30th September 2020

SuperFGD

A new 3D plastic scintillator technology for the near detector ND280 upgrade of the T2K experiment

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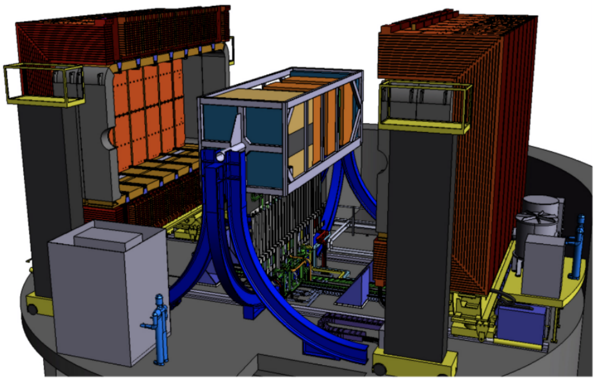


Outlook

Neutrinos

T2K

T2K (ND280) upgrade

SuperFGD

Summary

Neutrino Physics

Neutrinos

Why are neutrinos interesting?

Although predicted ~90 years ago many open questions remain

Neutrinos masses

What is their mass values? Normal/Inverted hierarchy?
And why it is so small? Majorana, Dirac?

CP violation in the lepton sector

Is it large? positive? negative? maximal?

Oscillation parameters

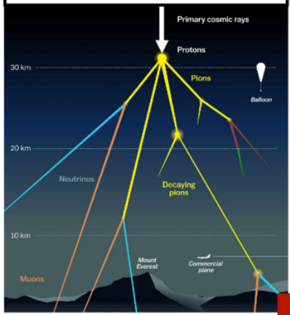
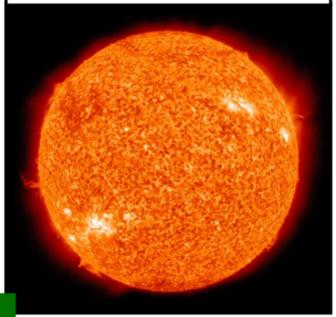
What are their values? Any connections PMNS - CKM?

↓

inputs for HEP theory, Cosmology and Astrophysics

Neutrino Oscillations

To answer some of this questions we study neutrino oscillations

Atmospheric	Accelerator	Reactor	Solar
			

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{U_{PMNS}}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

flavor eigenstates

mass eigenstates

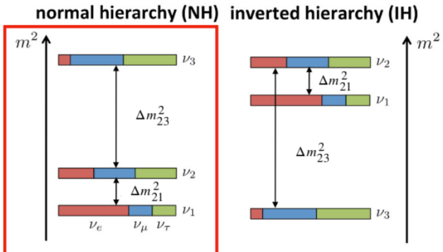
Neutrino Oscillations

Three mixing angles (PDG 2016):
$\theta_{23} = 45°$, $\theta_{12} = 34°$ and $\theta_{13} = 9°$

$$\Delta m^2_{ij} = m^2_j - m^2_i$$

$|\Delta m^2_{23}| = 2{,}4 \cdot 10^{-3}$ **eV**^{2}

$\Delta m^2_{21} = 7.6 \cdot 10^{-5}$ **eV**^{2}



89%

Accelerator

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

U_{PMNS}

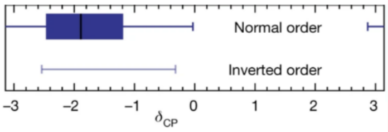
$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

flavor eigenstates

mass eigenstates

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\|\Delta m^2_{31,32}\|$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\|\Delta m^2_{31,32}\|$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\|\Delta m^2_{31,32}\|$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

δ_{CP} (3σ error bars):




T2K
J-PARC
Super-K

The T2K international collaboration

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

CERN

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
Italy INFN
U. Bari INFN
U. Napoli INFN
U. Padova INFN
U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU U. Kyoto U.
Miyagi U. Edu
Okayama U.
Osaka City U.
Tokyo Institute of Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
Wroclaw U.

Russia
INR RAS

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U.
L. Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh U. Rochester
U.
Washington

Vietnam
IFIRSE
IOP, VAST

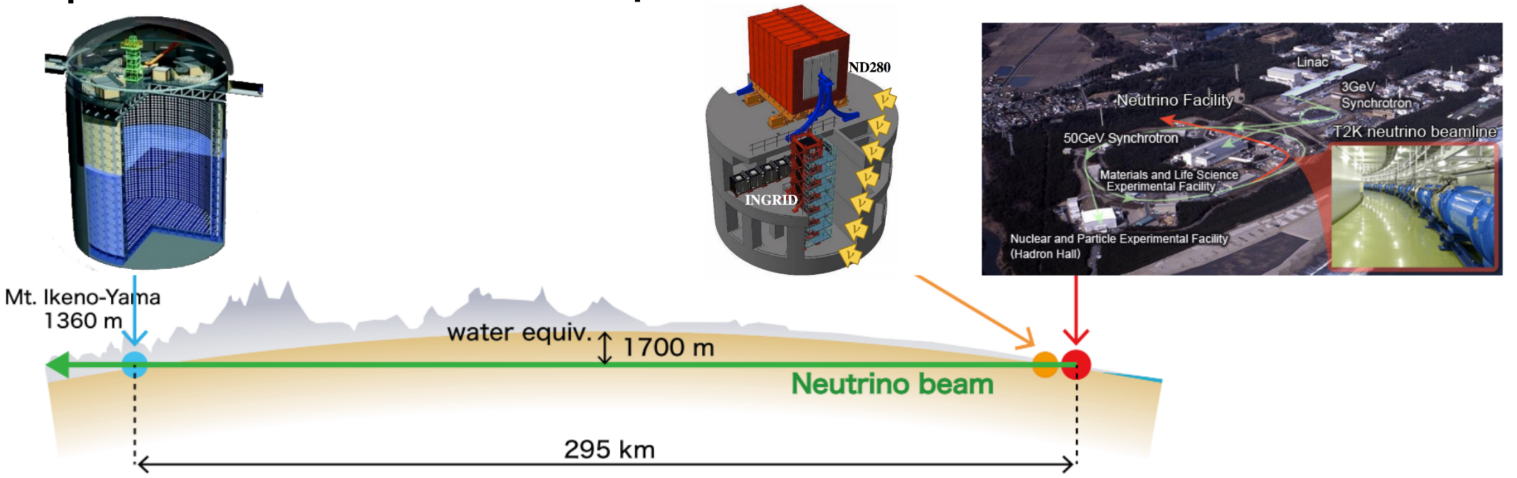
~500 members, 67 institutes, 12 countries

The Tokai-to-Kamioka (T2K) experiment

Far detector
Super Kamiokande

Near detector
complex

J-Parc
Neutrino Beam



@SK

Measure oscillated beam

←

@ND280

Characterize beam and neutrino interaction properties

←

@J-PARC

Create Neutrino's beam

T2K oscillation challenges

prediction vs measurement

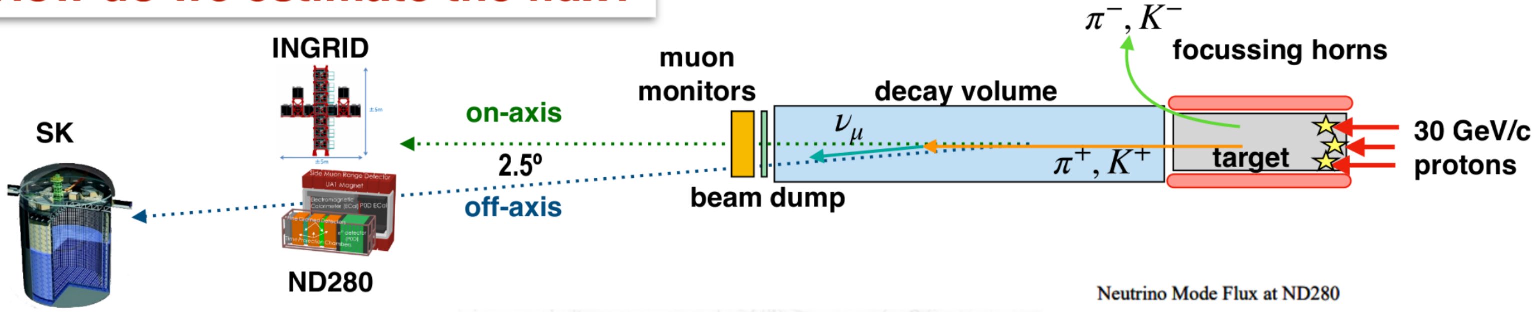
$$\frac{N^{far}_{evts}(\overrightarrow{\theta}^{reco}_{\nu})}{N^{near}_{evts}(\overrightarrow{\theta}^{reco}_{\nu})} = \frac{\int \sigma(E_\nu)\phi^{far}(E_\nu)P^{far}(\overrightarrow{\theta}^{reco}_{\nu} \mid E_\nu)P_{osc}(E_\nu)dE_\nu + Bkg^{near}(\overrightarrow{\theta}^{reco})}{\int \sigma(E_\nu)\phi^{near}(E_\nu)P^{near}(\overrightarrow{\theta}^{reco}_{\nu} \mid E_\nu) + Bkg^{far}(\overrightarrow{\theta}^{reco})}$$

- $\phi^{near,far}(E_\nu)$ — Flux energy and flavor depends on meson production modeling
- $\sigma(E_\nu)$ — Neutrino-nucleus cross-sections are not well known
- $P^{near,far}(\overrightarrow{\theta}^{reco}_{\nu} \mid E_\nu)$ — Observables depends on neutrino-interaction models
- $Bkg^{near,far}(\overrightarrow{\theta}^{reco}_{\nu})$ — Background depend on neutrino-interaction models

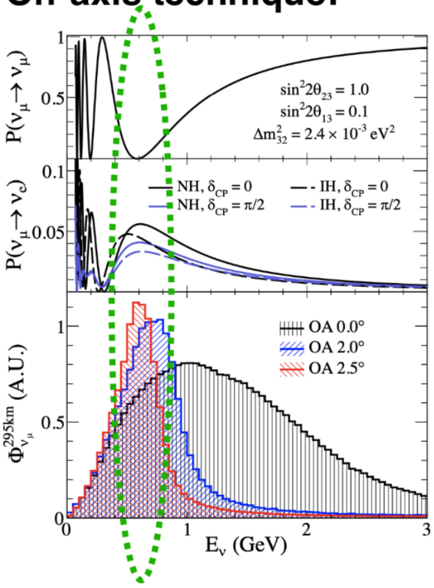
How T2K address this challenges?

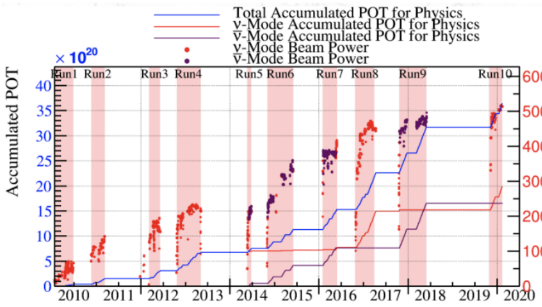
T2K beam (flux)

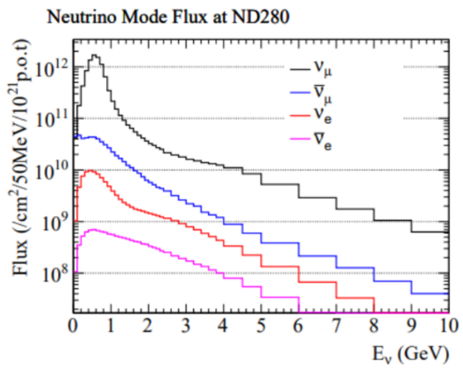
How do we estimate the flux?

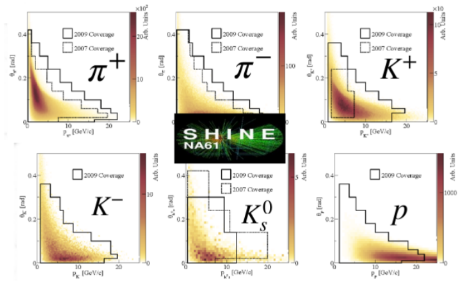


Off-axis technique:



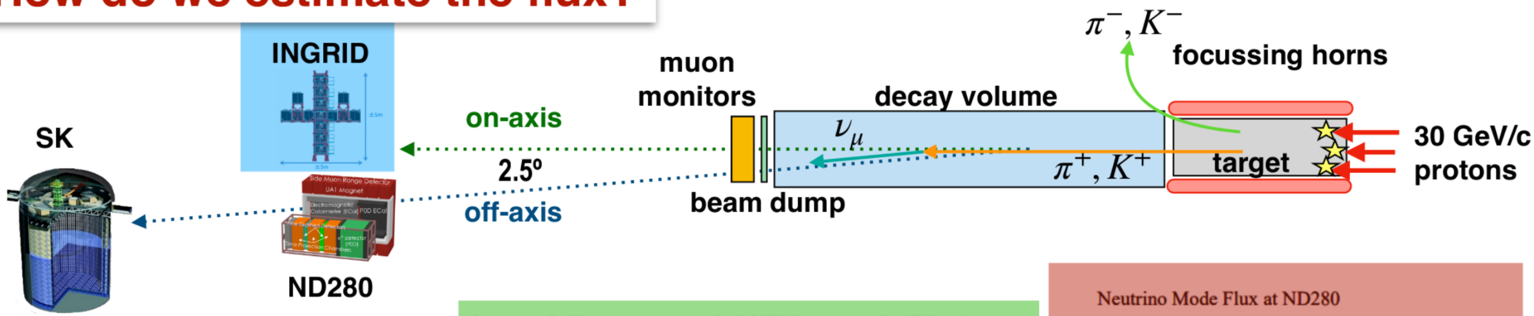




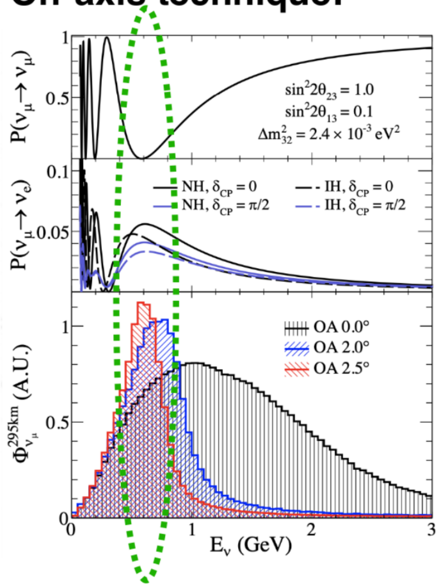


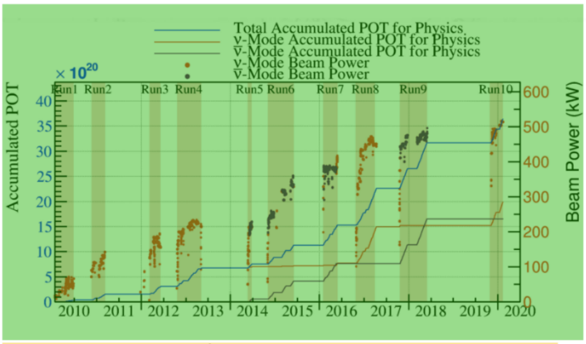
T2K beam (flux)

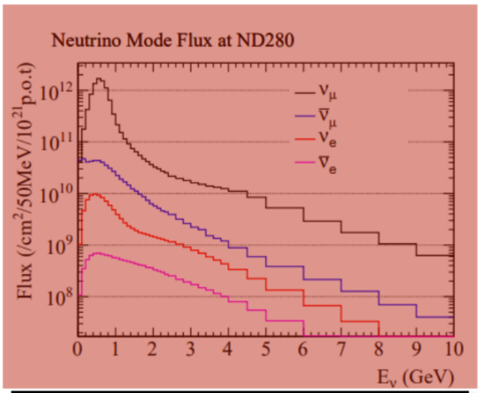
How do we estimate the flux?

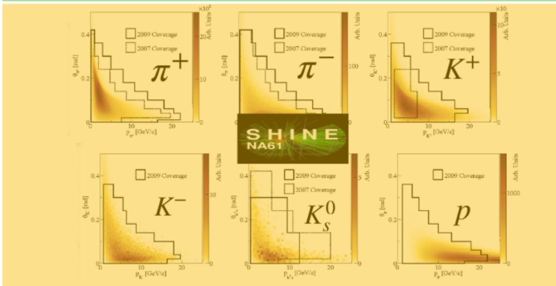


Off-axis technique:





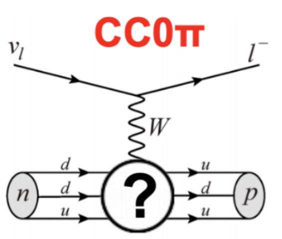


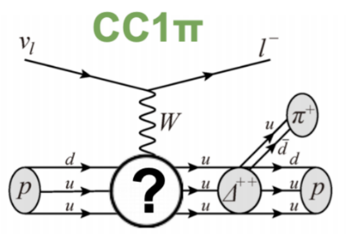


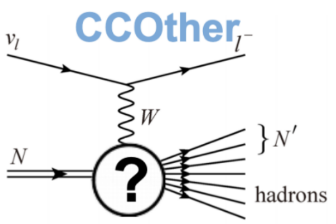
JPARC input (POT) + SHINE input (meson production) + INGRID input (beam alignment)
=
beam prediction

Neutrino interactions (model validation)

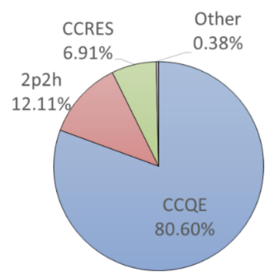
We work with CC0π topology for OA:





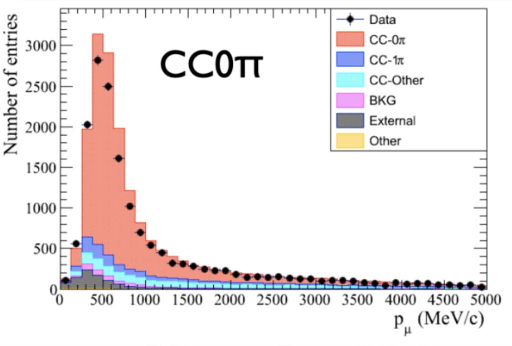


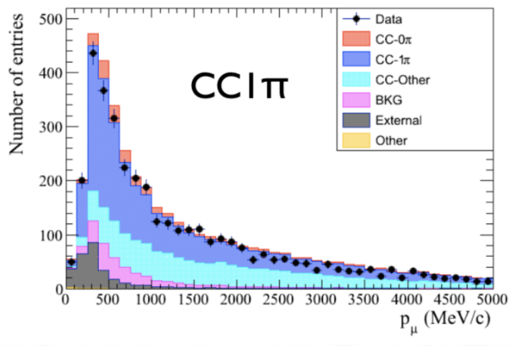
Interaction modes in CC0π topology: (NEUT, T2K ν_μ flux)

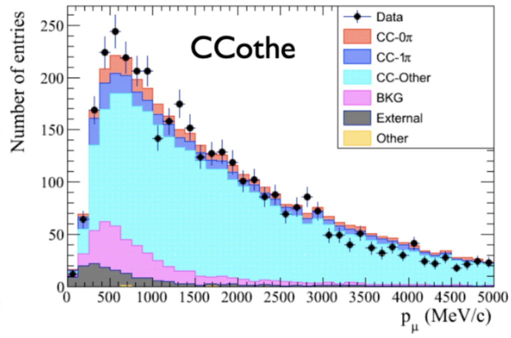


Easier to identify, better neutrino energy reconstruction

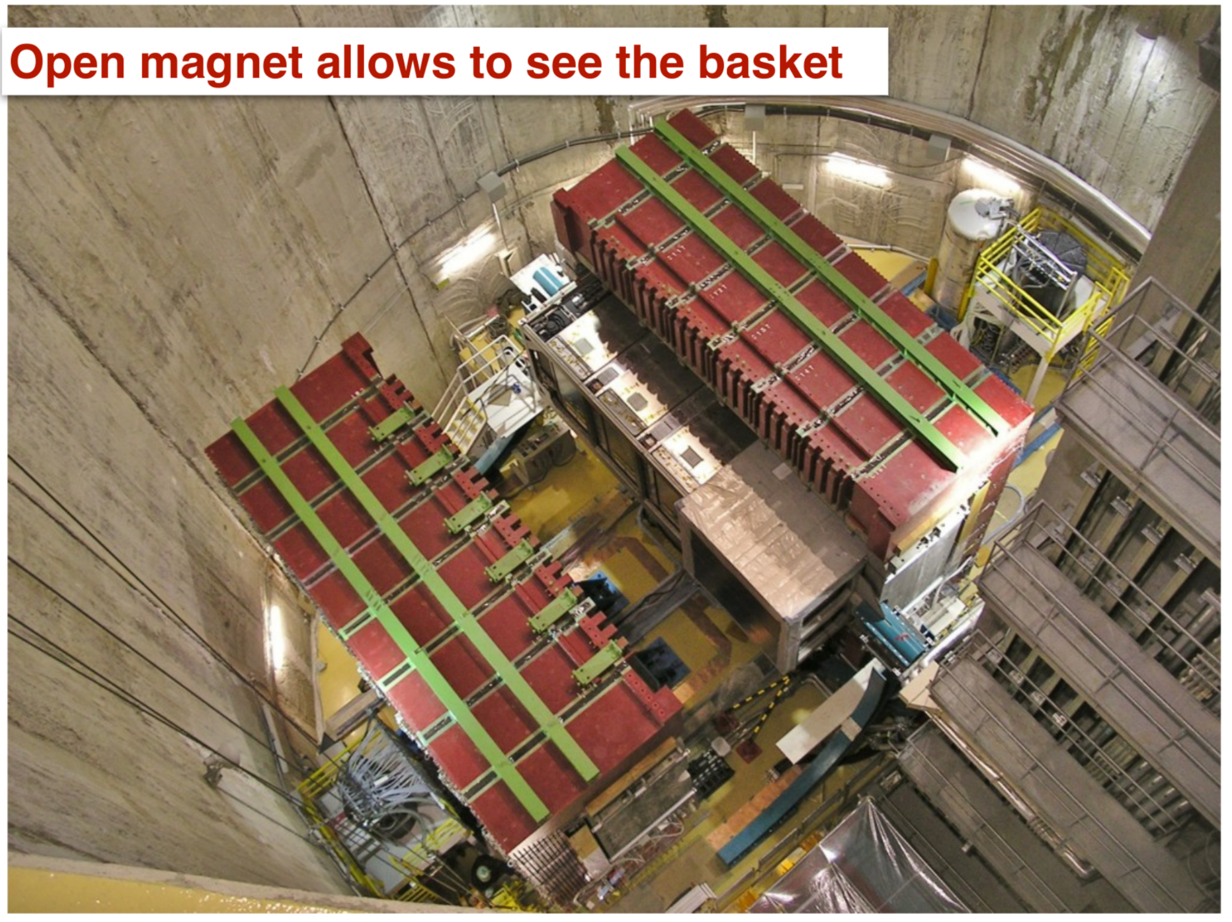
We measure data vs MC for all topologies to constrain model parameters (**shape**) and flux (**normalization**):



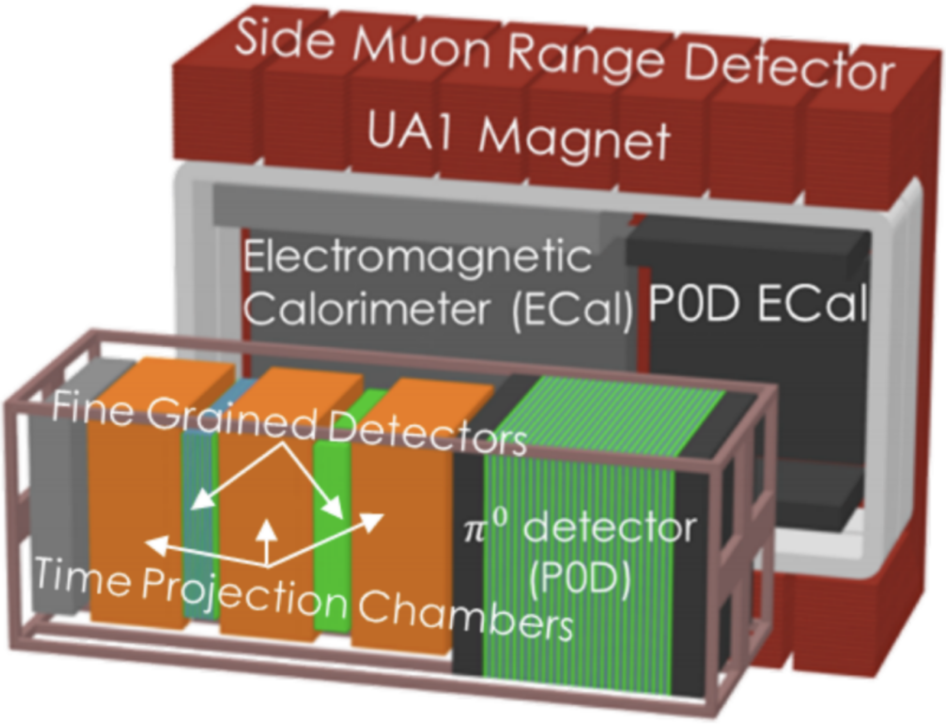




ND280

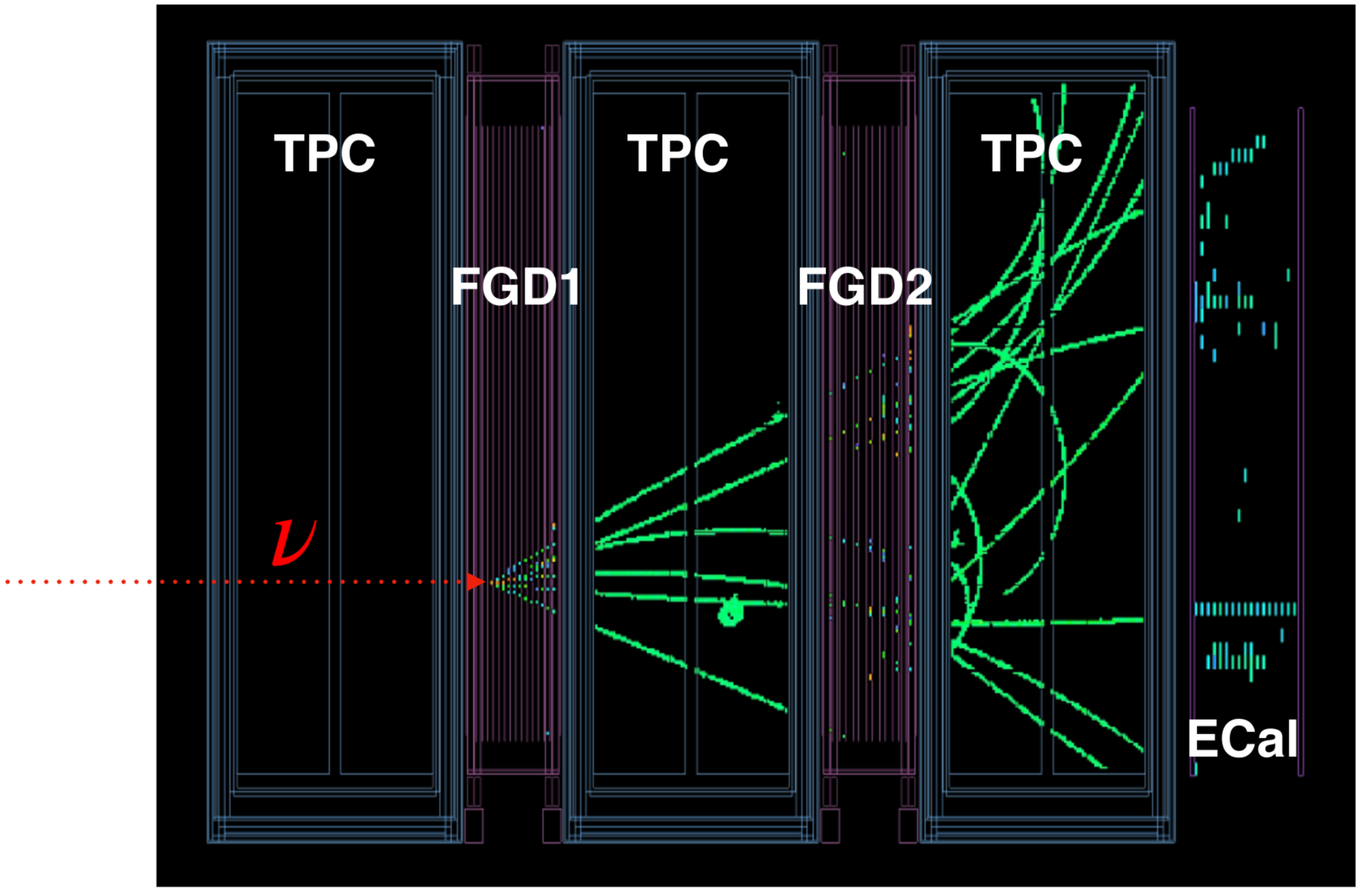


ND280



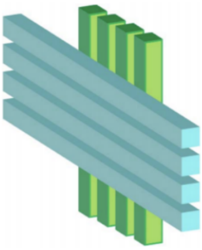
- ✦ Magnetized detector 0.2T
- ✦ inner volume (basket) fully surrounded by electromagnetic calorimeter
- ✦ Crucial sub-modules inside the basket

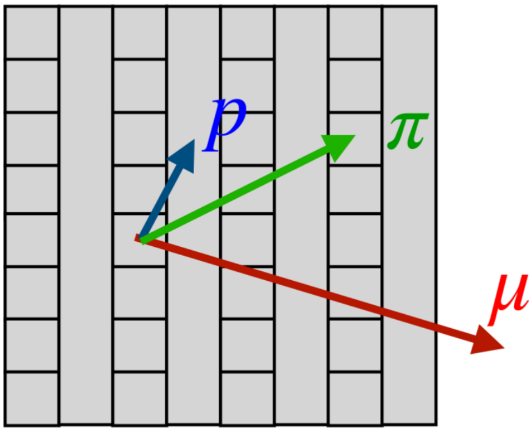
ND280

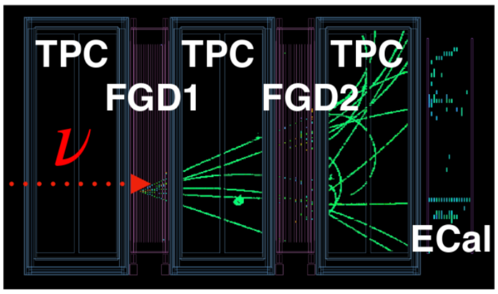


ND280 (FGDs)

FGDs







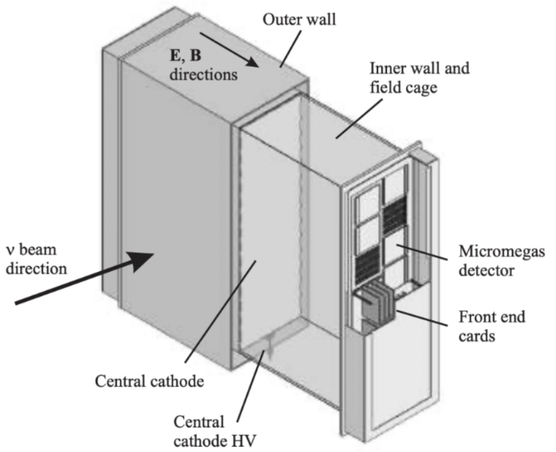
Provide a target mass for ν interactions (~1ton each)

Provide time reference (starts or ends in the FGD?)

Help with topology identification:
Count how many tracks do not scape the FGD: CC0π, CC1π, CCothers…

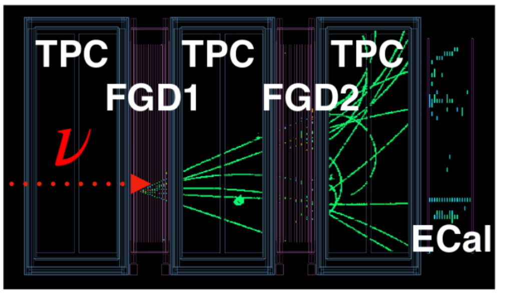
ND280 (TPCs)

Goal of the TPCs: PID

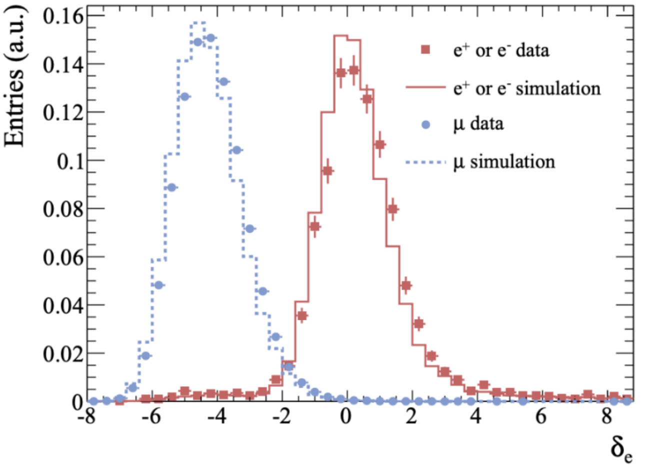


For each particle hypothesis:

1. We measure curvature (momentum)
2. For each momentum we compute expected dE/dx.
3. Expected vs Observed dE/dx pulls are used to perform PID



Electron hypothesis pull for electrons and muons



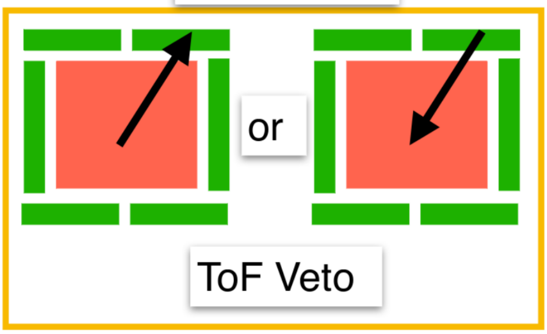
ECal & SMRD

ECal:

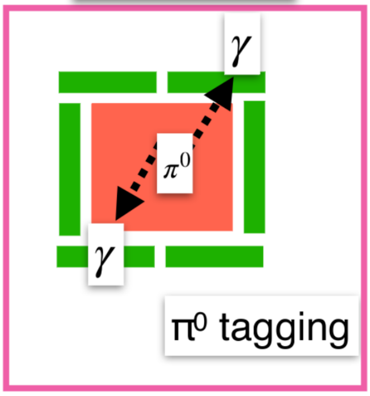
Ecal

basket

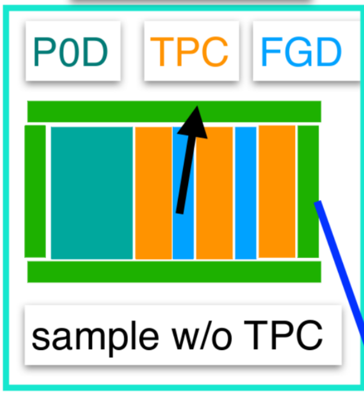
Front View

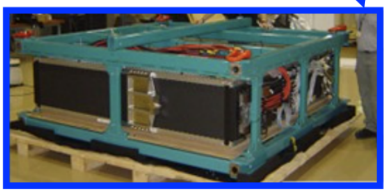


Front View



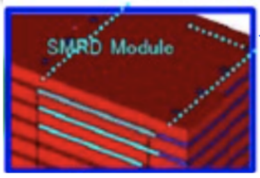
Side View



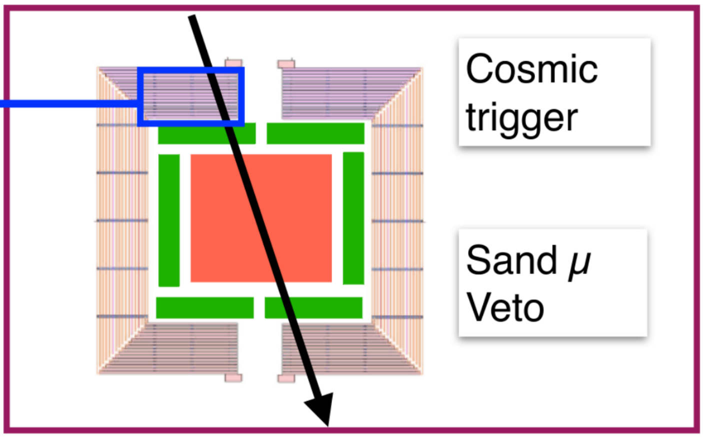


Blocks made of plastic scintillator bars

SMRD:

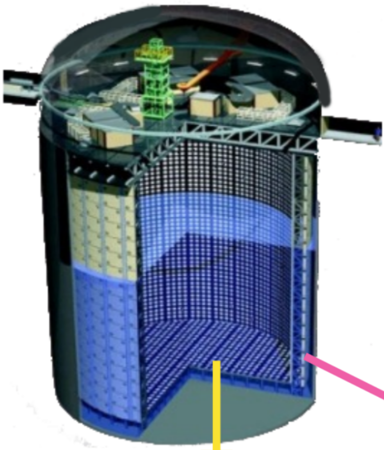


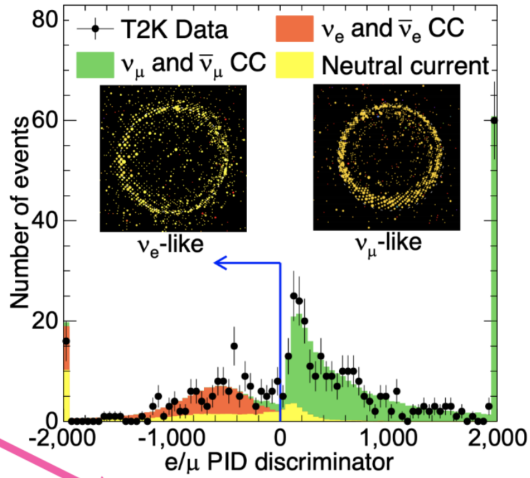
Scintillator panels in the magnet air gaps



T2K far detector: SuperKamiokande (SK)

22.5 kt FV Water Cherenkov Detector



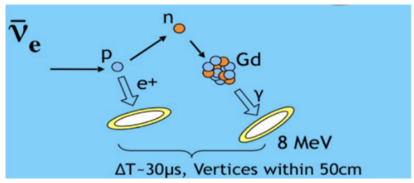


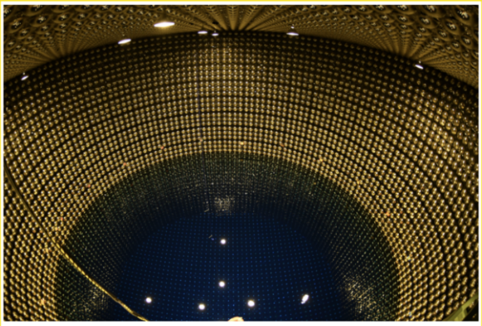
Particle ID via Cherenkov ring pattern:

Muons → **Sharp Rings**

Electrons → **Fussy Rings**

Recently SK phase V started:

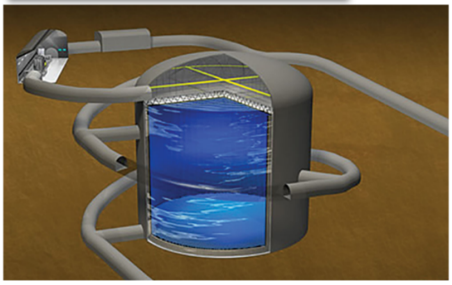




11,000 20" PMT inner detector 40% photo-coverage

2,000 8" PMT outer detector
Cosmic veto/exiting particles

Future (2027) HyperK



190 kt FV Water Cherenkov Detector

T2K oscillation measurements

With all elements under control:

$$\frac{N^{far}_{evts}(\overrightarrow{\theta}^{reco}_{\nu})}{N^{near}_{evts}(\overrightarrow{\theta}^{reco}_{\nu})} = \frac{\int \sigma(E_{\nu})\phi^{far}(E_{\nu})P^{far}(\overrightarrow{\theta}^{reco}_{\nu} \,|\, E_{\nu})P_{osc}(E_{\nu})dE_{\nu} + Bkg^{near}(\overrightarrow{\theta}^{reco})}{\int \sigma(E_{\nu})\phi^{near}(E_{\nu})P^{near}(\overrightarrow{\theta}^{reco}_{\nu} \,|\, E_{\nu}) + Bkg^{far}(\overrightarrow{\theta}^{reco})}$$

We do our OA studies:

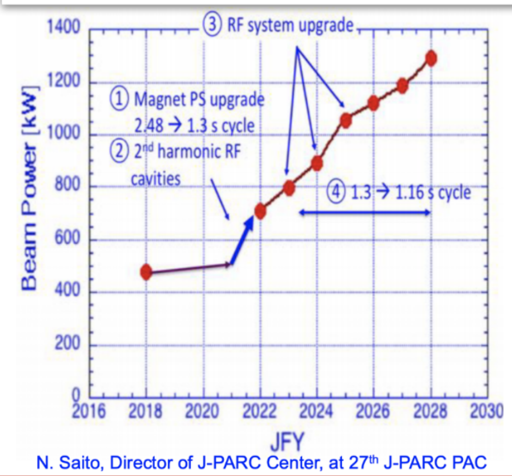
Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

Nature 580, 339–344(2020)

After >10 years, what is the future of T2K?

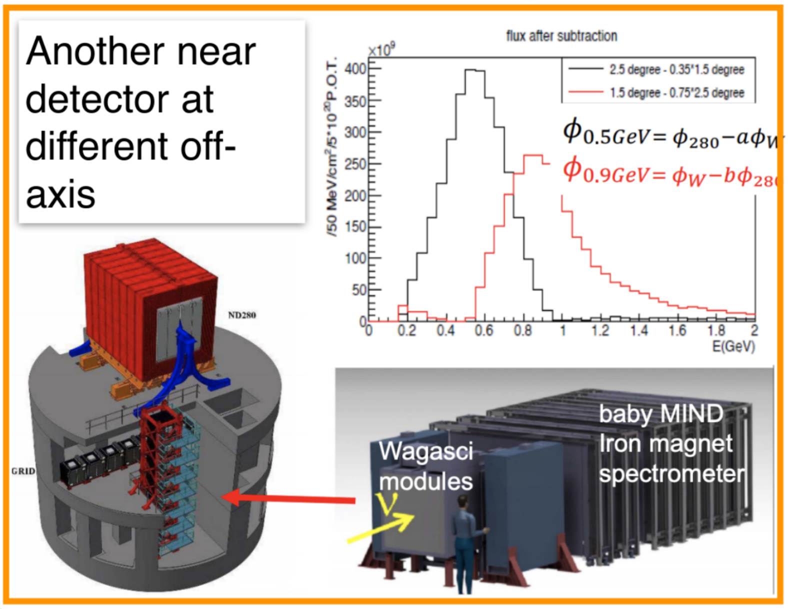
T2K-II

Beam power increase ~x2.6!



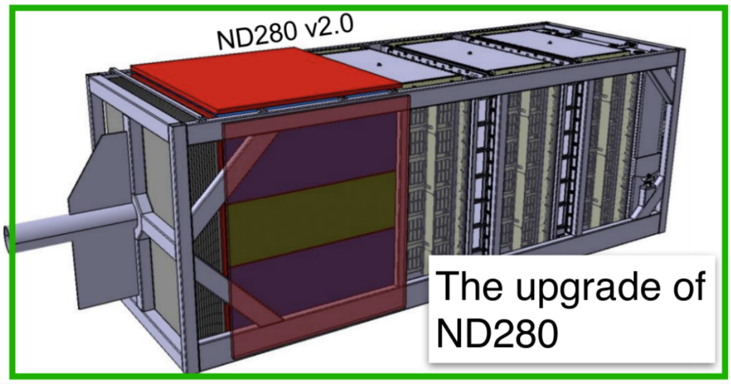
N. Saito, Director of J-PARC Center, at 27th J-PARC PAC

Another near detector at different off-axis



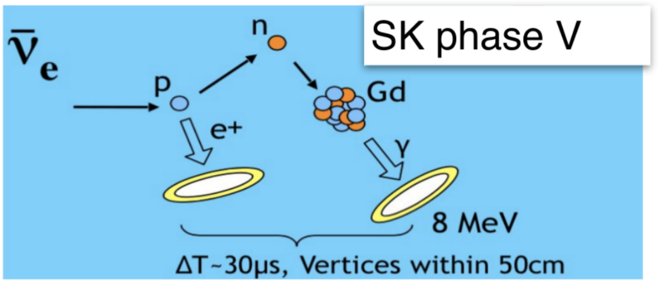
$\phi_{0.5GeV} = \phi_{280} - a\phi_W$

$\phi_{0.9GeV} = \phi_W - b\phi_{280}$



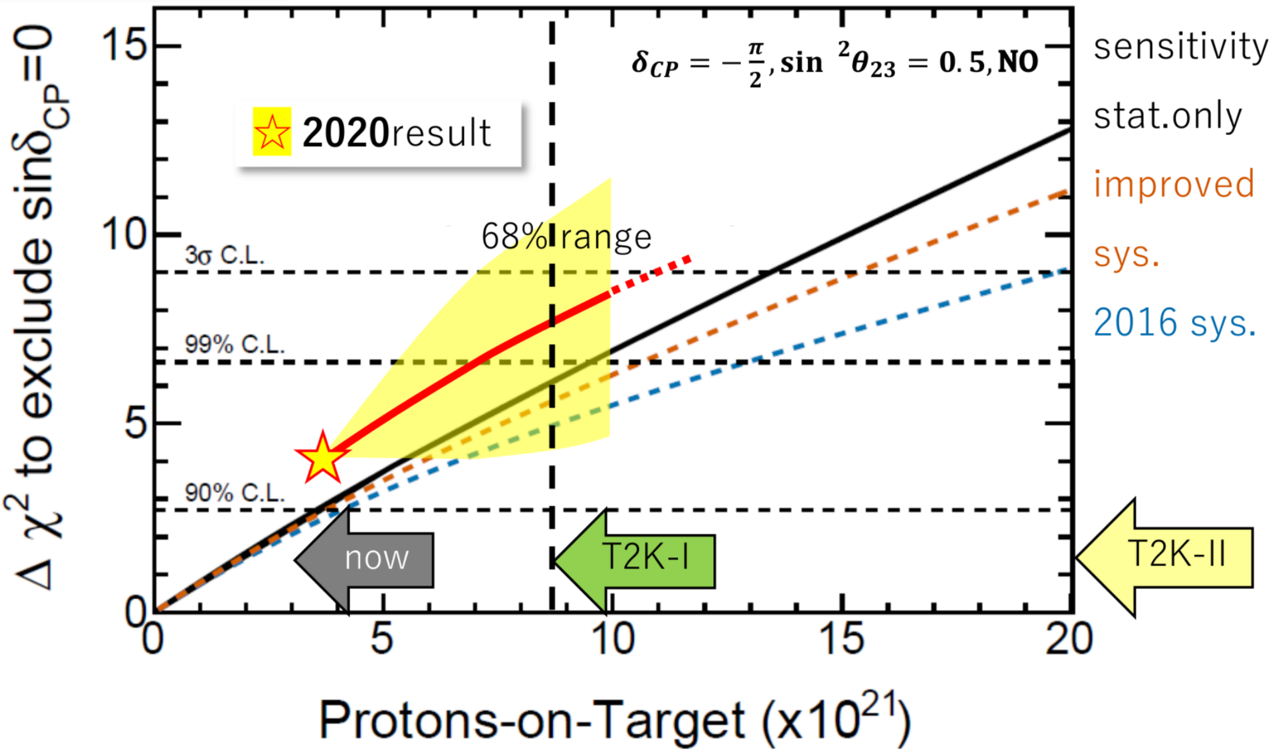
The upgrade of ND280

SK phase V



T2K-II

Influence in δ_{CP}

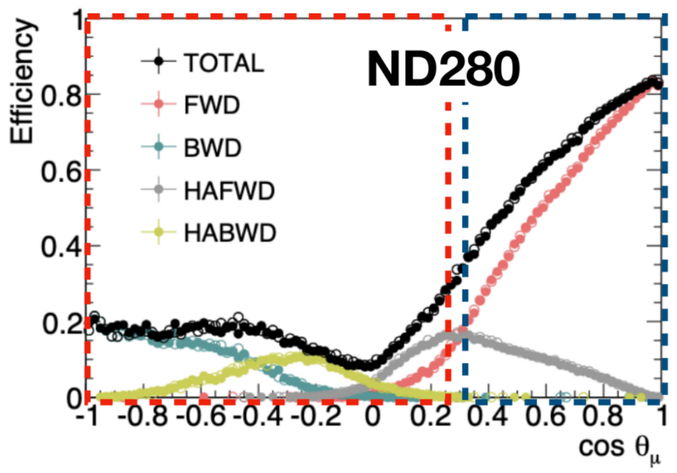


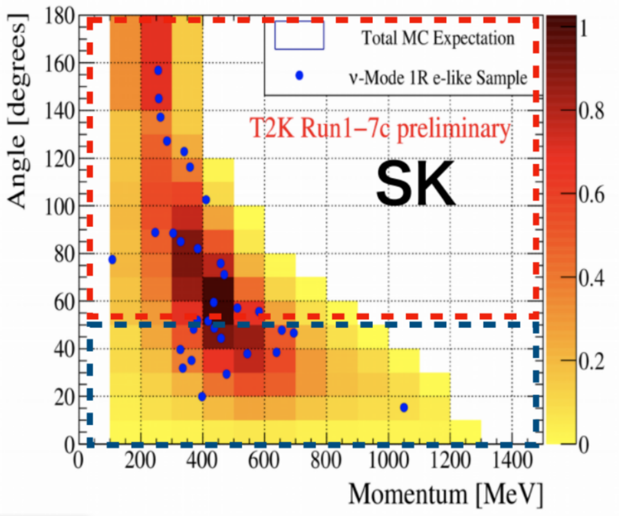
This does not include Hyper Kamiokande! (first T2K-II, then T2HK)

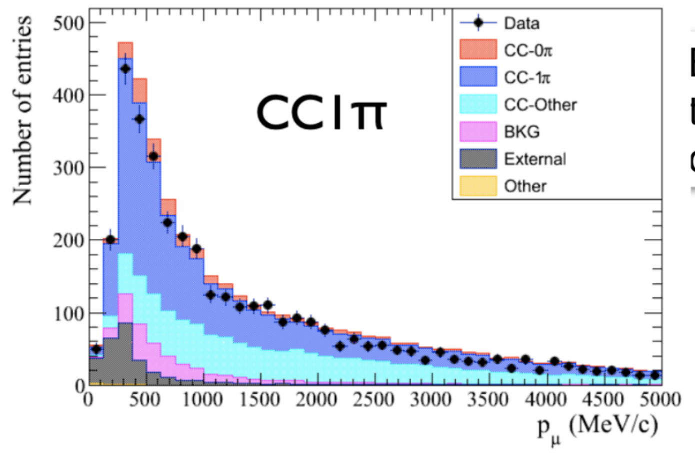
The ND280 upgrade project

Limitations of current ND280 detector

Efficiency is low in important phase-space





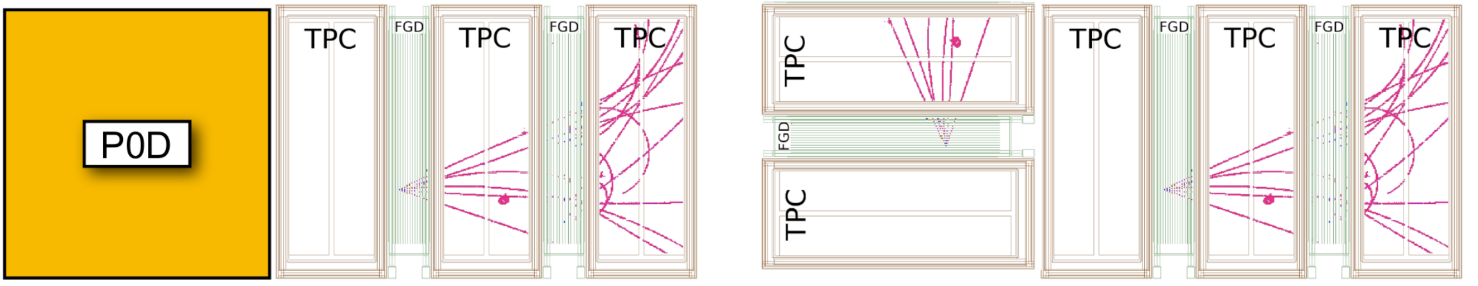


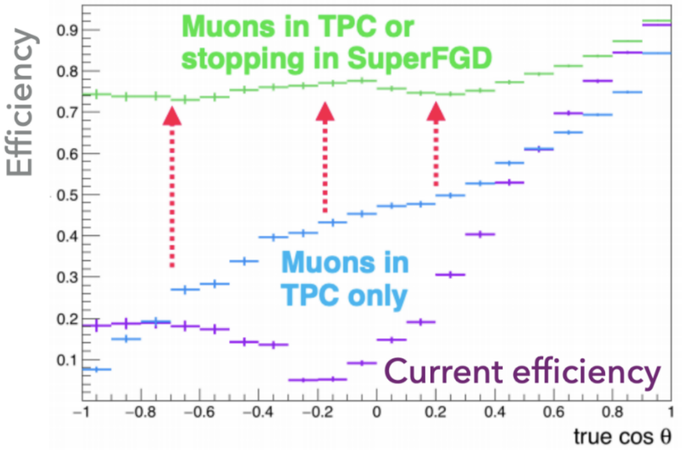
Bad purity for topologies different CC0π

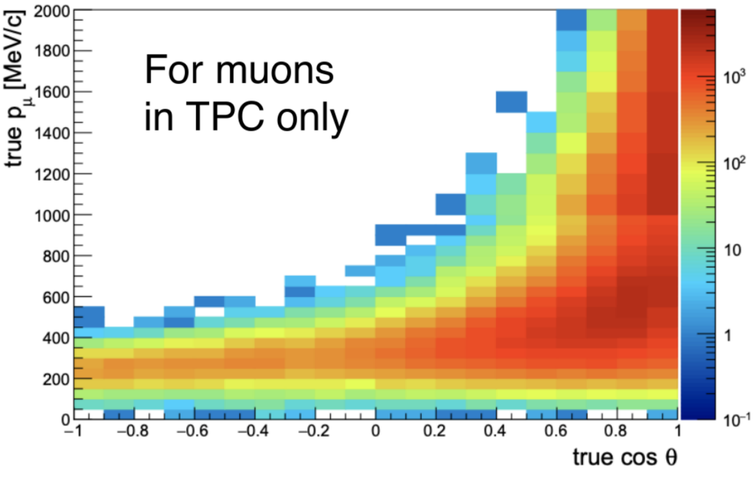
To validate models (reduce systematics) we need better target tracking and improved angular efficiency

ND280 upgrade improved angular eff.

To improve the efficiency we will add a complementary sandwich

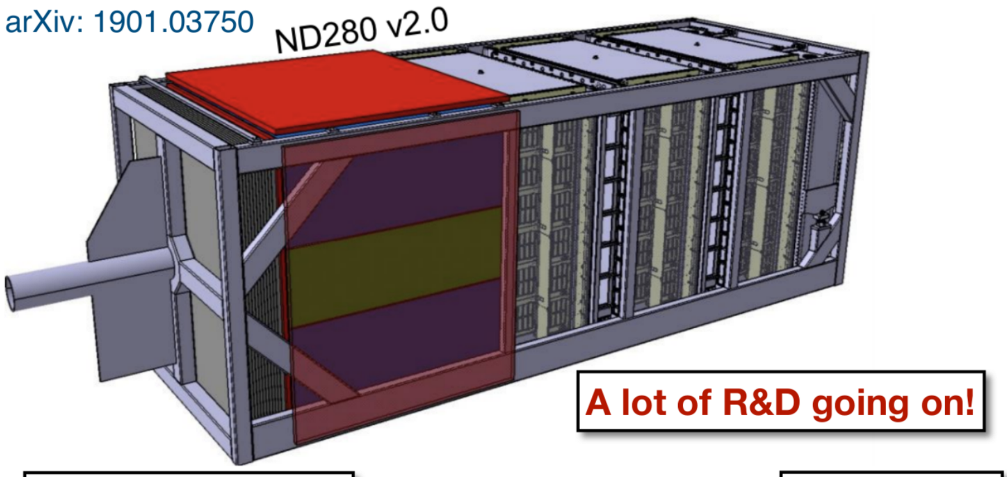


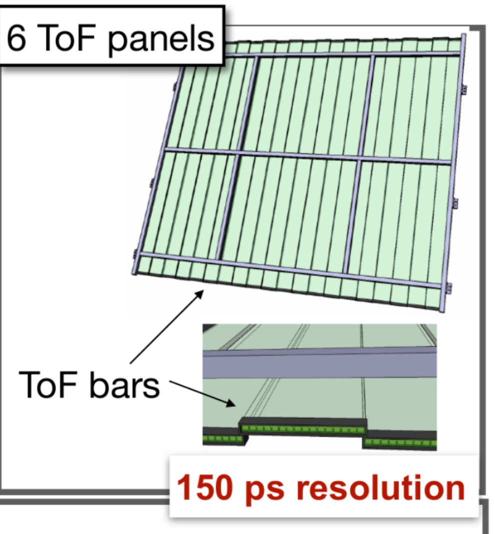


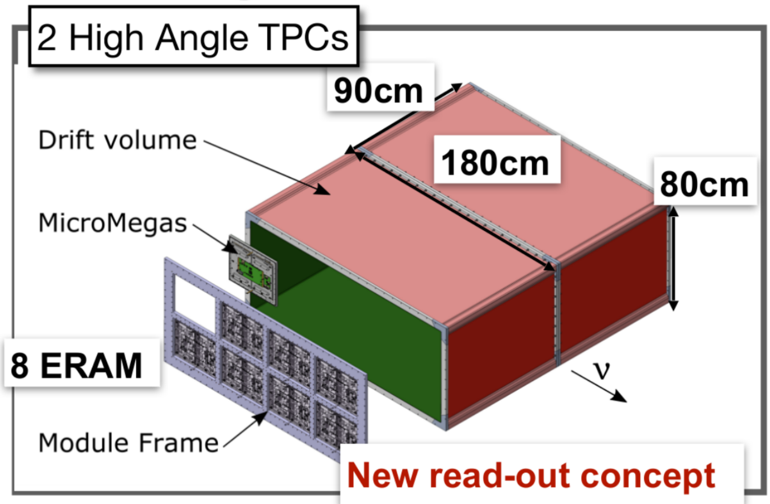


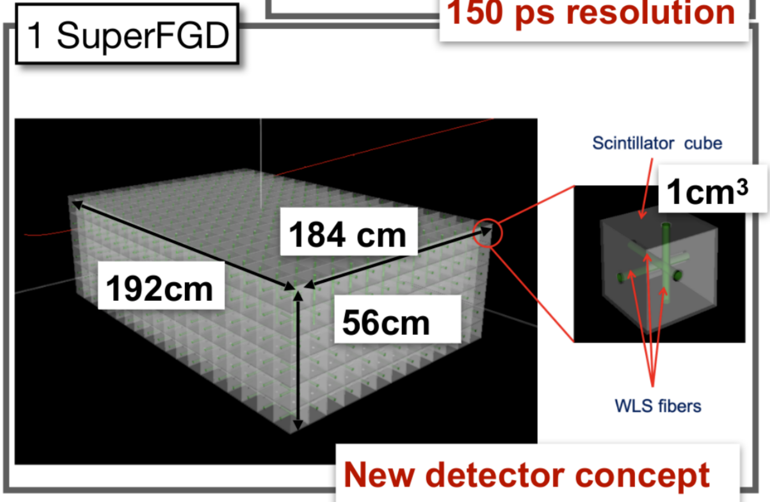
The ND280 upgrade

arXiv: 1901.03750





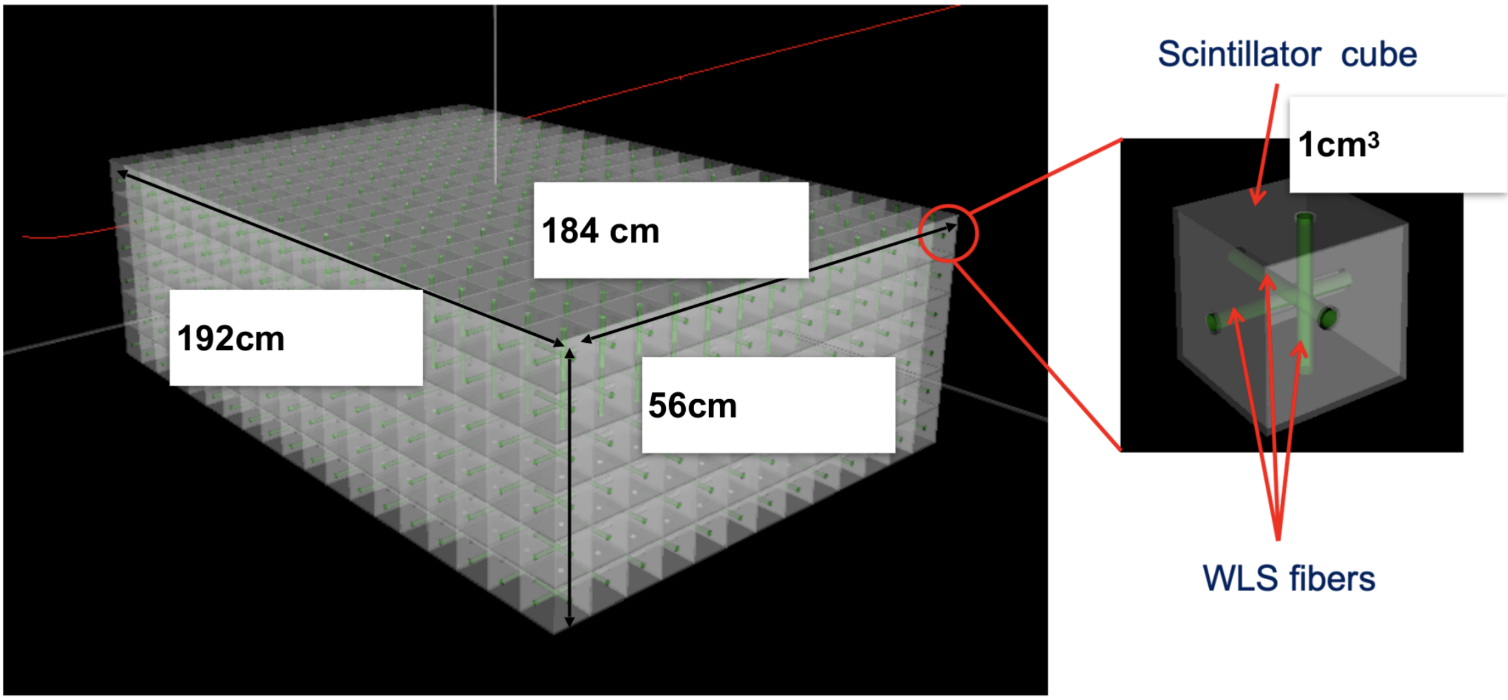




A new tracker concept (SuperFGD)

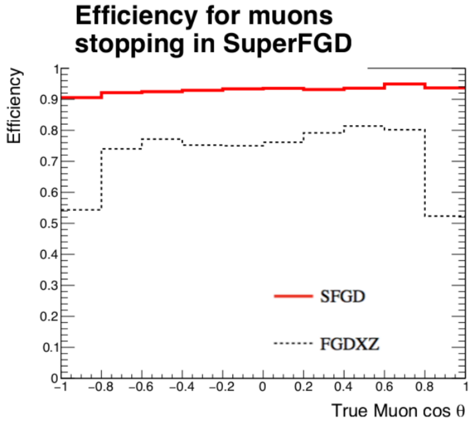
To improve granularity the new target will be a new 3D technology

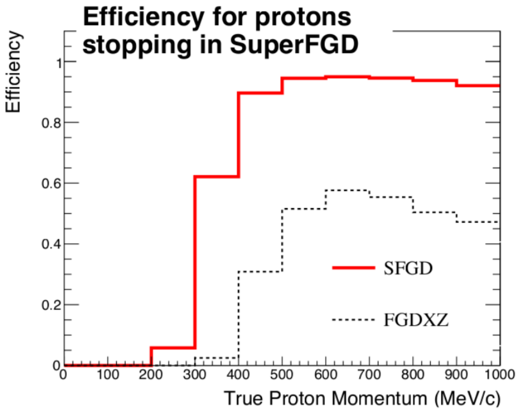
A fully-active fine-grained detector with three readout views JINST 13, P02006 (2018).



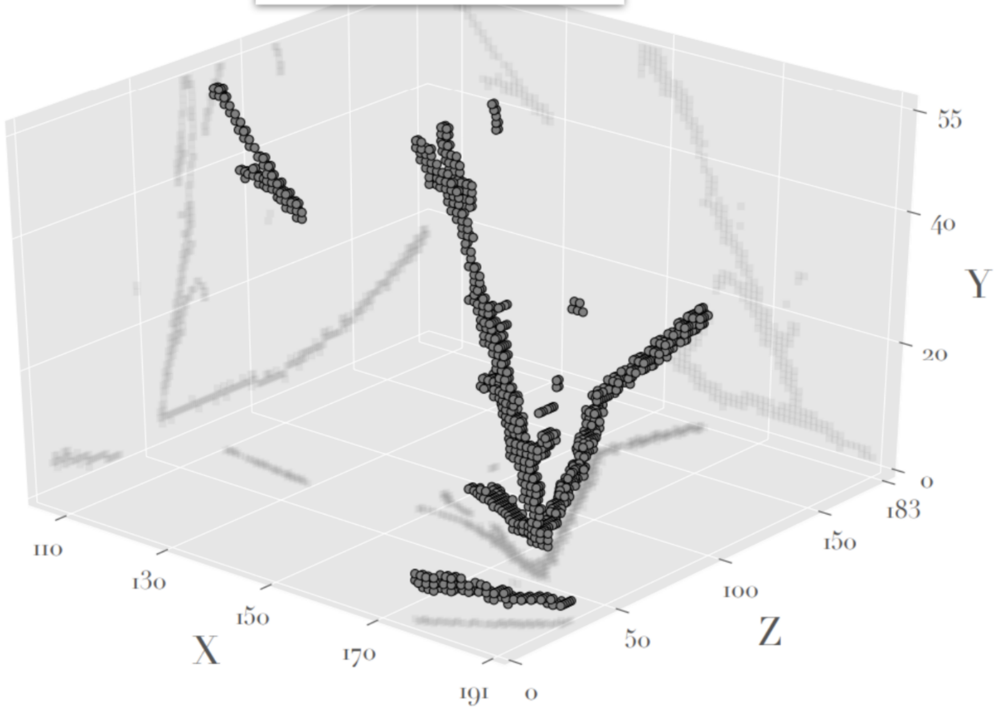
A new tracker concept (SuperFGD)

To improve granularity the new target will be a new 3D technology





3D concept



The ND280 upgrade

Estimated improvement in systematics:

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
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

Estimated improvement on statistics (x2):

Selection	Current-like	Upgrade-like
ν_μ (ν beam)	100632	199605
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	32671	60763
ν_μ ($\bar{\nu}$ beam)	16537	29593

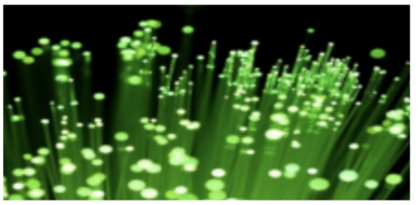
This does **not** include possible future analysis developments or model refinements based on new cross-section analysis!

SuperFGD R&D and final design

The SuperFGD: initial tests

PTP + POPOV + chemical edging + drilling

+



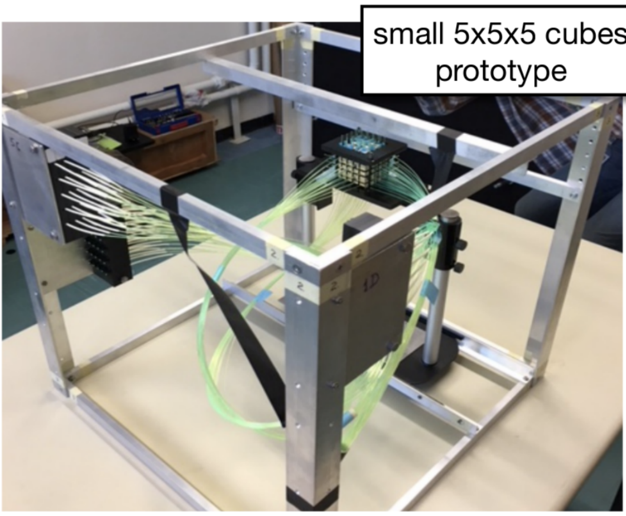
WLS Kuraray Y11 S-type

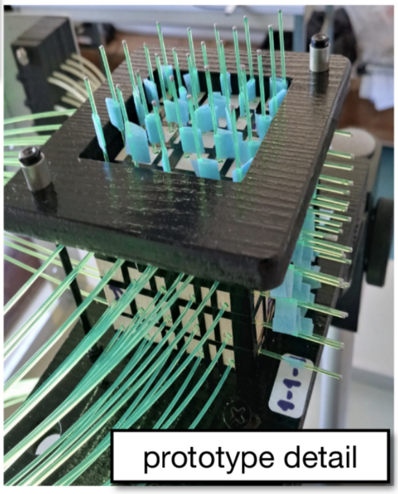
+

S13360-1325PE
(1.3x1.3mm^2)
2668 pixels
dark rate 70kHz
PDE=25%(500nm)

The SuperFGD: initial tests

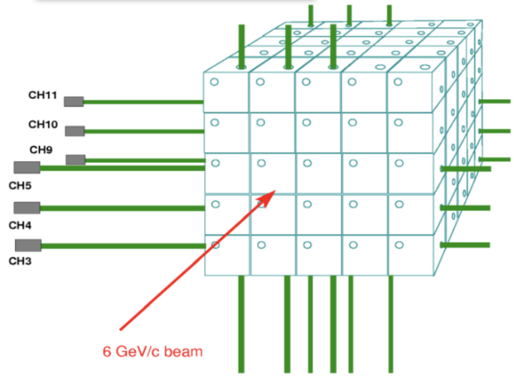
small 5x5x5 cubes prototype



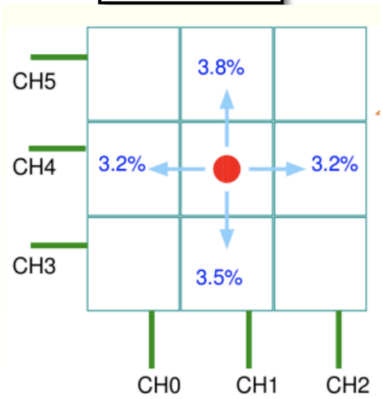


prototype detail

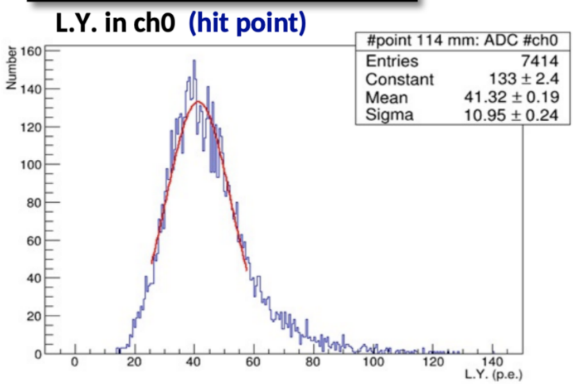
beamtest configuration



crosstalk



MIP light yield ~50p.e.



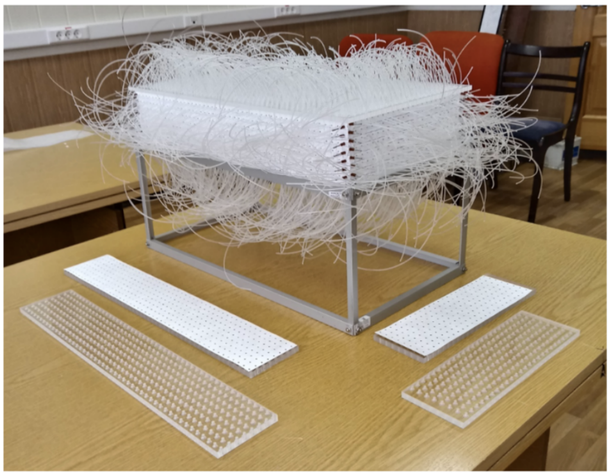
time resolution

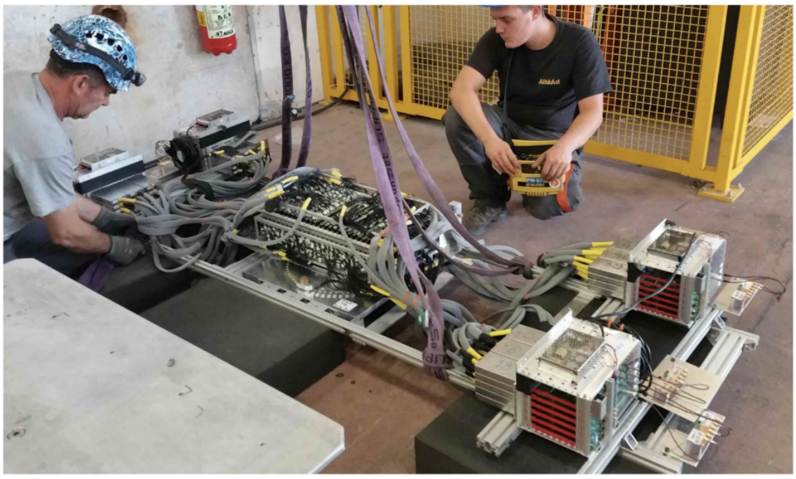
using fast (5GHz) sampling

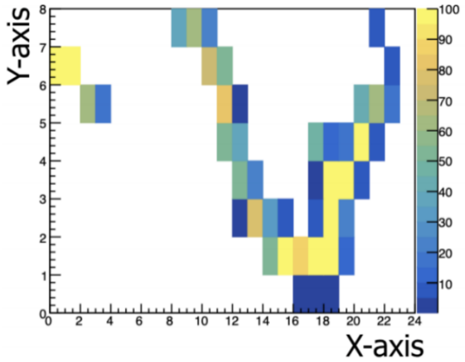
- $\sigma_t \sim 0.92$ns (1 fiber)
- $\sigma_t \sim 0.68$ns (2 fiber)

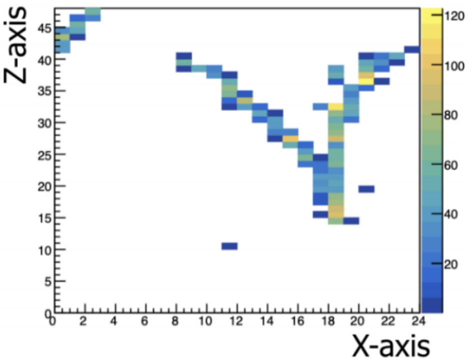
The SuperFGD: prototype-II

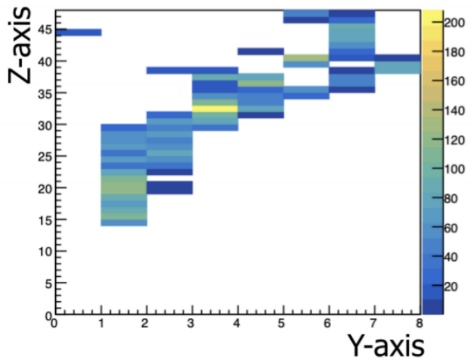
The SuperFGD Prototype Charged Particle Beam Tests arXiv: 2008.08861, submitted to JINST





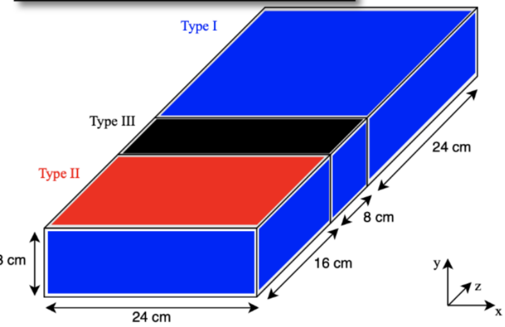






prototype-II: MPPCs

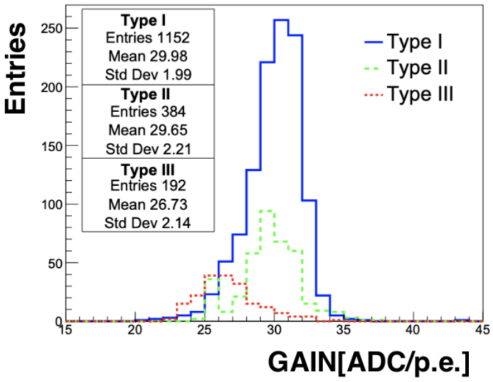
24x8x48 cubes

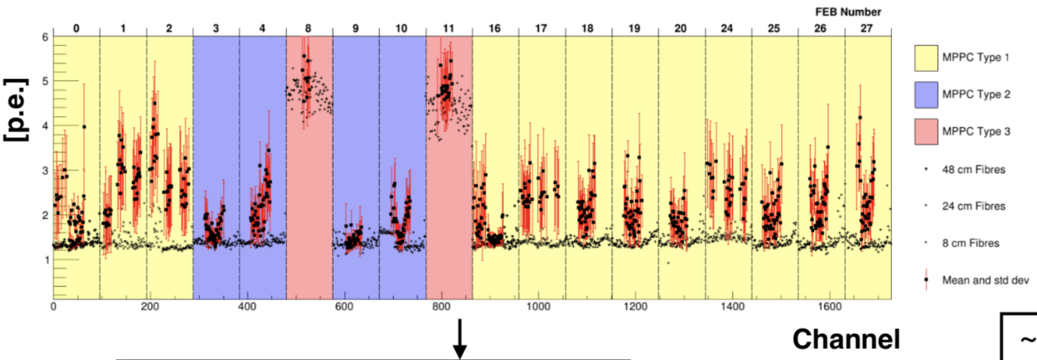


3 different MPPCs where tested

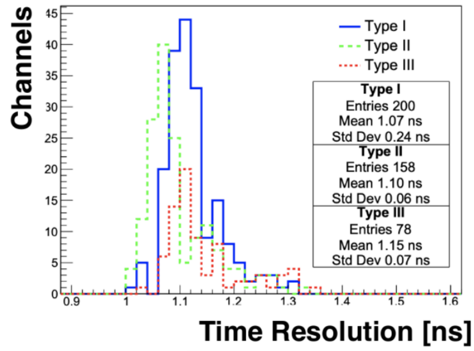
- Final SuperFGD will use Type I

Description	Type I	Type II	Type III
Manufacturer ref.	S13360-1325CS	S13081-050CS	S12571-025C
No. in Prototype	1152	384	192
Pixel pitch [μm]	25	50	25
Number of pixels	2668	667	1600
Active area [mm^2]	1.3×1.3	1.3×1.3	1.0×1.0
Operating voltage [V]	56–58	53–55	67–68
Photon detection eff. [%]	25	35	35
Dark count rate [kHz]	70	90	100
Gain	7×10^5	1.5×10^6	5.15×10^5
Crosstalk probability [%]	1	1	10





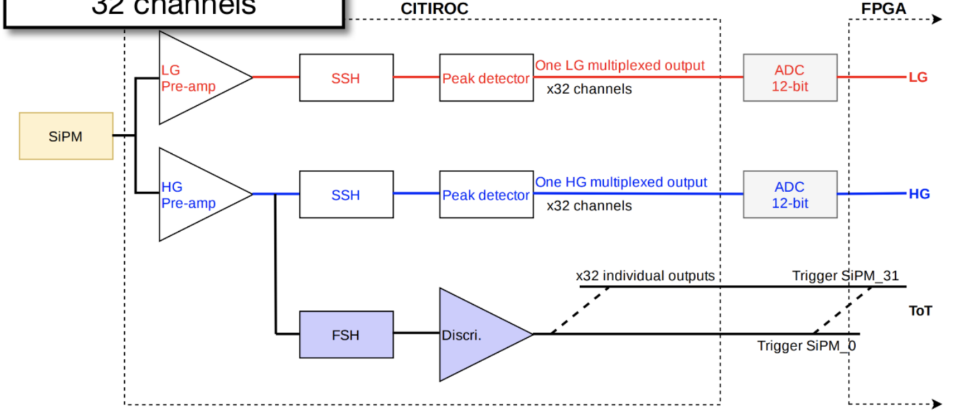
~1p.e thresholds for MPPC type I



~1.1 ns channel resolution (or better)

prototype-II: electronics (CITIROC)

Each CITIROC reads 32 channels



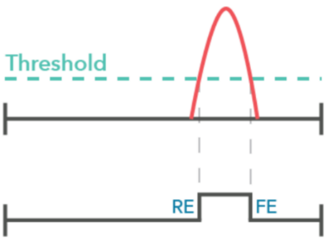
Each MPPC measurement provides three different reads:

HG: high gain (a.k.a high precision low dynamic range).

LG: low gain (a.k.a high dynamic range but lower precision).

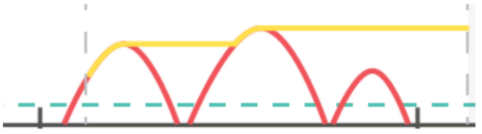
ToT: lower precision than LG but 'limitless' dynamic range.

If one channel above the threshold all 32 channels begin to be read during time T1



ToT = FE-RE

If several Rising Edges are recorded during the same T1, individual hit amplitudes are reconstructed using ToT



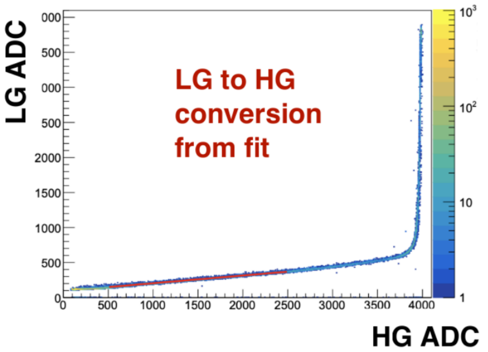
otherwise we use either HG or LG depending on ADC counts.

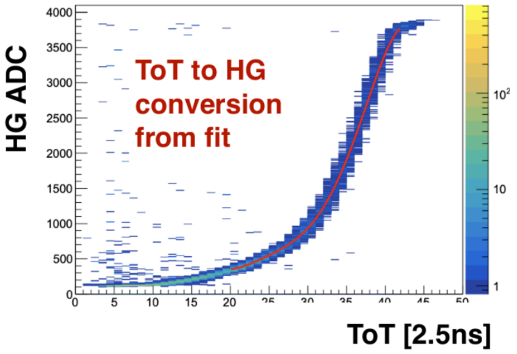
After T1, there is a dead time of ~10μs where only ToT is available.

- Fine for ND280 event rate and channel occupancy.

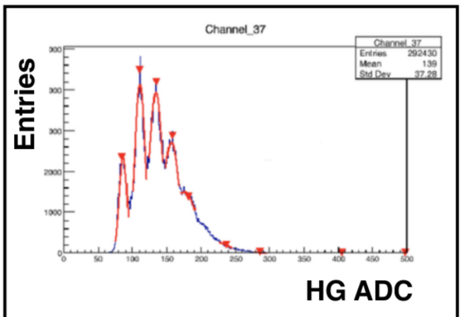
prototype-II: calibration

Convert LG and ToT to HG

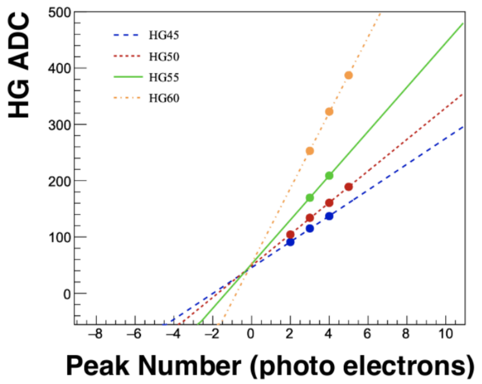




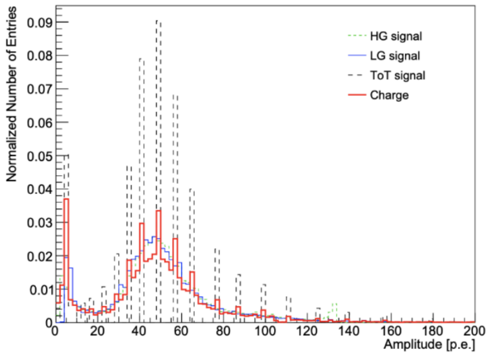
For each electronic channel do finger plot

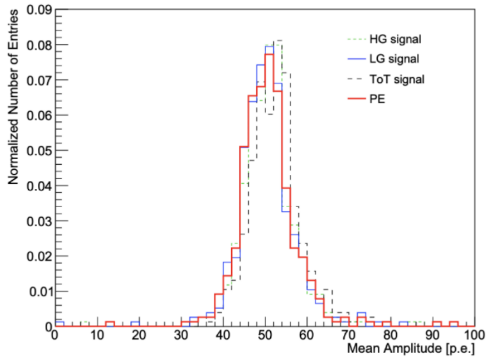


Use Finger plot to convert HG to photo electrons



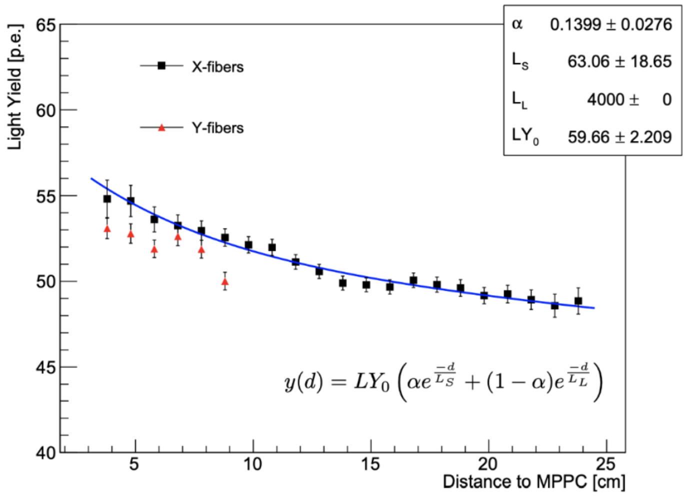
Results





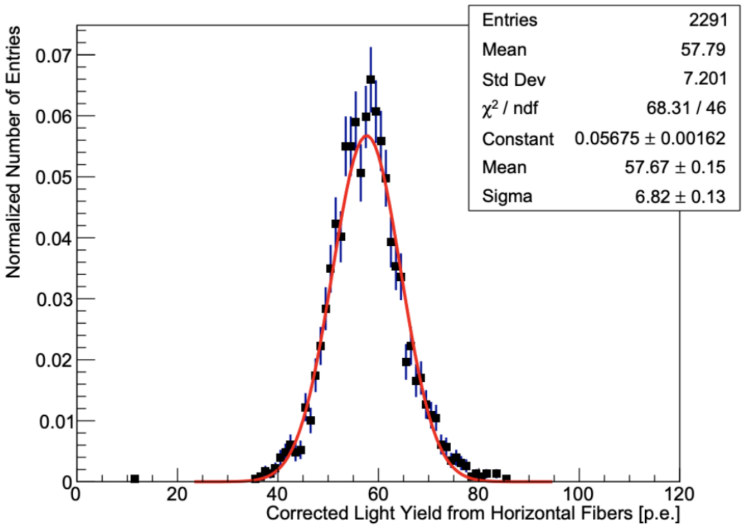
prototype-II: attenuation

MIPs have high light yield >50p.e and > 30p.e at maximum fiber length



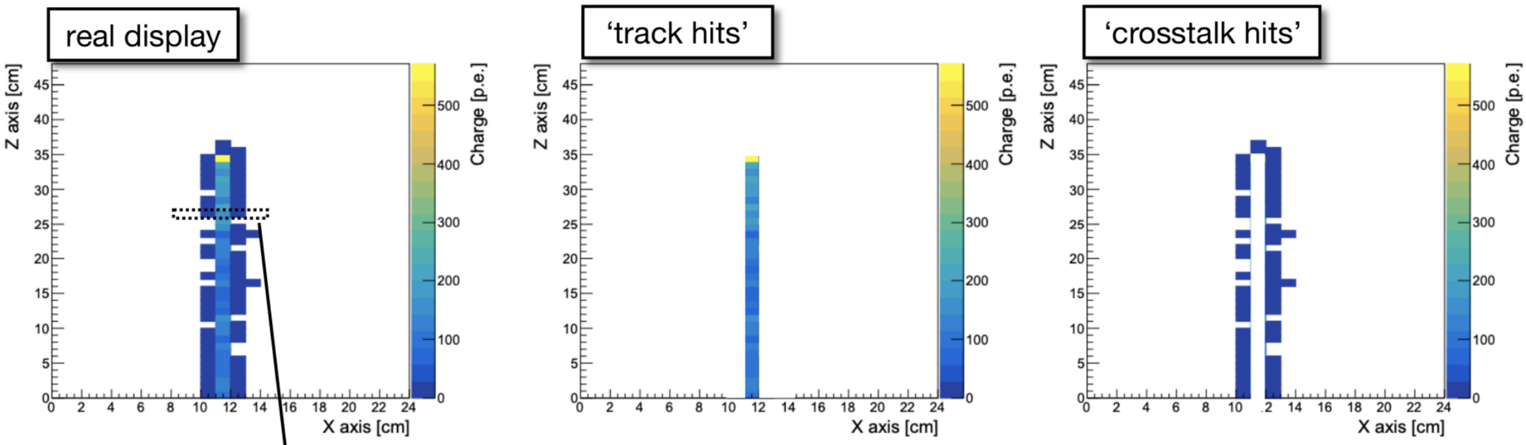
Measured with tracks, can be done with cosmics with installed SuperFGD

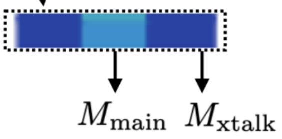
12% channel uniformity (MPPC type 1)

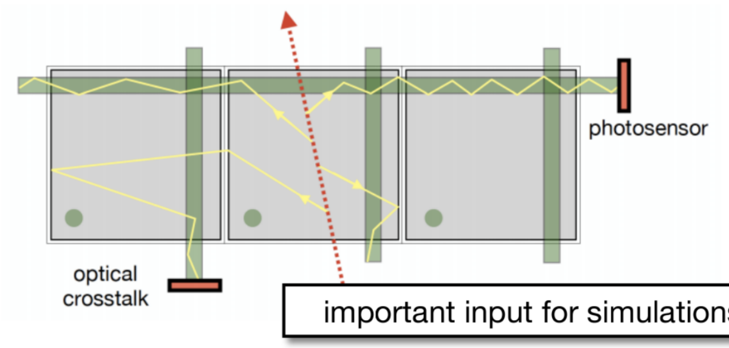


This might improve doing inter-calibration using cosmics.
Important for stand-alone SuperFGD dE/dx measurements

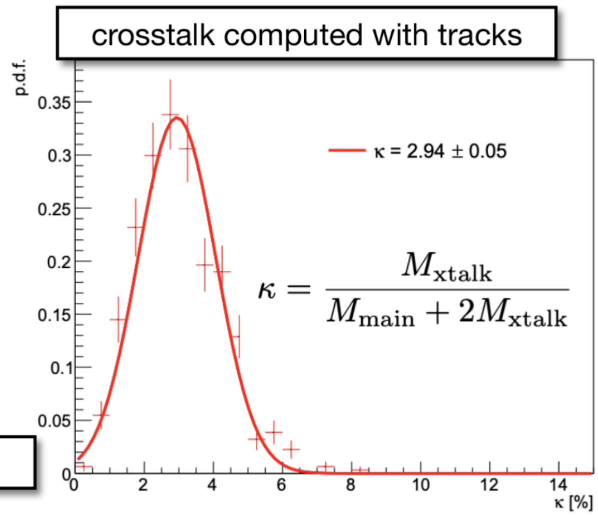
prototype-II: crosstalk





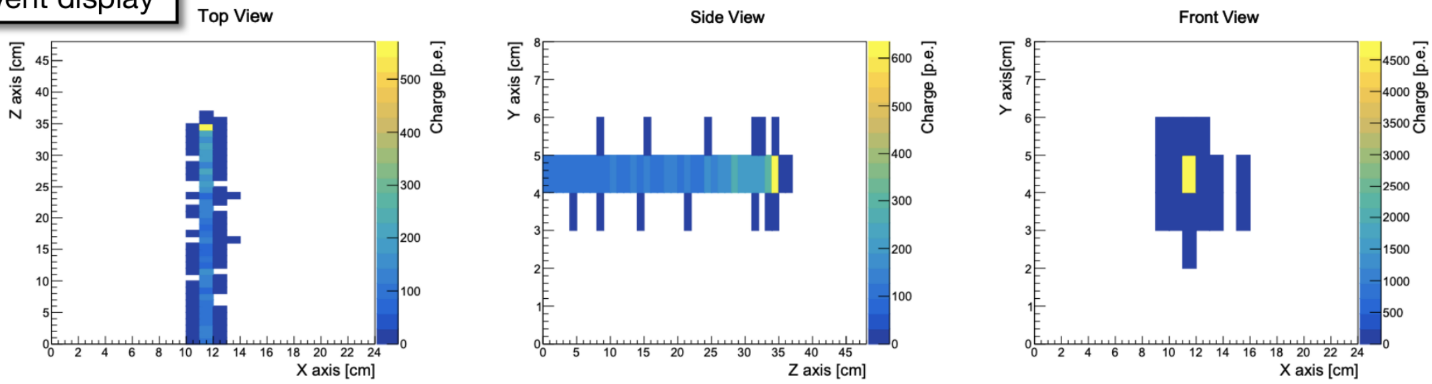


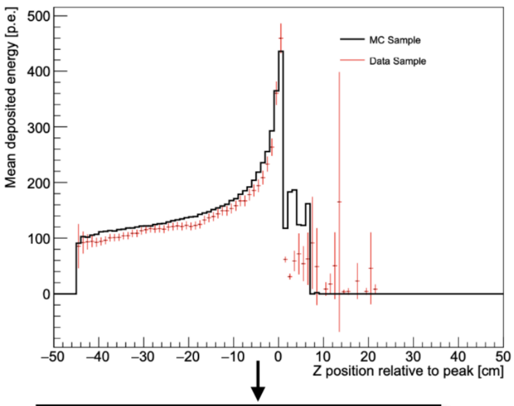
important input for simulations

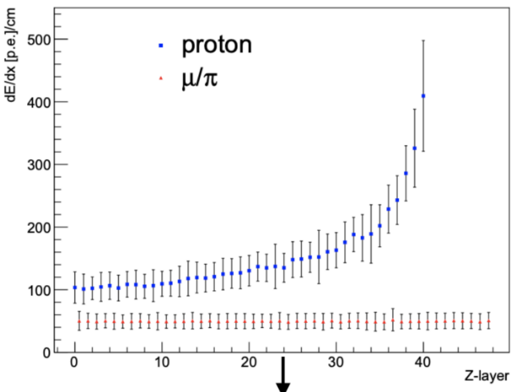


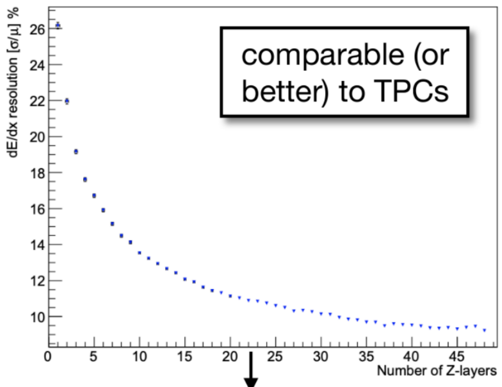
Prototype (CERN 2018) dE/dx

data event display









Stopping protons agreement with simulations ✓

Large μ-Proton separation at 0.8 GeV/c ✓

very high dE/dx resolution if ionization is ~stable (MIPs) ✓

The SuperFGD: cube production

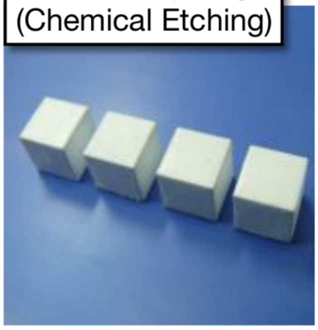
2M cubes are necessary

Injection

Cube size:
$10{,}025mm \pm 6\mu m$

PTP + POPOV

Surface Opacity (Chemical Etching)

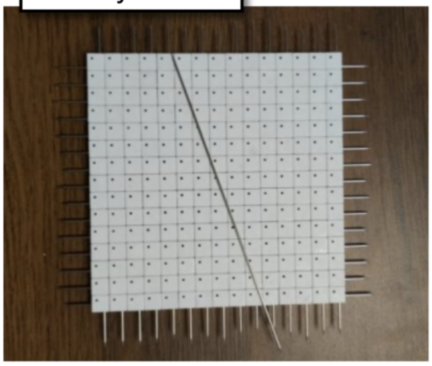


Cube size:
$10{,}25mm \pm 48\mu m$

Drilling

Hole alignment <50μm

Quality Check



cost-effective choices with good performance.

Production by UNIPLAST (Russia)
~100k month → **~2M in 2years**!

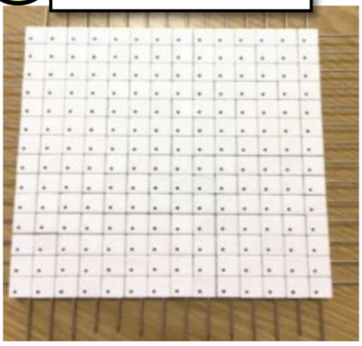
Removing of bad cubes

- Form (x,y) plane of 15x15 cubes using 1.4 mm diameter stainless steel needles
- Remove bad cubes
- Rotate by 90 deg each cube
- Insert needles, remove bad cubes

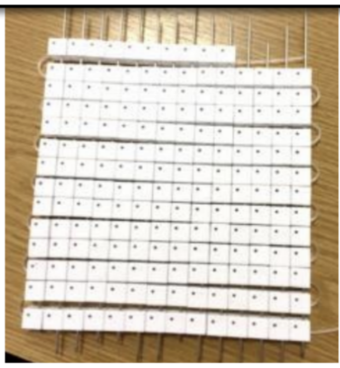
~5% of cubes rejected

The SuperFGD: cubes assembly

1 Use 1.4mm metallic needles



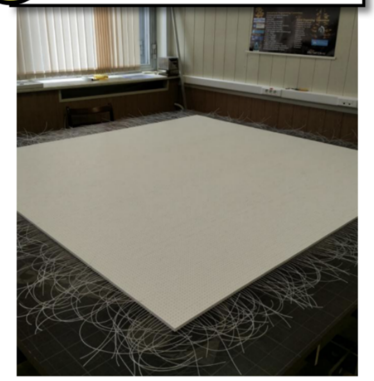
2 Remove needles and insert fishing lines (1.3mm flexible)



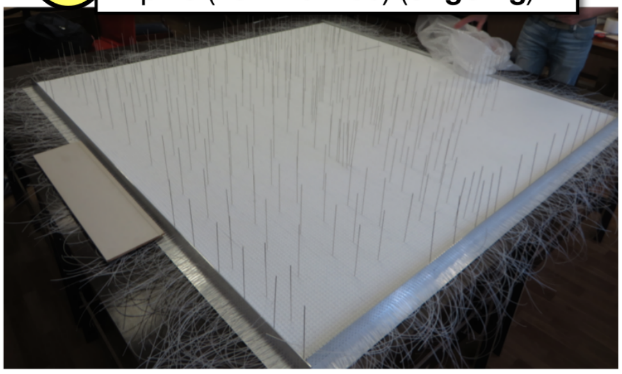
3 Remove remaining pins to form 1D arrays of 192 cubes

4 Align 1D arrays in 2D planes (194x184)

5 Form 2D planes (194x184)

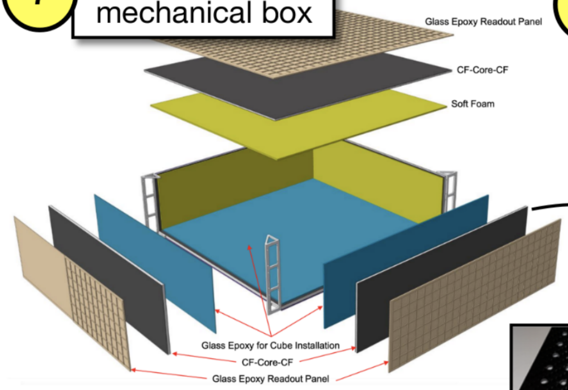


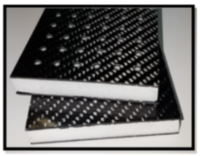
6 Check 3D alignment with metallic pins (194x184x56) (**ongoing**)



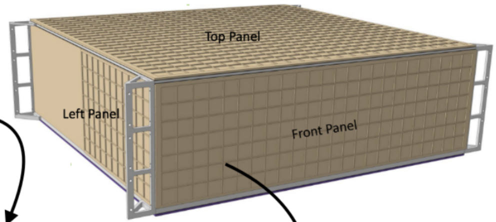
The SuperFGD: box and read-out

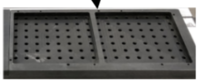
7 Prepare mechanical box





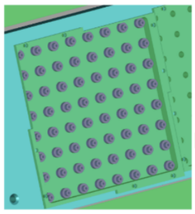
8 Mount SFGD stacking inside the box layer after layer and inserting fishing lines in box's holes



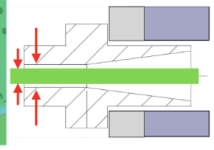


9 Replace fishing lines by WLS fibers

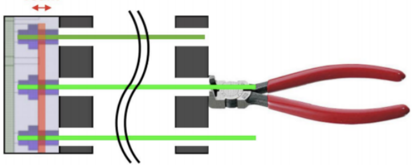
10 Add connector on one end



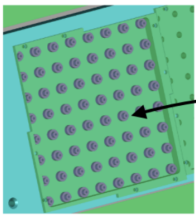
single connector xsec

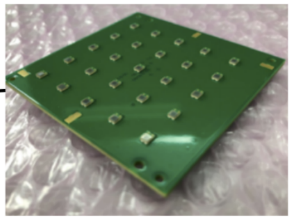


11 Cut fiber's other end

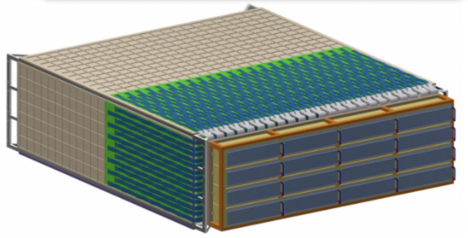


12 Clip 64 connector boards to MPPCs



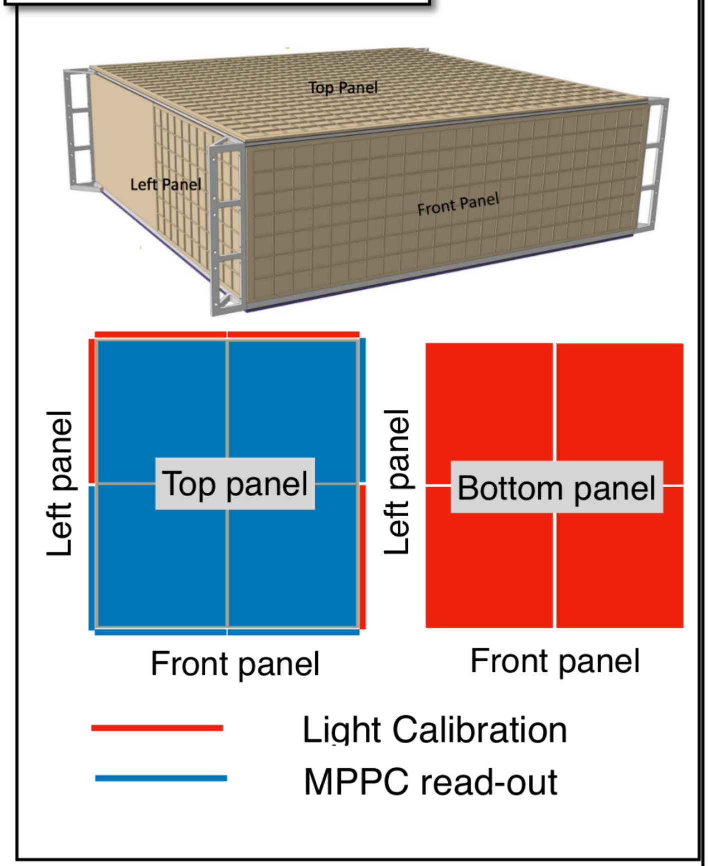


13 Add MPPC cables and electronics

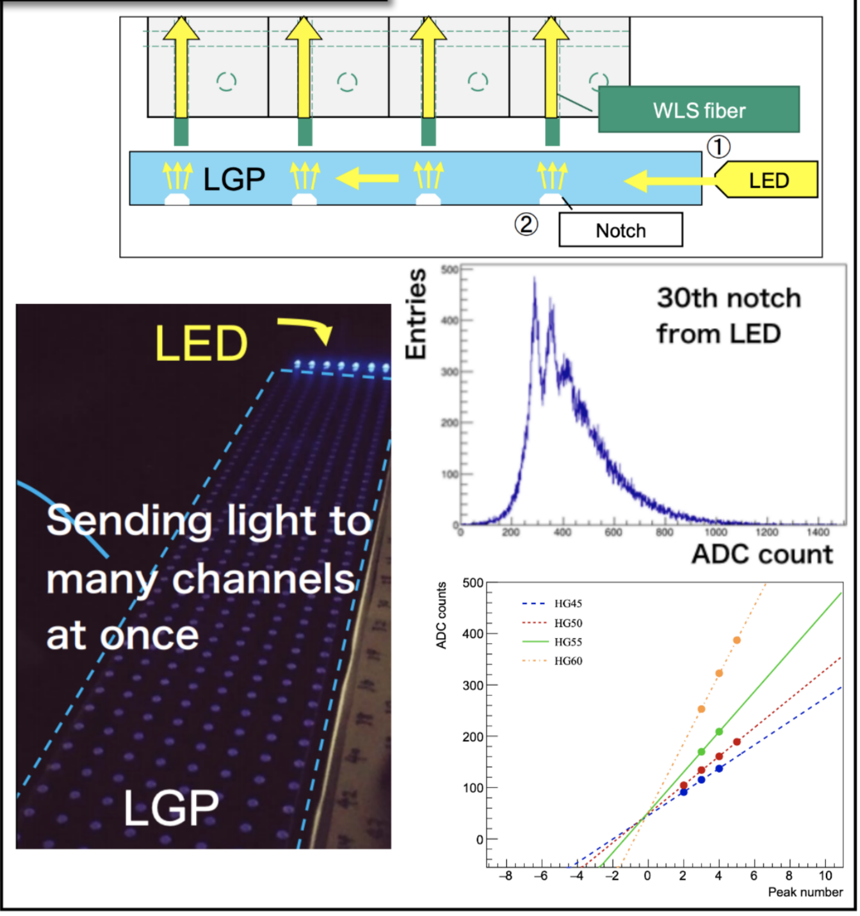


The SuperFGD: calibration system

calibration placement



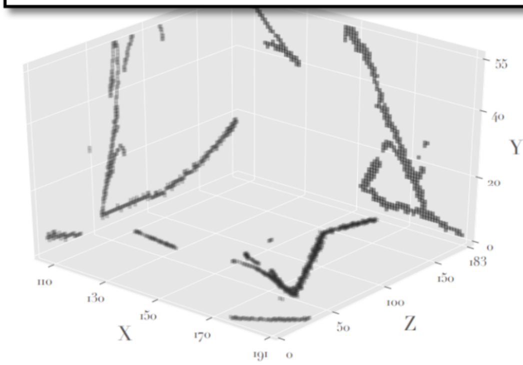
working principle



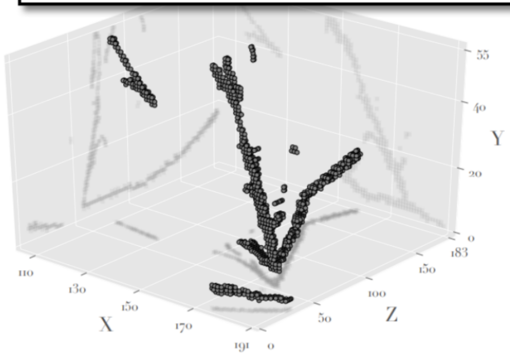
Towards reconstruction

3D reconstruction and signal classification

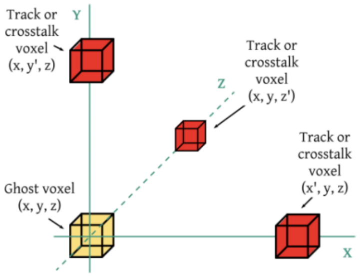
We start with 3 orthogonal 2D projections



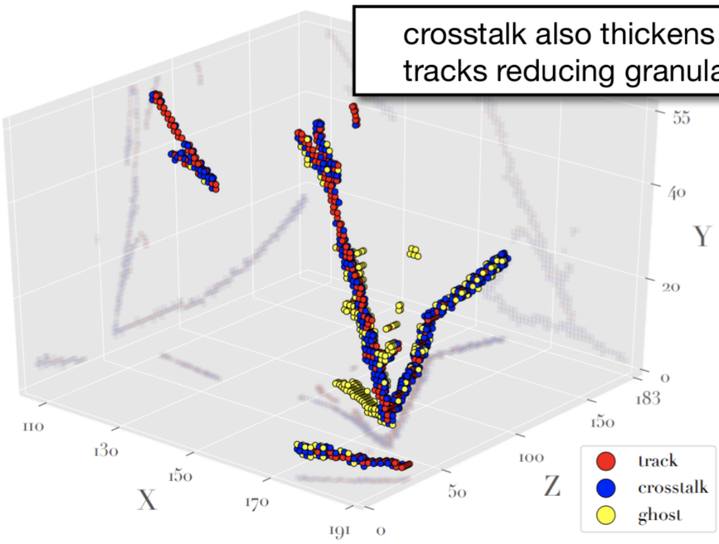
We match 2D hits into 3D hits



Geometrical ambiguities generate fake 3D hits (‘ghosts’)



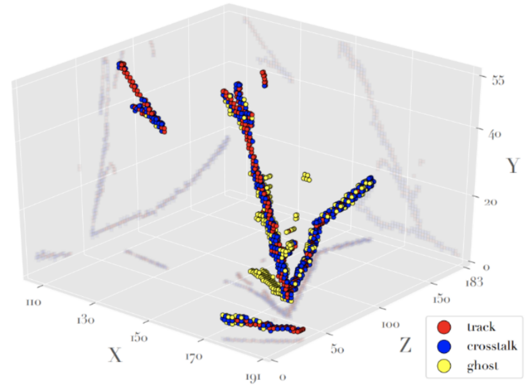
crosstalk also thickens the tracks reducing granularity



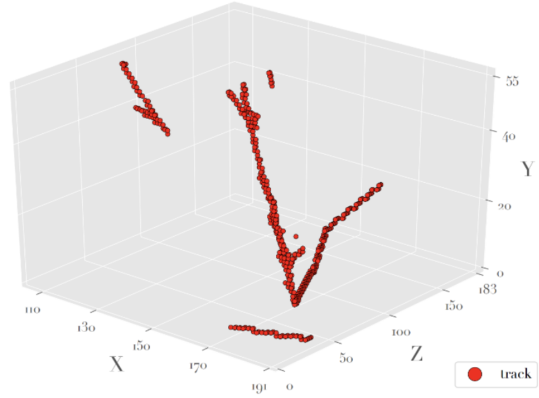
3D reconstruction and signal classification

Graph neural network for 3D classification of ambiguities and optical crosstalk in scintillator-based neutrino detectors

arXiv: 2009.00688, submitted to PRD

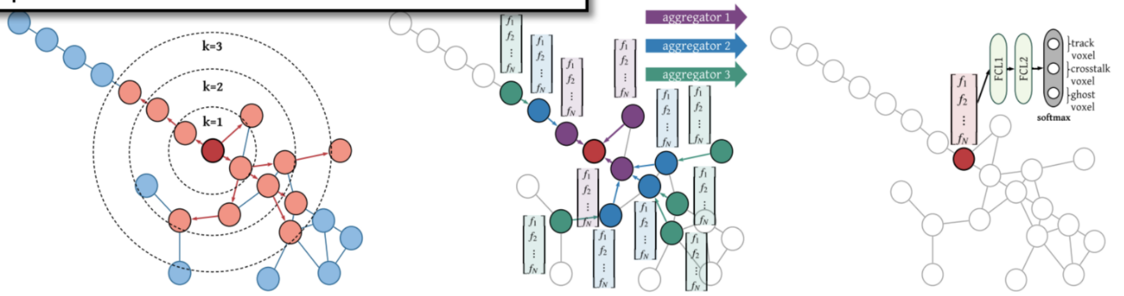


Is there a way to classify 3D hits such that we can remove ghosts and even crosstalk?



We tested Graph Neural Network based method:

For each event:



(a) Sample neighborhood.

(b) Aggregate feature information from neighbors.

(c) Use aggregated information as input for the fully connected layers and predict the label.

3D reconstruction and signal classification

We generated MC samples with realistic detector behaviour using isotropic particle guns (P-Bomb) and GENIE neutrino interaction generator

Testing	Level		GENIE Training Track	GENIE Training Crosstalk	GENIE Training Ghost	P-Bomb Training Track	P-Bomb Training Crosstalk	P-Bomb Training Ghost
GENIE Testing	**Per Voxel**	Efficiency	93%	90%	84%	93%	89%	80%
GENIE Testing	**Per Voxel**	Purity	93%	87%	91%	91%	86%	89%
GENIE Testing	**Per Event**	Efficiency	94%	94%	88%	94%	93%	88%
GENIE Testing	**Per Event**	Purity	96%	91%	92%	95%	91%	91%
P-Bomb Testing	**Per Voxel**	Efficiency	94%	93%	87%	95%	93%	88%
P-Bomb Testing	**Per Voxel**	Purity	95%	90%	92%	95%	91%	92%
P-Bomb Testing	**Per Event**	Efficiency	94%	94%	87%	95%	93%	88%
P-Bomb Testing	**Per Event**	Purity	96%	90%	92%	96%	91%	92%

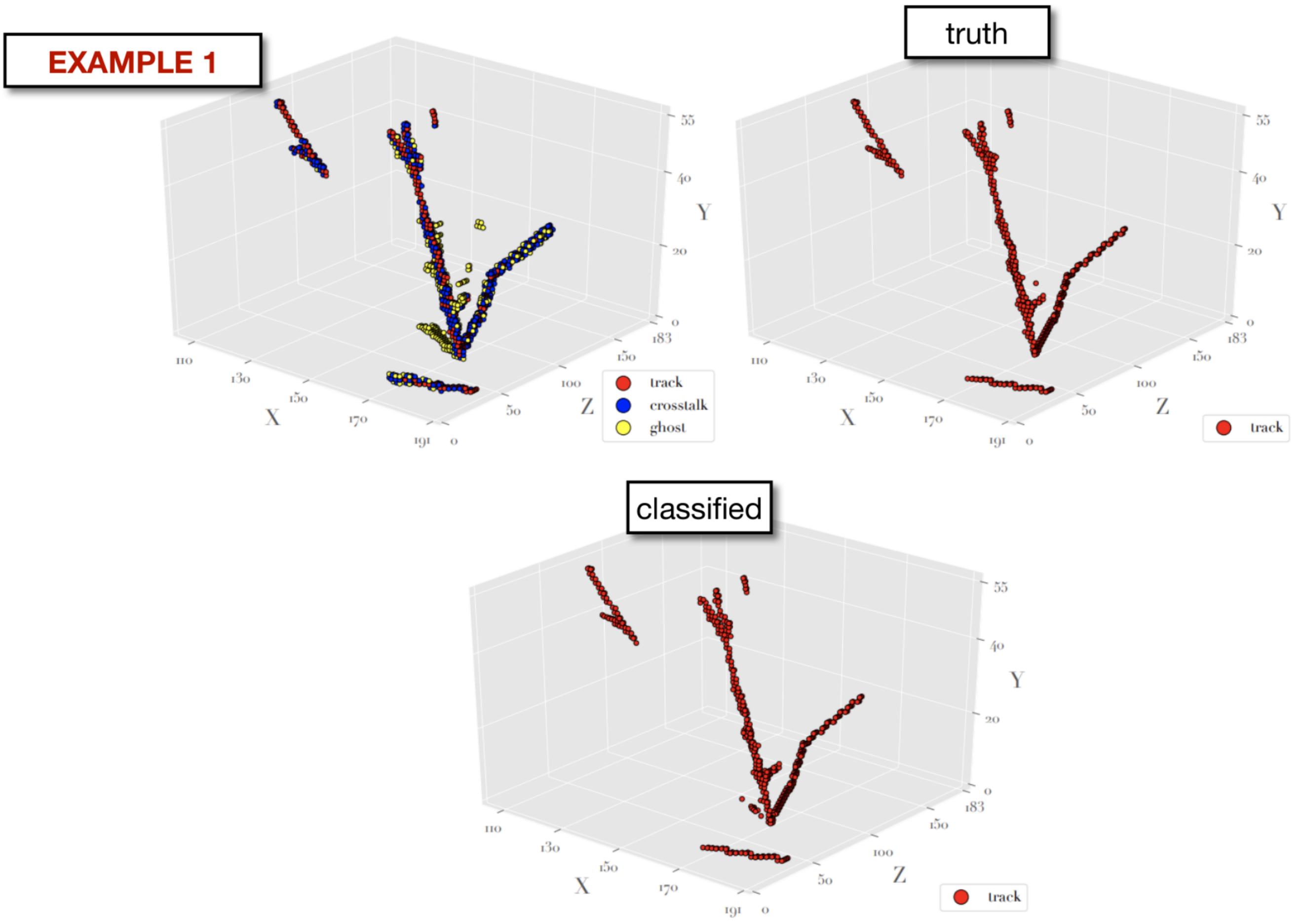
Performance comparison vs a simple charge cut

	GNN Track	GNN Other	Charge Cut Track	Charge Cut Other
Efficiency	94%	96%	93%	80%
Purity	96%	95%	80%	91%

GNN robustness to crosstalk miss-modeling

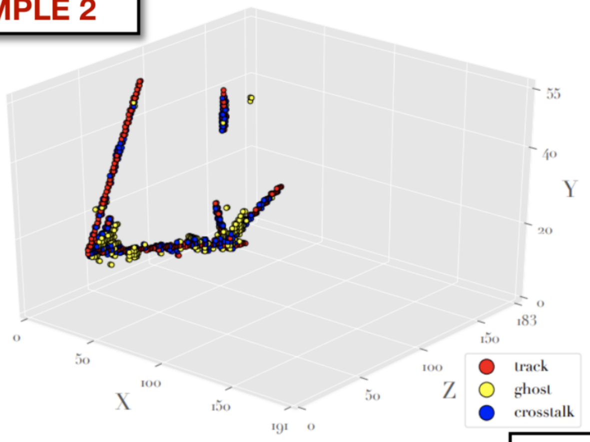
		Track	Crosstalk	Ghost
Nominal Crosstalk 2.7%	Efficiency	93%	90%	84%
Nominal Crosstalk 2.7%	Purity	92%	87%	91%
Crosstalk 2%	Efficiency	92%	89%	81%
Crosstalk 2%	Purity	94%	83%	89%
Crosstalk 5%	Efficiency	94%	89%	88%
Crosstalk 5%	Purity	86%	91%	93%

3D reconstruction and signal classification

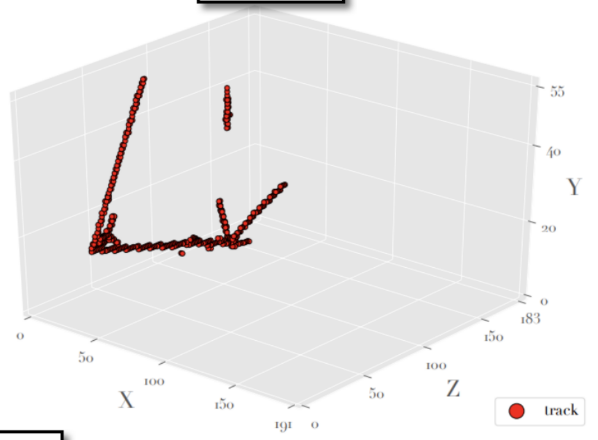


3D reconstruction and signal classification

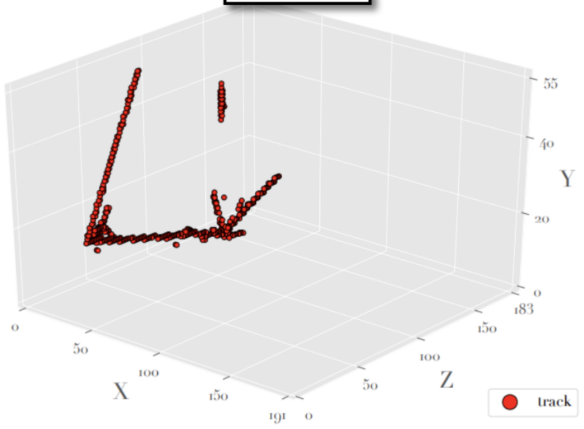
EXAMPLE 2



truth

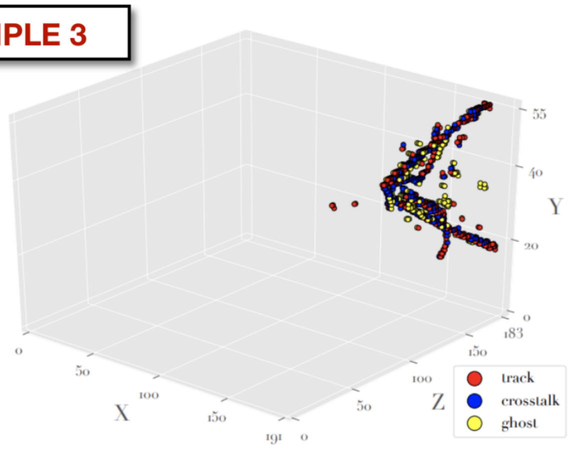


classified

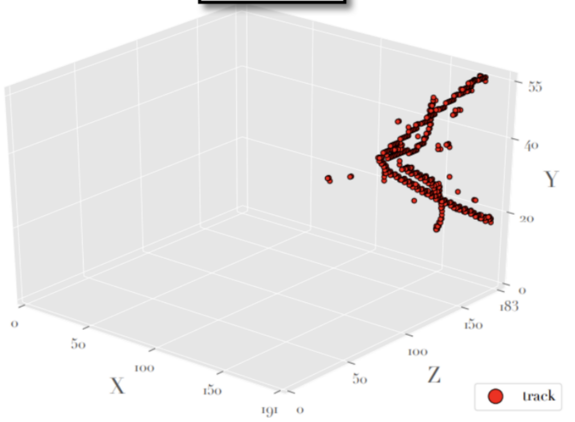


3D reconstruction and signal classification

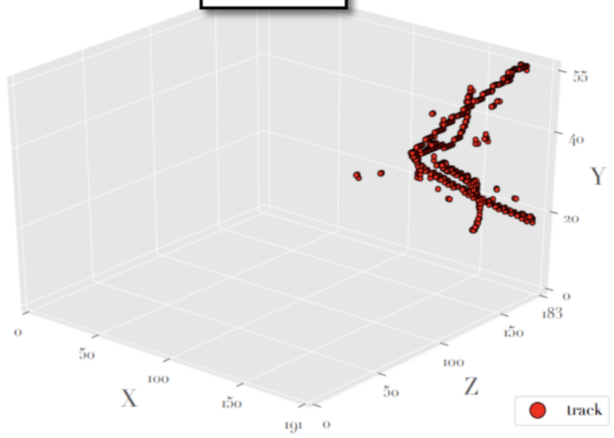
EXAMPLE 3



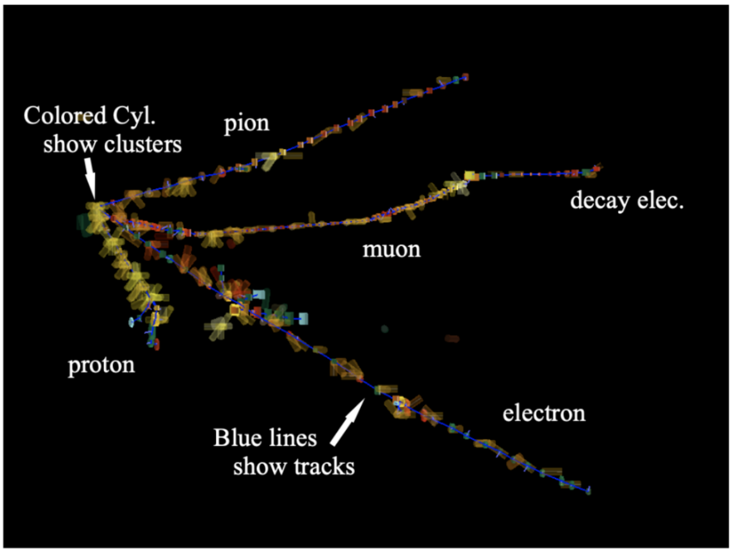
truth

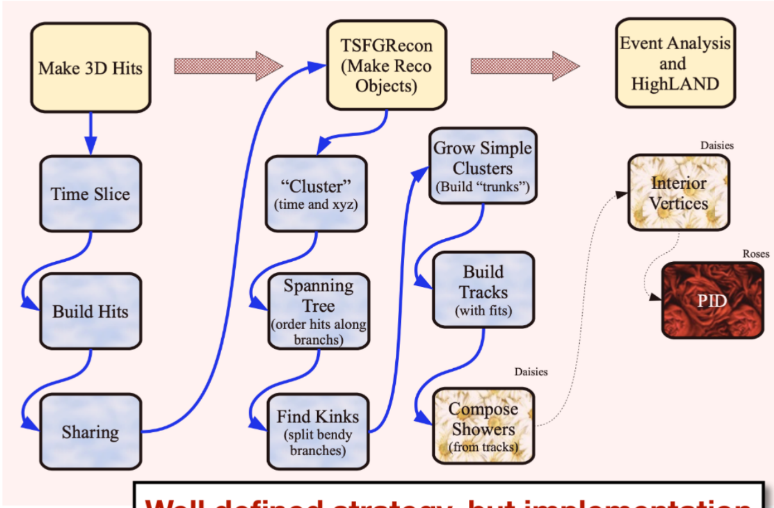


classified



Pattern recognition





Well defined strategy, but implementation and optimization is under development

Future plans

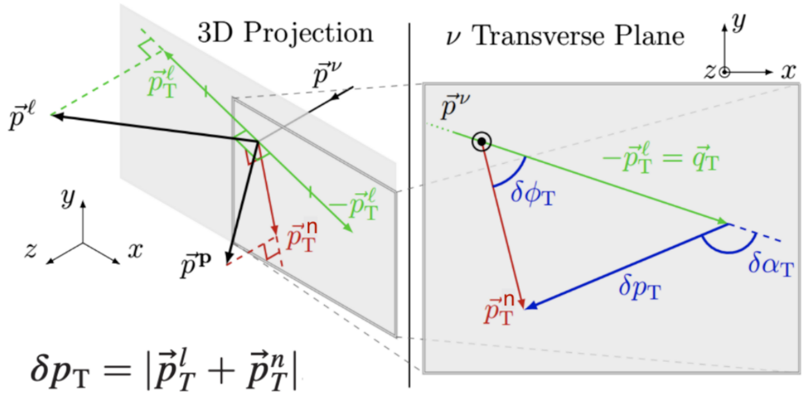
- Optimize kink finding, clustering and vertex finding algorithms.
  - Based on vertex resolution, tracking efficiency and angular and momentum resolution for reco tracks.
- From tracking develop SuperFGD stand-alone PID tools.

A lot of work in front of us!

New possibilities: Neutron tagging

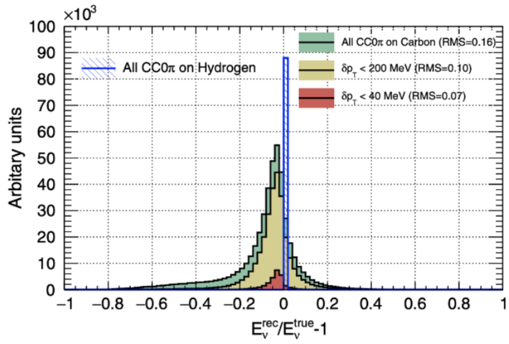
New method for an improved antineutrino energy reconstruction with charged-current interactions in next-generation detectors

PRD 101 (2020) 9, 092003



$$\delta p_{\mathrm{T}} = |\vec{p}^{\,l}_{T} + \vec{p}^{\,n}_{T}|$$

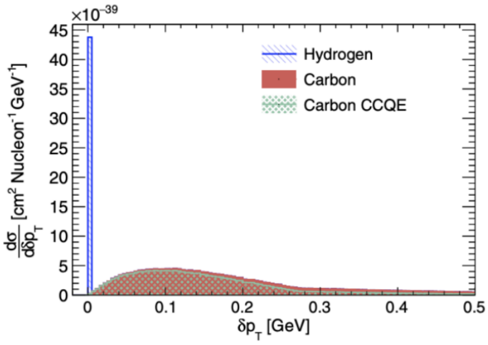
Identifying low δ_{P_T} events can improve neutrino energy reconstruction



antineutrino CCQE:

$$\bar{\nu}_\mu + p \rightarrow \mu + n$$

very low δ_{P_T} is a signature of ν interacting with hydrogen in plastic molecules



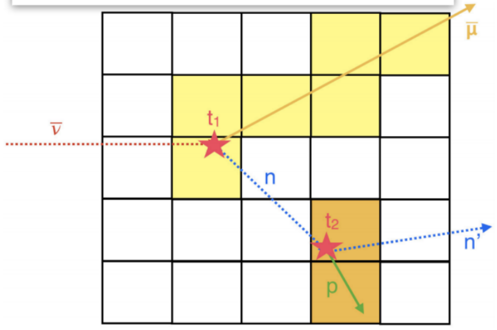
In order to measure δ_{P_T} in antineutrino interactions we need to measure the outgoing neutron

Impossible for current ND280

New possibilities: Neutron tagging

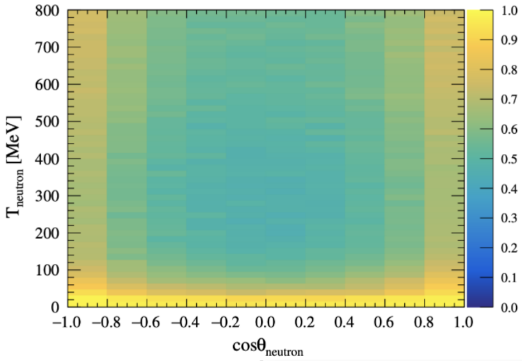
But possible with SuperFGD

We can identify neutrons as isolated delayed clusters



Neutron energy is reconstructed from time-of-flight kinematics (No-Relativistic) [t_2-t_1]

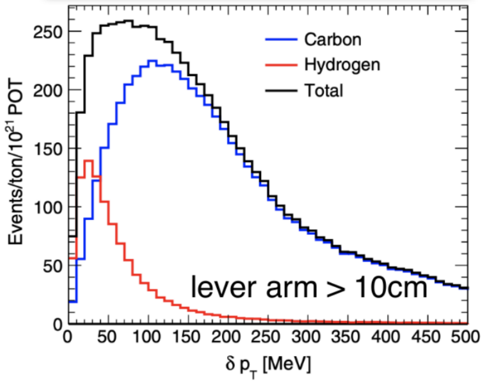
Efficiency in 2x0.6x2m³ SuperFGD like detector Using isotropic particle gun placed @ detector's center



Average efficiency ~50%

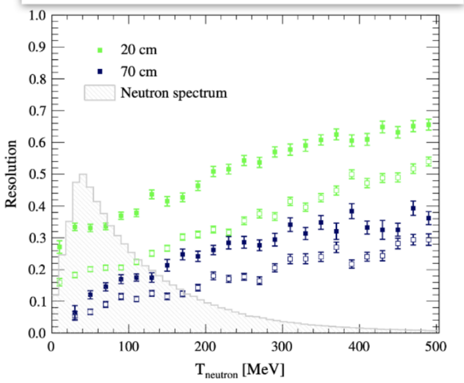
All other results are discussed for an hypothetic detector of 2x2x2m³ with average efficiency ~71%

Fraction of hydrogen interactions and δ_{P_T} including detector smearing

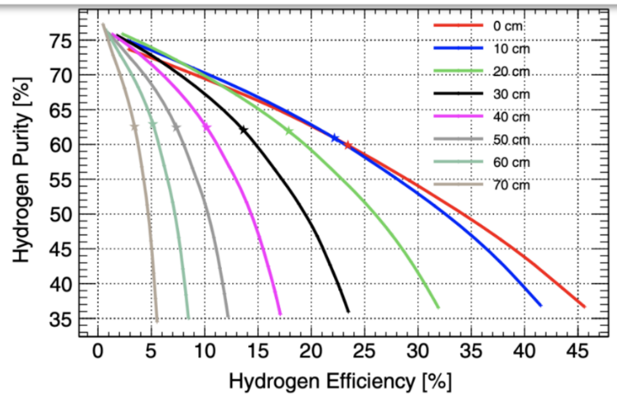


New possibilities: Neutron tagging

Neutron momentum resolution improves with lever-arm cuts:

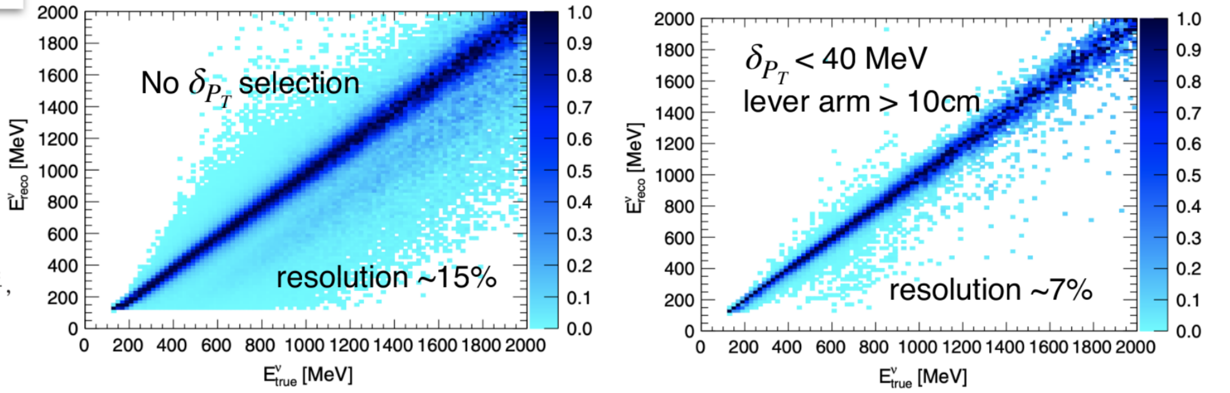


Better neutron momentum resolution translates in better δ_{P_T}, allowing to have better hydrogen selection purity



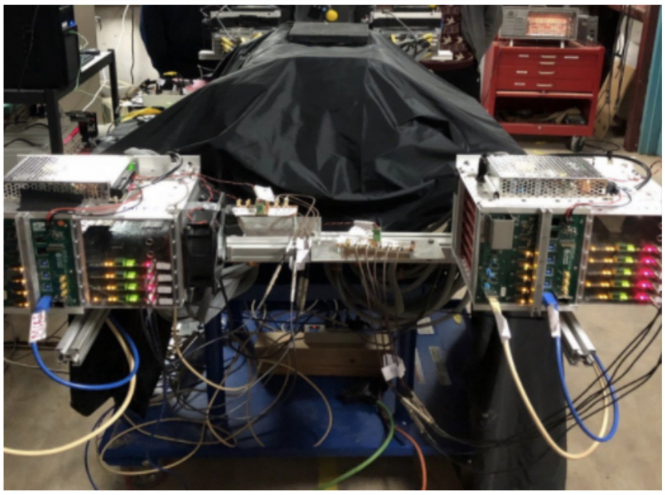
Results

$$E_\nu = \frac{m_n^2 - m_p^2 - m_\mu^2 + 2m_p E_\mu}{2(m_p - E_\mu + p_\mu \cos\theta_\mu)},$$

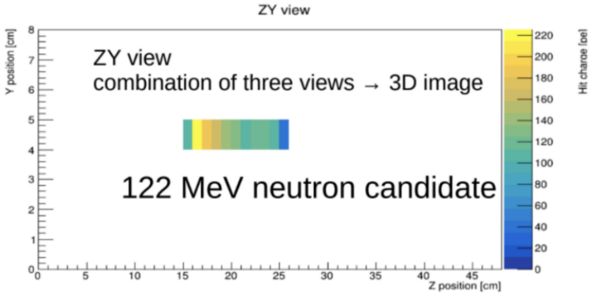


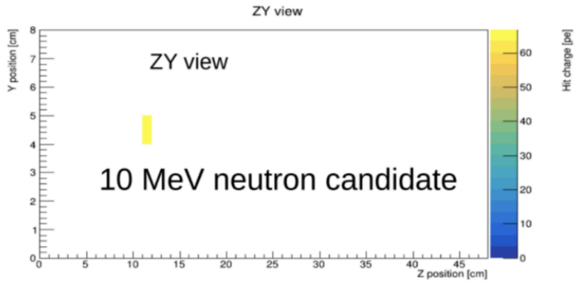
Neutron Beam Test (ongoing analysis)

Same prototype tested at CERN was send to LANL and used in neutron beam



Neutron energy is reconstructed using time of flight





The goal is to understand neutron capabilities in this type of detector and to measure neutron cross section in hydrocarbon using extinction method.

analysis ongoing

Summary & Conclusions

SuperFGD will be installed during ND280 upgrade activities along 2022

The ND280 upgrade, and SuperFGD, will decrease the systematic errors for the oscillation analysis, helping T2K to further measure neutrino oscillation properties and neutrino-nucleus interactions.

Since proposed in 2018, the fundamental concepts have been demonstrated:

- ✦ Assembly technique is working.
- ✦ High light yield for MIPS with controlled fiber attenuation.
- ✦ Working read-out and calibration methods.
- ✦ Fine granularity and good dE/dx resolution.

The final design is almost complete, but final tasks are ongoing:

- ✦ Electronic boards design and production
- ✦ 60k MPPCs test bench.
- ✦ Final box design and cooling.
- ✦ 80% detector cubes assembled in 2D planes
- ✦ We still need to put everything together: box + cubes + WLS fibers + MPPCs + electronics

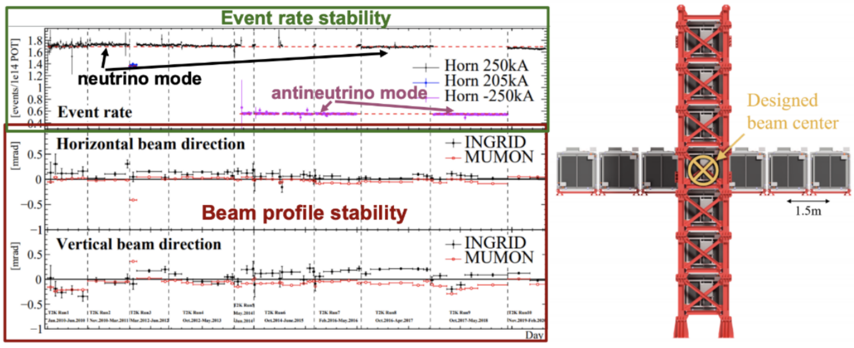
Massive efforts have started on the software end

- ✦ Slow control
- ✦ Reconstruction

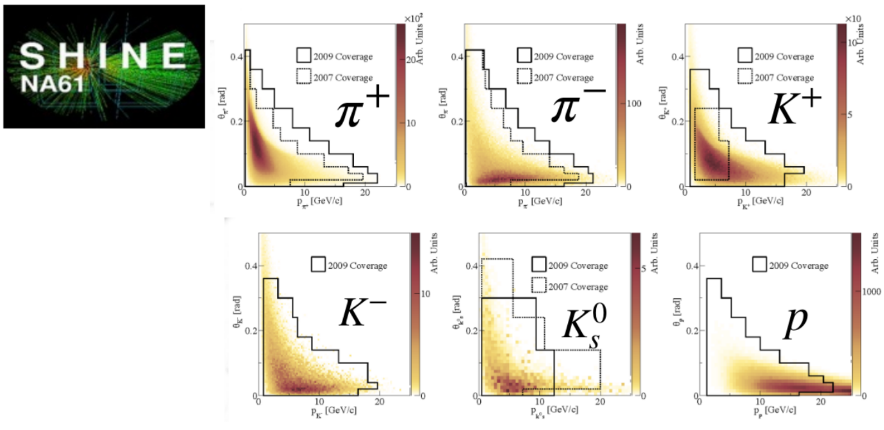
Back Up

T2K beam (flux)

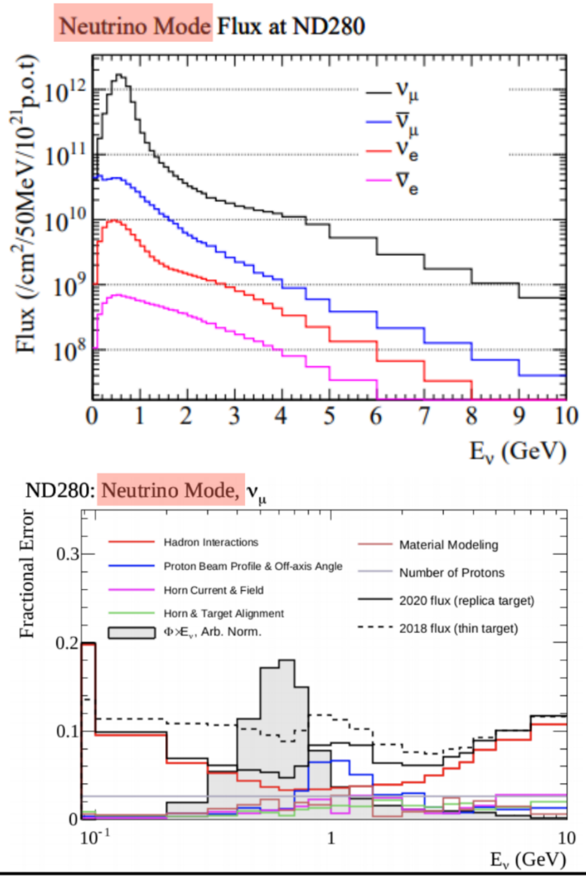
beam alignment and stability:



conversion from POT to mesons

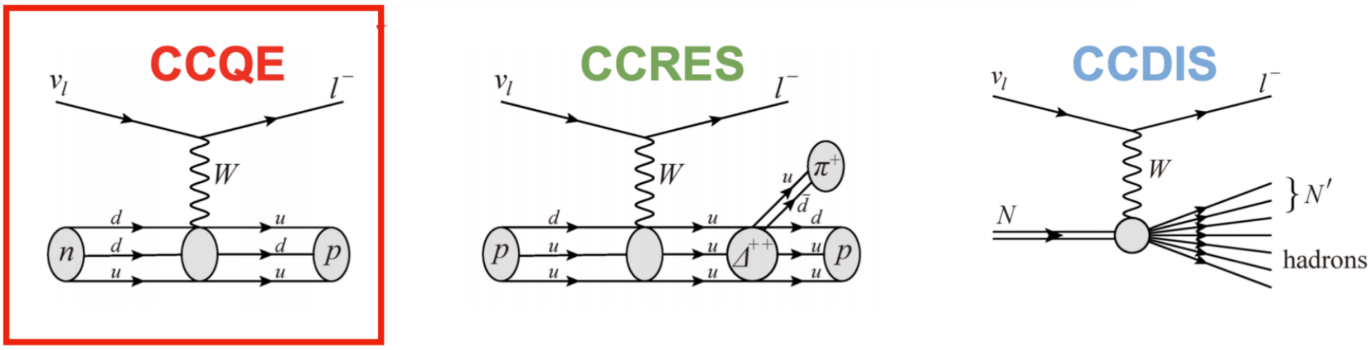


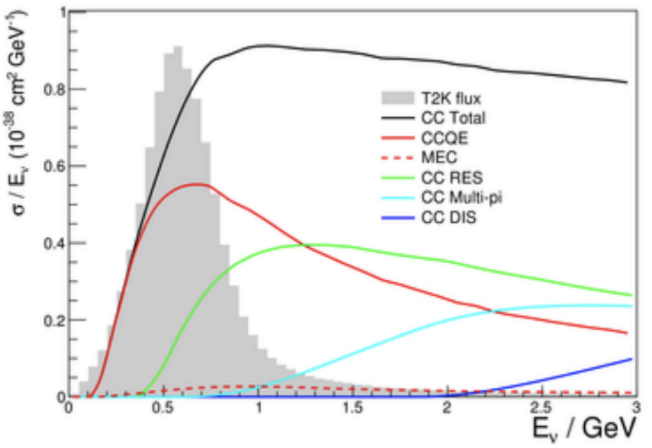
flux prediction

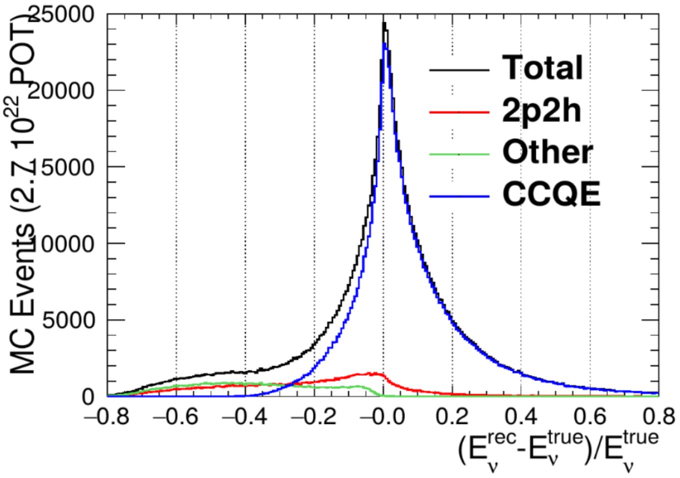


Neutrino Interactions

Look to the simplest neutrino interactions for the OA

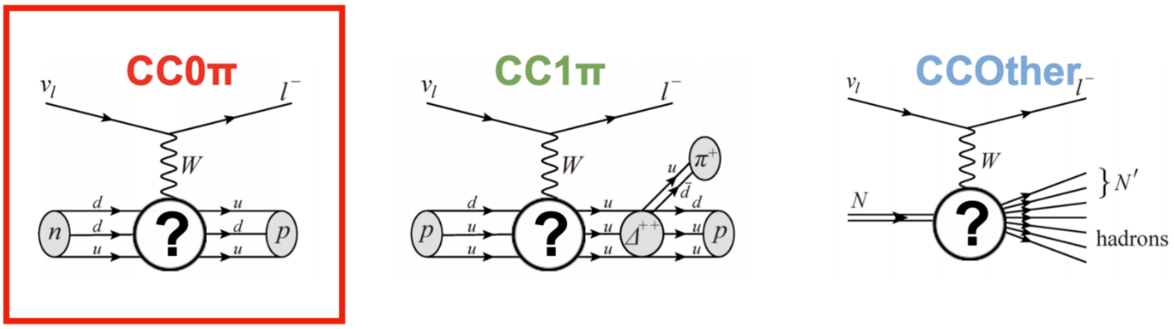


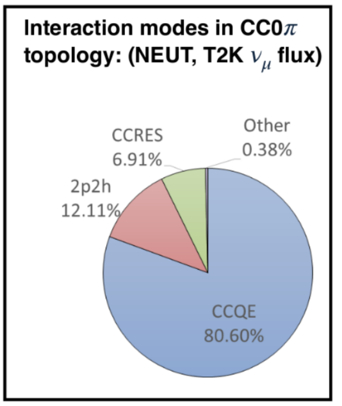




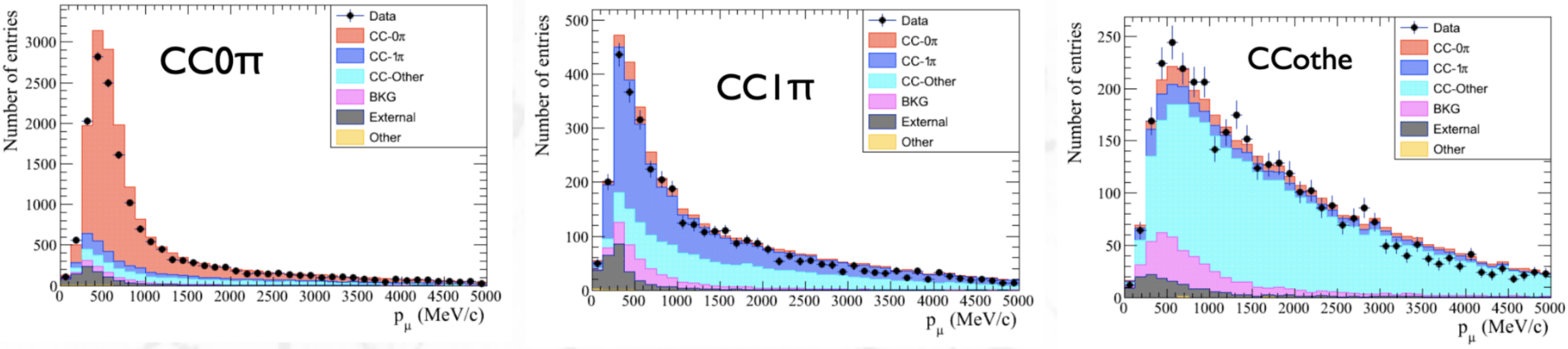
Neutrino Interactions

We work with CC0π topology for OA:





We measure data vs MC for all topologies to constrain model parameters (shape) and flux (normalization):



How do we validate neutrino interaction models?

First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K

PHYSICAL REVIEW D 101, 112001 (2020)

Measurement of the muon neutrino charged-current single π^+ production on hydrocarbon using the T2K off-axis near detector ND280

PHYSICAL REVIEW D 101, 012007 (2020)

First measurement of the charged current $\bar{\nu}_\mu$ double differential cross section on a water target without pions in the final state

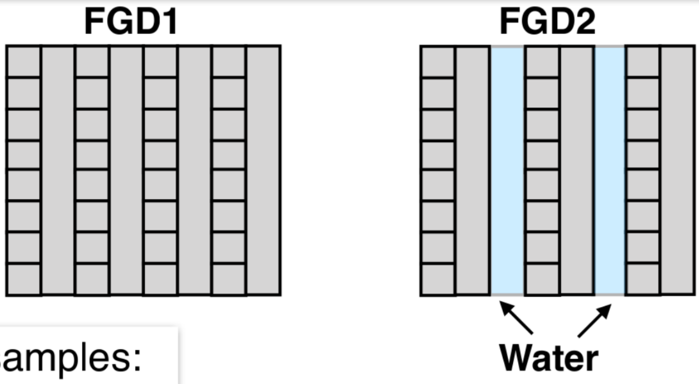
PHYSICAL REVIEW D 102, 012007 (2020)

Simultaneous measurement of the muon neutrino charged-current cross section on oxygen and carbon without pions in the final state at T2K

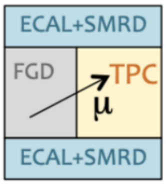
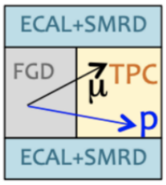
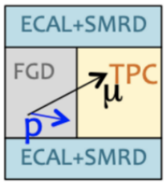
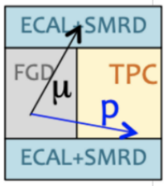
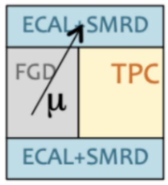
Accepted in PRD (2020), arxiv; 2004.05434

Cross Section Models

How do we validate neutrino interaction models using ND280?

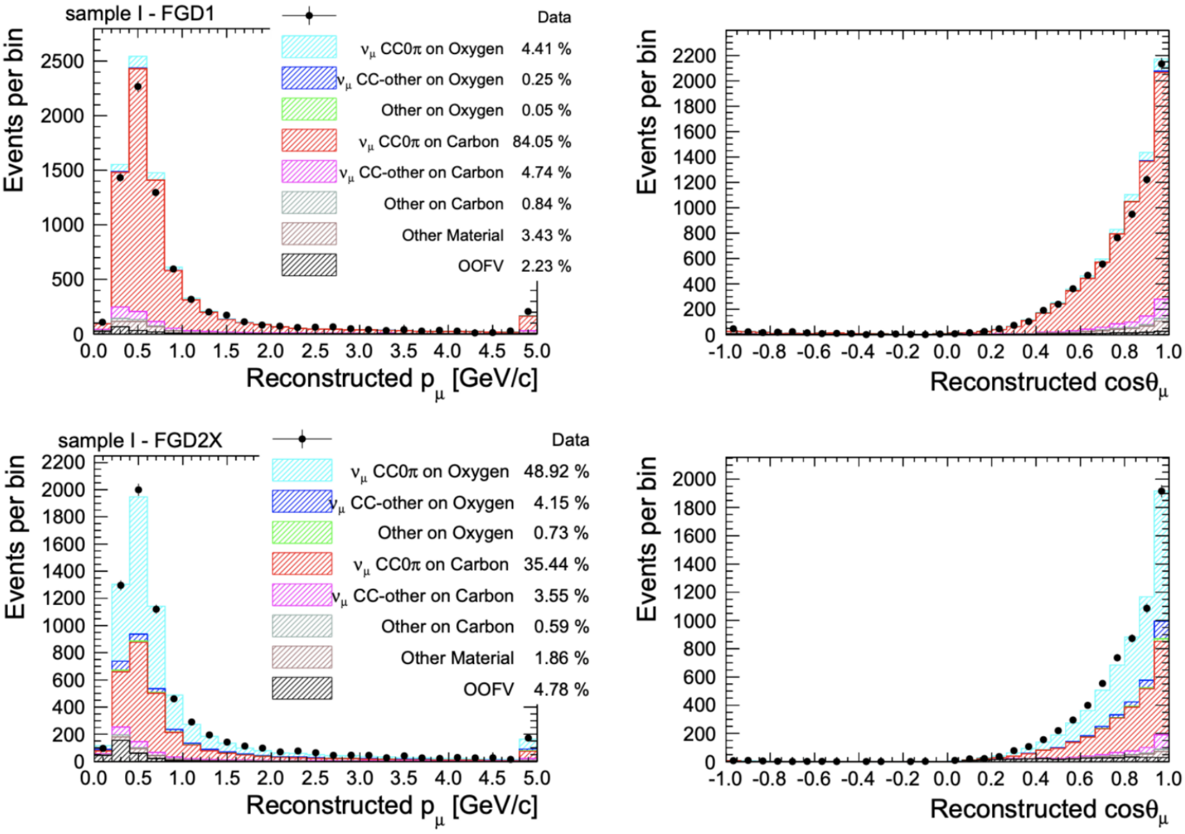


1. Define selection samples:

Signal sample	**I – μTPC** 	**II – μTPC+pTPC** 	**III – μTPC+pFGD** 	**IV – μFGD+pTPC** 	**V – μFGD** 
Description	Single μ candidate tracked in TPC	Both μ and *p* candiates are tracked in the TPC	μ tracked in the TPC and : • 1*p* tracked in the FGD • or multi *p*	μ tracked in FGD/Ecal and: • 1 *p* tracked in the TPC • or 1 *p* tracked in the TPC + multi *p* • or multi *p*	μ_{FGD} only reconstructed in the FGD/ Ecal

How do we validate neutrino interaction models using ND280?

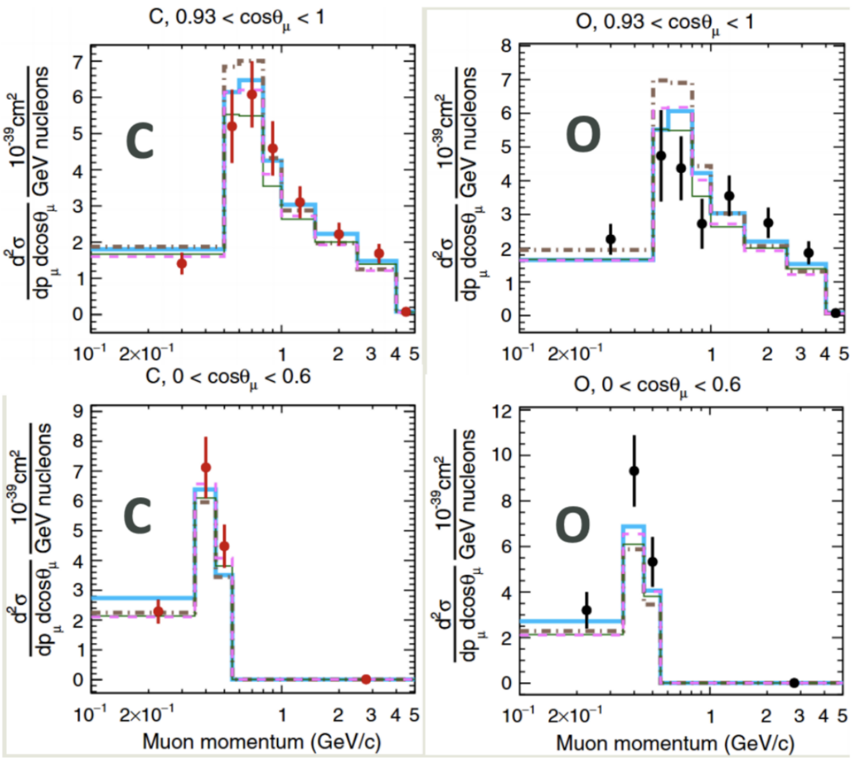
2. Compute MC vs data for each sample for different reconstructed variables



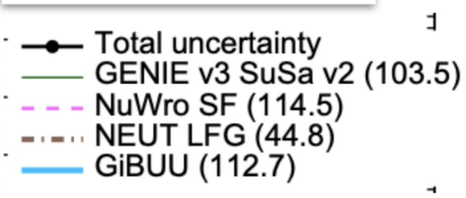
Cross Section Models

How do we validate neutrino interaction models using ND280?

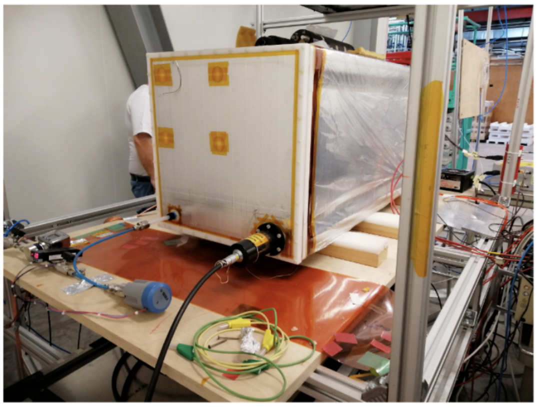
3. Compute differential cross-sections



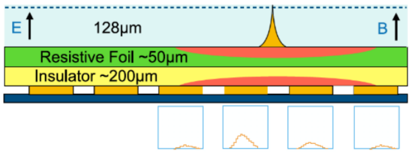
4. Compare data and models

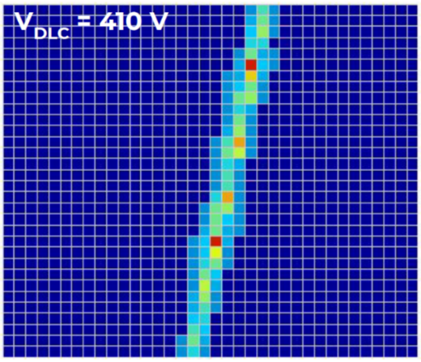


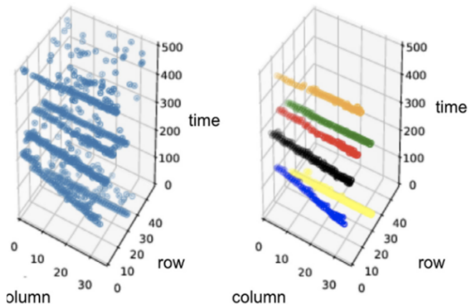
The High-Angle TPCs

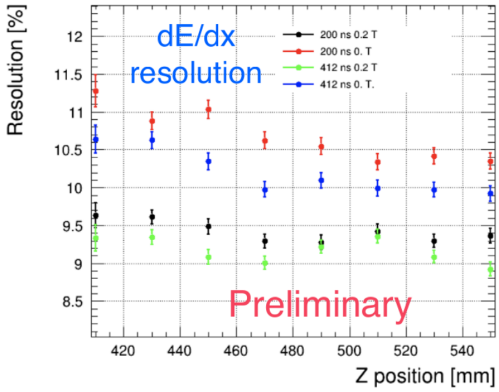


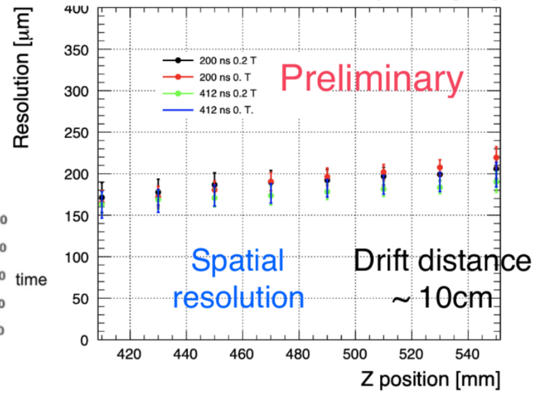
Parameter	Value
Overall x × y × z (m)	2.3 × 0.8 × 2.0
Drift distance (cm)	90
Magnetic Field (T)	0.2
Electric field (V/cm)	275
Gas AR-CF_4-iC_4H_{10} (%)	95 - 3 - 2
Drift Velocity $cm/\mu s$	7.8
Transverse diffusion ($\mu m/\sqrt{cm}$)	265
Micromegas gain	1000
Micromegas dim. z×y (mm)	340 × 410
Pad z × y (mm)	10 × 11
N pads	36864
el. noise (ENC)	800
S/N	100
Sampling frequency (MHz)	25
N time samples	511







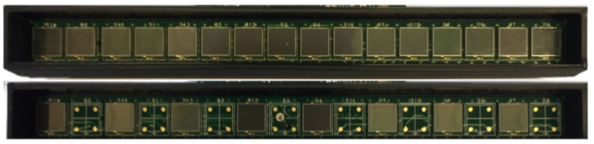


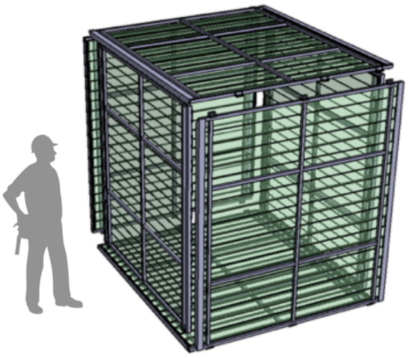


Final TPCs construction scheduled for 2021

The ToF system

- Time-of-Flight detector with time resolution ~ 150 ps (arXiv:1901.07785)
  - 2.3m x 12cm bars of EJ-200 cast plastic scintillator: no WLS fibers, high light output, long attenuation length (4m), fast timing
  - Signal summed from arrays of eight 6x6 mm^2 MPPCs (S13360-6050PE). Double-end readout





6 ToF panels ~full coverage

4/6 built and tested