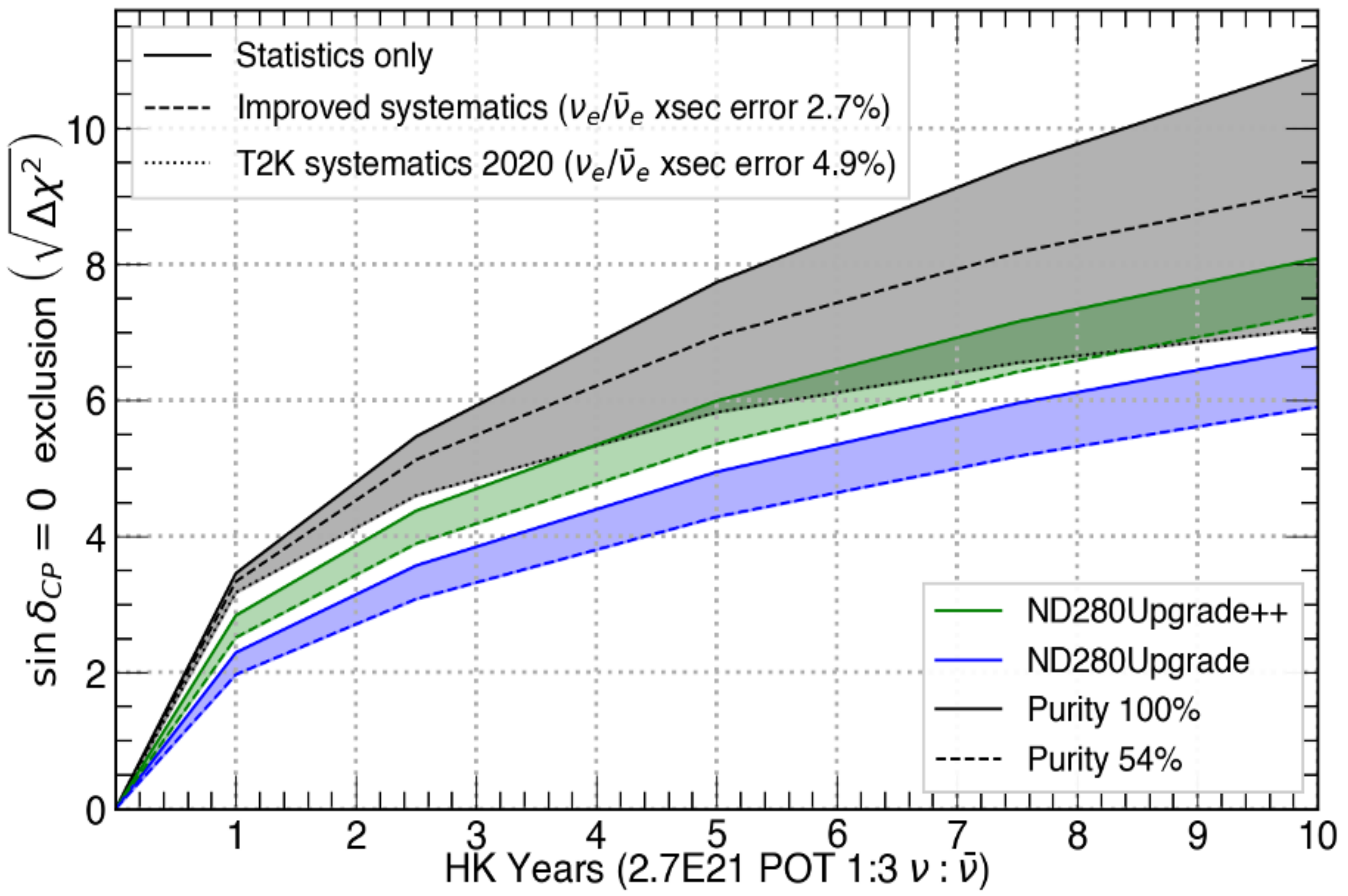
- Implemented ν_e and $\bar{\nu}_e$ samples in this fitter

- Studied their impact on our knowledge of $\nu_e/\bar{\nu}_e$ differences of cross-section, main systematic uncertainty for CP violation measurement





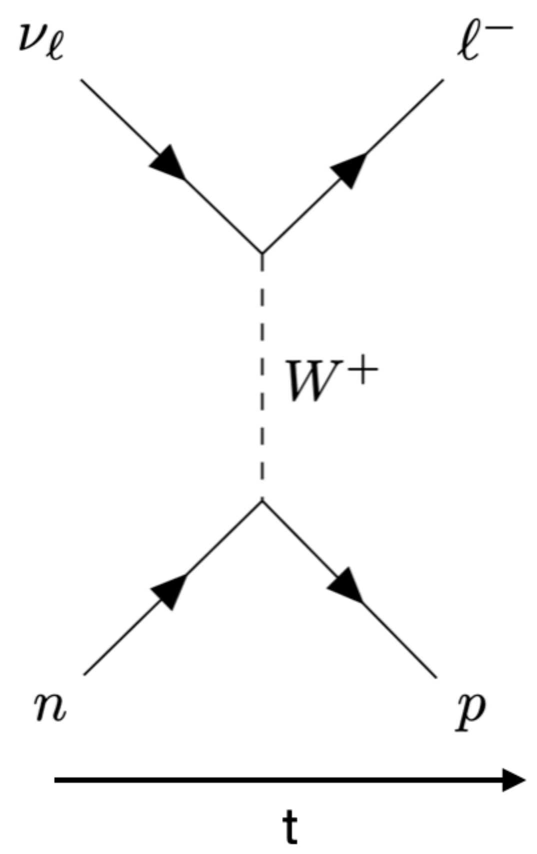


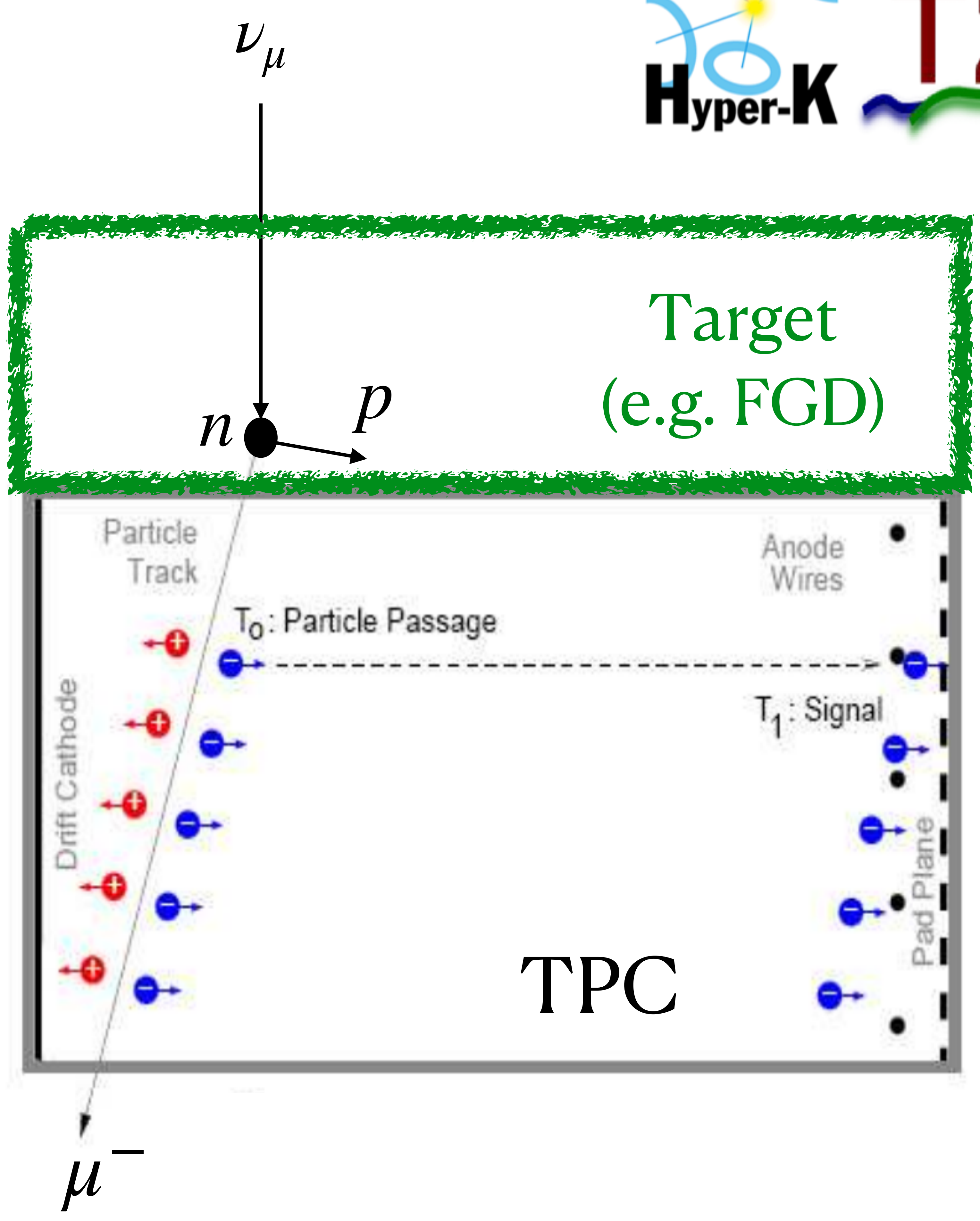


Reconstruction in the HA-TPCs of the upgraded ND280

TPC principle

- Ionization of TPC gas by particles originating from neutrino interaction
- Drift of ionization electrons towards anode plane thanks to electric field
- Reconstruction of the track trajectory thanks to the charge deposits on the anode plane



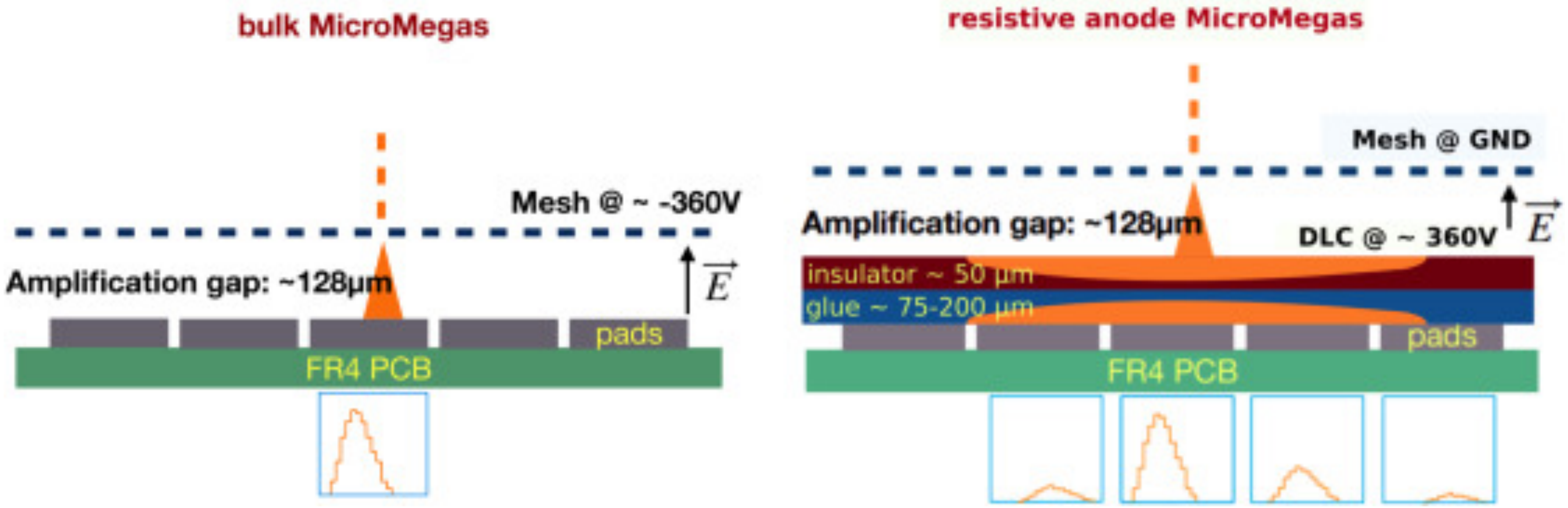


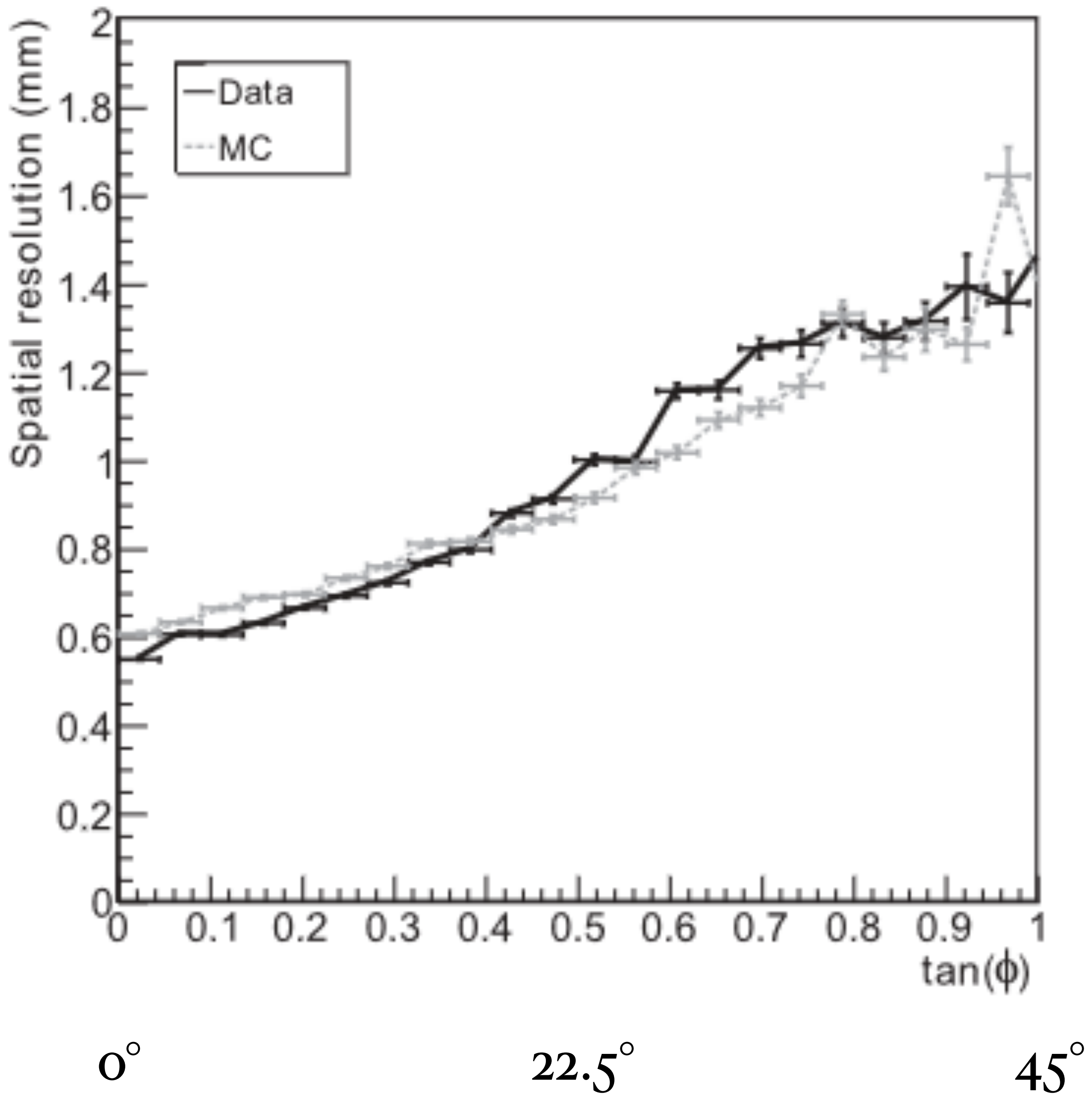
The Resistive Micromegas technology

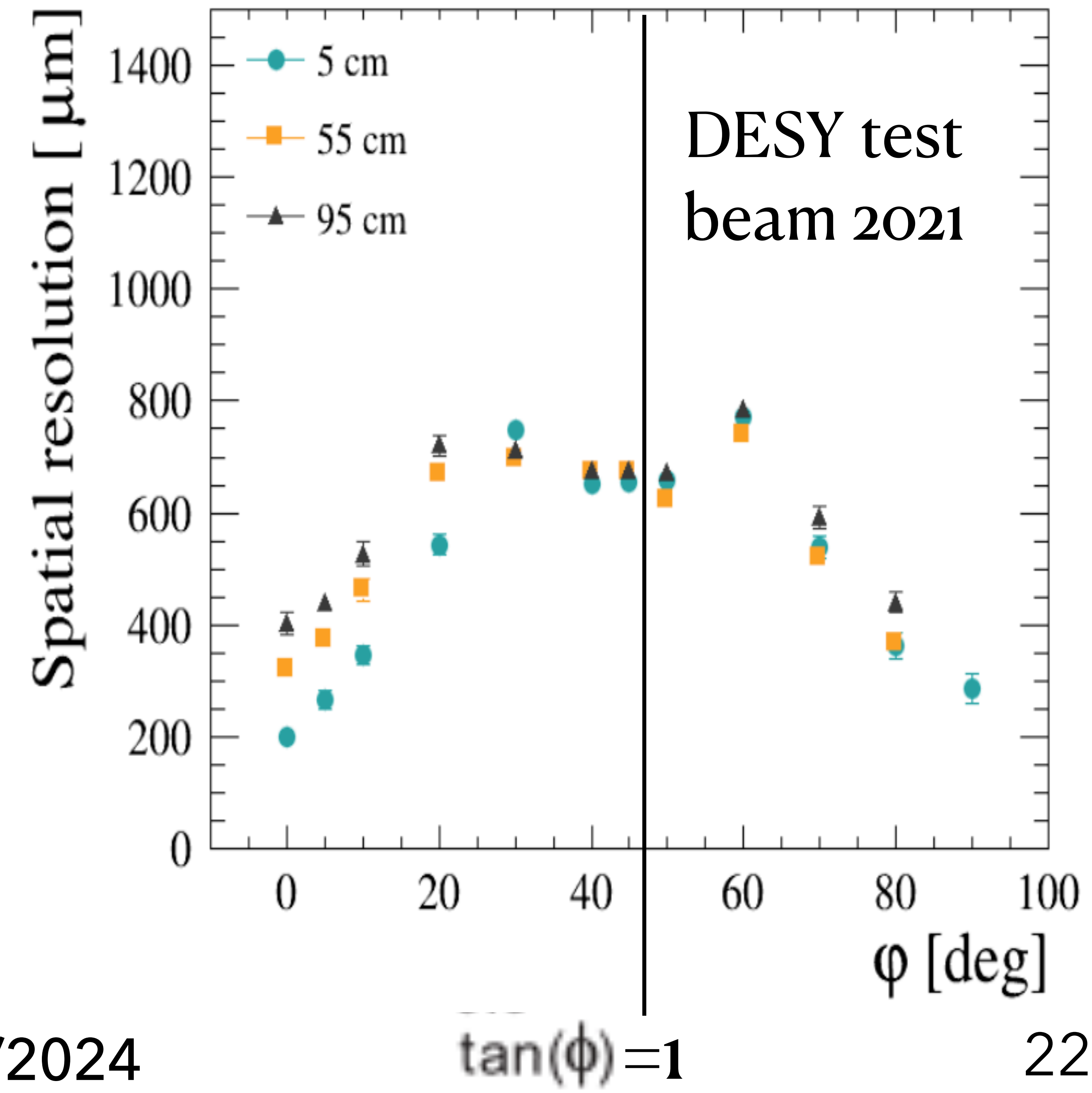
- Use layers of insulator and glue in order to spread the charge on the neighbor pads following a 2D gaussian function, the Dixit formula:

$$\rho(\vec{r},t) = \frac{RC}{4\pi t} \times \exp\left(-\frac{r^2RC}{4t}\right)$$

- Much more precise information of track position inside the leading pad
- Spatial resolution reduced from $\simeq [0.6,1.6]$ mm to $\simeq [0.2,0.8]$ mm

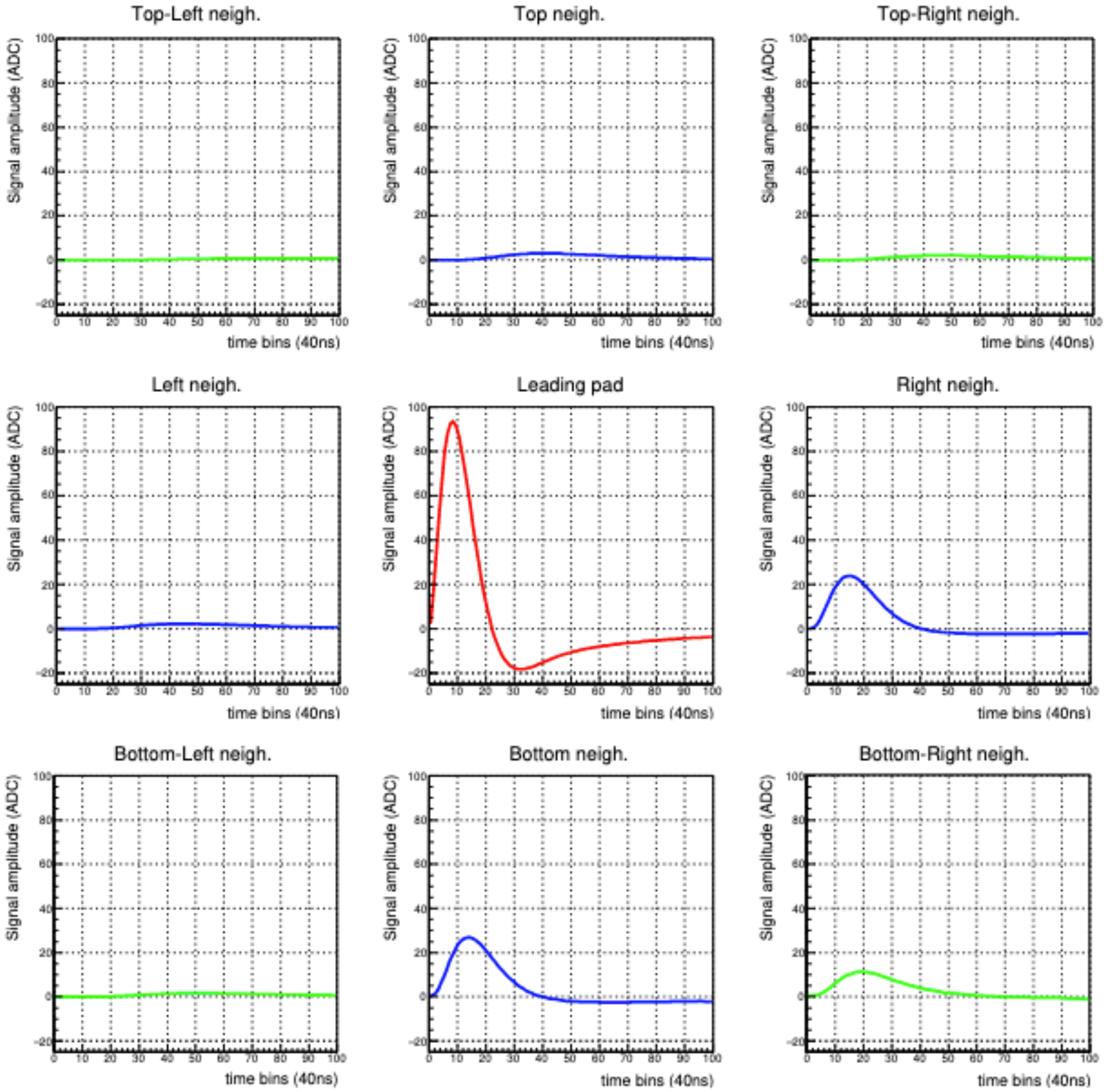


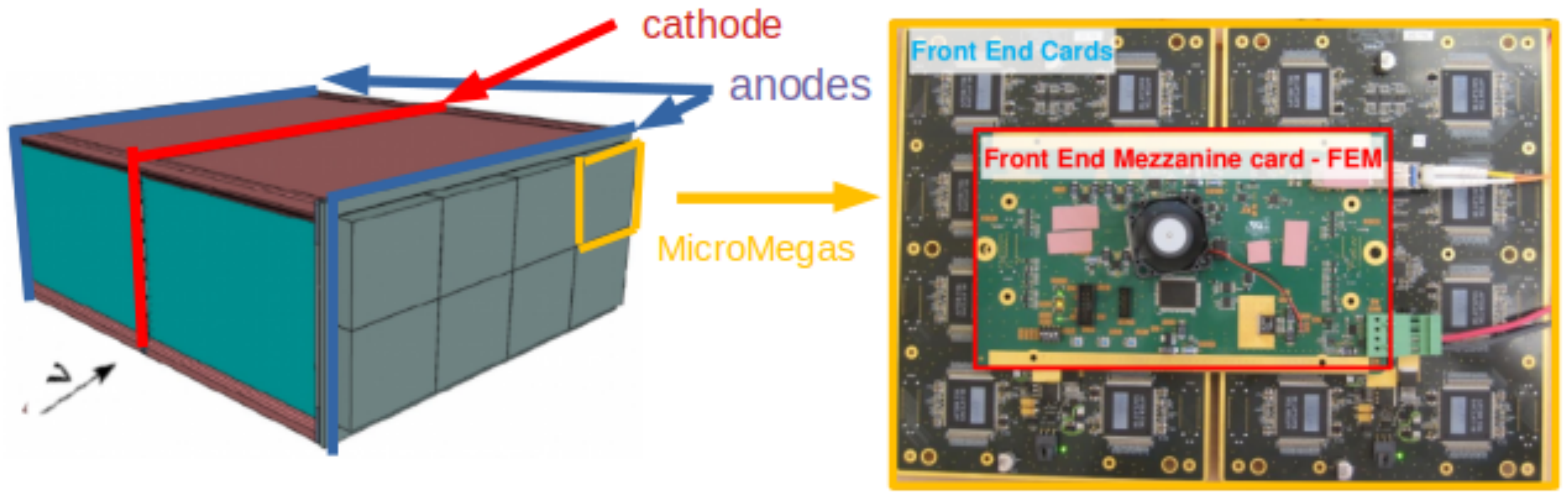




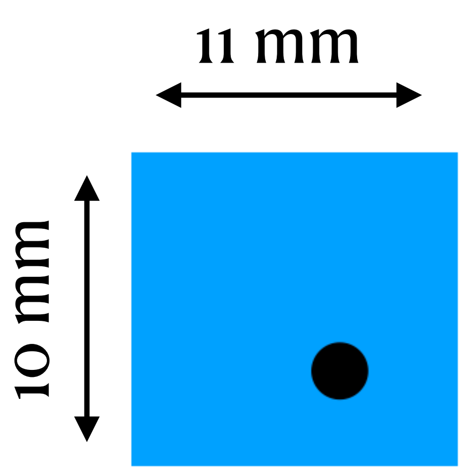
Waveforms

Waveforms: $\frac{dQ}{dt} * R$ (where R is the electronic response)

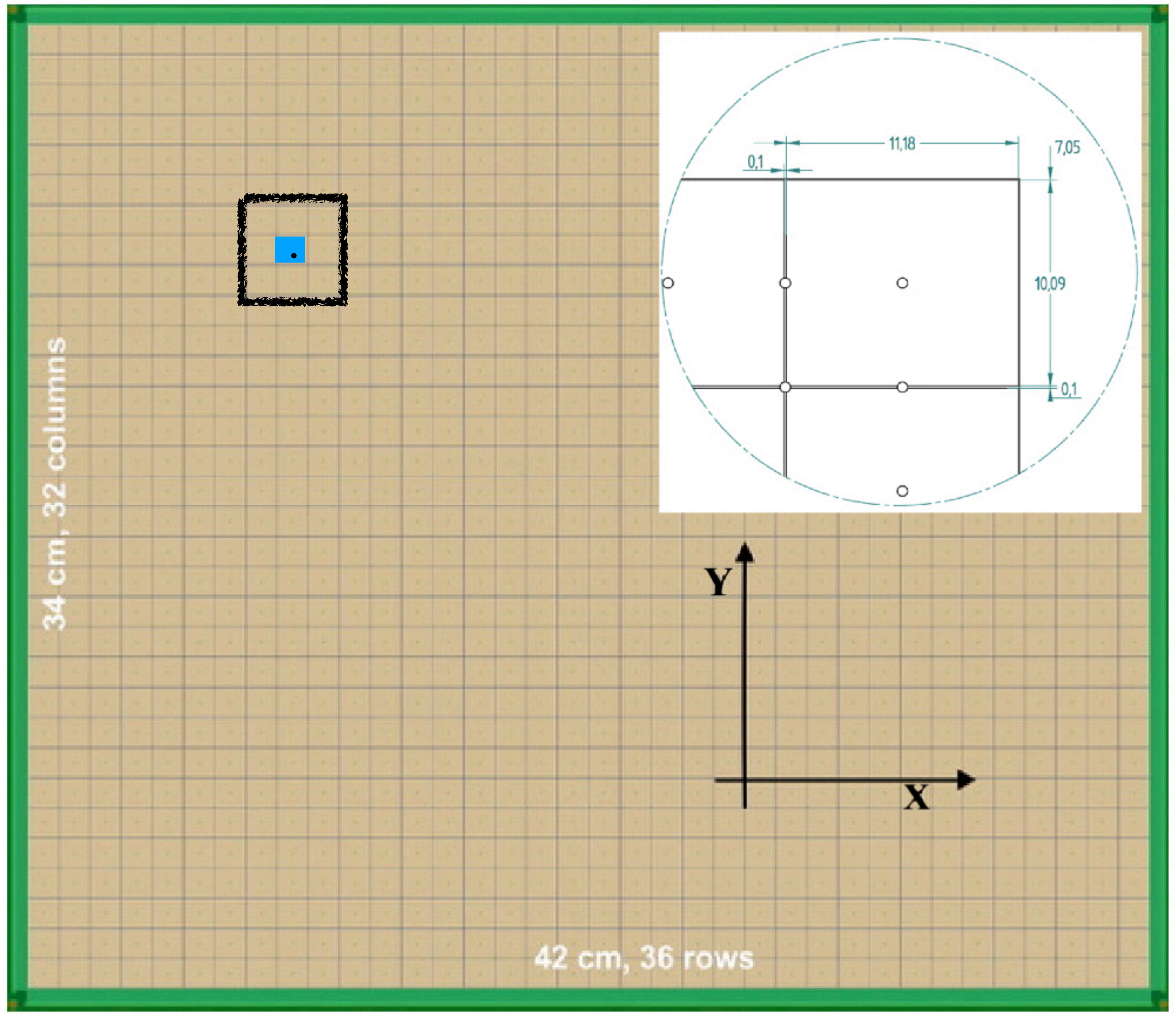




ERAM (Encapsulated Resistive Anode Micromegas)

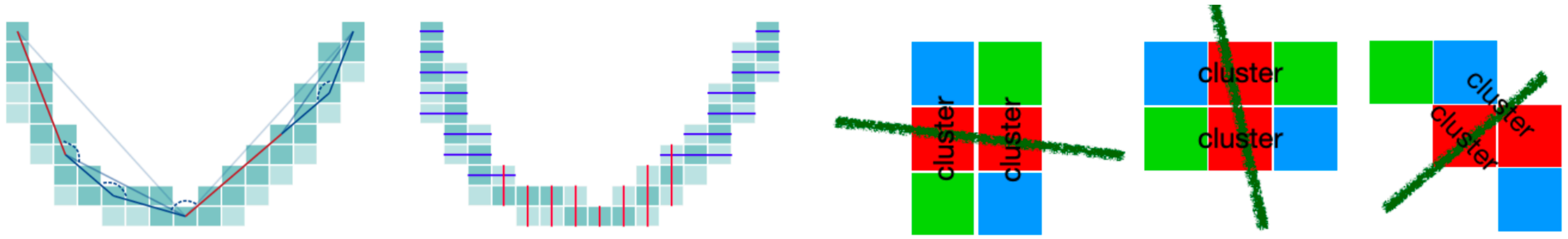


Position of charge deposit in the leading pad

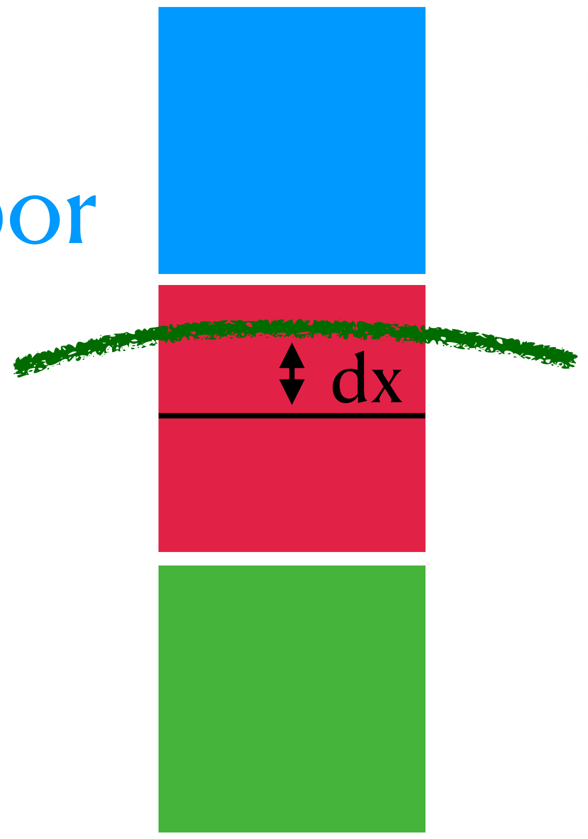


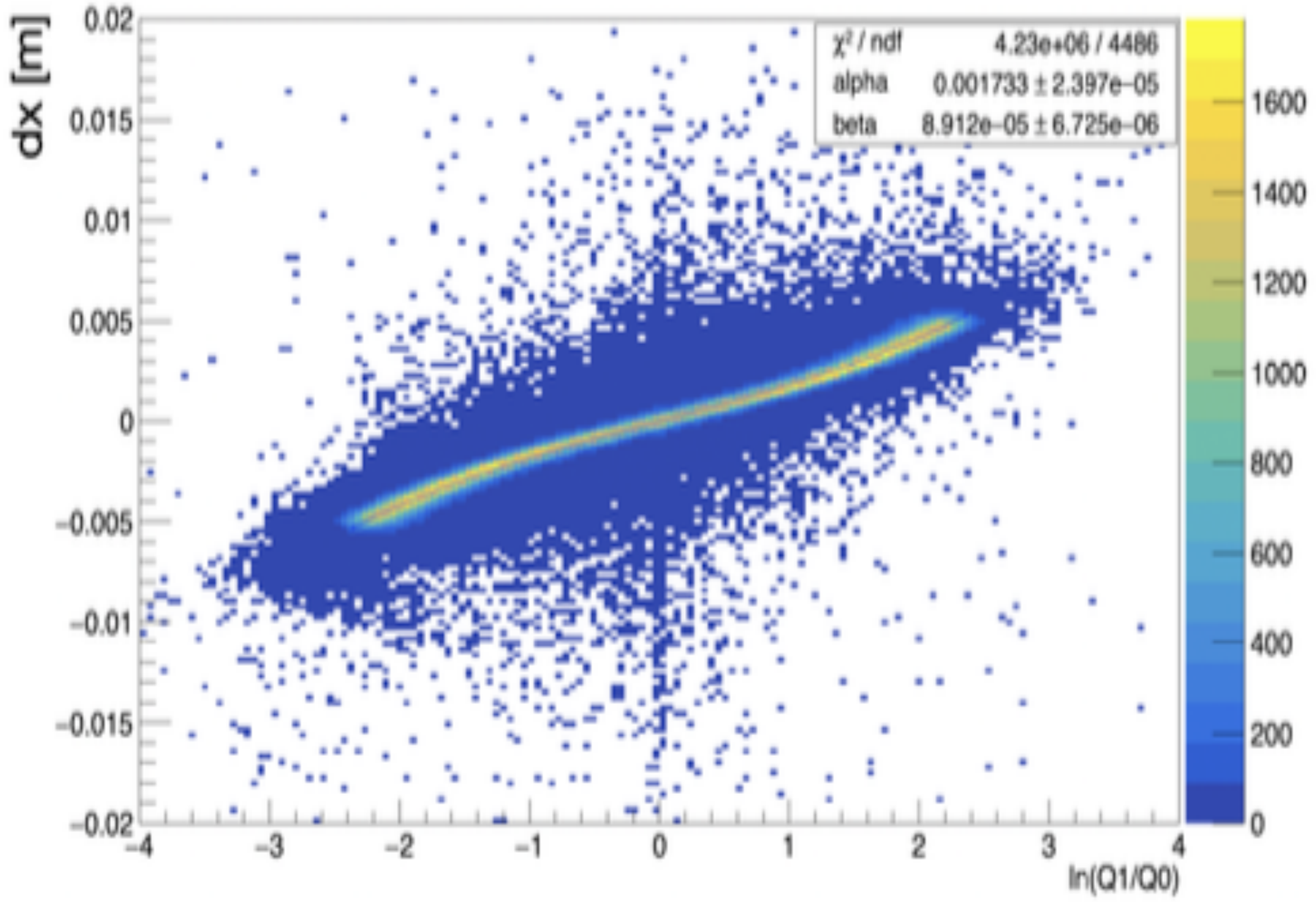
Reconstruction algorithm: logQ method

- Pattern recognition (recognize pieces of track)
- Merge fit (merge pieces of tracks between ERAMs)
- Clusters (groups of 2-4 pads perpendicular to the track)

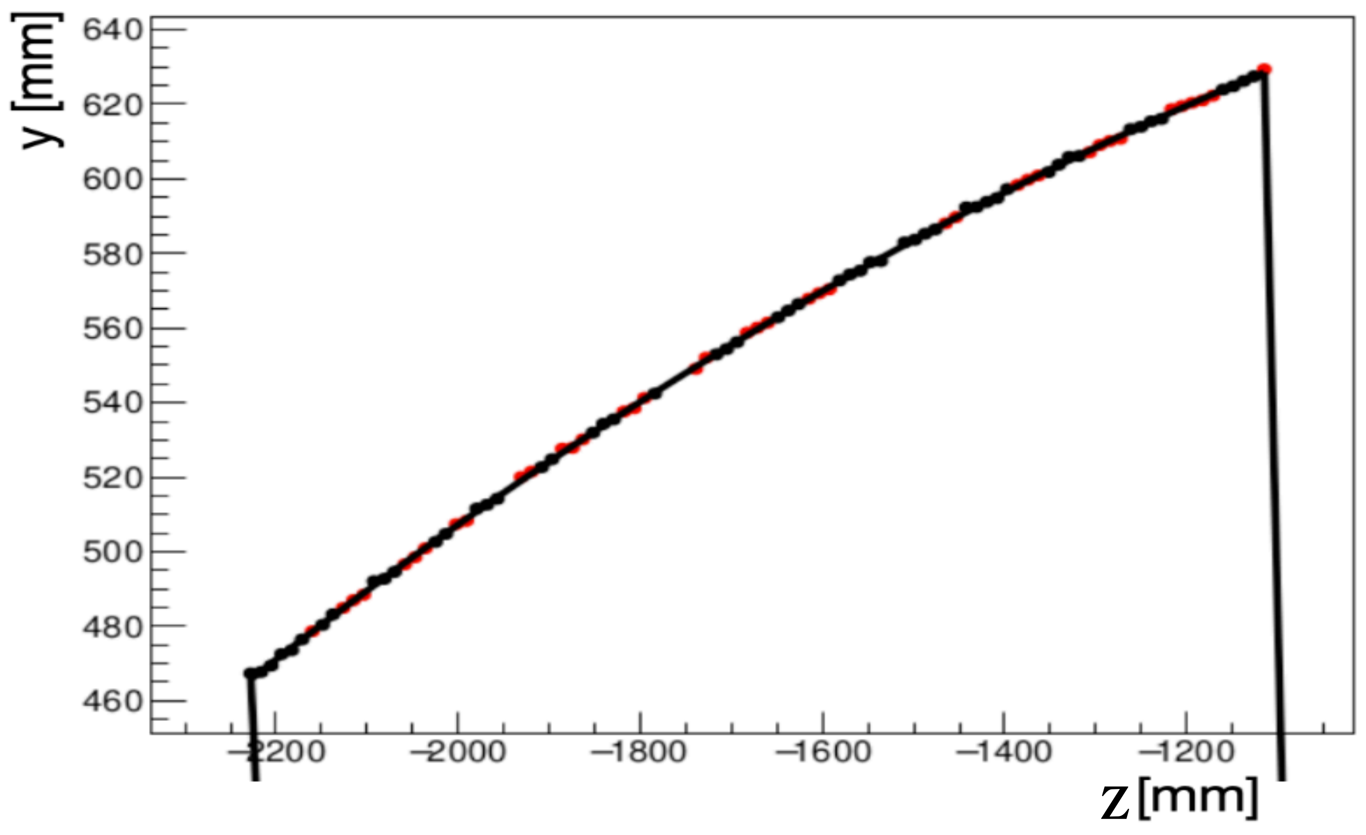


- For each cluster:
  - Look at the maximum of the waveform in the leading pad, first neighbor and, if possible second neighbor
  - Those maxima of waveforms are called respectively Q_0, Q_1, Q_2
  - Compute position of the track in the leading pad using $\ln\left(\frac{Q_1}{Q_0}\right)$ or $\ln\left(\frac{Q_2}{Q_1}\right)$





- Fit reconstructed points with a circle or parabola:
  - Get curvature to reconstruct momentum
  - Combine it with dEdx to identify the particle type



Reconstruction algorithm: Full Waveform fit

- New algorithm proposed by Pierre Billoir that don't need clusters

1. Use all the track hits (Qmax values) to define a (**u,v**) working frame

2. Put point charges (Q value is a free parameter) on the **v** axis, separated by a length Δv (5~10 mm)

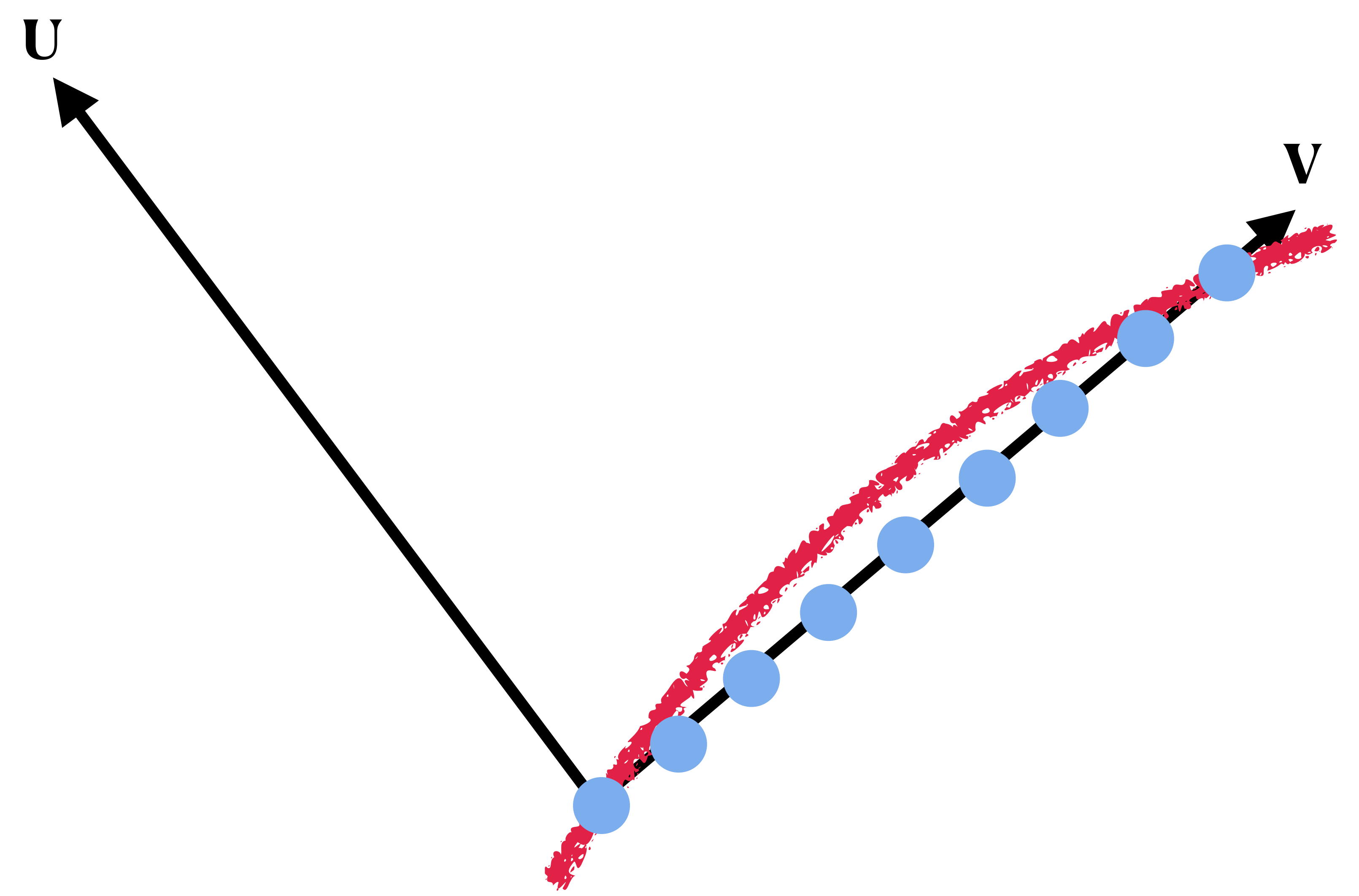
3. Use the Dixit formula to predict the waveform engendered by those point charges in the surrounding pads

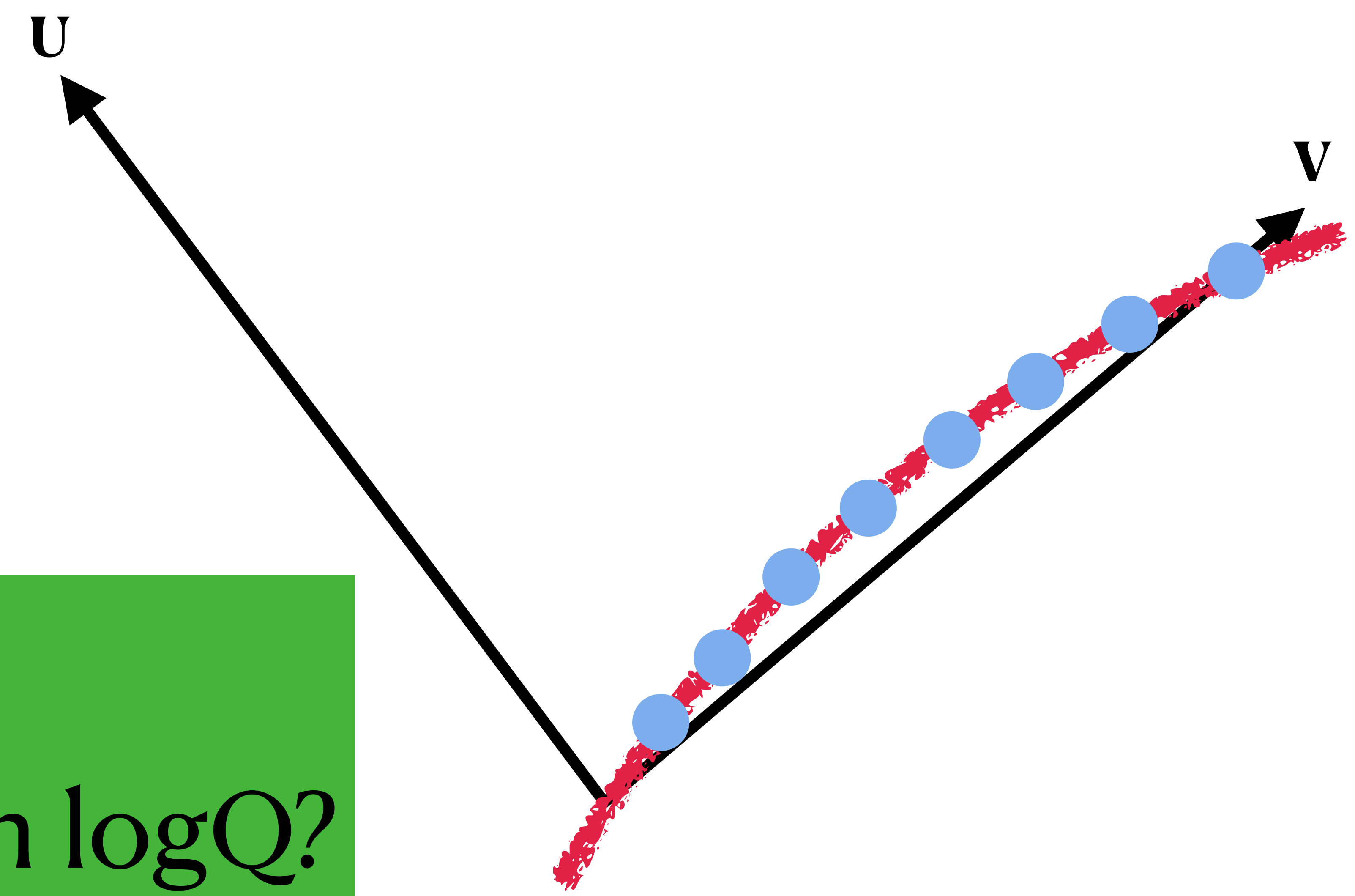
4. For a fixed v, move all the points along the **u** axis to minimize the χ^2 between observed waveforms and dixit-predicted ones:

$$\chi^2 = \sum_{i(pad)} \sum_{j(timebin)} \frac{(Q_{i,j}^{obs} - Q_{i,j}^{Dixit})^2}{\sigma_{i,j}^2}$$, using Runge-Kutta method

$(u_0, du/dv, q/p, t_0, dt/dv)$

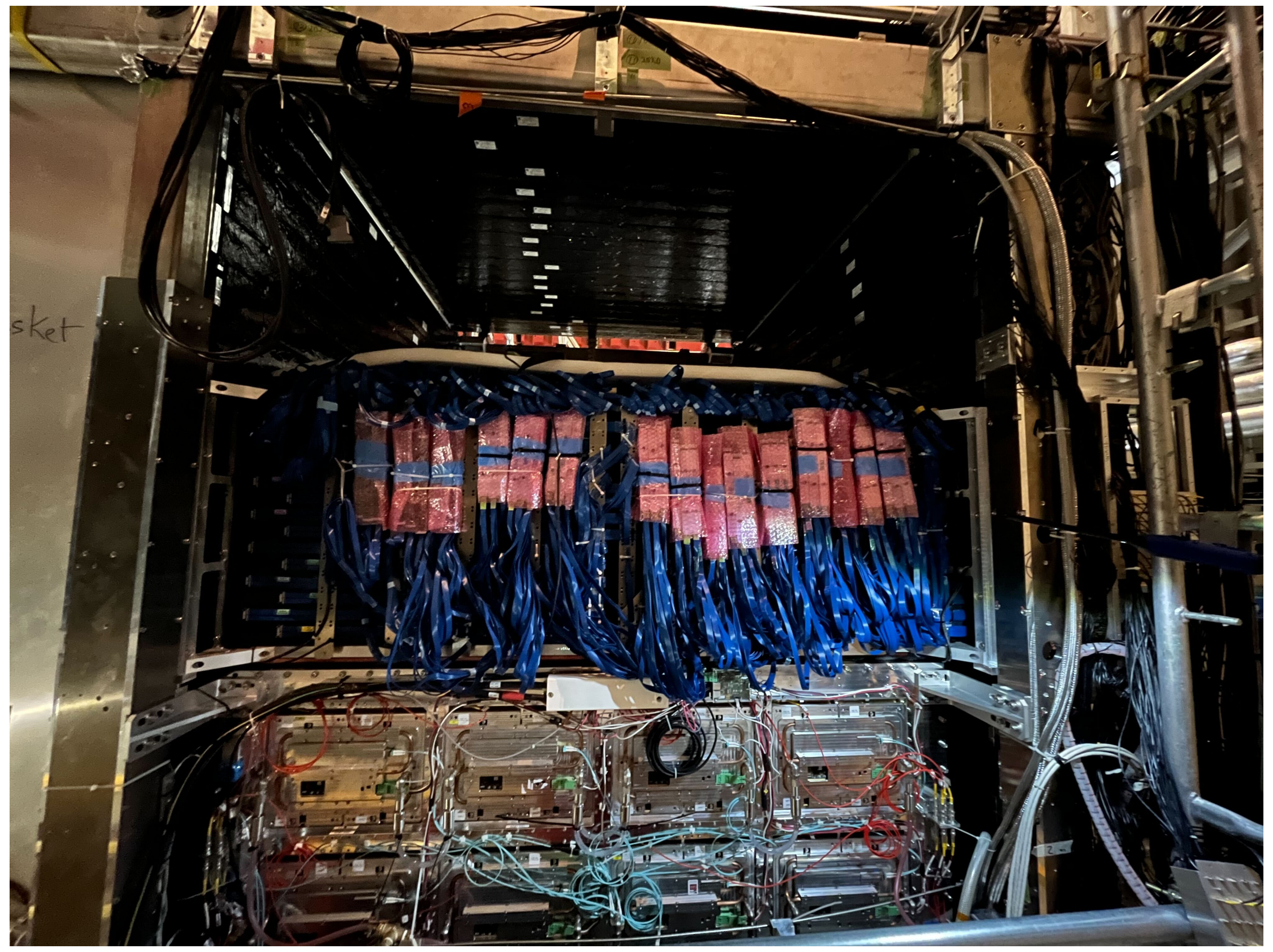
To be simplified?
Plots showing it's better than logQ?

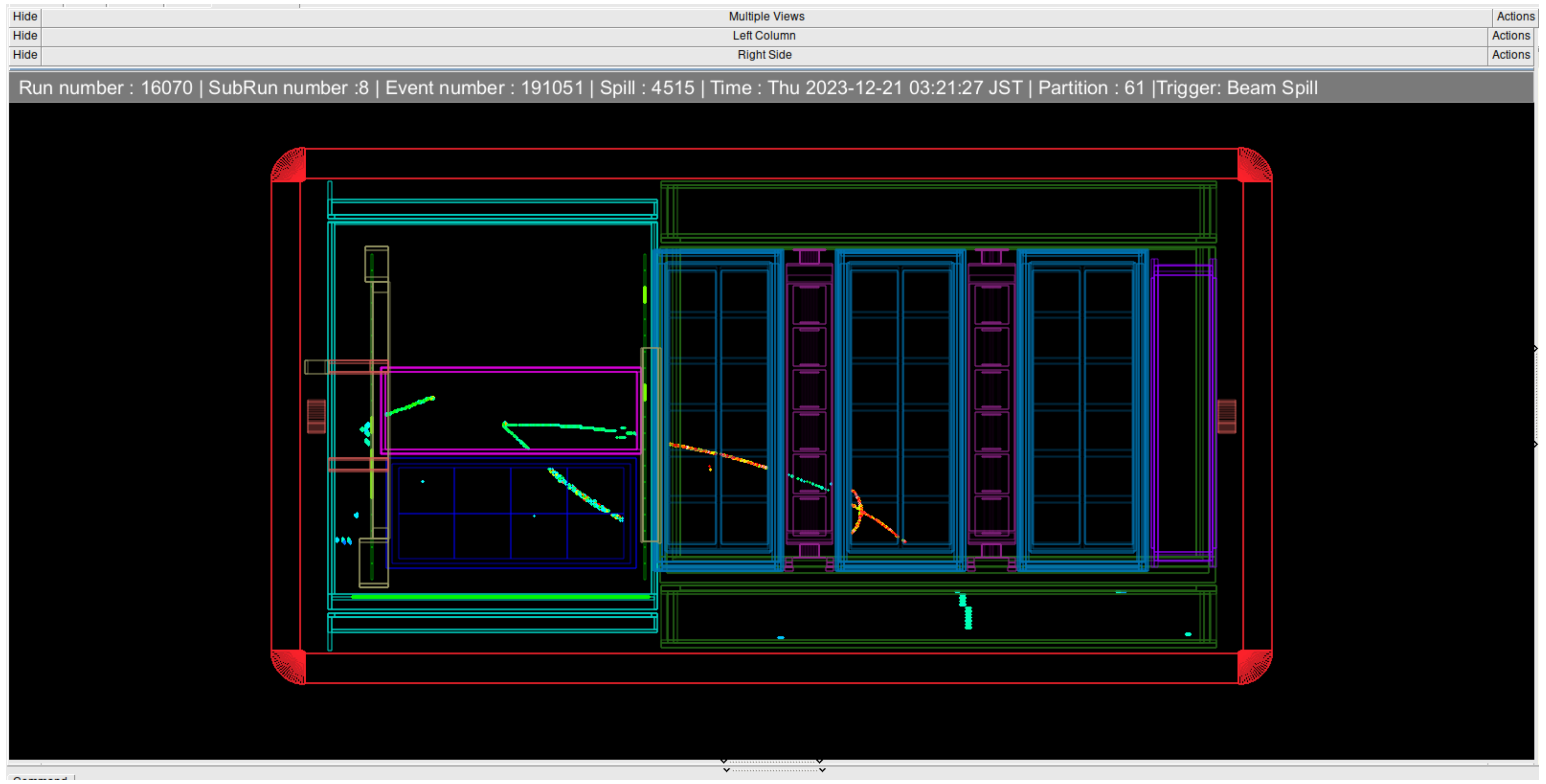


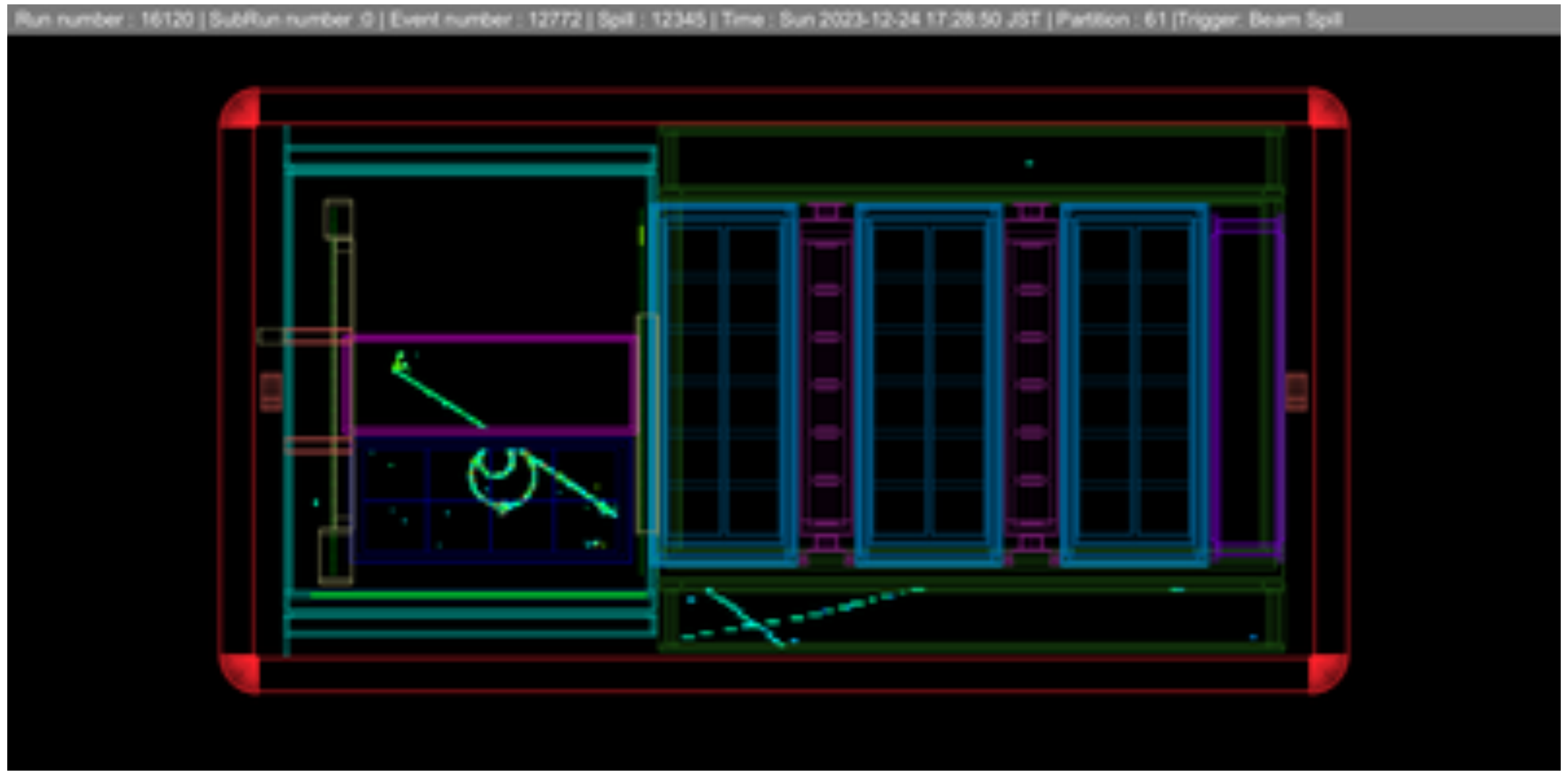


T2K-II: it is truly happening!

- SFGD, TOFs and bottom HA-TPC were installed end of 2023
- First data were taken!

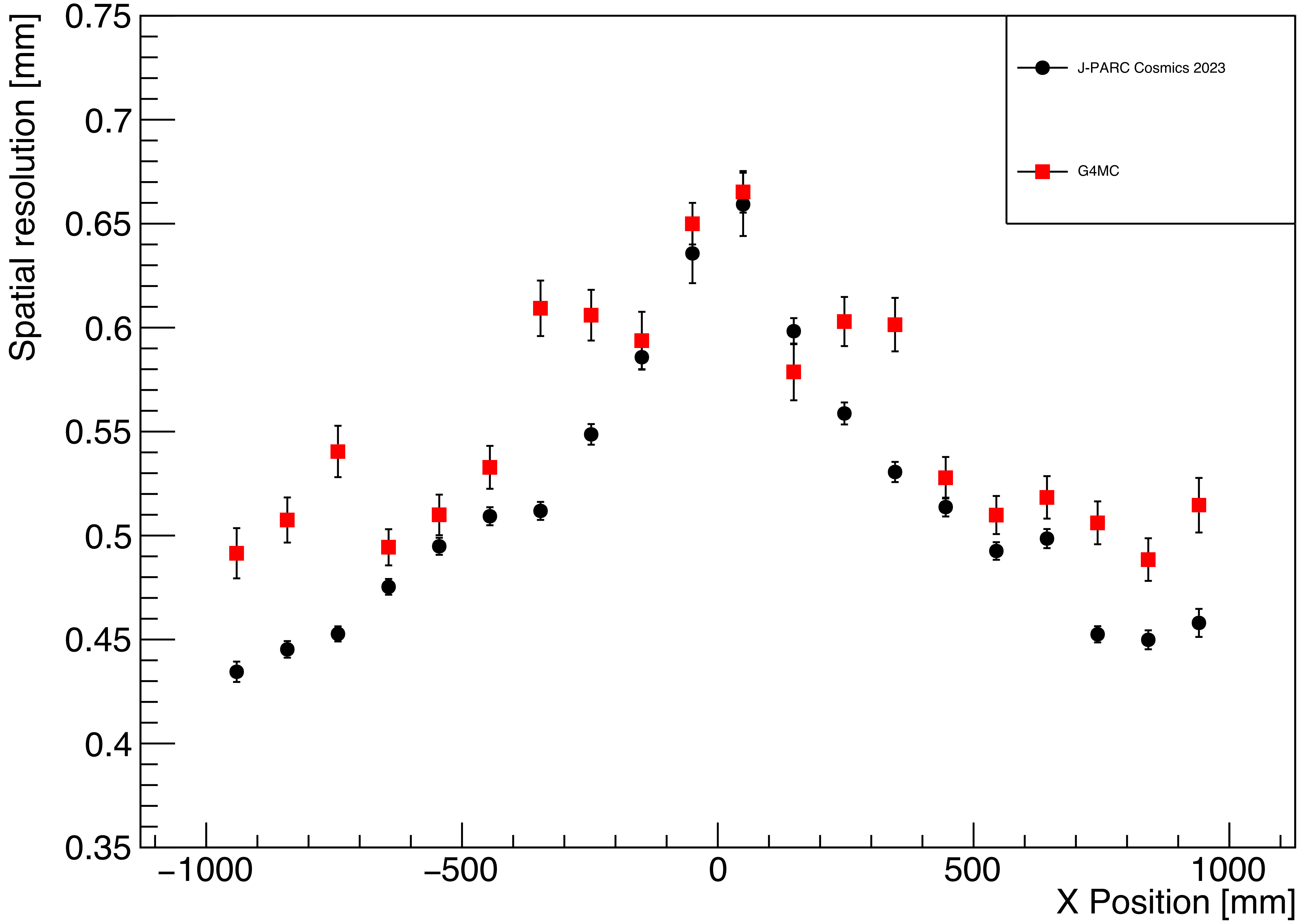


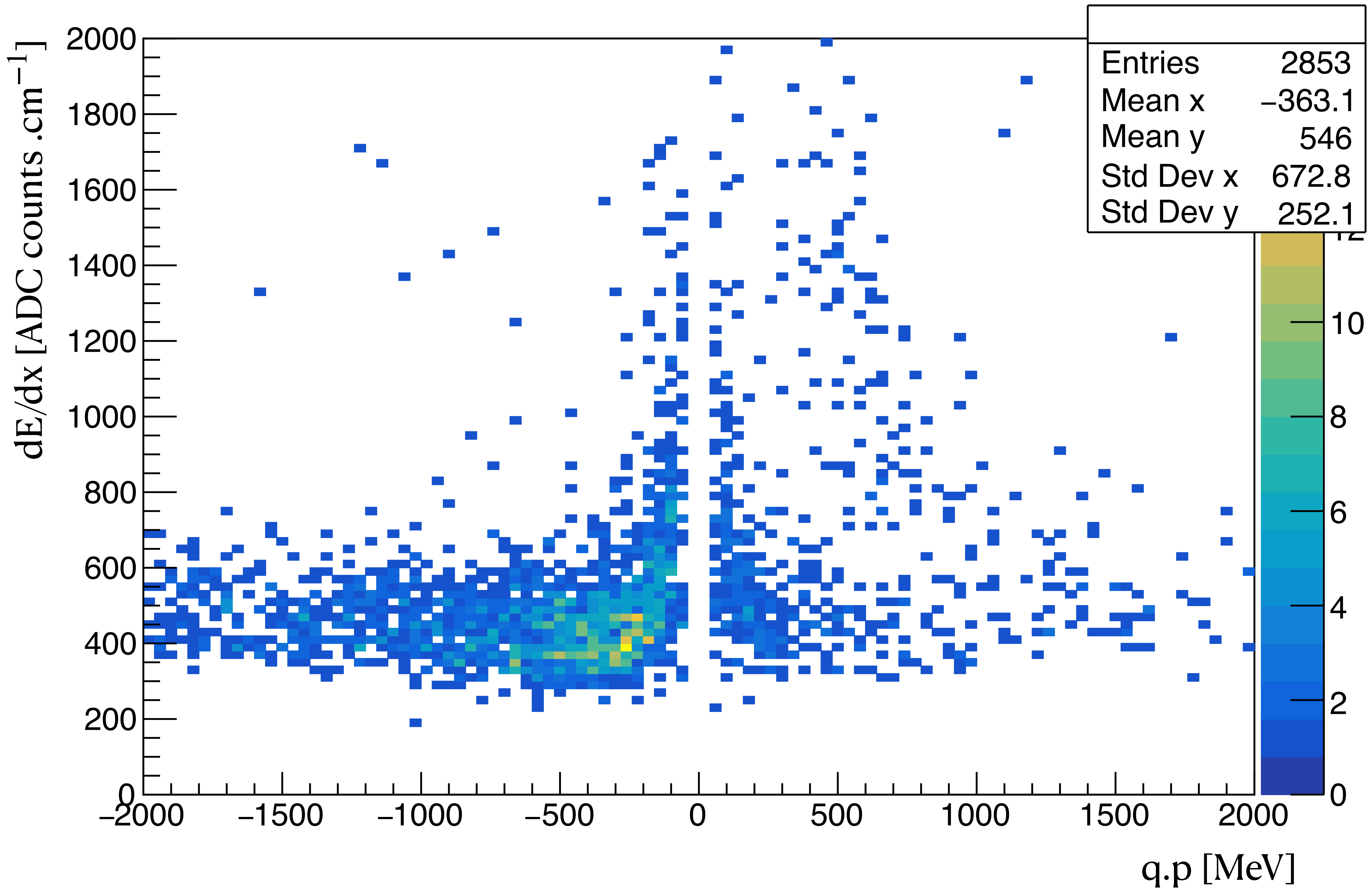




Analysis of first data taken by upgraded ND280

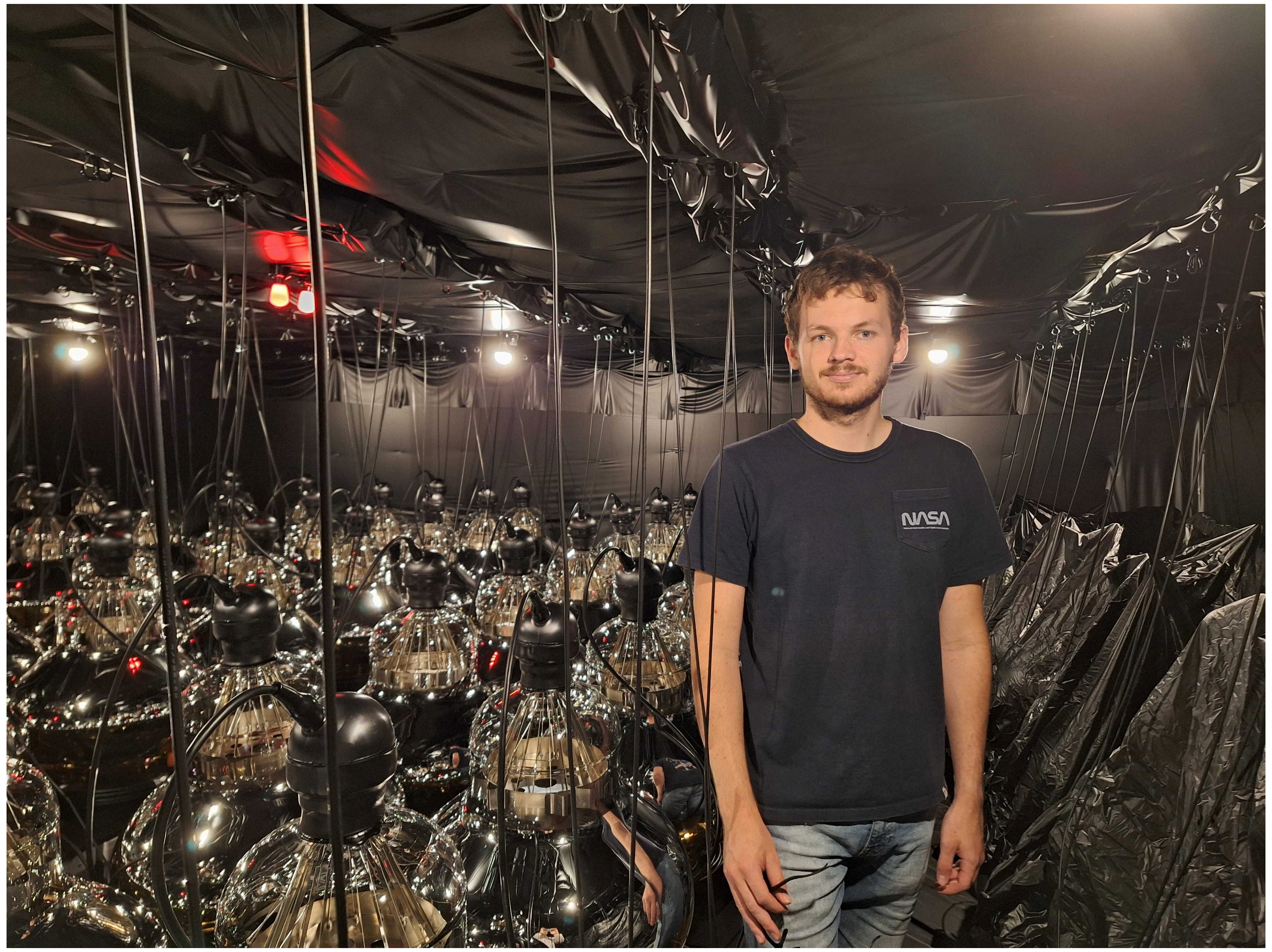
- Began to analyze real and G4MC cosmics data taken by the bottom HA-TPC at J-PARC in end of 2023
- Full reconstruction pipeline works for both real and simulated data!





Summary, ongoing activities

- Used new Near Detector Fitter (GUNDAM) to evaluate the impact of ND280 upgrade fit on our knowledge of $\nu_e/\bar{\nu}_e$ differences of cross-section in the T2K-II and Hyper-Kamiokande era
- Implementation of 2 new HA-TPC reconstruction algorithms in the official ND280 Software
- Use these algorithms to analyse simulated but also real data



HyperKamiokande PMT inspection and dark noise measurement