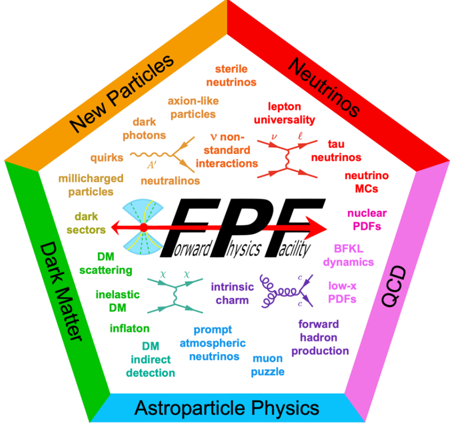


The FLArE Experiment for High Energy Neutrino and Dark Matter Searches at LHC

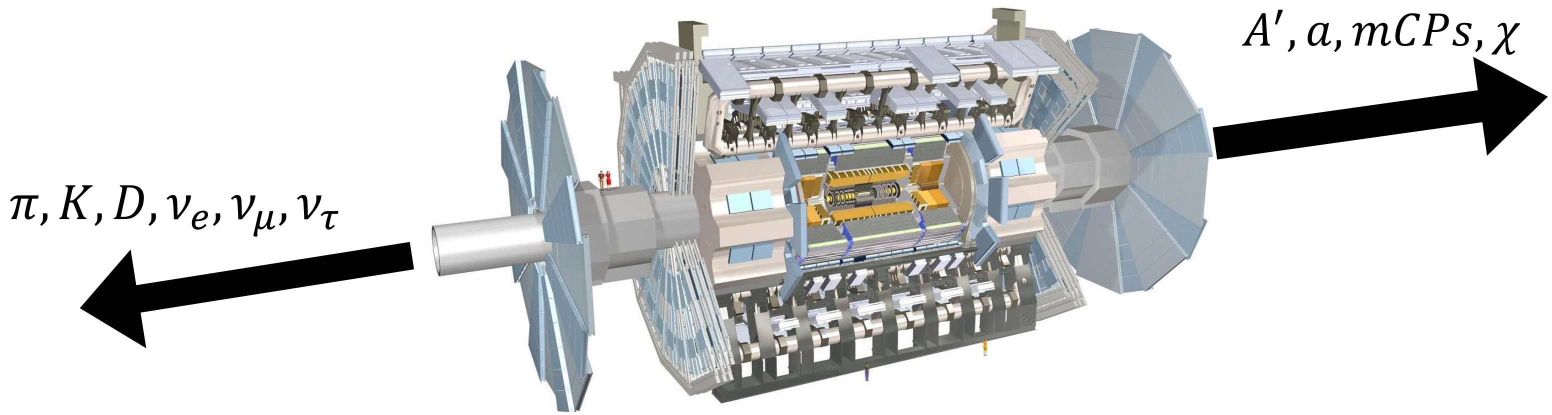
Jianming Bian (University of California, Irvine)

Milind Diwan (Brookhaven National Lab)

Jonathan Feng (University of California, Irvine)

TAU2023, University of Louisville, Louisville, Kentucky, USA, Dec 4 – 8, 2023

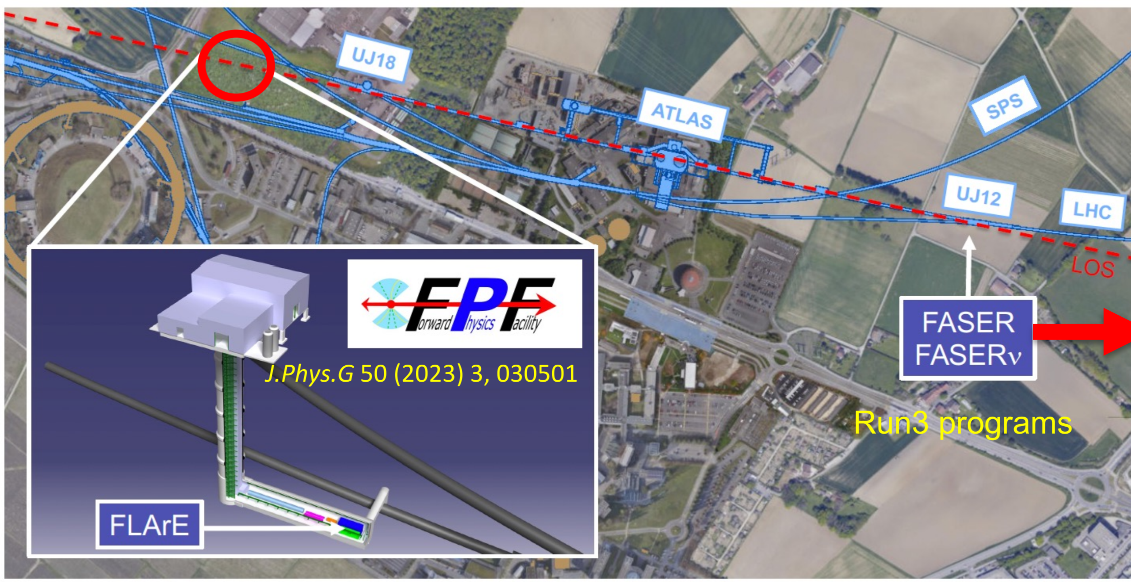
Forward Physics Facility (FPF) and FLArE

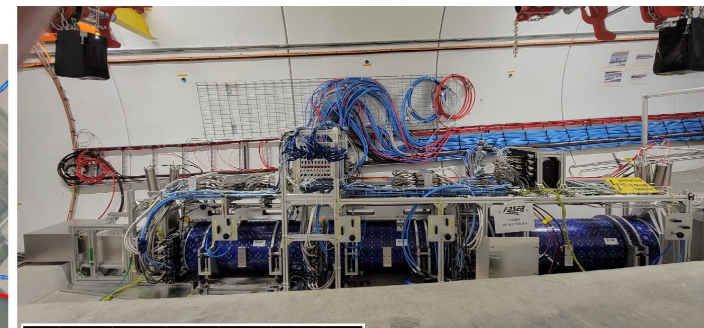


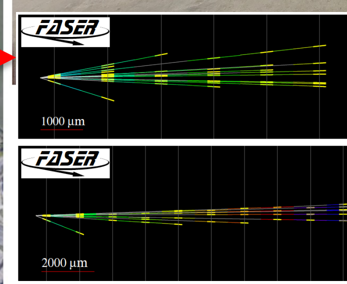
- Most interesting physics is believed to be at high pT, and so are we missing physics in the forward direction?
- The largest flux of high energy light particles, pions, kaons, D-mesons, and neutrinos of all flavors is in the forward direction.
- This could be true of new particles also: dark photons, axion-like particles, millicharged particles, light dark matter, etc.
- The high laboratory energies (>100 GeV), and kinematically focused nature of the particles presents a unique opportunity that should not be missed with the high-luminosity LHC.

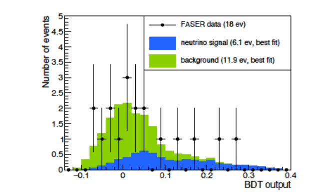
Forward Physics Facility (FPF) and FLArE

- FPF: Proposal to create forward underground space for experiments during HL-LHC
- FLArE: a liquid argon time projection chamber (LArTPC) detector for FPF to detect very high-energy neutrinos and search for dark matter at LHC@CERN
- The central goal of FPF is to extend the current LHC forward physics programs into the HL-LHC era with x10-100 exposure









PHYS. REV. D 104, L091101 (2021)
Phys.Rev.Lett. 131 (2023) 3, 031801

Dr Umut Kose's FASER talk on Friday

The FPF will be located 620-680 m west of the ATLAS IP along the line of sight (LOS). Also shown is the location of FASER and FASERν, which are also located along the LOS, but 480 m east of the ATLAS IP

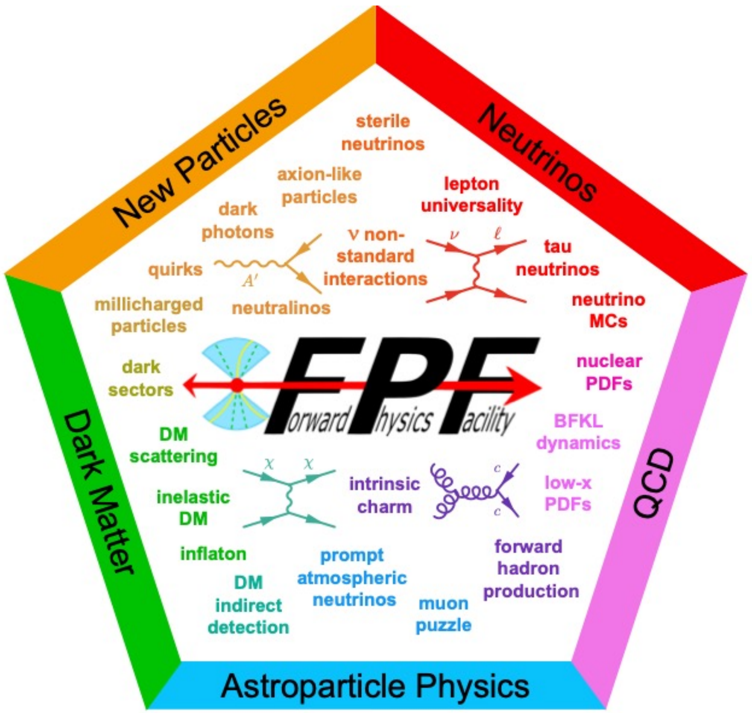
FPF Physics Goals

Neutrino physics

- Measure the flux of tau neutrinos
- Limit the oscillations of tau neutrinos into other neutrinos over the parameter range defined by the energy spectrum and distance
- Determine the cross section of neutrino interactions in the energy range of hundreds of GeV to few TeV
- QCD physics with far forward neutrinos

Dark matter search sector

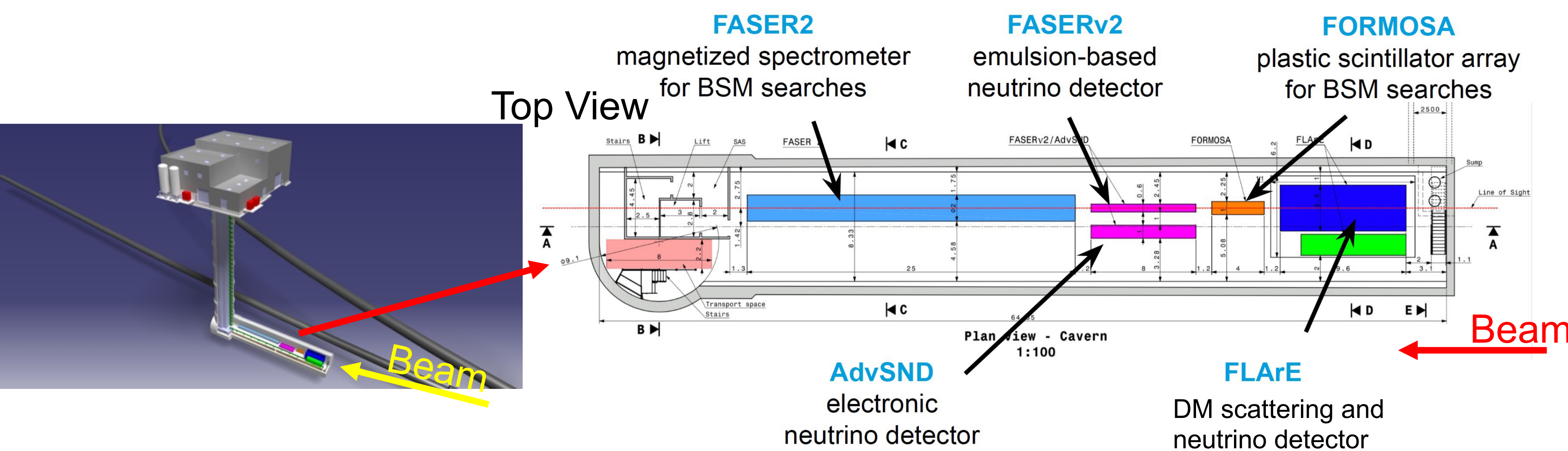
- Detection of dark photon and other dark sector particle decays in the detector volume
- Detection of light dark matter scattering in detector
- Search for milli-charged dark matter particles
- Search for dark tridents



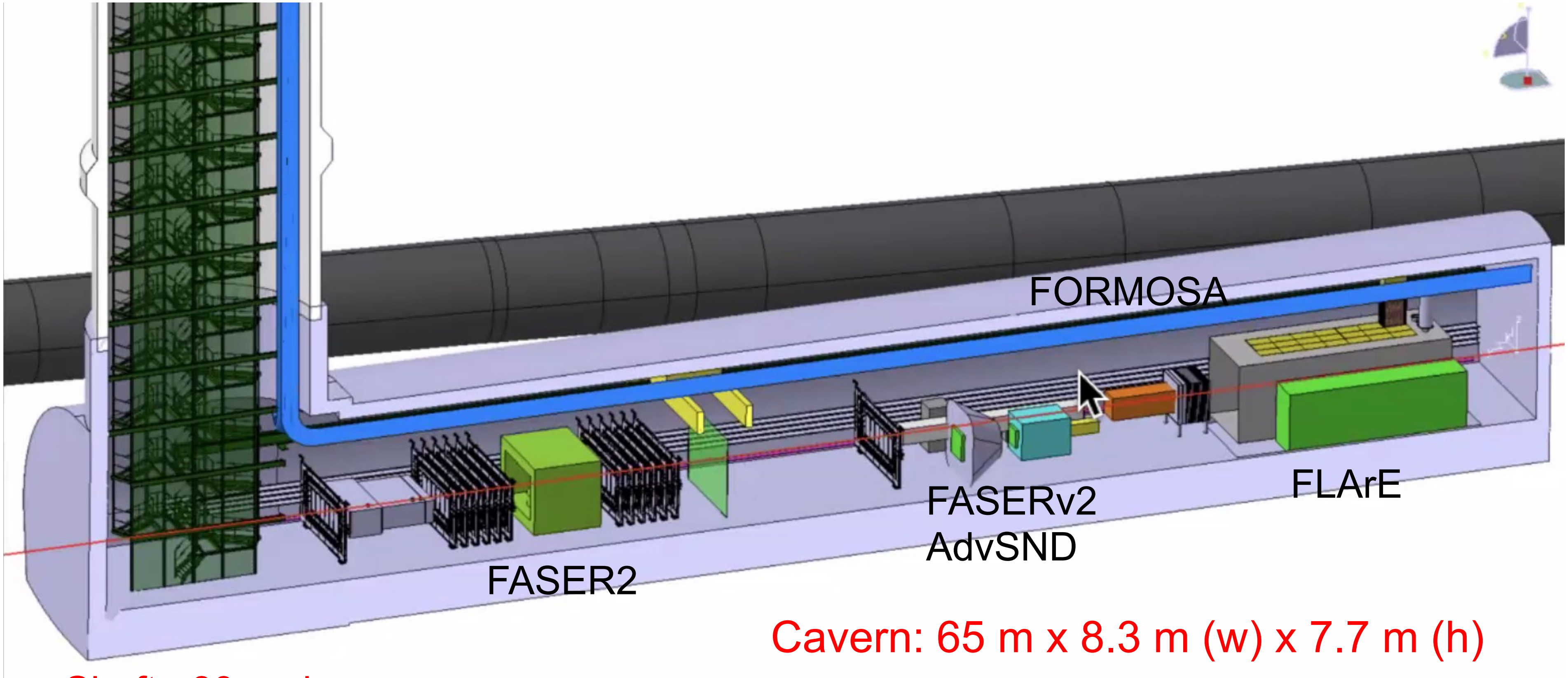
Dr. Yu-dai Tsai's talk on Friday

Proposed Detectors for FPF

Experiment	Science Priority	Technology
FASER 2	Long-live neutral particles decay	Large decay volume (super-conducting) magnetic spectrometer
FASERnu2	Neutrino Interactions	Tungsten/Emulsion 20 tons. Veto and interface tracker for muons
AdvSND	Neutrino Interactions on/off axis	Electronic fine grained detector with a magnetic muon spectrometer
FORMOSA	Milicharged particles	Scintillation bars with photomultiplier readout.
FLArE	DM scattering and neutrino interactions	Liquid Argon TPC 10-20 tons



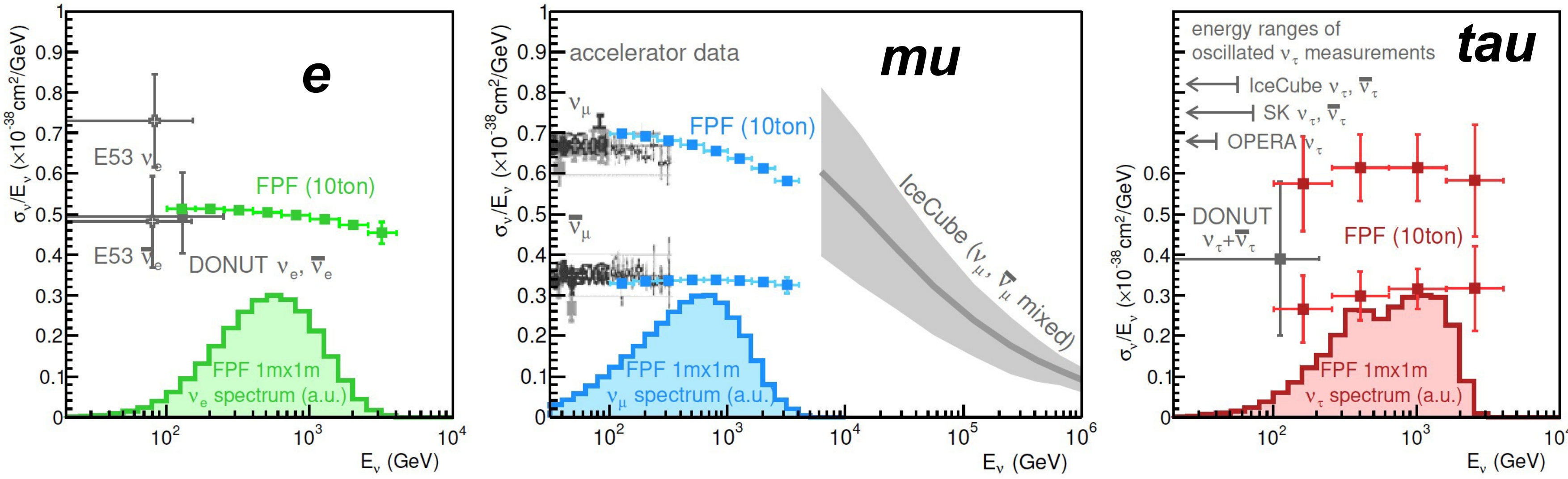
FPF Cavern and Detectors



Shaft ~80 m deep

- Preliminary numbers, but the constraints are well known.
- The LOS might change over the course of the run by 17 cm. and so we have to allow for that.
- Paying particular attention to the liquid argon space. This needs to accommodate a cryostat and cryogenics.
- There will be a 20 ton crane

Neutrino physics

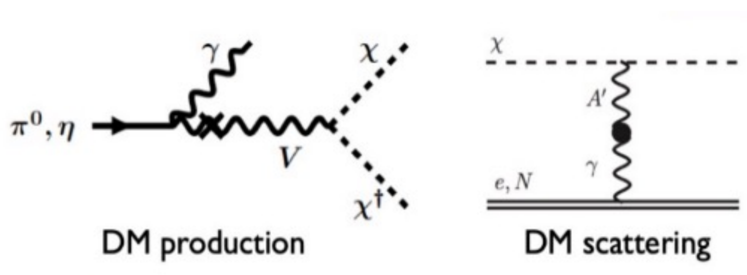


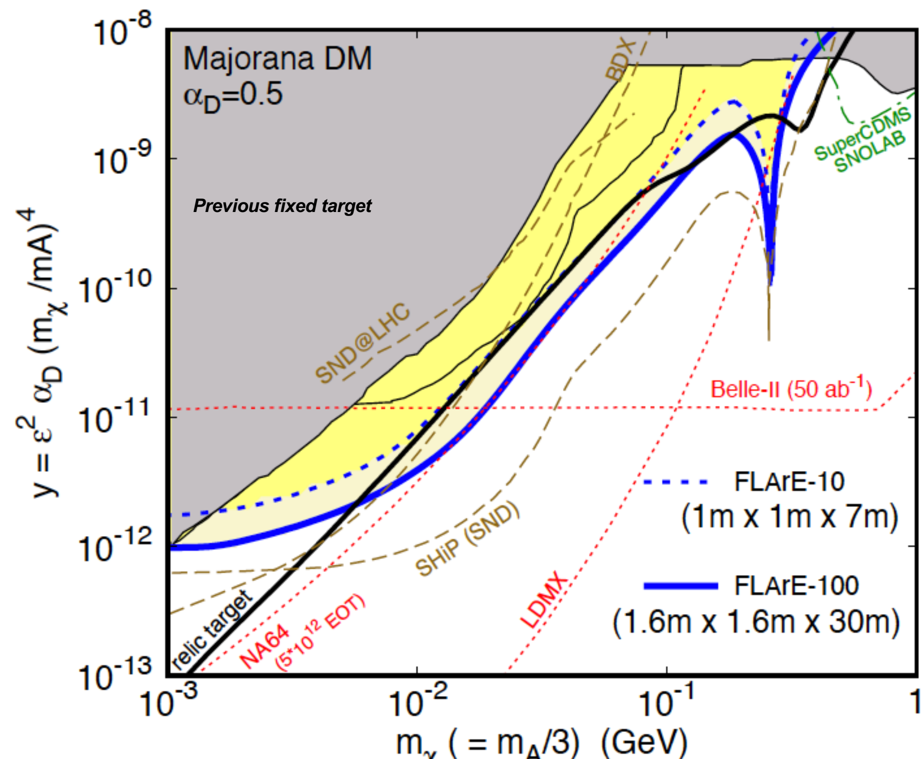
- The current data from accelerators ends around 300 GeV. FPF would provide data that fills in the gap between accelerators and atmospheric neutrinos.
- There are three proposed detectors at 10 ton each: FASER*v*2 (emulsion), AdvSND, and FLArE.
- Total rate will be ~100k electron neutrinos, ~1M muon, and ~few thousand tau neutrino events.

Light Dark Matter scattering

Elastic scattering from electrons or nuclei

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

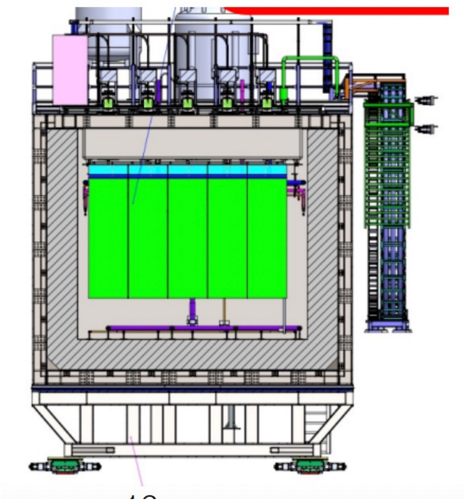




Batell, Feng, Trojanowski (2021)

Cryostat options for FLArE

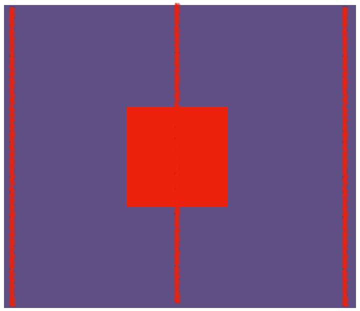
Very important for space considerations.



	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
MicroBooNE	3.8m dia x 12 m	Polyurethane Foam	**400mm**	32 kg/m³	**~13 W/m²**	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Nomex honeycomb+perforated Al	**665 mm+ (combined)**	25-35 kg/m³	**7-22 W/m²**	Yes
ICARUS-SBN	3.9m x 3.6m x 19.6m	Al extrusion+GTT foam	**665 mm+ (combined)**	25-35 kg/m³	**10-15 W/m²**	Yes
ProtoDUNE	7.9m x 8.55m x 8.55 m	GTT membranc	**800mm**	90 kg/m³	**~8 W/m²**	No
ND-LAr	3m x 5m x7m	GTT membrance	800mm	90 kg/m³	**~8 W/m²**	No
FLArE	~(1m x 1m x 7m)					No?

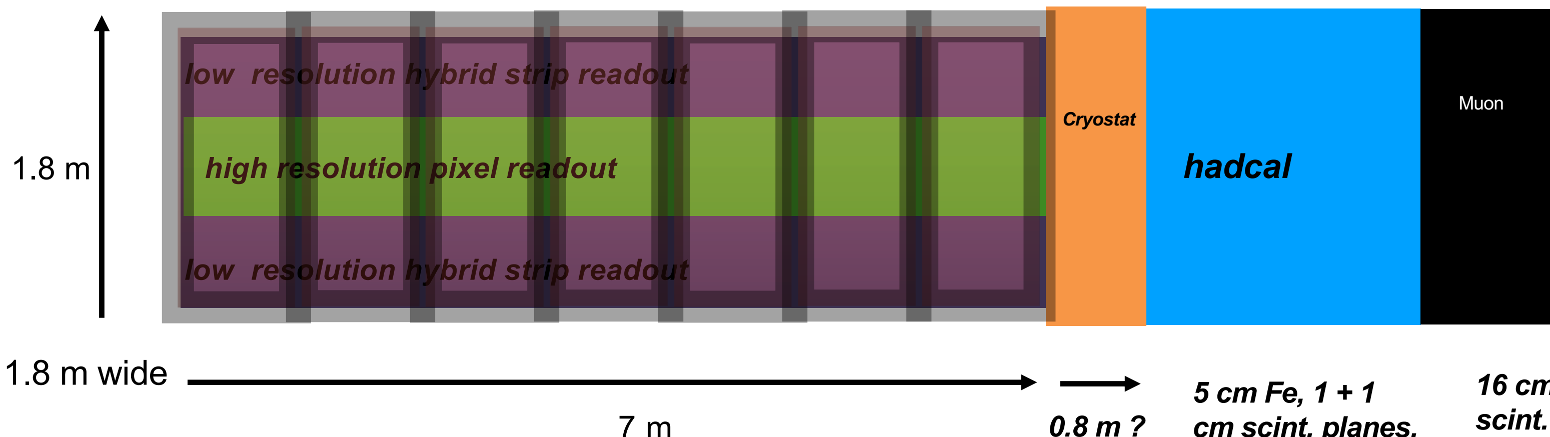
- Space in FPF hall currently is limited to 3.5 m X 3.5 m X 9.6 m for FLArE.
- 80 cm GTT membrane occupies 1.6 m out of 3.5 m. More space might be needed for corrugations.
- GTT is easy to install, DUNE ND-LAr design has installation from top, this would also simplify things.
- Further Engineering will be needed, but we can settle on GTT membrane for now.

FLArE Detector



Simulations have confirmed that these dimensions allow reasonable containment of neutrino events in LAr and total energy measurement.

They also fit within the cryostat allowed transverse space.

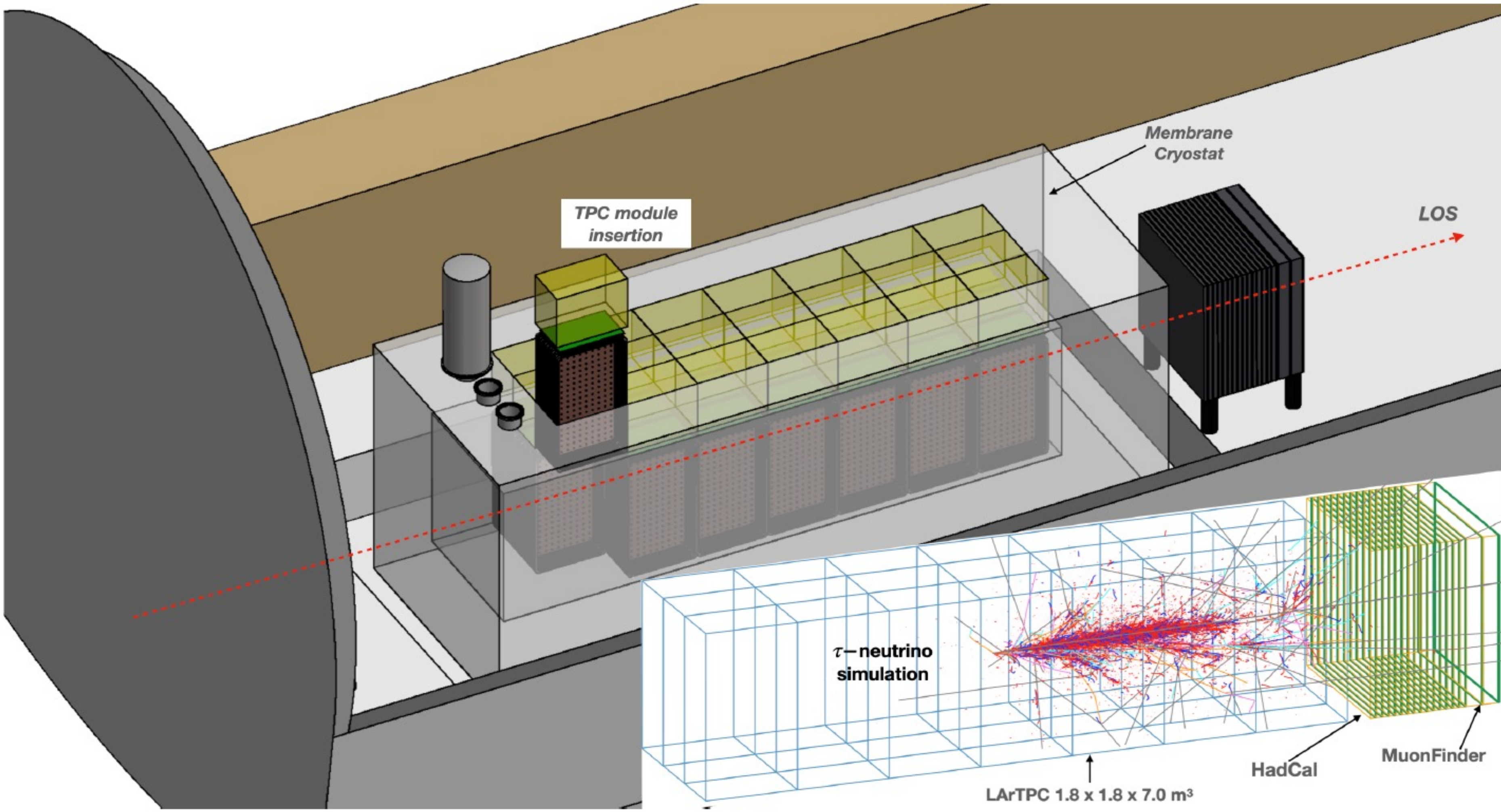


Geometry options in Conceptual Design:

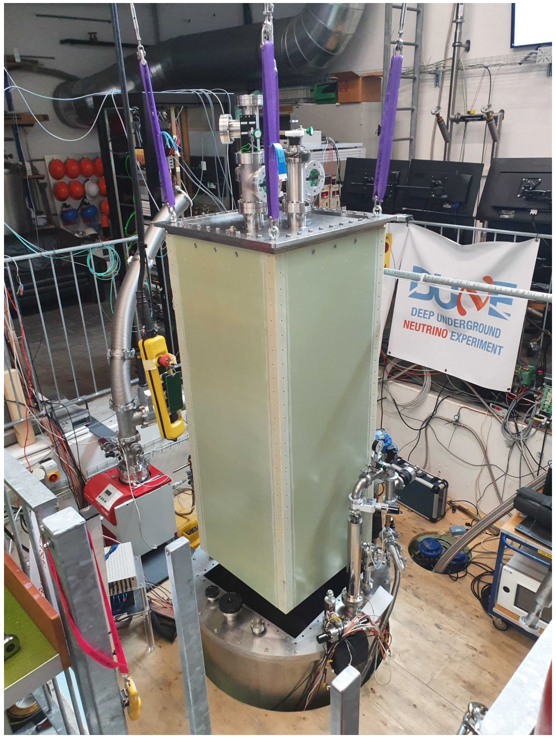
- ***2 X 7 vertical modules***
- ***3 X 7 vertical modules***
- ***0.45 m or 0.3 m gap***

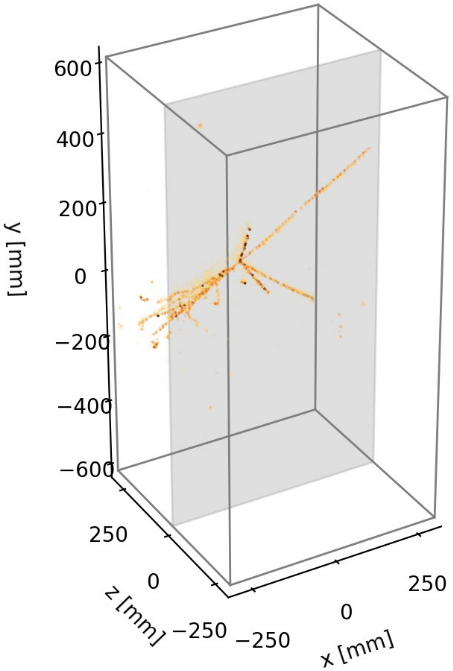
Option to use combined high / low resolution TPCs

FLArE Detector



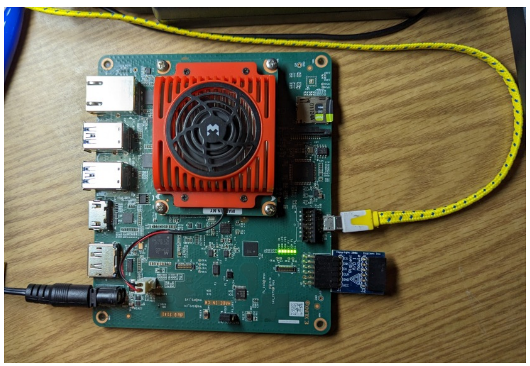
Benefit from the DUNE near detector design



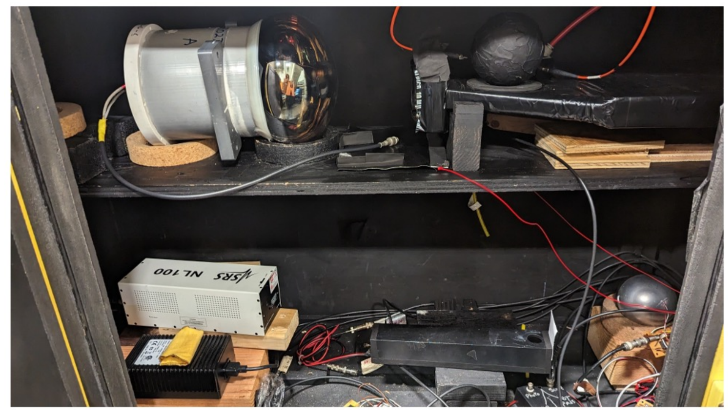


Hardware-based trigger studies

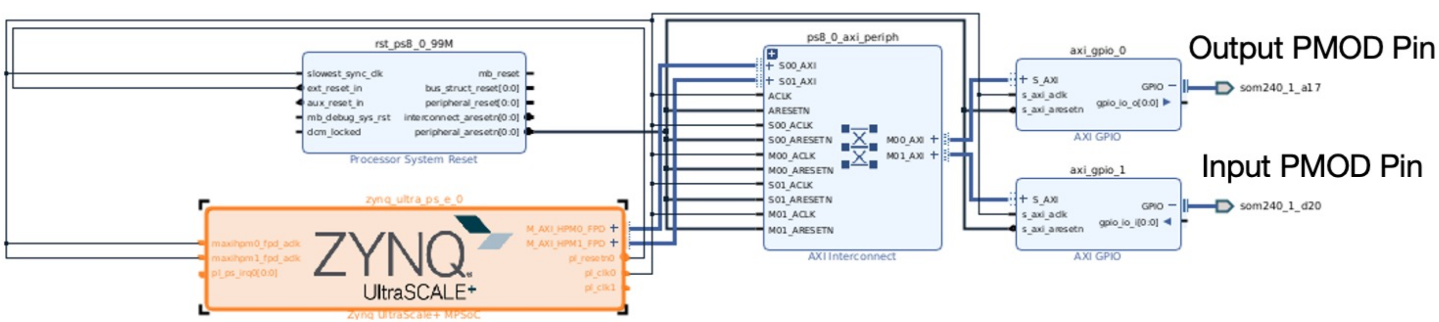
- FLArE trigger system will need to identify signal events from muon background.
  - 0.5 Hz/cm2 muon flux from ATLAS collisions gives 5 kHz rate in the 1m x 1m x 7m fiducial region
- Want to match signal events to ATLAS bunch crossings
  - Need fast trigger decisions to meet HL-LHC ATLAS 6 µs (30 µs) L0 (L1) trigger latency requirements
- Will try combination of traditional/ML methods for SiPM/event-level trigger decisions on GPU/FPGA.



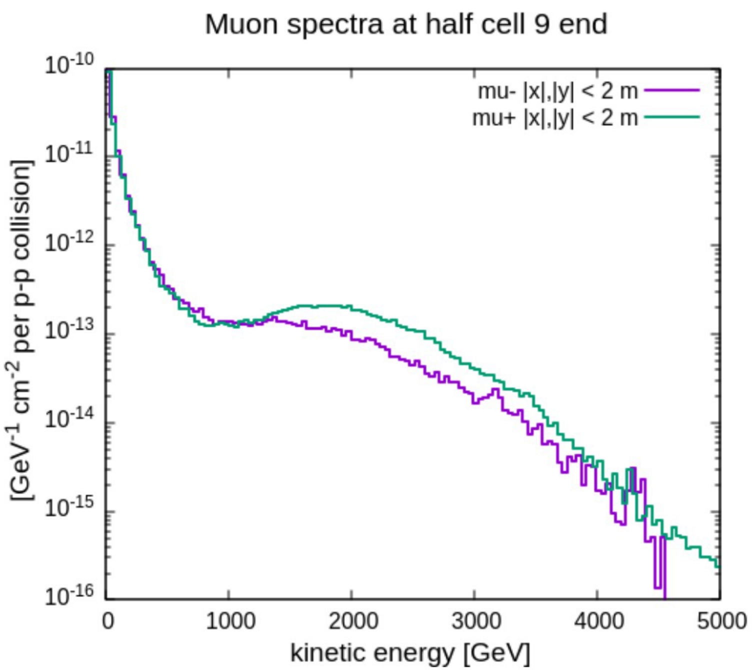
Xilinx Kria KV260 FPGA development board to GPU group server



- Teststand: Nitrogen laser and 1” PMT/SiPM in a dark box for realistic signal and dark noise pulses.



Experimental Condition Simulation



Approximate muon fluxes, rates of backgrounds

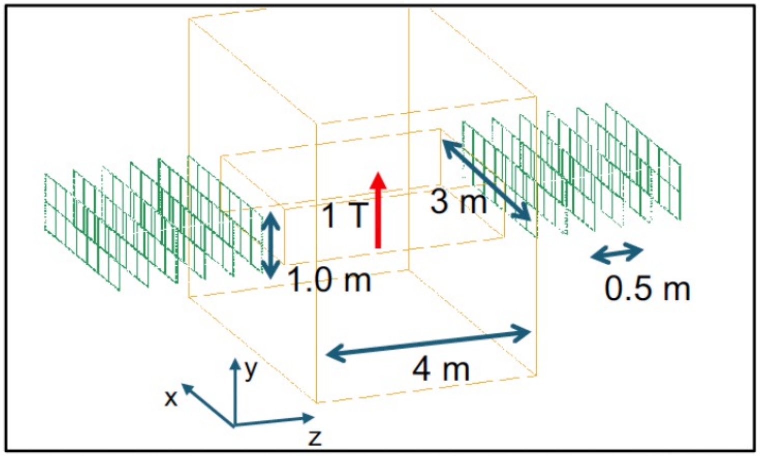
Minimum distance	612 m
Total Lumi/max lumi	3000/fb ; 5x10^{34} /cm2/sec
Lumi per day	~1 /fb assuming 10 year running
pseudorapidity coverage	>6.4, (~5.4-6.0 for off-axis)
Mu+/Mu- flux > 10 (100) GeV	1.5/0.93 (0.94/0.39) 10^{4} /cm^{2}/fb^{-1}
track density (from data)	1.7x 10^{4}/cm^{2}/fb^{-1}
max track density per sec (per crossing)	0.85/cm^{2}/sec (2x10^{-8}/cm2/crossing)
Tracks in detector/1 ms	8.5/m^2/1msec
Neutral hadron flux > 10 GeV (10^{-4} of muons)	~3 /cm^{2}/fb^{-1}
Total neutrino rate (all flavors)	~50/ton/fb^{-1}

arxiv 2105.06197

- This rate will be lower at 612 m.
- Both charged and neutral hadron interactions present significant background.
- Total neutrino interaction rate normalized to per ton per fb^{-1}
- Observed nu rate: ~45/ton/fb-1 at 480 m

Muon momentum measurement

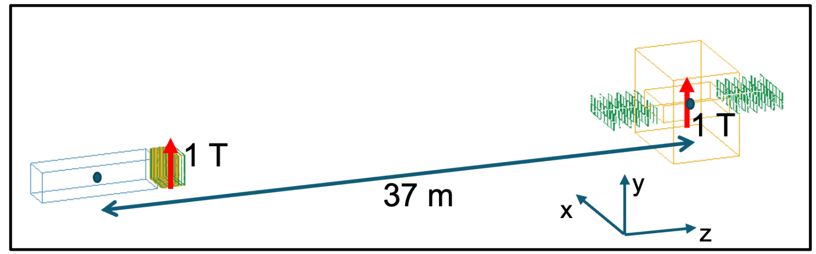
- Muons can easily pass through the detector, with a small portion of the energy deposited in the detector
- Propose to cooperate with FASER2's magnet, along with the magnetized HadCal and MuonFinder, in order to precisely reconstruct the muon momentum



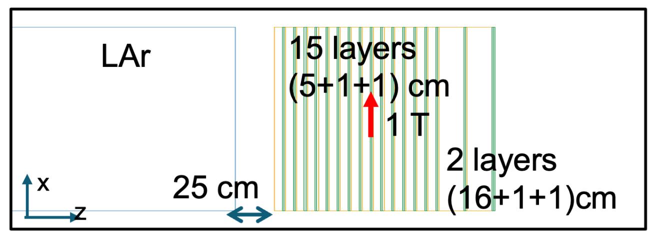
FASER2 magnetic volume (rectangular window): 3 m x 1 m (4 Tm)

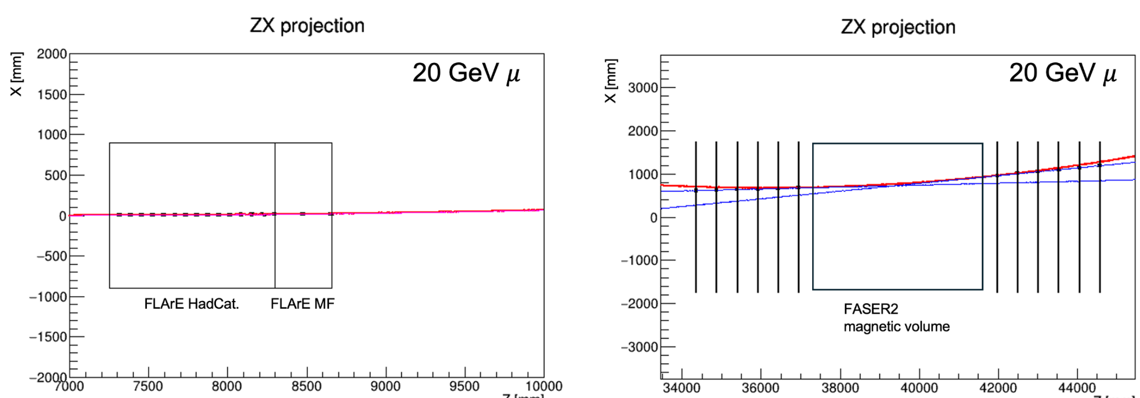
6 tracking stations, 50 cm apart, B = 1 T (fixed)

Complete geometry in the simulation:

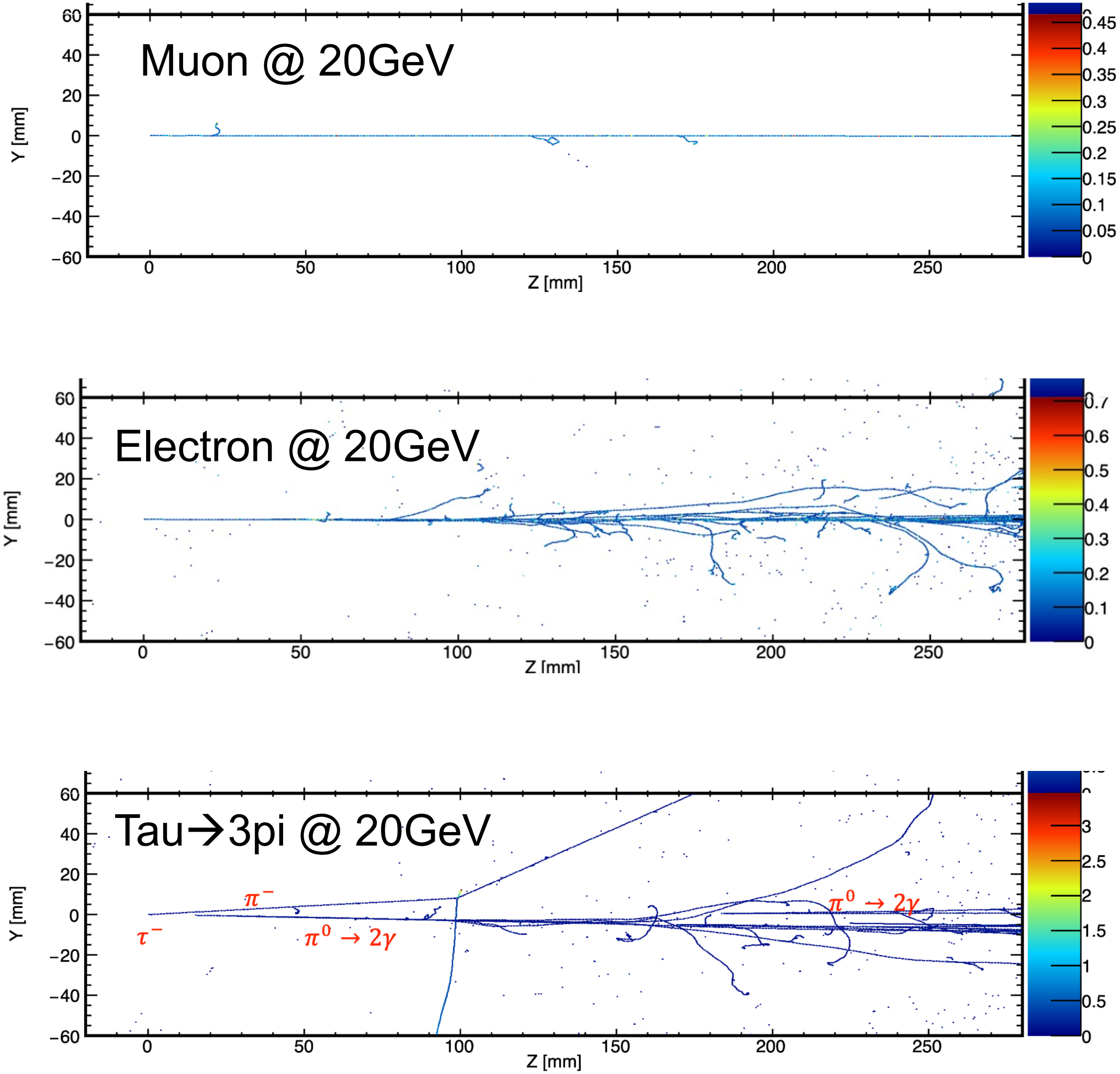


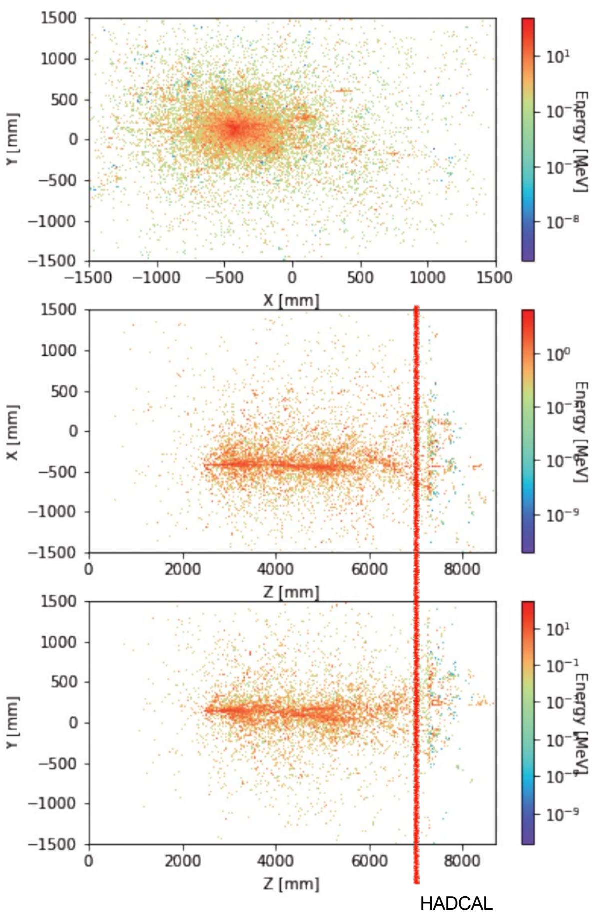
FLArE center to magnet center: 36.9 m
Magnetized HadCatcher and MuonFinder
B = 1 T (default, but still open to optimization)





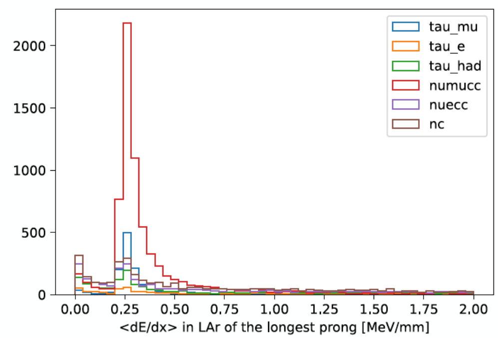
Event simulation in FLArE

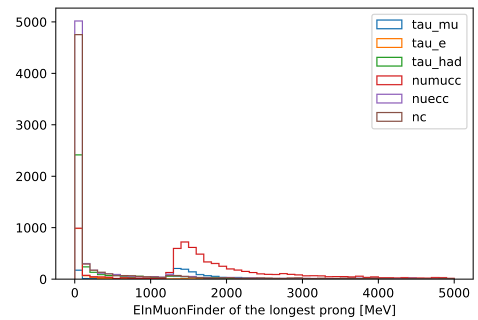




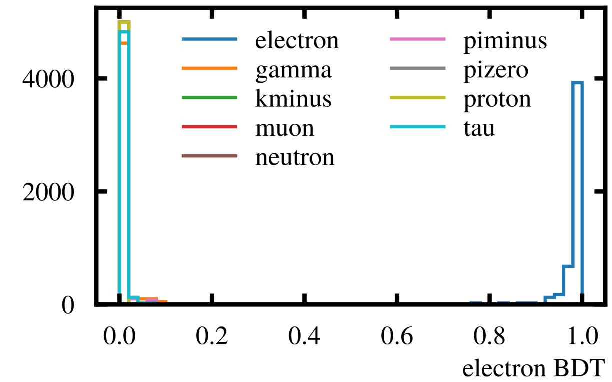
Reconstruction and Event Identification

ν_τ CC, $\tau \rightarrow \mu$ and ν_μ CC are distinct from other channels in dE/dx and energy deposit



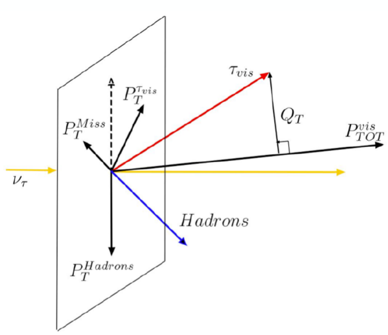


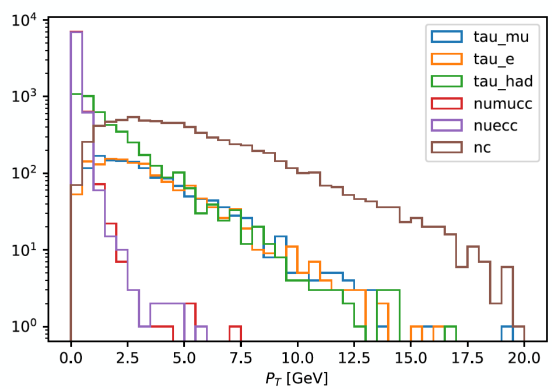
Singe Particle BDT

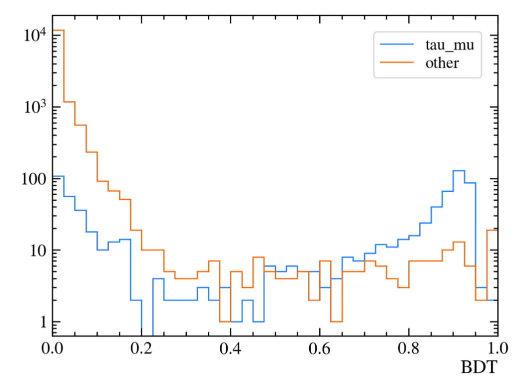


ν_τ CC, $\tau \rightarrow \mu$ have more neutrinos in the final state than ν_μCC, thus more missing momentum in the transverse plane

A BDT shows promising results to select ν_τ CC, $\tau \rightarrow \mu$ from backgrounds, working on other τ decay modes



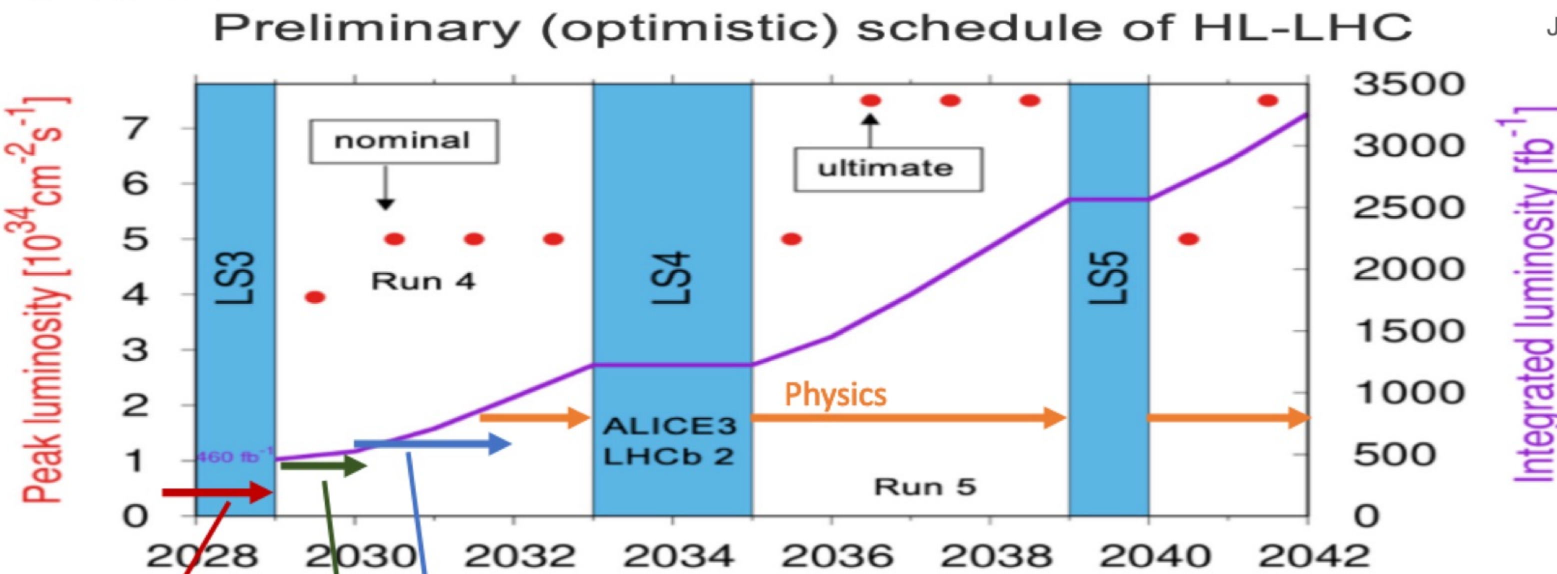




Possible FPF schedule

HL-LHC schedule from DG presentation, New-Year (on-line) meeting, 13/1/22

Jamie Boyd



Pure CE works

Installation and commissioning of the experiments

Installation of services (CERN technical teams, busy during LS3)

The FPF cavern is not connected to the LHC and no impact on HL-LHC running is foreseen.

Such a schedule would:

- Allow physics data taking for most of the luminosity of the HL-LHC
- Not overload CERN technical teams during LS3
- Design of facility would allow different experiments to come online at different times

Requirements:

- Can access the facility during LHC operations (RP study ongoing)
- Can complete CE works before the end of LS3

Construction independent to HL-LHC project
Reviews underway, schedule subject to change

Summary

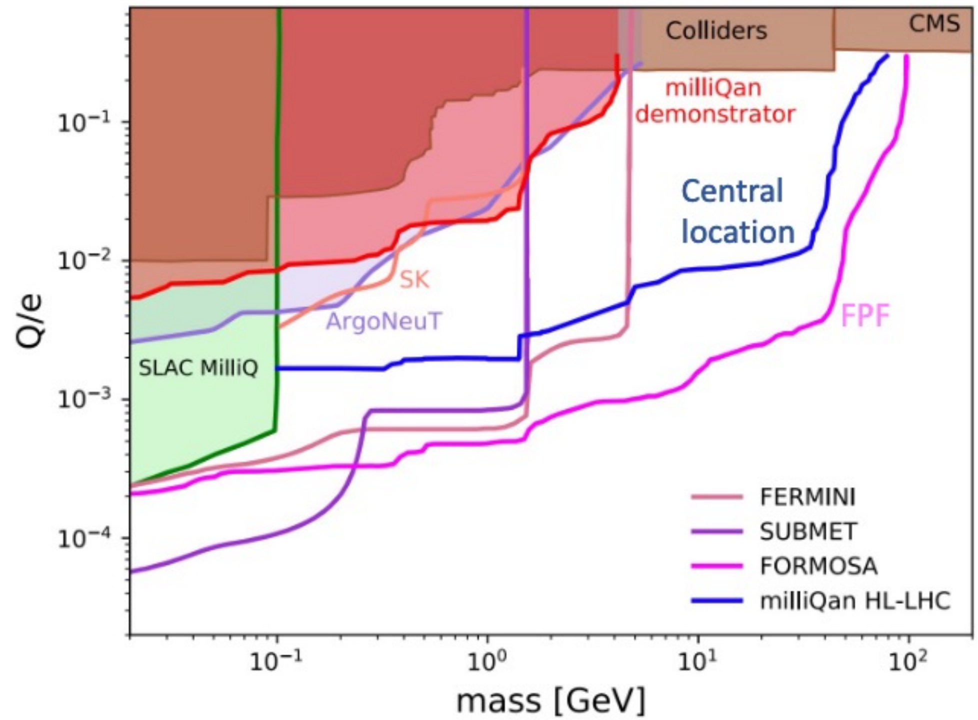
- A forward physics facility FPF is being considered at CERN for neutrino and dark matter physics.
- The physics interest is
  - Neutrino cross sections in the 1 TeV range: ~20-50 events/ton/day
  - Tau neutrino flux and associated heavy flavor physics: ~0.1-0.2 events/ton/day
  - Light dark matter search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

Thank you!

Backup

Milicharged particles

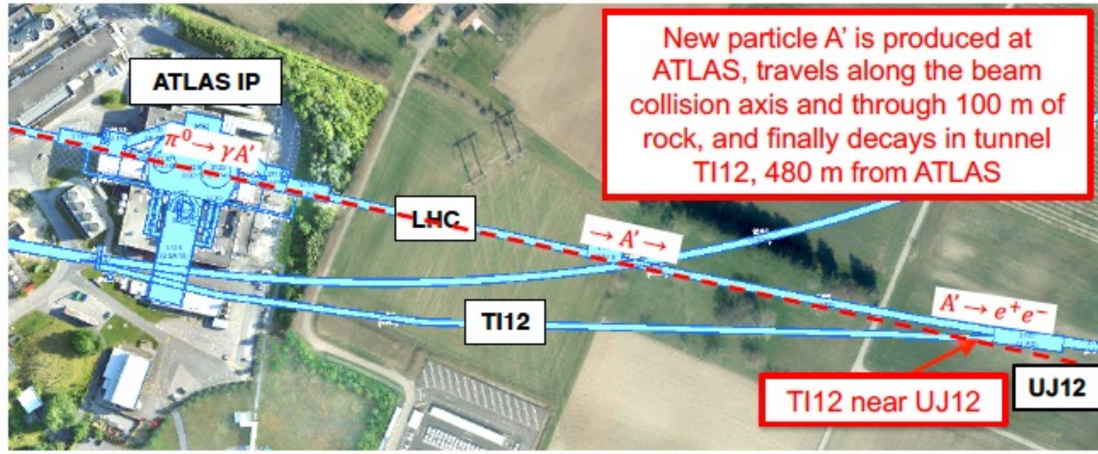
- These emerge in models with massless dark photons which couple weakly to dark particles.
- The idea is to see them using dE/dx in a low noise detector.
- Deep bars of scintillator coupled to PMTs: milliQan (central location) and FORMOSA (at FPF)
- The FPF sensitivity assumes high efficiency light sensitivity in 1 meter bars of plastic scintillator with coincidence of 4.
- How can we do better ? Is it possible to use a liquid argon TPC with very good single electron sensitivity (with 2phase)



Foroughi-Abari, Kling, Tsai (2020)

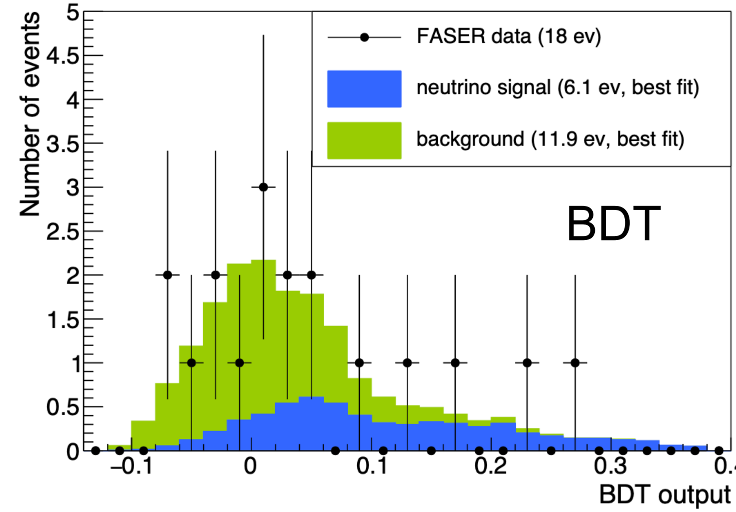
Current forward physics program with LHC Run 3

- 4 experiments in progress for LHC-run3 for 150fb^{-1} 2022-24.
- FASER (March 2019), Magnetic spectrometer for neutral decays.
- FASERnu (Dec 2019), Emulsion/tungsten detector (~1 ton)
- SND@LHC (Mar. 2021) Hybrid electronic and tungsten/emulsion detector. (~1 ton)
- Also MilliQan located near CMS (not forward); scintillation bars to see milli-charged particles.
- This program will provide excellent experience for the FPF.

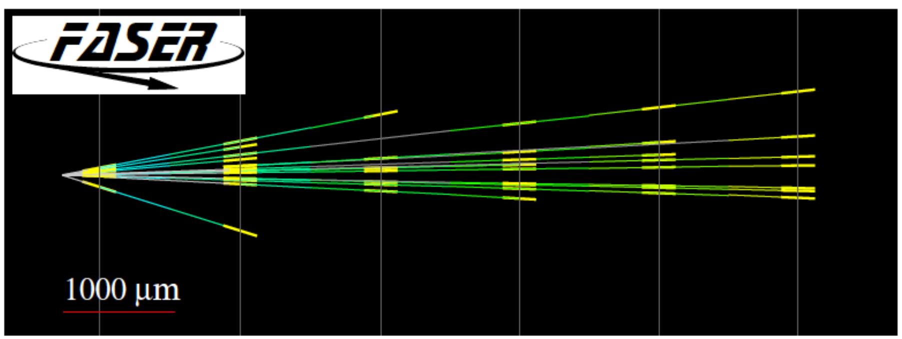


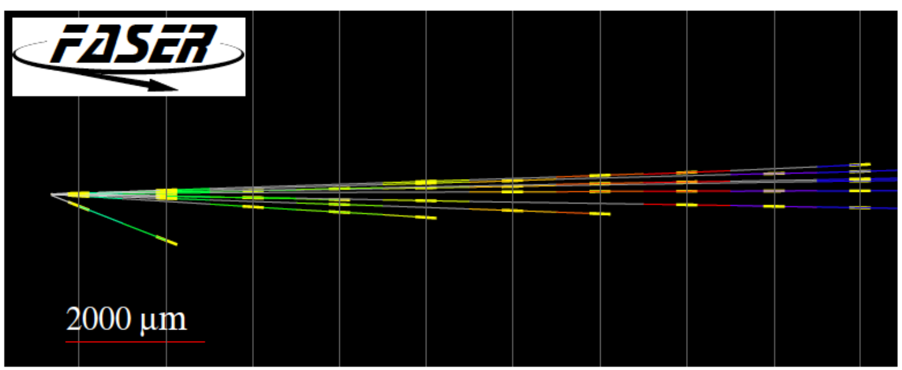
FASER results

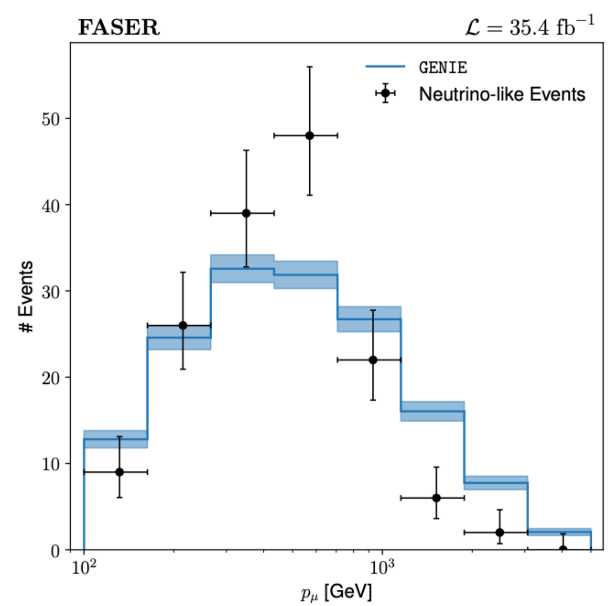
- 2018 pilot emulsion detector with 11 kg was deployed for 12.2 fb-1
- May 2021, first collider neutrinos detected at 2.7 sigma, announced 6 candidates with 12 backgrounds.
- Measured muon rate at that location
- Muon and neutrino rates in rough agreement with expectations
- First observation in 2023 based on 35.4 fb-1, 153 neutrino interactions with a significance of 16 sigma
- New NuE results see Tomoko Ariga's plenary talk at NuFACT



Phys.Rev.D 104 (2021) 9, L091101

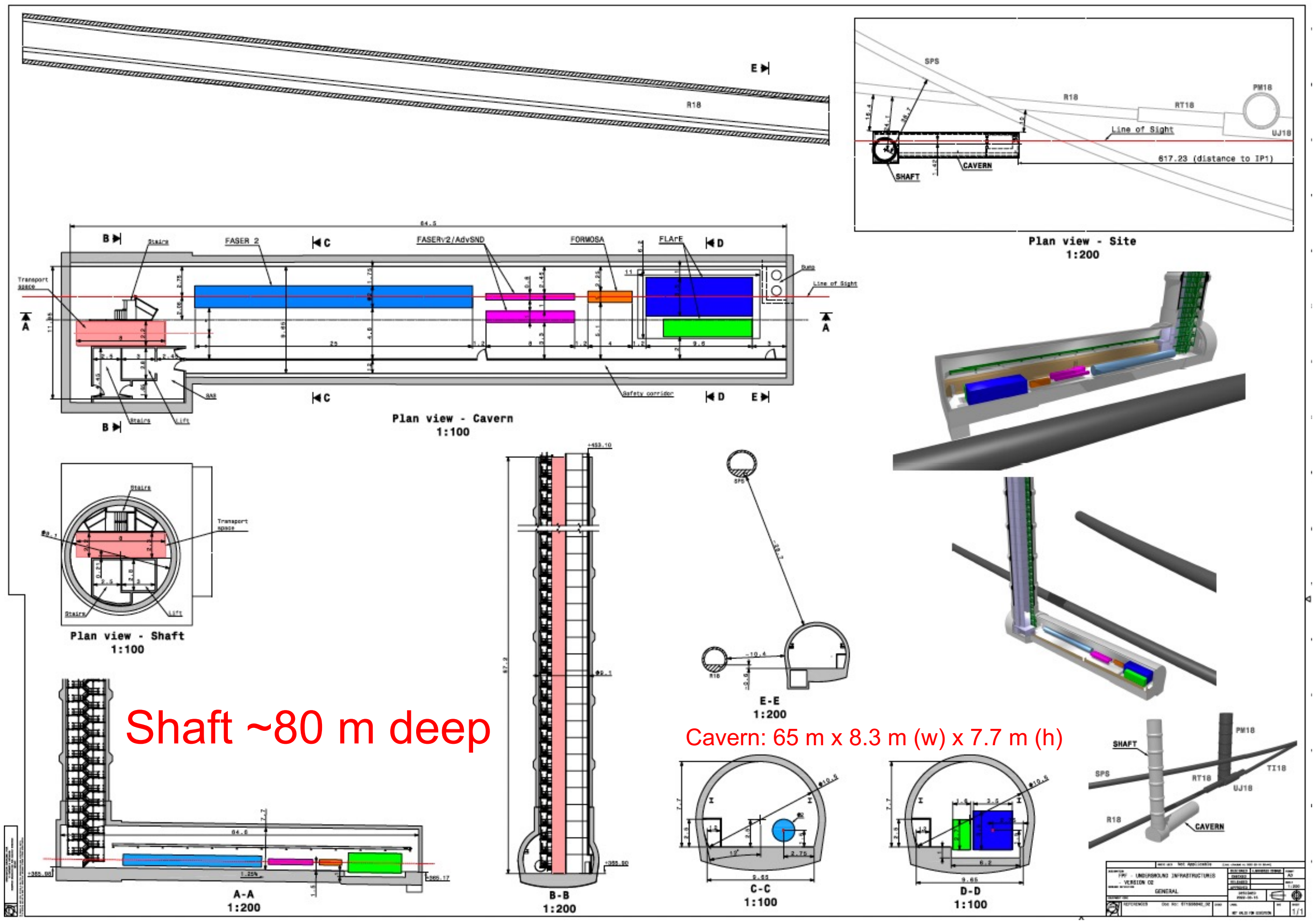






Phys.Rev.Lett. 131 (2023) 3, 031801

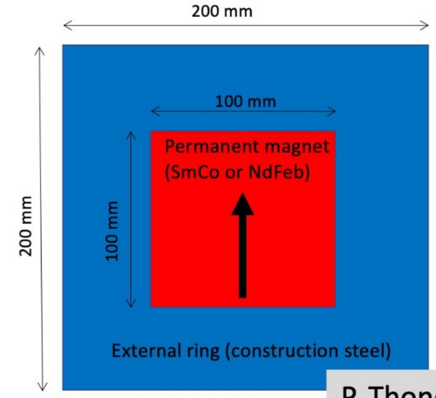
FPF Cavern and Shaft



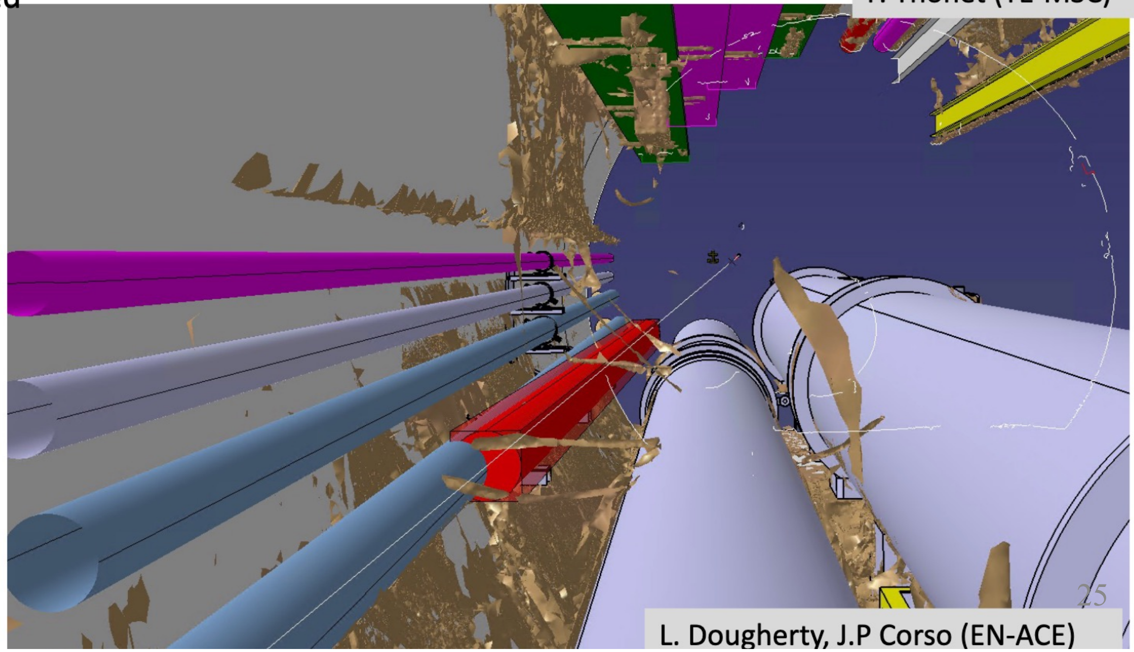
- Preliminary numbers, but the constraints are well known.
- The LOS might change over the course of the run by 17 cm. and so we have to allow for that.
- Paying particular attention to the liquid argon space. This needs to accommodate a cryostat and cryogenics.
- There will be a 20 ton crane
- The cost estimate as of now is 40 M CHF.

Sweeper Magnet: Ongoing Studies

- Preliminary design of sweeper magnet by TE-MSC
  - Based on permanent magnet to avoid power converter in radiation area
  - Consider 7m long (20x20cm^2 in transverse plane) magnet, 7Tm bending power
- To install such a magnet would require some modifications to cryogenic lines in relevant area
  - Possibility of modifications to be investigated with LHC cryo
  - Integration/installation aspects to be studied
- FLUKA and BDSIM studies ongoing to assess effectiveness of such a magnet in reducing the muon background in the FPF



P. Thonet (TE-MSC)


L. Dougherty, J.P Corso (EN-ACE)

Consider to add a sweeper magnet upstream of the FPF (e.g. where the LOS leaves the LHC beampipe) to deflect muons from the on-axis neutrino detectors.