SuperFGD detectors for T2K/HyperK and DUNE

Davide Sgalaberna (CERN)

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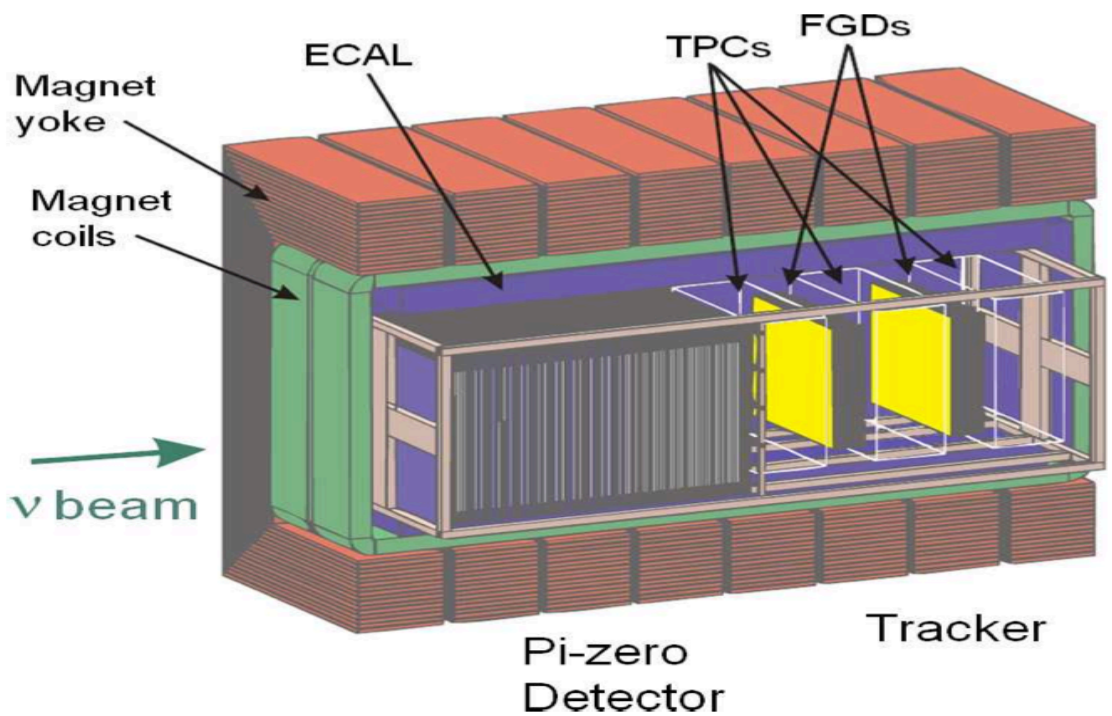
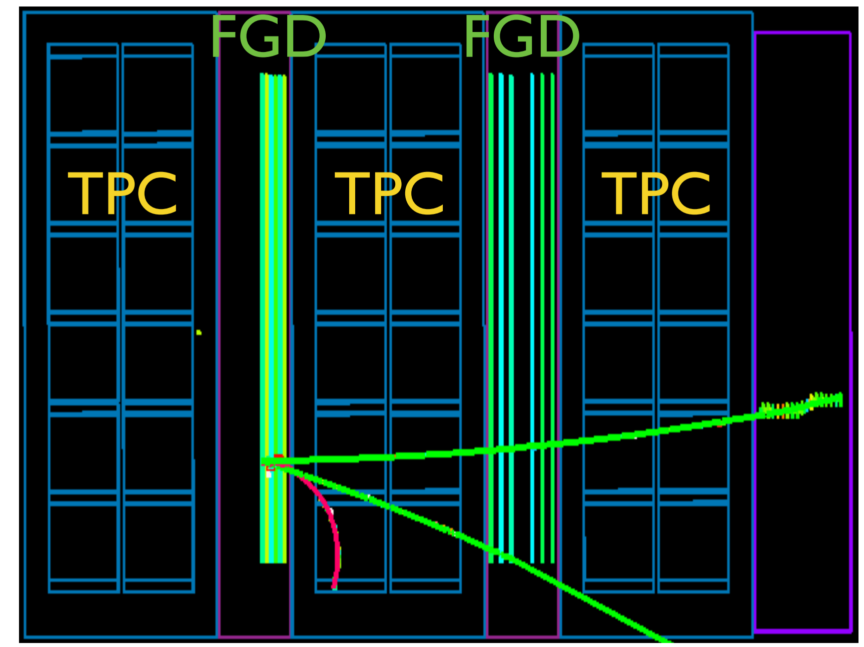
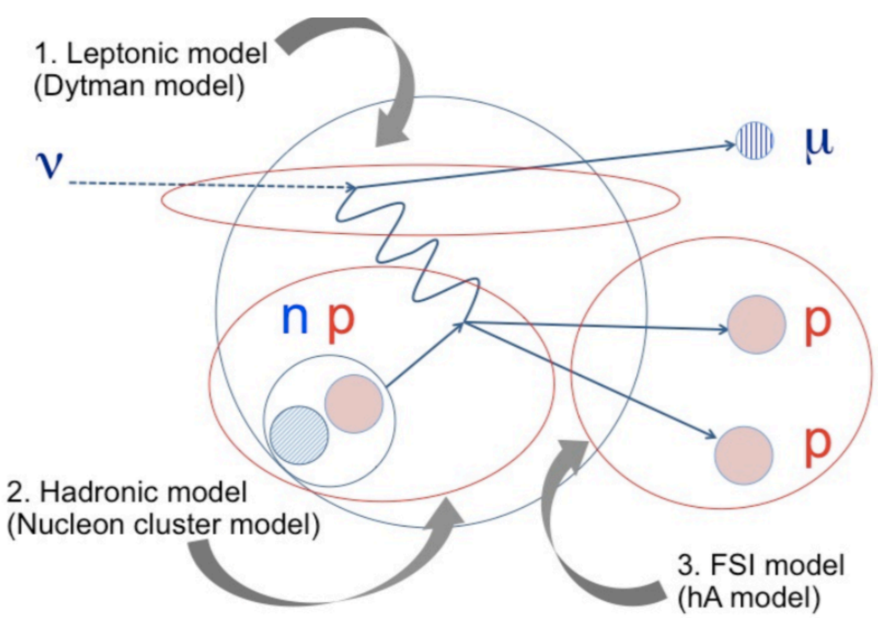
Introduction

- Recently a novel plastic scintillator technology has been proposed in the context of the T2K Near Detector upgrade to achieve the following goals
  - ✦ Perform particle tracking with relatively fine resolution
  - ✦ Capability to reconstruct tracks of particles propagating in the detector at any angle
  - ✦ Reduce the particle momentum threshold with respect to scint detectors of same granularity
  - ✦ Exploit all the advantages of plastic scintillator (Particle IDentification, timing resolution)
- T2K has decided to adopt it (Super Fine-Grained Detector - SuperFGD) as new active target of ND280 (it will be installed in end of 2021). CERN Neutrino Platform project (NP07)
- The DUNE collaboration has included it (3D Scintillator Tracker - 3DST) in the ND conceptual baseline
- Common R&D program will lead to neutron beam tests in Los Alamos

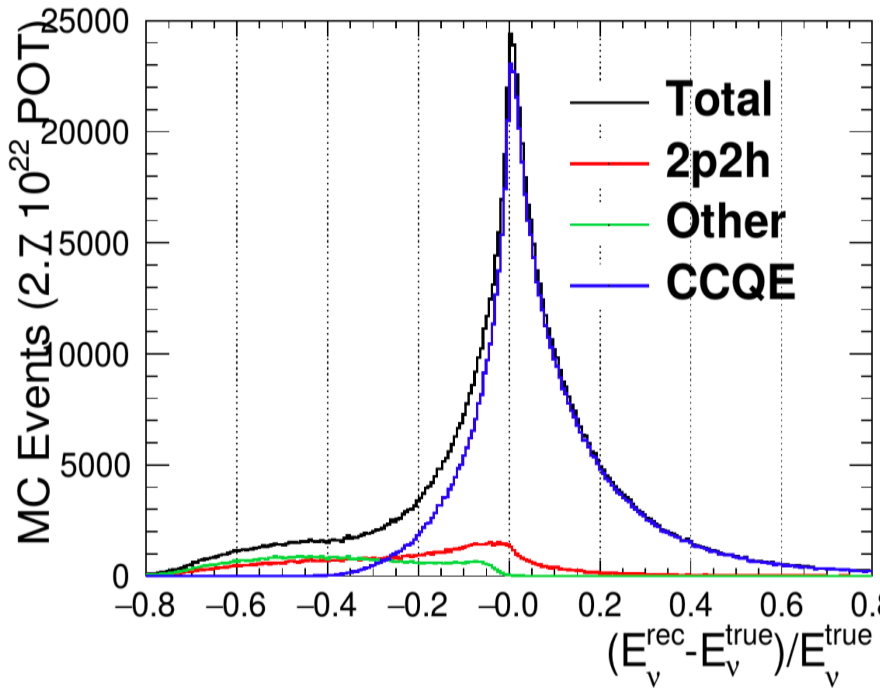
The T2K off-axis near detector: ND280



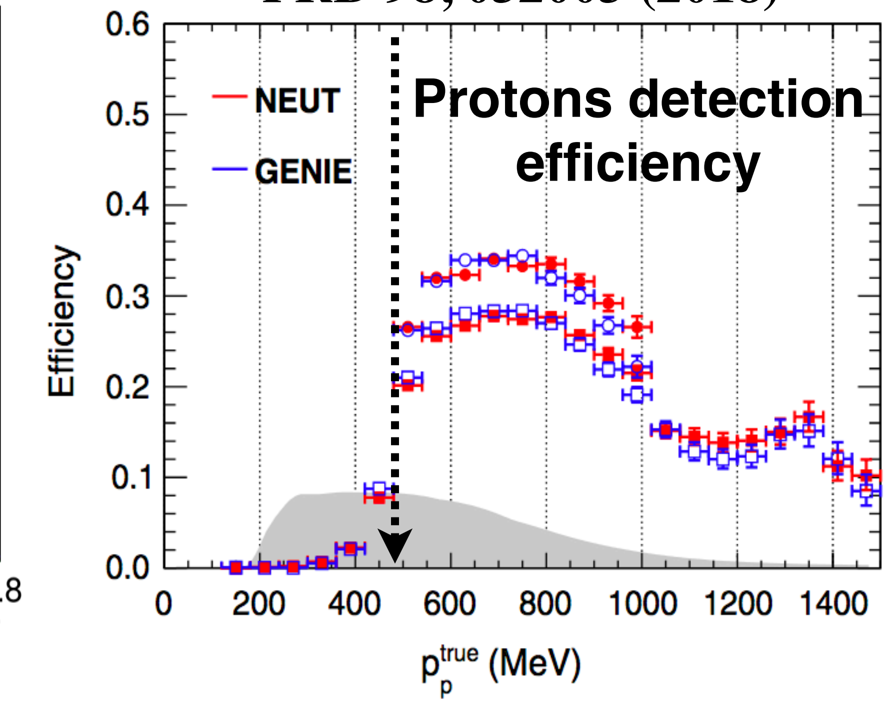




Nieves et al. PRC 83 045501 (2011)
Martini et al. Phys.Rev. D87 (2013) 013009



PRD 98, 032003 (2018)

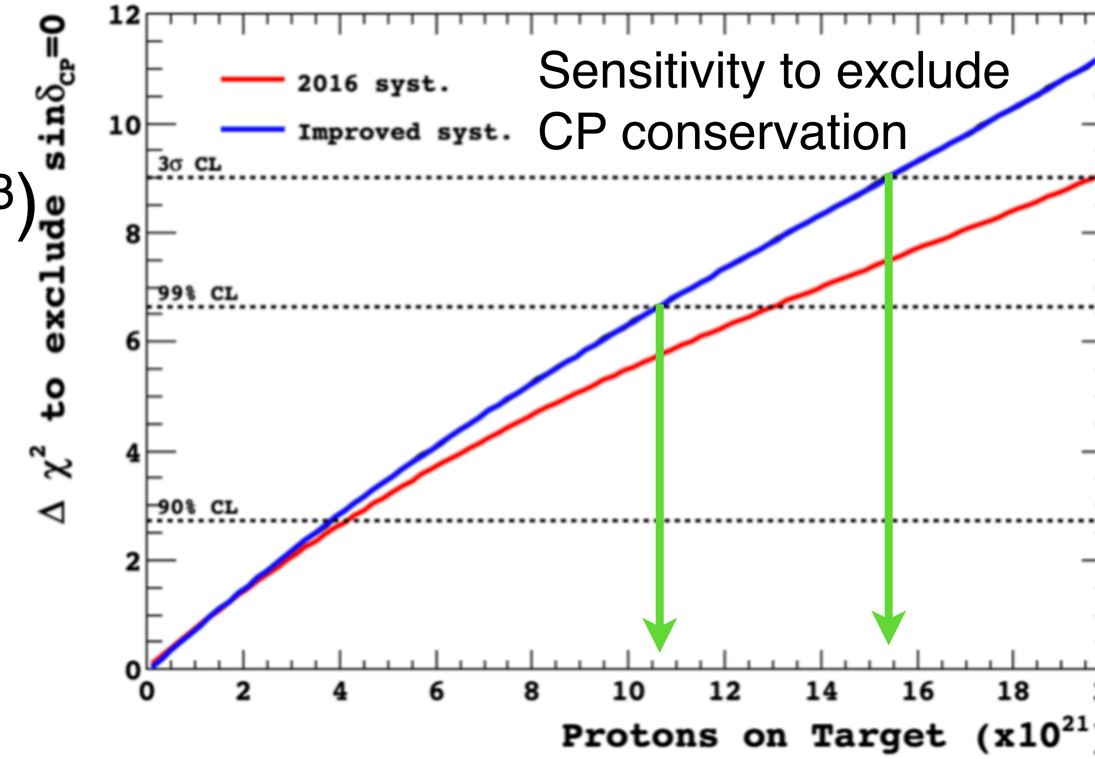


ND280 can not efficiently reconstruct particle tracks at any angle

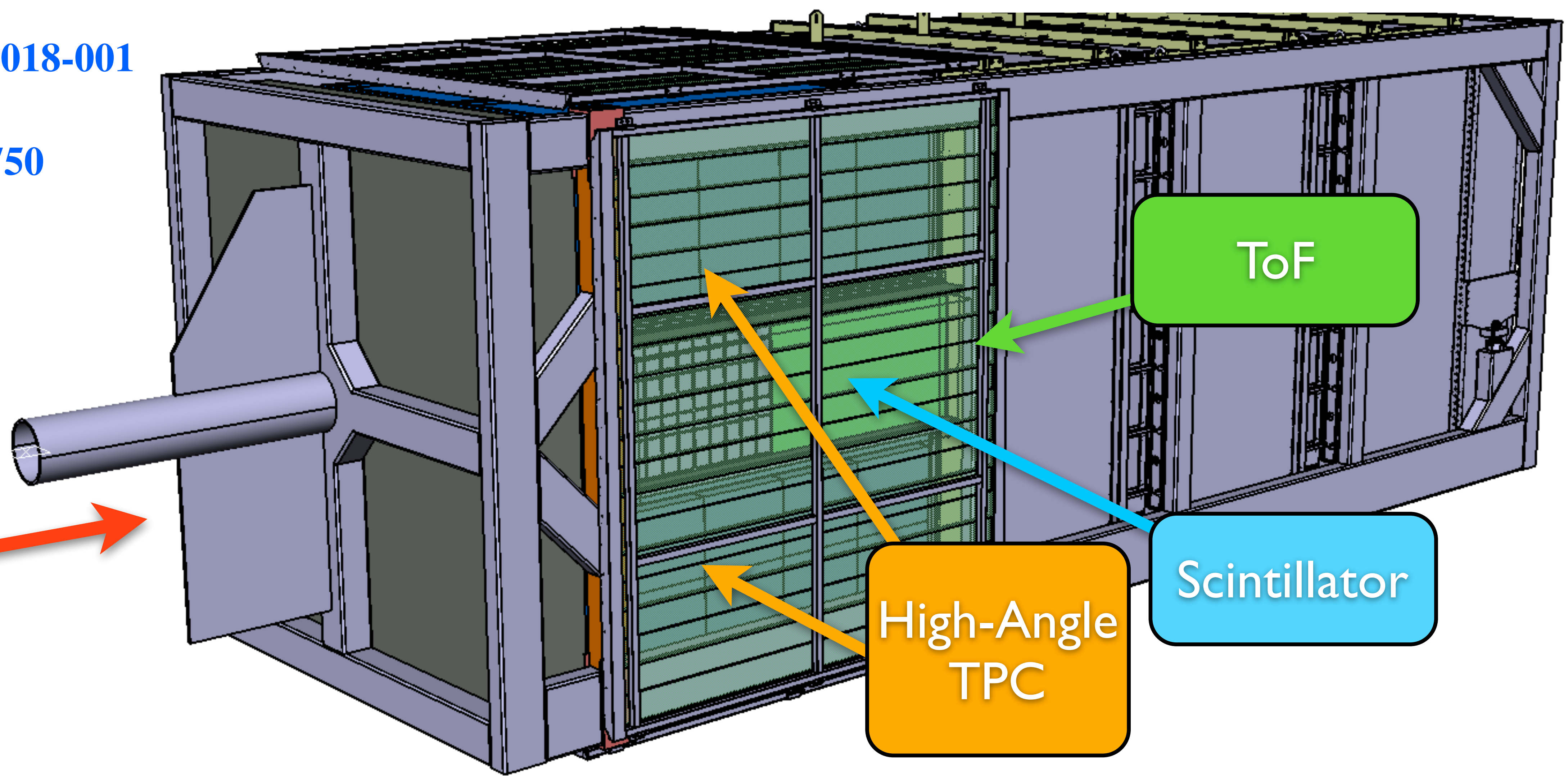
Also need to improve the sensitivity to nuclear effects: lower particle momentum threshold, high detection efficiency 4π and possibly precise neutron detection

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%

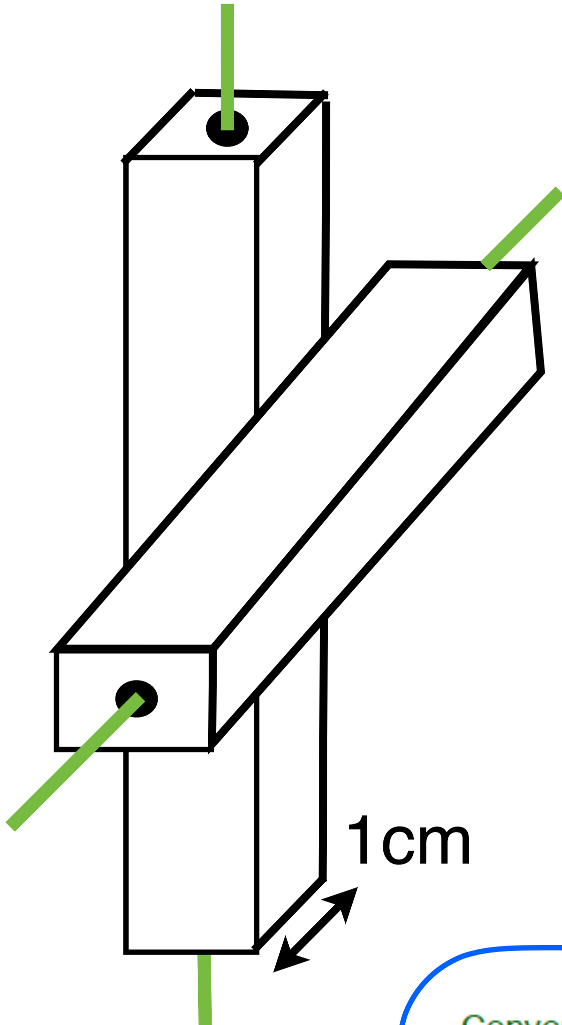


CERN-SPSC-2018-001
SPSC-P-357
arXiv:1901.03750



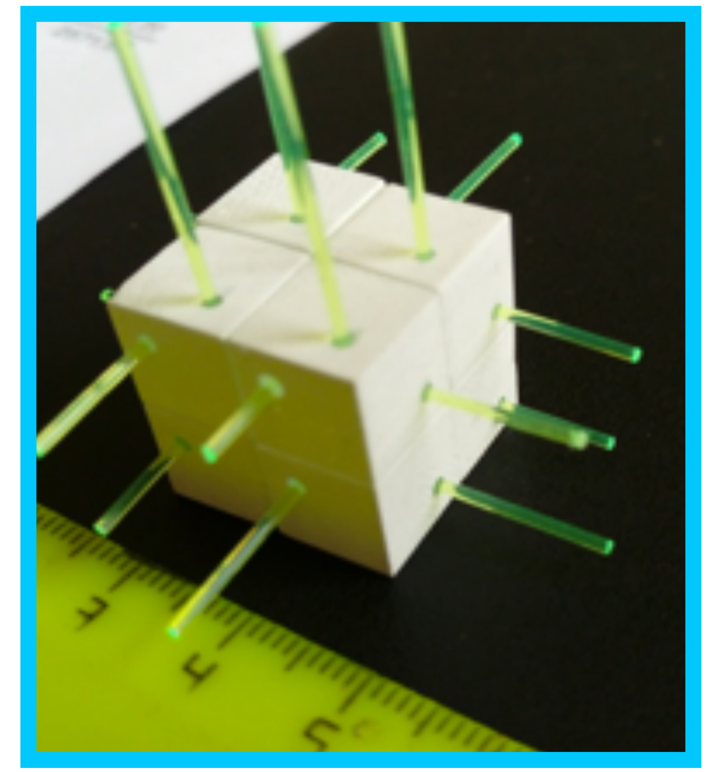
Fully active FGD with three views: SuperFGD

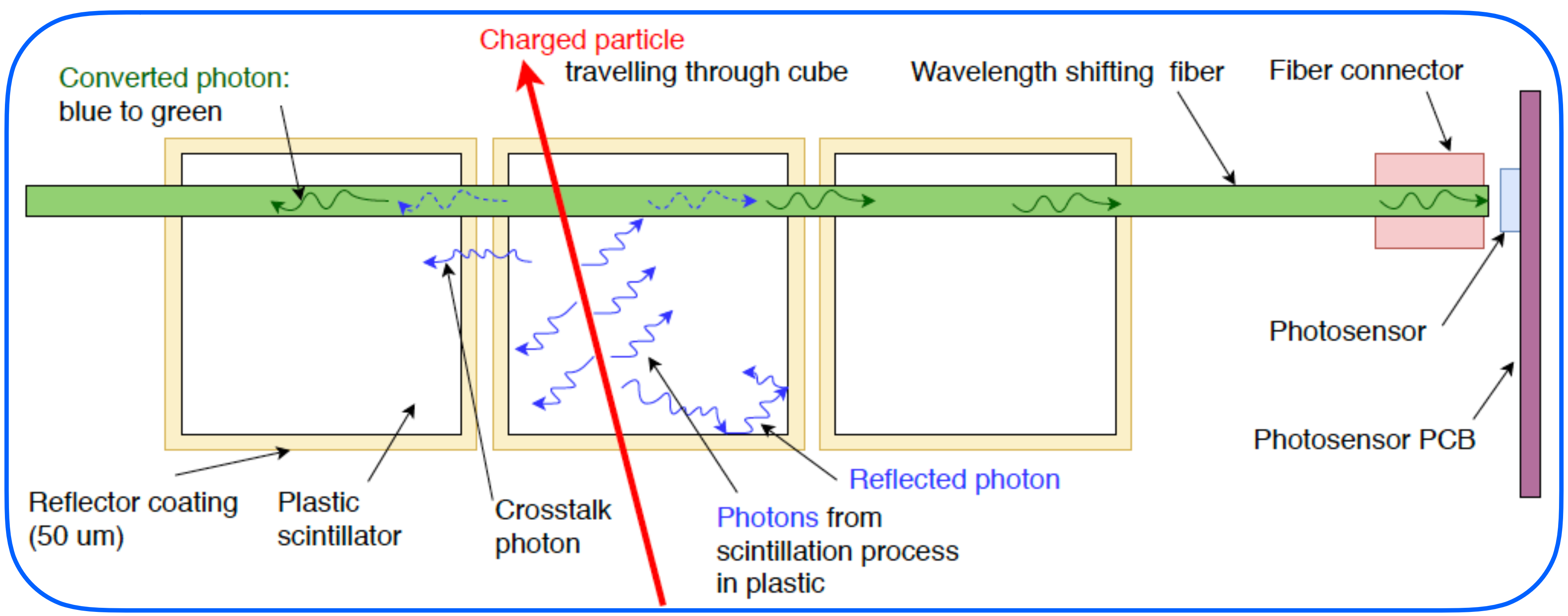
- Usually plastic scintillators made by long bars —> poor angular acceptance



2018 JINST 13 P02006

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)





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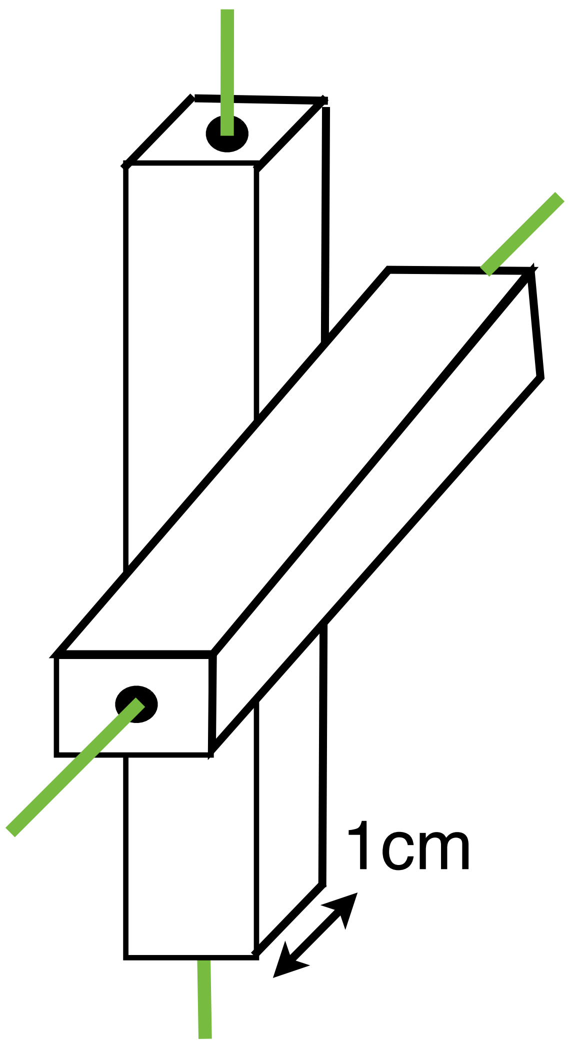

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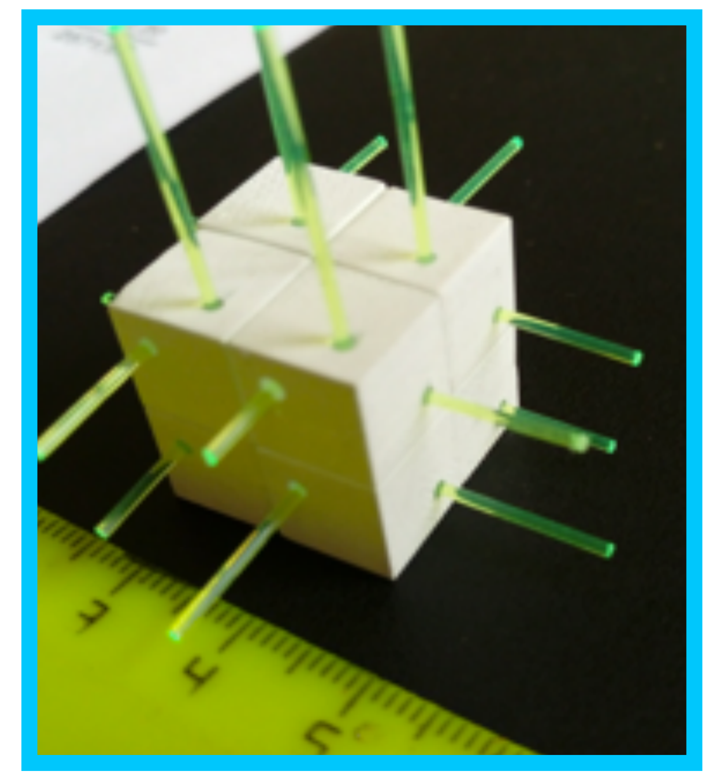


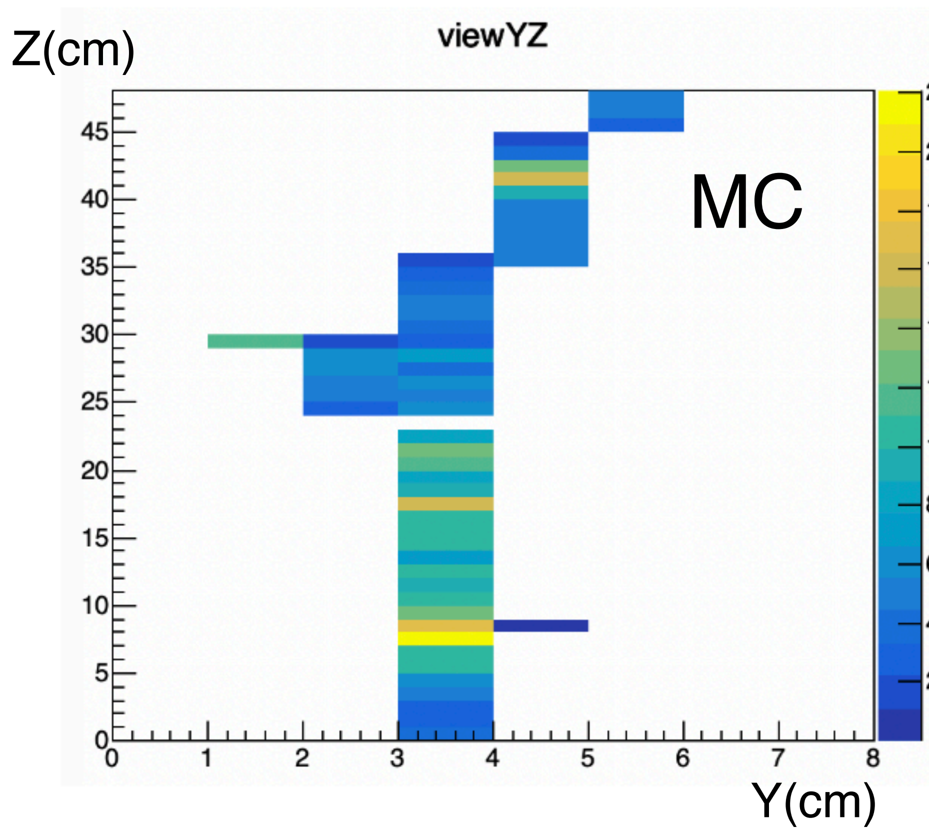
- Optically independent cubes —> spatial localization of scintillation light
- Lower momentum threshold: 1 single hit gives immediately XYZ
- Plastic scintillator provides very good time resolution
- Uniform material (just plastic) —> no systematics from different nuclei

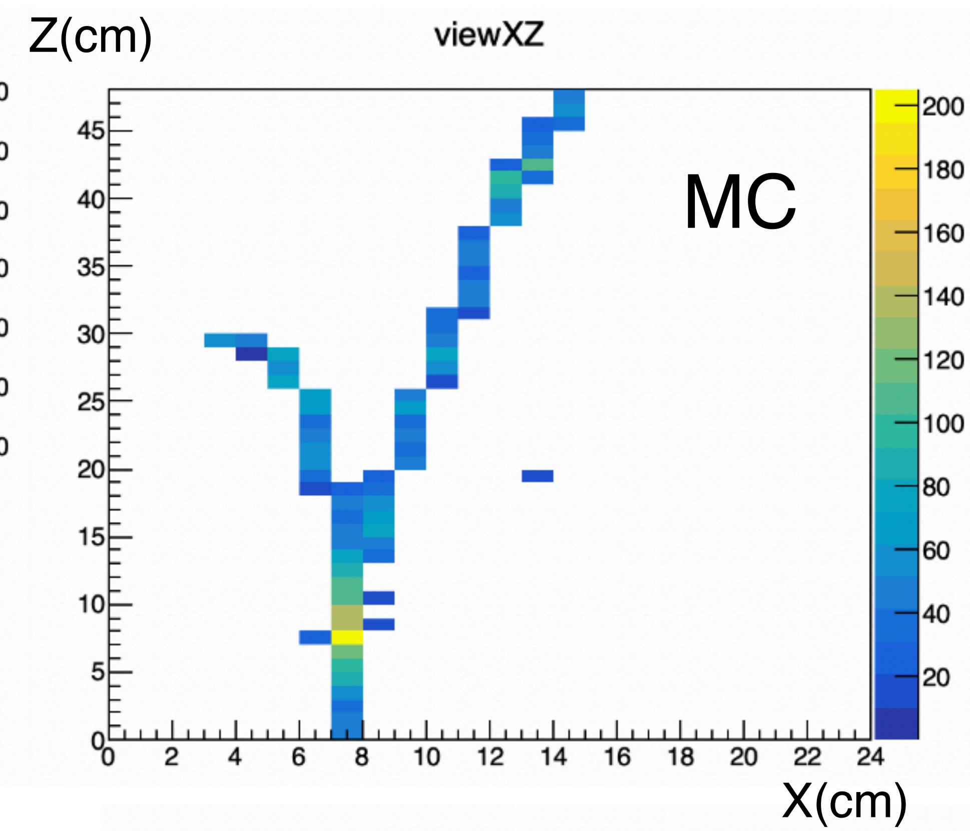
Fully active FGD with three views: SuperFGD

- Three views from XYZ WLS fibers —> 4π acceptance, 3D reconstruction

2D projections

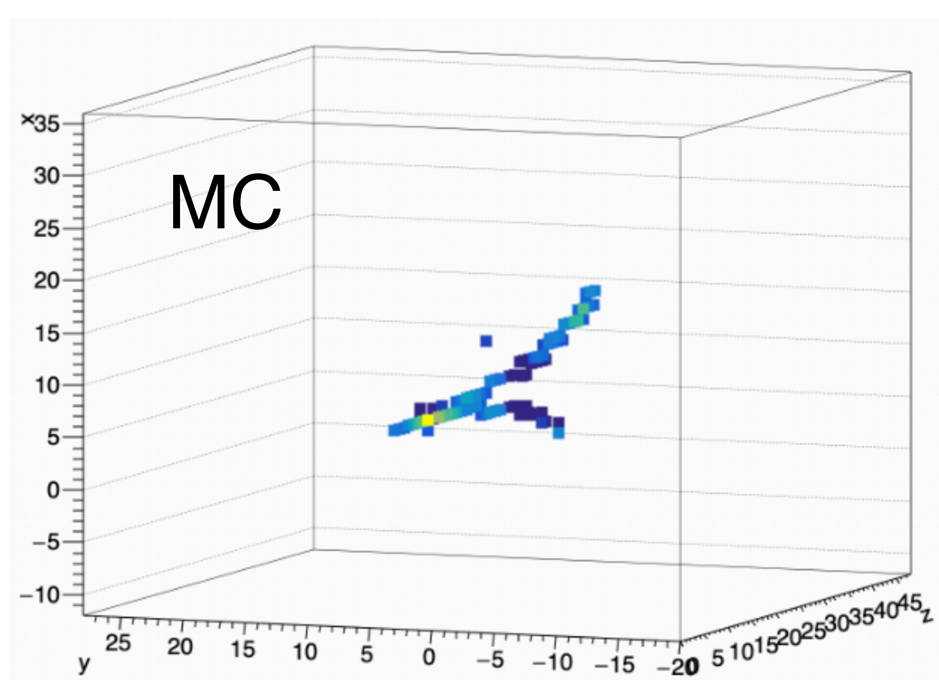
XY projection not shown here

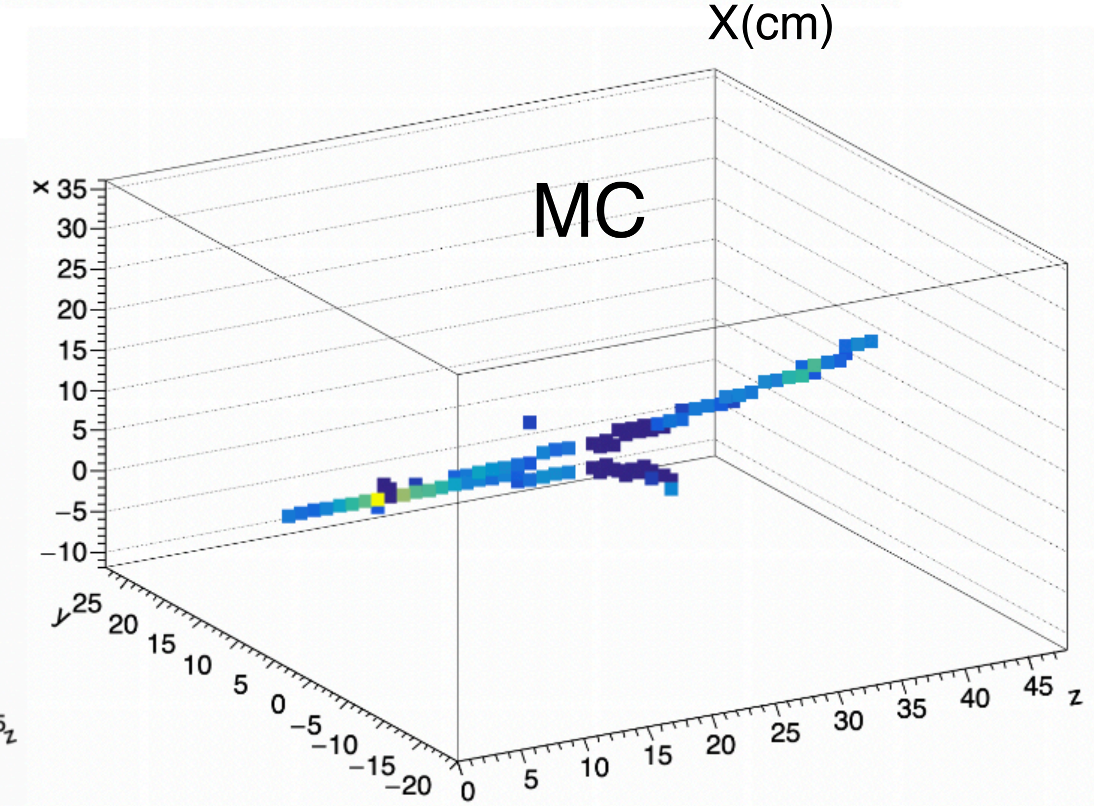




3D rotated views

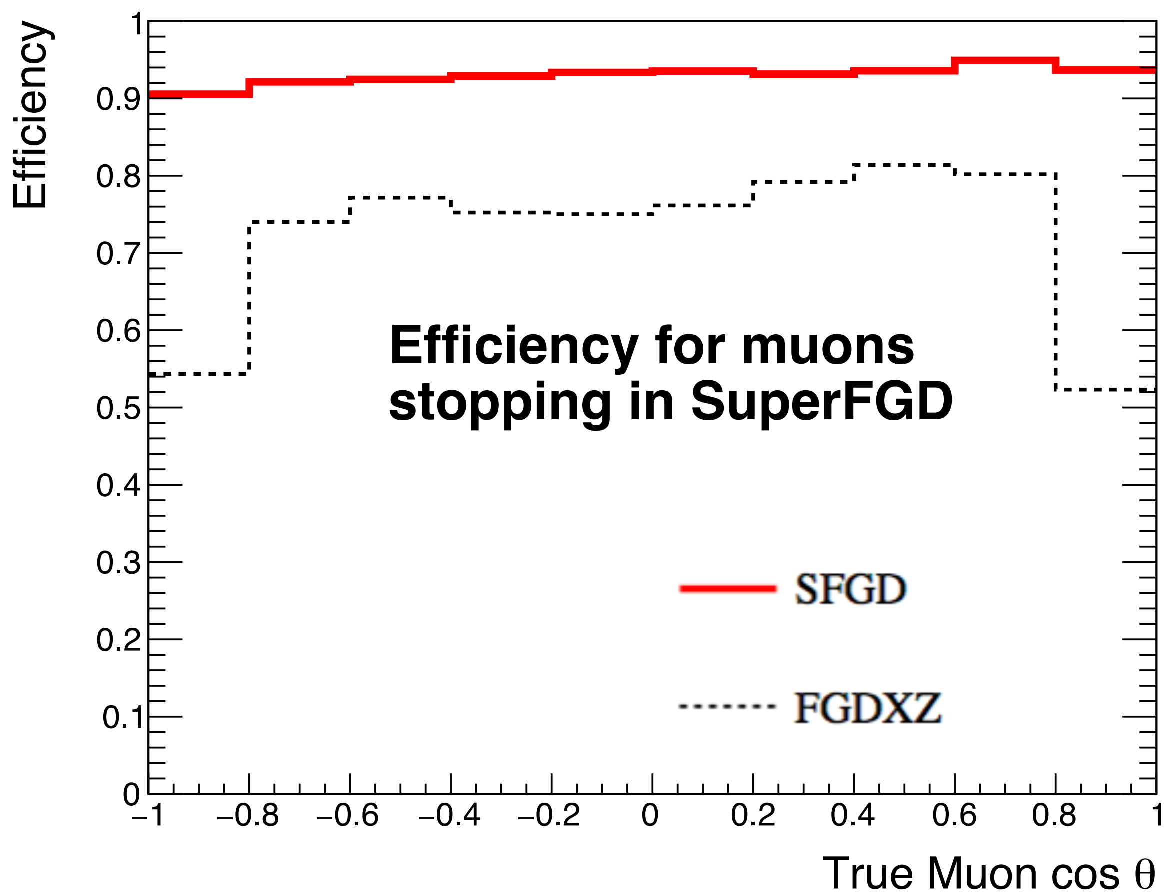
Example of a photon converting in SuperFGD

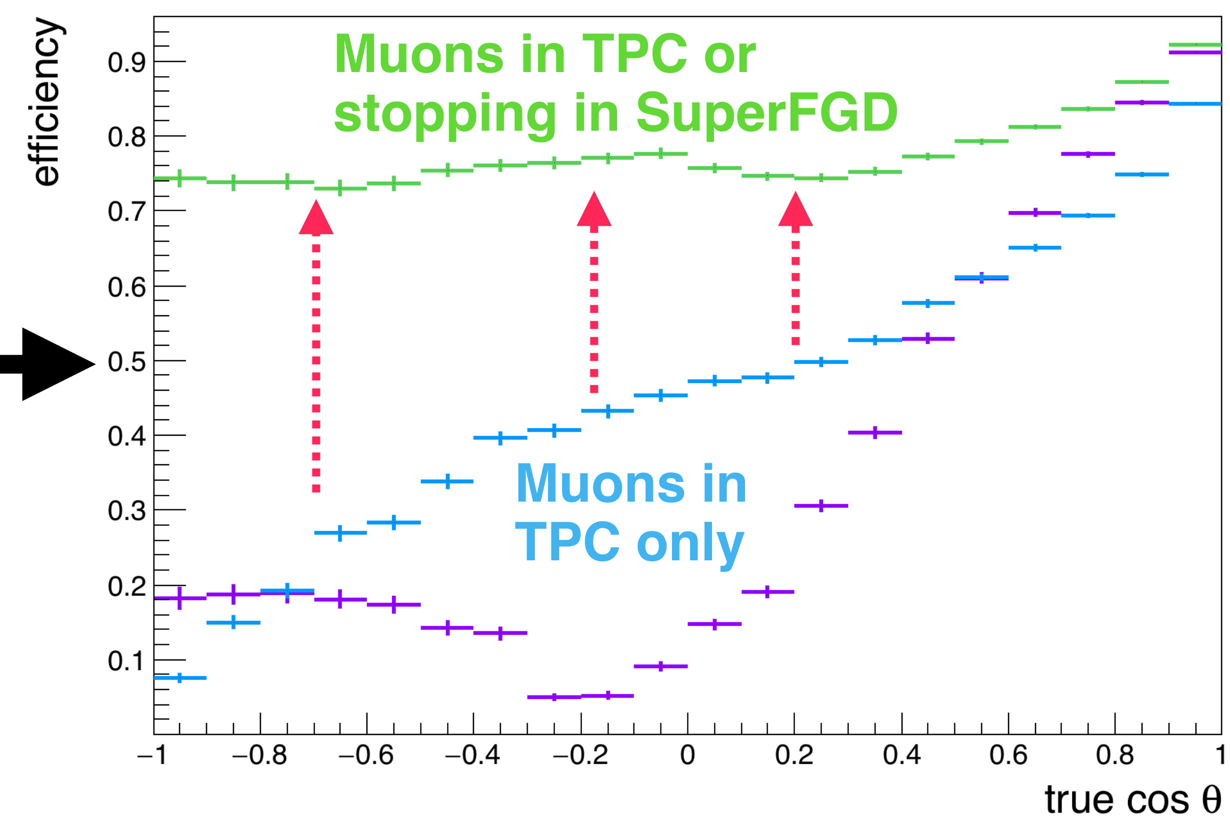




SuperFGD expected performances

- Cubic granularity allows to detect shorter tracks
- Three WLS fibers provides high efficiency at any angle





- By detecting muons stopping in SuperFGD expect ~15-20% more events
- Momentum resolution ~3% for stopping muons (by range)
- Low-momentum muons —> stronger constraint on the nucleus binding energy

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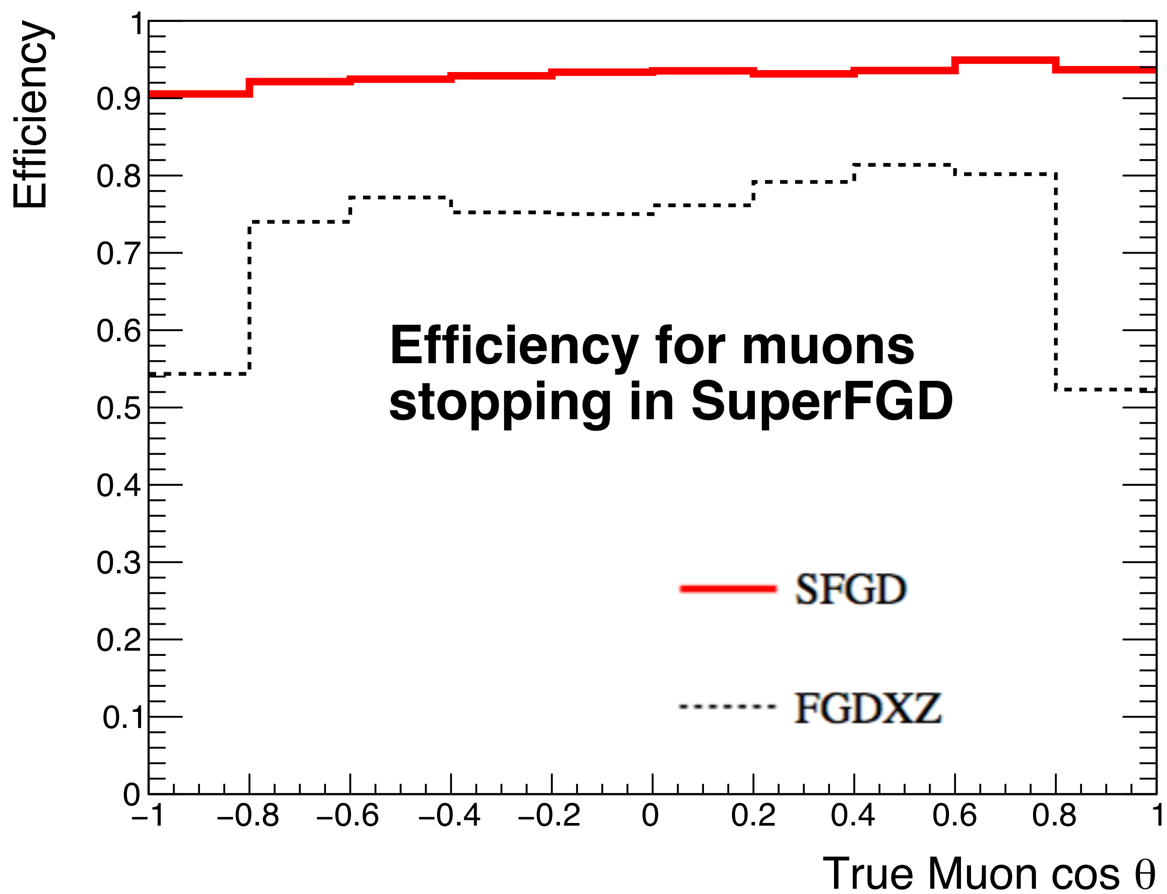
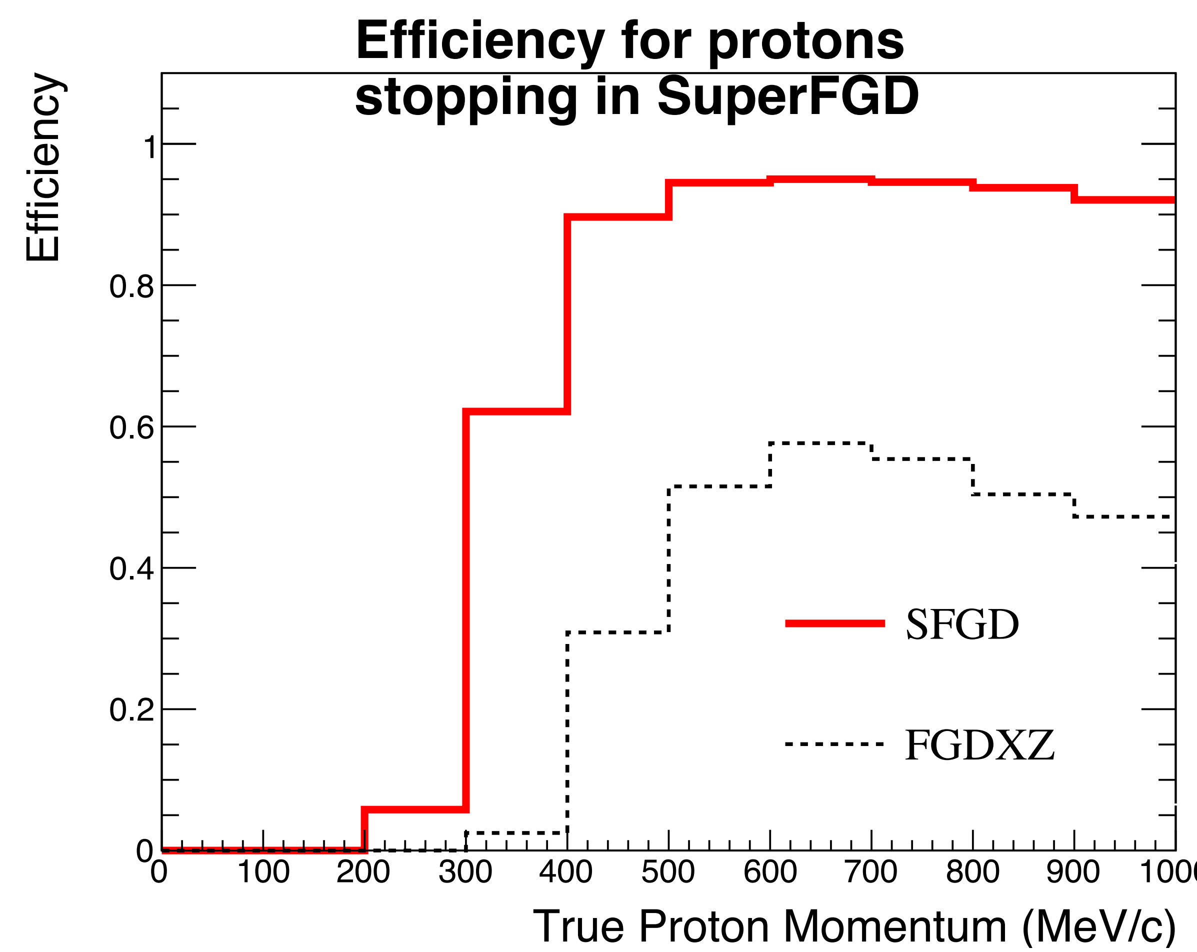


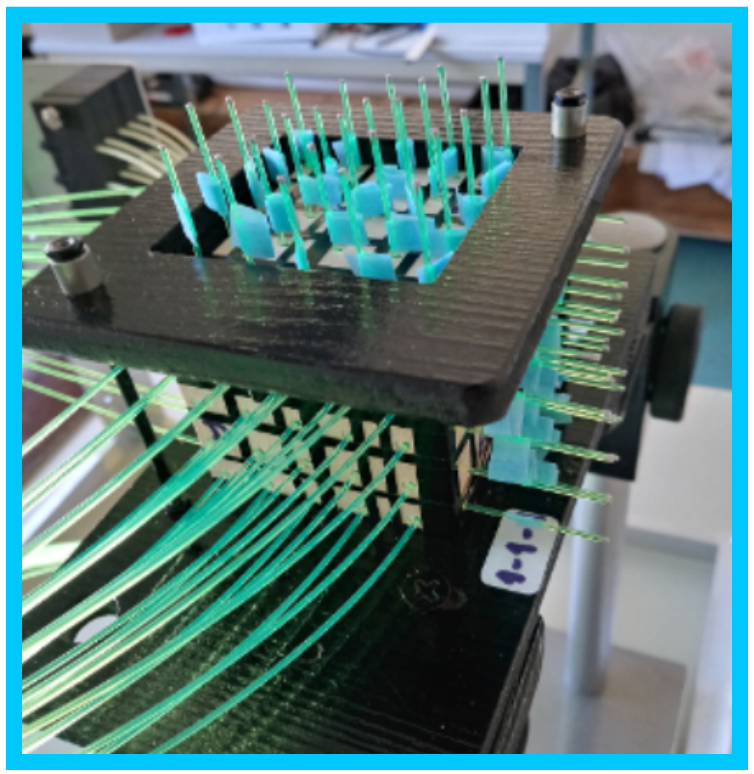


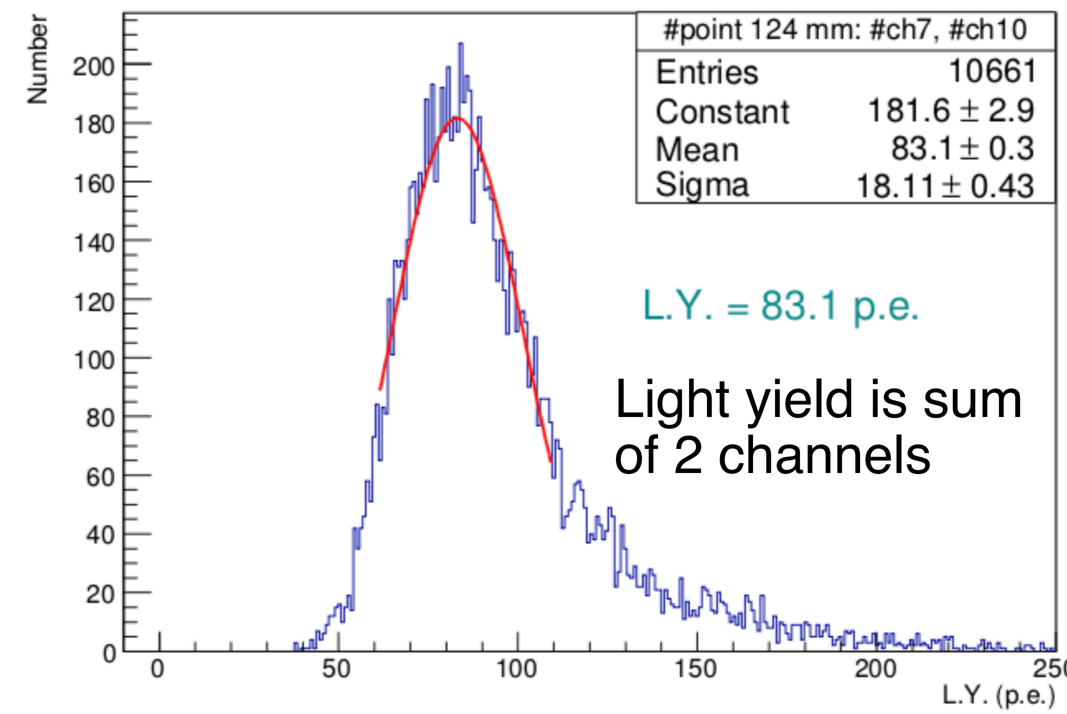
- Lower momentum detection threshold: ~300 MeV/c for protons (~450 MeV/c for current ND280 Fine Grained Detector scintillator)
- Better than 90% efficiency for stopping-muons at any angle

Characterization of the SuperFGD concept

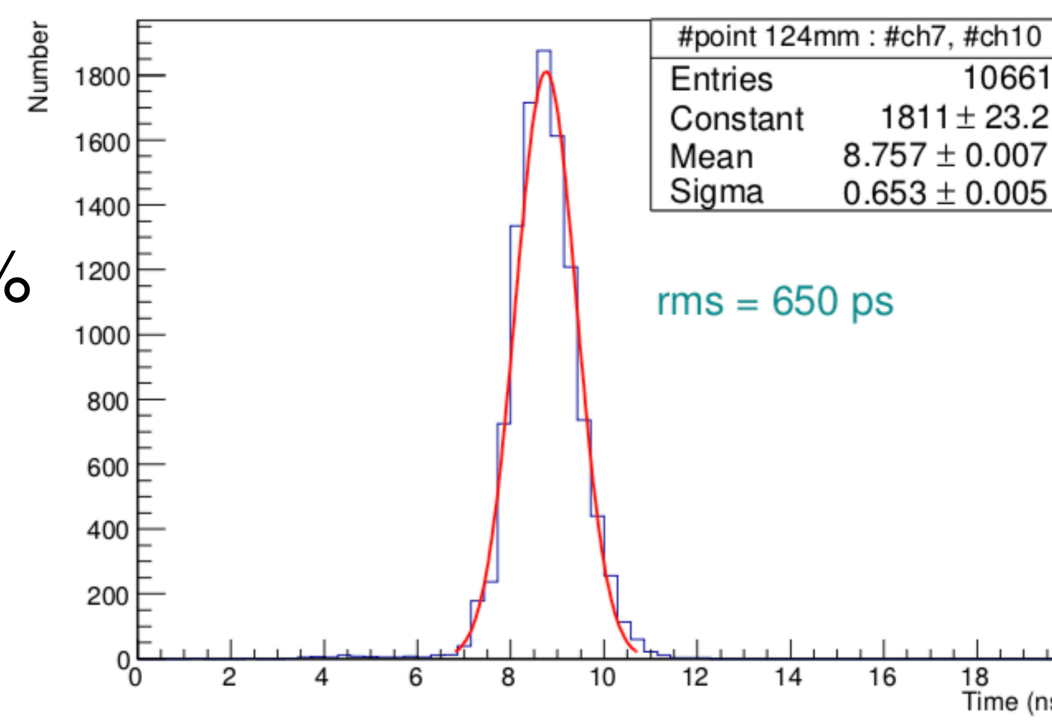
- Prototype 5x5x5 cm³, 1.3 m WLS fibers (Al-based paint at fiber end)
- Exposure to a 6 GeV π test beam at CERN
- Multi Pixel Photon Counter (MPPC)based readout

NIM A923 (2019) 134-138





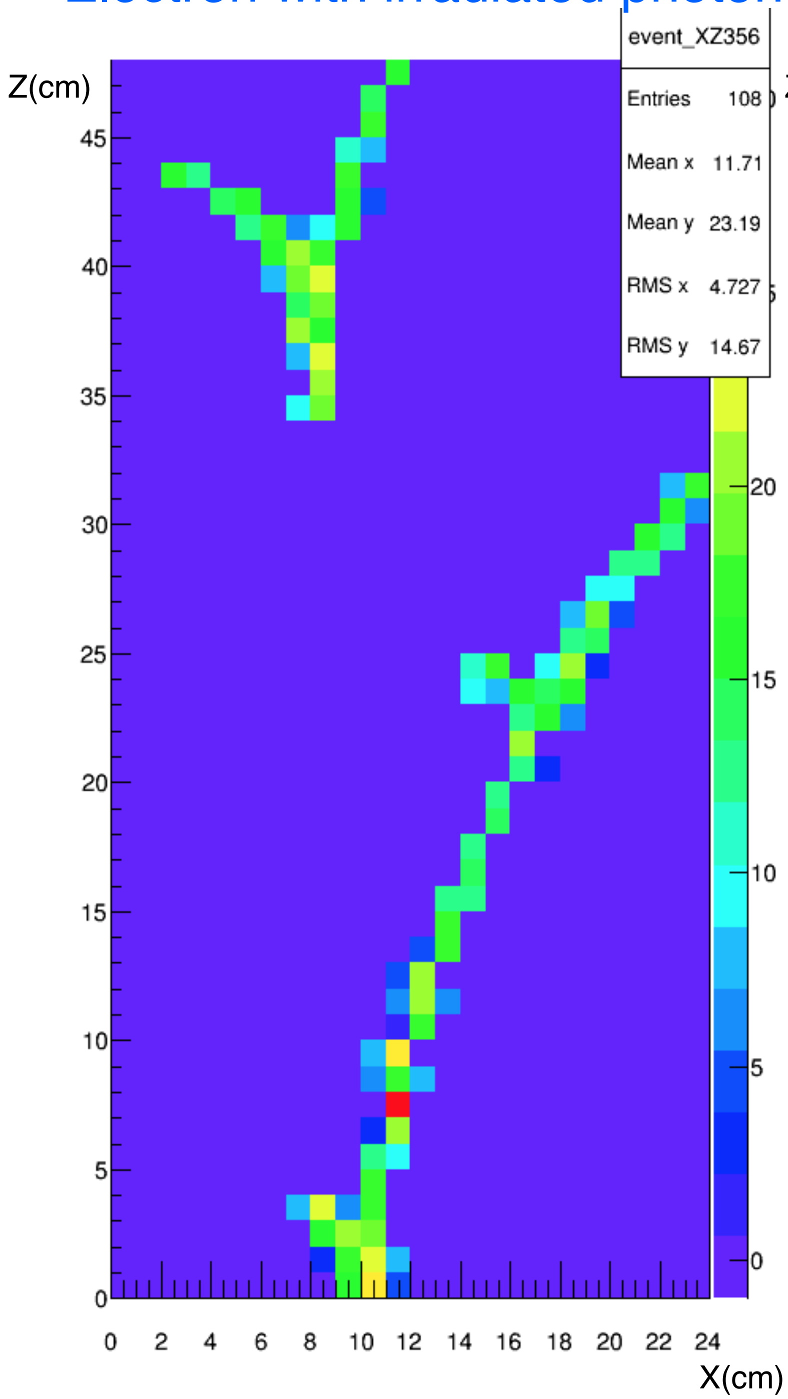
- Average light yield ~ 41 p.e. / fiber / cube (MIP)
- Light cross-talk between adjacent cubes ~ 3.7%
- Very good intrinsic time resolution (measured with a 5 GHz waveform digitizer)
  - $\sigma_t \sim 0.95$ ns (1 channel, 1 cube)
  - $\sigma_t \sim 0.65$ ns (2 channels, 1 cube)



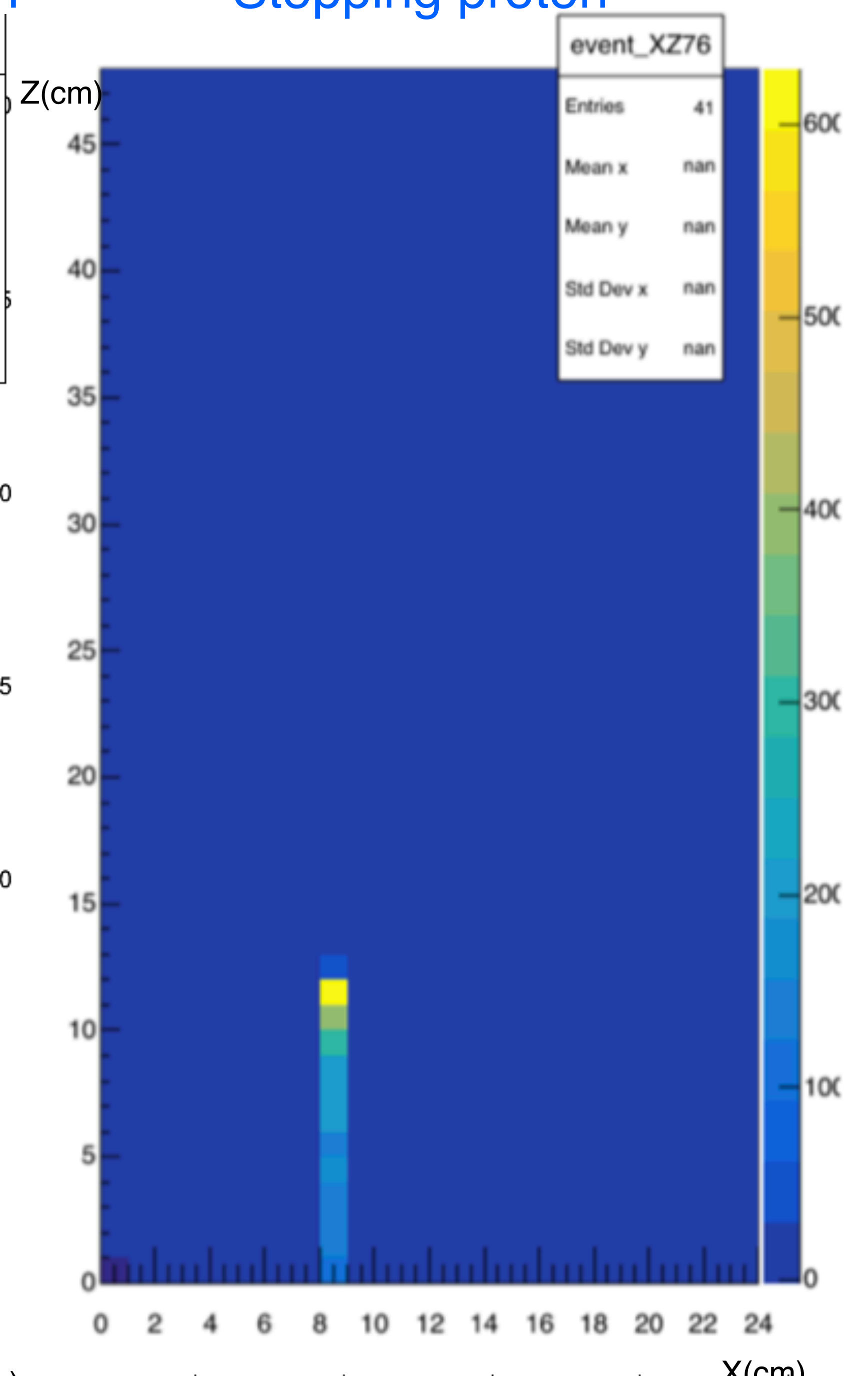
2018 beam-tests at CERN: SuperFGD

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

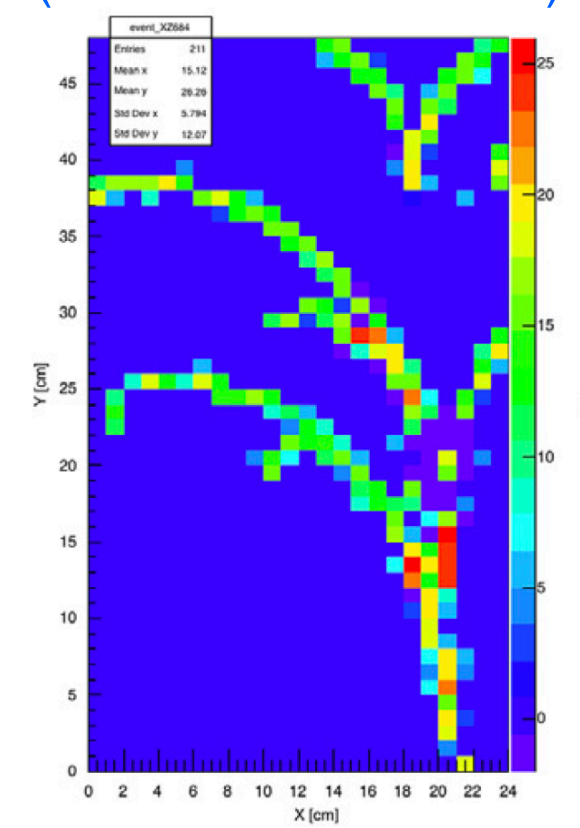
Electron with irradiated photon

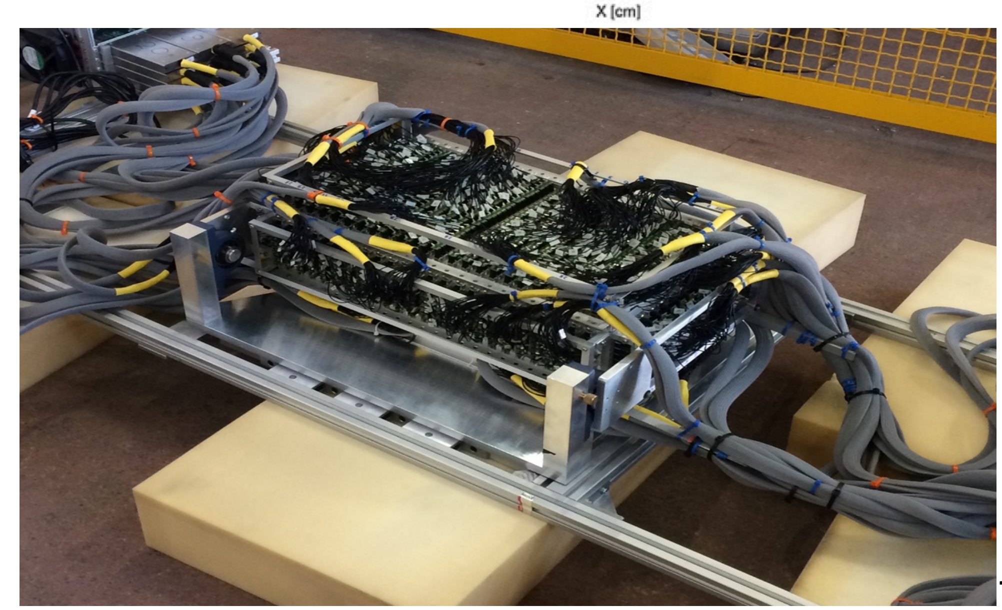


Stopping proton



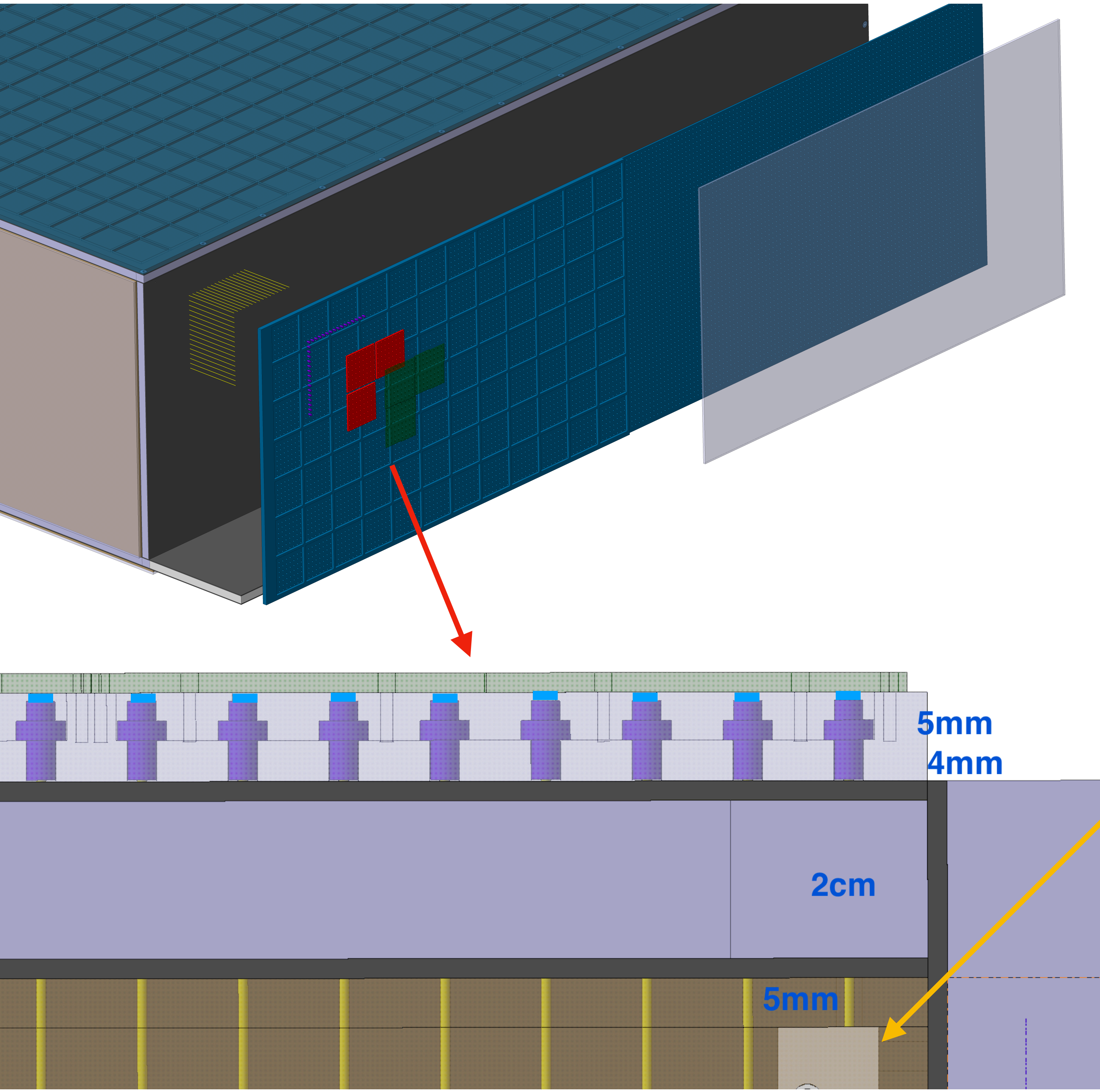
Pion interaction
(Time-over-Threshold)

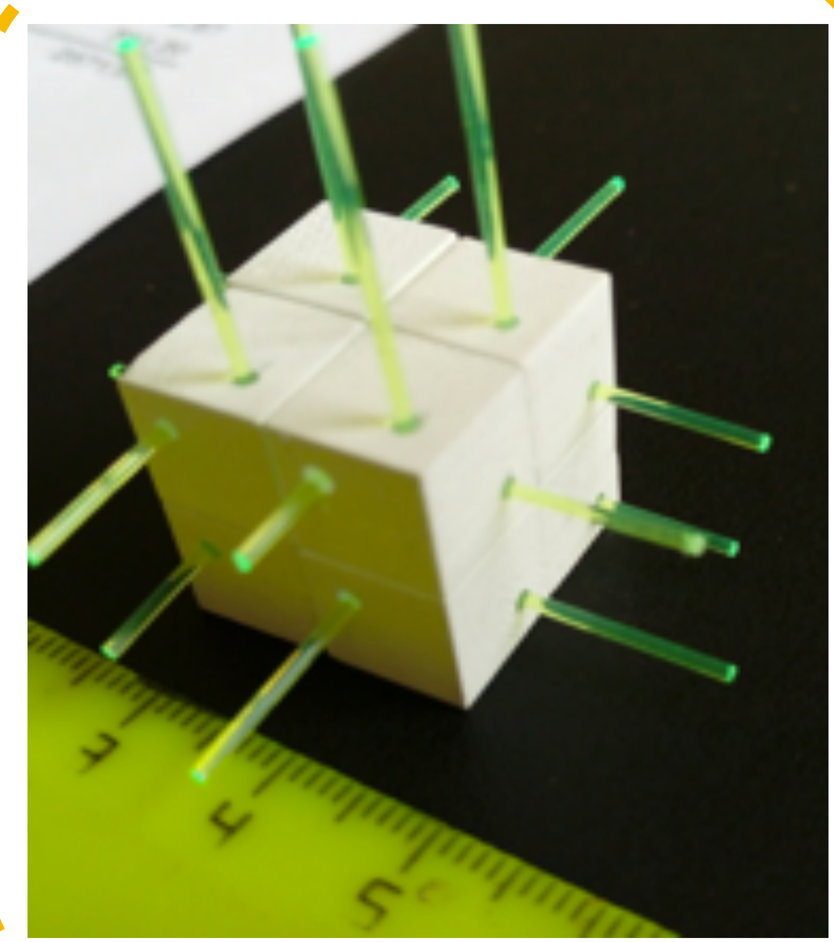




Integration of light readout in the mechanical box

Very compact design increases HA-TPC acceptance to low-momentum particles

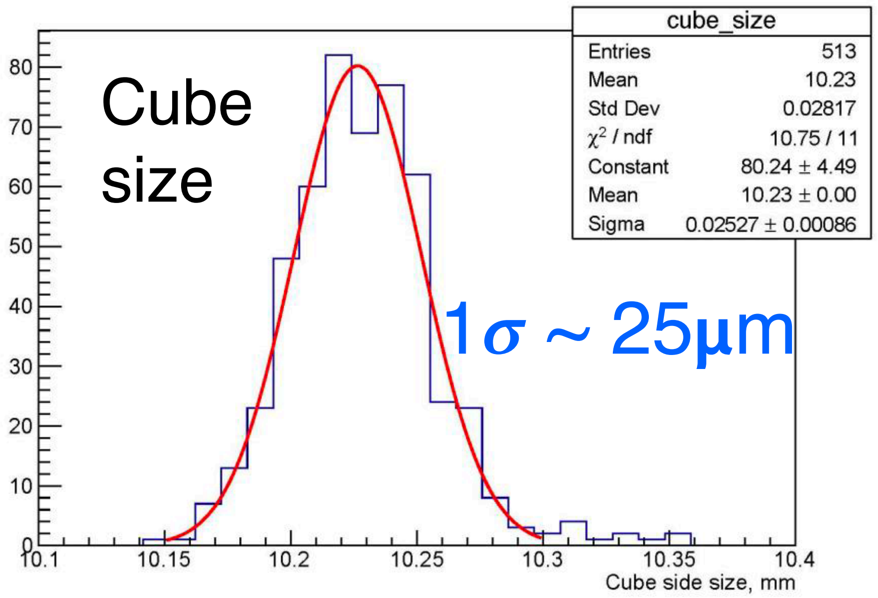


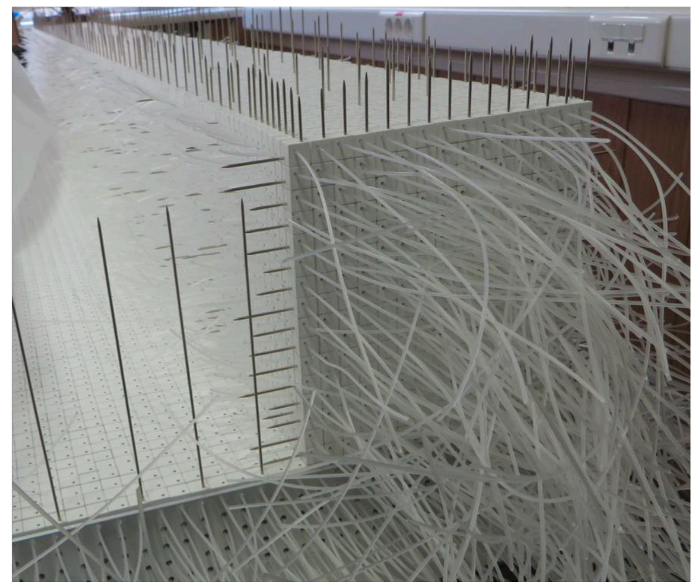


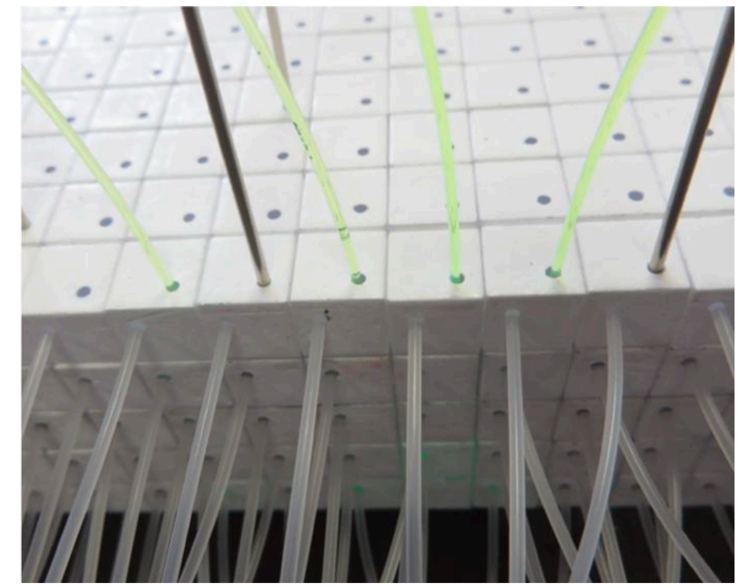
- The total no. of cubes is 1,978,368
- ~2 tons active mass
- Total no. of readout channels is 56,384

The detector assembly

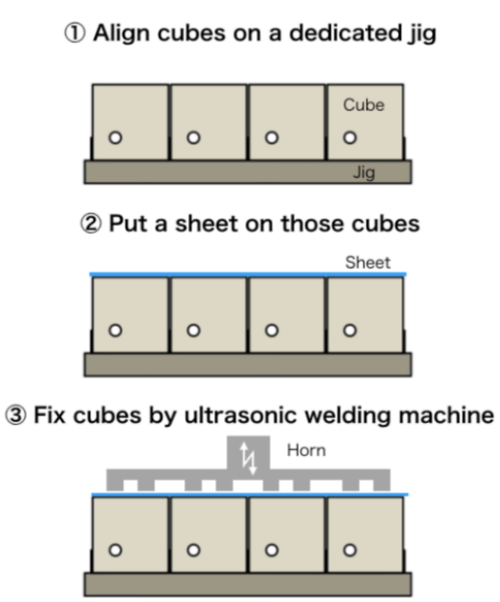
- About 300k cubes already manufactured (~17% of total # of cubes)
- Option 1: ∅1.3mm fishing lines of to align cubes, replace them with WLS fibers

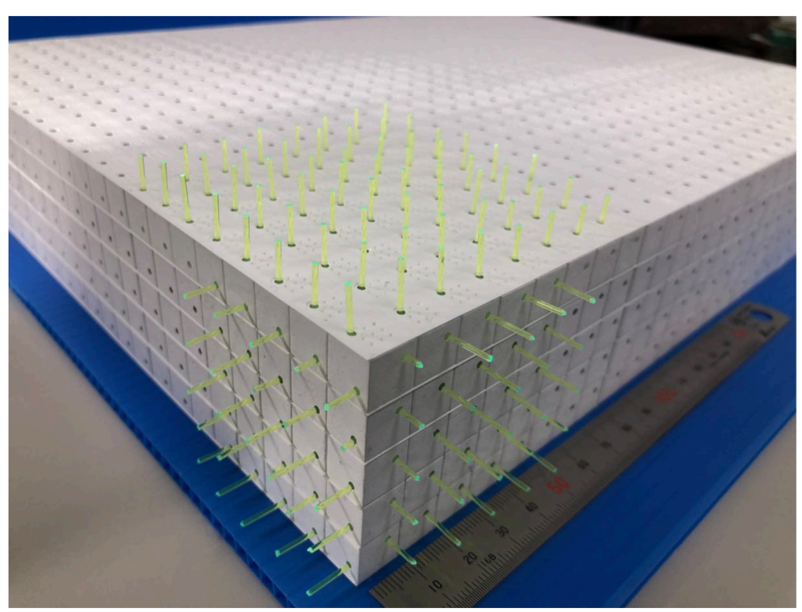






- Option 2: ultrasonic welding to fix the cubes to a thin (0.1mm) polystyrene sheet





The SuperFGD detector

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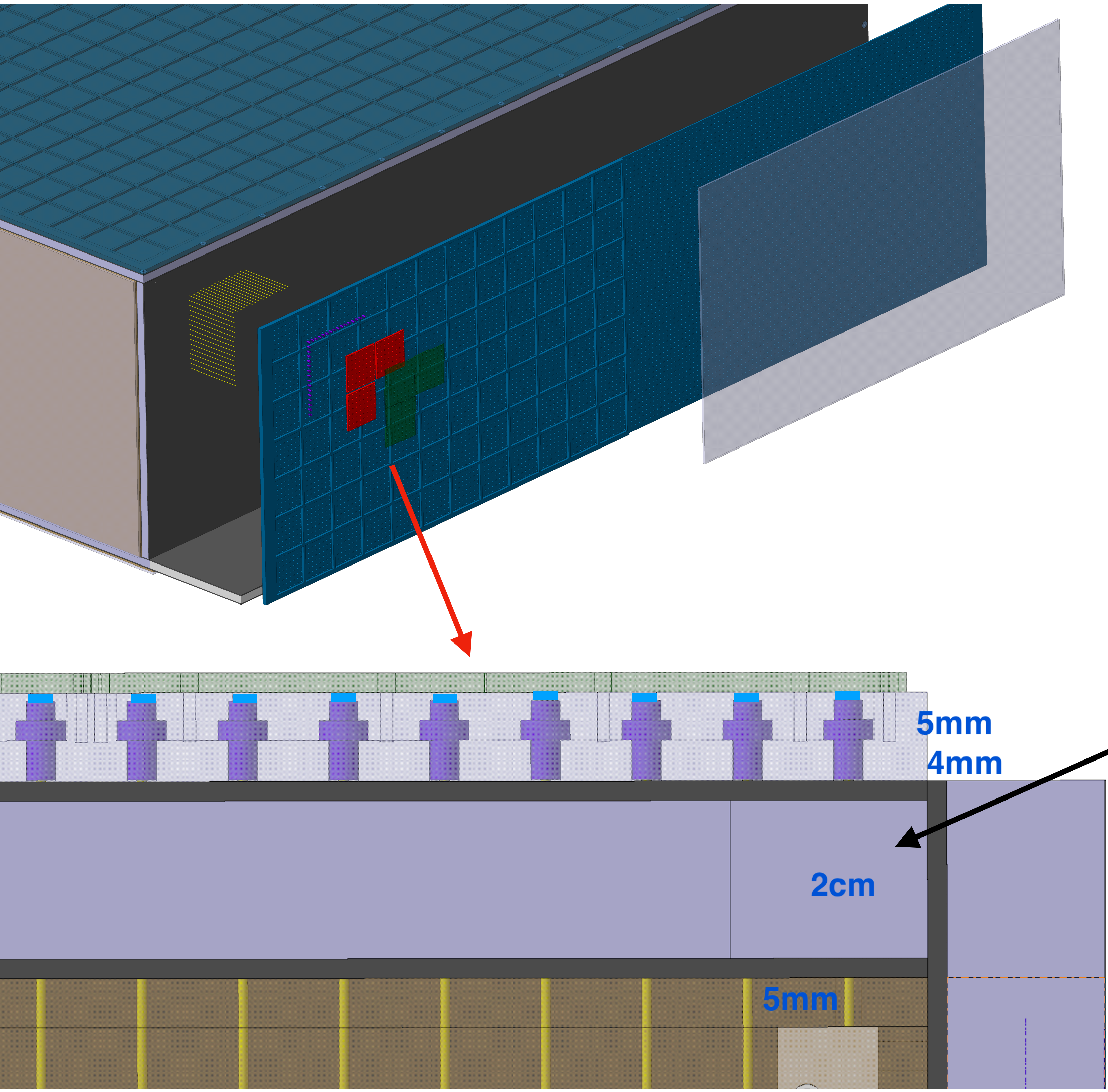
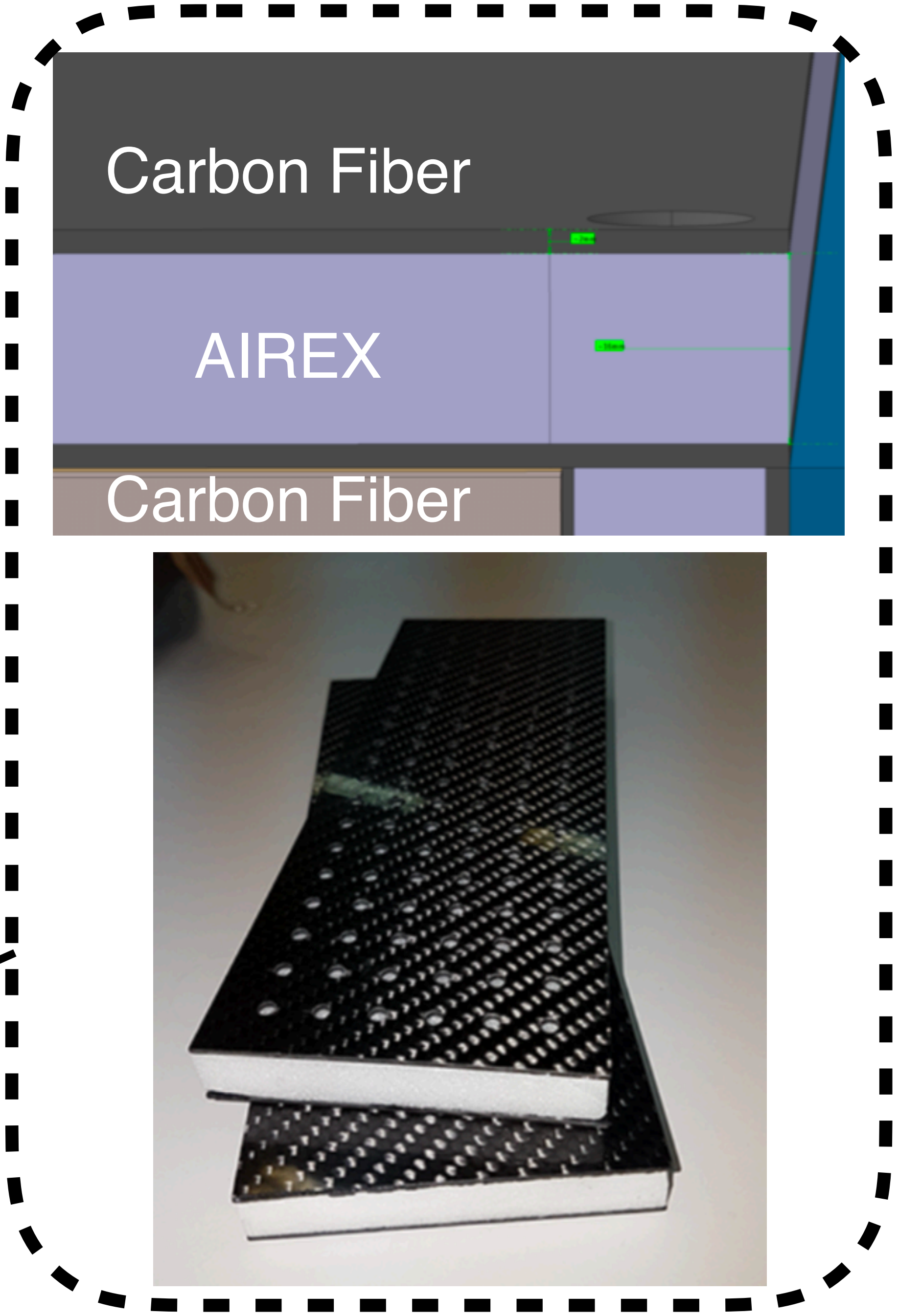
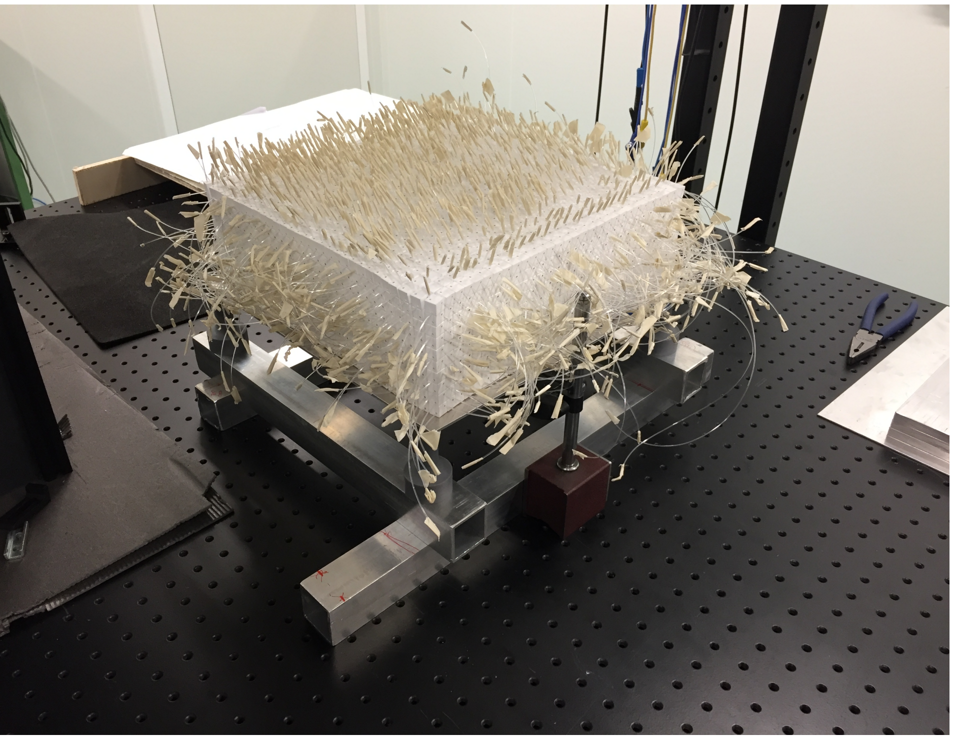
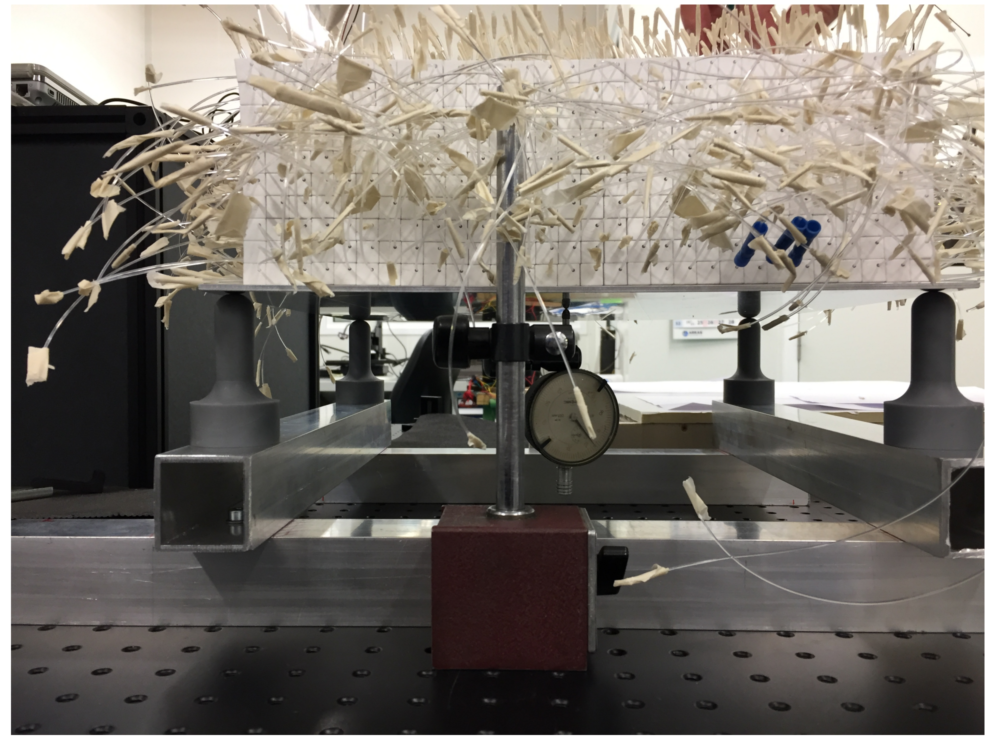
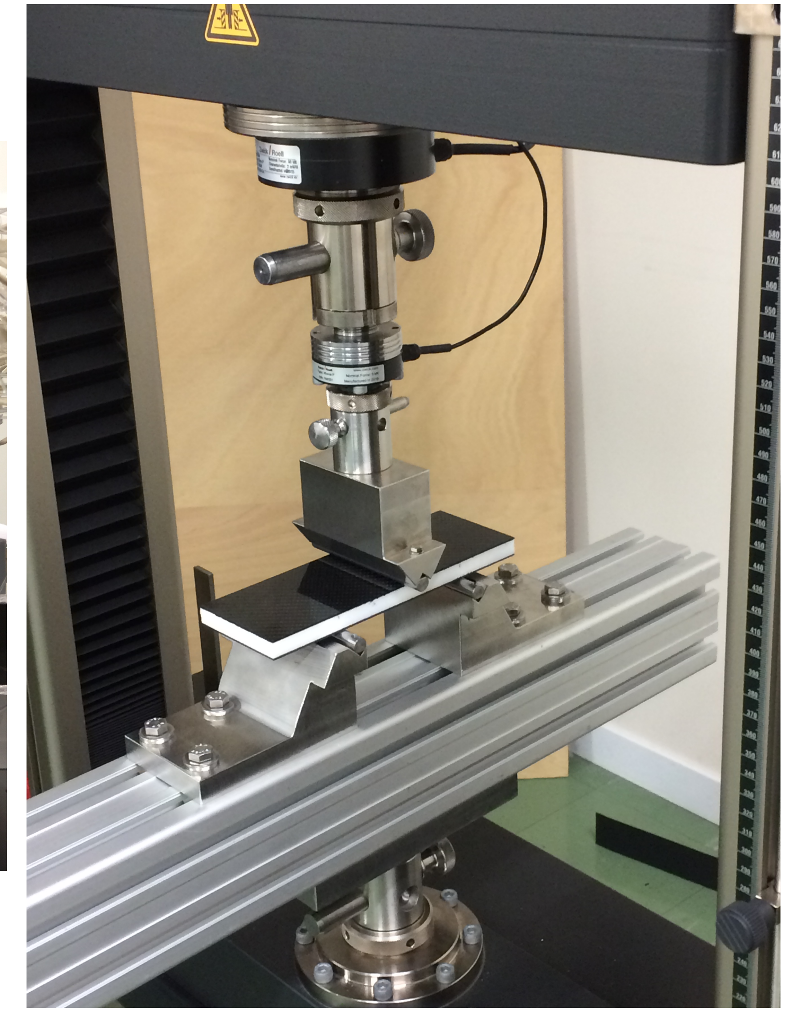




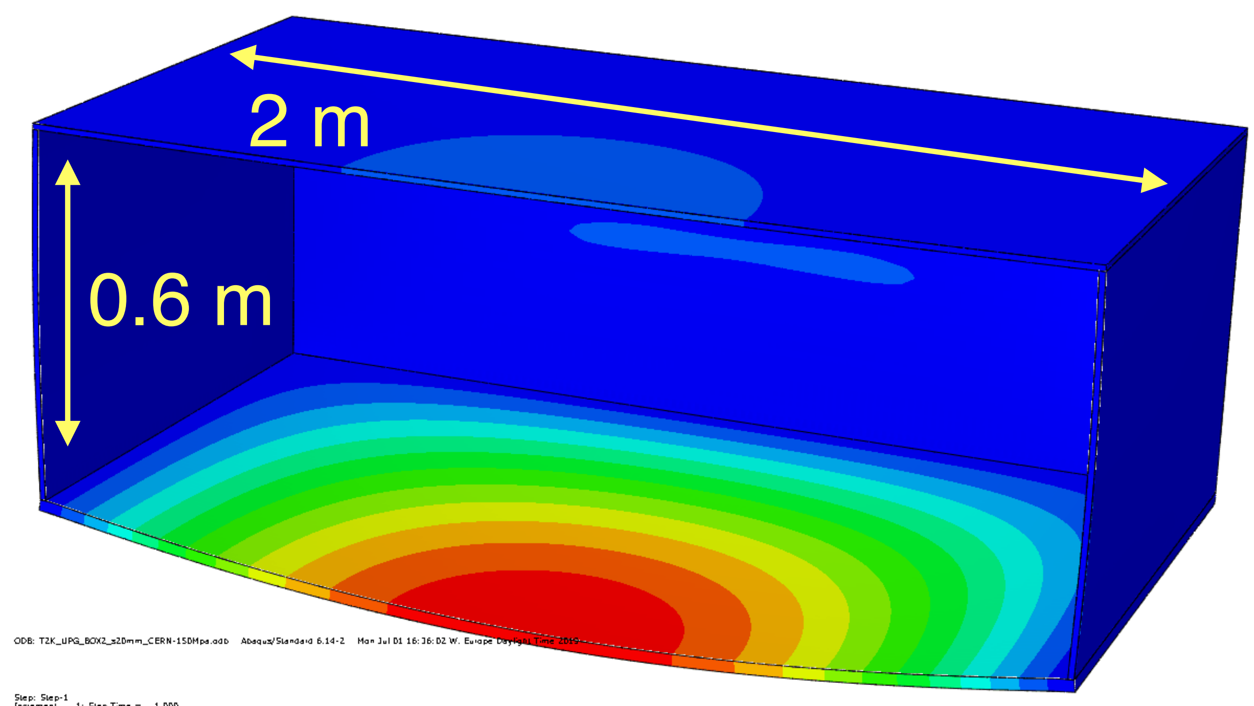
Mechanical tests of the carbon-fiber box







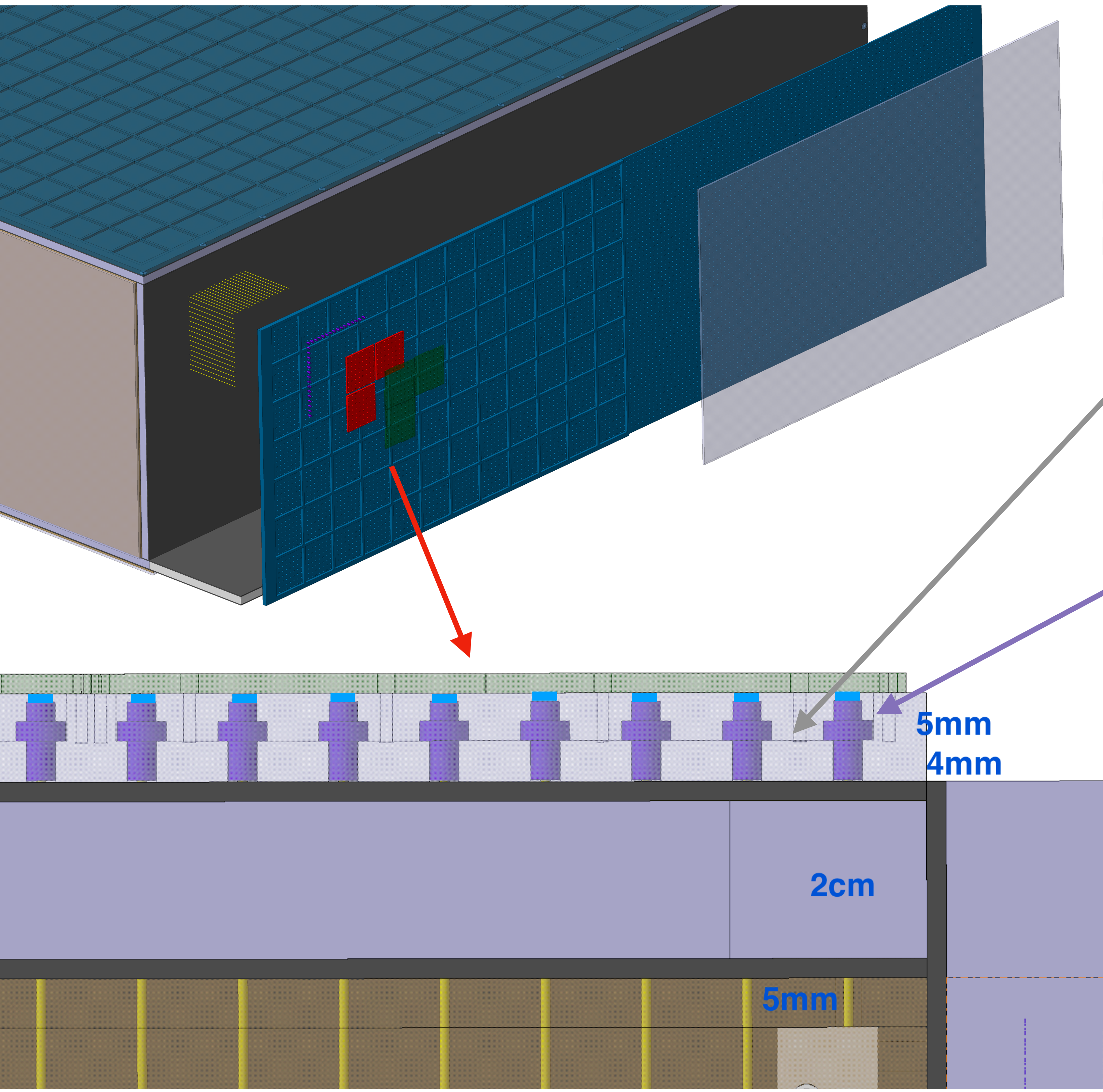
Finite Element Analysis performed with water instead of 2M cubes due to computational issues



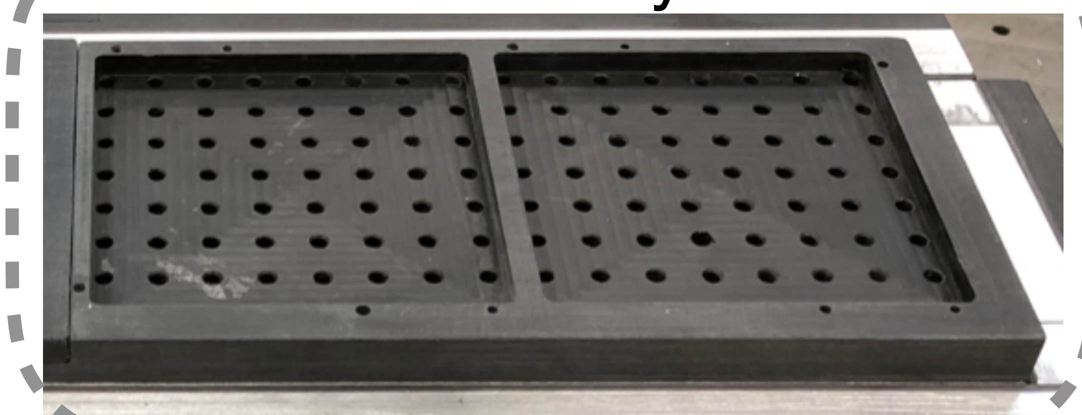
- Without pressure on the sides, the behavior is not very different from water
- Stress / deformation tests show that the holes (∅3mm, 10mm pitch) provide ~20% more deformation but far from breaking point
- AIREX thickness may be increased up to 3-4 cm to limit bottom maximal deformation to less then 5 mm

The SuperFGD detector

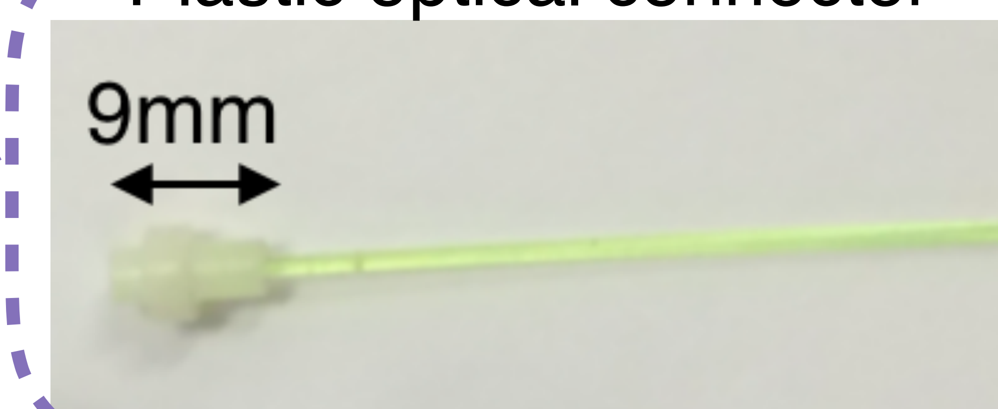
Very compact design increases HA-TPC acceptance to low-momentum particles



Plastic layer



Plastic optical connector



Important to provide a very precise alignment between the WLS fiber and the MPPC in a very small space

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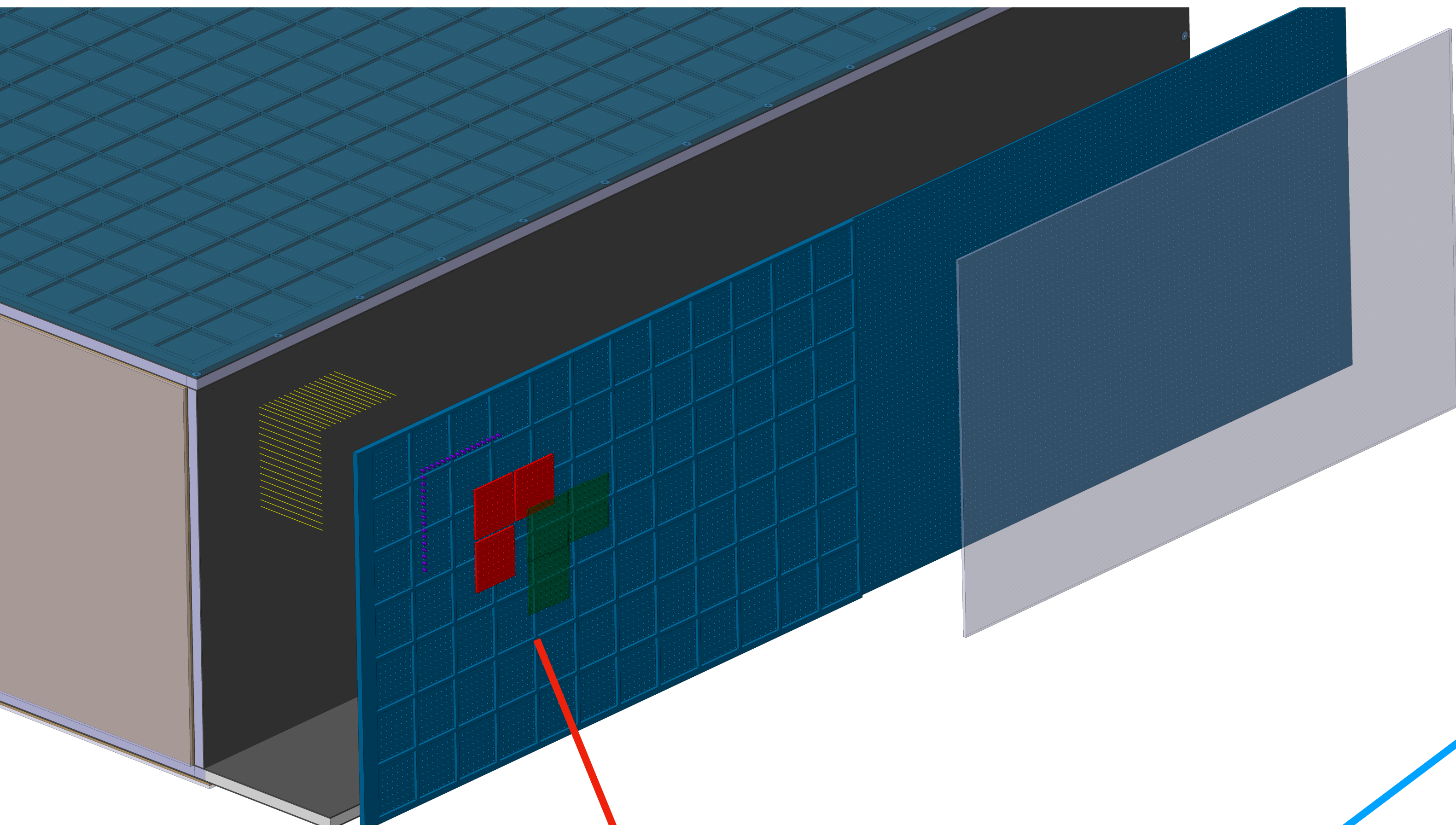

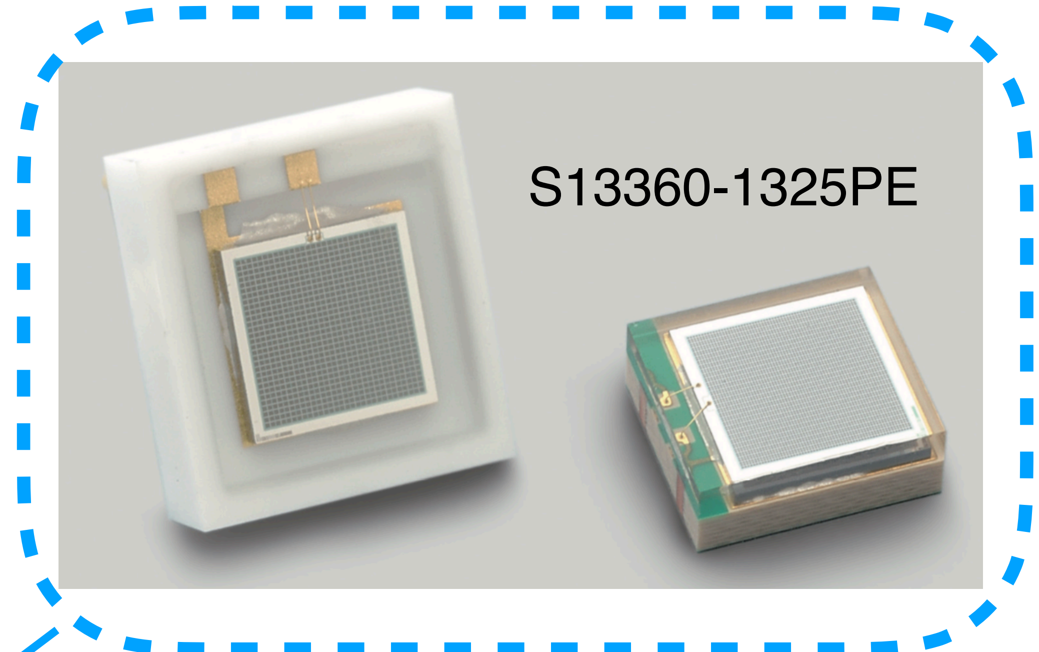

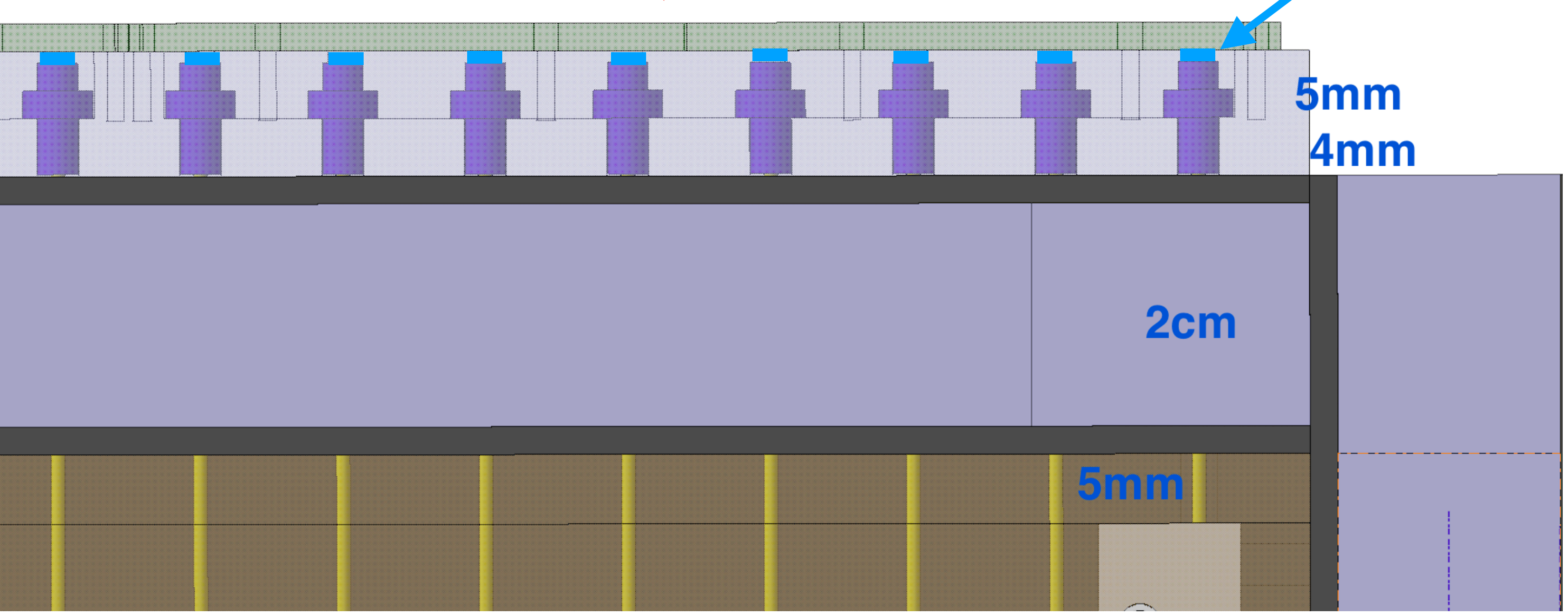

- Hamamatsu MPPC to count the scintillation photons produced in the cubes
- ~2,700 pixels to avoid saturation due to stopping particles, like protons near the neutrino interaction vertex

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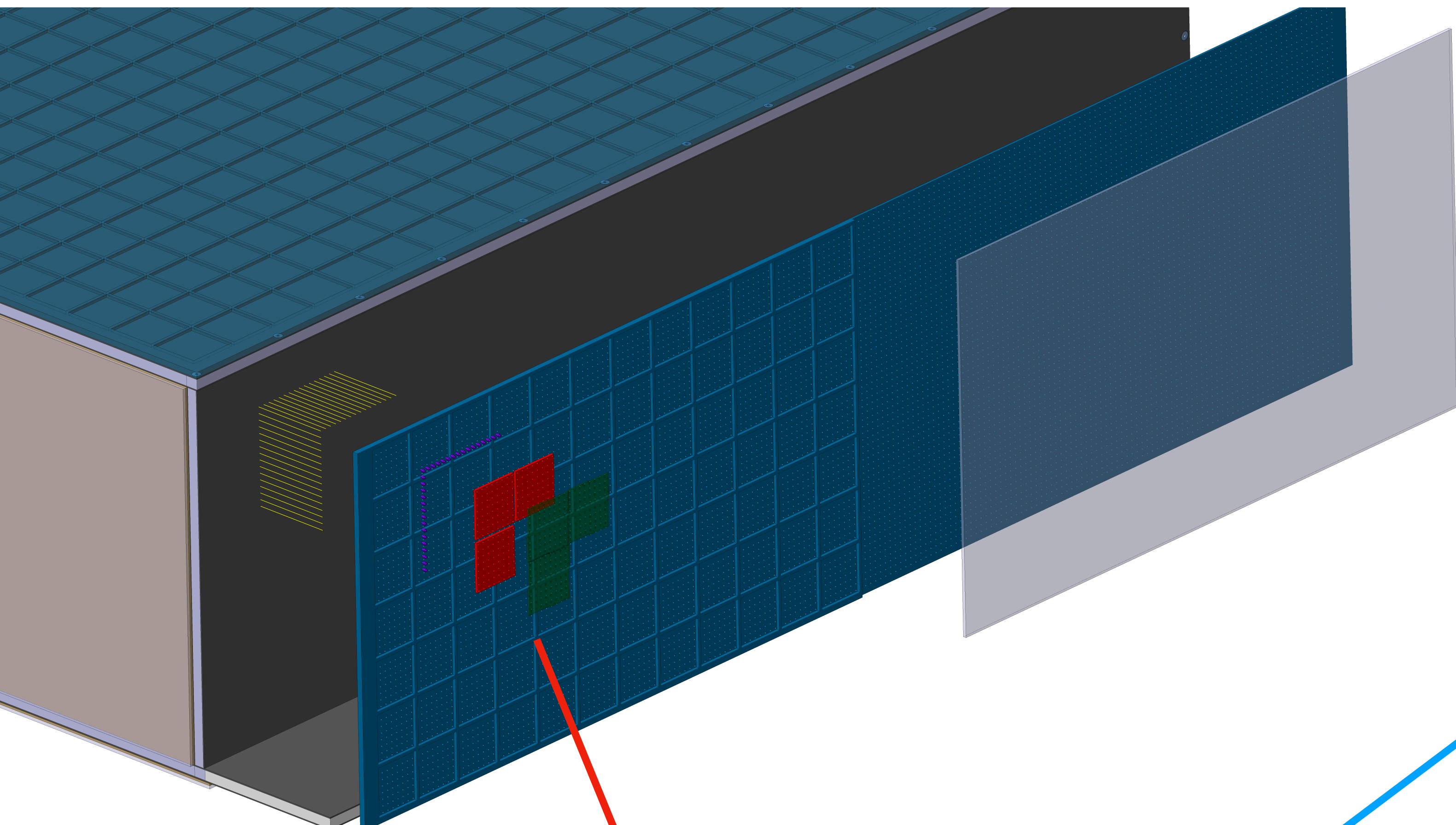

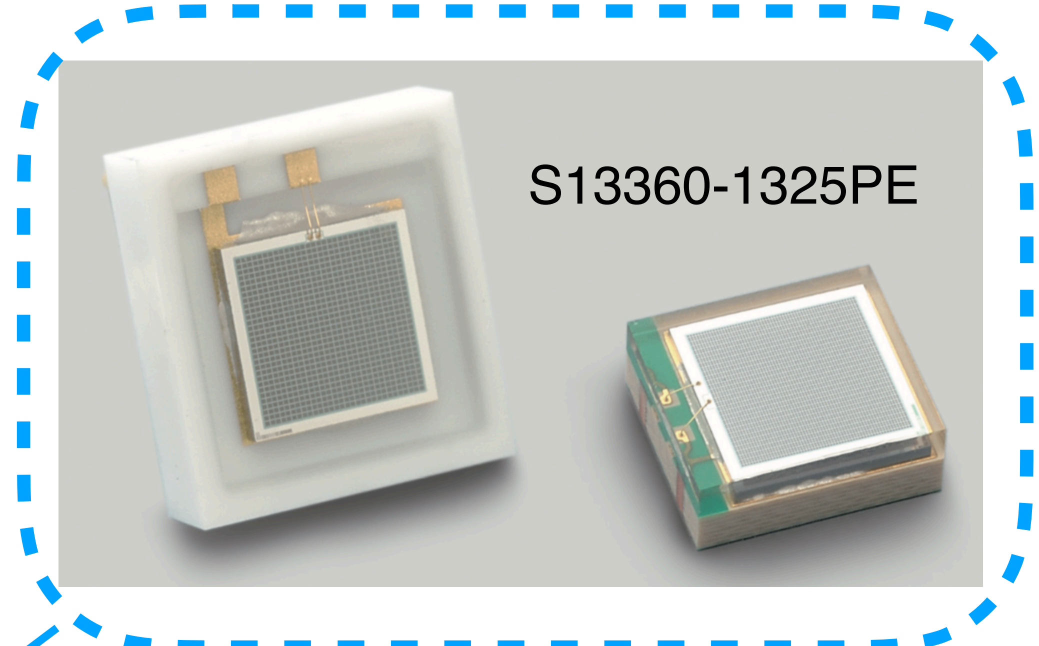

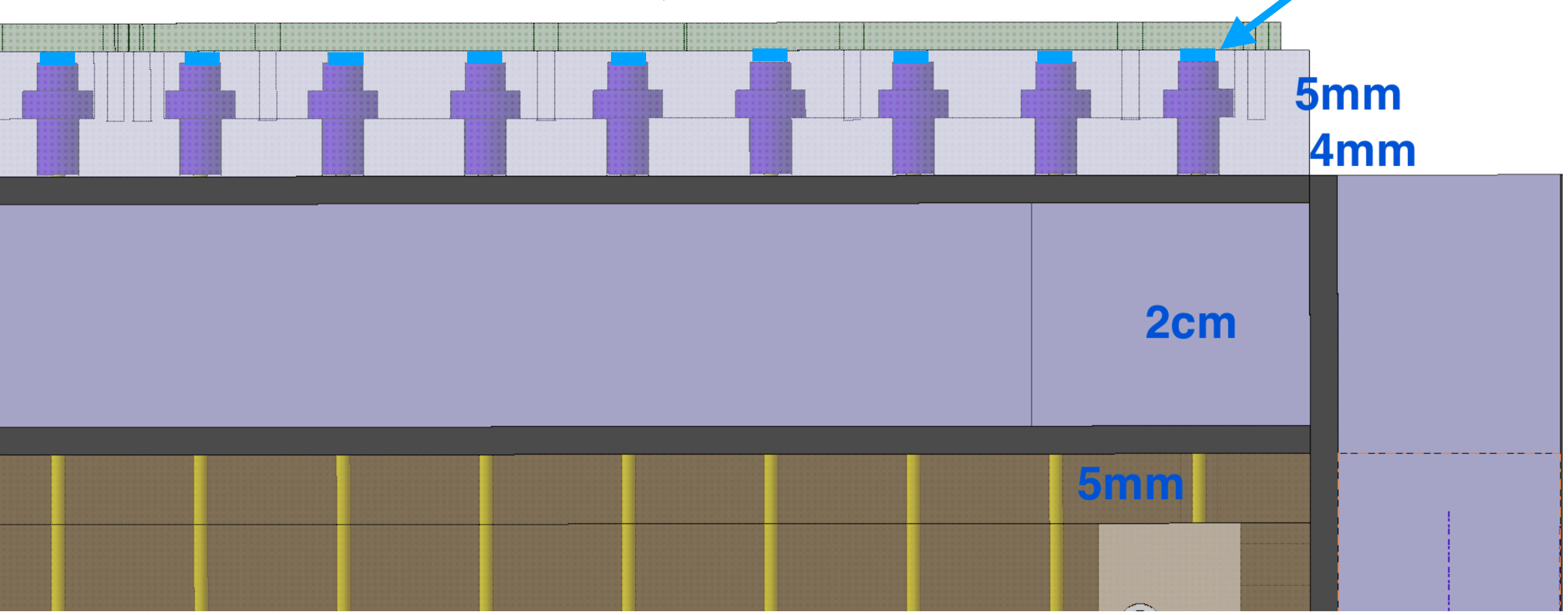

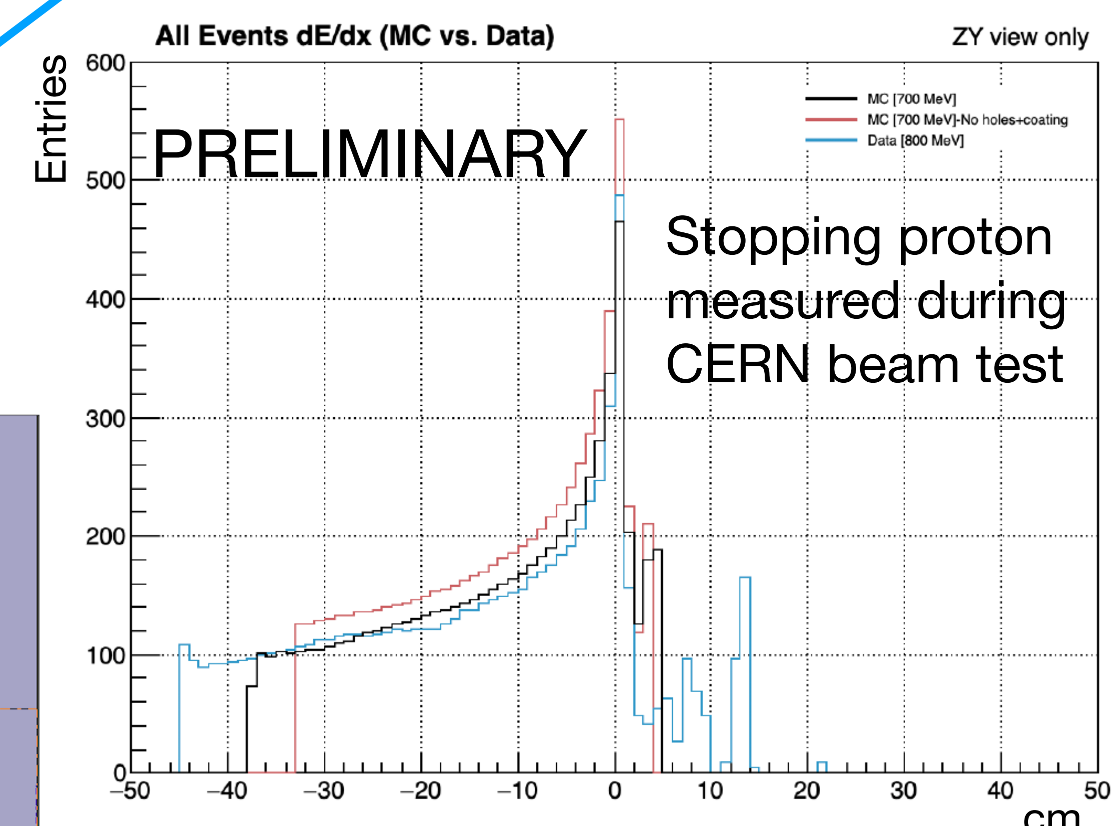

The SuperFGD detector

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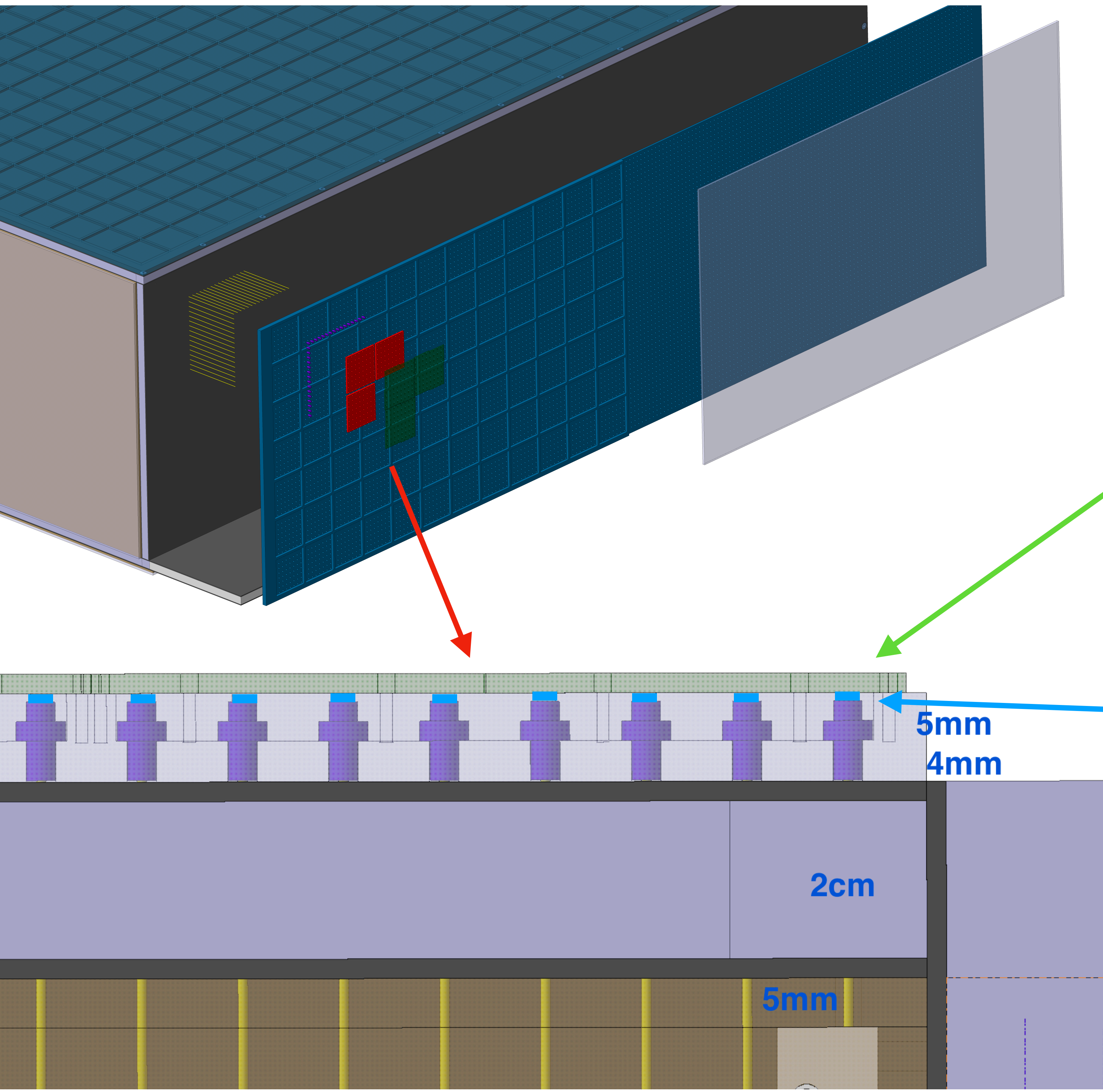

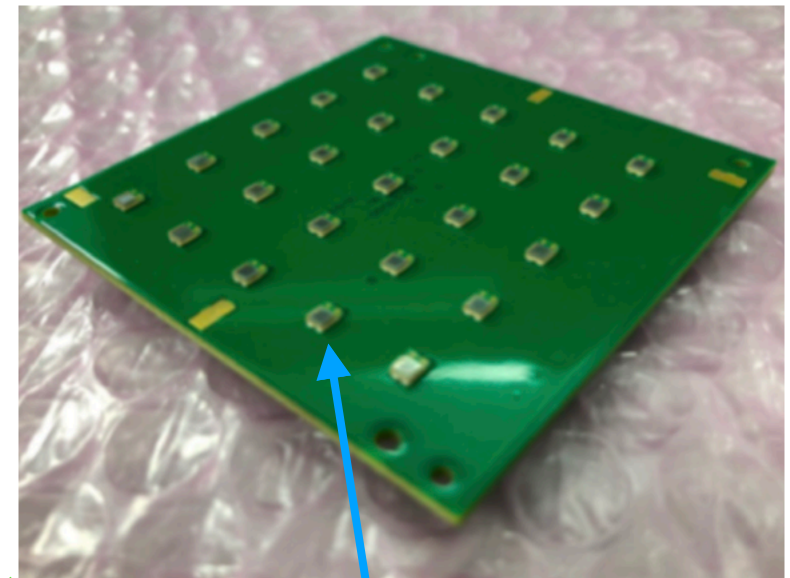

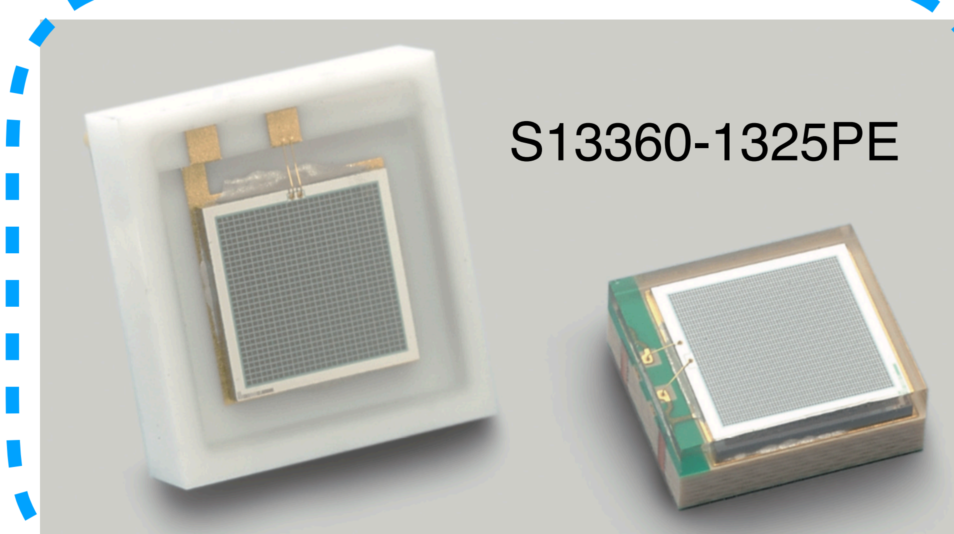

~ 4% X_{rad} from cubes to PCB

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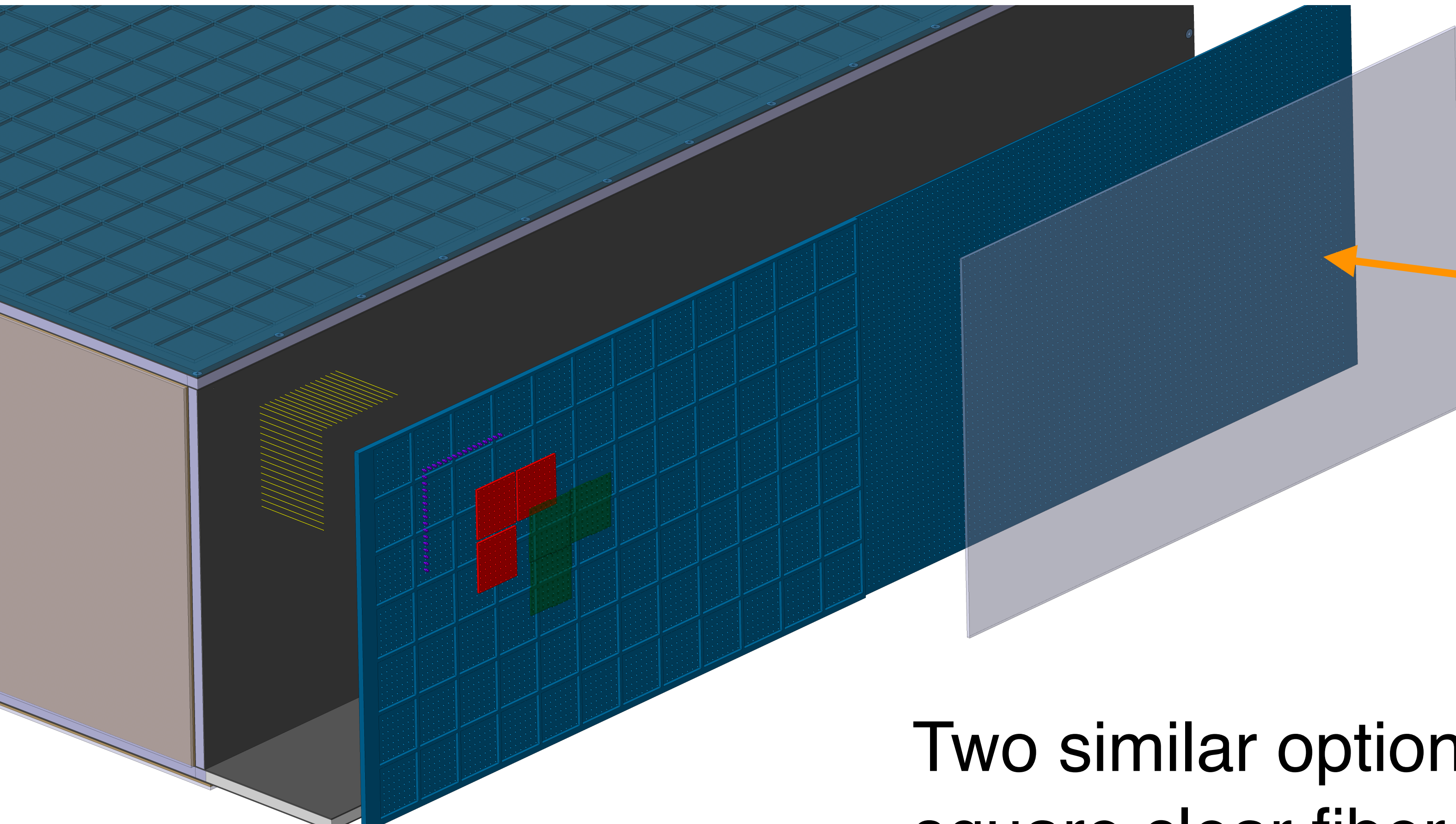
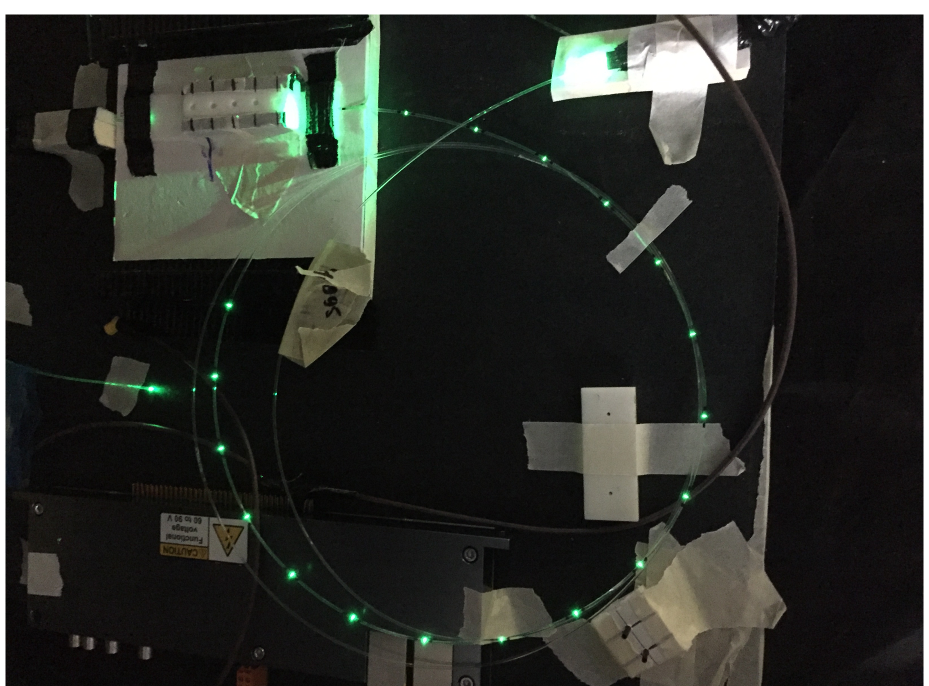
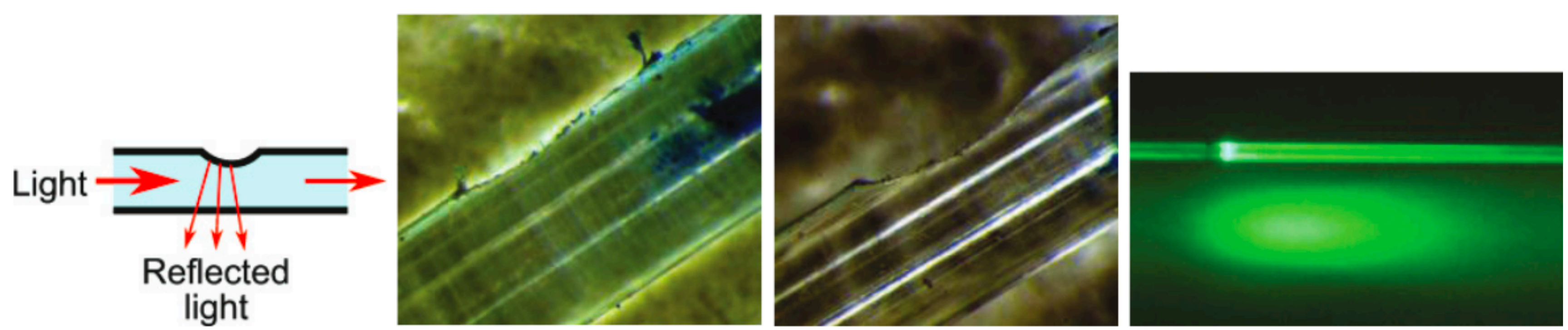


LED-based light injection system to calibrate the MPPCs from the not-instrumented WLS fiber end

Two similar options are being investigated: square clear fiber or light guide plate with "notches"

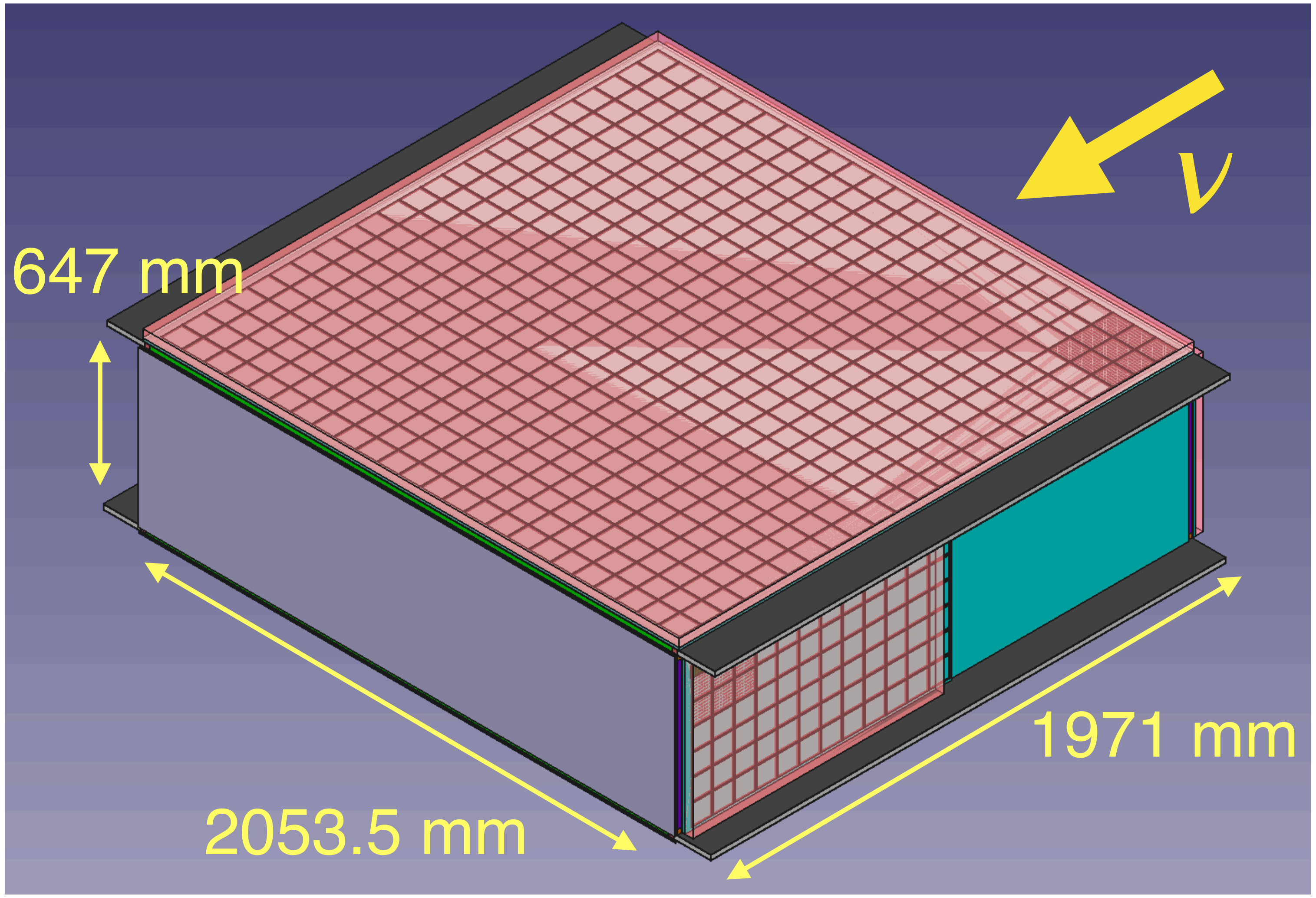


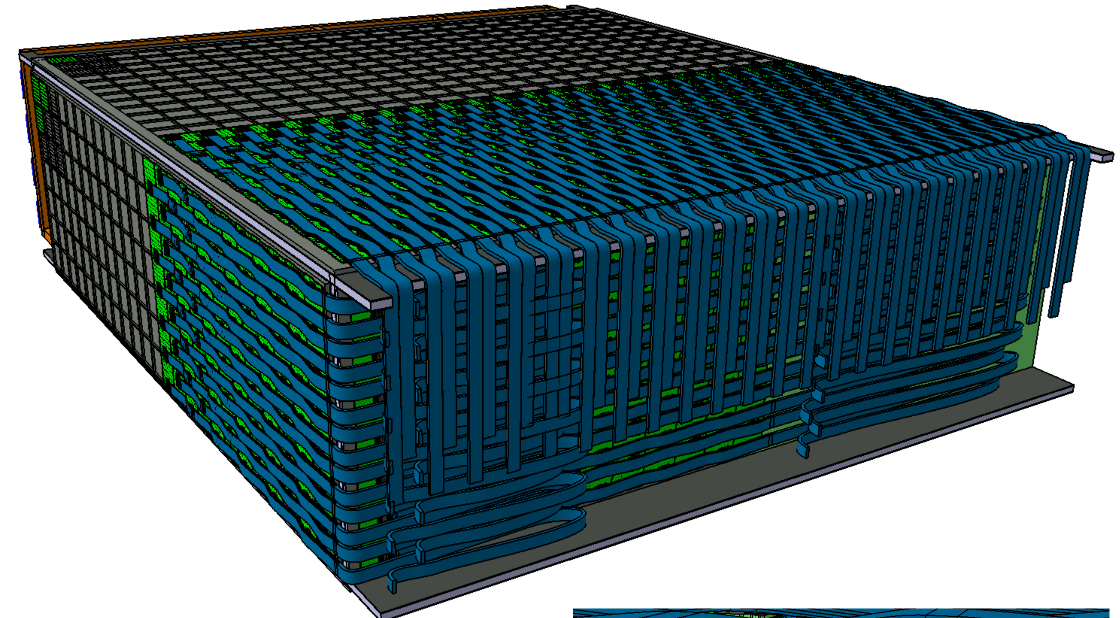
Physics Procedia 37 (2012) 402 – 409

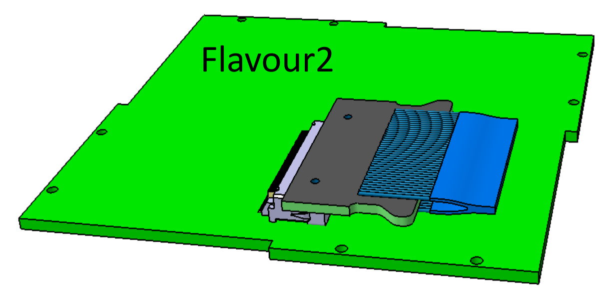


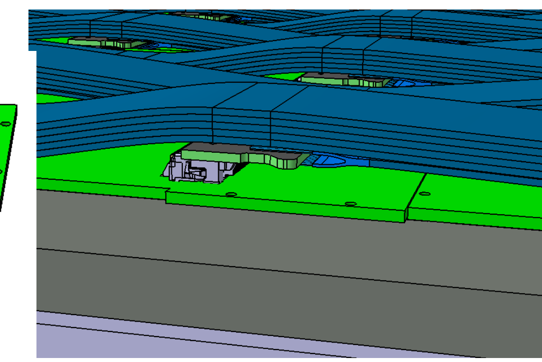
Each notch is coupled with a different WLS fiber that brings the light to the MPPC

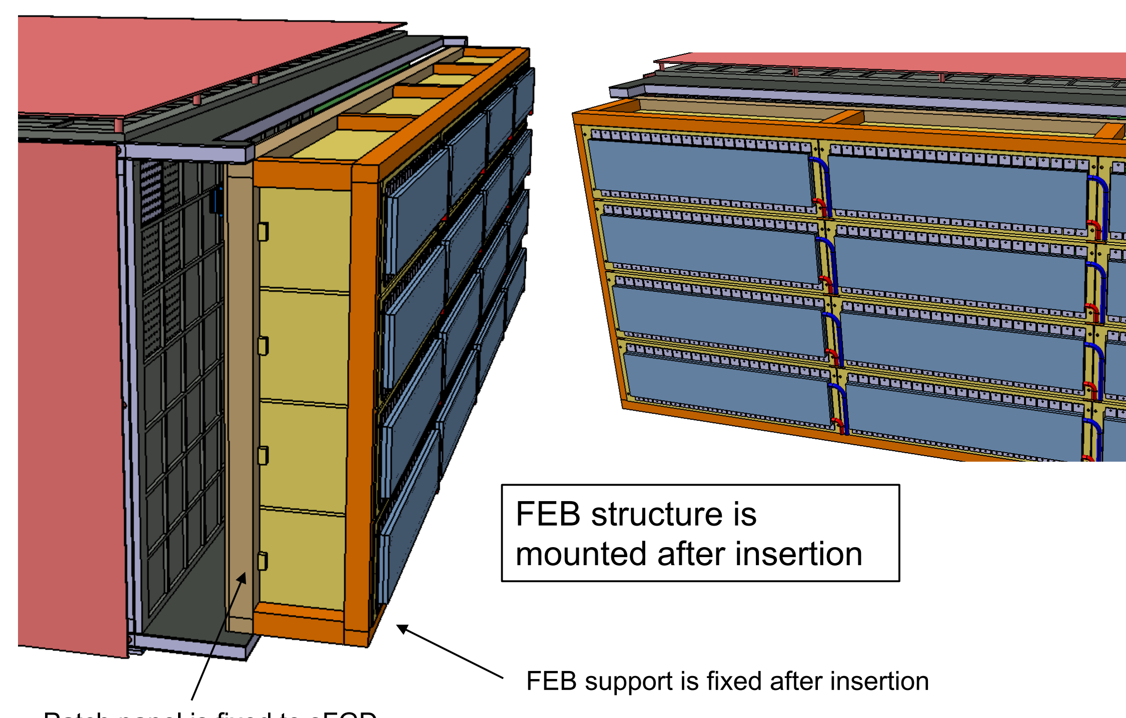
The SuperFGD detector











- Based on the CITIROC chip
- Measure highest peak point of the MPPC charge signal. Low/High gain mode, sensitive to both MIPs and stopping protons
- FPGA provides the timestamp with 400 MHz sampling rate, complementary measurement of the charge by Time-over-Threshold

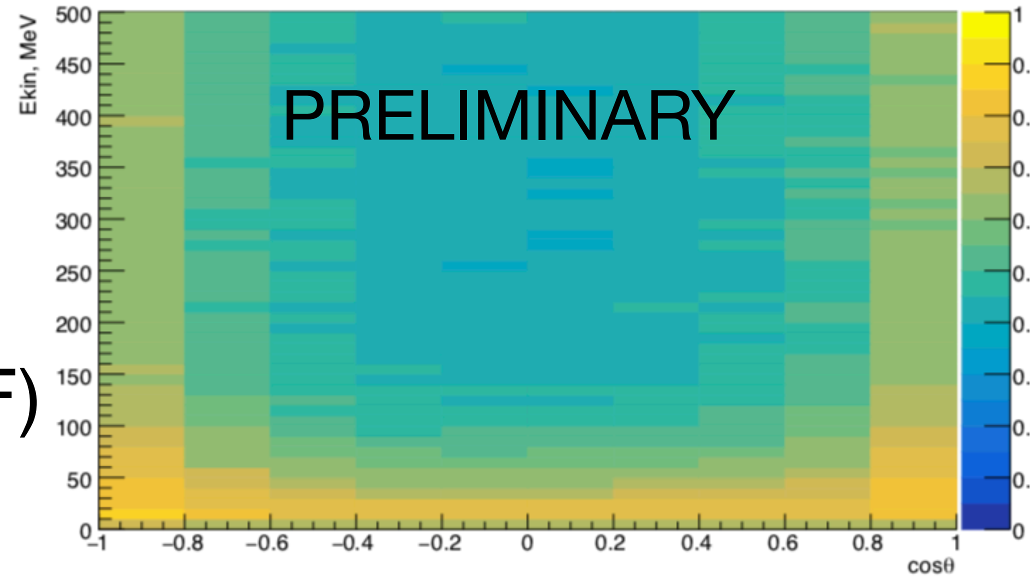
Neutron Detection

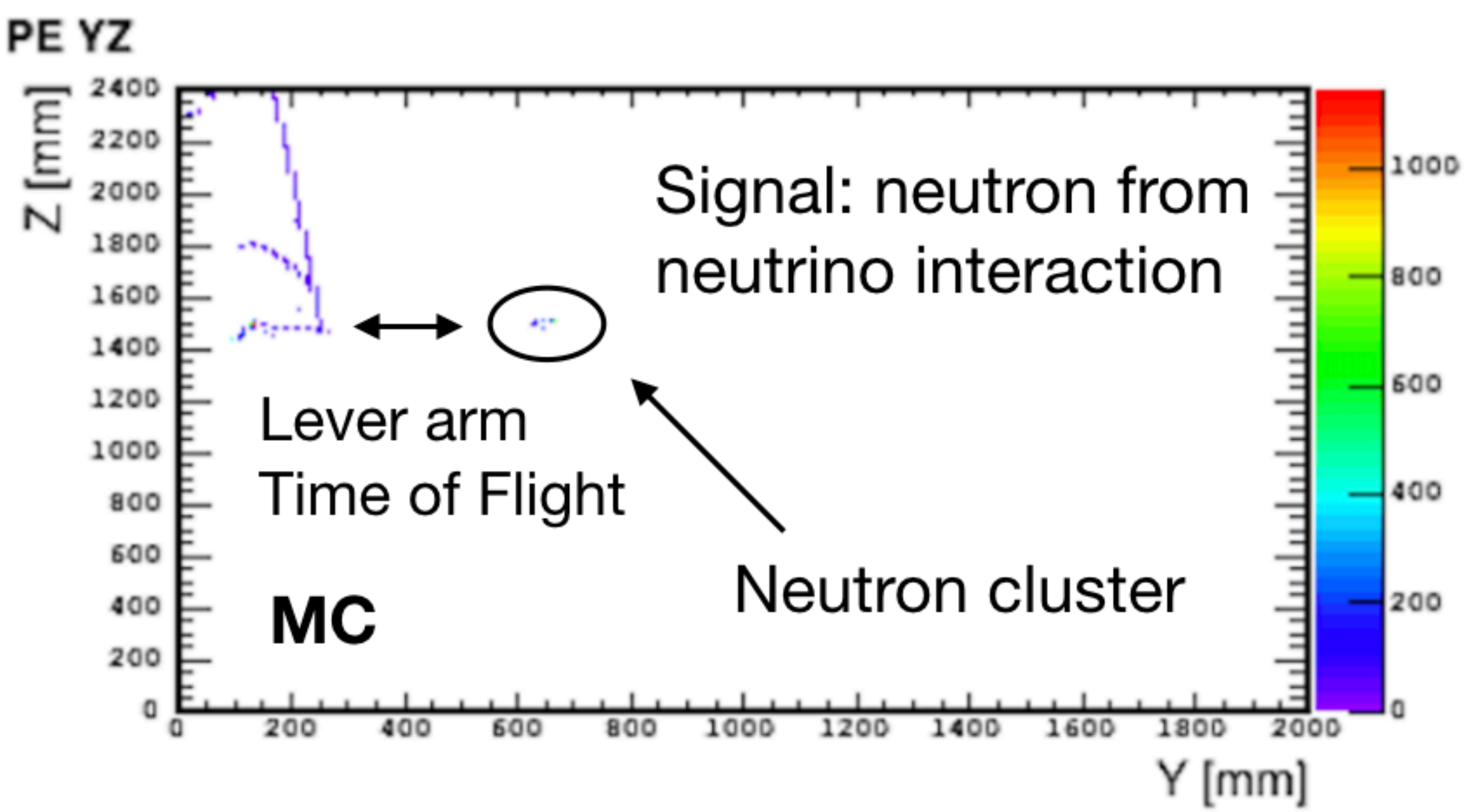
• Minerva experiment has demonstrated the potential of detecting neutrons produced by ν interactions in scintillator (arXiv:1901.04892)

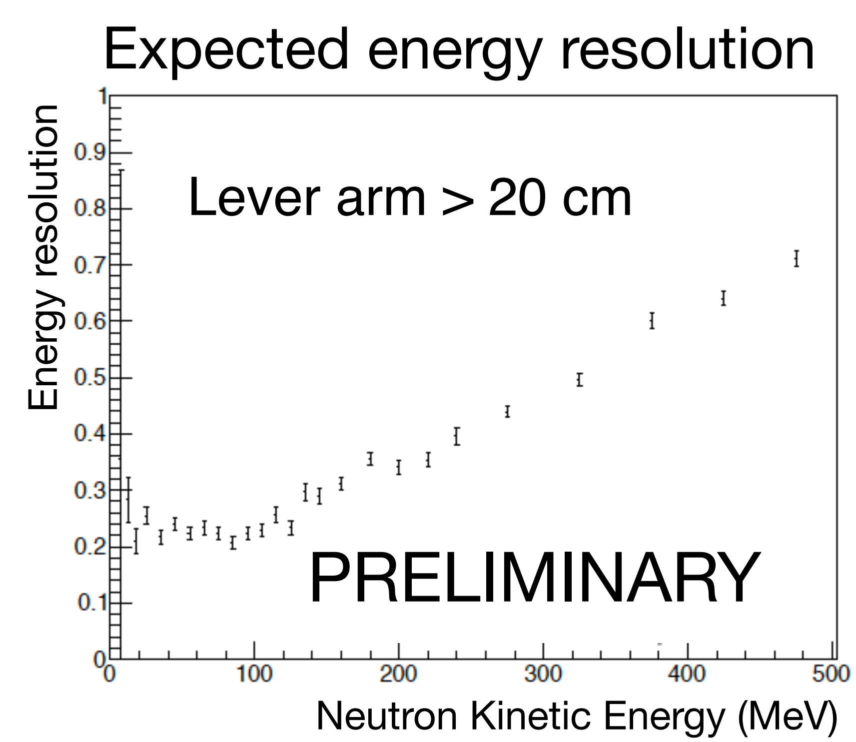
• SuperFGD has 3D granularity, much better spatial and timing resolution

• Precise neutron detection is a very powerful tool for the understanding of the ν interaction processes (e.g. 2p2h)

• Neutron kinetic energy by Time-of-Flight (ToF)

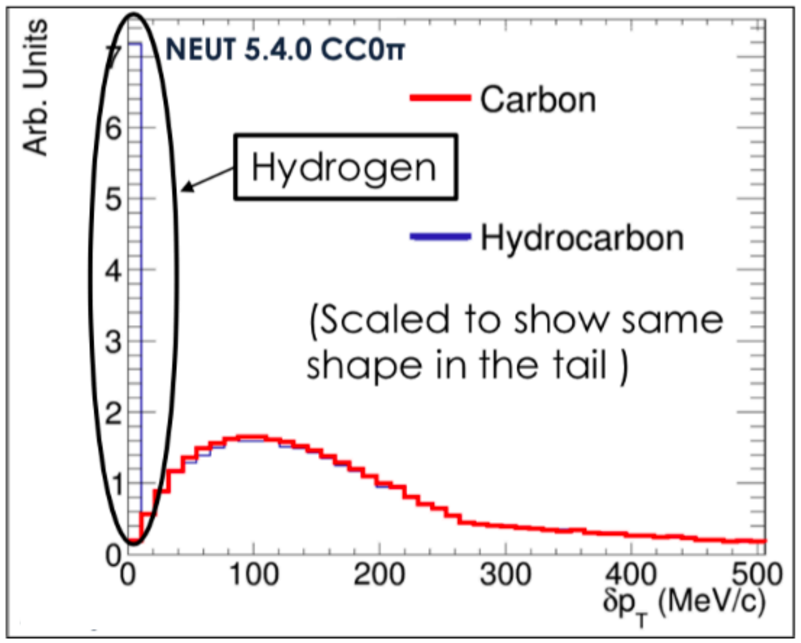




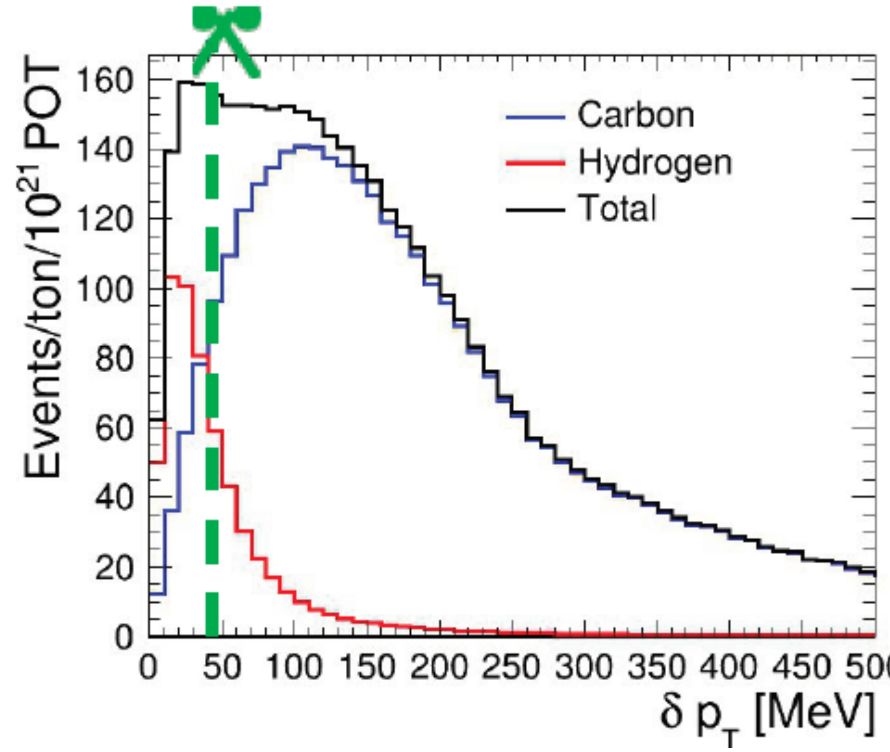


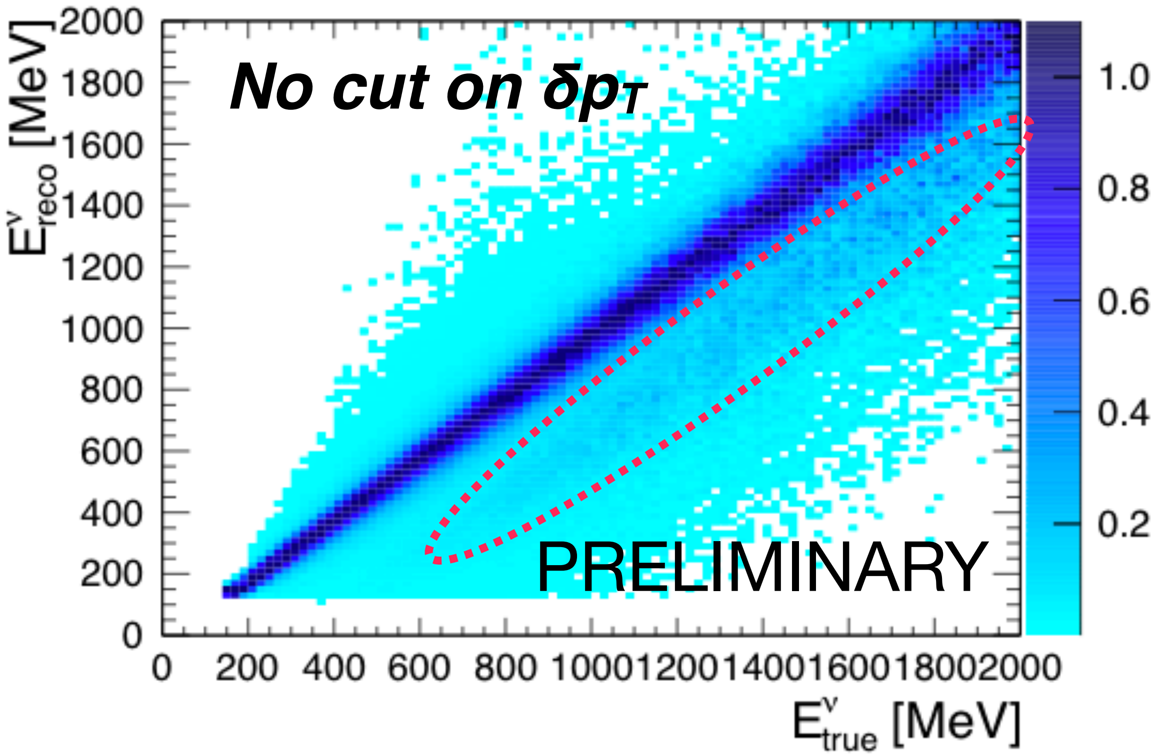
New method to infer $\overline{\nu}_\mu$ flux

- Isolate NuBar-hydrogen and NuBar-carbon interactions with low nuclear effects
- Use neutron kinematics to precisely compute the event transverse momentum



Detector smearing





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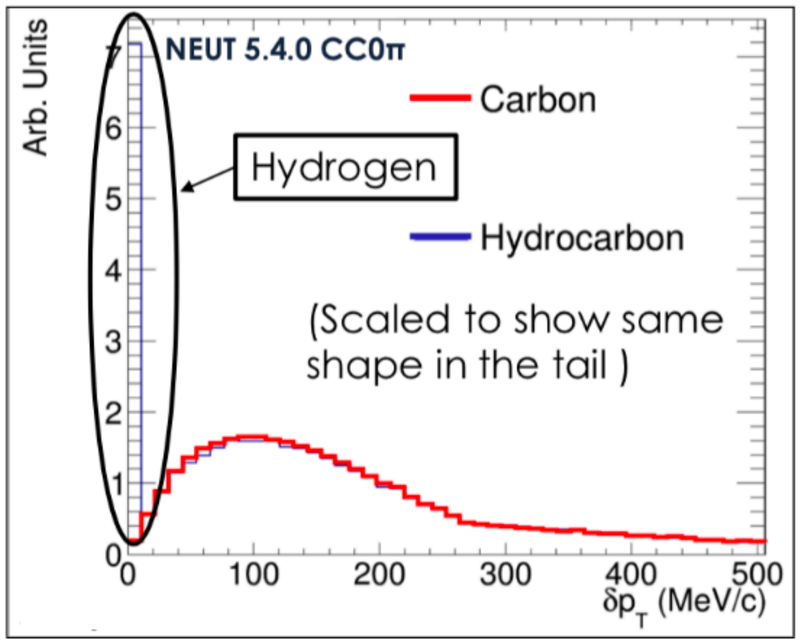

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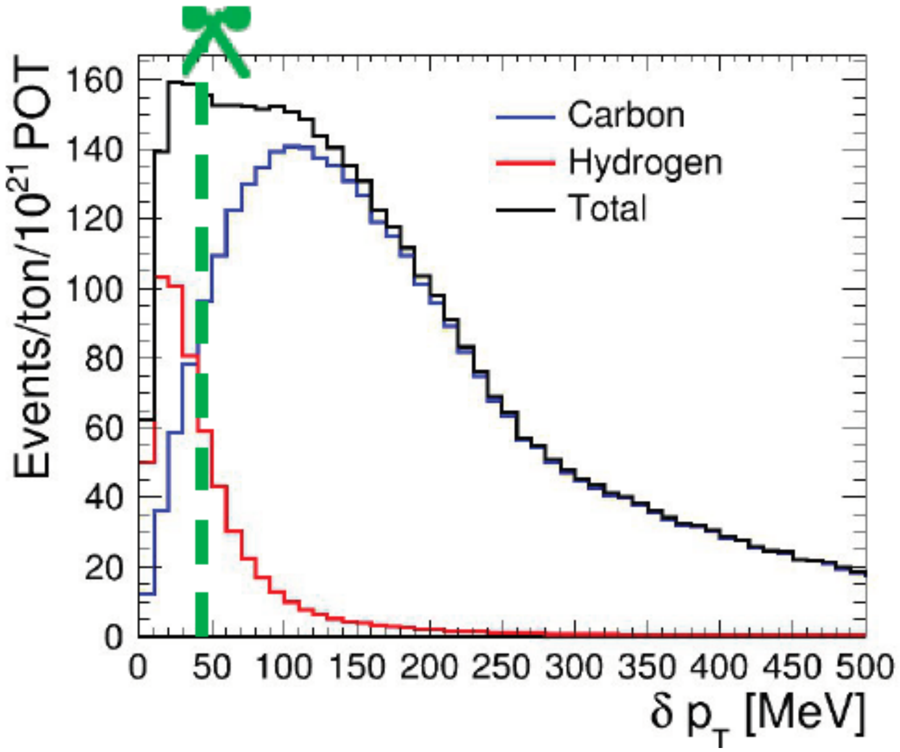
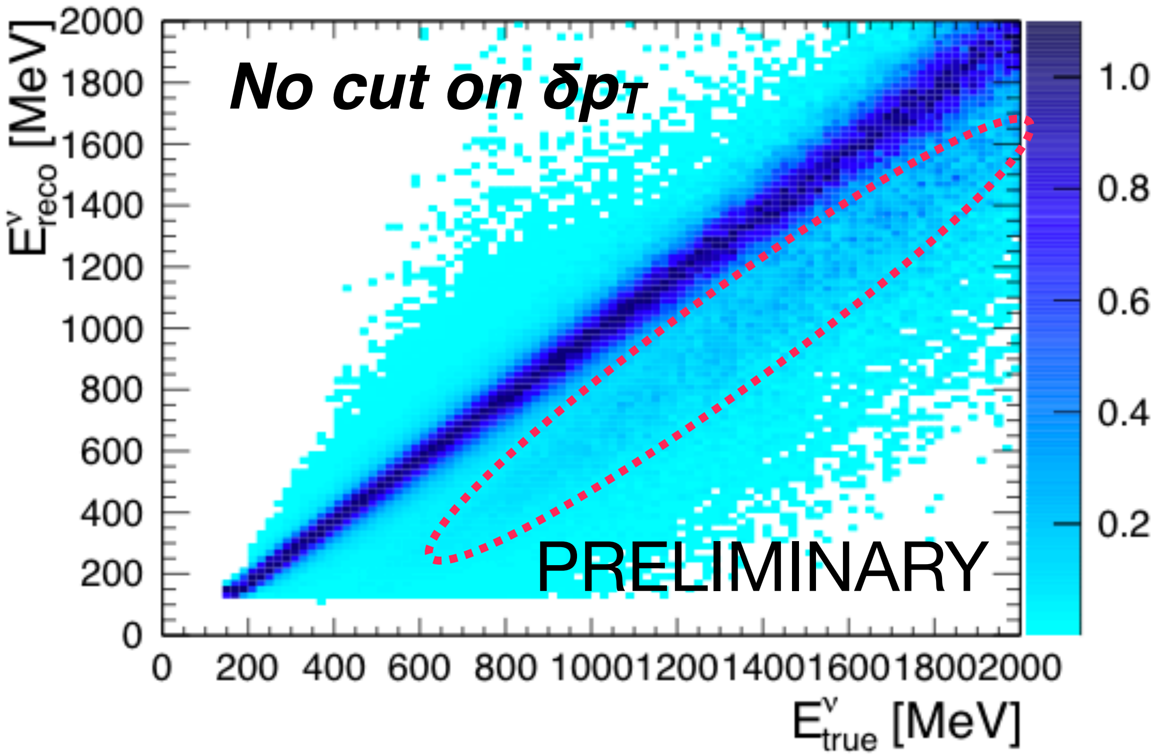
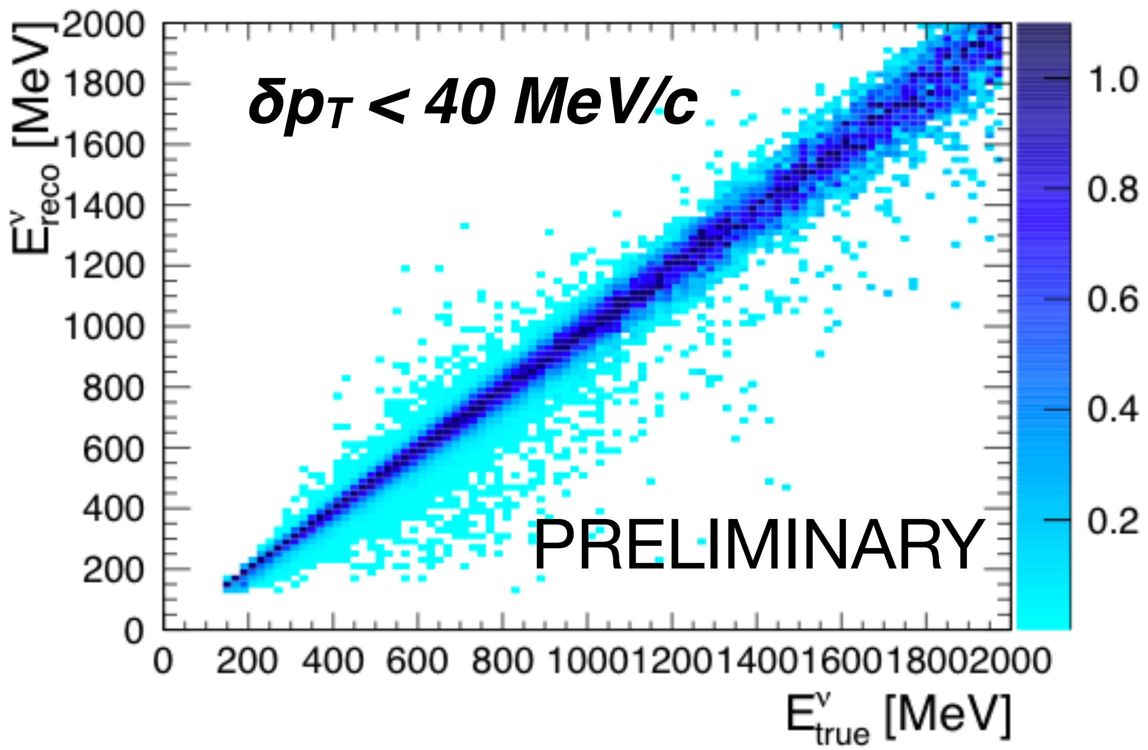




Cut on δp$_T$



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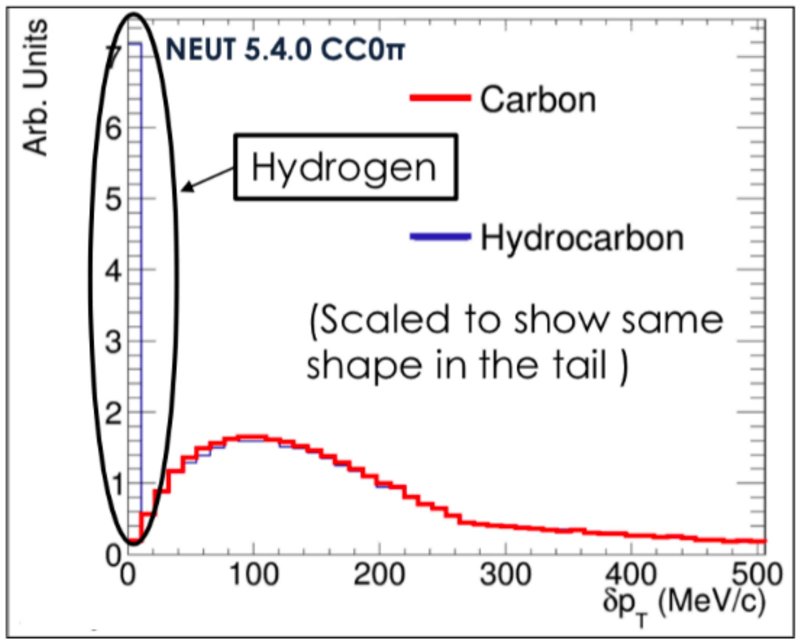

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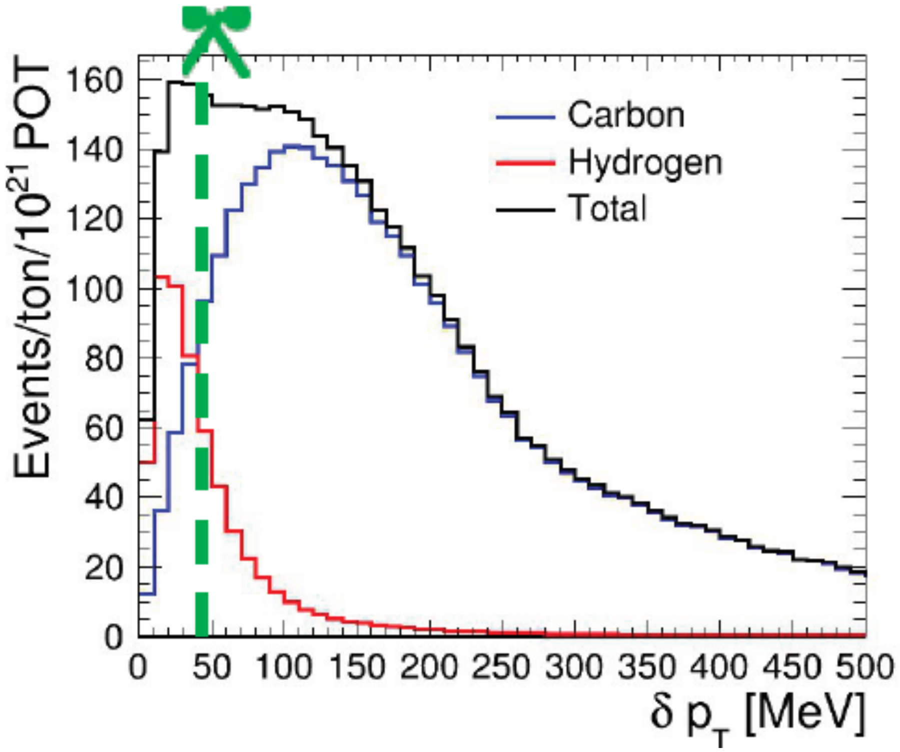
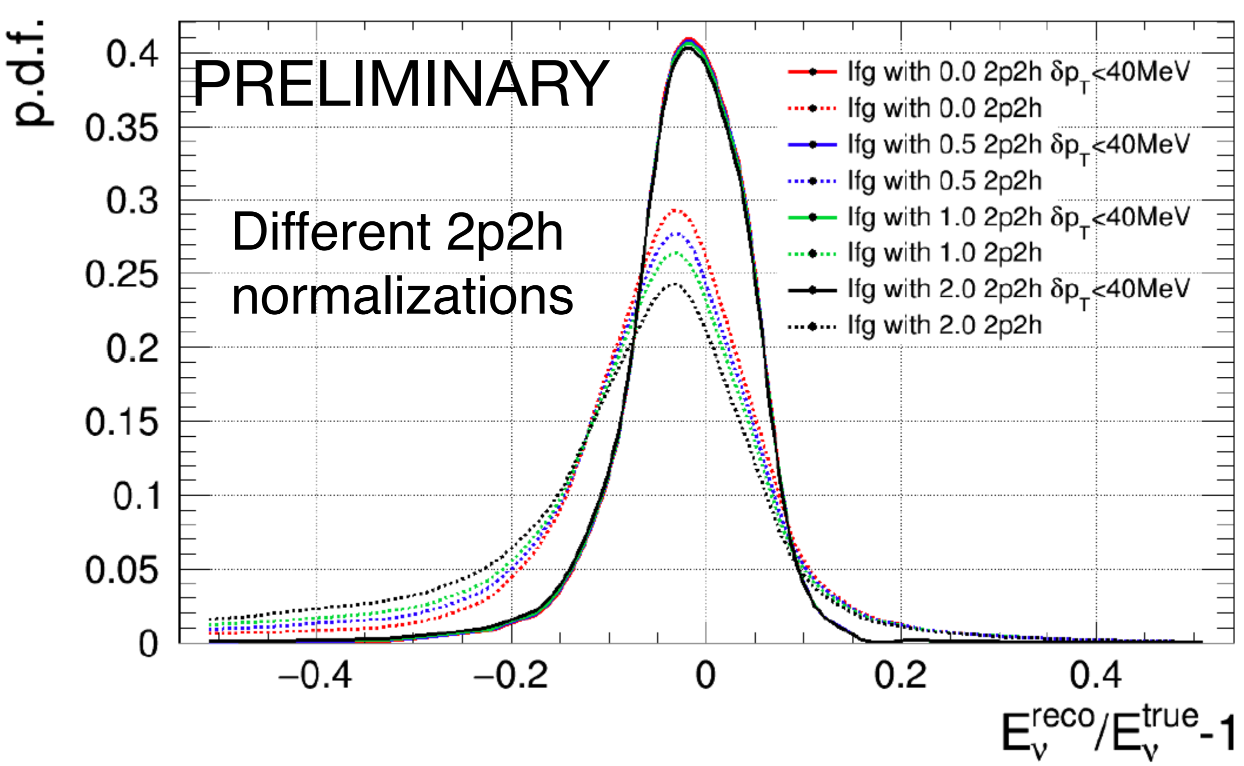
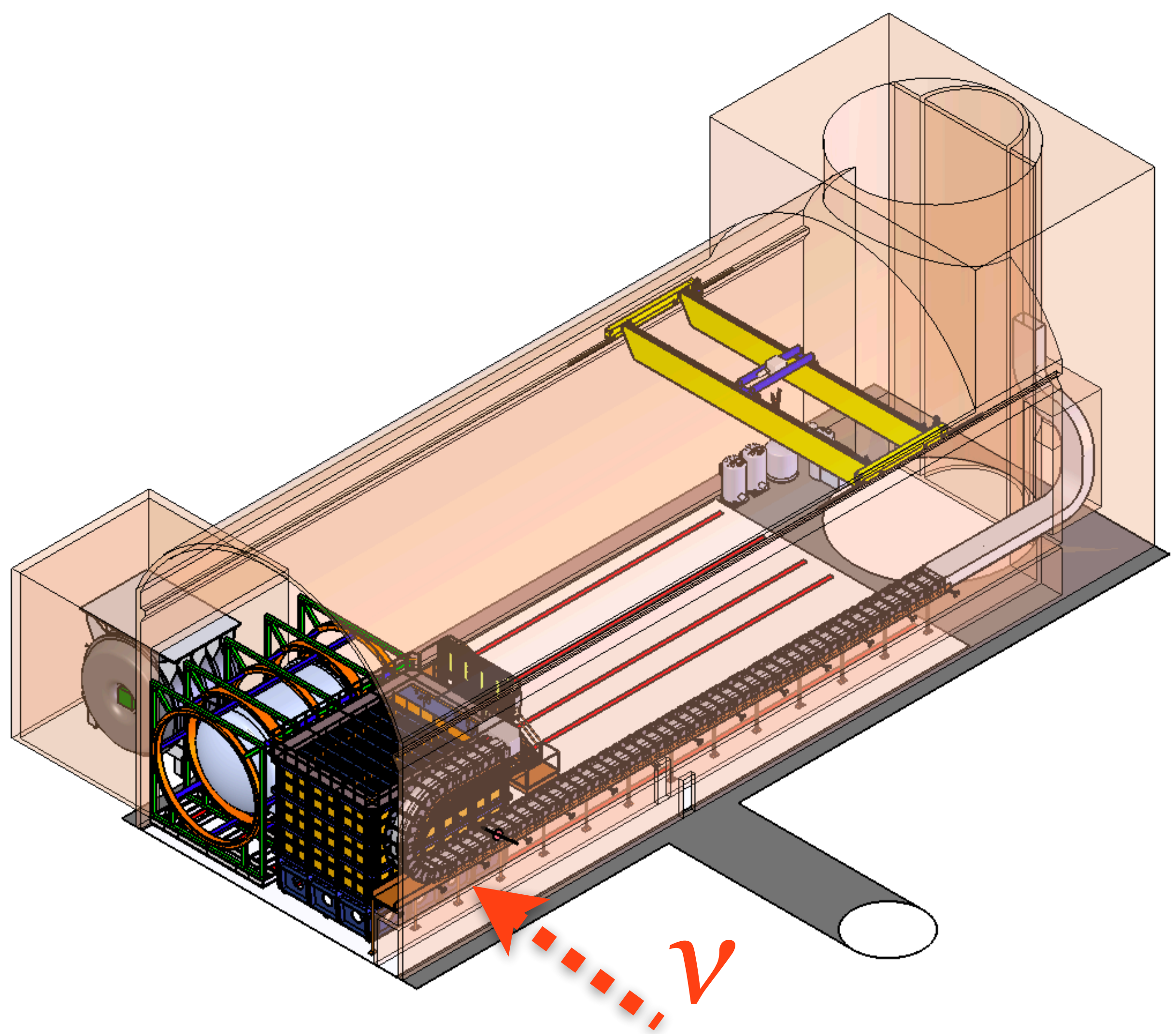




- NuBar energy resolution is reduced from ~13% to ~6-7% and almost no bias on E_{reco}
- E_{reco} weakly dependent on the interaction model and reduce correlations between flux and cross-section

The 3DST at the DUNE Near Detector

- DUNE ND conceptual baseline includes three main detector systems:
  - ✦ LAr, High-Pressure TPC and 3DST spectrometer
  - ✦ LAr and HP-TPC will move off-axis (range of ~30 m)



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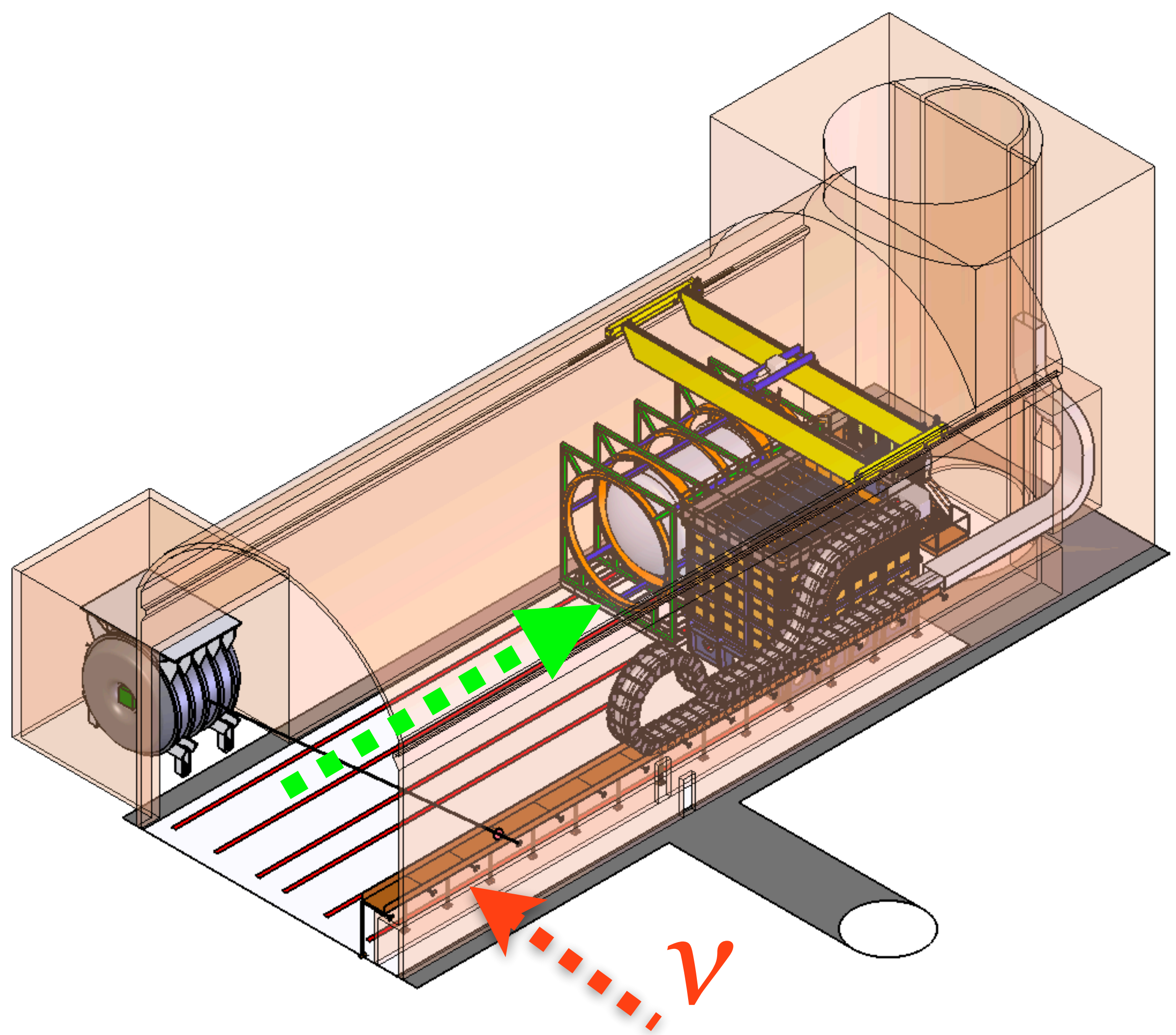
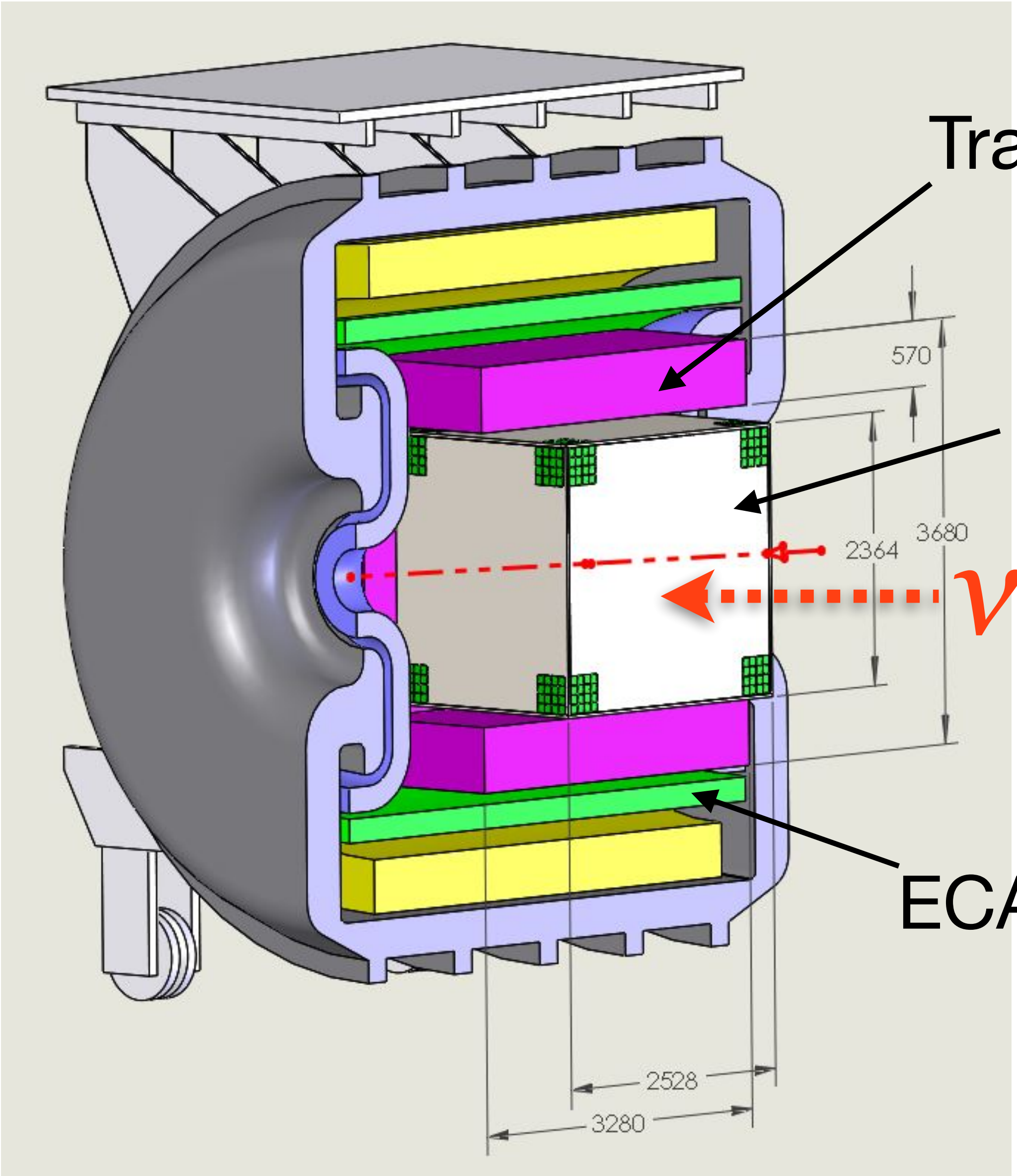
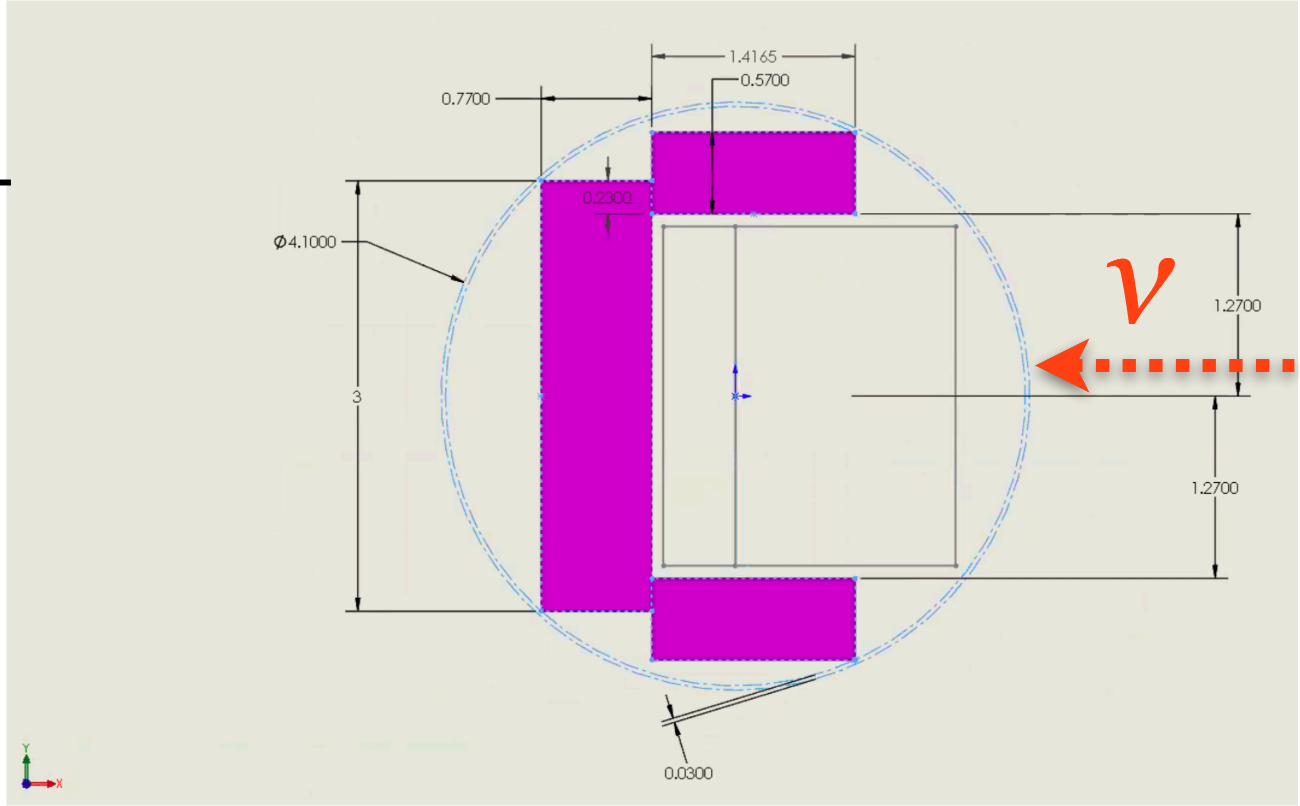
  - ✦ 3DST spectrometer will be the only on-axis detector



The 3DST at the DUNE Near Detector

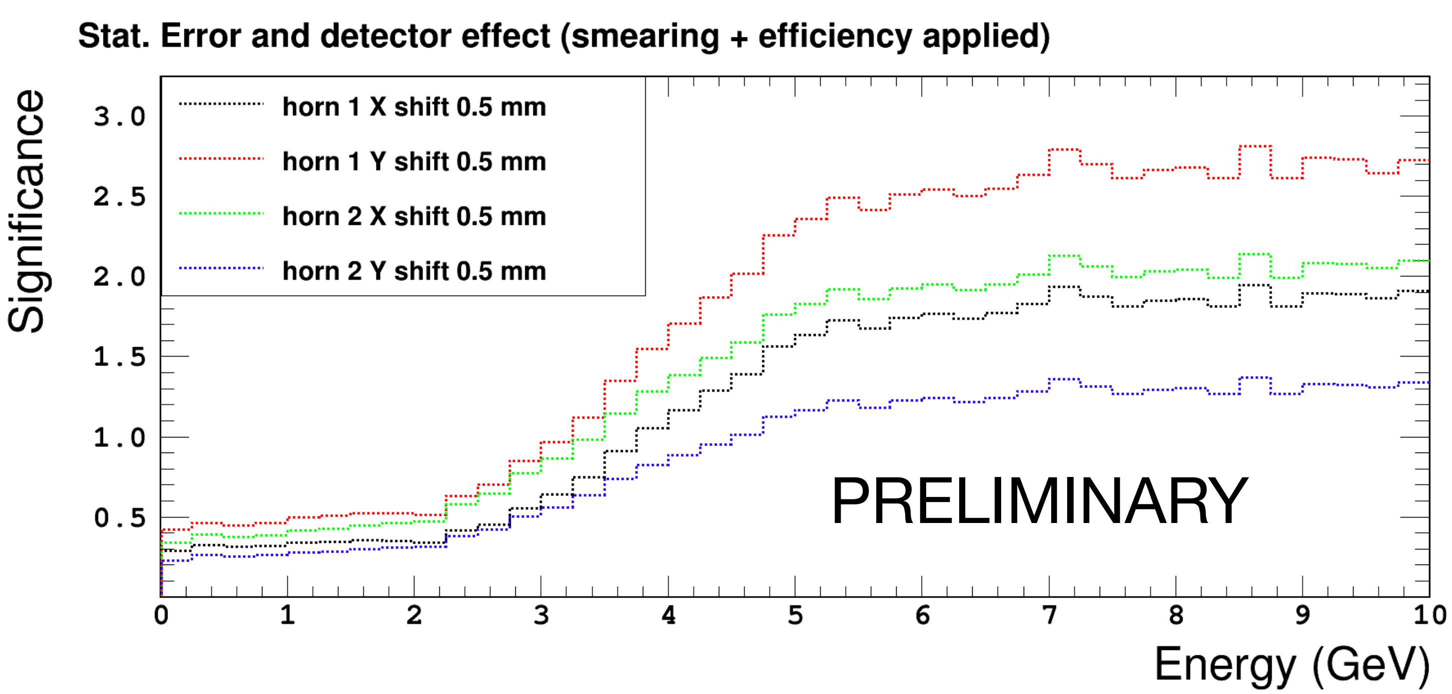
- 3DST-S similar to ND280: ~11 tons mass, low-density gas tracker, ECAL, magnet
- Most of the R&D made for the T2K-SuperFGD is common to DUNE-3DST though there is time for improvements, e.g. optimization of the cube size, electronics sampling rate, etc.





The 3DST physics program

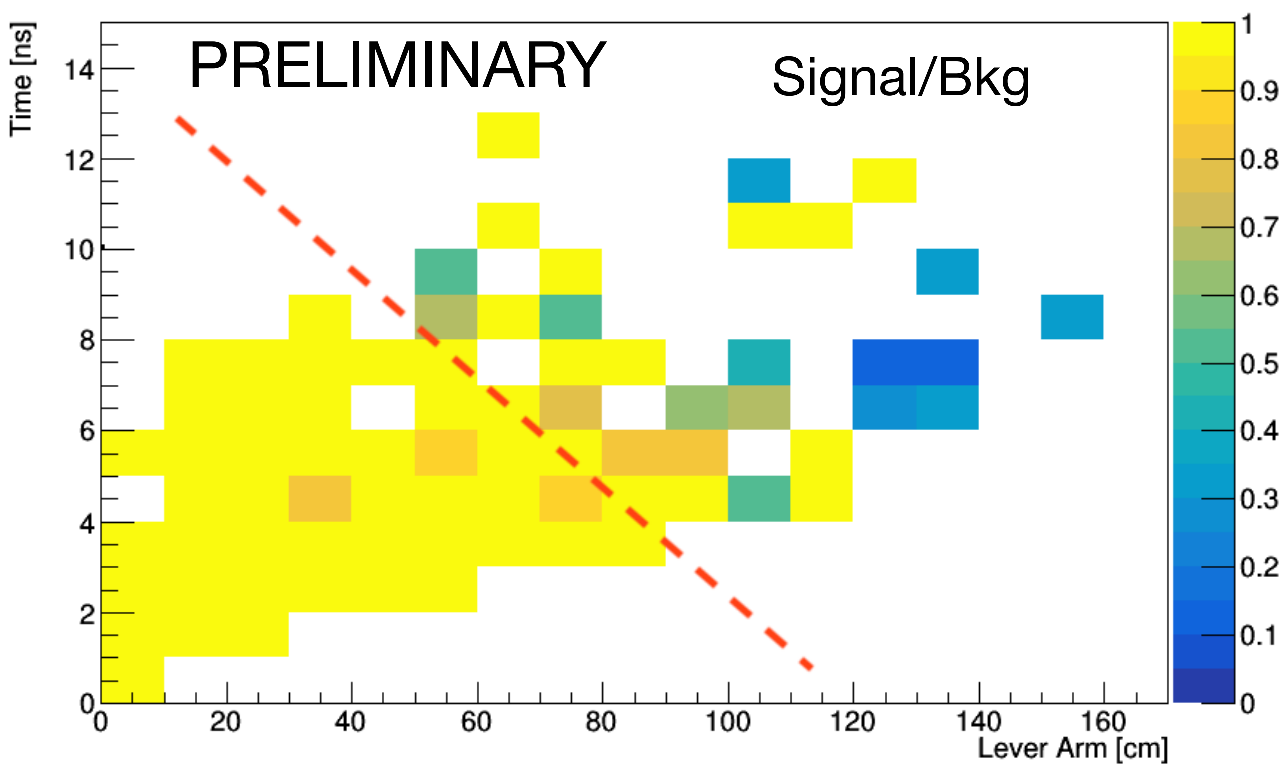
- The LAr and High-Pressure TPC will move to different off-axis locations while the far detector is on-axis
- We need a detector with large mass to stay always on-axis
- Monitor the beam spectrum to identify possible issues in the beamline, e.g. horn misalignment, target density variation, beam angle
- Simply off-axis event rate measurement is not sufficient to detect many of these effects that would impact mainly the on-axis beam spectrum



sqrt(chi2)	4 modules One-side rate	Muon spectrometer
Beam targ. dens.	1.9	7.9
Beam offset x	0.7	2.0
Beam theta	0.2	4.9
Beam theta phi	0.2	8.5
Horn 1 X 0.5 mm	1.9	4.1
Horn 1 Y 0.5 mm	0.7	8.3
Horn 2 X 0.5 mm	0.2	2.9
Horn 2 Y 0.5 mm	0.4	6.9

The 3DST physics program

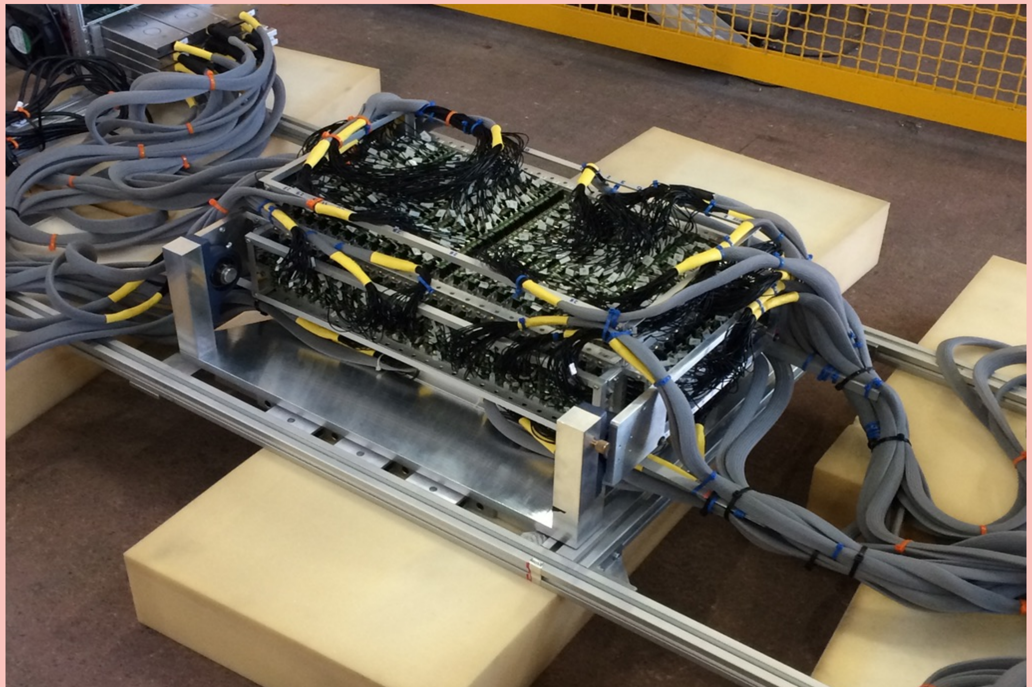
- Like SuperFGD also 3DST has high neutron detection efficiency and good expected neutron energy resolution by ToF
- Precision measurement of neutrino-CH interactions with neutrons kinematics
  - ✦ Modern neutrino interactions act at microscopic level and they intrinsically can predict any extrapolation from carbon to argon or any other nucleus
  - ✦ If the model doesn't work in CH, we can't trust it in Argon
  - ✦ Hard to measure the neutron kinematics in argon
- Anti-Neutrino flux measurement



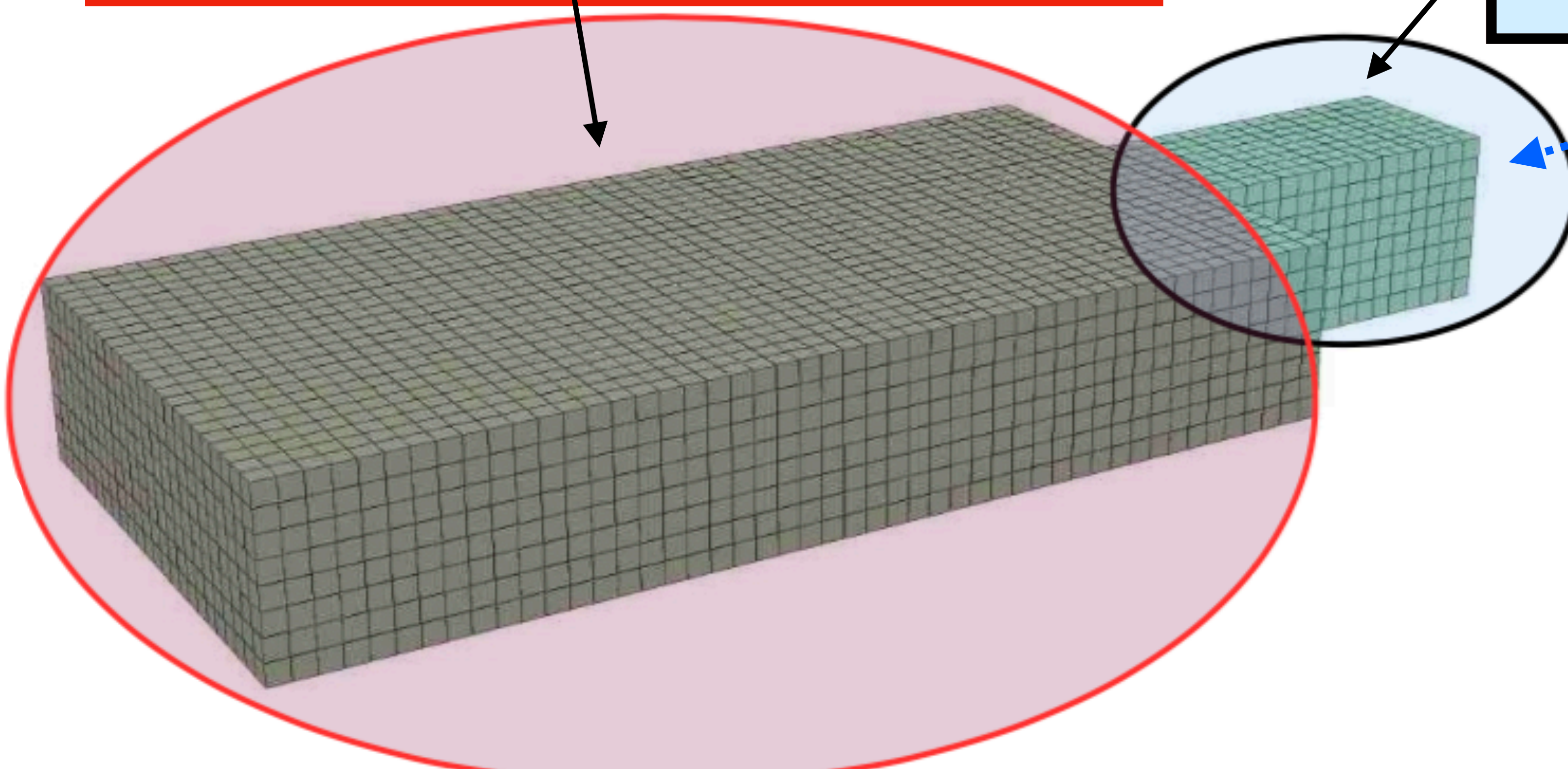
The precise knowledge of the 3DST response to neutrons exposure is mandatory and test beams are planned

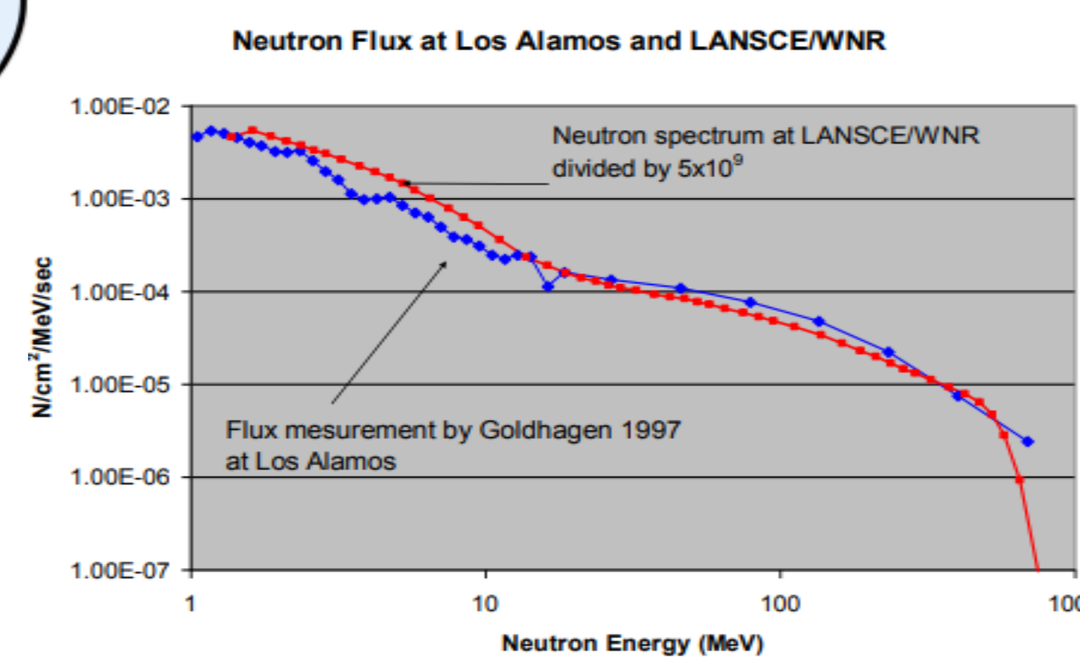
Neutron test beam in Los Alamos

CERN prototype



US-Japan prototype





SuperFGD/3DST prototypes will be exposed to neutron test beam in Los Alamos

Conclusions

- A novel plastic scintillator detector concept has been developed
- An intensive R&D program lead the T2K collaboration to adopt the SuperFGD technology as active neutrino target of the upgraded Near Detector. Plan to install it in 2021 and start data taking in 2022
- The SuperFGD in the upgraded ND280 may also be the off-axis near detector of the Hyper-Kamiokande experiment
- The DUNE collaboration has included 3DST (same technology as SuperFGD, higher mass) in the Near Detector conceptual baseline
- Several beam tests at CERN already performed
- Neutron beam test with SuperFGD / 3DST prototypes planned this year in Los Alamos under the common US-Japan funding program