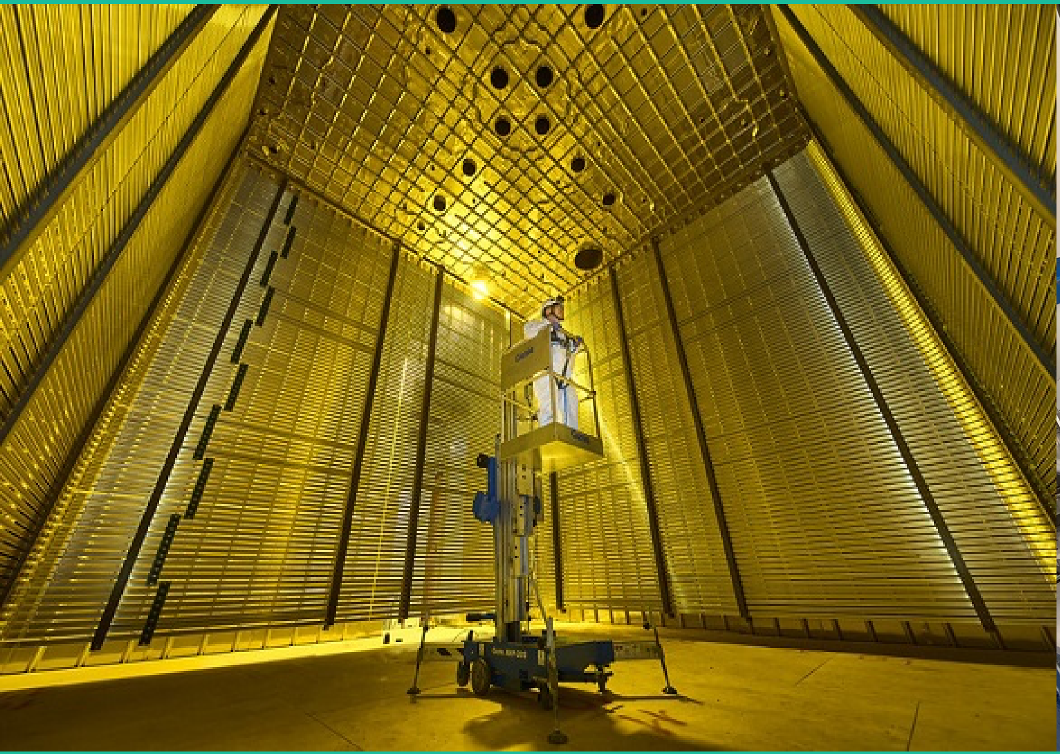
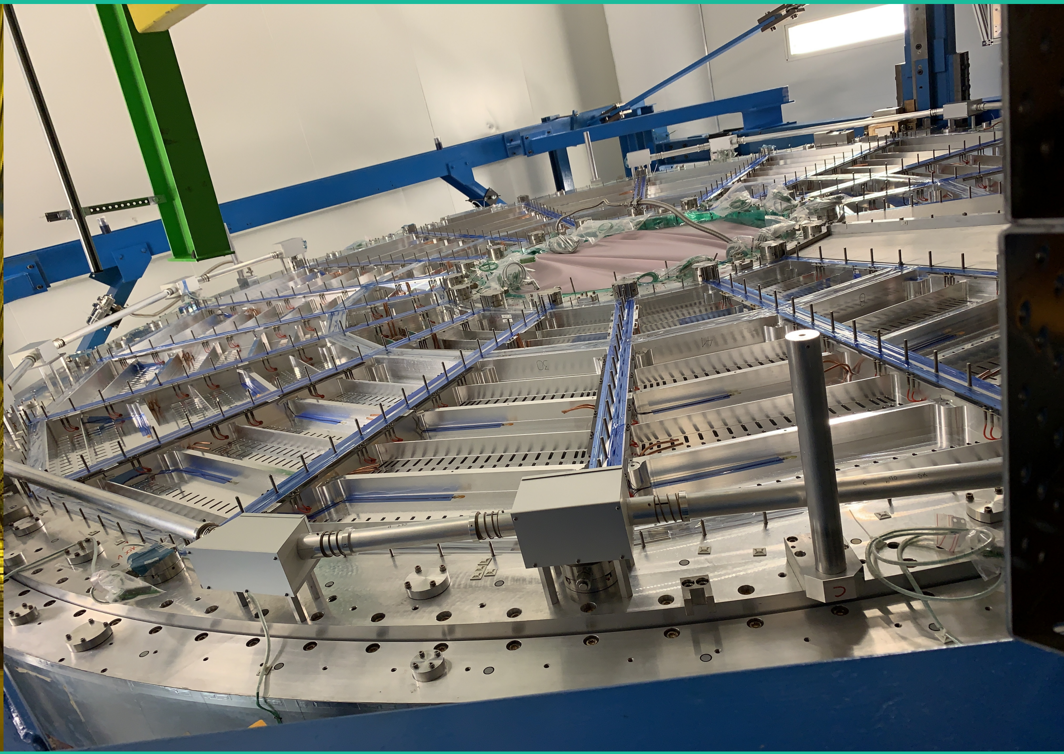




An Overview of Future Neutrino Experiments

Tanaz Angelina Mohayai
CIPANP, Orlando, FL
August 30, 2022

Fermilab

Big Picture

many un-answered questions in neutrino physics

- Are there more than 3 types of neutrinos?
- Which neutrino is the lightest?
- Do neutrinos oscillate differently than anti-neutrinos?
- How come neutrino mixing is large?
- Do we understand everything about neutrino interactions?

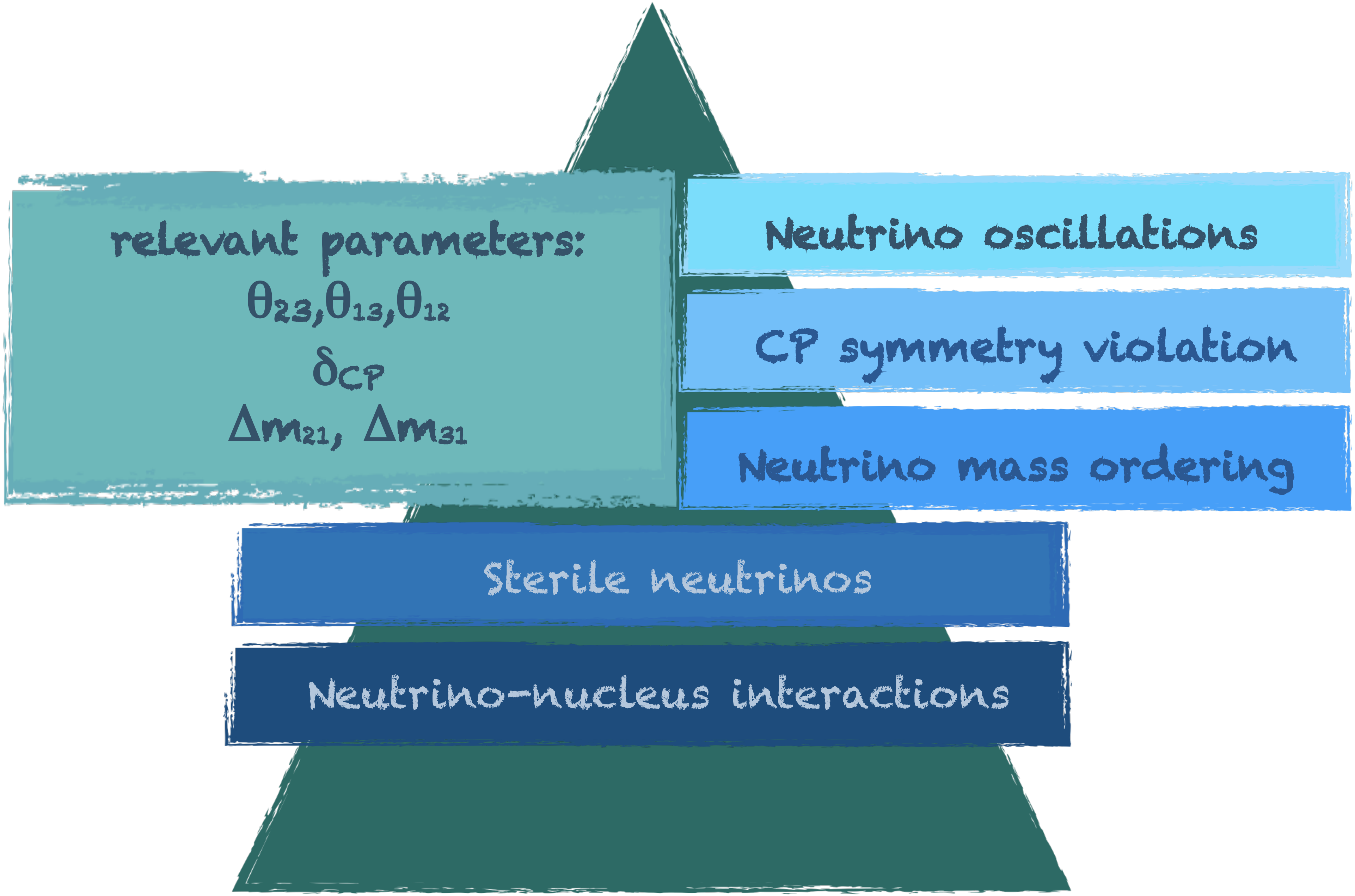
Neutrinos are weakly interacting

- Seek high energy and intense sources of neutrinos and build big detectors to maximize their chances of interacting

In this talk: an overview of future precision experiments positioned at various baselines from the artificial sources of neutrinos

- Short-baseline experiments at Fermilab will search for a possible 4th neutrino
- Long & medium-baseline experiments will study neutrinos more precisely

Big Picture


relevant parameters:
$\theta_{23}, \theta_{13}, \theta_{12}$
δ_{CP}
$\Delta m_{21}, \Delta m_{31}$
Neutrino oscillations
CP symmetry violation
Neutrino mass ordering
Sterile neutrinos
Neutrino-nucleus interactions

Neutrino Oscillation

- **Known:** neutrinos (neutral leptons with 3 flavors) oscillate! → have mass
  - **3 flavor states (ν_μ, ν_e, ν_τ)** are superpositions of **3 mass states (ν_1, ν_2, ν_3)**, parametrized by the **PMNS** matrix

PMNS Matrix

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

δ_{CP} = CP violating phase

$c_{jk} = \cos\theta_{jk}$ and $s_{jk} = \sin\theta_{jk}$

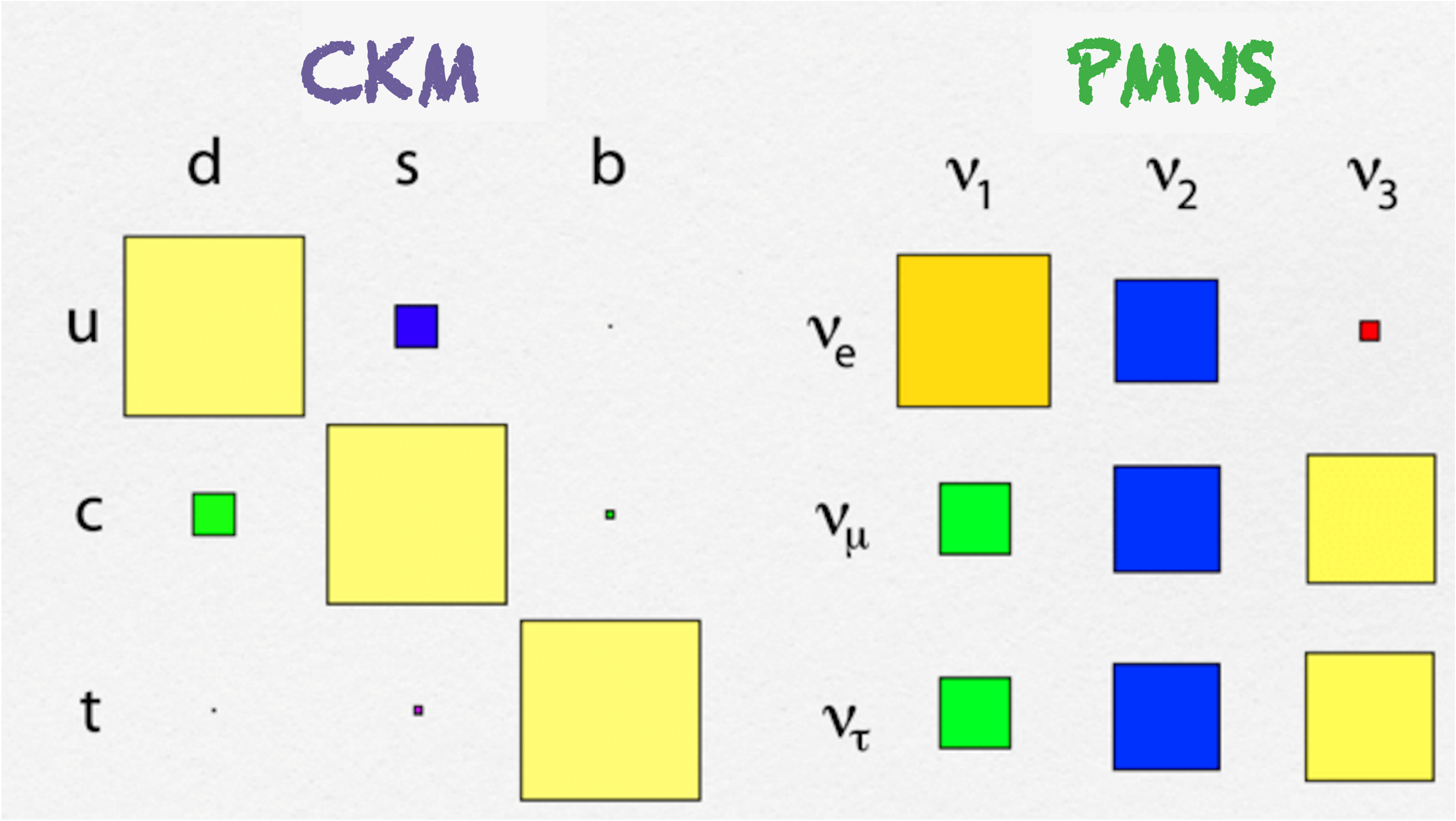
- **Measured (with ~3-5% precision)**: mixing angles θ_{23}, θ_{13}, θ_{12}
- **Unknowns:** δ_{CP}, θ_{23} octant

Is $\theta_{23} = 45^\circ$? Implies new symmetry $\nu_\mu = \nu_\tau$ in ν_3

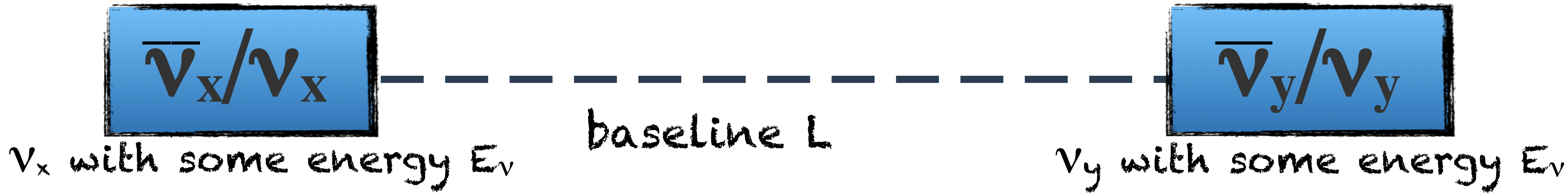
Do neutrinos violate CP symmetry, $\delta_{CP} \neq 0$ or $\pm\pi$?

CP Violation in Quark and Lepton Sectors

- Quarks mix too!
- **CP-violating phase** exists in both **CKM** and **PMNS**:
  - ★ Fully measured in the quark sector but too small to explain level of matter-antimatter asymmetry
  - ★ If neutrinos violate CP symmetry, they could be the key to why the universe is full of matter today



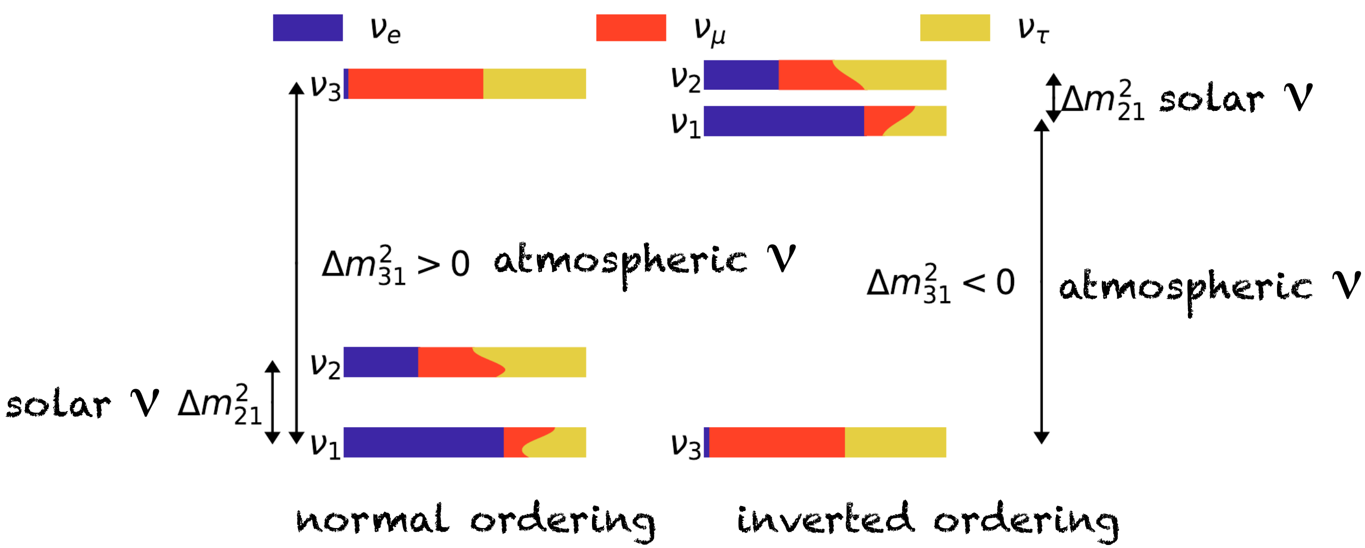
Neutrino Oscillation and Mass



simplified 2 flavor oscillation probability

$$P(\nu_x \to \nu_y) \propto \sin^2(2\theta)\sin^2\left(\frac{\boxed{\Delta m^2_{ij}}L}{4E_\nu}\right)$$

- Neutrino oscillations are sensitive to mixing angle, θ_{ij}, mass splitting squared term, **Δm^2_{ij}**:
  - ★ **Known (within ~1-3%):** Δm^2_{21}, Δm^2_{31}
  - ★ **Unknown:** mass ordering/sign of Δm^2_{31}



Neutrino Oscillation

$\overline{\nu}_\mu/\nu_\mu$ dominated source

baseline L

$\overline{\nu}_\mu/\nu_\mu$

ν_μ survival/disappearance

$\overline{\nu}_e/\nu_e$

ν_e appearance

- Neutrino oscillations are sensitive to **mixing angle, θ_{ij}**, mass splitting squared term, **Δm^2_{ij}**, **δ_{CP}**, and matter effects:

a more realistic case

$$P(\boxed{\nu_\mu \to \nu_e}) \approx \boxed{\sin^2\theta_{23}\ \sin^2 2\theta_{13}} \frac{\sin^2(\boxed{\Delta_{31}} - aL)}{(\boxed{\Delta_{31}} - aL)^2} \boxed{\Delta_{31}^2}$$
$$+ \boxed{\sin 2\theta_{23}\ \sin 2\theta_{13} \sin 2\theta_{12}} \frac{\sin(\boxed{\Delta_{31}} - aL)}{(\boxed{\Delta_{31}} - aL)} \boxed{\Delta_{31}} \frac{\sin(aL)}{(aL)} \boxed{\Delta_{21}} \cos(\boxed{\Delta_{31}} + \boxed{\delta_{CP}})$$
$$+ \boxed{\cos^2\theta_{23}\ \sin^2 2\theta_{12}} \frac{\sin^2(aL)}{(aL)^2} \boxed{\Delta_{21}^2}$$

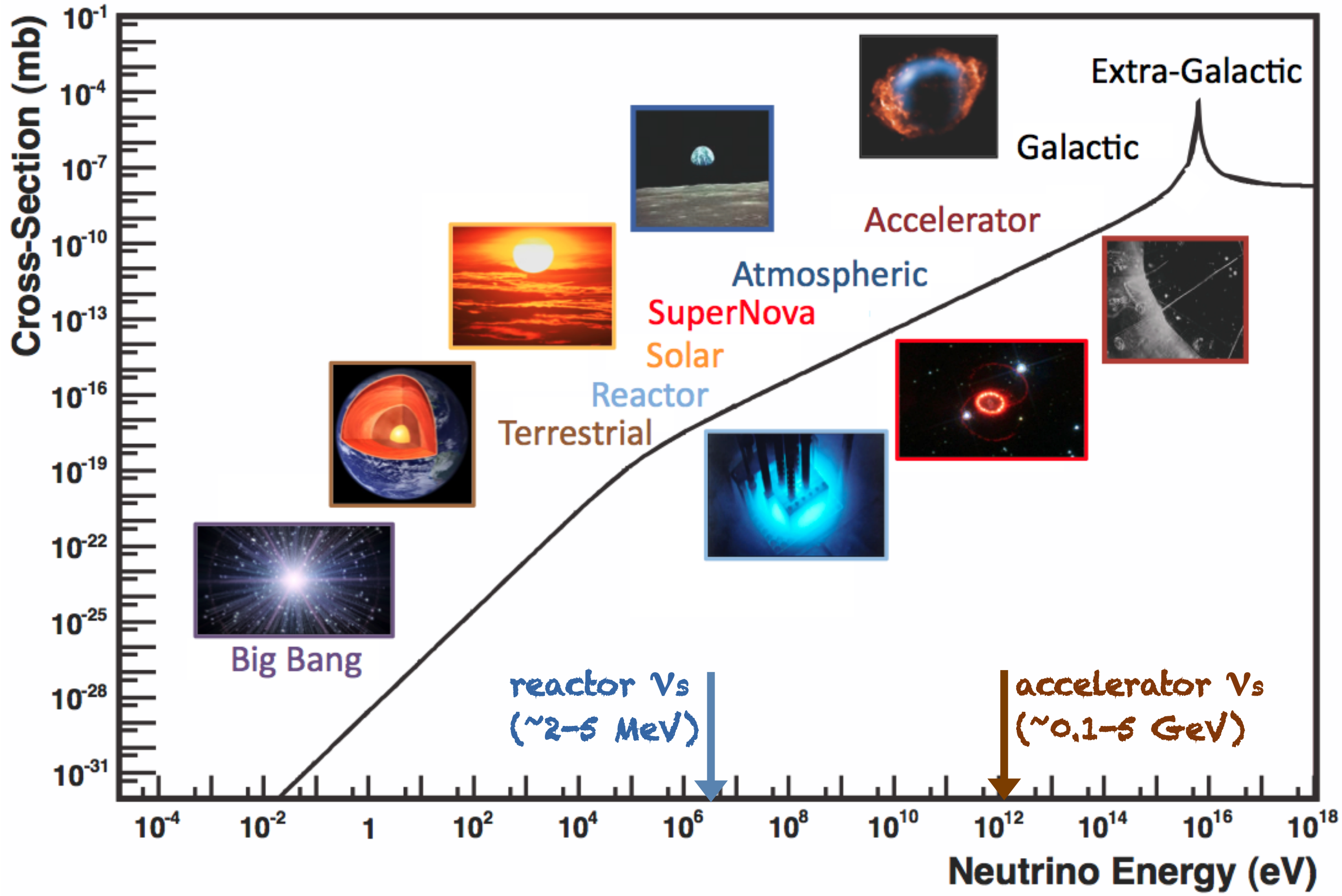
ν_e appearance

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_\nu}$$

L/E_ν can be controlled for short, medium, and long baselines

Neutrinos, omnipresent yet ghostly

- Neutrinos **weakly interact**, even though they come from **variety of sources**:
  - Wide ranges of energies & cross sections depending on the source
  - Experiments target specific range of energies & cross sections



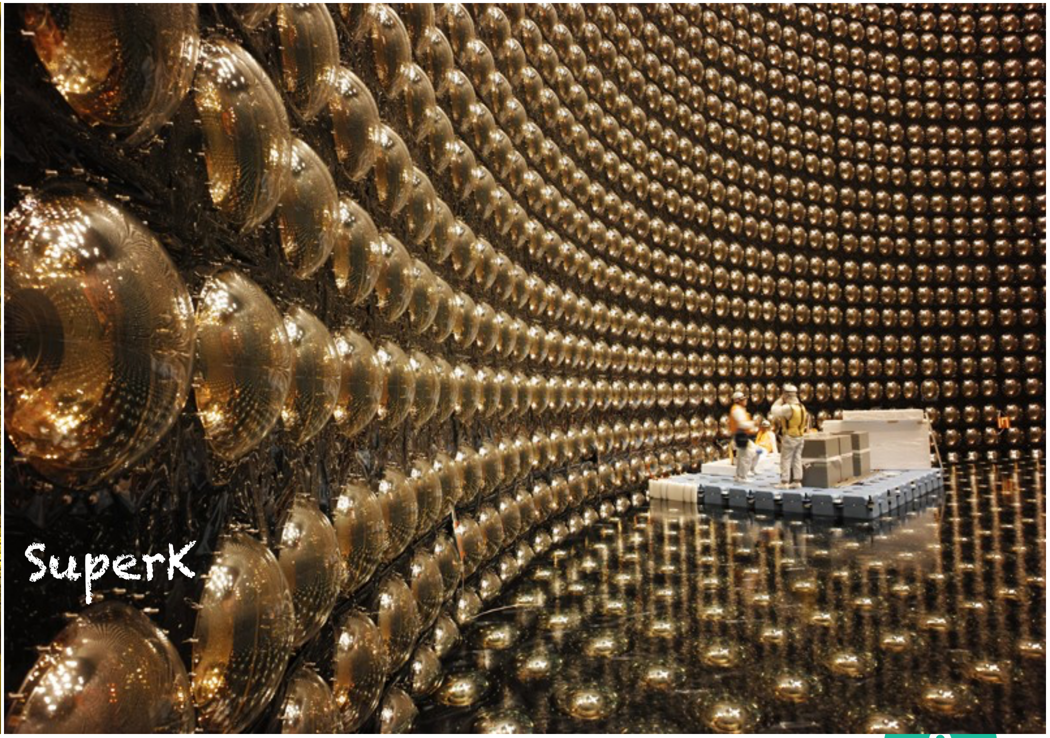
Neutrino Detectors

- Place a big detector (large mass) and heavy nuclear target when possible in the path of neutrinos to capture them

Examples of nuclear targets: argon, water

Liquid argon time projection chamber, LArTPC

Water Cherenkov detector



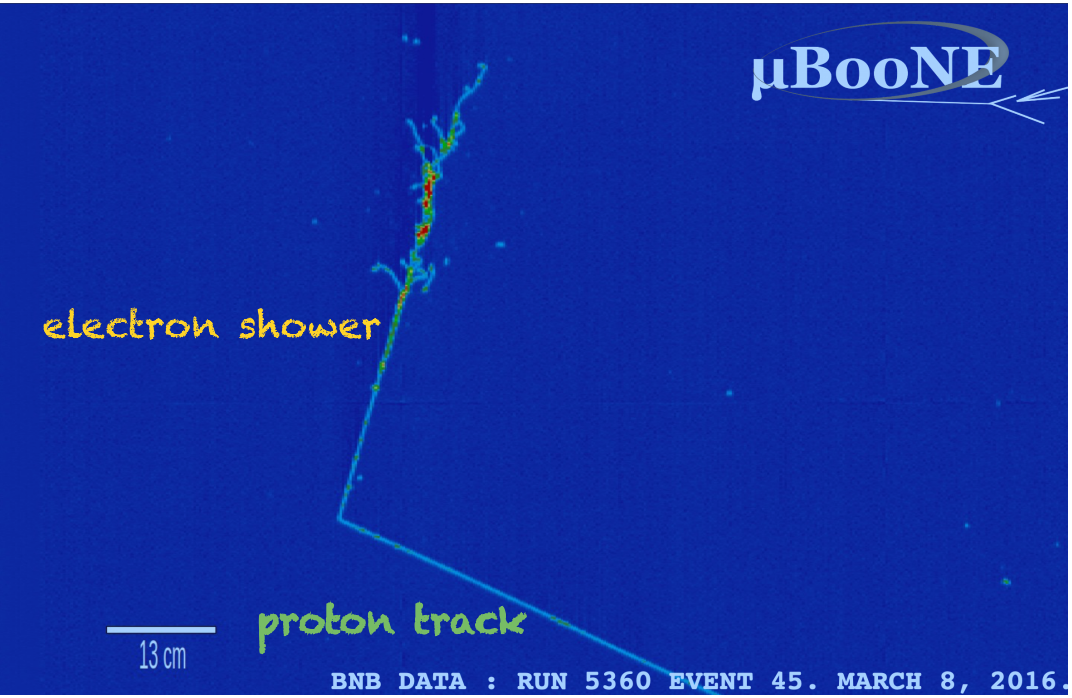
Neutrino Detectors

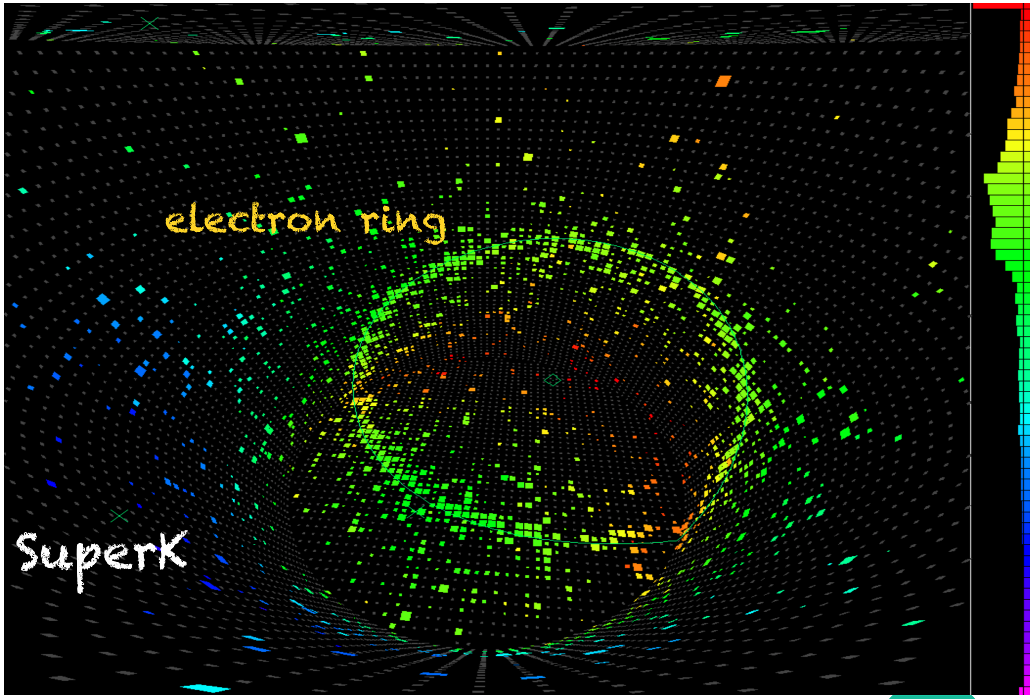
- Place a big detector (large mass) and heavy nuclear target when possible in the path of neutrinos to capture them
  - ★ Need superb detector resolution to efficiently reconstruct particles exiting a neutrino interaction

A ν_e interacting in 2 different detector technologies

Liquid argon time projection chamber, LArTPC

Water Cherenkov detector

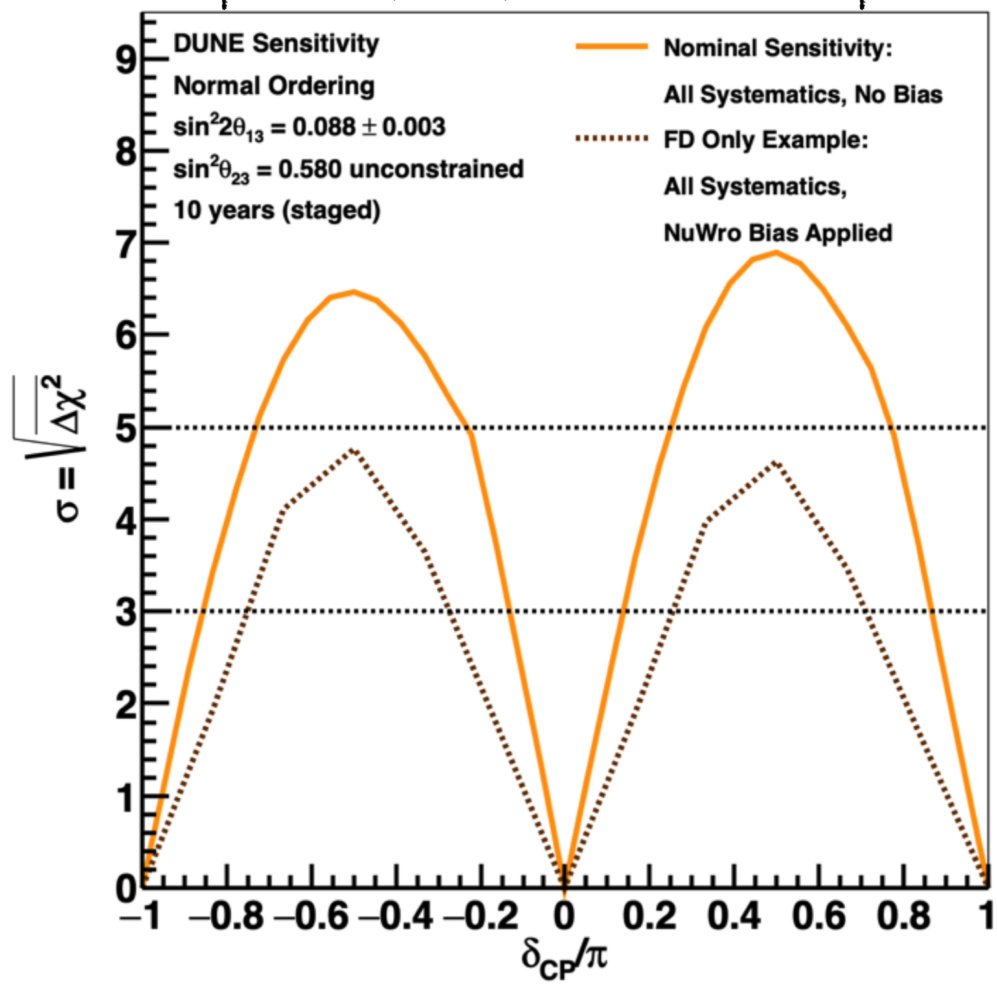




Detectors in Neutrino Oscillation Experiments

- Not always just one detector per experiment:
  - A set of **near detectors** placed at the source + **far detectors, FD** at some baseline L
  - **Near detectors** reduce uncertainties by precisely characterizing the spectrum and flavor composition of the neutrino beam before neutrinos oscillate at **FD**

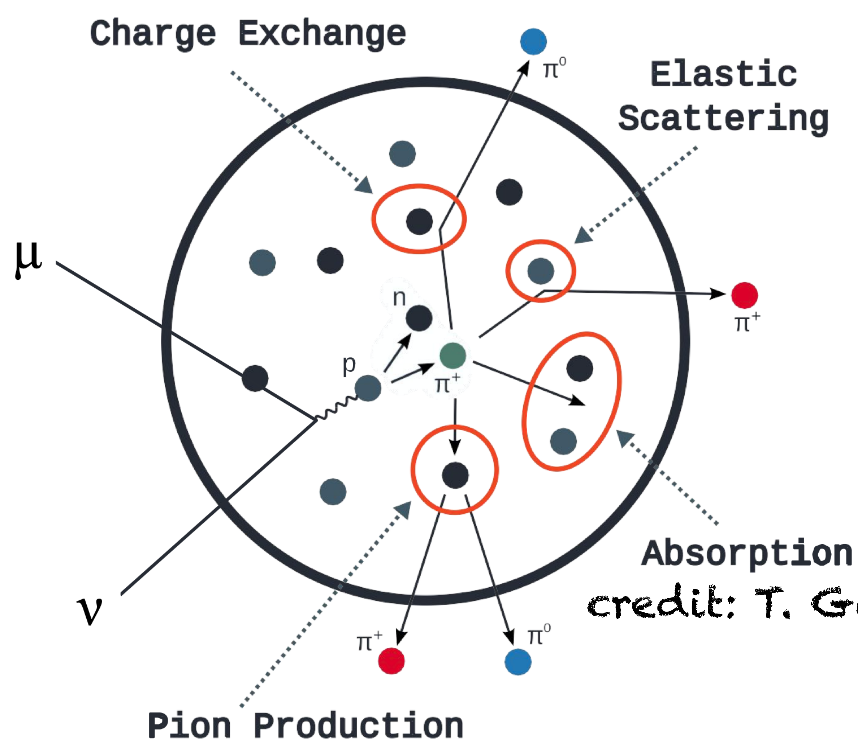
power of ND from DUNE example



Impact of Neutrino Interactions

- The use of heavy target nuclei makes things interesting!
  - ★ **Mis-modelings** lead to uncertainties in neutrino energy reconstruction and neutrino event rate estimation
  - ★ **Nuclear effects** not yet fully modeled
  - ★ In reducing these uncertainties, **neutrino experiments have played a major role in improving our understanding of the nucleus**

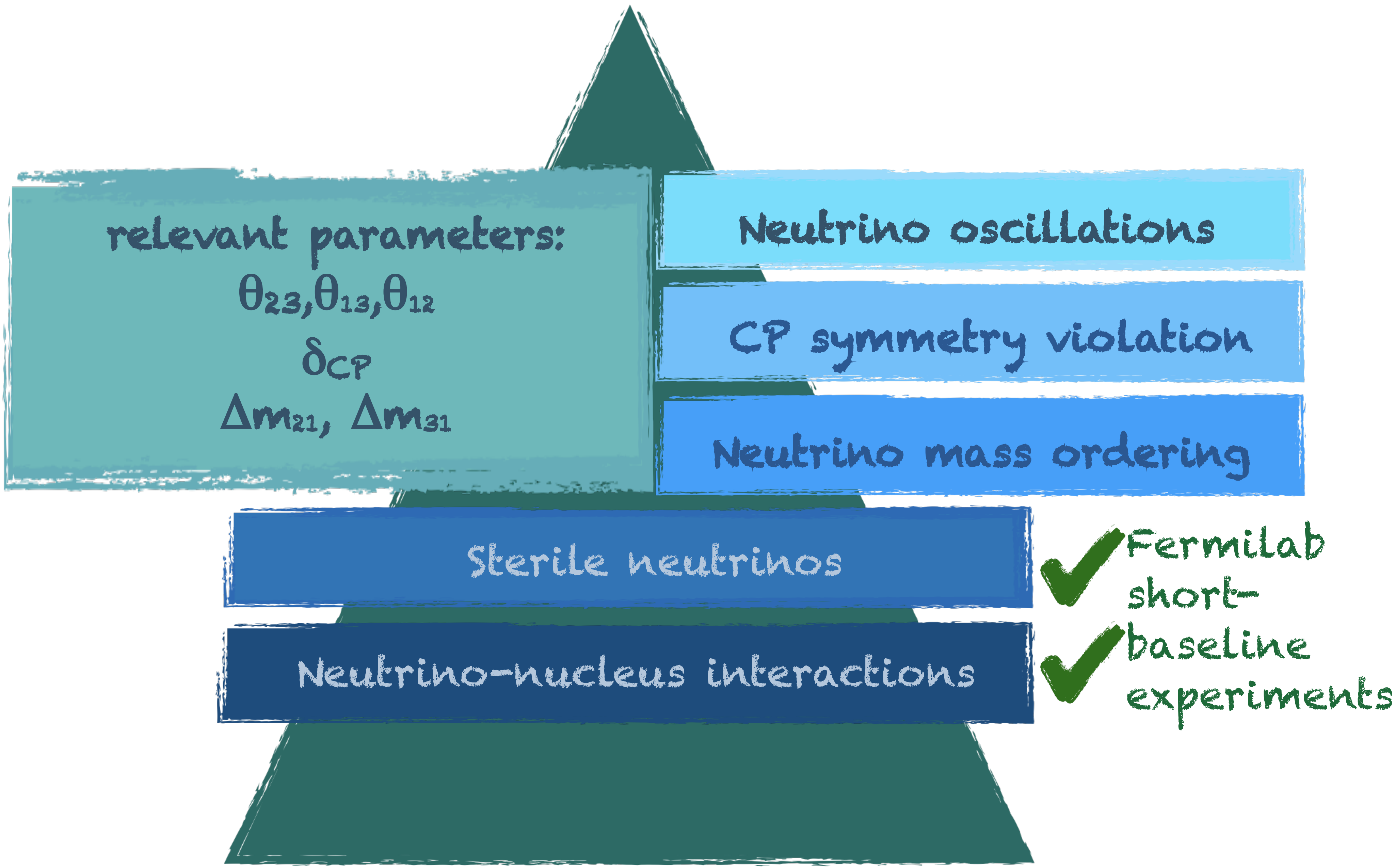
how high-energy neutrino physics intersects with nuclear physics!



credit: T. Golan

for an overview of neutrino cross sections, see O. Tomalak talk on Wednesday

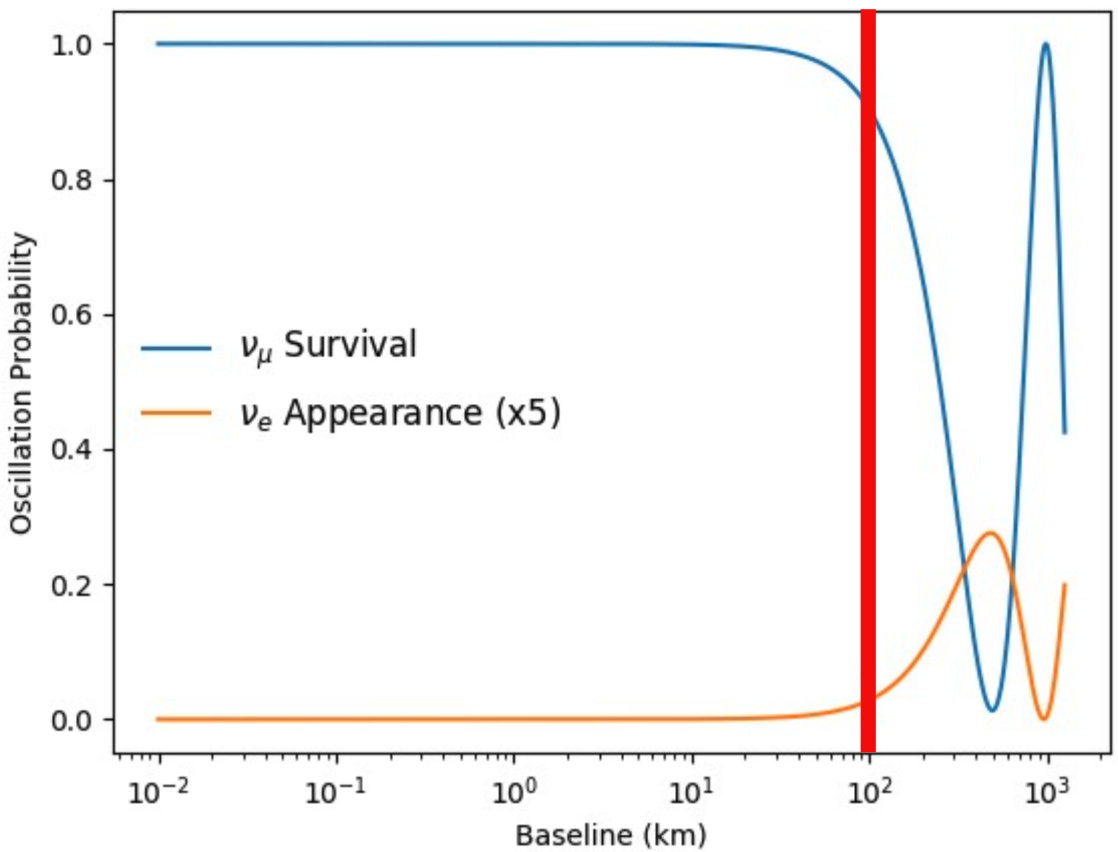
Big Picture



relevant parameters:
θ23,θ13,θ12
δCP
Δm21, Δm31
Neutrino oscillations
CP symmetry violation
Neutrino mass ordering
Sterile neutrinos
Neutrino-nucleus interactions
Fermilab short-baseline experiments

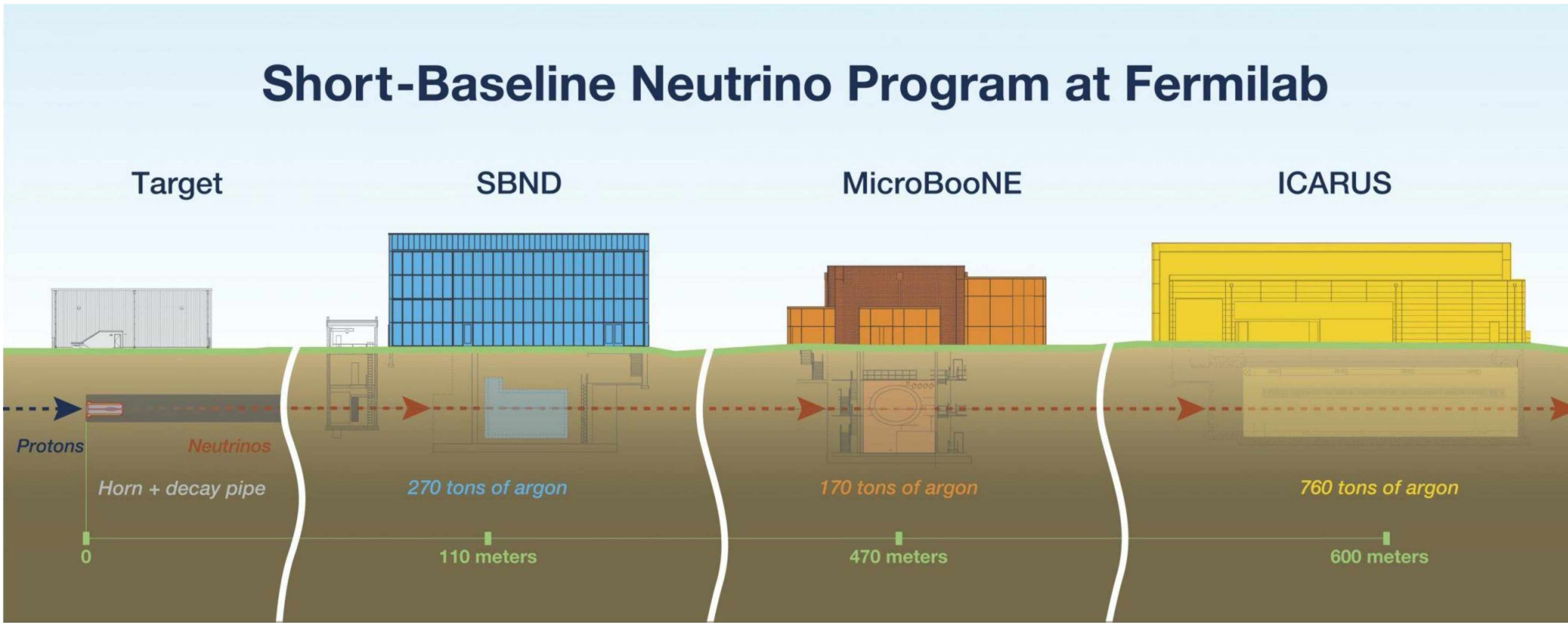
Strategy of Future Short-baseline Experiments

- **At short baseline (<100 km)**, we do not expect to see **oscillations**
- **Anomaly:** there is experimental evidence of **oscillations** at short baselines
  - A larger splitting due to an additional 4th neutrino causing oscillations at such short baselines (sterile neutrinos)



Future Short-baseline Experiments at Fermilab

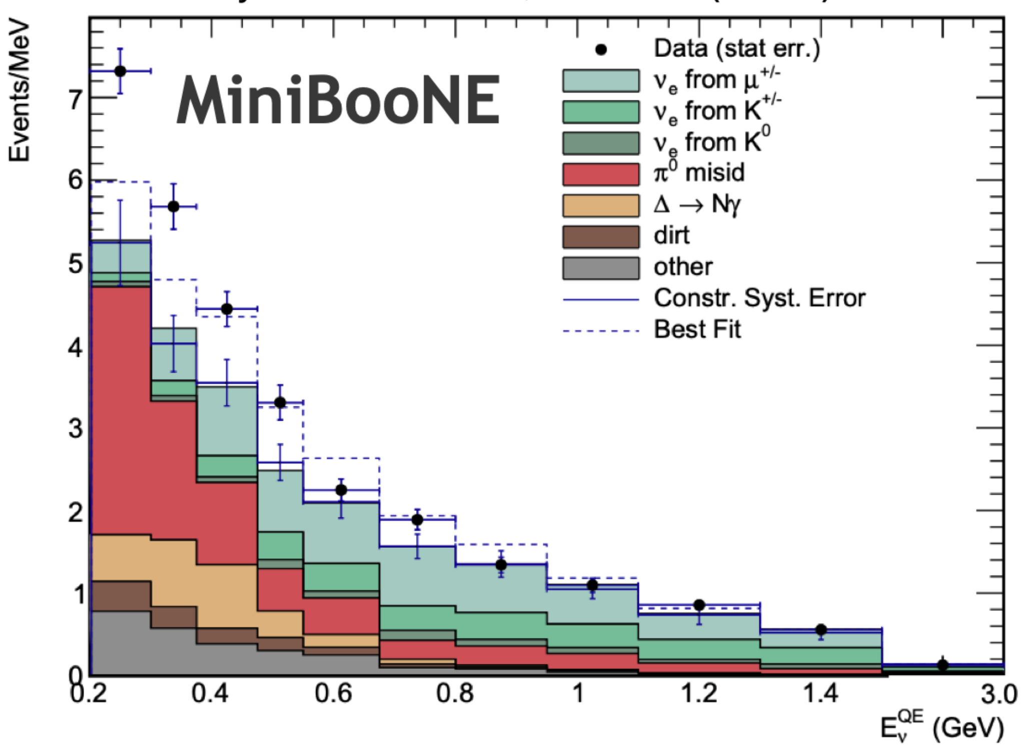
- Three LArTPCs placed in the same neutrino beam measuring short-baseline oscillations both in **appearance** and **disappearance** modes
  - ★ Physics goal: search for sterile neutrinos, as a possible explanation of the anomalies observed in LSND and MiniBooNE
  - ★ Also offers a **rich neutrino interaction cross-section program**



Brief Overview of LSND/MiniBooNE Anomaly

- LSND and MiniBooNE observed an excess of electron neutrinos at low energies
  - ★ One hypothesis states that this is potentially background from mis-identified photons

Phys. Rev. D 103, 052002 (2021)



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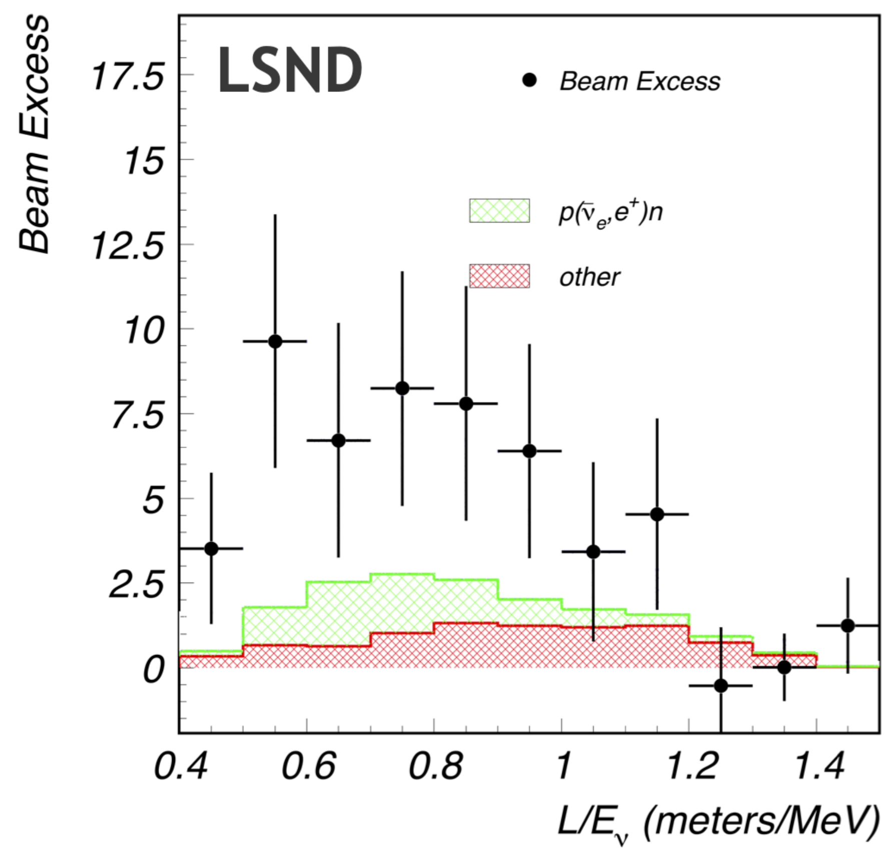
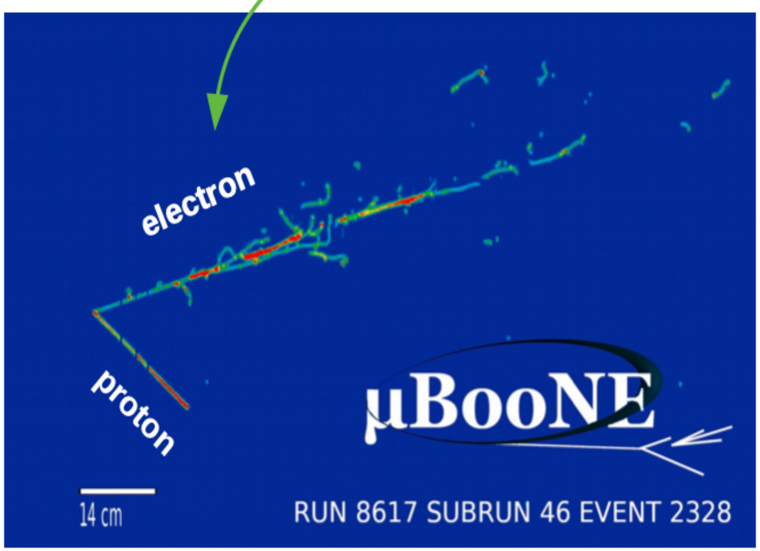
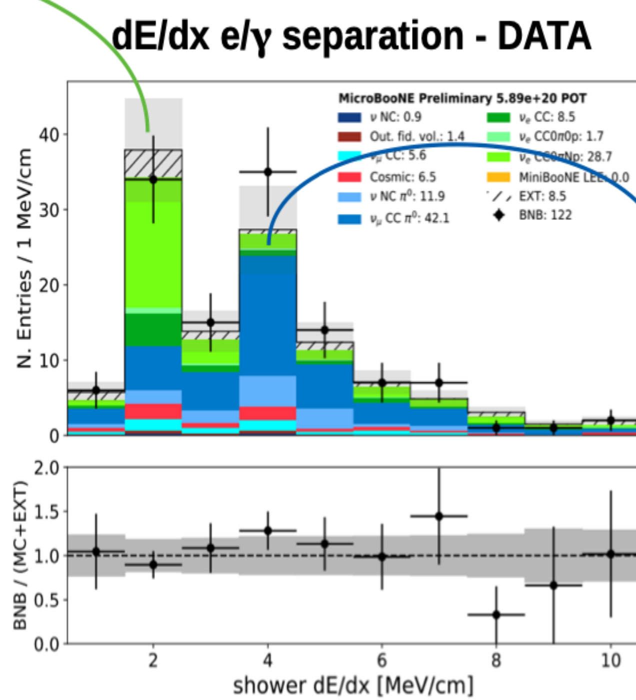


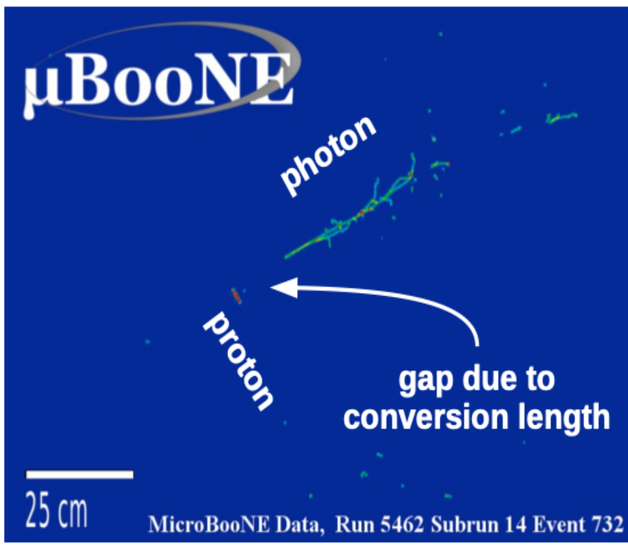
Specific Advantage of LArTPC Technology

- SBN experiments rely on LArTPC technology which can **more efficiently make the distinction between electrons and photons**



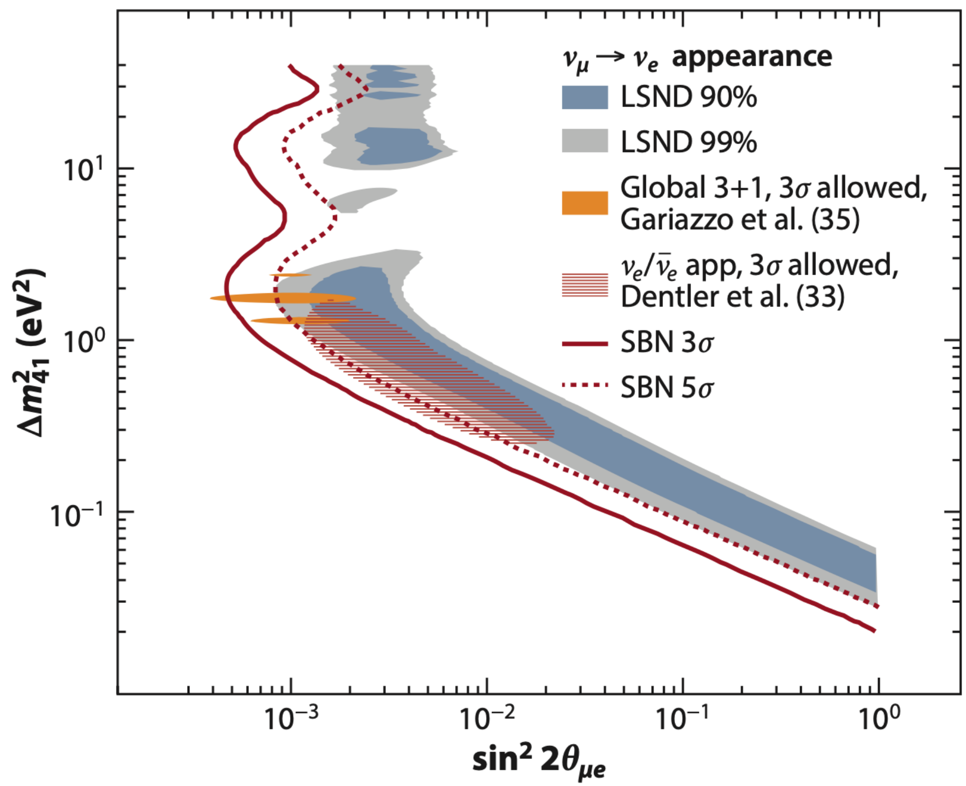
D. Caratelli's talk at ICHEP20





SBN Projected Performance

- SBN detectors can achieve **3σ coverage** and >**5σ coverage** of the **99% C.L. allowed region of the LSND signal**



Annu. Rev. Nucl. Part. Sci. 2019. AA:1–25

for latest measurements from MicroBooNE, see J. Barrow's talk on Thursday

for the latest on SBND and ICARUS, see J. Zennamo's talk later this evening

Big Picture

Future medium & long-baseline experiments

relevant parameters:
$\theta_{23}, \theta_{13}, \theta_{12}$
δ_{CP}
Δm_{21}, Δm_{31}

Neutrino oscillations ✔

CP symmetry violation ✔

Neutrino mass ordering ✔

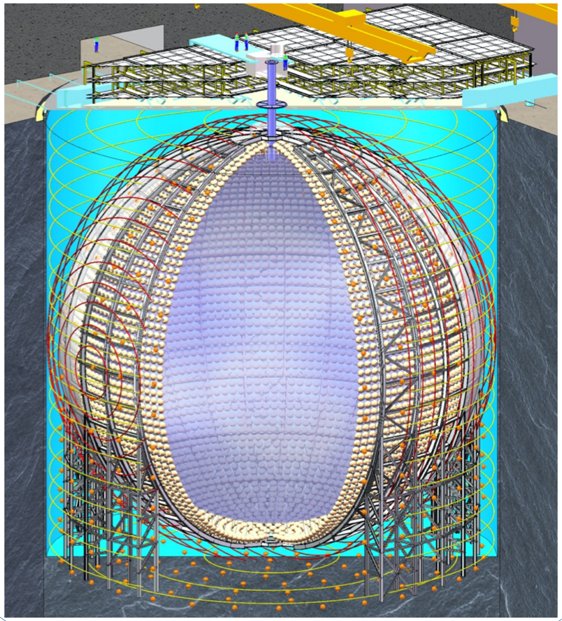
Sterile neutrinos

Neutrino-nucleus interactions ✔

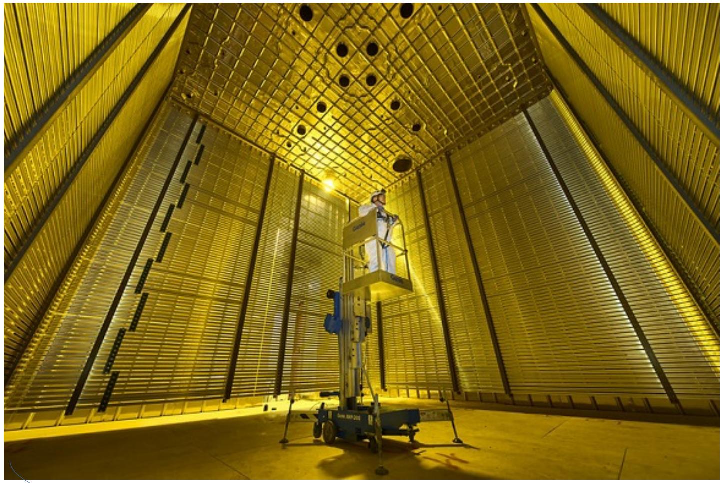
Future Oscillation Experiments – A Whole ν World

- **Physics goals of long-baseline (LBL) experiments, DUNE and T2HK/HyperK**: δ_{CP}, mass ordering (with atmospheric neutrinos in case of HyperK), $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, Δm^2_{32}, BSM, baryon number violation, supernova and solar neutrinos
- **Physics goals of medium baseline reactor anti-neutrino experiment JUNO**: mass ordering, $\sin^2(2\theta_{12})$, Δm^2_{32}, Δm^2_{12}, supernova, solar, and geo neutrinos, BSM, baryon number violation

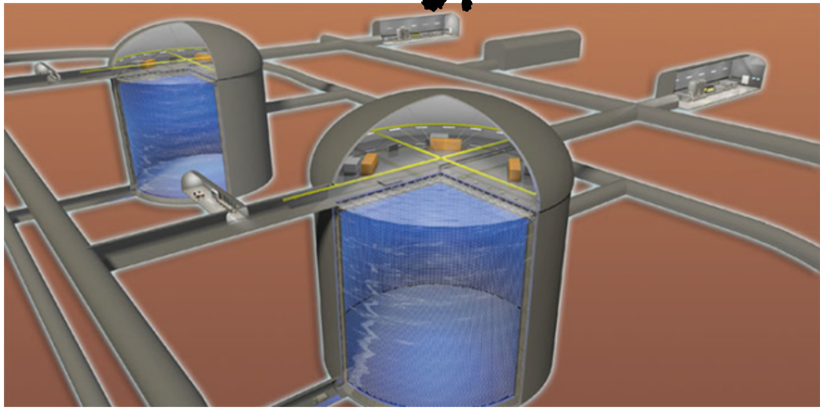
JUNO



DUNE



T2HK/HyperK



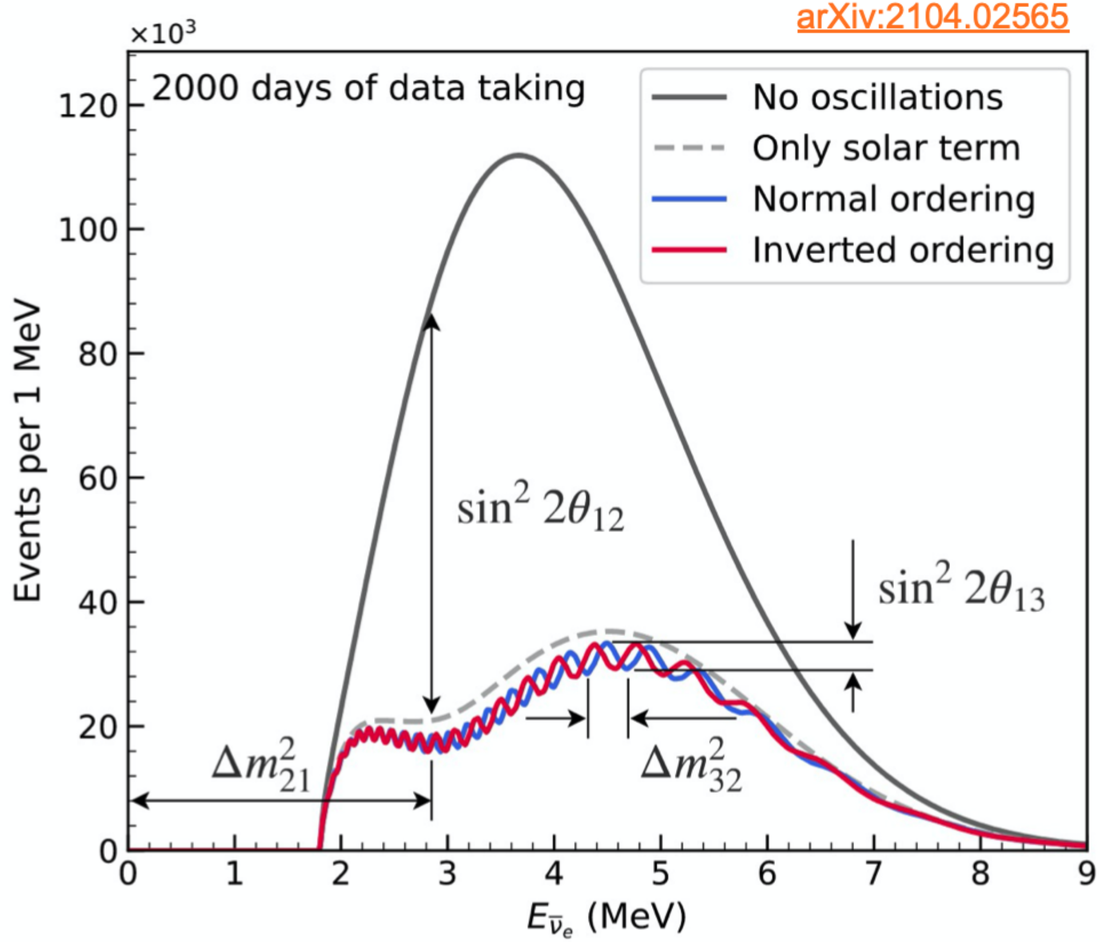
medium-baseline reactor anti-neutrino experiment

LBL oscillations using accelerator neutrinos

Projected Performance – JUNO

- Measures electron anti-neutrino disappearance over a medium-baseline:
  - Determines neutrino mass ordering to 4σ after 6 years of data taking
  - Measures **$\sin^2(2\theta_{13})$, $\sin^2(2\theta_{12})$**, **Δm^2_{32}, Δm^2_{12}**, at sub-percent levels

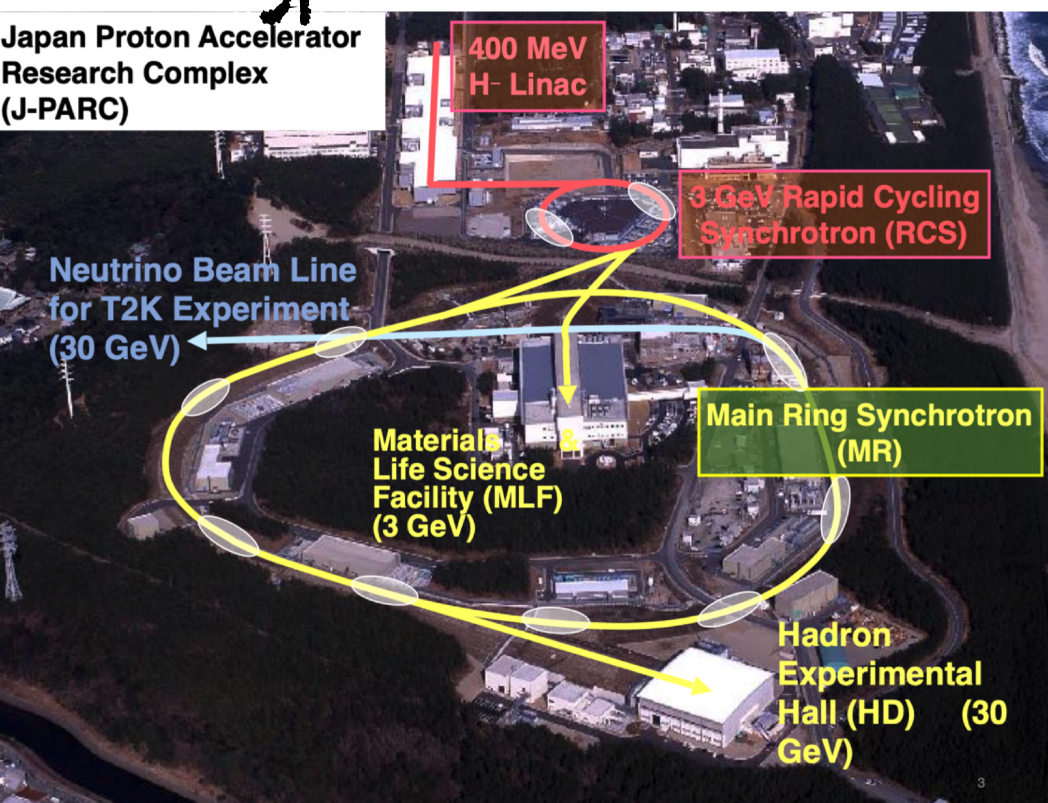
arXiv:2104.02565



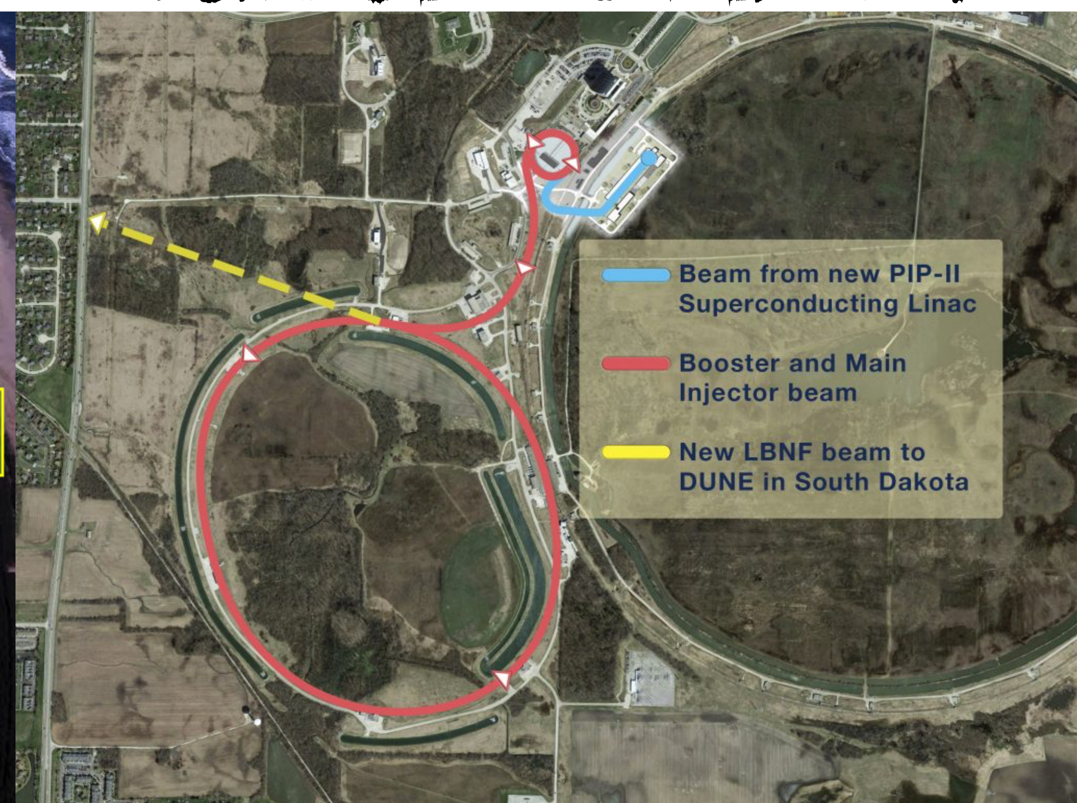
Neutrino Beams of Two Future LBL Experiments

- T2HK/HyperK neutrino beam:
  - ★ At J-PARC, **1.3 MW beam power**
  - ★ Narrow-band beam, far detector placed off the beam axis to observe neutrino flux peaked at ~600 MeV + near detectors at on and off-axis locations
- DUNE neutrino beam:
  - ★ At Fermilab, **1.2 MW beam power, upgradable to 2.4 MW**
  - ★ Wide-band beam, far detector placed on-axis to observe a broad spectrum of neutrino fluxes (0.5-5 GeV) + movable near detector for on and off-axis ν-flux measurements (DUNE-PRISM)

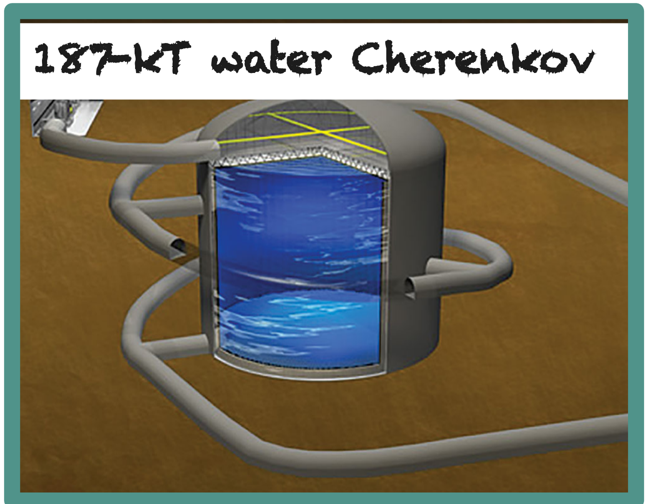
T2HK/HyperK Beam @ J-PARC

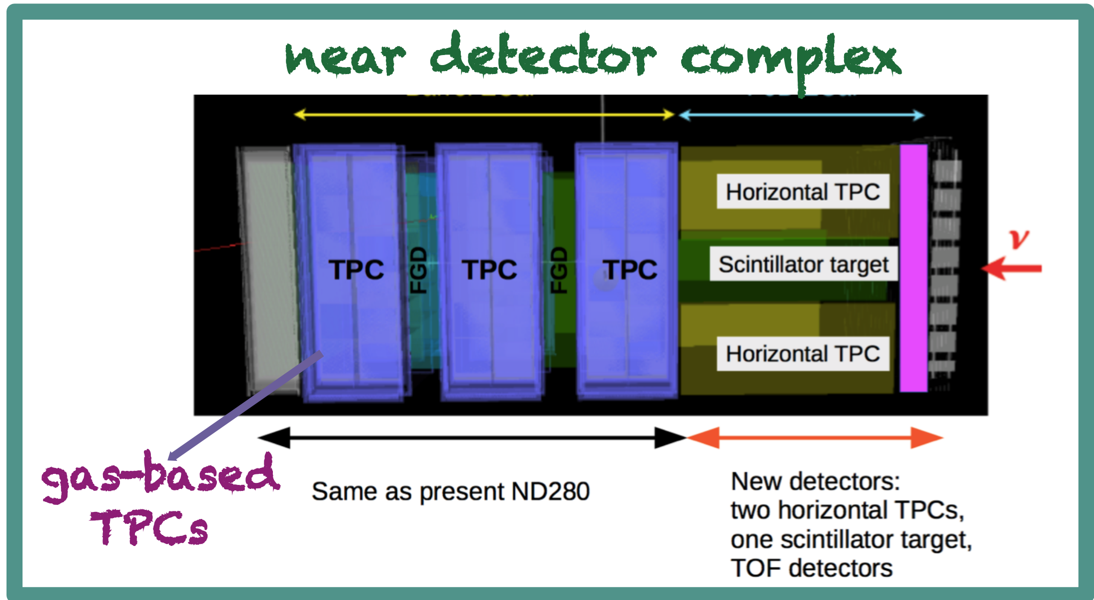


DUNE Beam @ Fermilab

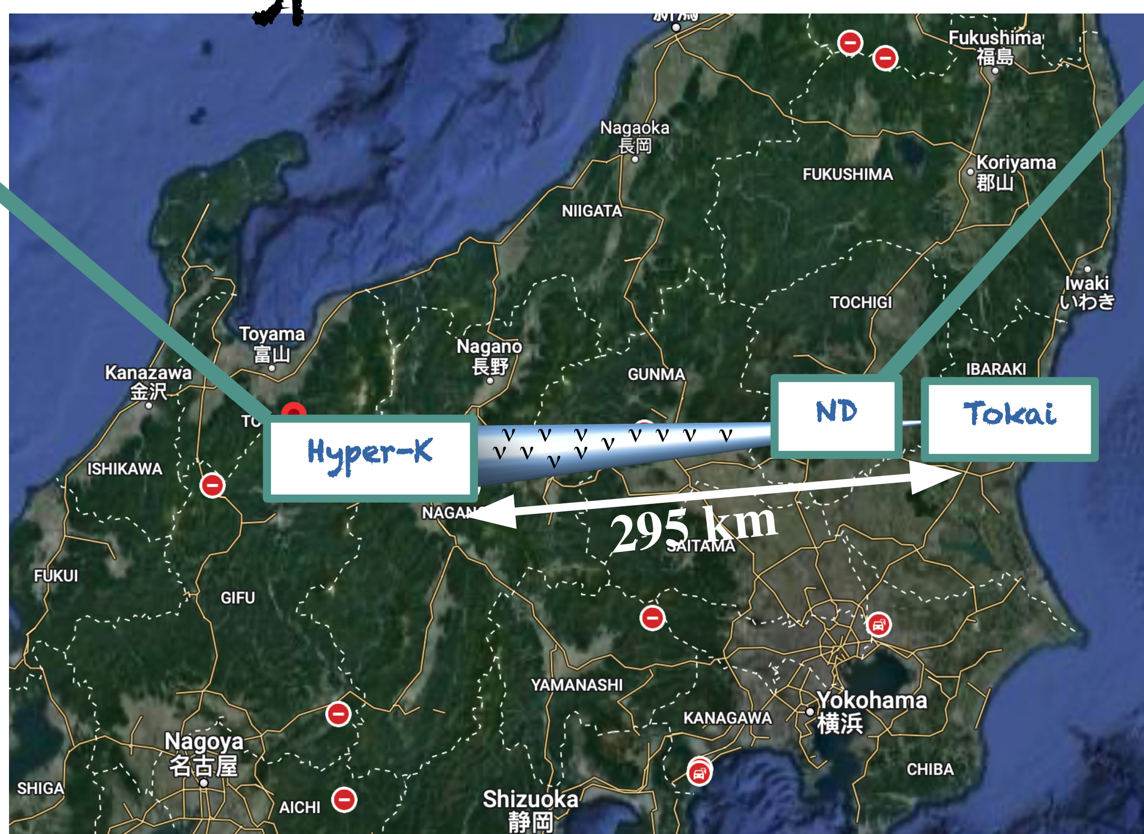


Near and Far Detectors of T2HK





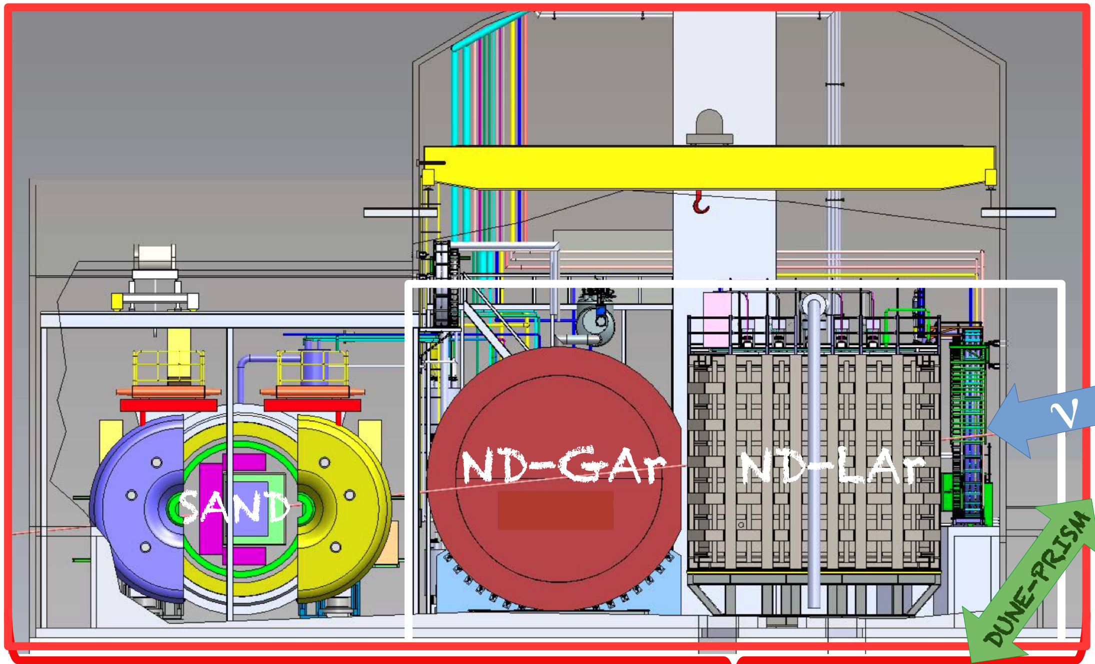
T2HK/HyperK



Near and Far Detectors of DUNE

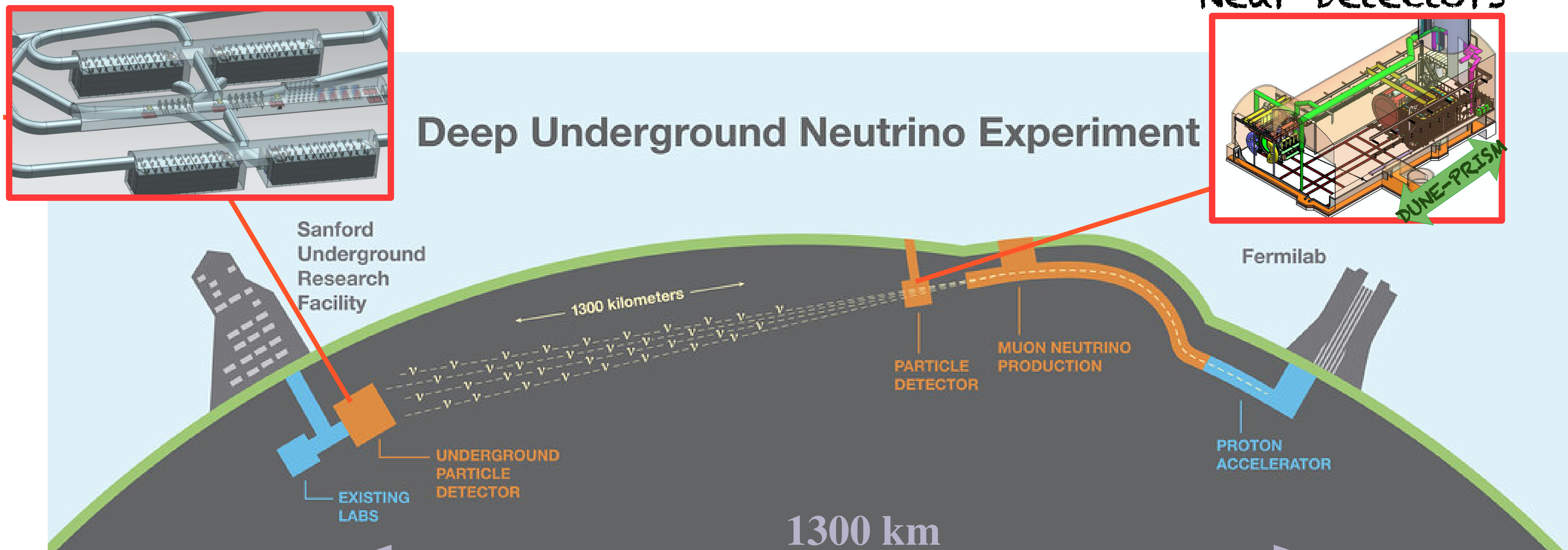
LArTPC ND-LAr + high pressure gas argon TPC, ND-GAr + a beam monitor, SAND

ND-LAr + ND-GAr move to off-axis positions to collect off-axis fluxes - DUNE-PRISM



> 40-kT LArTPC Far Detectors

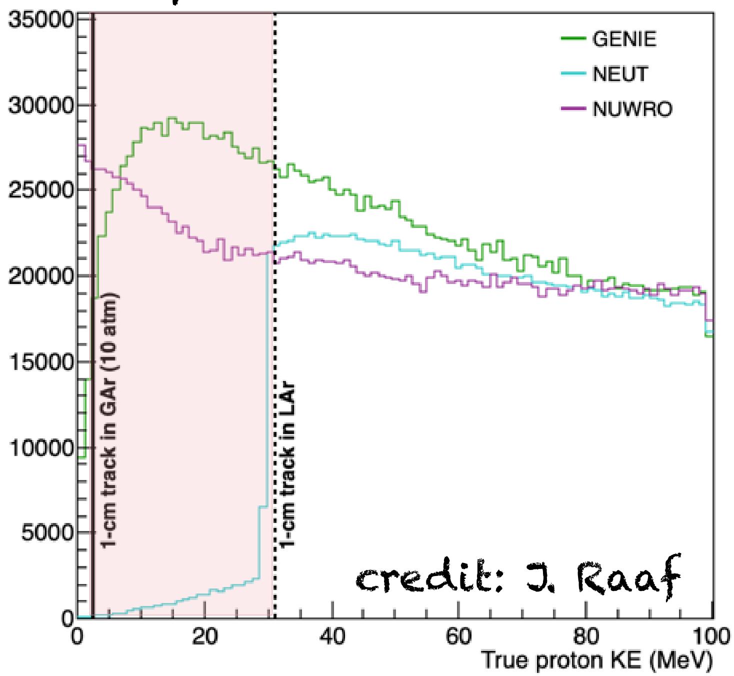
Near Detectors



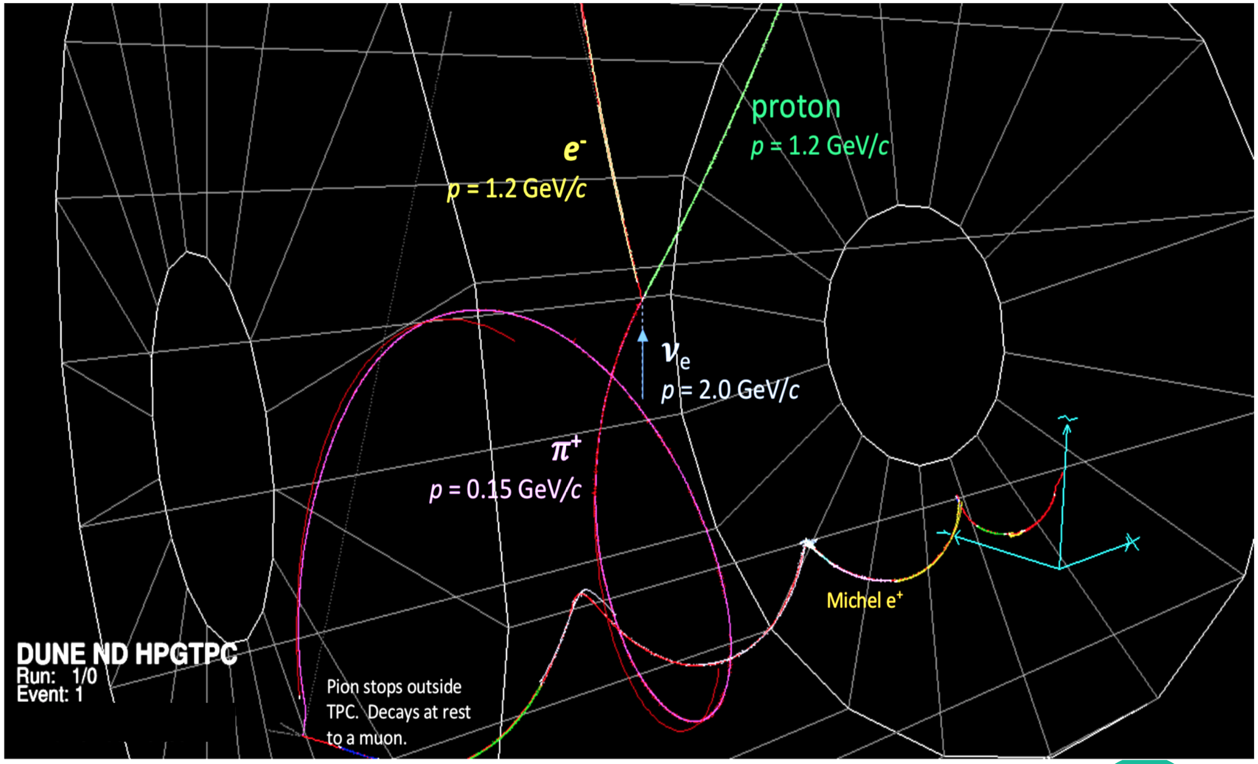
An Emerging Detector Technology for Neutrino Physics

- Low threshold gas TPCs for long-baseline oscillation physics (e.g. ND-GAr in DUNE & gas TPCs in ND280):
  - Low density, hence low detection threshold (e.g. lower than LArTPC), leads to high sensitivity to low energy **protons** or **pions**
  - **Reveals discrepancies between neutrino event generators at low energies,** getting us closer to choosing a more accurate interaction models

neutrino generator discrepancies at low proton KE, accessible with a high-pressure gas argon TPC



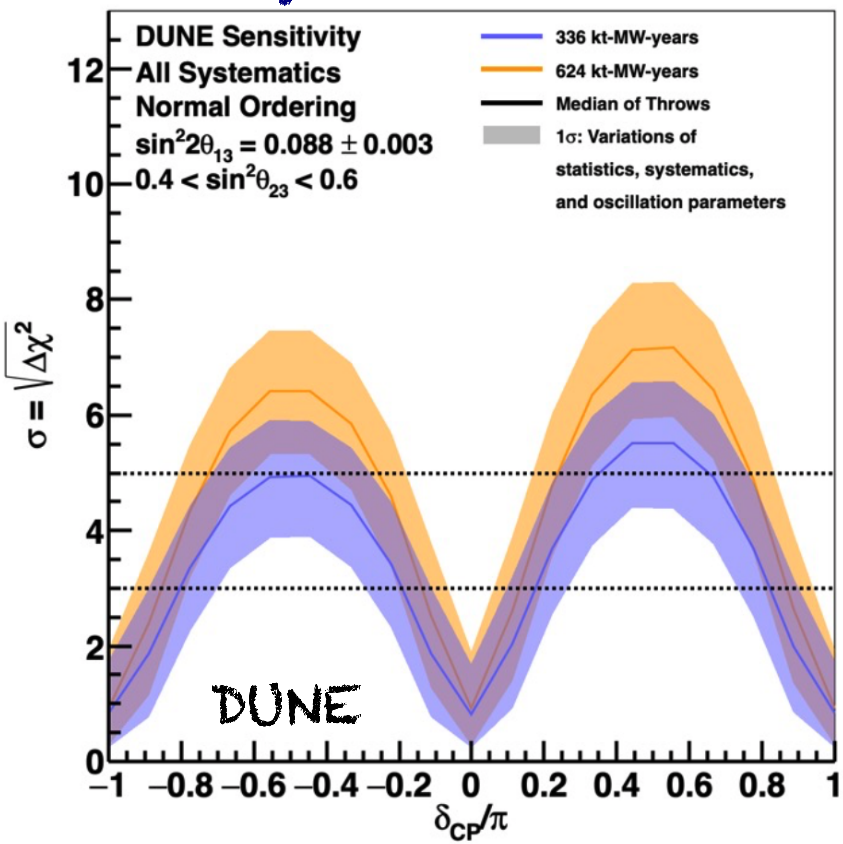
A detailed view of the ν-interaction vertex in ND-GAr near detector in DUNE



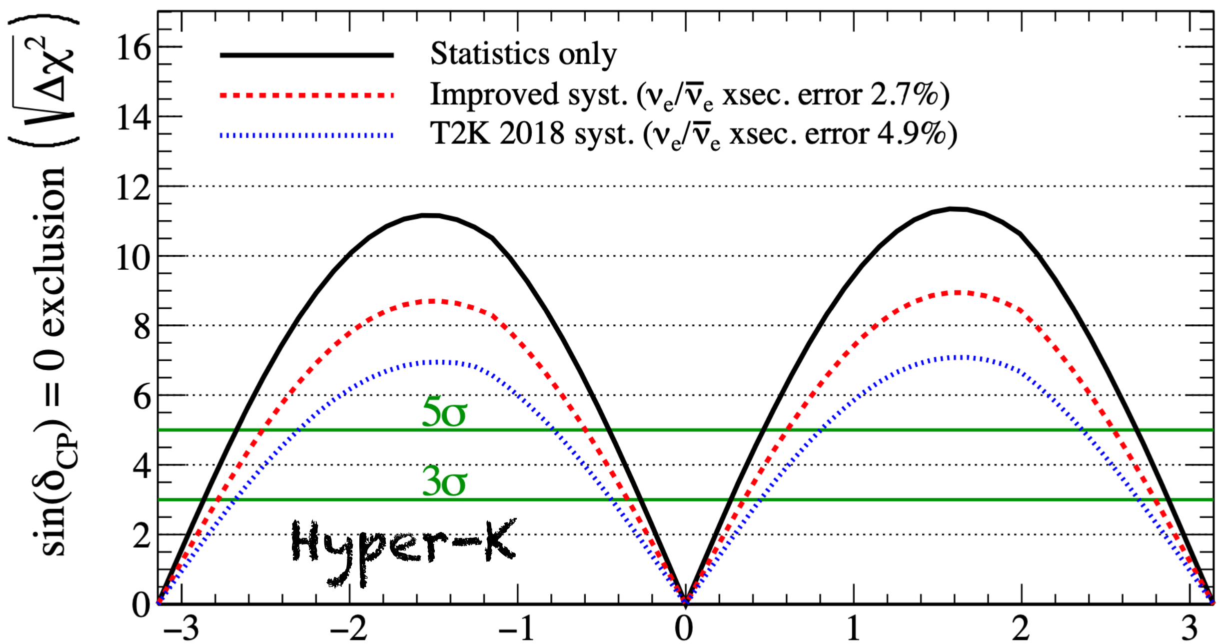
Projected Performance – Two Future LBL Experiments

- Assuming we know the mass ordering, both experiments can reach 5σ sensitivity to CP violation for most values of δ_{CP}

DUNE Physics TDR, arxiv:2002.03005



J. Wilson Neutrino2022 Talk

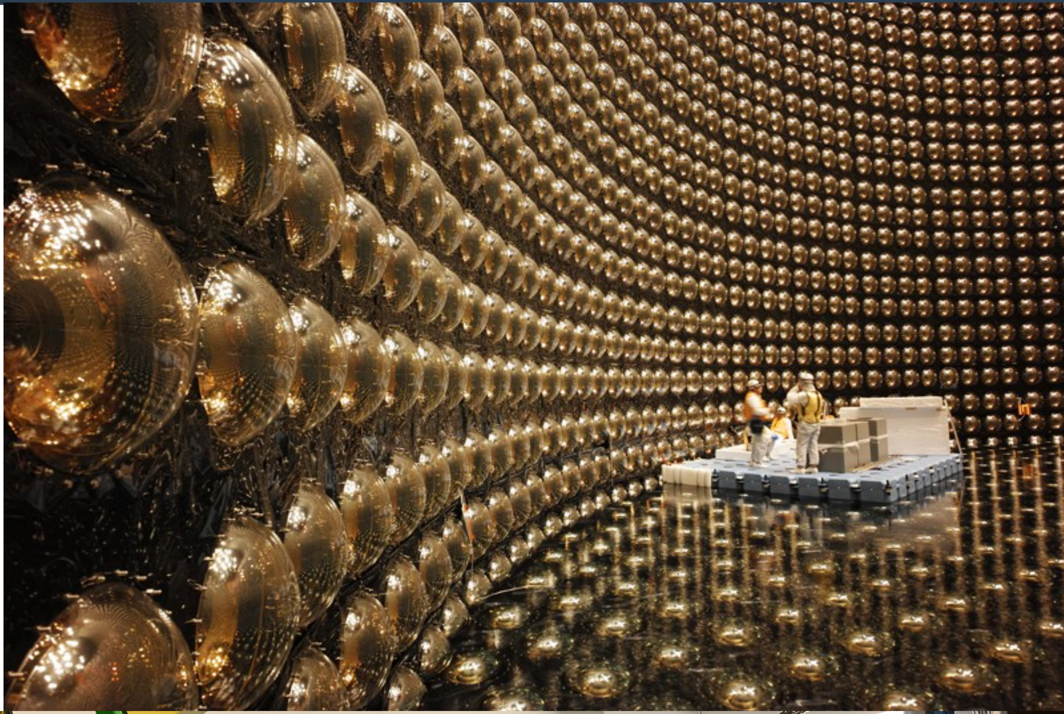


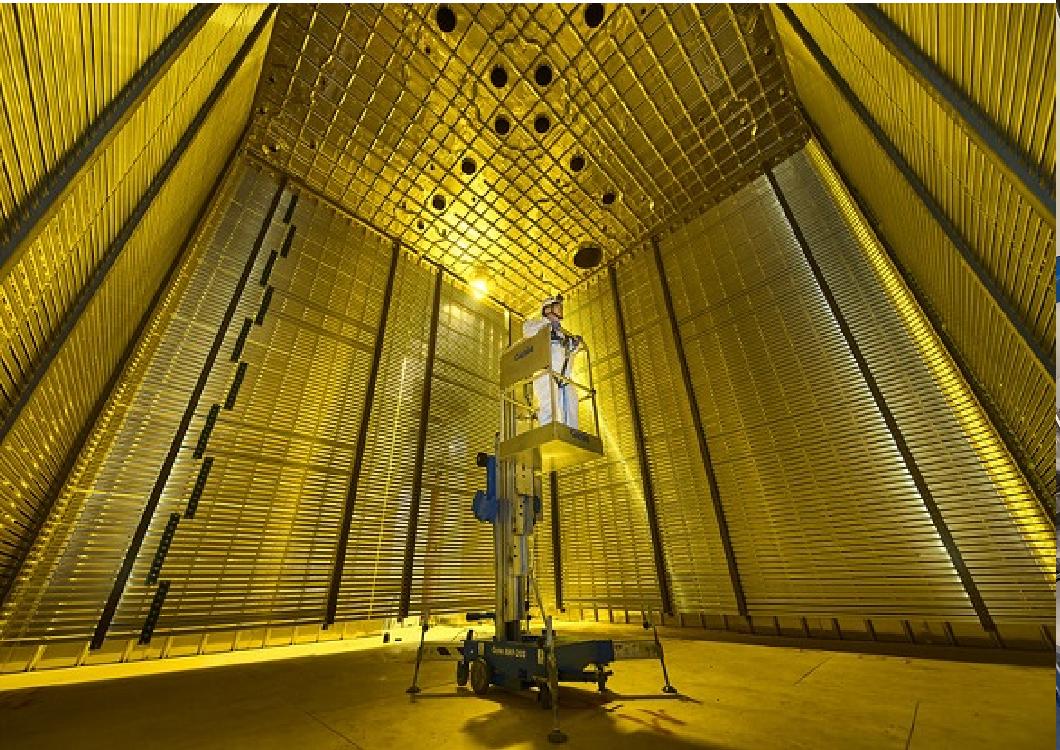
Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$

Summary

- Neutrinos have small interaction cross-sections:
  - ★ Many fundamental questions in neutrino physics remain un-answered
  - ★ Build larger detectors and seek more intense sources of neutrinos

- Future neutrino experiments are well suited to answer many of the un-answered questions:
  - ★ Understanding of neutrino-nucleus interactions is specifically crucial and calls for stronger collaboration among neutrino and nuclear physics communities

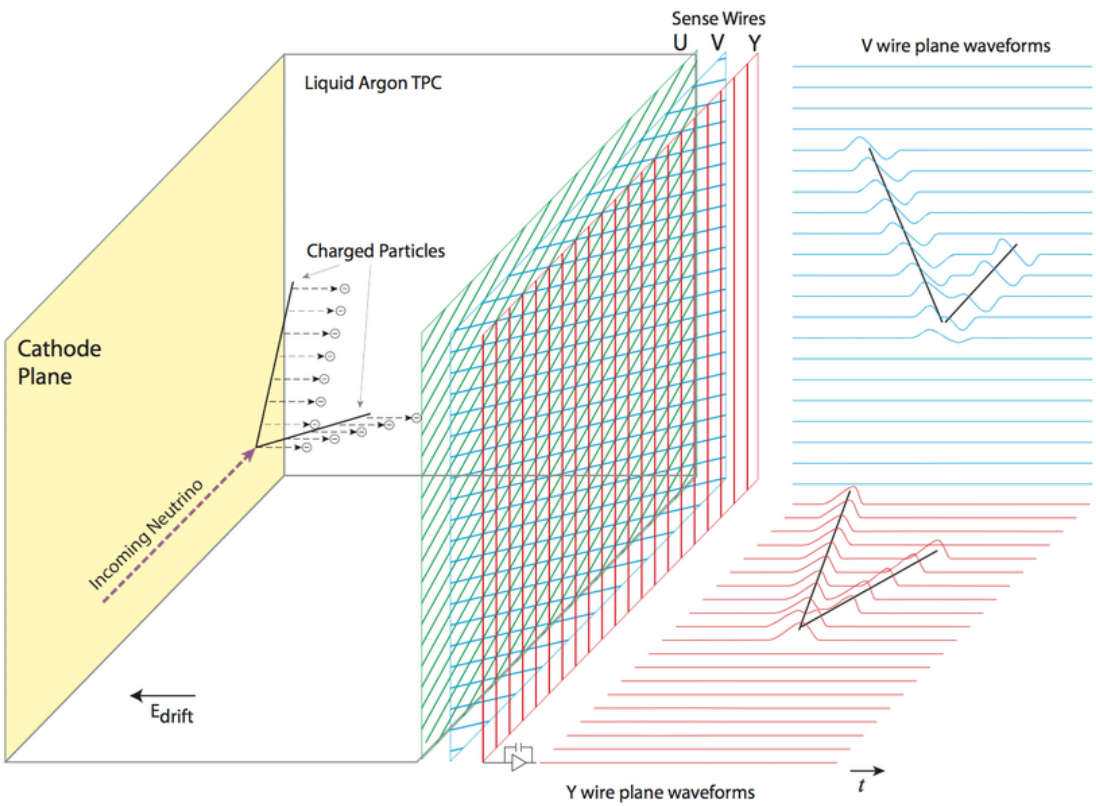


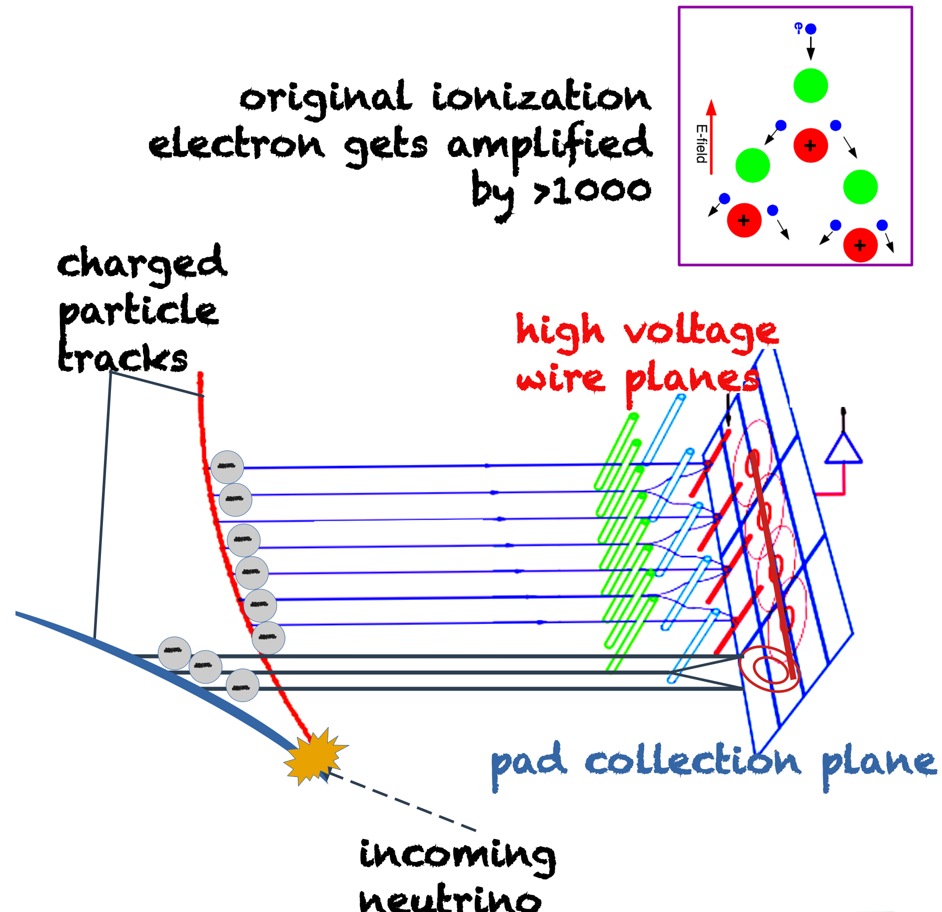


Additional Slides

Gas-argon TPC & LArTPC Working Principles

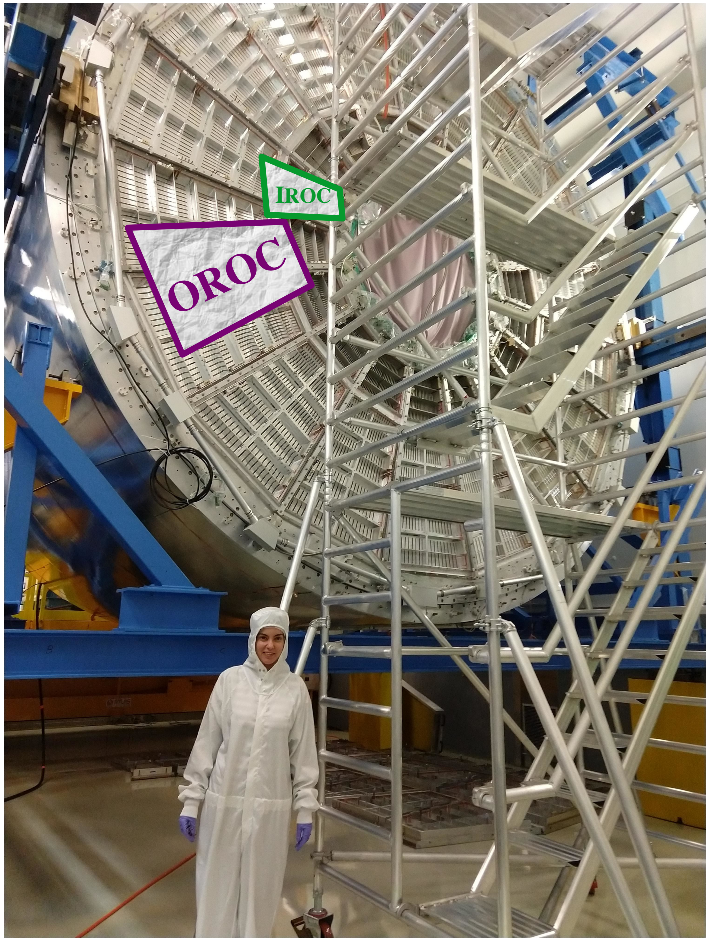
- Both TPCs but the key difference is the way signal gets collected:
  - In LArTPC, the ionization electrons are collected by wires (or pixels)
  - In a gas TPC, first the original ionization electron gets **multiplied** as it approaches amplification wires (or amplification foils), then **induced charge gets collected**:
    - The higher the voltage on the amplification wires, the lower the achieved detection threshold





ND-GAr Expected Performance

ALICE in clean room



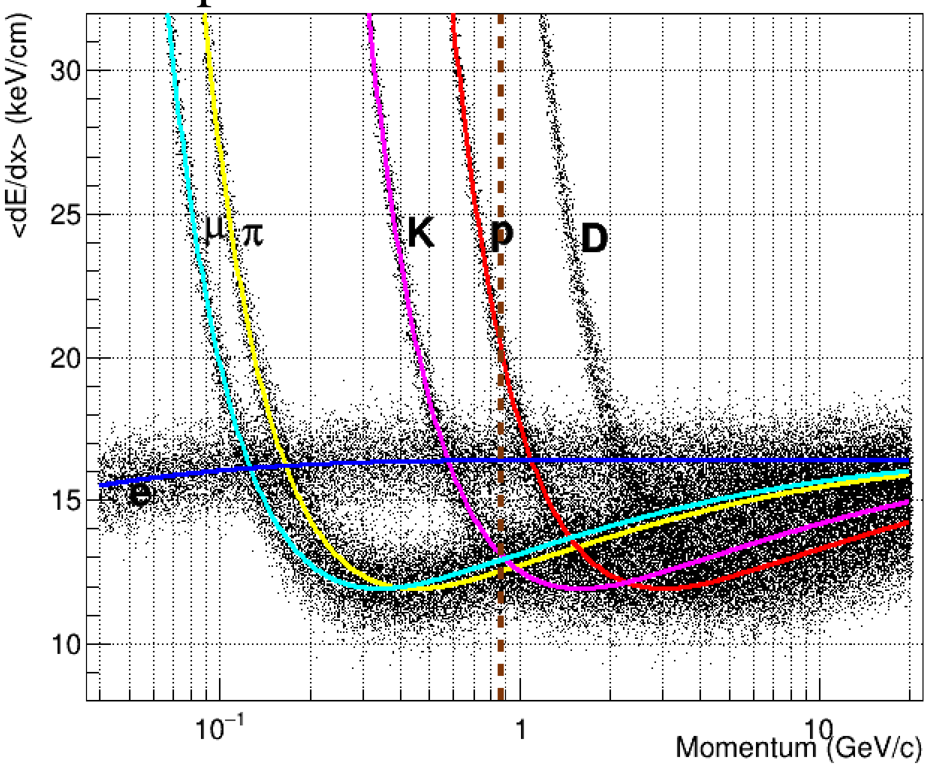
* extrapolated from ALICE & PEP-4

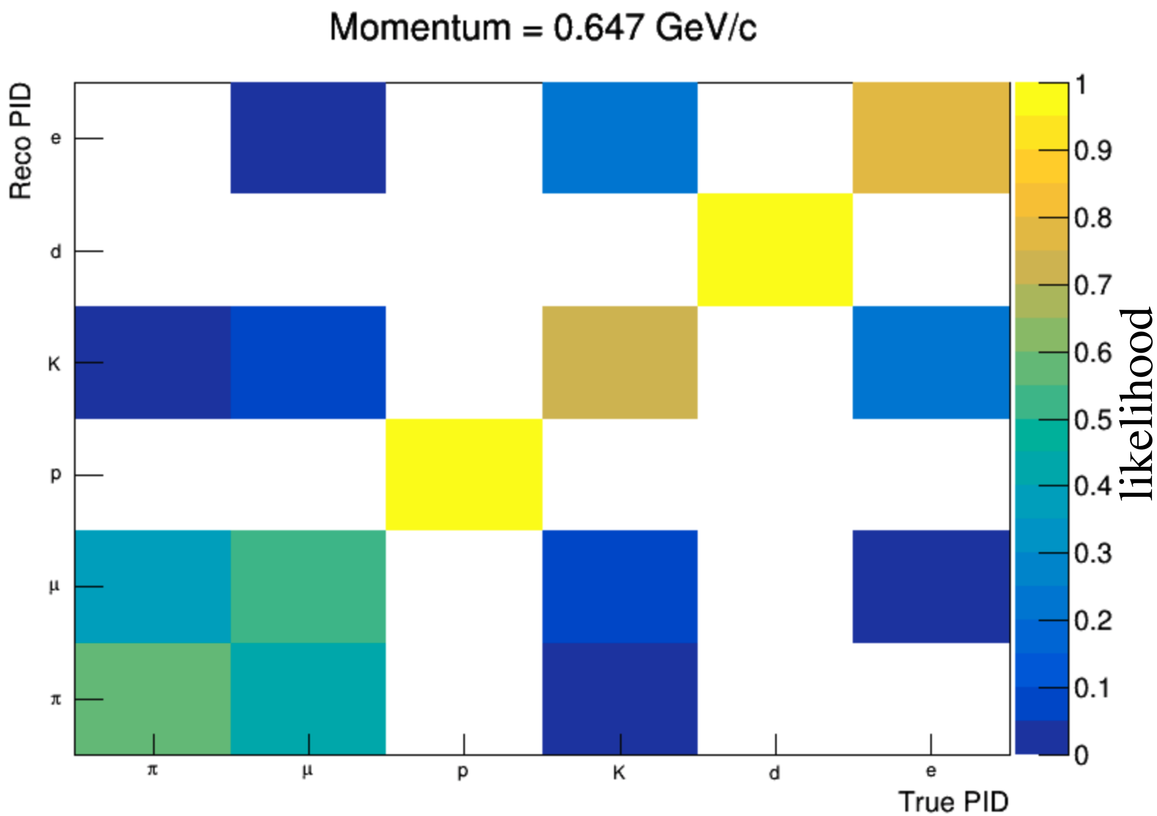
Parameter	Value	Comments
Single hit resolution $\sigma_\perp$	250 μm	*$\perp$ to TPC drift direction
Single hit resolution $\sigma_\parallel$	1500 μm	*$\parallel$ to TPC drift direction
Two-track separation	1 cm	*
$\sigma(dE/dx)$	5%	*
μ reconstruction: σ_p/p	(2.9%, 14%)	(core, tails), ν_μ CC events, LBNF flux
μ σ_p/p vs. track length	(10%, 4%, 3%)	(core),(1,2,3 m), ν_μ CC events, LBNF flux
Angular resolution	0.8°	ν_μ CC events, LBNF flux
Energy scale uncertainty	$\lesssim$ 1%	*(by spectrometry)
Proton detection threshold	5 MeV	kinetic energy
ECAL energy resolution	$6\%/\sqrt{E(\mathrm{GeV})} \oplus 1.6\%/E(\mathrm{GeV}) \oplus 4\%$	
ECAL pointing resolution	10° at 500 MeV	

- Need a reasonably-sized TPC for collecting 2M ν_μ CC events/ton of ^{40}Ar/year for constraining systematics:
  - TPC the size of ALICE is the right size if pressurized
  - Superb tracking efficiency, momentum resolution, & angular resolution
  - ALICE's **Inner** and **Outer** multi-wire proportional readout chambers (**IROC** and **OROC**) are available for use in HPgTPC (ALICE has upgraded to GEMs)
  - The read out system in the center of HPgTPC will need to be built

ND-GAr Expected Performance

dE/dx based on PEP-4, as implemented in our simulations

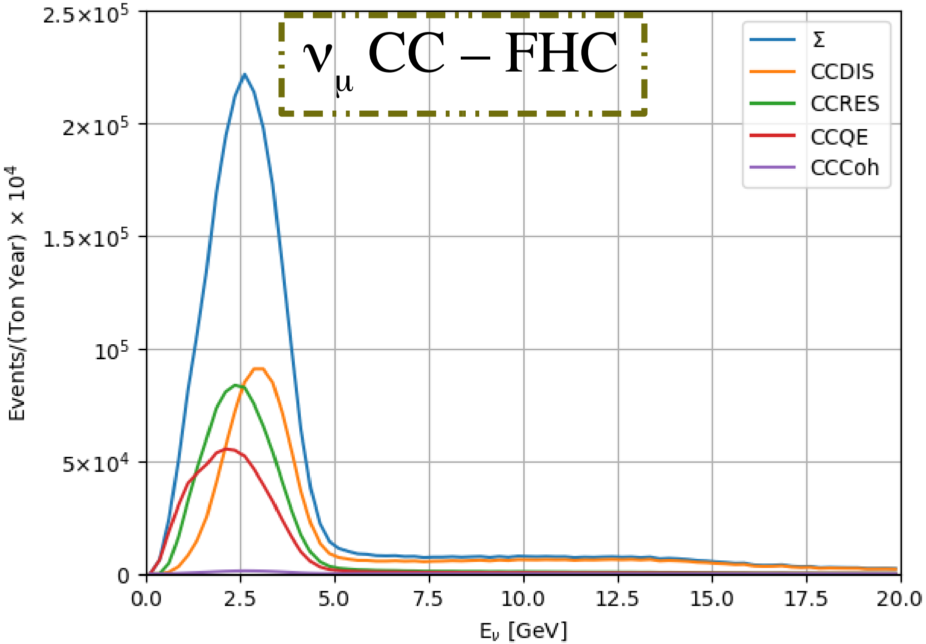


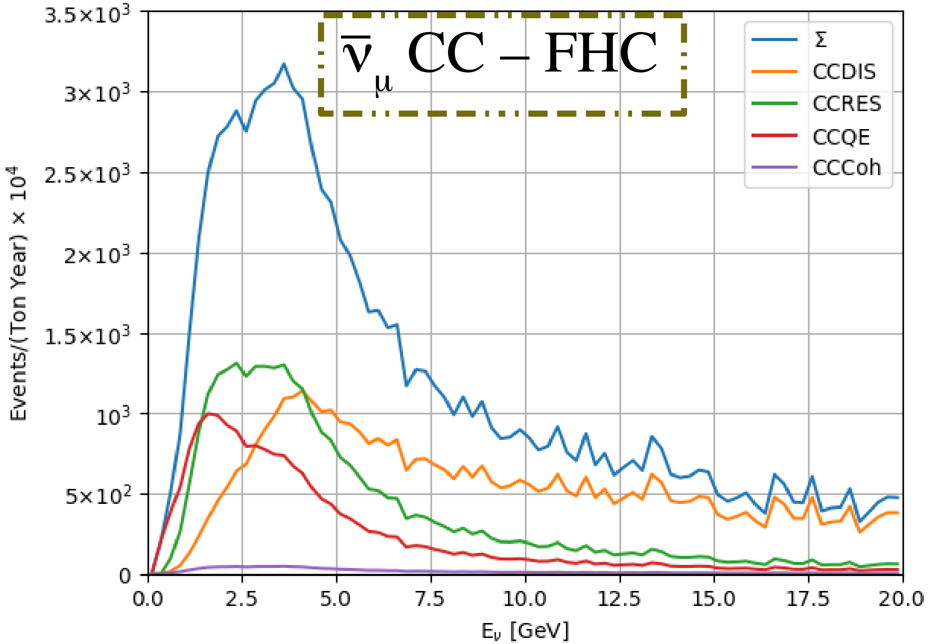


- Parametrized dE/dx particle ID implemented in GArSoft based on PEP-4 at 8.5 atm:
  - 0.8 keV/cm dE/dx resolution

FHC Mode, Optimized DUNE flux (Oct 2017), GENIE v2.12.10

Event Category	Events/Ton-year	Event Category	Events/Ton-year
ν_μ CC total	2.54E+06	$\bar{\nu}_\mu$ CC total	2.43E+02
ν_μ NC total	1.69E+02	$\bar{\nu}_\mu$ NC total	9.83E+01



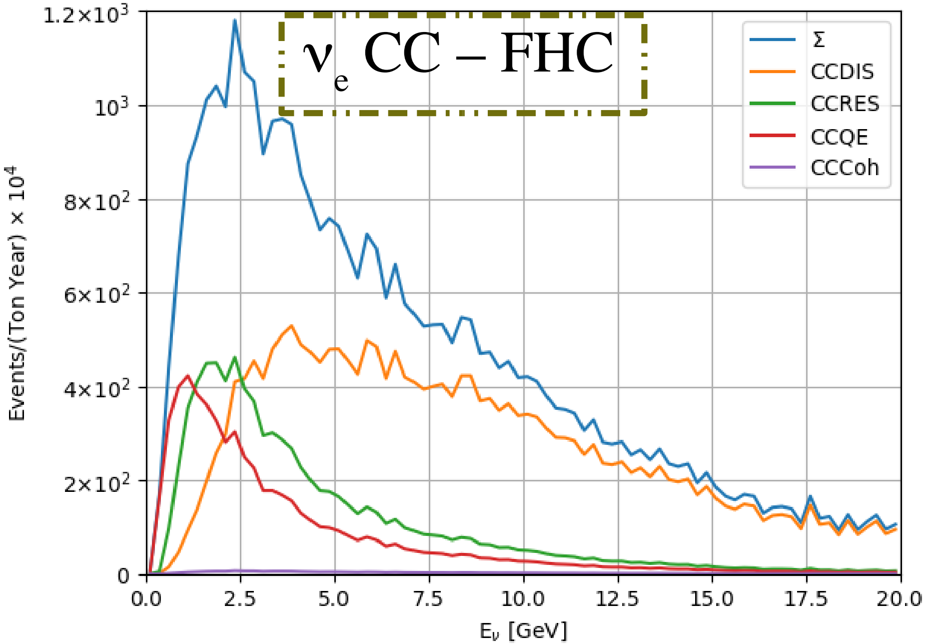


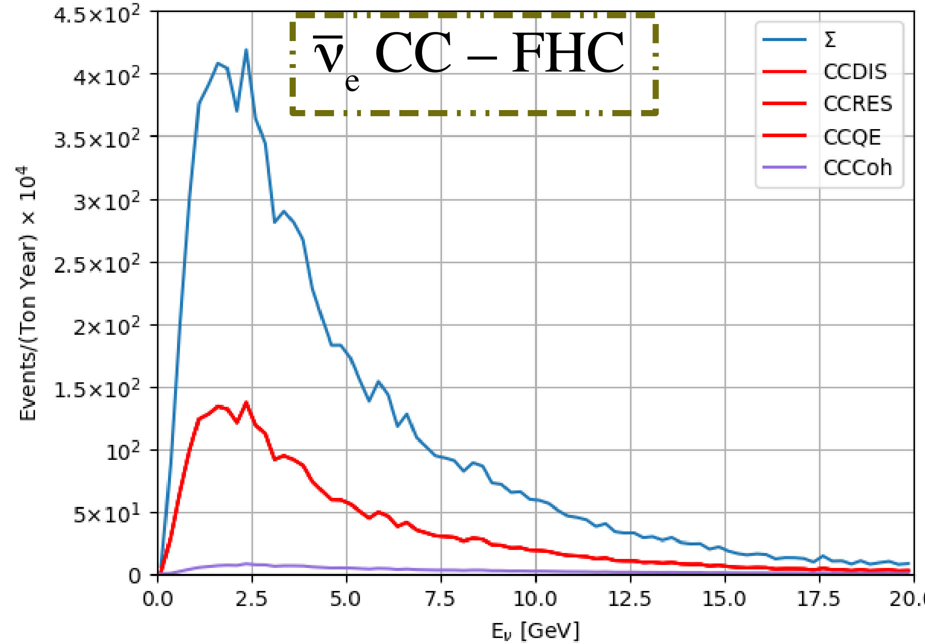
- **As an independent magnetized tracker**:
  - ν-interactions on a gaseous Ar target

ND-GAr Expected Performance

FHC Mode, Optimized DUNE flux (Oct 2017), GENIE v2.12.10

Event Category	Events/Ton-year	Event Category	Events/Ton-year
ν_e CC total	3.62E+04	$\bar{\nu}_e$ CC total	8.62E+03
ν_e NC total	6.05E+01	$\bar{\nu}_e$ NC total	9.83E+01





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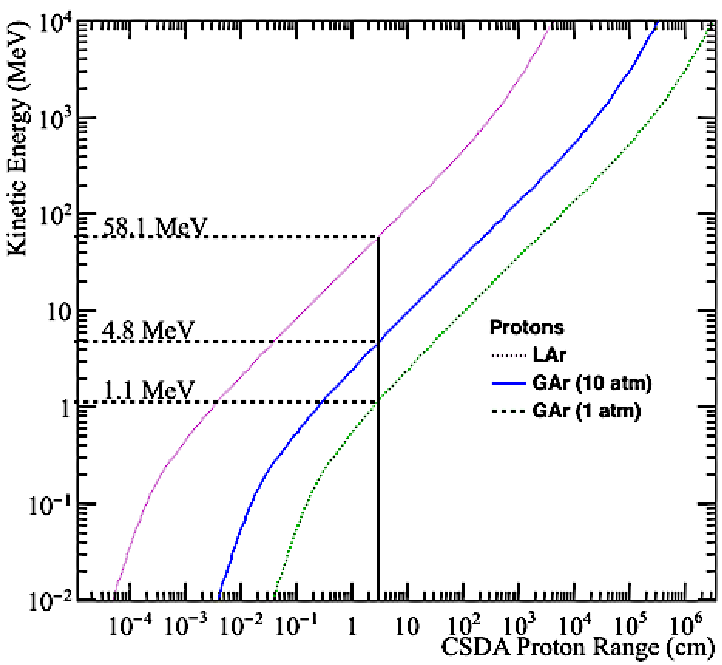
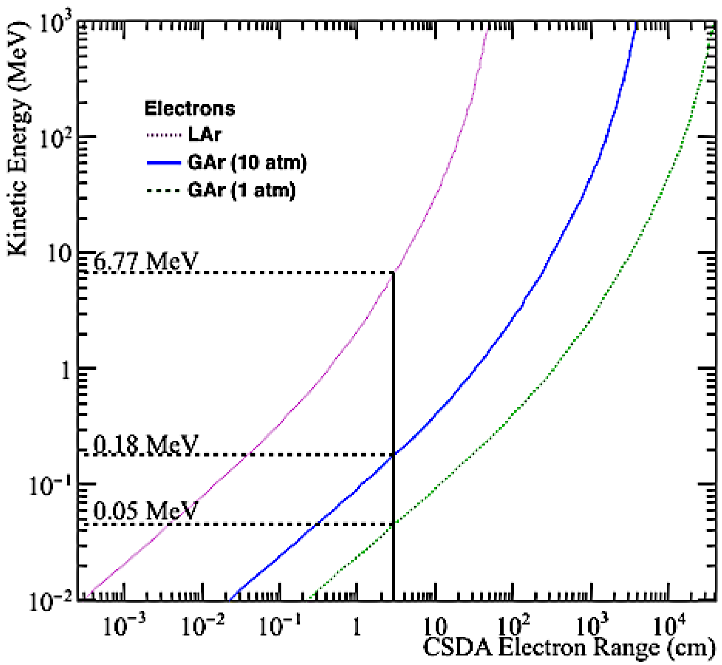
ND-GAr Expected Performance

- So, how low is the threshold for 10 atm GAr?
  - Range of a 5 MeV proton: 3 cm!
  - Ranges of less heavily ionizing particles (π, μ, e) >> proton range
- Assuming a 5 MeV detection threshold is conservative; may be able to go even lower



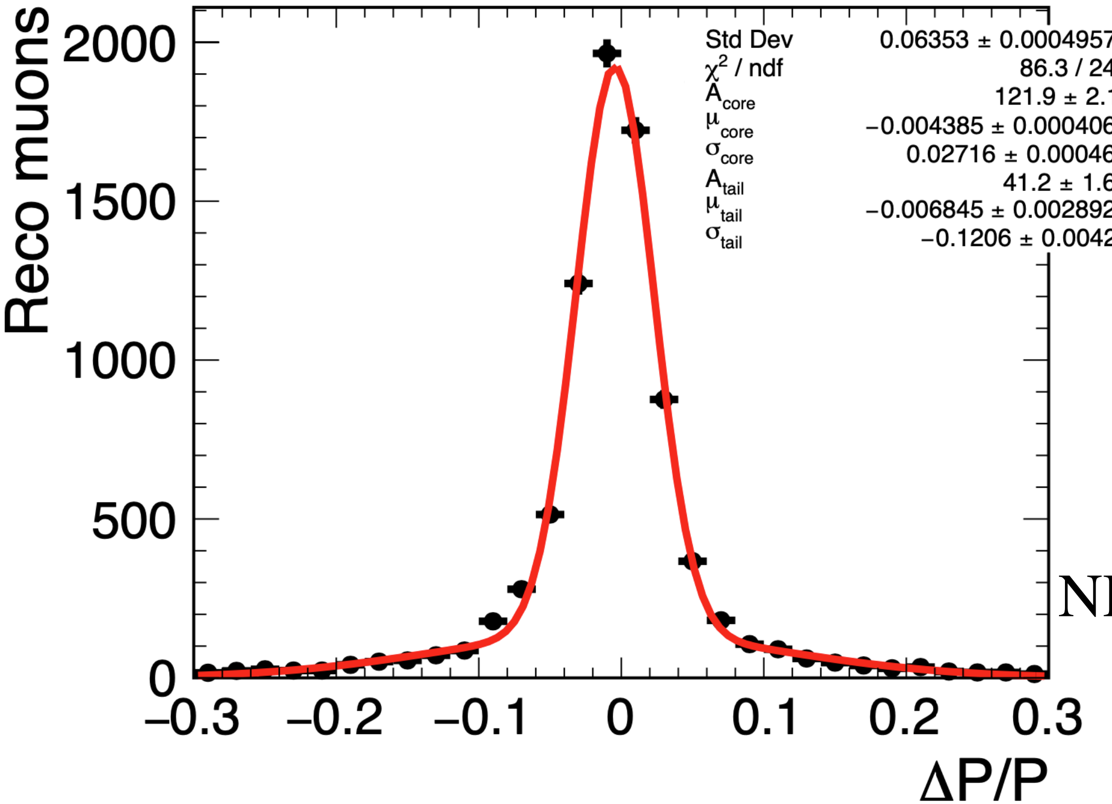


5 MeV K.E. particles

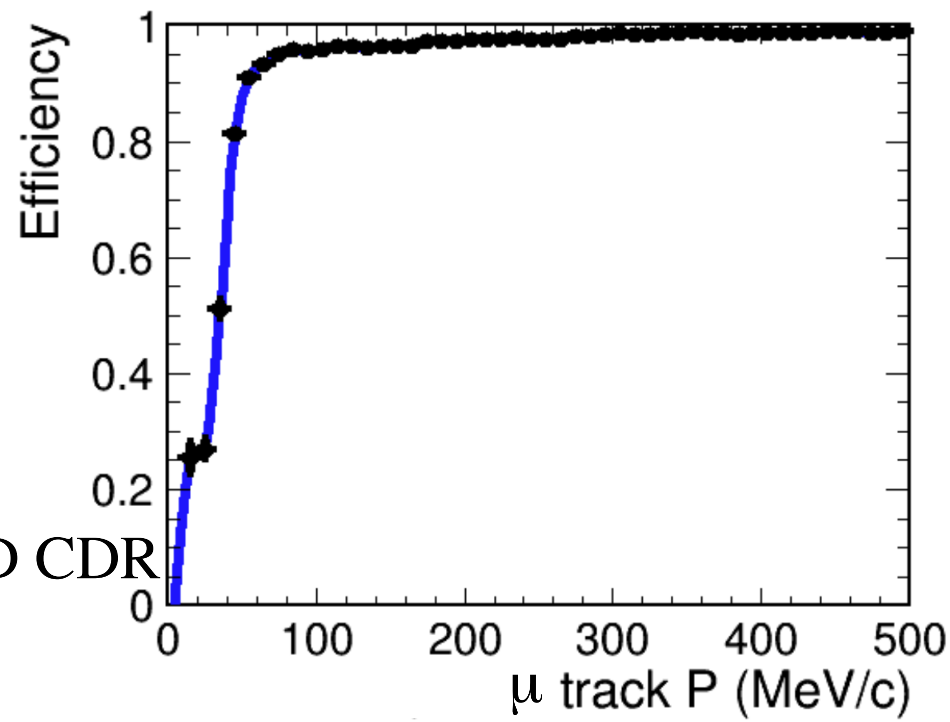
Species	Length (cm)
Protons	3
π^+	10
π^-	10
μ^+	15

J. Raaf

- GArSoft's expected tracking performance, thus far:
  - Momentum resolution (left) for μs from a sample of ν_μ CC events = 2.7%
  - Tracking efficiency (right) for μs from the same sample



ND CDR



Neutrino Oscillation Experiments

- Not always one detector per experiment:
  - A set of detectors placed at the source (near detector, ND) and another set (far detector, FD) placed at some baseline L

accelerator neutrinos

ND: $\overline{\nu}_\mu/\nu_\mu$ — baseline L — FD: $\overline{\nu}_\mu/\nu_\mu$

ν_μ survival/disappearance

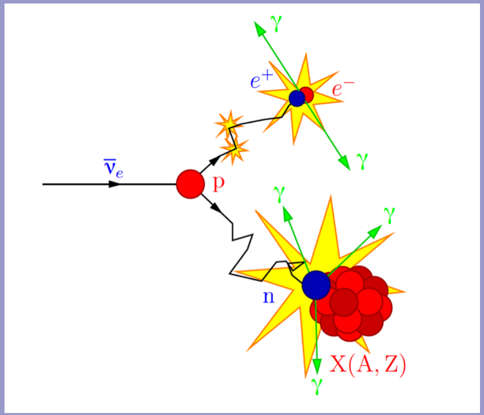
simplified observed neutrino event rate

$$\mathrm{N}(\vec{x}) = \underbrace{\overbrace{\Phi\,(E_\nu) \times \sigma\,(E_\nu) \times \varepsilon\,(\vec{x})}^{\text{ND}} \times P(\nu_\mu \to \nu_e)}_{\text{FD}}$$

near detectors in particular should be able to measure and constrain uncertainties in un-oscillated flux, Φ and cross section, σ + reconstruct neutrino energy very well (in detector effects ε)

Future Oscillation Experiments – Main Detectors

Inverse beta decay signal in JUNO's liquid scintillator



- Significant light collection for more sensitivity to lower energy neutrinos
- Background subtraction is crucial

A 6 GeV/c electron candidate in DUNE's LArTPC prototype that operated in the CERN test beam

- LArTPCs provide 3D tracking with unprecedented resolution
- TPCs have been around since the 1970s in the collider world but neutrino experiments have mostly been using LArTPCs

A muon neutrino candidate in a water Cherenkov detector, similar detector technology as HyperK

- Water, a cost-effective target material, easily scalable
- HyperK will be a scaled up version of the currently running SuperK water Cherenkov in T2K experiment

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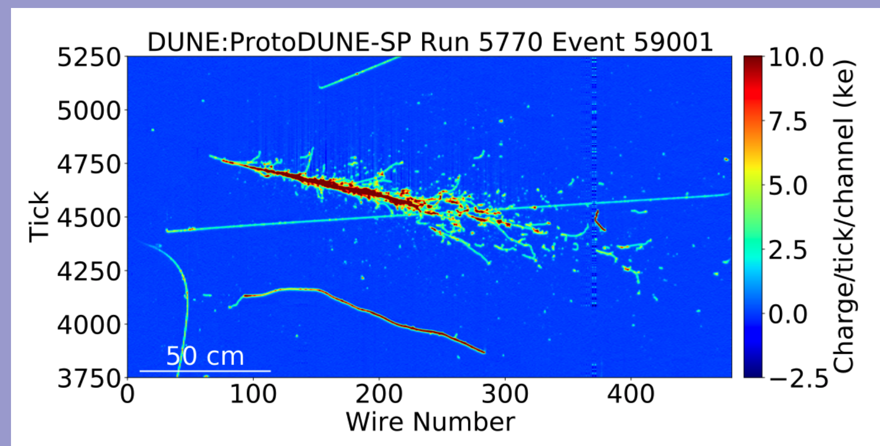

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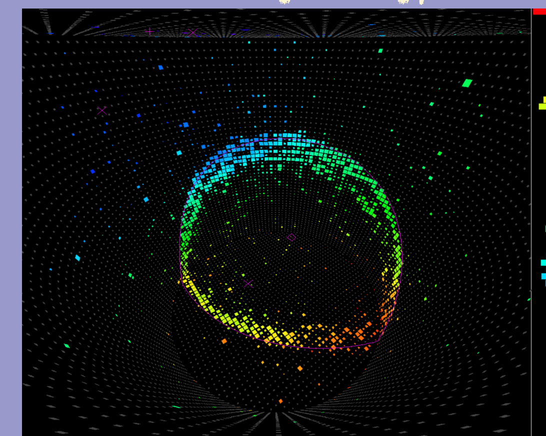

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Level of Neutrino Interaction Uncertainty Today

T2K https://doi.org/10.1038/s41586-020-2177-0

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

NOvA https://doi.org/10.1103/PhysRevLett.123.151803

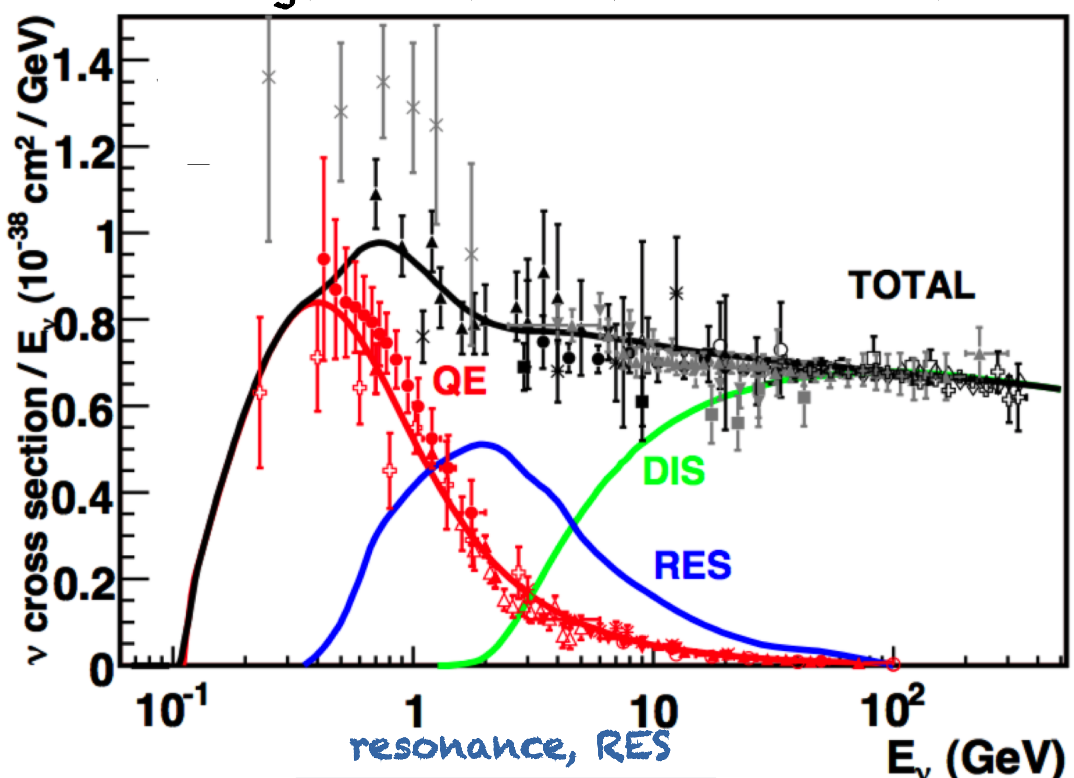
Source	ν_e Signal (%)	ν_e Bkg. (%)	$\bar{\nu}_e$ Signal (%)	$\bar{\nu}_e$ Bkg. (%)
Cross-sections	+4.7/-5.8	+3.6/-3.4	+3.2/-4.2	+3.0/-2.9
Detector model	+3.7/-3.9	+1.3/-0.8	+0.6/-0.6	+3.7/-2.6
ND/FD diffs.	+3.4/-3.4	+2.6/-2.9	+4.3/-4.3	+2.8/-2.8
Calibration	+2.1/-3.2	+3.5/-3.9	+1.5/-1.7	+2.9/-0.5
Others	+1.6/-1.6	+1.5/-1.5	+1.4/-1.2	+1.0/-1.0
Total	+7.4/-8.5	+5.6/-6.2	+5.8/-6.4	+6.3/-4.9

- From existing experiments, T2K and NOvA, the dominant sources of uncertainties are cross sections/neutrino interactions
- Future experiments need to do better!

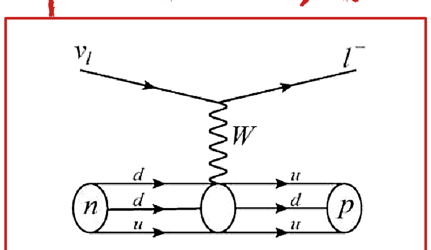
Neutrino Interactions

- We expect a specific range of energies in neutrino experiments:
  - Each experiment will be sensitive to a specific interaction type and a specific set of nuclear effects, affecting what we see in the detectors

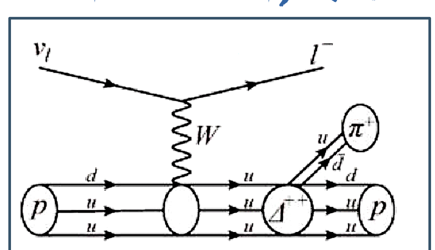
charged current interaction channels



quasi elastic, QE



resonance, RES



deep inelastic, DIS