Upgrade Project of the T2K Near Detector

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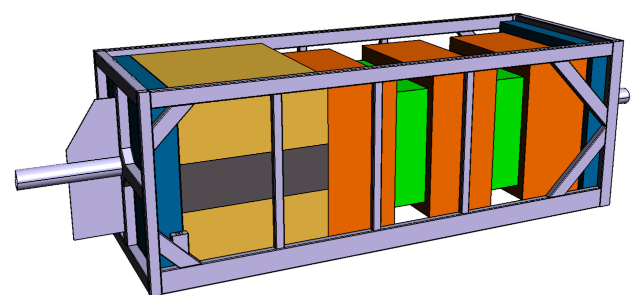
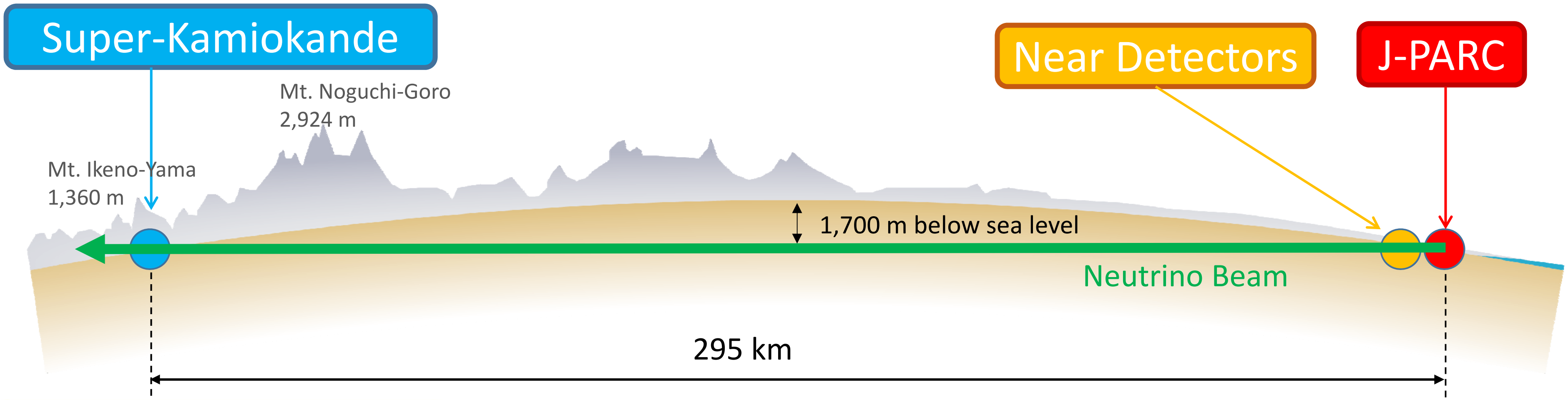
On behalf of the ND280 Upgrade Working Group

ICHEP 2018, Seoul

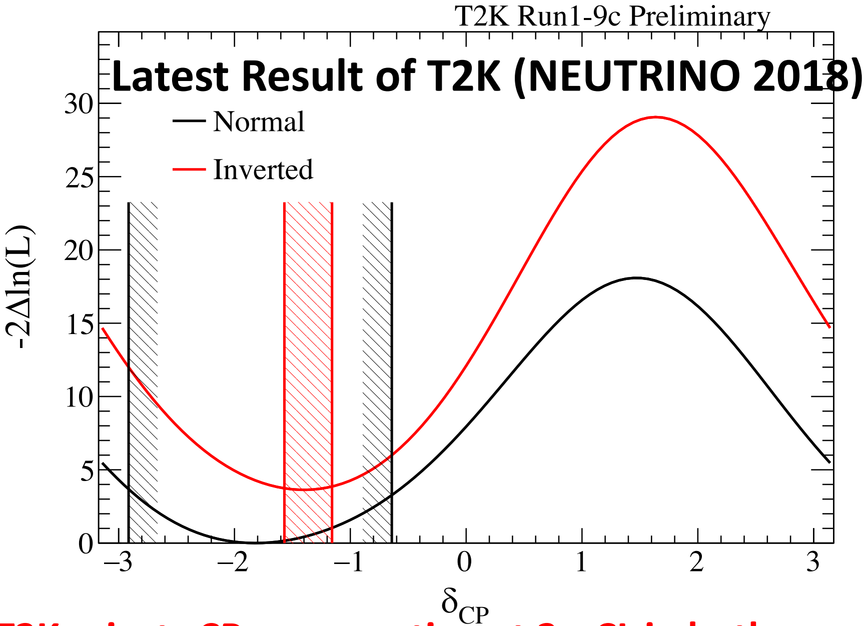


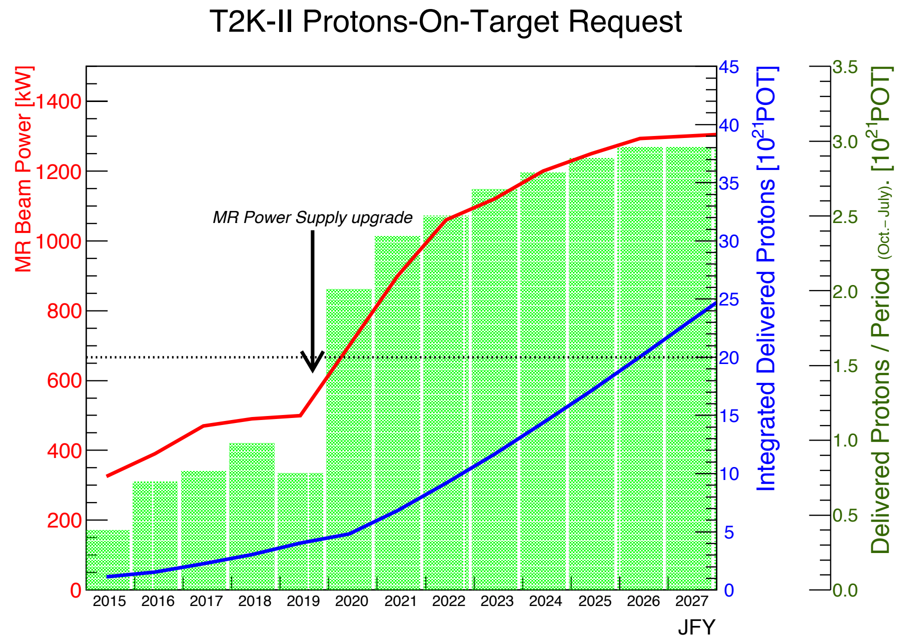
T2K Experiment



T2K to T2K-II

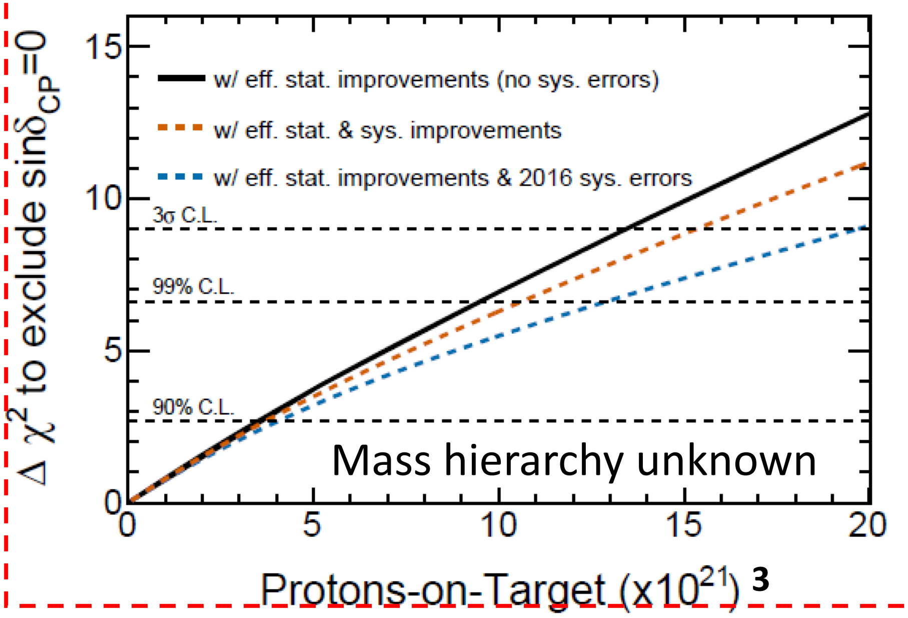
arXiv:1609.04111





T2K rejects CP conservation at 2σ CL in both mass hierarchies

- Beam power upgrade **(485 kW→1.3 MW)**
- Plan to accumulate 20×10^{21} POT by 2026
- Reaches $> 3\sigma$ sensitivity to CP violation in lepton sector (for ~40% of the δ_{CP} values with known mass hierarchy

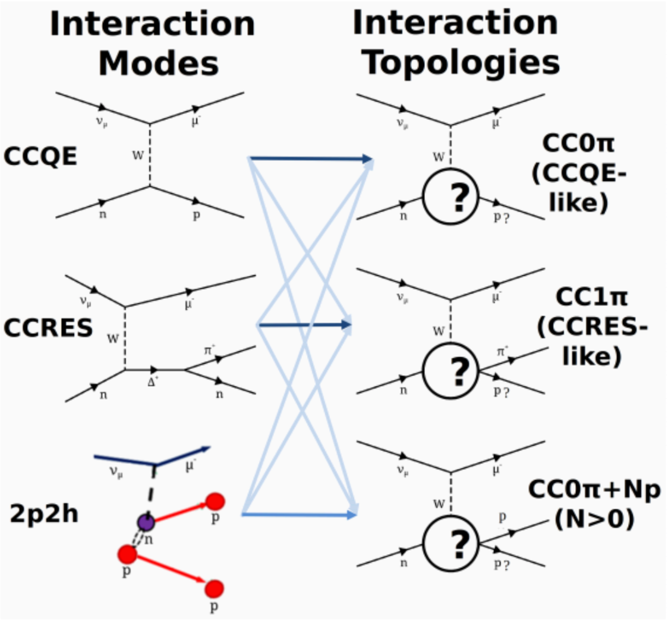


arXiv:1609.04111

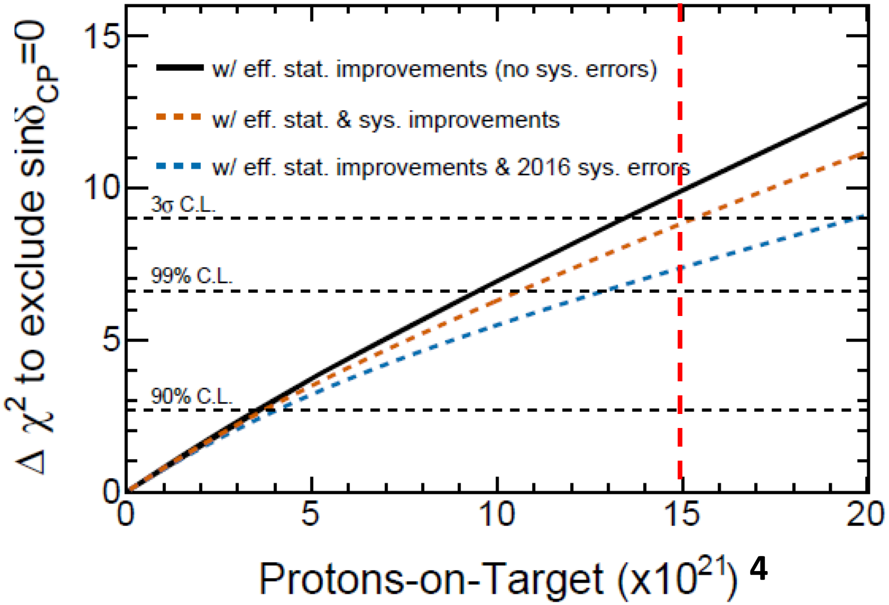
Impact of Systematic Uncertainties

Improved understandings of the systematic uncertainties allow to achieve the $> 3\sigma$ sensitivity with less POT:

- Flux uncertainty
- Detector uncertainty
- **Neutrino cross-section uncertainty**



Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

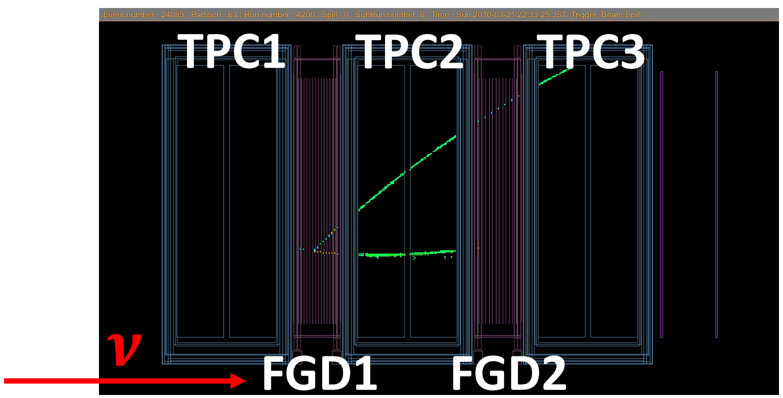


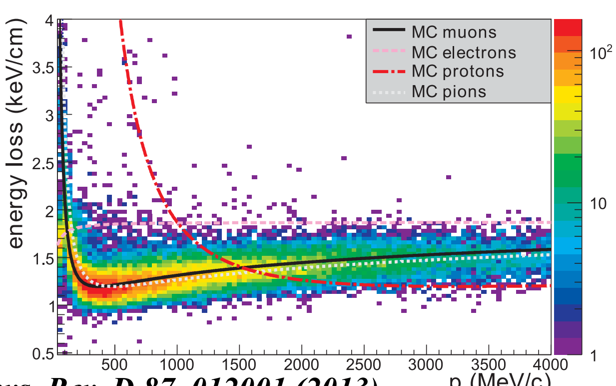
Goal to reduce the systematic uncertainty from ~6% to ~4%

→ND280 Upgrade

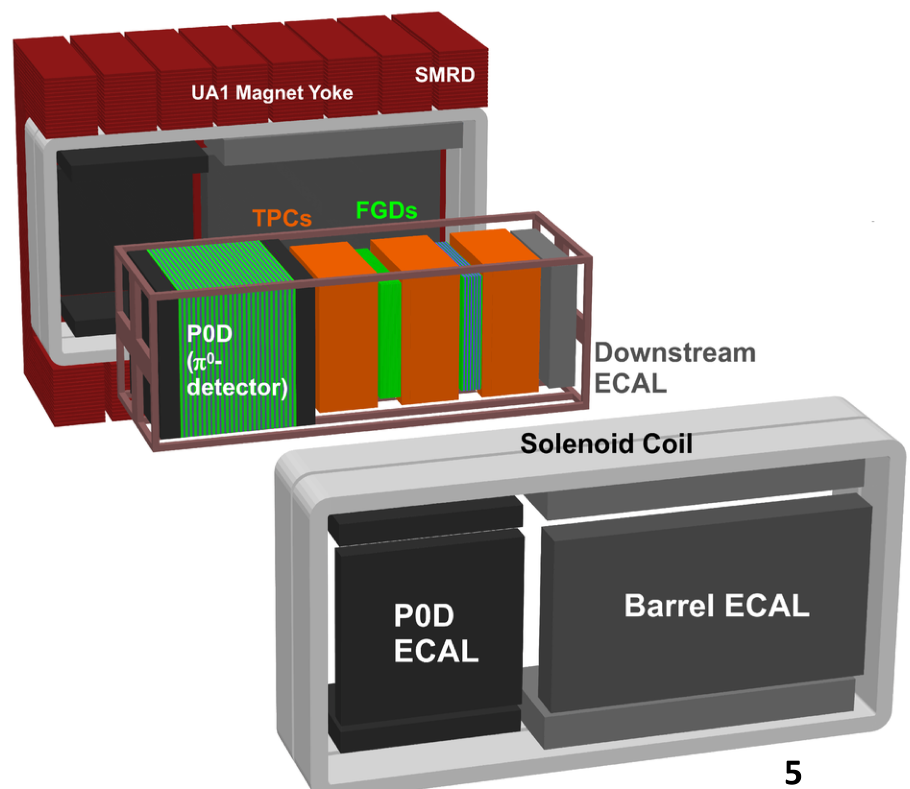
T2K Off-Axis Near Detector Complex: ND280

- Measures particles produced by neutrino interactions prior to oscillations
  - **3 Time Projection Chambers (TPCs)**
  - **2 Fine-Grained Detectors (FGD1, FGD2 w/ water target)**
    - Planes of plastic scintillator bars along horizontal and vertical directions
  - **π^0 Detector (P0D)**
  - **Electromagnetic Calorimeter (ECAL)**
  - **Side Muon Range Detector (SMRD)**
  - Magnetized by 0.2 T **UA1 Magnet**



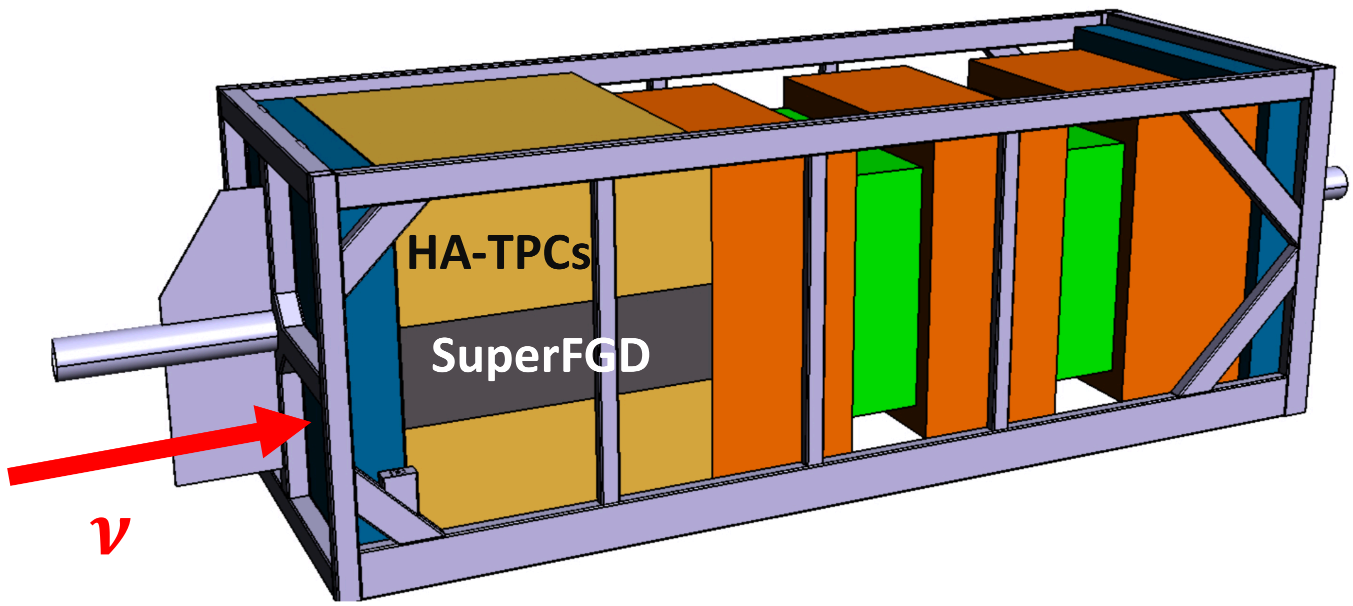


Phys. Rev. D 87, 012001 (2013)



ND280 Upgrade

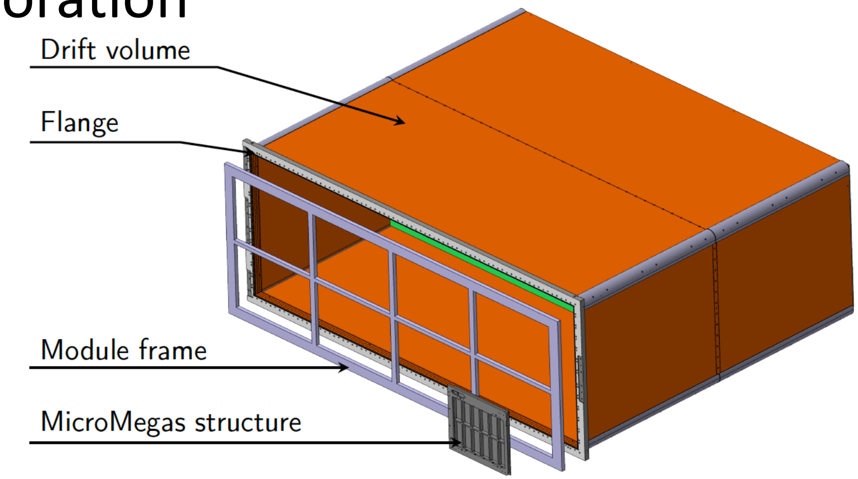
- Keep 2 FGDs, 3 TPCs, ECals
- Implement new upstream trackers:
  - **2 High-Angle TPCs (HA-TPCs)**
  - **1 fine-grained scintillator target (SuperFGD)**
  - **Time-of-Flight (ToF) counters around the new trackers**
    - Provides timing information for track reconstruction



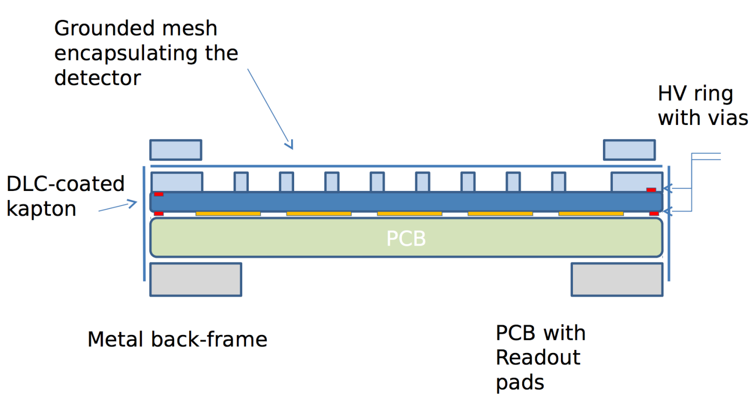
	Current (FGDs)	Upgrade (FGDs + SuperFGD)
Target mass (tons)	2.2	4.3

High-Angle TPC

- **Resistive Micromegas:**
  - Pads covered by resistive foil
  - Developed by the ILC-TPC collaboration
- **Field Cage Design:**
  - Thin field cage wall (~3 cm)
  - Multi-layer structure to minimize the material budget (~3% X_0)
  - Designs with carbon fiber and aramid fiber based layers in progress



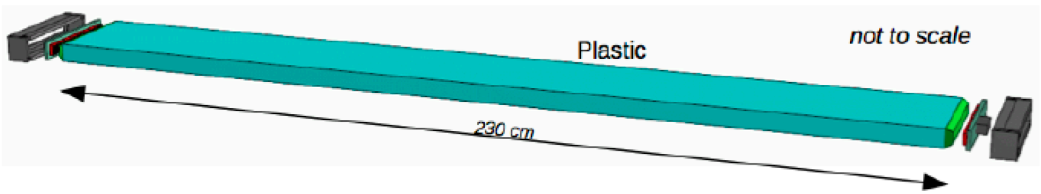
Parameters	Values/TPC
Dimensions	$1.8 \times 0.6 \times 2.0\ \mathrm{m}^3$
Drift distance	90 cm
Gas ratio (Ar, CF_4, iC_4H_{10})	95%, 3%, 2%
Pad dimensions	$11 \times 11\ \mathrm{mm}^2$
Micromegas dimensions	$340 \times 410\ \mathrm{mm}^3$
# Micromegas	16
# Channels	3.2×10^4

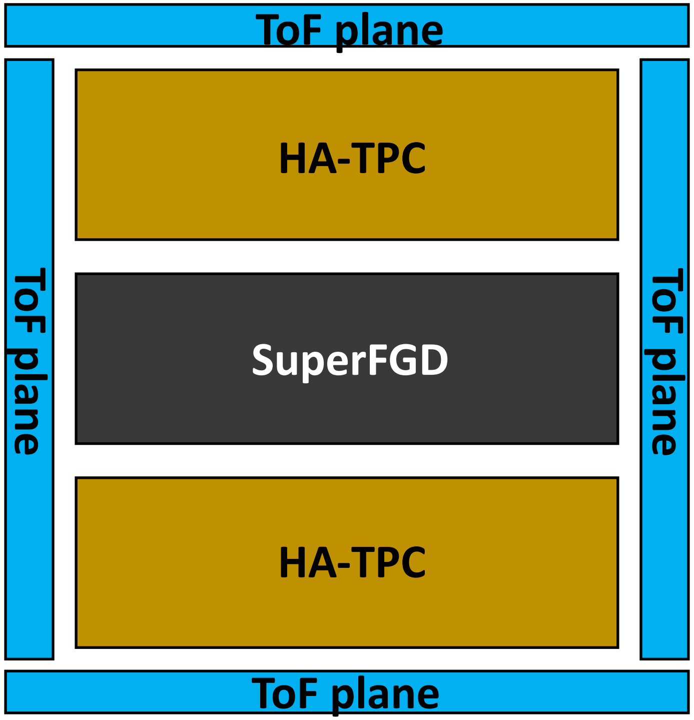


Horizontal ND280 TPC endplate - P. Colas

Time-of-Flight Counter

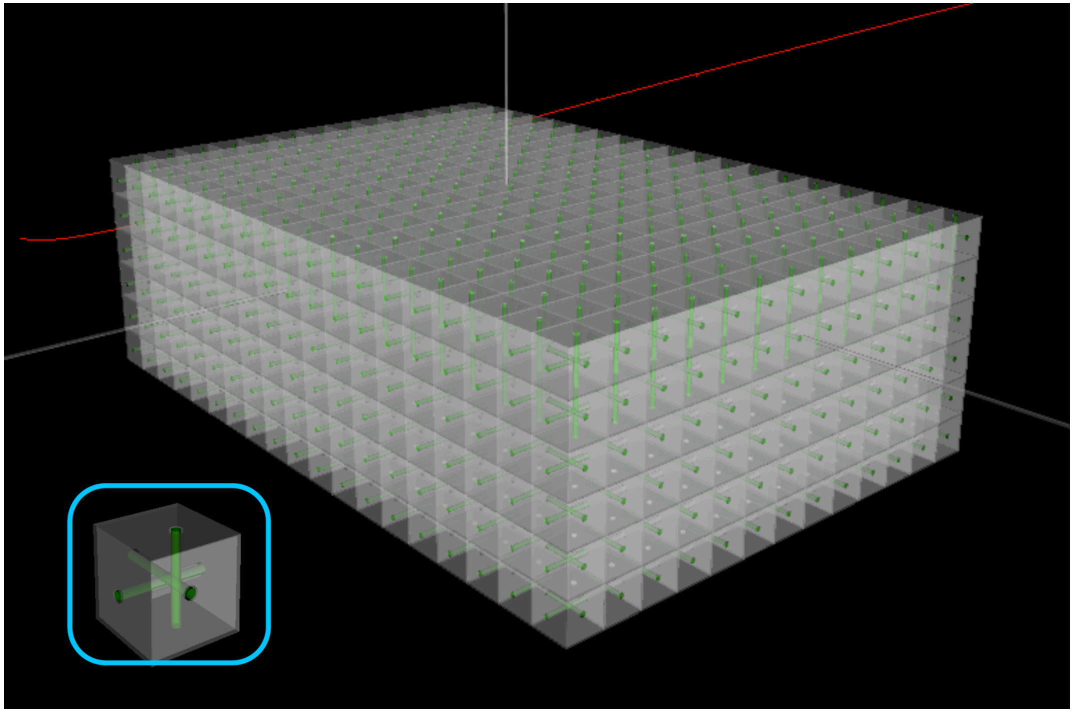
- ToF planes placed around the new trackers
- Provides timing information for track reconstruction
- Improved particle identification (p/e^+, electrons/muons)
- Out-of-fiducial-volume event rejection
- R&D with a cast plastic scintillator design
    - 8 photo-sensors ($6 \times 6\ \mathrm{mm}^2$)
    - Timing resolution is < 100 ps
    - R&D at University of Geneva (for SHiP)



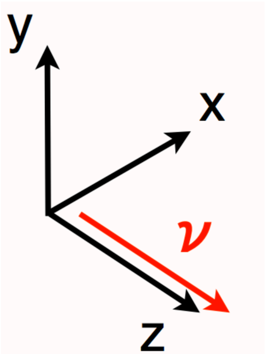


SuperFGD

arXiv:1707.01785



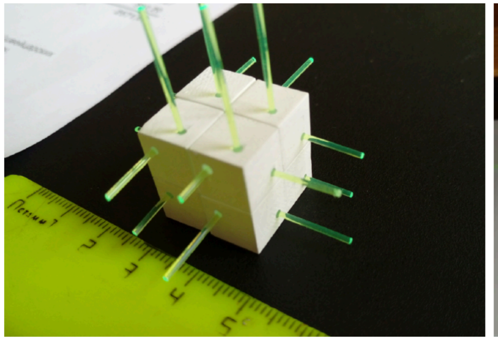
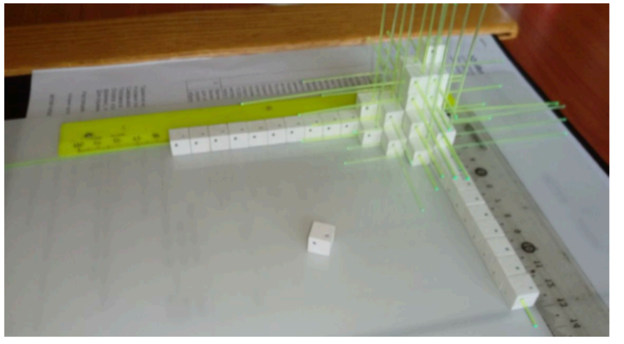
Parameter	Cube edge: 1 cm
# of cubes	2,160,000
# of channels	58,800
Total fiber length	65 km



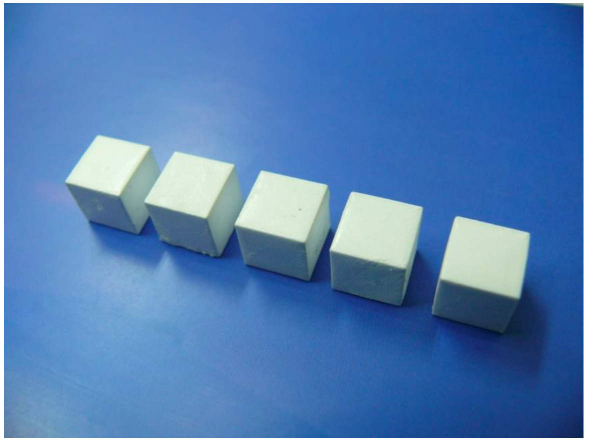
- 1.8 x 0.6 x 2.0 m^3 volume
- Consists of 1 x 1x 1 cm^3 plastic scintillator cubes with the reflector obtained by chemical etching
- WLS fibers along each side of the cubes, allowing the light yield measurement from three views by the MPPCs

SuperFGD Cube Production

- Prototype cubes produced by extrusion method
    - Uncertainty of the cube dimension was ~75 μm
- ~50 μm thickness reflector obtained by chemical etching by Uniplast (Russia)

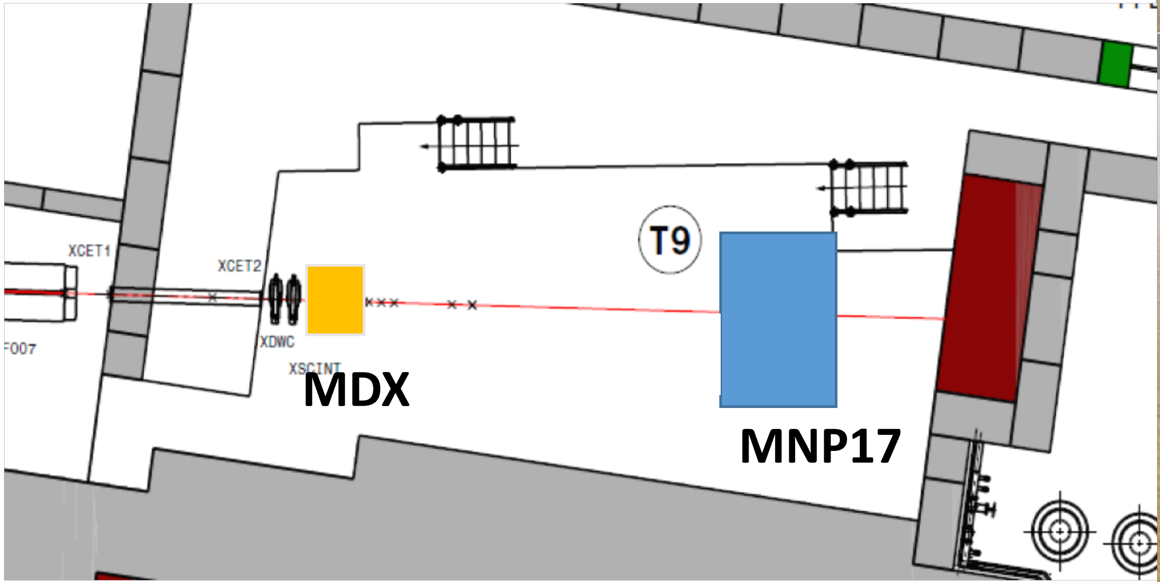



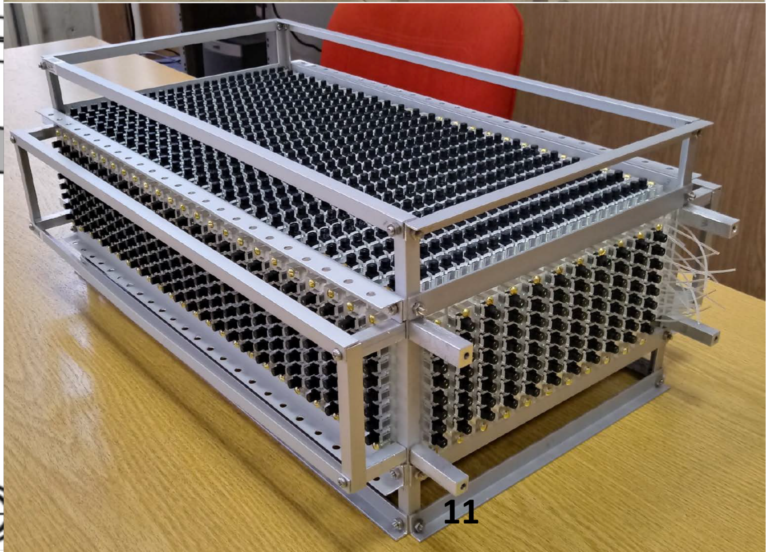
- Injection molding method established by INR RAS (Russia)
    - Uncertainty of the cube dimension reduced to ~35 μm with reflectors

SuperFGD Prototype Beam Tests

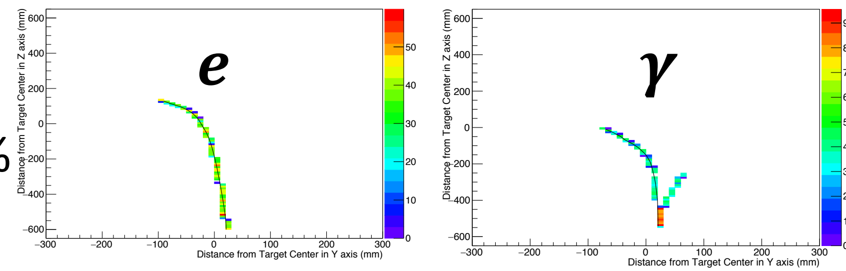
- Two beam tests completed, **one ongoing**
- **June 27 – July 11, 2018 @ CERN T9**
  - $8 \times 24 \times 48\ \mathrm{cm}^3$ prototype, CITIROC readout (Baby MIND electronics), magnetized by the MNP17 magnet platforms (0.2-1T)
  - 1,728 MPPC channels
  - Upstream MDX dipole magnet (0.5T) to prepare photon beam

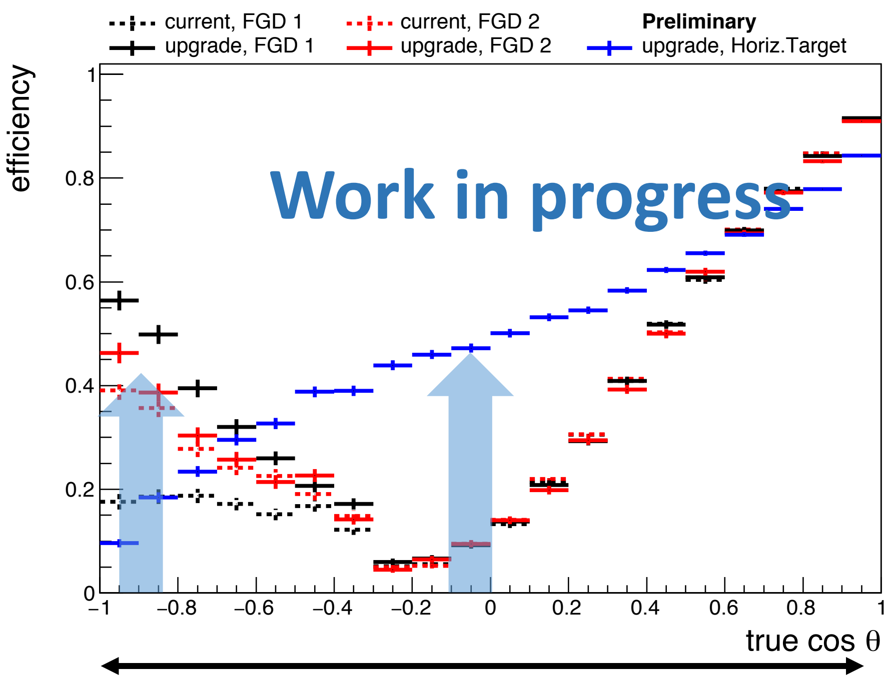




Simulation Studies

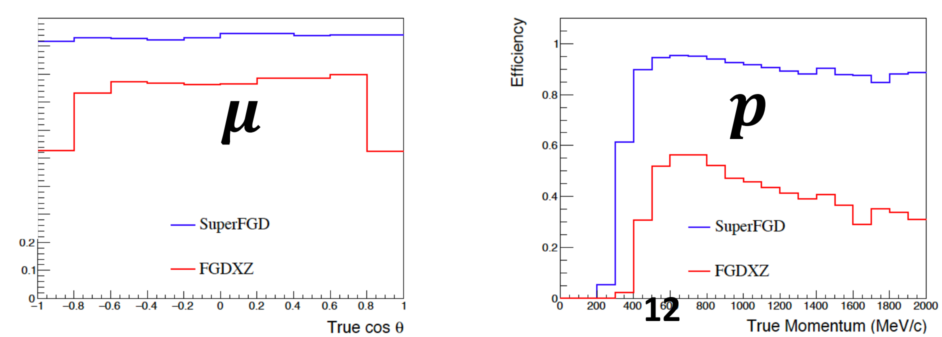
- **Wide angle acceptance**
- GEANT4 simulation of current and upgrade ND280 with T2K ν_μ flux prediction (1×10^{21} POT)
- ν_μ CC event selection using tracks reconstructed in TPCs
- Selection efficiency of backward going and wide-angle events increased by ~40%
- Reduces systematic uncertainties by 20-40 % than the current ND280





Backward-going **Forward-going**

- **High granularity**
- Reconstruction efficiency improvement in high-angle and low momentum tracks
  - e/γ separation for ν_e selection with the track light yield difference (1 and 2 MIPs)



Conclusions

- **ND280 Upgrade for T2K-II**
  - Wide angle acceptance and low momentum measurement by HA-TPCs, SuperFGD, and ToF counters
  - R&D and simulation studies in progress
  - **Proposal submitted on Jan 2018 (SPSC@CERN & PAC@J-PARC)**

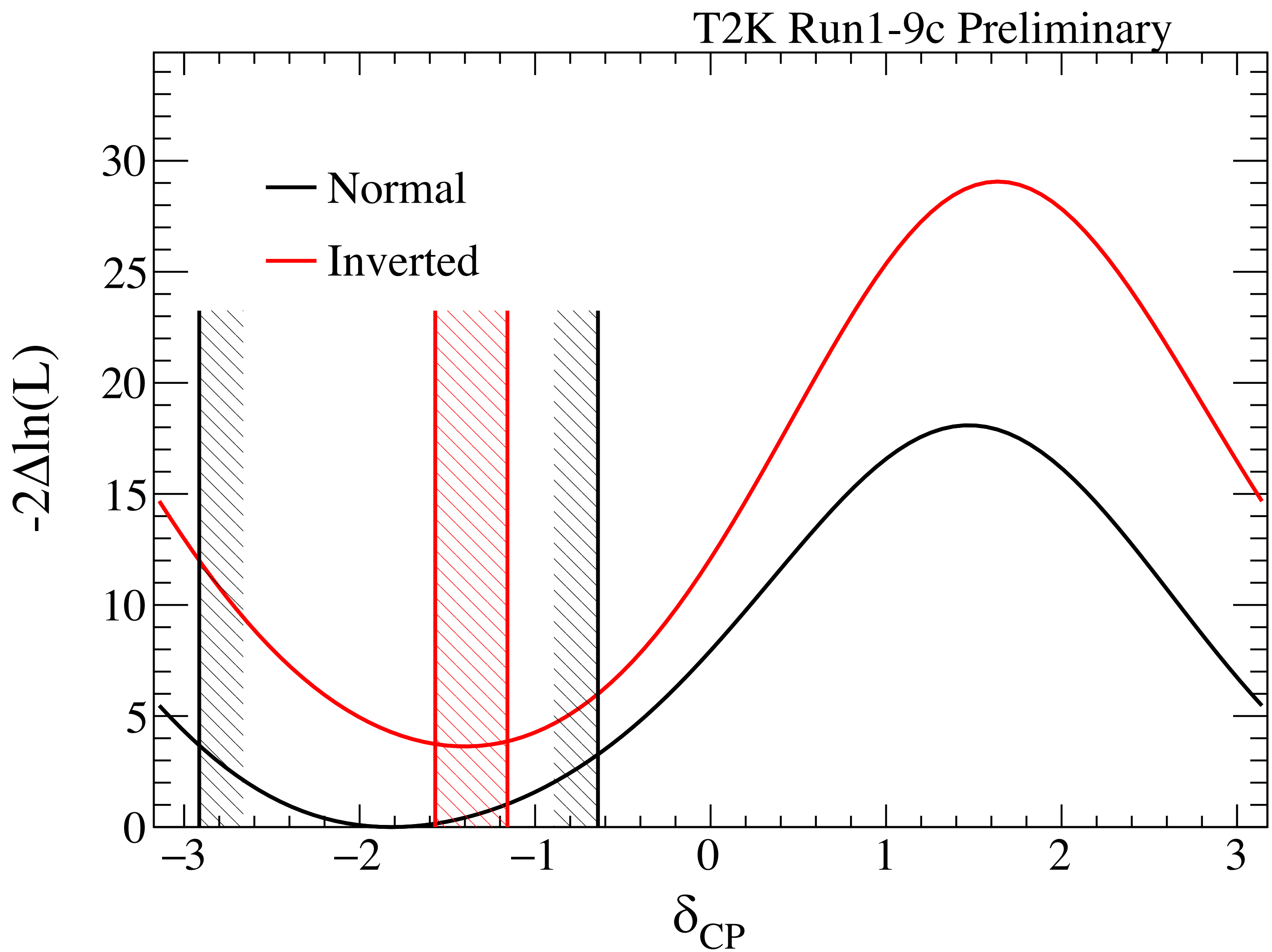
- **Plan for the ND280 Upgrade:**
  - June - August 2018: Prototype SuperFGD and HA-TPC beam test @ CERN
  - End of 2018: Technical Design Report
  - 2019-2020: Production at INR, integration at CERN, system test
  - **2021: Installation and commissioning in Japan**

- Open workshops every ~2 months
  - So far 8 open workshops were held since November 2016
- **The 9th open workshop at CERN on July 25 - 26:**
  - https://indico.cern.ch/event/724624/
  - **New members are always welcome!!**

Thank you very much!!

Back-Up Slides

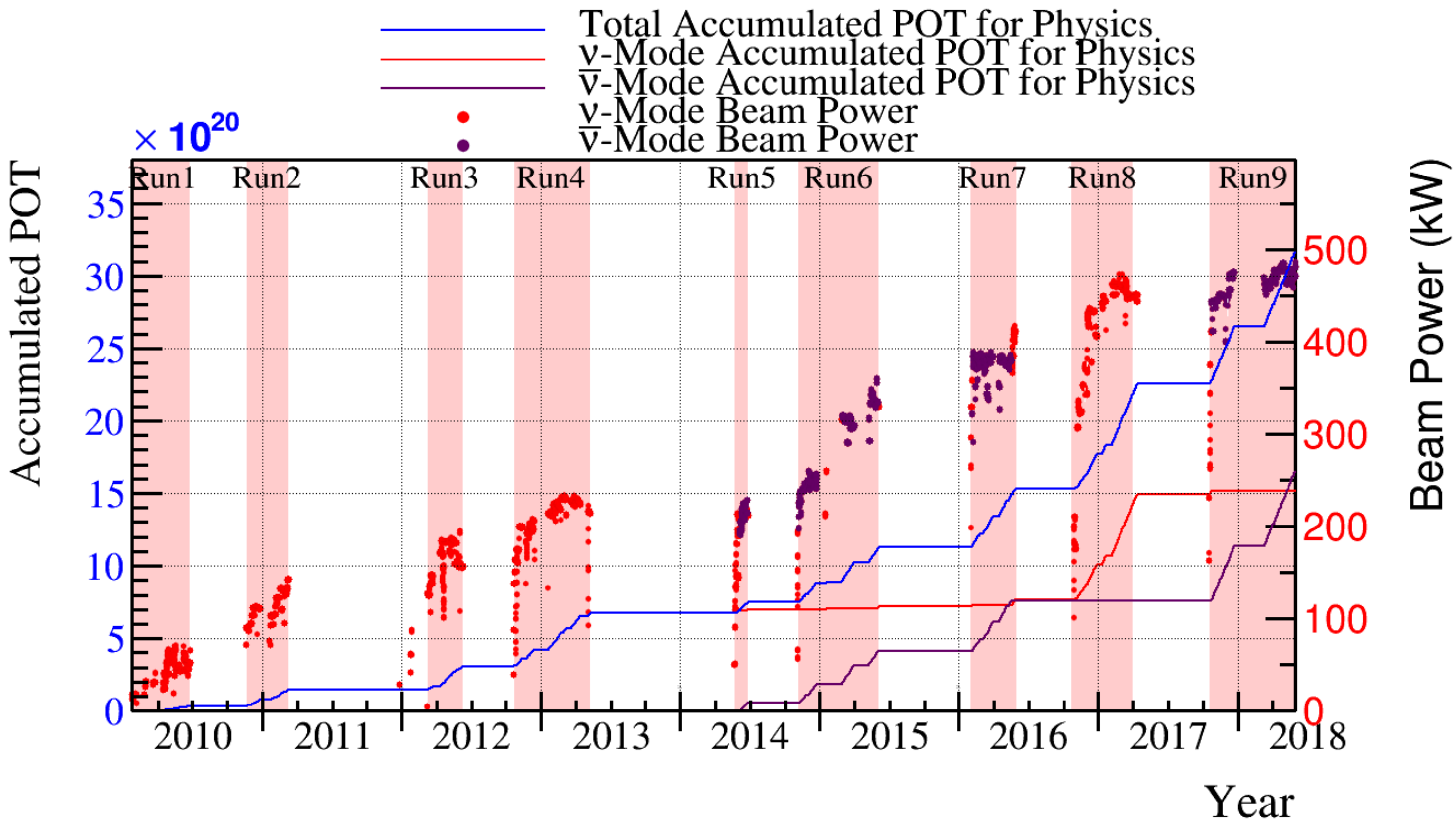
Latest Result of T2K (NEUTRINO 2018)



$\boldsymbol{\delta_{cp} = [-2.914, -0.642](NH), [-1.569, -1.158]\ (IH)}$ **at 2σ CL**

T2K rejects CP conservation at 2σ CL in both mass hierarchies

T2K Data Accumulation Summary



23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

ν-mode 1.51×10^{21} (47.83%)

$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

- **Neutrino statistics has doubled during 2016-2017 run**
- **Anti-neutrino statistics has doubled during the latest run**

Goals of ND280 Upgrade (1)

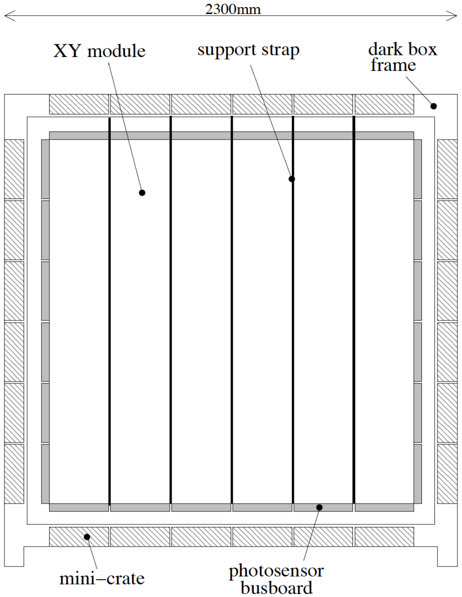
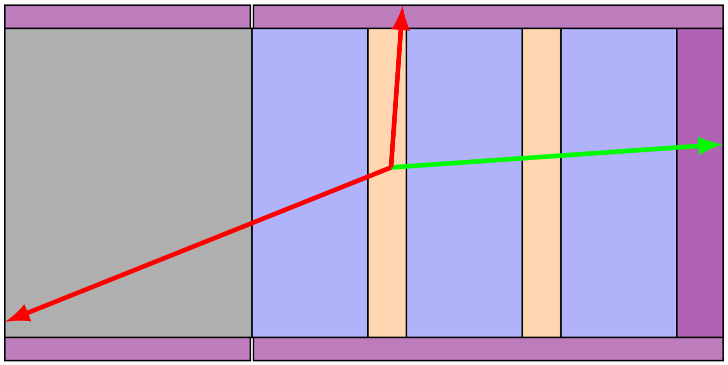
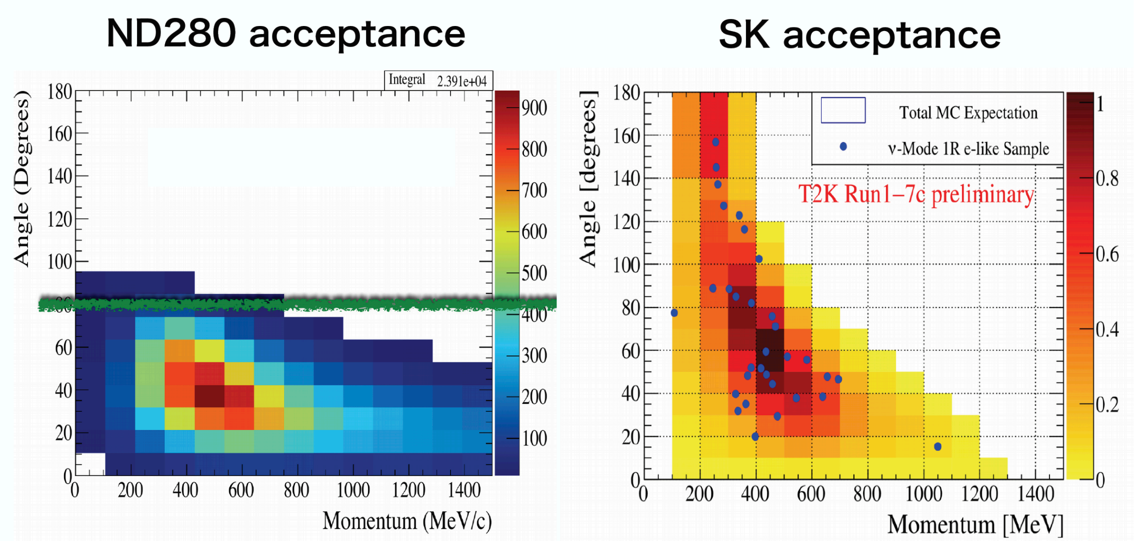


Figure 2: Cross-sectional view of an FGD, showing the locations of the scintillator modules, photosensors, support straps, electronics minicrates, and dark box.

arXiv:1204.3666

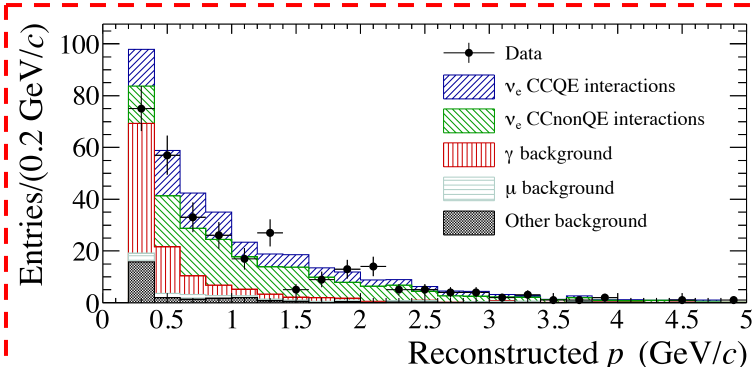
- **4π Acceptance**
  - Current ND280 has strong forward track acceptance yet low efficiency to the vertical and backward tracks
  - Detector with larger phase space to apply constraint on the cross section models



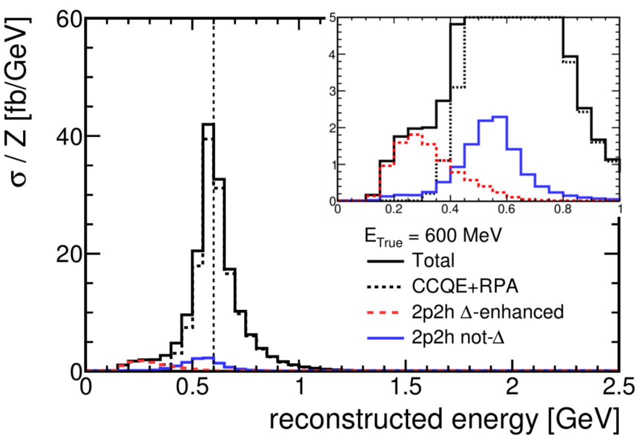


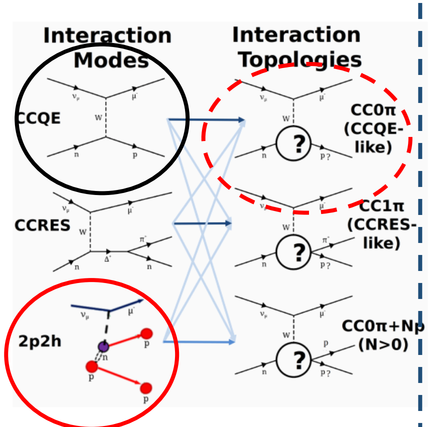
Goals of ND280 Upgrade (2)

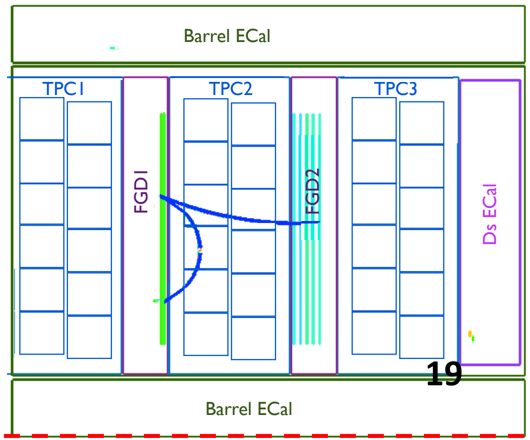
- **Low momentum (< 200 MeV/c) particle measurement**
  - **2p2h models**
    - Energy reconstruction bias
  - **Electron-photon separation**
    - ~23% of the ND events that are selected as ν_e are misidentified photons from ν_μ NC1π^0
  - Detector with higher granularity to be sensitive to low momentum



Phys. Rev. Lett. 113, 241803

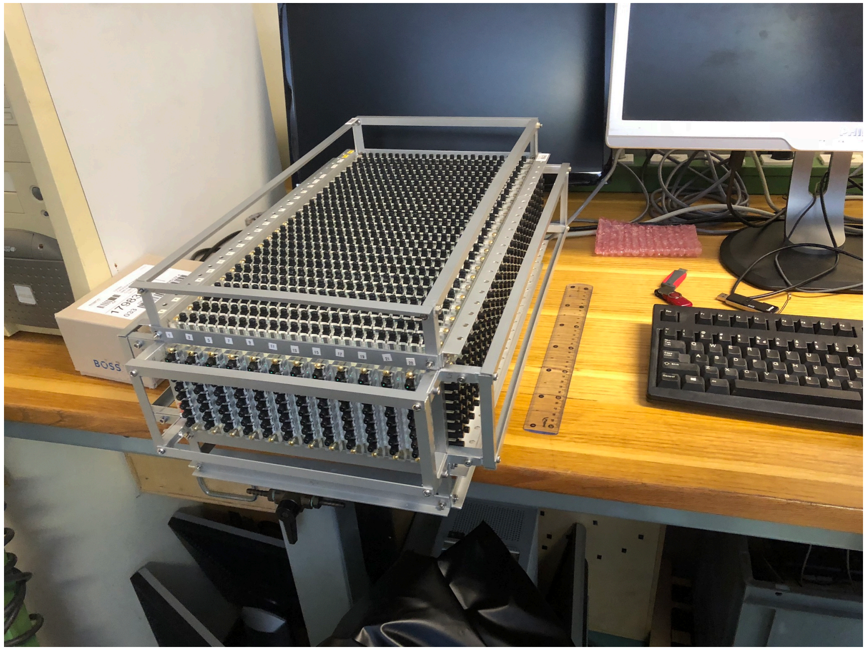






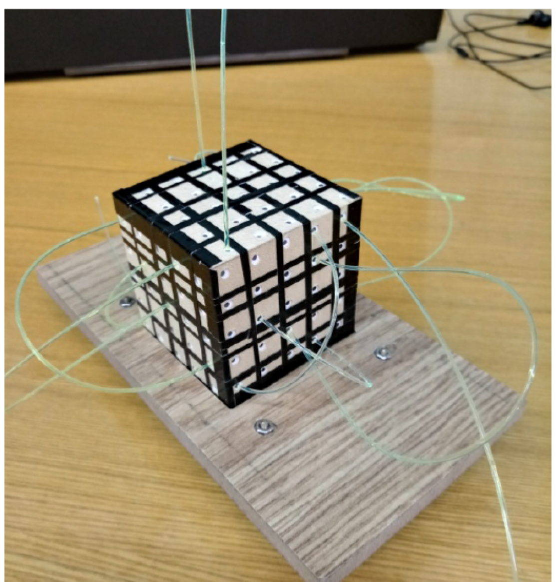
SuperFGD Assembly

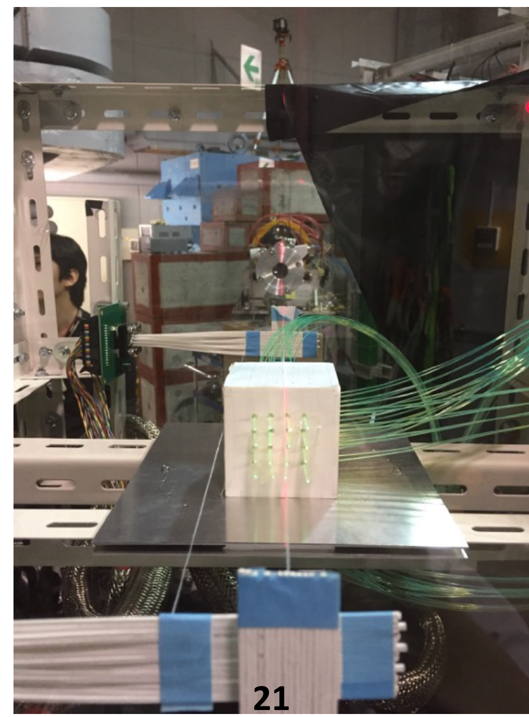
- Assembly method developed by INR RAS
- 1.3 mm ϕ fishing lines through the cubes to assemble, replaced with 1.0 mm ϕ WLS fiber line by line
- Feasibility proved with 9,216-cube prototype ($8 \times 24 \times 48\ \mathrm{cm}^3$)
- Other methods for an actual detector design under investigation



SuperFGD Prototype Beam Tests

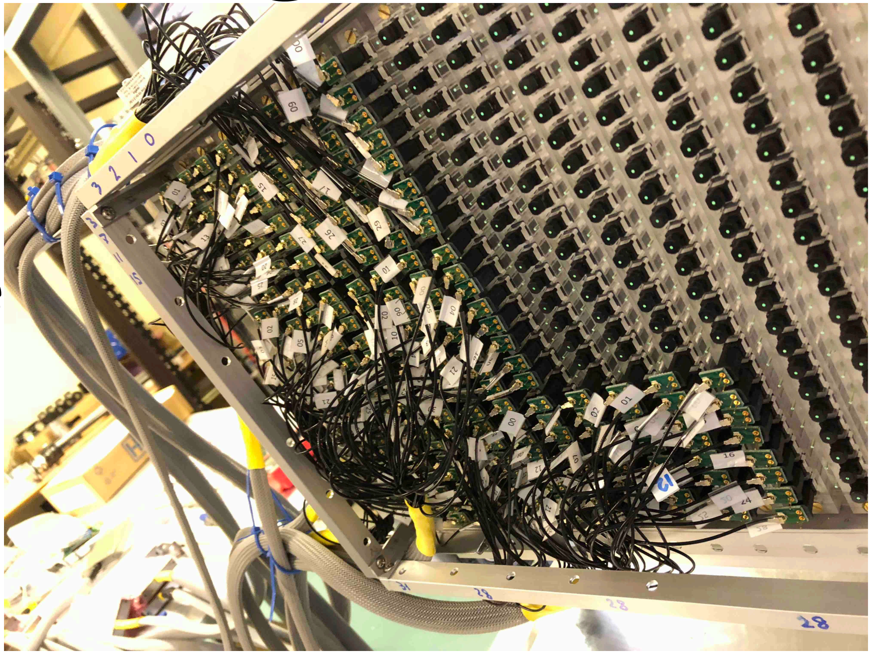
- **October 18 - November 1, 2017 @ CERN T10**
  - $5 \times 5 \times 5\ \mathrm{cm}^3$ prototype, digitizer readout
  - Light yield, cross-talk, timing resolution
- **June 1-3, 2018 @ Tohoku University**
  - $4 \times 4 \times 6\ \mathrm{cm}^3$ prototype, EASIROC readout
  - ~500 MeV/c positron beam
  - Position dependence, inner cube uniformity of light yield, test of different cube design

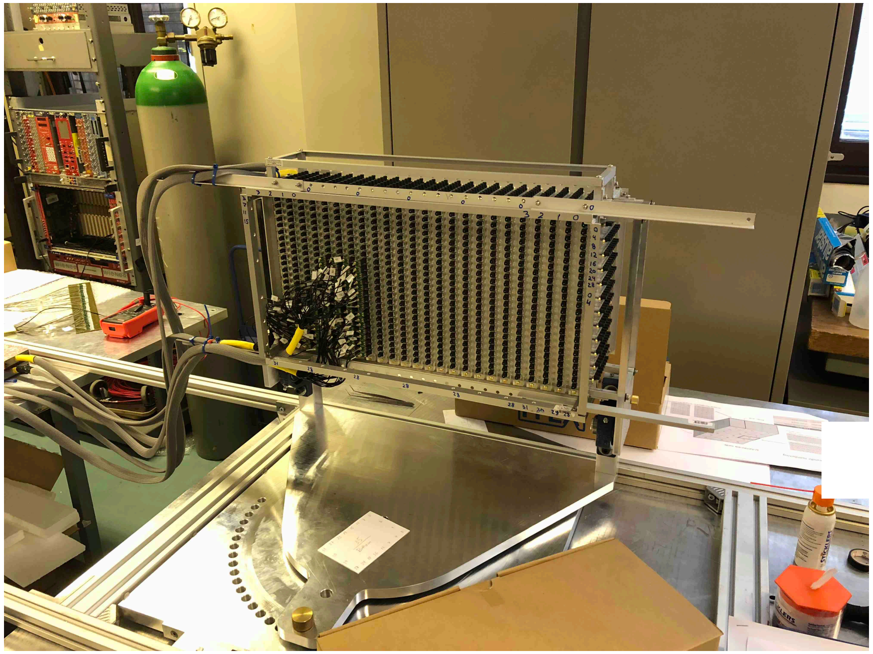


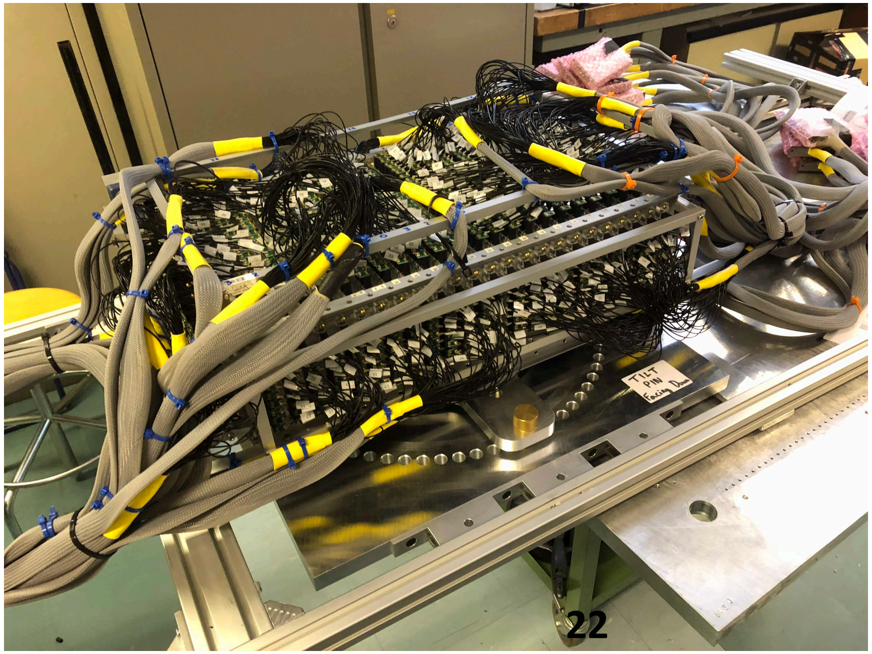


SuperFGD Prototype Beam Test @ CERN T9

- Using Baby MIND electronics with signal amplifications in the FE board (CITIROC)
- Uses micro-coaxial cables to provide connections between ceramic type MPPCs and FE boards
- Mechanical structure made in UniGe

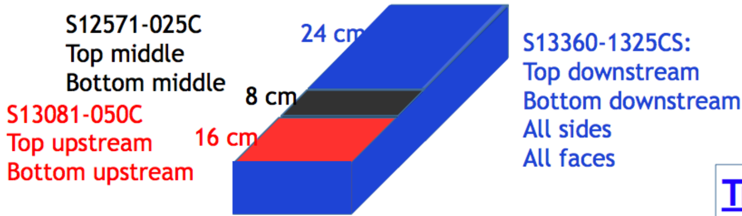






MPPCs for the Beam Test @ CERN T9

MPPC sorting/mapping



Three MPPC types:
- ×1160 type S13360-1325CS
- ×490 type S13081-050C
- ×200 type S12571-025C

Type S13360-1325CS and S13081-050C:
The MPPCs are **delivered** by the **manufacturer** usually according to **serial number**:
One bag per MPPC, with a small label indicating:
- Serial number
- V_{op} (operating voltage)
- Dark(uA)

Then 10 bags in a larger bag (without label)… and several larger bags/box.

The **sorting/cabling sequence**:
- Sorting MPPCs into groups according to operating voltage (V_{op}): range 100 mV.
- Further sorting into batches of 32 (to match cable bundles).
- Assembly onto cable bundles, registration in database.

Traceability:
- Each MPPC must be traceable back to its serial number and Vop.
- Until it is connected to the cable bundle and registered in the database, it must be kept in its bag.

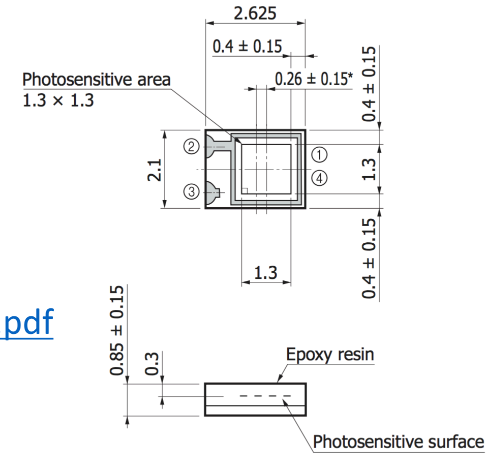
Sorting details:
The MPPCs must be kept separated by type.
The MPPCs are then sorted according to V_{op} in 100 mV ranges:
- S13360-1325CS:
  56.4<56.5, 56.5<56.7, 56.7<56.8, 56.8<56.9, 56.9<57.0, 57.1<57.2, 57.2<57.3 V
- S13081-050C:
  53.8<53.9, 53.9<54.0, 54.1<54.2, 54.2<54.3, 54.3<54.4, 54.4<54.5, 54.5<54.6, 54.6<54.7 V

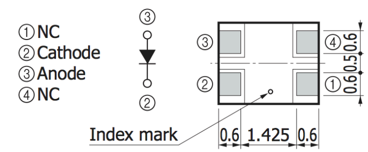
Since we do not expect exact multiples of 32 in each voltage range, some further choices will be made to put MPPCs from two adjacent ranges in the same 32-channel bundle.

D. Sgalaberna

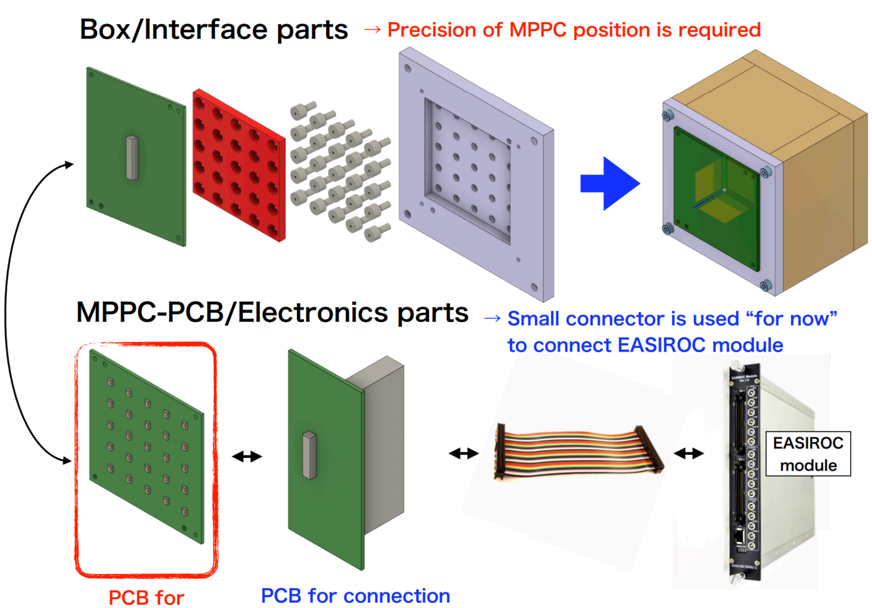
SuperFGD PCB-Box Integration

- Goal to minimize the space and material budget
- Surface mount type MPPC
  - https://www.hamamatsu.com/resources/pdf/ssd/s13360_series_kapd1052e.pdf
- Preliminary design and R&D in progress

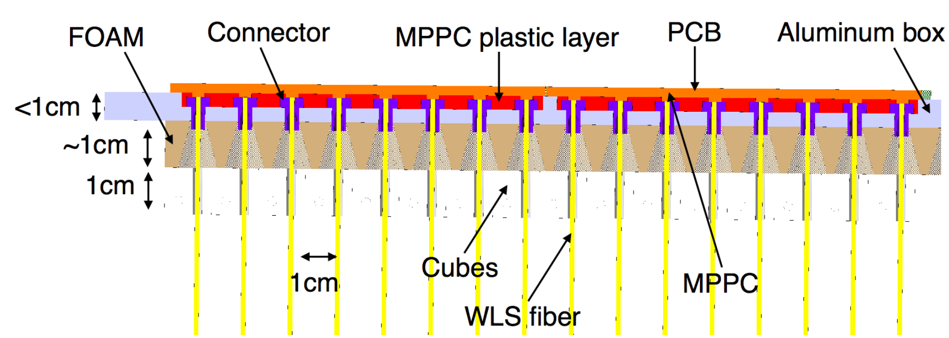




PCB & other components for the tests



- Plastic connectors inserted holes in the box
- The top layer could be just one CF or aluminum layer, i.e. not a CF-AIREX-CF like bottom —> to be studied with FEA
- Design very compact: thickness depends on the type of connector, but aim to <1 cm (from box to PCB)
- FOAM layer to avoid stresses to the fiber and compress the cubes
- Currently working on the tuning of the parameters



T. Matsubara

D. Sgalaberna

Intrinsic ν_e Component in the Flux

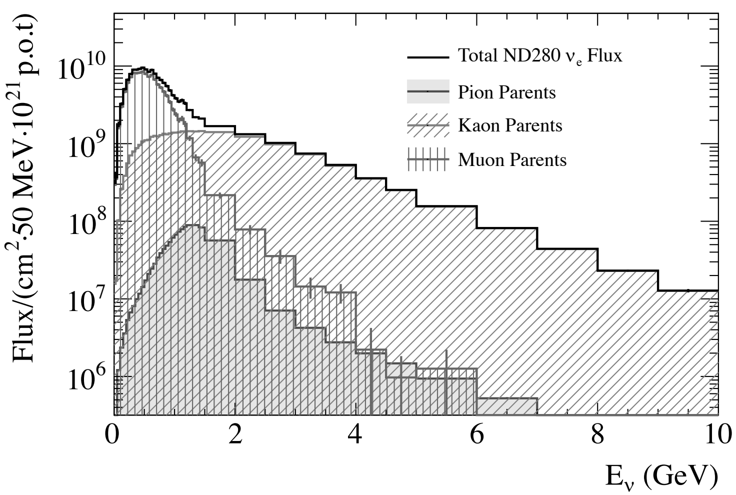
Phys. Rev. D. 89, 092003 (2014)

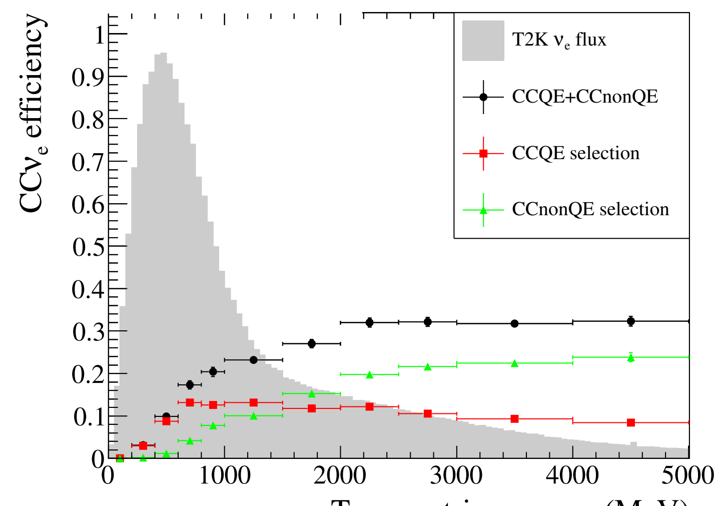
- Expected scaling factor obtained with 6.0e20 POT:

$$\begin{aligned} R(\nu_e) &= 1.01 \pm 0.06(\mathrm{stat}) \pm 0.06(\mathrm{flux} \oplus x.\,\mathrm{sec}) \\ &\quad \pm 0.05(\mathrm{det} \oplus \mathrm{FSI}) \\ &= 1.01 \pm 0.10, \end{aligned} \tag{4}$$

- $E_\nu < 1.2$ GeV dominated by muon decay:

$$\begin{aligned} R(\nu_e(\mu)) &= 0.68 \pm 0.24(\mathrm{stat}) \pm 0.11(\mathrm{flux} \oplus x.\,\mathrm{sec}) \\ &\quad \pm 0.14(\mathrm{det} \oplus \mathrm{FSI}) \\ &= 0.68 \pm 0.30 \end{aligned} \tag{5}$$





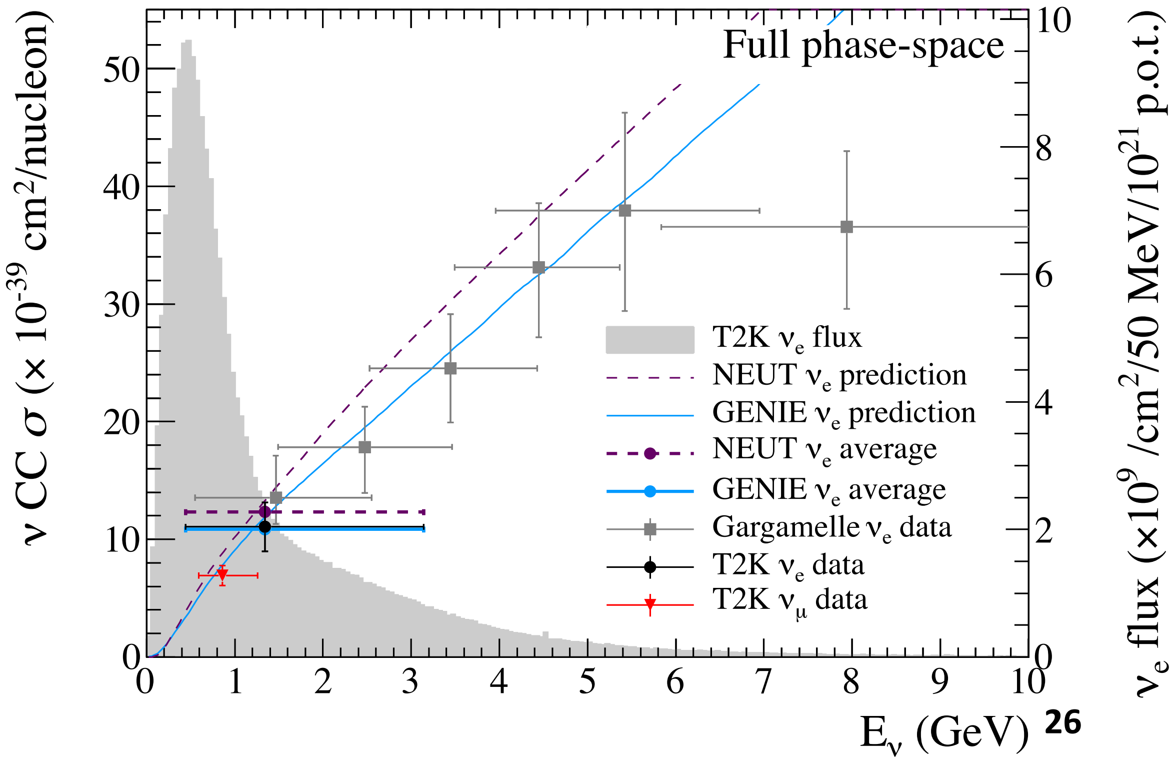
CC ν_e Inclusive Cross Section on Carbon

Phys. Rev. Lett. 113, 241803

- Total flux averaged cross section obtained with 6.0e20 POT:

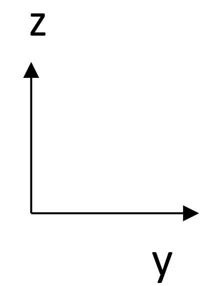
$$\langle\sigma\rangle_\phi = 1.11 \pm 0.10(\text{stat}) \pm 0.18(\text{syst}) \times 10^{-38} \text{cm}^2/\text{nucleon}$$

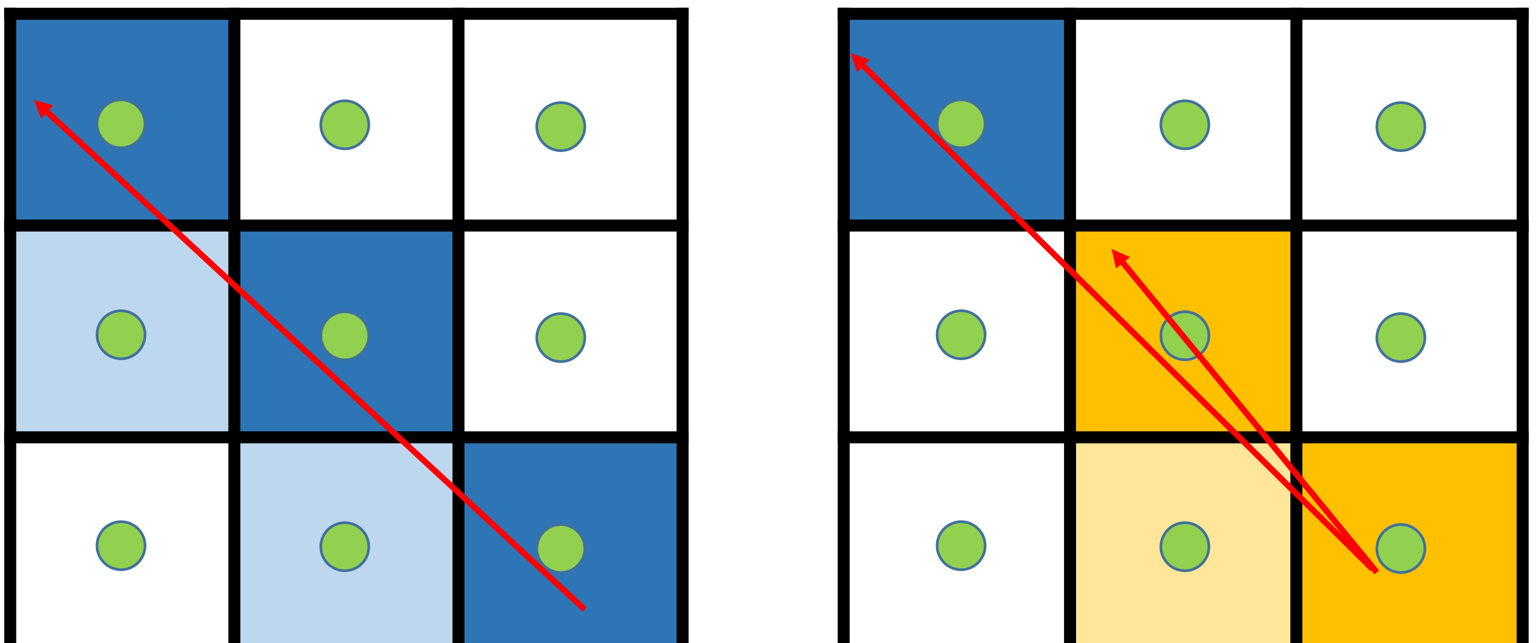
- Dominant components of systematic uncertainties:
  - Flux (13%)
  - Detector (8%)
  - Others (6%)



e/γ Separation in ND280 Upgrade Target

- Goal to distinguish e/γ events that are single-track, electron-like, low momentum (200 < p < 600 MeV/c)
- Distinction between 1 (e^-) and 2($\gamma \rightarrow e^-e^+$) MIP events using the MPPC light yield from the tracks
    - Considering the light yield before and after the e^-e^+ tracks split into different scintillator segments

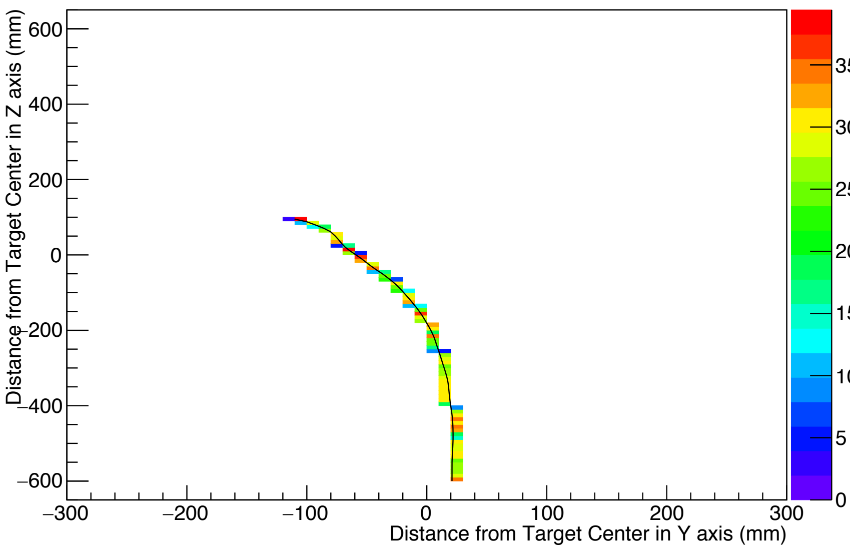




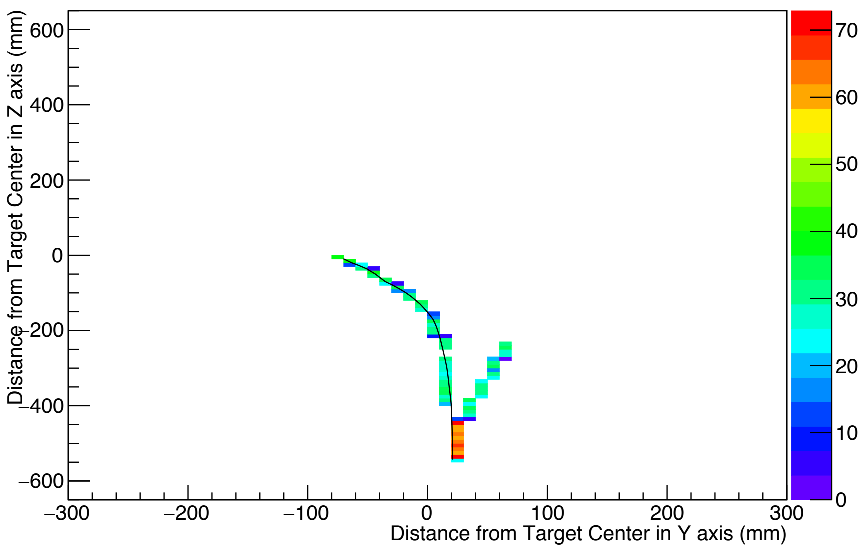
e/ γ Separation using Light Yield

- Preliminary algorithm to separate e/γ events using the total light yield for each view (YZ, XZ, XY)
  1. Locates the single electron track and the starting point using truth information
     - "Perfect pattern recognition"
  2. Split the track into two segments where the ratio between the mean values of the total p.e. is the largest
     - Ignores the first and last MPPC hits to avoid short path length

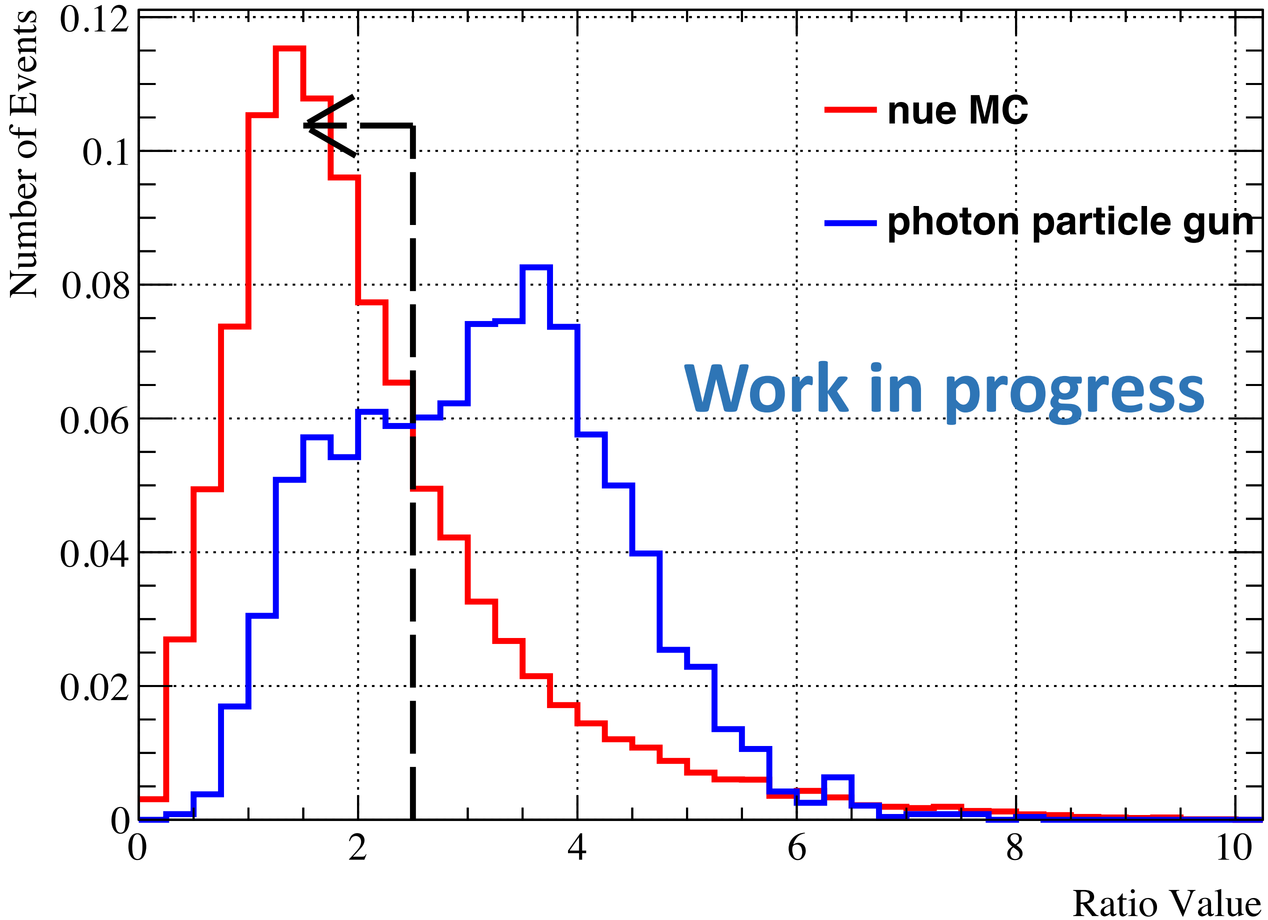
e Sample



γ Sample



SuperFGD: ν_e MC and γ 4π p-gun Comparison



77% efficiency to accept ν_e CC
39% to mis-ID γ p-gun sample
(19% if 2-trk-like count as rejected)

ND280 Upgrade ν_μ Selection

Comparison of predicted event rate of selected events (1×10^{21} POT) between ND280 current and upgrade:

Selection	Current-like	Upgrade-like
ν_μ (ν beam)	93,401	194,654
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	33,437	63,687
ν_μ ($\bar{\nu}$ beam)	17,998	33,773

ν_μ CC

		# of events	Purity (%)		
		(/10^{21} POT)	CC0π	CC1π	CC Other
current	FGD 1	50012	72.8	65.4	68.9
	FGD 2	48119	73.2	64.3	70.2
upgrade	FGD1	48332	74.6	65.0	69.6
	FGD2	45636	73.5	64.1	70.2
	SuperFGD	100686	73.9	72.9	70.9

ND280 Upgrade Sensitivity

CERN-SPSC-2018-001 ; SPSC-P-357

ND data fit tool adapted to ND280 Upgrade to evaluate how much the systematic uncertainties are reduced (8×10^{21} POT) :

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation	3.1	2.4
$(0.6 < E_\nu < 0.7$ GeV$)$		
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

On average the systematic uncertainties are reduced by about 30%