System for on-Axis Neutrino Detection (SAND)

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DUNE Neutrino Interaction School 2021

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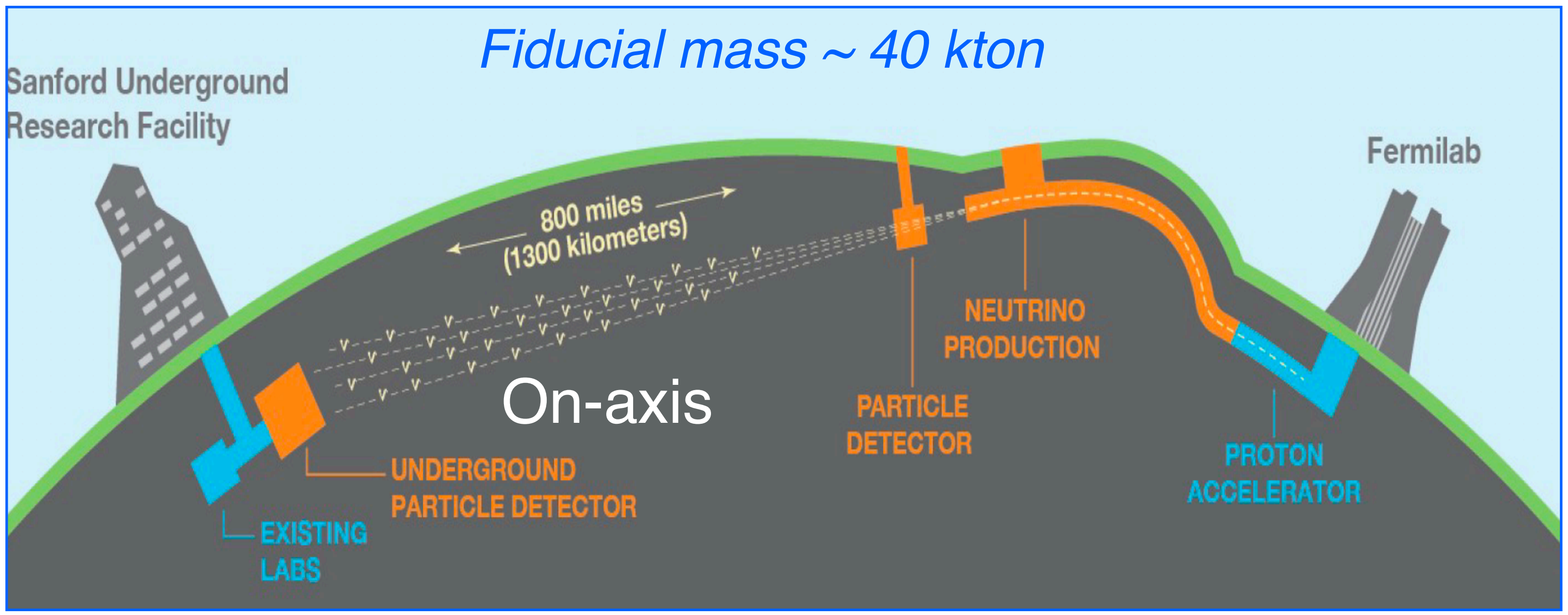
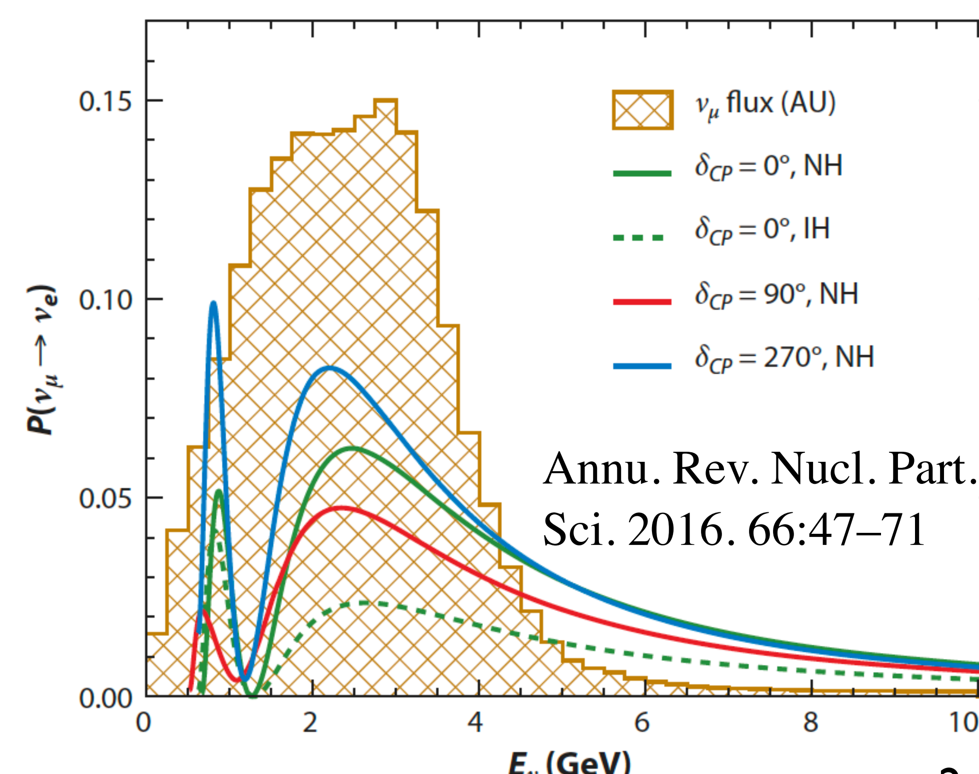
The DUNE experiment

Measure CP violating phase and neutrino Mass Hierarchy by searching for differences in the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities



Far Detector is "On the Neutrino Axis"
→ neutrino oscillations are measured by precisely reconstruct the spectrum normalization and shape

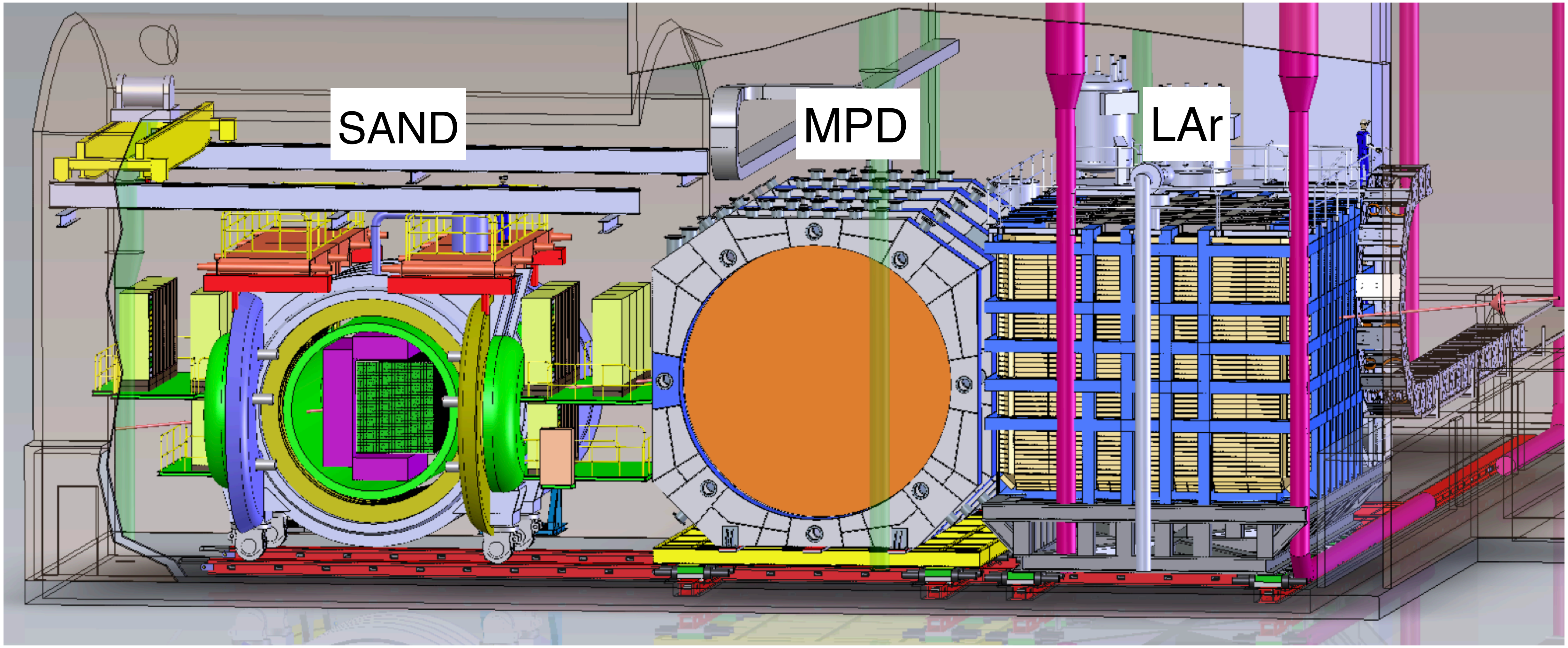
- Any distortion of the spectrum is a source of systematic uncertainty
- DUNE needs a Near Detector (ND) that can:
  - ✦ Measure the event rate in argon (flux + cross section)
  - ✦ Independent measurement of $\nu/\bar{\nu}$ flux
  - ✦ Monitor the beam and spectrum stability
  - ✦ Provide robustness to "unknown of unknown"



Annu. Rev. Nucl. Part. Sci. 2016. 66:47–71

The DUNE Near Detector

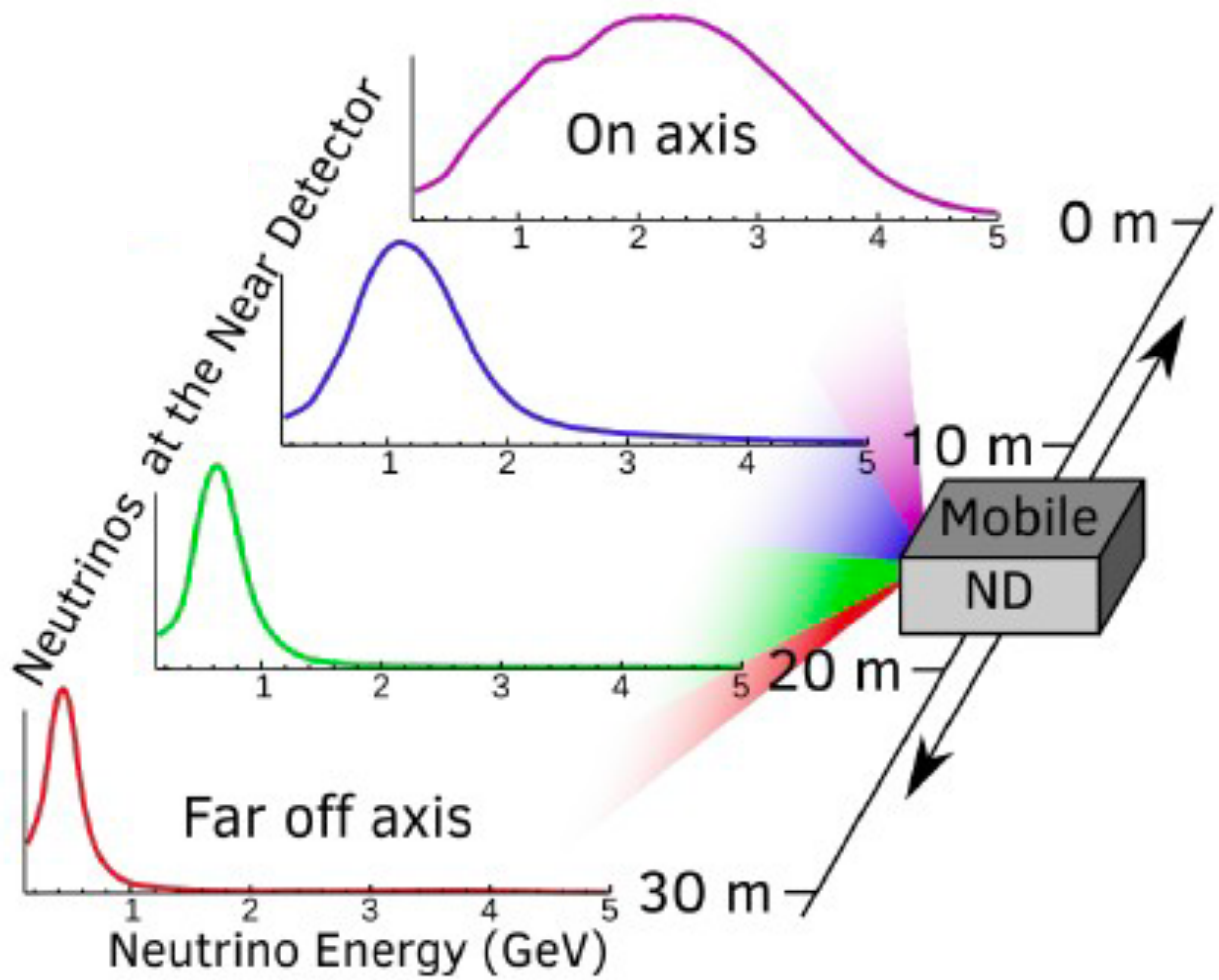
arXiv:2103.13910



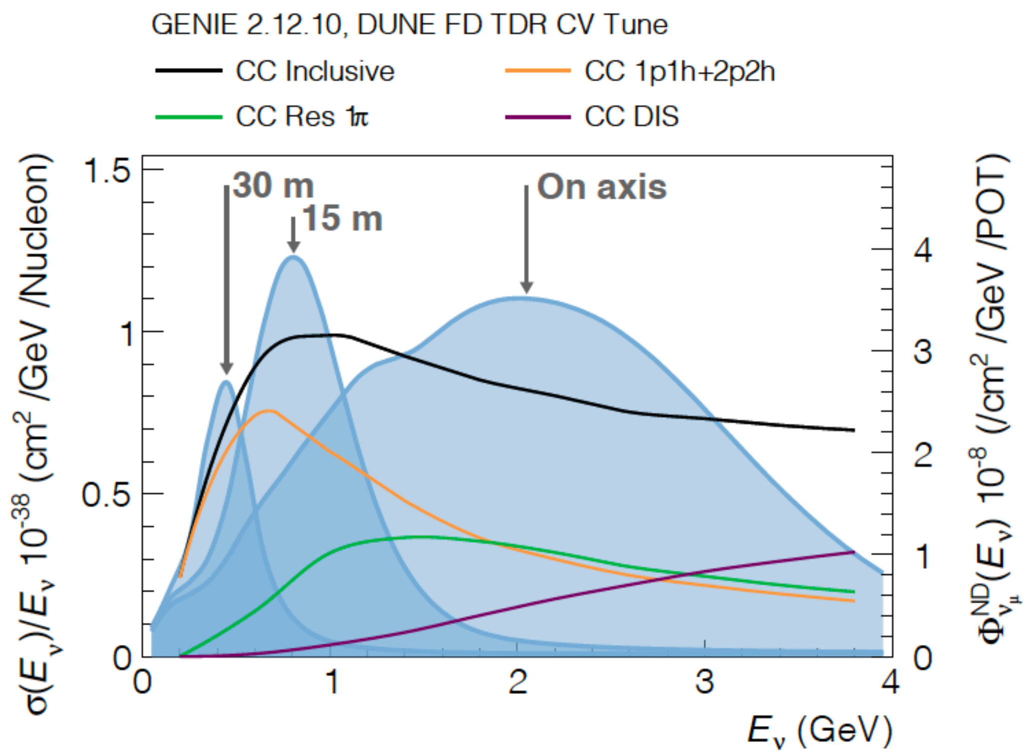
- Three main near detector complexes:
  - ✦ System for on-Axis Neutrino Detection (SAND)
  - ✦ HpTPC+ECAL (ND-GAR)
  - ✦ Liquid Argon (ND-LAr)
- Complementarity necessary to achieve:
  - ✦ Detection of ν interactions in argon nucleus, Low-momentum threshold for protons, Neutron detection, Beam monitor, ν flux estimation

Detector	Target (Fid. mass t)	# ν_μ CC ($X10^6$)
LAr	Ar (50)	80
HPgTPC	Ar (1)	1.5
SAND	CH (8)	12

The PRISM technique at the DUNE ND

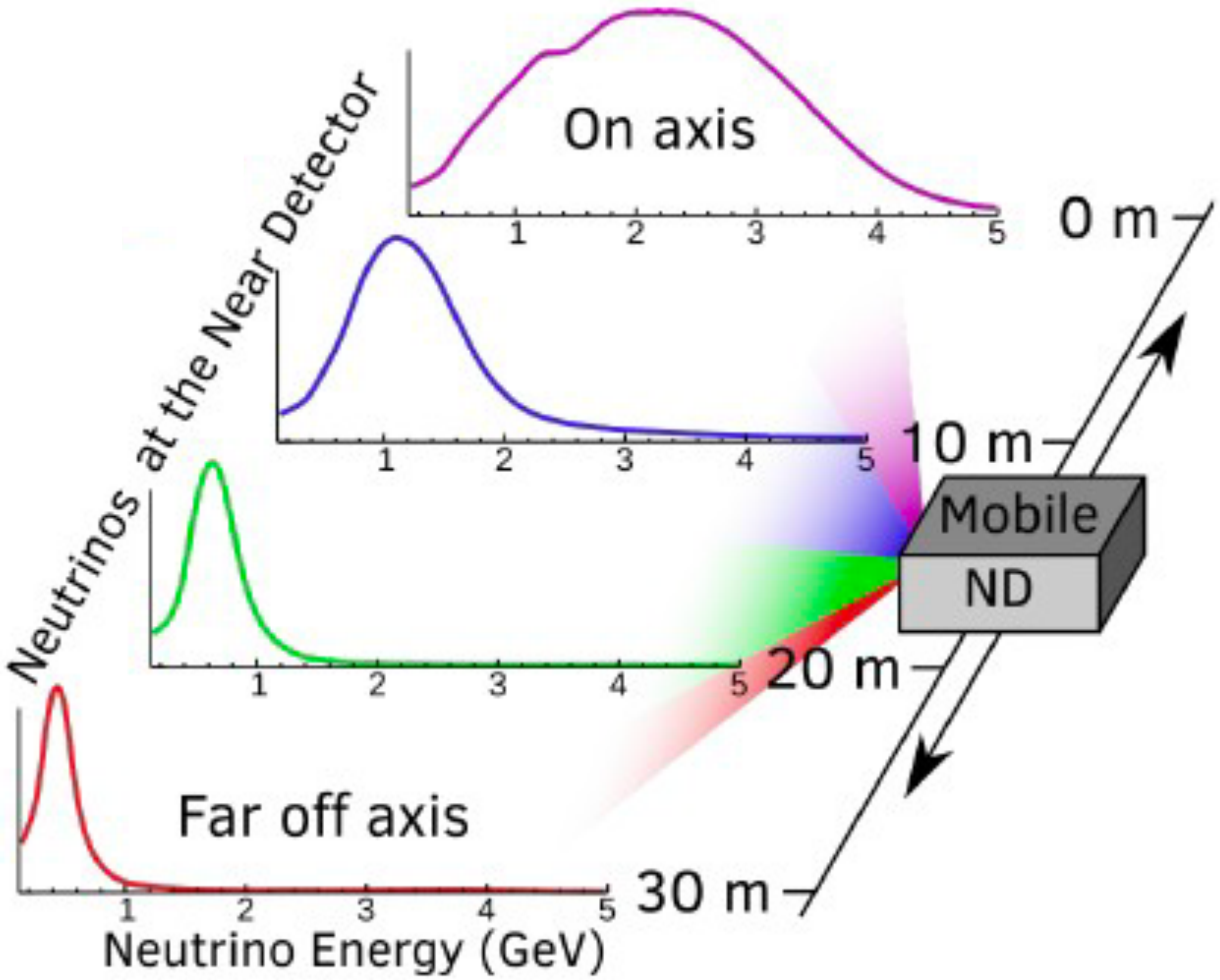


Details about the PRISM will be given later by L.Pickering



- The ND-LAr and ND-GAr detector complexes will move to different off-axis angles to study Ar-detector response as a function of the neutrino energy
- Thus, for a non-negligible time both detectors will not detect the "same neutrino beam" that goes to the Far Detector (FD)
- However, it's important to make sure the beam rate, profile and the event spectrum are stable over the time, i.e. no issues occurred in the ν beam line

The PRISM technique at the DUNE ND



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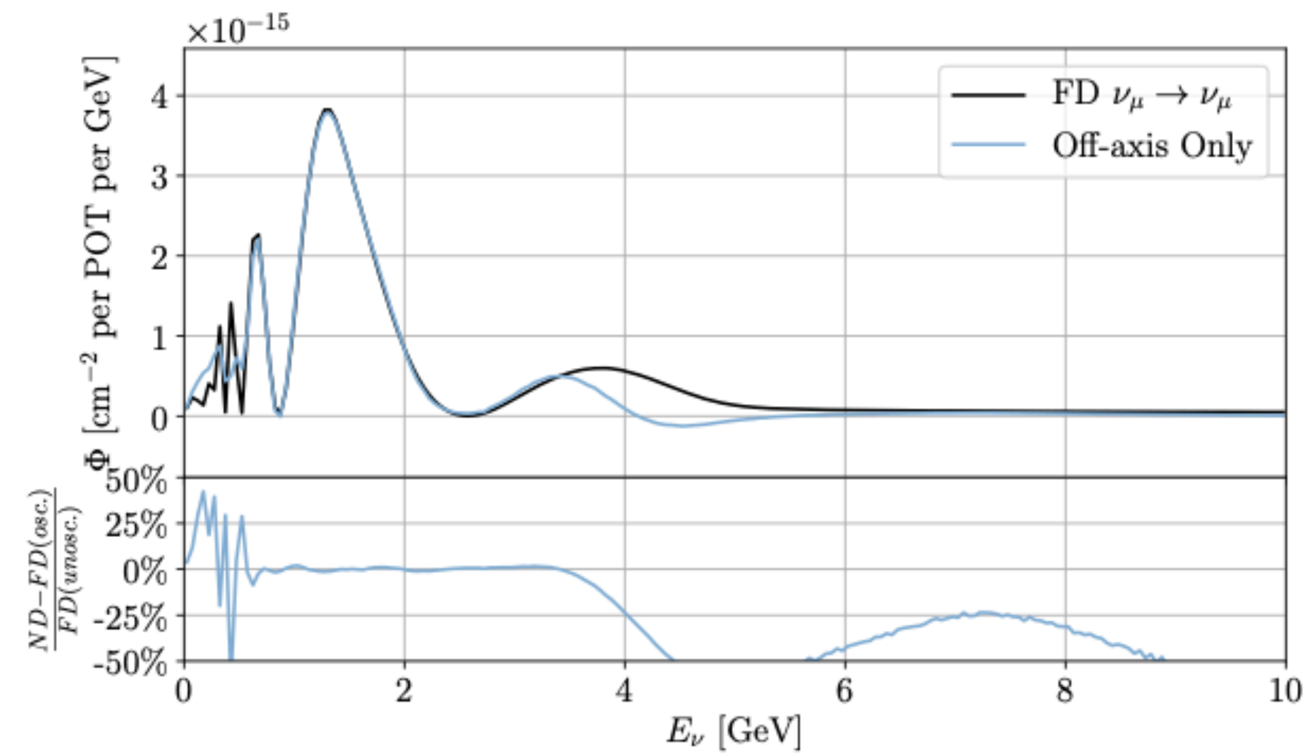

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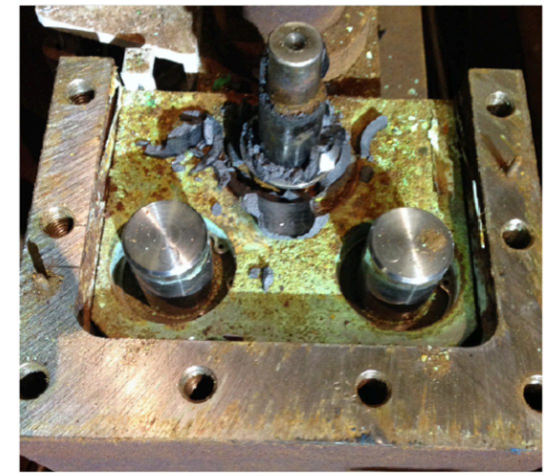
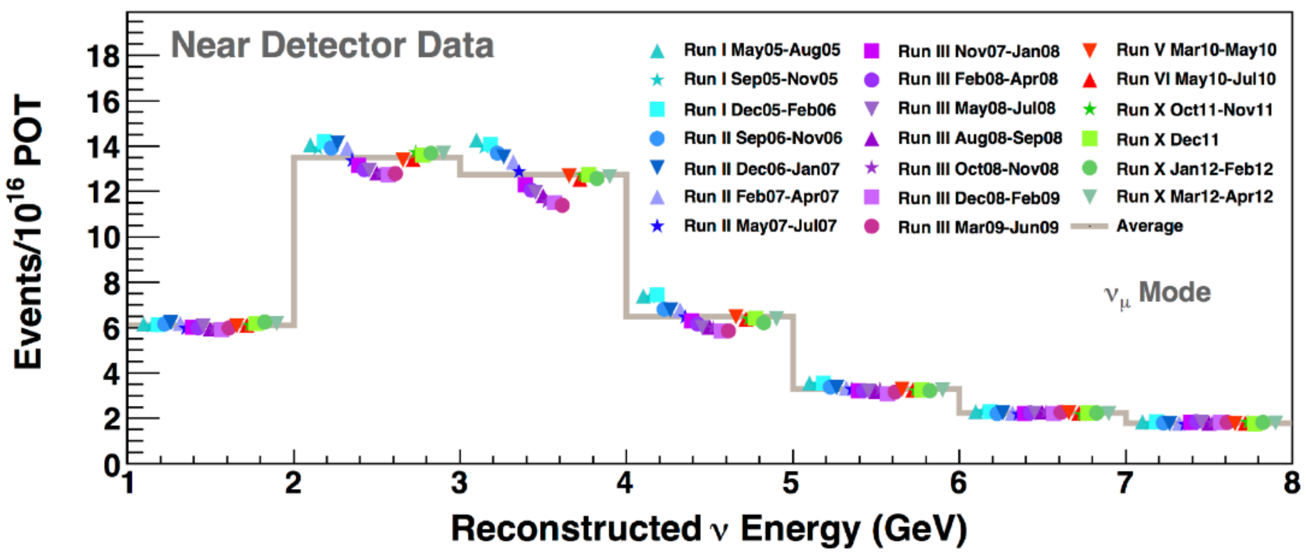
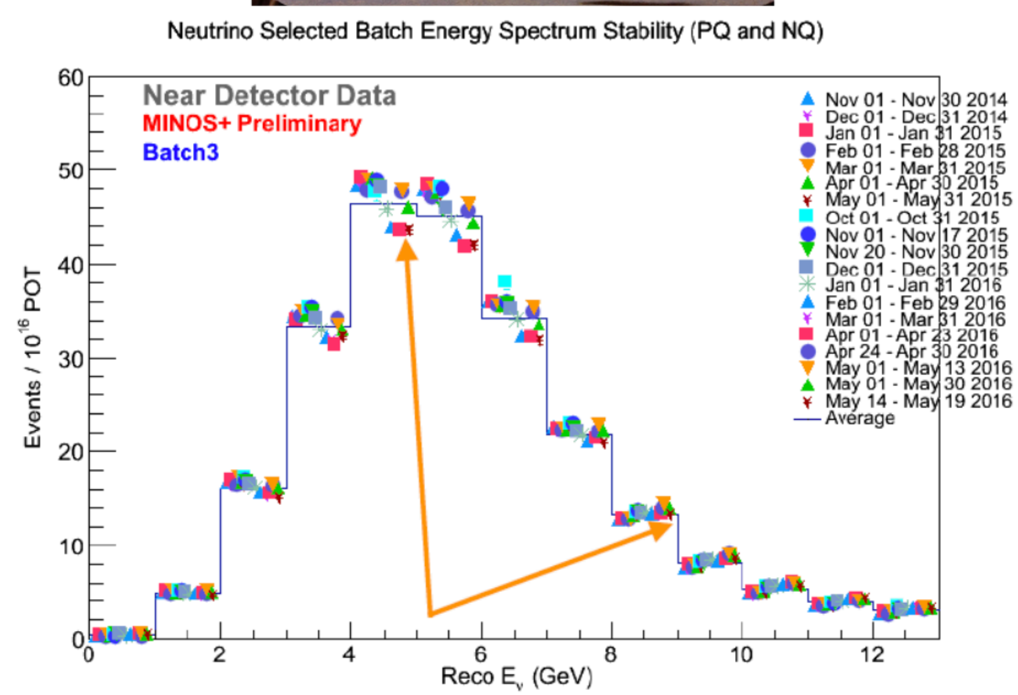
Importance of beam monitoring with DUNE-PRISM





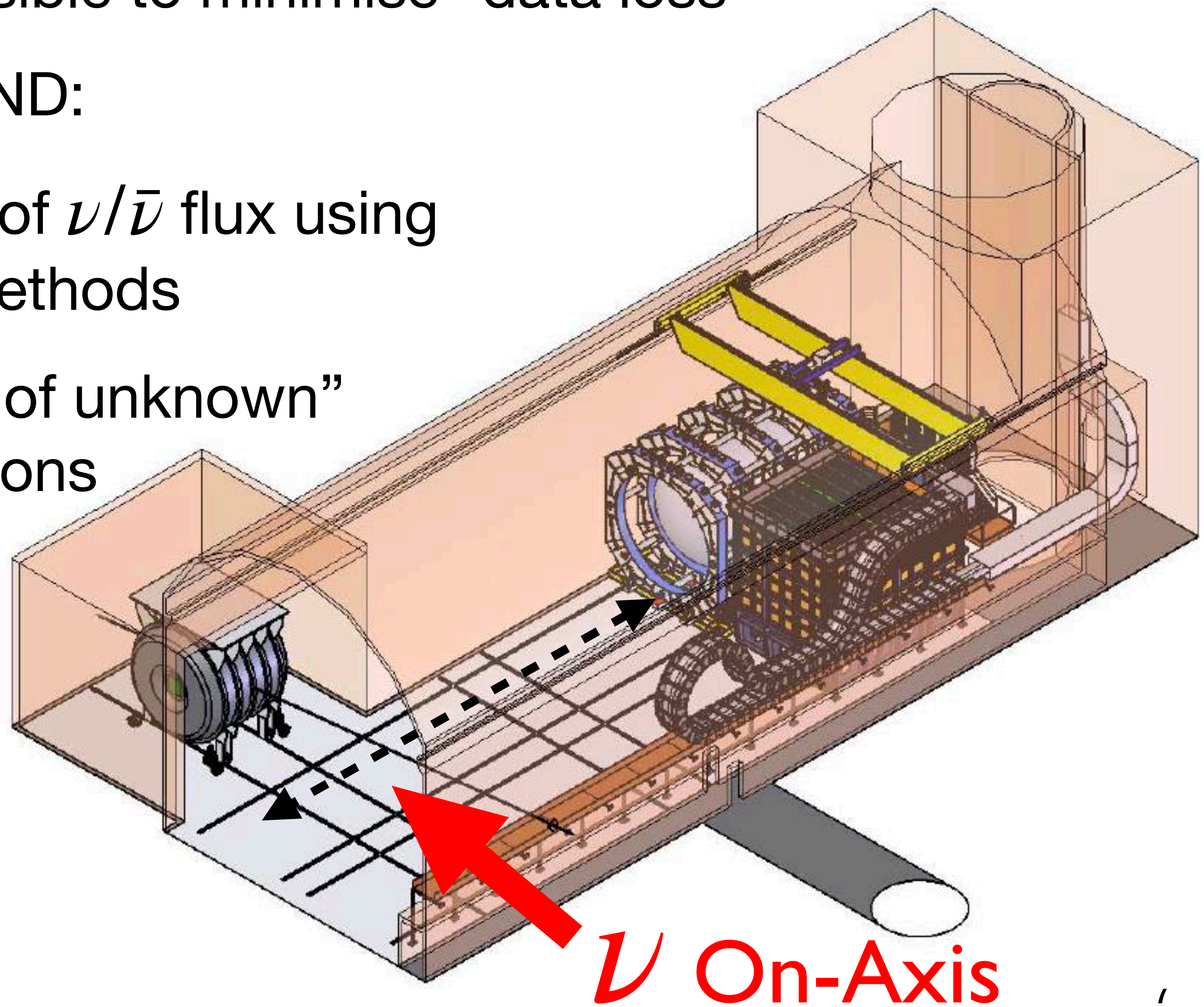


- MINOS ND (on-axis) found issues when looking at the time-dependent variation of the neutrino reconstructed energy spectrum
- NOvA (off-axis) didn't observe significative changes

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

The DUNE Near Detector

- 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
    - ✦ It must be massive (many tonnes) to be able to detect possible issues in the shortest time possible to minimise “data loss”
- Other important functions of SAND:
    - ✦ Complementary measurement of $\nu/\bar{\nu}$ flux using different but complementary methods
    - ✦ Robustness against “unknown of unknown” by measuring neutrino interactions in targets other then argon and neutron detection

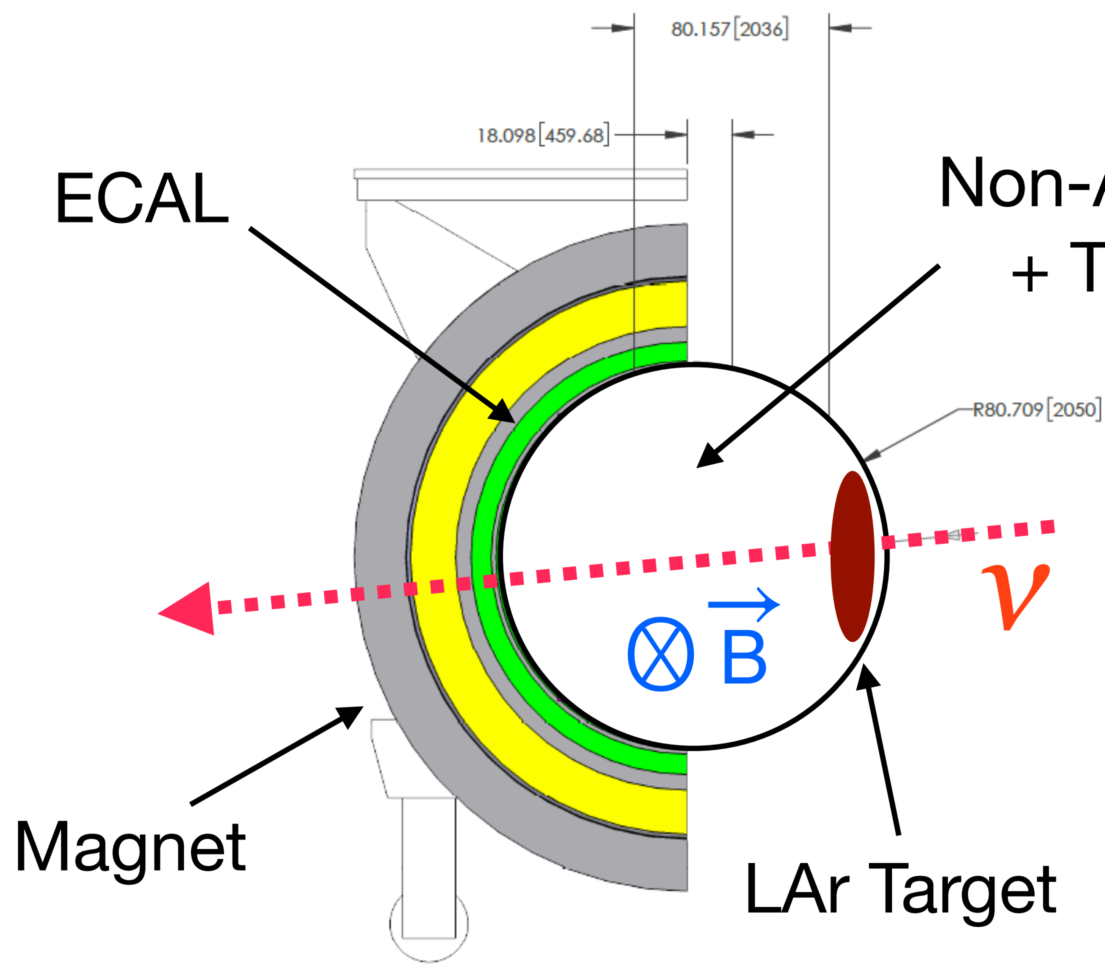


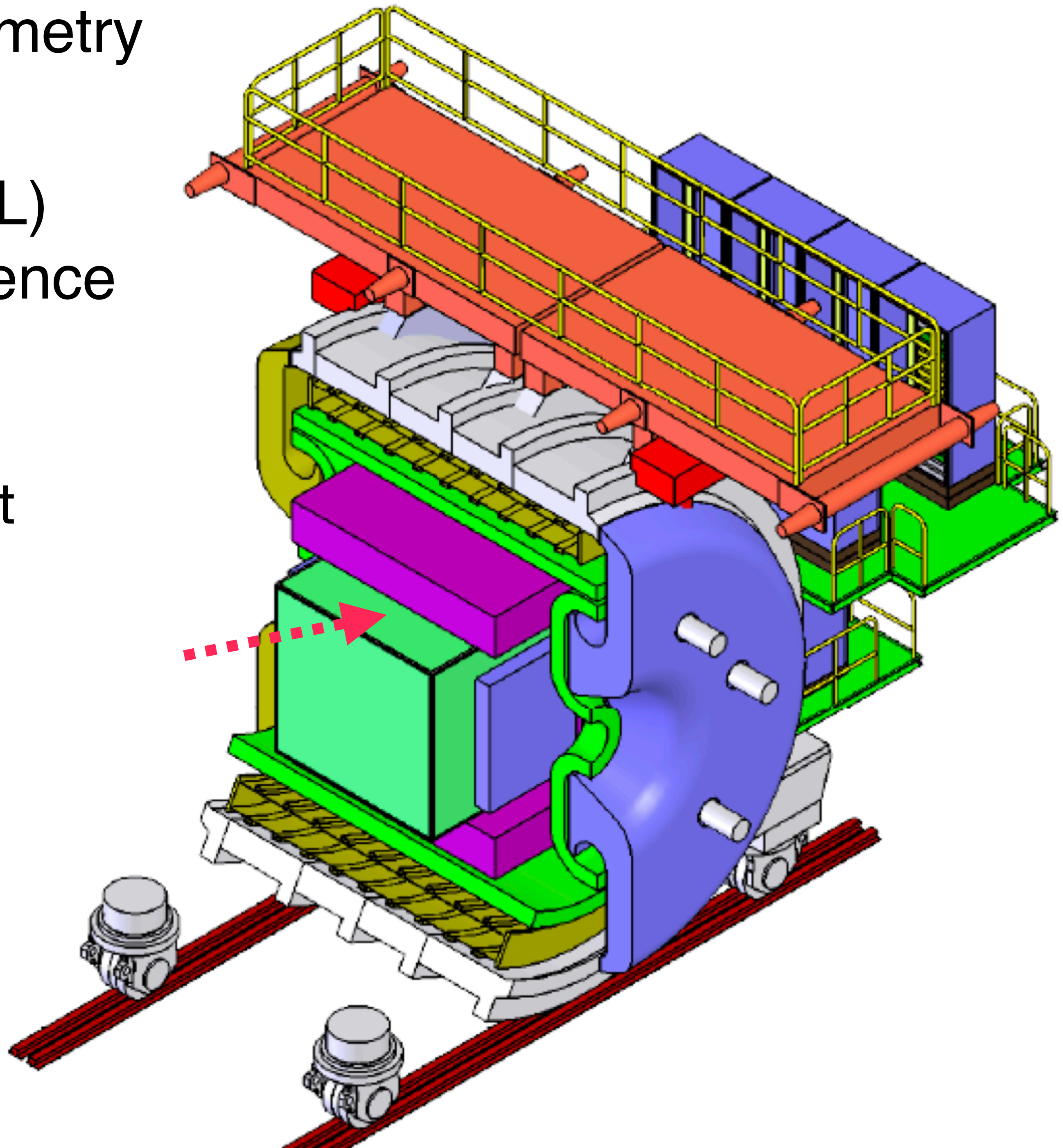
While ND-GAr and ND-LAr move to different off-axis angles SAND is always on-axis

System for on-Axis Neutrino Detection (SAND)

- SAND is a complex of several sub-detectors:
  - 1t thin LAr module (design in progress)
  - Tracker: non-argon massive target that also provides particle tracking and calorimetry
  - Everything surrounded by an Electromagnetic CALorimeter (ECAL) in a superconducting magnet Reference

The Tracker design still to be finalised (various options proposed)

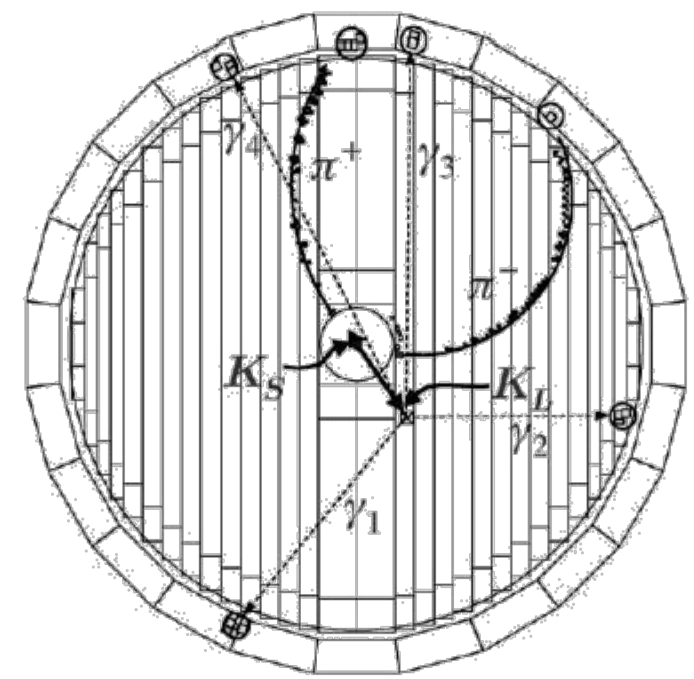


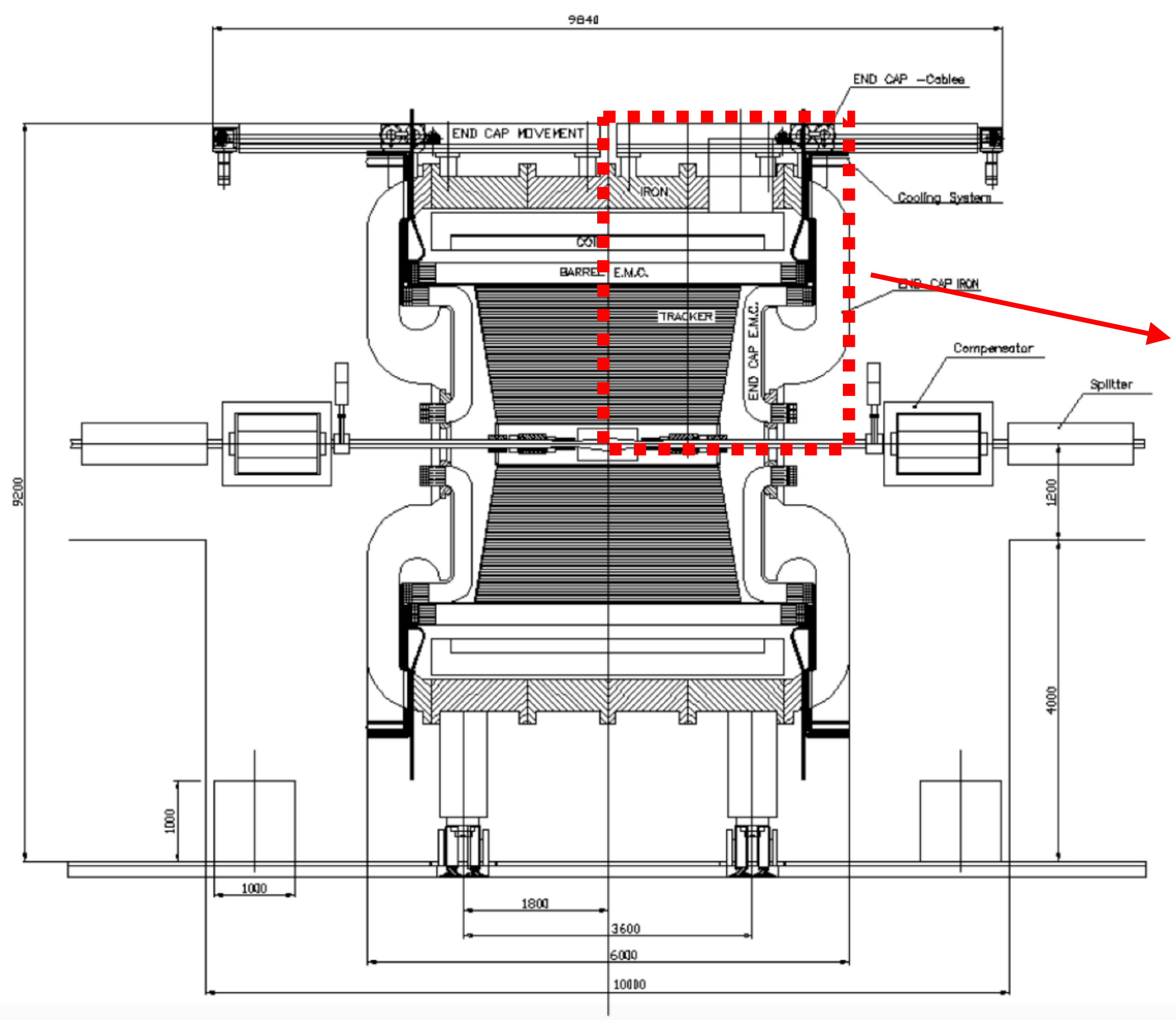


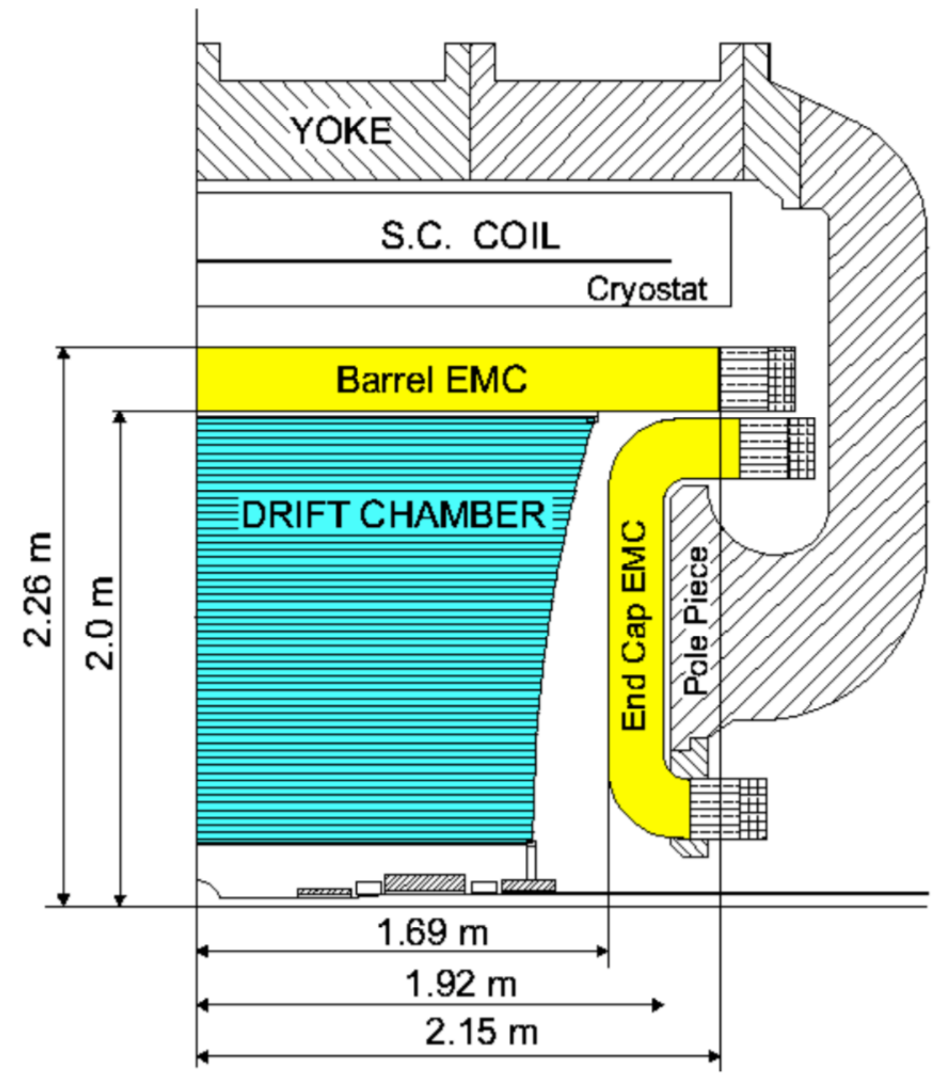
The superconducting magnet

NIM A 419 (1998) 320–325
NIM A482 (2002),364

- Both the superconducting magnet and ECAL are inherited from the KLOE detector operated at DAΦNE (LNF)







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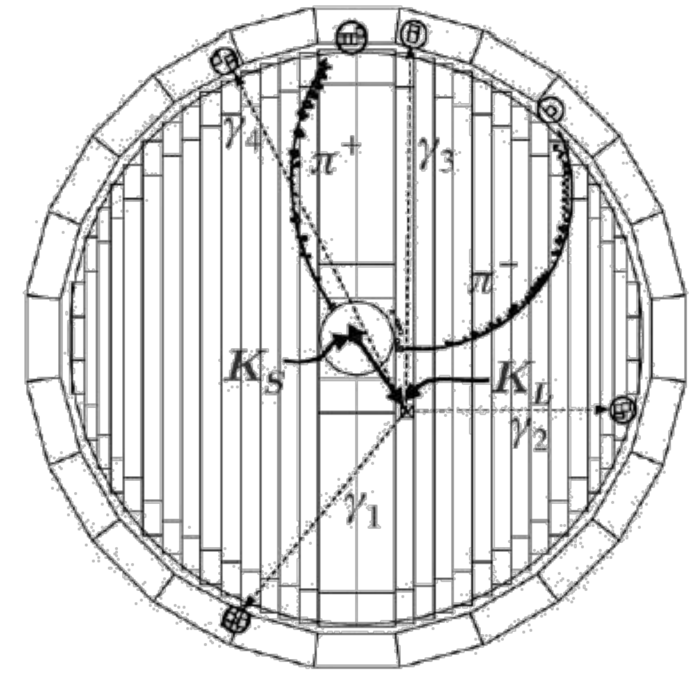
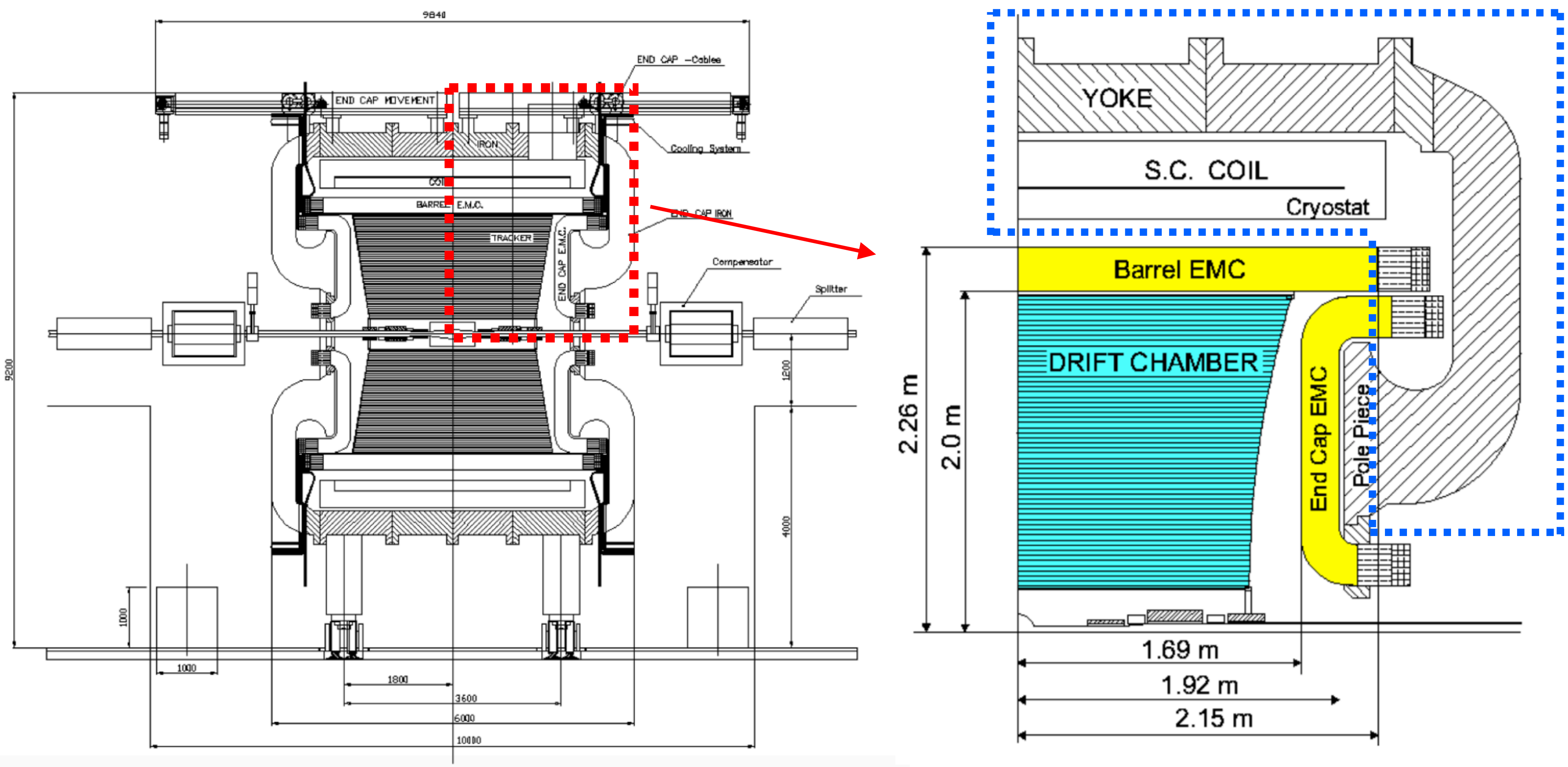
The superconducting magnet

- Both the superconducting magnet and ECAL are inherited from the KLOE detector operated at DAΦNE (LNF)
- Superconducting coil produces the magnetic field while the iron return yoke suppresses the fringe field outside the detector





KLOE magnet

The superconducting magnet

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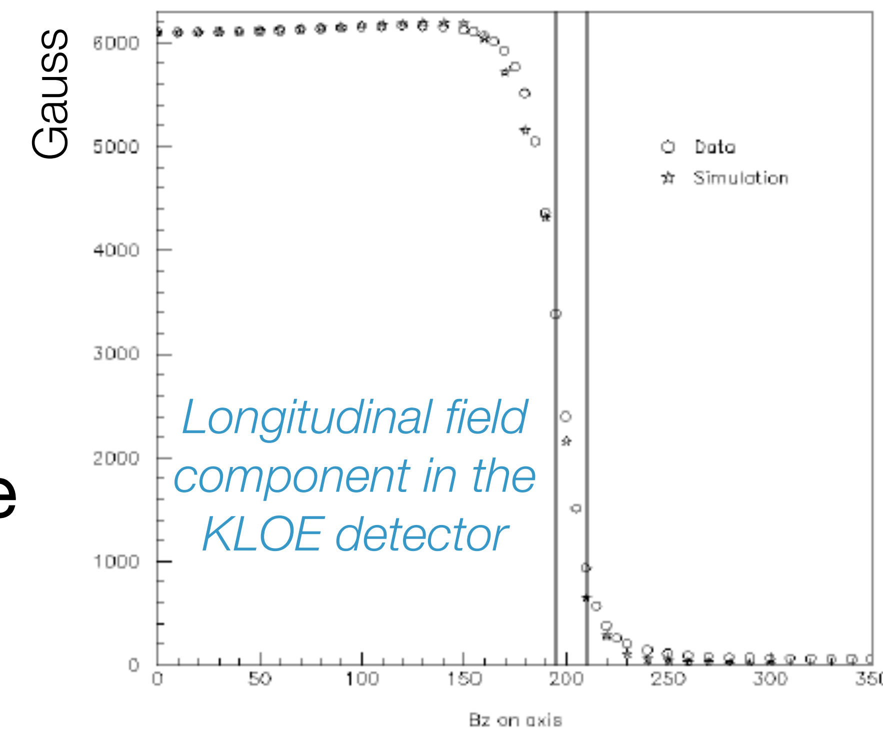
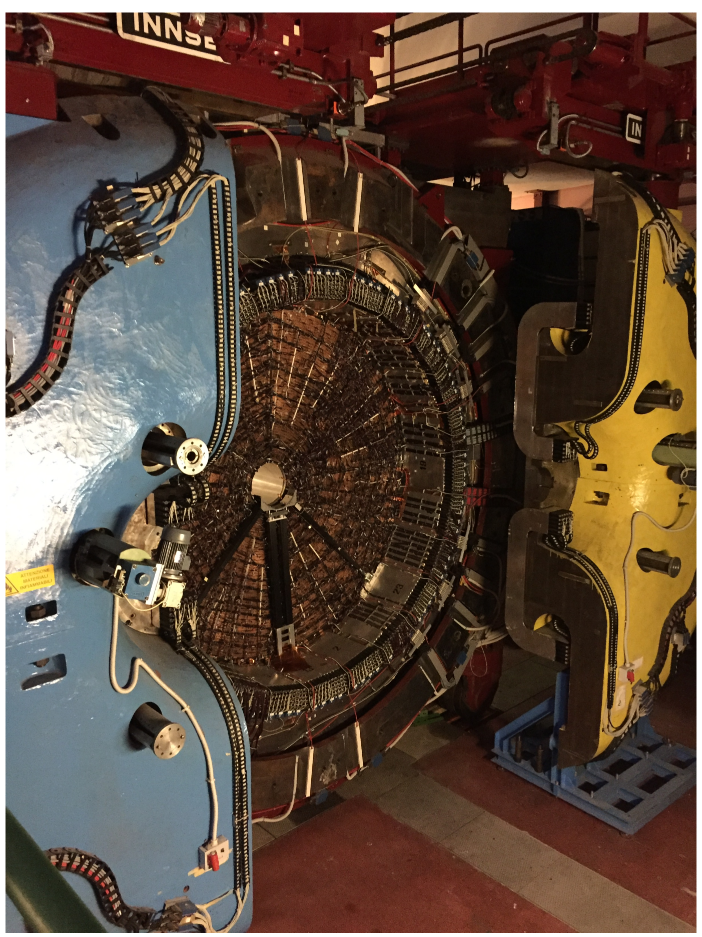
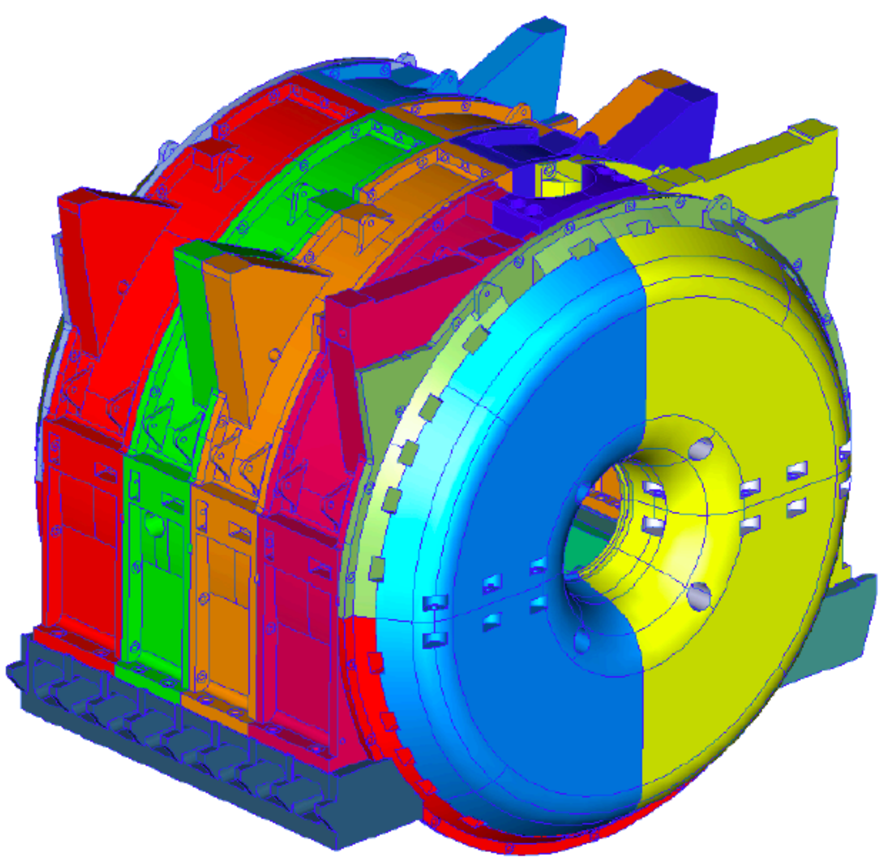
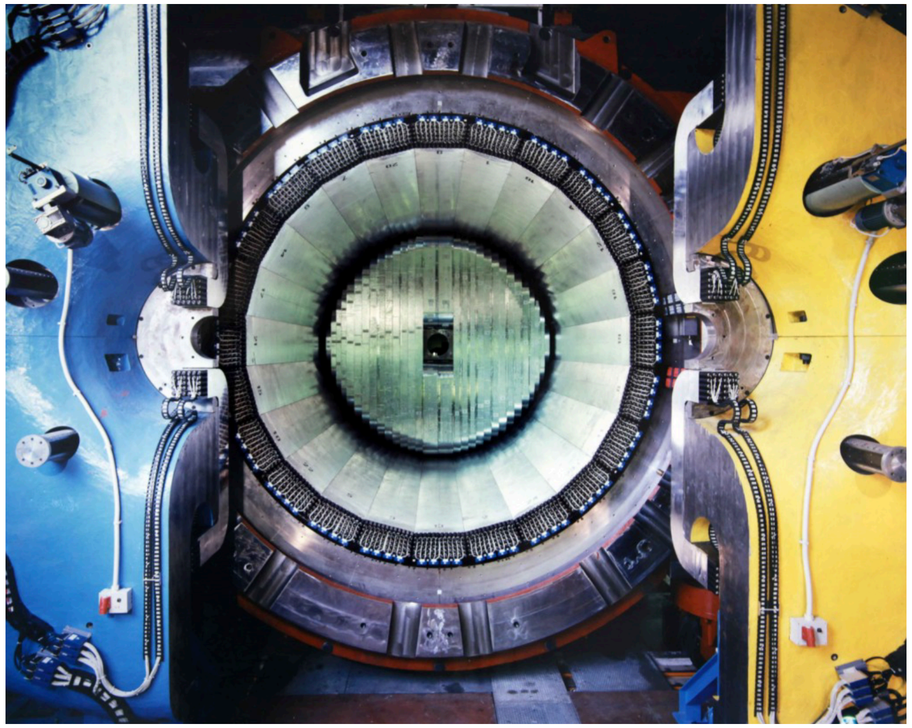
- B-field ~0.6 T (2.9 kA) in the center and quite stable for most of the inner volume (requisite for precise momentum reconstruction)
- Magnets have very large mass (~0.5 kt): potential large source of background → neutral particles (n,γ) produced by ν_μ interactions in magnet can give a vertex in the detector fiducial volume)









The Electromagnetic CALorimeter

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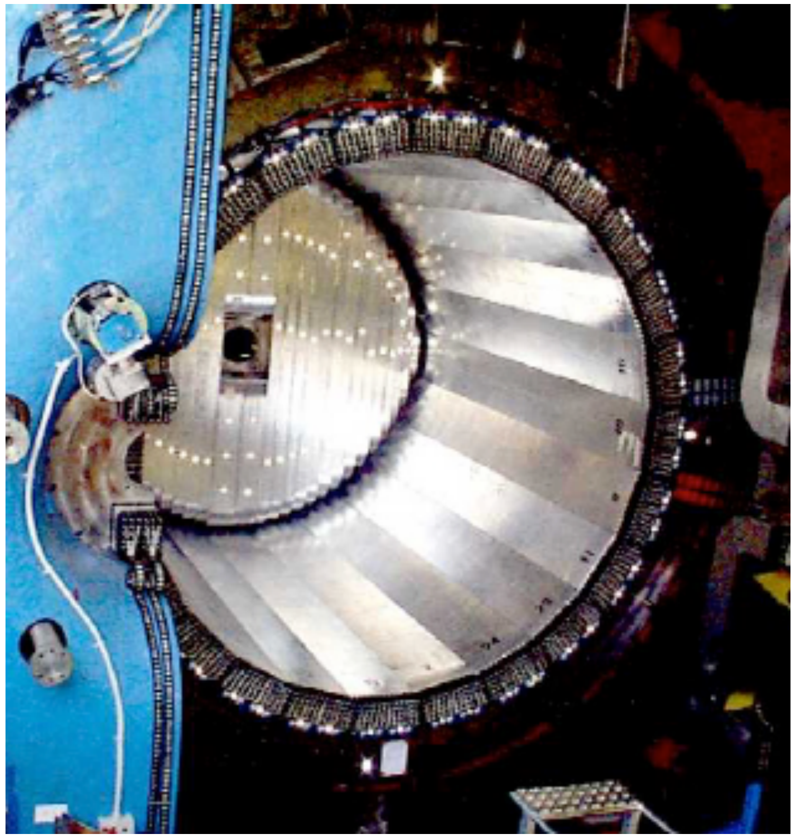
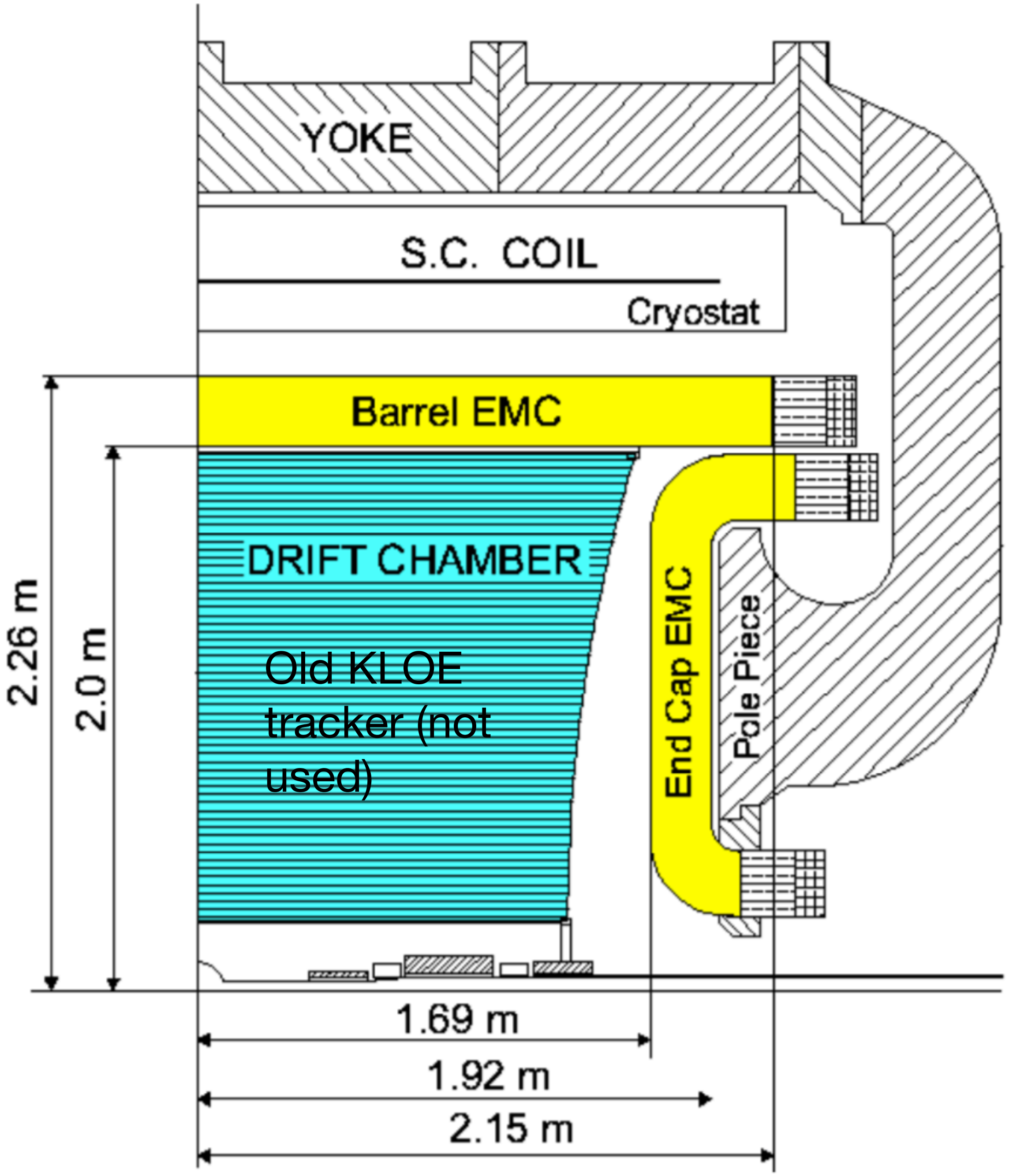


The ECAL contains all the energy of particles escaping the tracker, e.g. photons from EM shower or $\pi^0 \rightarrow \gamma\gamma$



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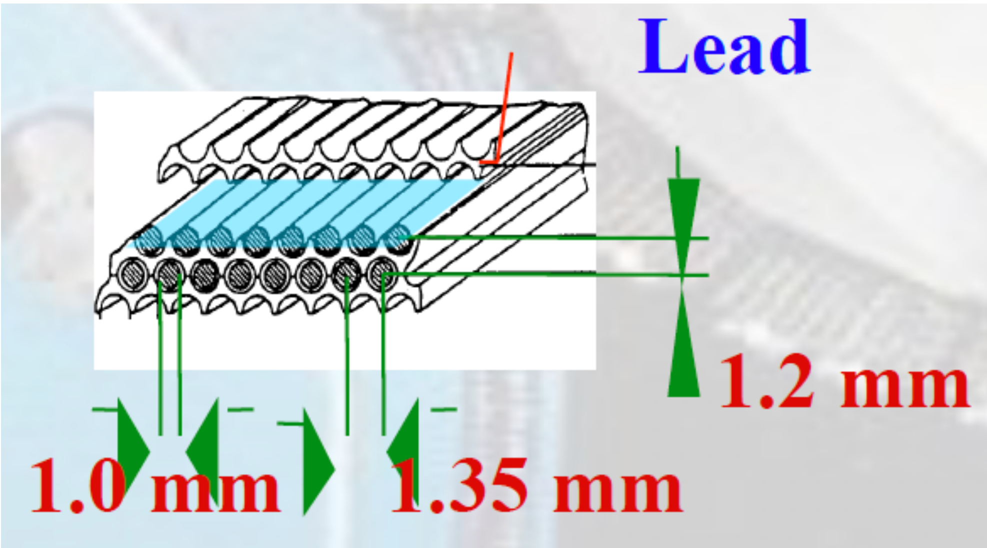
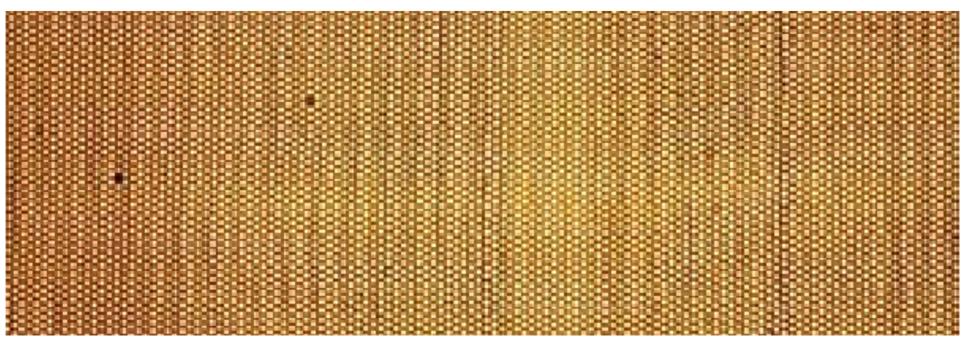
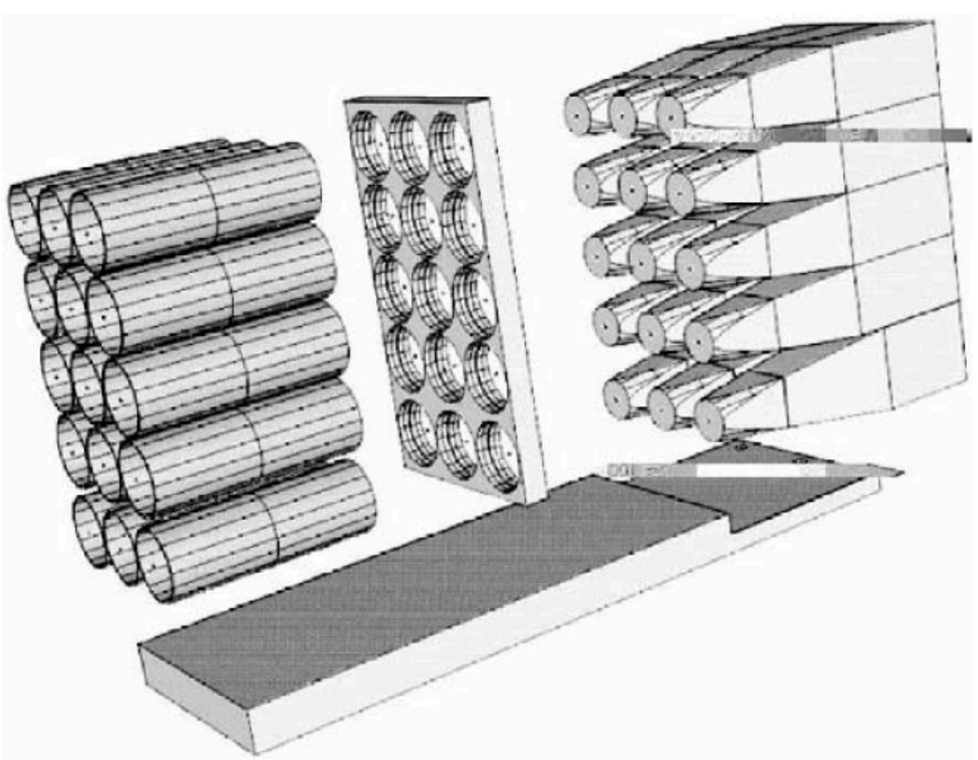
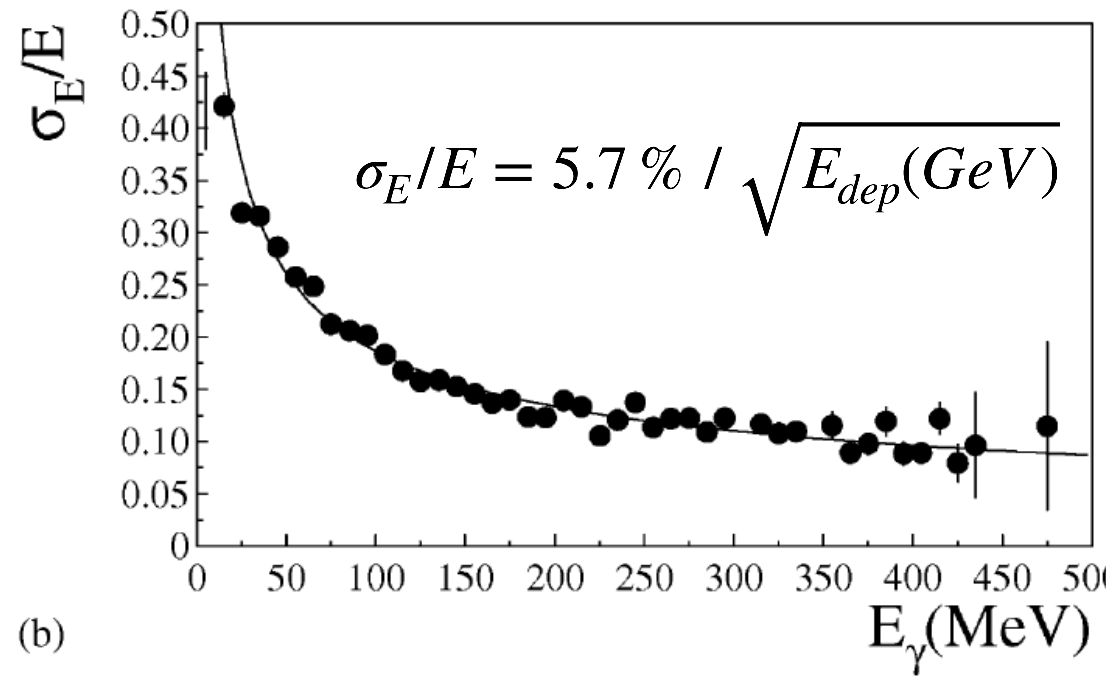






- KLOE electromagnetic calorimeter ~15 X_0 ECAL
- Module made of 5 bars 4.4cm granularity, 4880 channels
- 1 mm diameter scintillating fibers
- Lead:Fiber:Glue volume ratio = 42:48:10
- PMTs to read out the scintillation light



$$\sigma_t = 54\text{ ps} / \sqrt{E_{dep}(GeV)} + 50\text{ ps}$$

Very good energy and time resolution

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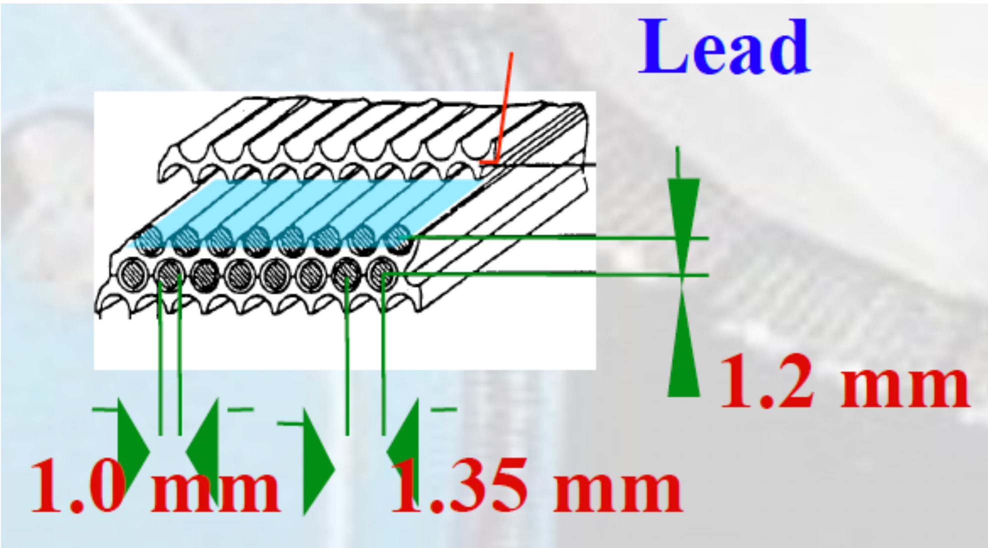

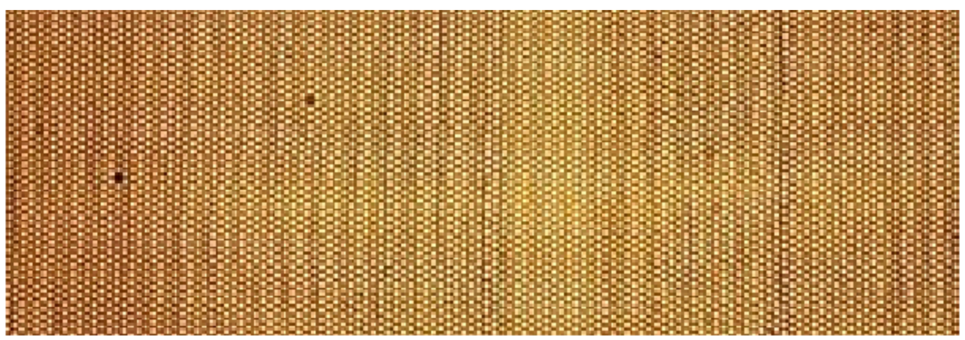

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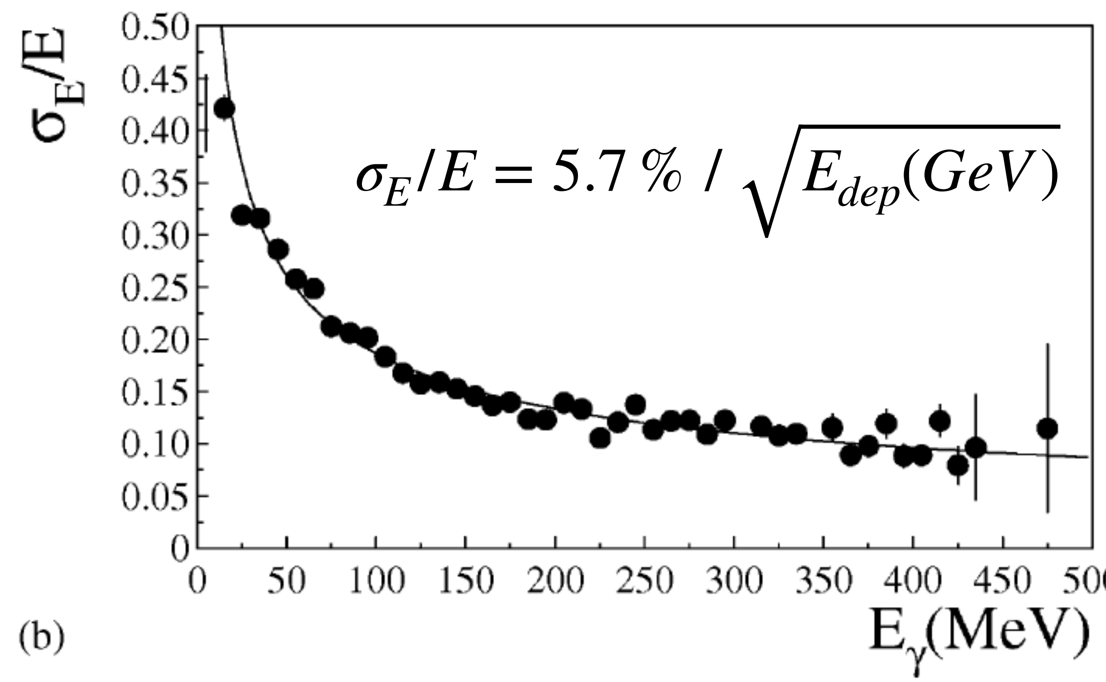
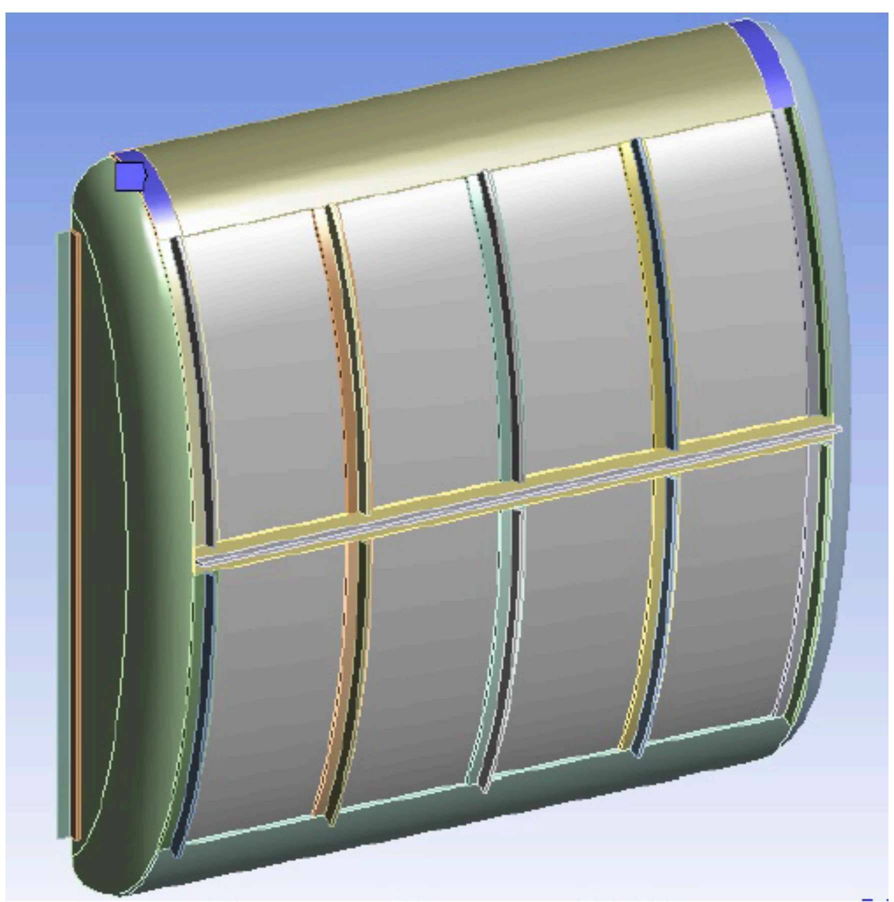


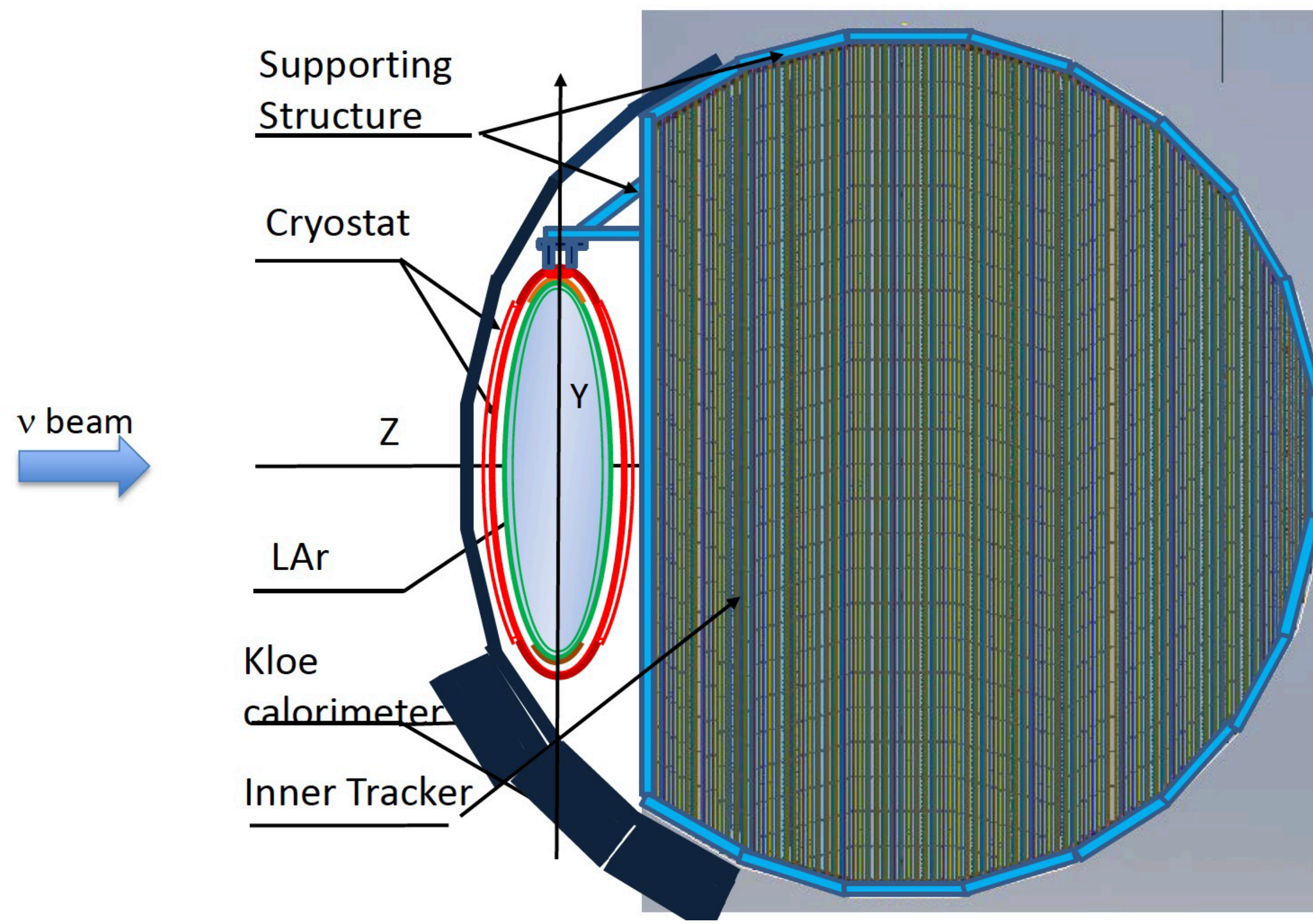
$$\sigma_t = 54\ \text{ps}\ /\ \sqrt{E_{dep}(GeV)} + 50\ \text{ps}$$

Very good energy and time resolution

Liquid-Argon target

- A “meniscus” volume filled with liquid argon will be upstream the Tracker
- Provide ~1t LAr-volume in a magnetised volume
- Optical readout instead of charge readout
- Also possibility to measure in the Tracker the neutron multiplicity and energy from ν-Argon interactions





- Detector design and R&D is in progress

The Inner Tracker

- Provide a massive non-argon target and particle tracking

    1. Mass for beam monitoring (in addition to ECAL)
    2. Measure neutrino interaction with event-by-event neutron detection with time of flight (ToF)
    3. Characterize nuclear effects in nuclei other than argon
    4. Isolate neutrino interaction in hydrogen to infer the neutrino flux

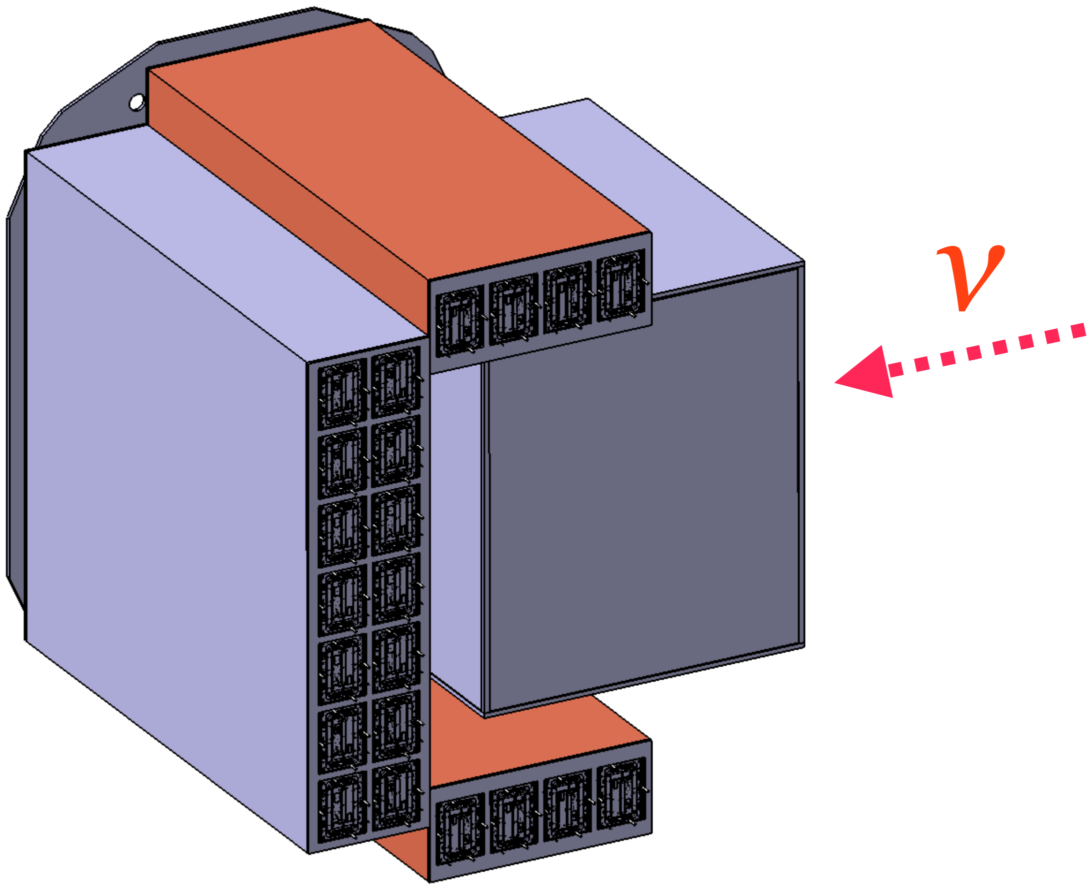
- Two main proposals:

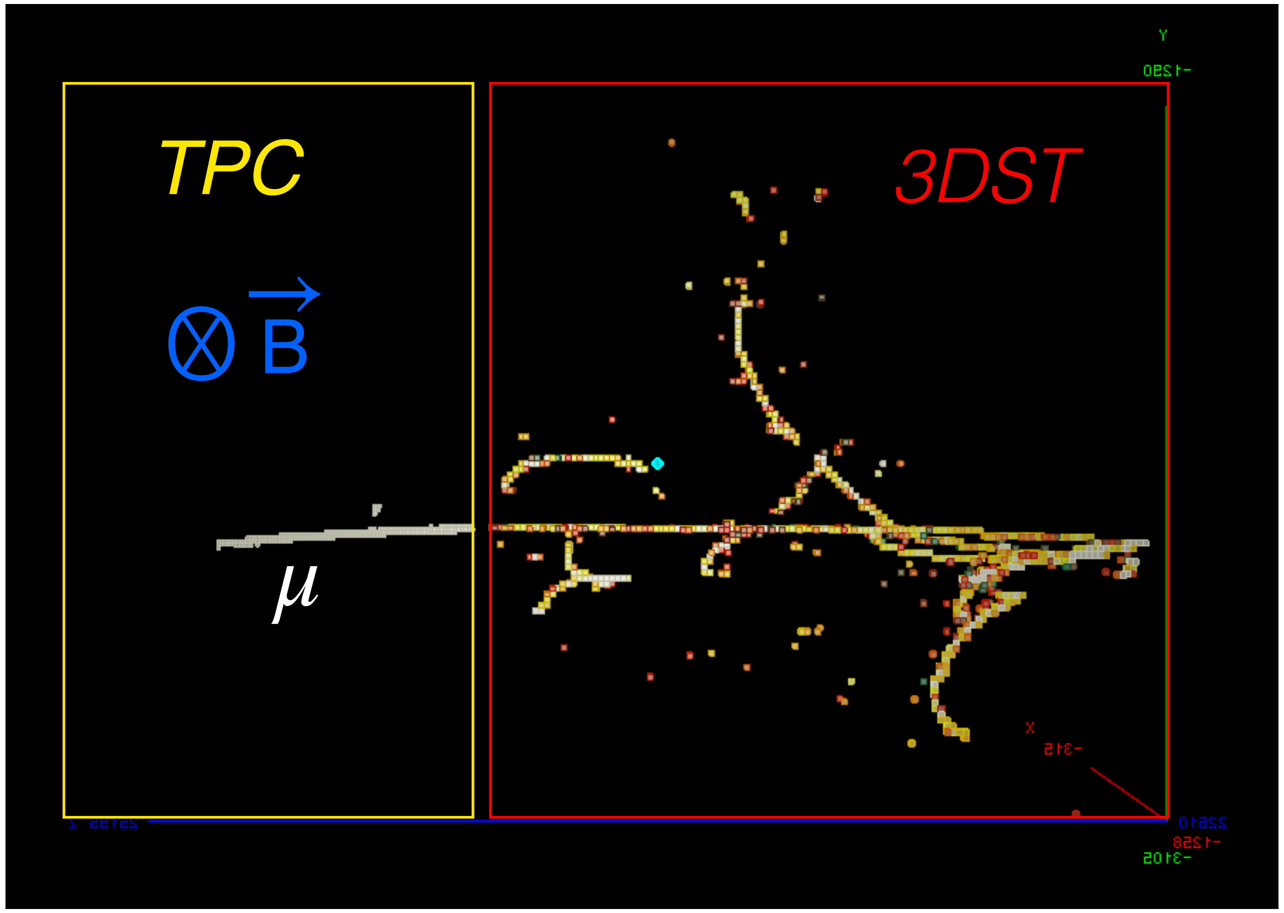
    ✦ The 3D-Projection Scintillator Tracker (3DST)
    + Time Projection Chambers (TPC)

    ✦ Straw Tubes with graphite / polypropylene target

- Process to finalise the design is ongoing

3DST+TPC inside SAND



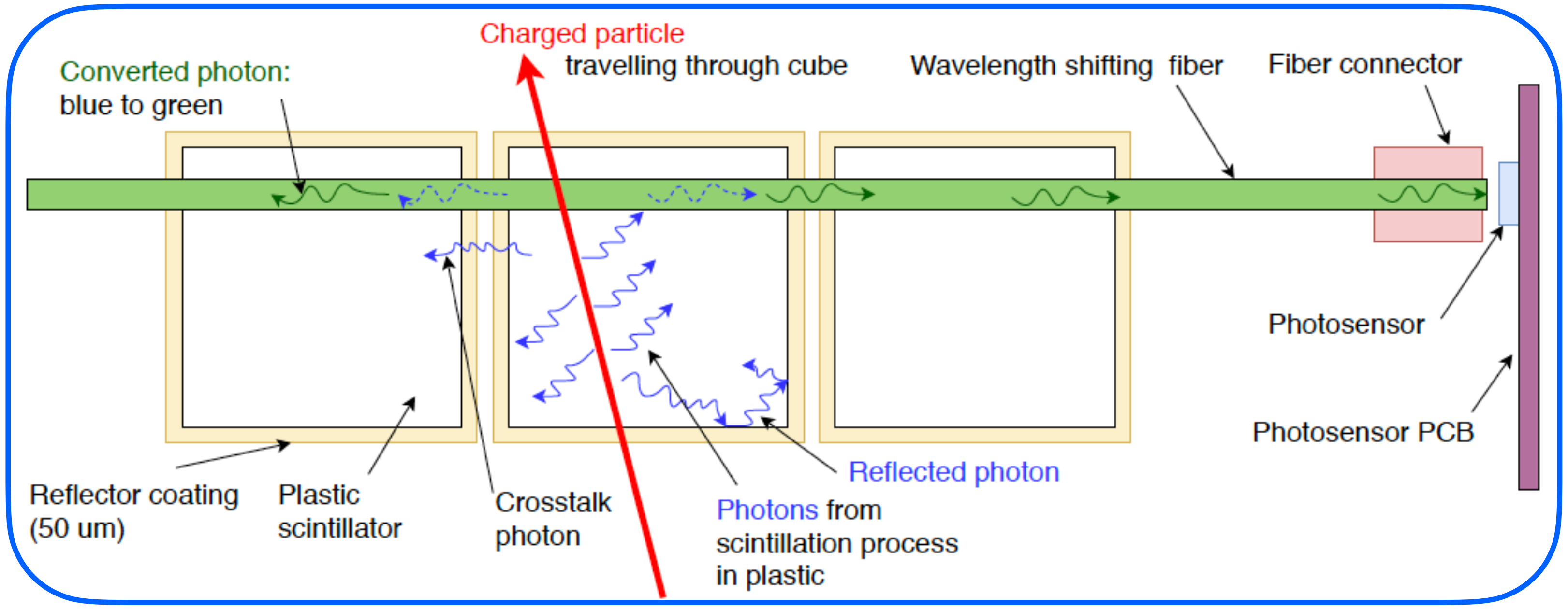


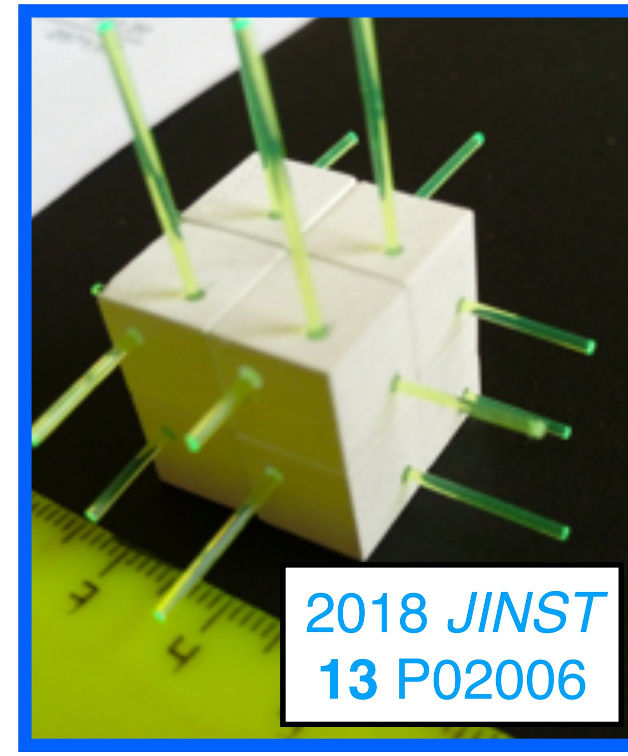
Event rate per year

FHC Beam Process	Rate	RHC Beam Process	Rate
All ν_μ-CC	1.5×10^7	All $\bar{\nu}_\mu$-CC	5.5×10^6
CC 0π	4.4×10^6	CC 0π	2.4×10^6
CC $1\pi^\pm$	4.3×10^6	CC $1\pi^\pm$	1.6×10^6
CC $1\pi^0$	1.3×10^6	CC $1\pi^0$	5.4×10^5
CC 2π	1.9×10^6	CC 2π	5.1×10^5
CC 3π	8.3×10^5	CC 3π	1.6×10^5
CC other	1.9×10^6	CC other	3.0×10^5
ν_μ-CC COH π^+	1.3×10^5	$\bar{\nu}_\mu$-CC COH π^-	1.1×10^5
$\bar{\nu}_\mu$-CC COH π^-	1.2×10^4	ν_μ-CC COH π^+	1.6×10^4
ν_μ-CC ($E_{\text{had}} < 250$ MeV)	2.4×10^6	$\bar{\nu}_\mu$-CC ($E_{\text{had}} < 250$ MeV)	1.9×10^6
All $\bar{\nu}_\mu$-CC	7.1×10^5	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
$\nu\, e \to \nu\, e$	2.0×10^3	$\nu\, e \to \nu\, e$	1.1×10^3

- 10.5t plastic scintillator as neutrino target
  - ✦ Fully-active, excellent energy resolution
  - ✦ Good tracking with momentum reconstruction by range
  - ✦ TPCs to precisely reconstruct the kinematics of particles exiting 3DST
- Event-by-event neutron detection and kinetic energy measurement with ToF

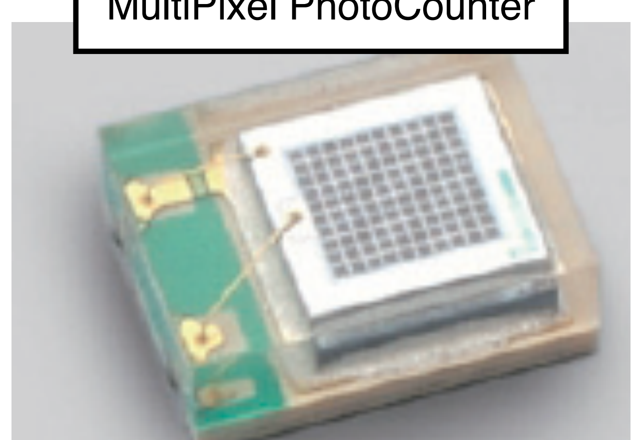
The 3D-Projection Scintillator Tracker (3DST)

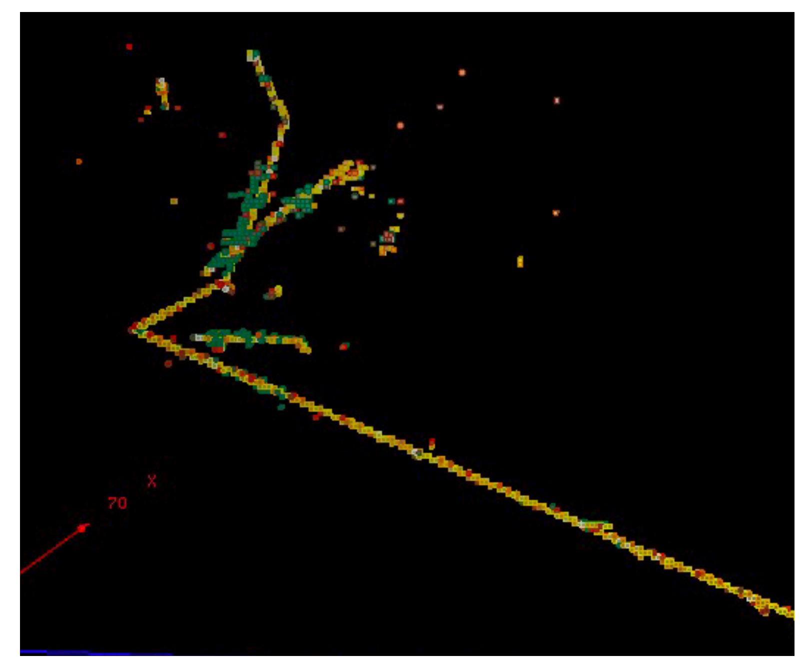




- Polystyrene doped with 1.5% pTP and 0.01% POPOP → cubes of 1.5 cm edge
- Wavelength shifting fibers ($\phi = 1$mm) capture the scintillation light and guide it to Silicon PhotoMultiplier
- Optically isolated cubes plus three orthogonal WLS provides isotropic detection
- High light yield, thus very good time resolution (~0.5 ns / cube)

Hamamatsu
MultiPixel PhotoCounter

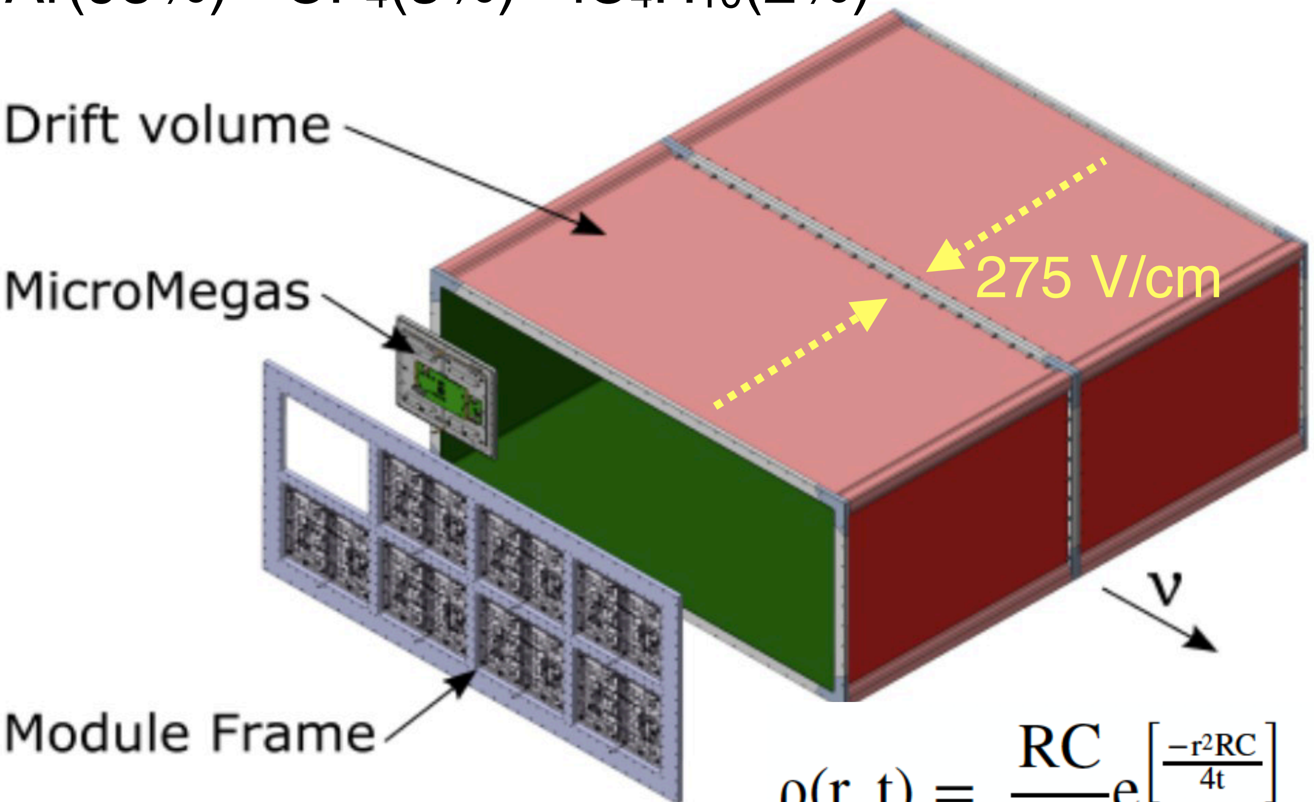


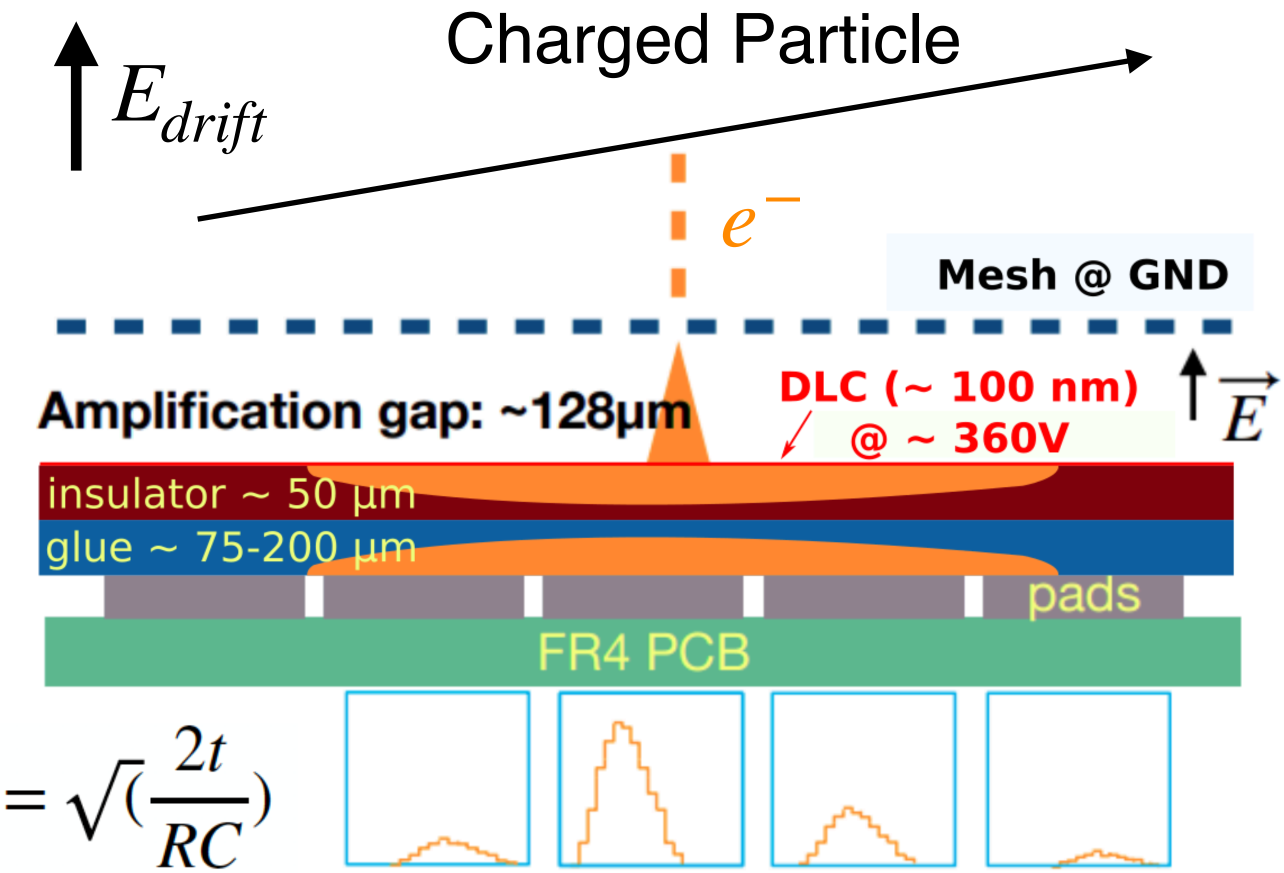


Same detector but x5 smaller is being built for T2K experiment

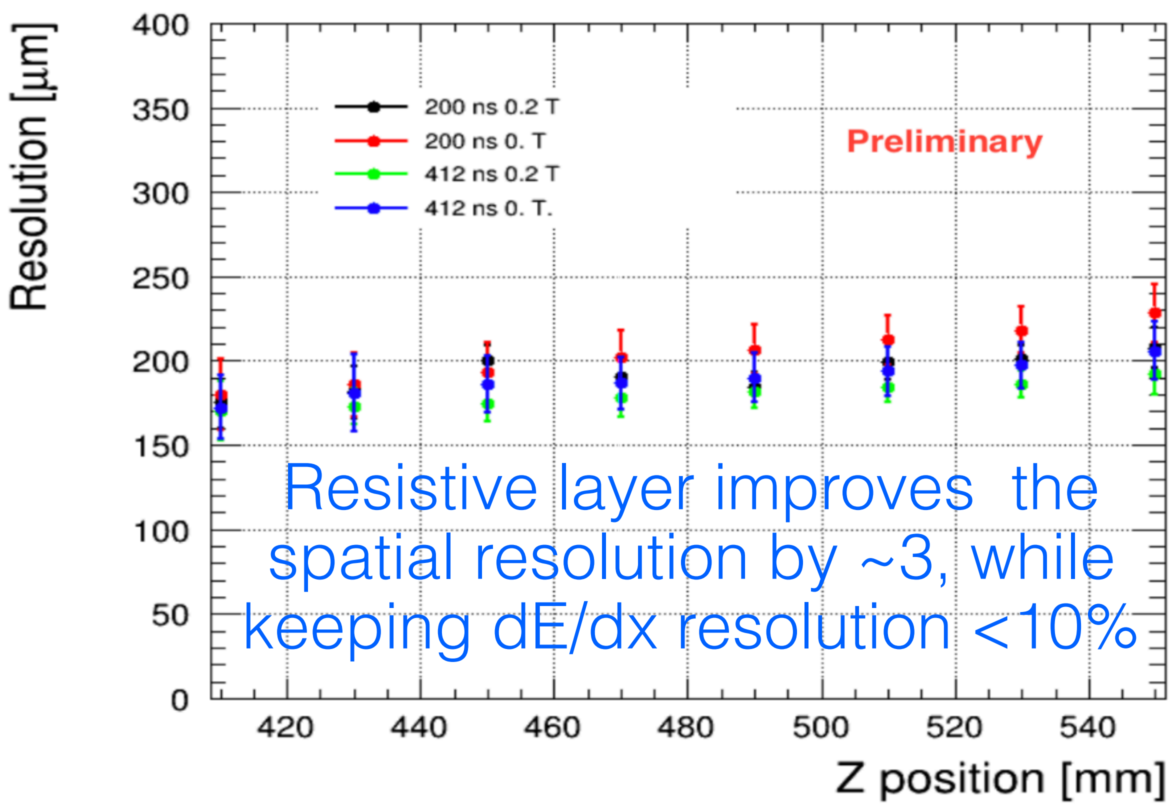
The Time Projection Chambers

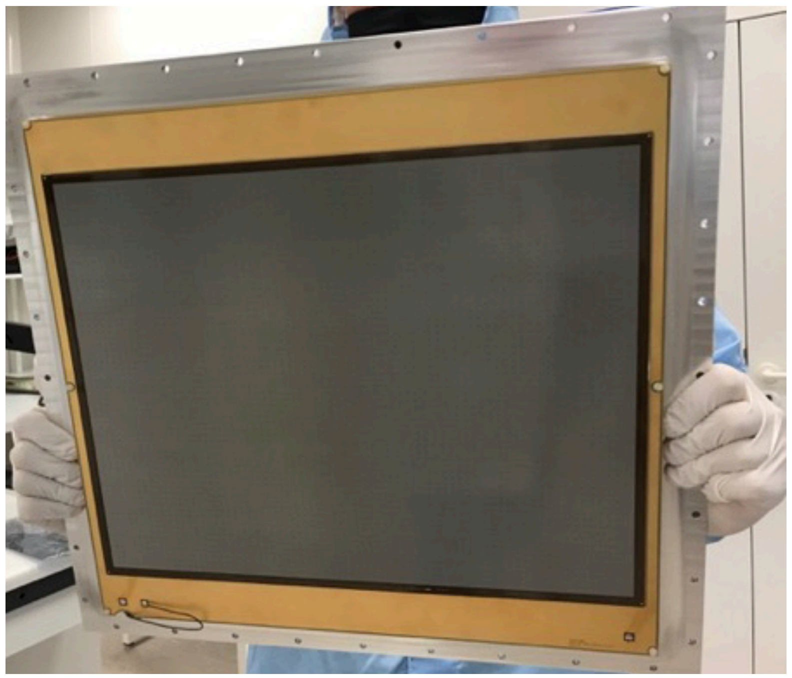
Ar(95%) - CF_4(3%) - iC_4H_{10}(2%)

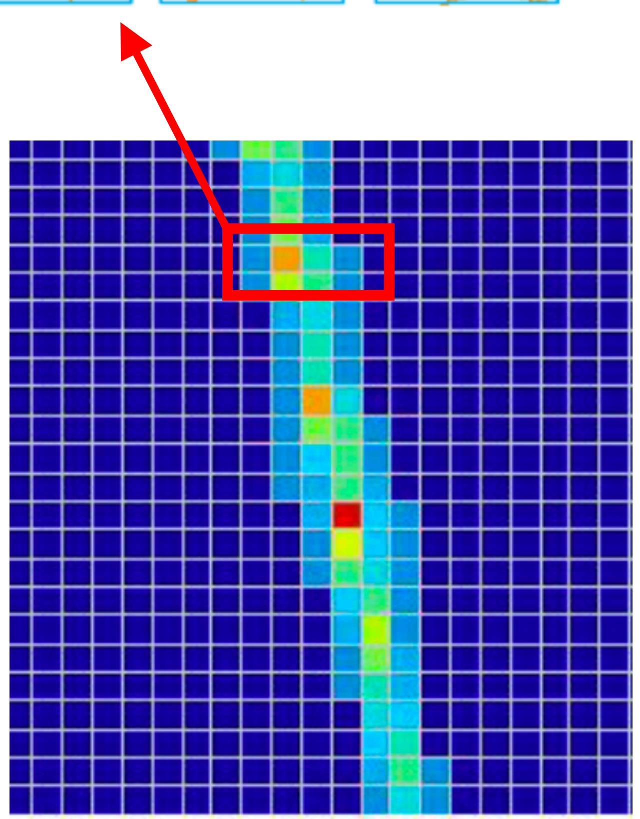




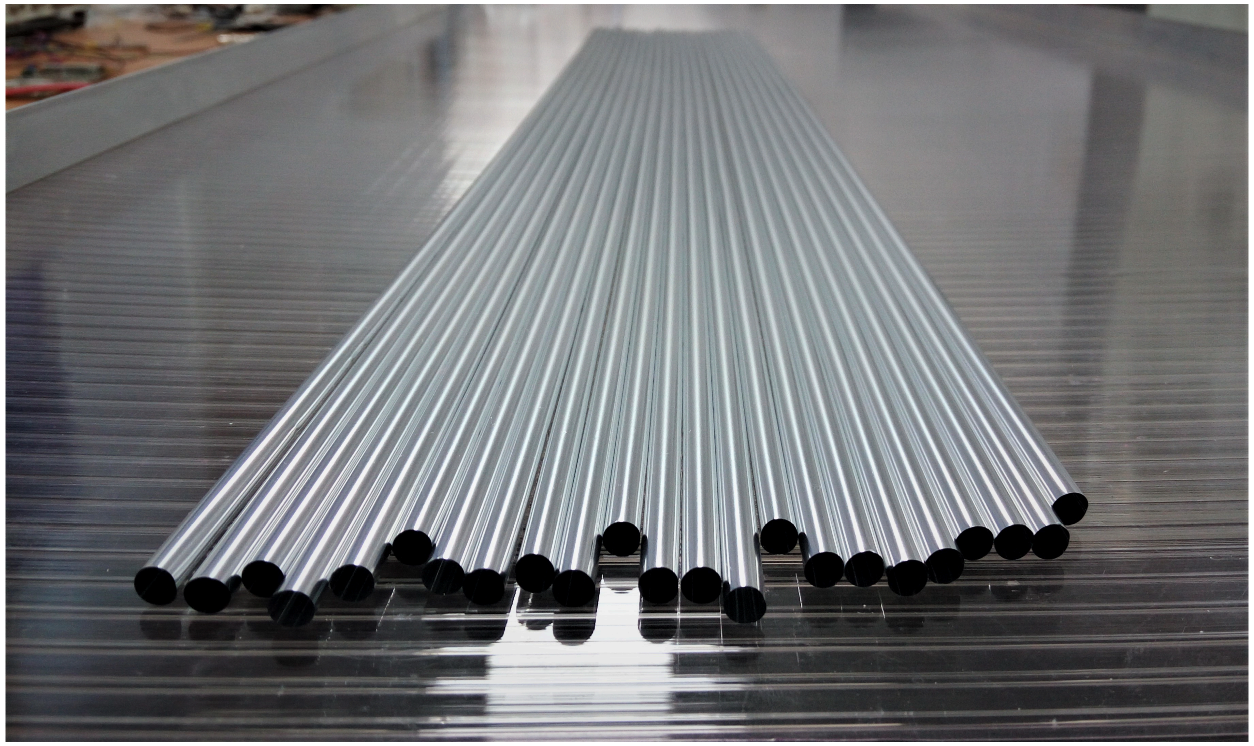
$$\rho(r,t) = \frac{RC}{2t} e^{\left[\frac{-r^2RC}{4t}\right]} \qquad \sigma_r = \sqrt{(\frac{2t}{RC})}$$



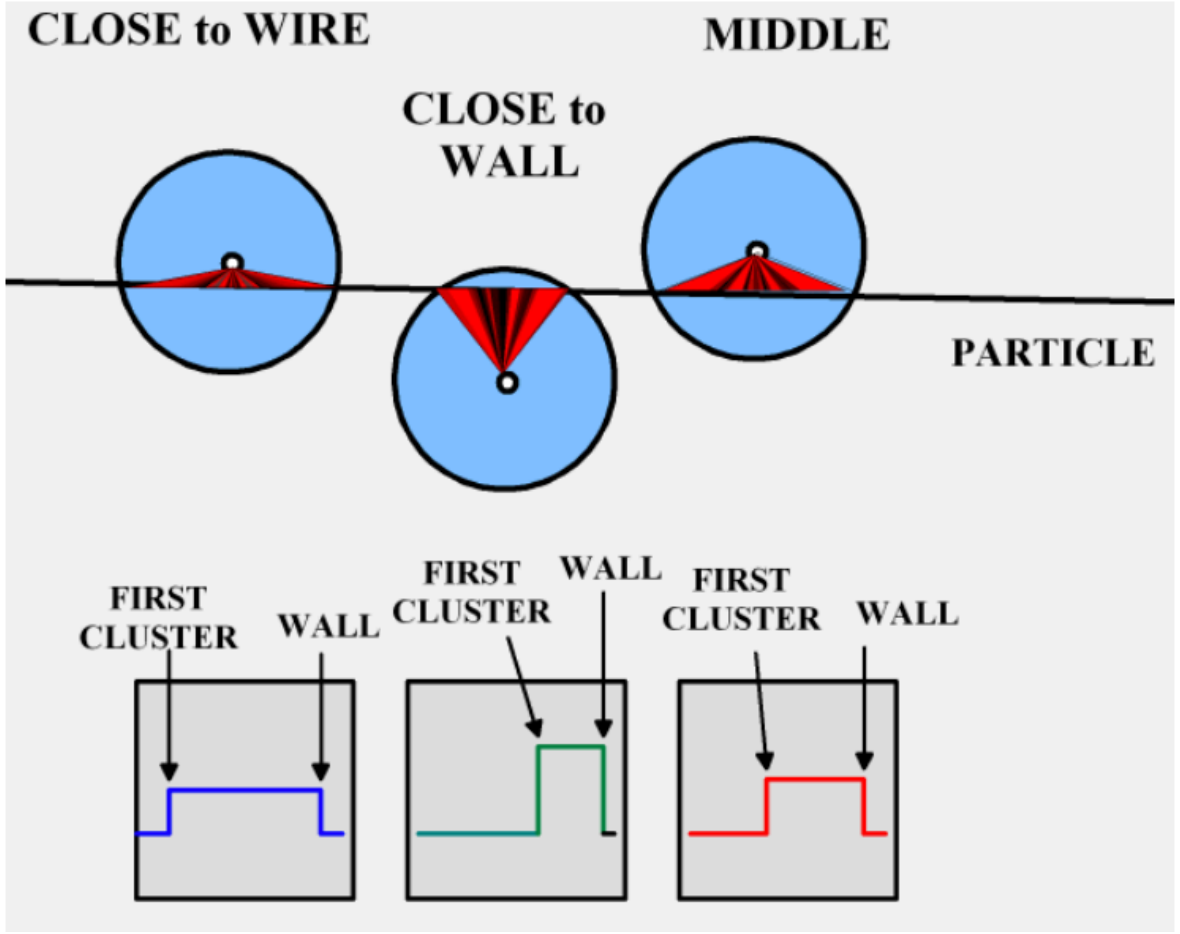


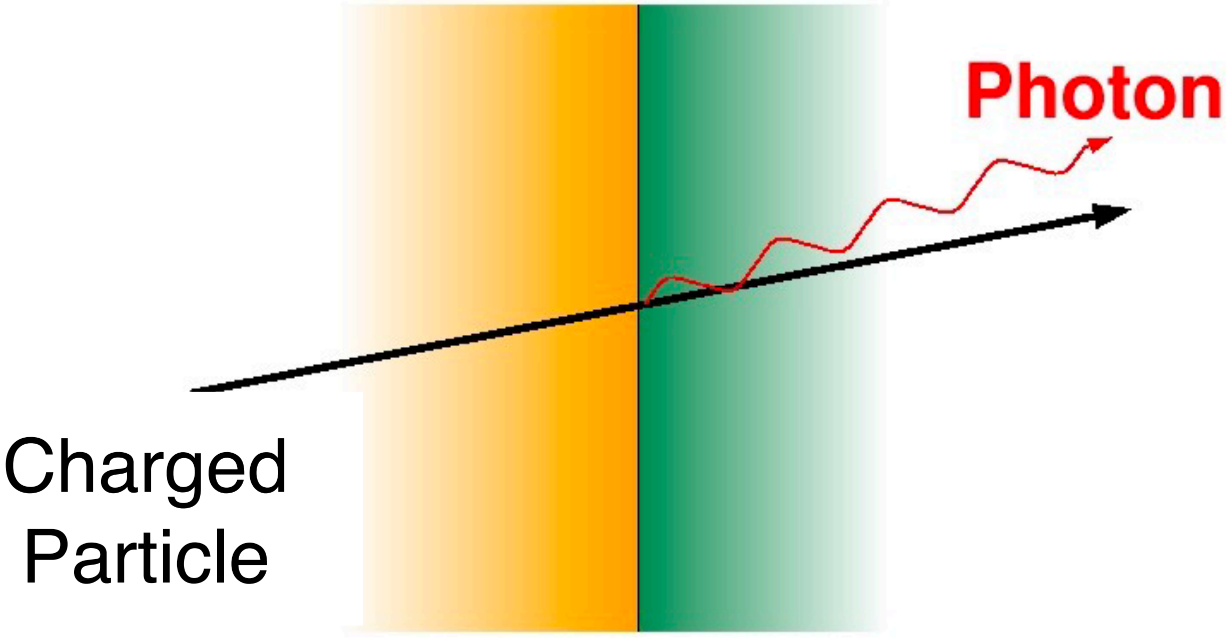


Low-density tracker option: Straw Tubes



- Filled with gas ionised by particles
- Ionized electrons drift to straw wire and create signal (several 100 eV)
- Radiator foils are place between layers of tubes → Transition Radiation generate signal ~10 keV
- Space-point resolution $< 200\ \mu m$
- Good e/π separation with transition radiation on radiator foils





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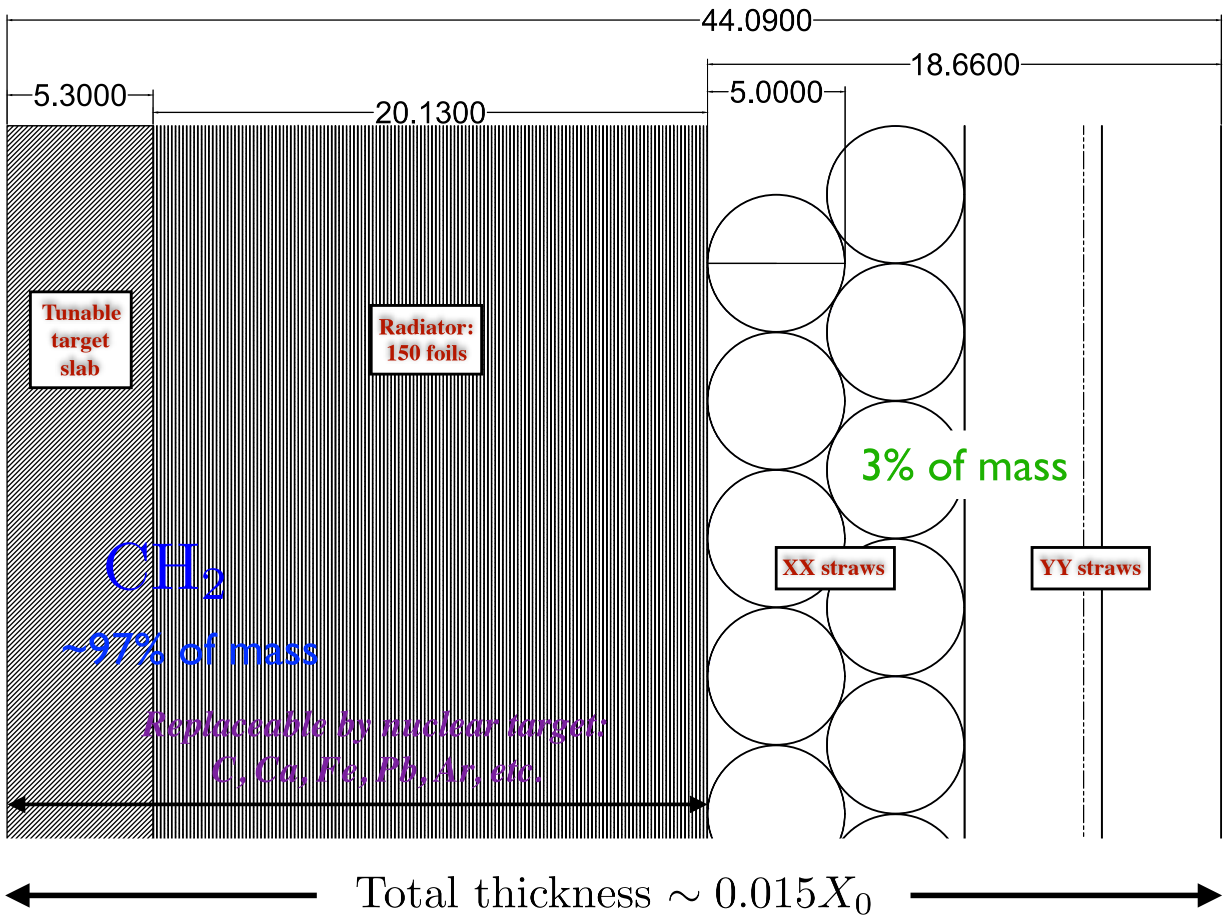
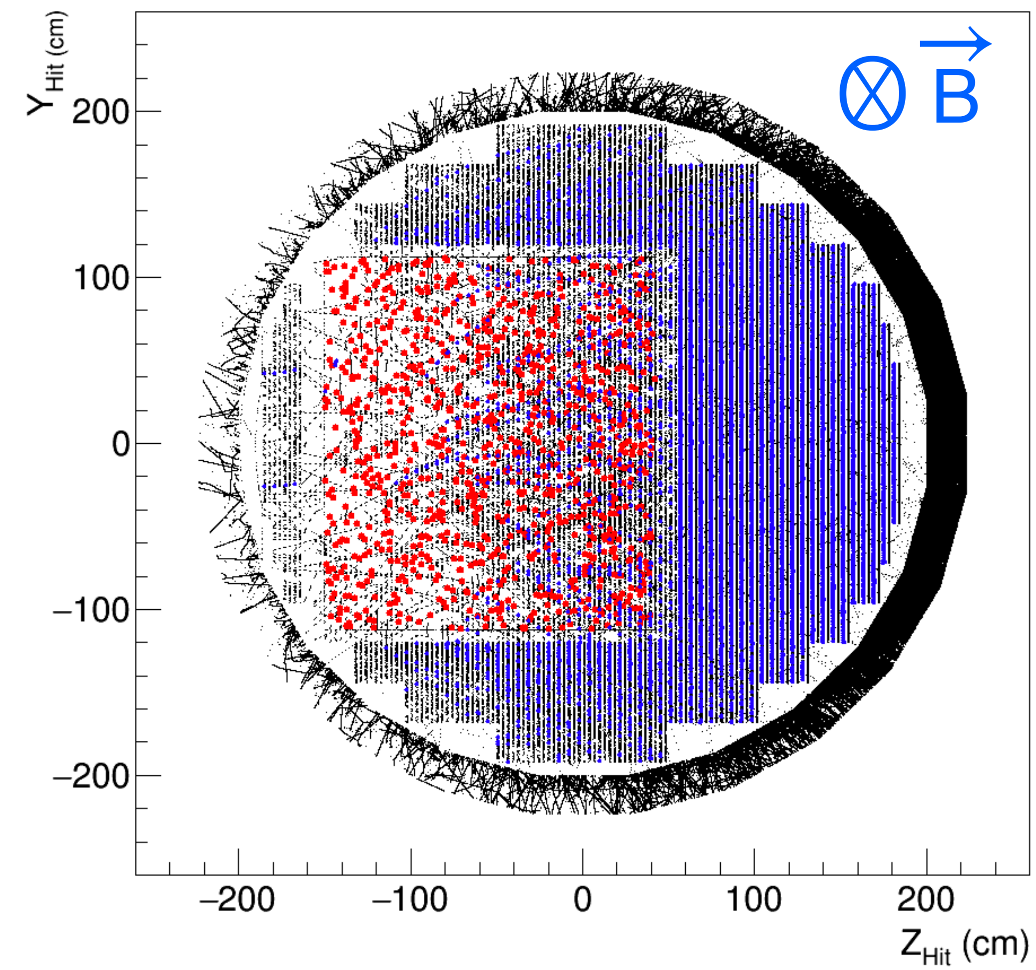
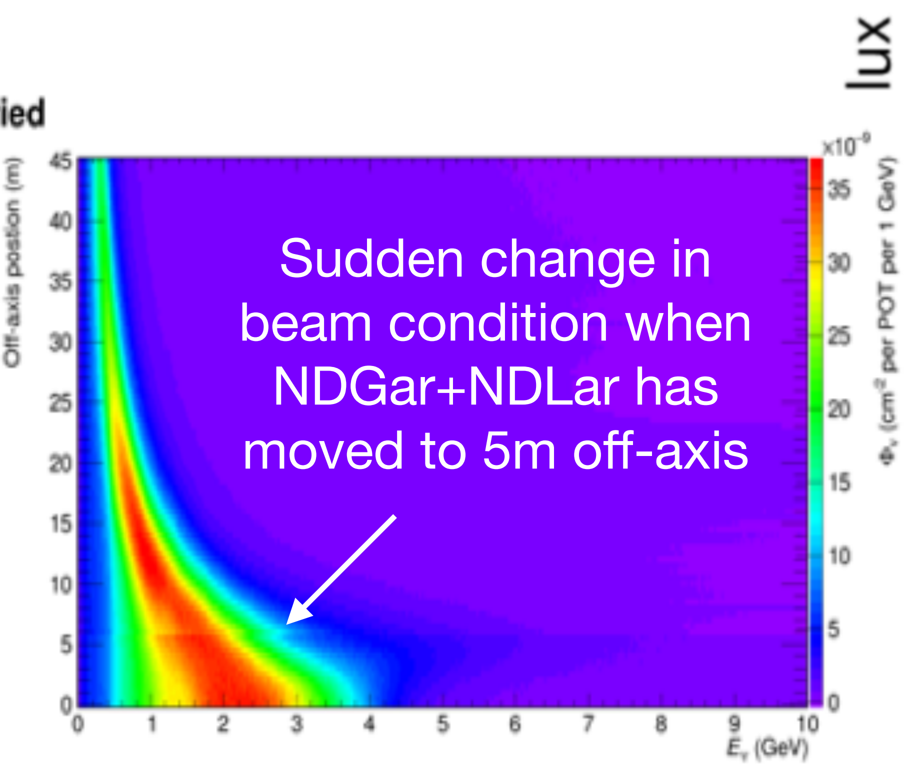


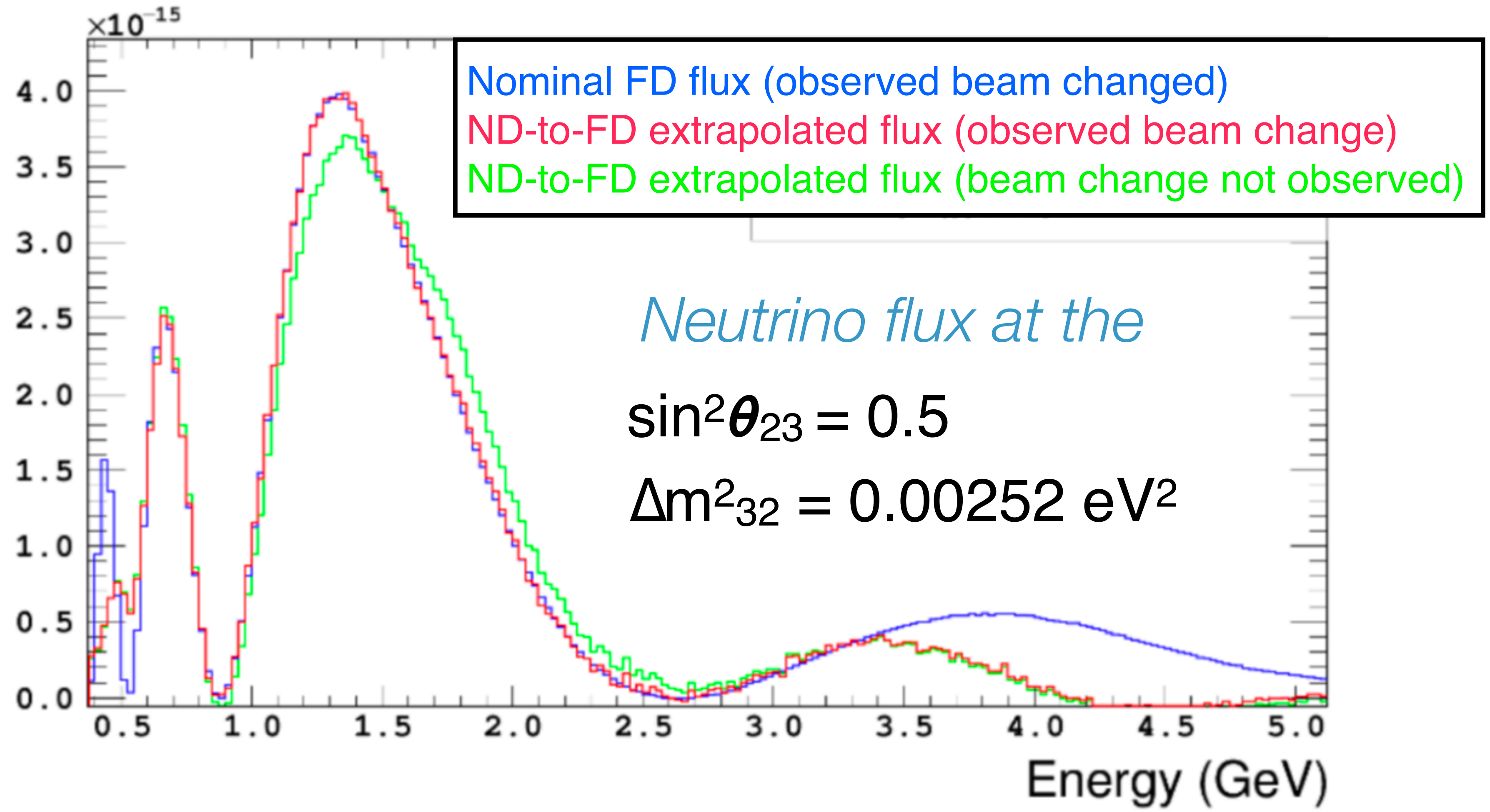


- 78 modules with CH_2 target and radiator (polypropylene) with Xe/CO_2 gas
- 7 modules with Graphite (C) target with Ar/CO_2 gas
- 5 modules w/o target w/o radiator with Ar/CO_2 gas
- ST full configuration: 0.018 g/cm^3, ~5.2t mass
    - ✦ physics measurements with both CH_2 and Graphite targets
    - ✦ Aim at subtracting the Carbon contribution to obtain interactions in H

An example of beam monitoring

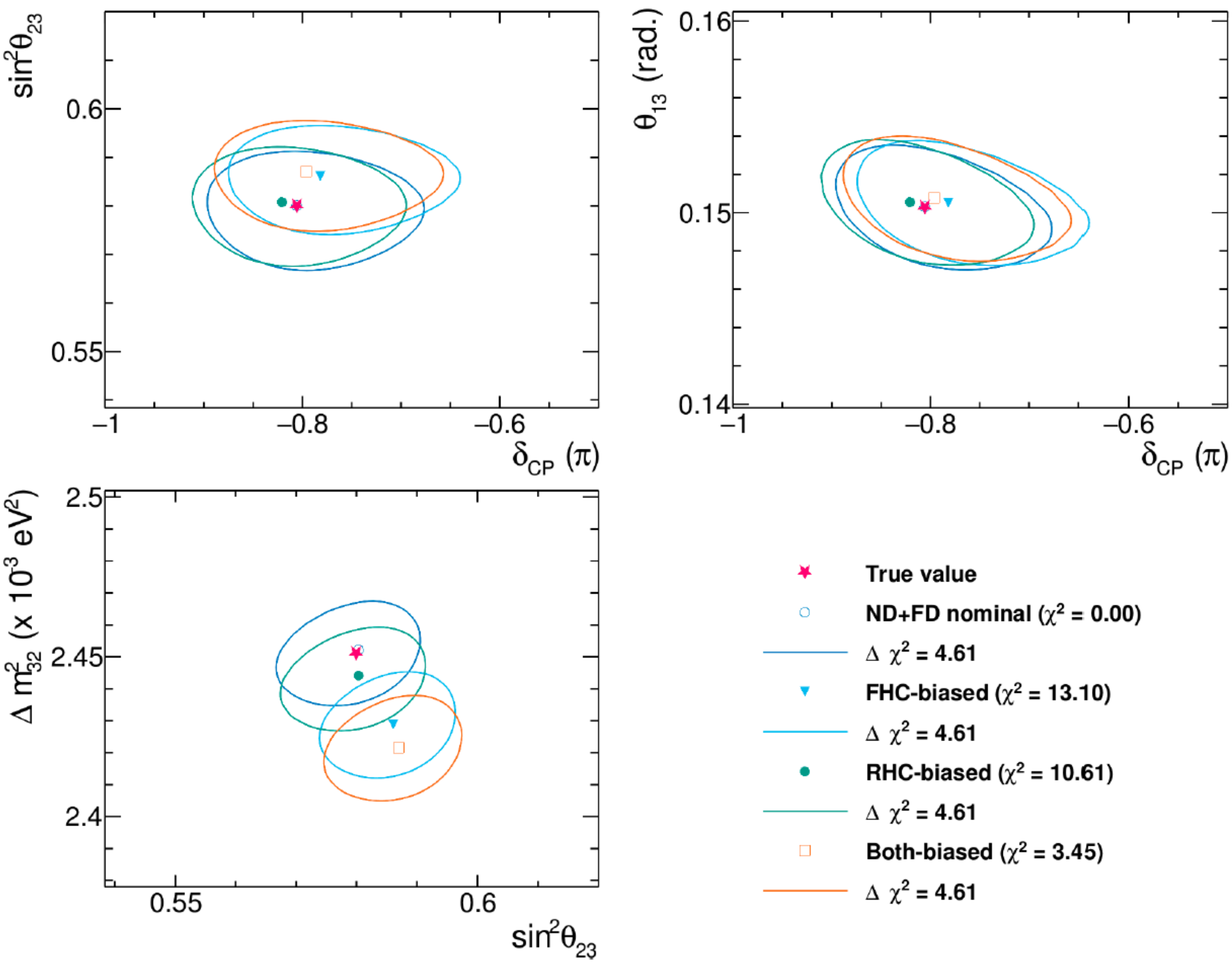
Example of a situation where ND-LAr and ND-GAr don't observe any change in the beam parameters when they move off-axis





A systematic distortion in the ν energy spectrum extrapolated to the far detector can't be observed

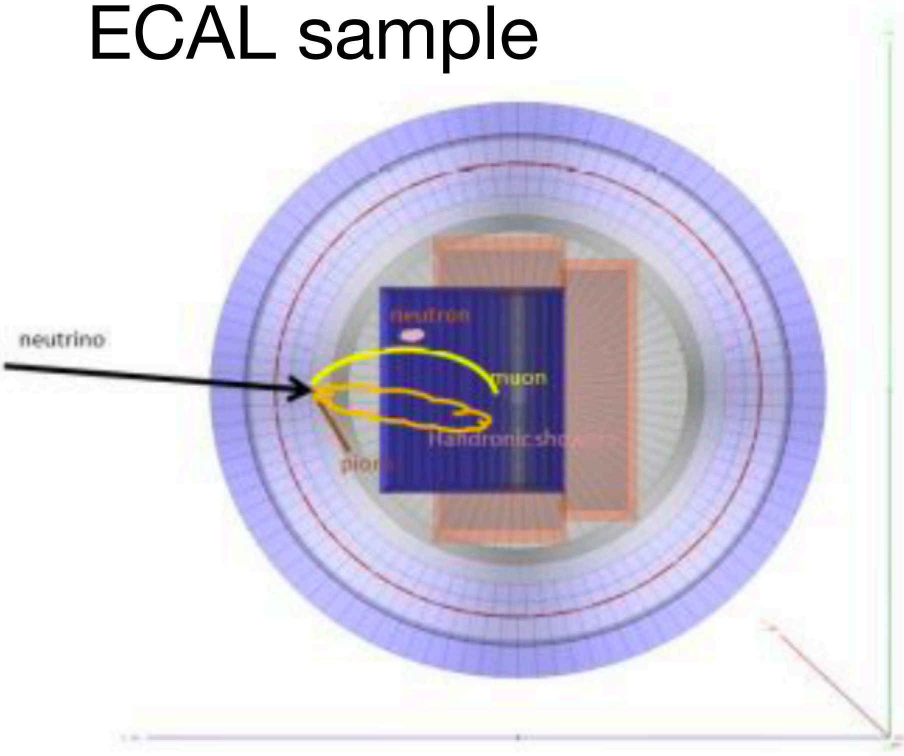
An example of beam monitoring



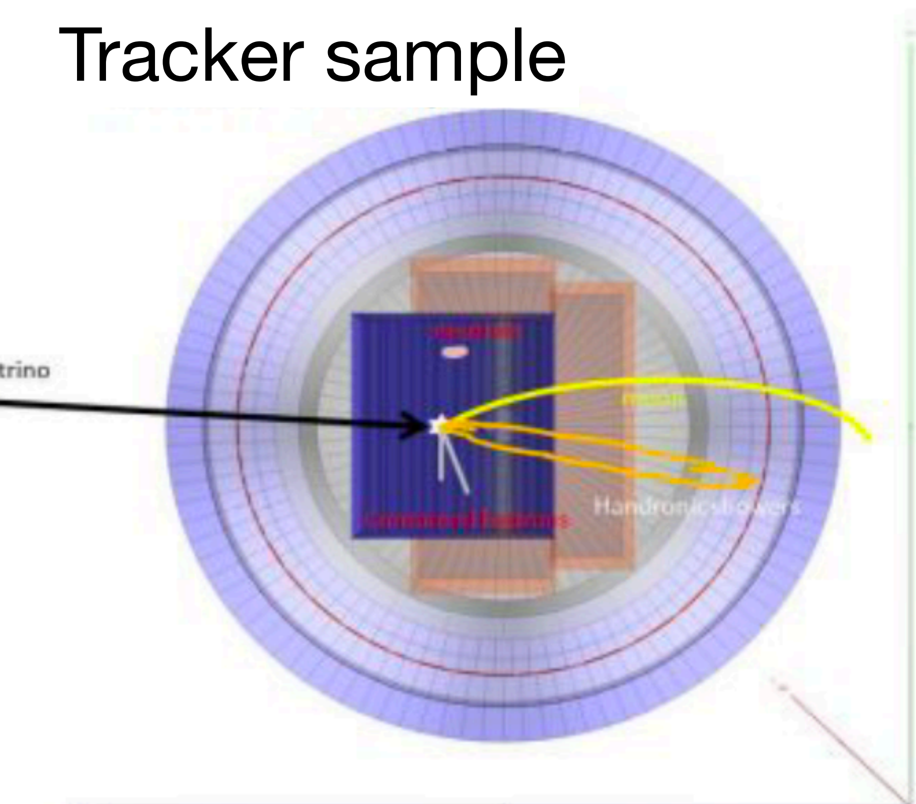
The measurement of the oscillation parameters will be affected by large biases

Beam monitoring performances

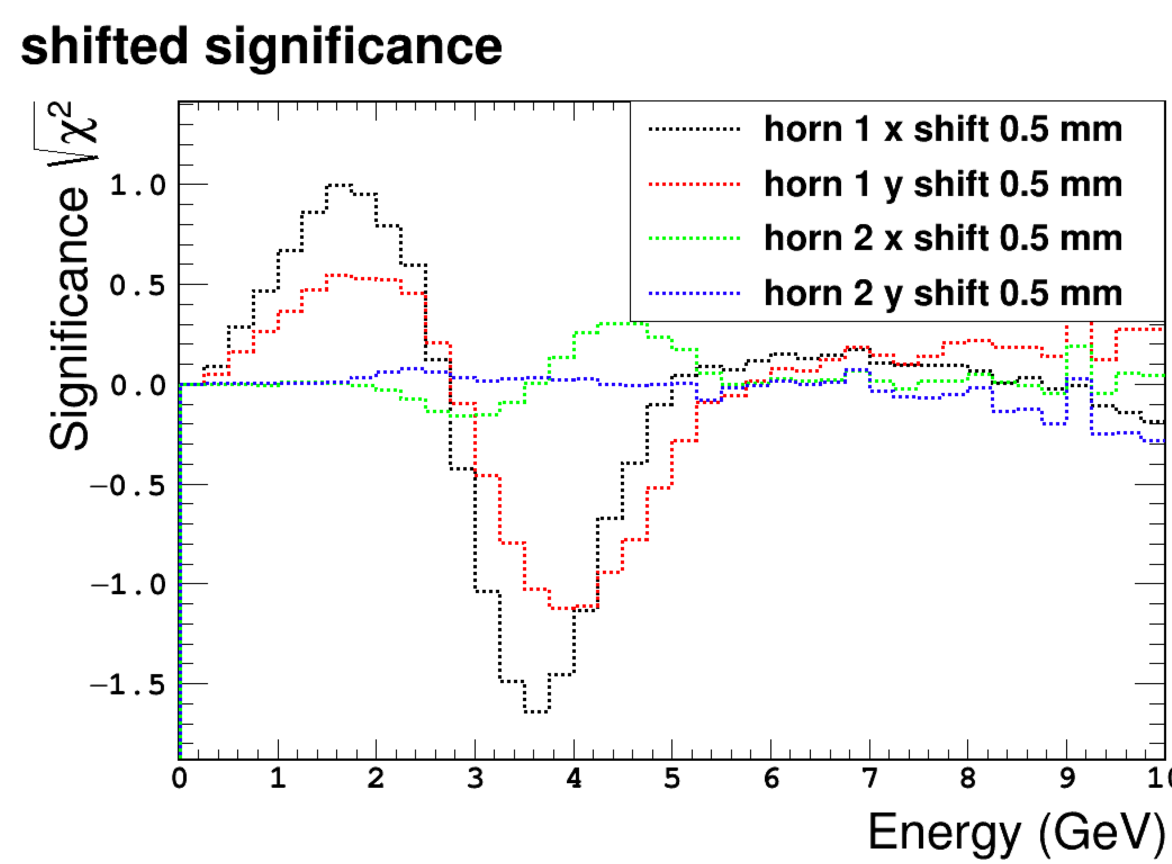
ECAL sample



Tracker sample

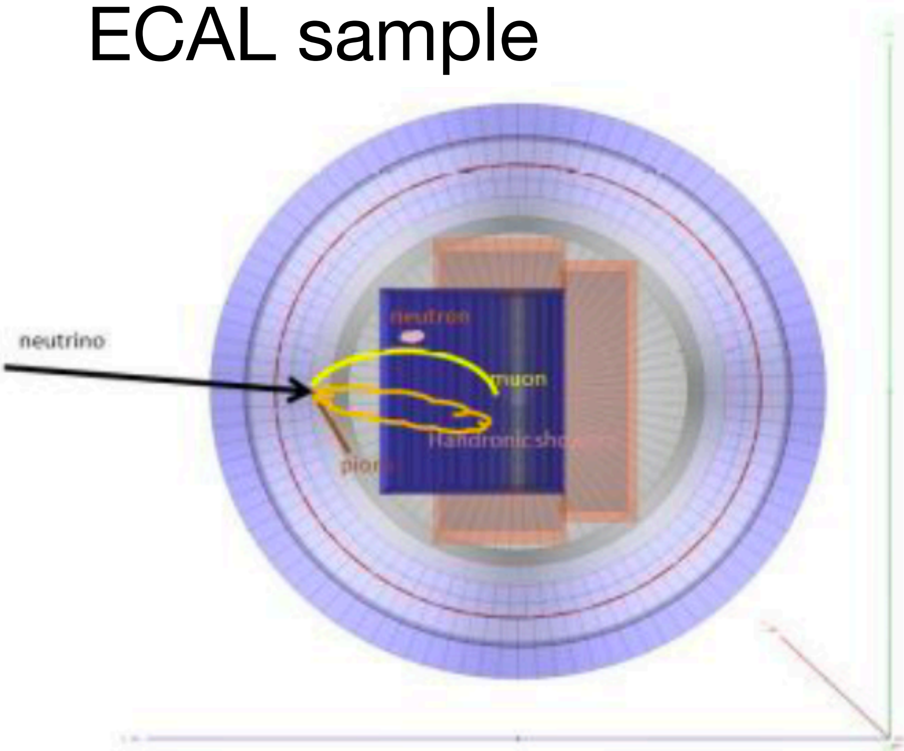


- An efficient beam and spectrum monitoring requires a large target mass
  - ✦ ECAL can provide ~14t target
  - ✦ The Tracker can provide an addition ~10t (5t), depending on the configuration
- Also measure the beam profile and position
- Identify unexpected spectrum distortions within a few days

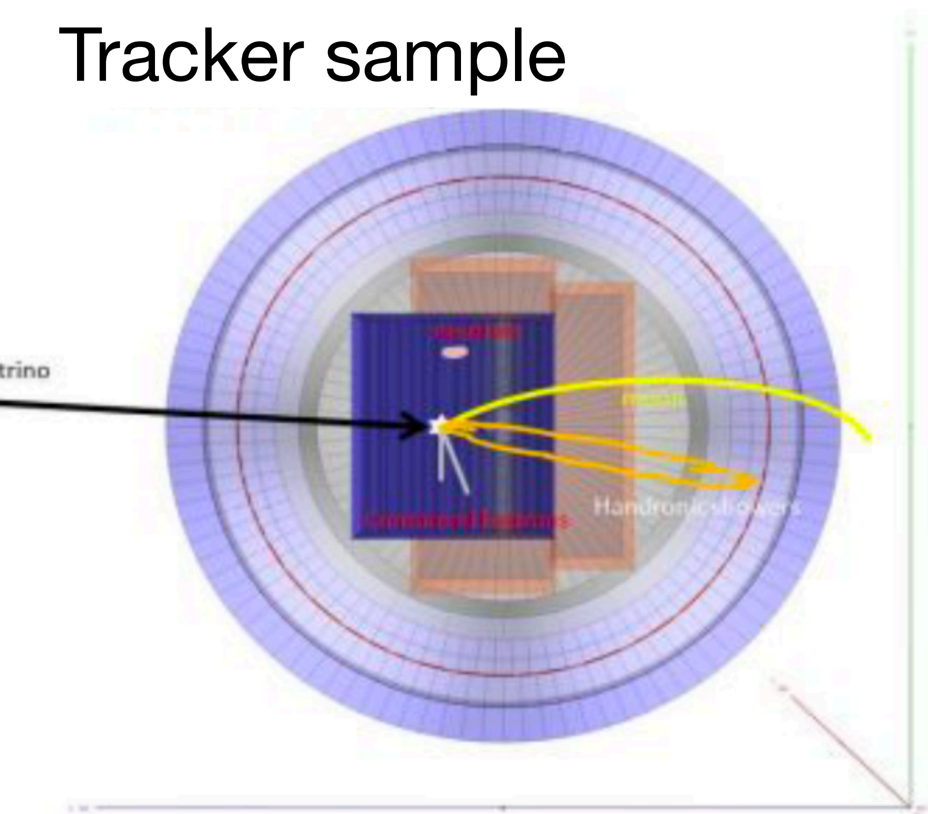


Beam monitoring performances

ECAL sample



Tracker sample



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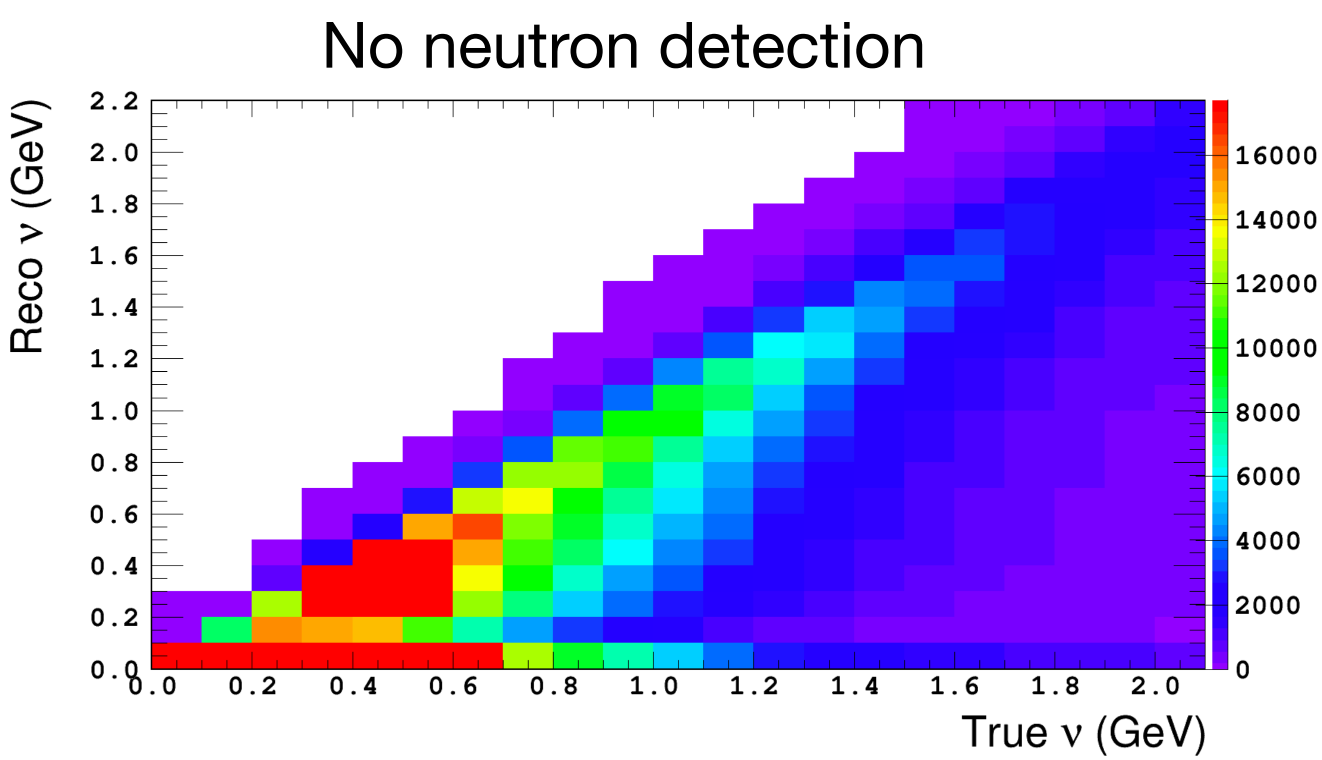
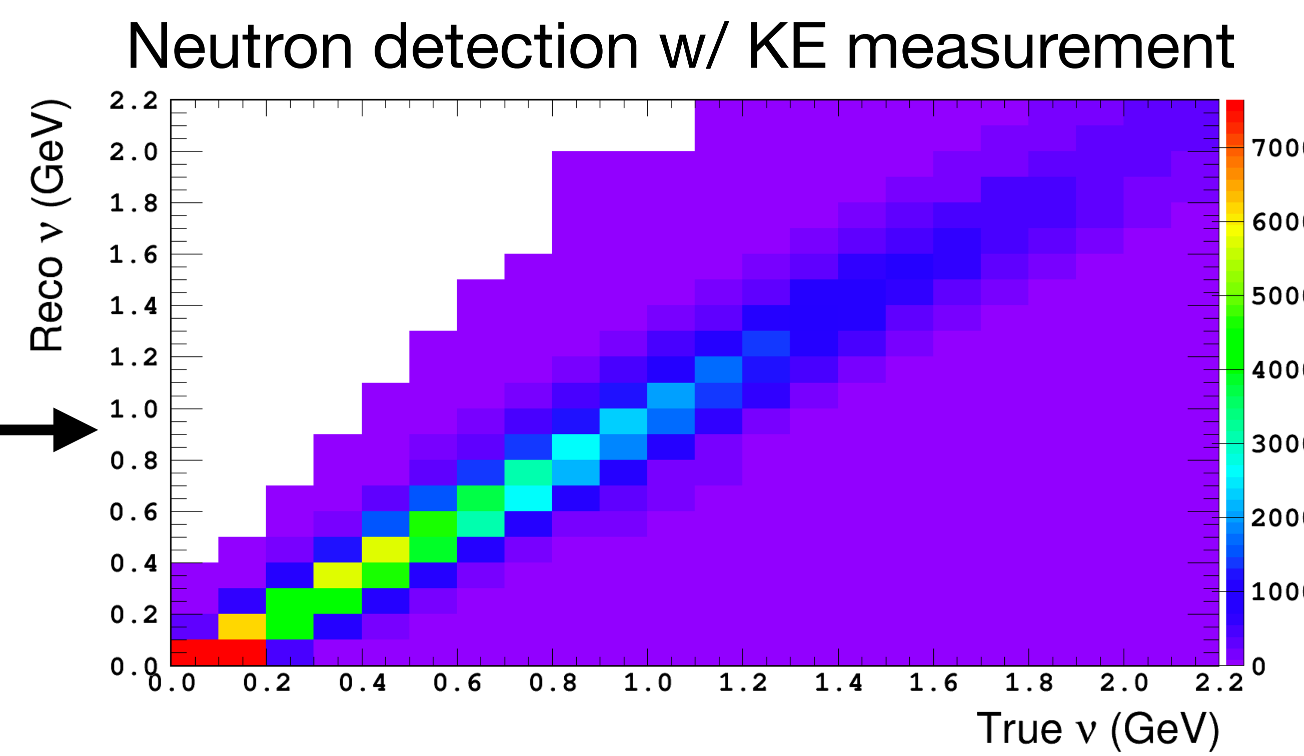
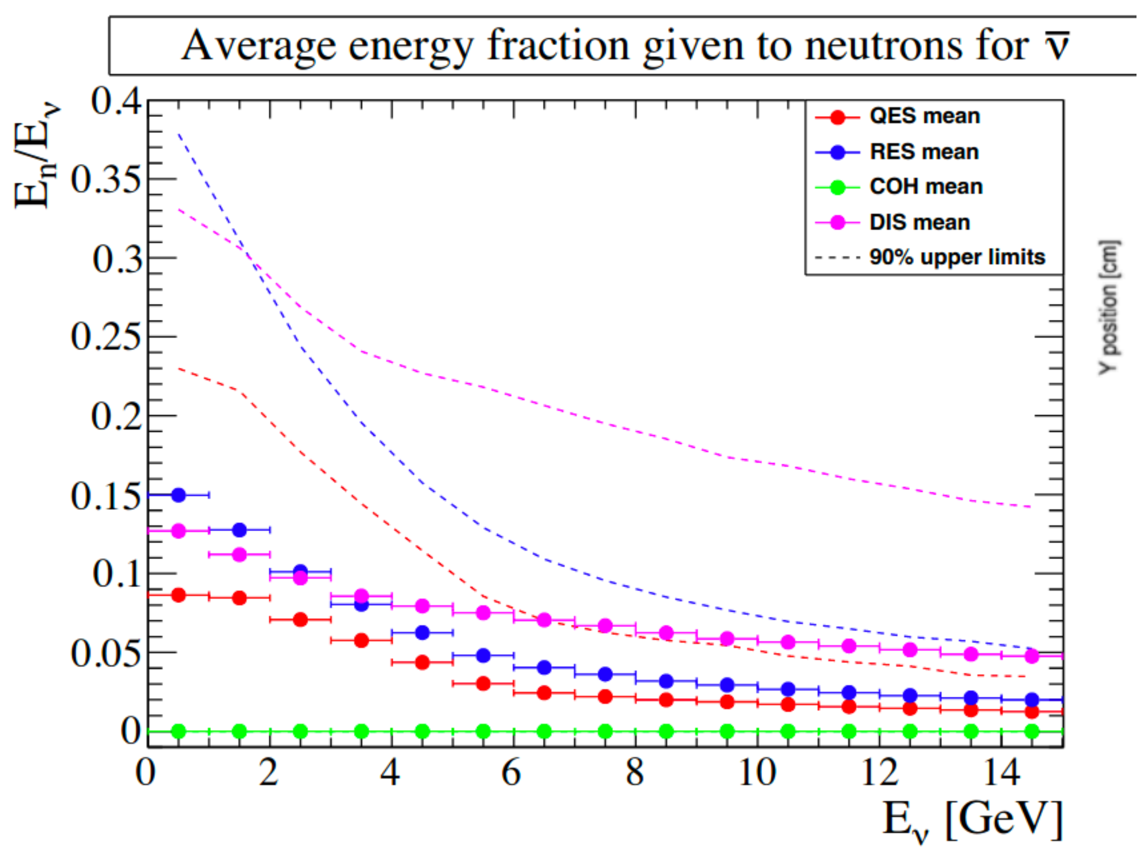
	Parameter description		Significance, $\sqrt{\chi^2}$	
Beam parameter	Nominal	Changed	Rate-only monitor	SAND
proton target density	1.71 g/cm^3	1.74 g/cm^3	0.02	5.6
proton beam width	2.7 mm	2.8 mm	0.02	3.6
proton beam offset x	N/A	+0.45 mm	0.09	4.3
proton beam *theta*	N/A	0.07 mrad	0.03	0.5
proton beam $\theta\phi$	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

Why detecting neutrons is important

Resolution on energy transferred to the nucleus (ν)



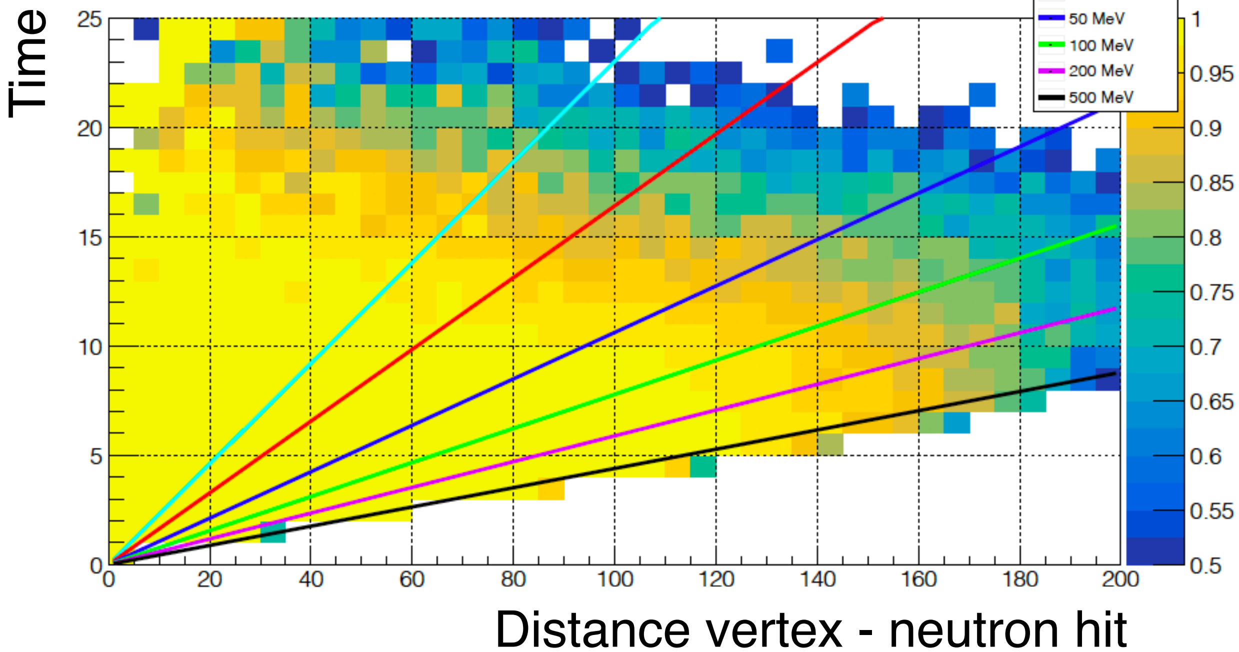




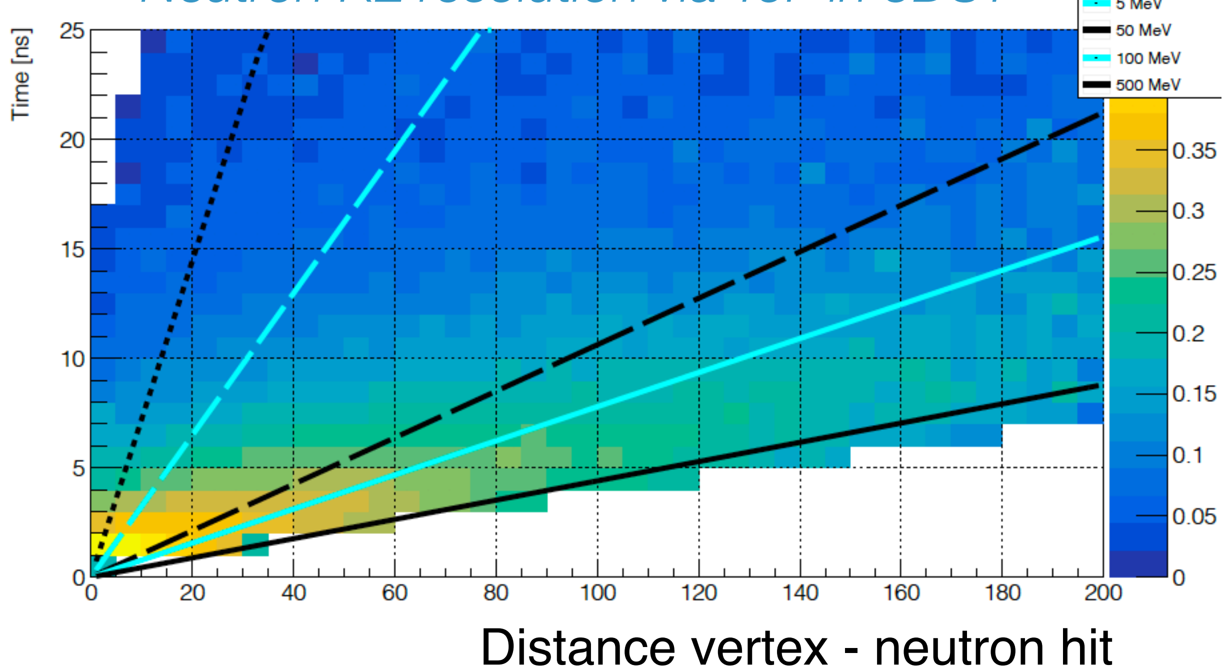
- Important to validate that the inferences one makes from studies of proton distributions can be successfully applied to predict neutrons (i.e. ν vs $\bar{\nu}$, which is the core of CP violation searches)
- Minerva has demonstrated the capability of detecting neutrons produced by antineutrino interactions (PRD 100, 52002)

Neutron detection with Time-of-Flight measurement

Rejection of neutrons from out-FV neutrino interactions with 3DST

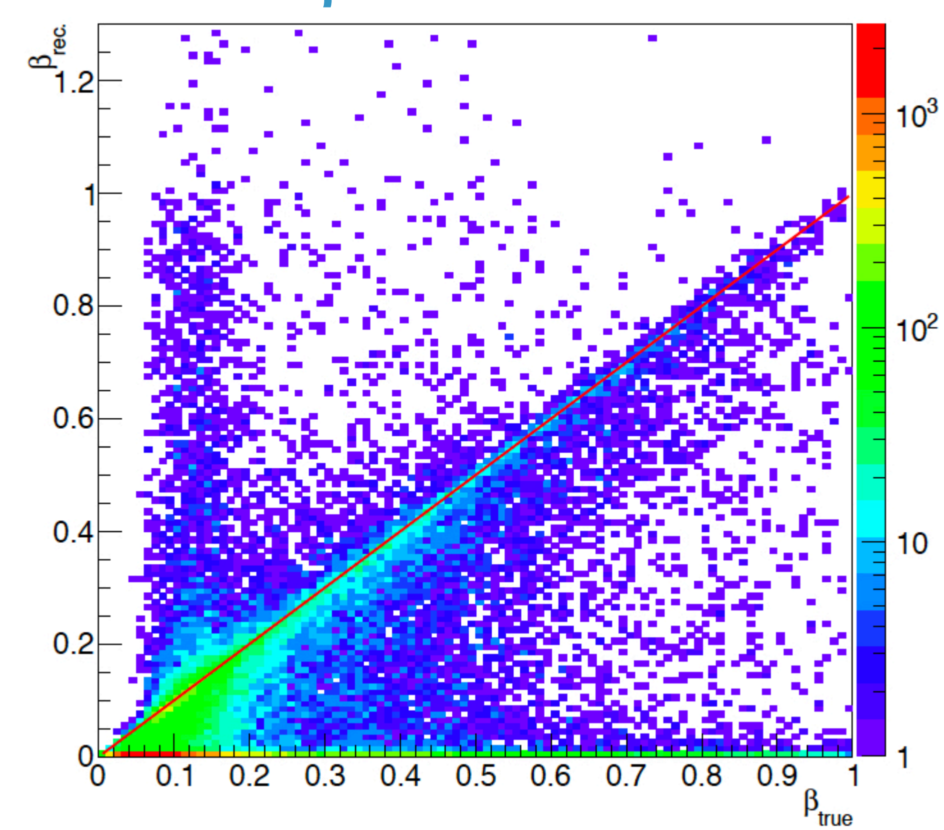


Neutron KE resolution via ToF in 3DST



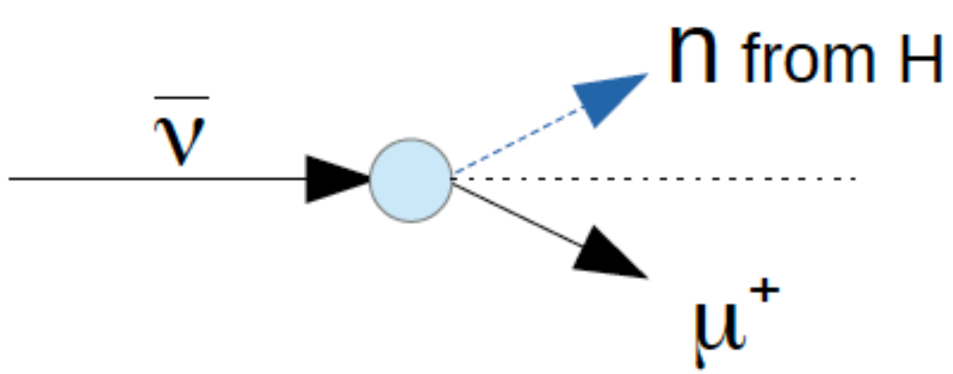
- A performant neutron detector requires
  - ✦ Large content of light nuclei (high energy transferred)
  - ✦ Excellent time resolution to measure its kinetic energy via ToF
- SAND has the unique capability of detecting efficiently measuring the energy of neutrons produced in both argon and other nuclei

Neutron β resolution with ECAL



Neutrino interactions in hydrogen

Interactions in hydrogen are very useful because not affected by nuclear effects



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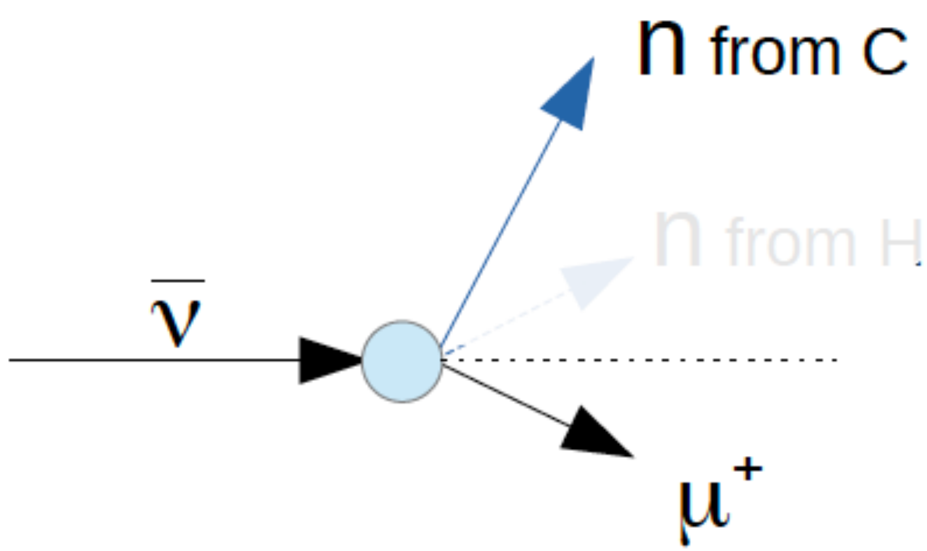

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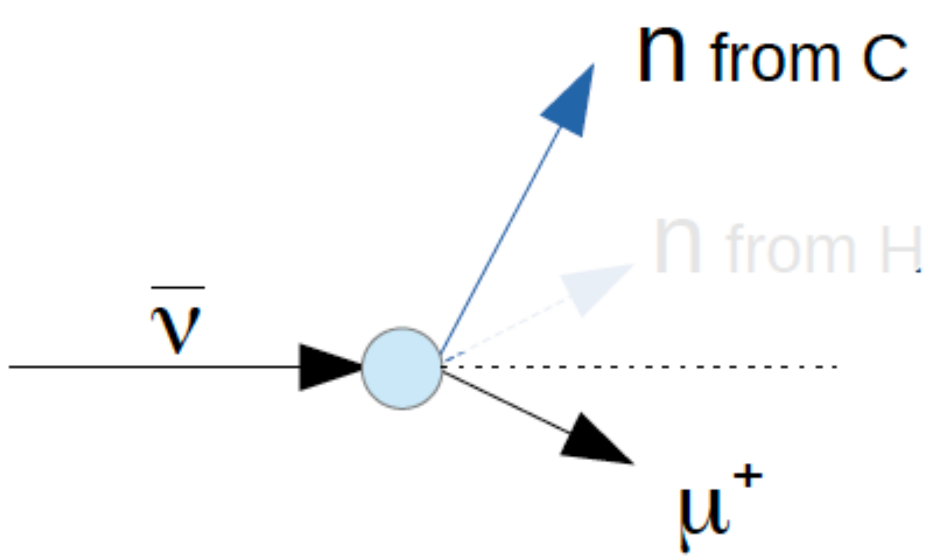
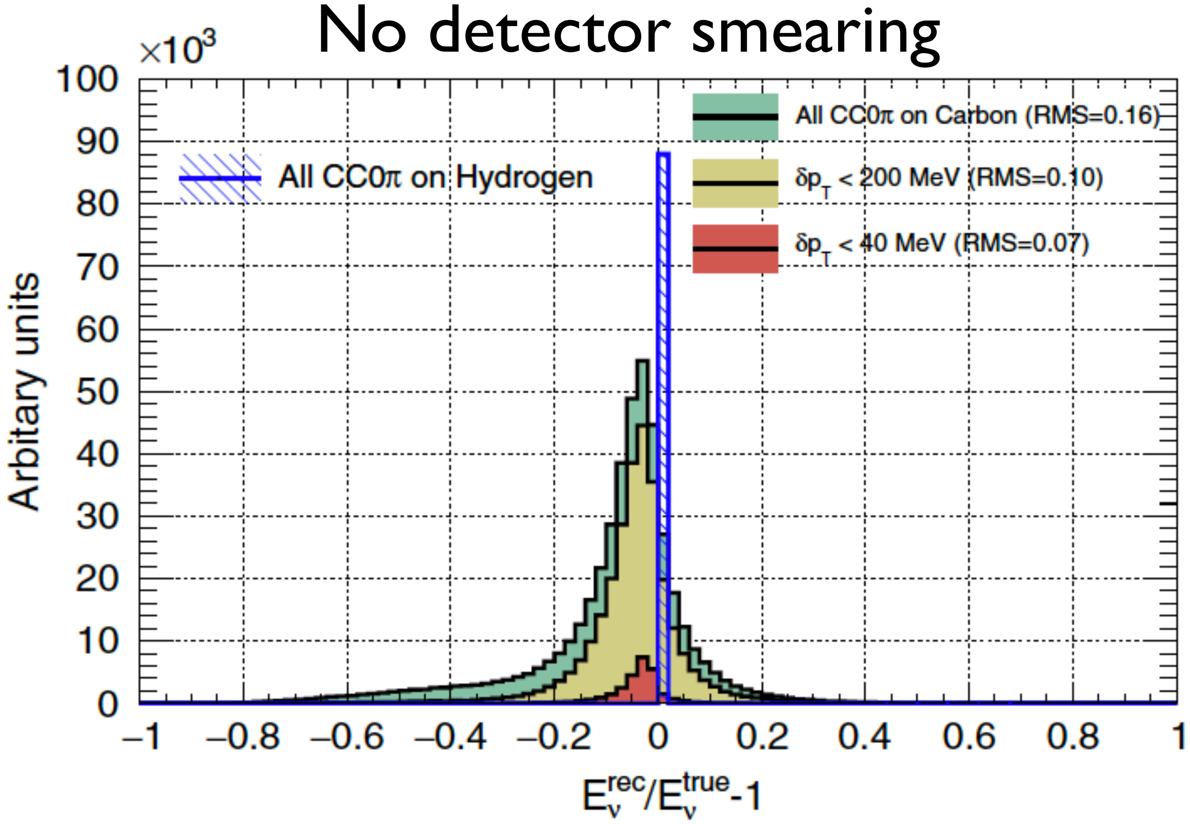


No detector smearing



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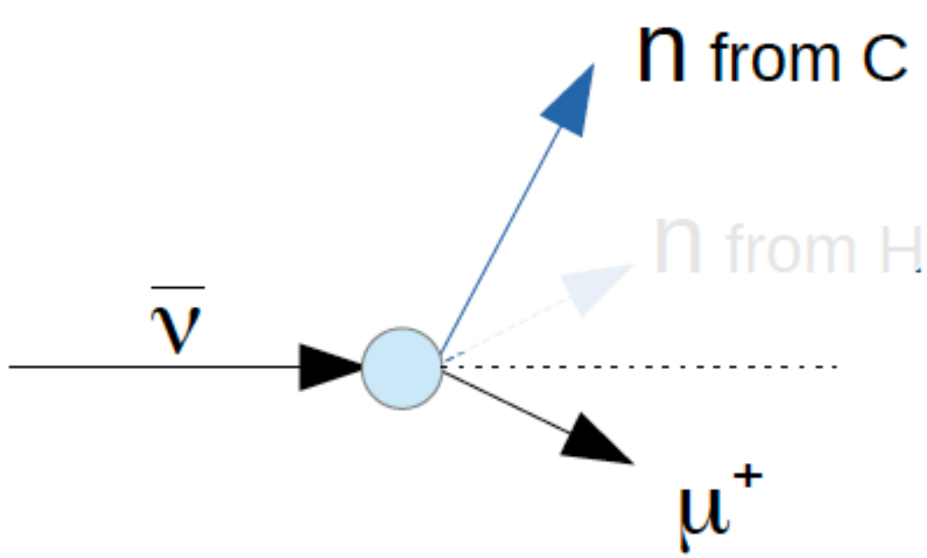

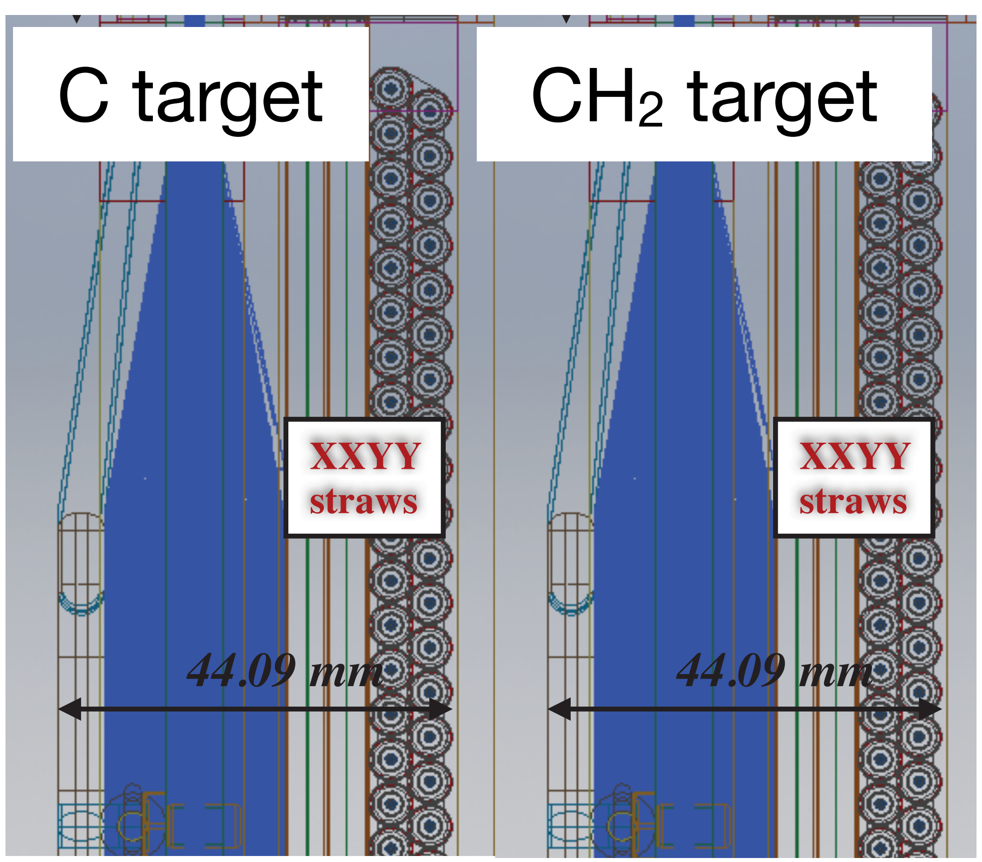

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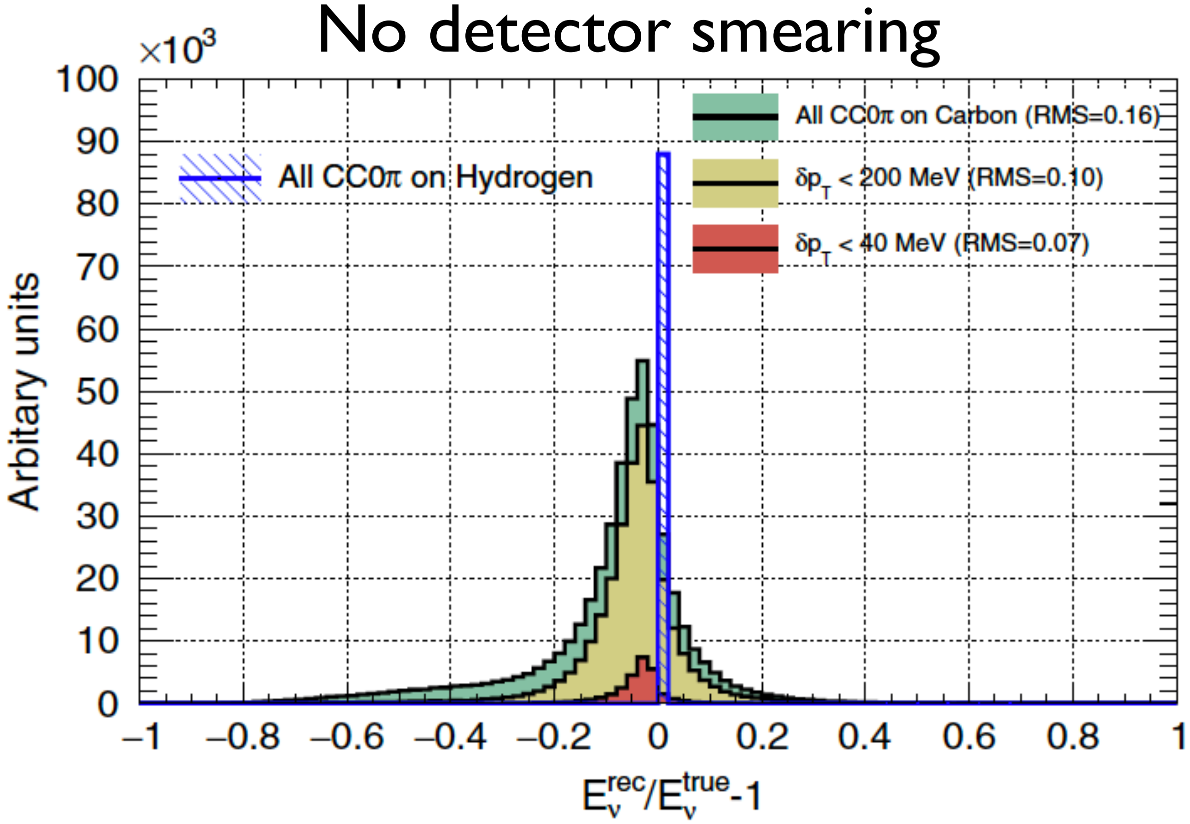
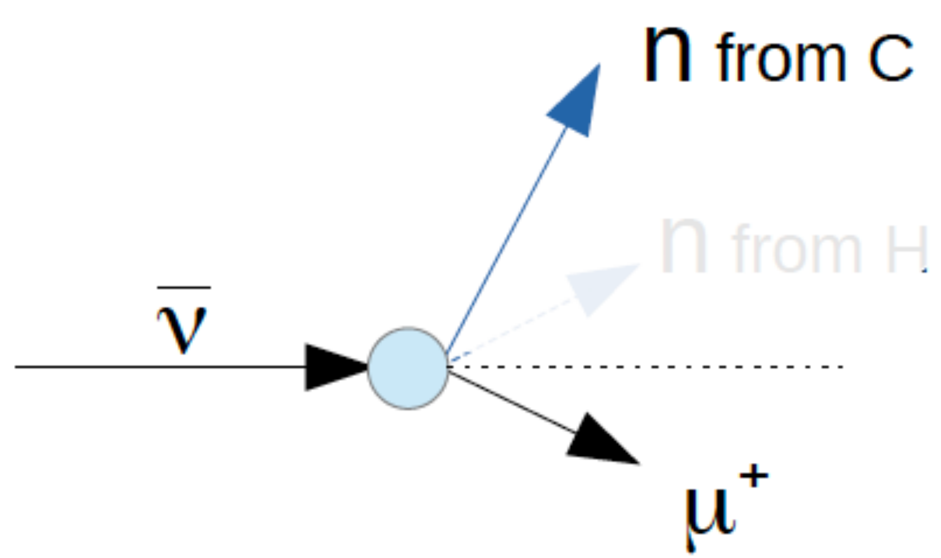
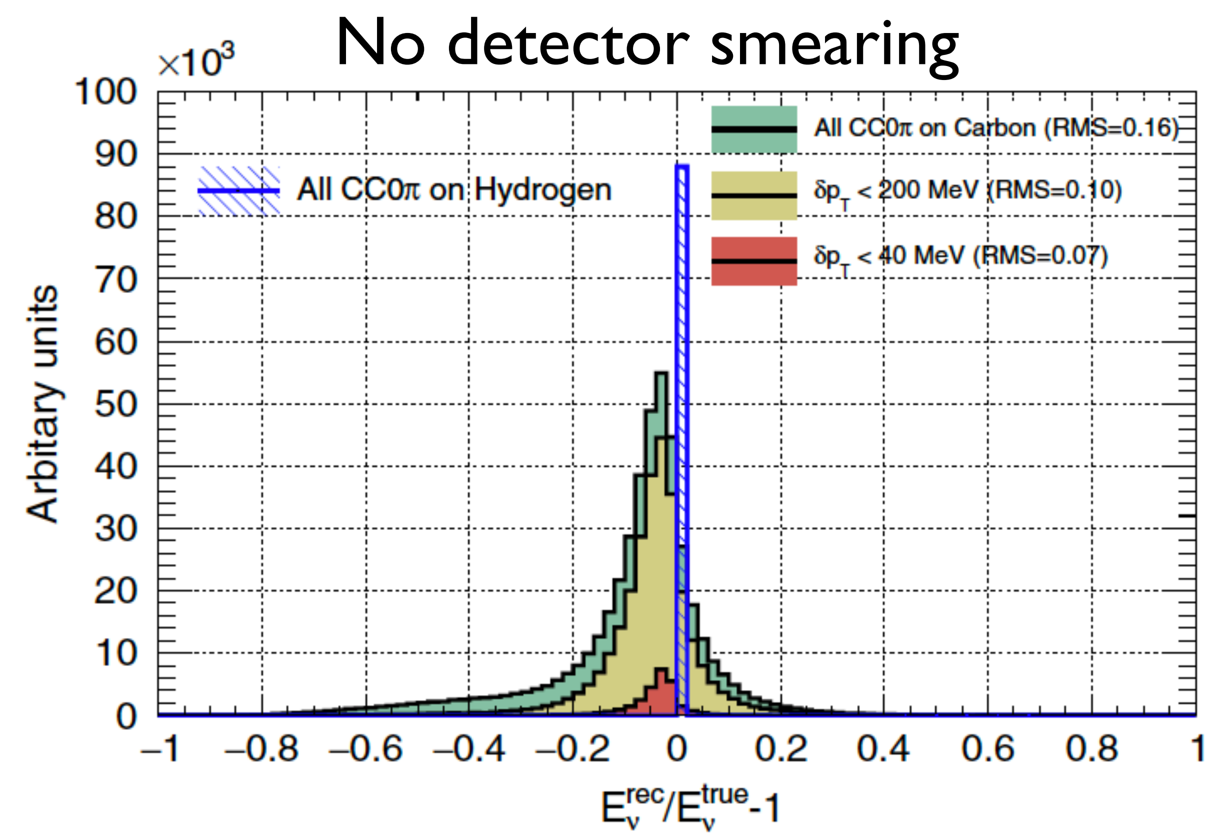


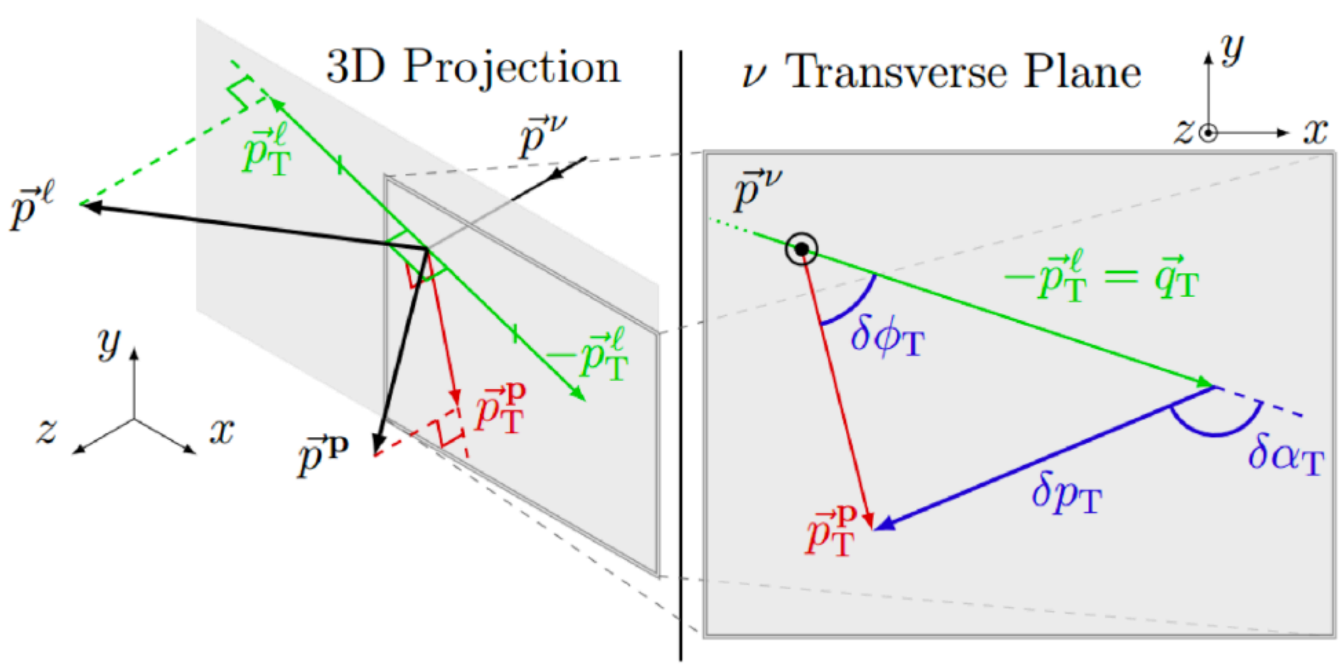
- Infer both the flux and the nucleon form factor
- By comparing C vs CH_2 target one can obtain the effect of neutrino interactions in Hydrogen

Neutrino interactions in hydrogen

Interactions in hydrogen are very useful because not affected by nuclear effects







- Infer both the flux and the nucleon form factor
- By selecting events with low transverse momentum we can obtain a sample enhanced by $\bar{\nu}$ -Hydrogen interactions

Conclusions

- SAND is the On-Axis ND complex to monitor the neutrino beam and energy spectrum
    - ✦ Identify possible issues in the beamline with only a few days data taking to avoid biases in the measurement of the oscillation parameters or loss of data

- However, SAND has also other important functions of SAND:
    - ✦ Complementary measurement of $\nu/\bar{\nu}$ flux using different but complementary methods based on interactions in hydrogen
    - ✦ Robustness against “unknown of unknown”, e.g. by measuring neutrino interactions in targets other then argon and with neutron energy reconstruction