ETH zürich

T2K SuperFGD R&D
and
Physics Toward 3DST

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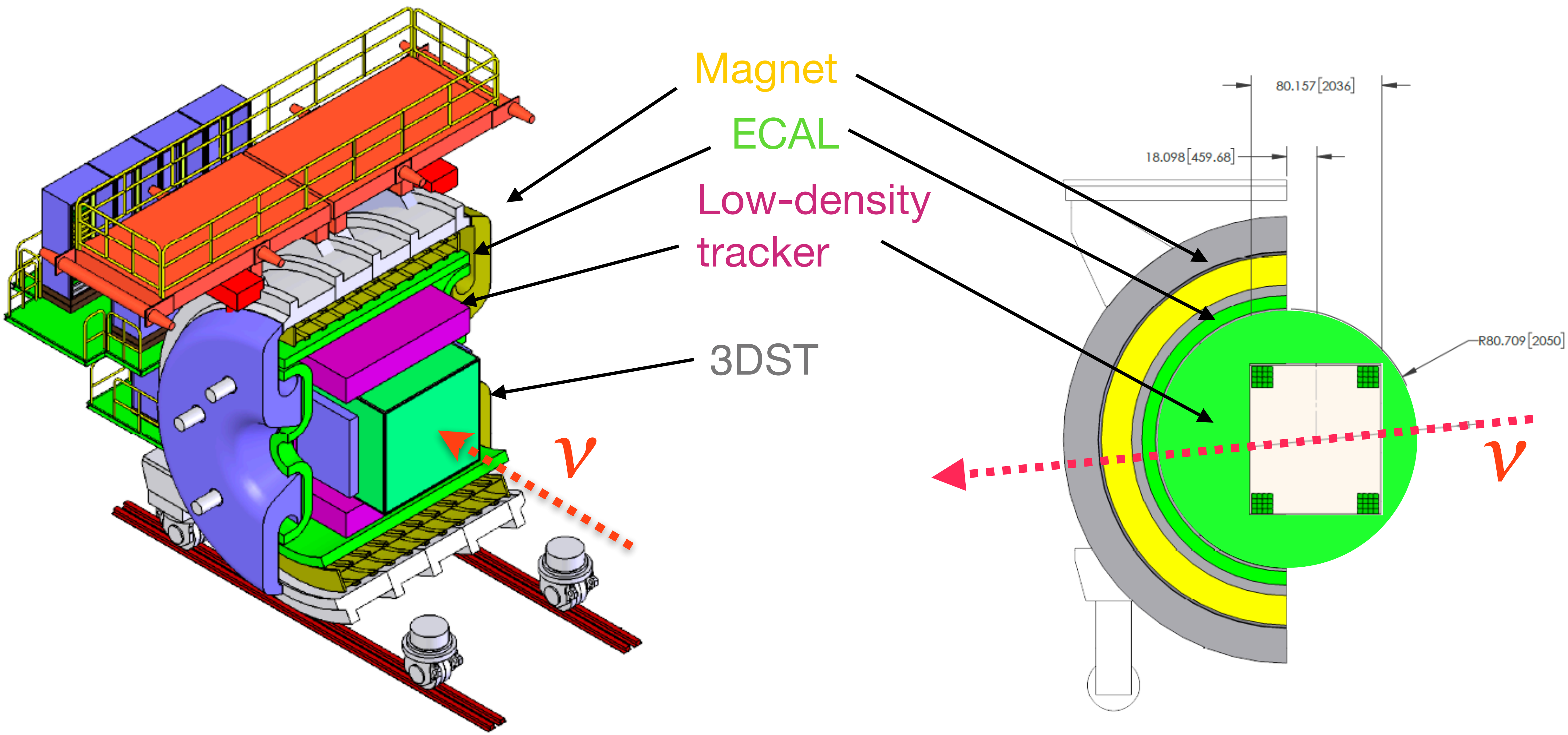
for the 3DST working group

28th June 2020

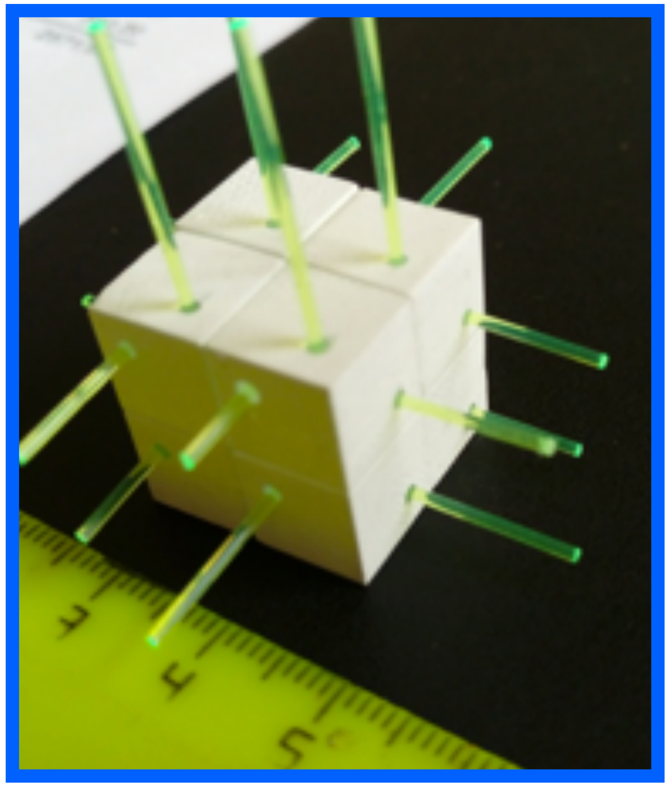
SAND meeting

System for on-Axis Neutrino Detection (SAND)

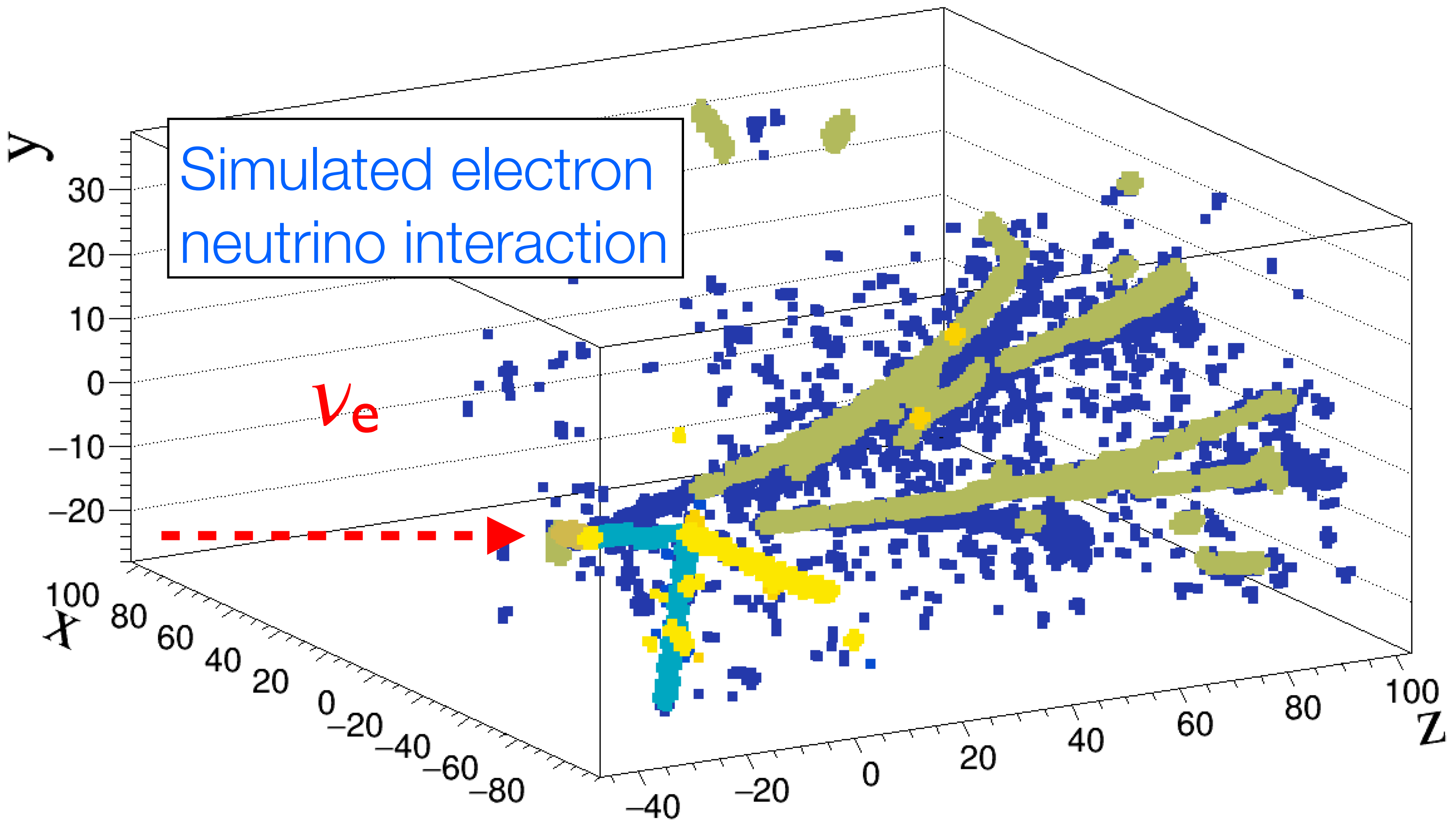


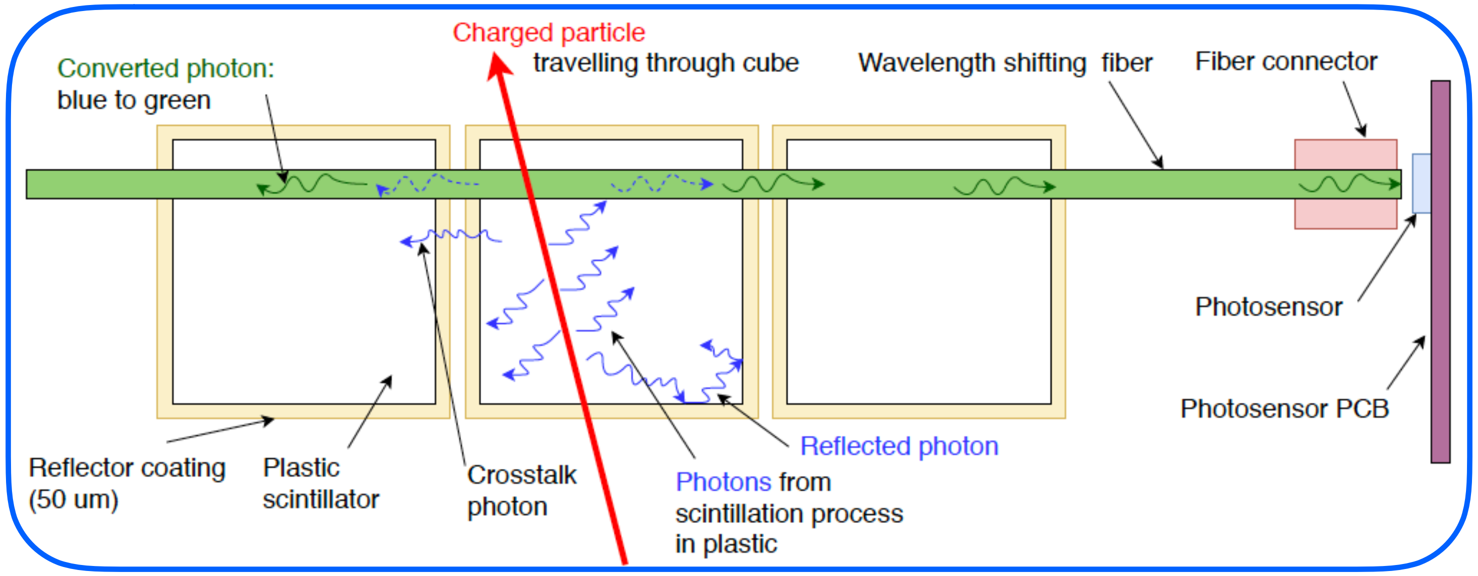
- 2.36 (width) x 2.36 (height) x 2.12 (length) m^3
    - ✦12.5 ton (11 ton) total (fiducial w/ 10cm outermost shell cut) mass
    - ✦Possibility to increase 3DST if necessary for beam monitoring
- Low-density tracker with density as low as possible for precise charged-particle tracking
- Event-by-event neutron detection and kinetic energy measurement

The 3-dimensional Scintillator Tracker (3DST)



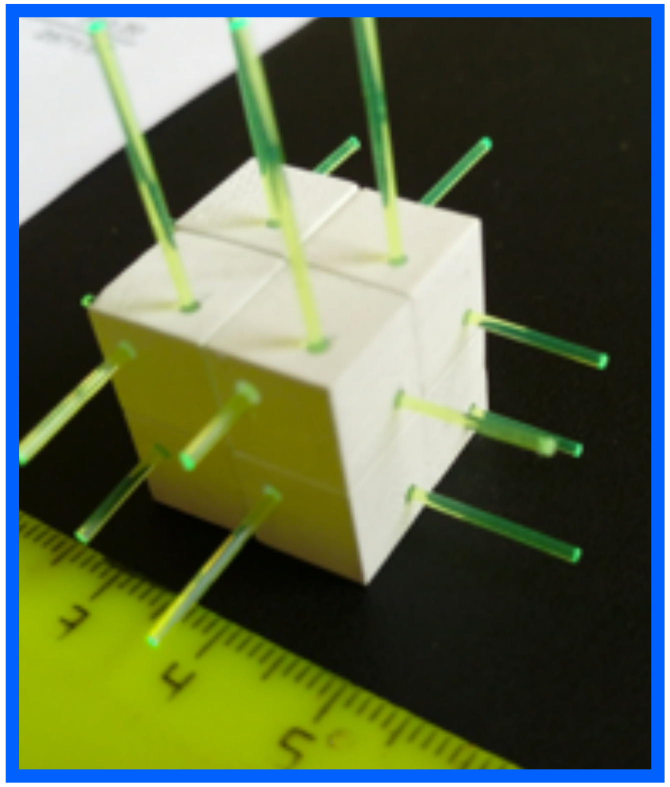
2018 *JINST* **13** P02006
NIM A936 (2019) 136-138





Polystirene-based Plastic scintillator
1.5% paraterphenyl and 0.01% POPOP
1x1x1 cm^3 cubes
Chemical etching as reflector
WLS fibers (Kuraray Y11, 2-clad, 1mm)

The 3-dimensional Scintillator Tracker (3DST)



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Event rate per year

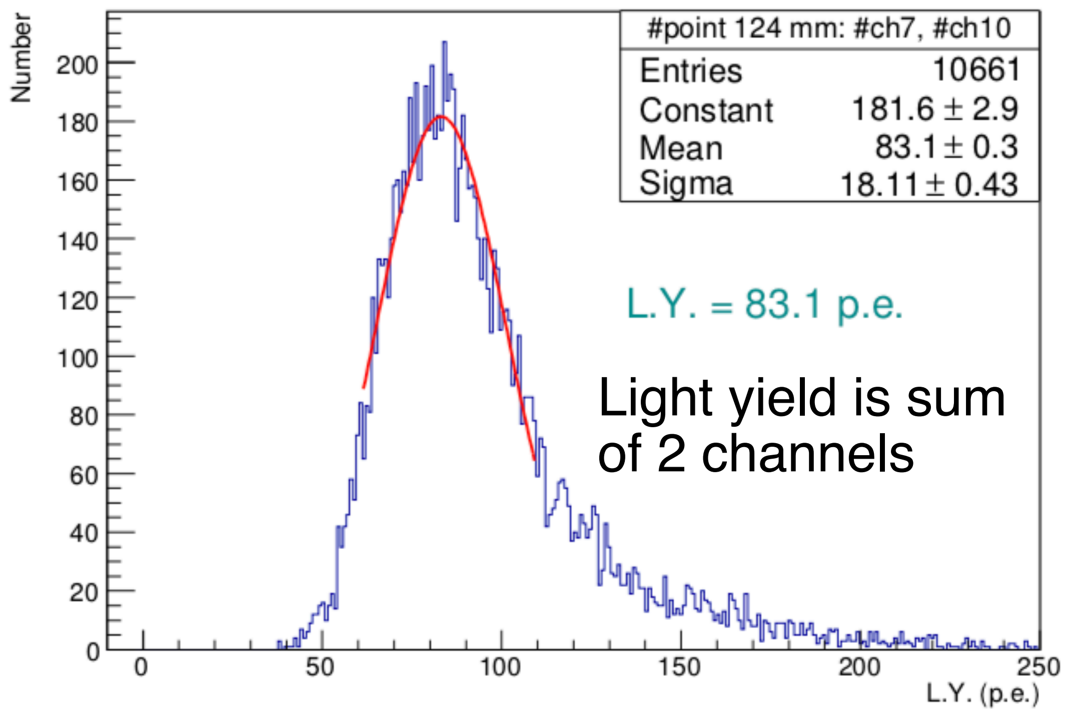
FHC Beam Process	Rate	RHC Beam Process	Rate
All ν_μ-CC	1.5×10^7	All $\bar{\nu}_\mu$-CC	5.4×10^6
CC 0π	4.4×10^6	CC 0π	2.4×10^6
CC $1\pi^\pm$	4.3×10^6	CC $1\pi^\pm$	1.5×10^6
CC $1\pi^0$	1.3×10^6	CC $1\pi^0$	5.3×10^5
CC 2π	1.9×10^6	CC 2π	5.0×10^5
CC 3π	8.7×10^5	CC 3π	1.7×10^5
CC other	1.8×10^6	CC other	2.8×10^5
ν_μ-CC COH π^+	1.3×10^5	$\bar{\nu}_\mu$-CC COH π^-	1.0×10^5
$\bar{\nu}_\mu$-CC COH π^-	1.2×10^4*	ν_μ-CC COH π^+	1.7×10^4*
ν_μ-CC ($E_{had} < 250$ MeV)	2.4×10^6	$\bar{\nu}_\mu$-CC ($E_{had} < 250$ MeV)	1.9×10^6
All $\bar{\nu}_\mu$-CC	7.0×10^5	All ν_μ-CC	2.3×10^6
All NC	5.3×10^6	All NC	2.9×10^6
All $\nu_e + \bar{\nu}_e$-CC	2.6×10^5	All $\bar{\nu}_e + \nu_e$-CC	1.7×10^5
$\nu e \to \nu e$	1.8×10^3*	$\nu e \to \nu e$	1.5×10^3*

- High detection efficiency for full solid angle (uniform >95% for muons)
- Momentum resolution by range (~2-3% for stopping muons or for the 3DST track segment if exiting)
- Protons down to 300 MeV/c can be detected (≥3 hits in each single view)
- Angular resolution at least 8-12 mrad (1D) for e^- of 1.5-2 GeV (from Minerva)
- *Synergy with project of T2K ND280 upgrade: 3DST will adopt exactly the same concept as SuperFGD, that will be start collecting data in 2022*

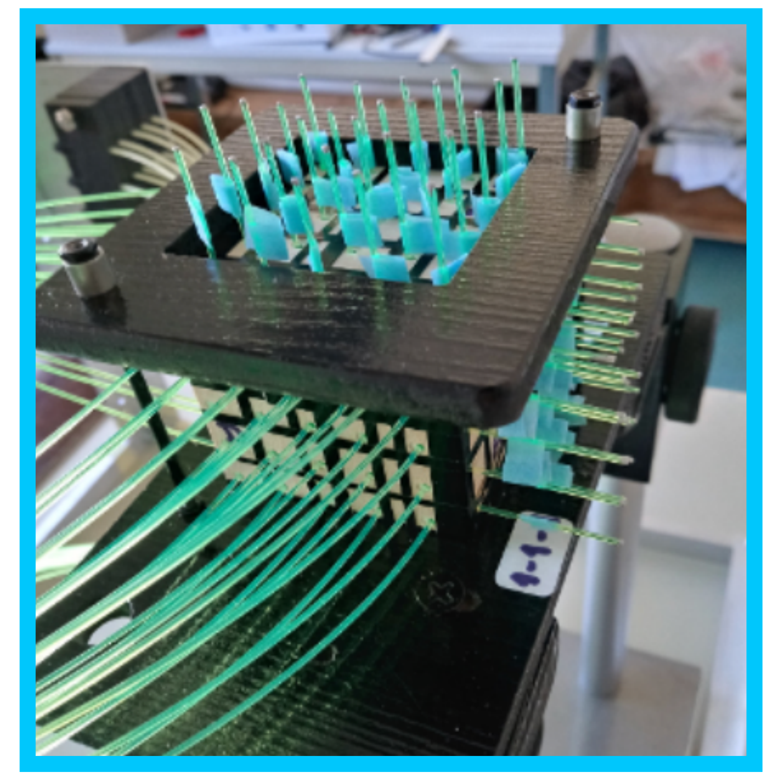
Characterization of the SuperFGD concept

- Prototype 5x5x5 cm^3, 1.3 m WLS fibers (Al-based paint at fiber end)
- Exposure to a 6 GeV π test beam at CERN

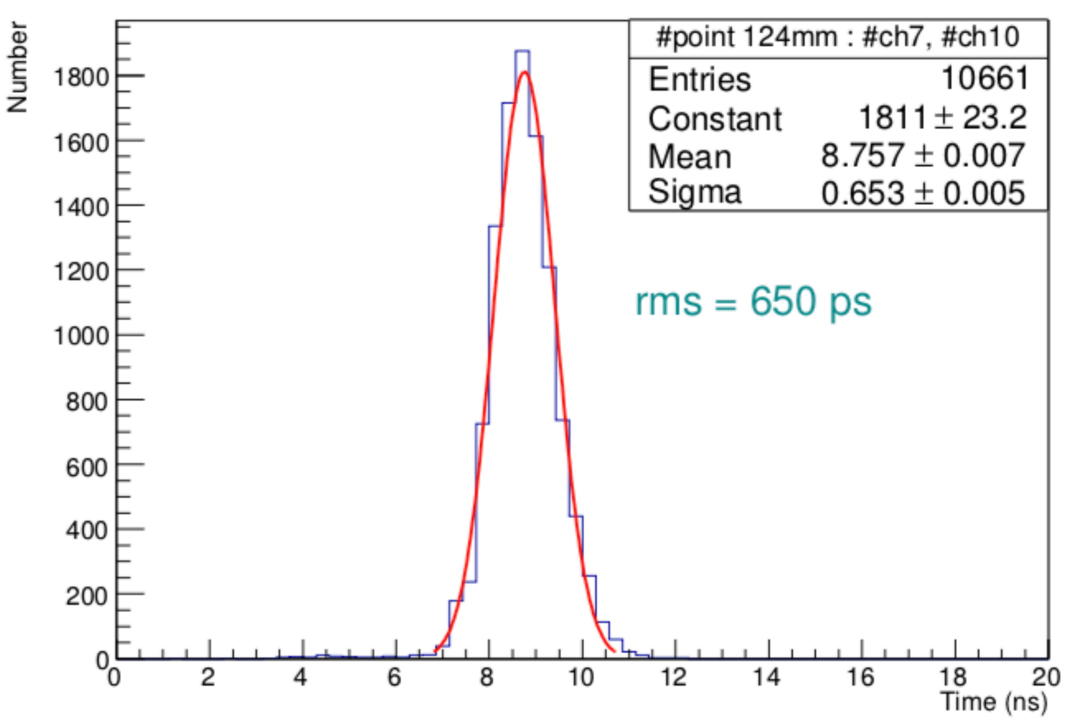
Light yield (# of photoelectrons)



NIM A923 (2019) 134-138



Time resolution for two channels

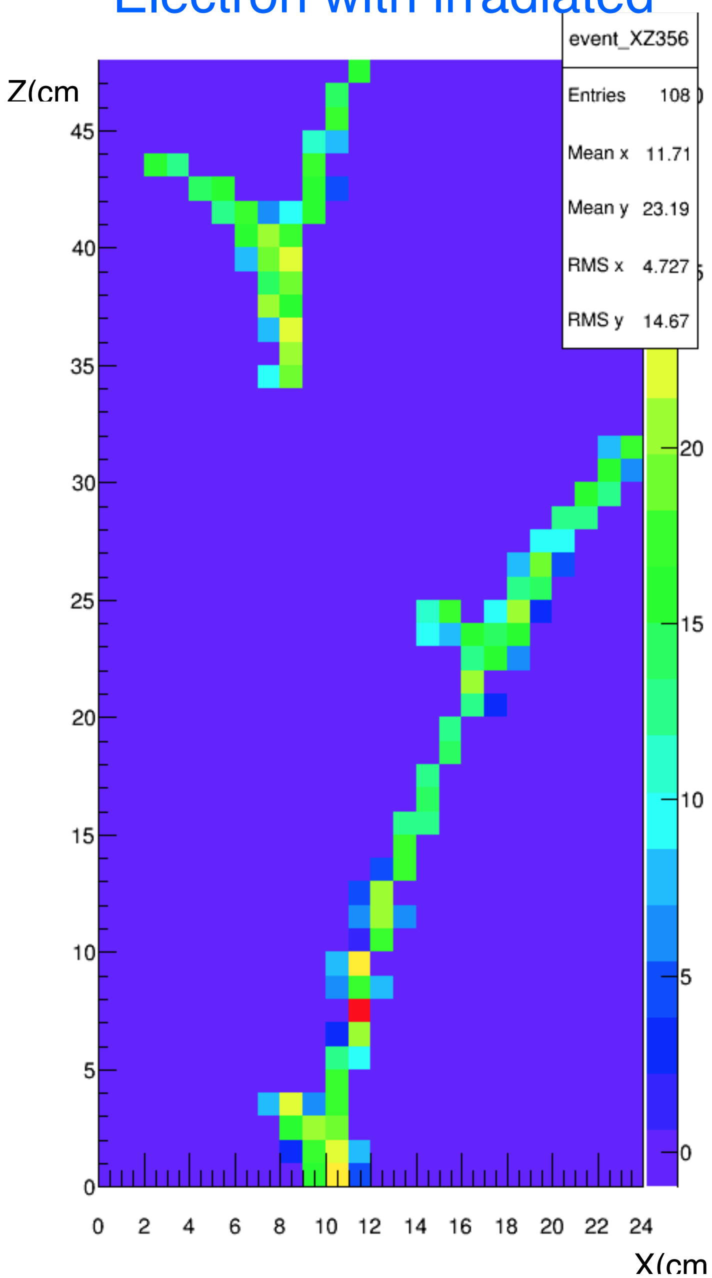


- Average light yield ~ 41 p.e. / fiber / cube (MIP)
- Cross-talk ~ 3.7%
- Very good intrinsic time resolution (measured with a 5 GHz waveform digitizer)
    - ✦ $\sigma_t \sim$ 0.95 ns (1 channel, 1 cube)
    - ✦ $\sigma_t \sim$ 0.5 ns (1 cube, MIP, 3 WLS fibers)

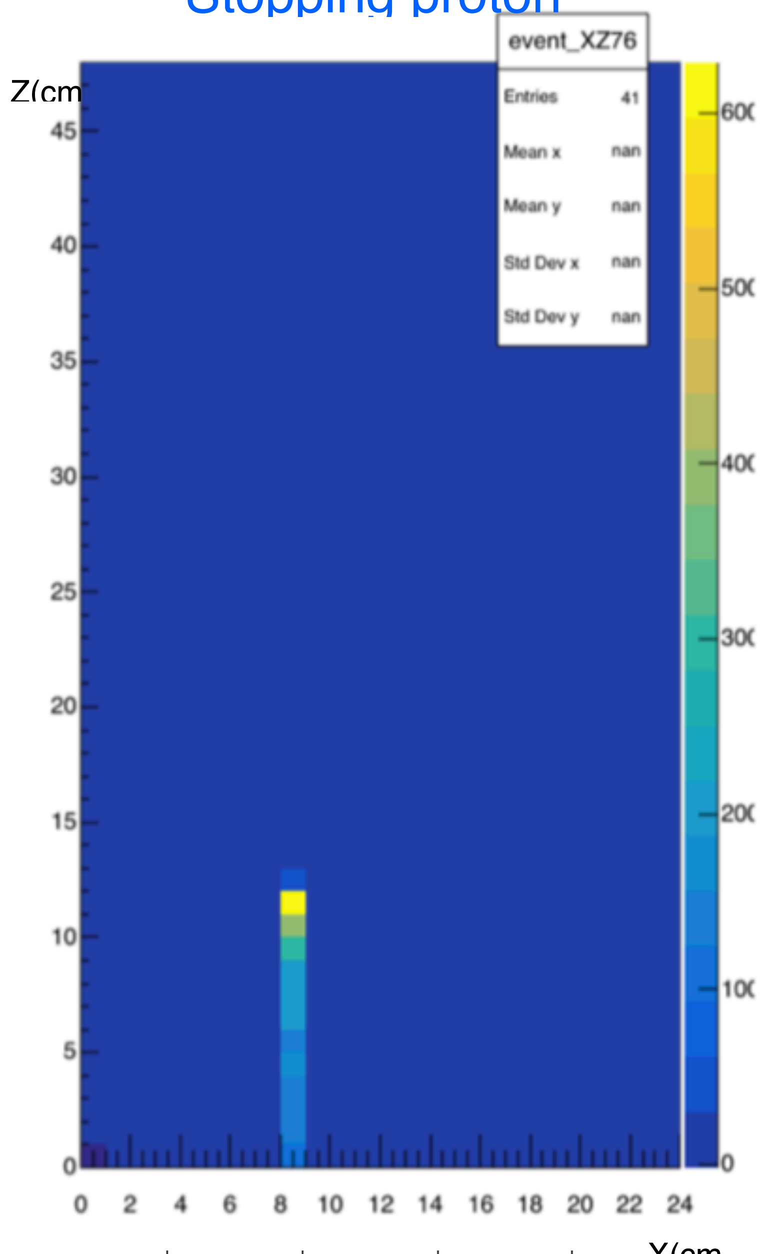
2018 beam-tests at CERN: SuperFGD

- Beam tests at CERN performed with a 10,000 cubes prototype confirmed the previously obtained results
- The good-quality data will be used to validate the event reconstruction tools and tune the detector response

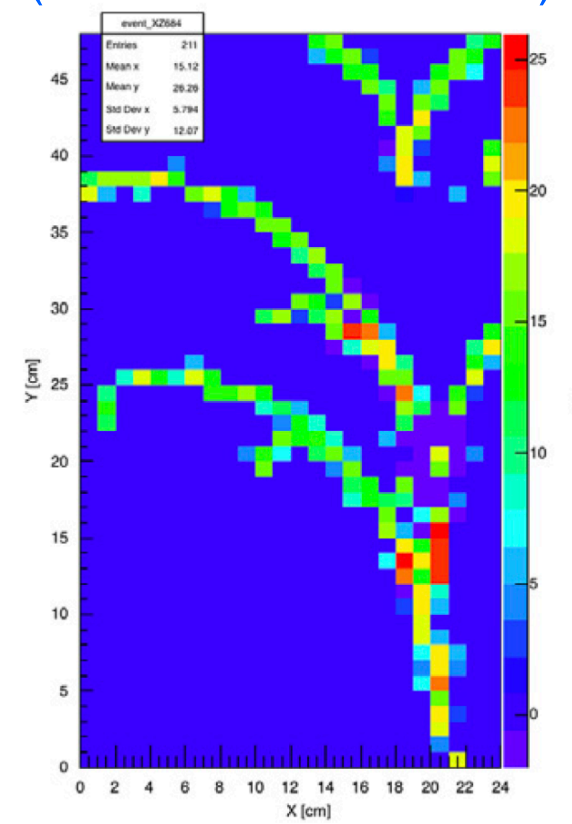
Electron with irradiated

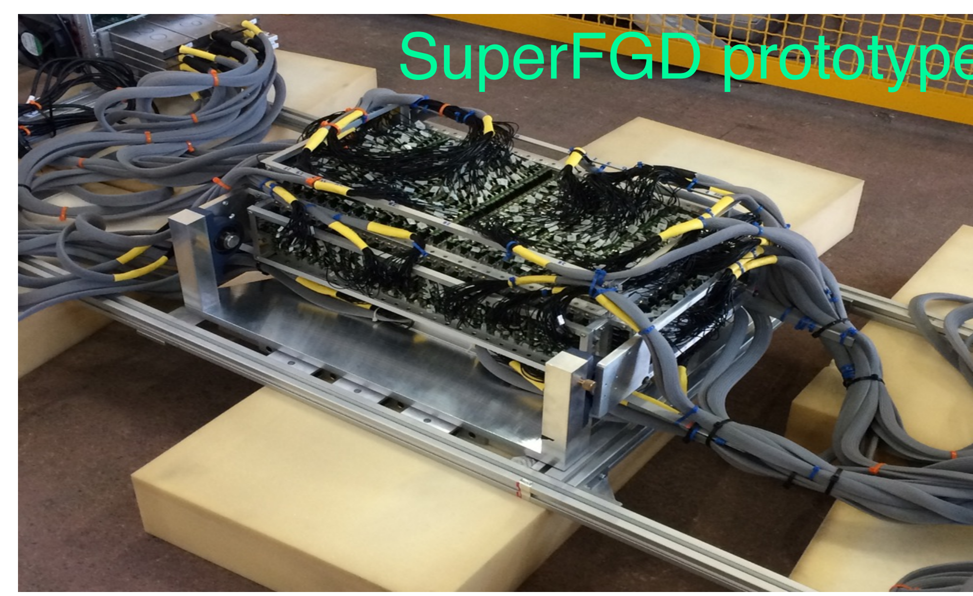


Stopping proton



Pion interaction
(Time-over-Threshold)

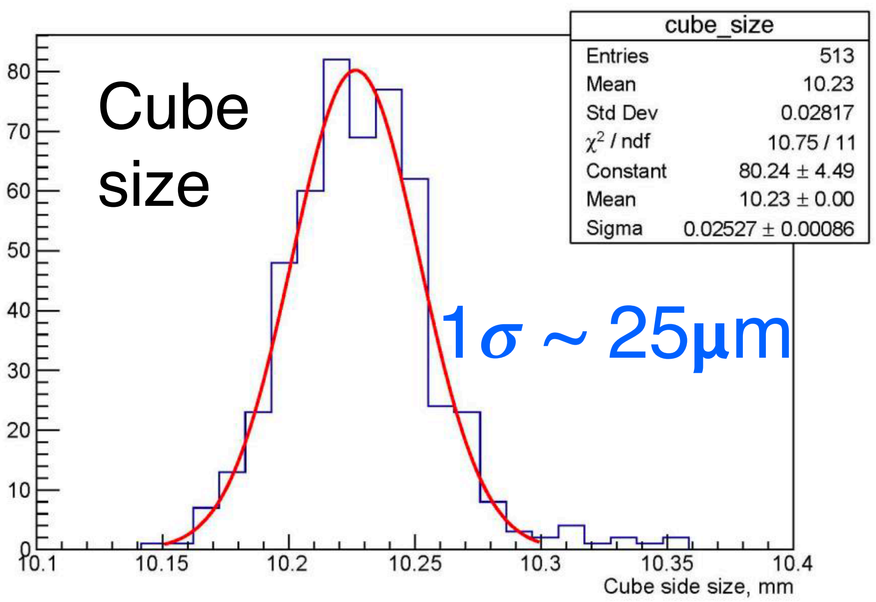


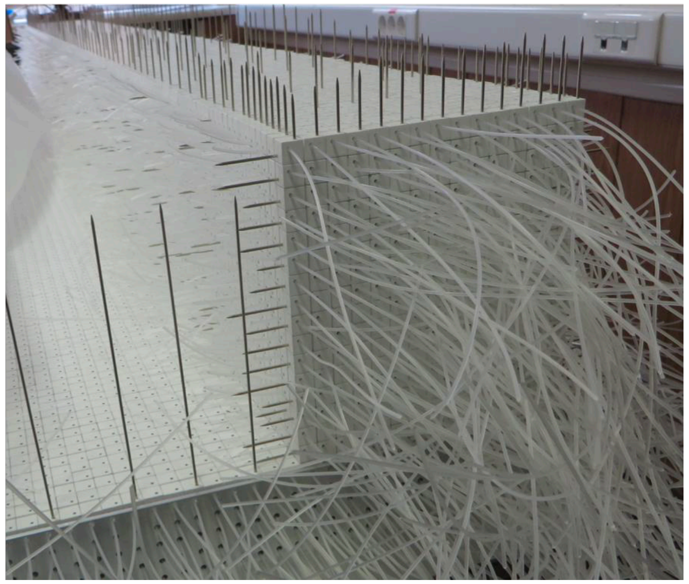


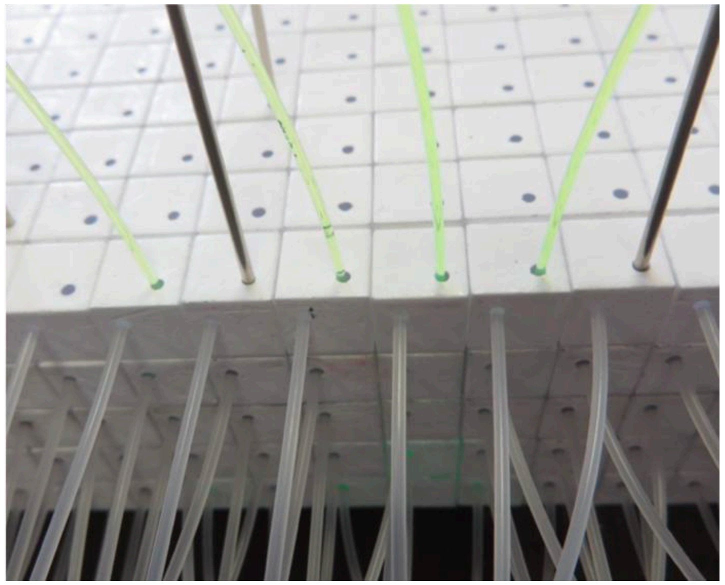
Results not public yet but paper being submitted to peer-review journal

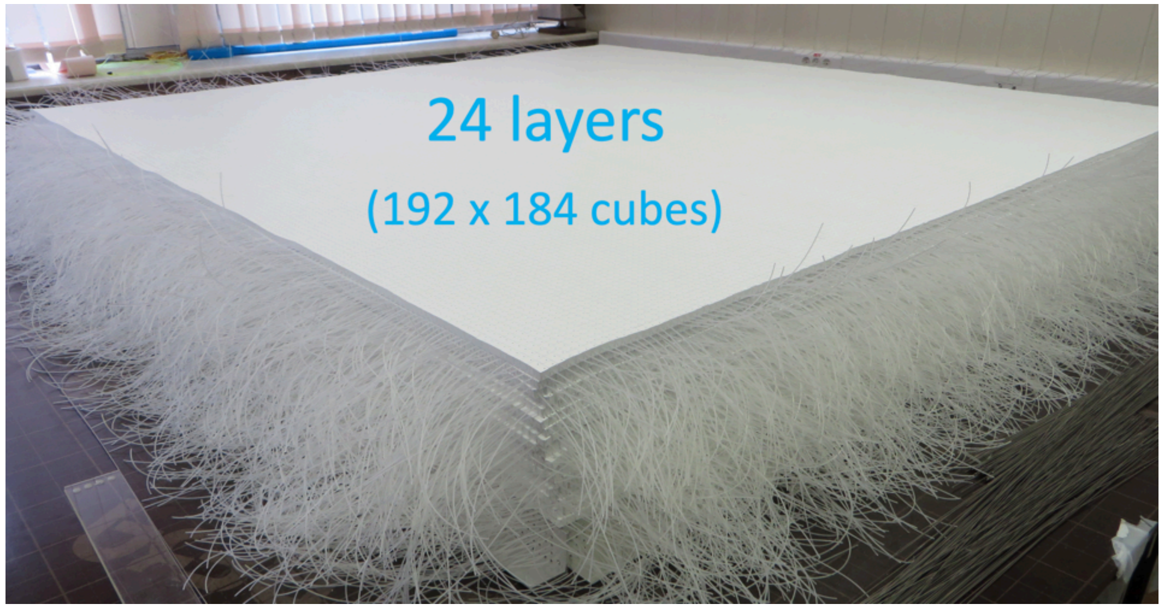
The SuperFGD cubes and assembly

- About 1.5M cubes already manufactured (~75% of total # of cubes) at UNIPLAST
- Assembly ∅1.3mm fishing lines of to align cubes
  - ✦ Eventually replace fishing lines with WLS fibers





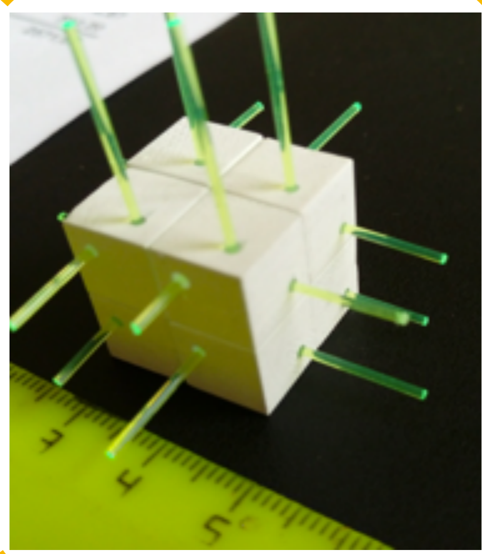




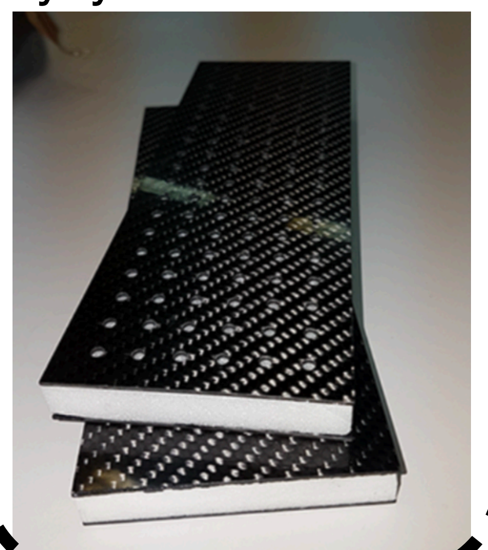
- Already ~75% of the layers assembled at INR Moscow
- Also developed another assembly method: ultrasonic welding to fix cubes to 0.1mm polystyrene sheet

The SuperFGD readout interface

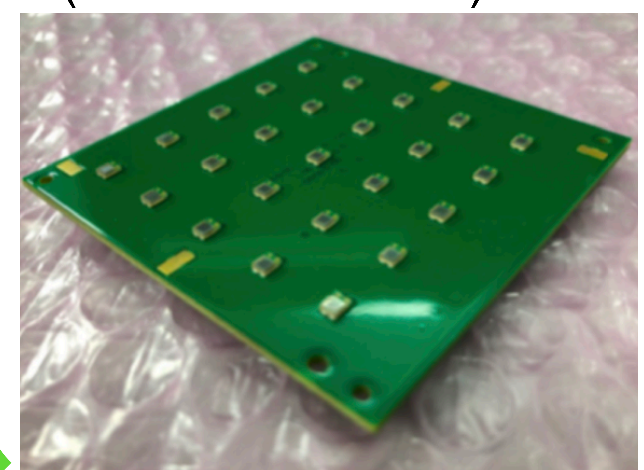
CERN-SPSC-2018-001 SPSC-P-357, arXiv:1901.03750

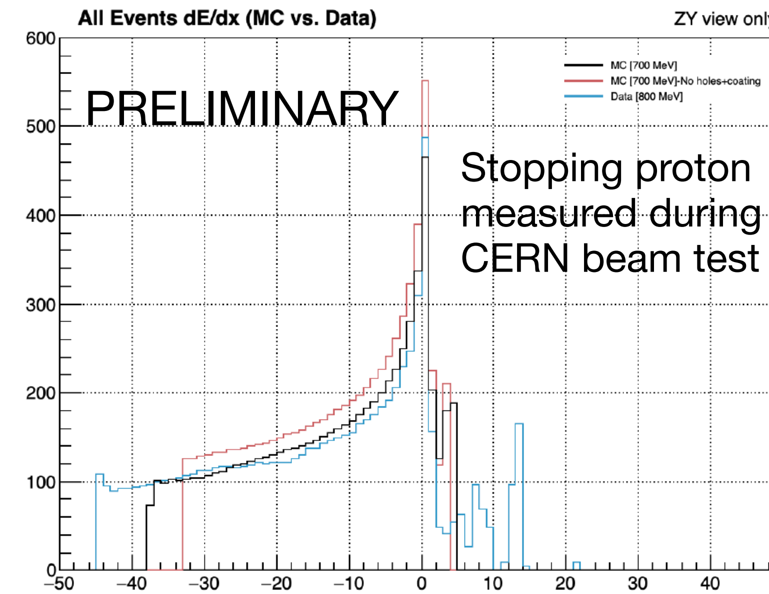


Carbon fiber dyvyncell sandwich



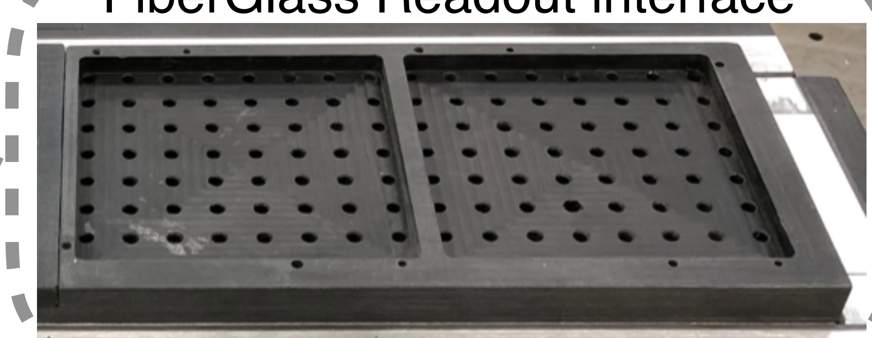
Hamamatsu MultiPixel PhotoCounters (S13360-1325PE)

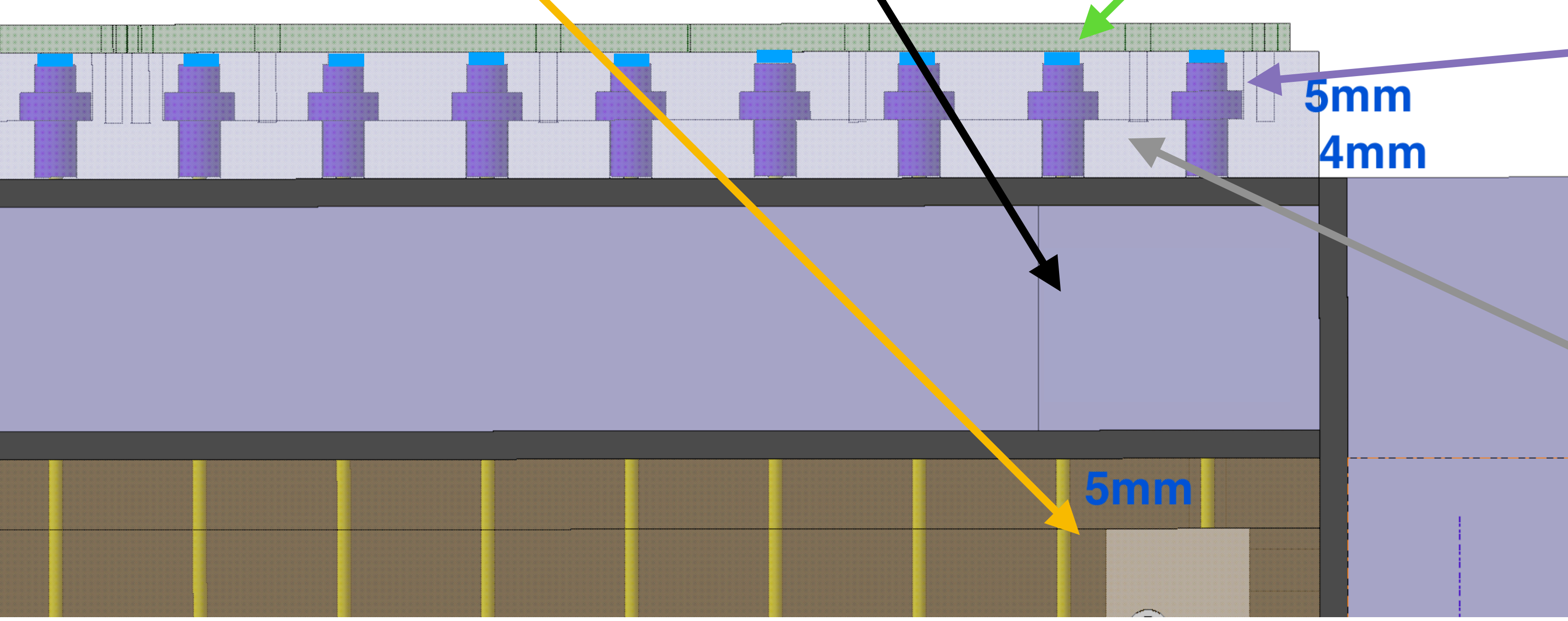




optical connector

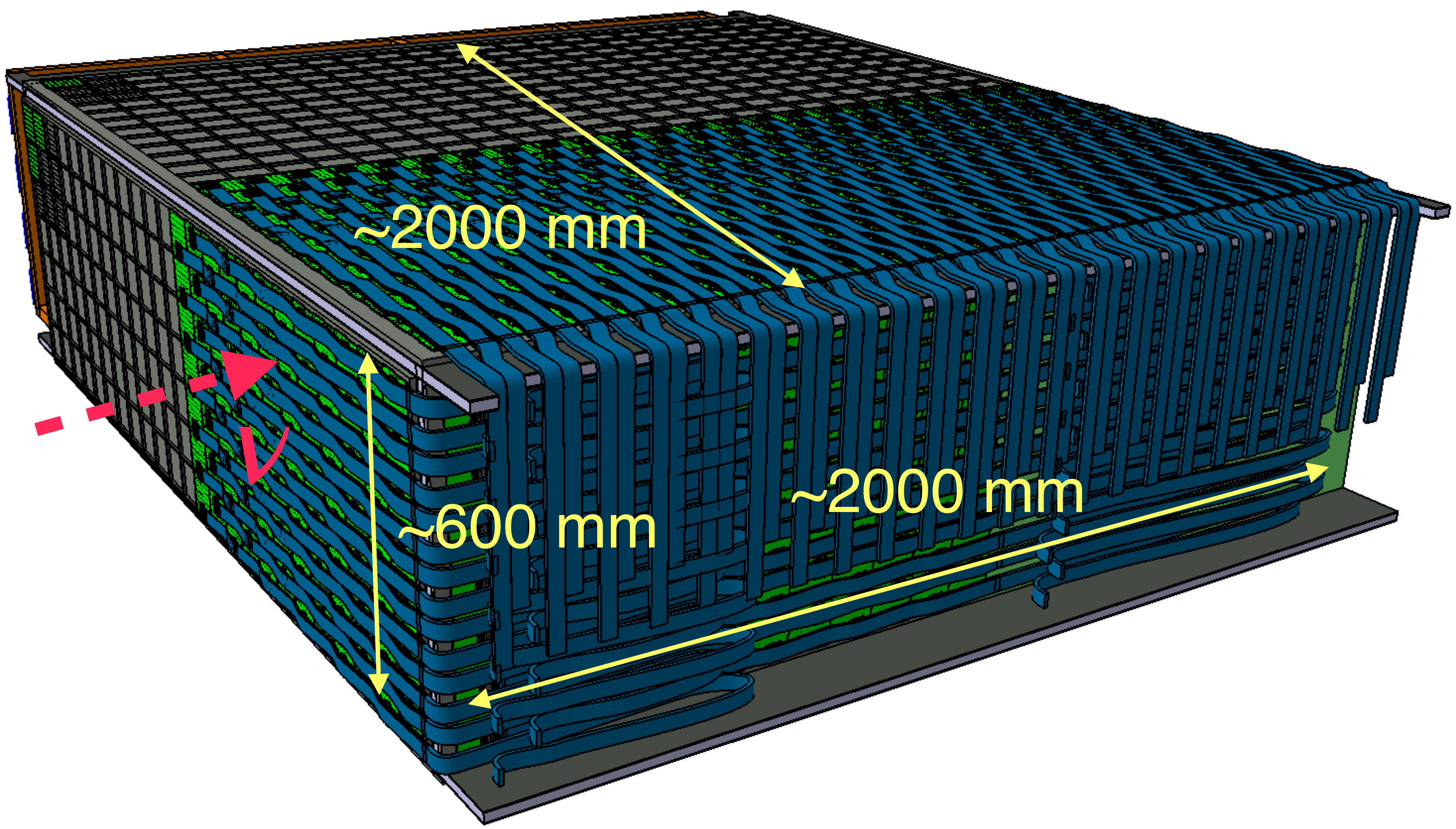
FiberGlass Readout interface

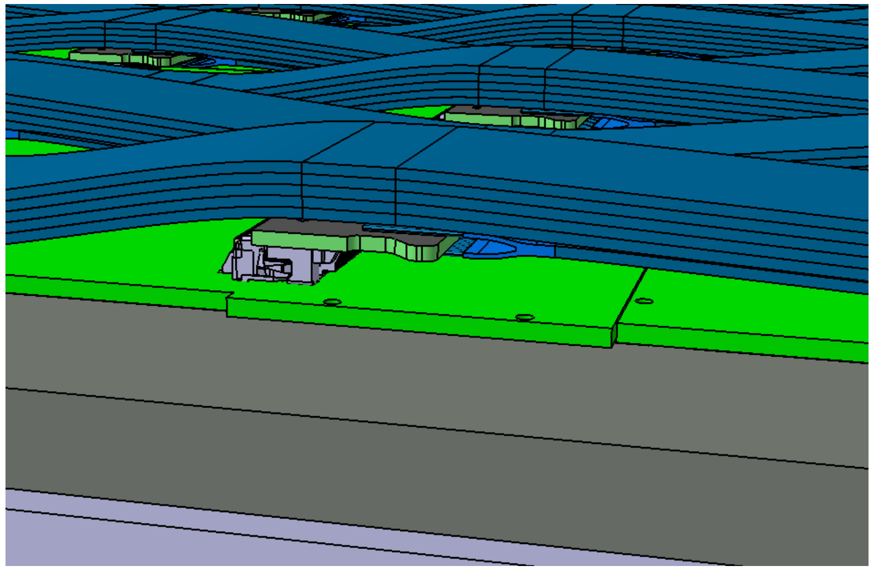


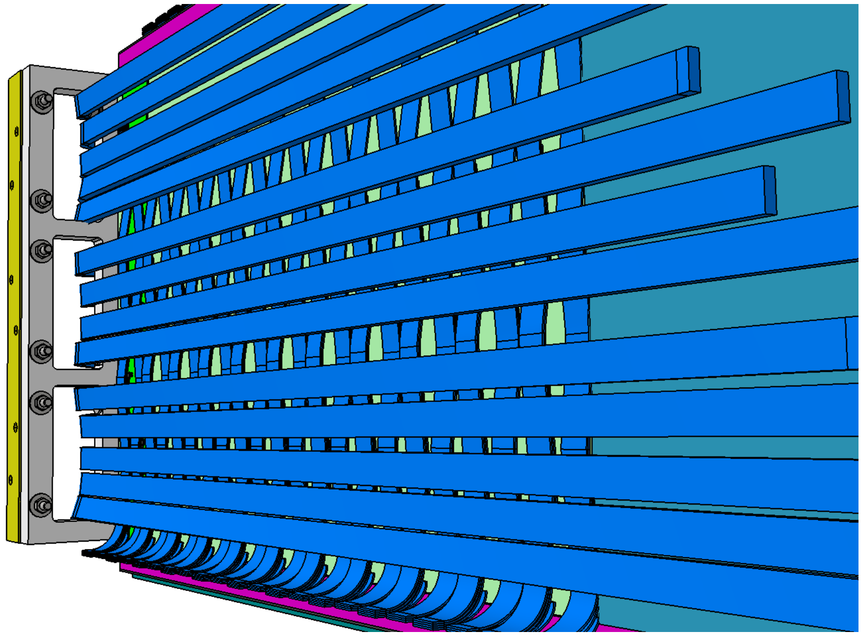


The SuperFGD readout

- Flat cables bring the analog signal from MPPCs to FEBs placed at left / right sides of SuperFGD
- Brakets at four corners to fix the SuperFGD detector to the mechanical frame



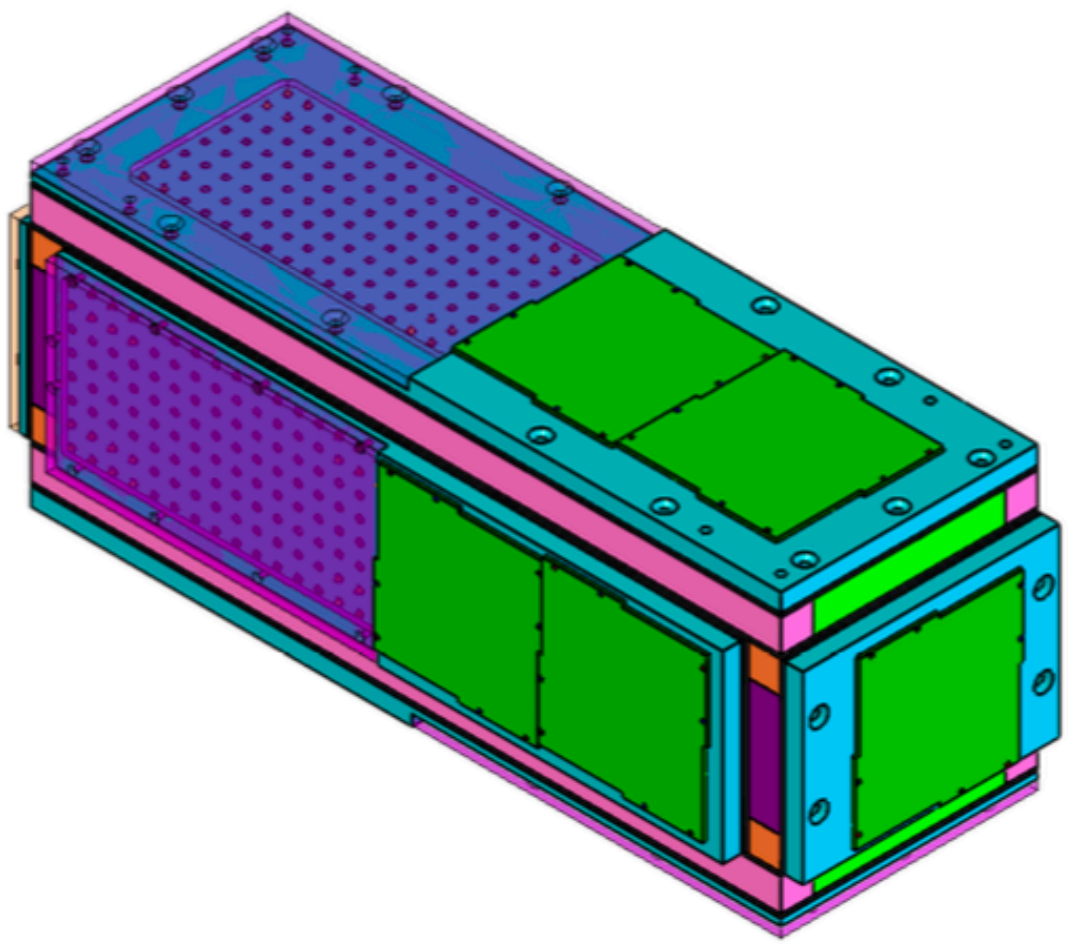


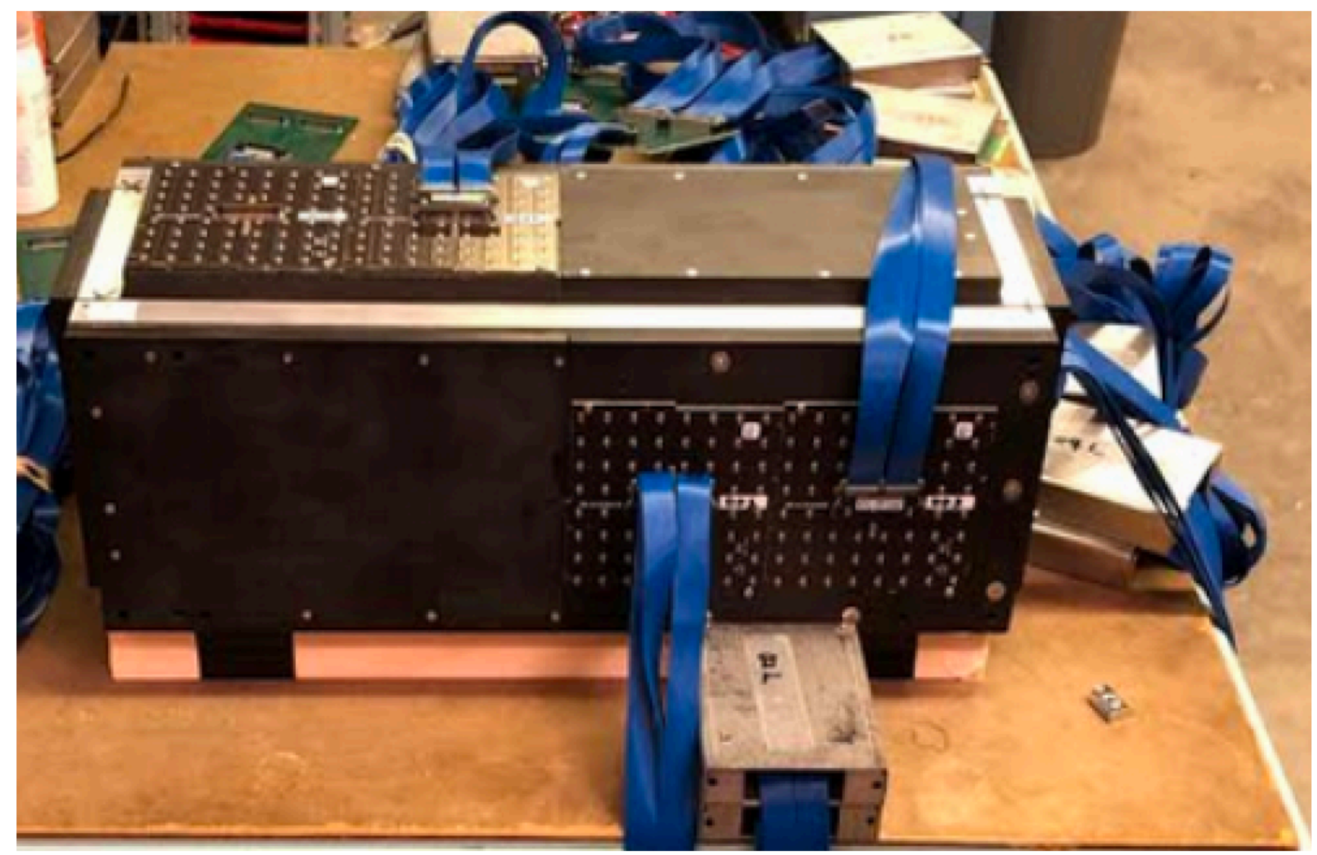


- Electronics based on CITIROC chip, same as Baby MIND: Charge peak + ToT, high/low dynamic range. No strict requirements on time resolution at T2K
- For 3DST electronics conceptual design is ongoing for additional requirements:
  - ✦ Time resolution per channel as low as 200 ps

The US-Japan prototype

- Prototype with joint resources from US and Japan
- First running prototype that adopts the SuperFGD design
  - ✦ 8 (width) x 32 (length) x 8 (height) cubes (~1cm^3)
  - ✦ 2048 cubes (1cm^3 each), 576 channels
- Exposed to neutron test beam at LANL

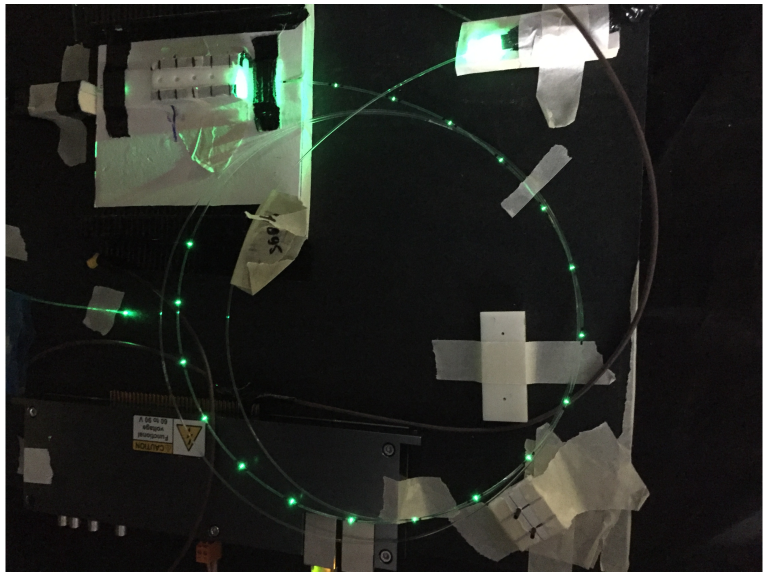




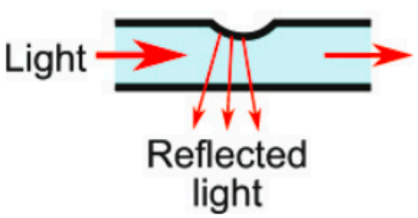
- More details about LANL beam tests in Guang's talk

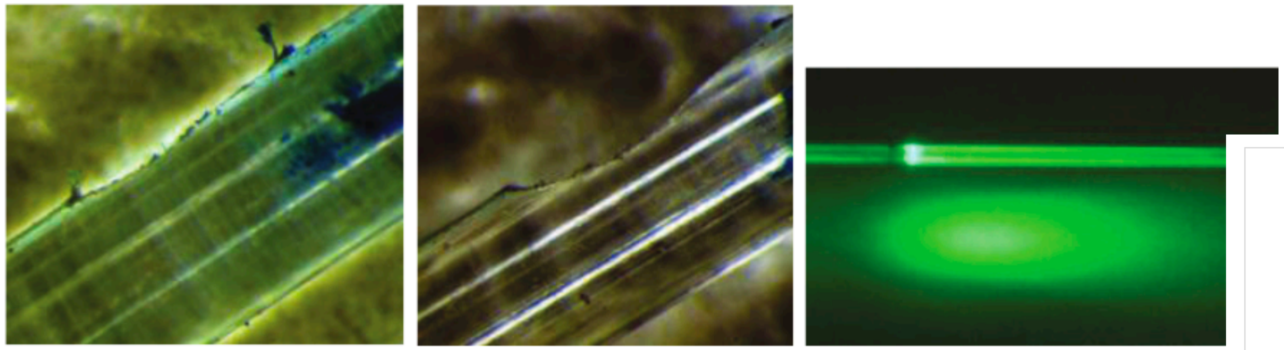
Candidate calibration system for 3DST

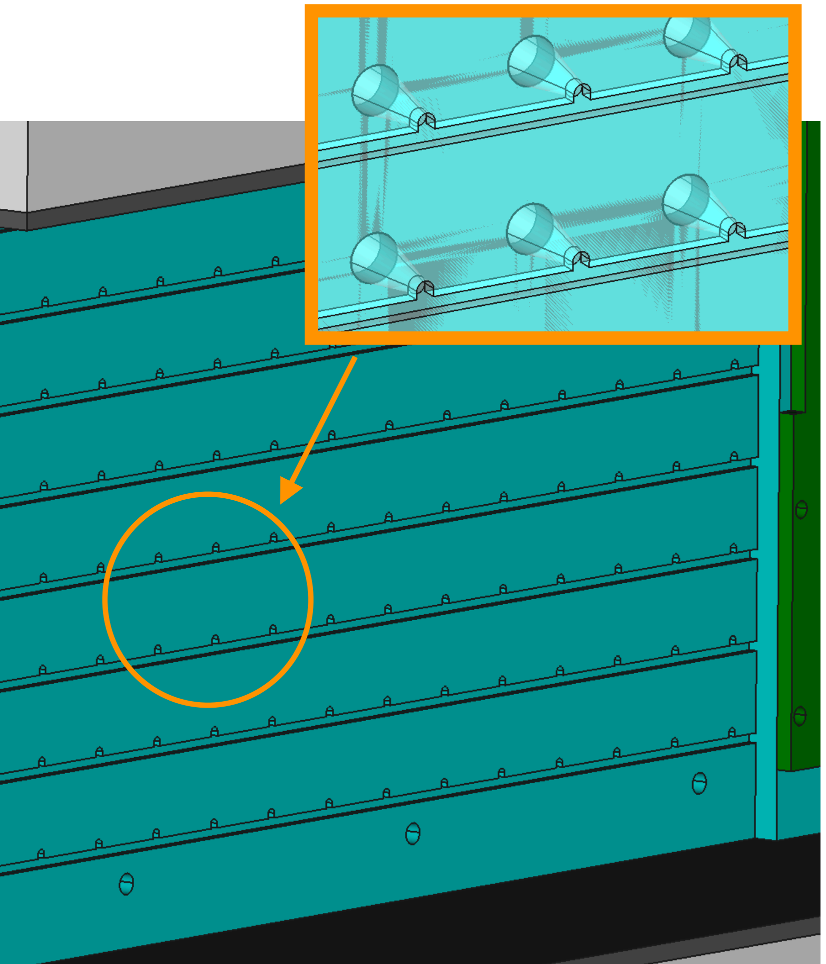
- A very compact LED calibration / monitoring system for MPPCs is required
- Clear square fiber with “notches” to scatter light toward WLS fiber cladding

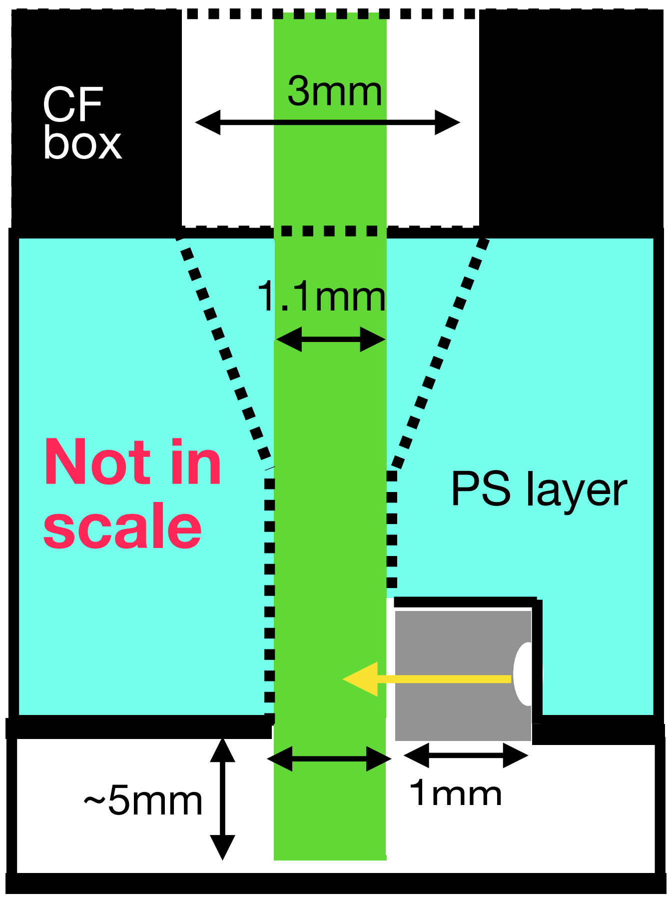


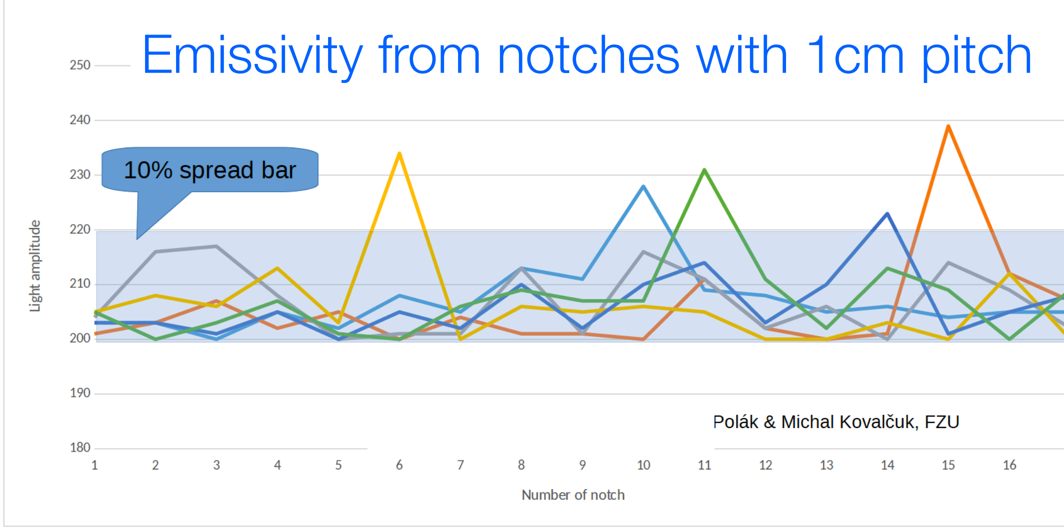
Physics Procedia 37 (2012) 402 – 409



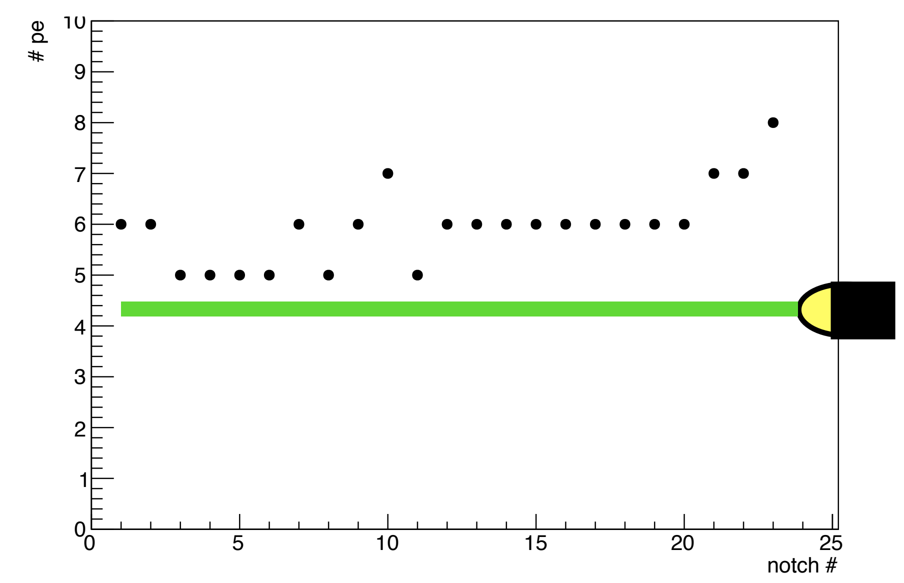








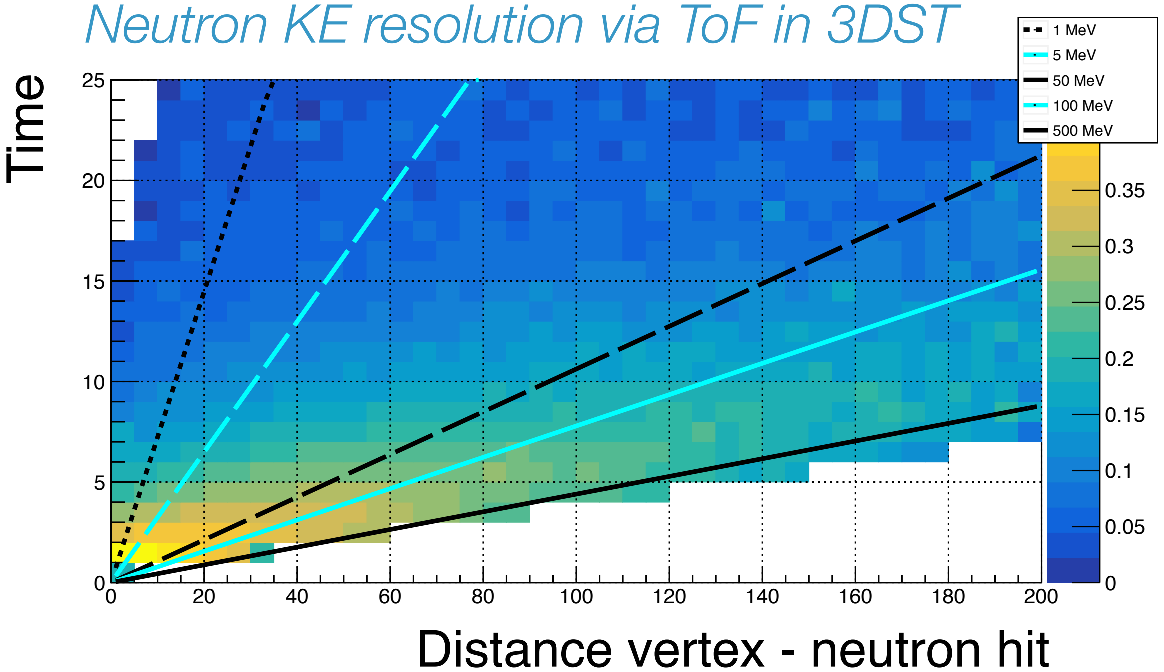
First tests of coupling notched-WLS fibers



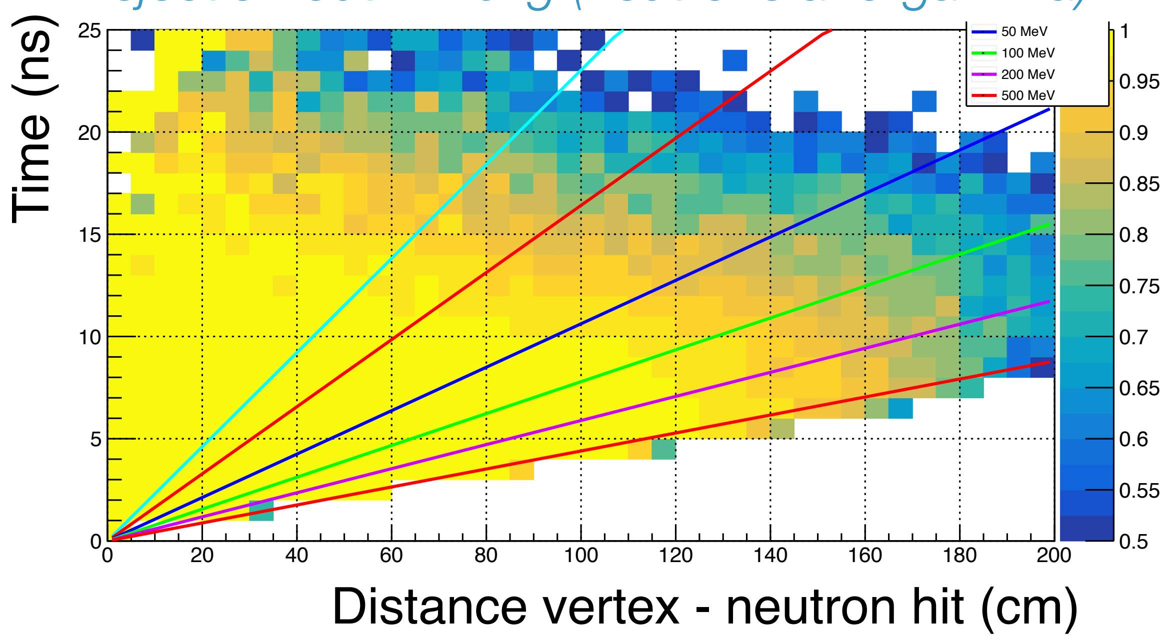
Neutron detection with Time-of-Flight measurement

- 3DST is the idal detector for detecting neutrons w/ high purity and efficiency and precise measurement of ToF
  - ✦ Large mass (all interactions in relatively short length)
  - ✦ Low energy threshold (1p.e.~60 KeV)
  - ✦ Fully active to neutrons (low-A nuclei & scintillating)
  - ✦ Excellent time resolution

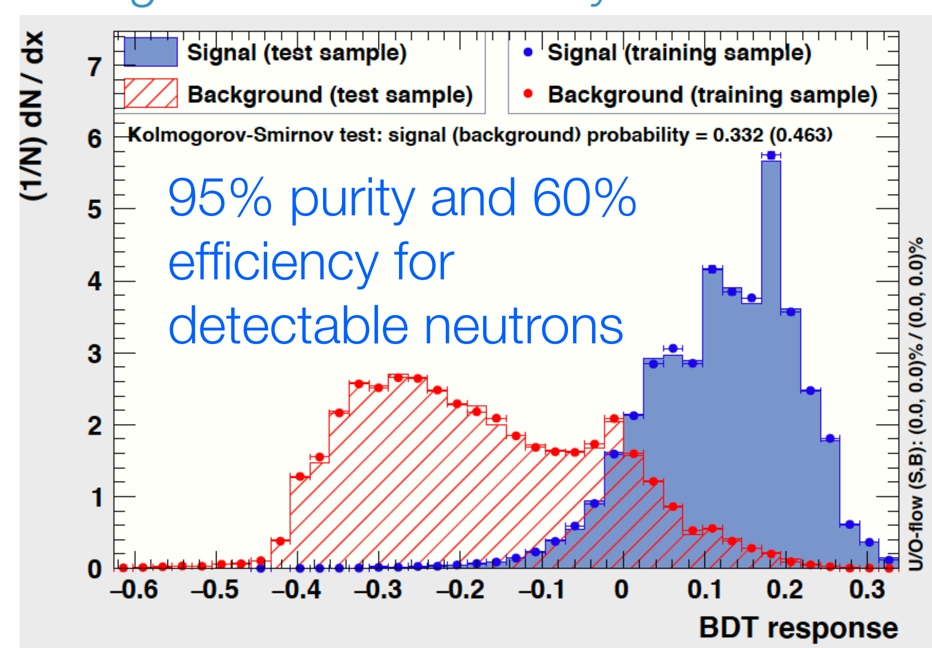
Neutron KE resolution via ToF in 3DST



Rejection out-FV bkg (neutrons and gamma)



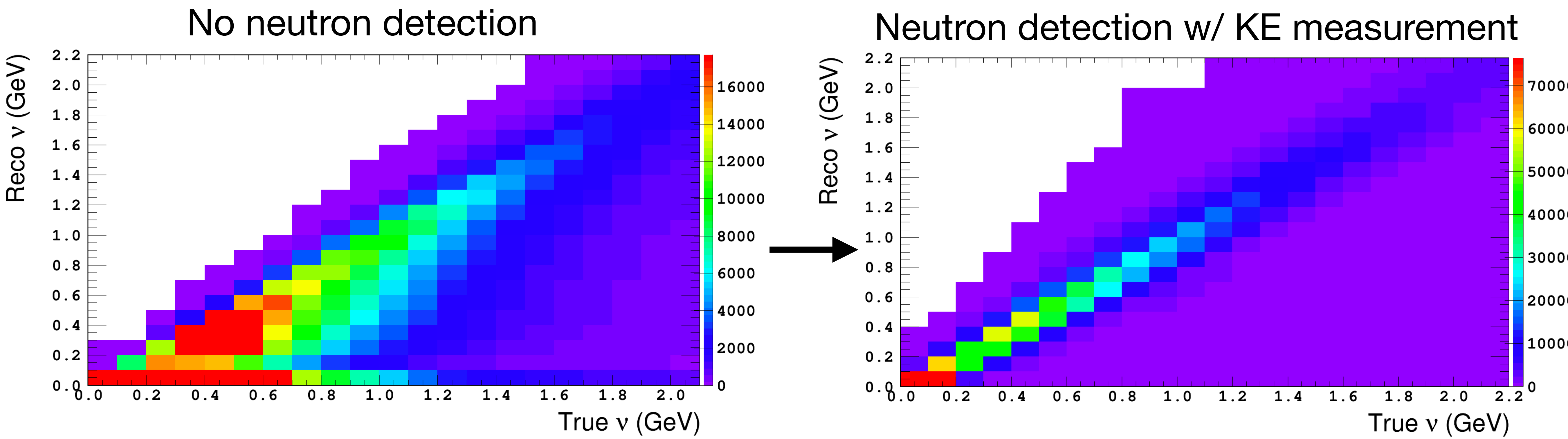
Rejection of gammas / secondary neutrons from 3DST



3DST has the unique capability of measuring neutron kinetic energy with resolution ~20% and almost background free

Why detecting neutrons is important

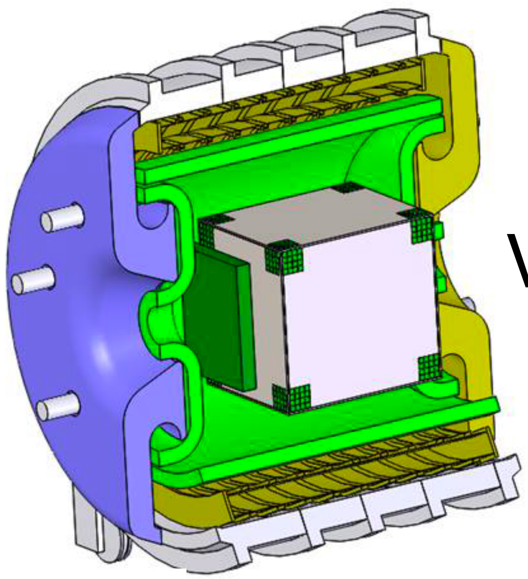
Resolution on energy transferred to the nucleus (ν)



- Important to validate that the inferences one makes from studies of proton distributions can be successfully applied to predict neutrons
- Minerva has demonstrated the capability of detecting neutrons produced by antineutrino interactions (PRD 100, 052002)
- Also important for measuring the AntiNu flux by selecting AntiNu-Hydrogen interactions requiring no transverse momentum imbalance, with energy resolution down to ~5% and limited model dependence (PRD 101 (2020) 9, 092003)

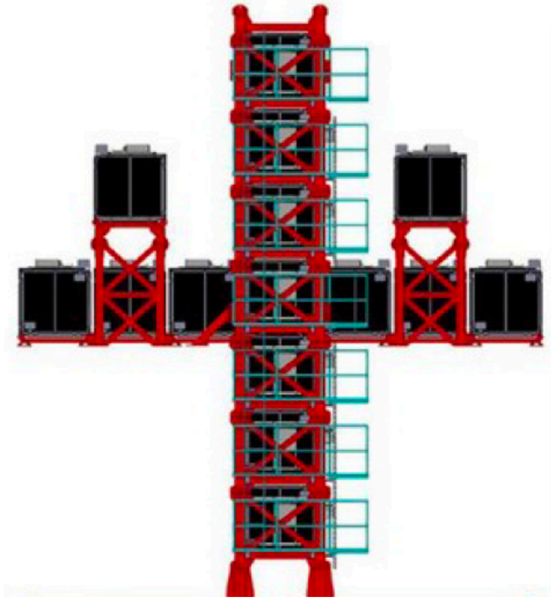
Beam monitoring performances

- 3DST+ECAL provides the largest mass among SAND options (…and there is still space available for increasing it)
- Excellent energy resolution (novel detector, hence a lot still to explore)
- TPC best option for complementing 3DST in spectrum measurement



VS

T2K INGRID ND



Beam parameter	Parameter description		Significance, $\sqrt{\chi^2}$	
	Nominal	Changed	Rate-only monitor	SAND
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	5.6
proton beam width	2.7 mm	2.8 mm	0.02	3.6
proton beam offset x	N/A	+0.45 mm	0.09	4.3
proton beam $theta$	N/A	0.07 mrad	0.03	0.5
proton beam $\theta\phi$	N/A	0.07 mrad θ and 1.5707 ϕ	0.00	1.0
horn current	293 kA	296 kA	0.2	11.9
water layer thickness	1 mm	1.5 mm	0.5	4.2
decay pipe radius	2 m	2.1 m	0.5	7.0
horn 1 along x	N/A	0.5 mm	0.5	4.6
horn 1 along y	N/A	0.5 mm	0.1	3.6
horn 2 along x	N/A	0.5 mm	0.02	0.9
horn 2 along y	N/A	0.5 mm	0.00	0.8

Compared with four 7-ton modules that measure the rate at 0,1,2,3 meters from the on-axis position (28 ton in total)

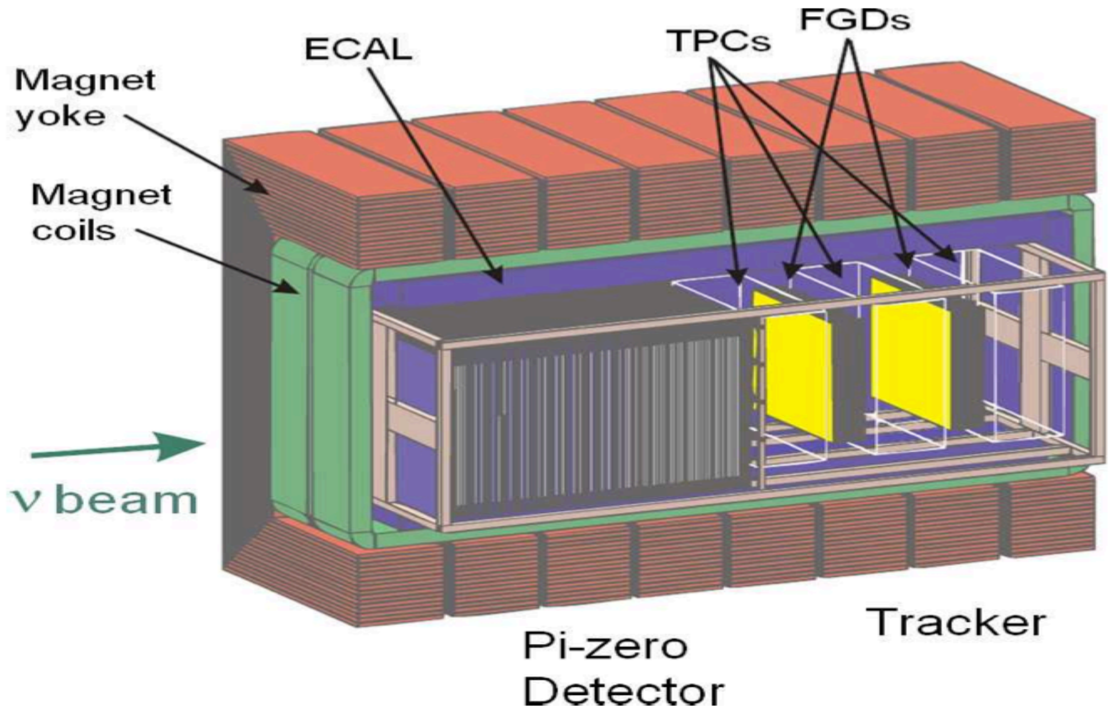
Test statistic: $\Delta\chi^2$ between 1week simulated data and nominal distribution, large data sample

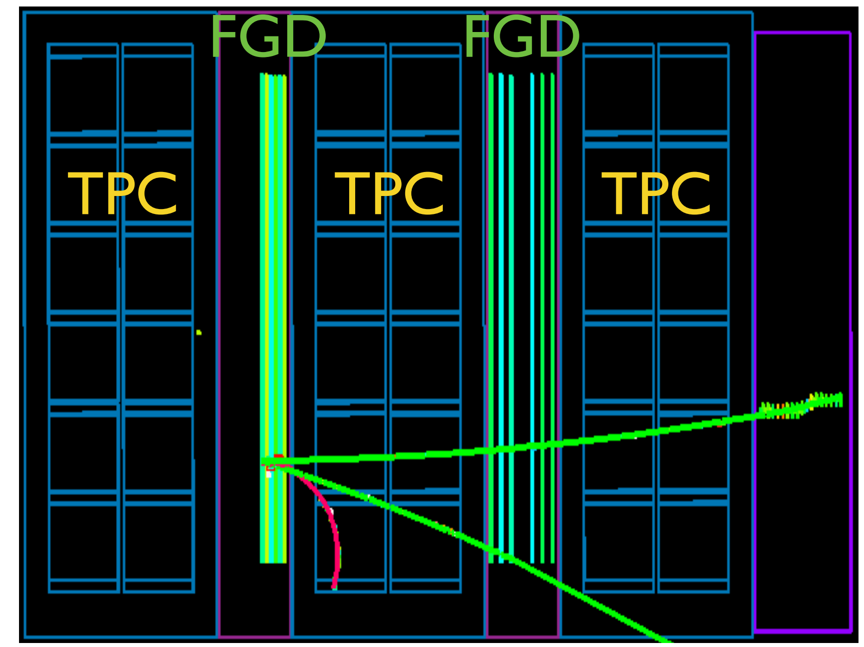
1 week exposure

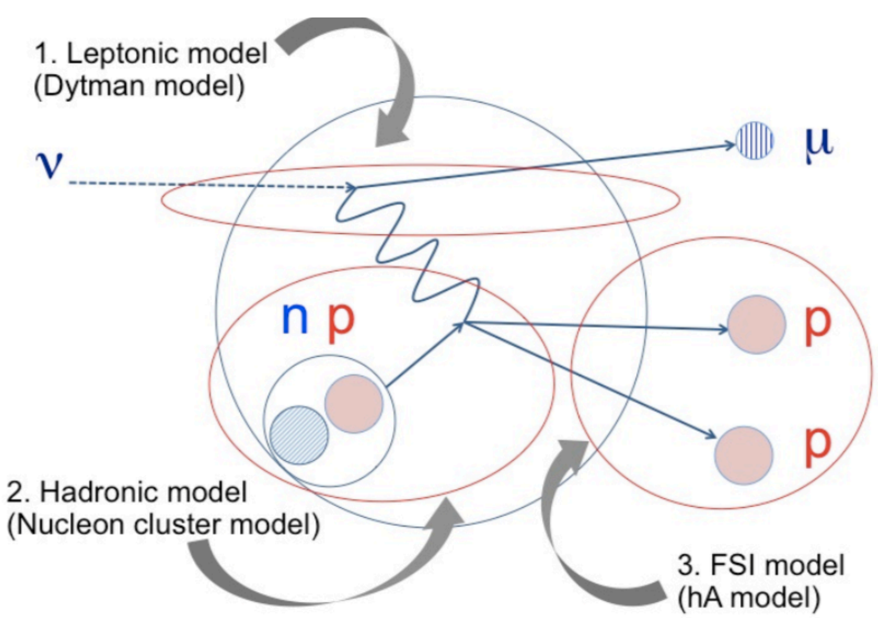
- The SAND spectrometer is very sensitive to even small variations of the beam parameters compared to just measuring the neutrino event rate
- With 3DST module, ~11 cm uncertainty on the beam center can be achieved with 1 week data taking. Improvements are expected by using also ECAL

BACKUP

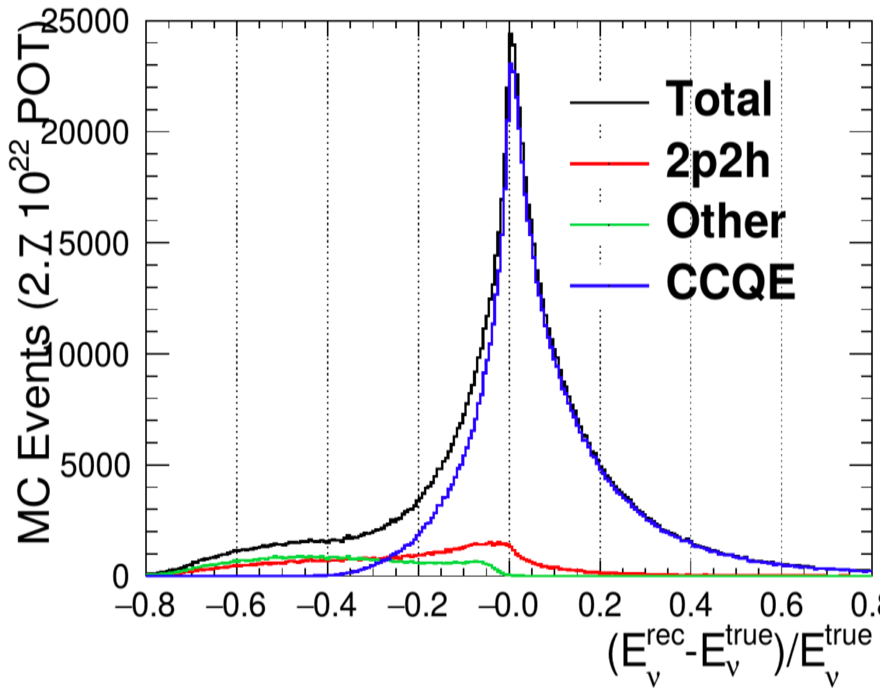
The T2K off-axis near detector: ND280



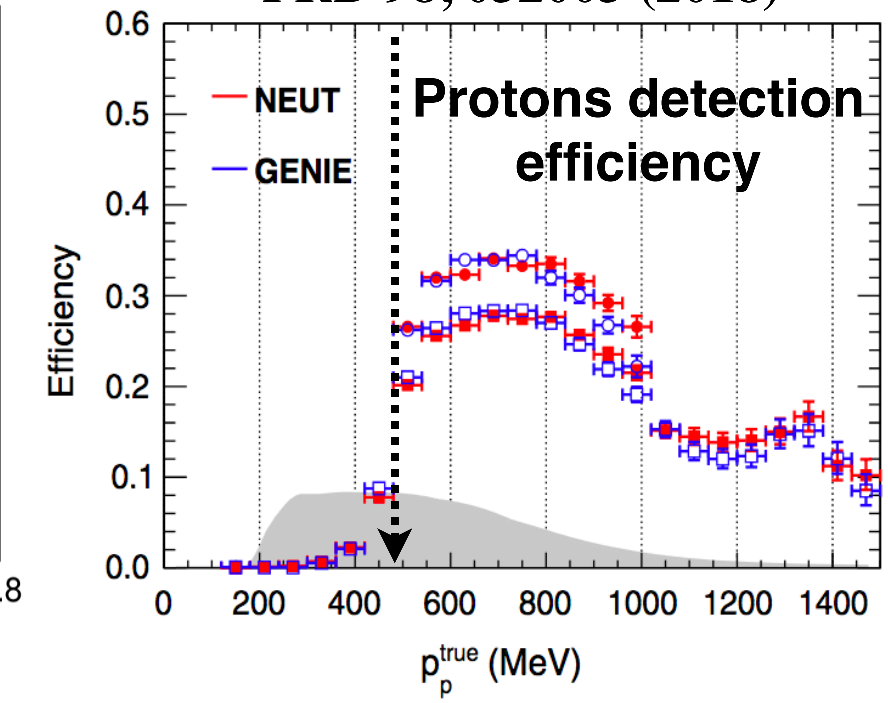




Nieves et al. PRC 83 045501 (2011)
Martini et al. Phys.Rev. D87 (2013) 013009



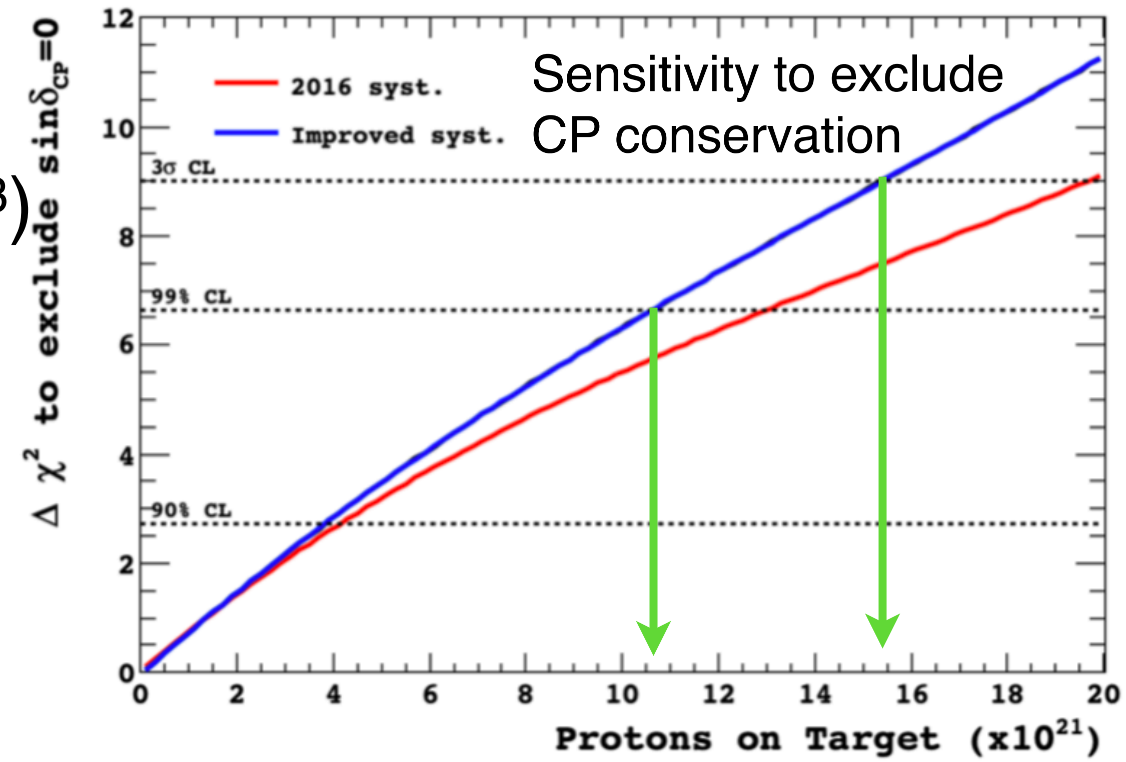
PRD 98, 032003 (2018)



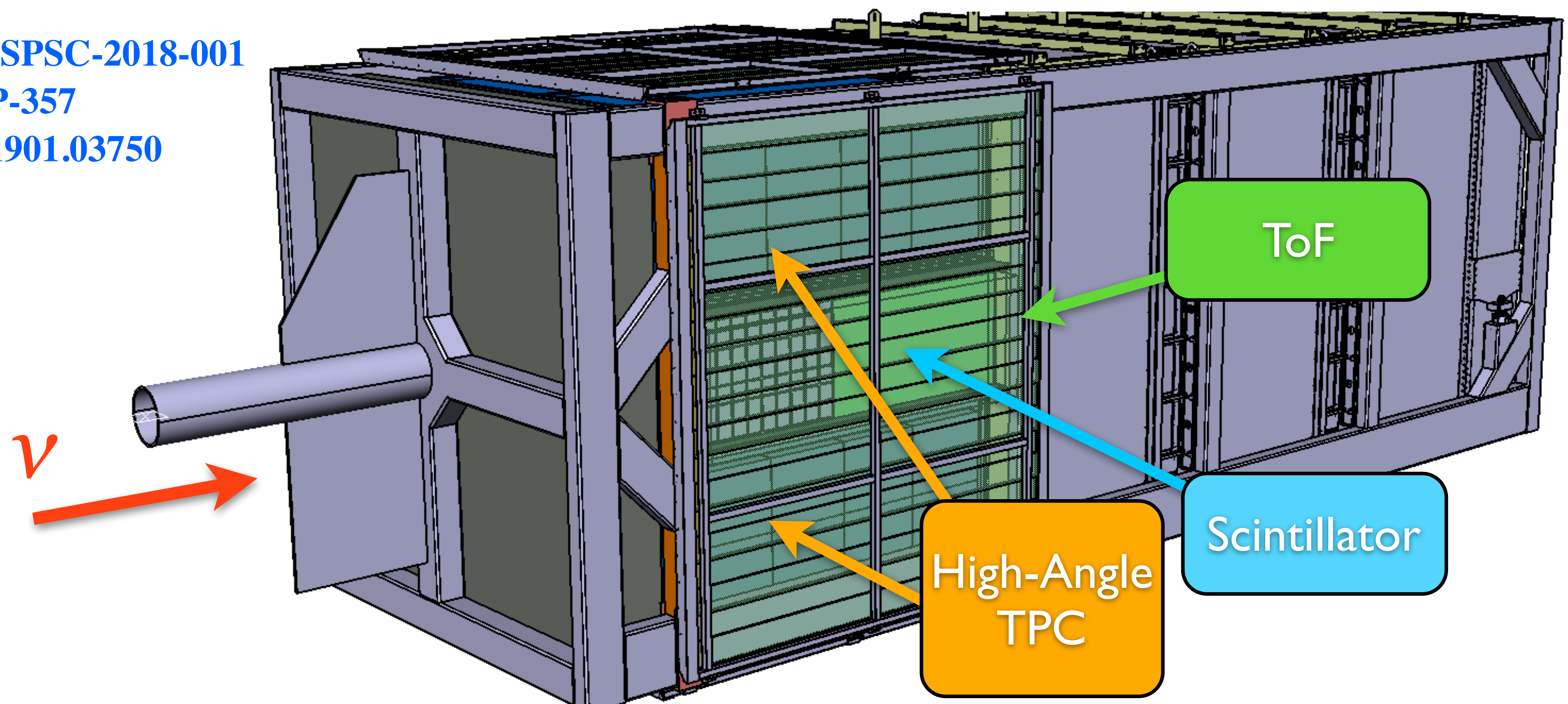
ND280 can not efficiently reconstruct particle tracks at any angle
Also need to improve the sensitivity to nuclear effects: lower particle momentum threshold, high detection efficiency 4π and possibly precise neutron detection

The T2K Near Detector upgrade

- Keep the electromagnetic calorimeter
- Horizontal active target detector (~2x2x0.6 m^3)
- Two High-Angle TPCs
- Time-of-Flight detector around new tracker
- B-field of 0.2 T
- Expect total systematic uncertainty below 4%

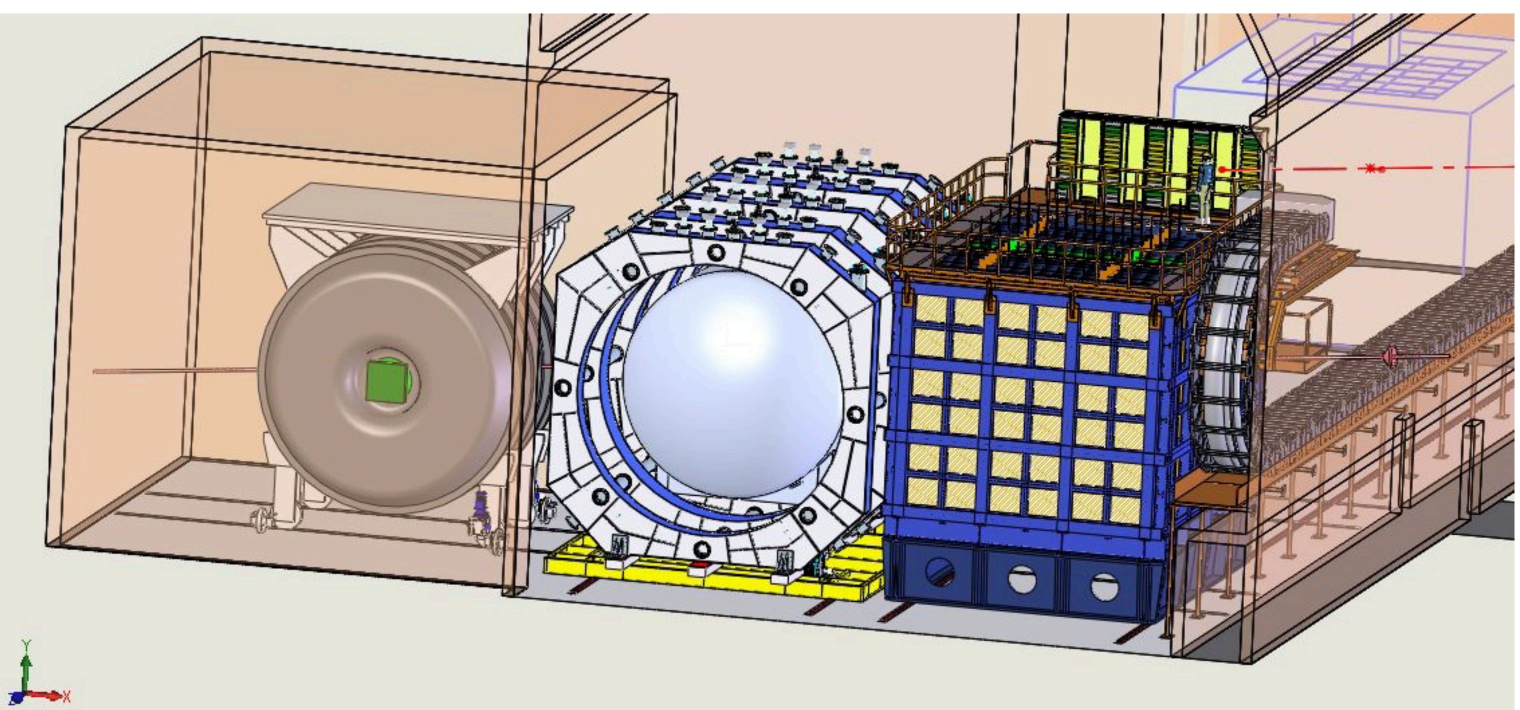


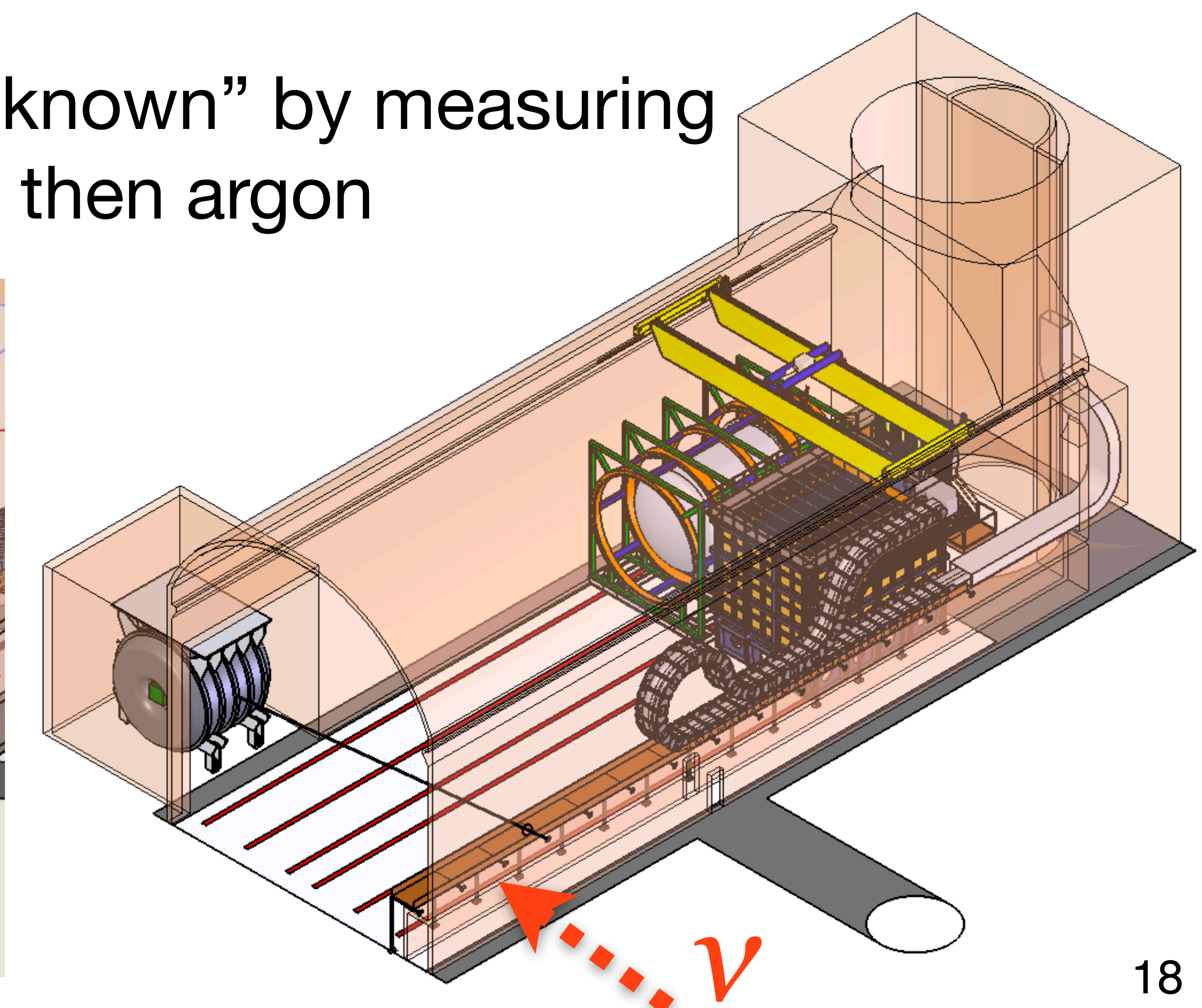
CERN-SPSC-2018-001
SPSC-P-357
arXiv:1901.03750



The Near Detector system

- ArCube and MPD systems will move off-axis (DUNE-PRISM)
- We need a detector system always on the neutrino axis: *SAND*
  - ✦ Precise beam monitoring in a few-days basis of event rate, beam width and spectrum
- Other important functions of SAND:
  - ✦ Complementary measurement of $\boldsymbol{\nu}$ / $\bar{\boldsymbol{\nu}}$ flux using different but complementary methods
  - ✦ Robustness against “unknown of unknown” by measuring neutrino interactions in targets other then argon





Document on usefulness of v-C^{12} measurements

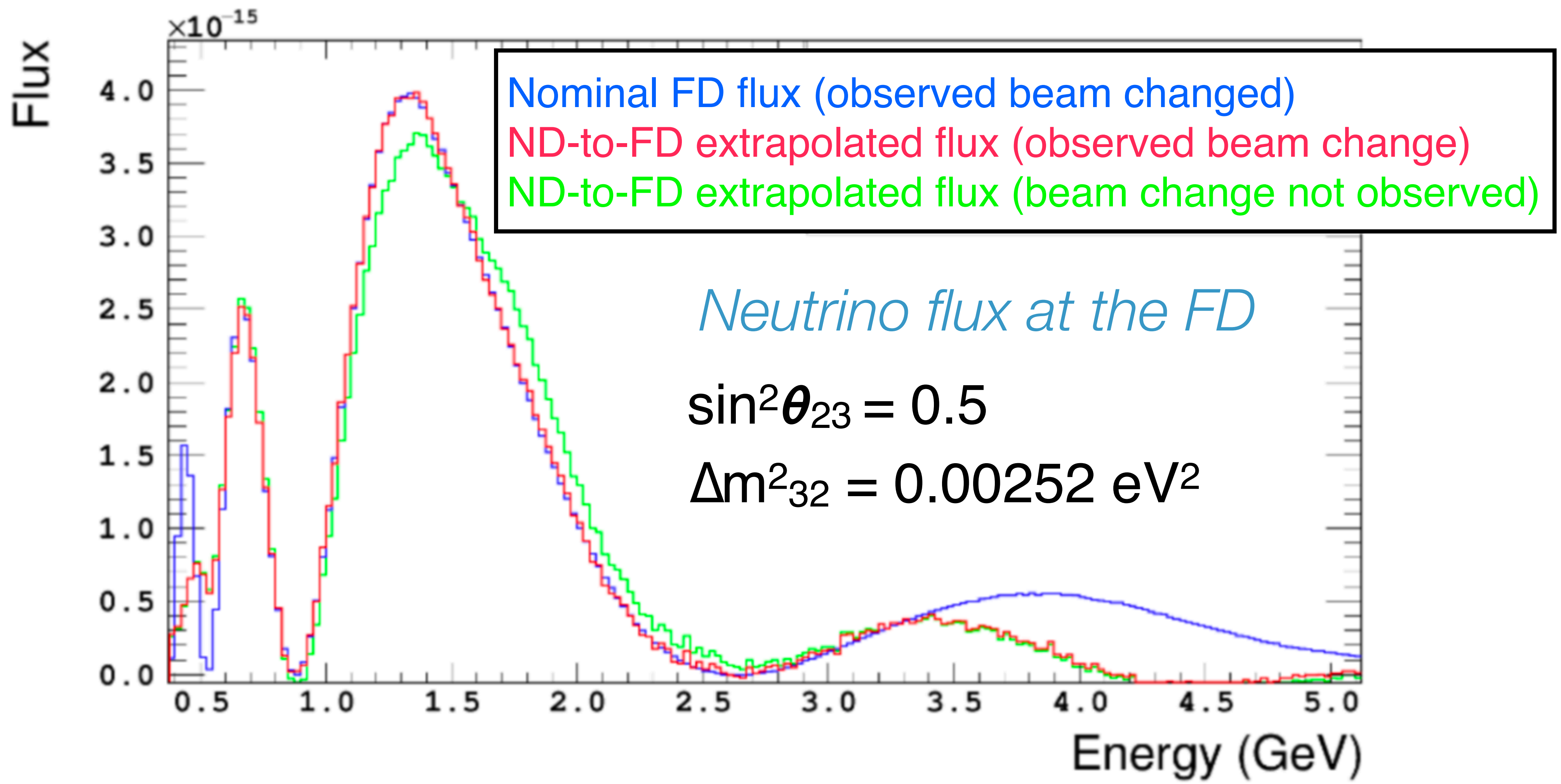
- A new document is available in docdb

> Constraining neutrino-interactions on an Argon target using Carbon data in modern nuclear models
>
> Stephen Dolan Sara Bolognesi Davide Sgalaberna
> Guillermo Megias Maria Barbaro Juan Antonio Caballero
>
> September 16, 2019 docdb-16058-v1

- Written in collaboration with theorists expert in the field of neutrino interaction modeling
- In a few words: the physics of neutrino interactions with carbon and argon targets can be modelled using the same tools without extensive empirical tuning. Theoretical models, that are not yet in the generators, are able to improve modelling of electron scattering on argon through model modifications inspired by carbon data. These models naturally allow extrapolation between different nuclear targets.
- More details can be found in S.Dolan’s talk later

Importance of beam monitoring for DUNE-PRISM

- DUNE-PRISM relies on a good knowledge of the neutrino flux
- Example from the NUMI beam: Minerva and MINOS ND found problems by looking at the time-dependent variation of the neutrino reconstructed energy spectrum, while NOvA (off-axis) didn't observe significative changes
- We fake a similar case at DUNE, i.e. ArCube and MPD don't observe any change in the beam parameters when they move off-axis



If the same happens to DUNE, PRISM wouldn't see it but the FD flux would change —> need a ND system always on the beam axis

3-dimensional Scintillator Tracker (3DST)