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

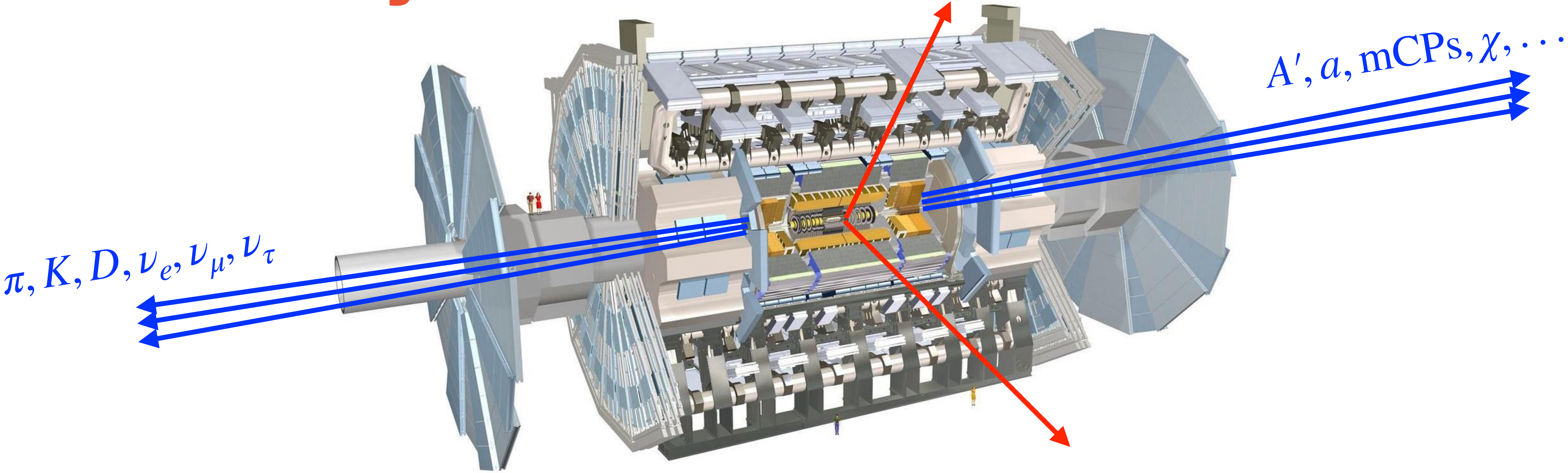
Wenjie Wu

University of California, Irvine

LLP2024 @ University of Tokyo
July 2, 2024

UCI
CERN
HEISING-SIMONS FOUNDATION
Brookhaven National Laboratory

Forward Physics at LHC

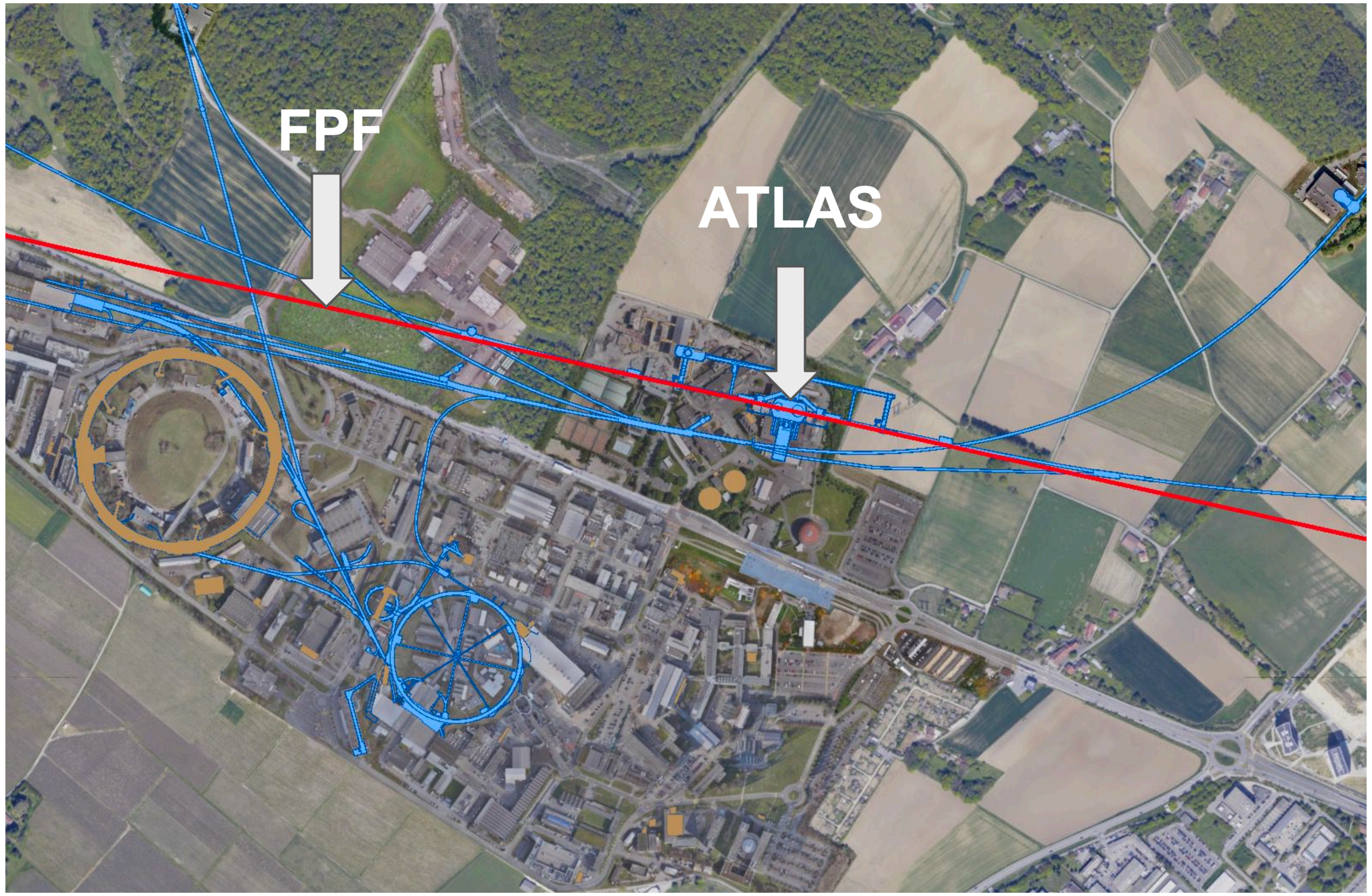


- Existing LHC experiments primarily focused on high-p_T physics, for searches of heavy particles (*W, Z, t, h,* …)
- Most of the inelastic *pp* collisions produce particles travel approximately parallel to the beamline and escape through the blind spots
  - SM: pions, kaons, and other light mesons, 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

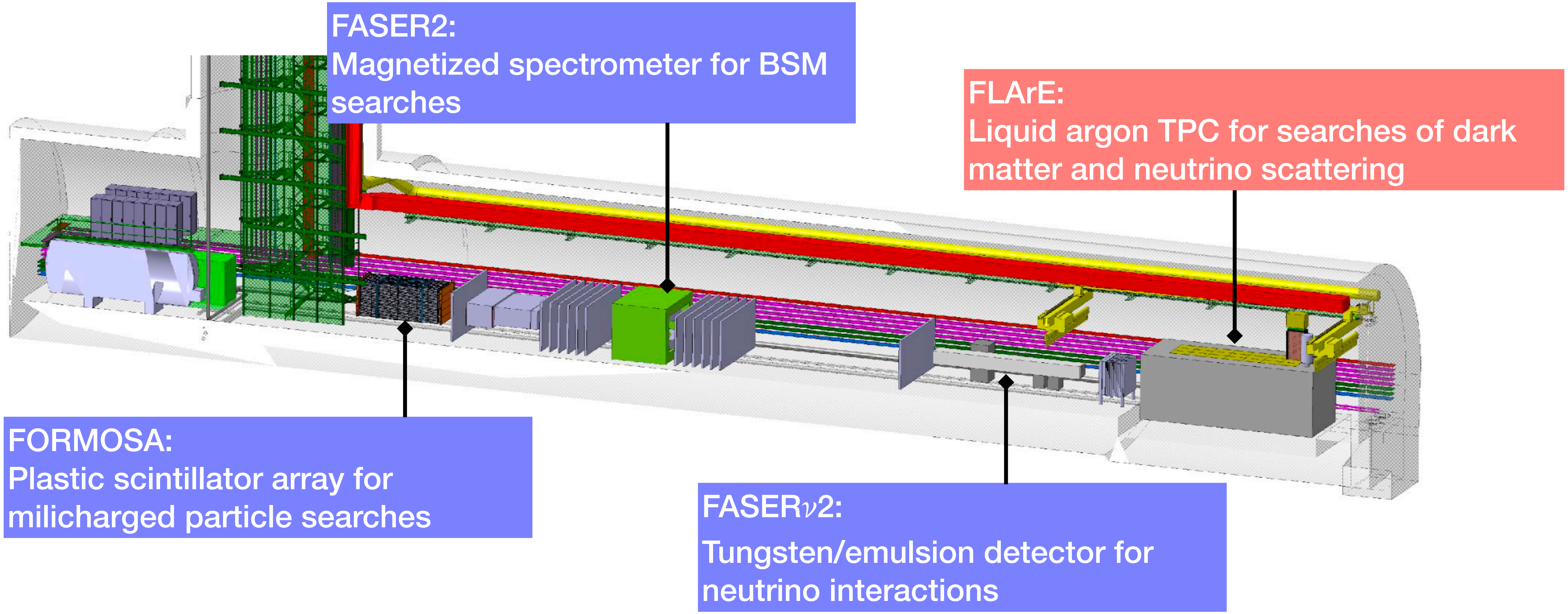
- Forward Physics Facility (FPF) is a proposal to realize these opportunities, by creating a space to host a suite of experiments at the far forward region

- 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, 10 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



FASER2:
Magnetized spectrometer for BSM searches

FLArE:
Liquid argon TPC for searches of dark matter and neutrino scattering

FORMOSA:
Plastic scintillator array for milicharged particle searches

FASERν2:
Tungsten/emulsion detector for neutrino interactions

Diverse technologies optimized for SM and BSM physics

Synergies exist between FPF detectors

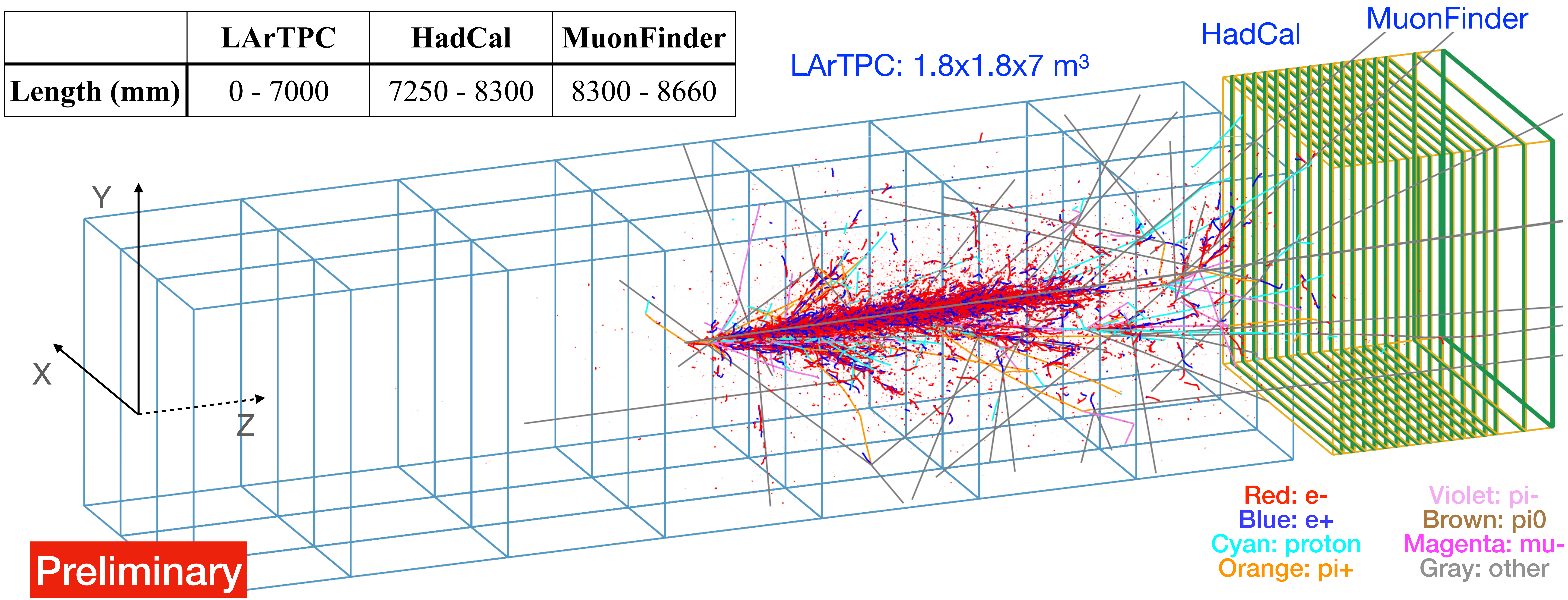
(See Felix's talk for an overview of the FPF project, Friday, July 5)

(And talks for the running experiments FASER, FASERν, milliQan experiments at this workshop)

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

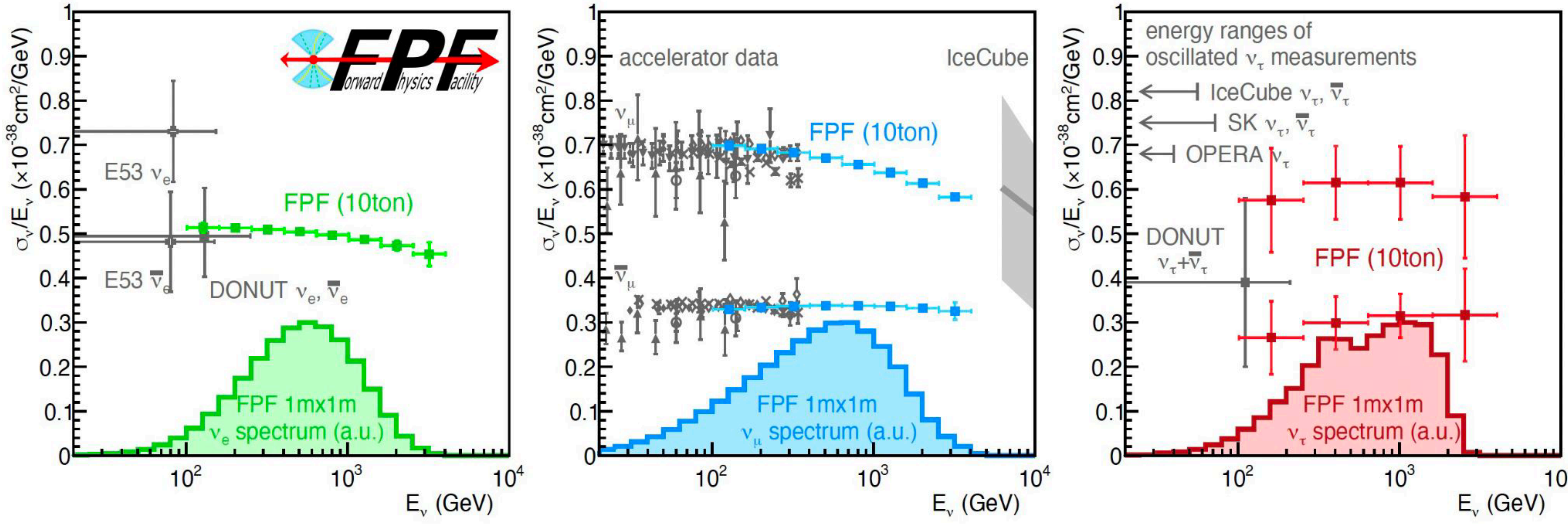
	LArTPC	HadCal	MuonFinder
Length (mm)	0 - 7000	7250 - 8300	8300 - 8660

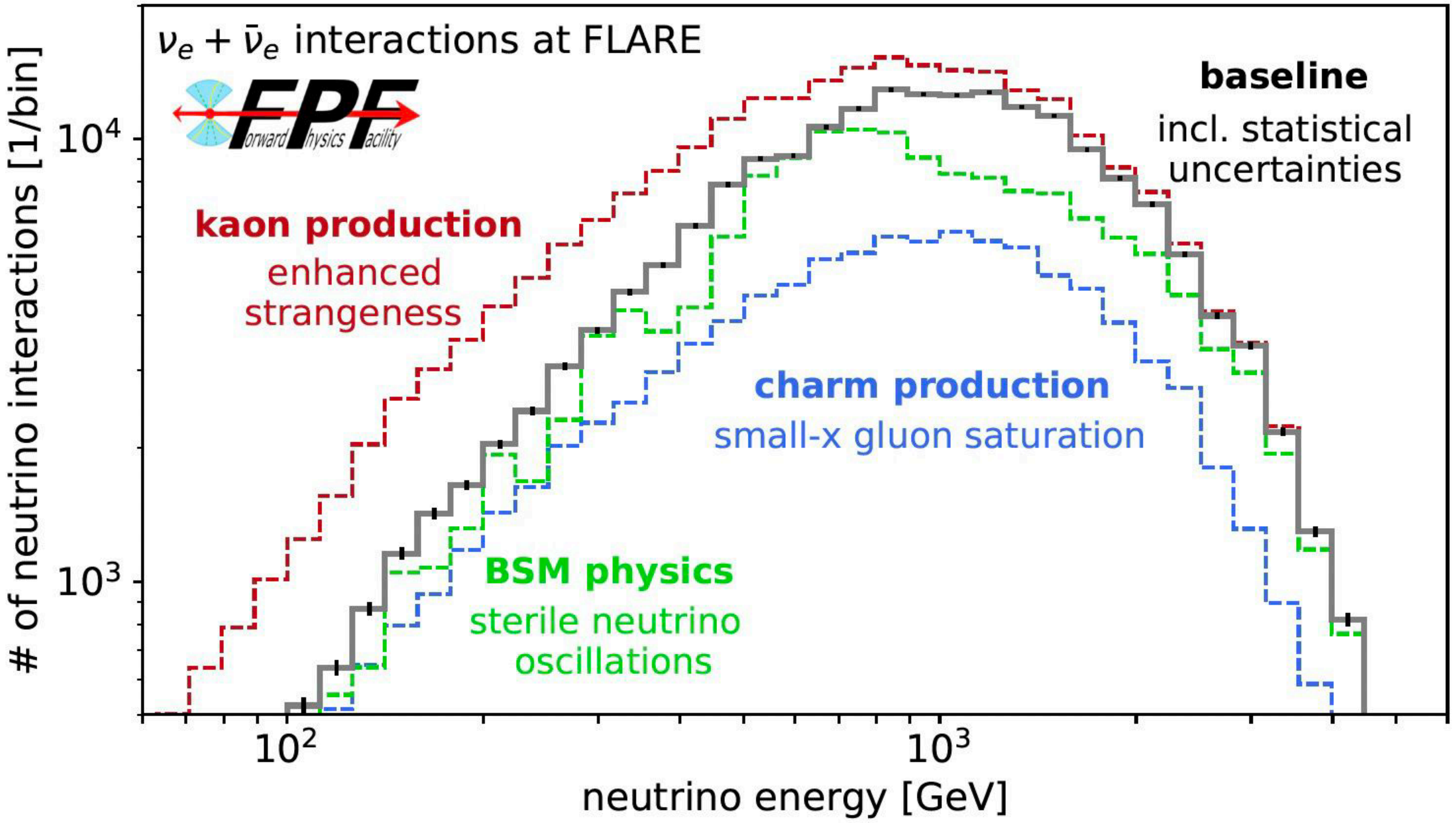


Neutrino Physics

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

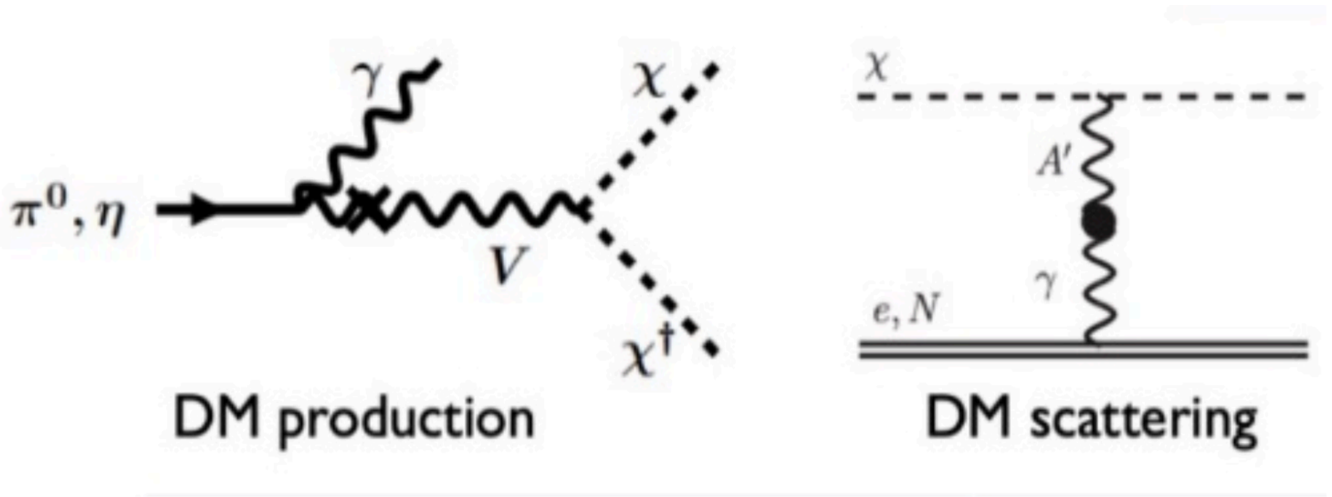
- Neutrinos from LHC provide data that fills in the gap between the current accelerator and atmospheric neutrinos
- **FLArE is an excellent option for a broad purpose neutrino detector**
  - will see 10^5 ν_e, 10^6 ν_μ, 10^4 ν_τ interactions at ~TeV energies
- By measuring the neutrino flux, we can probe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



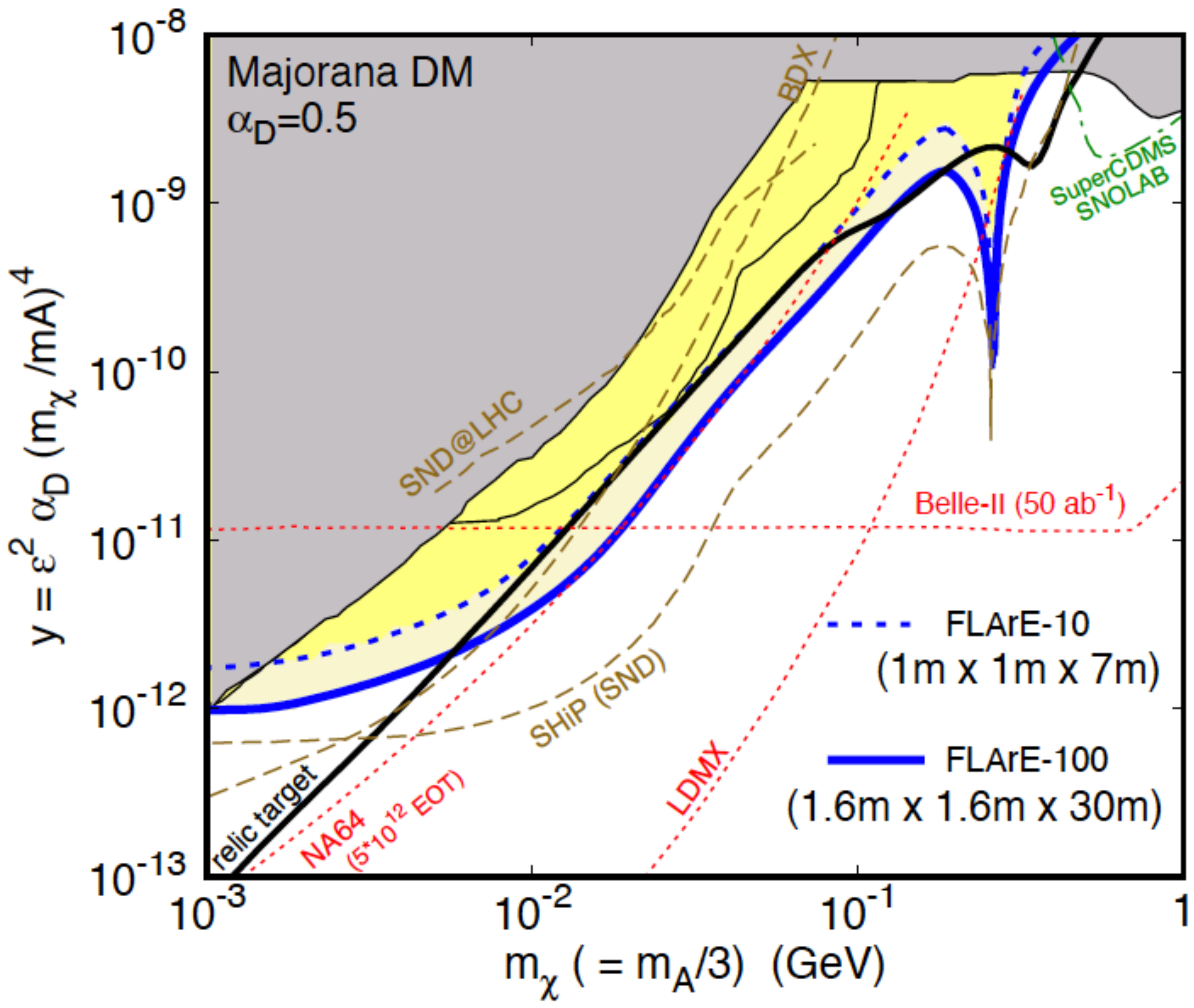


Light Dark Matter Scattering

Elastic scattering from electrons and nuclei



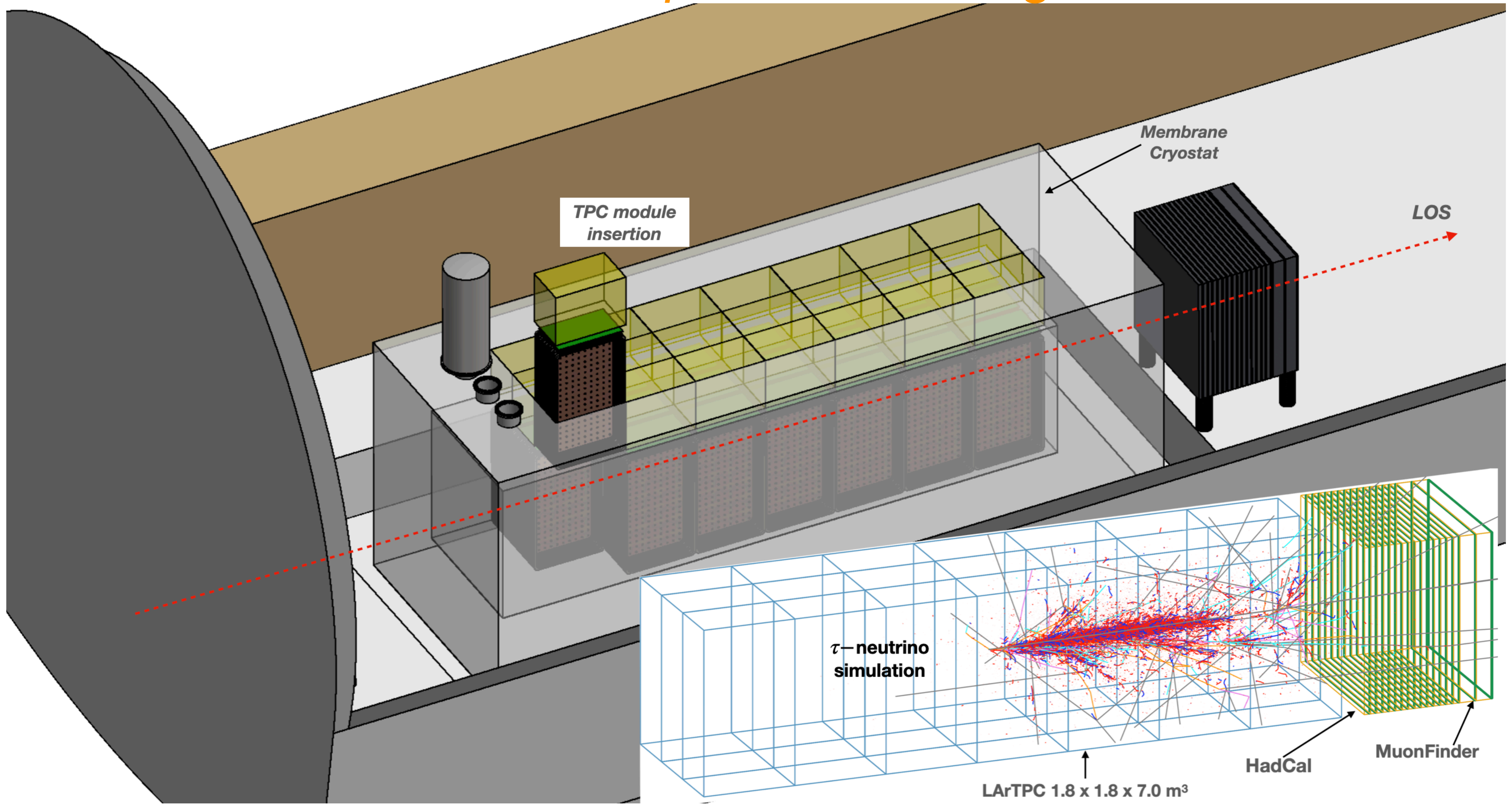
- Mass of χ alters the kinematics of the outgoing electron or nucleus
- Signal is at low energy (~ 1 GeV). **Need high kinematic resolution and low threshold**
- Background is from neutrino interactions and muons
- The sensitivity plot assumes reasonable cuts for background reduction
- Make use of the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



PhysRevD.103.075023, PhysRevD.104.035036

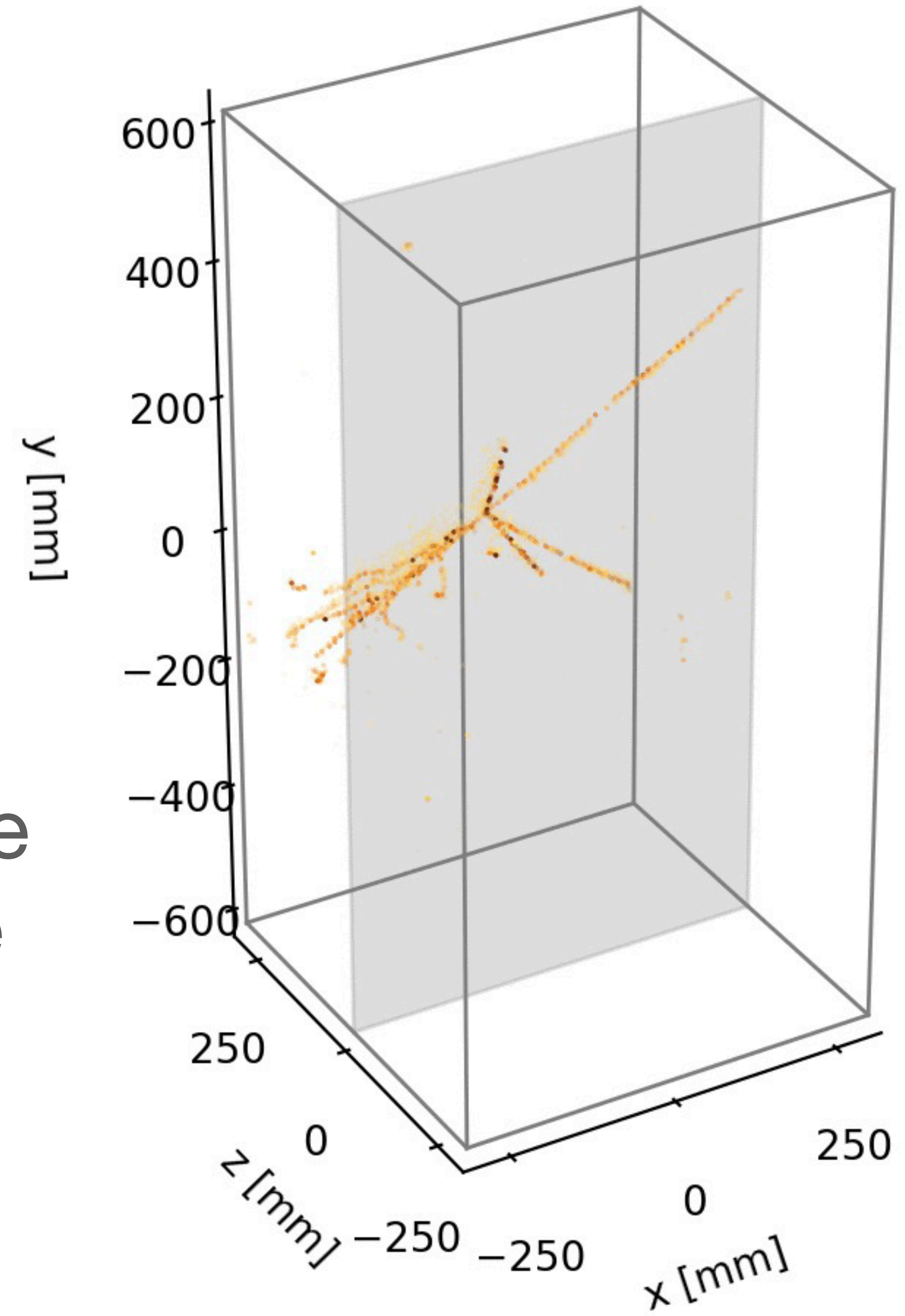
Reference Design of TPC

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



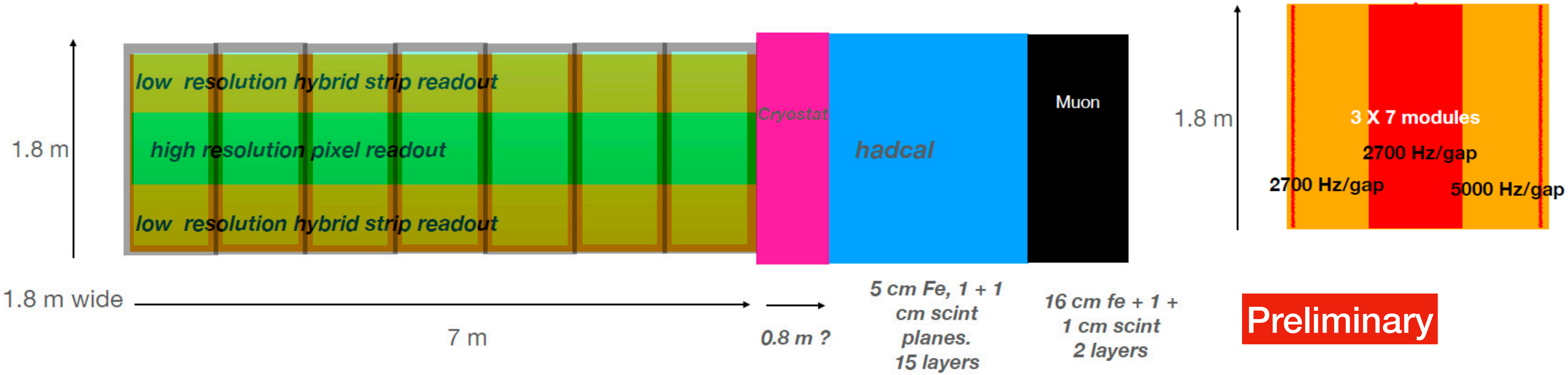
Inspired by the DUNE ND-LAr concept
https://doi.org/10.3390/instruments5040031

Each module is a TPC, with a cathode plane in the middle



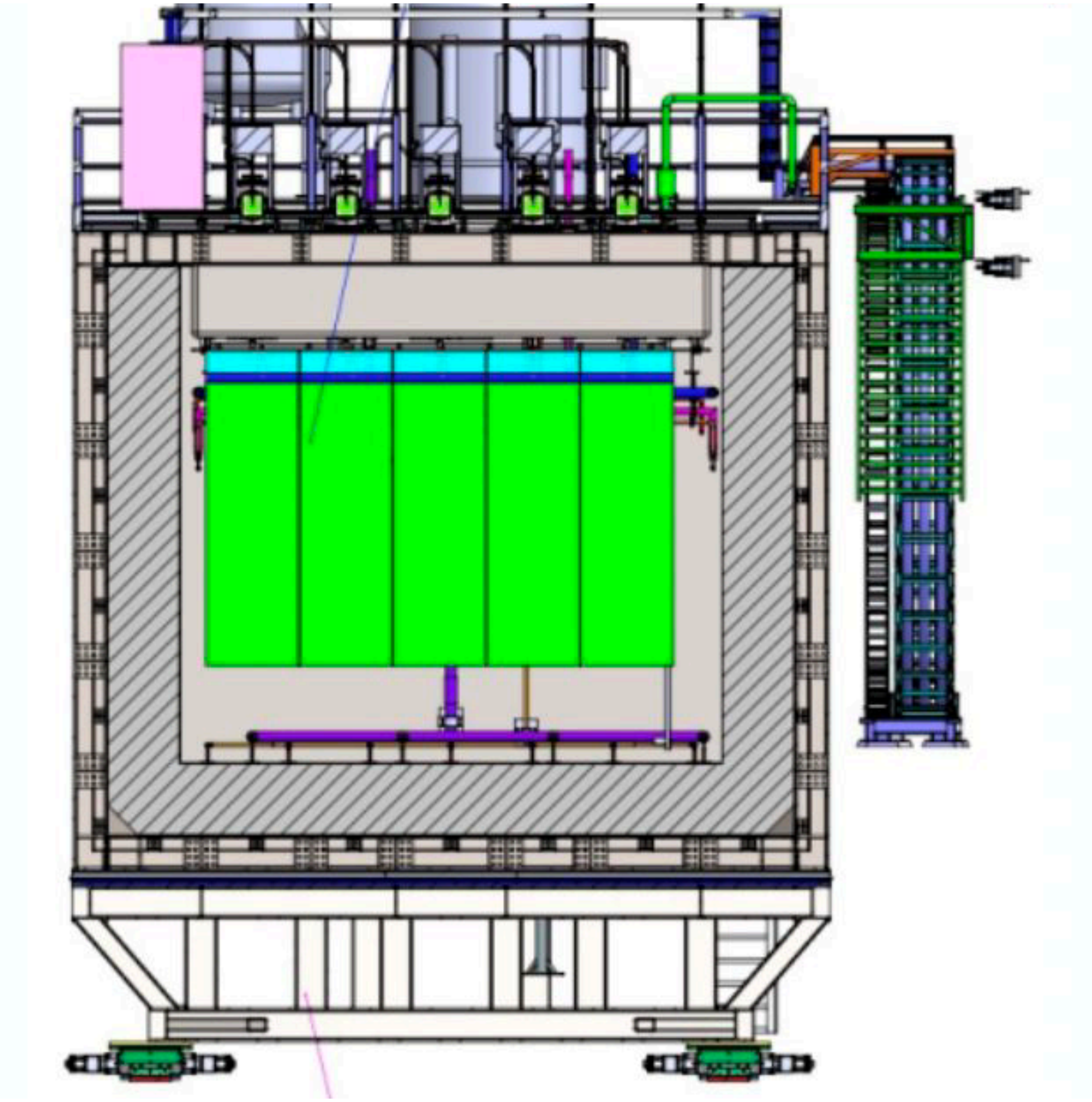
- Reference design of the TPC is a modular LAr TPC
  - segmentation for light collection (trigger)
  - reducing space charge effect from muon background with small drift distance (30 cm)
- Taking full advantage of the **R&D in LAr technologies in the community**

Reference Design of TPC



- Reference: 3 x 7 for the modular TPC. Each module is 0.6 m x 1.8 m x 1 m
- Simulations show reasonable containment of neutrino interactions in LAr for energy measurement
- Pixel-based anode → high number of readout channels
  - Possibly reduce channel by using strip-based or wire anodes in non-fiducial region
- Magnetized hadron calorimeter and muon catcher downstream

Cryostat Options for FLArE

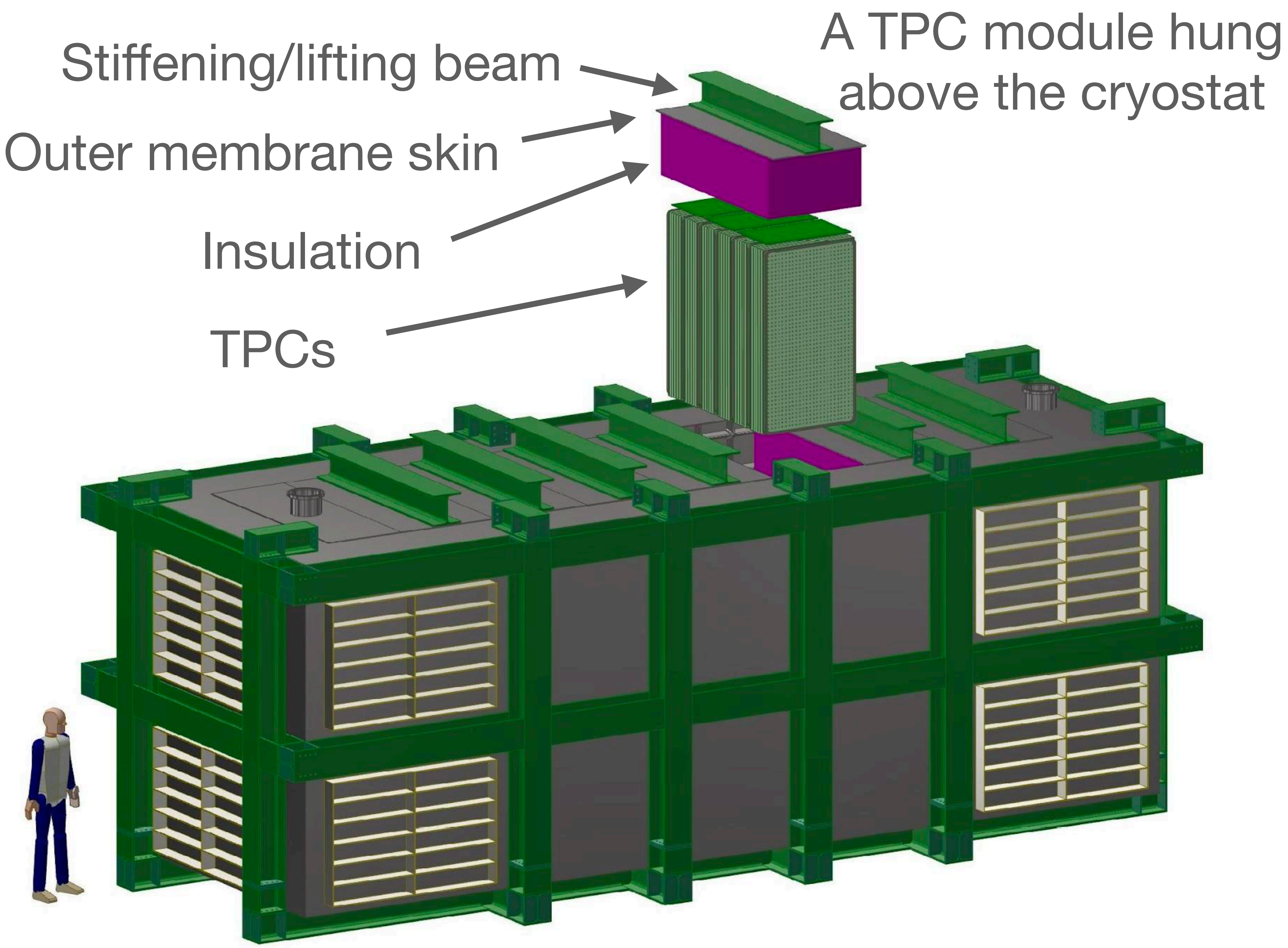


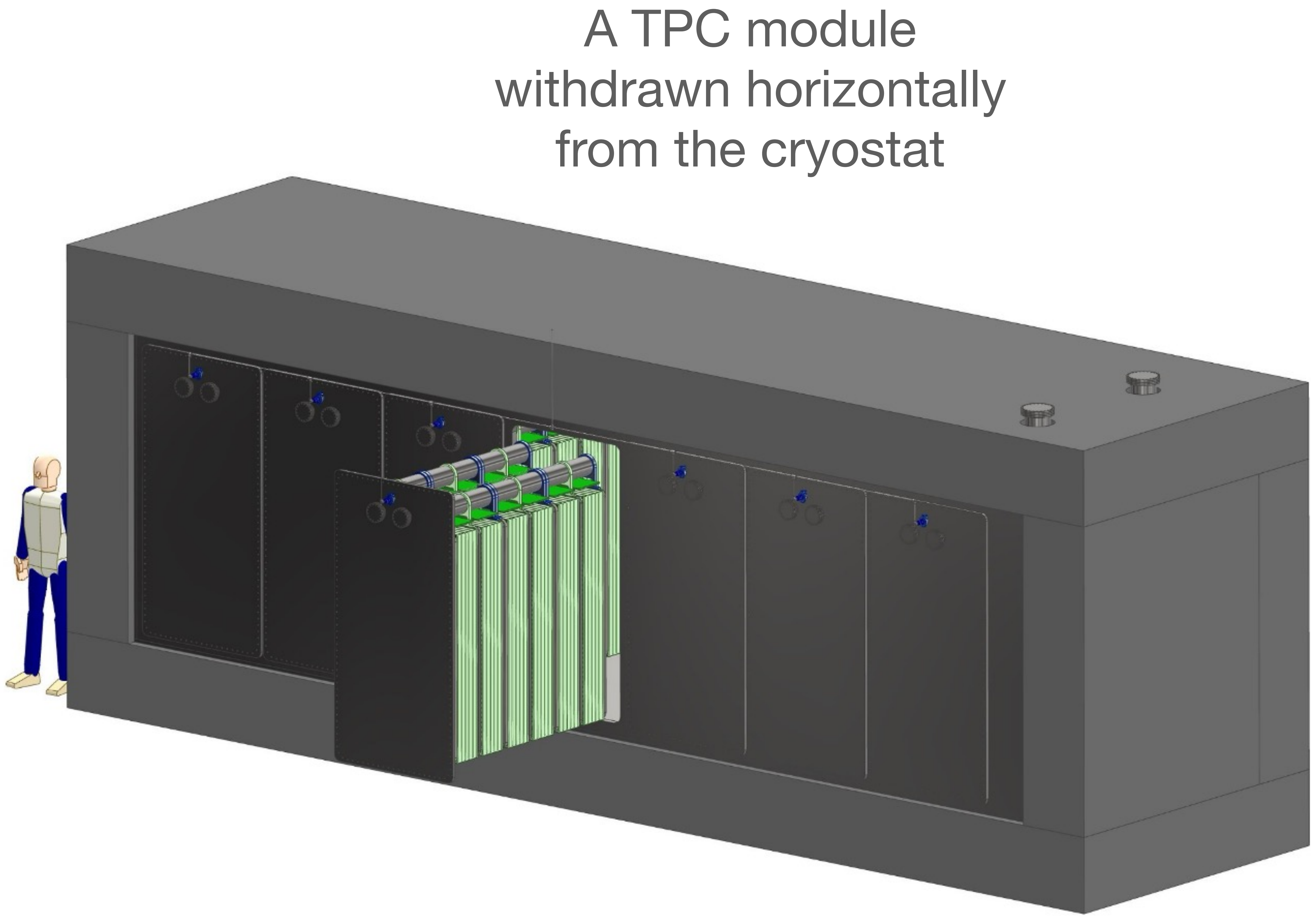
- Reference design is GTT membrane cryostat (used in ProtoDUNE, DUNE ND-LAr)
- 80 cm GTT membrane occupies 1.6 m out of 3.5 m available space
  - About 1.9 m x 1.9 m cross section allowed for detector
- Other options: single-wall? Vacuum-insulated?
- **BNL contracted an engineering firm (Bartoszek Engineering)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

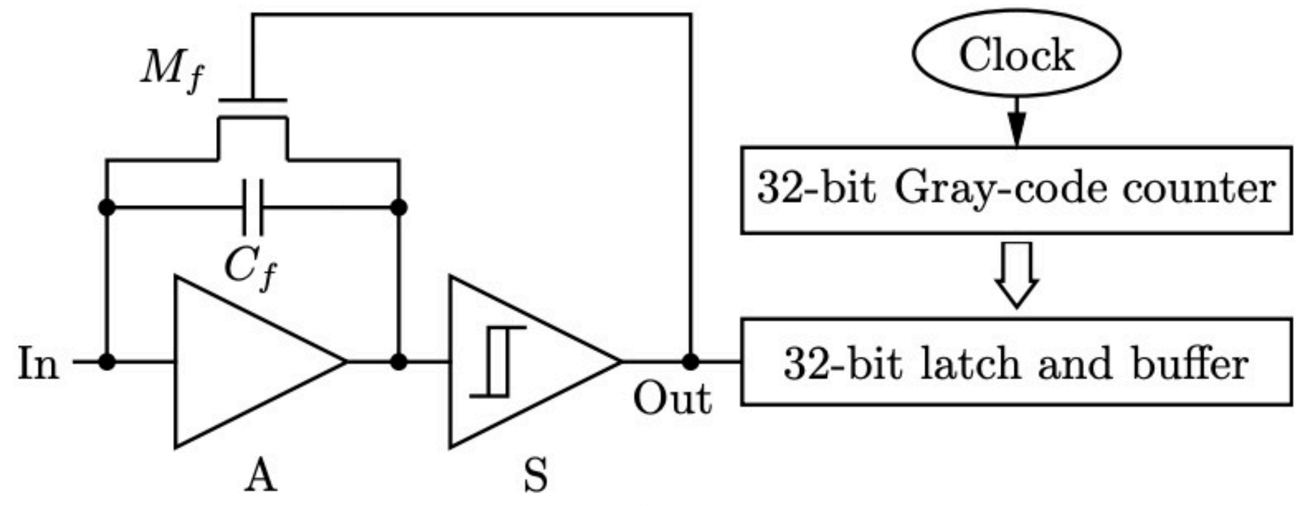
Horizontal insertion of TPC modules
* reduced requirement on the vertical space
* more work needs go into insulation and sealing



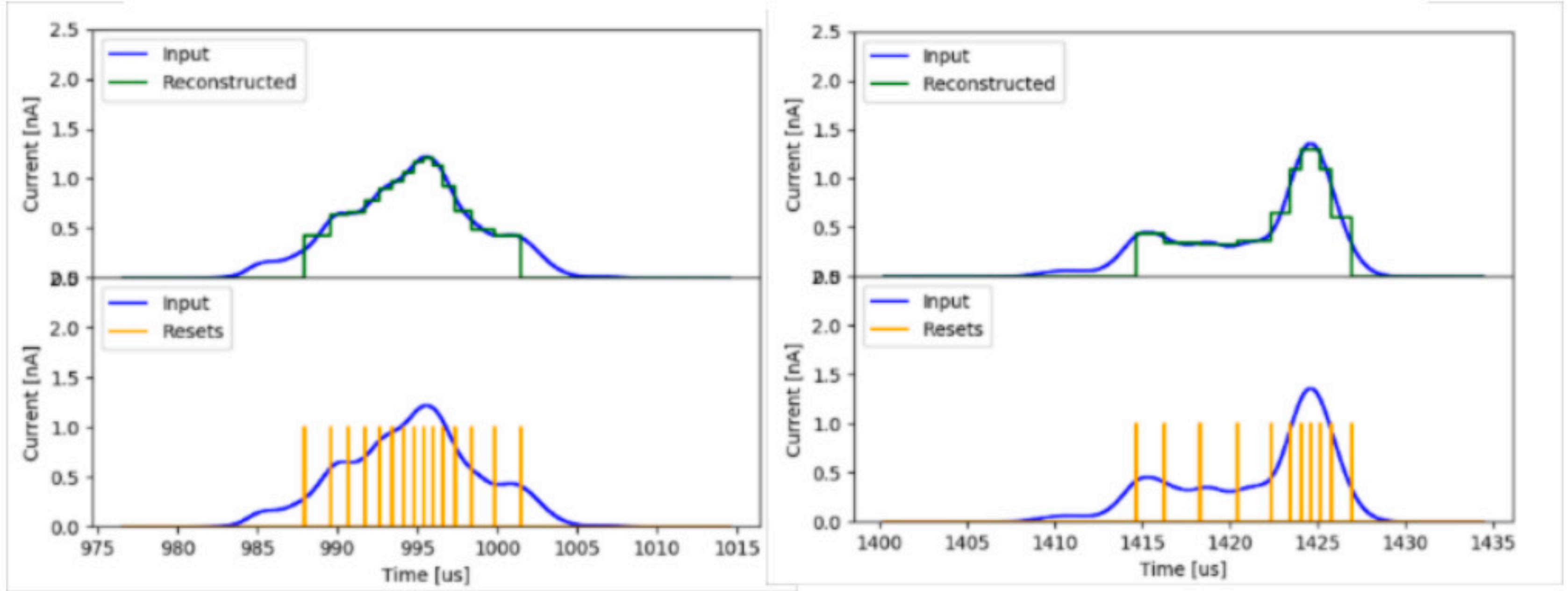


Charge Readout

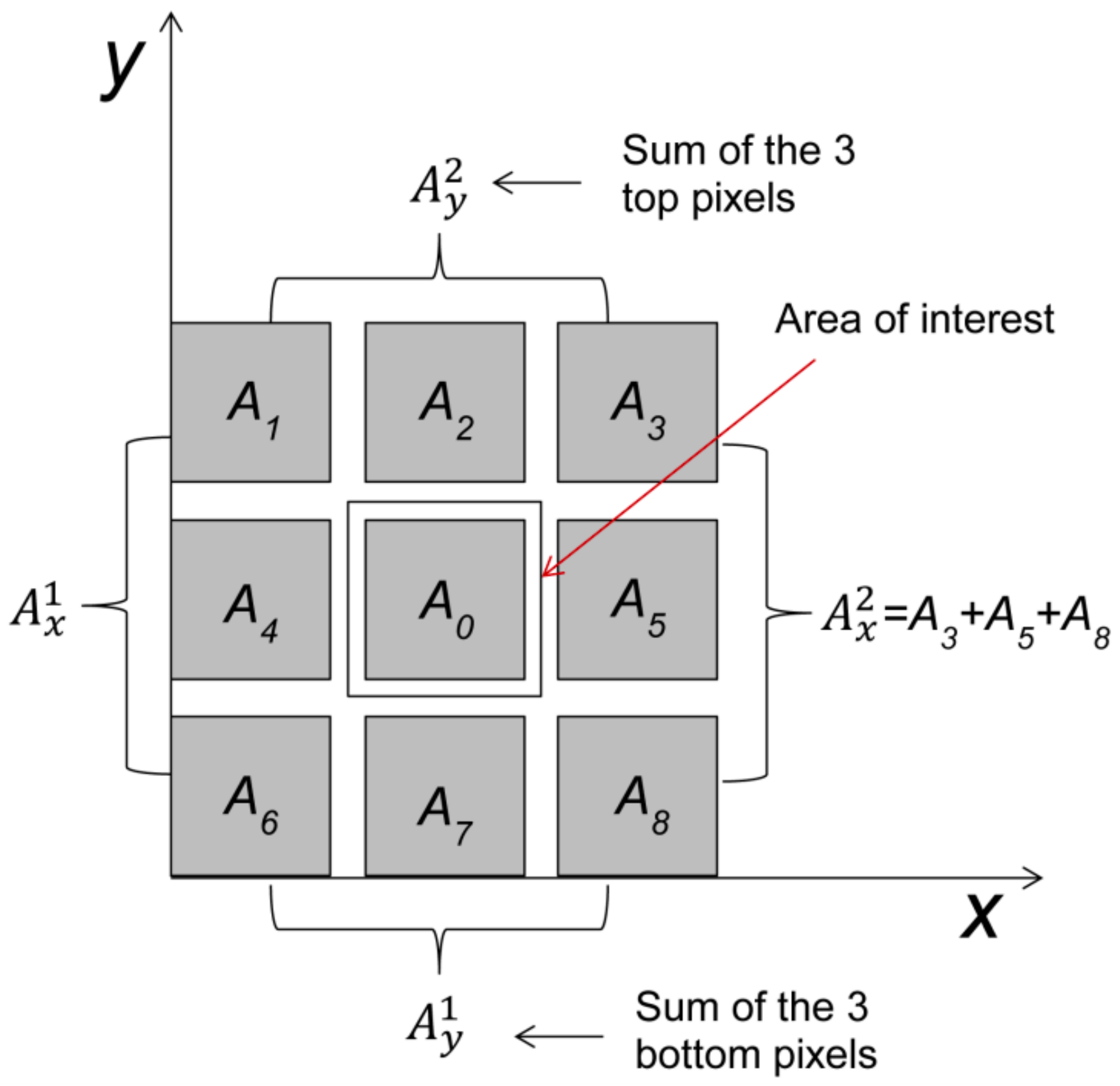
- Anode pixel readout is important to achieve < 1mm resolution
- Pitch size strongly affects the number of readout channels and the heat load!

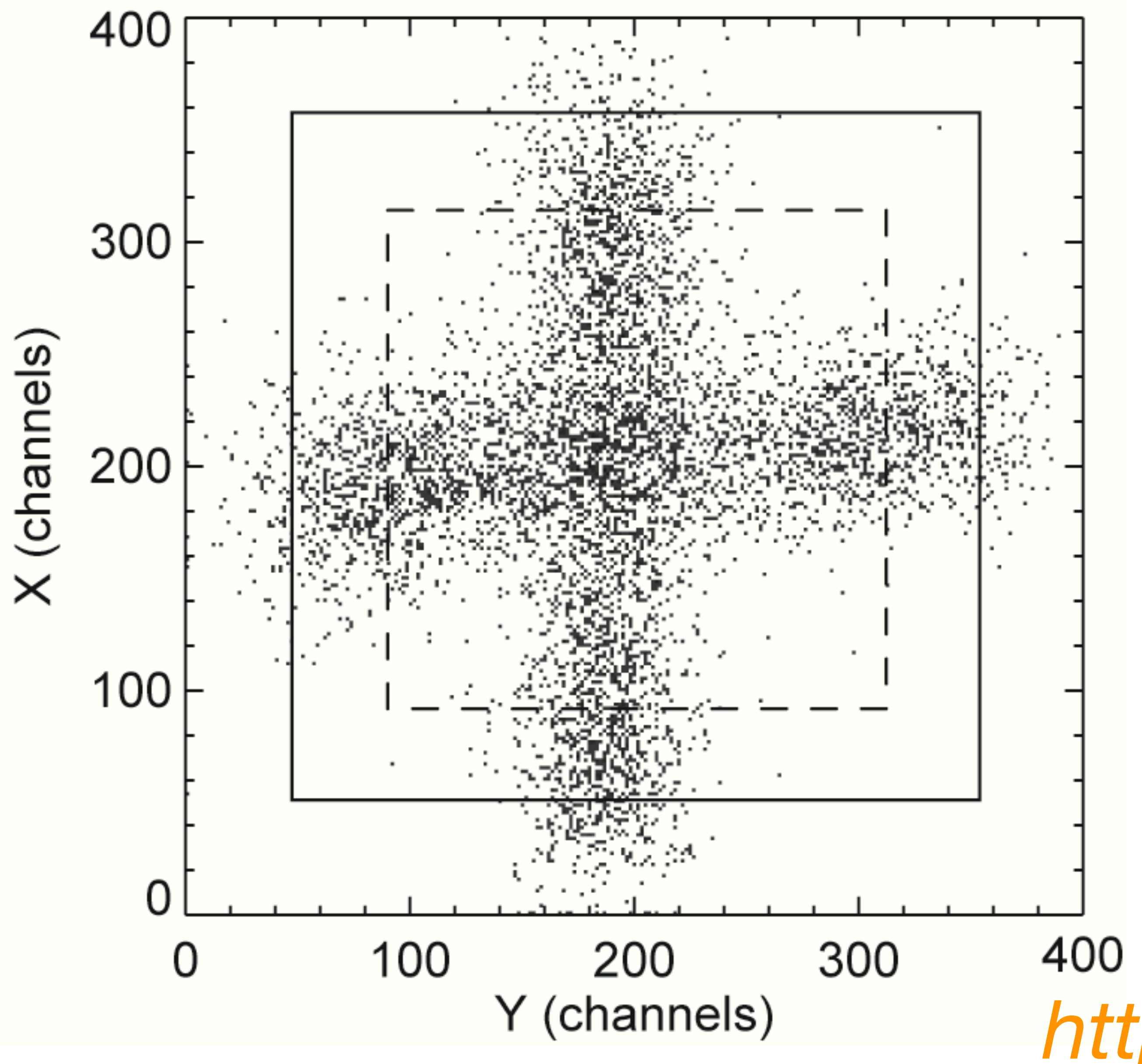


Q-Pix: Charge Integrate/Reset (CIR) circuit



https://doi.org/10.1103/PhysRevD.106.032011





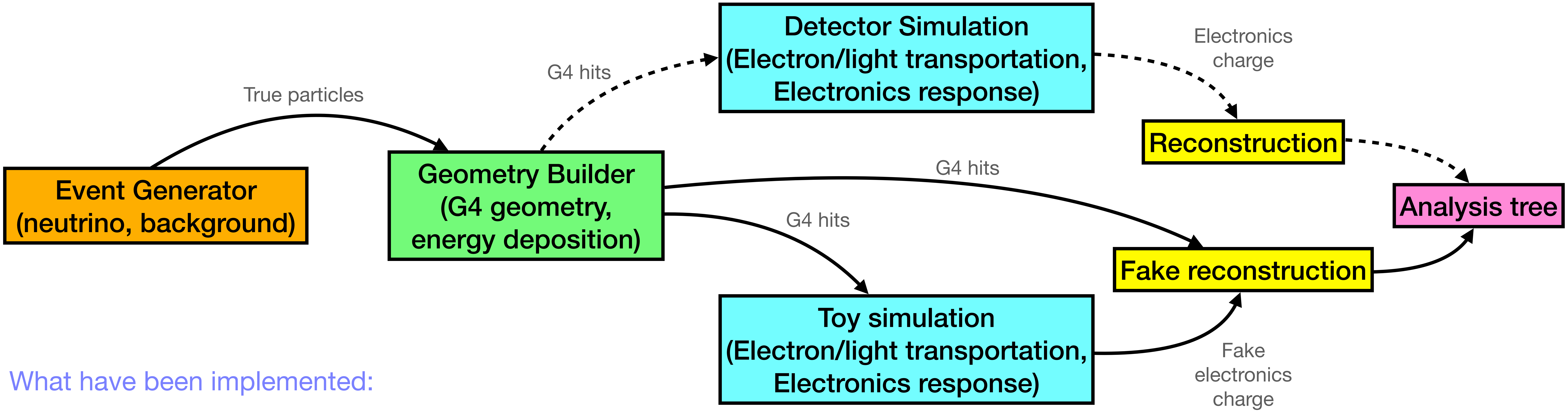
- Idea: achieve resolutions smaller than pixel size by using signals induced in neighboring pixels
  - Resolution down to 250 um for a 1.7 mm x 1.7 mm pixel

https://doi.org/10.1016/j.nima.2017.04.030

Simulation Framework

→ Current working strategy

⇢ Ultimate goal



Event Generator (neutrino, background)

True particles

Geometry Builder (G4 geometry, energy deposition)

G4 hits

Detector Simulation (Electron/light transportation, Electronics response)

Electronics charge

Reconstruction

G4 hits

G4 hits

Toy simulation (Electron/light transportation, Electronics response)

Fake electronics charge

Fake reconstruction

Analysis tree

What have been implemented:

- GENIE
- Single Particle
  - Muon
  - Neutron
  - …

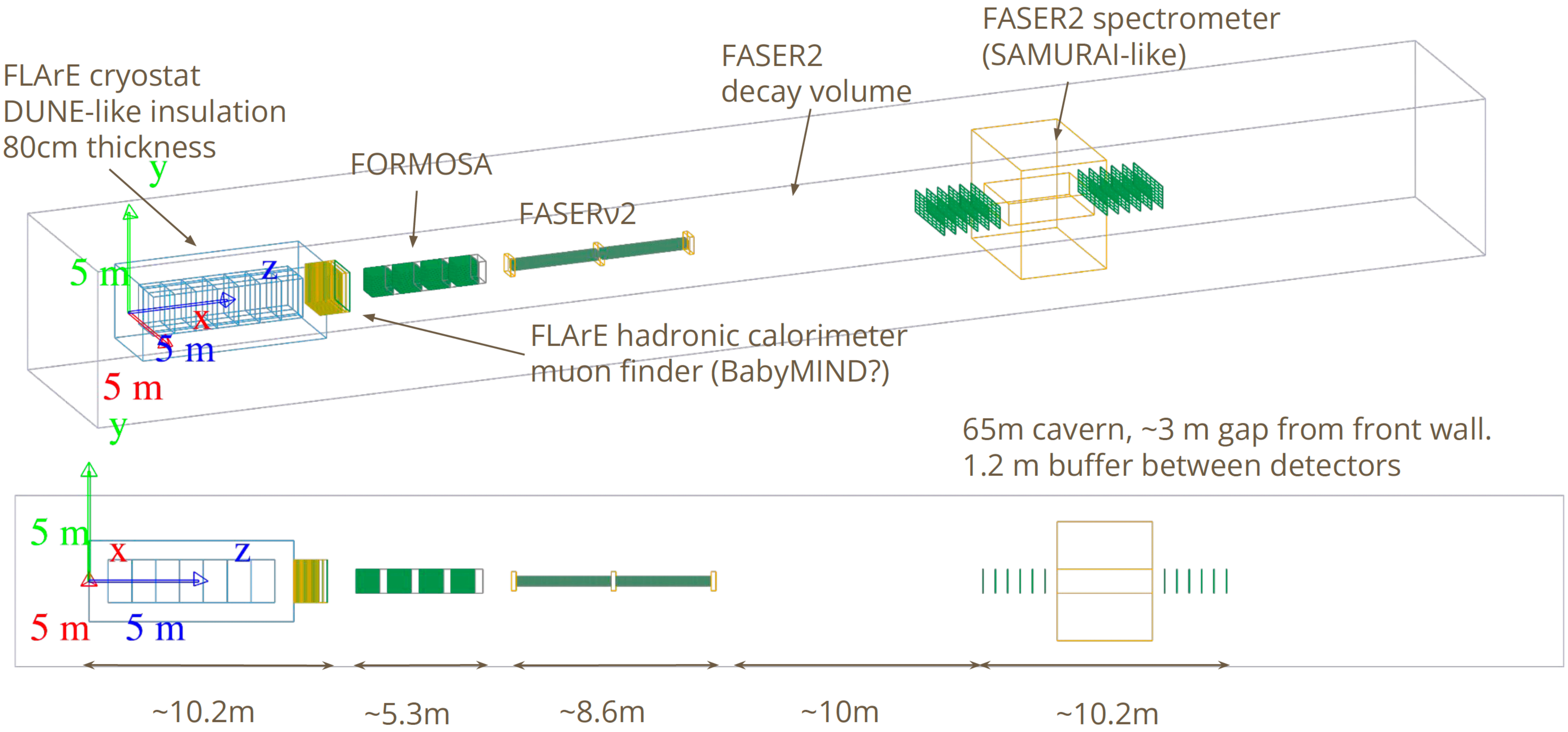
- TPC volume
- HadCal
- MuonCatcher
- FORMOSA
- FASERnu2
- FASER2 Magent
  - SAMURAI
  - Crystal Pulling

Toy diffusion of electrons

- Pseudo variables
- Muon momentum fit

Ntuple

FPF Cavern in Simulation



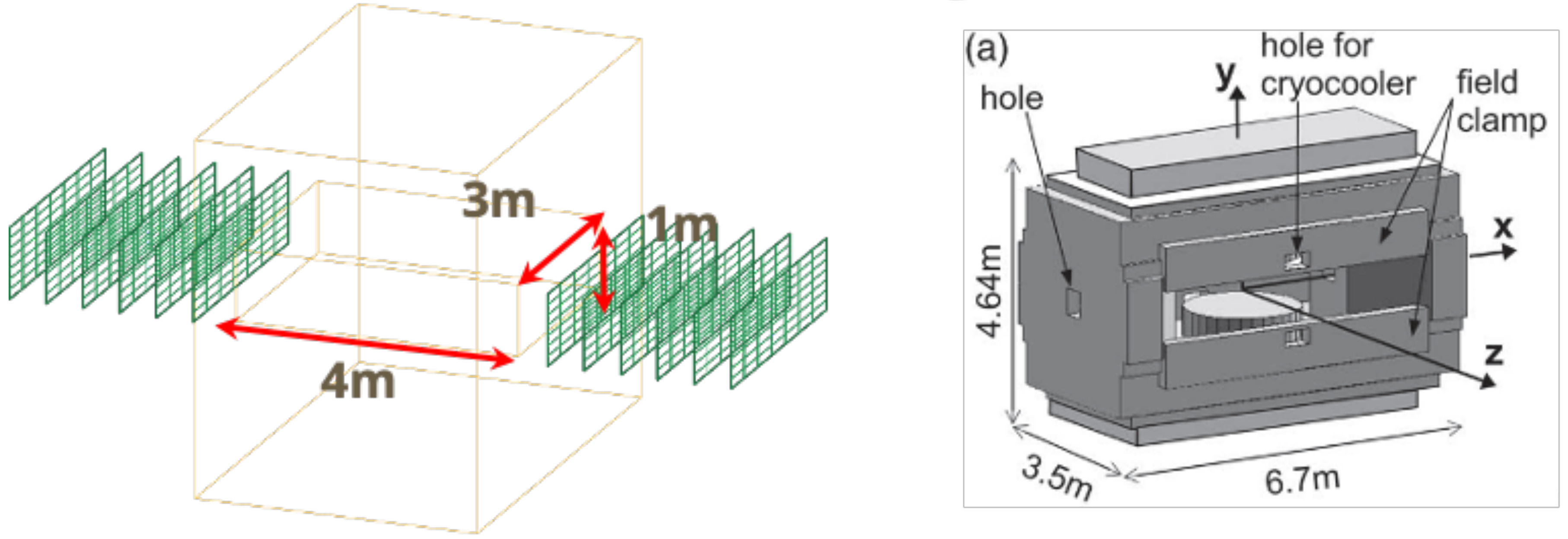
65m cavern, ~3 m gap from front wall.
1.2 m buffer between detectors

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

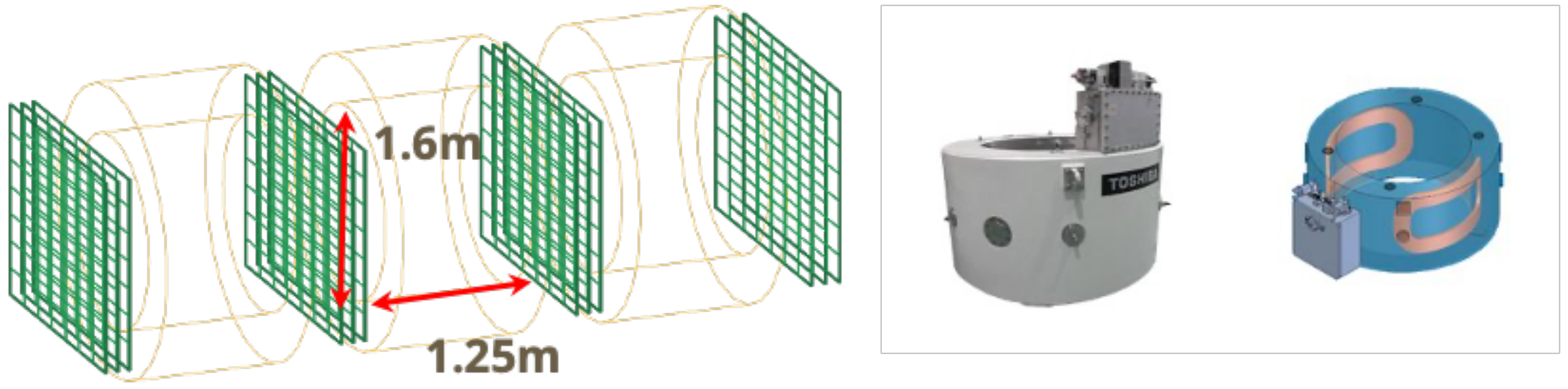
Muon Acceptance

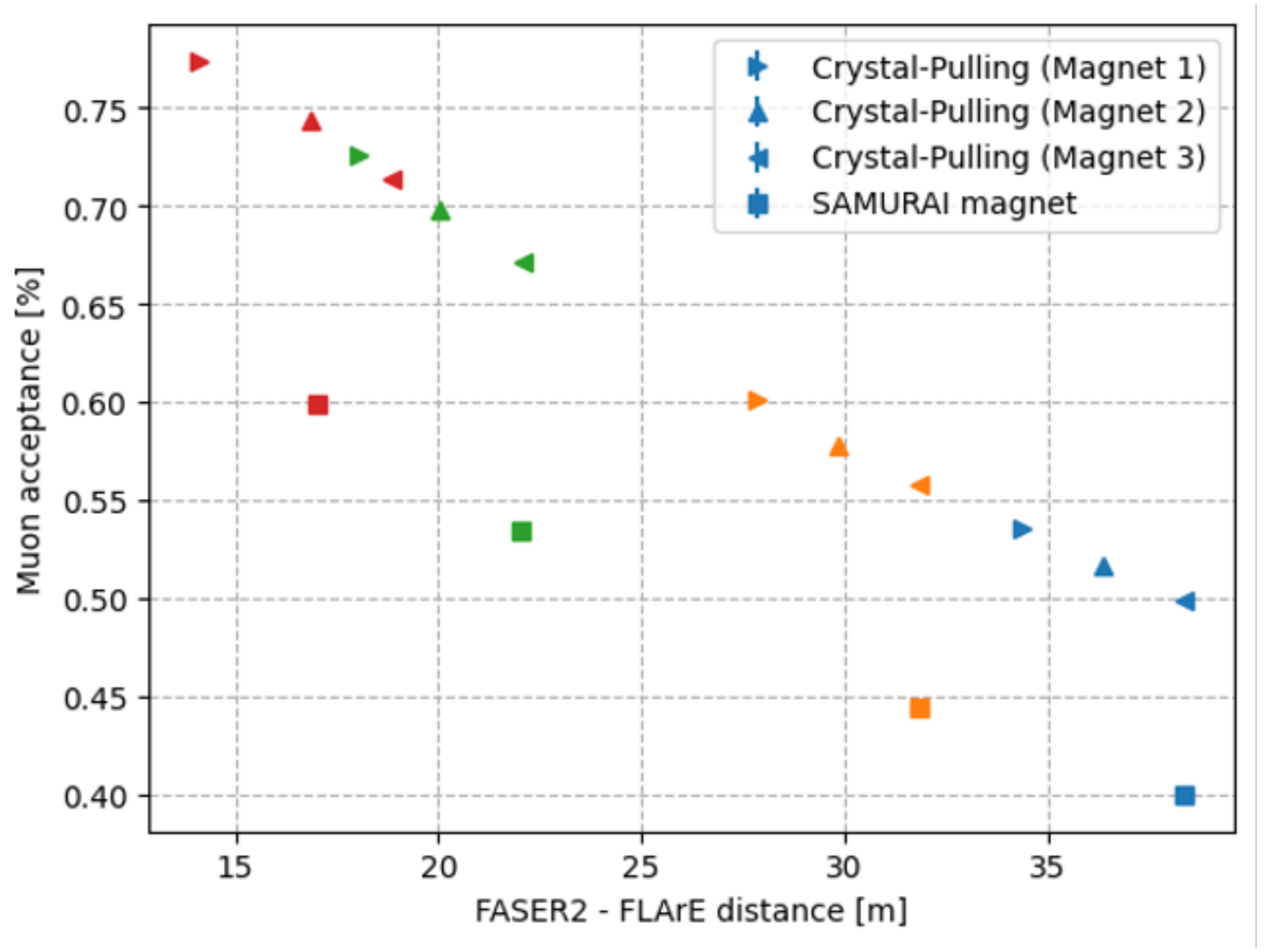
- Acceptance study for the muons produced by ν_μ CC events in FLArE
- Propose to coordinate with FASER2 magnet, along with magnetized calorimeter @ FLArE
- Acceptance is mainly driven by the FLArE-FASER2 distance, which depends on the detector arrangements in the FPF
  - Better performance only if detectors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

SAMURAI-like magnet



TOSHIBA Crystal-pulling magnets

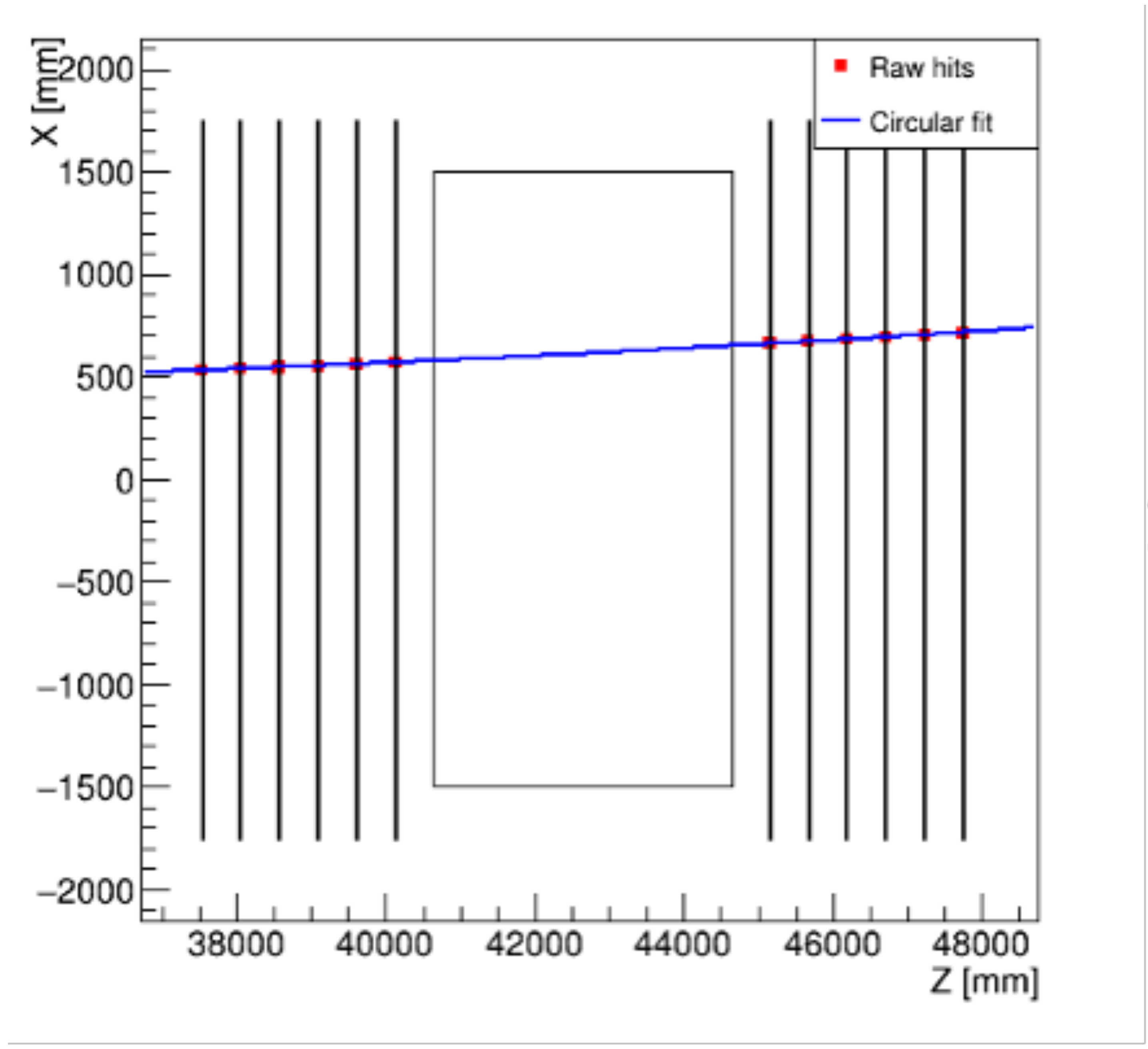


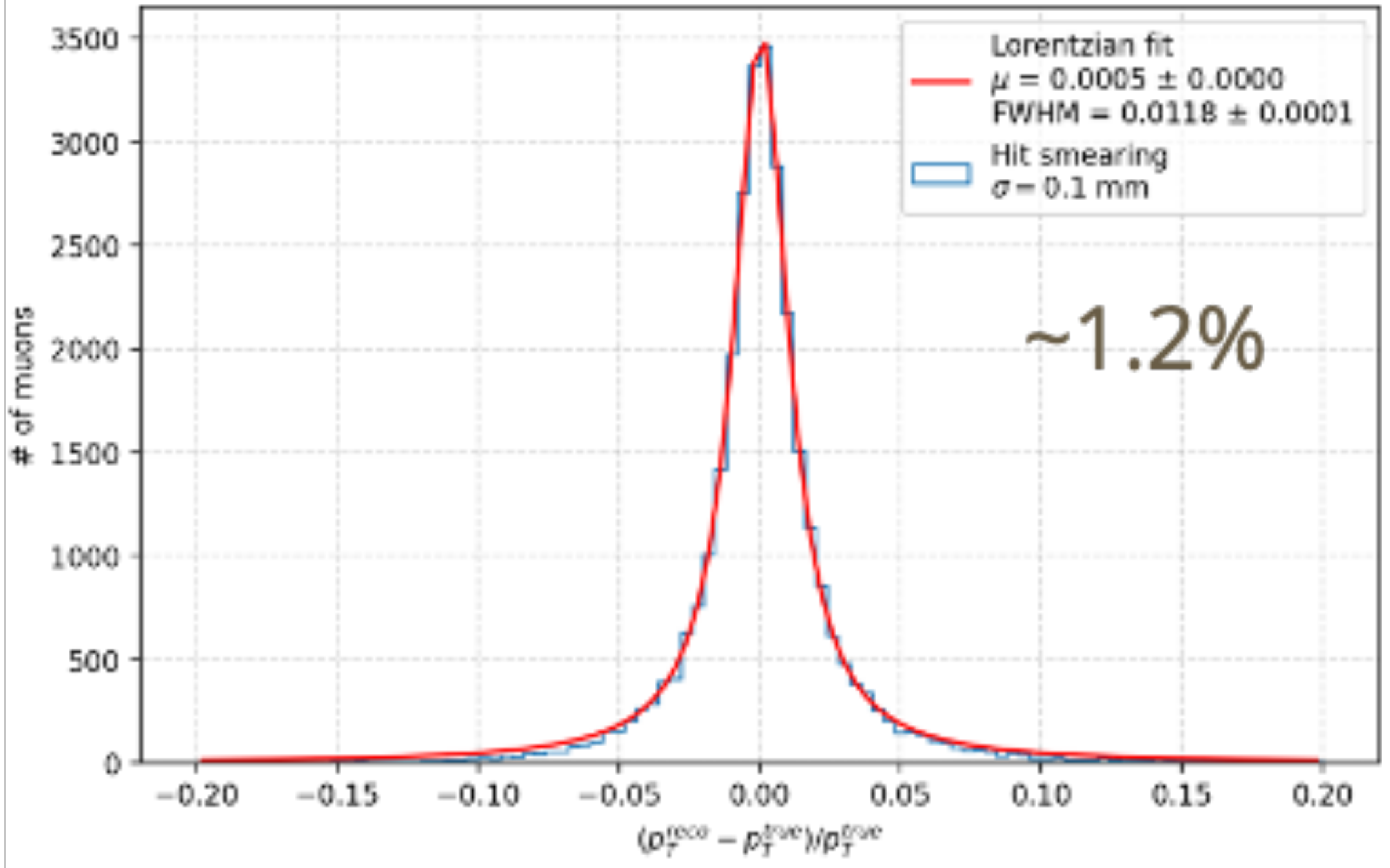


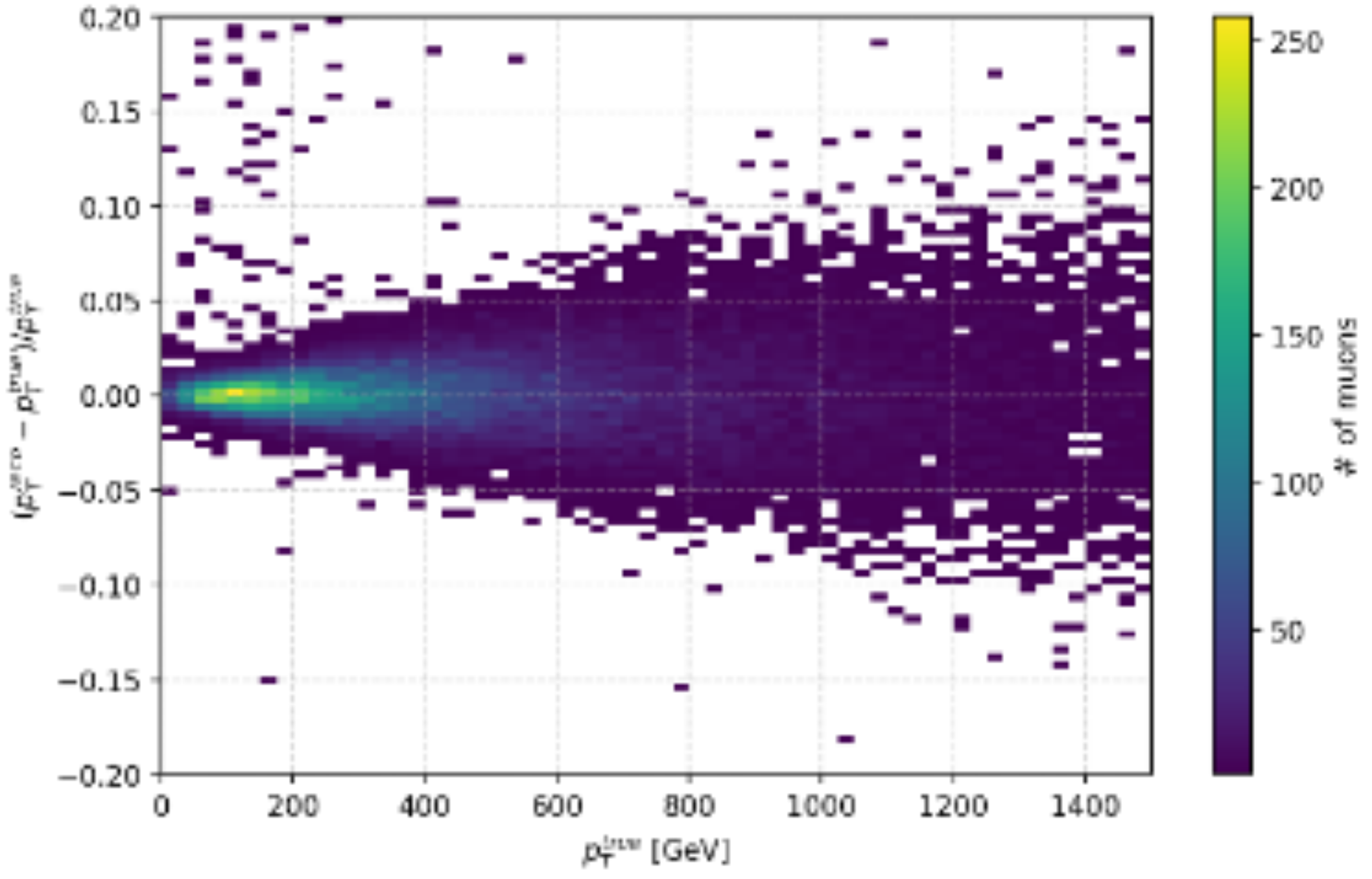
Muon Momentum Reconstruction

- 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

(Momentum reconstruction with Crystal-Pulling magnets is still on-going)



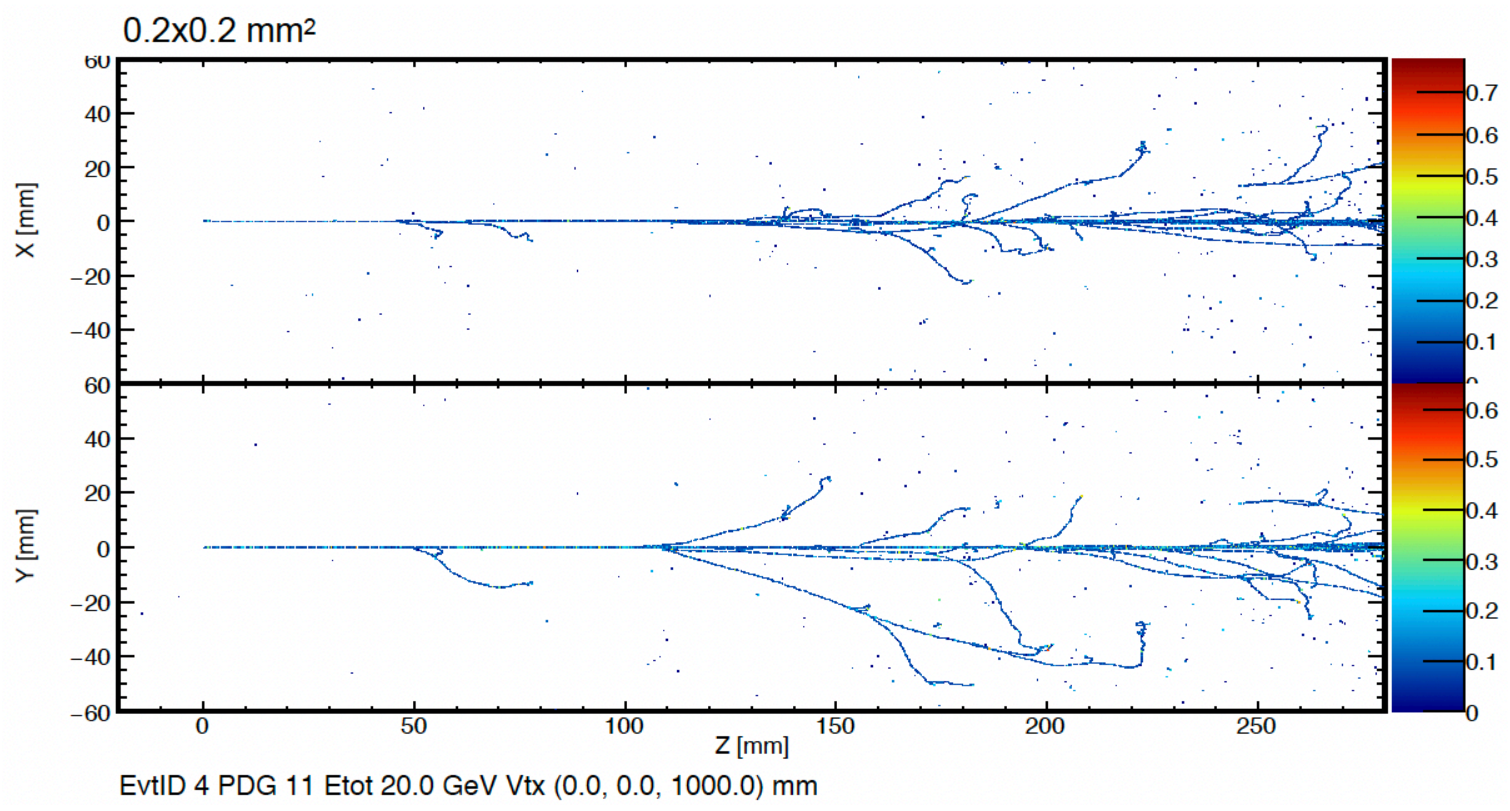




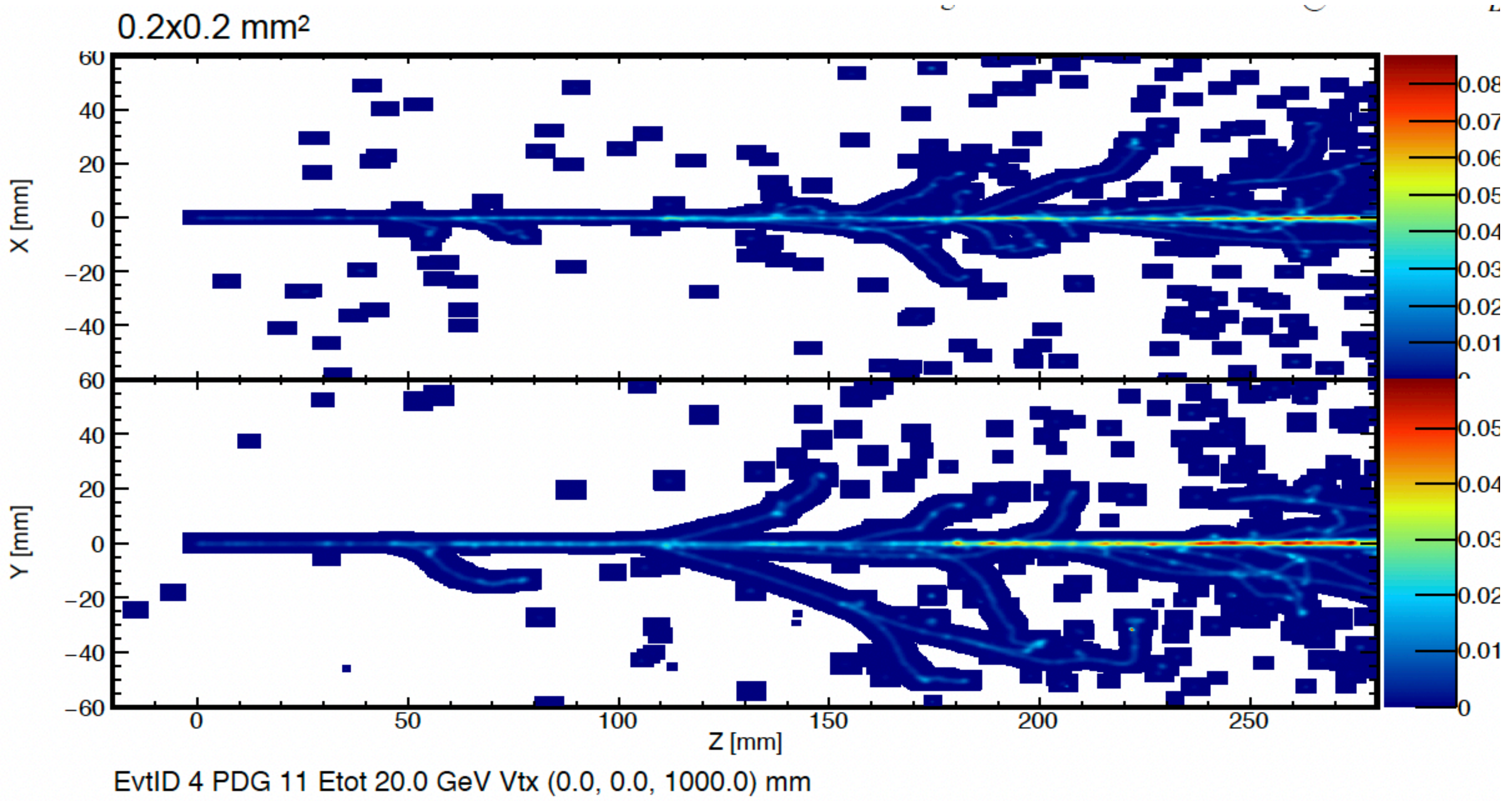
Particle Identification

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

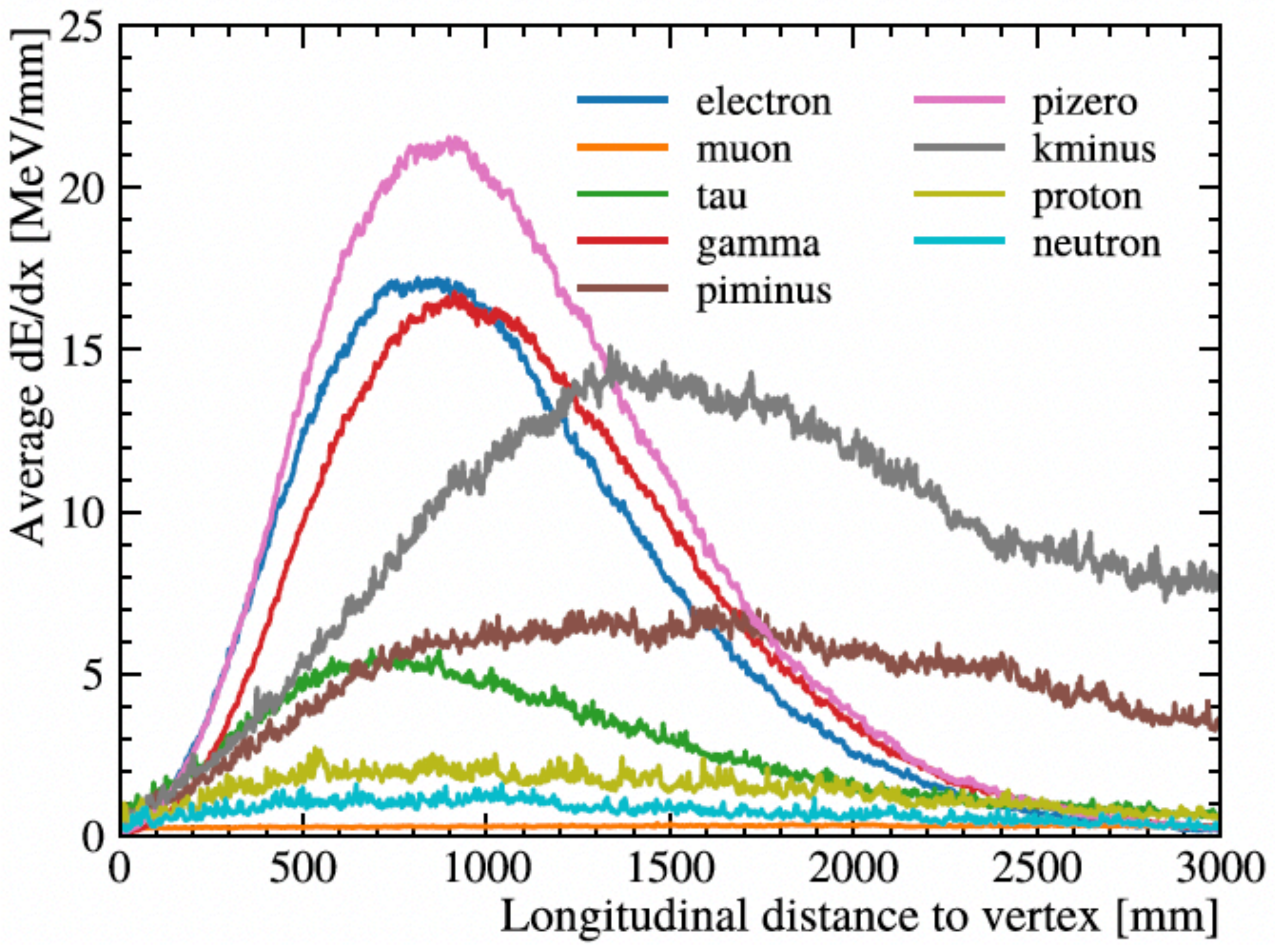
Single electron

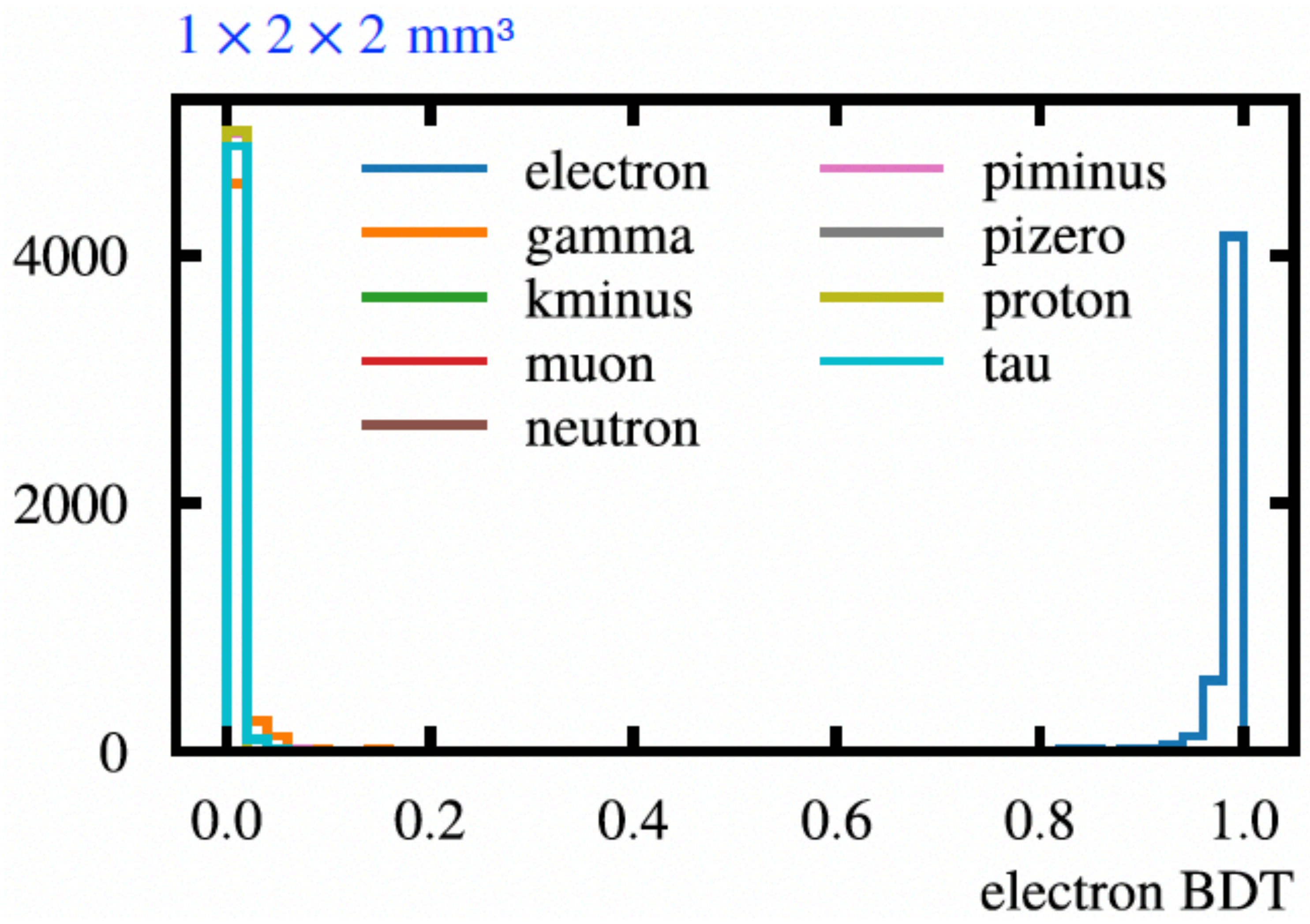


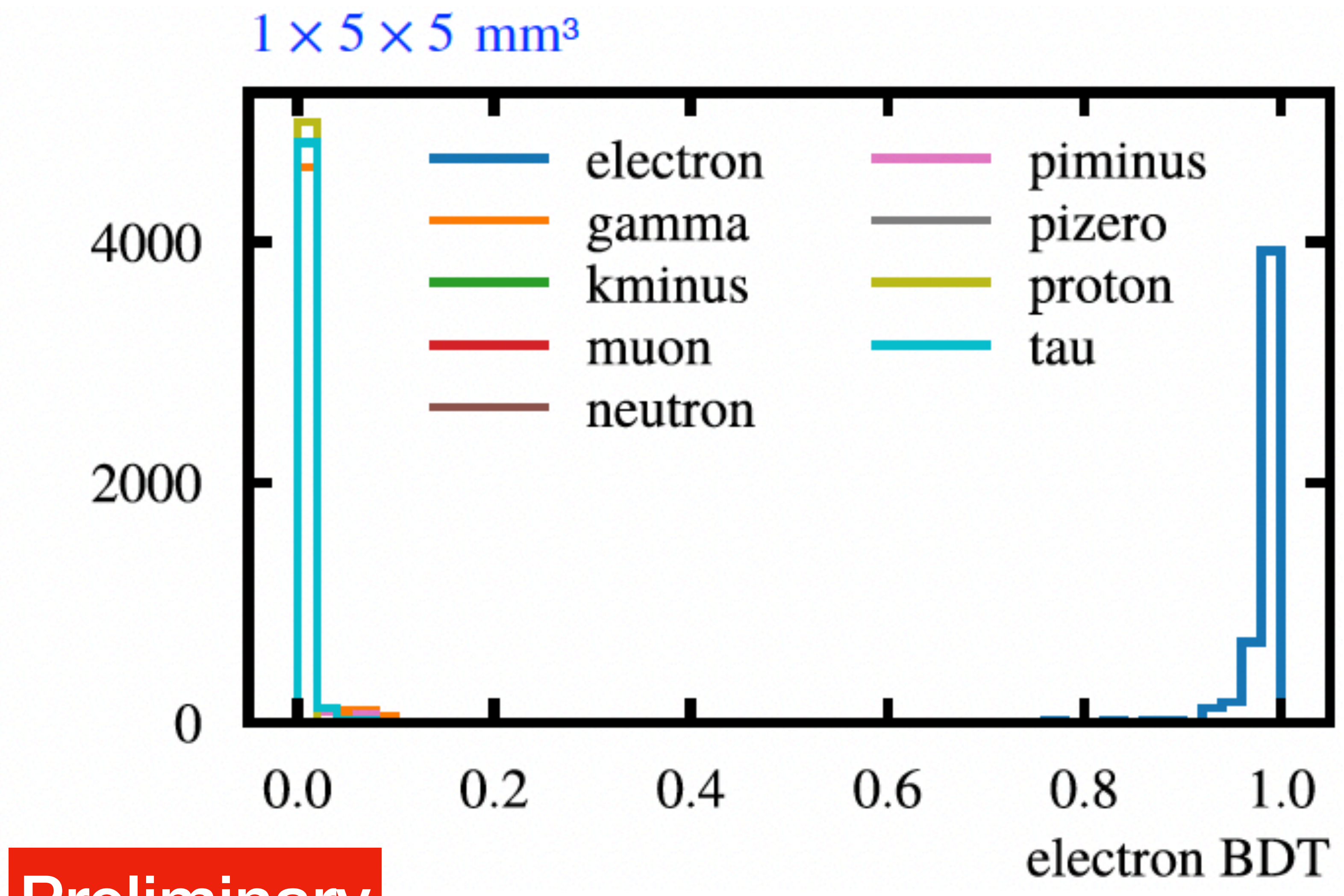
Single electron w/ diffusion



- 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





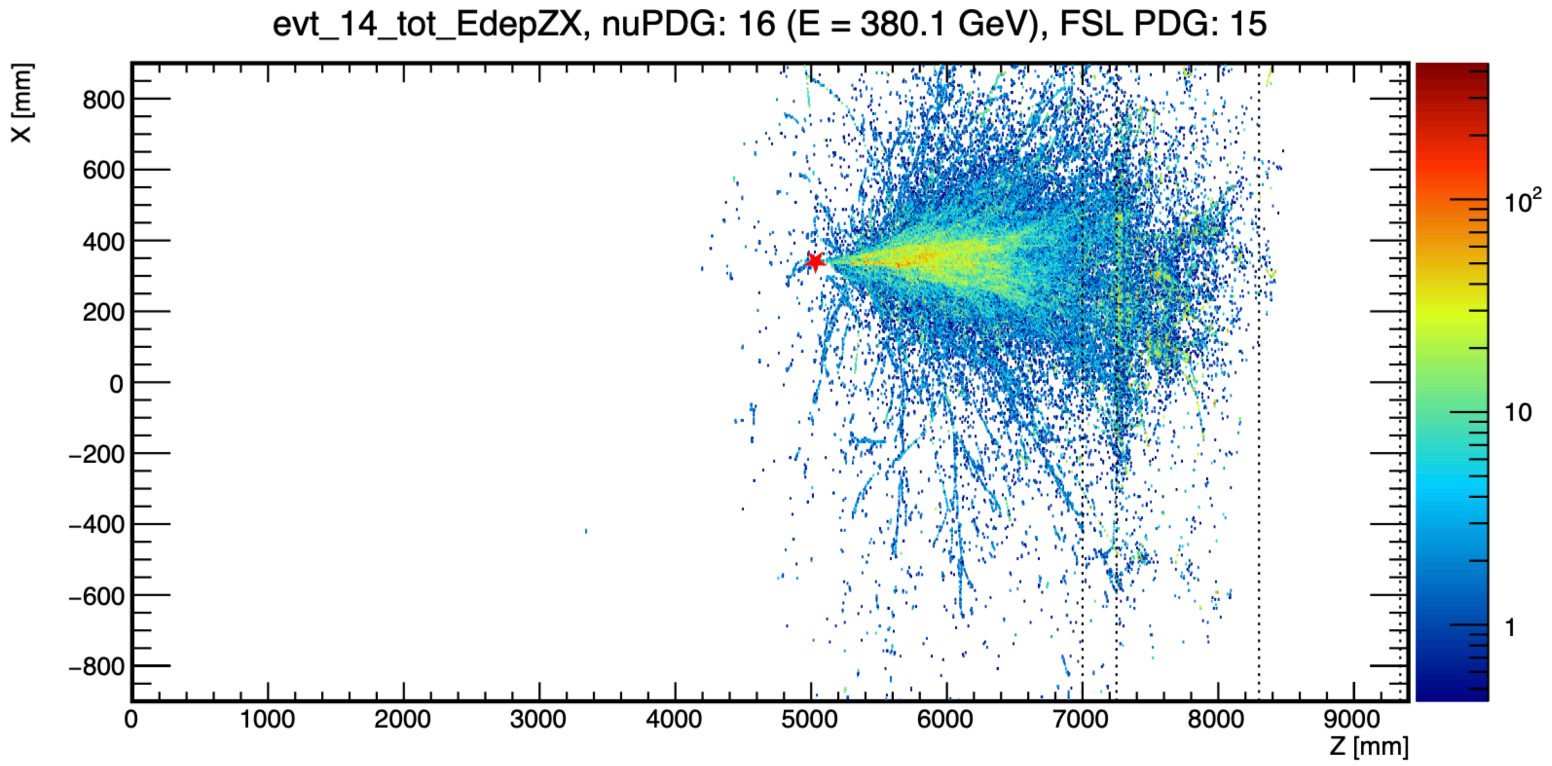


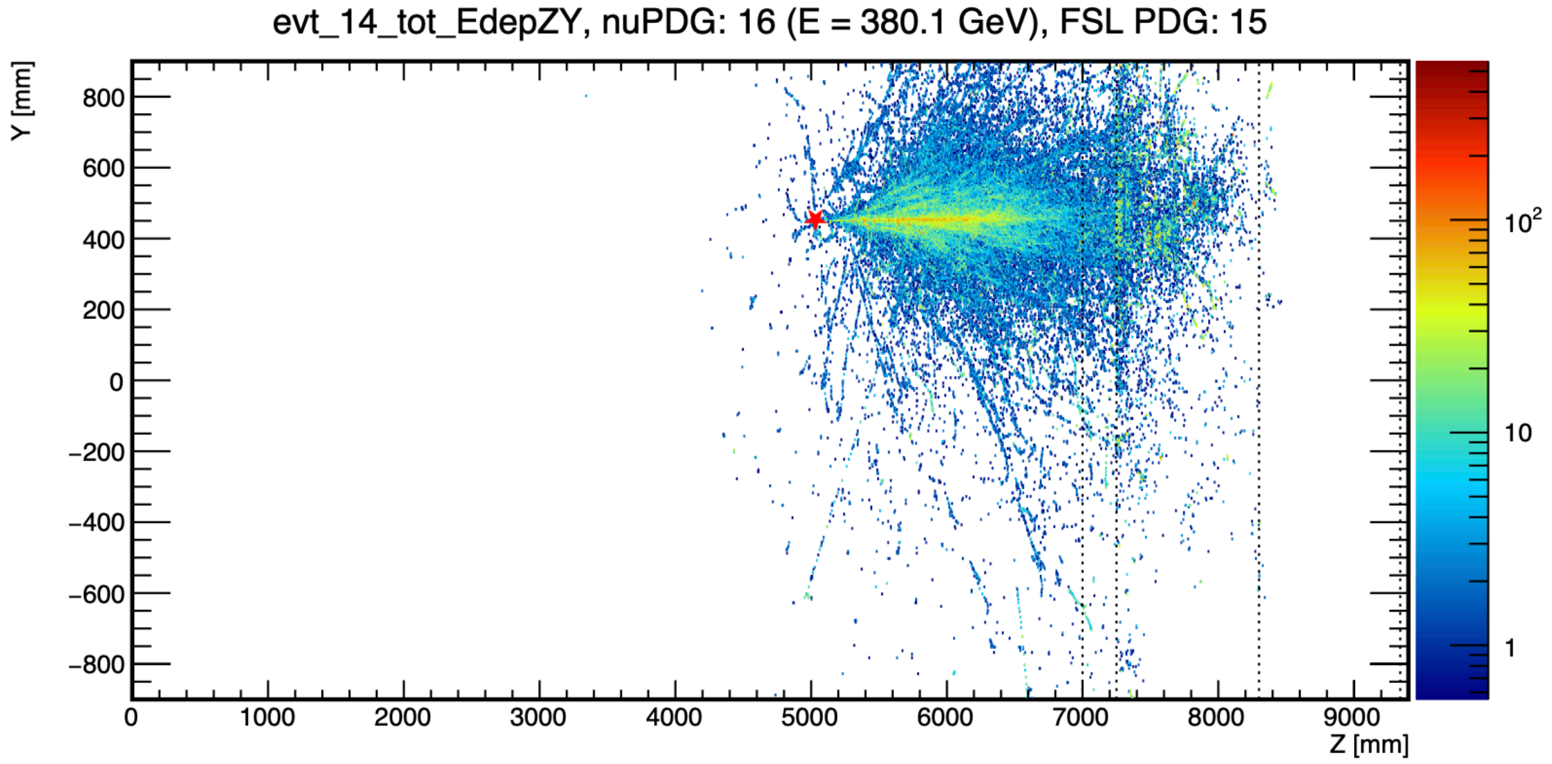
Preliminary

ν_τ Identification

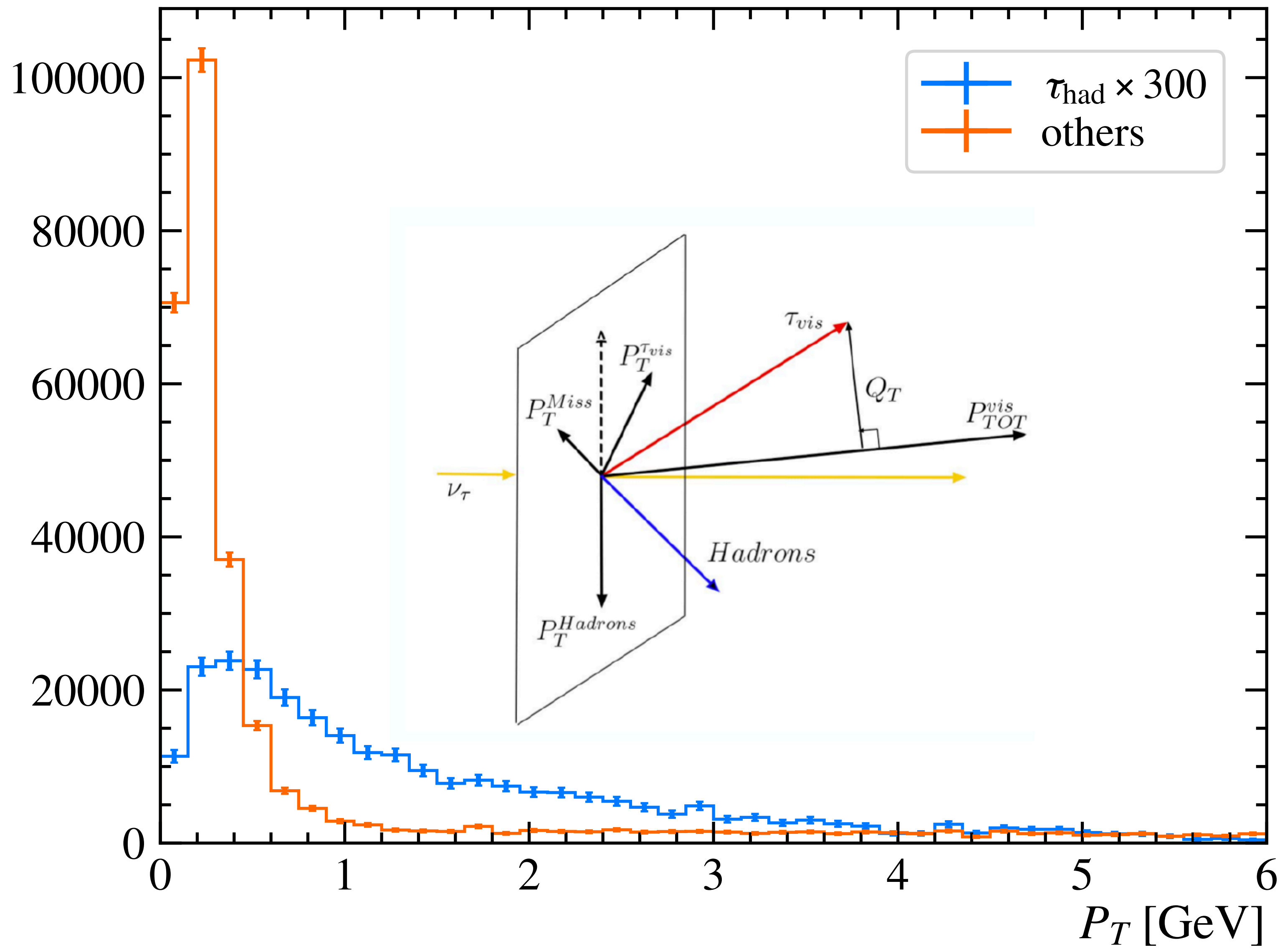
Consider τ_{had} (hadronic decay of CC tau) as the signal

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

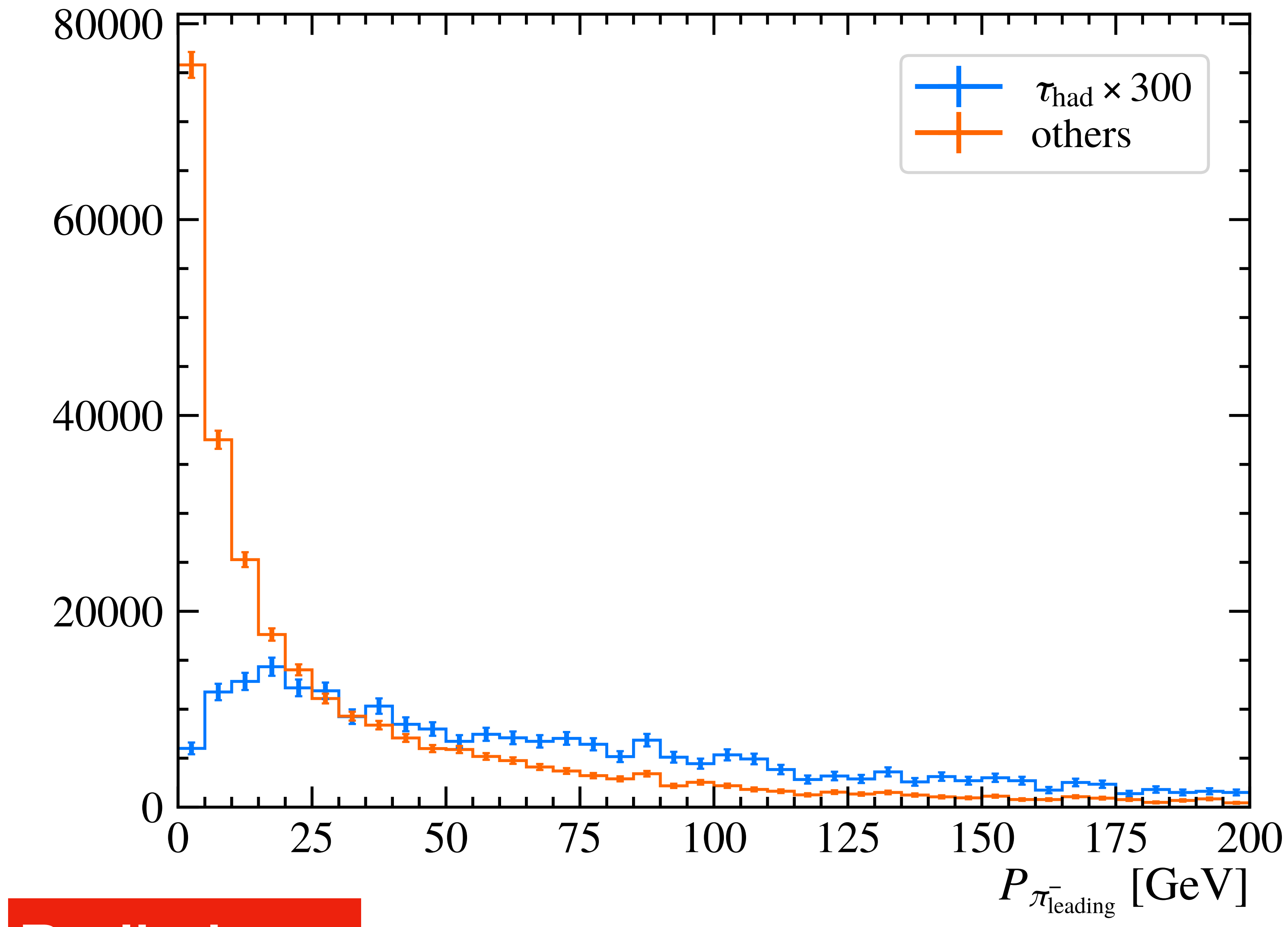




τ_{had} have more neutrino in the final state contributing to the missing momentum in the transverse plane



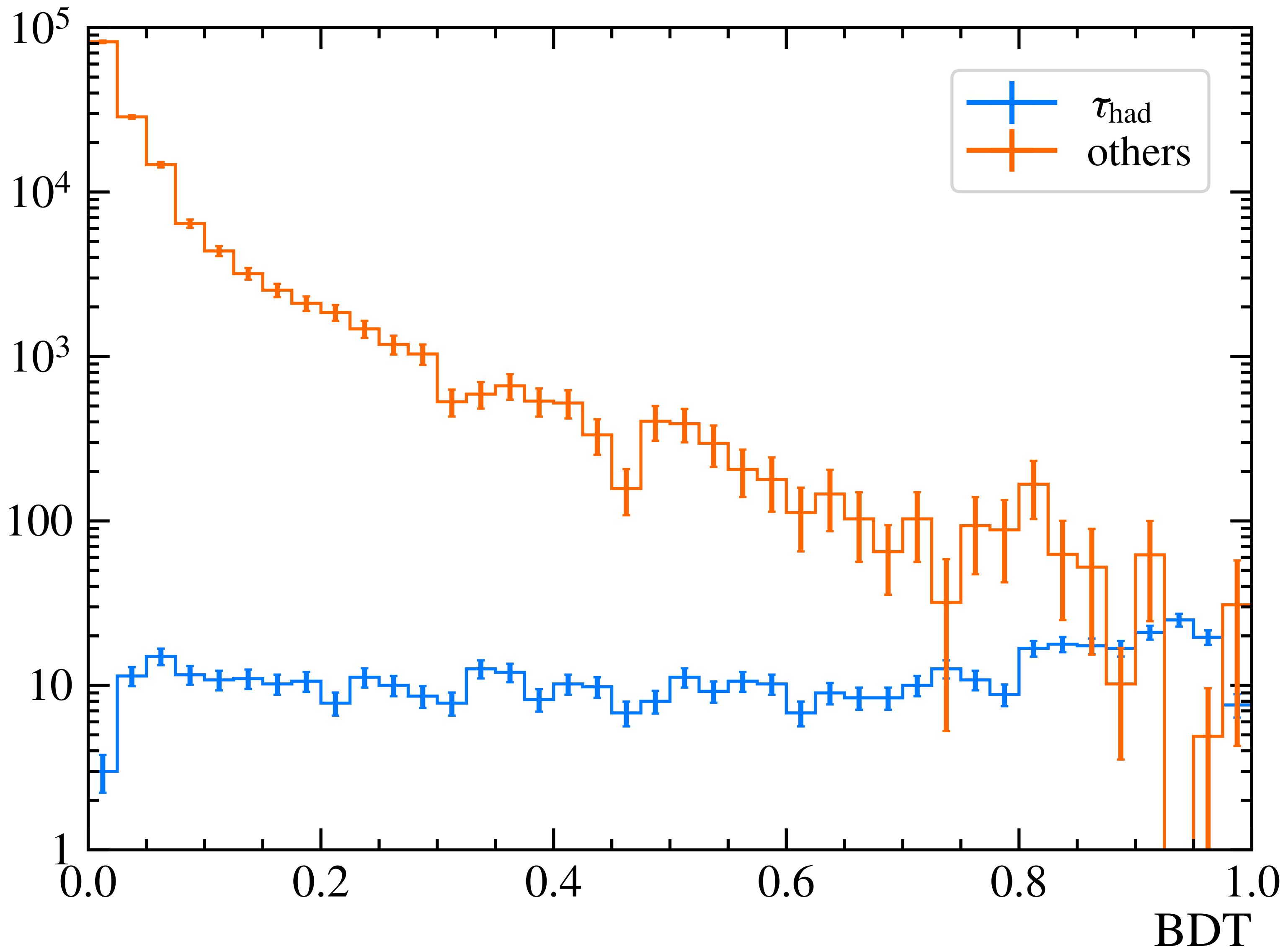
τ_{had} generally has a more energetic π^- in the final state



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

Also working on other τ decay modes

Preliminary



Summary

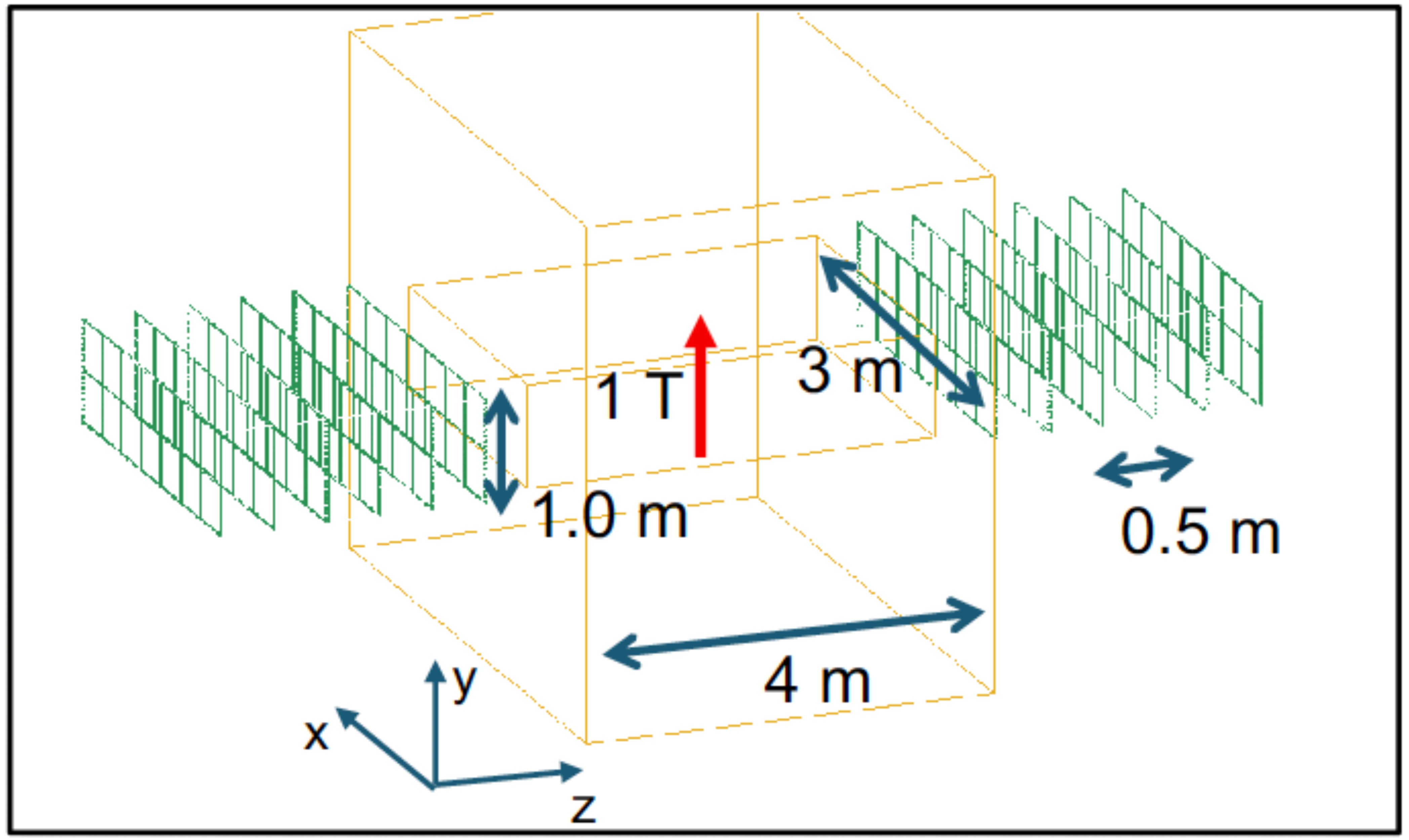
- A forward physics facility (FPF) is being considered at CERN for neutrino and dark matter physics
- Liquid Argon detector FLArE for FPF is being planned
- Detector capability, event rate, and backgrounds of FLArE are preliminary studied, showing that a LAr detector is feasible
- Engineering and simulation work towards a CDR is underway

Thank you!

Backup Materials

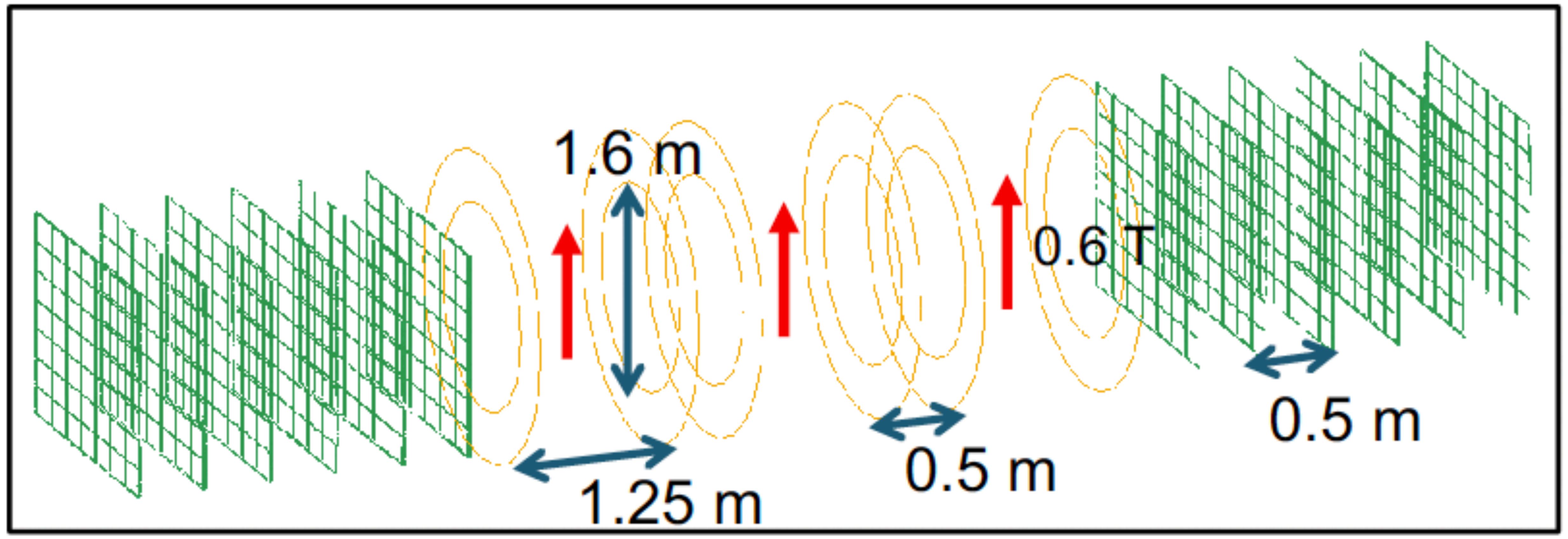
Magnet geometries

<u>SAMURAI magnet</u>



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

<u>Crystal-Pulling magnet</u>

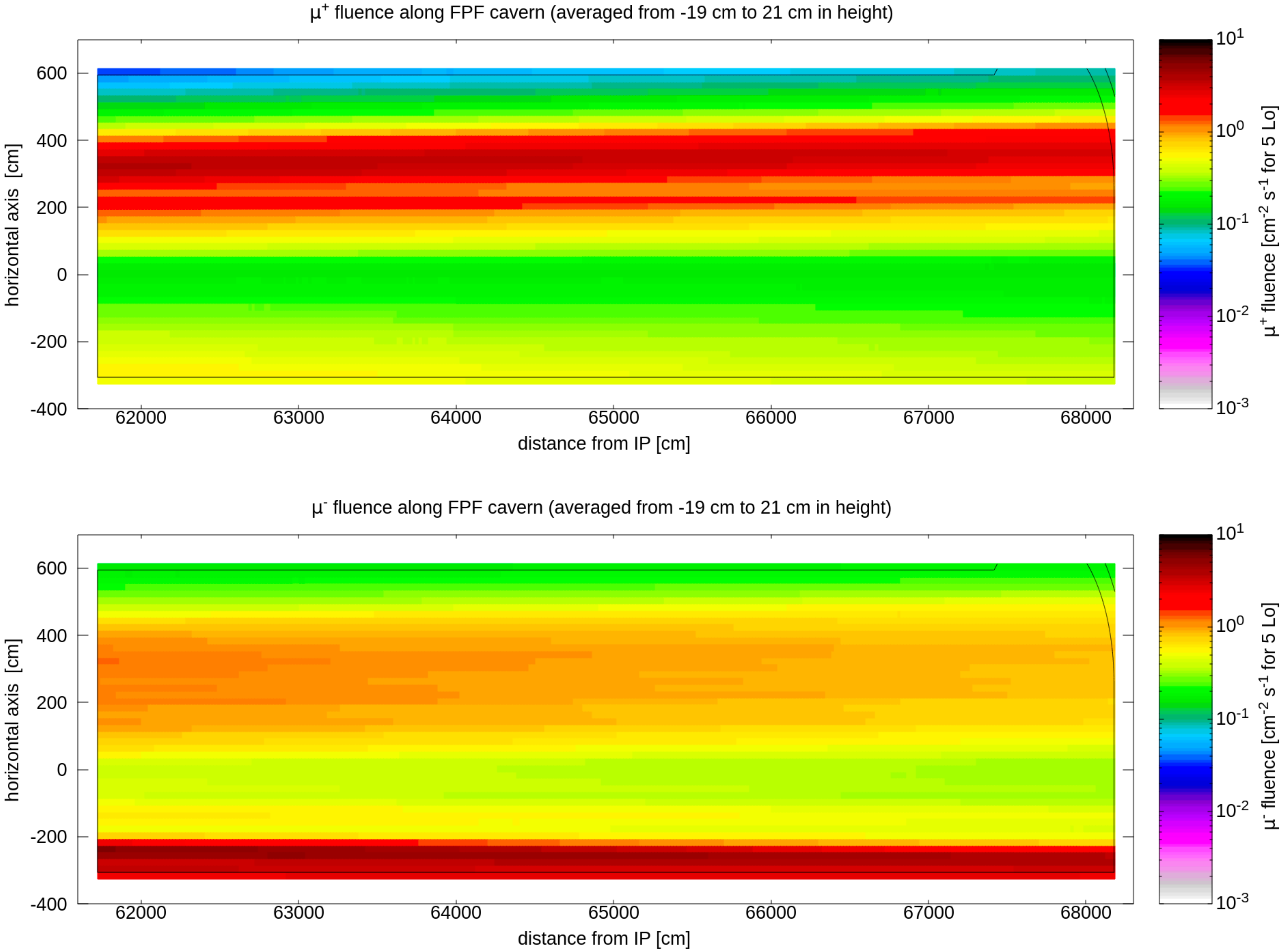


3 magnets, 50cm apart
Circular window: 1.6 m (diameter) x 1.25 m
6 tracking stations, 50 cm apart
B = 0.6 T (vertical)

- 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/

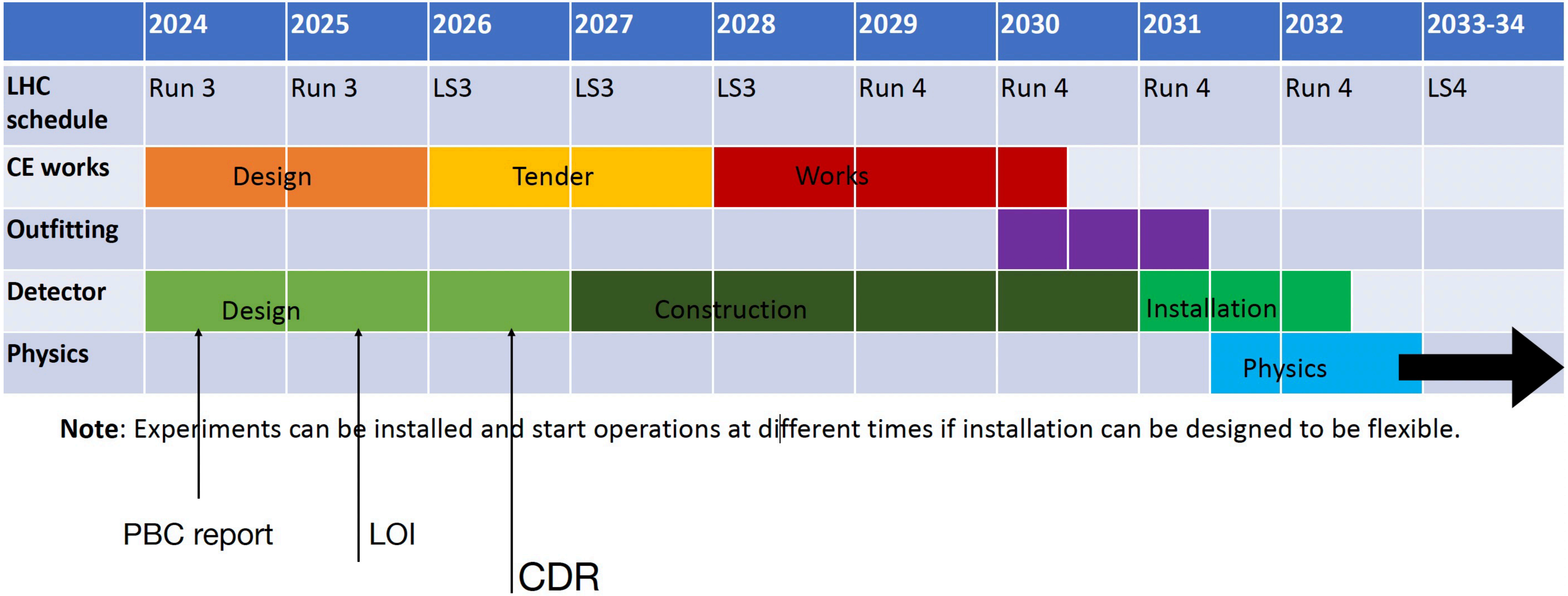


- Fluence in the horizontal plane in FPF location from CERN FLUKA team (20 cm from LOS in vertical plane)
  - Clear hot spot at ~2 m from the LOS
- Muon flux
  - ~0.6 Hz/cm^2 (0.15 mu+, 0.45 mu-)
  - ~6 tracks/ms per m^2 of detector
- Neutron flux ~0.1 Hz/cm^2 is mostly at low energies

Hardware-based trigger studies

- FLArE trigger system will need to identify signal events from muon background.
  - 0.5 Hz/cm^2 muon flux from ATLAS collisions gives 5 kHz rate in the 1m x 1m x 7m fiducial region.
- Want to match signal events to ATLAS bunch crossings.
  - Need fast trigger decisions to meet HL-LHC ATLAS 6 μs (30 μs) L0 (L1) trigger latency requirements.
- Will try combination of traditional/ML methods for SiPM/event-level trigger decisions on GPU/FPGA.

Possible FPF Timeline



	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033-34
LHC schedule	Run 3	Run 3	LS3	LS3	LS3	Run 4	Run 4	Run 4	Run 4	LS4
CE works	Design		Tender		Works					
Outfitting							🟪	🟪		
Detector	Design			Construction				Installation		
Physics								Physics		➡

Note: Experiments can be installed and start operations at different times if installation can be designed to be flexible.

PBC report

LOI

CDR

Aim to fit US FLArE efforts into the ASTAE portfolio