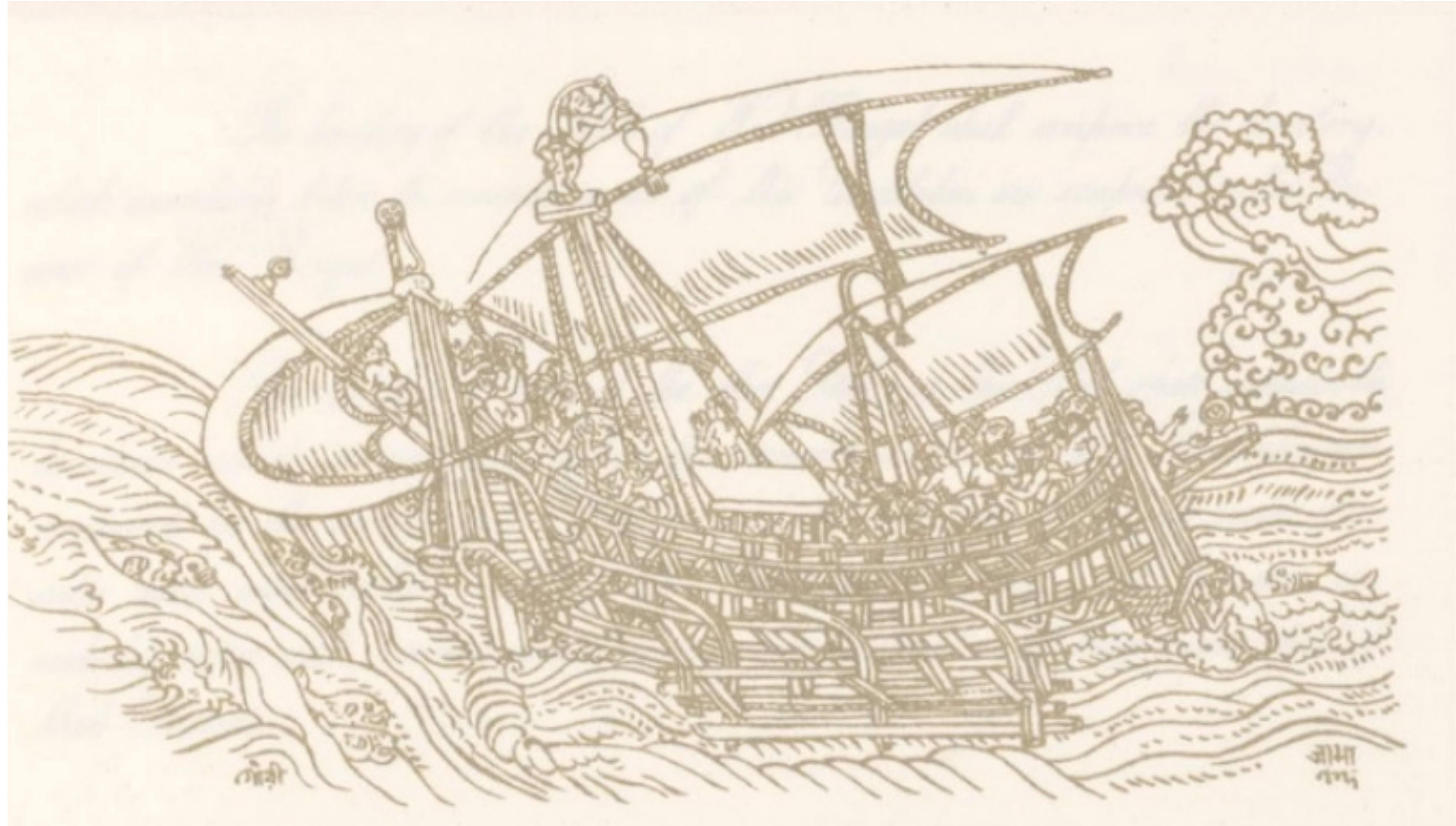
Progress towards a far forward liquid argon neutrino detector at the high luminosity LHC

Milind V. Diwan (Brookhaven National Laboratory)
for the FLARE technical design group.

The physics and technical groups have over 50 people now.

FPF 5, at CERN, Nov 16, 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.

Key experimental considerations

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

Huge investment from CERN in liquid argon technology => Can it lead to another unique experimental program ? How can FLARE benefit from it ? ProtoDUNE, and LAr-R&D platforms are operating on a very large scale.

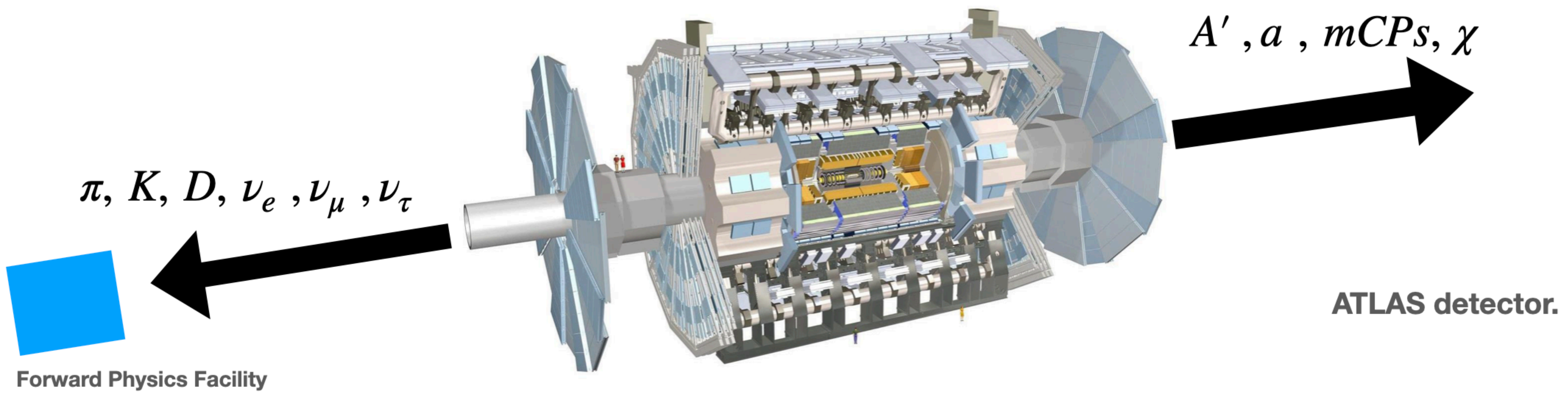
Thoughts and process for project organization. (extremely preliminary)

Expected timeline within the US and how they might interse

More about this at the end.

Design details (to be covered by Jianming and Steven)

- Containment, hadron, muon detection
- Beam related backgrounds
- Spatial and time resolution.
- Liquid argon detector for FPF very preliminary design.



High level experimental considerations for each topic

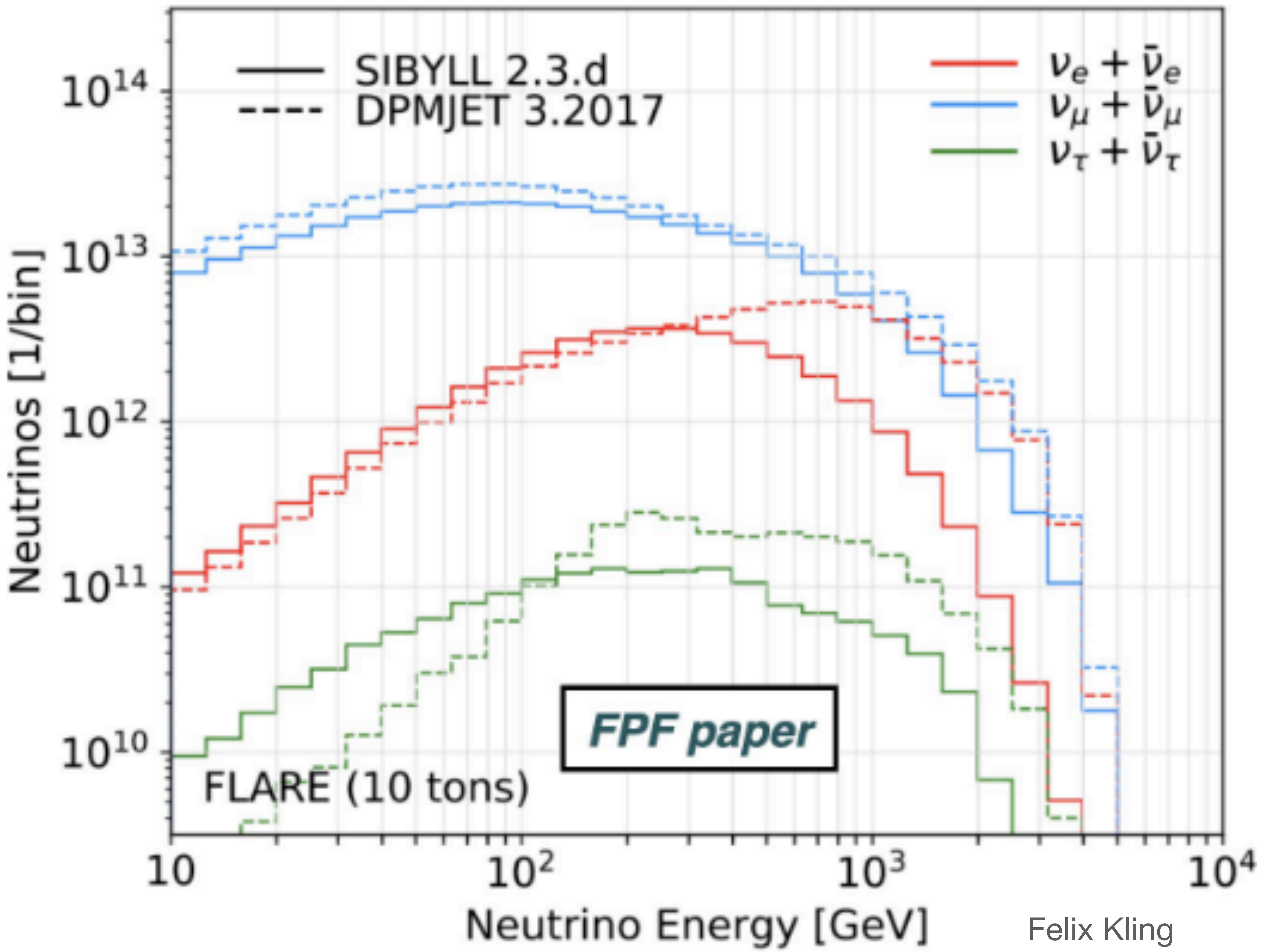
- ***High energy muon neutrino interactions require tagging of ~ 1TeV muons and containing and measuring the hadronic shower.***
    - Some exclusive states may need to be measured for determining the flux. Kinematics at the vertex would be desirable.
- ***High energy electron neutrinos require separation of single electron showers from the large events***.
    - For >300 GeV there is large contribution from charm. Energy resolution is needed.
- ***Tau neutrino detection needs excellent kinematic measurements of the tau decay products (focus on leptonic channels)***
    - Spatial resolution < 1 mm scale needed at the vertex if vertex based separation is desired. These studies need time to mature.

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.

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.



Felix Kling

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 next^n 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 (this is a work in progress)

Physics topic	Events/ 3000/fb-1/10 ton	Fiducial Event containmen	Elec ID	dE/dx	Mu ID	Tau ID	Hadronic shower	Muon momentum	Practical Energy threshold	Energy resolution	Lepton kinematics	vertex kinematics Spatial 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			Yes		10 GeV	30%	yes	
Tau neutrino cross section	5E+03	yes	yes	yes	yes	yes	yes	yes	10 GeV	30%	yes	yes
Charm and QCD measurements	rates >100 GeV	yes	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	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	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 coordinatior		

A single detector may not be able to fulfill all these requirements, but broad capability is desirable.
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, and a hadron containment calorimeter.
- 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.
  - 100 GeV tau lepton has $\gamma c\tau \sim 5mm$ (detection will most likely have backgrounds.), however the transverse decay length is invariant ~ 100 μm, and so we need transverse resolution of < 1 mm.
  - 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. (see Pietropaolo, LNGS-92-20)

Key technical issues for noble liquid detectors are: (To be covered by Bian and Linden.)

- **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.**

Tau detection with LAr

In fig. 3 we show a typical event generated by MonteCarlo as it is seen by the LAr TPC. In fig. 4 we show the jump in the ionization along the event development where we have excluded the large angle low energy tracks. This jump corresponds to the ionization due to two minimum ionizing particles.

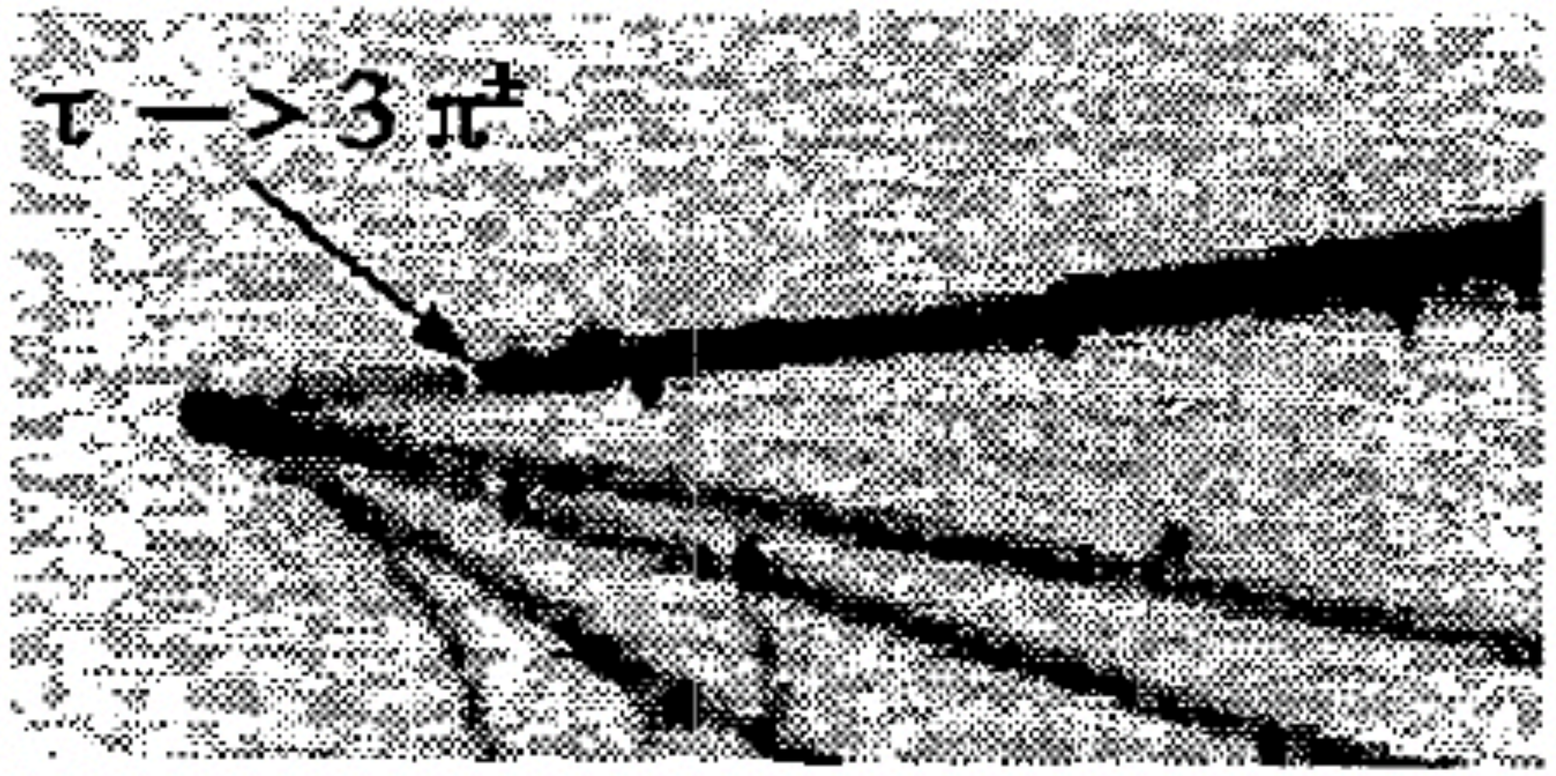


Fig.3 Simulation of a ν_τ CC interaction followed by τ decaying in $3\pi^{\pm}$.

LNGS - 92/20
January 1992

THE ICARUS LIQUID ARGON TPC:
A NEW DETECTOR FOR ν_τ SEARCH*

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)
- Snowmass does not guarantee resources. It is just an endorsement of science.

US side of the process

Apologies in advance for boring you.

- All funds for particle and nuclear physics activities come from DOE and NSF. (including salaries at the national labs)
    - Dollars are classified as either “Research” or “Project (construction)”
- Decisions on deploying both research and project dollars depend on the guidance made in the P5 (particle physics prioritization) subpanel every 5-7 years.
- P5 subpanel reports to the HEPAP (permanent) panel which is charged by the DOE and NSF.
- The P5 process starts with a community (Snowmass) report which was completed earlier this year.
- Next P5 report is expected in late 2023. Chair of this is announced.
    - ***P5 will need enough information on FPF and FLARE to map it into the physics and financial roadmap for the US from now to the end of the decade. This information could be a CDR or a white paper (due summer 2023).***
    - ***Along with the report, a credible estimate will be needed. We must define “credible”.***

Extremely Preliminary plan for later discussion

	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 detetor 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 exceution 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

- Let's unlock a new source of neutrinos => the LHC, with the Forward Physics Facility.
- 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.