KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

International Conference on the Physics of the Two Infinities

The T2K near detector upgrade

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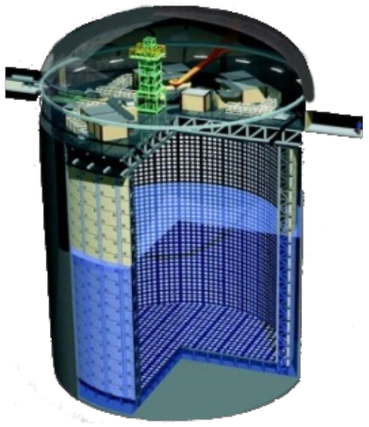
cesar.jesus-valls@ipmu.jp

29th March 2023

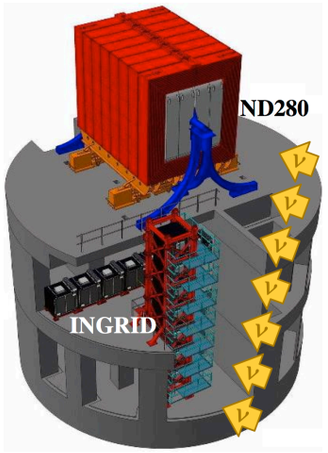
On behalf of the T2K collaboration

The T2K experiment

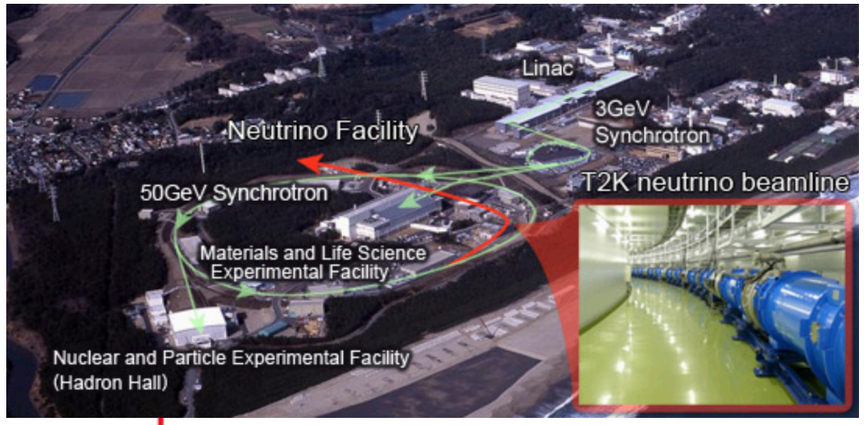
Far detector
Super Kamiokande

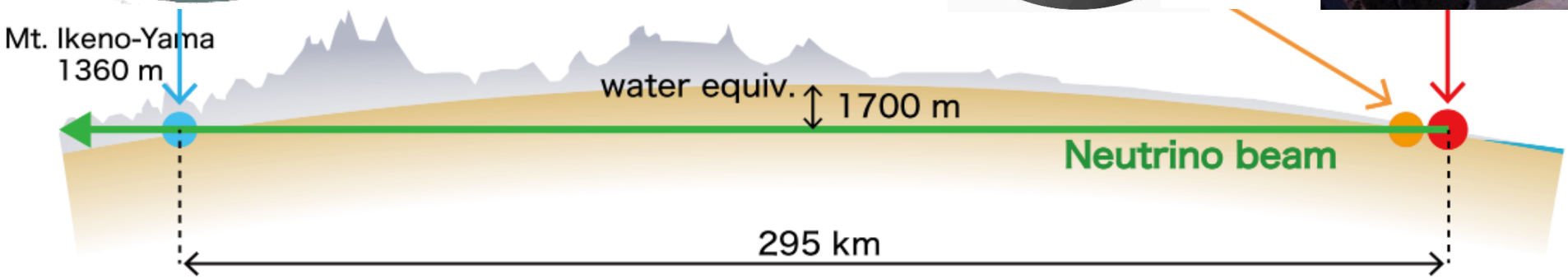


Near detector
complex 280m



J-Parc
Neutrino Beam



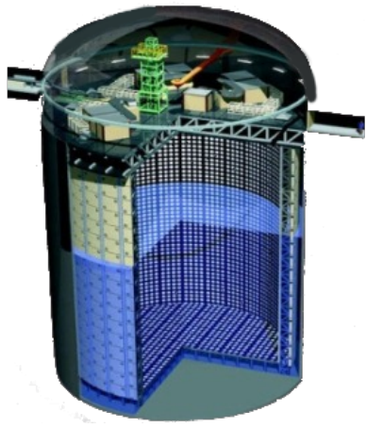


check T2K plenary Link

@SK @ND280 @J-PARC

The T2K experiment

Far detector
Super Kamiokande



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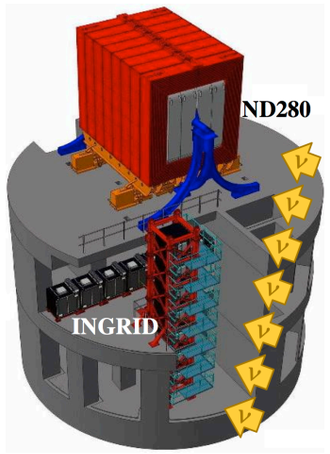

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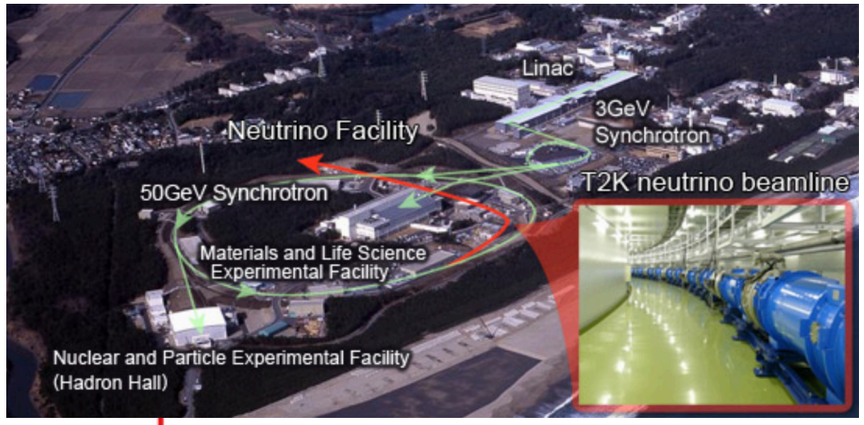
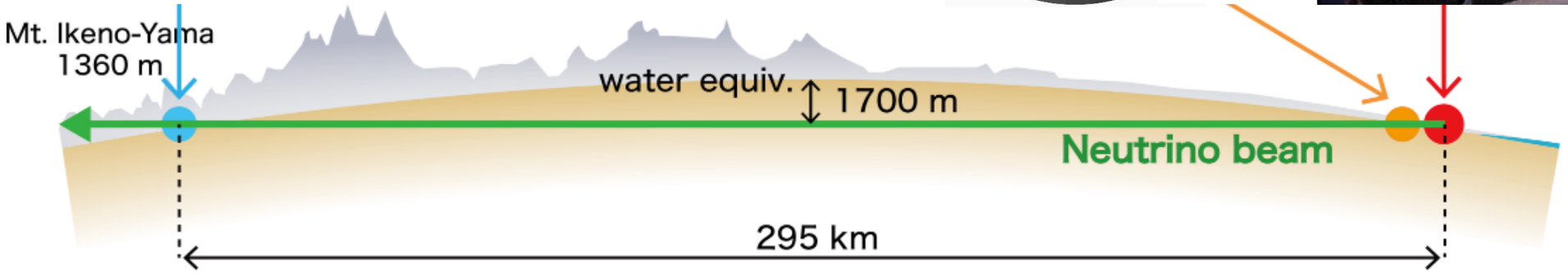
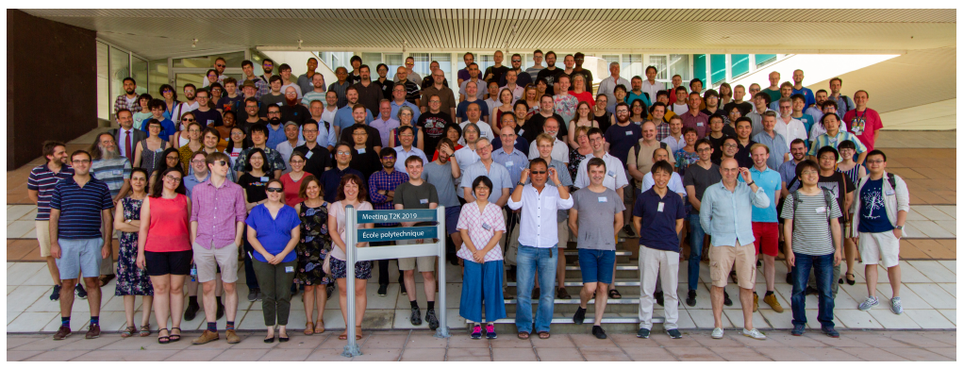




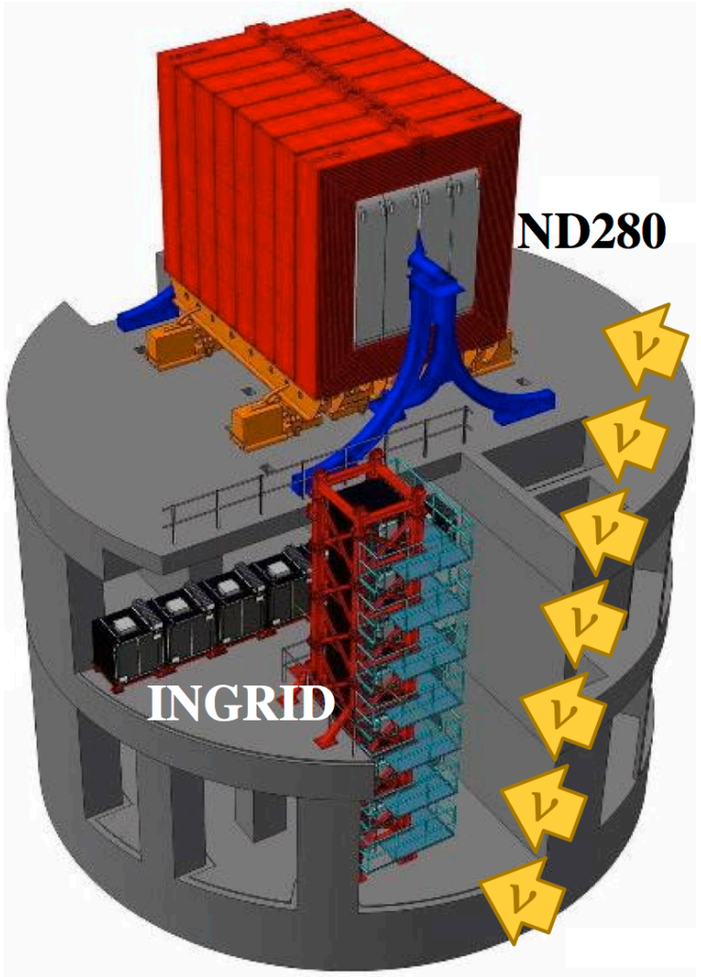
@SK **@ND280** **@J-PARC**

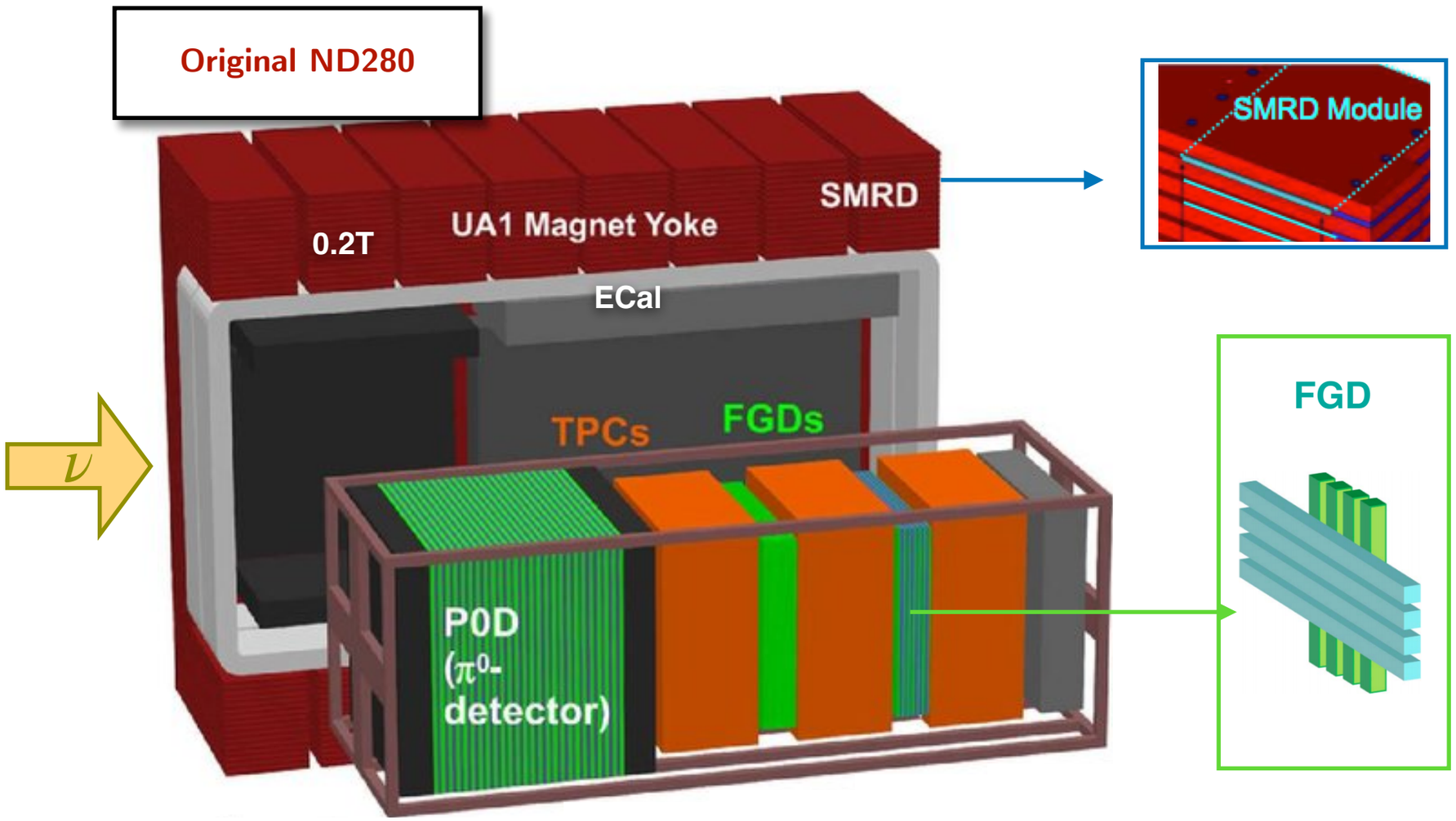
check T2K plenary Link

- Discovery of $\theta_{13} > 0$.
- First hints of $\delta_{CP} \neq \{0, \pi\}$
- Leading sensitivity to $\Delta m^2_{23}, \theta_{23}, \delta_{CP}$.



The ND280 detector





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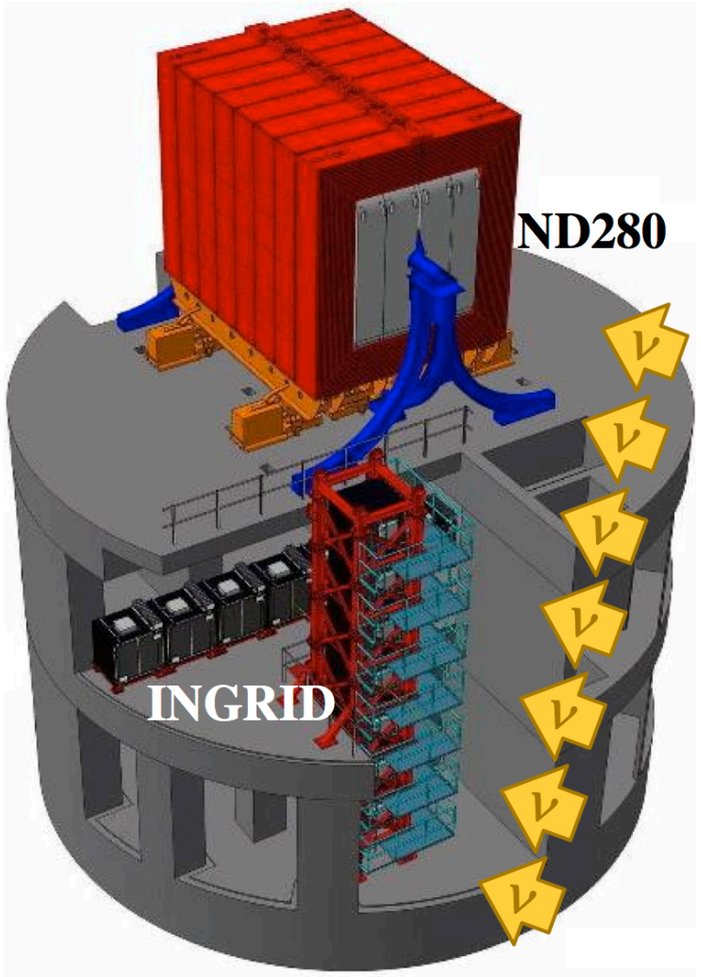
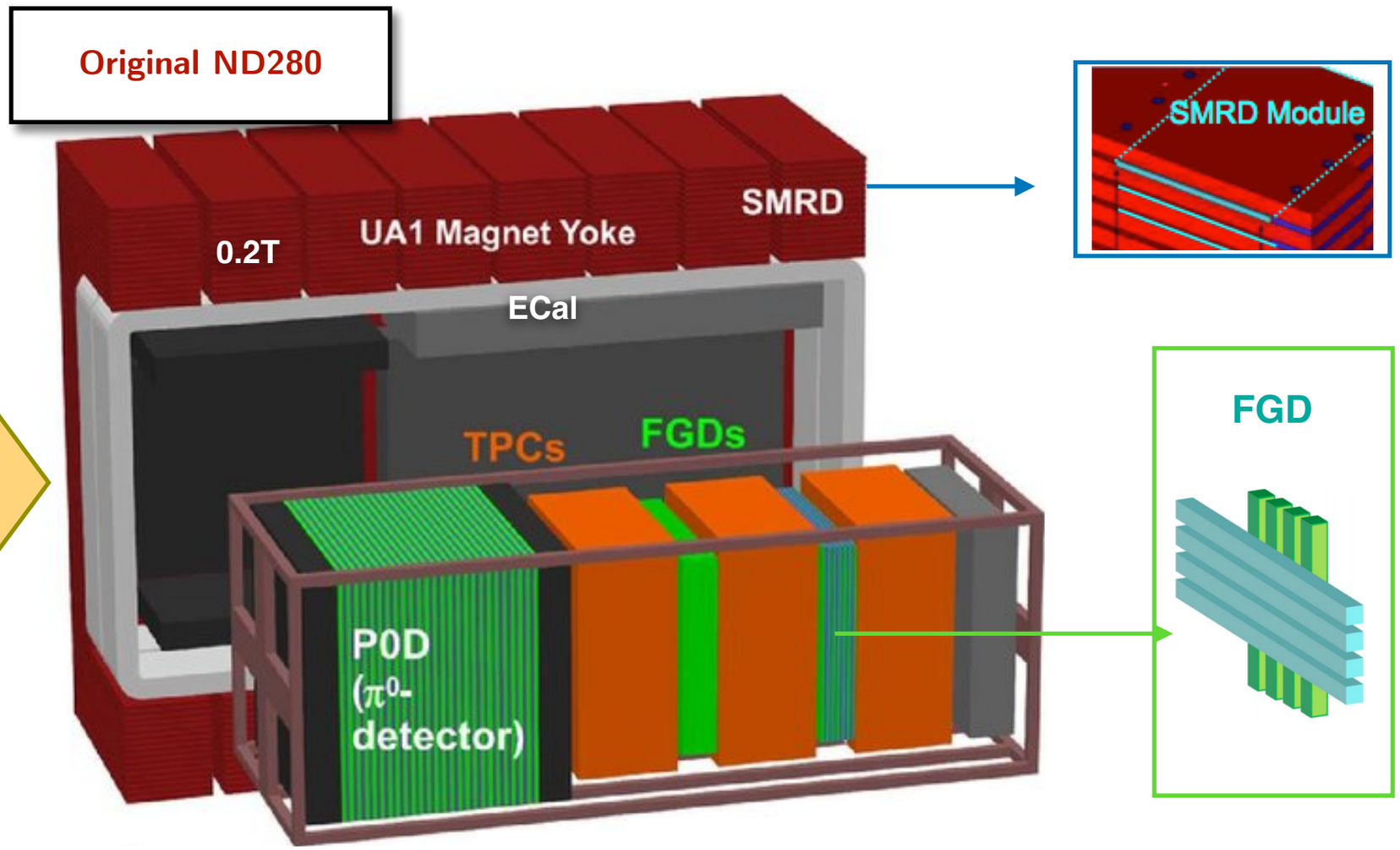
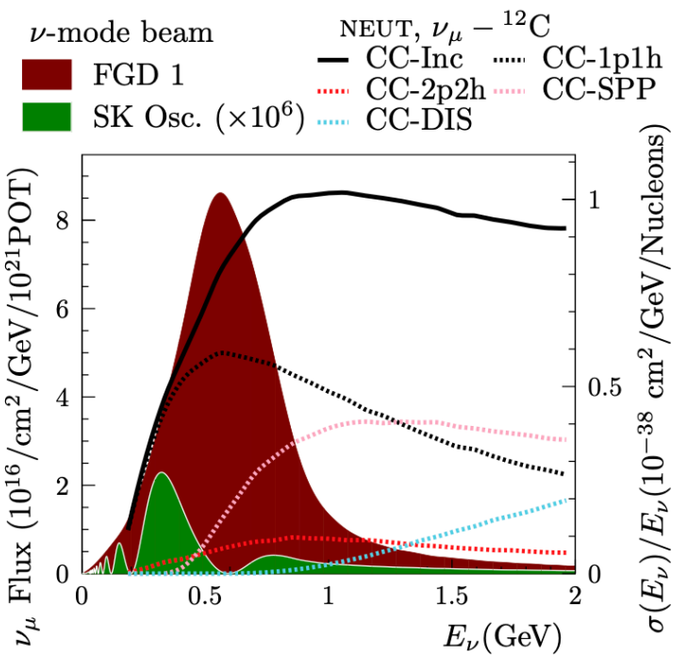
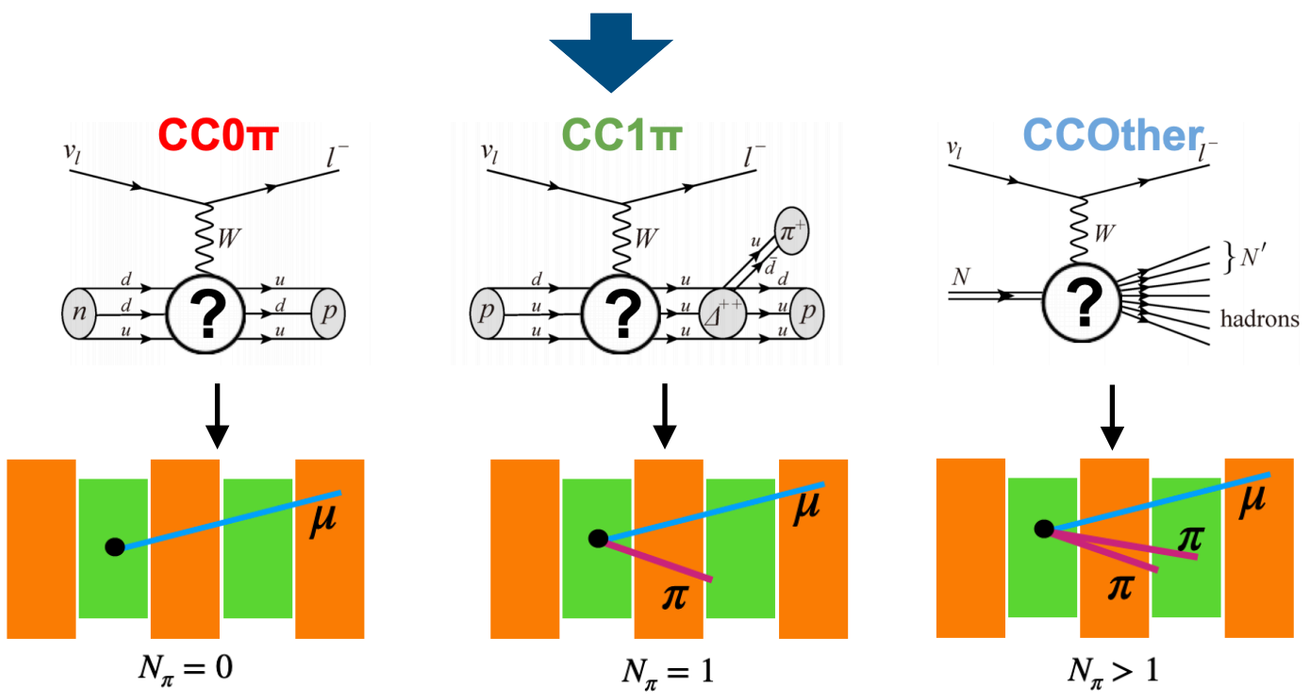






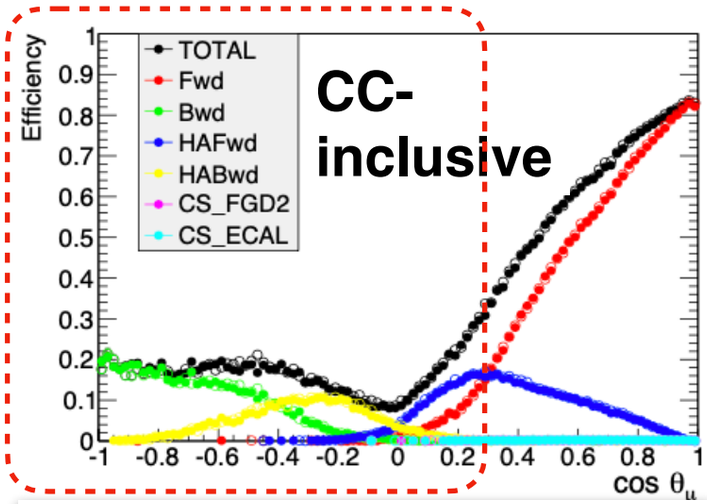


The ND280 upgrade: Overview

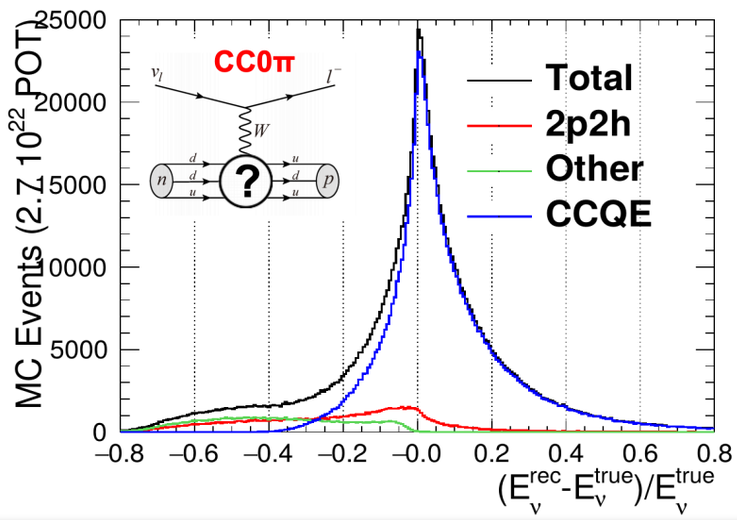
Motivations

- ND280 is an essential component of T2K.
- Over years statistical errors ↓ so we need systematic errors ↓.

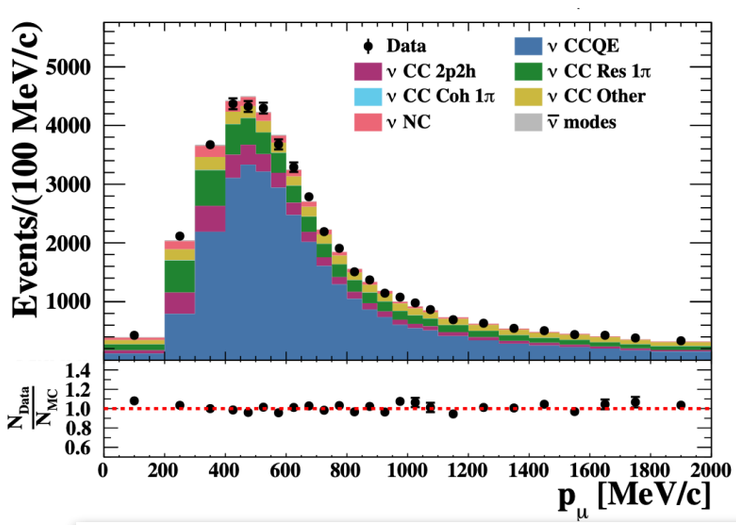
What can we improve?



Efficiency is mainly forward



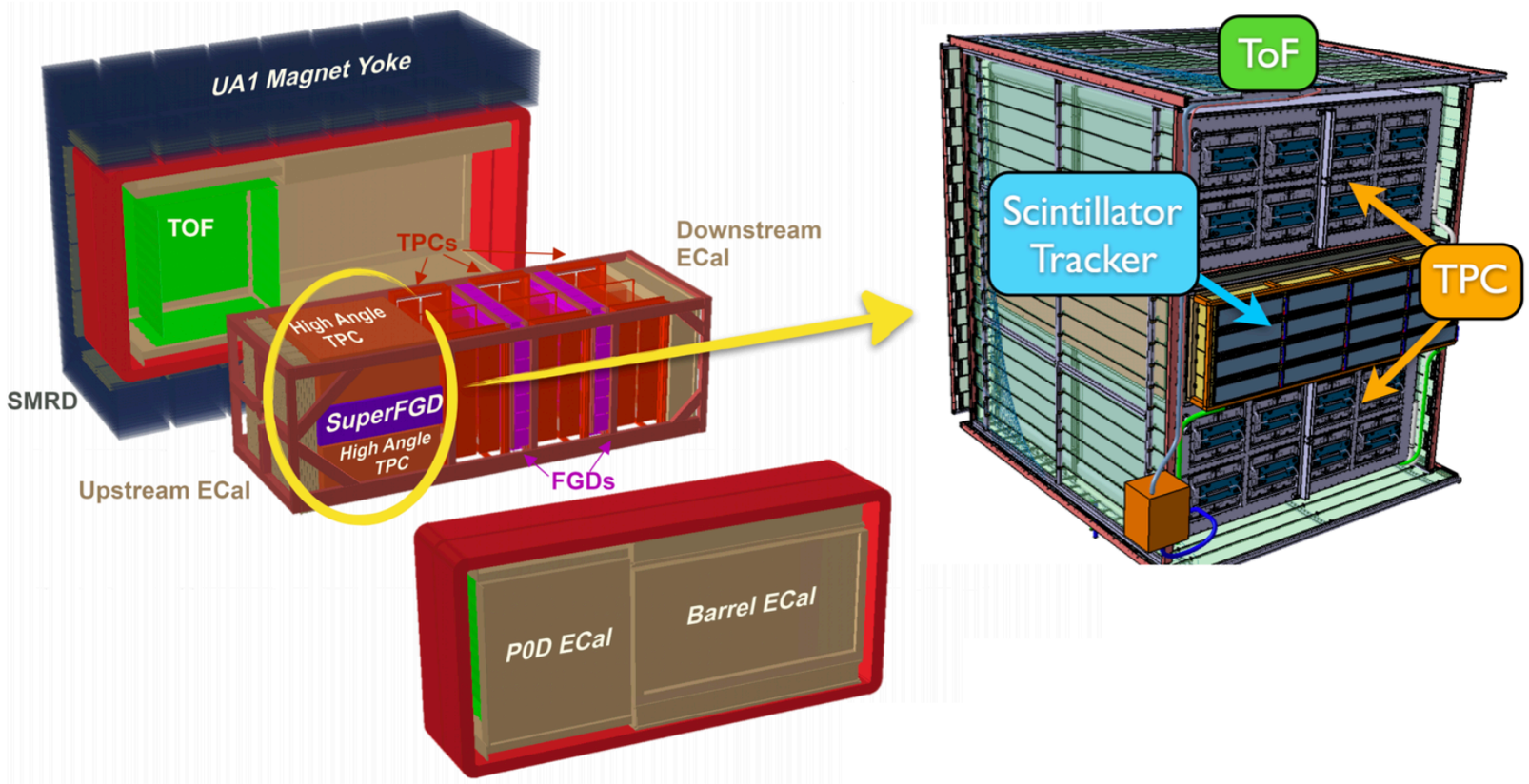
Hadronic information is essential



purity ↑ requires PID ↑

The ND280 upgrade: Design

2019 TDR e-print: 1901.03750 + **Beam upgrade (×2.6 more neutrinos!)** PTEP 2021 (2021) 3, 033G01



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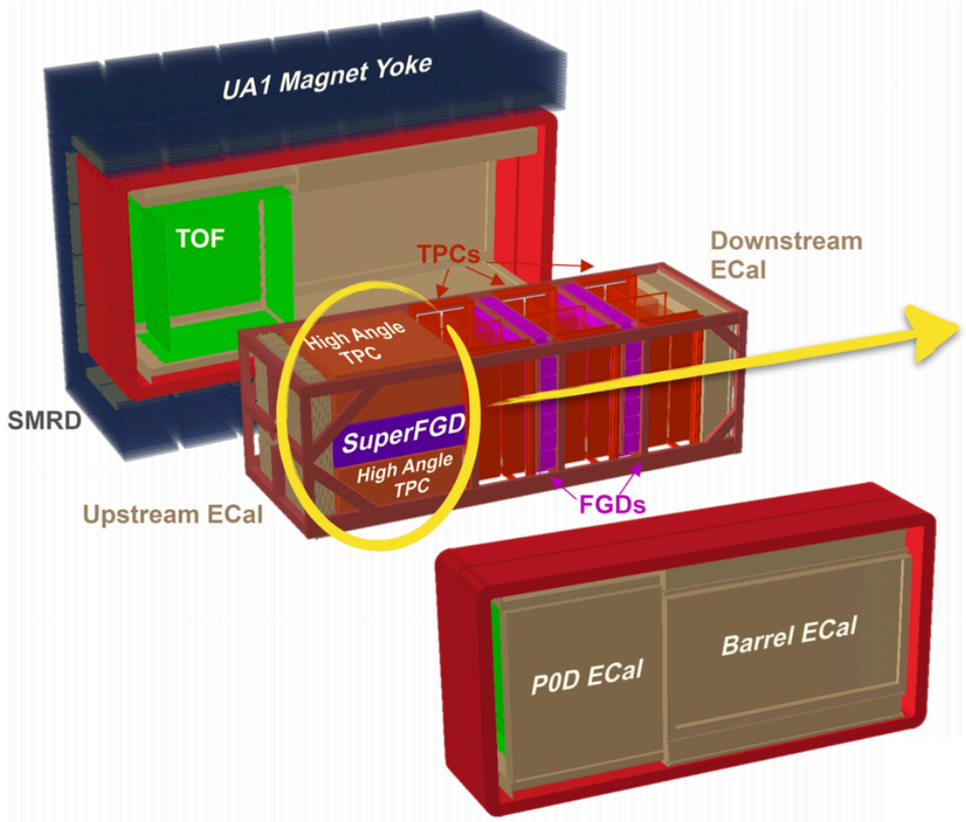

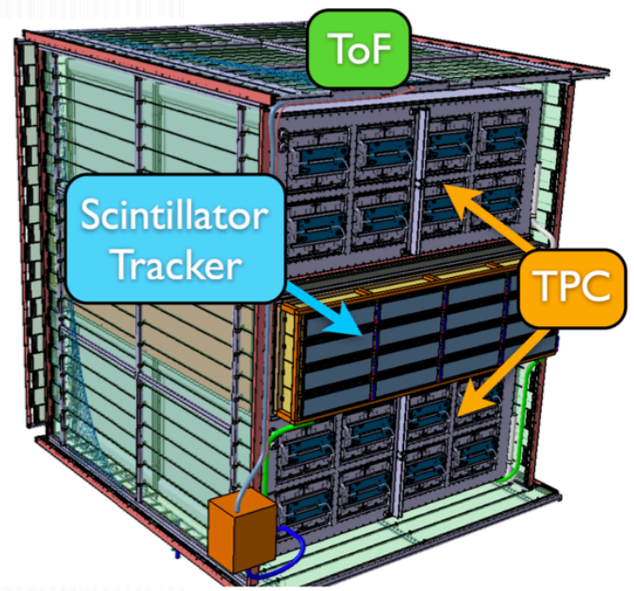

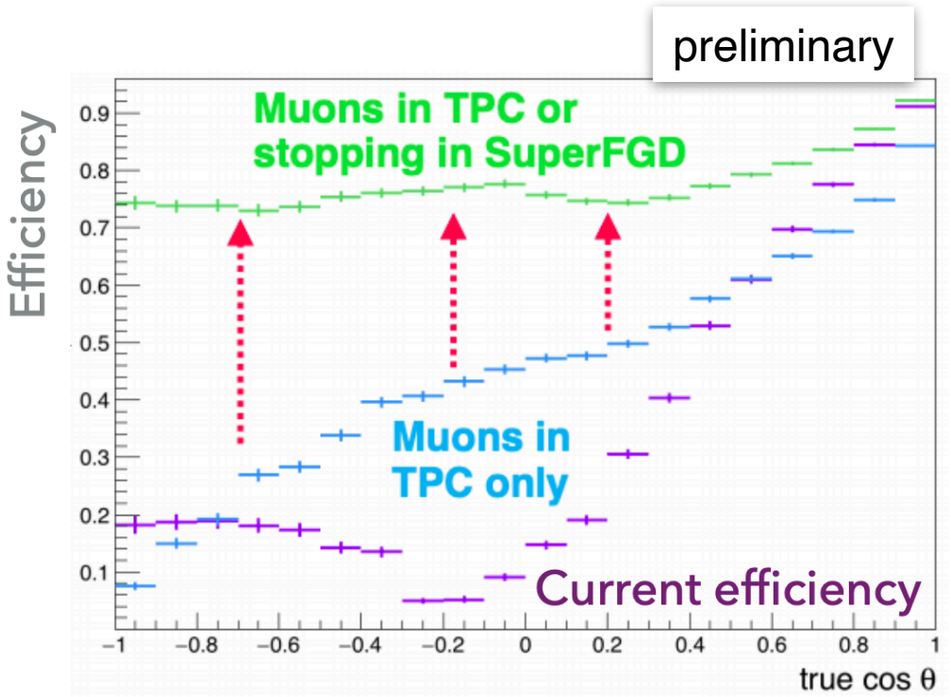

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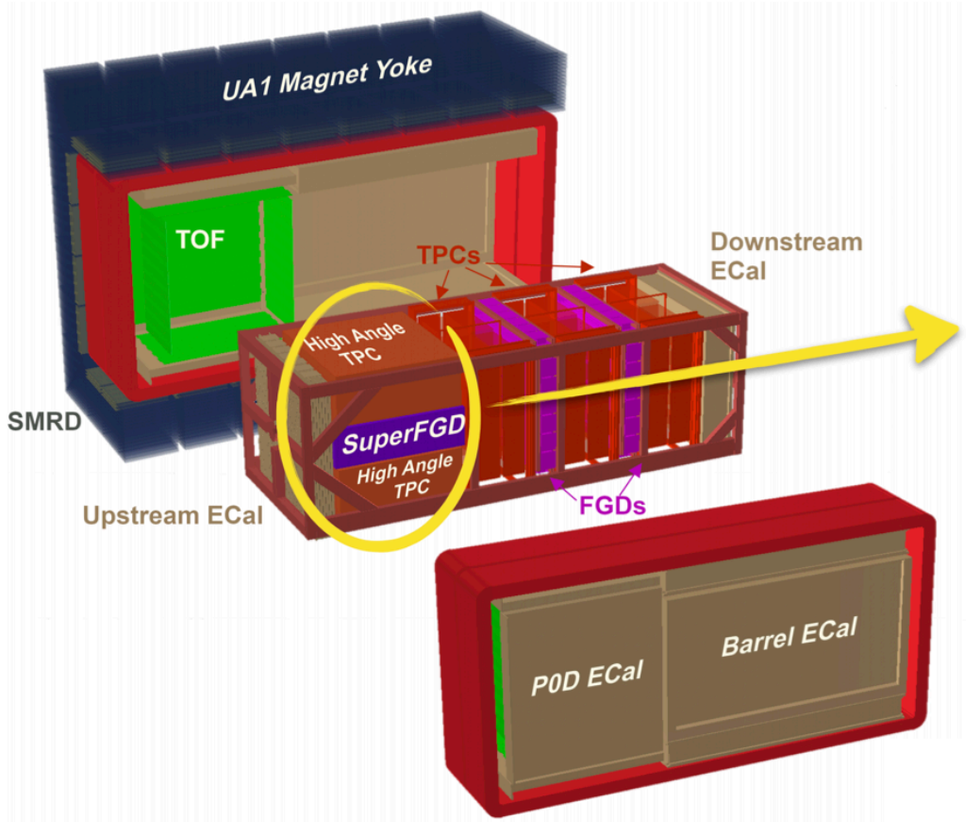
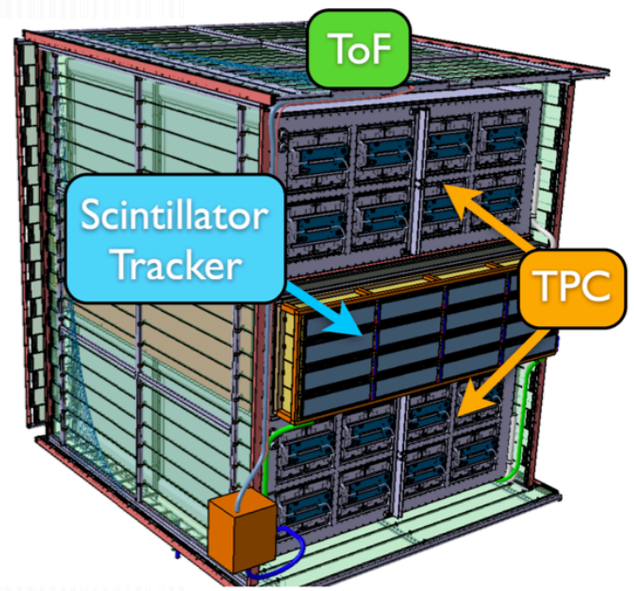
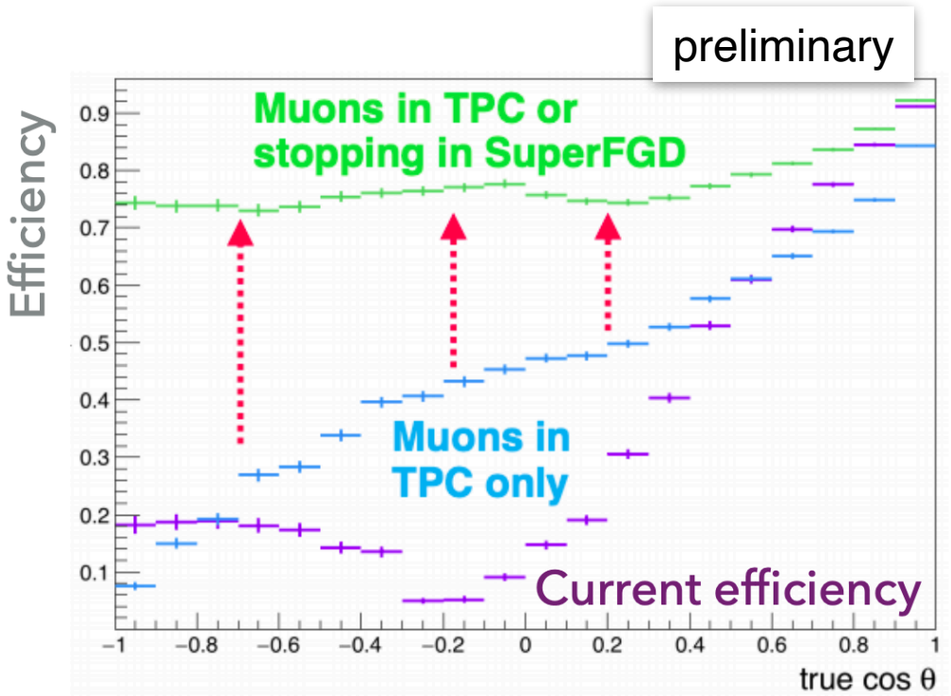
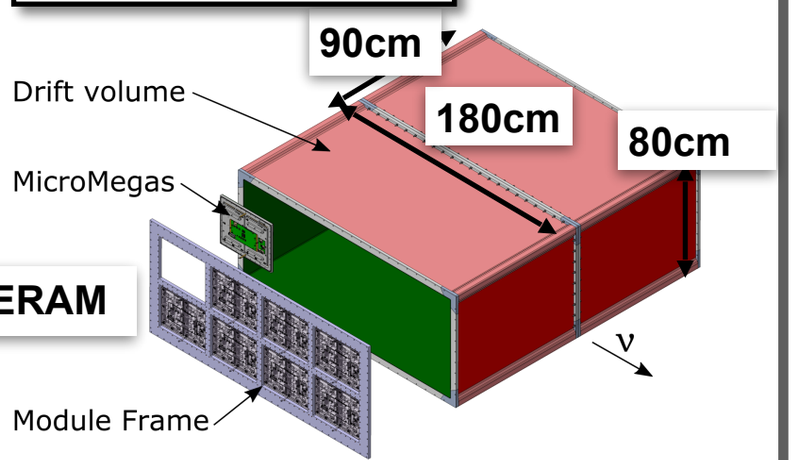




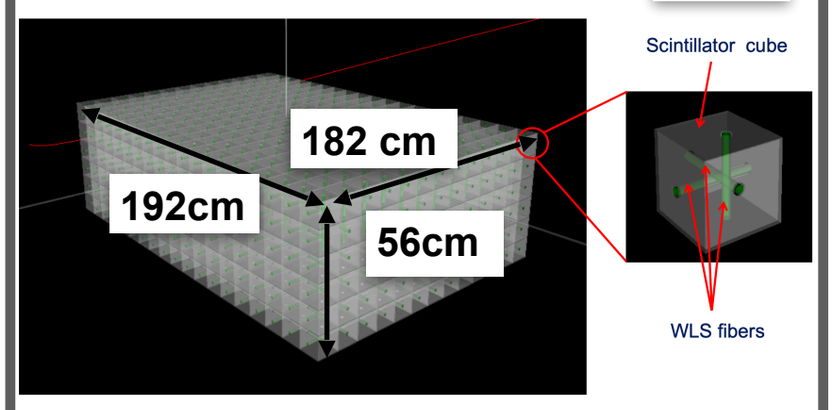


Three novel technologies in ND280

2 High Angle TPCs



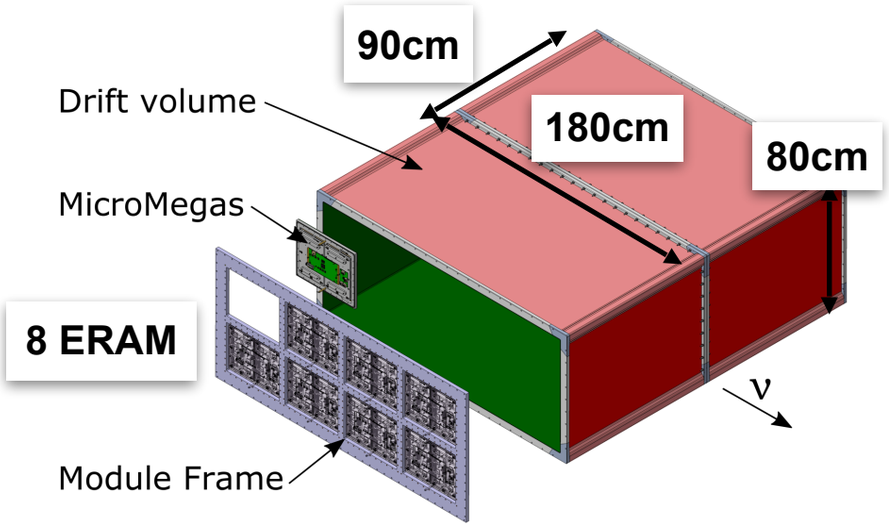
1 SuperFGD



6 ToF panels

The novel high-angle TPCs

2 new identical TPCs



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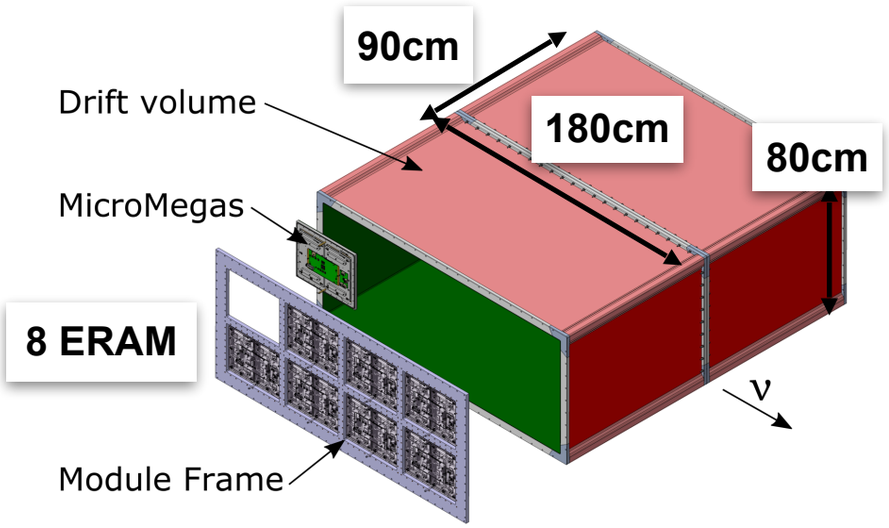
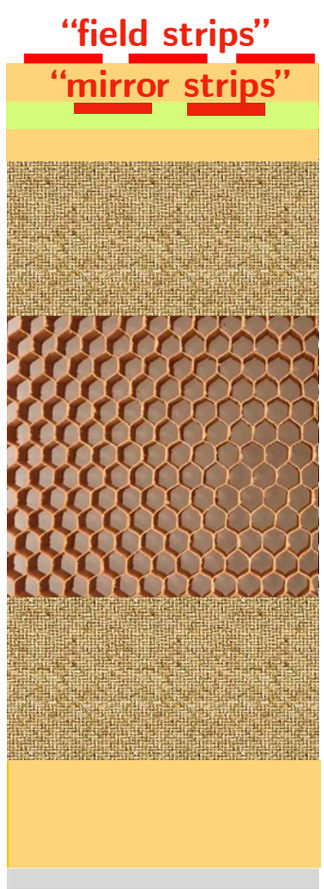


Field cage composition



Cu strips & Glue & Kapton (100μm)

Aramid Fiber 2mm

Aramid Honeycomb 35mm

Aramid Fiber 2mm

Kapton (125μm)

Al foil (50μm)

Original 12cm & 3.4% X_0

NEW 4cm & 2% X_0

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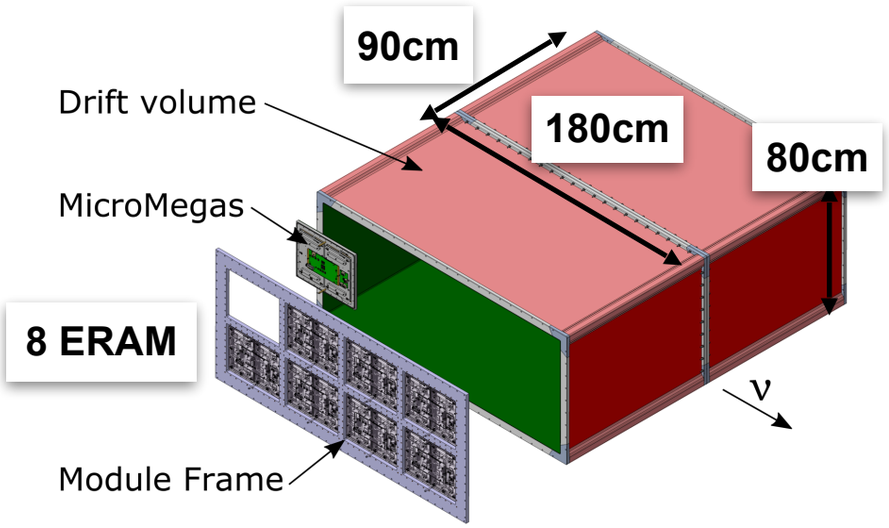

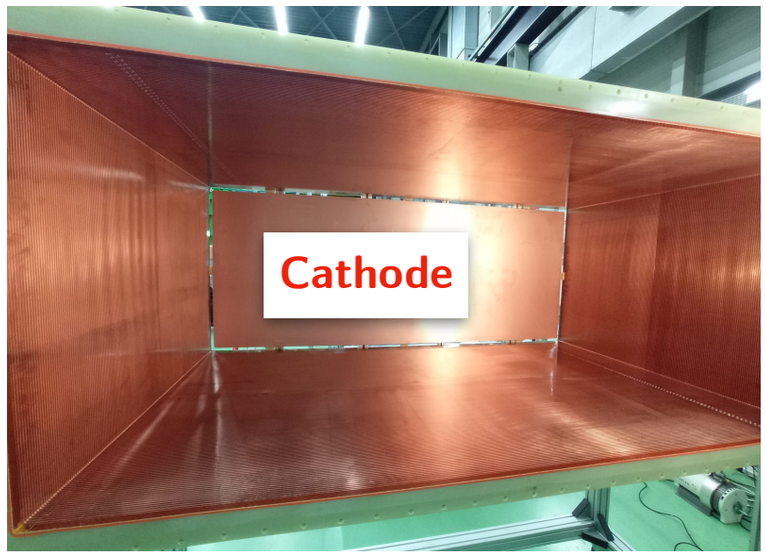

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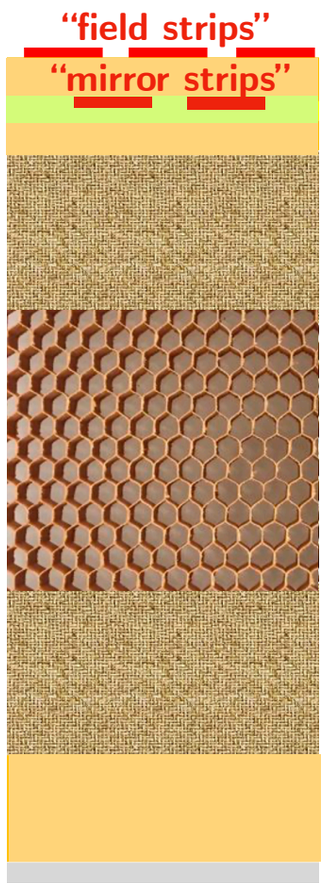

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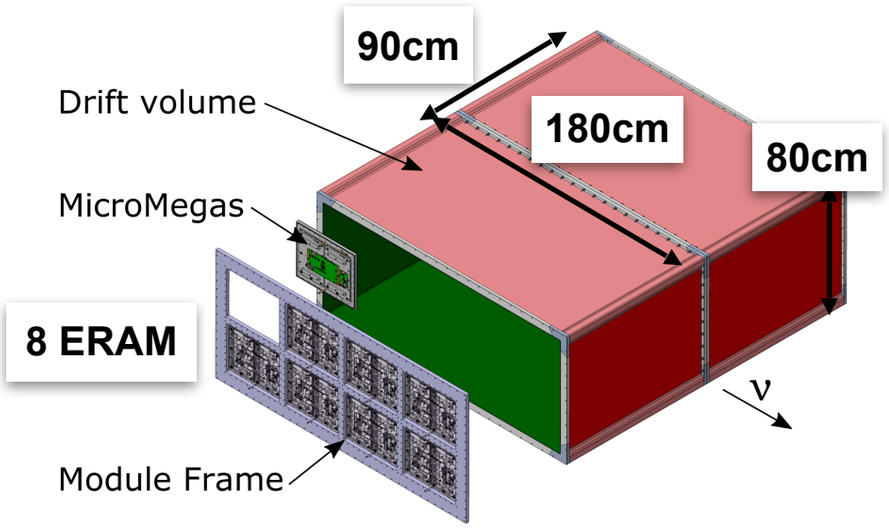
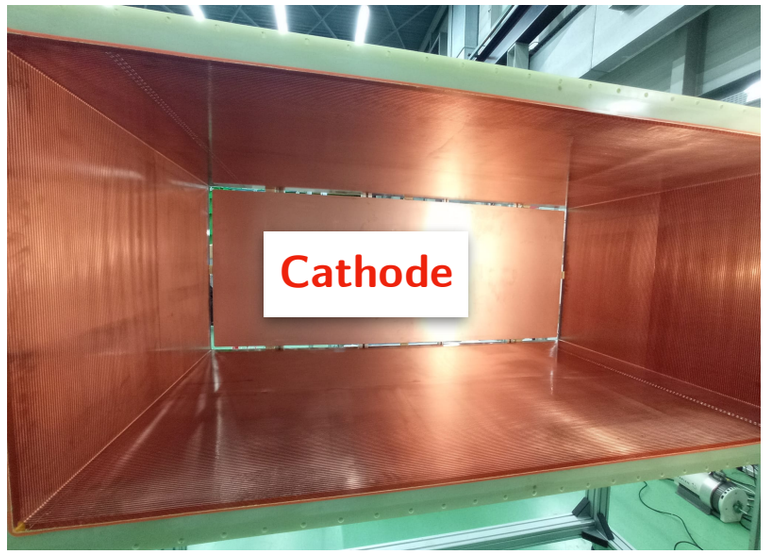
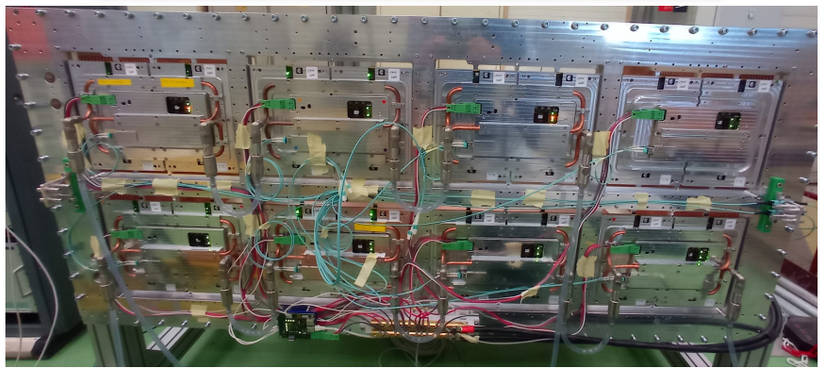




Anode plane with 8 ERAMs



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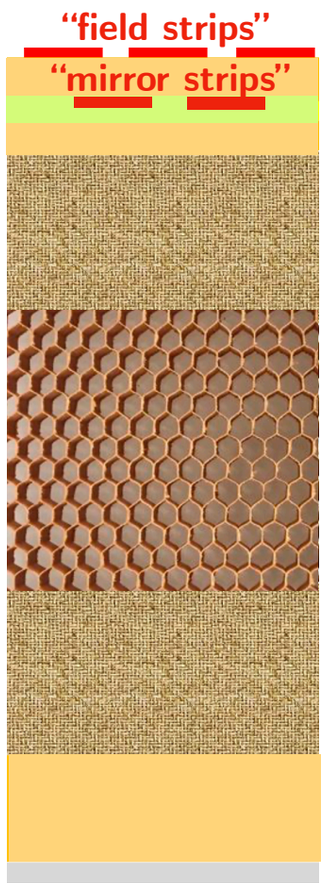

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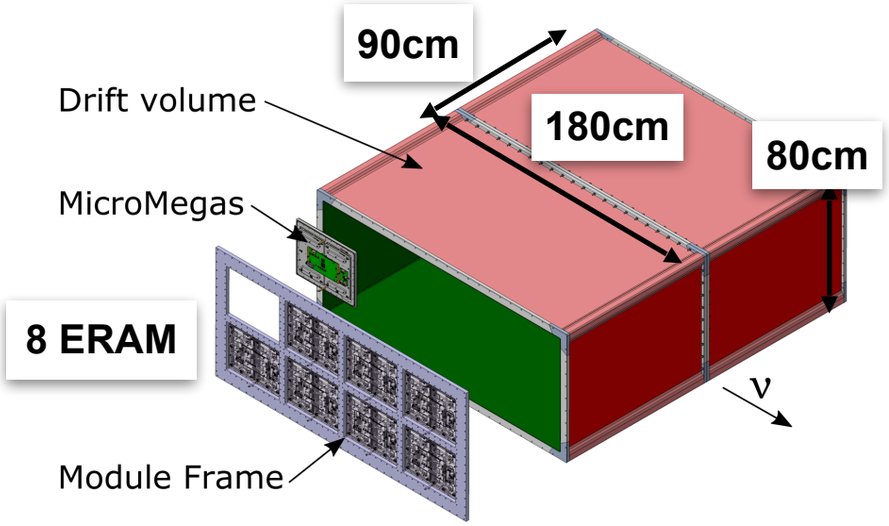

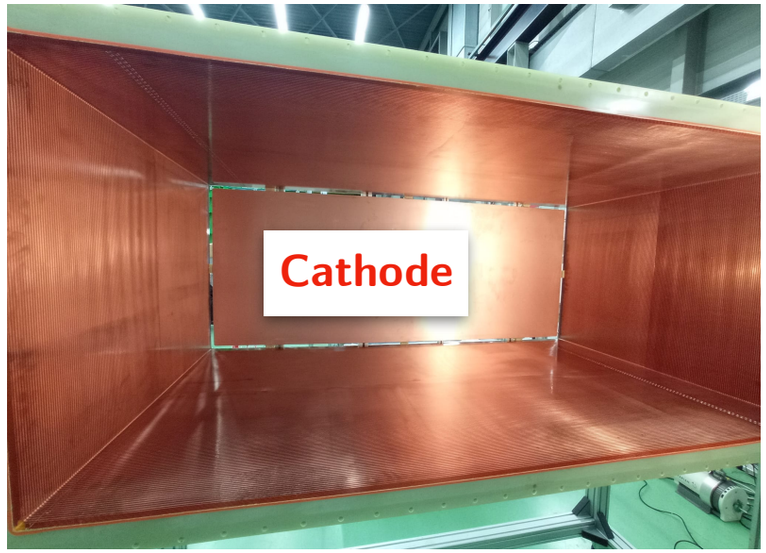

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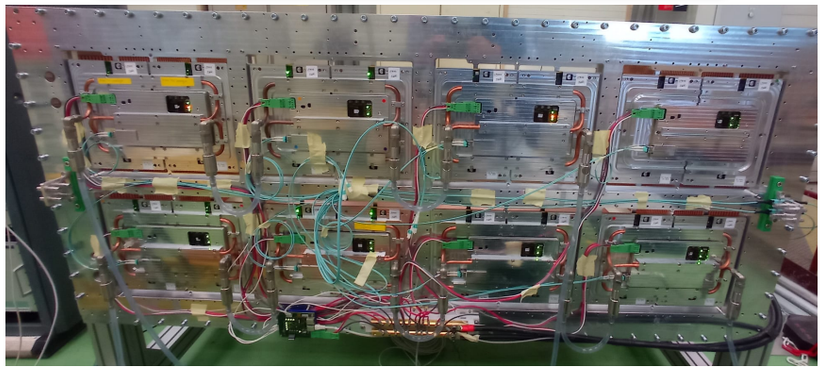

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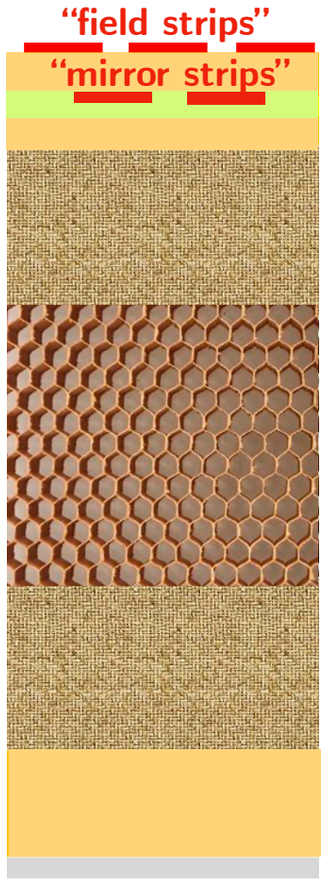

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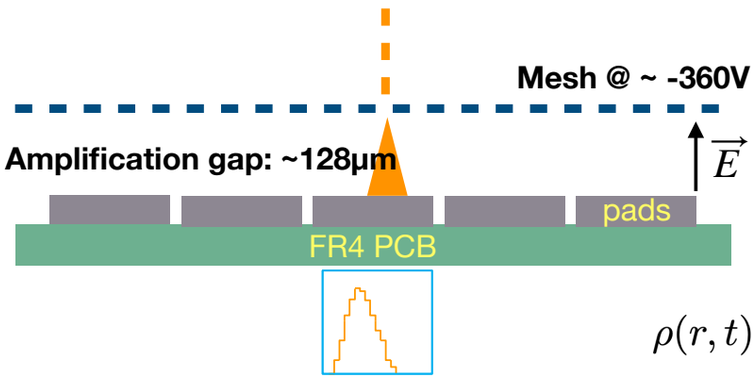
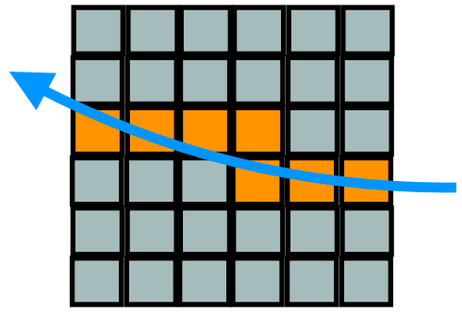
Original ND280 TPCs

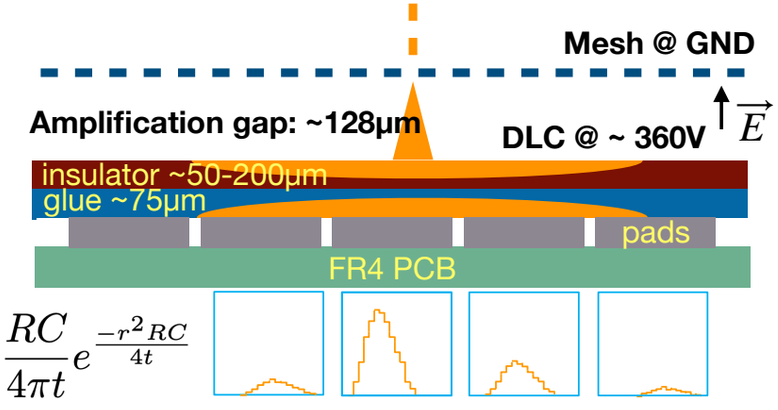
Bulk Micromegas



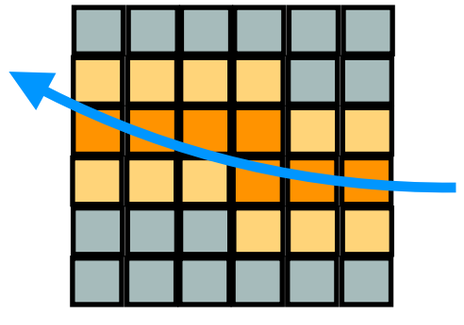


NEW ND280

Resistive Micromegas



$$\rho(r,t) = \frac{RC}{4\pi t} e^{\frac{-r^2 RC}{4t}}$$



TPCs development

Field cage R&D and validation

4 prototypes (2 small 2 large), hundreds of validation tests
Production readiness 2023 → final construction ongoing

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ERAM R&D and validation

- First ERAM prototype in 2018. Beam test @CERN
  Old electronics & module layout.

Concept validation

NIMA 957 (2020) 163286 • e-Print: 1907.07060

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Final design validation

NIMA 1025 (2022) 166109 • e-Print: 2106.12634

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- Third ERAM module in 2021. Beam test @DESY
  Updated resistivity

ERAM characterization & simulation validation

- e-Print: 2212.06541 (Dec 2022)

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Production characterization, gain and spreading of 40 ERAMs

- e-Print: 2303.04481 (March 2023)

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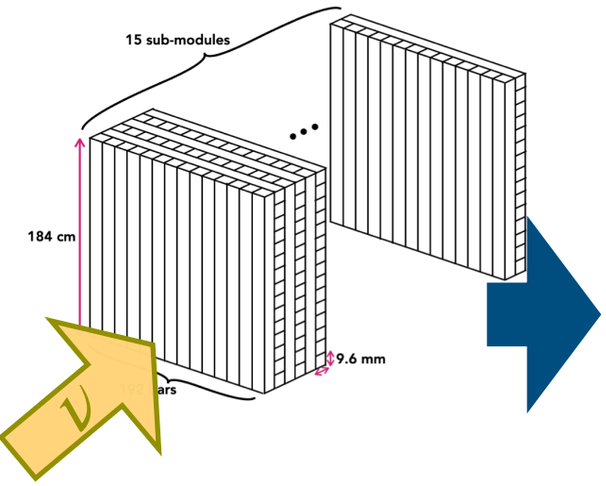
Achievements

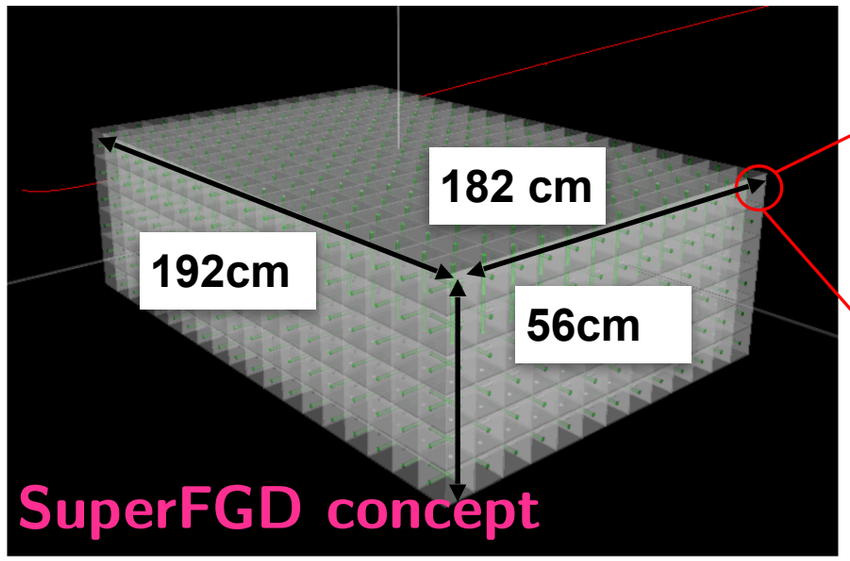
- Dramatic dead volume reduction.
- First experiment using resistive Micromegas.
- Same dE/dx performance and $> \times 2$ better momentum performance with <33% pads.

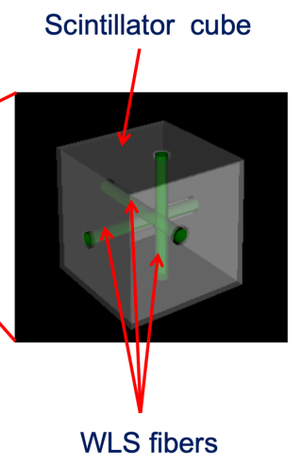
The SuperFGD neutrino target

A novel neutrino target concept for T2K in 2017

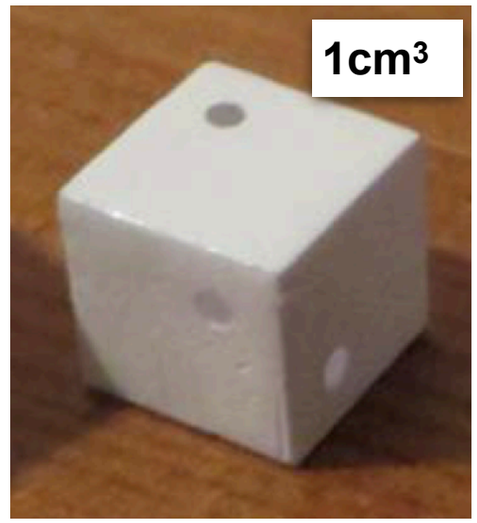
FGD concept







Picture of a single cube



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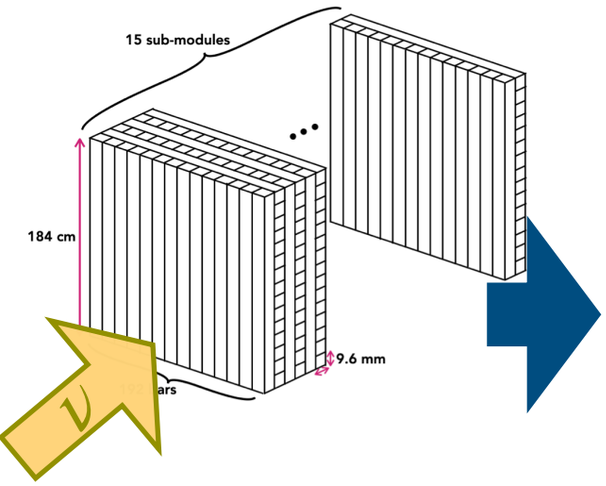
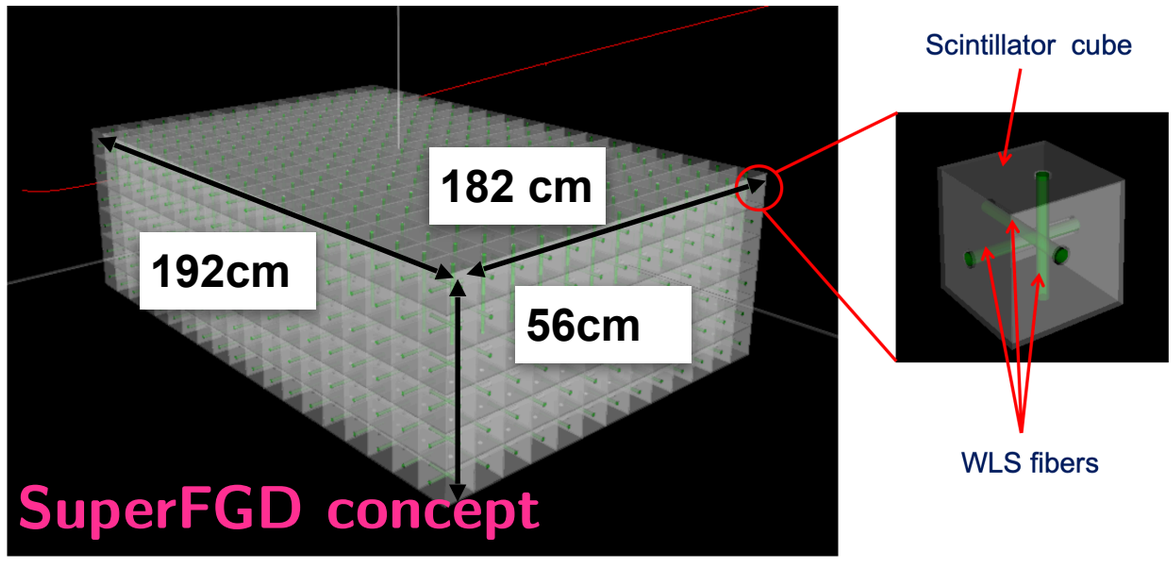
The SuperFGD neutrino target

A novel neutrino target concept for T2K in 2017

FGD concept





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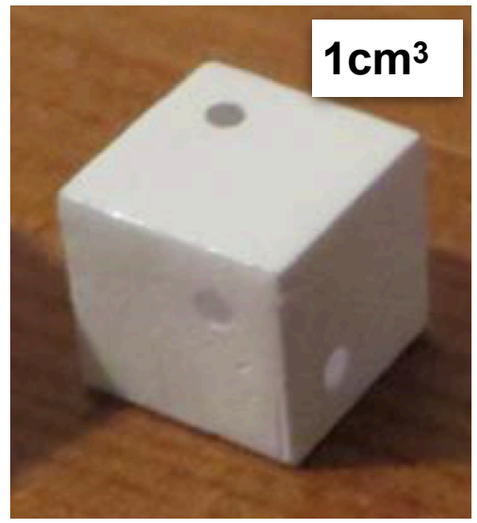
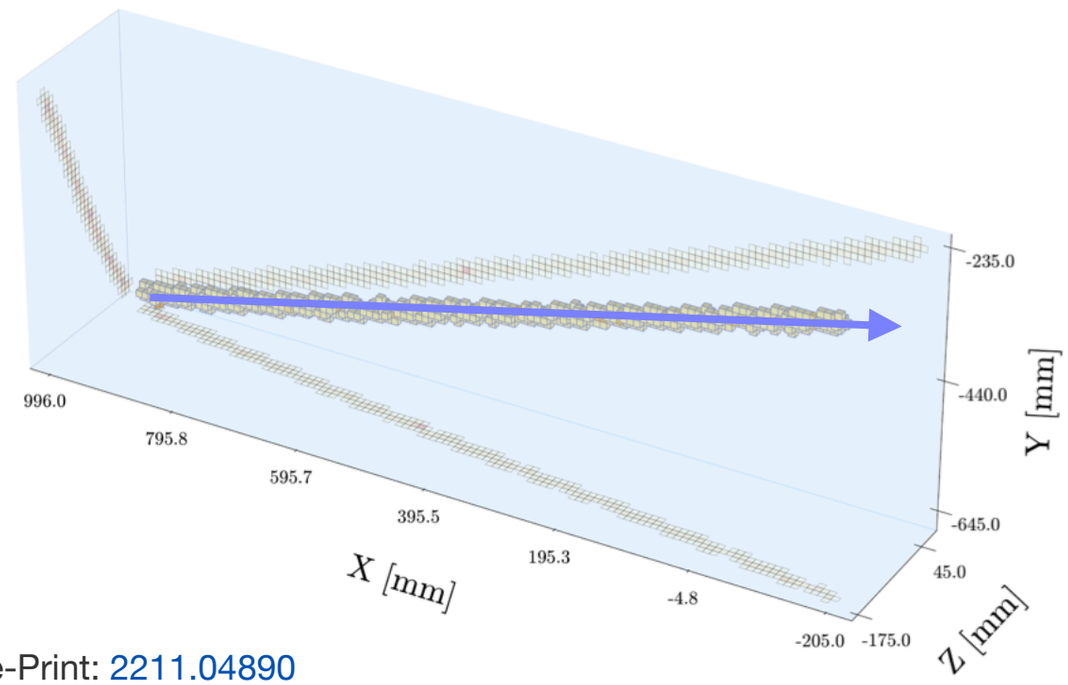
Picture of a single cube



Three 2D projected hits are merged into 3D tracks



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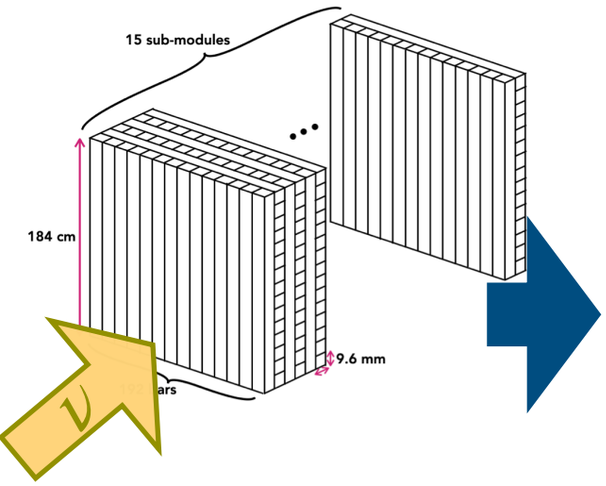
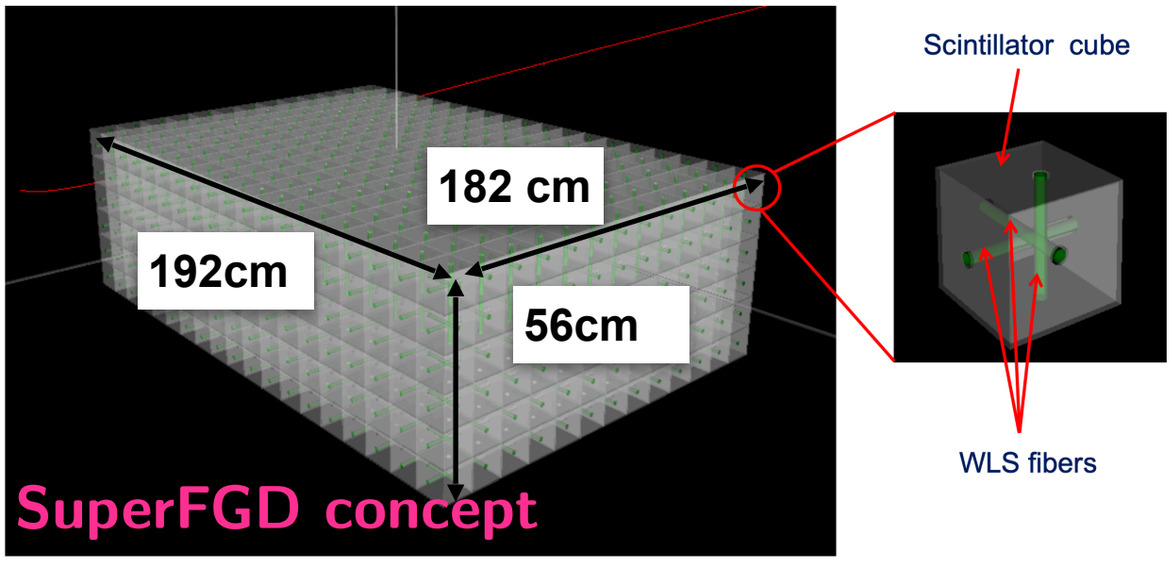
PRD 103 (2021) 3, 032005 • e-Print: 2009.00688

The SuperFGD neutrino target

A novel neutrino target concept for T2K in 2017

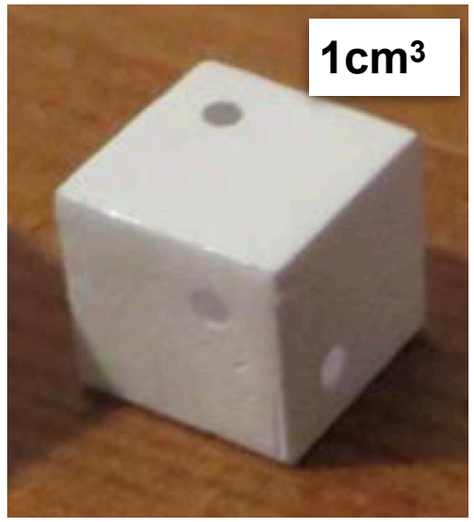
FGD concept

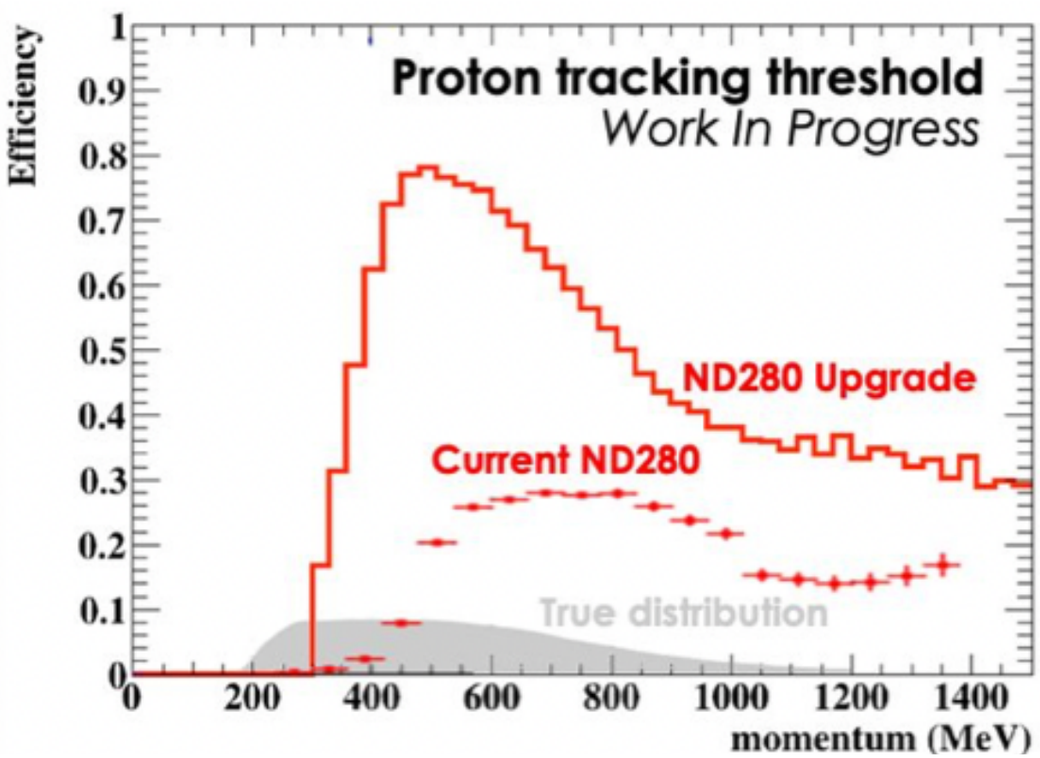




JINST 13 (2018) 02, P02006 • e-Print: 1707.01785

Picture of a single cube





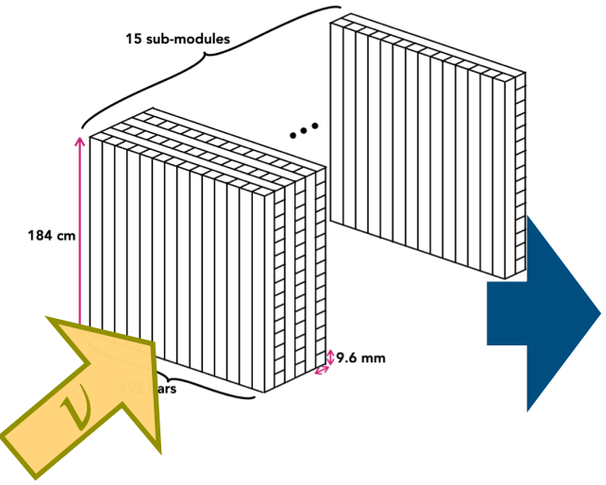
Benefits w.r.t ND280 FGDs

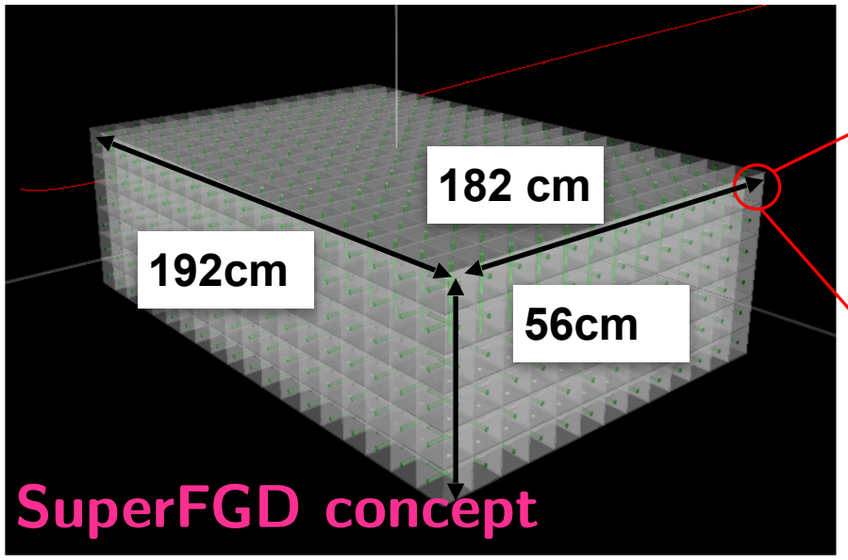
- Large target mass of 2 tons (same as FGD1+FGD2).
- Isotropic efficiency.
- Lower detection threshold.

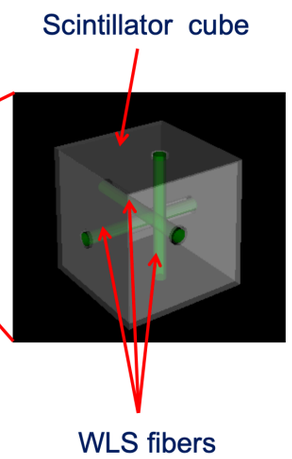
The SuperFGD neutrino target

A novel neutrino target concept for T2K in 2017

FGD concept







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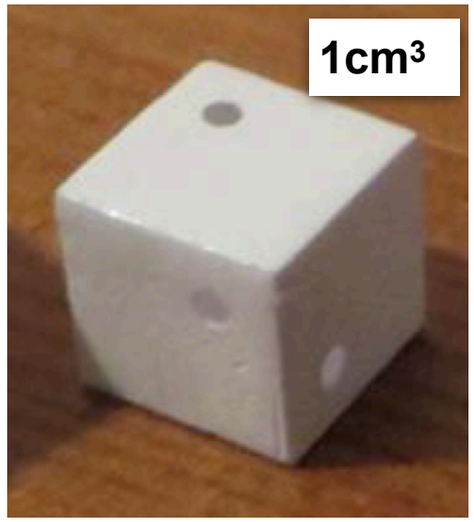
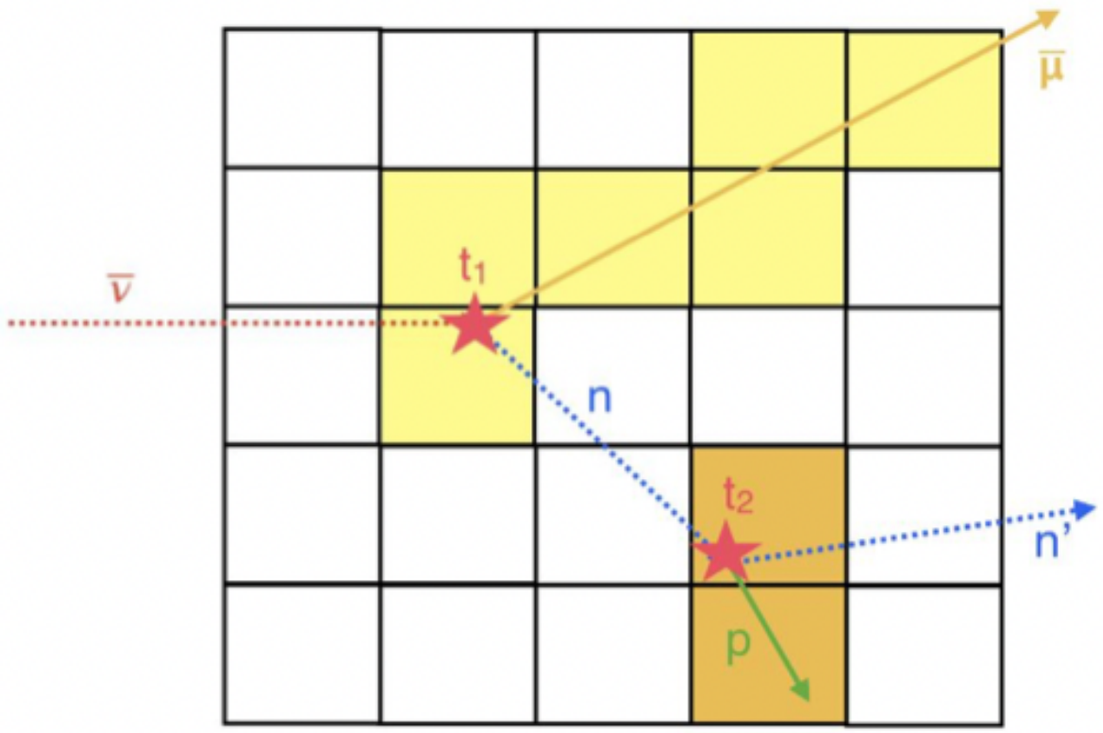
Picture of a single cube





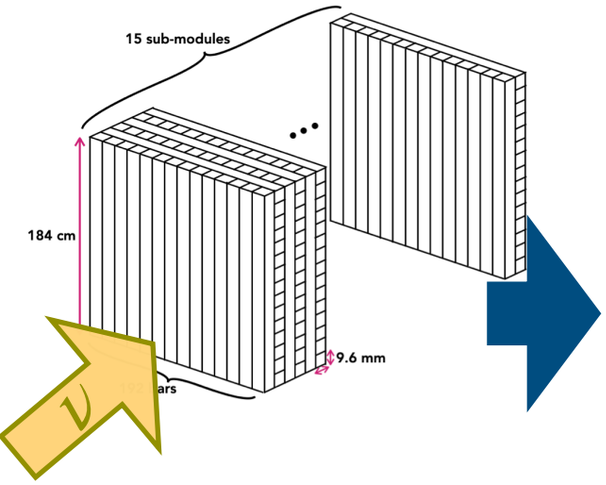
Benefits w.r.t ND280 FGDs

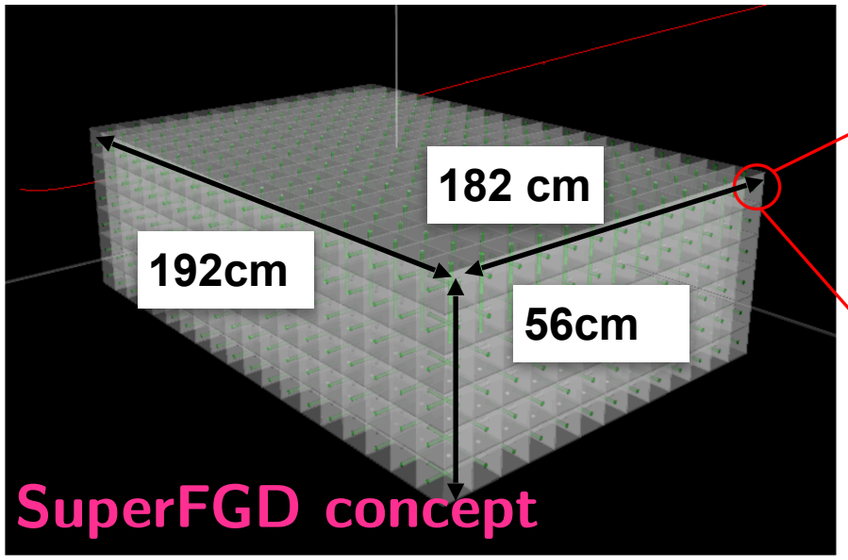
- Large target mass of 2 tons (same as FGD1+FGD2).
- Isotropic efficiency.
- Lower detection threshold.
- 3D granularity

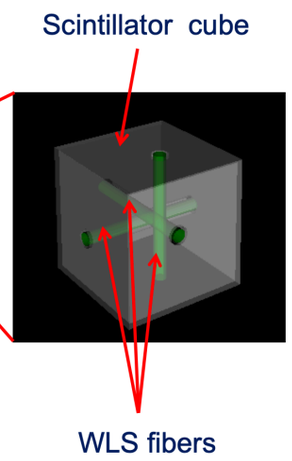
The SuperFGD neutrino target

A novel neutrino target concept for T2K in 2017

FGD concept







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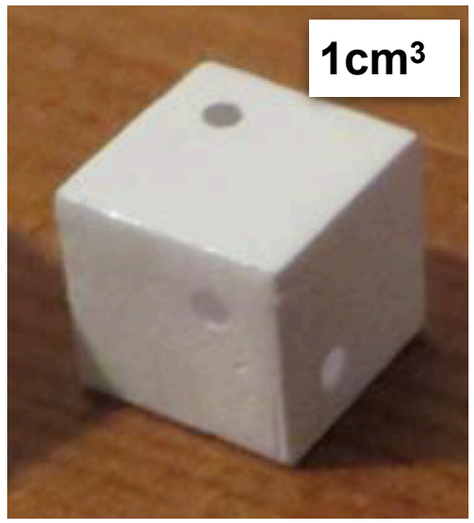
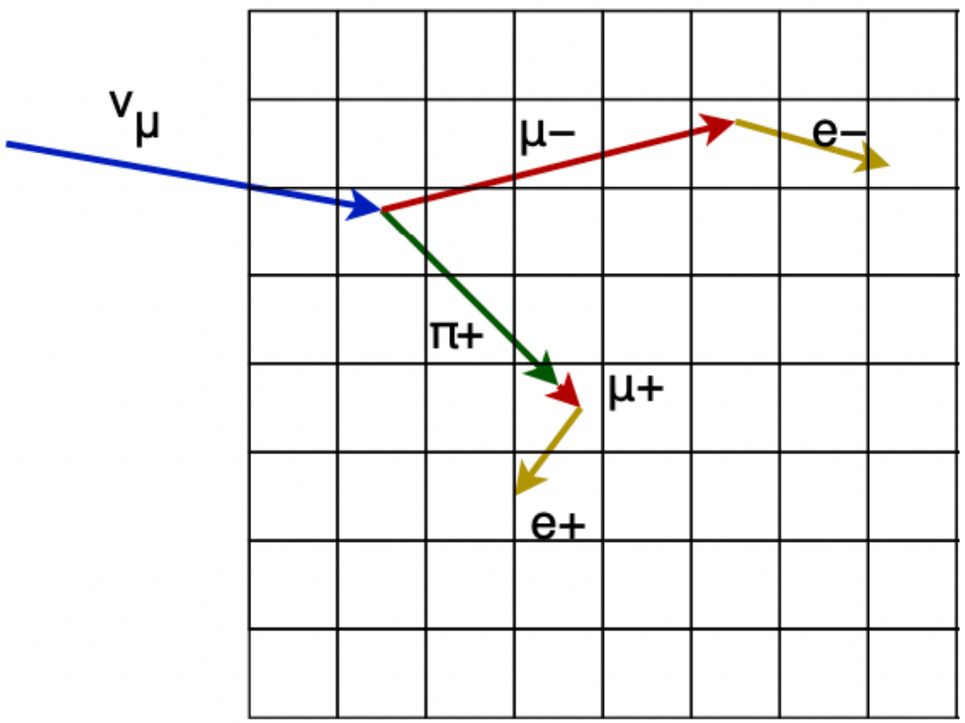
Picture of a single cube





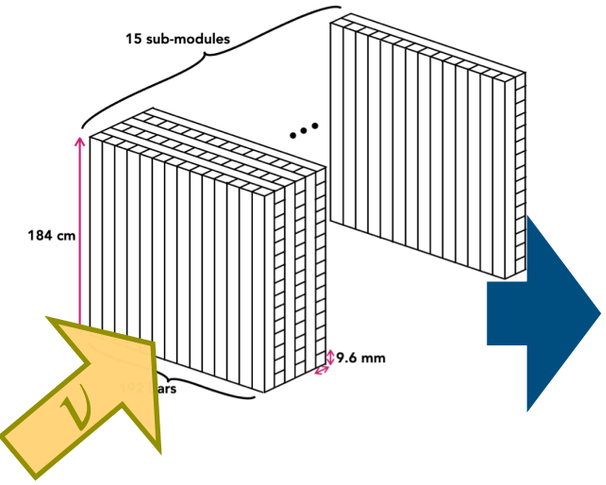
Benefits w.r.t ND280 FGDs

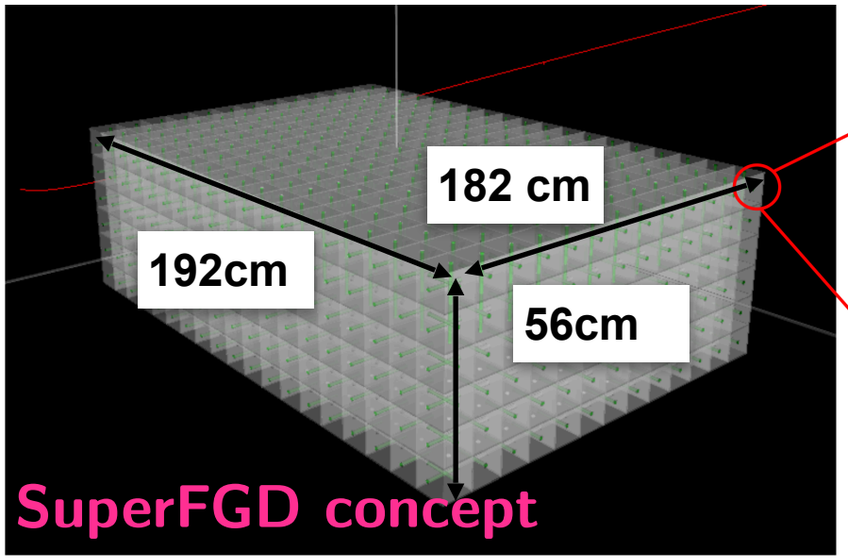
- Large target mass of 2 tons (same as FGD1+FGD2).
- Isotropic efficiency.
- Lower detection threshold.
- 3D granularity
- Excellent time resolution <1ns MIP.

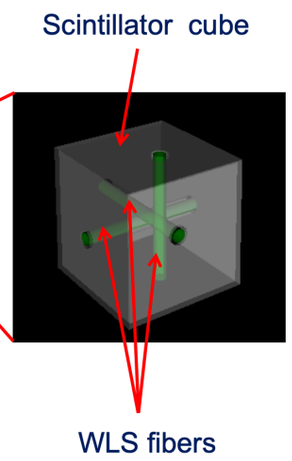
The SuperFGD neutrino target

A novel neutrino target concept for T2K in 2017

FGD concept

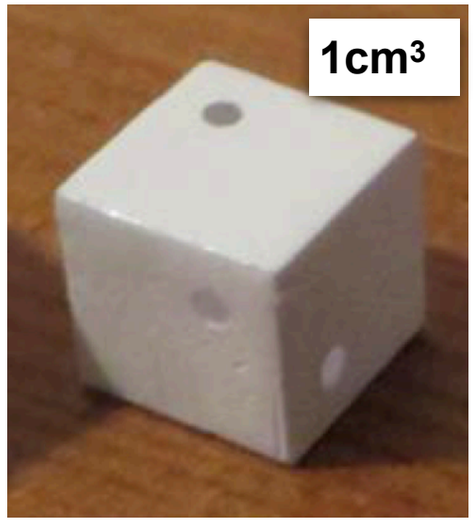


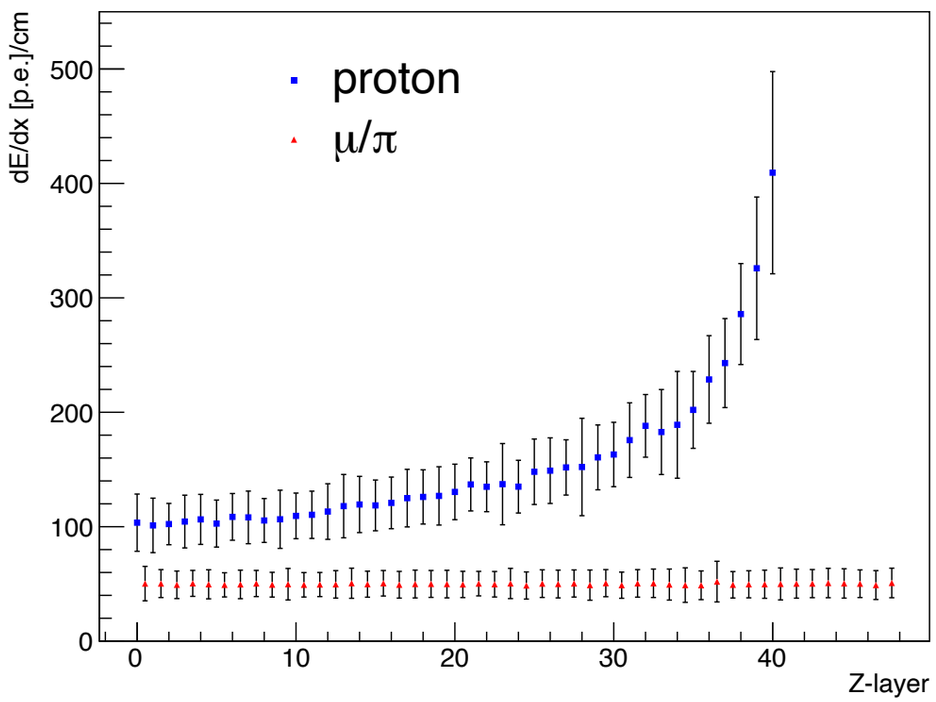




JINST 13 (2018) 02, P02006 • e-Print: 1707.01785

Picture of a single cube



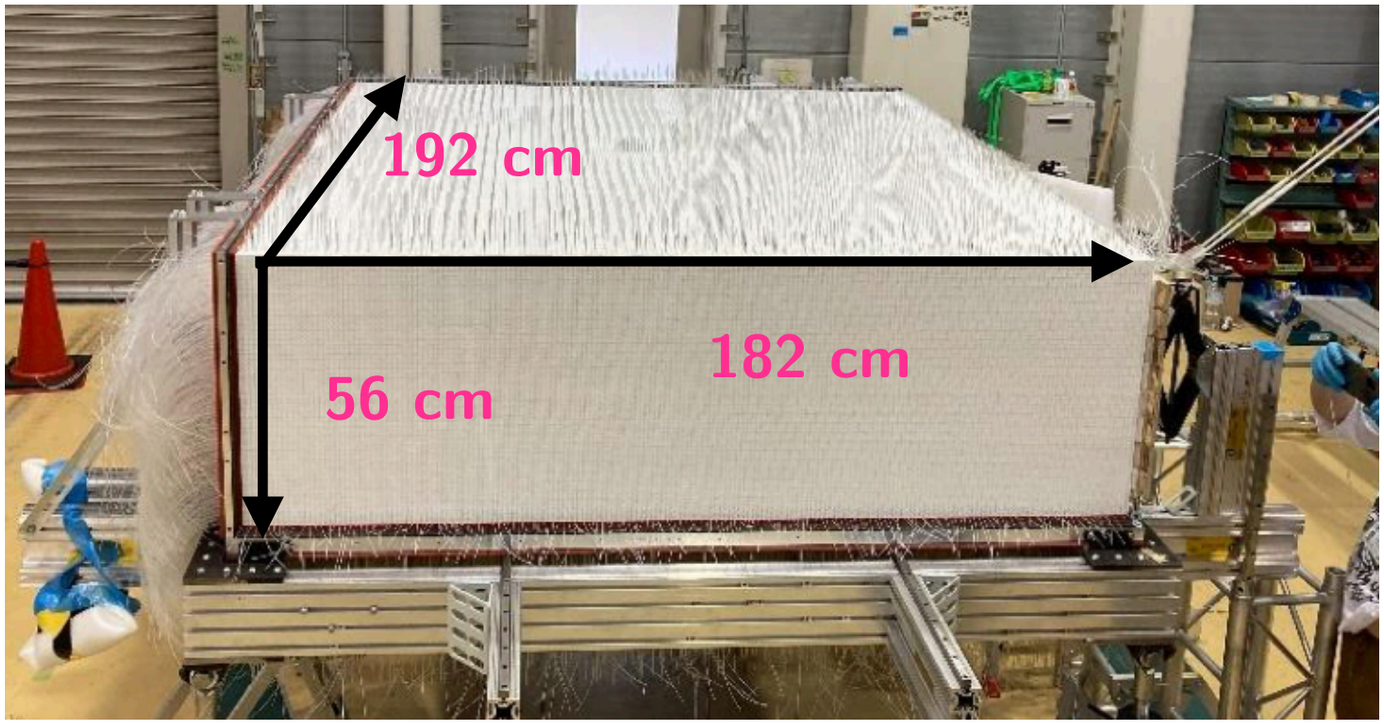


Benefits w.r.t ND280 FGDs

- Large target mass of 2 tons (same as FGD1+FGD2).
- Isotropic efficiency.
- Lower detection threshold.
- 3D granularity
- Excellent time resolution <1ns MIP.
- Very enhanced PID, e.g. proton bragg peak ID, e/γ separation

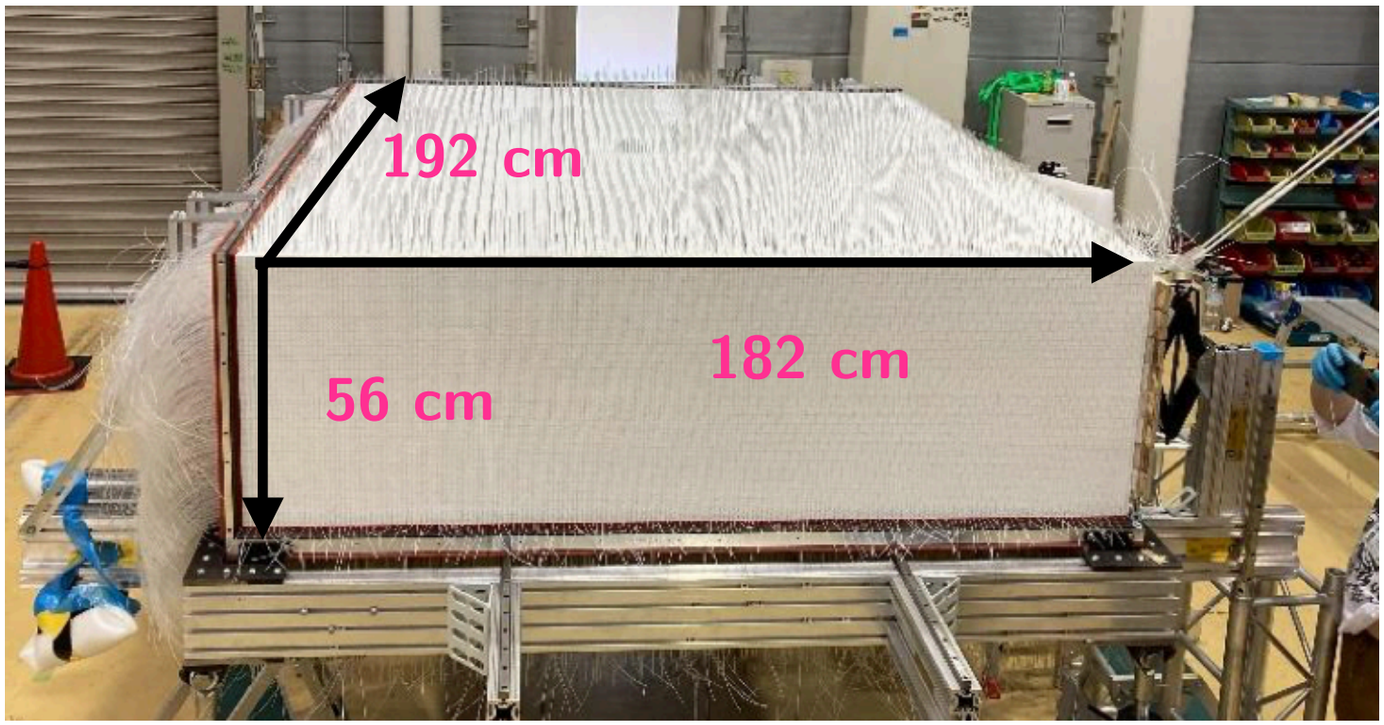
The SuperFGD neutrino target

Before closing the box

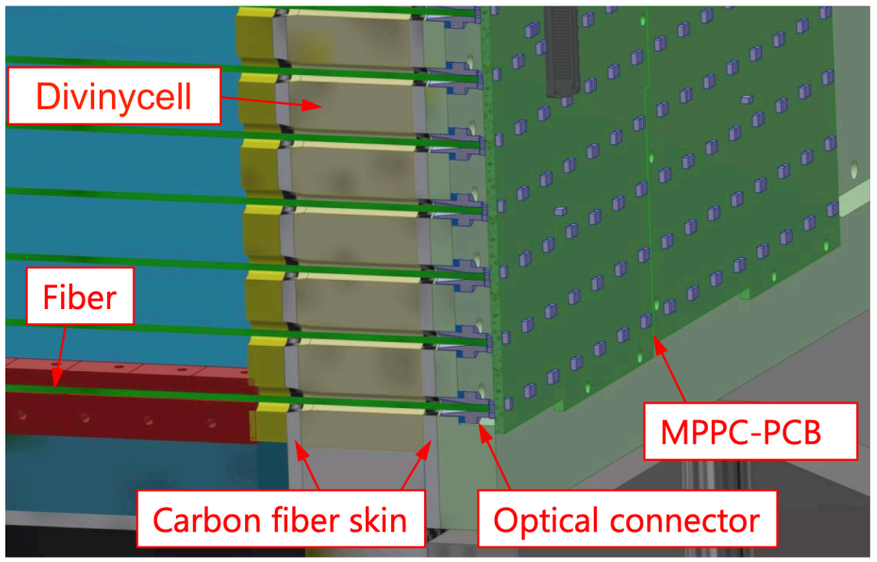


The SuperFGD neutrino target

Before closing the box



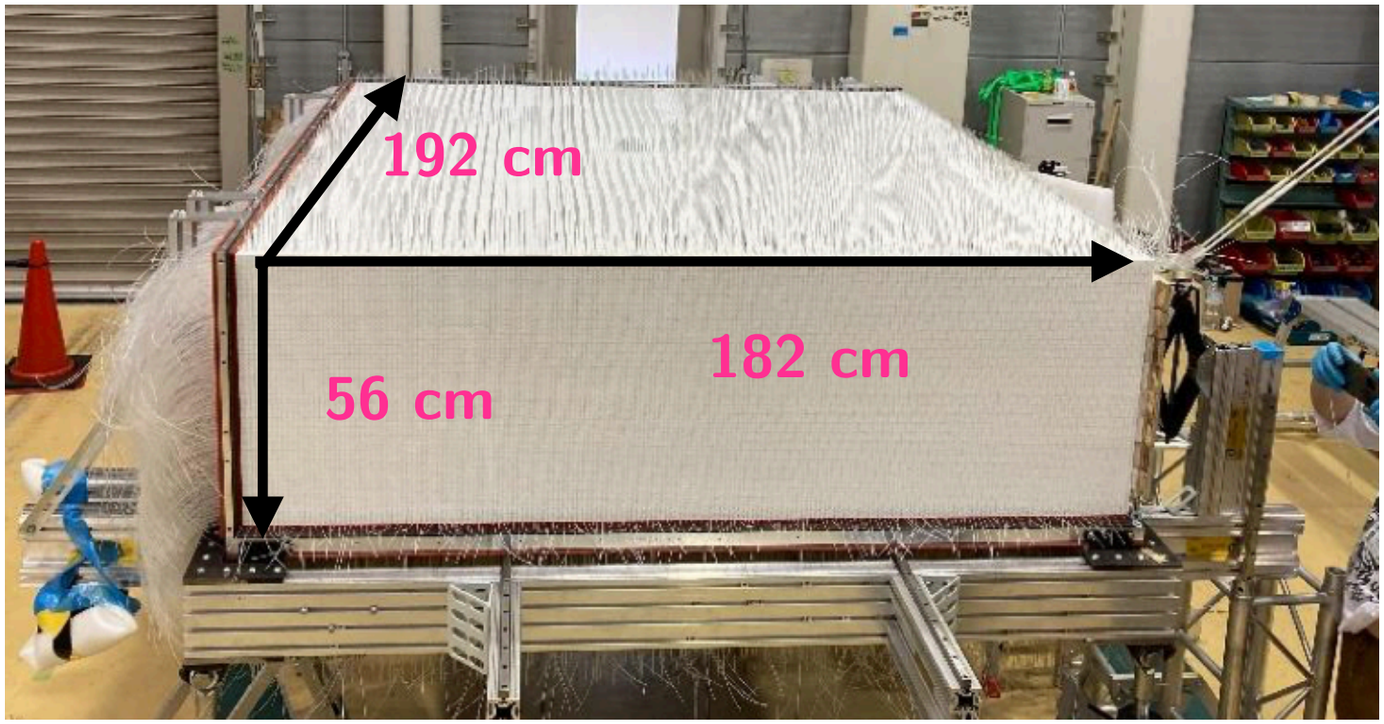
Box concept



- 120k holes of 3mm (50µm tolerance).
- Integrated 8x8 MPPC readout interface.
- 4cm thickness, sag of 0.5cm under 2 tons.

The SuperFGD neutrino target

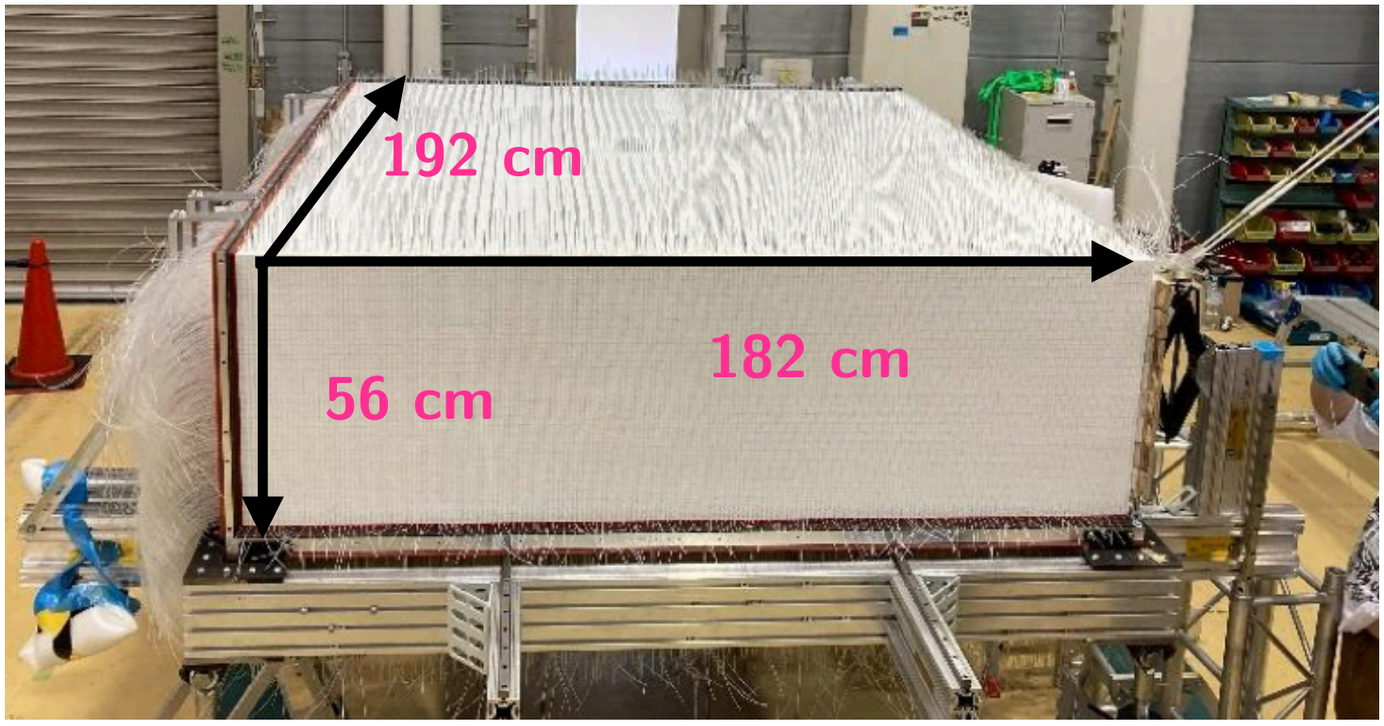
Before closing the box



Box in assembly basket

The SuperFGD neutrino target

Before closing the box

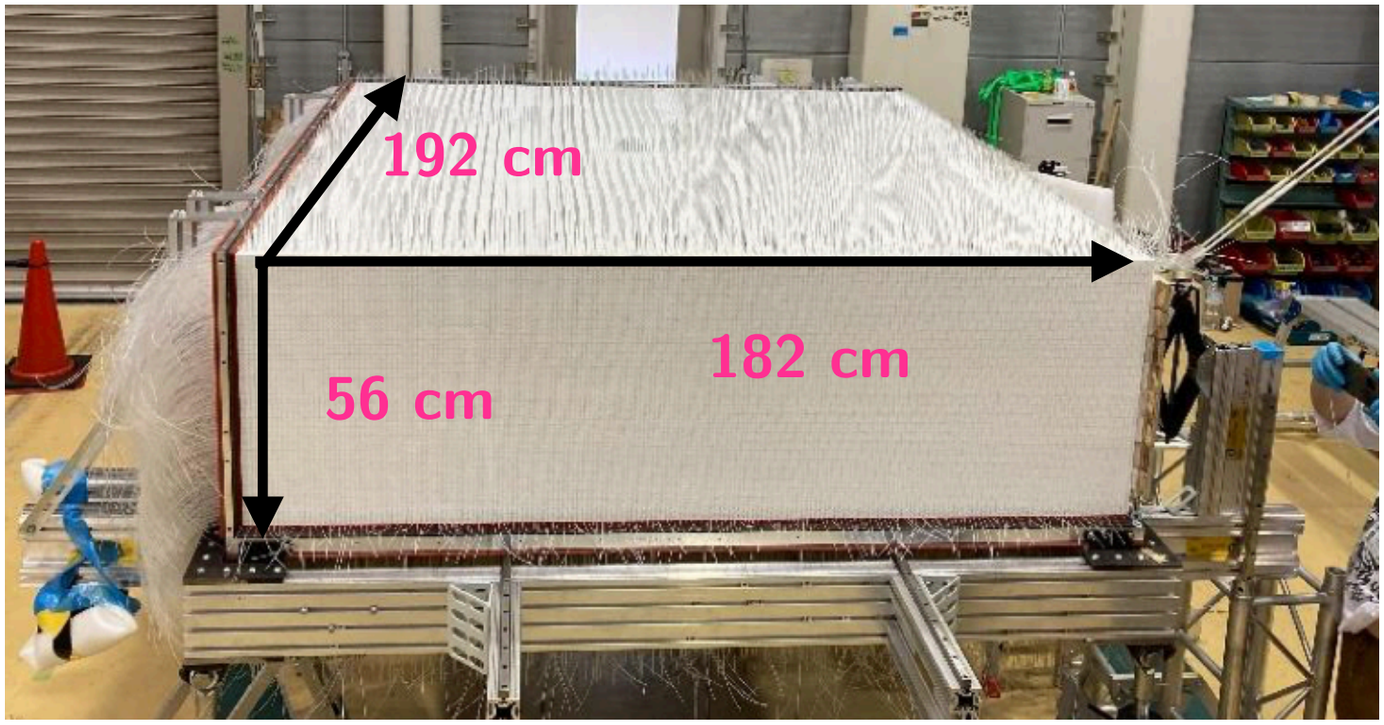


Box in assembly basket

WLS Fiber insertion

The SuperFGD neutrino target

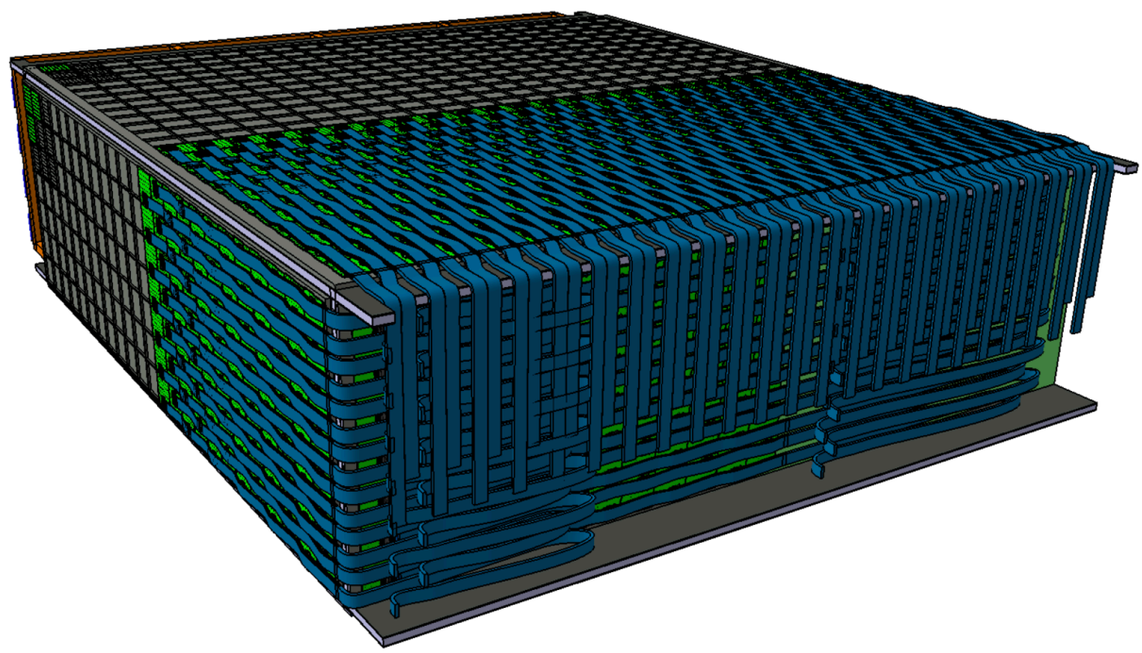
Before closing the box



Box in assembly basket

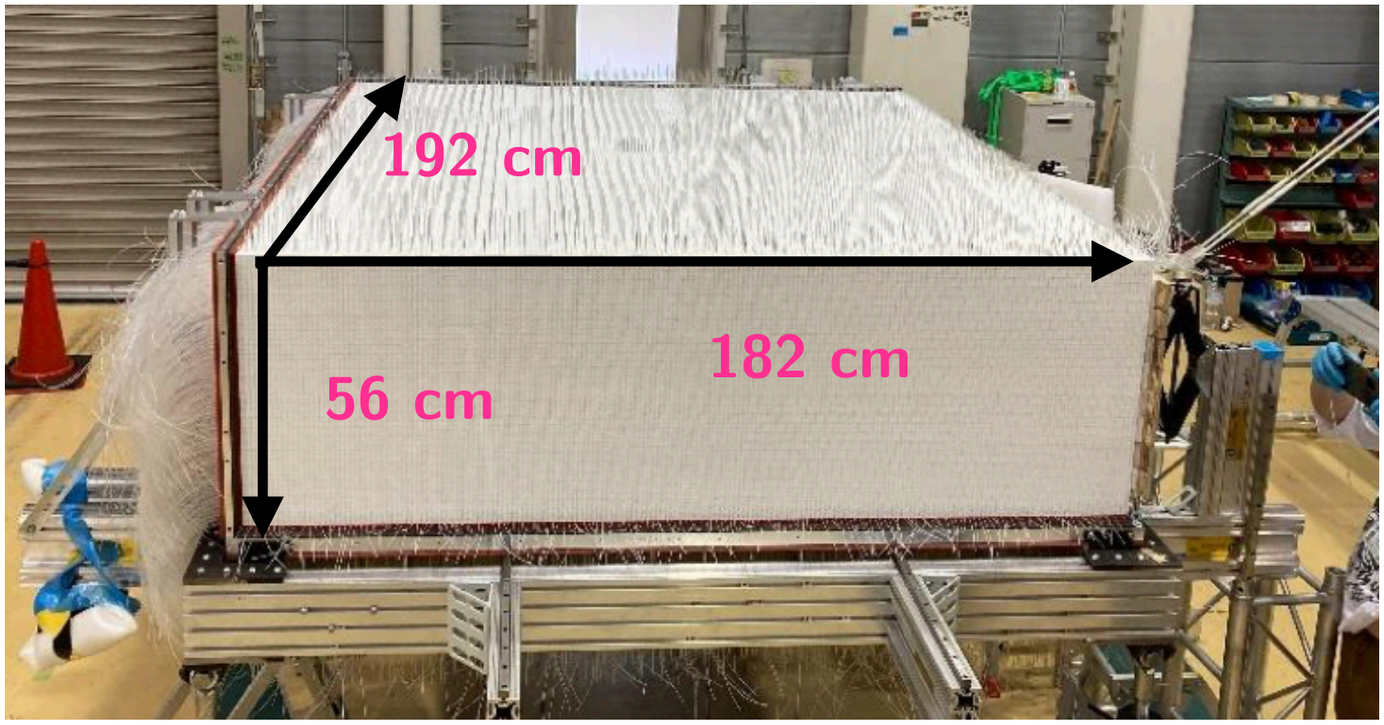
WLS Fiber insertion

Cabling



The SuperFGD neutrino target

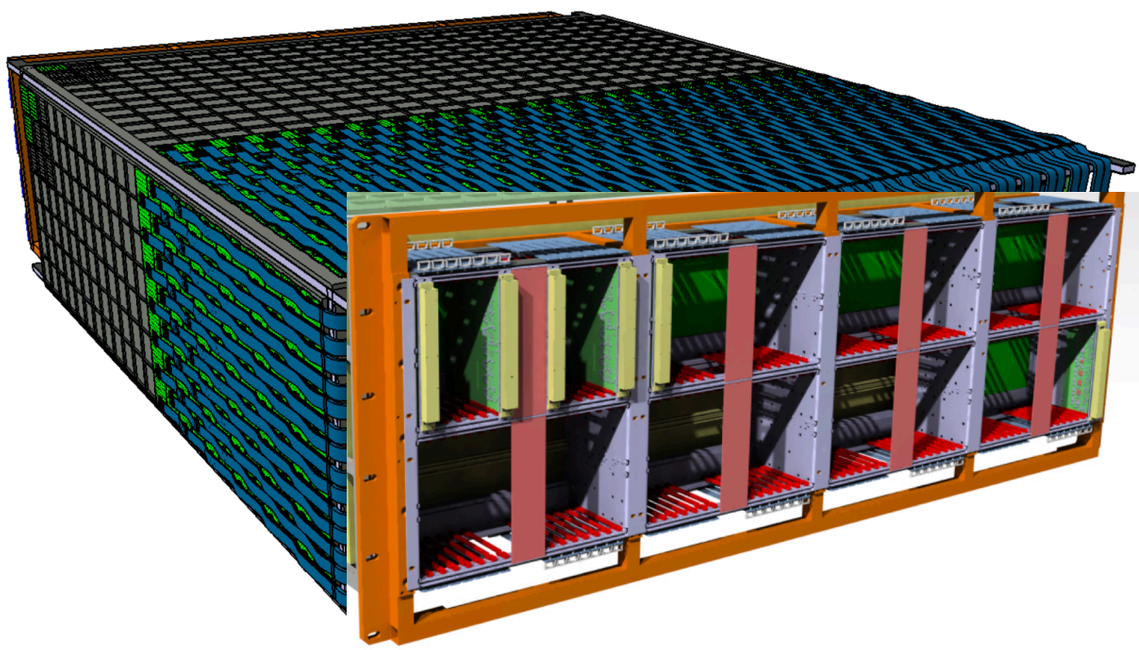
Before closing the box



Box in assembly basket

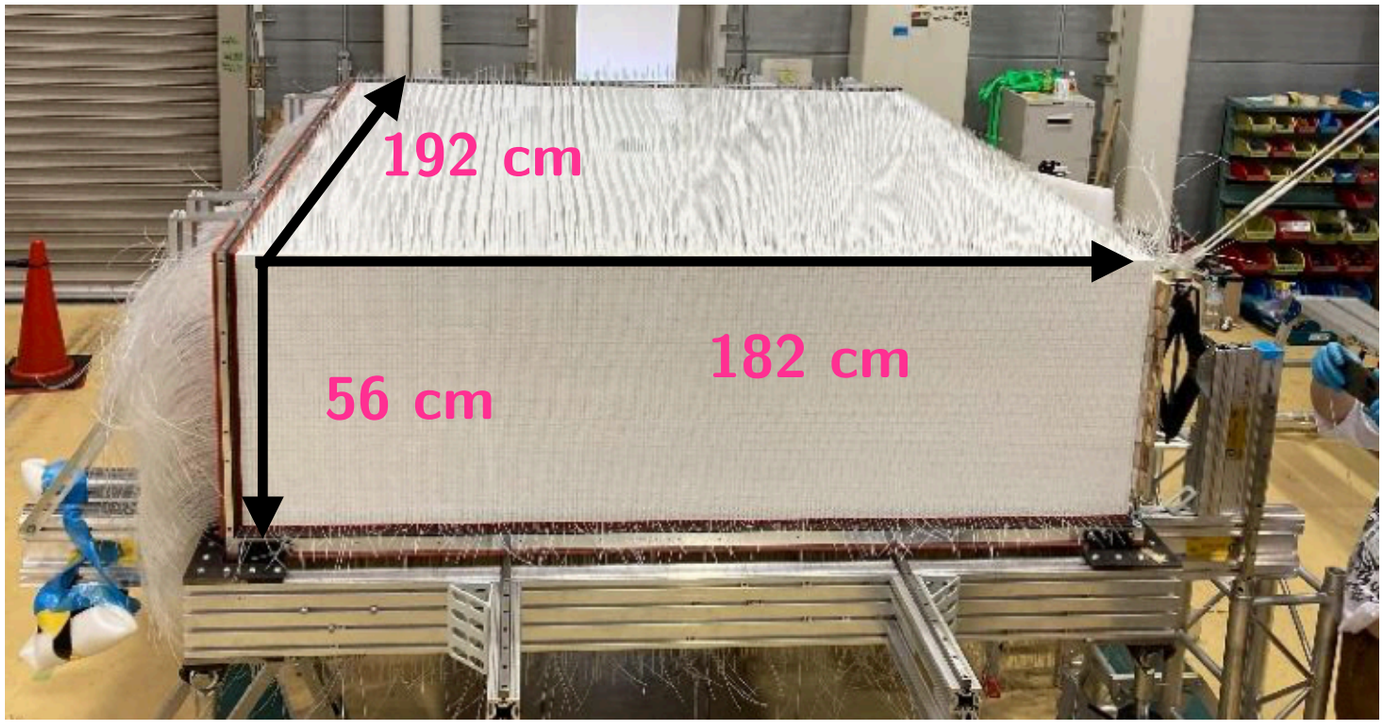
WLS Fiber insertion

Electronics



The SuperFGD neutrino target

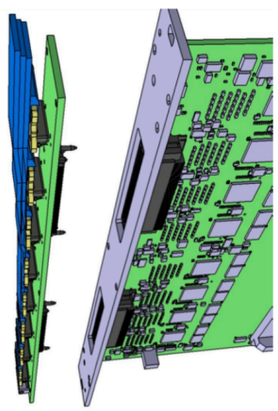
Before closing the box

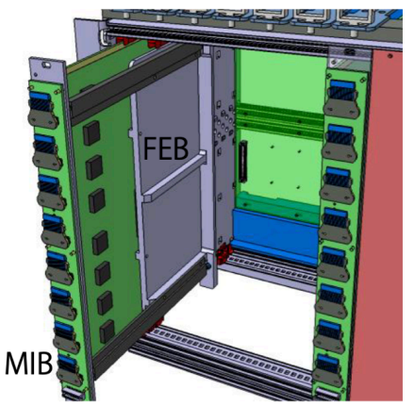


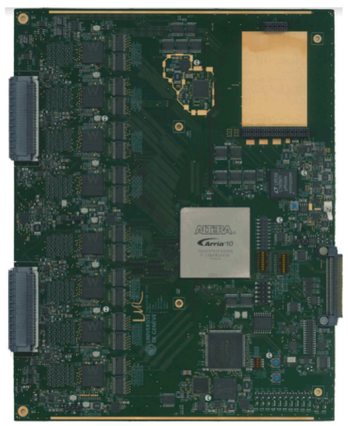
Box in assembly basket

WLS Fiber insertion

Electronics



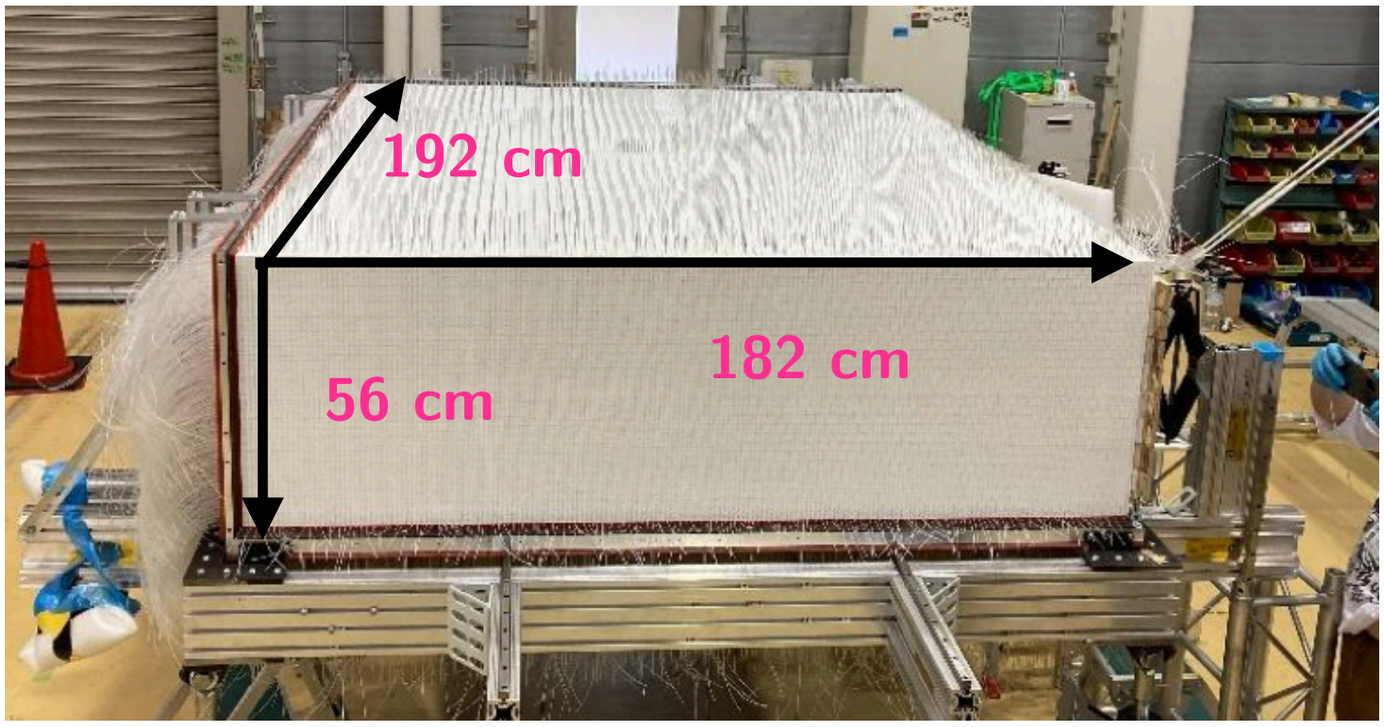




- High dynamic range (HG, LG, ToT).
- Sampling rate 400Mhz.

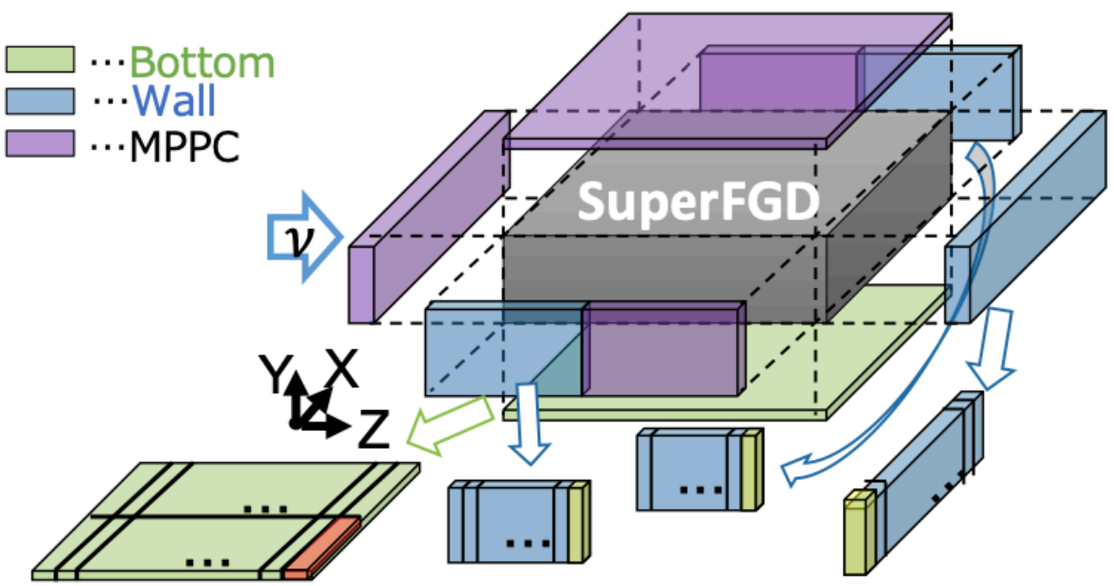
The SuperFGD neutrino target

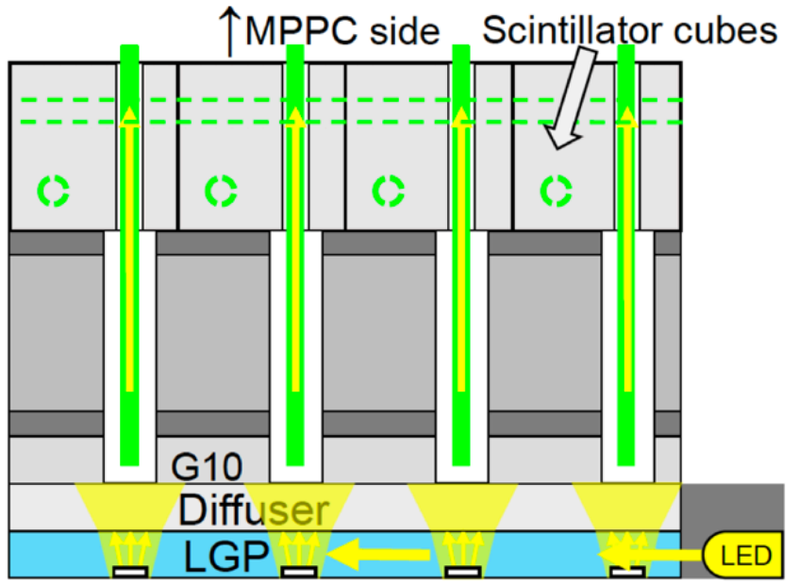
Before closing the box

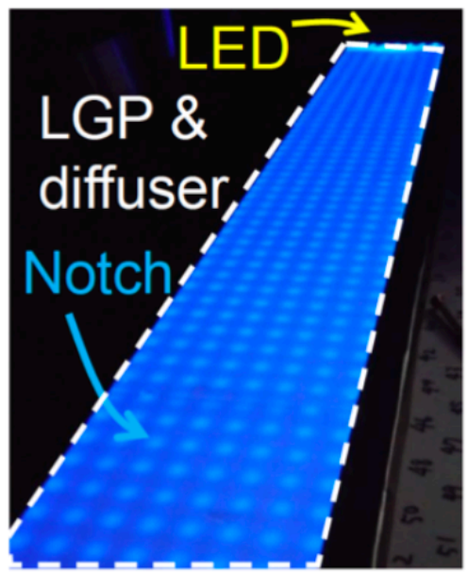


Box in assembly basket

Calibration system in opposite fiber end

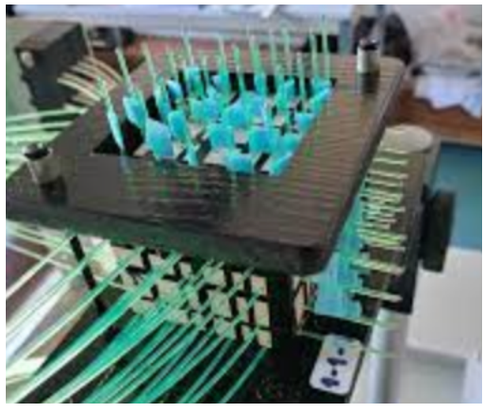




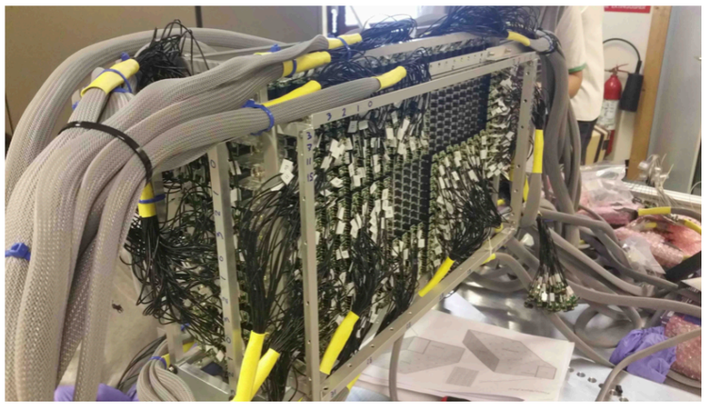


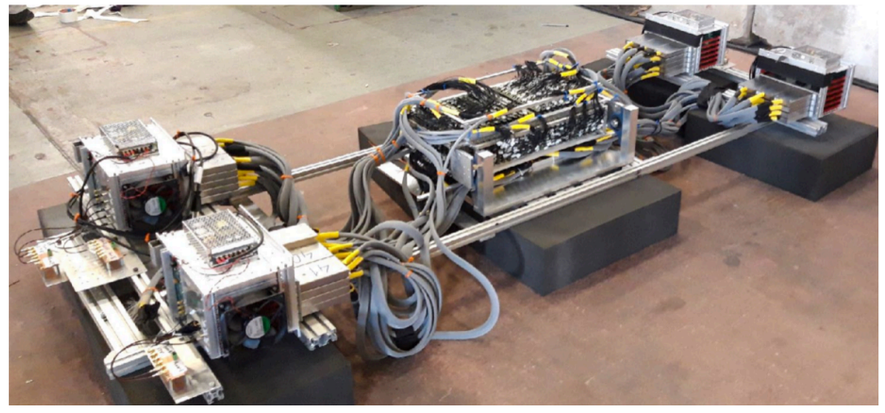
SuperFGD prototype tests

The 5x5x5 cubes prototype



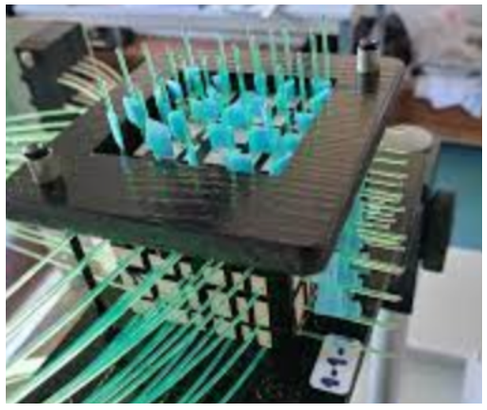
The 24x8x48 cubes prototype



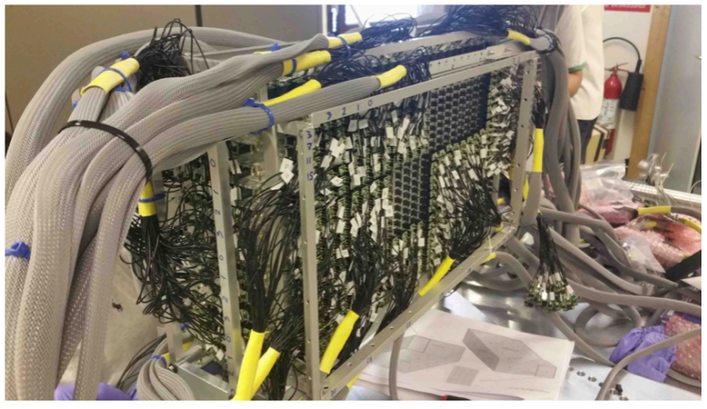


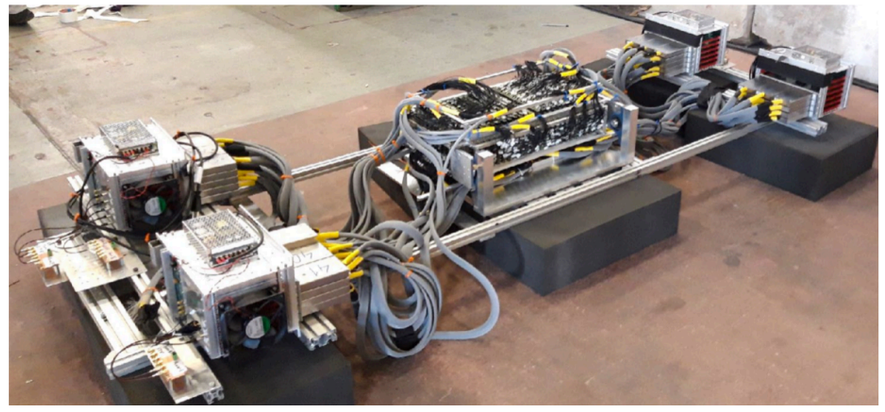
SuperFGD prototype tests

The 5x5x5 cubes prototype



The 24x8x48 cubes prototype





SuperFGD R&D and characterization

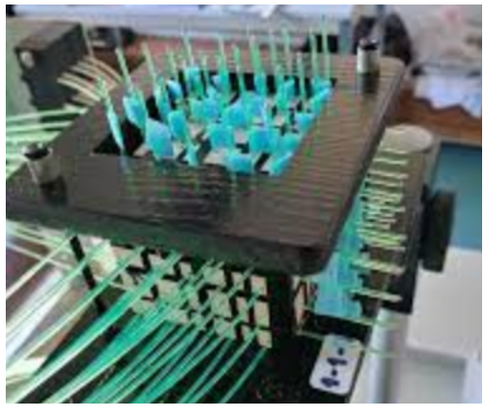
- 5x5x5 prototype, 2018, tested with cosmic

Proof-of-concept

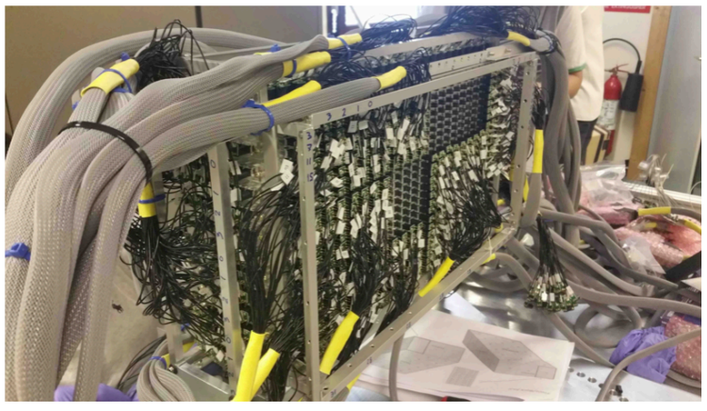
NIMA 923 (2019) 134-138 • e-Print: 1808.08829

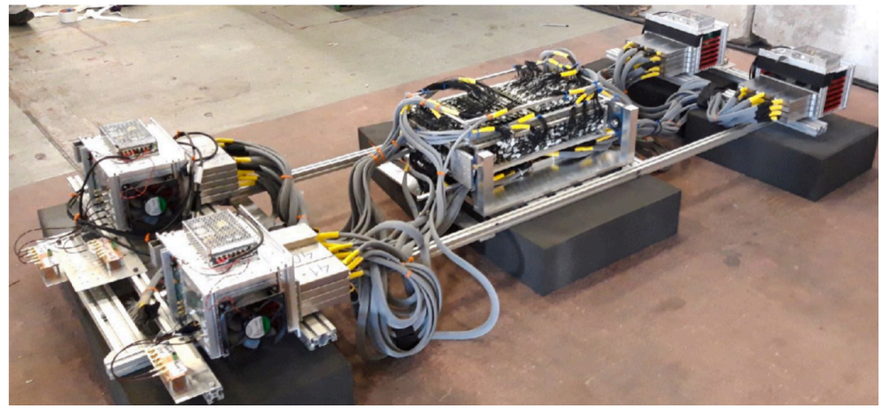
SuperFGD prototype tests

The 5x5x5 cubes prototype



The 24x8x48 cubes prototype





SuperFGD R&D and characterization

- 5x5x5 prototype, 2018, tested with cosmic

Proof-of-concept

NIMA 923 (2019) 134-138 • e-Print: 1808.08829

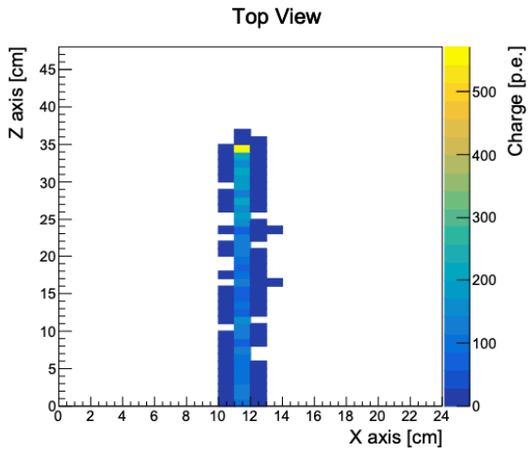
- 24x8x48 prototype, 2018, beam test @CERN

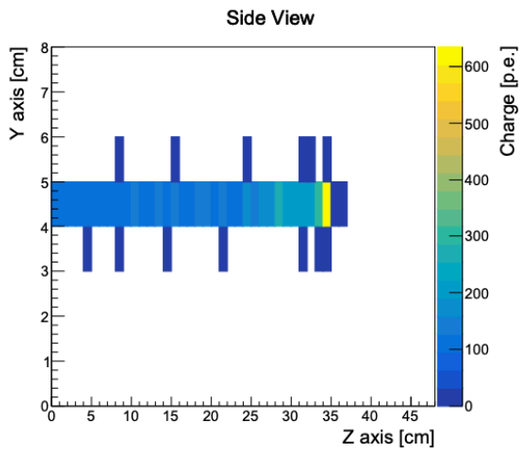
Demonstration and characterization

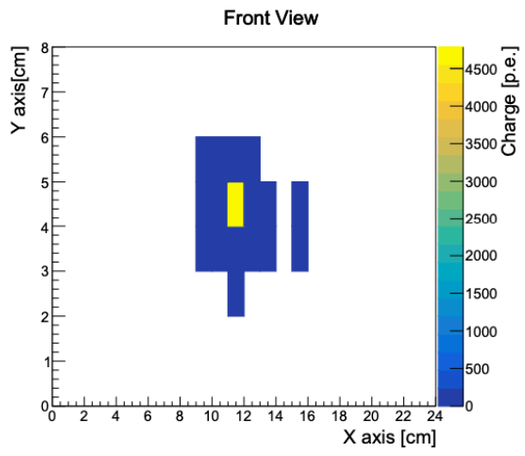
JINST 15 (2020) 12, P12003 • e-Print: 2008.08861

timing studies

JINST 18 (2023) 01, P01012 • e-Print: 2206.10507

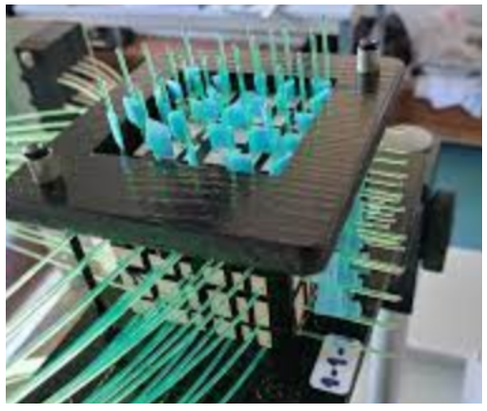




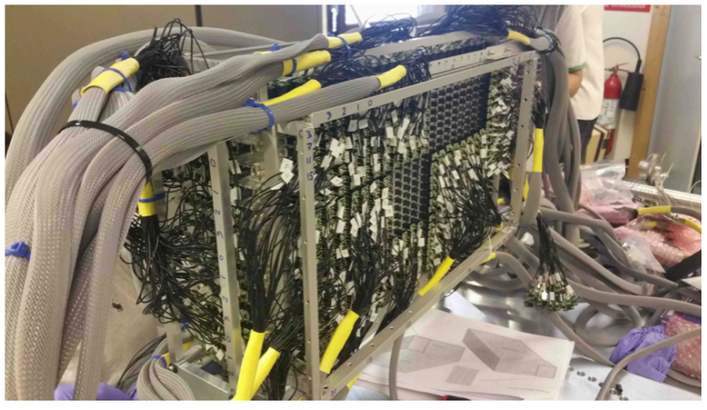


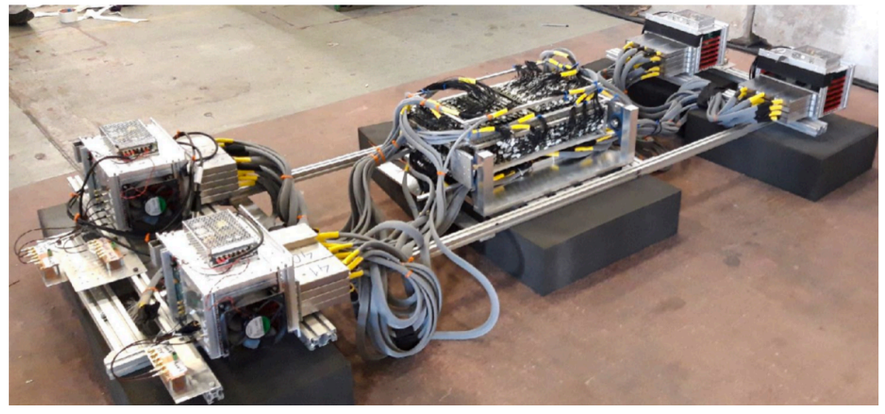
SuperFGD prototype tests

The 5x5x5 cubes prototype



The 24x8x48 cubes prototype





SuperFGD R&D and characterization

- 5x5x5 prototype, 2018, tested with cosmic

Proof-of-concept

NIMA 923 (2019) 134-138 • e-Print: 1808.08829

- 24x8x48 prototype, 2018, beam test @CERN

Demonstration and characterization

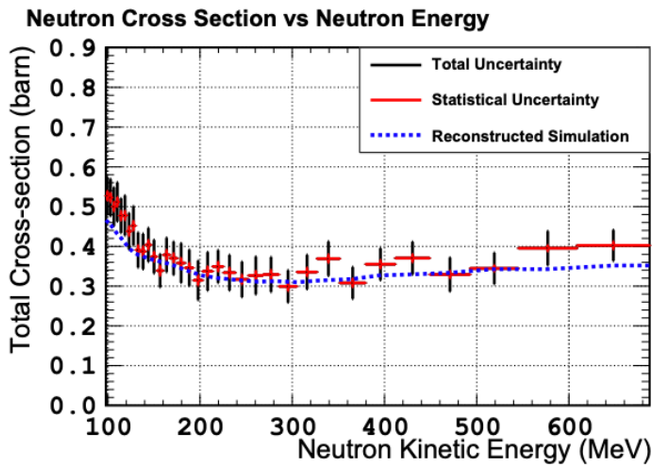
JINST 15 (2020) 12, P12003 • e-Print: 2008.08861

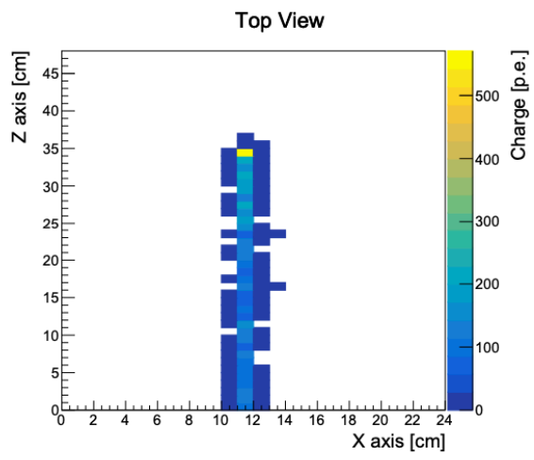
timing studies

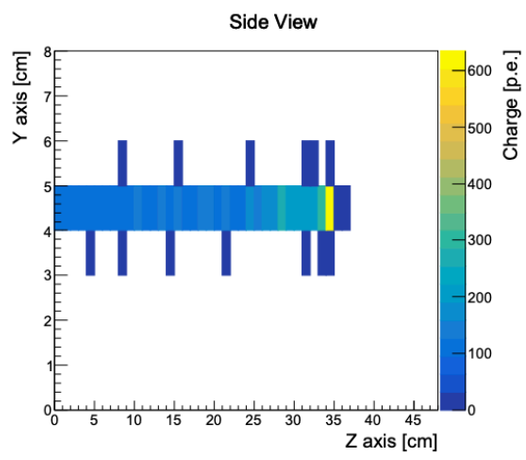
JINST 18 (2023) 01, P01012 • e-Print: 2206.10507

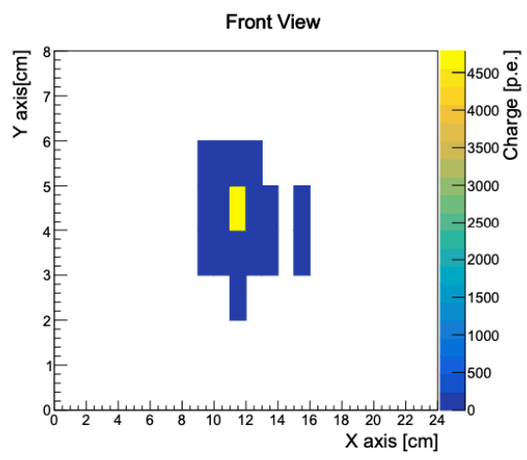
Demonstration of neutron kinematics & first physics measurement

- e-Print: 2207.02685, PLB 840 137843





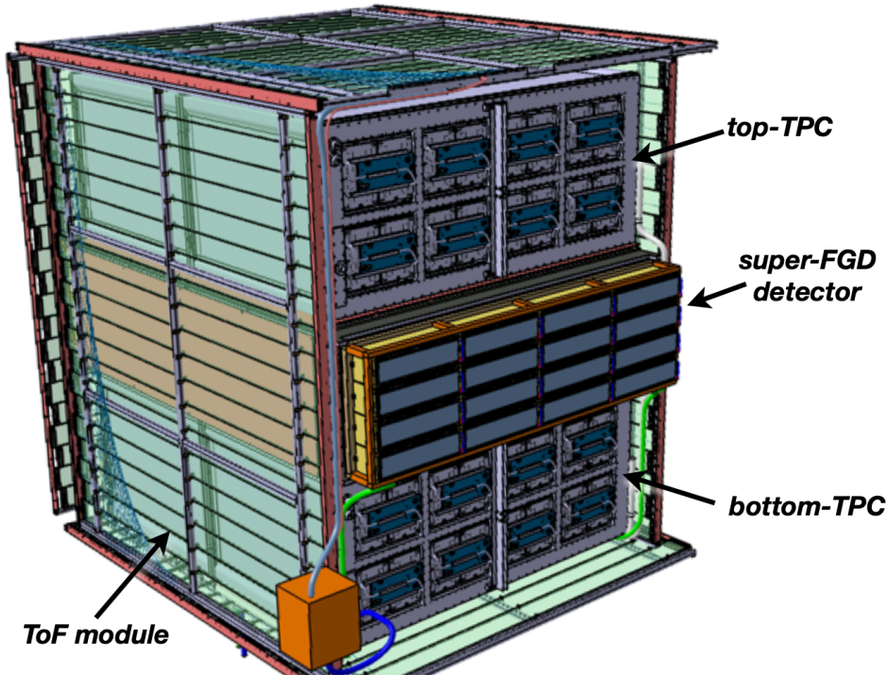




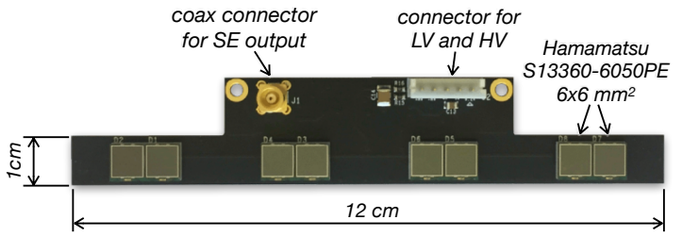
- 24x8x48 prototype, 2019 & 2020 beam test @LANL

The ToF panels

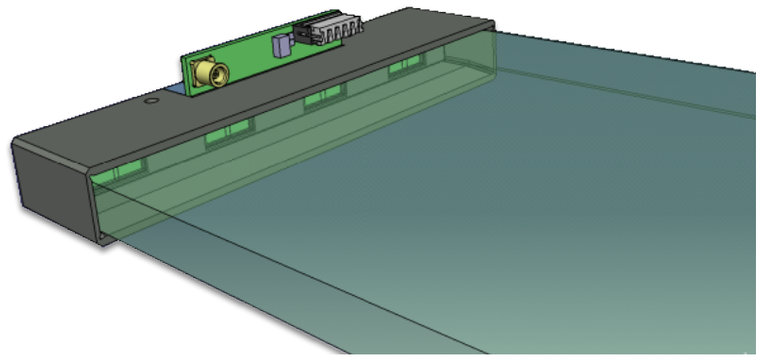
Six 2x2 m^2 ToF panels envolve TPCs & SuperFGD



Planes made of scintillator bars



JINST 17 (2022) P01016 • e-Print: 2109.03078



The ToF panels

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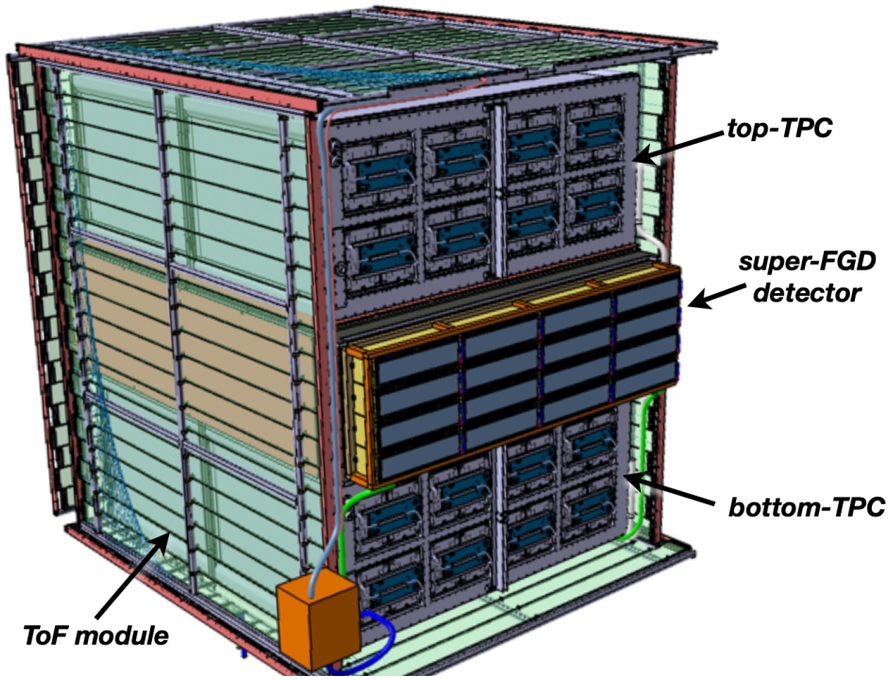

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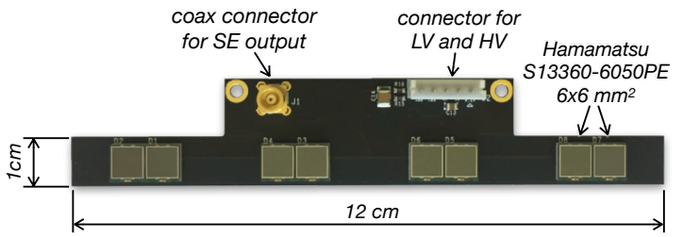
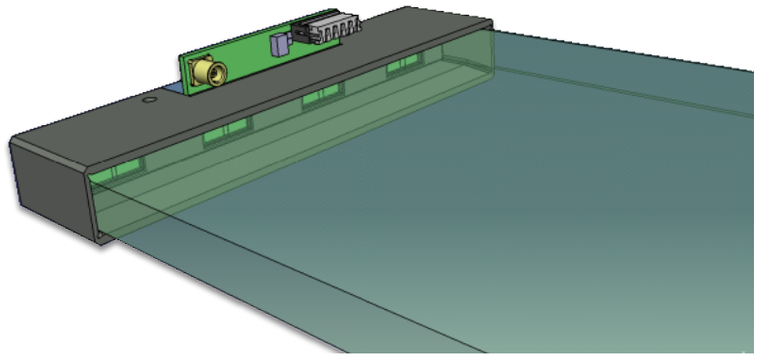


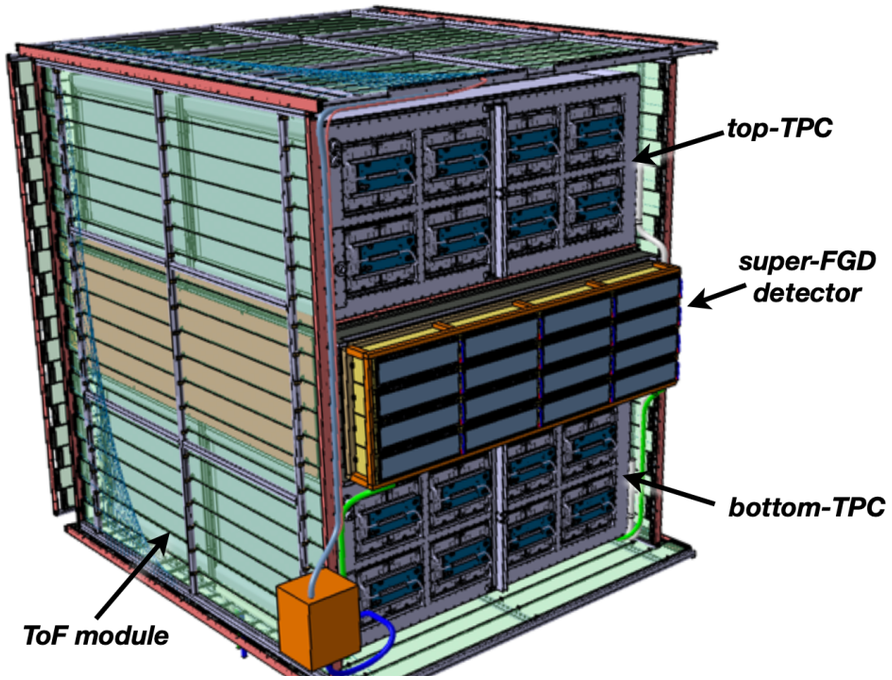
JINST 17 (2022) P01016 • e-Print: 2109.03078



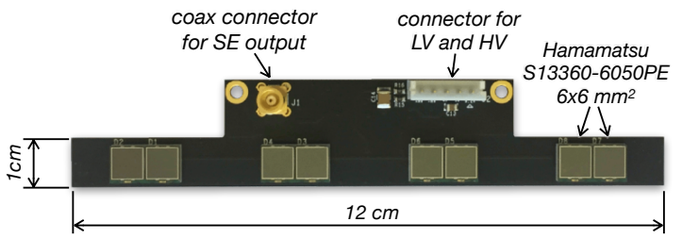
ToF setup at CERN

The ToF panels

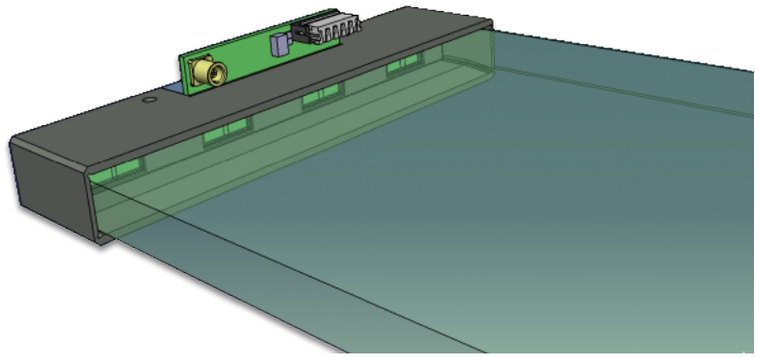
Six 2x2 m^2 ToF panels envolve TPCs & SuperFGD



Planes made of scintillator bars

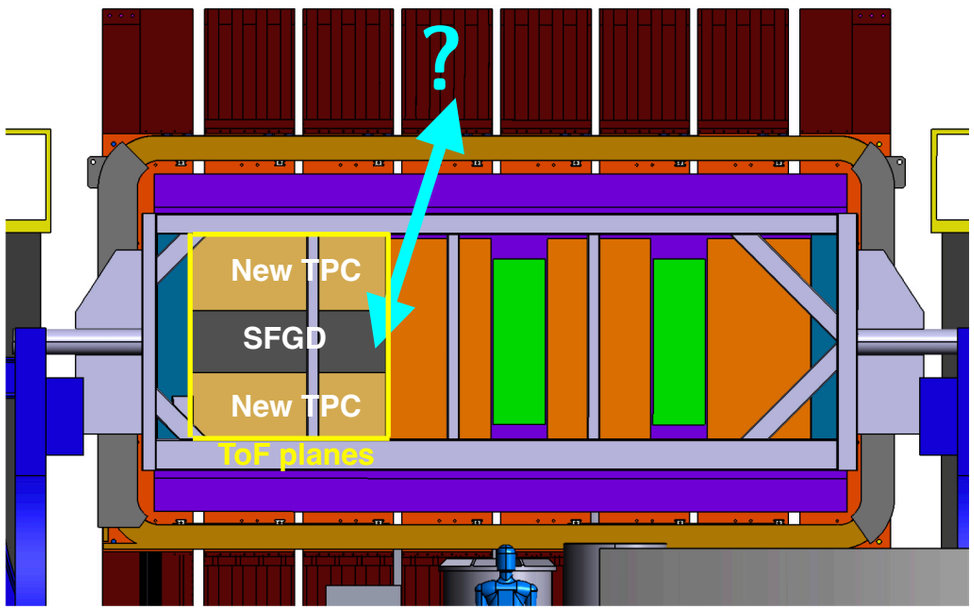


JINST 17 (2022) P01016 • e-Print: 2109.03078



ToF setup at CERN

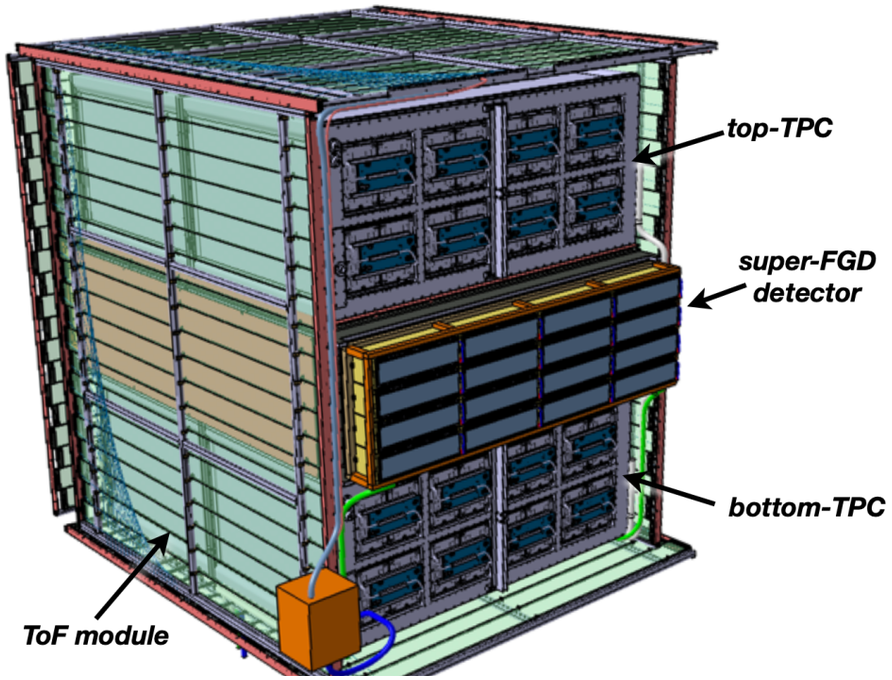
Goal



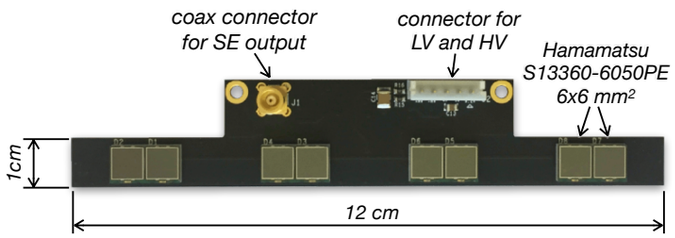
- Discriminate particle sense of motion

The ToF panels

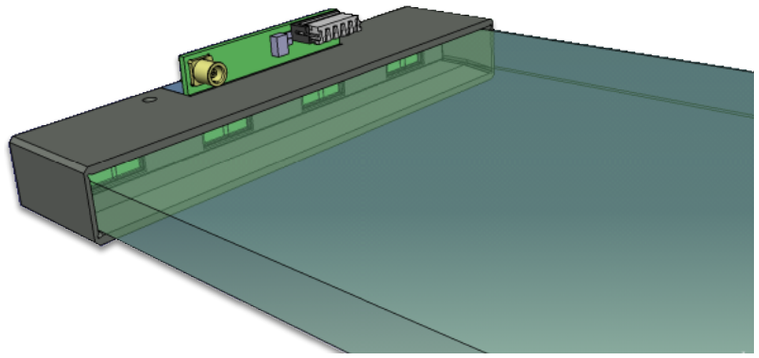
Six 2x2 m^2 ToF panels envolve TPCs & SuperFGD



Planes made of scintillator bars

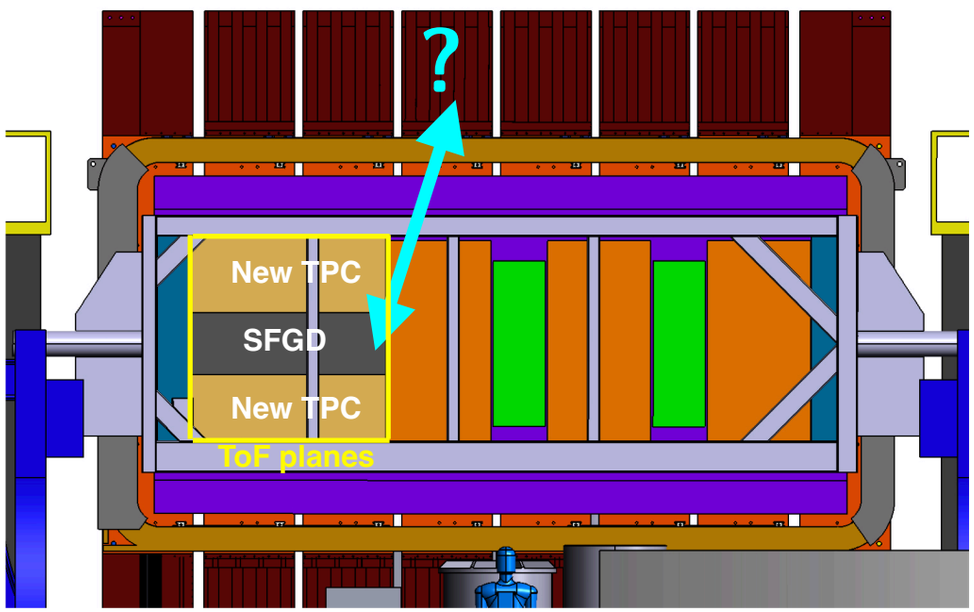


JINST 17 (2022) P01016 • e-Print: 2109.03078



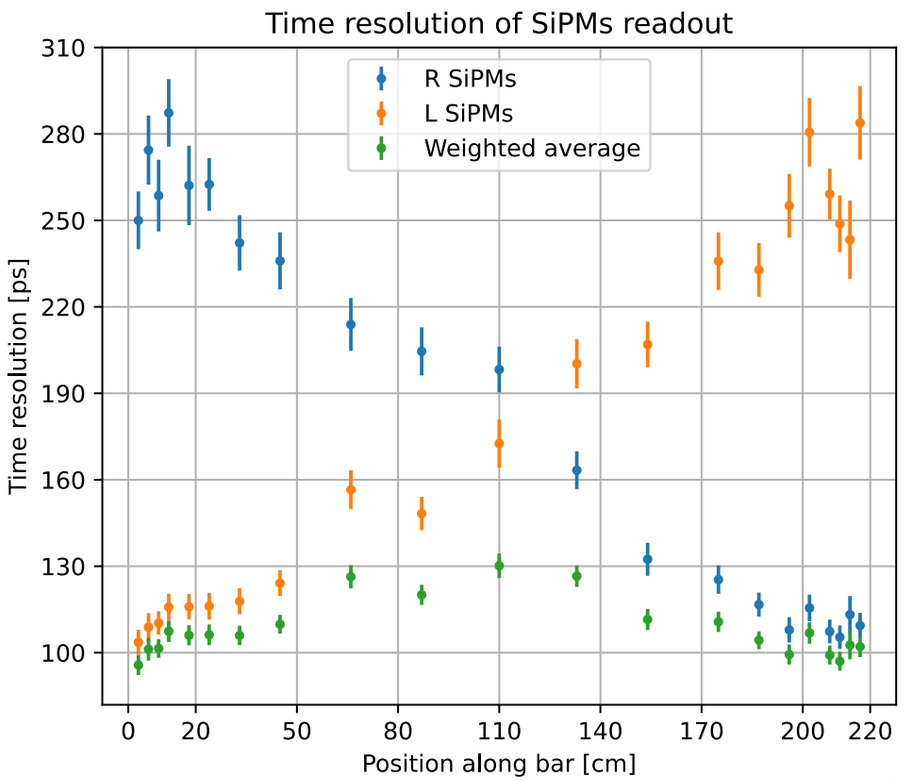
ToF setup at CERN

Goal



- Discriminate particle sense of motion

- Characterization ongoing: $\sigma_t \leq 130$ ps!
- Full ToF system currently being commissioned at CERN.



Updated w.r.t 10.5281/zenodo.6769059

Conclusions

- The ND280 upgrade is near to its completion. All final sub-detectors are being assembled. Integration, commissioning & first data taking in 2023.

Conclusions

- The ND280 upgrade is near to its completion. All final sub-detectors are being assembled. Integration, commissioning & first data taking in 2023.

- Combination of improvements is expected to boost T2K physics potential (see back up!).

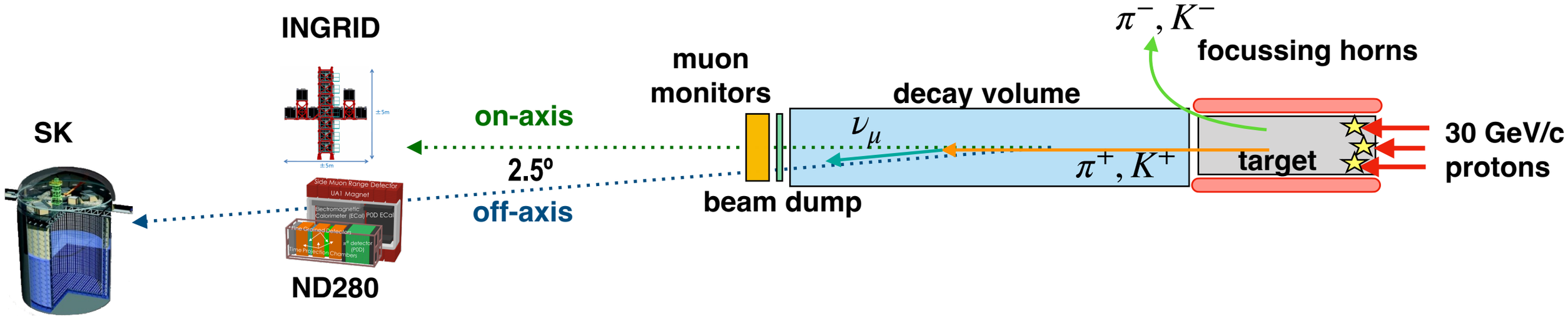
  some examples *PRD* 105 (2022) 3, 032010 & *PRD* 101 (2020) 9, 092003 & *PRD* 106 (2022) 3, 032009

  - Improved efficiencies and purities + completely new analysis methods & variables.
  - Better understand & constrain key systematics → push best limits in Δm^2_{23}, θ_{23}, δ_{CP}.

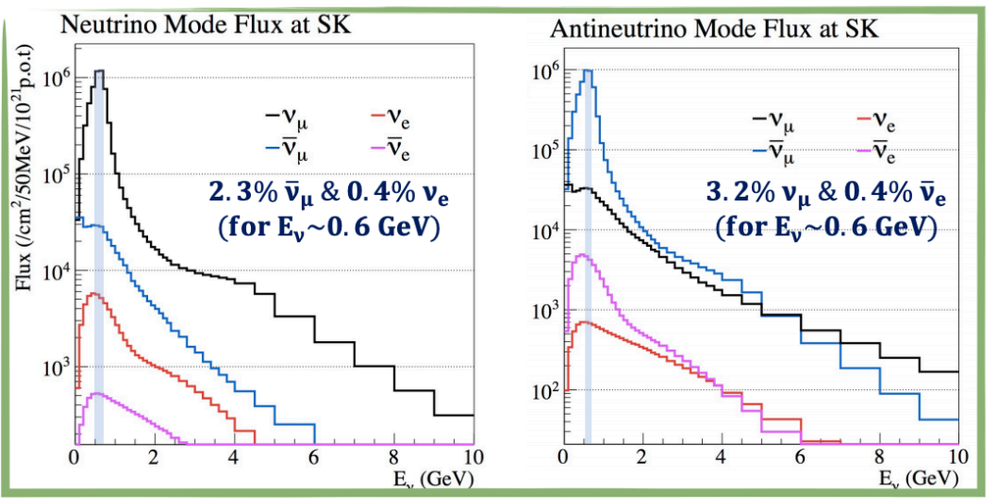
Back Up

The T2K neutrino beam

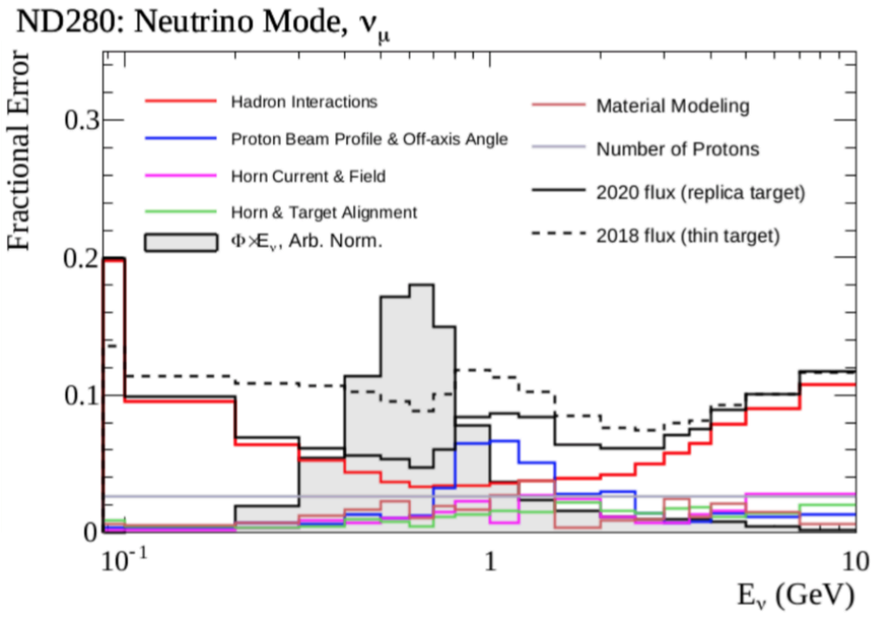
T2K neutrino beam line uses off-axis technique:



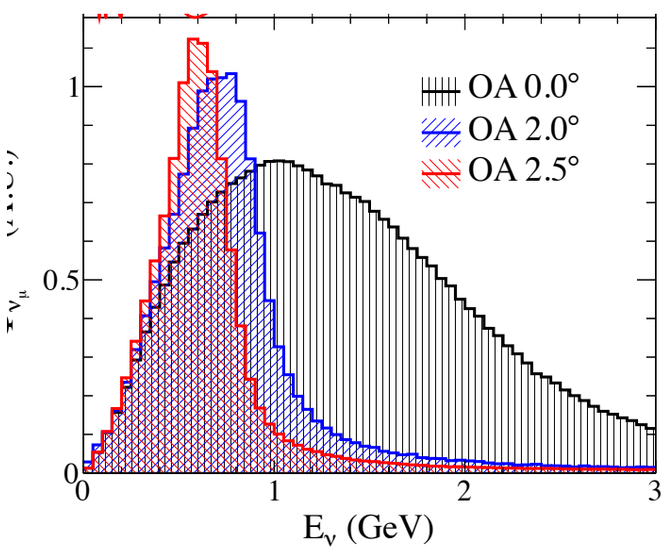
Highly pure ν_μ or $\bar{\nu}_\mu$ flux



Flux model uncertainty:



Narrow peak @ 0.6 GeV



- T2K uses NA61/SHINE experiment on meson production data to model the flux production.
- New analysis used T2K replica target in NA61/SHINE -> Error in flux from 8% to 5%.

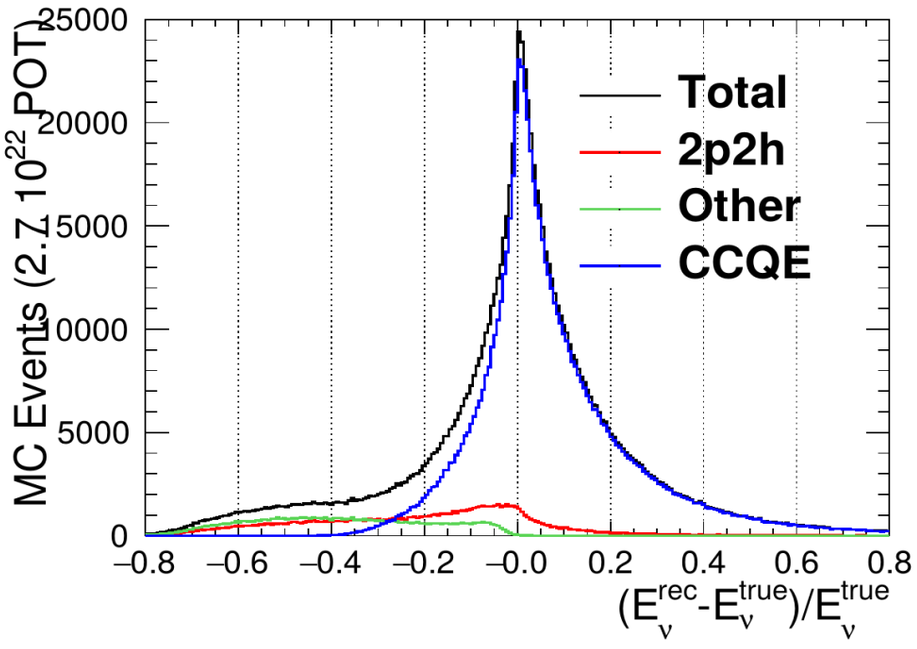
Neutrino Interactions and the OA

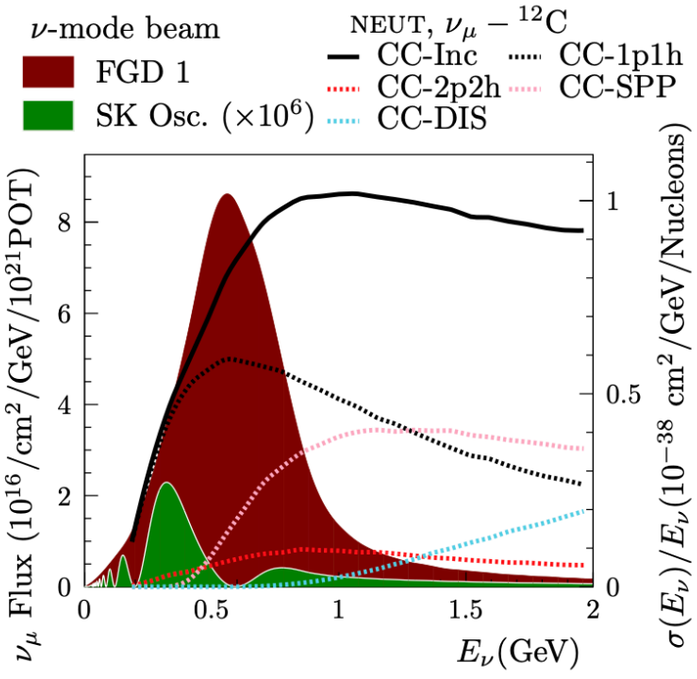
The oscillation probability depends on E_ν

but

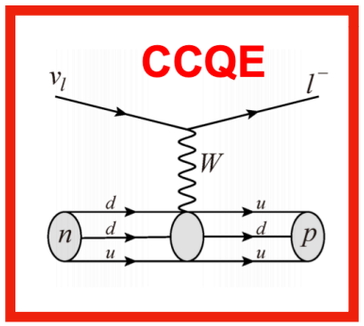
The E_ν resolution heavily depends on the interaction type

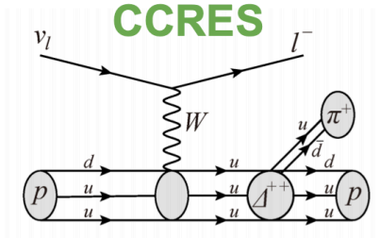
E_ν is reconstructed from the outgoing tracks

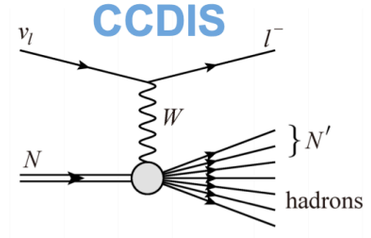


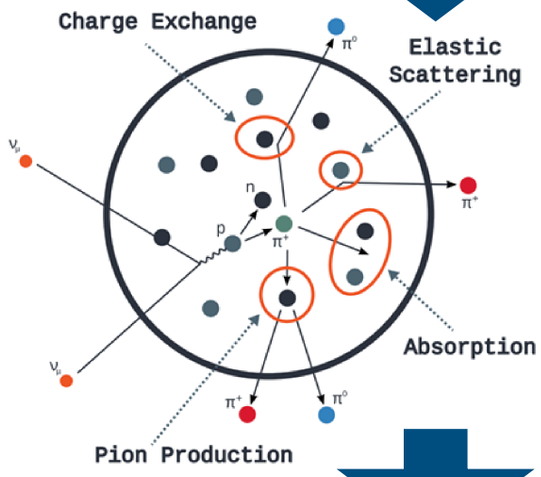


Mainly CCQE for T2K flux

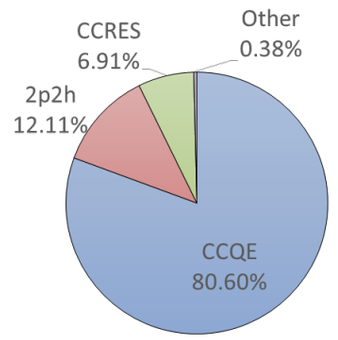




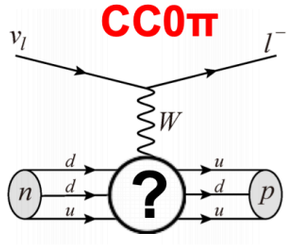


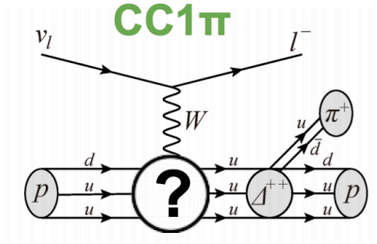


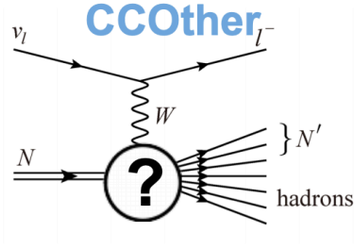
Interaction modes in CC0π topology: (NEUT, T2K ν_μ flux)



We work with interaction topologies

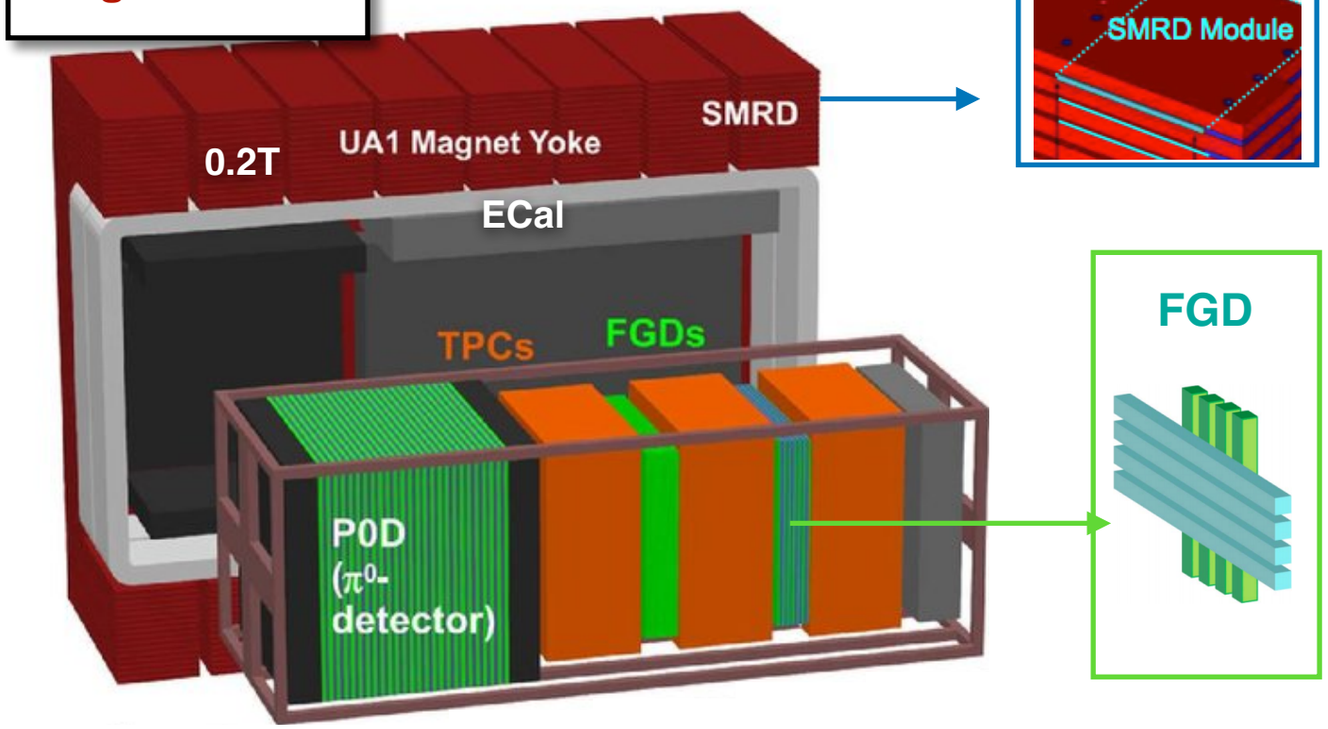






The ND280 detector

Original ND280



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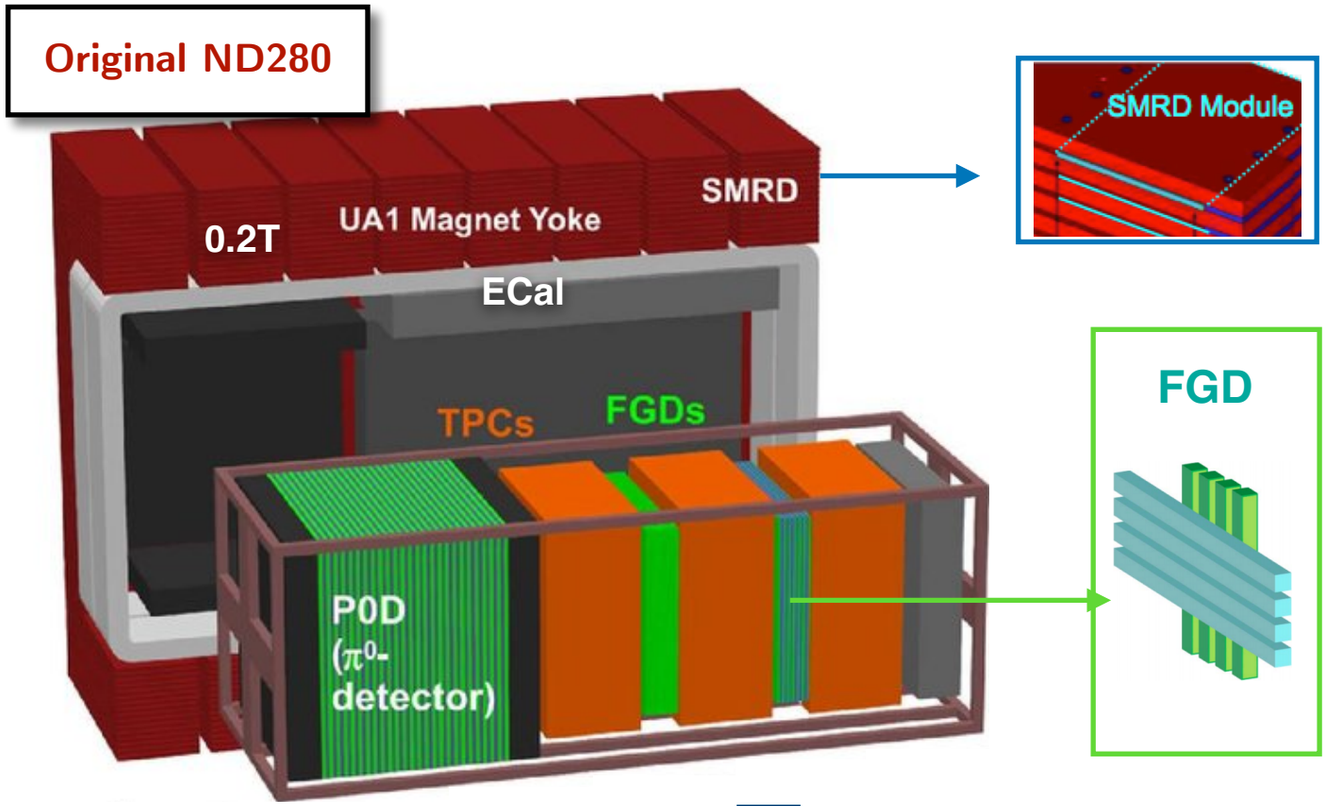

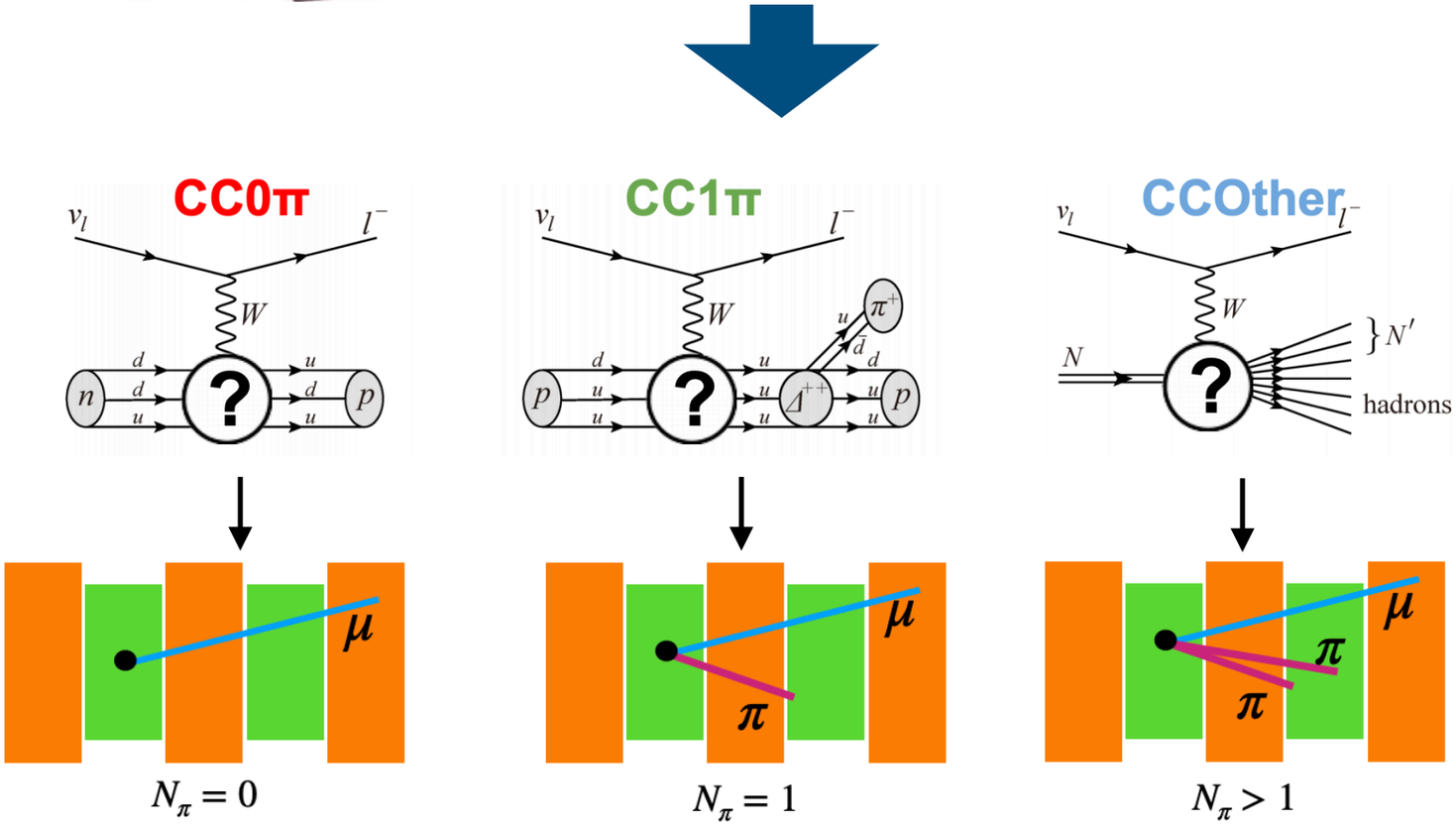

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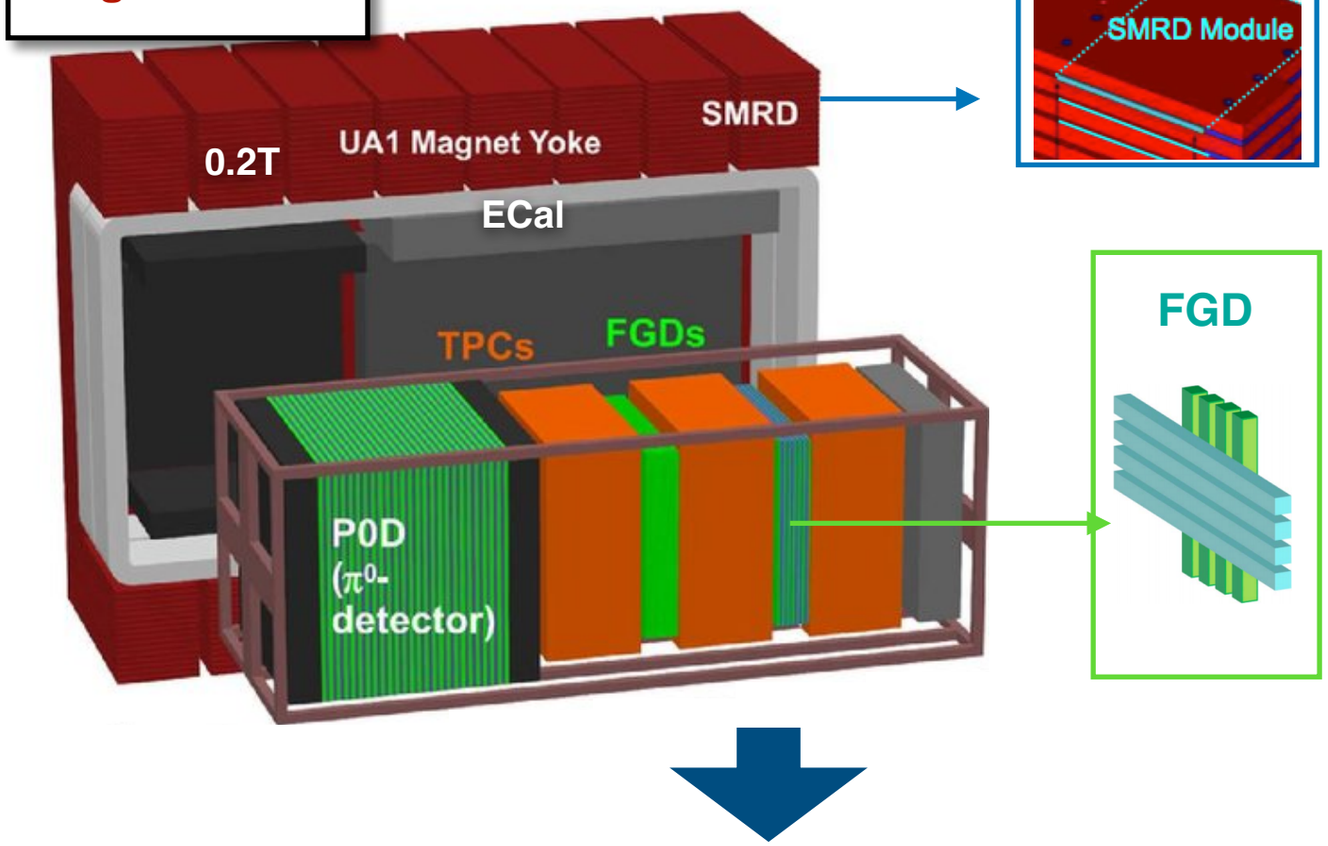
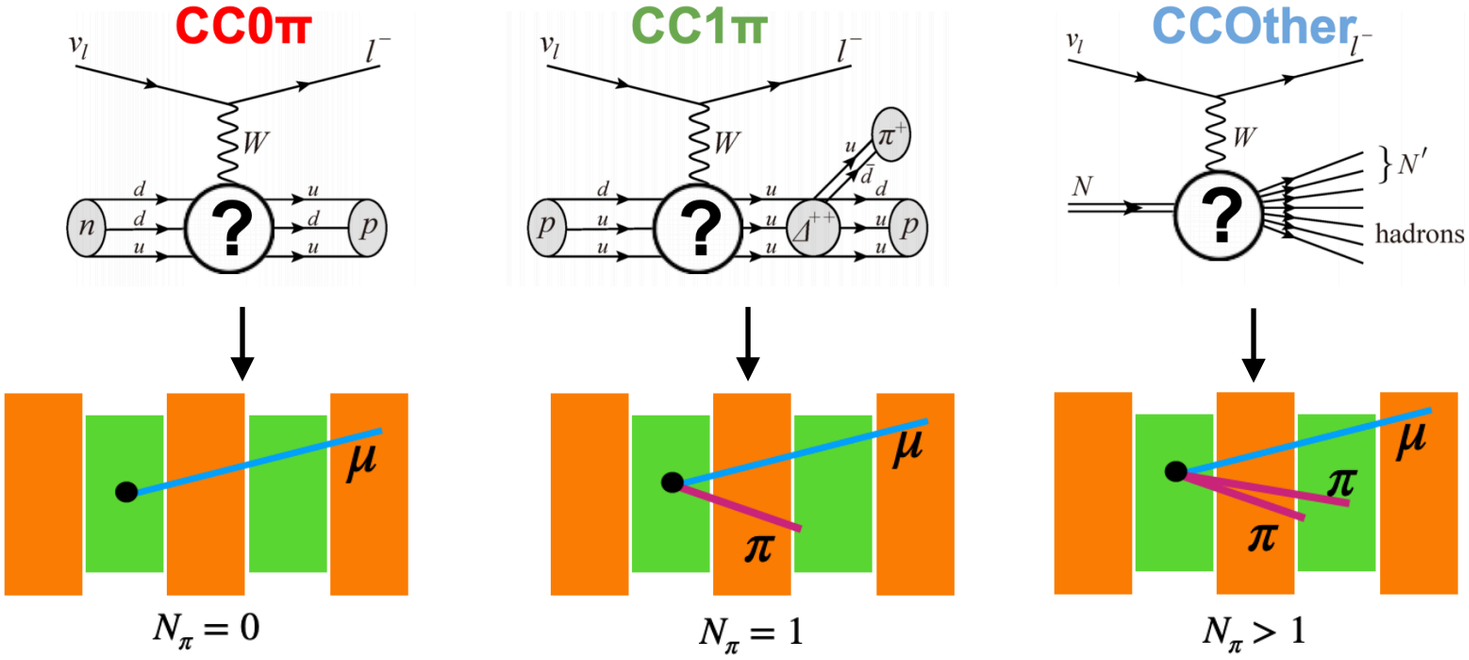




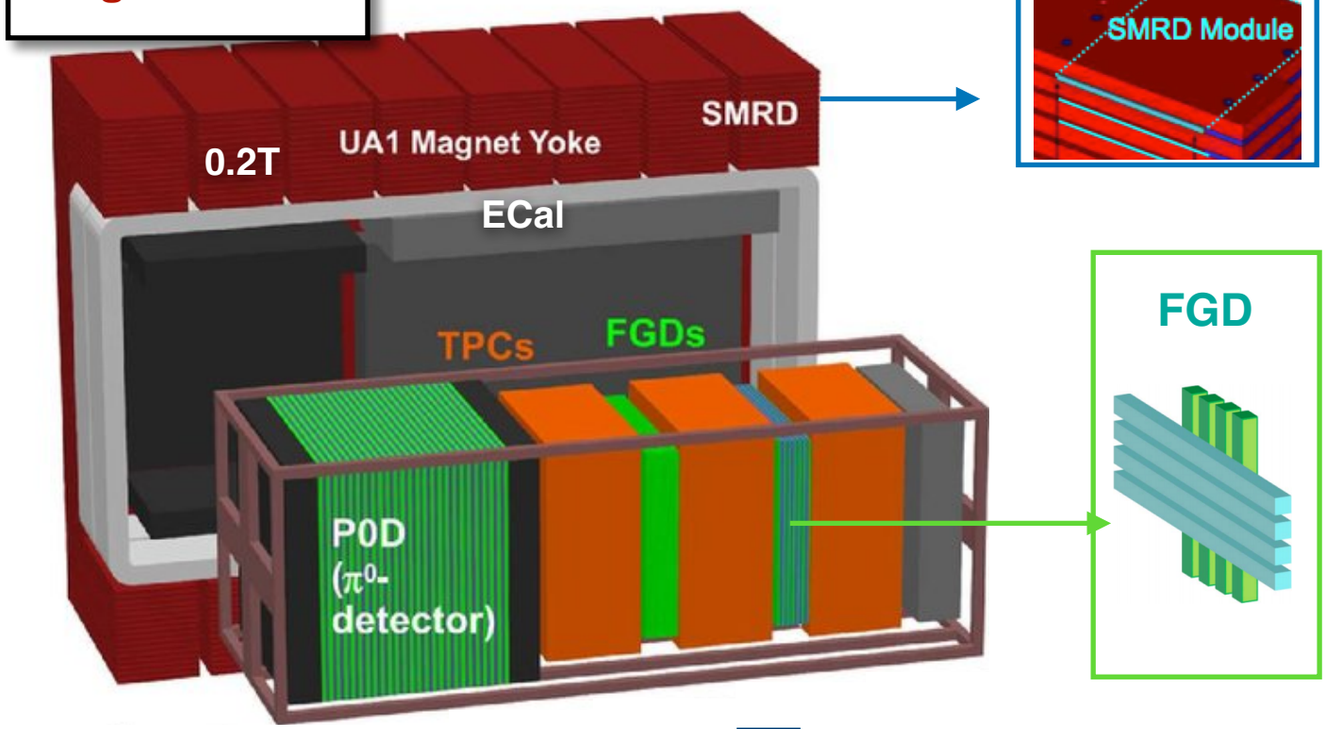
Latest OA results

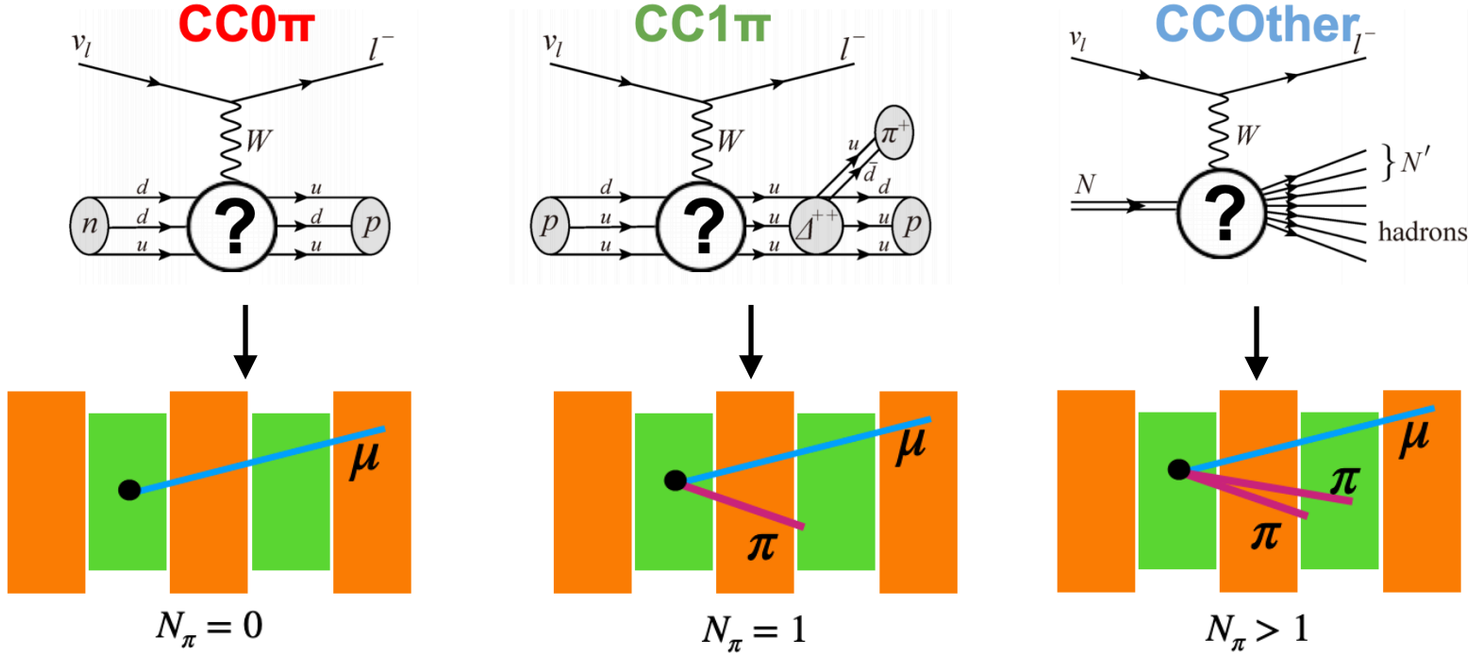
e-Print: 2303.03222

Selection	Topology	Target	Eff. (%)	Pur. (%)
ν_μ in ν-mode	0π	FGD1	48.0	71.3
		FGD2	48.0	68.2
	$1\pi^+$	FGD1	29.0	52.5
		FGD2	24.0	51.3
	Other	FGD1	30.0	71.4
		FGD2	30.0	71.2
$\overline{\nu}_\mu$ in $\overline{\nu}$-mode	0π	FGD1	70.0	74.5
		FGD2	69.0	72.7
	$1\pi^-$	FGD1	19.3	45.4
		FGD2	17.2	41.0
	Other	FGD1	26.5	26.3
		FGD2	25.2	26.0
ν_μ in $\overline{\nu}$-mode	0π	FGD1	60.3	55.9
		FGD2	60.3	52.8
	$1\pi^+$	FGD1	30.3	44.4
		FGD2	26.0	44.8
	Other	FGD1	27.4	68.3
		FGD2	27.1	69.5

The ND280 detector

Original ND280





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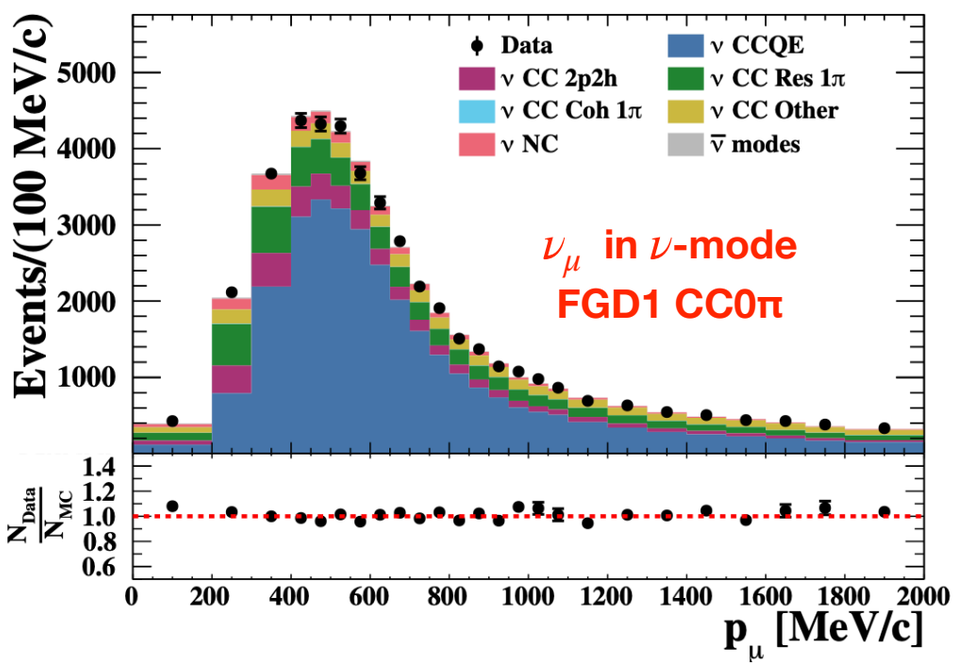
		FGD2	26.0	44.8
	Other	FGD1	27.4	68.3
		FGD2	27.1	69.5



Neutrino Interactions and the OA

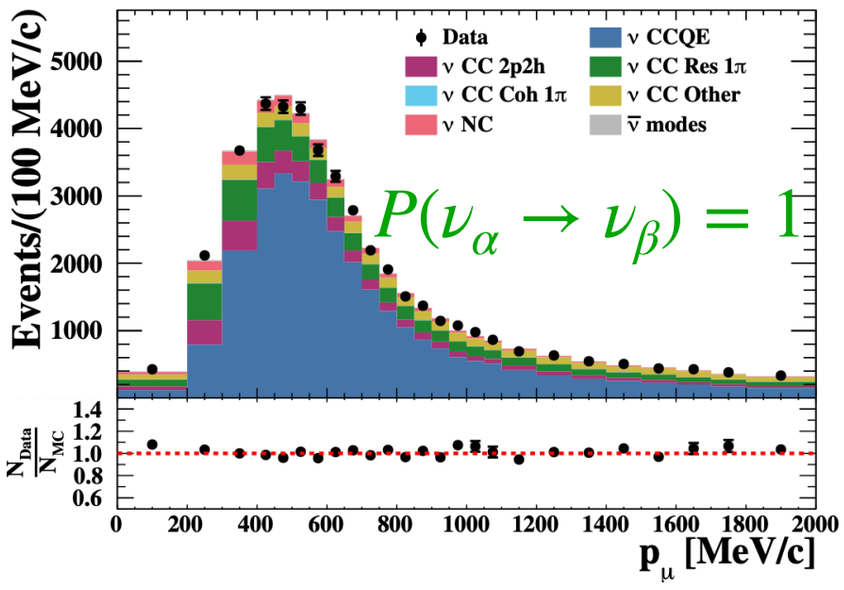
Event rate prediction

$$N_i^{exp}(E_\nu) = P(\nu_\alpha \to \nu_\beta) \times \sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$$

Oscillation probability — Neutrino flux

Expected event rate — Interaction cross-section — Detector efficiency

At ND280



$N_i^{exp}(E_\nu)$ VS $N_i^{obs}(E_\nu)$

$\sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$

Constrain nuisance parameters

Neutrino Interactions and the OA

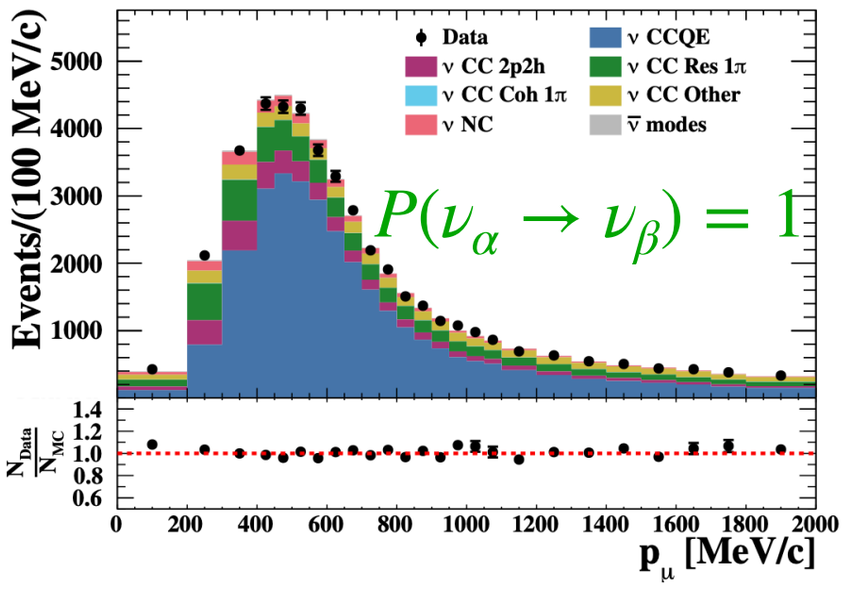
Event rate prediction

Oscillation probability — Neutrino flux

$$N_i^{exp}(E_\nu) = P(\nu_\alpha \to \nu_\beta) \times \sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$$

Expected event rate — Interaction cross-section — Detector efficiency

At ND280



$N_i^{exp}(E_\nu)$ VS $N_i^{obs}(E_\nu)$

$\sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$

Constrain nuisance parameters

Measure neutrino interaction cross-sections (fit additional normalization parameters)

6 ν_μ or $\bar{\nu}_\mu$ CC inclusive

PRD arXiv: 1302.4908

PRD arXiv: 1801.05148

PTEP arXiv: 1904.09611

PRD arXiv: 1407.4256

PRD arXiv: 1509.06940

PRD arXiv: 1706.04257

3 ν_e or $\bar{\nu}_e$ CC inclusive

PRL arXiv: 1407.7389

PRD arXiv: 1503 . 08815

JHEP arXiv: 2002.11986

12 ν_μ or $\bar{\nu}_\mu$ CC0π

PRD arXiv: 1602.03652

PRD arXiv: 1708 . 06771

PRD arXiv: 1908.10249

PRD arXiv: 2002.09323

PRD arXiv: 2004.05434

PRD arXiv: 1503.07452

PRD arXiv: 1411.6264

PRD arXiv: 1403.3140

PRD arXiv: 1910.09439

PRD arXiv: 1802.05078

PRD arXiv: 2102.03346

PTEP arXiv: 2004.13989

4 ν_μ or $\bar{\nu}_\mu$ CC1π

PRD arXiv: 1605.07964

PRL arXiv: 1604.04406

PRD arXiv: 1909.03936

PRD arXiv: 1704.07467

Neutrino Interactions and the OA

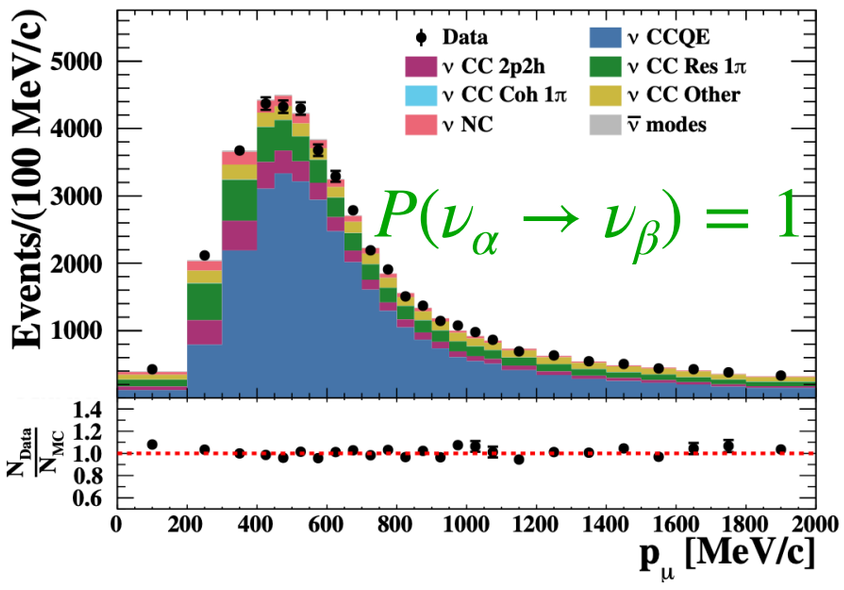
Event rate prediction

Oscillation probability — Neutrino flux

$$N_i^{exp}(E_\nu) = P(\nu_\alpha \to \nu_\beta) \times \sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$$

Expected event rate — Interaction cross-section — Detector efficiency

At ND280

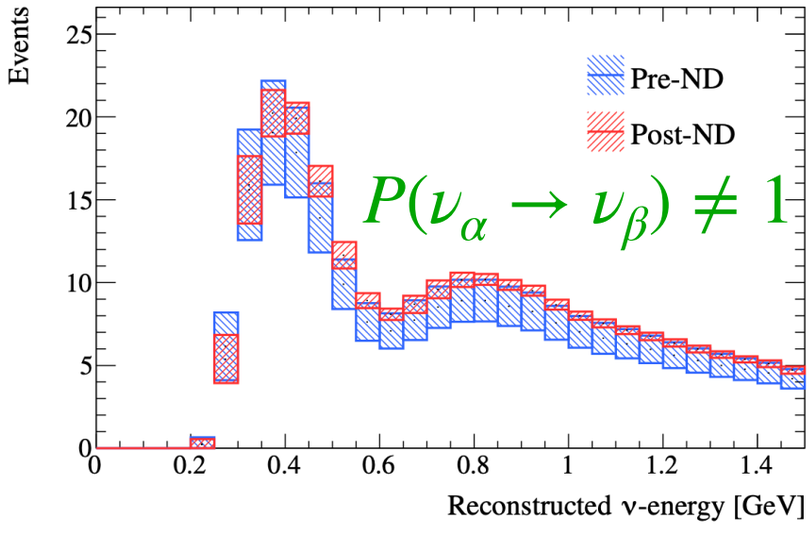


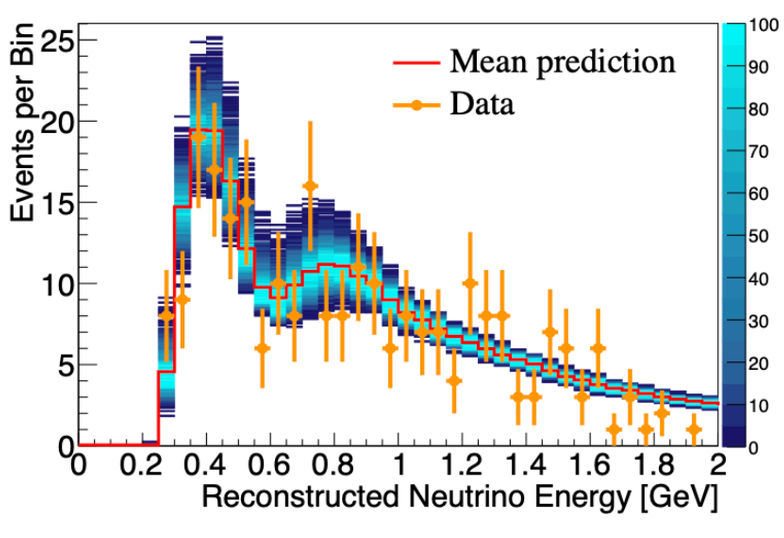
$N_i^{exp}(E_\nu)$ VS $N_i^{obs}(E_\nu)$

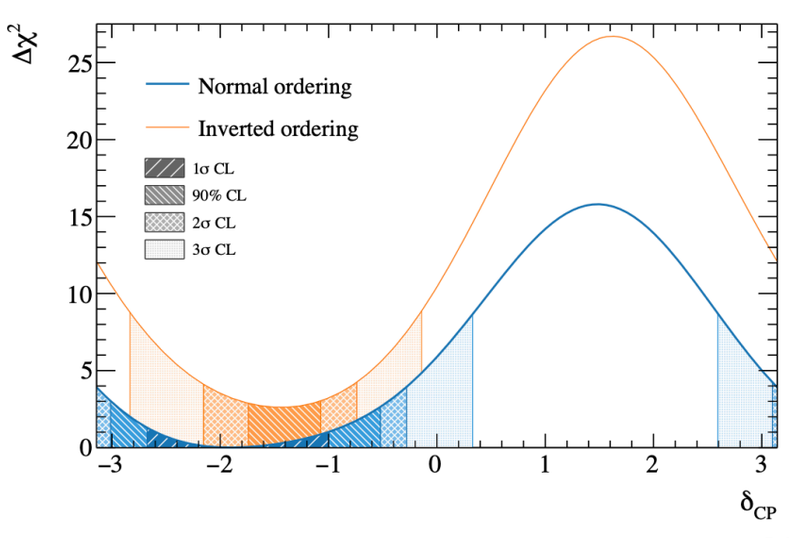
$\sigma_i(E_\nu) \times \Phi_\nu(E_\nu) \times \epsilon_i(E_\nu)$

Constrain nuisance parameters

Measure neutrino oscillations (Calculate event rate at SK and fit PMNS values)

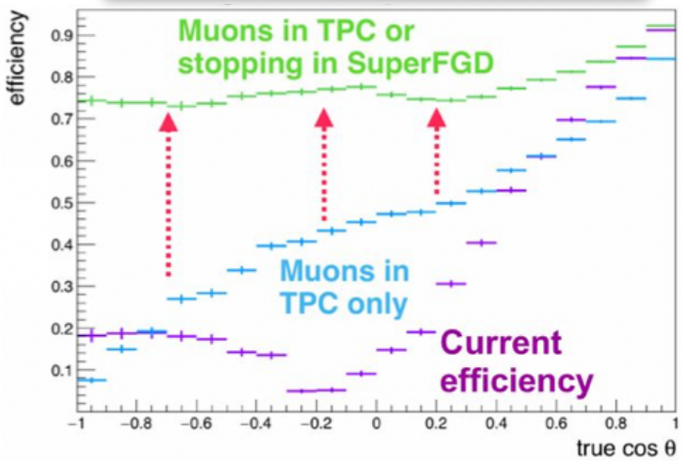




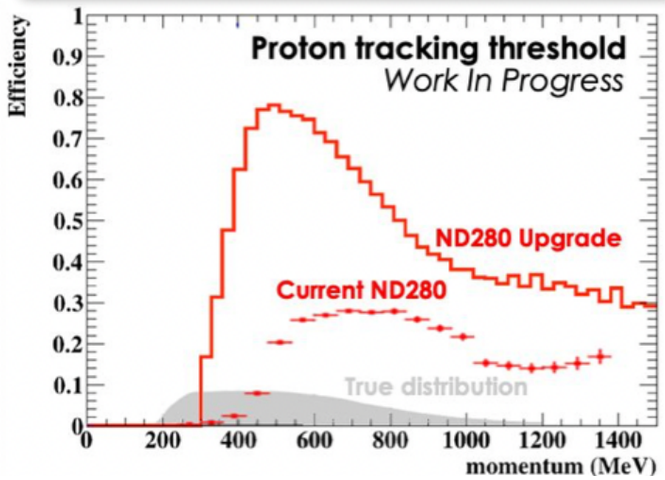


New detector capabilities

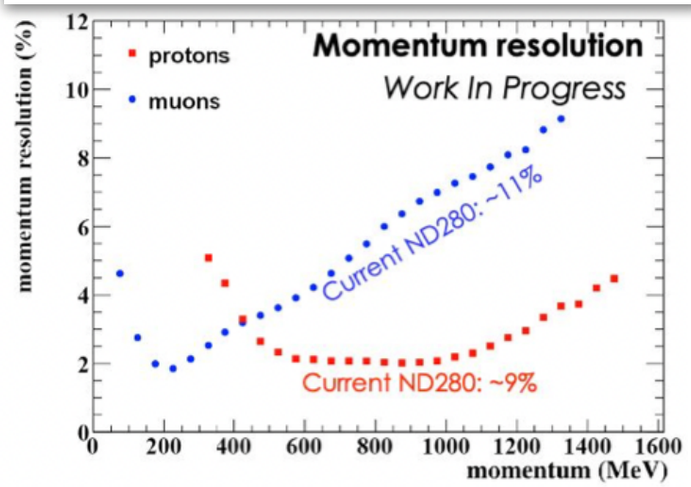
Extended angular domain



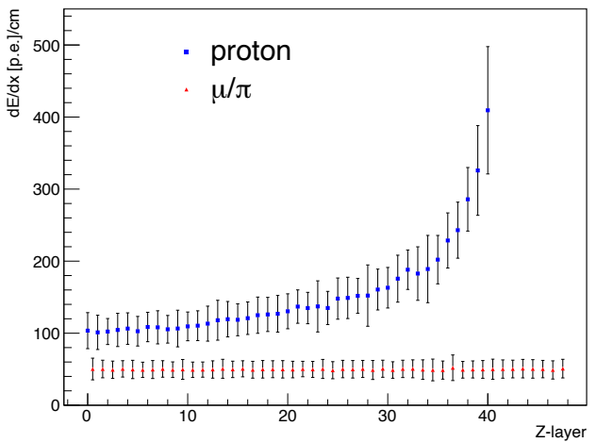
Extended momentum domain



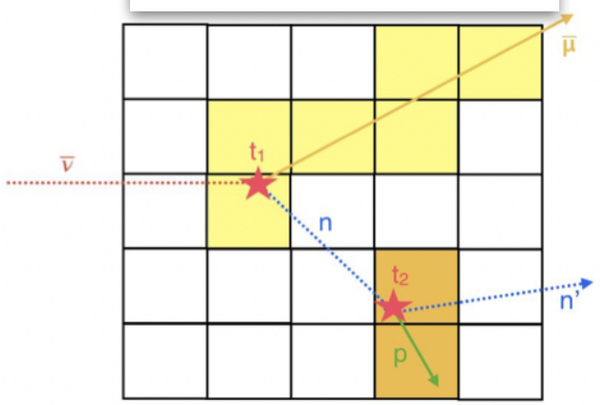
Better momentum reconstruction



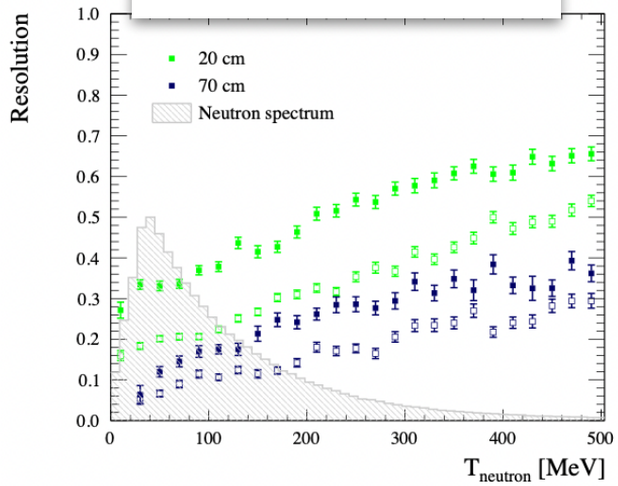
Bragg peak for proton PID



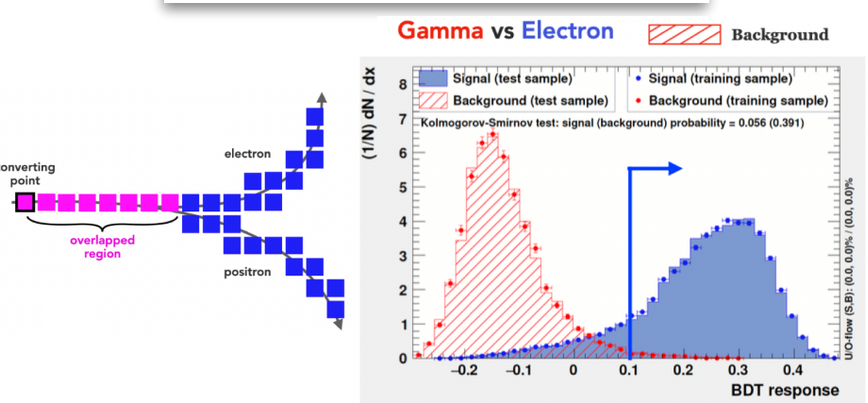
Neutron detection



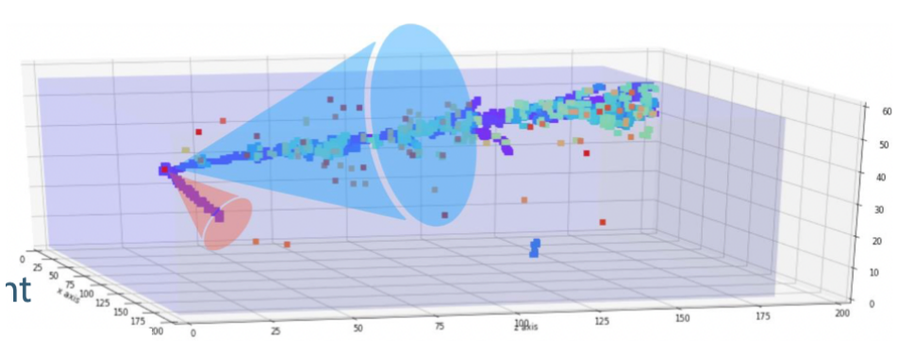
... with kinematics!



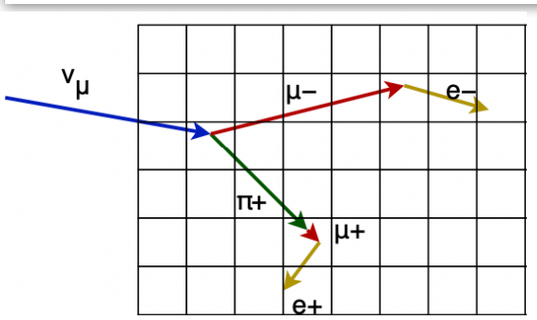
Improved e/γ separation



Improved electron reconstruction



Boosted Michel Electron tagging

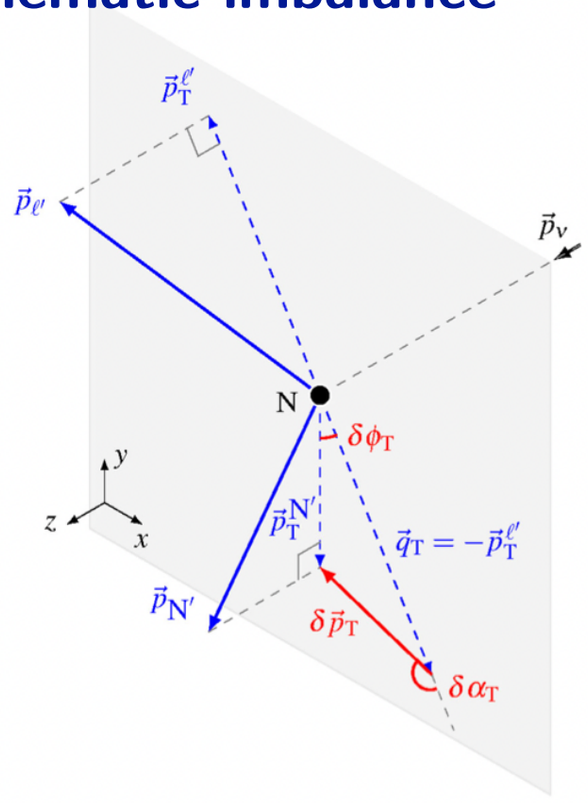


Muon mean lifetime ≈ 2 μs, hit resolution $\sigma_t \approx 1$

New analysis possibilities

some examples

Detailed studies of transverse kinematic imbalance



- High quality hadronic information will be game-changing.
  In addition to (p_ℓ, θ_ℓ) can use $(p_N, \delta_{p_T}, \delta_{\alpha_T}, E_{vis}...)$:

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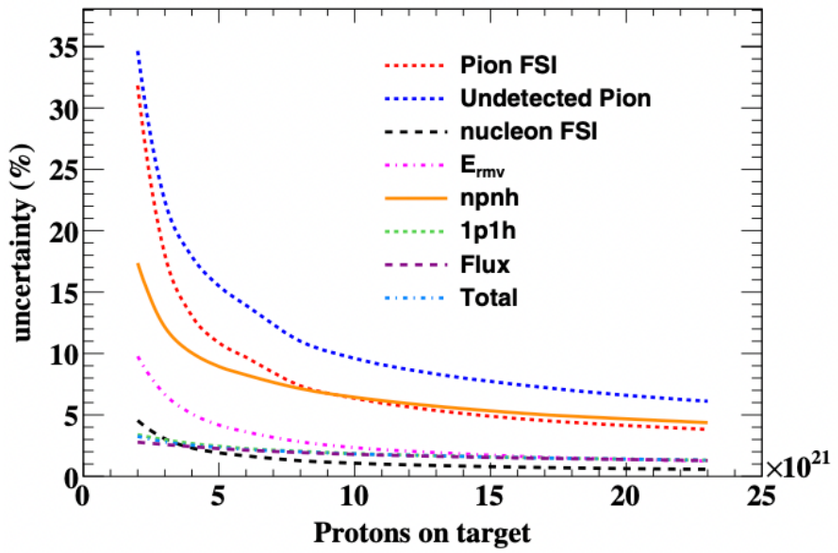
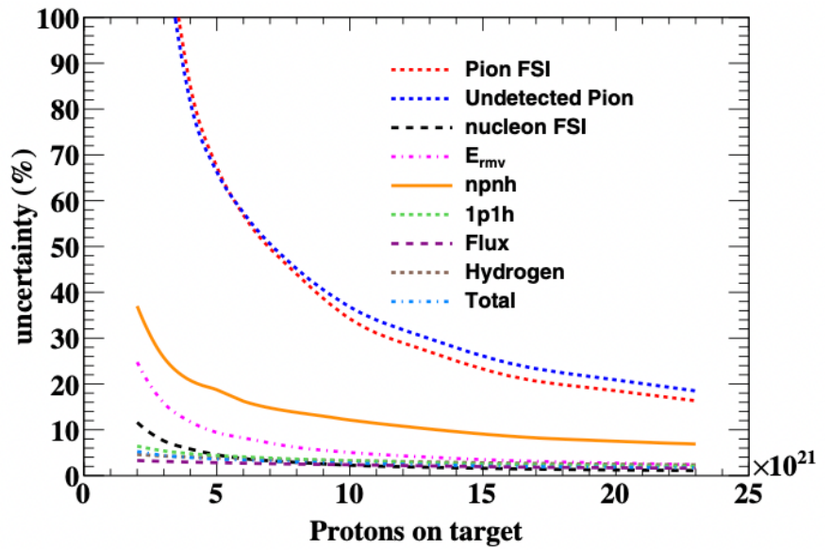
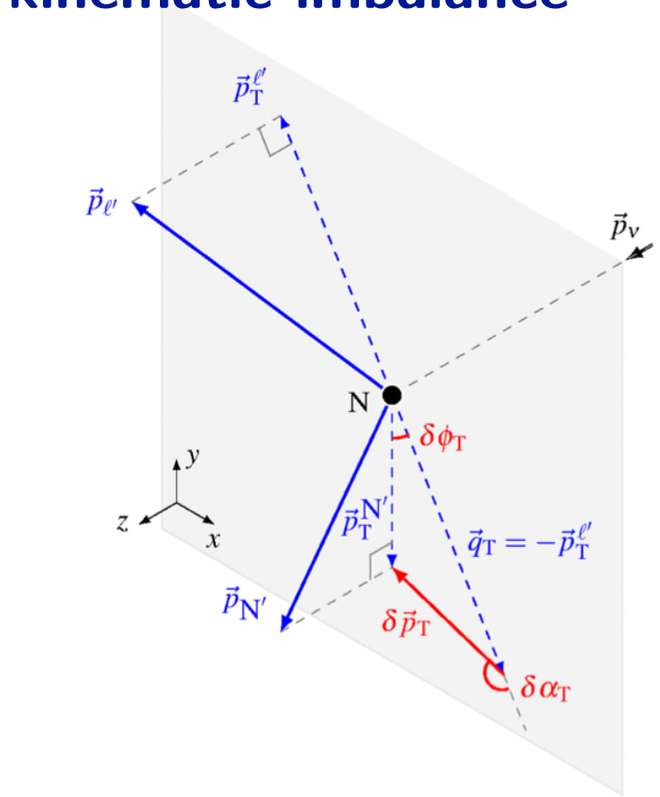




New analysis possibilities

some examples

Detailed studies of transverse kinematic imbalance



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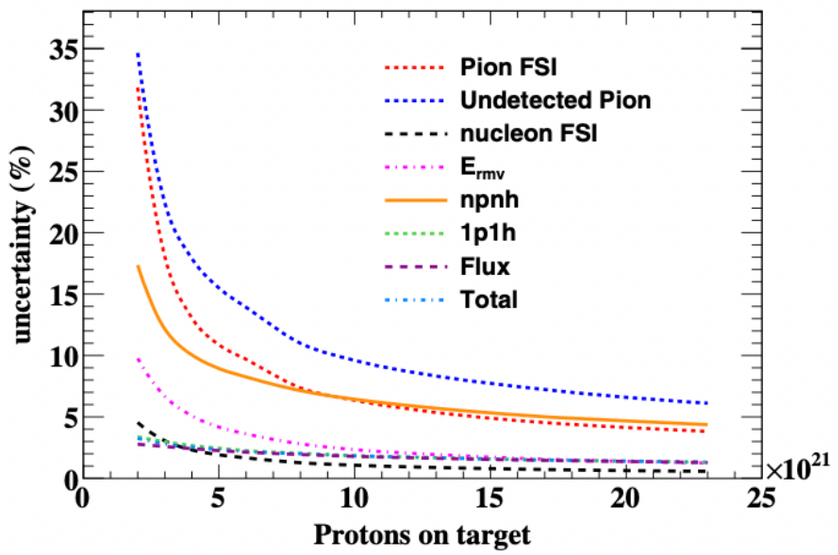

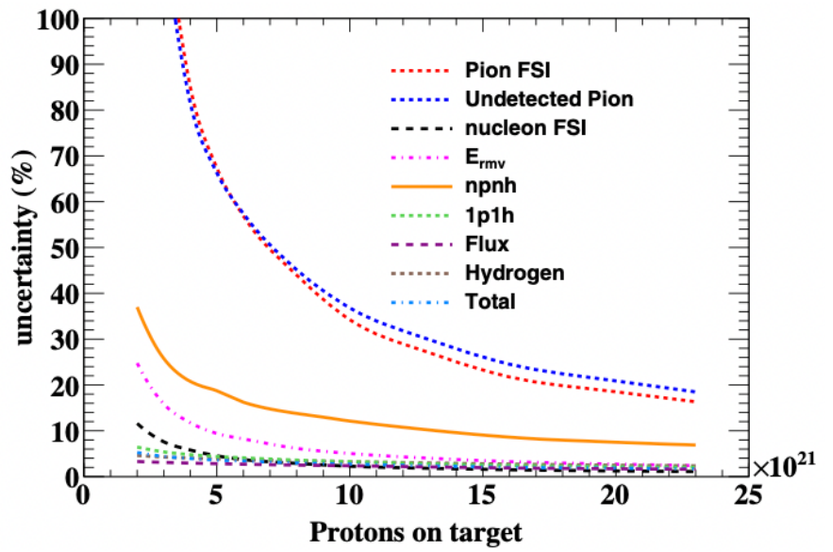

- Low δ_{p_T} can be used to identify events with low nuclear effects

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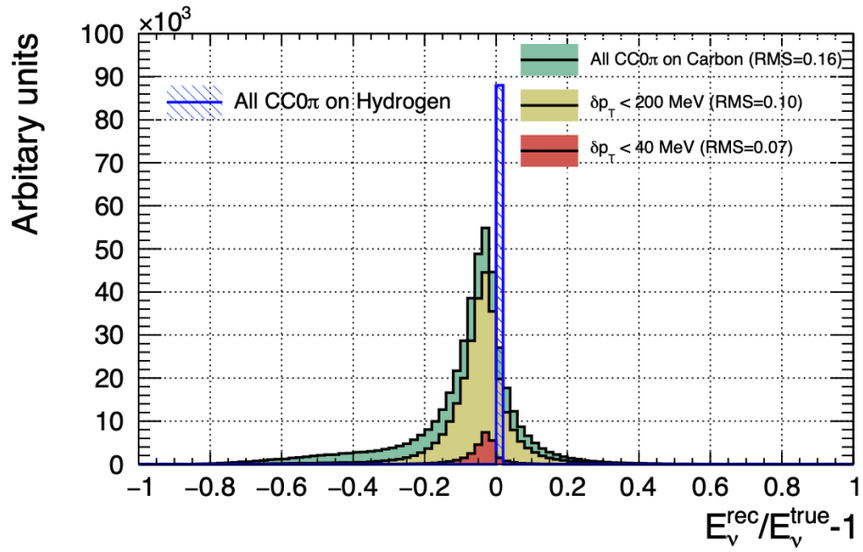
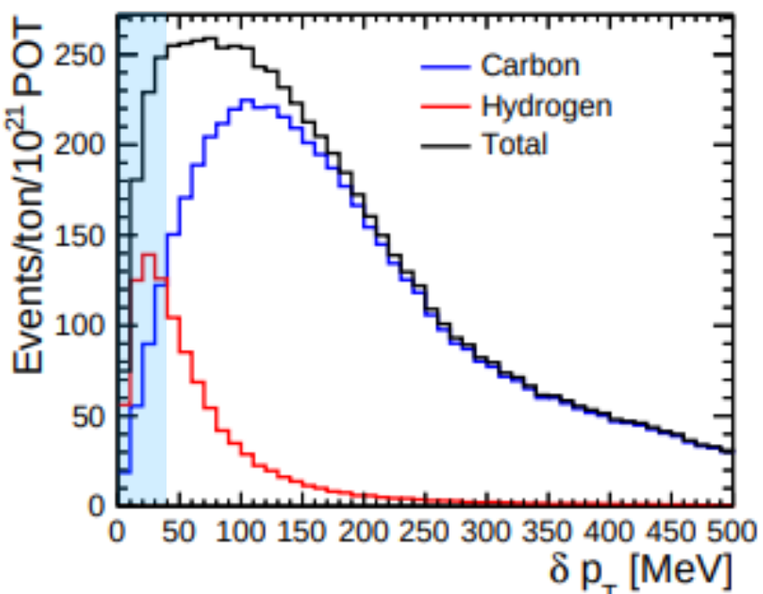
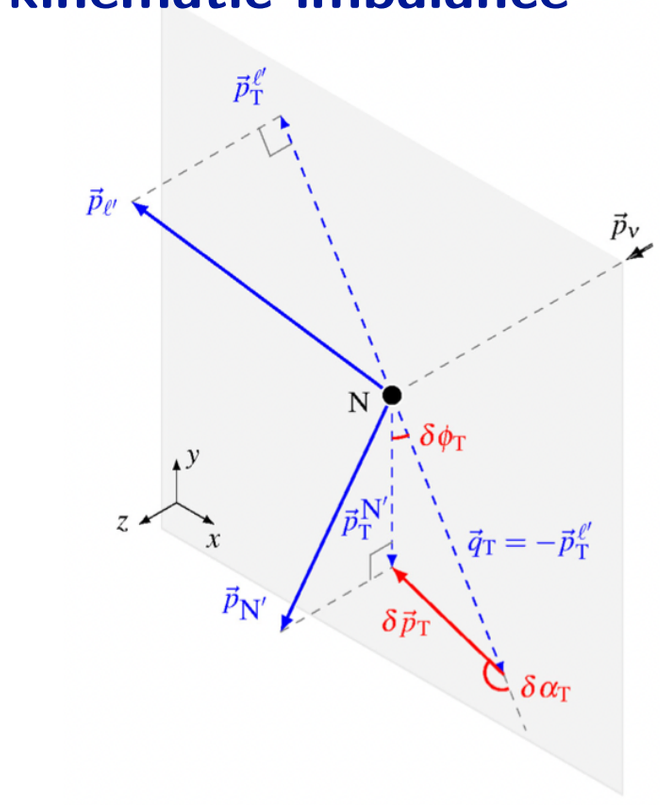




New analysis possibilities

some examples

Detailed studies of transverse kinematic imbalance



- High quality hadronic information will be game-changing. In addition to (p_ℓ, θ_ℓ) can use $(p_N, \delta_{p_T}, \delta_{\alpha_T}, E_{vis}...)$:

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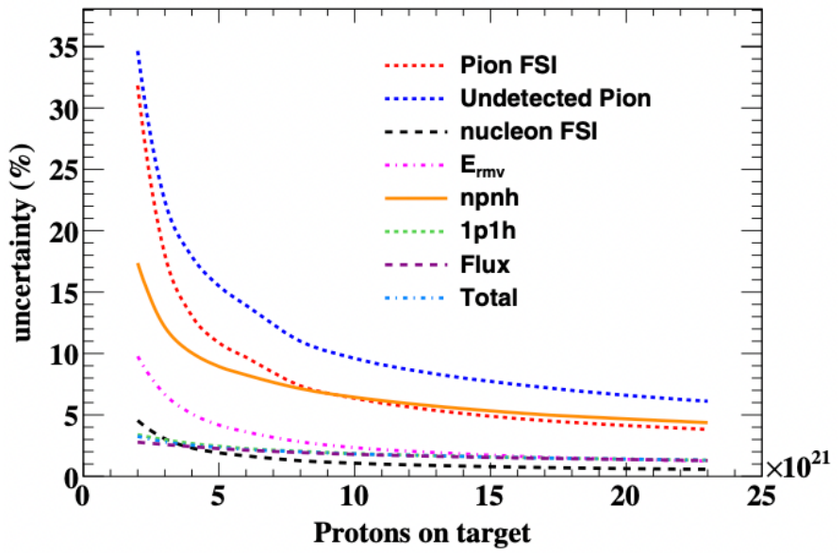

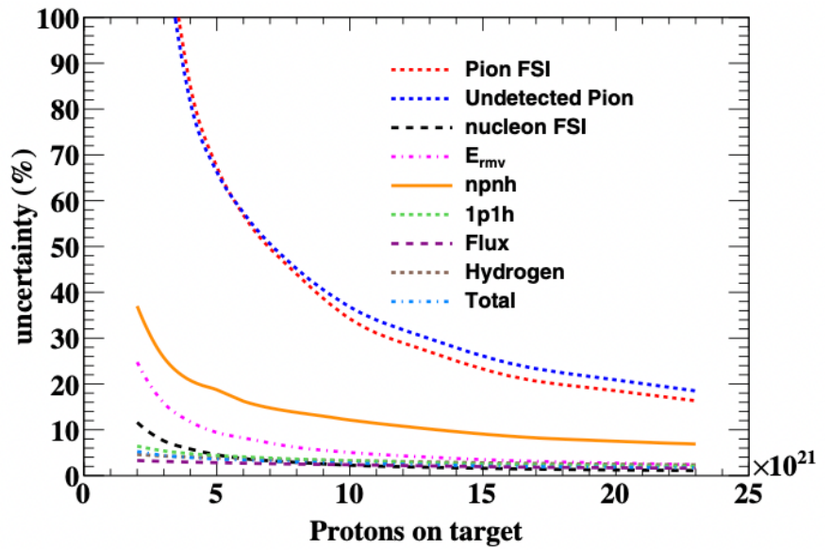

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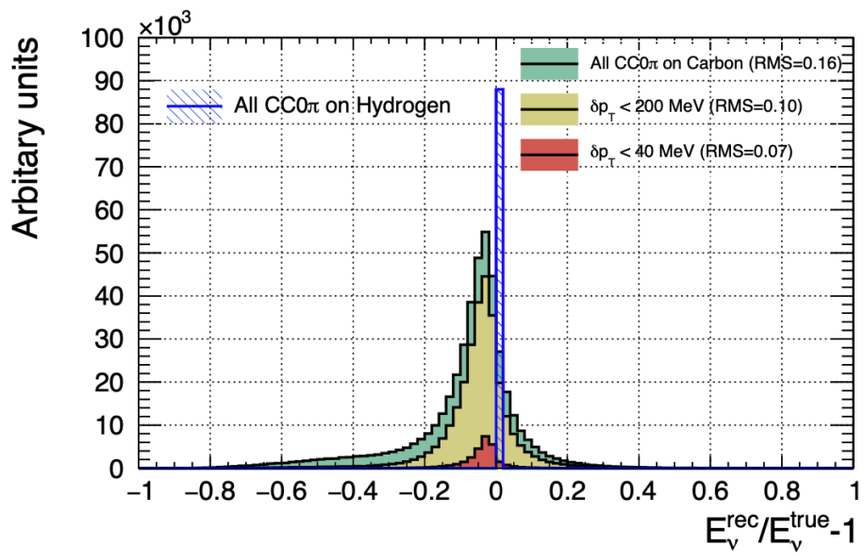

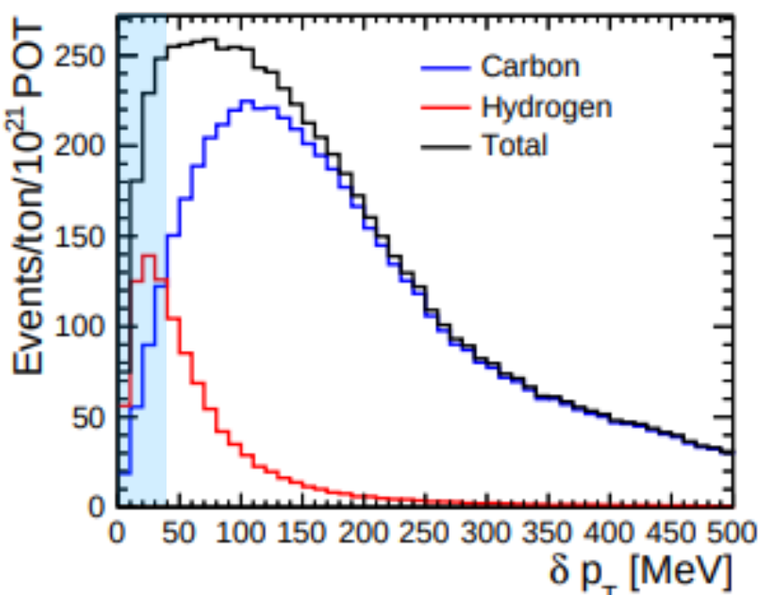

- Use δ_{α_T} to learn about FSI.

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