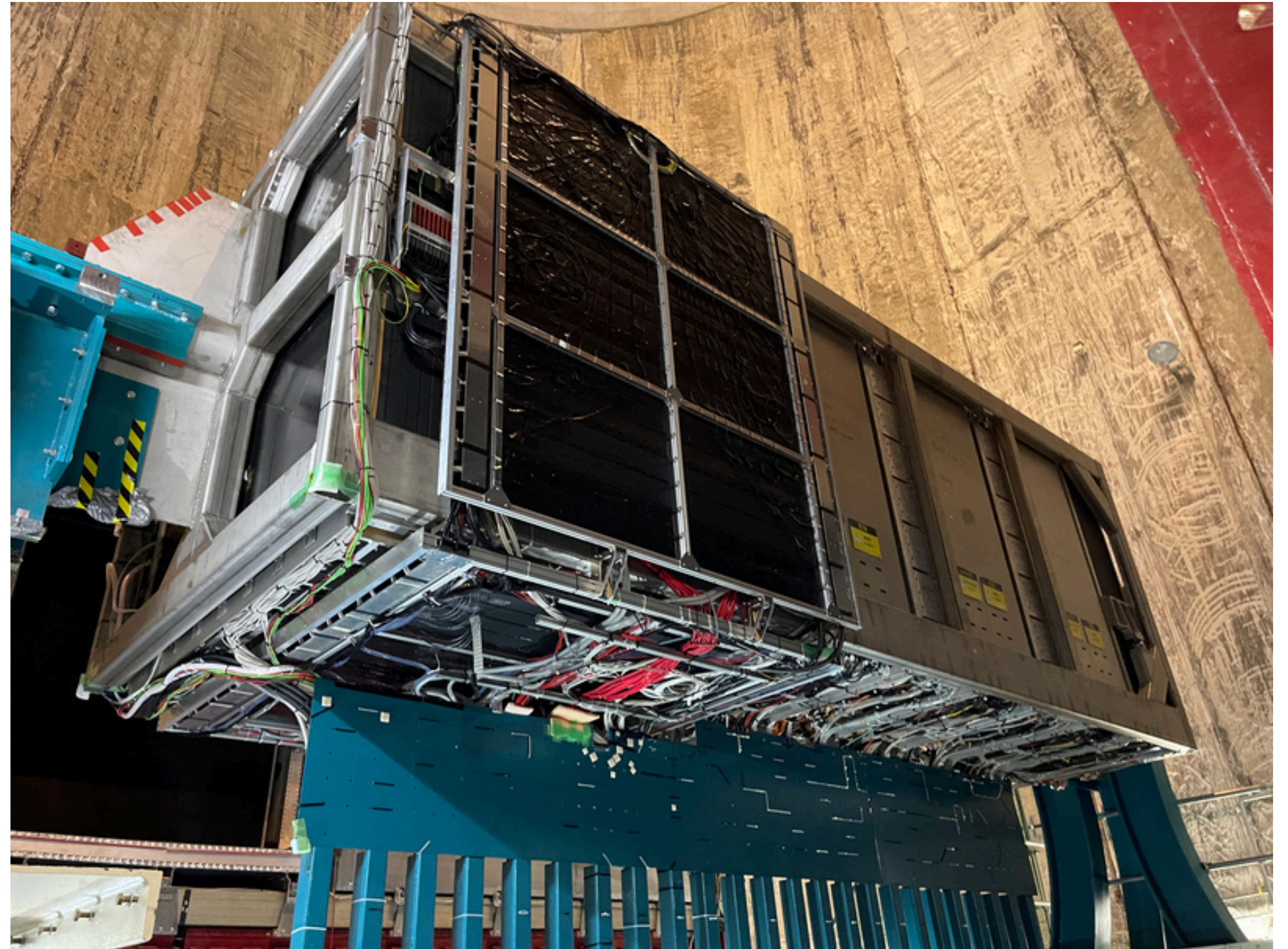


# The upgrade of the ND280 near detector of T2K

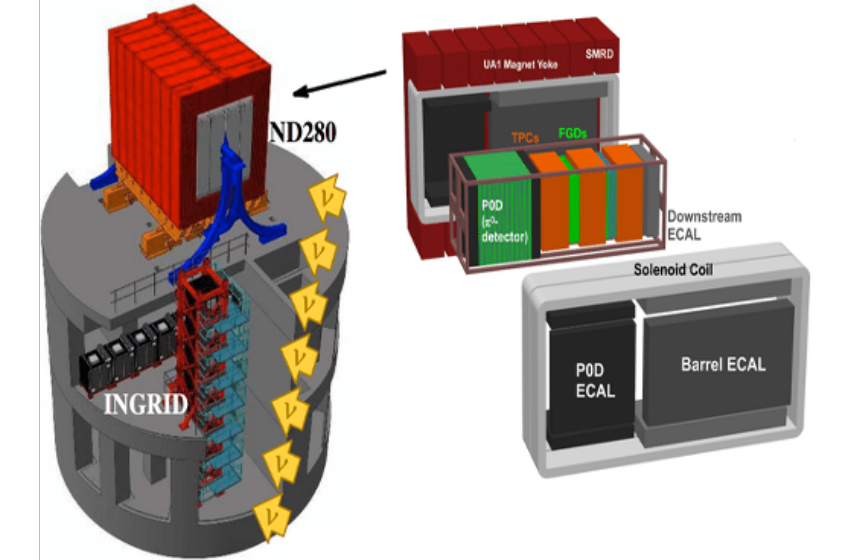
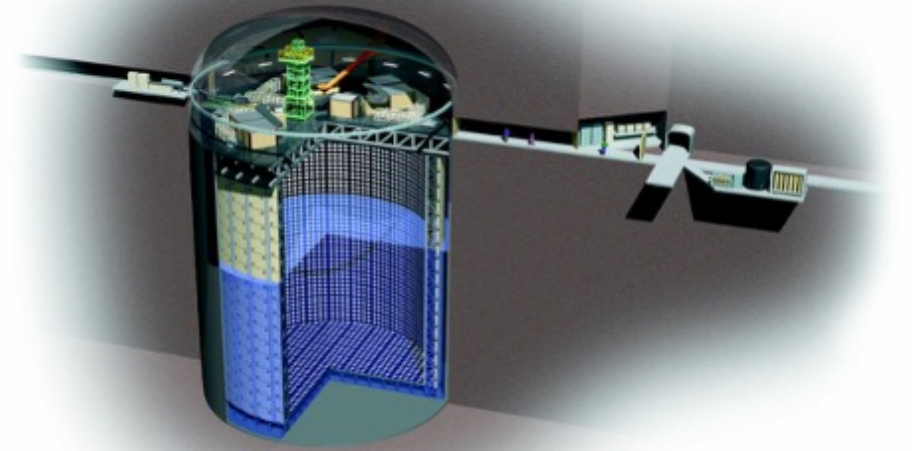


# The **Upgrade** of the **ND280 near detector** of **T2K's** overview

---

- What is **T2K** (and a Long Baseline Neutrino experiment)
- T2K goals and status
  - Neutrino oscillations
  - Neutrinos interactions
- What is the **ND280 Near Detector**
  - What's its impact on the oscillation analysis
  - Why we needed an upgrade? Limitations and improvements on its physics potential
- The **ND280 Upgrade**
  - Installation, integration and commissioning
  - First performances

# Tokai - 2 - Kamioka (T2K) experiment



Long Baseline (LBL) Neutrino Experiment, studying Neutrino Oscillations

- High intensity  $\sim 600$  MeV  $\nu_\mu$  or  $\bar{\nu}_\mu$  beam produced at J-PARC (Tokai)
- Neutrinos detected at the **Near Detectors** and at the **Far Detector (Super-Kamiokande)**

# Neutrino Oscillation

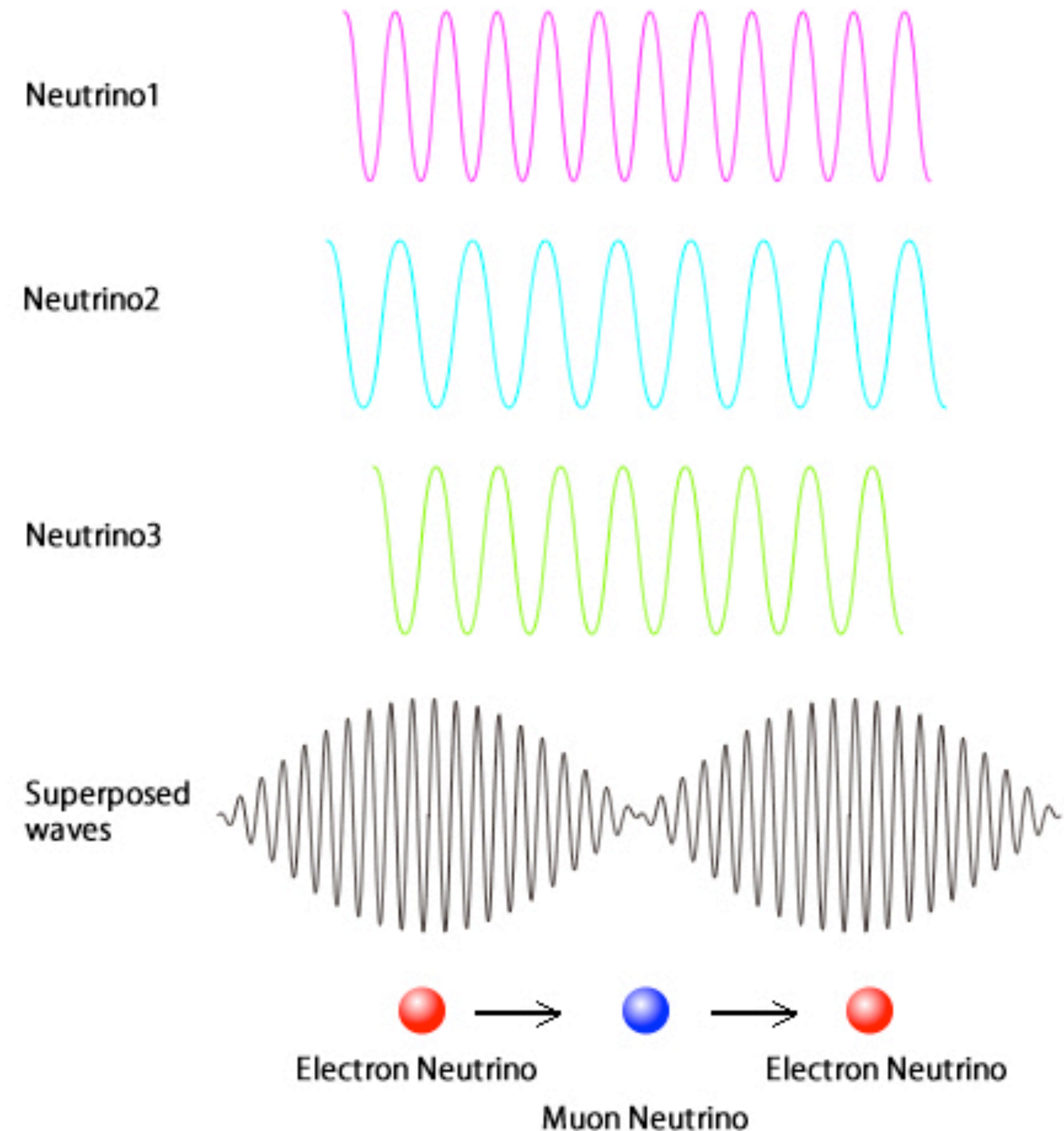
- Quantum interference phenomenon
- 3 flavour eigenstate ( $\nu_e, \nu_\mu, \nu_\tau$ ) and 3 mass eigenstate ( $\nu_1, \nu_2, \nu_3$ )

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour  
eigenstate

PMNS matrix  
(Pontecorvo-  
Maki-  
Nakagawa -  
Sakata)

Mass  
eigenstate



# Neutrino Oscillation

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospherics and LBL  
 $\theta_{23} \sim 45^\circ$   
 $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3} \text{ eV}^2$

Reactors  
 $\theta_{13} \sim 10^\circ$   
 LBL  $\theta_{13}$  and  $\delta_{CP}$

Solar and reactors  
 $\theta_{12} \sim 35^\circ$   
 $\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{ eV}^2$

Neutrino oscillation can be described knowing 5 parameters:

- 3 angles:  $\theta_{12}, \theta_{23}, \theta_{13}$
- 2 mass differences:  $\Delta m^2_{12}, \Delta m^2_{32}$
- 1 phase :  $\delta_{CP}$

*Quite precise measurements on almost all parameters BUT ..*

# Neutrino Oscillation

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

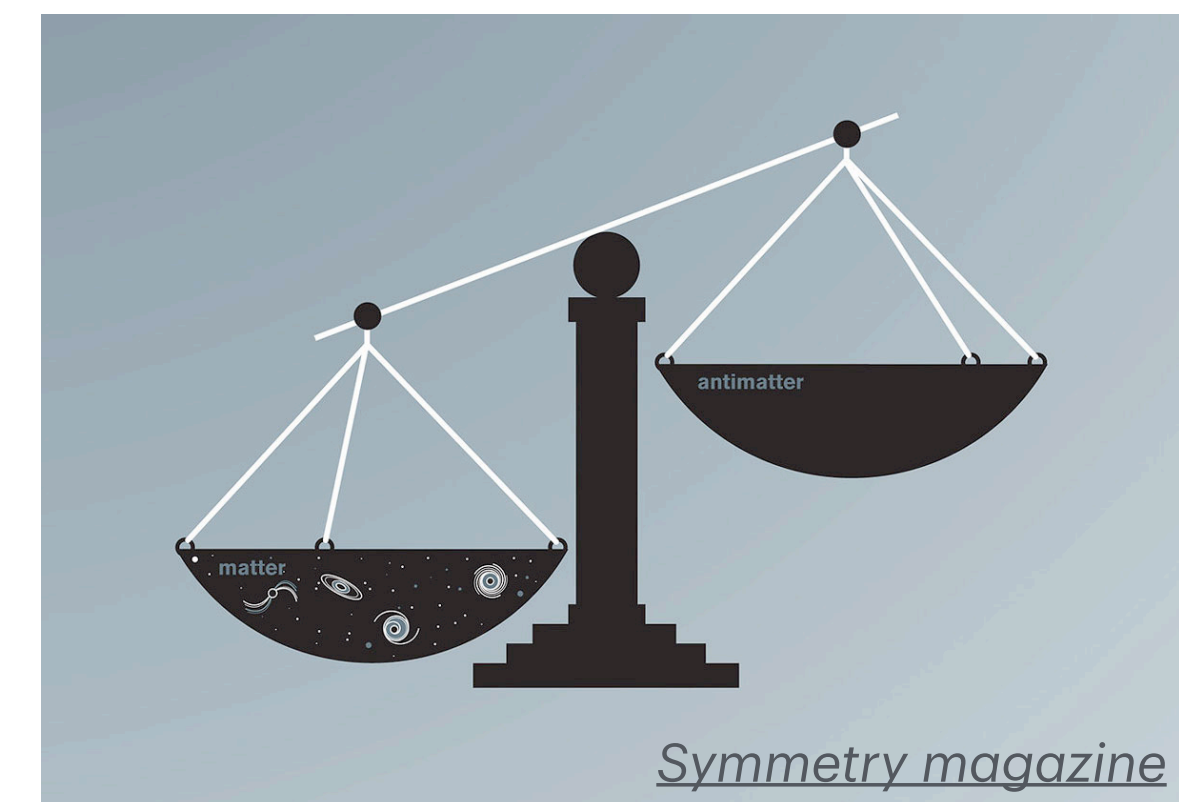
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Still unanswered questions:

- Is  $\delta_{CP} = 0$  or is CP symmetry broken?  $\rightarrow \delta_{CP}$  value



# Neutrino Oscillation

## PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

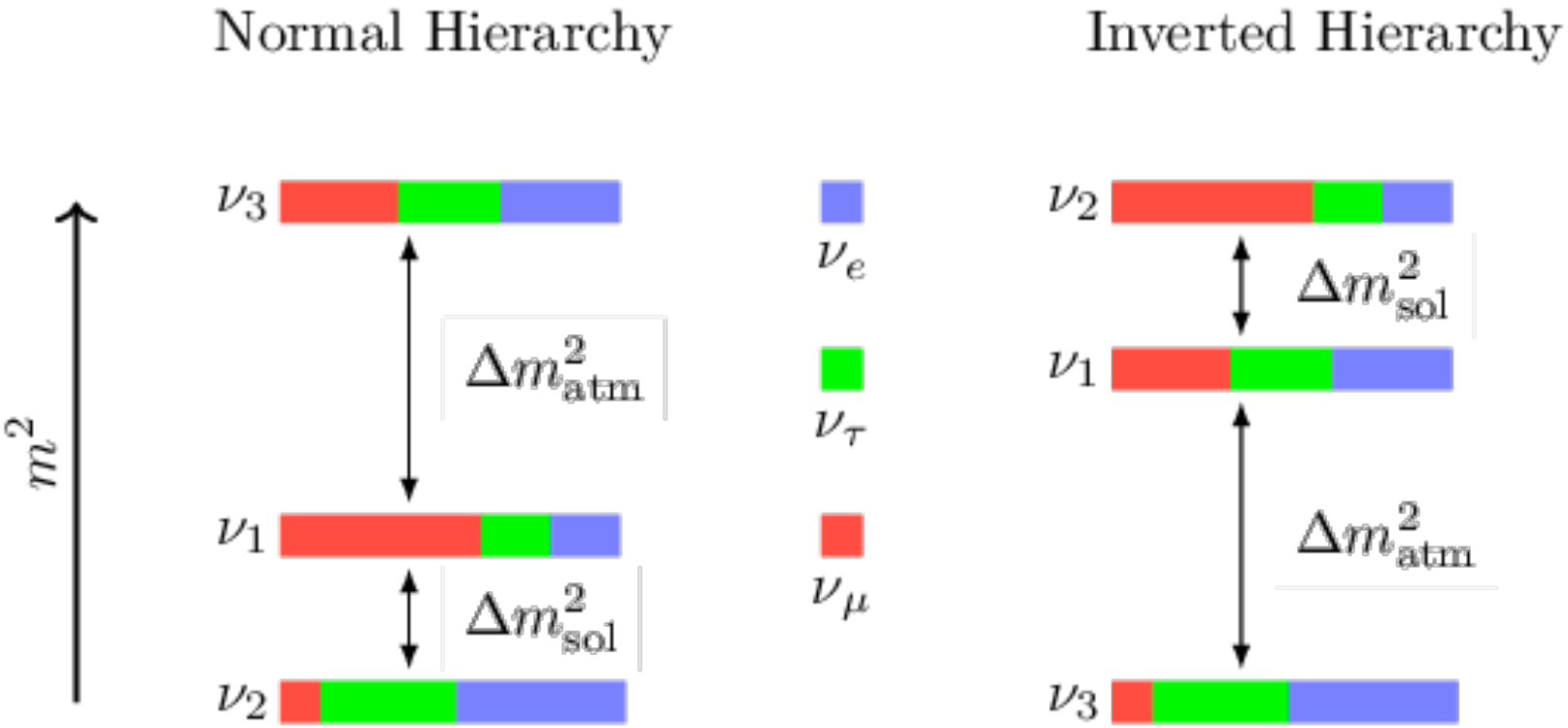
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### Still unanswered questions:

- Is  $\delta_{CP} = 0$  or is CP symmetry broken?  $\rightarrow \delta_{CP}$  value
- What is the sign of  $\Delta m^2_{32}$ ?  $\rightarrow$  Neutrino Ordering/Hierarchy



# Neutrino Oscillation

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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Still unanswered questions:

- Is  $\delta_{CP} = 0$  or is CP symmetry broken?  $\rightarrow$   $\delta_{CP}$  value
- What is the sign of  $\Delta m^2_{32}$ ?  $\rightarrow$  Neutrino mass ordering/hierarchy
- $\theta_{23}$  is larger or smaller of  $45^\circ$ ?  $\rightarrow$  Determination of  $\theta_{23}$  octant

# Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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Solar and reactors  
 $\theta_{12} \sim 35^\circ$   
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Long Baseline (LBL) experiments sensitive to 5 of the PMNS parameters:

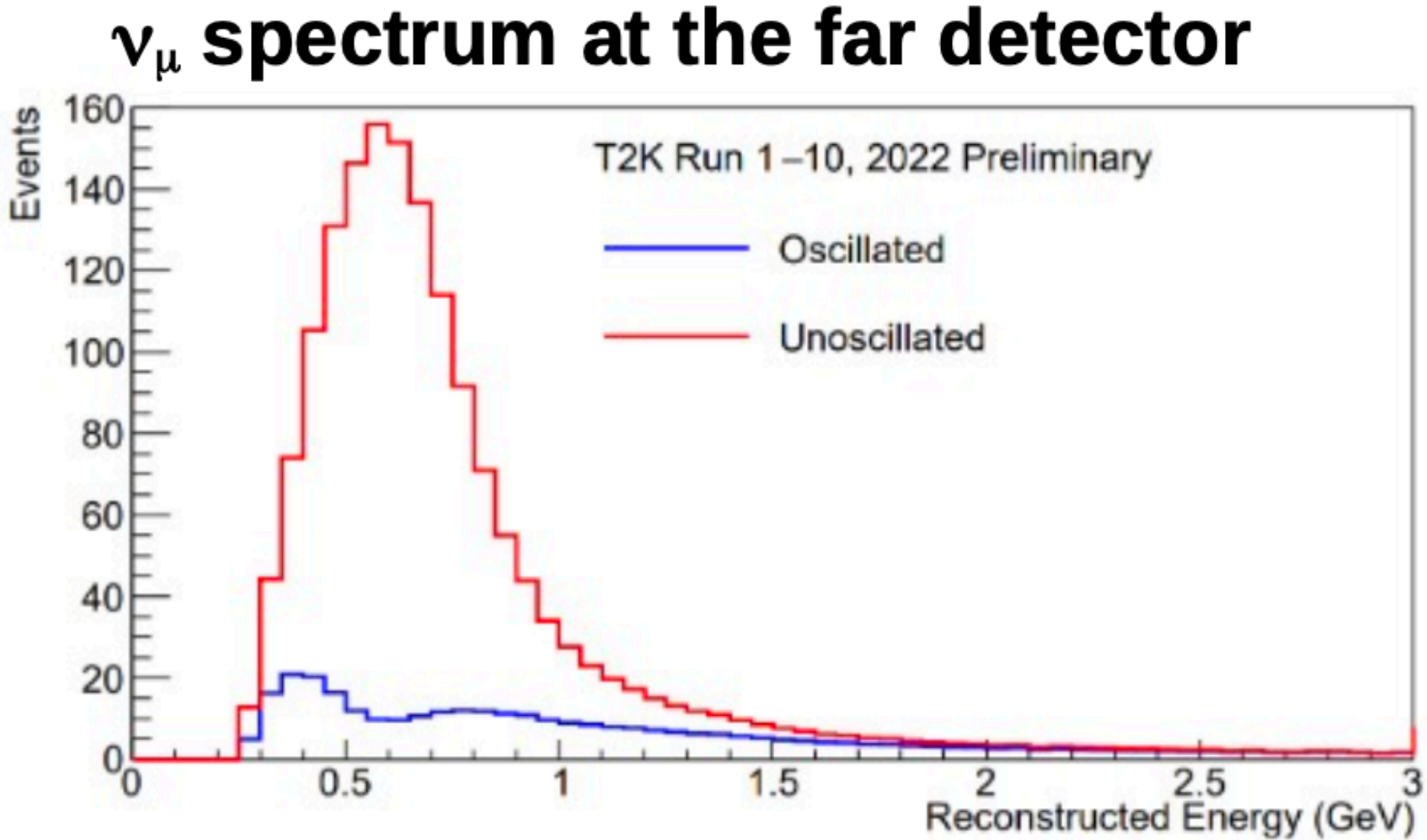
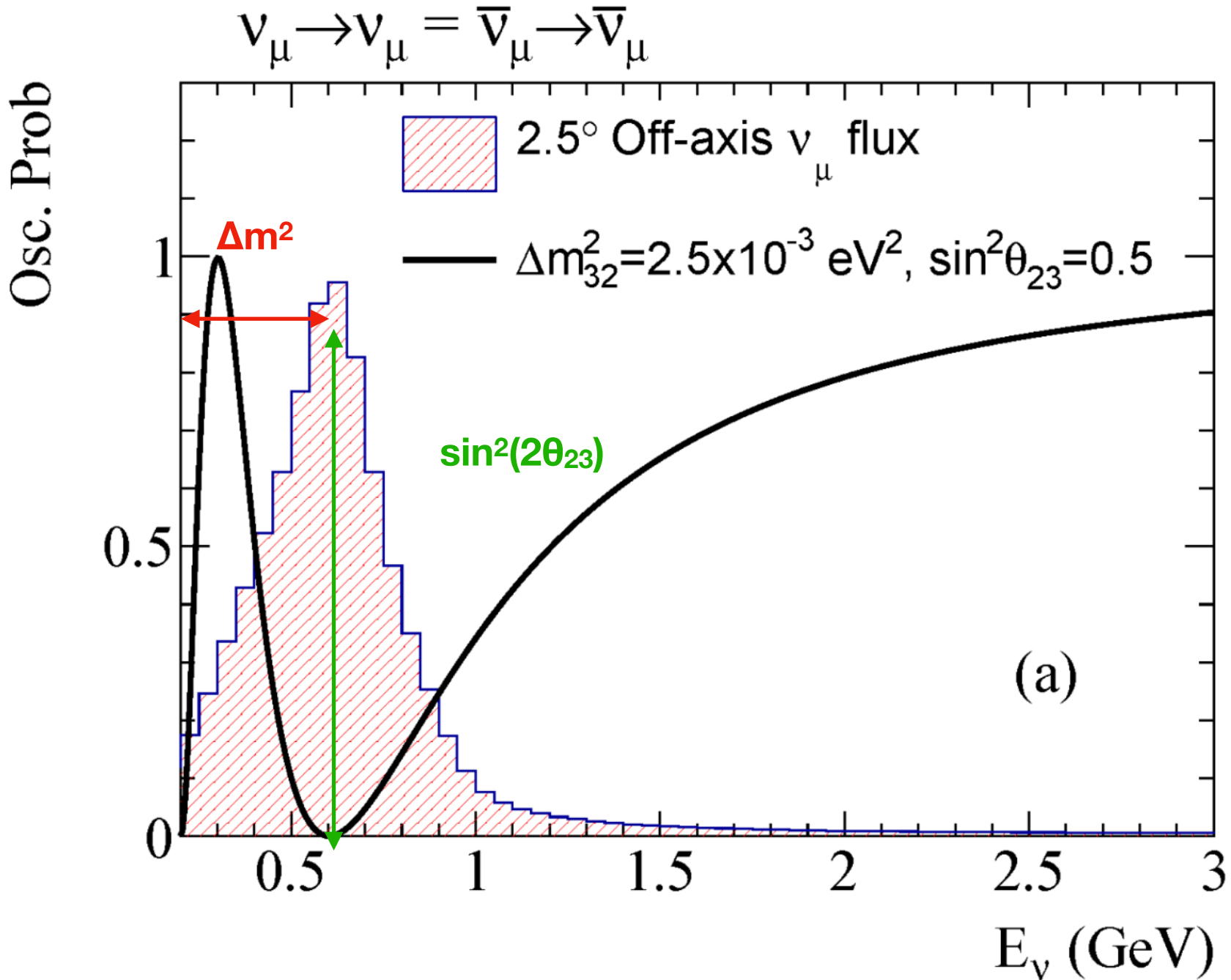
- $\theta_{23}, |\Delta m^2_{32}| \rightarrow$  LBL provides the most precise measurements of these parameters
- $\delta_{CP}$  and sign of  $\Delta m^2_{32}$  (Normal or Inverted ordering)  $\rightarrow$  still unknown BUT accessible to LBL
- $\theta_{13} \rightarrow$  dominated by reactor experiments

# T2K physics goals

## $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$

- Same oscillation probability for  $\nu$  and  $\bar{\nu}$
- Sensitive to  $|\Delta m^2_{32}|$  and to  $\sin^2(2\theta_{23}) \rightarrow$  T2K's world leading measurements
- No sensitivity to mass ordering and  $\delta_{CP}$



# T2K physics goals

## $\nu_e$ and $\bar{\nu}_e$ appearance

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}]$$

$$(\mp)\alpha \frac{J_0 \sin \delta_{CP}}{A(1-A)} \sin \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$

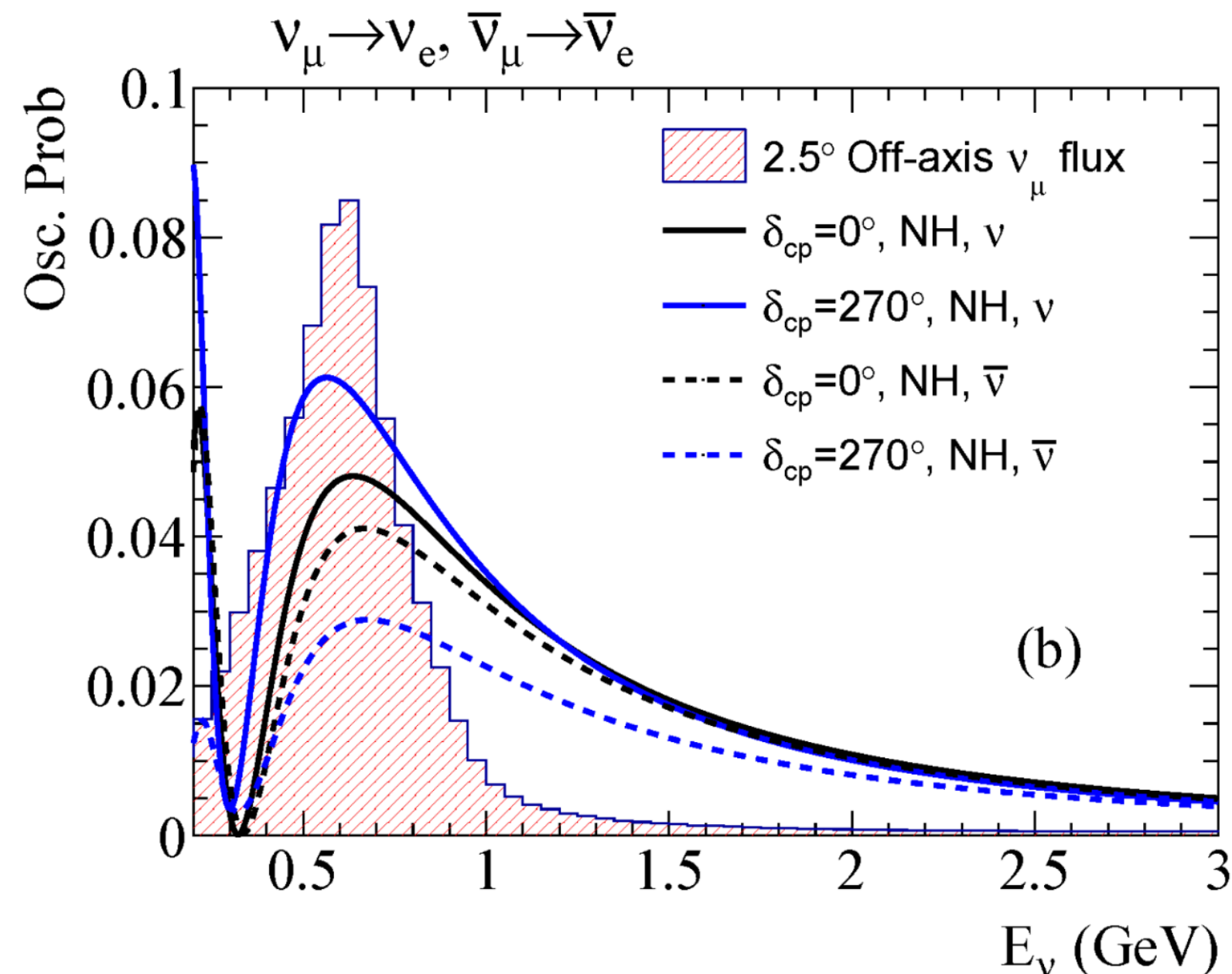
$$+\alpha \frac{J_0 \cos \delta_{CP}}{A(1-A)} \cos \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2 \sim 1/30$$

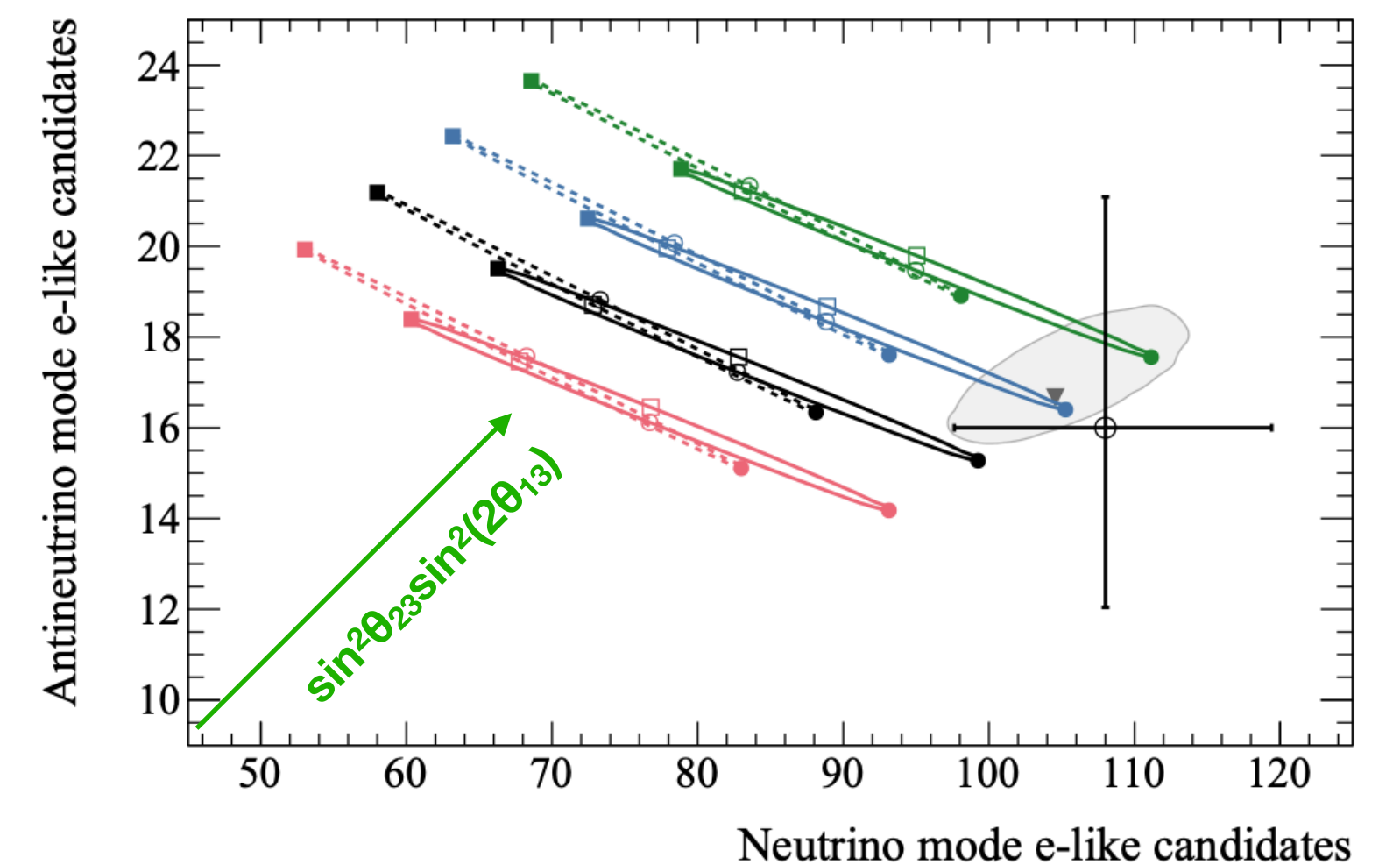
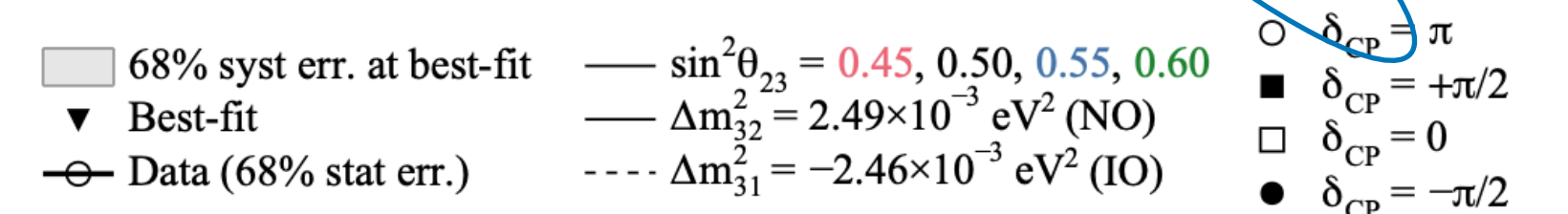
$$J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13}$$

$$A = (\mp) 2\sqrt{2} G_F n_e E / \Delta m_{31}^2$$

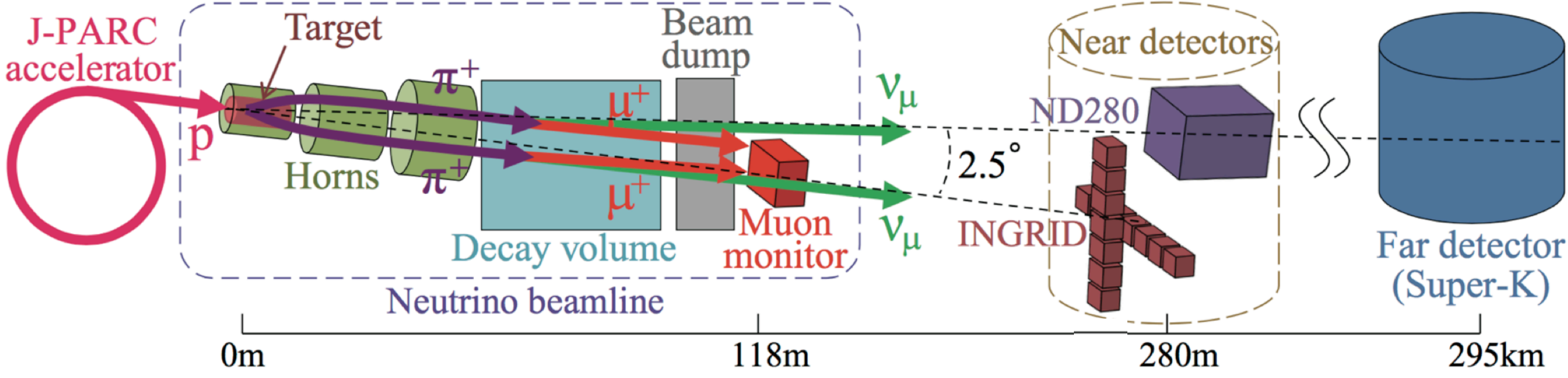
Sensitivity to  $\delta_{CP}$ , to the mass ordering and  $\theta_{23}$  octant



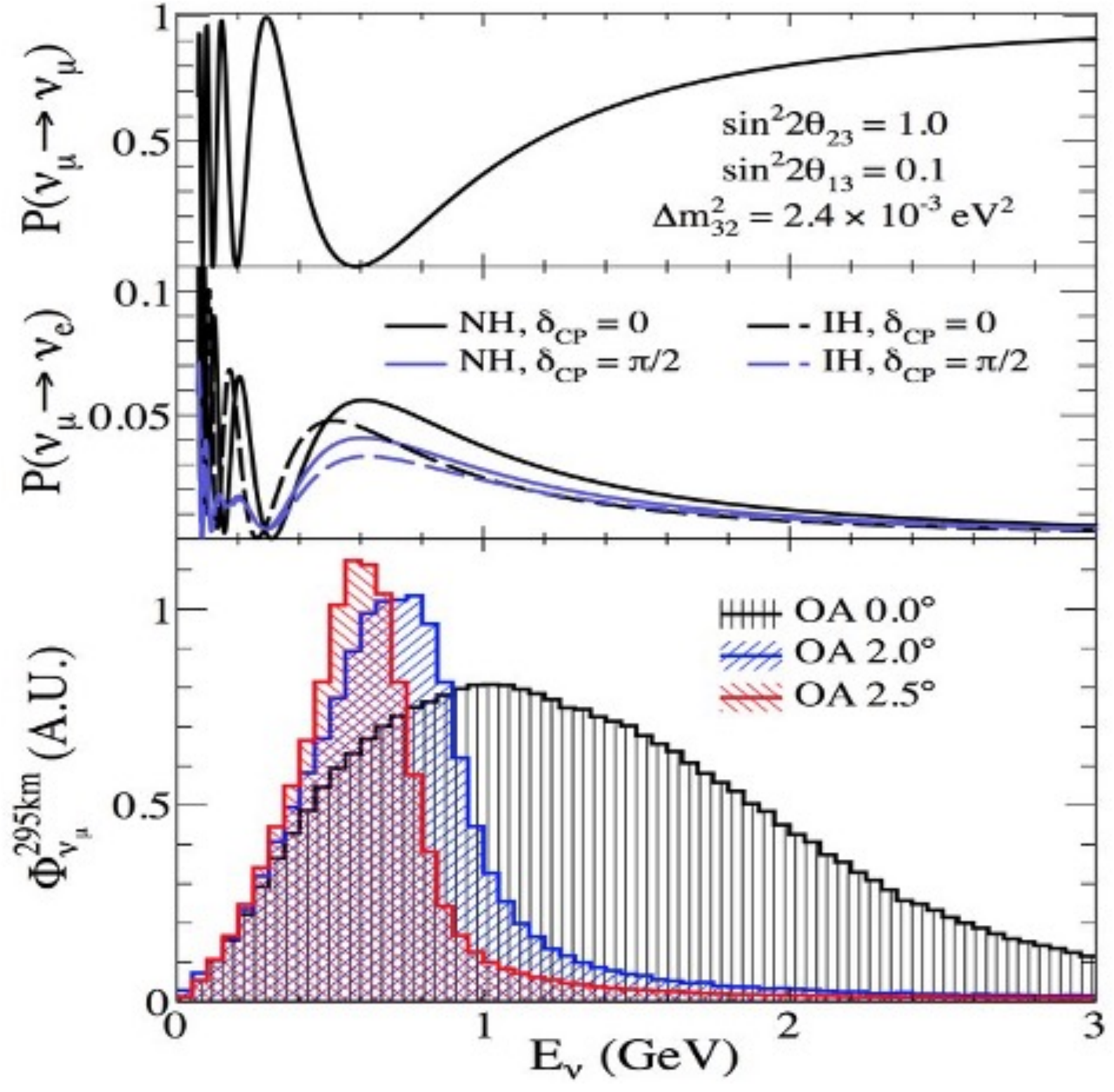
— Normal ordering  
... Inverted ordering



# The T2K neutrino beam line and the off-axis technique

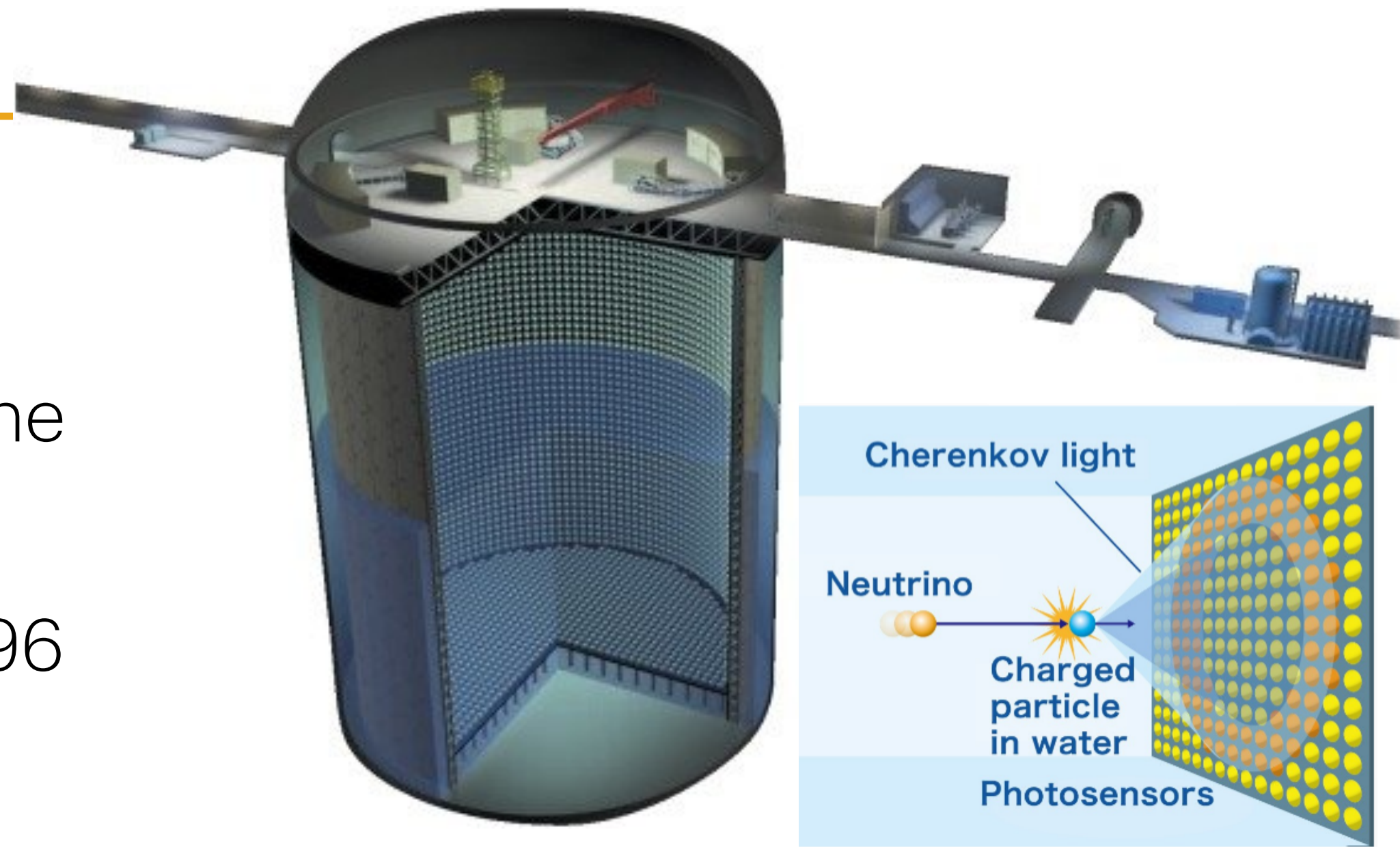


- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- p+C interactions producing hadrons (mainly pions and kaons)
- Hadrons are focused and selected in charge by 3 electromagnetic horns
  - $\nu_\mu$  are produced by focussing  $\pi^+ \rightarrow \mu^+ + \nu_\mu$  (Forward Horn Current, FHC)
  - Reversing the horn current (RHC)  $\bar{\nu}_\mu$  are produced from  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Off-axis technique  $\rightarrow$  detectors intercept a narrow-band beam. Off axis tuned to maximise the flux at maximum of the oscillation probability

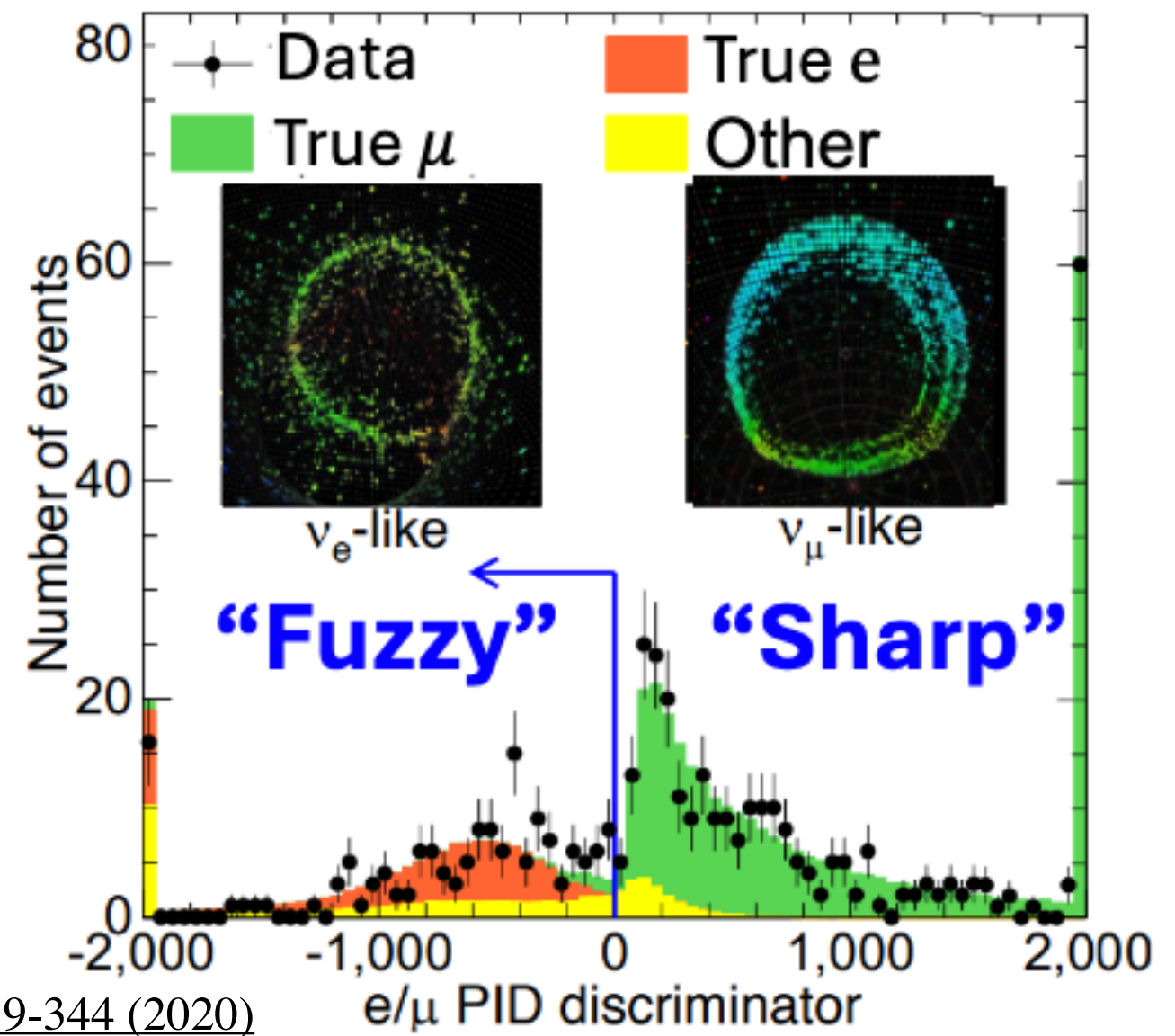
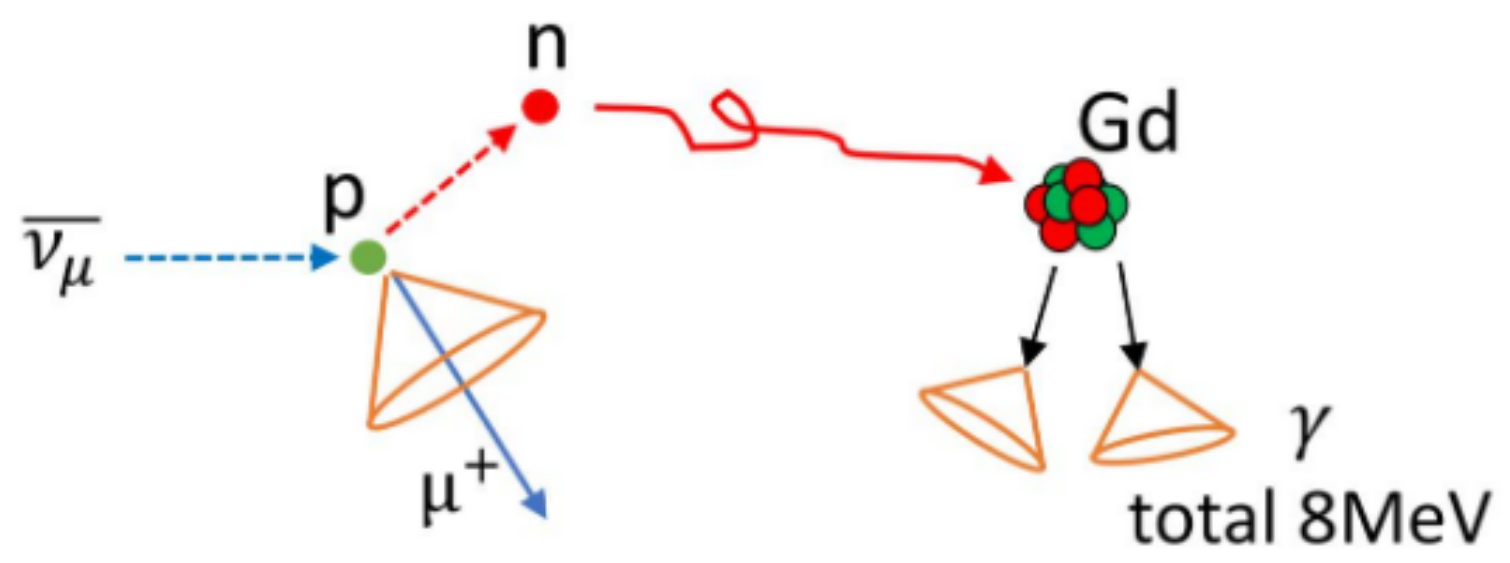


# Super-Kamiokande

- 50 kton water Cherenkov detector
  - ~11k 20" PMTs for the inner detector, ~2000 8" PMTs for the outer detector, used as veto
- ~1000 meters underground in Kamioka, operated since 1996
- Different shape of Cherenkov ring → discrimination e/ $\mu$
- Added 0.03% Gd in 2022 → improve neutron tagging efficiency



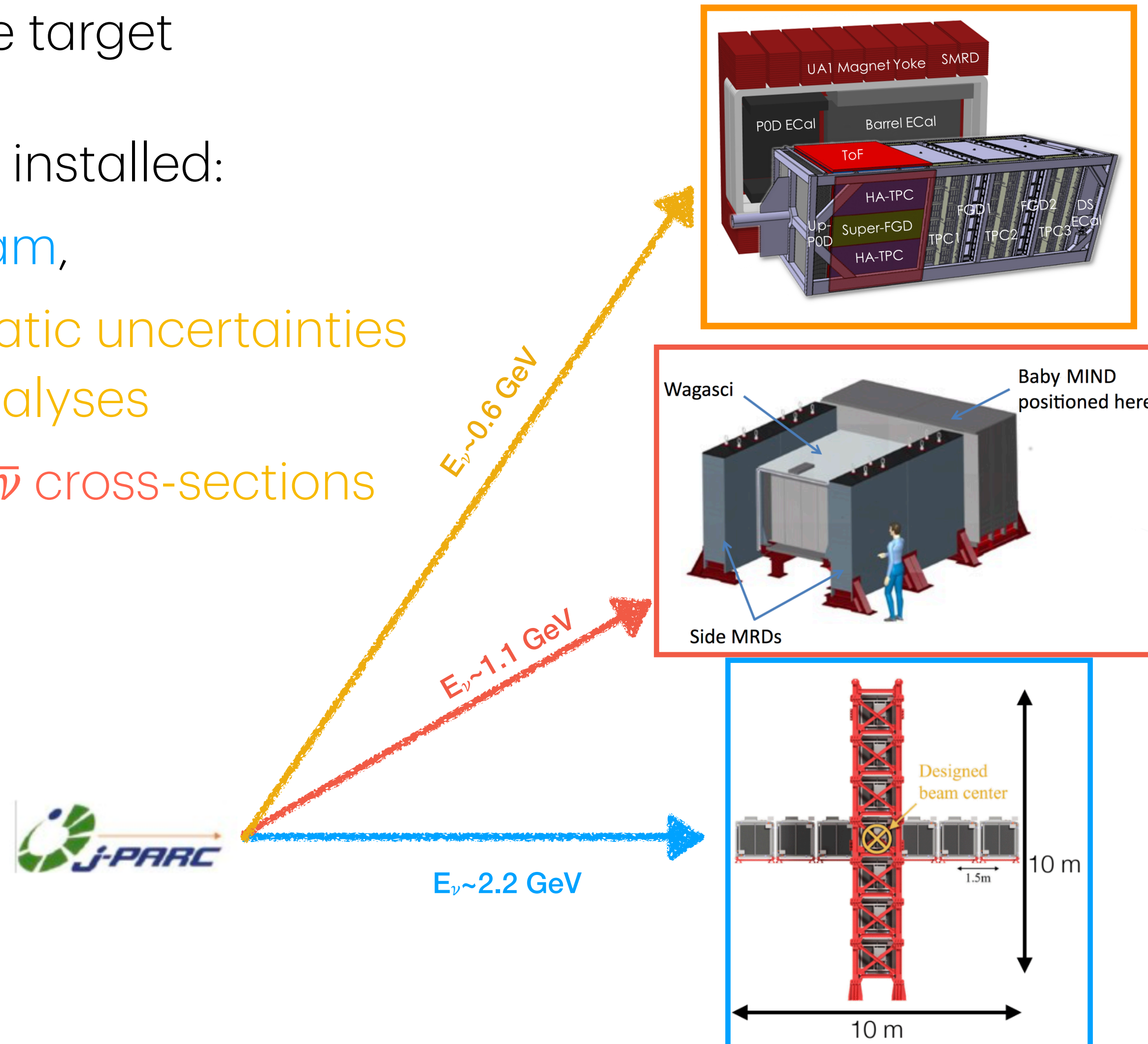
Signature of a neutron capture by Gadolinium



Nature 580, 339-344 (2020)

# Near Detector complex

- At 280 m from the target
- Several detectors installed:
  - Monitor the beam,
  - Reduce systematic uncertainties in oscillation analyses
  - Measure  $\nu$  and  $\bar{\nu}$  cross-sections



## Off-Axis ND280

Constrain systematics in T2K oscillation analyses — Measure neutrino cross-sections

In operation since 2010 (upgraded in 2023)

## WAGASCI/BabyMIND

Cross-sections on water

Installed in 2019

## INGRID: on-axis detector

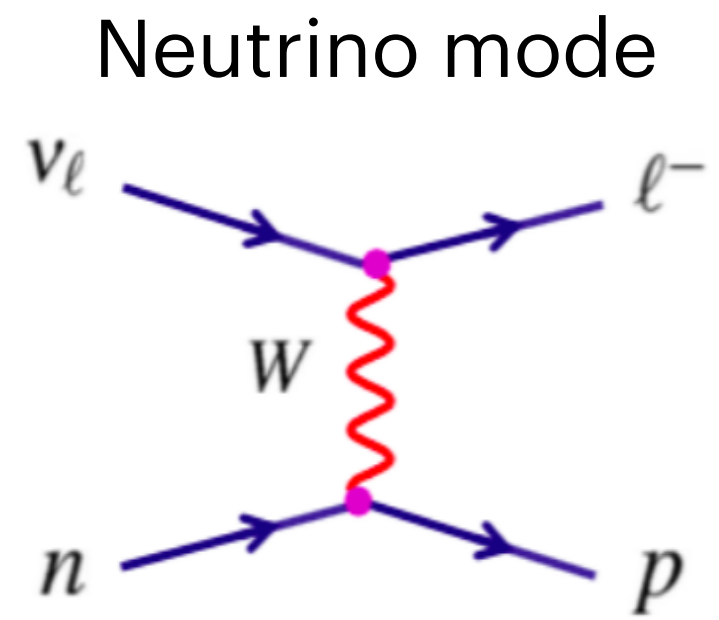
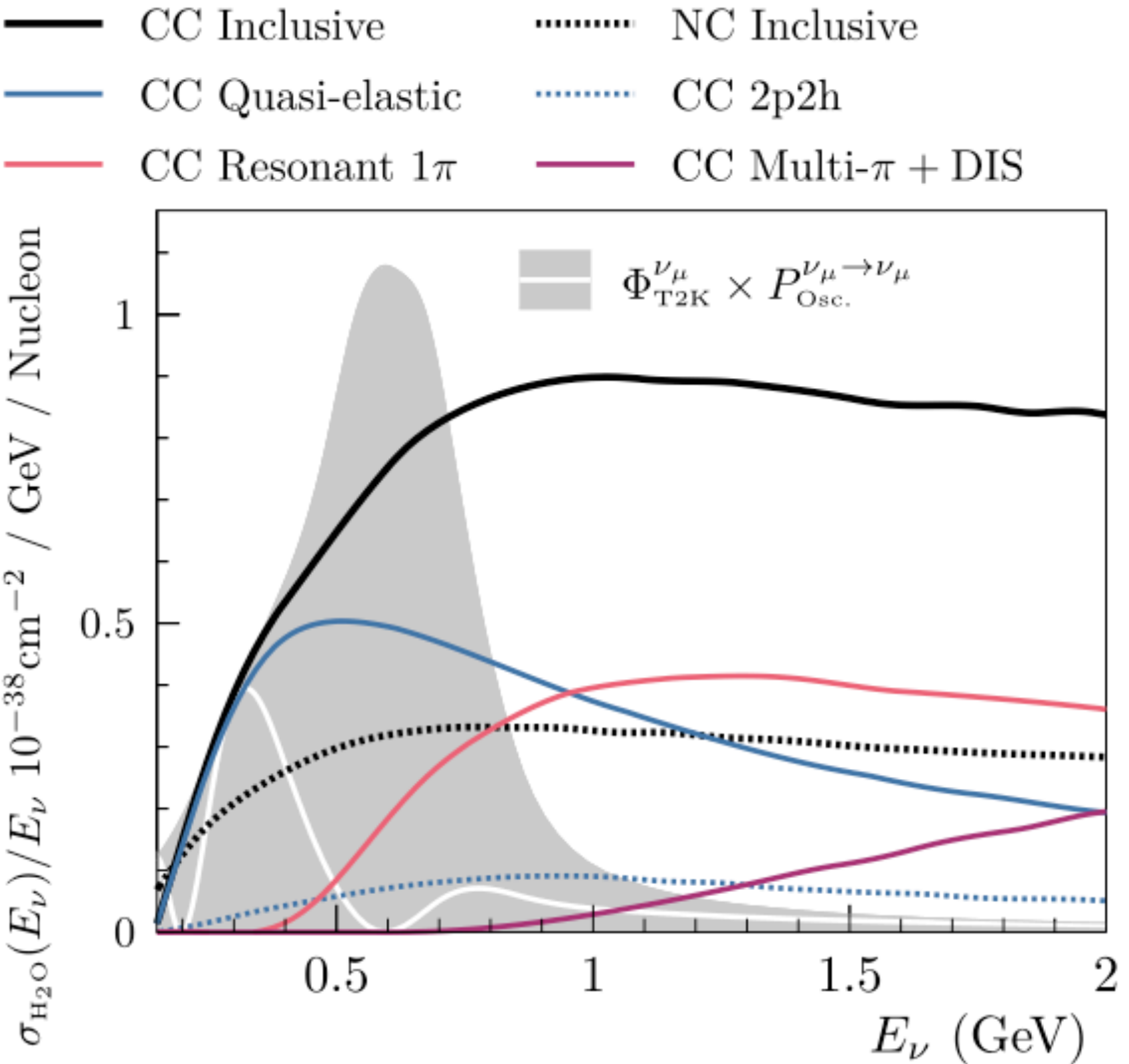
Monitoring  $\nu$  beam profile day-by-day

Cross-section measurements

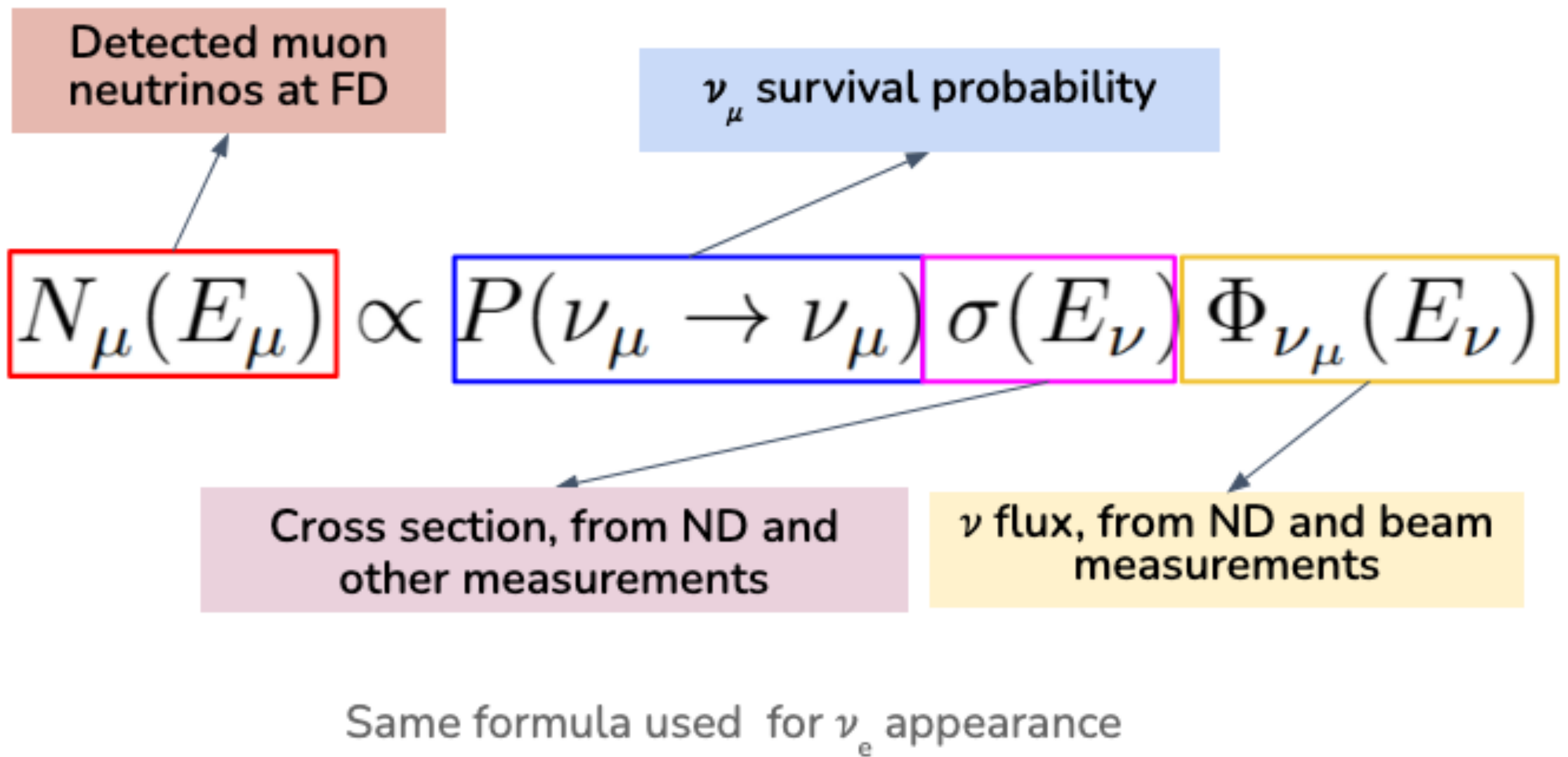
In operation since 2009

# Neutrino Interactions at T2K

- At T2K energies dominated by **CC QuasiElastic** channel
- Significant **2particles-2holes (2p2h)** and **Resonant** contributions

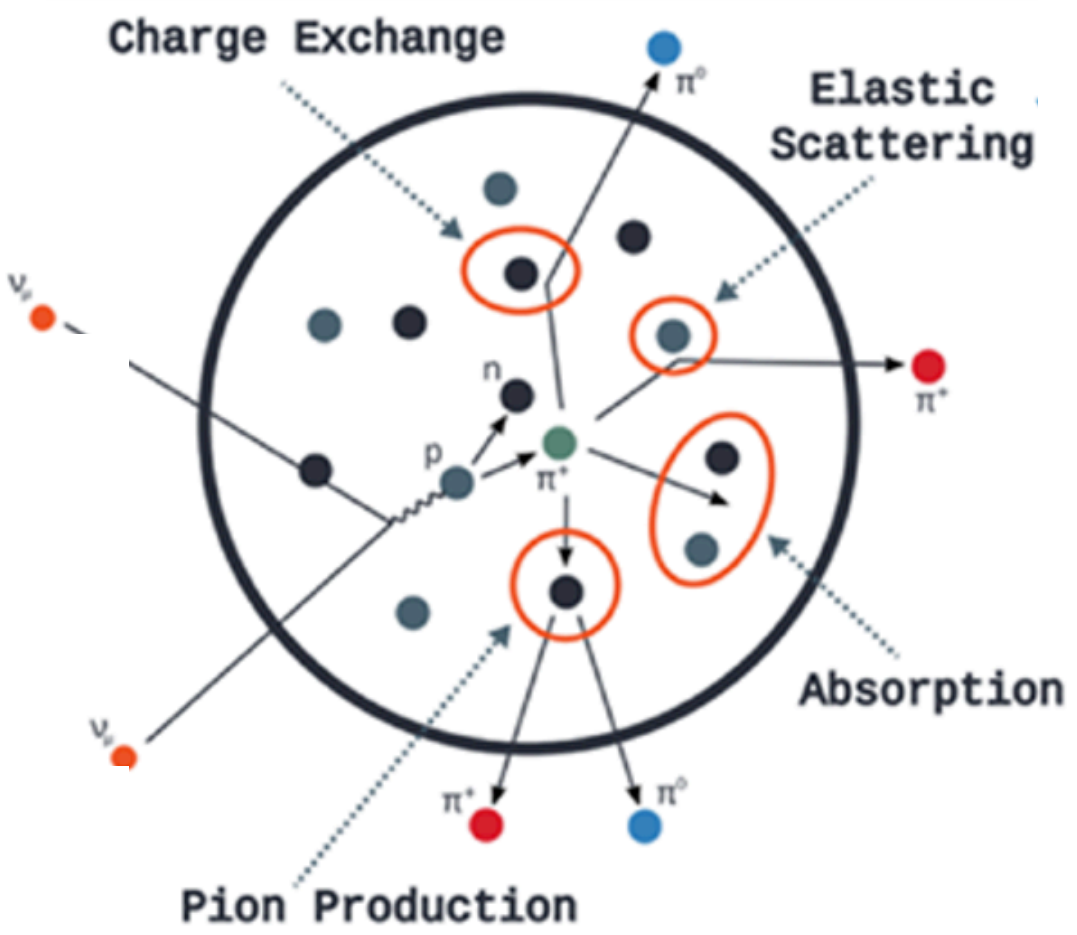
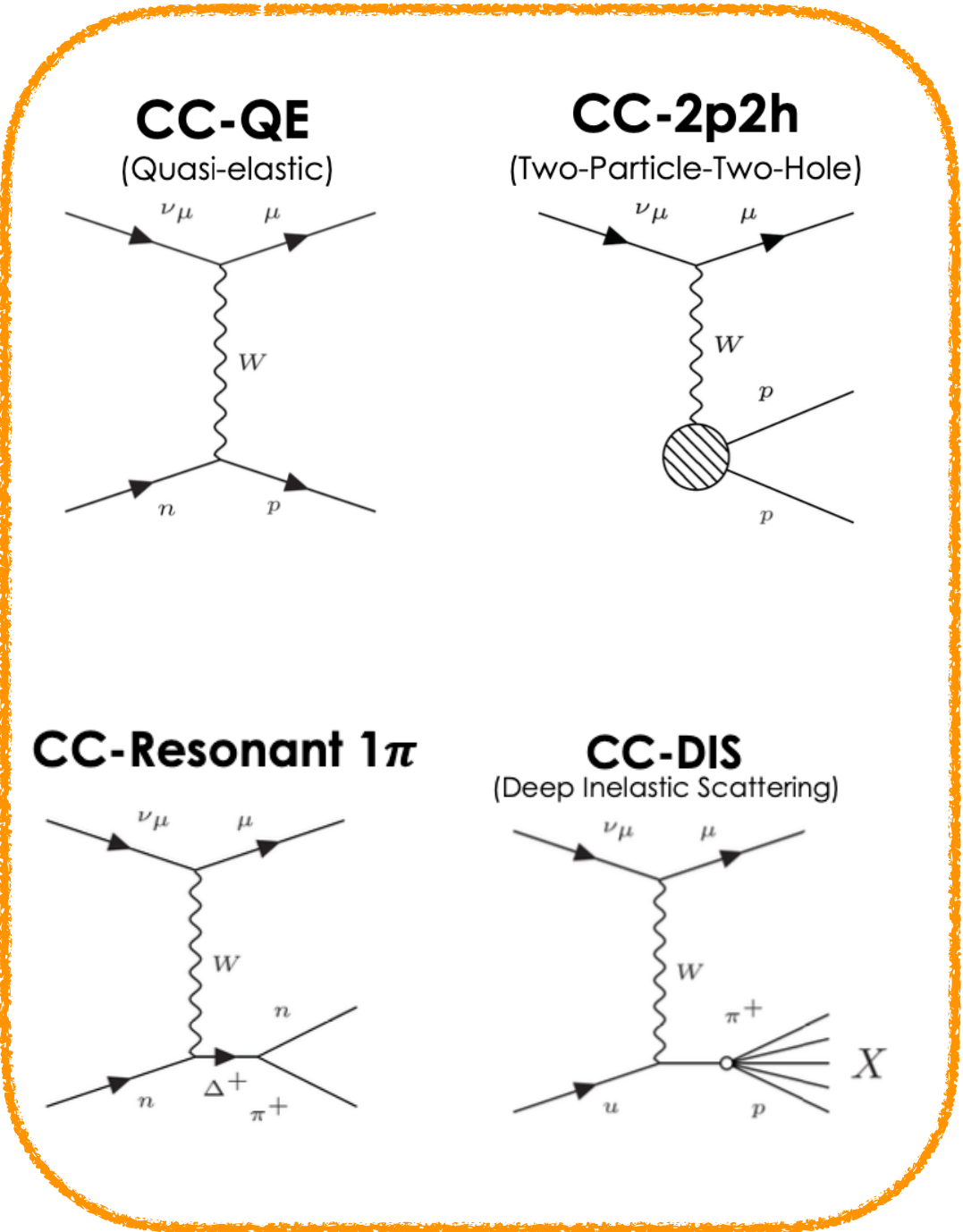


Charged Current (CC) interaction reveals the flavor from the outgoing charged lepton

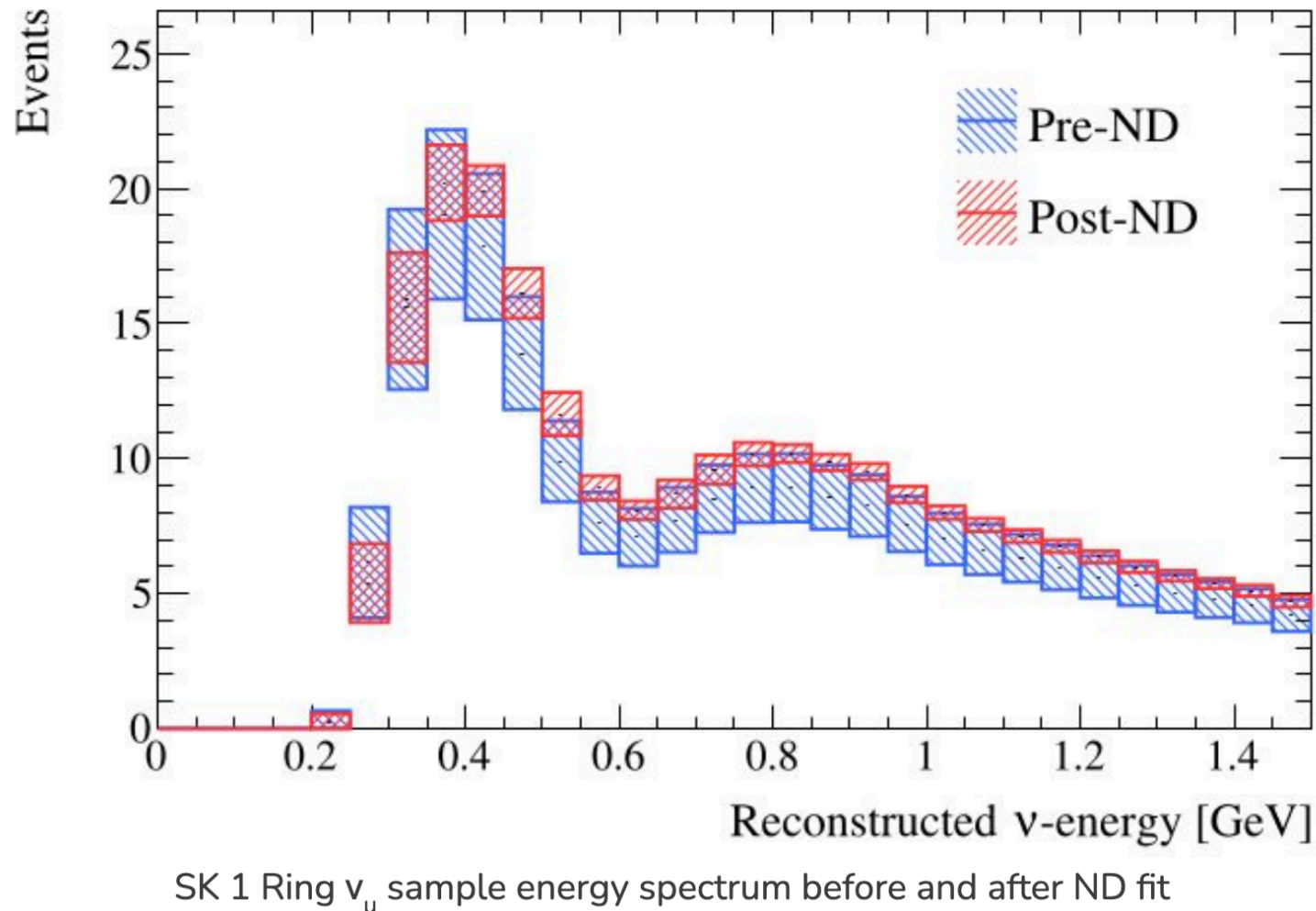
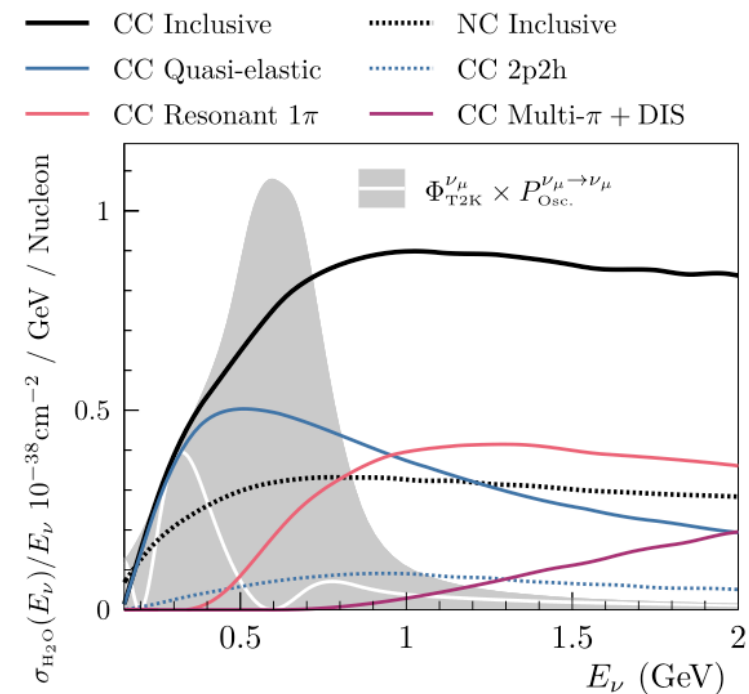
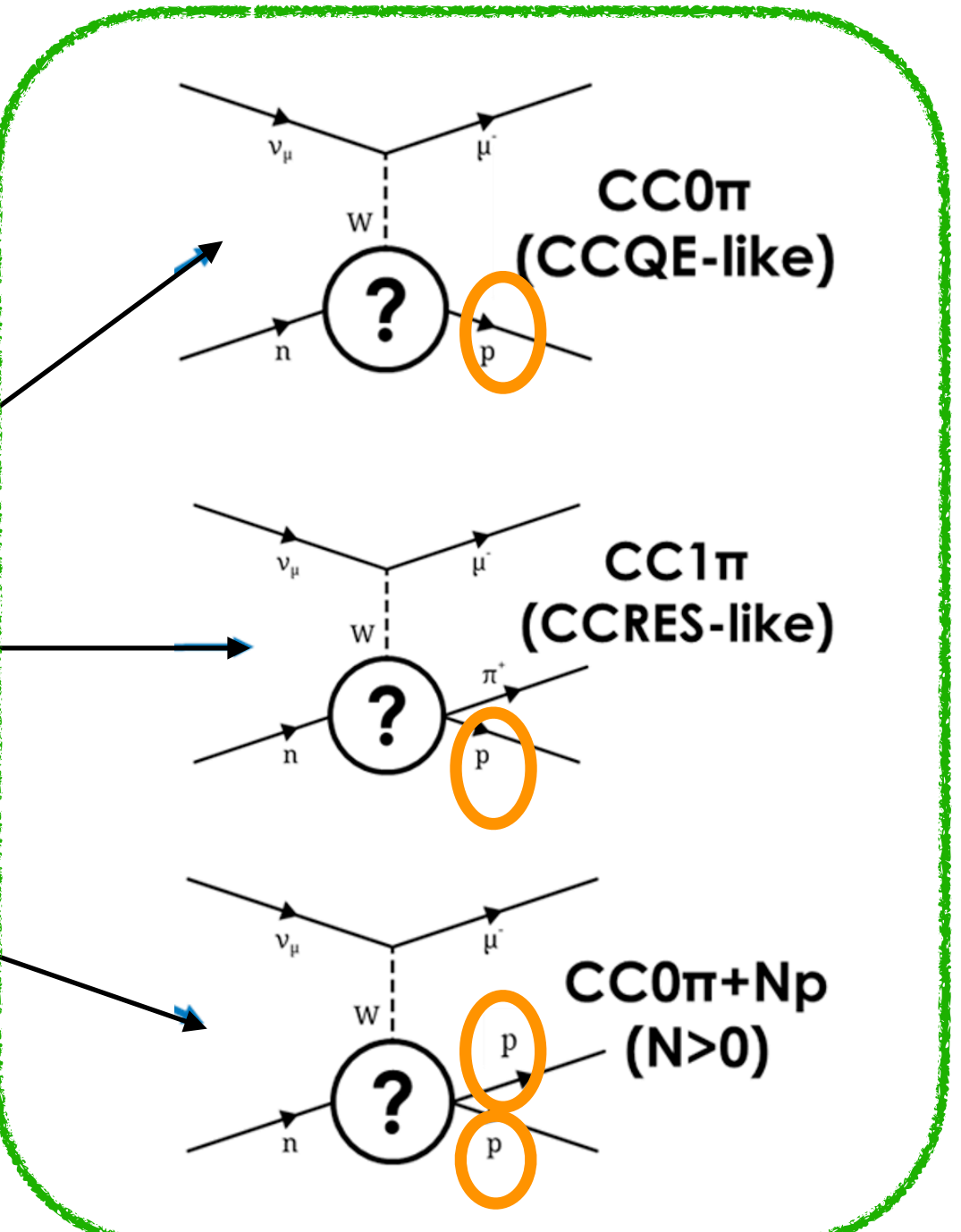


# Neutrino Interactions at T2K

## Generator



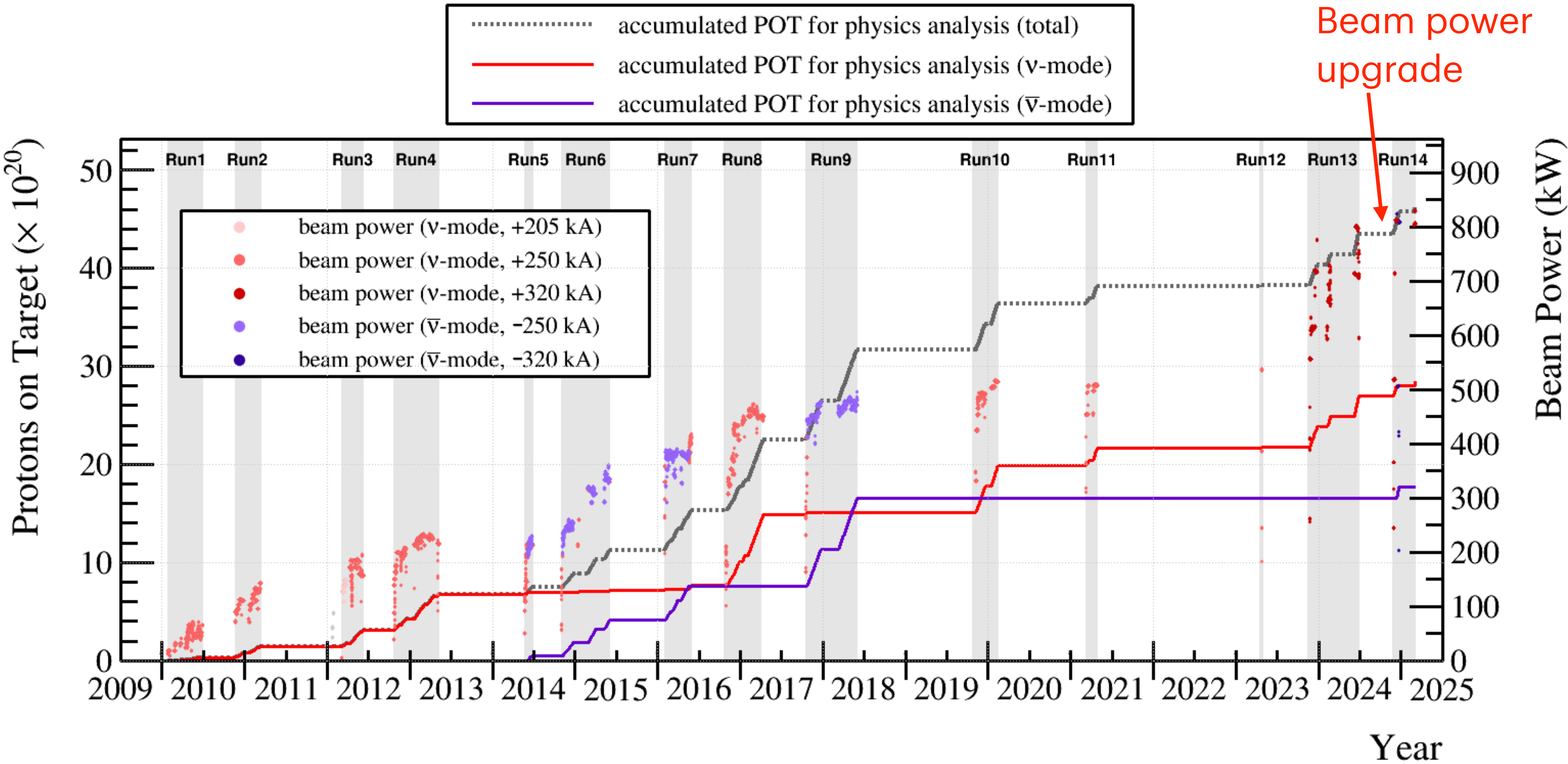
## Observables

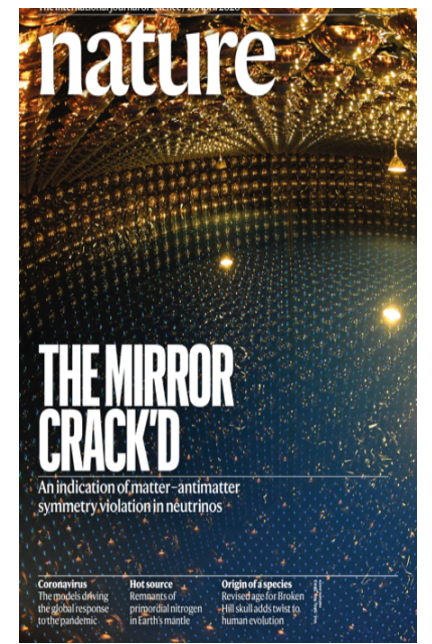


- Many Final States having protons (neutrons) → Important to be able to detect them
- Mis-modelling of these contribution might bias the neutrino energy reconstruction → important to have a correct model with Near detector data
- Fits to Near Detector data help to reduce the uncertainty on the reconstructed neutrino energy (e.g. from 17% to 3% for CC-0 $\pi$  event rate)

# T2K data-taking

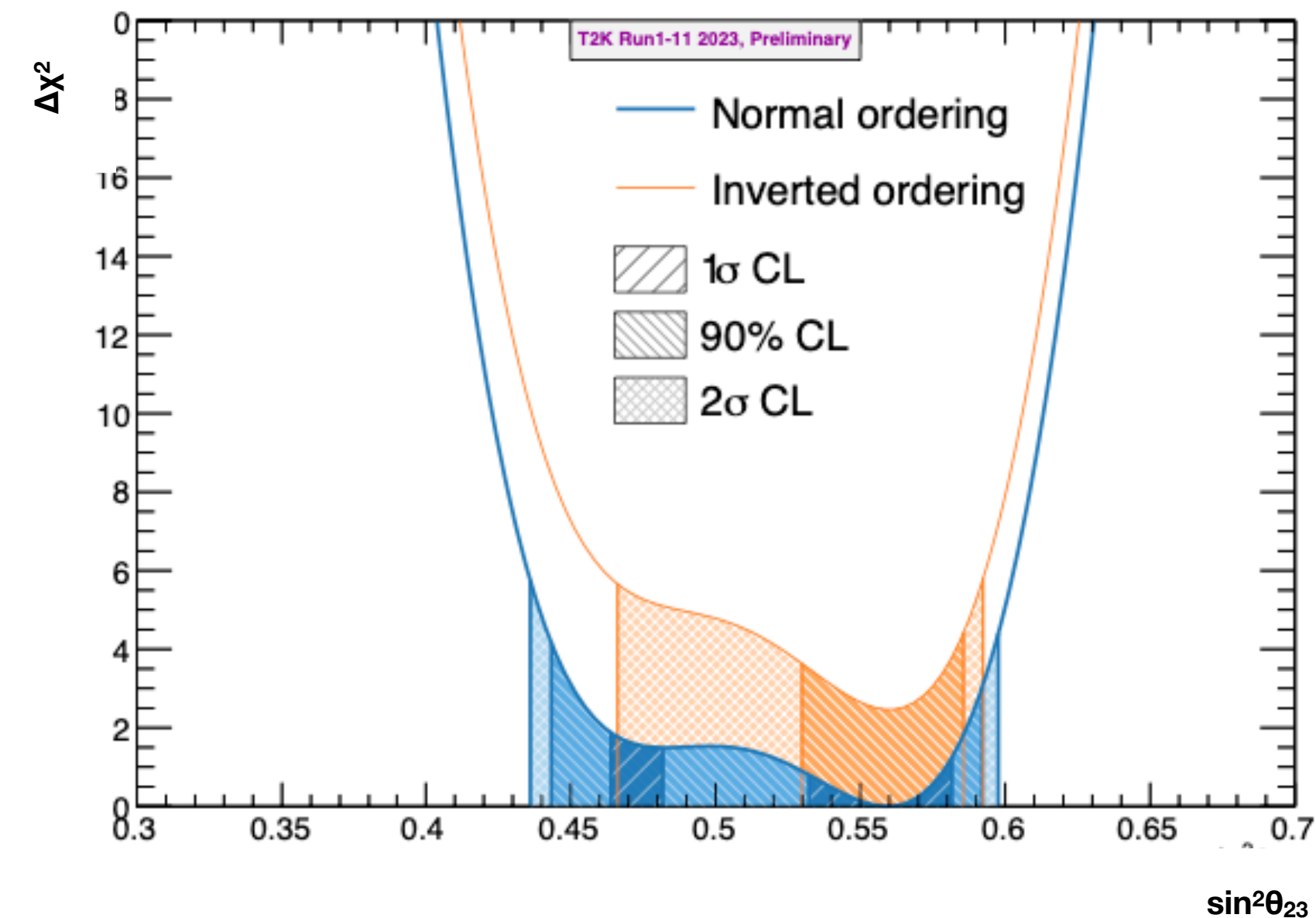
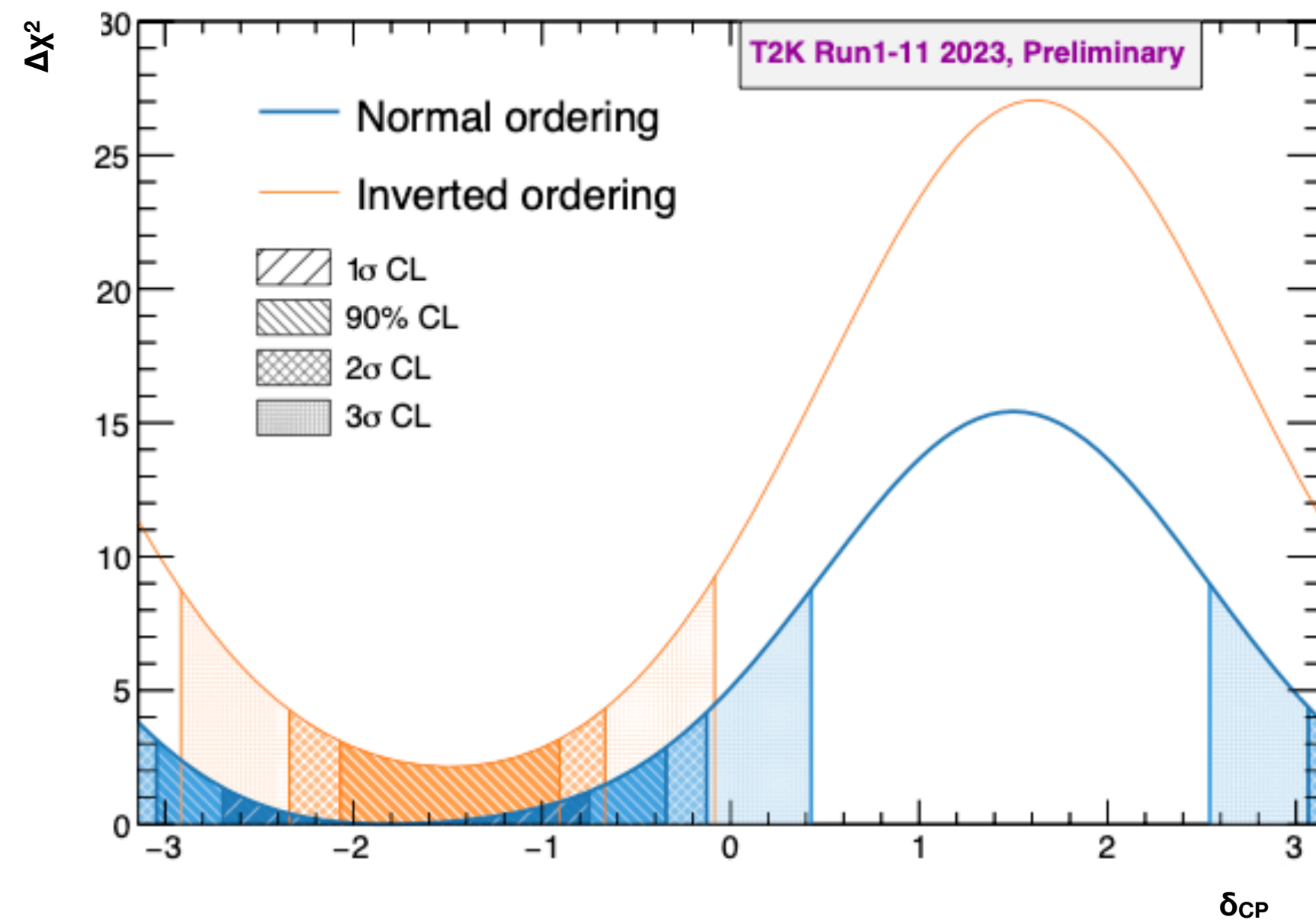
June 2024:  
Beam power  
upgrade





# T2K latest results

- Preference for  $\delta_{CP} \sim -\pi/2$  but CP conserving values are within the  $2\sigma$  interval
- Slight preference for Normal Ordering and upper octant but none of them is significant



## *How we can extend the physics potential?*

- Combine results with other experiment (SK, NOvA)
- Make an upgrade..

# T2K current limitations: beam power

- Limited statistics available
- June 2024 → Beam power increased to 800 kW! (~500 kW before upgrades)
- Steady improvements to reach 1.3 MW by 2027 → increase T2K statistics by a factor of 3 by 2027

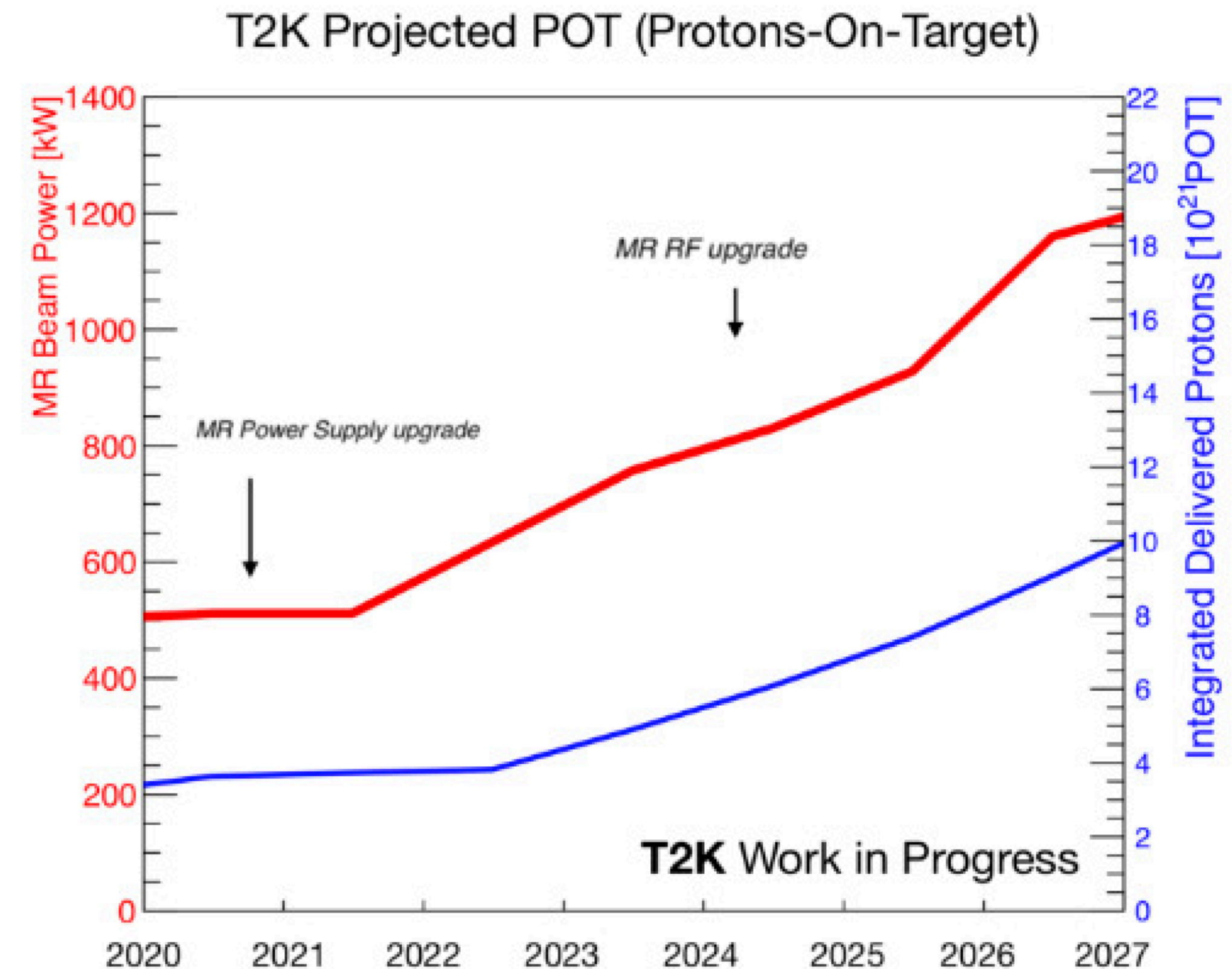
Larger statistics



Better control of systematic uncertainties

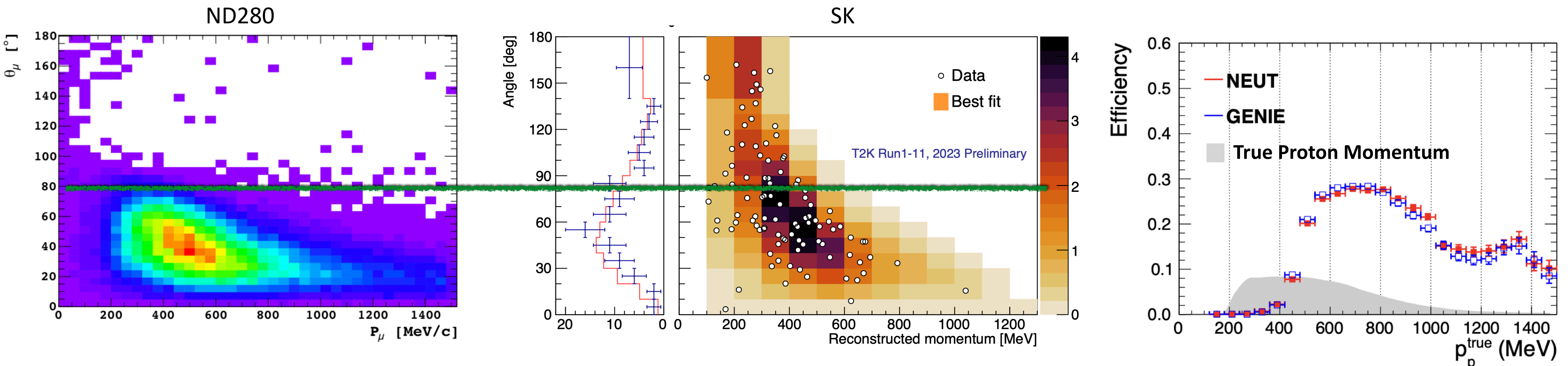


ND280 Upgrade



# T2K current limitations: ND constrains

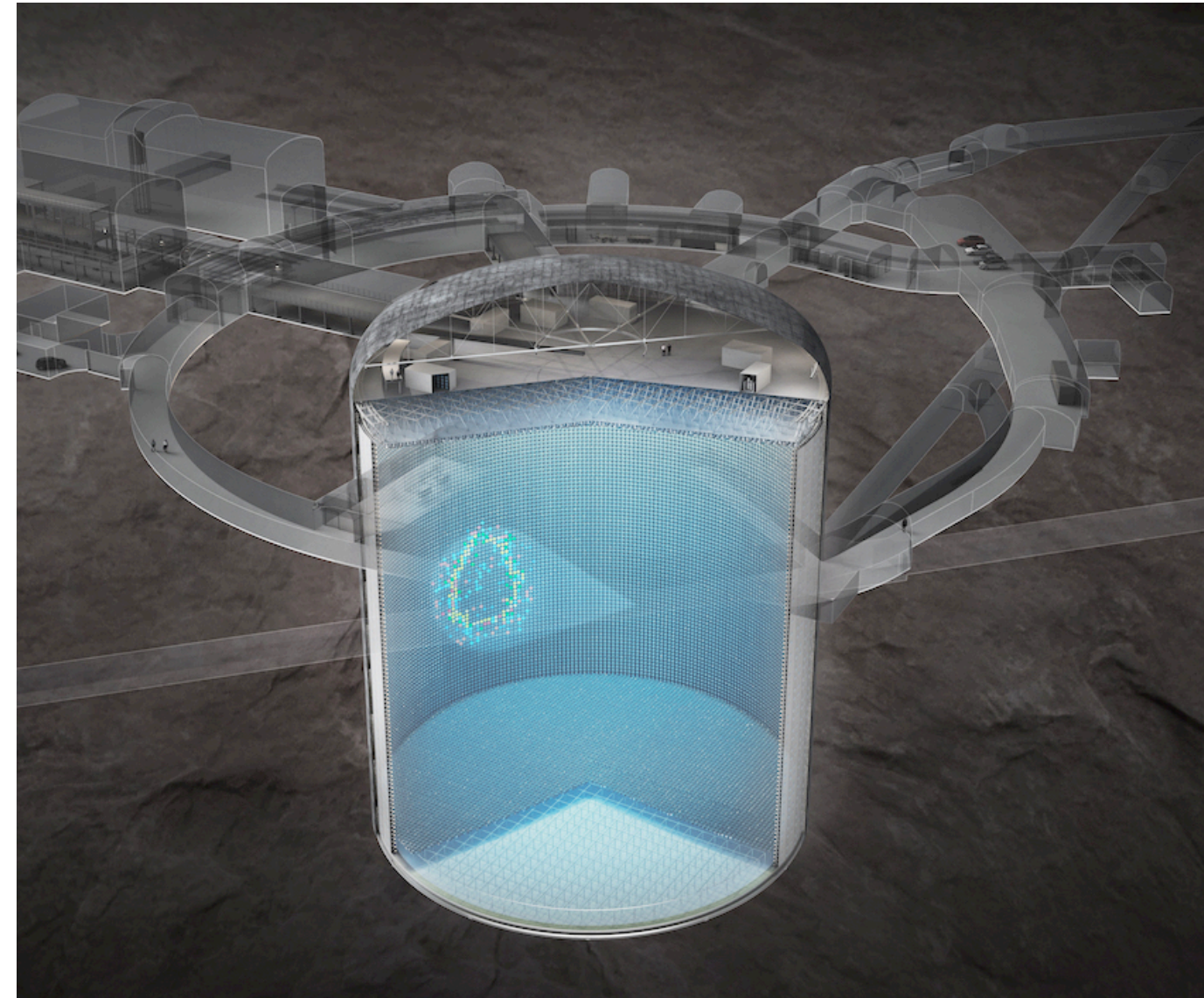
- Limited angular acceptance of ND280 wrt SK → Limited constrains on systematics
- Proton reconstruction threshold at 400 MeV/c → Limited event topology and neutrino reconstruction
- Blind to neutrons → Limited Identification and reconstruction of anti- $\nu_\mu$  events
- Limited track direction determination → Limited rejection of Out-Of-Fiducial-Volume (OOFV) interactions



# T2K current limitations: SK..

## The Hyper-Kamiokande detector

- 71m height x 68m diameter cylindric tank
- 260kton of water
- **~x10 fiducial mass of SK**
- 40k PMTs



## The New generation of LBL experiments is getting closer!

- HK Cavern excavation completed in July!
- Data taking expected in 2028

*But this is another story..*



# The ND280 "classic" ..

## 2 Fine-Grained Detectors (FGDs)

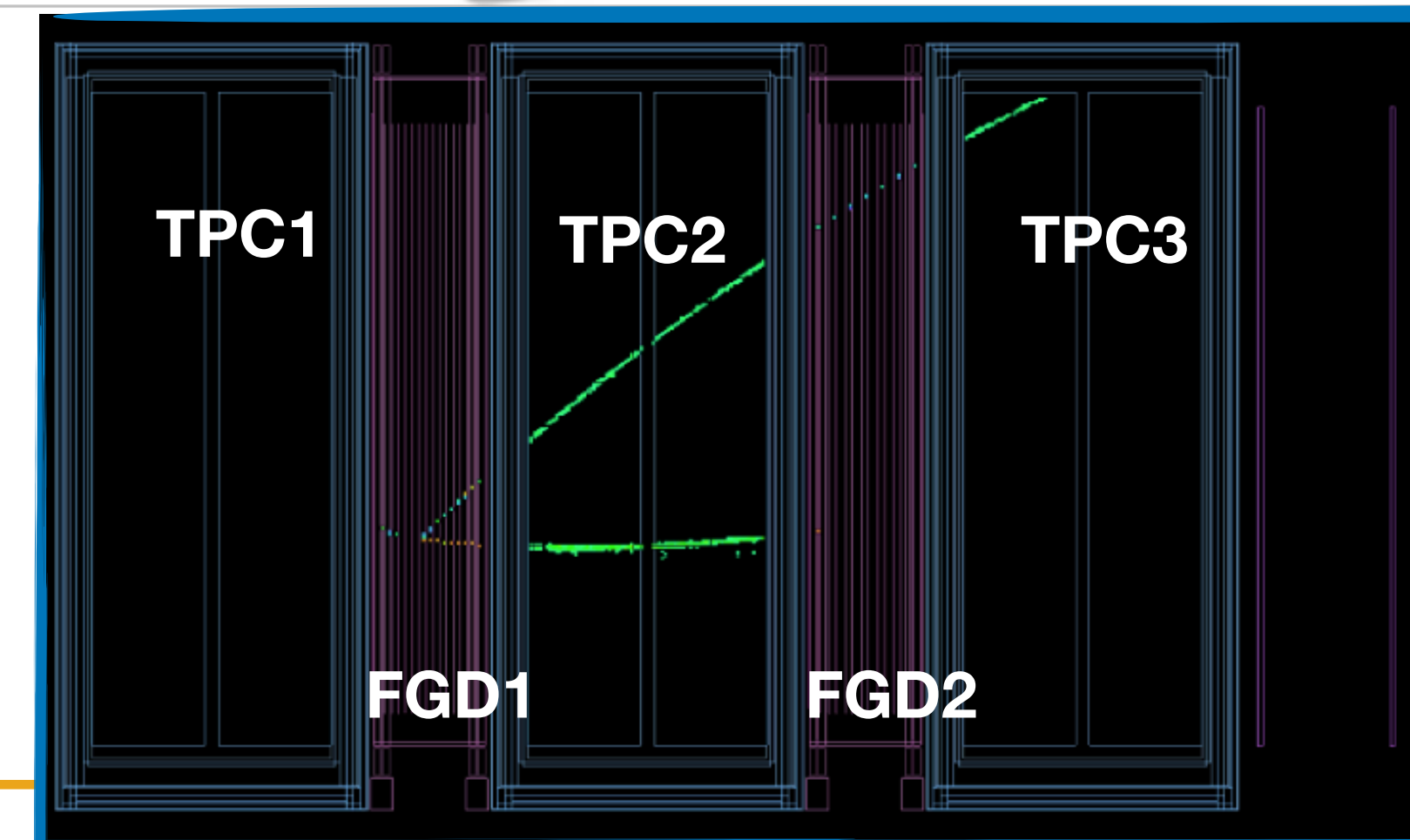
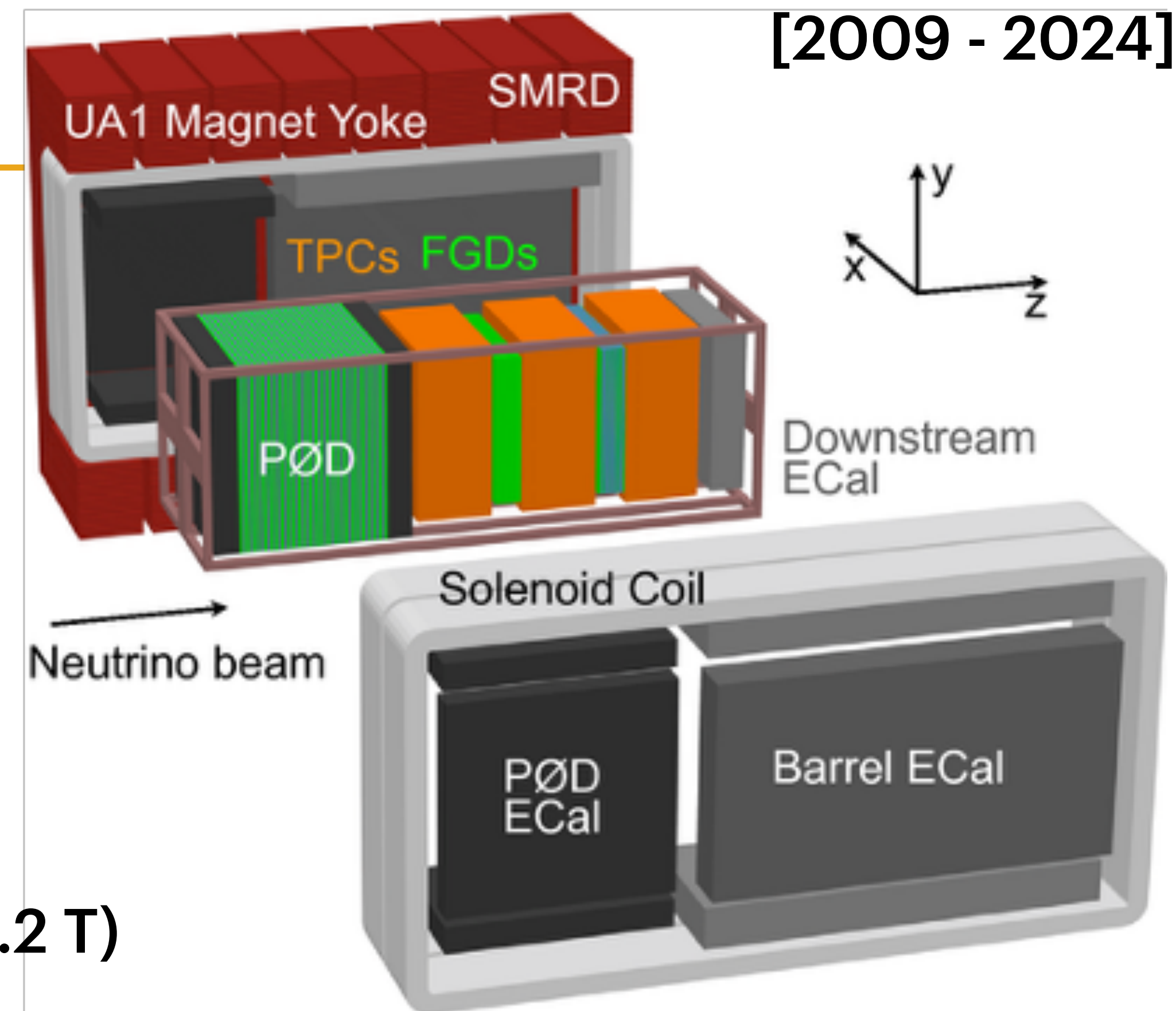
- Active targets (2.2 tons)
- Plastic scintillator bars & water bags (FGD2)
- Short-range hadrons tracking

## 3 Time Projection Chambers (V-TPCs)

- Volume:  $2.5 \times 2.5 \times 1 \text{ m}^3$  each
- T2K gas mixture: Ar-CF<sub>4</sub>-iC<sub>4</sub>H<sub>10</sub> (95-3-2)
- 72 MicroMegas readouts

## $\pi^0$ Detector (POD)

- Layers of scintillators, metal, H<sub>2</sub>O + ECal
- $\nu_\mu \rightarrow \pi^0 \rightarrow \gamma \rightarrow e^+e^-$
- One of the largest  $\nu_e$ -like background



# ... And its upgrade

[2024 - .. ]

Three new sub-detector types [arXiv:[1901.03750](https://arxiv.org/abs/1901.03750)]:

## Super Fine Grained Detector (SFGD):

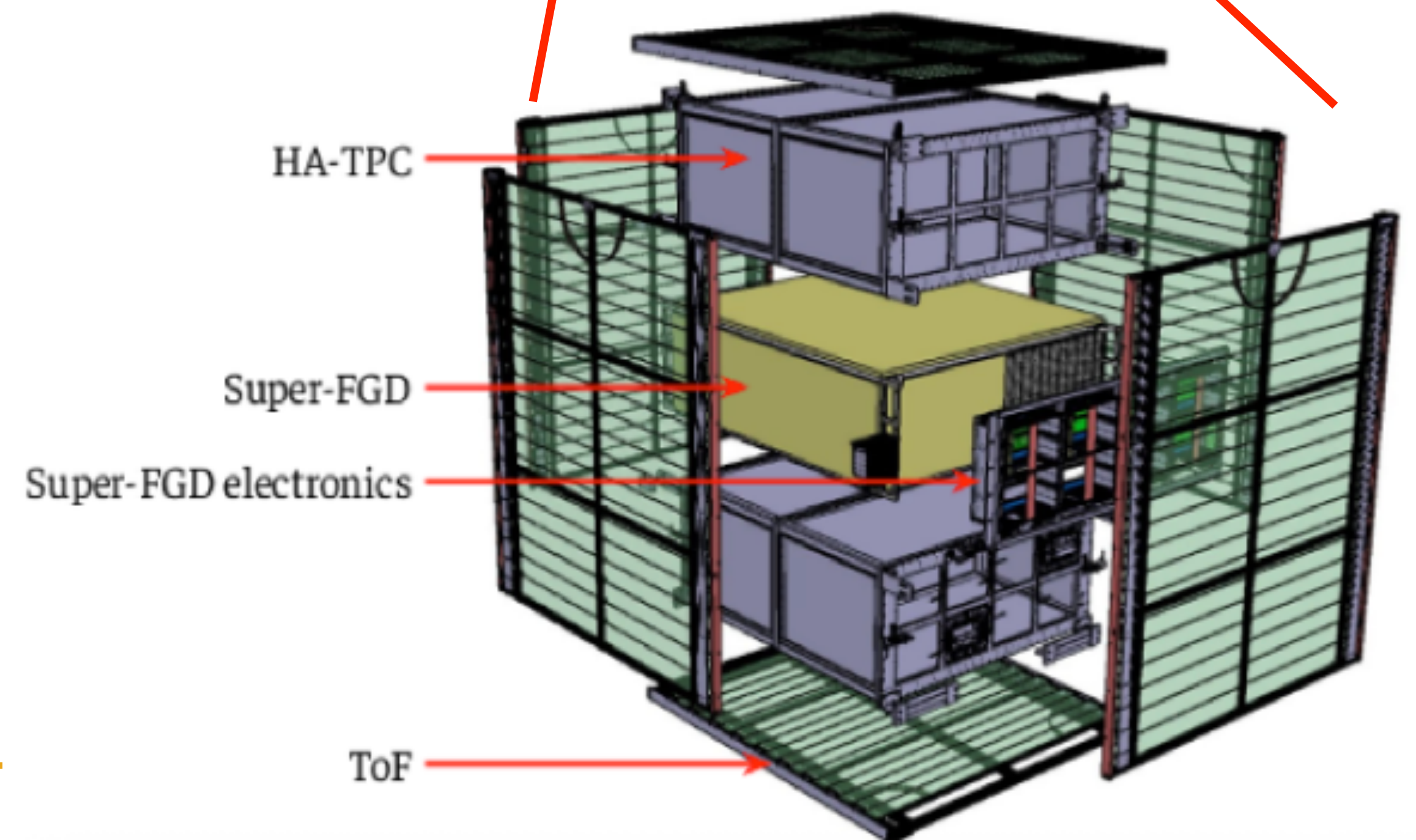
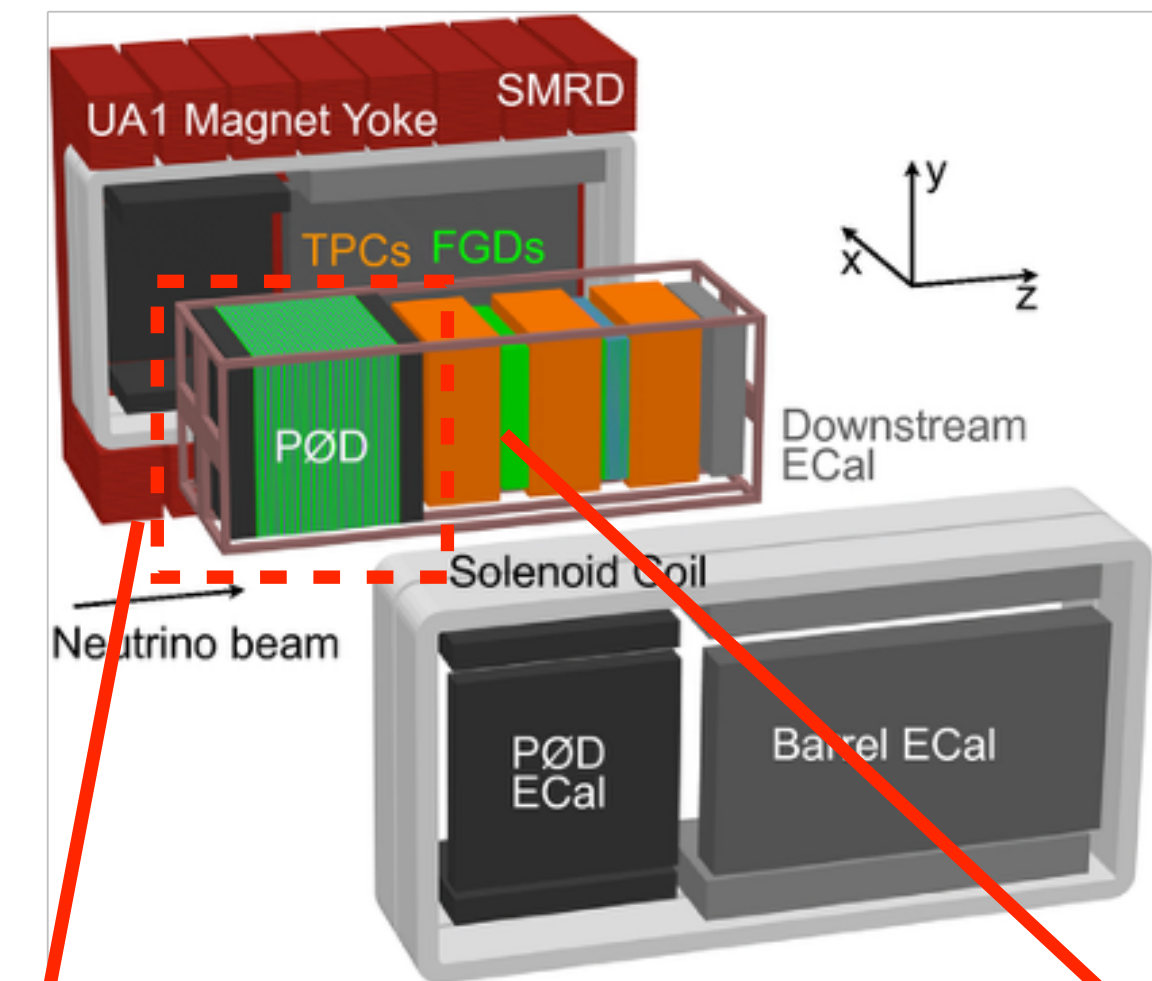
- 2 tons active target and tracker
- 2M 1-cm<sup>3</sup> scintillator cubes
- Isotropic hadron reconstruction at low momentum

## 2 High-Angle TPCs (HATs):

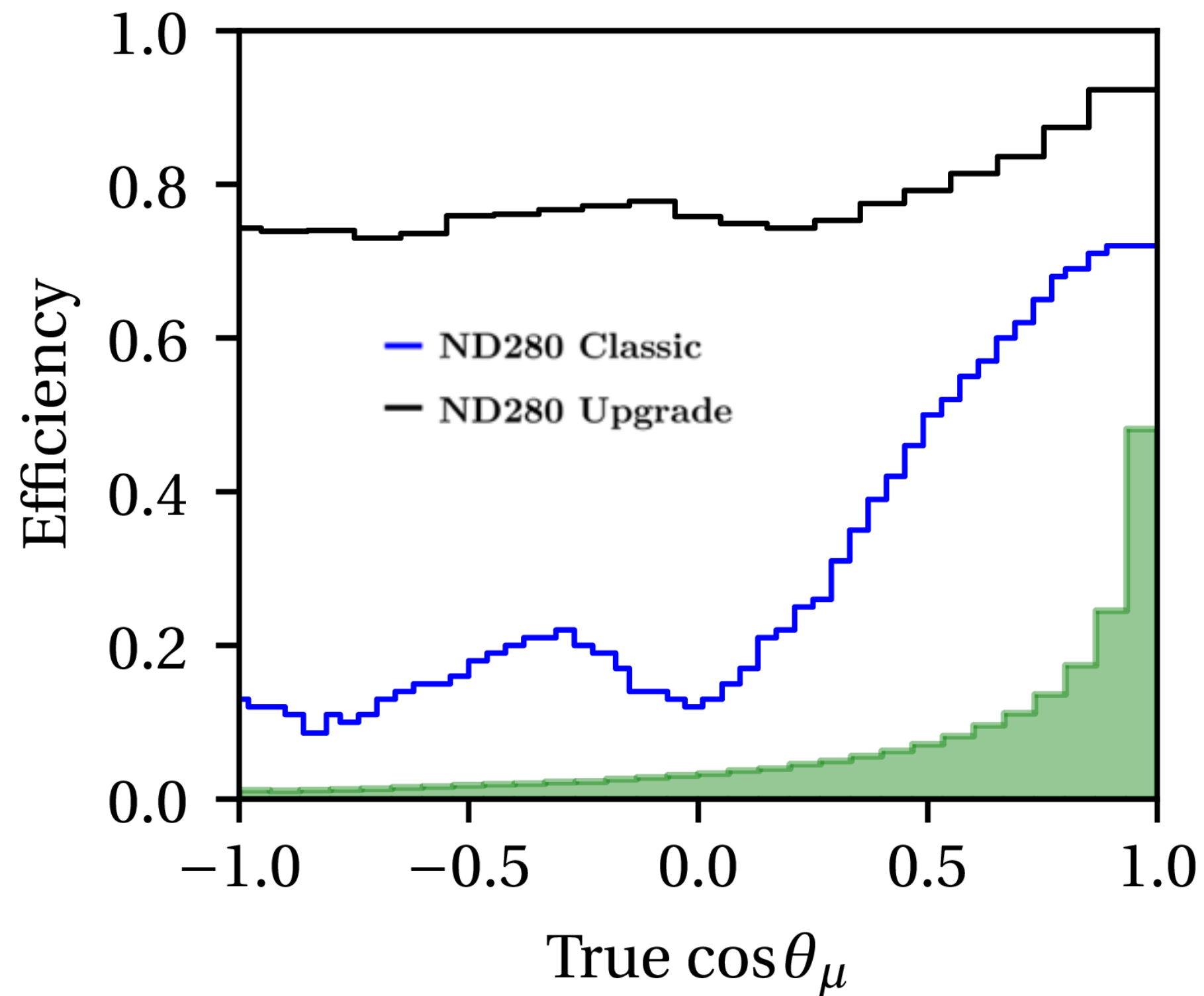
- Innovative E field cage design
- New resistive MicroMegas (ERAMs)
- High-angle scattering particle reconstruction

## 6 Time-of-Flight (ToF) panels:

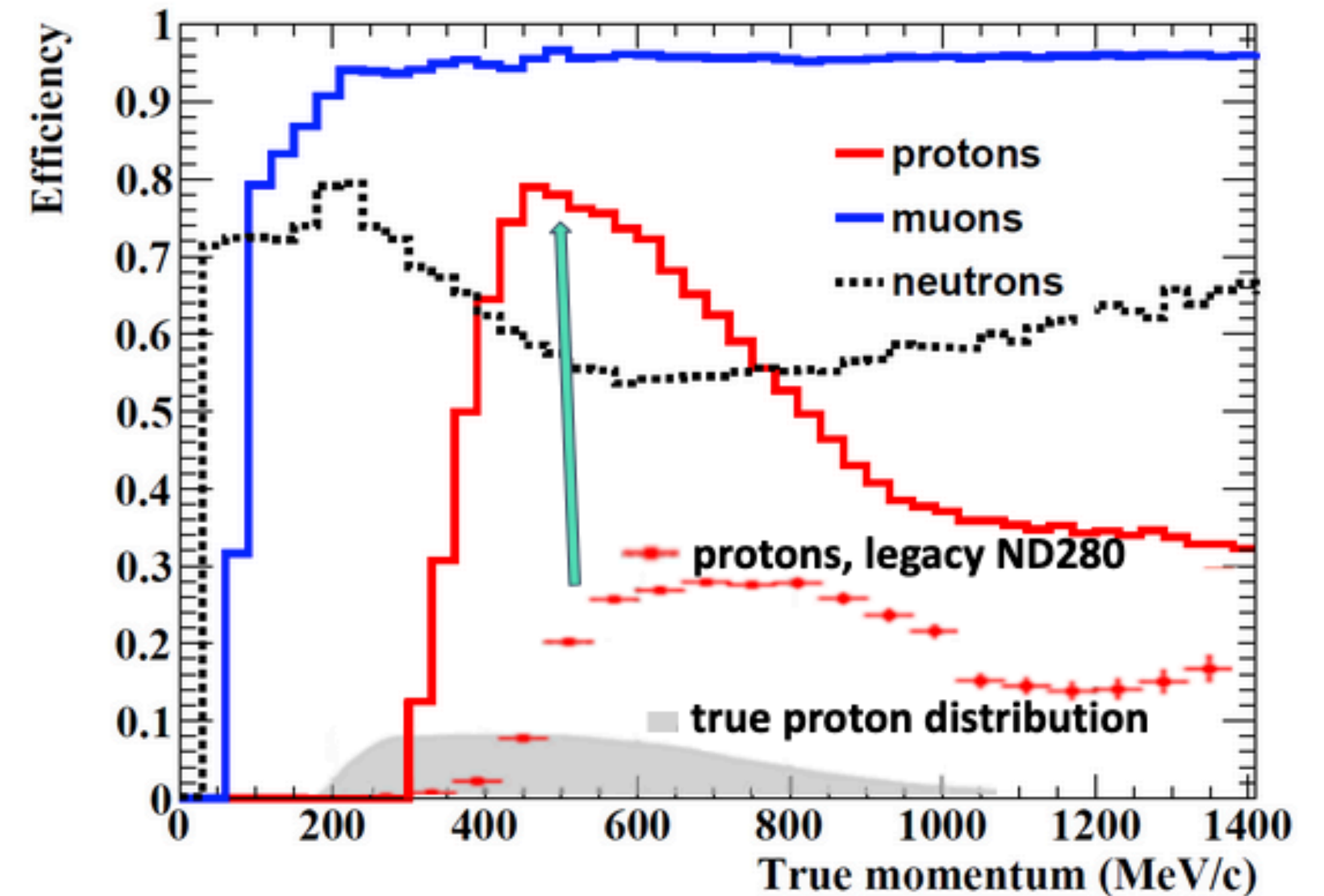
- Plastic scintillator bars
- Track orientation ~  $4\pi$  angular coverage
- Improvement of OOFV events rejection & PID



# ND280 Upgrade goals



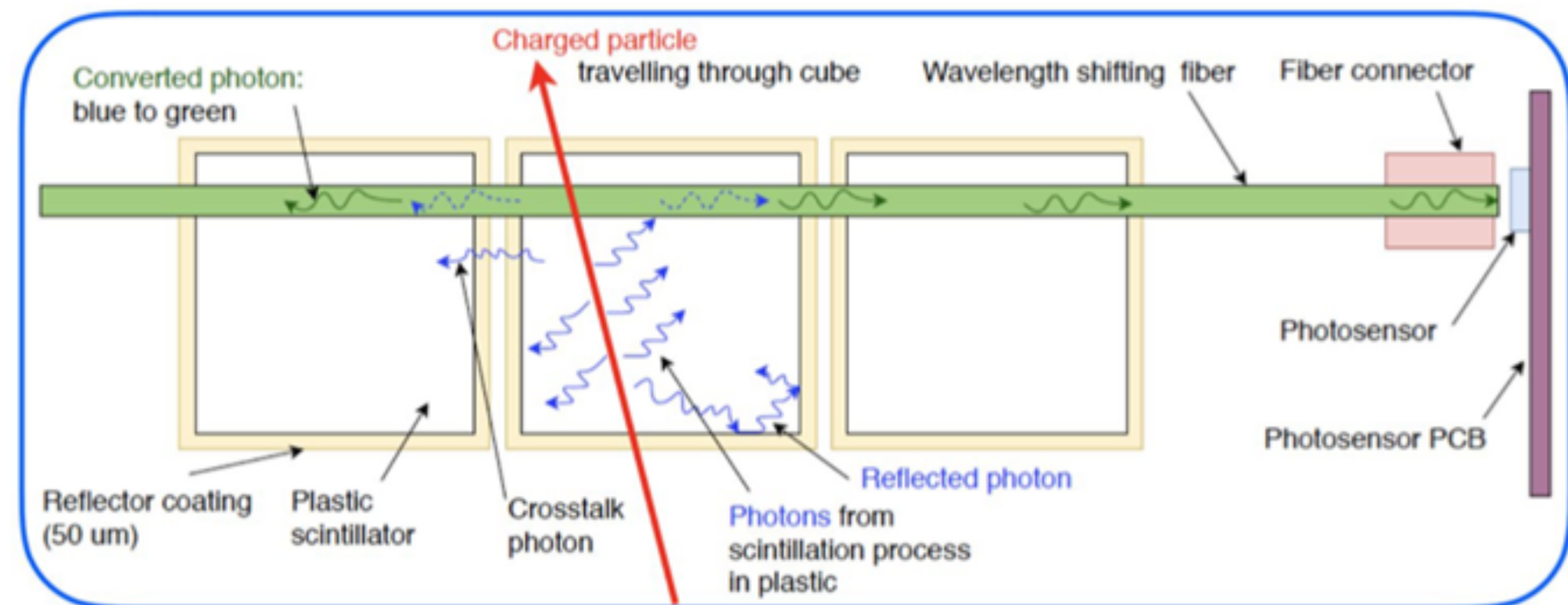
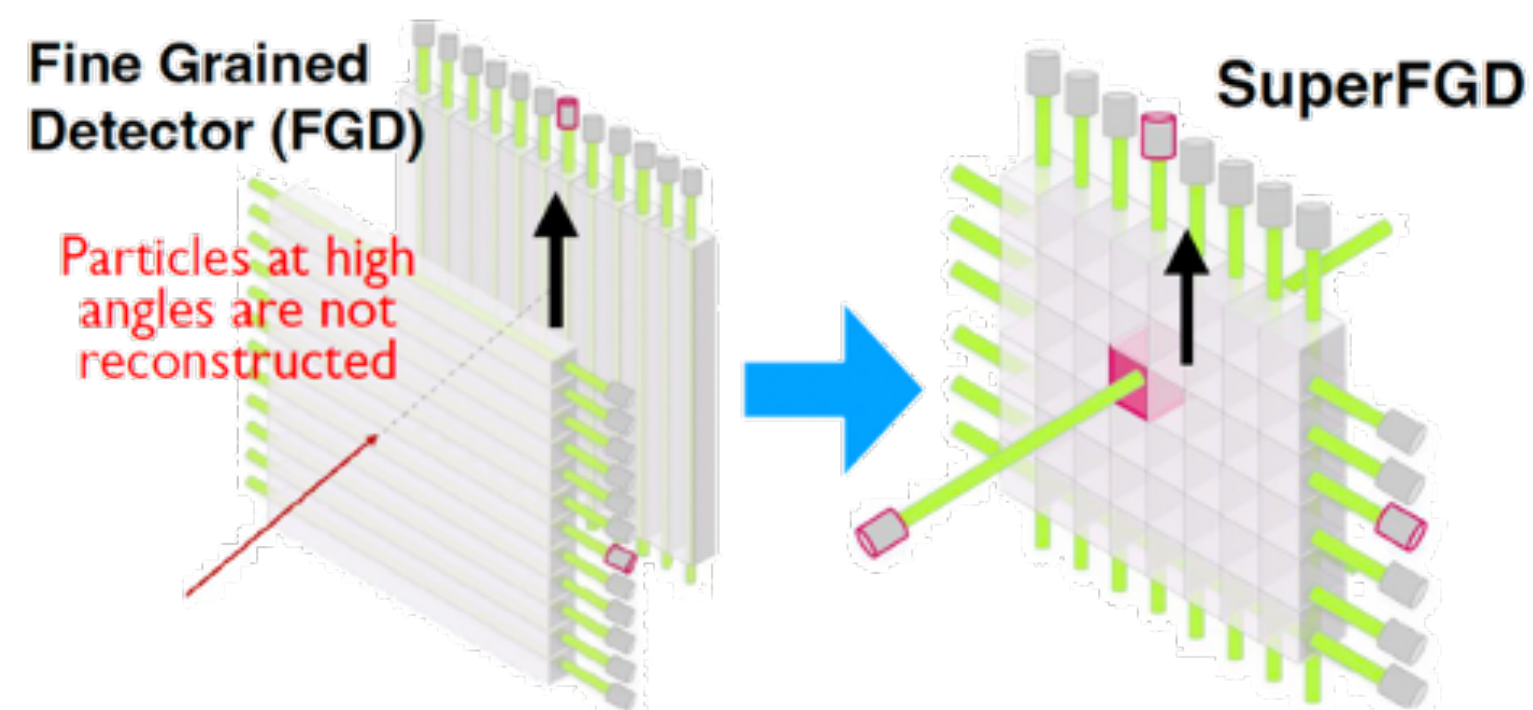
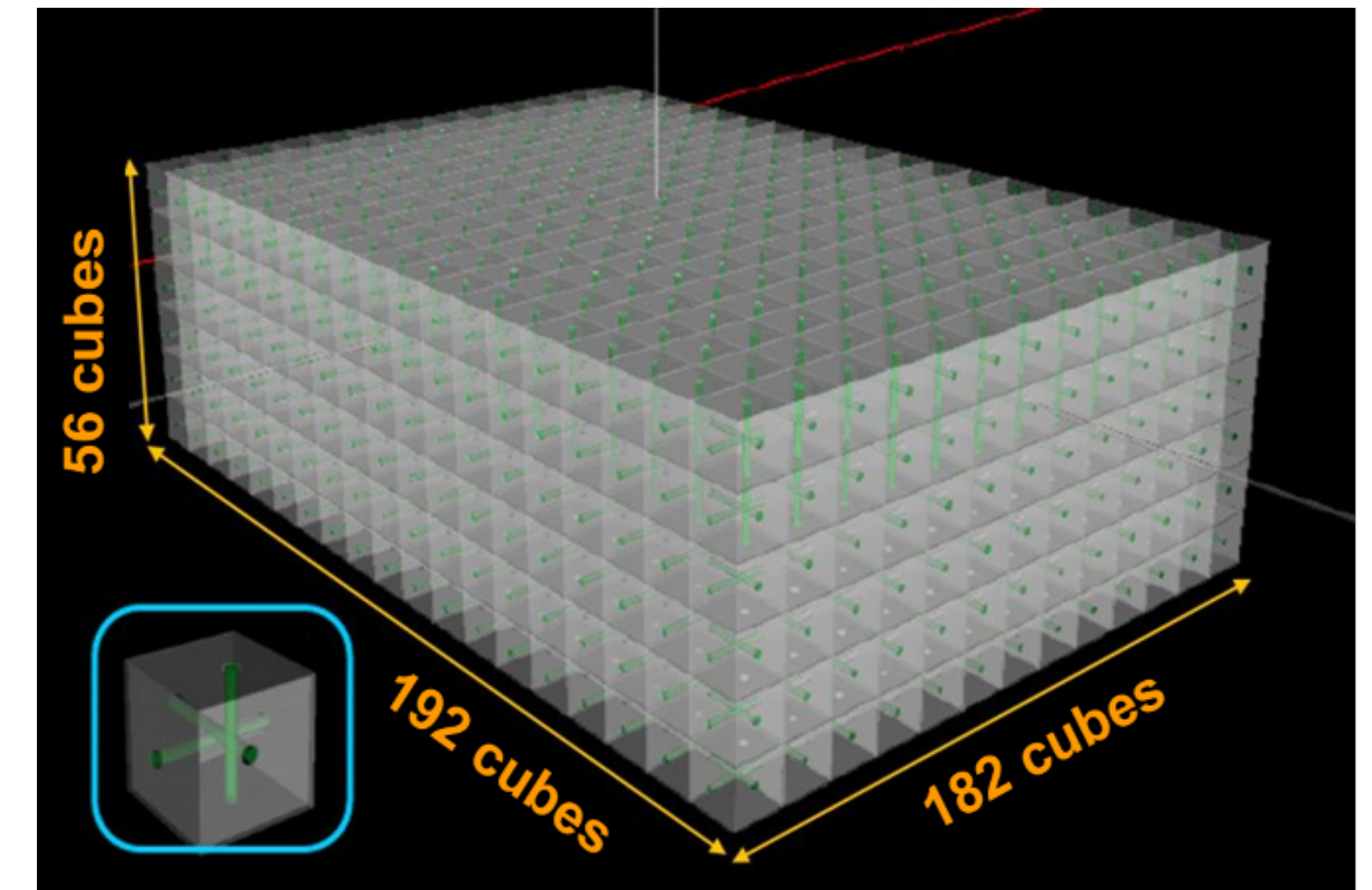
- Achieve  $4\pi$  acceptance
- Double the neutrino target fiducial mass



- Lower proton tracking threshold
- Neutron detection via sFGD Time of Flight
- Reduction of OOFV events

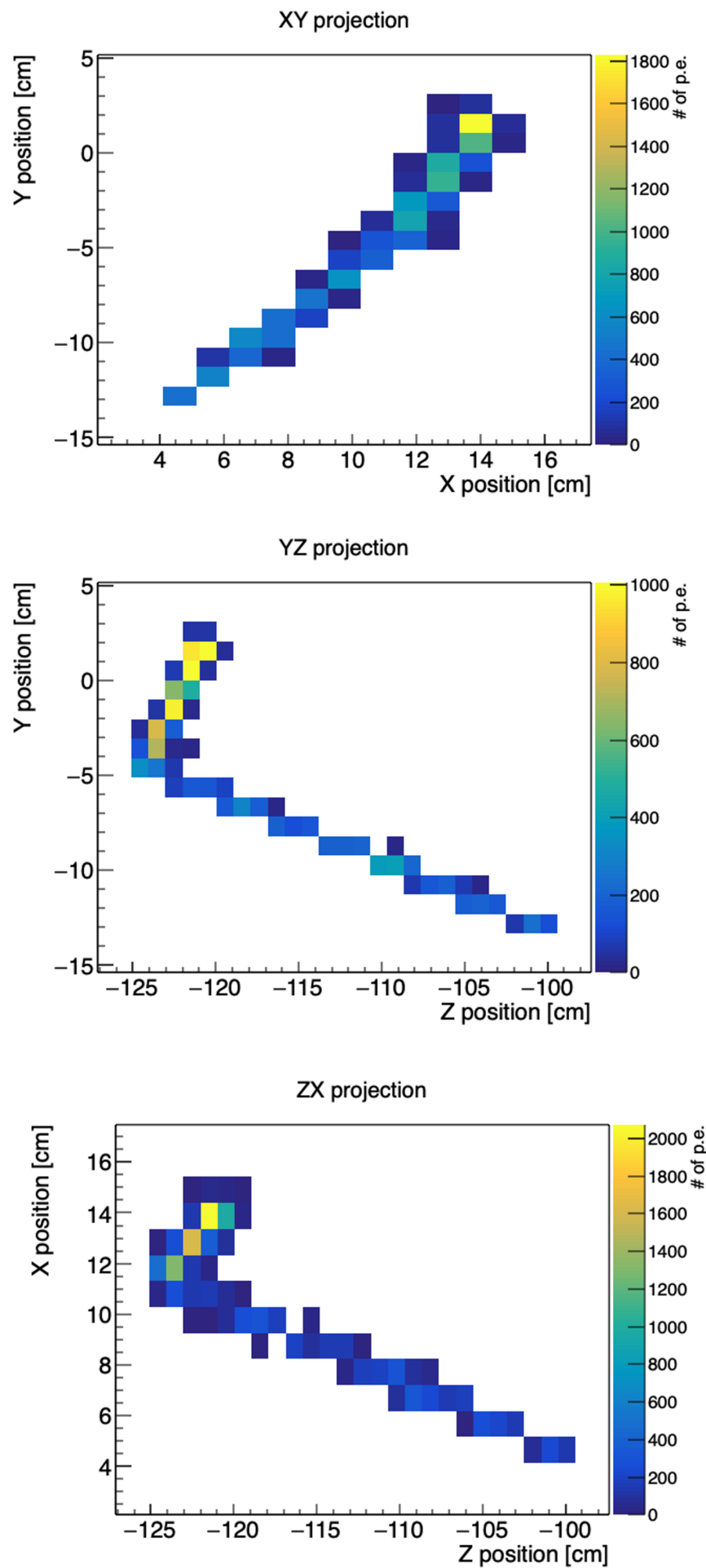
# The Super Fine Grain Detector (sFGD)

- 2 tons of fiducial mass (2m x 0.6m x 2m)
- High granularity and 3D tracking: 2M cubes (1cm<sup>3</sup> each) and each cube is crossed by 3 orthogonal fibres
- 56k WLS fibres doubled with SiPMs
- Reconstruction of fully contained (high angle) tracks

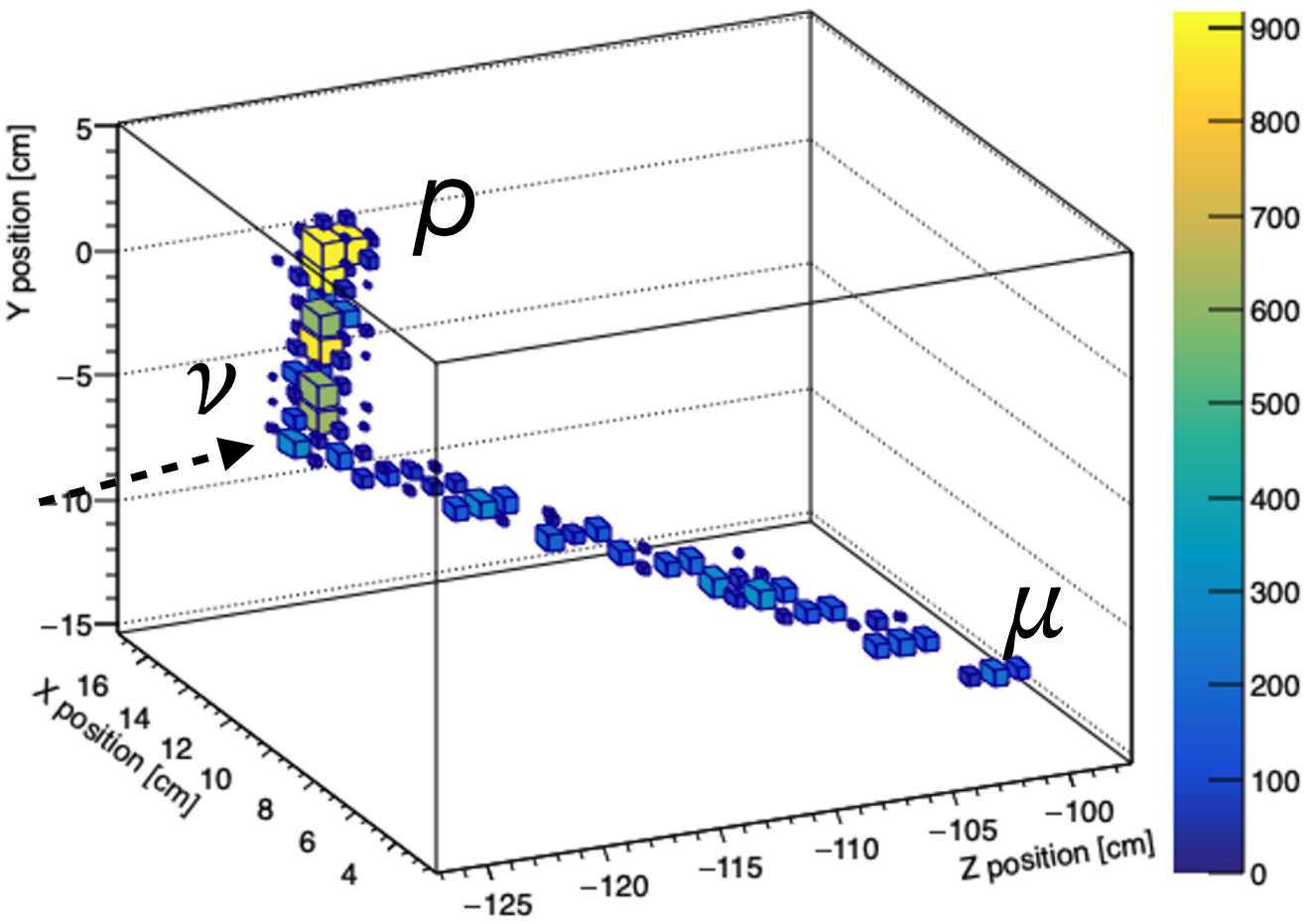


# The SFGD track reconstruction

Three projections with time, charge and 2D position information

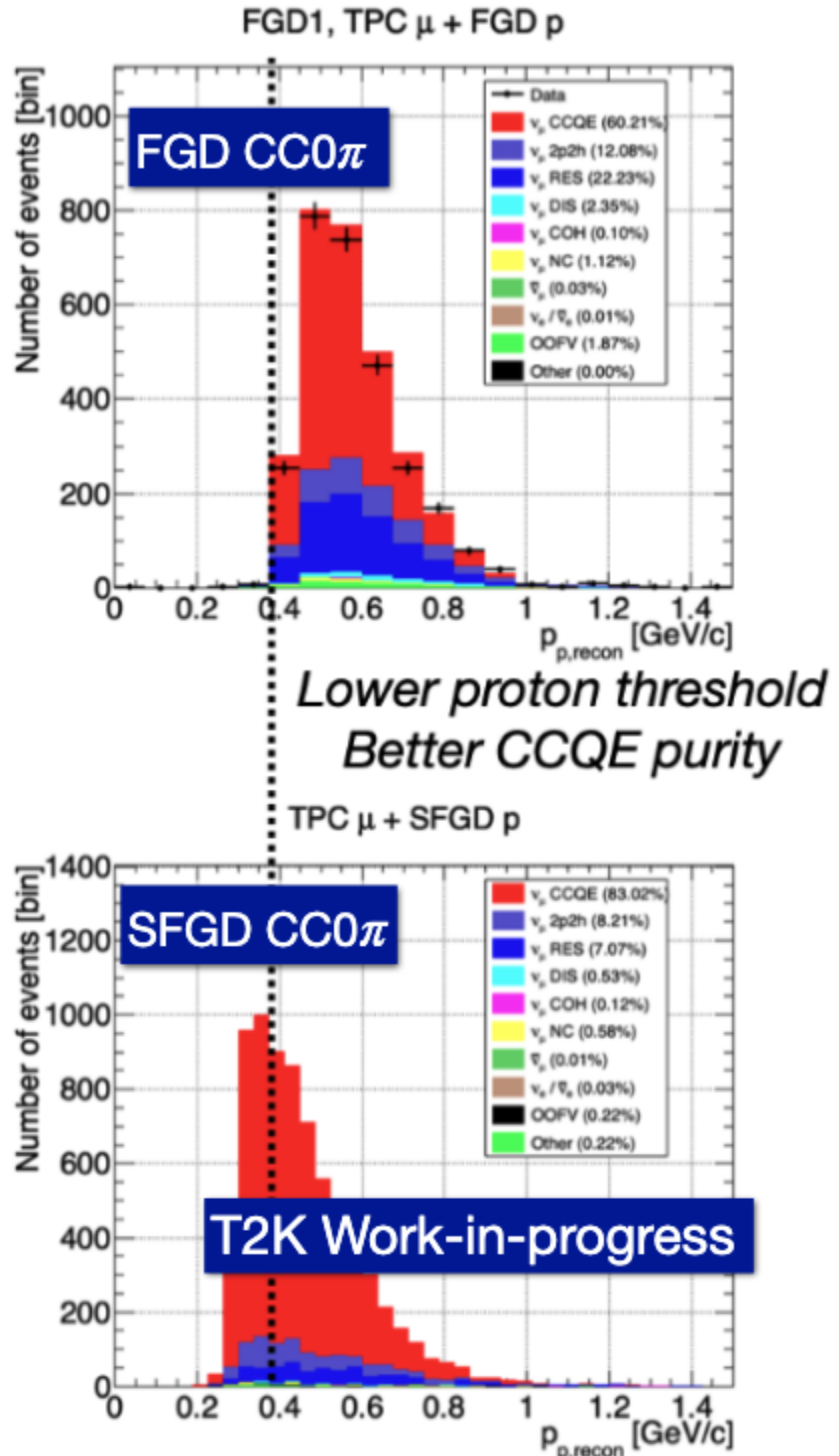


- Build 3D hits:
- Light attenuation
  - Charge sharing
  - Cube time reconstruction



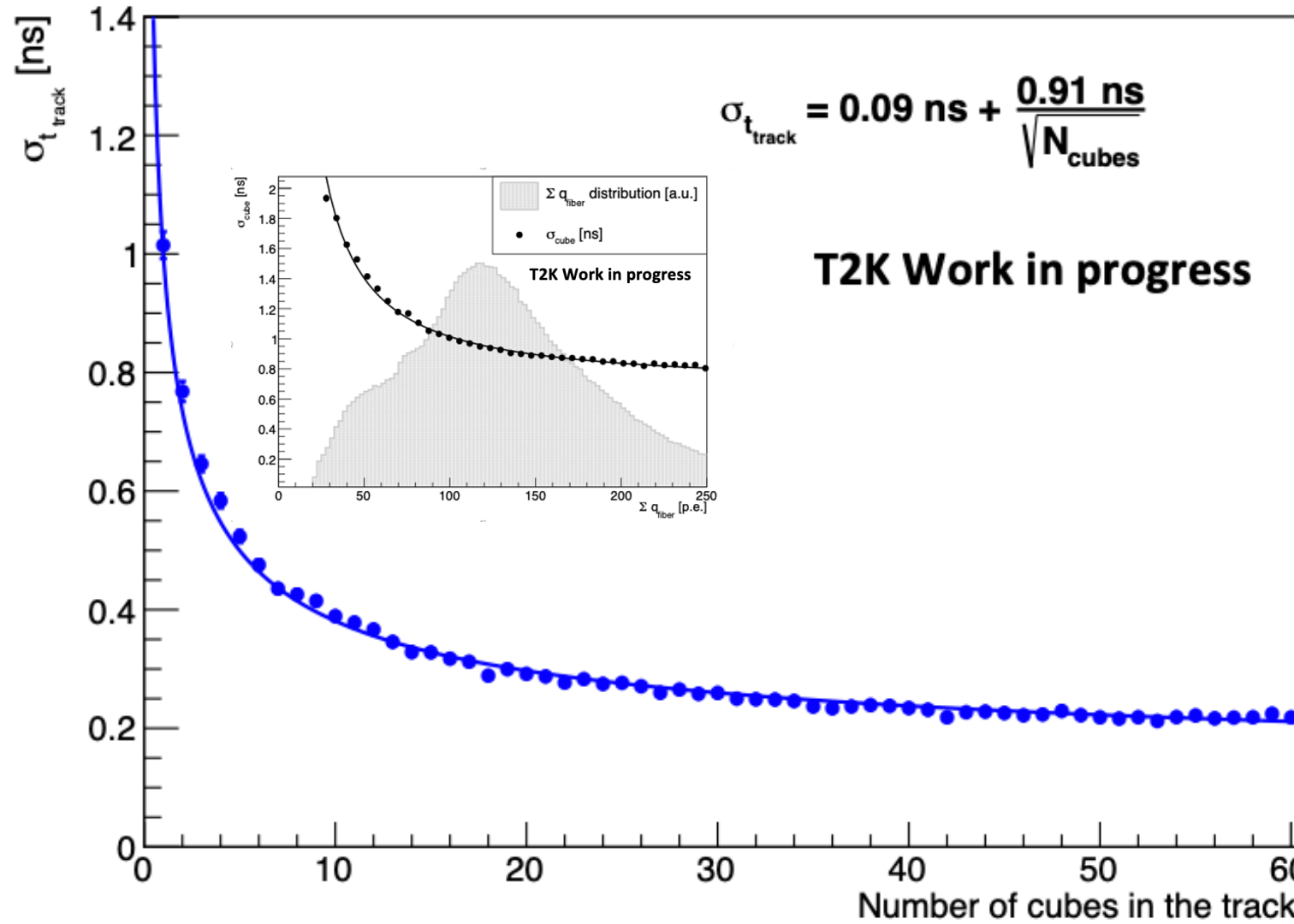
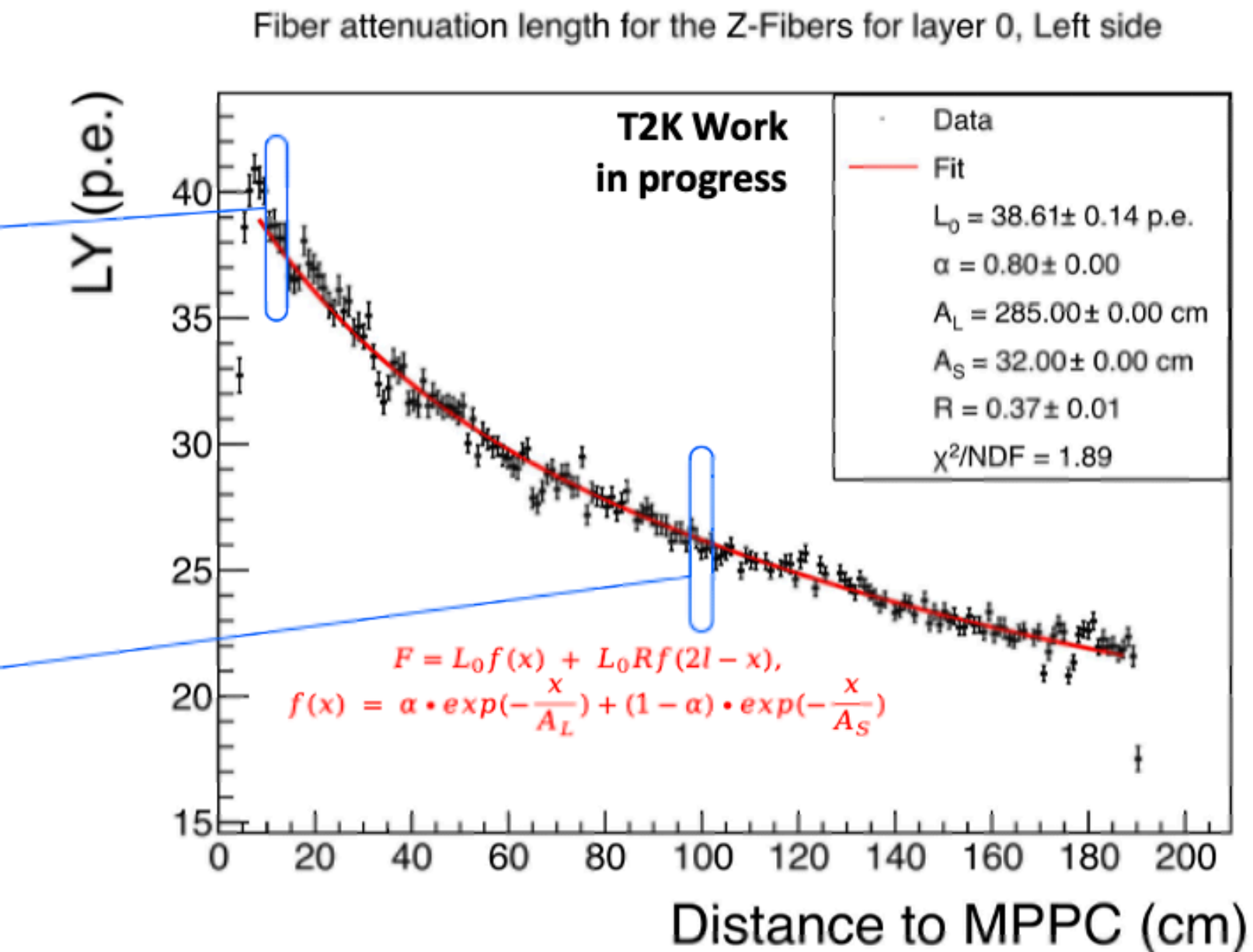
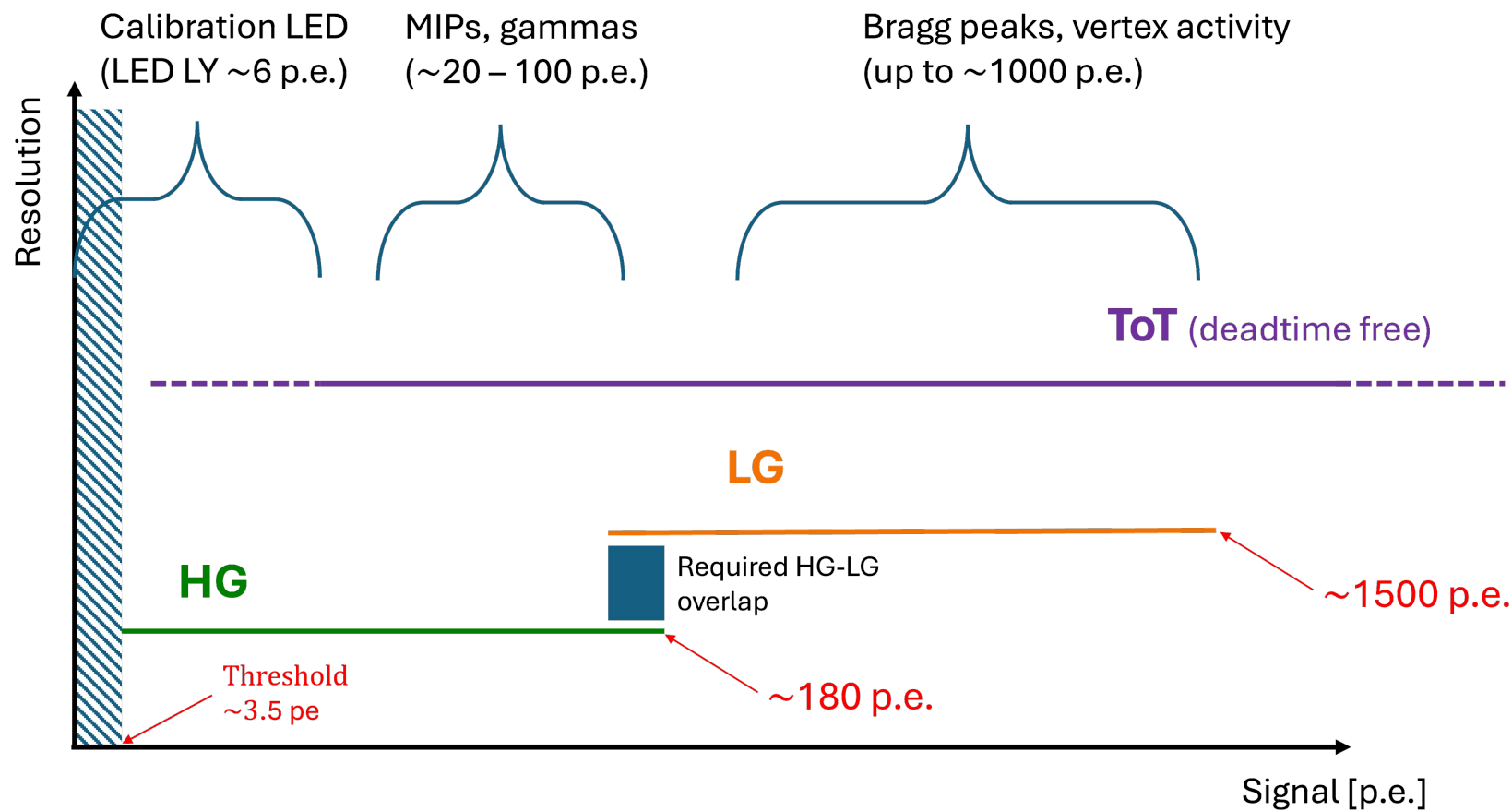
Improved track, cluster and vertex resolution

## Proton threshold + purity



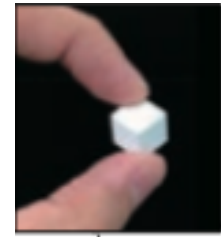
# sFGD commissioning

- 3 charge readout modes to cover a wide dynamic range, from few p.e. (calibration) up to ~1500p.e. (Bragg peaks, vertex activities)
- Light yield along the fibre modelled considering attenuation and reflections → charge reconstruction
- Achieved a sub-ns time resolution for a single cube and ~200ps resolution for long tracks → Time of flight measurements



# SFGD Assembly

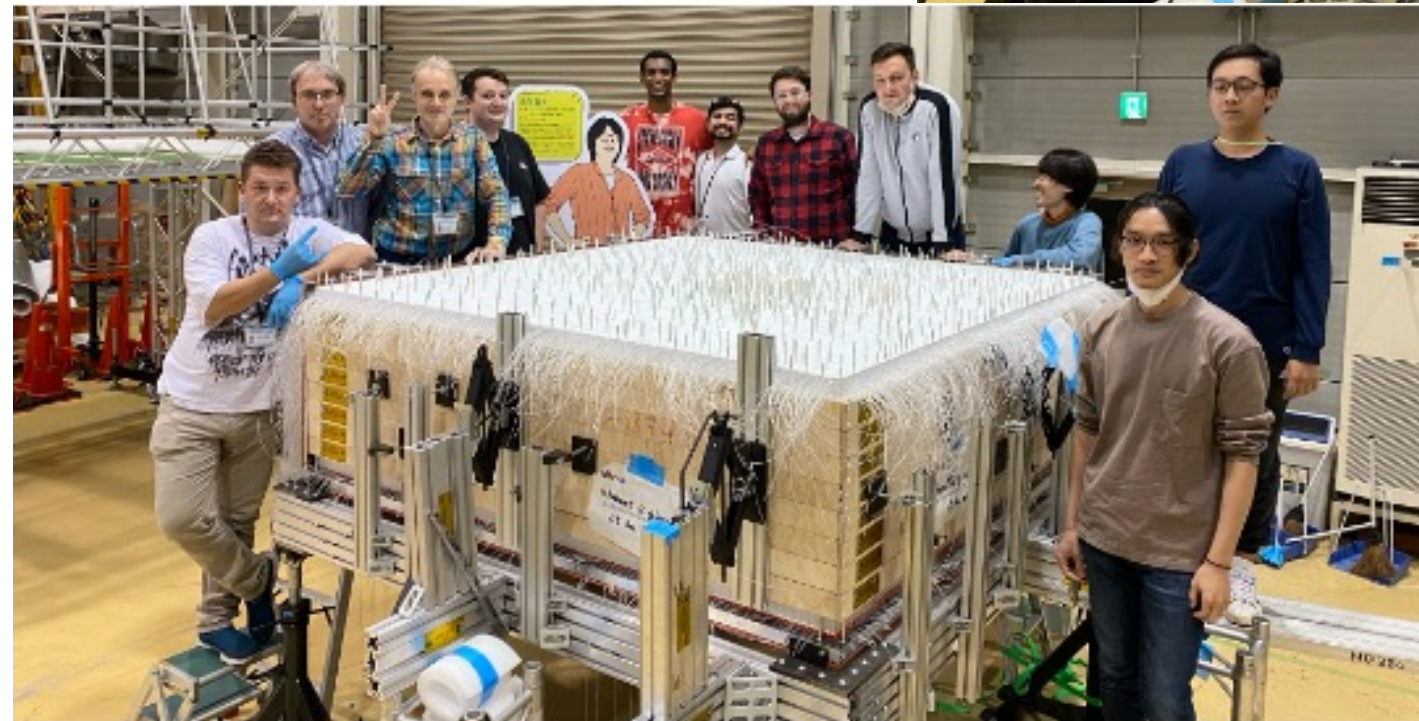
Installation into the JPARC Pit



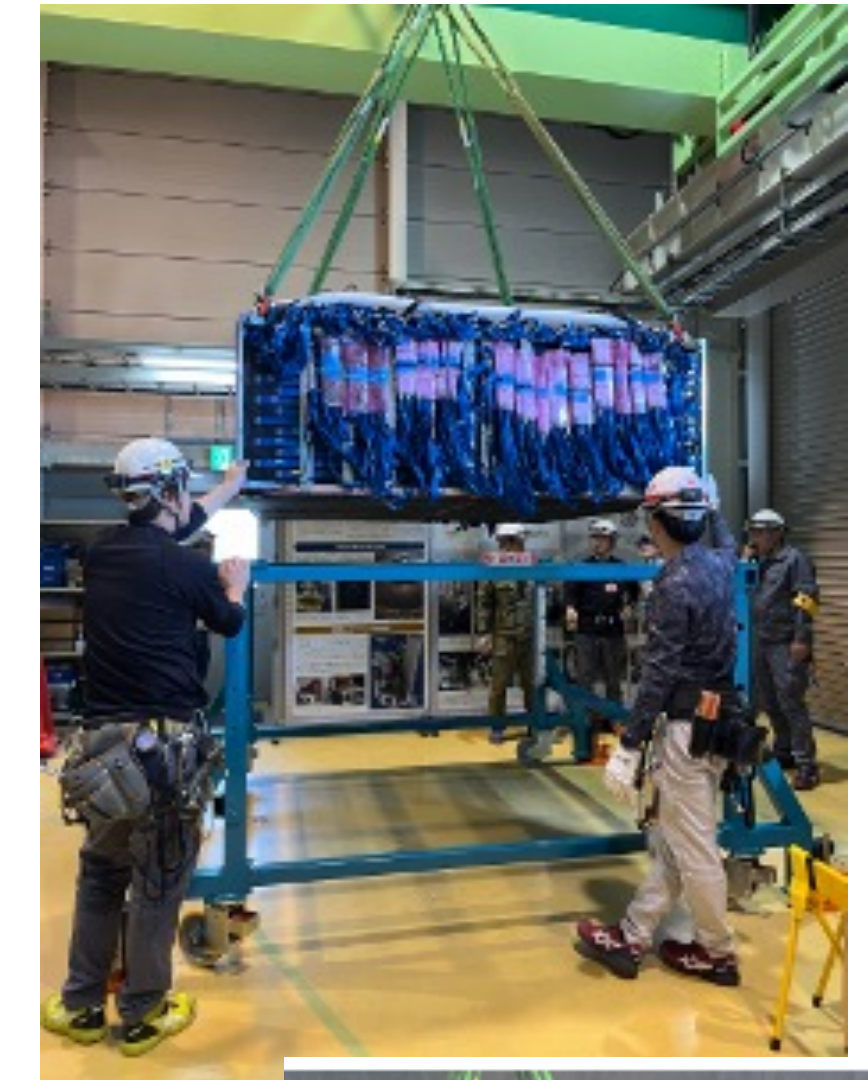
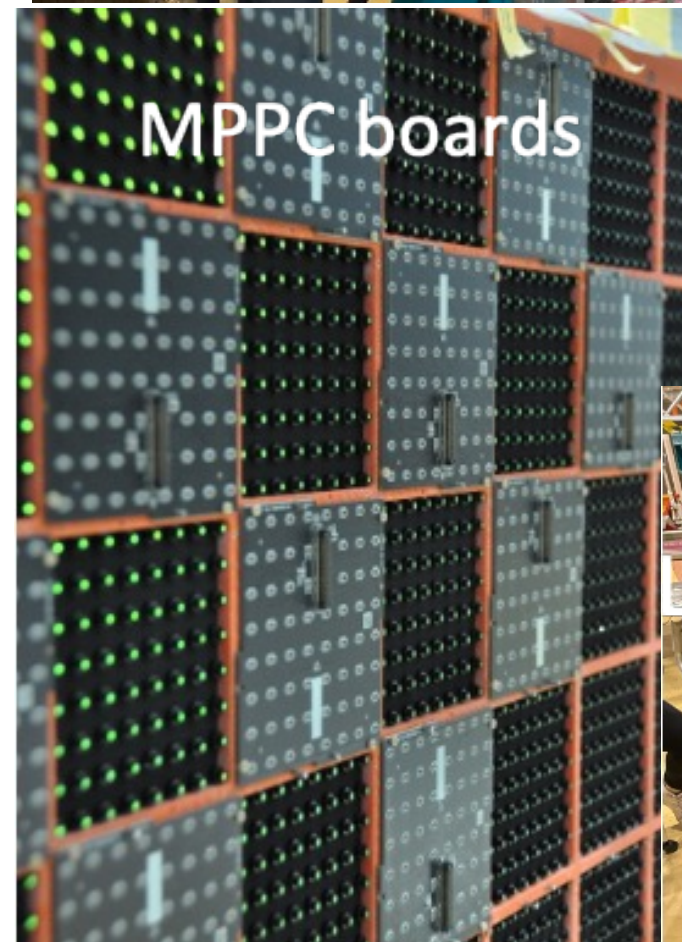
Single unit



Layers assembly



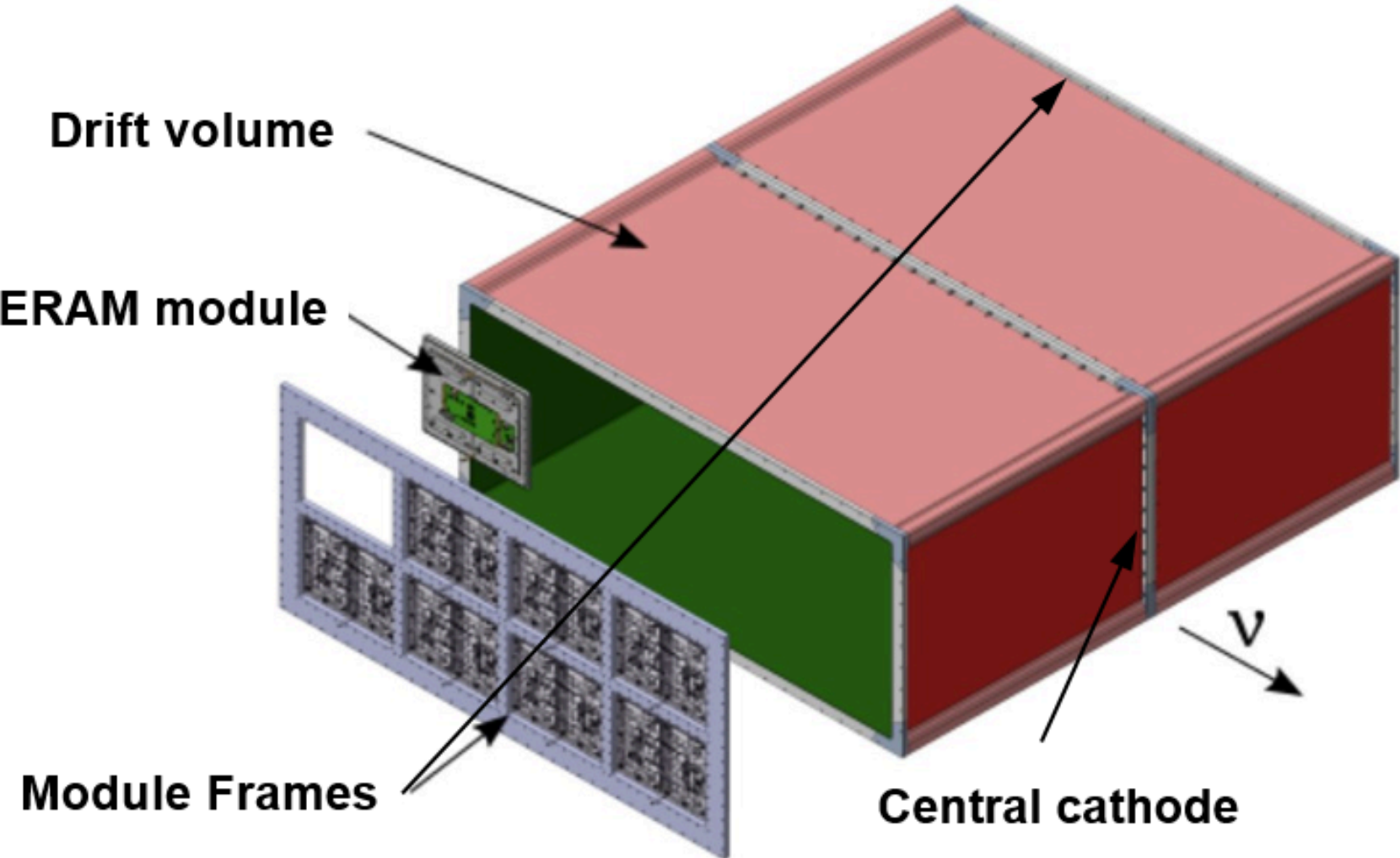
Removing fishing lines, inserting fibres



Co

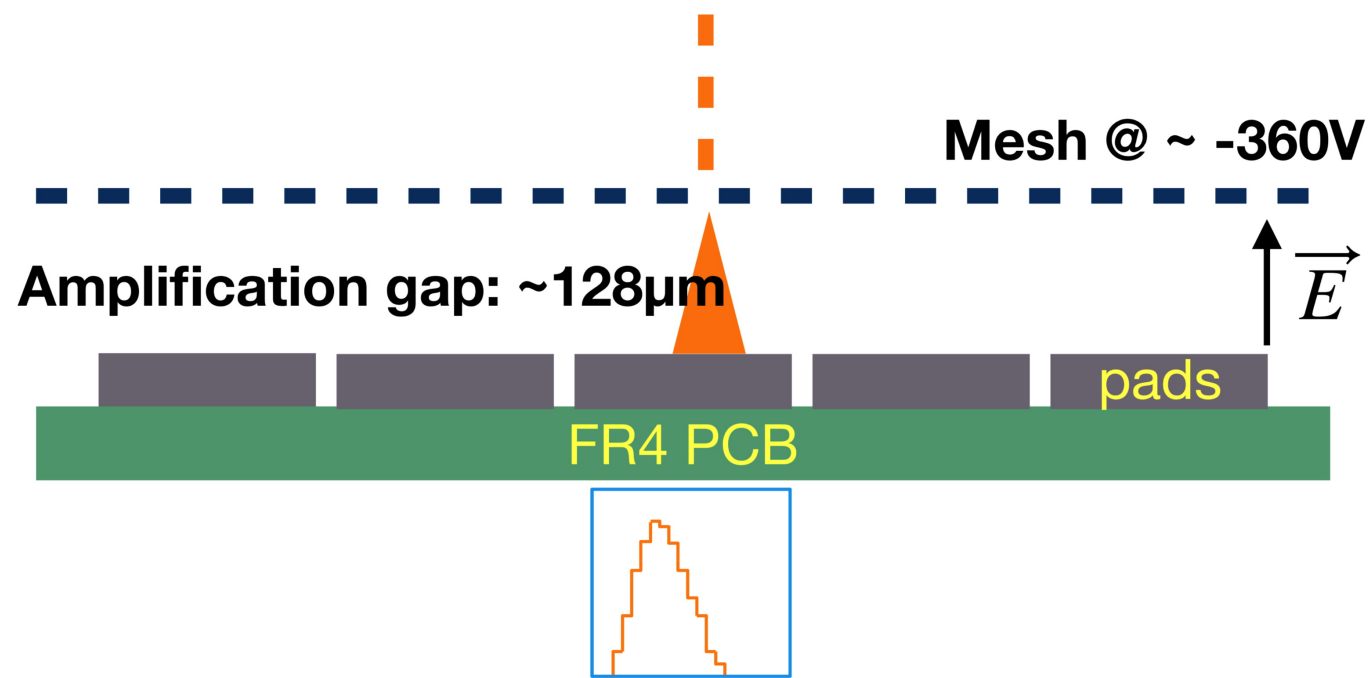
# The High-Angle-TPCs (HAT)

- Argon based gas TPCs with a central cathode and two 1m drift volumes per TPC
- Uniform E field of  $\sim 275$  V/cm
- New field cage design: single gas-tight box with field and mirror strips
- New resistive MicroMegas allowing charge spreading across several pads to improve the spatial resolution



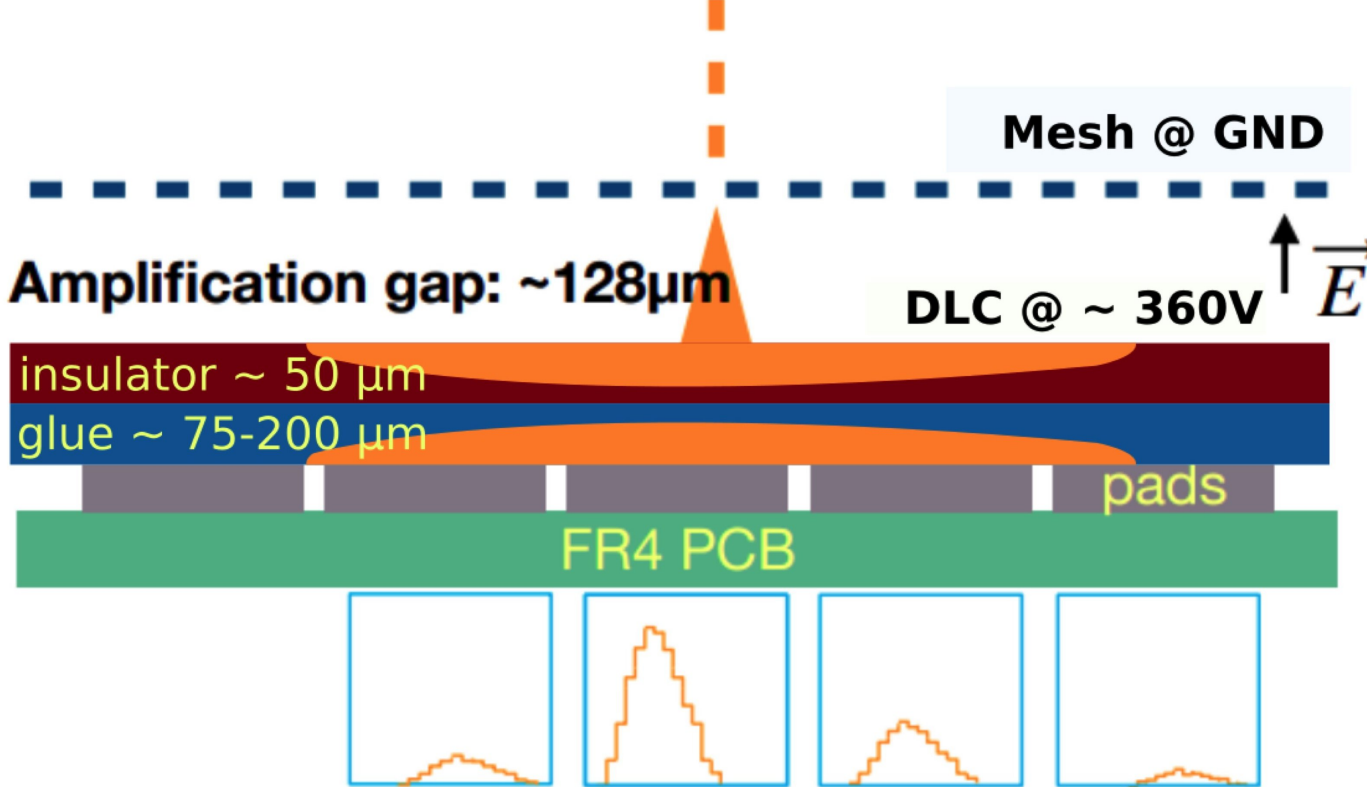
### Bulk MicroMegas

Vertical TPCs: charge on single pad.  
Spatial resolution : 600-1600  $\mu\text{m}$



### Resistive MicroMegas

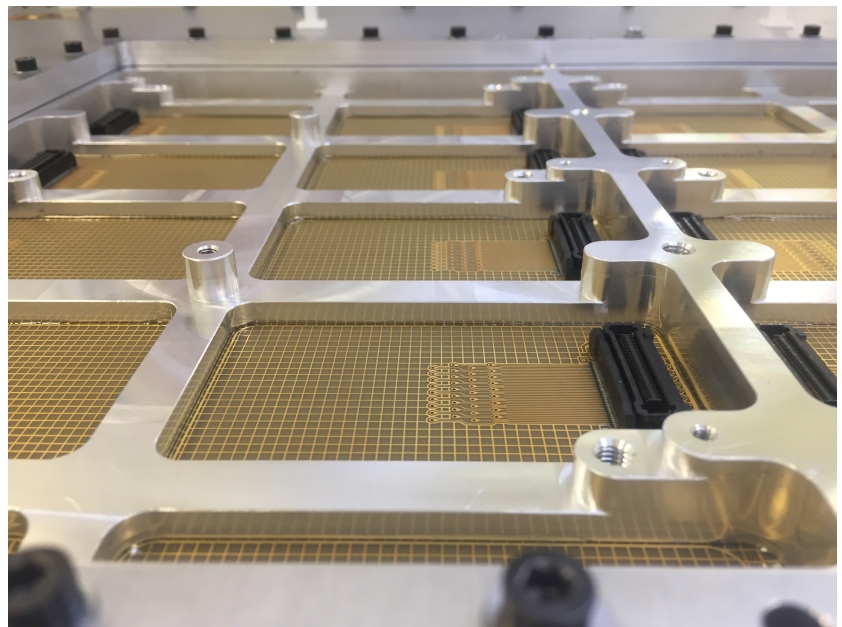
HAT TPCs: charge on multiple pads.  
Spatial resolution : 200-800  $\mu\text{m}$



Front of ERAM module

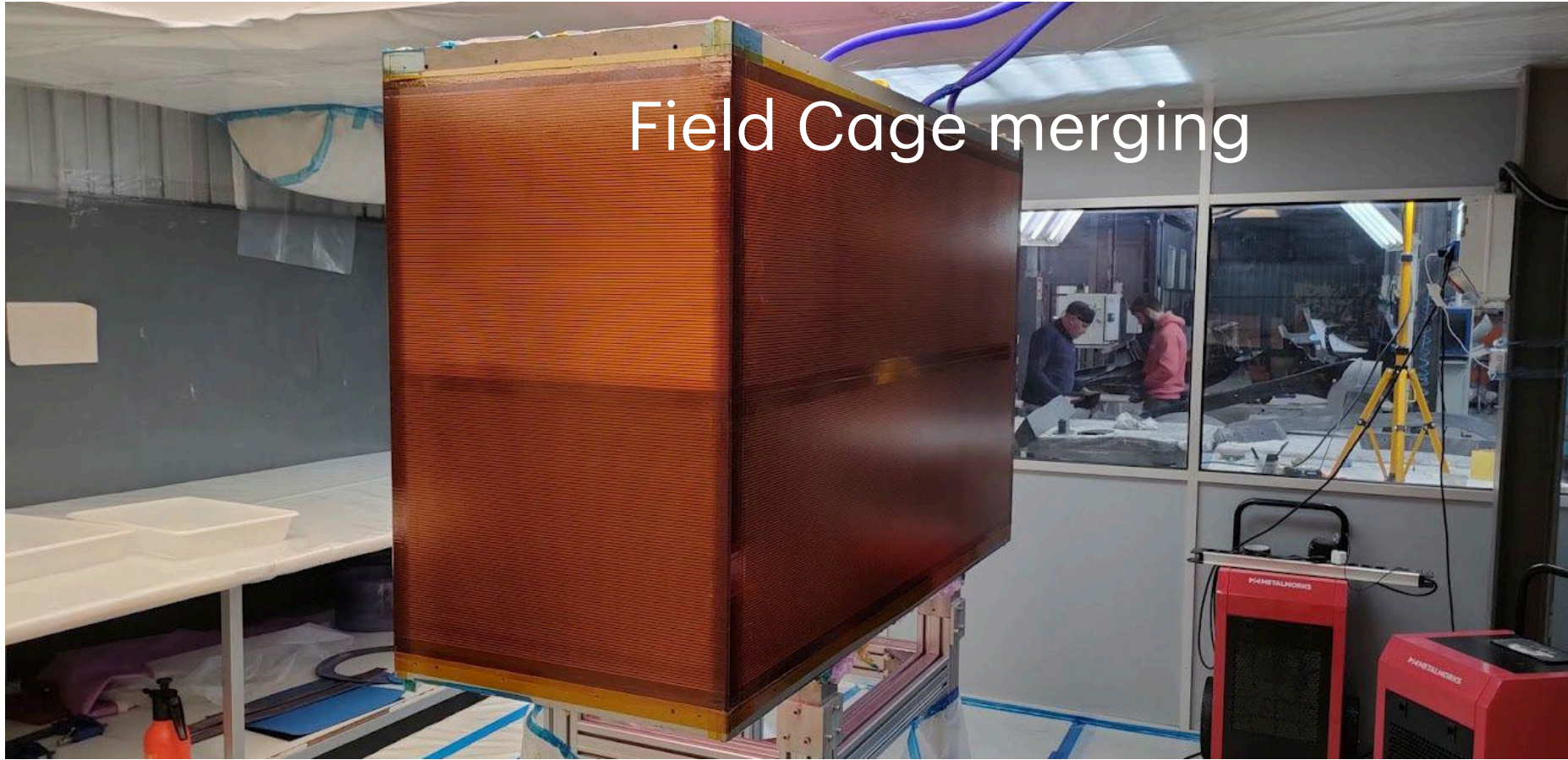


Back of ERAM module

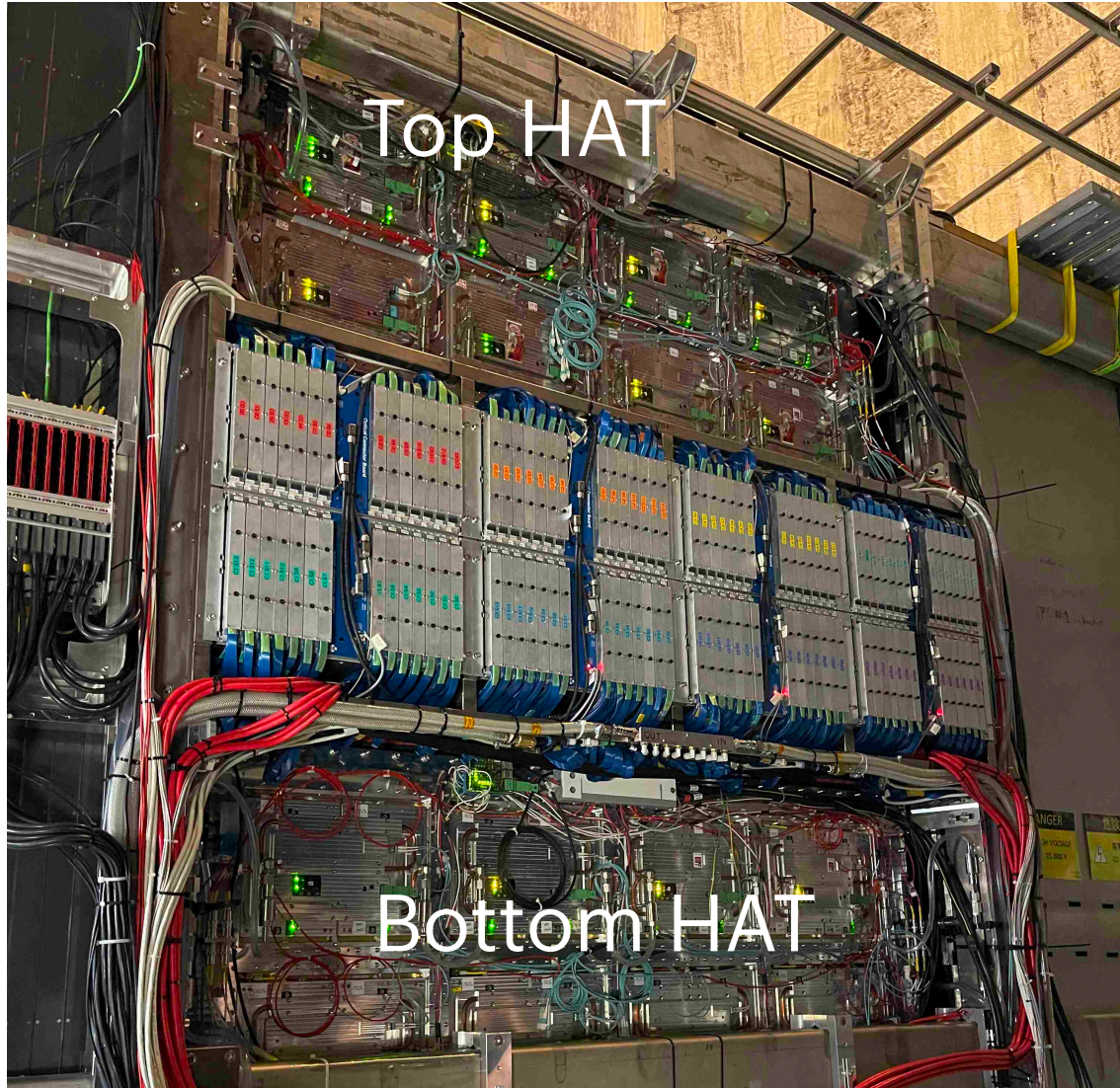
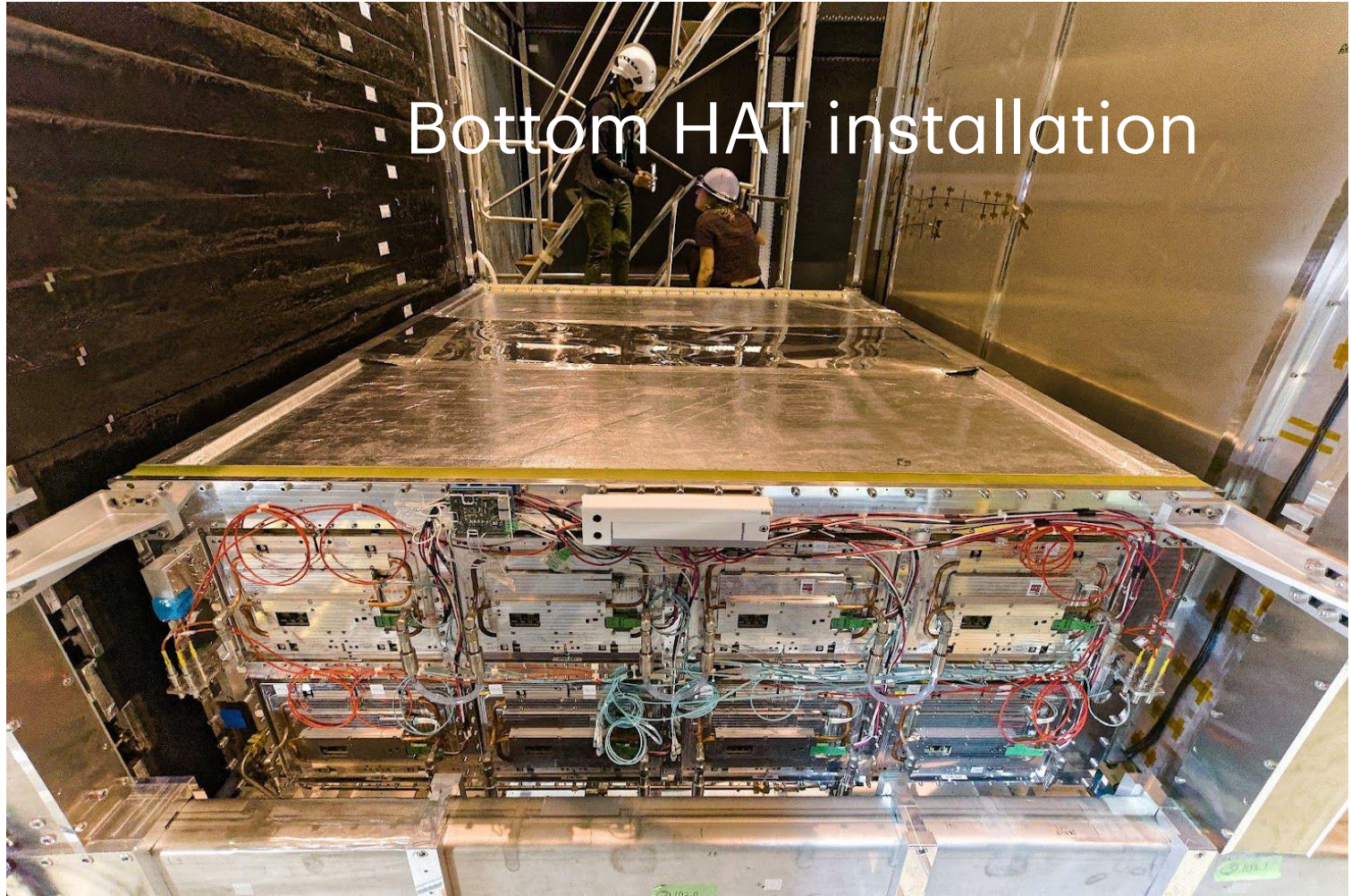


# The HAT assembly

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# The HAT commissioning

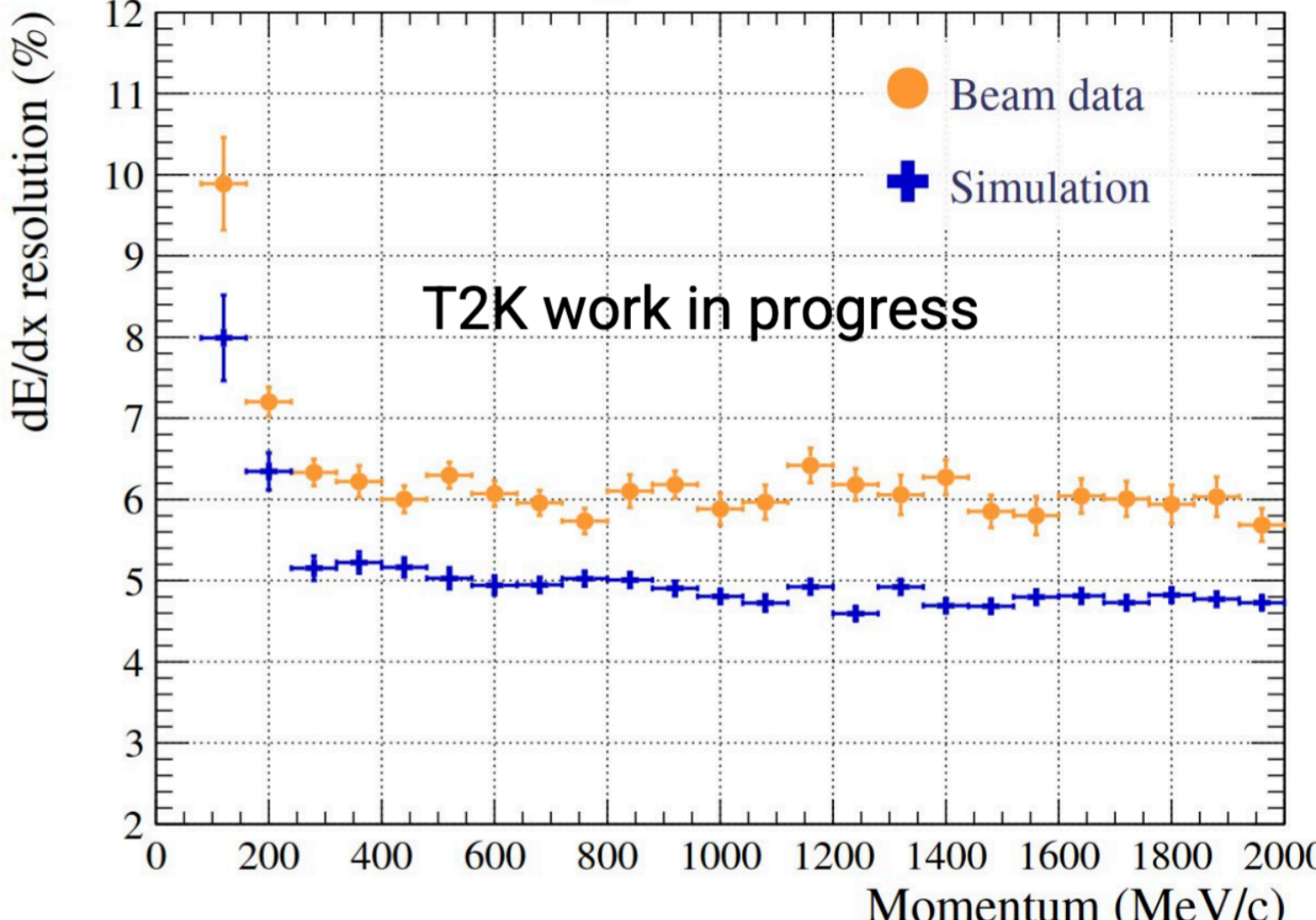
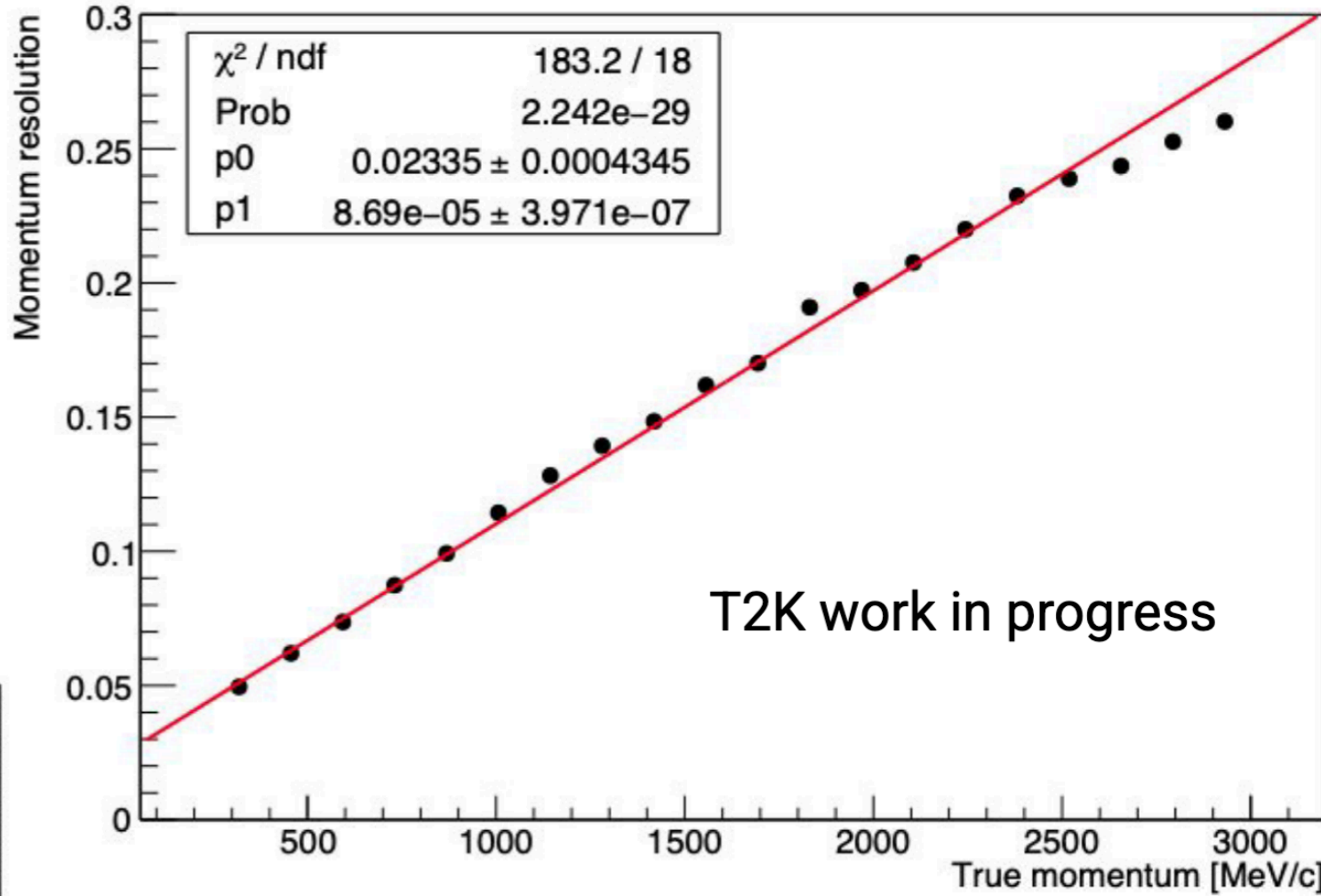
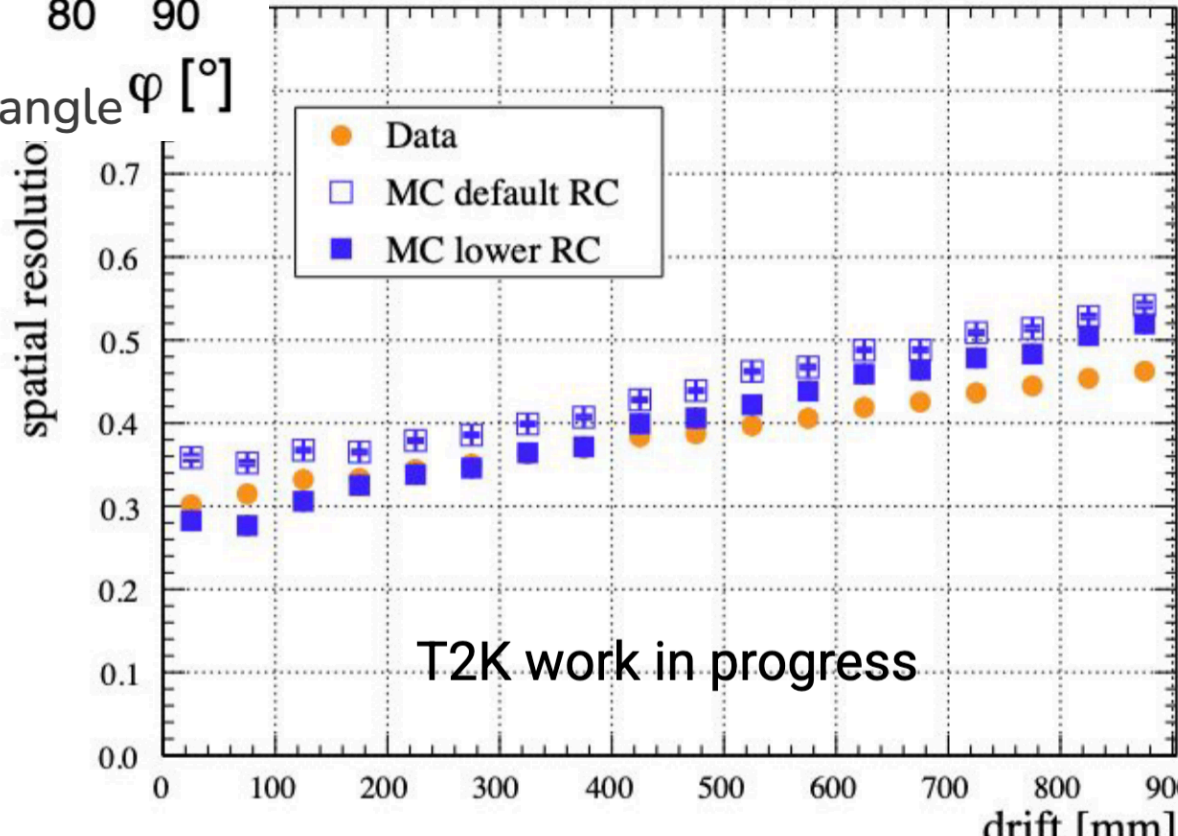
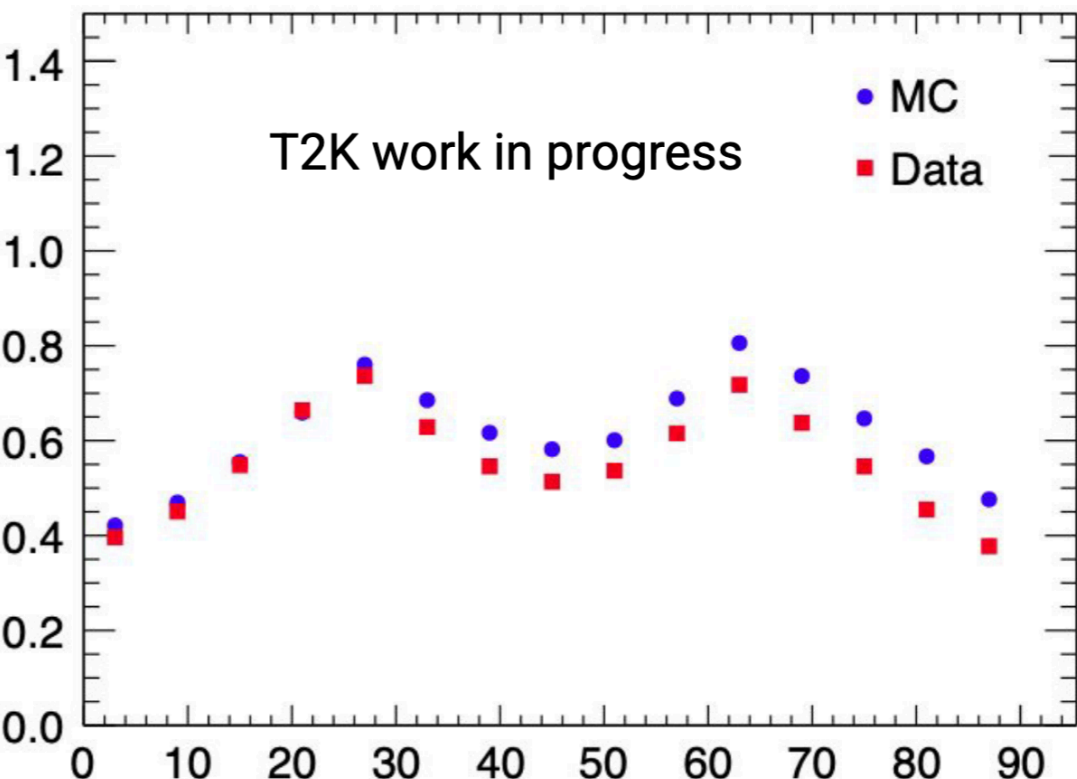
[NIM-A \(2019\) 163286](#)

[NIM-A \(2021\) 166109](#)

[NIM-A \(2023\) 168248](#)

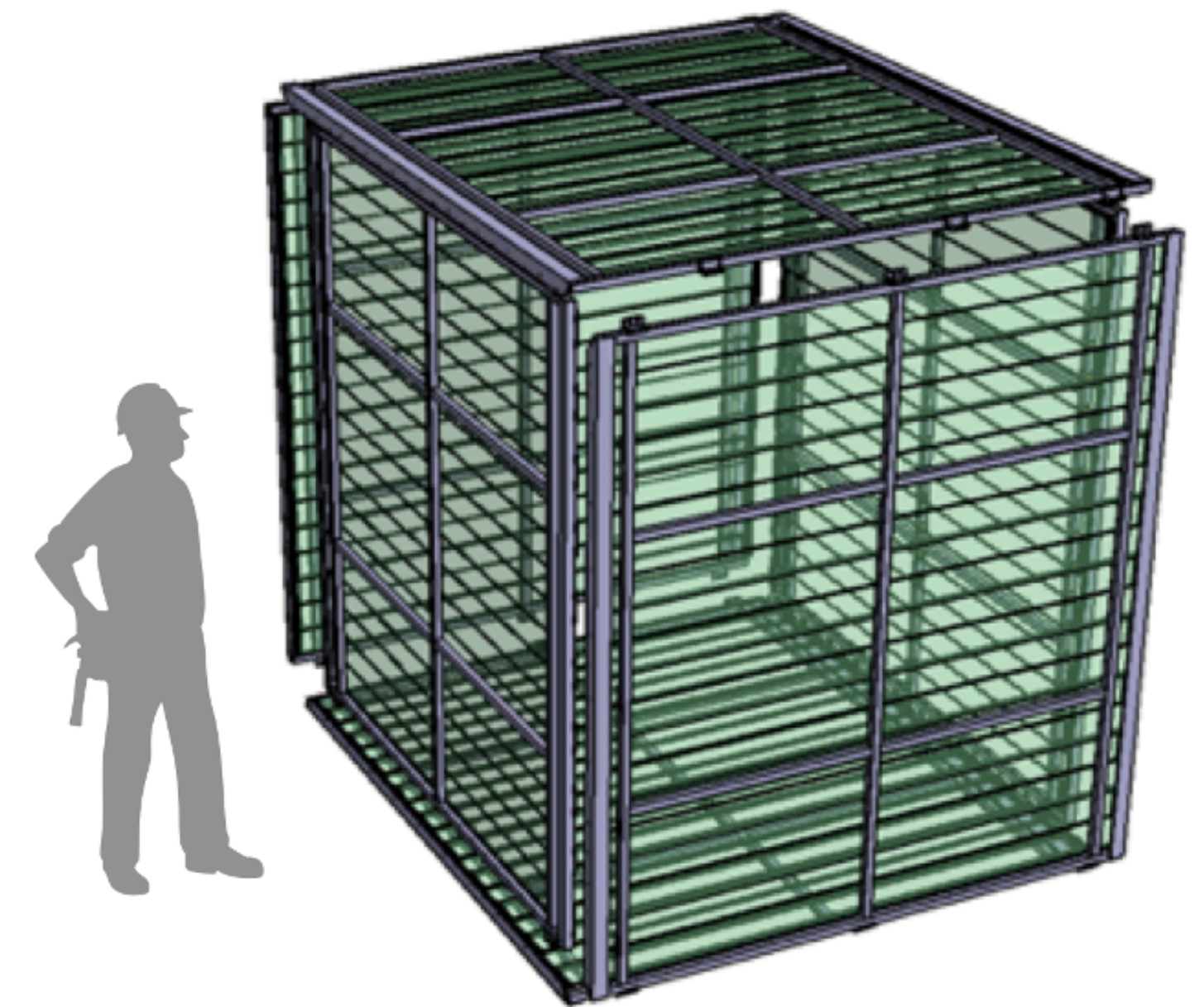
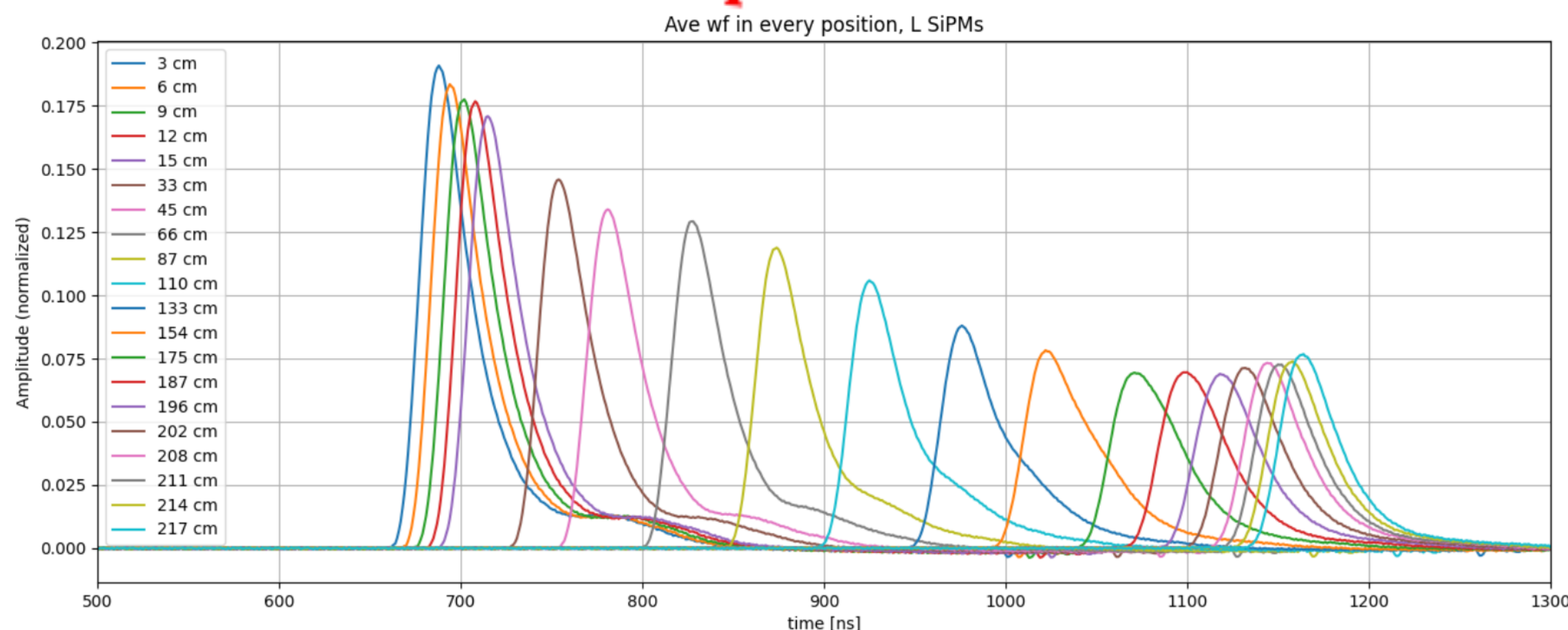
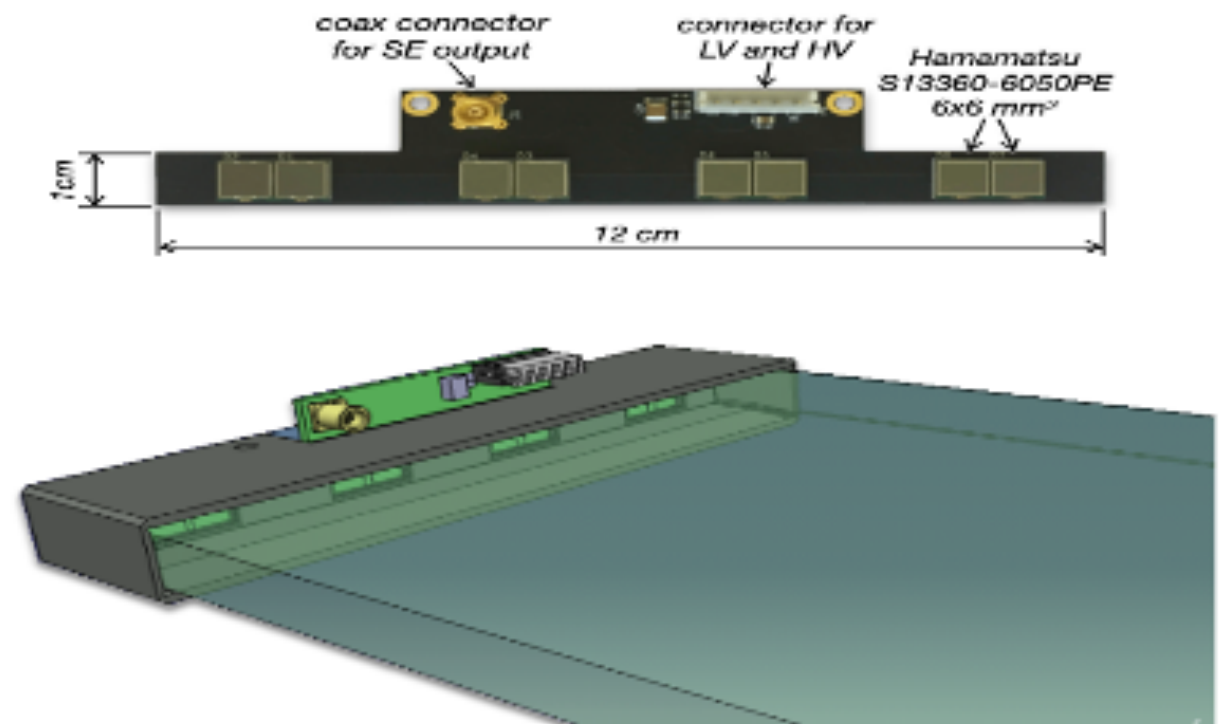
+ others in preparation

- Spatial resolution between 350-500 $\mu\text{m}$  stable with drift distance
- Momentum resolution of 10% at 1 GeV
- $dE/dx$  resolution of 6%, stable with drift and track angles



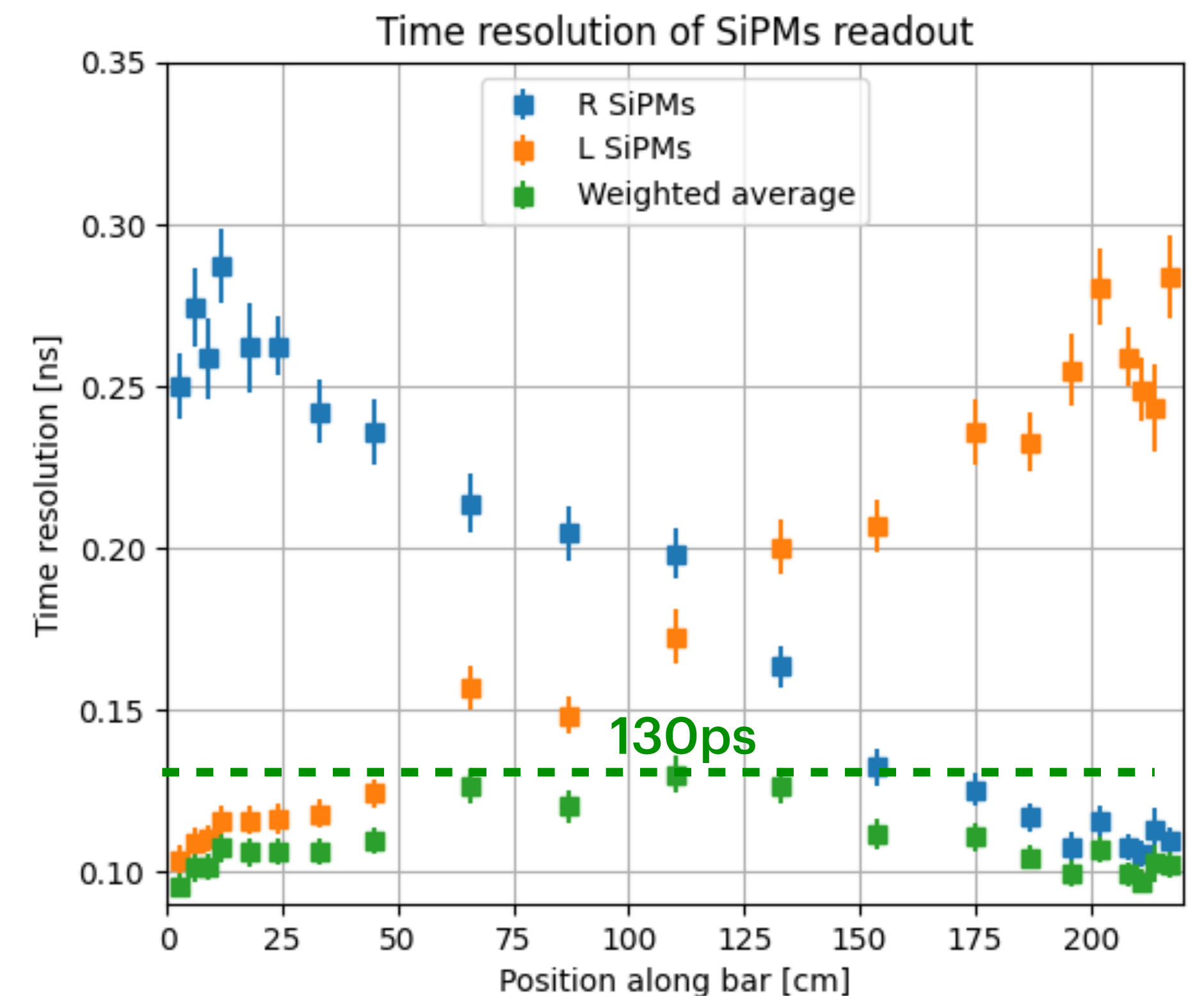
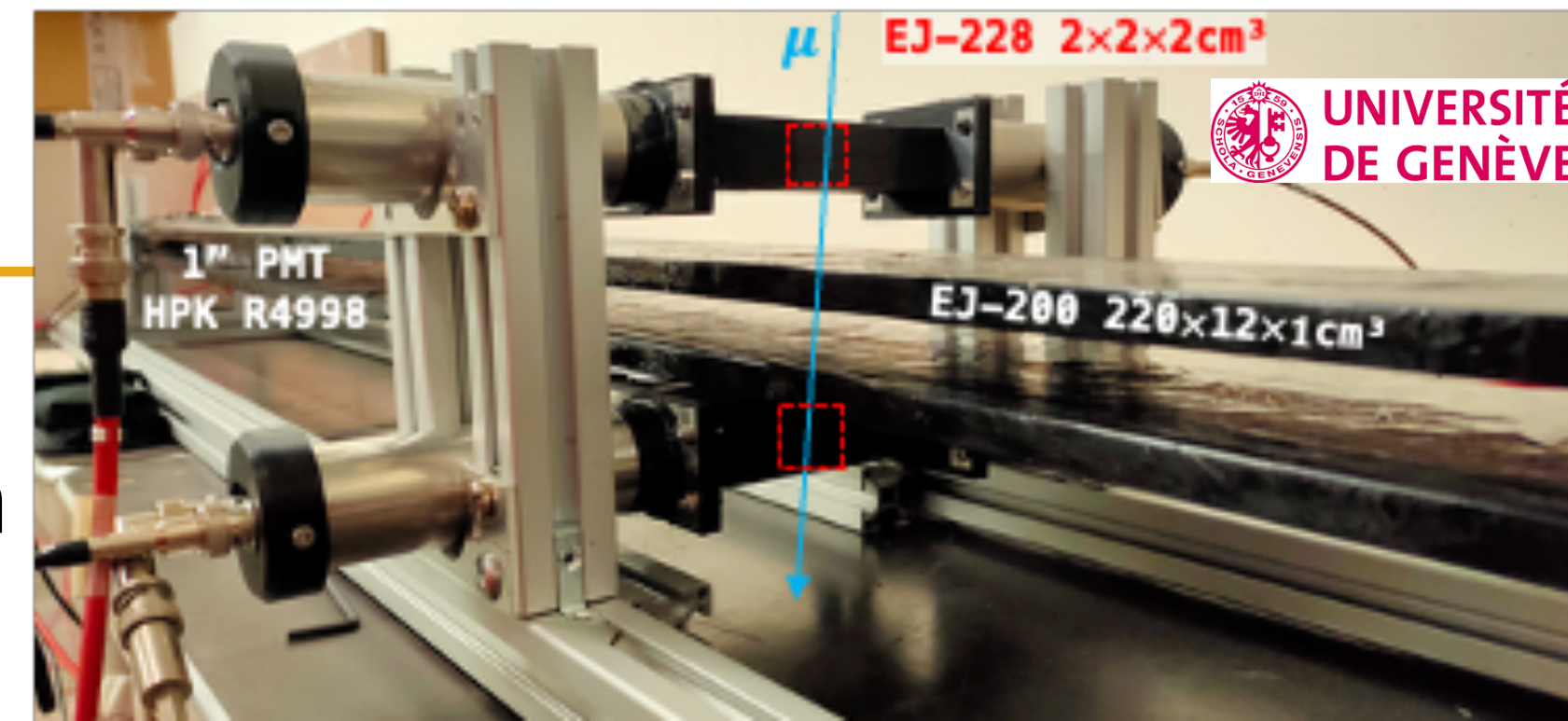
# The Time of Flight (ToF) detector

- 6 panels, each of 240 x 220 cm<sup>2</sup> active area
- 20 plastic (EJ-200) scintillator bars per panel (220 x 12 x 1 cm<sup>3</sup>)
  - Fast scintillation signal (rise 0.9ns , decay 2.1ns)
  - Light emitted at  $\lambda = 425\text{nm}$
  - High light yield: 10000 ph/1 MeV e<sup>-</sup>
  - Light Attenuation length of 380cm
- Readout done by arrays of 8 SiPMs per bar end (24% coverage).



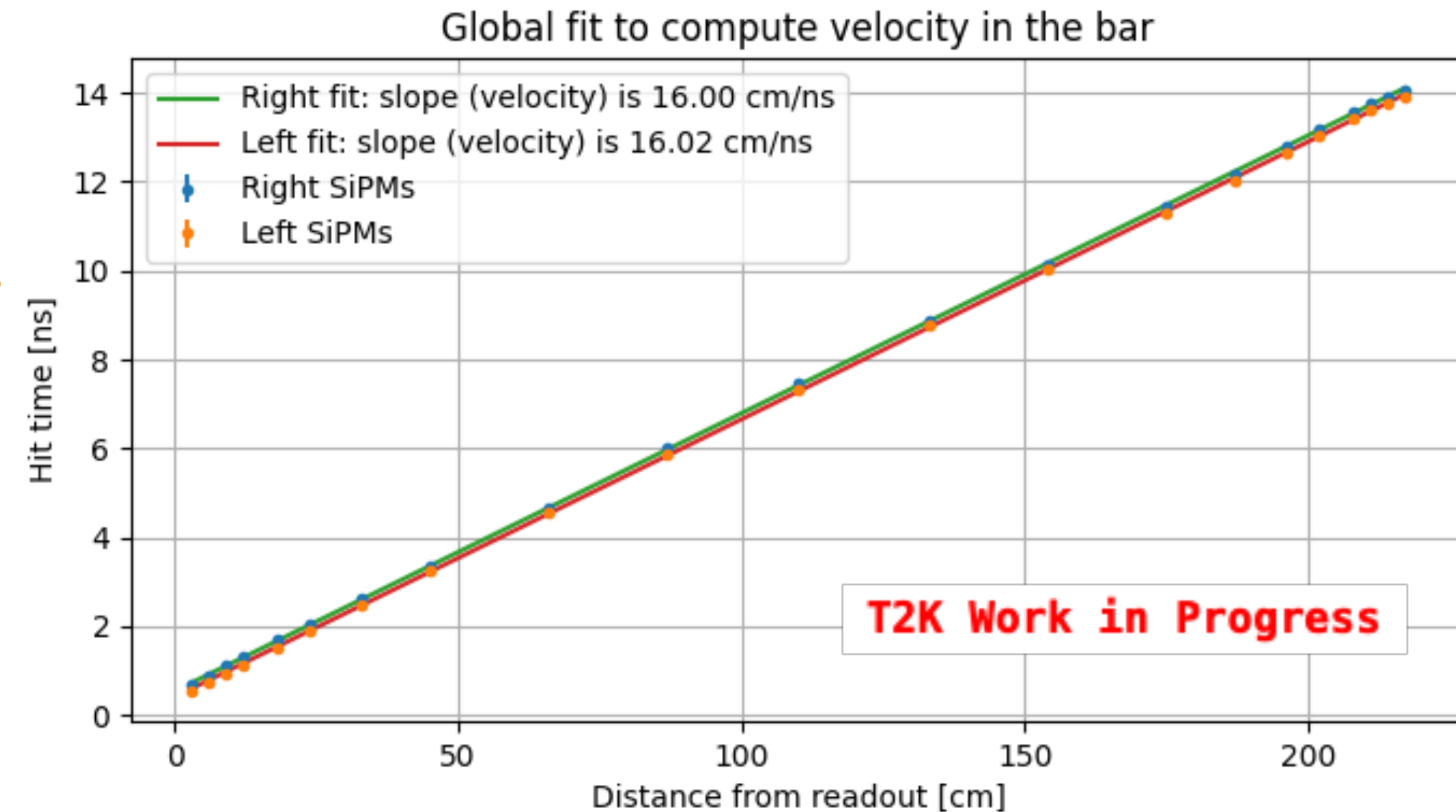
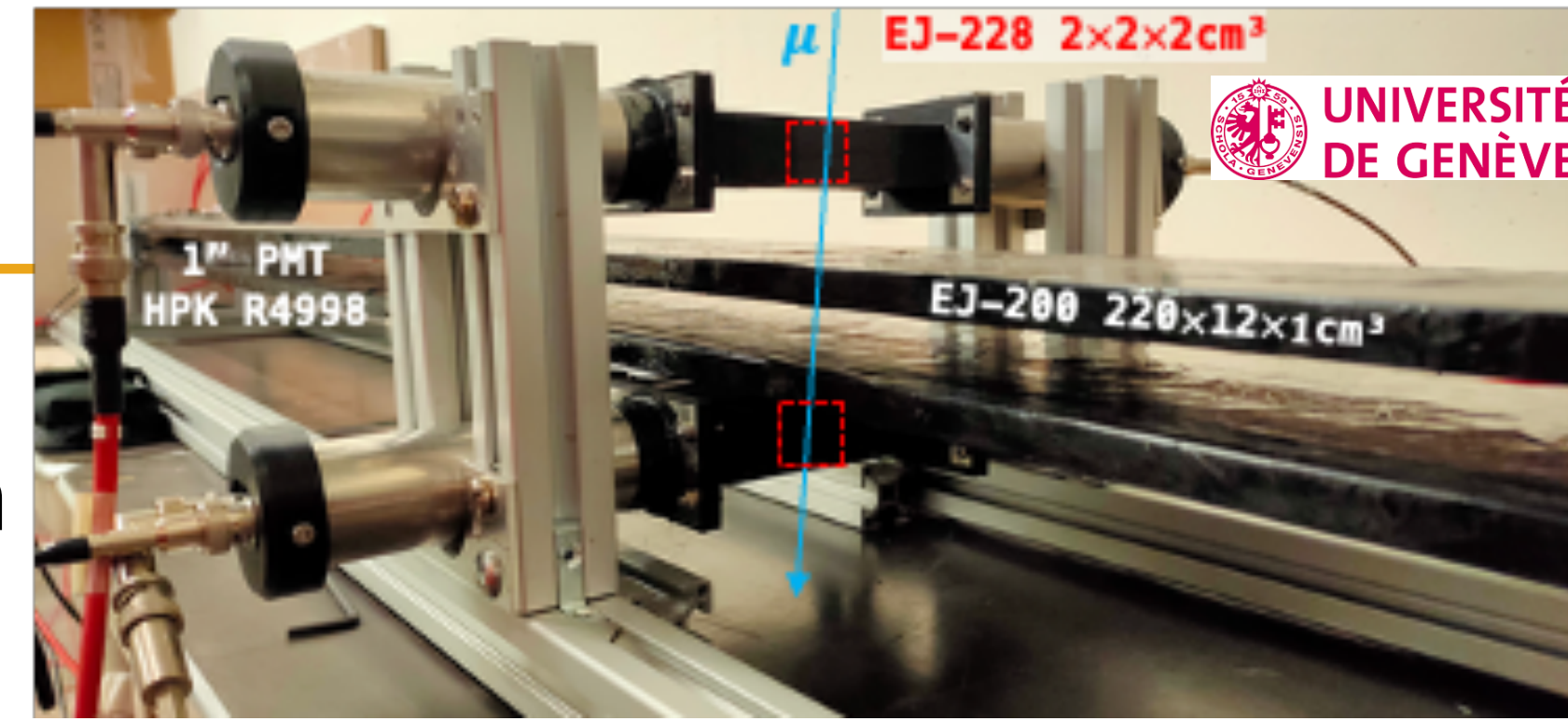
# Characterisation of a ToF bar

- Use of external trigger to select cosmic rays at a given interaction point along the bar.
- Time measurements between trigger and bar readout :  
 $\Delta t = t_{\text{Trigger}} - t_{\text{SiPM}}$  for 20 measurements along the bar
- **130ps resolution achieved nearly position independent!**



# Characterisation of a ToF bar

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 $\Delta t = t_{\text{Trigger}} - t_{\text{SiPM}}$  for 20 measurements along the bar
- **130ps resolution achieved nearly position independent!**
- **Effective light velocity inside the bar about 16 cm/ns**

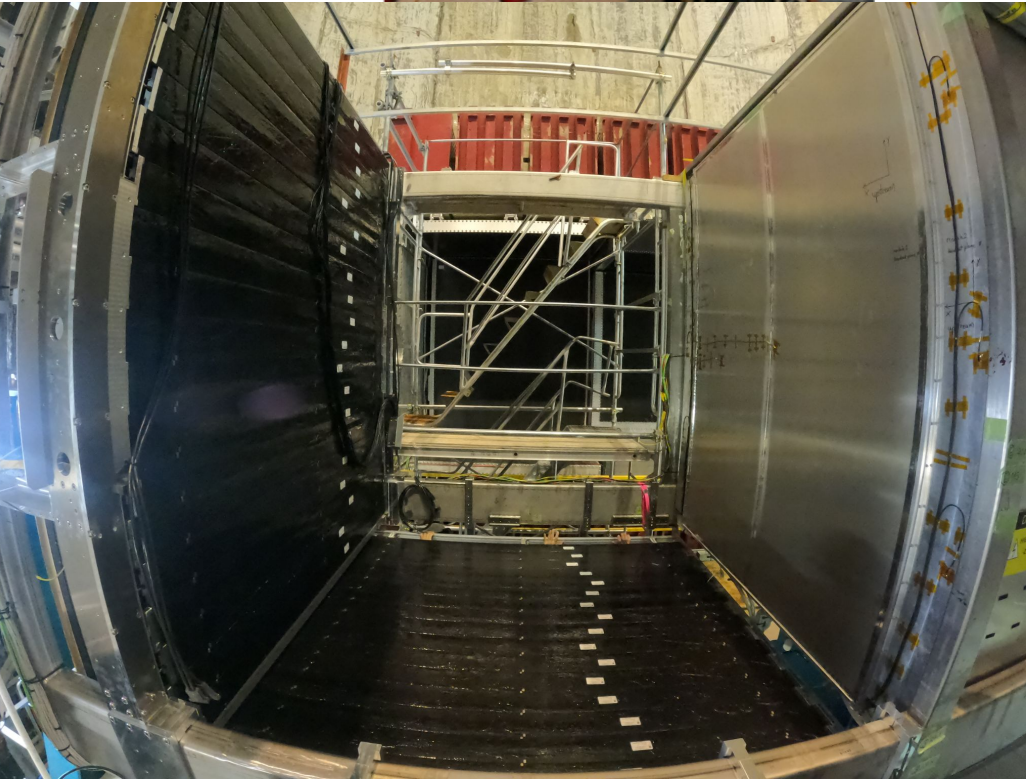
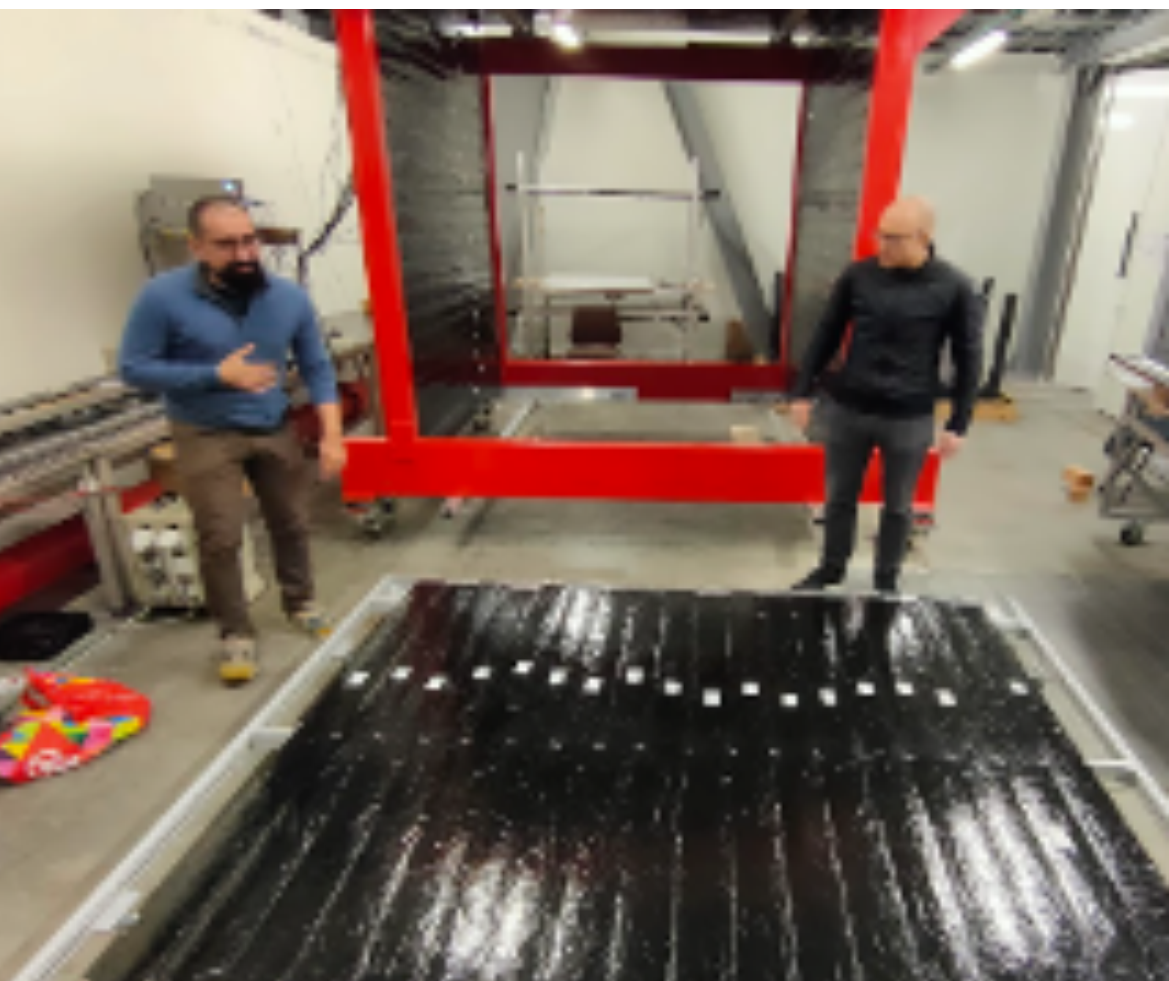
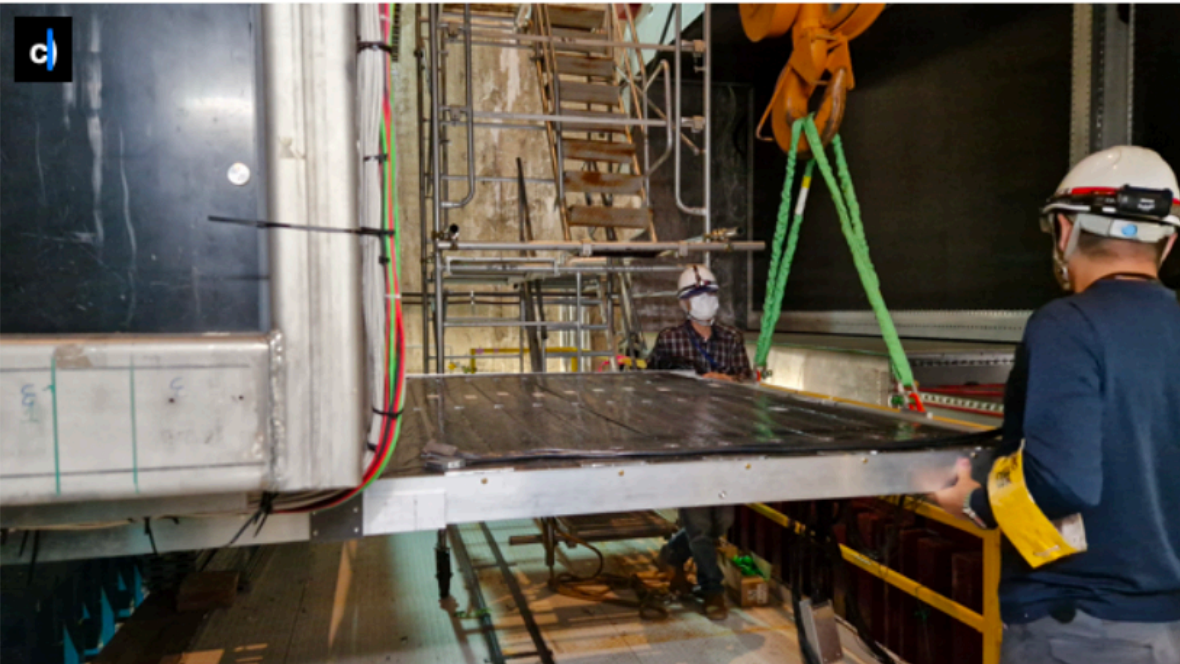


# ToF assembly

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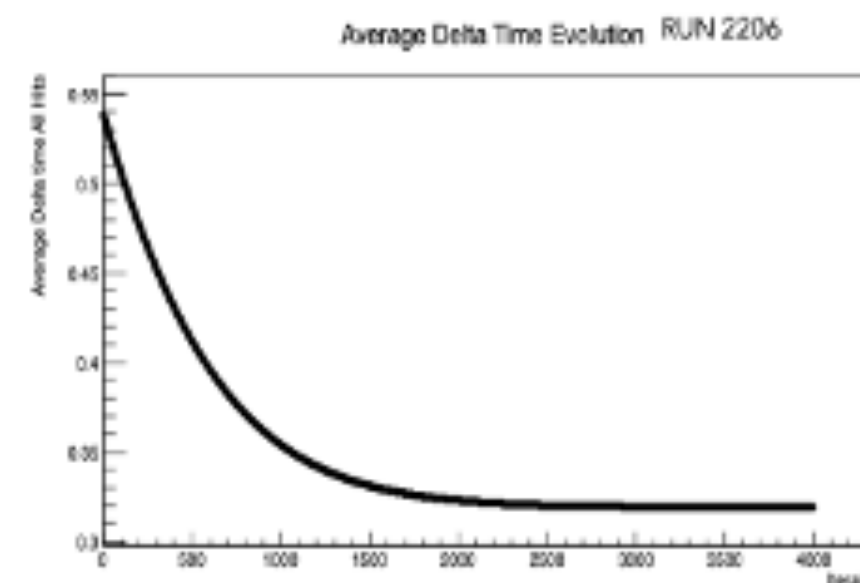
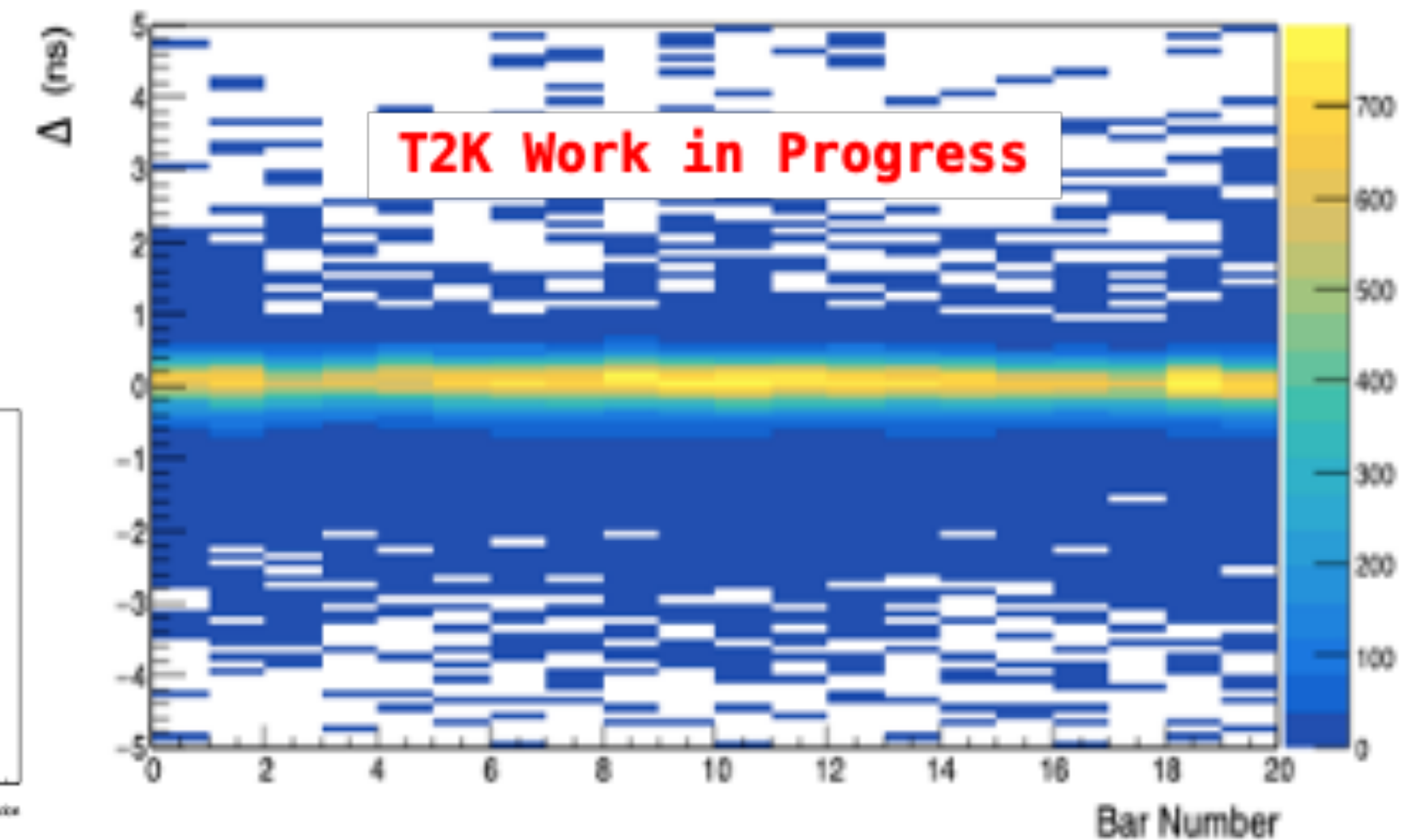
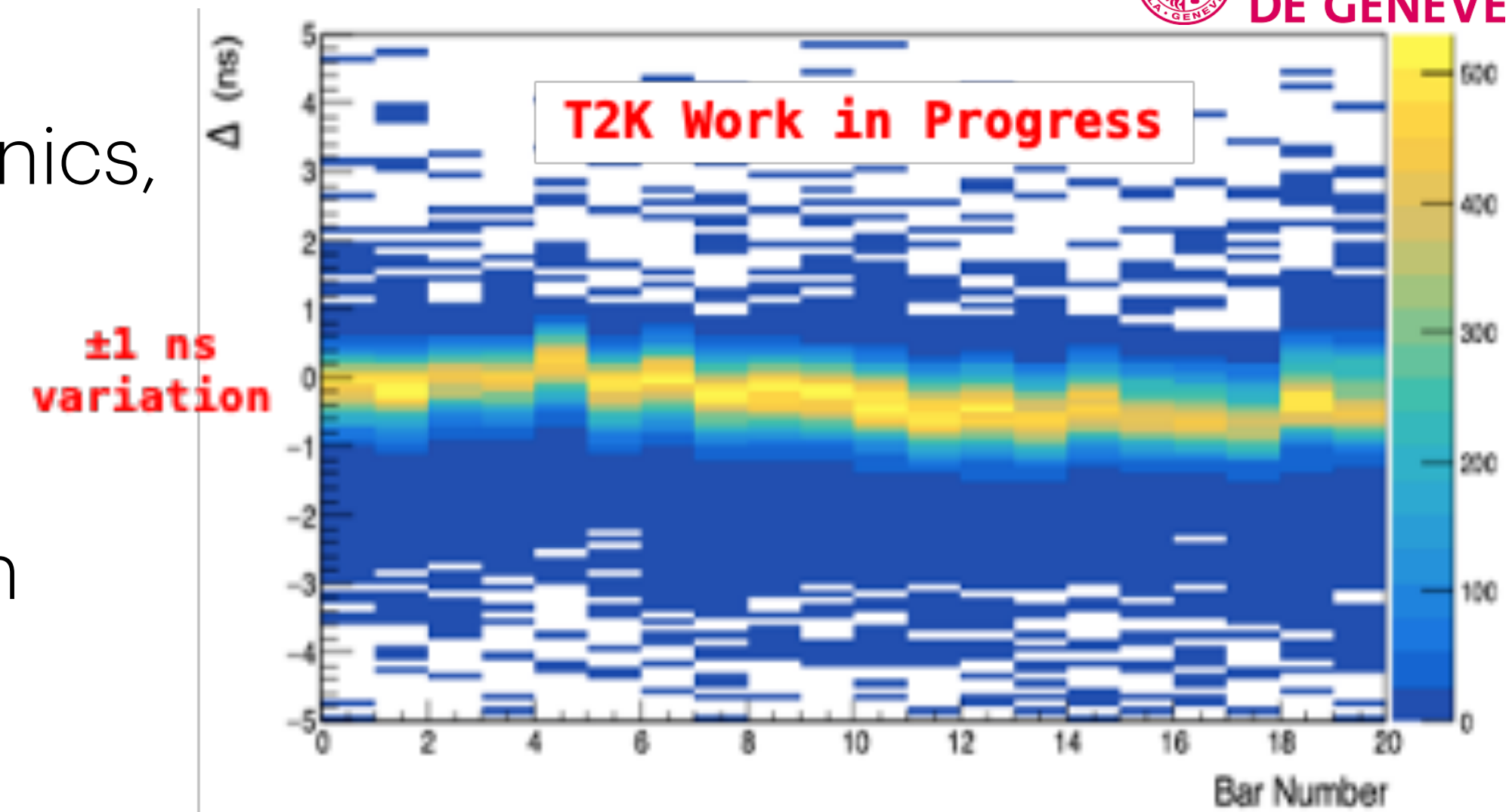


@ CERN



# ToF commissioning : channel time calibration

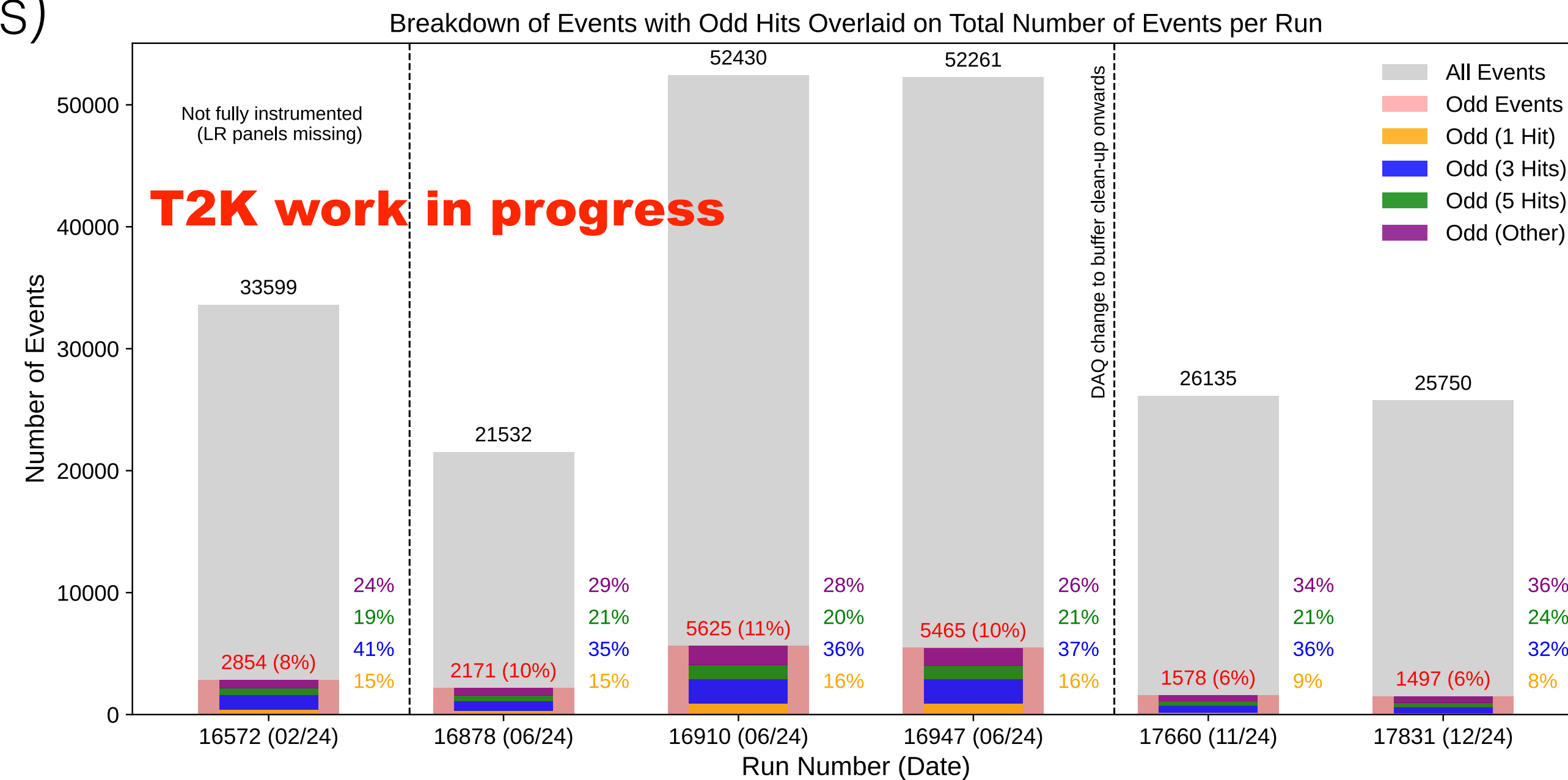
- Time resolution can be degraded: cable lengths, electronics, SiPMs response, etc can introduce delays.
- Calibration procedure without a reference clock, using cosmic muons based on the estimation of the mismatch (per hit pair):  $\Delta = (t_1^{\text{measured}} - t_2^{\text{expected}}) - (s_1 - s_2)$
- Iterative offset estimation based on Markov Chain
- Relative offset between all channel hit pairs reduced from 1 ns to O(100ps)



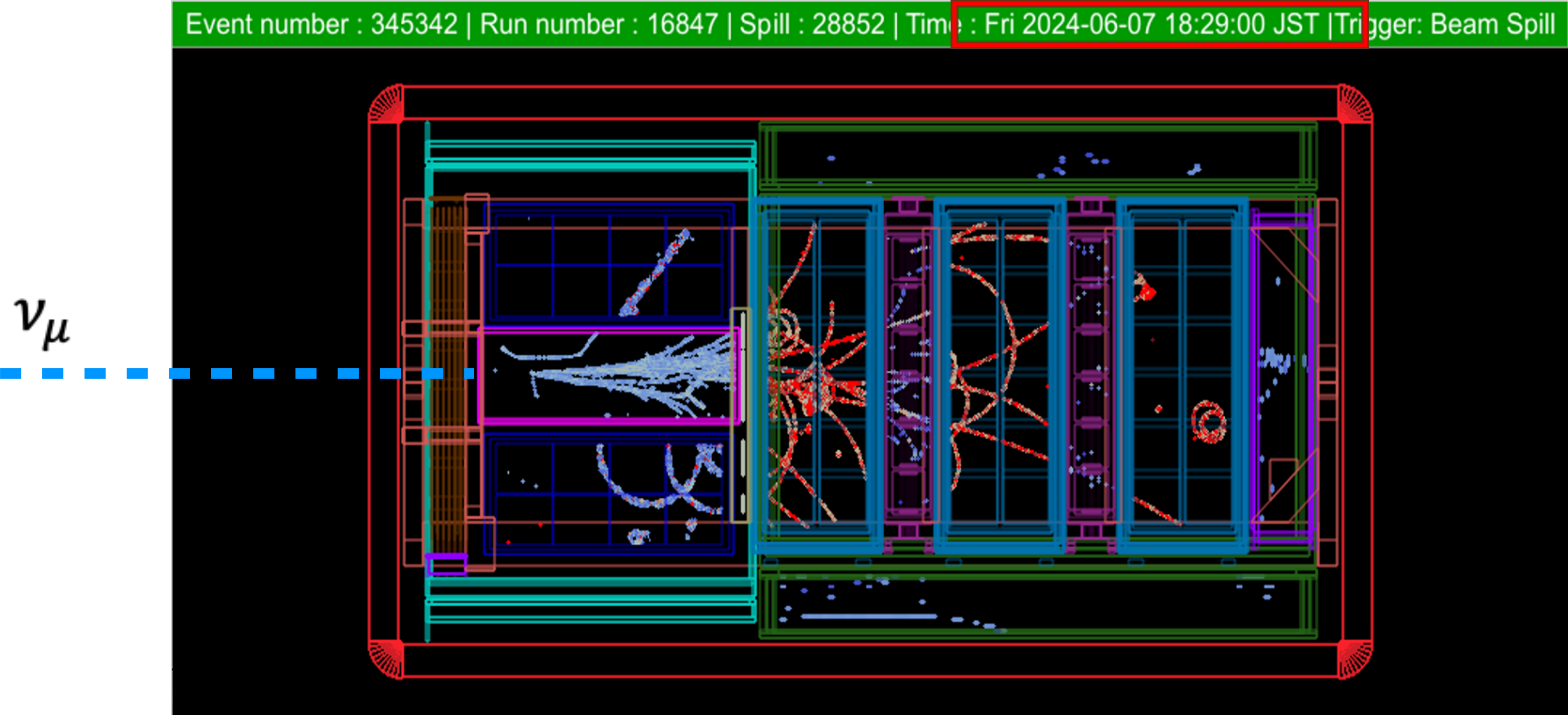
arXiv:[2508.07846](https://arxiv.org/abs/2508.07846)

# ToF commissioning: hit efficiency

- ToF Data Acquisition (DAQ) requires a signal from both ends of a bar
- Odd number of hits observed due to the used coincidence window and DAQ's event association
- Origin determined :
  - 1/3 from **cross-talk** (neighbouring channels)
  - 2/3 **missing hits** (delays > 20ns, high amplitudes)



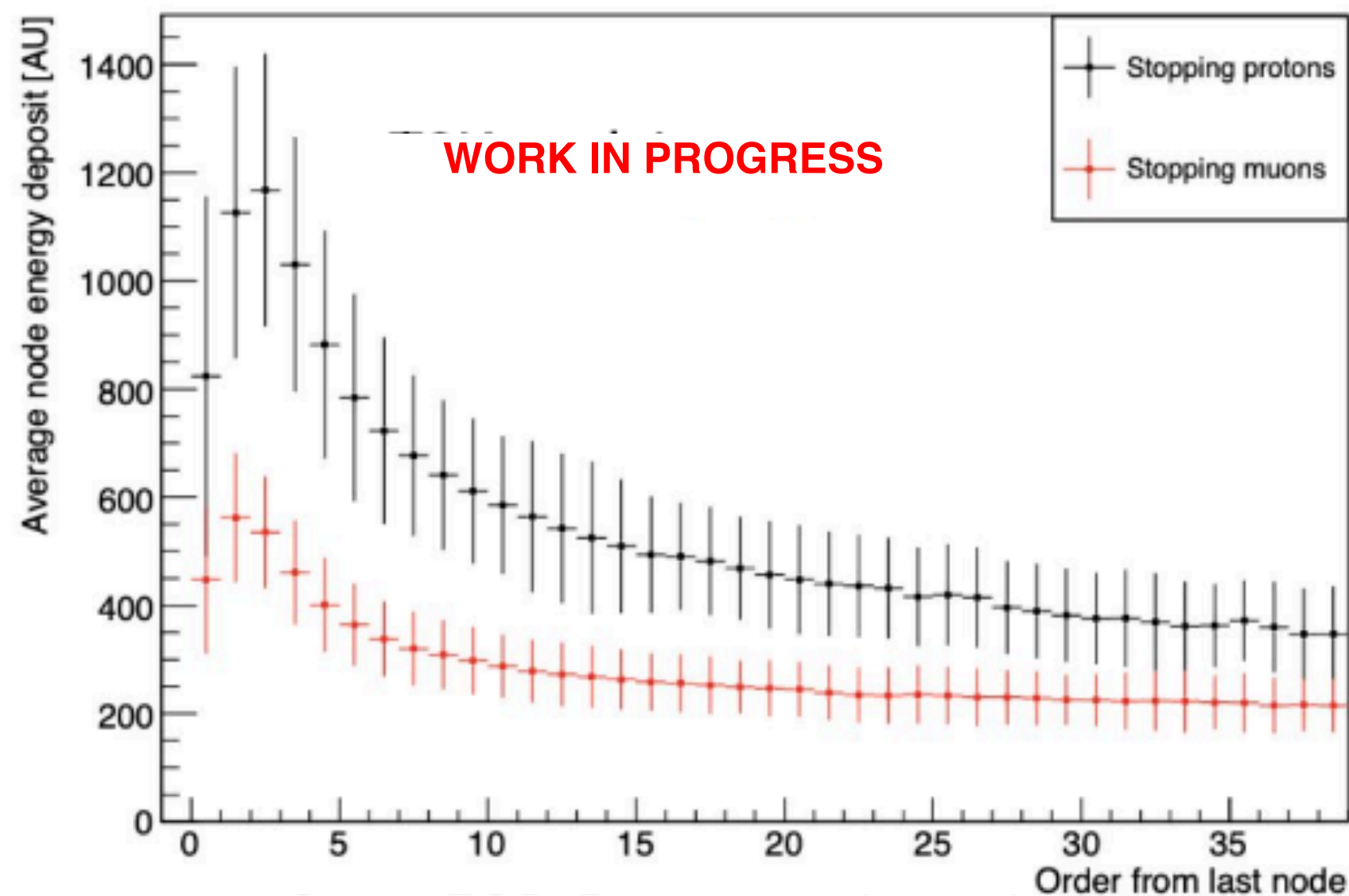
# First Neutrino Event with the Upgrade



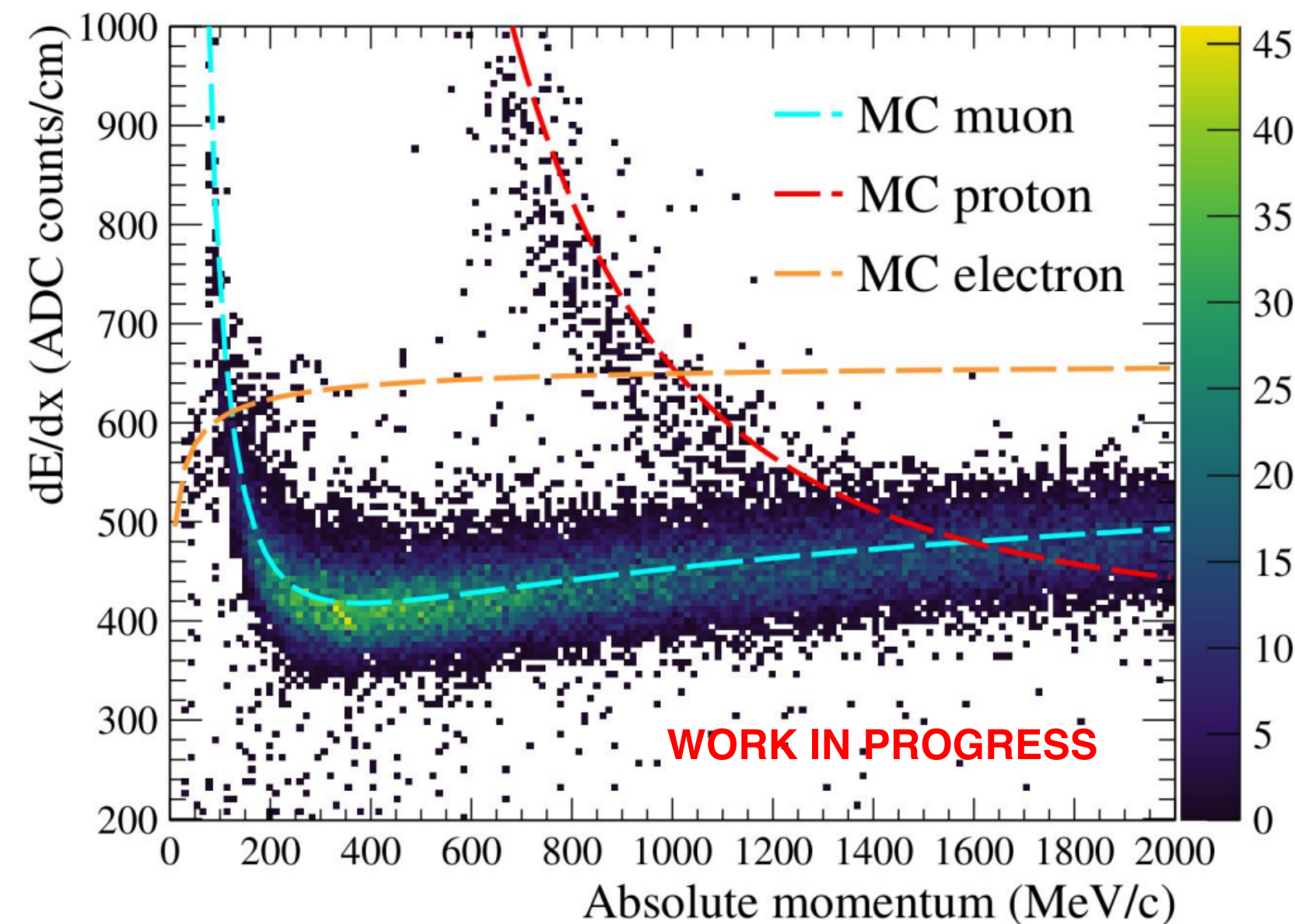
# Particle identification

- PID for sFGD tracks based on Bragg peak
- HAT dE/dx particle identification enhanced by the improved spatial resolution ( $< 0.5\text{mm}$ )
- HAT  $\mu$ -p separation for momenta above  $1300\text{MeV}$  can be improved by ToF PID

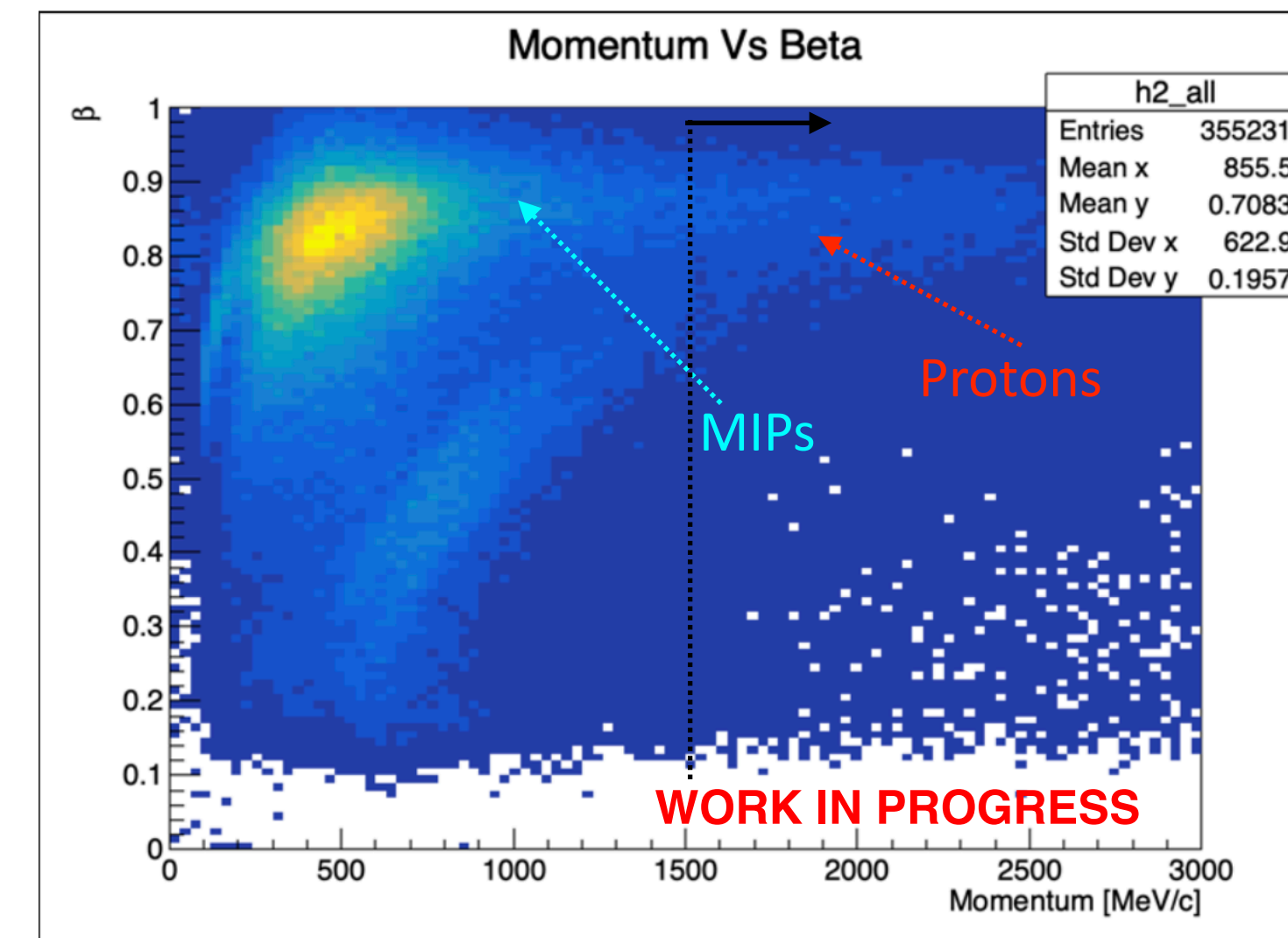
Bragg peak studies in SuperFGD



HAT PID by dE/dx - Horizontal tracks

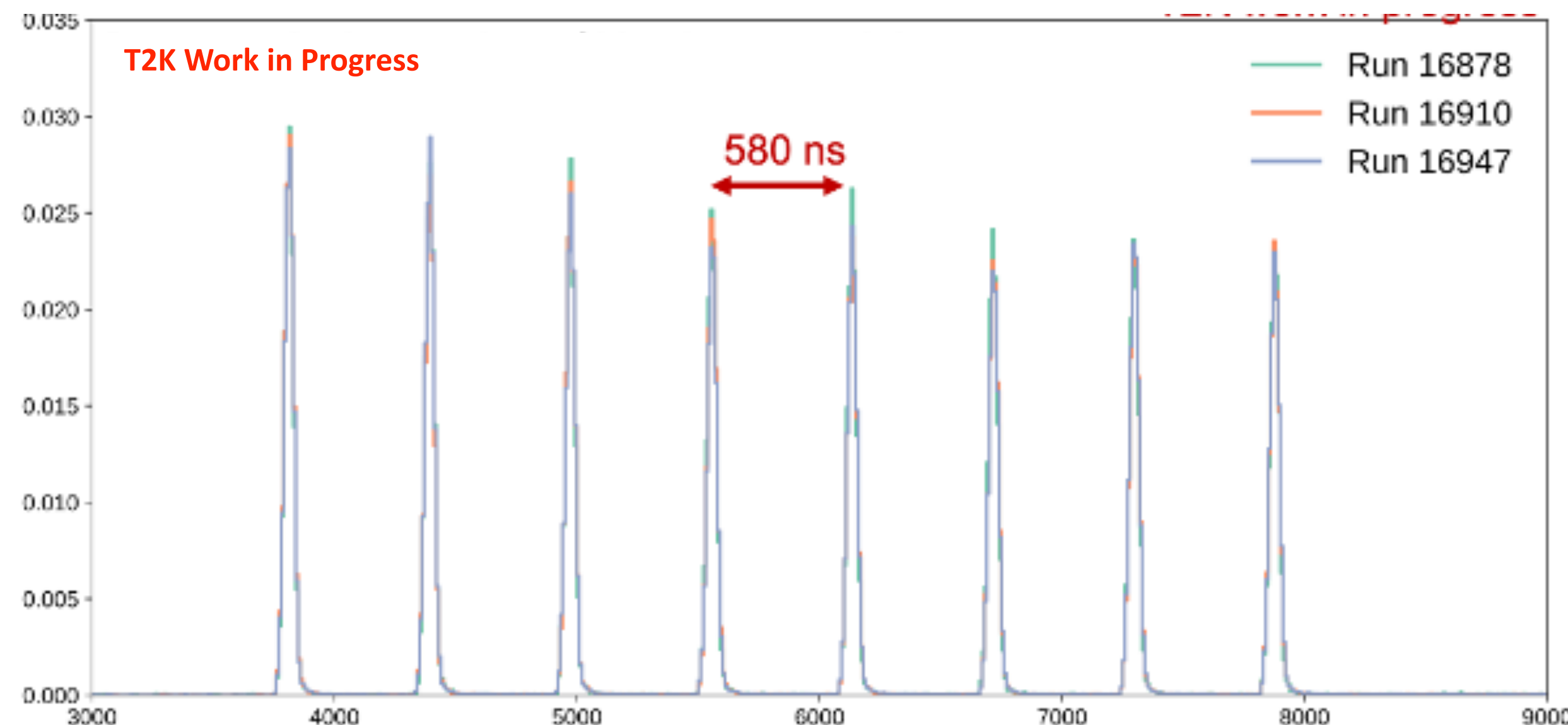
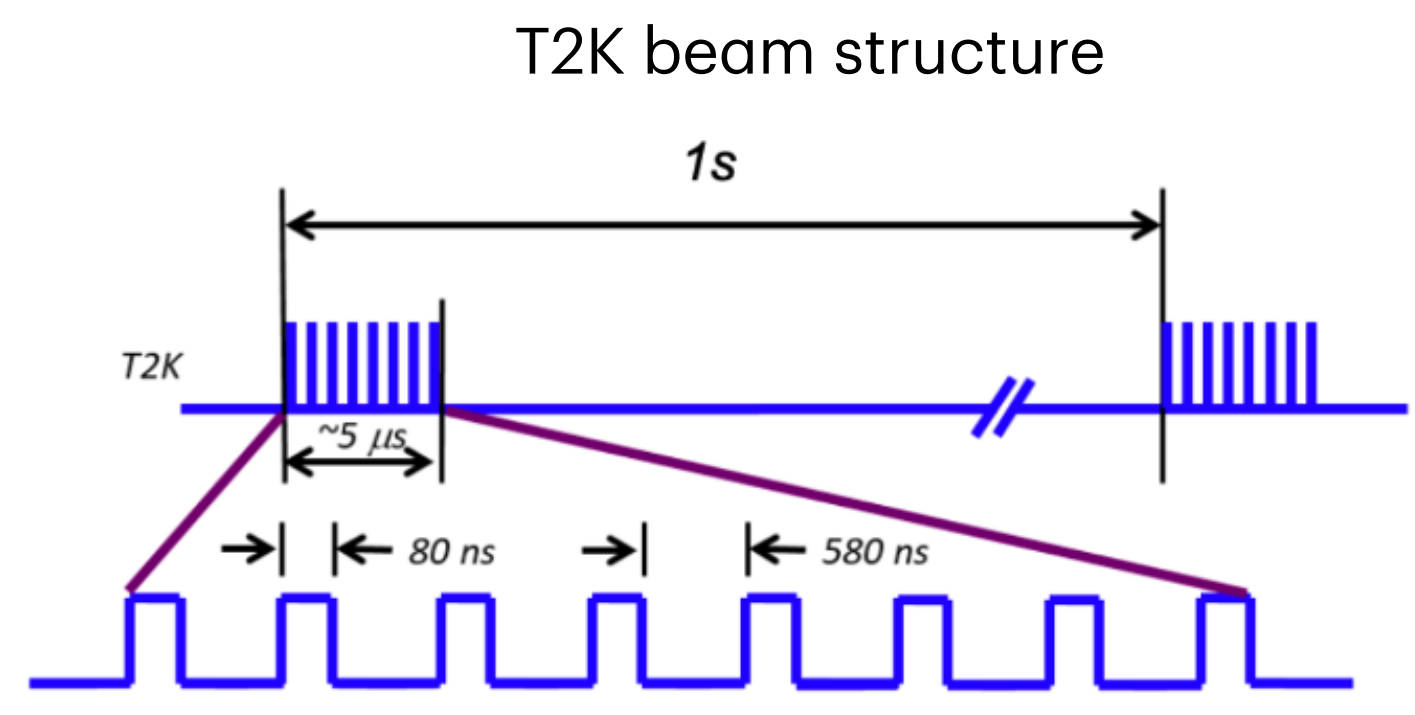
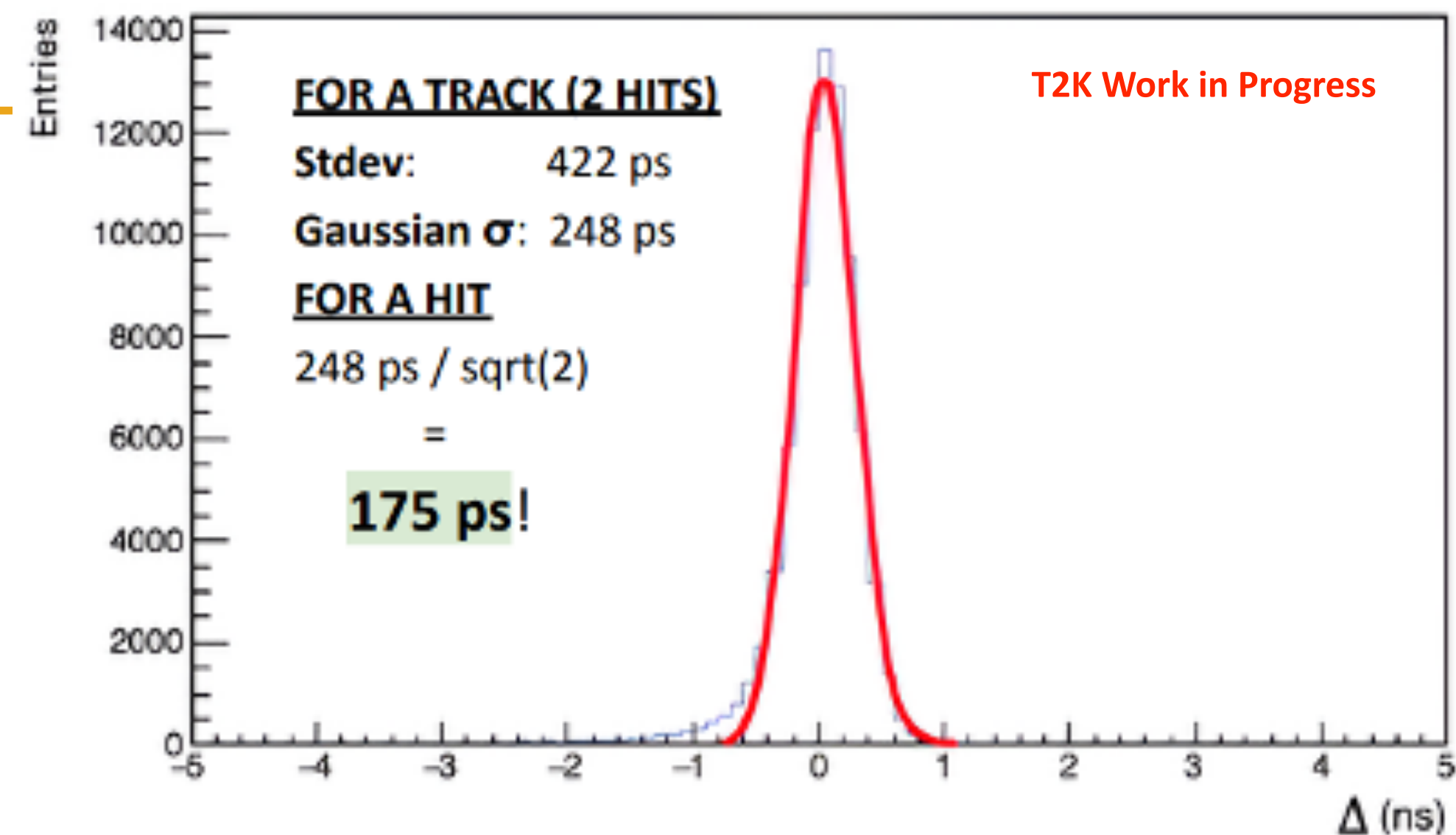


$\mu$ -p separation by momentum using TOF-SFGD time of flight (MC)



# ToF time resolution

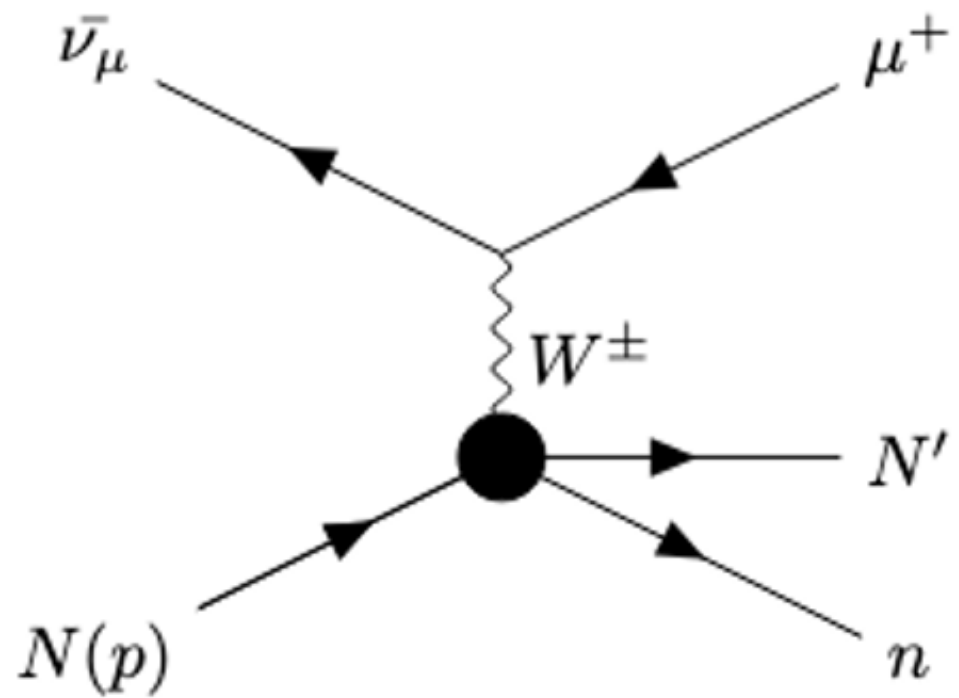
- Time resolution with the full detector of 175ps after standalone calibration. Expected to be reduced with external position reference
- Beam profile clearly resolved: 8 bunches - 20ns wide, 580ns spaced, every spill. Stability along multiple runs.
  - Additional beam monitoring
  - $T_0$  for HAT
  - Possible detection of neutron activities (tails) or new physics!



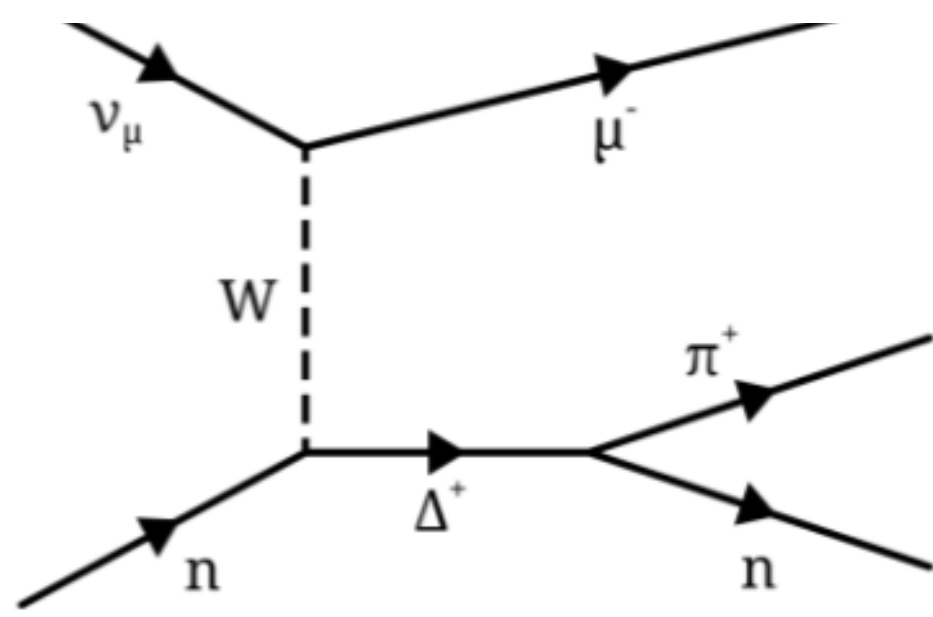
# sFGD Neutron detection

CC-neutron interaction in SFGD cubes, 2D view

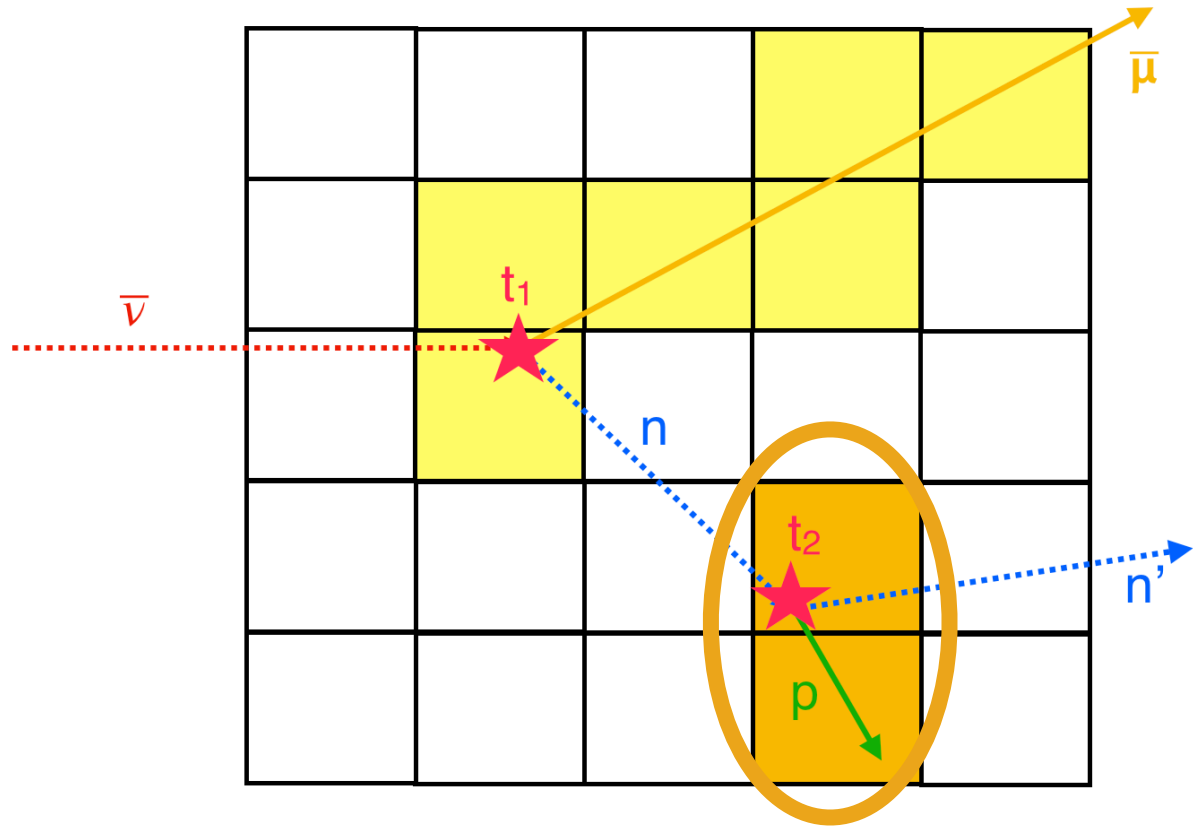
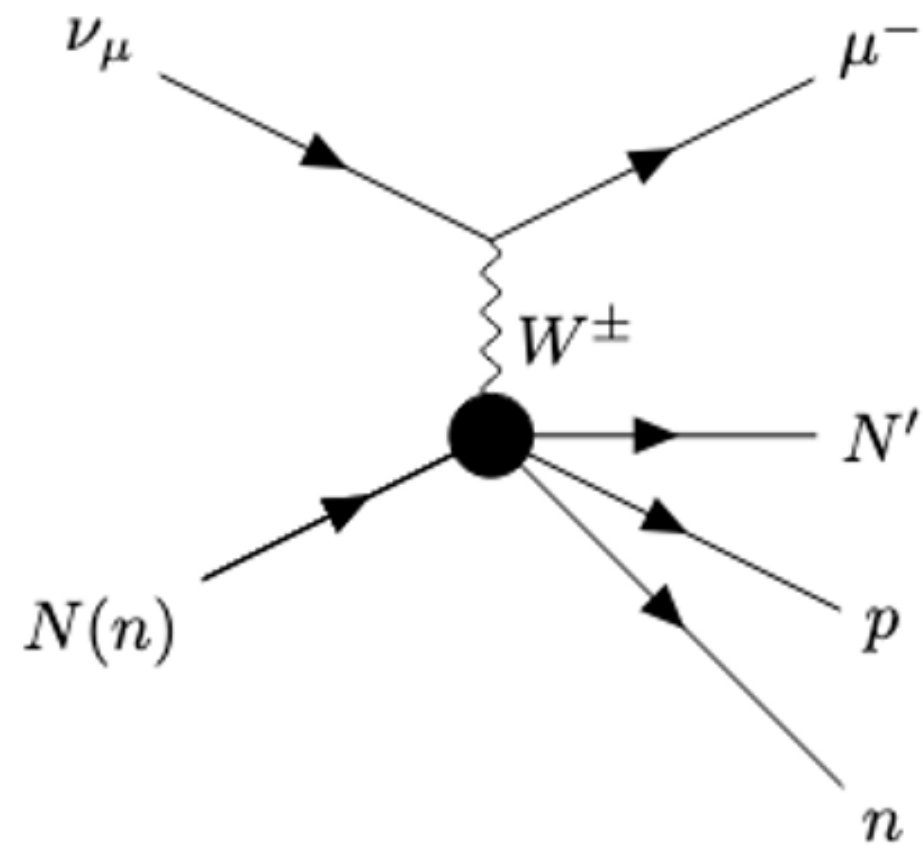
Quasi-elastic  $\bar{\nu}_\mu$  CC



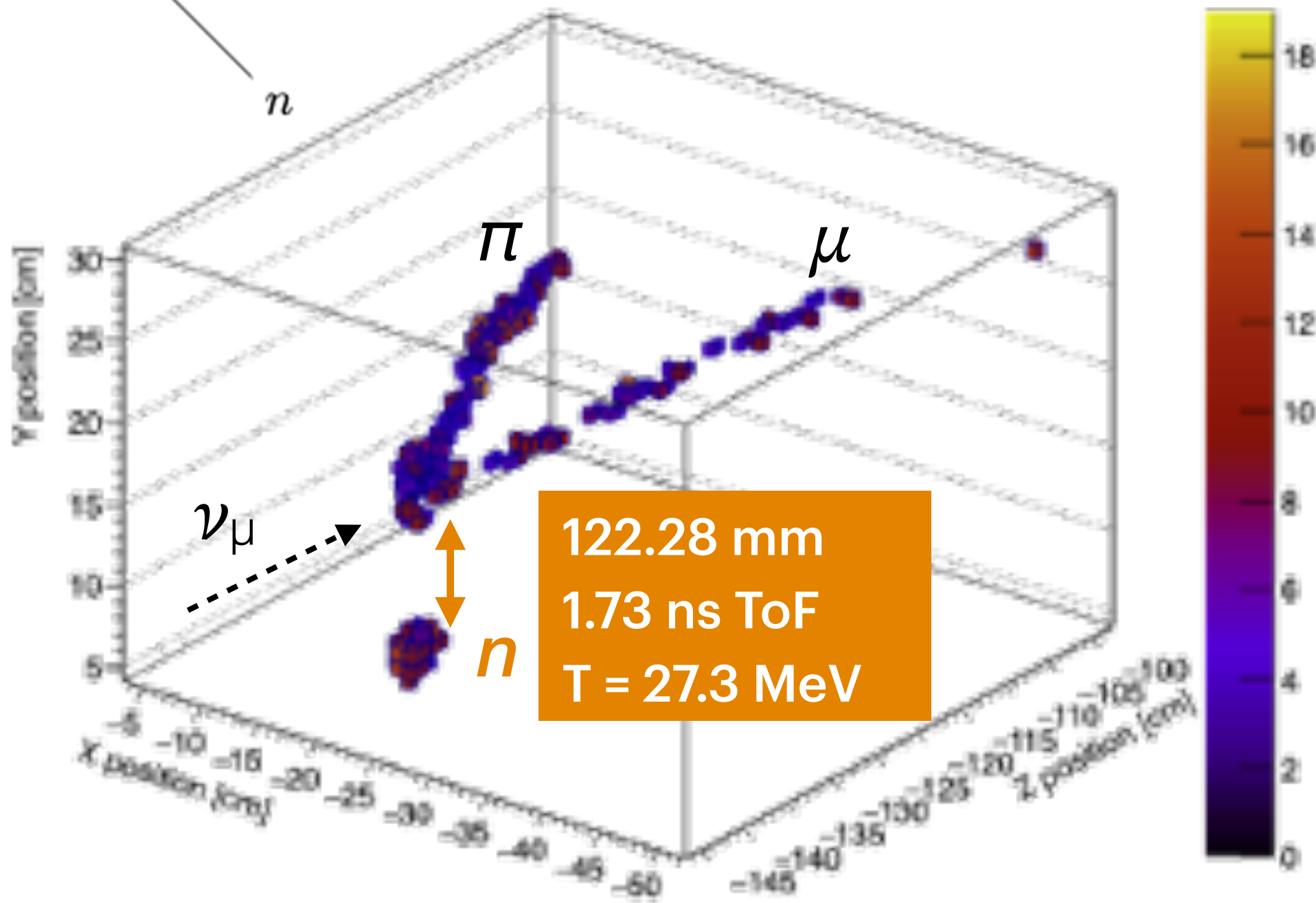
Single pion production  $\nu_\mu$  CC



2p2h-np  $\nu_\mu$  CC



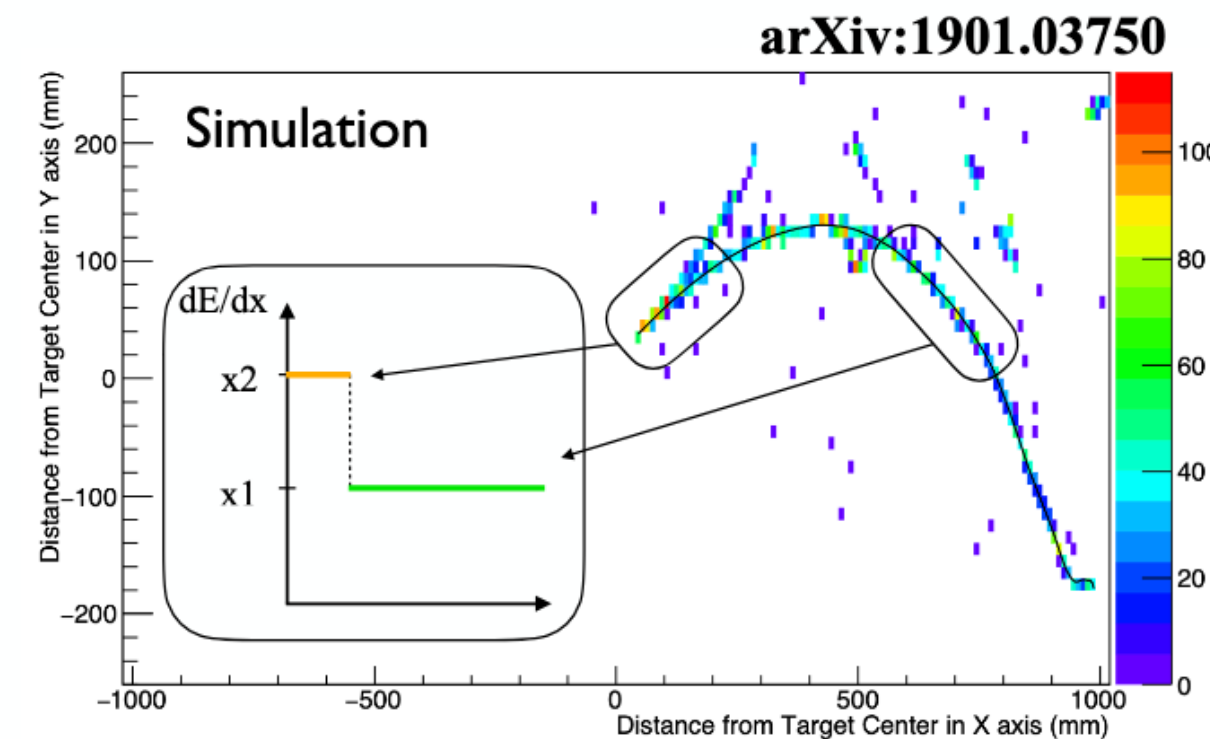
- Neutron detection helps in discriminating  $\nu_\mu$  and  $\bar{\nu}_\mu$  and give access to the full kinematics for  $\nu_\mu$  CC events with neutrons
- Neutrons re-scatter emitting proton "blips" which in the sFGD are seen as isolated energy deposits
- From the time of flight and  $t_1-t_2$  distance the neutron kinetic energy can be inferred.
- $\bar{\nu}_\mu$  energy resolution for events strongly improved (from 15% to 7%)



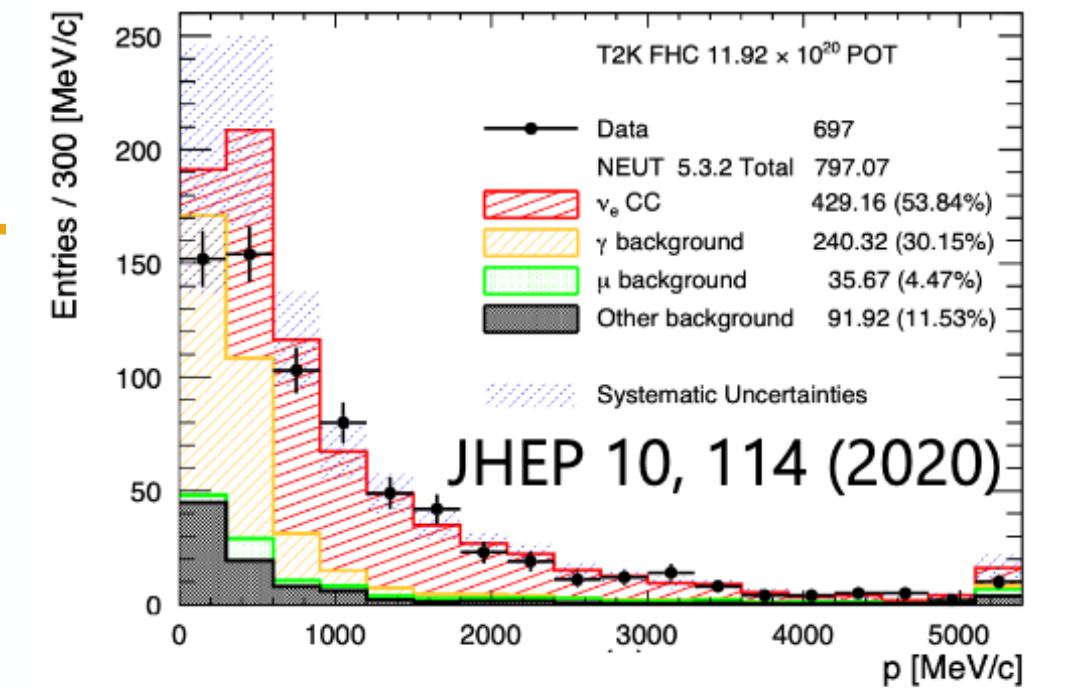
# Background rejection

## $\gamma \rightarrow e^+e^-$ discrimination

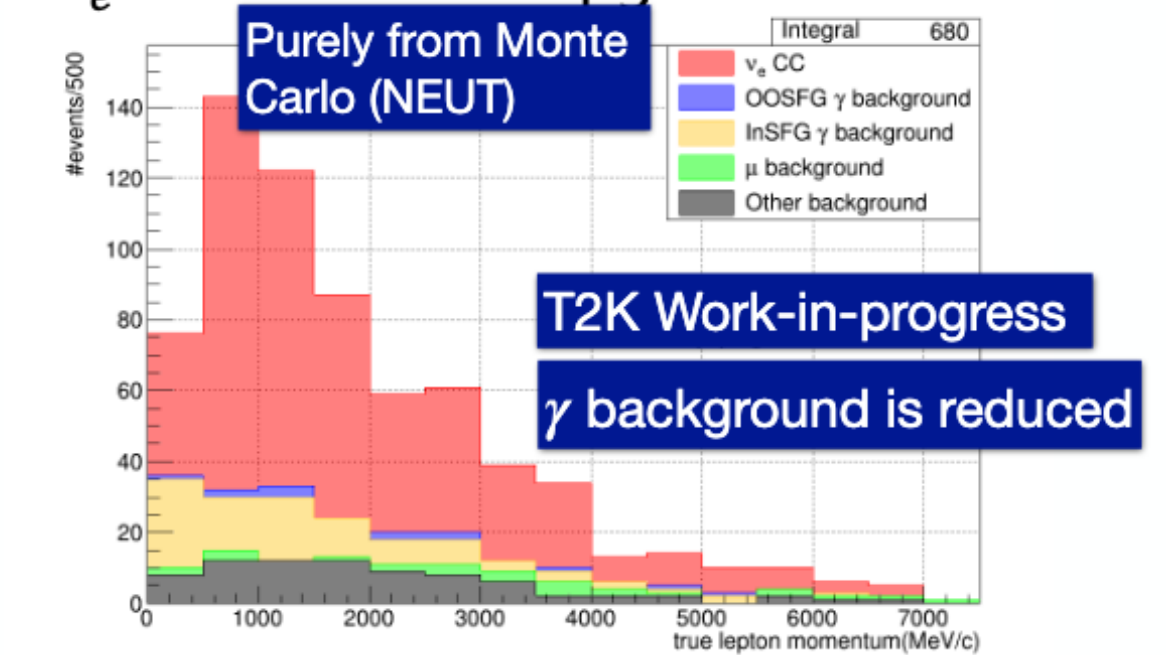
- Main background for  $\nu_e$  events :  $\pi^0$  production from a  $\nu_\mu$  event
- sFDG long radiation length and granularity allow to better reject  $\gamma \rightarrow e^+e^-$  events



## $\nu_e$ selection with original ND280

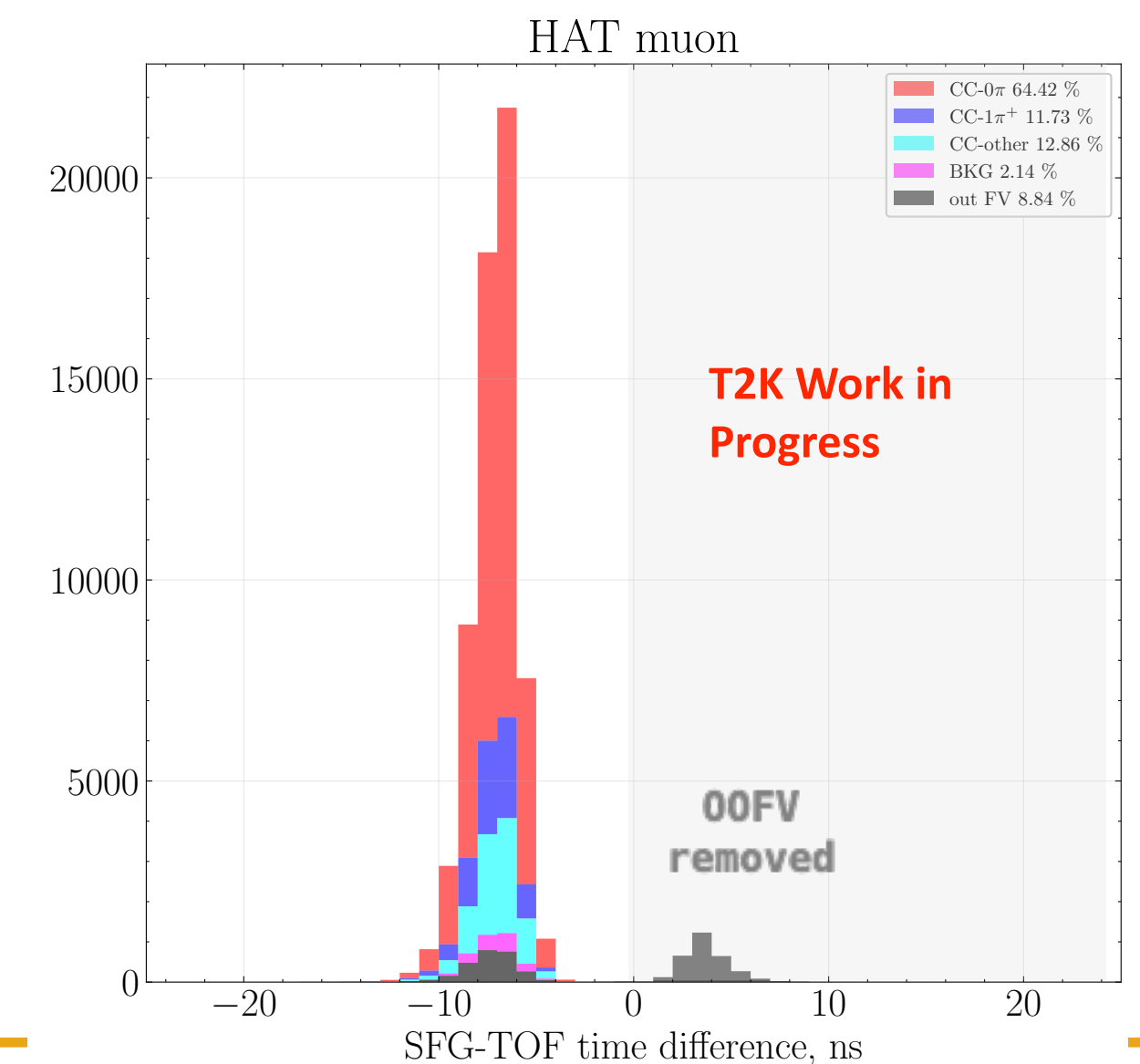


## $\nu_e$ selection with upgraded ND280



## Out of Fiducial Volume Events rejection

- Some tracks originated outside the Fiducial Volume can mimic CC events
  - ToF-sFGD time difference can help to reject these events
- Forward-going muons:  $\Delta t = t_{\text{sFGD}} - t_{\text{ToF}} \approx -10$  ns.
- OOFV/backward-going tracks:  $\Delta t > 0$ .
- Cut on  $\Delta t$  allow a rejection of  $\sim 50\%$  OOFV (MC)



# Summary

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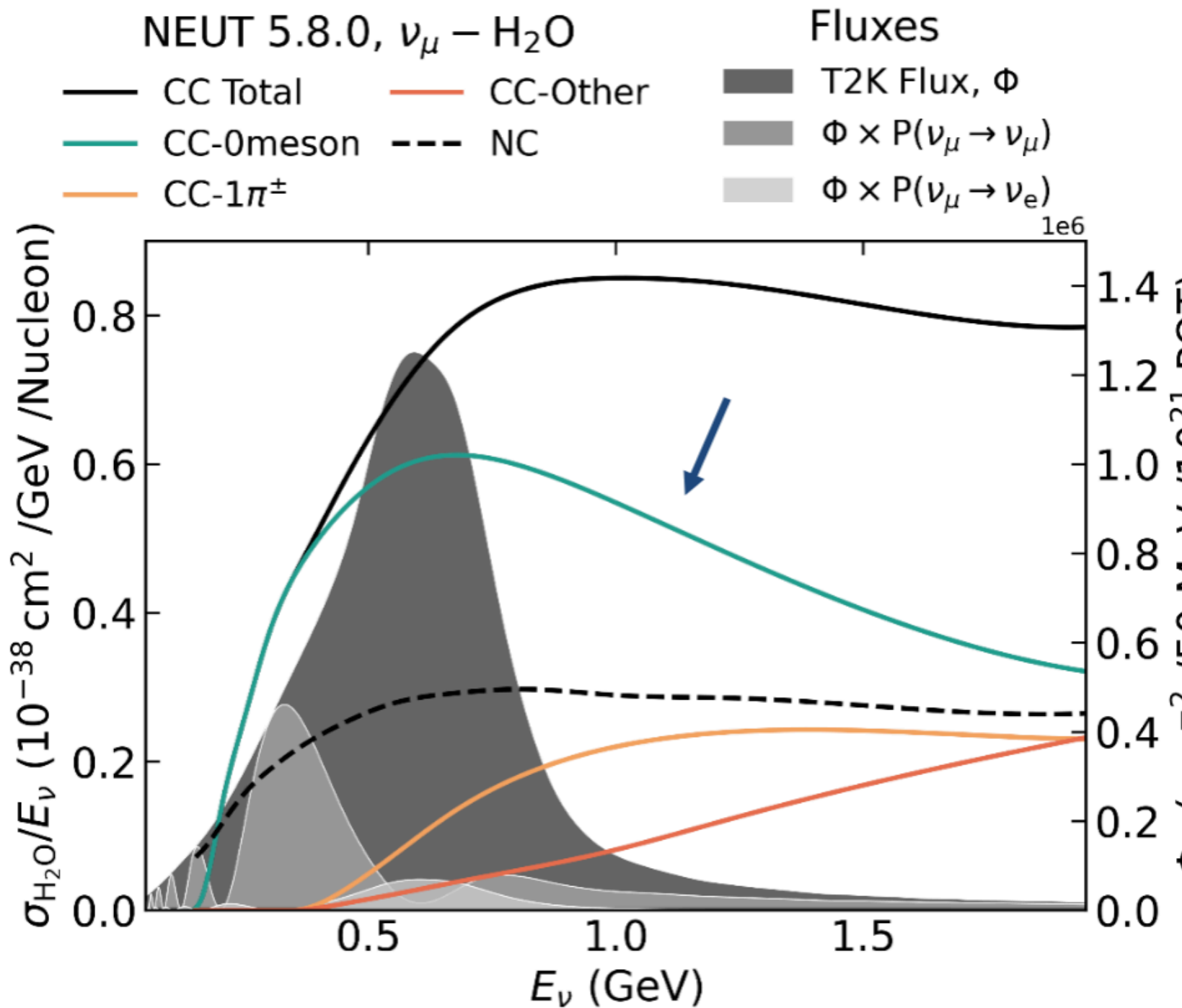
- T2K is a long baseline experiment aiming at precise measurement of  $\theta_{23}$ ,  $\Delta m^2_{32}$  and looking for neutrino mass ordering and CP violation
- Upgrades on the beamline, near detector and far detector have been completed
  - Neutrino beam running stably at ~800 kW
  - ND280 upgrade installation completed and seeing neutrino interactions!
- Physics potential of ND280 enhanced and new events selection are being developed
- New stringent systematics constraints for oscillation measurements are expected soon!

*Stay tuned!*

Extra material

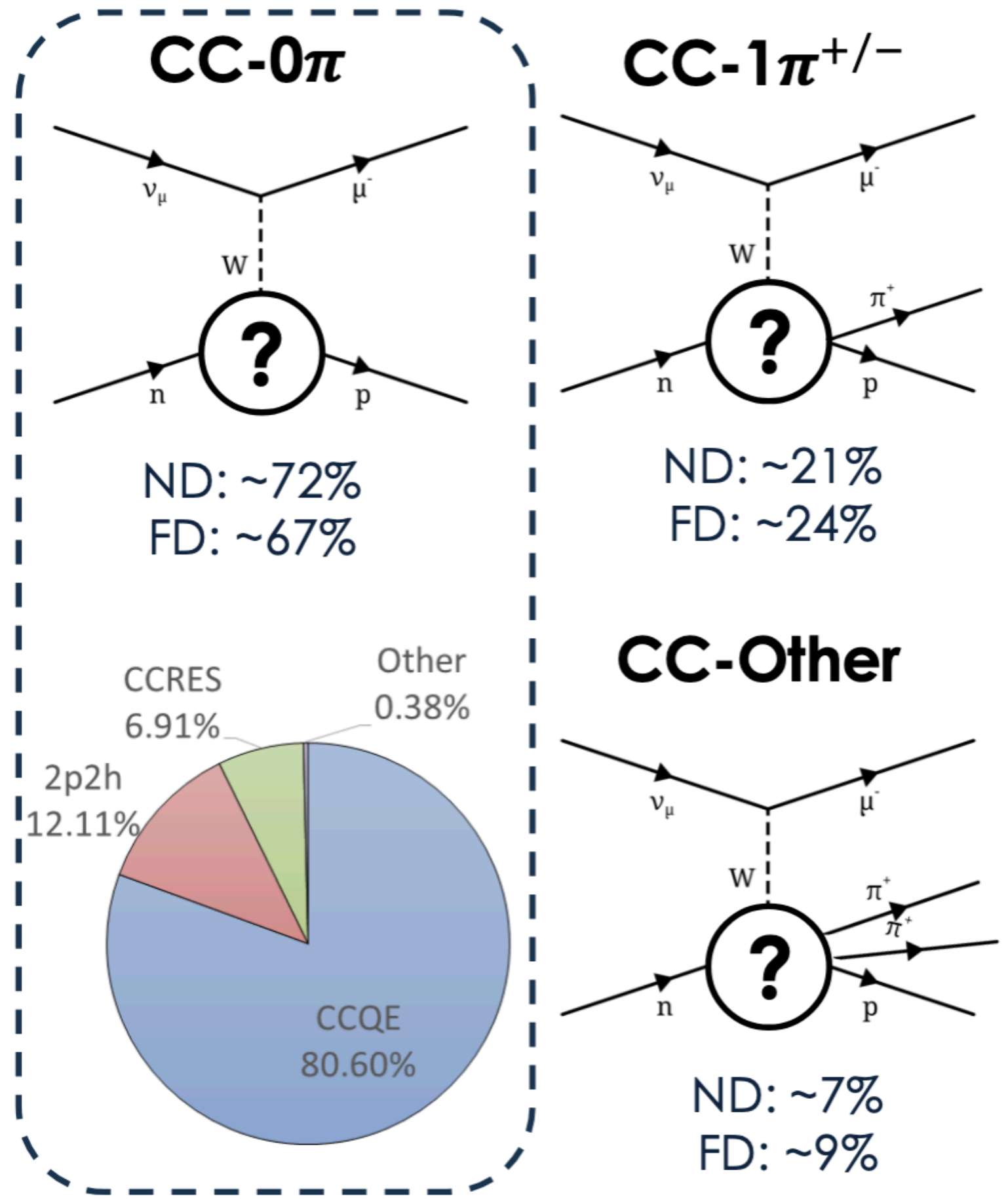
# Neutrino interaction at T2K

Courtesy of S. Dolan



Plot from L. Pickering  
[Hayato, Y., Pickering, L. Eur. Phys. J. Spec. Top. 230, 4469–4481 \(2021\)](#)

Percentages show contribution to  $\nu_\mu$  CC interactions at the near (before oscillation) and far (after oscillation) detector sites for  $E_\nu < 2$  GeV simulated with NuWro



# Neutrino beam line upgrade

- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48s to 1.36s
- Several upgrades done on the neutrino beamline to cope with higher beam power
- Horn being operated at 320 kA instead of 250 kA → ~10% increase in the  $\nu$  flux

**New horn PS for 320 kA/1Hz operation**

**New horns 1 and 2**  
Increasing cooling capability for the heat generated by beam

**New OTR**  
Improving performance of beam monitors

**New FVD2 magnet**  
New short FVD2 installed

**New target**  
New target cooling system

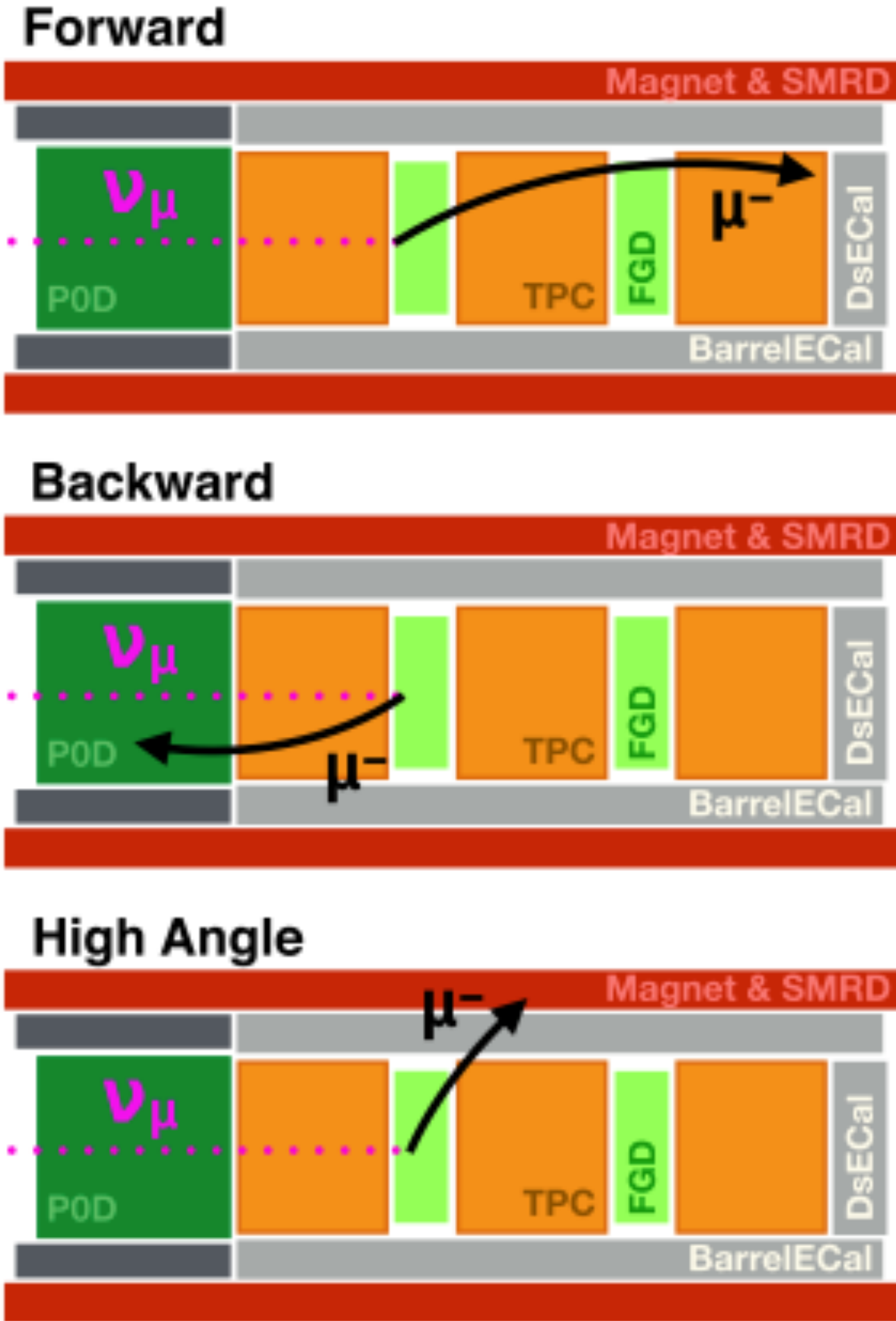
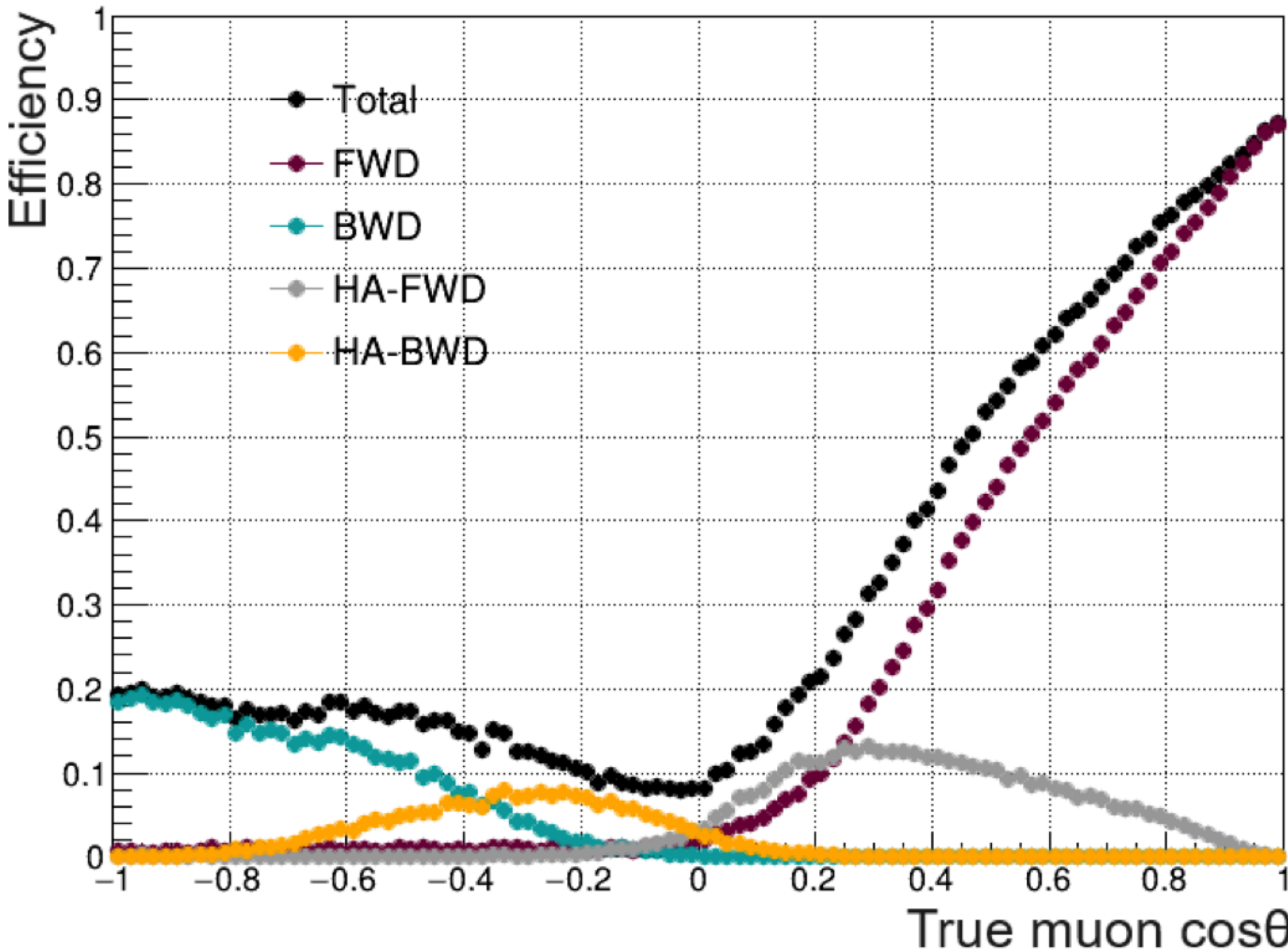
**New MUMON Si (Half sensors)**  
Improving performance of beam monitors

**New water tank for radioactive water disposal**  
Increasing capability of radio-active waste handling

**Improving maintainability under higher radio-active environment**

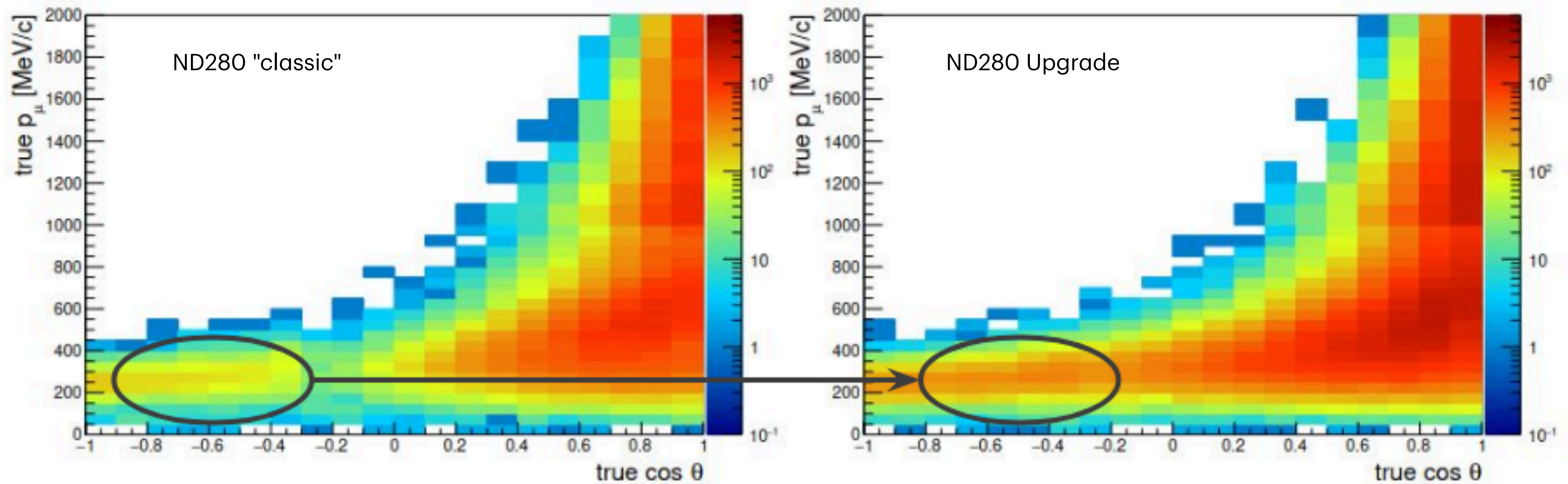
# ND280 - classic limits

- Limited high angle muon reconstruction efficiency due to the absence of the TPCs in the high angle region



# ND280 Upgrade

- Expected improvement in the angular acceptance of ND280 thanks to the upgrade

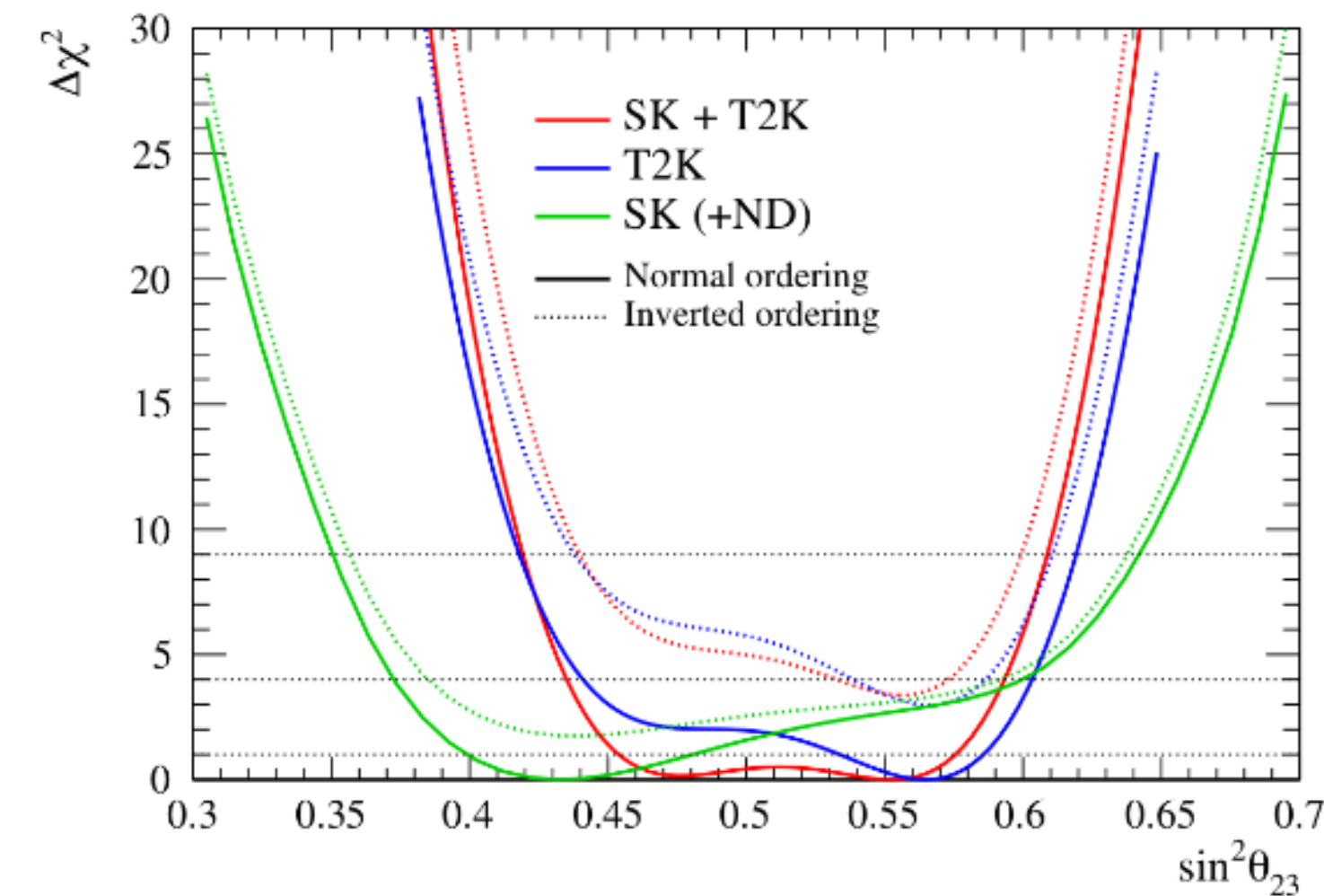
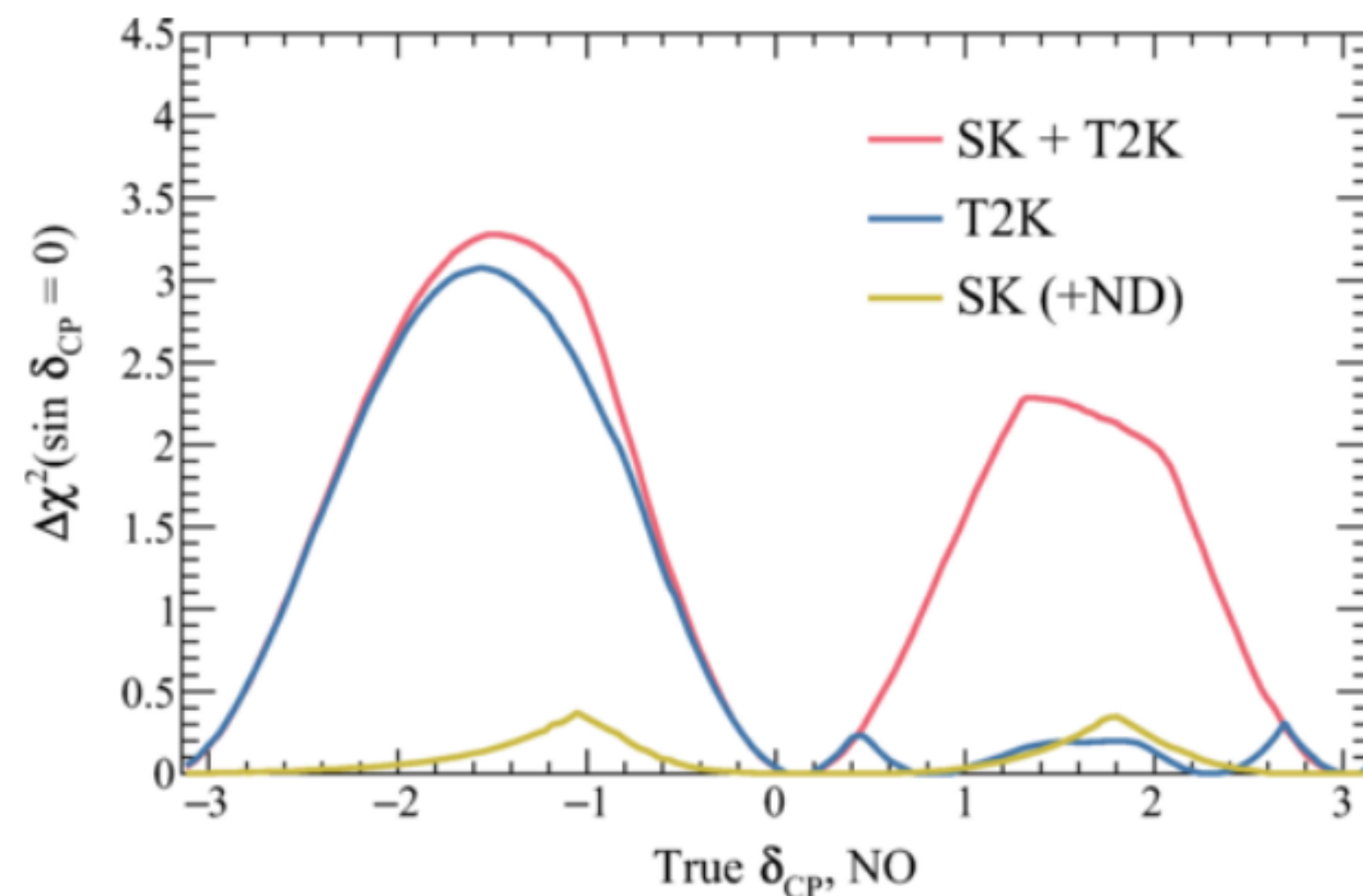


# How to improve..?

## T2K-SK joint analysis:

- Helps to break the degeneracy between  $\delta_{\text{CP}}$  and the mass ordering
  - T2K: shorter baseline, more direct access to  $\delta_{\text{CP}}$
  - SK: longer baseline, more sensitivity to Mass Ordering

- Super-K and T2K have different preferences for the octant of  $\theta_{23}$ .
- No strong preference for octant in joint fit.
- Limited preference for normal mass ordering, with the inverted ordering rejected at  $1.2\sigma$



[Phys. Rev. Lett. 134, 011801](#)

# How to improve..?

## T2K-NOvA joint analysis:

- Different energies and baselines -> different sensitivities to oscillation parameters
  - T2K: shorter baseline, more sensitivity to  $\delta_{CP}$  but degeneracy for  $\delta_{CP} \approx 0, \pi$
  - NOvA: longer baseline, better sensitivity to mass ordering but degeneracy for  $\delta_{CP} \pm \pi/2$

- Individual fits from T2K and NOvA are consistent with the joint fit results.
- Constraints for inverted mass ordering are improved

