



THE UNIVERSITY OF TOKYO

**ETH** zürich



# The T2K Near Detector Upgrade

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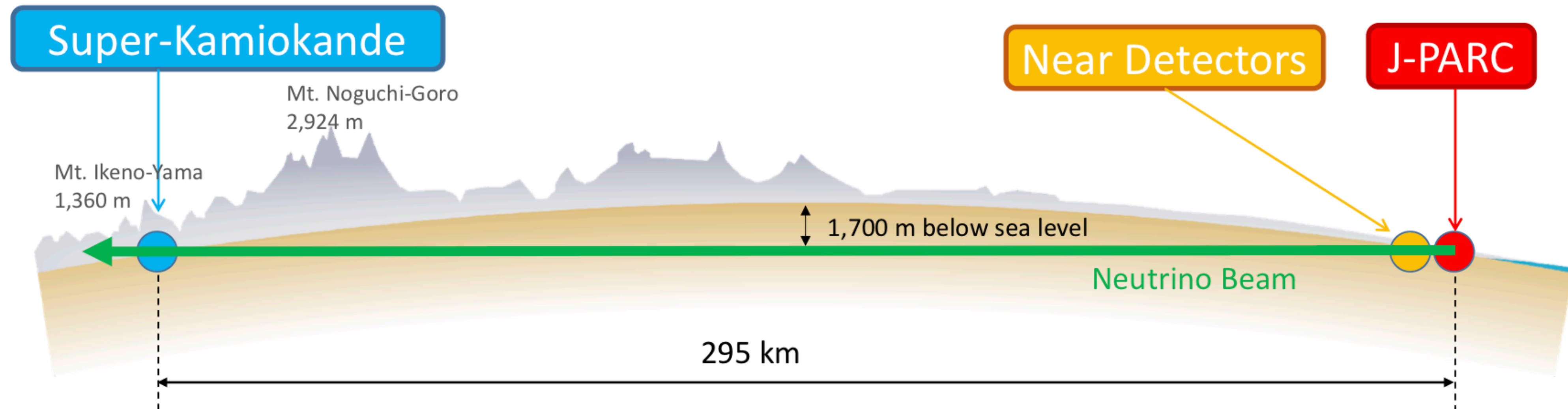
# Outline

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- Introduction to the T2K experiment
- Plans for the upgrade of near detector ND280
- Design of new detectors: SuperFGD, High-Angle TPC and Time-of-Flight detector
- Expected improvement with the ND280 upgrade
- Conclusion and Future

# T2K Experiment Overview

- Long-baseline **neutrino oscillation** experiment.
  - J-PARC accelerator and neutrino beamline : Generate neutrino beam.
  - On- and off-axis near detectors (280 m) : Monitor the beam and constrain the systematics.
  - Far detector Super-Kamiokande (295 km) : Detect oscillated neutrinos.
- Physics Goals:
  - Test of **CP symmetry** in the leptonic sector.
  - Precise measurements of  $\theta_{23}$  and  $\Delta m_{32}^2$
  - Determination of mass ordering, and the octant of  $\theta_{23}$ .



# Recent Status and Future of T2K

## ● Neutrino oscillation measurements:

- Disfavored the CP conservation at the  $2\sigma$  C.L. [[Phys. Rev. D 103 \(2021\), 112008](#), [Phys. Rev. D 103 \(2021\), L011101](#), [Nature 580 \(2020\) 7803, 339-344](#)]

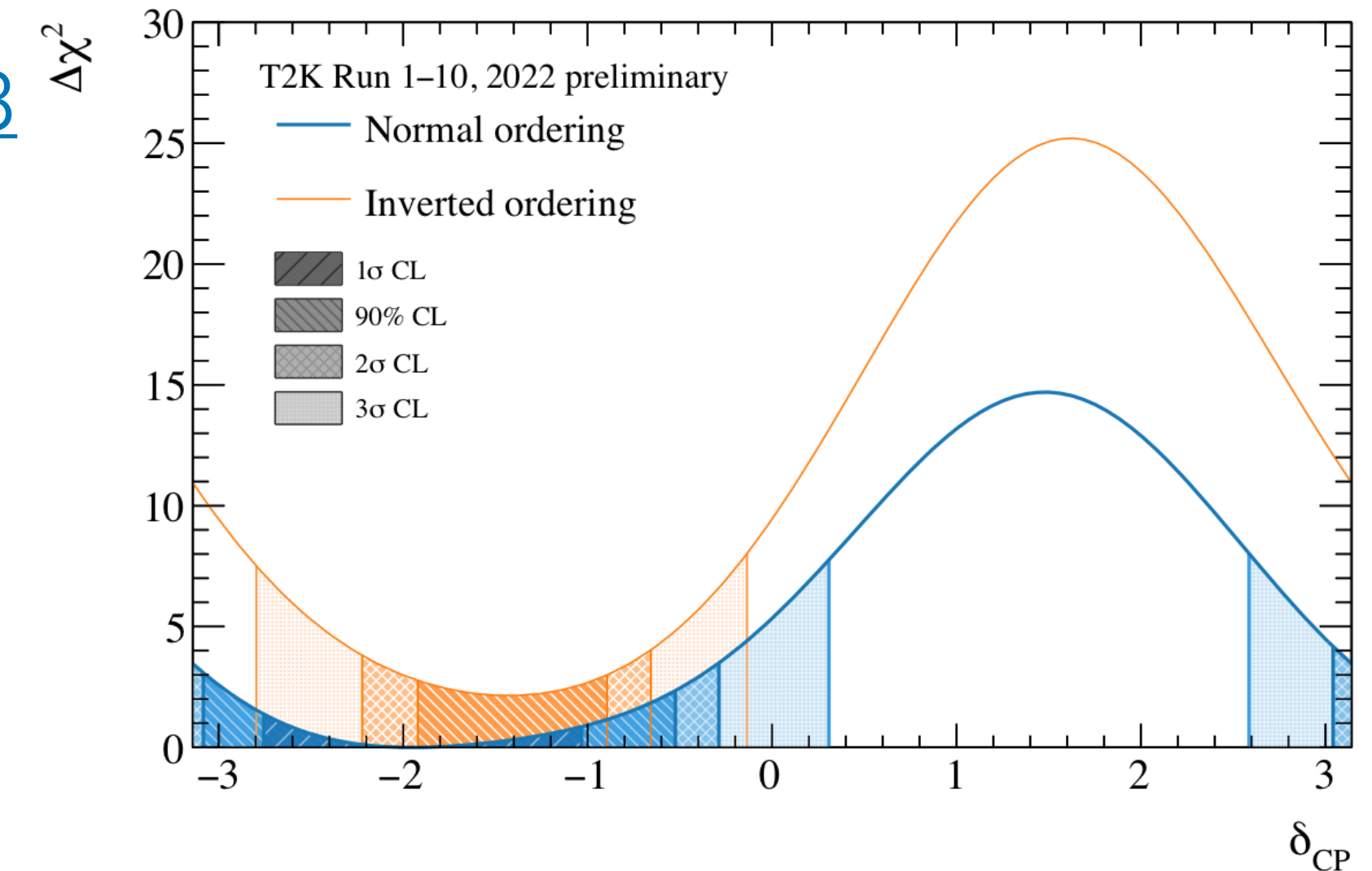
## ● Cross-section measurements

- Keep updating results on various channels,  $\nu$  types and target material. [[PTEP 2021 \(2021\) 4, 043C01](#), [Phys. Rev. D 101, 112004 \(2020\)](#), [JHEP 2020, 114 \(2020\)](#)]

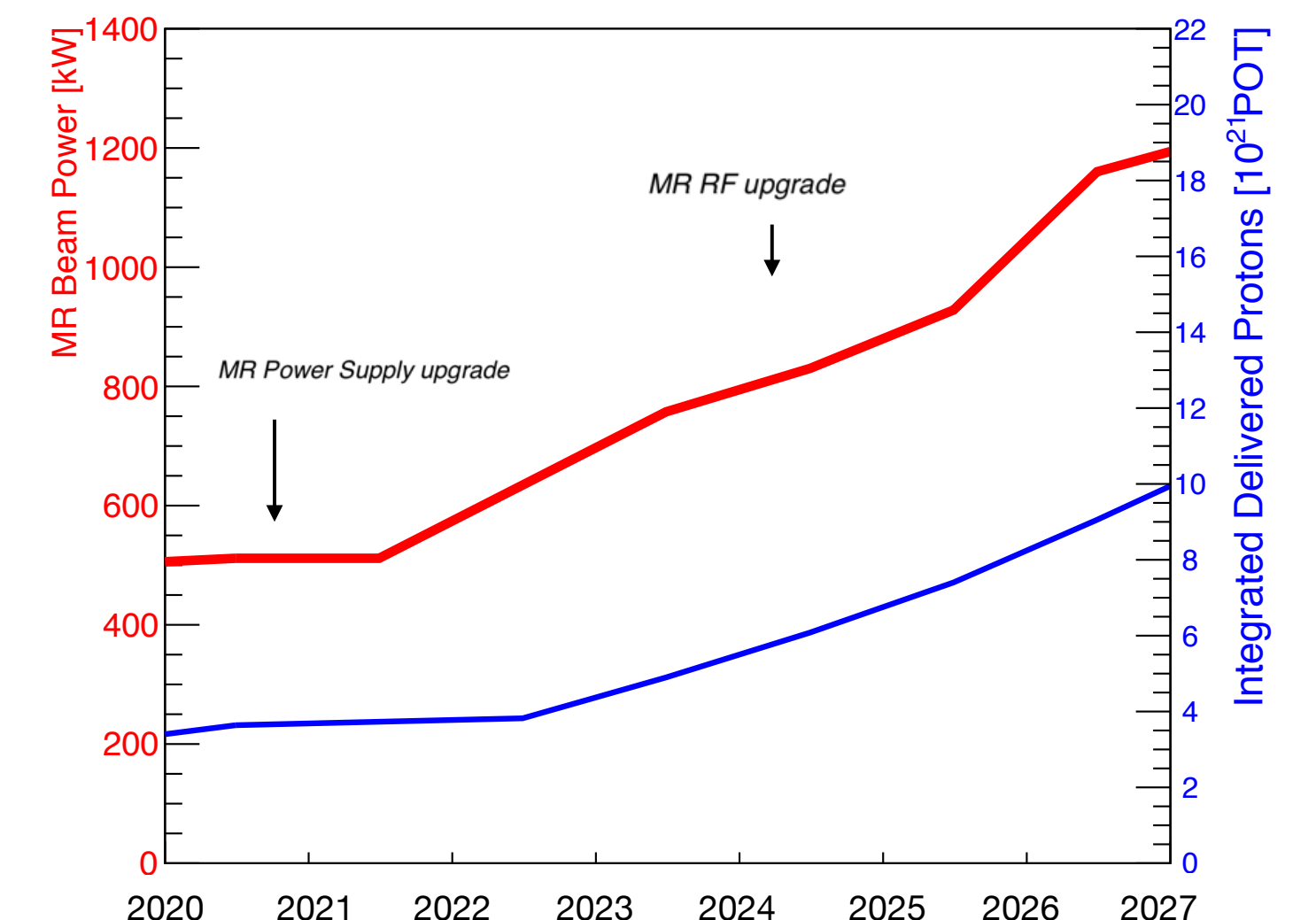
## ● In order to search for CP violation at $> 3\sigma$ C.L., these are the expected upgrades:

- Neutron tagging using Gd at Super-Kamiokande.
- J-PARC accelerator upgrade (double repetition rate&beam power).
- Near detector ND280 upgrade in 2023.
- Hyper-Kamiokande project.

From T2K talk at Neutrino 2022

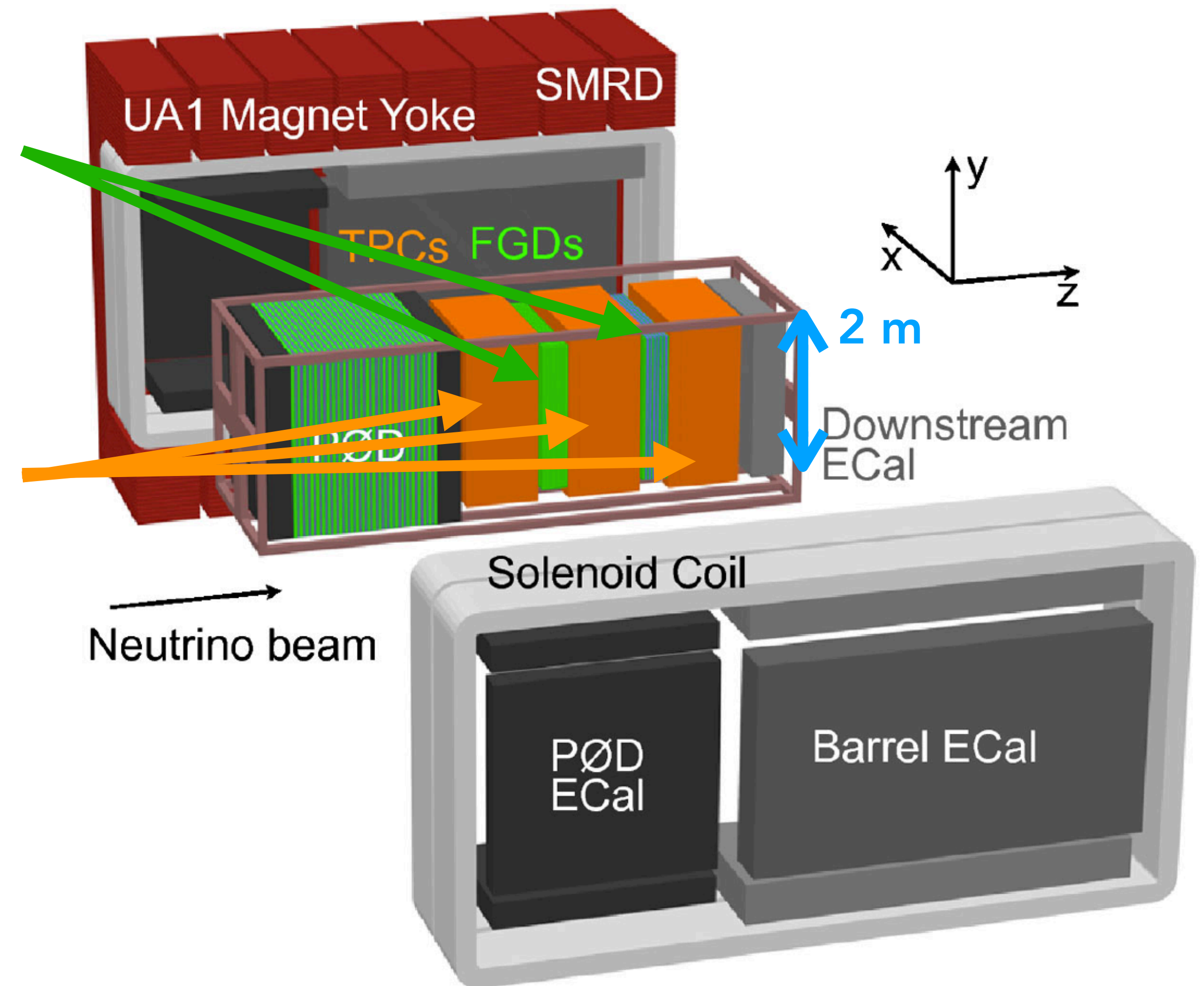


T2K Projected POT (Protons-On-Target)



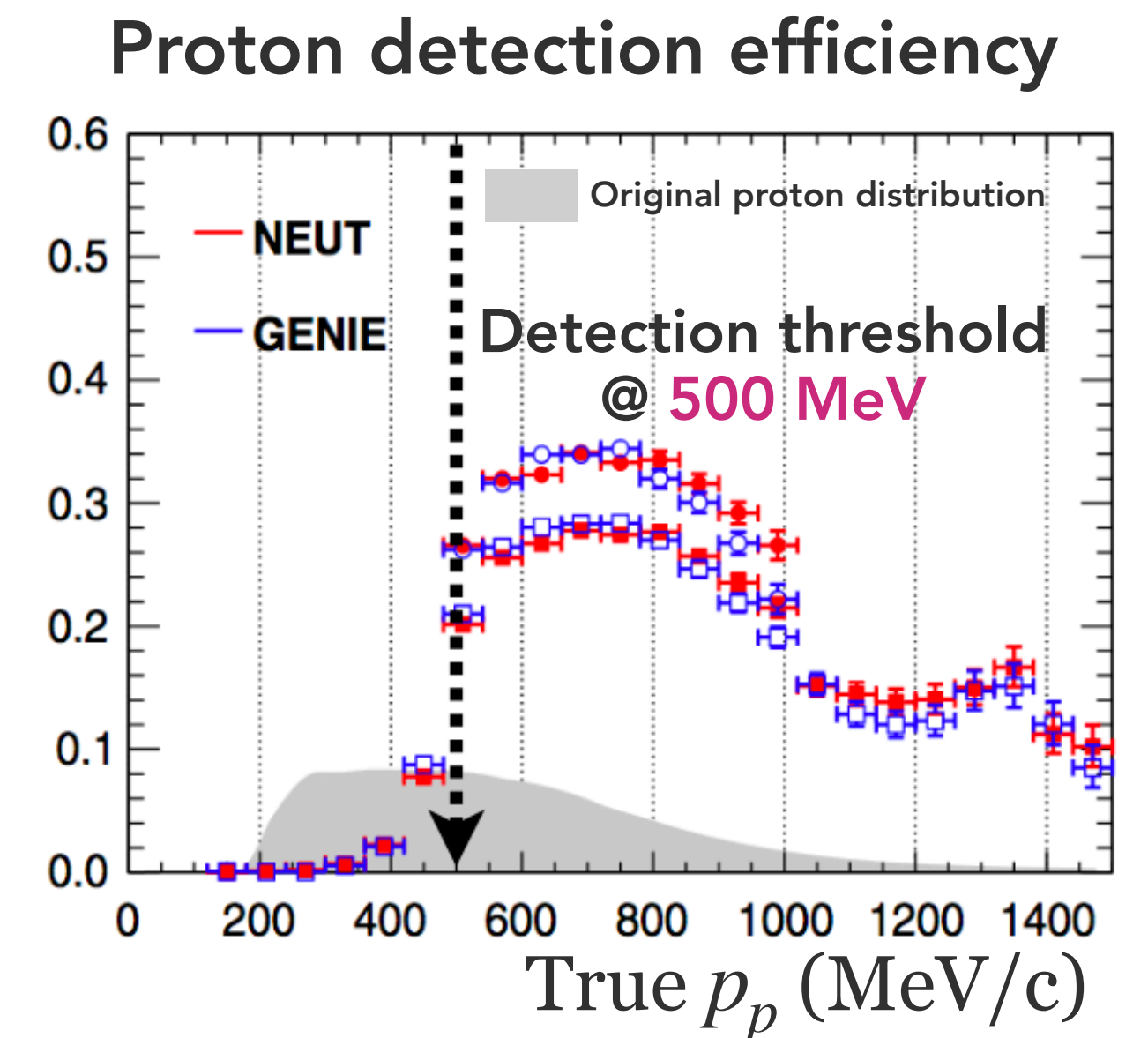
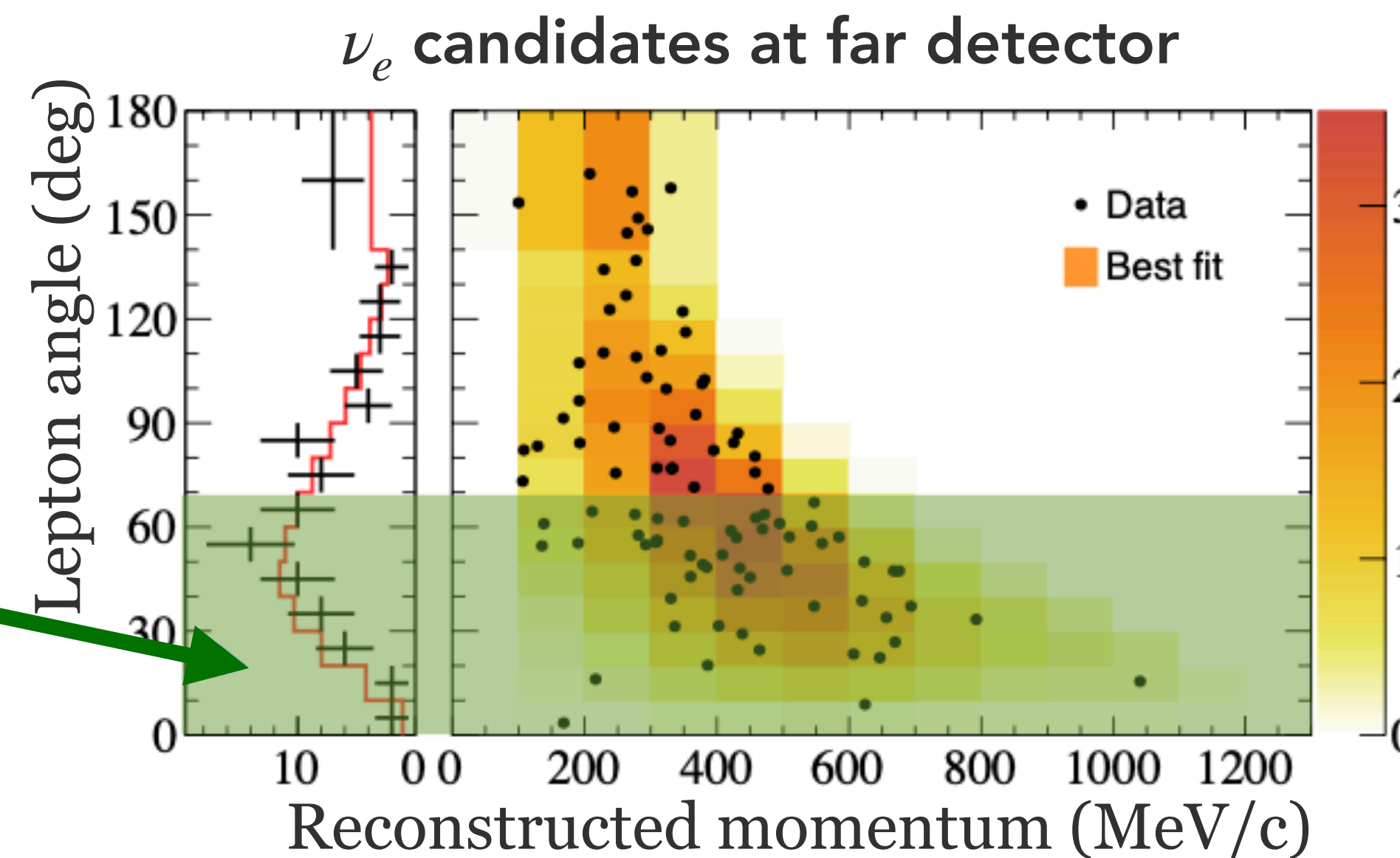
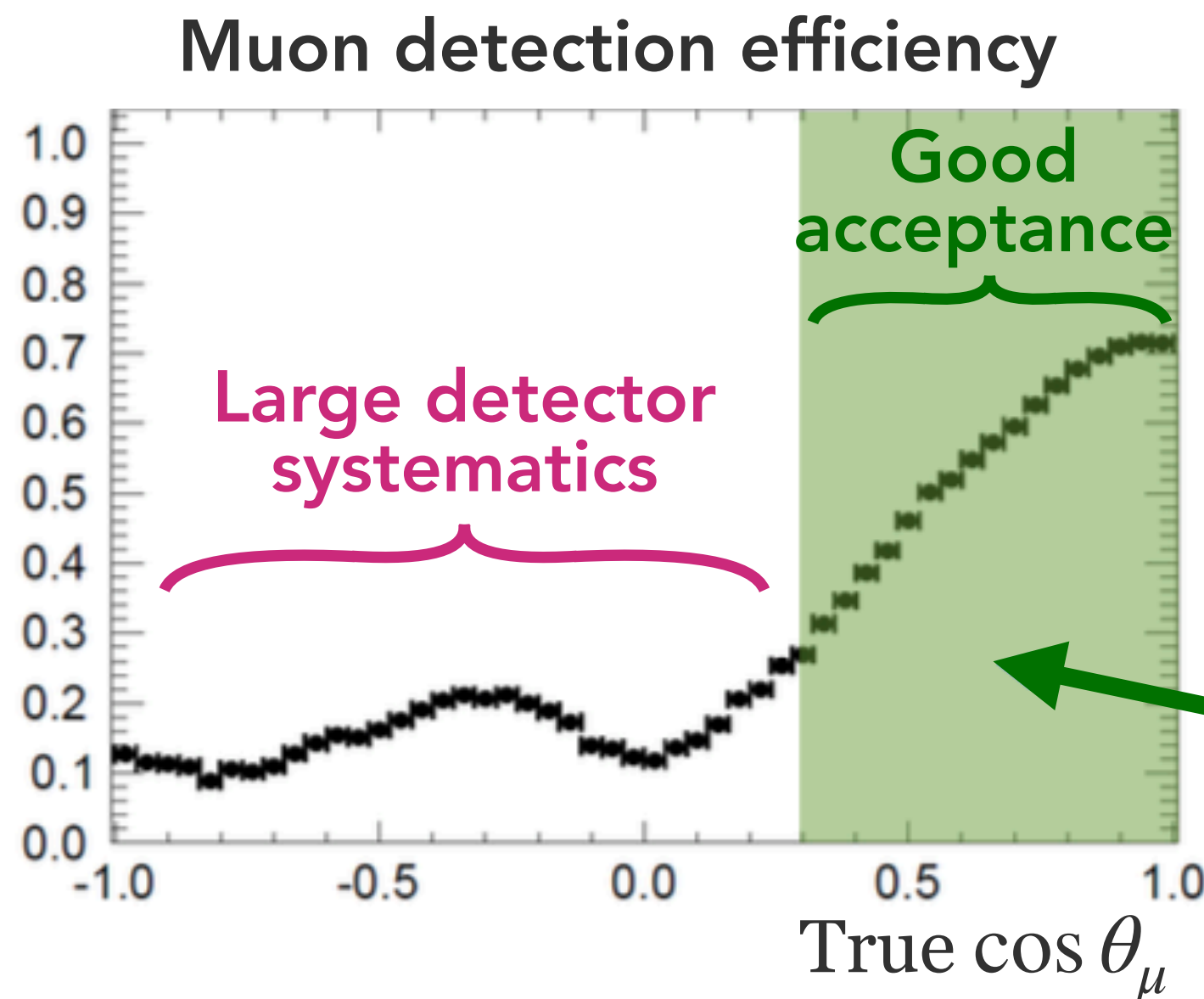
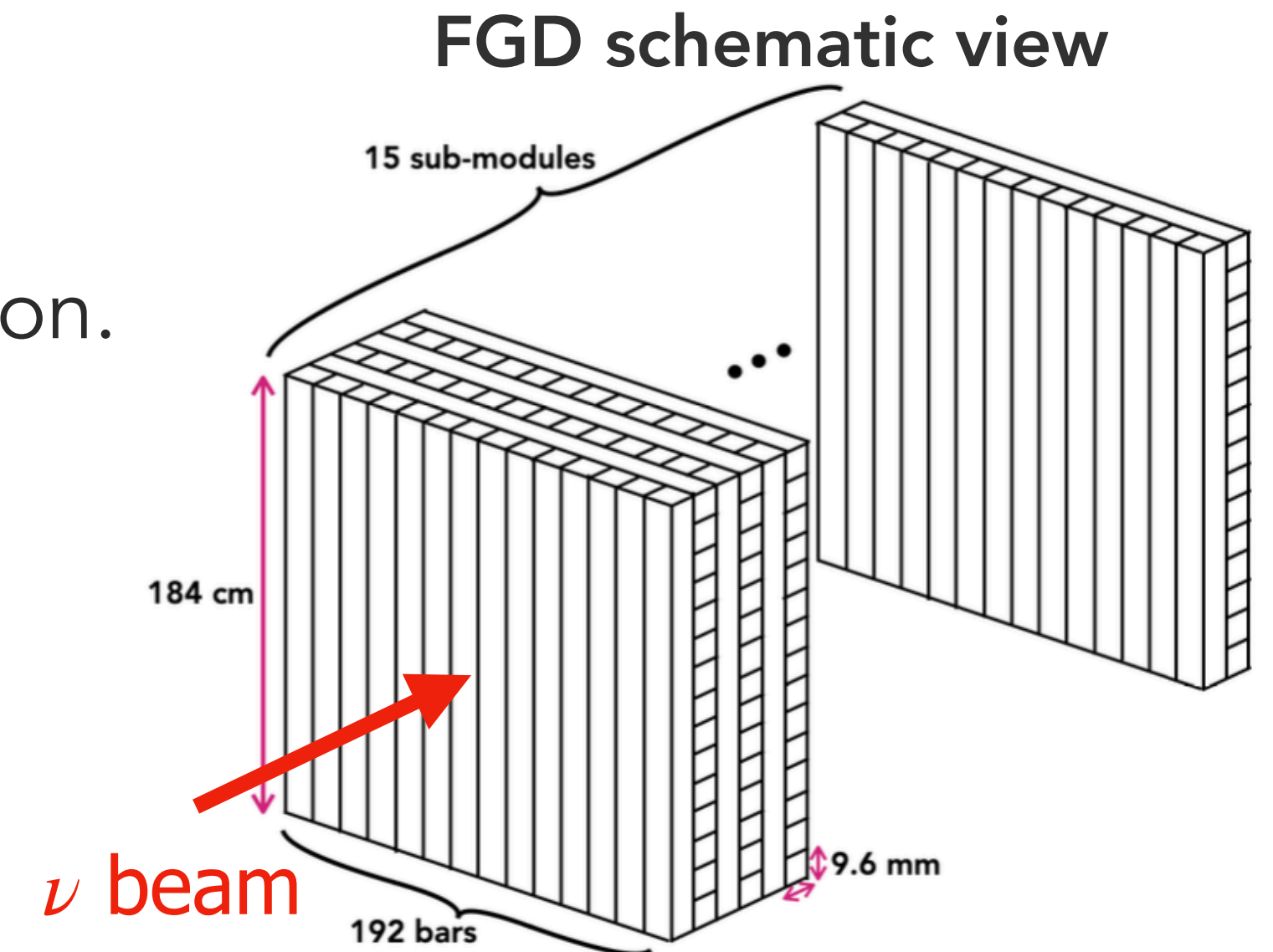
# T2K Near Detector “ND280”

- T2K near detector complex “ND280” is located 280 m downstream the  $\nu$  generation target.
  - Measure the neutrino cross-sections and constrain the uncertainties in the oscillation analysis.
- Tracking detectors
  - Targets are two Fine-Grained Detectors (FGD). FGD1 consists of scintillator and FGD2 consists of scintillator+water.
  - Three Time Projection Chambers (TPC) filled mainly with Ar gas provide particle ID based on  $dE/dx$  and momentum measurement.
- Surrounded by
  - Side Muon Range Detector (SMRD)
  - Electromagnetic Calorimeters (ECal)
  - Pi-0 detector (P0D)
- 0.2 T horizontal dipole magnetic field is applied.



# Limitations of Current ND280

- Limited acceptance for particles with a **large scattering angle**.
  - TPCs are located at downstream of FGDs.
  - FGDs consist of scintillator bars perpendicular to the beam direction.
- **High detection threshold** for protons.
  - Short protons cannot be reconstructed in FGD.
- No **neutron** information.
- Poor **electron/photon separation** for the  $\nu_e$  measurements.

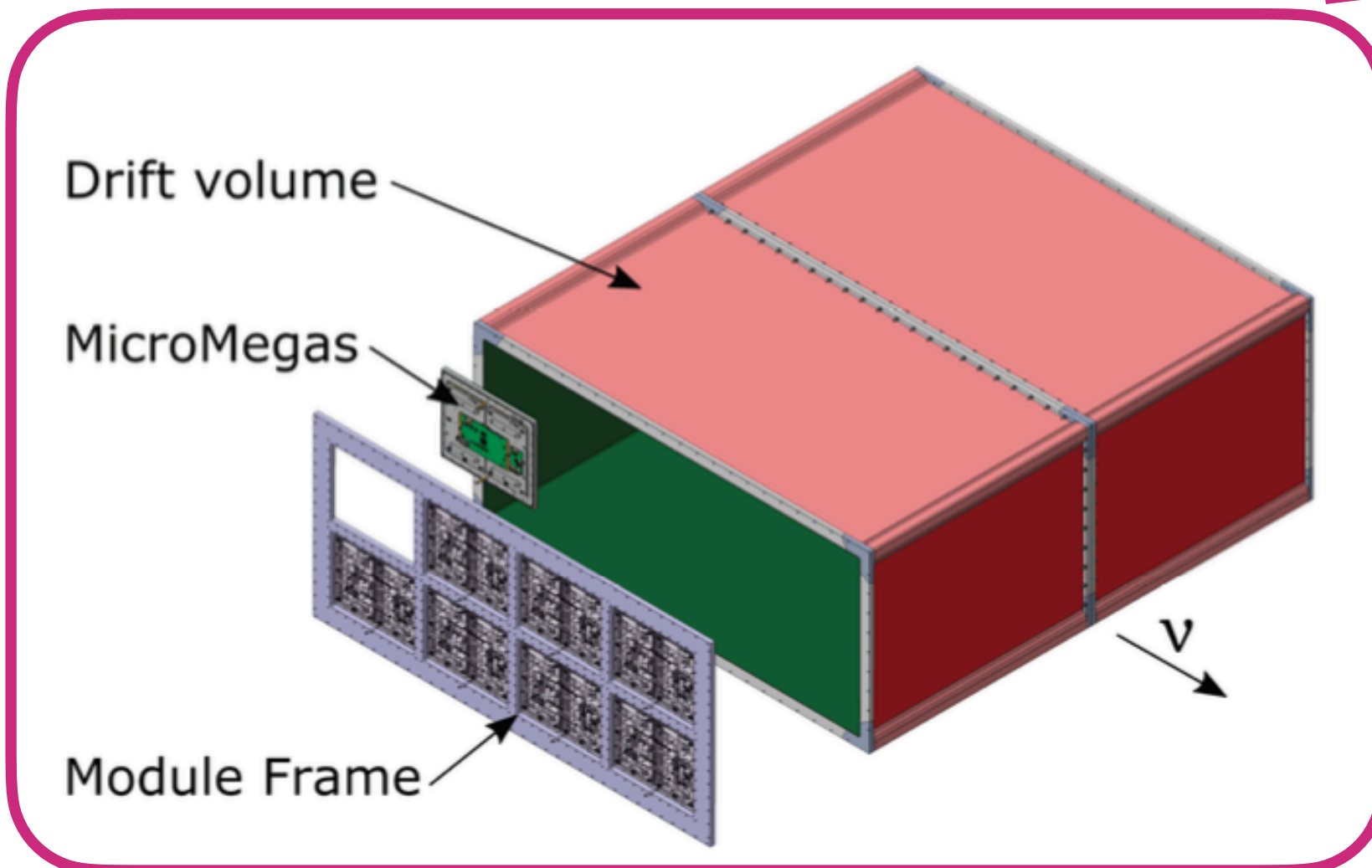
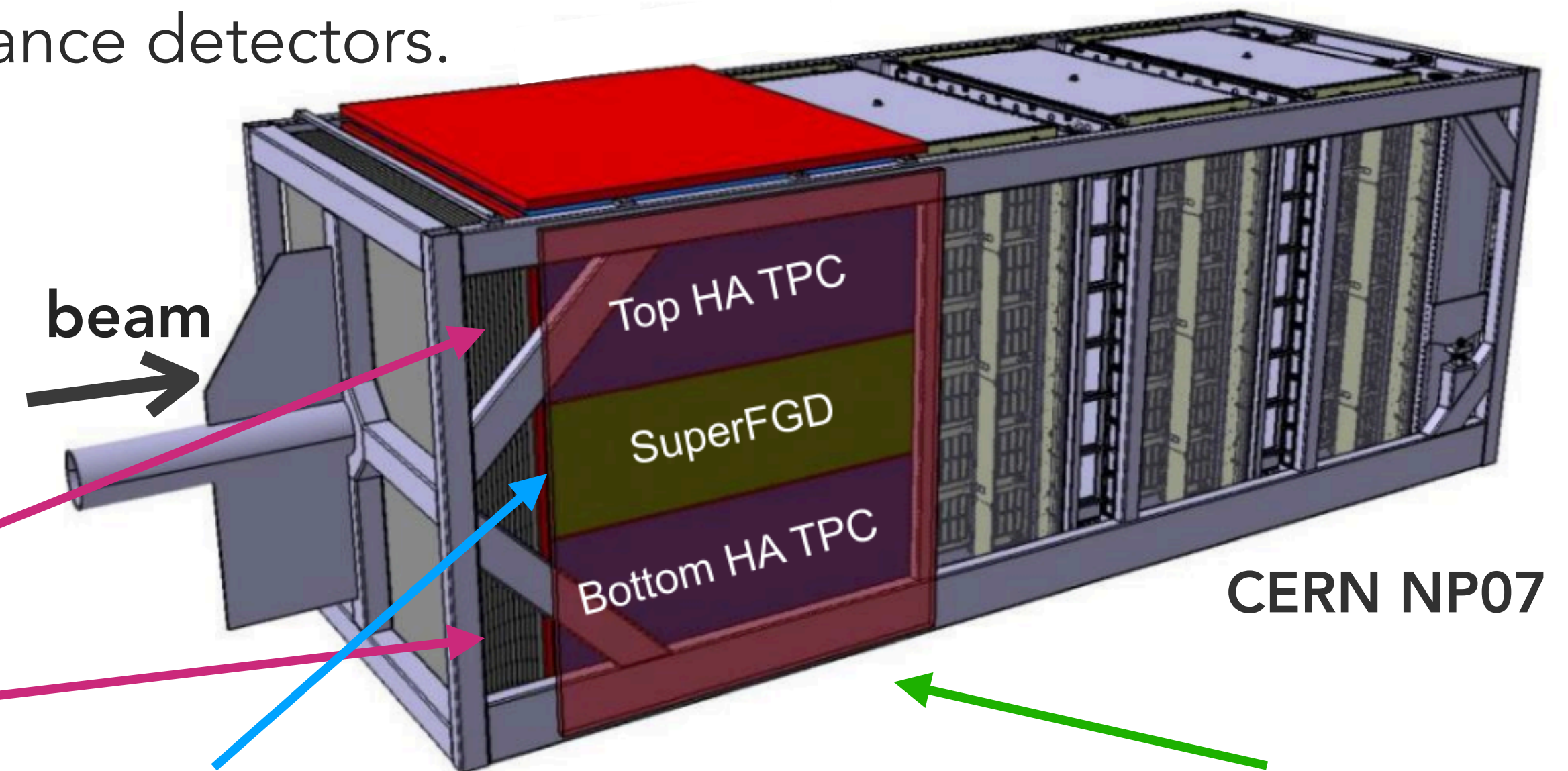


# ND280 Upgrade

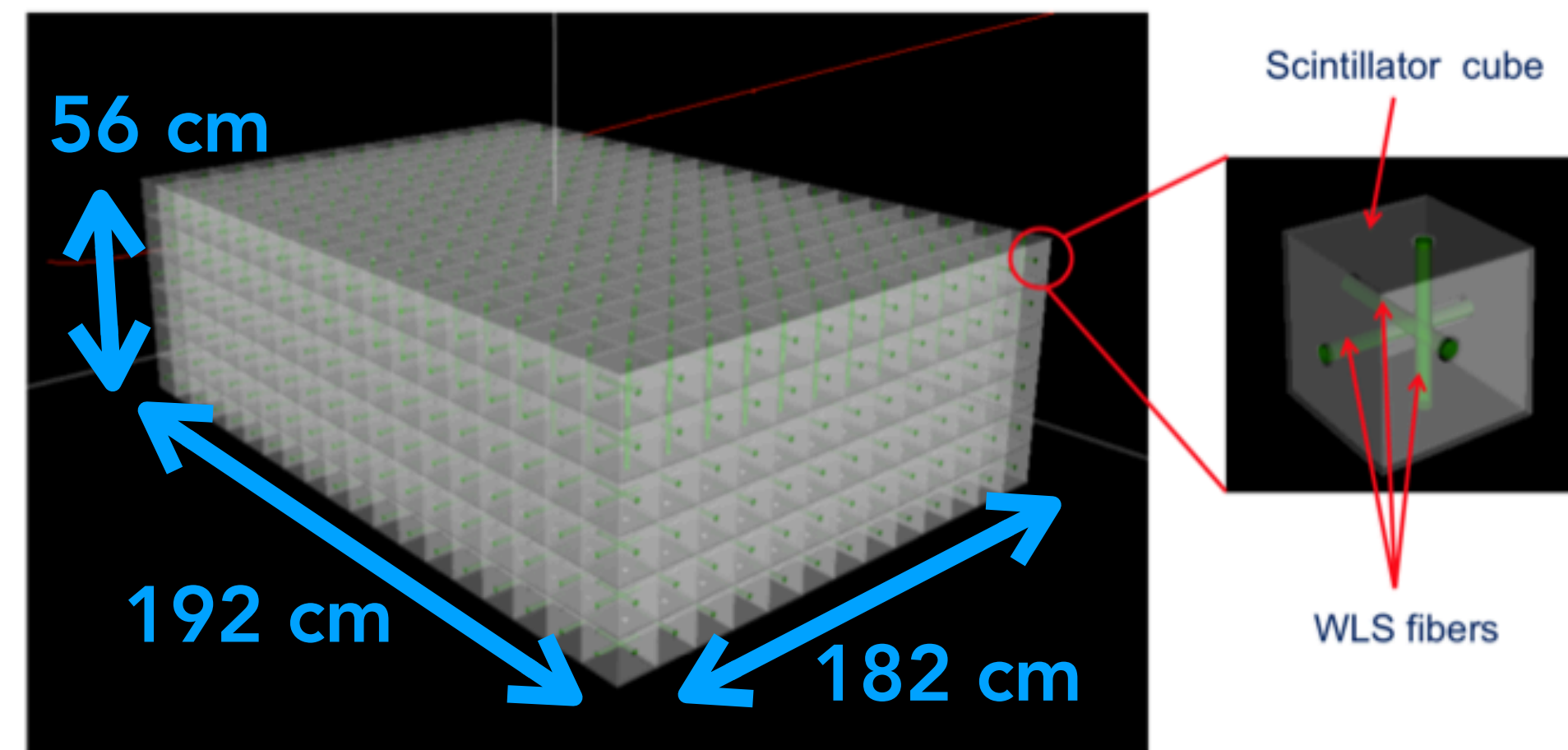
- Pi-0 detector will be replaced with new  $4\pi$  acceptance detectors.

- **SuperFGD** : fully active plastic scintillator.
- **High-Angle TPC**: high resolution tracking of charged particles.
- **Time-of-Flight** : Provide time information.

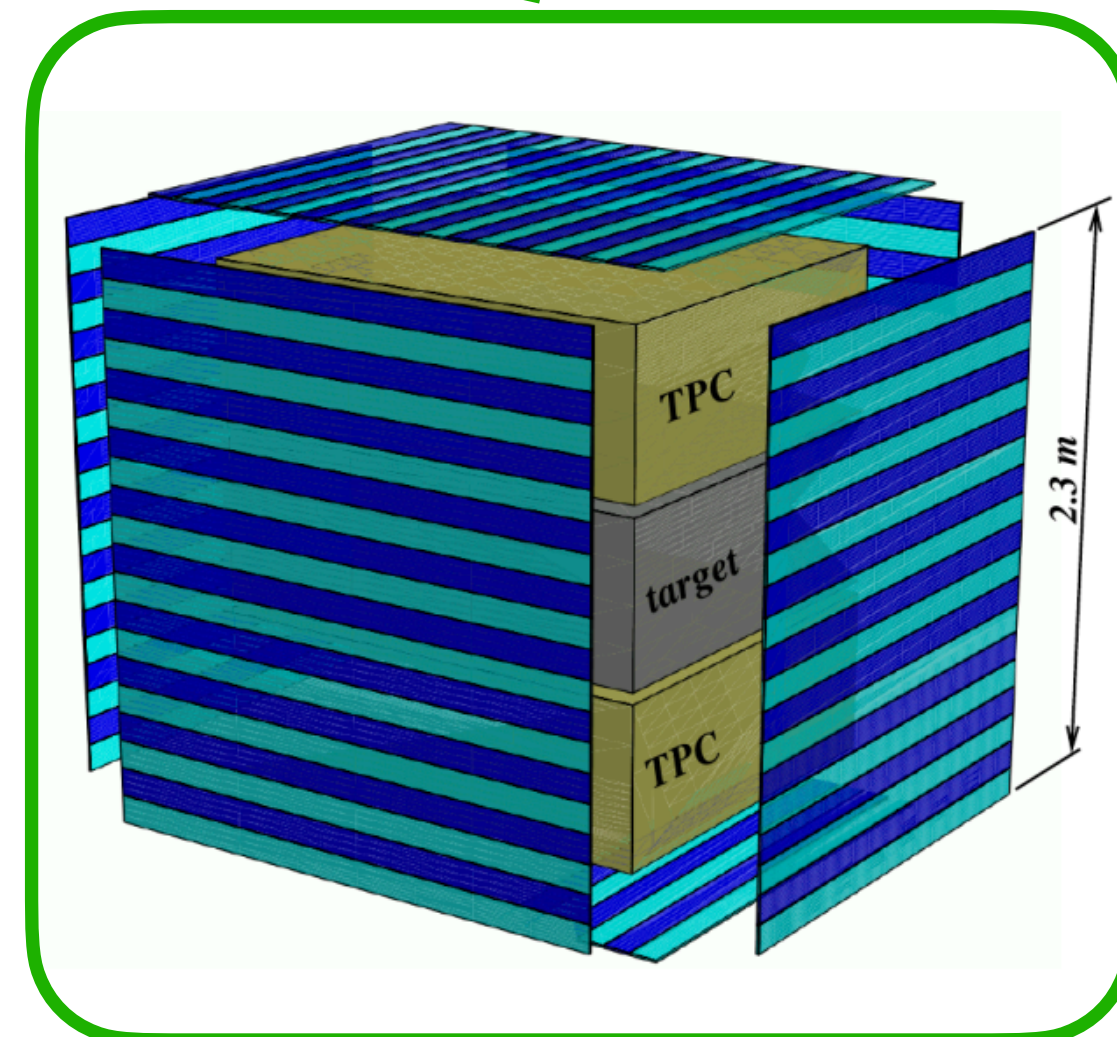
- Technical Design Report on [arXiv:1901.03750](https://arxiv.org/abs/1901.03750)



High-Angle TPC (HATPC)



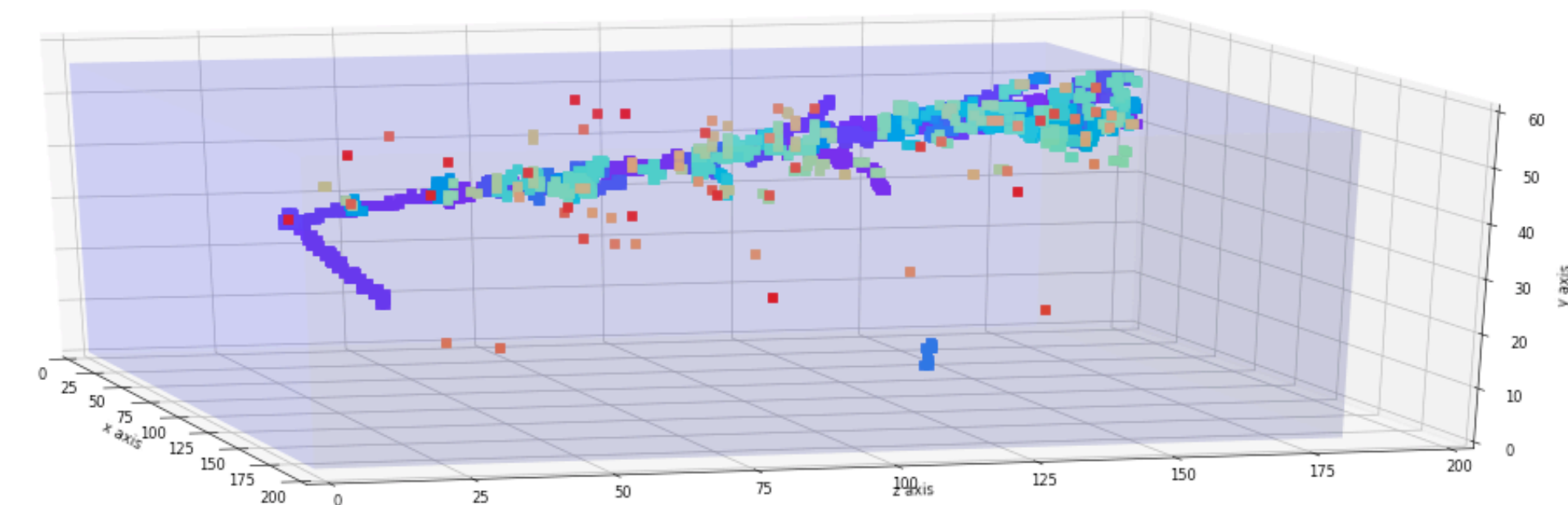
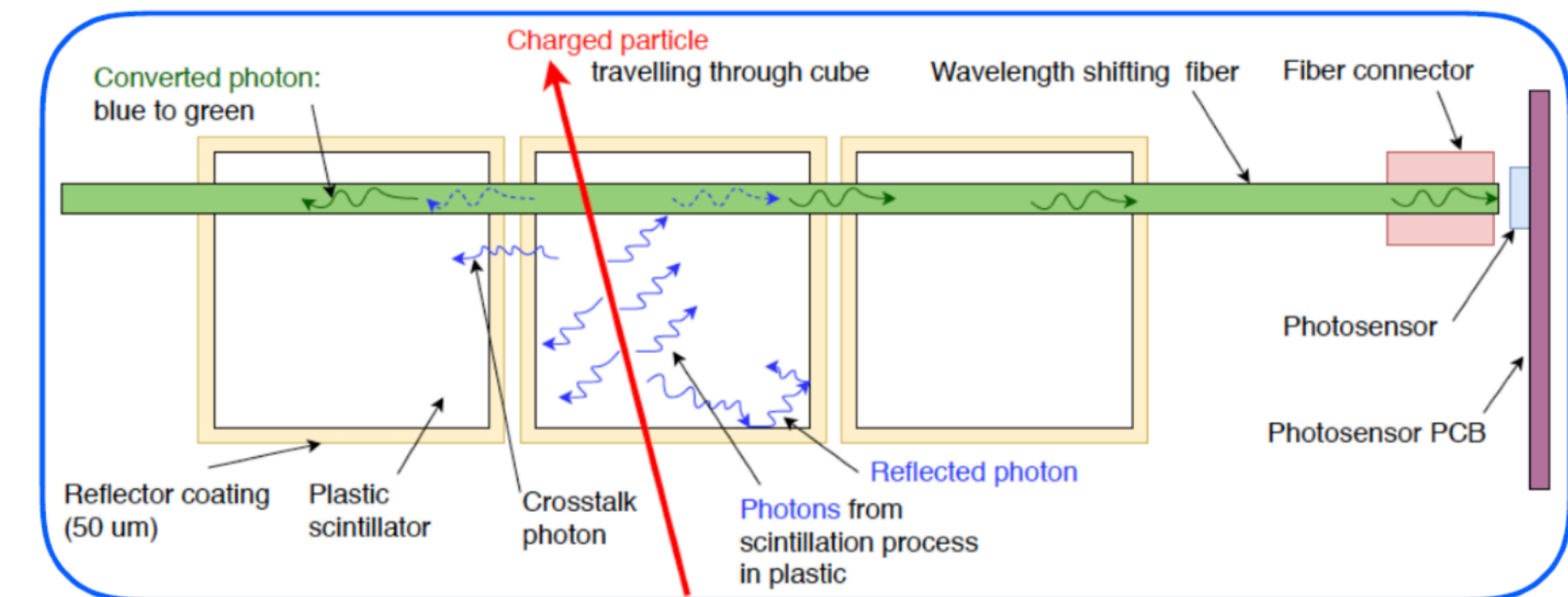
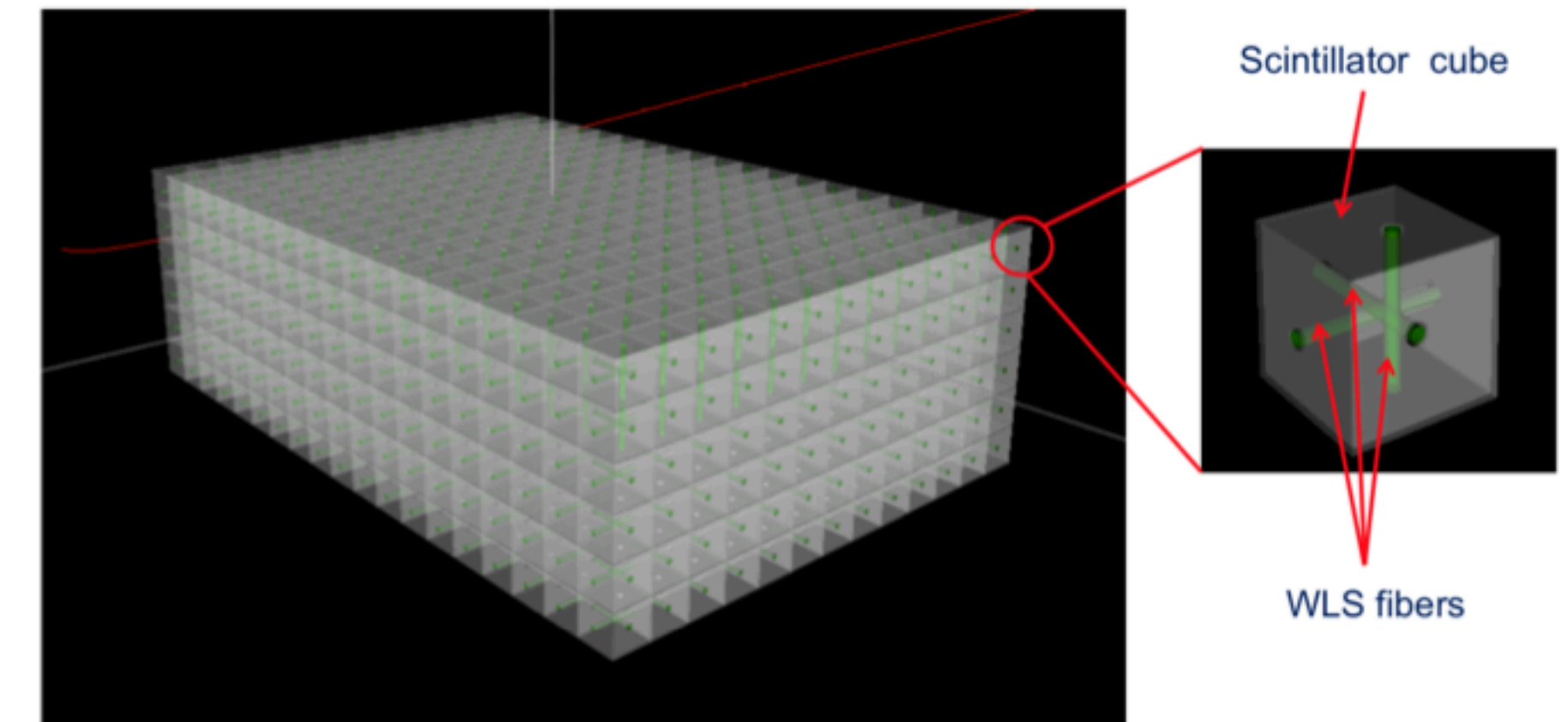
Super Fine-Grained Detector (SuperFGD)



Time-of-Flight (TOF)

# SuperFGD

- Fully active plastic scintillator.
  - Consists of **~2.1M plastic scintillator cubes** ( $1 \text{ cm}^3$ ).
  - 2.2 tons target mass.
  - Photons are read out through wave-length shifting (WLS) fibers in **three orthogonal directions** and detected by Multi Pixel Photon Counters (MPPC).
- Expected features of SuperFGD
  - 3D tracking&reconstruction capability.
  - Lower energy threshold for protons ( $500 \rightarrow 350 \text{ MeV/c}$ ).
  - Neutron kinematics measurement using time of flight [[Phys. Rev. D 101, 092003](#)].
  - Better electron/photon separation capability.



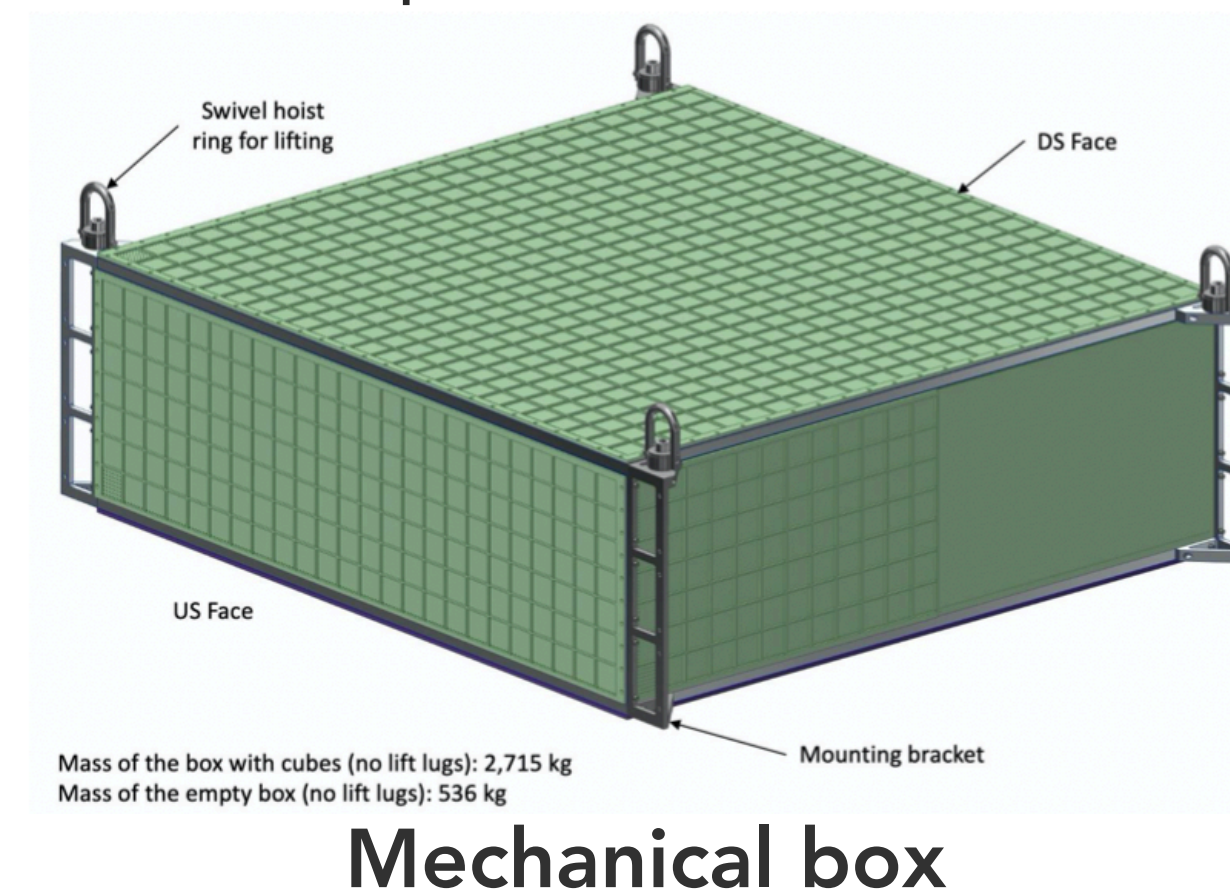
# SuperFGD Construction&Performance

## ● Cubes and box

- All (~2.1 M) cubes have been produced at INR and delivered to J-PARC.
- All (~57 k) fibers have been produced and will be inserted into the cubes.
- Box design has been validated with prototypes.
  - It needs to withstand 2 tons of weight and earthquakes.

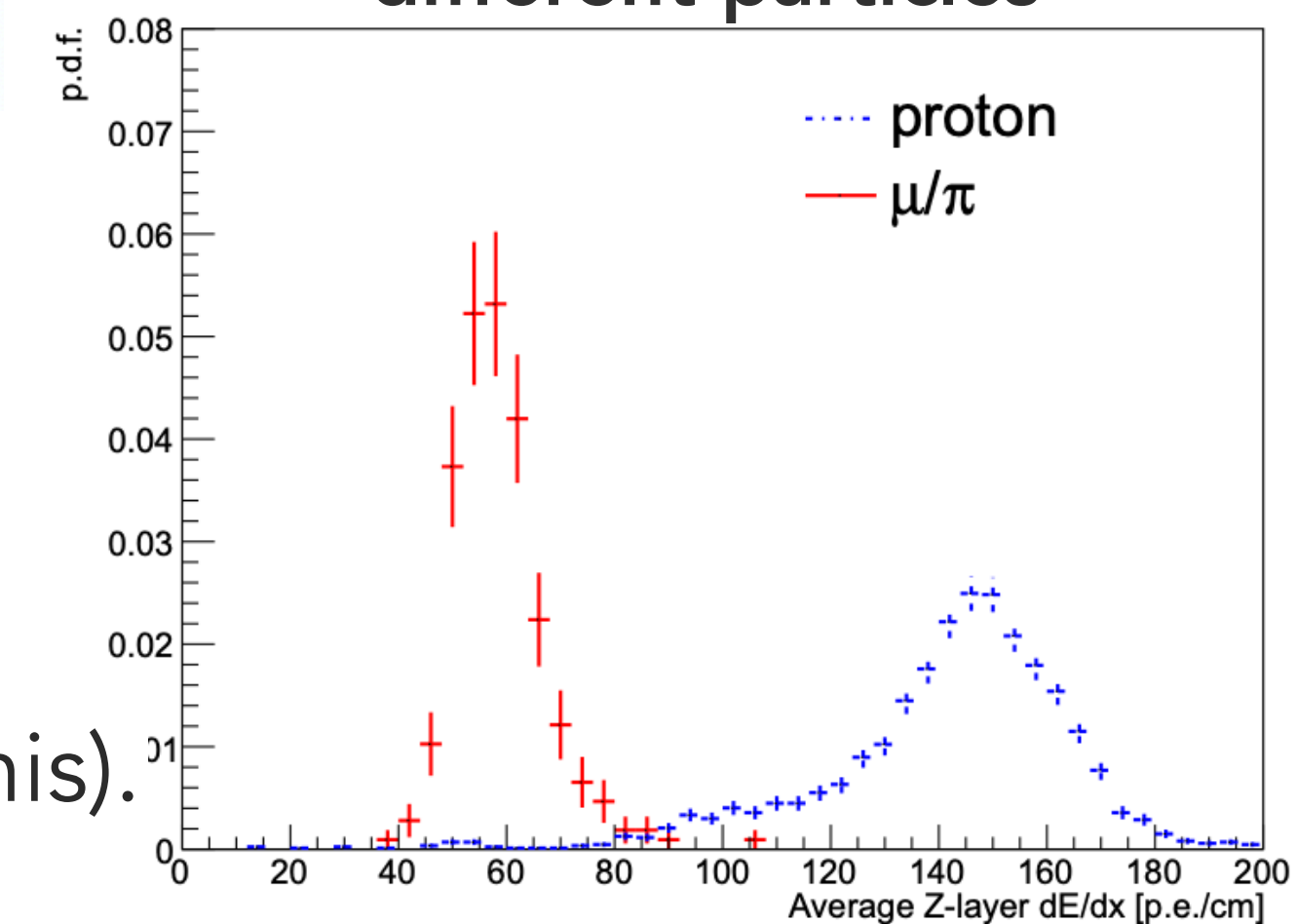
## ● Electronics

- Design of the readout front-end is finished.
- 400 MHz sampling provides 2.5 ns timing information.
- Integrated calibration system for the regular MPPC calibration.



**Scintillator cubes**

**Measured dE/dx for different particles**

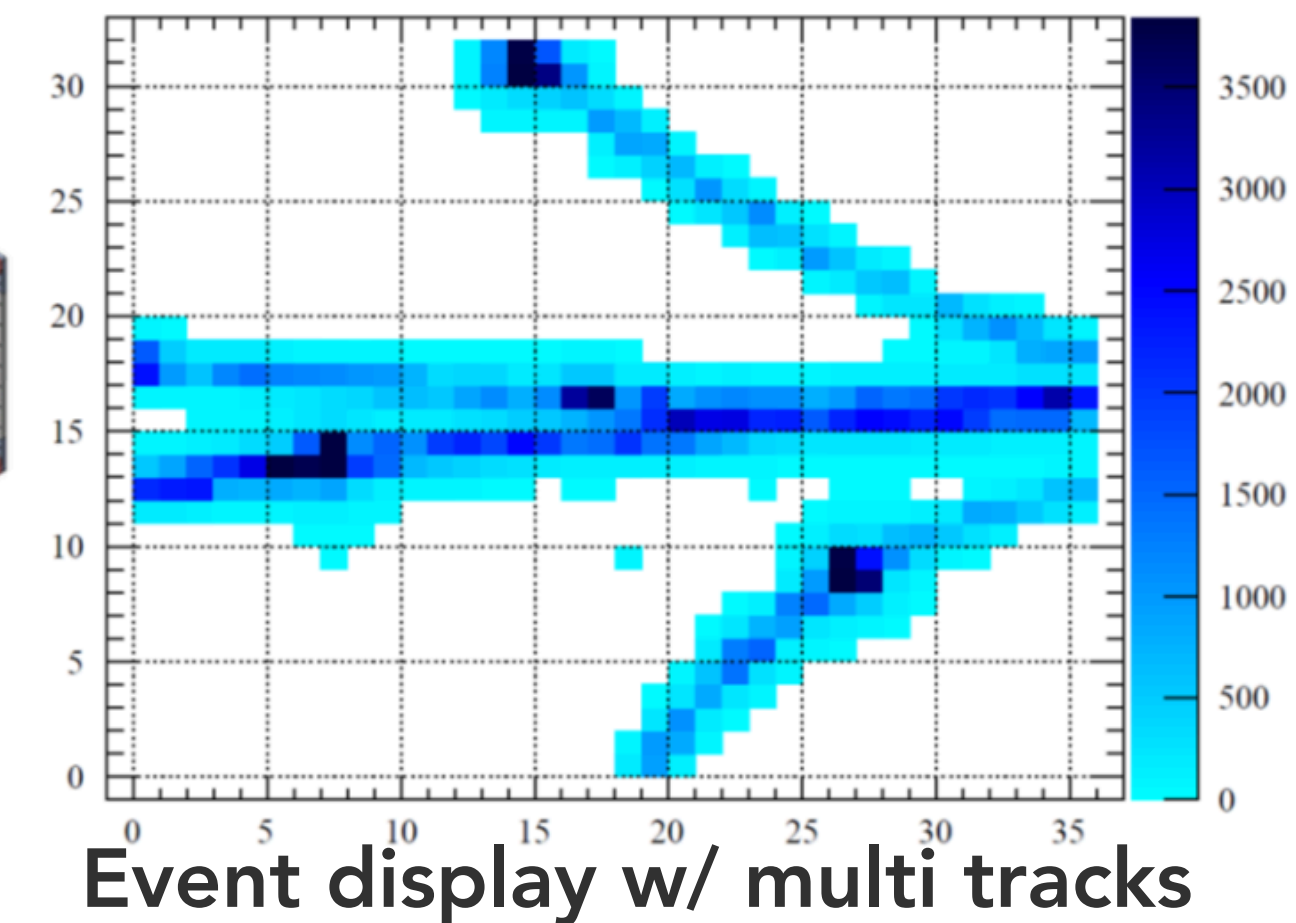
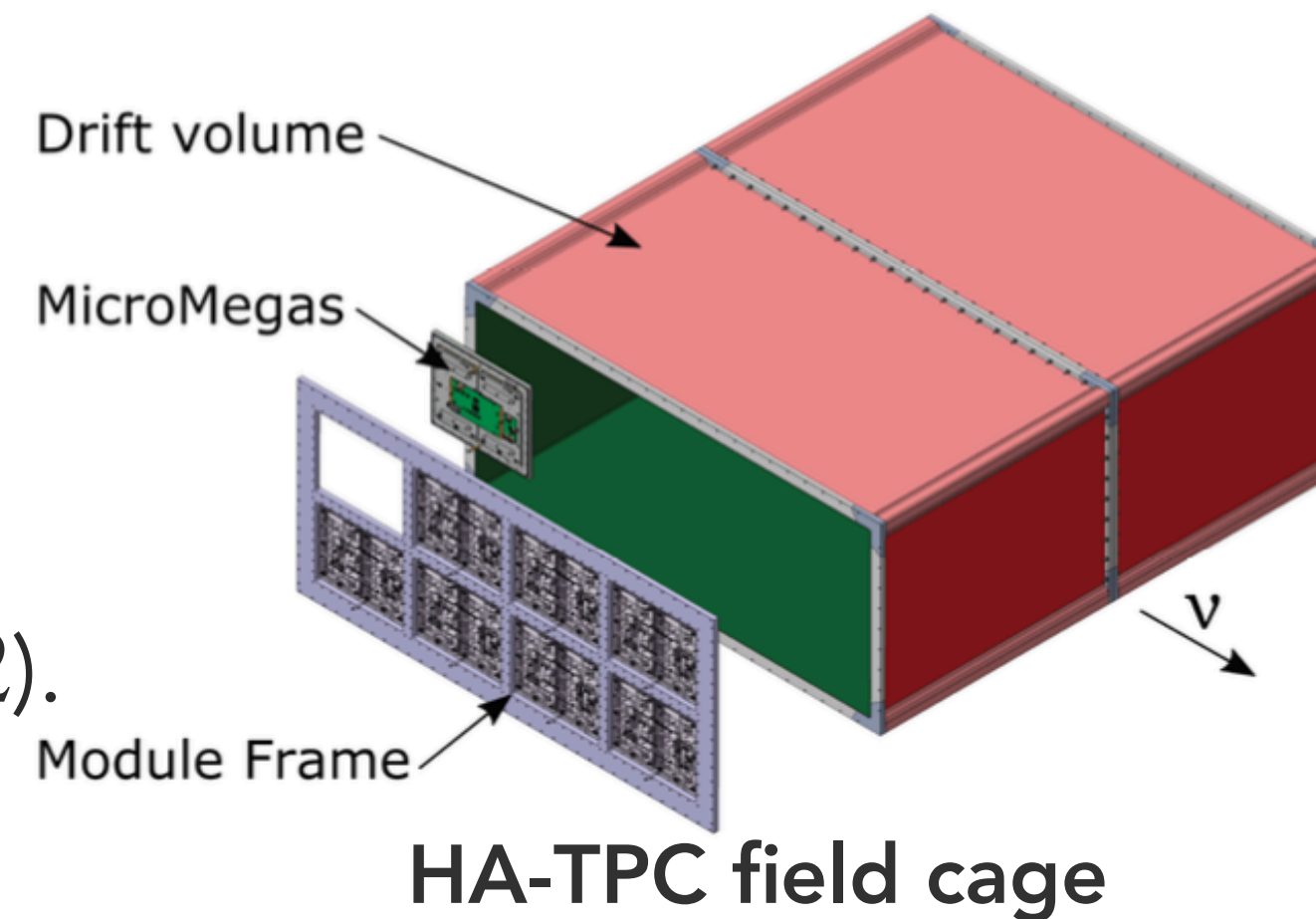


## ● Prototype beam test at CERN and LANL

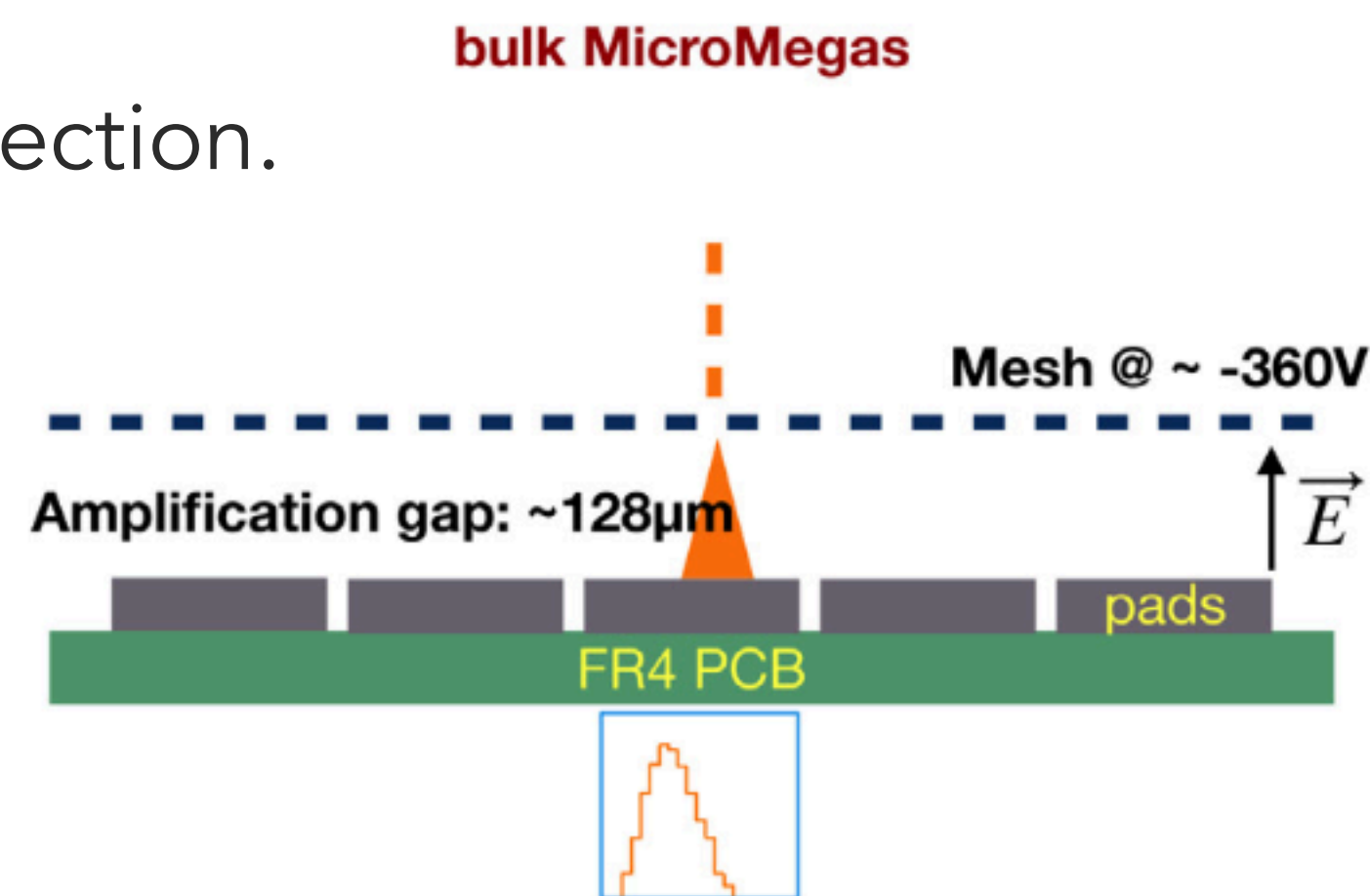
- Charged particle test beam at CERN [[DOI:10.1016/j.nima.2018.09.048](https://doi.org/10.1016/j.nima.2018.09.048), [JINST 15 P12003 \(2020\)](#)].
- Neutron test beam at LANL [[arXiv:2207.02685](https://arxiv.org/abs/2207.02685)] (talk by Ciro right after this).
- Positron test beam at Tohoku Univ.

# High-Angle TPC

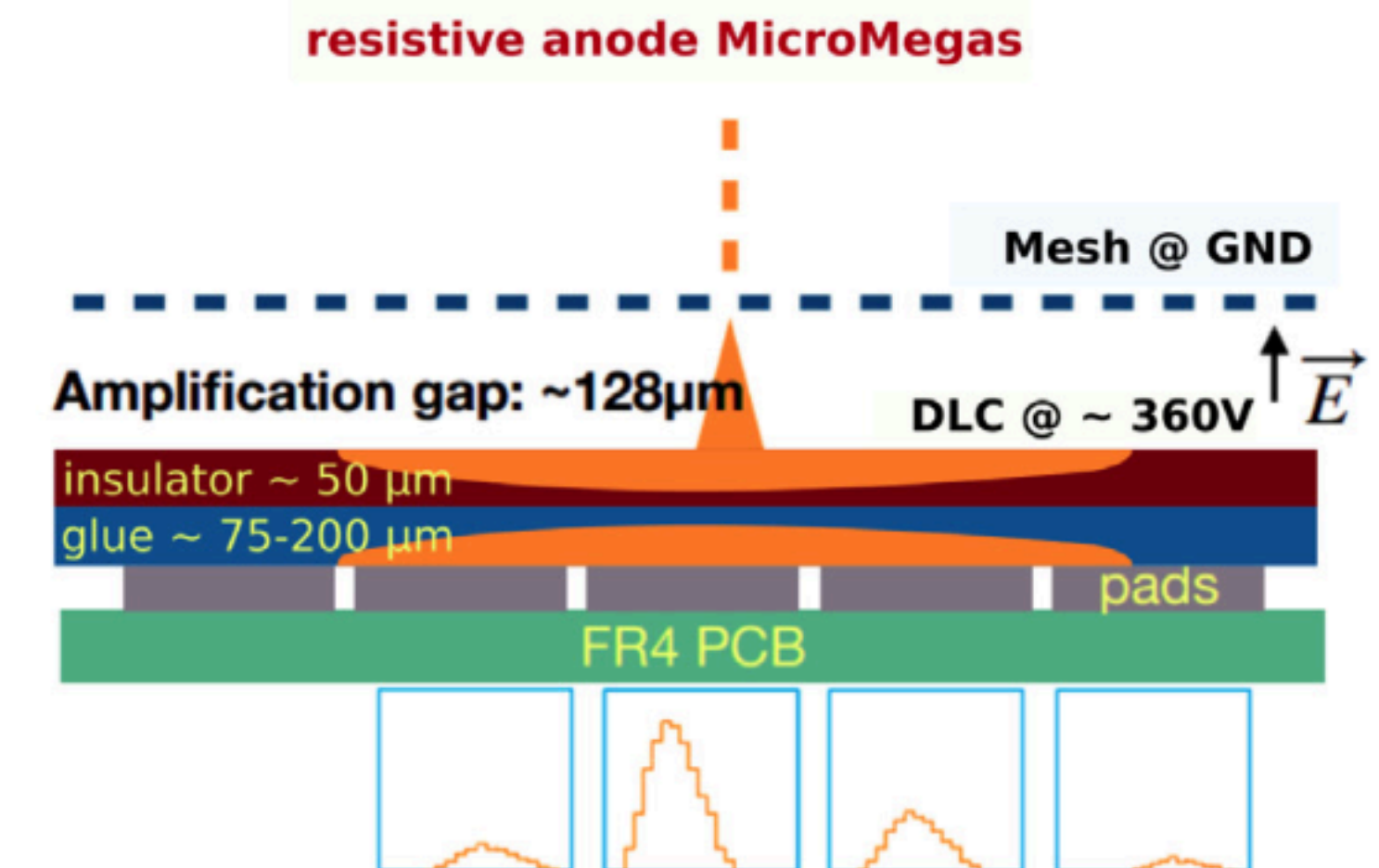
- Two new TPCs are produced.
  - Provides **tracking** and **particle ID**.
  - Dimensions:  $1.865 \times 2.0 \times 0.82 \text{ m}^3$ .
  - Composite material for the field cage.
  - Same T2K gas ( $\text{Ar} : \text{CF}_4 : \text{iC}_4\text{H}_{10} = 95 : 3 : 2$ ).



- Bulk Micromegas readout module replaced by new **resistive Micromegas Modules (ERAM)**.
  - Spread the charge over multiple pads, improving the **spatial resolution** and reducing the number of readout pads.
  - No need for spark protection.

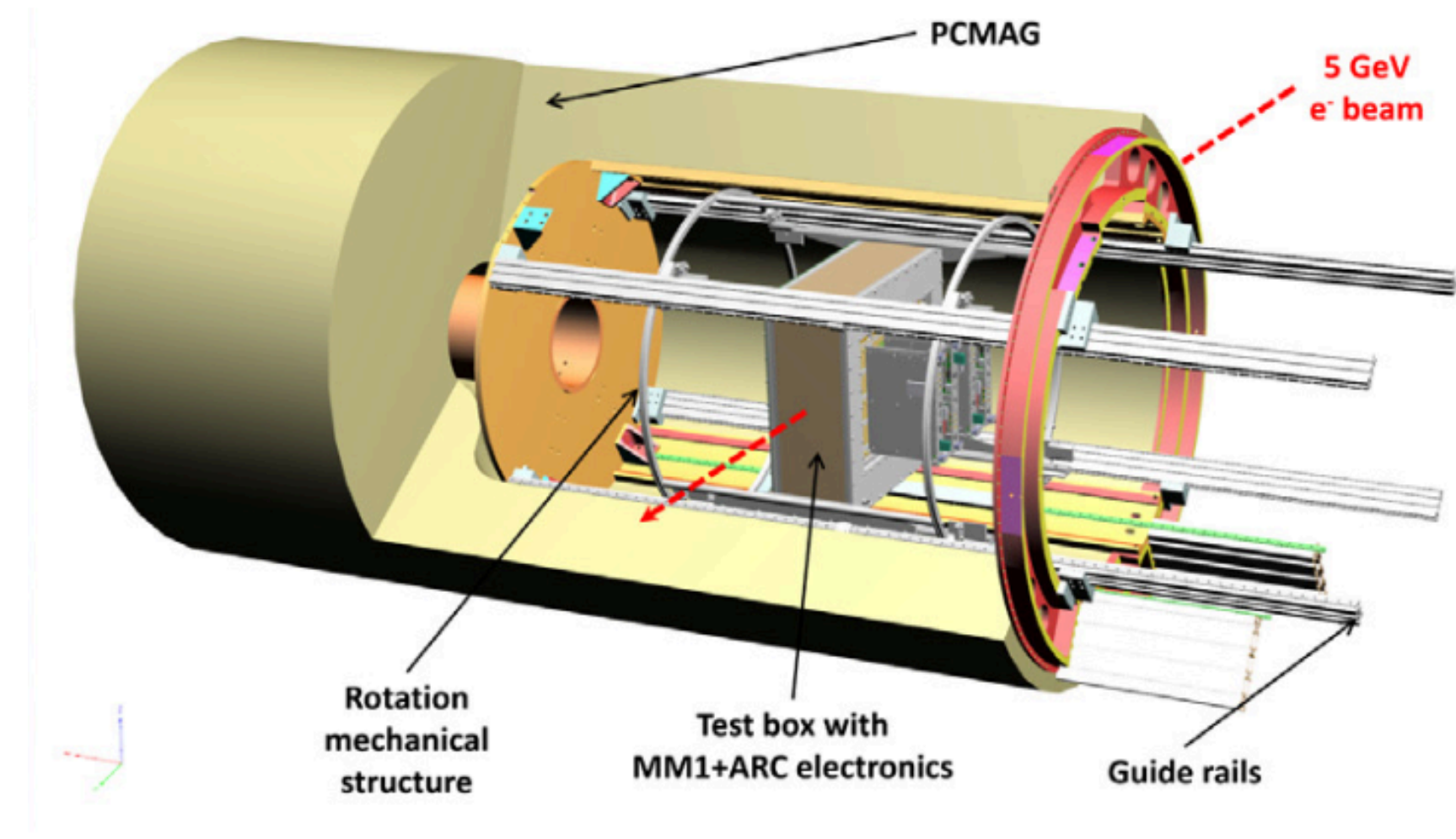
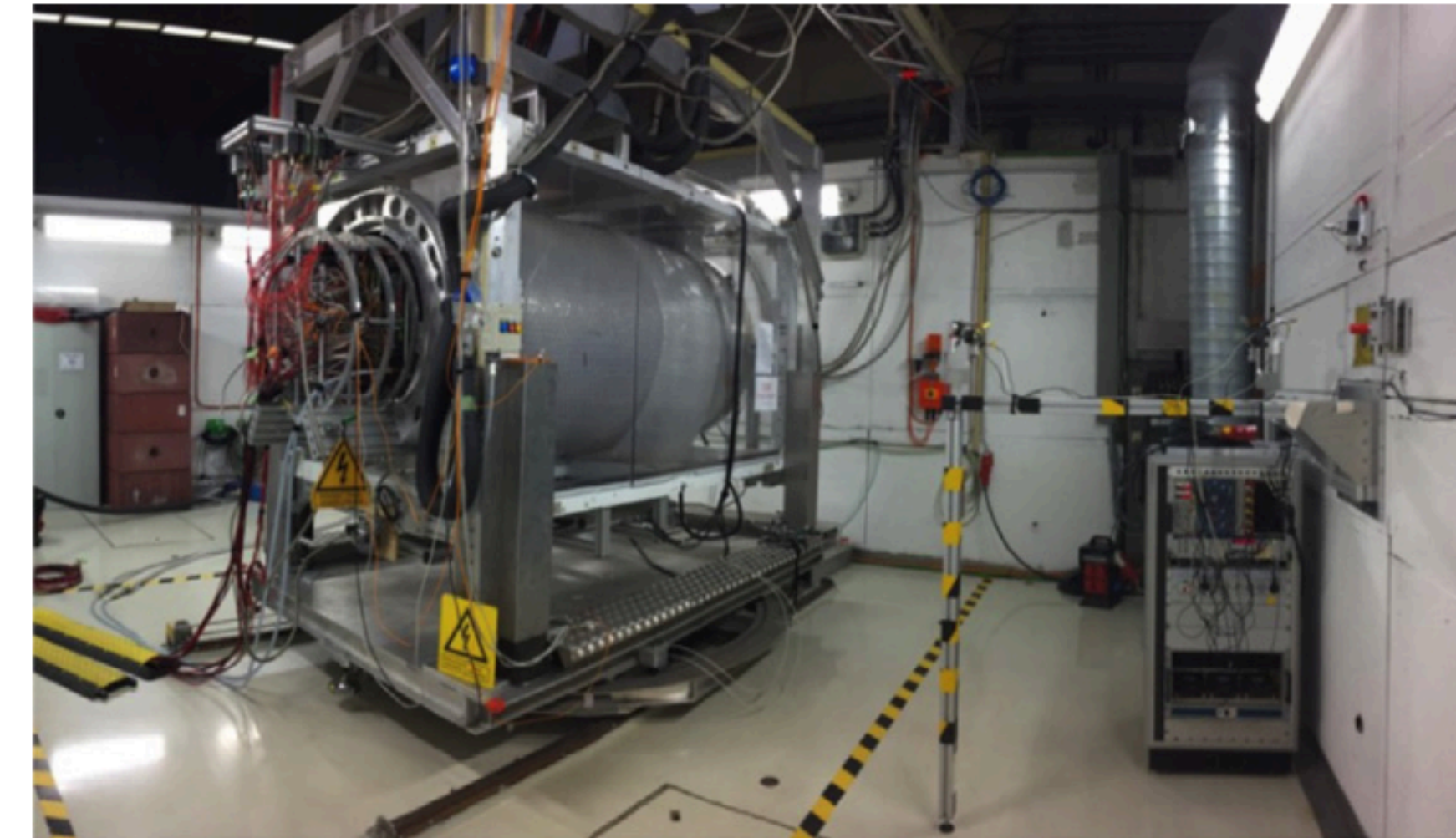


upgrade



# HA-TPC Test Beam Performance

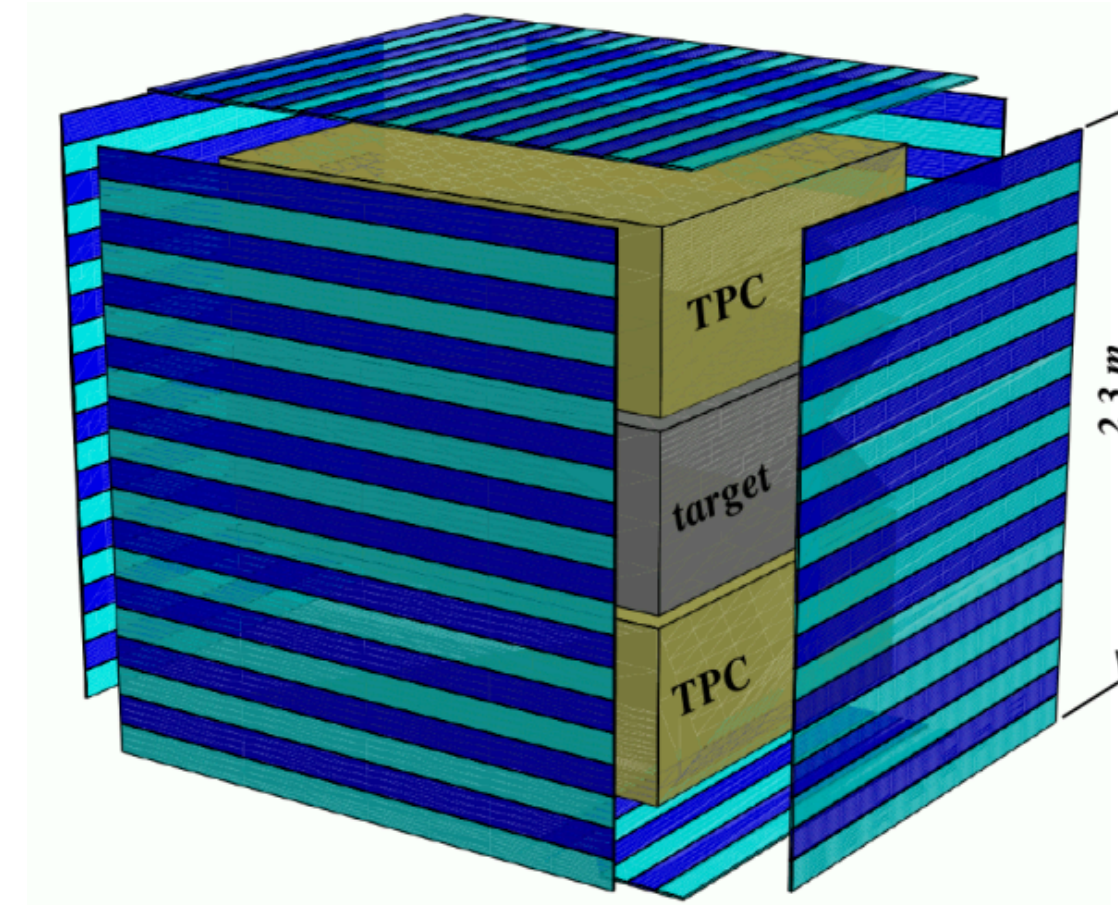
- Prototypes have been tested in test beams at DESY/CERN
  - CERN 2018 [[DOI:10.1016/j.nima.2019.163286](https://doi.org/10.1016/j.nima.2019.163286)]
  - DESY 2019 [[DOI:10.1016/j.nima.2021.166109](https://doi.org/10.1016/j.nima.2021.166109)]
  - DESY 2021 (analysis ongoing)
  - CERN November 2021 (analysis ongoing)
    - Sources are  $\mu$ ,  $e$ ,  $p$ ,  $\pi$  (up to 5 GeV/c), cosmic, and  $^{55}\text{Fe}$  (for calibration)
    - Various configurations were tested.
- Confirmed that it fulfills:
  - Spatial resolution  $< 0.8$  mm for all angles.
  - $dE/dx$  resolution  $< 10\%$ .
  - ▶ Fully satisfy the requirements for the ND280 upgrade.
- New reconstruction algorithms are being developed based on test beam data.



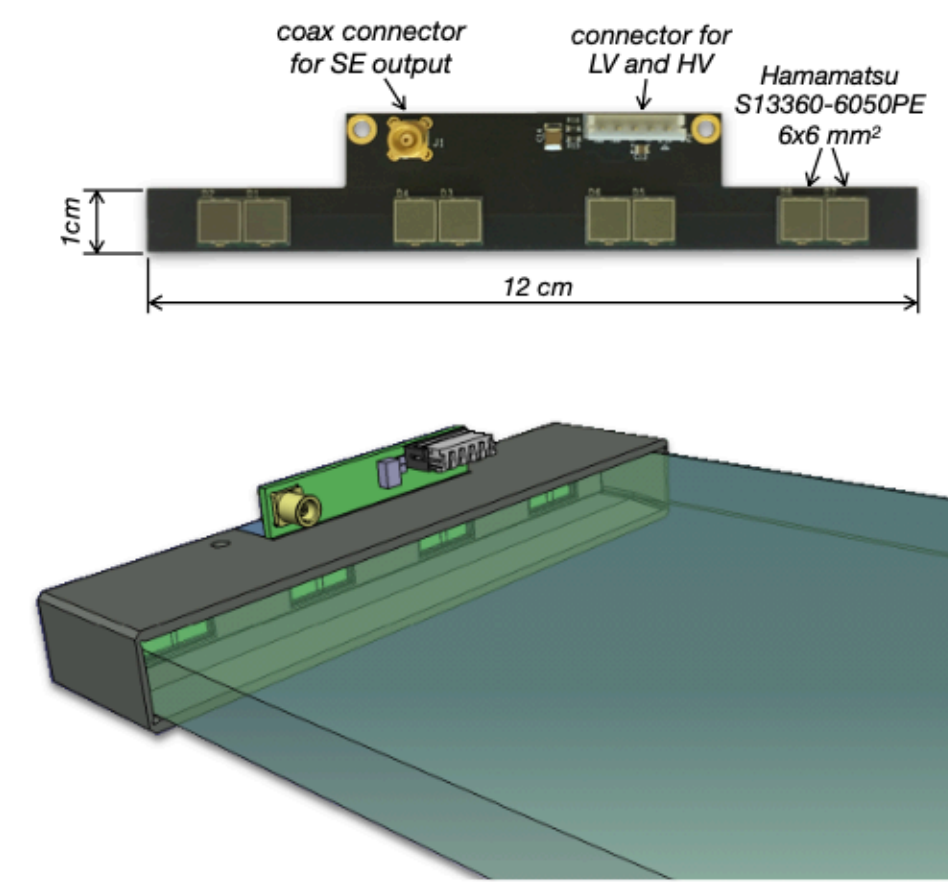
Beam test setup at DESY

# Time-of-Flight Detector (TOF)

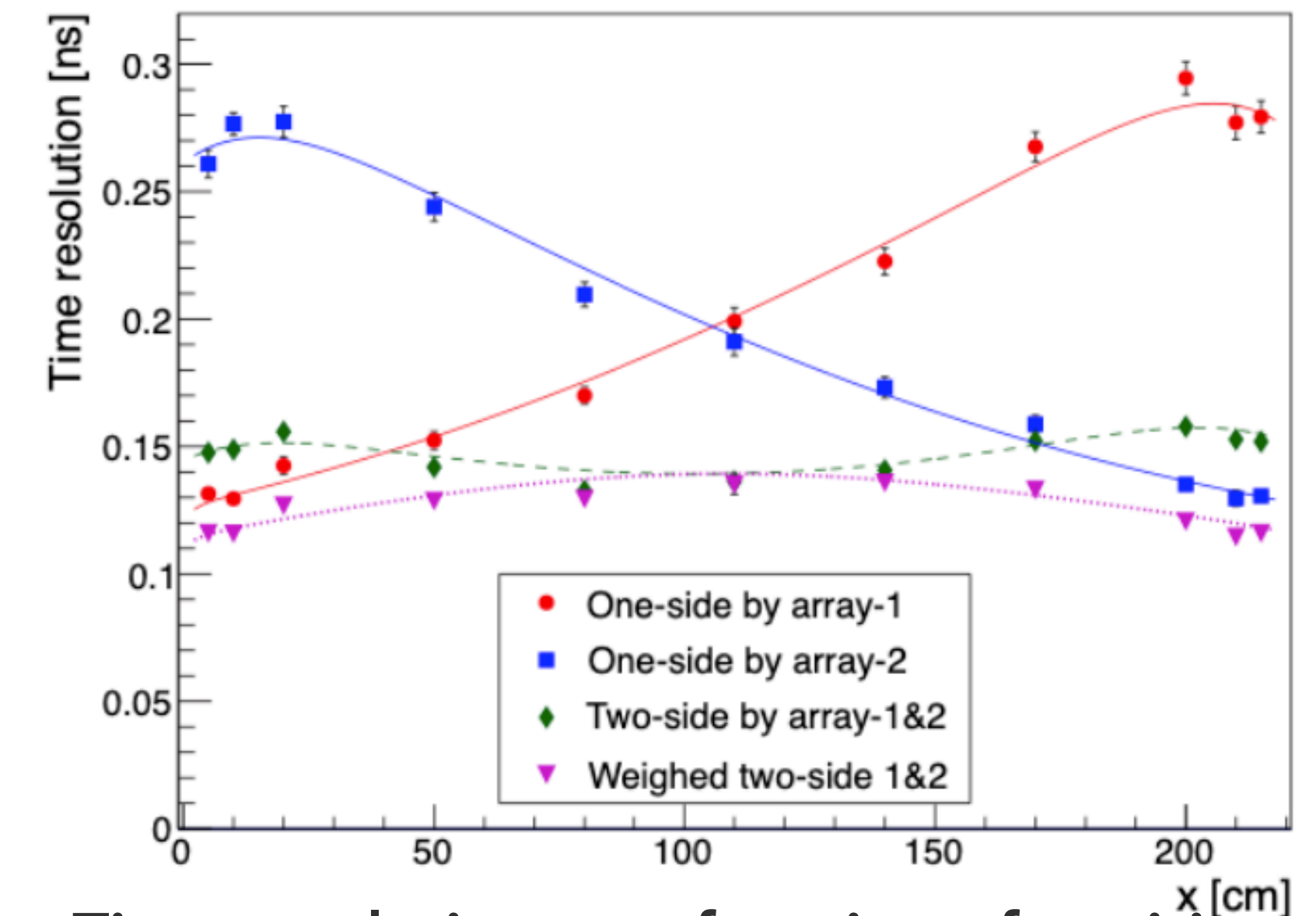
- Six TOF planes will cover 2 HA-TPCs and SuperFGD.
  - Each plane of  $2.2 \times 2.4 \text{ m}^2$  consists of 20 scintillator bars.
  - Readout with 16 MPPCs at both ends of each bar.
- Provide a time stamp for each track.
  - To identify the **direction of the tracks** and **reduce the background**.
  - The cosmic trigger for the calibration of SuperFGD and HA-TPCs.
- The average double sided **time resolution** of one bar was measured to be **0.14 ns** [[JINST 17 P01016 \(2022\)](#)]
  - It satisfies the requirements of ND280 upgrade.



TOF schematic view



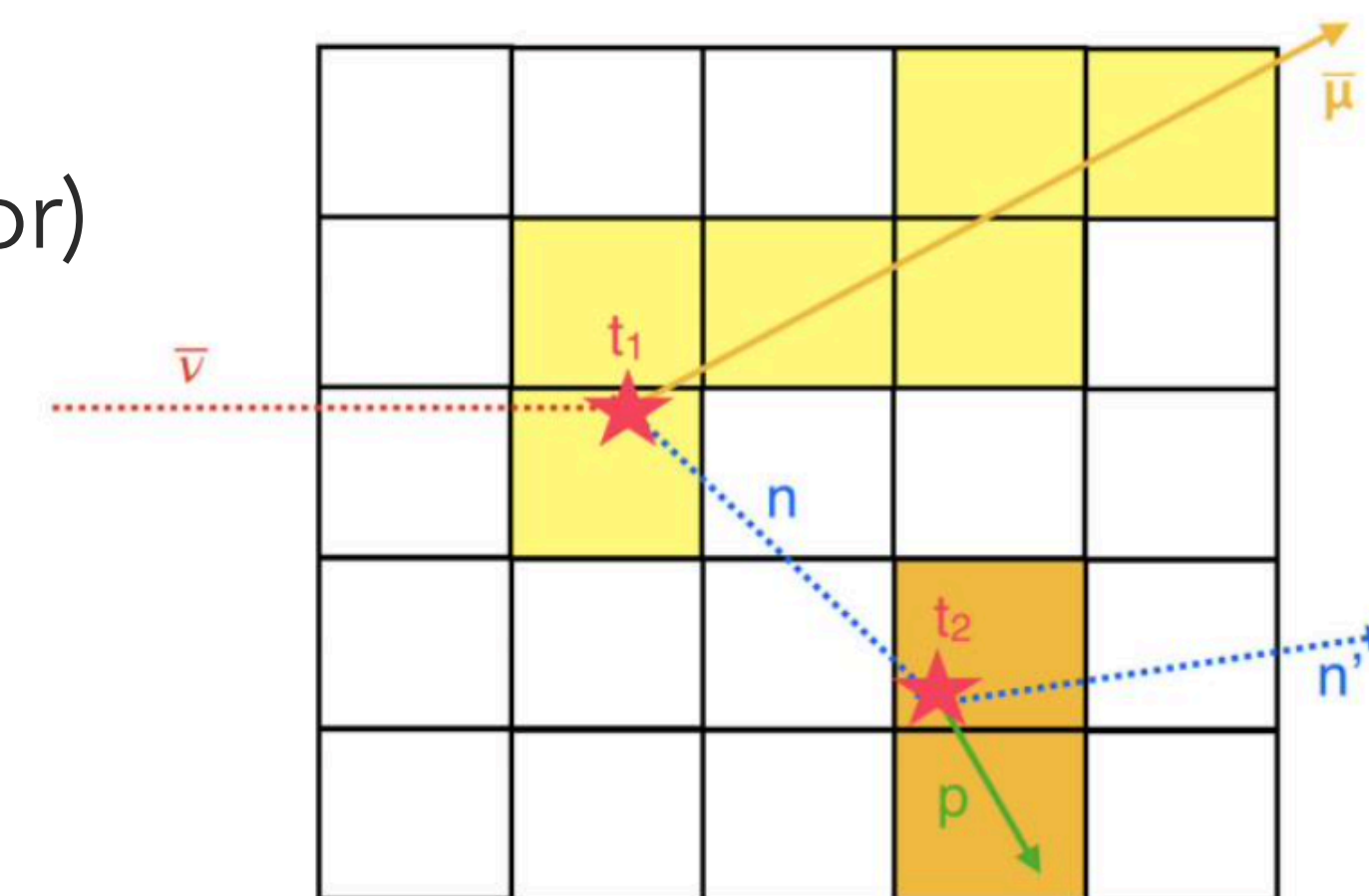
Scintillator bar and end-cap



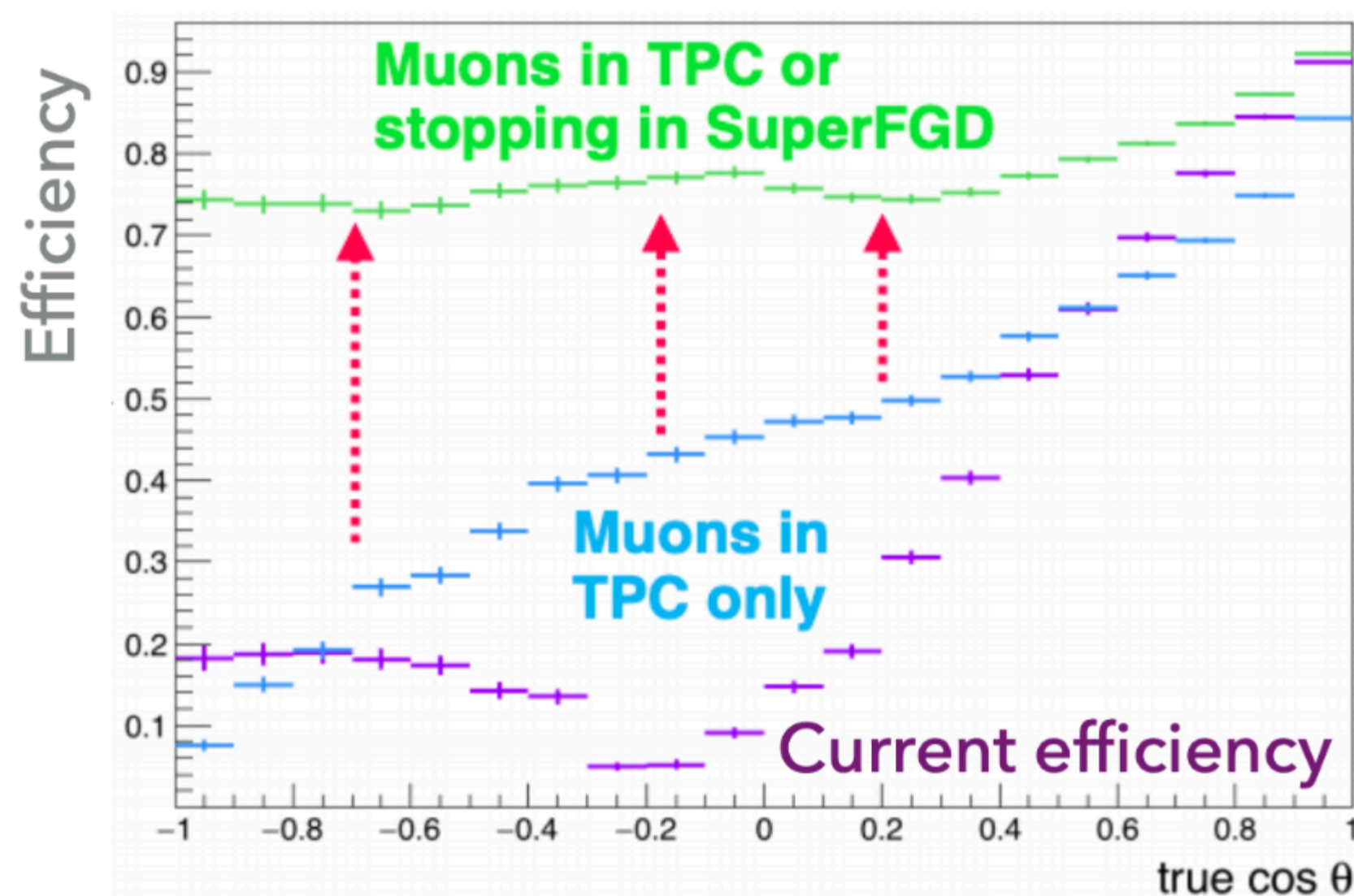
Time resolution as a function of position

# Expected Performance

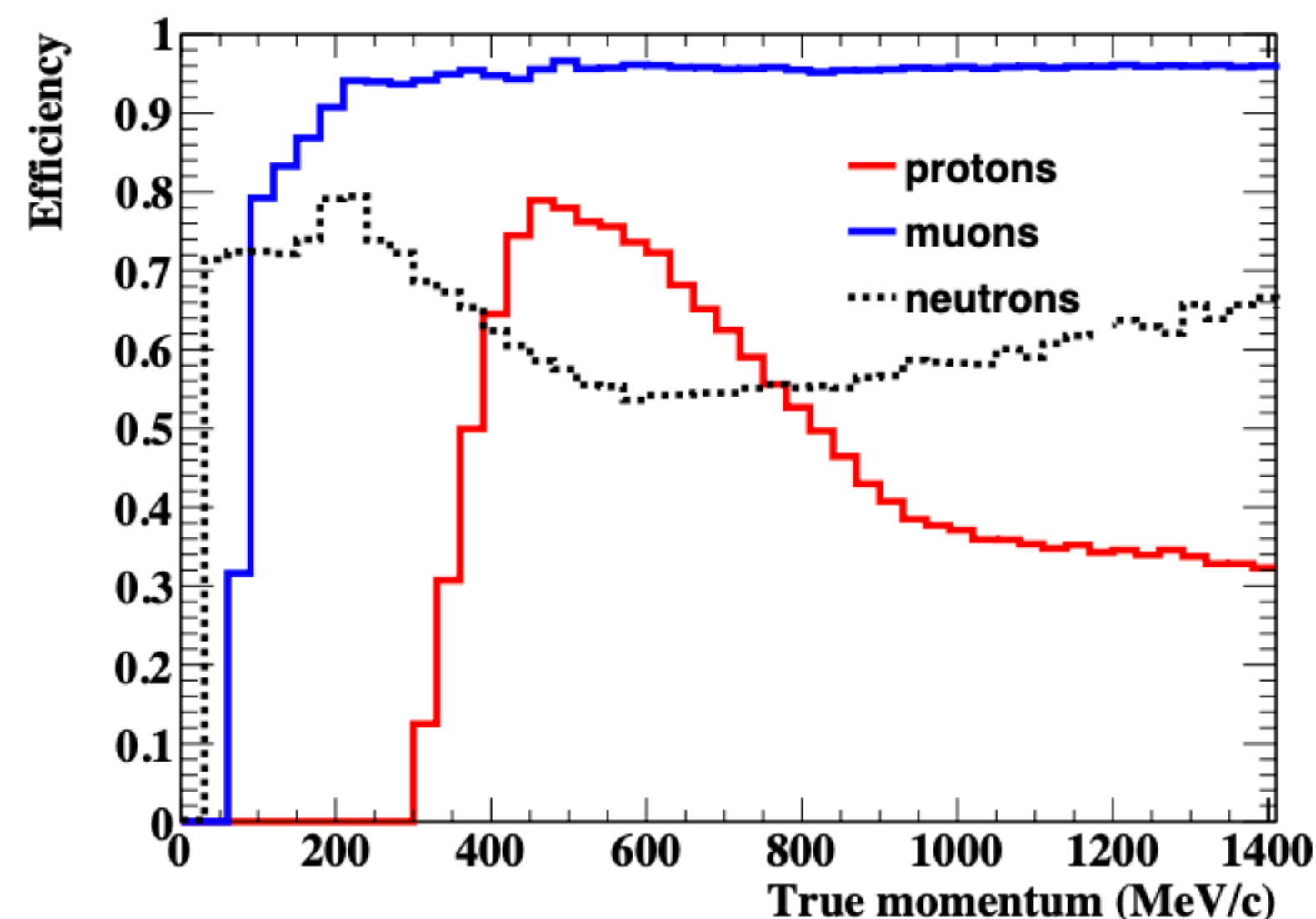
- Improved kinematic range
  - Better efficiency for the entire phase space (similar to the far-detector)
  - 3D tracking for both lepton and hadrons.
    - Allow access to transverse variables.
    - Better understanding of nucleon FSI and other nuclear effects.
    - Reduce neutrino energy bias.
- Better separation of electron/photon.



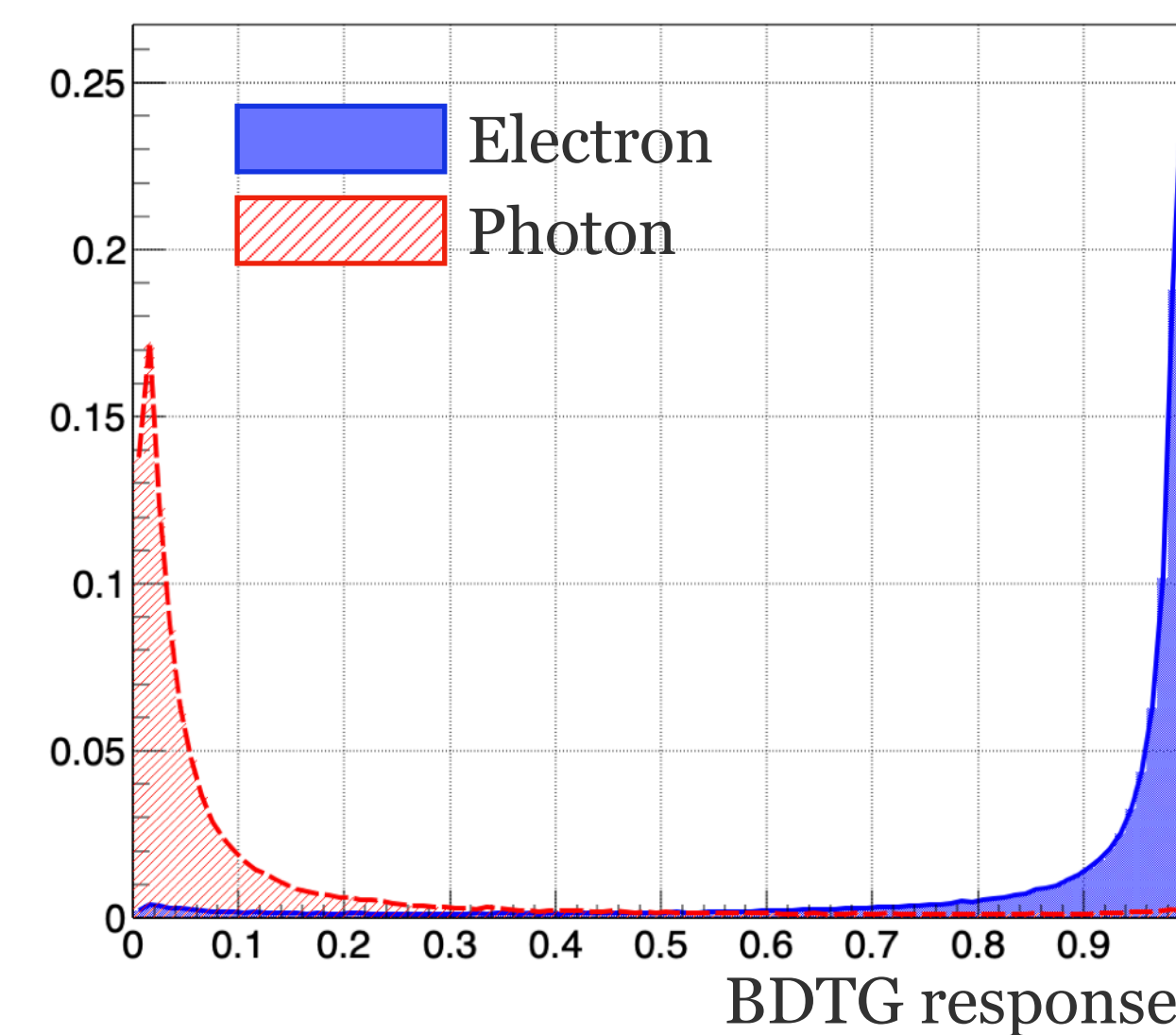
Neutron detection using ToF



Muon detection efficiency vs angle



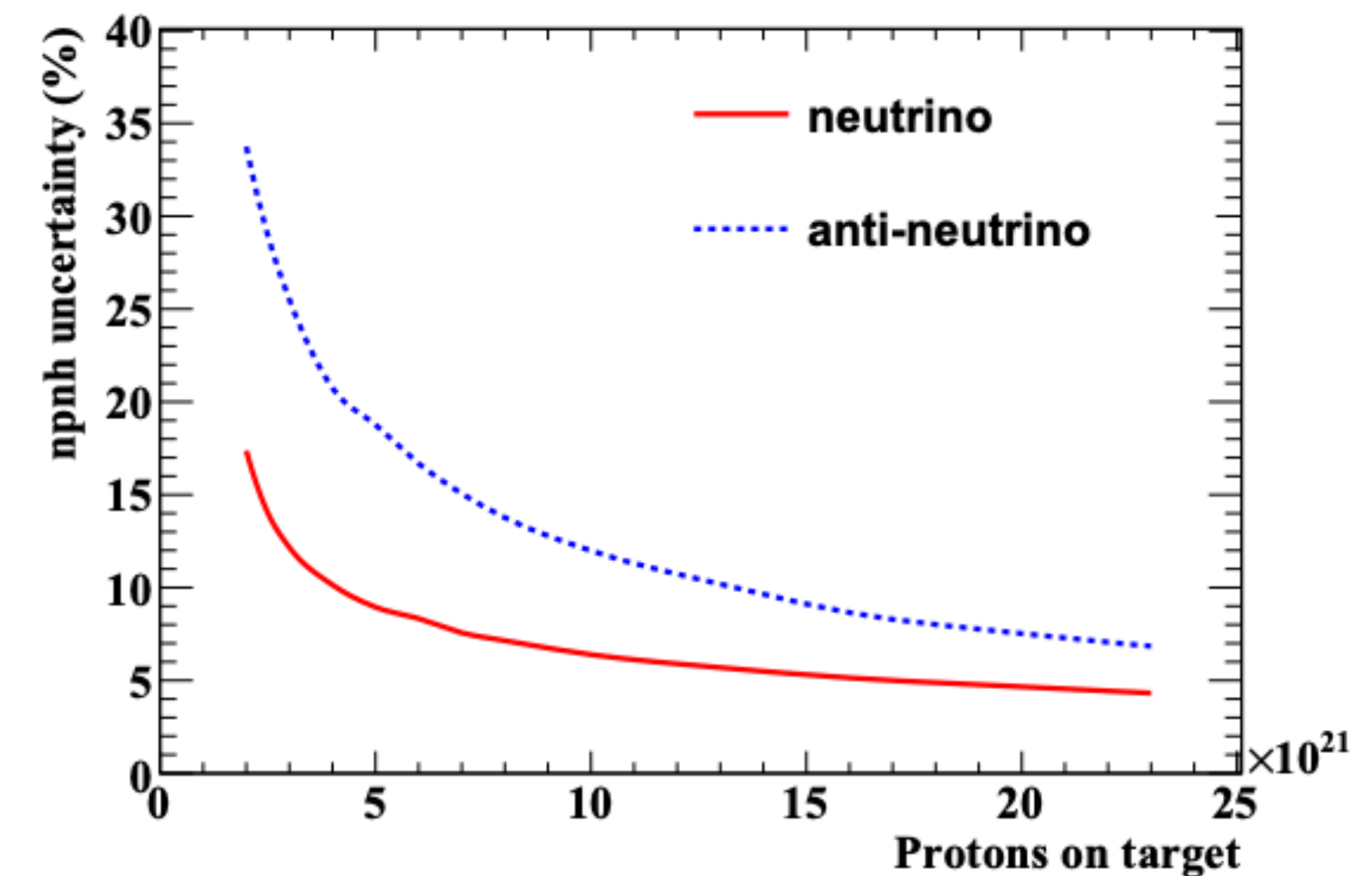
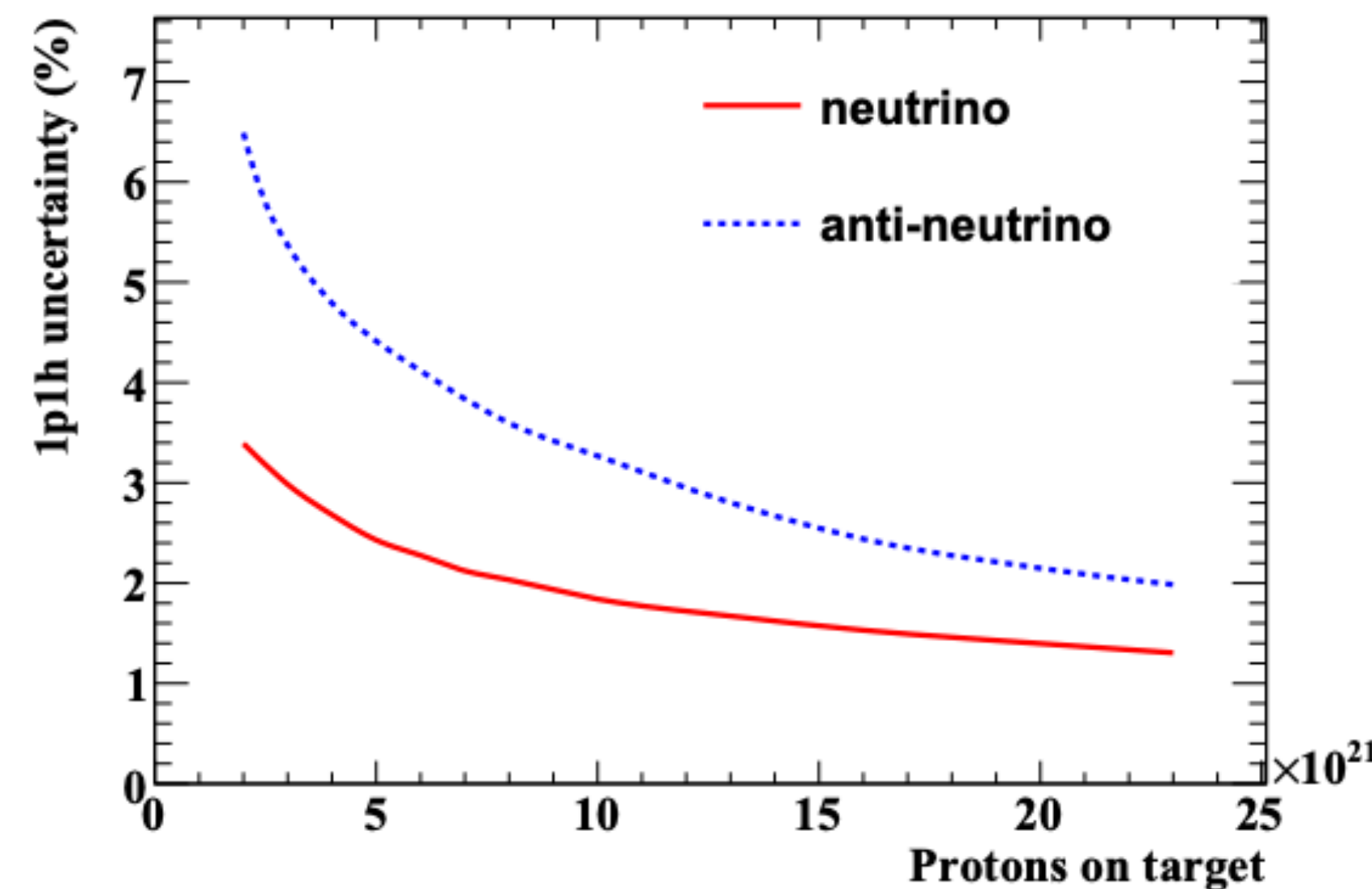
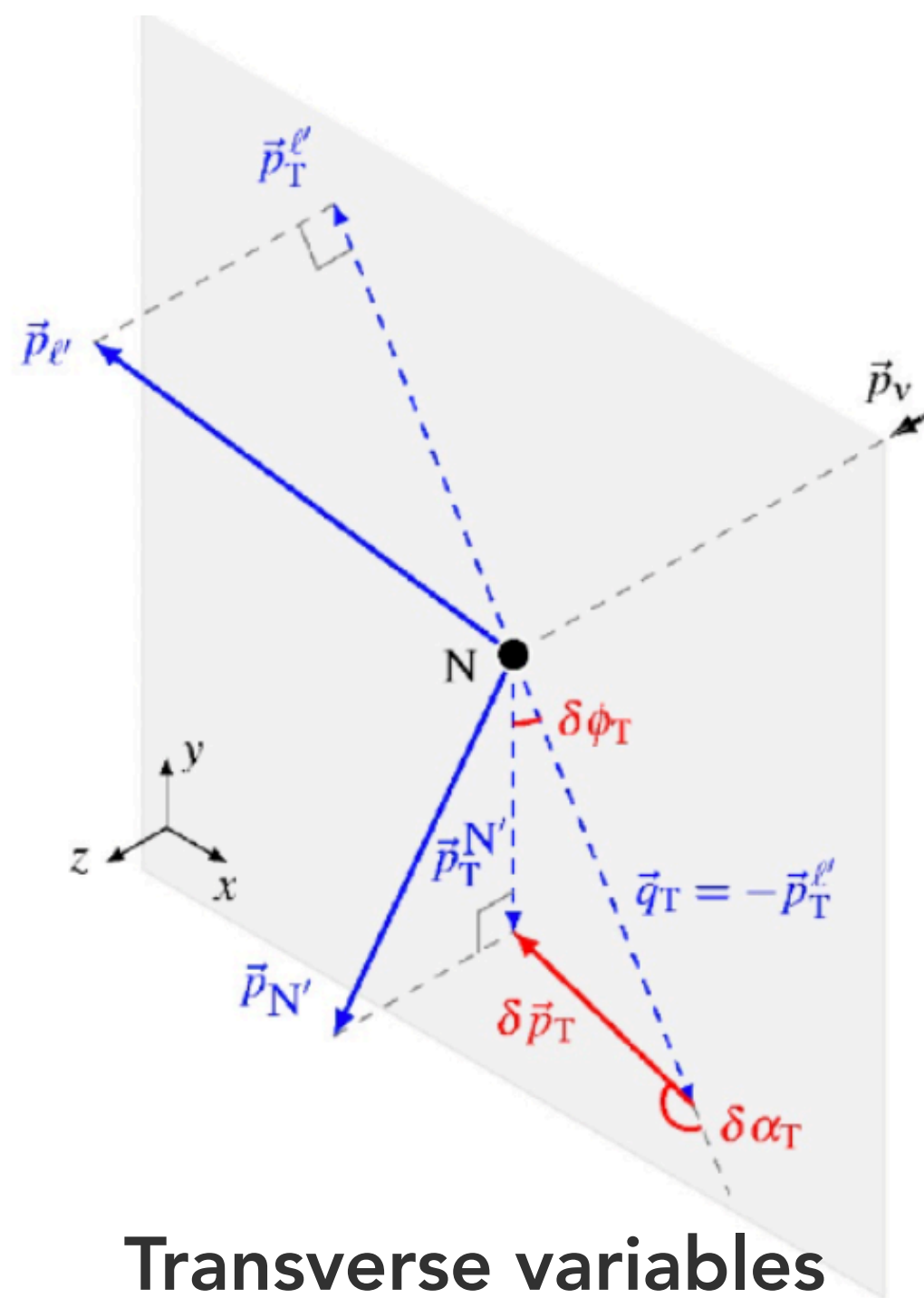
Efficiencies as a function of momentum



Electron/photon separation

# Physics Sensitivity Studies

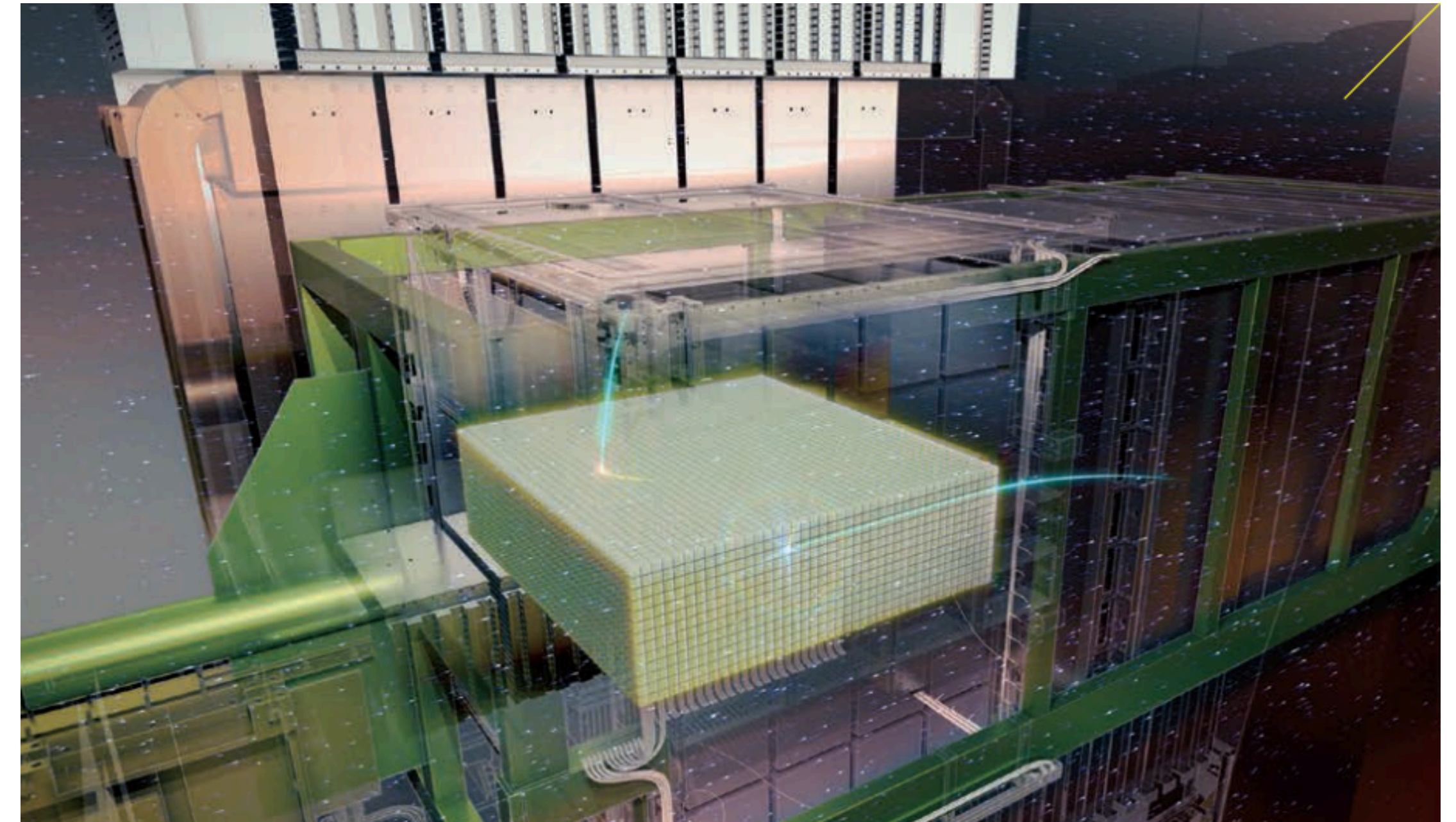
- Expected physics sensitivity using the upgraded detectors was studied [[arXiv:2108.11779](#)]
  - By adding new transverse variables:  $\delta p_T, \delta \alpha_T, E_{\text{vis}}$ .
- Allows a **constraint on 1p1h** (CCQE) as good as  **$\sim 1.5\%$**  ( $\sim 2\%$ ) in  $\nu$  ( $\bar{\nu}$ ) interactions.
  - For **nph**, a **constraint better than 5% (10%)** in  $\nu$  ( $\bar{\nu}$ ) interactions.



## 1 $\sigma$ sensitivity to the 1p1h and npnh xsec normalization

# Summary

- Goal of T2K is to search for CP violation with a significance of  $>3\sigma$ .
  - We are aiming to reduce total systematics with upgraded near detectors.
- ND280 upgrade is in the preparation stage
  - Installation is expected in the first half of 2023.
  - The tested performance of SuperFGD, HA-TPC and ToF planes fully meets the requirements of the ND280 upgrade.
  - ND280 upgrade shows the impressive ability to constrain key systematic uncertainties.



Taken from: <http://j-parc.jp/c/topics/quarterly/index.html>

# Thank you for your attention!

# T2K-Related Talks in NuFACT 2022

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- Plenary
  - Status of T2K (Laura Kormos)
- WG1 (Neutrino Oscillation Physics)
  - T2K improved neutrino-nucleus interaction model tuned to global data (Stephen Dolan)
  - Latest results on T2K Near Detector constraints for neutrino oscillation measurements (Callum Wilkinson)
  - T2K oscillation analysis results: latest analysis improvements at the far detector (Kenji Yasutome)
- WG2 (Neutrino Scattering Physics)
  - T2K latest results on neutrino-nucleus cross section (Andrew Cudd)
- WG3 (Accelerator Physics)
  - First result of the high repetition operation in J-PARC MR (Takaaki Yasui)
  - Proton Beam Monitor Upgrades for the J-PARC Neutrino Extraction Beamline (Megan Friend)
  - New muon monitor for J-PARC neutrino experiment (Takashi Honjo)
- WG6 (Detectors)
  - The T2K Near Detector upgrade (Aoi Eguchi) [[this talk](#)]
  - Total neutron cross section measurement on CH with a novel 3D-projection scintillator detector (Ciro Riccio)
  - Construction of a new scintillation tracker in T2K experiment (Masaki Kawaue)
  - 3D segmented scintillator neutrino detector SuperFGD for T2K experiment (Christopher Mauger)
  - Characterization of the ERAM detectors for the High Angle TPC of the T2K ND upgrade (Claudio Giganti, Matteo Feltre)

# Backup

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# Current Systematic Uncertainties

- The systematic uncertainties on the predicted event rates in the SK samples.
  - Total systematics error is  $\sim 6\%$ .
  - The goal is to bring this number down to  $\sim 4\%$  for T2K-II, and to  $\sim 3\%$  or below for Hyper-Kamiokande.

Taken from: [Phys. Rev. D 103 \(2021\), 112008](#)

TABLE XIII. Fractional uncertainty (%) on event rate by error source and sample, calculated with expected event rates generated according to the nominal oscillation parameter values from Table III. The final column is the fractional uncertainty (%) on the ratio of FHC/RHC events in the one-ring  $e$  sample. The final row, “all systematics,” does not include the effects of any oscillation parameters.

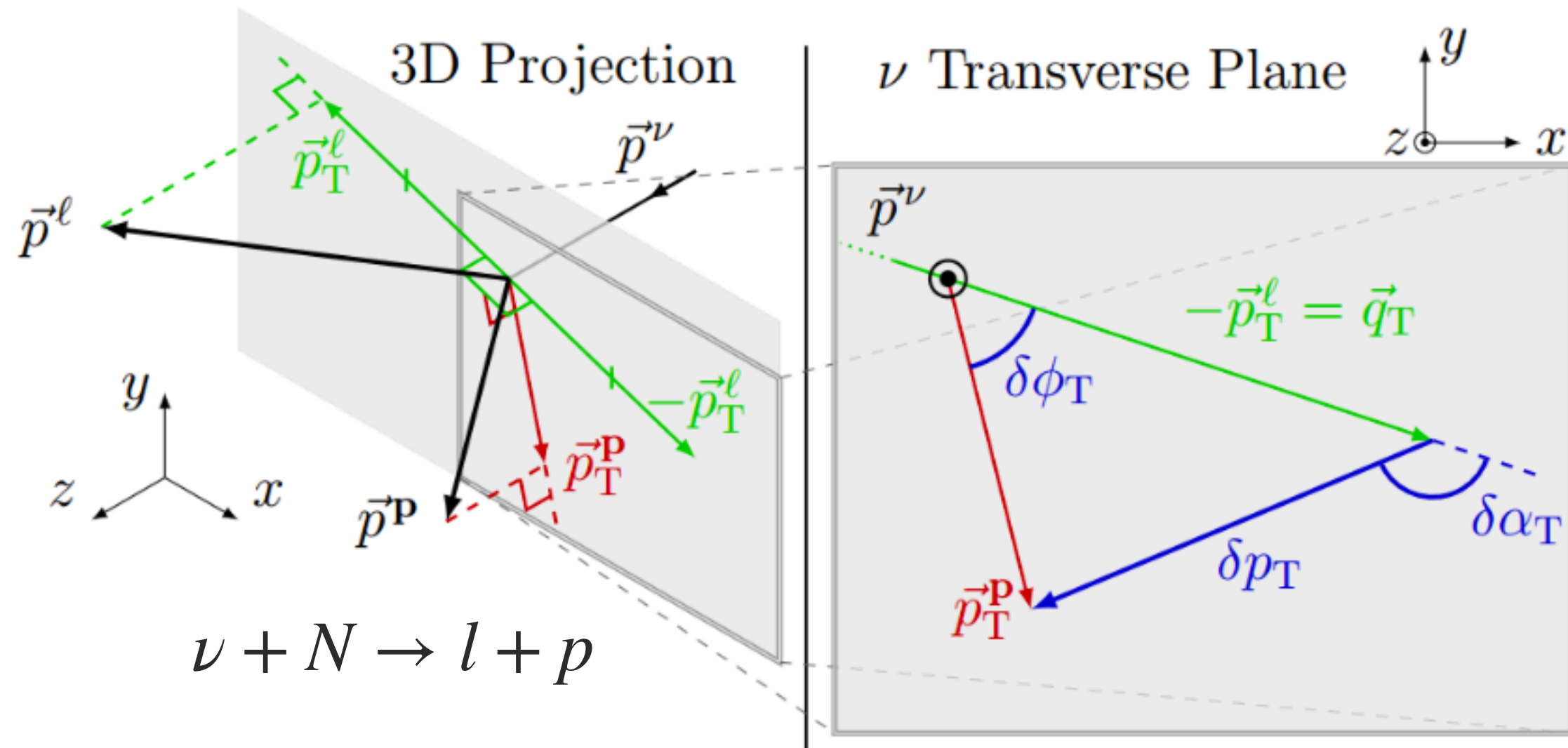
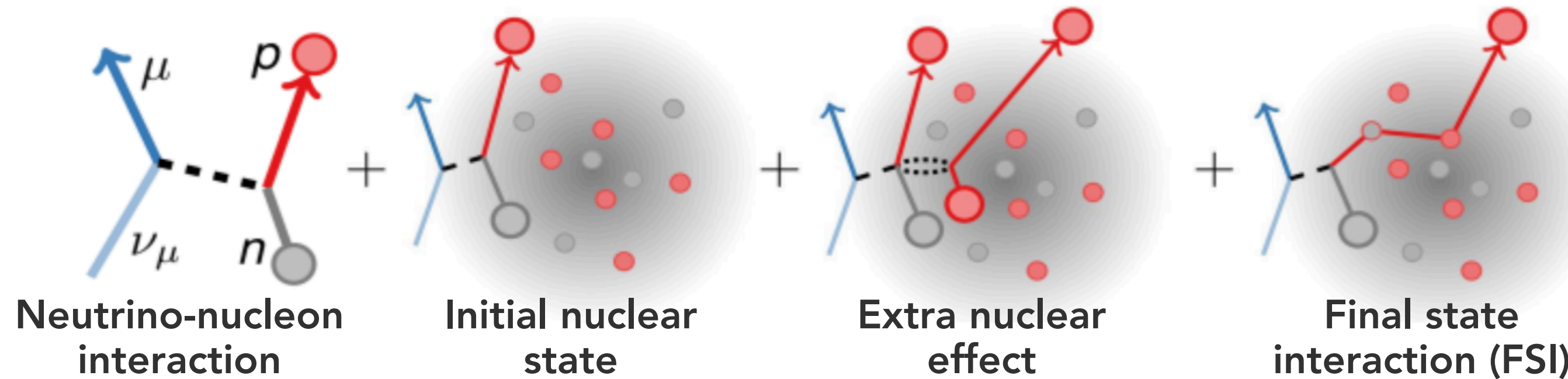
Error source	One-ring $\mu$		One-ring $e$			
	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
SK detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI + SI + PN	2.2	2.0	3.0	2.3	11.4	1.6
Nucleon removal energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1 $\gamma$	0.0	0.0	1.1	2.6	0.3	1.5
NC other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2 \theta_{23}$ and $\Delta m_{21}^2$	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2 \theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All systematics	5.1	4.5	8.8	7.1	18.4	6.0

# Neutrino Interaction Uncertainties

- Better understanding of the neutrino interaction is critical for the future oscillation analysis.
  - We need to deal with complex multi-body effects.

$$\begin{aligned}
 N_{\nu_\alpha}^{ND}(E_\nu) &= \Phi_{\nu_\alpha}^{ND}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma_{\nu_\alpha}^{ND}(E_\nu) \\
 N_{\nu_\beta}^{FD}(E_\nu) &= \Phi_{\nu_\beta}^{FD}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma_{\nu_\beta}^{FD}(E_\nu) \times P_{\nu_\alpha \rightarrow \nu_\beta}(E_\nu)
 \end{aligned}$$

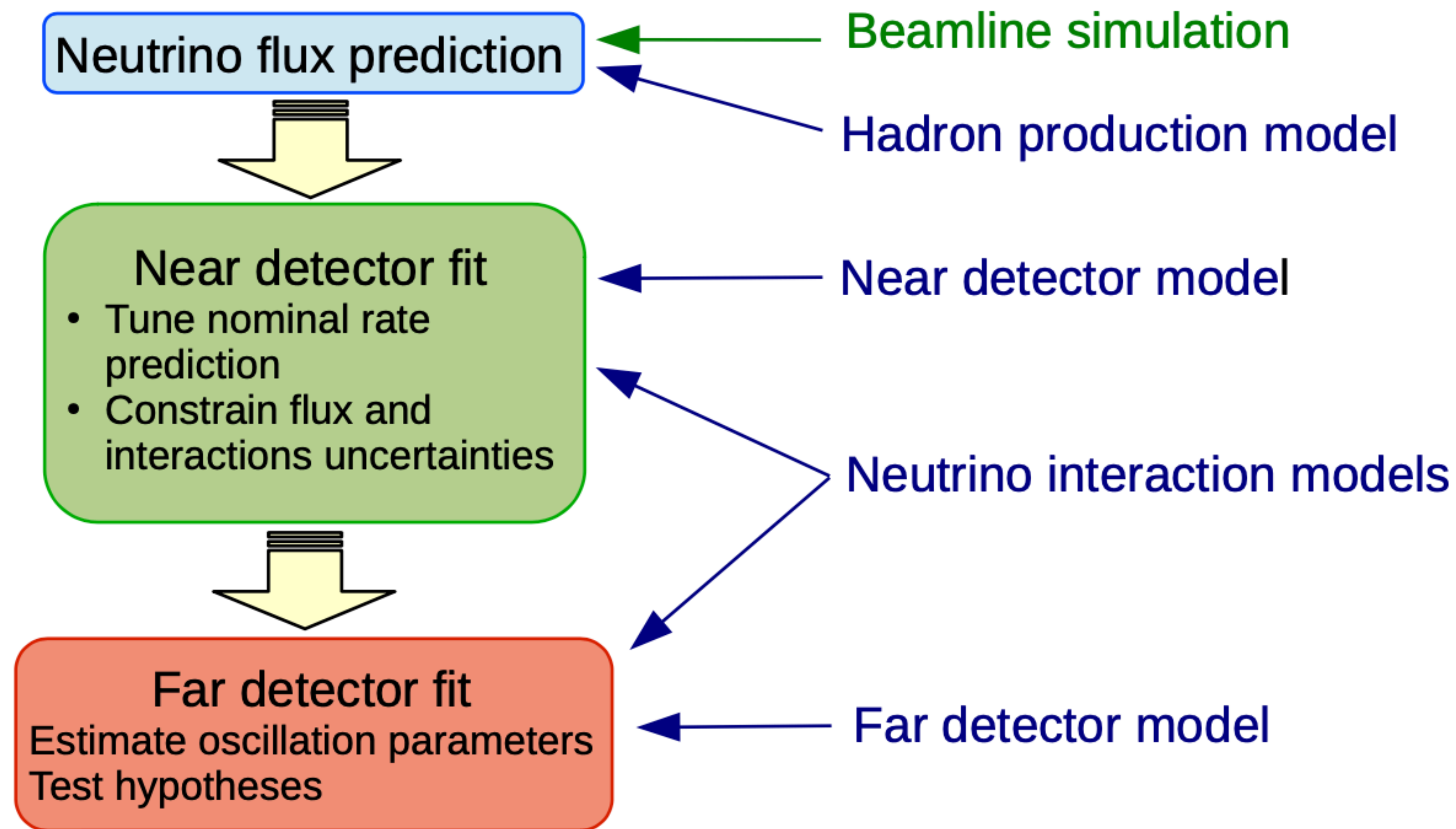
Flux model
Detector model
Interaction model
Oscillation probability



- Powerful variables to directly measure the nuclear effect.
  - Missing momentum  $\delta p_T = |\vec{p}_T^l + \vec{p}_T^p|$
  - Transverse boosting angle  $\delta\alpha_\tau = \arccos \frac{-\vec{p}_T^l \cdot \delta\vec{p}_T}{|\vec{p}_T^l| \cdot |\delta\vec{p}_T|}$
  - Visible energy  $E_{\text{vis}} = E_\mu + T_p$ 
    - $\delta p_T$  vanishes in the absence of nuclear effects

# Oscillation Analysis Overview

- Compare observed data at the far detector to predictions based on a model of the experiment to make measurements.
  - Produce both frequentist and Bayesian results.



Near and far detector fits done sequentially or simultaneously depending on analysis