Developments in the Forward Physics Facility and FLArE

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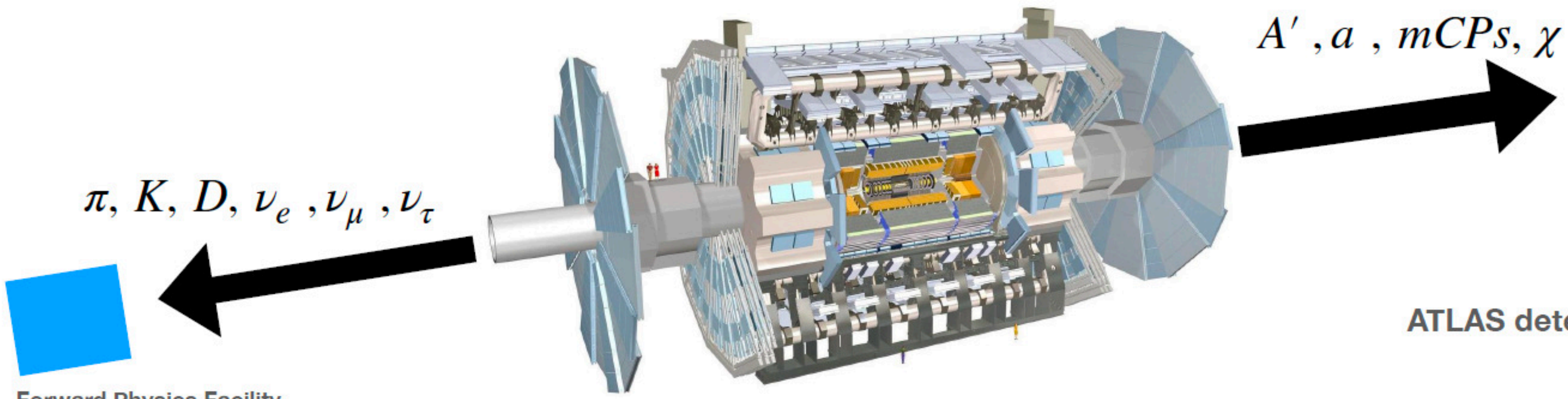
on behalf of the FLArE technical working group

BNL Intensity Frontier briefing
January 16th, 2025

Forward Physics Facility

RECENT OVERVIEW:
https://arxiv.org/abs/2411.04175



HL-LHC: Large flux of **high energy** (>100 GeV) **light particles in the forward direction** ($\eta \geq 7$) from the ATLAS IP that would be missed by the big high-p_T detectors:

- pions, kaons, D-mesons, and **neutrinos of all flavors;**
- but also possible ***LLPs***: dark photons, axions, millicharged particles, light dark matter, etc.

Unique opportunity for a **Forward Physics Facility** hosting a diverse suite of medium-size detectors.

- BNL is actively involved in the design and development of **FLArE** (**F**orward **L**iquid **Ar**gon **E**xperiment), a liquid argon time-projection chamber for the FPF.

FPF Site

The site is on CERN land in France, ~600m from ATLAS.

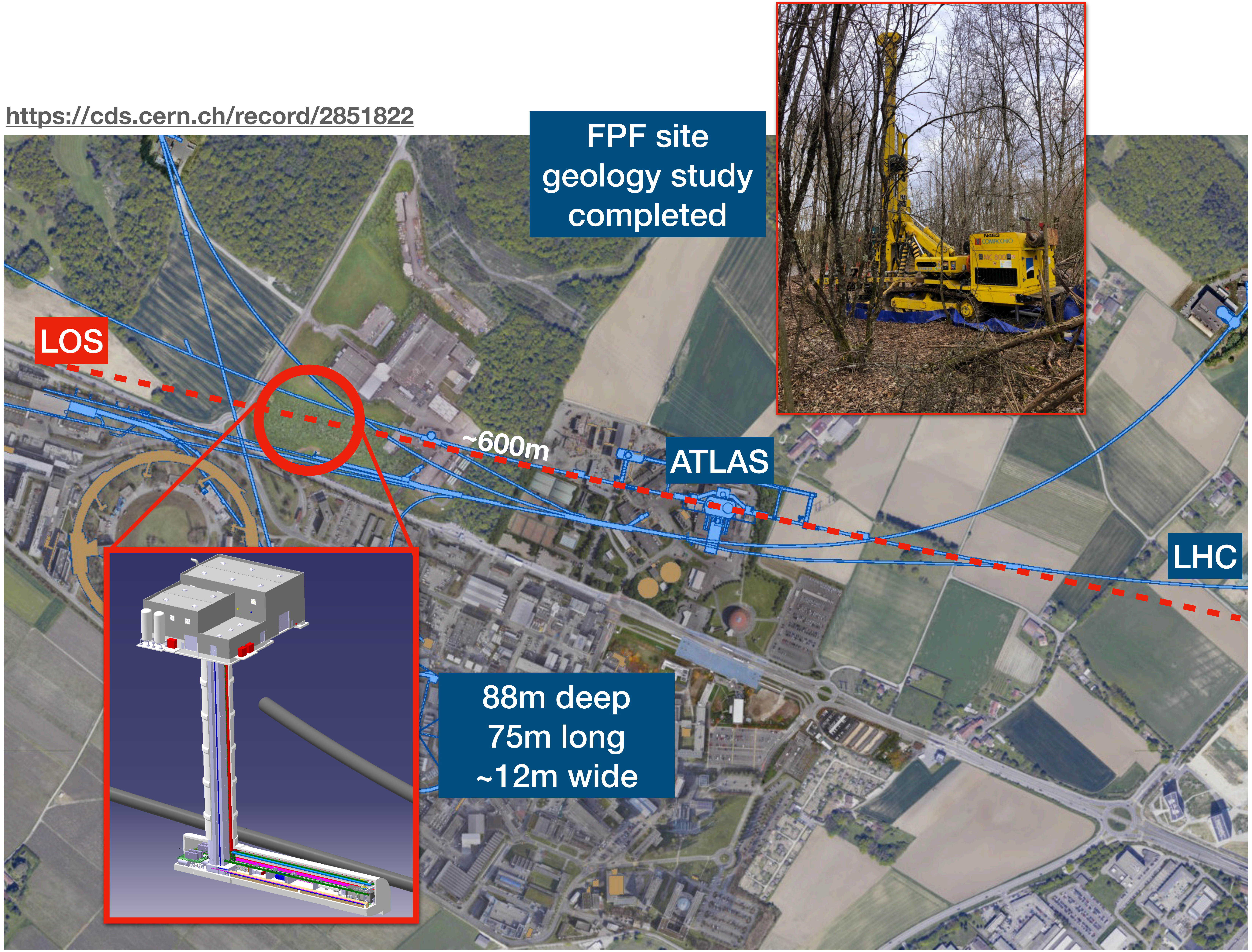
Shielded by ~200m of rock.

Disconnected and independent from LHC tunnel.

Vibration studies: construction will NOT disrupt LHC operations

Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2030)

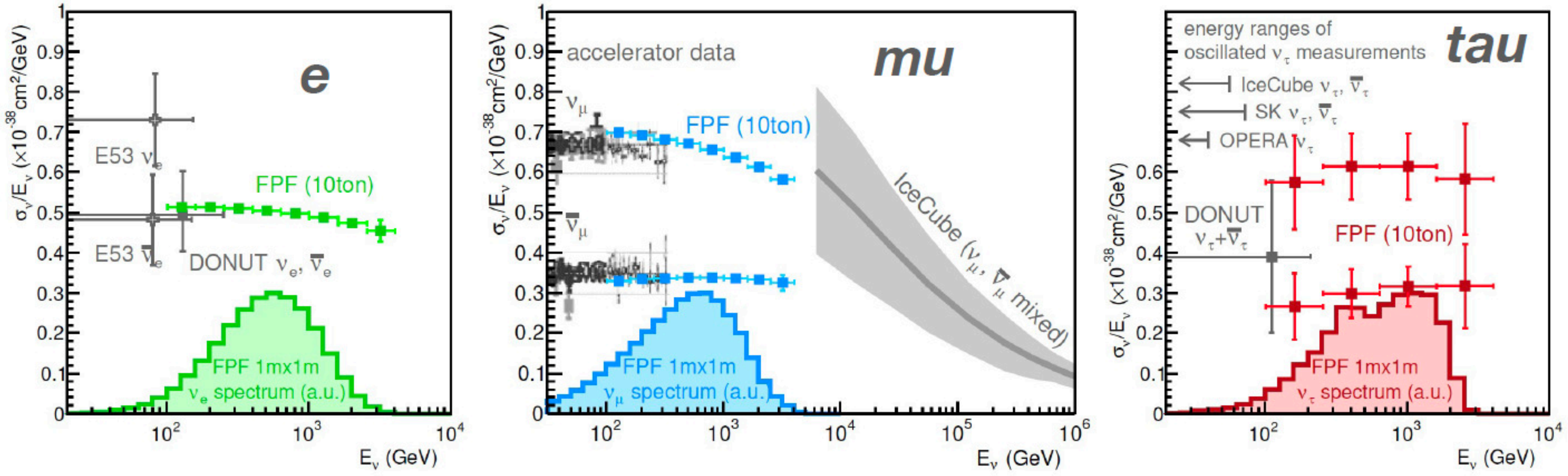
https://cds.cern.ch/record/2851822



https://indico.cern.ch/event/1275380/contributions/5387310/

Physics: μ, e, τ neutrinos!

https://doi.org/10.1088/1361-6471/ac865e



HL-LHC: **most intense artificial source** of neutrinos of all **3 flavors**!

Energies **bridge the gap** between accelerator and atmospheric data.

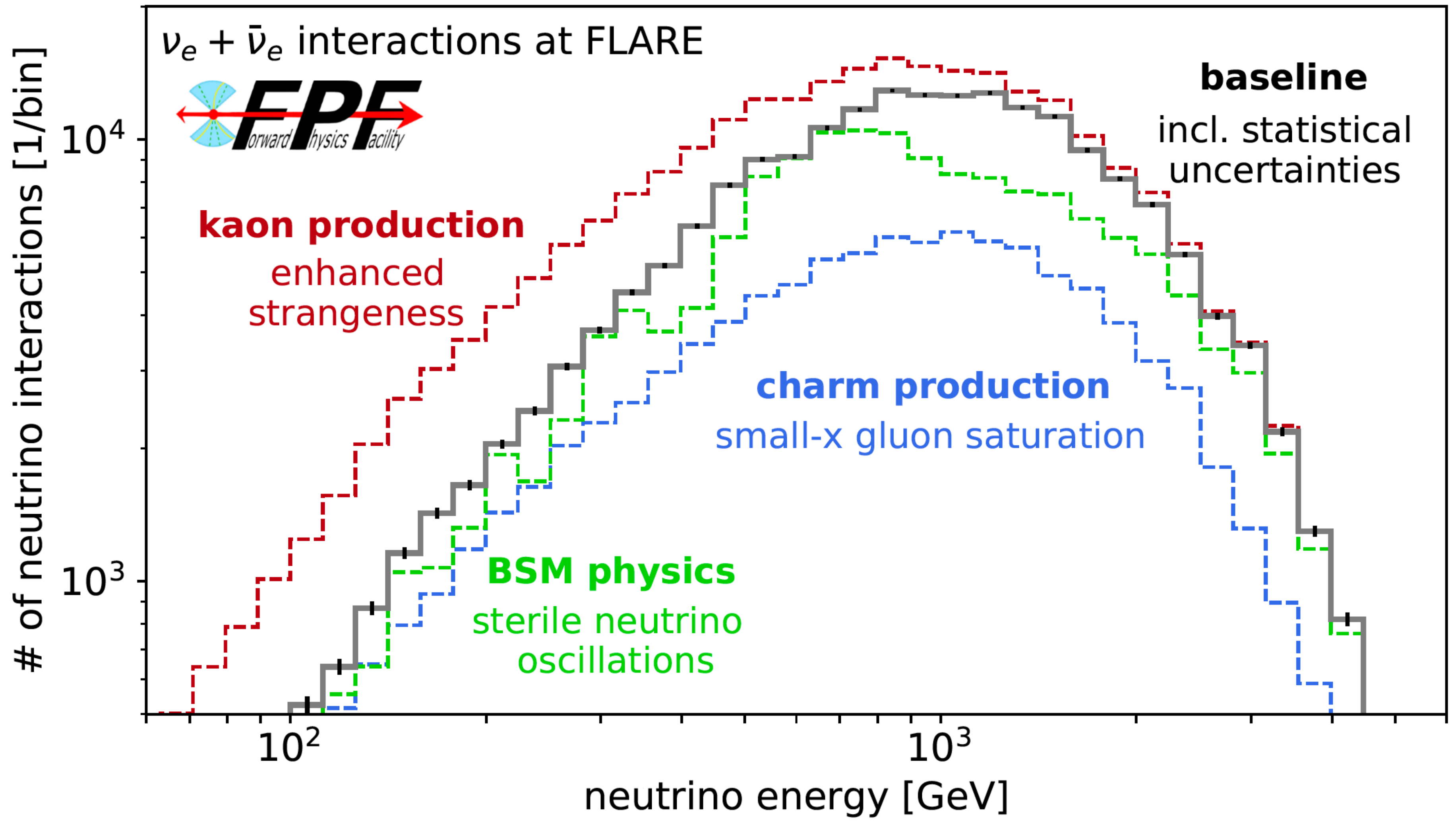
Rate: **20-50 events/ton/fb^{-1}**

LAr TPC (**FLArE**) is an **excellent option** for a broad purpose neutrino detector**:**

- **Muon, electron ID is easy**
- **Tau ID requires much more work (~mm resolution)**

Evts/ton/fb^{-1}	ν	$\bar{\nu}$	TOT
e	2.1	1.0	3.1
mu	15	5	20
tau	0.1	0.05	0.15

At HL-LHC, 1 fb^{-1} approximately per day!

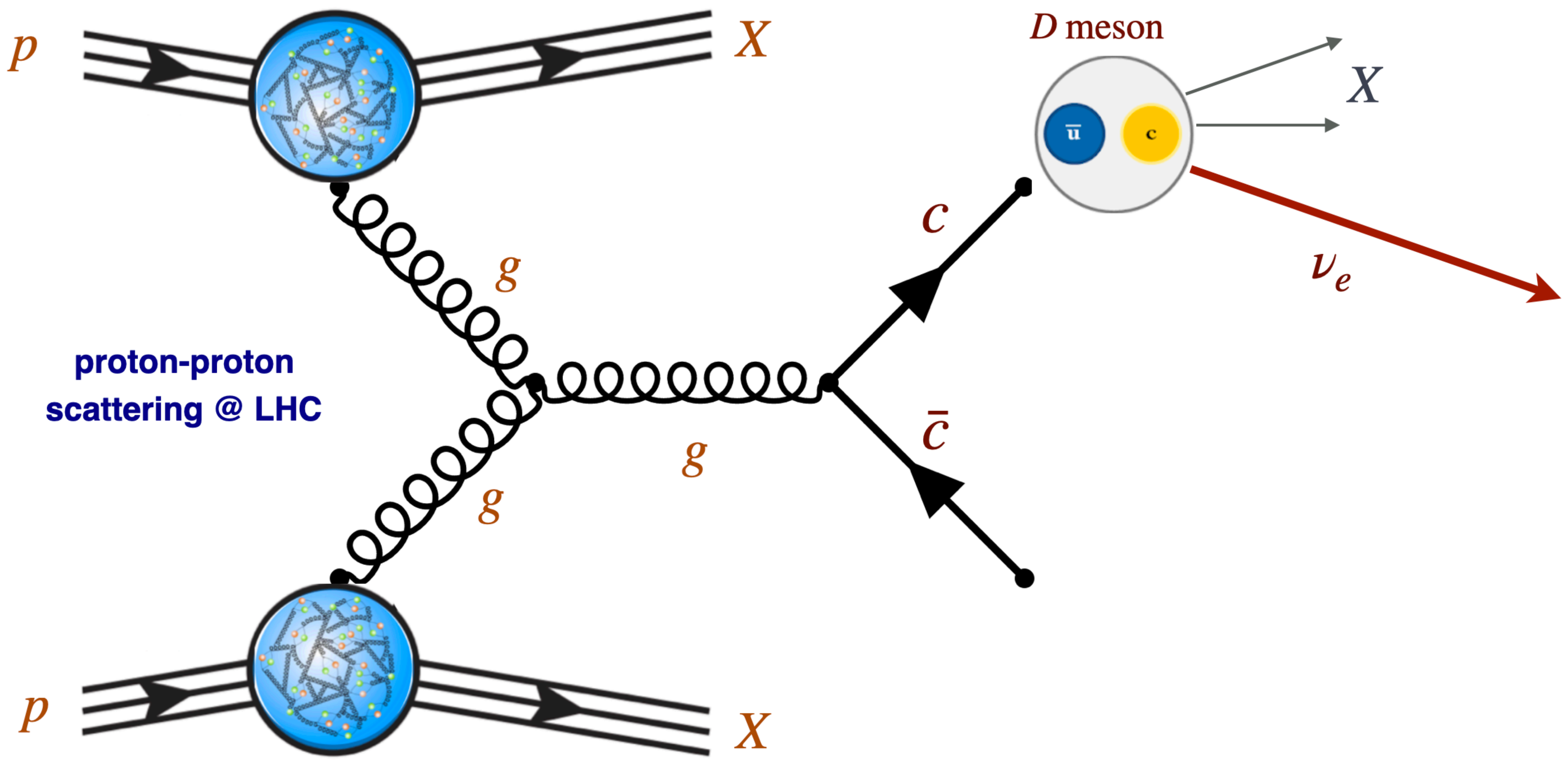


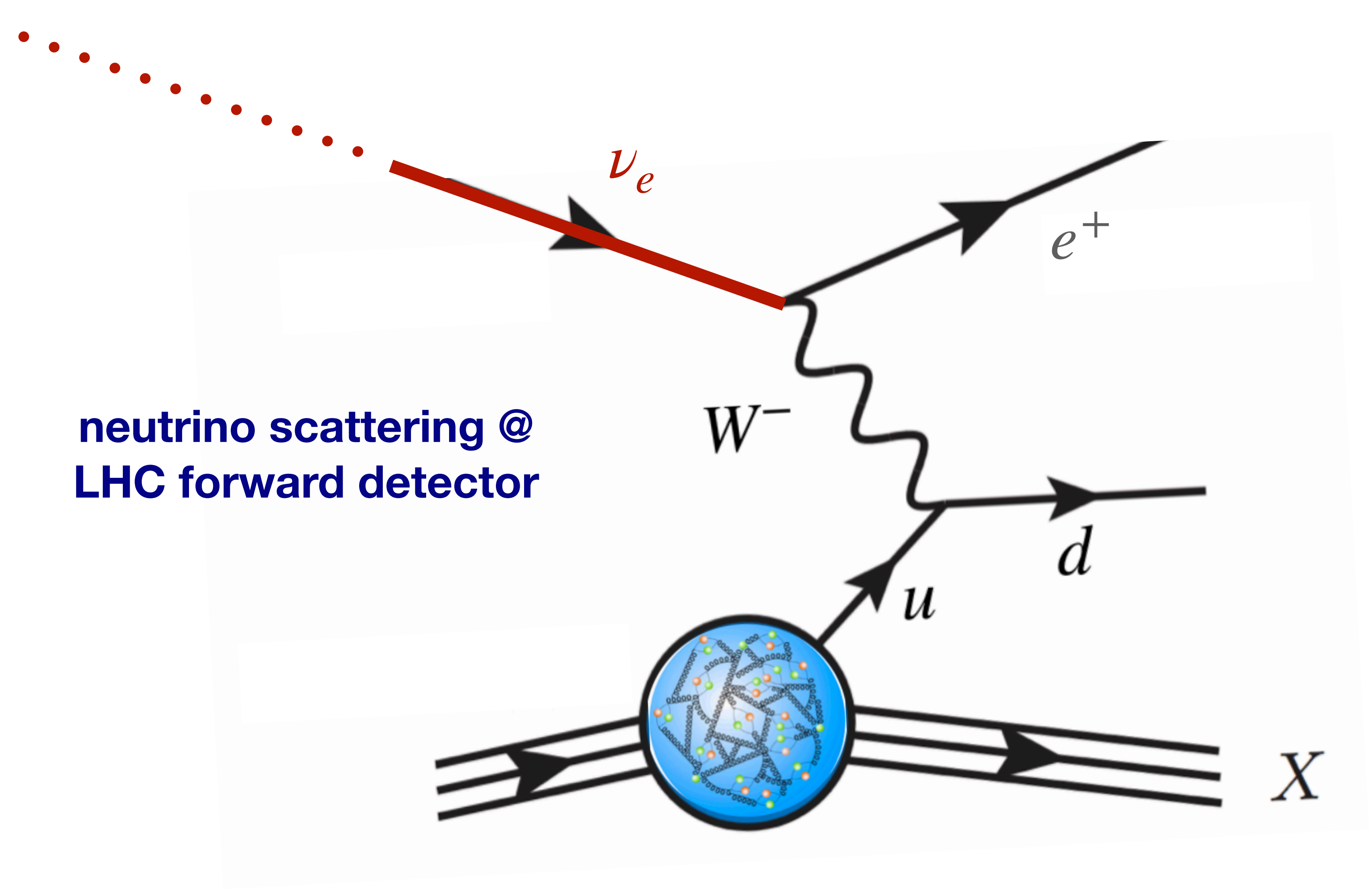
Brookhaven National Laboratory

Physics: Standard Model and QCD

…using neutrinos as probes

- **DIS with TeV neutrinos** (“Neutrino-Ion Collider”)
- Cross-sections for atmospheric neutrinos
- **Nuclear PDFs, strangeness** from charm
- Neutrino flavor universality (τ neutrinos)





- **Small-x gluon** & large-x (intrinsic) charm
- **D-meson** fragmentation
- Cross-sections for **UHE neutrinos**
- Cosmic rays modeling **(muon puzzle)**

Juan Rojo’s BNL HET seminar
https://indico.bnl.gov/event/17262/

Physics: BSM and Dark Matter

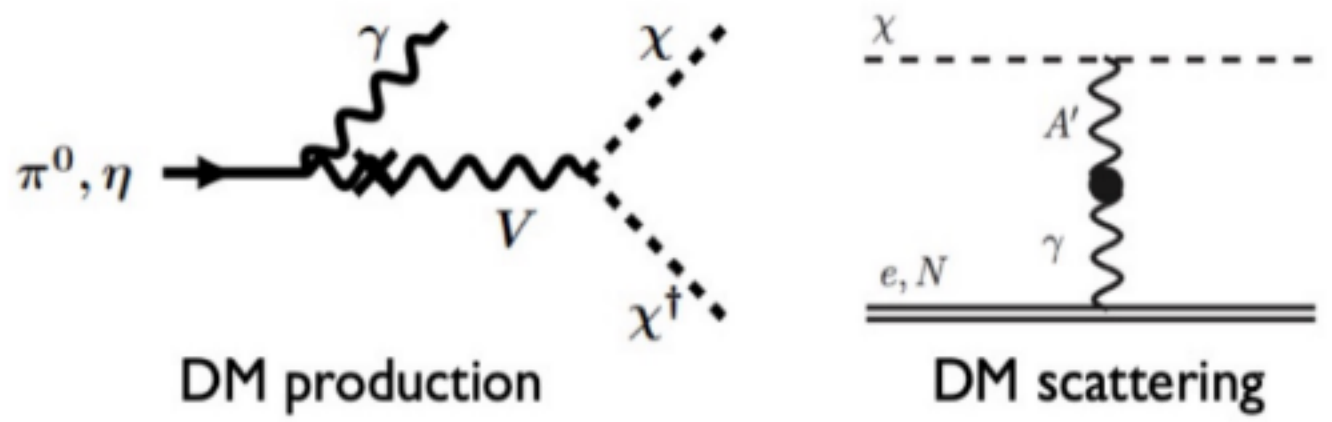
Direct DM detection from nuclear or electron scattering:

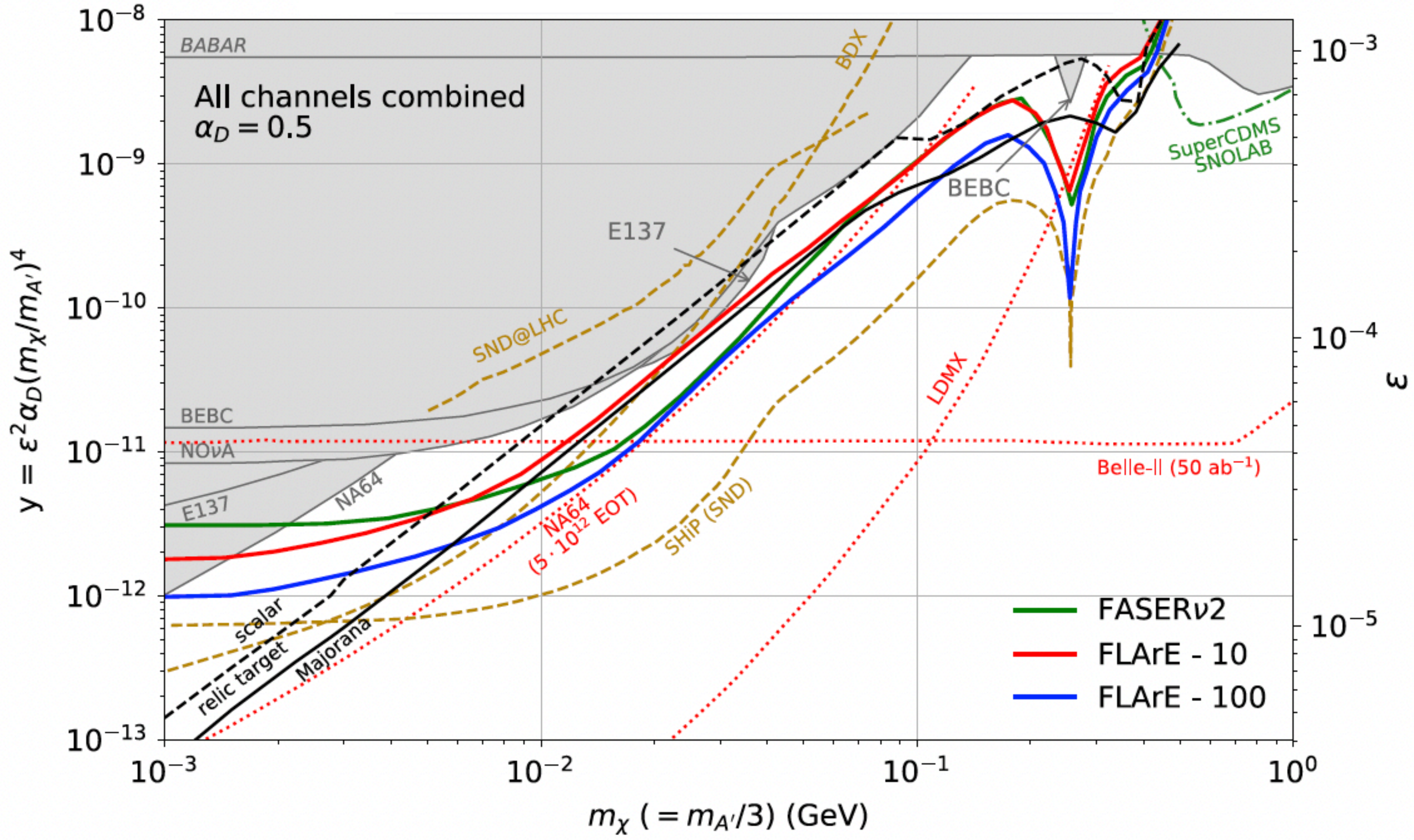
- **Need high kinematic resolution.** LAr TPCs can go as low as ~10-20 MeV thresholds.
- Target sensitivity indicated by relic density can be achieved with **10 tons of LAr.**
- Dominant background is neutrino (elastic) scattering and muons coming from IP.

LArTPC (FLArE) can combine **low thresholds, high spatial resolution** (~mm), and **sufficient target mass** (10 ton) for the **job.**

Light DM produced via dark photon decay

DM scattering in the detector



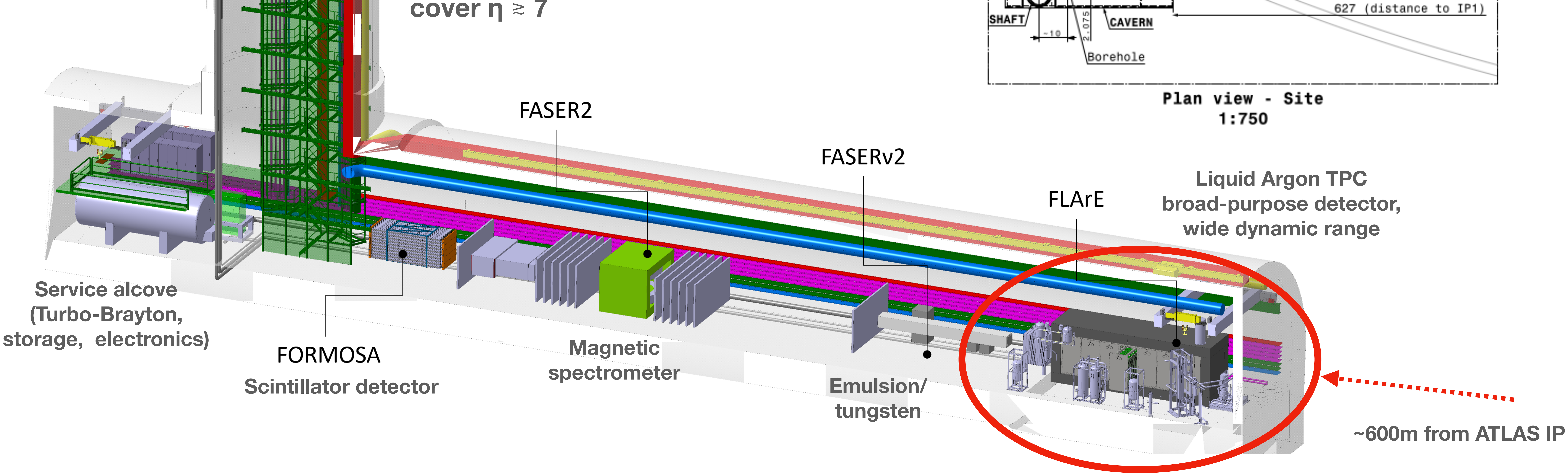


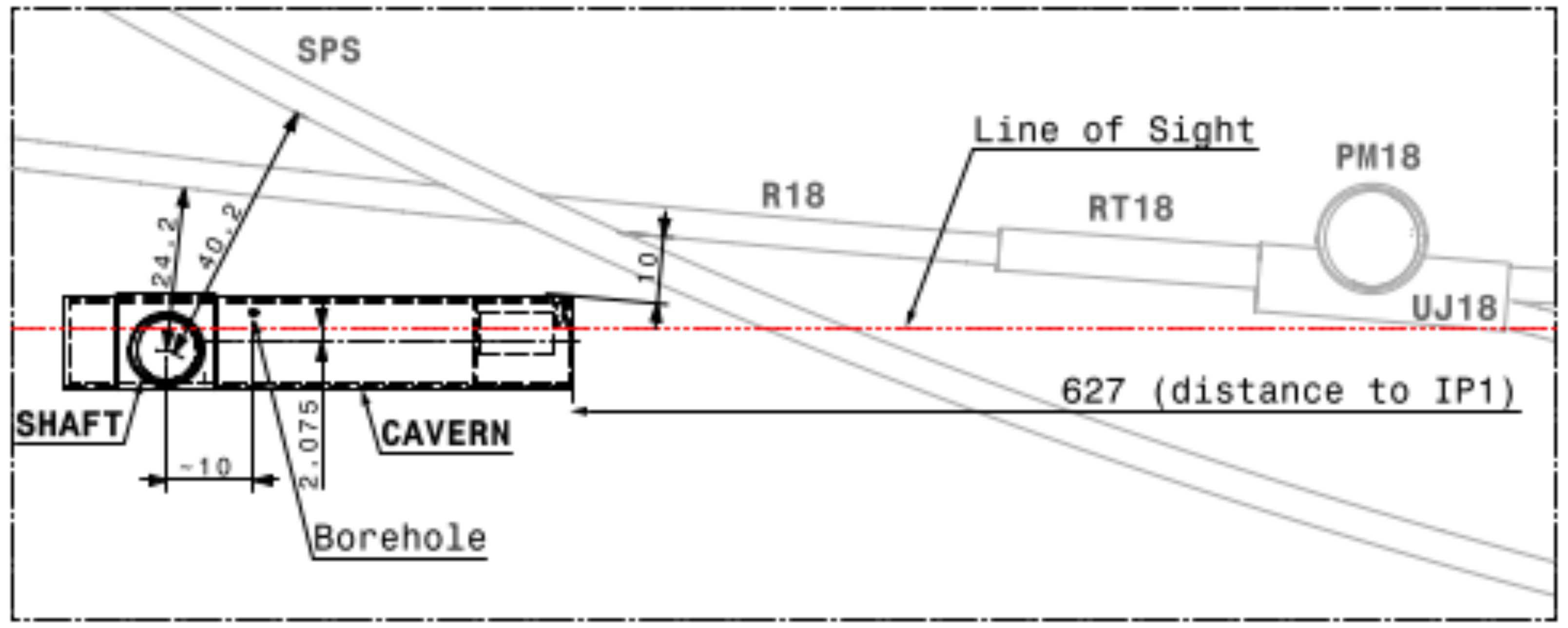
https://doi.org/10.1103/PhysRevD.104.035036
https://doi.org/10.1103/PhysRevD.103.075023

FLArE @ Forward Physics Facility

Baseline design

FPF covers η > 5.5, experiments on LOS cover η ≳ 7





Plan view - Site
1:750

<u>Good energy containment</u> (high density), <u>high spatial resolution</u> (for τ neutrinos) and <u>low threshold</u> (for DM scattering)

Brookhaven National Laboratory

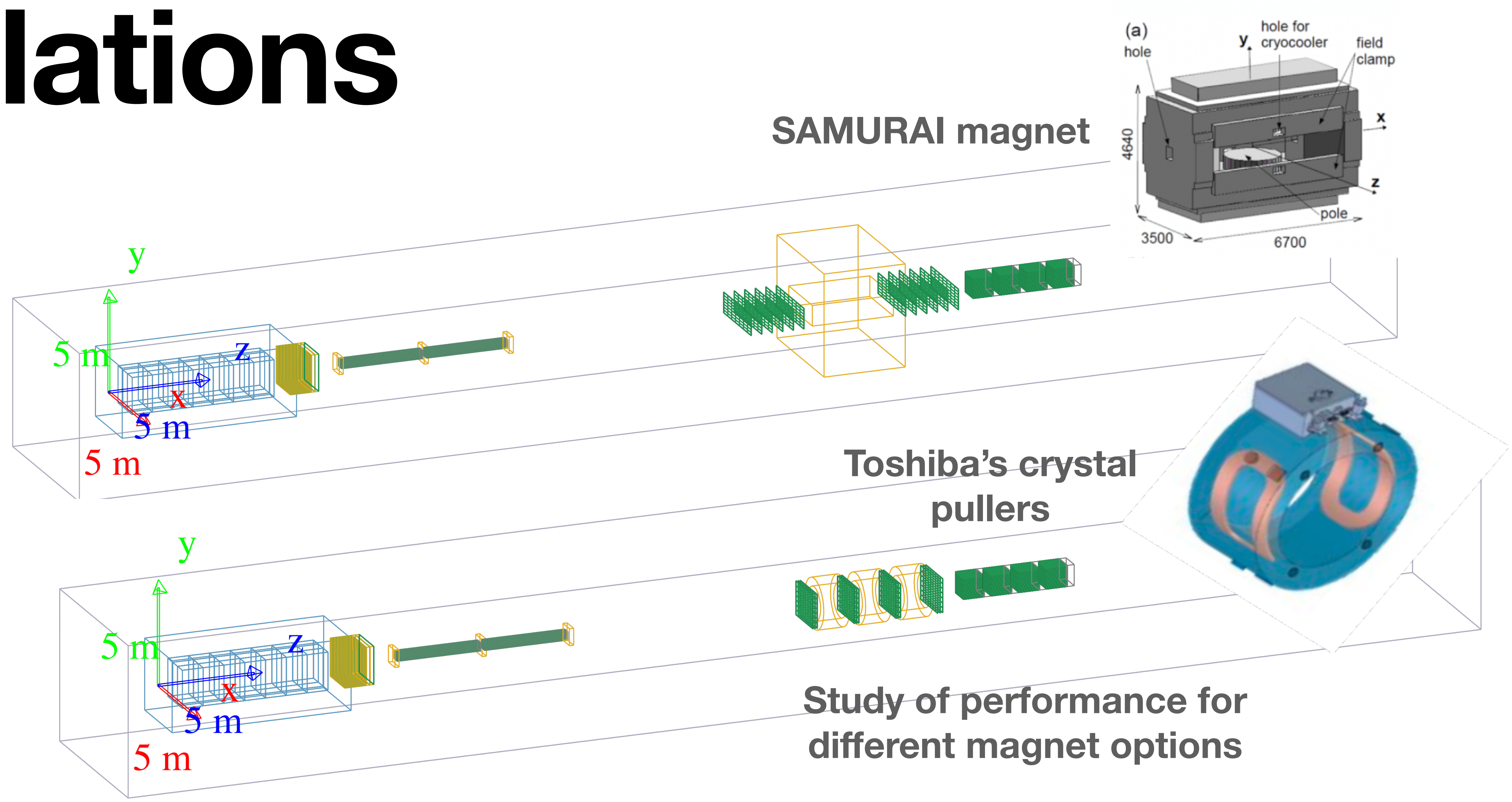
FPF and FLArE Simulations

Full **GEANT4 simulation** of all detectors in the FPF is ready and installed on **lxplus.cern.ch:**

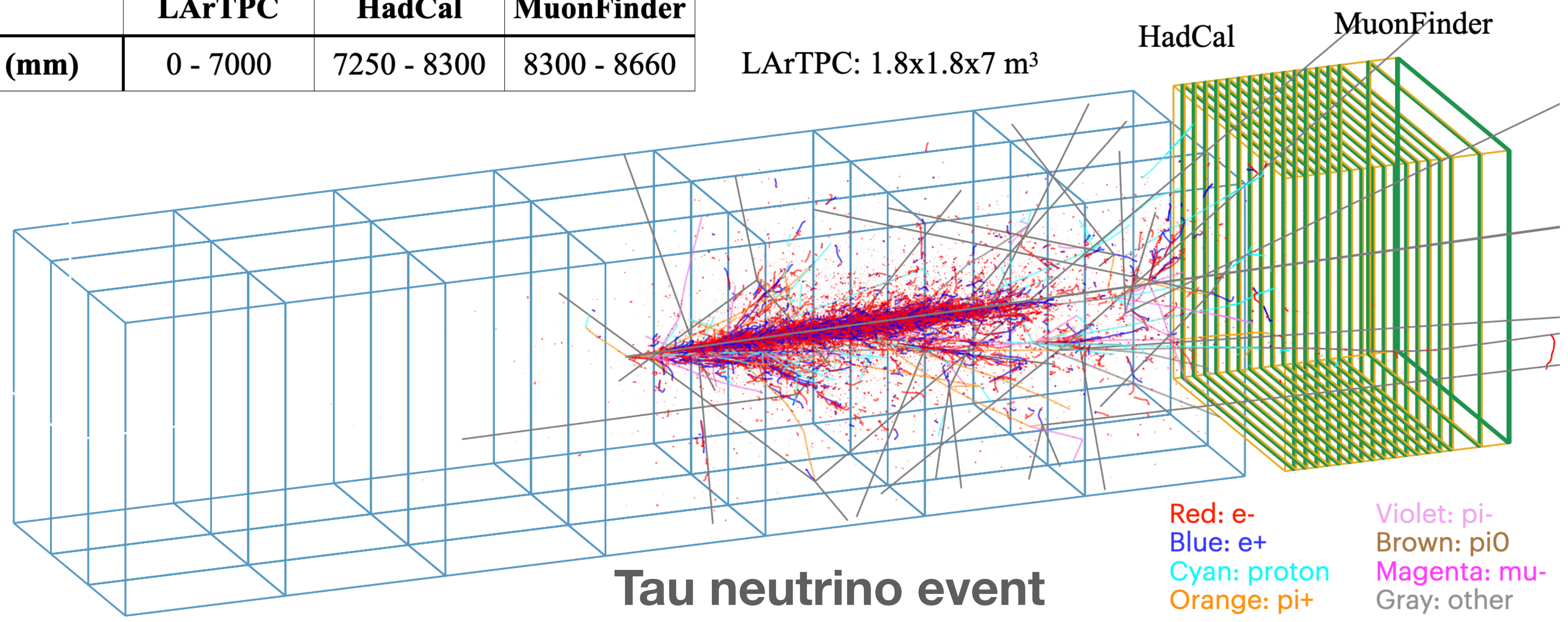
Flexible geometry implementation for study of different hall configurations.

Multiple event generators:

- μ, e, τ neutrino fluxes;
- backgrounds from IP (from FLUKA radiation studies);
- + working on FORESEE (package for DM models).



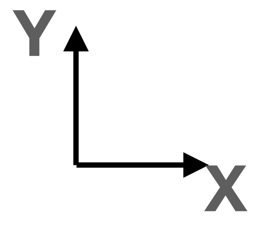
	LArTPC	HadCal	MuonFinder
Z (mm)	0 - 7000	7250 - 8300	8300 - 8660



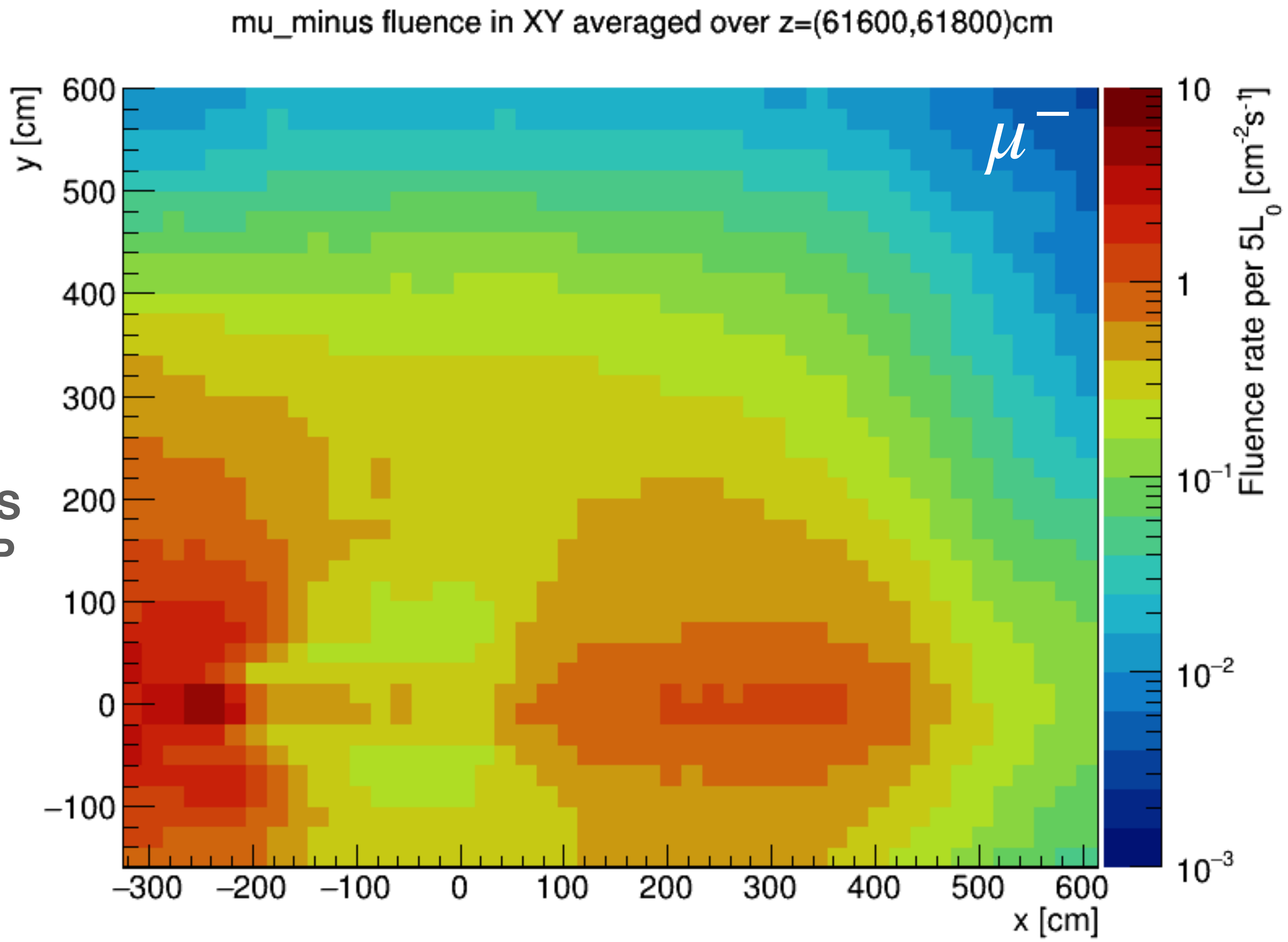
Tau neutrino event simulated in FLArE

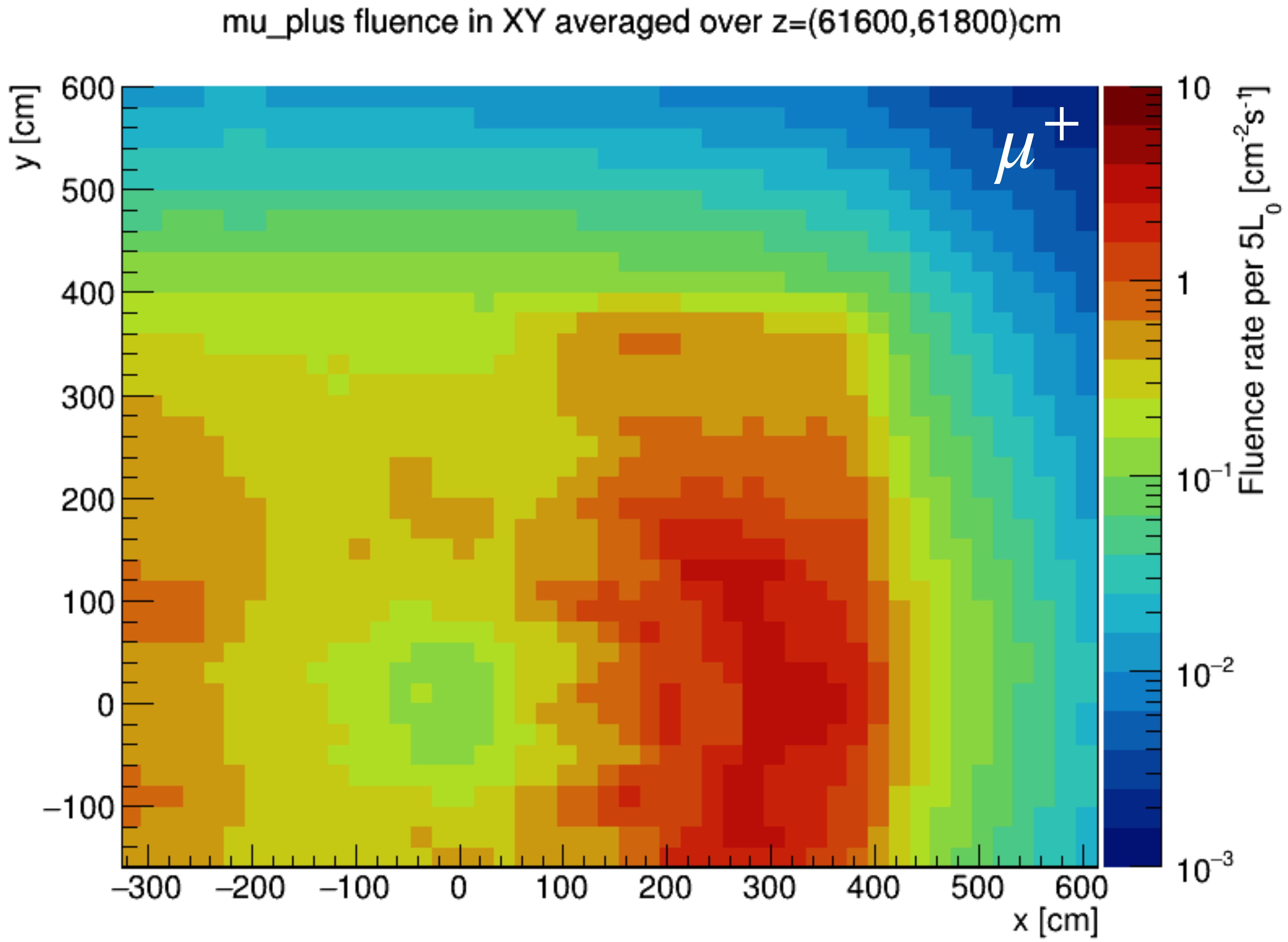
Muon background

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



(0,0) is the LOS from ATLAS IP



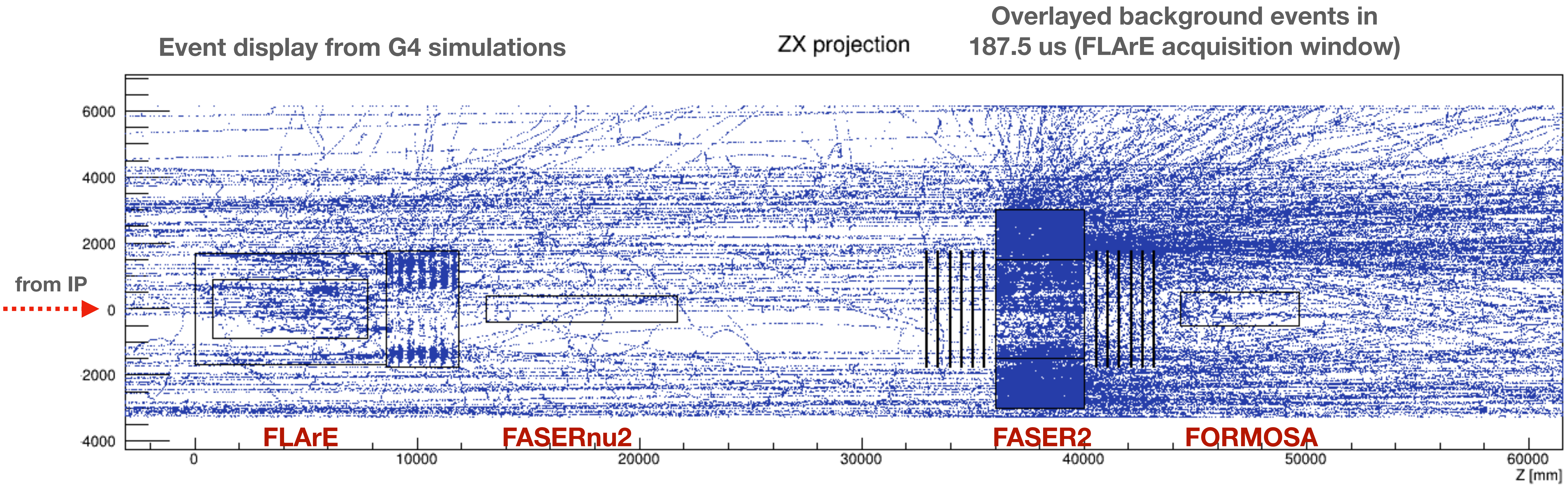


Muon rate at the FPF from CERN FLUKA team. **Hotspots at +/- 2m from LOS**.

Muon flux: **0.6 Hz/cm²** at $5*10^{34}$/cm²/sec (0.15 mu+, 0.45 mu-).

- Space charge/track overlaps sustainable if TPC drift length is ~30 cm, but trigger R&D needed!

Muon background



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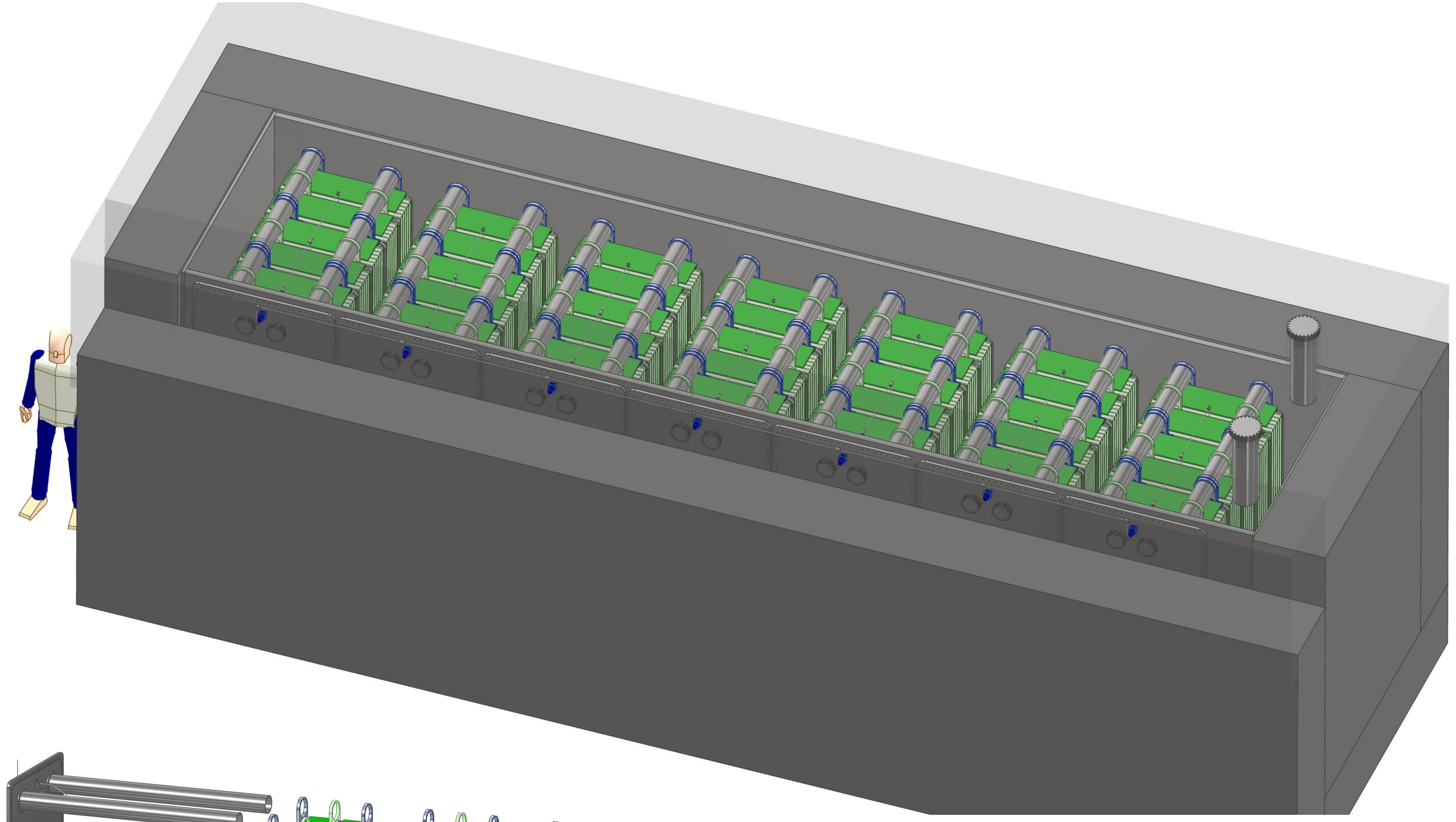
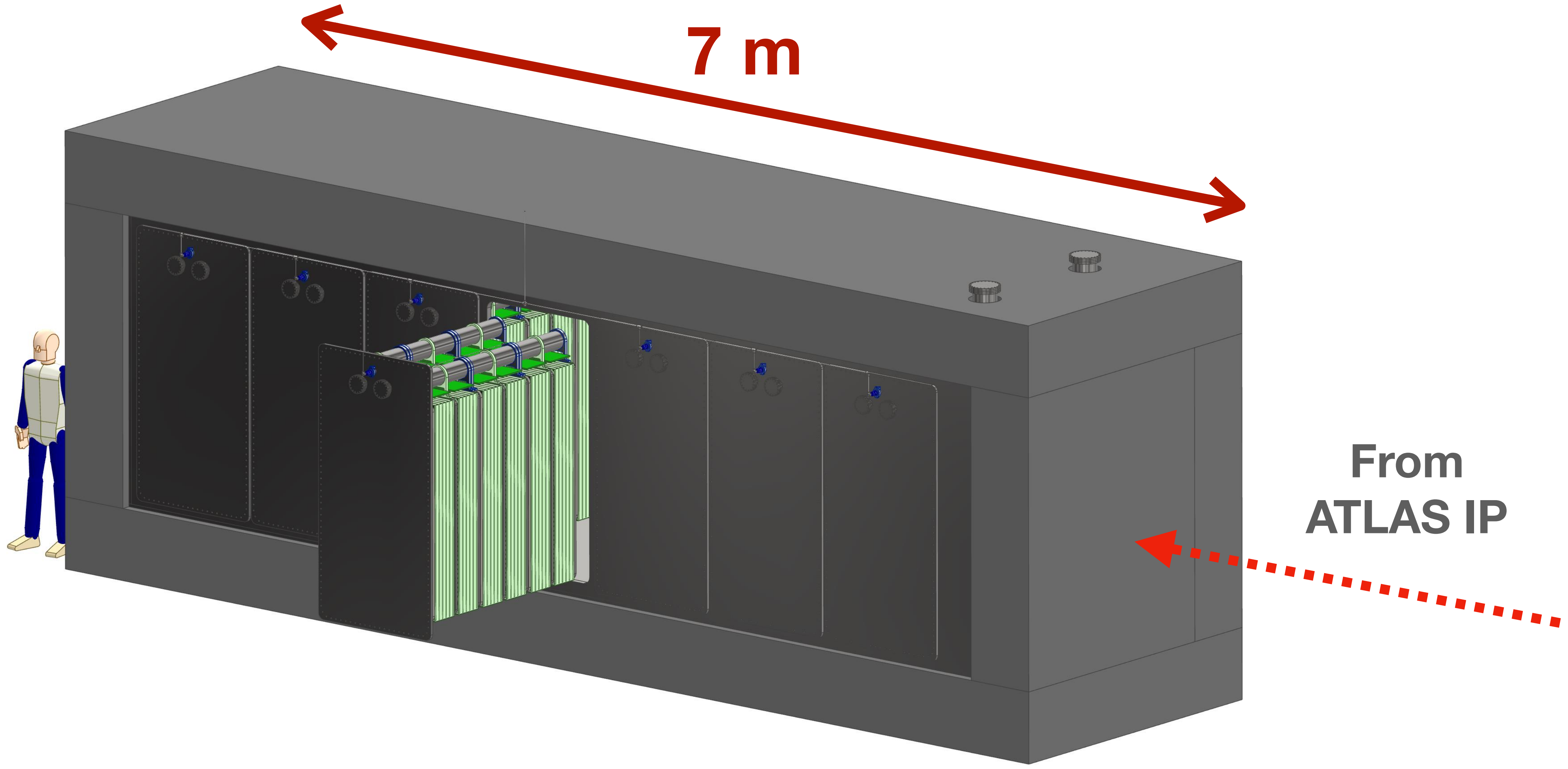
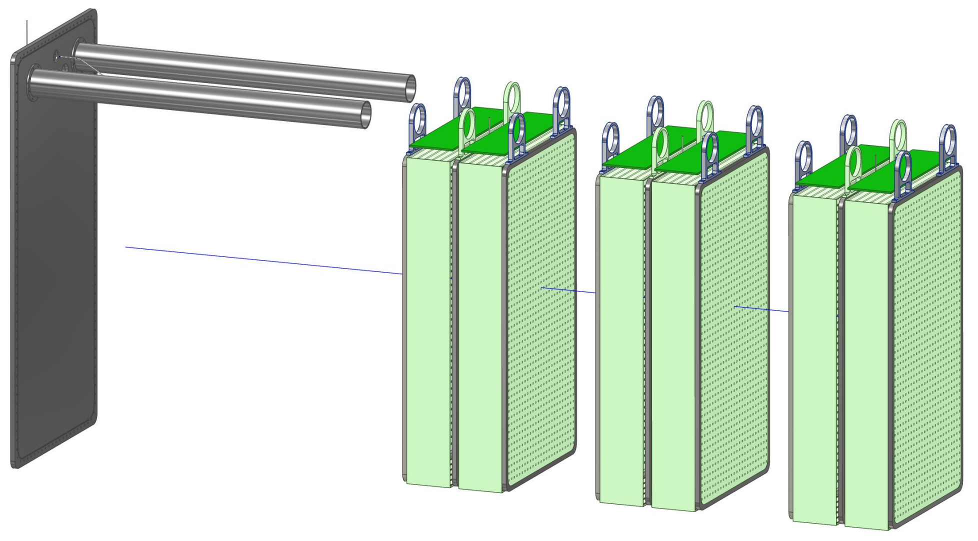
FLArE Detector design

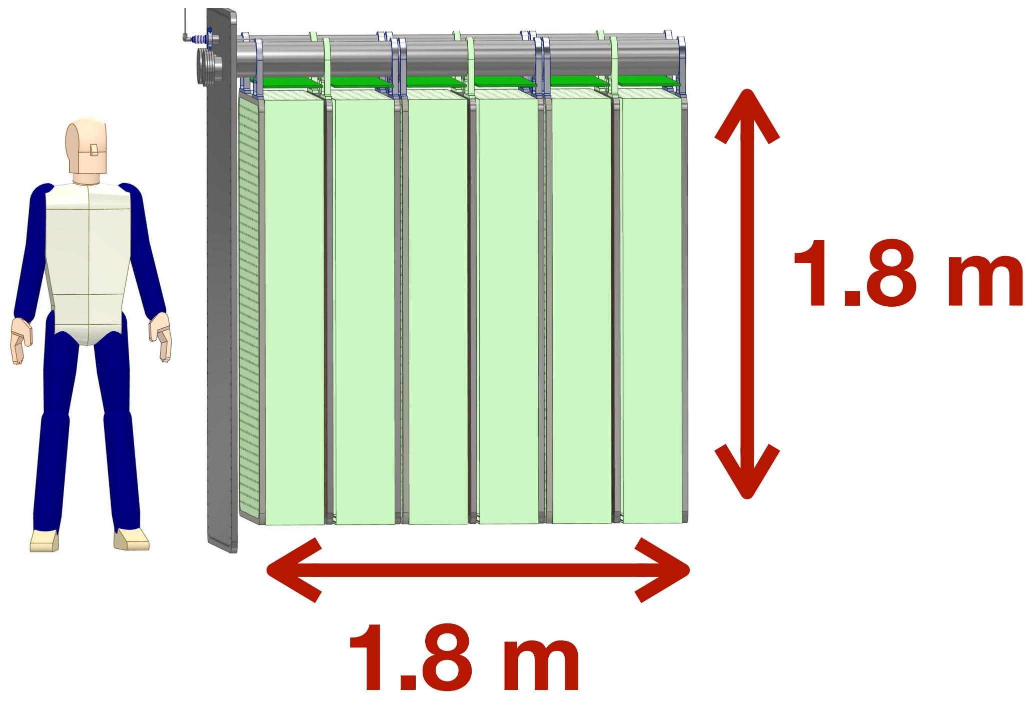
Baseline: foam-insulated cryostat, “filing cabinet” concept
10-ton fiducial LAr mass, 30-ton active volume







Modules “hanging” from the door, installed from the side of the cryostat

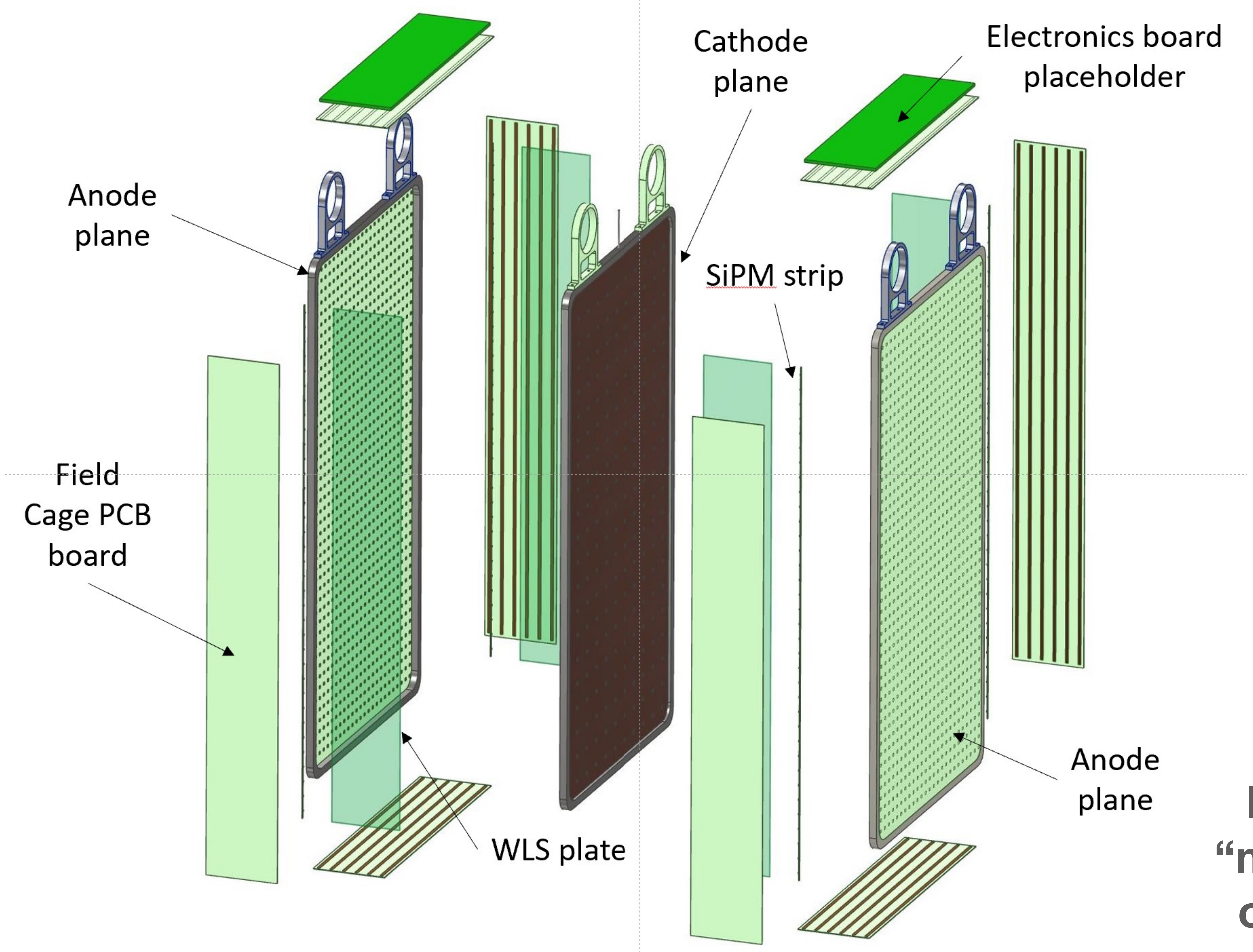


3x7 modular LAr TPC: segmentation for light collection (trigger) and background mitigation (small drift gap ~30cm).

LAr volume: **1.8 m x 1.8 m x 7 m**

Limited space in the cavern, baseline option is **side installation** (“filing cabinet” cryostat).

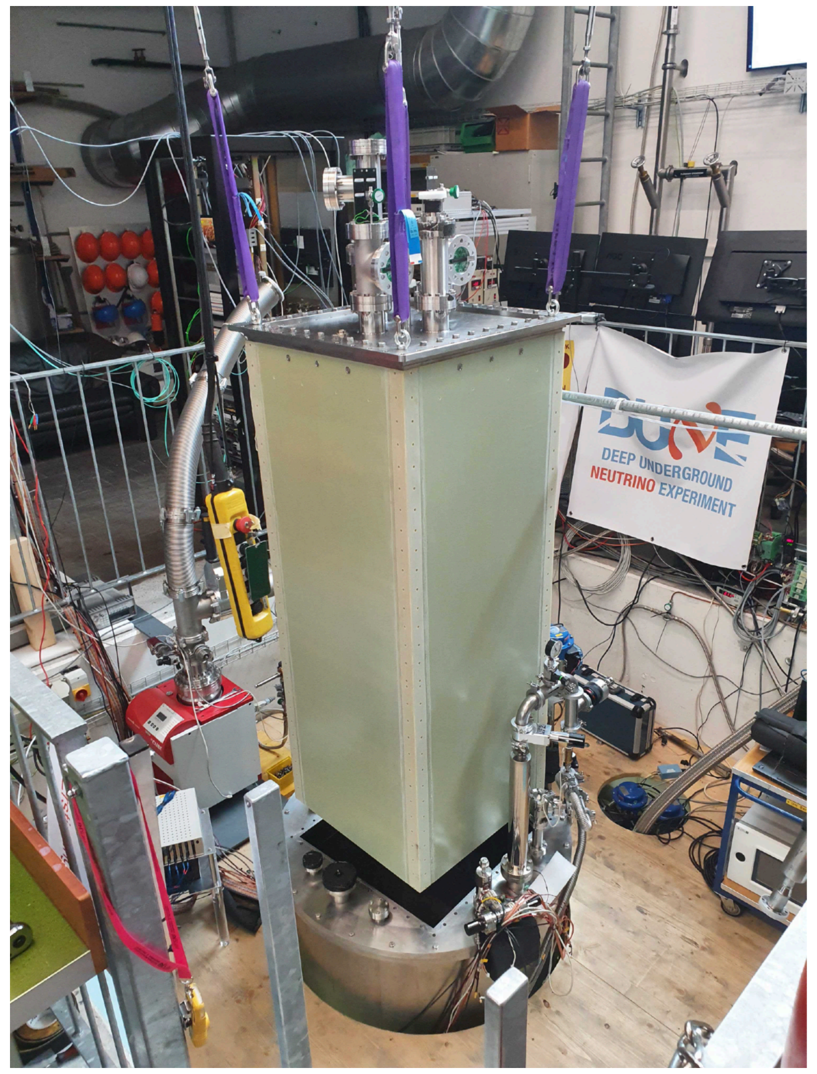
TPC modules



Pixellated anode: ~72000 channels/anode
Photodetection: ~50 SiPMs/anode
Cathode HV: ~15kV (E ~ 500V/m)

Inspired by the DUNE near detector concept

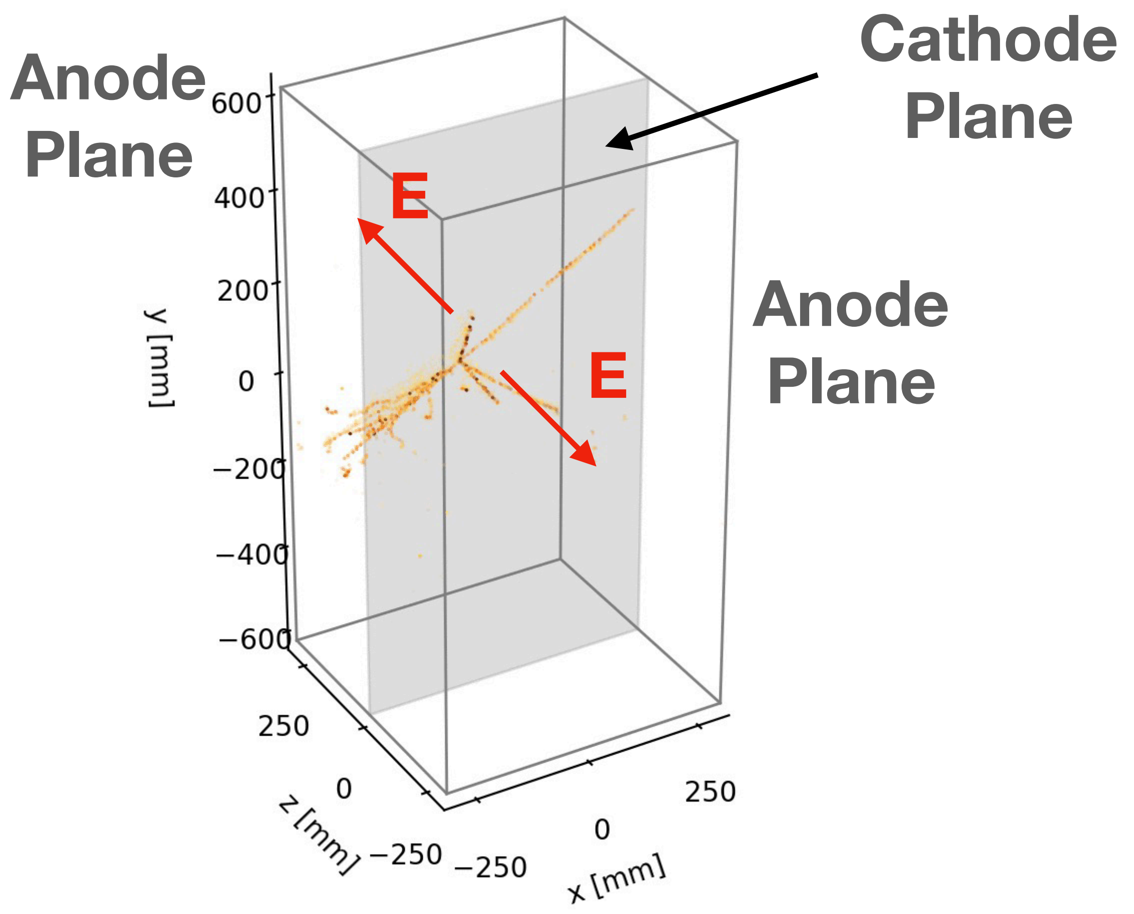
https://doi.org/10.3390/instruments5040031

Lawrence Berkeley National Laboratory
University of Bern

Each module is two "mini" TPCs, sharing a cathode plane in the middle

Drift gap ~30 cm

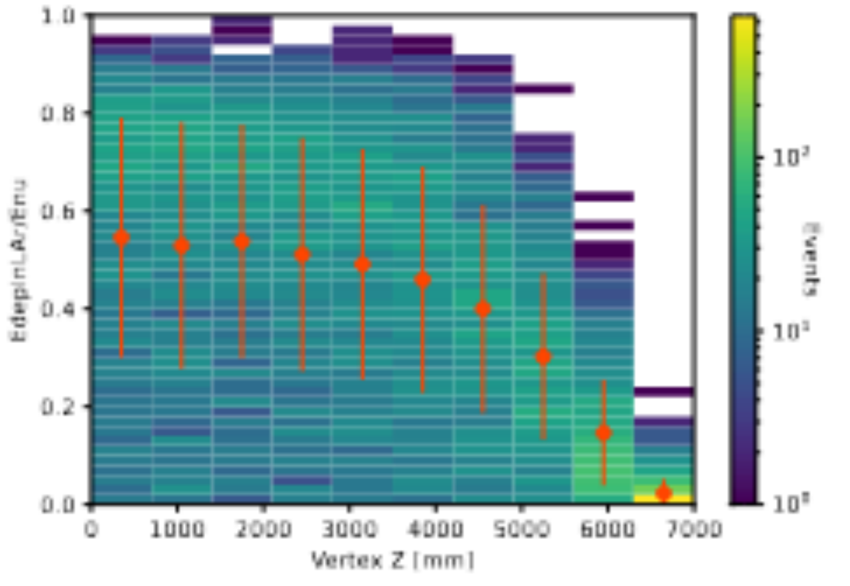


Downstream calorimeter

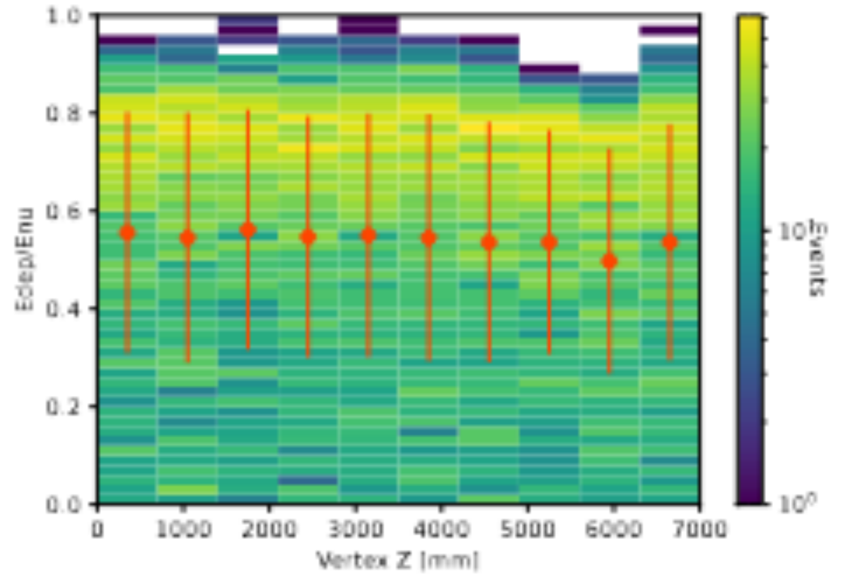
BabyMIND concept

Simulations show the need for a downstream calorimeter to improve **event/energy containment.**

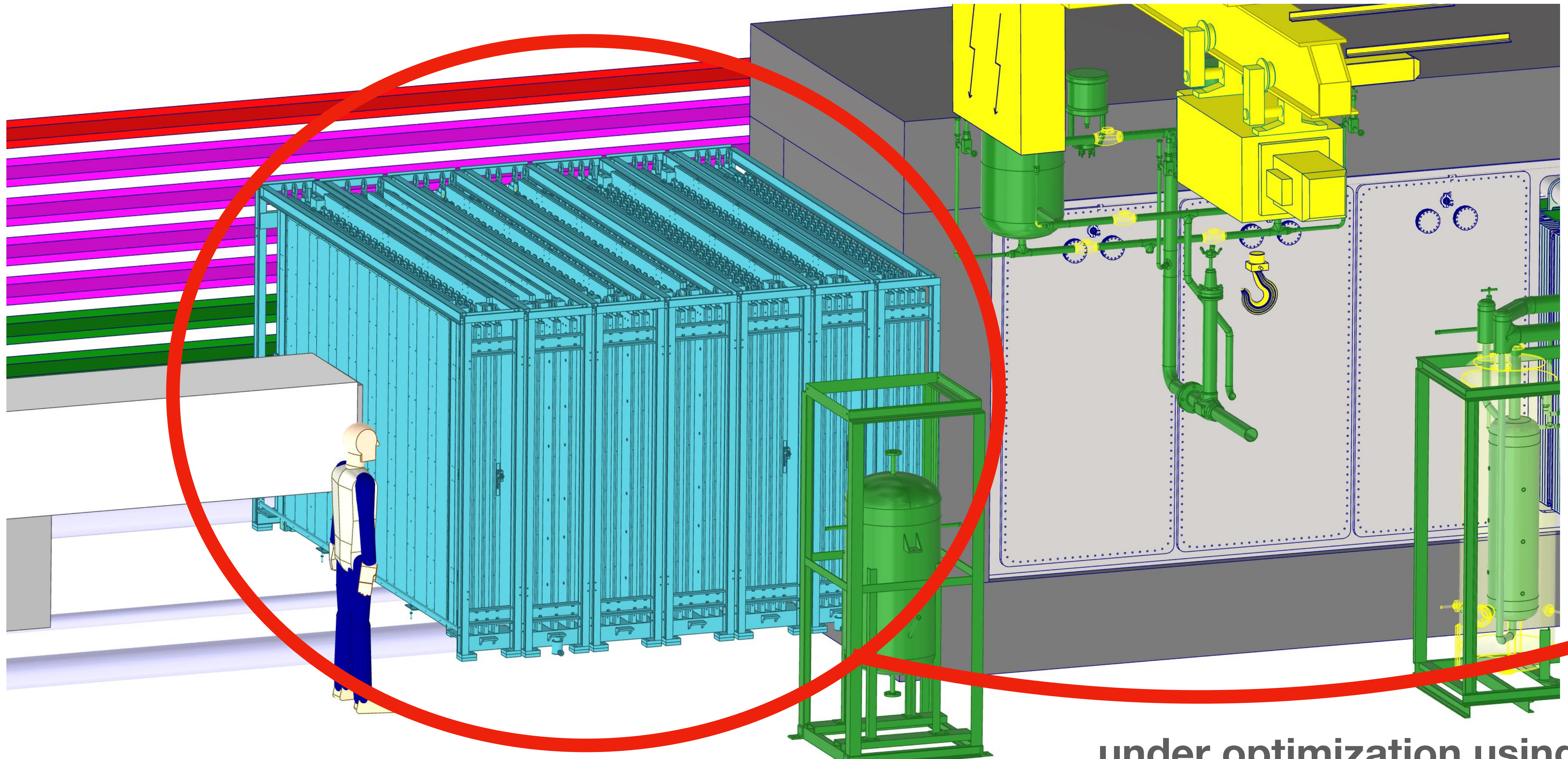
Bonus if magnetized: momentum measurement for uncontained “soft” (<20 GeV) muons that don’t reach FASER2



(a) Energy containment without HadCal for the size $1.8 \times 1.8 \times 7\ m^3$.



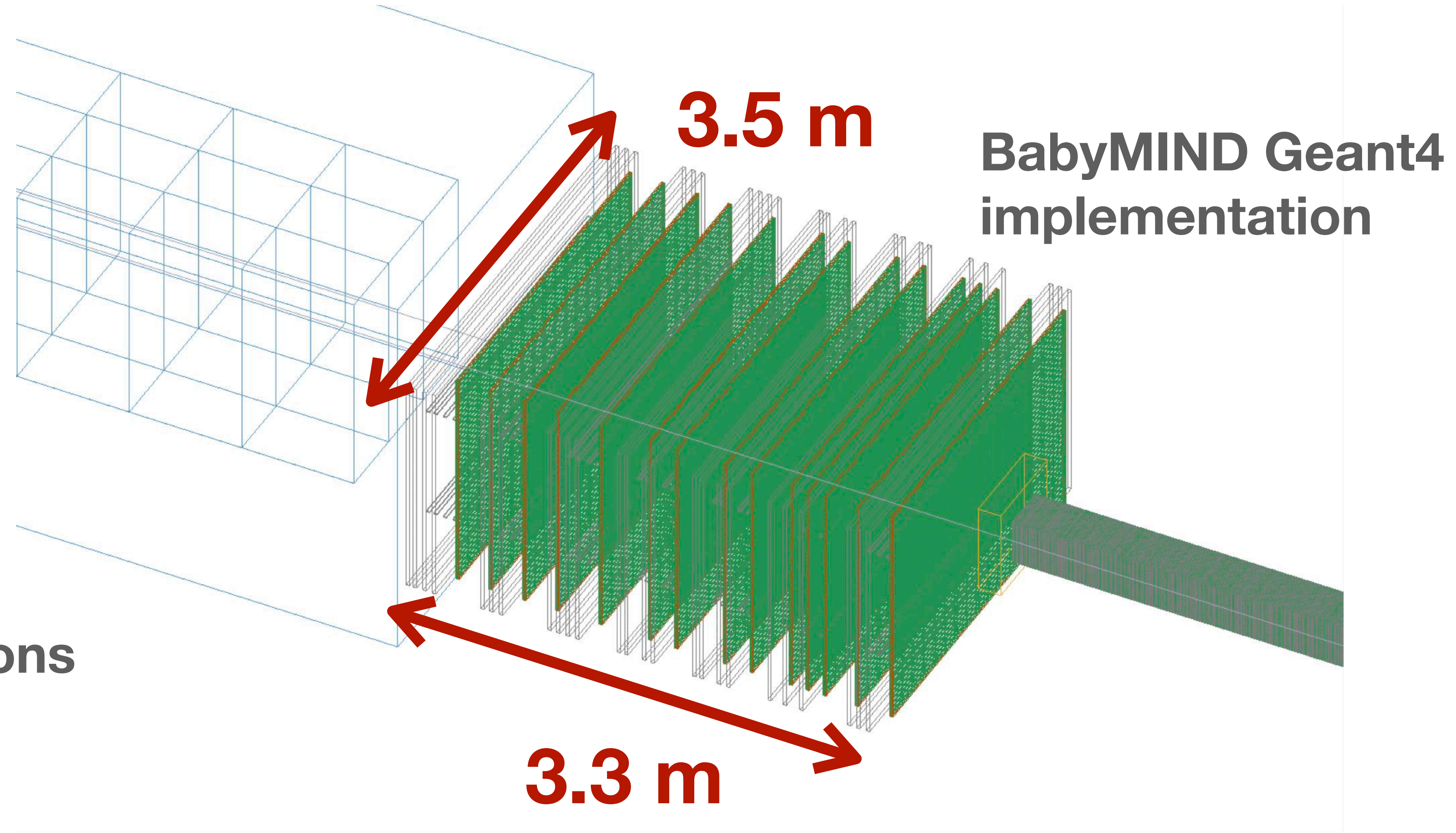
(b) Energy containment with HadCal for the size $1.8 \times 1.8 \times 7\ m^3$.



https://doi.org/10.1088/1748-0221/12/07/C07028

BabyMIND concept: Fe/Scint calorimeter, with clever magnetization scheme (1.5 T)

under optimization using simulations for muon tagging/reco

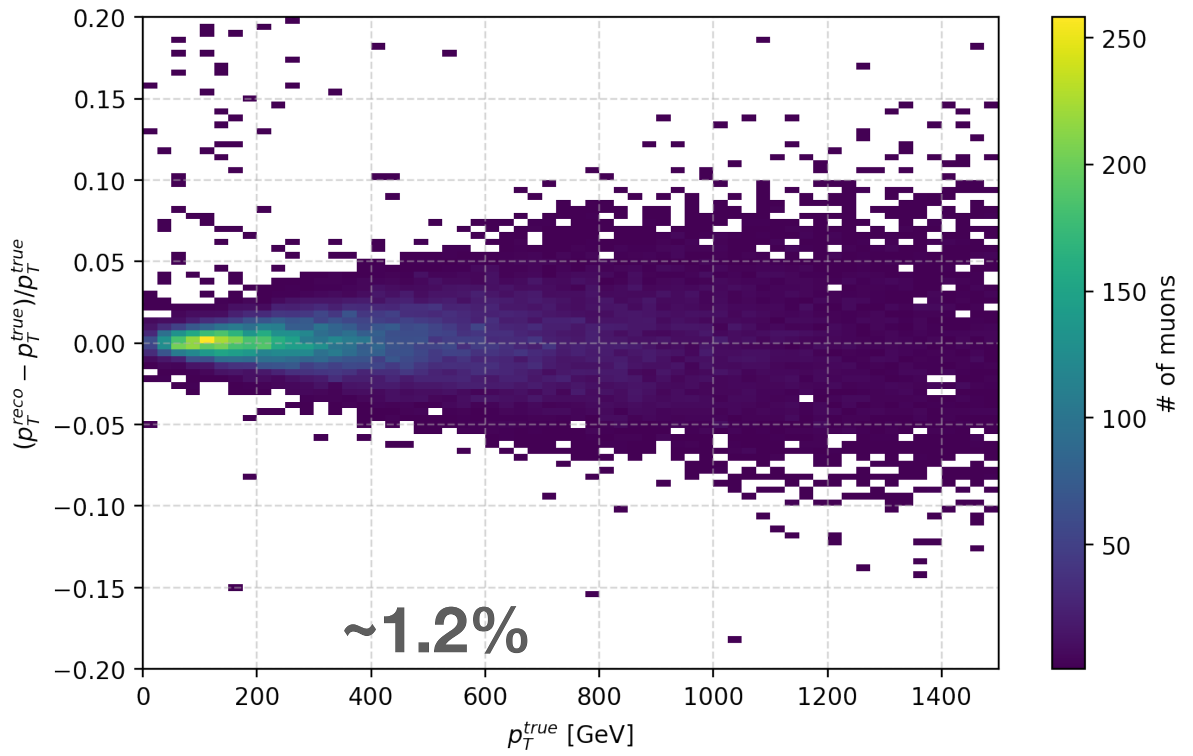


Other simulation studies

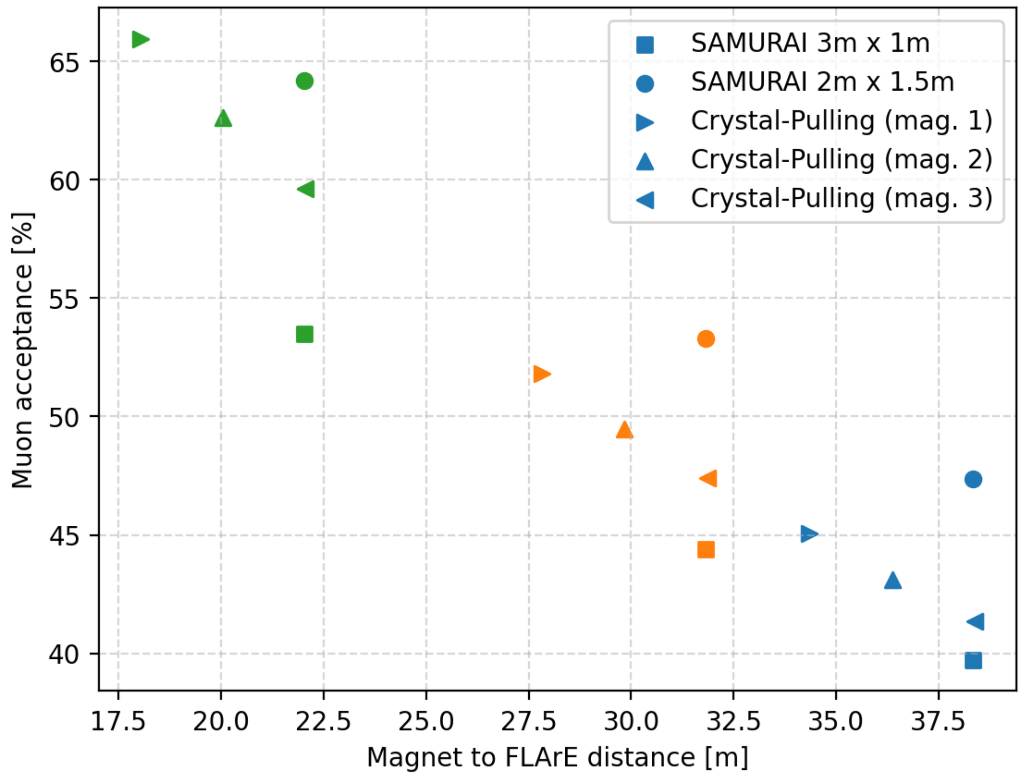
Mostly studies supporting technical design. Note in preparation, should be ready soon!

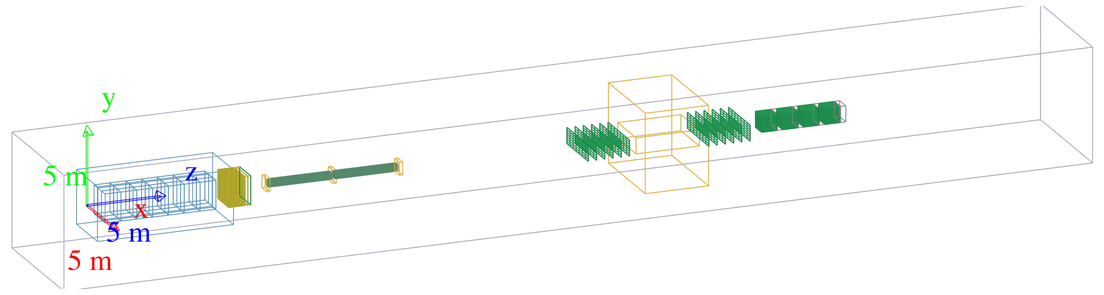
- **Muon acceptance/reconstruction** studies:
  - Synergy with FASER2 magnet (45-55% acceptance). Need optimization of BabyMIND.
- Effect of **pitch size** (nominal: 5mm):
  - Balance between spatial resolution, number of readout channels (72k/anode) and heat load
- AI/ML techniques for **particle ID:**
  - Looking at statistical Tau ID from dE/dx distributions
- **Background** studies.

Momentum resolution @ FASER2

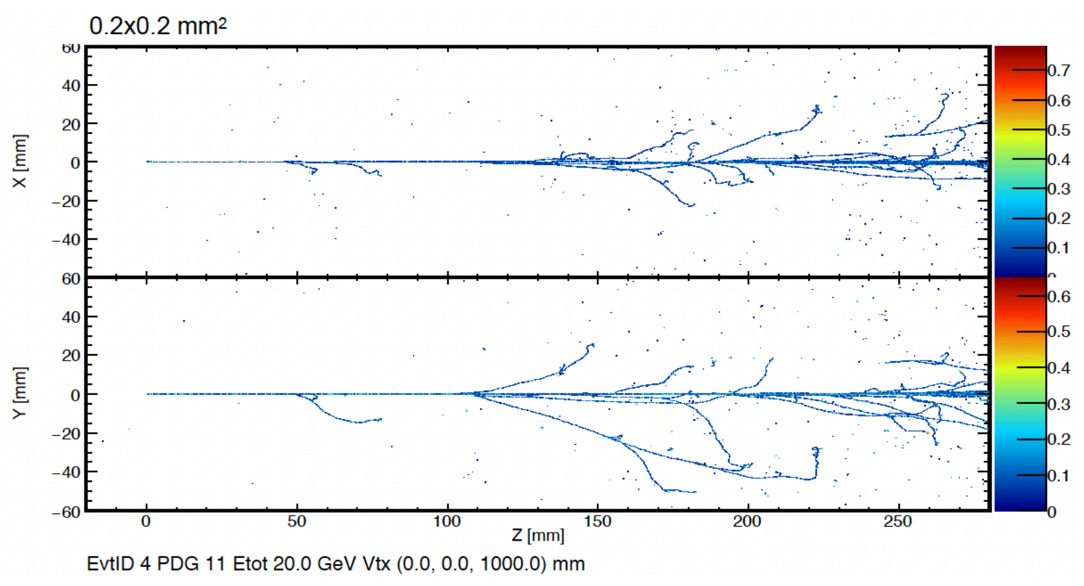


Acceptance @ FASER2

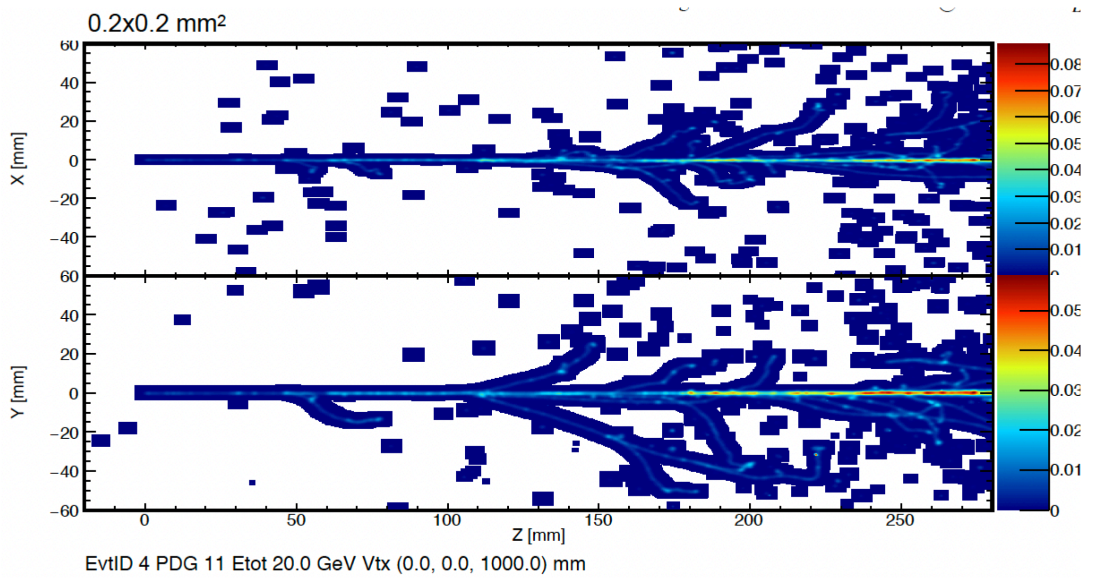




Single electron



Single electron (w/ diffusion)



Summary

Diverse and exciting physics potential from **neutrino physics** to **QCD** and wide range of **BSM searches** at the **Forward Physics Facility (FPF)** at CERN.

BNL Intensity Frontier & Instrumentation groups involved in the development of technical design and simulations for a **liquid argon detector (FLArE)** at the FPF.

- Backgrounds and engineering considerations necessitates a **modular detector**.
- Cryogenics and **baseline TPC design** quite advanced. Further field cage calculations needed to finalize HV distribution.
- Great benefits from **DUNE ND-LAr** past R&Ds (pixellated readout, etc..).
- Full **Geant4 simulation package** has been developed for FLArE/FPF. Studies ongoing for detector design (backgrounds, acceptance, …)

Two technical notes on detector design and simulation are in preparation towards the 2026 European Particle Physics Strategy Update (EPPSU).

Thank you!

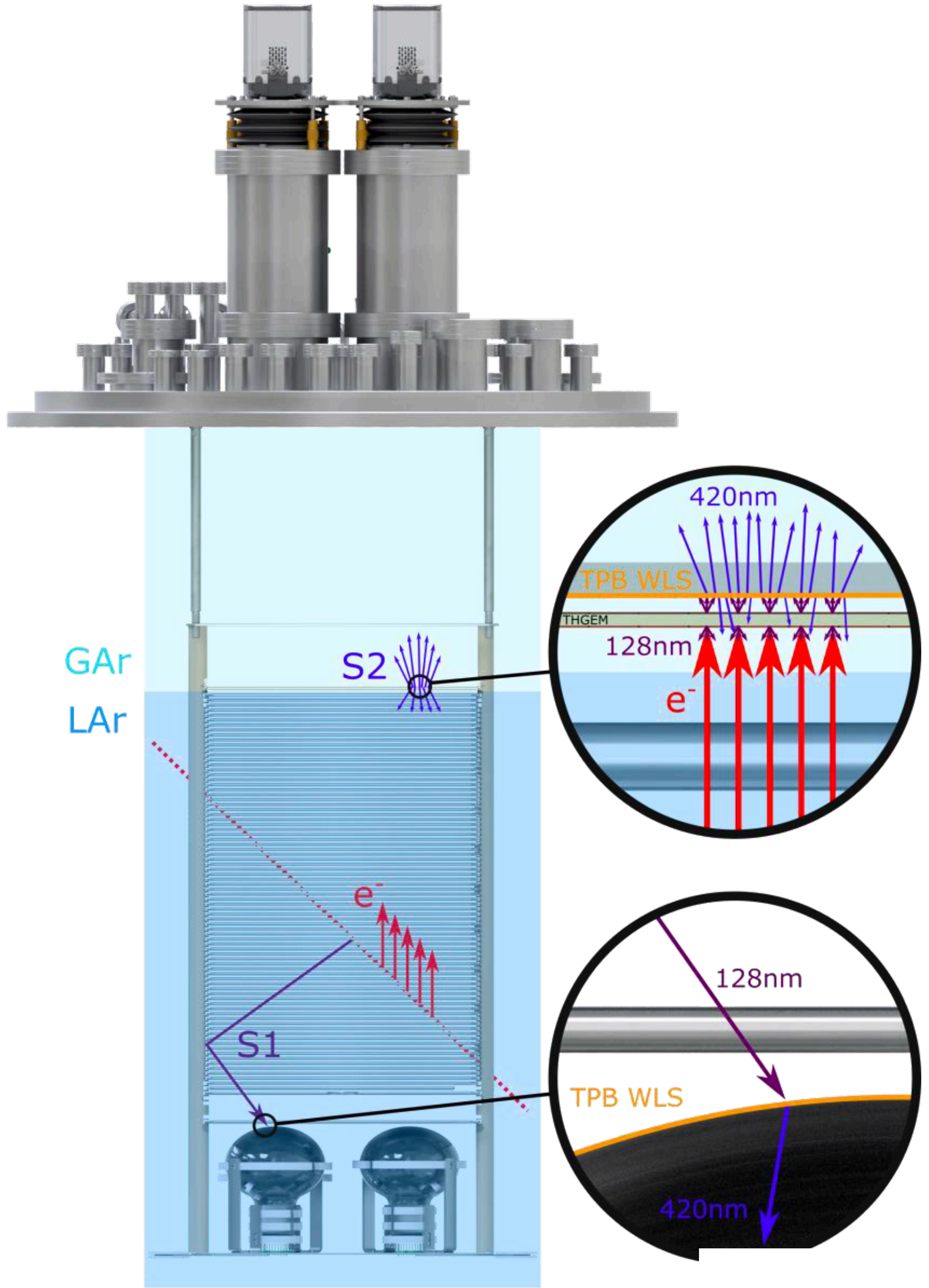
Alternative option

ARIADNE @ FLArE

Fully-optical readout using **Timepix cameras** in double-phase TPCs.

- Electrons drift towards the extraction grid situated below the liquid level
- A THGEM (THick-Gaseous Electron Multiplier) amplifies drift charge, generating secondary scintillation light (S2)
- WLS (Wavelength Shifting) before imaging with Timepix3 camera.

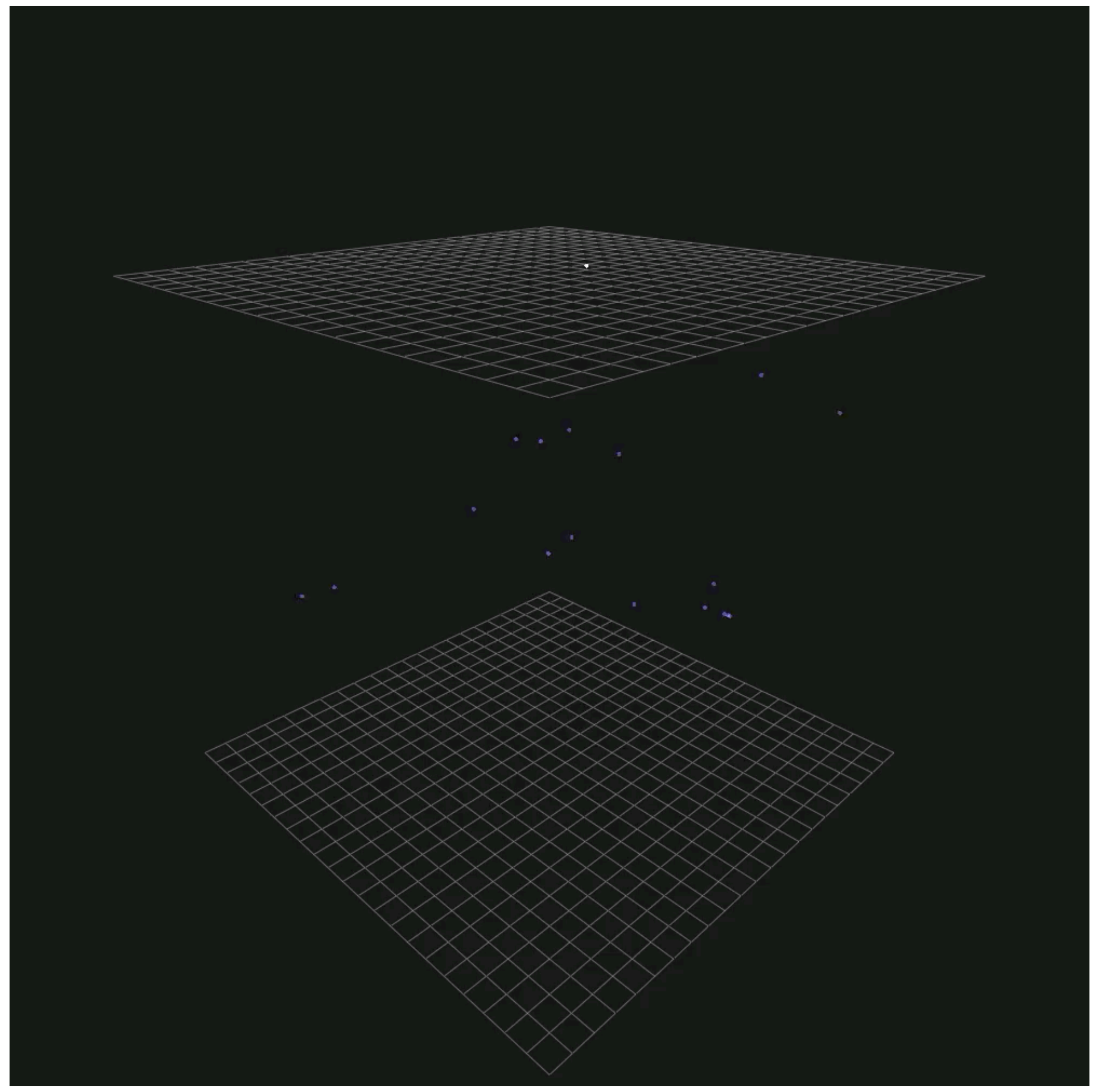
Discussions for a possible implementation in FLArE (Kostas Mavrokoridis, Liverpool U.)

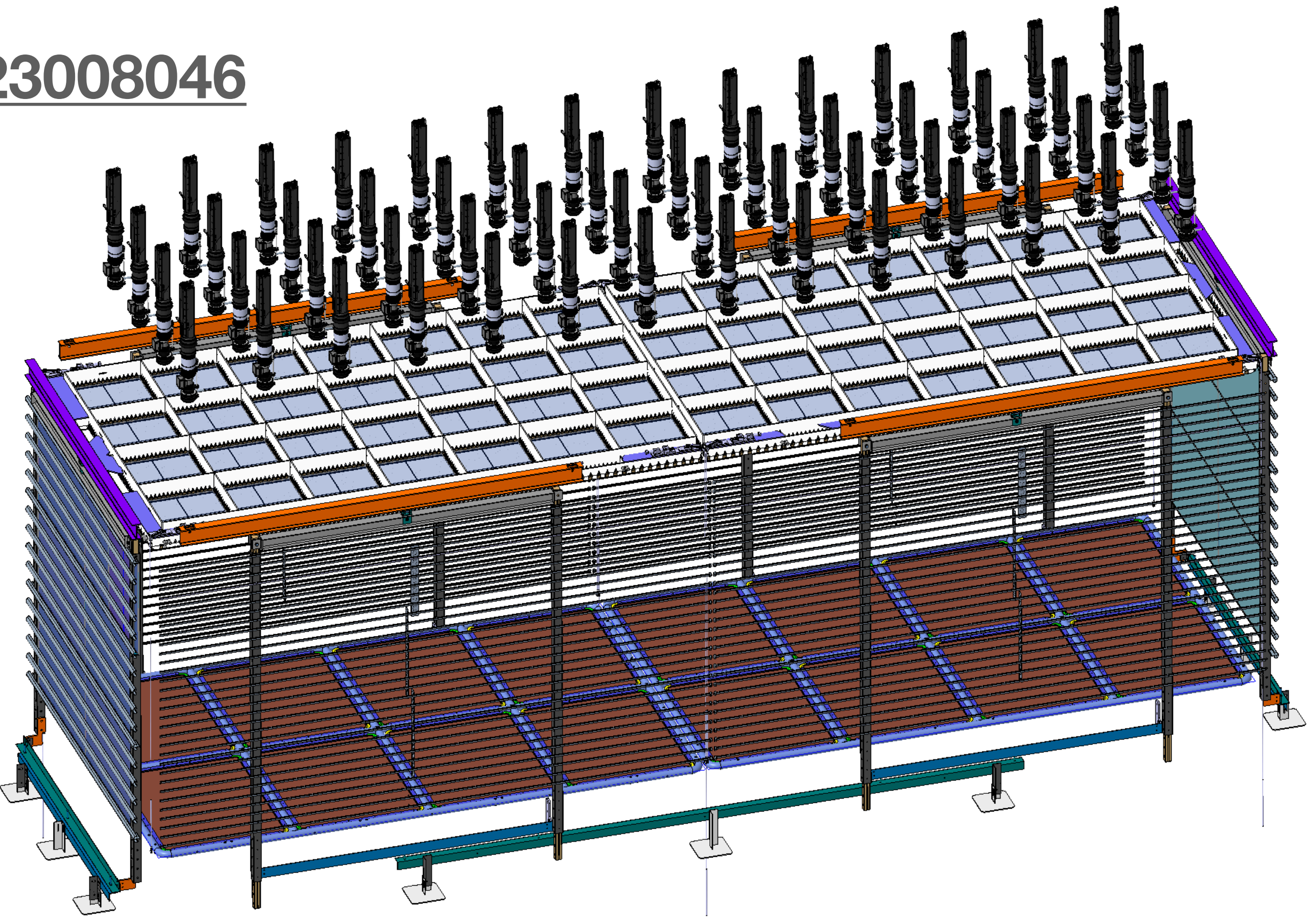


https://doi.org/10.3390/psf2023008046

ARIADNE (**AR**gon Im**A**ging **D**etectio**N** chamb**E**r)

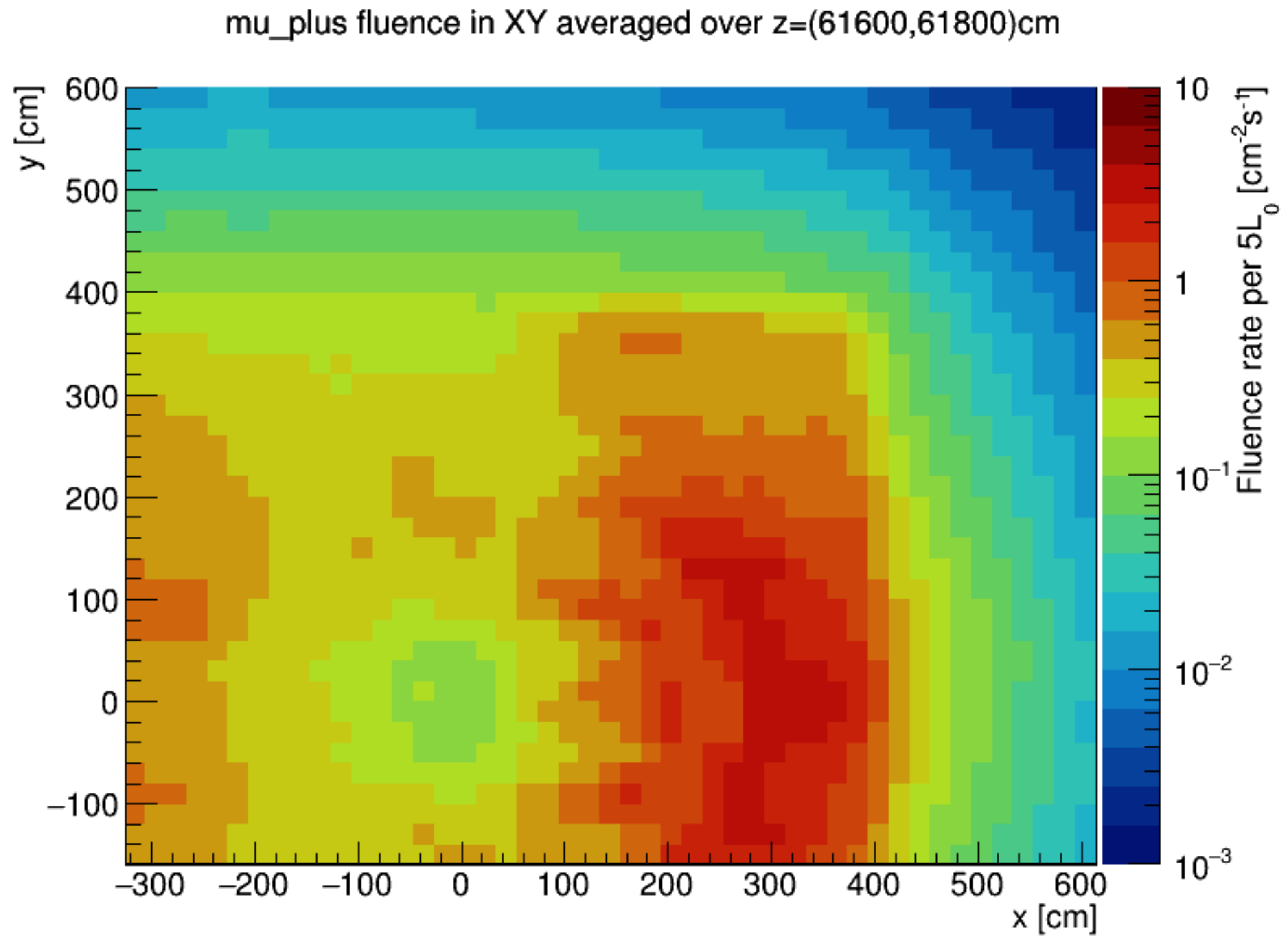
Continuous streaming, 10ms slice (playing 1ms jump per frame)

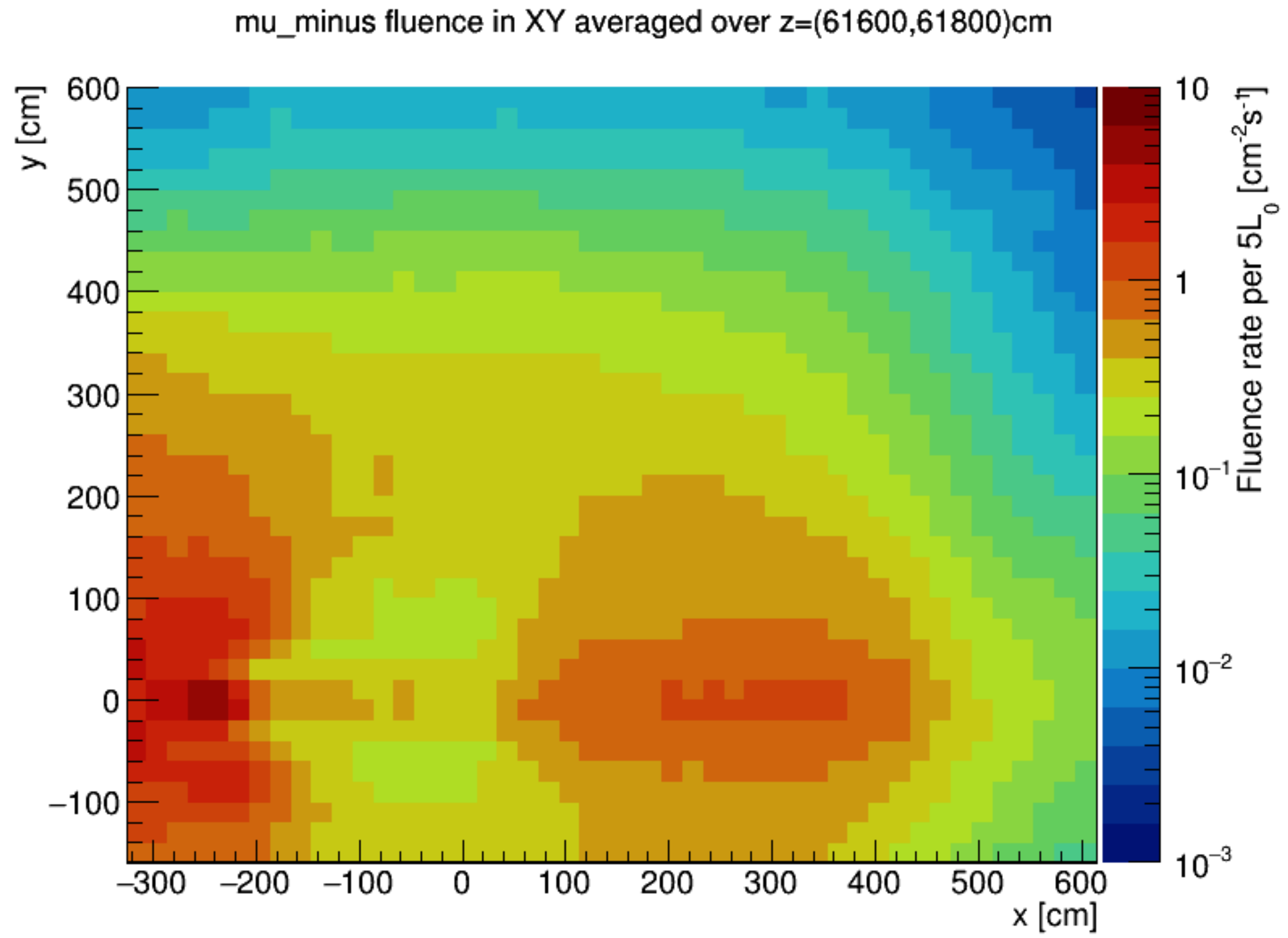


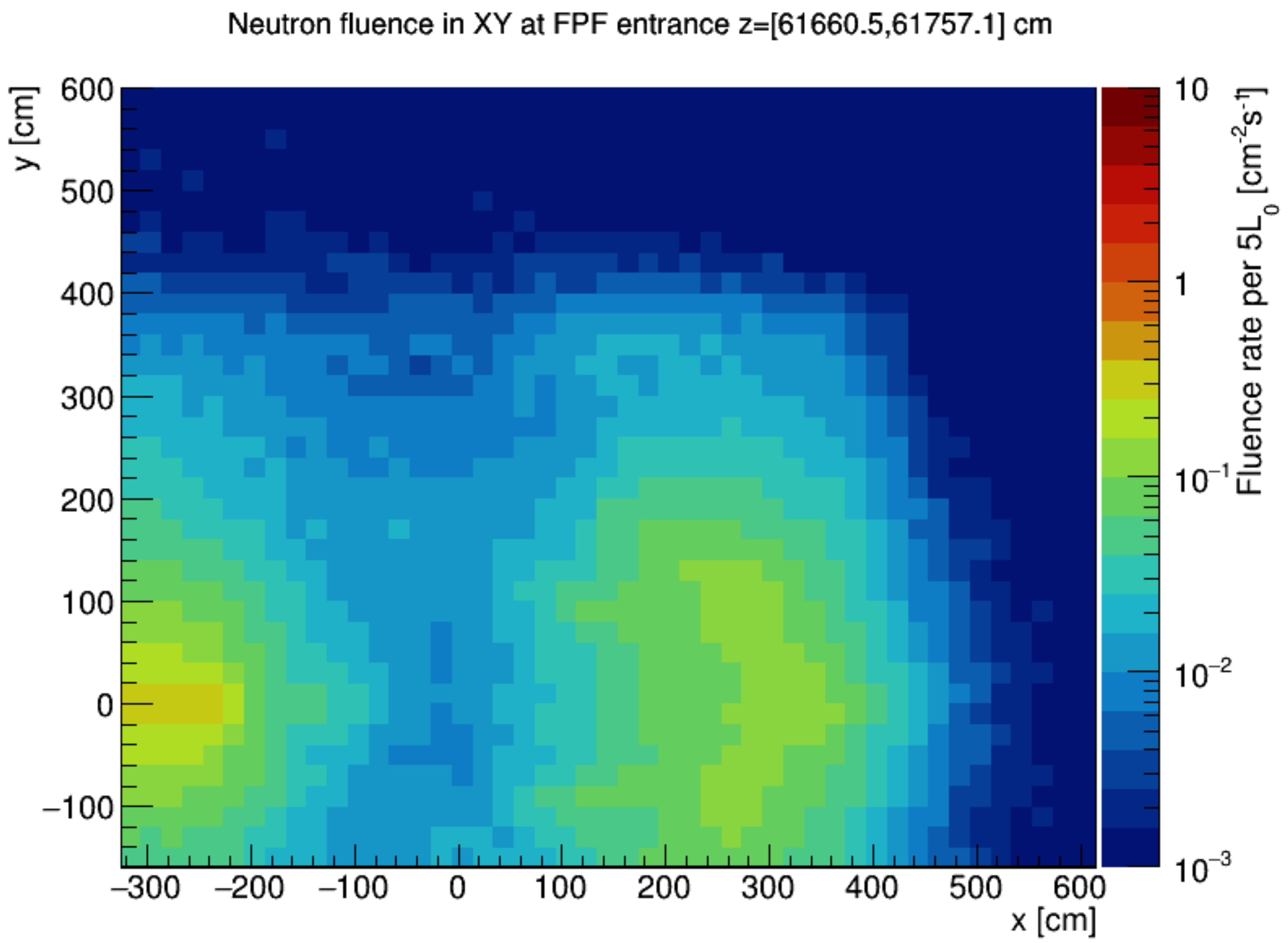


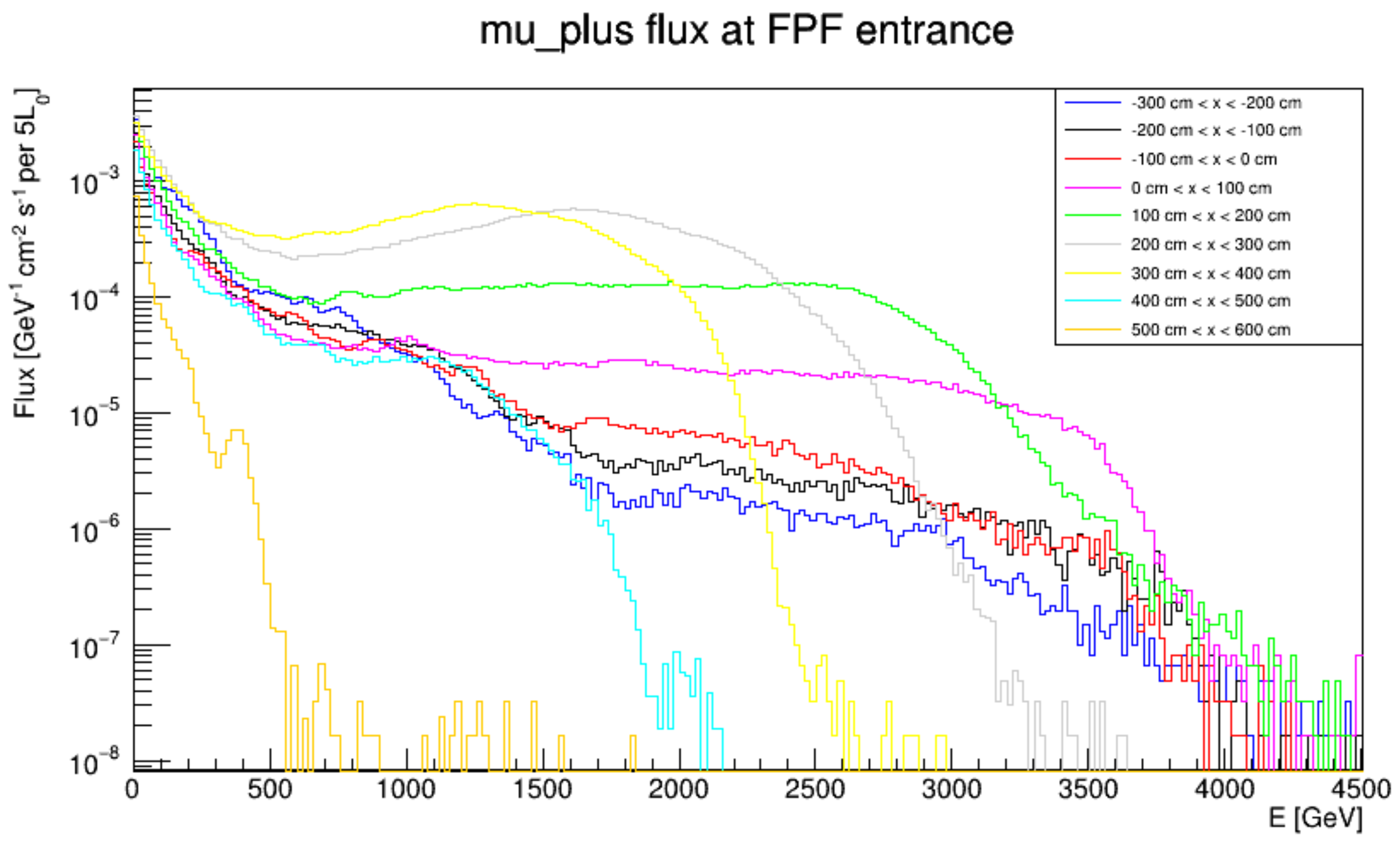
ARIADNE @ FLArE concept

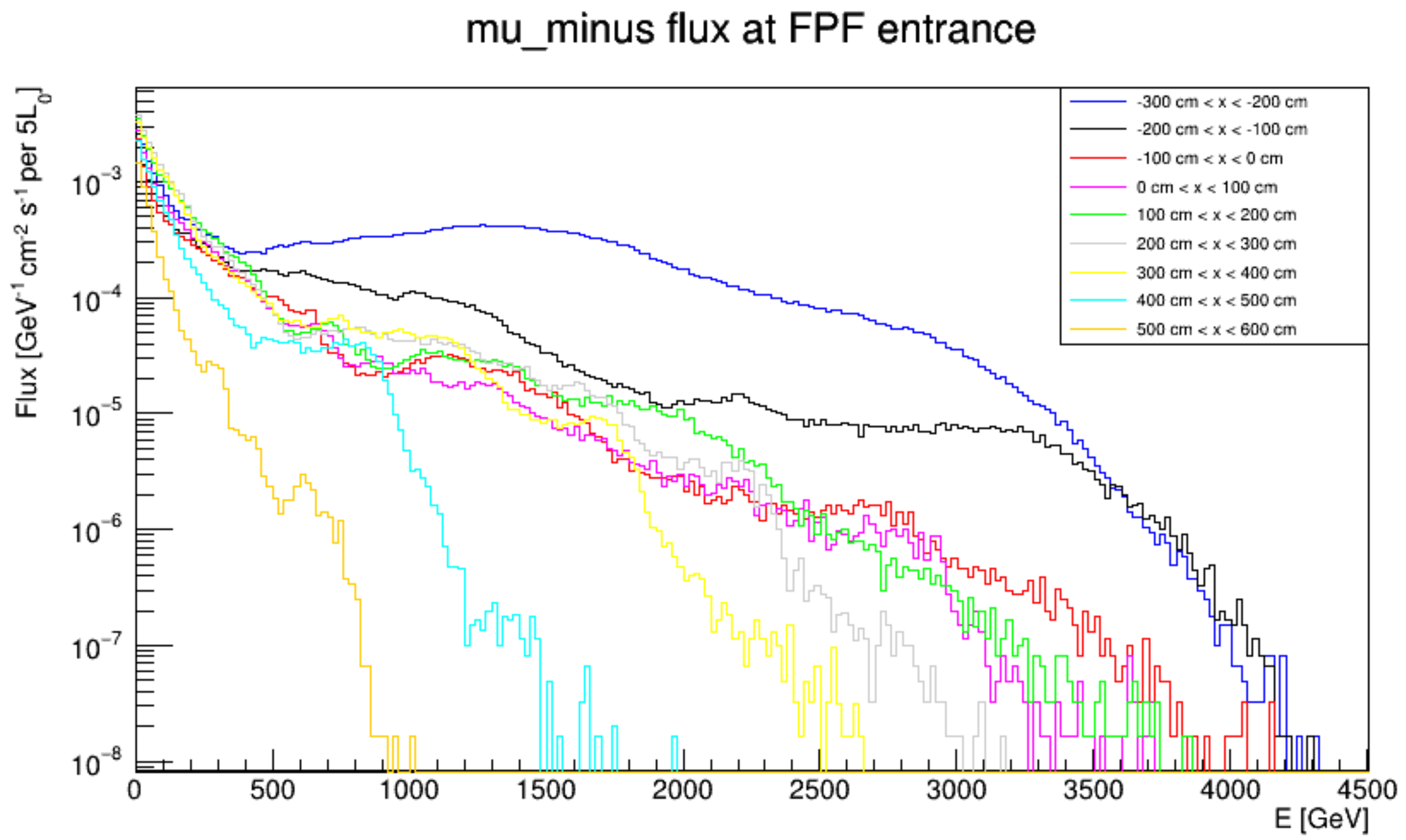
Backgrounds

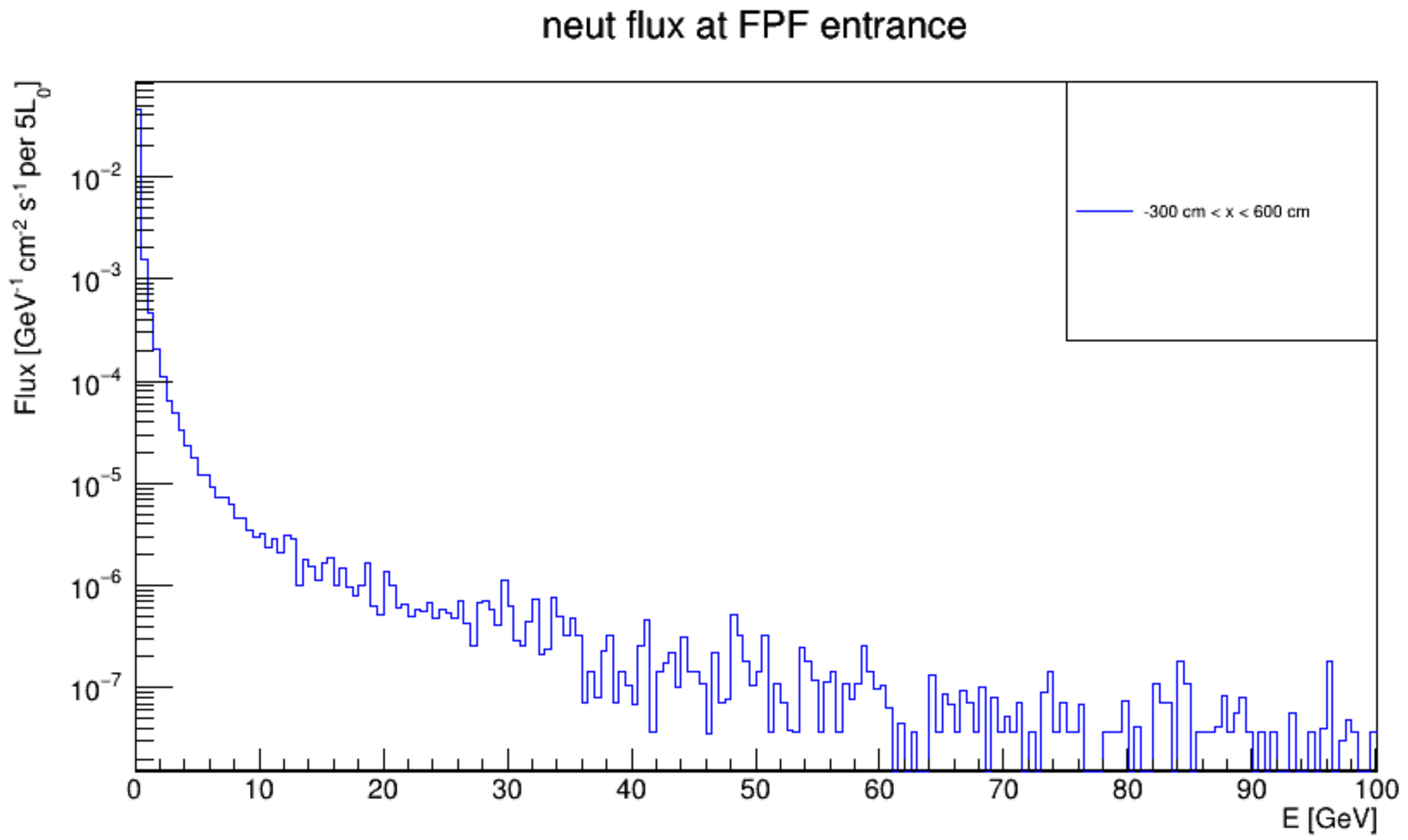








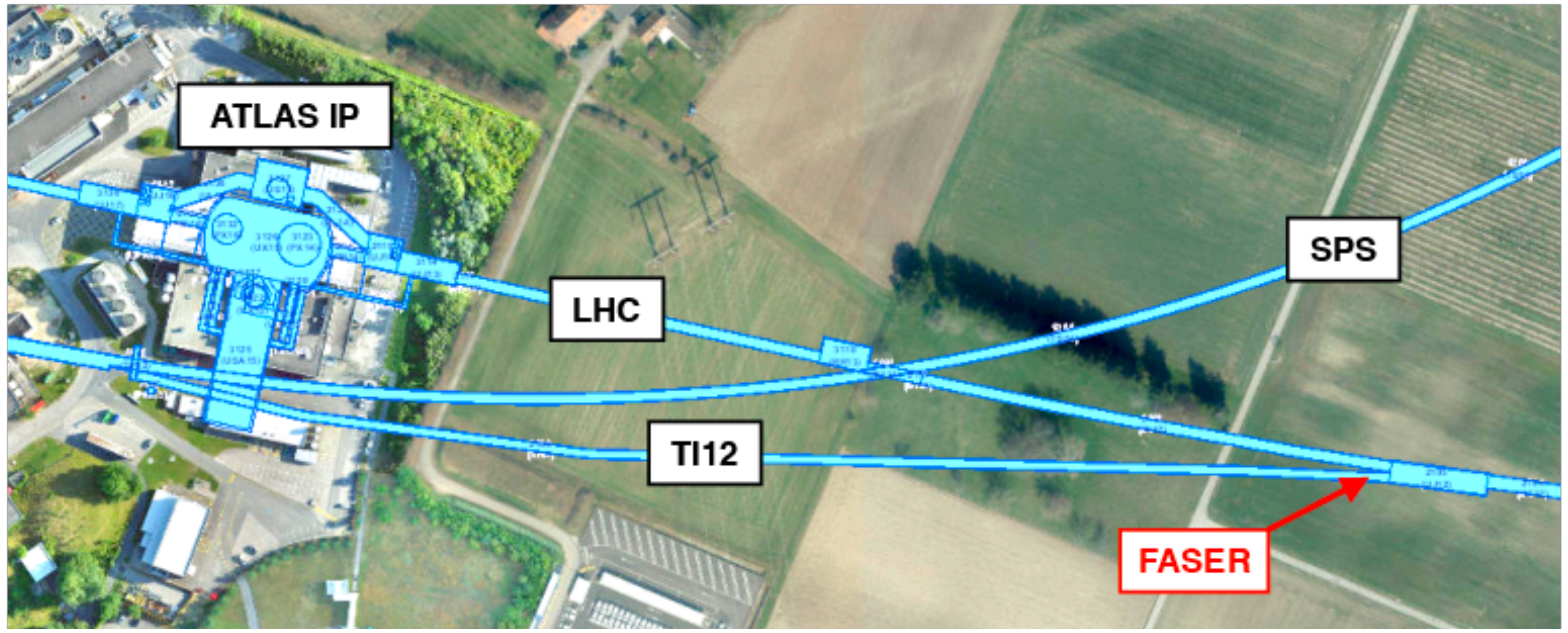


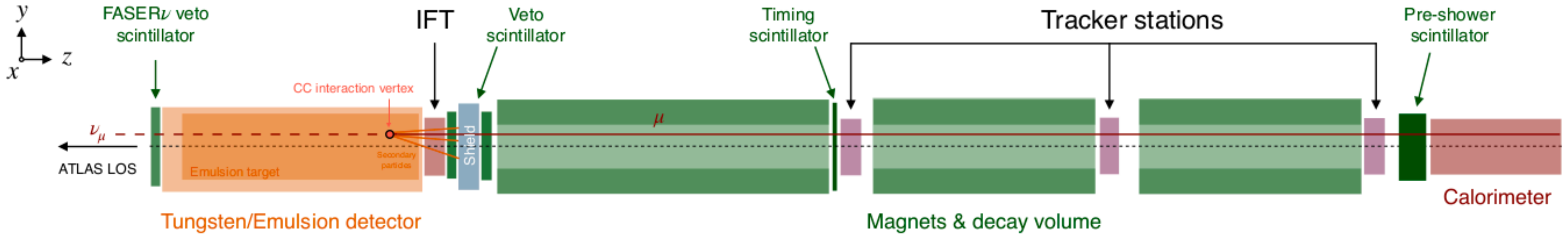


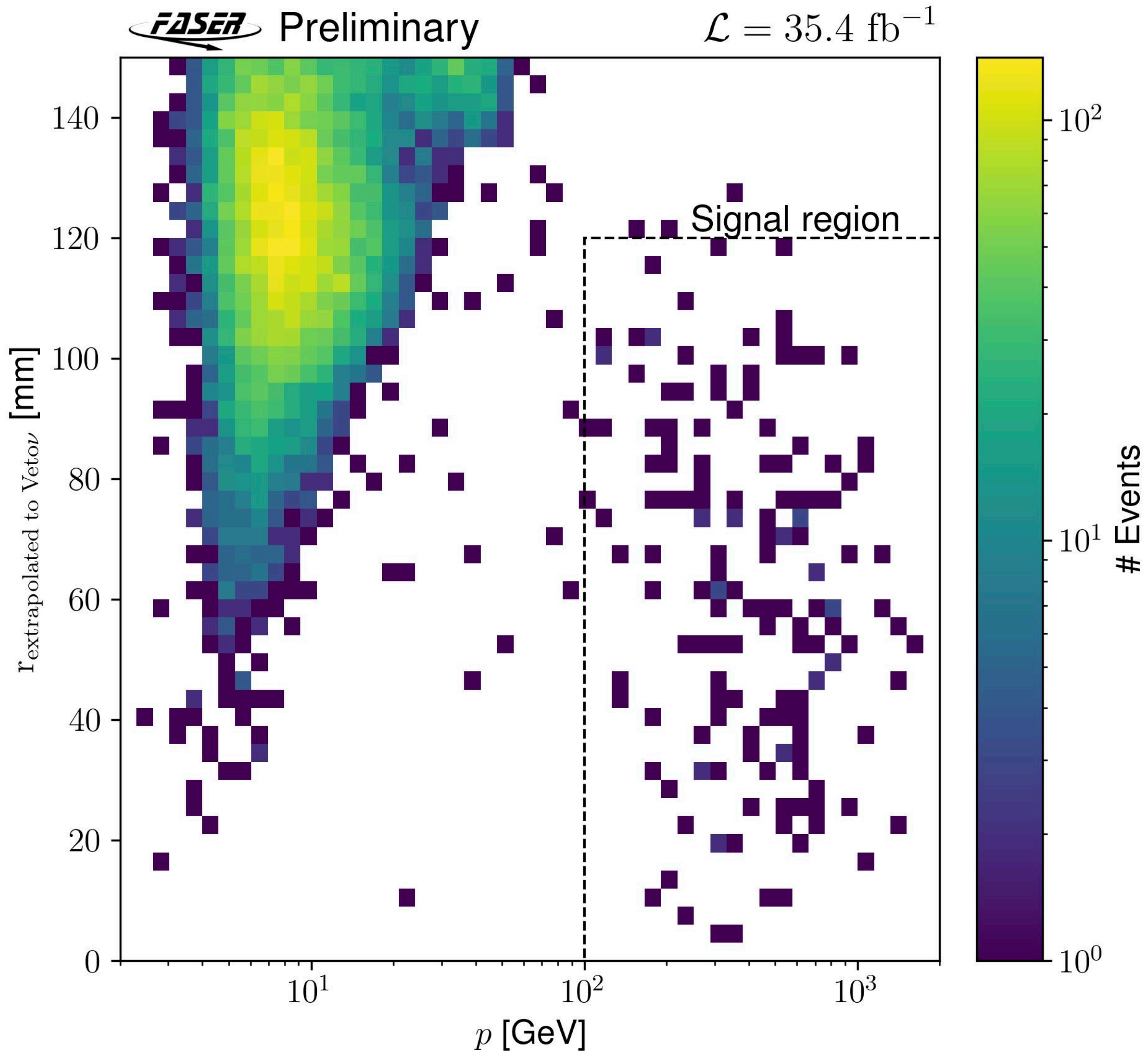
Pathfinder programs

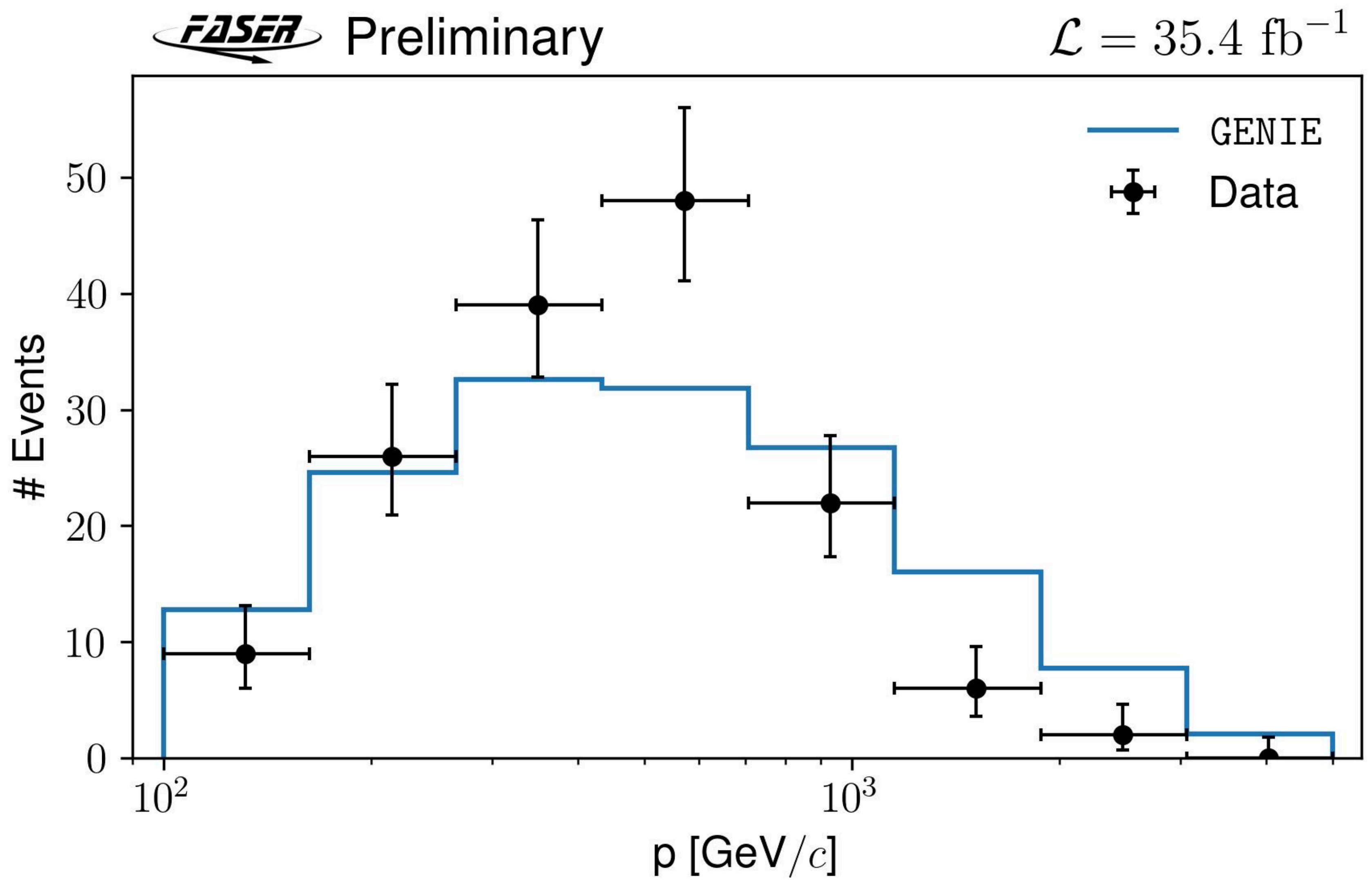
First neutrinos @ LHC!

- ~150 (muon) neutrino candidates at FASER over **basically no background**!
- Expected $O(10^3)$ by the end of Run 3









Candidate	Events
n_0	153 (151 ± 41)
n_{10}	4
n_{01}	6
n_2	64014695

https://doi.org/10.1103/PhysRevLett.131.031801

ν_e candidate: Pika-nu!

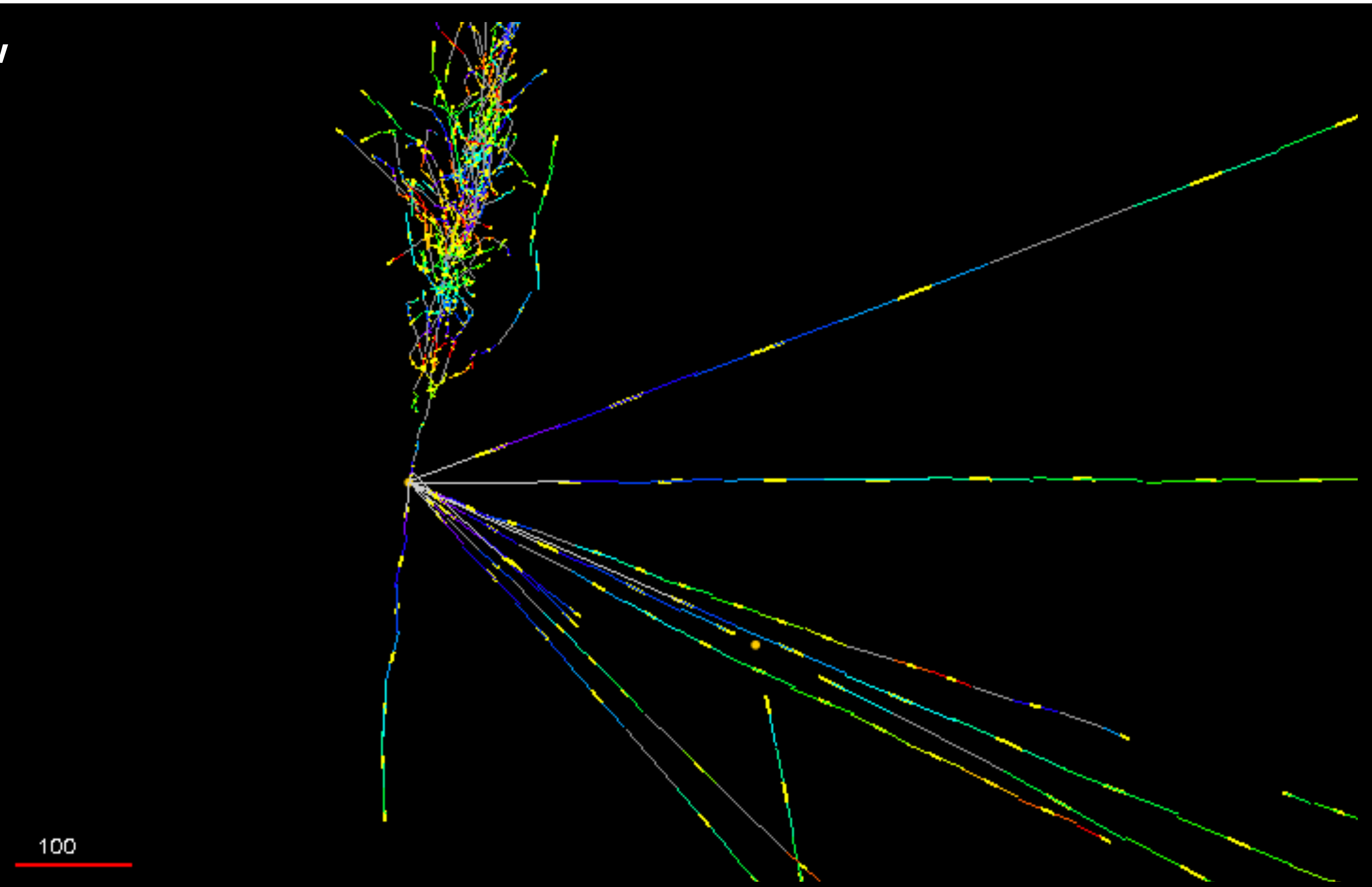
https://moriond.in2p3.fr/QCD/2023/WednesdayMorning/Gwilliam.pdf

FASER

Preliminary

- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

Beam view



Side view