Forward Liquid Argon Experiment (FLArE) at the High Luminosity LHC

- High Energy Neutrino and Dark Matter Searches

Wenjie Wu

Institute of Modern Physics

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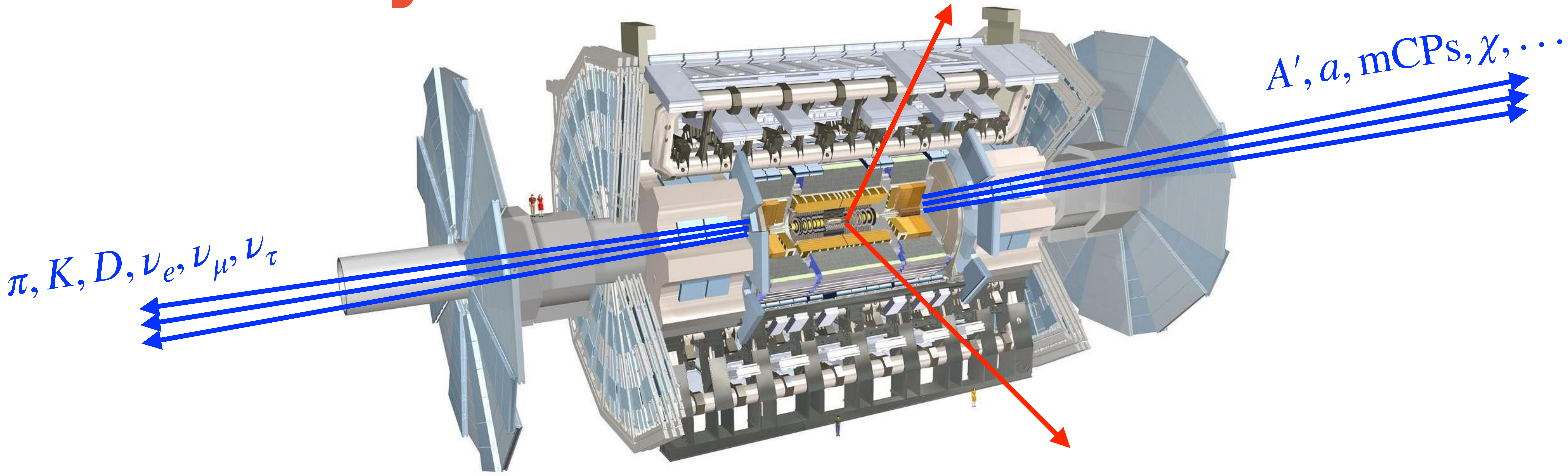
Forward Physics at LHC

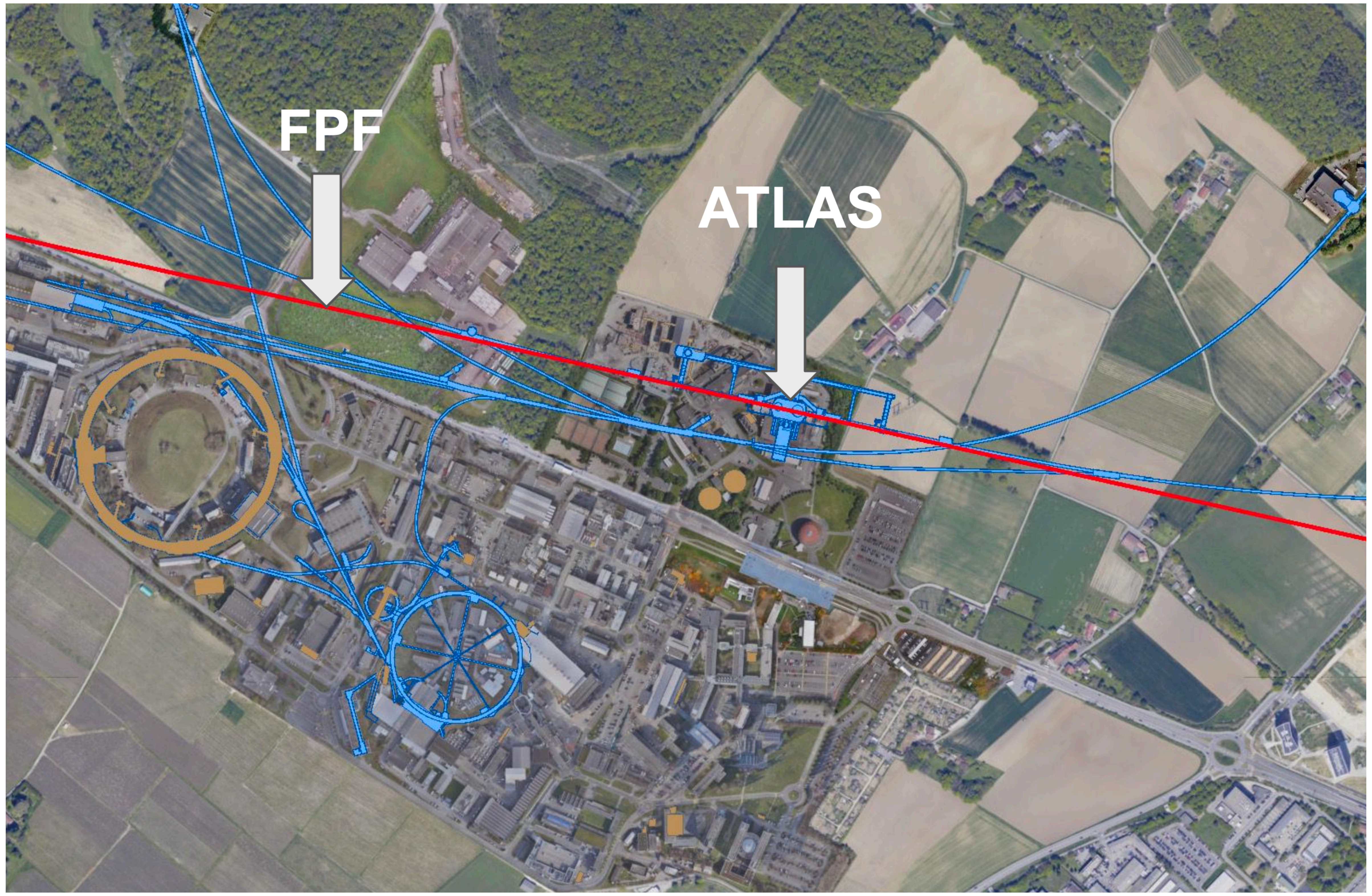


- Existing LHC experiments primarily focused on high-p_T physics, for searches of heavy particles (*W, Z, t, h,* …)
- Most of the inelastic *pp* collisions produce particles travel approximately parallel to the beamline and escape through the blind spots
  - SM: pions, kaons, and other light mesons, and neutrinos of all flavors at highest human-made energies
  - New physics searches: new gauge bosons, new scalers, sterile neutrinos, dark matter, milicharged particles, axion-like particles, …
- The potential to study these particles is a unique opportunity for groundbreaking discoveries in HL-LHC

Forward Physics *Facility* at LHC

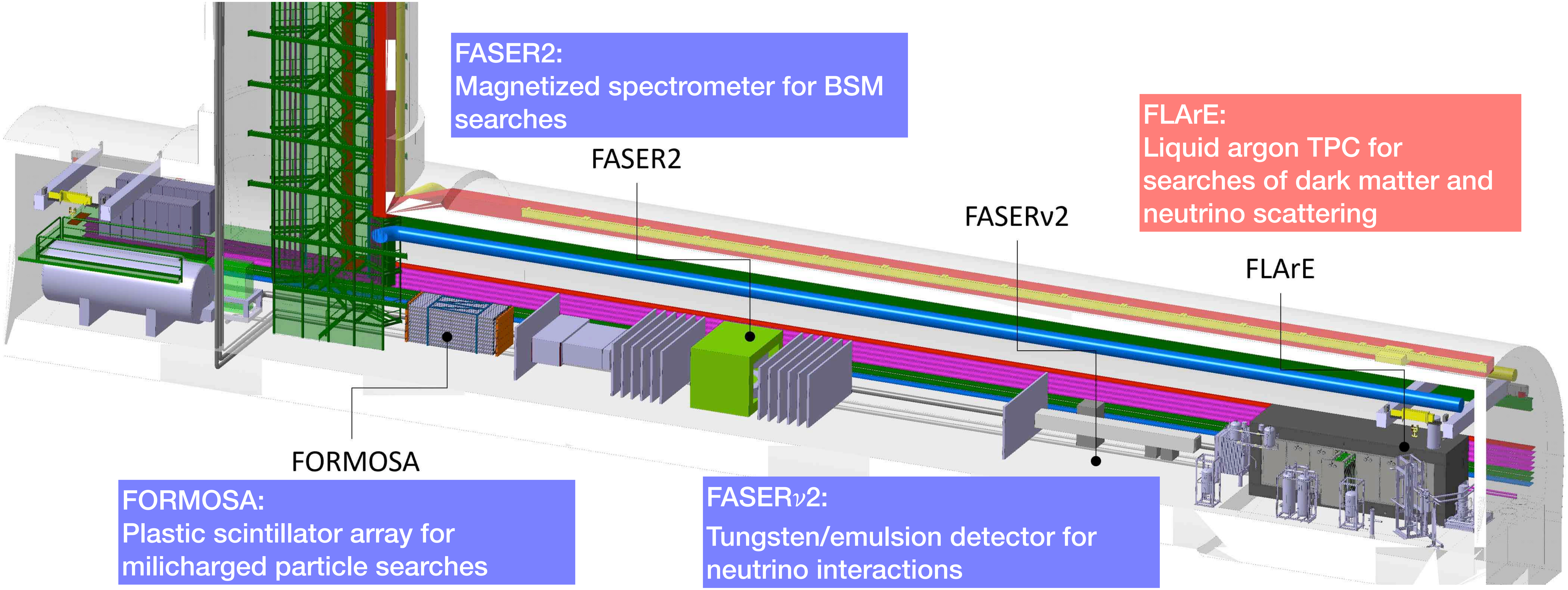
- Forward Physics Facility (FPF) is a proposal to realize these opportunities, by creating a space to host a suite of experiments at the far forward region

- The primary goal is to extend the current LHC forward physics program into HL-LHC era with x10-100 exposure
- Comprehensive site selection study performed by the CERN civil engineering
- ~600 m west of the ATLAS IP along the line of sight (LOS)
- ~75 m long, 12 m wide cavern, disconnected from LHC tunnel
- Shielded from ATLAS by ~200 m of rock



Civil Engineering Studies:
https://cds.cern.ch/record/2886326/
https://cds.cern.ch/record/2851822/

Forward Physics *Facility* at LHC

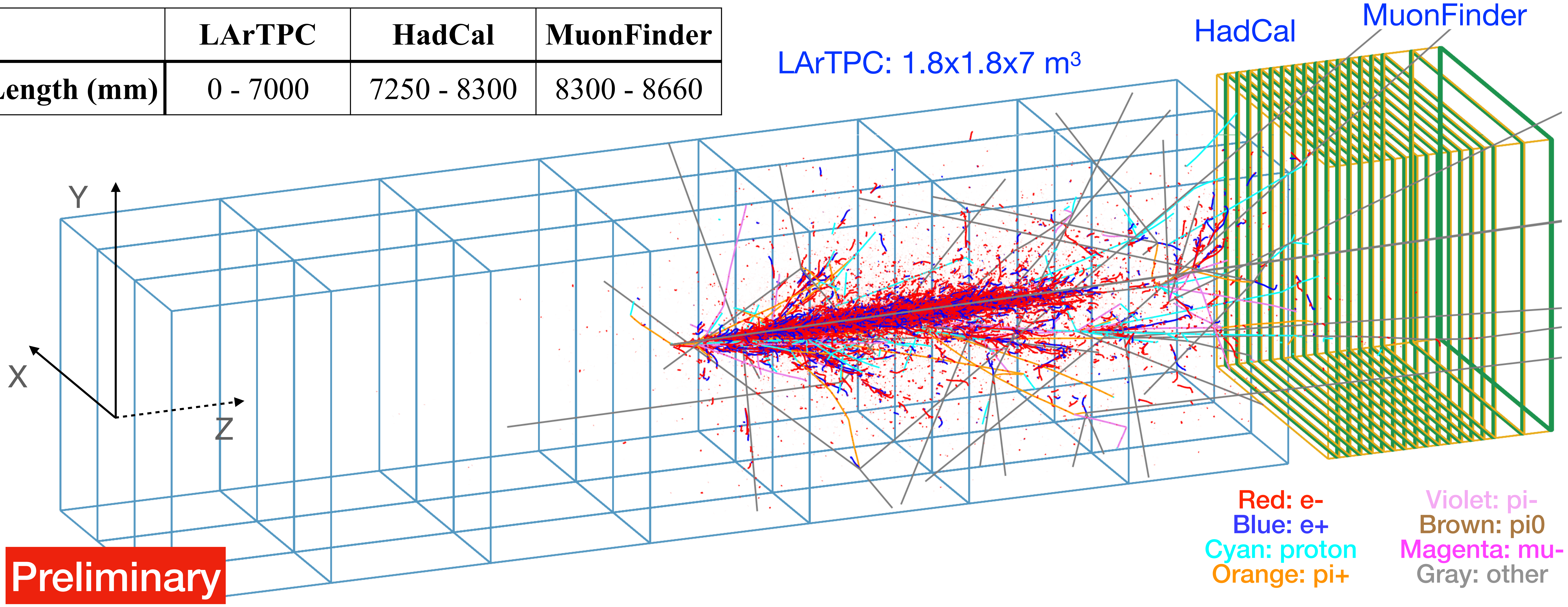


Diverse technologies optimized for SM and BSM physics
Synergies exist between FPF detectors

Forward Liquid Argon Experiment (FLArE)

- FLArE: a liquid argon time projection chamber (LArTPC) detector in FPF to detect neutrinos and dark matter from LHC
    - Fiducial mass of 10 tons (1x1x7 m^3) is needed for good statistics and sensitivity to dark matter
    - Detector needs to have good energy containment and resolution for neutrino physics
    - Muon and electron ID. Very good spatial resolution (~1 mm) for tau neutrino detection

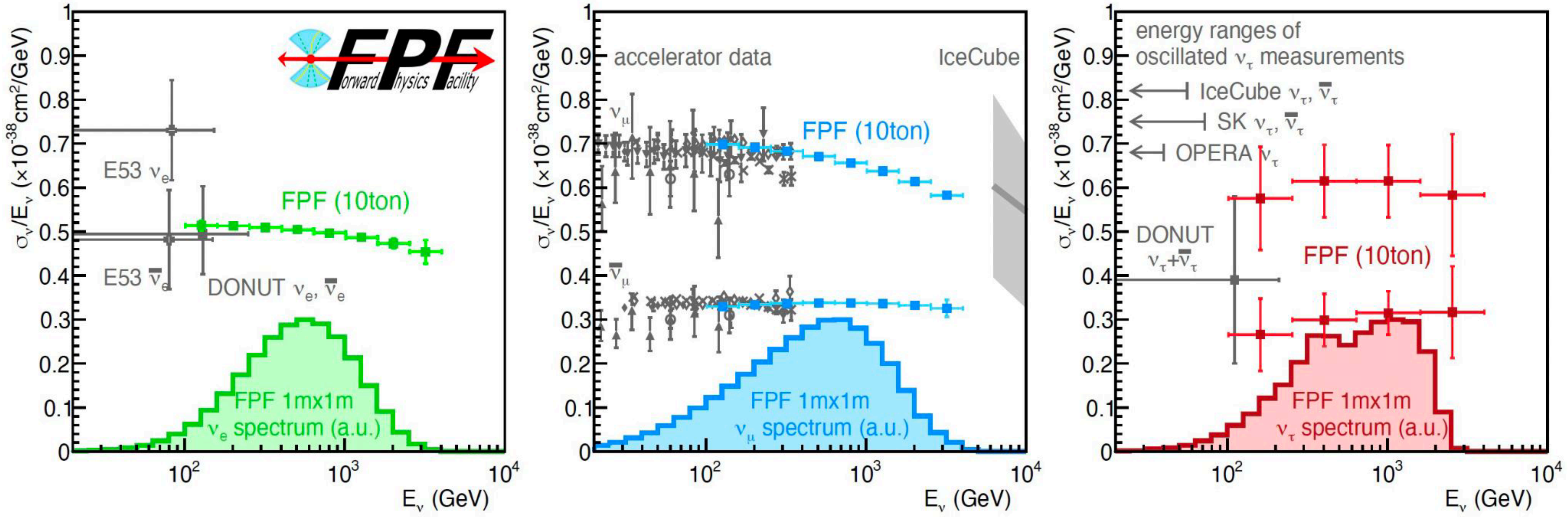
	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660

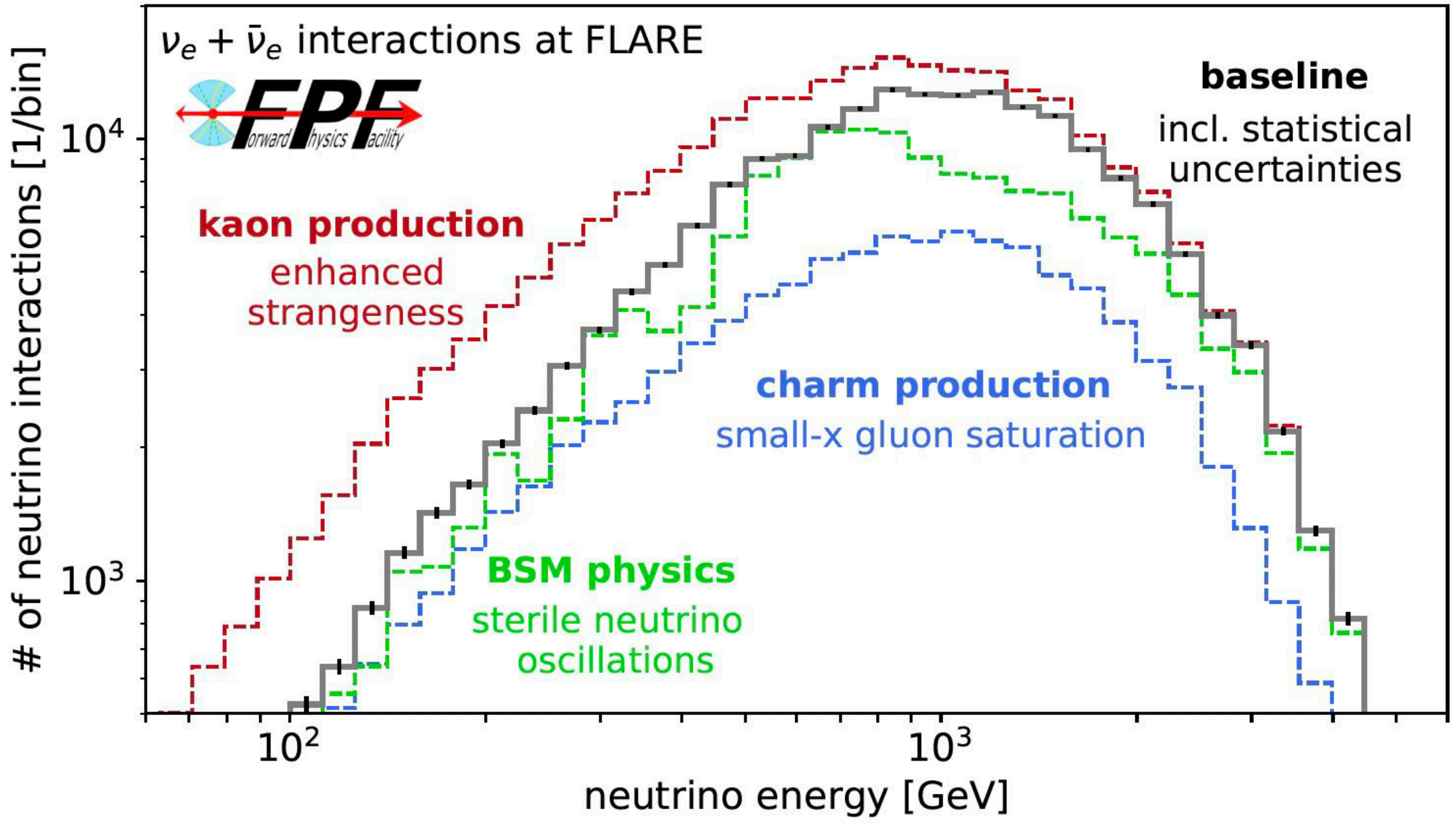


Neutrino Physics

https://www.osti.gov/biblio/1972463

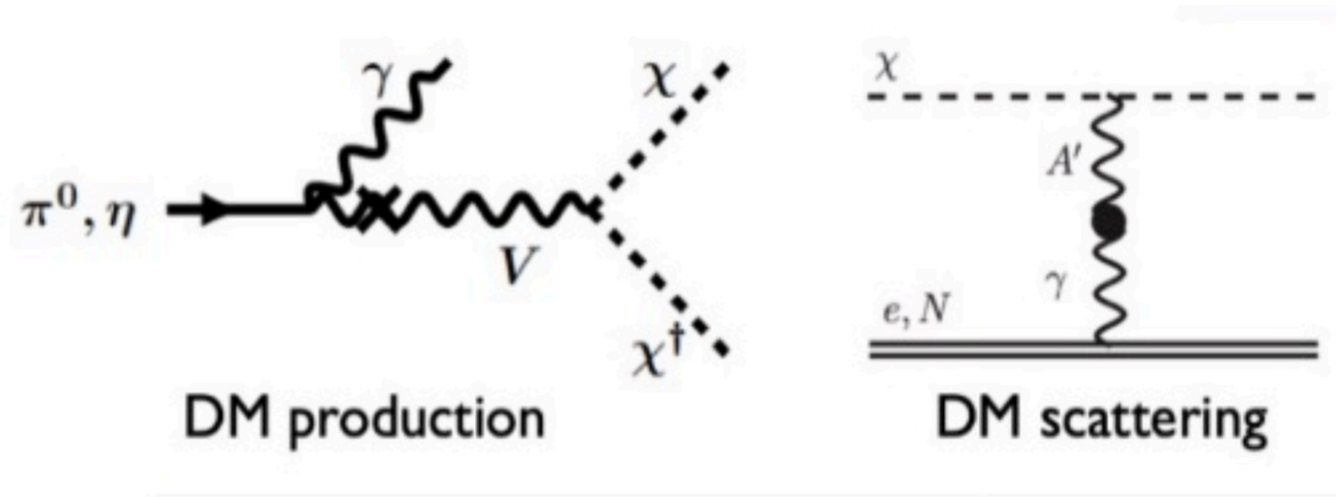
- Neutrinos from LHC provide data that fills in the gap between the current accelerator and atmospheric neutrinos
- **FLArE is an excellent option for a broad purpose neutrino detector**
  - will see 10^5 ν_e, 10^6 ν_μ, 10^4 ν_τ interactions at ~TeV energies
- By measuring the neutrino flux, we can probe **hadron production** in the forward region and provides insights into the underlying physics



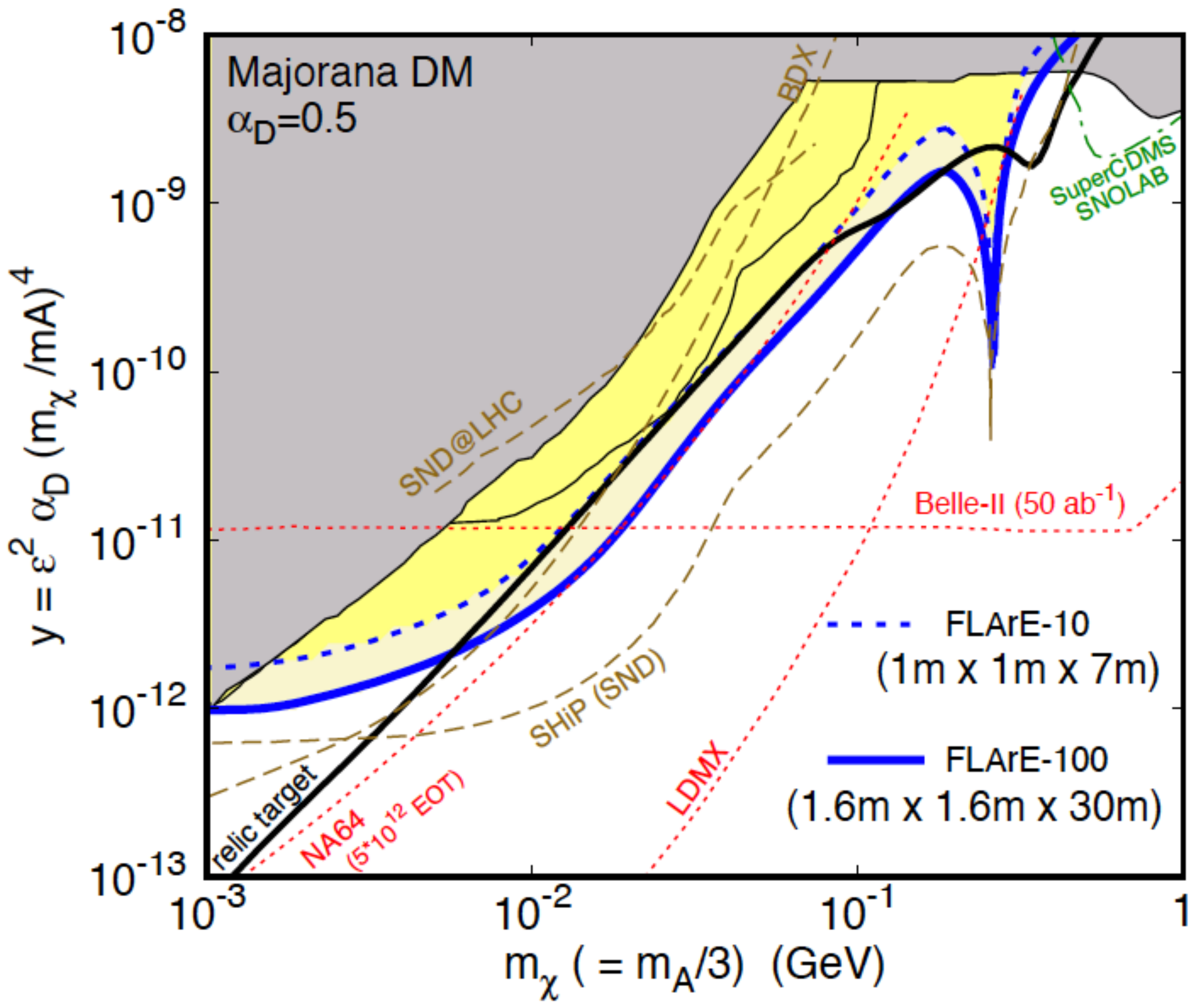


Light Dark Matter Scattering

Elastic scattering from electrons and nuclei



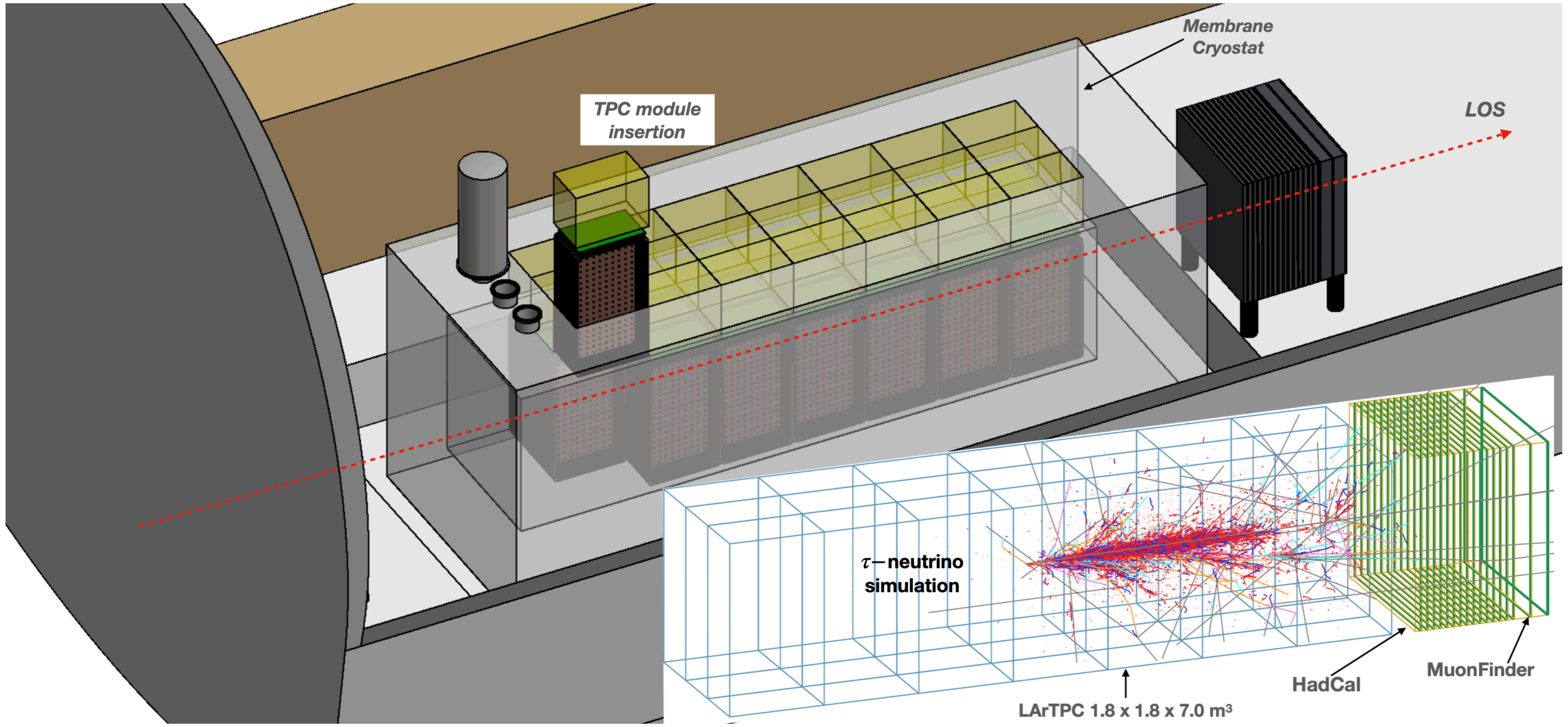
- Mass of χ alters the kinematics of the outgoing electron or nucleus
- Signal is at low energy (~ 1 GeV). **Need high kinematic resolution and low threshold**
- Background is from neutrino interactions and muons
- The sensitivity plot assumes reasonable cuts for background reduction
- Make use of the huge flux of mesons for this direct detection technique to get to the relic density target



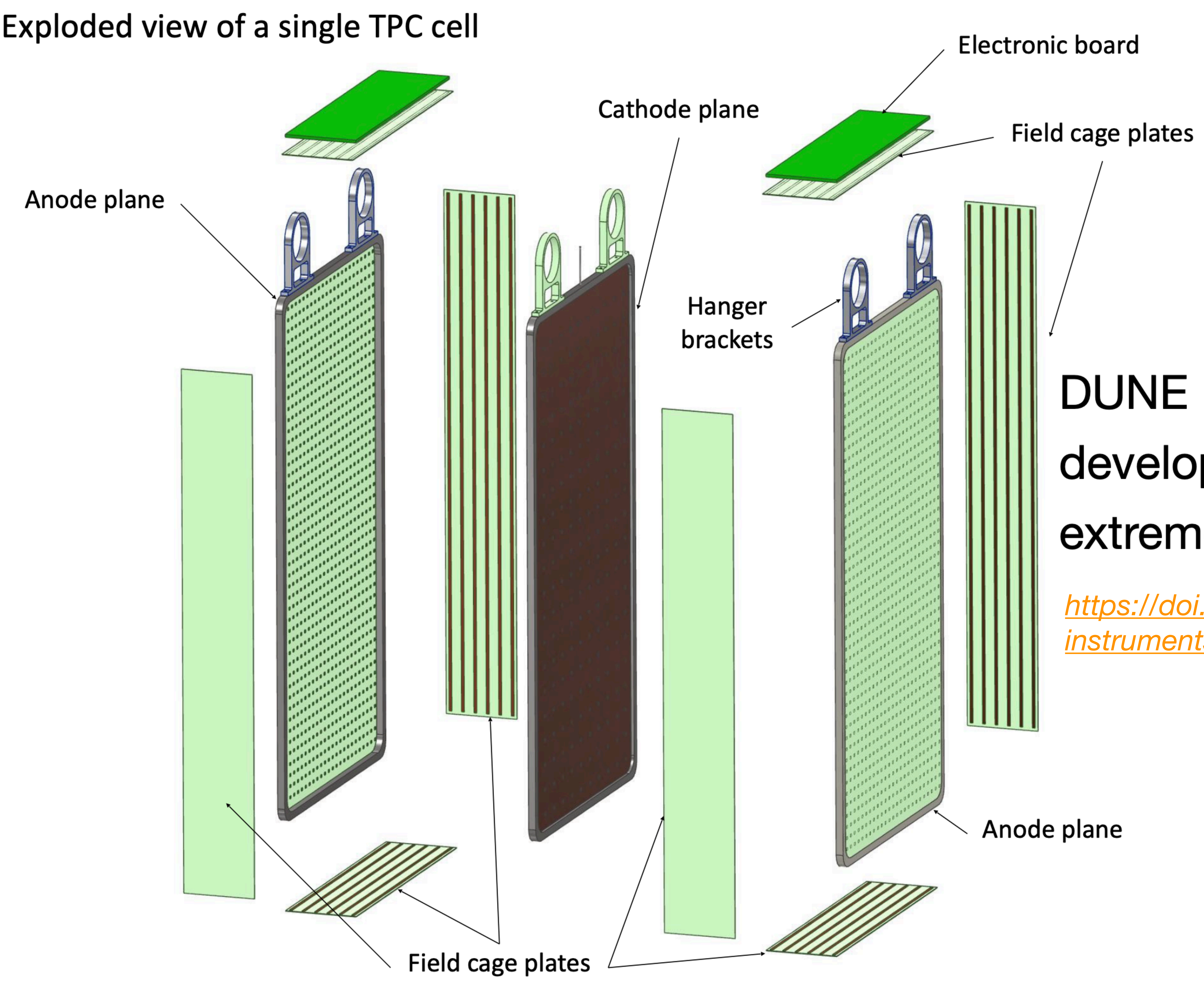
PhysRevD.103.075023, PhysRevD.104.035036

Reference Design of TPC

https://www.osti.gov/biblio/1972463



- Reference design is a 3 x 7 modularized TPC. Each module is 0.6 x 1.8 x 1 m^3
  - segmentation for light collection (trigger)
  - reducing space charge effect from muon background with small drift distance (30 cm)
- Simulations show reasonable containment of neutrino interactions in LAr for energy measurement
- Pixel-based anode → high number of readout channels
- Magnetized hadron calorimeter in the back: based on Baby-MIND concept



Gap: 30 cm

Voltage: 15k

Total #channels ~160k/module

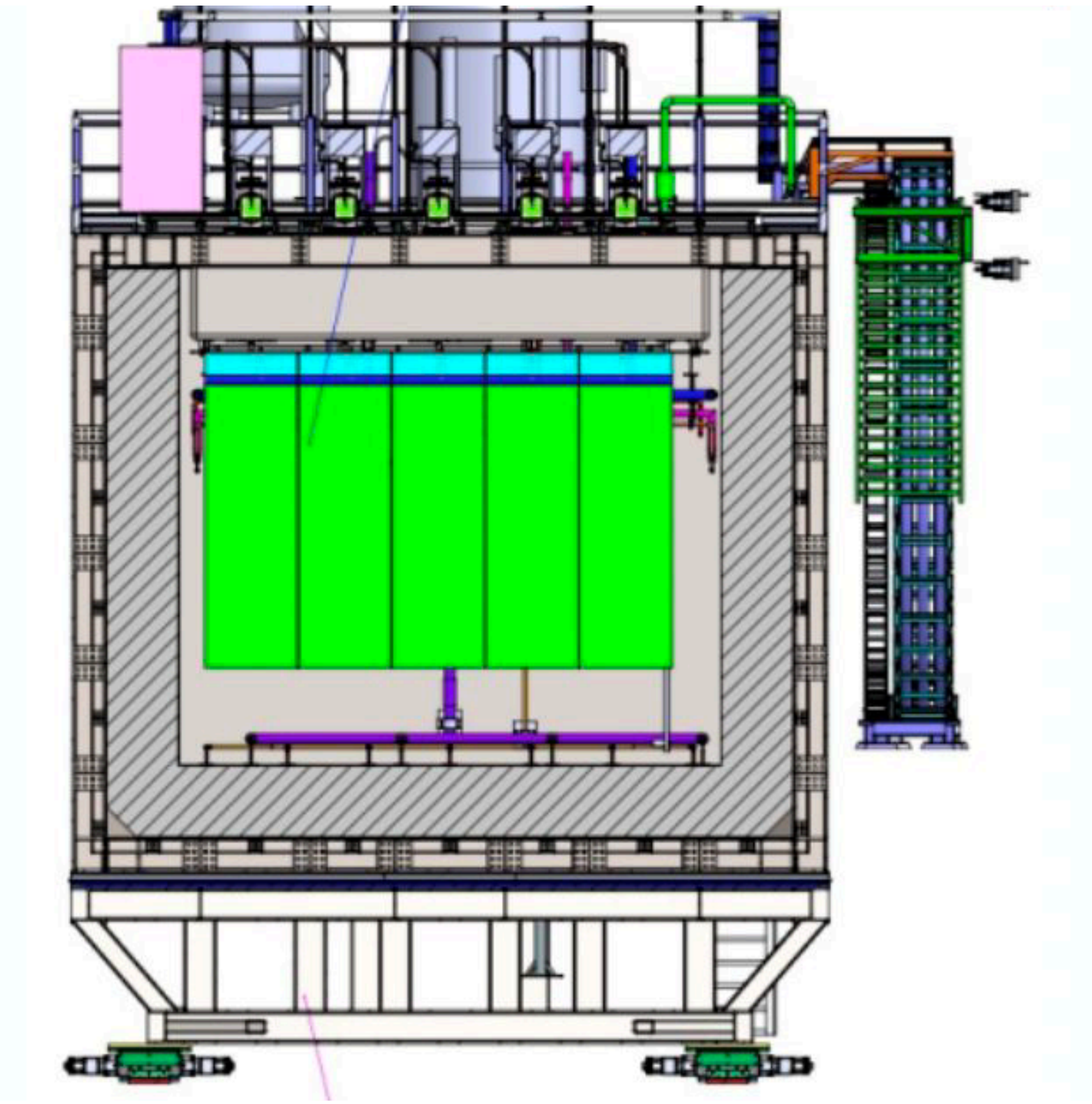
21 modules

SiPM channels TBD

DUNE ND development is extremely helpful.

https://doi.org/10.3390/instruments5040031

Cryostat Options for FLArE

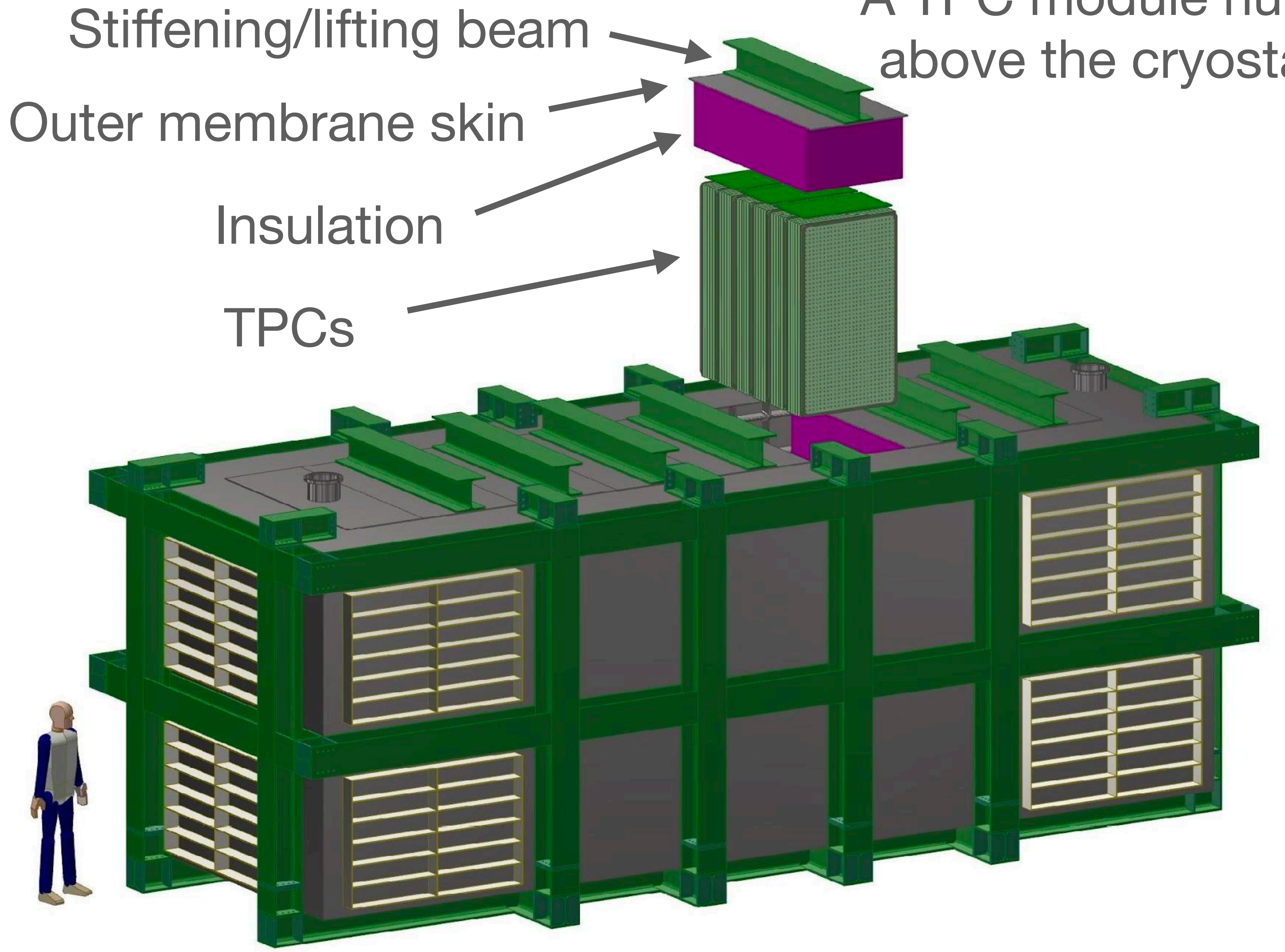


- Reference design is GTT membrane cryostat (used in ProtoDUNE, DUNE ND-LAr)
- 80 cm GTT membrane occupies 1.6 m out of 3.5 m available space
  - About 1.9 m x 1.9 m cross section allowed for detector
- Other options: single-wall? Vacuum-insulated?
- **BNL contracted an engineering firm (Bartoszek Engineering) working toward a conceptual design of the cryostat and installation plan**

TPC Installation Options for FLArE

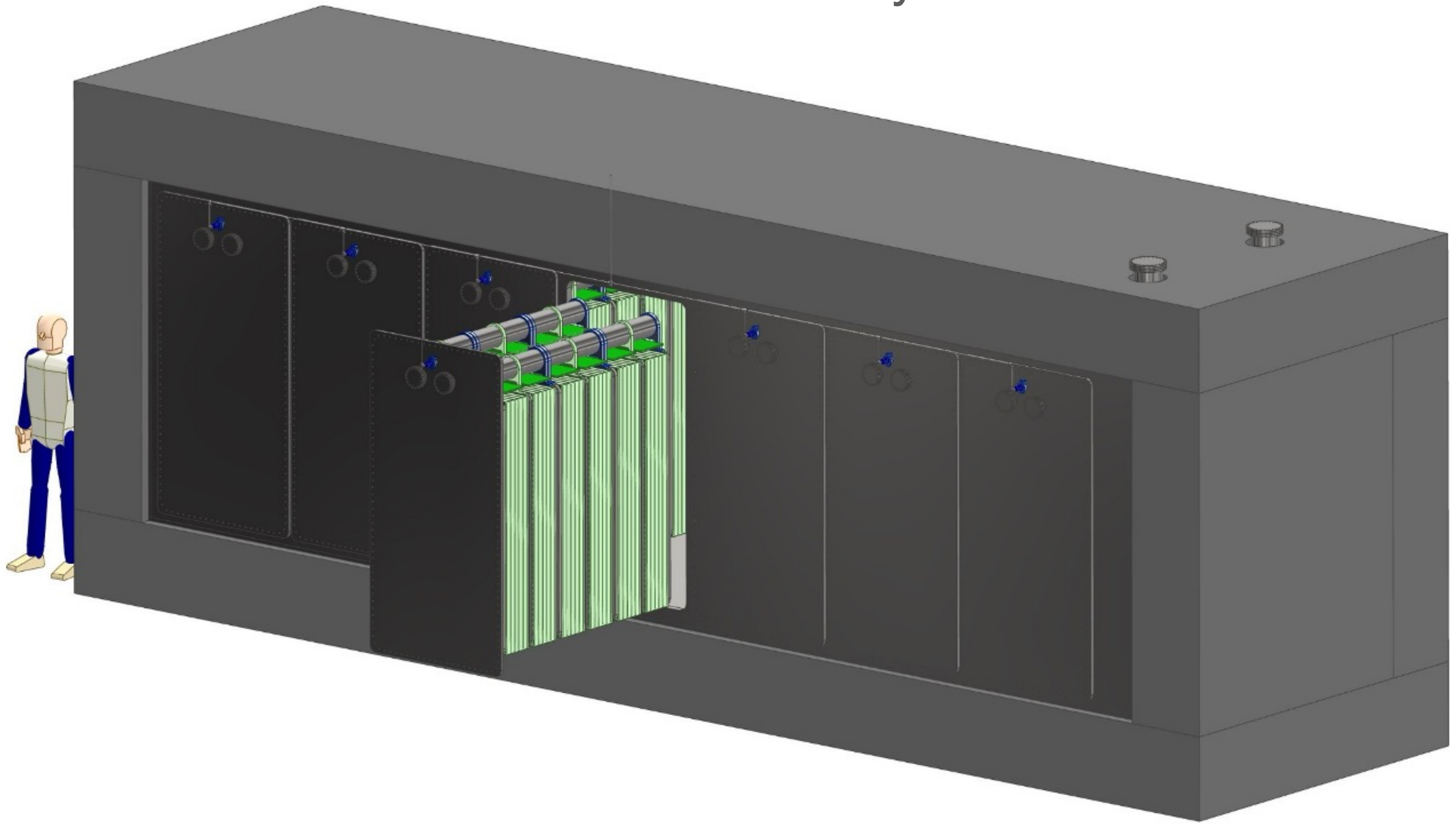
Installation from top
* similar to DUNE ND-LAr and SBND design

Horizontal insertion of TPC modules
* reduced requirement on the vertical space
* more work needs go into insulation and sealing

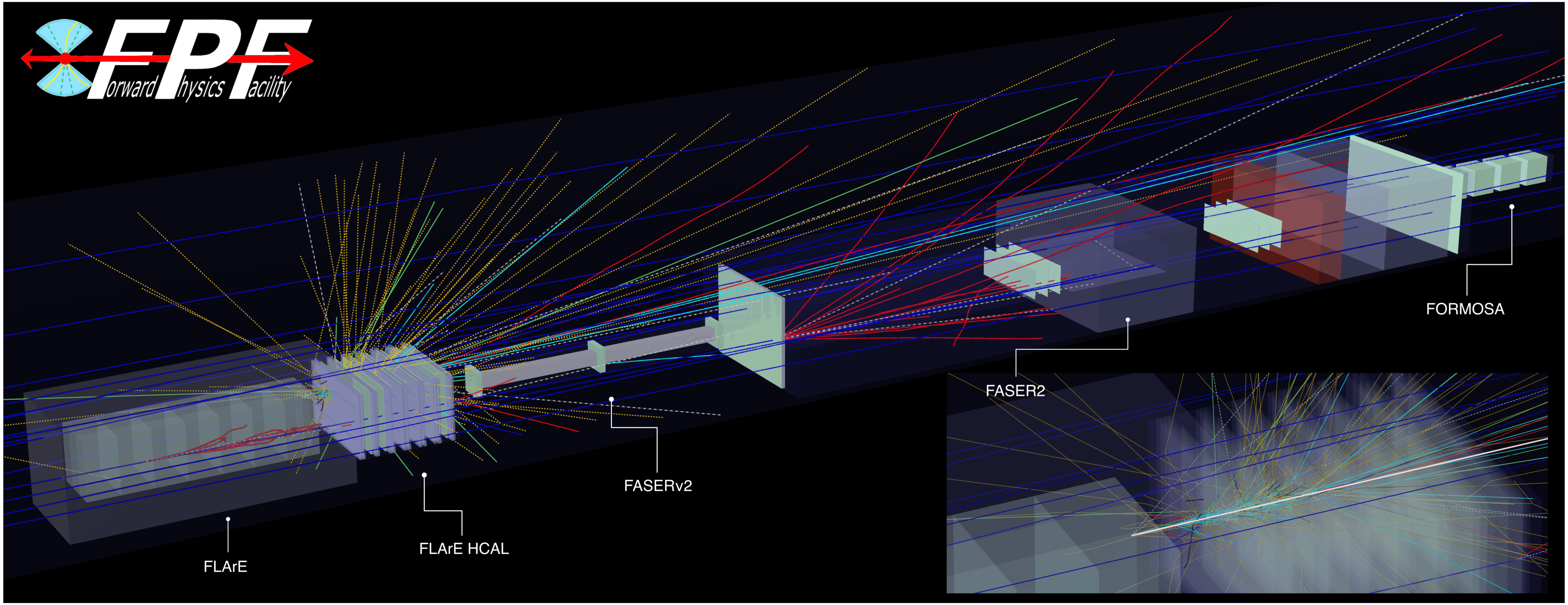


A TPC module hung above the cryostat

A TPC module withdrawn horizontally from the cryostat



Simulation Framework



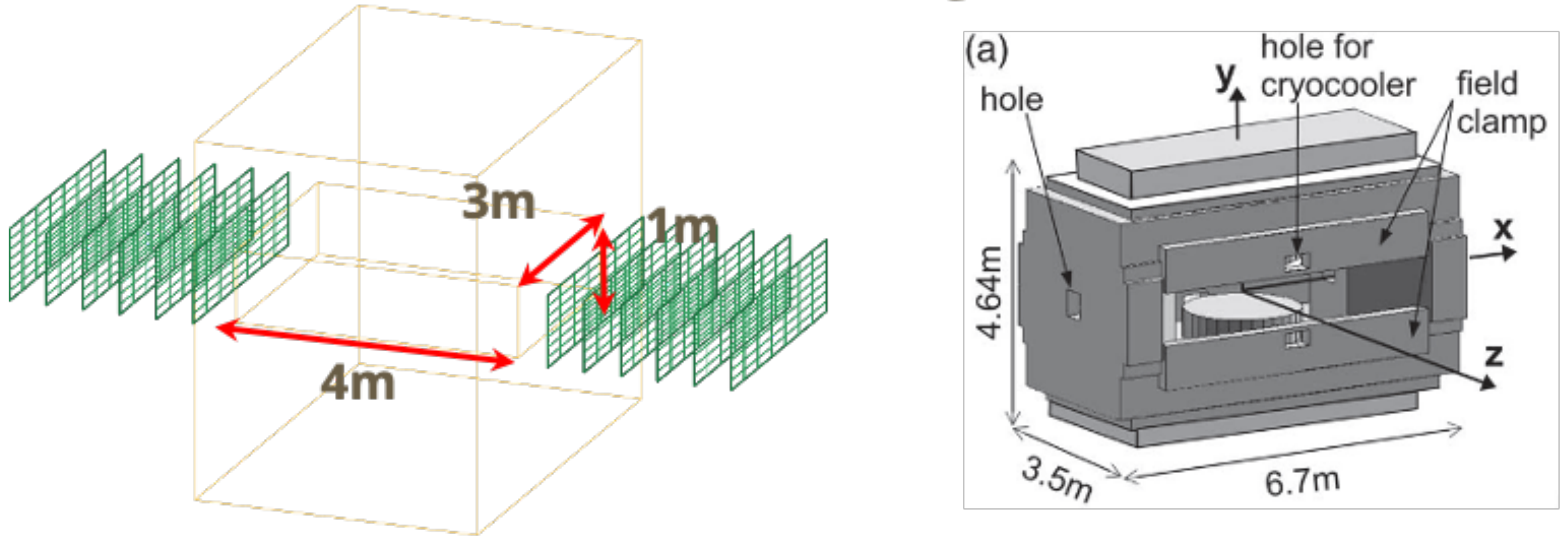
Different detector arrangements in the hall can be easily plugged into the simulation framework

FPFSim Github: https://github.com/FPFSoftware/FPFSim

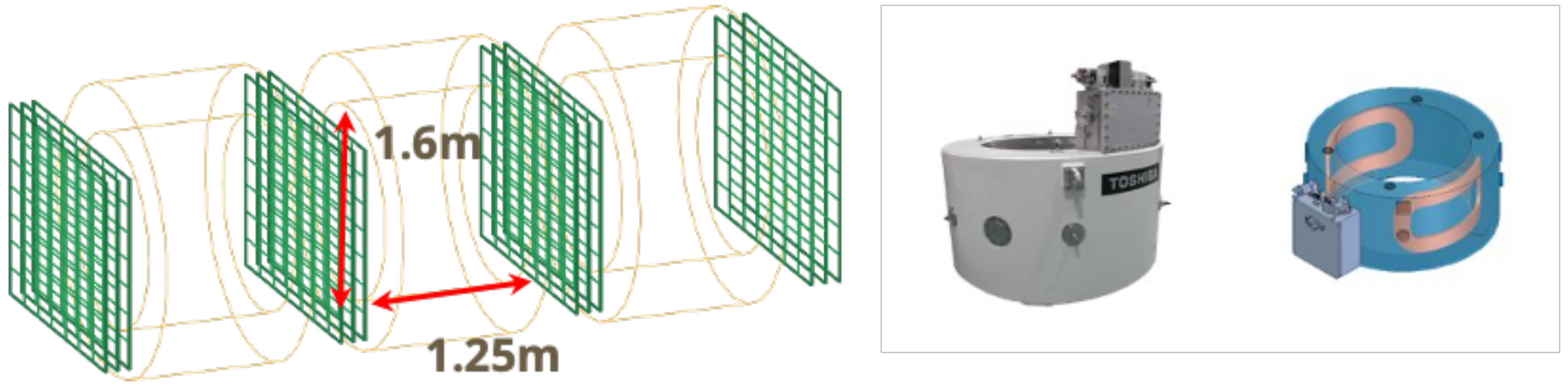
Muon Acceptance

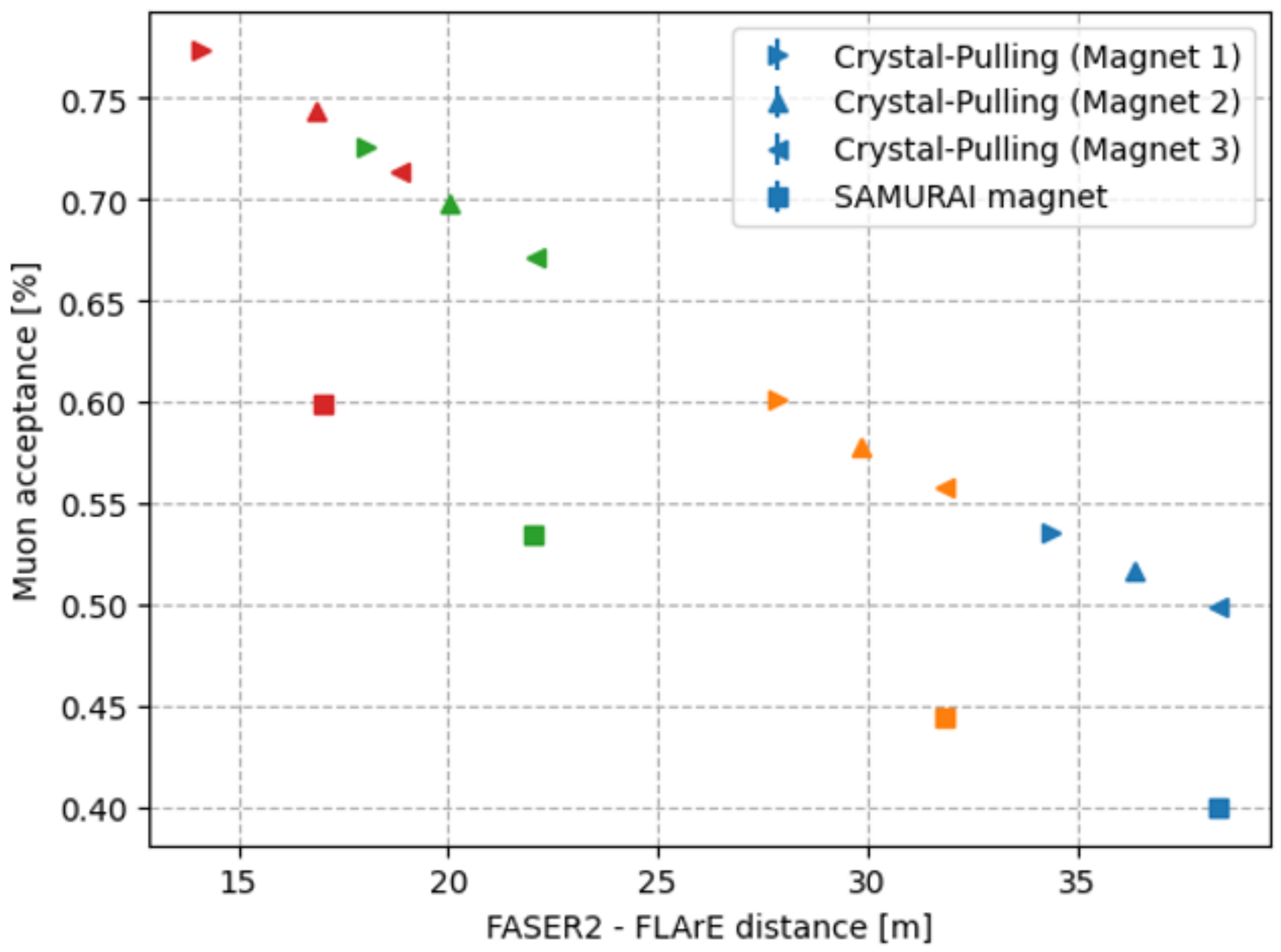
- Acceptance study for the muons produced by ν_μ CC events in FLArE
- Propose to coordinate with FASER2 magnet, along with magnetized calorimeter @ FLArE
- Acceptance is mainly driven by the FLArE-FASER2 distance, which depends on the detector arrangements in the FPF
  - Better performance if detectors are closer

SAMURAI-like magnet



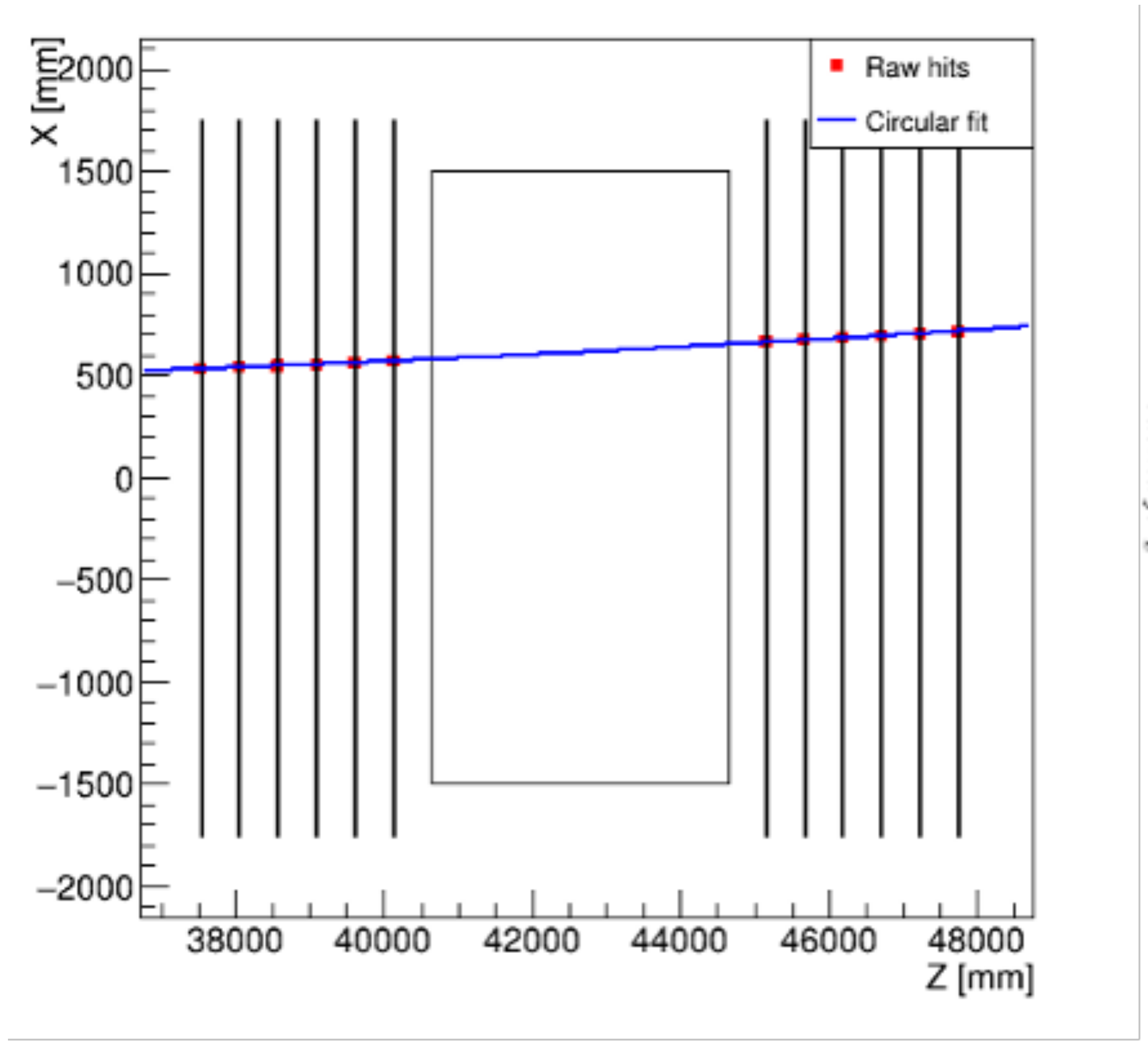
TOSHIBA Crystal-pulling magnets

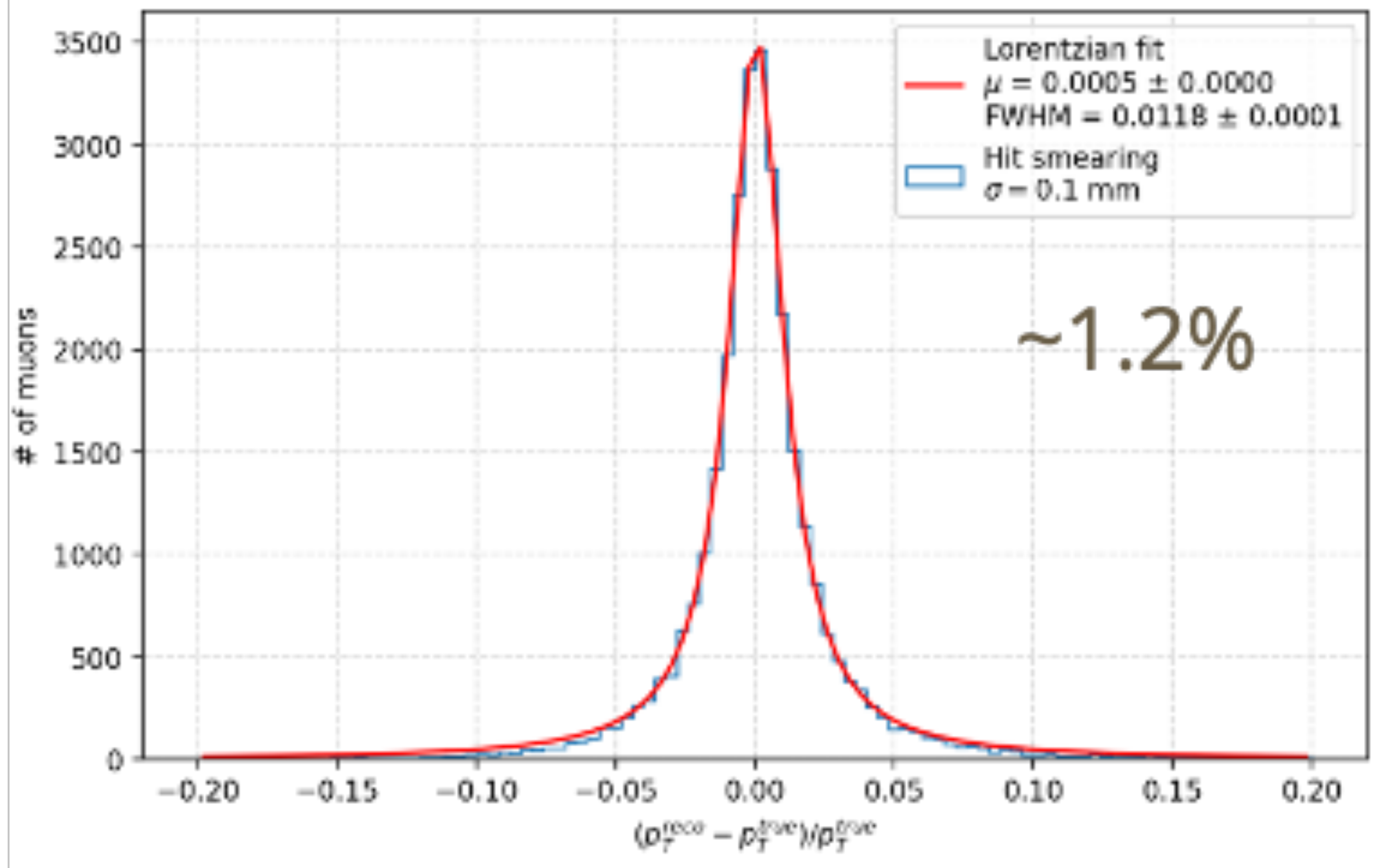


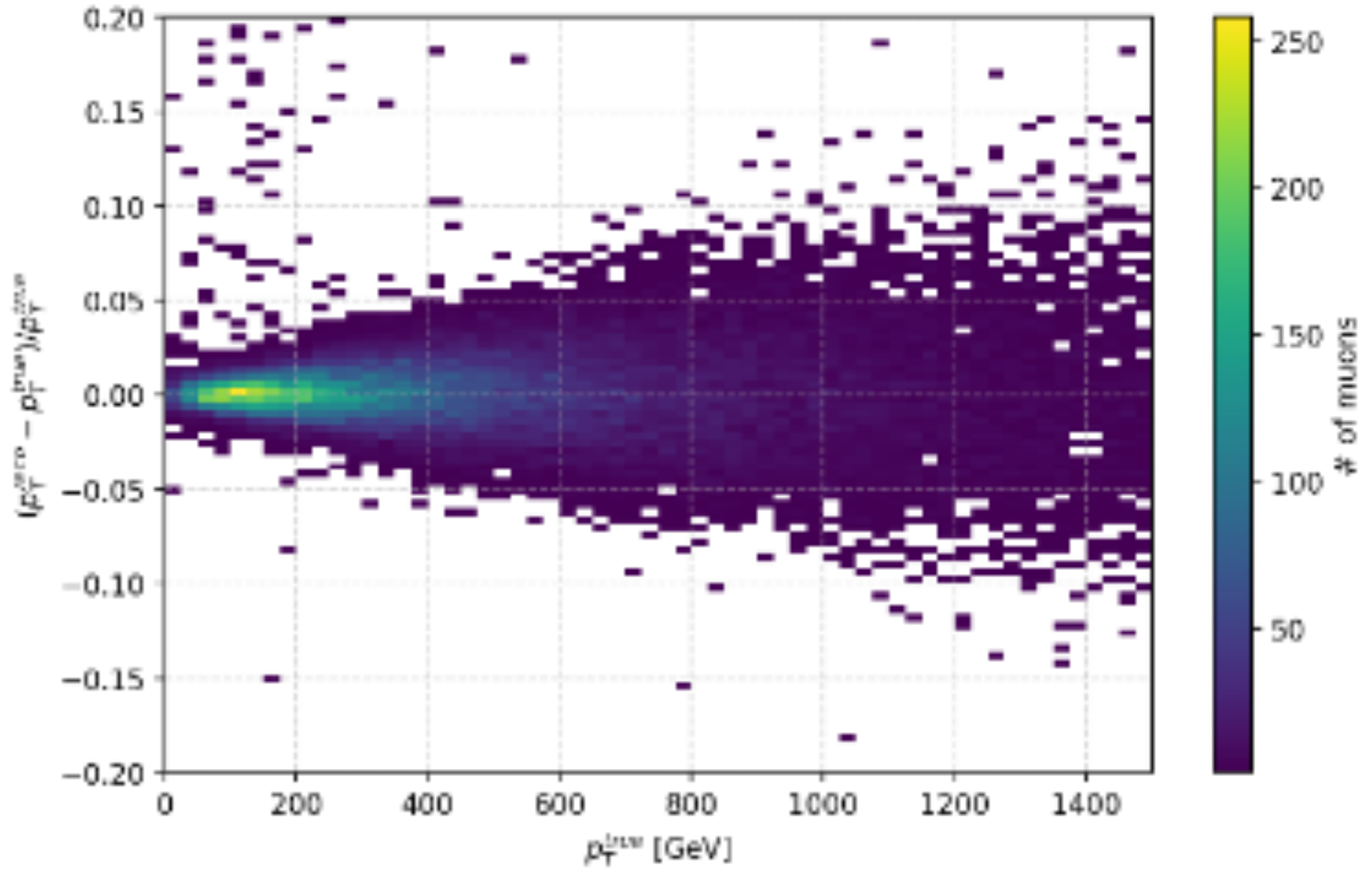


Muon Momentum Reconstruction

- Coordinate with FASER2 detector
  - Linear fits to the tracking stations, analytical computation of the circumference tangent to both lines
- Added gaussian smearing of simulated hits on the tracking stations
  - 0.1 mm smearing → 1.2% resolution for the SAMURAI magnet
  - Good linearity over the whole momentum range



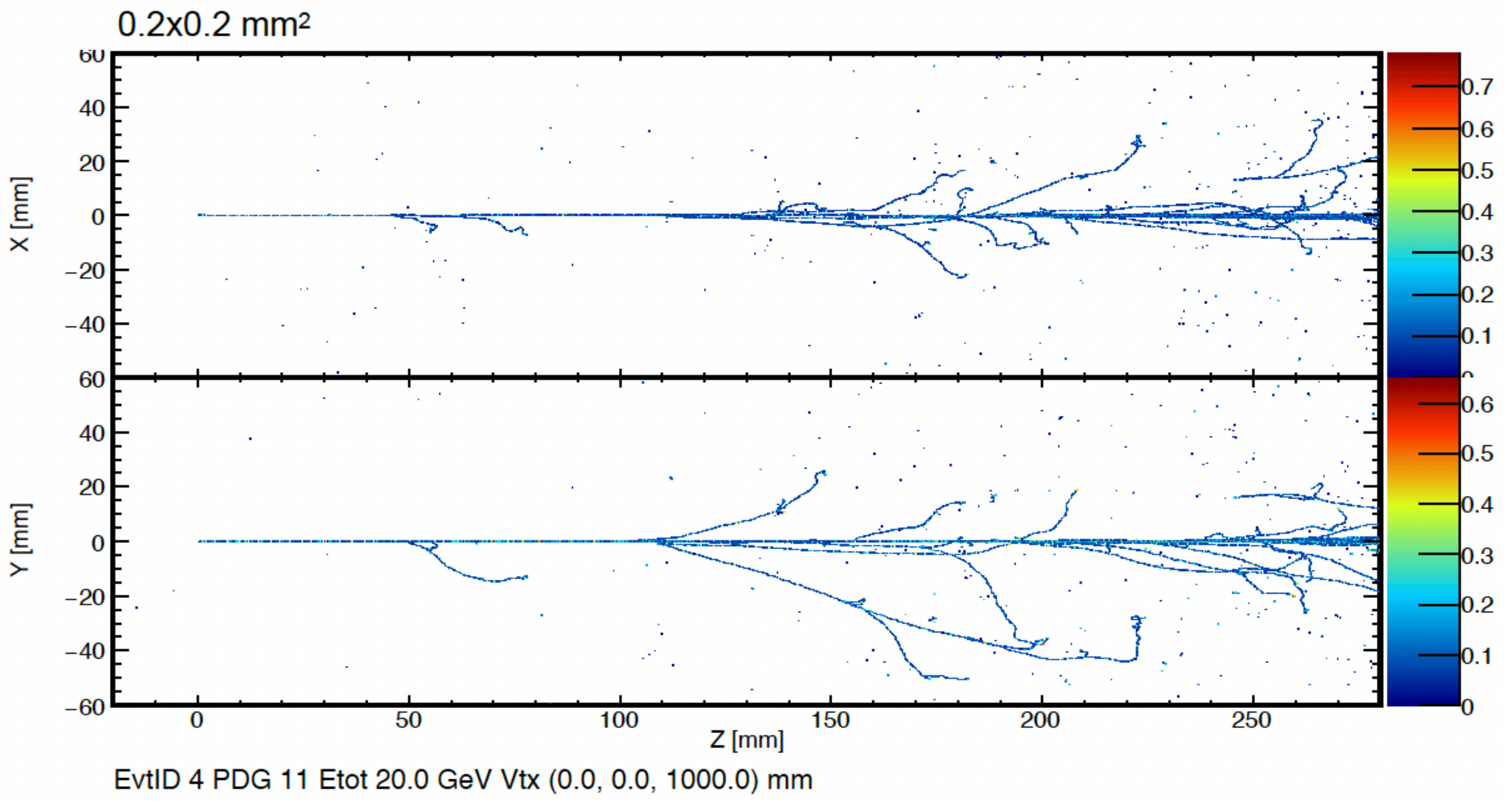




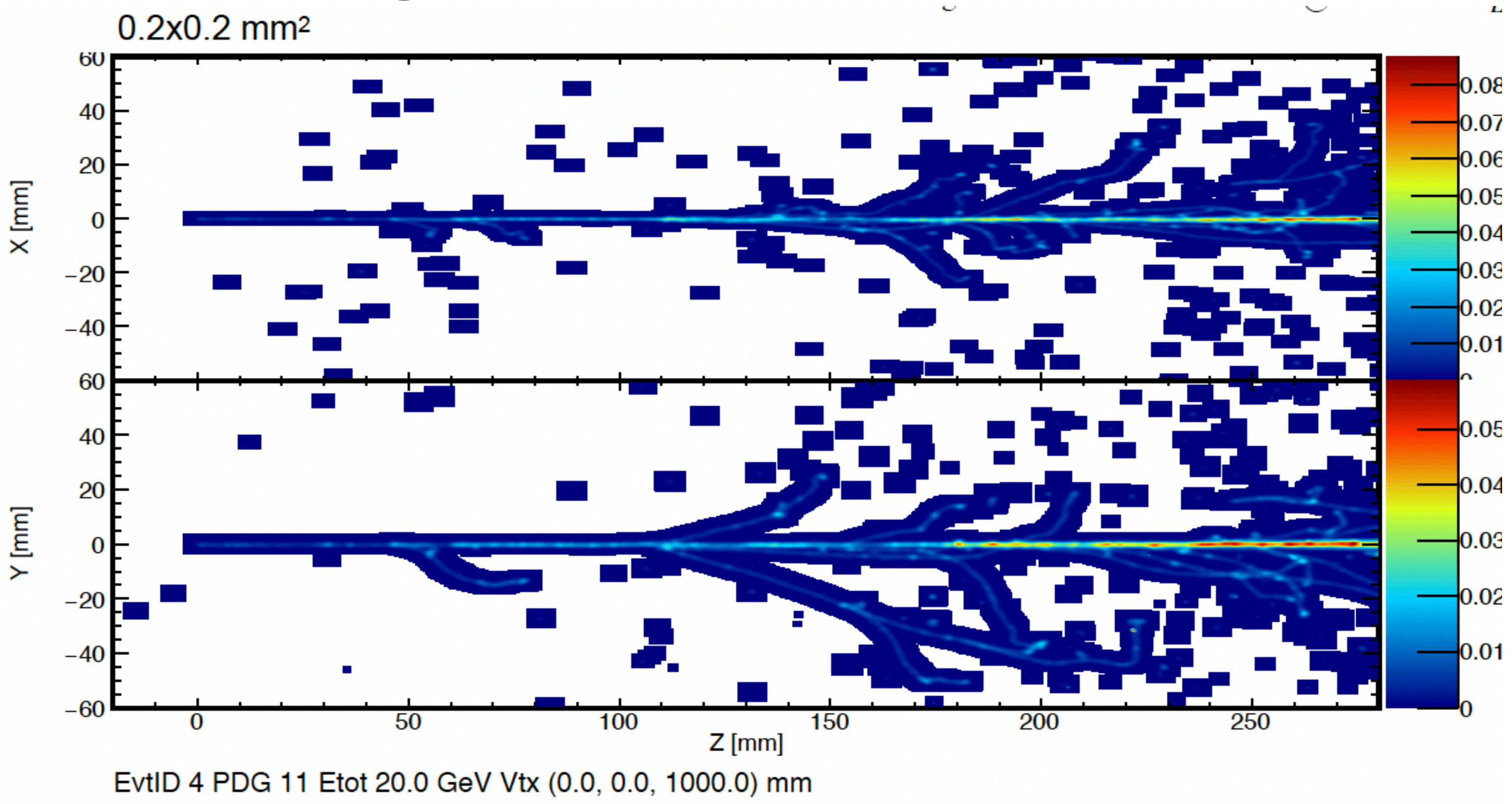
Particle Identification

- The distribution of collected electrons depends on the diffusion effect and the pixel size
- Toy electron propagation in the simulation to add diffusion effect

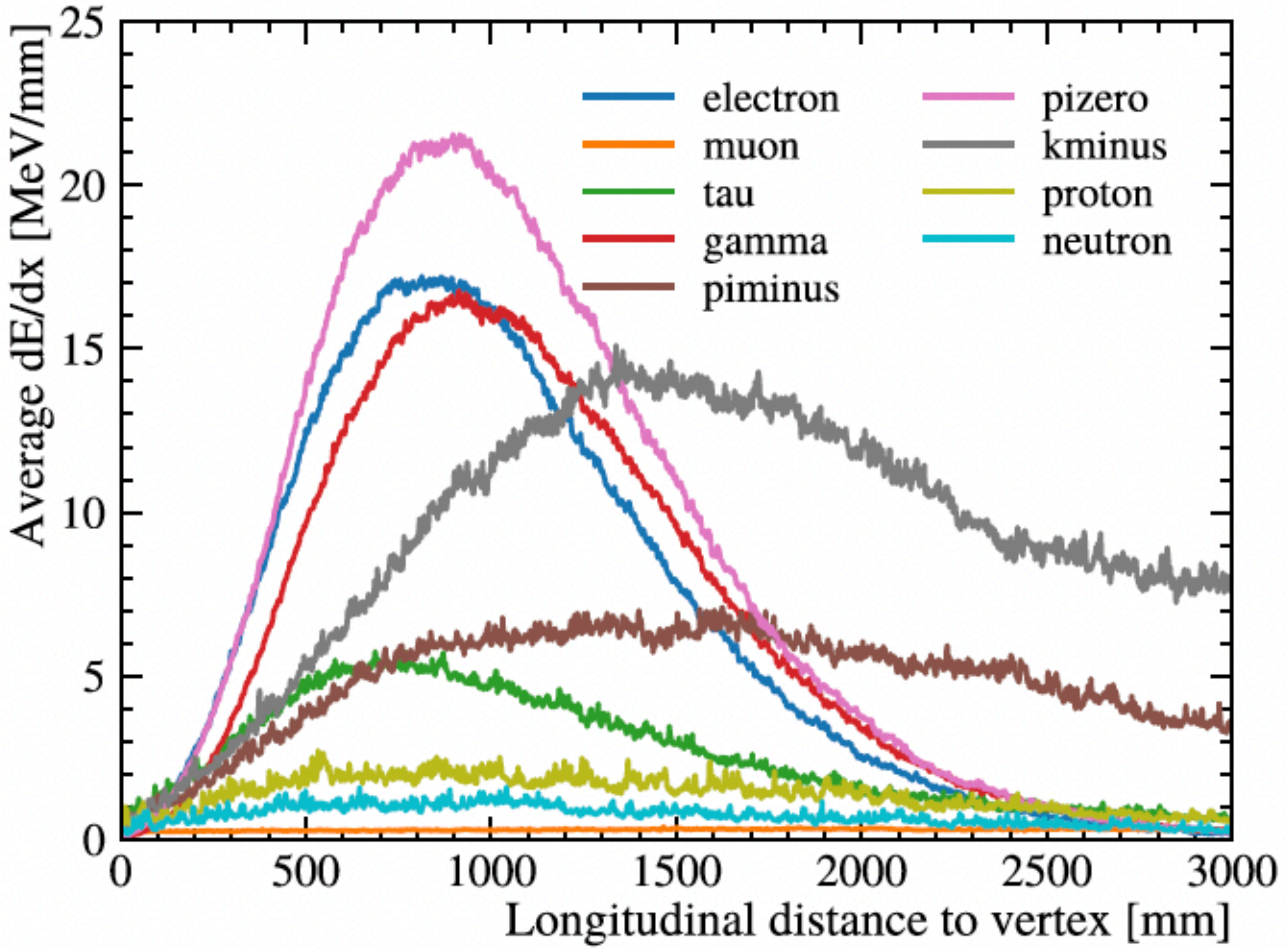
Single electron

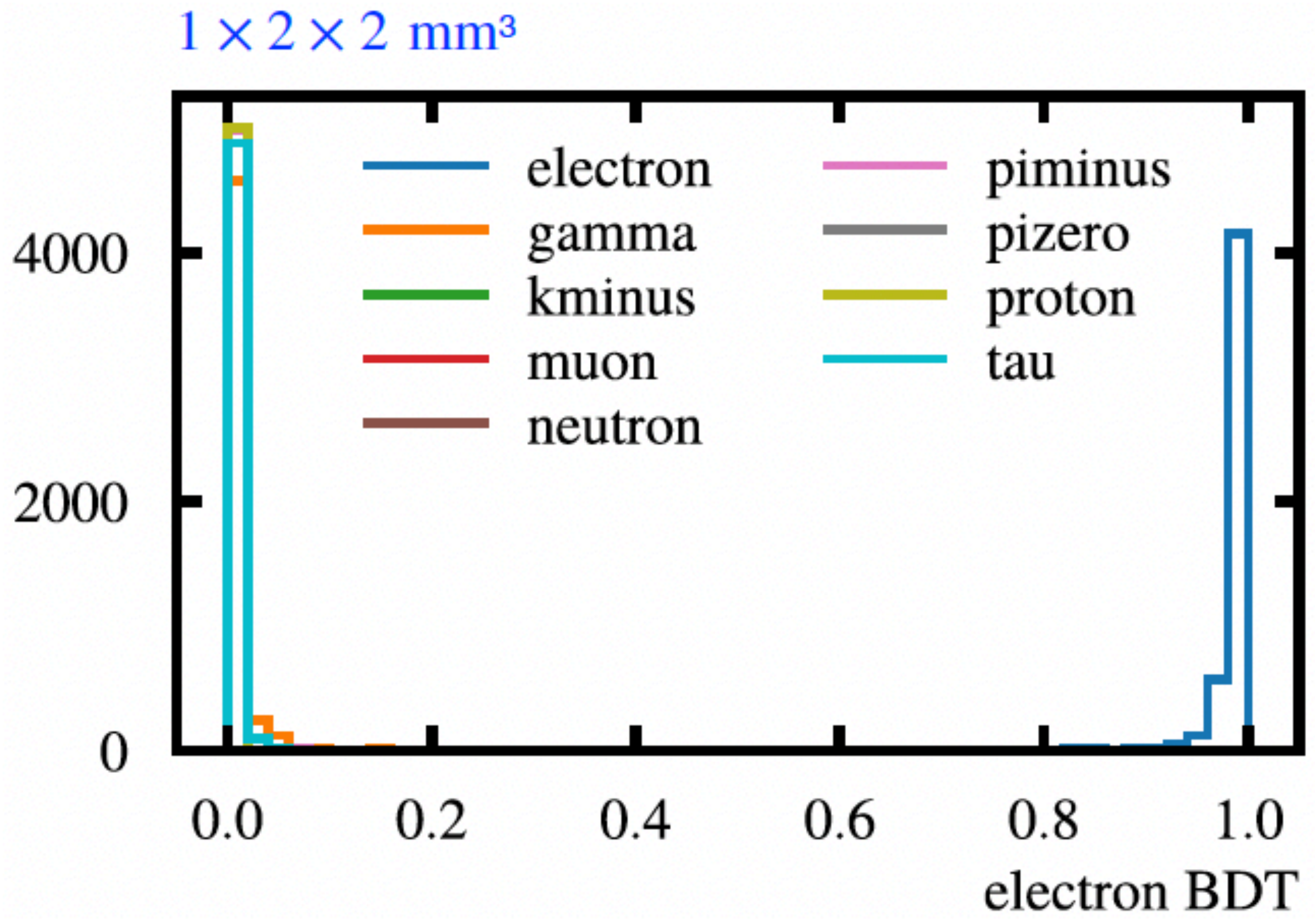


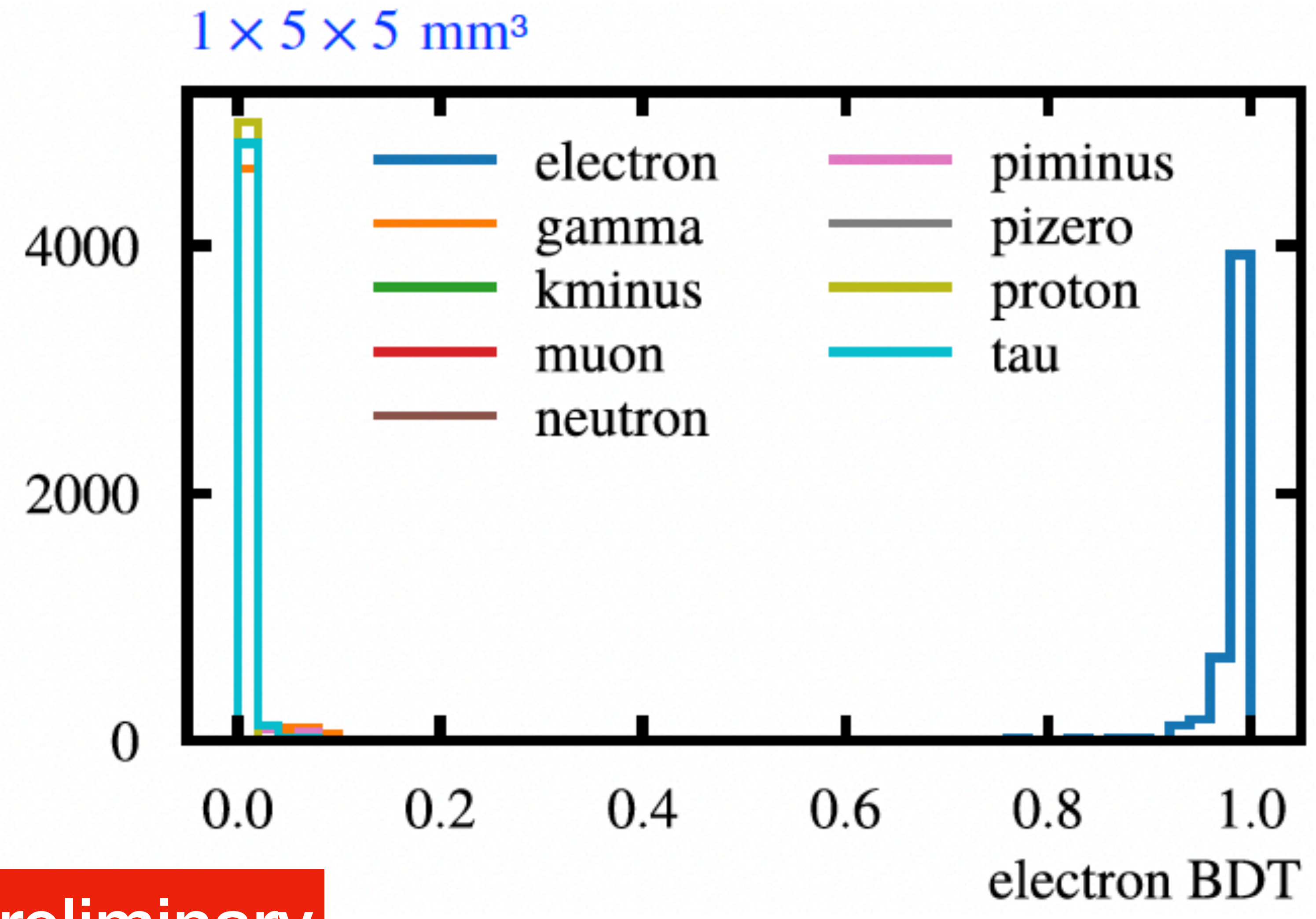
Single electron w/ diffusion



- Use the dE/dx distribution along the track for different type of particles w/ different assumptions of the pixel size
- Construct a log-likehood based on the dE/dx distribution and train a BDT for PID





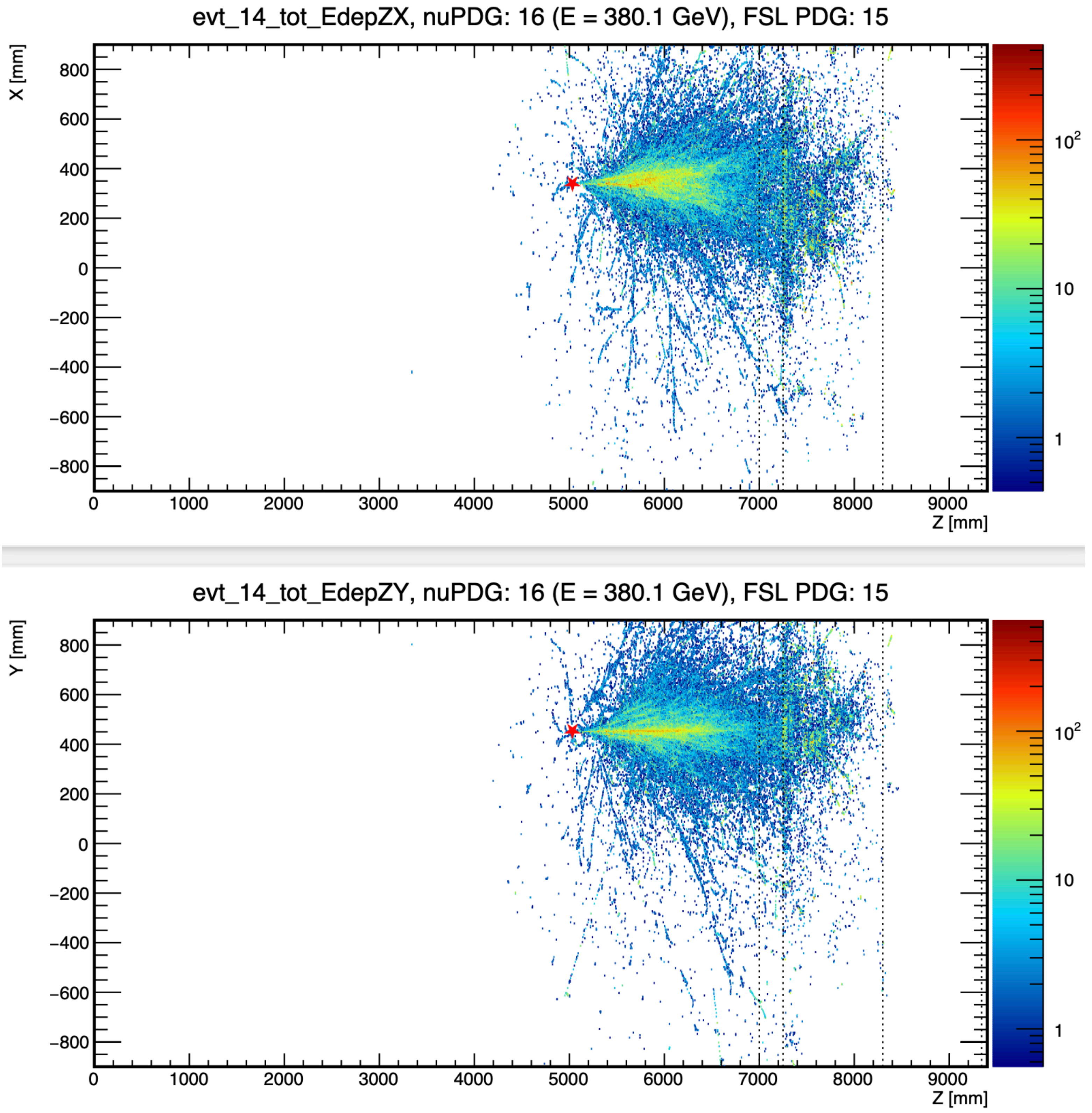


Preliminary

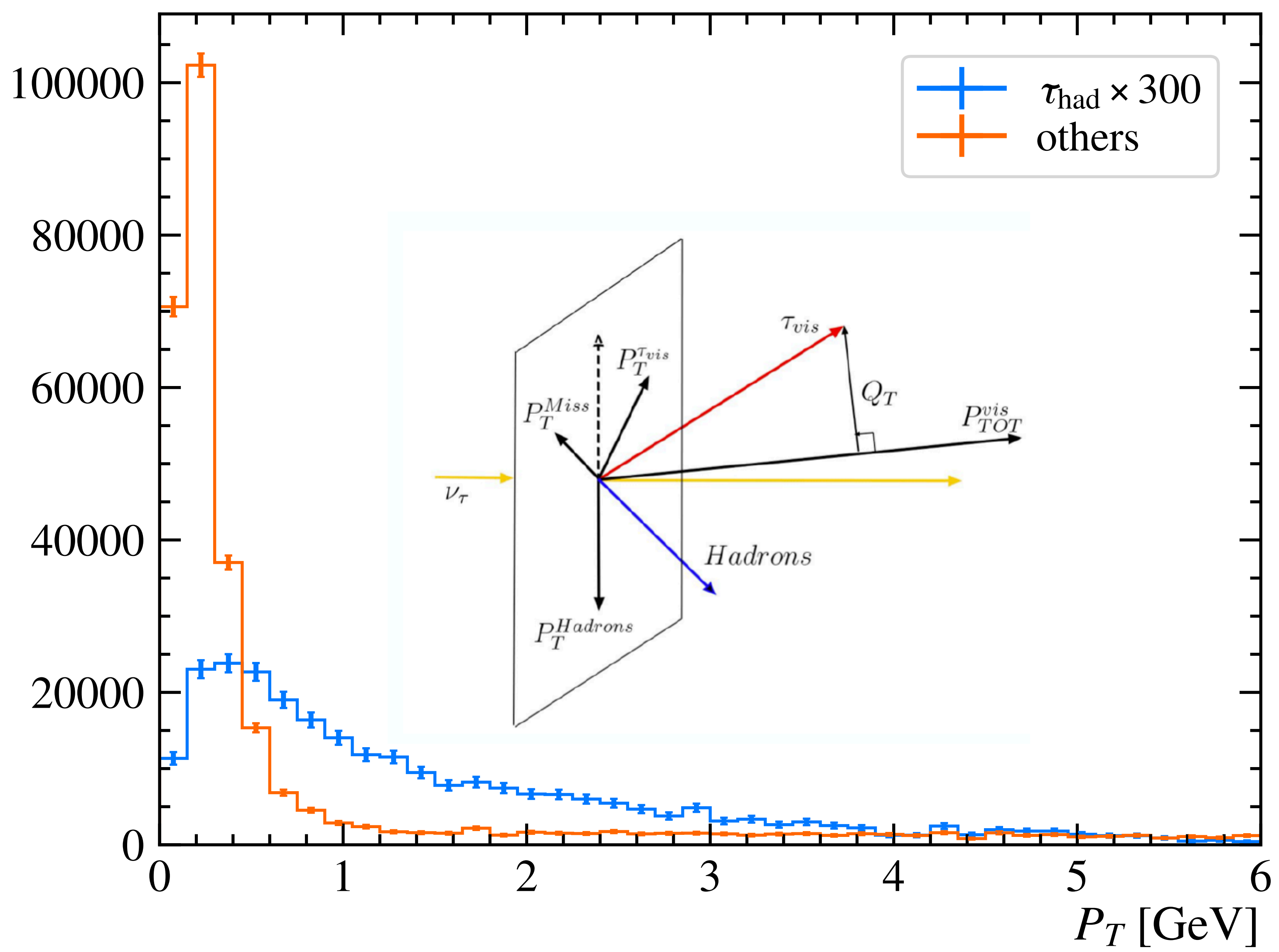
ν_τ Identification

Consider τ_{had} (hadronic decay of CC tau) as the signal

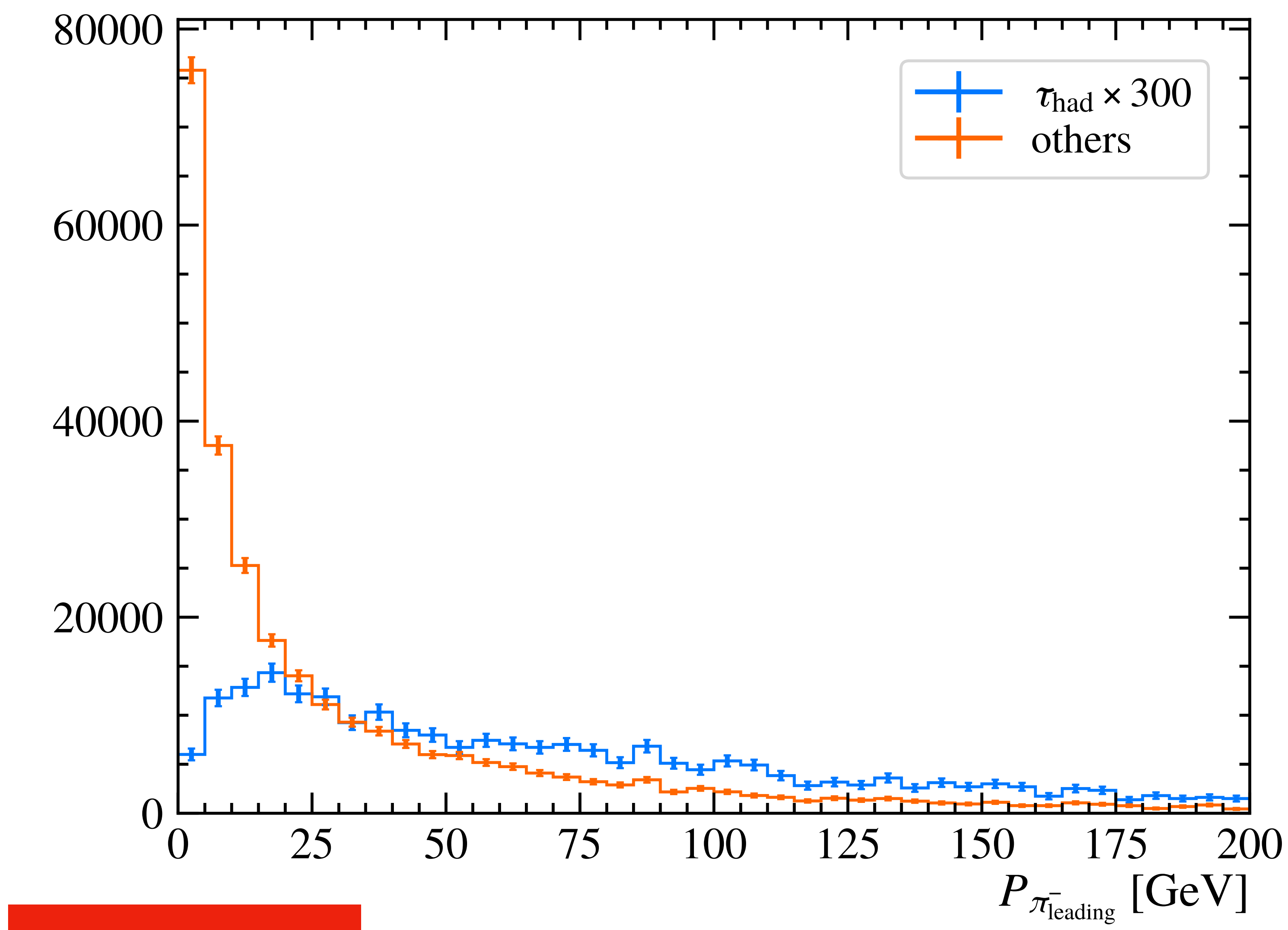
ν_τ CC, $\tau^- \rightarrow \pi^- \nu_\tau$



τ_{had} have more neutrino in the final state contributing to the missing momentum in the transverse plane



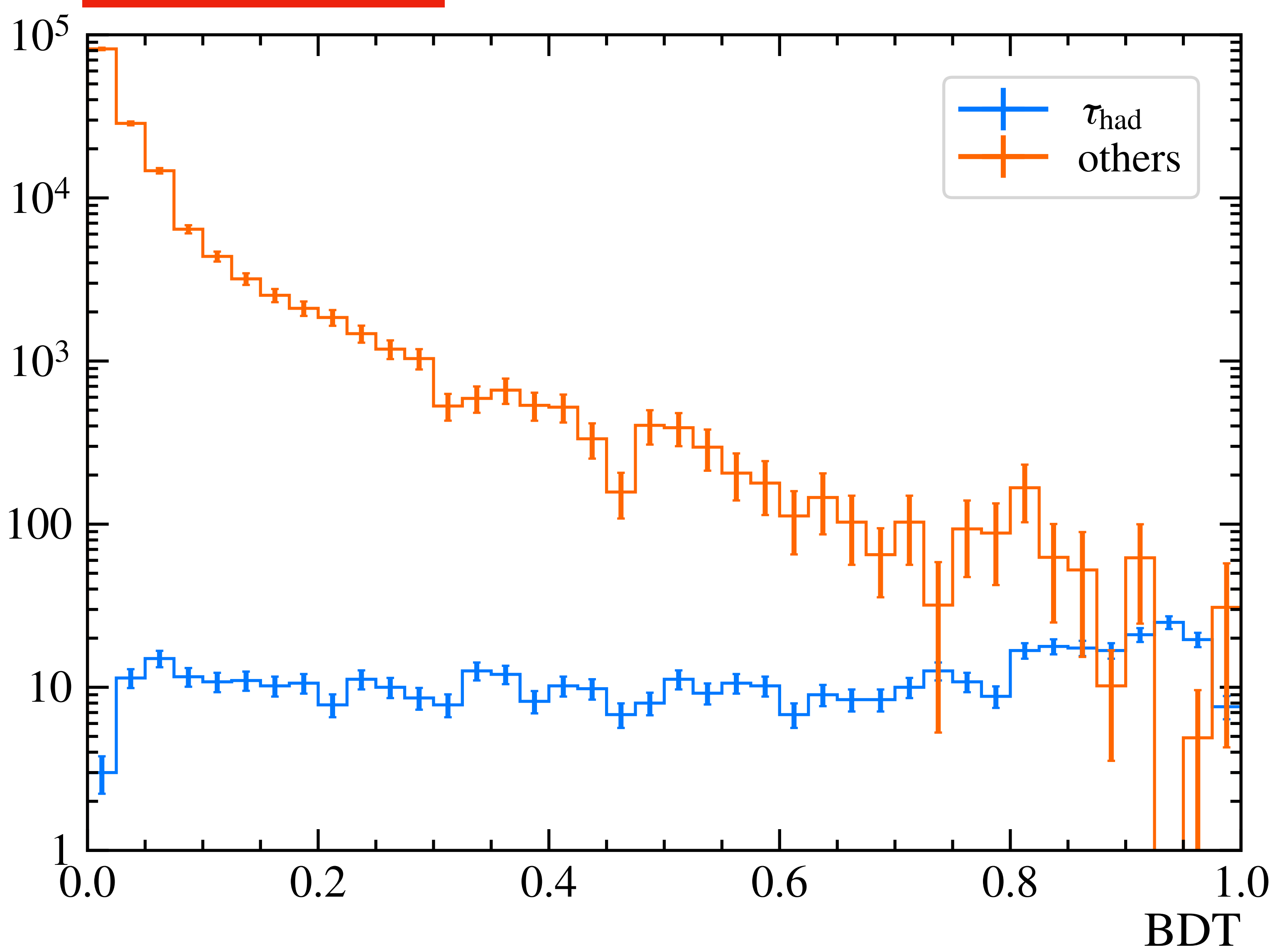
τ_{had} generally has a more energetic π^- in the final state



A BDT shows promising results to select ν_τ CC events from other backgrounds

Also working on other τ decay modes

Preliminary



Summary

- A forward physics facility (FPF) is being considered at CERN for neutrino and dark matter physics
- Liquid Argon detector FLArE for FPF is being planned
  - Neutrinos in the 1 TeV range: ~20-50 events/ton/day
  - Tau neutrino flux and associated heavy flavor physics: ~0.1-0.2 events/ton/day
  - Light dark matter search with decays and interactions
- Detector capability, event rate, and backgrounds of FLArE are preliminary studied, showing that a LAr detector is feasible
- Engineering and simulation work towards a CDR is underway

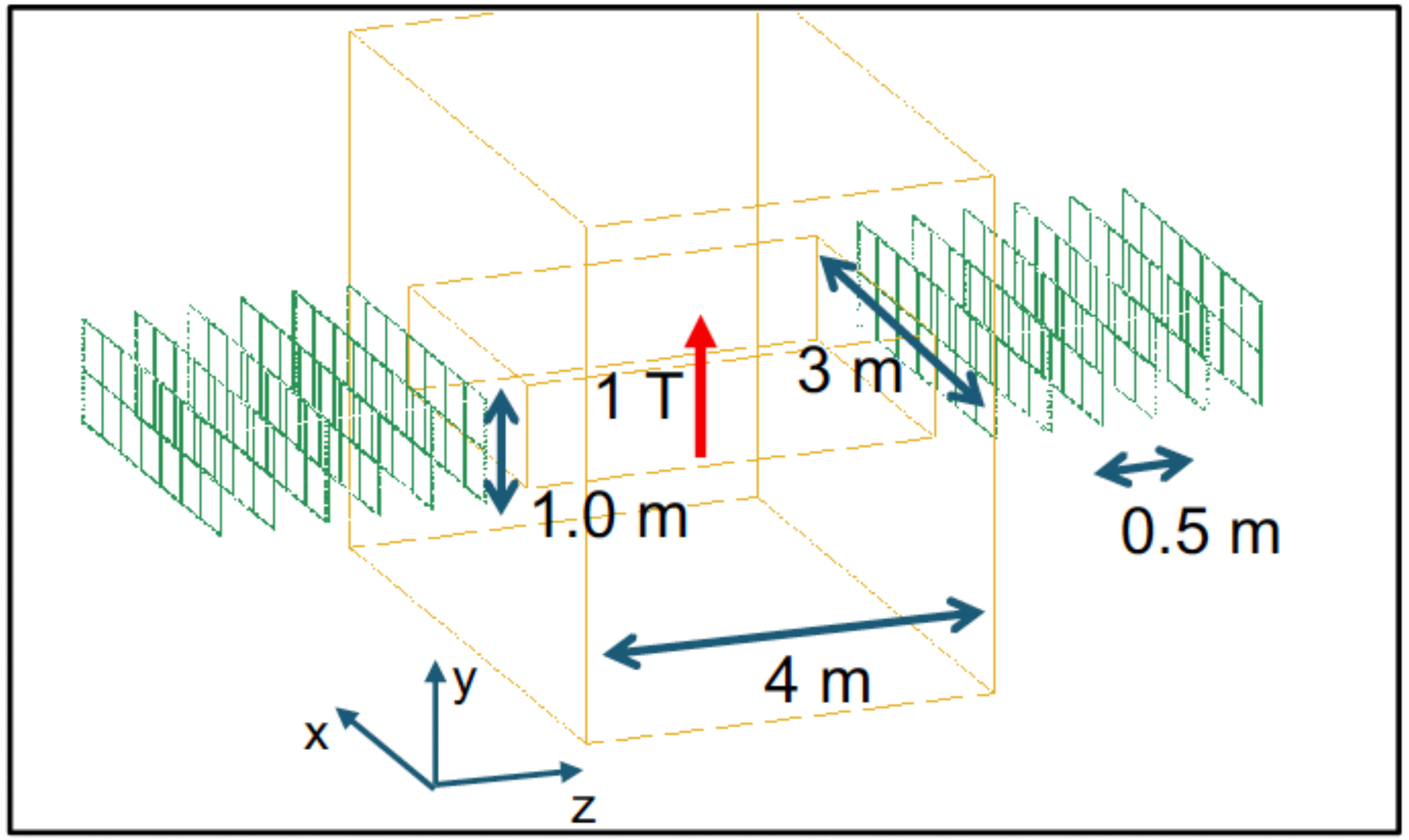
Simulation and performance studies: CERN-PBC-Notes-2025-006
Technical design and optimization of the detector: CERN-PBC-Notes-2025-007

Thank you!

Backup Materials

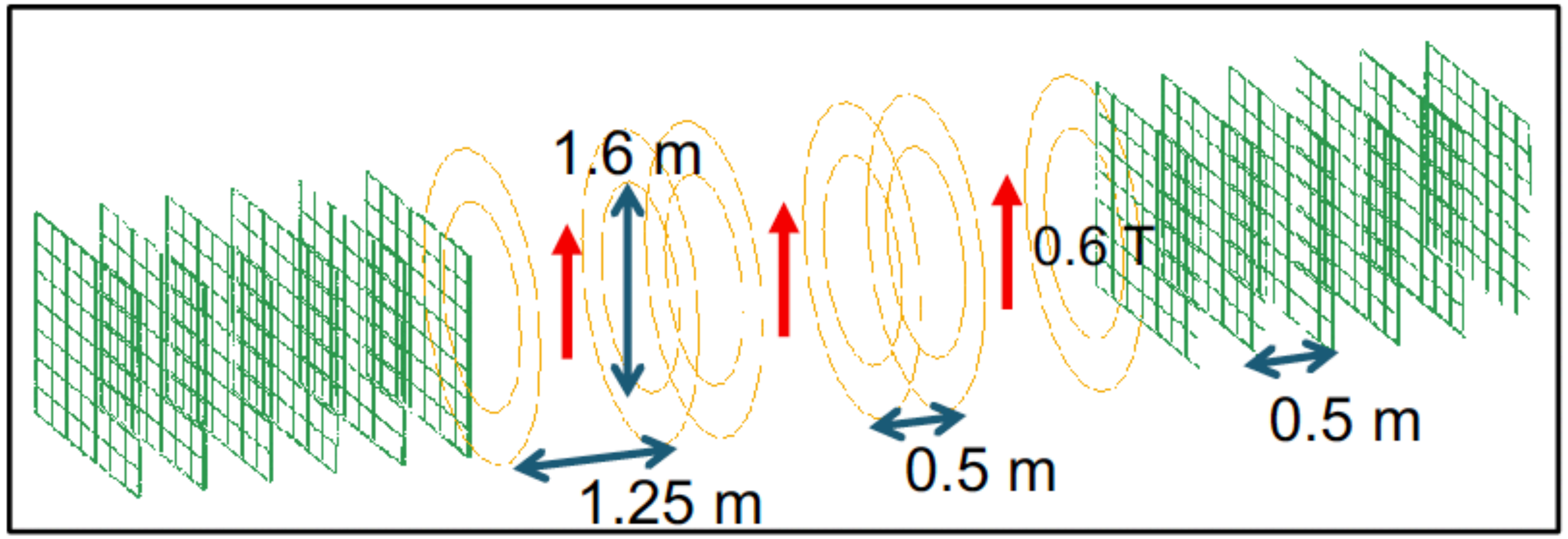
Magnet geometries

SAMURAI magnet



Rectangular window: 3 m x 1.0 m (4 Tm)
6 tracking stations, 50 cm apart
B = 1 T (vertical)

Crystal-Pulling magnet

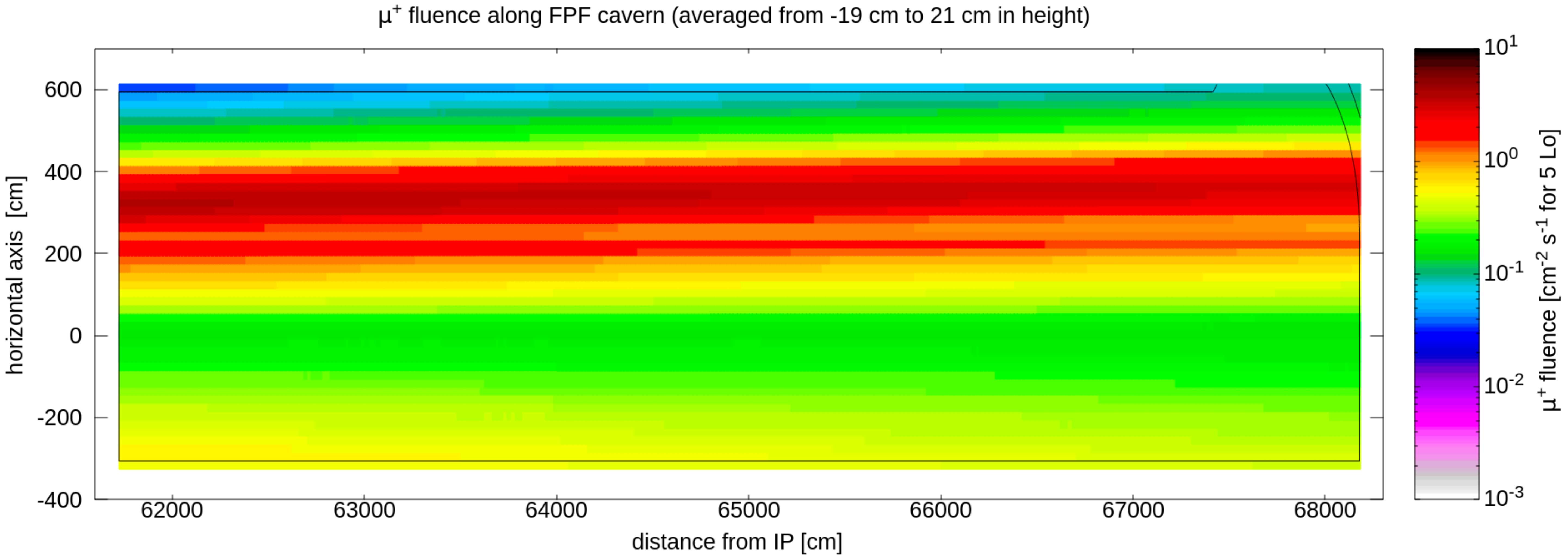


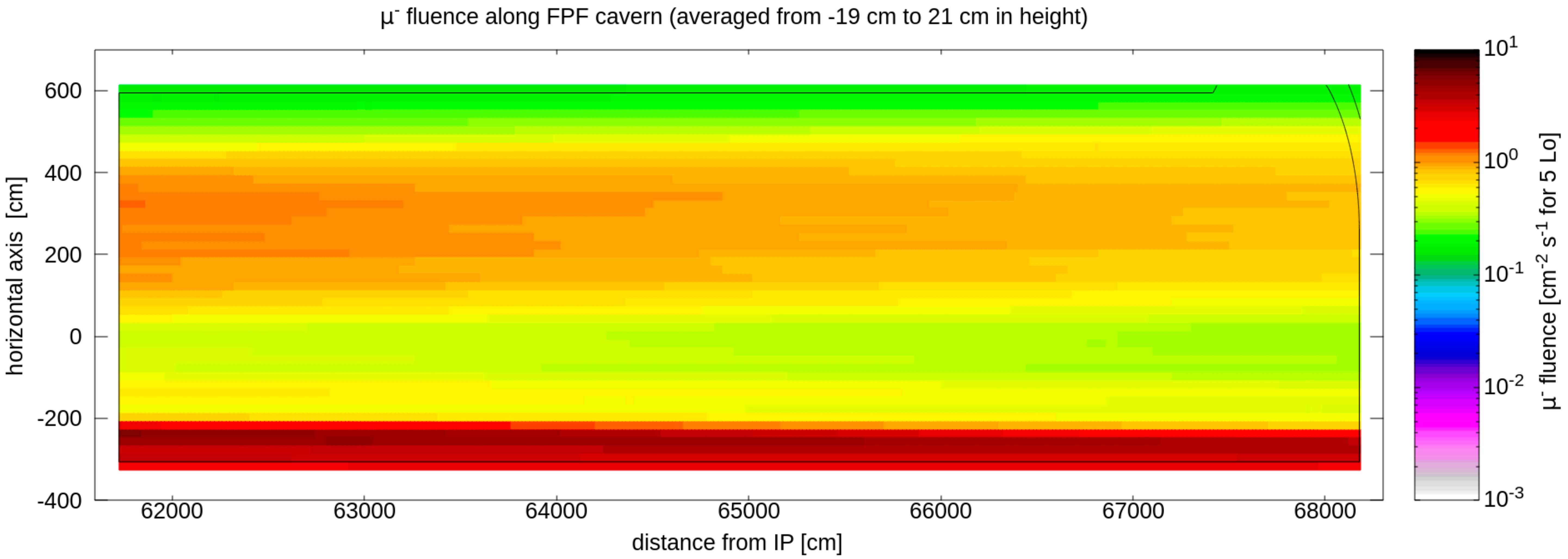
3 magnets, 50cm apart
Circular window: 1.6 m (diameter) x 1.25 m
6 tracking stations, 50 cm apart
B = 0.6 T (vertical)

- Magnets probably too close + it makes more sense to place tracking stations in between!
- Field to be made horizontal (bending in vertical plane)

Muon Background

https://cds.cern.ch/record/2851822/





- Fluence in the horizontal plane in FPF location from CERN FLUKA team (20 cm from LOS in vertical plane)
  - Clear hot spot at ~2 m from the LOS
- Muon flux
  - ~0.6 Hz/cm^2 (0.15 mu+, 0.45 mu-)
  - ~6 tracks/ms per m^2 of detector
- Neutron flux ~0.1 Hz/cm^2 is mostly at low energies