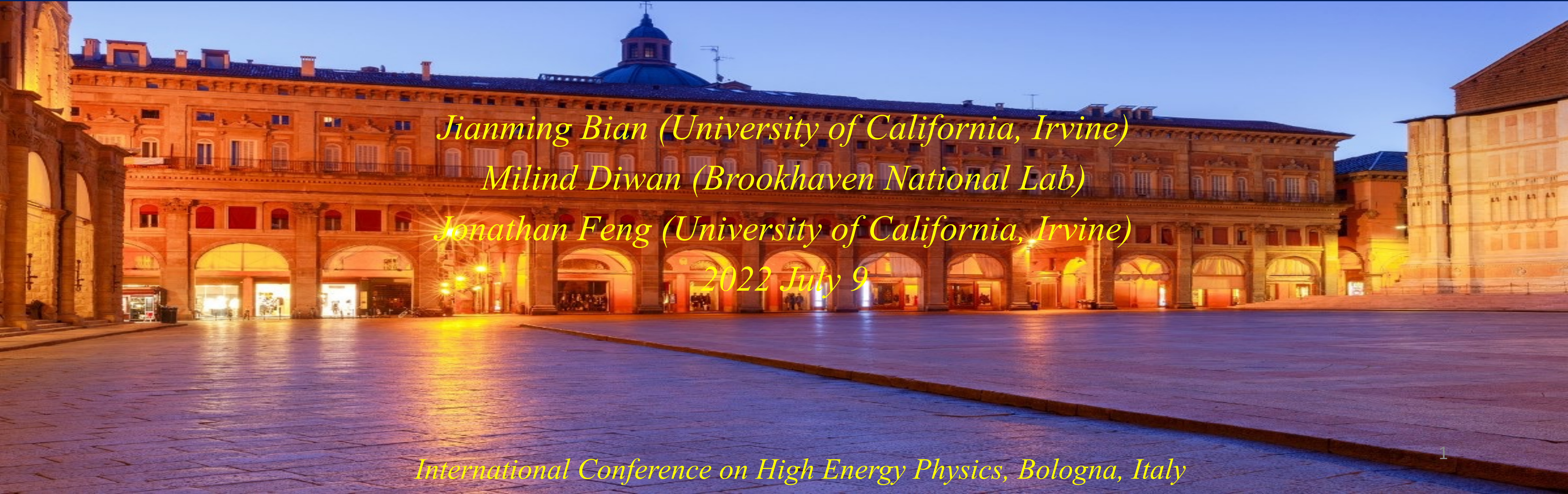
FLArE: Forward Liquid Argon Experiment for High Energy Neutrino and Dark Matter Searches at LHC



Jianming Bian (University of California, Irvine)

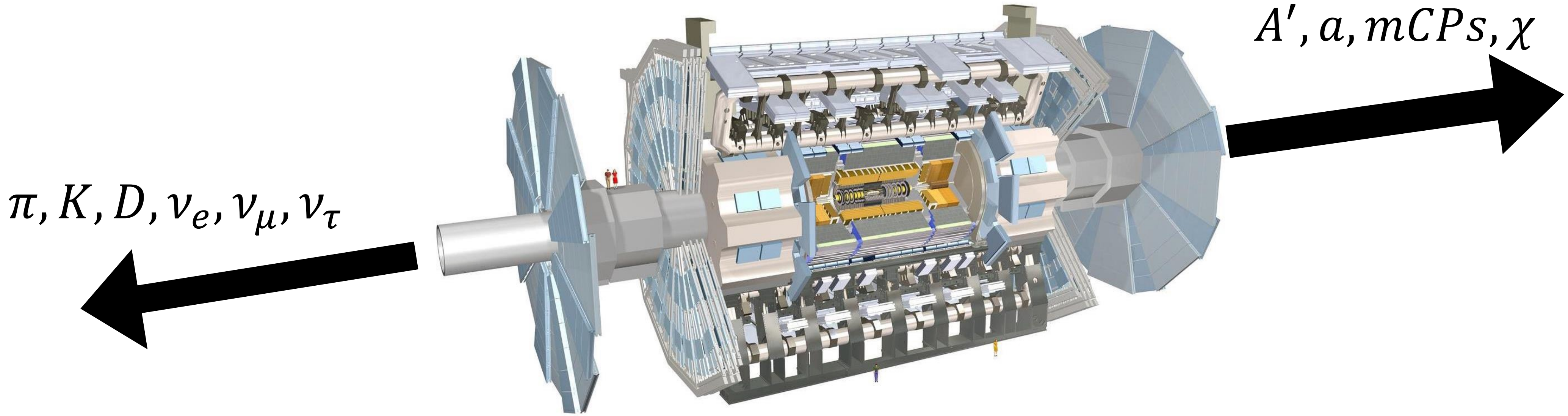
Milind Diwan (Brookhaven National Lab)

Jonathan Feng (University of California, Irvine)

2022 July 9

International Conference on High Energy Physics, Bologna, Italy

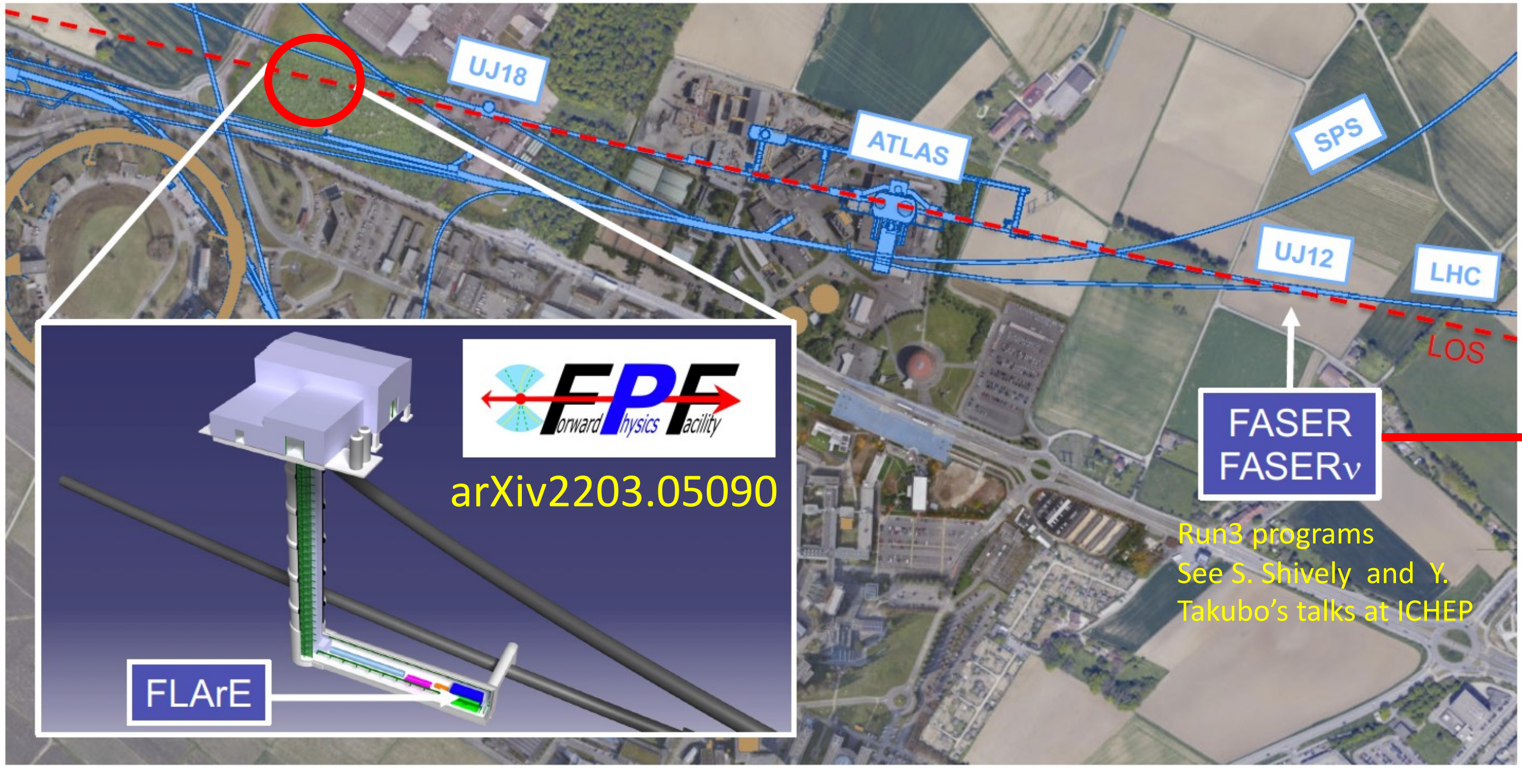
What are we missing ?

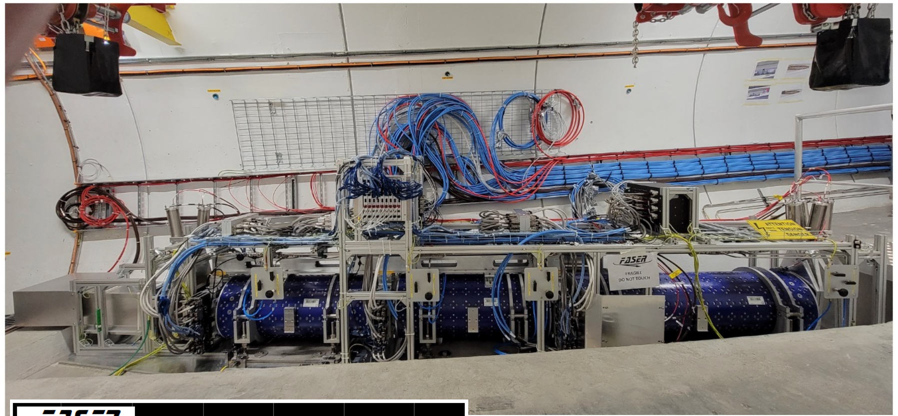


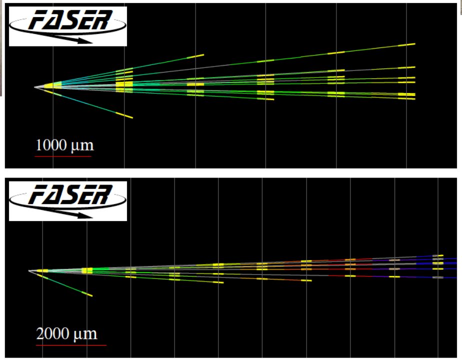
- Most interesting physics is believed to be at high pT, and so are we missing physics in the forward direction?
- The largest flux of high energy light particles, pions, kaons, D-mesons, and neutrinos of all flavors is in the forward direction.
- This could be true of new particles also: dark photons, 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







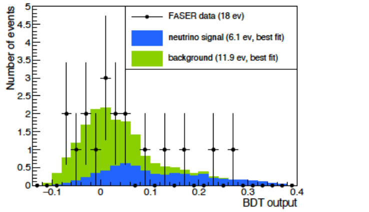


FIG. 6. The BDT outputs of the observed neutral vertices, and the expected signal and background distributions (stacked) fitted to data. Higher BDT output values are associated with neutrino-like vertex features.

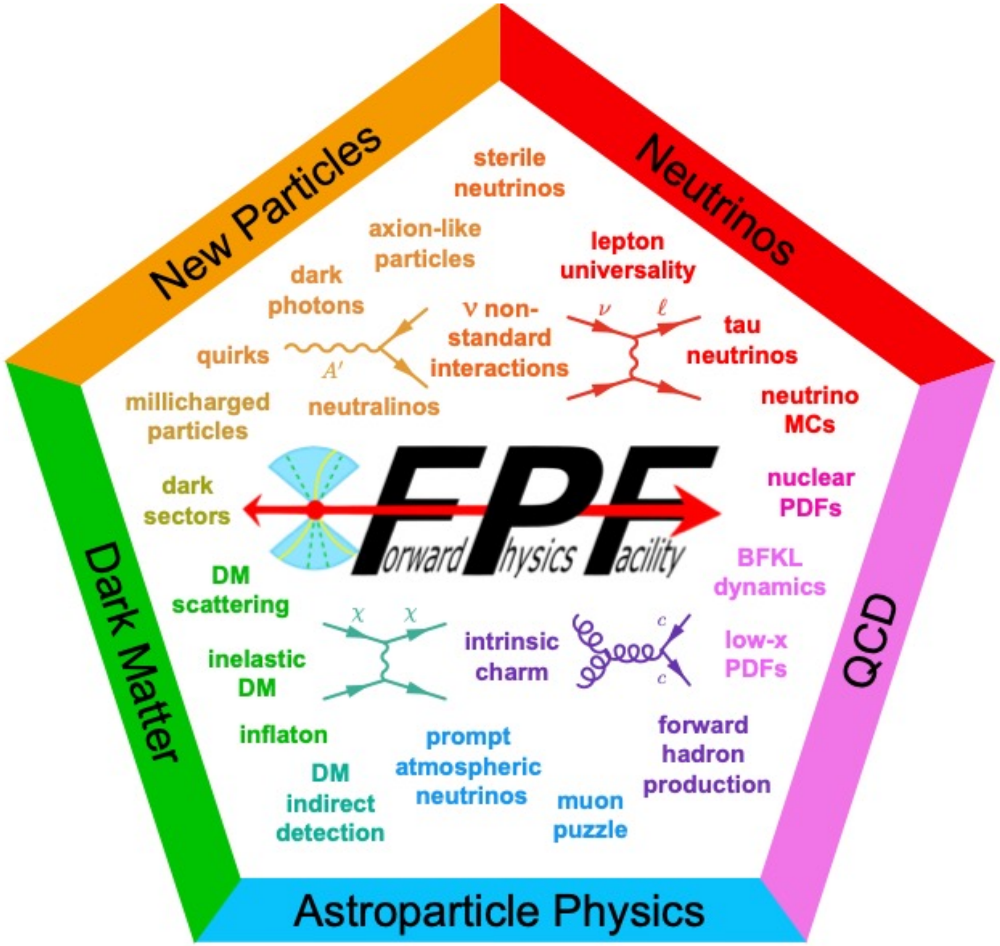
PHYS. REV. D 104, L091101 (2021)

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

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

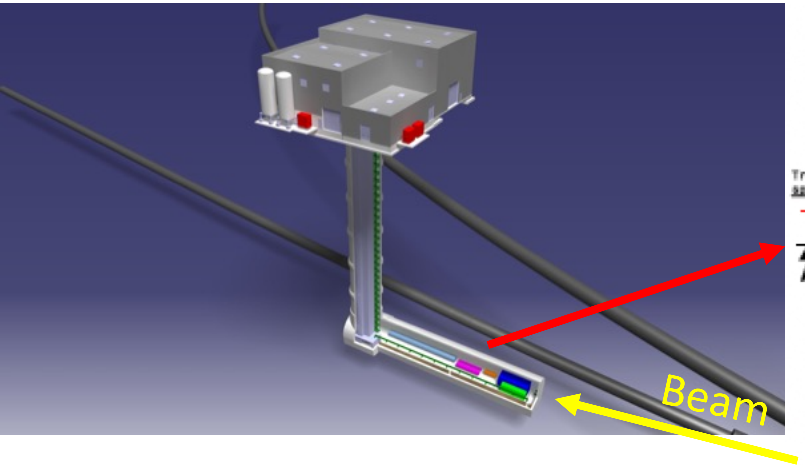


Dark matter search sector

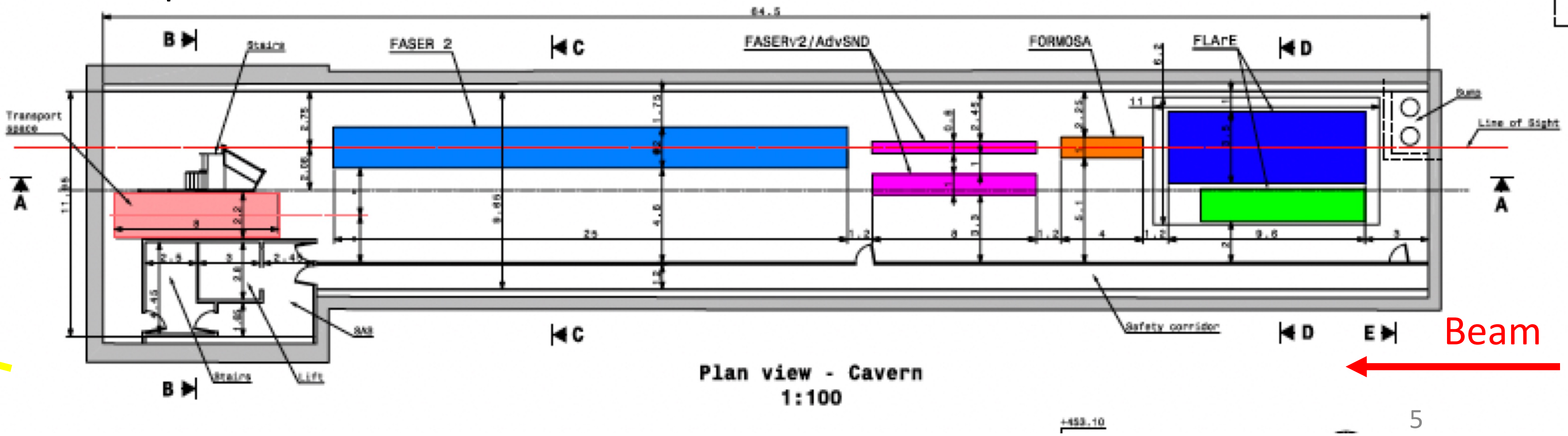
- Detection of dark photon and other dark sector particle decays in the detector volume
- Detection of light dark matter scattering in detector
- Search for milli-charged dark matter particles
- Search for dark tridents

Proposed Detectors for FPF

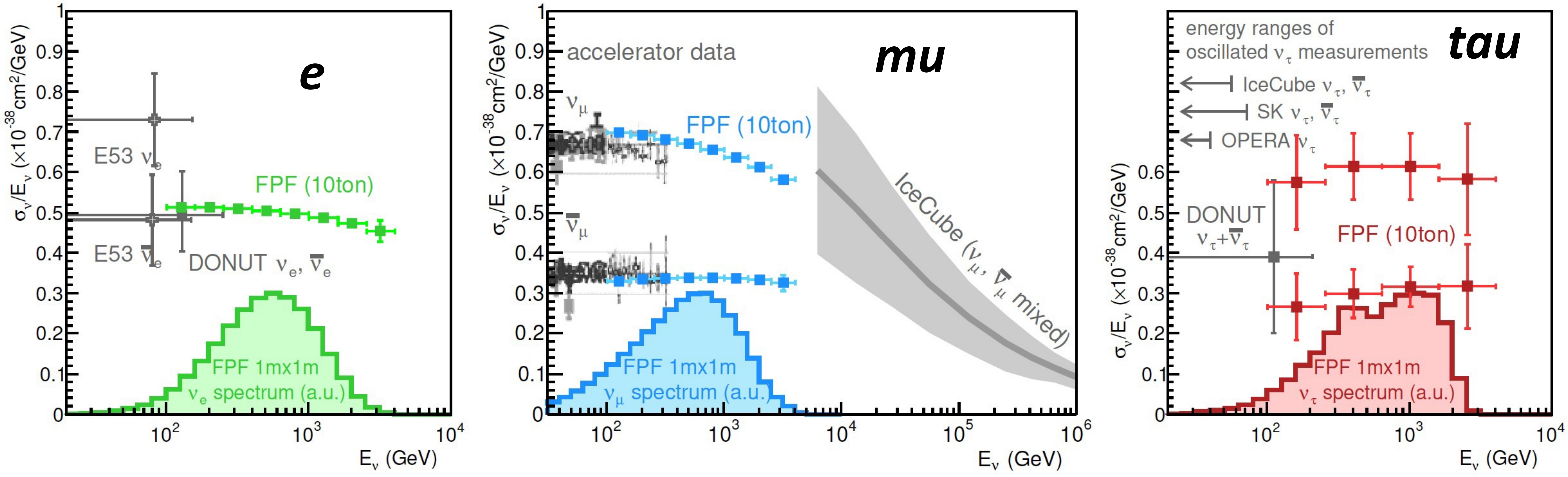
Experiment	Science Priority	Technology
Faser 2	Long-live neutral particles decay	Large decay volume (super-conducting) magnetic spectrometer
FASERnu2	Neutrino Interactions	Tungsten/Emulsion 20 tons. Veto and interface tracker for muons
AdvSND	Neutrino Interactions on/off axis	Hybrid electronic and tungsten/emulsion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



Top View



Neutrino physics

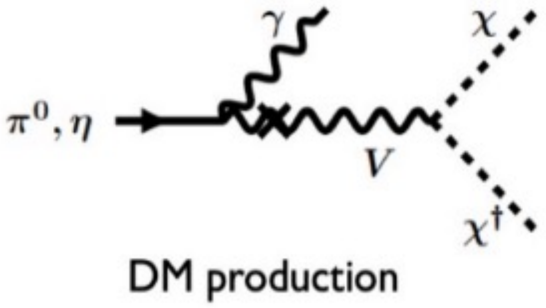


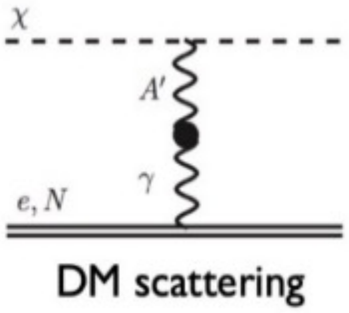
- The current data from accelerators ends around 300 GeV. FPF would provide data that fills in the gap between accelerators and atmospheric neutrinos.
- There are three proposed detectors at 10 ton each: FASER*v*2 (emulsion), SND(TBD), and FLArE.
- Total rate will be ~100k electron neutrinos, ~1M muon,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

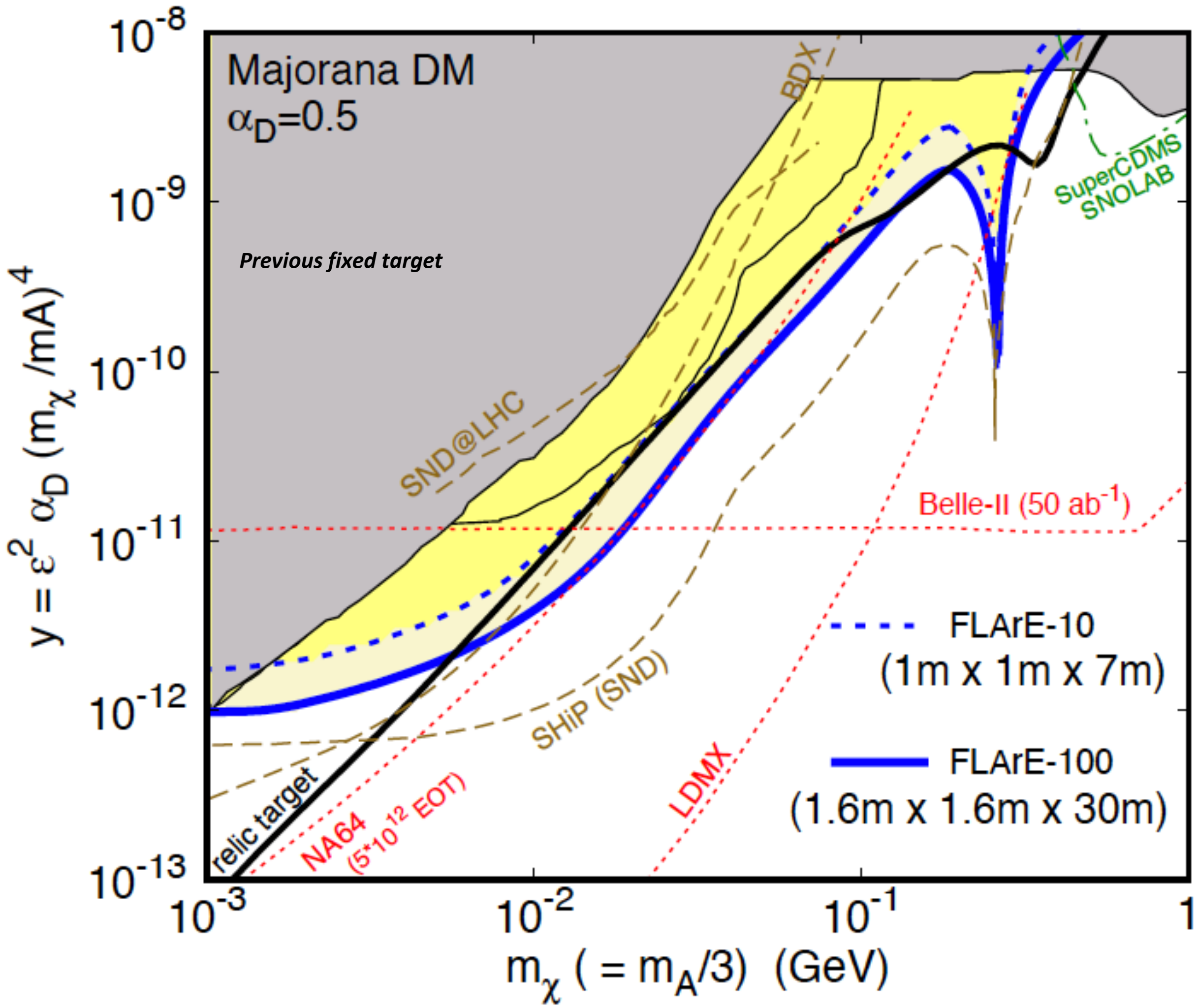
Light Dark Matter scattering

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.



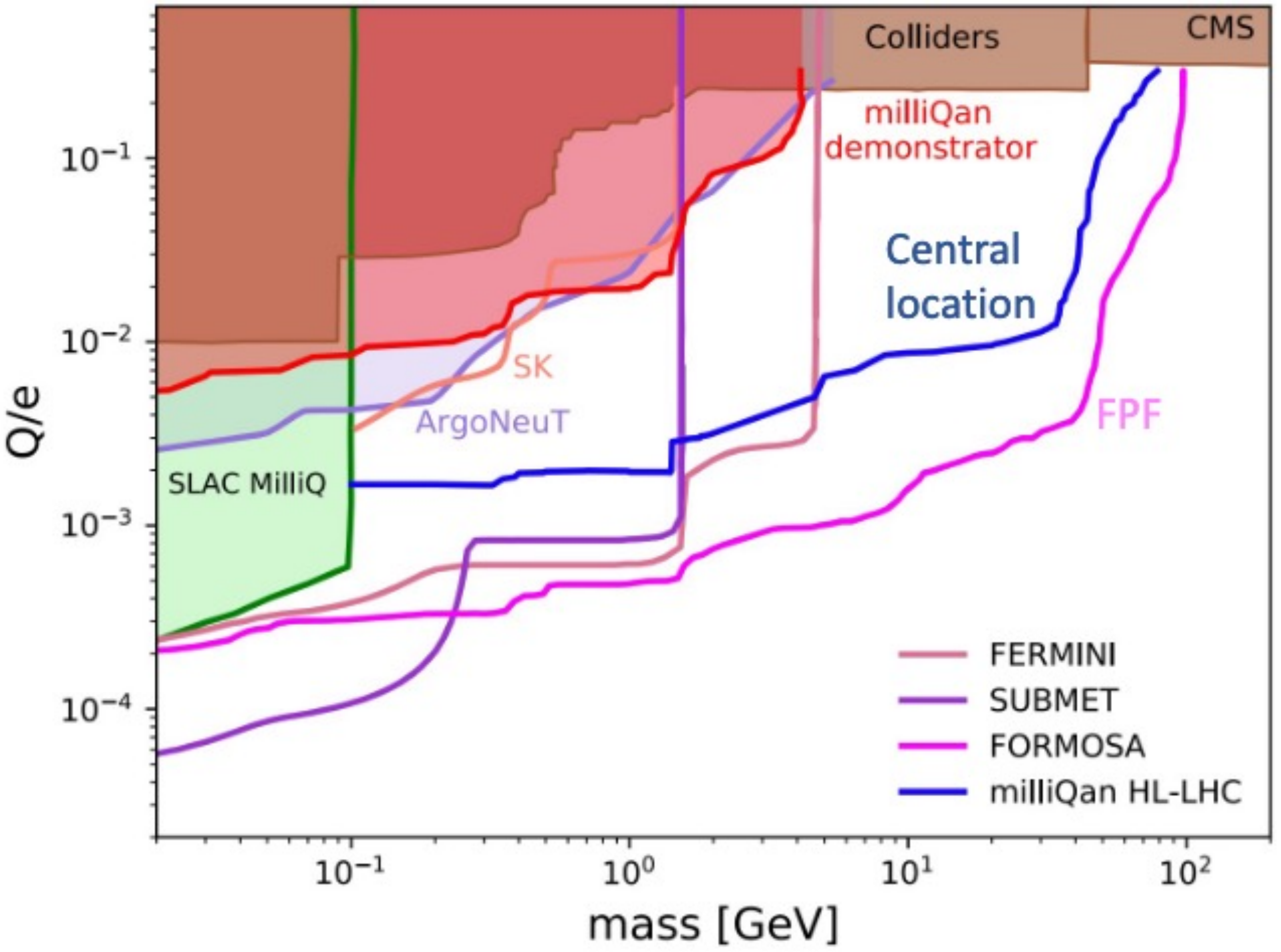




Batell, Feng, Trojanowski (2021)

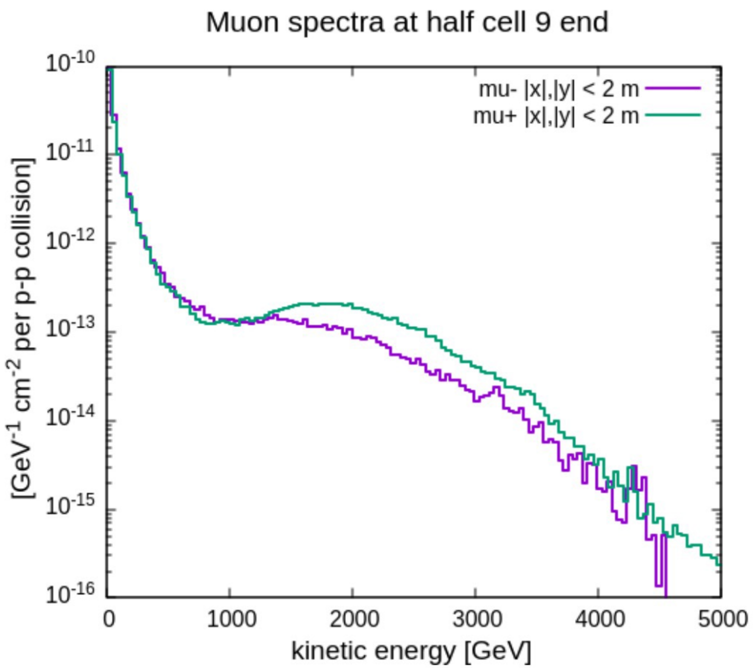
Milicharged particles

- 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)

Experimental conditions (without sweeping magnet, very preliminary, work in progress)



Approximate muon fluxes, rates of backgrounds

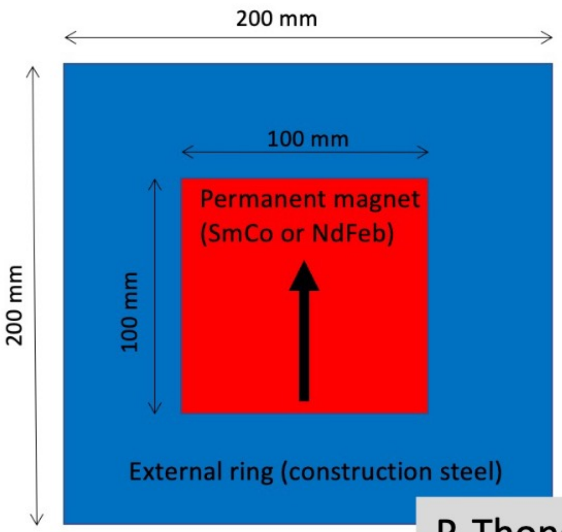
Minimum distance	612 m
Total Lumi/max lumi	3000/fb ; 5×10^{34} /cm2/sec
Lumi per day	~1 /fb assuming 10 year running
pseudorapidity coverage	>6.4, (~5.4-6.0 for off-axis)
Mu+/Mu- flux > 10 (100) GeV	1.5/0.93 (0.94/0.39) 10^4 /cm^2/fb^{-1}
track density (from data)	1.7x 10^4/cm^2/fb^{-1}
max track density per sec (per crossing)	0.85/cm^2/sec (2×10^{-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

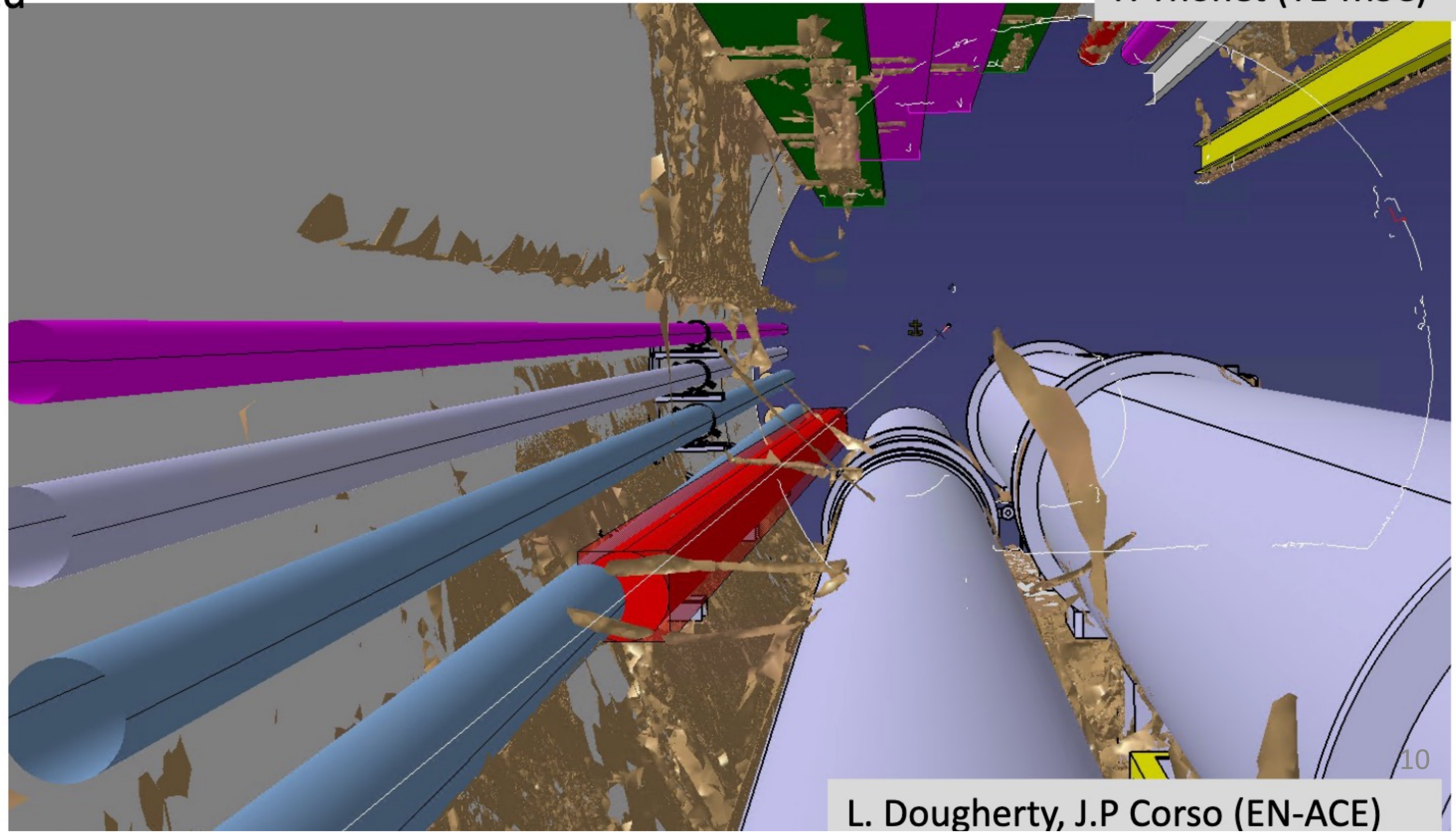
- This rate will be lower at 612 m.
- Both charged and neutral hadron interactions present significant background.
- Total neutrino interaction rate normalized to per ton per fb^{-1}
- Observed nu rate: ~45/ton/fb-1 at 480 m

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)

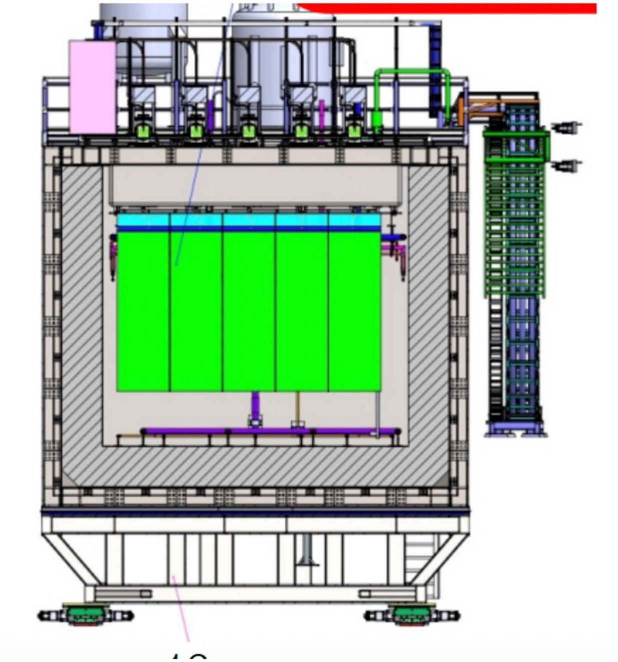


L. Dougherty, J.P Corso (EN-ACE)

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.

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/m^3	**~13 W/m^2**	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Nomex honeycomb+perforated Al	**665 mm+ (combined)**	25-35 kg/m^3	**7-22 W/m^2**	Yes
ICARUS-SBN	3.9m x 3.6m x 19.6m	Al extrusion+GTT foam	**665 mm+ (combined)**	25-35 kg/m^3	**10-15 W/m^2**	Yes
ProtoDUNE	7.9m x 8.55m x 8.55 m	GTT membranc	**800mm**	90 kg/m^3	**~8 W/m^2**	No
ND-LAr	3m x 5m x7m	GTT membrance	800mm	90 kg/m^3	**~8 W/m^2**	No
FLArE	~(1m x 1m x 7m)					No?

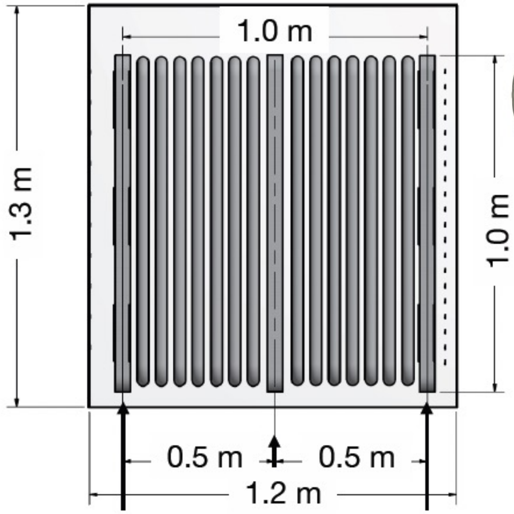
Yichen Li

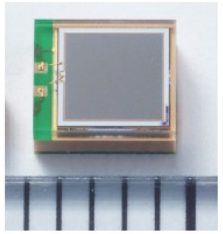
- Space in FPF hall currently is limited to 3.5 m X 3.5 m X 9.6 m for FLArE.
- 80 cm GTT membrane occupies 1.6 m out of 3.5 m. More space might be needed for corrugations.
- GTT is easy to install, DUNE ND-LAr design has installation from top, this would also simplify things.
- Further Engineering will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

FLArE Detector Preliminary Sketch (without HadCal and Muon Catcher)

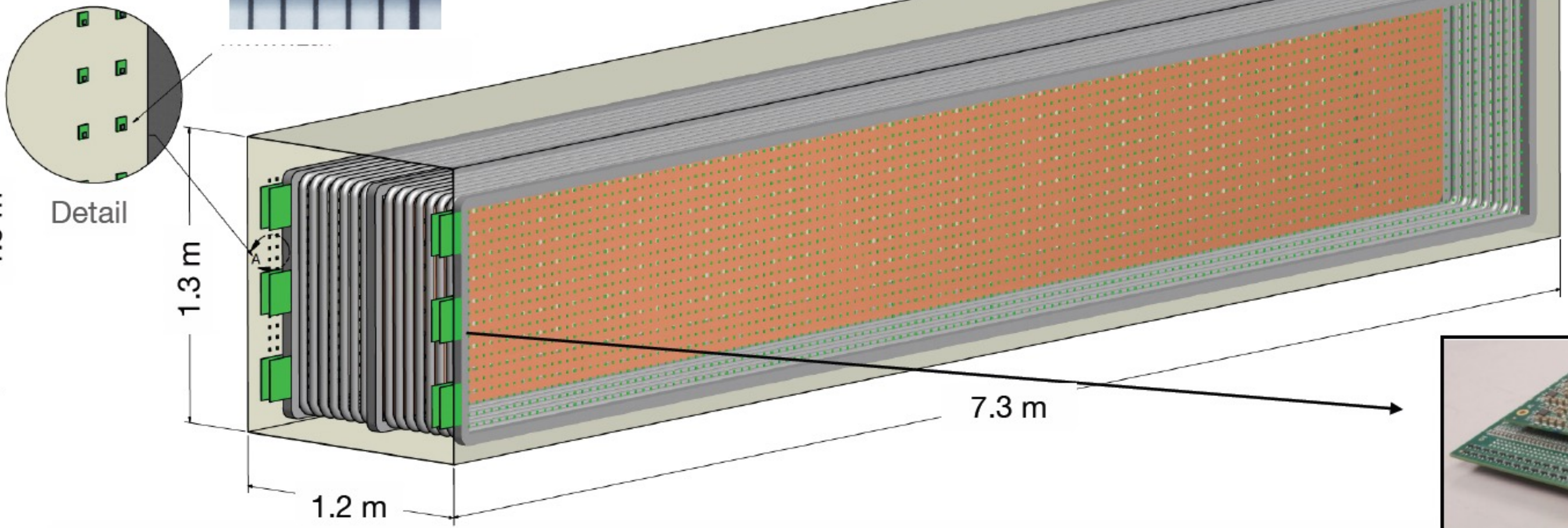
Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

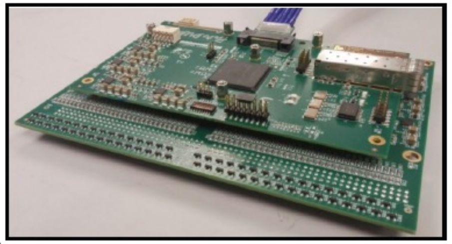
TPC-side view 2



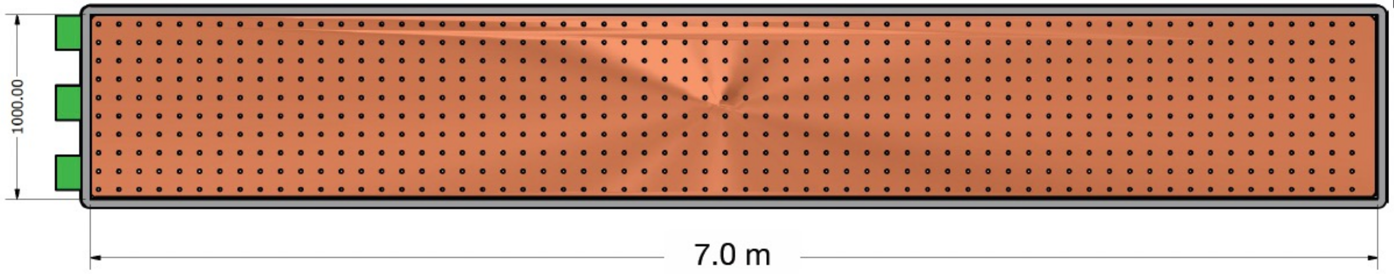


Hamamatsu
S14160 SiPM
6x6 mm
2800 units

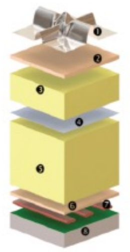




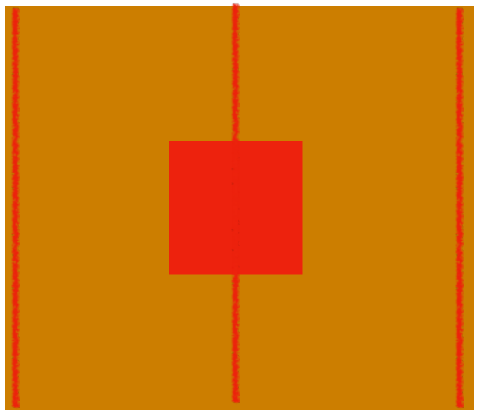
DUNE Front End Motherboard



TPC anode plane -side view 1

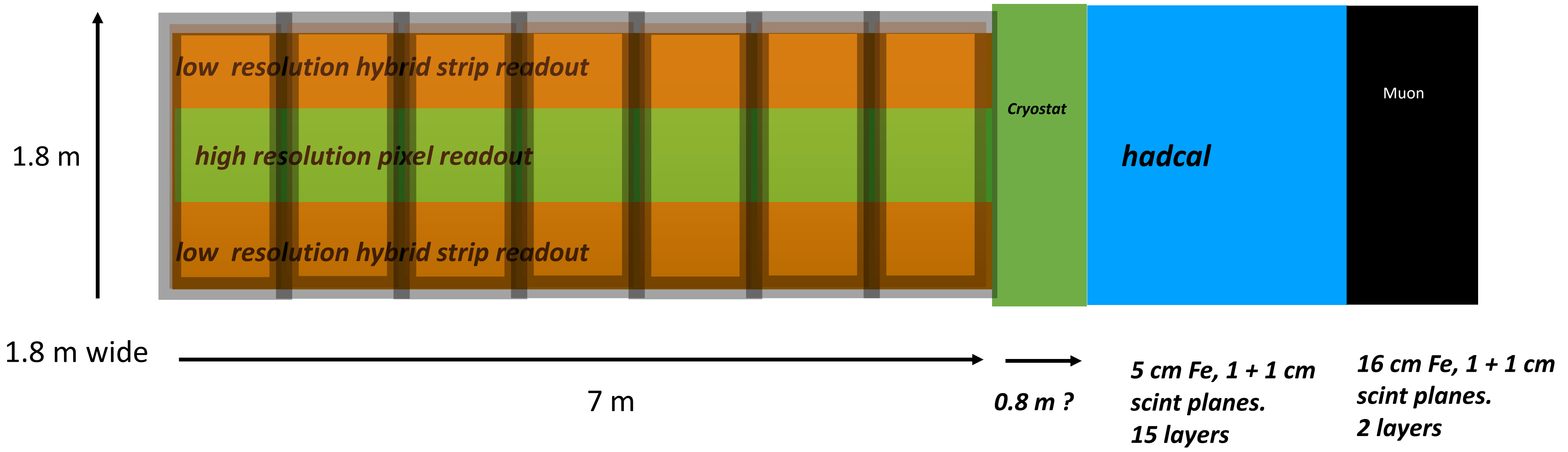


Cryostat Insulation



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.



(Preliminary Parameters)

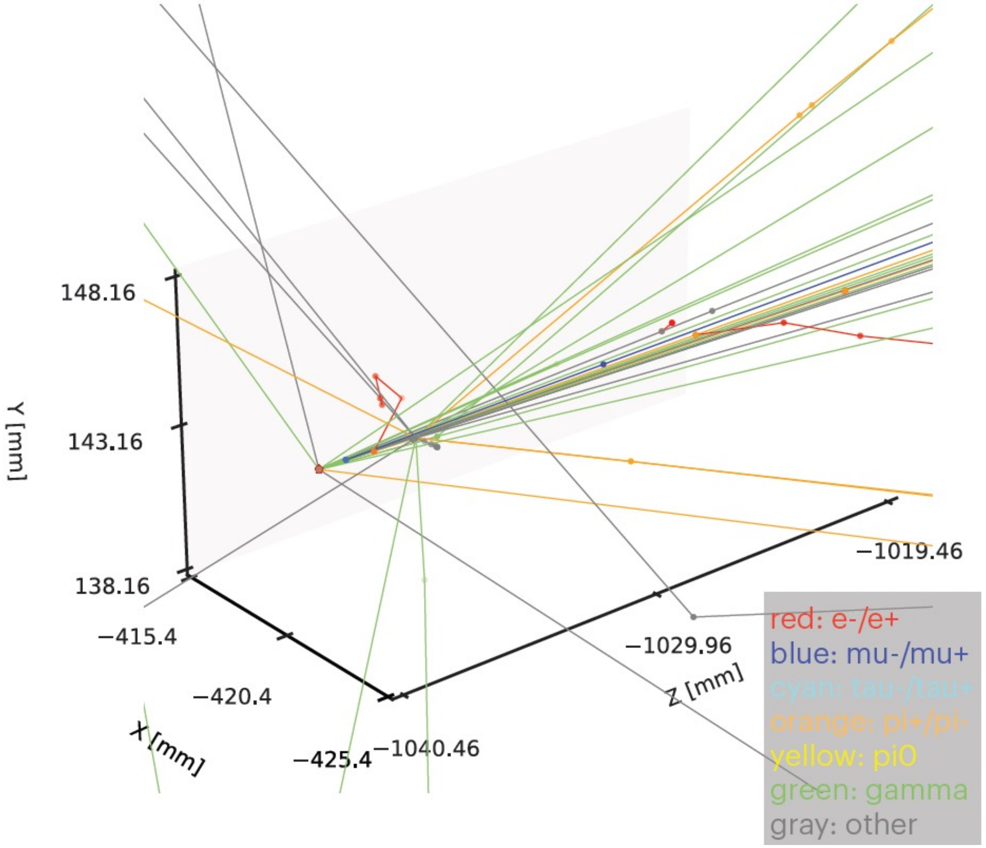
Carry two options into Conceptual Design

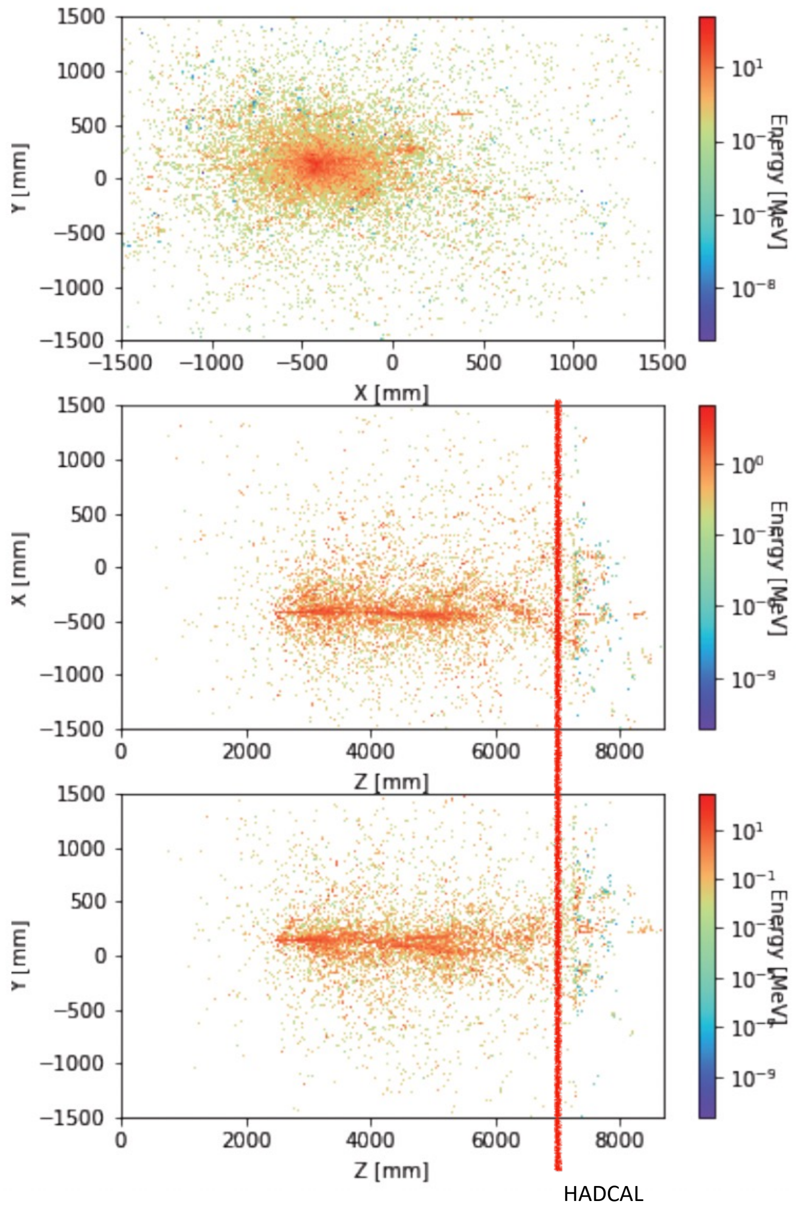
either 2 X 7 vertical modules with 0.45 m gap
or 3 x 7 vertical modules or with 0.3 m gap

Tau Neutrino event simulation in FLArE

ν_τ CC (E_ν = 230.7 GeV)

$\tau^-(102.9\ \mathrm{GeV}) \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-(74.7\ \mathrm{GeV})$





First conclusions from simulations:

1) **Need 1.8 X 1.8 to contain transverse events in fiducial of 1 m x 1 m x 7 m.**

2) **Need Hadronic calorimeter to contain showers that start downstream.**

3) **Even a modest resolution is sufficient.**

4) **excellent muon identification could result in quick selection of ν_τ events.**

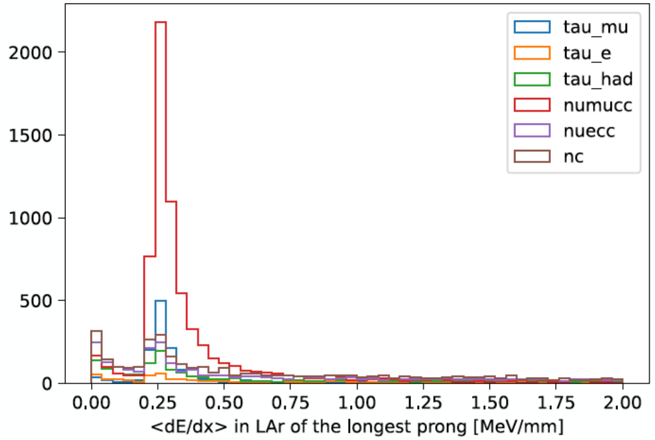
5) **Studies: can we combine spatial resolution in drift dimension with kinematics to get good S/N ?**

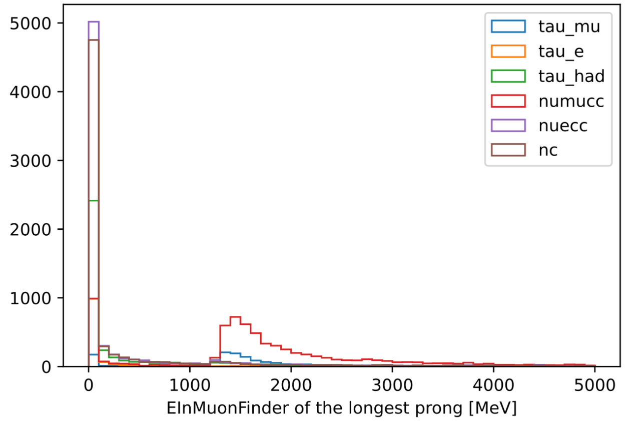
Identify ν_τ CC at FLArE

TABLE I. Dominant decay modes of τ^-. All decays involving kaons, as well as other subdominant decays, are in the "Other" category.

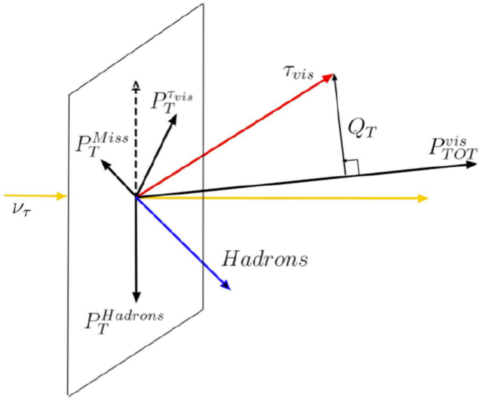
Decay mode	Branching ratio
Leptonic	35.2%
$e^-\bar{\nu}_e\nu_\tau$	17.8%
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic	64.8%
$\pi^-\pi^0\nu_\tau$	25.5%
$\pi^-\nu_\tau$	10.8%
$\pi^-\pi^0\pi^0\nu_\tau$	9.3%
$\pi^-\pi^-\pi^+\nu_\tau$	9.0%
$\pi^-\pi^-\pi^+\pi^0\nu_\tau$	4.5%
Other	5.7%

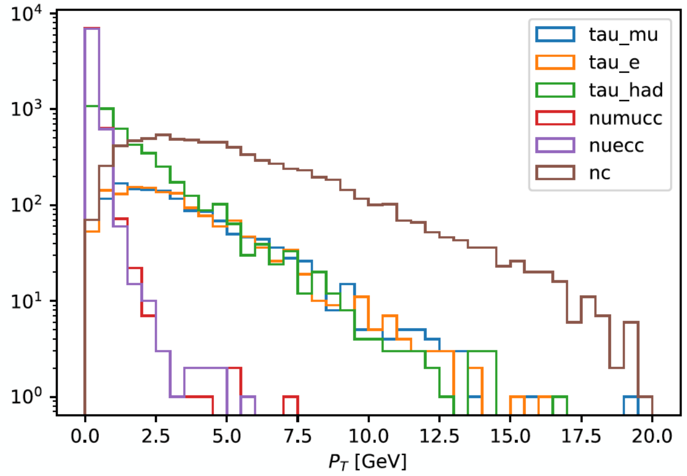
ν_τ CC, $\tau \rightarrow \mu$ and ν_μ CC are distinct from other channels in dE/dx and energy deposit



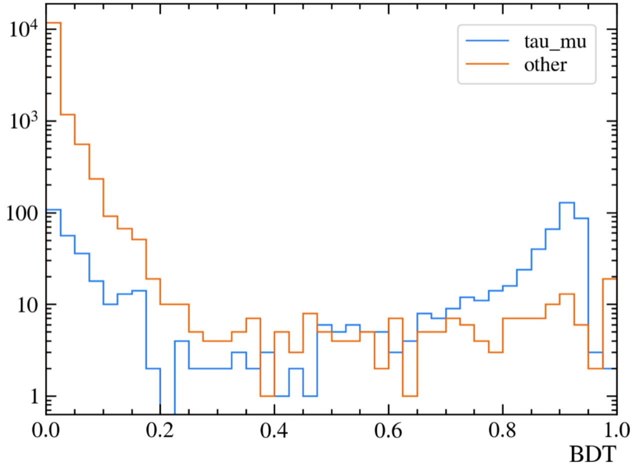


ν_τ CC, $\tau \rightarrow \mu$ have more neutrinos in the final state than ν_μCC, thus more missing momentum in the transverse plane





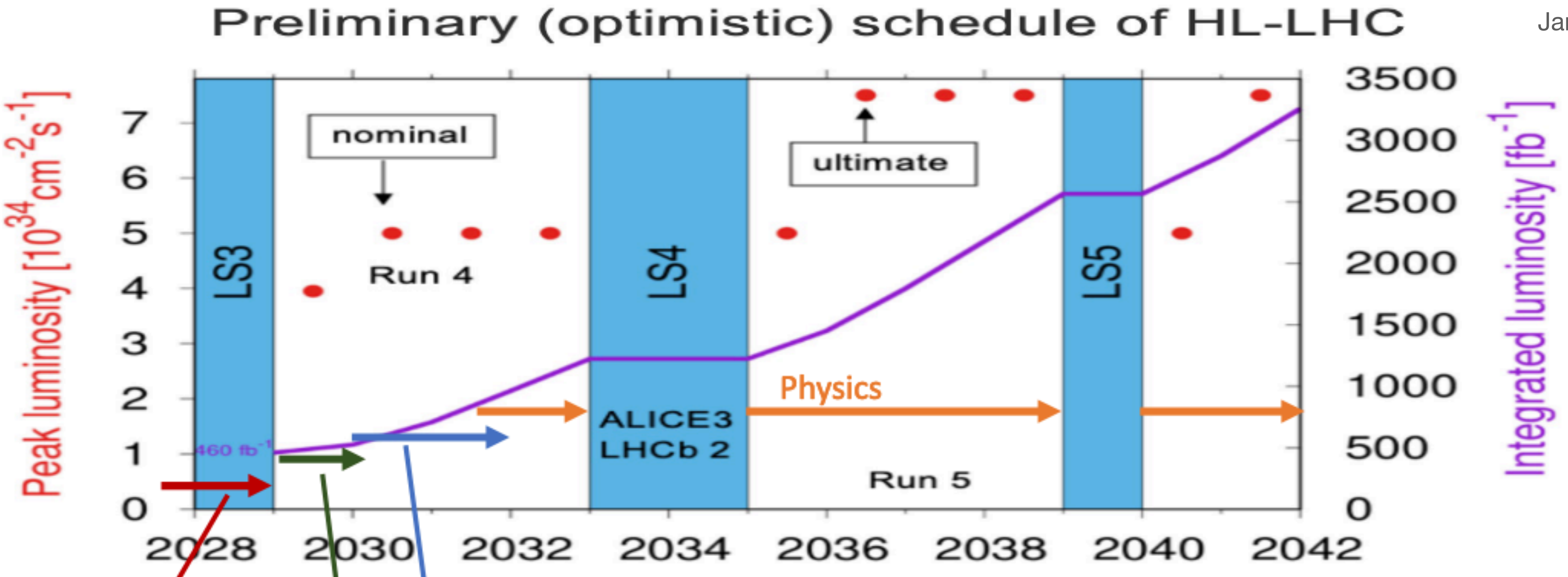
A BDT shows promising results to select ν_τ CC, $\tau \rightarrow \mu$ from backgrounds, working on other τ decay modes



Possible FPF schedule

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

Jamie Boyd



Pure CE works (including ~~connection to LHC)~~

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

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

Installation and commissioning of the experiments

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

Summary

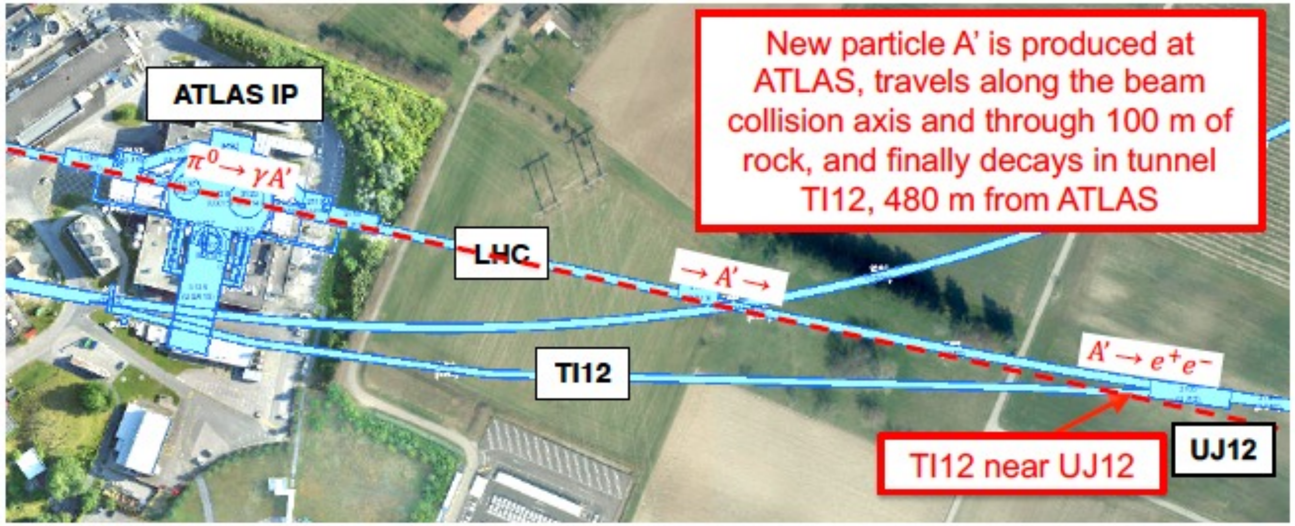
- A forward physics facility FPF is being considered at CERN for neutrino and dark matter physics.
- The physics interest is
  - Neutrino cross sections in the 1 TeV range: ~20-50 events/ton/day
  - Tau neutrino flux and associated heavy flavor physics: ~0.1-0.2 events/ton/day
  - Light dark matter search 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

Thank you!

Backup

Current forward physics programs with Run 3

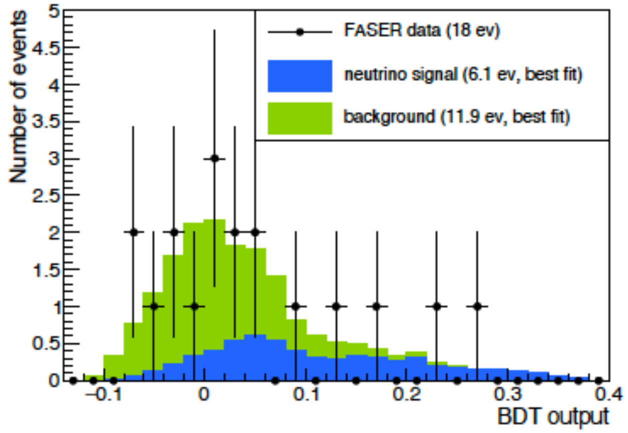
- 4 experiments in progress for LHC-run3 for 150fb^{-1} 2022-24.
- FASER (March 2019), Magnetic spectrometer for neutral decays.
- FASERν (Dec 2019), Emulsion/tungsten detector (~1 ton)
- SND@LHC (Mar. 2021) Hybrid Emulsion/active target. (~1 ton)
- Also MilliQan located near CMS (not forward); scintillation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



FASERν pilot run

First collider neutrinos detected at 2.7 sigma.

- 2018 pilot emulsion detector with 11 kg was deployed for 12.2/fb
- May 2021, announced 6 candidates with 12 backgrounds.
- Same stack able to measure the muon rate at that location.
- muon and neutrino rates in rough agreement with expectations.
- https://arxiv.org/abs/2105.06197



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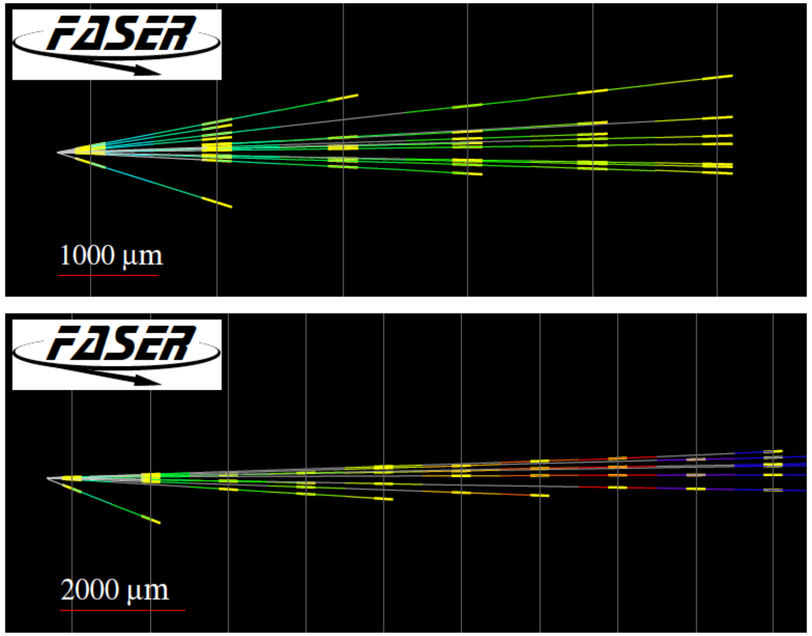


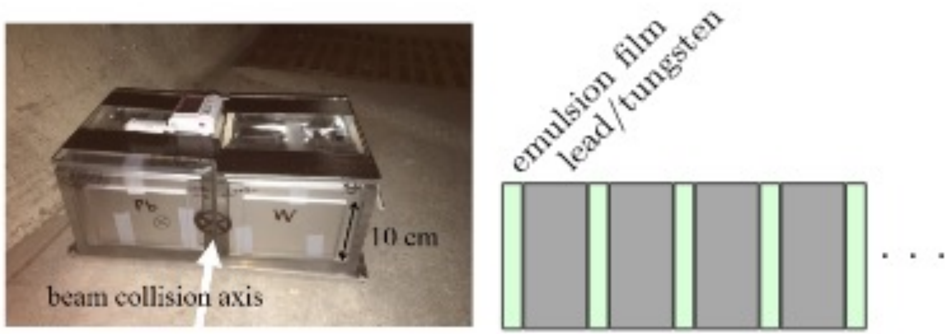


FIG. 1. Structure of the pilot emulsion detector. Metallic plates (1-mm-thick lead or 0.5-mm-thick tungsten) are interleaved with 0.3-mm-thick emulsion films. Only a schematic slice of the detector is depicted.

Neutrinos at FPF

Uncertainties are large. 2105.08270 (Kling) is standard simulations. 2002.03012 (Bai et al.) and 2112.11605 is deep analysis of the tau neutrino flux.

Needs detailed Monte Carlo

- $c\tau(\pi, K^{\pm}, K_L) = 7.8m, 3.7m, 15m$
- $\pi \to \nu_\mu, K \to \nu_\mu, K \to \nu_e$ will be affected by the LHC magnets and shielding.

$D^{\pm} \to e/\mu$ (semi)leptonic (33%) m=1870MeV, $c\tau$=311 μm (decay to τ is very small)

$D^{0} \to e/\mu$ (semi)leptonic (13%) m=1865MeV, $c\tau$=122 μm (no decay to τ due to mass)

$D_s^{\pm} \to e/\mu$ (semi)leptonic (6%) $m = 1968 MeV$, $c\tau = 150 \mu m$

$D_s^{\pm} \to \tau\nu_\tau$ (5.5%) p_{cm} = 182 MeV. This would be the main source of ν_τ

$B^{\pm} \to l^{\pm}\nu_l X$ (11 %) m=5279 MeV, $c\tau$=491 μm (most decays are to D which decay to neutrinos)

$B^{\pm} \to D\ X(>95\%)$

$B^0, \bar{B}^0 \to l^{\pm}\nu_l X$ (11 %) m=5279MeV, $c\tau$=455μm

$B^0, \bar{B}^0 \to D\ X$ (>90%)

$\Lambda_c \to l\nu_l X(\sim 10\%)$ m=2286MeV, $c\tau$=60μm (e/μ modes only)

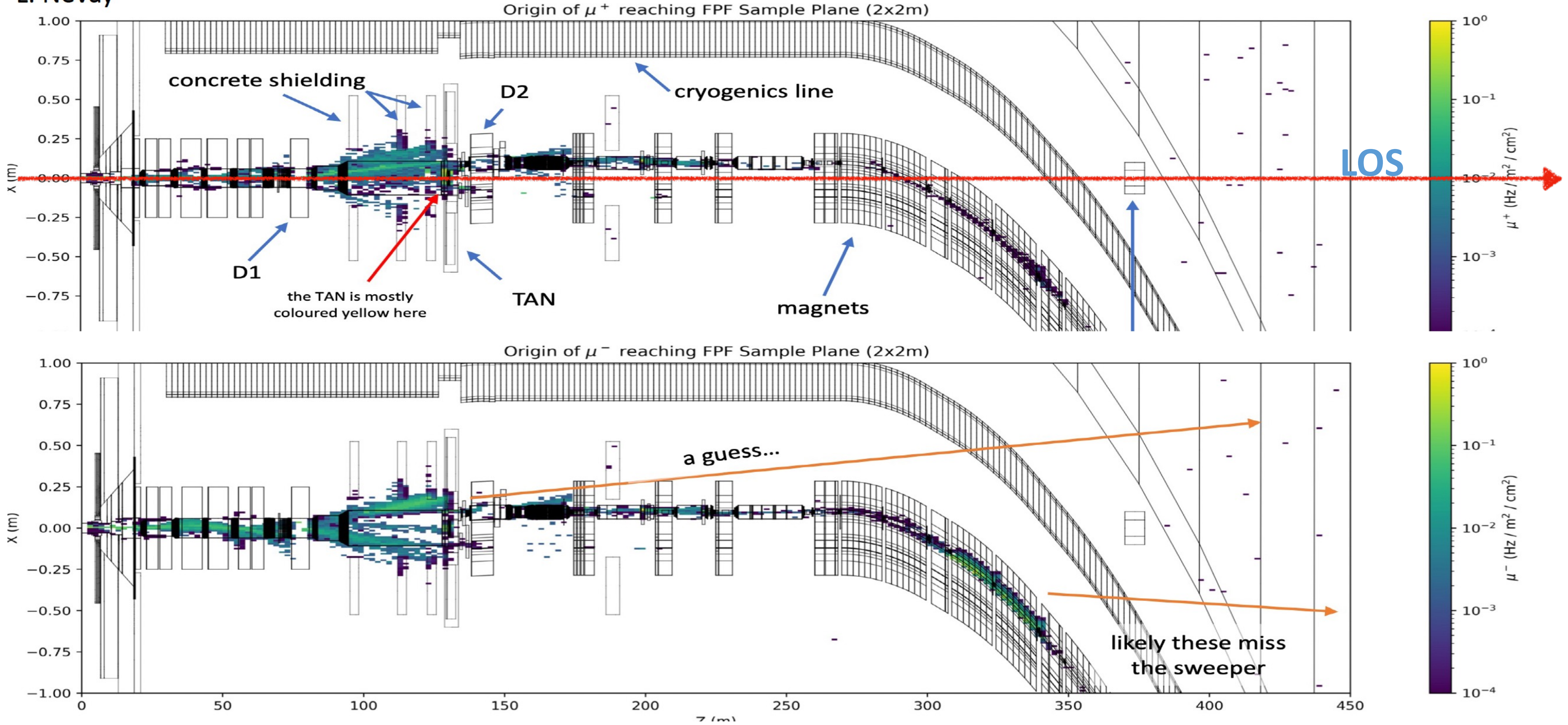
$\tau^{+} \to X\bar{\nu}_\tau$ (100%) m=1776 MeV, $c\tau$=87μm

Electron neutrino flux above 300 GeV is charm dominated.

Needs modeling of forward production in the PP interaction

New HL-LHC geometry BDSIM simulation. Where to place a sweeper magnet ?
Any Placement requires movement of cryogenic lines and other services. But so far possible.

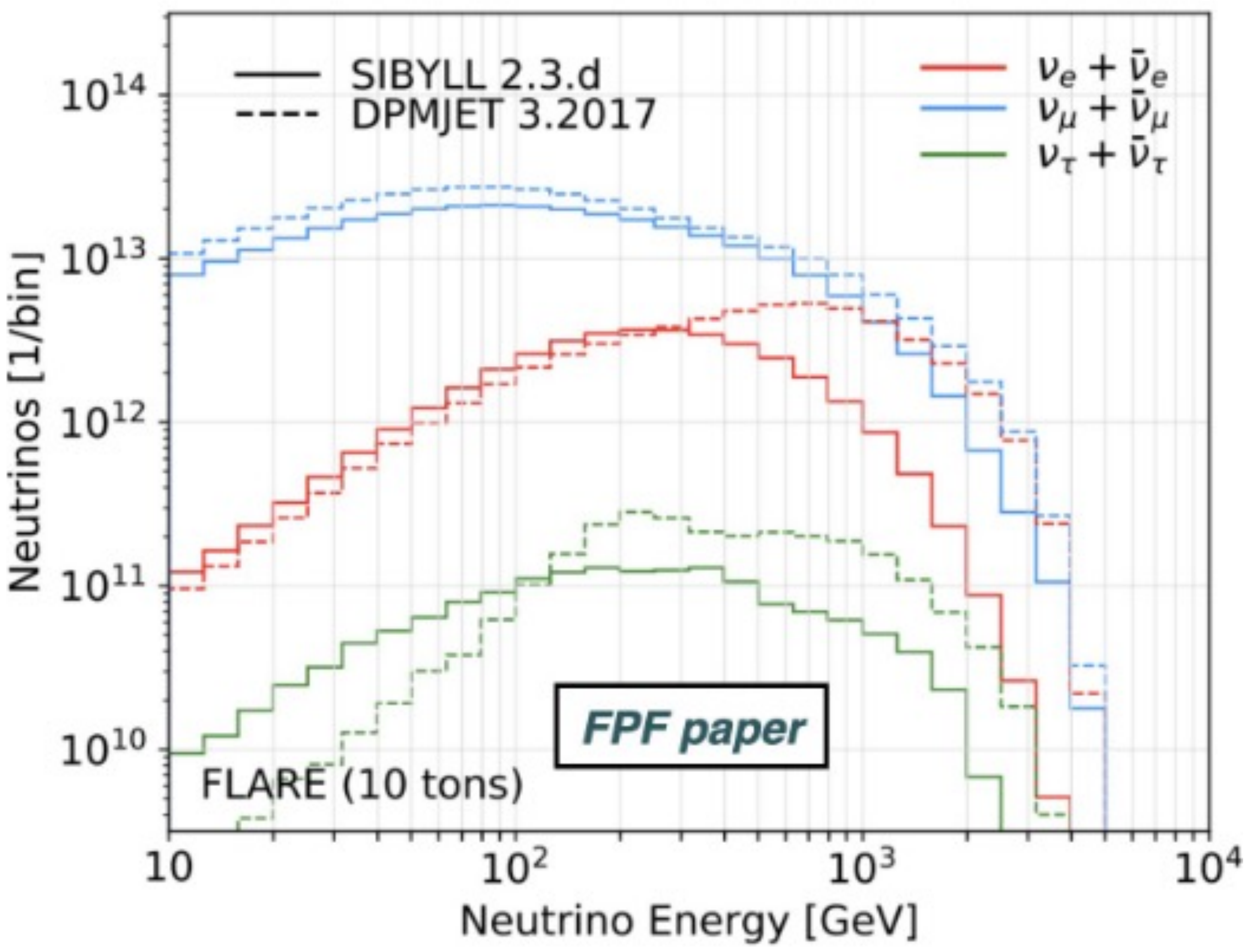
L. Nevay



The MU+ and MU- have very different spatial distributions. And the rate is actually higher away from the LOS. We have to assume that this will be solved with ultimate rate of << 1 Hz/cm2 at the FPF. it will need more people !

Neutrino event rates (with large uncertainties)

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

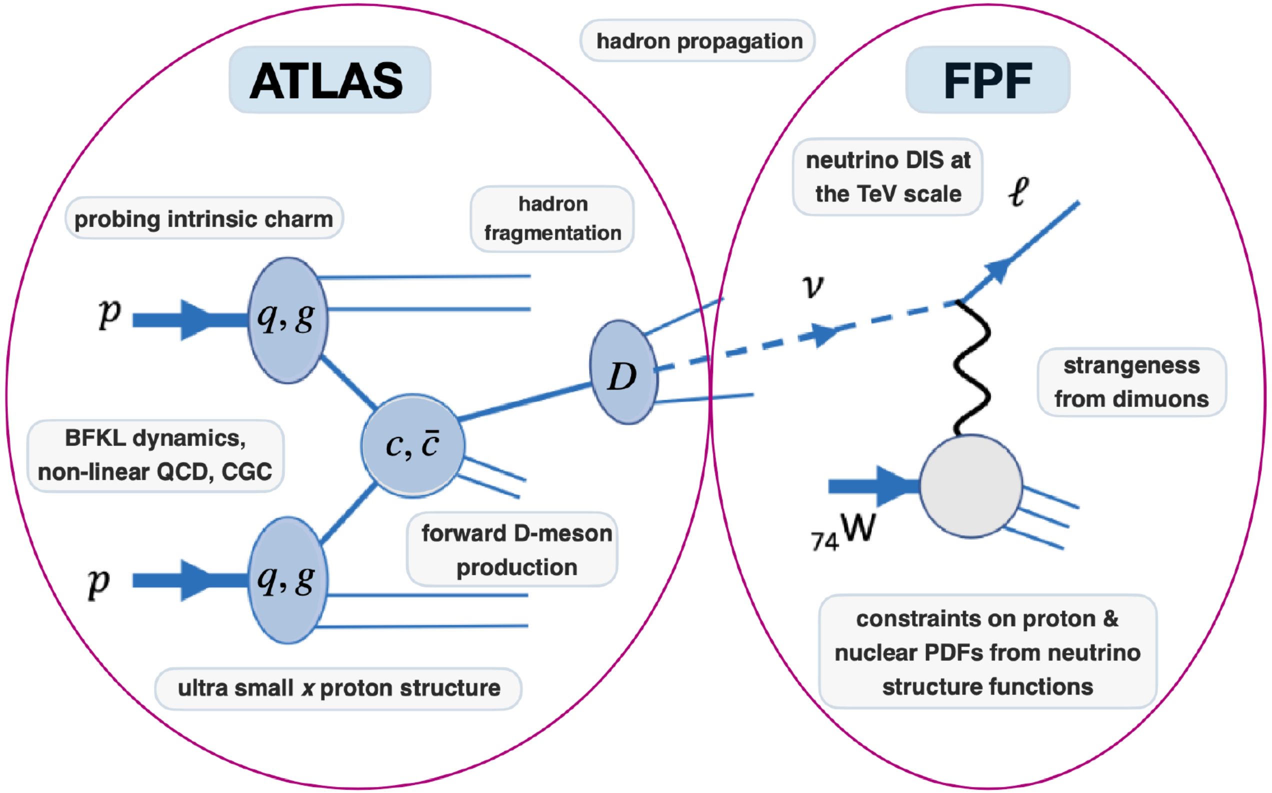


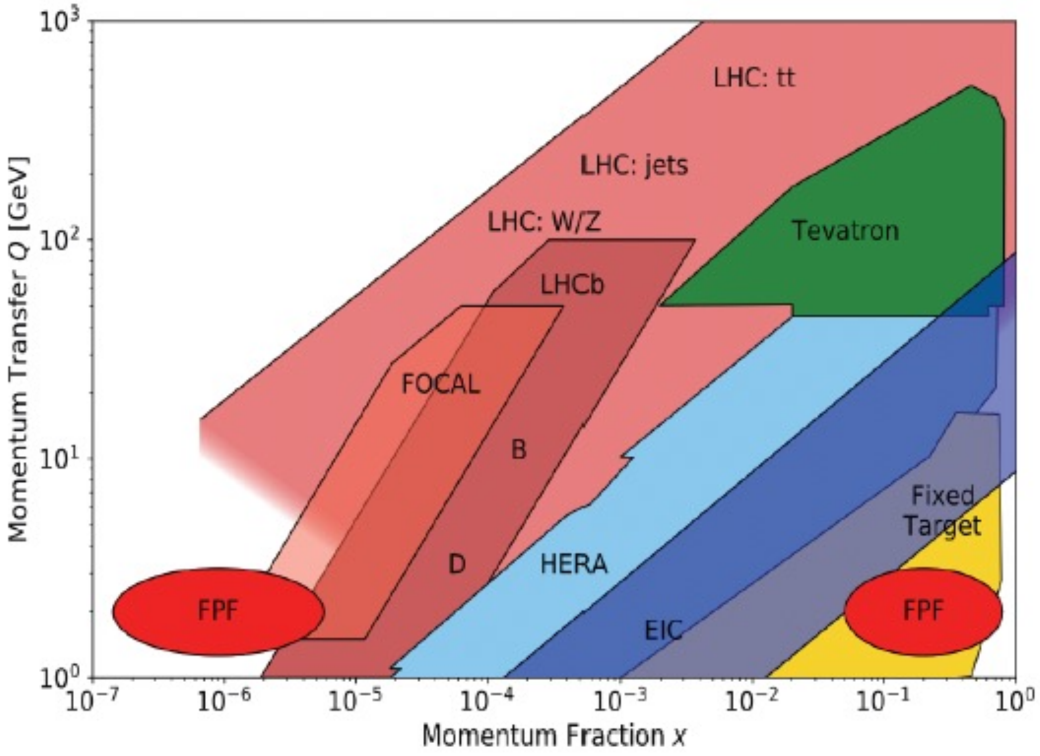
During HL-LHC fb^{-1} is approximately per day.

Mean energy of interactions is ~500 GeV

QCD interest

Neutrino interactions neutrino-ion collisions at $\sqrt{s} \approx 50 GeV$



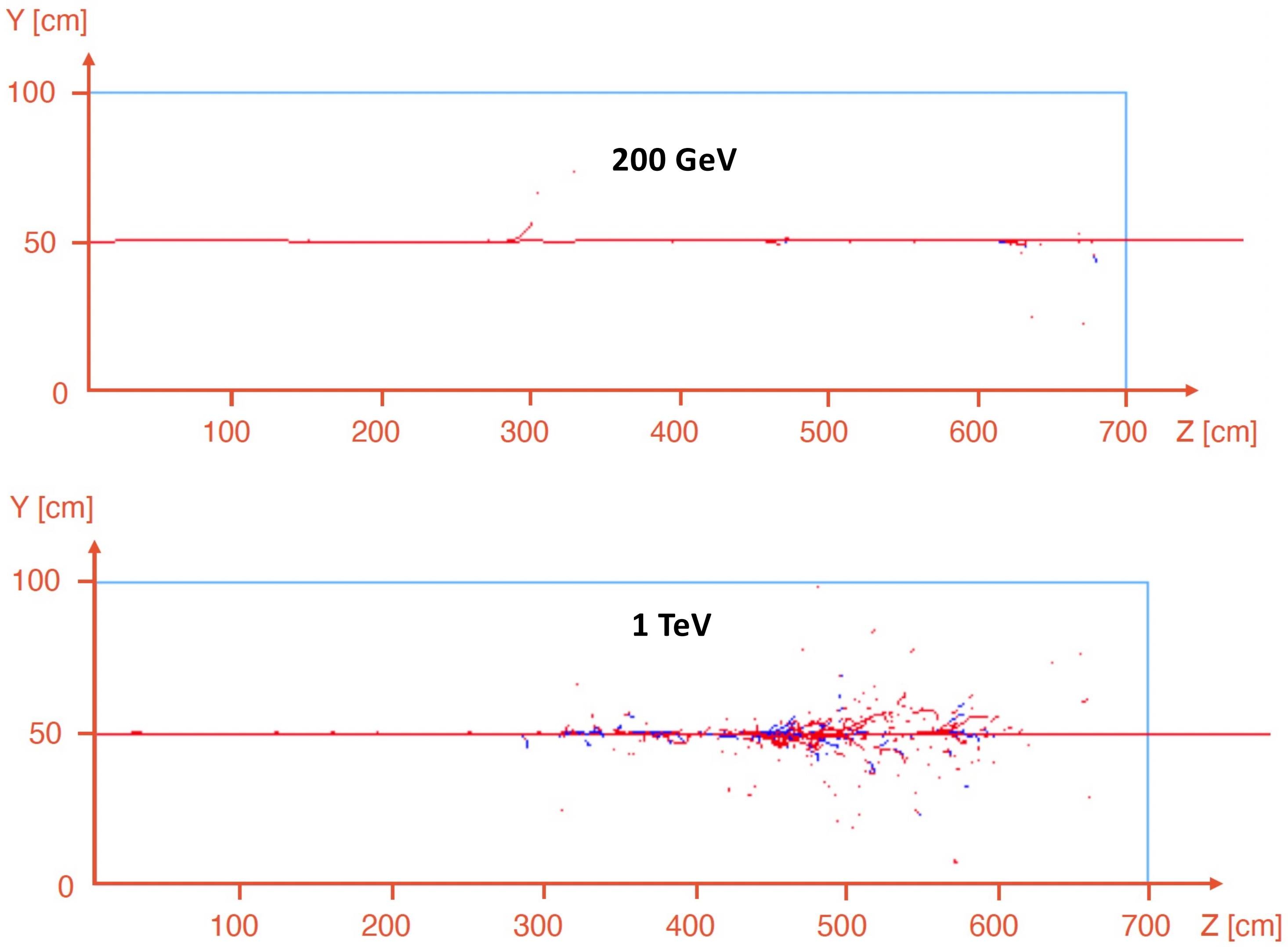


- ***Forward hadron production, instrinsic charm (large-x), ultra-small x proton structure***
- ***Extremely well motivated by the astrophysics UHE cosmic rays.***

Preliminary Parameters for the FLArE Detector

Cryostat outer	**3.5 m X 3.5 m X 9.6 m**	**Membrane**
Insulation thickness	0.8 m	including corrugations
Detector dimension	1.8 m X 1.8m x 7 m	good for >90 % containment
Fiducial volume	1 m x 1m x 7 m (10 tons)	Length may be adjusted later
TPC Modules	2 X 7 or 3 X 7	Keep two options
Module opt1 dimensions	0.9 m (W) X 1.8 m (H) X 1 m (L)	Central cathode: gap: 0.45 m
Module opt2 dimensions	0.6 m (W) X 1.8 m (H) X 1 m (L)	gap: 0.3 m
Anode design fiducial region	5 mm x 5 mm for 1 m x 1 m	80000 chan/mod
Anode design containment region	10 mm x 10 mm for 0.8 m x 1 m	16000 chan/mod
photon sensor	Bare SiPM or X-ARAPUCA	~50 chan/mod
Downstream cryo wall	80 cm	Can it be thinned down
HADCAL	2 m x 2 m x (5 cm Fe + 1+1 cm scint, 15 layers) x (1.05 m)	Optimize for resolution
Murange	• 2 m x 2 m x (16 cm Fe + 1 + 1 cm scint, 2 layers) x (0.36 m)	Increase to 1 m to get clean muID

Muon simulation in FLArE



- ***Muon flux above 1 Hz/cm2 presents a difficult problem for all detectors.***
- ***For Liquid argon TPC, the flux also presents a space charge problem for large gaps.***
- ***Showering muons will also present a trigger problem since if the incoming muon is missed the event will look like a neutrino.***