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Progress towards a far forward liquid argon neutrino detector at the high luminosity LHC

**Milind V. Diwan (Brookhaven National Laboratory)
for the FLARE technical design group.
(I have a lot of help)**

Physics Beyond Colliders Annual Workshop, CERN, Nov 7-8, 2022.



Gauri Bhanja, Jabha, and Nandalal

Outline

The Physics and initial detector requirements

FPF and FLARE has both SM (neutrinos and QCD) and BSM (light dark matter and rare searches) science programs.

Partial list of physics topics and required detector capability will be provided.

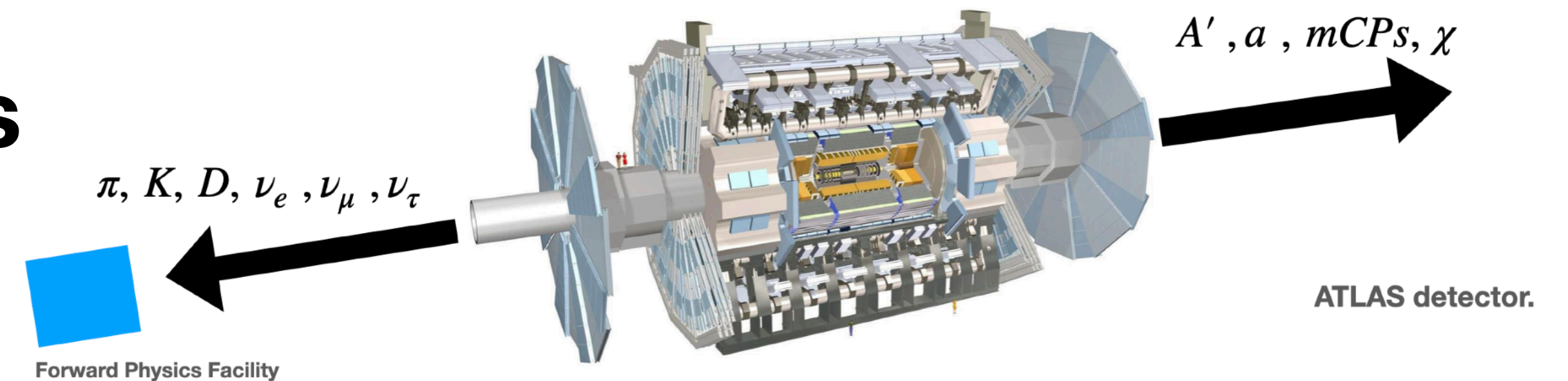
Key experimental considerations

Containment, hadron, muon detection

Beam related backgrounds

Spatial and time resolution.

Liquid argon detector for FPF very preliminary design.

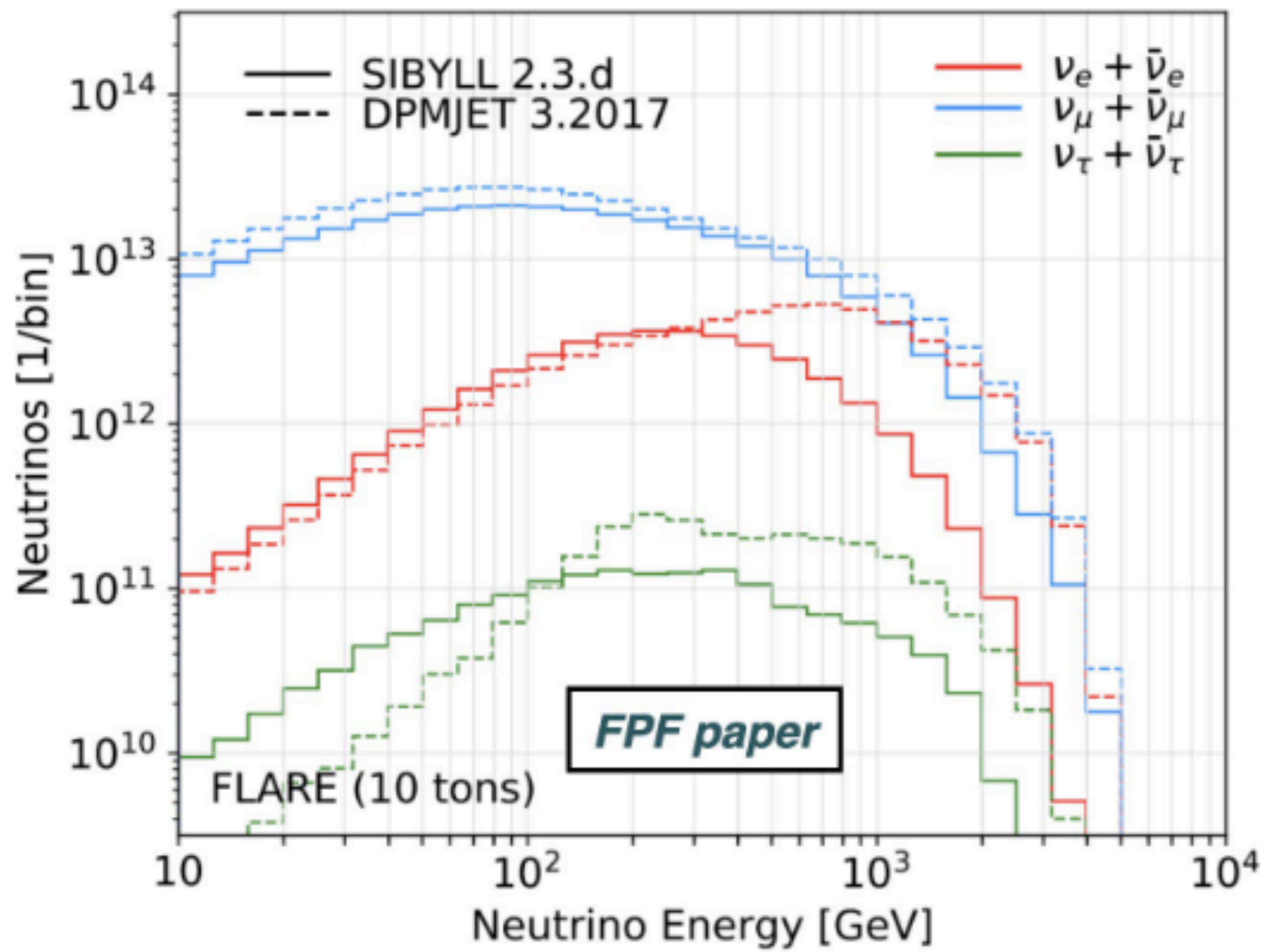


Thoughts and process for project organization. (extremely preliminary)

Neutrino event rates @600 meters (with large uncertainties)

Muon and electron neutrino spectra require detailed simulation of the beam line. The tau flux requires deeper understanding of charm production in the pp collision.

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



During HL-LHC fb⁻¹ is approximately per day.

Mean energy of interactions is ~500 GeV

Flux and cross section errors.

How do we deal with unknown flux and cross sections ?

- *The cross section and flux determination will be in a joint theoretical and experimental program. Evolving step by step like any other program.*
 - Detailed simulations of the neutrino beam including HL-LHC geometry are needed for muon and electron components.
 - Well known cross sections (inverse muon decay and elastic scattering) can be used to extract flux.
 - The ratio of high energy electron and tau neutrinos can be well constrained.
 - Theoretical advances are needed in nextⁿ to leading order calculations.
- External data will be needed on charm production
- *FPF and EIC (at BNL) would be running at the same time and informing each other.*

Rare searches considerations

Focus on a small set for detector design

- Neutrino-electron elastic scattering requires excellent angular and energy resolution.
- Dark matter electron scattering is also forward and needs to be distinguished from neutrino-electron scattering using energy and angular resolution. Other backgrounds are also possible and need kinematic cuts.
- Trident detection and measurement:
 - These are very rare events
 - Need excellent lepton ID and kinematic measurements
 - Muon momentum measurement needed for the low energy muon.

Preliminary high level physics requirements for FPF detectors

Physics topic	Events/ 3000/fb-1/10 ton	Fiducial Event containment	Electron ID	Muon ID	Tau ID	Hadronic shower	Muon momentum	visible Energy threshold	Energy resolution	Lepton kinematics	vertex kinematics patial resolution
Muon neutrino cross section	1E+06	Partial		Yes		Yes	may be	10 GeV	30%	yes	
Electron Neutrino Cross section	1E+05	yes	Yes			Yes		10 GeV	30%	yes	
Tau neutrino cross section	5E+03	yes	yes	yes	yes	yes	yes	10 GeV	30%	yes	yes
Charm and QCD measurements	rates >100 GeV	yes	yes	yes	yes	yes	yes	100 GeV	30%	yes	yes
Sterile Neutrino oscillations tau neutrinos	5E+03	yes	yes	yes	yes	yes	yes	10 GeV	10-20%	yes	
Neutrino electron elastic scattering	200	yes	yes					1 GeV	10%	yes	yes
Inverse muon decay	1000			yes			may be	11 GeV	20%	yes	yes
Neutrino tridents	>25 (on Ar)		yes	yes	may be		Yes	100 GeV	30%	yes	yes
Light Dark matter scattering on electrons	BSM physics	yes	yes					< 1 GeV	10%	yes	yes
Light dark matter scattering nucleons	BSM physics	yes				yes		< 1 GeV	10%		
Tagged neutrinos with ATLAS for charm/QCD studies	rates > 100 GeV	may be	yes	yes	yes	yes	yes	>100 GeV	Requires timing and DAQ coordination		

*A single detector may not be able to fulfill all these requirements.
Additional technical requirements are due to the muon radiation flux and ability to trigger.
Consideration of combined physics capability of all detectors is valuable.*

Basic requirements for far forward Liquid argon TPC

- Detector needs to be at 0 degrees to the collision axis.
- Some off-axis data might be very useful for neutrinos from high mass particles.
- Fiducial mass of 10 tons at few hundred meters is needed for good statistics and sensitivity to dark matter.
- Detectors need to have good energy containment (high density) and resolution (~ 10 interaction lengths, live detector) for neutrino physics.
- Detector needs muon and electron ID.
- Detectors need low (~ 100 MeV) threshold for dark matter elastic scattering
- Detectors need <1 mm scale spatial resolution if we want to detect tau neutrinos with low backgrounds.
 - Only emulsion is guaranteed for this scale, but it cannot be triggered.
 - The only other detector with this possibility is a liquid argon time projection chamber.

Key technical issues for noble liquid detectors are:

- **LHC muon radiation (space charge and pile up limitations => go to short gap 30-50 cm**
- **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.**

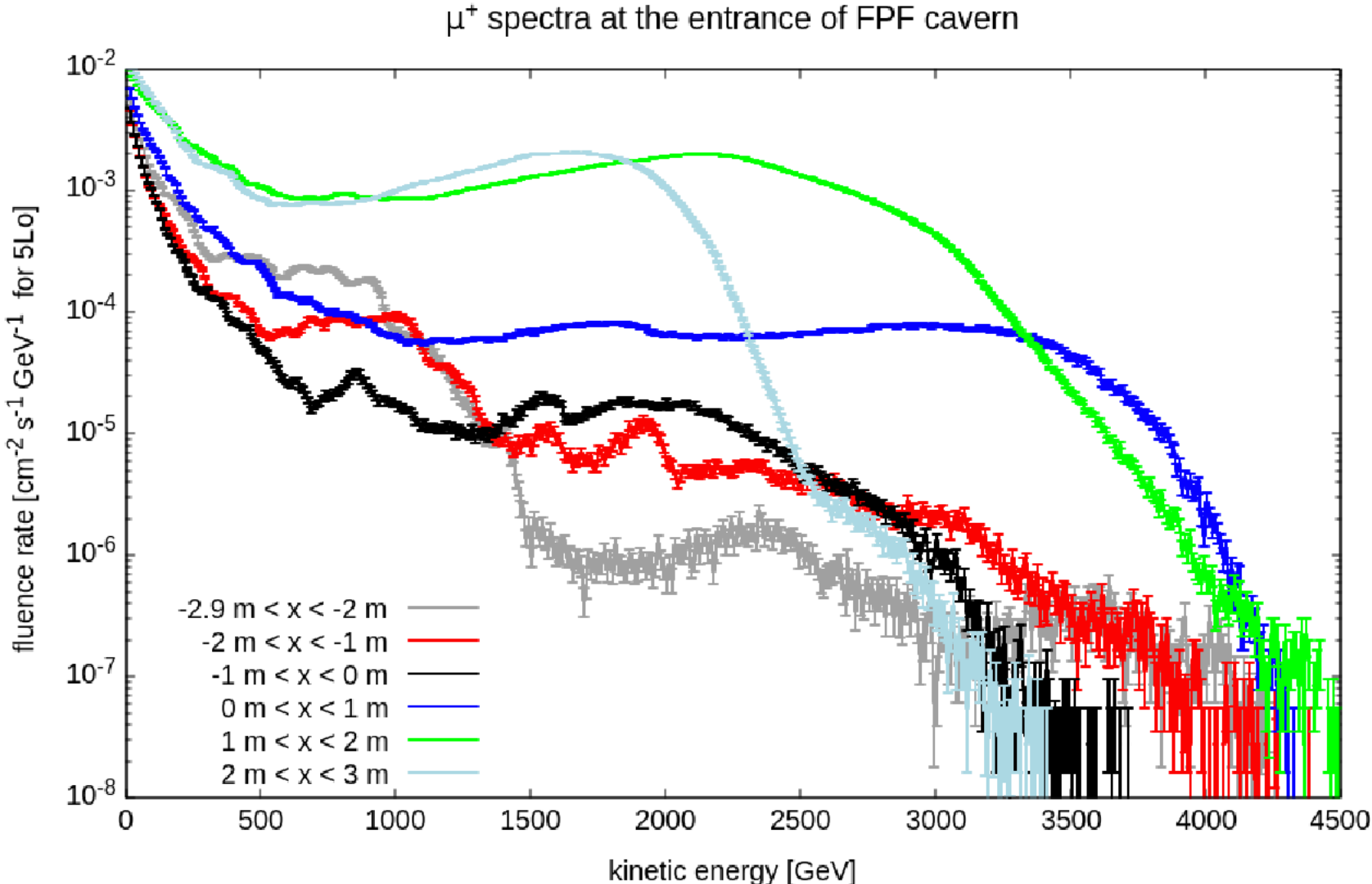
Muons

Looking in slices 0.5m wide, 1m high, covering region +/-2m away from the LOS in horizontal plane
Muon flux from FLUKA simulation in Hz/cm²

Slice	-2 - -1.5m	-1.5 - -1m	-1 - -0.5m	-0.5 – 0m	0 – 0.5m	0.5 – 1m	1 – 1.5m	1.5 – 2m
Mu+ flux	0.29	0.23	0.17	0.15	0.21	0.41	0.71	1.24
Mu- flux	0.44	0.34	0.28	0.29	0.40	0.62	0.78	0.84
Total flux	0.72	0.57	0.45	0.44	0.61	1.03	1.49	2.08

Over 1m x 1m square the rate is ~0.5Hz/cm²

2

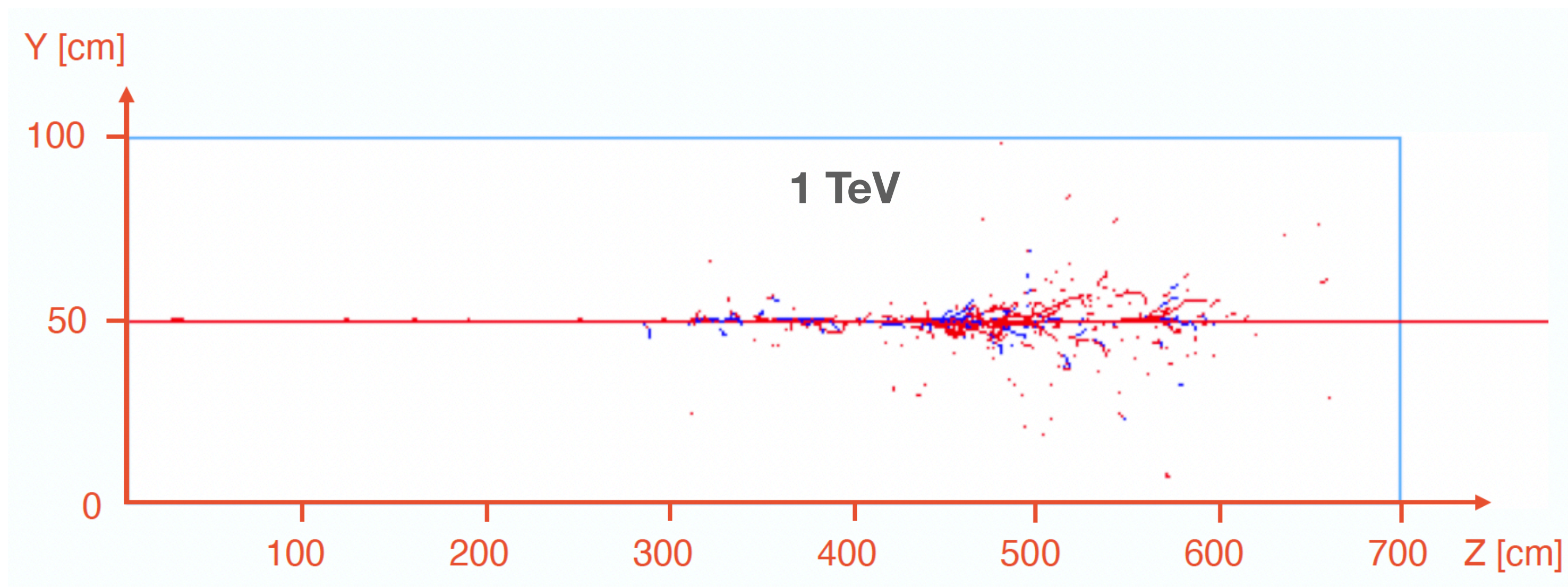
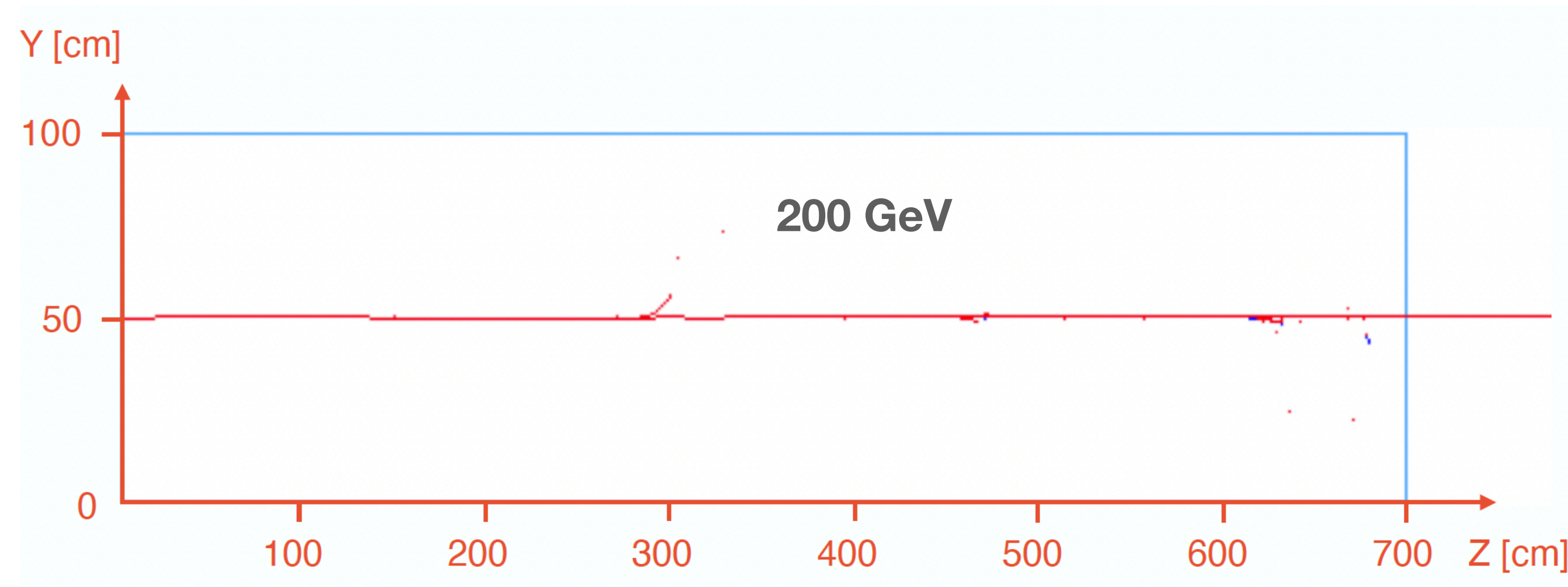


These rates allow comfortable margin for backgrounds
of factor of ~2

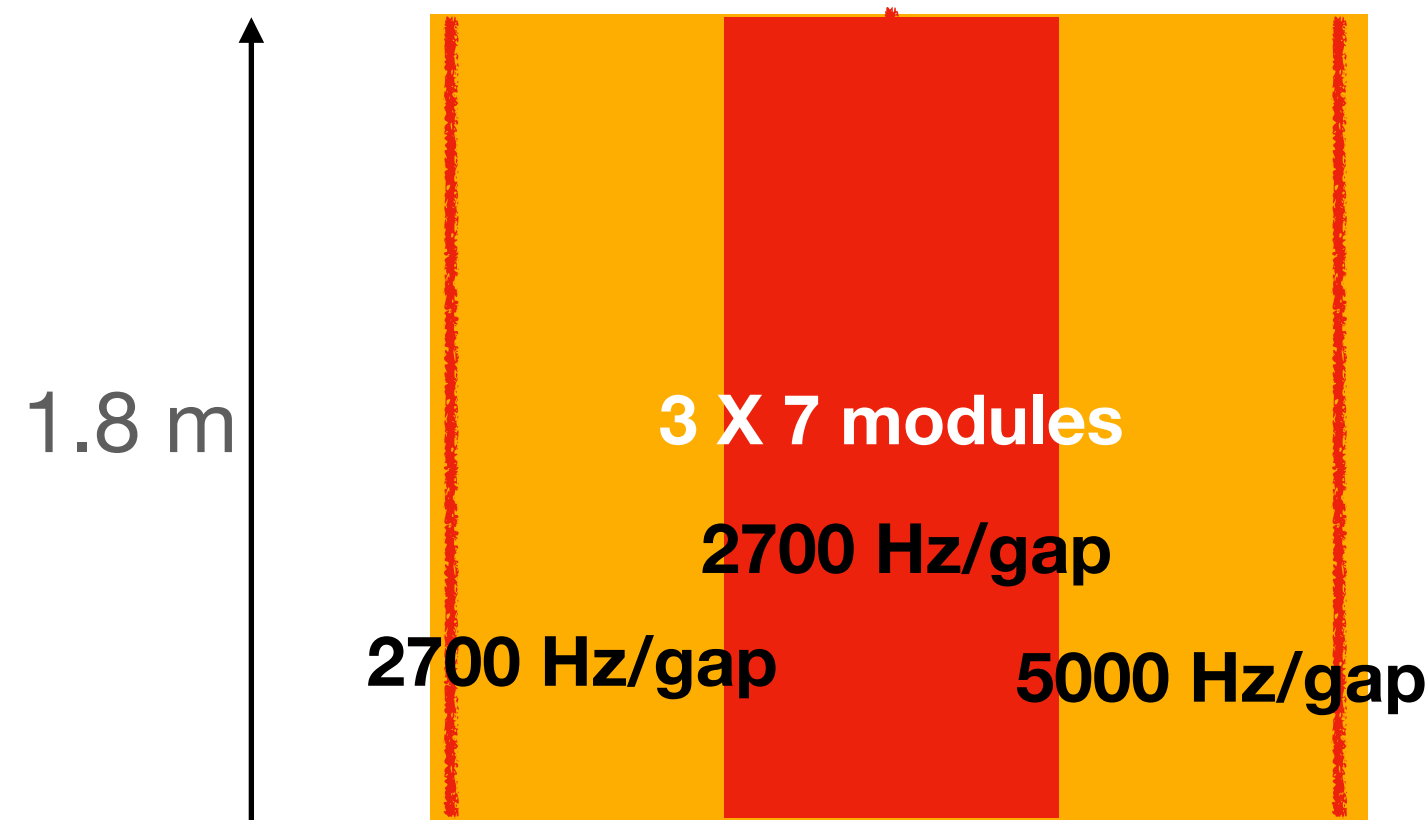
From J. Boyd talk

Muon spectrum ranges from ~10 GeV to multi-TeV

Muon simulation in liquid argon.



- *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.*

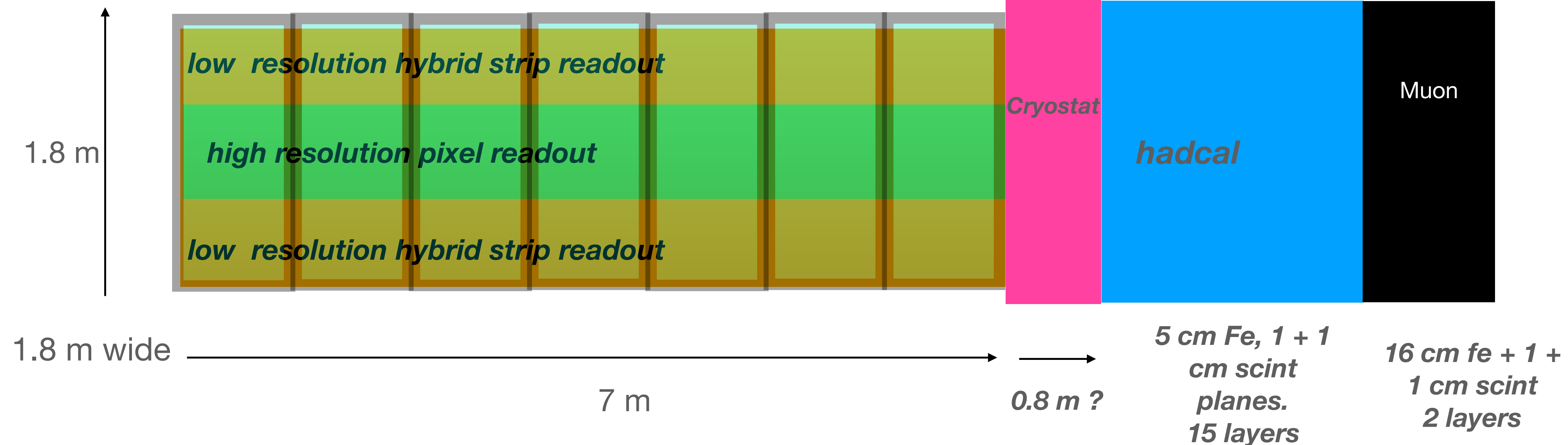


Simulations have confirmed that these dimensions allow reasonable containment of neutrino events in LAr and total energy measurement. They also fit within the cryostat allowed transverse space.

Gap is 30 cm => ~0.5 msec of drift => ~ 1.3 muons/drift

HV is ~500V/cm => ~15kV (very tolerable)

Space charge ~ 0.003 pC/cm³/sec is manageable for 0.3 m drift with 500V/cm (i.e. ICARUS: 10⁻⁴ pC/cm³/sec with 1.5 m drift)



Carry two options into Conceptual Design

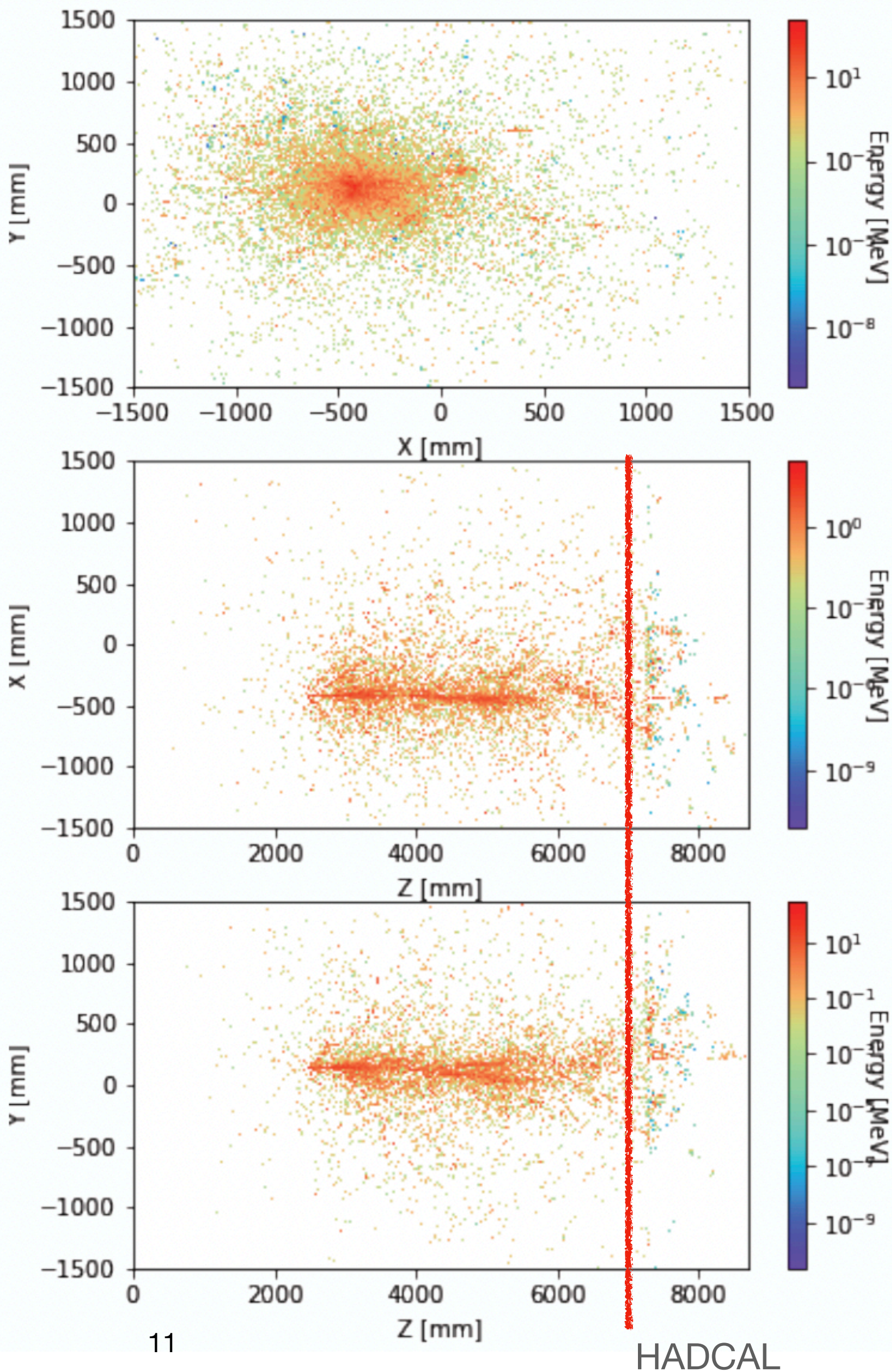
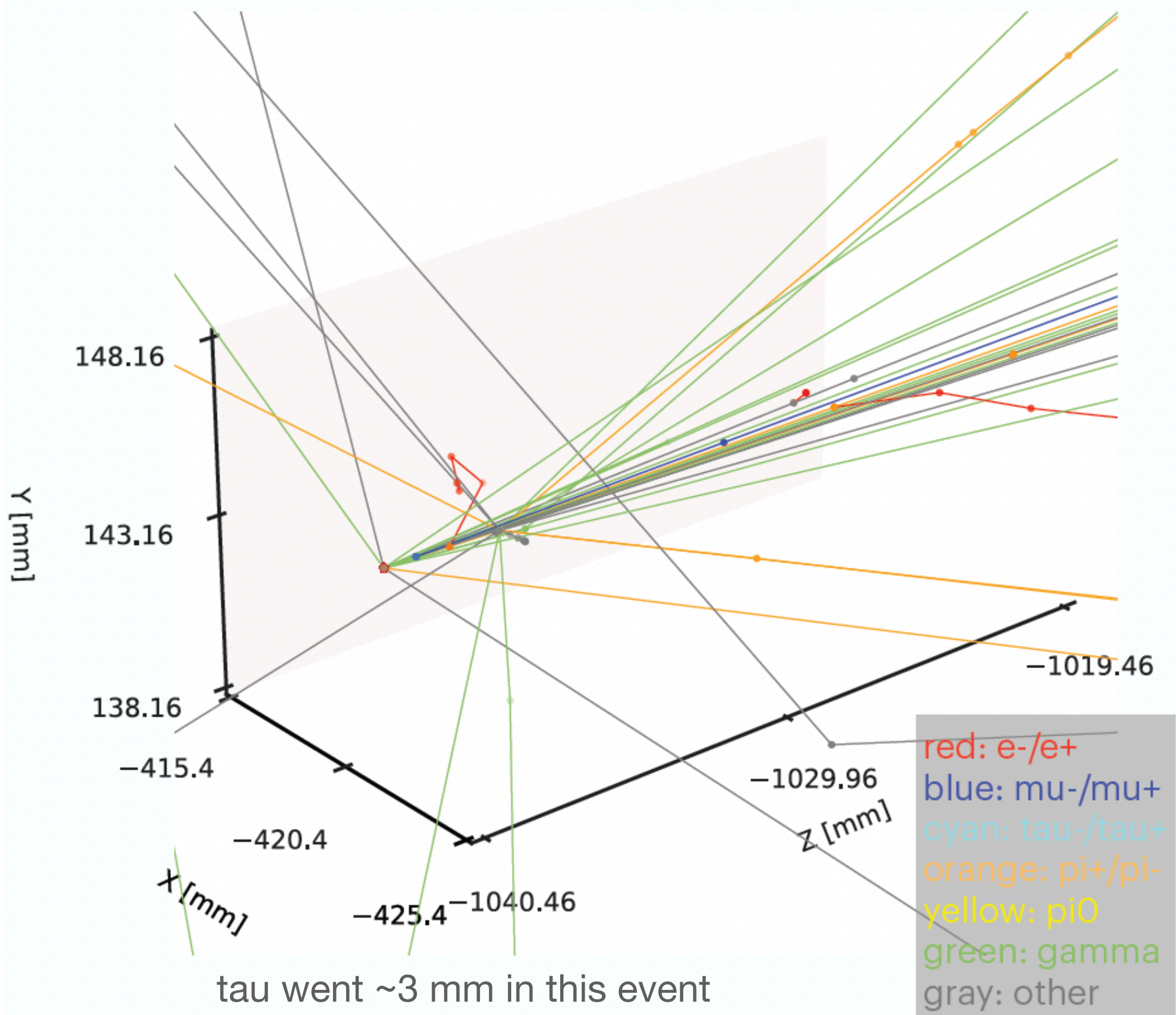
*either 2 X 7 vertical modules with 0.45 m gap
or 3 x 7 vertical modules or with 0.3 m gap*

None of this is optimized

Tau Neutrino event simulation in a LAR TPC. Kinematic separation combined with high vertex resolution seems to be very promising. But a lot of work is needed.

ν_τ CC ($E_\nu = 230.7$ GeV)

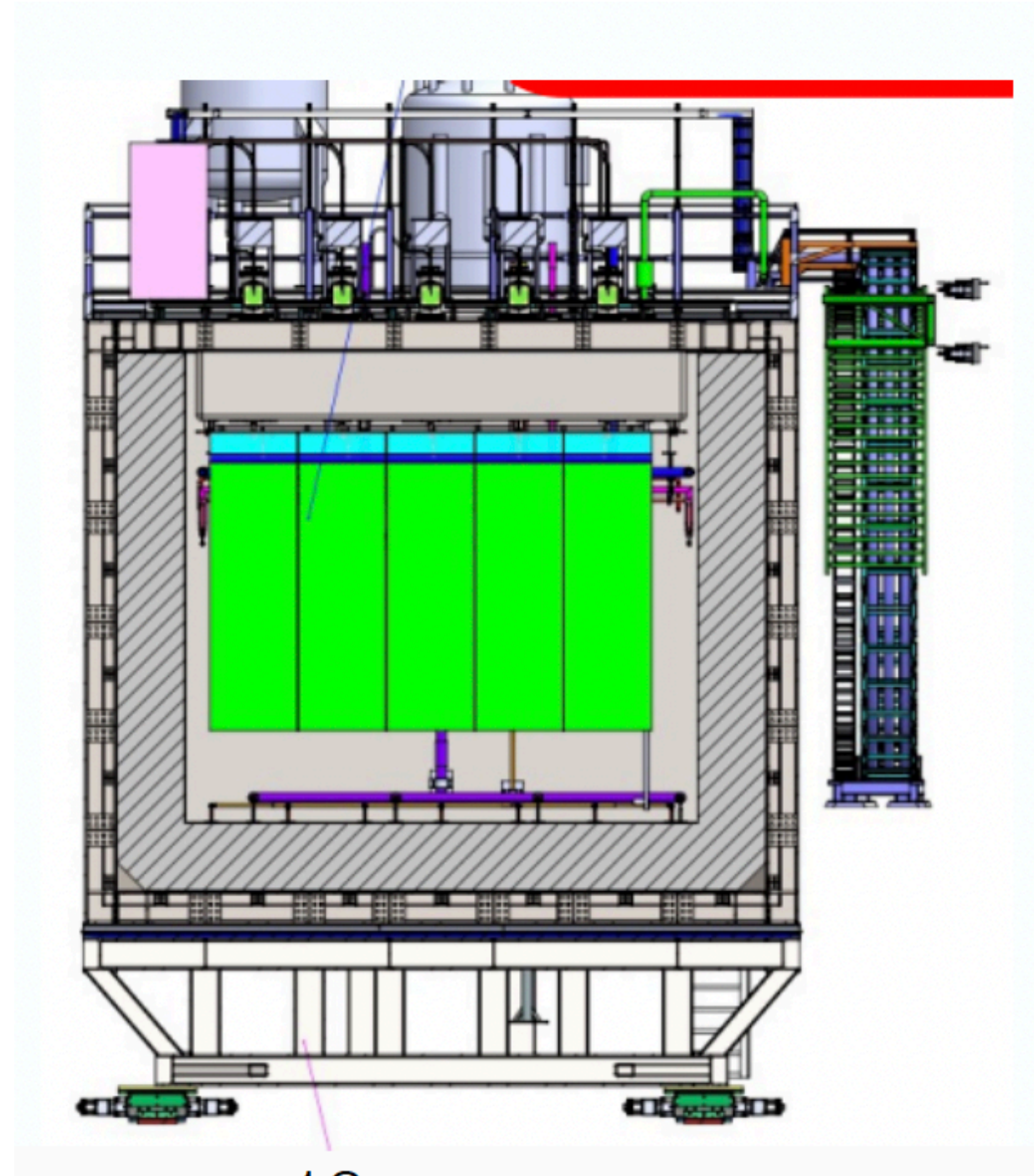
$\tau^-(102.9 \text{ GeV}) \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-(74.7 \text{ GeV})$



1. 1.8 X 1.8 to contain transverse events in fiducial of 1m x 1m x 7m.
2. Hadronic calorimeter to contain showers that start downstream.
3. Even a modest energy resolution is sufficient.
4. Excellent muon identification results in quick selection of nutau events.
5. We expect to combine spatial resolution in drift dimension with kinematics to get good S/N.

Cryostat options

Very important for space considerations.



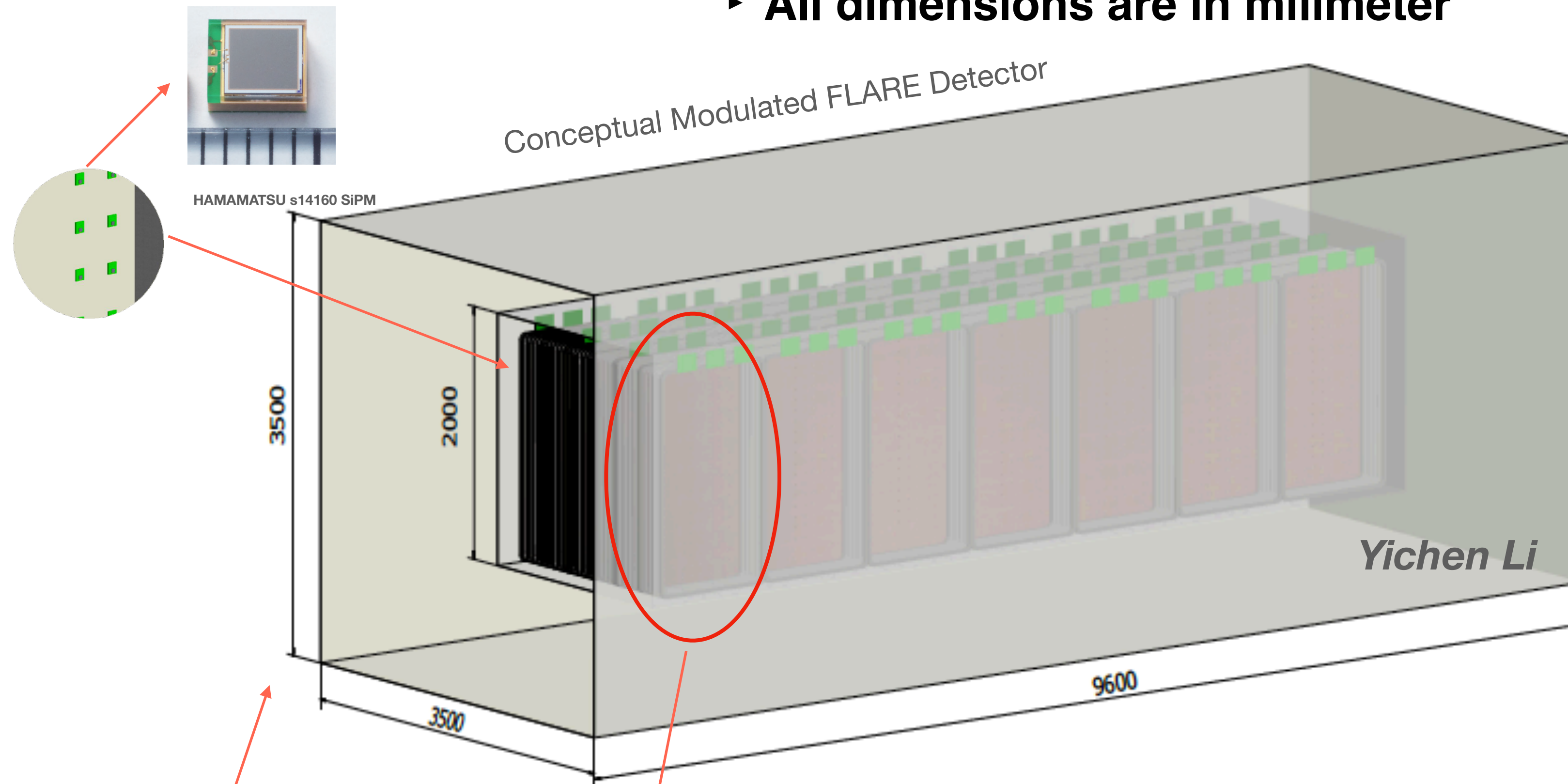
	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
CAPTAIN	2.58m dia x 2.9m	MLI	44mm(bottom) 71mm(side)	<1kg/m ³ (MLI only)	~1.5 W/m²	No
MicroBooNE	3.8m dia x 12m	Polyurethane Foam	400mm	32 kg/m ³	~13 W/m²	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Perforated Al honeycomb(In) Nomex honeycomb(Out)	665 mm+ (combined)	25-35 kg/m ³	7-22 W/m²	Yes
ICARUS-SBN	3.9m x 3.6m x 19.6m	Al extrusion(In) GTT foam no membrane(Out)	665 mm+ (combined)	25-35 kg/m ³	10-15 W/m²	Yes
ProtoDUNE	7.9m x 8.55m x 8.55m	GTT membrane	800mm	90 kg/m ³	~8 W/m²	No
ND-LAr	3m x 5m x 7m	GTT membrane	800mm	90 kg/m ³	~8 W/m²	No
FLArE	~(1.8m x 1.8m x 7m)	GTT Membrane	800mm	90 kg/m³	~8W/m²	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 needed for corrugations.*
 - *We will benefit from the huge experience for GTT cryostat in the CERN neutrino platform.*
- *The DUNE ND-LAR design has installation from top for simplification.*
- *We intend to benefit from the development for ND-LAR.*

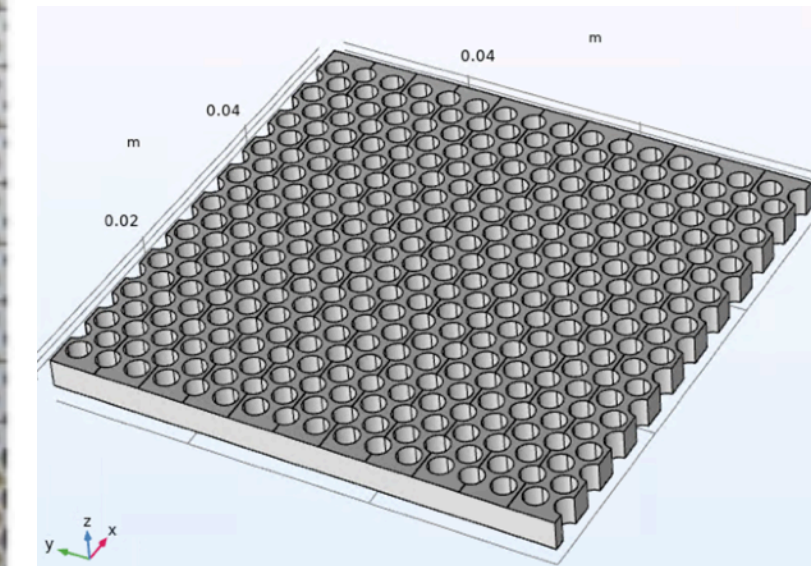
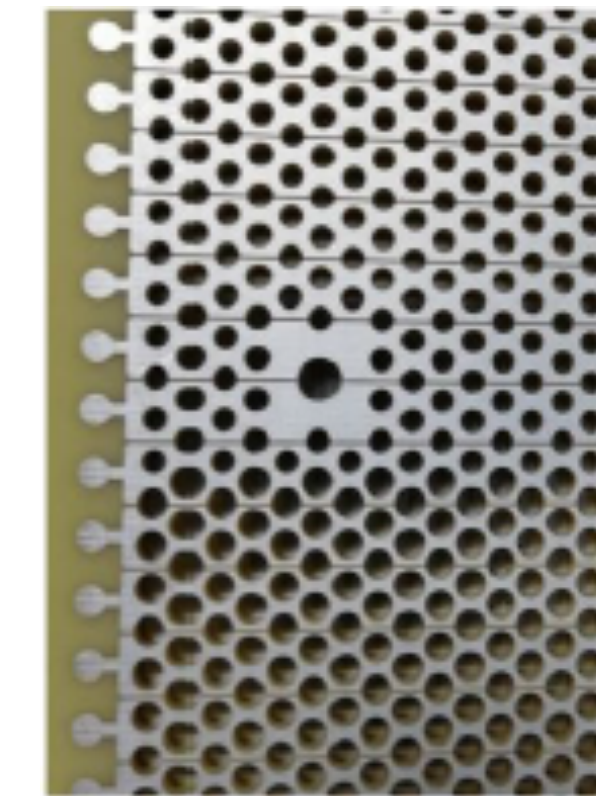
Yichen Li

► All dimensions are in millimeter

Conceptual Modulated FLARE Detector

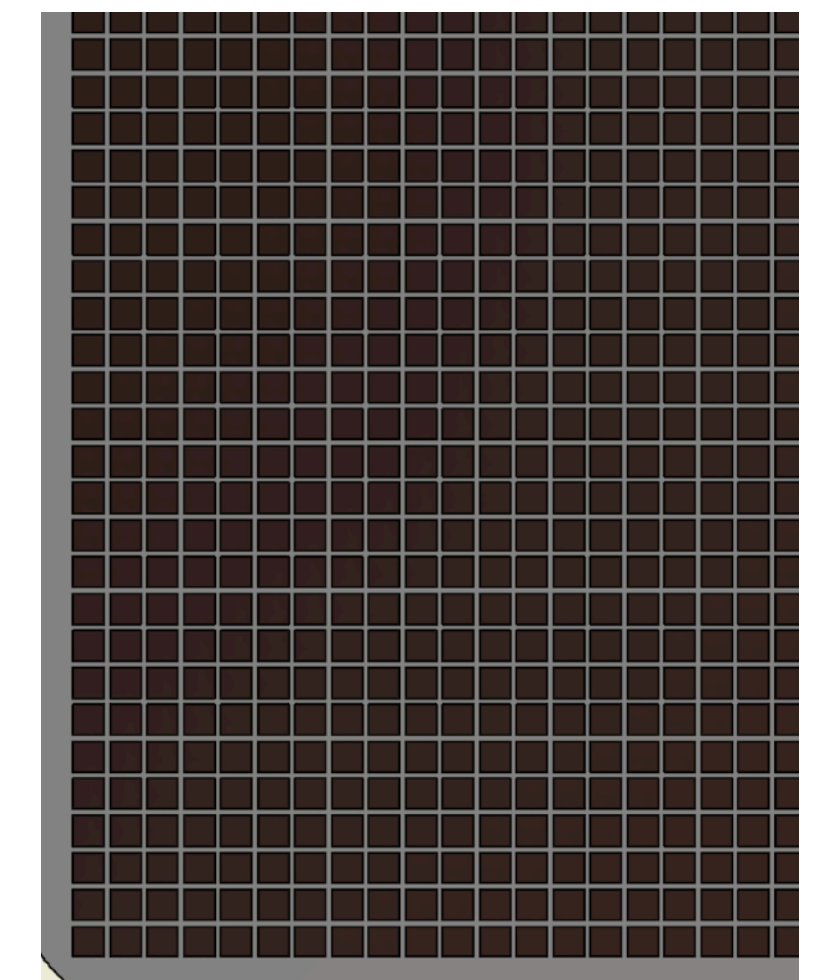


Anode Readout
Option 1: Perforated PCB with strips

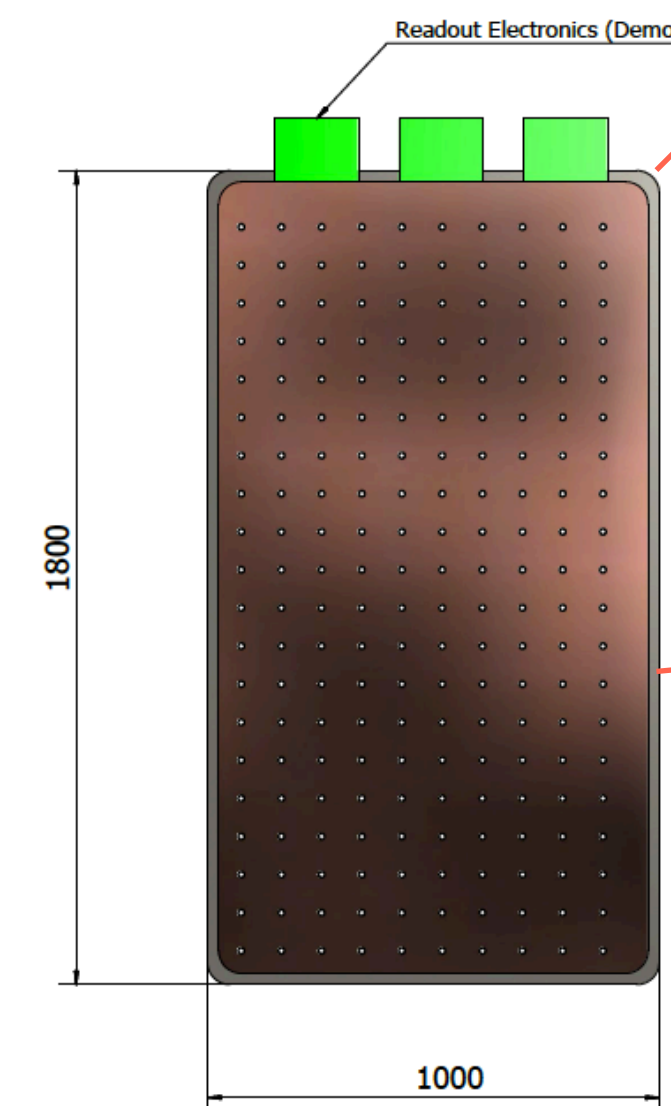
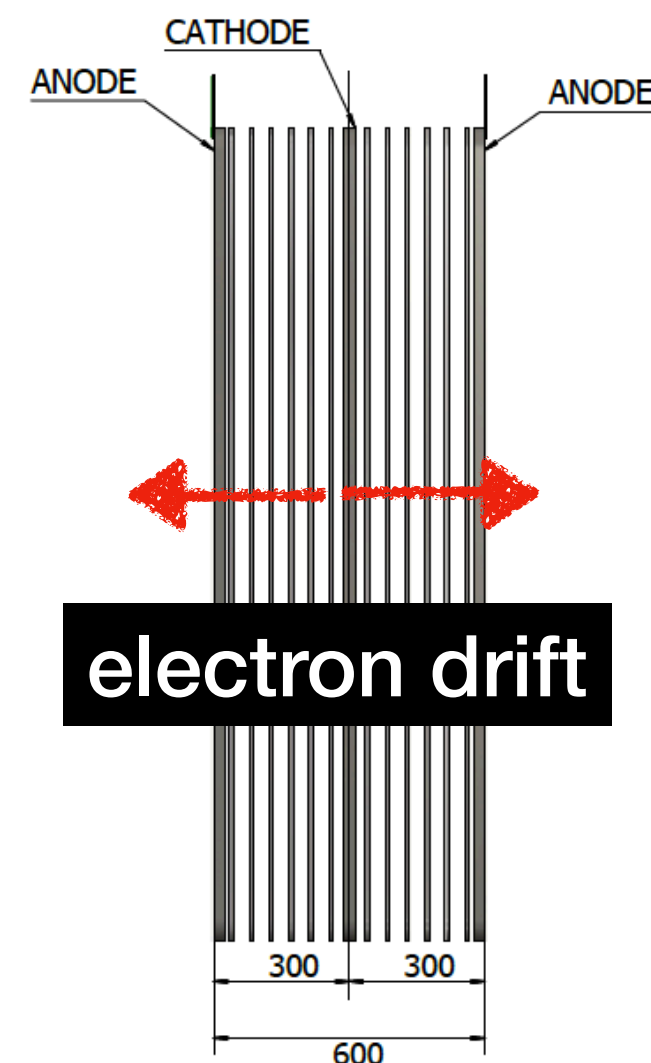
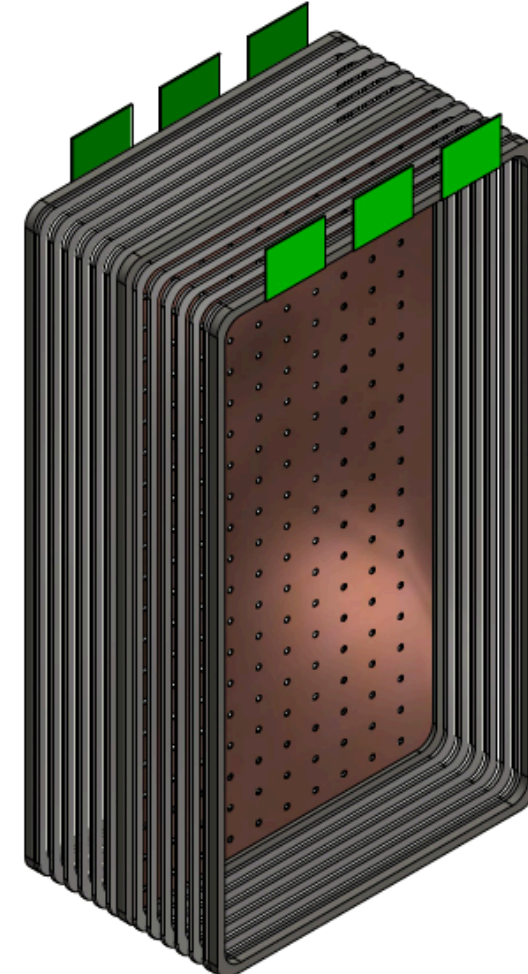


Developed for DUNE

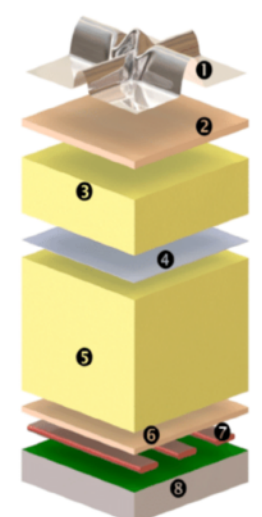
Anode Readout
Option 2: Pixel Readout



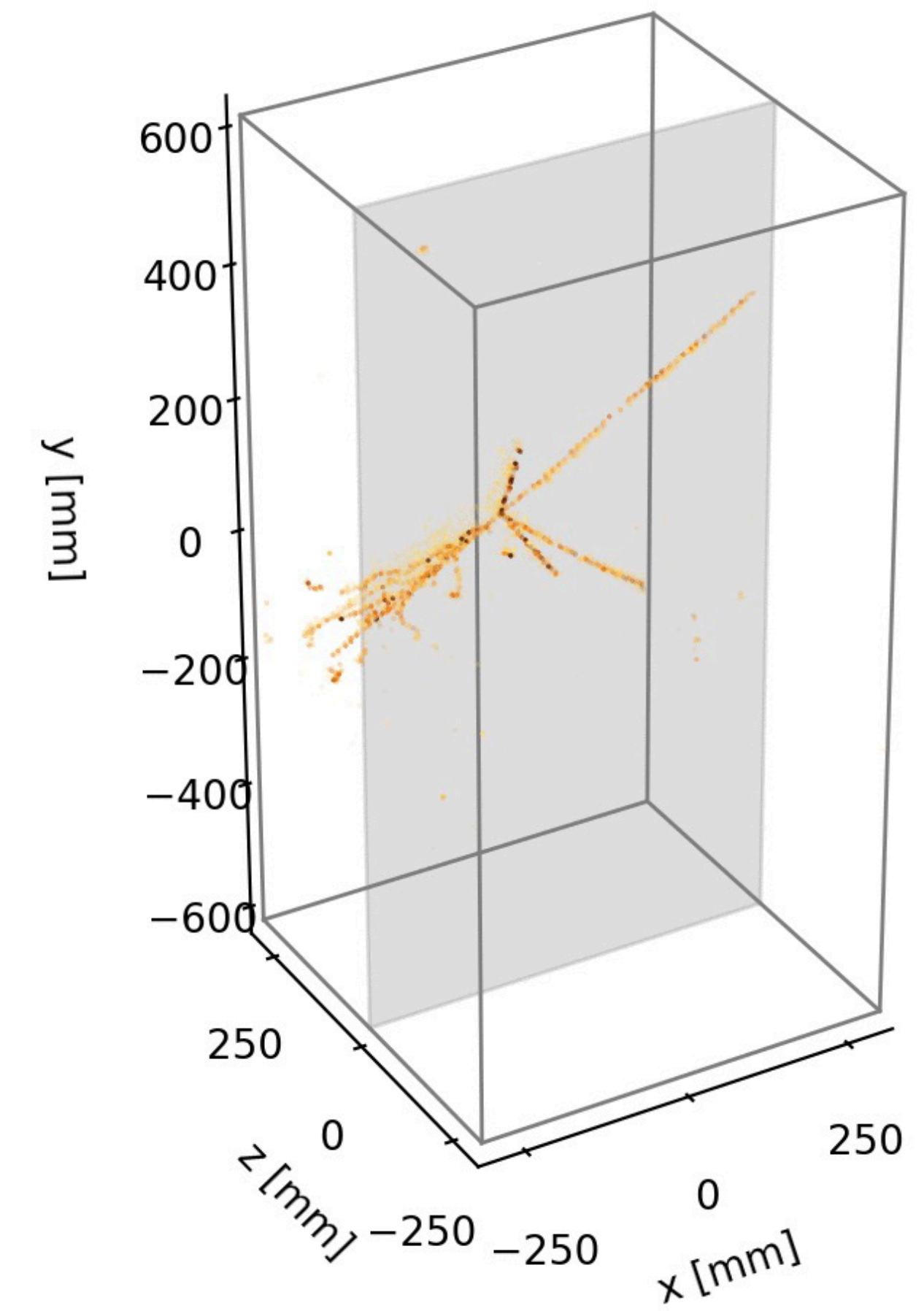
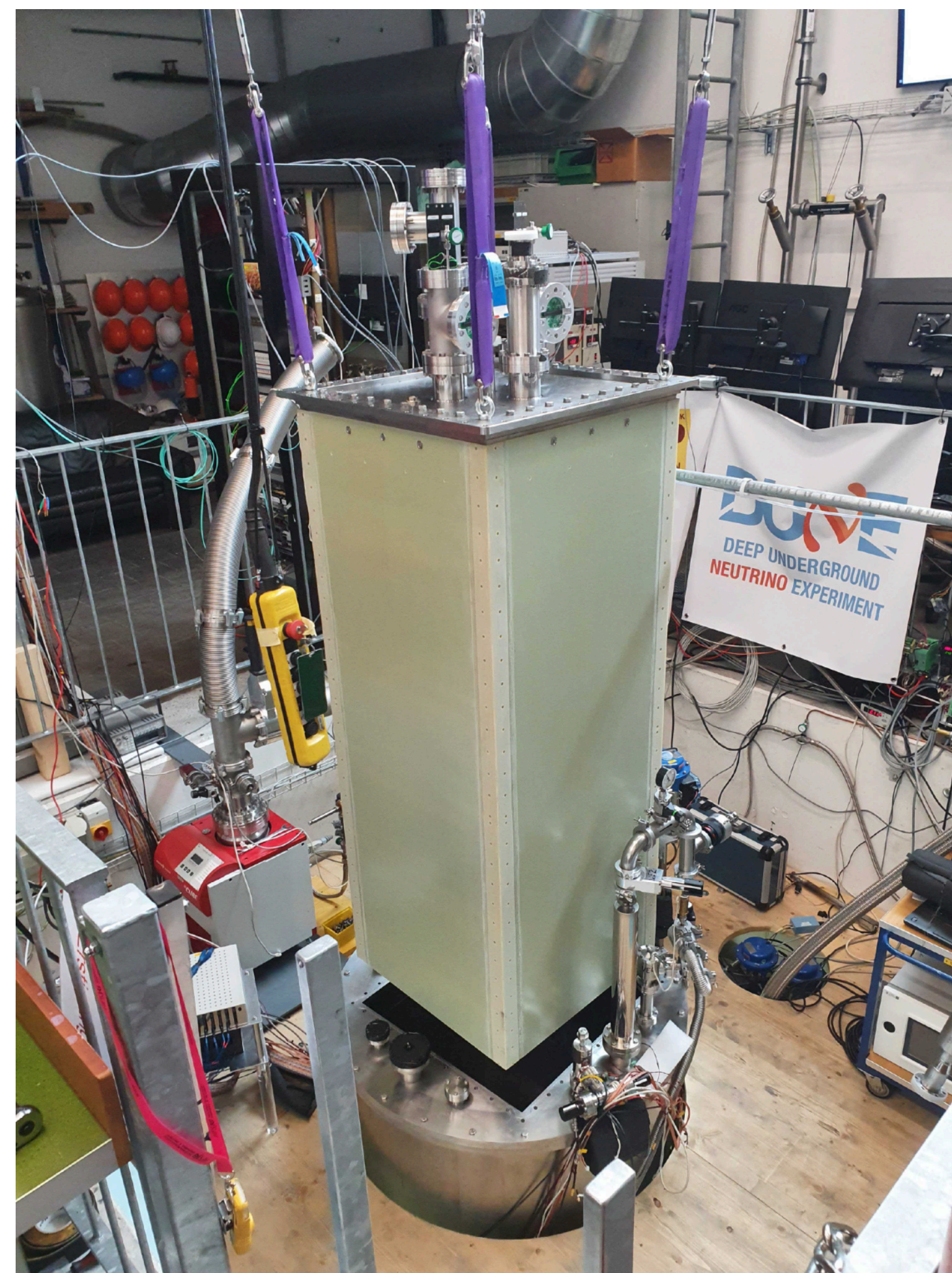
SINGLE TPC MODULE



Membrane Cryostat
Insulation

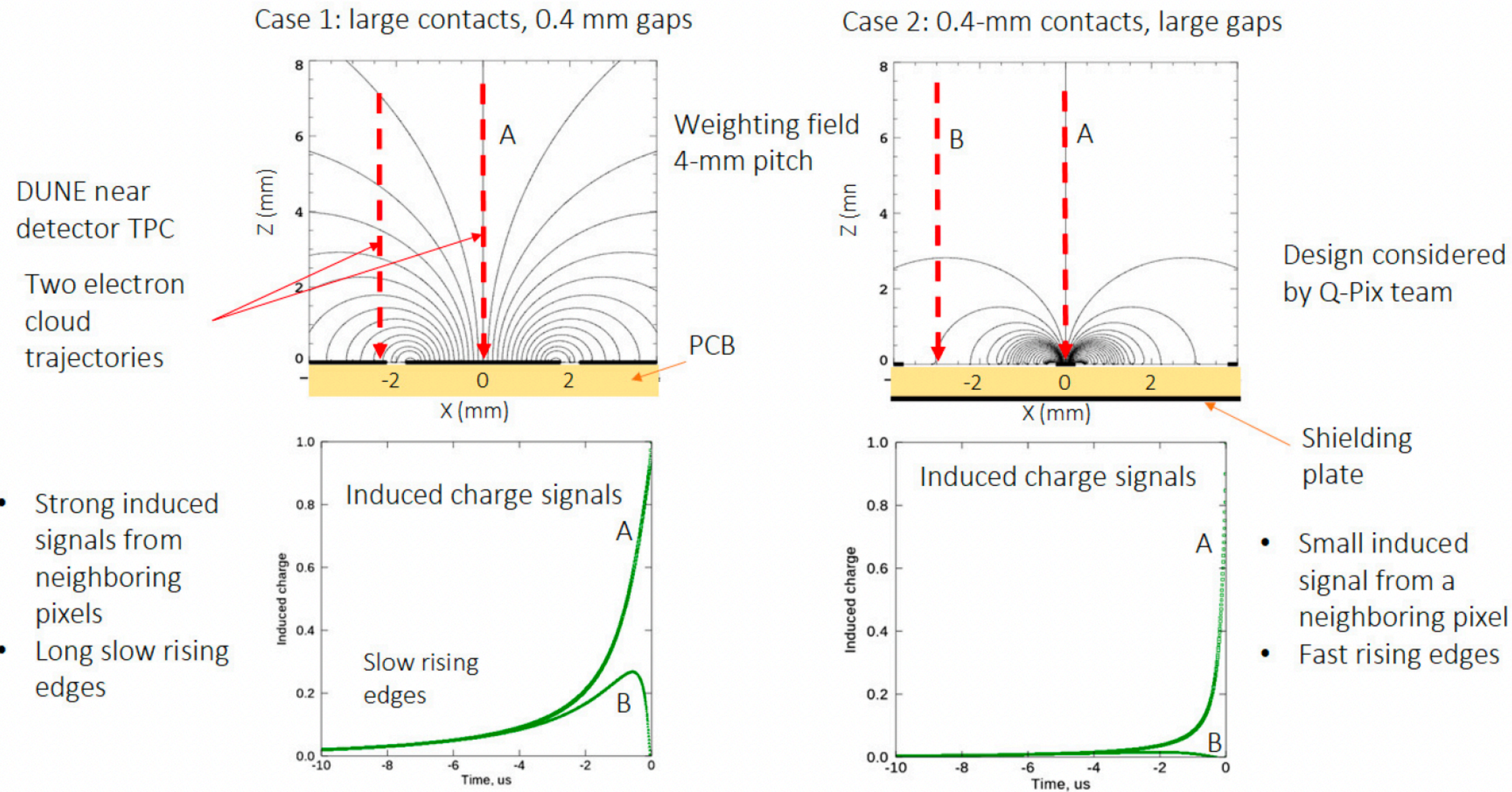


FLARE will Benefit from the DUNE near detector concepts.



Considerations for spatial resolution

Both multi-track separation and single track resolution are important



A. Bolotnikov

Three effects determine the track resolution

Diffusion. For 500 V/cm and 300 mm drift transverse (longitudinal) diffusion will be 0.4 (0.7) mm.

Shape of the induced current pulse. Depends on the geometry and grid arrangement

Amplification electronics and noise. Pixel size is highly correlated to all of the above.

Progress towards project planning and organization

- Tremendous progress was made to make the scientific case at the US community study in Seattle (July 2022) (Snowmass21)
 - Energy frontier Vision states: *Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.*
- We have formed working groups with main focus on FLARE (with considerable US involvement)
 - [FPF physics](#) (Brian Battell, Sebastian Trojanowski, MVD) (> 50 total participants in both groups)
 - [FLArE Technical design](#) (Steve Linden, Jianming Bian, MVD)
- There is modest funding in place with a mandate to produce a conceptual design report by early 2023.
 - Funding comes (this is not directly from the agencies)
 - Heising Simon's Foundation jointly with UCI (thanks to Jonathan Feng and UCI)
 - BNL laboratory directed R&D program for scientific development and R&D
 - BNL Program development program will pay for engineering and project planning
- ***BNL is "strongly interested in the forward physics facility (both for collider related searches and neutrino studies) and will support activities and personnel to the best of our abilities. " to further the conceptual design.***

Extremely Preliminary plan

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
(HL)-LHC nominal schedule	Run3	Run3	Run3	Run3	LS3	LS3	LS3	Run4	Run4	Run4	Run4	LS4
FPF/FLARE milestones		Pre-CDR and physics proposal	R&D and detector prototypes	CDR	Start of civil construction. Technical Design report for detector.	Detector construction start	Long lead items for detector	End of civil constr. Install services	Detector install	Detector Commissioning and physics start	Physics running with full complement of detectors	
CERN reviews		Agreement on process	LHCC review	LHCC review CDR	Approve program directors and resource board organization	LHCC review of TDR	Approve entire scope of FPF and the execution plan					
US reviews	Snowmass process	P5 process for prioritization	DOE Research program portfolio discussion	DOE/NL review institutional review process for 413.3b determination or equivalent of CD0	Assume US works under the small project umbrella. PD-1 Approve Conceptual Design and Cost Range	PD-2 Approve Project Performance Baseline	PD-3 Approve Project Execution				PD4 review/completion of project.	

Augusto Ceccucci: US bureaucracy is not so bad after it makes a decision !

Will be discussed in the FPF5 meeting with Albert de Roeck

- What is missing ?
 - This is just a preliminary plan with no input from sponsors (DOE/NSF).
 - Collaboration formation in US is part of the process of discussion with US agencies.
 - Information is needed from important partners in Europe/Japan/Others to make this a fully international plan.
 - The most important constraint is to start physics running during Run4.
 - To be exempt from 413.3b, US project scope must be under \$50M (this is negotiated).
 - 413.3b is a document that provides rules for project approval. NL = national lab.

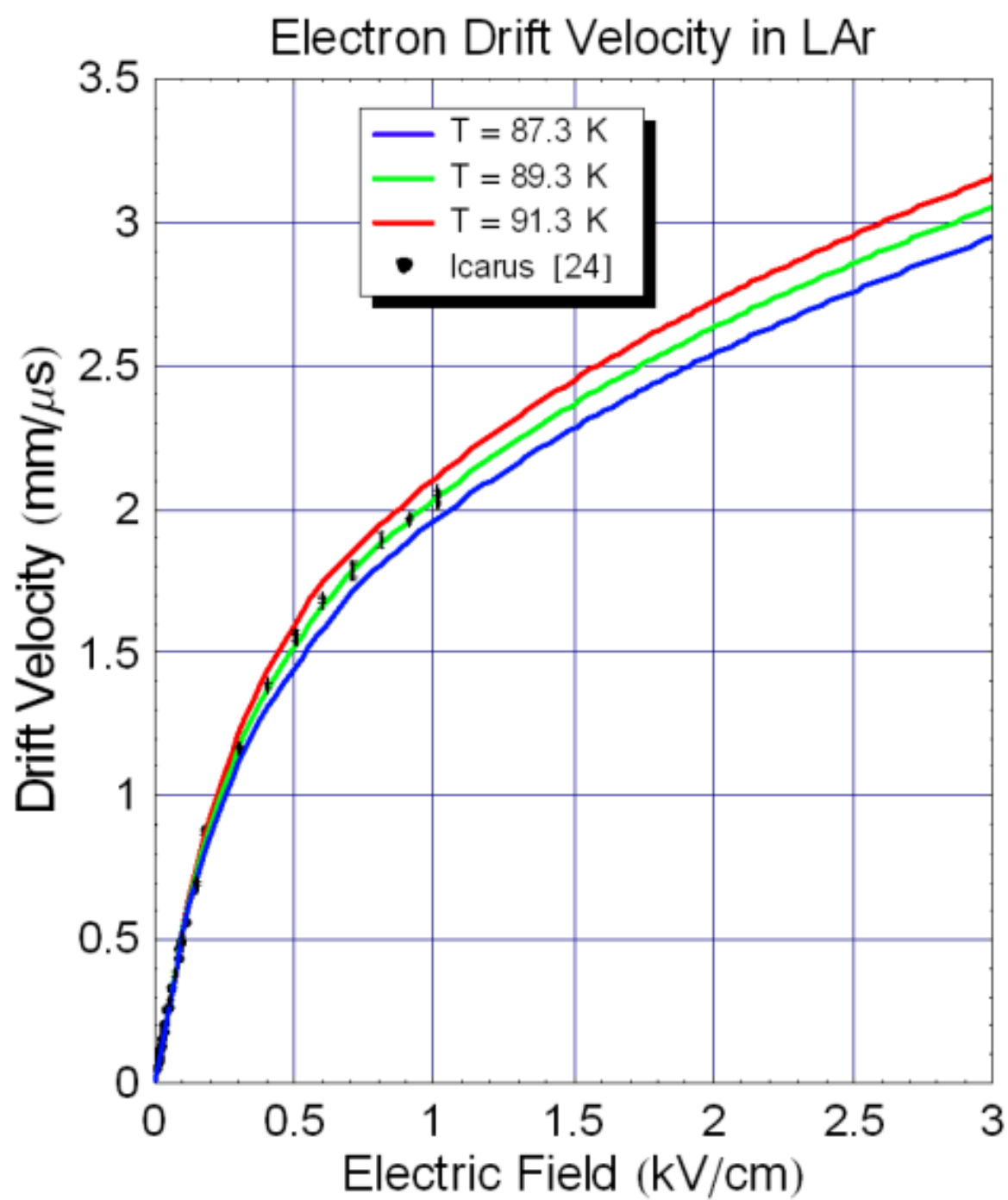
Conclusion

- A forward physics facility(FPF) is being considered at CERN for neutrino and dark matter physics. It will unlock a new source of neutrinos => the LHC.
- The FPF is decoupled from the LHC sufficiently that its schedule could be independent of the HL-LHC upgrades.
 - The headline physics interest is
 - Neutrinos 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.
- Preliminary examination of event rates and backgrounds suggests that a LAr detector is feasible and ground-breaking.
- Muon backgrounds, and engineering considerations necessitates a modular TPC detector.
- A LAr TPC requires much more advanced readout for ultimate spatial resolution, and a trigger system that can find contained events in the presence of muons. Timing could associate events with the ATLAS bunch crossing (studies are needed).
- Cost ? We now have a very modest funding to produce a conceptual design by mid-2023. DUNE R&D investment has made this much easier.

Backups

Drift velocity and diffusion

Electron drift velocity [22, 23, 24, 25]

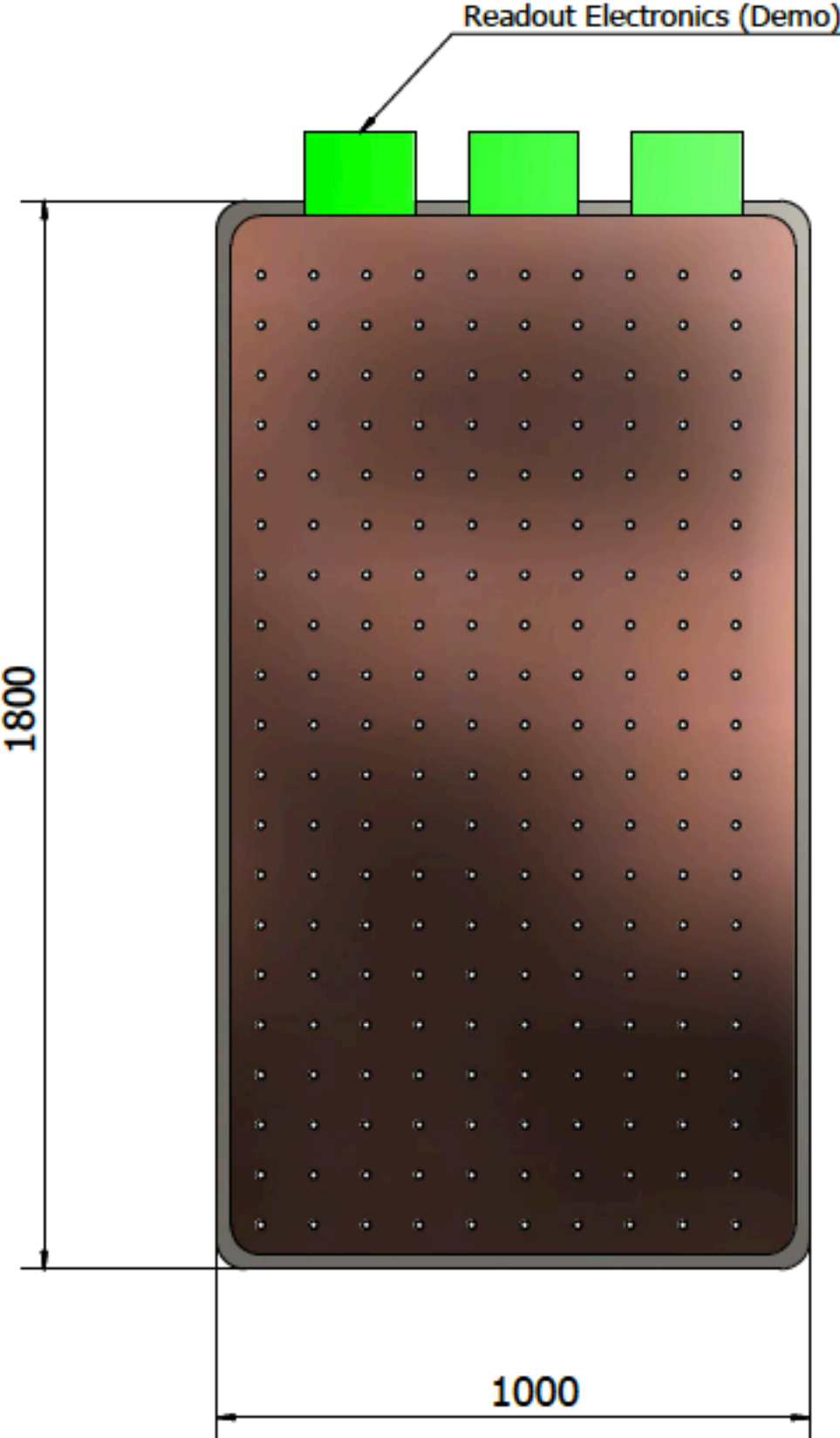
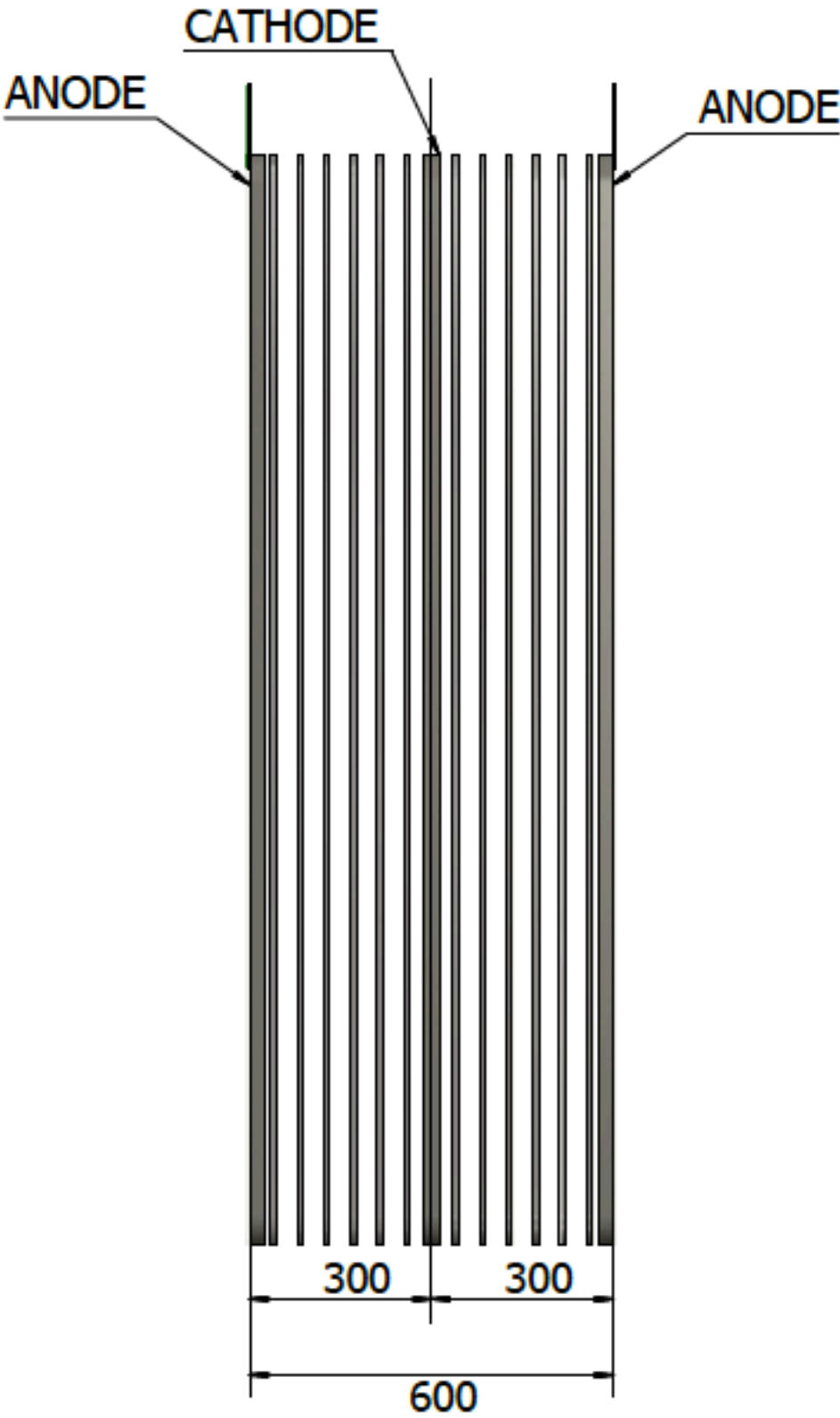
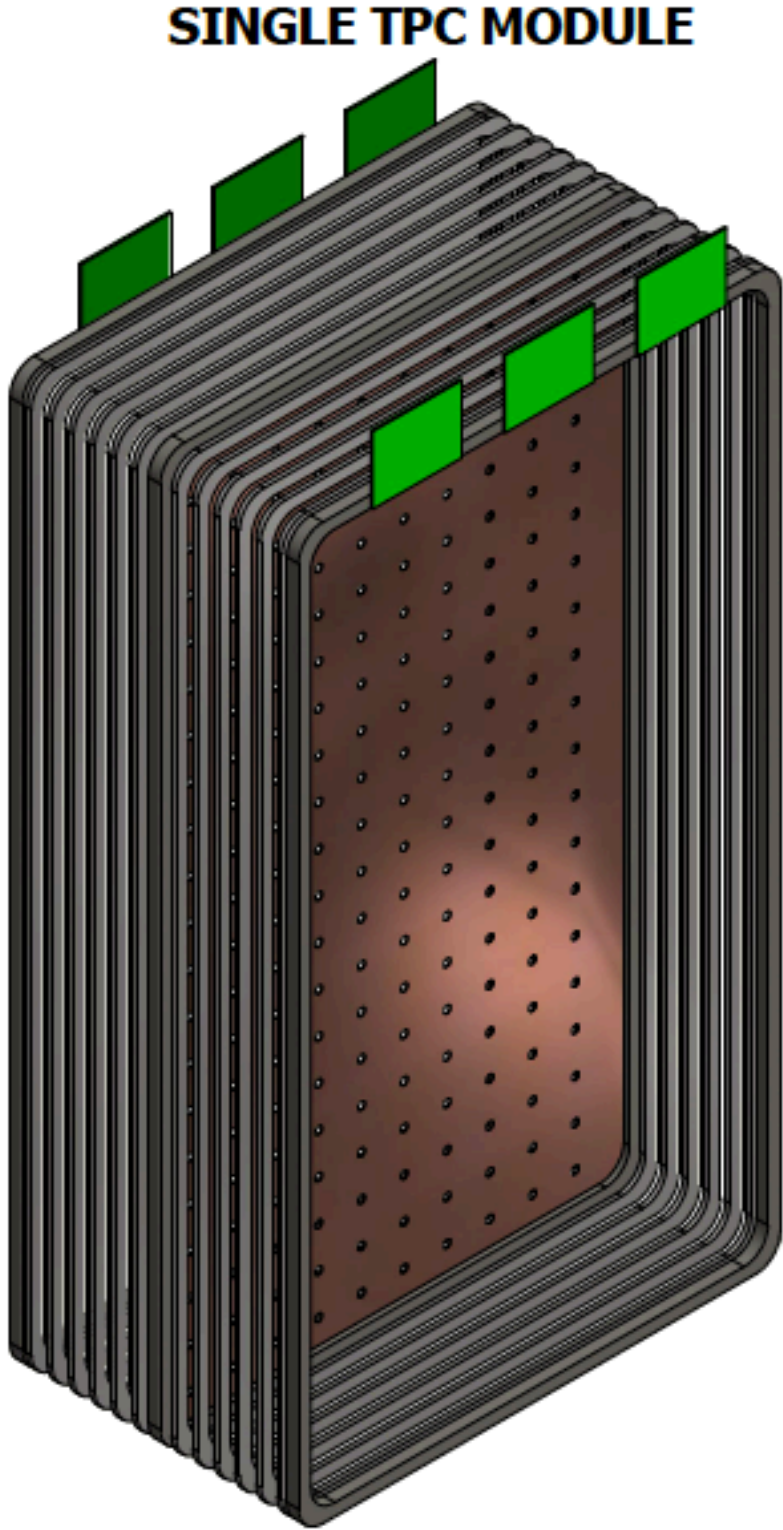


Electron transverse diffusion coefficient: $D_t = 13 \text{ cm}^2 / \text{s}$
Electron longitude diffusion coefficient: $D_l = 5 \text{ cm}^2 / \text{s}$

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

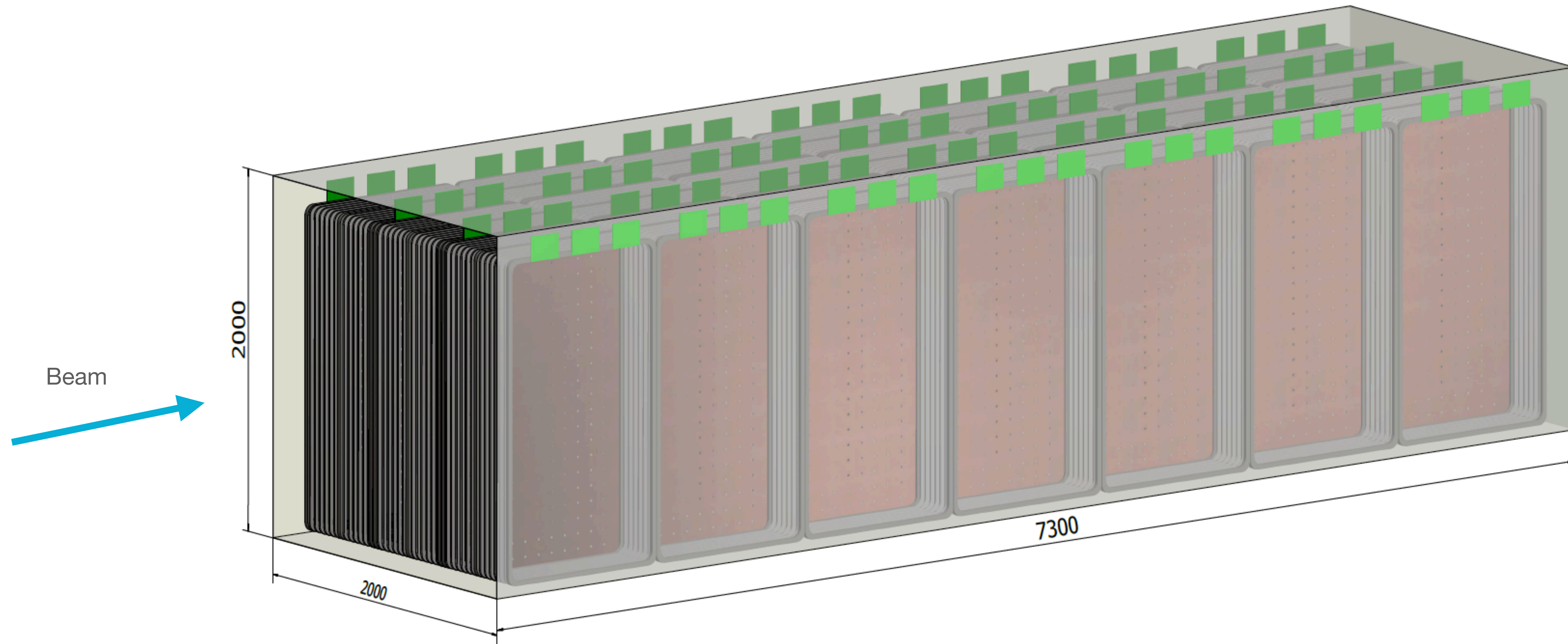
	500 mm at 1 KV/cm, 250 us	250 mm at 2 KV/cm, 100 us
Long. (FWHM)	0.5 (1.2) mm	0.3 (0.7) mm
Transverse (FFHM)	1.1 (2.6) mm	0.7 (1.7) mm

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



electron drift

Yichen Li



- ***Preliminary conceptual drawing of FLARE detector with the idea of modulated TPCs***
 - ***Membrane Cryostat similar to DUNE design***
 - ***Inner volume $\sim 29\text{m}^3$ (2m x 2m x 7.3m inner dimensions), LAr mass ~ 40 ton***
 - ***Membrane insulation thickness ~ 0.75 m***
 - ***Heat leak into cryostat from wall ~ 480 W (assuming 7.2 W/m² flux)***
 - ***Outer dimensions: 3.5m x 3.5m x 9.6m***
 - ***TPC is contracted with 3x7 modules***
 - ***Detector oval dimensions: 1.8 m x 1.8 m x 7.0 m***
 - ***Dimensions of individual module: 0.6 m x 1.8 m x 1.0 m***
 - ***Electric Field arrangement:***
 - ***Perpendicular to the beam direction***
 - ***Cathode at the center of each TPC module, 2x anodes at the ends***
 - ***Drift distance: 0.3 m***
 - ***Alternative arrangement: 2x7***

Basic detector requirements for FLARE from studies

Item	Choice	Comments
Liquid fill	LAr or LKr or LAr/LXe mix	LKr allows compact events and EM showers, but radioactivity may limit utility.
Cryostat and TPC dimensions	Keep the total to active volume ratio small. Need to fit into FPF space.	Cryostat, field cage, HV design must be integrated.
Cathode/anode and gap size	Central cathode with two anode planes. (makes two drift volumes). Gap < 0.5 m	more channels, better for HV safety and space charge. cathode must be transparent to light
Photon readout	SiPM's. Cannot use PMTs to keep the unused volume small.	Will need large number of channels.
Wavelength shifter for scintillation light	LAr: 128 nm, LKr: 150 nm, LXe: 170nm	DUNE development of ARAPUCA.
SiPM density, timing resolution and trigger	This requires detailed simulations and R&D. A minimum density is needed for recognizing contained events versus muons for trigger. Timing resolution is needed to associate with LHC bunch.	
Anode electrode design	Pixels versus wires	Simple wire geometry may not be possible because of straight thru muons. Need Simulation input.
Anode readout pitch	1-2 mm	Depends on kinematic resolution needed and also signal to noise.
Electronics	Cold electronics for low noise; how do we optimize for best drift resolution	Need < 1 mm resolution in drift dimension

Nominal configuration

To be detailed in a spread sheet and developed into a detail for a conceptual design parameters.

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