Forward Physics Facility

- A Host of Future Experiments at LHC

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On behalf of the FPF Working Groups

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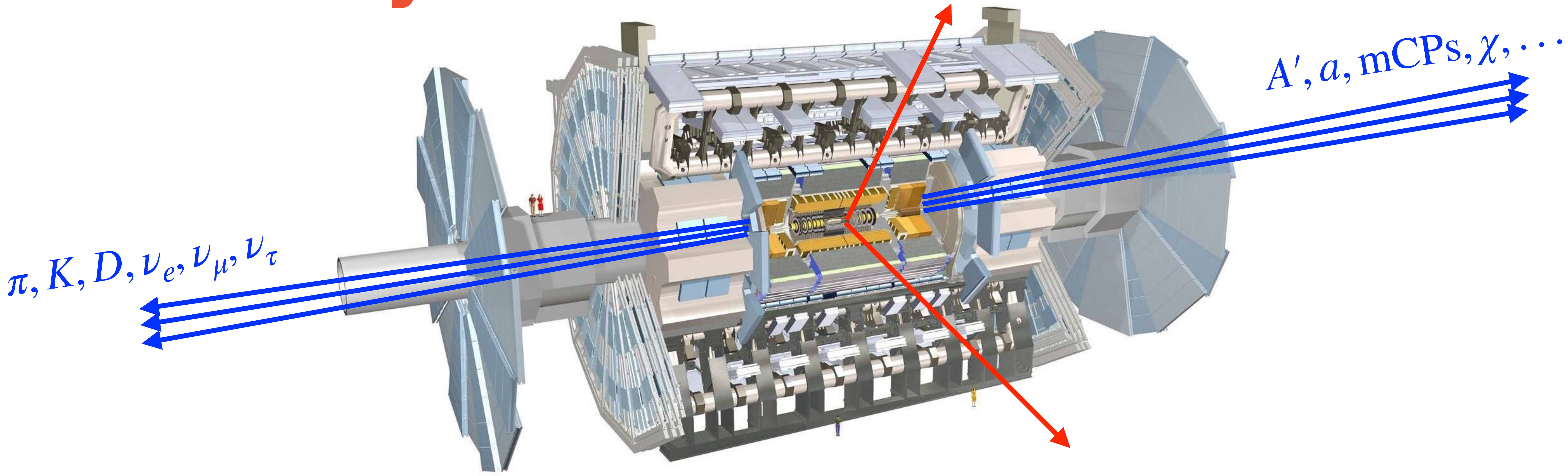
Forward Physics at LHC

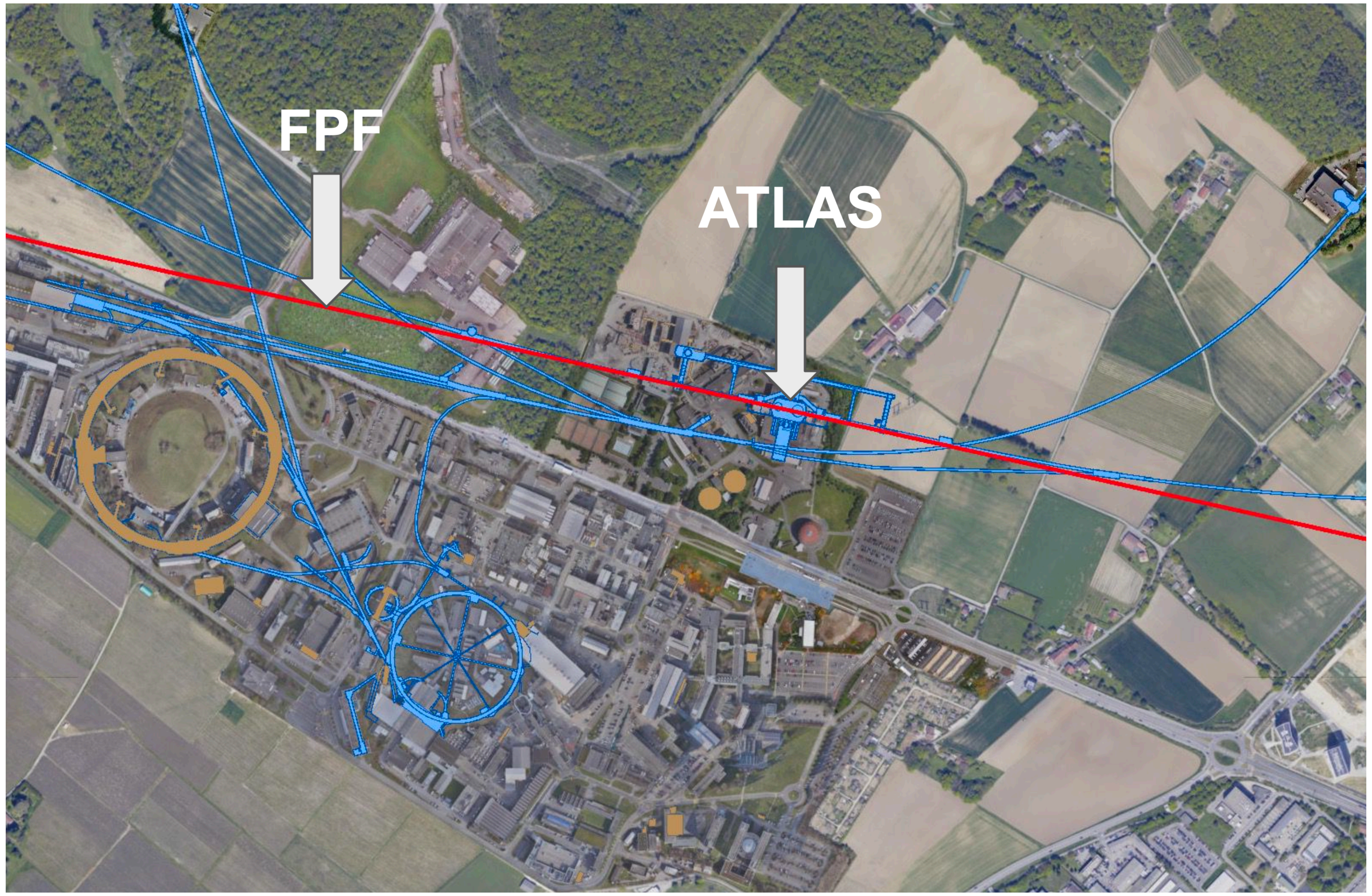


- Existing LHC experiments primarily focused on high-p_T physics, for searches of heavy particles (*W, Z, t, h,* …)
- Most of the inelastic *pp* collisions produce particles travel approximately parallel to the beamline and escape through the blind spots
  - SM: pions, kaons, and other light mesons,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

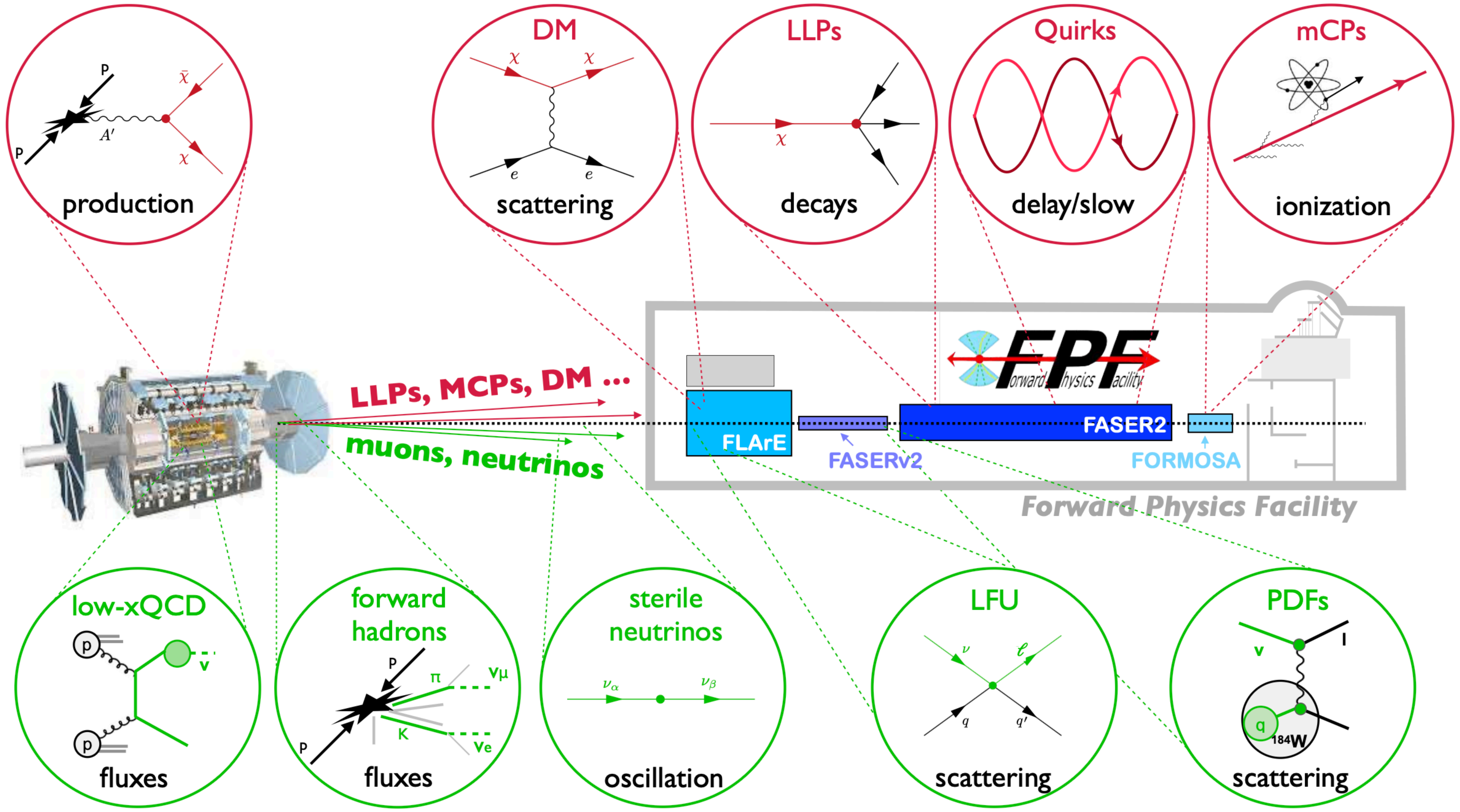
- The primary goal is to extend the current LHC forward physics program into HL-LHC era with x10-100 exposure
- Comprehensive site selection study performed by the CERN civil engineering
- ~600 m west of the ATLAS IP along the line of sight (LOS)
- ~75 m long, 12 m wide cavern
- Shielded from ATLAS by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



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

Physics Motivation

- The FPF has a rich and broad physics program
- Three main physics motivations
  - Beyond Standard Model (BSM) “dark sector” searches
  - Collider neutrinos
  - QCD Physics



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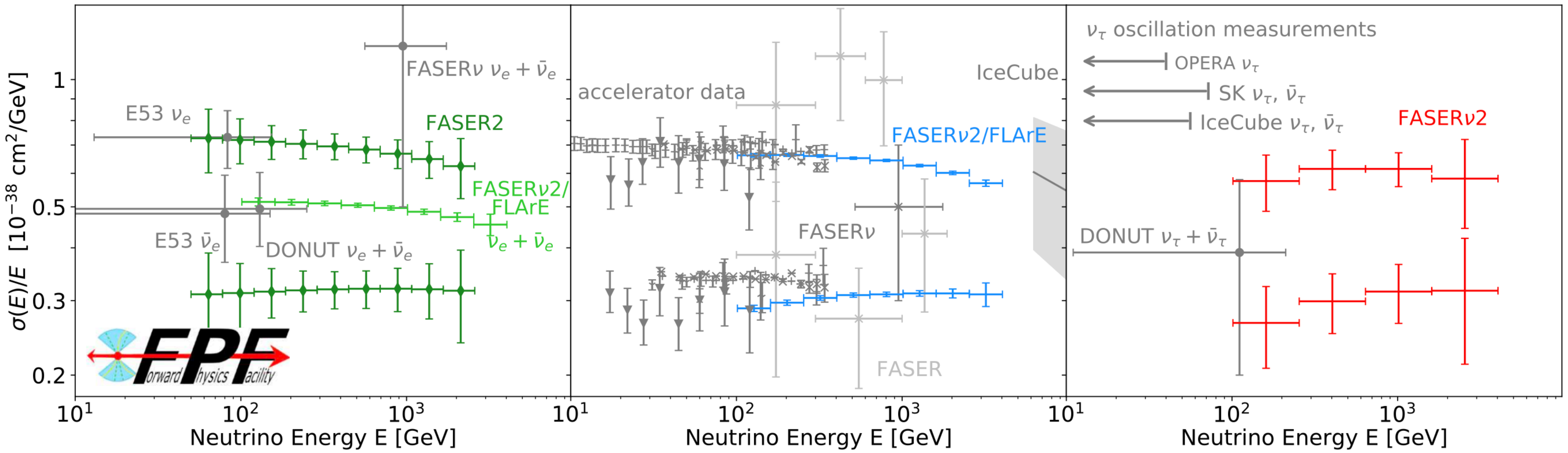
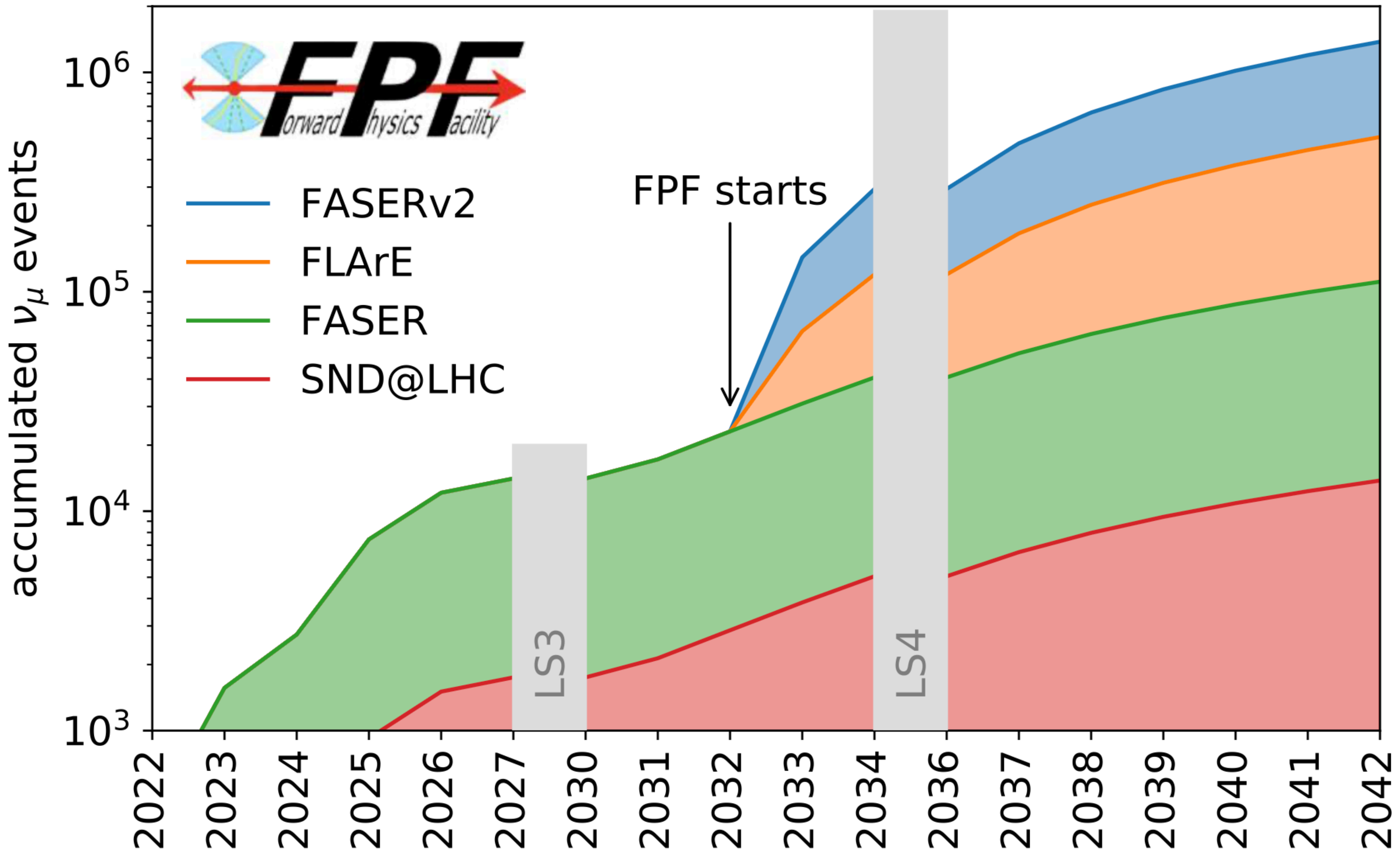
Neutrino Physics

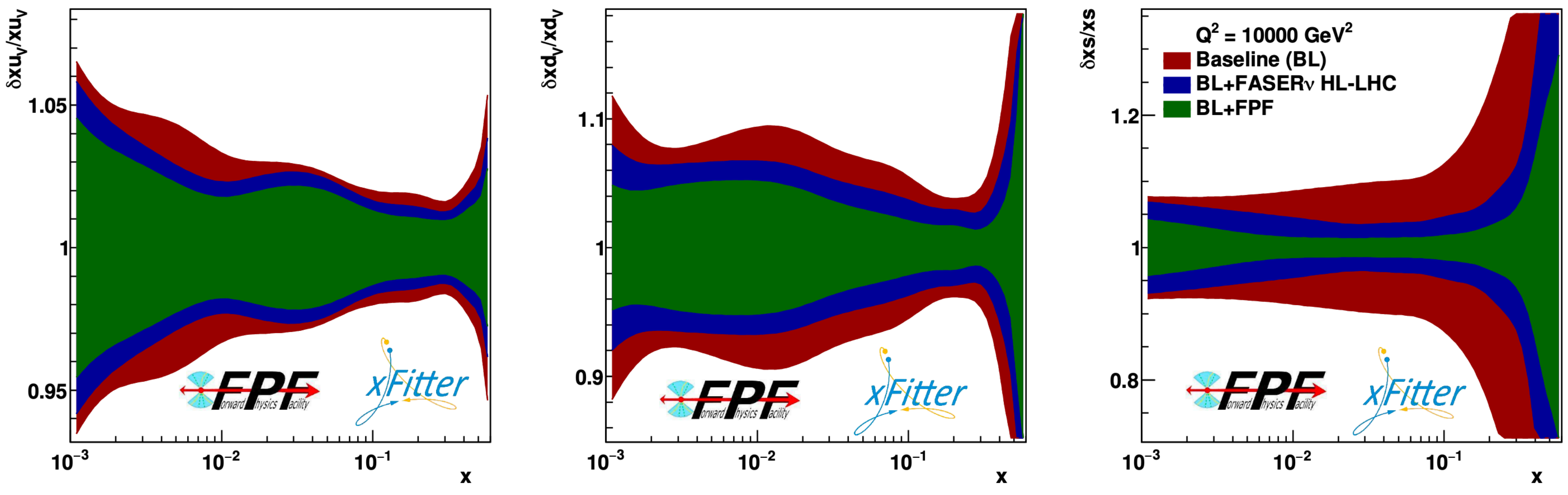
- Neutrinos from LHC provide data that fills in the gap between the current accelerator and atmospheric neutrinos
- **FASER and SND@LHC have made the first observation of of neutrinos at the LHC**
- FPF will see ~10^5 ν_e, 10^6 ν_μ, 10^4 ν_τ interactions at ~TeV energies
  - 100x more statistics compared to running exp.
- Tau Antineutrino Observation and Tau Neutrino Precision Physics

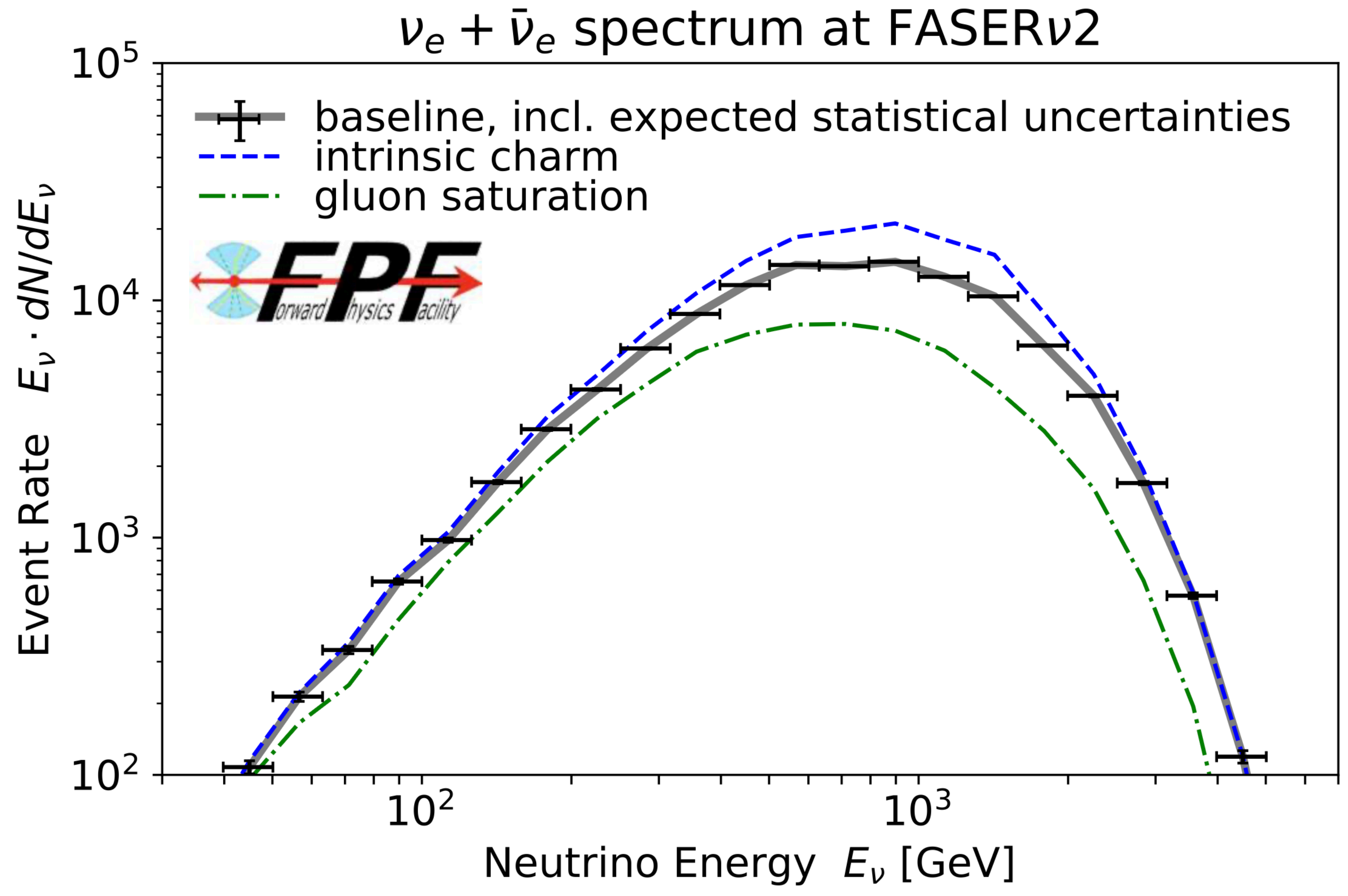




QCD

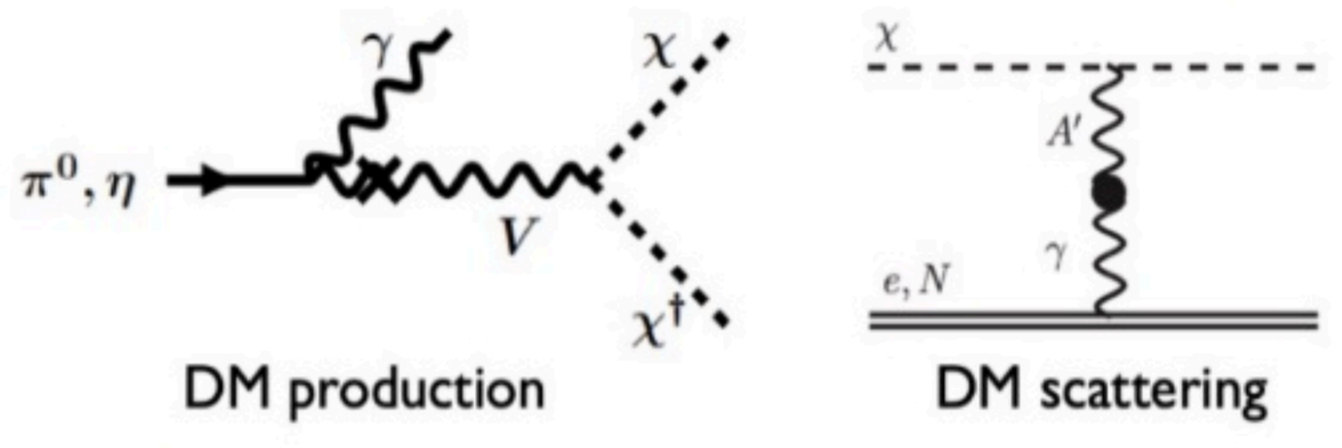
- The intense beam of TeV neutrinos and muons can serve as powerful tools for studying QCD
- Proton and nuclear parton distribution functions (PDFs) in poorly understood regimes
- Neutrino flux measurements provide a novel method to probe and constrain forward hadron production, providing insights into the underlying physics
- Both scattering and production measurements can refine our understanding of QCD



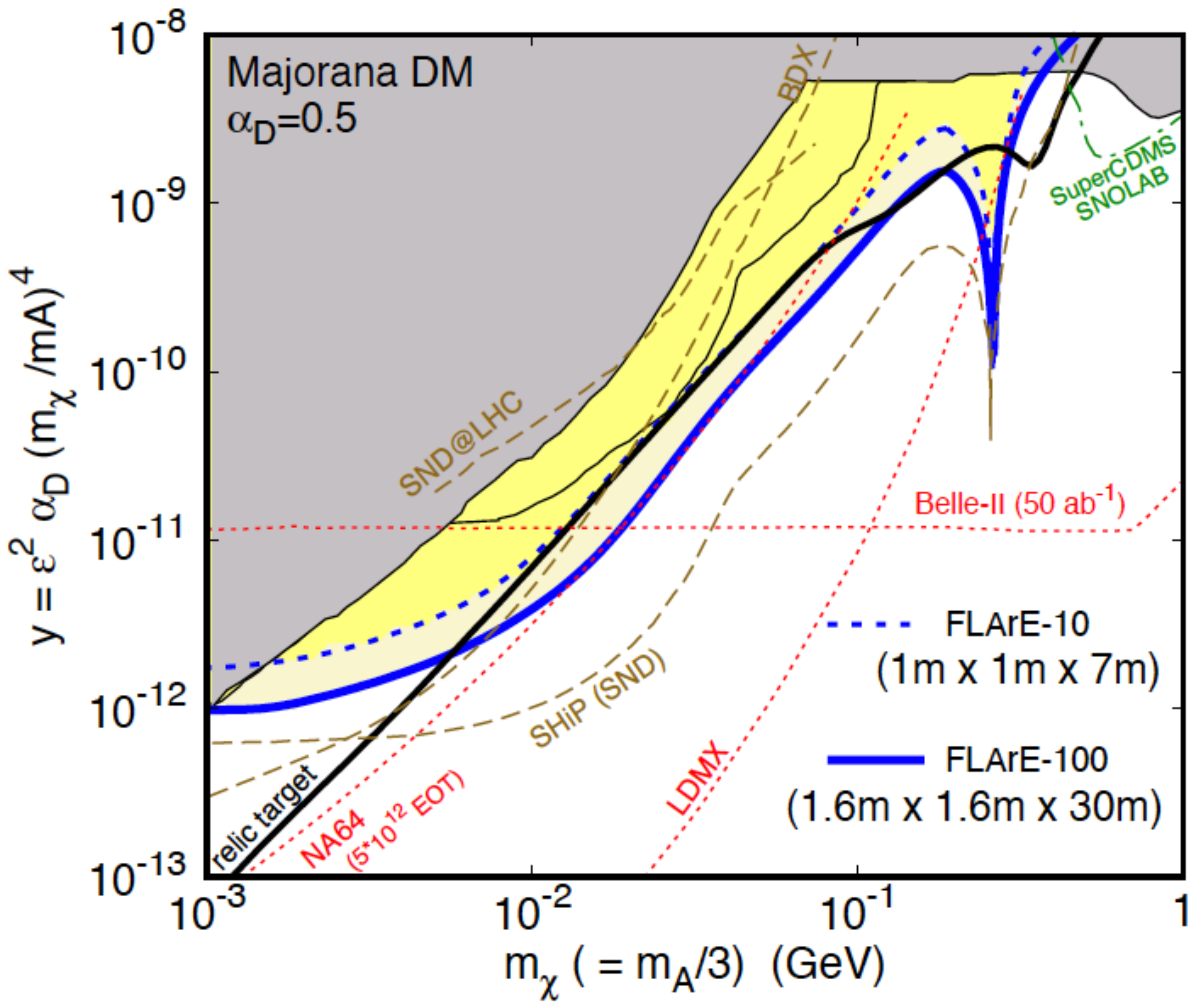


Light Dark Matter Scattering

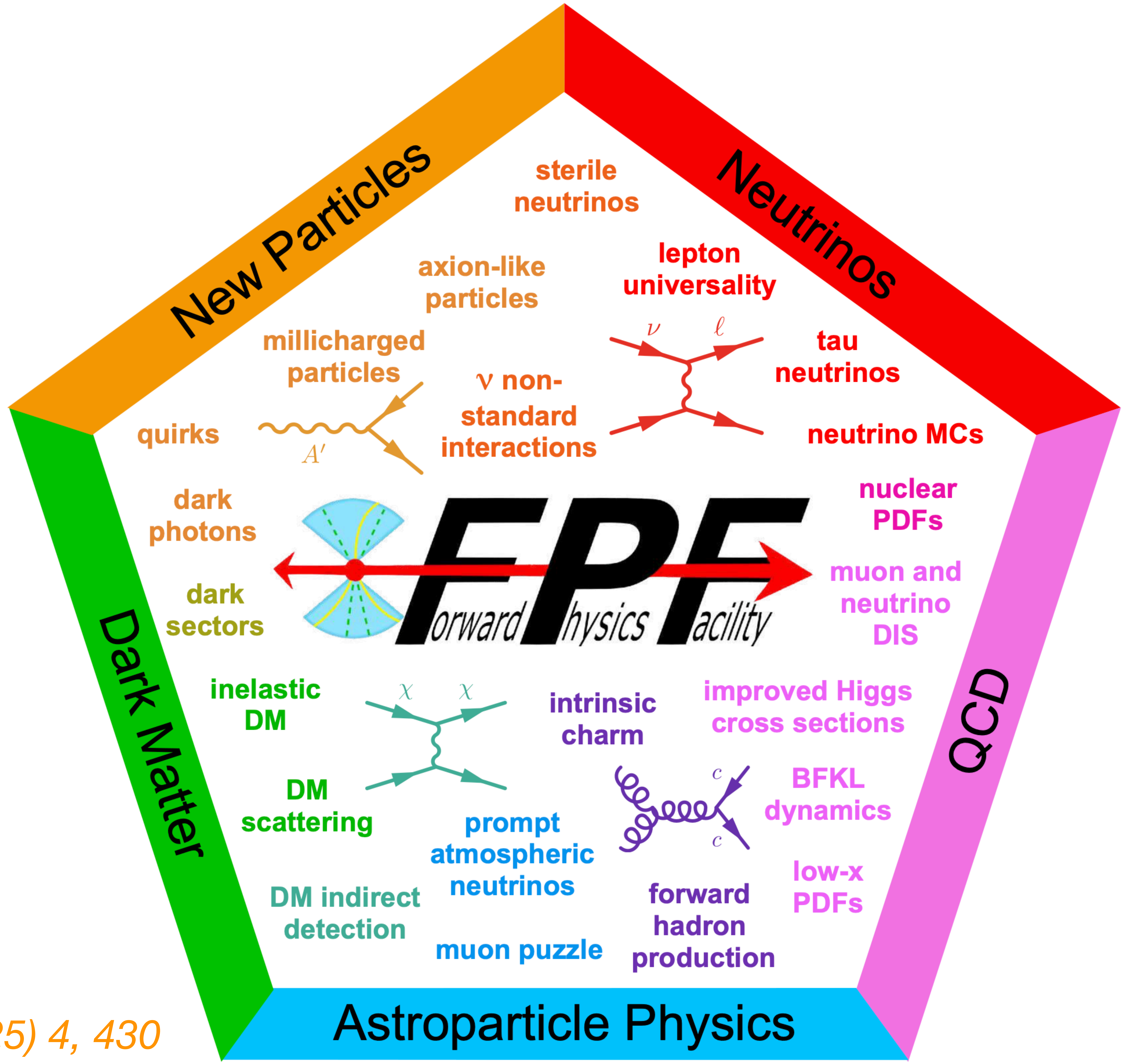
Elastic scattering from electrons and nuclei



- 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



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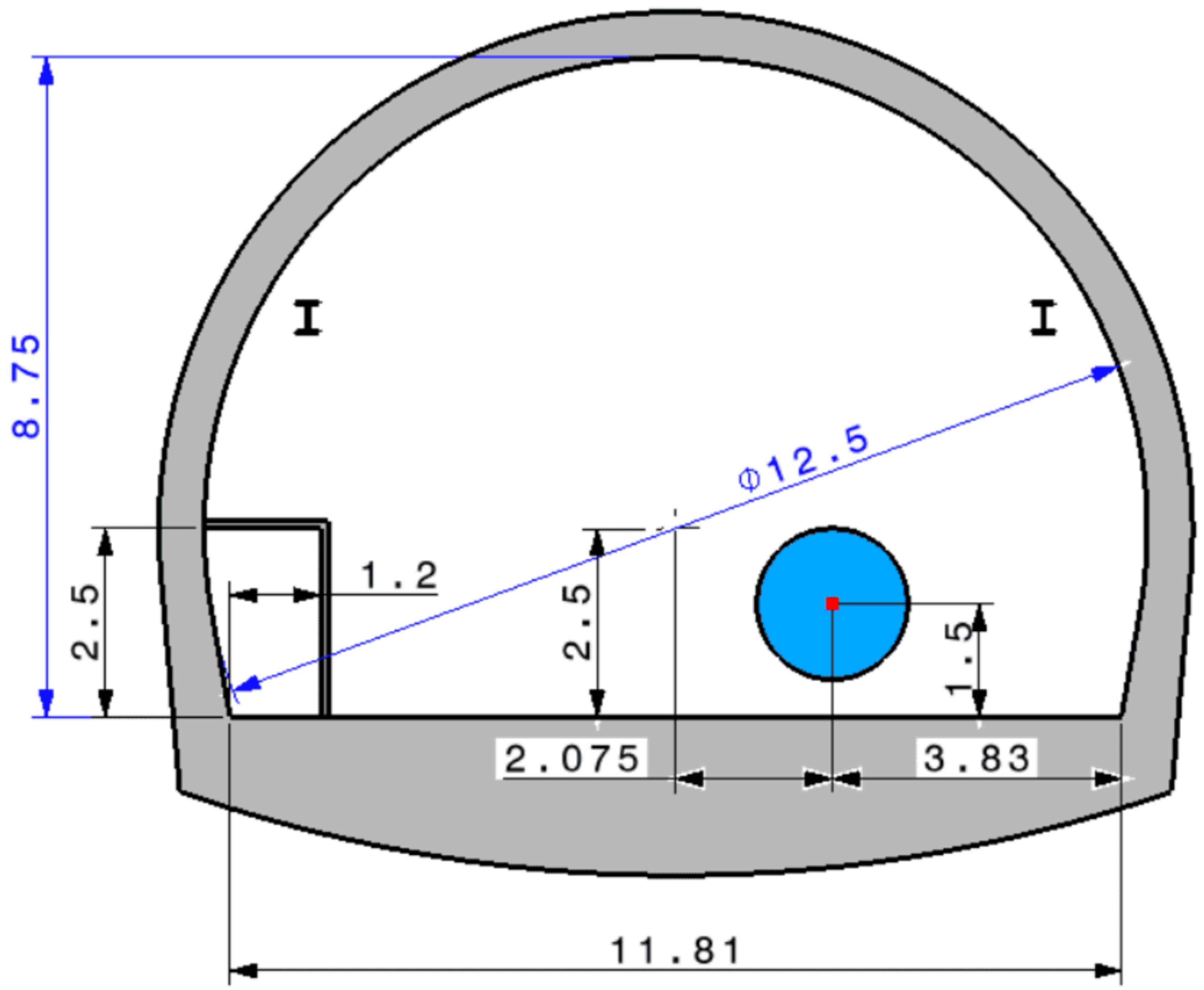
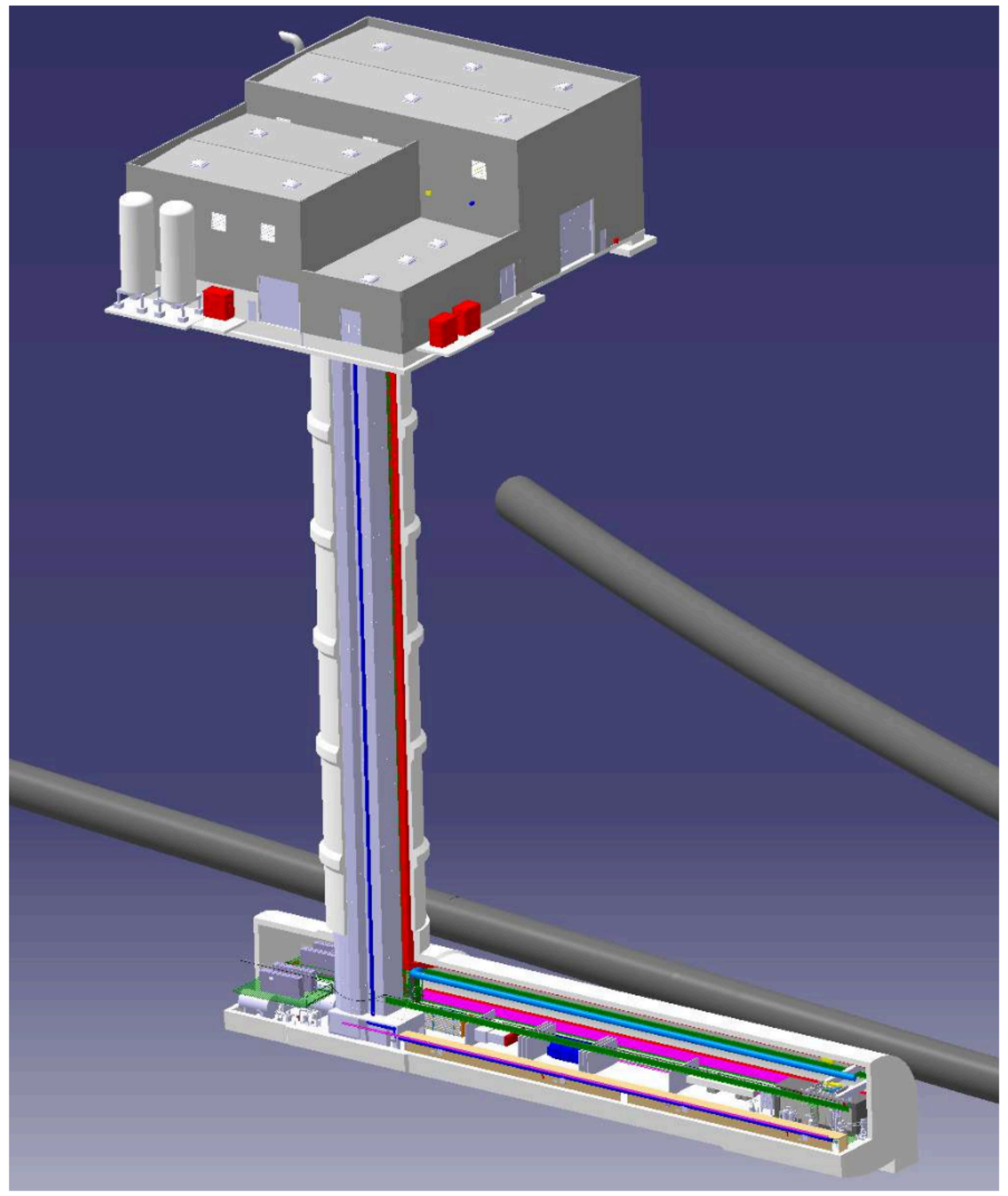
The Facility

- The facility is disconnected from LHC tunnel
- Vibration and safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running
- Geological study of the core sample taken from the proposed location verifies there is no showstopper for excavation



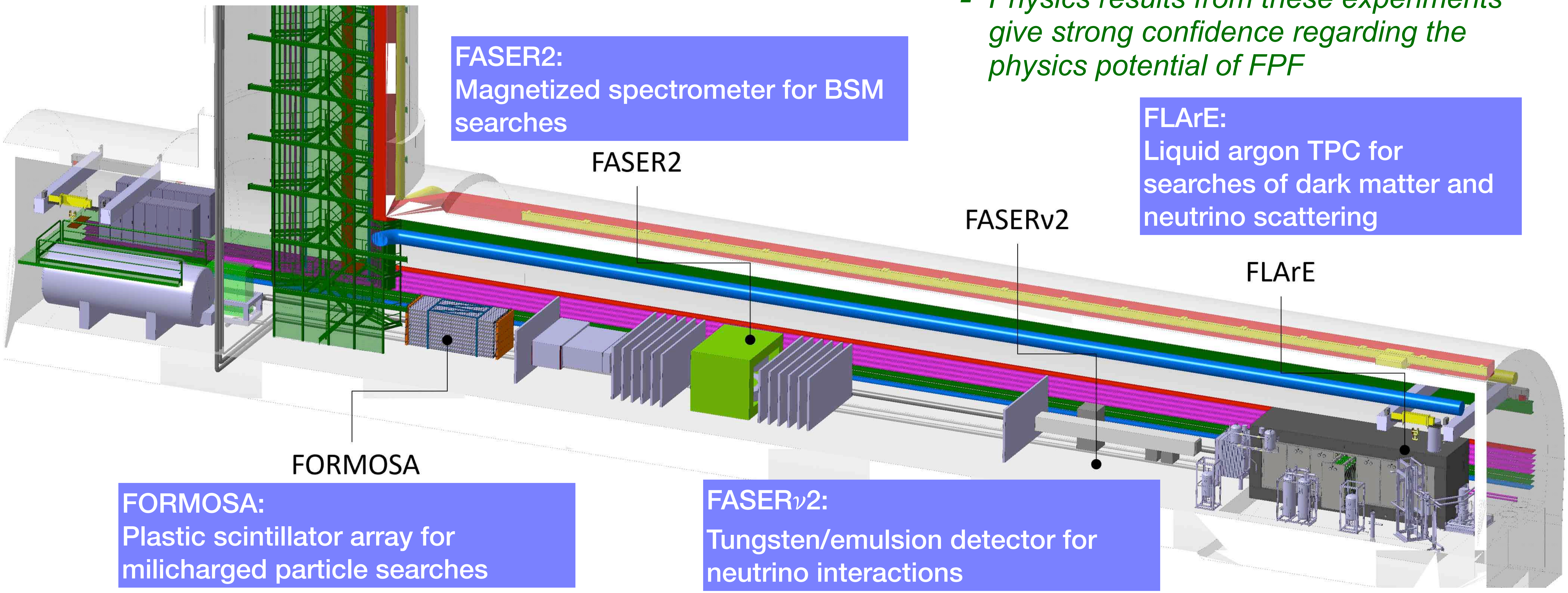


Core sample taken from 100 m underground

FPF Experiments

Pathfinder versions of the detectors:

- *FASER, FASERν, milliQan*
- *Physics results from these experiments give strong confidence regarding the physics potential of FPF*



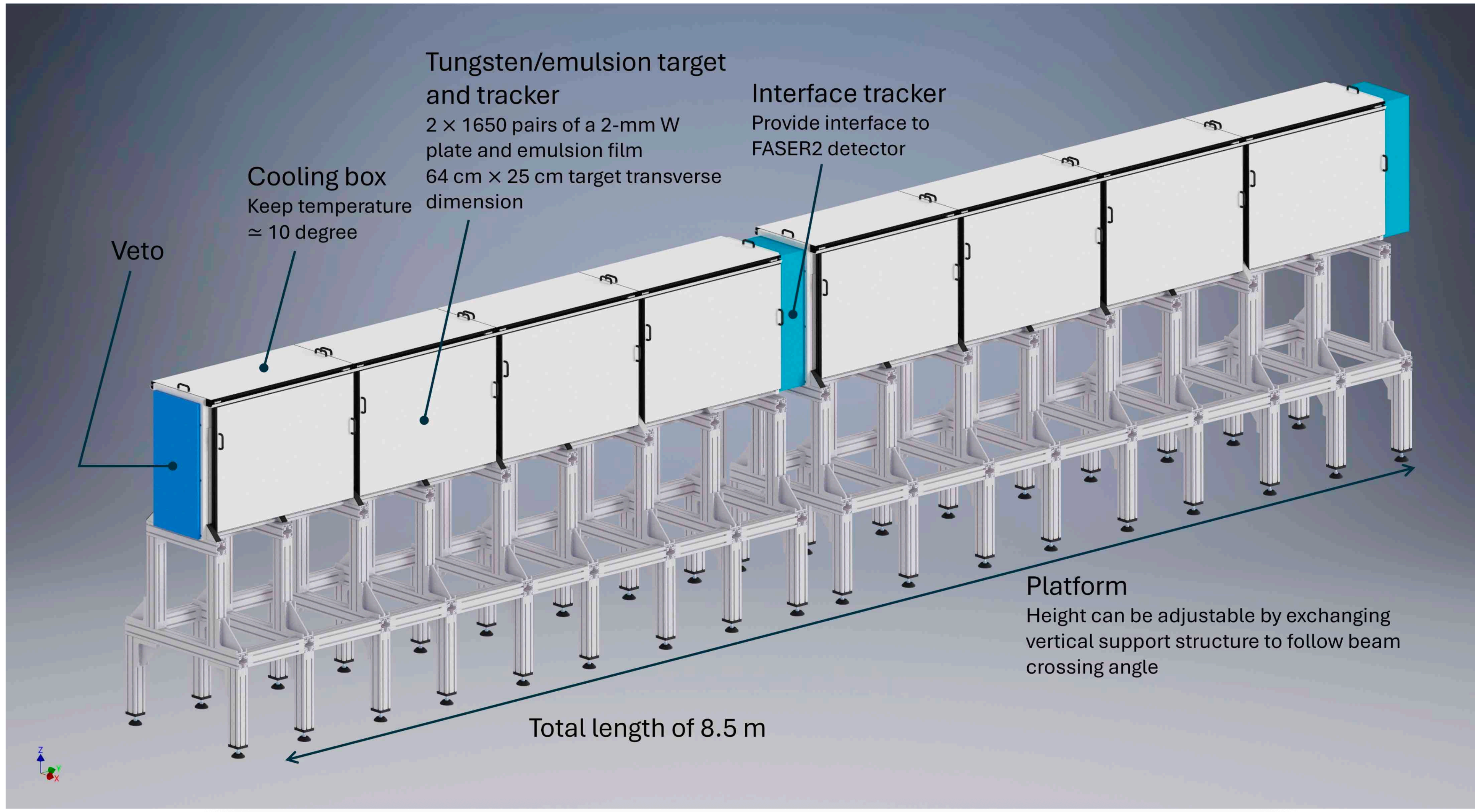
Diverse technologies optimized for SM and BSM physics

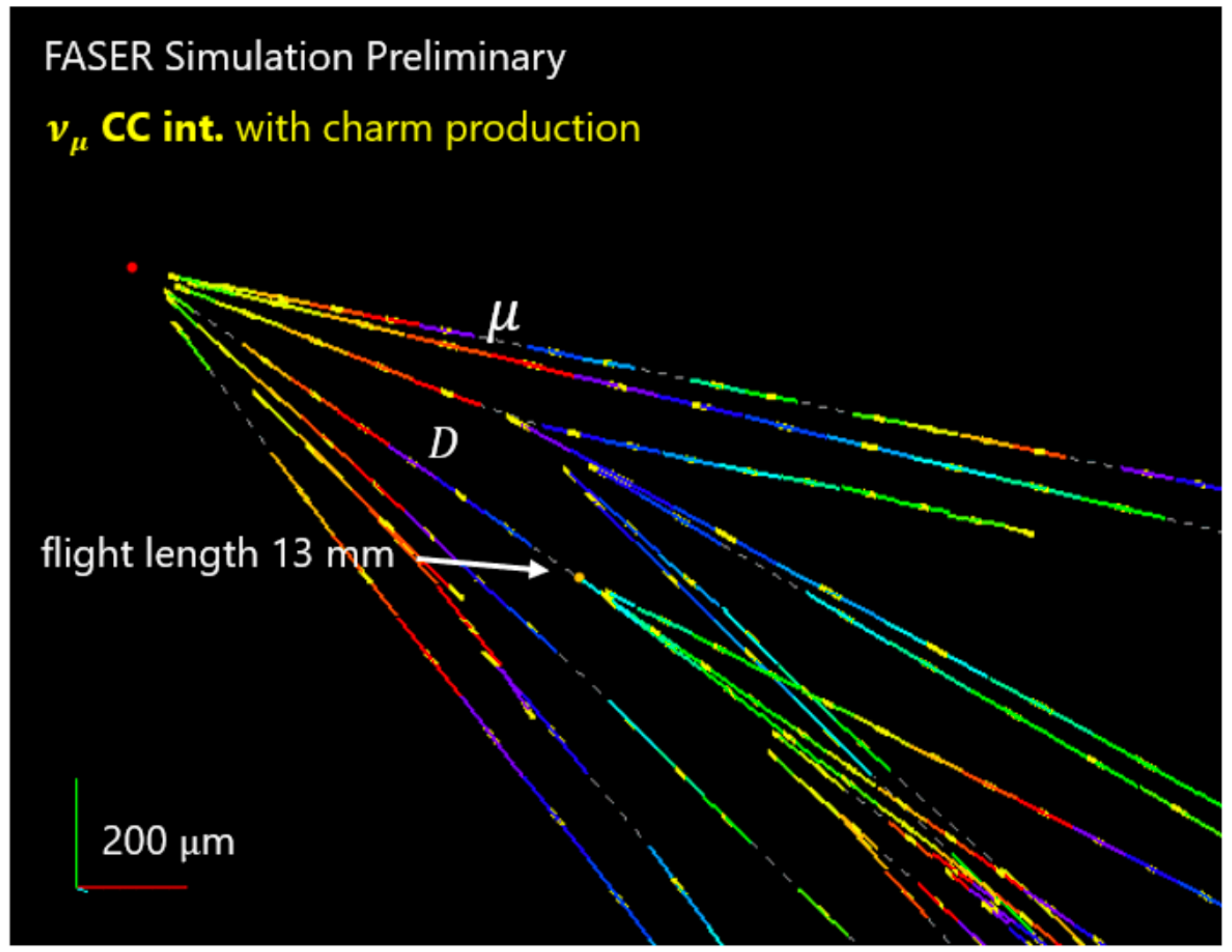
Synergies exist among FPF detectors

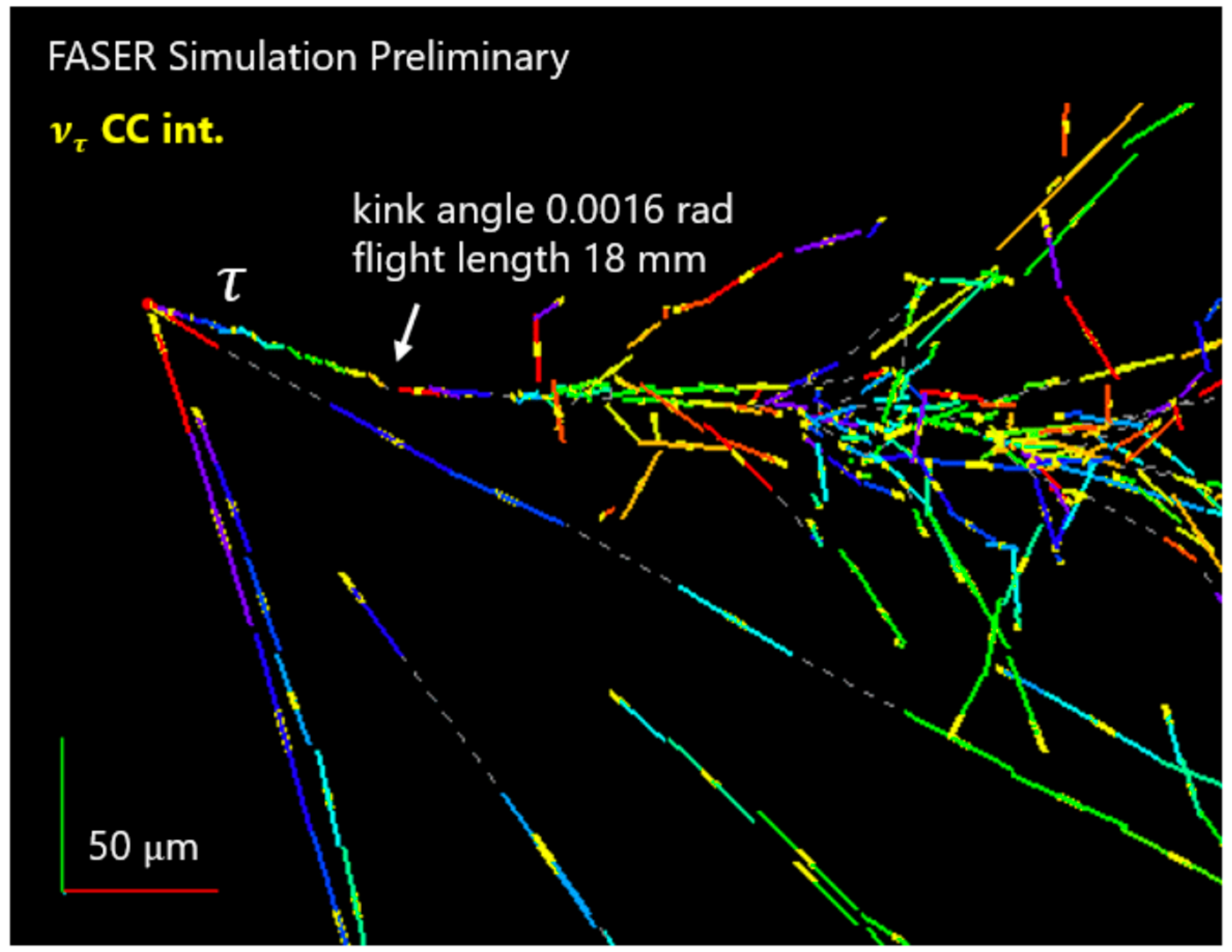
Many opportunities for new groups

FASERν2 Detector

- Emulsion detector, scaled up version of FASERν
  - 20 tons target mass
- Electronic detectors (Interface tracker) to allow to tag events and connect muons from neutrino interactions with those reconstructed in the FASER2 spectrometer (for charge/momentum measurement)
- Emulsion needs to be replaced with track occupancy of O(10^5) tracks/cm^2 (about 2months of HL-LHC running)
- Superb position (~0.3 um) and direction reconstruction (~0.05 mrad)

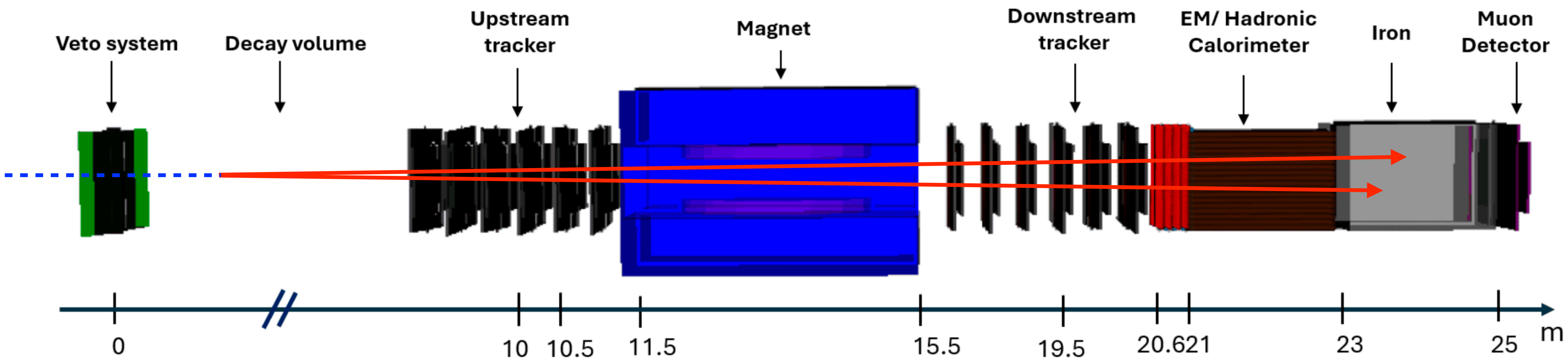






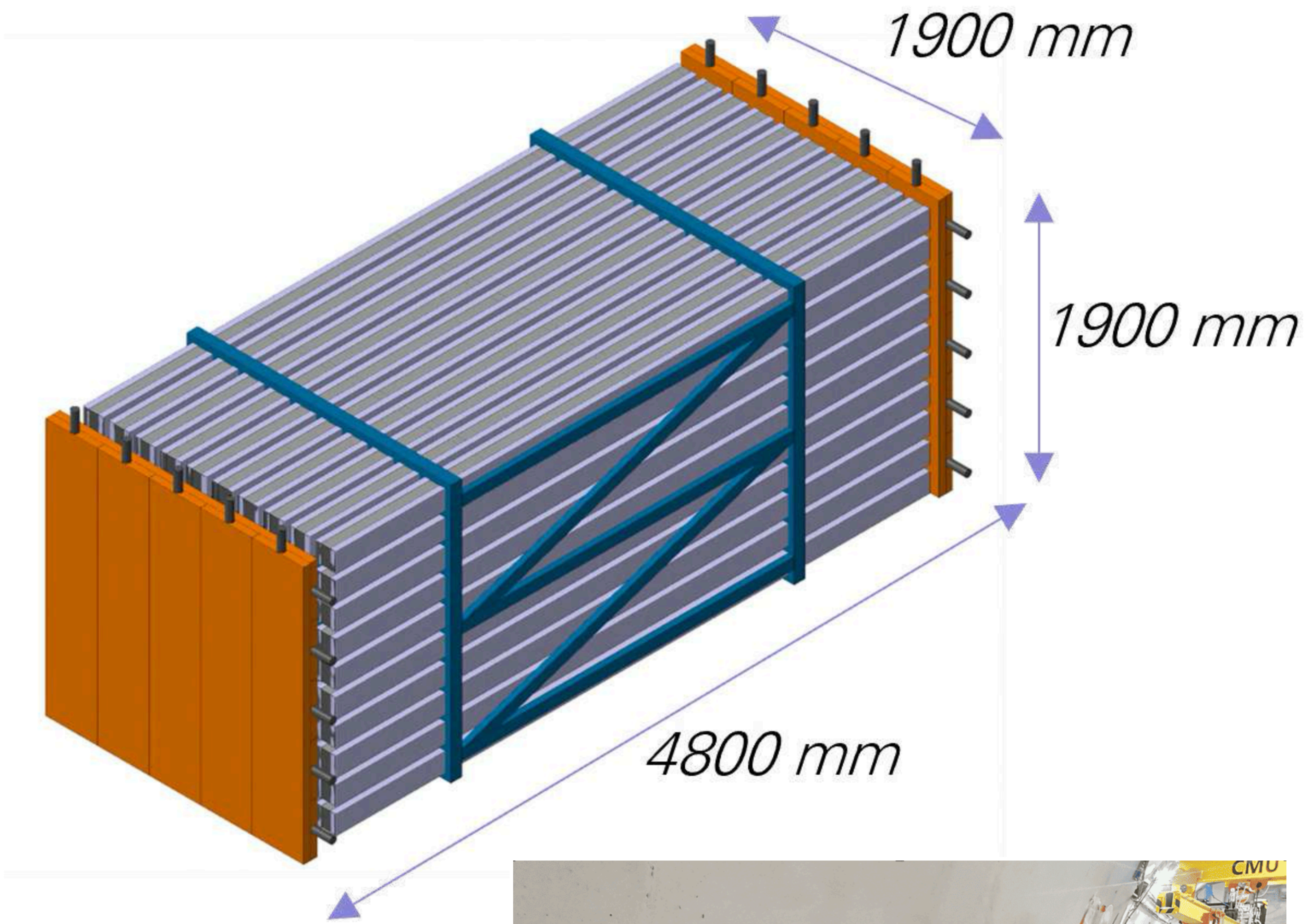
FASER2 Detector

- FASER2 is a scaled up version of the FASER experiment
- Designed to search for decaying BSM LLPs
  - 100x larger transverse size to FASER, and 7x longer decay volume
  - measure charge/momentum of muons from neutrino interactions in FLArE and FASERv2 upstream
- Two options for magnet:
  - Custom made super-conducting dipole (2Tm bending power 1.7x1.7m^2 square air-core aperture)
  - 4 off-the-shelf crystal-puller magnet units (2Tm (central) bending power 1.6m diameter air-core aperture)



FORMOSA Detector

- FORMOSA is a scintillator based millicharged particle detector (similar to the running milliQan experiment)
- Idea is to see low scintillation signal in multiple bars pointing at IP
- Baseline design: 20x20 array of scintillator bars (with surrounding scintillators to veto backgrounds)
- At start of 2024 a small demonstrator detector was installed in TI12 (FASER location) to study the performance with a large rate of through going muons from the IP. Using this demonstrator the DAQ concept for FORMOSA has been validated.



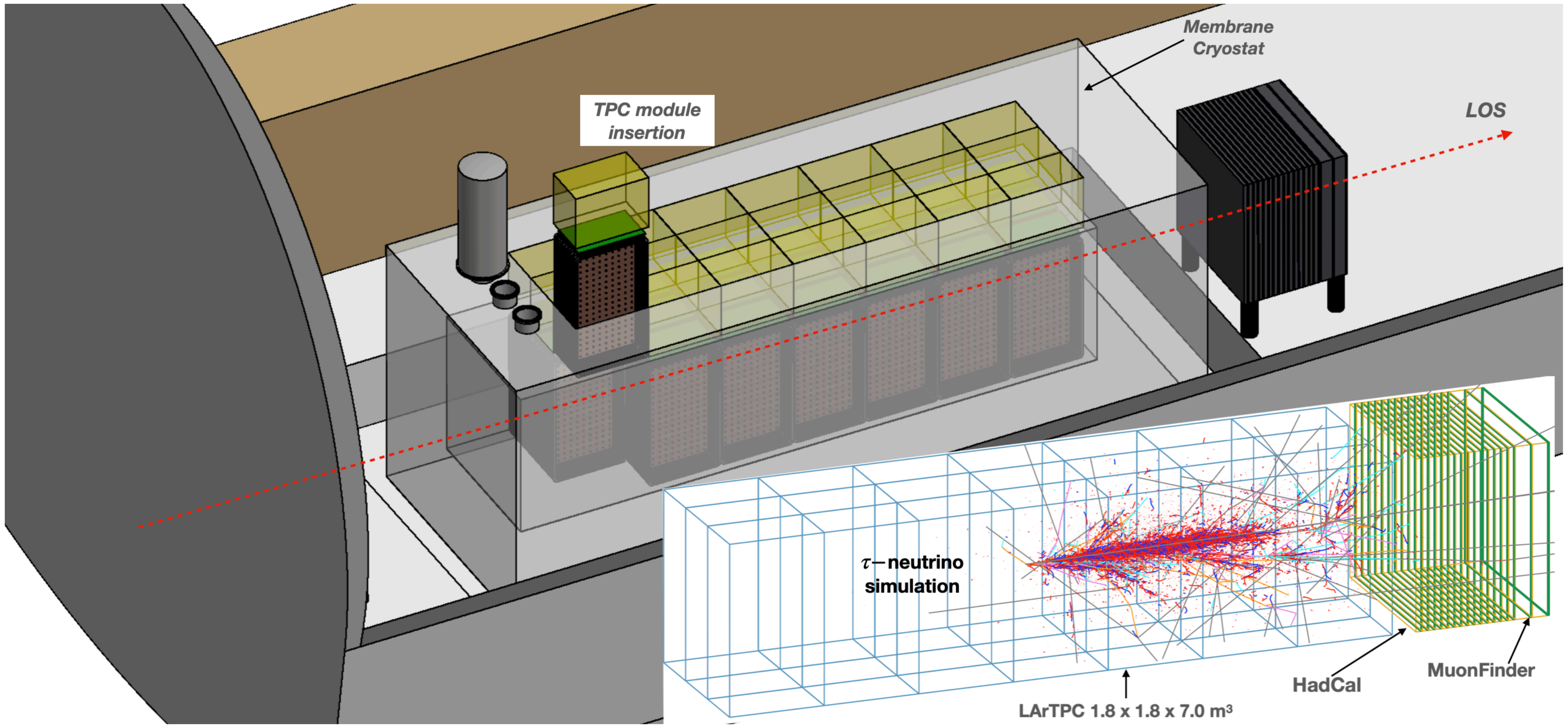
FORMOSA demonstrator
2x2x4 arrays of 5x5x80 cm^3 scintillator bars

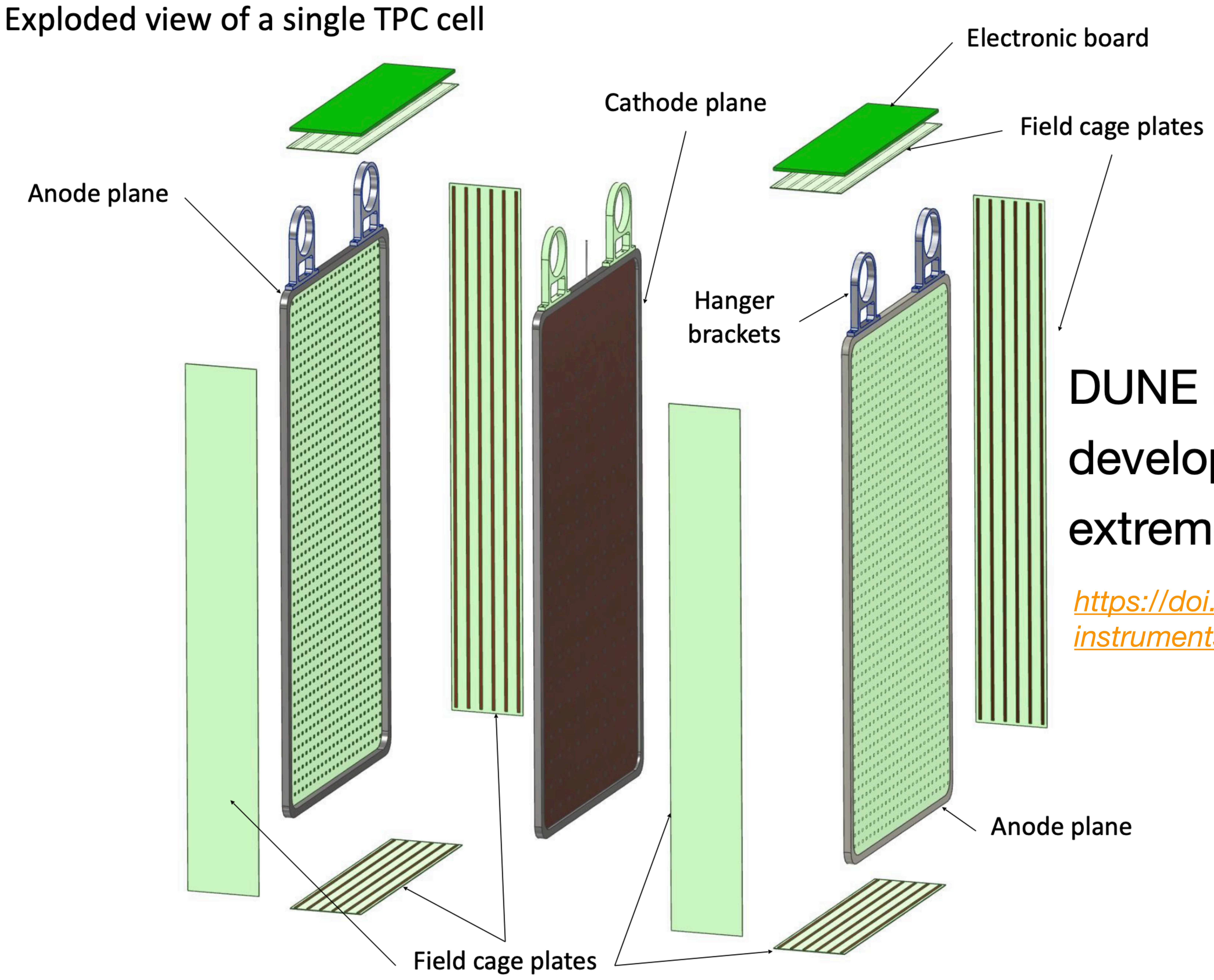
Forward Liquid Argon Experiment (FLArE)

- 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

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)





Gap: 30 cm

Voltage: 15k

Total #channels

~160k/module

21 modules

SiPM channels

TBD

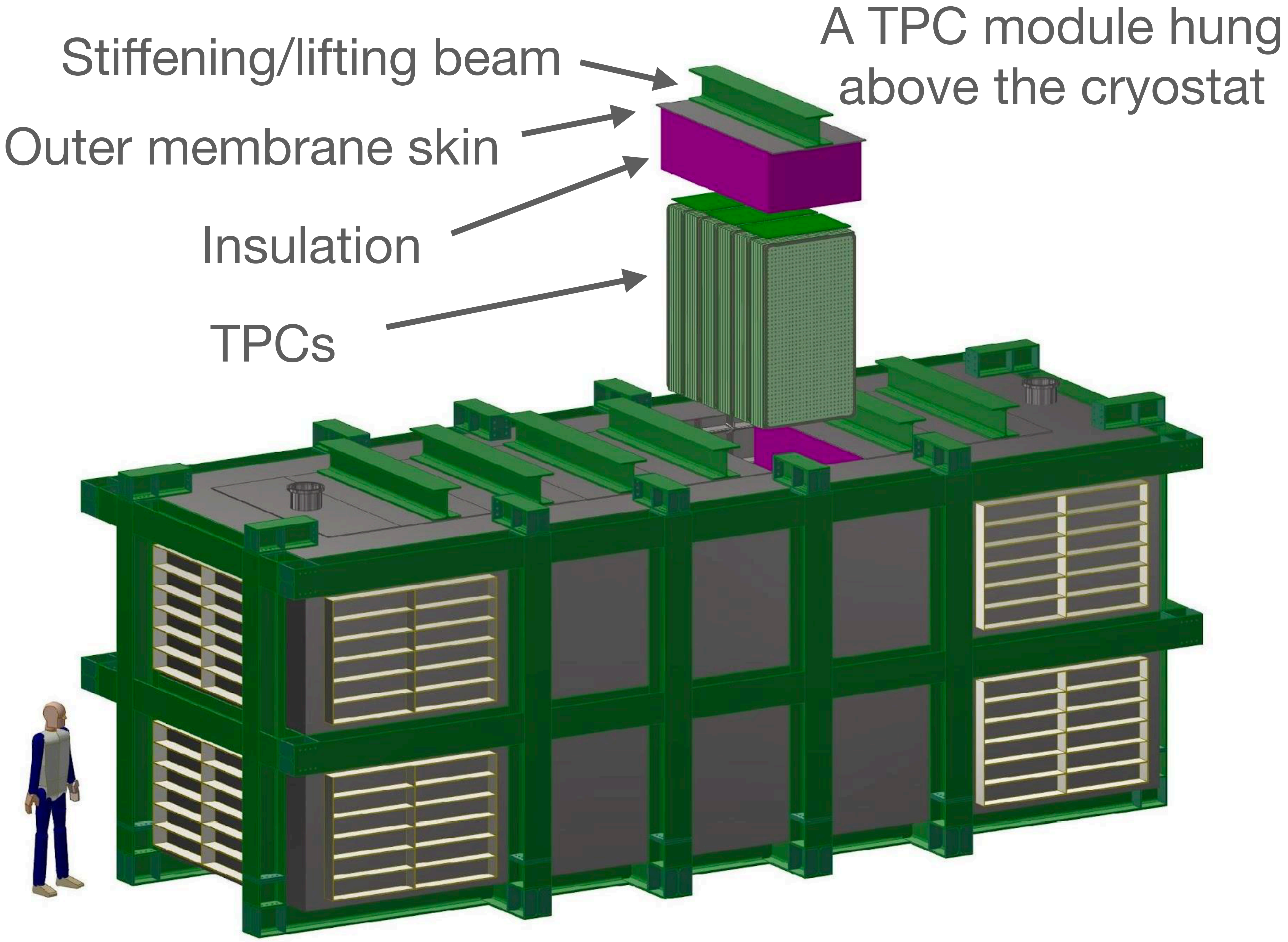
DUNE ND development is extremely helpful.

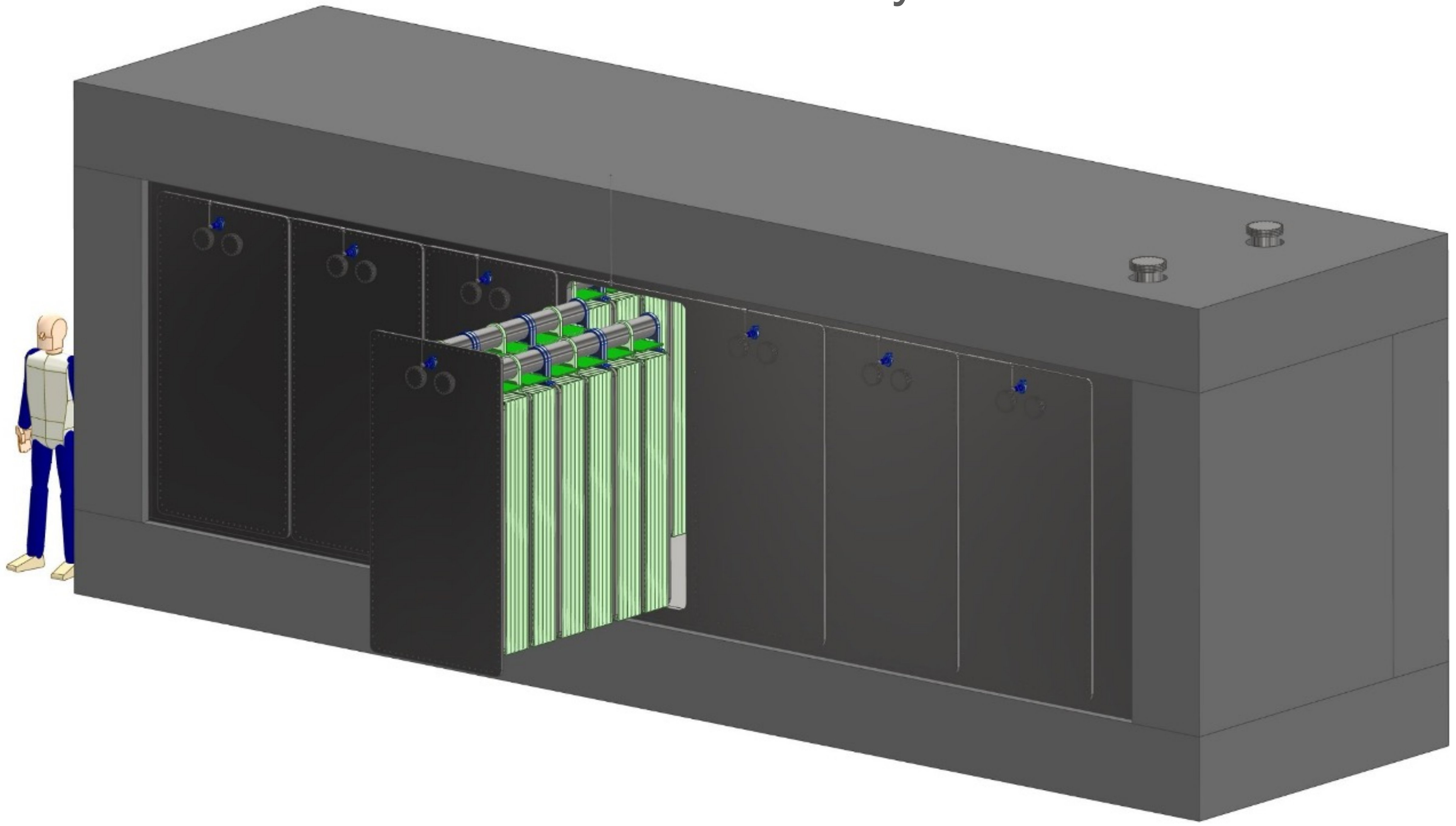
https://doi.org/10.3390/instruments5040031

TPC Installation Options for FLArE

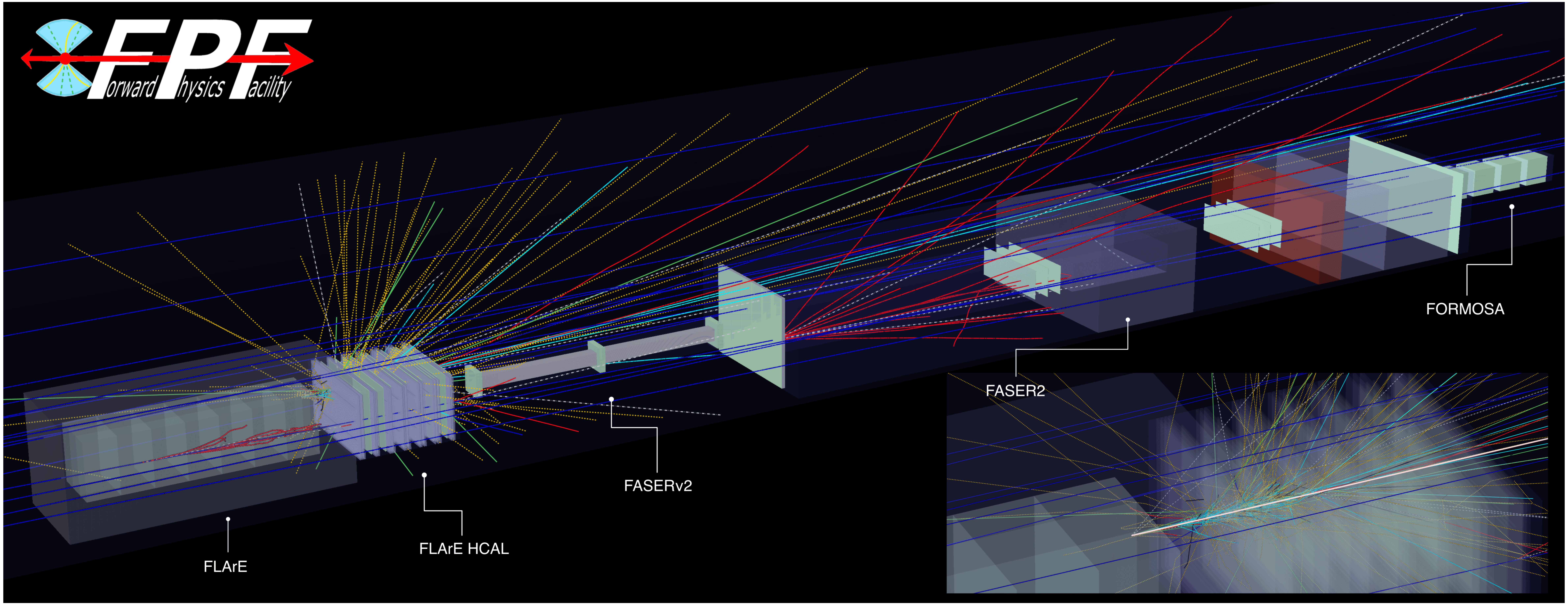
Installation from top
* similar to DUNE ND-LAr and SBND design

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





Simulation Framework



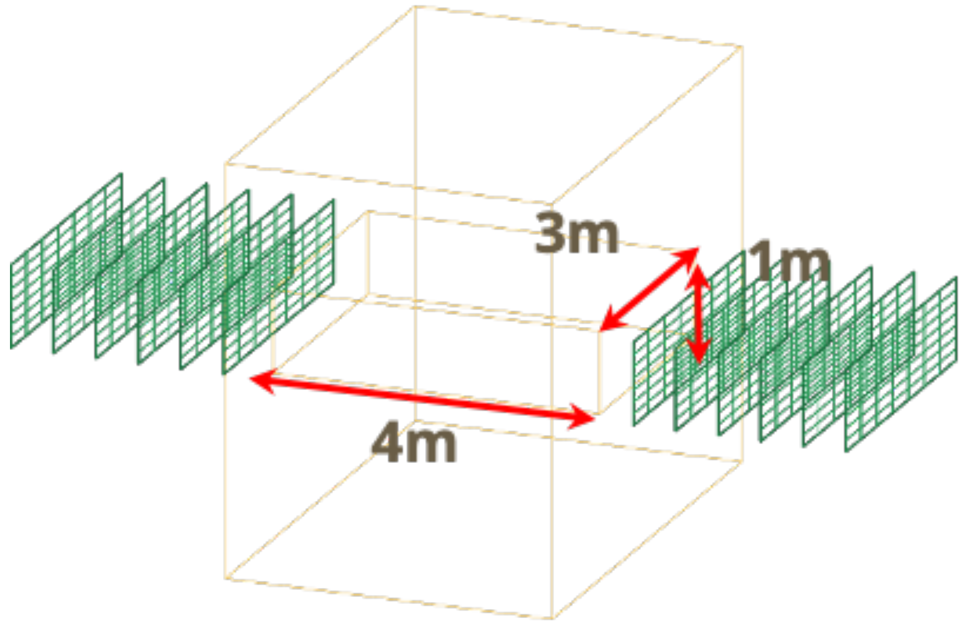
Different detector arrangements in the hall can be easily plugged into the simulation framework

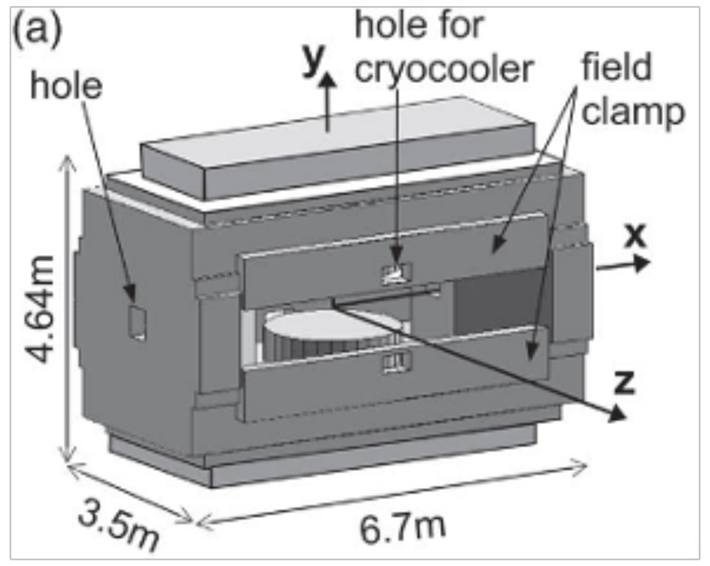
FPFSim Github: https://github.com/FPFSoftware/FPFSim

Muon Acceptance

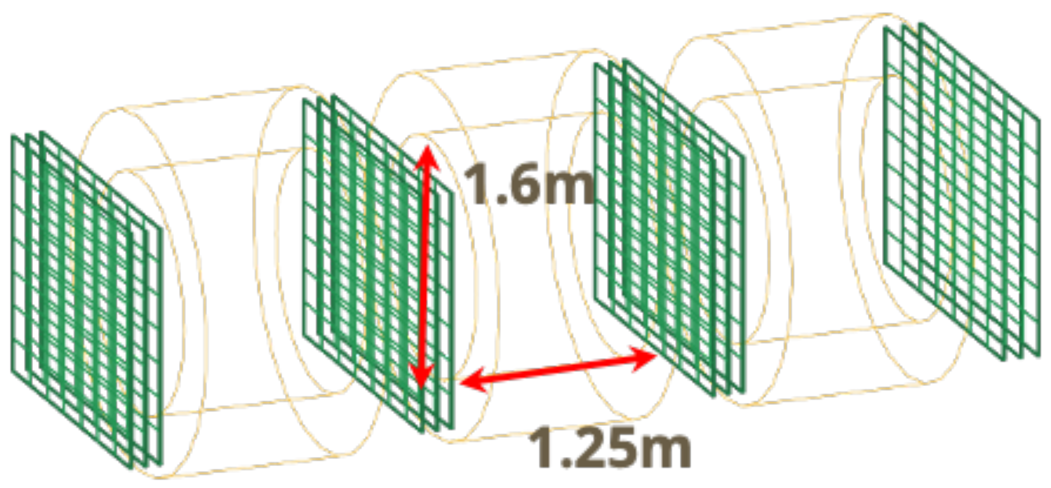
- Acceptance study for the muons produced by ν_μ CC events in FLArE
- Propose to coordinate with FASER2 magnet, along with magnetized calorimeter @ FLArE
- Acceptance is mainly driven by the FLArE-FASER2 distance, which depends on the detector arrangements in the FPF
  - Better performance if detectors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

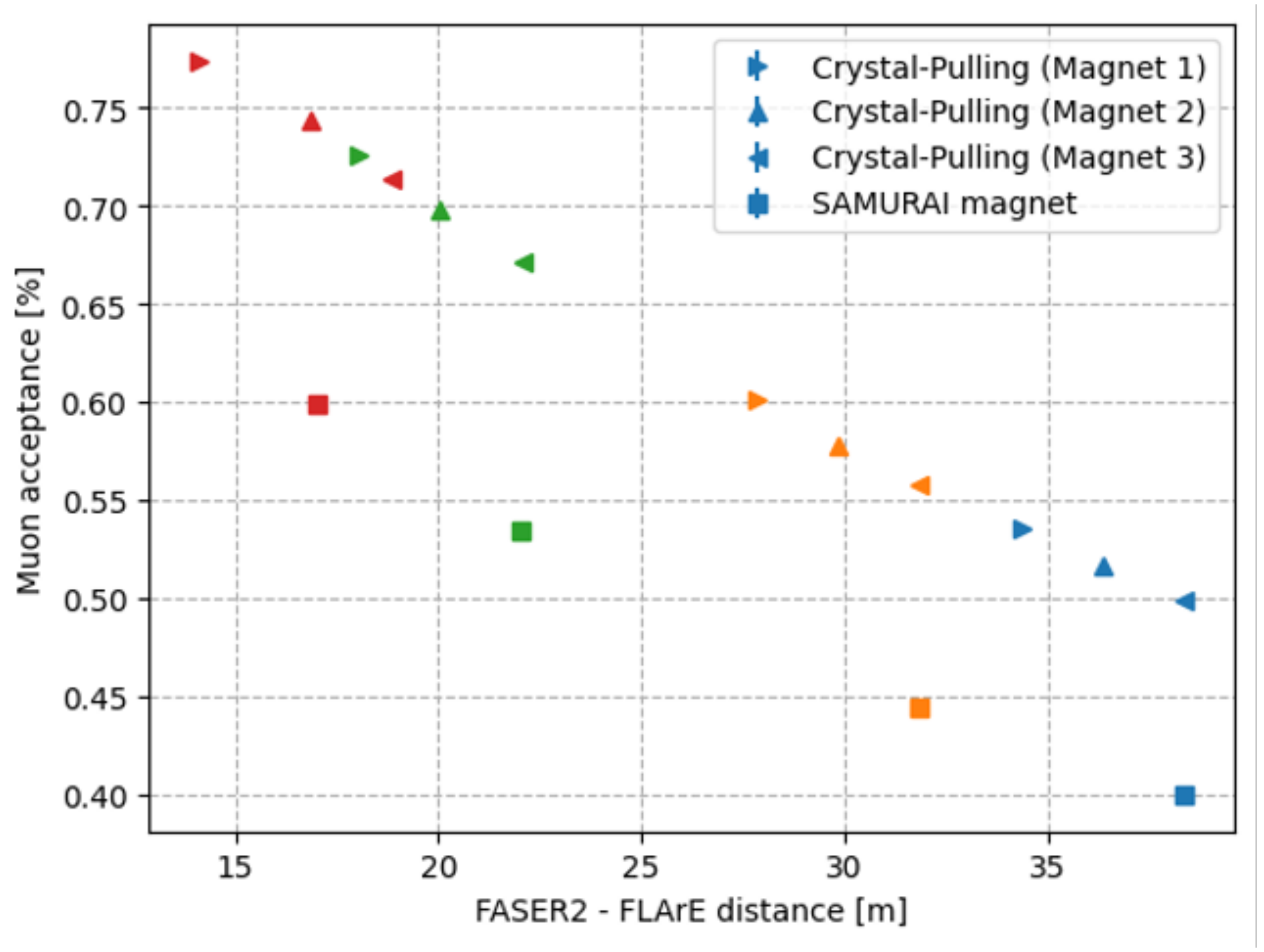
SAMURAI-like magnet





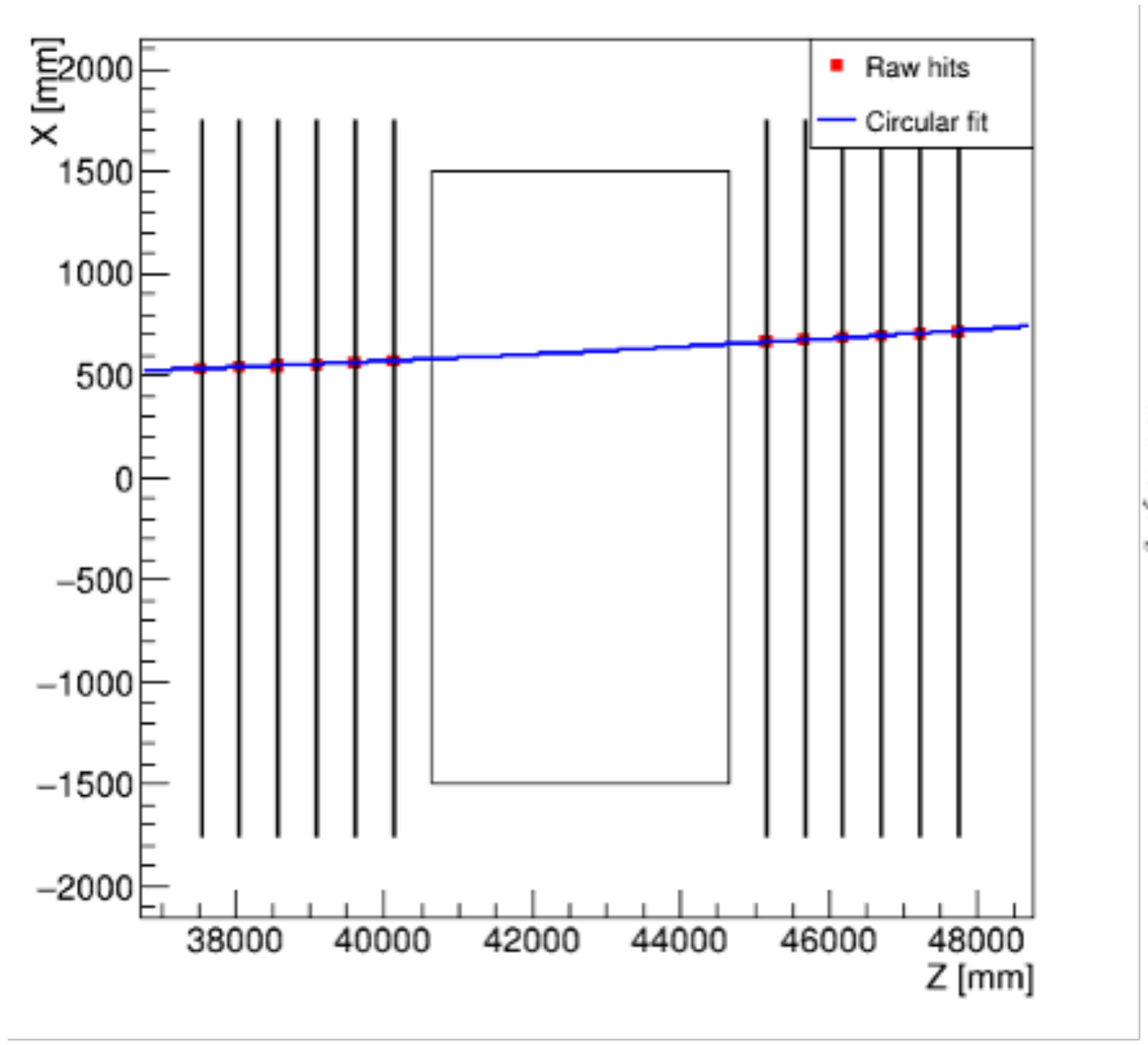
TOSHIBA Crystal-pulling magnets

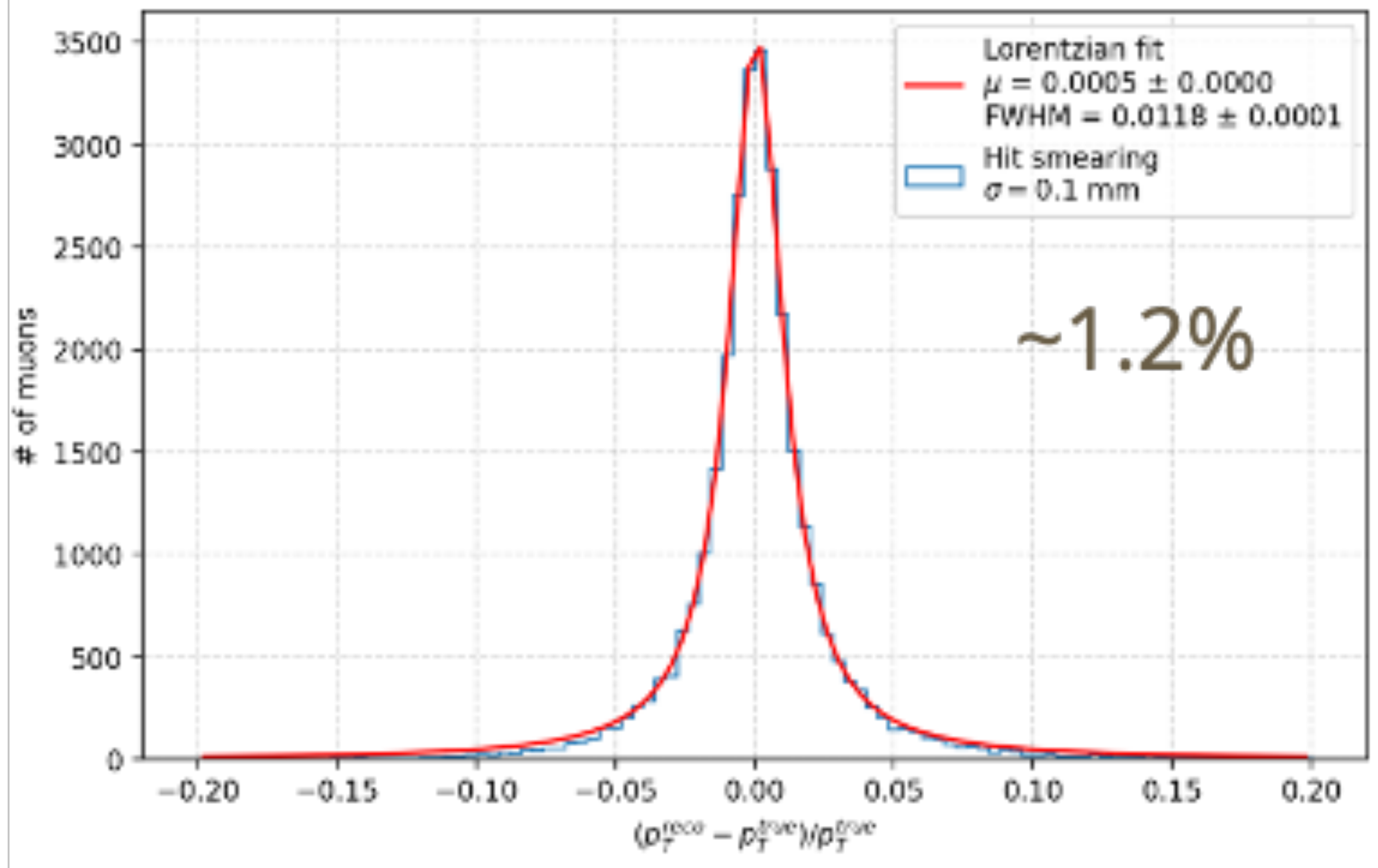


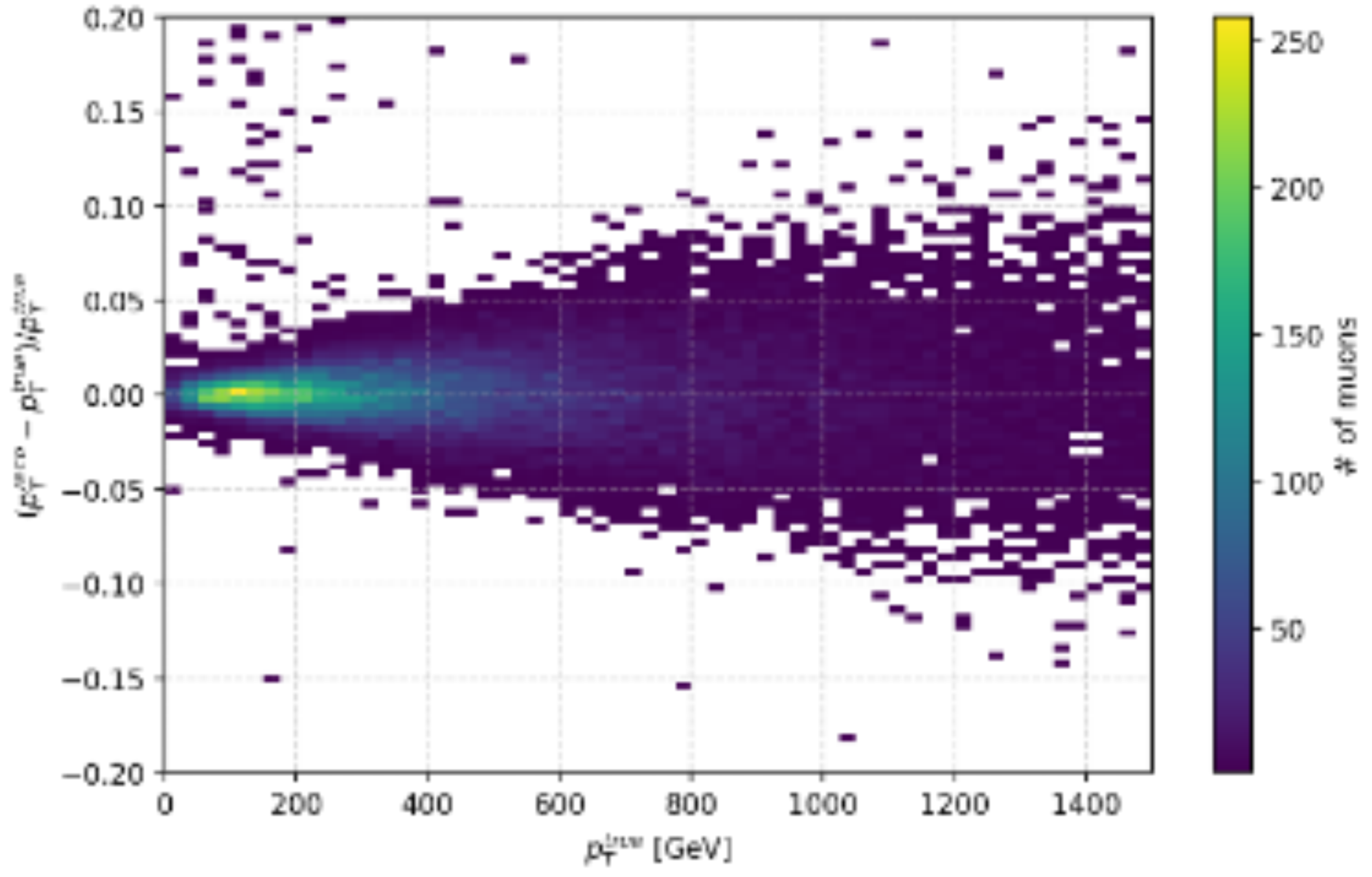


Muon Momentum Reconstruction

- 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







FPF Timeline and Cost

Year	2025	2026	2027	2028	2029	2030	2031	2032	2033
(HL-)LHC Nominal Schedule	Run 3	Run 3/LS-3	LS 3	LS 3	LS 3	LS 3/Run-4	Run 4	Run 4	Run 4
FPF Milestones	LOI and physics proposal	R&D and prototype detectors	CDR, long lead items, magnet	Start of civil construction	TDR for detectors	Detector construction start	Major equipment acq.	End of civil construction, Install services	Detector installation and commissioning
Experiment Core Costs (kCHF)		154	1275	3473	7257	11220	9503	6978	741

Forward Physics Facility

LETTER OF INTENT:

THE FORWARD PHYSICS FACILITY

Will be released soon

Summary

- A forward physics facility (FPF) is being considered at CERN for neutrino and dark matter physics
  - Facility looking good from CERN side (radiation protection, safety, civil engineering, etc.)
- The FPF greatly expands the physics program of LHC
- Broad and interdisciplinary physics program, highlighting
  - Neutrinos in the 1 TeV range: ~200-500 events/ 10 ton/day
  - Tau neutrino flux and associated heavy flavor physics: ~1-2 events/10 ton/day
  - Discovery science with BSM searches and rare phenomena
- Beam is already there, cost is modest
- FPF input to ESPPU summarizing physics program (Eur.Phys.J.C 85 (2025) 4, 430), LOI will be released soon

Contact: https://fpf.web.cern.ch/
Useful Link: https://pbc.web.cern.ch/, https://pbc.web.cern.ch/fpf-resources
White papers: https://arxiv.org/abs/2411.04175

Stay tuned!

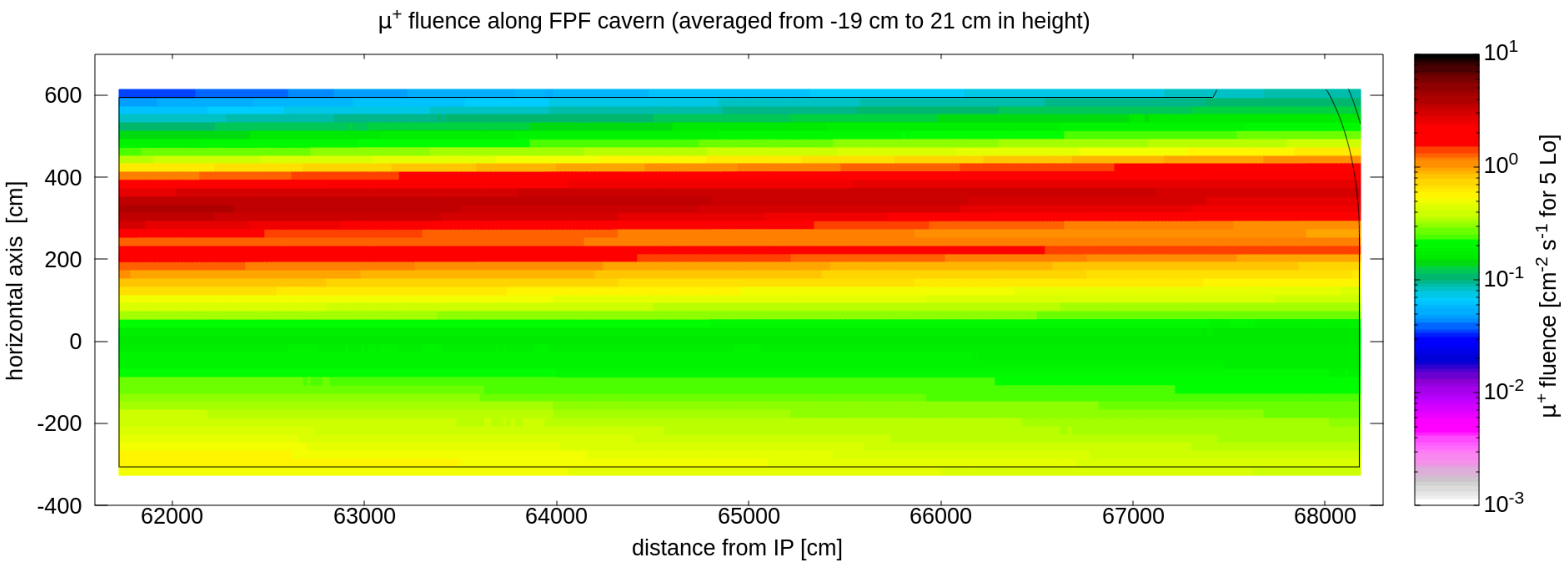
Photograph from FPF8 workshop at CERN Jan 25 (114 registrants)

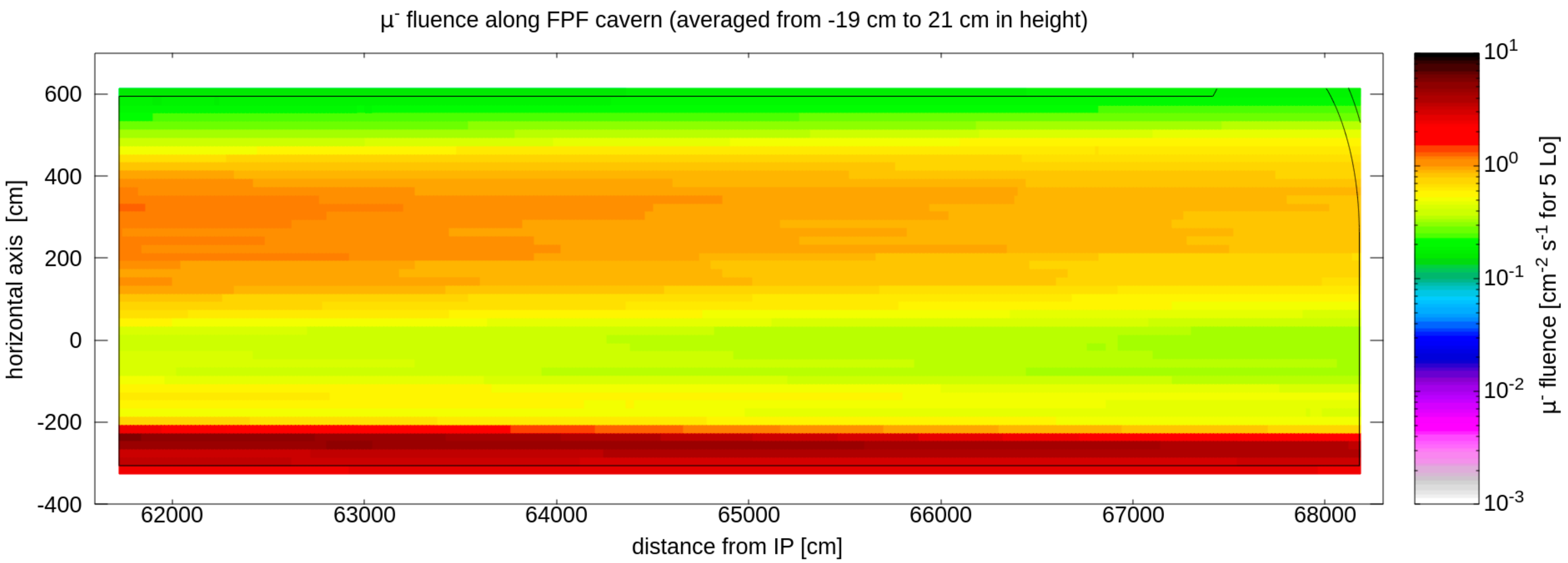
Thanks!

Backup Materials

Muon Background

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

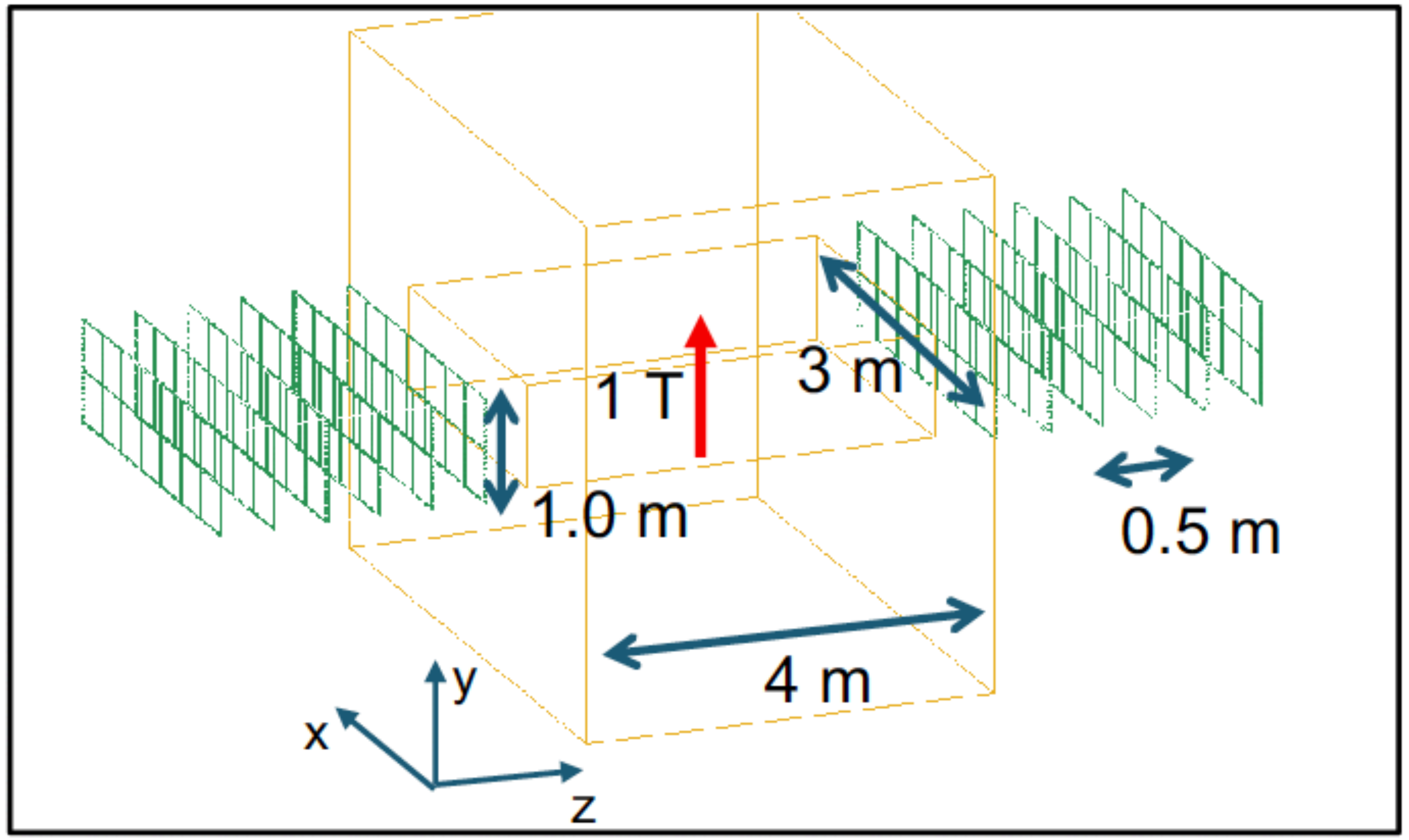




- Fluence in the horizontal plane in FPF location from CERN FLUKA team (20 cm from LOS in vertical plane)
  - Clear hot spot at ~2 m from the LOS
- Muon flux
  - ~0.6 Hz/cm^2 (0.15 mu+, 0.45 mu-)
  - ~6 tracks/ms per m^2 of detector
- Neutron flux ~0.1 Hz/cm^2 is mostly at low energies

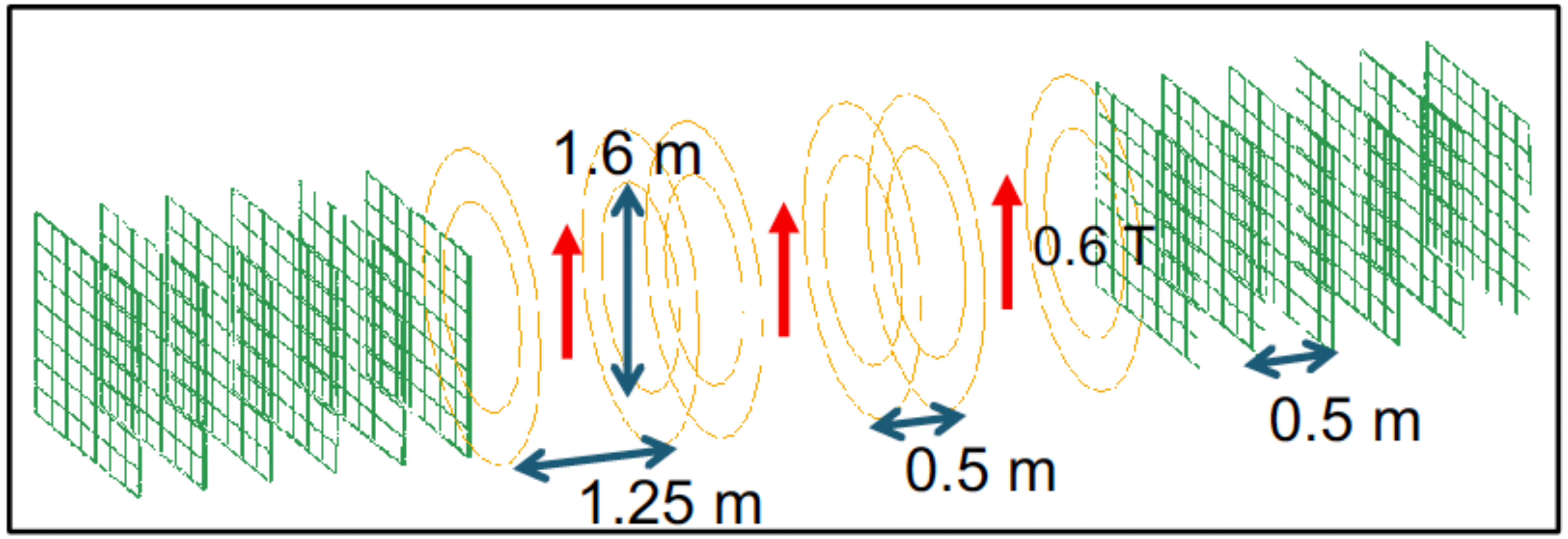
Magnet geometries

SAMURAI magnet



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

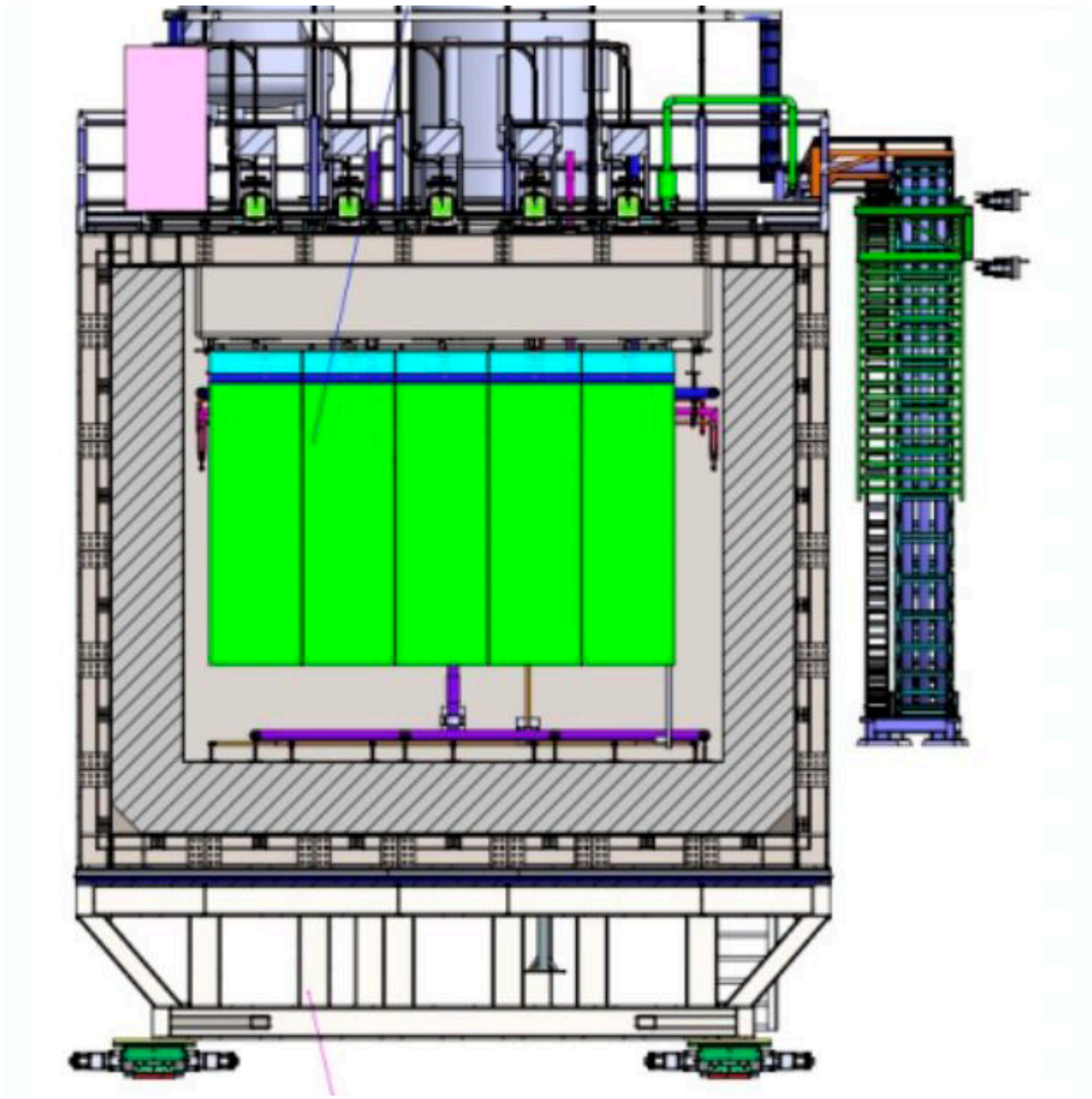
Crystal-Pulling magnet



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)

Cryostat Options for FLArE

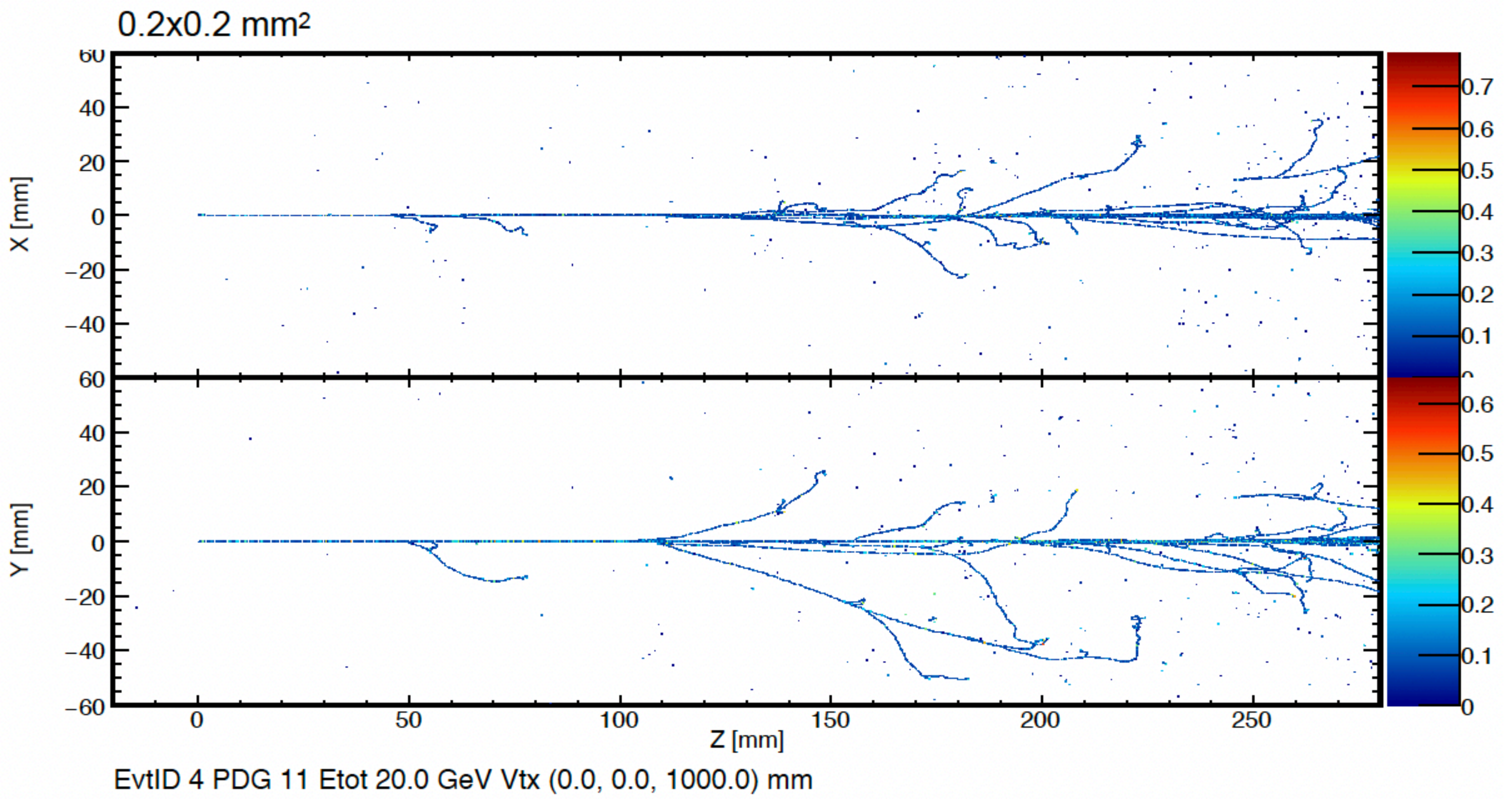


- Reference design is GTT membrane cryostat (used in ProtoDUNE, DUNE ND-LAr)
- 80 cm GTT membrane occupies 1.6 m out of 3.5 m available space
  - About 1.9 m x 1.9 m cross section allowed for detector
- Other options: single-wall? Vacuum-insulated?
- **BNL contracted an engineering firm (Bartoszek Engineering)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

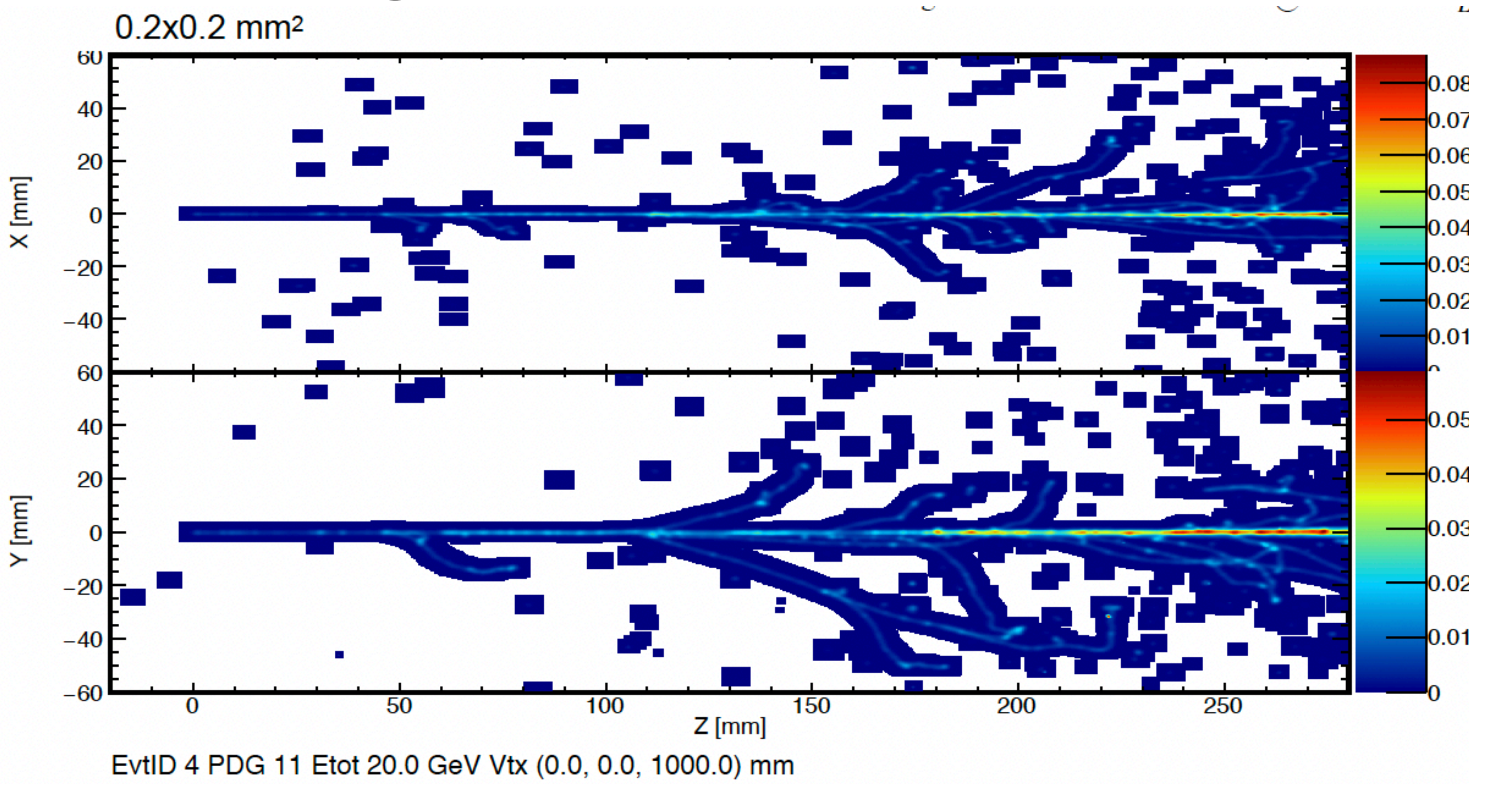
Particle Identification

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

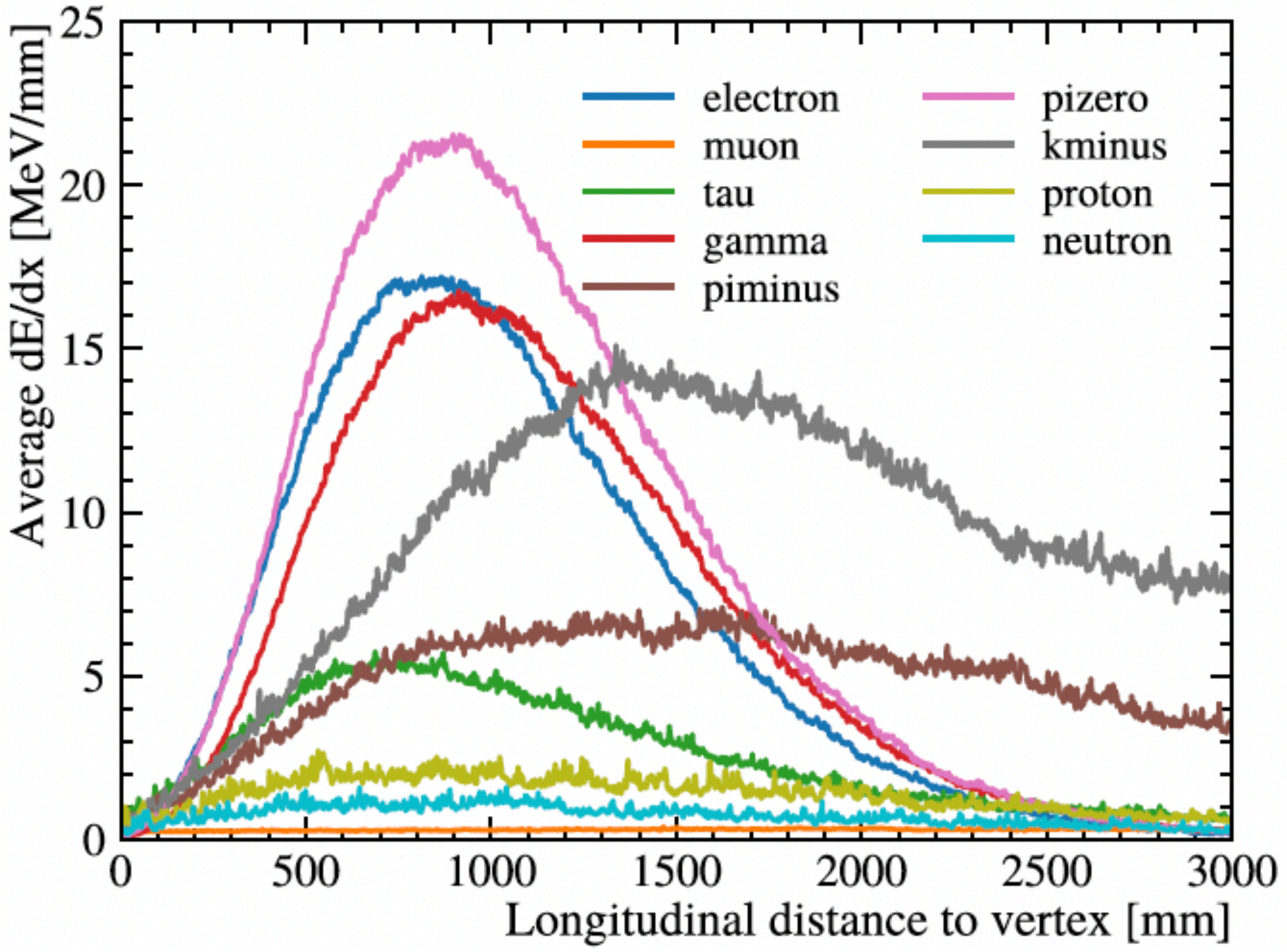
Single electron



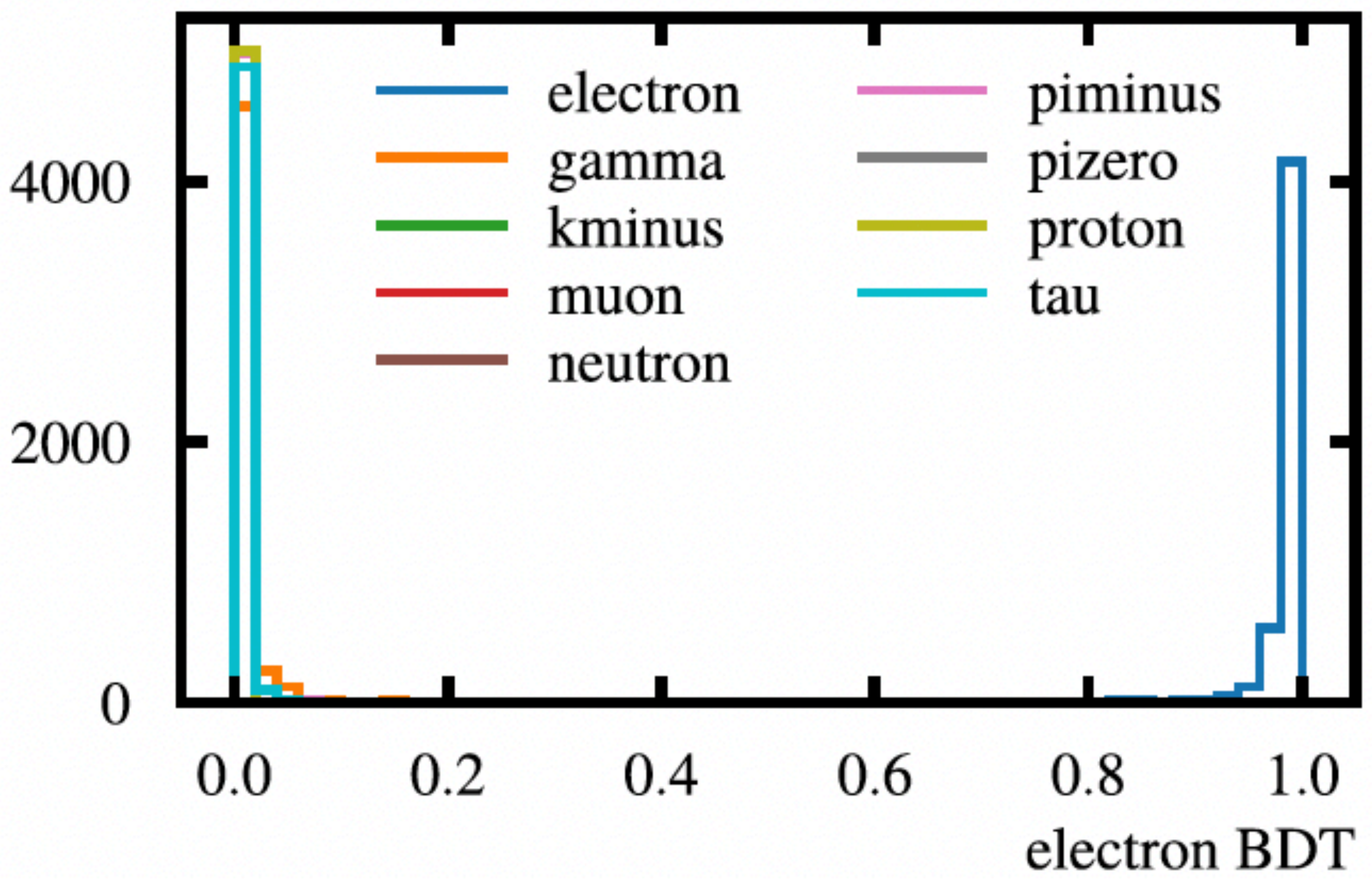
Single electron w/ diffusion



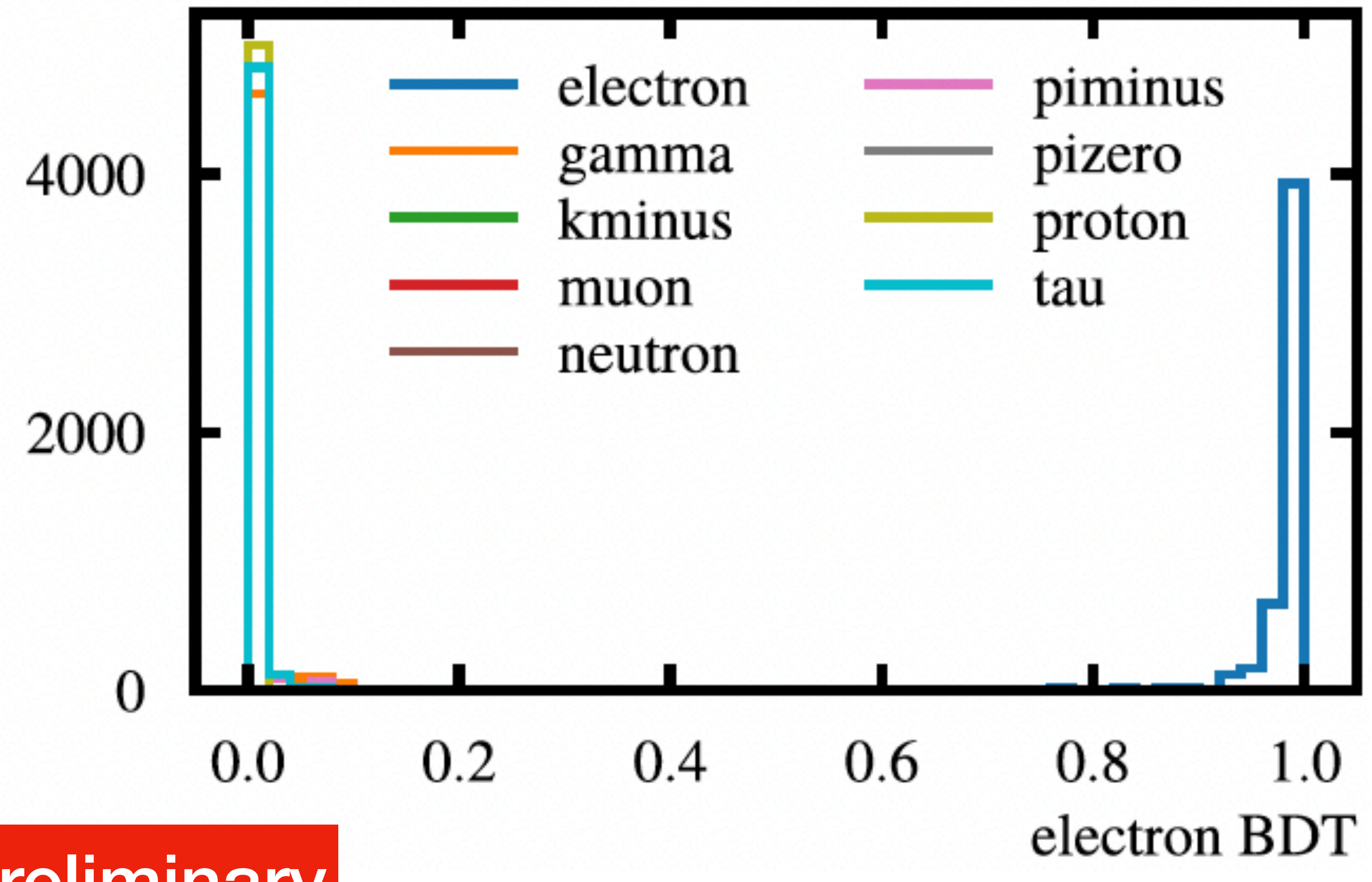
- Use the dE/dx distribution along the track for different type of particles w/ different assumptions of the pixel size
- Construct a log-likehood based on the dE/dx distribution and train a BDT for PID



$1 \times 2 \times 2$ mm³



$1 \times 5 \times 5$ mm³

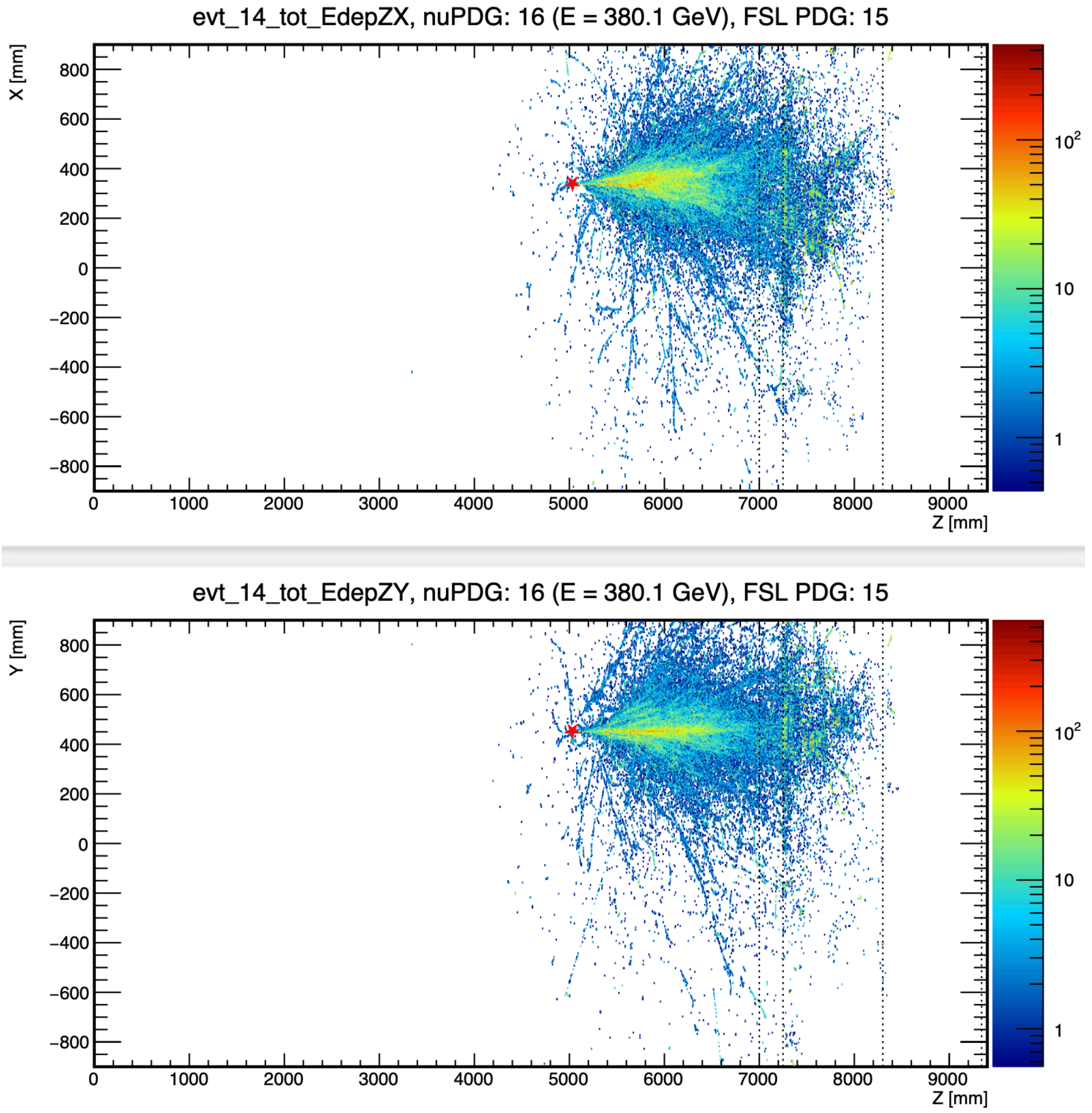


Preliminary

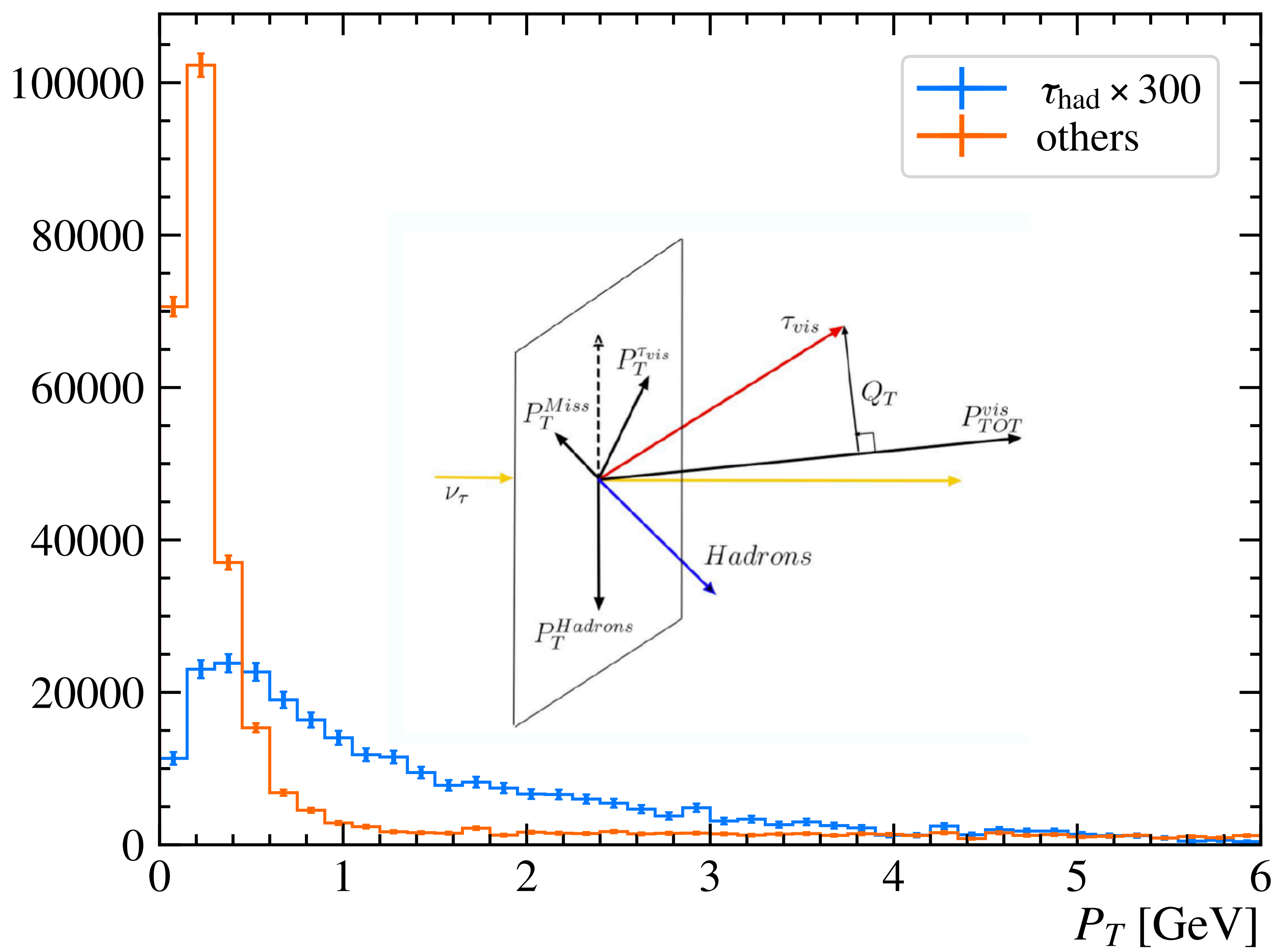
ν_τ Identification

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

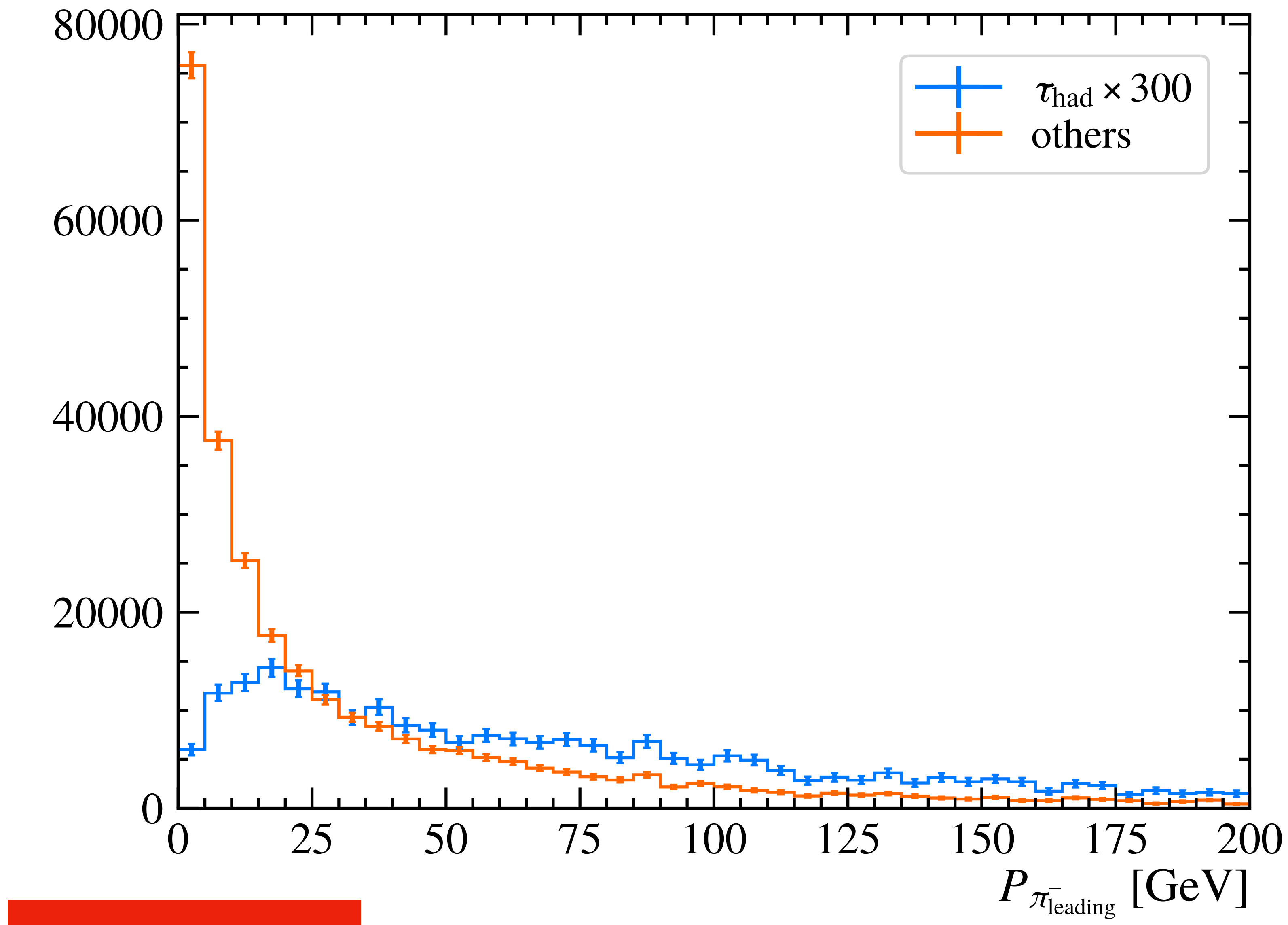
ν_τ CC, $\tau^- \to \pi^- \nu_\tau$



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