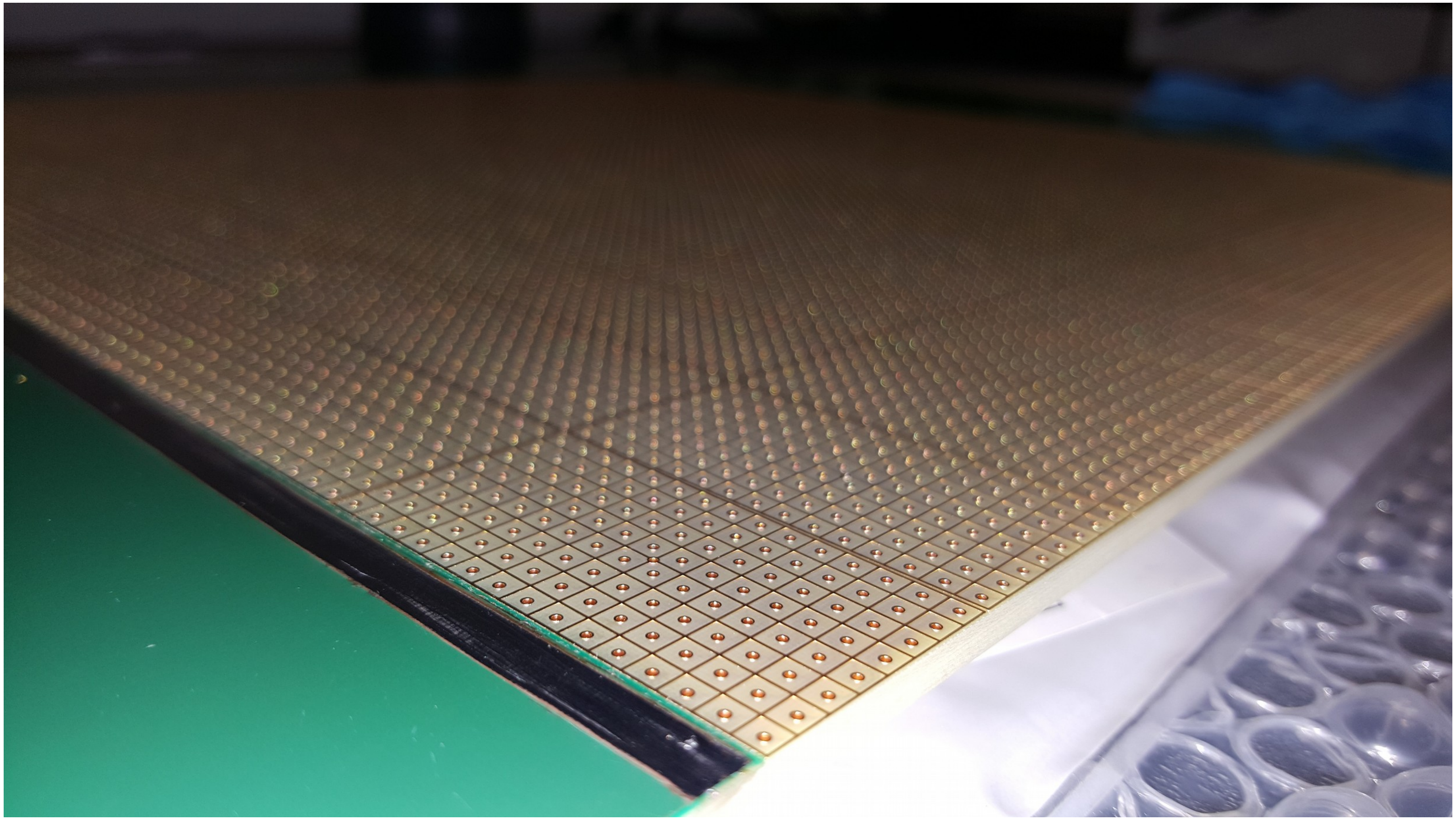
Musings on Requirements for a Pixel Based LArTPC



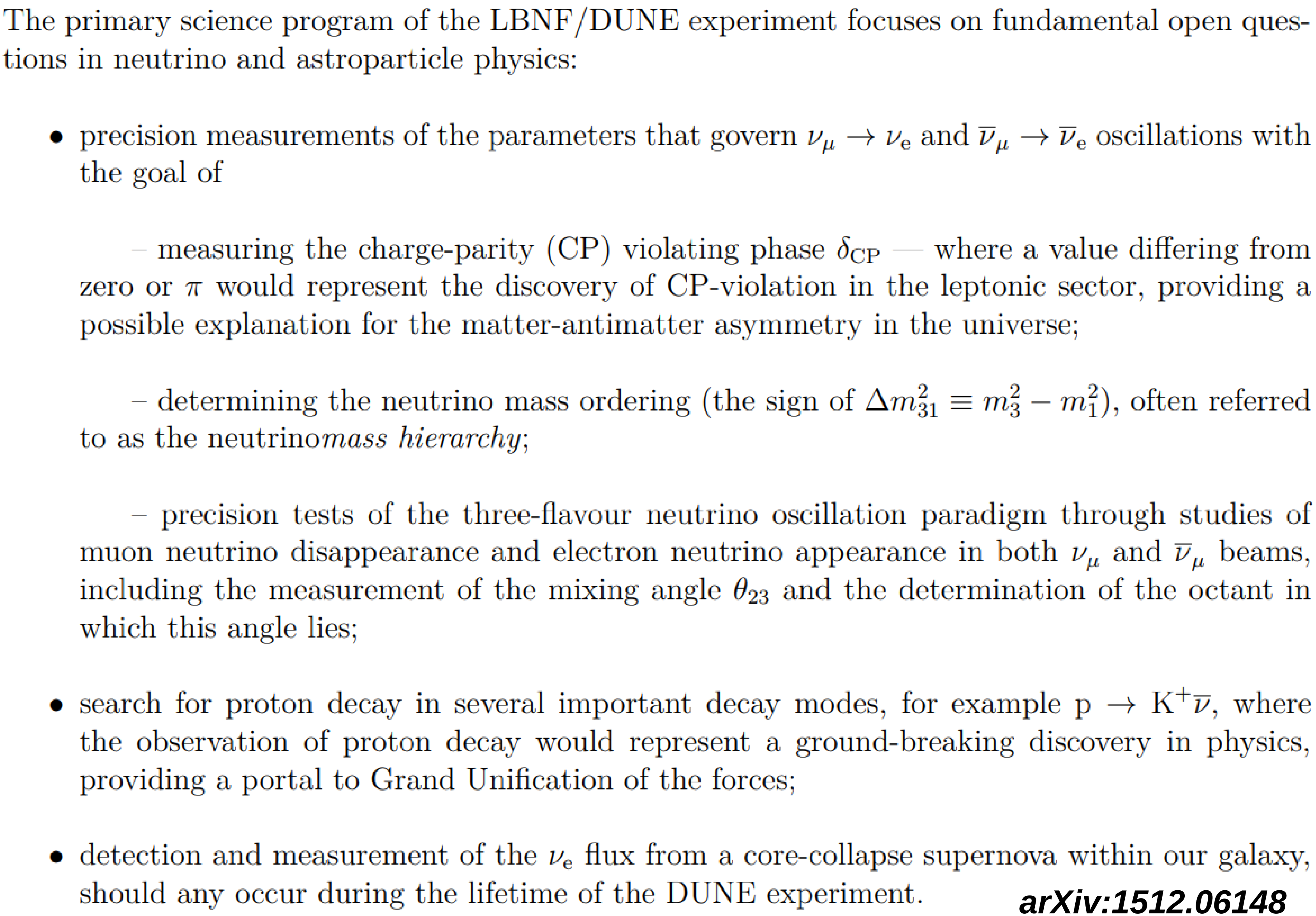
Jonathan Asaadi

University of Texas at Arlington

Requirements

- **Thinking about what are the requirements of a pixel based LArTPC, I will use the “Primary Science Drivers” as defined in the DUNE Conceptual Design Report (CDR: arXiv:1512.06148) as well as the “Guiding Principles” for the Far Detector Design (arXiv: 1601.05471)**
  - Trying to think about both the detector performance and the physical detector requirements to guide the ideas which will help us evaluate the viability of a pixel based LArTPC for the DUNE far detector
- **Will also rely on the most recent DUNE Interim Design Report for the Single Phase module (IDR: arXiv:1807.10327) to better elucidate the design choices which are at the base of the current detector design**
  - Includes electronics performance, anode plane assembly (APA) quality assurances, photon detection assumptions, etc...

Primary Science Program for DUNE



The primary science program of the LBNF/DUNE experiment focuses on fundamental open questions in neutrino and astroparticle physics:

- precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations with the goal of

  – measuring the charge-parity (CP) violating phase δ_{CP} — where a value differing from zero or π would represent the discovery of CP-violation in the leptonic sector, providing a possible explanation for the matter-antimatter asymmetry in the universe;

  – determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), often referred to as the neutrino*mass hierarchy*;

  – precision tests of the three-flavour neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and $\overline{\nu}_\mu$ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies;

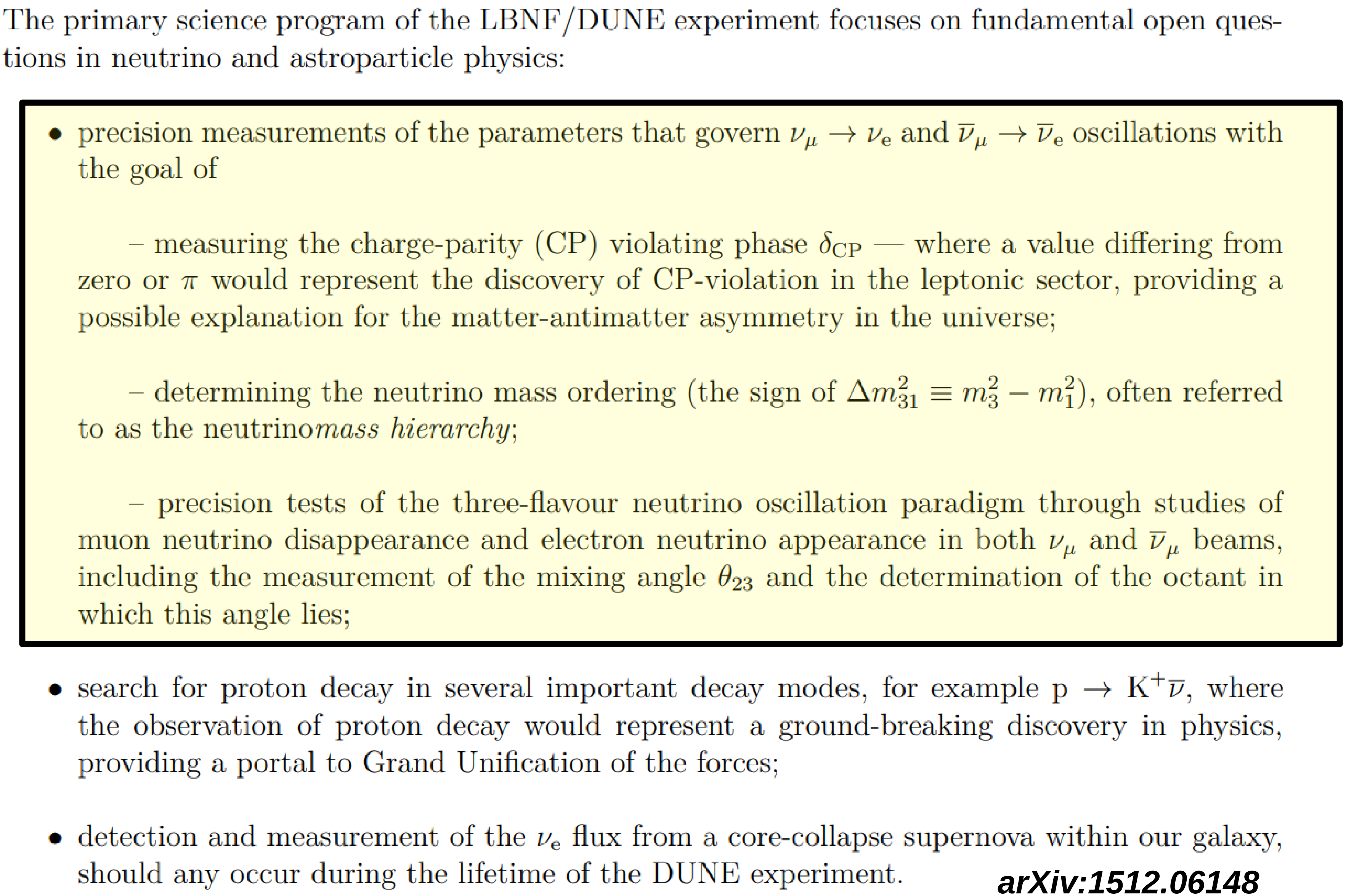
- search for proton decay in several important decay modes, for example $\mathrm{p} \to \mathrm{K}^+\overline{\nu}$, where the observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces;

- detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy, should any occur during the lifetime of the DUNE experiment.

arXiv:1512.06148

- **Additional scientific goals (atmospheric and solar neutrinos, NSI, dark matter signatures) are seen as being possible using the detector performance requirements for the primary program**

Primary Science Program for DUNE



The primary science program of the LBNF/DUNE experiment focuses on fundamental open questions in neutrino and astroparticle physics:

- precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations with the goal of

  – measuring the charge-parity (CP) violating phase δ_{CP} — where a value differing from zero or π would represent the discovery of CP-violation in the leptonic sector, providing a possible explanation for the matter-antimatter asymmetry in the universe;

  – determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), often referred to as the neutrino*mass hierarchy*;

  – precision tests of the three-flavour neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and $\overline{\nu}_\mu$ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies;

- search for proton decay in several important decay modes, for example $p \rightarrow K^+\overline{\nu}$, where the observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces;

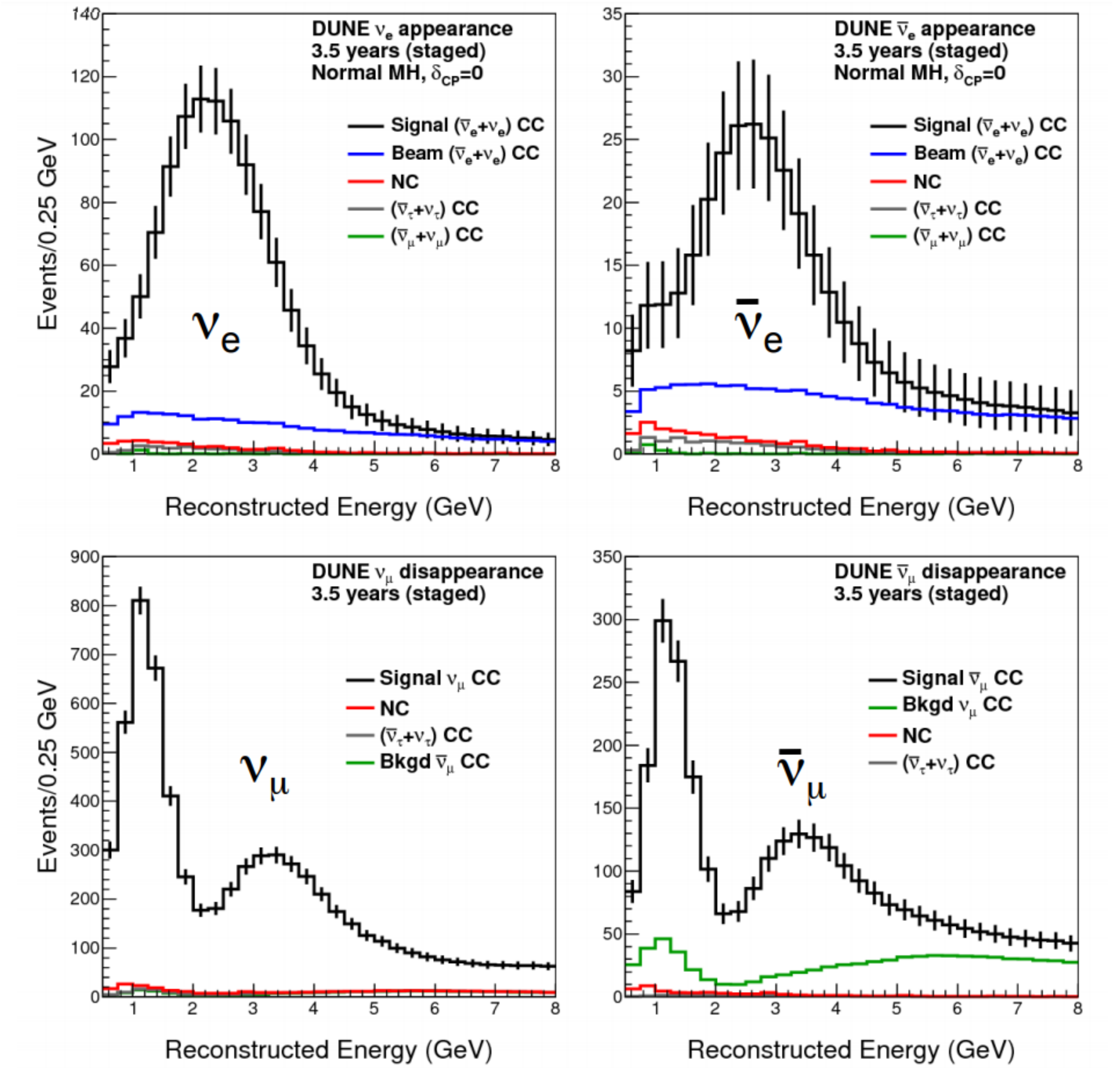
- detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy, should any occur during the lifetime of the DUNE experiment.

arXiv:1512.06148

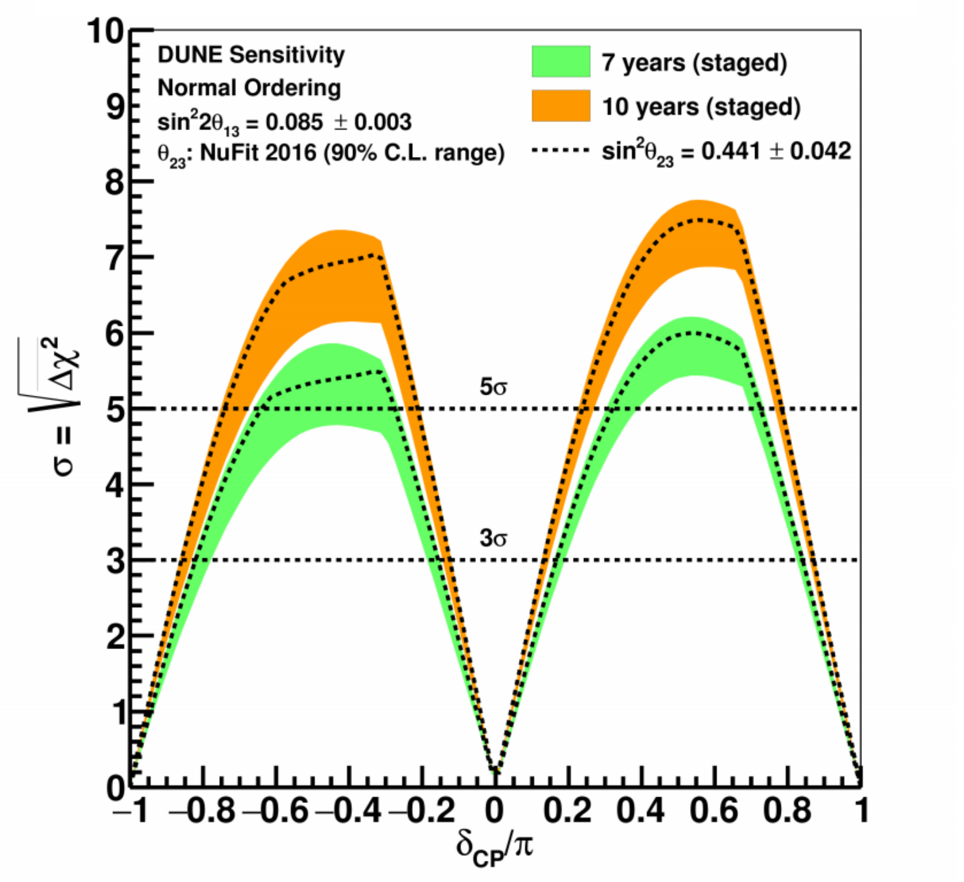
- **Additional scientific goals (atmospheric and solar neutrinos, NSI, dark matter signatures) are seen as being possible using the detector performance requirements for the primary program**

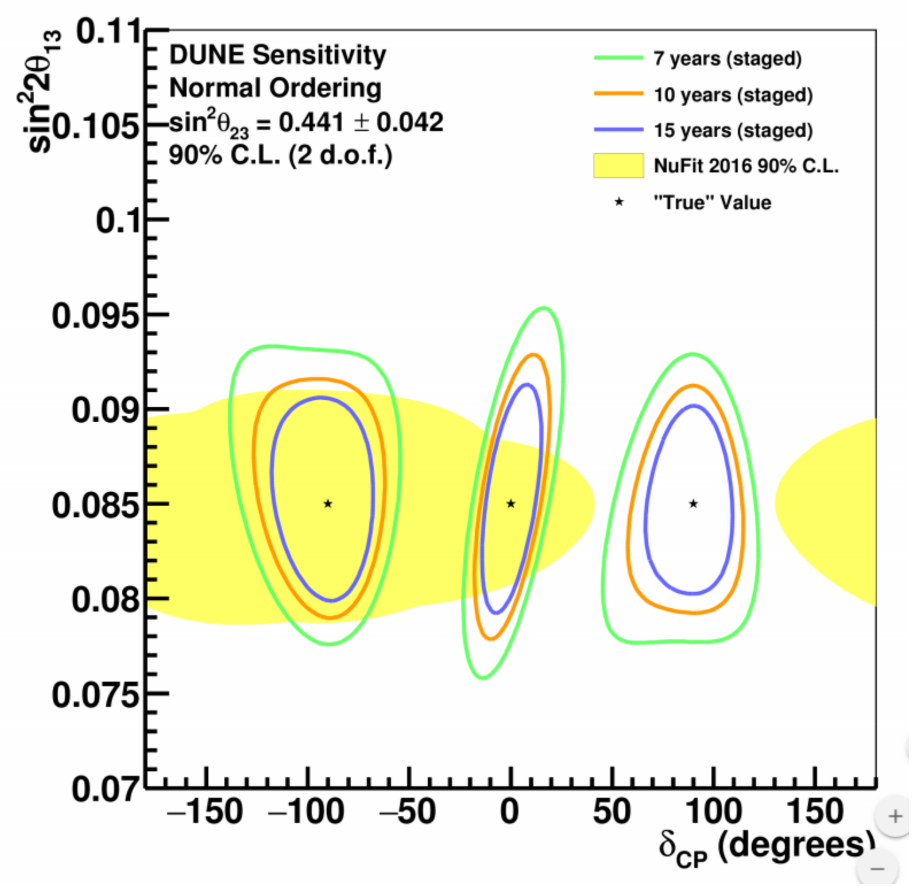
DUNE Oscillation Physics

- **DUNE's sensitivity to the oscillation parameters is based on fast Monte Carlo Detector Response and an efficiency based on a previous hand-scan of data**
  - Updated results from DUNE shown at Neutrino 2018 using fully automated reconstruction match (do better) then CDR assumptions
- **Simultaneous fit to all four spectra is used to extract oscillation parameters**
  - An assumed 5% residual flux uncertainty expected after constraints from the near detector



DUNE Oscillation Physics

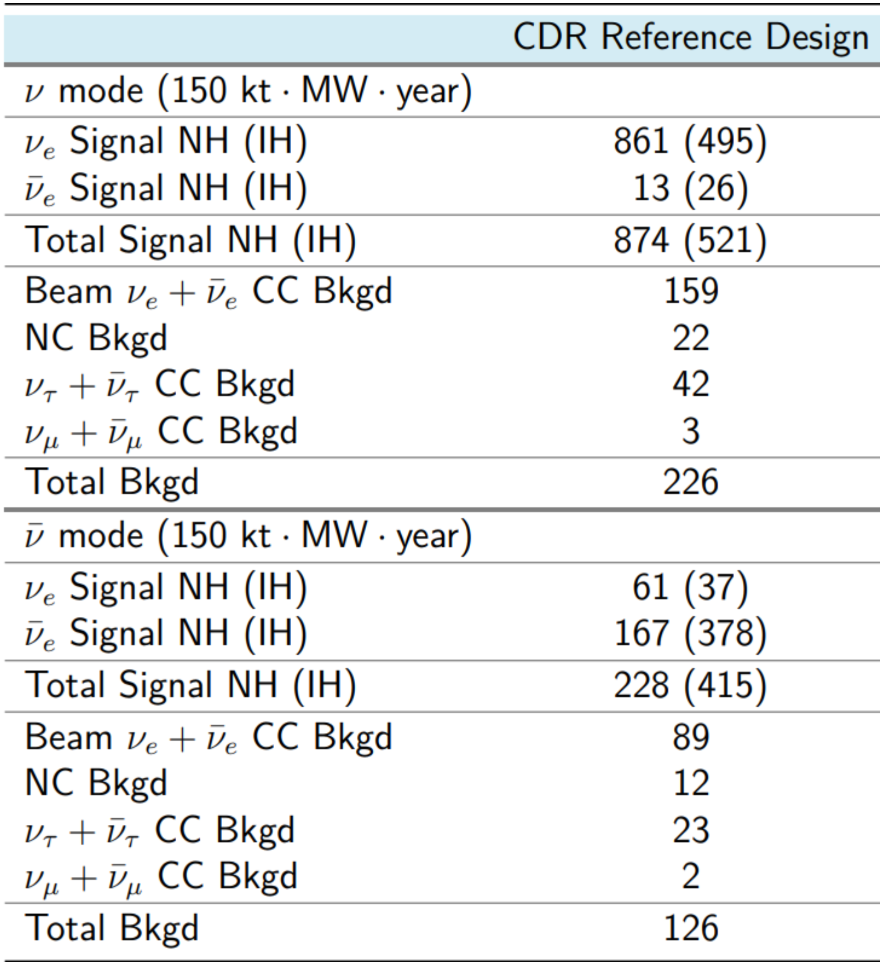




- **Example: CP Violation Sensitivity along with the simultaneous measurement of $\sin^2 2\theta_{13}$**
  - Bands represent variations in the central value of θ_{23}

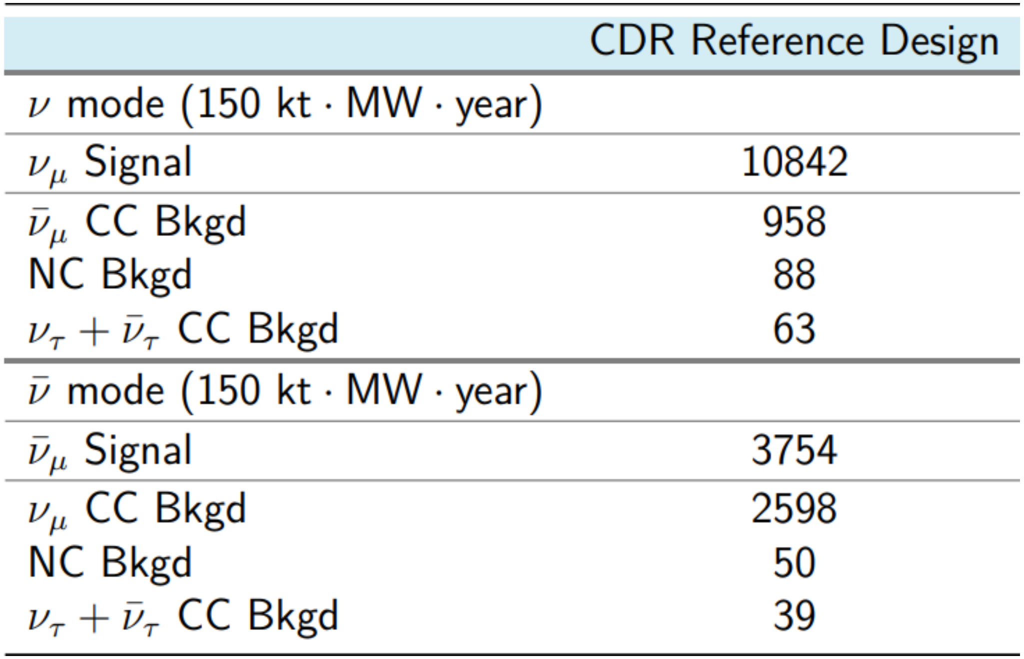
DUNE Oscillation Physics

ν_e and $\bar{\nu}_e$ appearance rates



	CDR Reference Design
ν mode (150 kt · MW · year)	
ν_e Signal NH (IH)	861 (495)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)
Total Signal NH (IH)	874 (521)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159
NC Bkgd	22
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3
Total Bkgd	226
$\bar{\nu}$ mode (150 kt · MW · year)	
ν_e Signal NH (IH)	61 (37)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)
Total Signal NH (IH)	228 (415)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89
NC Bkgd	12
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2
Total Bkgd	126

ν_μ and $\bar{\nu}_\mu$ appearance rates



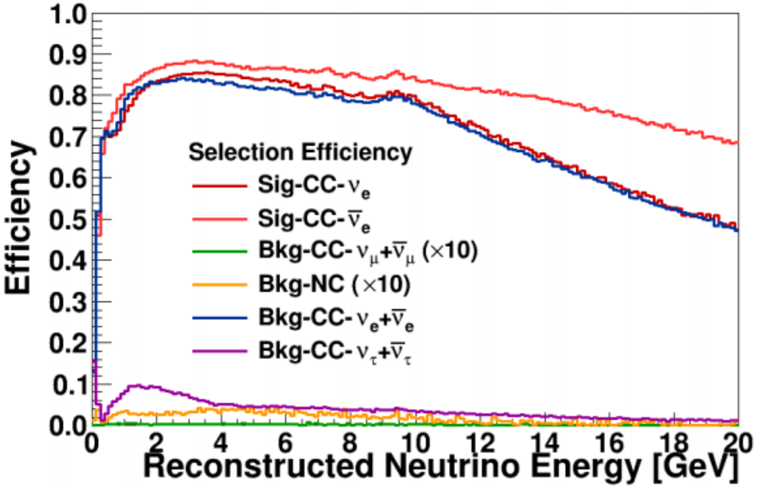
	CDR Reference Design
ν mode (150 kt · MW · year)	
ν_μ Signal	10842
$\bar{\nu}_\mu$ CC Bkgd	958
NC Bkgd	88
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	63
$\bar{\nu}$ mode (150 kt · MW · year)	
$\bar{\nu}_\mu$ Signal	3754
ν_μ CC Bkgd	2598
NC Bkgd	50
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	39

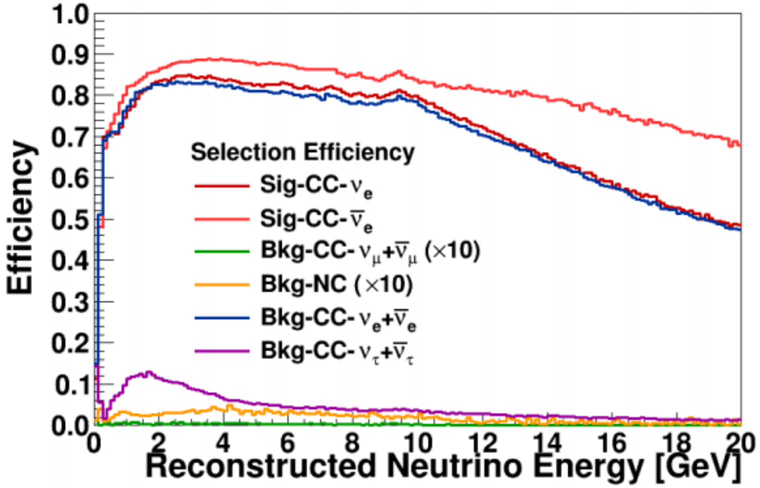
- **These numbers are for ~7 years running**
  - **(3.5 neutrino mode / 3.5 anti-neutrino mode)**

DUNE Oscillation Physics

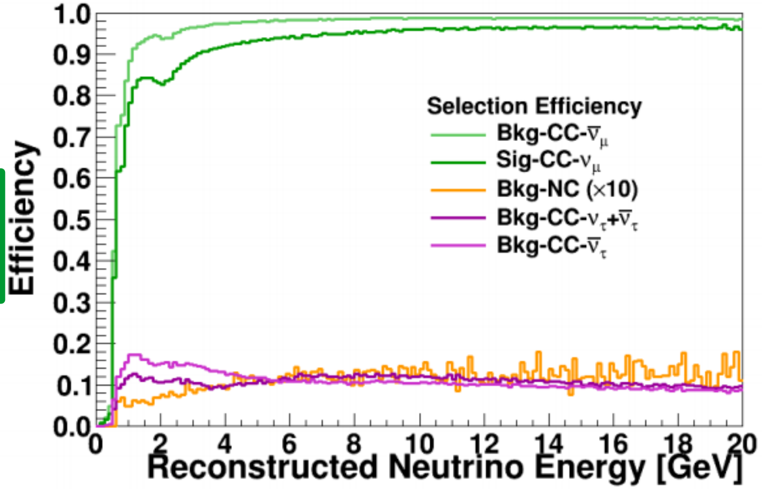
- **Bulk of the signal lives between 1 GeV < E_ν < 5 GeV**
  - ~ 80% (95%) ν_e (ν_μ) signal selection efficiency
  - < 5% background from NC

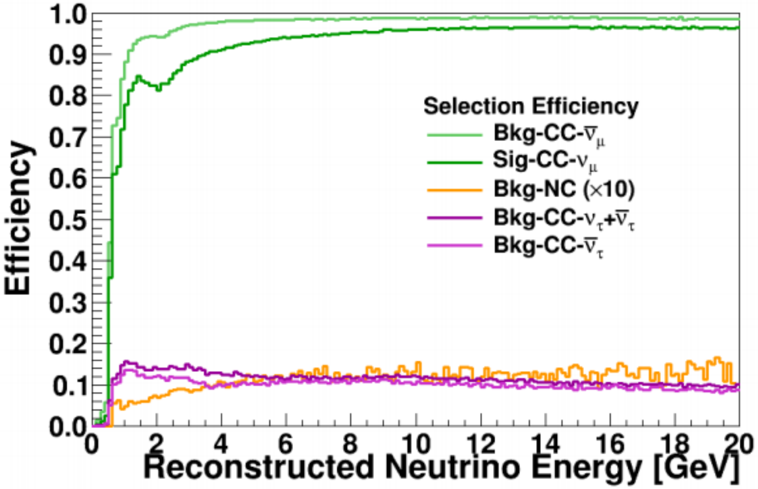
ν_e
appearance sample





ν_μ
disappearance sample





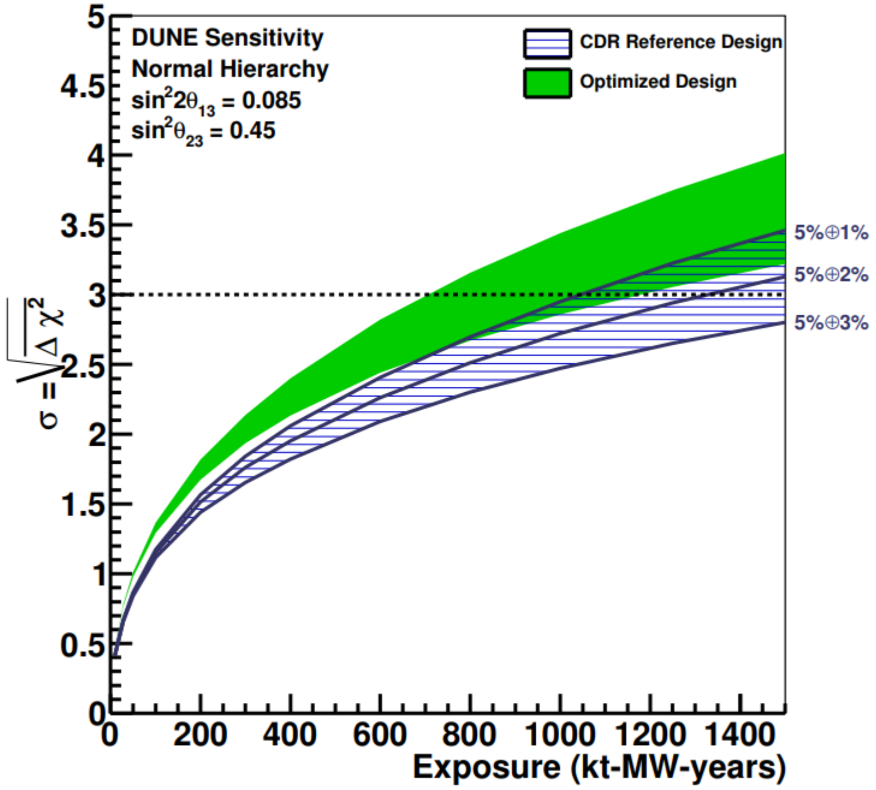
Neutrino Beam Mode

Anti-Neutrino Beam Mode

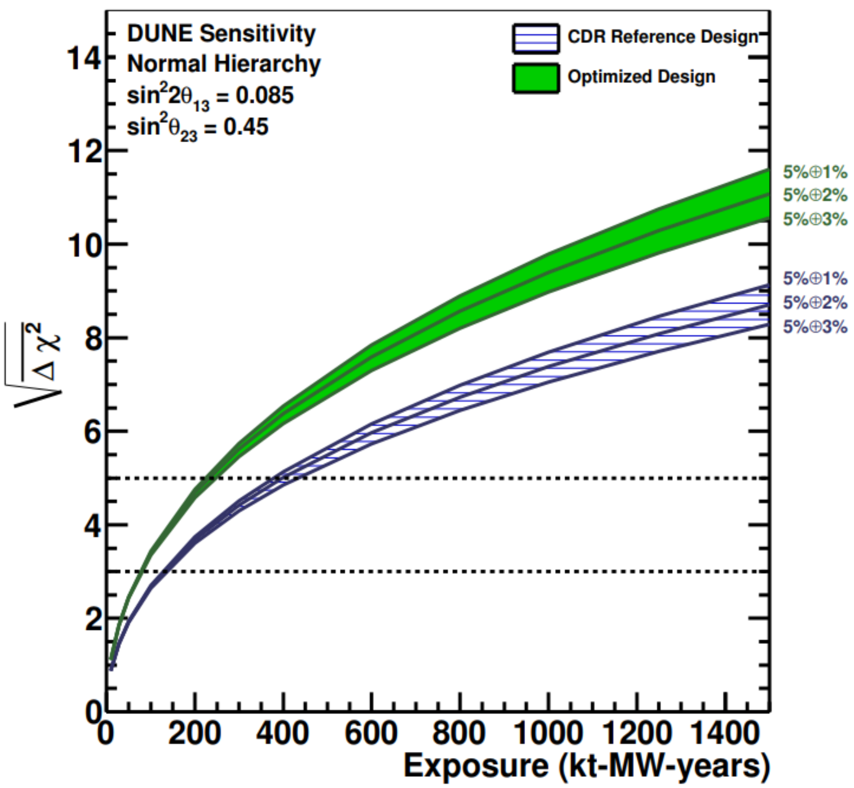
DUNE Oscillation Physics

- **Uncertainties in both the signal and the backgrounds effect the achievable sensitivity at DUNE**
  - *Turning a negative into a positive:* If we can demonstrate smaller backgrounds or better signal measurements with a pixel based detector this is where the physics motivation will come from!

75% CP Violation Sensitivity

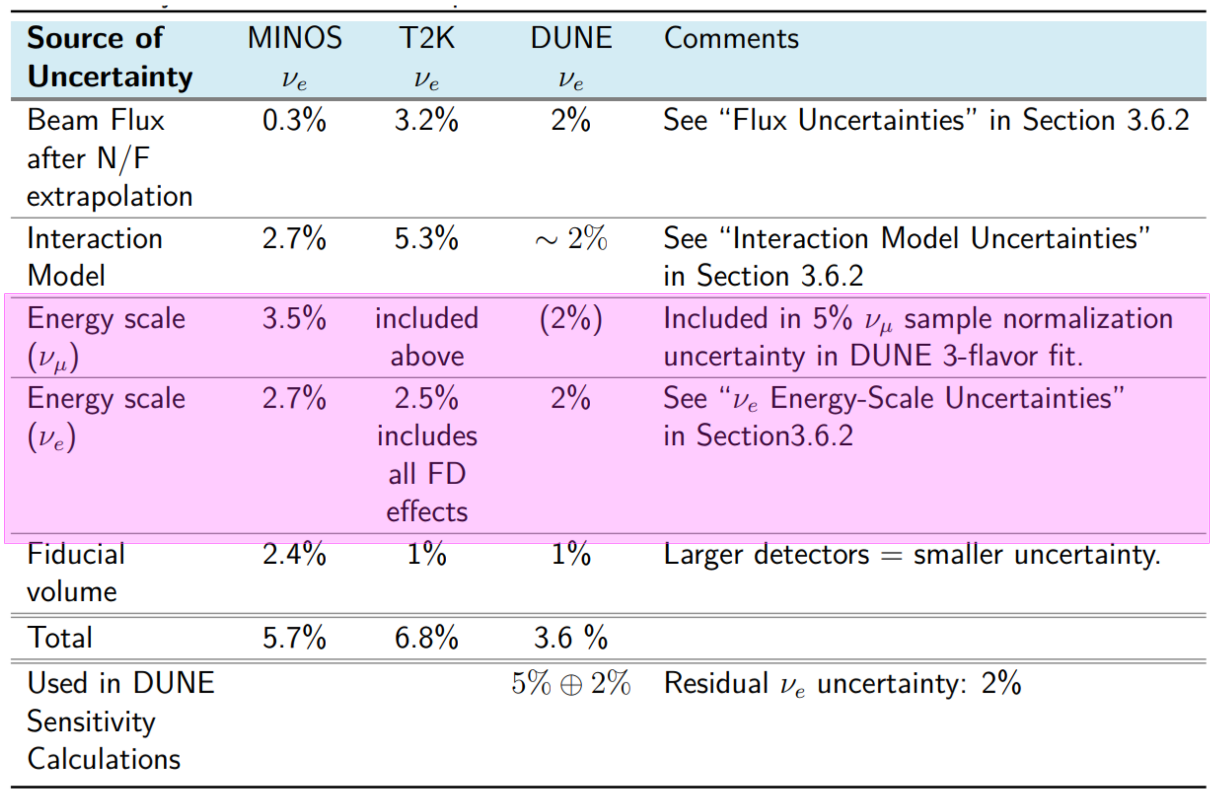


100% MH Sensitivity

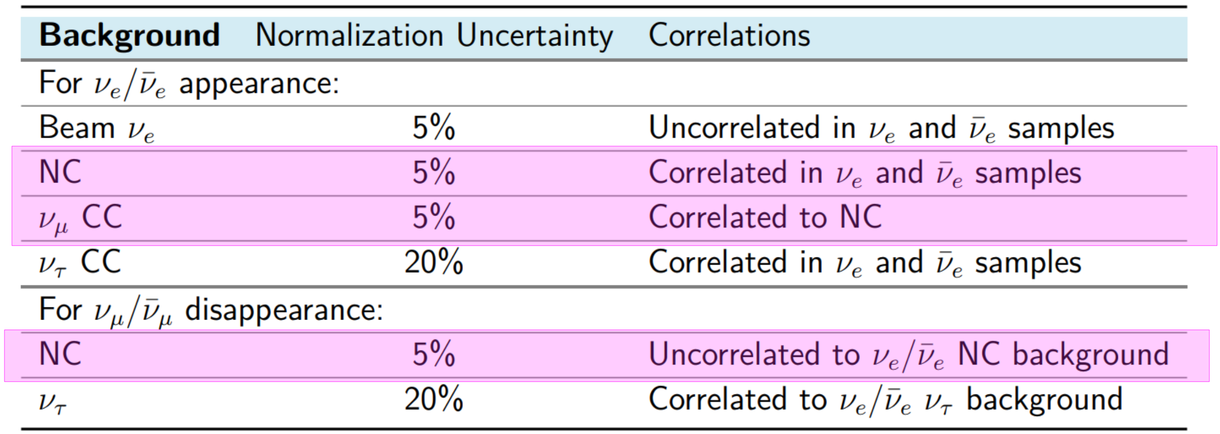


DUNE Oscillation Physics

- **If a pixel based LArTPC can perform better in the energy scale calculation (either from improved angular or shower energy measurements) or reduce the amount of background in the sample (and thus reduce the uncertainty on the background), then there might be a robust physics motivation**



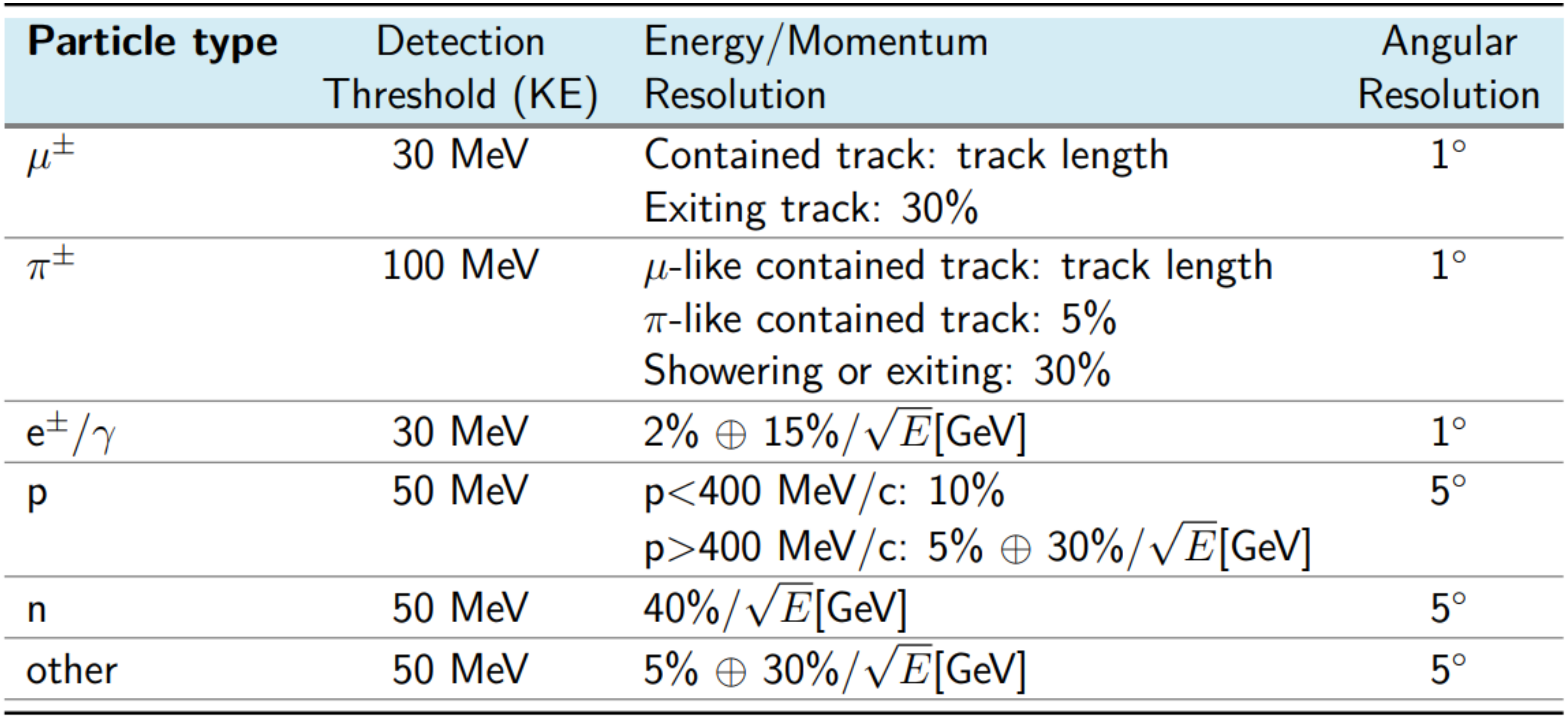
Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	3.2%	2%	See "Flux Uncertainties" in Section 3.6.2
Interaction Model	2.7%	5.3%	$\sim 2\%$	See "Interaction Model Uncertainties" in Section 3.6.2
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in 5% ν_μ sample normalization uncertainty in DUNE 3-flavor fit.
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%	See "ν_e Energy-Scale Uncertainties" in Section3.6.2
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	6.8%	3.6 %	
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$	Residual ν_e uncertainty: 2%



Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

DUNE Oscillation Physics

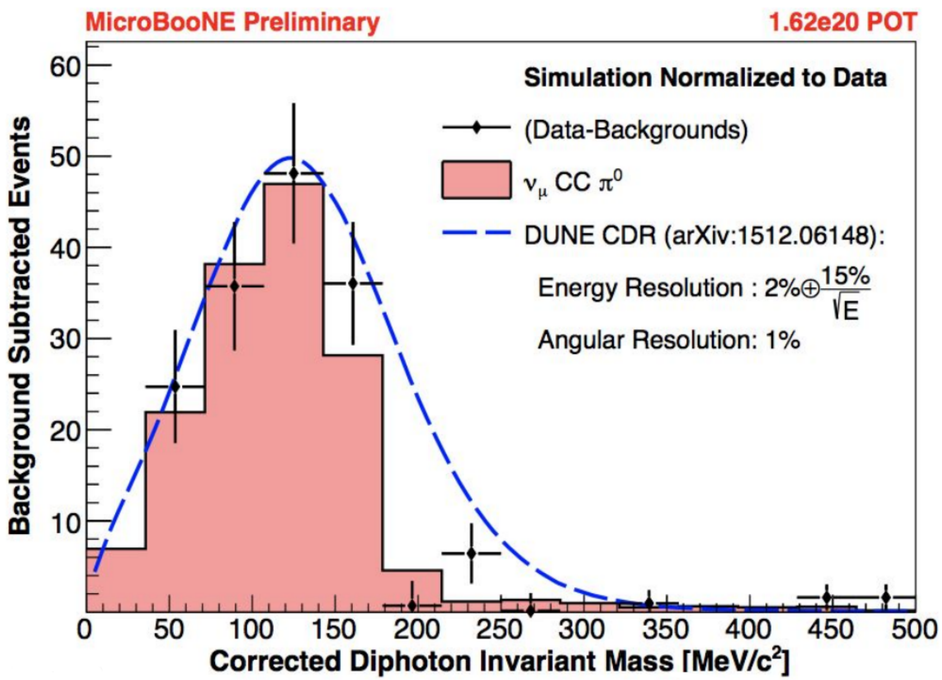
- **These measurements depend critically on the performance of the energy and angle reconstruction of individual particles**
  - The oscillation parameters are in terms of reconstructed neutrino energy which depends on these

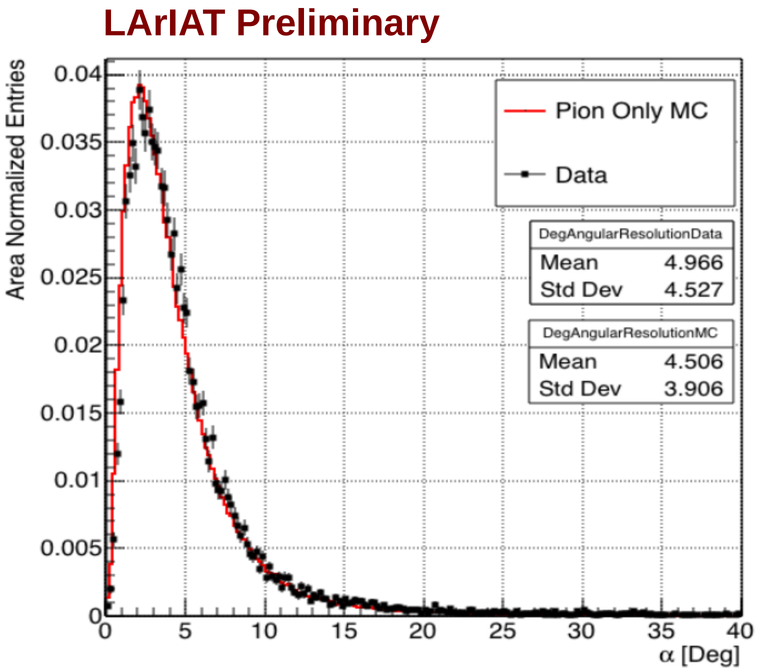


Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^\pm$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^\pm$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
$e^\pm/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}[\mathrm{GeV}]$	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}[\mathrm{GeV}]$	5°
n	50 MeV	$40\%/\sqrt{E}[\mathrm{GeV}]$	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}[\mathrm{GeV}]$	5°

- **1 degree angular resolution for minimum ionizing tracks and showers (electron/photon)**

Current state of the art in LArTPC's





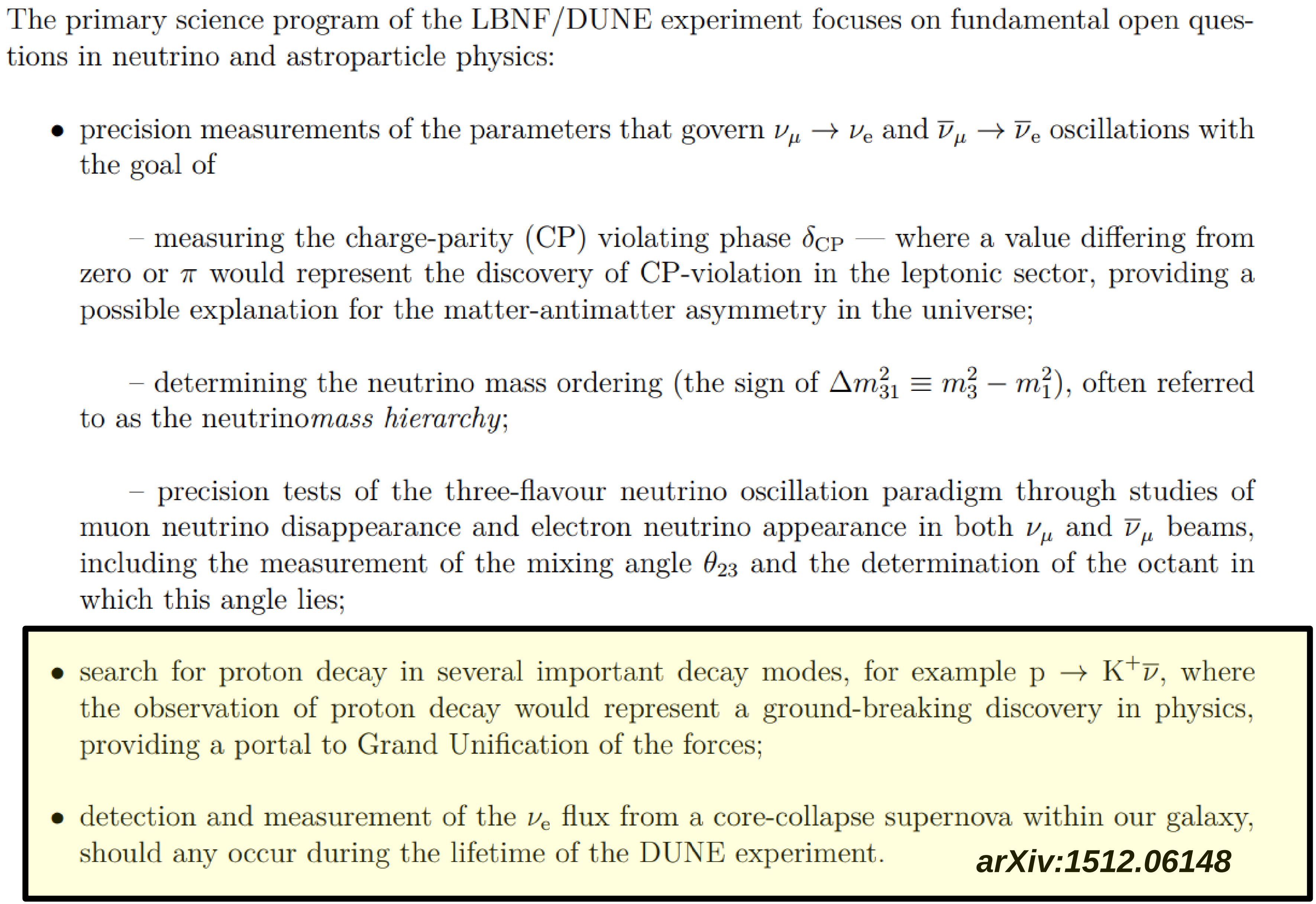
- **MicroBooNE ν_μCC π^0 result (μBooNE Public Note: 1032) shows a reconstructed π^0 mass peak and compares it with the assumptions from the DUNE CDR**
  - Achieves the energy resolution needed in the DUNE CDR
  - Note: The selection efficiency here is ~6% to achieve a 64% purity

- **LArIAT inclusive π^--hadronic cross-section uses "kinks" in the reconstructed pion tracks to identify hadronic interaction points**
  - Optimized tracking algorithm achieves 4 degree scattering angle resolution on pions with kinetic energy between ~400-1100 MeV
  - Note: Not the ultimate sensitivity for these tracking detectors, but used to identify interaction points

Very rough summary (Oscillations)

- **In order to achieve the DUNE oscillation measurements a number of reconstruction based requirements must be met**
  - ~ 80% (95%) ν_e (ν_μ) signal selection efficiency
  - < 5% background from NC
  - 1 degree angular resolution on electromagnetic showers and MIP like tracks
  - 2% + 15%/sqrt(E) energy resolution on showers
  - 100 MeV or less kinetic energy threshold on most particle species
    - 50 MeV threshold on protons (key for identifying ν_eCC-QE samples)
- **These requirements have correlations with each other which I am not paying close attention to**
  - Instead just letting this serve as a flavor of the things we should be thinking of when evaluating detector performance and the gains to be made in considering a pixel based far detector
- **Development in wire based reconstruction is continuing to advance the field of LArTPC's towards achieving these requirements**
  - Current protoDUNE charged particle test beam run will do a lot to further inform these requirements

Primary Science Program for DUNE



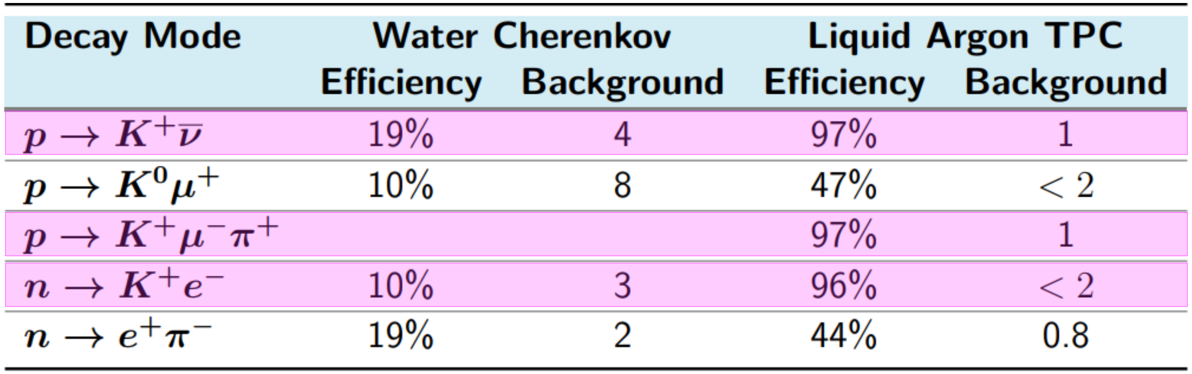
The primary science program of the LBNF/DUNE experiment focuses on fundamental open questions in neutrino and astroparticle physics:

- precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations with the goal of
  - – measuring the charge-parity (CP) violating phase $\delta_{\rm CP}$ — where a value differing from zero or π would represent the discovery of CP-violation in the leptonic sector, providing a possible explanation for the matter-antimatter asymmetry in the universe;
  - – determining the neutrino mass ordering (the sign of $\Delta m^2_{31} \equiv m^2_3 - m^2_1$), often referred to as the neutrino*mass hierarchy*;
  - – precision tests of the three-flavour neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and $\overline{\nu}_\mu$ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies;
- search for proton decay in several important decay modes, for example $p \rightarrow K^+\overline{\nu}$, where the observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces;
- detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy, should any occur during the lifetime of the DUNE experiment.

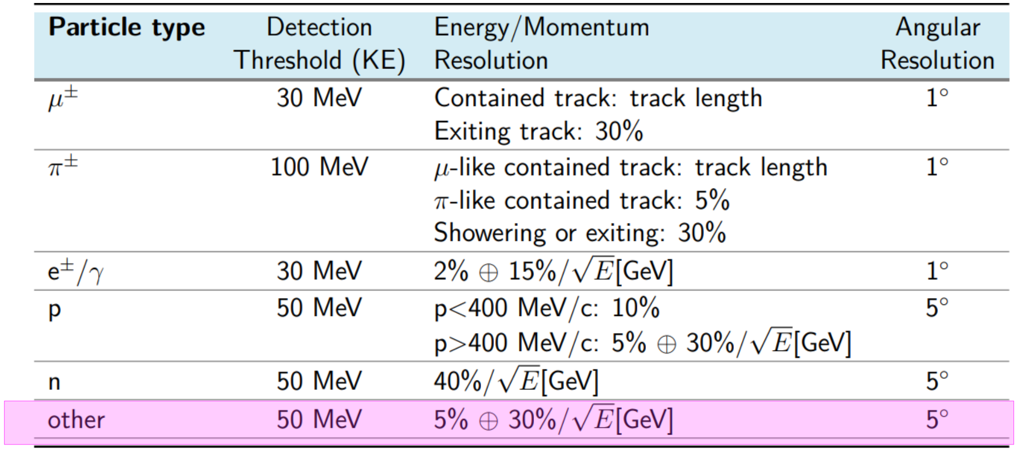
arXiv:1512.06148

Nucleon Decay Channels

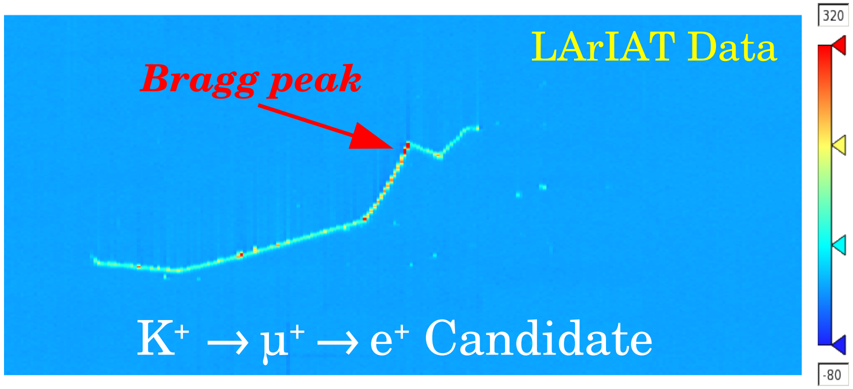
- **Current nucleon decay channels (as well as $n\bar{n}$-oscillation studies) rely on the (assumed) high tracking efficiency and particle identification techniques available in LArTPC's**
  - These are currently being tested in data using the LArIAT experiment for a sample of Kaons and anti-protons (which mimic the $n\bar{n}$-oscillation signature)
  - DUNE also further studying identification techniques in the far detector

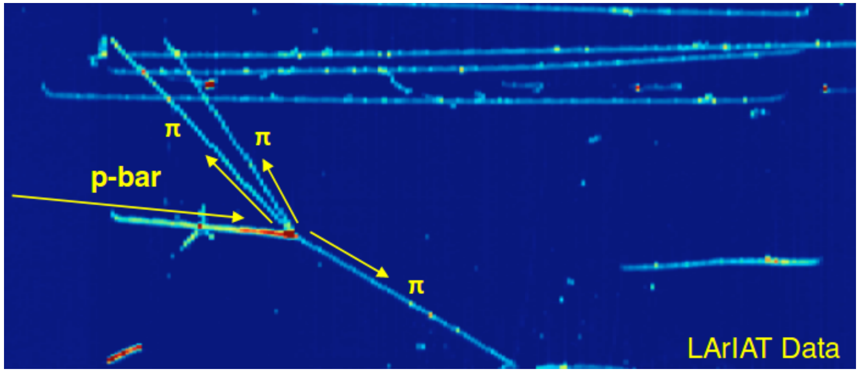


Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8



Particle type	Detection Threshold (KE)	Energy/Momentum Resolution	Angular Resolution
$\mu^\pm$	30 MeV	Contained track: track length Exiting track: 30%	1°
$\pi^\pm$	100 MeV	μ-like contained track: track length π-like contained track: 5% Showering or exiting: 30%	1°
$e^\pm/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{E}$[GeV]	1°
p	50 MeV	p<400 MeV/c: 10% p>400 MeV/c: $5\% \oplus 30\%/\sqrt{E}$[GeV]	5°
n	50 MeV	$40\%/\sqrt{E}$[GeV]	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{E}$[GeV]	5°



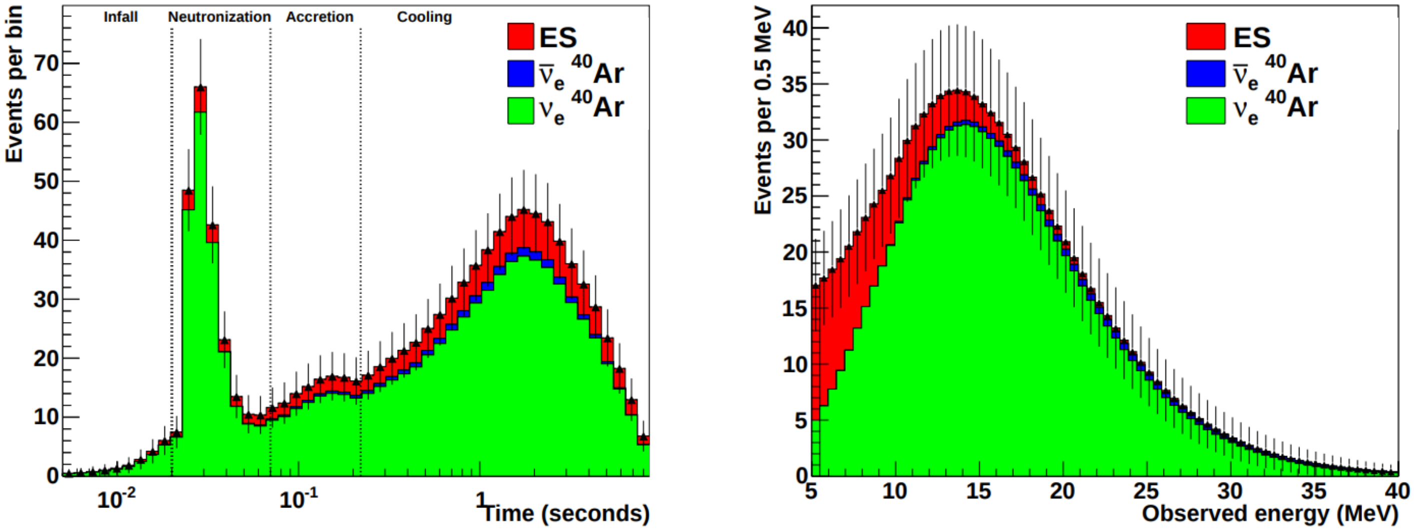


Supernova Burst Neutrinos

- **The observation of supernova burst neutrinos during the DUNE era represents “discovery” level physics opportunity**
  - The ability to reconstruct low energy neutrino interactions separate from backgrounds that come in a short time window represent a unique challenge for this detector technology

Channel	Events “Livermore” model	Events “GKVM” model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

Event rates for a 40kT LArTPC for a core collapse supernova at 10 kpc using charged current (CC) and elastic scattering (ES)



Very rough summary (nucleon decay and Supernova ν’s)

- **The inclusion of nucleon decay searches and supernova neutrino detector puts additional requirements on the DUNE detector since neither of these processes can be externally triggered**
  - The energy regime in which these processes occur is also different then the energies of the particles coming from beam neutrinos
- **The stated requirements for the DUNE detector (DAQ and components) from the DUNE CDR and IDR can be summarized as follows:**
  - Zero deadtime (as stated in the IDR)
    - CDR requires > 90% uptime
  - Self-triggering
    - Energy thresholds of ~5 MeV with “high” efficiency
    - Handle a total bandwidth of data from all 4 modules of 30 PB/year
      - Includes “bursts” from possible supernova candidate (30 seconds full readout)
    - Control on natural backgrounds (e.g. Ar39) one key aspect

Hardware/Detector Requirements

- **Another aspect to consider is the individual detector components which have to meet certain requirements in order to achieve the physics sensitivities outlined above**
  - For example: The readout electronics must have a sufficient dynamic range to detect a 5 MeV electron and record a 1 GeV proton directed at the wire planes
- **In considering the case for a pixel based DUNE far detector, there may be examples where some of the design requirements can be more easily achieved when compared to a wire based readout**
  - For example: Achieving the flatness and planarity of the massive Anode Plane Assemblies (APA's) is quite an engineering feat since they have to withstand the tension of the wires
    - Tileable flat PCB pixel boards could potentially solve this engineering challenge quite easily
- **In the next few slides I go over just a few example requirements that I thought might be of interest when considering how a pixel based detector must perform**

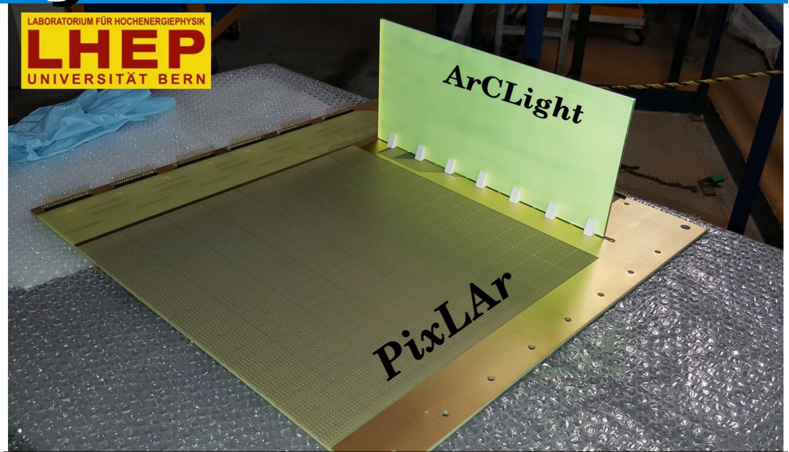
Readout Electronic Requirements

- **Since part of the discussion here at this workshop surrounds ongoing work with new pixel based readout chips, I thought it would be worthwhile to outline the requirements as stated in the DUNE IDR (arXiv: 1807.10327)**
  - < 1000 e- noise requirement
  - 20 year expected lifetime for the electronics
    - Assumes any design will have the electronics inaccessible in the LArTPC
  - ~~Peaking time between 1 and 3 microseconds~~
    - This is particular to the drift time between wire planes
  - ~~Adjustable baseline~~
    - Driven by the bi-polar nature of the induction pulse compared to the collection pulse
  - ~~ADC Sampling frequency of 2MHz~~
    - Match of the shaping time of 1microsecond (via Nyquist condition)
  - Linear response for an input up to 500,000 e-
    - Minimizing saturation to less then 5% for beam events
  - Dynamic range of 3000:1
    - Implies a 12-bit ADC
  - ADC cannot contribute “significantly” to the overall noise
  - Power consumption must be < 50 mW / channel
    - Lower is seen as more desirable

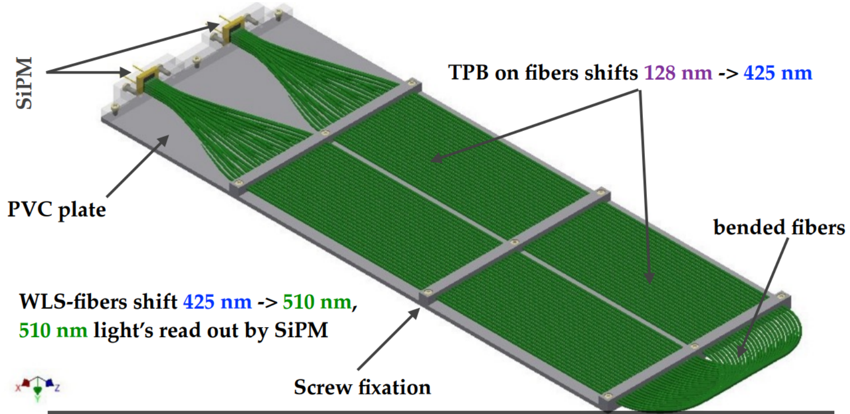
Note: I put a strike through the listed requirements which I don’t think necessarily apply to a pixel based readout

Light Detection System

- **The opacity of the pixel plane means different ideas for photon detection will have to be explored if this system is to be implemented**
- **Some of this work has been started by different groups (ArgonCube Collaboration and the Arapuca groups)**
  - See arXiv: 1711.11409 for summary of the ArcLight detector
  - Recent pixel based testbeam run (PixLAr) had both these systems deployed
    - Analysis ongoing
- **Other ideas also being pursued in the context of the ArgonCube collaboration include a wavelength shifting fibers coated with TPB (Light Collection Module)**
  - Dubna group continuing tests in collaboration with University of Bern
    - Preliminary results look encouraging



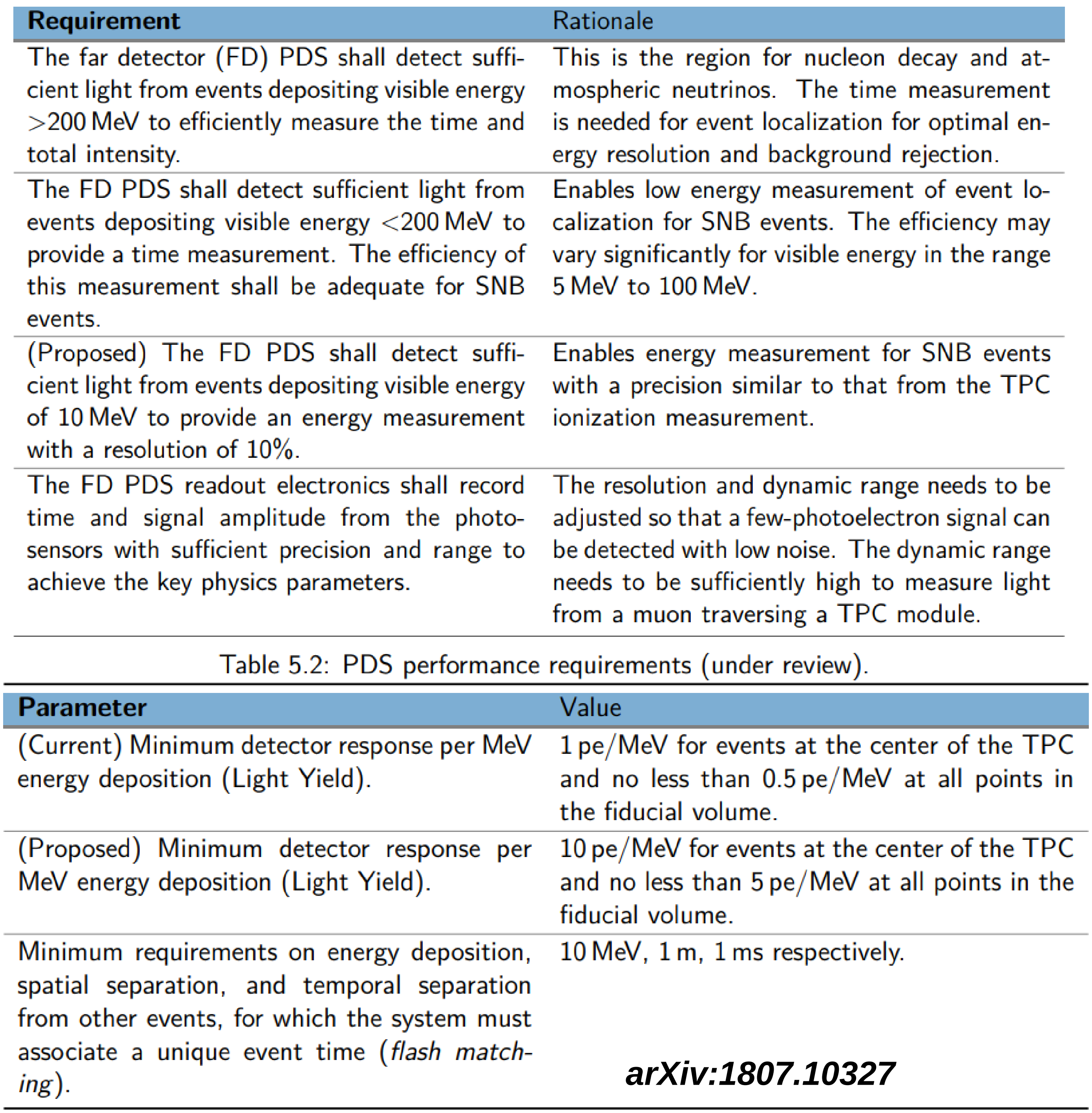
Pixel PCB w/ ArcLight



Light Collection Module (LCM)

Light Detection System

- **Current stated photon detector system performance metrics in order to achieve DUNE's primary physics goals**



Requirement	Rationale
The far detector (FD) PDS shall detect sufficient light from events depositing visible energy >200 MeV to efficiently measure the time and total intensity.	This is the region for nucleon decay and atmospheric neutrinos. The time measurement is needed for event localization for optimal energy resolution and background rejection.
The FD PDS shall detect sufficient light from events depositing visible energy <200 MeV to provide a time measurement. The efficiency of this measurement shall be adequate for SNB events.	Enables low energy measurement of event localization for SNB events. The efficiency may vary significantly for visible energy in the range 5 MeV to 100 MeV.
(Proposed) The FD PDS shall detect sufficient light from events depositing visible energy of 10 MeV to provide an energy measurement with a resolution of 10%.	Enables energy measurement for SNB events with a precision similar to that from the TPC ionization measurement.
The FD PDS readout electronics shall record time and signal amplitude from the photosensors with sufficient precision and range to achieve the key physics parameters.	The resolution and dynamic range needs to be adjusted so that a few-photoelectron signal can be detected with low noise. The dynamic range needs to be sufficiently high to measure light from a muon traversing a TPC module.

Table 5.2: PDS performance requirements (under review).

Parameter	Value
(Current) Minimum detector response per MeV energy deposition (Light Yield).	1 pe/MeV for events at the center of the TPC and no less than 0.5 pe/MeV at all points in the fiducial volume.
(Proposed) Minimum detector response per MeV energy deposition (Light Yield).	10 pe/MeV for events at the center of the TPC and no less than 5 pe/MeV at all points in the fiducial volume.
Minimum requirements on energy deposition, spatial separation, and temporal separation from other events, for which the system must associate a unique event time (*flash matching*).	10 MeV, 1 m, 1 ms respectively.

arXiv:1807.10327

Construction of the APA

- **The DUNE-APA's are large and heavy assemblies in order to accommodate all the wire planes under tension**
  - The flatness requirement of the APA's is the same as the wire plane spacing (+/- 0.5 mm) so the frame needs to be robust
- **Moreover, the wiring, tension, and testing is a non-trival and time consuming process**
  - ProtoDUNE having just completed this process will have many "lessons learned" to hopefully make this process easier

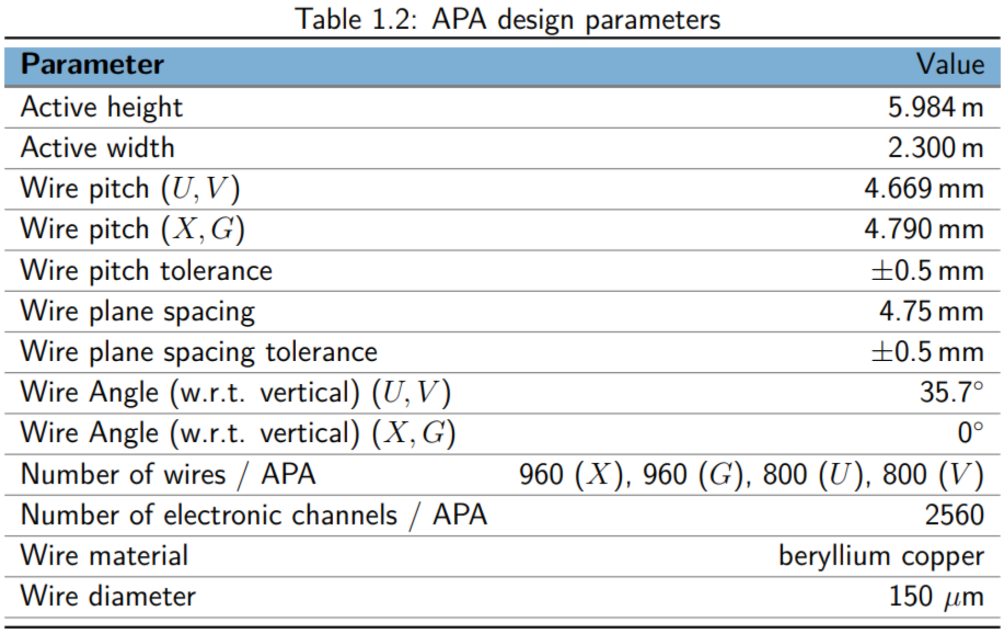
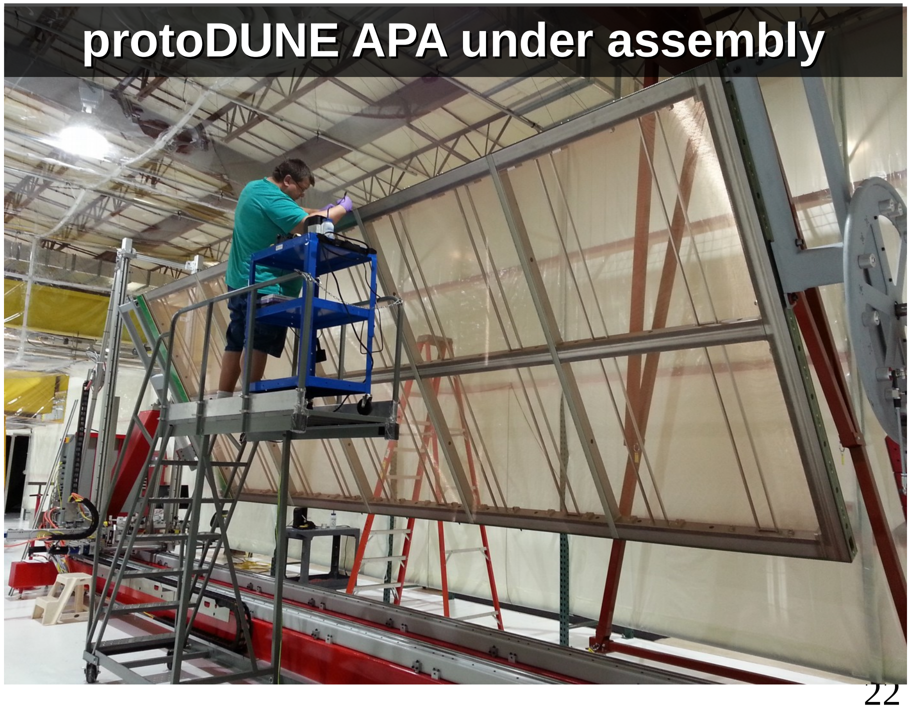


Table 1.2: APA design parameters

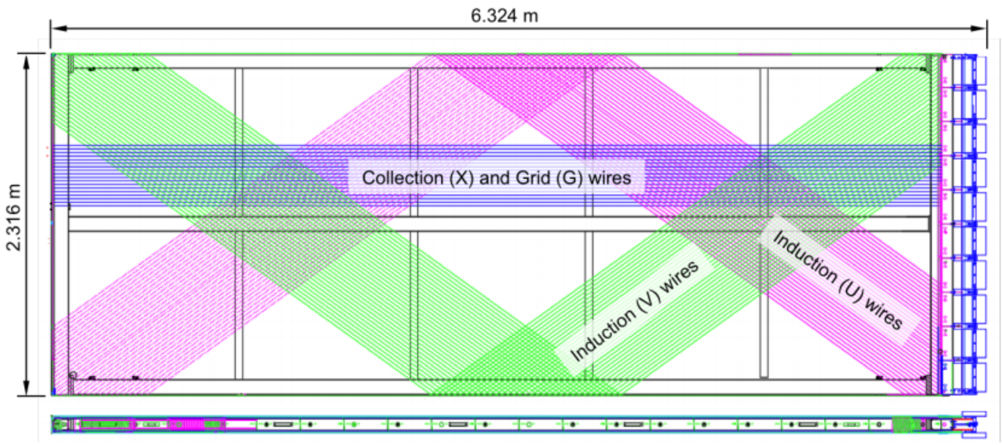
Parameter	Value
Active height	5.984 m
Active width	2.300 m
Wire pitch (U, V)	4.669 mm
Wire pitch (X, G)	4.790 mm
Wire pitch tolerance	±0.5 mm
Wire plane spacing	4.75 mm
Wire plane spacing tolerance	±0.5 mm
Wire Angle (w.r.t. vertical) (U, V)	35.7°
Wire Angle (w.r.t. vertical) (X, G)	0°
Number of wires / APA	960 (X), 960 (G), 800 (U), 800 (V)
Number of electronic channels / APA	2560
Wire material	beryllium copper
Wire diameter	150 μm

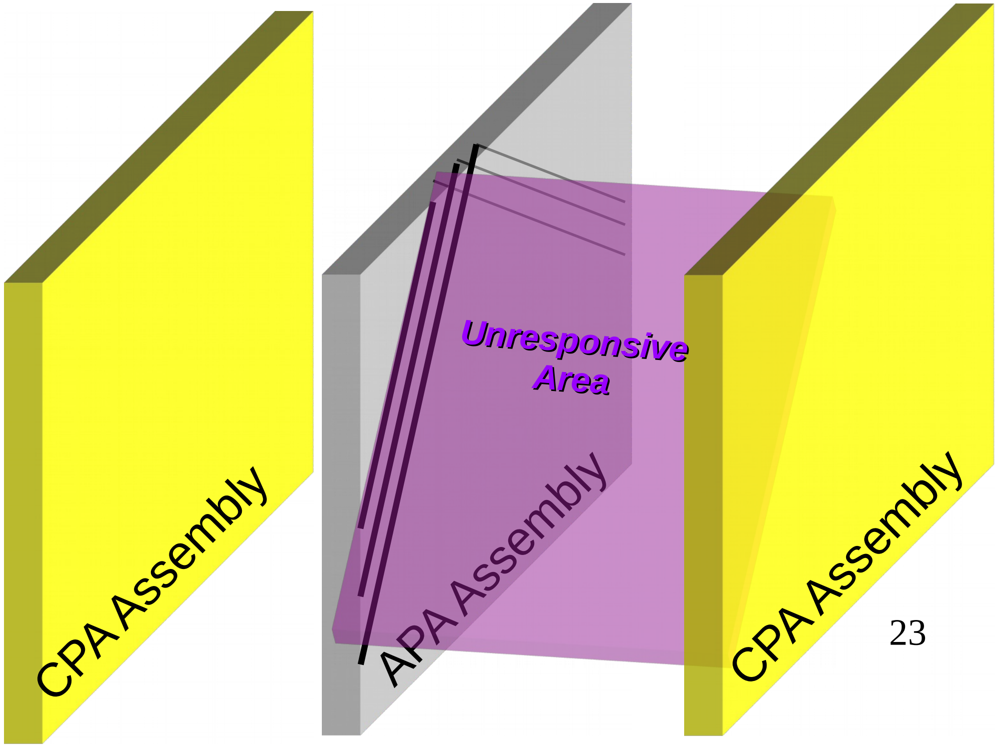


protoDUNE APA under assembly

Construction of the APA

- **One example of "strict controls" that has to be in place in the wrapped wire readout of the current DUNE APA's in the number of consecutive channels which are allowed to be non-functioning**
  - If a wire is found electrically unresponsive it can effect multiple drift volumes
    - One unresponsive wire represents a rectangular area of approximately 4.5 mm x 6706 mm x 3530 mm
      - Assuming this is in the middle of the APA
- **The same effected pixel channels would represent significantly less detector volume**
  - Assuming the pixel pitch of the same order as the wire plane (~ 4.5 mm) this is only a small rectangular volume of approximately 4.5 mm x 4.5 mm x 3530 mm





Summary

- **Above was a very rough overview of some of the high-level requirements on the DUNE far detector in order to achieve the "primary physics goals" and a brief review of some of the individual component requirements for the detector**
  - This says nothing of the requirements on the DUNE near detector in order to achieve the constraints on the flux and intrinsic beam backgrounds
    - These represent some additional challenges considering the need to measure neutrino interactions in a high flux environment
- **Any of the places where a pixel based LArTPC can achieve the same or better performance in the identification, classification, and reconstruction of neutrino events can enhance the physics reach of DUNE**
  - See Roxanne's talk on some of the simulation work ongoing to evaluate these possibilities
- **Additional thoughts about requirements and places where pixel detectors could have greater value are welcome!**

Thank you for your attention!

Discussion / Feedback / Questions