Liquid argon and other detection techniques (and requirements)

An attempt to consider what is necessary/sufficient for a physics program.

Sources:

- FASER, FASER-nu proposals.
- Event rates from Felix Kling and from 2002.03012 (our work)
- Light DM detection far forward…2101.10338
- Liquid argon facility considerations - Resnati (may 2021)
- Civil Engineering study March 1-4, 2021 (John Osborne via Jamie Boyd)
- microboone/protodune TDRs
- First LHC neutrino events ! 2105.06197

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Basic beam/source parameters for HL-LHC

Parameter	**Value**	**Comment**
p-p Collision energy	14 TeV	
Crossing frequency	40 MHz	
Bunch spacing	25 ns	Use to reject non beam backgrounds
Bunch length	90 mm	
Half Crossing angle	250 micro-rad	Will move the axis (sideways?) by 15 cm at 612 m
Crab crossing	yes	Will spread collisions over larger length
Peak Luminosity	5 x 10^{34} /cm^{2}/sec	Could go higher by 50%.
Total/inelastic X-sec	111/85 mbarn	
peak N events/crossing	135	Spread out over ~9 cm and 300 ps
Total integrated Lumi	3000 /fb	10 times more than run II
Per year Lumi	350 /fb	This could be important for physics output
Start of operations	Year 2027	Reviews, Underground construction, and detector installation must complete.
Years of operation	10 years	Is it possible to change or upgrade detectors during this time ?
p-Pb (NN Luminosity)	>100 /pb @ ecm(NN) ~ 8 TeV	This is in a short run. orders of magnitude less than p-p.

Bordry 2018

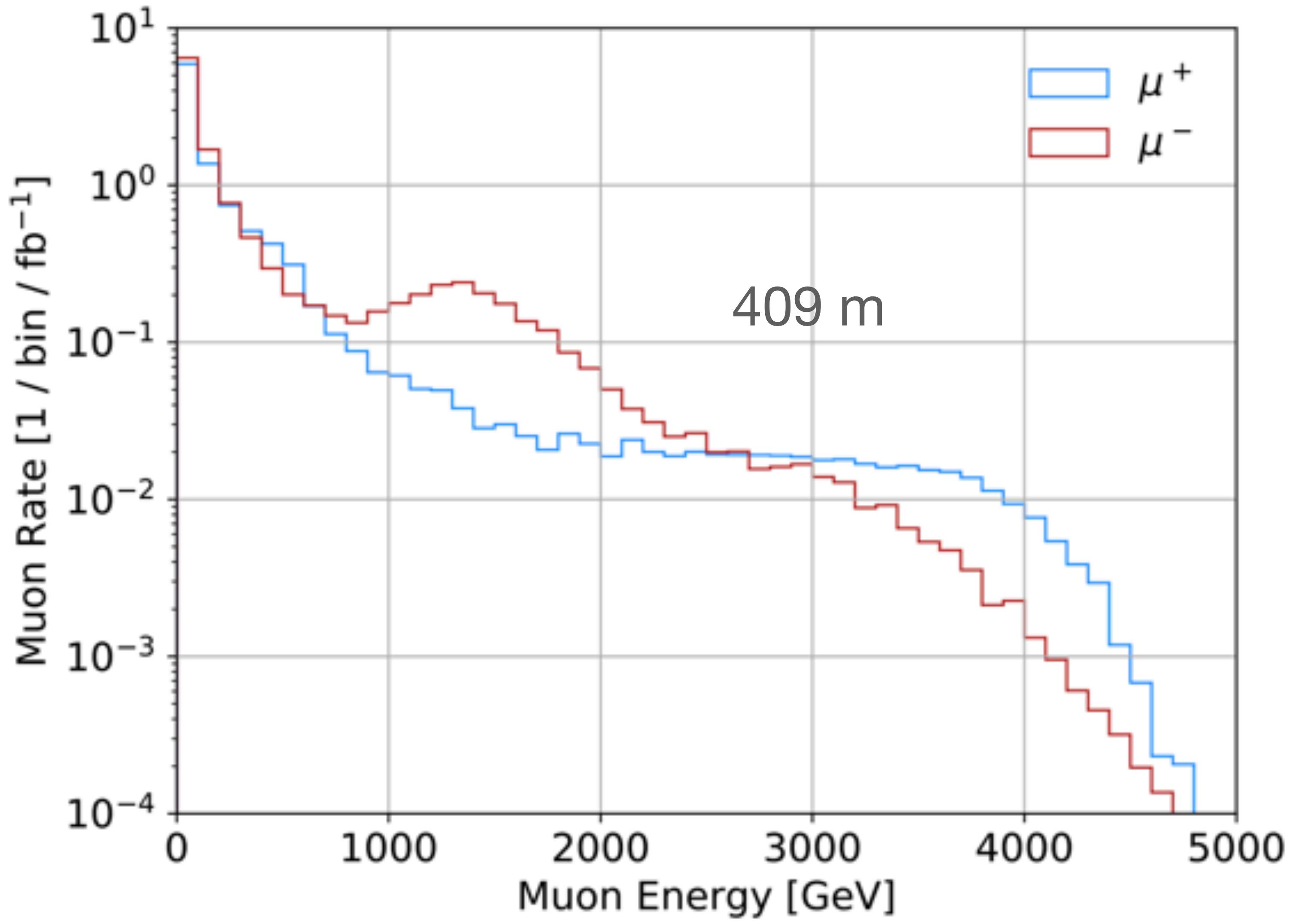
Scientific goals for the FPF

These may have to turn into priorities, otherwise decisions could become difficult.
These are no exclusive goals, but they serve to define the detector capabilities.

- Goals for neutrino physics (focus on these for the rest of this talk)
    - 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.
- Goals for dark sector physics.
    - Detection of dark sector photon decays in the detector volume
    - Detection of light dark matter scattering in detector
    - Search for milli-charged dark matter particles.

Experimental conditions

Approximate fluxes, rates of backgrounds



- **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**

Minimum distance	612 m
Total Lumi/max lumi	3000/fb ; 5x10^{34} /cm2/sec
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 (2x10^{-8}/cm2/crossing)
Neutral hadron flux > 10 GeV (10^{-4} of muons)	~3 /cm^2/fb^{-1}
Total neutrino rate (all flavors)	~50/ton/fb^{-1}

2105.06197

Tau neutrino flux and oscillations measurement

Current best measurement from Pilot run

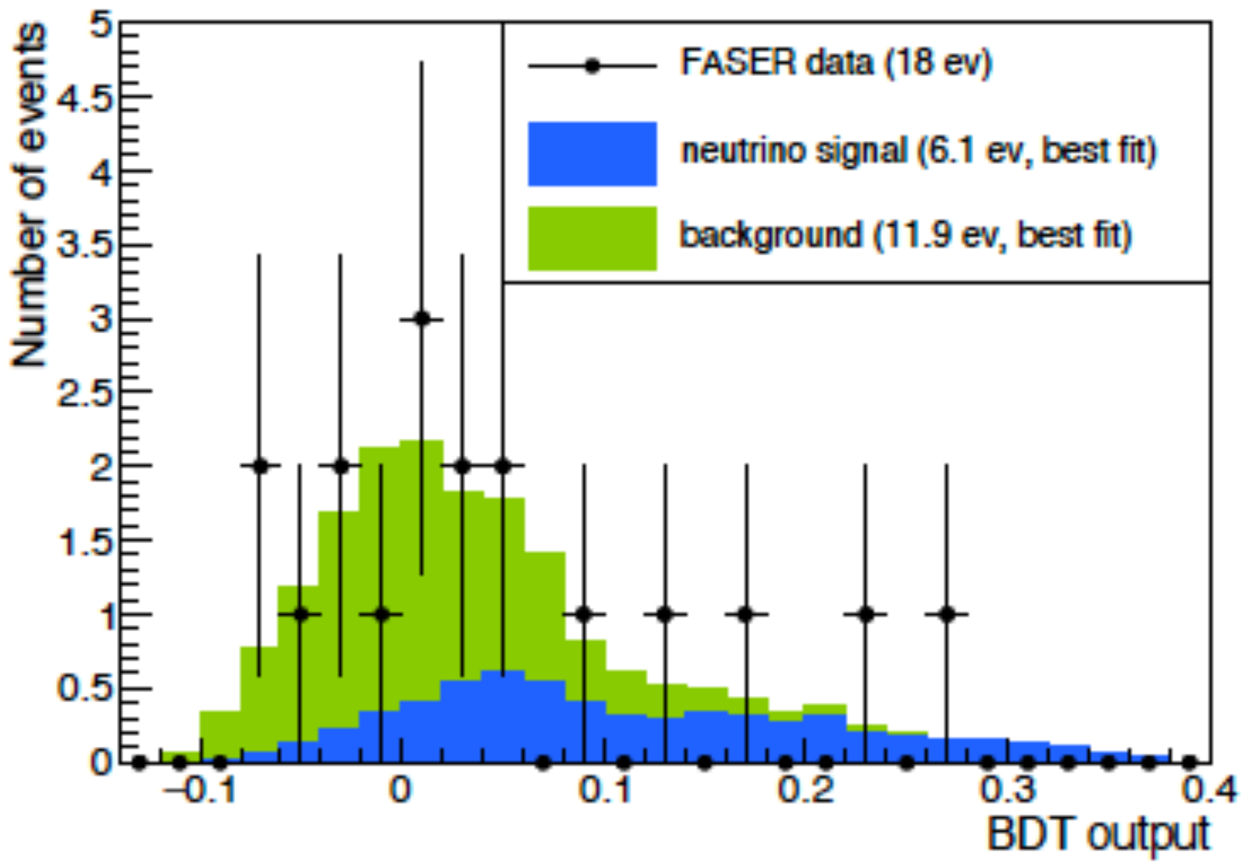
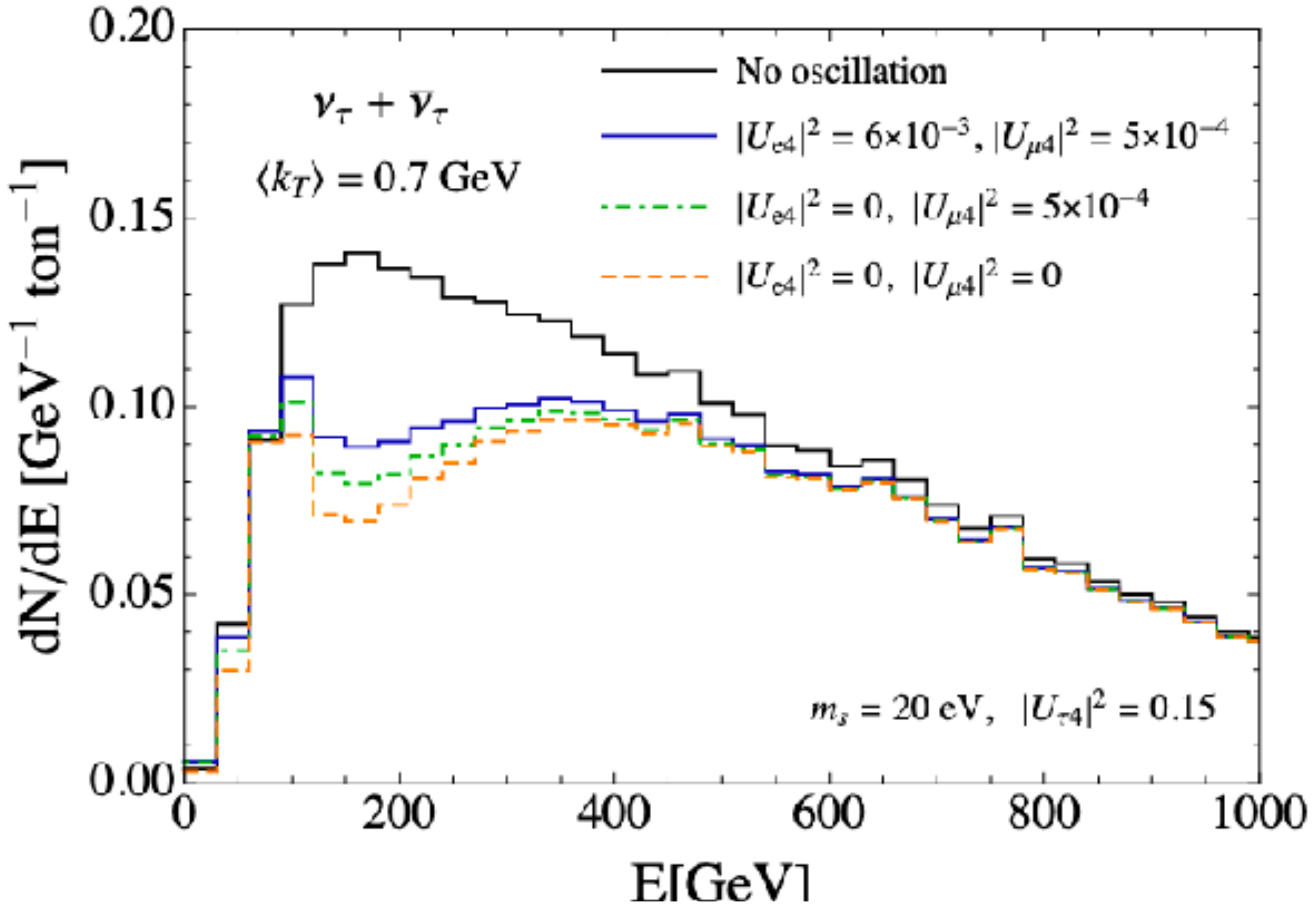


FIG. 6. The BDT outputs of the observed neutral vertices, and the expected signal and background distributions (stacked) fitted to data. Higher BDT output values are associated with neutrino-like vertex features.

Challenge

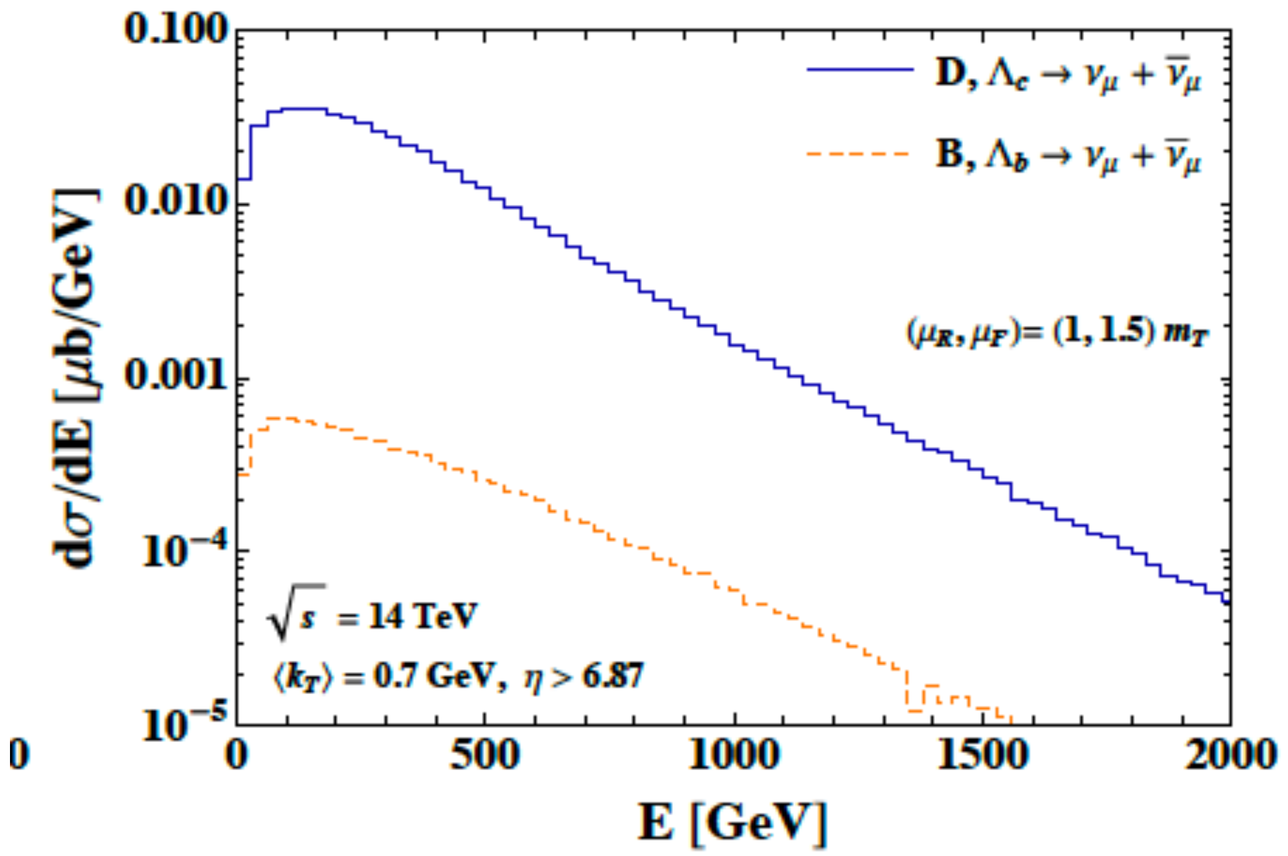


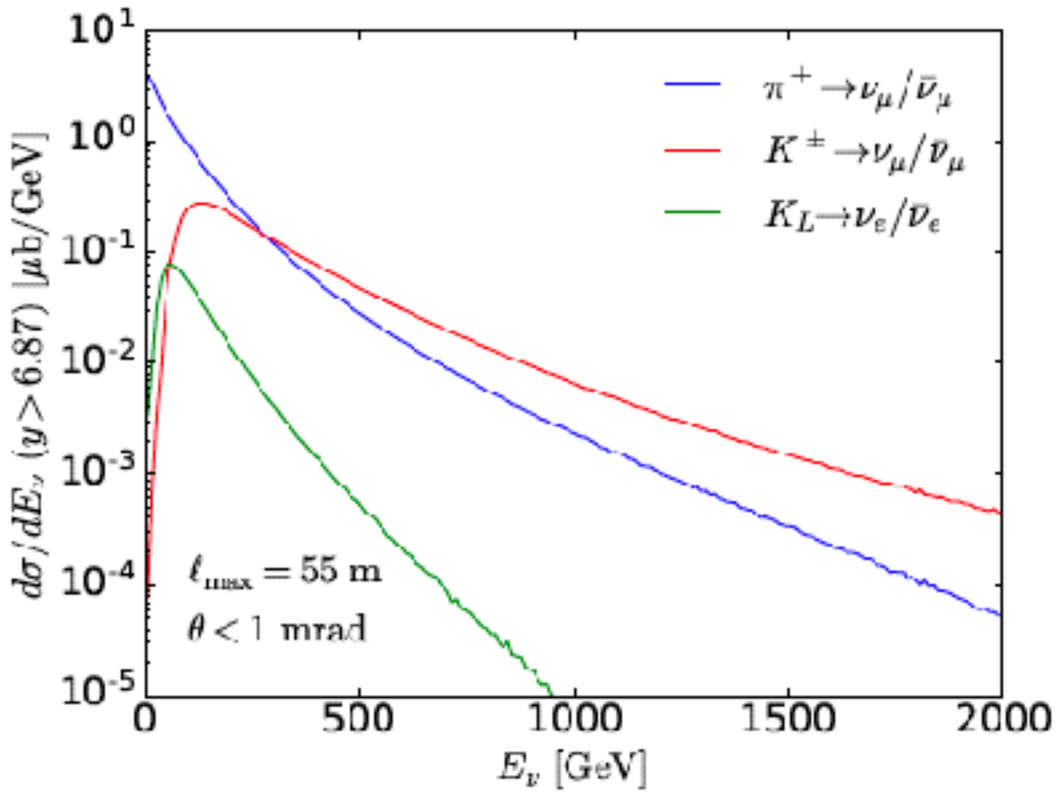
2002.03012

$$P(\nu_\alpha \to \nu_\beta) \simeq \delta_{\alpha\beta} - 4(\delta_{\alpha\beta} - |U_{\beta n_\nu}|^2)\,|U_{\alpha n_\nu}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right),$$

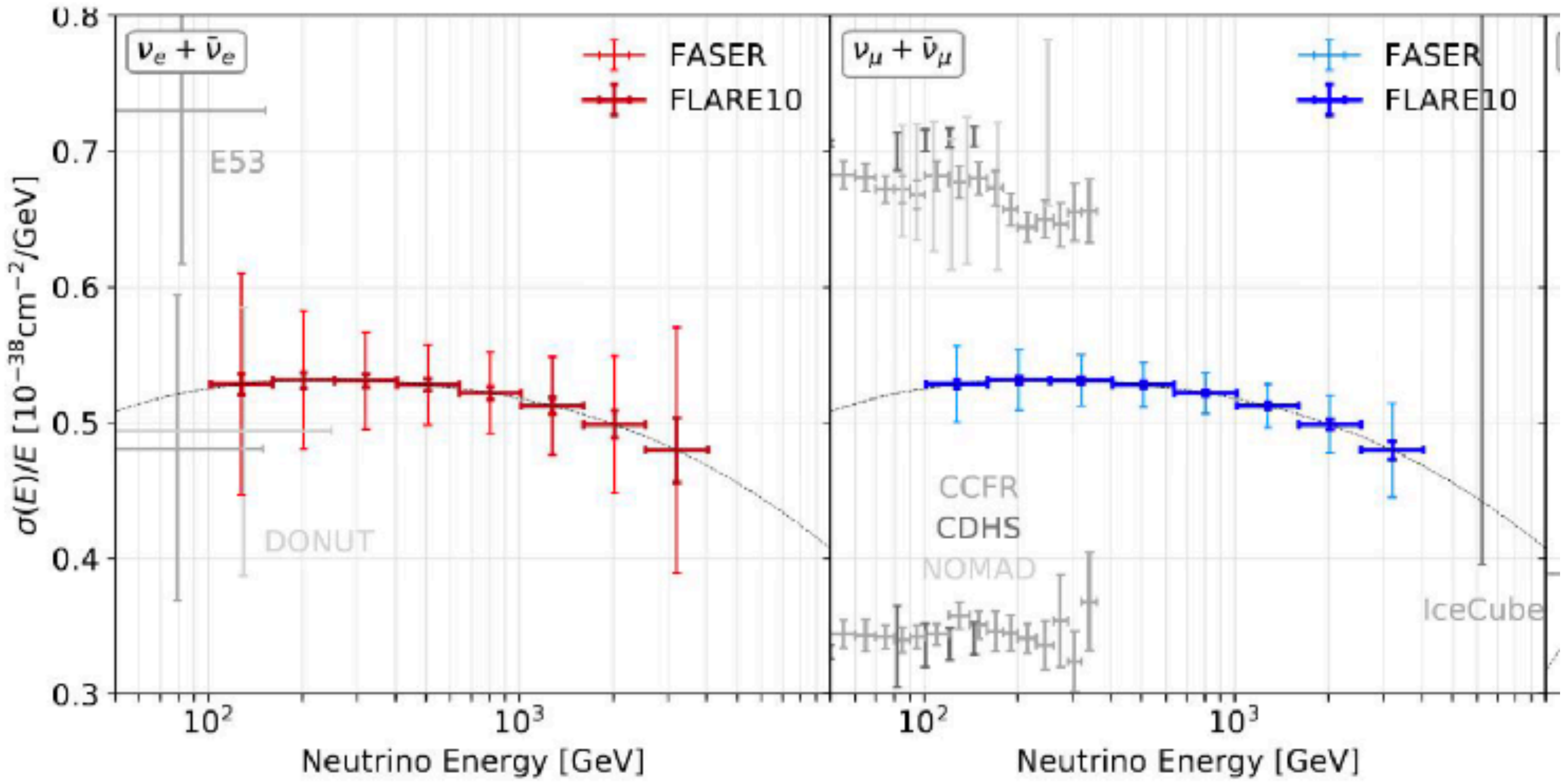
- **To obtain precise information on tau neutrino flux and cross section, low background measure of nu-taus is needed. Emulsion (FASER-nu) experiment with muon identification will be the tool.**
- **Given the poor absolute normalization of the tau neutrino flux, a distortion in the energy spectrum is the best signal for oscillations.**
- **Oscillations: Sensitivity to sterile neutrinos with mass ~ 10 eV through ν_τ disappearance. Essentially a two neutrino scenario at short distances (600m) and large energy > 100 GeV. Current constraints (Icecube) suggest that $|U_{\tau4}|^2 < 0.15$ is possible.**
- **With current constraints, $\nu_\mu \to \nu_\tau, \nu_e \to \nu_\tau$ (through the sterile channel) could partially fill in the distortion. Constraints on $|U_{e4}|^2$ are improving.**
- **However, to perform this measurement we need to measure the tau neutrino energy with ~20% resolution.**

Neutrino cross section measurements





Uncertainties on this are very large.

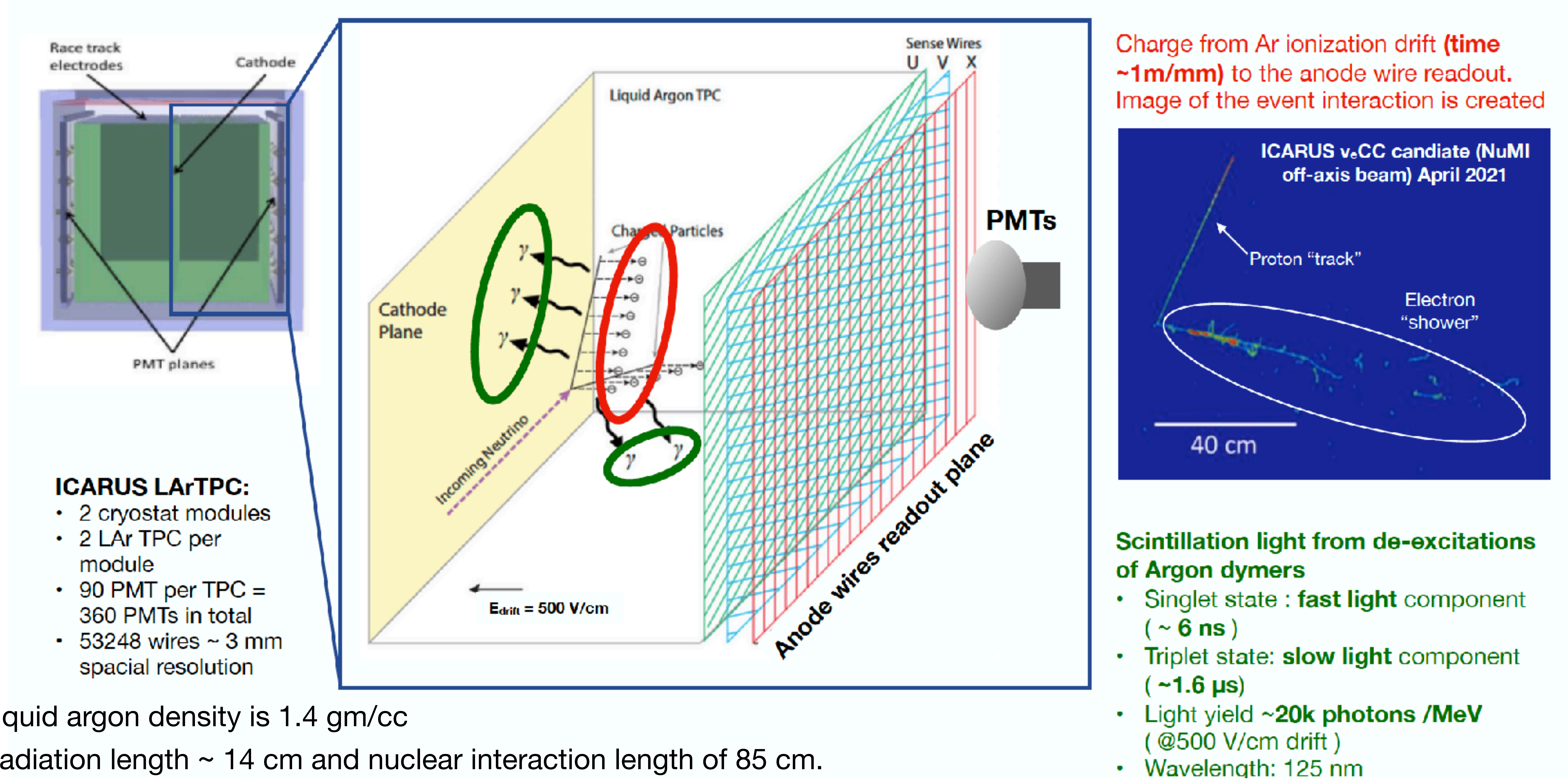


- Muon and electron neutrinos have two components: from heavy meson decays and pi, k decays (larger); both of these have large uncertainties. These could improve with more data, studies…
- In-situ normalization for the flux using exclusive measurement with CCQE or Low-nu method could be useful. Inverse Muon Decay might be crucial (but rate is low).
- Need e/mu identification needed for electron neutrino cross section and studies of charm hadron yields (with cut on E>500GeV)
- Need charge identification for muons. Magnetic spectrometer is needed.
- Dense calorimeter for CC/NC identification for muon events.
- Is it possible to tag mu/e neutrino events with collisions that may have a heavy flavor ? Extremely good Timing will be needed along with integration with collider data. This may improve the precision on the measurement at the cost of statistics.

Detector capabilities needed for neutrino physics
Neutrino event rates are somewhat on the low side for various predictions. Ref: F.Kling

Physics	Signature	Signal rate/3000/fb into a 1x1x7 m detector at 620 m.	Detector mass needed for physics	Capabilities
Measure nu-tau flux	Decay signature of tau. Kink over few mm	200/ton	10 tons.	Vertex reconstruction with kink detection. Muon ID to reduce background.
nu-tau oscillations	Distortion in energy spectrum of total energy.	200/ton	~100 tons if using kinematic reconstruction with exclusive decays.	Kinematic reconstruction with tracking and calorimetry. CC nu-tau interaction energy measurement.
nu_mu/nu_e cross section	Long muon track or high density EM shower.	numu: 25k/ton (mainly from Pi decays) nue: 5k/ton	10 tons	Excellent muon and electron ID. Calorimetry for energy measurement Include hadronic absorber.
Charm production	Electron neutrinos > 500 GeV	nue: 5k/ton	10 tons	Excellent electron ID with low background.
Electro-weak measurements	$\nu_\mu\ \bar{\nu}_\mu DES\ CC/NC$	20k/ton, 6k/ton for CCnu and CCbarnu 13k/ton for NC	100-1000 tons	Muon Charge identification, CC/NC separation. Hadronic calorimeter.
neutrino electron elastic scattering. Inverse muon decay.	Extremely forward electro-magnetic shower. Very forward Muon	6/ton (inclusive) 20/ton (IMD)	100 tons	Excellent electron ID, and kinematic resolution. IMD might be important for flux normalization.

Liquid argon scientific capabilities



Charge from Ar ionization drift **(time ~1m/mm)** to the anode wire readout. Image of the event interaction is created

ICARUS LArTPC:

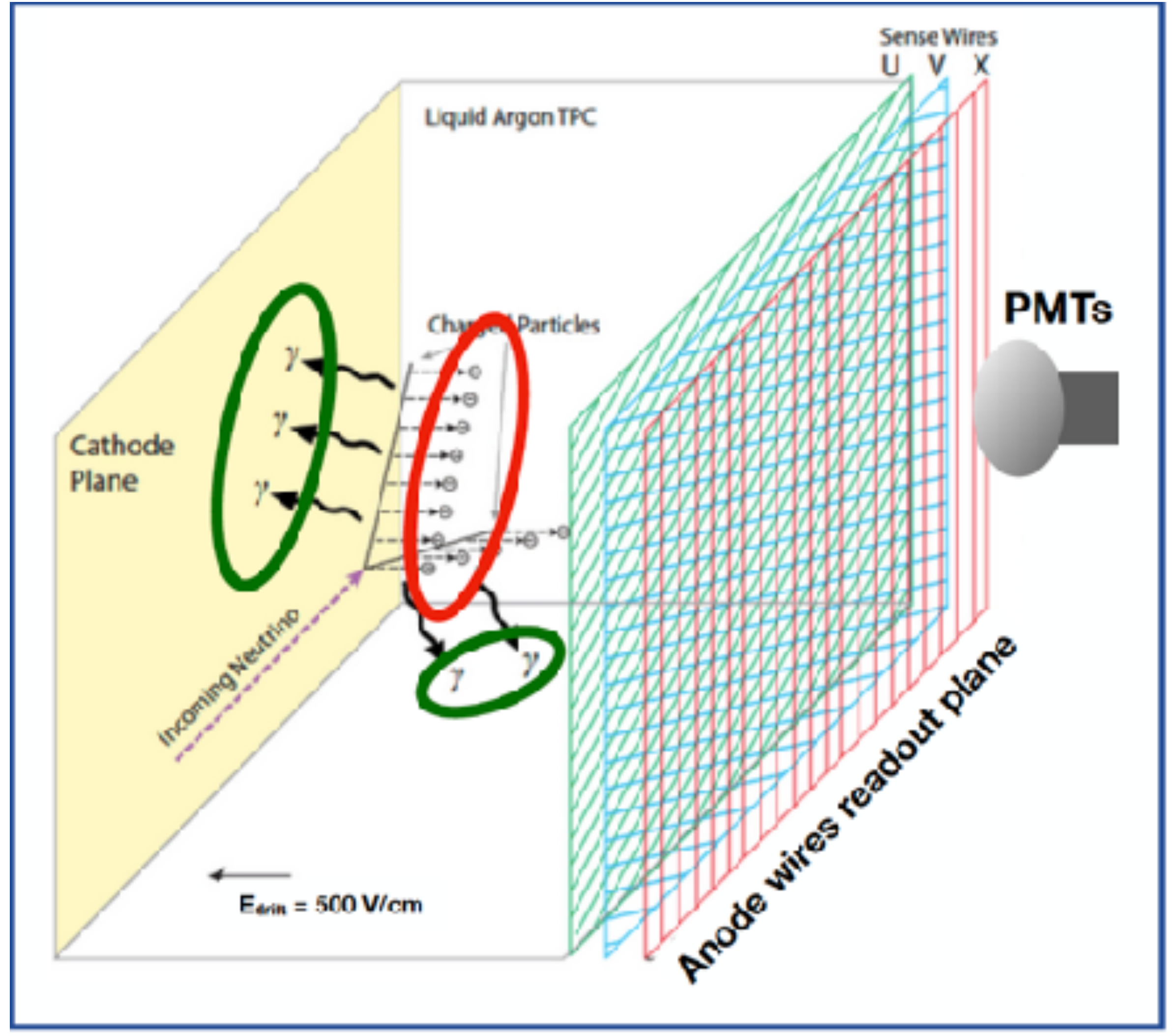
- 2 cryostat modules
- 2 LAr TPC per module
- 90 PMT per TPC = 360 PMTs in total
- 53248 wires ~ 3 mm spacial resolution

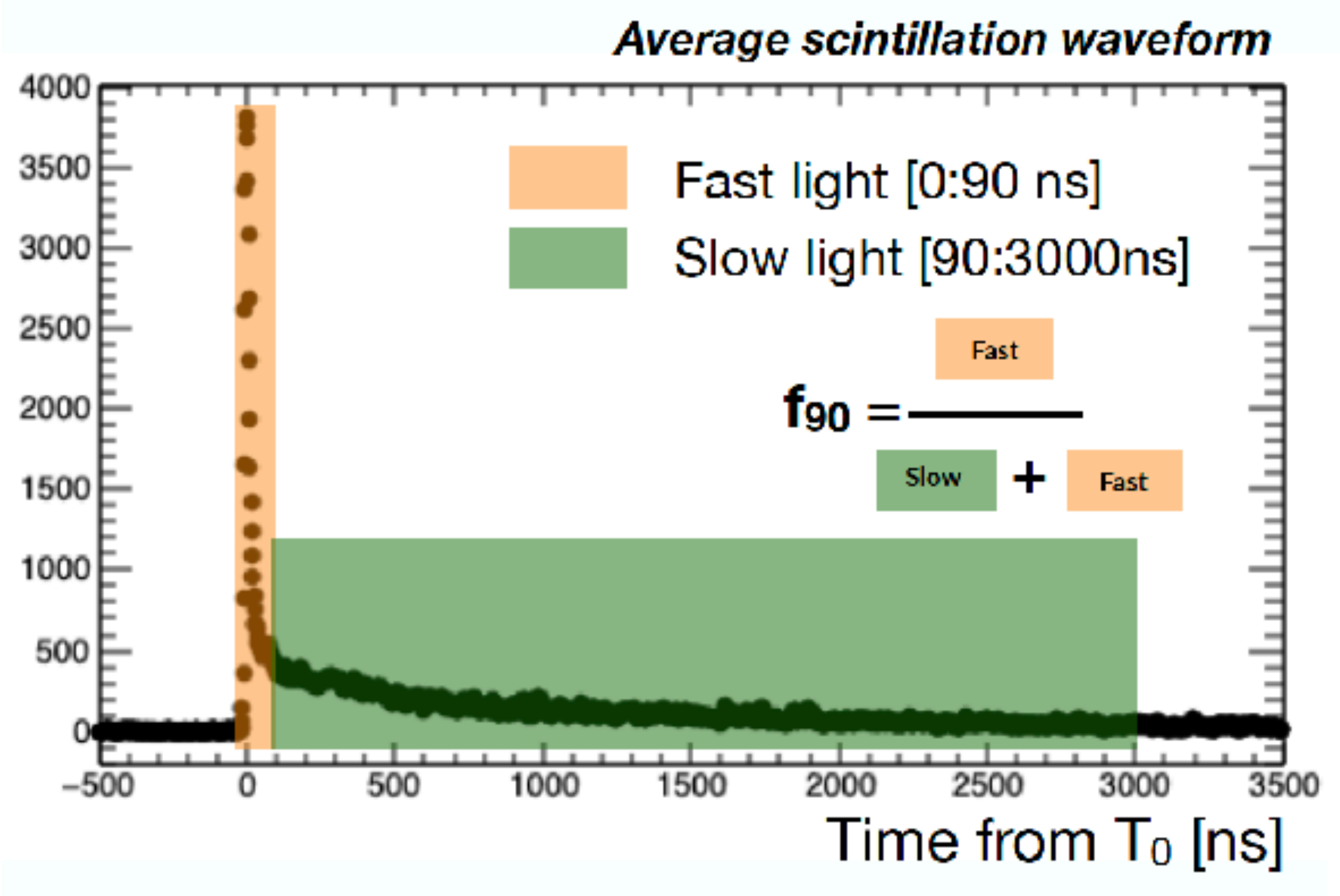
Scintillation light from de-excitations of Argon dymers

- Singlet state : **fast light** component (~ **6 ns**)
- Triplet state: **slow light** component (**~1.6 µs**)
- Light yield ~**20k photons /MeV** (@500 V/cm drift)
- Wavelength: 125 nm

- Liquid argon density is 1.4 gm/cc
- Radiation length ~ 14 cm and nuclear interaction length of 85 cm.
- Excellent muon/gamma/ electron identification.
- Good choice for neutrino cross section measurement, higher mass is needed for nu+e elastic scattering.

Liquid argon technical issues

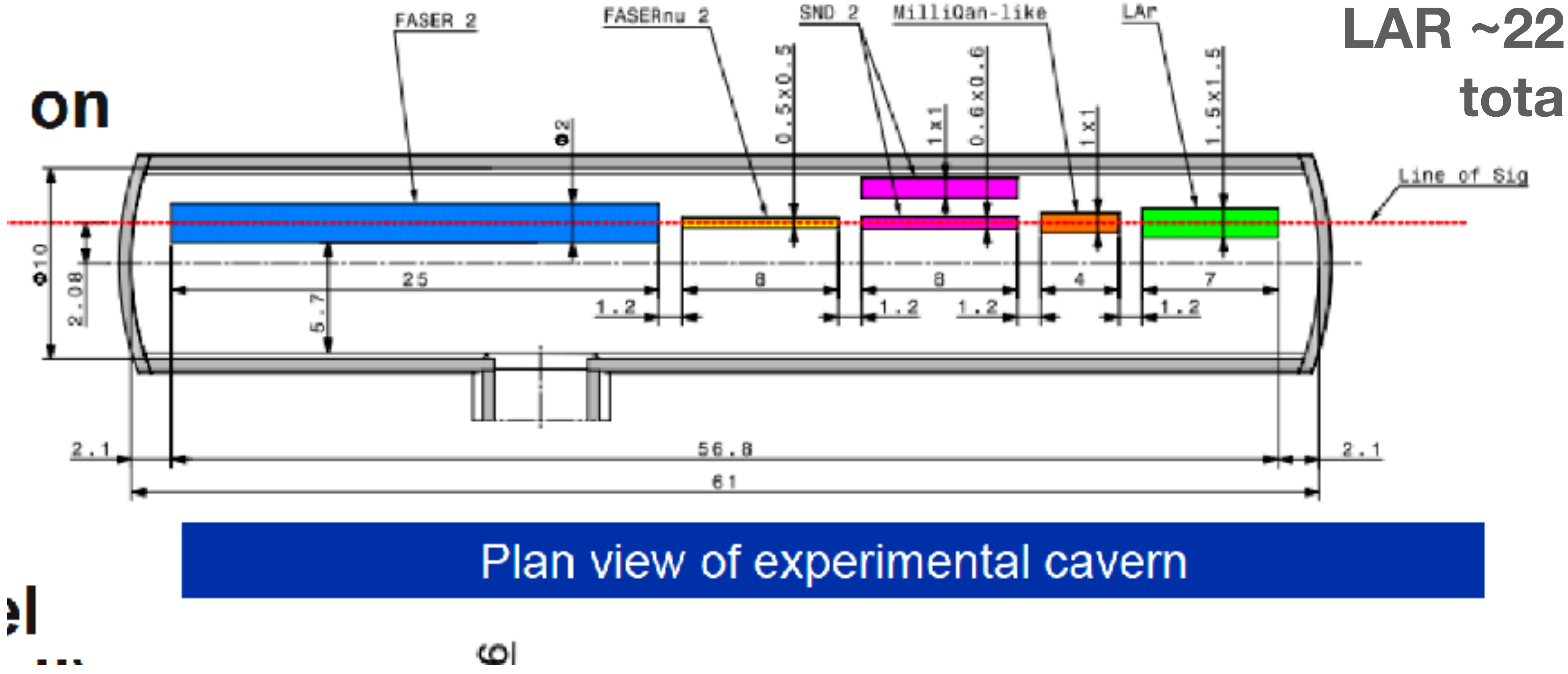




Given the slowness of the drift, we need to consider the scintillation as the primary readout to isolate events from bunch crossings.

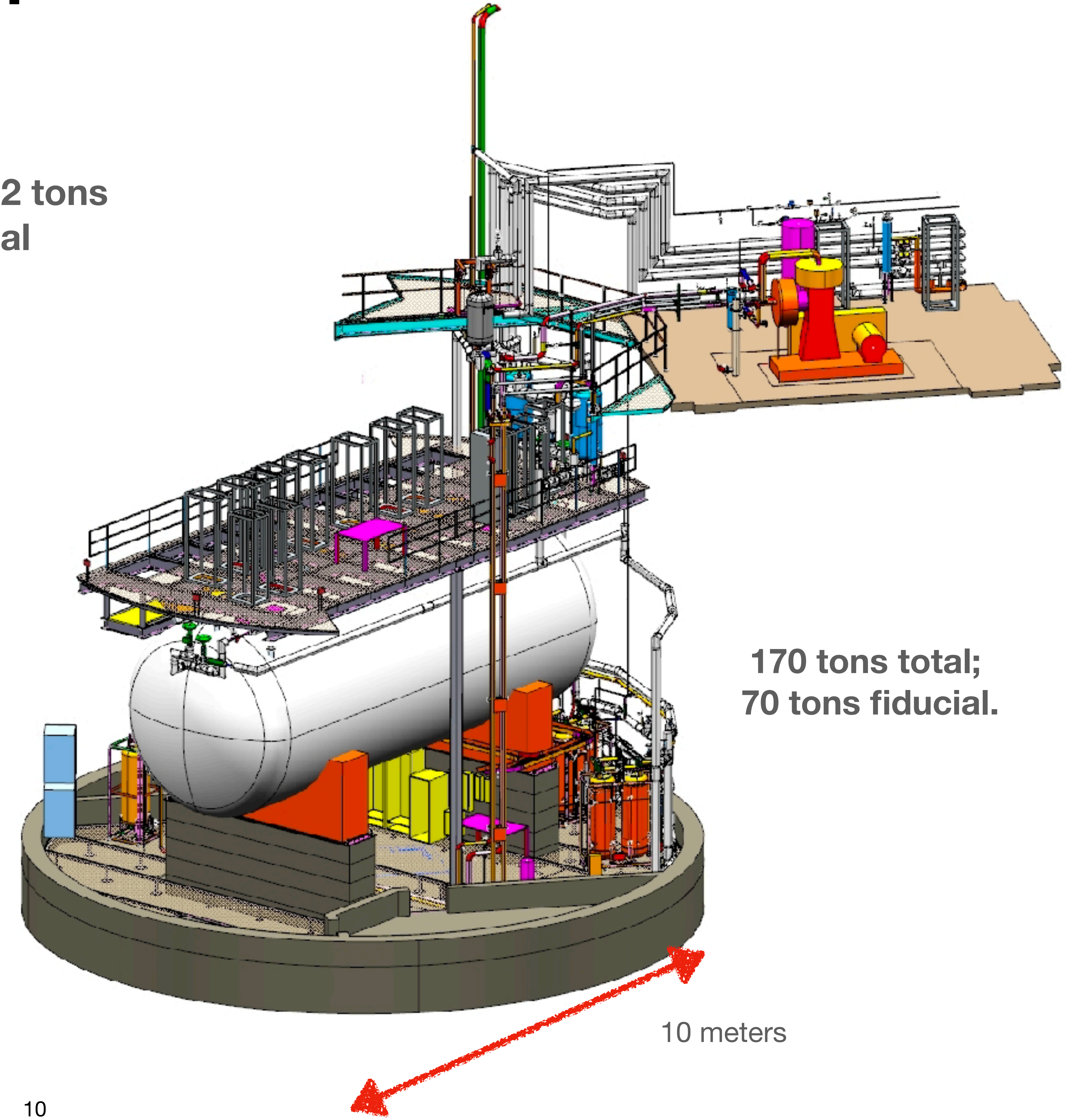
- Liquid argon time projection chamber will have drift time of ~0.5 msec if drift length is 0.75 m. During this time there will be 20000 bunch crossings.
- For a liquid argon detector with cross section of ~2 m^2 there will be <8.5 tracks through the detector and ~10^{-3} neutral hadrons. These must be separated from neutrino events.
- For extremely forward events, the wire readout cannot be used because of isochronous events (all wires get hit at the same time).
- To reduce geometry related ambiguity, pixel readout is needed.
- A high density photon readout is needed to measure the time of the events to isolate events related to bunch crossings.
- Possible Analysis path: isolated events for each crossing -> reject those entering the detector -> match the pattern to TPC pixel readout.

Space considerations (based on old pictures)



LAR ~22 tons total

- overhead Crane might be a good idea for such a long 60 m tunnel.
- Considerable space is needed for cryogenic and support equipment for the liquid argon detector.
- The space probably does scale with the size of the detector.
- Possible to consider a parallel tunnel for support equipment ?



170 tons total;
70 tons fiducial.

10 meters

Conclusion

- **Presented a very preliminary survey of scientific requirements and detector capabilities that are needed. An integrated approach to the detectors in the FPF will yield the best science.**
- Focus was on neutrino physics (mainly because it is a well known target of opportunity and it also represents a background to any new physics).
- The physics interest as presently seen is (in increasing difficulty)
  - tau neutrino flux and associated heavy flavor physics,
  - neutrino cross sections in the 1TeV range,
  - tau neutrino oscillations, and
  - perhaps electroweak measurements.
- A preliminary table of needed detector capabilities shows that the needs are quite different for these measurements.
- Liquid argon has excellent EM-shower and muon ID and could be a good candidate for some of these measurements.
- For a liquid argon TPC, the rate of muon background is comparable to the cosmic ray backgrounds in present short baseline detectors at FNAL. However it is beam related, and therefore timing cannot be used to reject it.
- Given the geometry (extremely forward), a pixel readout and high density scintillation measurement is needed to isolate neutrino events for each bunch crossing and contained in the detector.

Event rate table

Rate depends on the angular acceptance as well as mass. This creates some peculiarities. Simulation uncertainties add to the variation.

calculation	faser-pilot	faser-nu	Faser-nu proposal	flare-10	From JB
Normalization mass*fb	**ton*fb**	**1 ton*fb**	**1 ton*fb**	**1ton*fb**	**1ton*fb**
angular range	**~10cm/480m**	**25 cm/480m**	**25 cm/480**	**1 m / 620 m**	**—**
numu/anti-numu	**23.0/6.0**	22/5.9	114	7/2.1	43
nue/anue	**3.7/2.1**	3.42/1.97	7.22	1.1/0.53	10
nutau/anutau	**0.063/0.034**	0.078/0.034	0.12	0.049/0.019	0.13

Observed total: 45/ton/fb