Probing the SM at the low energy scale .

FLC Long talk

Eldwan Brianne
DESY
29st July 2019

DEEP UNDERGROUND NEUTRINO EXPERIMENT

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Outline.

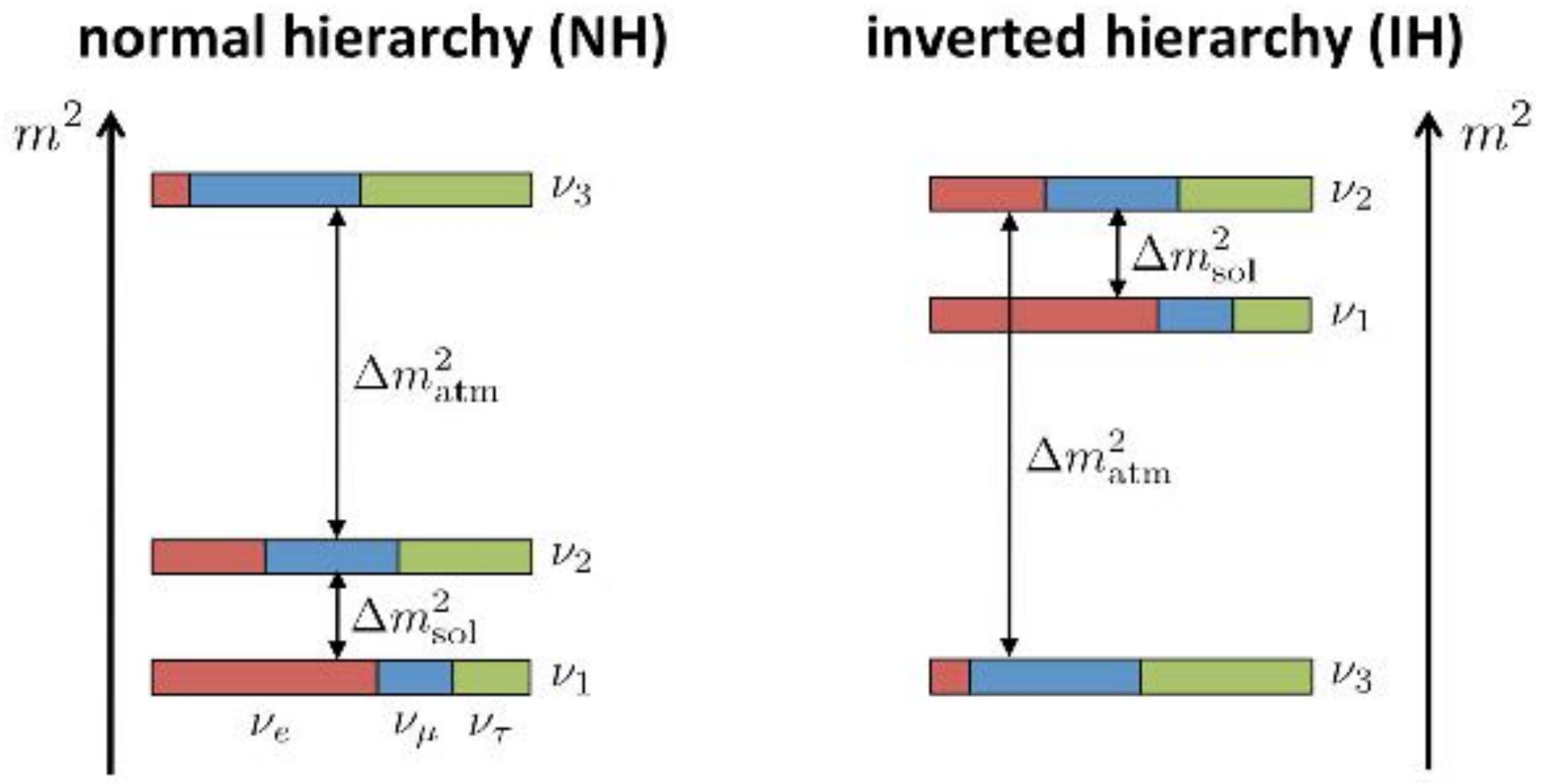
1. Neutrino oscillations
2. How to measure oscillations?
3. The DUNE Experiment
4. The Beam
5. The Far Detector concept
6. The Near Detector concept
7. The Multi-purpose detector
8. ECAL: Design and optimisation studies
9. Outlook and Conclusion

Neutrinos.

The primary questions

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}_{U_{\rm PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Neutrino oscillations hypothesised in 1957 ➠ Nobel prize 2015
- Described by the PMNS Matrix (similar to CMK) where the flavour eigenstates are a superposition of mass eigenstates
  - Parametrised by angles (θ_{12}, θ_{23}, θ_{13}) and a phase (δ_{cp})
- The remaining questions
  - **Neutrino mass hierarchy**
    - Are the states ν_1 & ν_2 lighter or heavier than ν_3?
  - **CP violation**
    - $\delta_{cp} \neq (0, \pi)$? Neutrino / Anti-neutrino asymmetry
  - **Octant of θ_{23}**
    - $\sin\theta_{23} \neq 0.5$? Mixing in which way?



Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Neutrinos.

Oscillations?

- Oscillation formula (1st order approximation)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

Matter effect! (a)

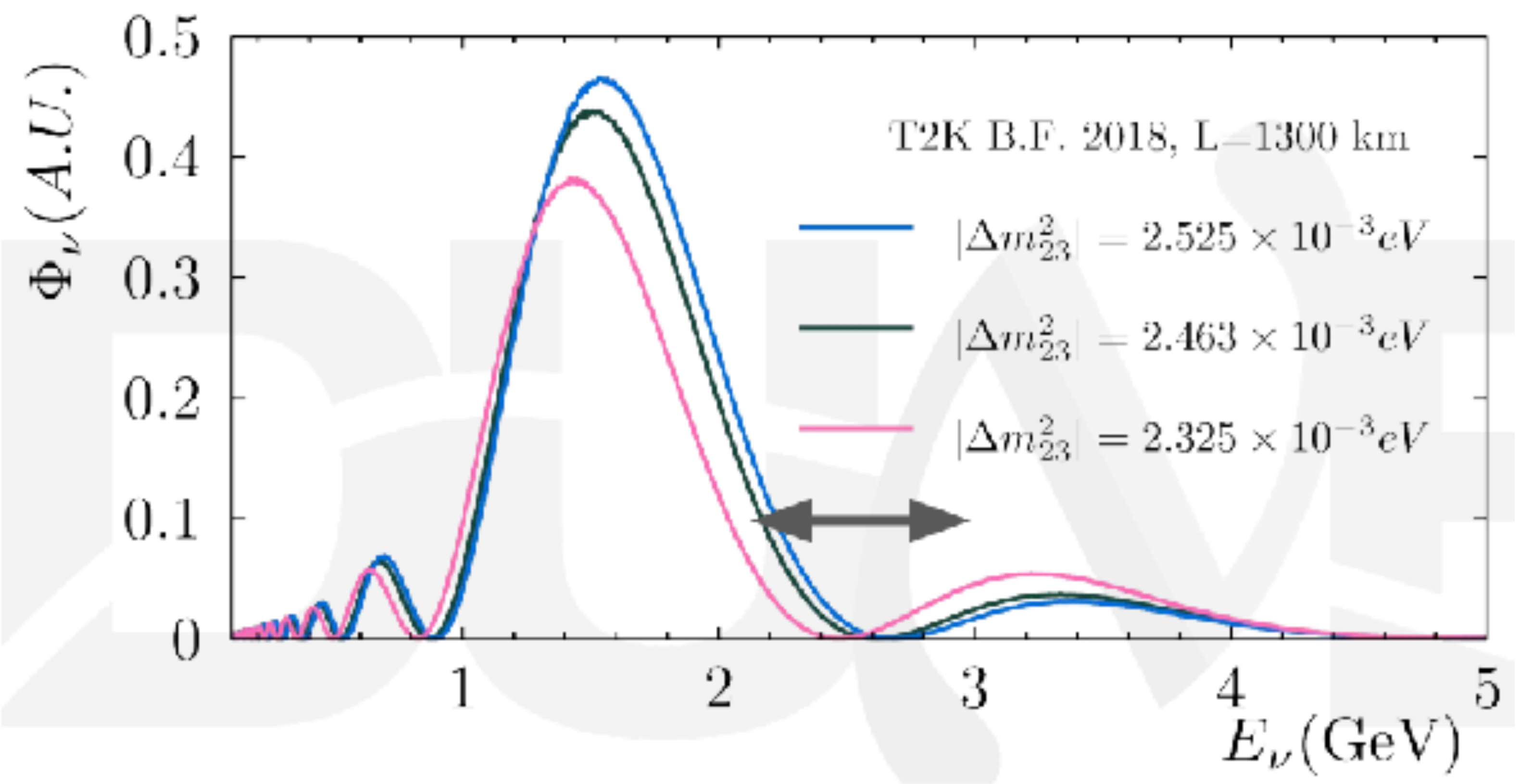
Neutrino mass effect ($\Delta m^2 E/L$)

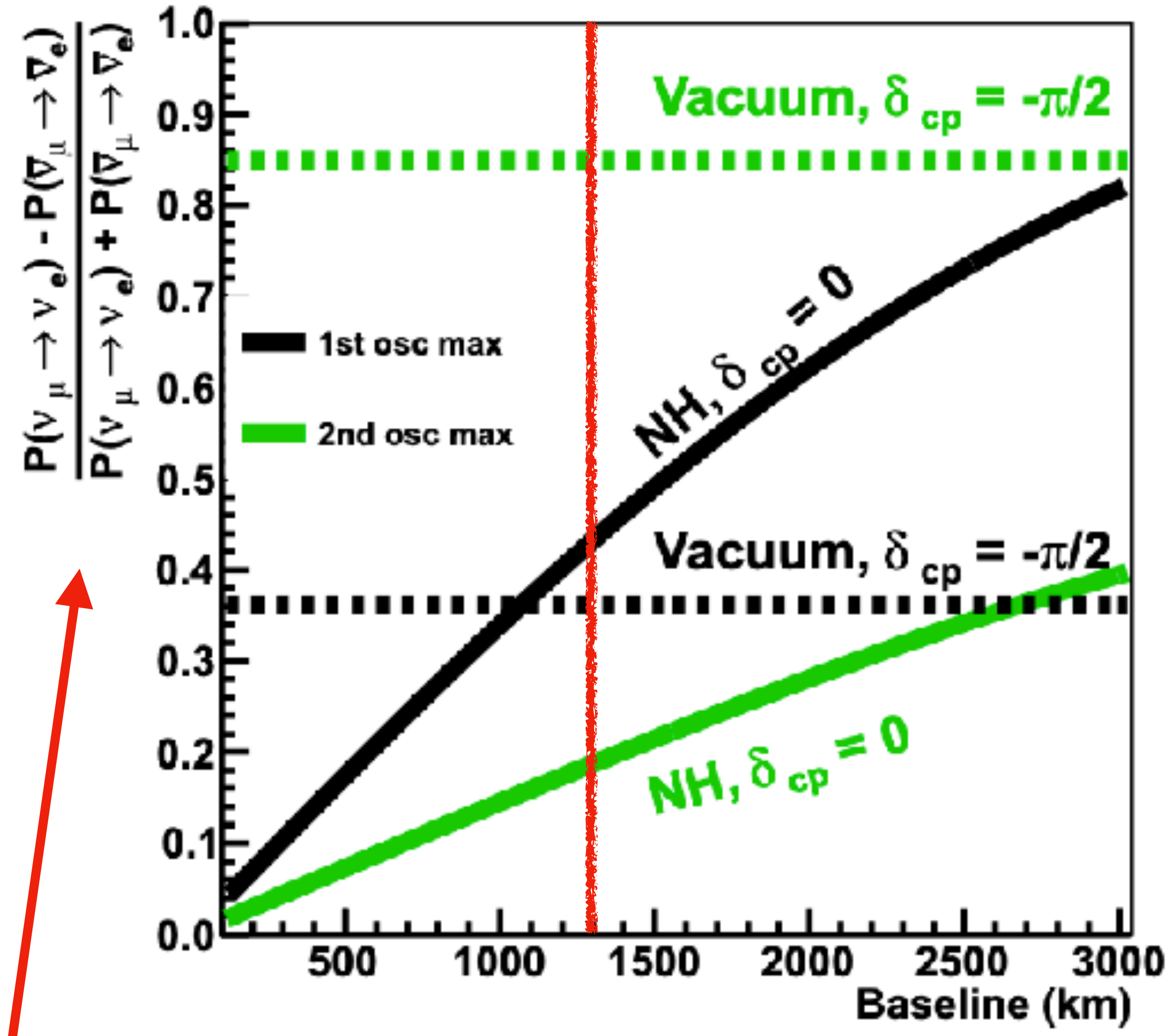
CPV effect

- **Asymmetry**

$$
A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) + \text{matter effects}
$$

- Matter effect creates asymmetry (even with δ_{cp} = 0 or π) ➠ Need for a long-baseline at second oscillation maximum to have ***better CP sensitivity***





arXiv:1311.0212v3

Measure δ_{cp} and mass ordering at the same time

The Long Baseline Neutrino Analysis.

How to measure oscillations?

- Want to measure oscillation probability
- However, **detector effects** ➠ need for unfolding / not so easy to cancel systematics
- In reality, this is not easy, need to understand
  - **The neutrino flux**
  - **Cross-section ratios**
  - **Extrapolation near to far**
  - **Detector effects (near and far)**
  - **Relation true to reco neutrino energy**

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi^{far}_{\nu_e}(E_\nu)}{\phi^{far,no-osc}_{\nu_\mu}(E_\nu)} = \frac{\phi^{far}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu)}$$

$$\frac{dN^{det}_\nu}{dE_{rec}} = \int \phi^{det}_\nu(E_\nu) * \sigma^{target}_\nu(E_\nu) * T^{det}_{\nu_\mu}(E_\nu, E_{rec})\, dE_\nu$$

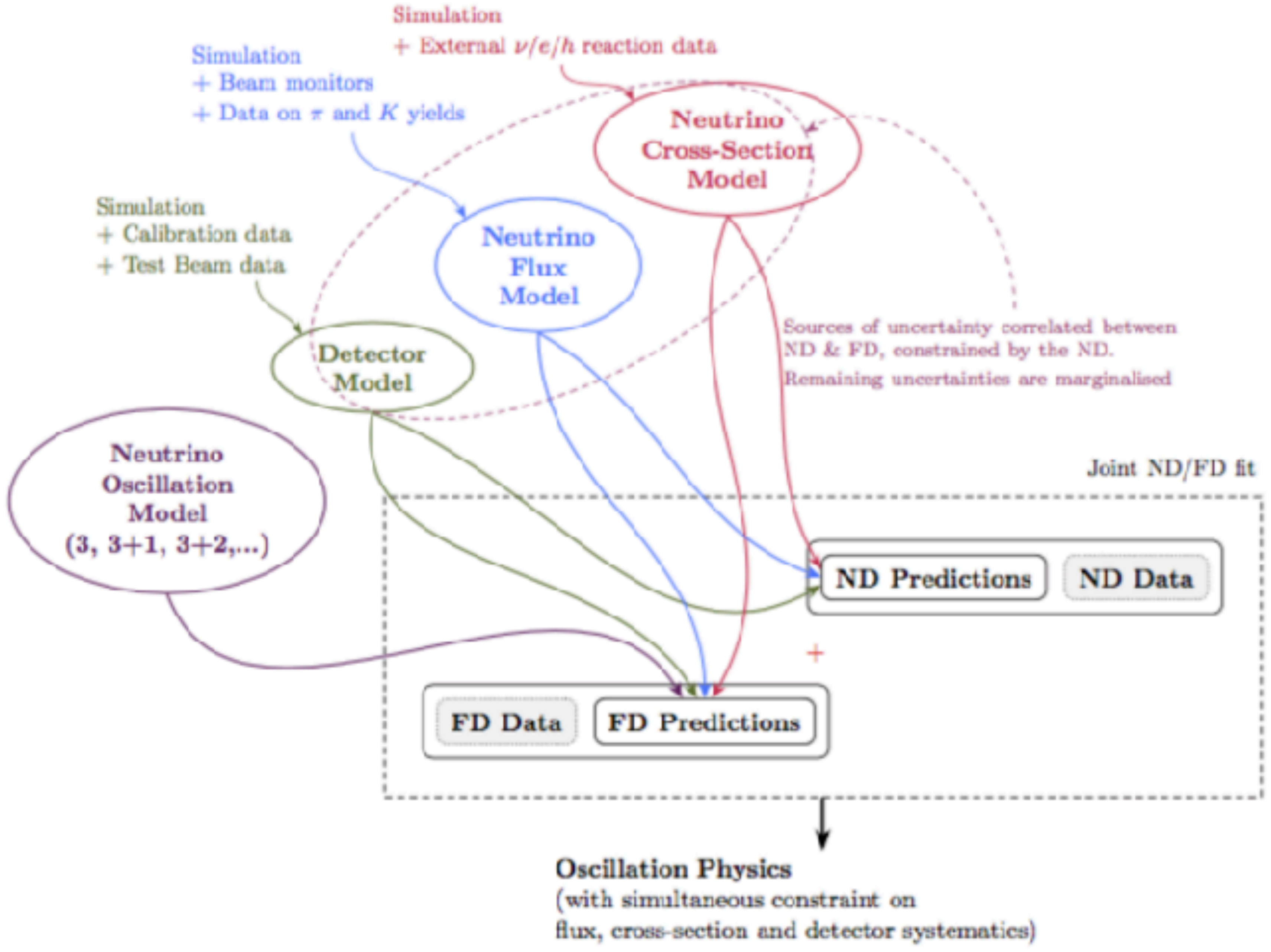
$$\frac{dN^{far}_{\nu_e}}{dE_\nu} \Big/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * F_{far/near}(E_\nu)$$

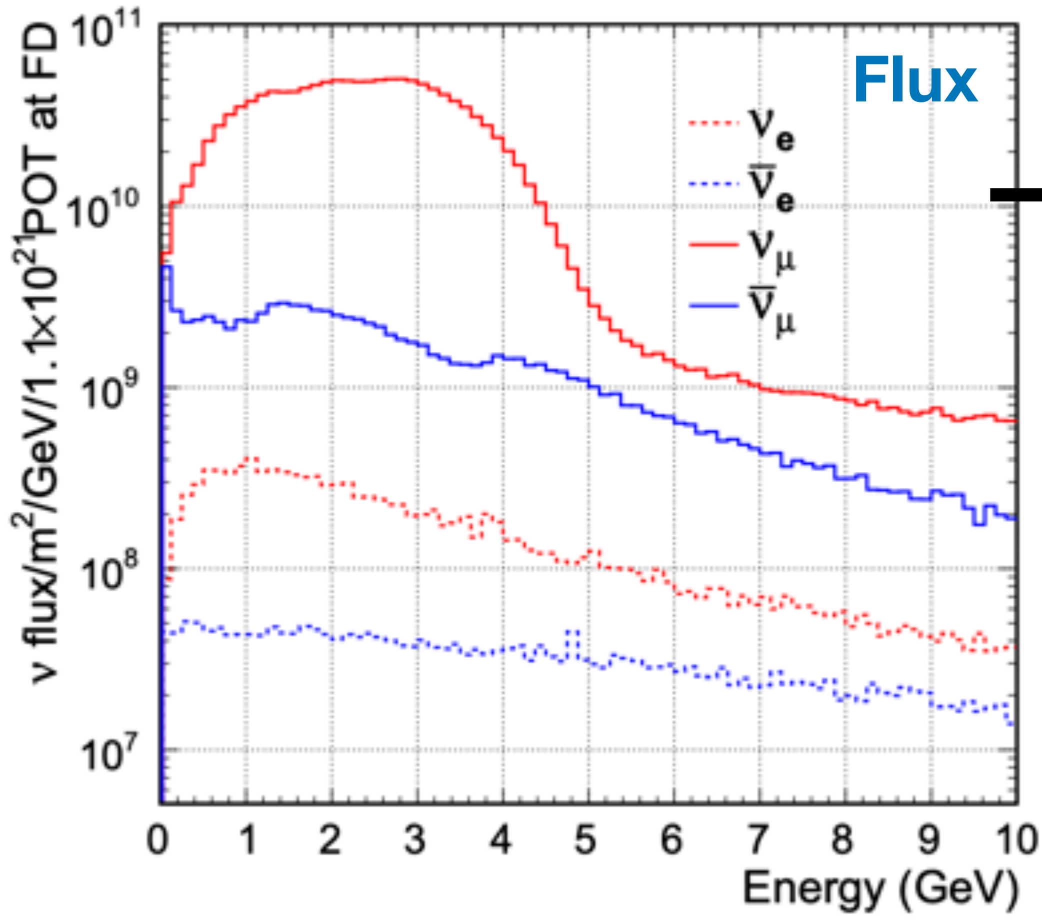
$$\frac{dN^{near}_{\nu_e}}{dE_\nu} \Big/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * \frac{\phi^{near}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu)}$$

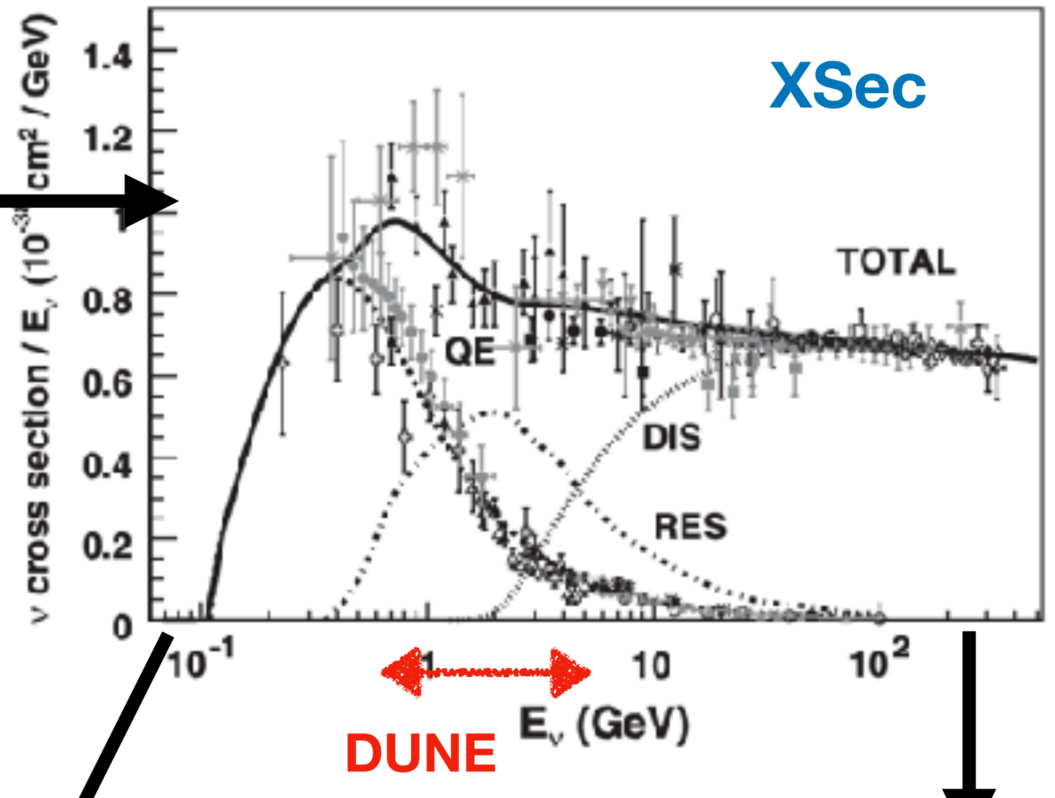
The Long Baseline Neutrino Analysis.

In plots..

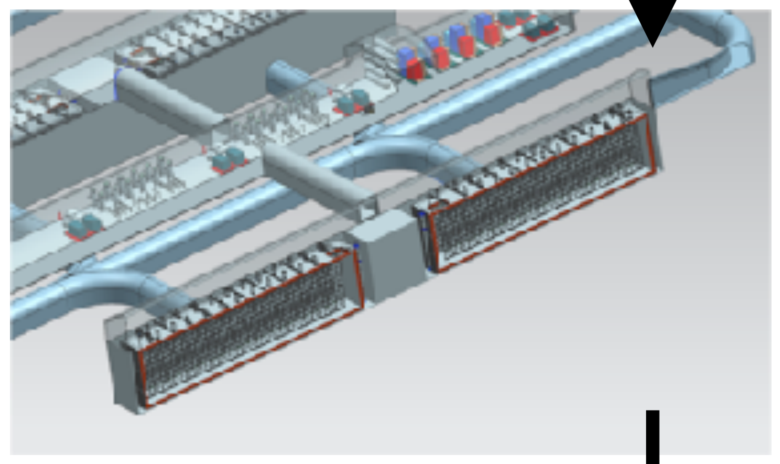
- Measure the flux/XSec at the ND (ν_μ CC, ν_e CC) ➠ *Provide as many samples as possible!*
- Measure ν_μ disappearance and ν_e (ν_τ) appearance at the FD
- Perform oscillation fit ➠ **joint ND/FD fit** / Need a good understanding of systematics (flux, XSec, detector) and model



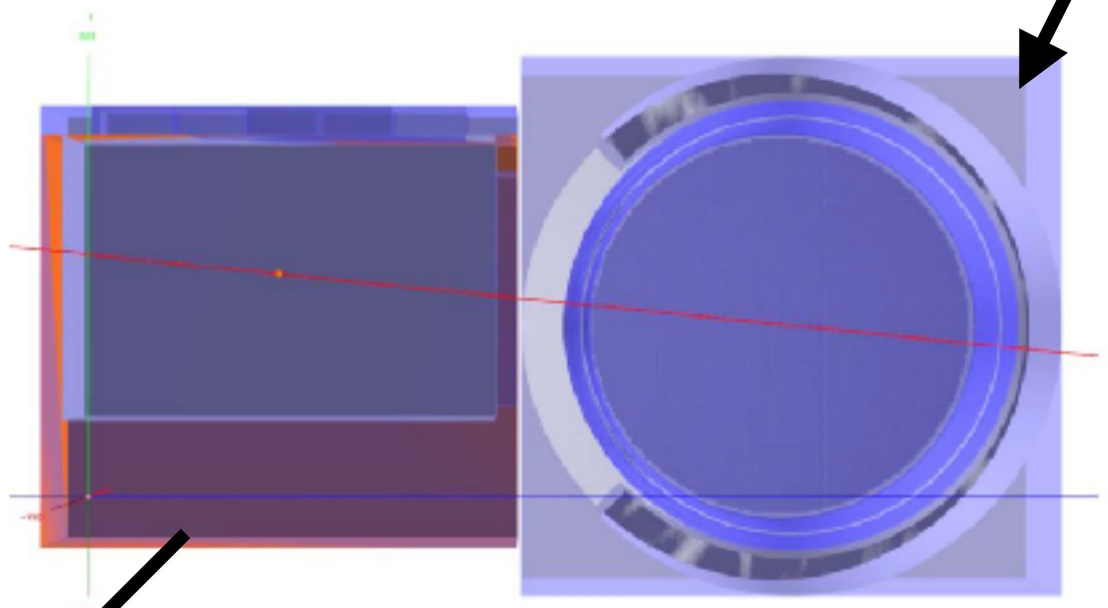


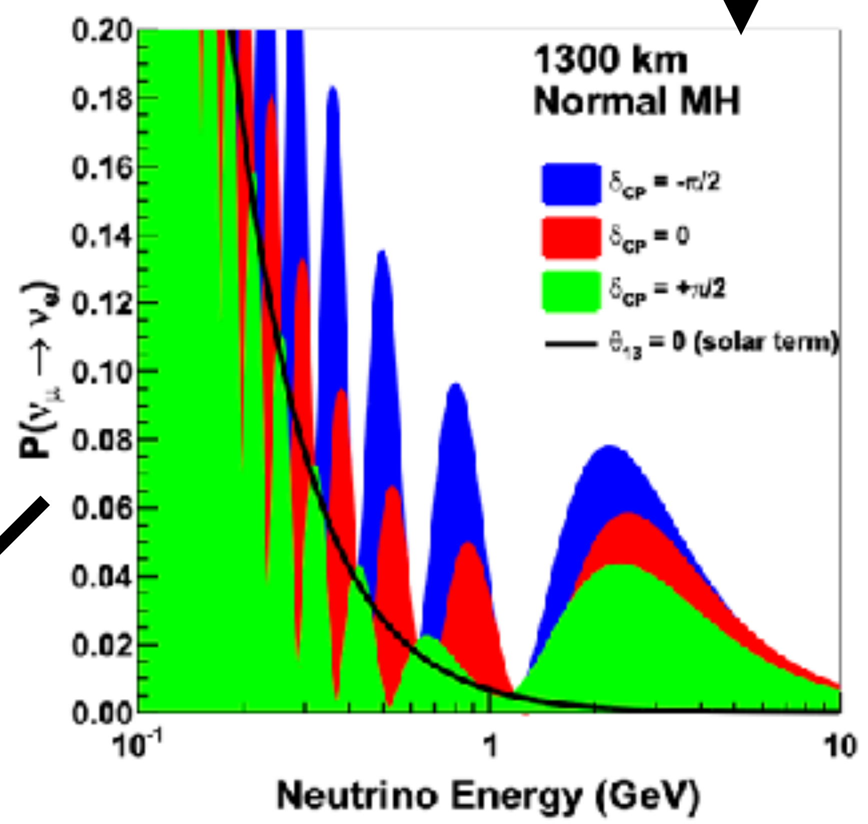


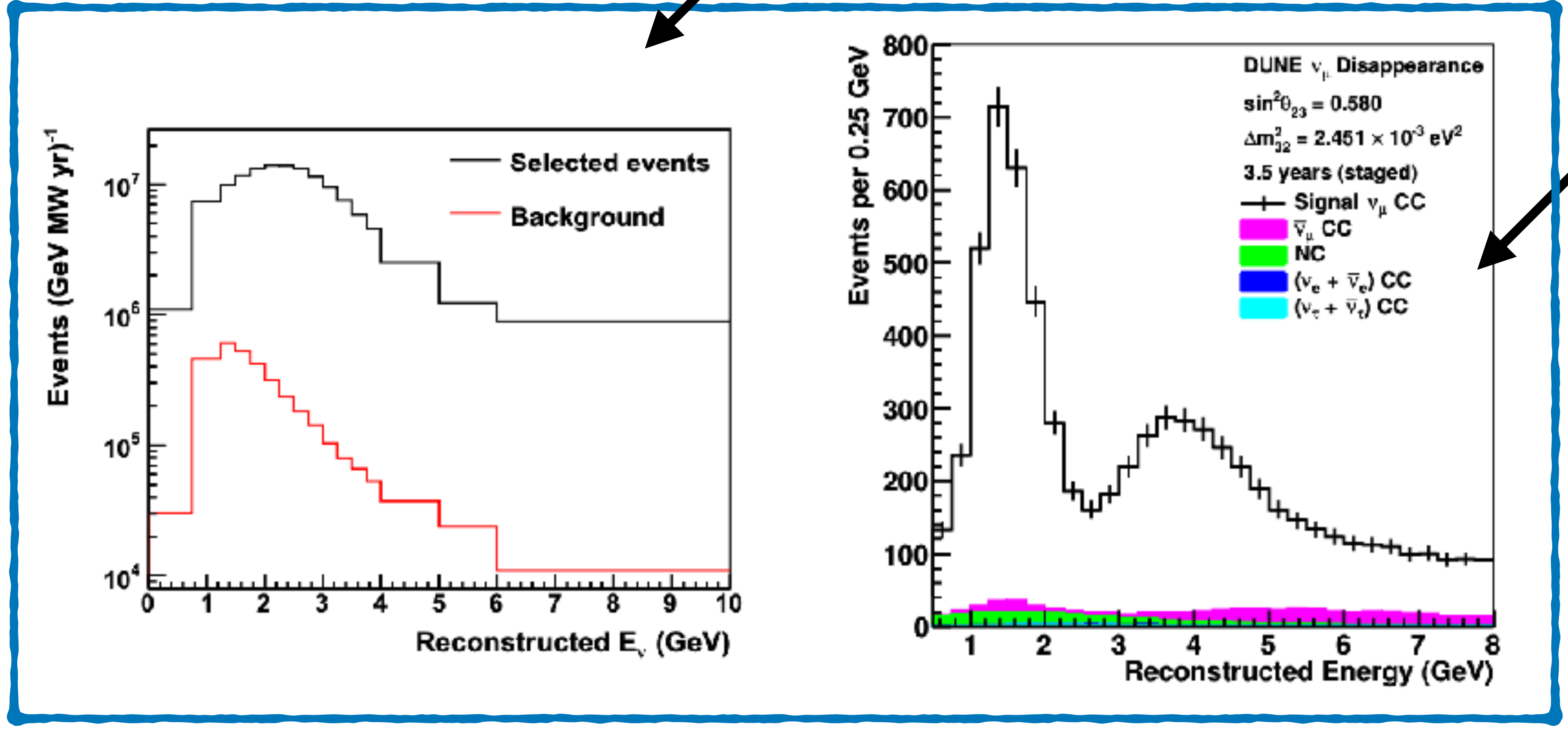
FD



ND





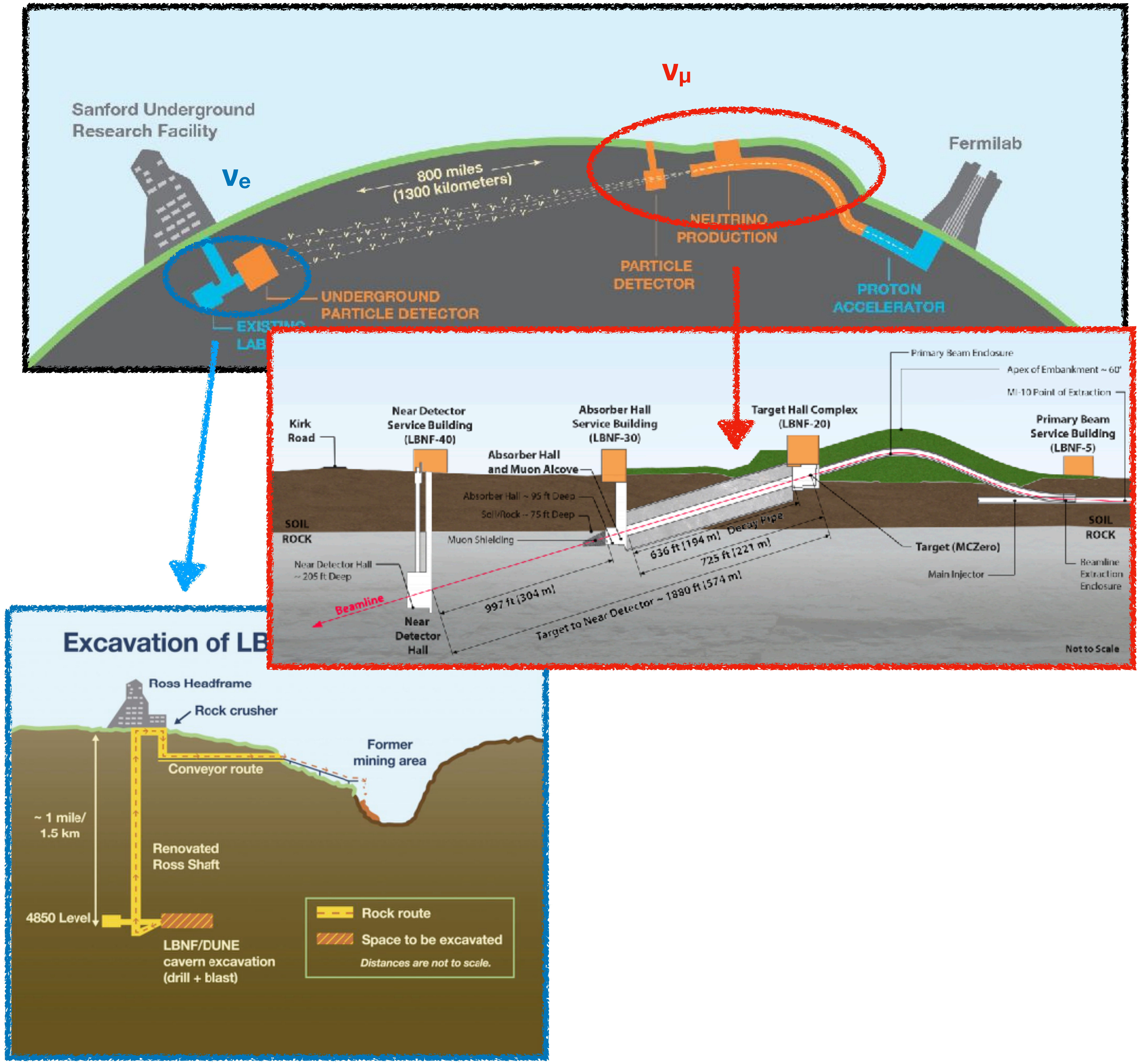


Combined Fit ND + FD + Systematics

The DUNE Experiment.

Deep Underground Neutrino Experiment

- **The next generation neutrino experiment**
- Goals:
  - **Neutrino oscillations** ➠ measure ν_μ disappearance and ν_e and ν_τ appearance (both FHC and RHC)
  - Measure δ_{cp} over 75% of the phase space with a **precision up to 5σ**, determine mass hierarchy and precise measurement of the mixing angles (θ_{23} octant)
  - *Beyond the SM physics*: neutrino tridents, DM, sterile neutrinos…
- Other searches: neutrino supernovae, proton decay…



The DUNE Collaboration.

A growing community

- International Collaboration
    - 31 countries, 177 institutes, 1000+ collaborators
- Fast growing community!
- Last CM at Fermilab (20-24 May)
    - ~ 250+ participants
- Followed by intense ND workshop (25-27 May)
    - Focus on answering questions from the LBNC (ND review committee)

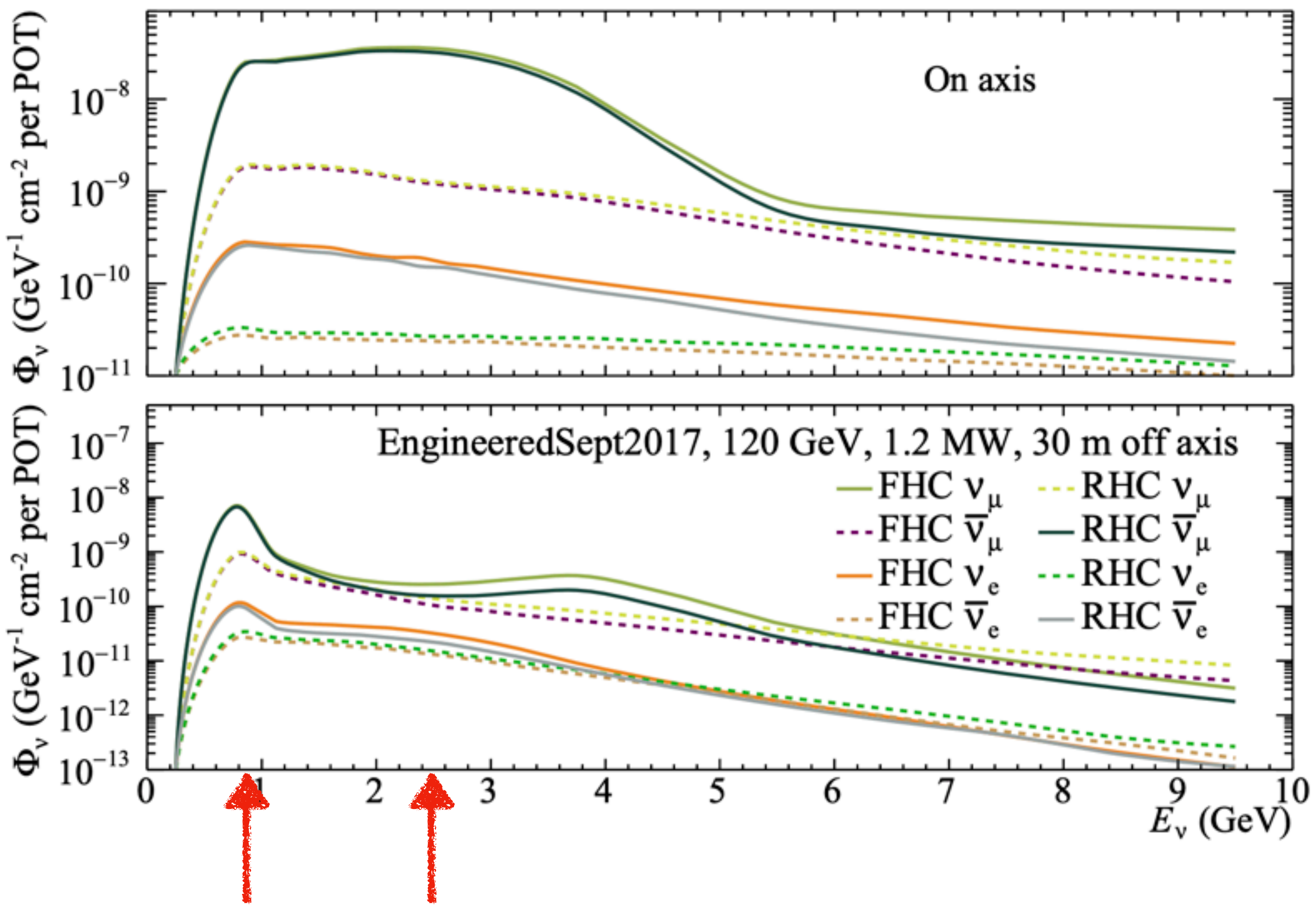
Time for Germany!

I am here!

The Neutrino beam.

Long Baseline Neutrino Facility (LBNF)

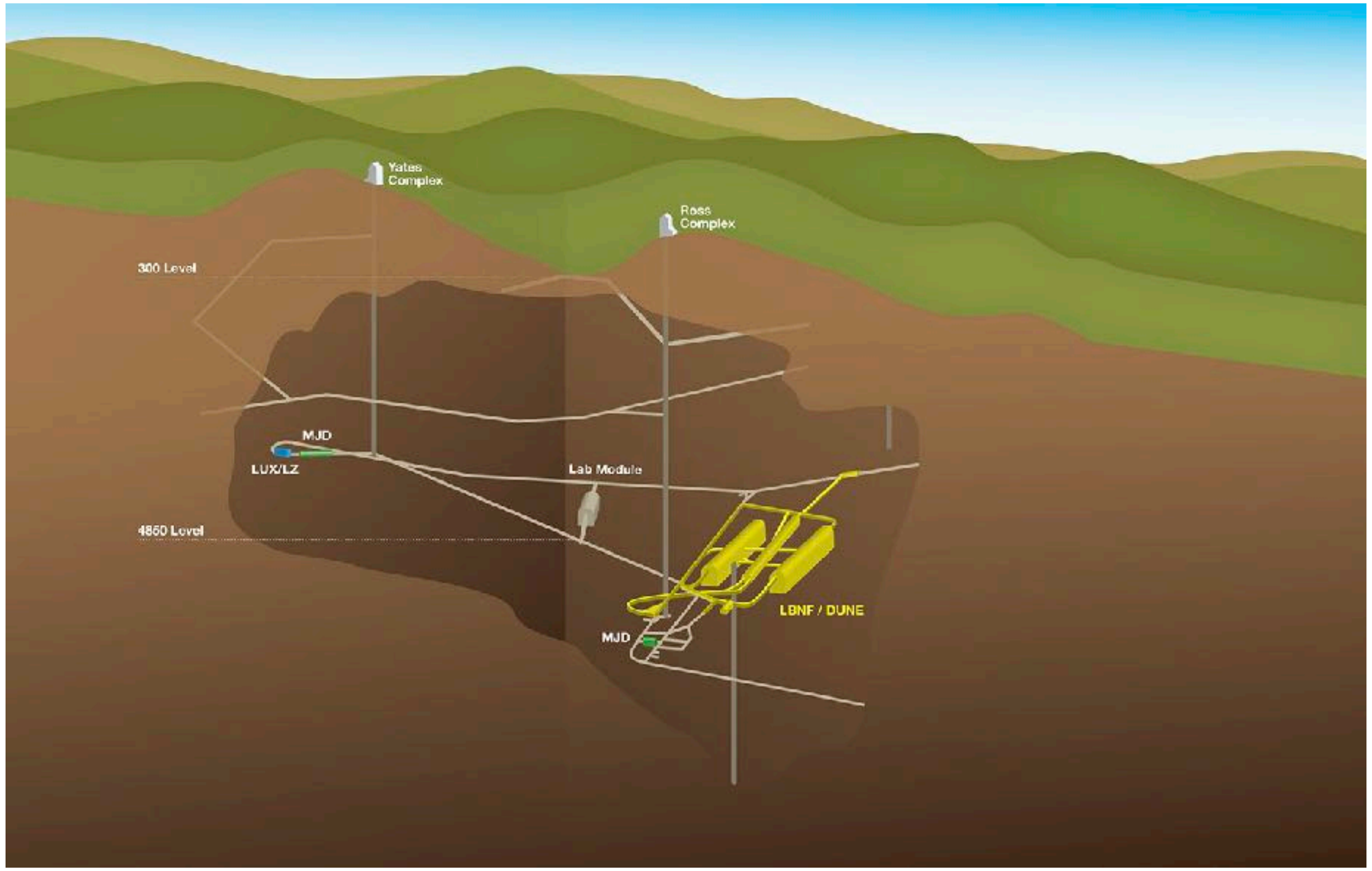
- 120 GeV proton beam on target
- **1.2 MW** beam power, upgradable to 2.4 MW
- Beamline and focusing system optimised for *maximum CP sensitivity*
- Wide-band beam (1st and 2nd oscillation maxima)



The Far Detector complex.

Sanford Underground Research Facility (SURF)

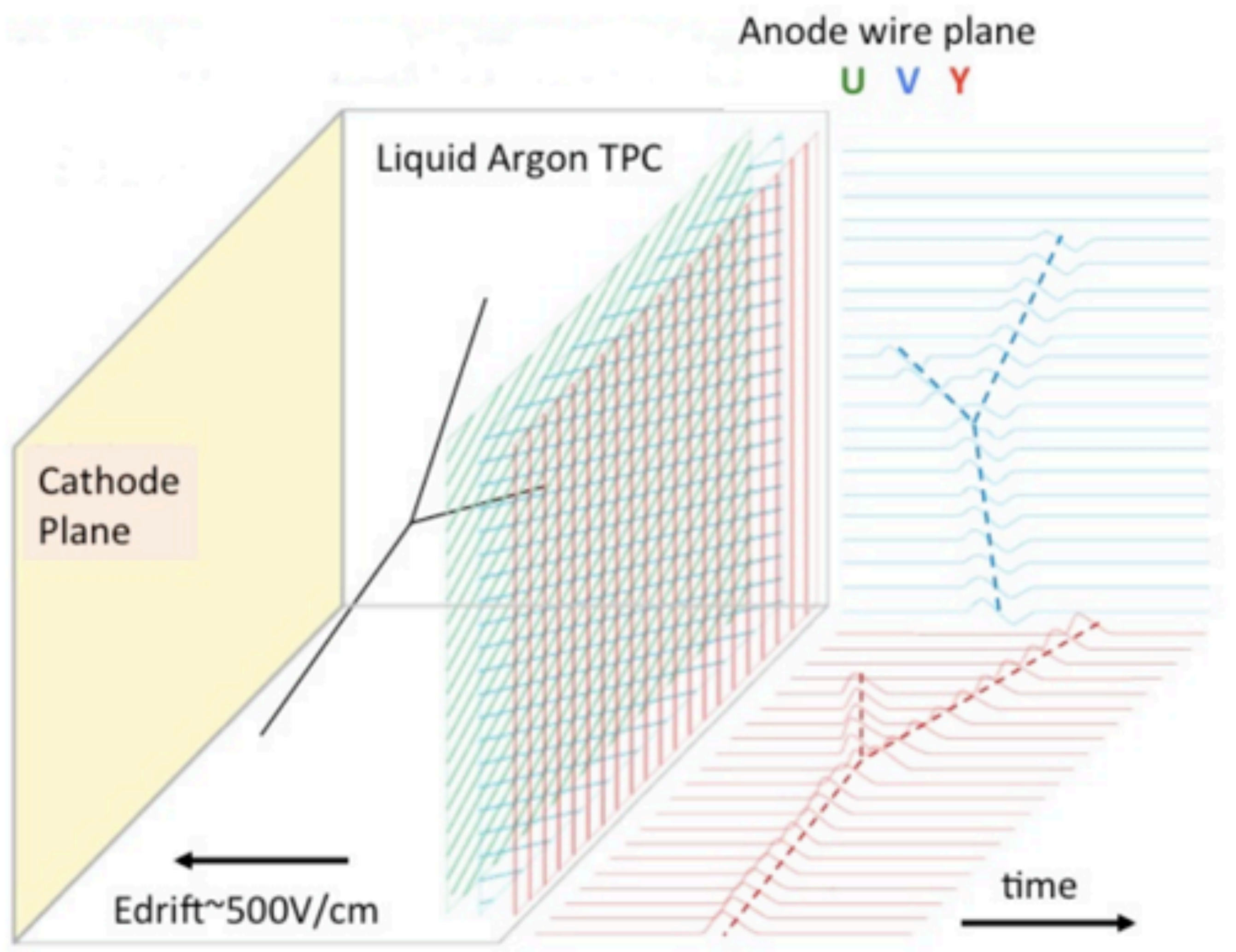
- South Dakota Laboratory at ~1300 km from Fermilab
- **Four 10-kt** Fiducial LAr TPC modules, located 1.48 km underground
- Excavation in 2019
- First module operational in 2024
- Start of run: 2 FD modules (20 kt), 1.2 MW beam power, with ND
- +1 year: 3 FD modules (30 kt)
- +3 years: 4 FD modules (40 kt)
- +6 years: upgrade to 2.4 MW beam

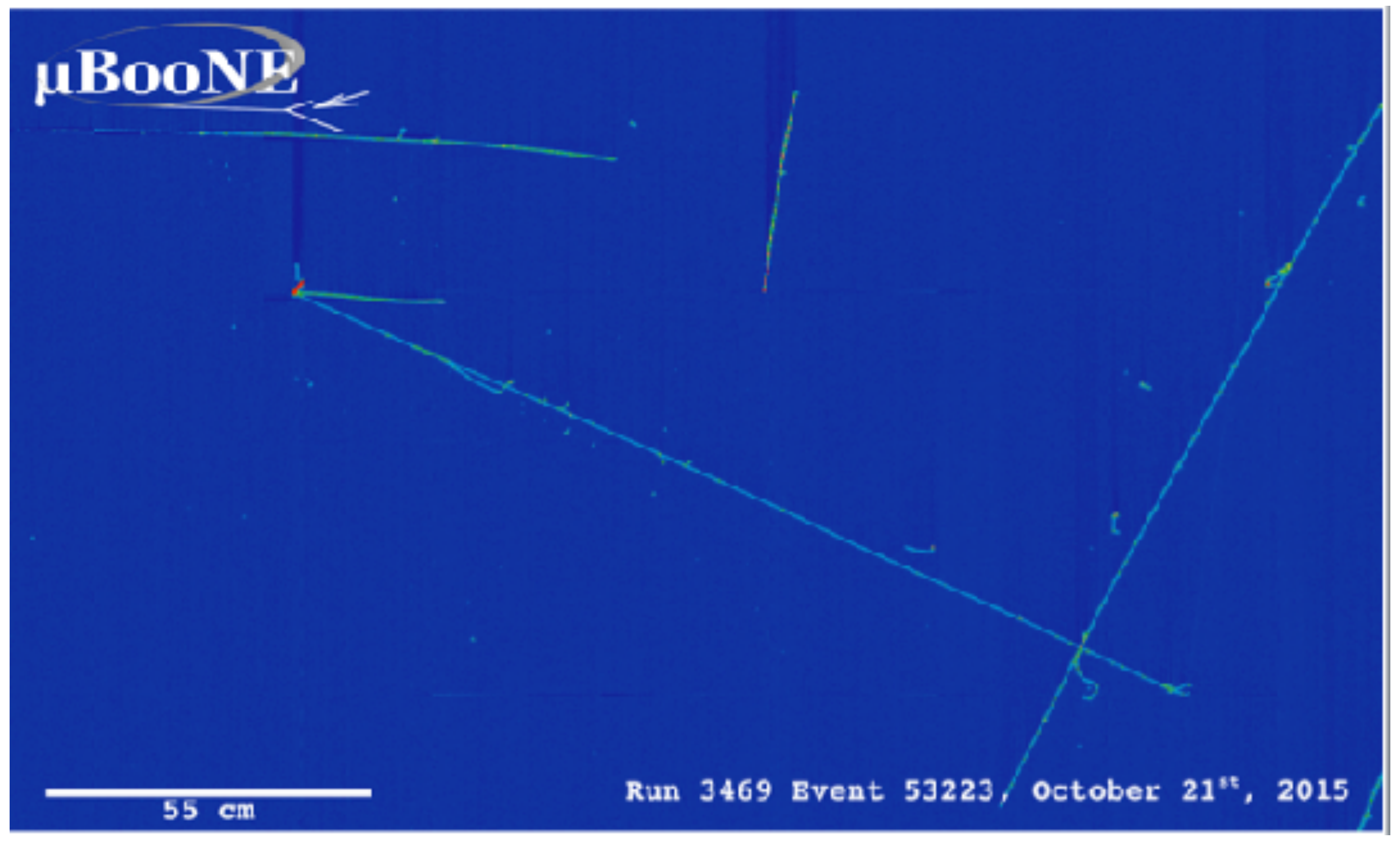


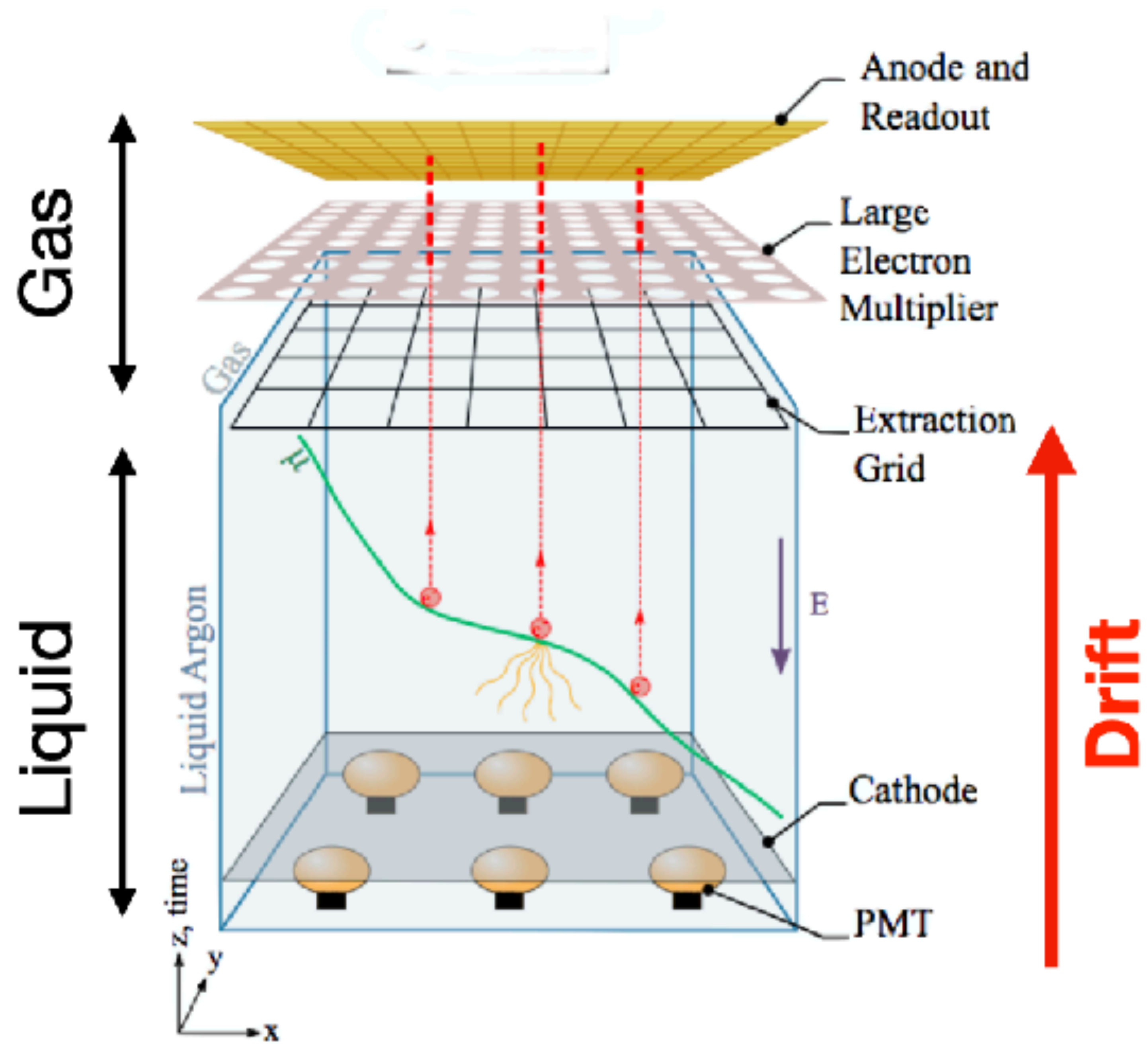
The Far Detectors.

Technology and Prototypes

- Large LAr TPC
  - Ar is cheap & abundant
  - High resolution imaging **(~mm)**
  - Homogenous calorimeter
  - Proven technology for neutrino detection: MicroBoone, ICARUS…
- Two technologies:
  - **Single-phase** (SP), only LAr with no amplification, one collection plane
  - **Dual-phase** (DP), LAr and GAr with amplification in the gas, 2 collection planes



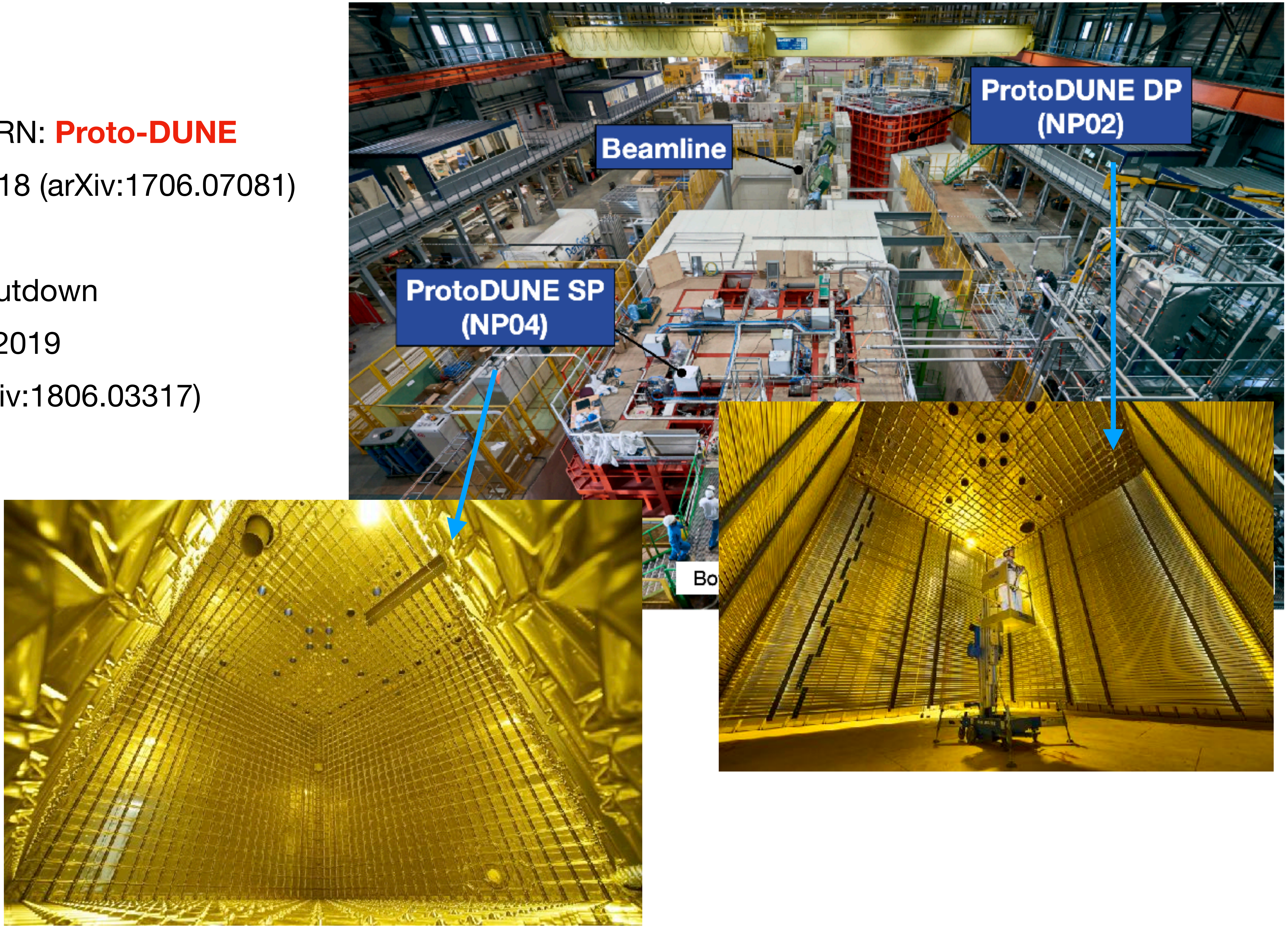




The Far Detectors.

Technology and Prototypes

- Two prototypes are constructed at CERN: **Proto-DUNE**
- Proto-DUNE SP finished in autumn 2018 (arXiv:1706.07081)
  - 6x7x7 m^3, 0.77kt FM
  - Started taking data before LHC shutdown
- Proto-DUNE DP finished in June/July 2019
  - Demonstrator 4t in 2016/2017 (arXiv:1806.03317)
  - 6x6x6 m^3, 300t FM
  - Filling with LAr just finished

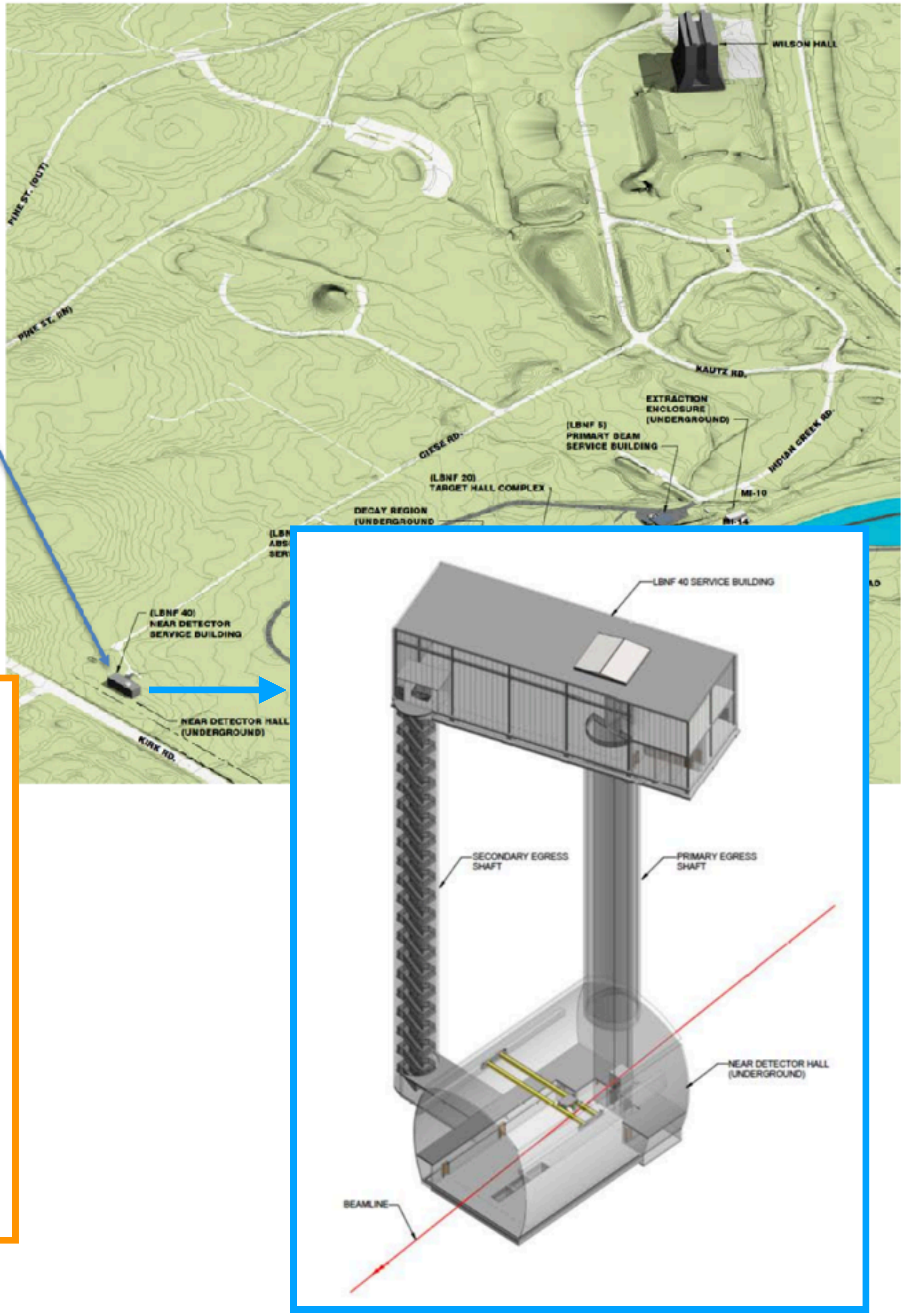


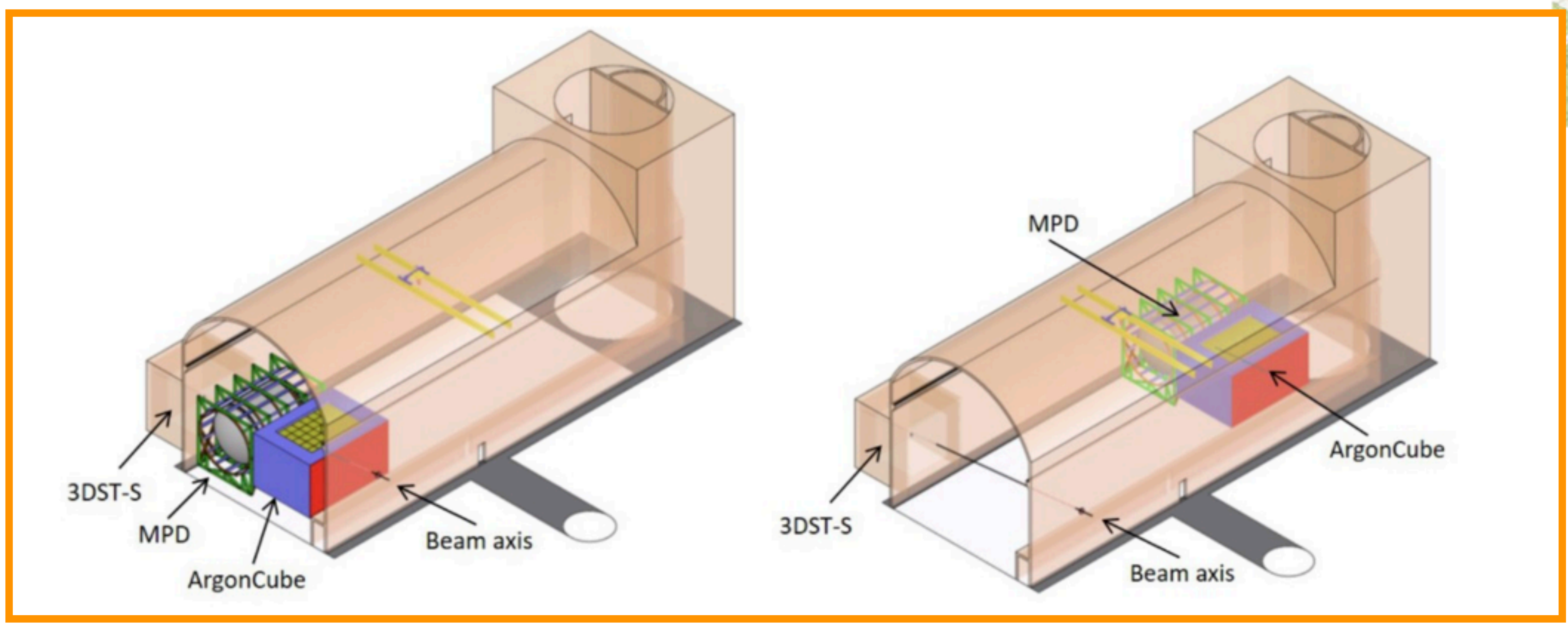
The Near Detector Complex.

Fermilab

- Located at Fermilab
- ~ 60m underground
- Hall size ~ 42m x 15m
- Allow for moving the detectors off axis ➠ **DUNE-PRISM** concept (https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=8106)

You are here

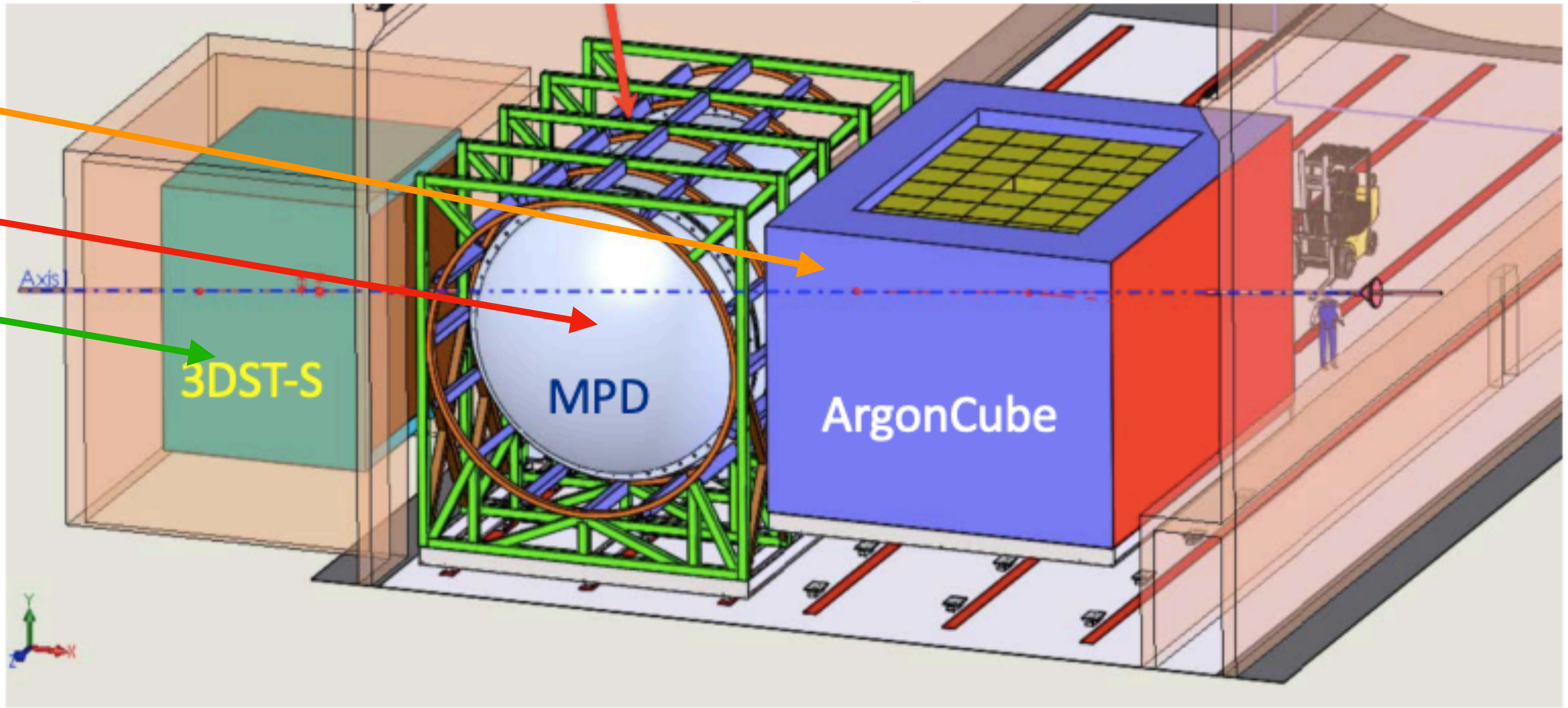




The Near Detectors

Fermilab

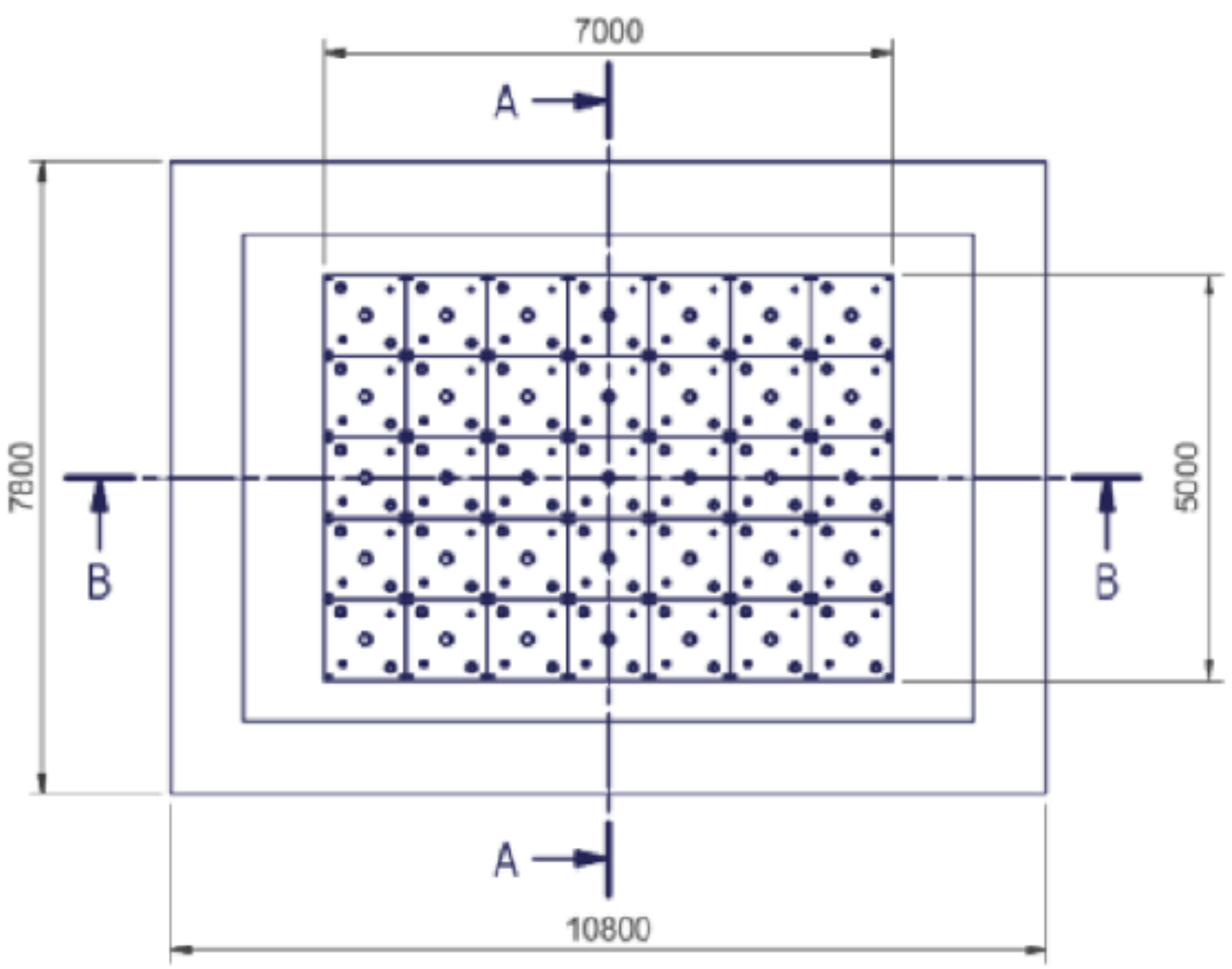
- 3 detectors
  - ArgonCube (LArTPC) using pixel readout
  - Multi-purpose detector (MPD): HP GArTPC + ECAL + Magnet
  - Beam monitor (and more…): 3DST-S
- **Goals of the ND**
  - Measure the neutrino flux
  - Measure the neutrino energy
  - Predict rate at the FD
  - Constrain XS models
  - Identify possible bias at the FD
  - Beam monitoring
- **Crucial element** to achieve the DUNE physics program

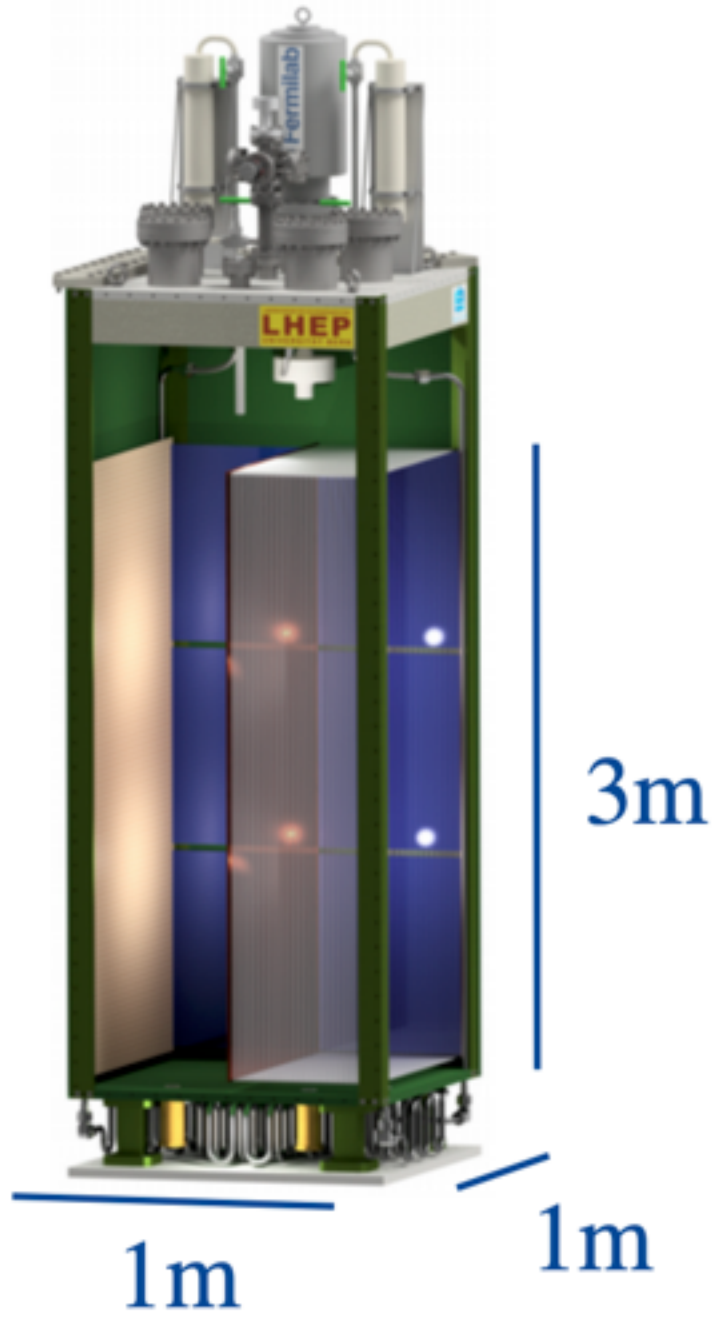


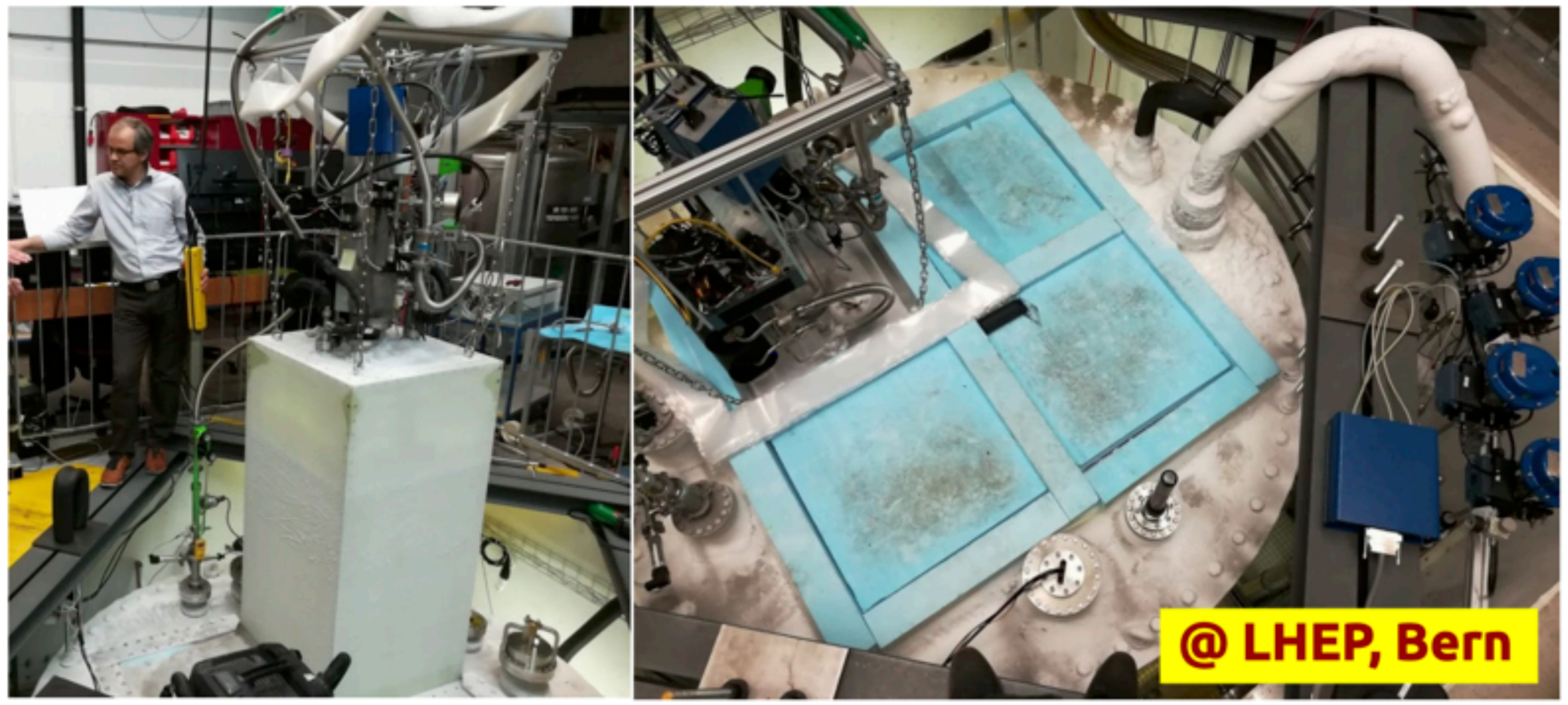
The Liquid Argon TPC

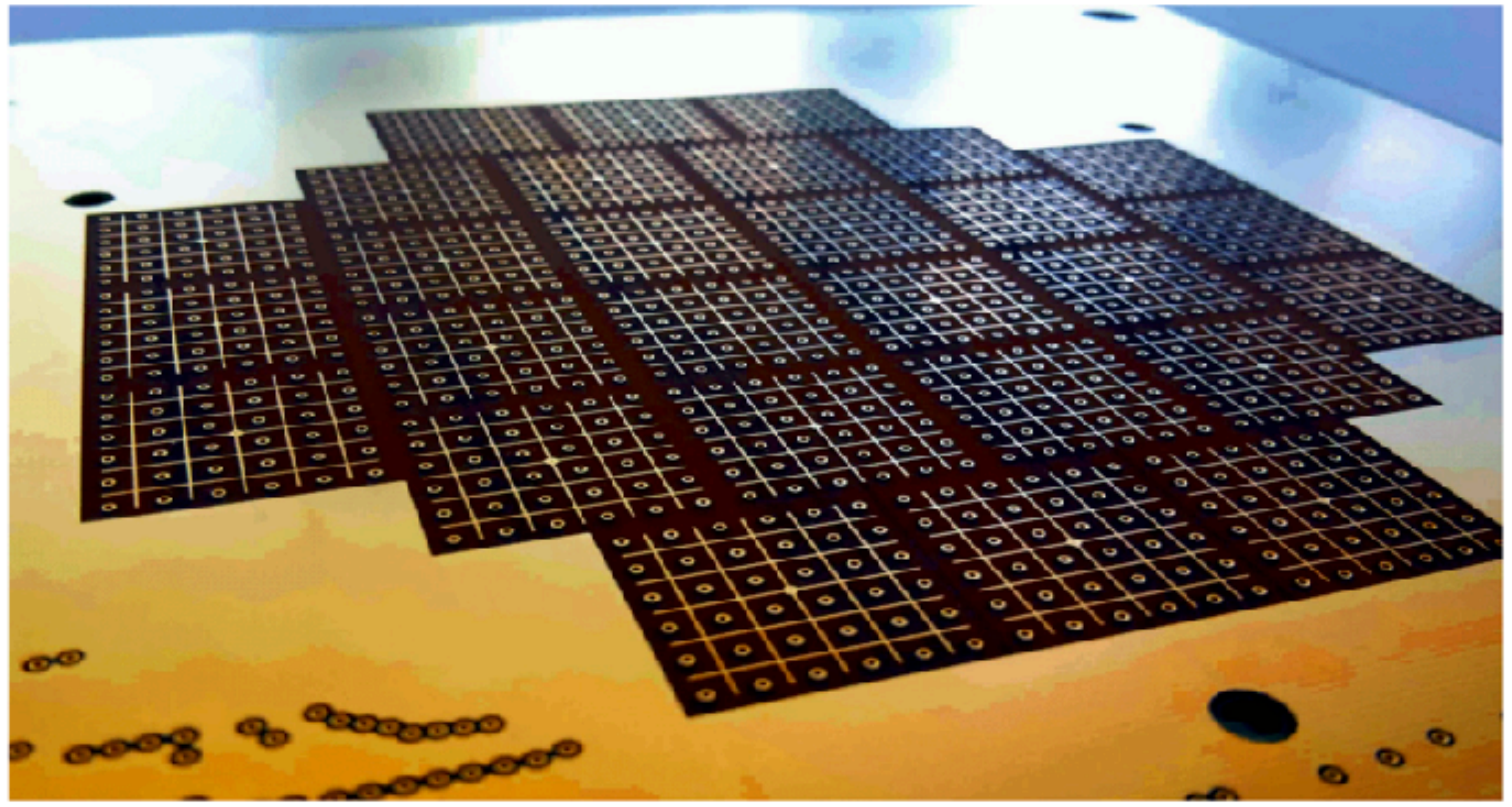
A modular LAr TPC

- 150t LAr TPC of 5x7x3 m³ FV
- **Modular concept** ➠ 30 modules of 1x1x3 m³
- <u>Readout</u>: Pixel pads 2.9 mm pitch with FE ASICs + light readout system using SiPMs (t_0)
- *Demonstrator 2x2* planned for next year at Fermilab (Proto-DUNE ND)





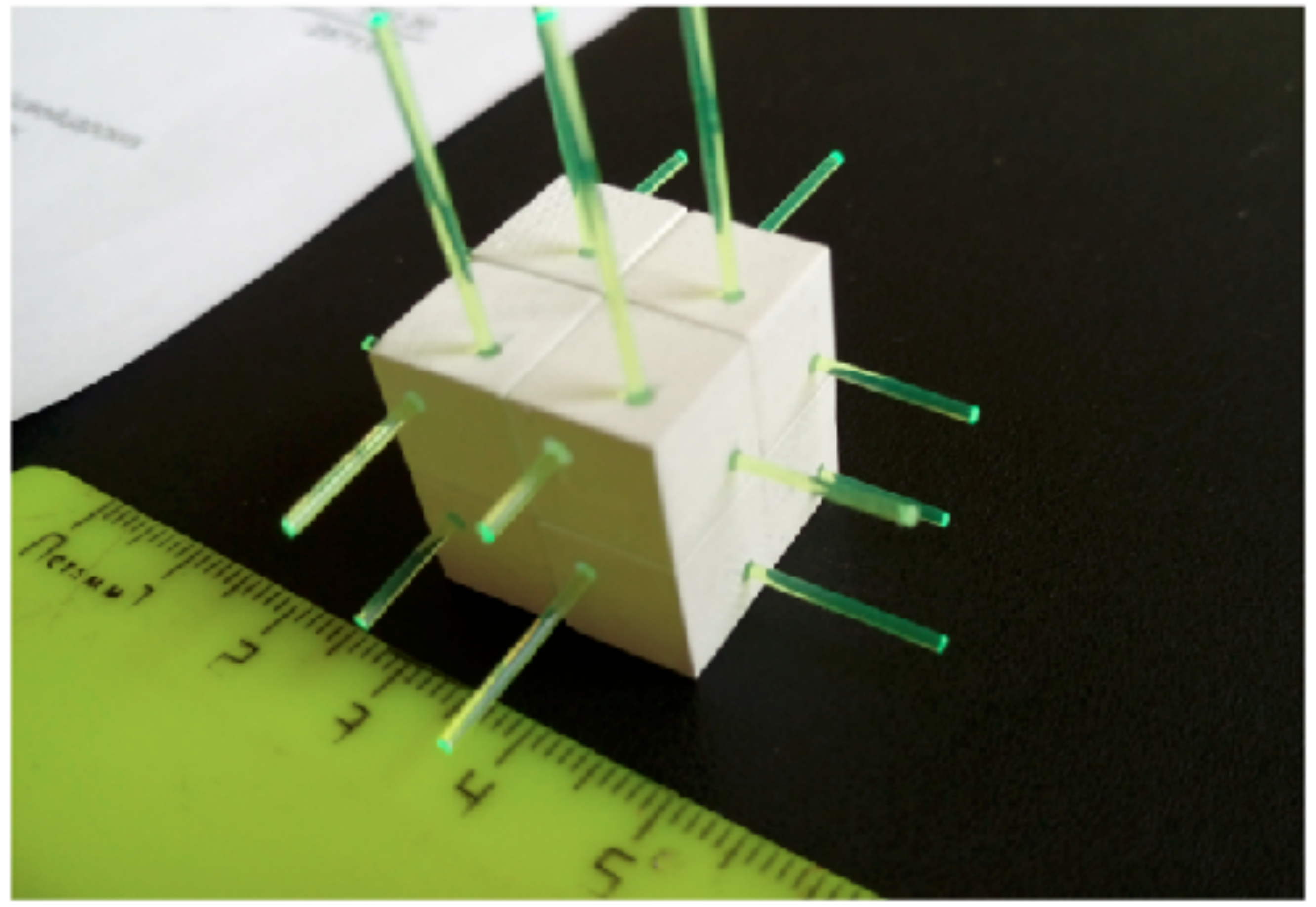


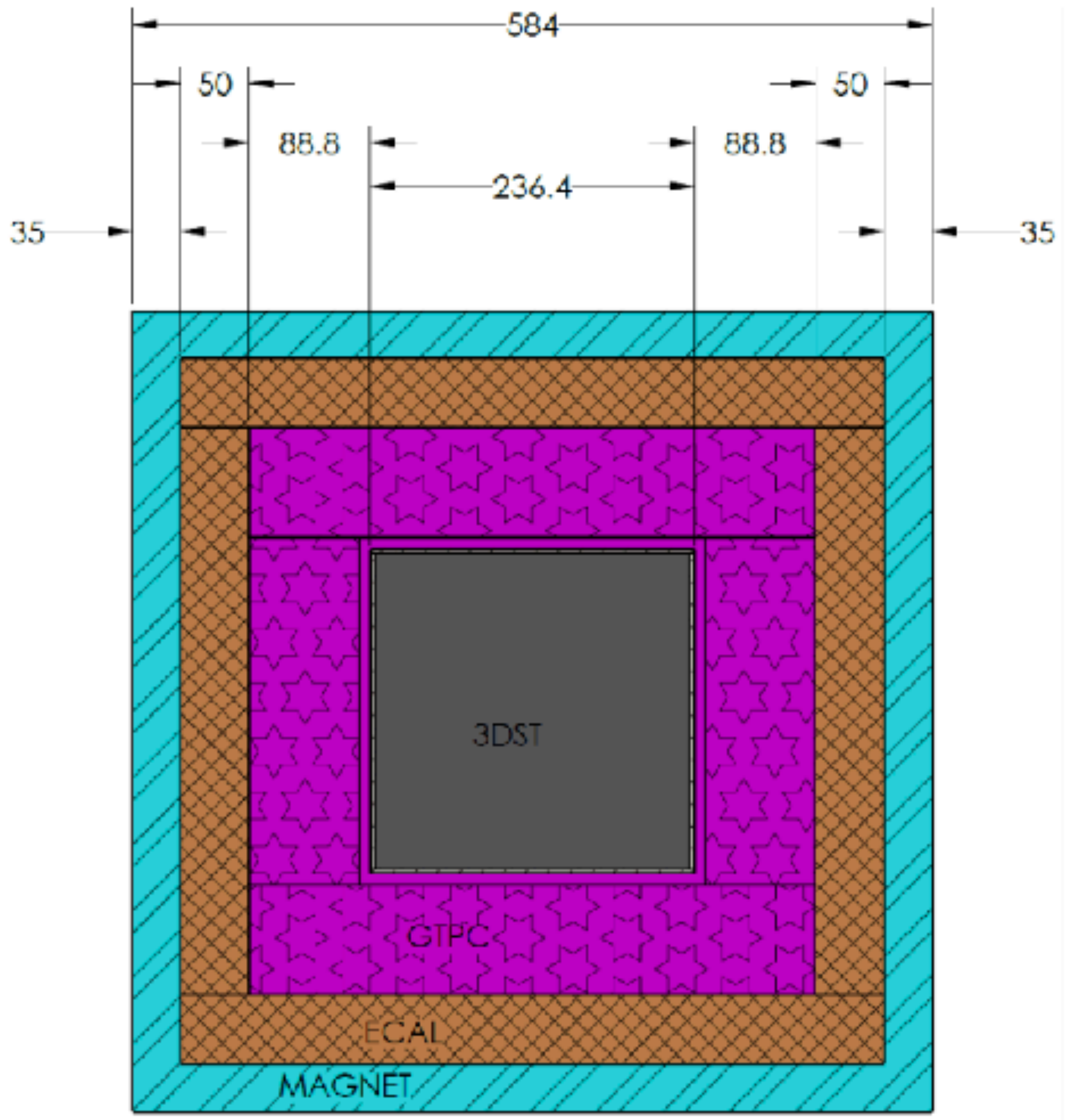


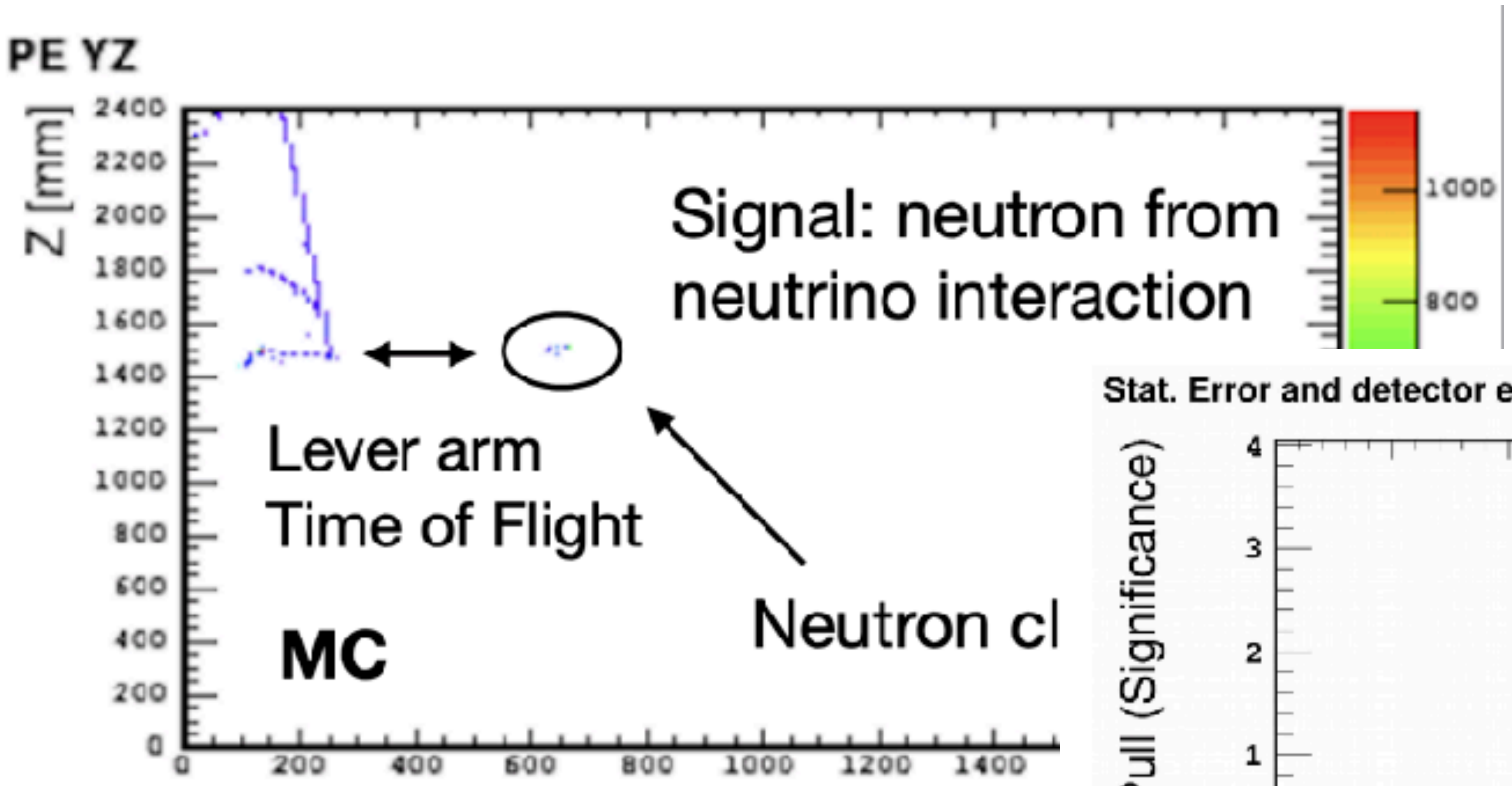
The 3DST Spectrometer (3DST-S)

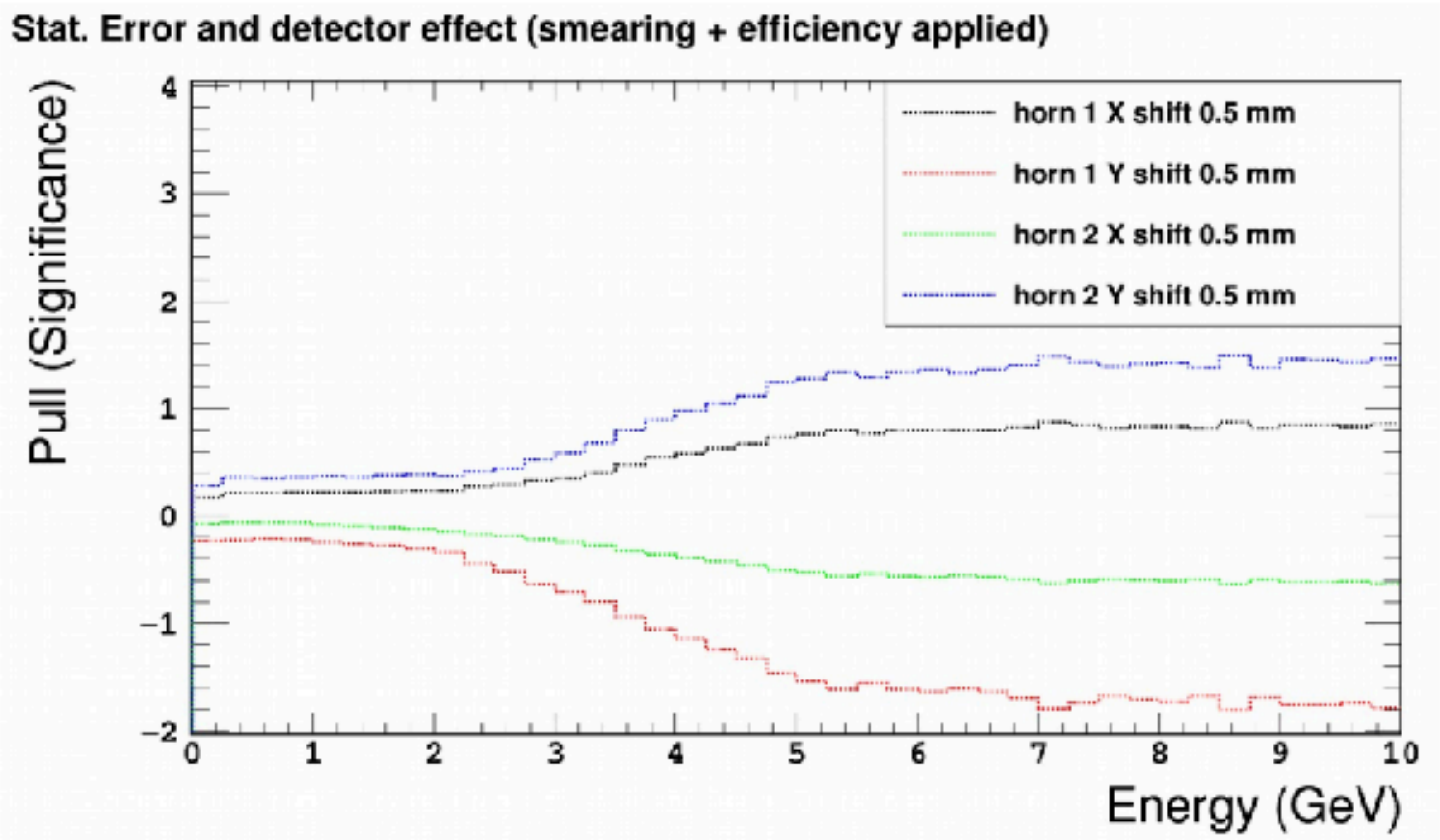
A beam monitor and more!

- Based on the **T2K ND280 FDG** detectors
- Scintillator cubes of 1x1x1 cm^3
- Light collected with *3 WLS fibres* readout with SiPMs
- Surrounded by TPCs and ECAL inside a magnet
- Firstly, **a beam monitor**
  - Monitor beam rate and position on few days scale
- But also:
  - **Neutrino energy reconstruction with neutrons!** (ToF)
  - **Can provide insights into neutrino interactions on H and C**





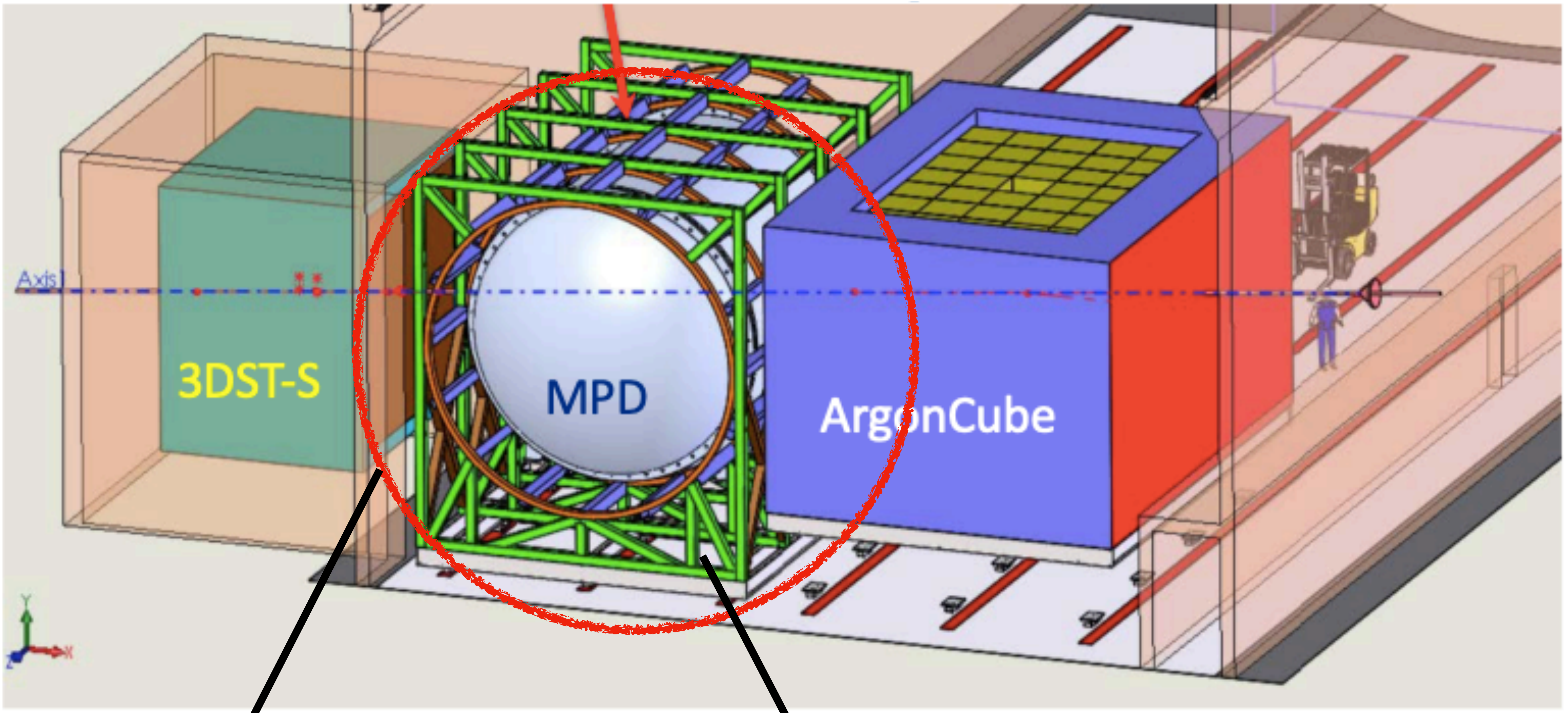


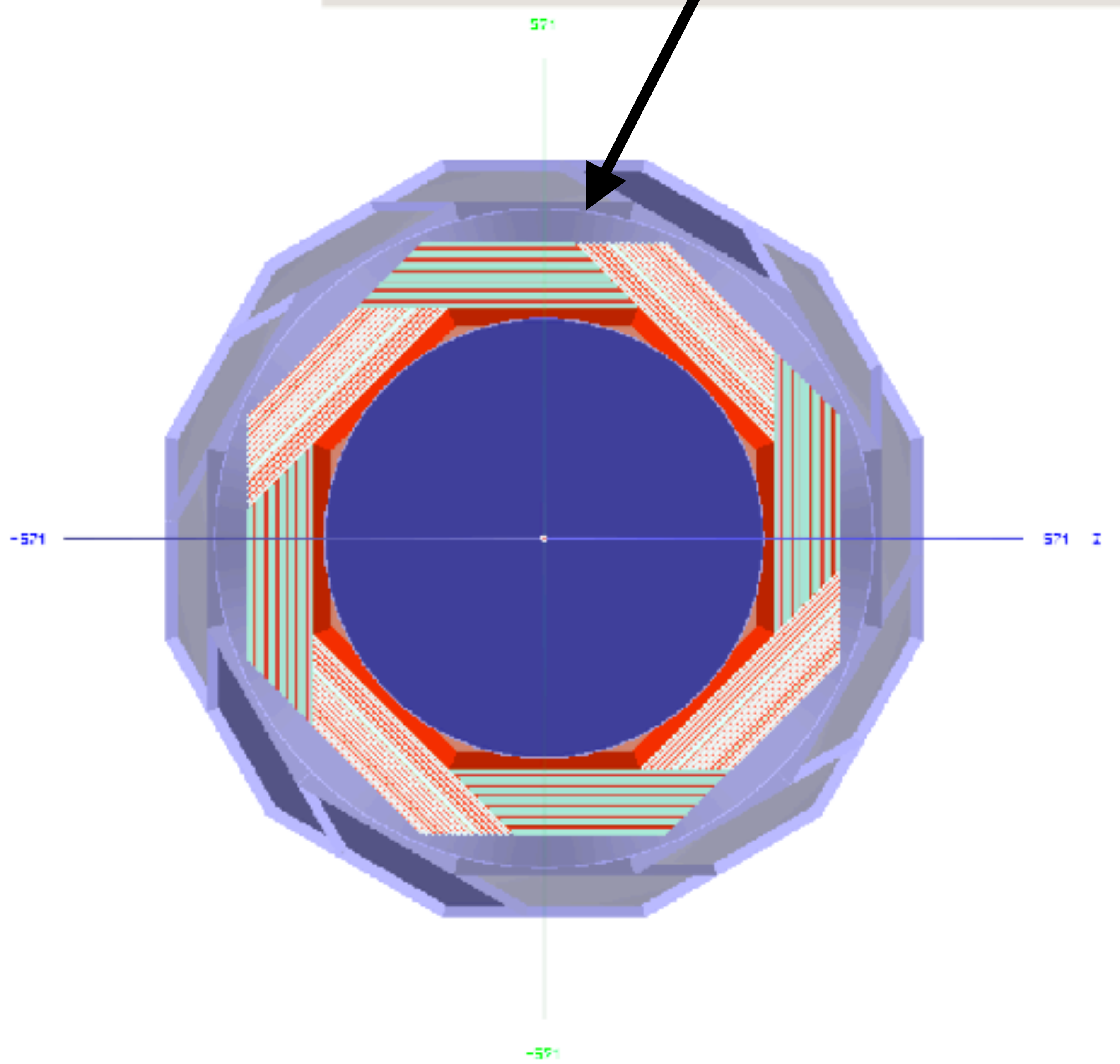


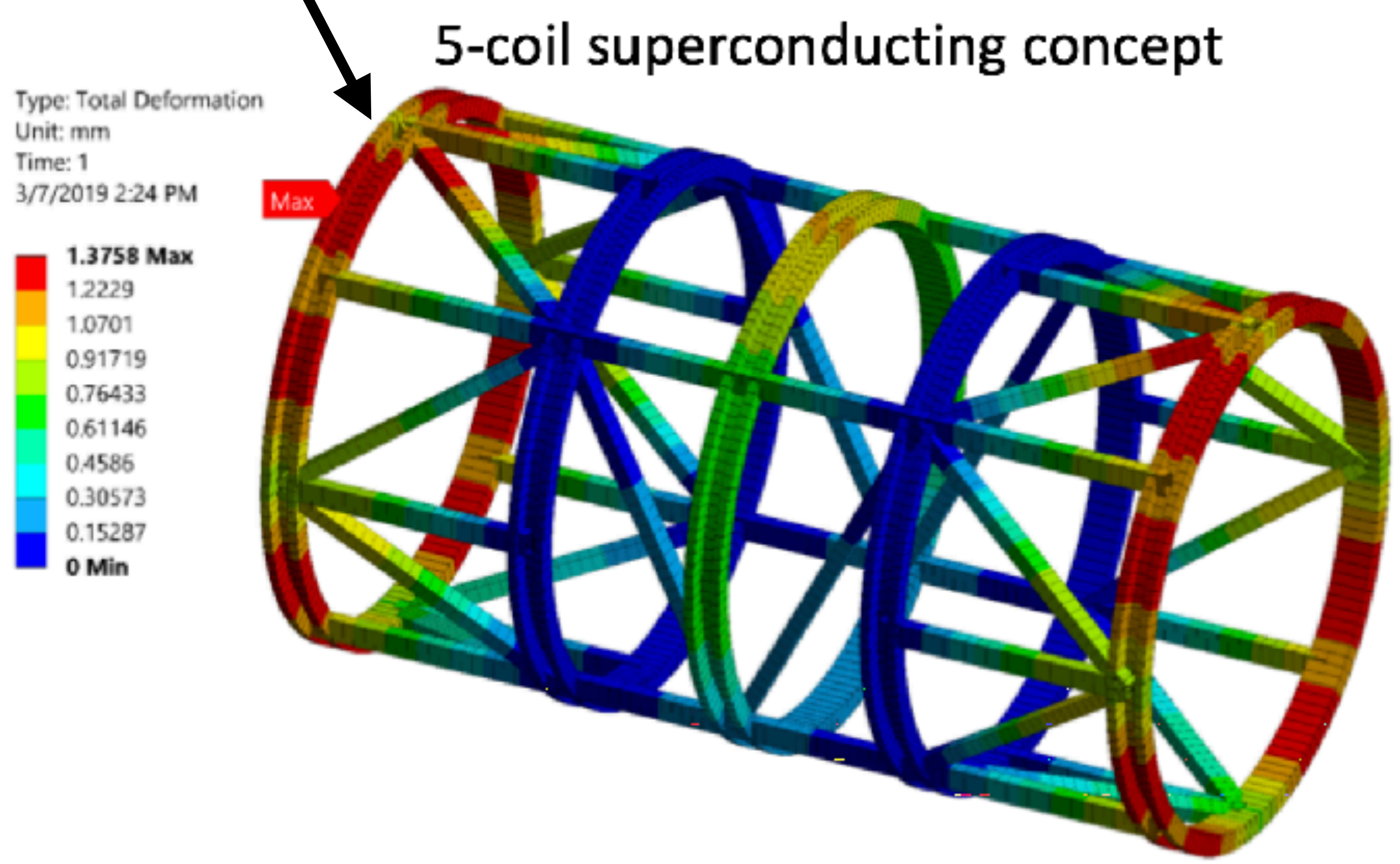
The Multi-Purpose Detector (MPD)

GArgonaut!

- A detector with
  - **High Pressure Gas Ar TPC**
  - Surrounded by a **high performance ECAL**
  - In a magnetic field of 0.5T provided by a superconducting **Helmholtz-coil-like magnet**
- **Its role**
  - Measure **particle interactions** from the LAr TPC (forward muons, sign…)
  - Provide samples on Ar but **lower threshold** compared to LAr ➠ improve models, reduce uncertainties
  - **Flat acceptance** over the full angular range ➠ mirrors FD acceptance



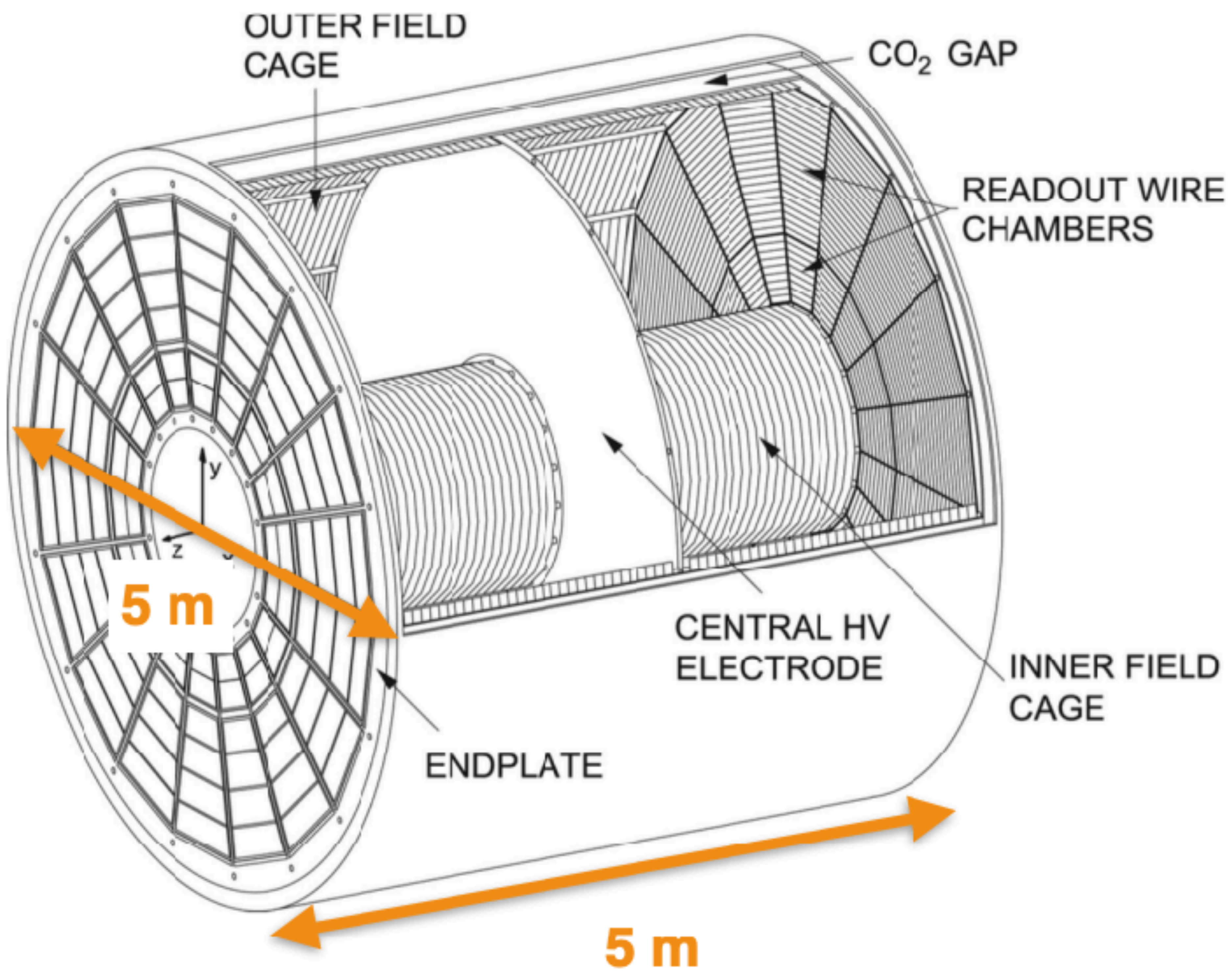




The Multi-Purpose Detector (MPD)

The ALICE TPC at 10 atm and the magnet

- Central detector - the HPgTPC
  - Design inspired by the **ALICE TPC** ➟ use their MWPC as ALICE is being refurbished
  - However few changes:
    - Higher pressure, **10 atm instead of 1 atm** (test ongoing with an ALICE chamber at that pressure)
    - **Gas mixture** ➟ 90:10 Ar:CH4, 1t FM
  - Just need to fill central hole
  - Other TPC designs are considered (sPHENIX, NA49)



The M

The ALICE

ALICE readout chamber acquisition

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  - Other

AP

EADOUT WIRE
HAMBERS

INNER FIELD
CAGE

The Multi-Purpose Detector (MPD)

The ALICE TPC at 10 atm and the magnet

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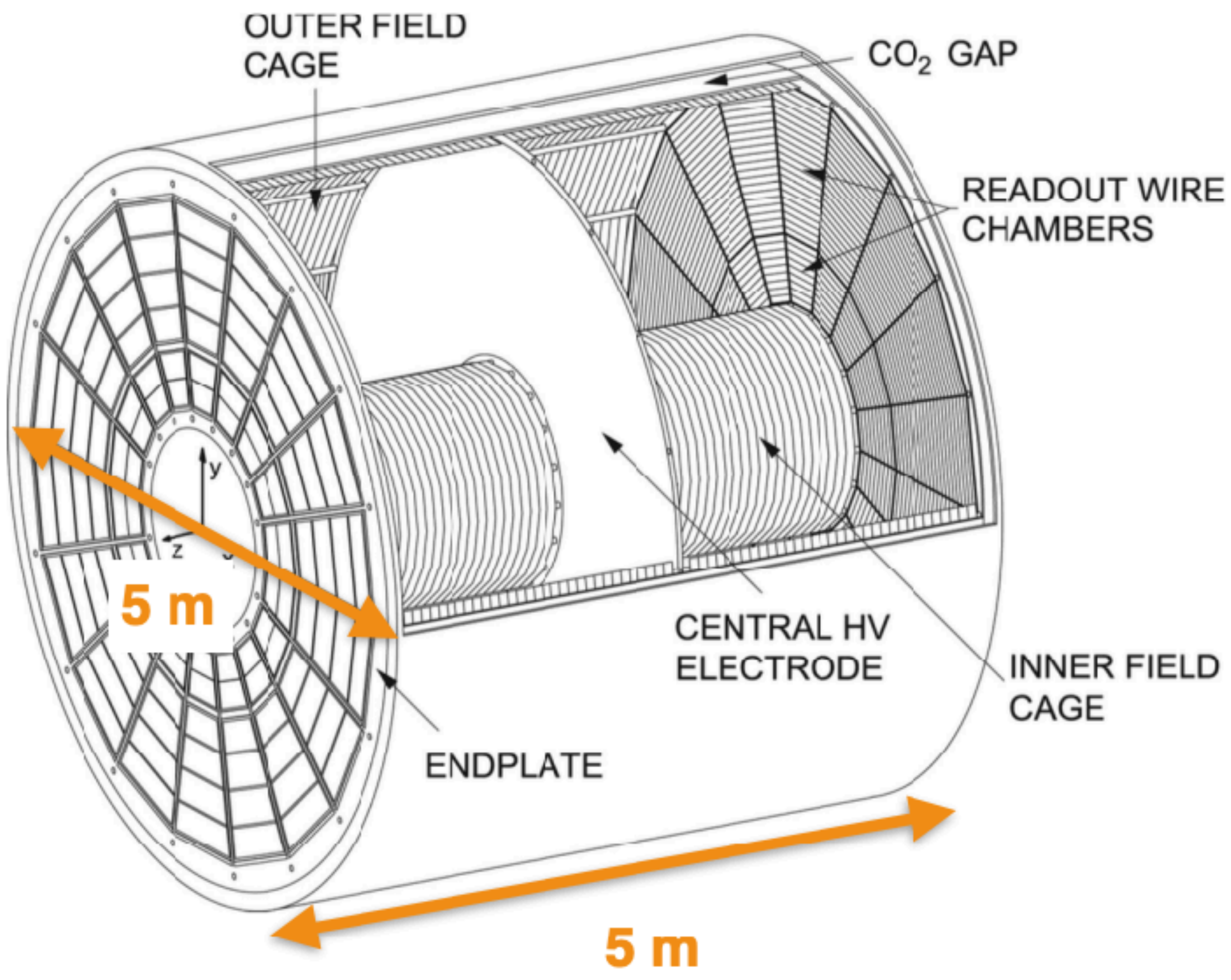
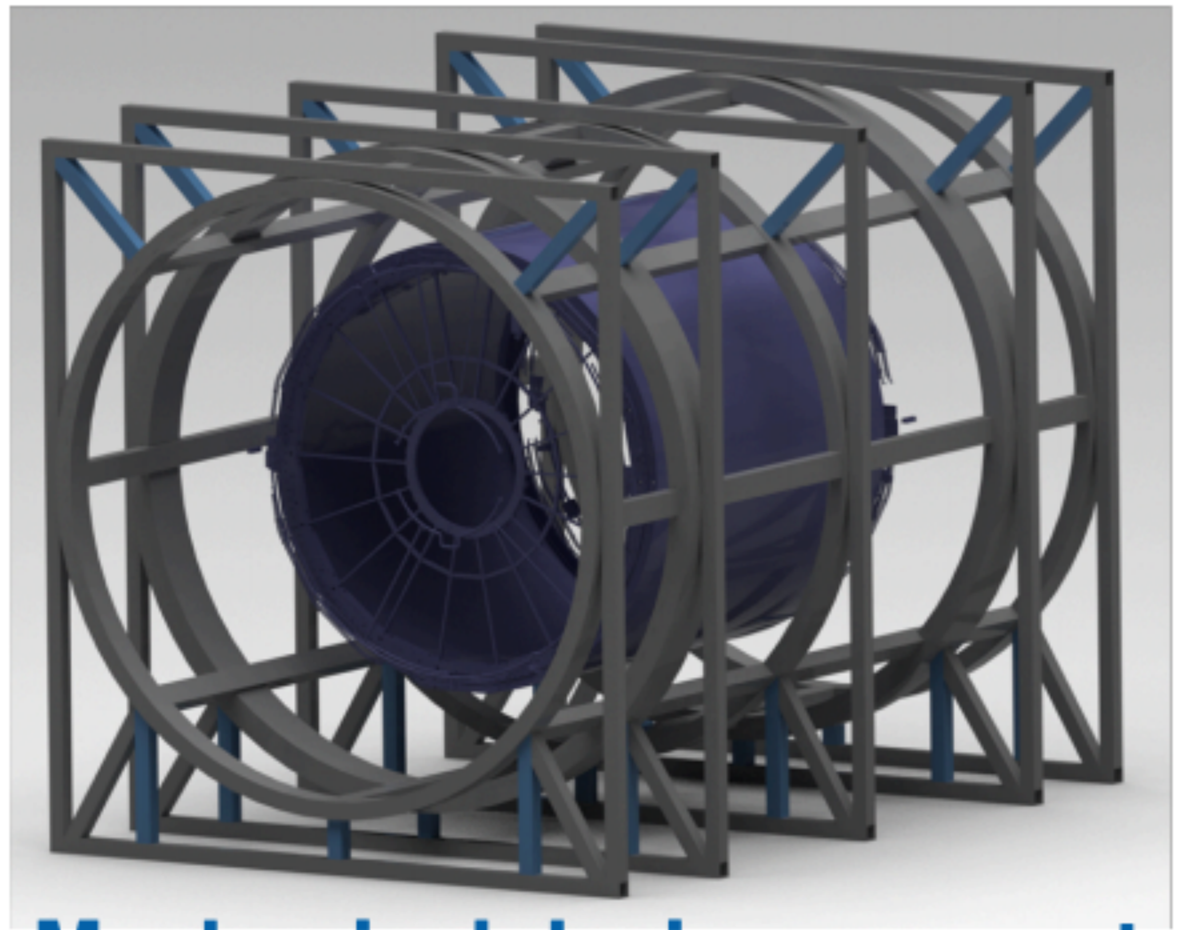




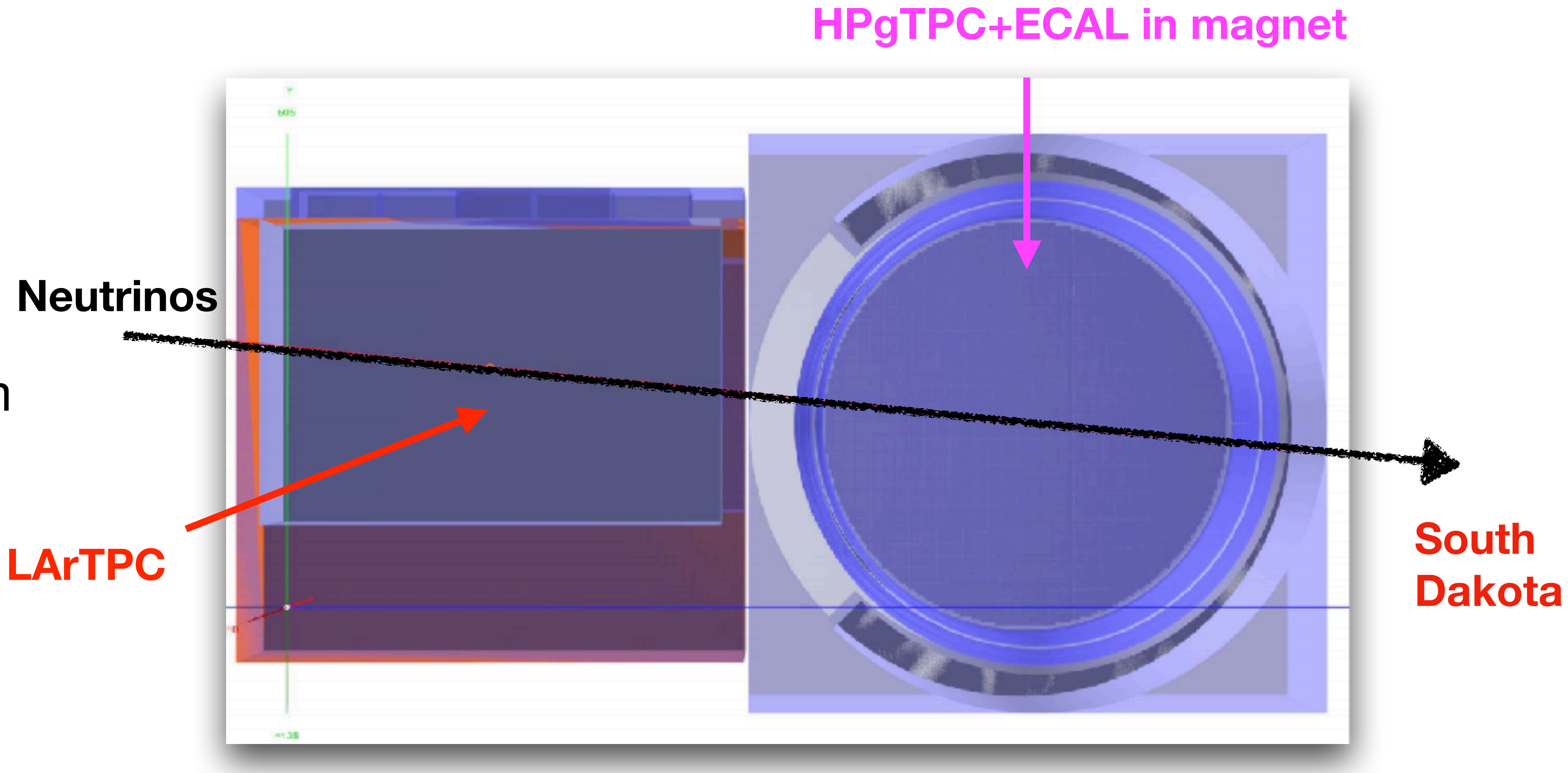
Mechanical design concept

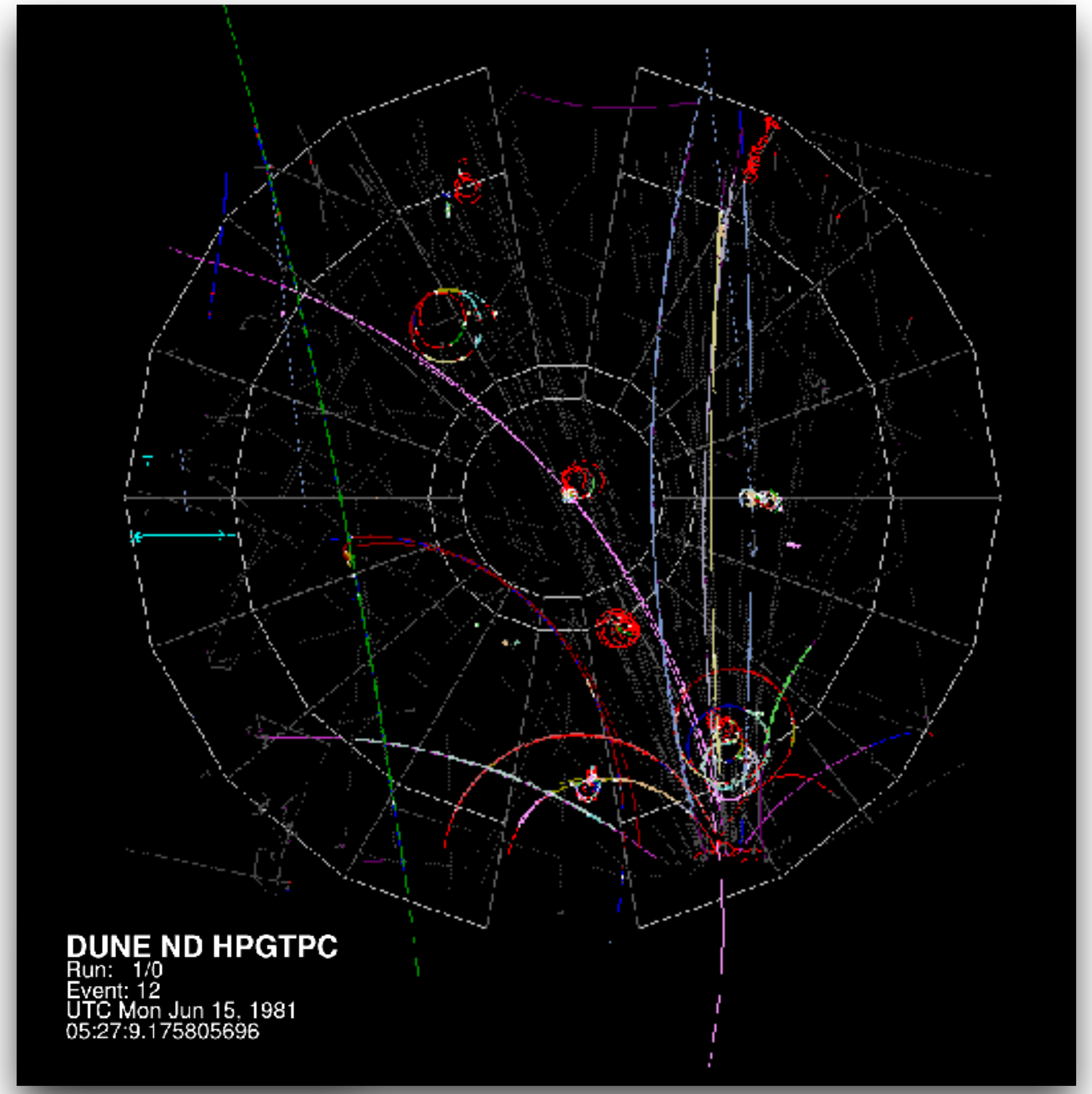
- Magnet of 0.5T
- Helmholtz coil design ➠ **minimise material** (mass) to reduce background interactions

The goals for the ND ECAL.

Physics requirements

- **The role of the ND** is to provide constraints on systematics: beam energy spectrum, beam composition, model ν-Ar interactions…
    - ➠ Rich physics potential!
- **The role of the ECAL**
    - Primarily needed to reconstruct photons / electrons (identify neutral pions and electrons from NC, CC events)
        - ➠ Good ***energy resolution*** needed over a broad range of energies from few MeV to few GeV
    - Reconstruction of the π^0 energy and association to decay vertex
        - ➠ ***Angular resolution***
    - Identification of neutrons coming from ν-Ar interactions
        - ➠ ***Precise timing*** for ToF measurement
    - Help in **background rejection** (reject events outside the TPC/ coming from the ECAL)
    - Additional: Particle catcher + muon id/tracker from the LArTPC
- ➠ **A case for a high granular ECAL!**



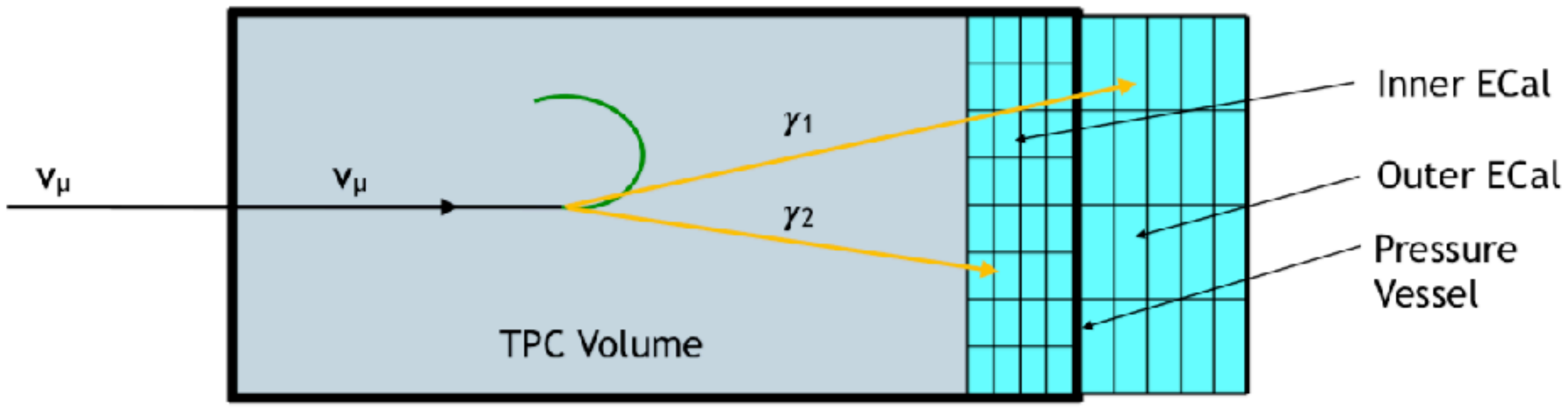


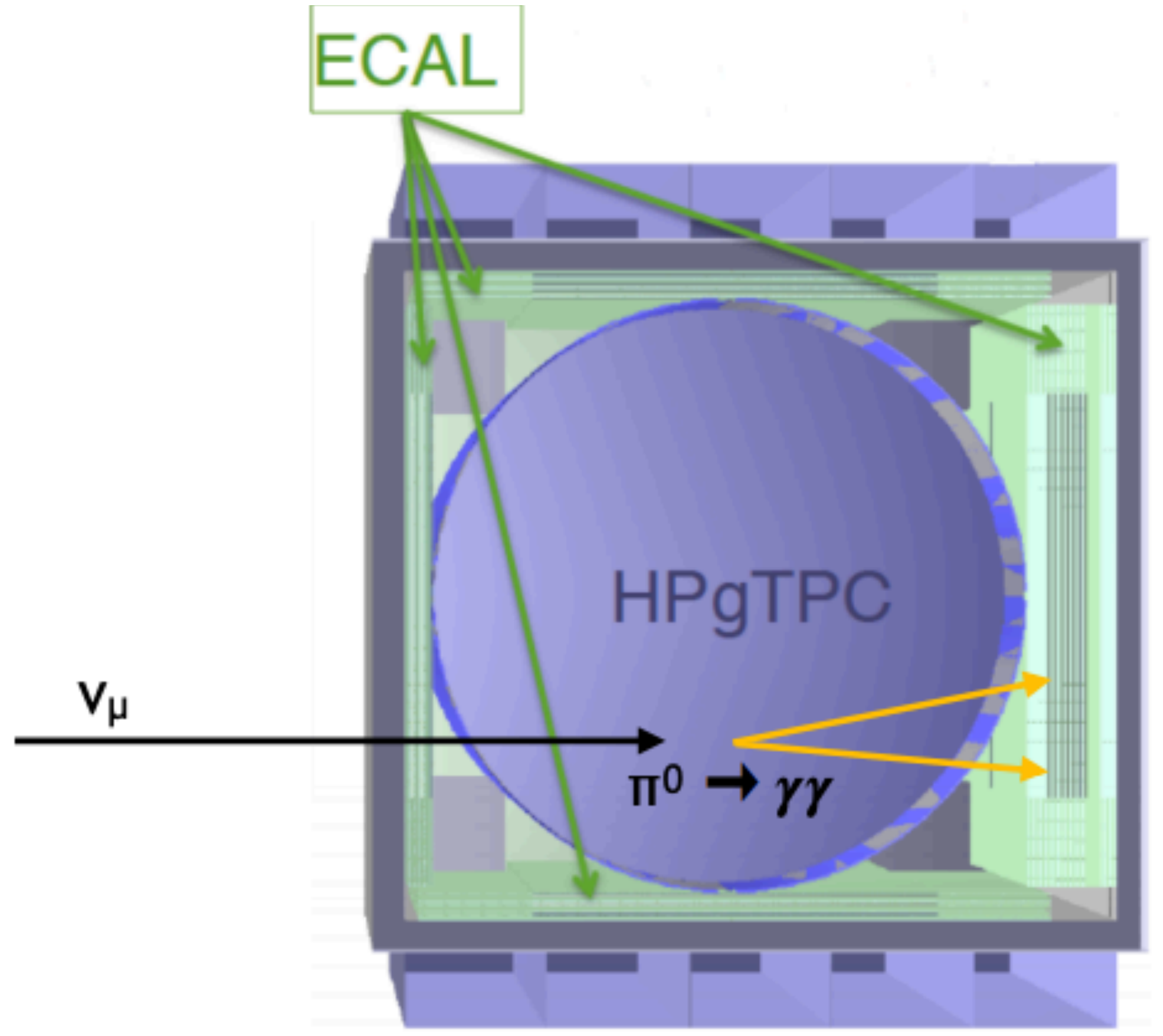
10 nu-interaction per spill (~x4 more)

The MPD ECAL Concept

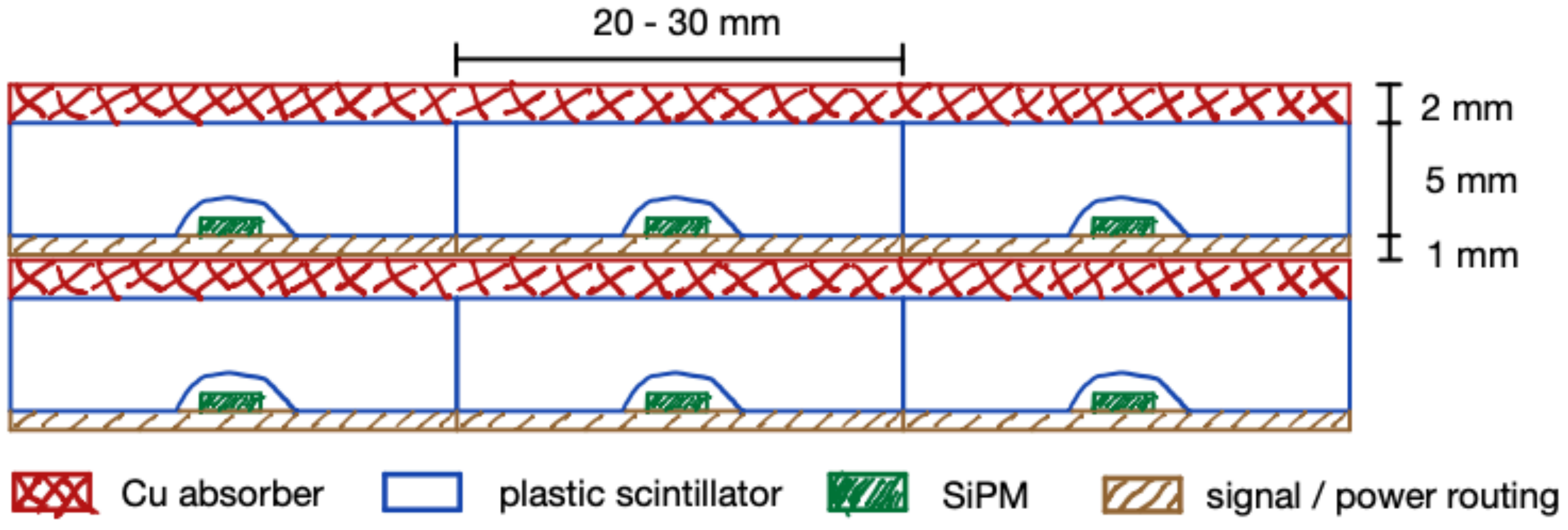
A high performance calorimeter

- **First simulation studies** have been done at MPP in the last years *(Lorenz Emberger)*
  - Motivation stated in the last slide
- First rough concept implemented in Geant4
  - Sampling calorimeter based on CDR geometry : 1.8 mm Pb absorber + 1 cm plastic scintillator
- Studies of calorimeter performance
  - **2D/3D segmentation** of the active material ➠ study of the benefits of granularity
  - **Influence of the absorber** material, thickness
  - **Influence of the pressure vessel**
  - **Neutral pion** identification and vertex reconstruction
  - **Neutron detection** efficiency
- Provided first **understanding** of the capabilities of such concept and dependency of the performance on some parameters



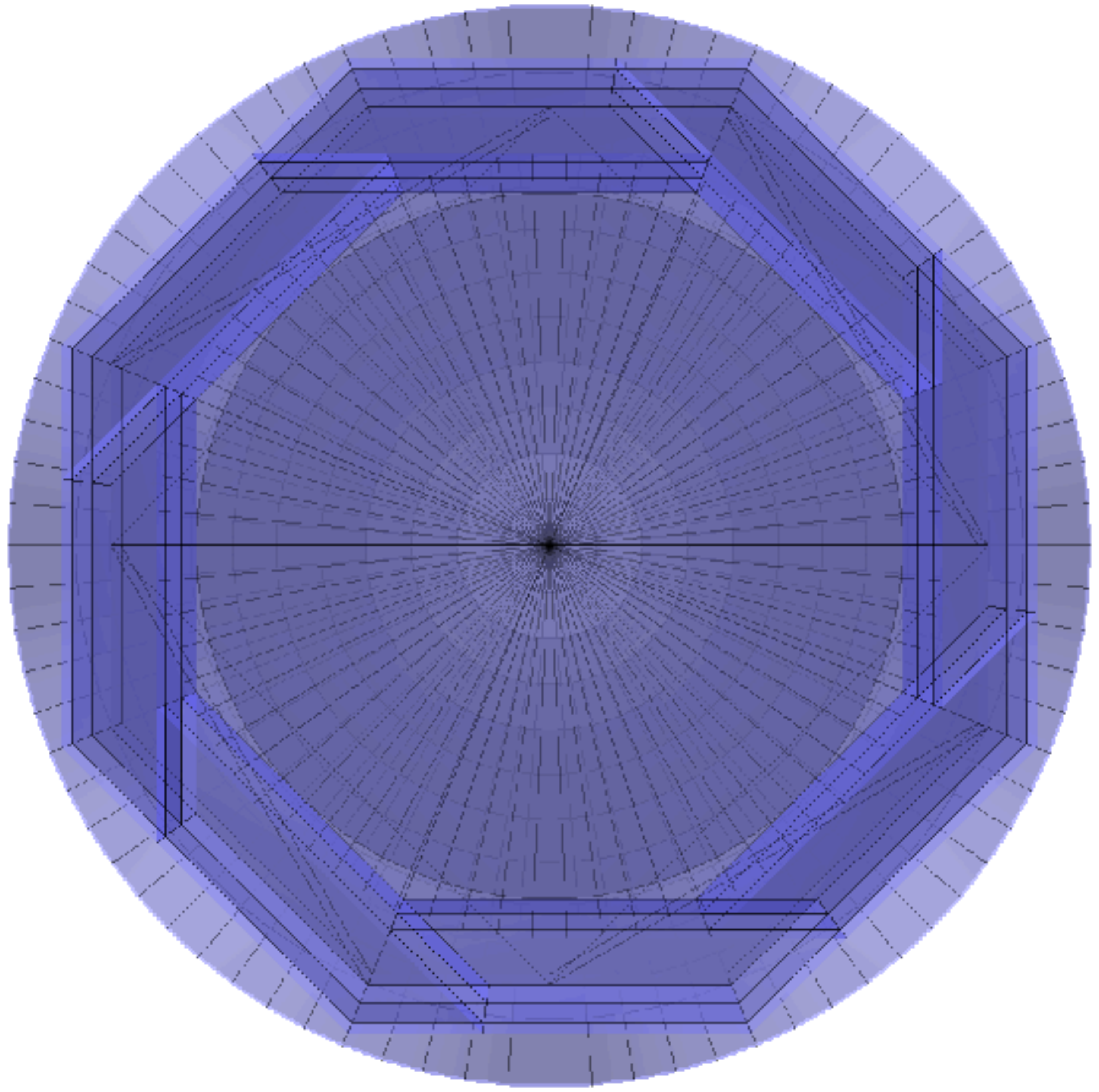


arXiv:1810.03677

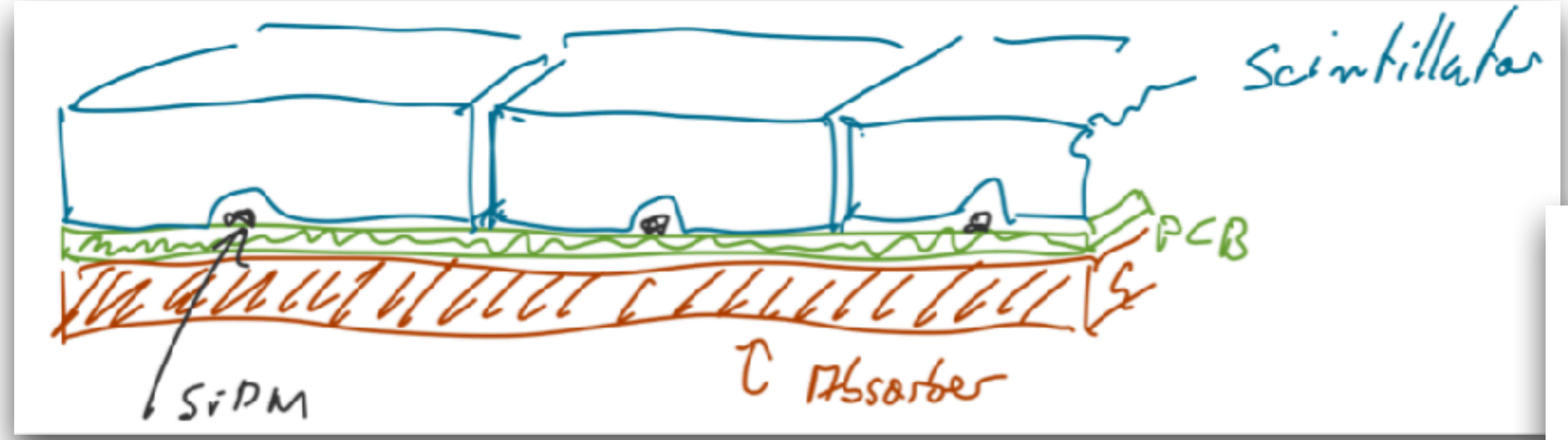


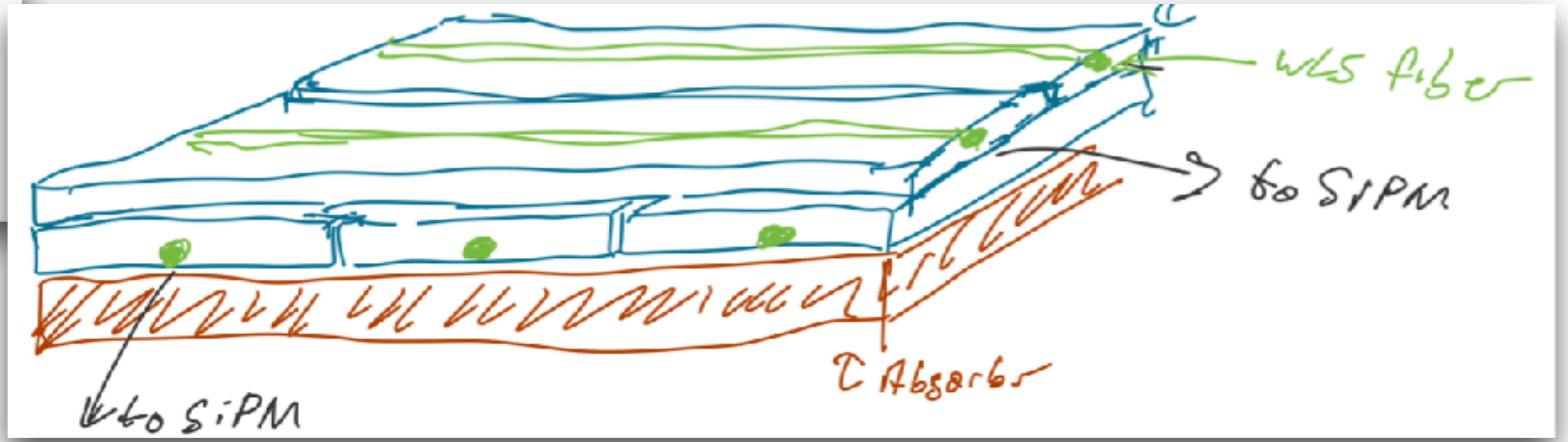
Towards a more realistic detector.

Geometry and integration with GArSoft



- Previous studies based on standalone Geant4
  - Need to integrate into a common framework ➠ **GArSoft**
  - *More realistic* ECAL geometry (cubic ➠ octagonal)
- Full granularity ➠ excessive channel count ➠ **not necessary** as shown in former study
  - Combine **high granularity layers** (HG) using SiPM-on-tile and **low granularity layers** with strips (LG) - crossed on same layer or every consecutive layer





Optimisation goals.

Taking into account the physics

- **Goals**:
  - Optimisation of the overall design guided by former results
  - Optimisation of the **cost**: absorber/scintillator material, channel count.. etc…
  - Main design driver ➠ **calorimeter energy resolution**, **angular resolution!**
  - Software framework versatile now enough to study several designs!
- **Design**:
  - Setup A (light pink) → 80 HG, 5 mm tile ➠ sanity check with Lorenz results (fully granular ECAL)
  - **Setup B** (purple) → 8 HG, 5 mm tile + 97 LG, 2 mm Cu, cross-layers, 5 mm Sc ➠ **Granularity for the back layers**
  - **Setup C** (red) → 8 HG + 47 LG (HG: 2mm Cu/LG: 4 mm Cu), cross-strips, 10 mm Sc ➠ **Sc/absorber thickness**
  - **Setup D** (blue) → 8 HG + 12 LG, 2 mm Cu + 35 LG, 4 mm Cu, 10 mm Sc ➠ **thinner absorber in front layers**
  - **Setup E** (green) → 8 HG, 10 mm Sc + 92 LG, 2 mm Cu, cross-layers, 5 mm Sc ➠ **thinner absorber for LG layers**
  - Setup F (orange) → 8 HG, 3 mm tile + 100 LG, 2 mm Cu, cross-layers, 5 mm Sc ➠ thinner HG tile

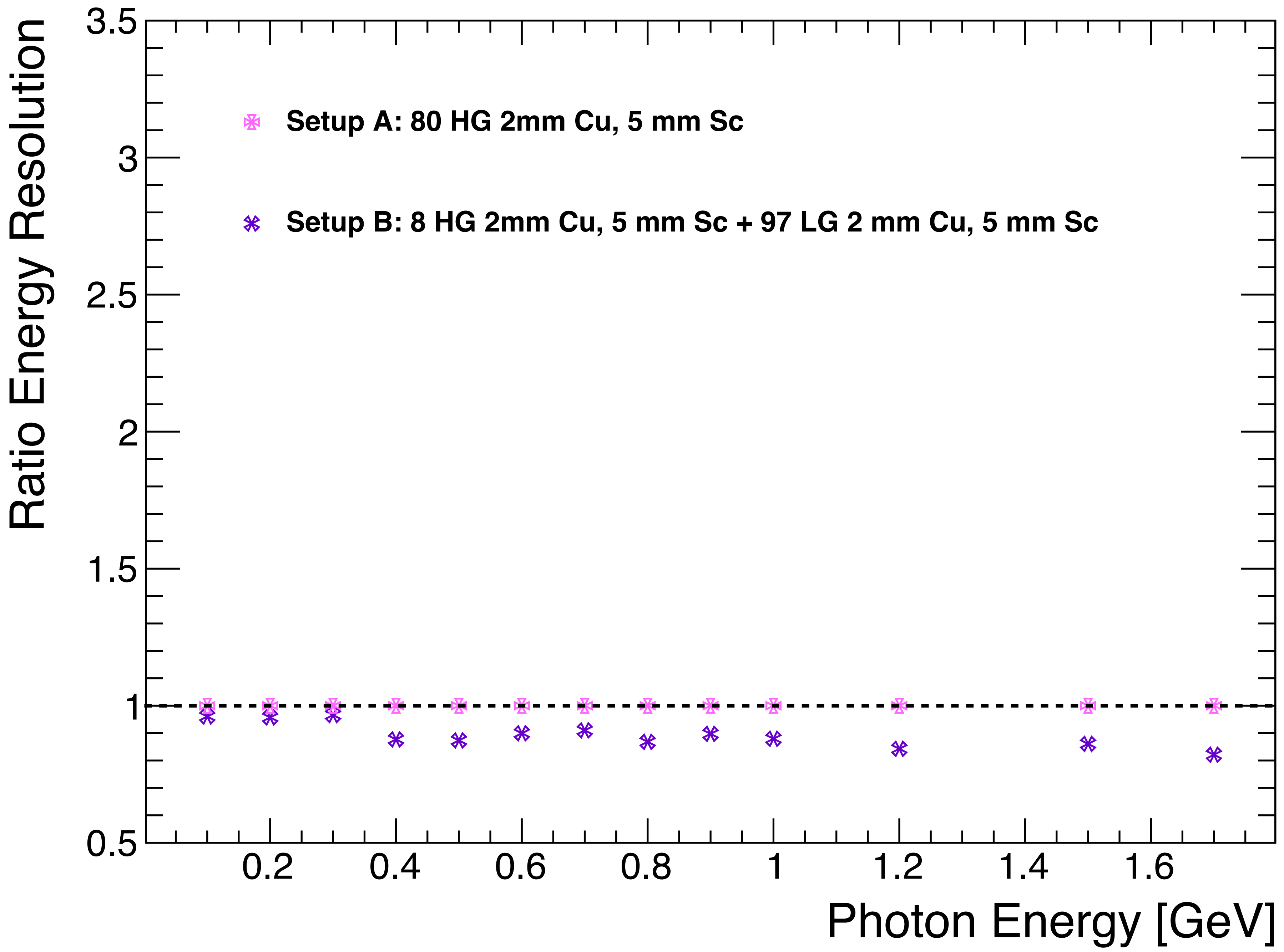
Color index used as legend for the following plots

Simulation studies.

Influence of the granularity

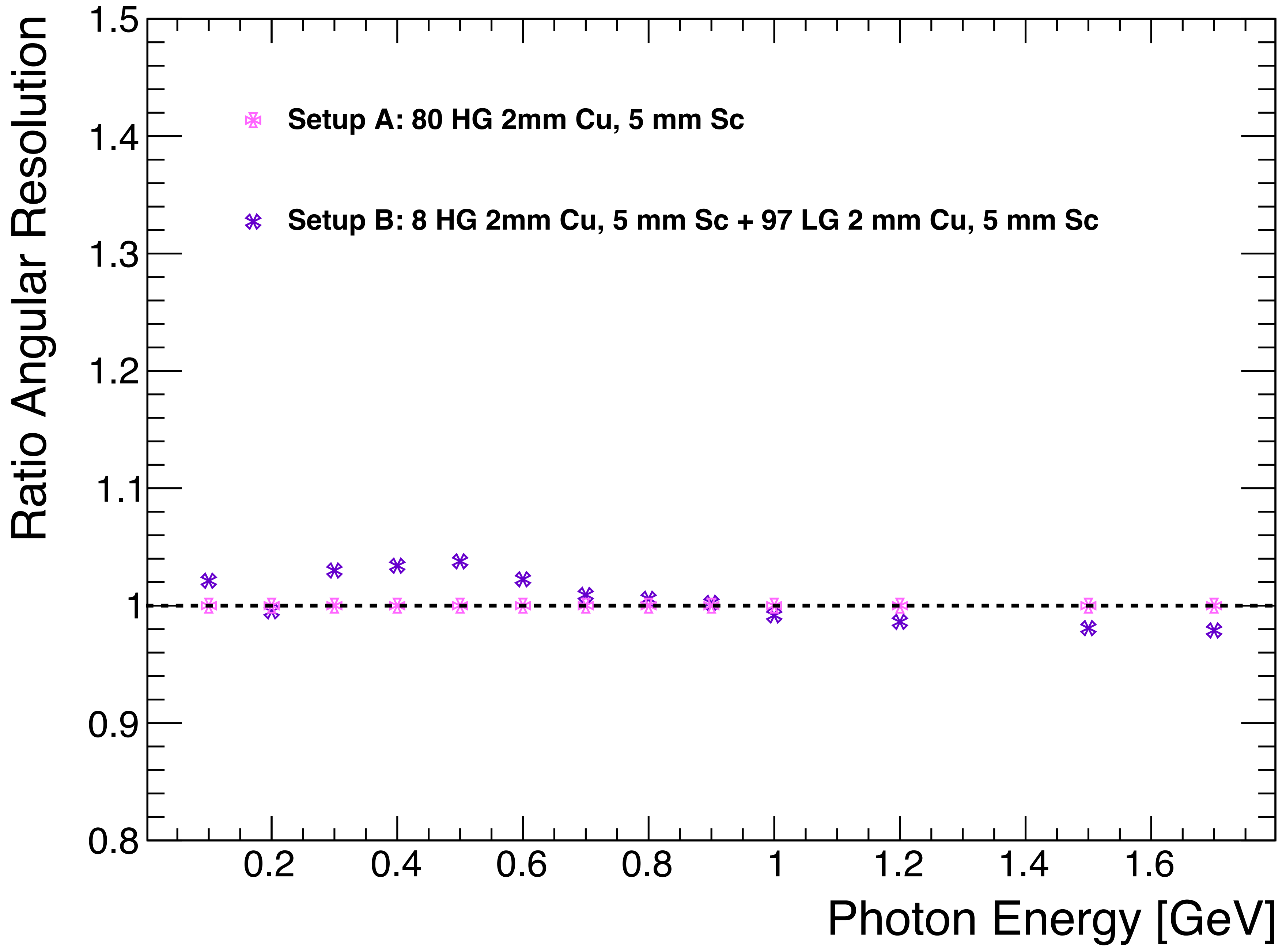
- Change of the granularity of the back layers
- Using strips with WLS crossed perpendicularly between layers

- Slight improvement of the energy resolution ~5-10% ➠ more layers ➠ less leakage
- Angular resolution not much affected (~2%) by using strips instead of tiles ➠ viable option to reduce channel count!



Setup B (8 HG + 97 LG)

Setup A (full granular)



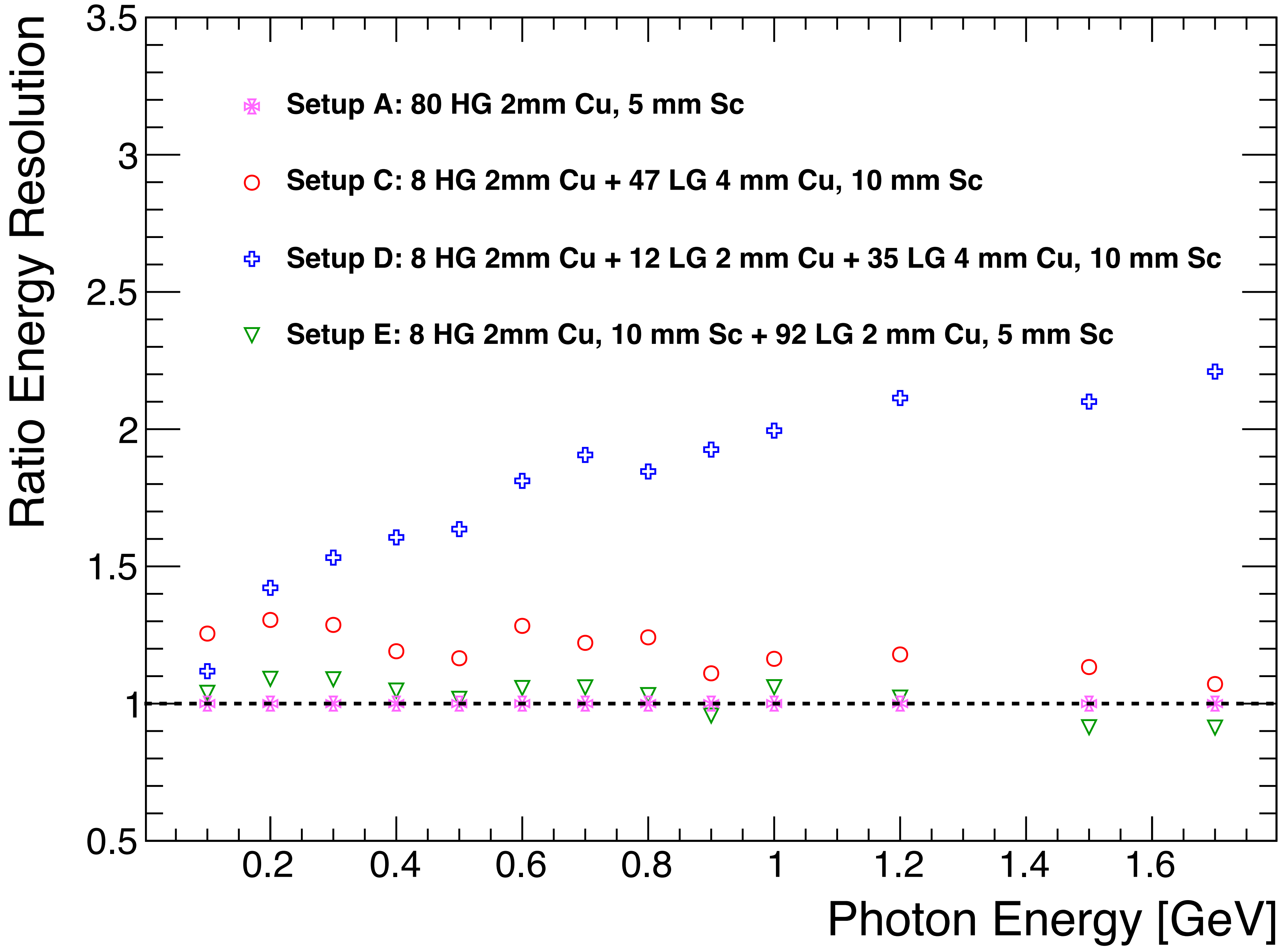
Setup B (8 HG + 97 LG)

Setup A (full granular)

Simulation studies.

Influence of the absorber thickness

- Change of the absorber thickness
  - 2 mm Cu for HG layers
  - 2/4 mm Cu for LG layers
- Energy resolution mostly affected by
  - change in ratio scintillator thickness / absorber thickness ➠ sampling fraction / frequency
  - Leakage
- Angular resolution is slightly affected depending on the configuration
  - Mainly dominated by front layers
  - ➠ thinner absorber in the front layers ➠ shower evolves deeper in the calorimeter, gives better lever arm on the direction

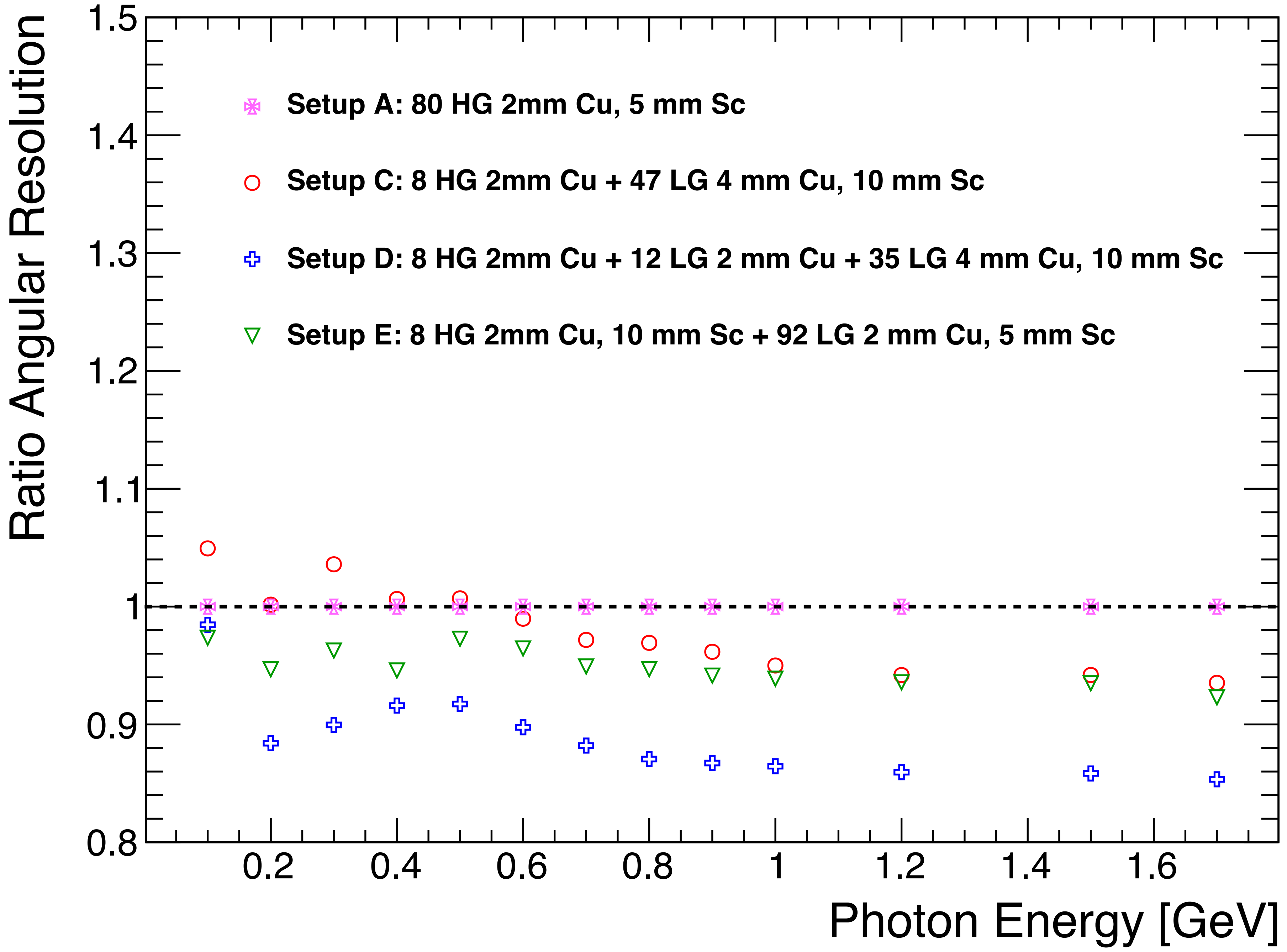


Setup A (2 mm Cu)

Setup C (2 + 4 mm Cu)

Setup D (2 + 4 mm Cu)

Setup E (2 mm Cu)



Setup A (2 mm Cu)

Setup C (2 + 4 mm Cu)

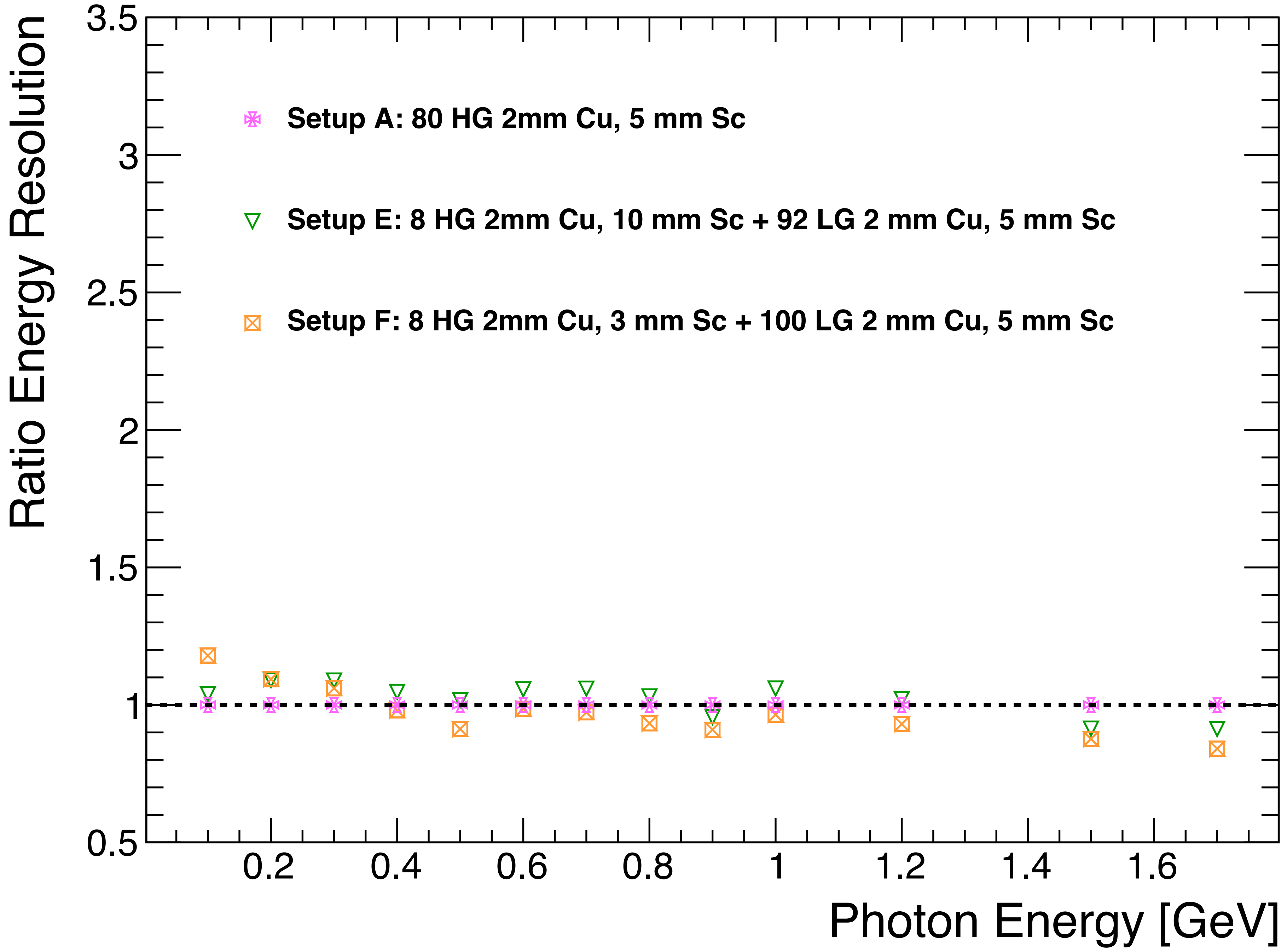
Setup D (2 + 4 mm Cu)

Setup E (2 mm Cu)

Simulation studies.

Influence of the scintillator thickness

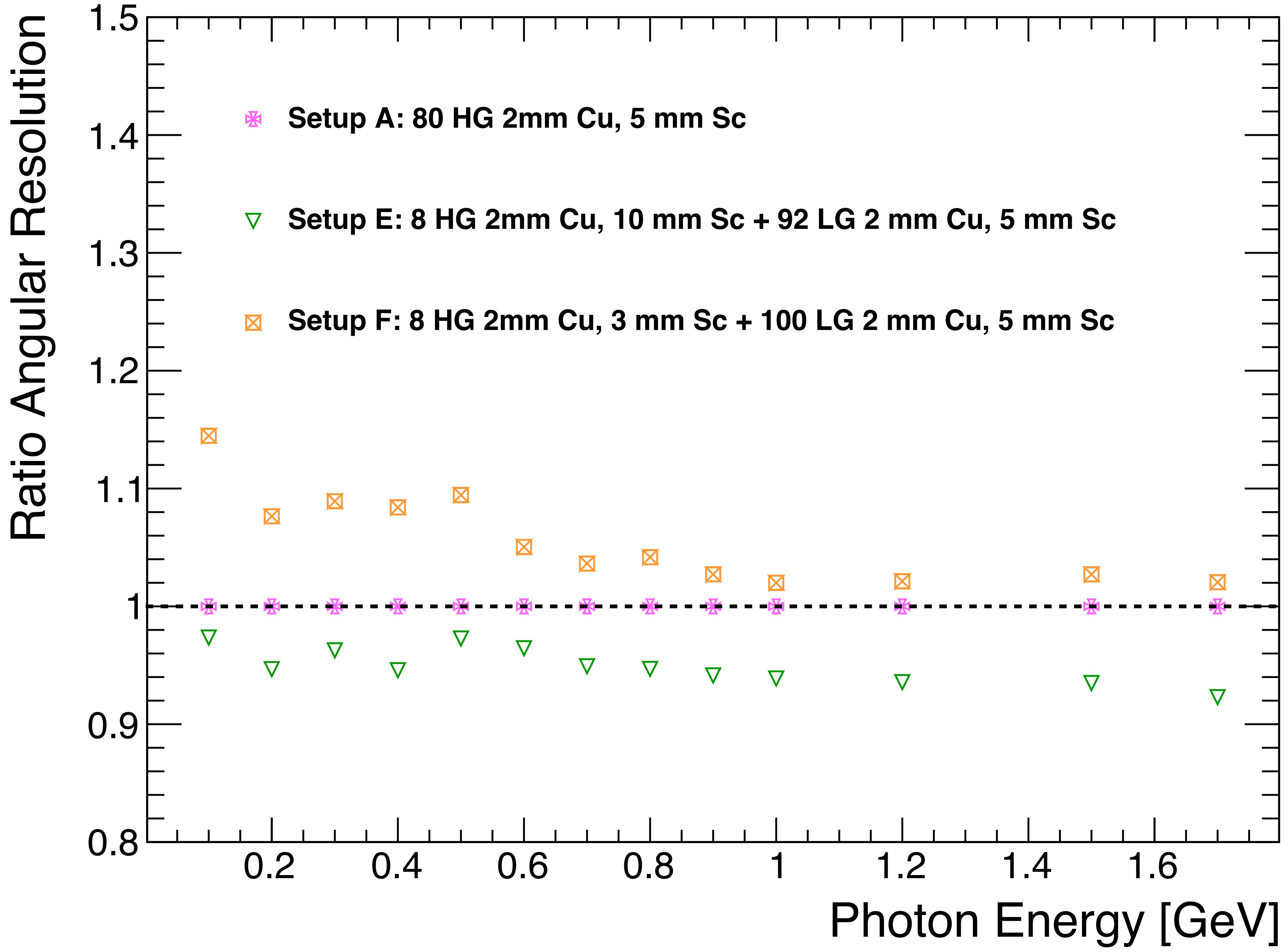
- Change in scintillator thickness for the front layers
  - 3, 5 and 10 mm
- Overall, not much change except at low energies
- Change most significant for 3 mm tiles especially at low energies ➠ effect of the threshold
- Better angular resolution for thicker tiles
  - ➠ Mostly due to the PCA that favours high energetic depositions



Setup A (5 mm Sc)

Setup E (10 mm Sc)

Setup F (3 mm Sc)



Setup A (5 mm Sc)

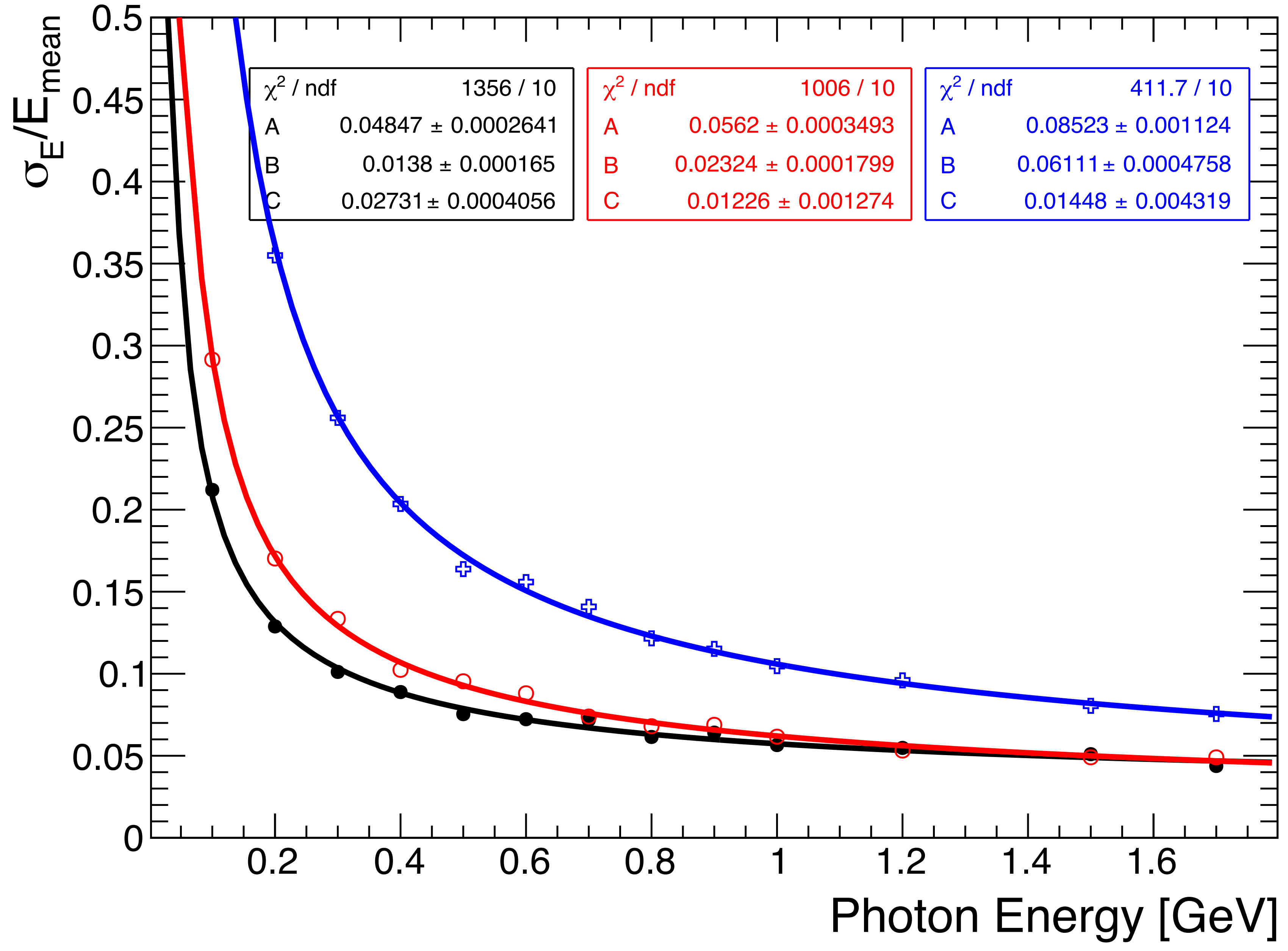
Setup E (10 mm Sc)

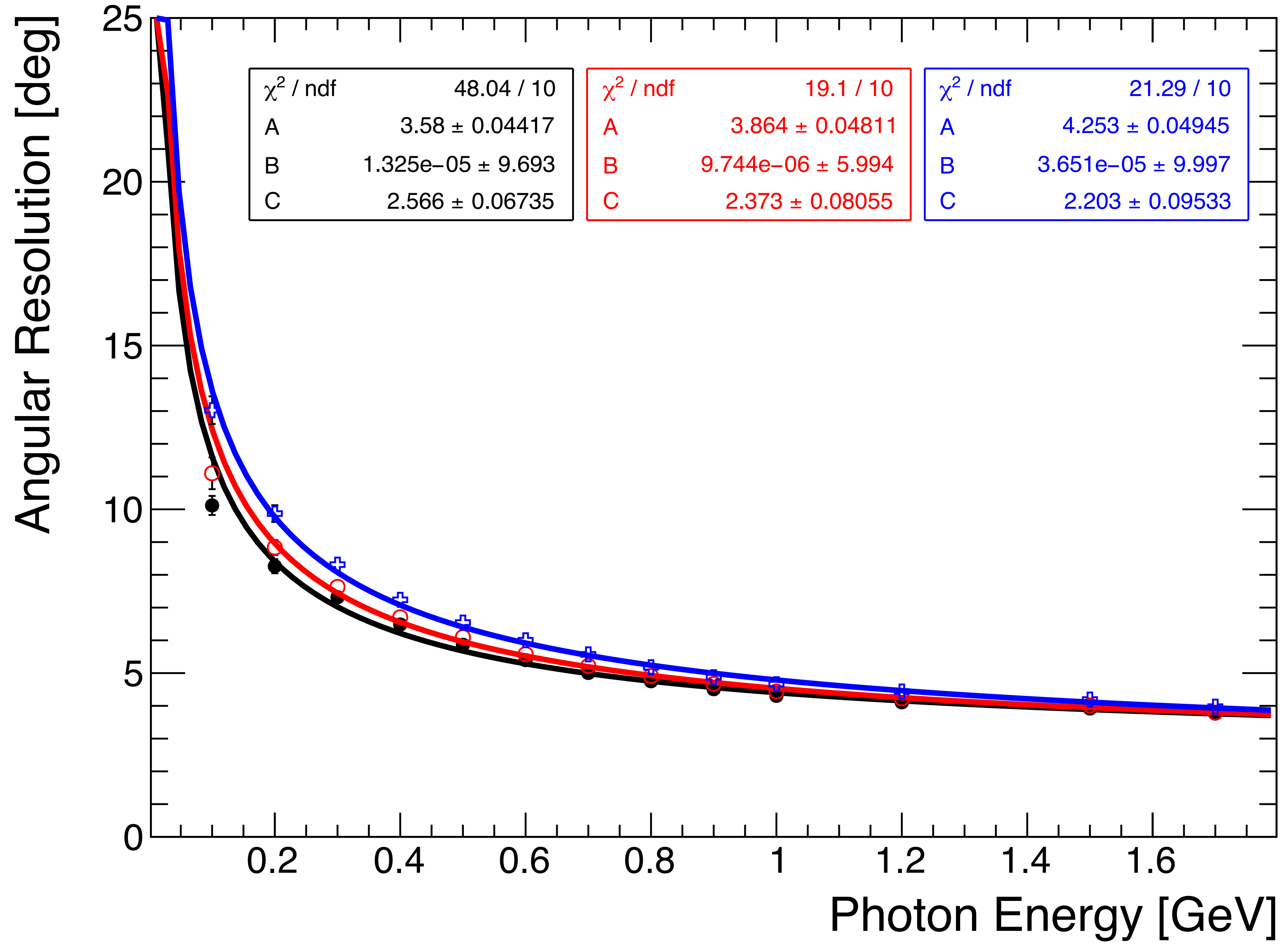
Setup F (3 mm Sc)

Simulation studies.

Influence of the pressure vessel

- Look at the influence of the pressure vessel
  - Case if the ECAL is fully outside the PV ➠ easier from the engineering side
- Different thicknesses
  - **0.5**, **1** and **2** X_0 of steel
- Until when the pressure vessel becomes a significant problem?
- Angular resolution get slightly affected over $1X_0$
- Energy resolution gets heavily affected ➠ pressure vessel should stay below $1X_0$ to keep energy resolution below 6% / Sqrt(E)

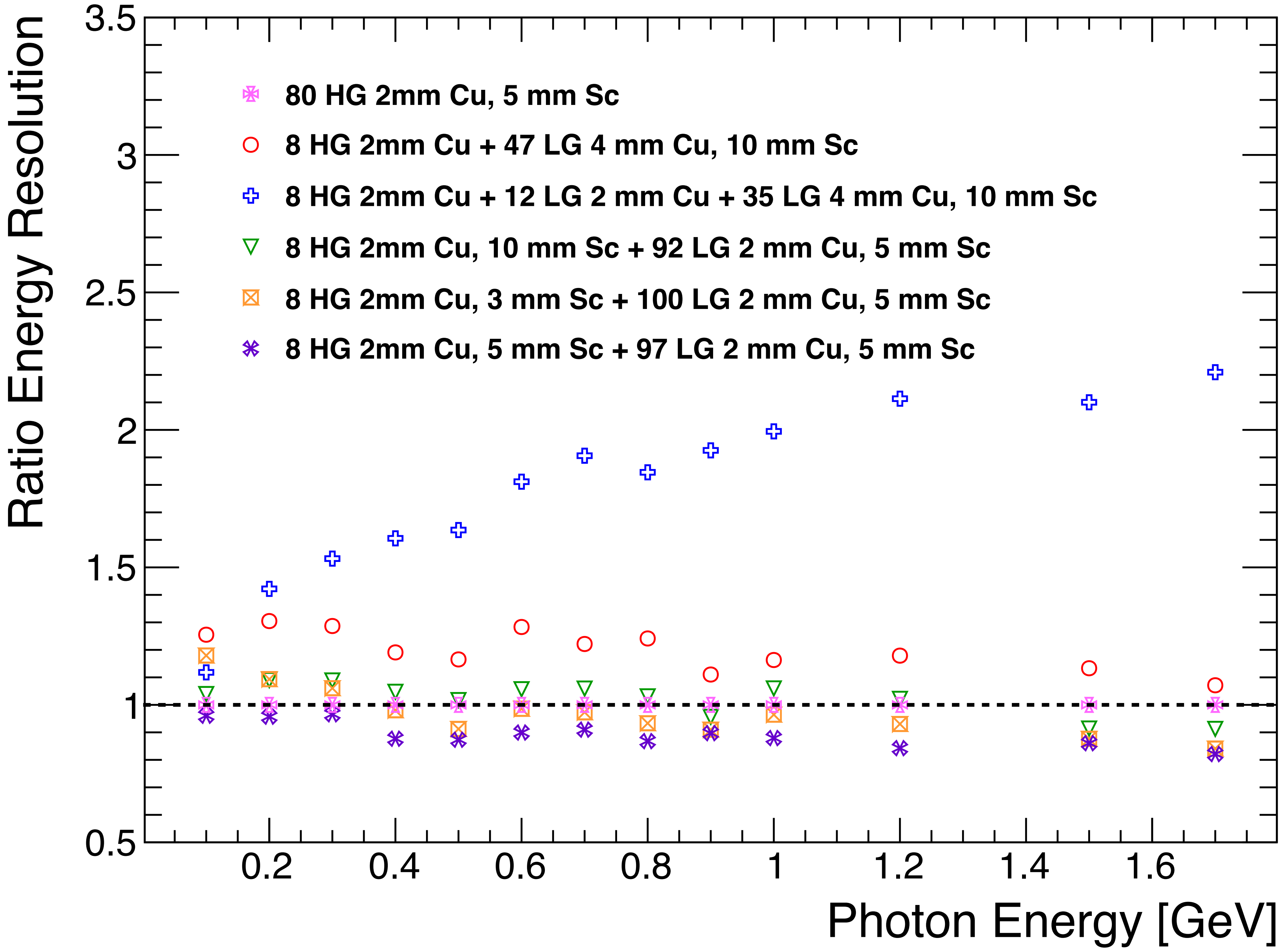


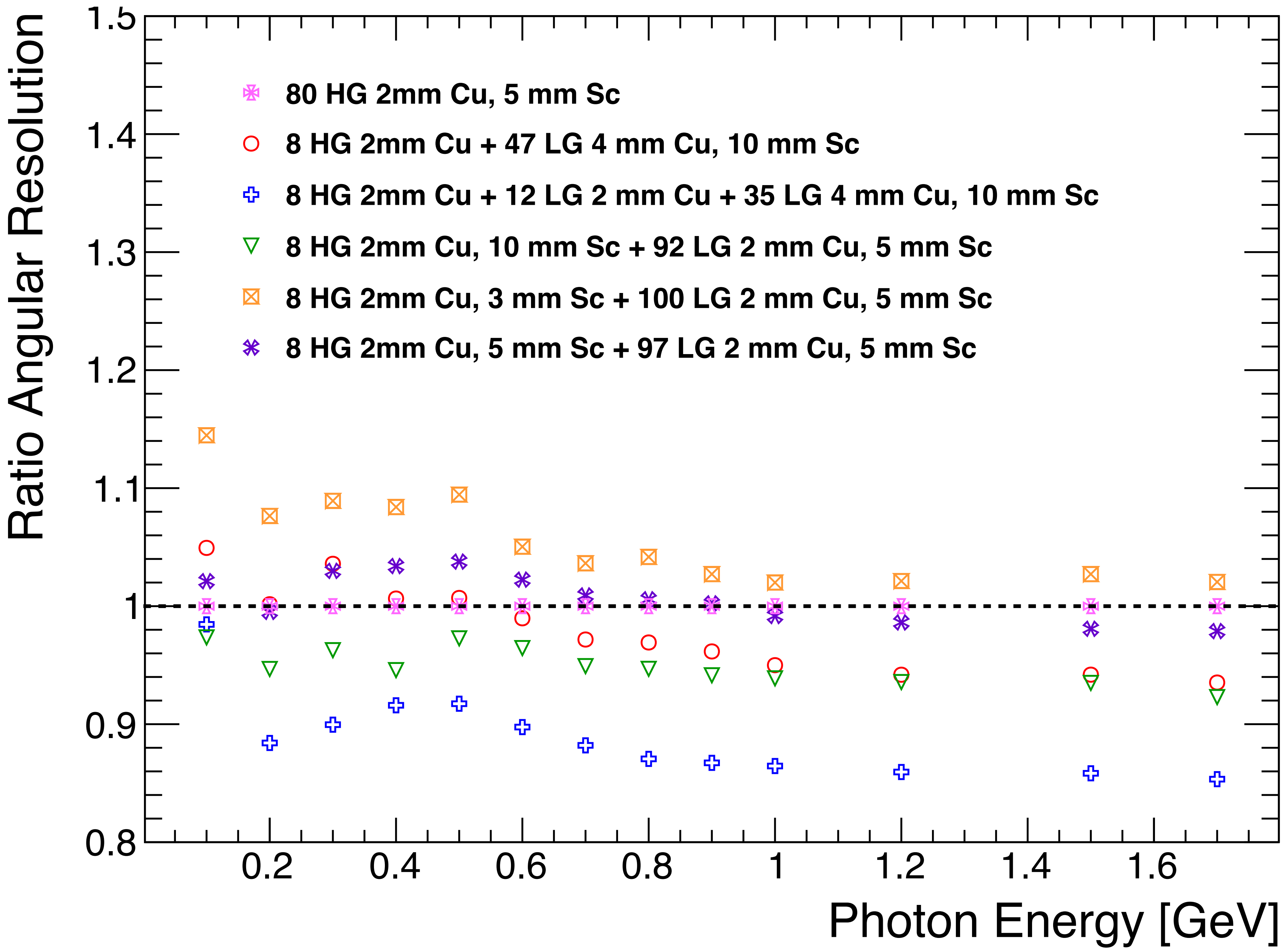


Simulation studies.

Full comparison

- Full comparison between the setups
- To take away
  - Angular resolution dominated by front layers ➠ granularity in the back layers does not matter much ➠ strips can be used
  - Thinner absorber with small Molière radius in the front is preferred for angular resolution
  - Shower containment is important for high energies ➠ more layers or thicker absorber in the back ➠ around 12-14 X_0 needed
  - Thicker scintillator in the front helps in the angular resolution





Motivation.

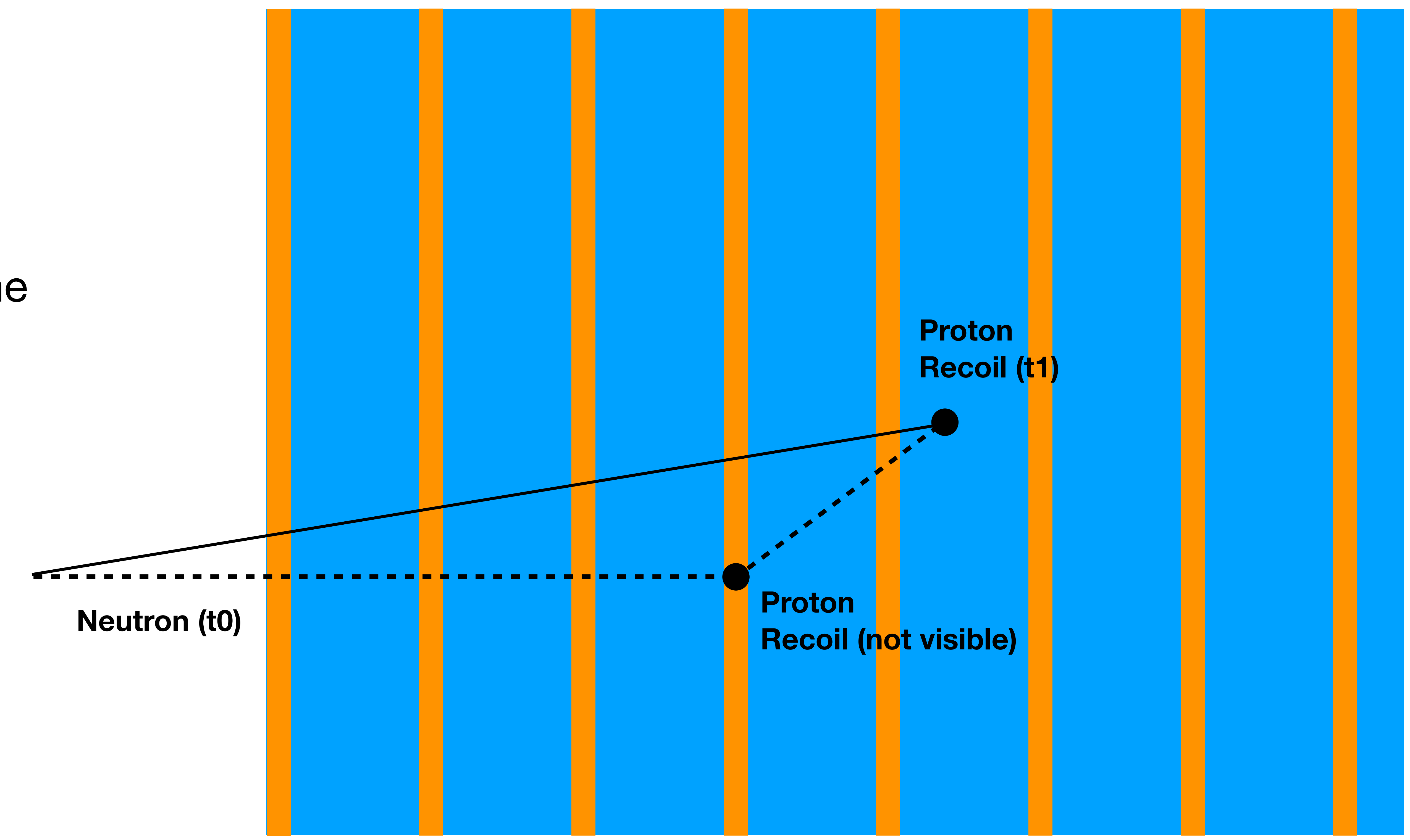
Pushing the limits

- **Neutron production** for anti/neutrinos on Ar target is highly uncertain
  - Neutron energy is a source of ***neutrino energy mis-reconstruction***
- Neutron energy measurement:
  - **Time of flight** (ToF) by measuring the time between the production vertex and the located hit
  - Technique demonstrated in simulation with the 3DST (full scintillator-based detector)
  - Technique can be used with the ECAL
    - Need for ***precise time measurement*** (sub-ns)
    - **Advantage** ➠ long lever arm with the ECAL (~3 m from TPC center)
    - **Challenge** ➠ need to identify hits that belong to a neutron!

Neutron energy reconstruction.

ToF technique

- Typical proton recoil energies: few MeVs - however depends on the simulation model used
- **First interaction** missed ➠ travel distance under-estimated
- **Scattered neutron** is slower ➠ ToF is over-estimating the initial neutron kinetic energy
- In the ECAL case:
  - Due to passive absorber ➠ more chance to have *scattered neutrons*
  - ➠ Expect low left tail in the energy reconstruction
- Sensitive parameters:
  - **Amount of H** ➠ thickness active material
  - **Absorber** ➠ thickness / material Z



Parameters for this preliminary study.

Setup

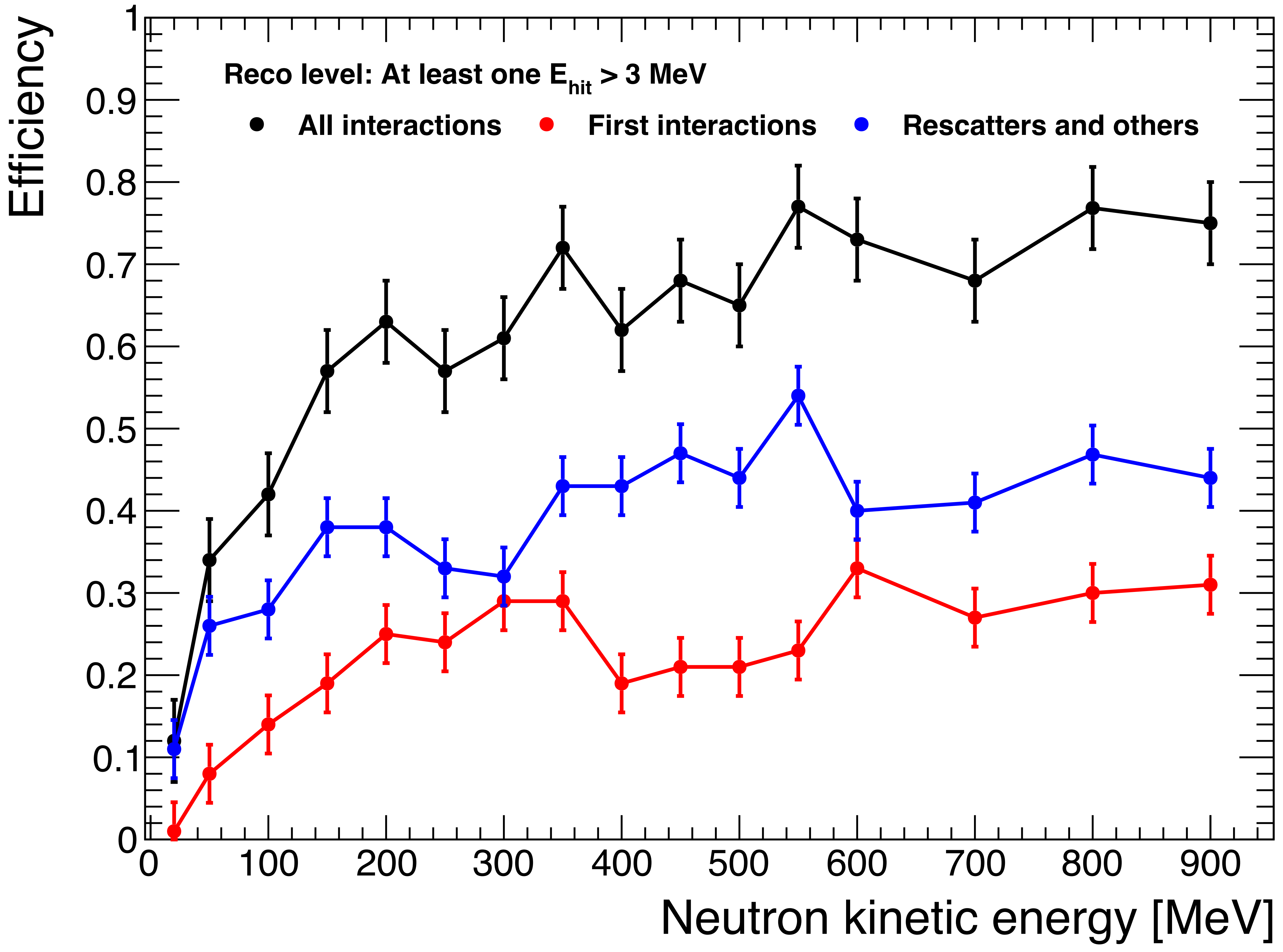
- Single neutron gun placed at ~3m or ~1m from the ECAL front face
- Comparison of several *ECAL models*
- Two levels
  - **Simulation level** ➠ Geant4 step
  - **Reconstruction level** ➠ reconstructed calorimeter hit
- Assumes **250 ps time resolution**
- Requirements:
  - First hit in time with **at least 3 MeV** of deposited energy
- Classified as **first interaction** / **scatter** based:
  - On the distance between the primary neutron endpoint and the reconstructed hit (d < 6 cm ~ 2-3 tiles)

Neutron energy reconstruction.

Baseline setup

Efficiency

- 2 mm Cu + 5 mm Sc (80 layers)
- Overall efficiency of above **50-60%**
  - Mostly **dominated** by rescatters



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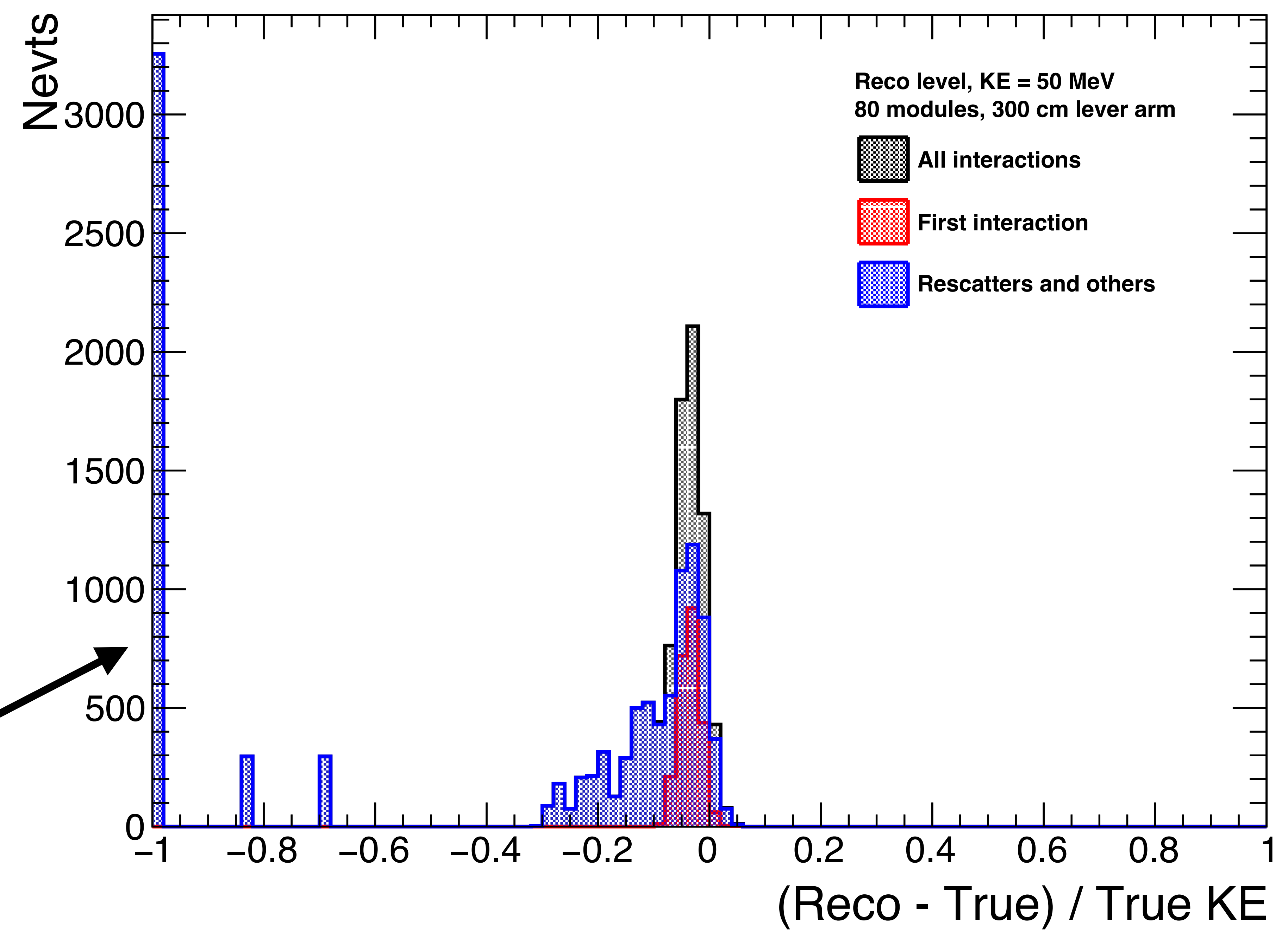
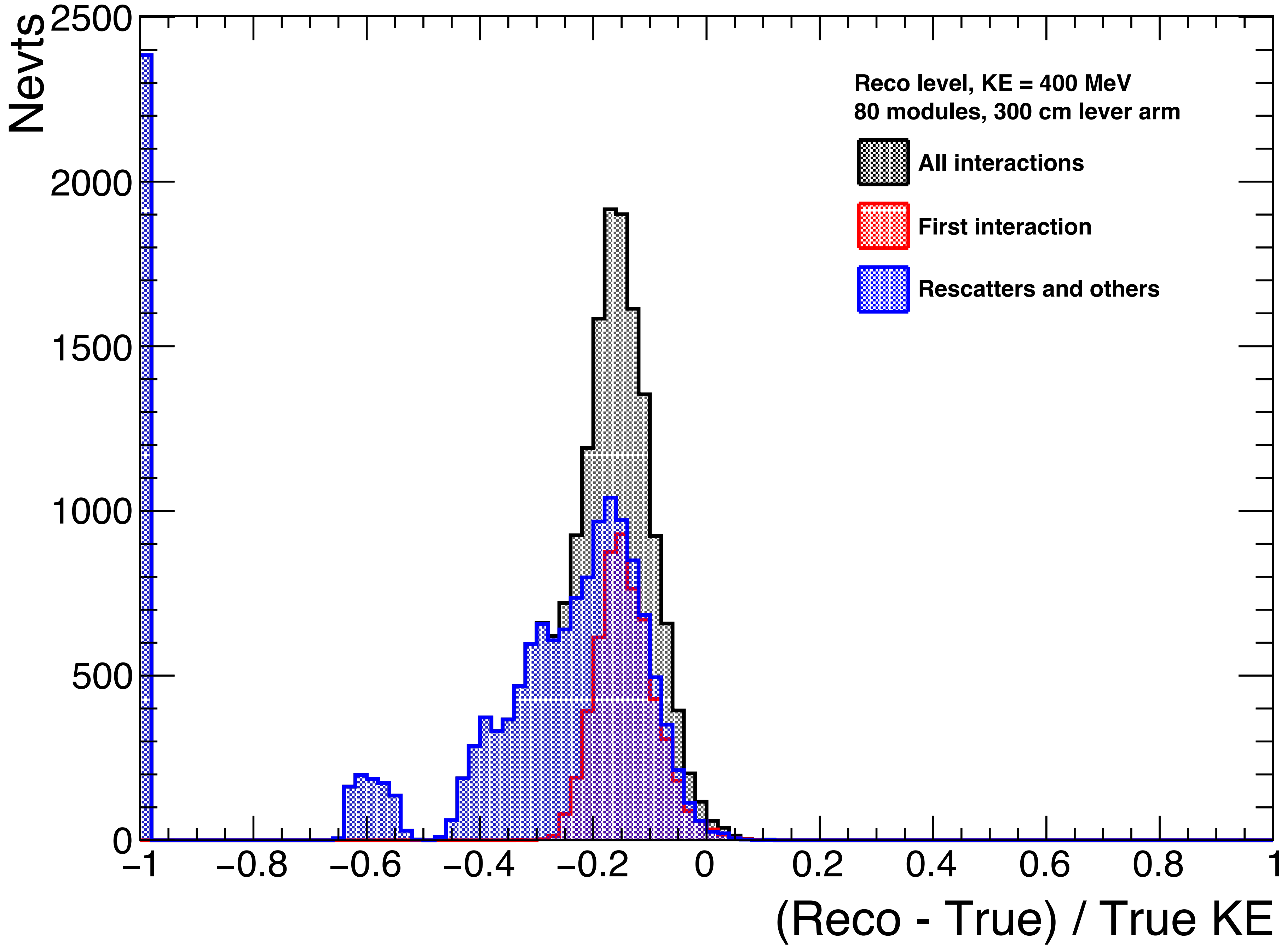
Energy reconstruction

- @ 50 MeV: large fraction at -1 (very delayed events due to nucleus de-excitations)
- @ 400 MeV: Rescatter get more pronounced
- Rescatter more pronounced at higher KE energies





Neutron energy reconstruction.

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Energy reconstruction

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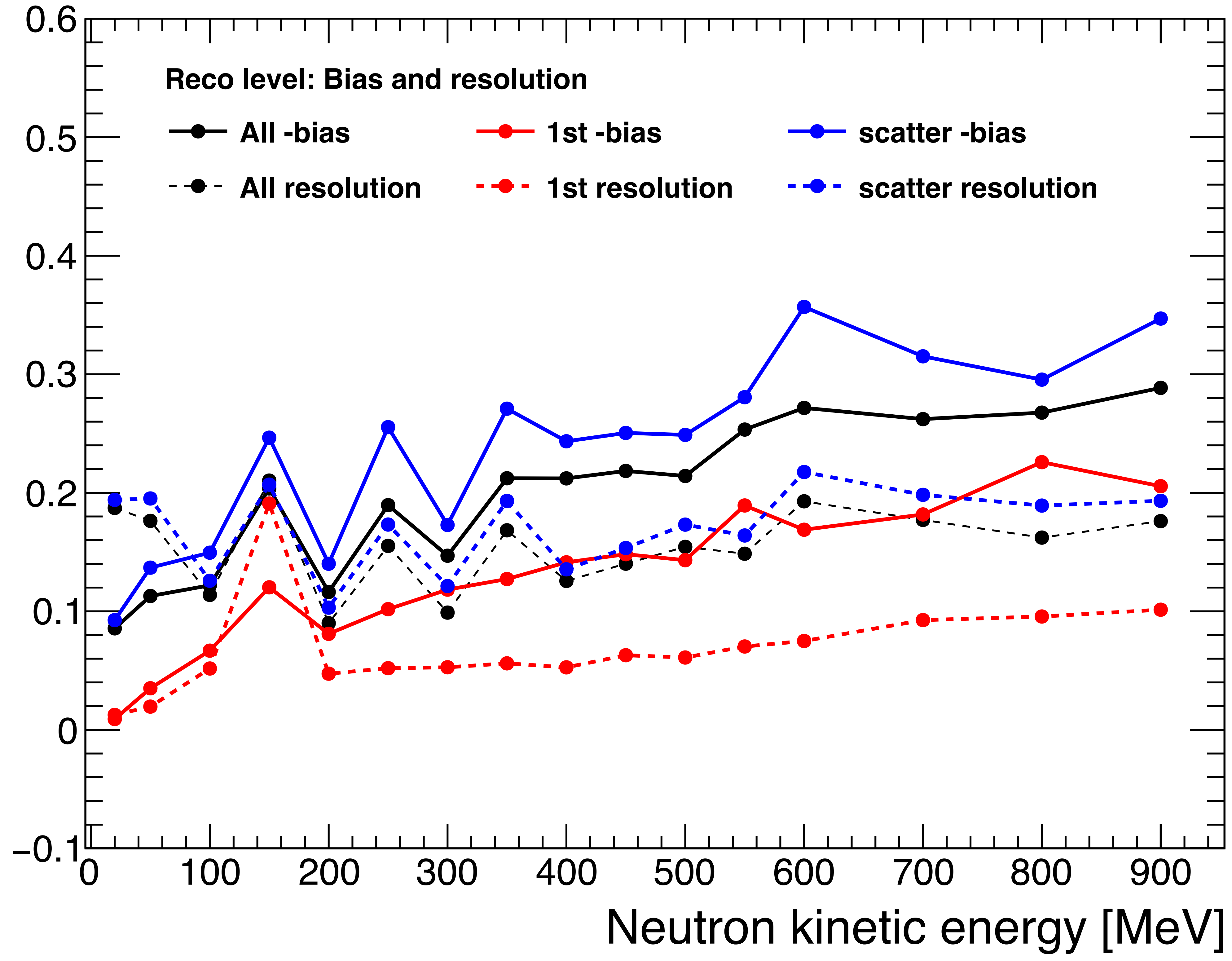
- Rescatter more pronounced at higher KE energies

Overall picture

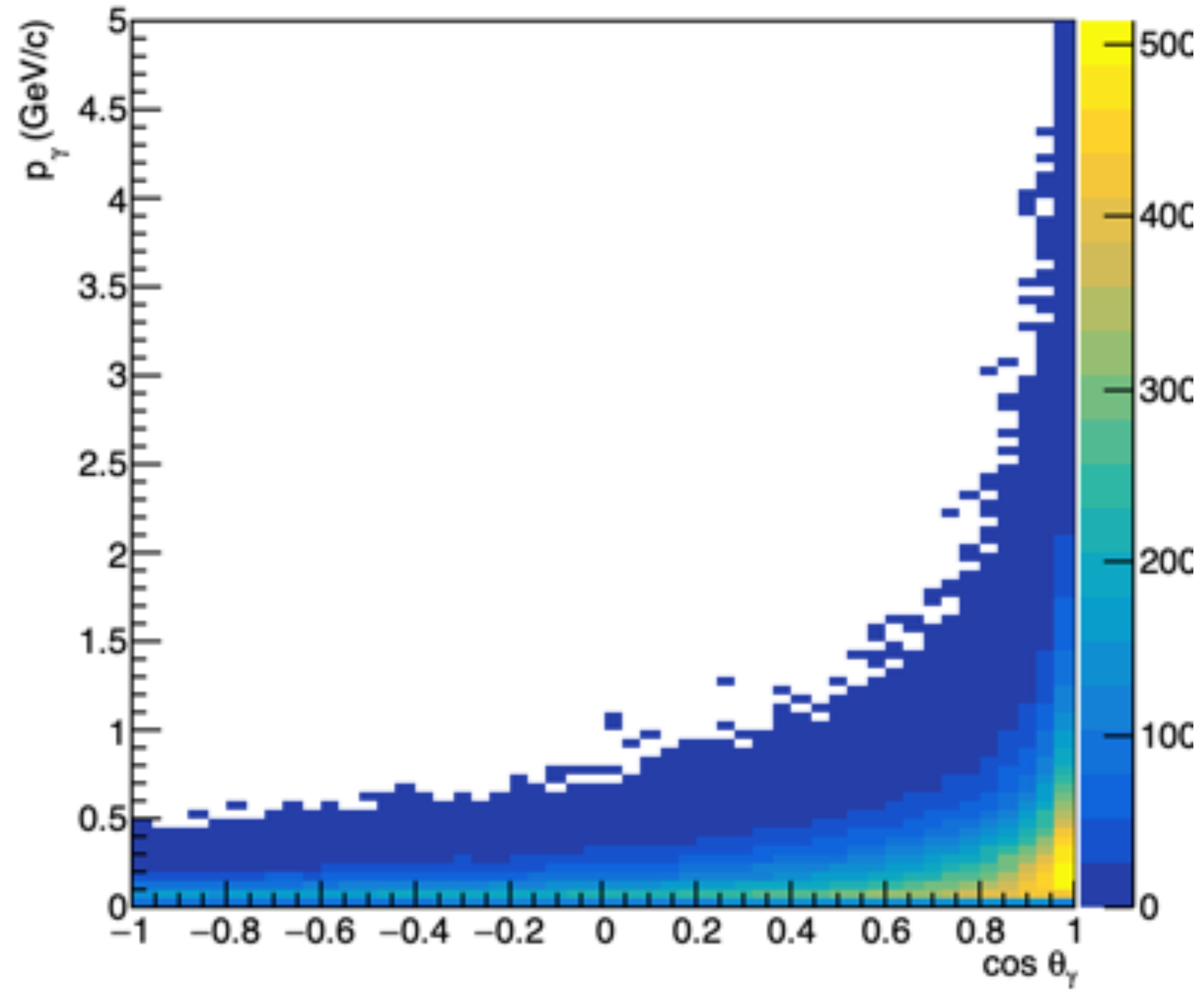
- Bias increases with KE - RMS slightly increases
- Adding rescatters worsen the bias and resolution ➠ potential to improve this by cutting on the layer

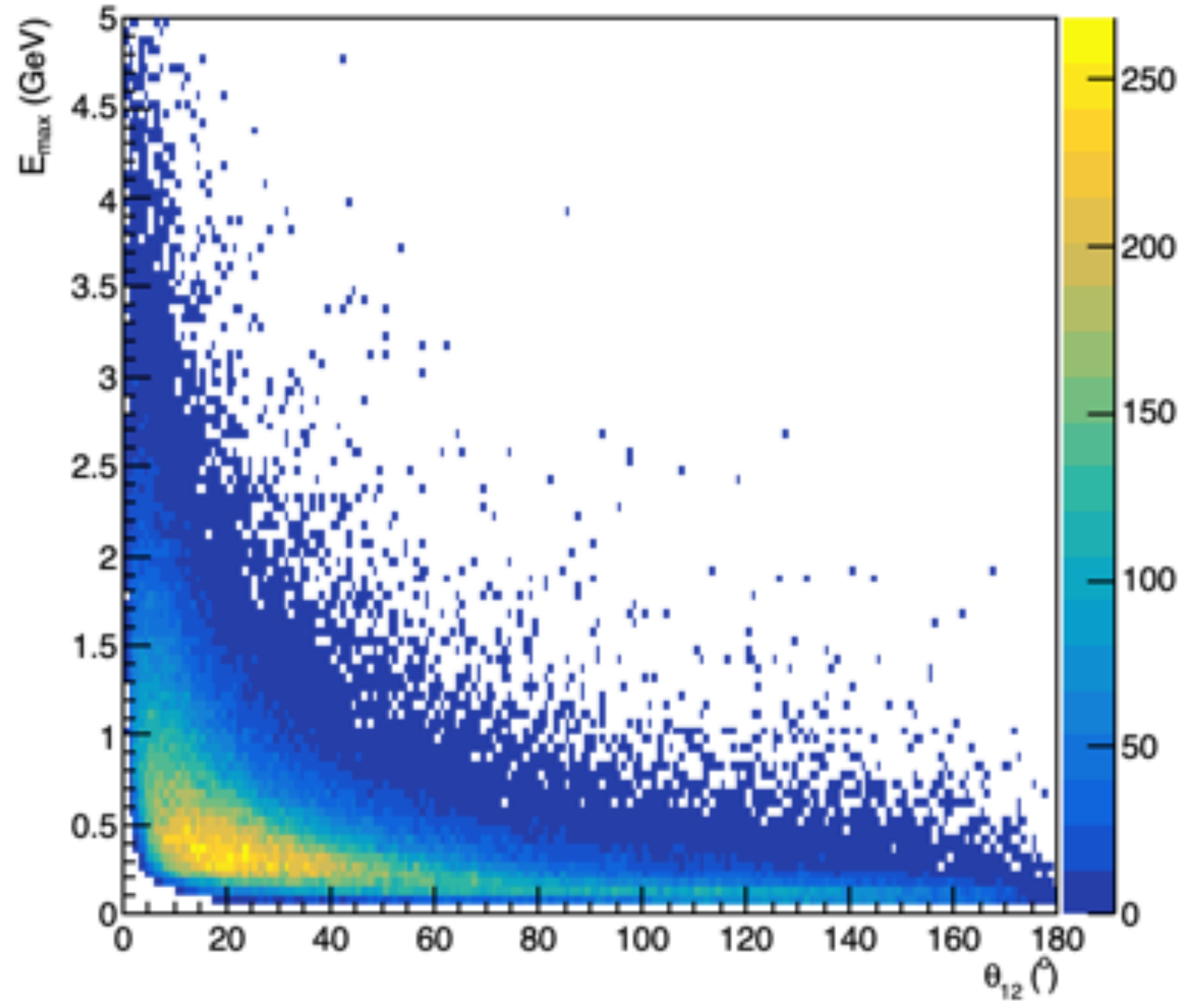


Where to optimise?.

Guided by the physics

- **Understand** π^0 production in DUNE to help in ECAL design considerations
- Momentum of π^0 ➠ guide the *dynamic range* needed and the needed *granularity* (angular separation)
- Kinematics:
    - π^0 s up to 5 GeV/c
    - π^0 s below 1 GeV/c ➠ large angle between the photons
- Angular distribution:
    - High energy photon lead to very small angular separation
    - Low energy photons ➠ angular separation typically around 20 degrees and above
        - Contains most of the events - 2.5 cm granularity ➠ few degrees

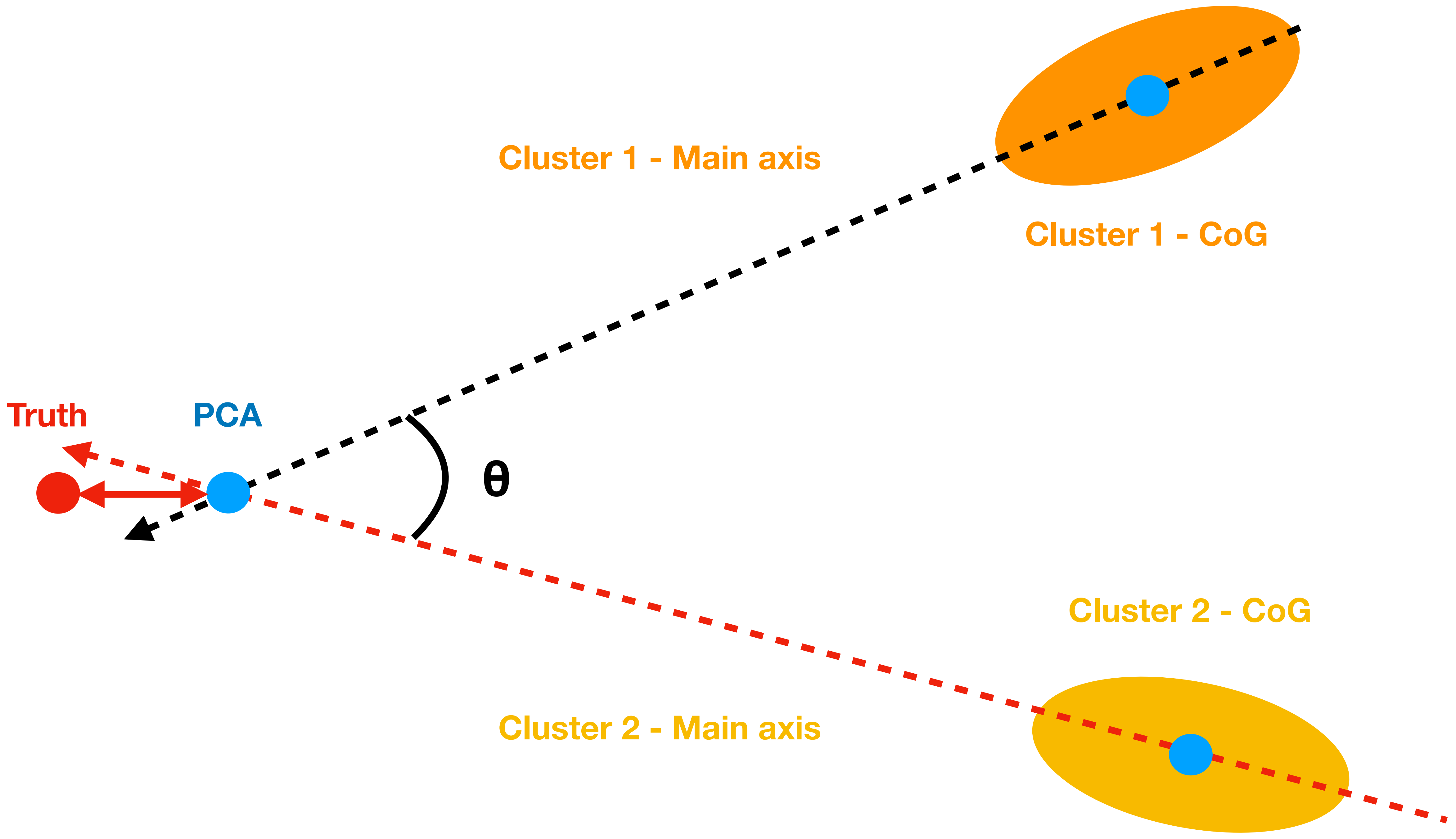




First look into neutral pion reconstruction.

Setup and method

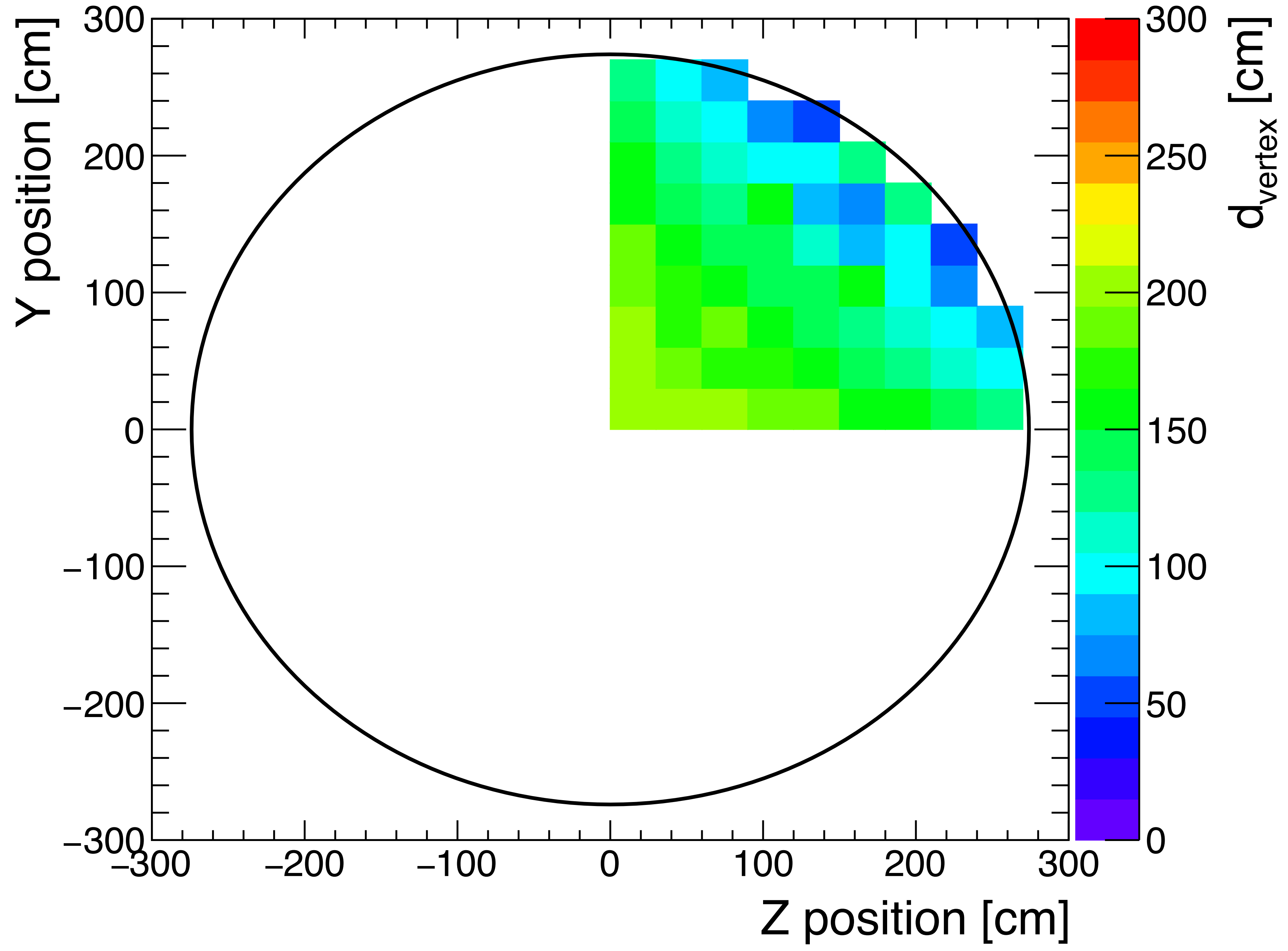
- Shooting π^0 s in the z direction between 0 and the TPC radius at intervals of 15 cm (x position fixed)
- **Simple Method** (no MC info used):
  - Take the *two most energetic clusters* (some case have more than two clusters)
  - Take the direction from the cluster main axis and calculate the PCA between the two cluster axis
  - Calculate the angle between the two cluster axis and reconstruct the π^0 mass
  - Calculate the 3D distance between the true vertex and the geometrical determined one
  - χ^2 minimization can be done after using the energy and geometrical information combined (not yet included)
- Work in progress

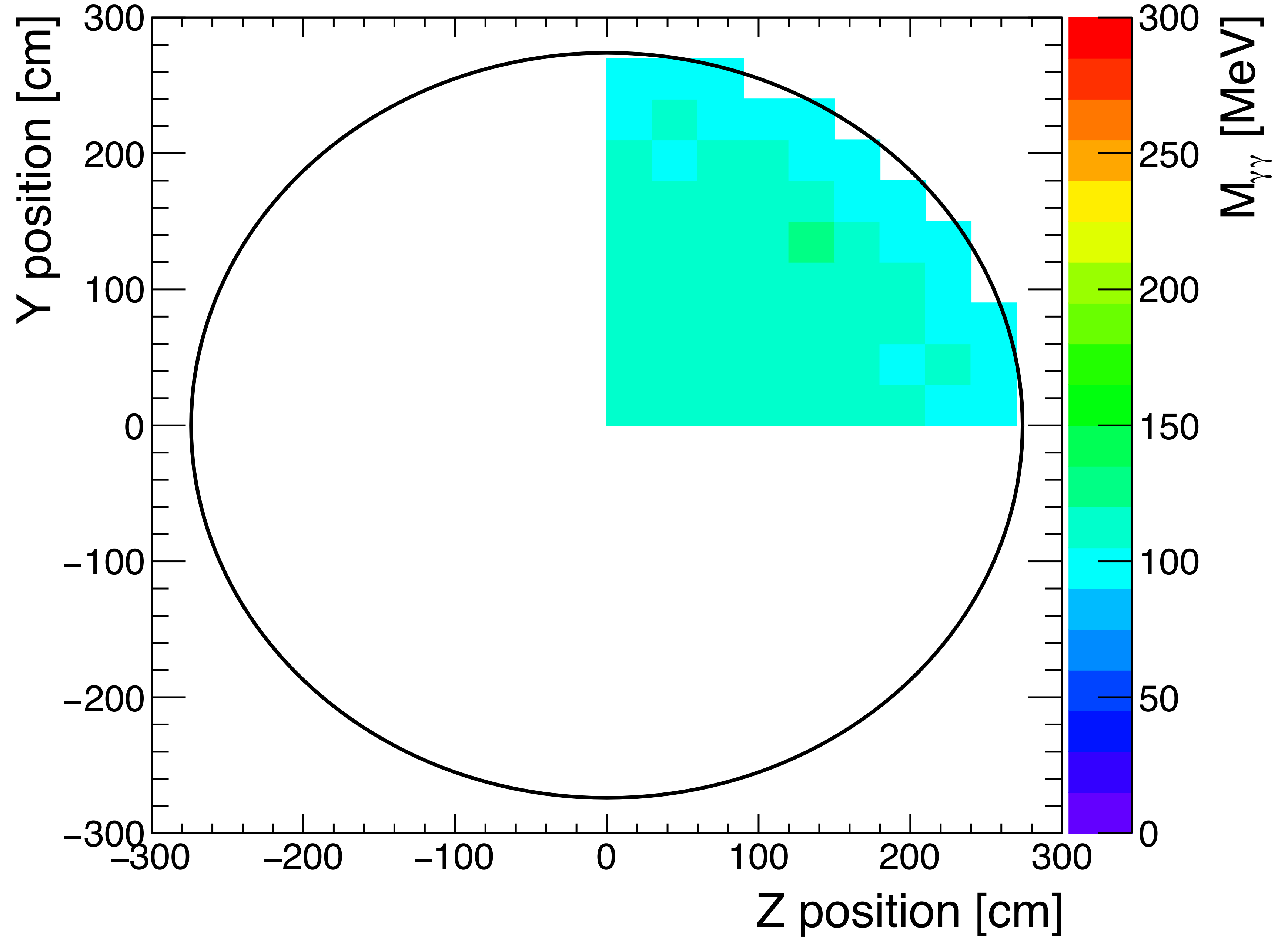


Neutral pion reconstruction.

Work in progress

- Case shown: 400 MeV neutral pion
- Look at the distance to the true vertex and reconstructed invariant mass as function of the vertex position
- π^0 s reconstructed between 100-150 MeV ➠ clustering effect
- Distance to the truth vertex around 150 - 200 cm ➠ mostly the z-coordinate is badly reconstructed
- Factor ~x5 worse than more complete studies
  - Not yet using the χ^2 minimization ➠ *important for the position resolution*
  - Clustering *not optimized*

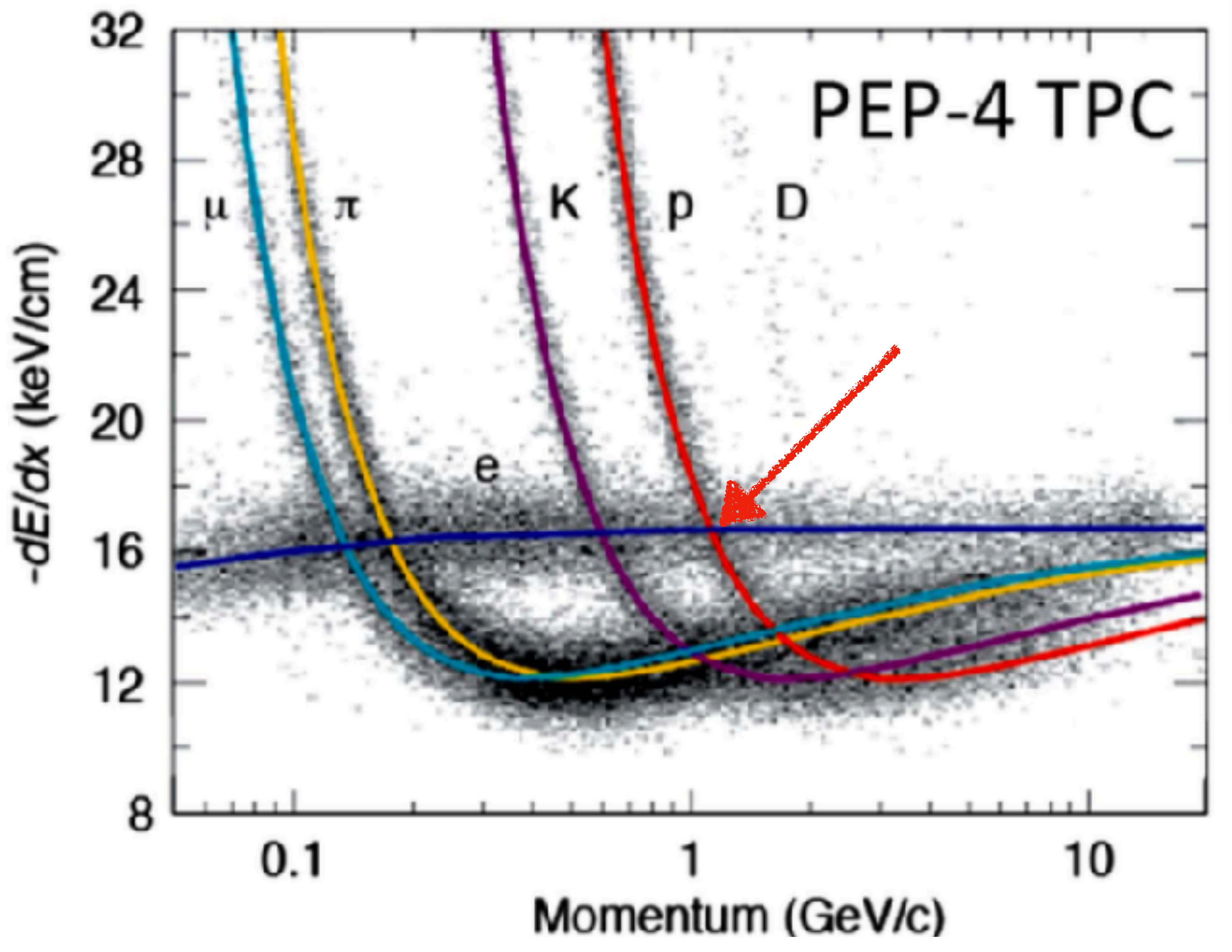




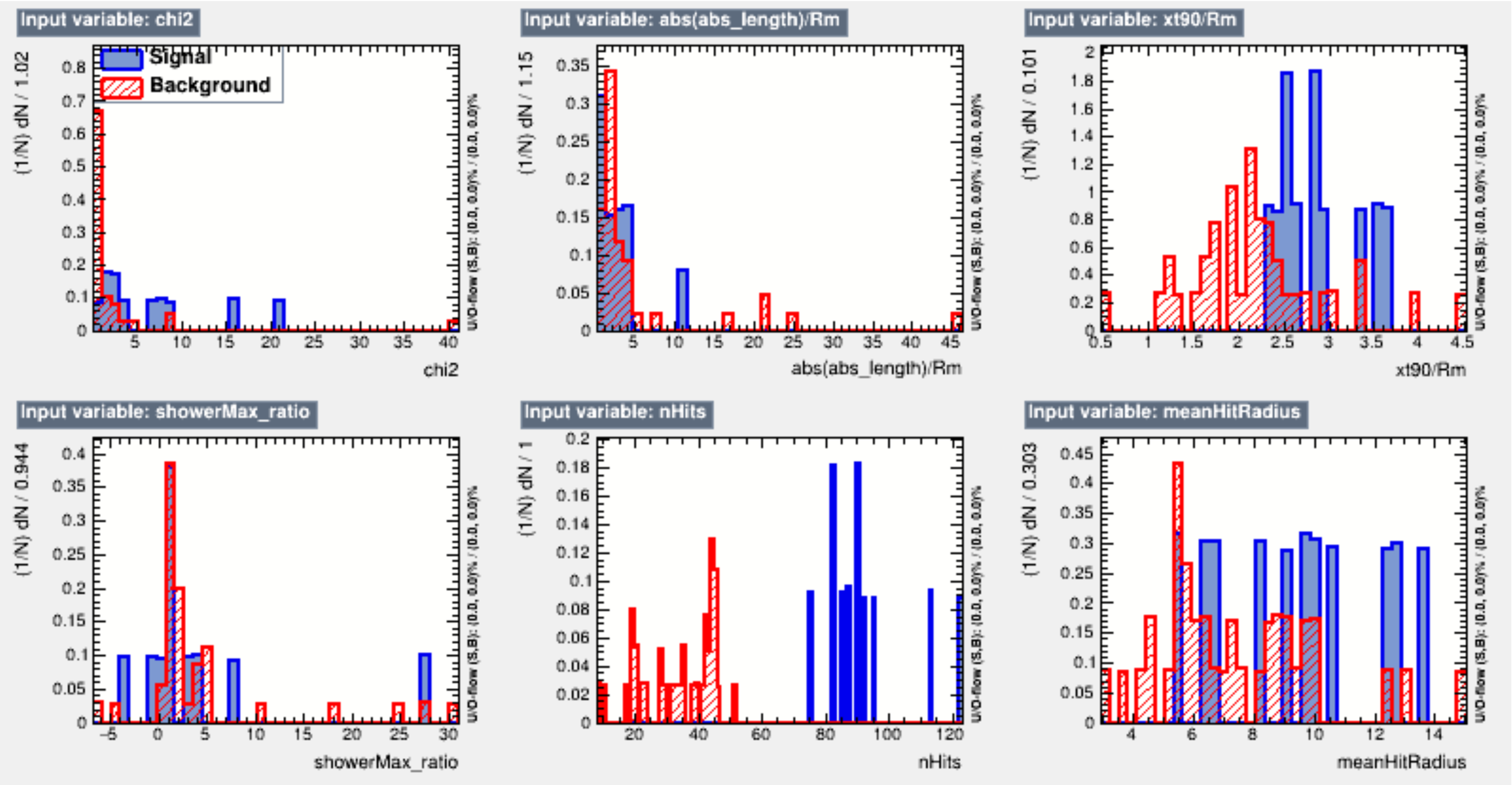
Particle identification.

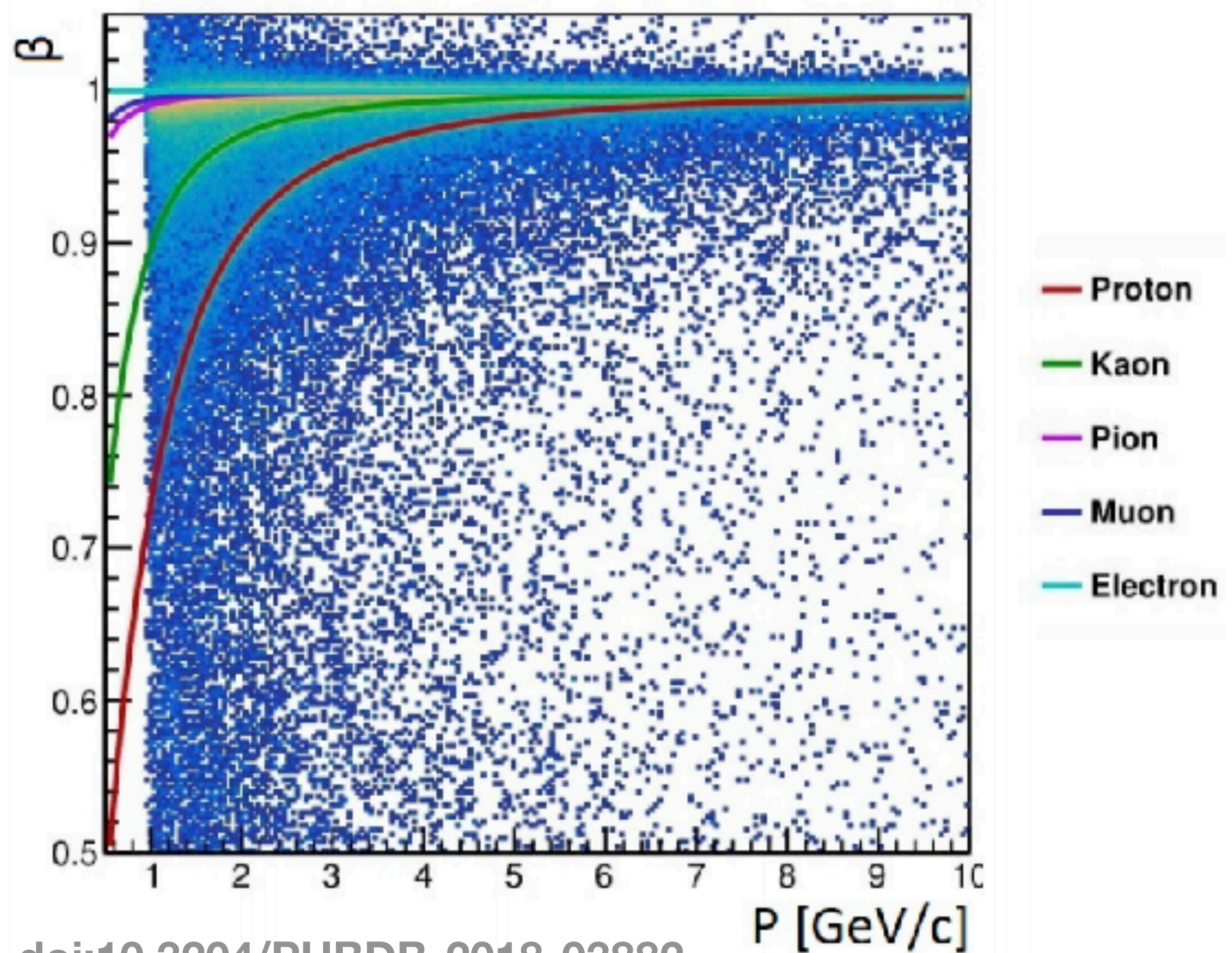
Work in progress

- ECAL needs to be complementary to the HPgTPC
- Example
  - Separation muon / pion
  - Separation proton / positron around 1 GeV
- Use of shower shape variables: shower start, number of hits, shower size … combined with TMVA techniques (Likelihood, BDT…)
- Alternatively, time of flight technique could be used combined with dE/dx



Work in progress



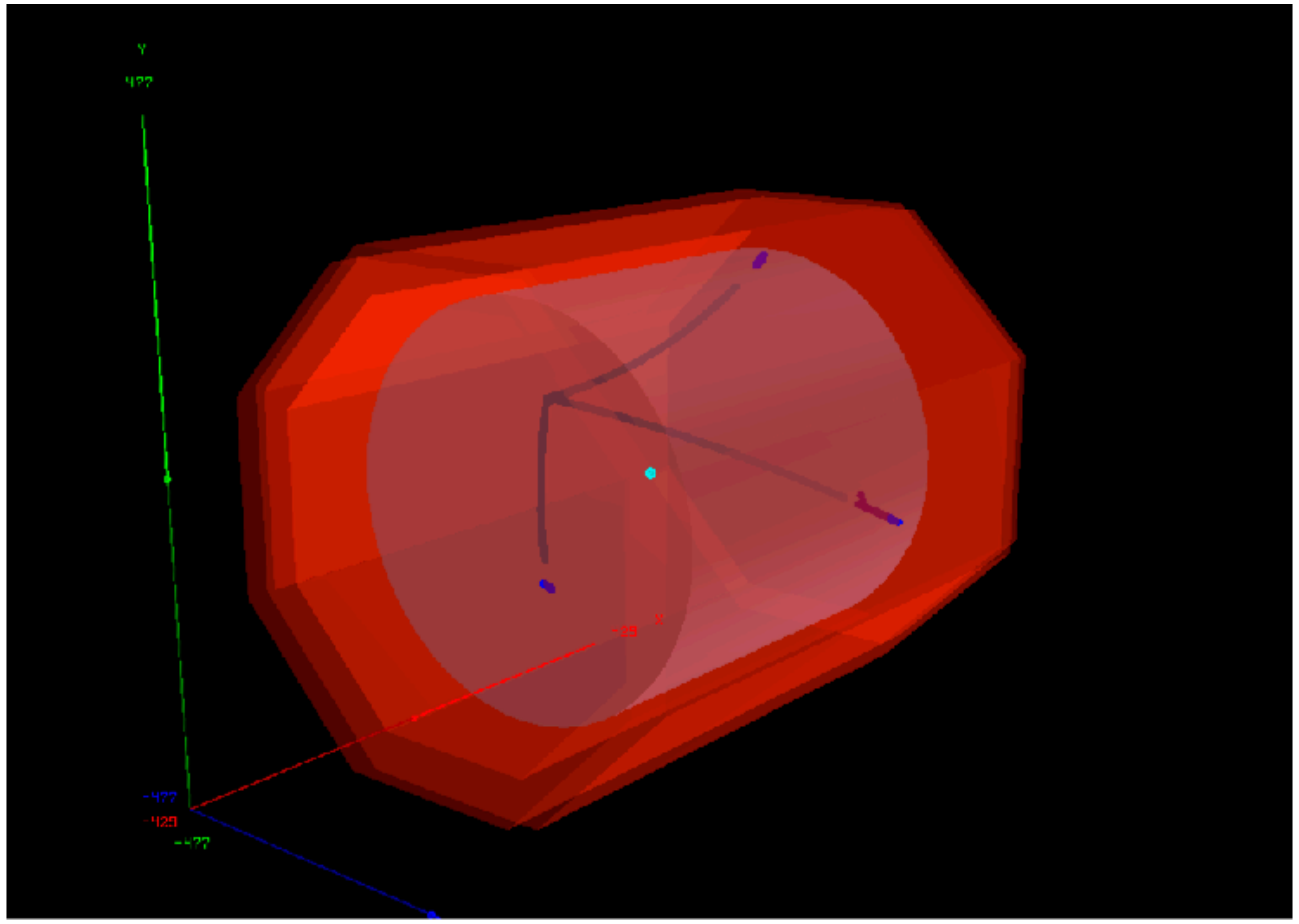


doi:10.3204/PUBDB-2018-03882

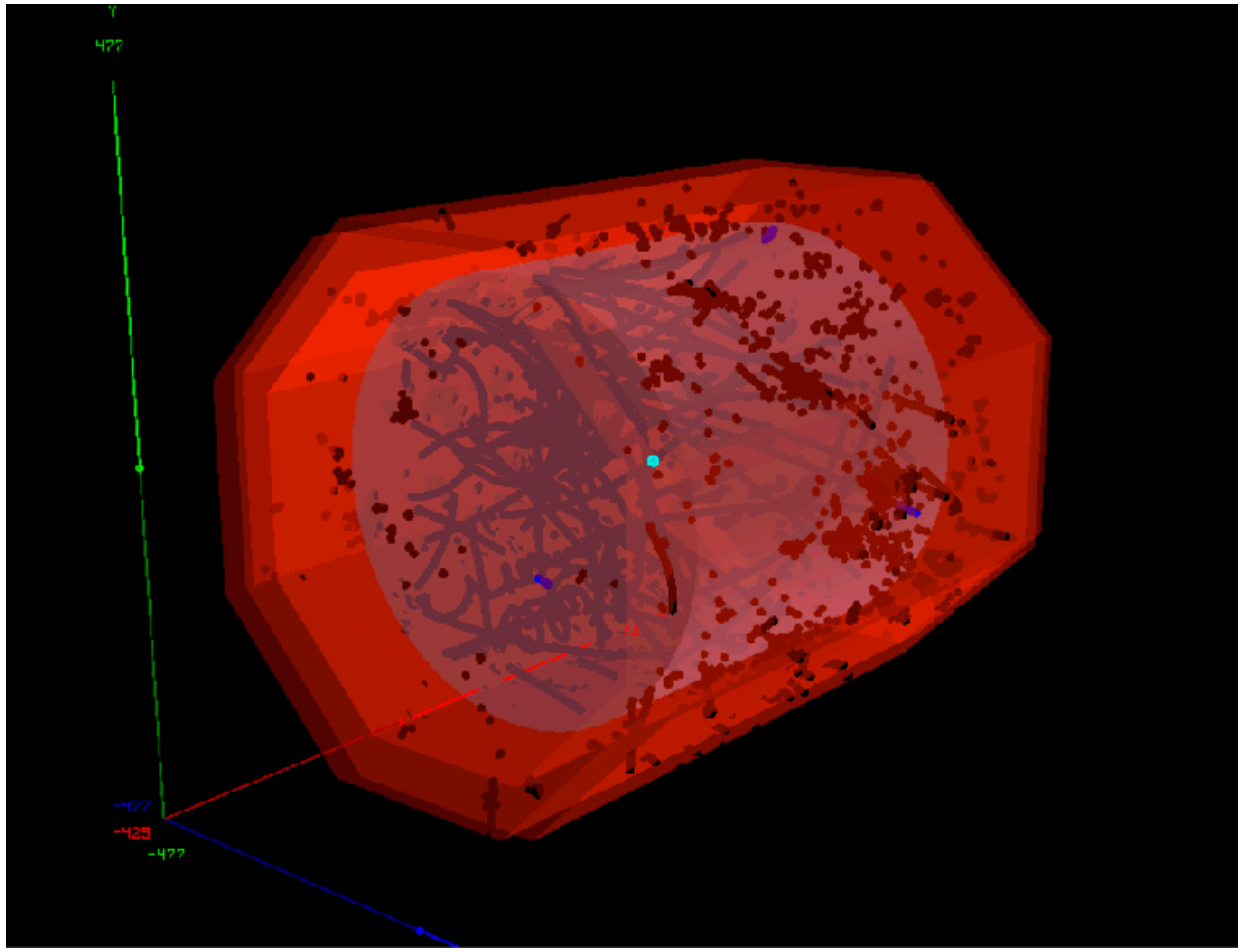
Background suppression.

Timing as a powerful tool

- Due to ECAL mass (300t) ➠ ~60 interactions are expected in the ECAL / 0.2 in the HPgTPC per spill (10 μs)



Signal Only

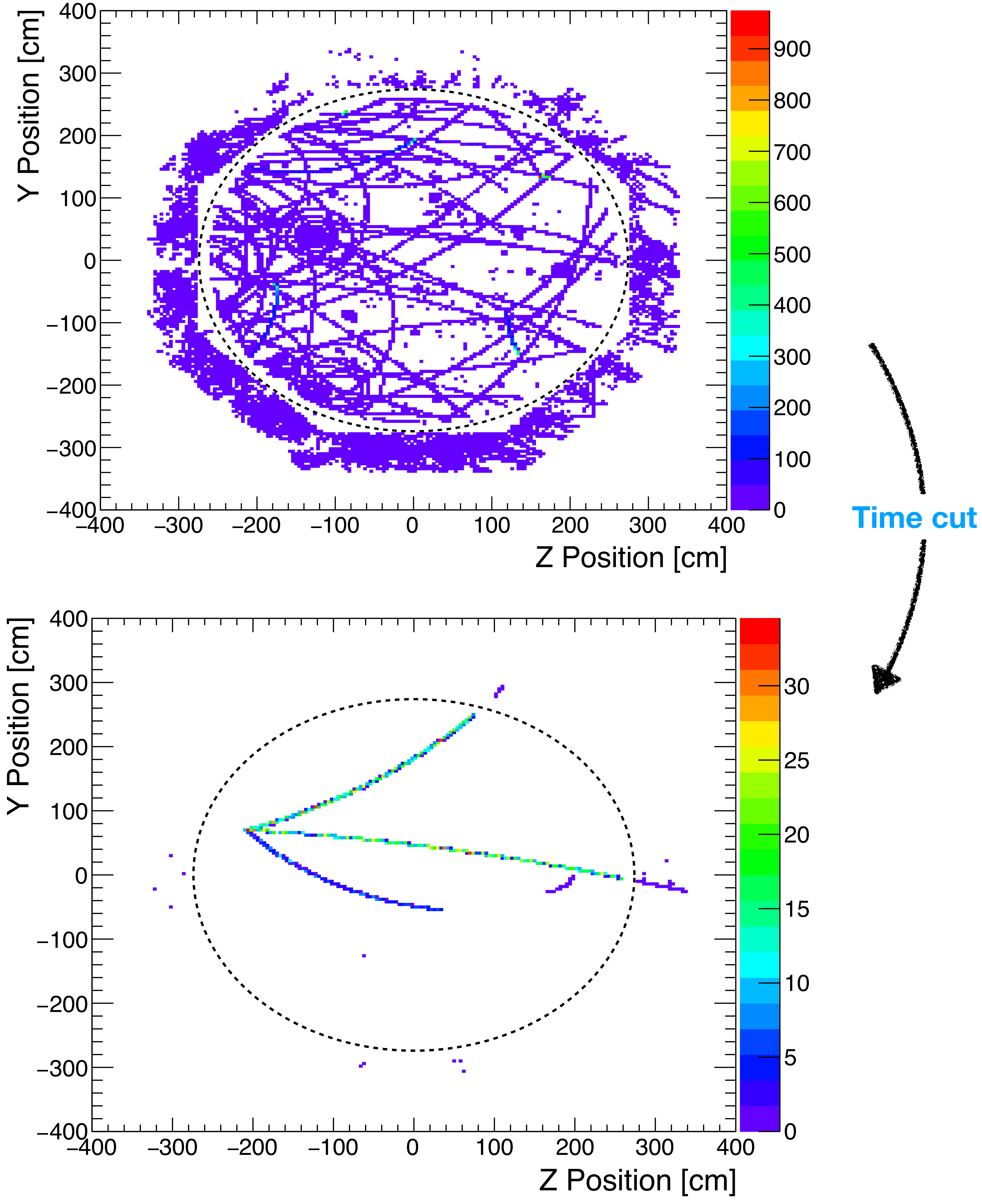


Signal + Background

Background suppression.

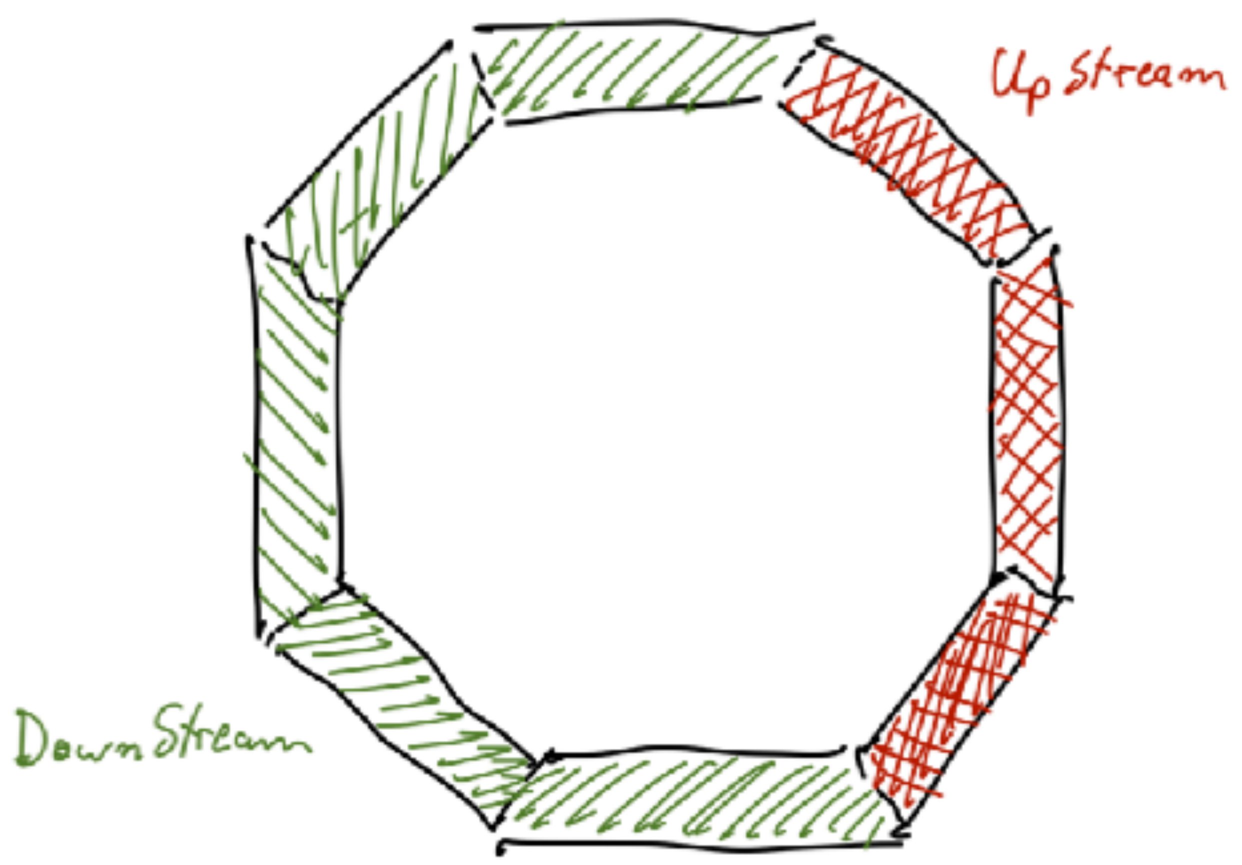
Timing as a powerful tool

- Due to ECAL mass (300t) ➟ ~60 interactions are expected in the ECAL / 0.2 in the HPgTPC per spill (10 μs)
- Use timing as a tool to remove background (assumes 60 interactions uniformly spread over the full spill time)
  - On MC first (needs to be assessed after reconstruction)
  - Use the muon track as t_0
  - Use time window of 50 ns (1 ns time resolution)
- Caveats
  - Assumes perfect association TPC tracks to ECAL Clusters
  - What about tracks that don't reach the ECAL? (no time information)
  - No reconstruction
- Other backgrounds are being assessed (gamma from ECAL converting in gas / can mimic ν_e interaction)



Real considerations.

Trade between performance, cost, feasibility..



- Limited space: place inside the pressure vessel? Feasible?
- Cost: cost scales with size of the TPC, mostly the surface, number of layers and granularity
- Fixed-target style ➠ different ECAL modules upstream/downstream
- Use strips with WLS fibres to reduce the channel count

	DS Segments (3)	US Segments / Endcap (7)
HG Layers (0.5 cm of Sc)	8	6
HG Tile size	2.5 x 2.5 cm^2	2.5 x 2.5 cm^2
HG Absorber thickness (Cu)	2 mm	2 mm
LG Layers	72	54
LG strip width (0.5 cm of Sc, crossed)	4 cm	4 cm
LG Absorber thickness (Cu)	2 mm	2 mm
Total thickness	11 X_0	9 X_0
Number of channels	~ 2.8 - 3 M	
Copper volume	~ 31.8 m^3	
Sc volume	7 m^3 (tiles) - 63 m^3 (strips)	
Fiber length	~ 320 km	

Conclusion and Outlook

The most exciting times!

- Neutrinos are fun! The DUNE experiment is the next generation neutrino experiment that will probe the SM to great details
- New generation TPC detectors are the large scale are being built!
- The near detector is a crucial piece of the DUNE physics program
- The MPD will provide
  - a large acceptance muon spectrometer for muons exiting the LAr detector
  - a statistically significant independent sample of neutrino interactions on Ar gas
- An ECAL design is on its way
- Detailed optimisation studies are ongoing
  - EM **energy resolution and angular resolution** investigated for several models to understand the impact of each parameters
    - **Best achieved**: ~$5\%/\sqrt{E} + 1\%$ - ~$3.5°/\sqrt{E} + 2°$
  - The ECAL may **have potential in neutron energy reconstruction** with ToF
    - Energy resolution below 20% for a large range of neutron KE - however bias in the reconstruction
    - Improvements possible
  - **Neutral pion reconstruction/Particle identification** is work in progress, still place for improvements
  - Important tool for background suppression!

Backup Slides.