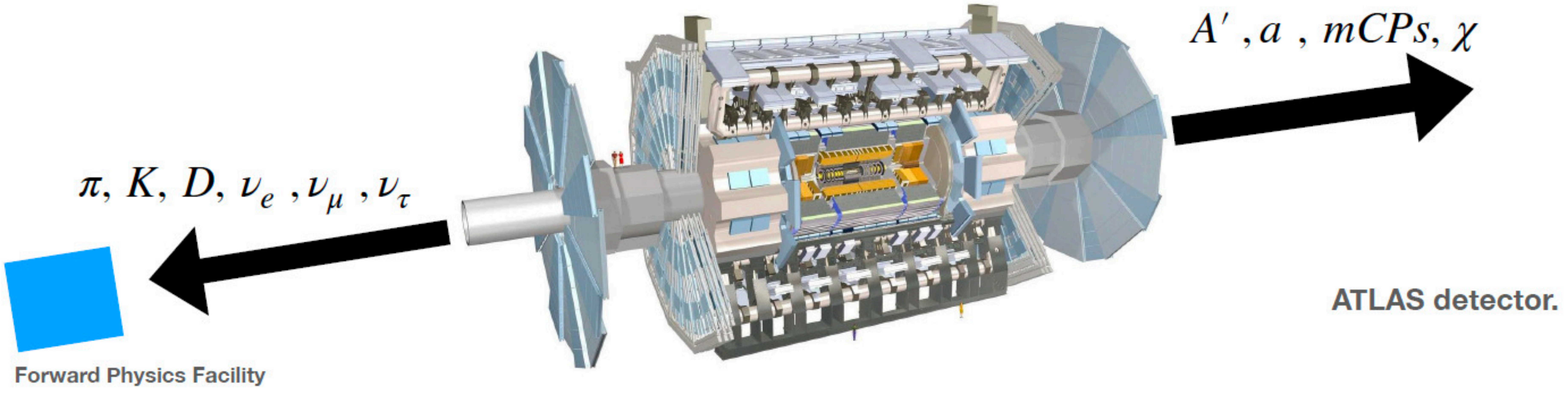
FLArE: Forward Liquid Argon Experiment

Matteo Vicenzi (Brookhaven National Laboratory)
mvicenzi@bnl.gov

on behalf of the FLArE technical group
https://indico.cern.ch/category/15544/

LLP13 Workshop - June 21st, 2023

Forward Physics Facility



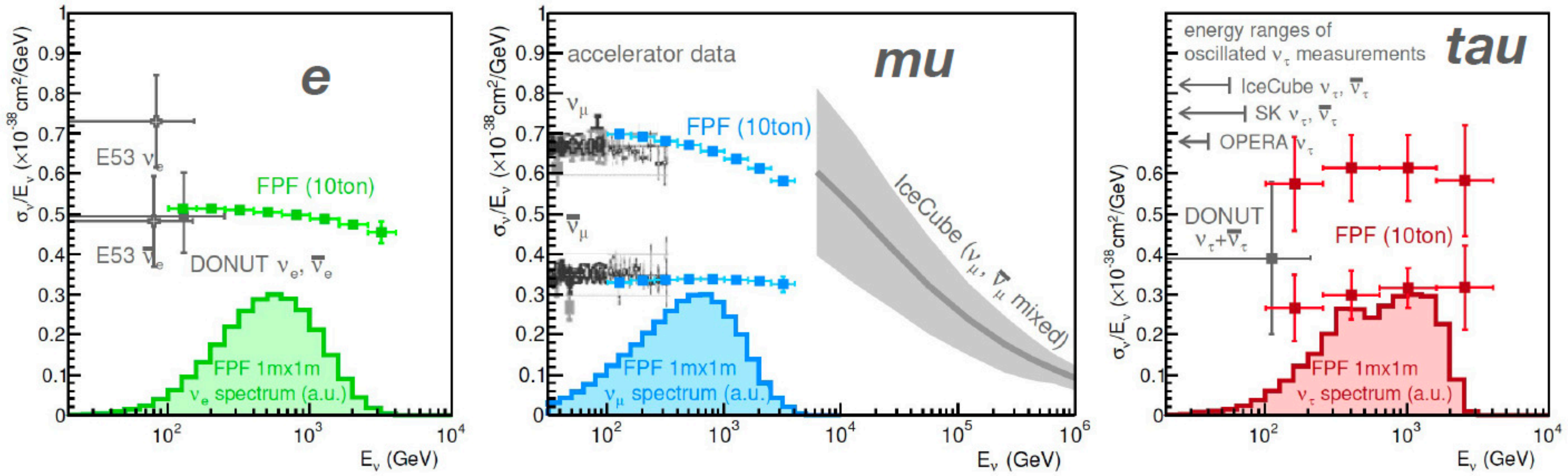
- **Forward Physics Facility**: Large flux of high energy (>100 GeV) light particles (pions, kaons, D-mesons, and neutrinos of all flavors) in the forward direction.
  - But also *LLPs*: dark photons, millicharged particles, light dark matter, etc.
- Unique opportunity for a detector with good energy containment (high density), high spatial resolution (for τ neutrinos) and low threshold (for DM scattering)

⟶ a liquid argon TPC: **FLArE**

Physics: Neutrinos and SM

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

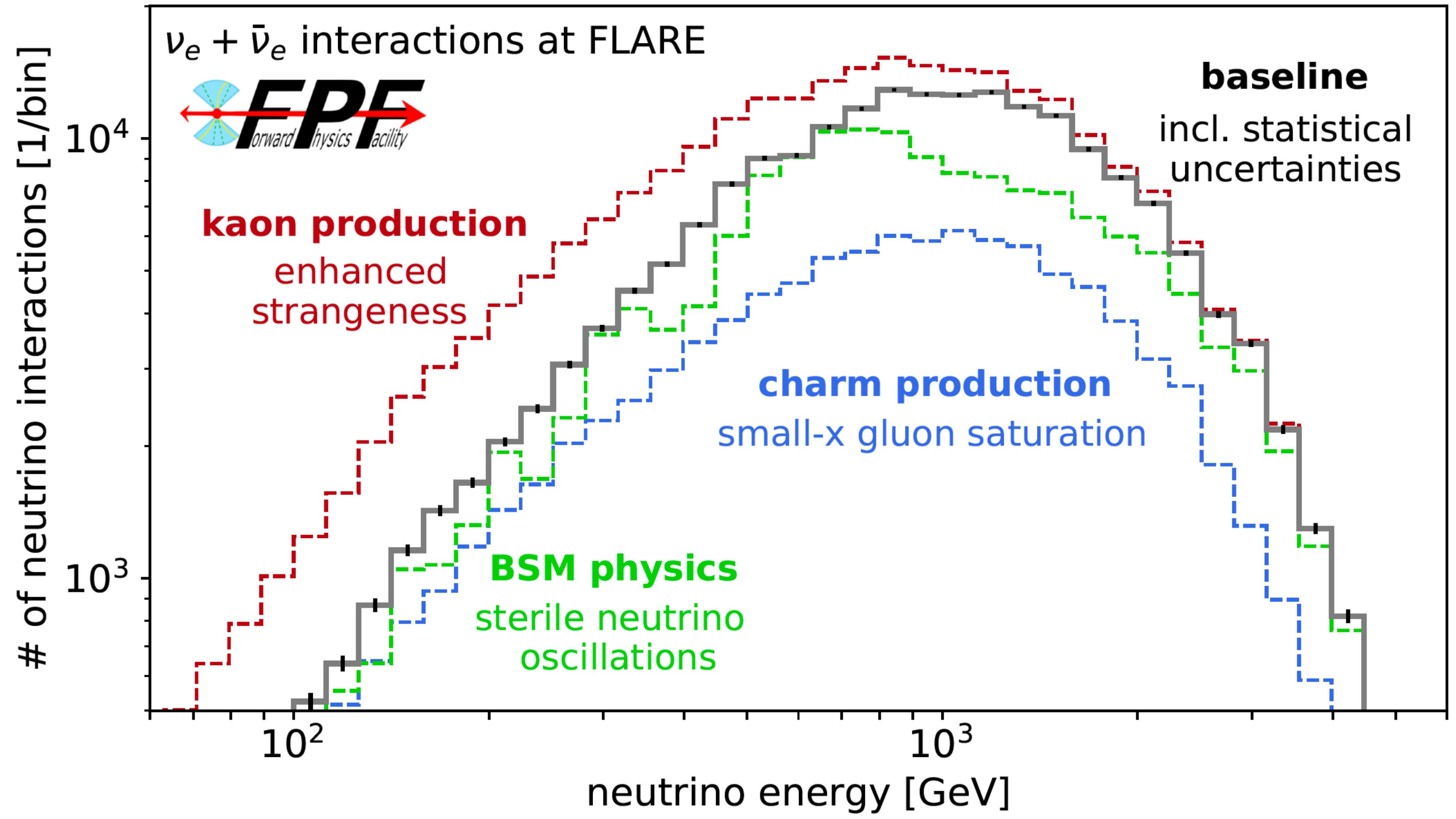
- FPF bridges the gap between accelerator and atmospheric data.
- Fluxes have very high uncertainties – both an opportunity (measure them!) and a challenge (large systematics!)
- **FLArE is an excellent option for a broad purpose neutrino detector.**



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

Neutrino rate:
20-50 events/ton/fb^{-1}

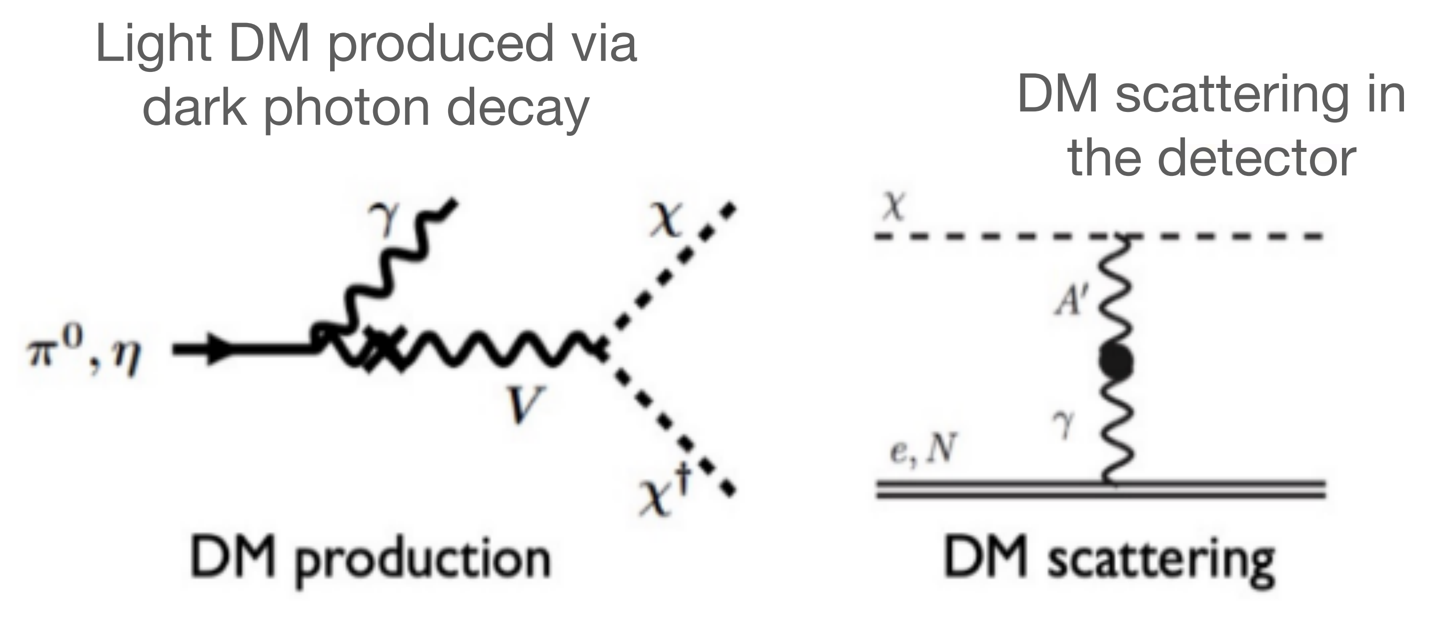
At HL-LHC, 1 fb^{-1} approximately per day!

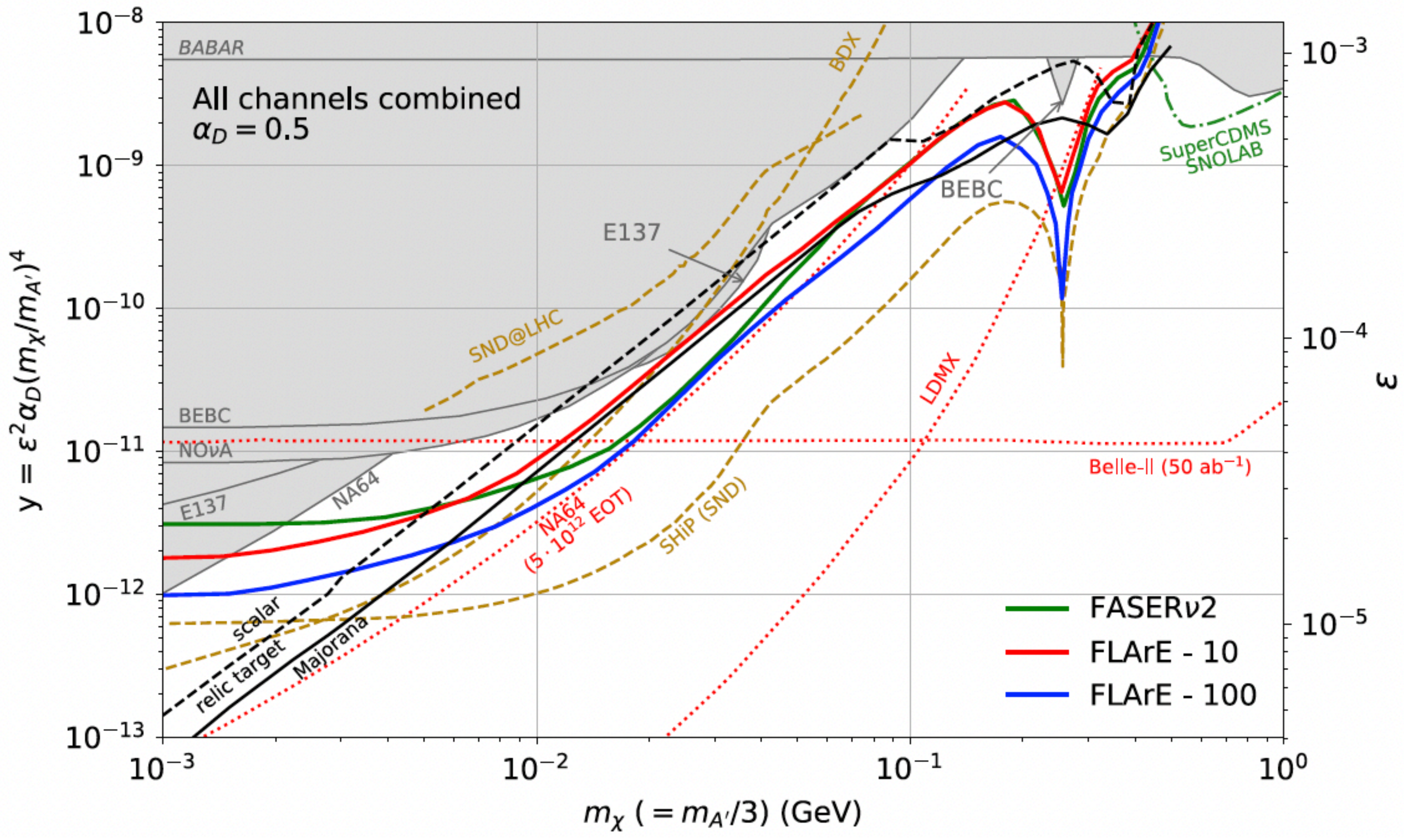


- Tau and high energy electron fluxes from charm production in the pp collision — handle on QCD models!

Physics: Dark Matter

- Direct DM detection from <u>nuclear</u> or <u>electron</u> scattering.
- Signal is at low energy (~1 GeV). **Need high kinematic resolution.** LAr TPCs can go as low as from ~10-20 MeV for thresholds.
- Dominant background is neutrino (elastic) scattering and muons coming from IP.
  - Requires veto of passing-through muons (scintillators) or volume fiducialization.
  - Mitigated by kinematic cuts (low momentum transfers)
- Target sensitivity indicated by relic density can be achieved with **10 tons of LAr**

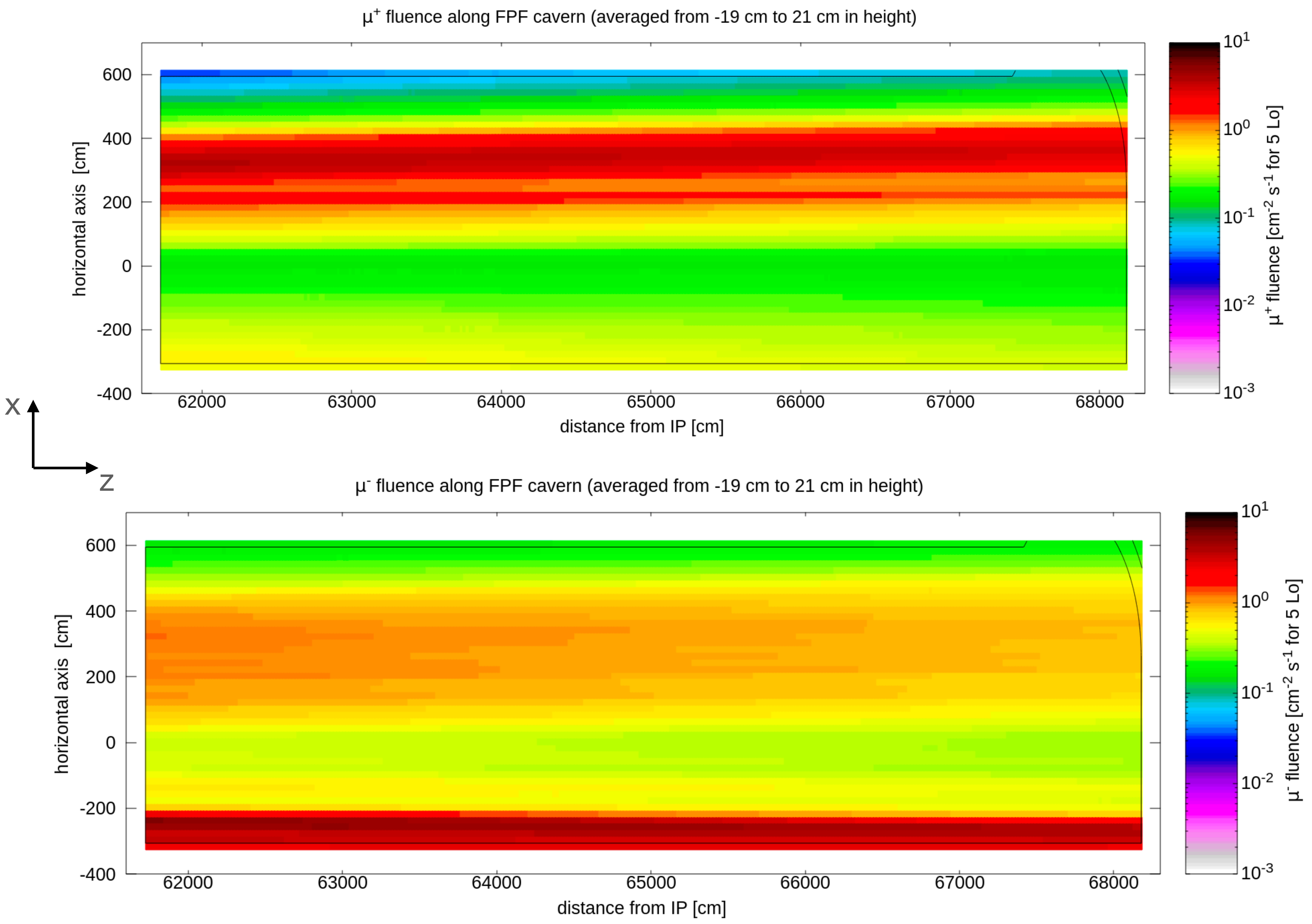




https://doi.org/10.1103/PhysRevD.104.035036
https://doi.org/10.1103/PhysRevD.103.075023

Background rates

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



x=0 is the ATLAS axis. Crossing angle in the horizontal plane is included.

- Fluence in x/z plane in FPF location from CERN FLUKA team (20 cm from LOS in vertical plane).
    - Clear hotspots at ~2m from LOS in horizontal.
- Possible issue for all detectors, looking into a sweeper magnet.
- **Muon flux**:
    - **0.6 Hz/cm^2** at 5*10^{34}/cm^2/sec (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.

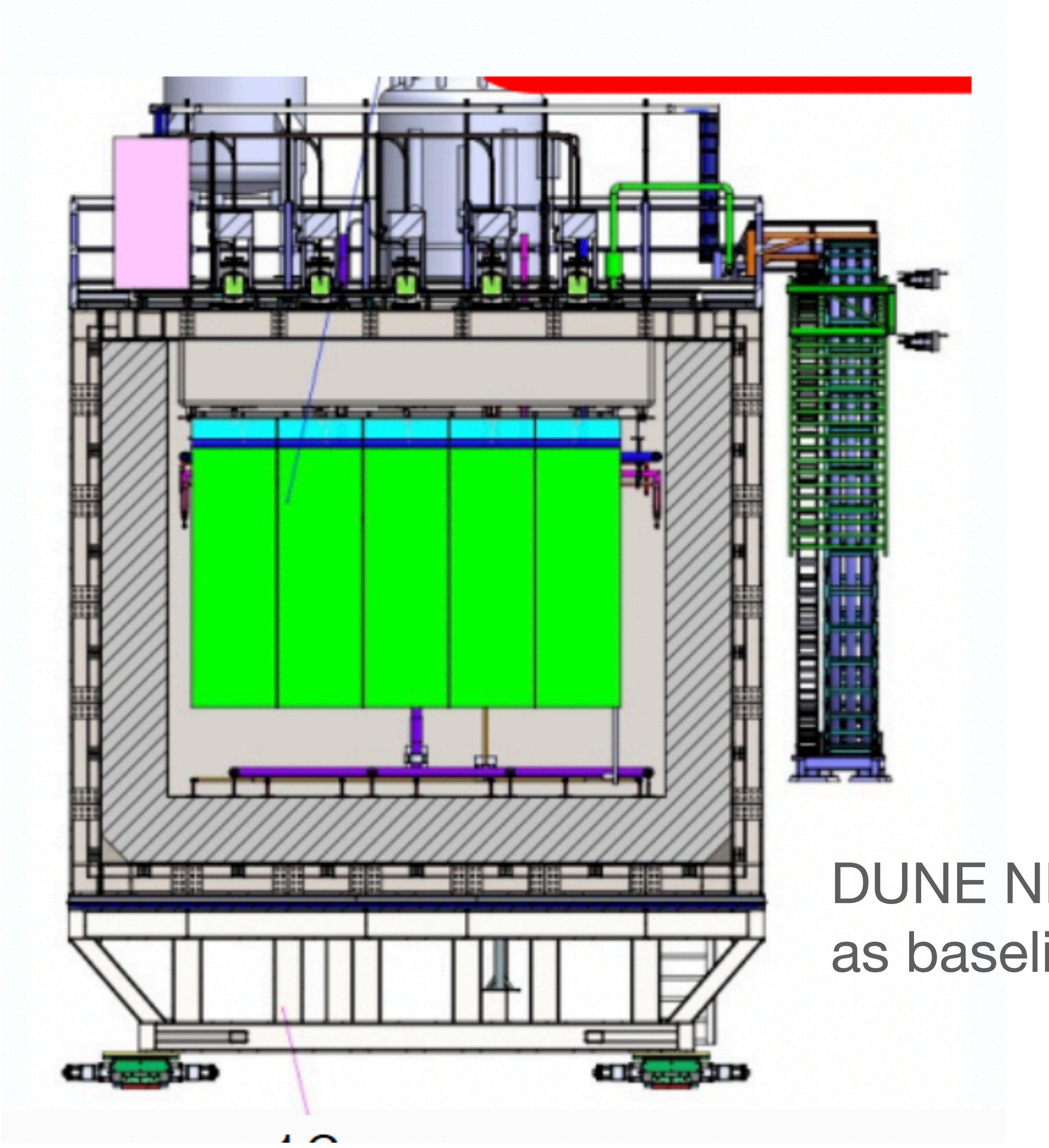
Technical requirements

- Dark matter detection:
  - Fiducial mass of 10 tons is needed for good statistics and sensitivity at ~600 m.
  - Low (~100 MeV) threshold for dark matter elastic scattering (need to catch isolated recoiling electrons).
- Neutrino physics:
  - Good event/energy containment (high density) and resolution (~10 interaction lengths, live detector).
  - Muon and electron ID, and a hadron/muon magnetized calorimeter.
  - Tau neutrino detection requires <1 mm scale spatial resolution. Only emulsion is guaranteed for this scale, but it cannot be triggered. The next best thing is a liquid argon TPC.
- **Key technical issues for FLArE**:
  - Muon background (space charge and pile up limitations) from the high luminosity running of LHC
  - Triggering on contained events/reject muons → Excellent photon sensors (SiPM) and DAQ
  - Spatial resolution → Pixel anodes.
  - Heat load on the cryogenic system → dominated by electronics.

Cryostat options

	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?

Yichen Li

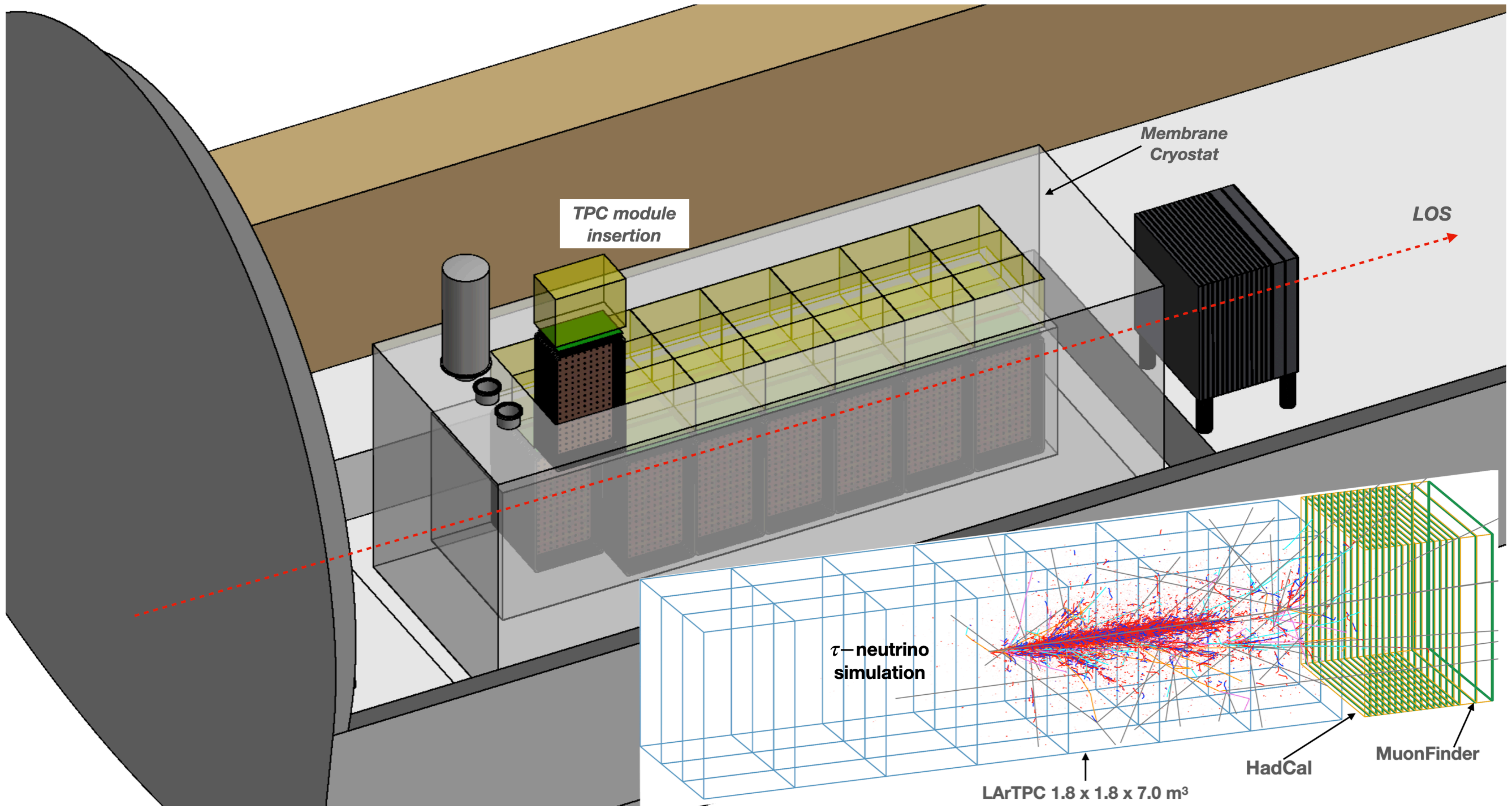


DUNE ND-LAr-*like* cryostat as baseline option

- 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, but DUNE ND-LAR design has installation from top, which simplify things.
- BNL **recently contracted an engineering firm** (Bartoszek Engineering) for conceptual design of FLArE cryostat and detector installation.

Modular TPC

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

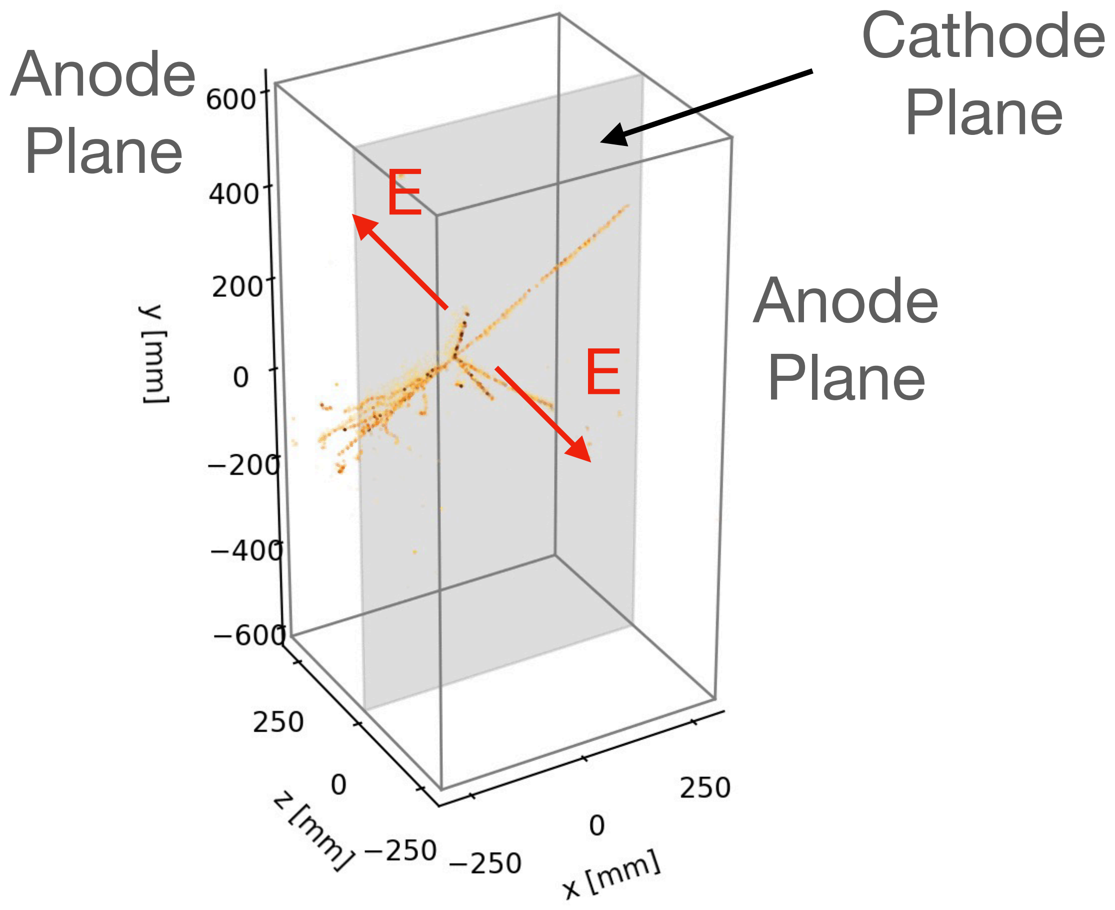


Inspired by the DUNE near detector concept

https://doi.org/10.3390/instruments5040031

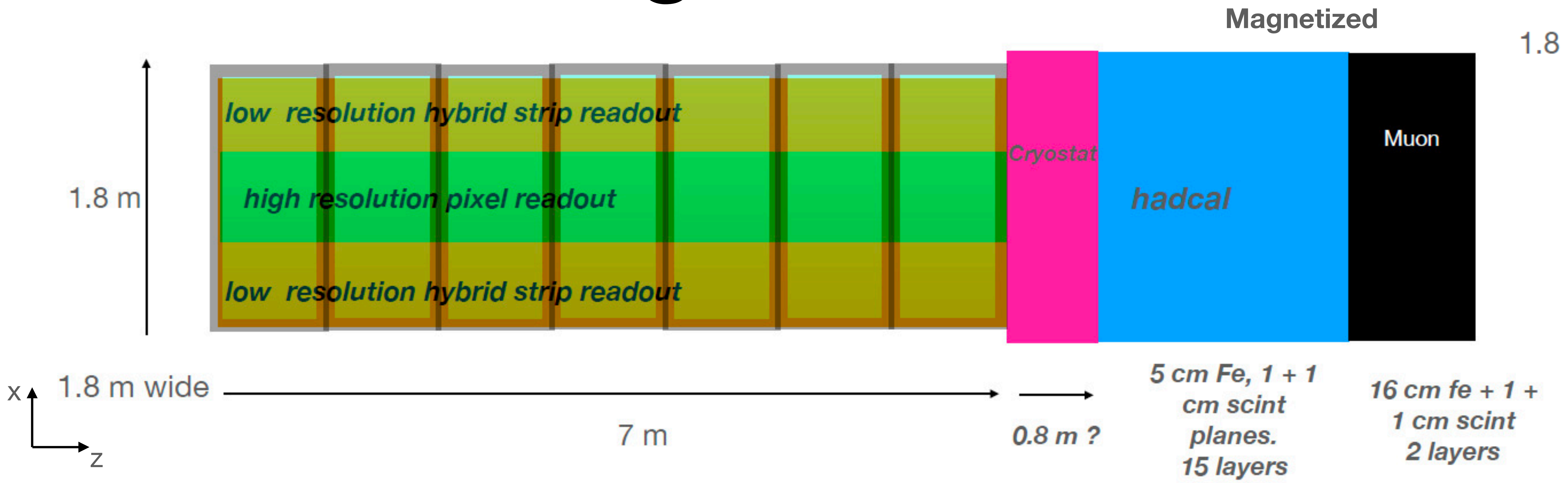
Lawrence Berkeley National Laboratory
University of Bern

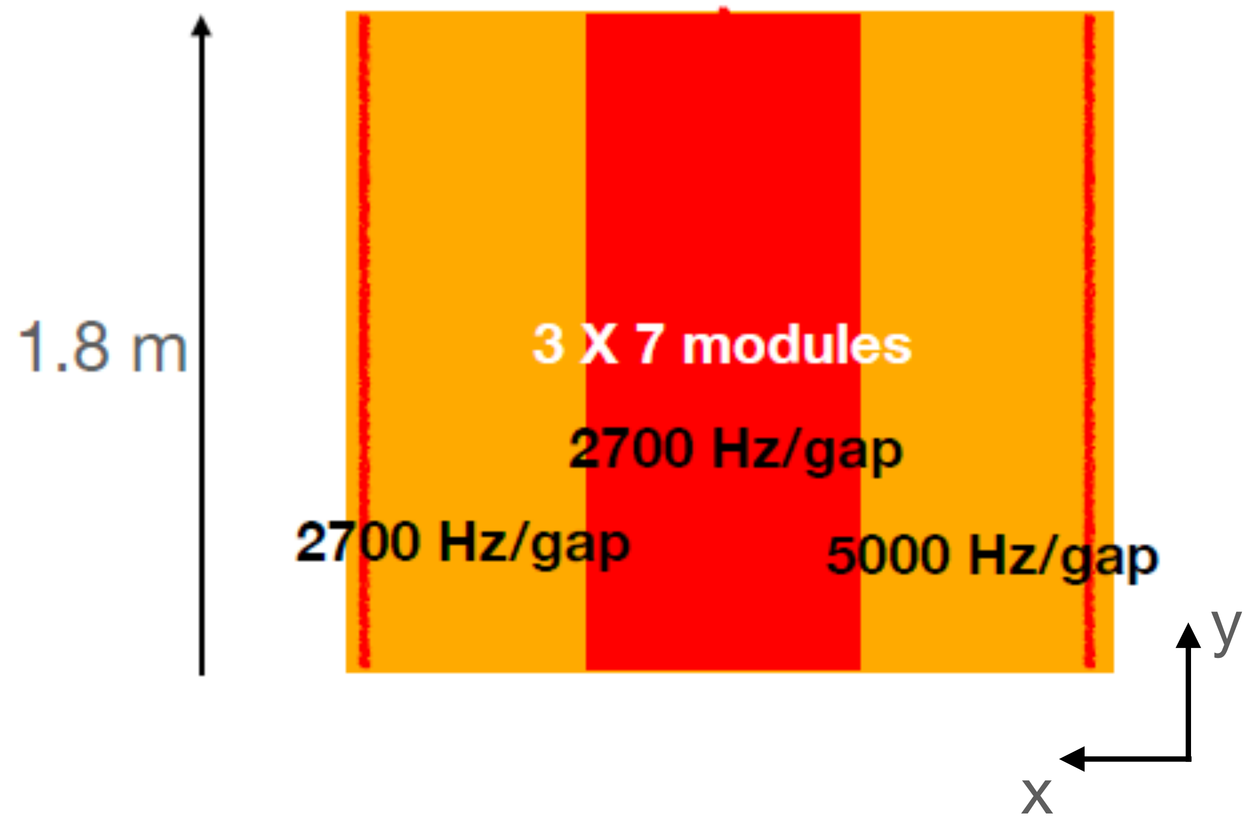
Each module is a "mini" TPC, with a cathode plane in the middle



- FLArE is a <u>modular</u> LAr TPC: segmentation for light collection (trigger) and reducing space charge intensity from muon rate with small drift gap (30cm).
- Taking full advantage of **recent R&Ds in LAr technologies**!

Detector design





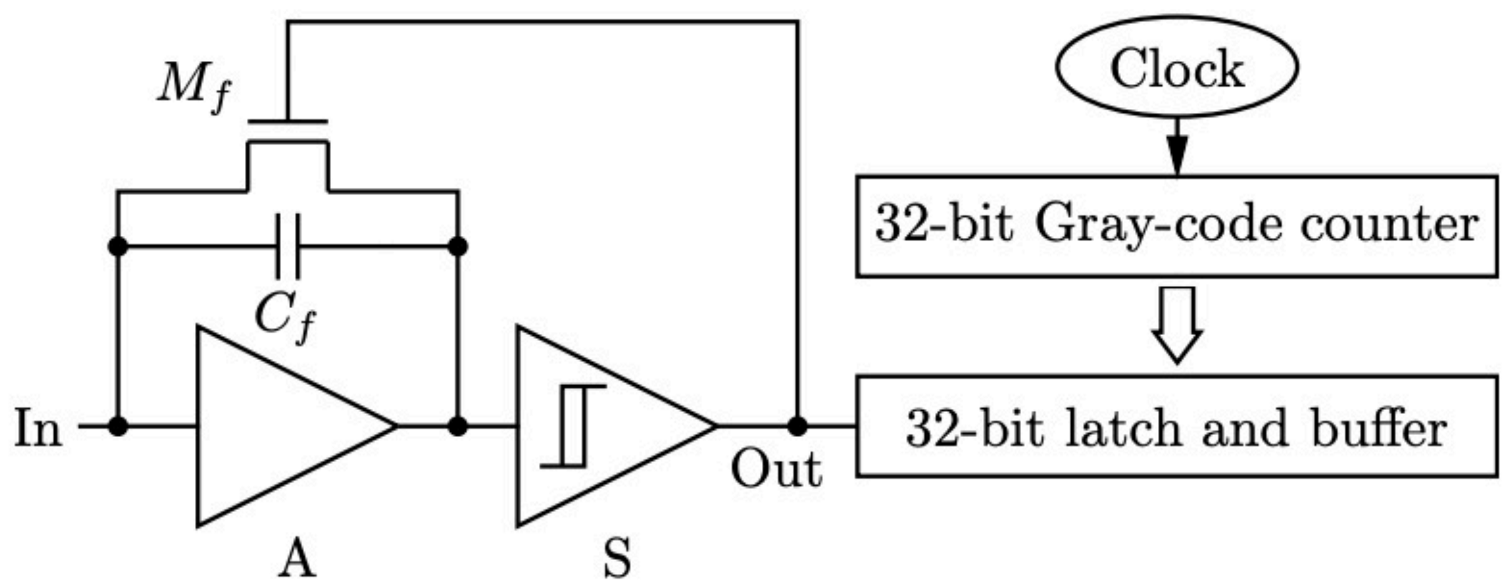
None of this has been optimized yet – all numbers are preliminary!

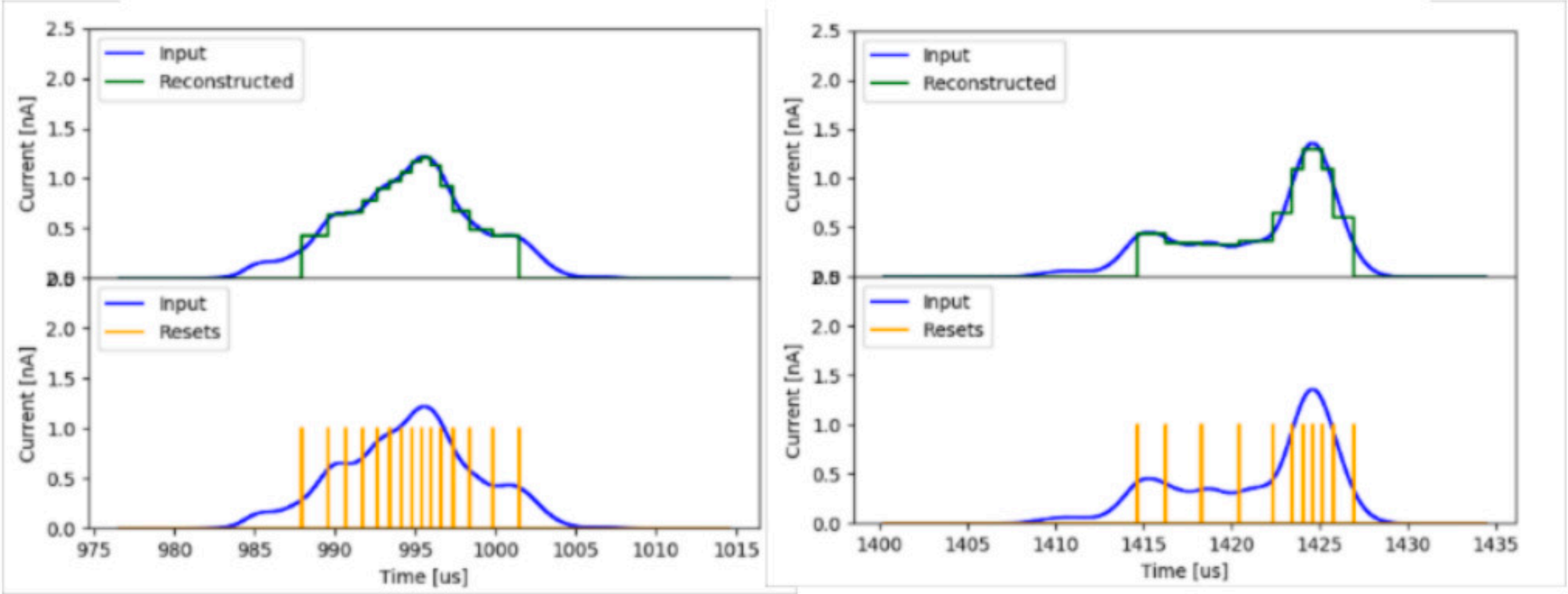
- Conceptual Design is **3 x 7 vertical TPC modules** with 0.3 m gap. Each module is then 0.6 m X 1.8 m X 1 m. Orientation of drift is completely open for discussion to get < 1 mm space point resolution.
- Simulations show **reasonable containment of neutrino events** in LAr and total energy measurement.
- Pixel-based anode → very high number of channels. Reduce channel count by using **strip-based or wire anodes in non-fiducial region**. Fiducial mass is 10 tons, total active mass is ~30 tons.
- Magnetized hadron/muon calorimeter downstream.

Charge readout

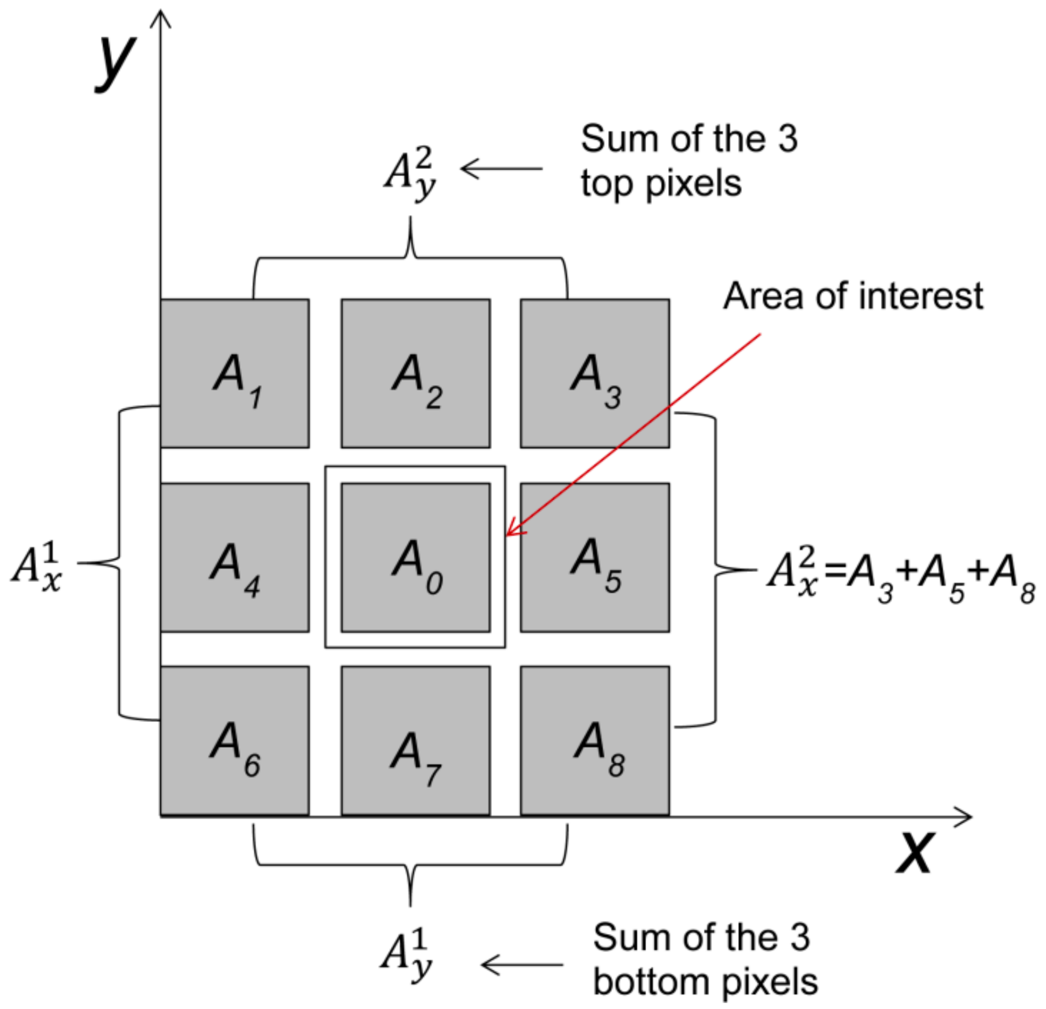
- Anode pixel readout is important to achieve <1 mm resolution.
- LArPix vs Q-Pix
- Pitch size strongly affects the number of readout channels and the heat load!

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

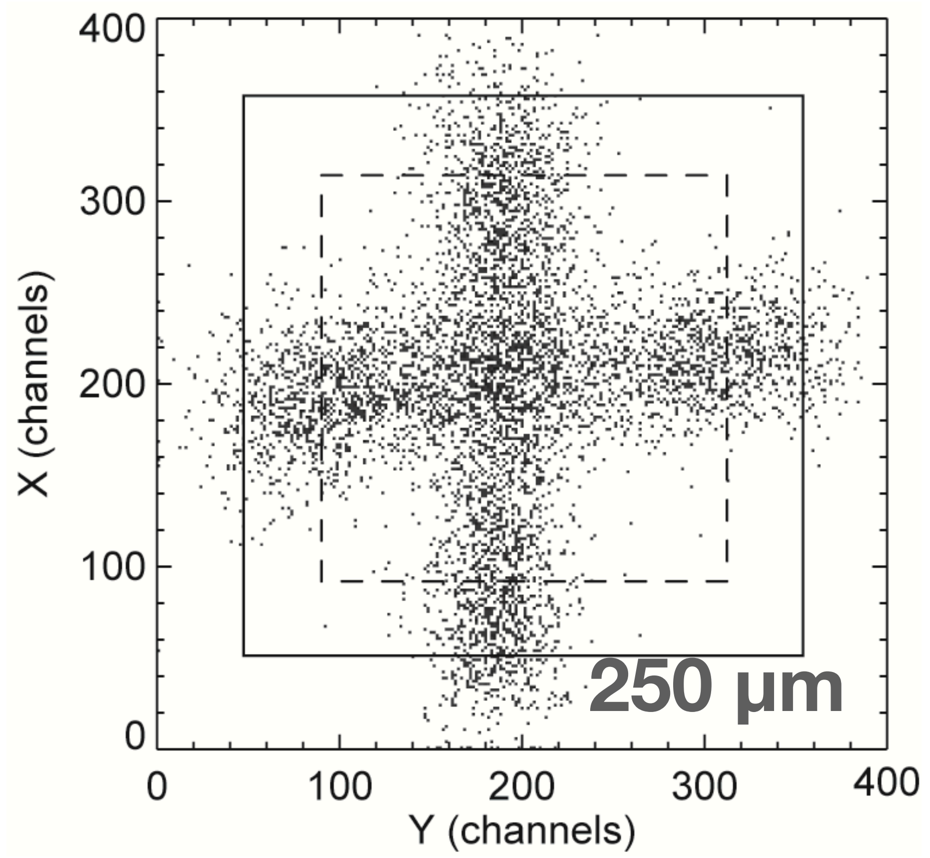




https://doi.org/10.1103/PhysRevD.106.032011



1.7 x 1.7 mm² pixel



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

- Idea: achieve resolutions smaller than pixel size by using signals induced in neighboring pixels.
- E.g: resolution down to 250 μm for a 1.7 x 1.7 mm² pixel

Nominal configuration

- Photodetectors needed for triggering – e.g. ARAPUCA (photon is trapped through wavelength shifting and dichroic short-pass filters; readout by one or more internal SiPMs).
- Timing could associate events with the ATLAS bunch crossing (studies are needed).
- Magnet concept for hadronic calorimeter & muon tagger under study.

	Value	Remarks
LAr detector fiducial mass	$>$10 tons	
Active dimensions	1.8 m $\times$ 1.8 m $\times$ 7 m	not including cryostat
Cryostat dimensions	3.5 m $\times$ 3.5 m $\times$ 9.6 m	membrane type
TPC modules/drift length	3 $\times$ 7 (gap: $\sim$30 cm)	short gap TPC
TPC height	1.8 m	
Spatial resolution	$<$1 mm	in drift and tranverse dimension
Charge readout	pixels	pixel/wire hybrid approach possible
Trigger and light readout	SiPMs/WLS-plates	needed for neutrino trigger and time
Background muon rate	$\sim 1/\text{cm}^2/\text{s}$	at luminosity $5 \times 10^{34}/\text{cm}^2/\text{s}$
Neutrino event rate	$\sim 50/\text{ton}/\text{fb}^{-1}$	for all flavors of neutrinos
Hadronic calorimeter (hadmu)	$\sim 6 - 10\lambda$	interactions lengths
Dimensions	1.8 m $\times$ 1.8 m $\times$ 1.05 m (depth)	Fe/scint sandwich
Muon tagger and momentum	1 Tesla magnetized Fe/scint	same as the hadmu

Summary

- FLArE is a modular liquid argon detector for neutrino and dark matter physics being considered for the Forward Physics Facility (FPF) at CERN.
- Preliminary examination of event rates and backgrounds suggests that a LAr detector is feasible and ground-breaking.
- It offers particle ID and reconstruction of track angle and kinetic energy over a large dynamic range, from ~ 10 MeV to many hundreds of GeV, complementary to detectors tuned for specific searches.
  - Interest toward a uniform measure of sensitivity for all proposed experiments in the FPF (ensuring recasting & reinterpretations) but discussions not yet developed.
- Design choices will require further R&D: TPC charge readout electronics must be optimized for high spatial resolution and the trigger design will require detailed simulations and software development.
- Goal is drafting a conceptual design document in 2024.

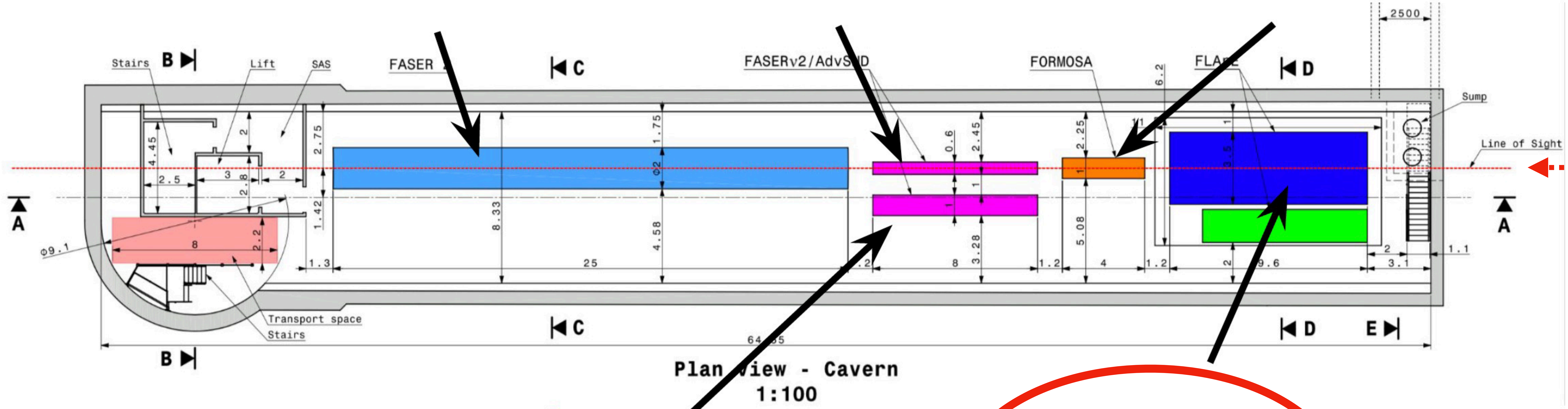
Backup

FLArE @ Forward Physics Facility

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches



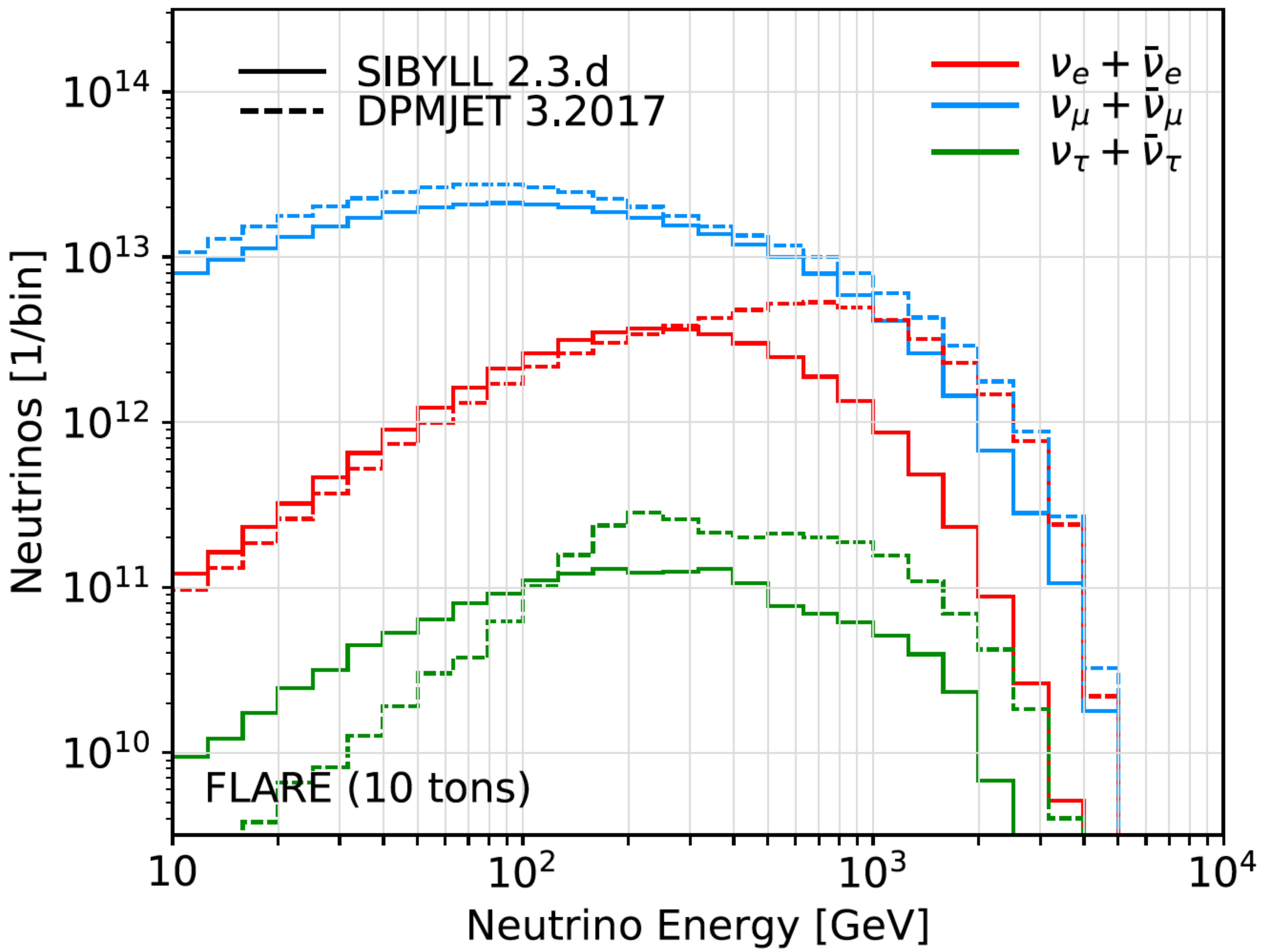
~600m from ATLAS IP

AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

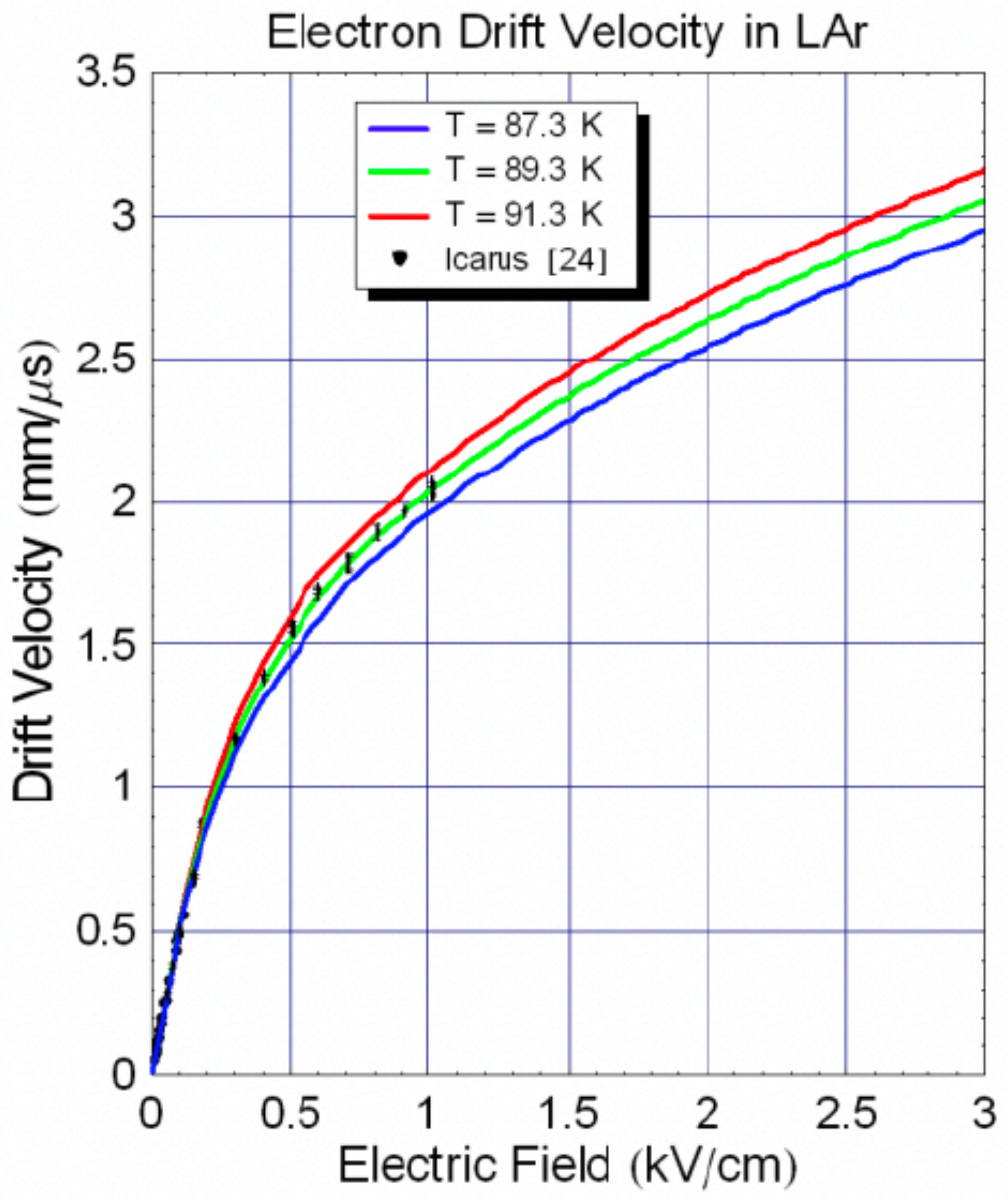
FPF covers η > 5.5,
experiments on
LOS cover η ≳ 7

Physics: Neutrino fluxes



Diffusion

Electron transverse diffusion coefficient: . D_t = 13 cm^2 /s
Electron longitude diffusion coefficient: D_l = 5 cm^2 /s



t = 500 [mm] / 2.0 [mm/us] = 250 us
T = 250 [mm] / 2.5 [mm/us] = 100 us
1D case $\sigma_l = \sqrt{2D_l t}$ = 0.5 [mm]
2D case $\sigma_t = \sqrt{4D_t t}$ = 1.1 [mm]

	500 mm at 1 KV/cm, 250 us	250 mm at 2 KV/cm, 100 us
σ_l (FWHM)	0.5 (1.2) mm	0.3 (0.7) mm
σ_t (FFHM)	1.1 (2.6) mm	0.7 (1.7) mm

There should be no fundamental limit to getting < 1 mm resolution

Tentative timeline

- Begin CE works, installation of services in LS3, followed by installation and commissioning of experiments in early Run 4. Physics begins in Run 4 and continues to the end of the HL-LHC era (~2031-42).