3DST-S concept, integration and physics

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on behalf of the 3DST-S working group

ND Workshop: Magnet Systems

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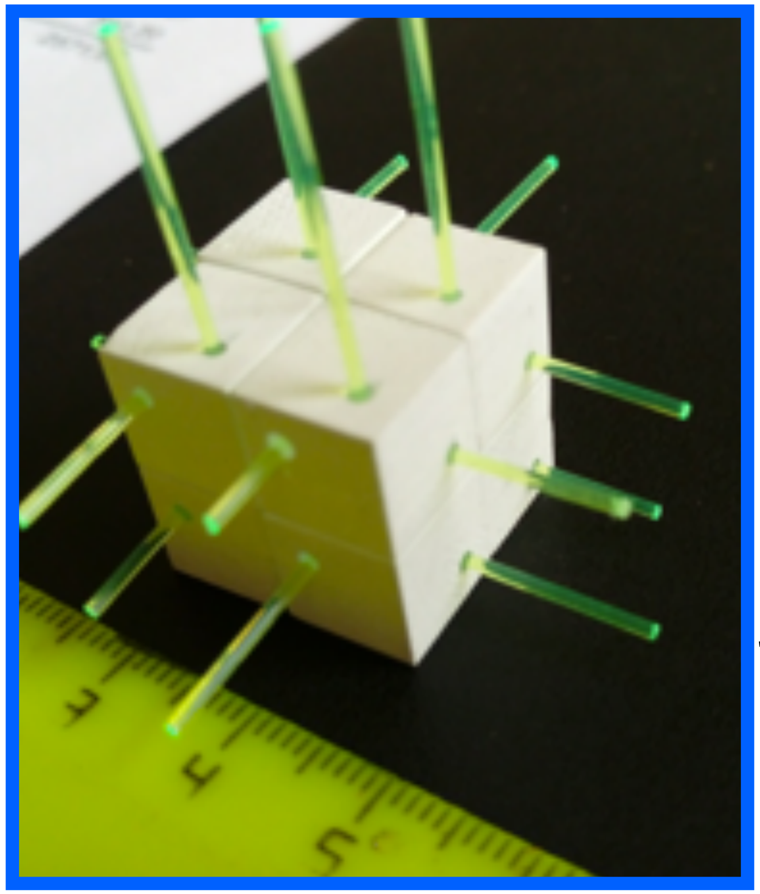
The physics case for 3DST-S

- Measuring CP violation by detecting a spectrum distortion requires a precise beam monitoring with the following functionalities in a few-days basis
  - Event rate: requires a large-mass active detector
  - Beam width: requires relatively large width and segmentation
  - Spectrum: requires a spectrometer to measure the particle momenta
- Measure the neutrino and antineutrino flux using different but complementary methods
  - Neutrino+electron scattering
  - Transverse-momentum imbalance + neutron detection
  - Low-Nu method
- Precise measurements of neutrino interactions in Carbon with neutron detection
  - Complementary measurements to Argon target detectors
  - Form a robust ND system as a whole against uncertain and unknown systematic error sources
- The key tool is detecting and measuring the neutron energy on an event-by-event basis
  - Lack of knowledge on neutron content is a known source of uncertainty in calorimetric energy reconstruction. Different for neutrino and antineutrino interactions
  - Powerful avenue to explore and improve interaction models and measure the flux with minimal cross-section model dependence

The concept and the requirements

The 3DST Spectrometer (3DST-S)

3DST



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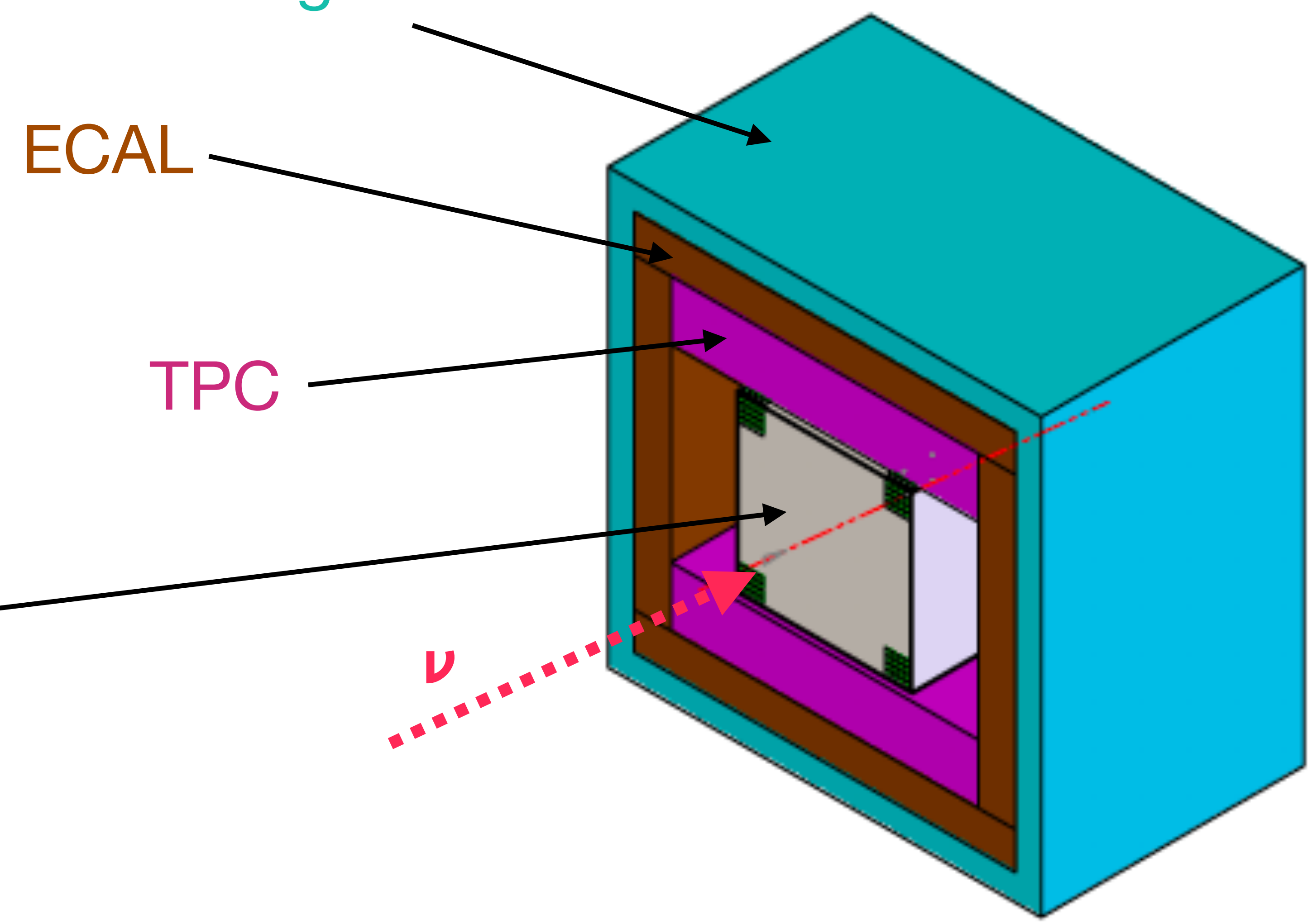
3DST-S



- Muon detection efficiency >90% at 4π
- Muon p resolution by range ~2-3%
- Detect protons above ~300 MeV/c
- Very good neutron detection capability

- Magnet w/ B-field = 0.6 T
- Gas Tracker:
  - space-point resolution <0.5 mm
  - 5% p resolution @3 GeV/c
- ECAL with at least 10 X_{rad} for π^0 and γ

T2K Near Detector will be upgraded with 2 tons 3DST-like detector and TPC

The original conceptual configuration of 3DST-S

- The dimensions account for a realistic design of 3DST and are based on the TPCs that will be installed in the T2K upgraded ND280
- A muon tagger in front of the Downstream ECAL to μ / $\pi^{\pm}$ separation
- Simulation studies were done with 2.4x2.4x2 with 10cm off-shell FV cut

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Active volume: 2.24x2.24x2 m³
  10,637,312 tons (1.06 g/cm³)
  139,776 channels (1cm³ cube)
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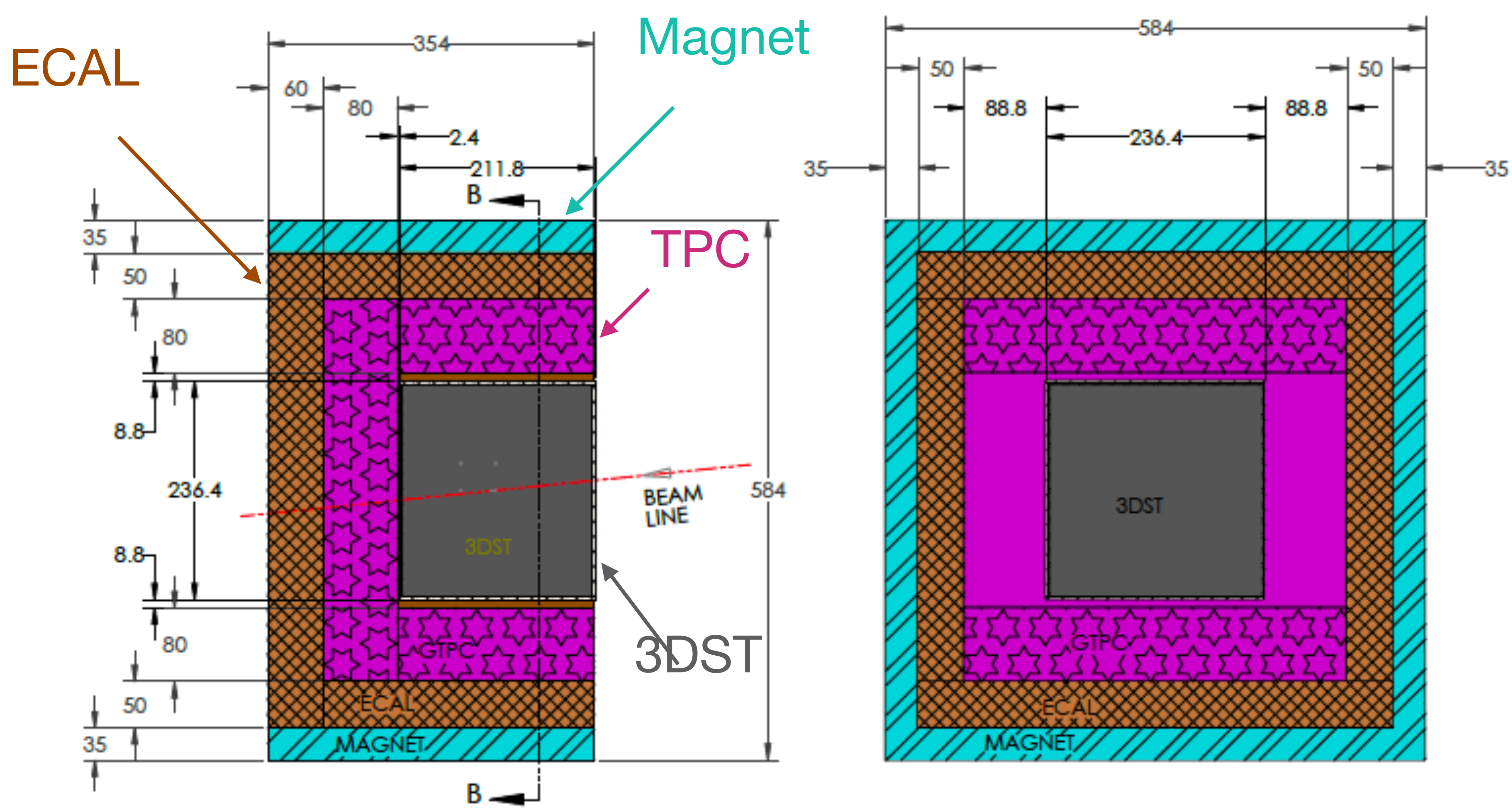

The 3DST event rate

- Event rate for 1.46×10^{21} POT / year (80 GeV beam, three horns, optimized)
- Applied a 10 cm out-of-FV cut:
  - ✦ Fiducial Volume = 2.2 x 2.2 x 1.8 m^3
  - ✦ Fiducial Mass = 8.7 tons (only 3DST)

Channel	ν mode	$\bar{\nu}$ mode
ν_μ CC inclusive	13.6×10^6	5.1×10^6
CCQE	2.9×10^6	1.6×10^6
CC π° inclusive	3.8×10^6	0.97×10^6
NC total	4.9×10^6	2.1×10^6
ν_μ-e^- scattering	1067	1008
ν_μ CC coherent	$1.26\ \times10^5$	$8.6\ \times10^4$
ν_μ CC low-ν (ν <250 MeV)	1.48×10^6	$8.8\ \times10^5$
ν_e CC coherent	2.1×10^3	719
ν_e CC low-ν (ν <250 MeV)	2.1×10^4	$4.7\ \times10^3$
ν_e CC inclusive	2.5×10^5	0.56×10^5

- The FV will have different definitions depending on the physics measurement
- Depending on the ECAL design, additional mass could be achieved for some physics channels

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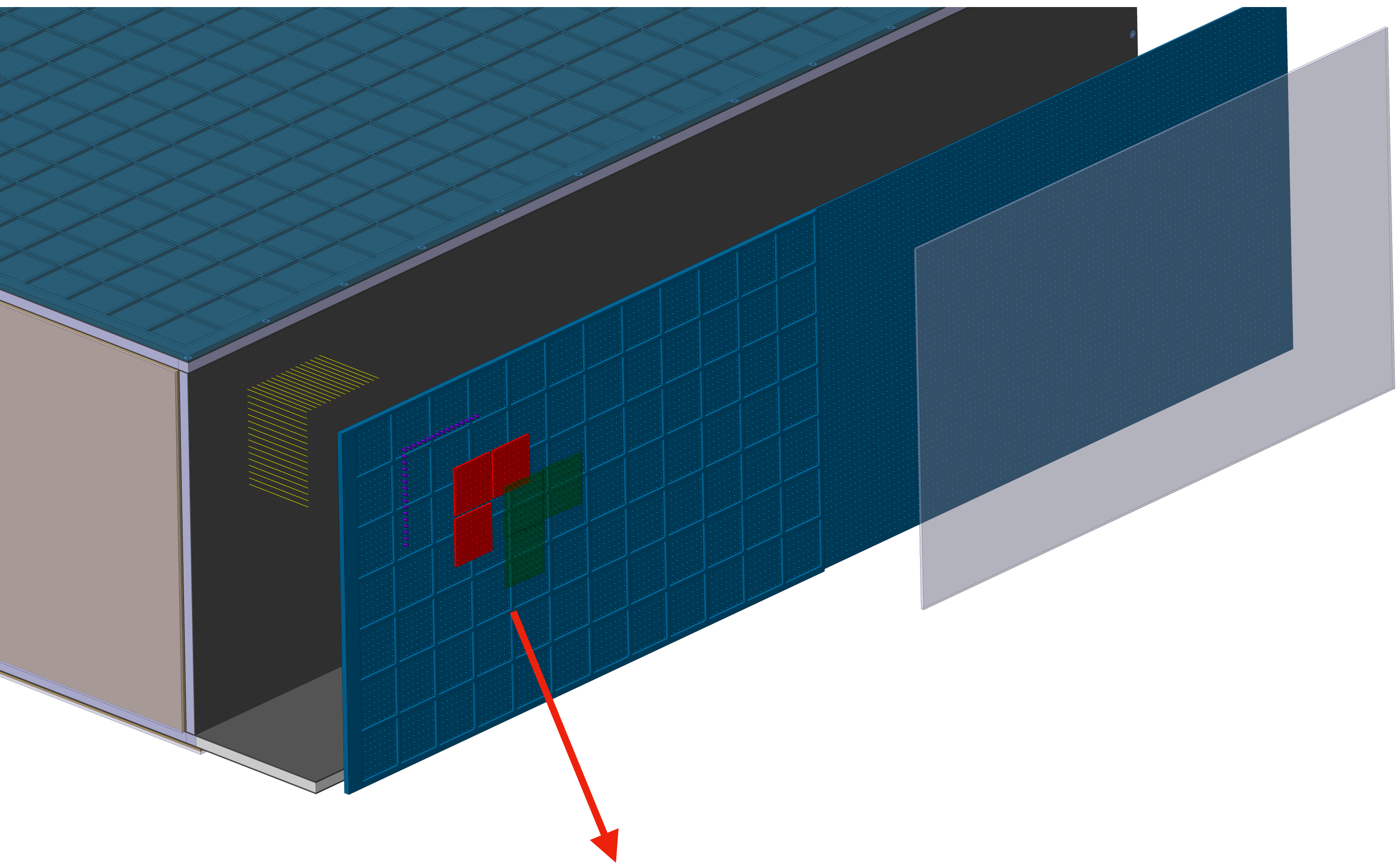
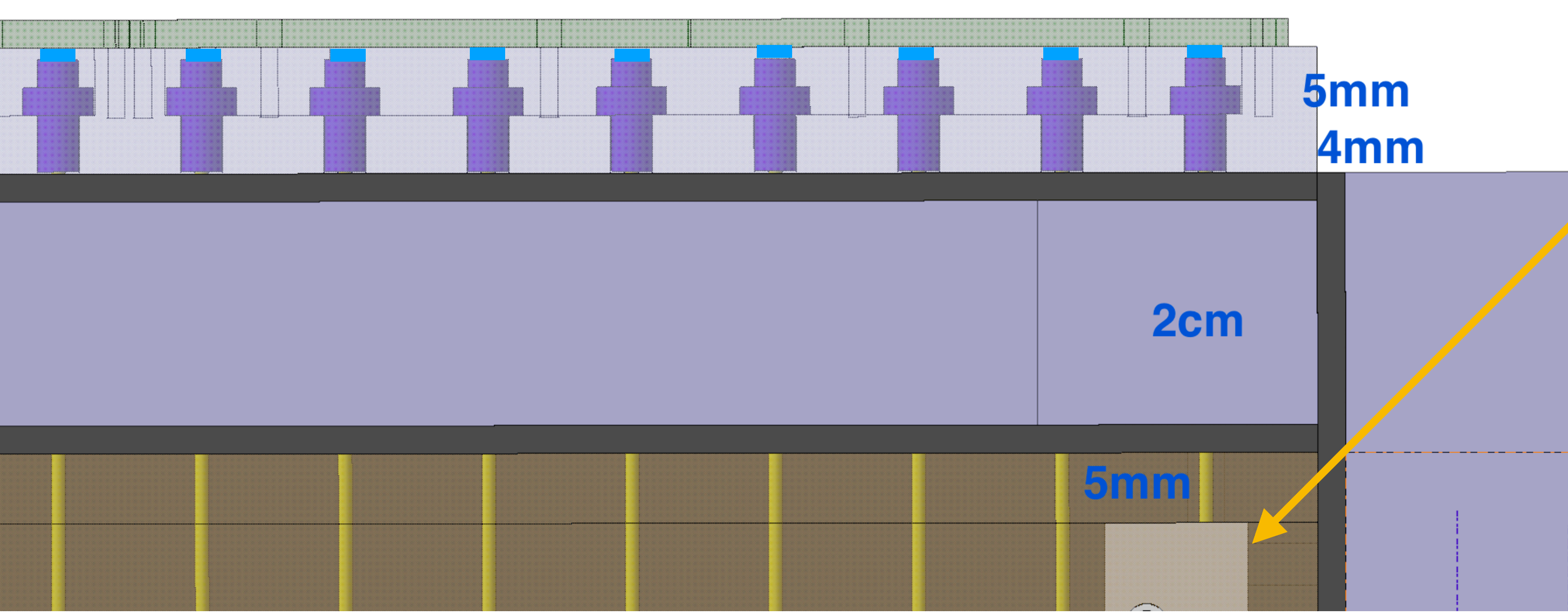
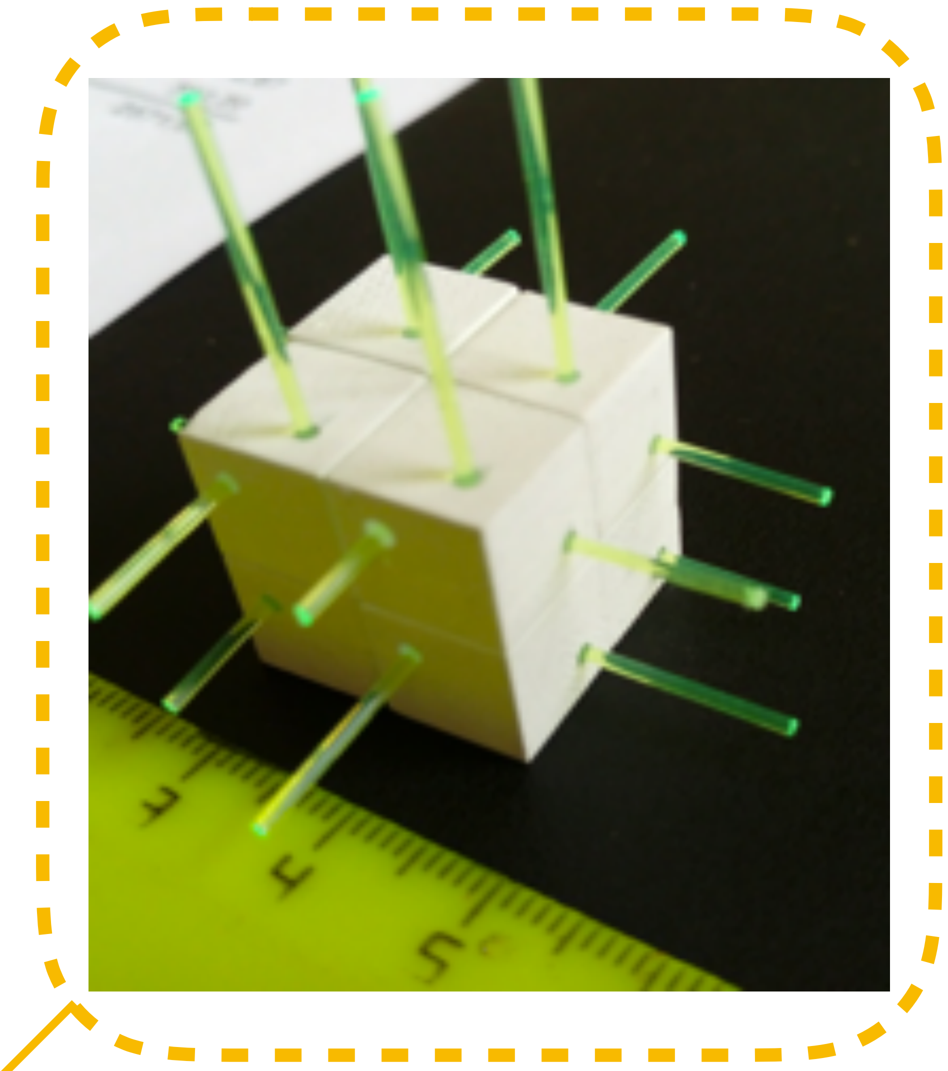
SPSC-P-357
arXiv:1901.03750

The 3DST design

The design is based on the R&D performed for the T2K SuperFGD detector







Cubes assembly methods developed and tested for few-million cubes. Other methods being studied

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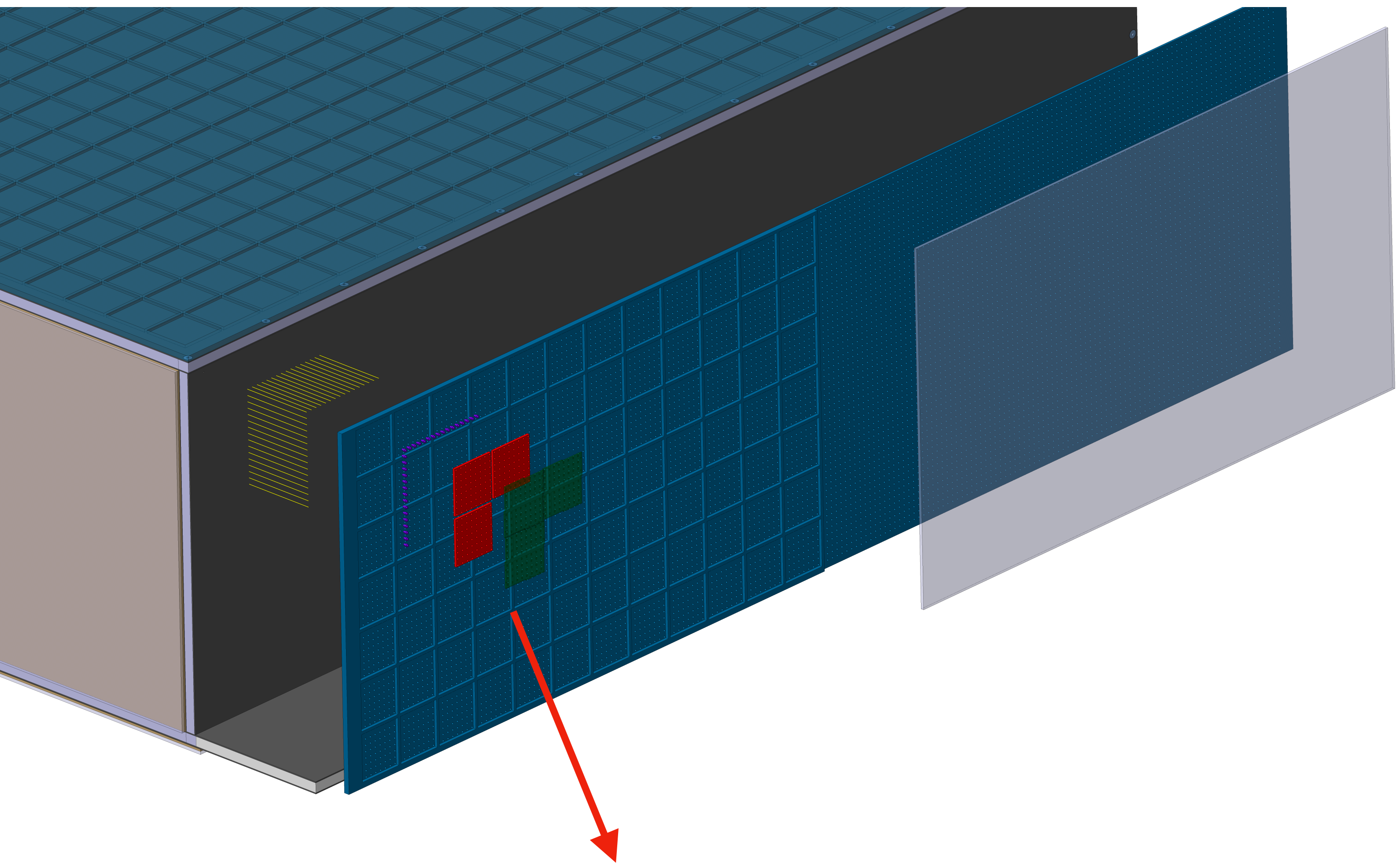

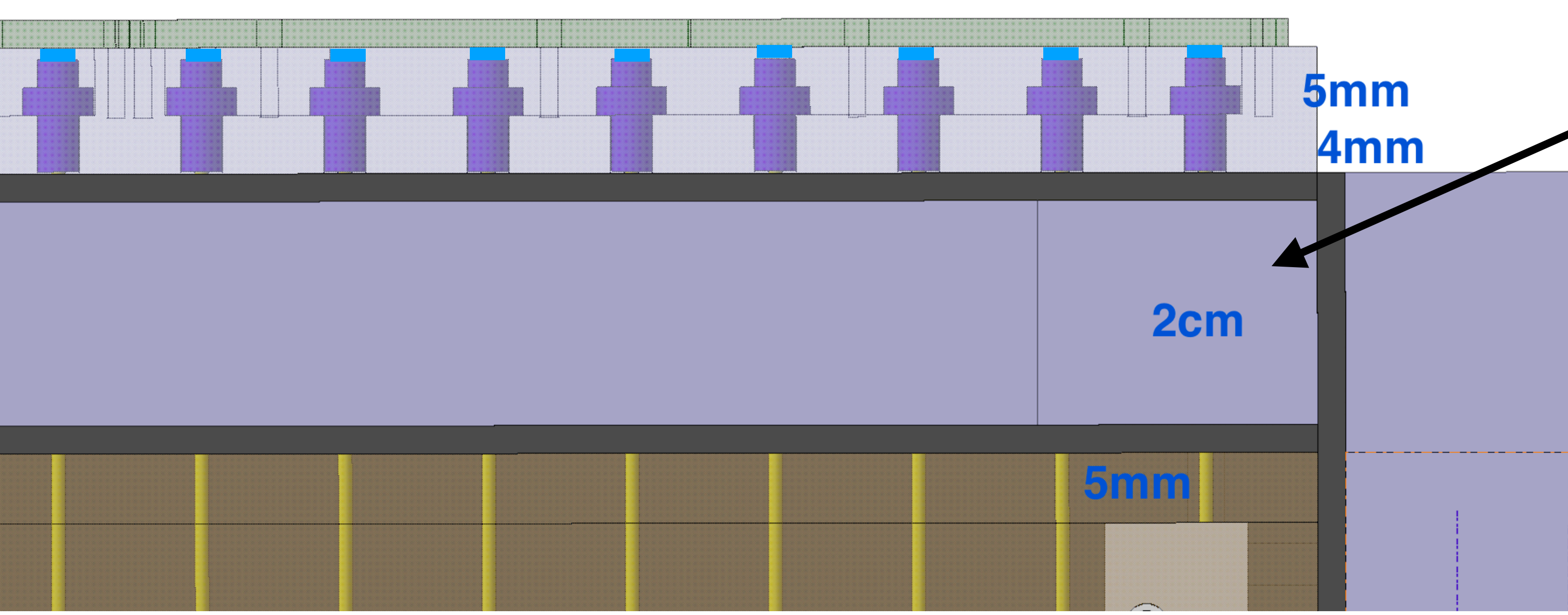

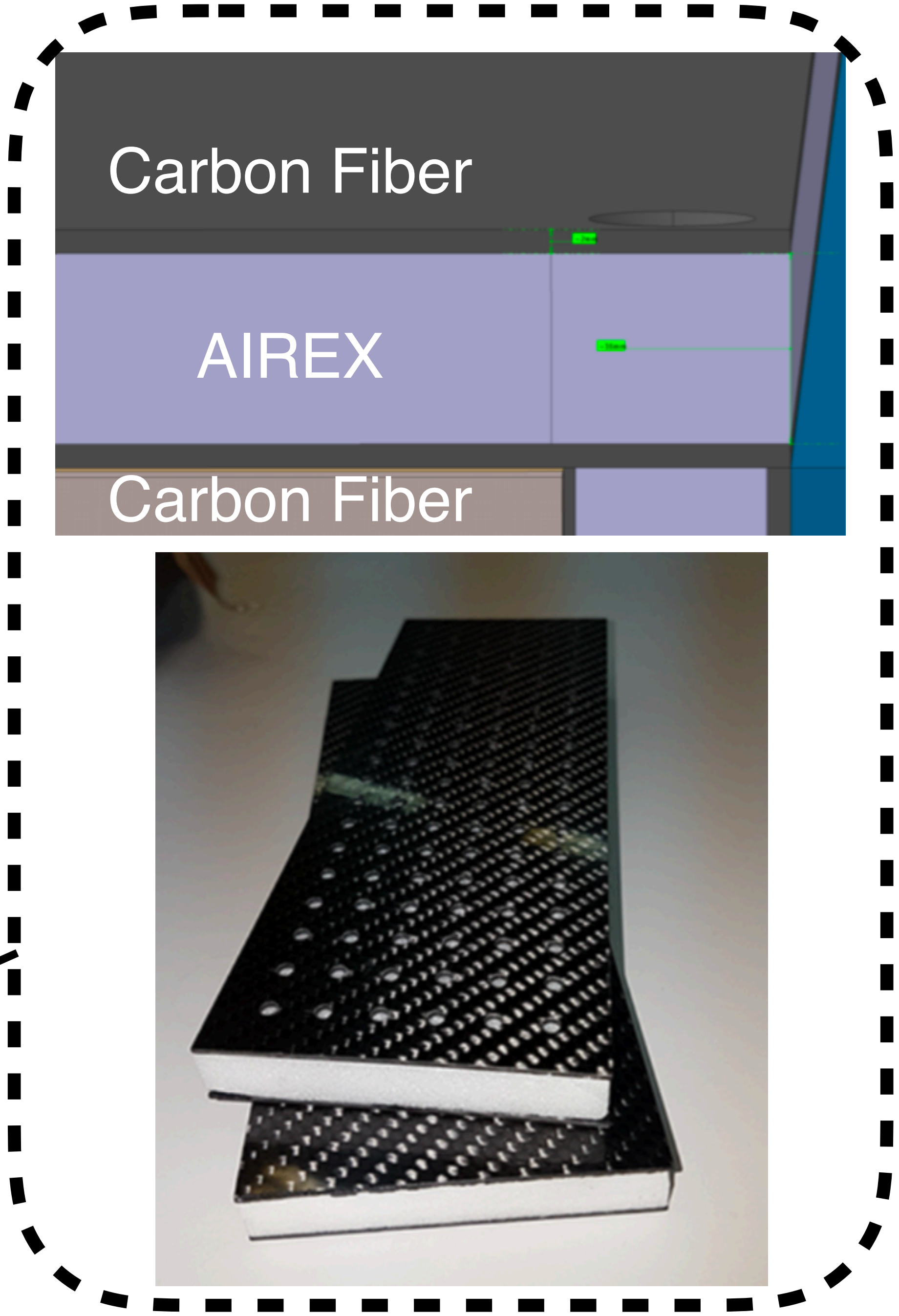

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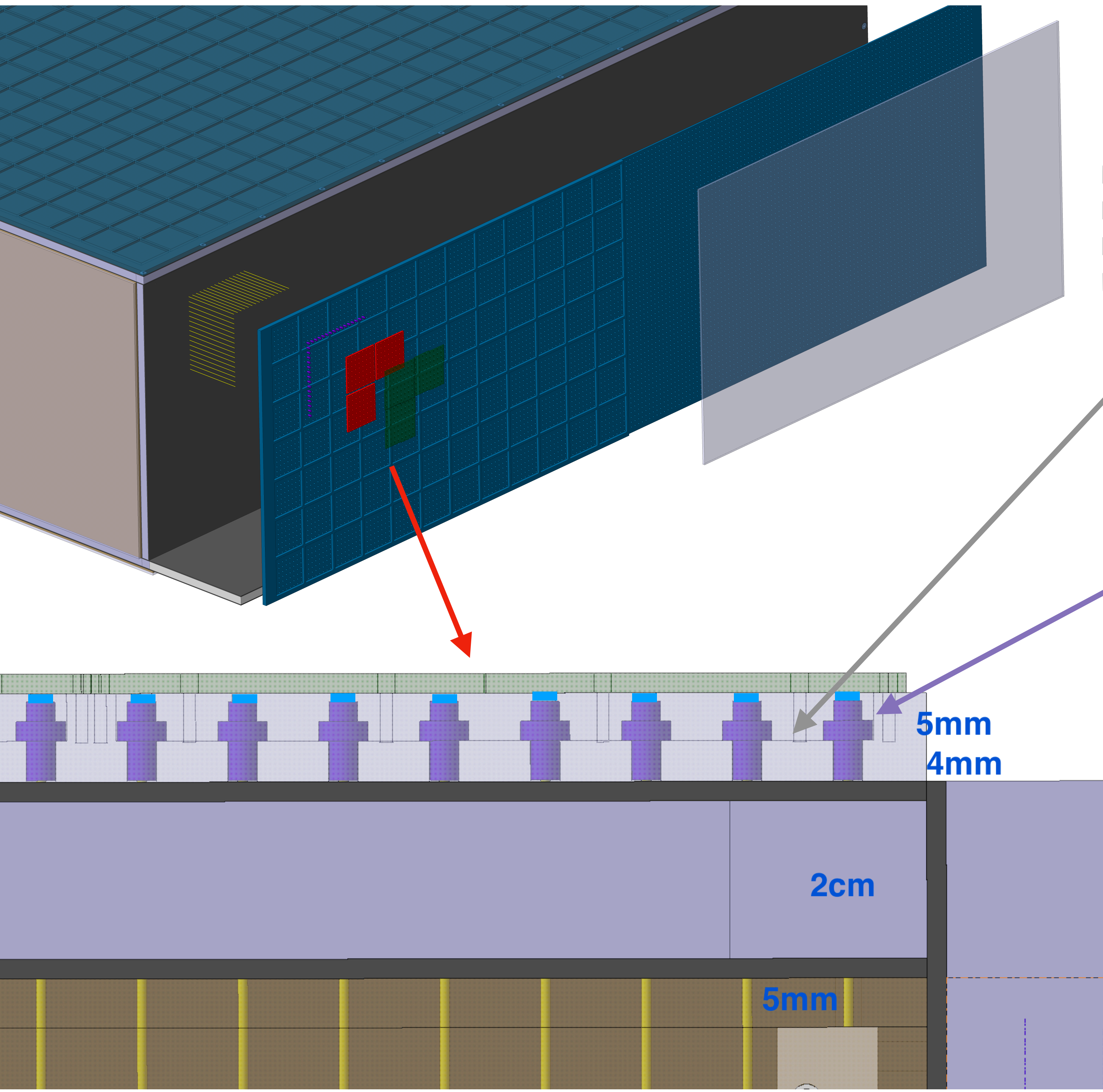
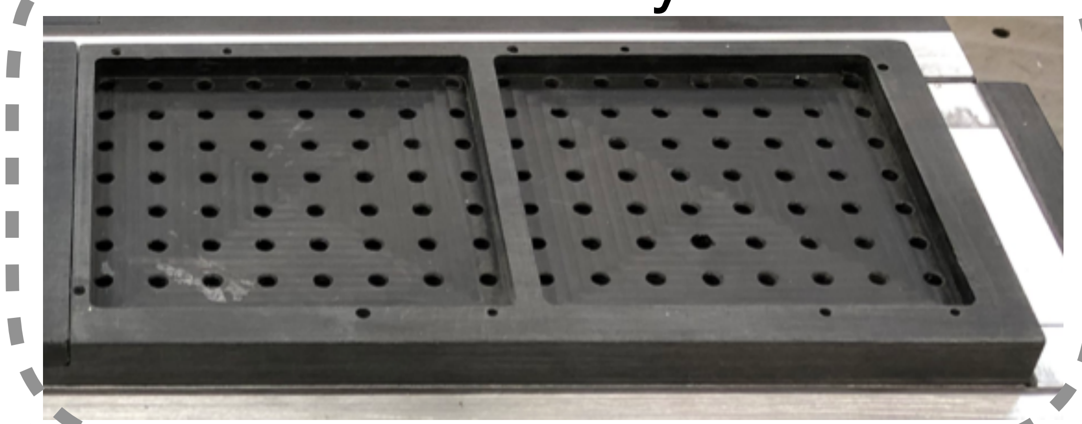
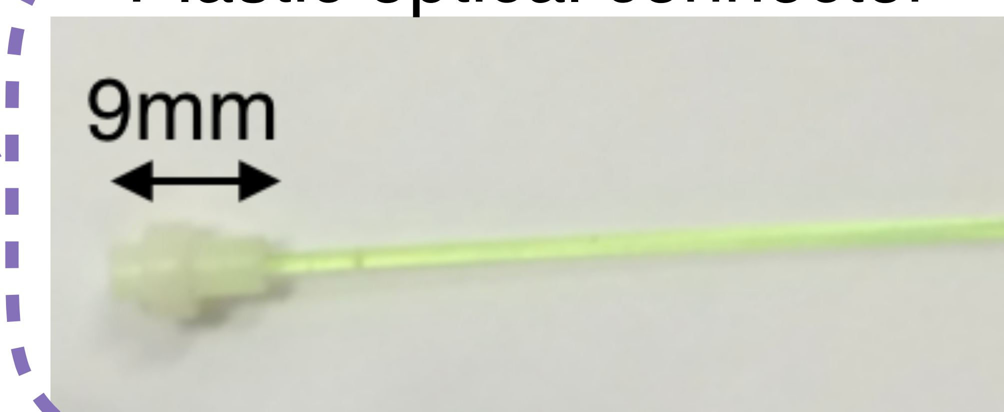


Plastic layer



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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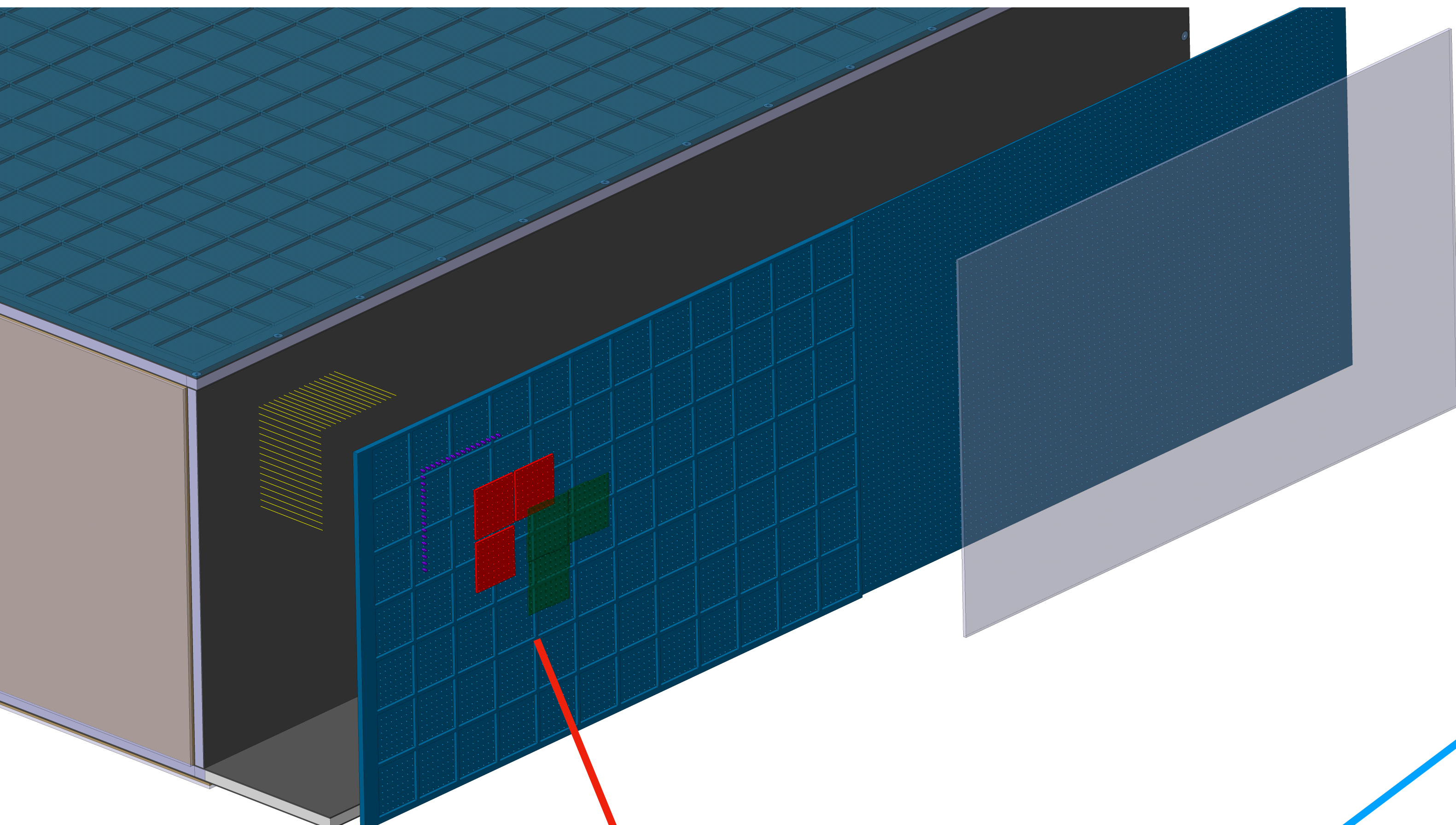

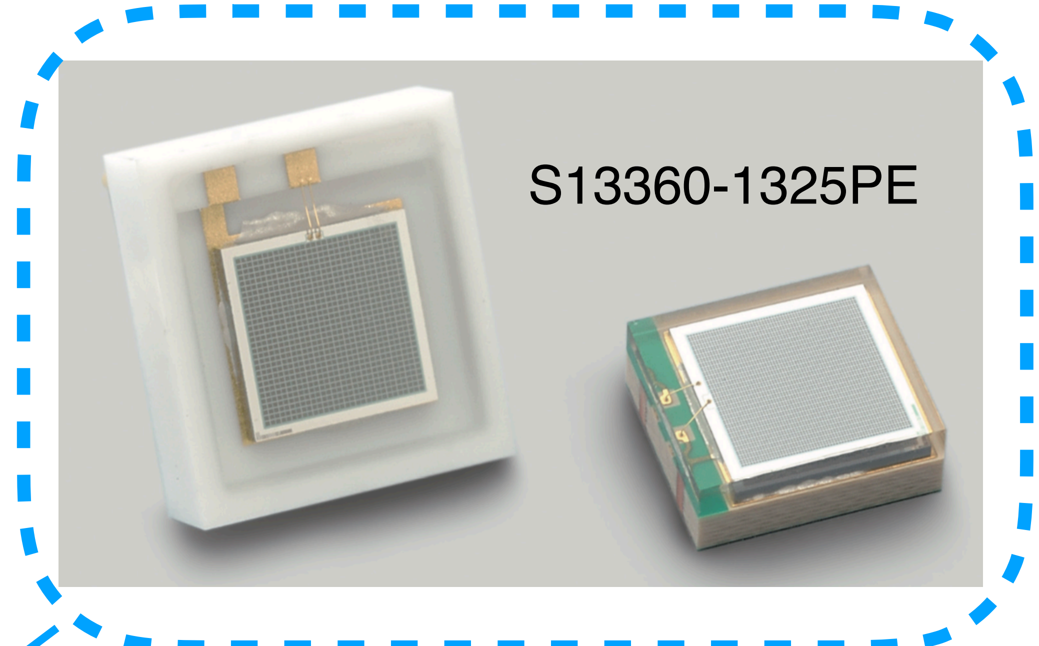

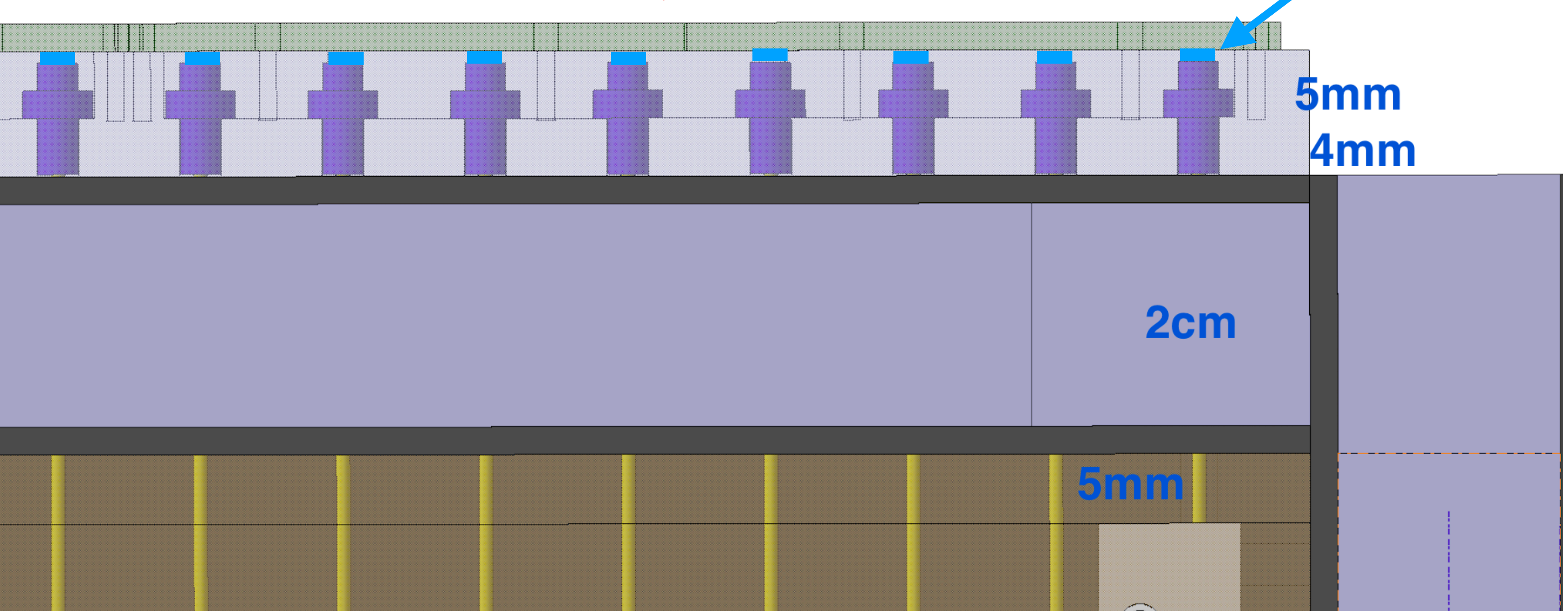

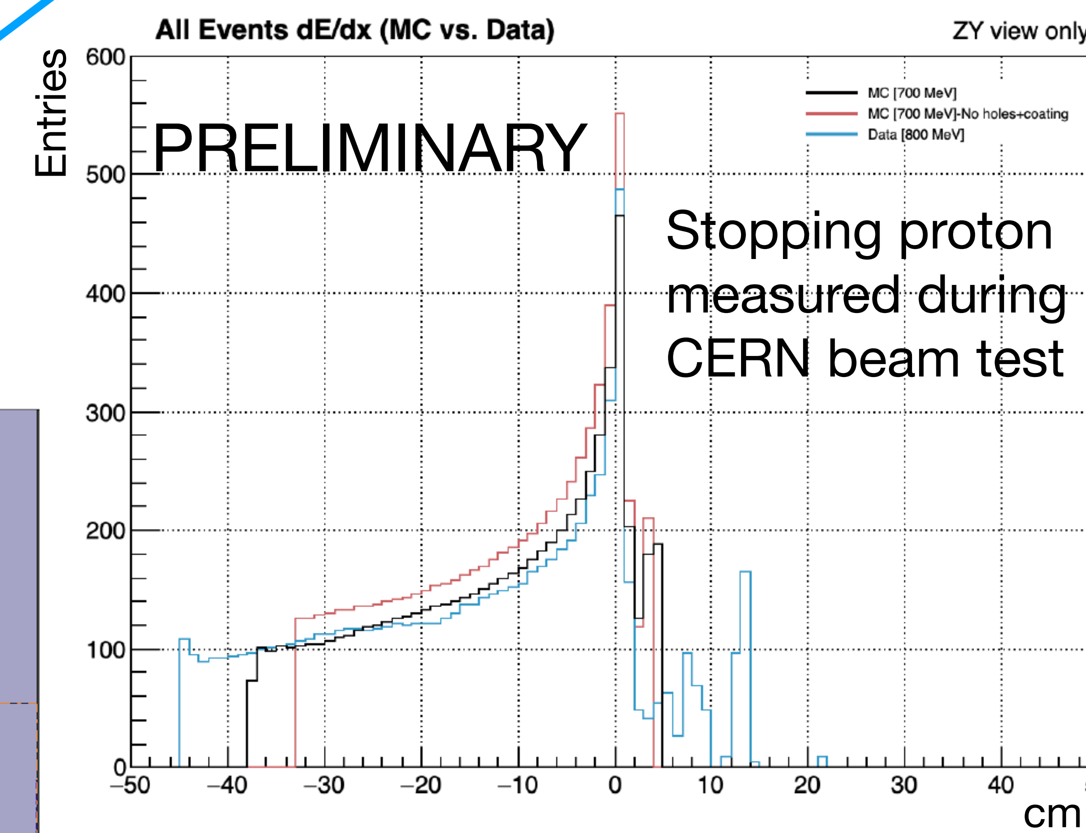

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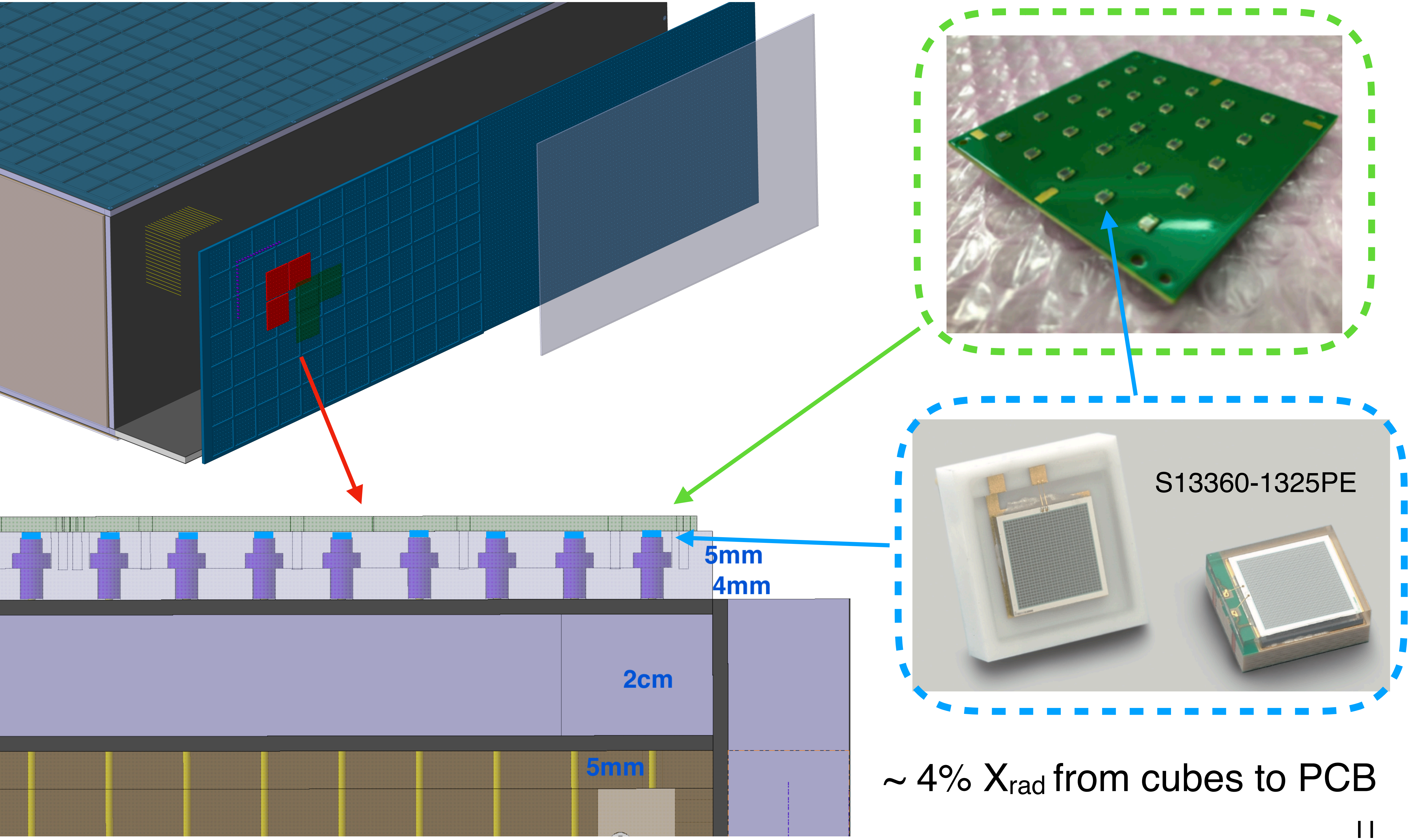
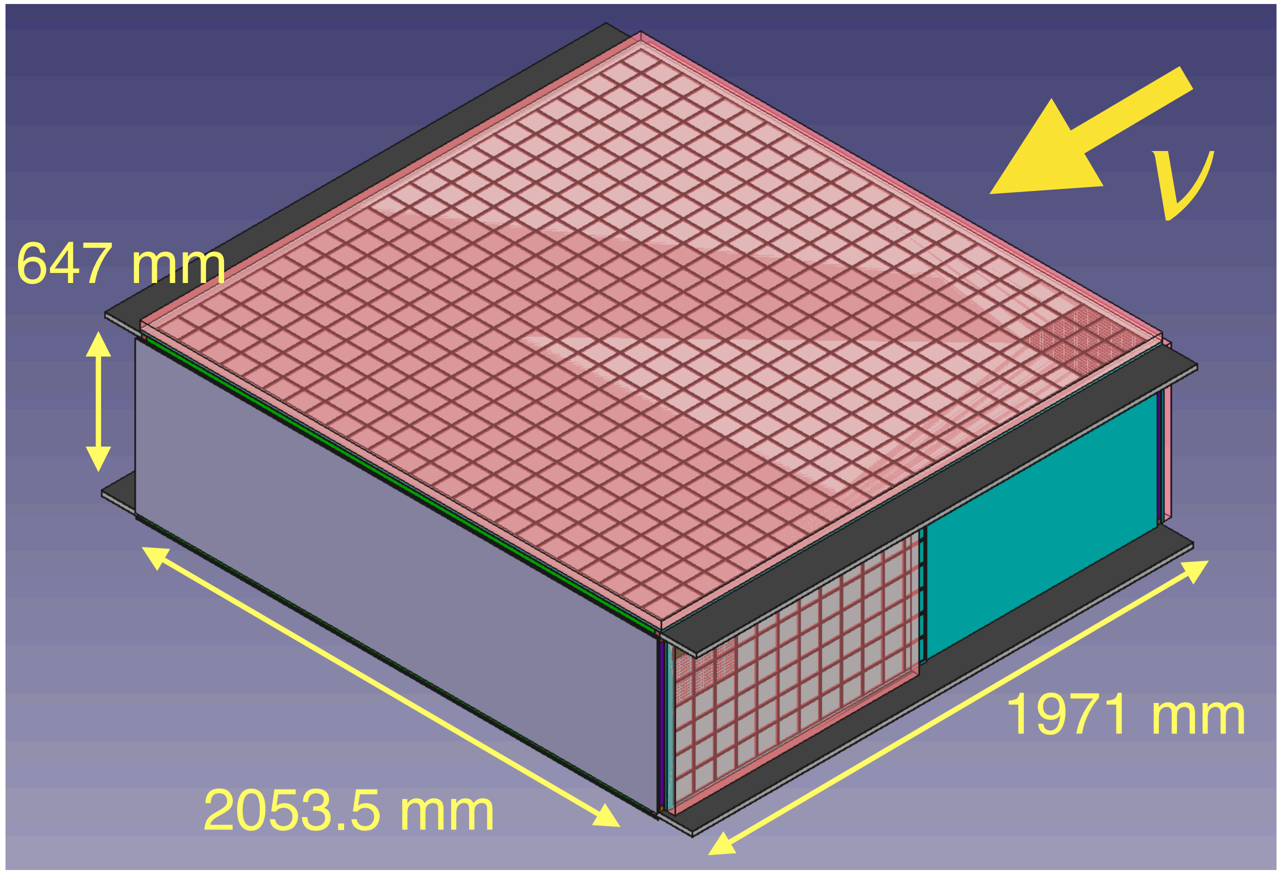
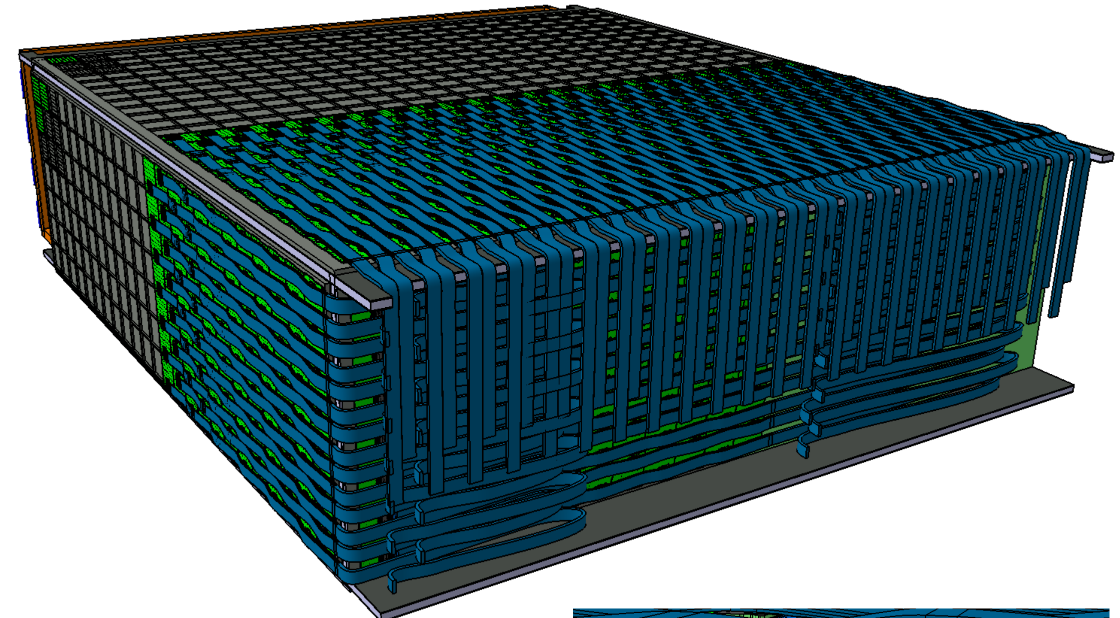
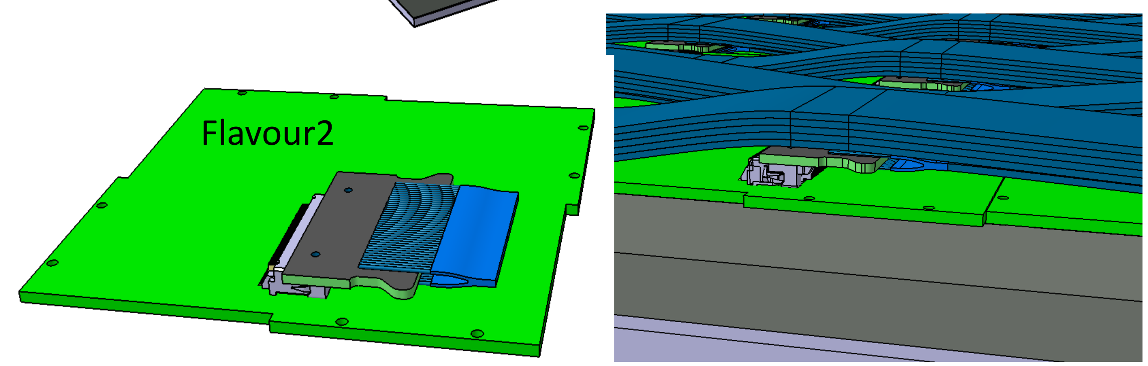


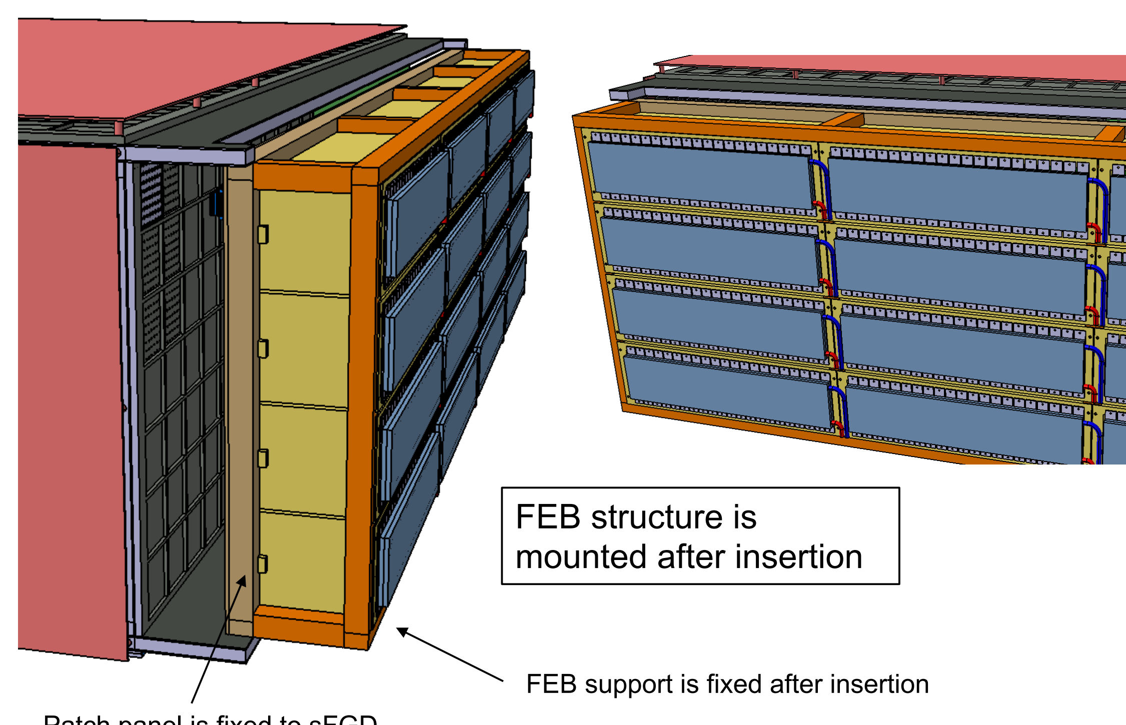
~ 4% X_{rad} from cubes to PCB

Front-End Electronics: example from T2K







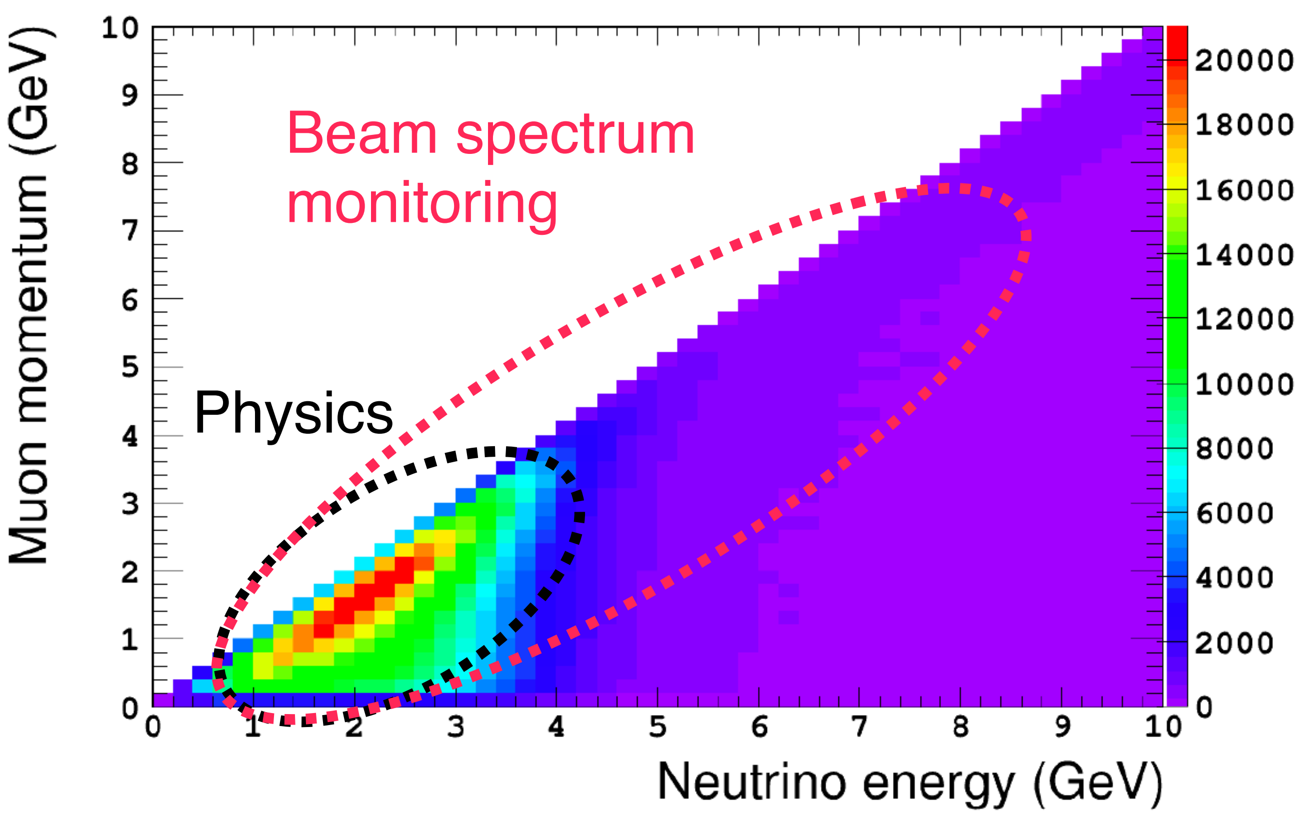


- Based on the CITIROC chip
- Measure highest peak point of the MPPC charge signal. Low/High gain mode, sensitive to both MIPs and stopping protons
- FPGA provides the timestamp with 400 MHz sampling rate, complementary measurement of the charge by Time-over-Threshold
- Another possible option is FEE on the detector, e.g. on back side of MPPC-PCB (much more compact)

The requirements for the Gas Tracker and B-field

•The gas tracker is required to measure muons at 1-3 GeV/c for physics and higher energy important for beam spectrum monitoring (see later) and low-momentum pions and protons exiting 3DST

•Considering the TPCs developed for the T2K ND upgrade and B-field of 0.6 T



•Current T2K TPCs have dp/p~10% at 1 GeV/c (if better is dominated by p_{Fermi})

•Thanks to Resistive MicroMegas, new T2K TPCs have d_{xy} ~ factor 2 better

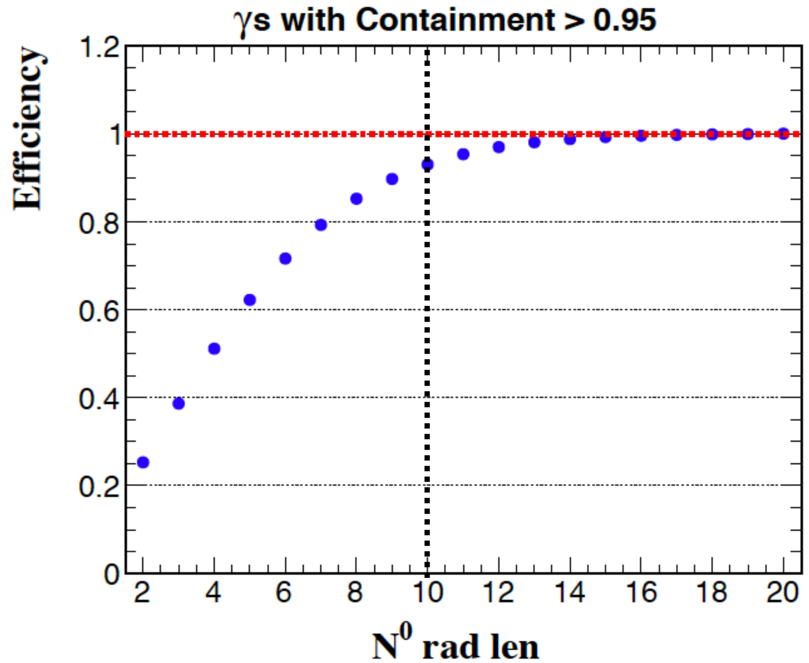
$$\frac{\delta p_T}{p_T} \sim 10\% \frac{p_T(\mathrm{GeV})}{6}$$ (B-field=0.6T)

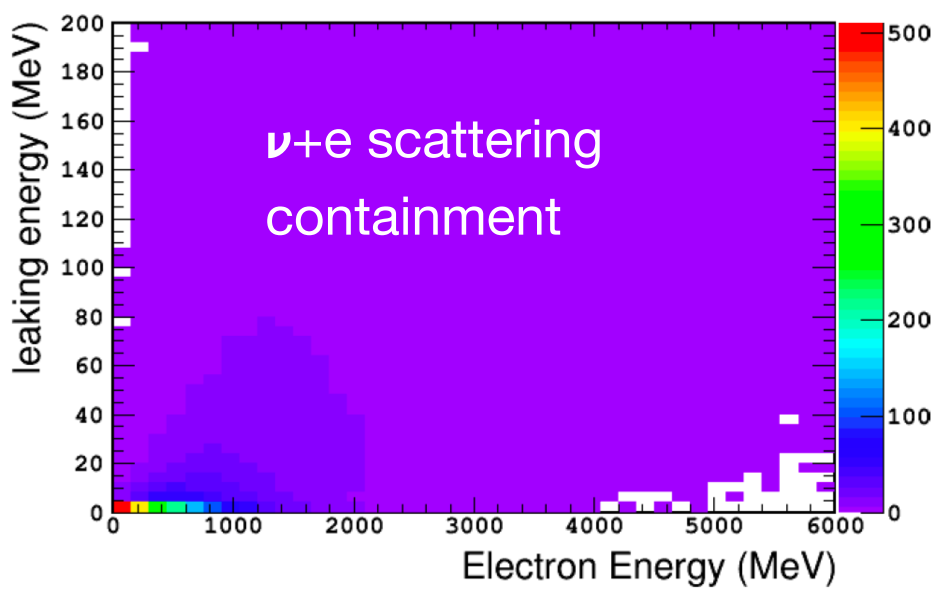
The T2K TPCs are developed by CEA/ Saclay, CERN (Resistive MicroMegas), U.Padova and IFAE (Field Cage)

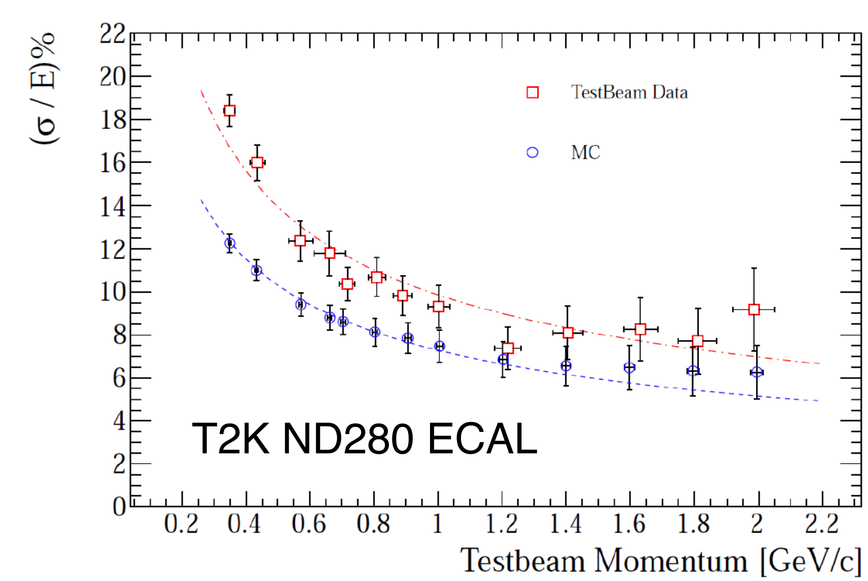
Parameter	Value
Overall x × y × z (m)	2.0 × 0.8 × 1.8
Drift distance (cm)	90
Magnetic Field (T)	0.2
Electric field (V/cm)	275
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2
Drift Velocity $cm/\mu s$	7.8
Transverse diffusion ($\mu m/\sqrt{cm}$)	265
Micromegas gain	1000
Micromegas dim. z×y (mm)	340 × 410
Pad z × y (mm)	10 × 11
N pads	36864
el. noise (ENC)	800
S/N	100
Sampling frequency (MHz)	25
N time samples	511

The requirements for the ECAL

- The ECAL must contain the shower produced by photons from neutrino interactions, electrons from ν+e scattering, electrons from ν_e interactions
  - ✦ At least 10 X_{rad} are necessary
- Energy resolution better than 10% for EM showers (like T2K ND ECAL)
- Angular resolution ~1 degree or better for ν+e scattering
- Good time resolution to
  - ✦ Identify 3DST in-going photons (bkg)
  - ✦ Separate e/μ above 1GeV/c



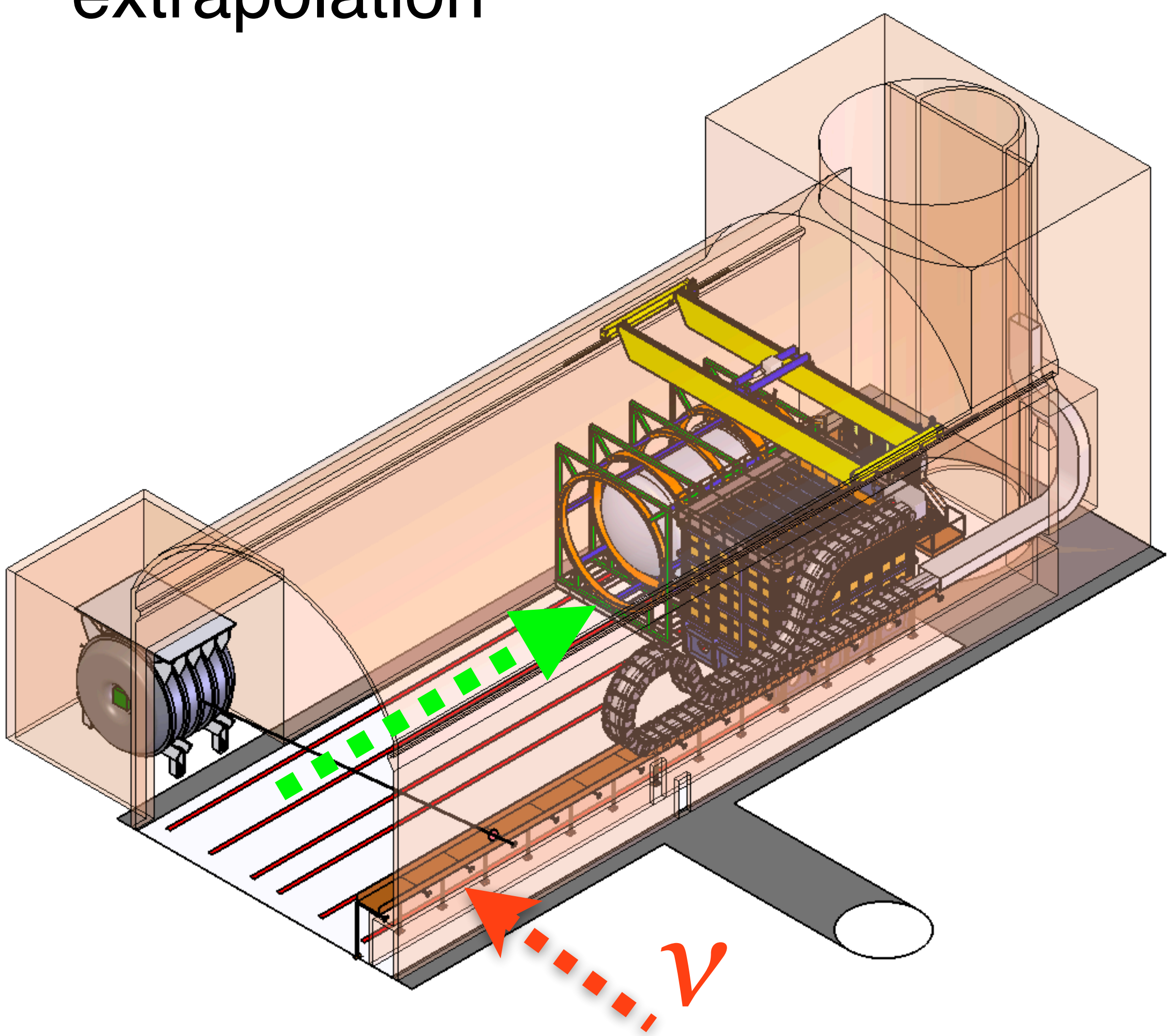


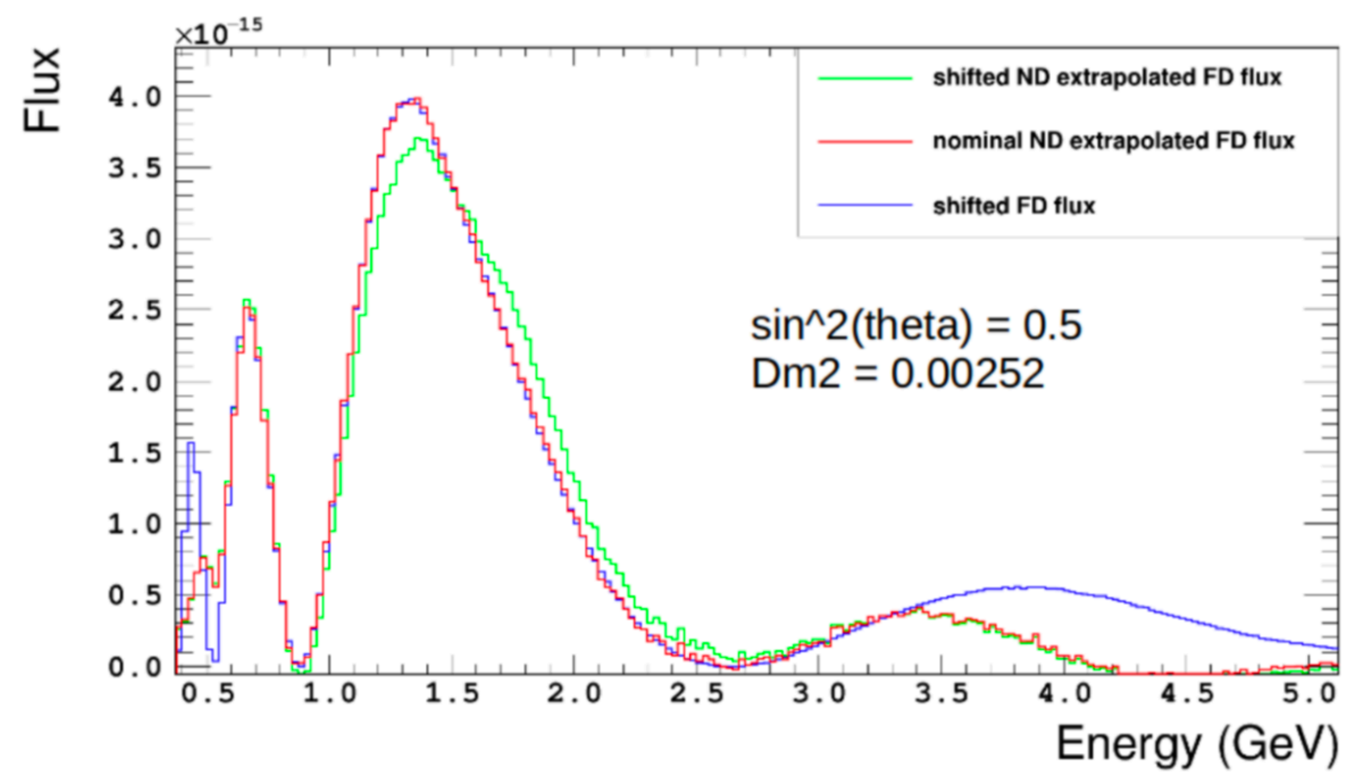


Beam Monitoring

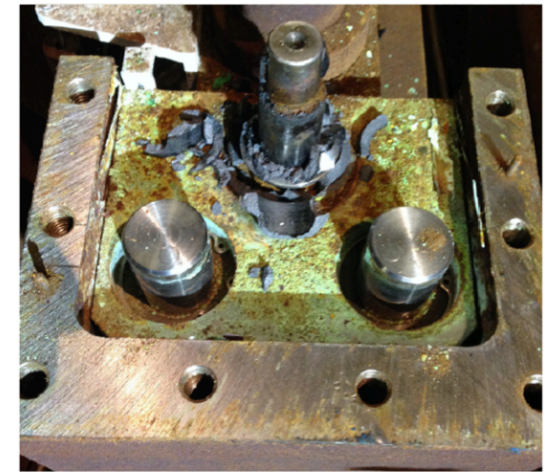
Importance of beam monitoring with DUNE-PRISM

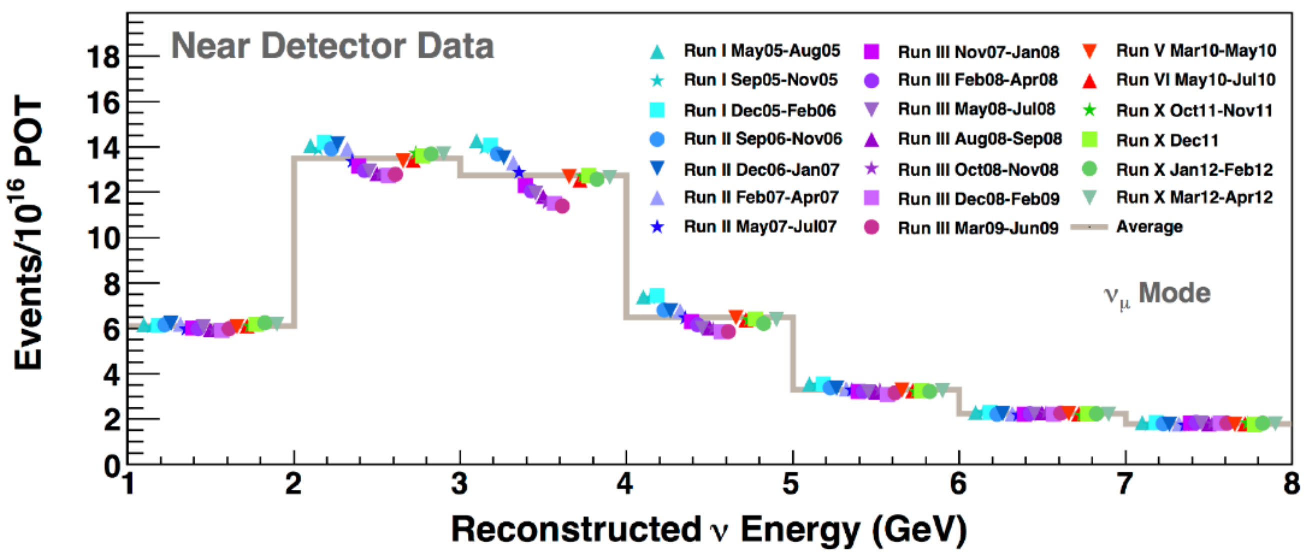
- DUNE ND conceptual baseline includes three main detector systems:
  - ✦ LAr, High-Pressure TPC and 3DST spectrometer
  - ✦ LAr and HP-TPC will move off-axis (range of ~30 m)
  - ✦ 3DST spectrometer will be the only on-axis detector
- The PRISM relies on a good knowledge of the flux
- Undetected problems in the beamline would result in a wrong ND—>FD extrapolation

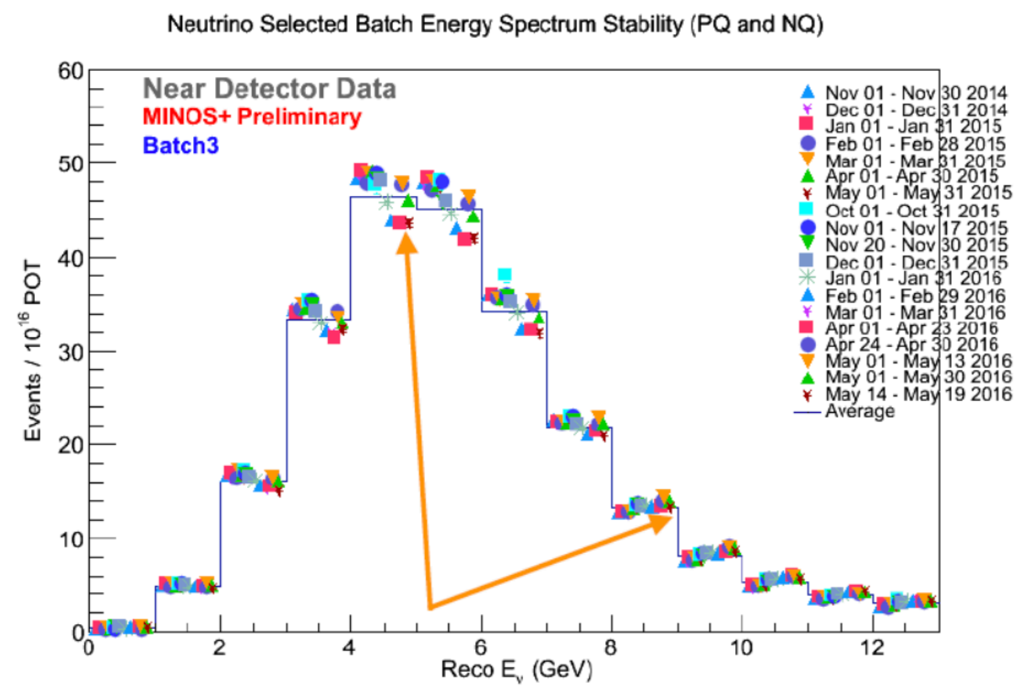




The importance of beam monitoring for PRISM





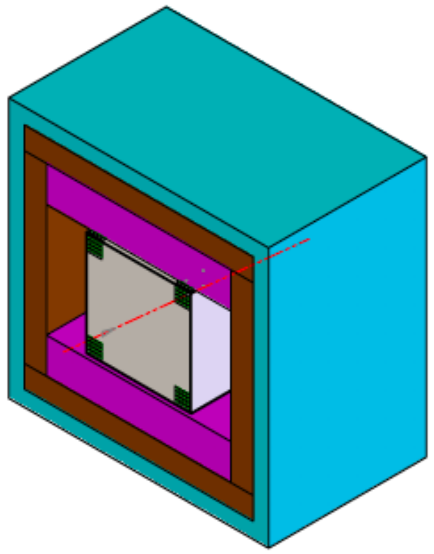


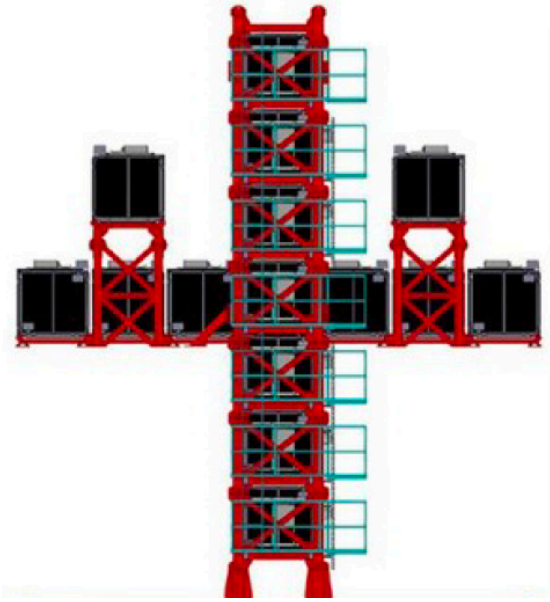
- MINOS ND found problems by looking at the time-dependent variation of the neutrino reconstructed energy spectrum
- NOvA (off-axis) didn't observe significative changes

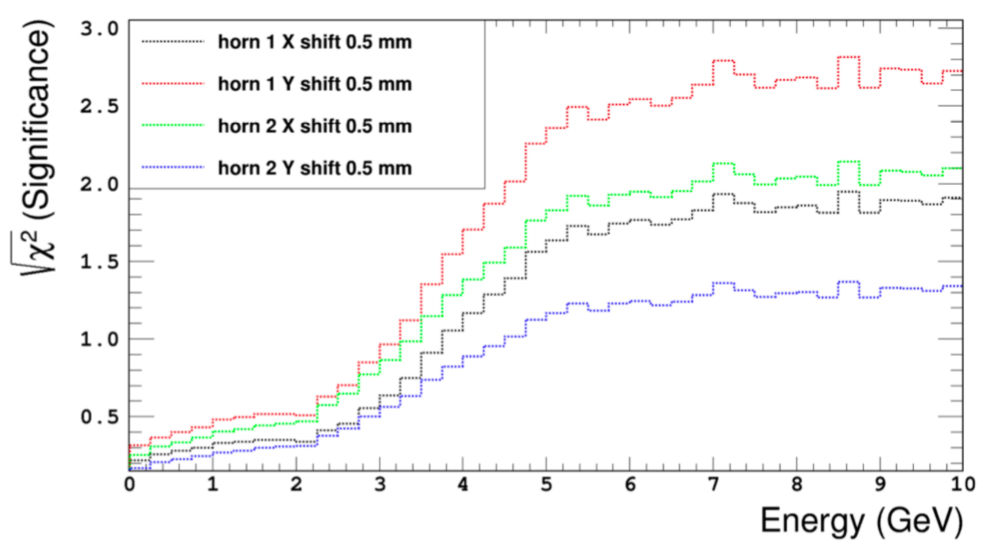
- Critical if we measure the CP phase by observing a spectrum distortion

Beam monitoring with 3DST-S

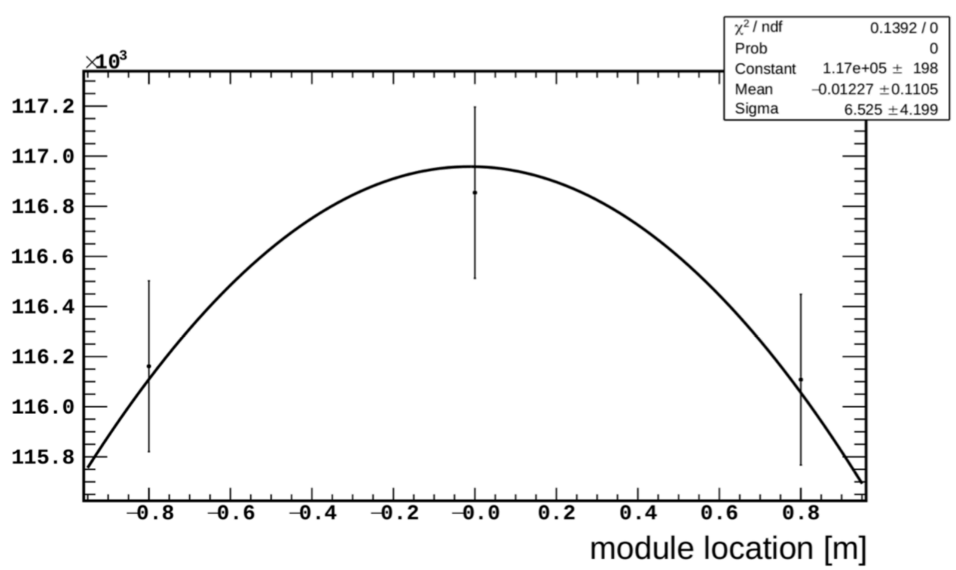
- 3DST-S can detect issues in the beamline very efficiently by measuring the muon spectrum
- Compared with four 7-ton modules that measure the rate at 0,1,2,3 meters from the on-axis position (28 ton in total)







	Significance, $\sqrt{\chi^2}$	
Changed beam parameter	Rate-only monitor	3DST-S
proton target density	1.9	7.8
proton beam width	3.0	6.6
proton beam offset x	0.7	20.0
proton beam theta phi	0.2	12.5
horn 1 along x	1.9	8.8
horn 2 along x	0.7	12.8
horn 1 along y	0.2	9.9
horn 2 along y	0.4	6.3

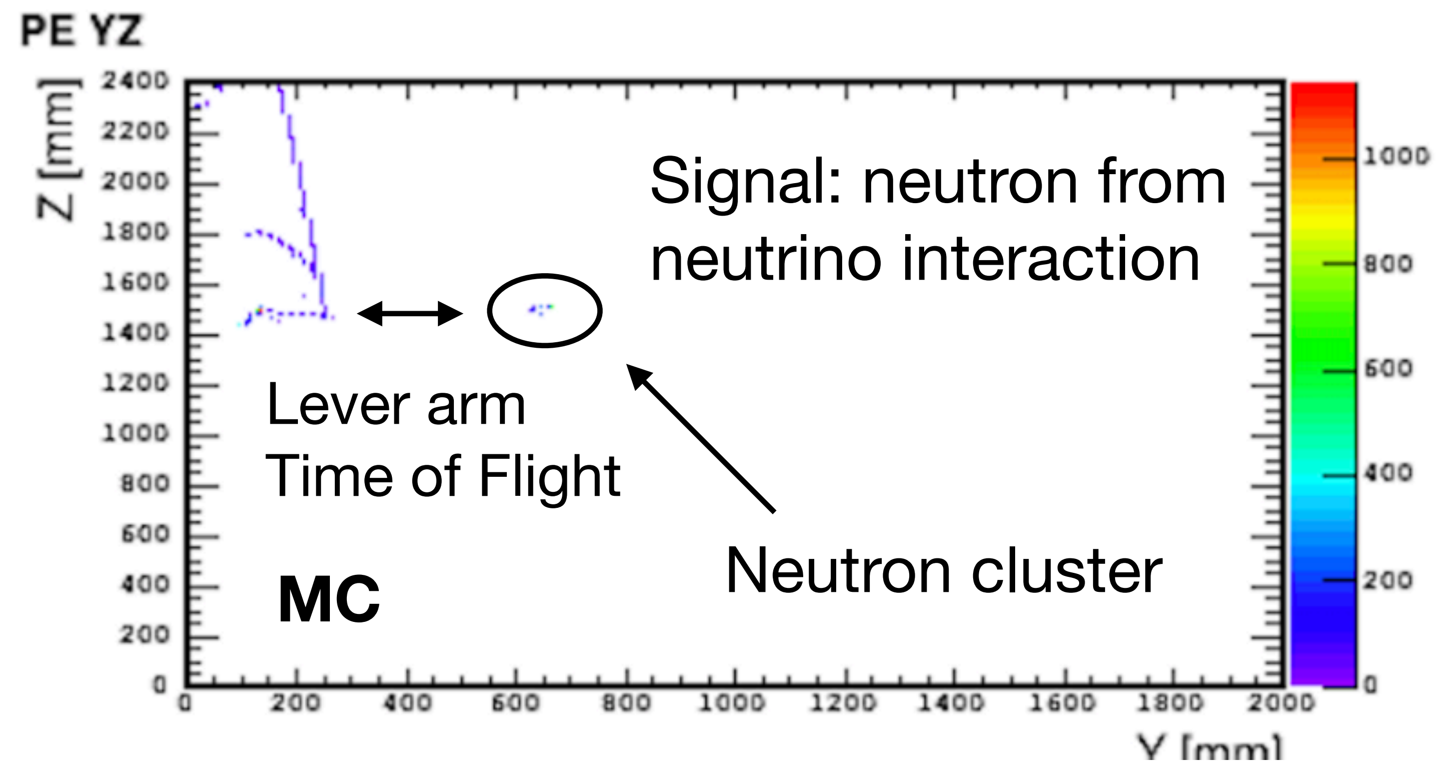


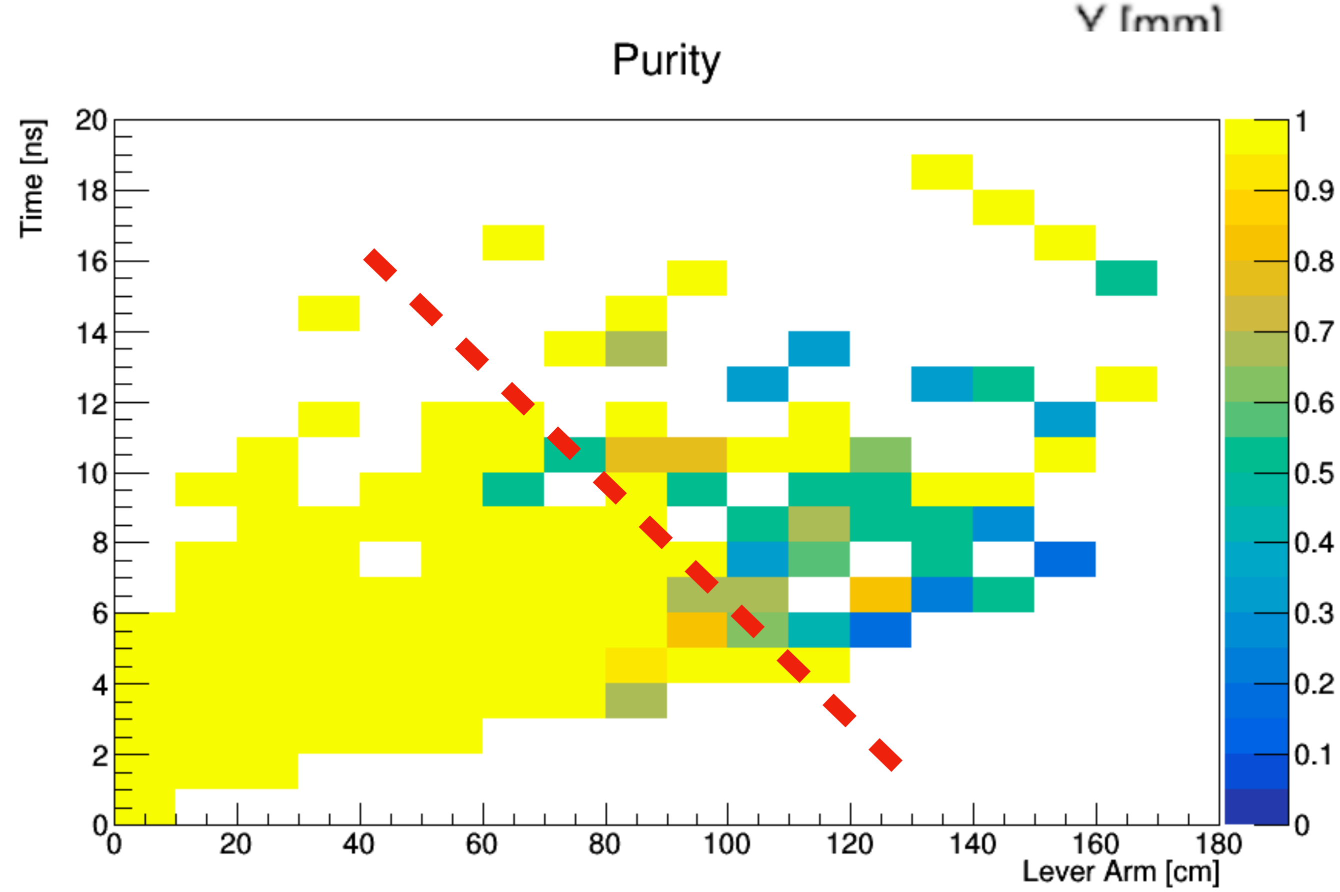
- Using single 3DST module, ~11 cm uncertainty on the beam center can be achieved with 1 week data taking
- See Guang's talk for details

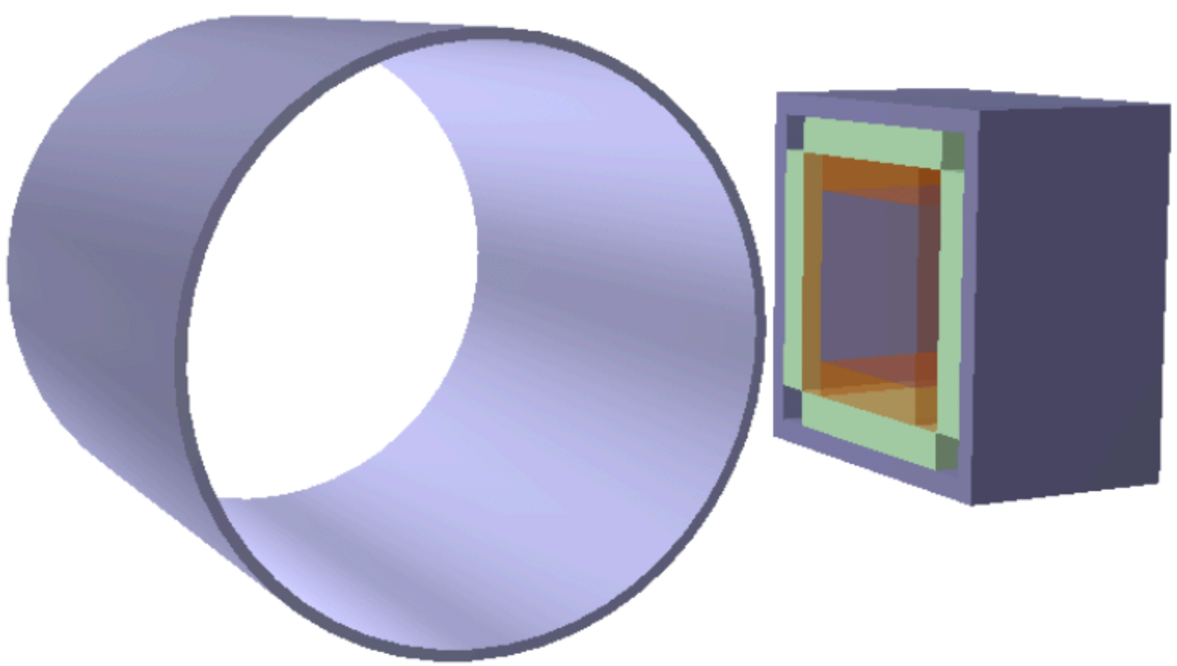
Neutron detection

Neutron detection performance

- Simulated 10k spills (time structure recommended by Beam WG)
- Simulated neutrons produced by neutrino interactions in rock, magnet, ECAL, HpGasTPC
- FV cut —> inner core of 1x1x1 m^3
- Conservatively require deposited energy > 0.5 MeV per cube







- Out-FV neutron bkg can be controlled with ~100% purity
- If purity >90% we obtain ~45% efficiency (E_{dep}>0.5MeV, conservative)

Neutron detection performance

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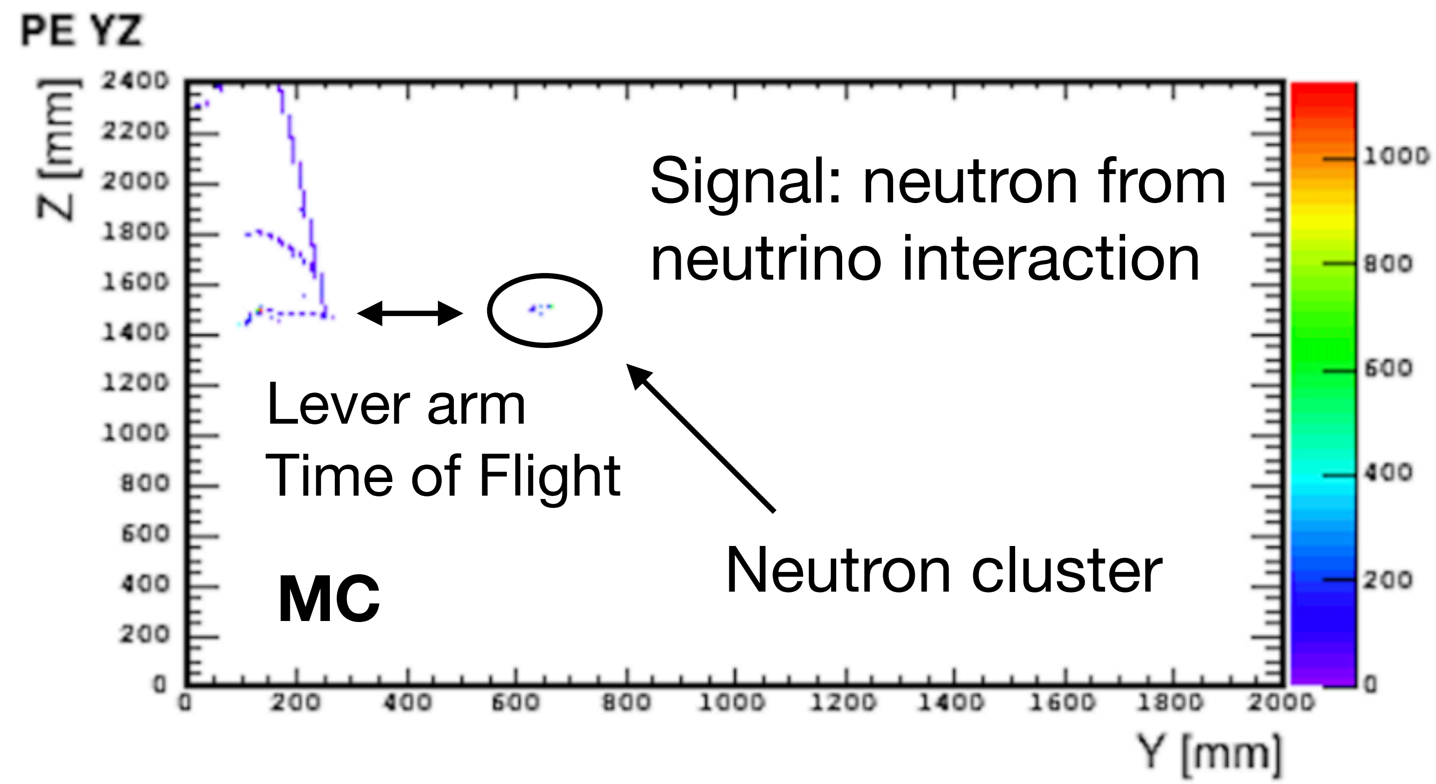
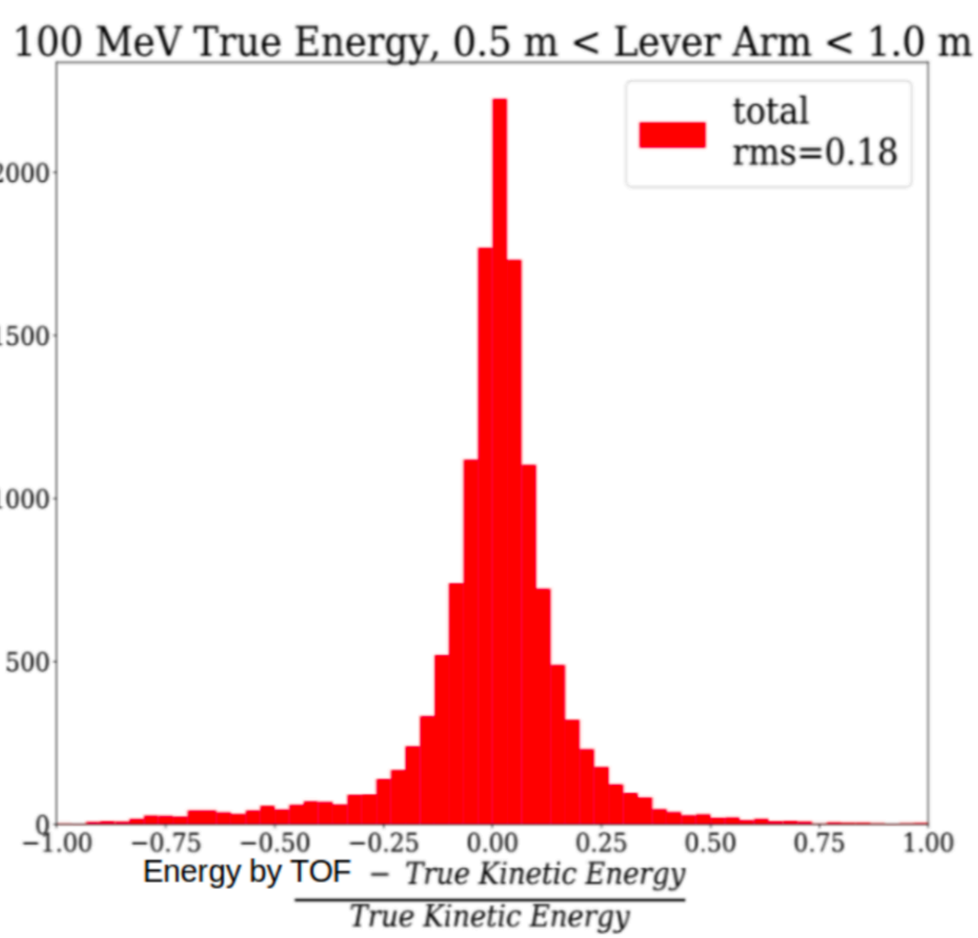
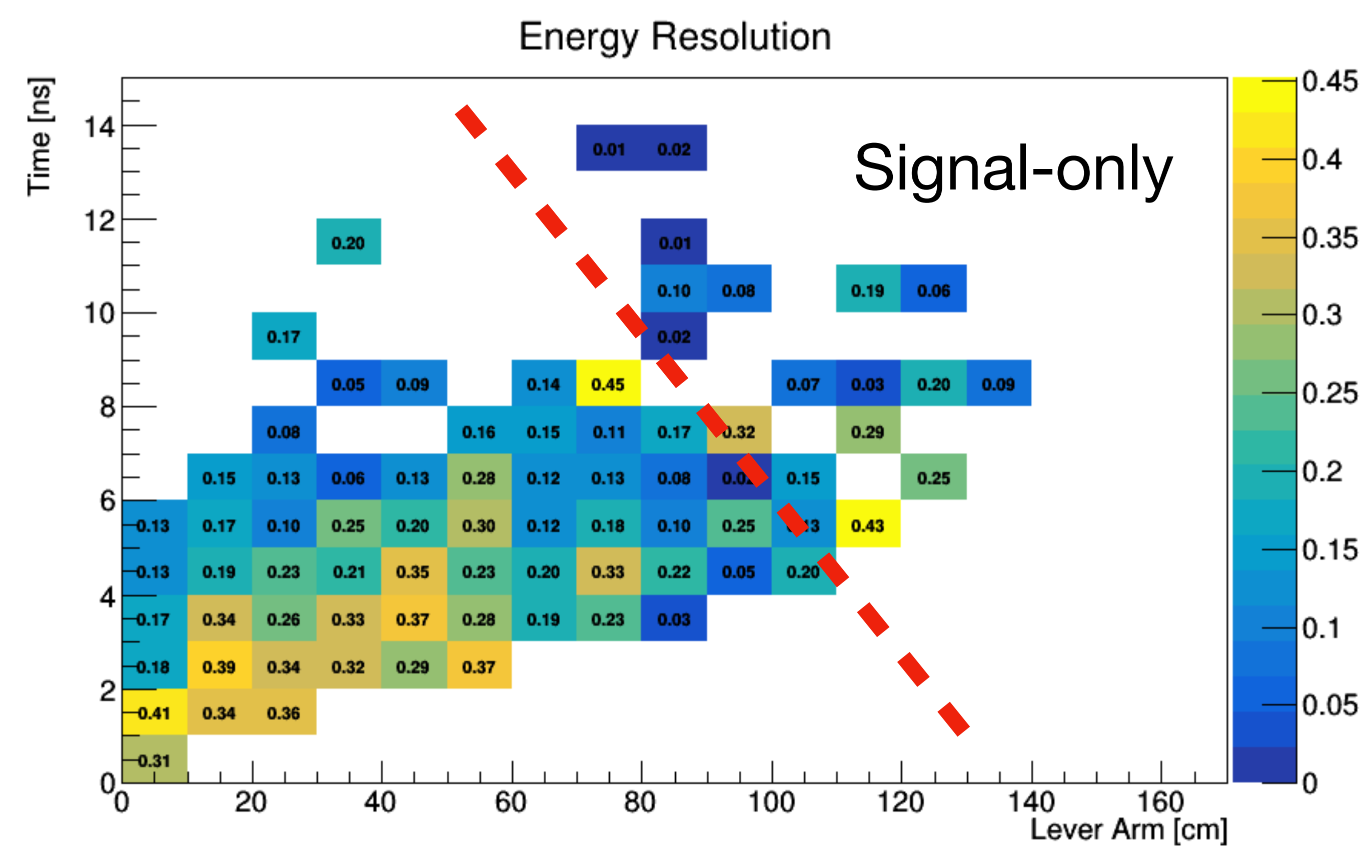


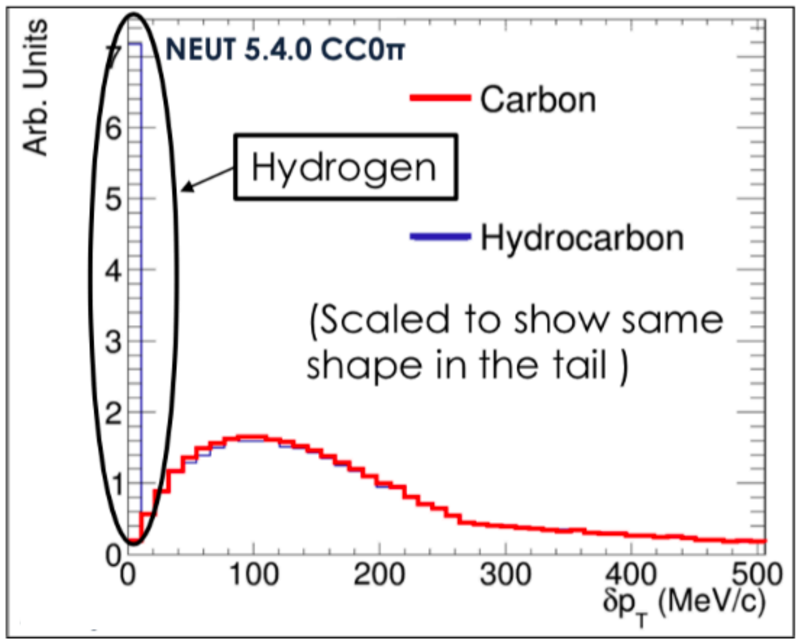




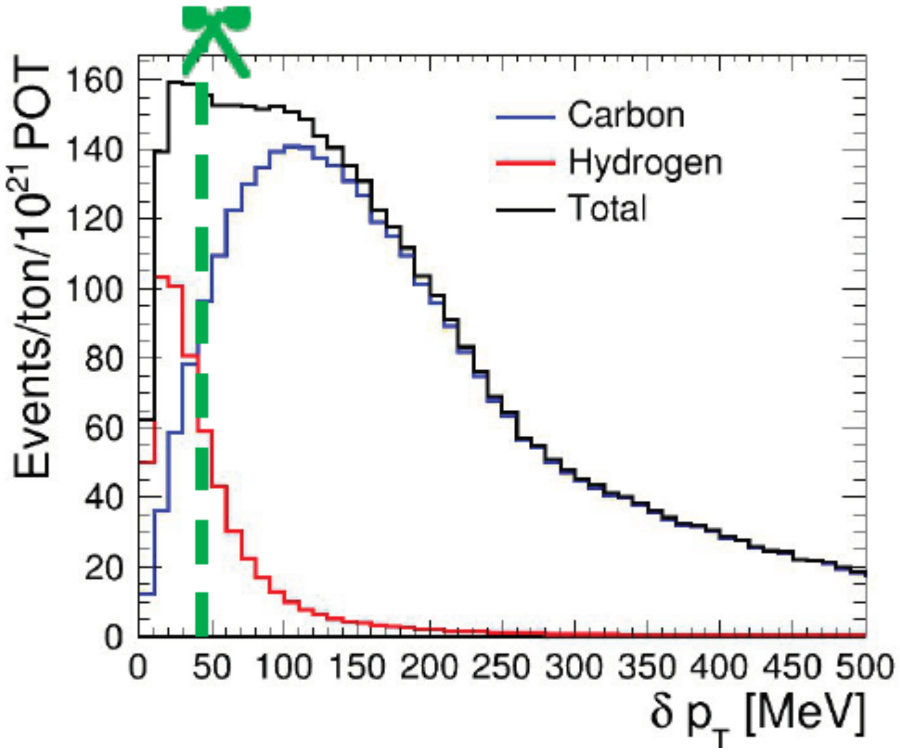
Flux measurement

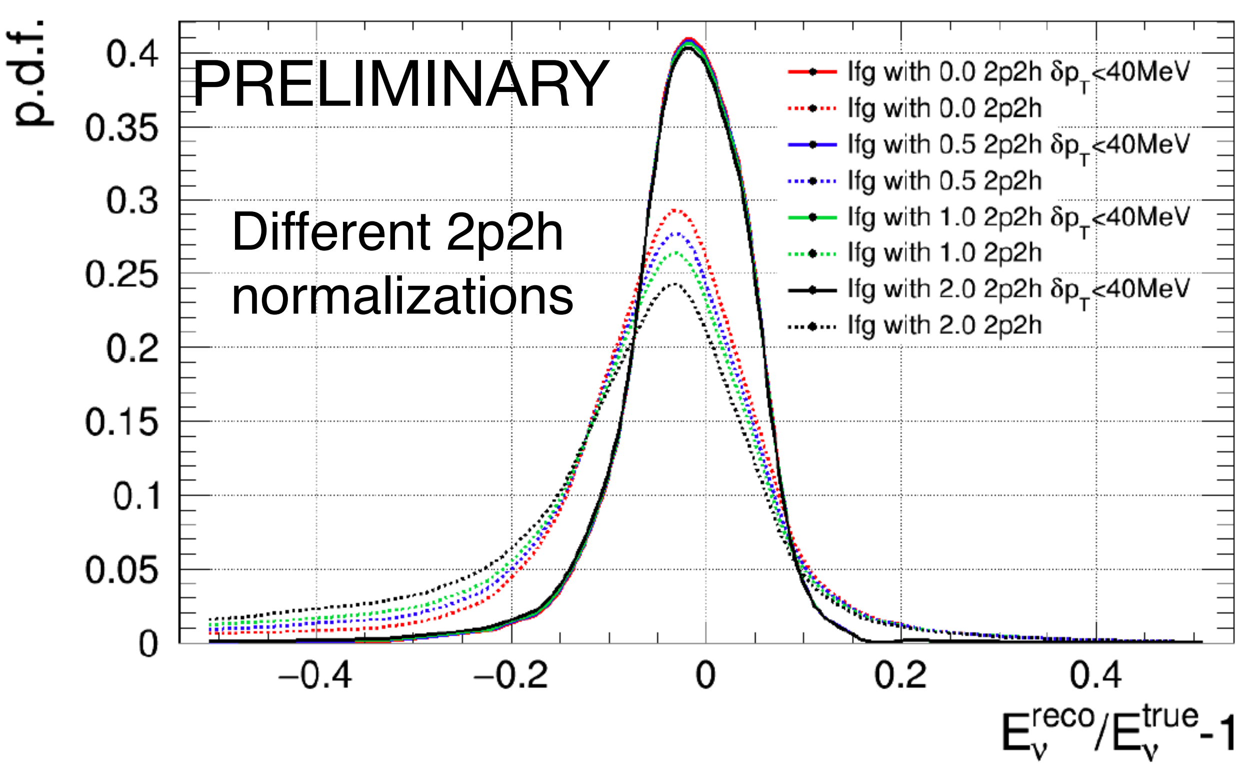
New method to infer $\bar{\nu}_\mu$ flux: the T2K case

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



Detector smearing

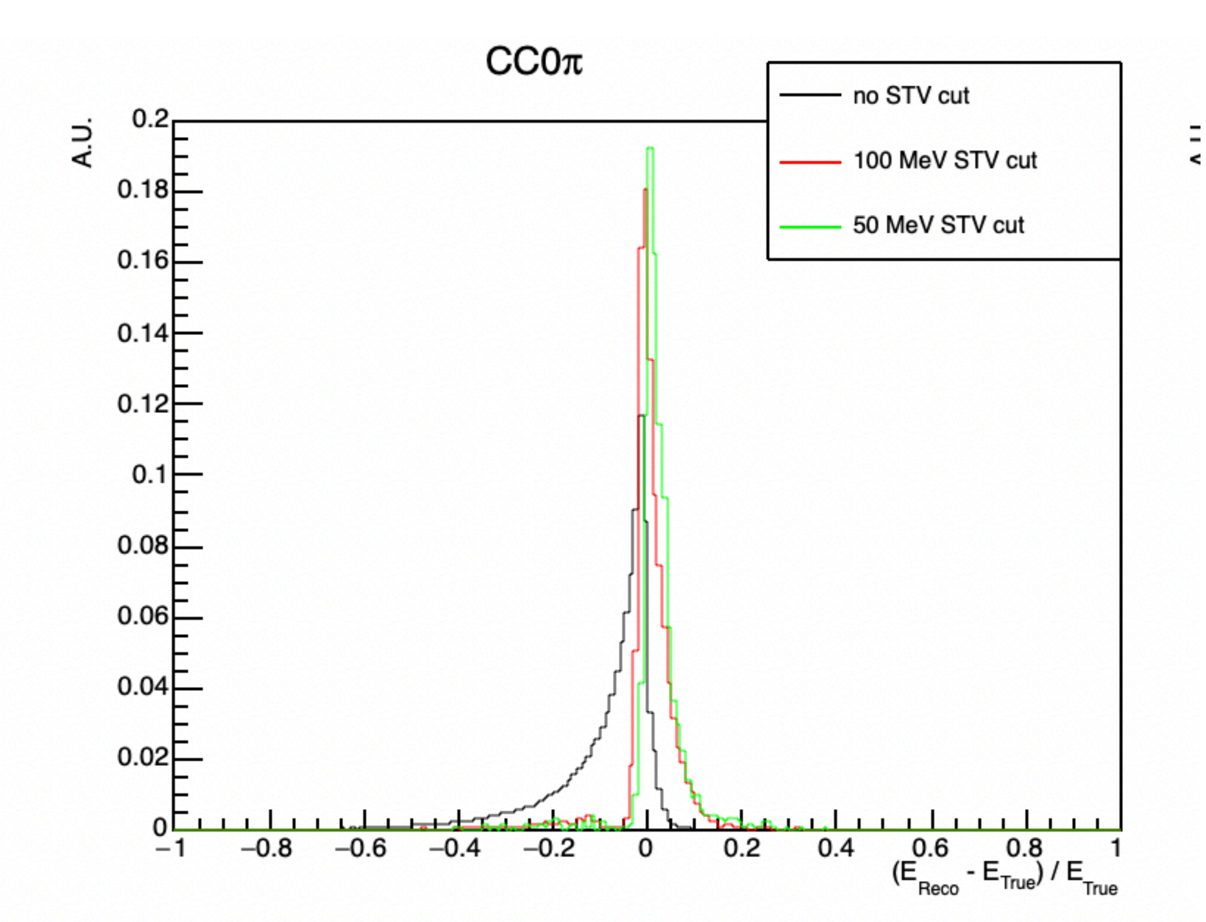


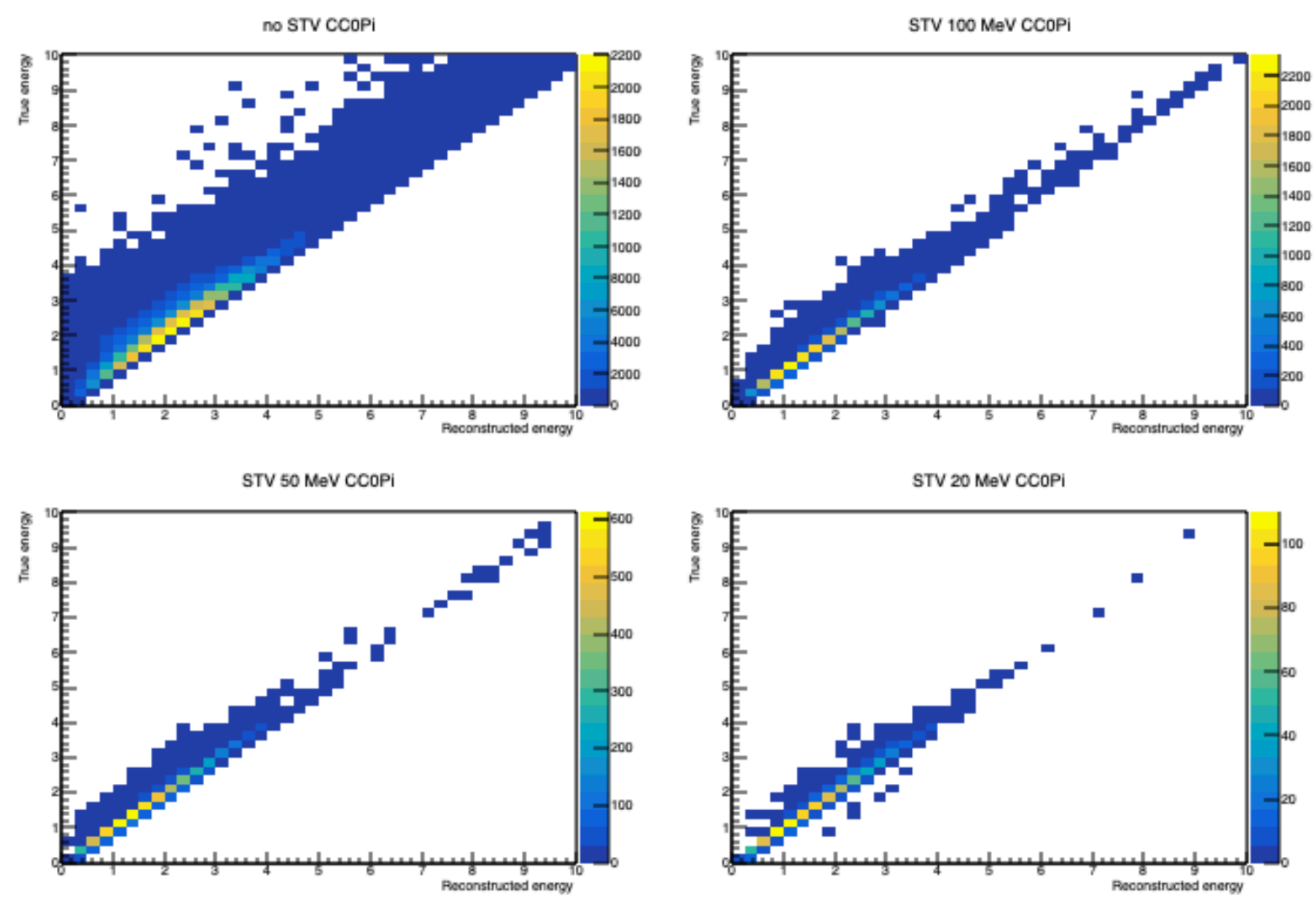


- NuBar energy resolution is reduced from ~13% to ~6-7% and almost no bias on E_{reco}
- E_{reco} weakly dependent on the interaction model and reduce correlations between flux and cross-section

New method to infer $\bar{\nu}_\mu$ flux: the DUNE case

- Isolate NuBar-hydrogen and NuBar-carbon interactions with low nuclear effects
- Use neutron kinematics to precisely compute the event transverse momentum
- Select CC0pi0prot events (no vertex activity)
- 4% momentum resolution for muons + 30% for neutron energy, apply efficiency based on bkg rejection study + conservative energy threshold cut (45%)

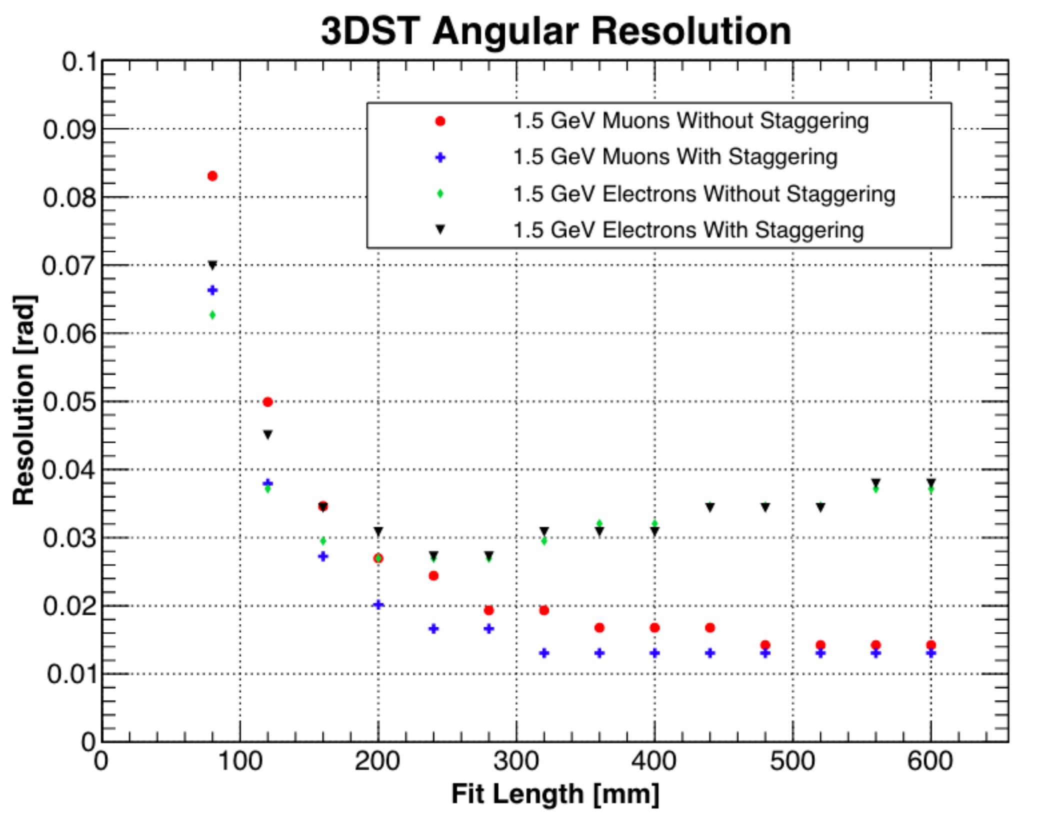


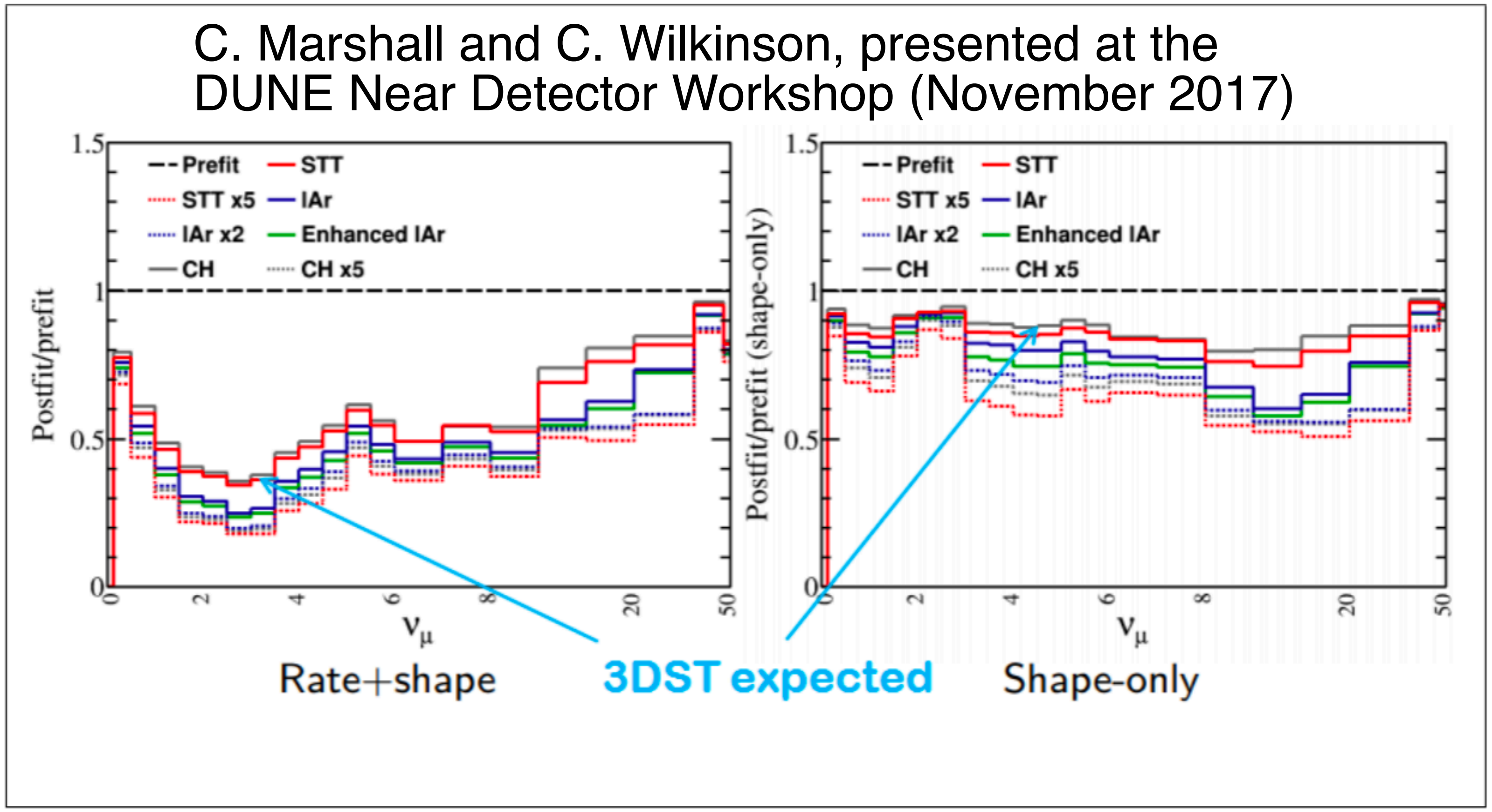


- Collect ~23k events per year with $dp_T < 100$ MeV/c
- AntiNu energy resolution from 13% to 7%, no bias and model-independent

Nu+e scattering

- It allows to infer the Nu+NuBar flux normalization
- Important but no informations neither on the flux shape nor on the “sign”
- Minerva has used it to normalize the flux. 3DST-S can do better
- ECAL with >10 X_{rad} can contain the electron shower



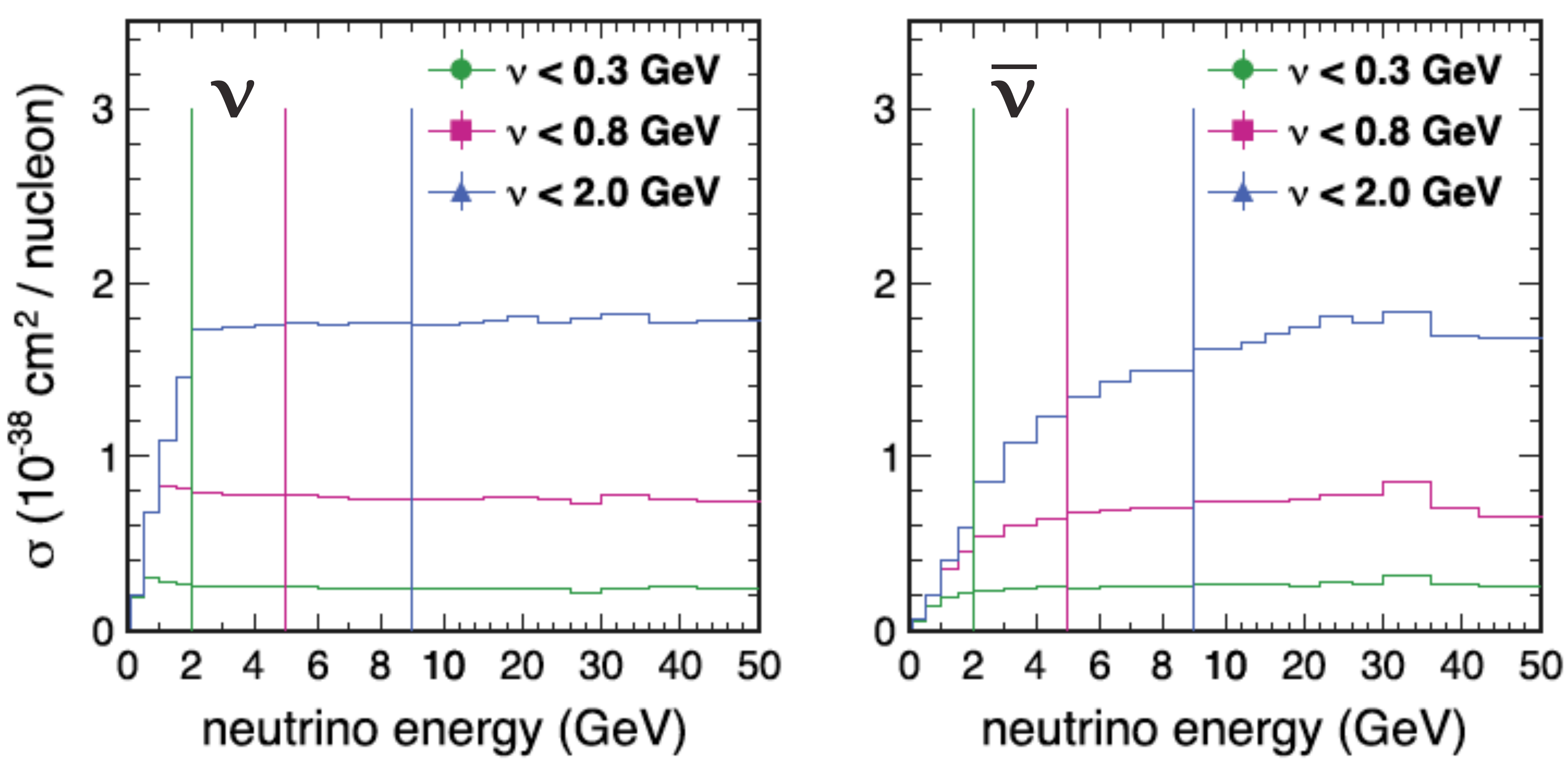


Low-ν method at Minerva

- Low-$\boldsymbol{\nu}$ successfully used by Minerva (Phys. Rev. D 94, 112007 (2016), Phys. Rev. D 95, 072009 (2017))

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi}\left(\int_0^1 F_2 dx - \frac{\nu}{E_\nu}\int_0^1 [F_2 \mp xF_3]dx + \frac{\nu}{2E_\nu^2}\int_0^1 \left[\frac{Mx(1-R_L)}{1+R_L}F_2\right]dx + \frac{\nu^2}{2E_\nu^2}\int_0^1 \left[\frac{F_2}{1+R_L} \mp xF_3\right]dx\right)$$

At limit $\nu_o << E_\nu$ (low- ν sample) → $\boldsymbol{\sigma}$ ($\nu < \nu_0$,E) const in neutrino energy

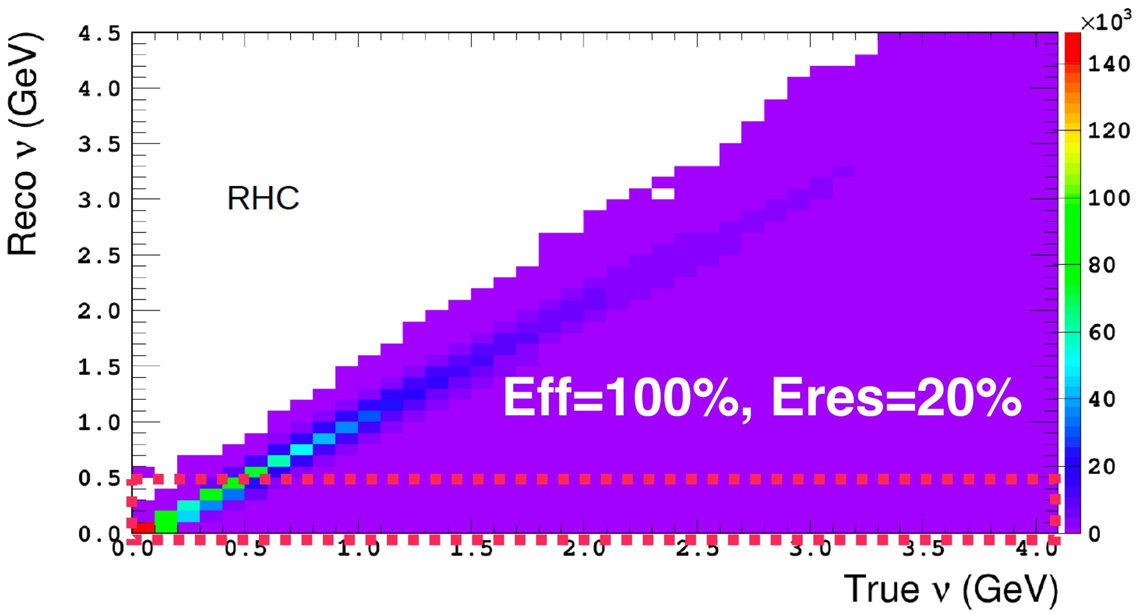


- Absolute normalization from world average at larger energy (where precisely measured)
- Dominant uncertainty from calorimetric reconstruction of $\boldsymbol{\nu}$, i.e. neutrons and protons

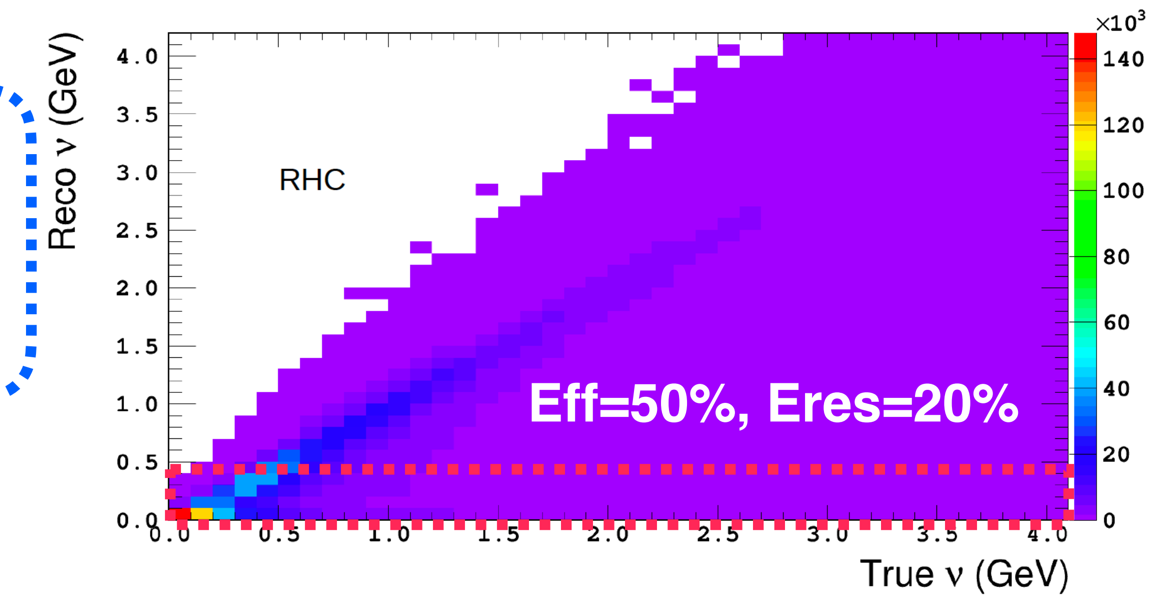
Good $\boldsymbol{\nu}$ resolution important, in particular for antineutrinos < 2 GeV

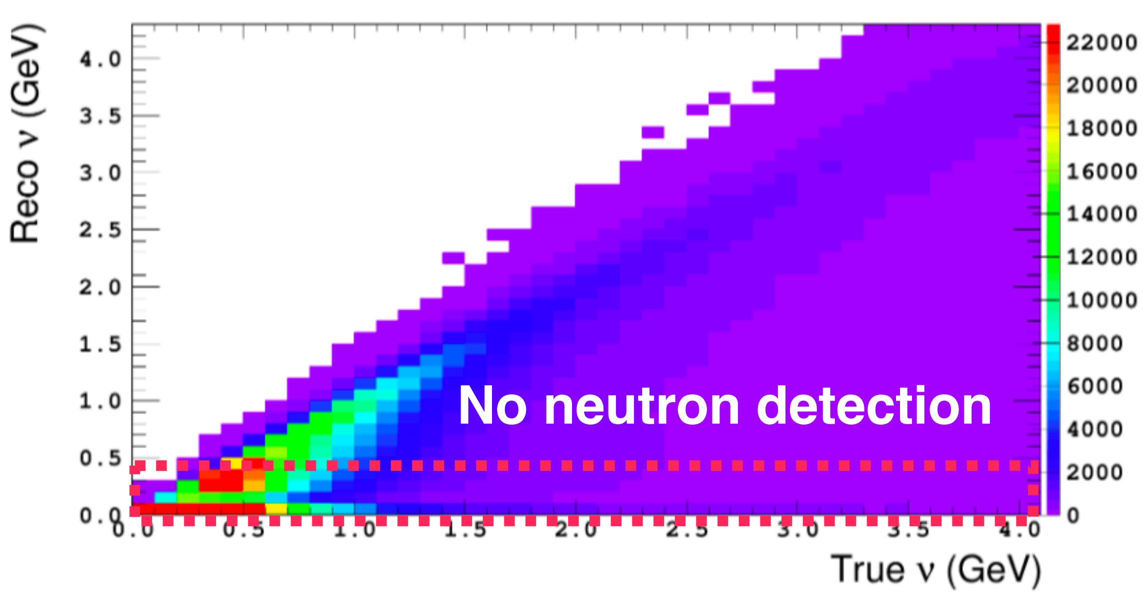
Low-ν method at 3DST

- 3DST will do better than Minerva, in particular on neutrons
- Missing energy from neutrons strongly affect the systematic uncertainties
- First look to **ν** resolution if we detect neutrons with different efficiencies (NuBar)



3DST will be in between





These plots shows it's worth investigating the low-**ν** method in 3DST for both the Nu and NuBar flux (neutrons can carry a large energy fraction in both cases)

Comments on the flux measurement

• In order to measure the neutrino and antineutrino flux shape and normalization, it’s important to develop different methods independent from the hadron-production measurements

1. Nu+e scattering —> Nu+NuBar normalization

2. STV+neutrons —> NuBar flux shape and normalization

3. Low-Nu —> Nu and NuBar shape and normalization (using world-average data at higher energy)

• 3DST has the potential of performing all the three measurements with the advantage (2. and 3.) of using the neutron energy infomation and including correlations between all the measurements

• This feature makes it complementary to all the other detectors

Importance of C —> Ar

Importance of Nu-C measurements for Nu-Ar modeling

- Stephen will talk about the importance of precisely measuring interactions in carbon for neutrino-argon interaction modeling more in detail
- Validation at a different A with high precision would provide much more confidence on the neutrino - argon interaction model
    - ✦ Neutrons detection with energy reconstruction
    - ✦ Capability to separate different nuclear effects is of great importance
- In a few words, the physics is the same (potentials are different). If the model doesn't work on carbon we can't trust the model on argon, even if the ND LAr data fit provide a relatively good g.o.f. (too many parameters involved)
- Wrote a DUNE internal note together with theorists experts in the field, that will be uploaded to docdb in the next few days before the collaboration meeting

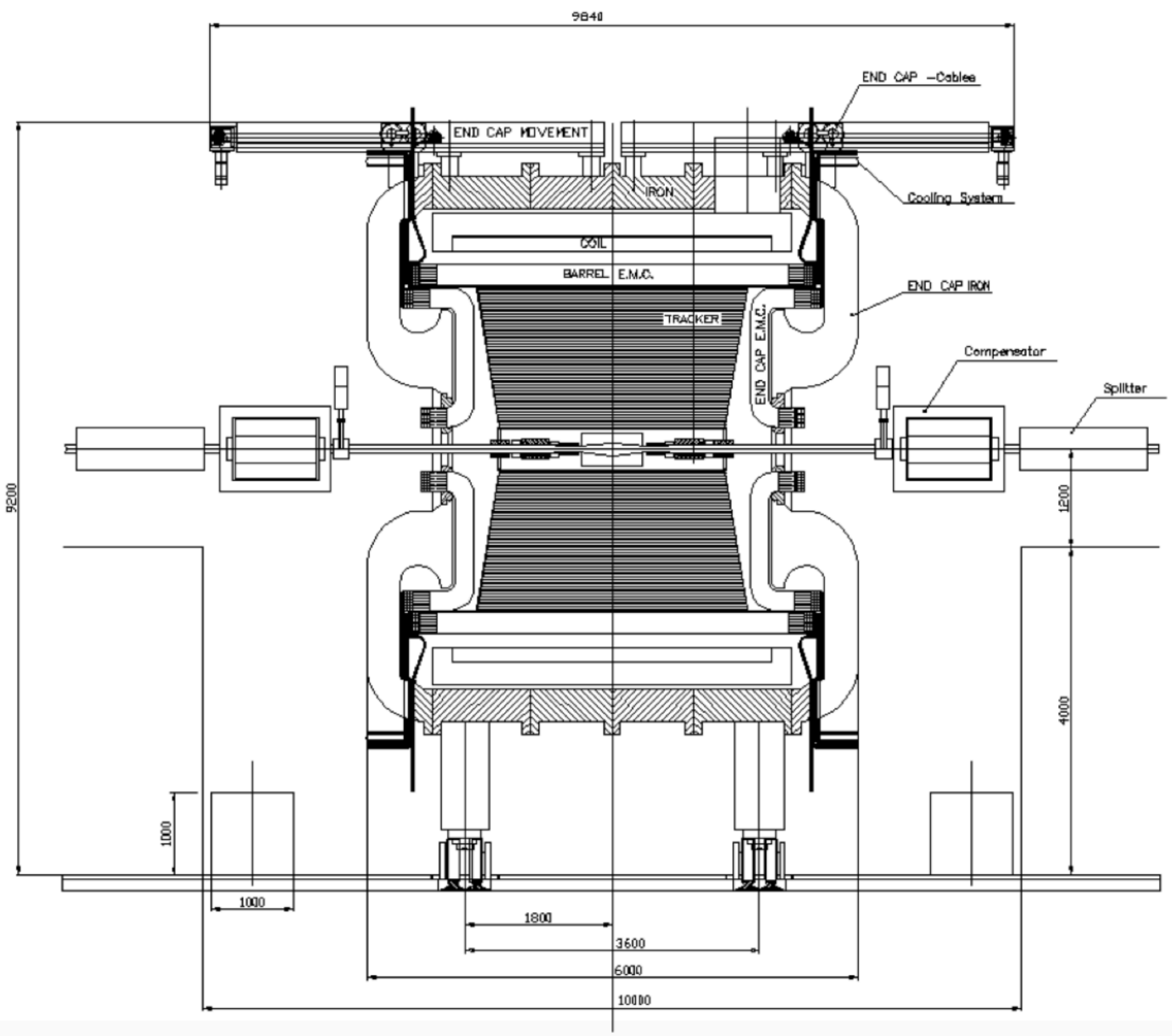
3DST+KLOE

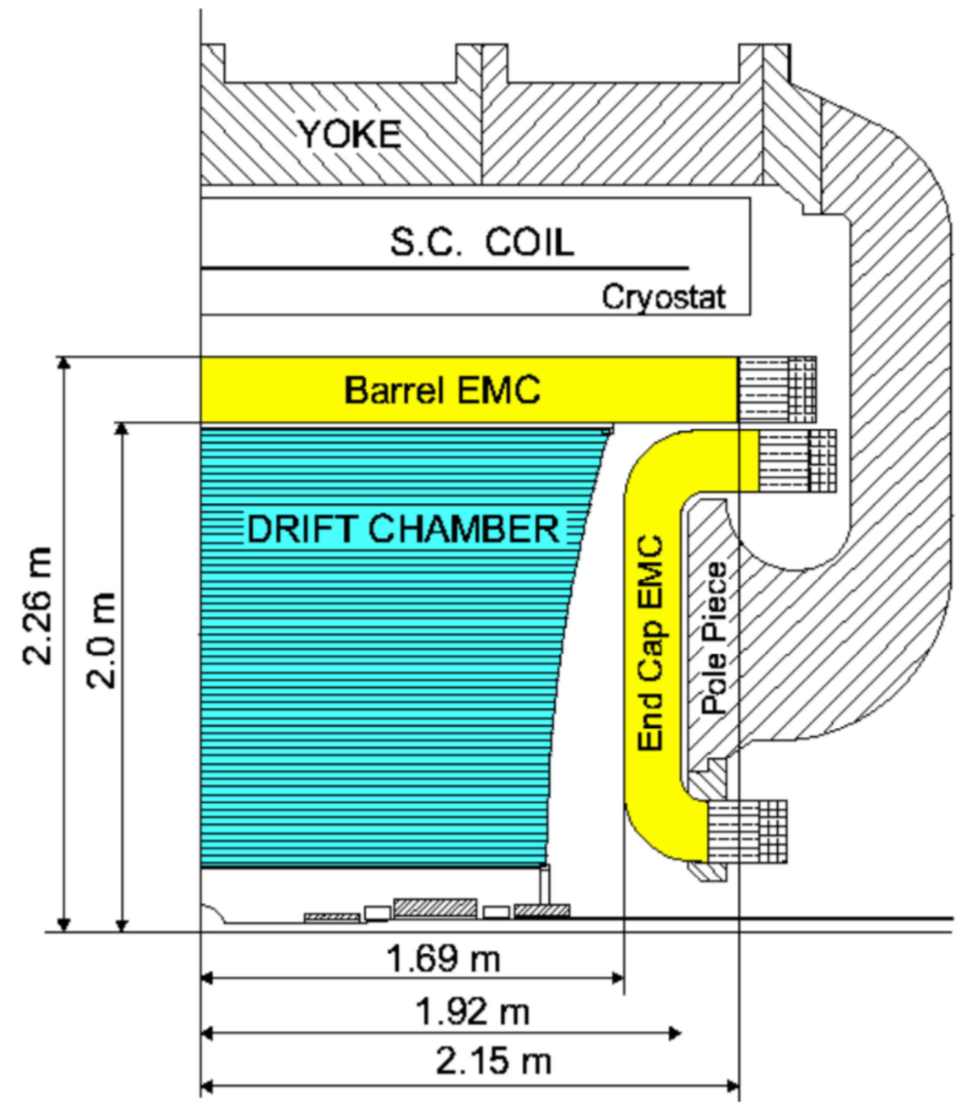
Introduction 3DST+KLOE

- In 3DST-Spectrometer the detailed designs of ECAL and magnet were lacking
    - While we had considered KLOE option much earlier, after the June 2019 LBNC meeting we started investigating the option of 3DST+KLOE in earnest
- The 3DST+Tracker model was modified in order to fit the inner volume of the KLOE Magnet+ECAL, trying to keep the same active mass as the original configuration
- An initial informal meeting between the KLOE and 3DST representatives was held on July the 17th via video

The KLOE geometry

- We extracted the informations about the KLOE detector from:
  - ✦ https://indico.fnal.gov/event/15025/contribution/0/material/slides/0.pdf
  - ✦ Nuclear Instruments and Methods in Physics Research A 419 (1998) 320–325
- KLOE parameters: B-field ~ 0.6 T in the center, ~15 X_0 ECAL

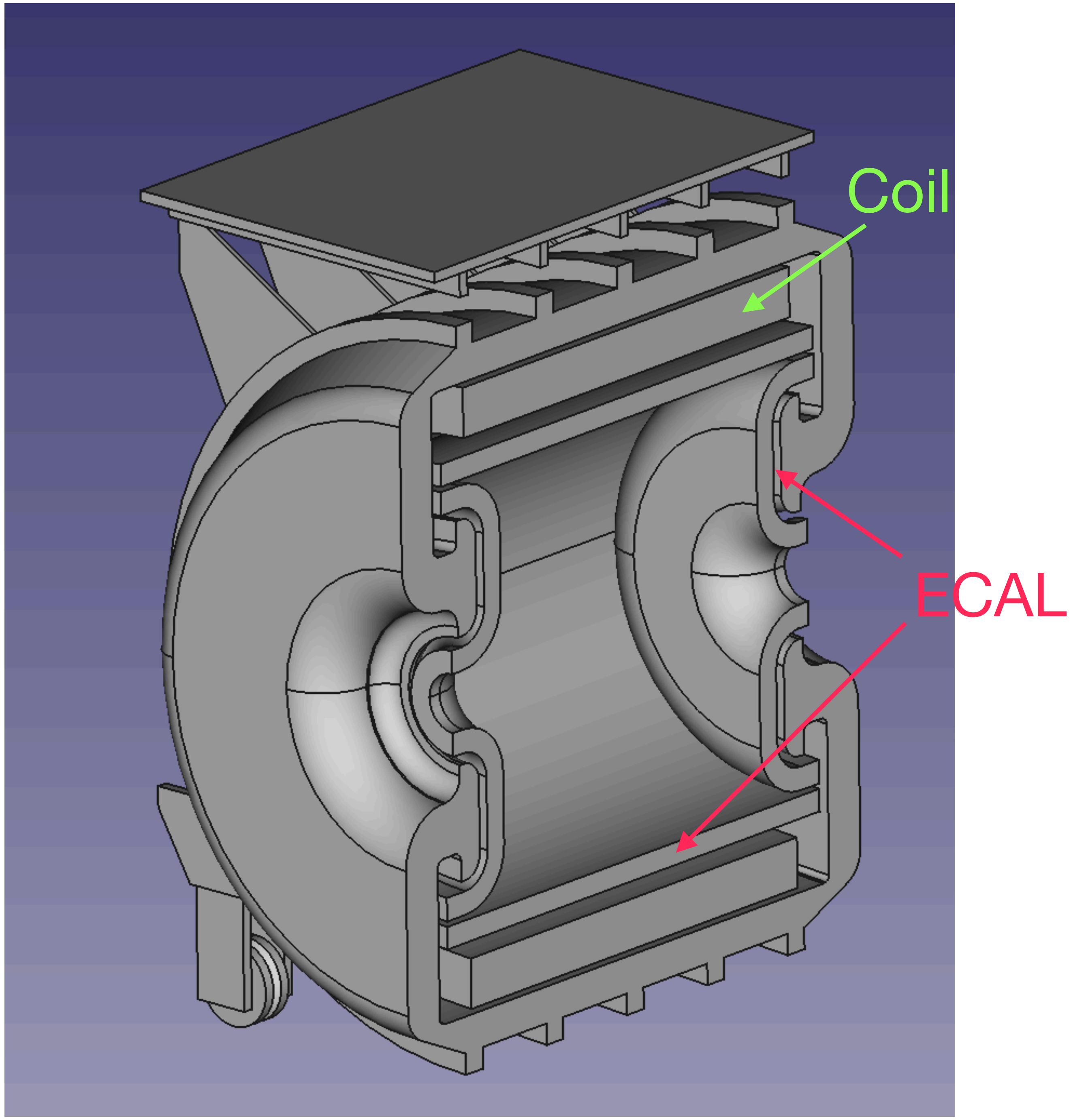


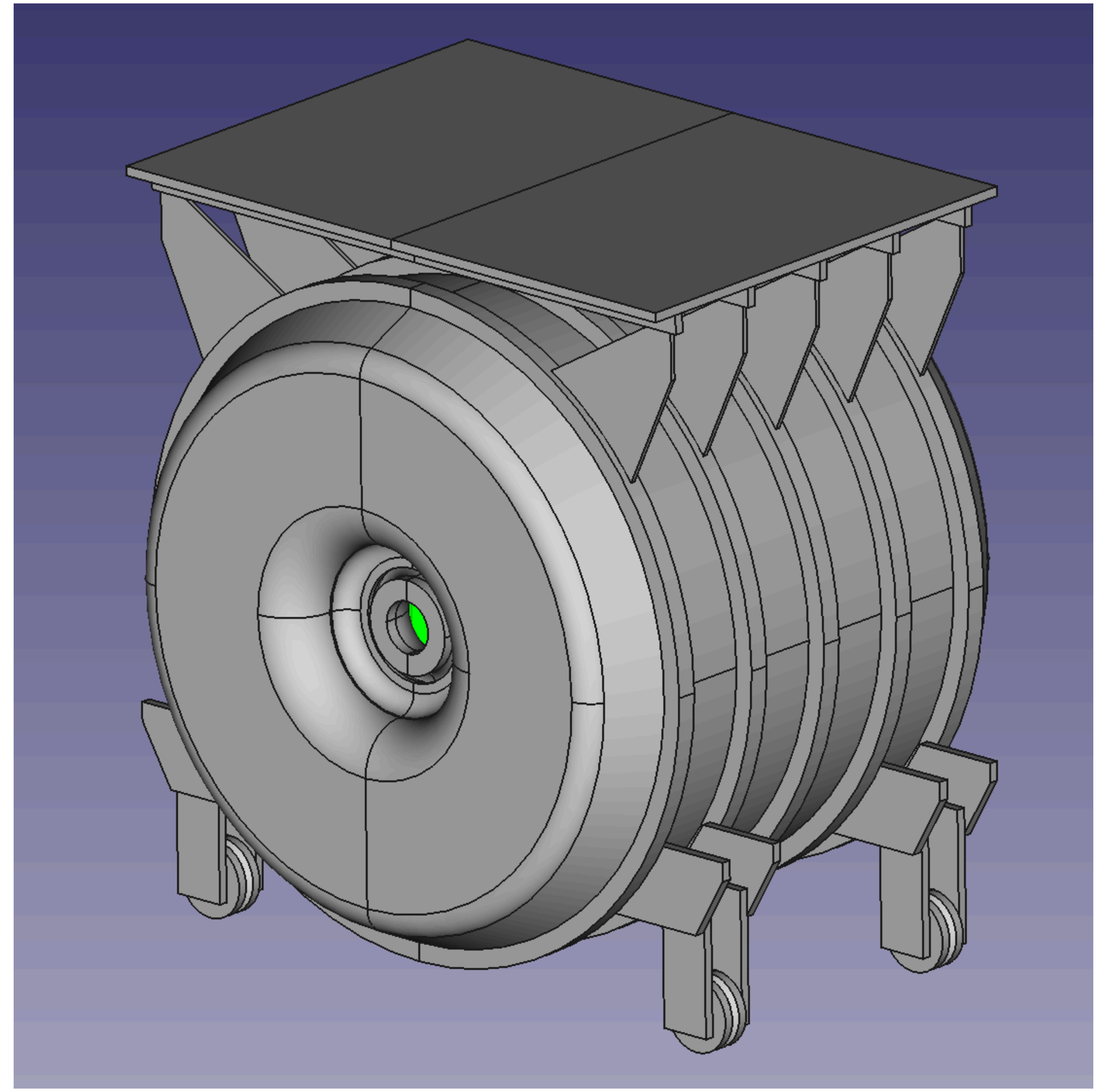


- Bob Flight (engineer at U. Rochester) took these drawings and extracted all the necessary informations (digitized the dimensions where needed)

The KLOE model

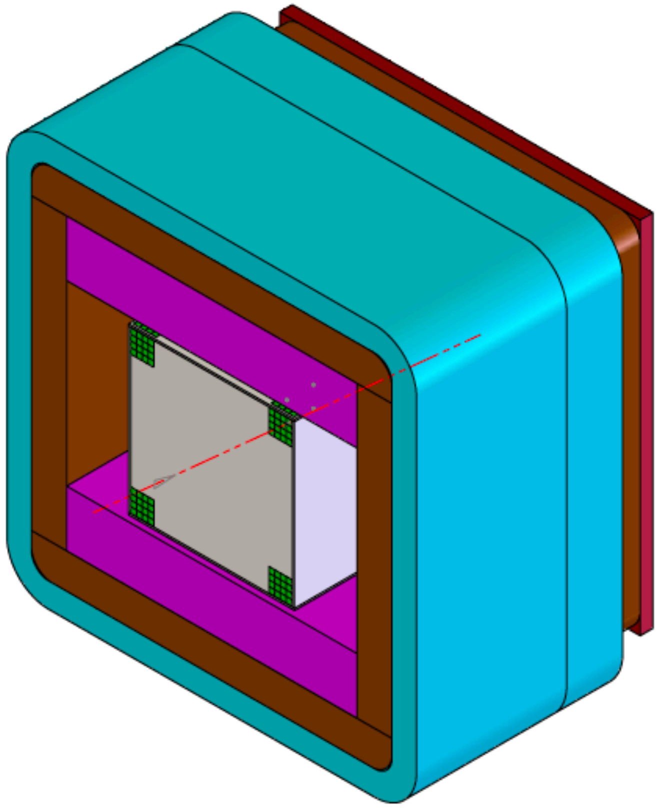
By Bob Flight

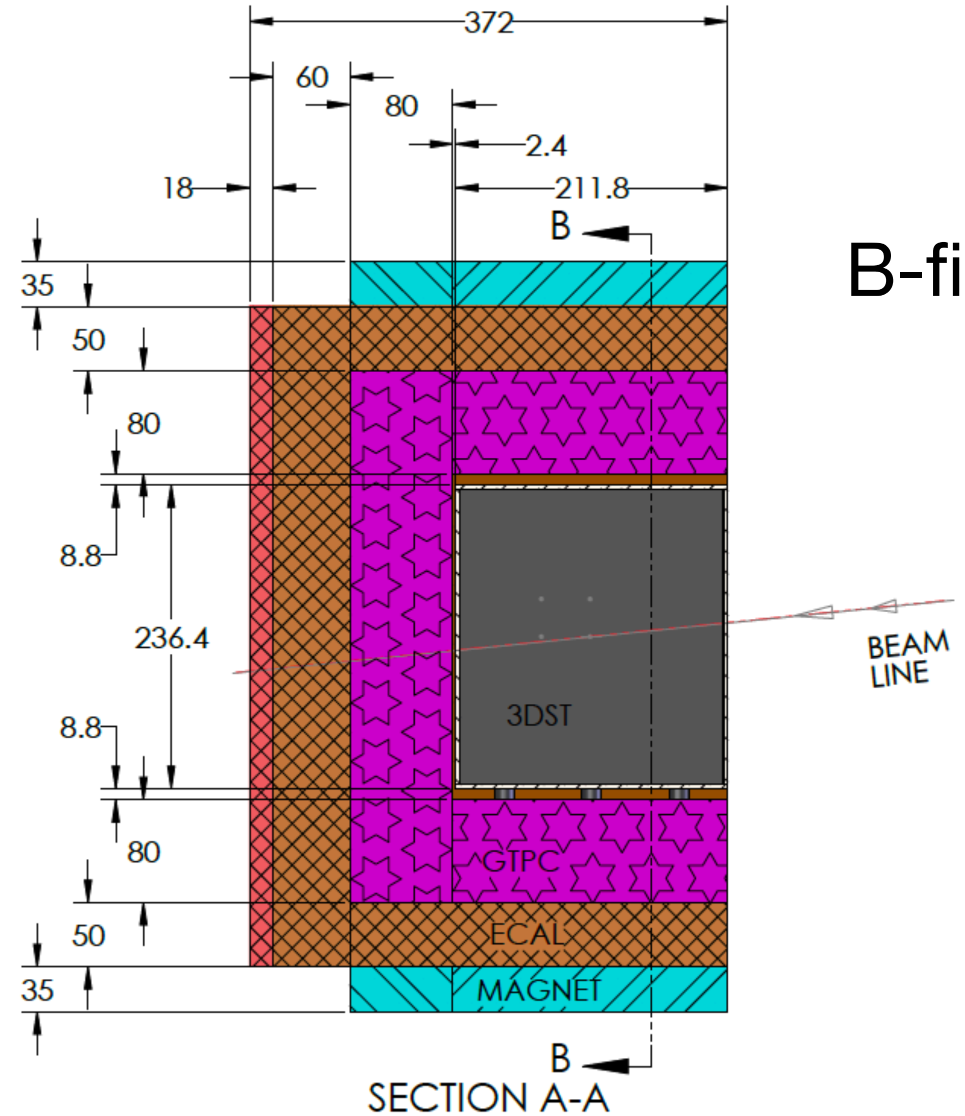




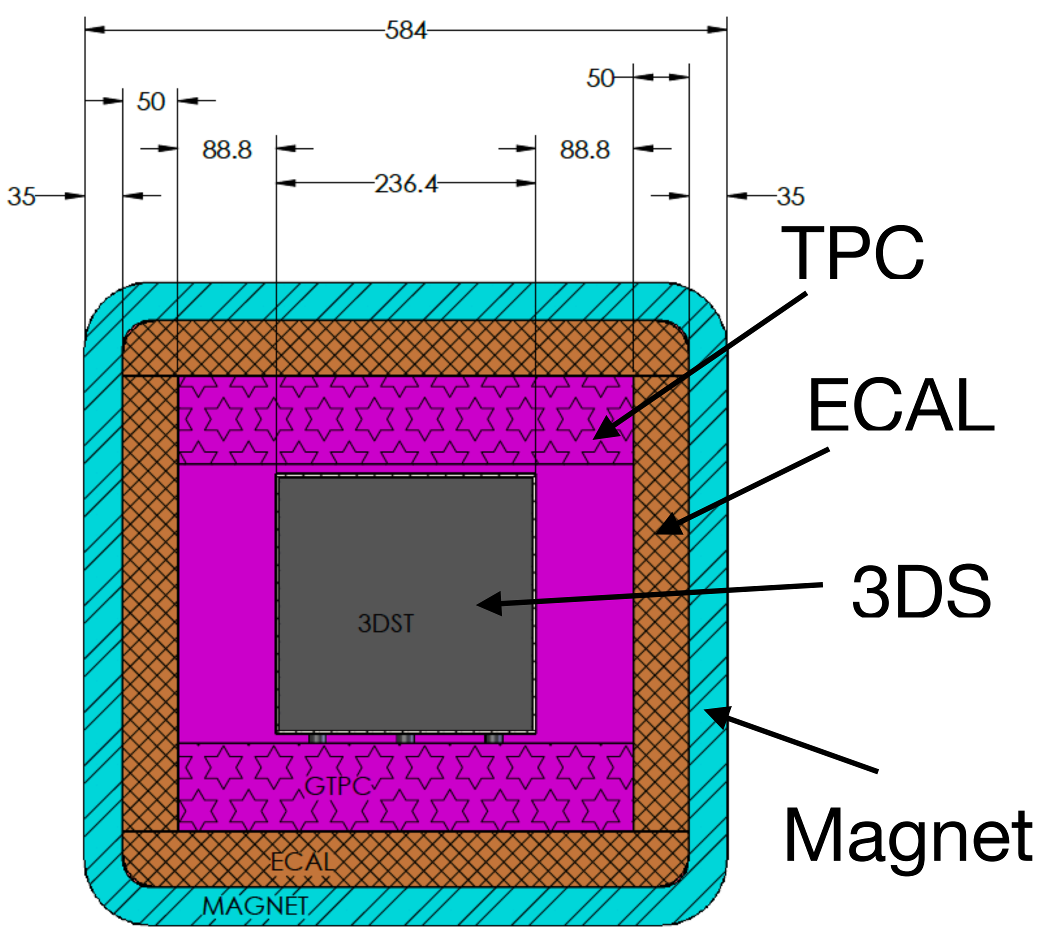
- Estimated the available space in the ECAL inner volume
- Update the dimensions of 3DST + Tracker to keep the same mass as in the original configuration and at the same time to fit the available space

The original 3DST-Spectrometer conceptual design



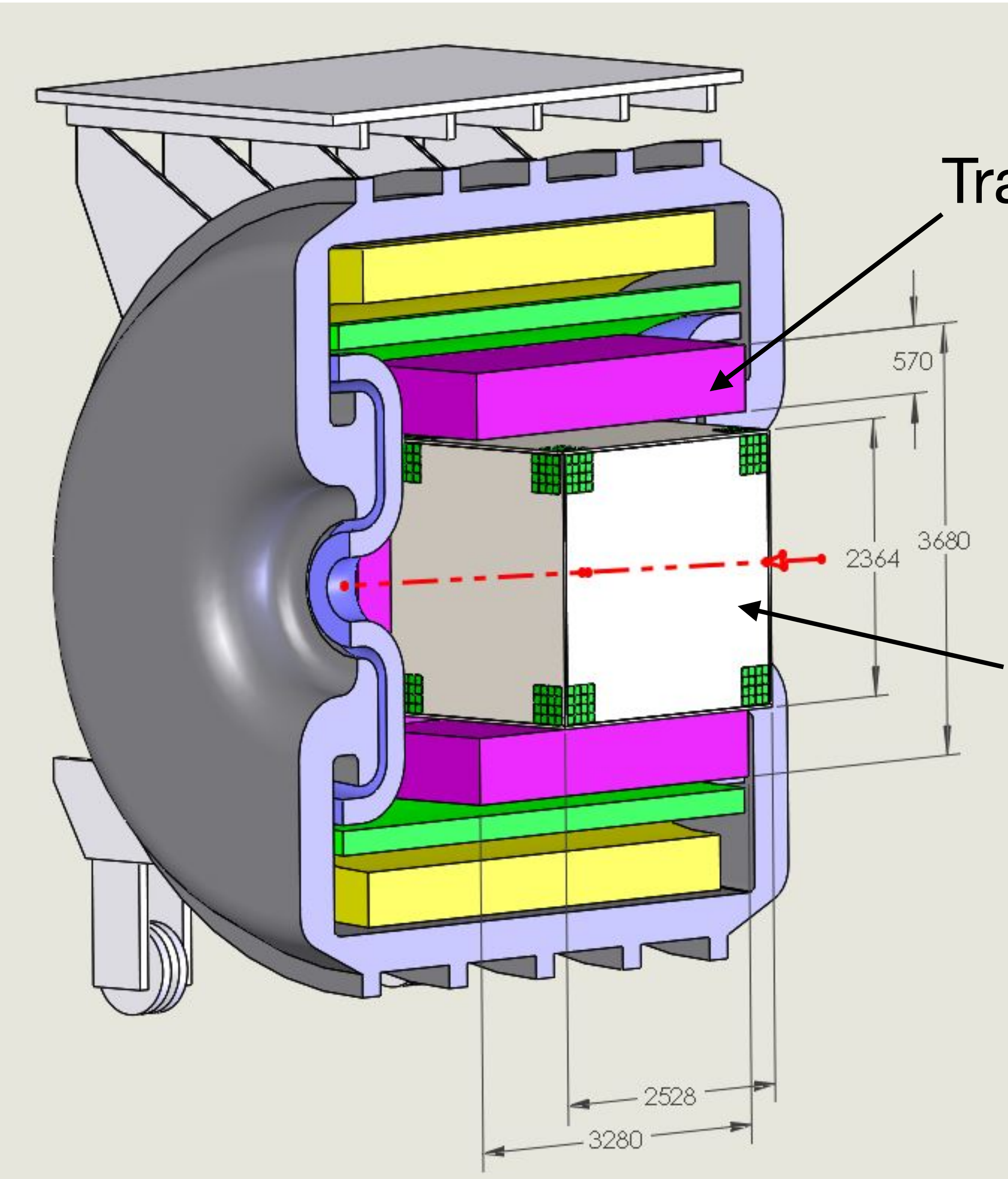


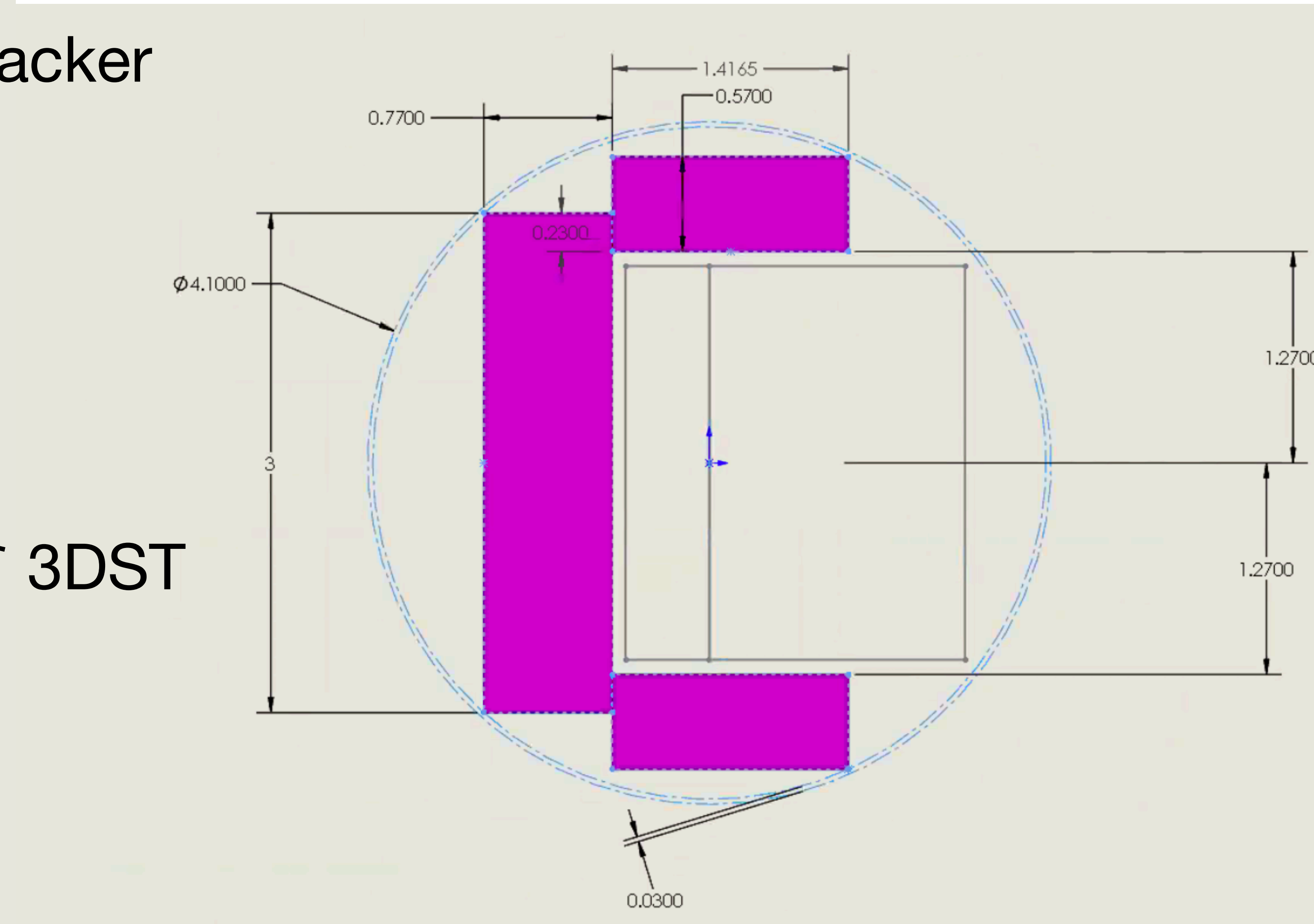
B-field = 0.6 T



- The initial configuration size was 2.4x2.4x2 m^3
- The dimensions were updated when moving from a concept to a more detailed design, that includes the mechanical box, the light readout system, the segmentation due to the channel readout (e.g. SiPM-PCBs with 8x8 channels)
- The 3DST active volume is then 2.24x2.24x2 m^3

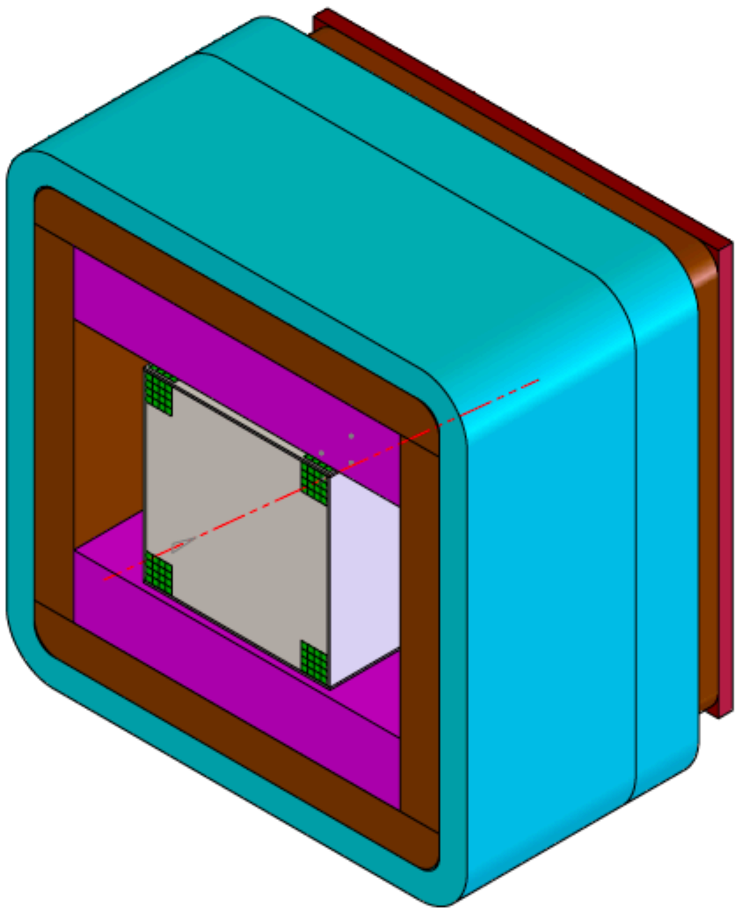
3DST inside KLOE

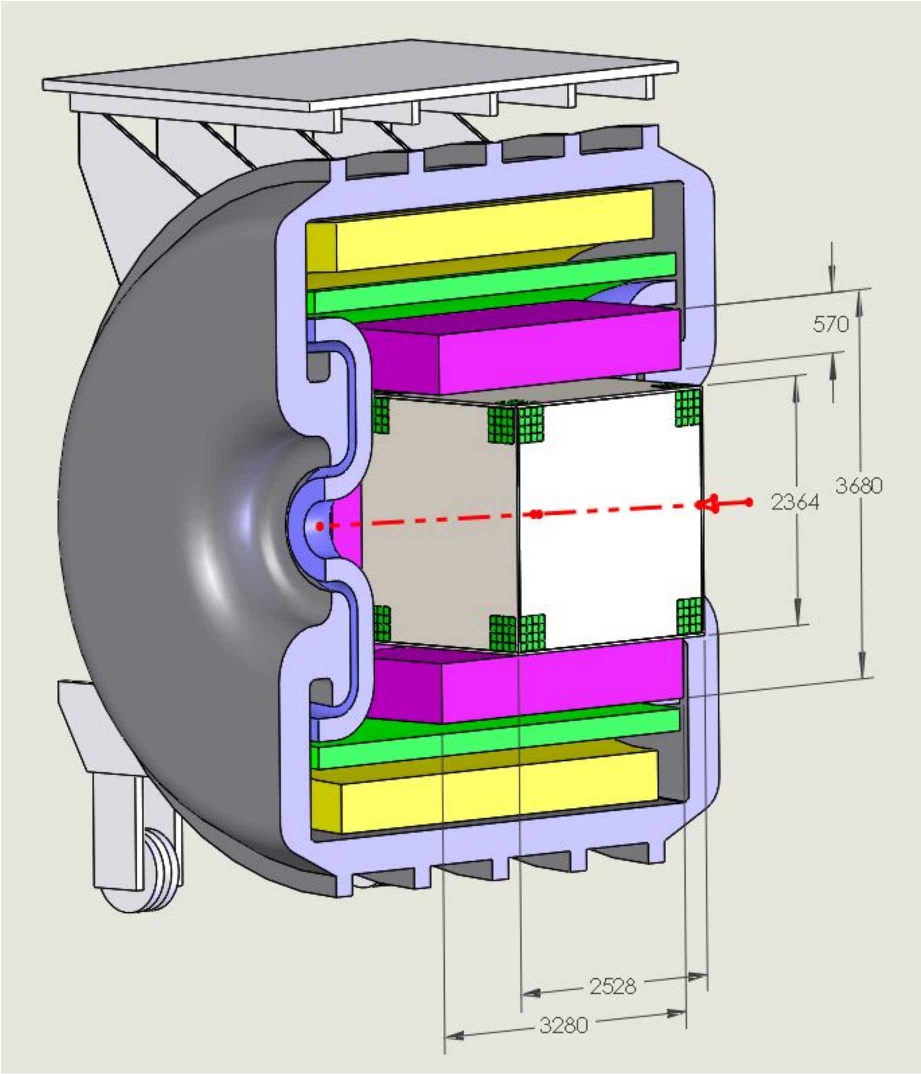




- Some spare KLOE Barrel-ECAL modules would be available to cover the "beam-pipe" holes in the ECAL
- More space along X direction could be available and 3DST could be made wider, in case more active mass is necessary, in particular for beam monitoring

Comparison with the original 3DST configuration





Original active volume: 2.24x2.24x2 m^3
10,637,312 tons (1x1x1 cm^3 per cube, 1.06 g/cm^3)
Active volume of 3DST inside KLOE: 2.24x2.4x1.92 m^3
10,941,235 tons (1x1x1 cm^3 per cube, 1.06 g/cm^3)

It seems possible to integrate 3DST inside KLOE while keeping the same active mass. Our initial thoughts are that KLOE+3DST combination should provide us approximately performances similar to the original 3DST-S configuration

Thoughts about physics studies of 3DST+KLOE

- Beam monitoring
  - ✦ KLOE parameters are the same as for the original 3DST-S
  - ✦ Performances mainly driven by the total mass
  - ✦ Though we don't expect major differences, it is important to perform these studies again with the new geometry to demonstrate the capabilities to the collaboration
- Neutrons
  - ✦ Efficiency and energy resolution would be the same (higher efficiency if ECAL is included)
  - ✦ Out-FV neutron background must be studied again, given the different masses of ECAL / magnet, in particular upstream of 3DST
- Neutrino and AntiNeutrino flux
  - ✦ A lot will depend on the neutron out-FV background rejection
  - ✦ Worth investigating the low-nu method, combining it with STV+neutron and nu+e scattering

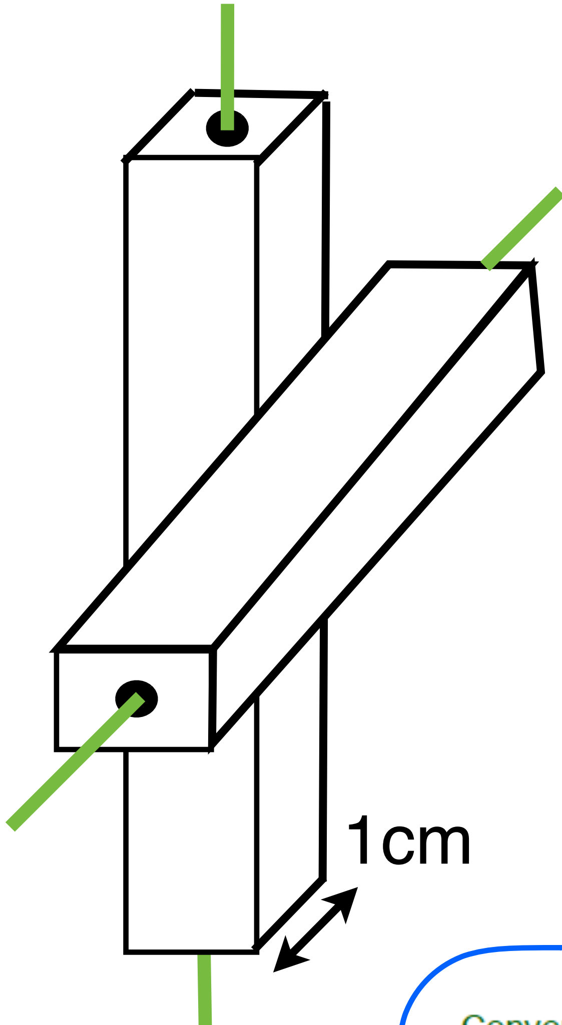
Overview of documents in preparation

- Two notes in preparation to be released in the upcoming weeks:
- "3DST-S white paper"
    - Summary of the 3DST-S conceptual design, R&D and physics studies performed
    - https://cernbox.cern.ch/index.php/s/KK1hnwEn9JIzDcS (PRELIMINARY)
- "Constraining neutrino-interactions on an Argon target using Carbon data: A-scaling approaches in neutrino nucleus interactions"
    - Not a 3DST WG note. Written in collaboration with theorists expert in the field of neutrino interaction modeling
    - https://onedrive.live.com/?authkey=%21AJRXcGHEKtoAk4c&cid=BFE7B61EB9446D00&id=BFE7B61EB9446D00%2159423&parId=BFE7B61EB9446D00%2157555&o=OneUp
    - See Stephen Dolan's talk

BACKUP

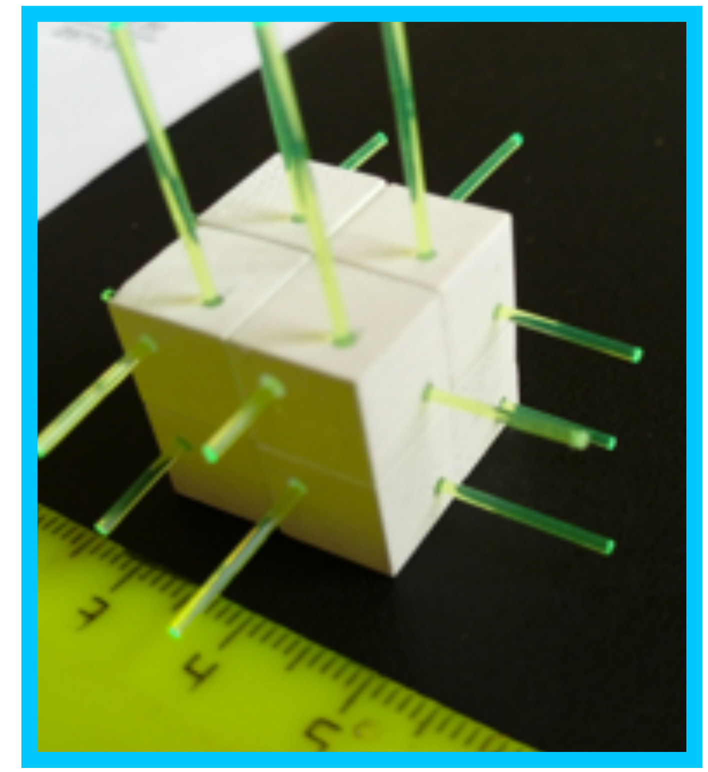
Fully active FGD with three views

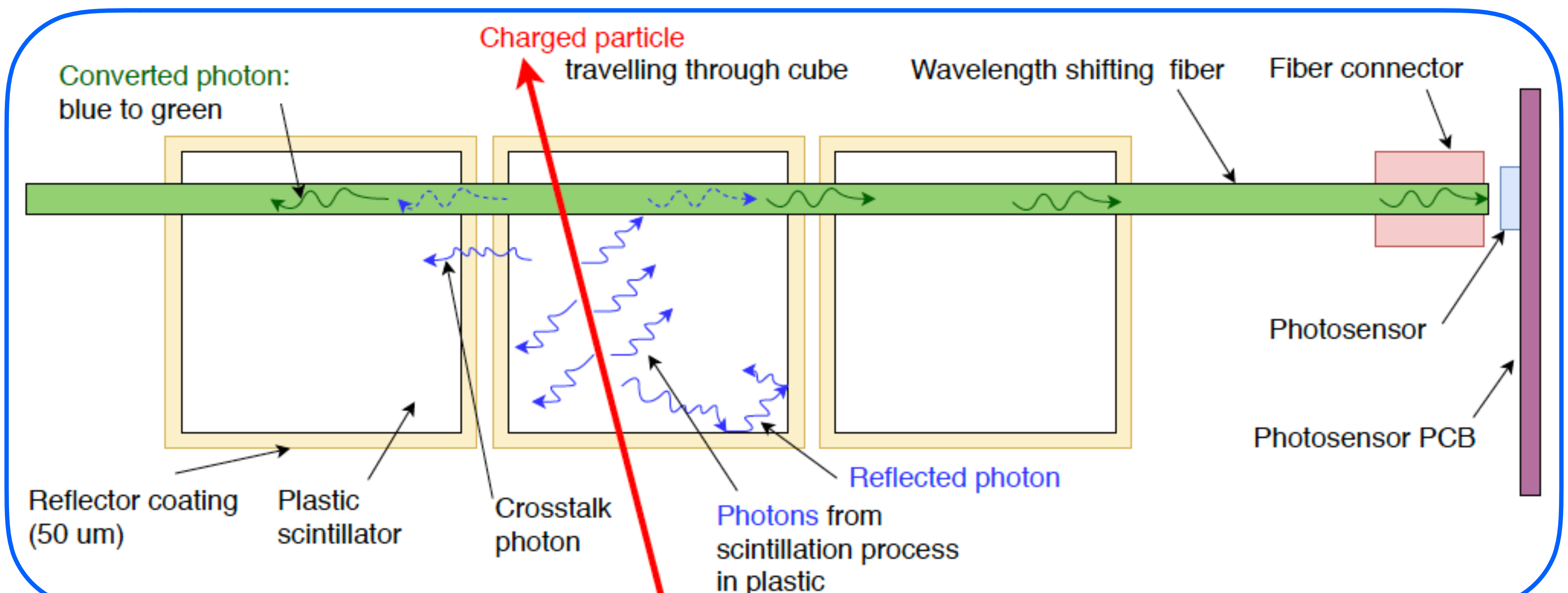
- Usually plastic scintillators made by long bars —> poor angular acceptance



2018 JINST 13 P02006

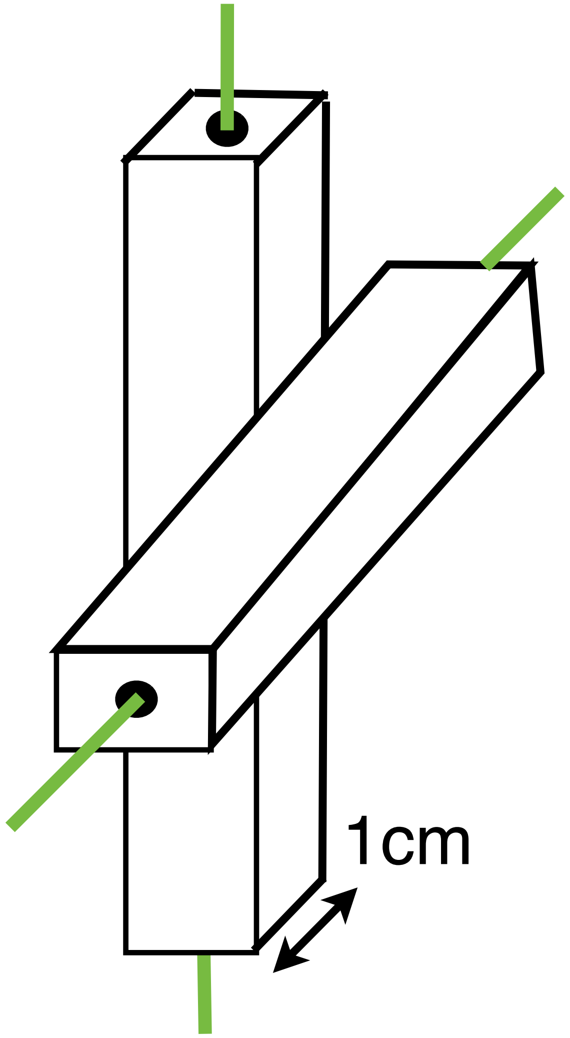
Polystirene-based Plastic scintillator
1.5% paraterphenyl and 0.01% POPOP
1x1x1 cm^3 cubes
Chemical etching as reflector
WLS fibers (Kuraray Y11, 2-clad, 1mm)
Multi Pixel Photon Counter detector





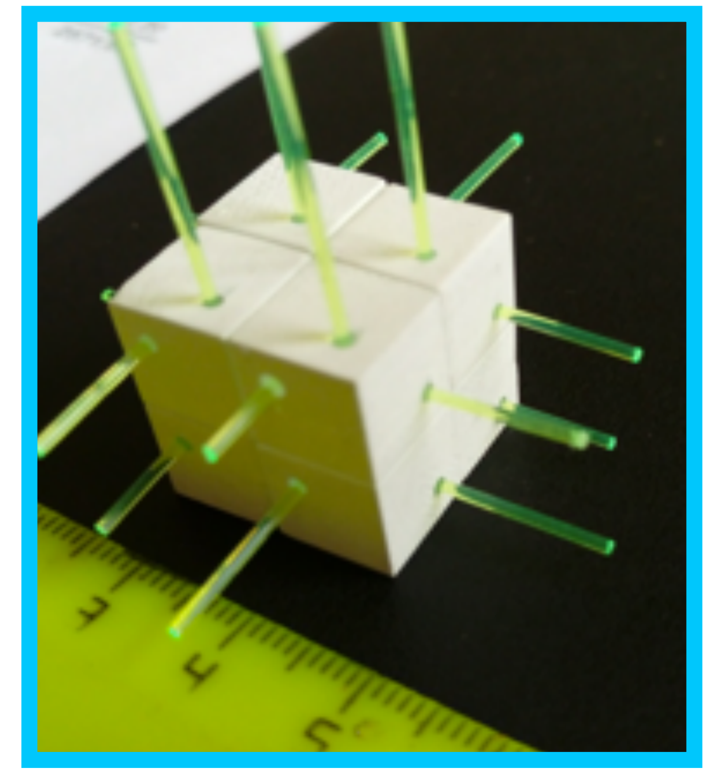
Fully active FGD with three views

- 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)
Multi Pixel Photon Counter detector



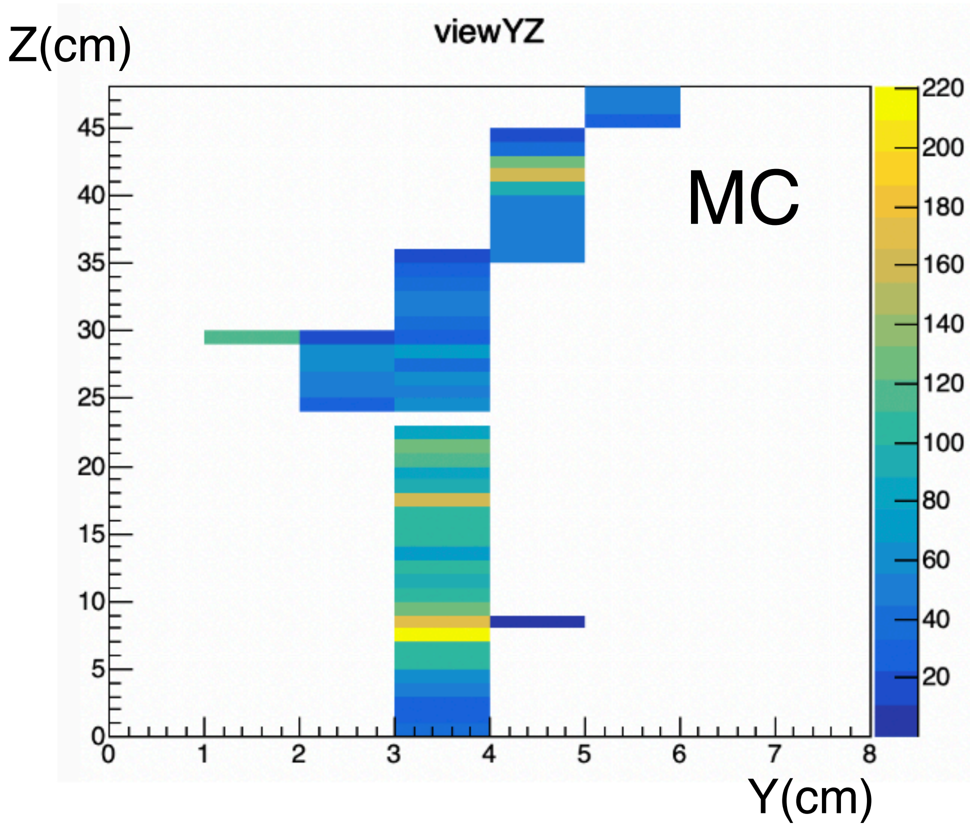
- Optically independent cubes —> spatial localization of scintillation light
- Lower momentum threshold: 1 single hit gives immediately XYZ
- Plastic scintillator provides very good time resolution
- Uniform material (just plastic) —> no systematics from different nuclei
- It will be installed in the T2K near detector in 2022 (***SuperFGD***)

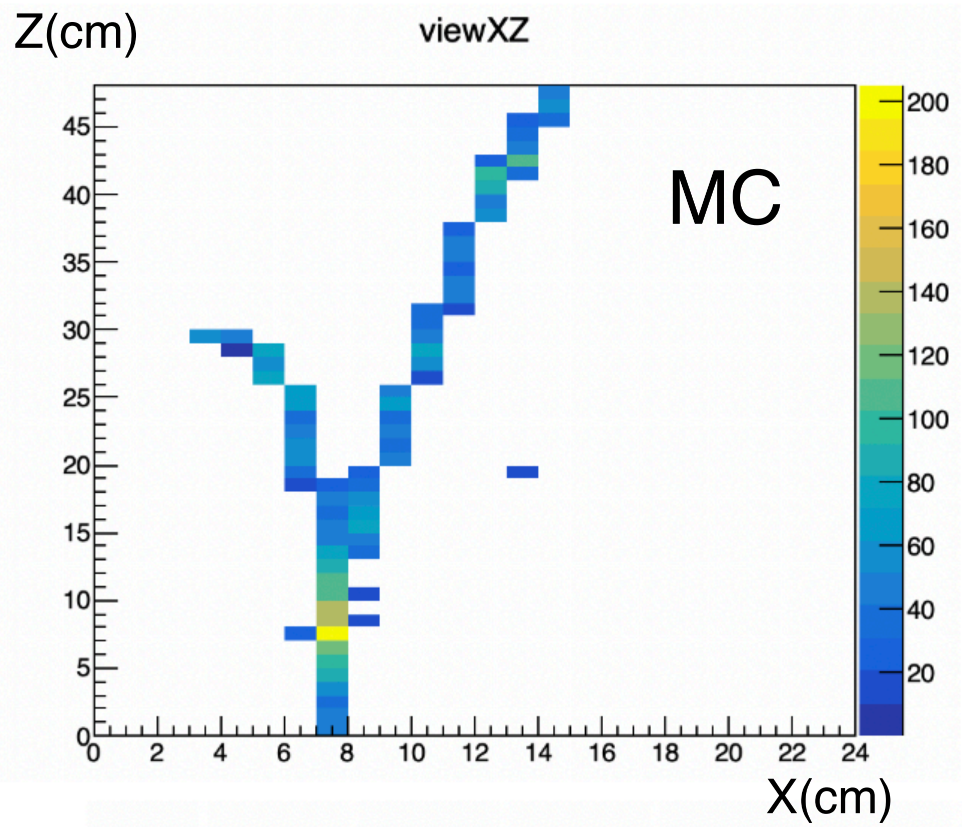
Fully active FGD with three views

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

2D projections

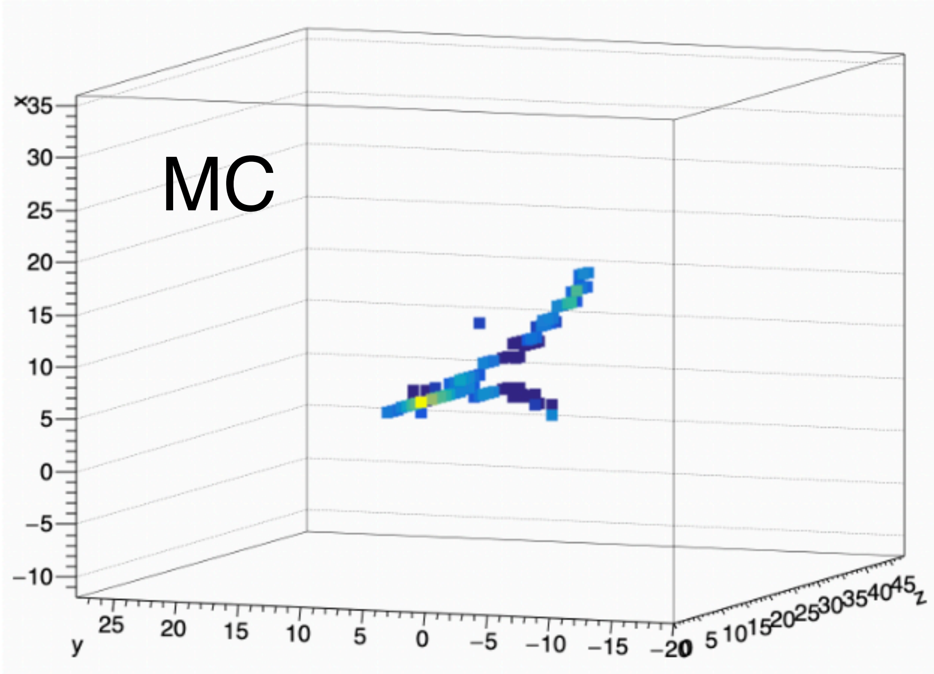
XY projection not shown here

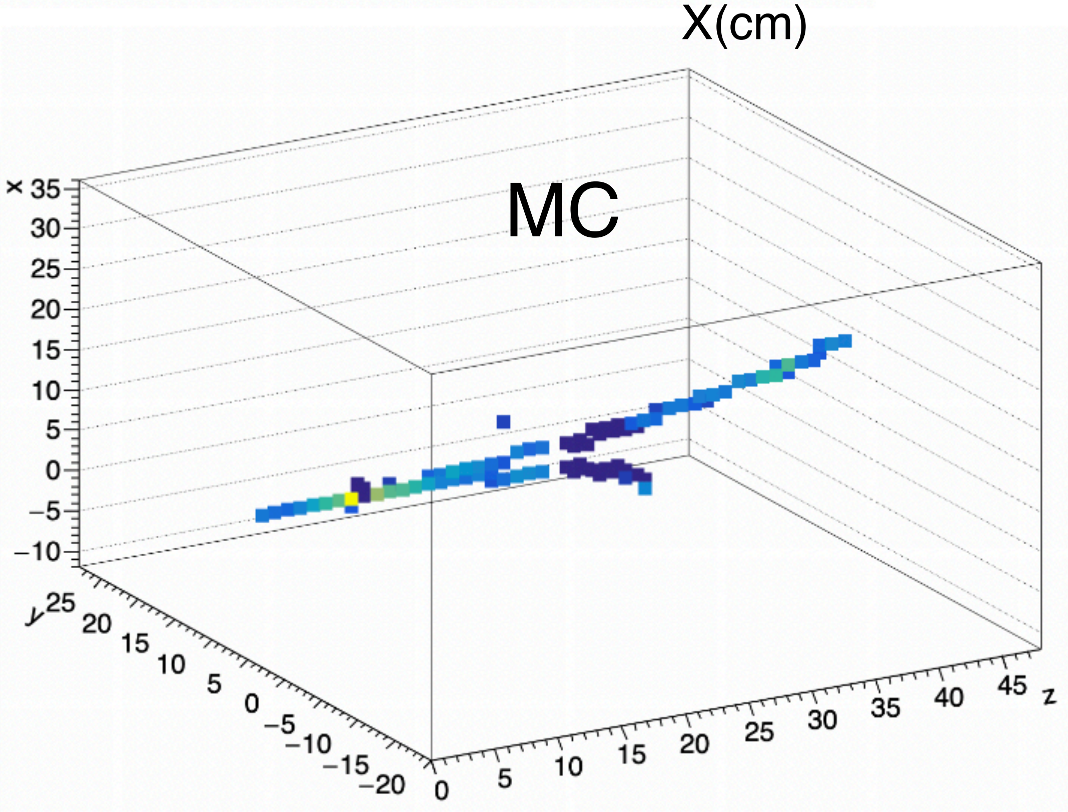




3D rotated views

Example of a photon converting in SuperFGD

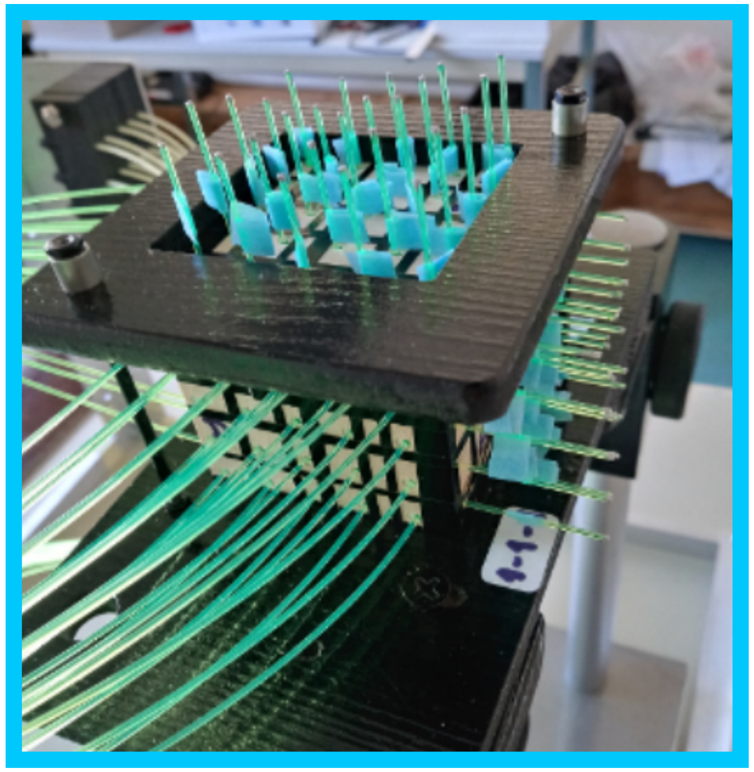


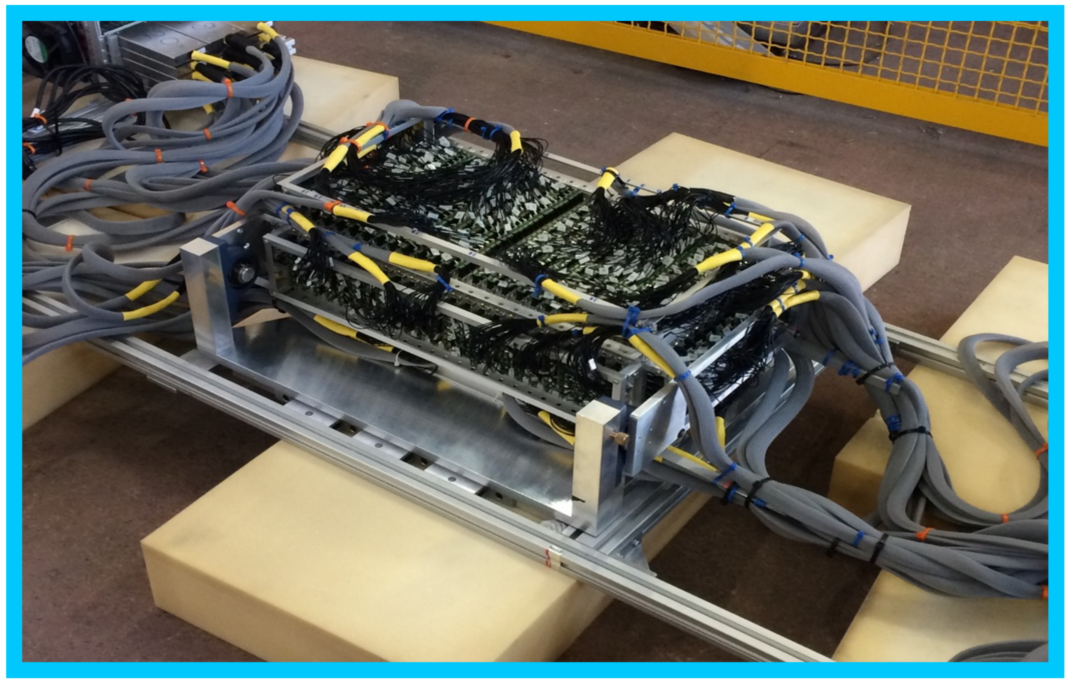


Characterization of the cube response

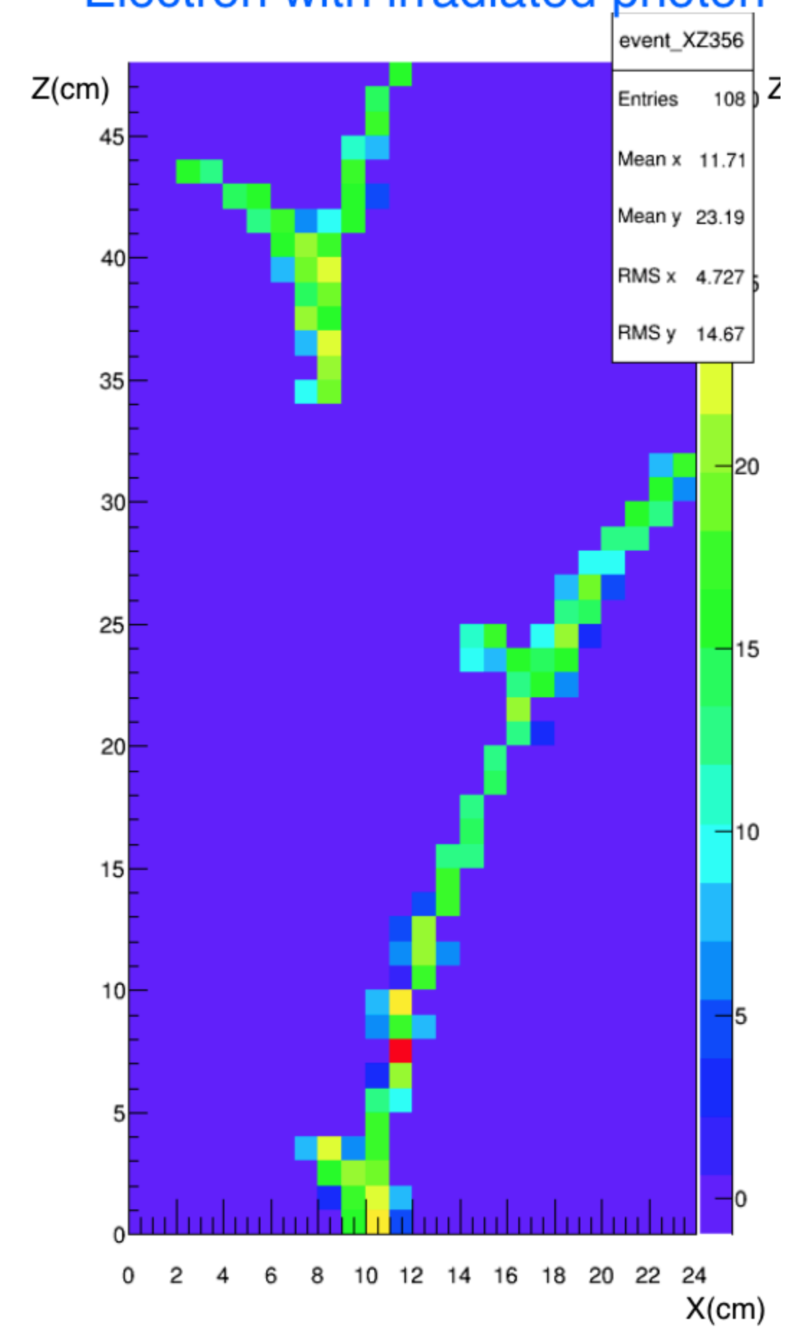
- Two prototypes exposed to CERN test beam to characterize the cube response
  - ✦ 5x5x5 cm^3 (125 cubes), 1.3 m WLS fibers (Al-based paint at fiber end)
  - ✦ 24x48x8 cm^3 (10,000 cubes) to provide also particle tracking

NIM A923 (2019) 134-138





Electron with irradiated photon

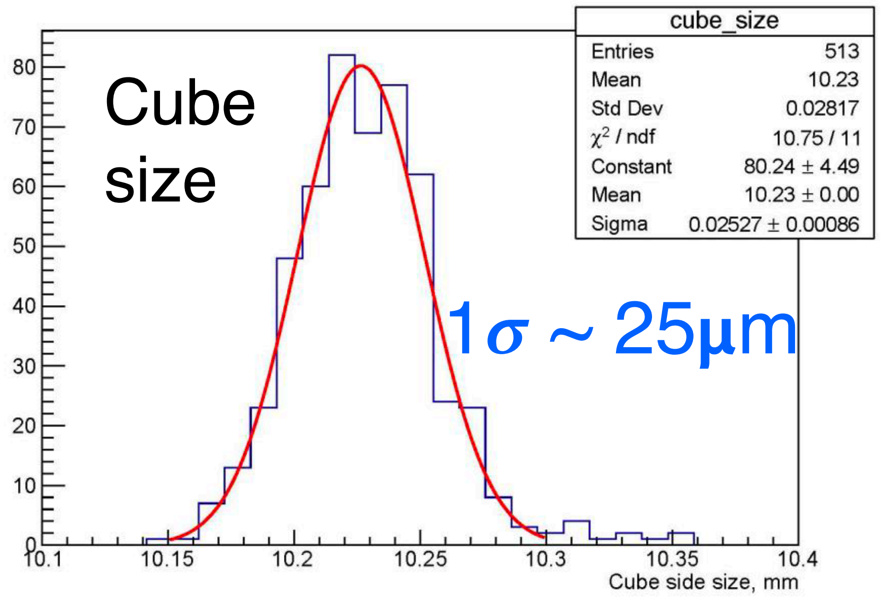


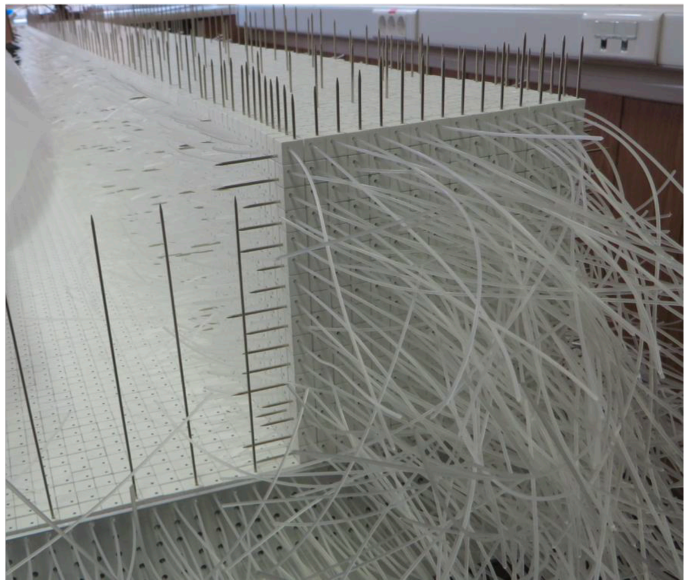
- Light yield ~ 41 p.e. (1fiber, 1cube, MIP)
- Light cross-talk between adjacent cubes ~ 3.7%
- Intrinsic time resolution ~ 0.95 ns (1fiber,1cube,MIP)

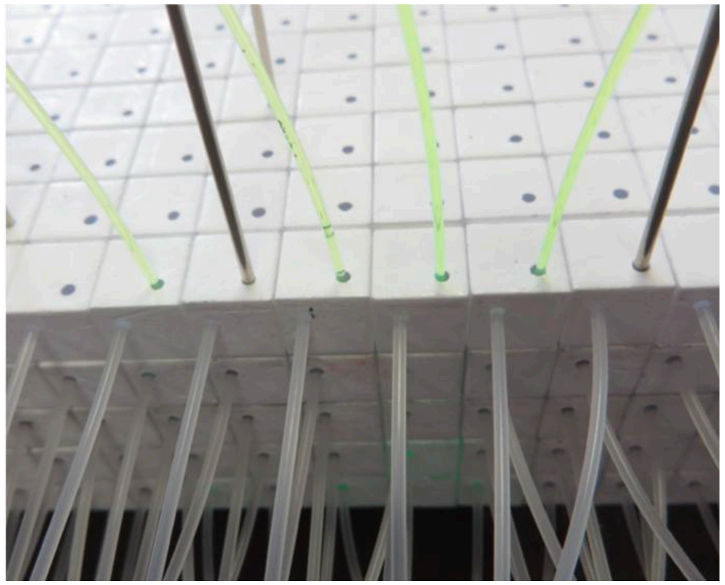
Other two prototypes will be ready soon to test the latest version of the detector configuration

The detector assembly

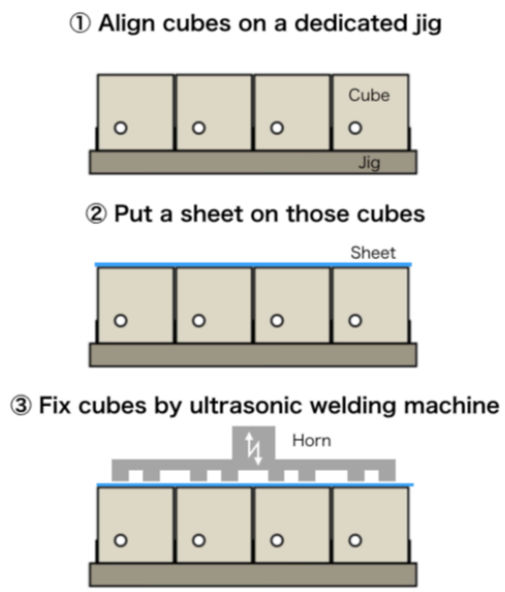
- About 300k cubes already manufactured (~17% of total # of cubes)
- Option 1: ∅1.3mm fishing lines of to align cubes, replace them with WLS fibers

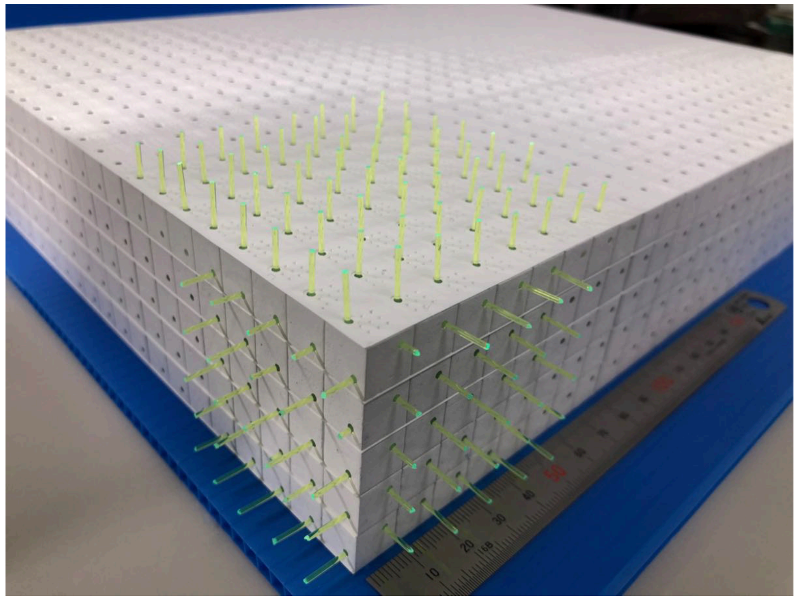




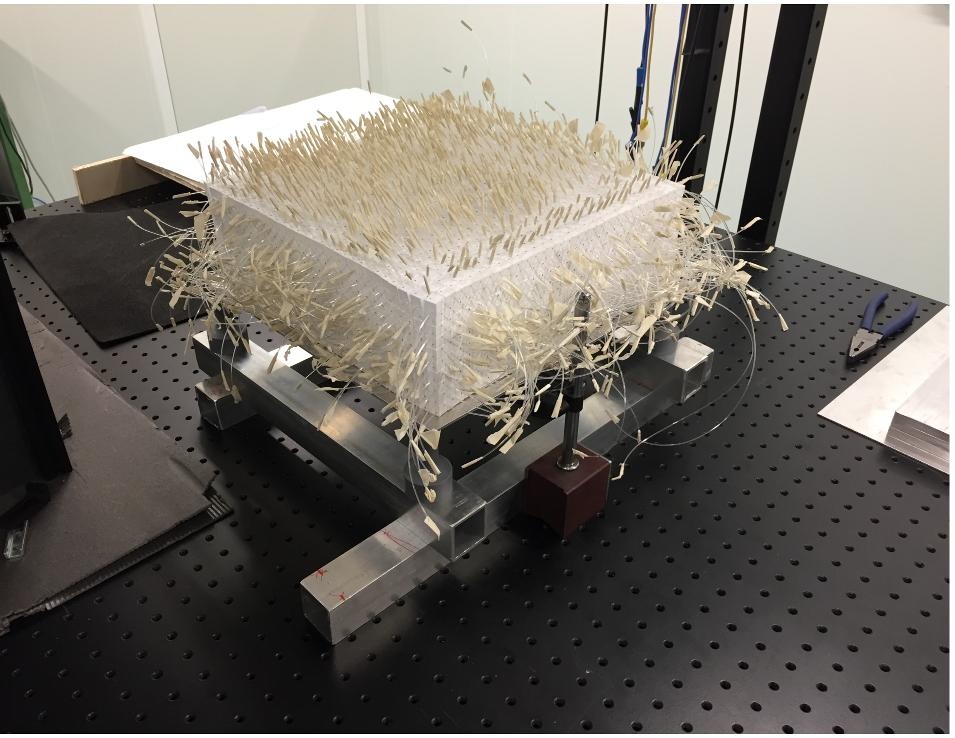


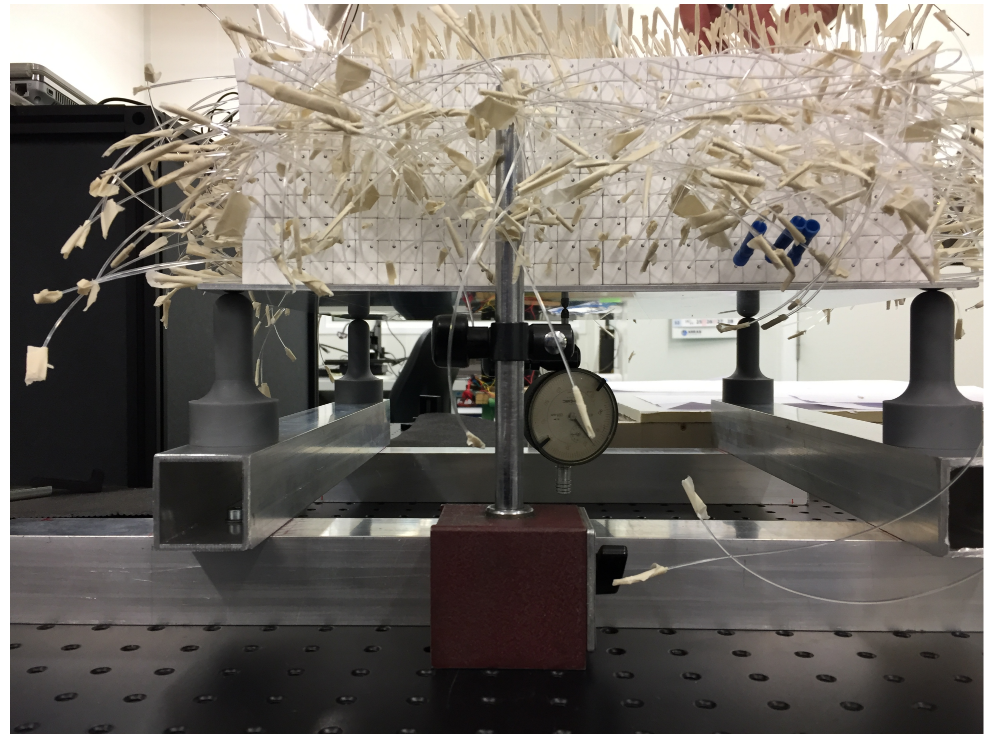
- Option 2: ultrasonic welding to fix the cubes to a thin (0.1mm) polystyrene sheet

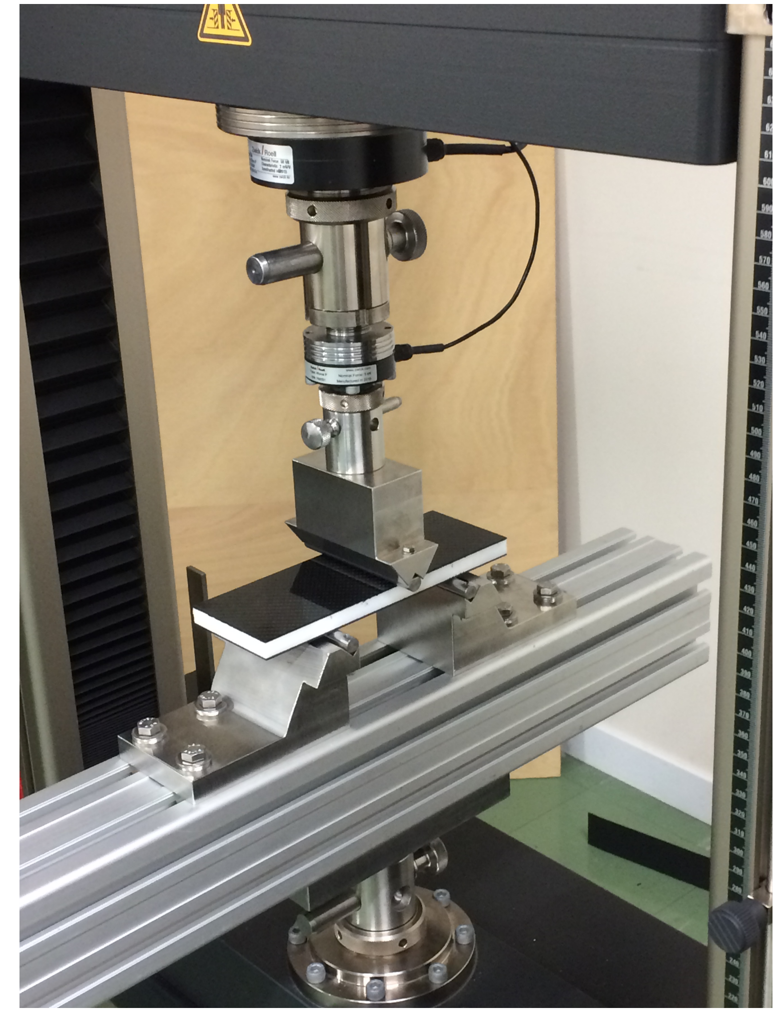




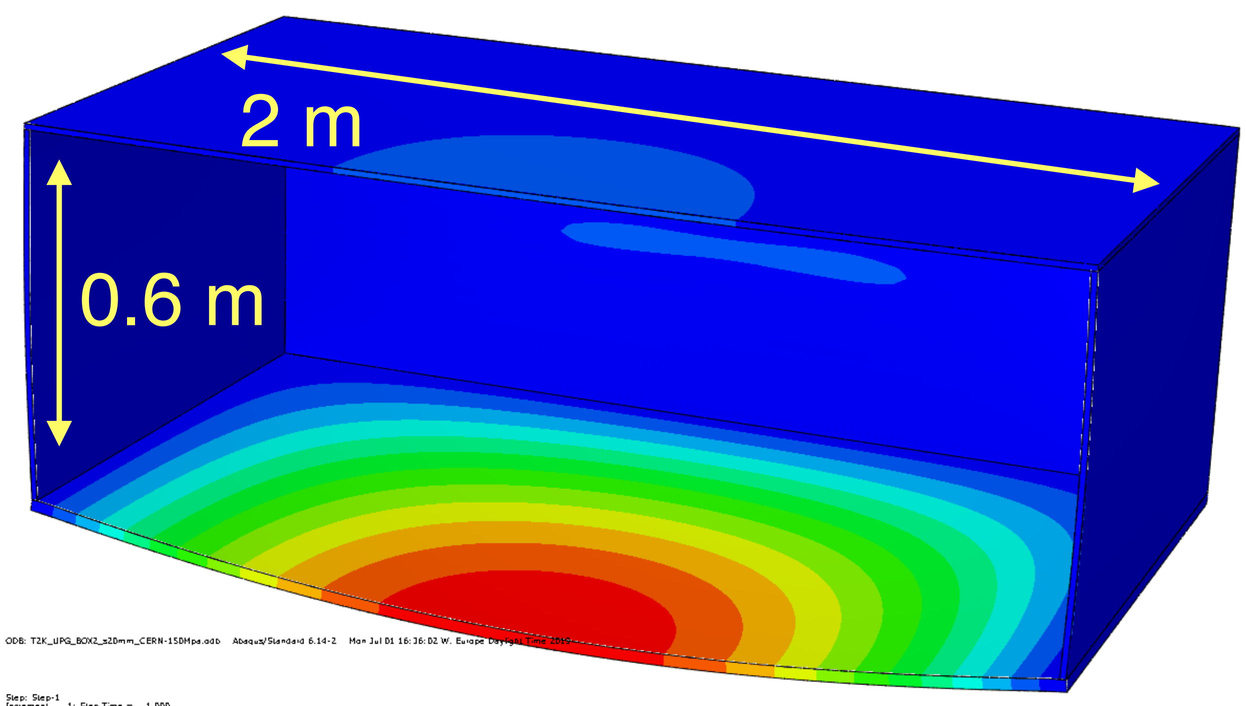
Mechanical tests of the carbon-fiber box







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

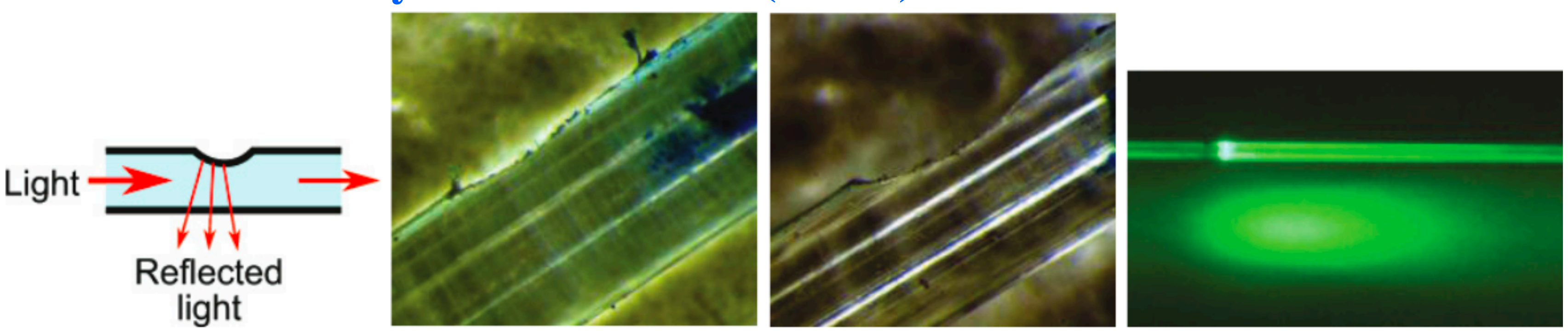


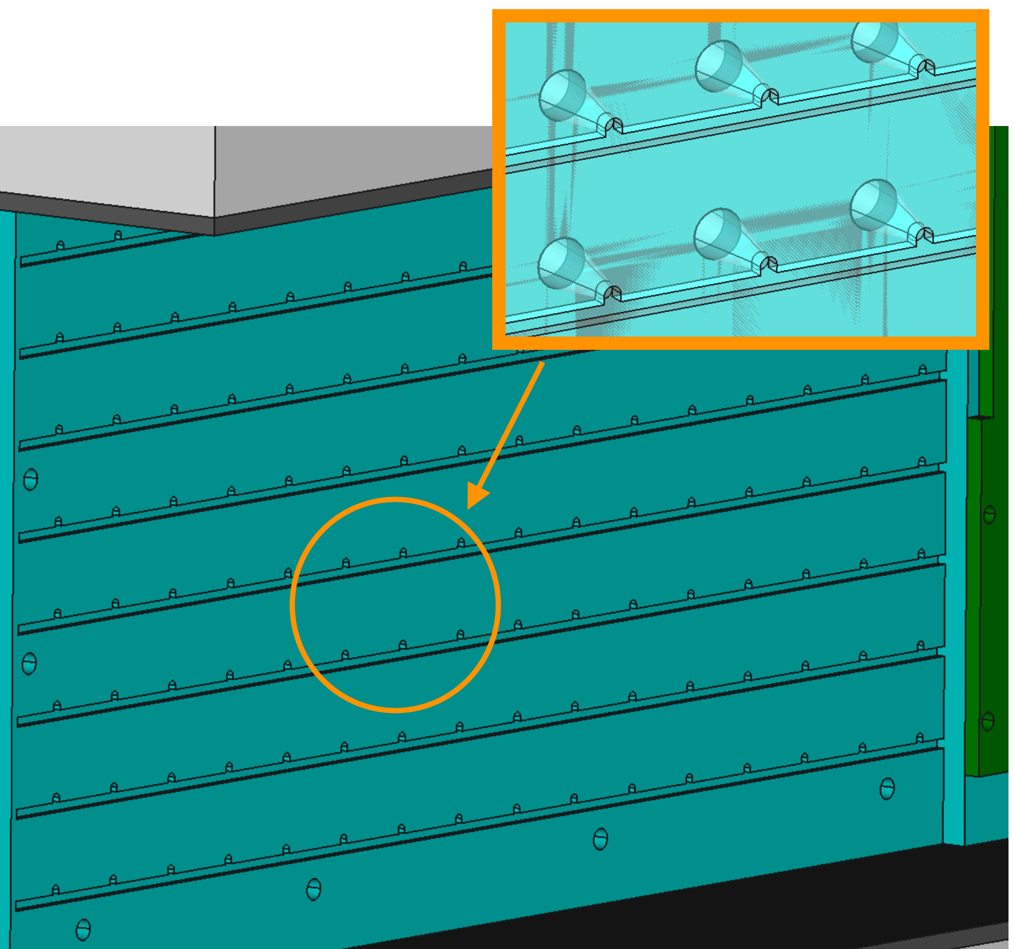
- Without pressure on the sides, the behavior is not very different from water
- Stress / deformation tests show that the holes (⌀3mm, 10mm pitch) provide ~20% more deformation but far from breaking point
- AIREX thickness may be increased up to 3-4 cm to limit bottom maximal deformation to less then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

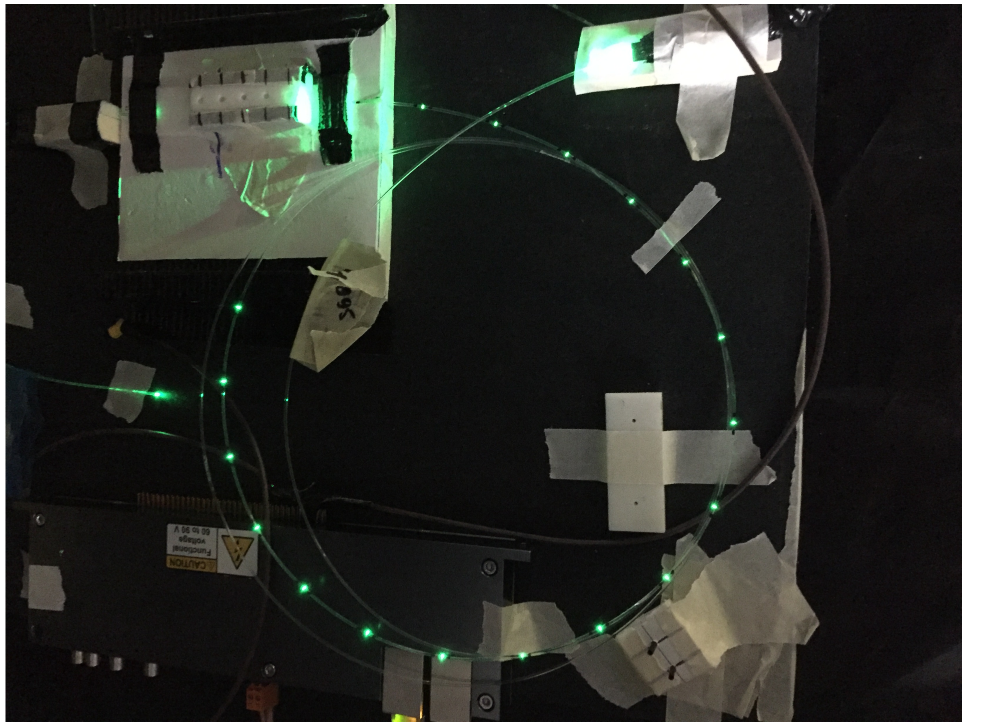
The options for the MPPC calibration system

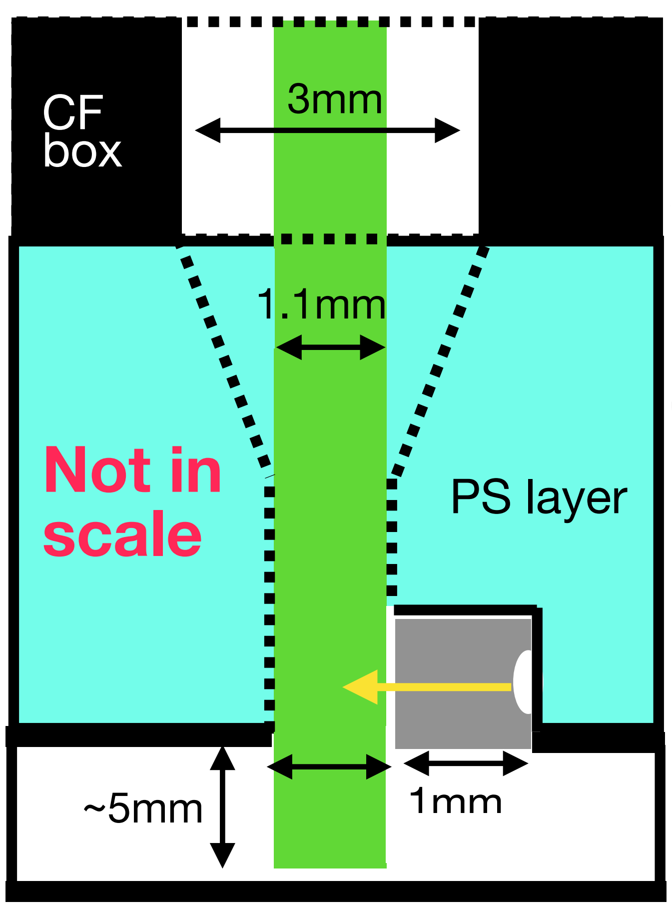
- A very compact LED calibration / monitoring system for MPPCs is required
- Evoluation of the concept proposed for the CALICE detector
- Two similar options, with either clear square fiber or light guide plate, both “notched”, are being investigated

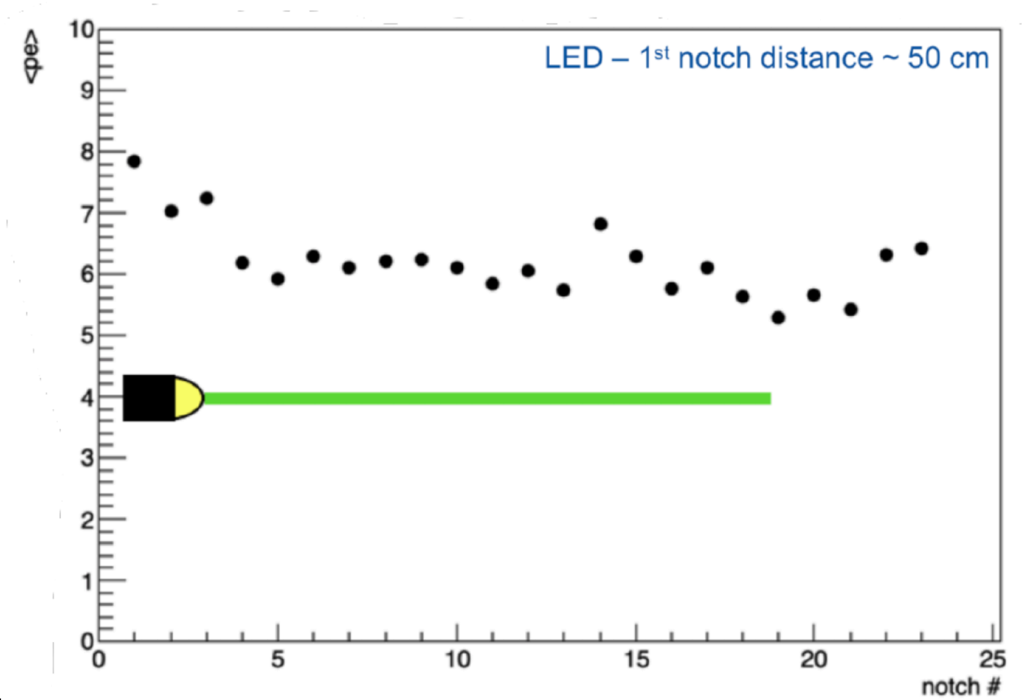
Physics Procedia 37 (2012) 402 – 409







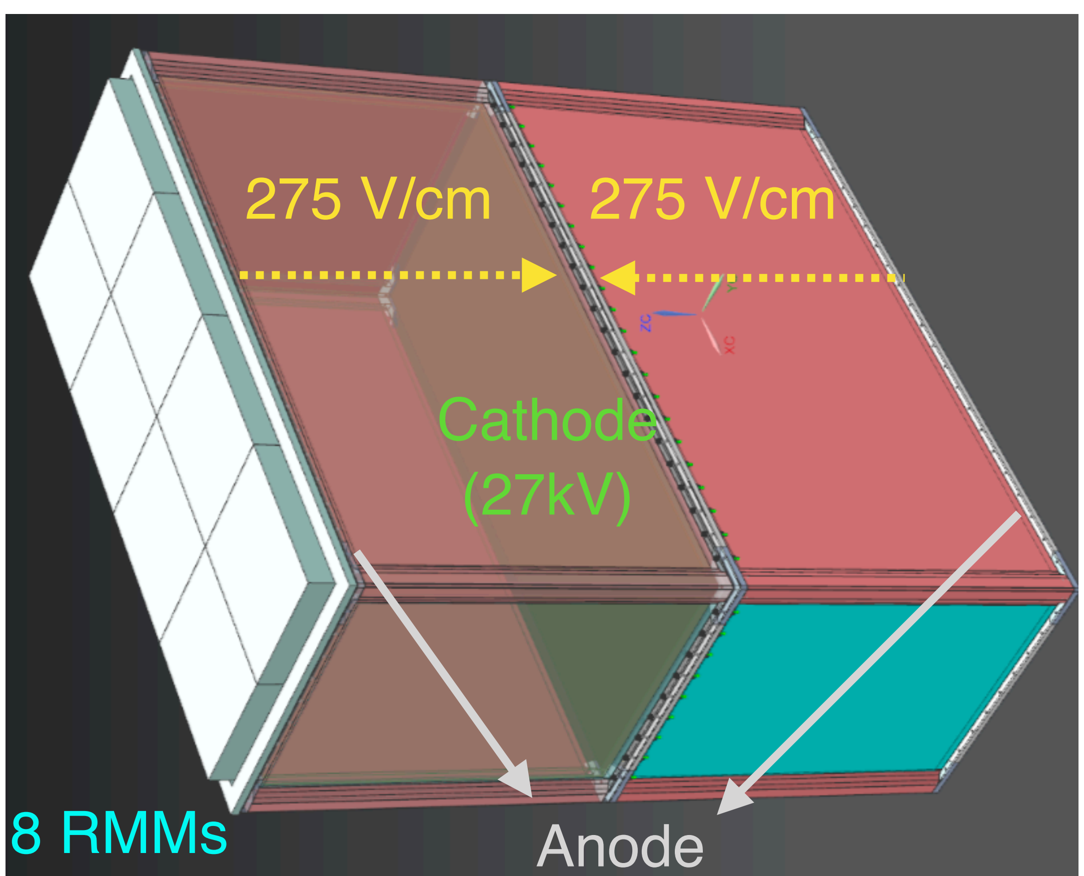




The Field Cage

- Boxes joined in middle of the detector (cathode location) and closed at opposite ends by the end-plates that include the module frames
- Cathode (RMM) flatness <0.1mm (<0.2mm), cathode-RMM // < 0.2mm
- E-field distorsion below 10^{-4} even close to the walls
- Composite sandwich structure:
  - ✦ Thickness: ~3 cm
  - ✦ Low material budget: ~2% X_{rad}
- Cathode: copper-clad G10/rohacell

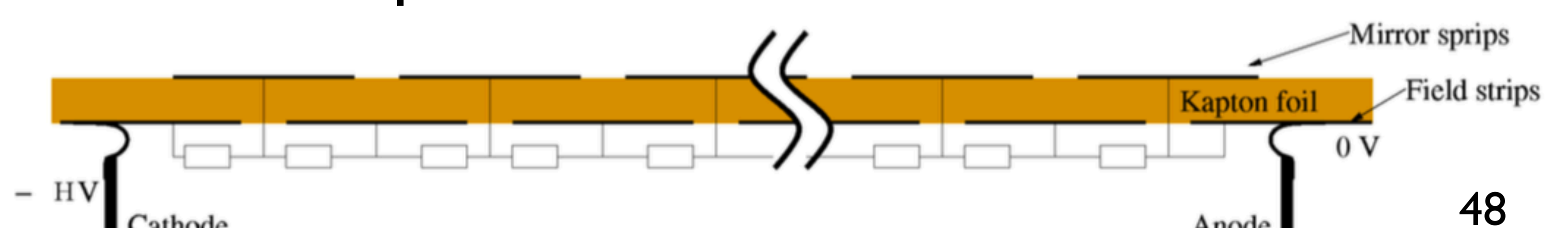
Layer of the wall	Material	thickness d d (mm)	average X_0 (mm)	d/X_0 (%)
1 (inner layer	Double layer strip foil	~0.05	143	0.08
2	Polymide film (Kapton)	0.01	285	<0.01
3	Aramid Fiber Fabric (Twaron)	2.0	~240	0.70
4	Aramid honeycomb panel (Nomex)	25	14300	0.17
5	Aramid Fiber Fabric (Twaron)	2.0	~240	0.07
6 (outer layer)	Copper foil	0.01	143	0.07
Total		~30		1.7



Walls joining cathode/anodes covered by field-shaping electrodes

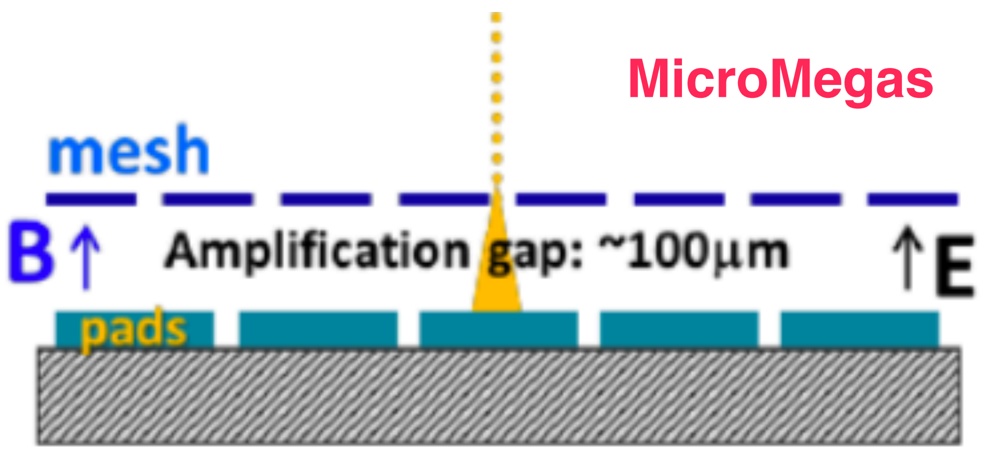
- ✦ Kapton foil as insulator (40µm)
- ✦ Copper coated strips (5µm)
- ✦ Pads to connect electrically strips with precision resistors

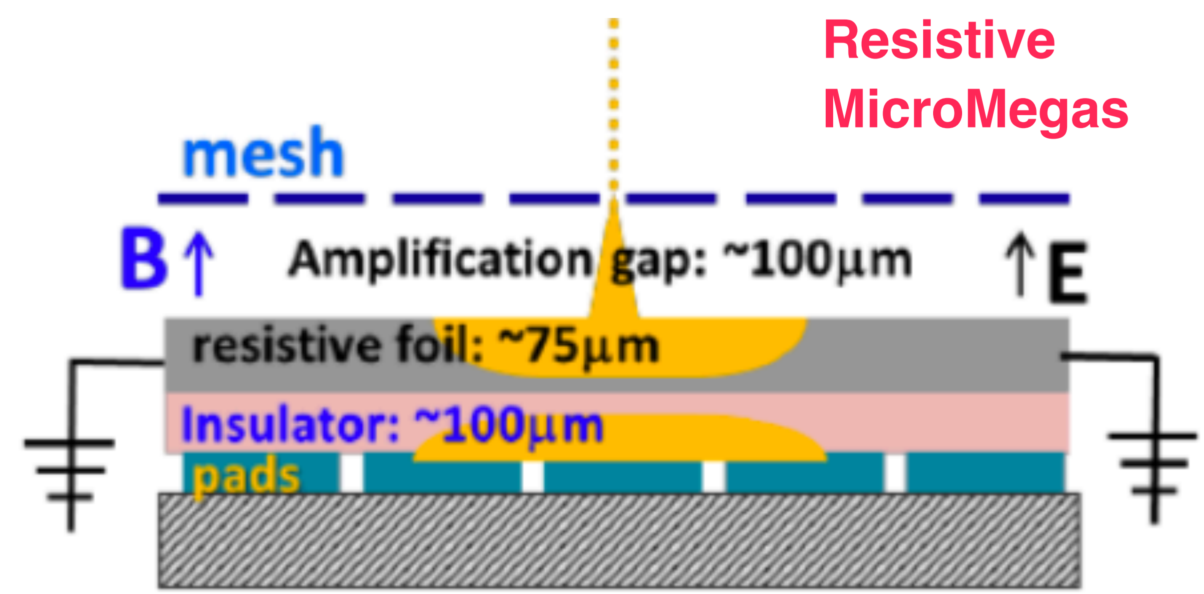
Mirror strips on the external side



Resistive MicroMegas

- MicroMegas (MM) invented by a Saclay-CERN collaboration
- Further development for ILC-TPC

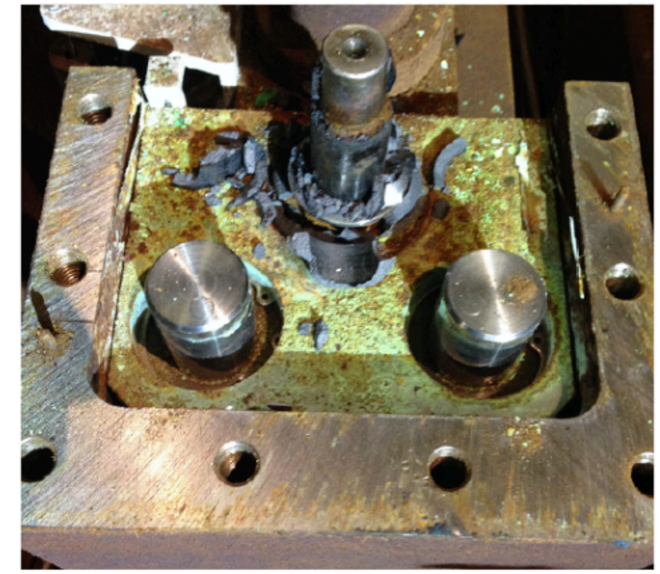


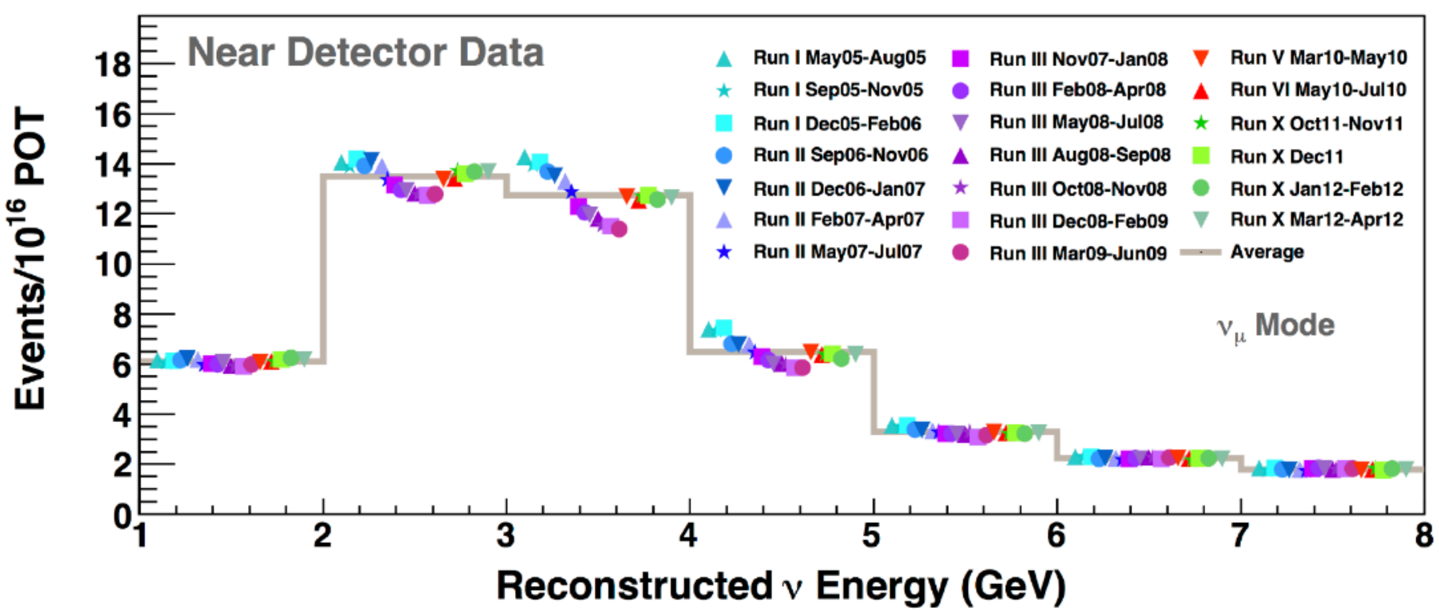


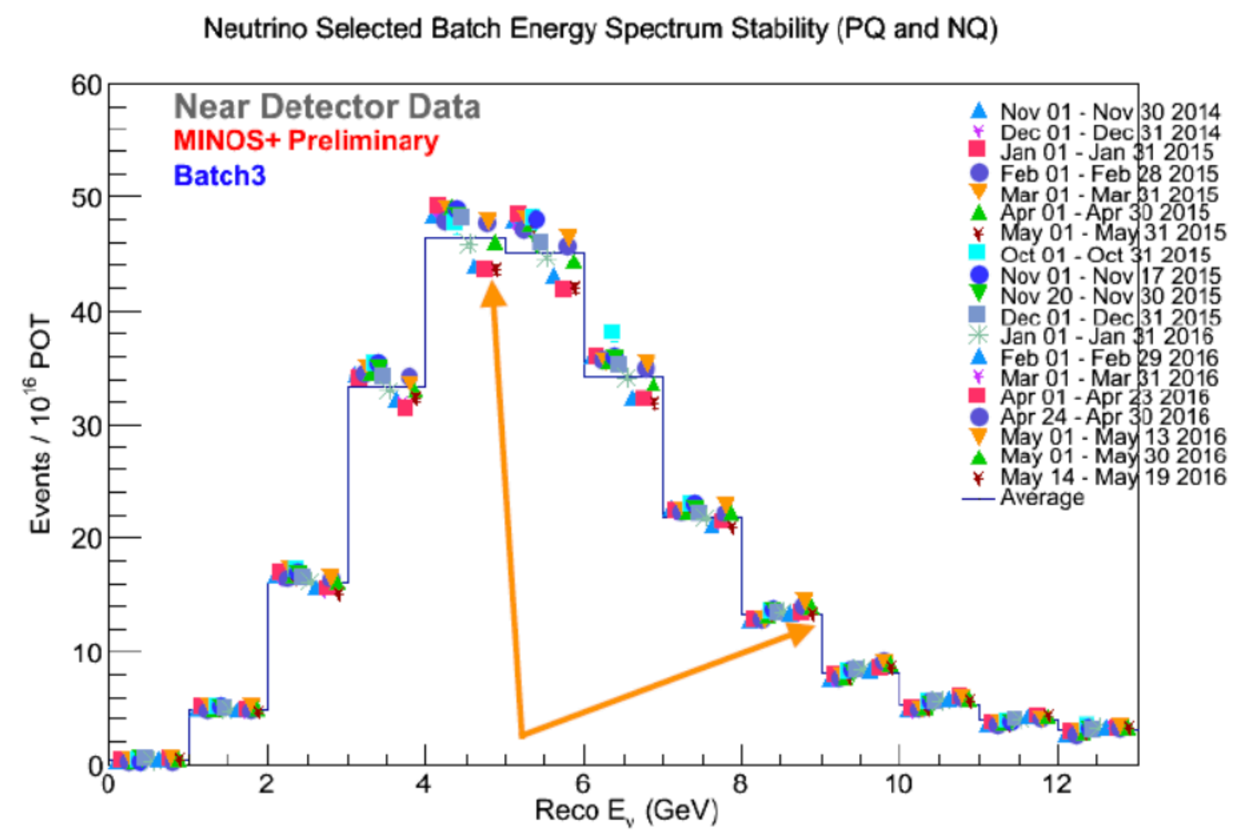
$$\rho(r,t) = \frac{RC}{2t} e^{-r^2 RC/(4t)}$$

- Charge deposited by the avalanche spreads with time as Gaussian
- Improved space-point resolution compared to MicroMegas
  - ✦ Achieve same resolution as V-TPCs with a lower # of channels (larger pads)
  - ✦ Better space-point resolution than V-TPC with same # of channels
- MM discharges are naturally suppressed: no protection diodes for FE boards

Example of beam spectrum monitoring







- MINOS ND found problems by looking at the time-dependent variation of the neutrino reconstructed energy spectrum
- NOvA (off-axis) didn't observe anything