The Forward Liquid Argon Experiment (FLArE) at FPF

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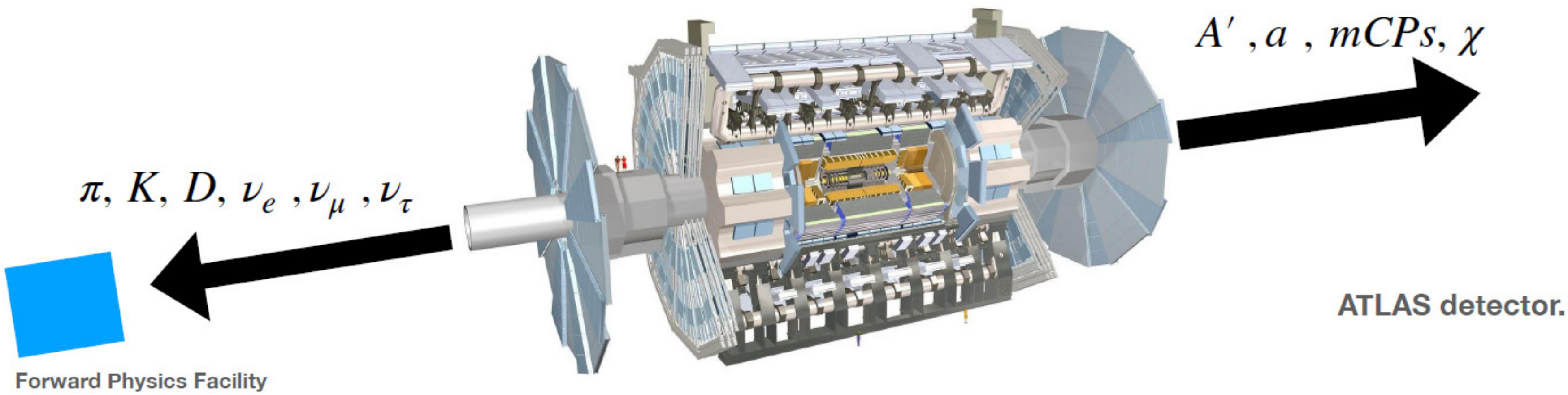
12th LLP Workshop

3 November 2022

FLArE Motivation



Detector capabilities at the LHC and other modern colliders are primarily at large angles off-axis

Are we missing physics in the forward direction?

Largest flux of high-energy light particles (neutrinos, pions, kaons, etc.) is in the forward direction

This could also be true of new particles – light dark matter, hidden photons, millicharged particles, etc

Lots of opportunities for a detector with:

- Good energy containment (high density)
- High spatial resolution (detect tau neutrinos)
- Low threshold (for dark matter elastic scattering)

→ **Liquid argon TPC** as part of the FPF

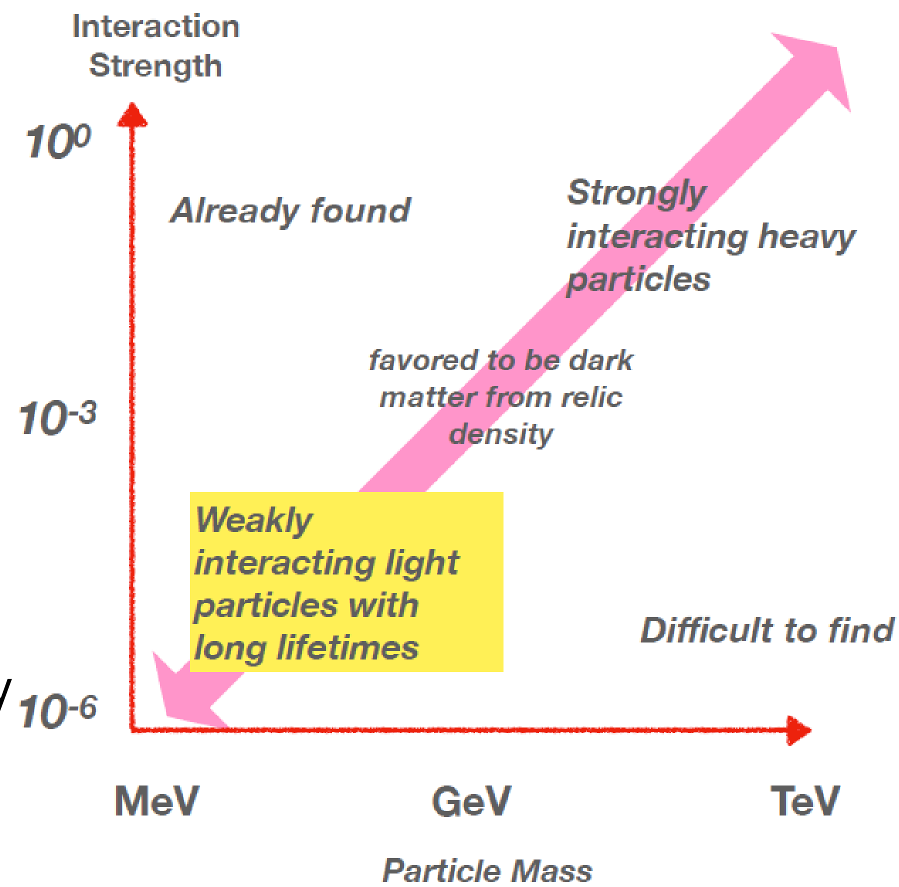
Physics Program - Overview

SM program:

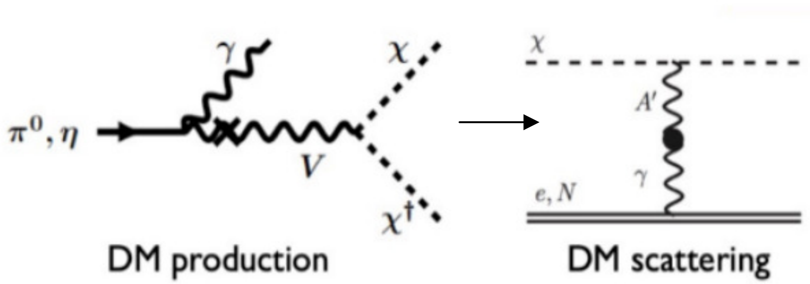
- Focus on high-energy neutrinos
- First large statistics sample of tau neutrino events
- Probes of QCD via prompt neutrinos

BSM program:

- Focus on weakly-interacting light particles from the dark sector
- Produced in rare decays of copiously produced forward mesons
- Particles are long-lived and either decay or scatter in FPF



Physics Program – Light Dark Matter



Production of light DM could occur via decay of mesons

High fluxes of these mesons are produced in the forward direction

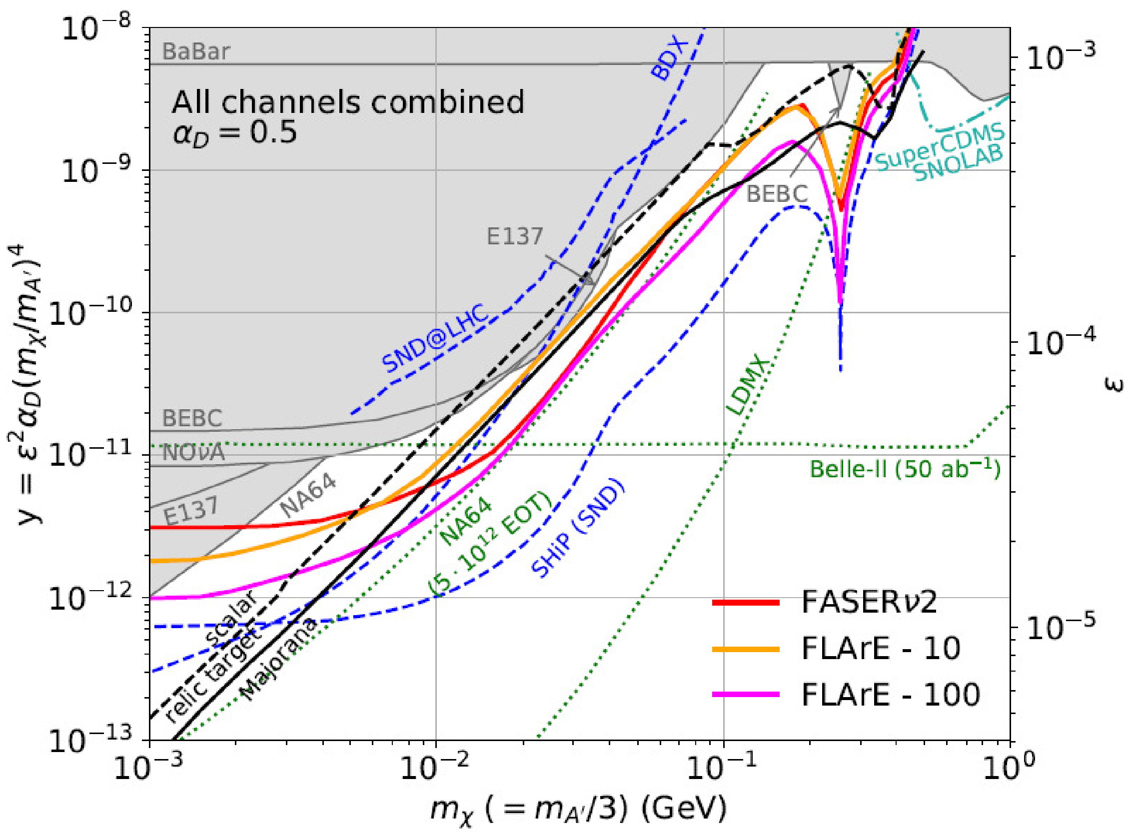
Detection via nuclear or electronic scattering

Signal is at low energy (~1 GeV)

High kinematic resolution needed

Assuming reasonable background rejection, target sensitivity indicated by relic density can be achieved

Complementary with both missing transverse energy collider searches and direct detection of relic DM



Physics Program – Neutrinos

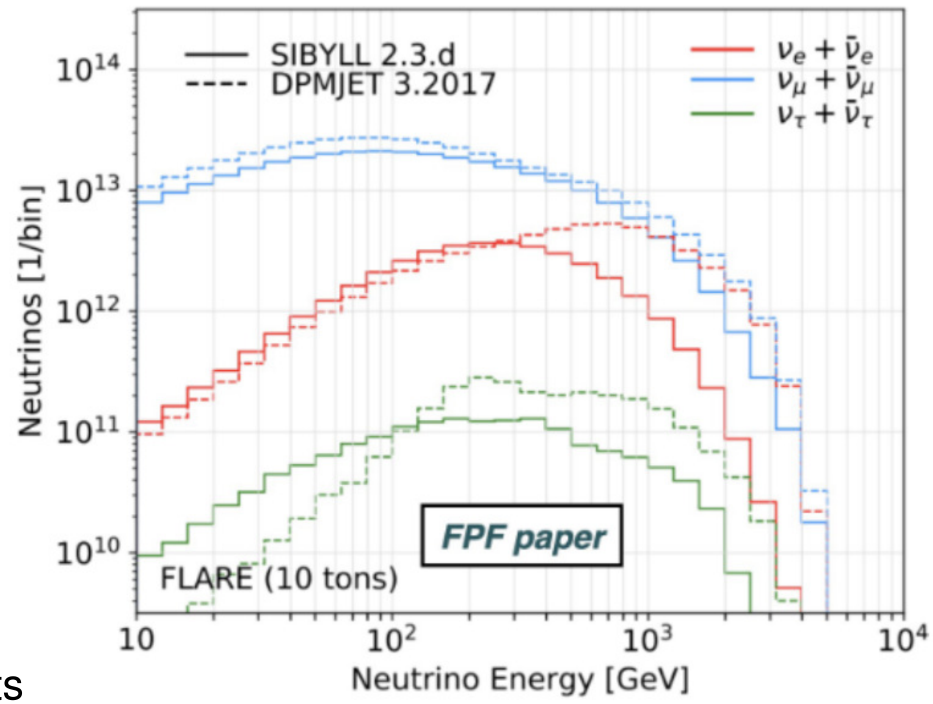
The LHC is the source of the highest-energy artificially-produced neutrinos.

But these are predominantly produced in the forward direction and thus have gone undetected.

Opportunities for both SM and BSM physics.

Fluxes have very high uncertainties – both an opportunity (measure them!) and a challenge (large systematics!)

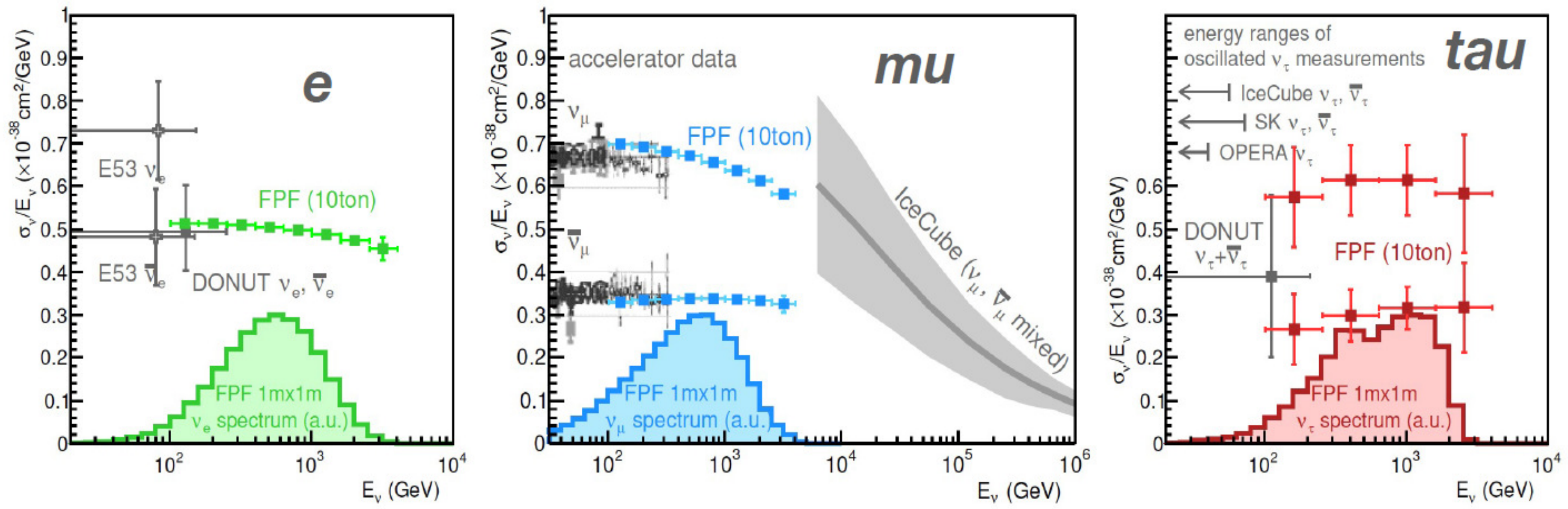
Will be the largest sample of tau neutrino events ever collected



Detector			Interactions at FPF			
Name	Mass	Coverage	CC $\nu_e+\bar{\nu}_e$	CC $\nu_\mu+\bar{\nu}_\mu$	CC $\nu_\tau+\bar{\nu}_\tau$	NC
FASERν2	20 tonnes	$\eta \gtrsim 8.5$	178k / 668k	943k / 1.4M	2.3k / 20k	408k / 857k
FLArE	10 tonnes	$\eta \gtrsim 7.5$	36k / 113k	203k / 268k	1.5k / 4k	89k / 157k
AdvSND1	2 tonnes	$7.2 \lesssim \eta \lesssim 9.2$	6.5k / 20k	41k / 53k	190 / 754	17k / 29k
AdvSND2	2 tonnes	$\eta \sim 5$	29 / 14	48 / 29	2.6 / 0.9	32 / 17

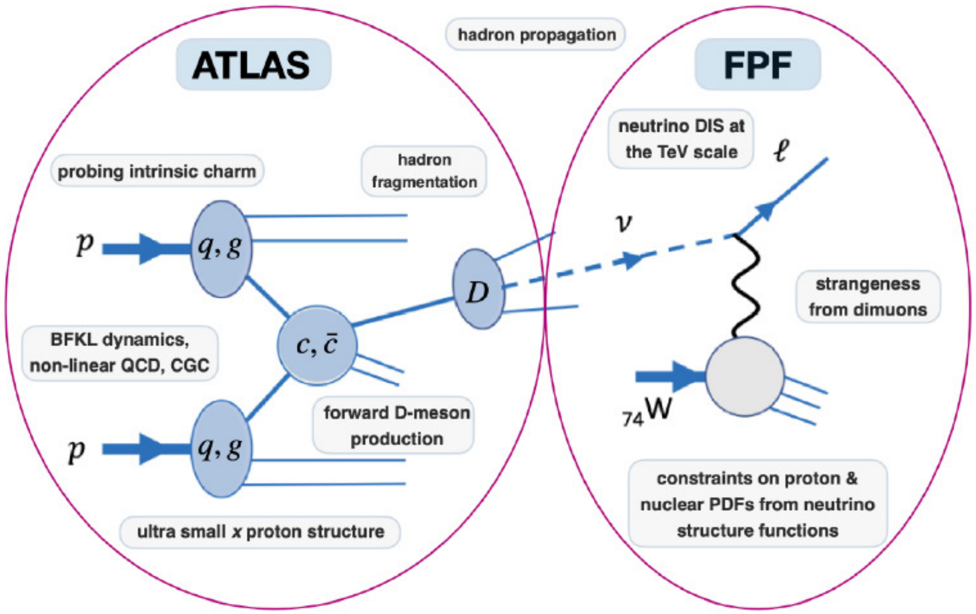
Estimated number of neutrino interactions using two different event generators, Sibyll 2.3d and DPMJET 3.2017

Physics Program – Neutrinos



- The current data from accelerators ends around 300 GeV. FPF would provide data that fills in the gap between accelerators and atmospheric neutrinos.
- FLArE is the best option to tag these events and measure rates.
- Highest rates are muon neutrinos, but large high sensitivity measurements can be made for all flavors!

Physics Program - QCD



QCD physics accessed both by production in forward direction and by DIS at FPF.

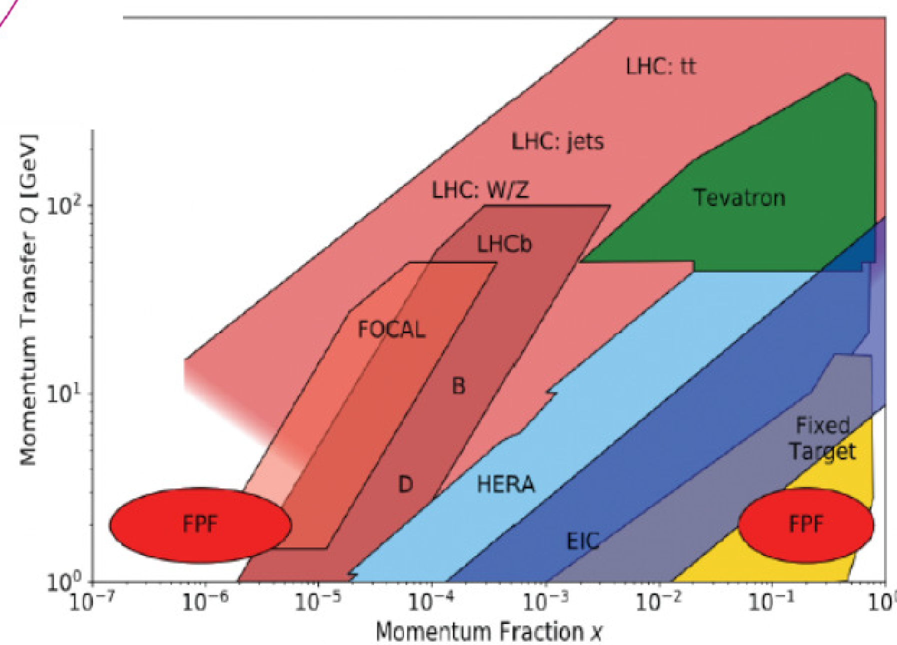
Access to unexplored kinematic regions at low Q, high x and low Q, low x

Can study:

At low x: small-x proton structure, BFKL dynamics

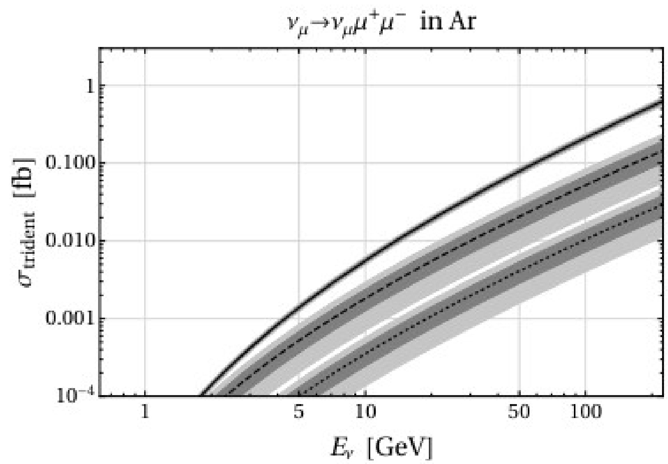
At high x: intrinsic charm

Via DIS: nuclear structure functions

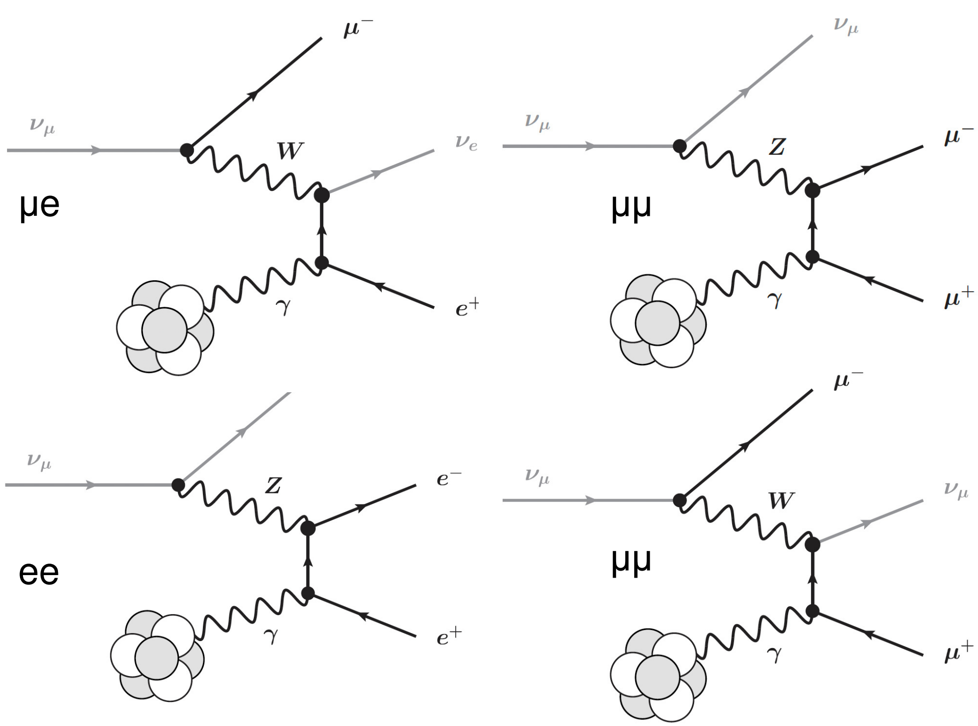


Physics Program – Neutrino Tridents

• Neutrino induced production of charged lepton pairs in the presence of a nucleus.
• Mediated by electroweak interactions at tree level and sensitive to new physics.
• Rare process. μ+μ- has evidence from (CHARM-II) and CCFR.
• Various interaction modes possible: the cleanest could be **coherent** scattering to μ+μ- final state.



W. Altmannshofer, 1902.06765

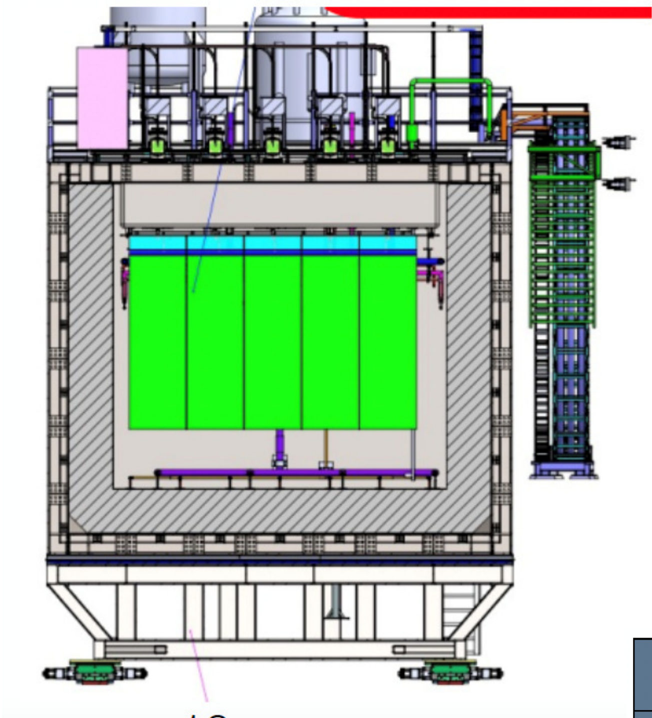


• **Challenge**: small opening angle between the muons
→ likely crucial to go below 100mrad resolution
• If 30 mrad resolution could be achieved, up to ~20-25 events could be detected.
• Neutrino-induced backgrounds:
– CCRES single-pion production (could be rejected based on too soft pions/muons)
– CCDIS associated with charm (could be rejected based on non-purely leptonic nature)

There is a strong physics case for a liquid argon TPC in the forward region at the LHC.

What are the technical requirements and constraints?

Cryostat



- 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.

→ About 1.9 m x 1.9 m cross section allowed for detector.

- Installation from top (like DUNE ND) seems ideal
- But coordination with CERN engineering is needed (e.g. can a crane be available?)

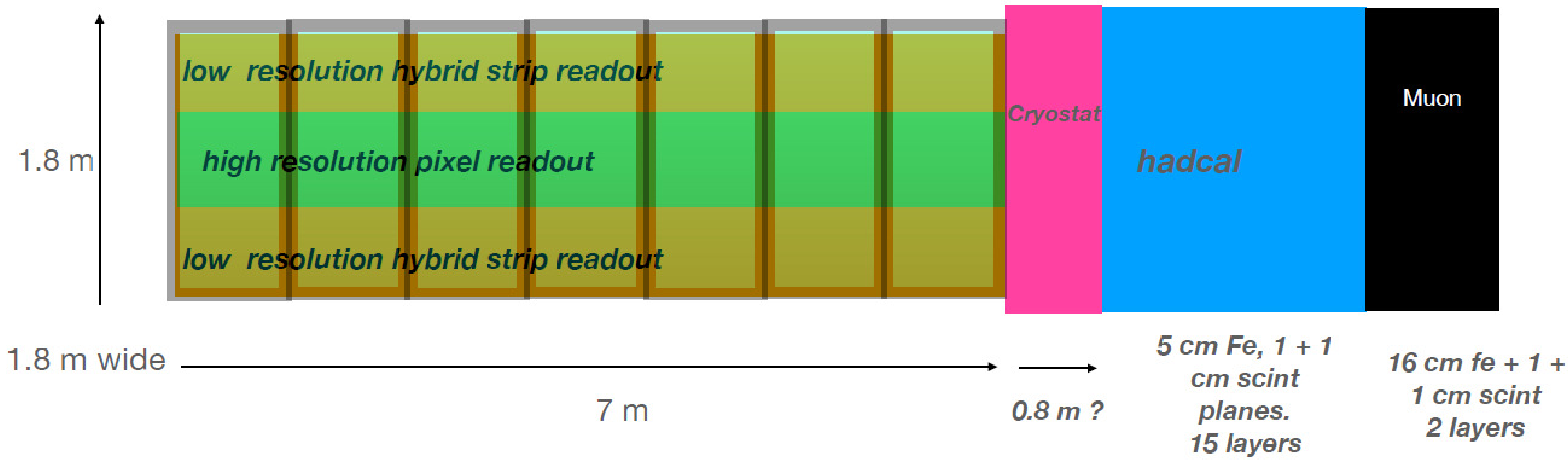
	Cryostat Inner Dimensions	Insulation Type	Insulation Thickness	Insulation density	Heat leak	Cold shield
MicroBooNE	3.8m dia x 12 m	Polyurethane Foam	**400mm**	32 kg/m³	**~13 W/m²**	No
ICARUS-GS	3.9m x 3.6m x 19.6m	Nomex honeycomb+perforated Al	**665 mm+ (combined)**	25-35 kg/m³	**7-22 W/m²**	Yes
ICARUS-SBN	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

Detector Dimensions

Basic requirements:
- Contain neutrino events
- Keep drift lengths reasonable
- Fit within cryostat

Carry two options into conceptual design:
-3x7 modules with 30 cm. drift length
-2x7 modules with 45 cm. drift length

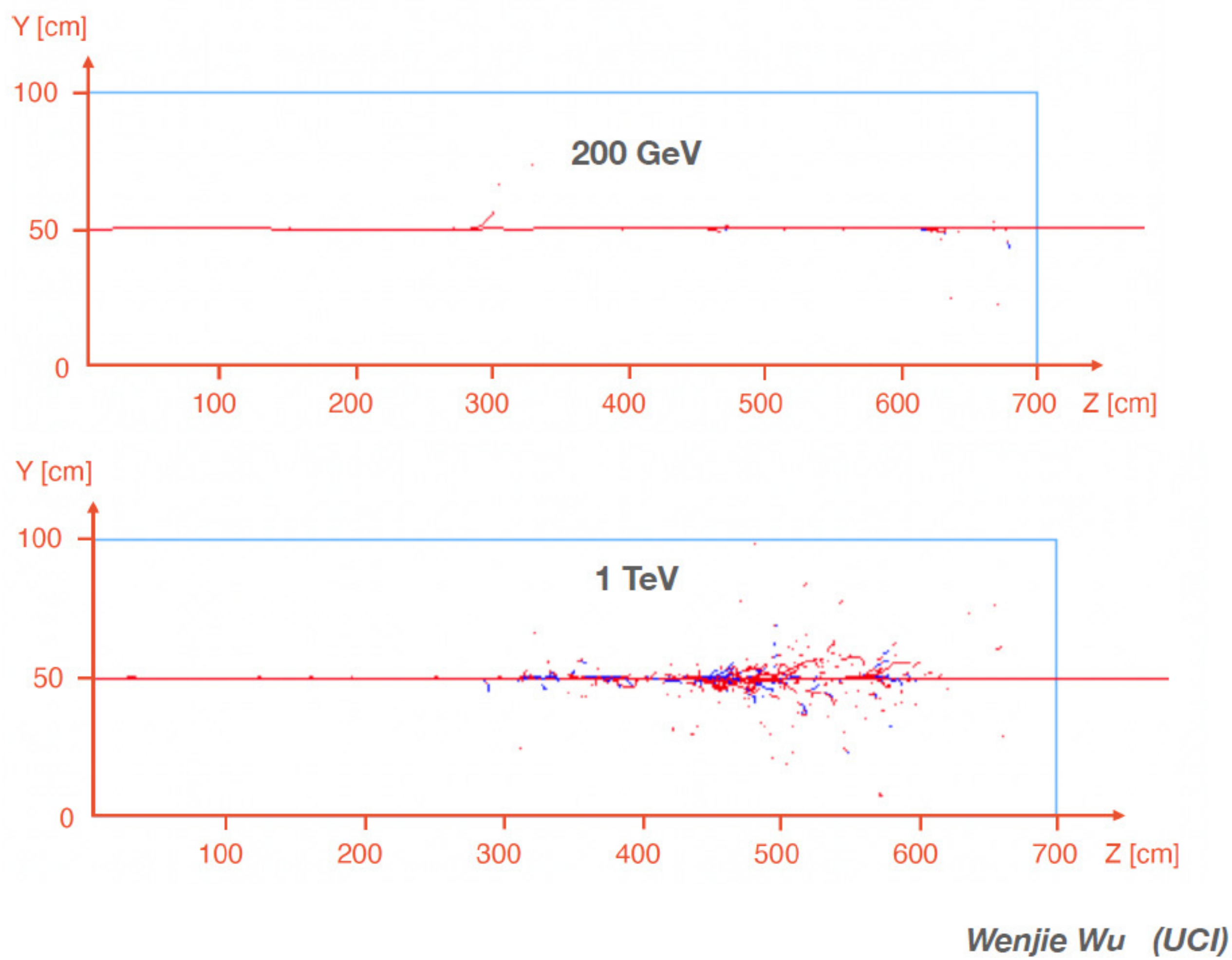


Pixel-based anode → very high number of channels

Could use lower-resolution strip-based readout for outer modules, pixels for fiducial region

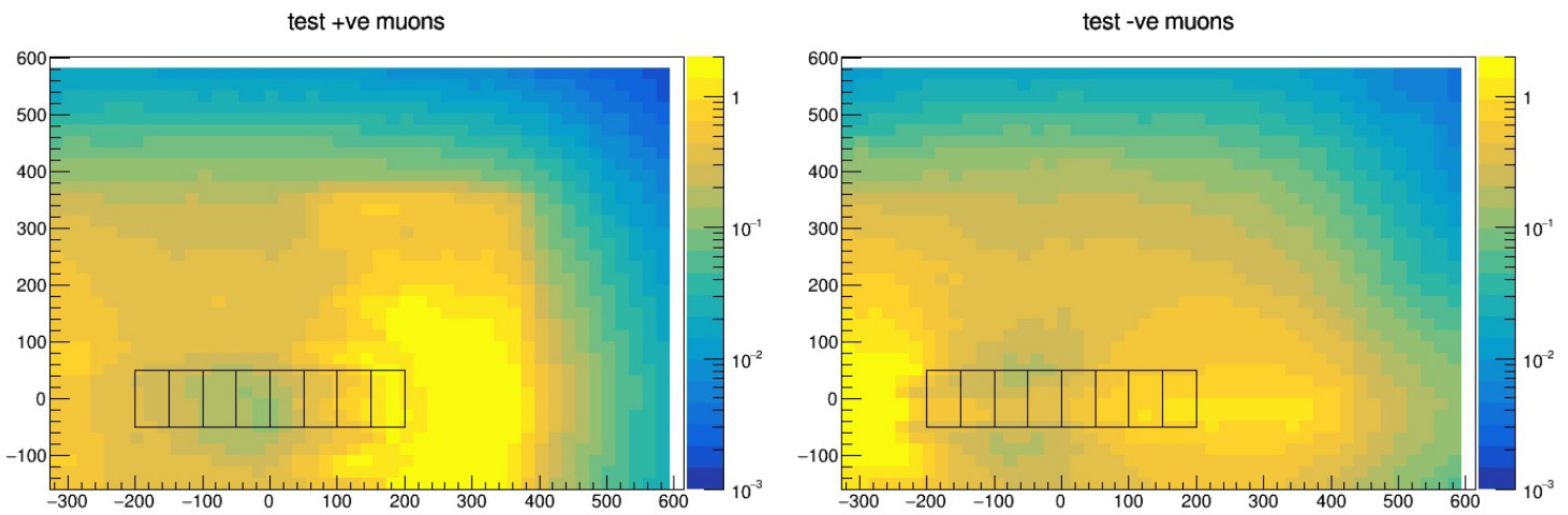
None of this has been optimized yet – all numbers are preliminary!

Muons



- Muon flux above 1 Hz/cm^2 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.

Muon Flux



FLUKA simulation of muon fluxes at the FPF has been performed, including full magnetic maps.

Flux of **0.6 hz/cm²** for full 1.8 x 1.8 m. FLArE cross-section, **0.5 hz/cm²** in 1 x 1 m. fiducial region.

These numbers are promising, but note hot spots off-axis. Muon veto capability is very important!

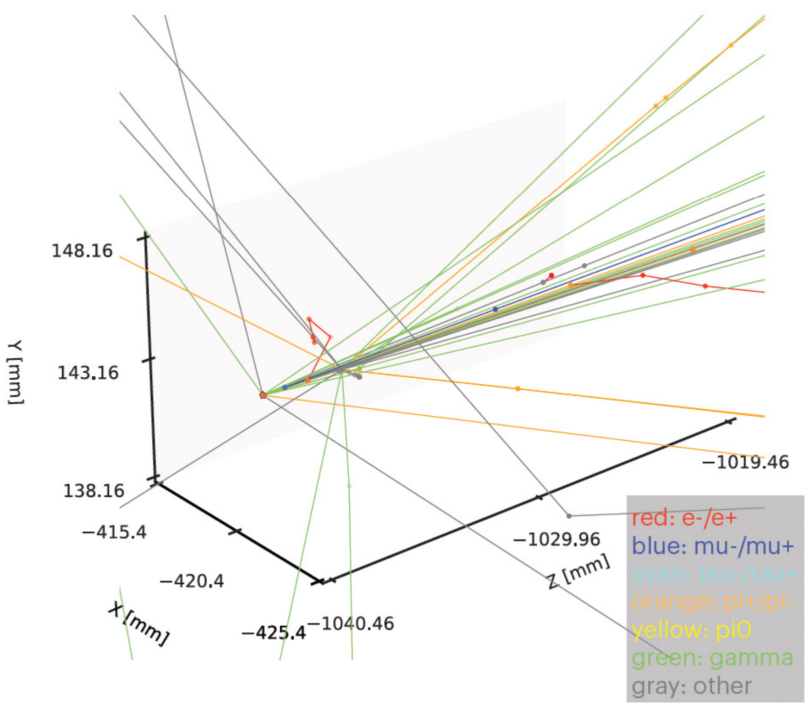
Tau Neutrino Events

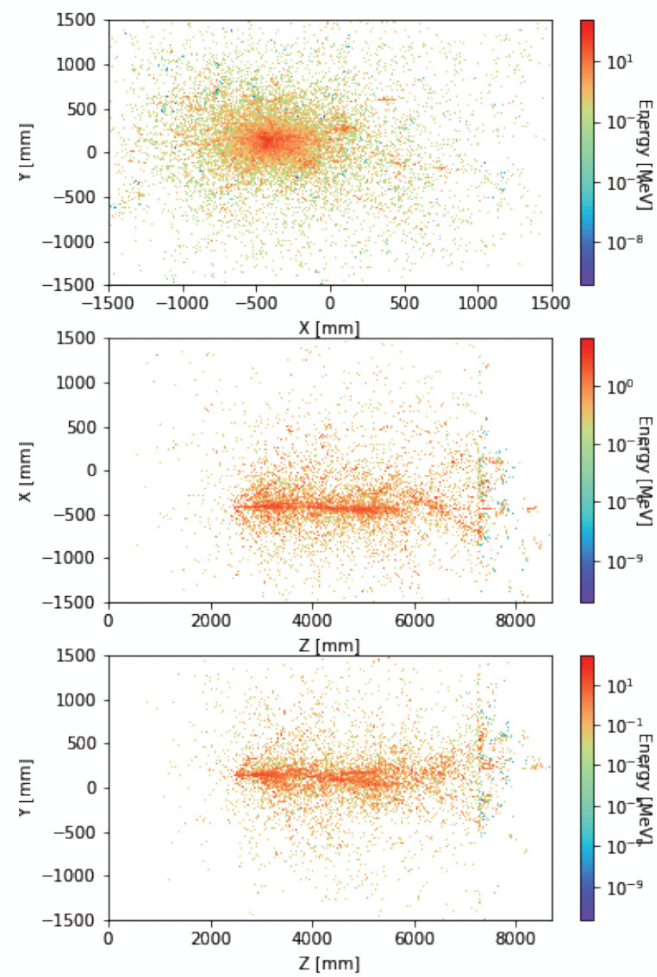
Studies of LArTPC tau neutrino events in simulation are underway.

Very good vertex resolution is needed – ongoing work to determine just *how* good

ν_τ CC (E_ν = 230.7 GeV)

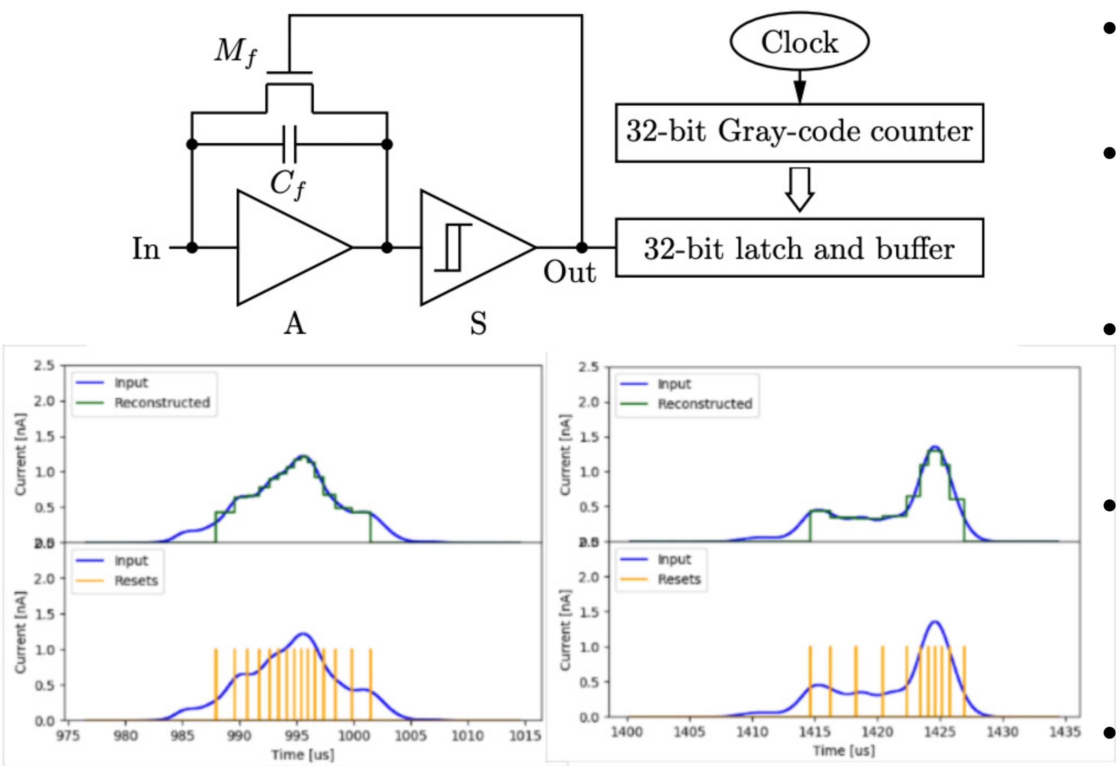
$$\tau^-(102.9\ \text{GeV}) \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-(74.7\ \text{GeV})$$





Pixelized Anode: Q-Pix

Charge Integrate/Reset (CIR) circuit

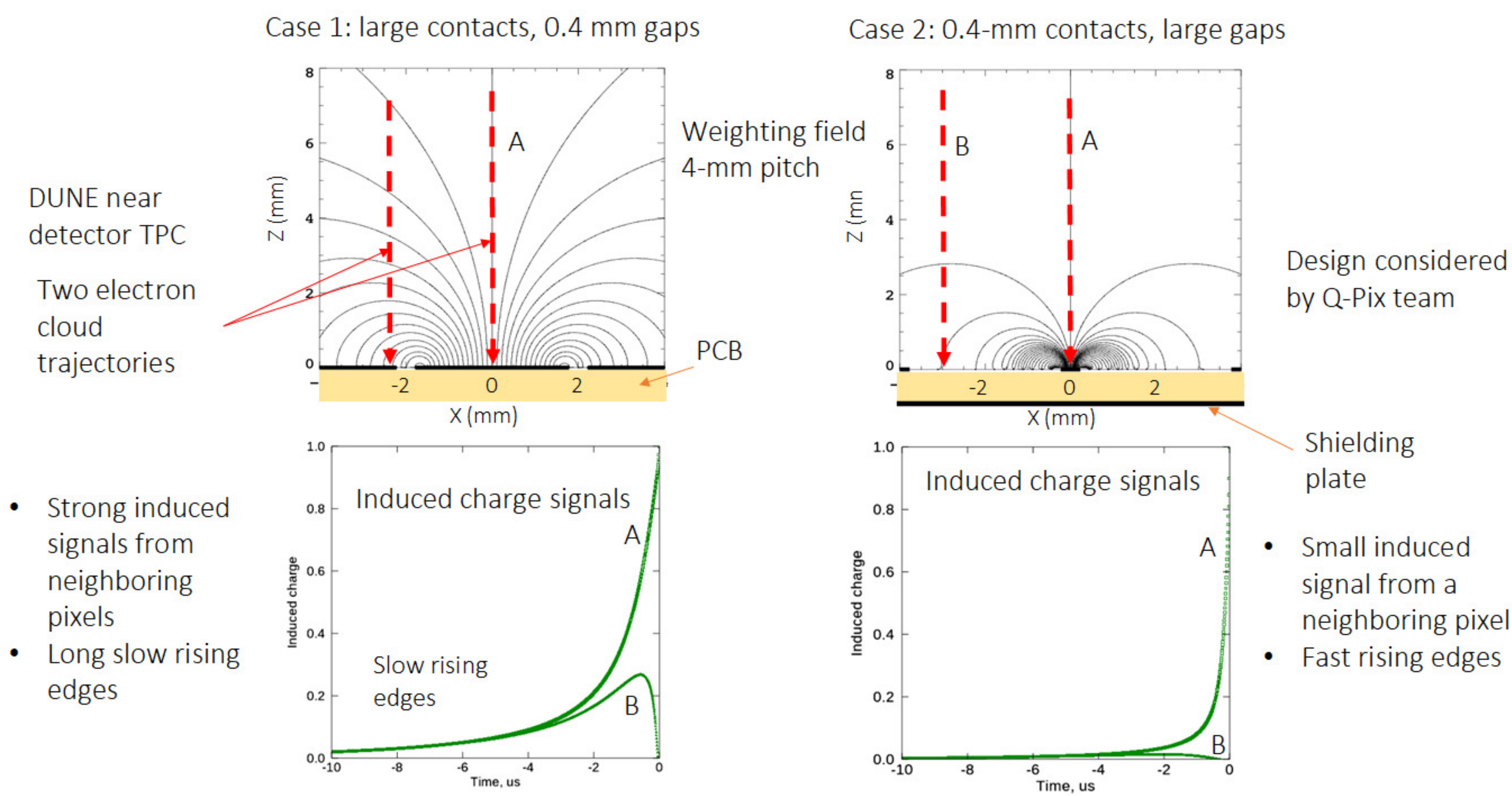


Q-Pix Collaboration, arXiv:2203.12109v1 [physics.ins-det]

- Charge amplifier continuously integrates incoming current
- When the charge reaches a certain threshold, the amplifier resets
- The reset time is captured and stored and used for charge signals reconstruction as illustrated
- However, Charge/Reset circuit stops following input signals if polarity changes
- This happens when a pixel captures the induced signal generated by an electron cloud collected on a neighboring electrode
- For Q-Pix approach, it is important to have electrode designs that minimize induced signals

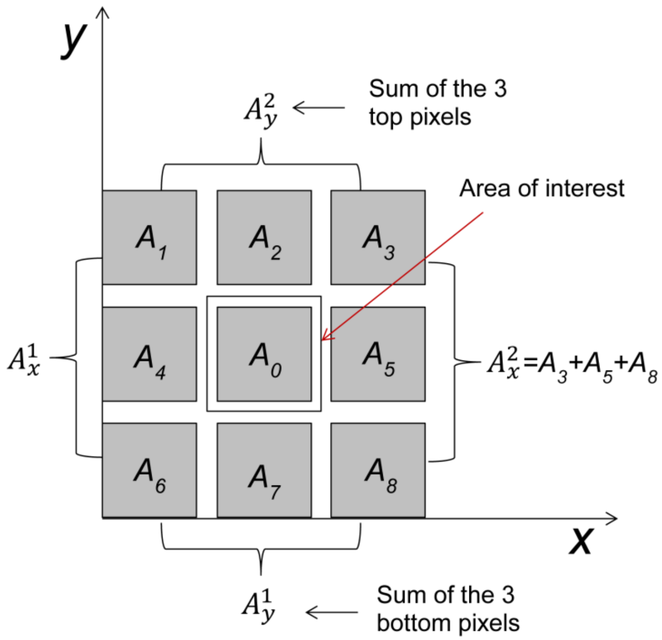
Pixelized Anode: Q-Pix

From A. Bolotnikov (BNL):



Frisch-grid and shielding electrodes can be added for additional field shaping.

Subpixel Position Resolution



Very small pixel sizes might lead to impractically large channel counts.

Information from neighboring pixels can be used to achieve resolutions smaller than pixel size.

Similar concept to some noise reduction techniques.

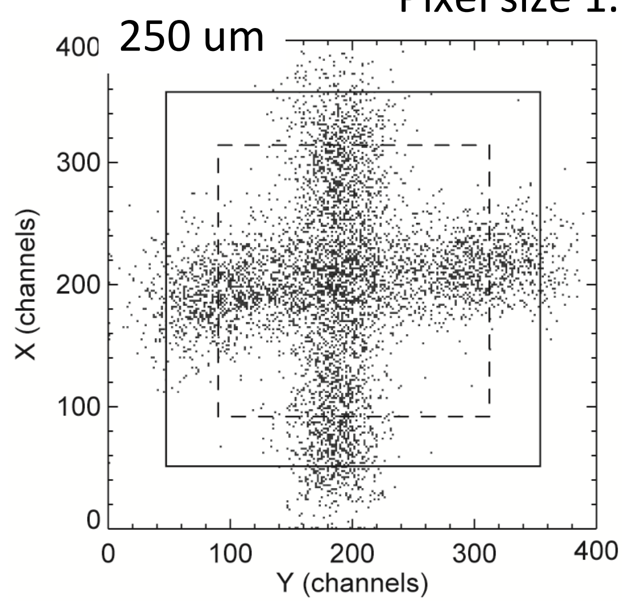
See Giraldo et al., https://doi.org/10.1016/j.nima.2017.04.030

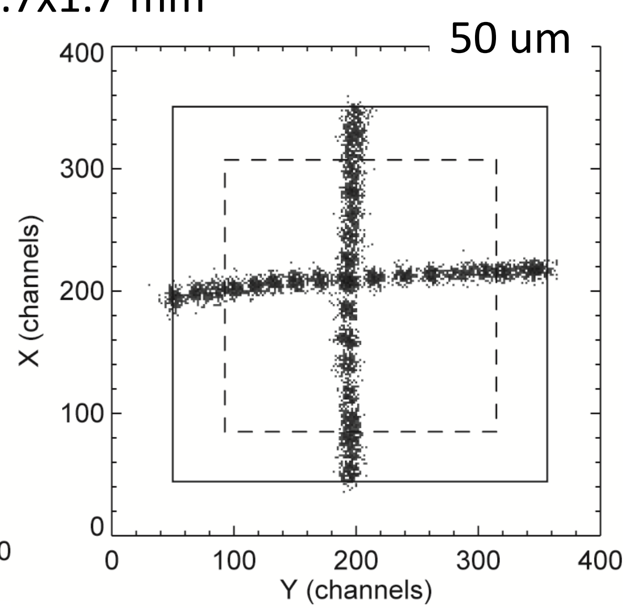
15x15x5 mm CdZnTe pixel detector

Illuminated by a pulsed laser

Resolution down to 250 μm (left, 0.25 MeV) or 50 μm (right, 1 MeV)

Pixel size 1.7x1.7 mm





Nominal Configuration

Everything here is provisional – currently in process of developing this for CDR.

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

Conclusion

- A Forward Physics Facility (FPF) is being considered at CERN for neutrino and dark matter physics.

- FLArE is a noble liquid detector being planned for the FPF.

- Preliminary examination of event rates and backgrounds suggests that a LAr detector is feasible and ground-breaking. (DUNE investment has made this much easier)

- A LArTPC 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).

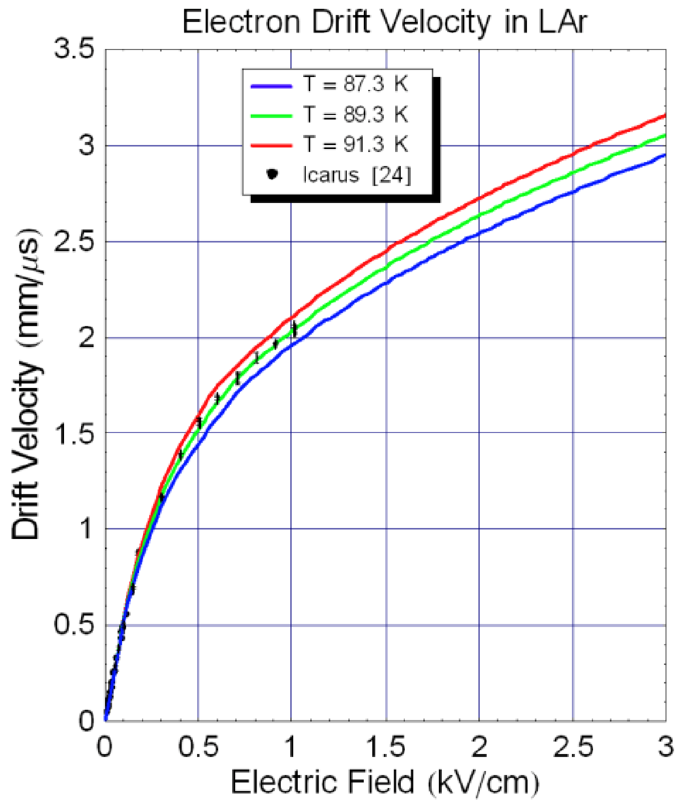
- This project is ideal for an international partnership centered at CERN. The small detector or modules could be build anywhere.

- US based Physics and Technical working groups have formed:
  https://indico.cern.ch/category/14011/ (Brian Battell, Sebastian Trojanowski, Milind Diwan)
  https://indico.cern.ch/category/15544/ (Jianming Bian, Steven Linden, Milind Diwan)

Backup

Diffusion

Electron transverse diffusion coefficient: . D_t = 13 cm² /s
Electron longitude diffusion coefficient: D_l = 5 cm² /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